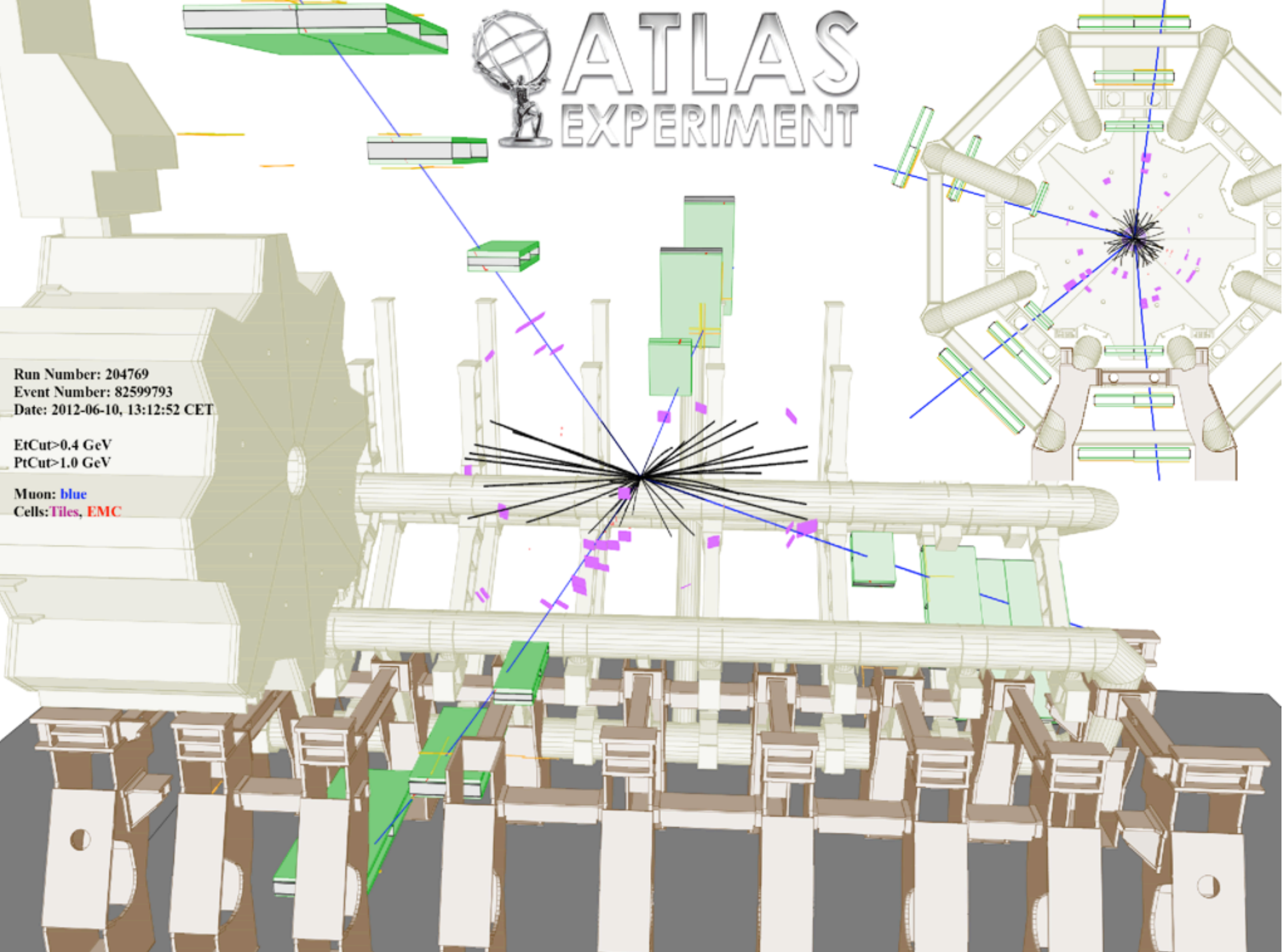


Probing the Higgs Yukawa couplings at the LHC

K. Nikolopoulos
University of Birmingham

UNIVERSITY OF BIRMINGHAM

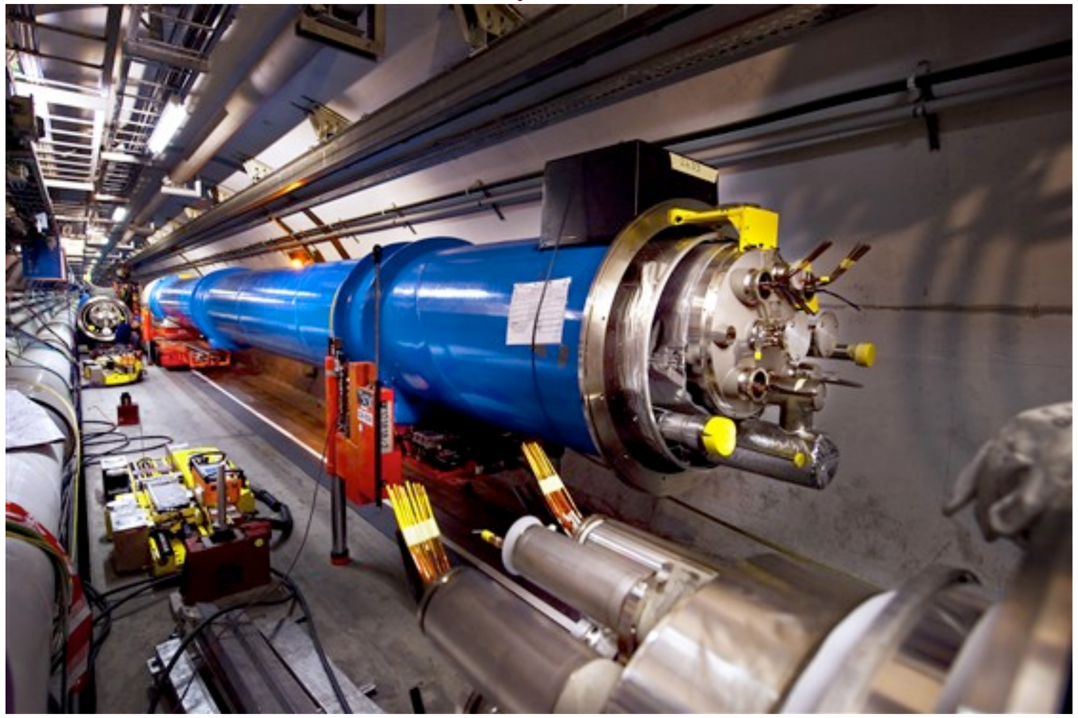
Particle Physics Seminar

25th September 2015, LAL Orsay, France

This project has received funding from the European Union's 7th Framework Programme for research, technological development and demonstration under grant agreement no 334034 (EWSB)

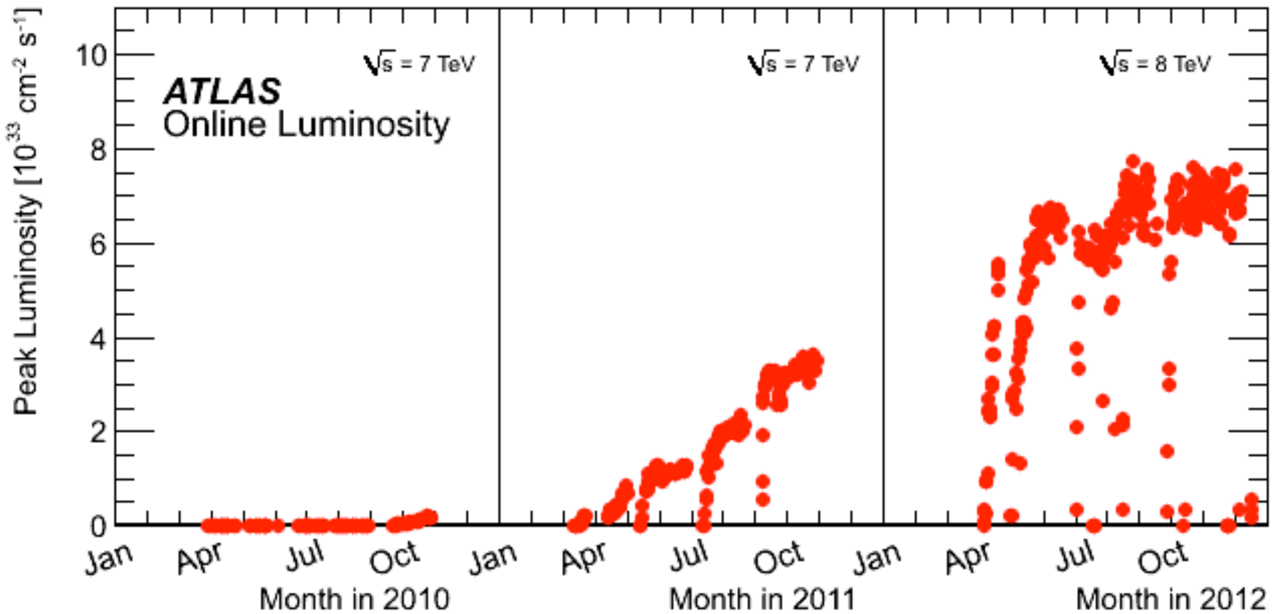
Large Hadron Collider Run I

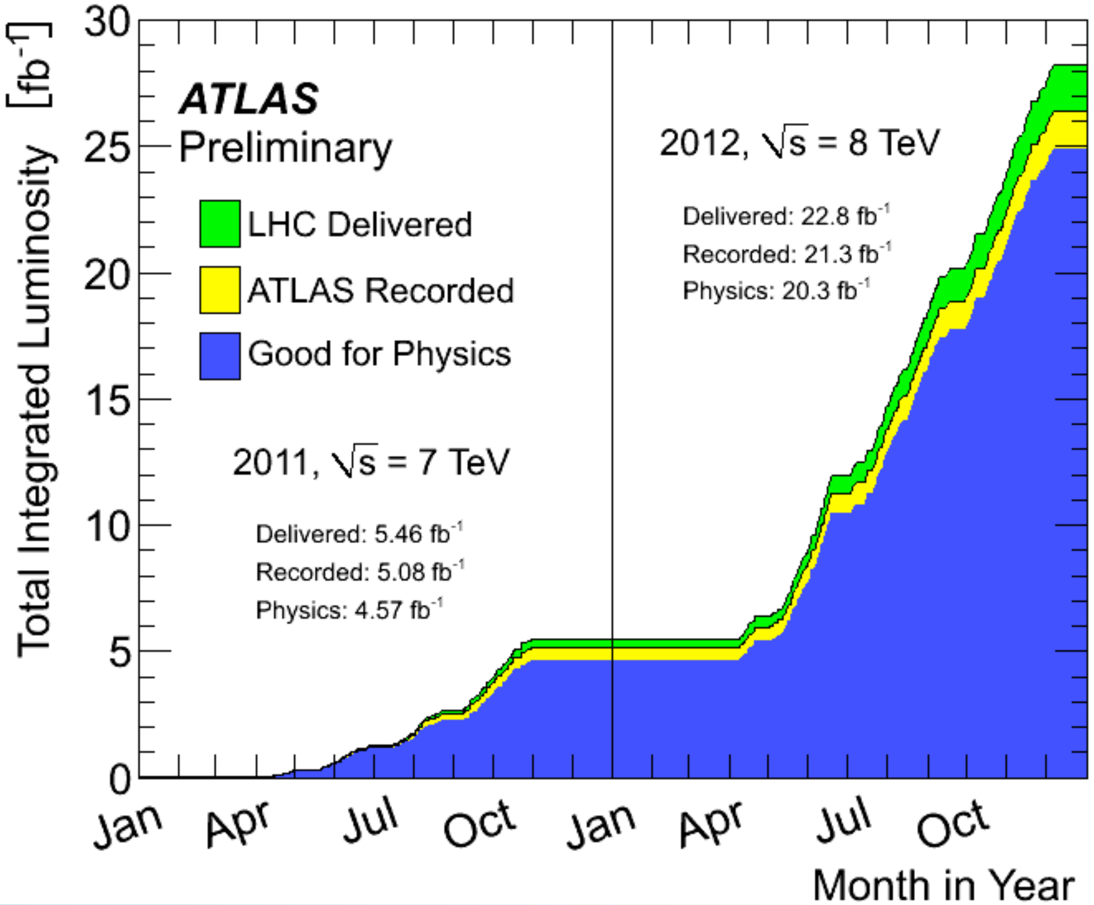
1232 superconducting dipoles with B field of (up to) 8.3T
1.9K → the coolest place in the universe!

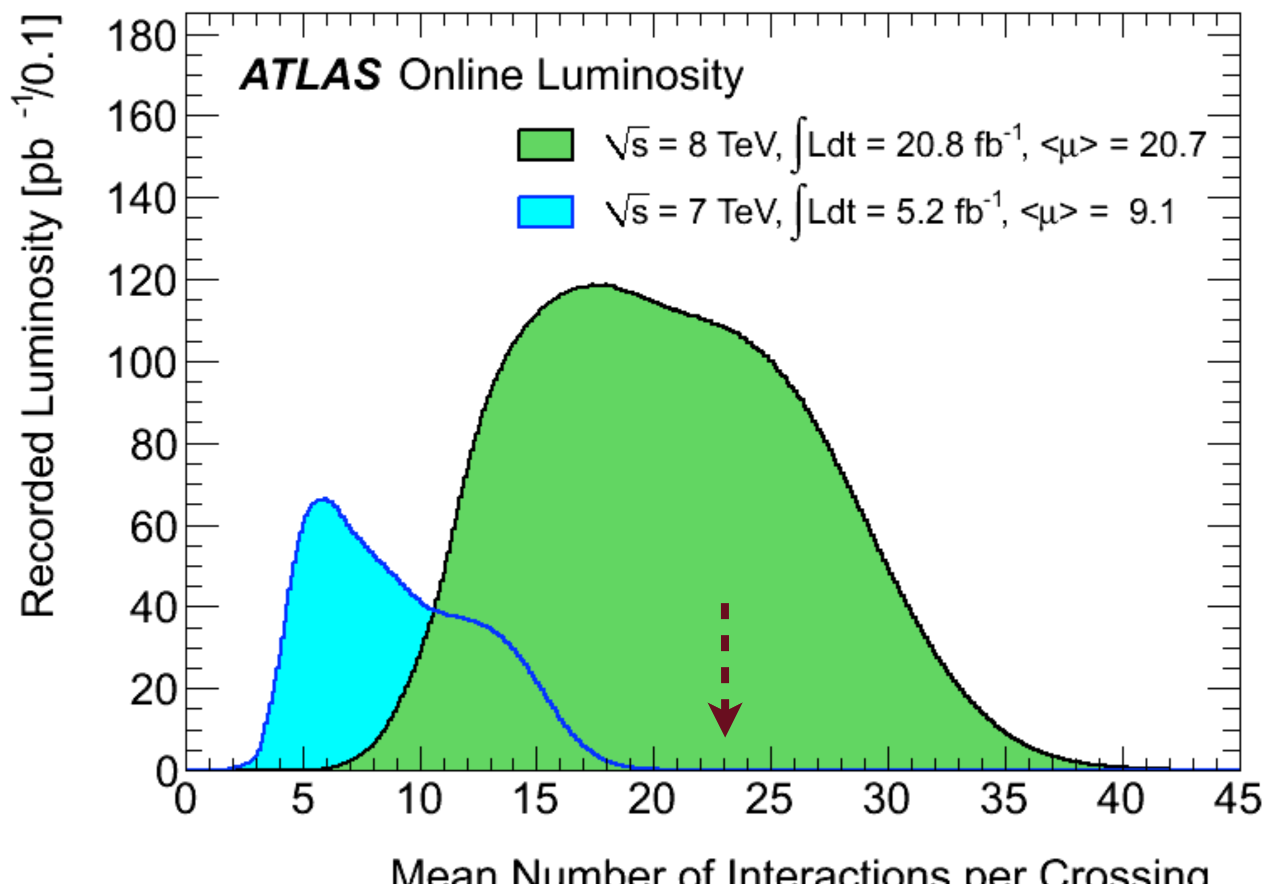


Peak Luminosity [$cm^{-2}s^{-1}$]

2.07×10^{32} 3.65×10^{33} 7.73×10^{33}

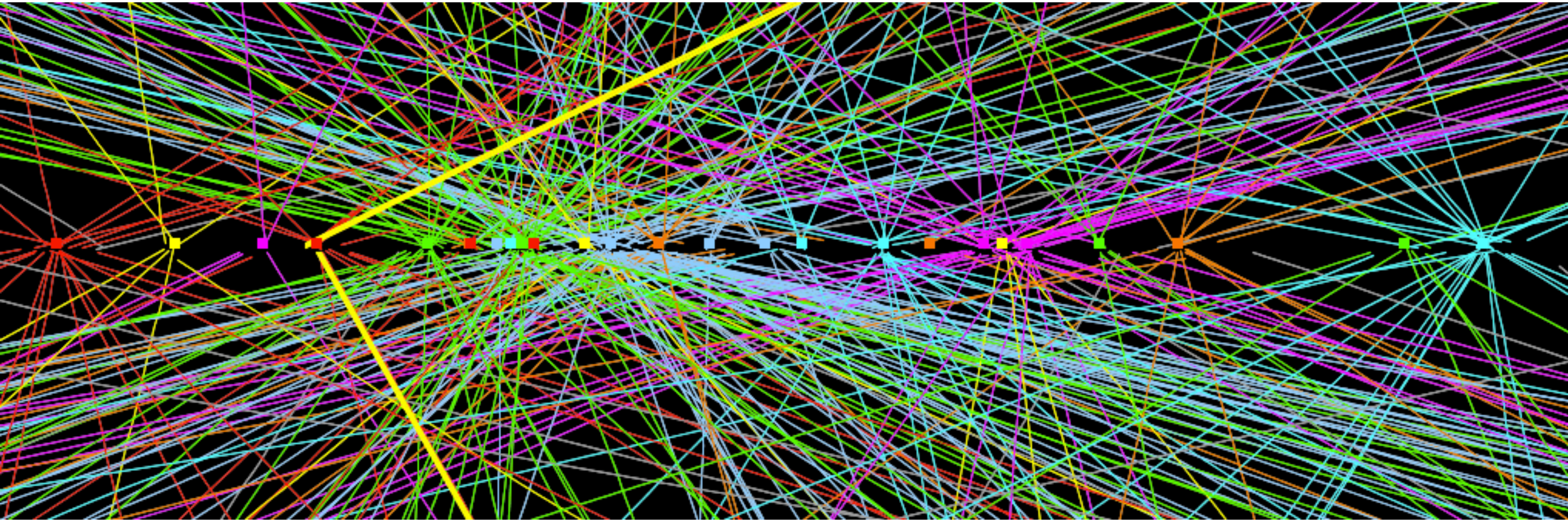




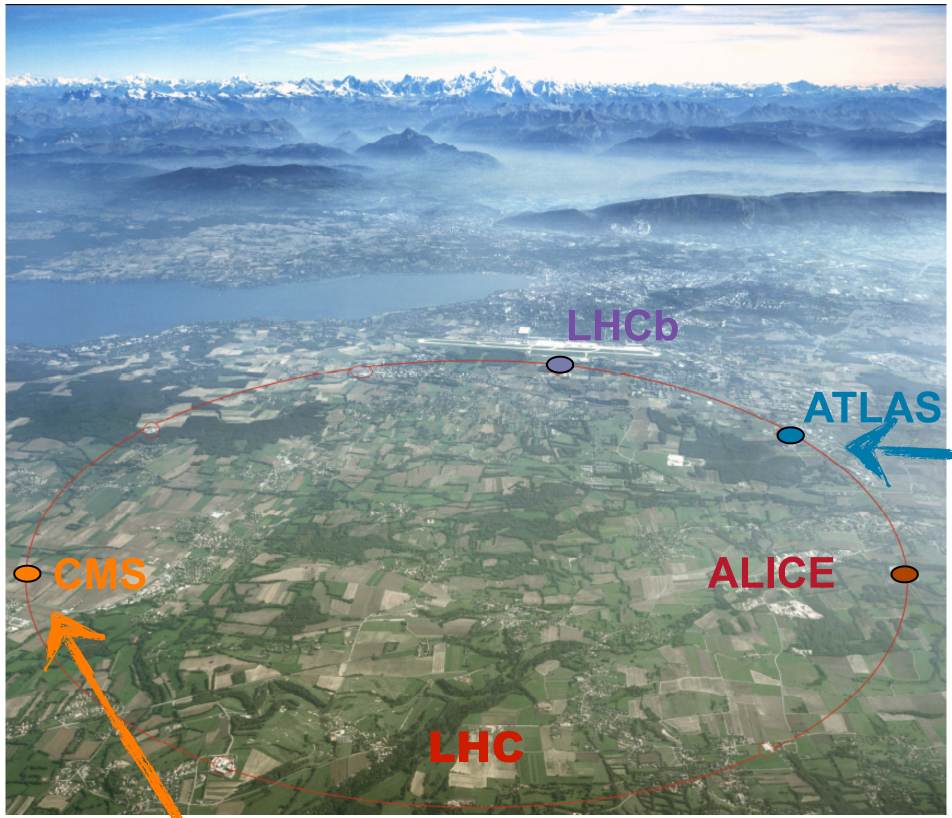


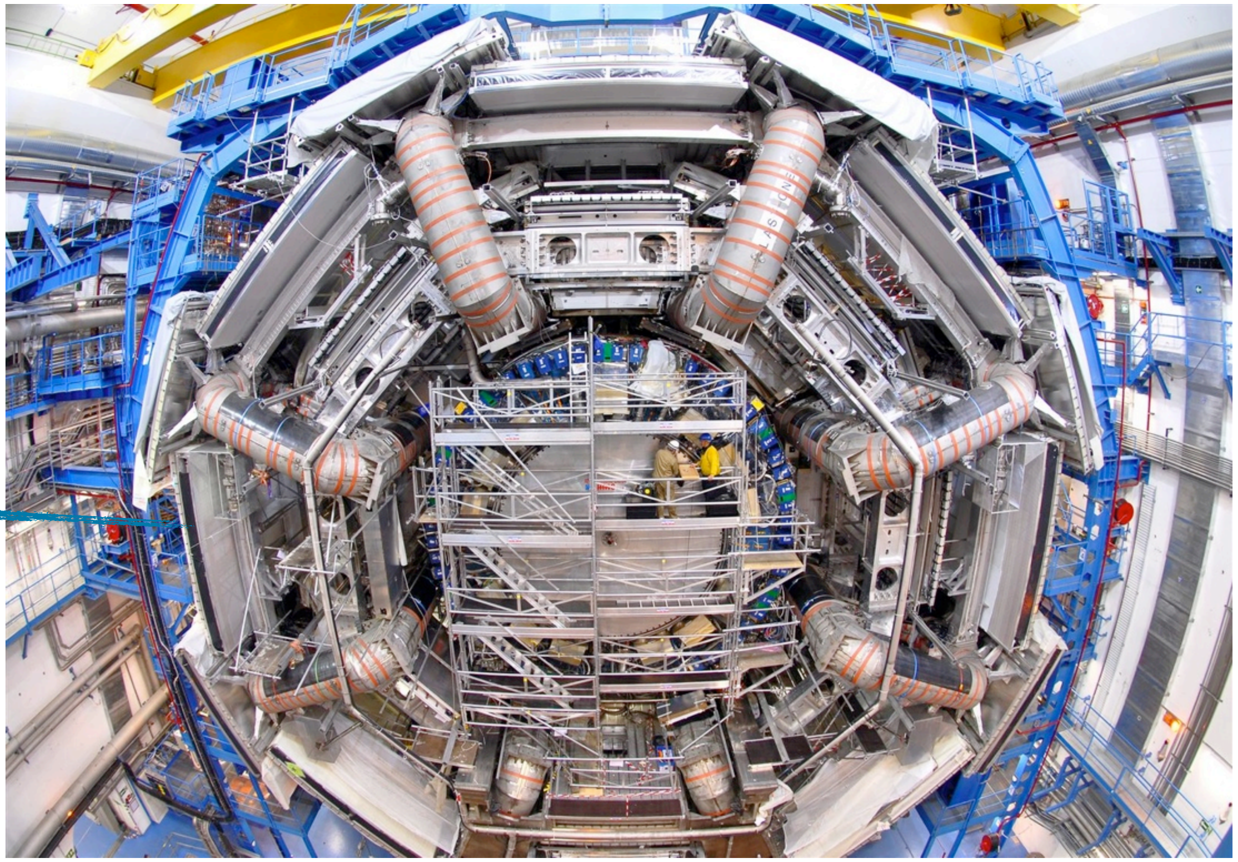
Pile-up

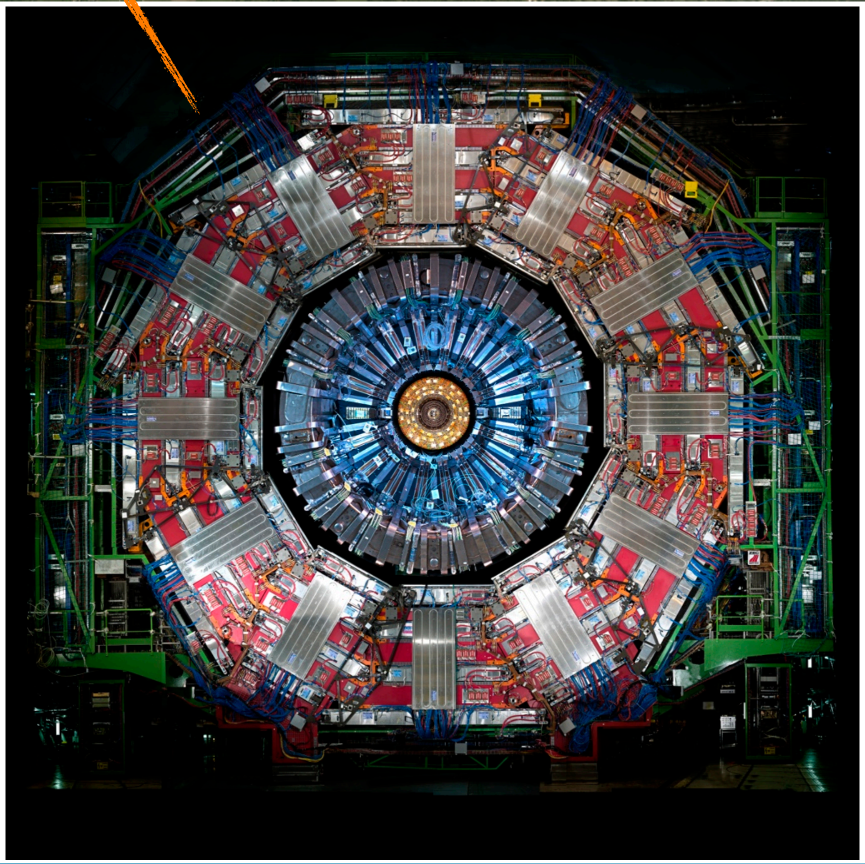
Z→μμ candidate with 25 reconstructed vertices from the 2012 run.
Only good quality tracks with pT>0.4GeV are shown



The LHC experiments

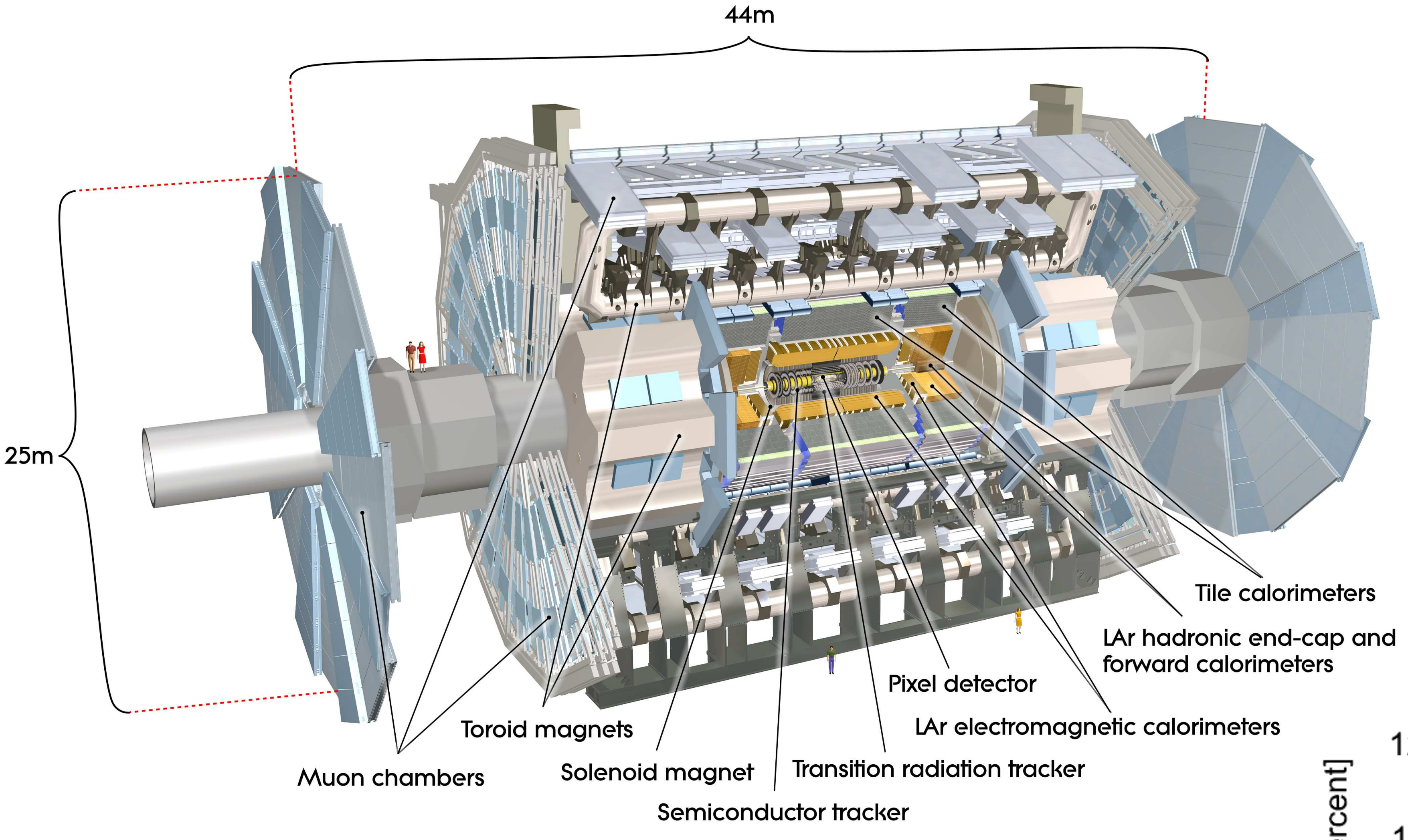






ATLAS Collaboration: 38 countries, 177 institutions, ~2900 scientific authors

A Toroidal LHC ApparatuS

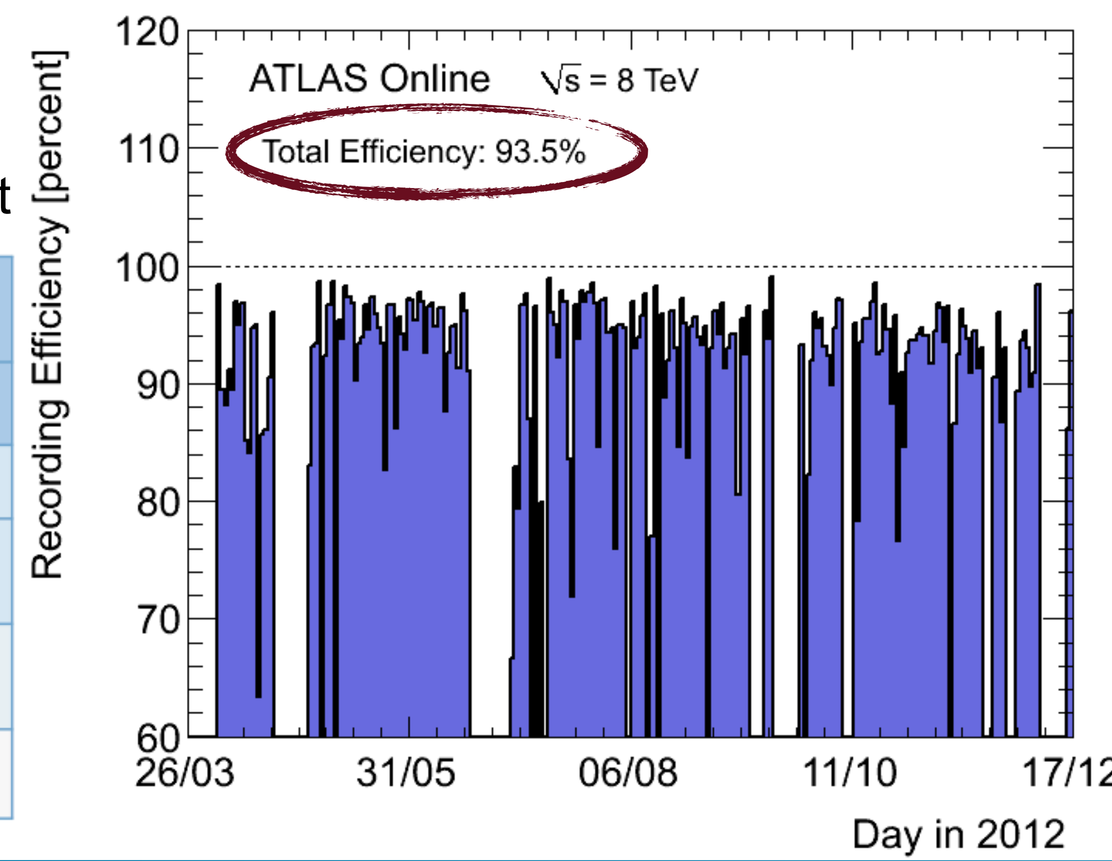


	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling Liquid Argon
Hadron Calorimetry	plastic scintillator (barrel) Liquid Argon(endcap)
Muon	independent system with trigger capabilities
Trigger	3 Level Implementation from 40 MHz to 400 Hz

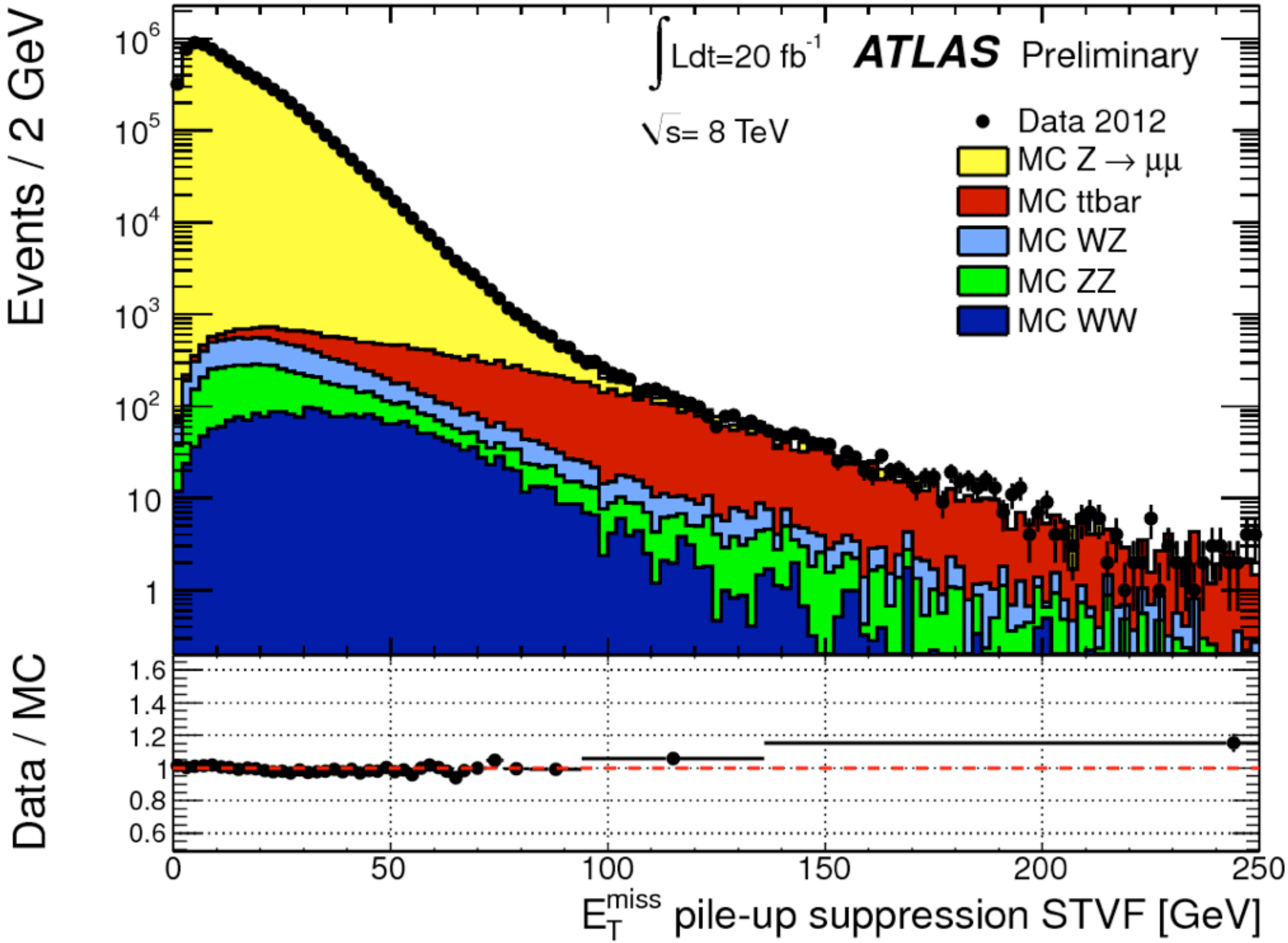
⇒ General purpose detector designed for the harsh LHC environment

ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										

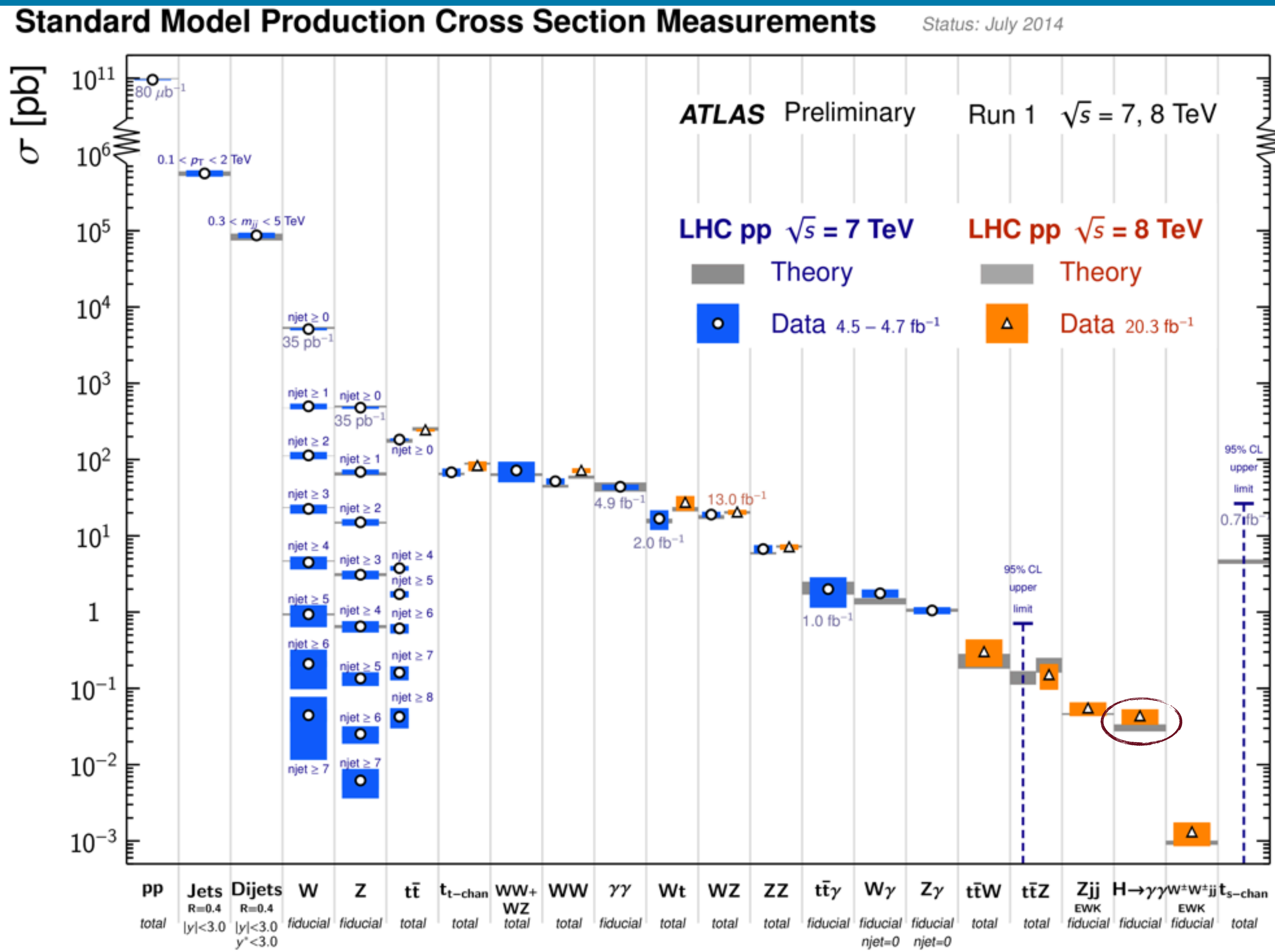
Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.



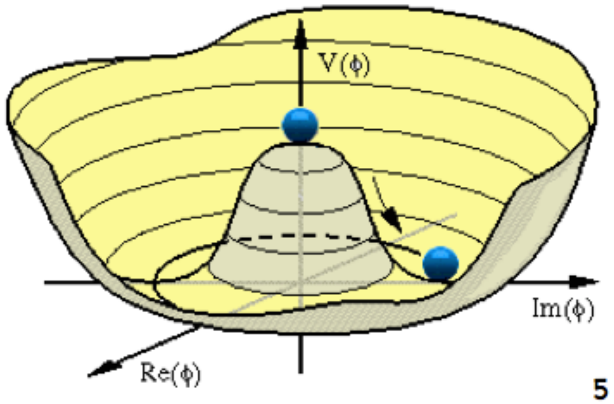
ATLAS performance overview



Snapshot of cross section measurements



The Standard Model Higgs boson



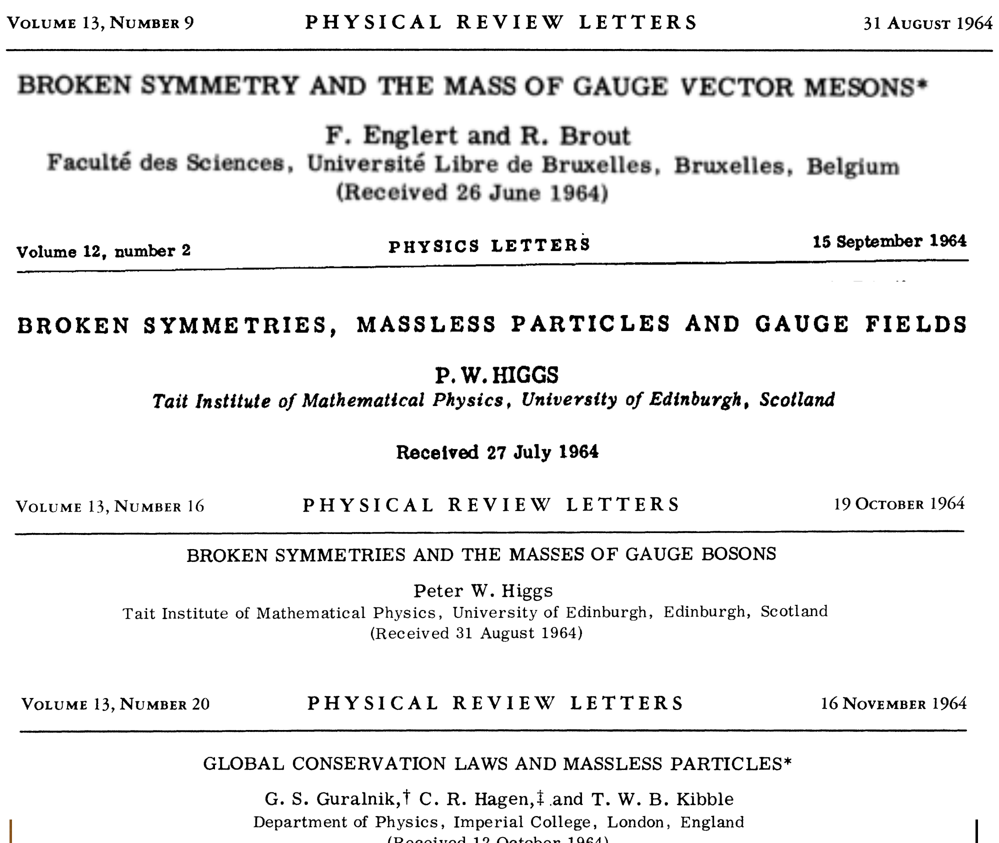
→ Unification of electromagnetic and weak interactions through $SU(2)_L \otimes U(1)_Y$ local gauge symmetry; massless carriers

→ Symmetry spontaneously broken - Higgs field's non-zero VEV

→ Three degrees of freedom of Higgs field → longitudinal polarizations of the vector bosons [Mod.Phys.Lett. A29 (2014) 1450046], fourth is the Higgs boson.

- h→VV defined by symmetry breaking
- h→ffbar is ad hoc Yukawa coupling $\propto m_f$

[Phys.Rev.Lett. 19 (1967) 1264]



VOLUME 13, NUMBER 9 — PHYSICAL REVIEW LETTERS — 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

Volume 12, number 2 — PHYSICS LETTERS — 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 — PHYSICAL REVIEW LETTERS — 19 OCTOBER 1964

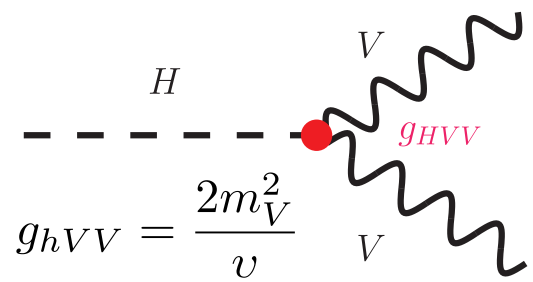
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

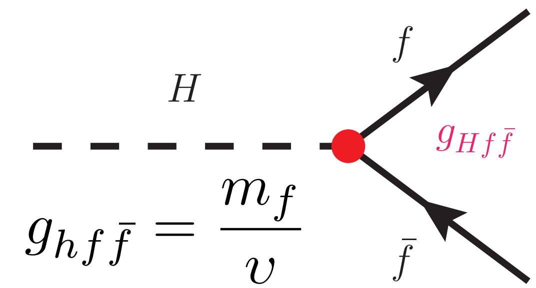
VOLUME 13, NUMBER 20 — PHYSICAL REVIEW LETTERS — 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)



$$g_{hVV} = \frac{2m_V^2}{v}$$



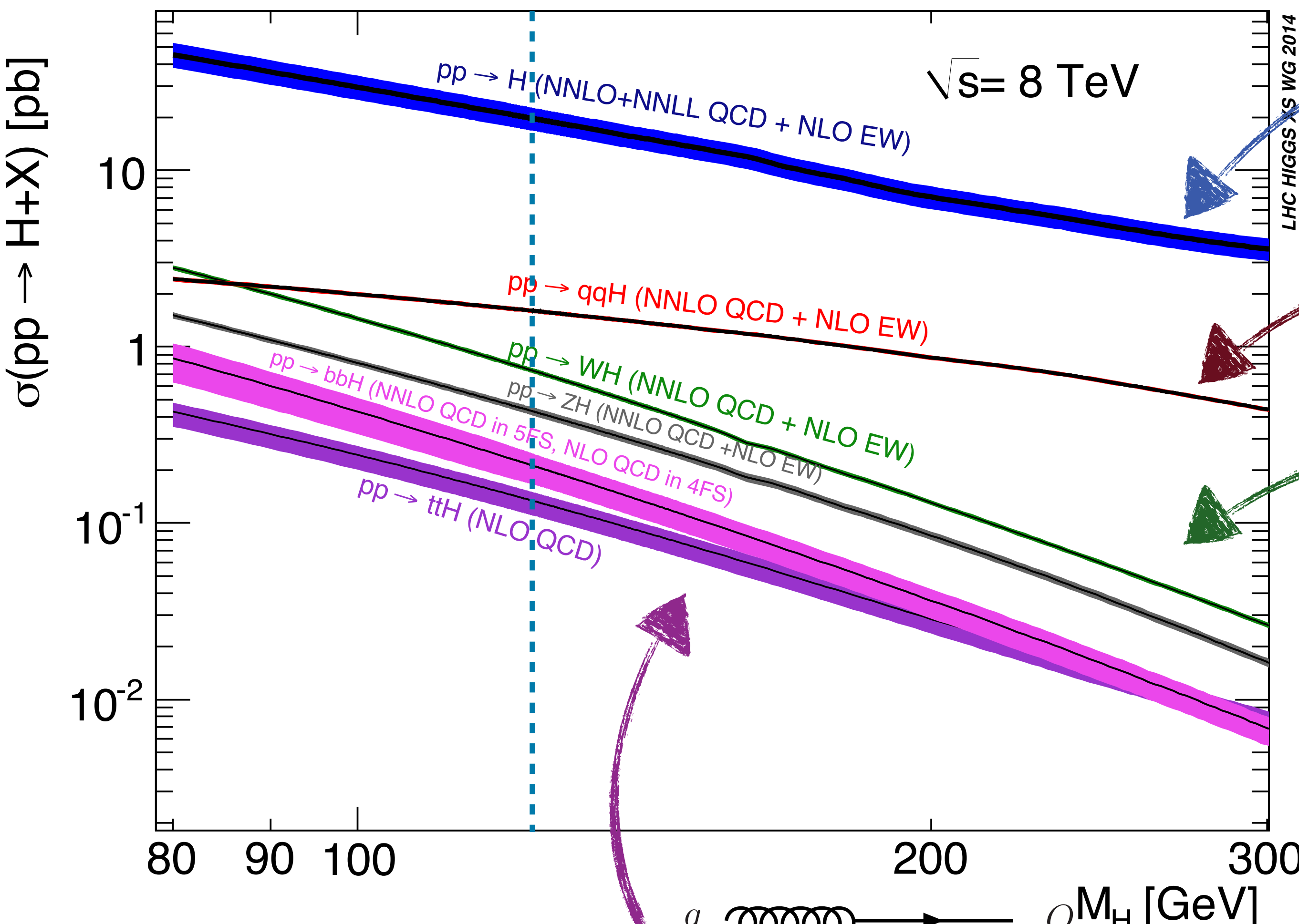
$$g_{hf\bar{f}} = \frac{m_f}{v}$$

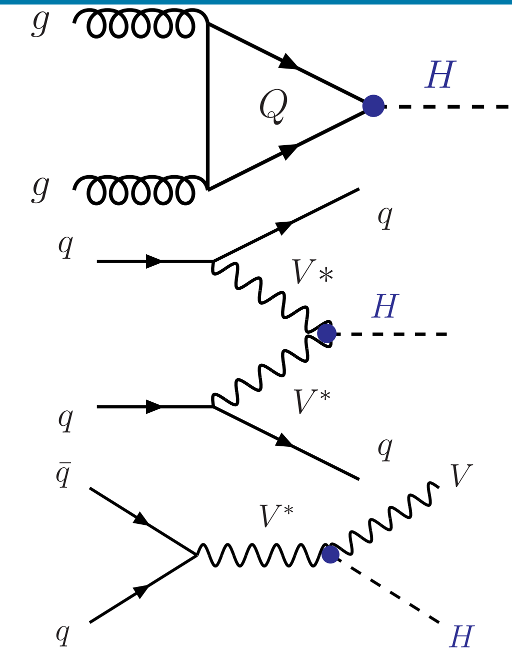
BUT Yukawa couplings are ad hoc:

- BSM scenarios predict enhanced Yukawa couplings
- Unitarity bounds (through EFT) for fermion mass generation scale (1st/2nd gen) Λ<20TeV $\Lambda \sim \sqrt{\frac{v^3}{m_f}}$

[Phys. Rev. Lett. 59, 2405 (1987); Phys.Rev. D71 (2005) 093009]

SM Higgs boson production and decay at the LHC

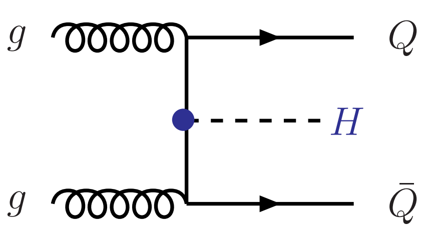




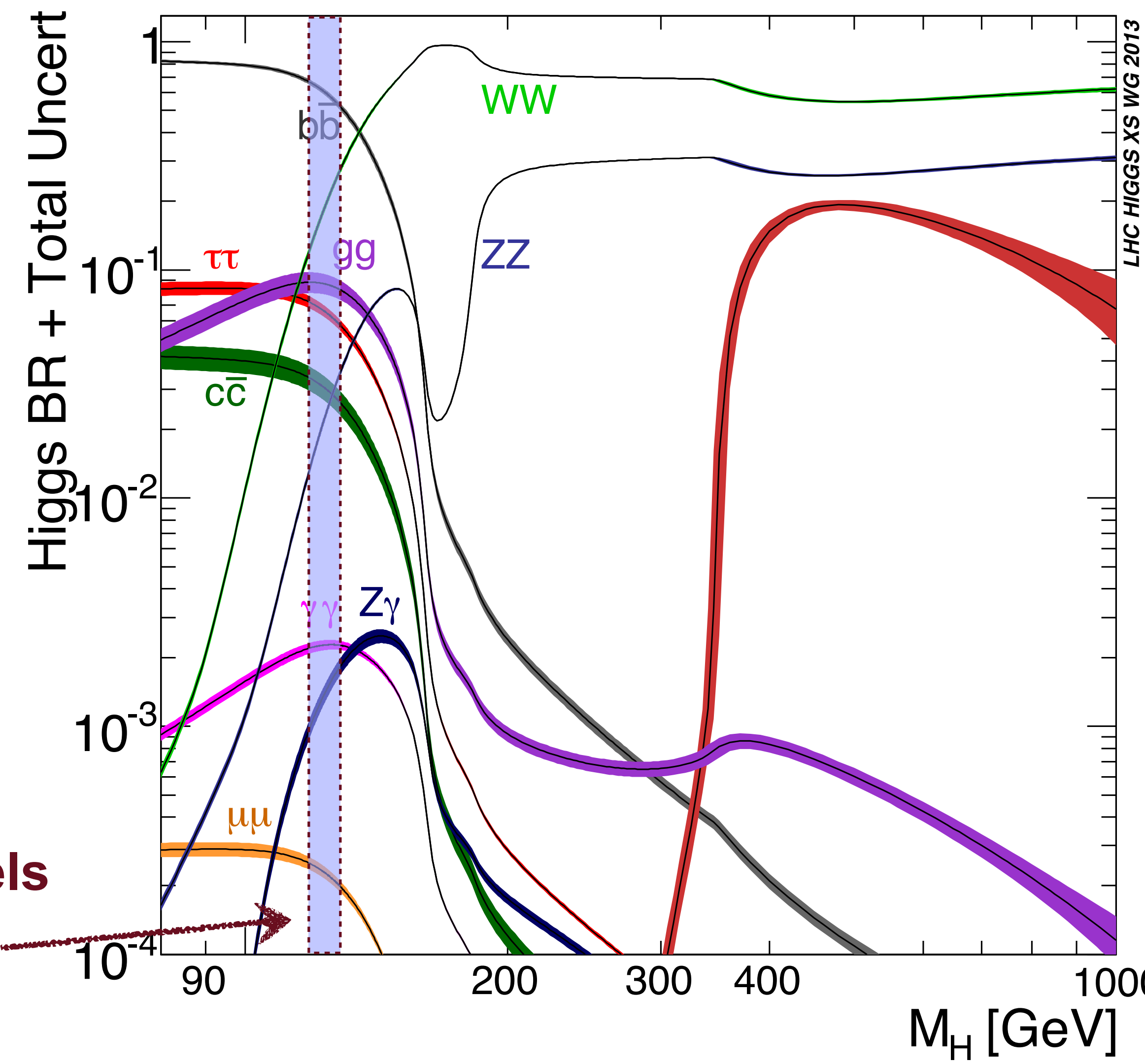
86%
m_h = 125 GeV

7%
m_h = 125 GeV

5%
m_h = 125 GeV

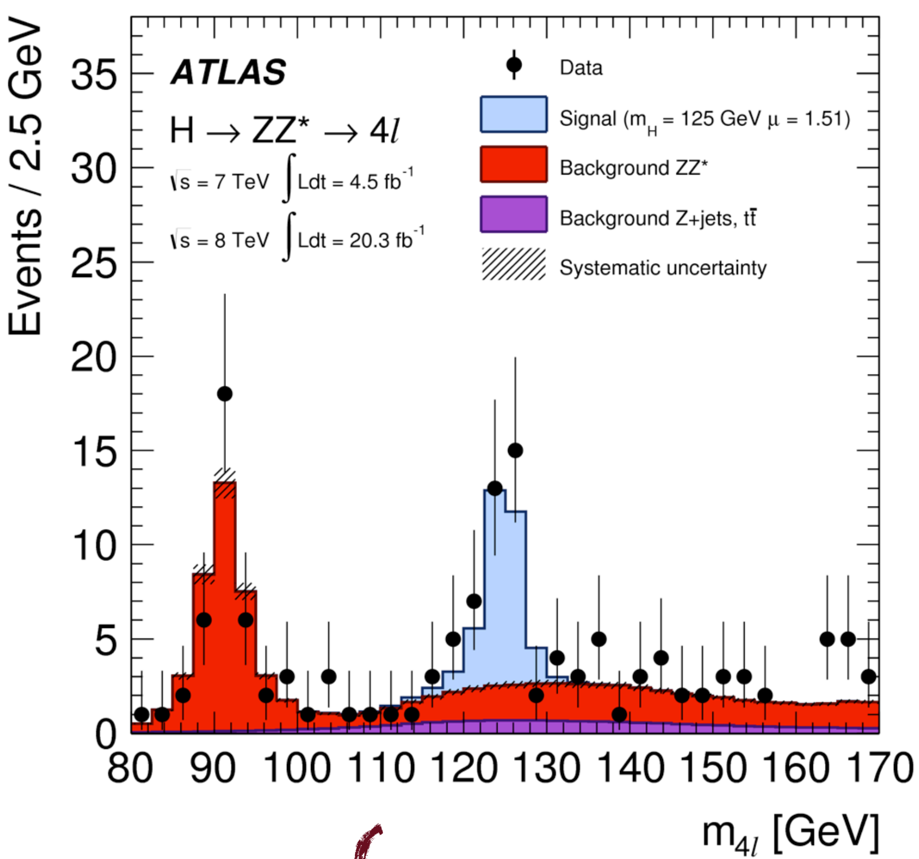


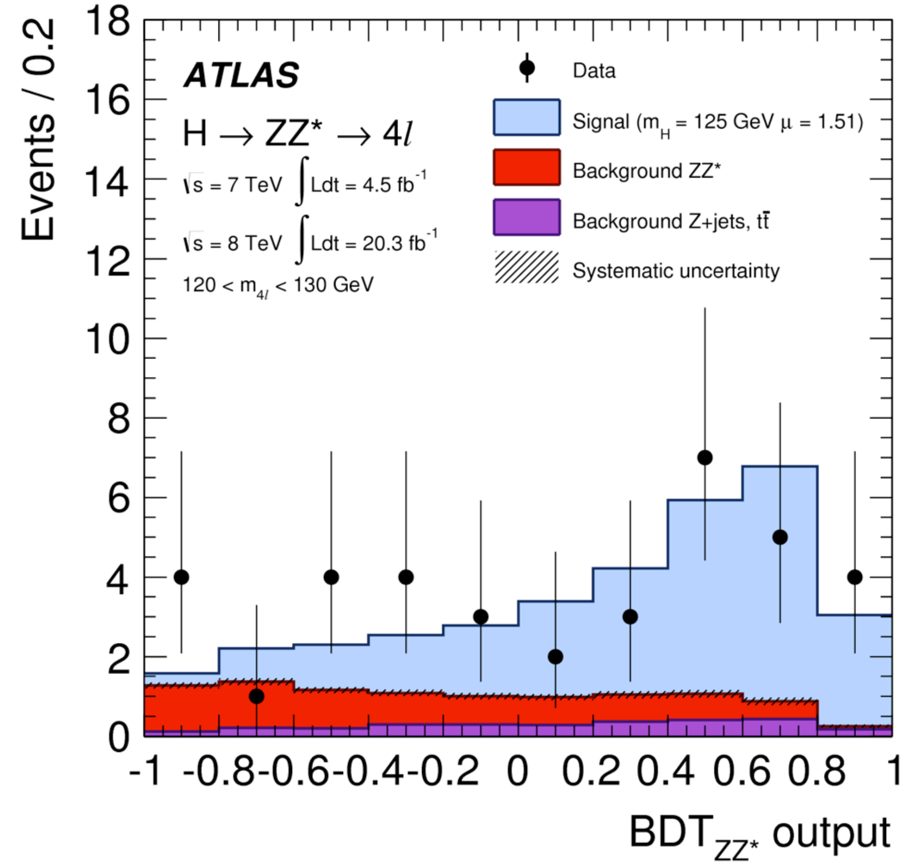
1.5%
m_h = 125 GeV



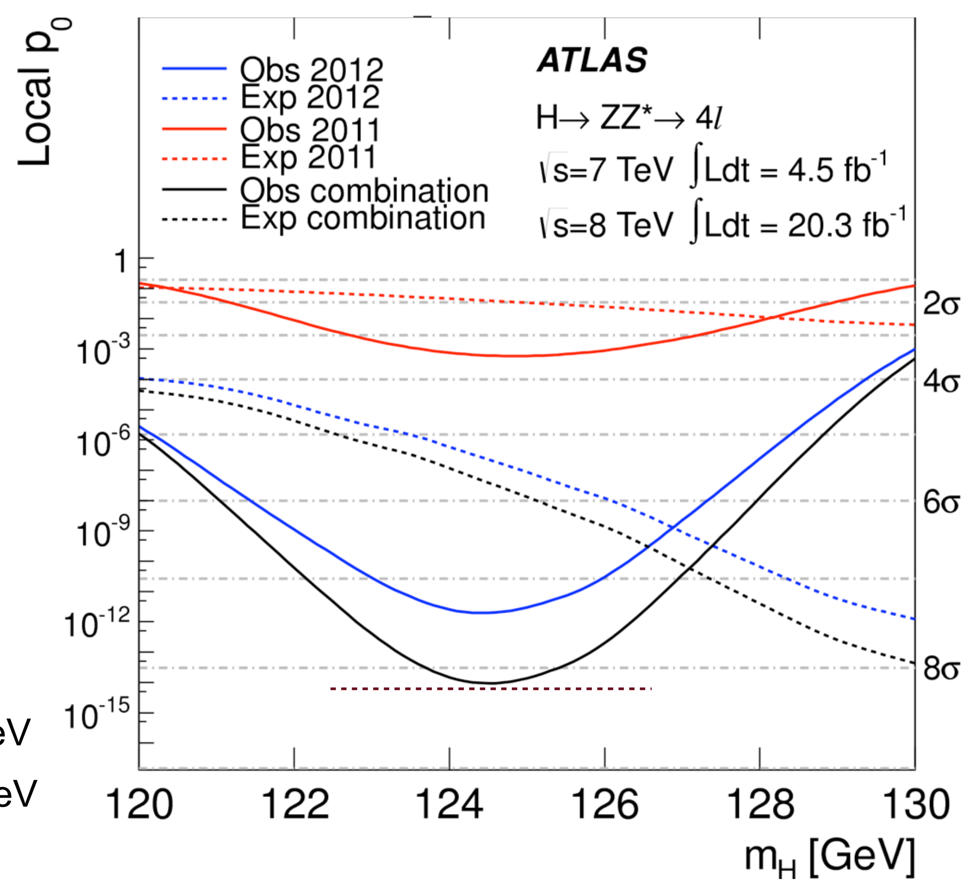
m_h~125 GeV gives access to several decay channels
Gauge bosons: γγ, ZZ*, WW*, Zγ
Fermions: bb, ττ, μμ

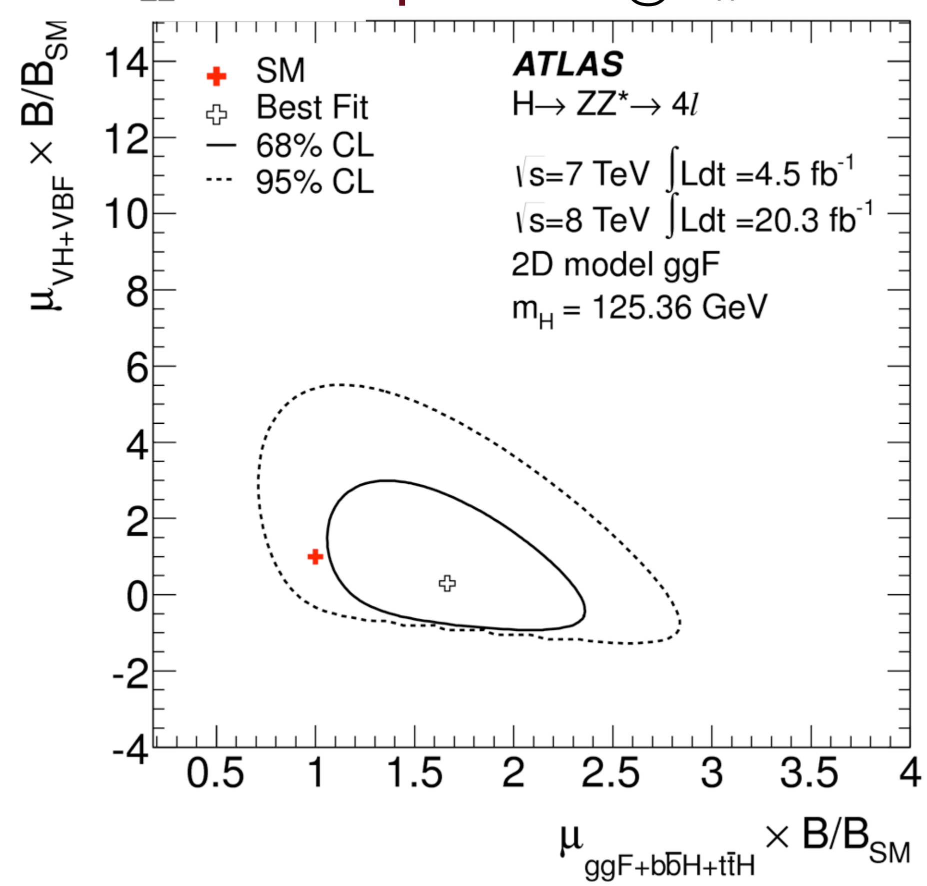
$h \rightarrow ZZ^* \rightarrow 4l$





μ=1.5 ± 0.4 @ m_H = 125.36GeV





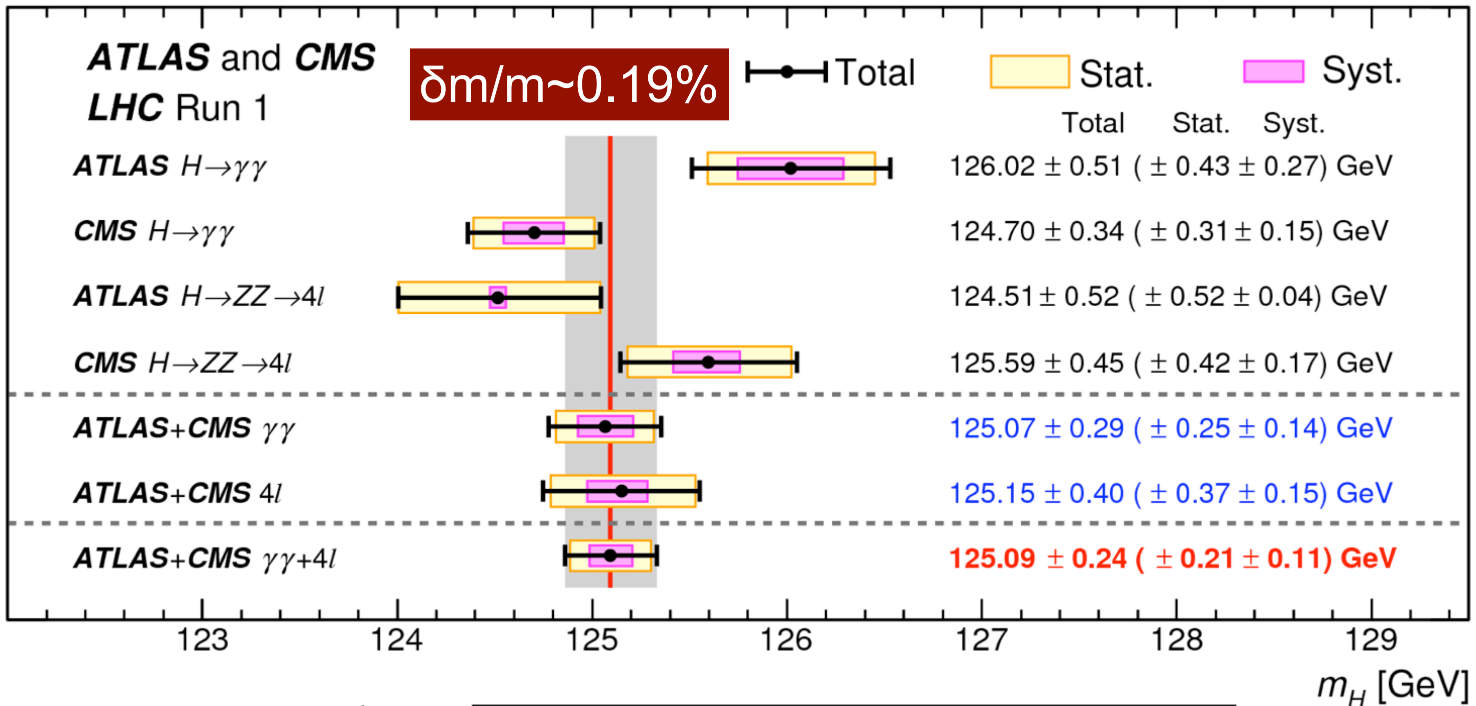
8.2σ (5.8σ) @ m_h =124.51 GeV

8.1σ (6.2σ) @ m_h = 125.36GeV

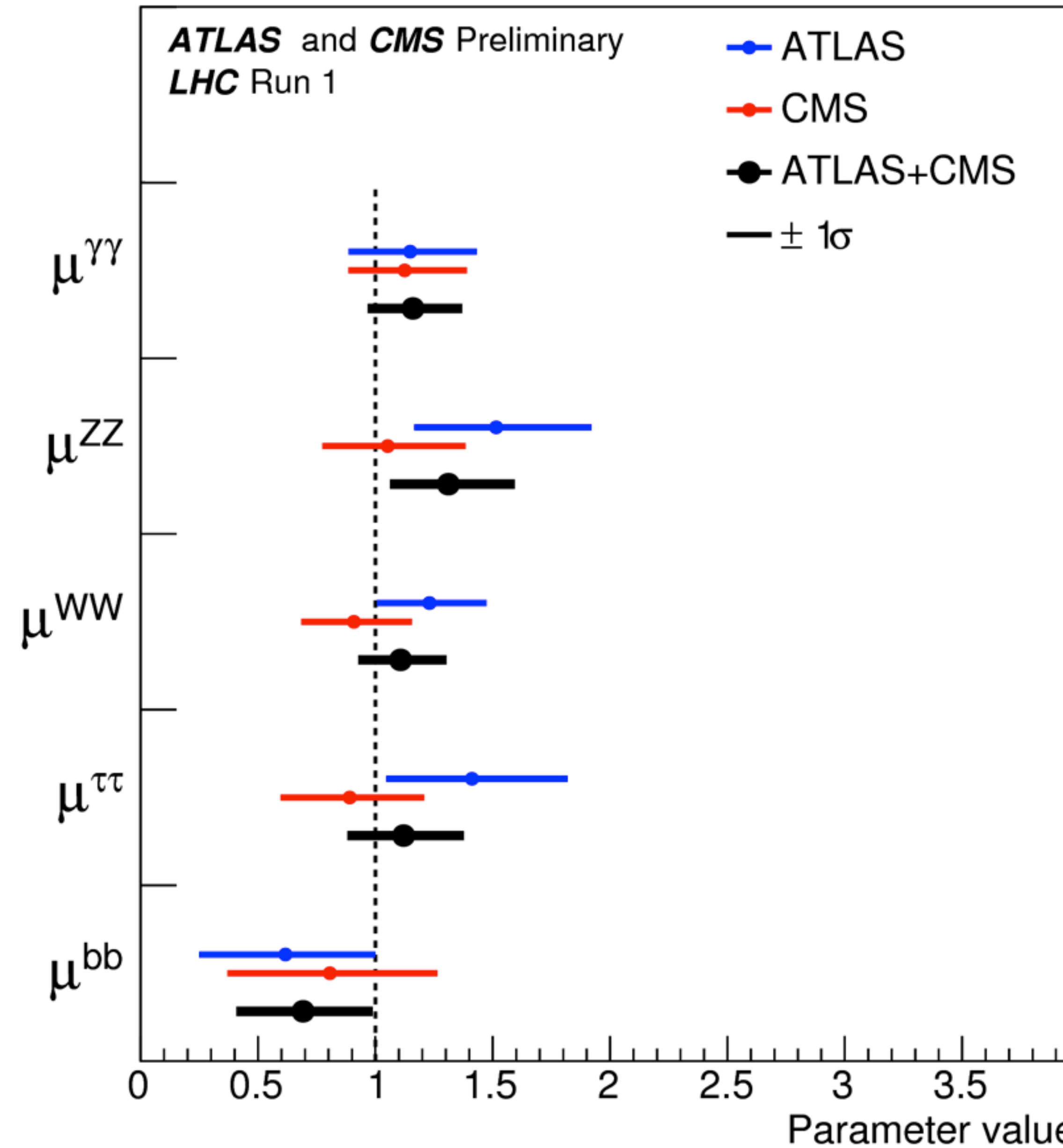
The Standard Model Higgs boson

- ATLAS measurement: 125.36 $^{+0.37}$ (stat) $^{+0.18\ 0.41}{}_{-0.15}$ (syst) GeV
- CMS measurement: 125.02 $^{+0.26}{}_{-0.27}$ (stat) $^{+0.14}{}_{-0.15}$ (syst) GeV

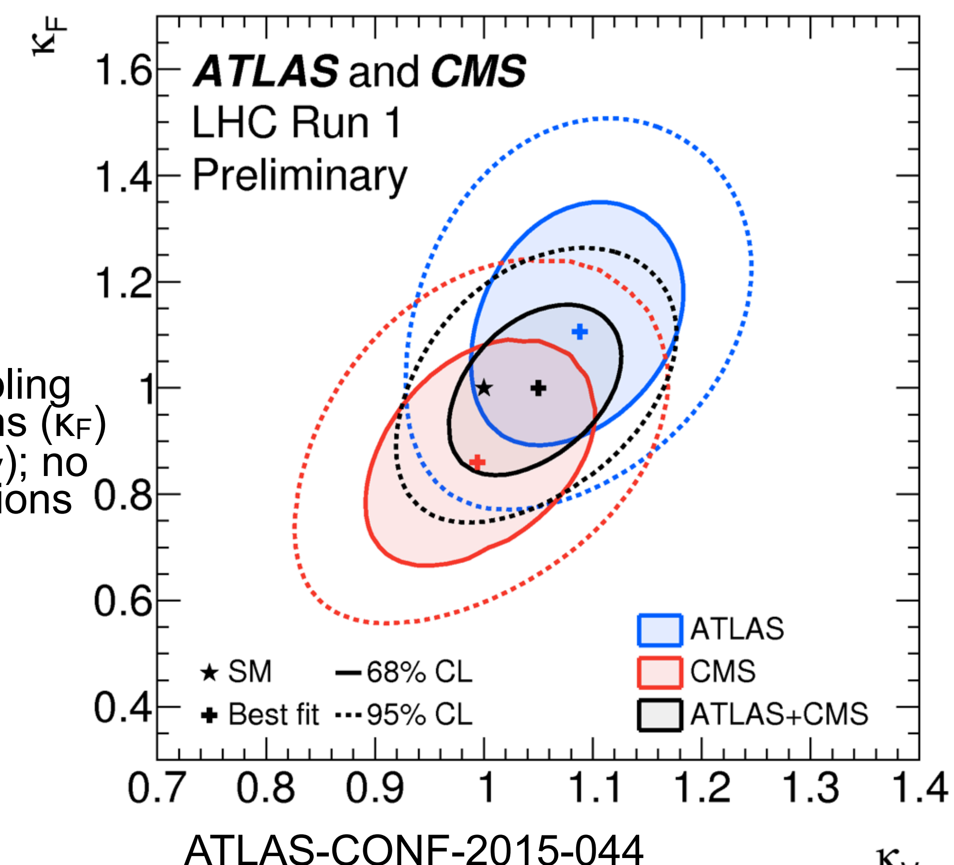
Phys.Rev.Lett 114 (2015) 191803



ATLAS-CONF-2015-044



Common coupling scaling: Fermions (κ_F) and Bosons (κ_V); no BSM contributions

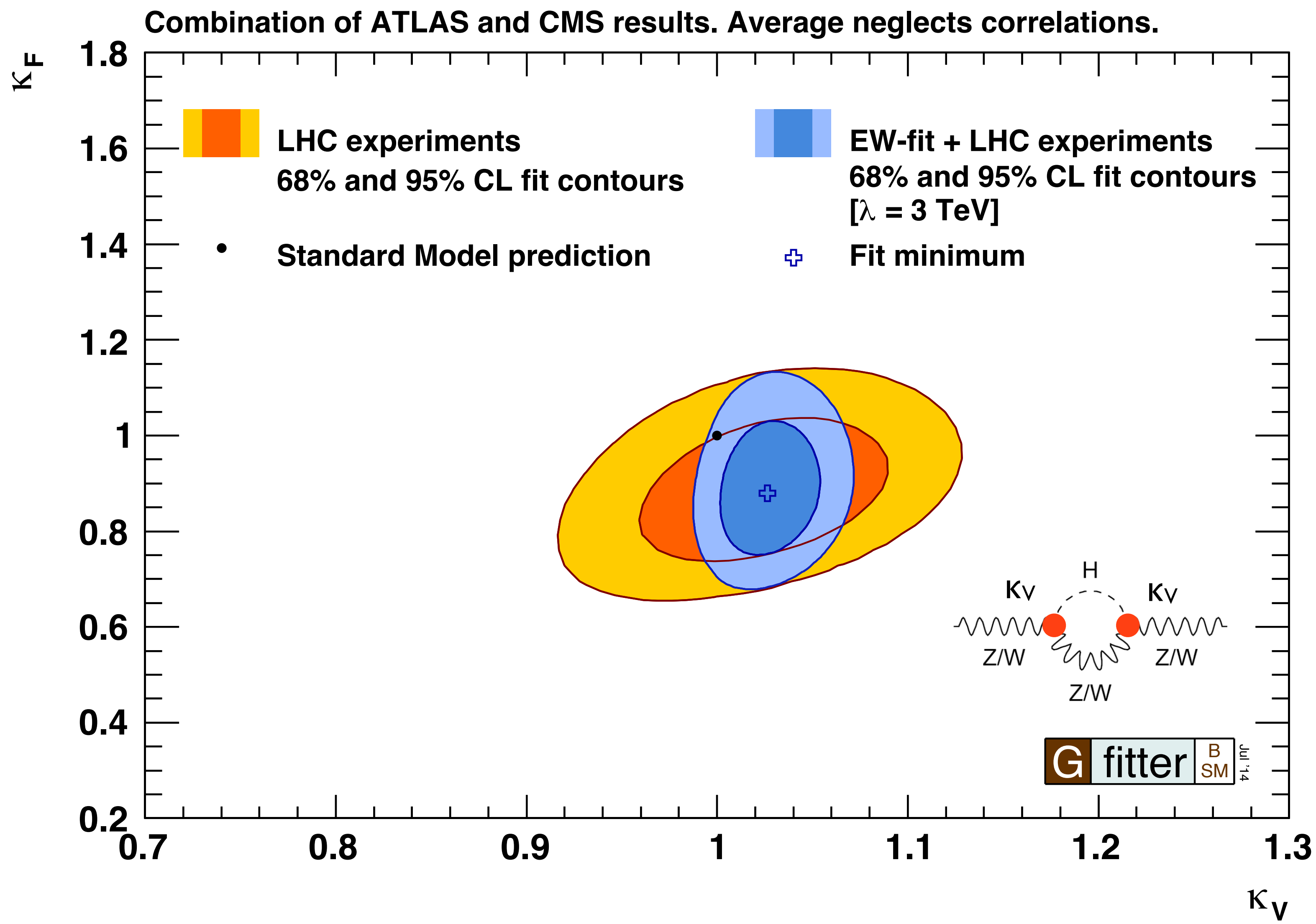


ATLAS-CONF-2015-044

This was not unexpected, given the level of agreement of the SM predictions with the precision electroweak data

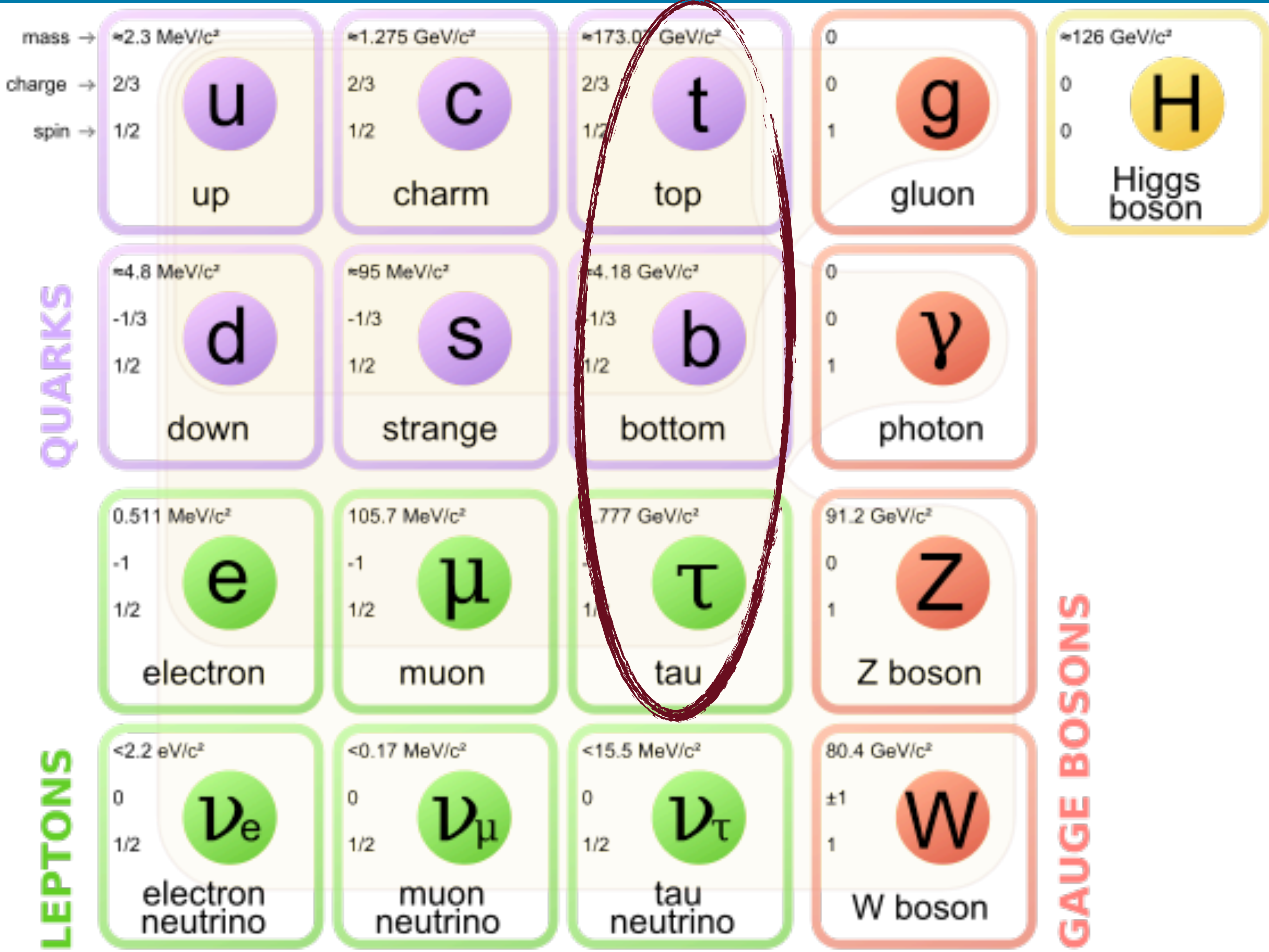
Higgs boson and precision electroweak observables

Common coupling scaling for all Fermions (κ_F) and for all Bosons (k_V); no BSM contributions



Global EW fit still more precise for κ_V than Higgs boson measurements
κ_V>1 preferred (many BSM scenarios require κ_V<1)
Global EW fit has ~ no effect on determination of κ_F

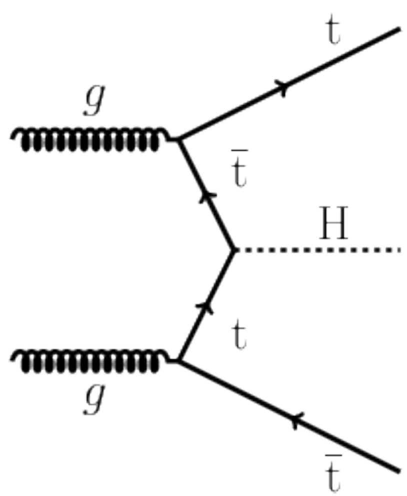
Experimental information on Yukawa couplings essential to fully characterize the observed Higgs boson!

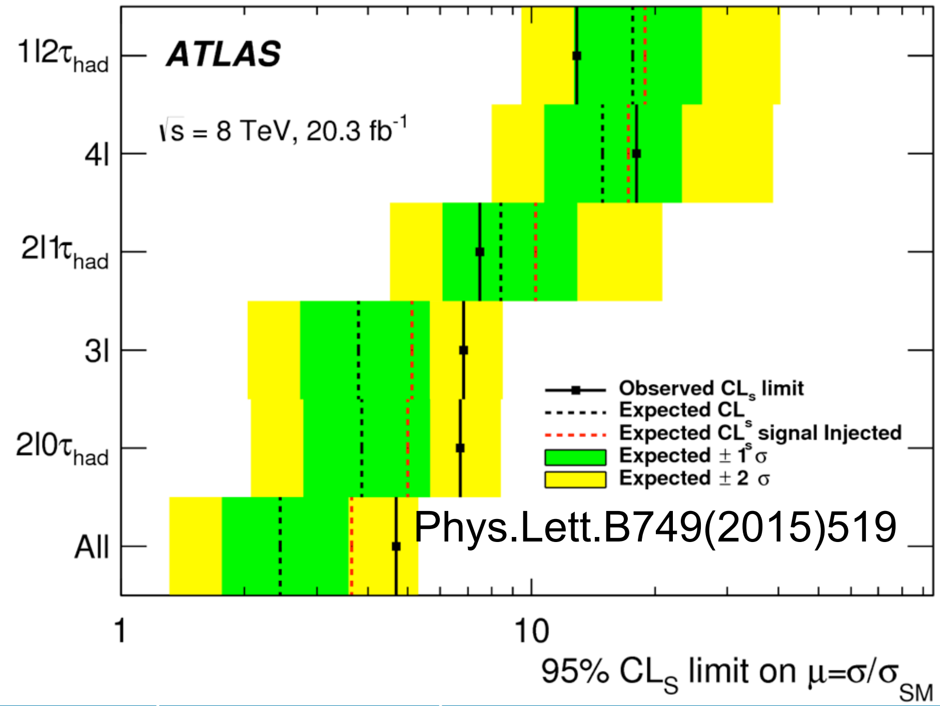

mass →
charge →
spin →
QUARKS
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
2/3
t
top
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
4.18 GeV/c²
1/3
1/2
b
bottom
0
0
1
g
gluon
0
0
1
γ
photon
≈126 GeV/c²
0
0
H
Higgs boson
LEPTONS
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
777 GeV/c²
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
GAUGE BOSONS

top quark

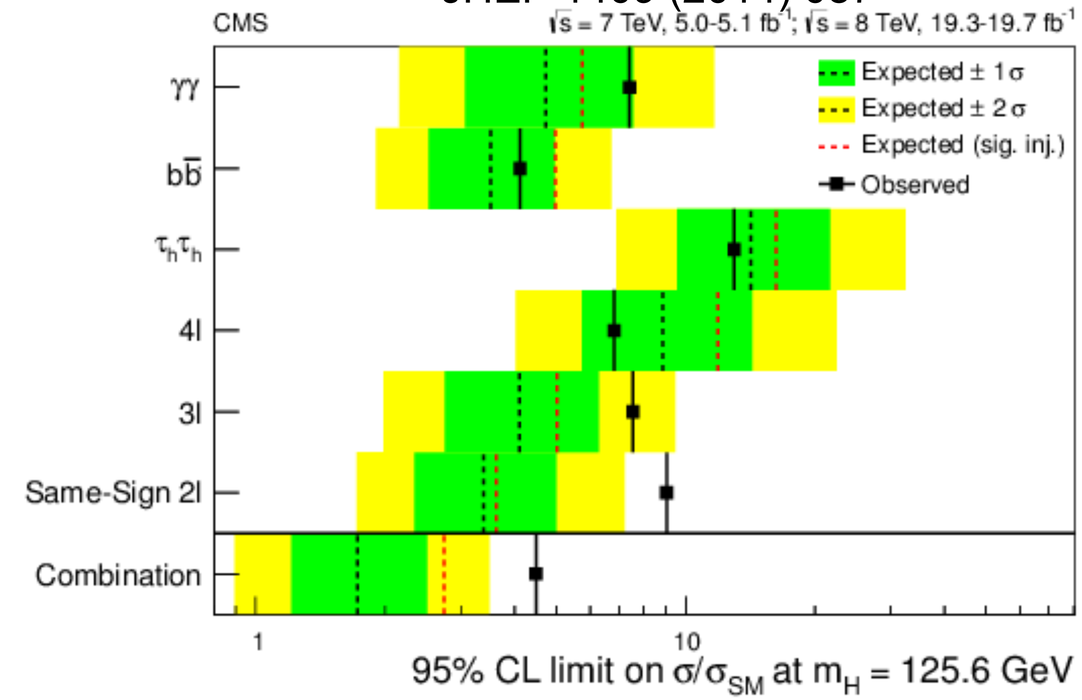
top-quark, m_t~173 GeV, has a Yukawa coupling of O(1) → ubiquitous in LHC Higgs boson production

- tth direct probe → discriminate of BSM contributions in ggh
- Complex final states → Extensive use of MVA

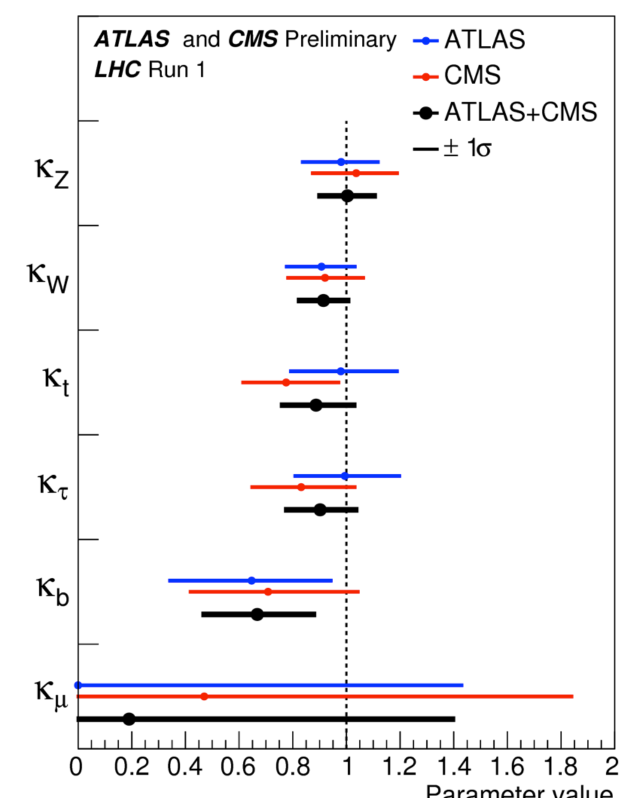




JHEP 1409 (2014) 087



m_h=125 GeV	$\mu^{95\%}_{upper}$	Significance	Reference
CMS (125.6 GeV)	4.5 (1.7)	3.4(1.2)	JHEP 1409(2014) 087
ATLAS bb	3.4 (2.2)	1.4(1.1)	Eur.Phys.J. C75 (2015) 7 349
ATLAS multi-leptons	4.7 (2.4)	1.8(0.9)	Phys.Lett.B749(2015)519
ATLAS γγ (125.4 GeV)	6.7 (4.9)	-	Phys.Lett. B740(2015) 222
ATLAS Couplings (125.36 GeV)	-	2.5(1.5)	arXiv:1507.04548



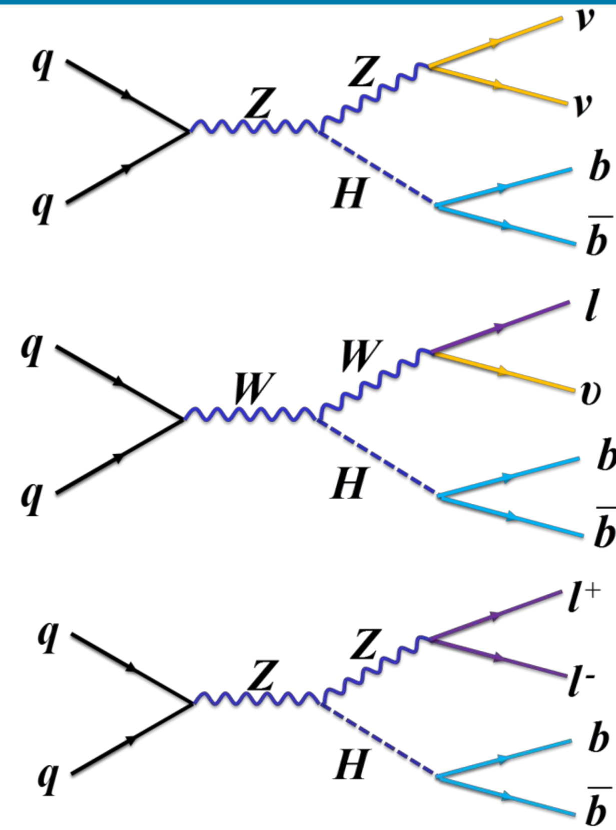
ATLAS-CONF-2015-044

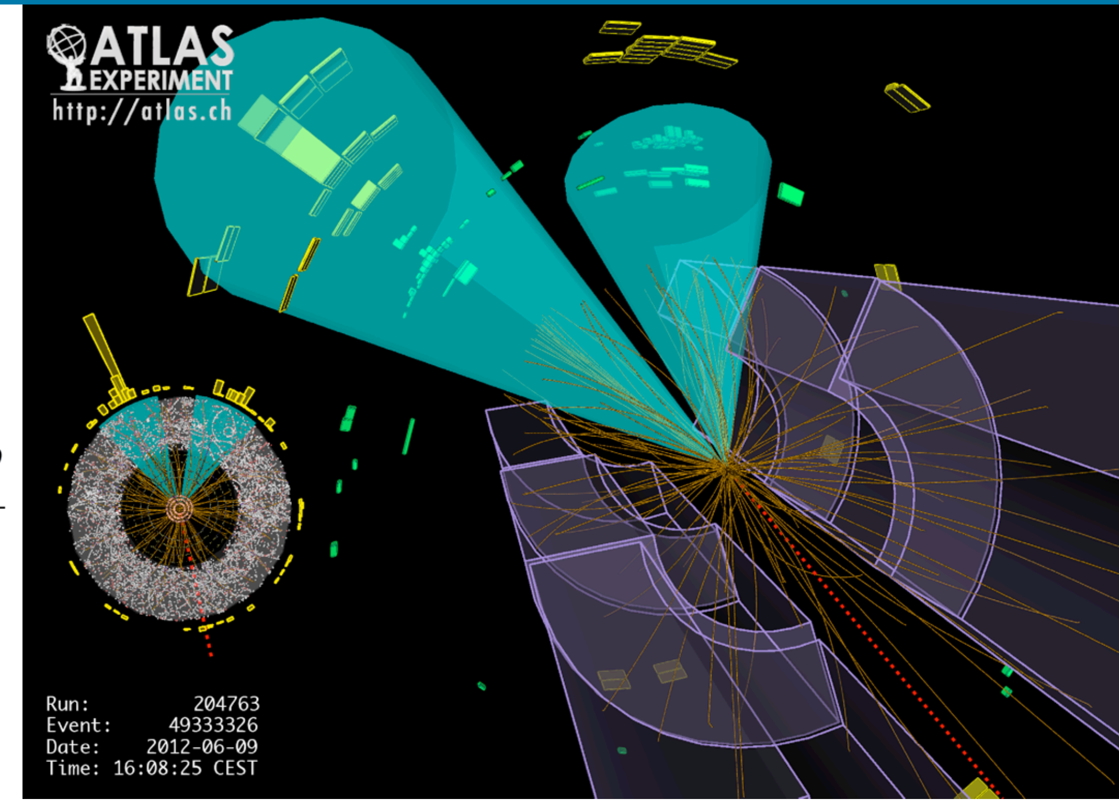
- Analyses approaching SM sensitivity
- Some excess over background observed
- ATLAS tth→γγ projection gives 8.2σ for 3000 fb^{-1} [ATL-PHYS-PUB-2014-012]
    - Naively (both multi-leptons and γγ statistics limited) feasible in Run II/III

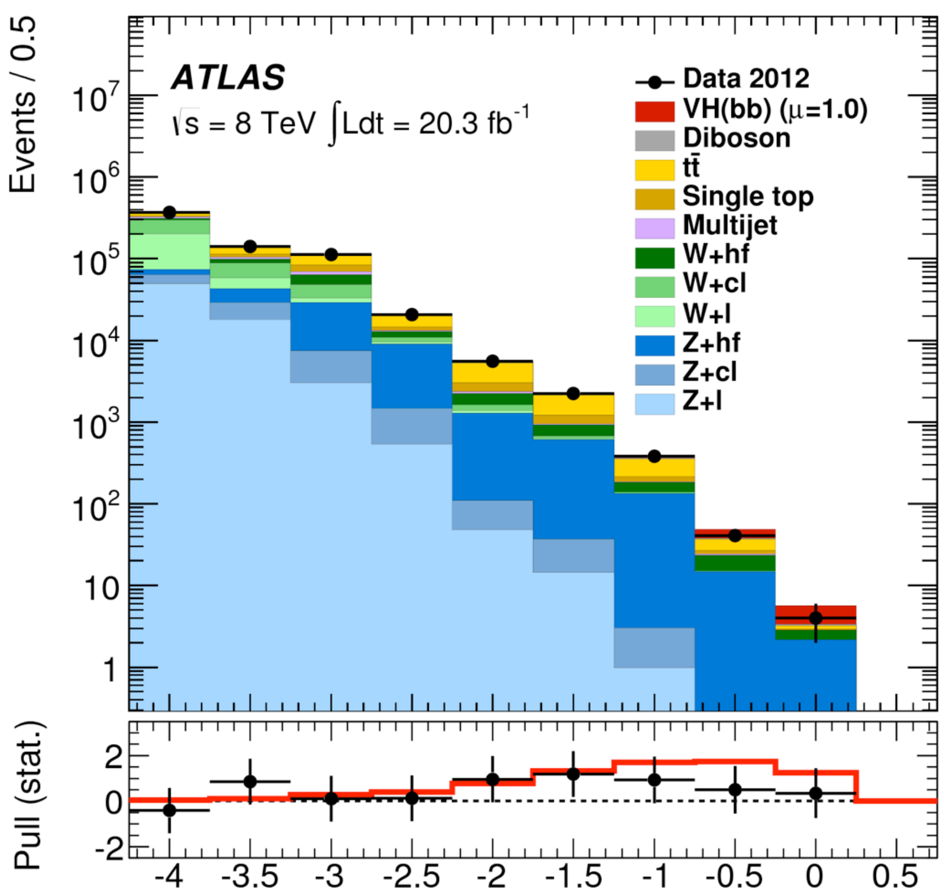
h→bb : Results

- Largest BR (58%@m_H=125 GeV) but large QCD background
- Exploit associated production with W/Z
  - Complex final states
- Backgrounds: W/Z+jets and top
- Final discriminant: BDT_{VH}

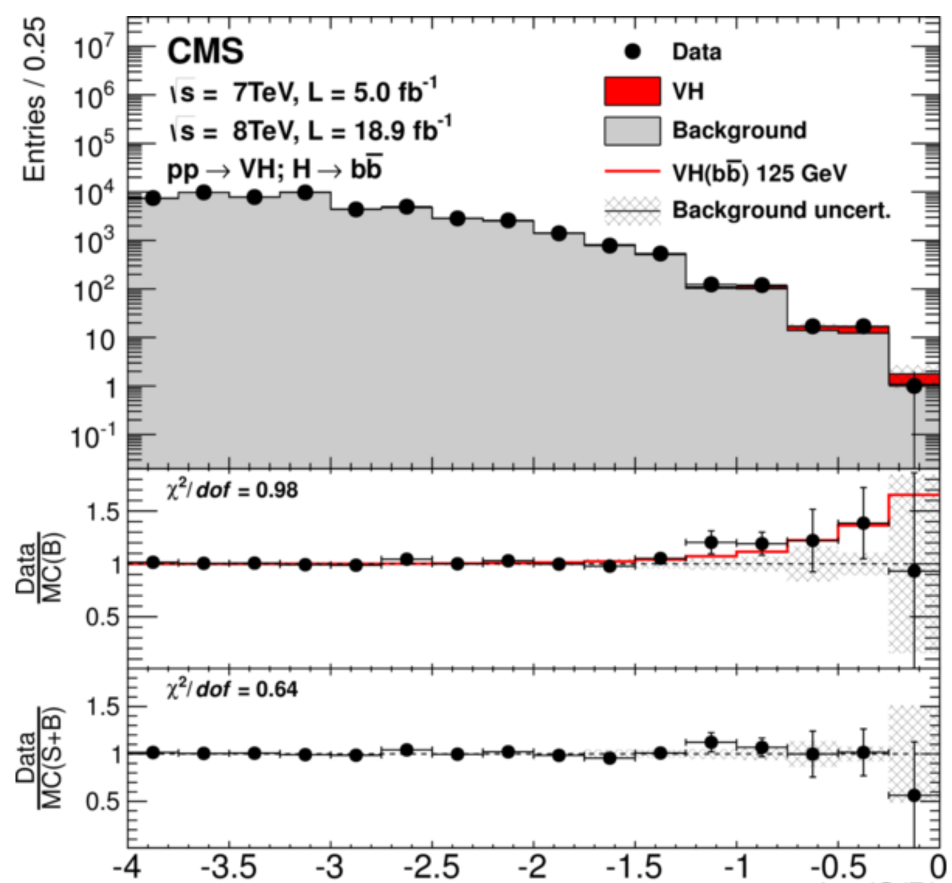
m_H= 125 GeV	Significance	$\mu^{95\%}_{upper}$
ATLAS	1.4σ (2.6σ)	1.2 (0.8)
CMS	2.1σ (2.1σ)	1.89 (0.95)







JHEP 01 (2015) 069



Phys.Rev. D89 (2014) 012003

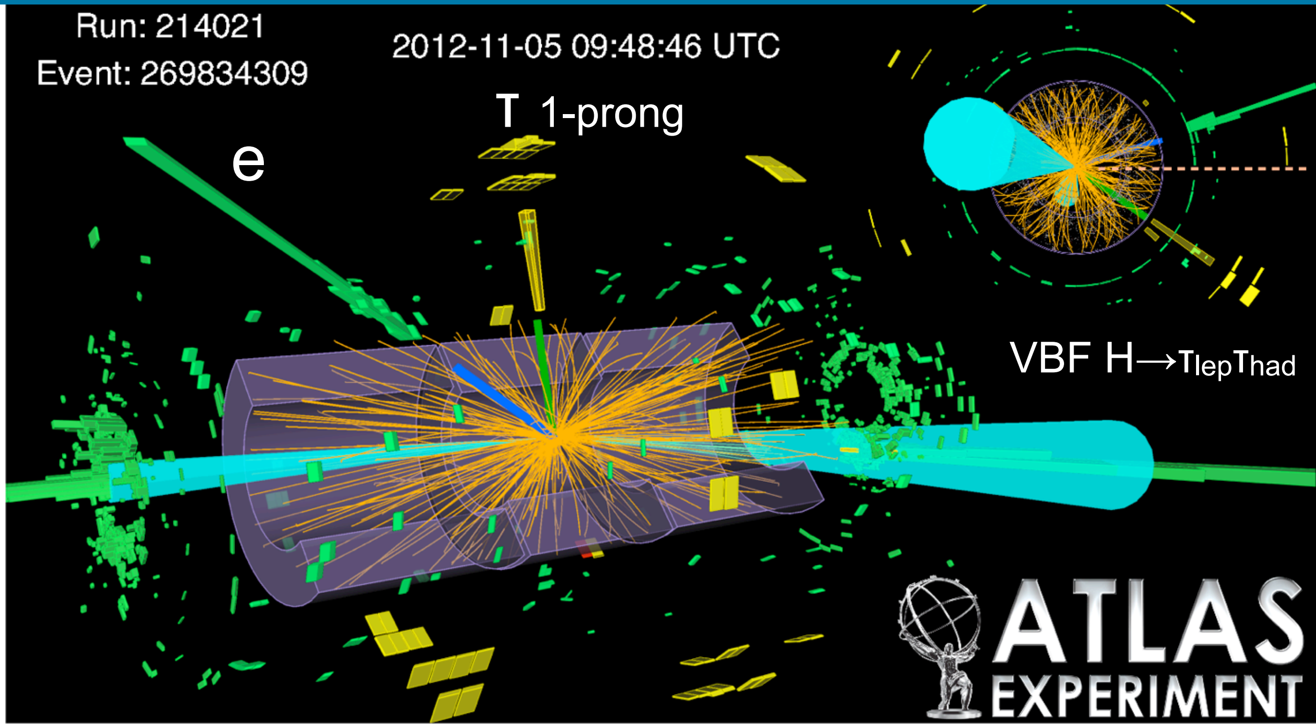
Run I dataset ~SM sensitivity ATLAS/CMS observe excess over expected background → no firm evidence yet

Despite challenging pile-up conditions, evidence for SM within reach for LHC Run II/III

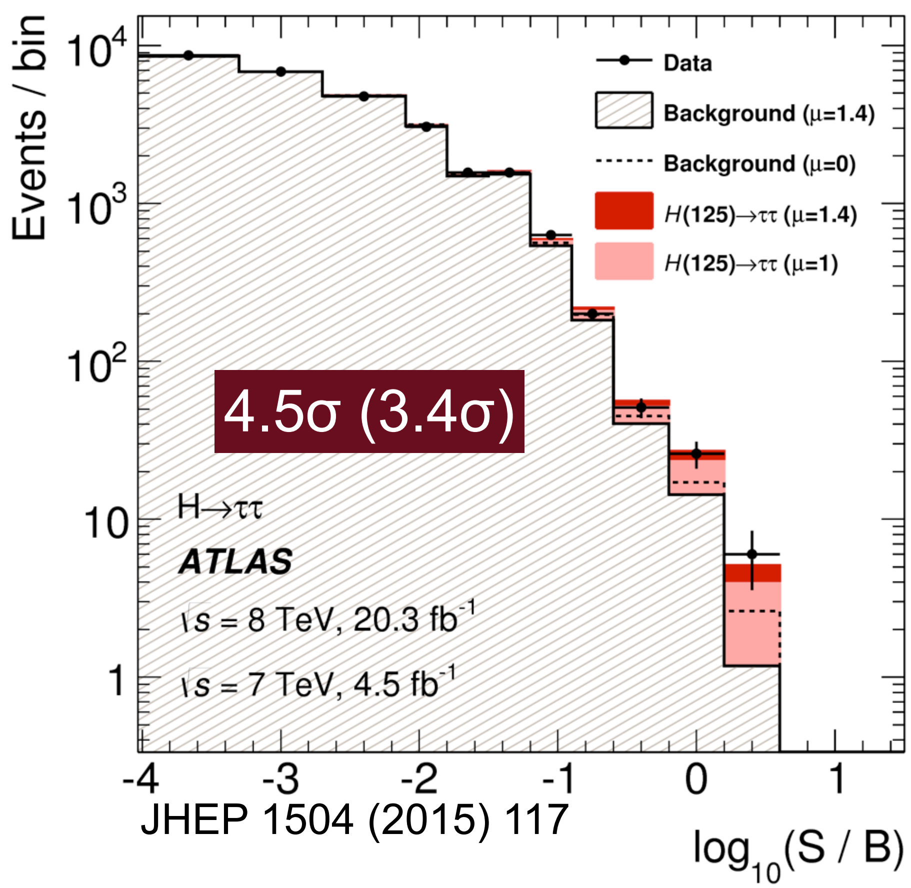
[ATLAS projections ≳3σ expected with 300fb^{-1} ATL-PHYS-PUB-2014-011]

h→ττ

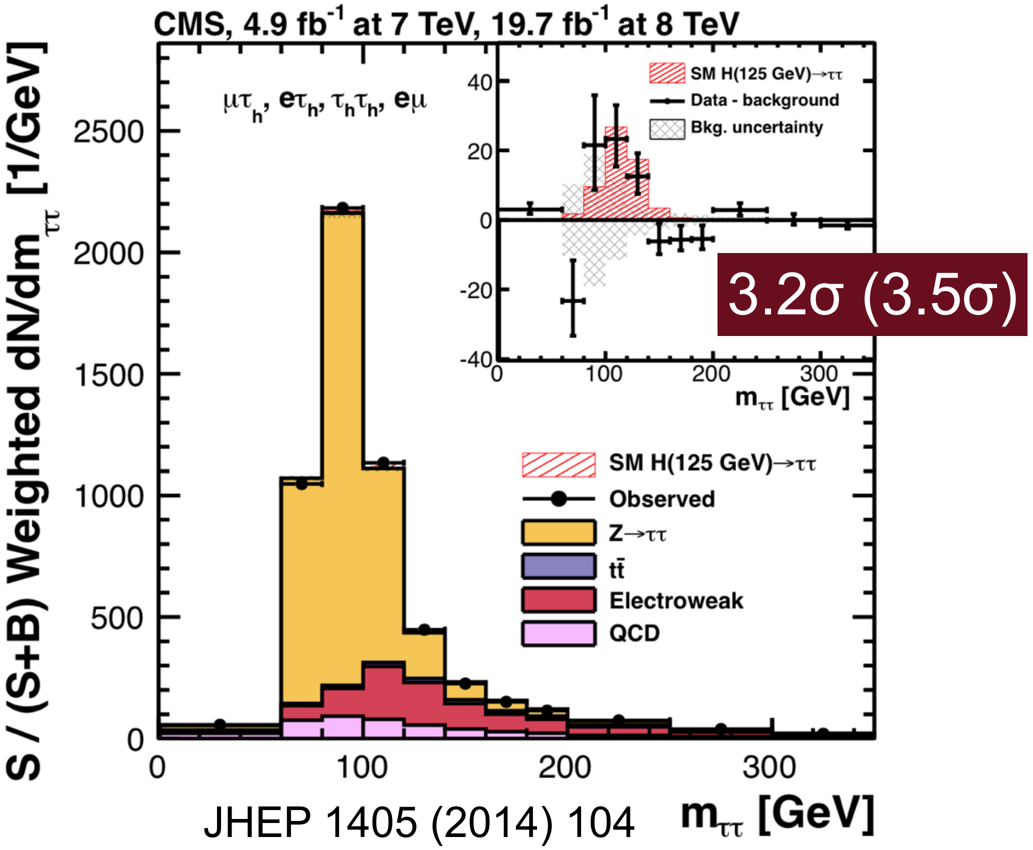
- Most promising for down-type fermion/lepton couplings
- Backgrounds
  - Z → ττ dominant [embedding]
  - "Fakes": Multijet, W+jets, top [data-driven]
  - "Other": Dibosons/H->WW* [MC]
- Substantial sensitivity from VBF and boosted topologies
  - Three sub-channels: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- BDT for each category: *di-tau properties* ($m_{\tau\tau}$, $\Delta R_{\tau\tau}$, ...), *jet topology* (m_{jj}, $\Delta\eta_{jj}$, ...), *event activity/topology* (scalar/vector pT sum, object centralities, ...)



ep_T = 56 GeV, τ_{had} p_T = 27 GeV, MET=113 GeV, $m_{j1,j2}$=1.53 TeV, $m_{\tau\tau}^{MMC}$=129 GeV, BDT score = 0.99. S/B ratio of this bin 1.0

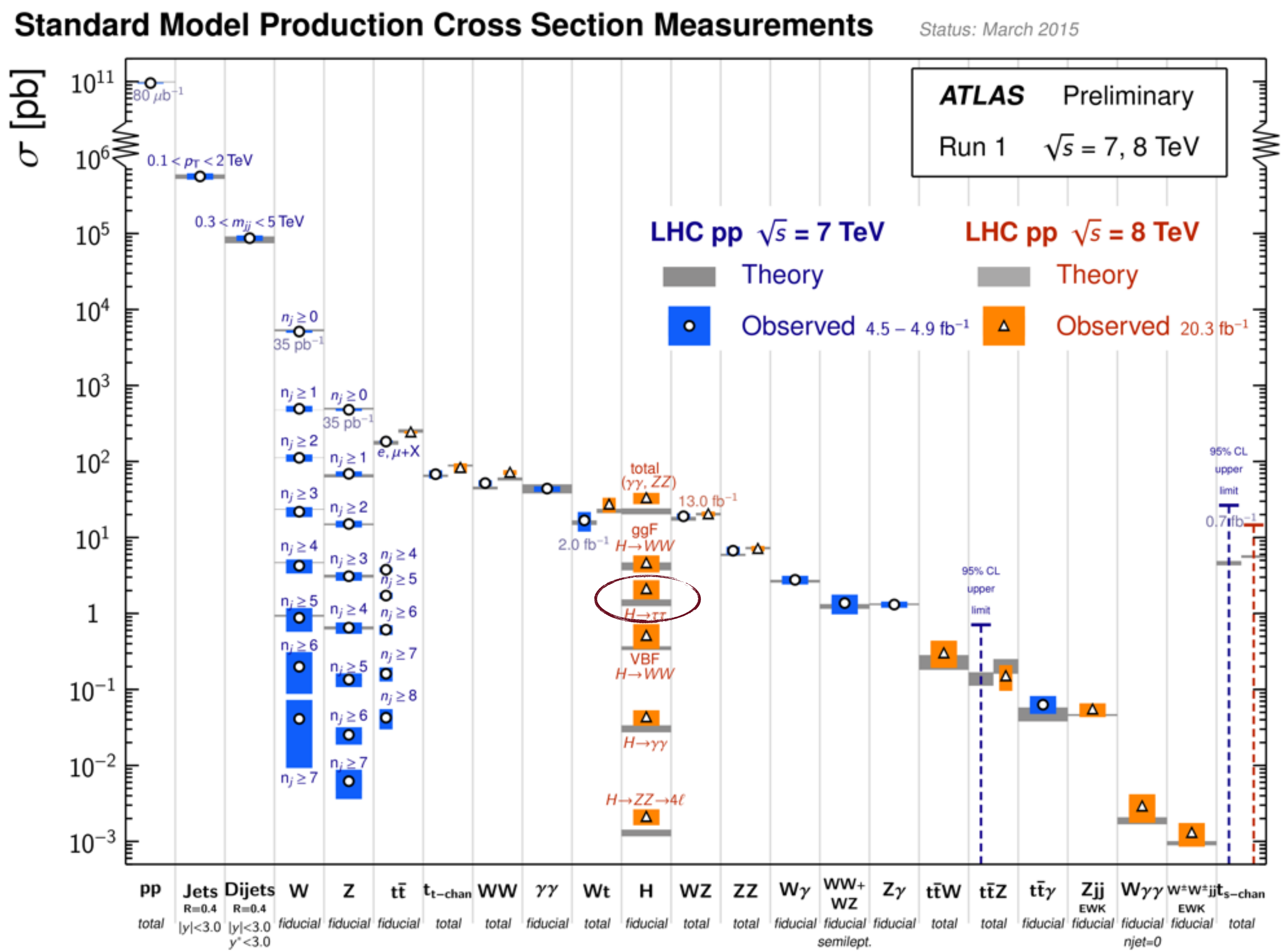


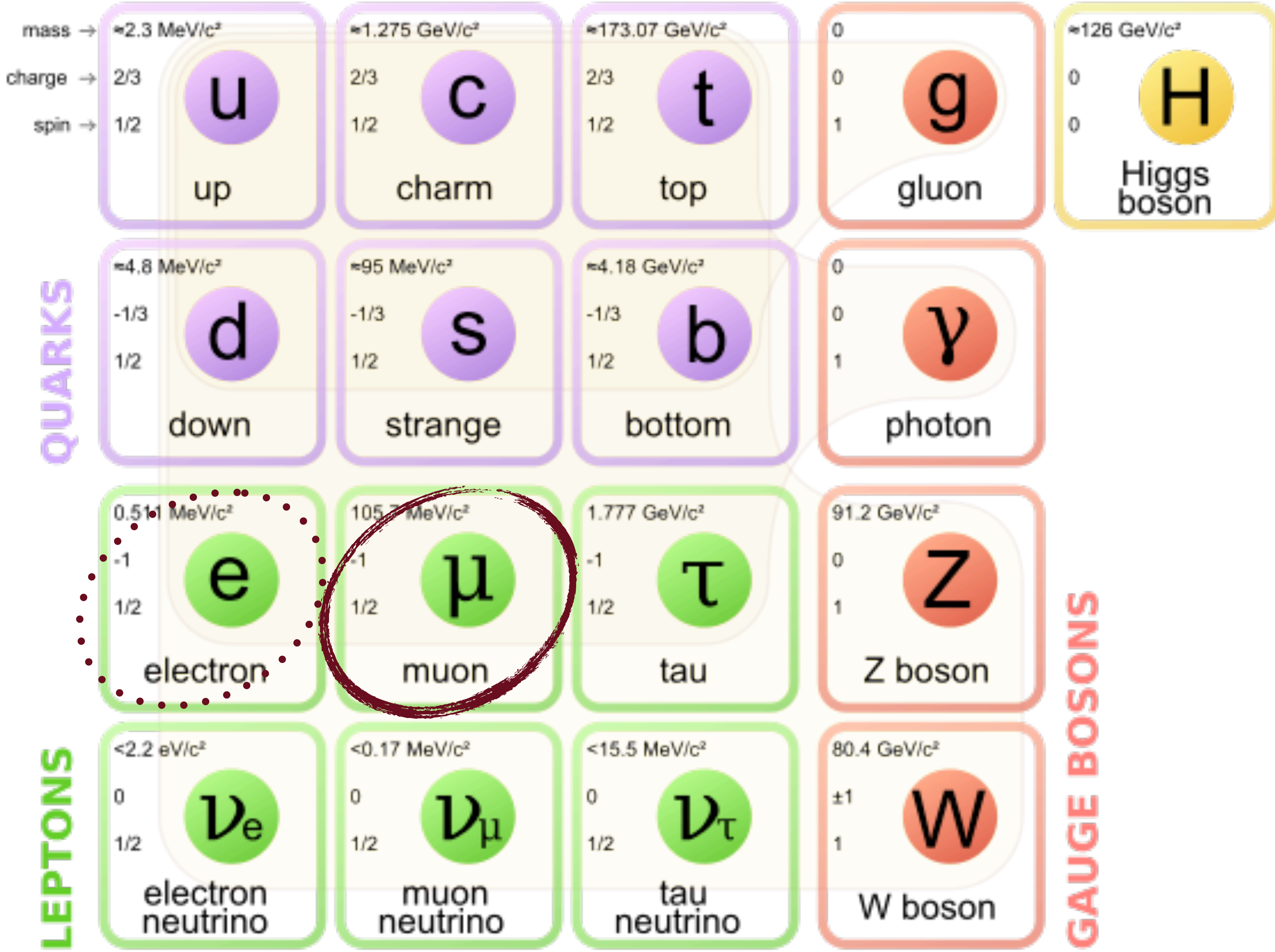
JHEP 1504 (2015) 117



JHEP 1405 (2014) 104

$h \rightarrow \tau\tau$



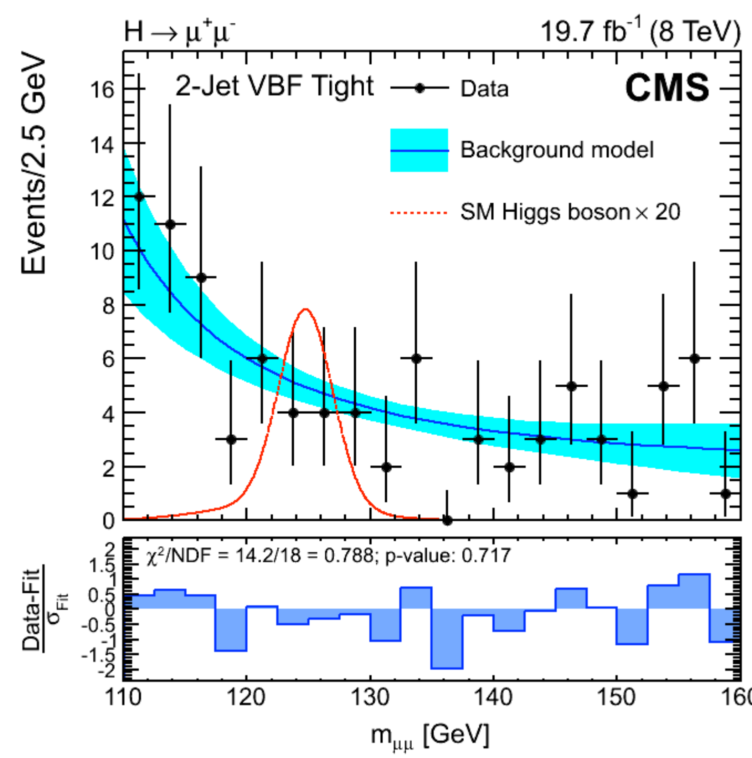

mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

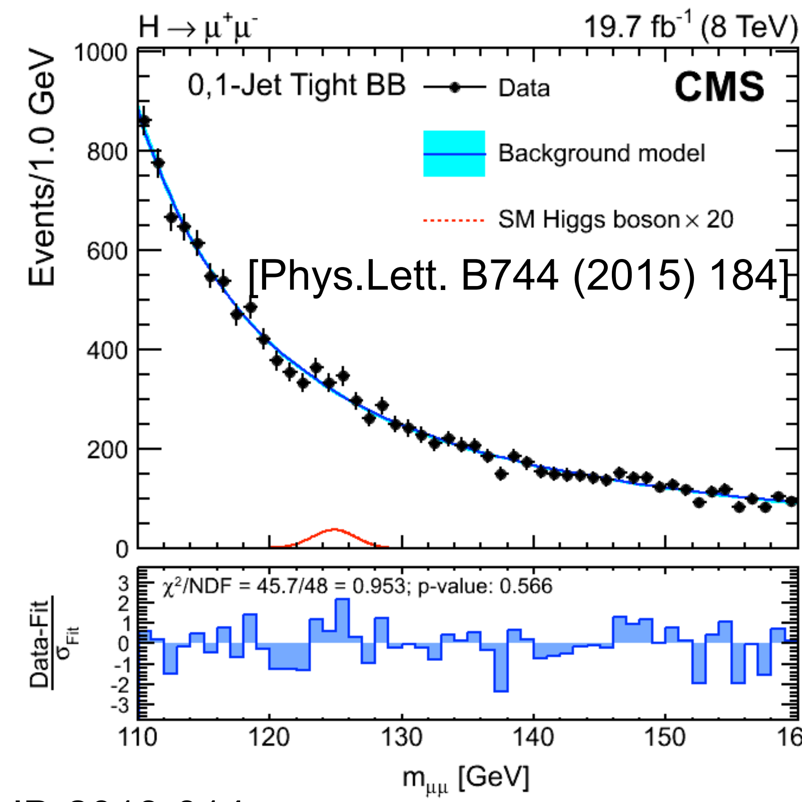
h→μμ

- Attainable probe for 2nd gen. Yukawa
- $BR_{SM} \sim 2 \cdot 10^{-4}$(125GeV);S/B ~0.2%

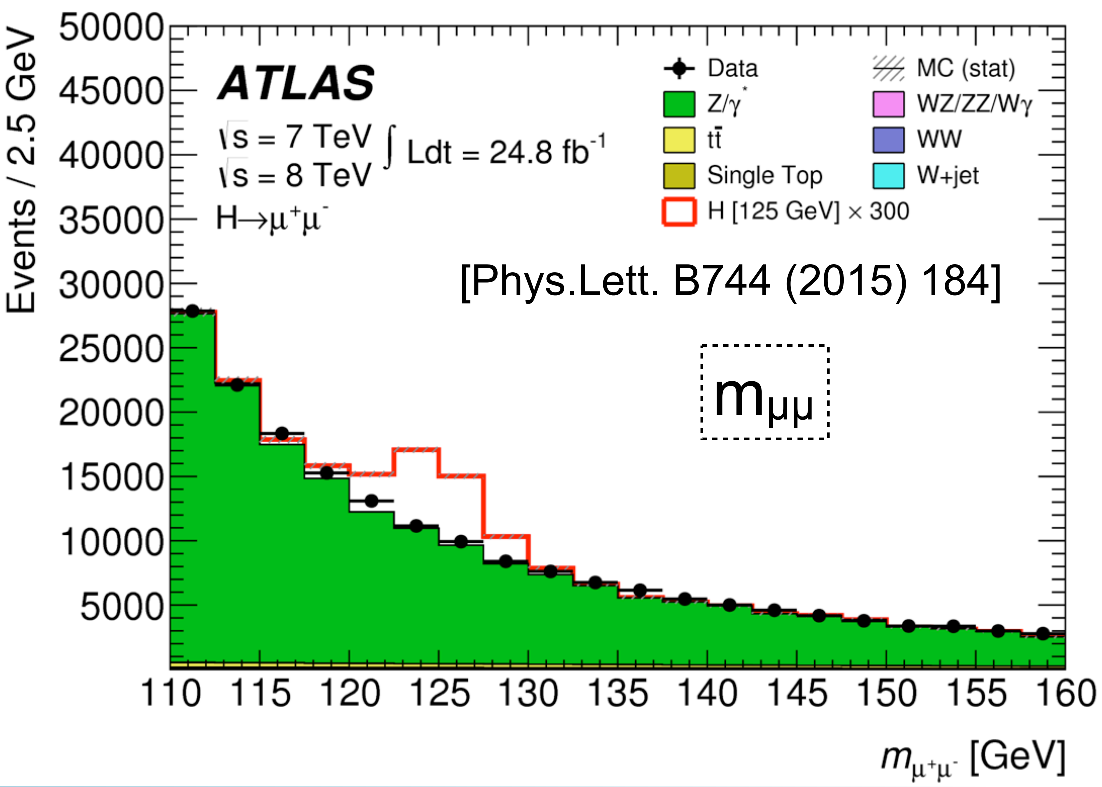
Simple Final State (ATLAS analysis)

- $\mu^+\mu^-$ (pT>25,15 GeV, $pT_{\mu\mu}$>15 GeV)
- backgrounds: Z/γ*→μμ, top, dibosons
- Categorization: central/non-central muons
- Parametric background Model: BW+Expo
- 95% CL upper limit @m_H=125 GeV:
  - ATLAS : 9.8 (8.2)xSM
  - CMS : 7.4 (6.5)xSM





no universal Higgs coupling to fermions



ATLAS-PHYS-PUB-2013-014

$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

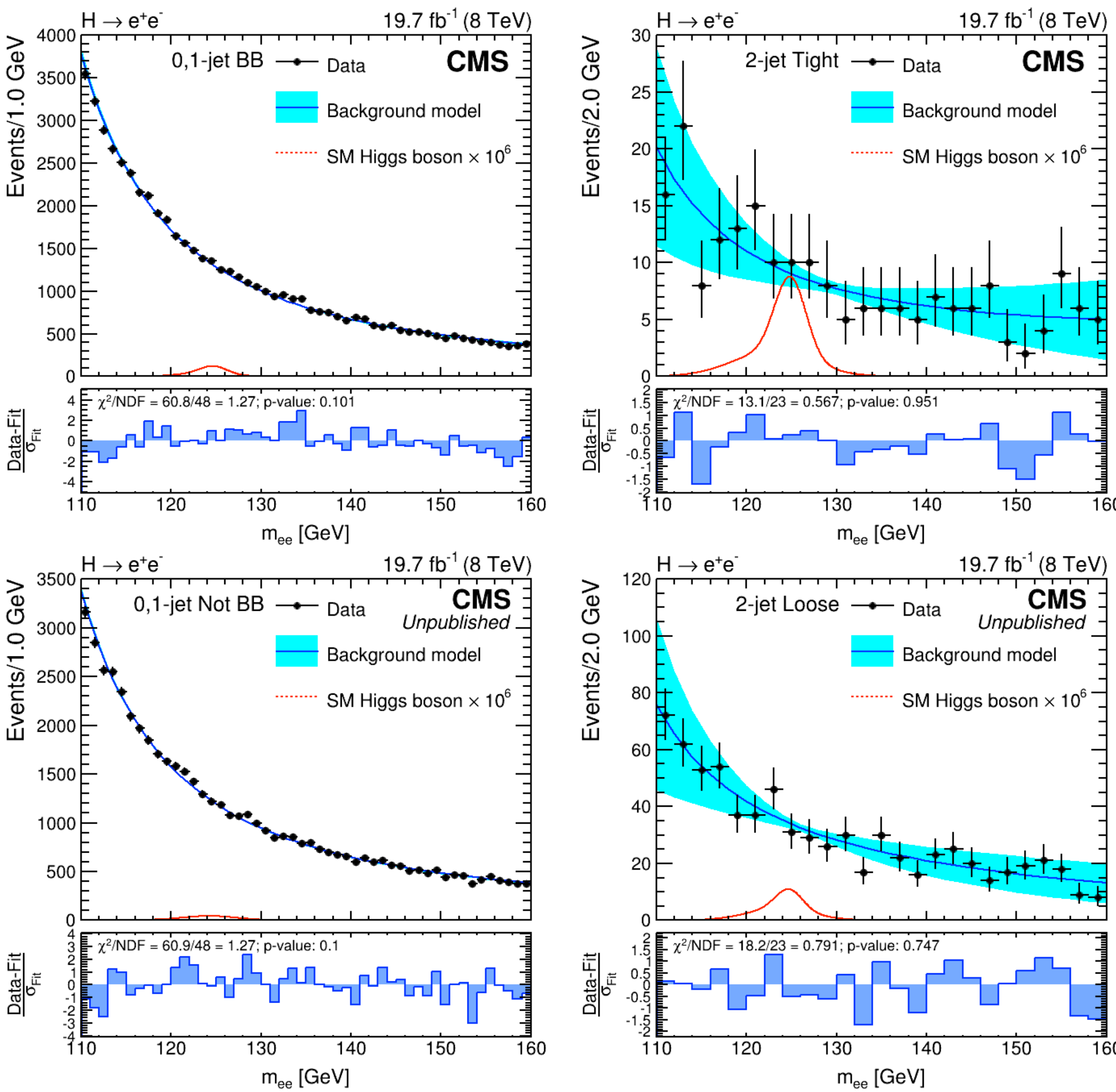
conservative extrapolation
(no IBL, Run I categorisation)

ATLAS/CMS combination (with improvements) could provide firm evidence in Run II/III

h→ee

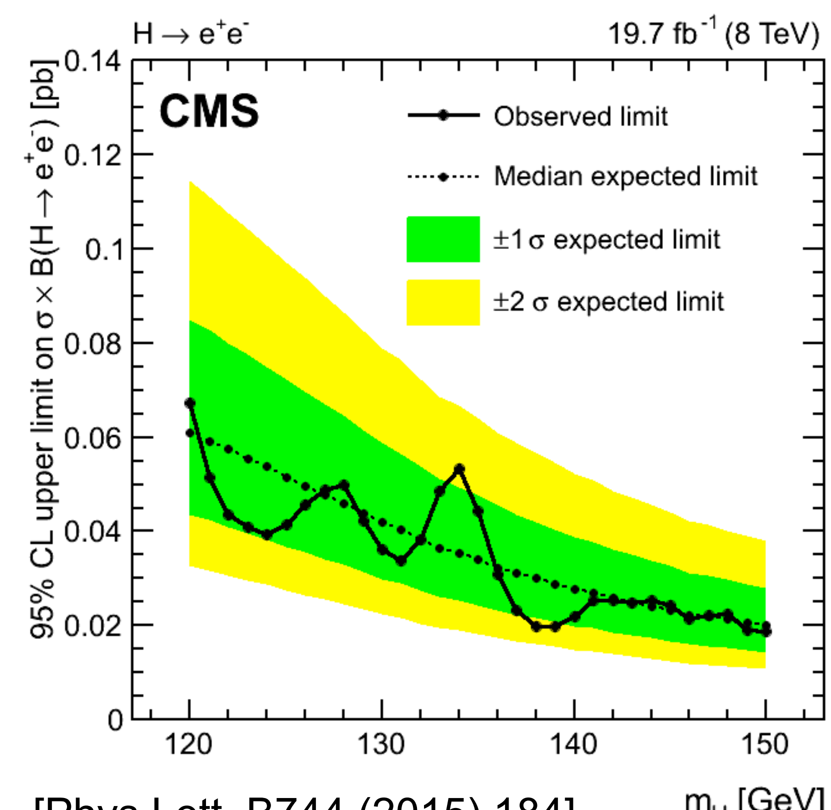
Very rare decay of the SM Higgs
- $BR_{SM}(h\rightarrow ee) \sim 5\cdot10^{-9}$

[non-Yukawa suppressed contributions need to be included Phys.Lett. B727 (2013) 424]
- $BR_{SM}(h\rightarrow \tau\tau/\mu\mu)/BR_{SM}(h\rightarrow ee) \sim 1.2\cdot10^{7}/4.4\cdot10^{4}$



CMS performed this search
- in parallel with $h\rightarrow\mu\mu$
- simple final state: two opposite-charged electrons, pT>25GeV

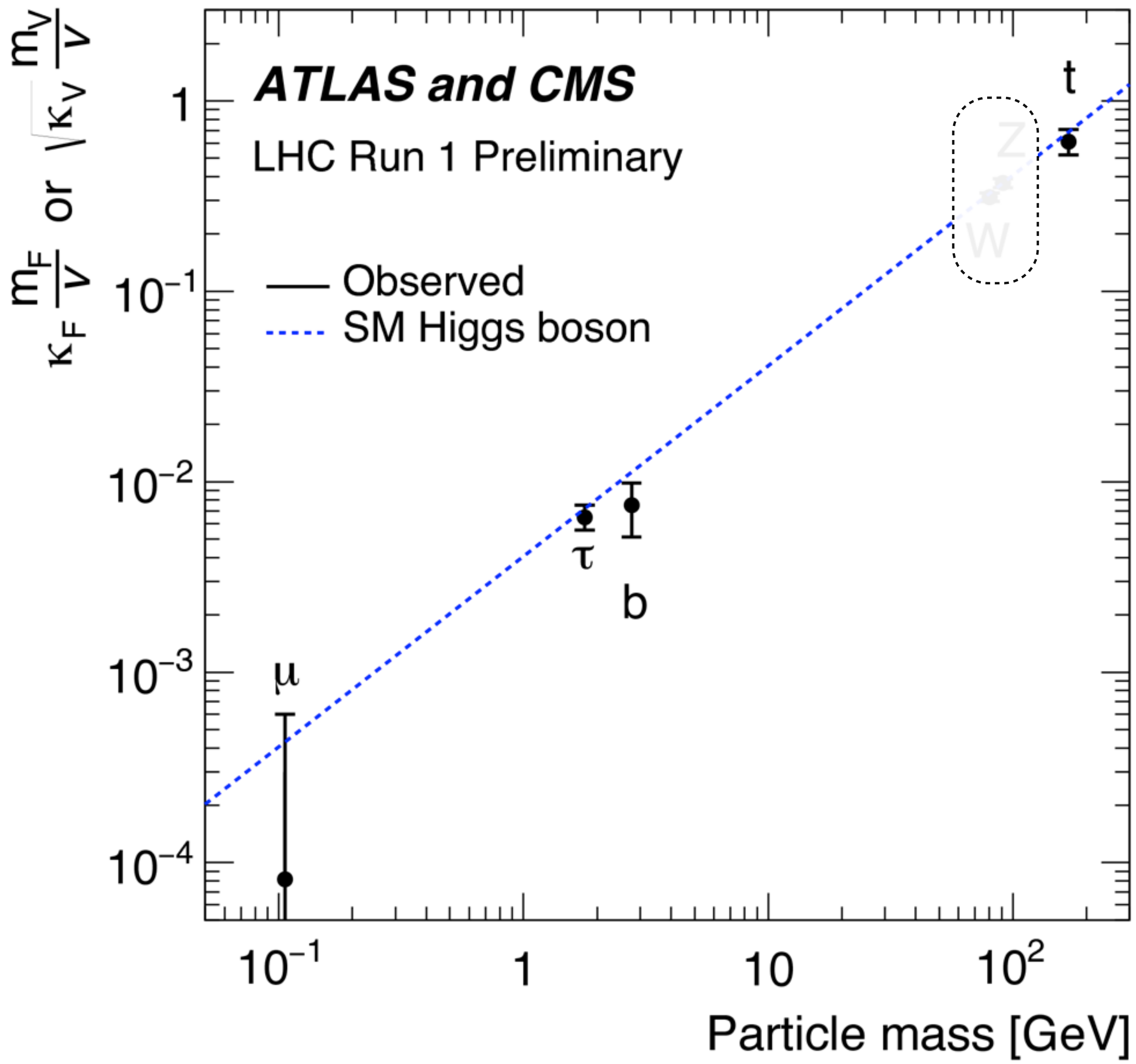
- backgrounds: $Z/\gamma^*\rightarrow ee$, and some ttbar
- Categorization: central/non-central electrons + 2 jet categories
- Parametric background model
- 95% CL upper limit $BR(h\rightarrow ee)<1.9\cdot10^{-3}$



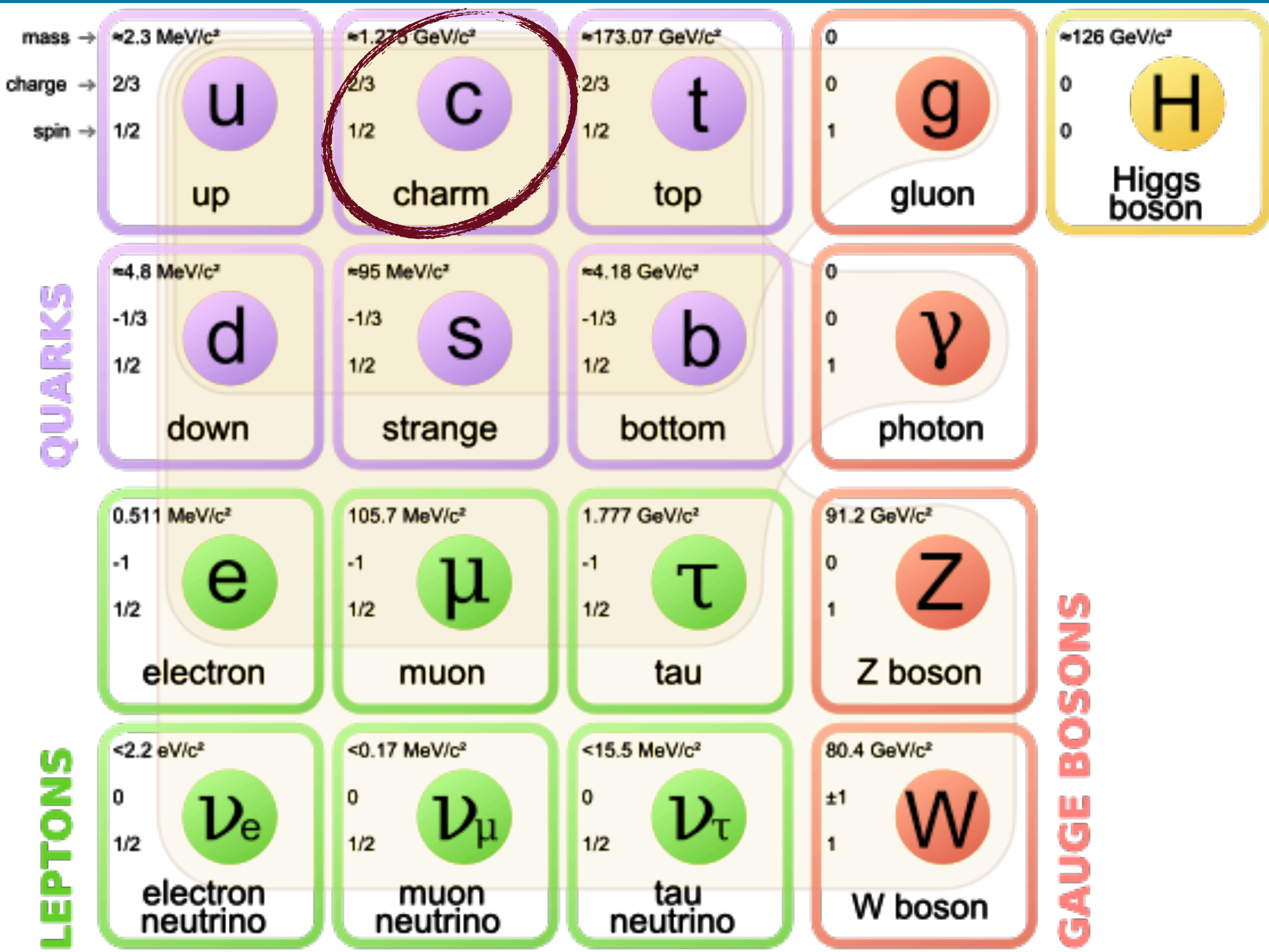
[Phys.Lett. B744 (2015) 184]

Yukawa couplings so far...

ATLAS-CONF-2015-044



- No conclusive direct evidence for h→ffbar, with the exception of h→ττ
  - h→bb and tth are within reach in LHC Run II/III
- Indirectly; Higgs boson should be coupling to top-quark in the gluon fusion loop
- h→μμ is feasible in LHC (maybe already in Run II/III)...
  - otherwise 1st/2nd generation Yukawa couplings completely unconstrained
  - h→ee has too low rate in the SM



mass
charge
spin
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

Charm-quark Yukawa coupling

Recent substantial activity on probing the charm-quark Yukawa coupling at the LHC.
Two lines of attack (non-exhaustive list of references):

→ Charm-tagging either at decays h→ccbar or production pp→hc
[Phys.Rev. D89 (2014) 3, 033014; Phys.Rev. D92 (2015) 033016, arXiv:1507.0291]

→ Exclusive decays h→Qγ
[Phys.Lett. B82 (1979) 411; Phys.Rev. D27 (1983) 2762; Yad.Fiz. 46, 864 (1987); Phys.Rev. D88 (2013) 053003; Phys.Rev. D90 (2014) 113010, JHEP 1508 (2015) 012]

These searches are sensitive to BSM physics
[arXiv:1508.01501, arXiv:1504.04022, Phys. Rev. D 80, 076002, Phys. Lett. B665 (2008) 79]

Charm Tagging

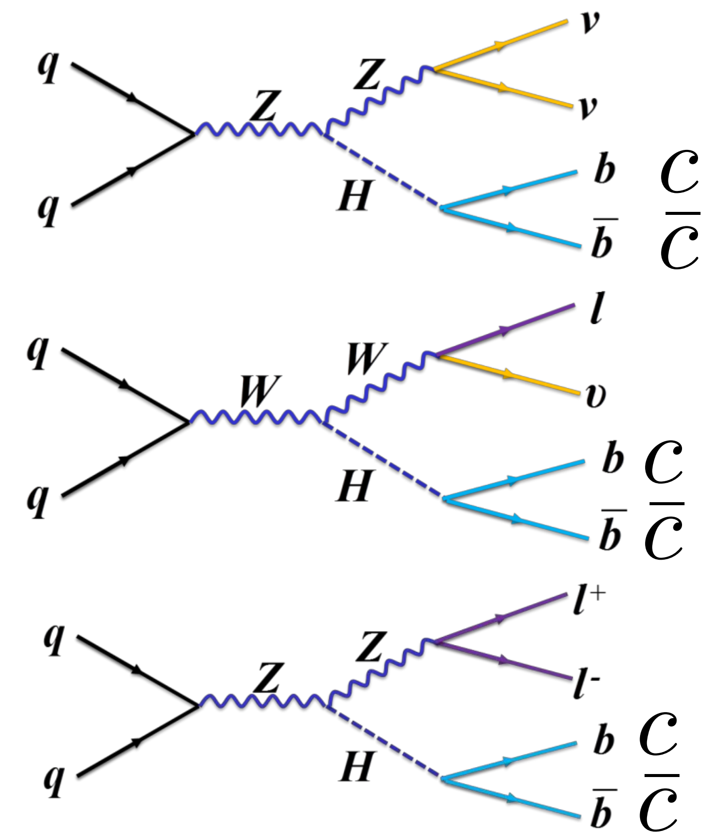
One may "re-interpret" the h→bbbar search for anomalous h→ccbar production

→ In the SM BR(h→ccbar)/BR(h→bbbar) ~ 5.1%

→ Enhancement Y_c: ↑BR(h→ccbar), ↓BR(h→bbbar) [through ↑Γ_h]

→ Constrains only a linear combination of μ_b and μ_c

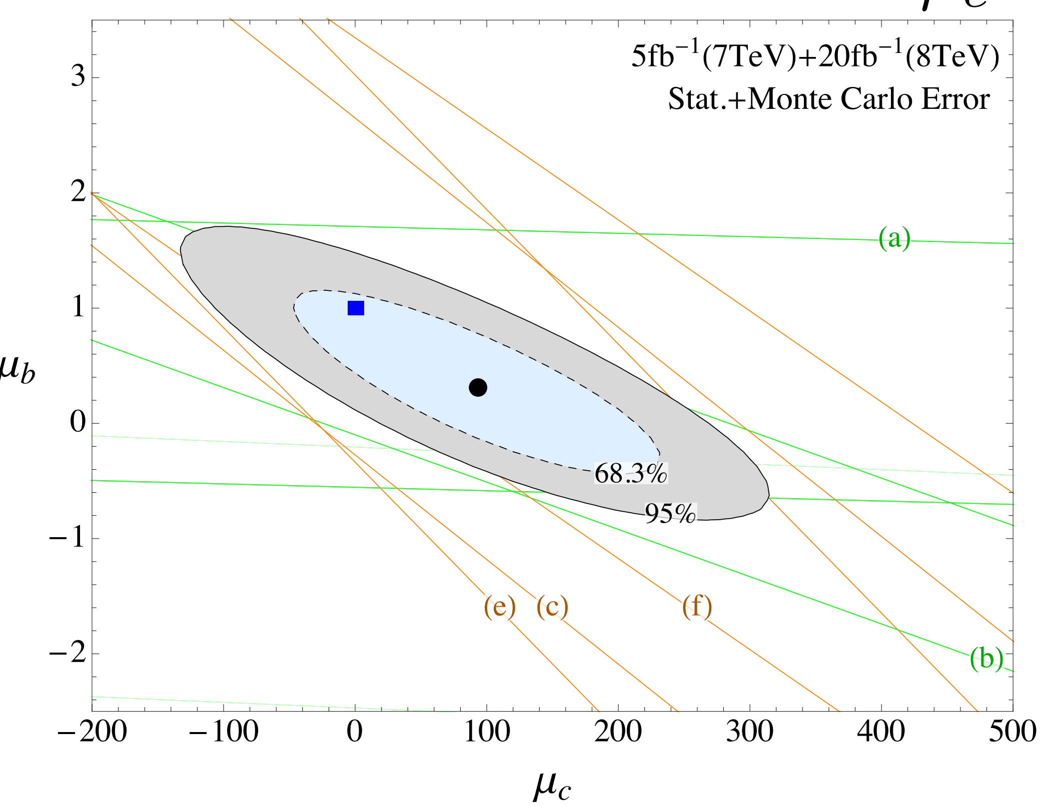
→ Need multiple b-tagging points



$$\mu_b = \frac{\sigma\, \mathrm{BR}_{b\bar{b}}}{\sigma_{\mathrm{SM}} \mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}} \to \frac{\sigma\, \mathrm{BR}_{b\bar{b}}\, \epsilon_{b_1} \epsilon_{b_2} + \sigma\, \mathrm{BR}_{c\bar{c}}\, \epsilon_{c_1} \epsilon_{c_2}}{\sigma_{\mathrm{SM}} \mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}\, \epsilon_{b_1} \epsilon_{b_2}}$$

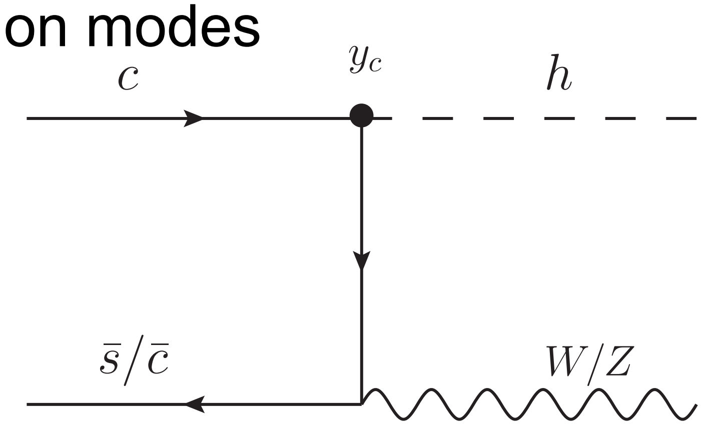
$$= \mu_b + \frac{\mathrm{BR}^{\mathrm{SM}}_{c\bar{c}}}{\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}} \frac{\epsilon_{c_1} \epsilon_{c_2}}{\epsilon_{b_1} \epsilon_{b_2}}\, \mu_c\,,$$

$$\mu_c = 95^{+90(175)}_{-95(180)} \text{ at } 68.3(95)\% \text{ CL.}$$



[Phys.Rev. D92 (2015) 033016]

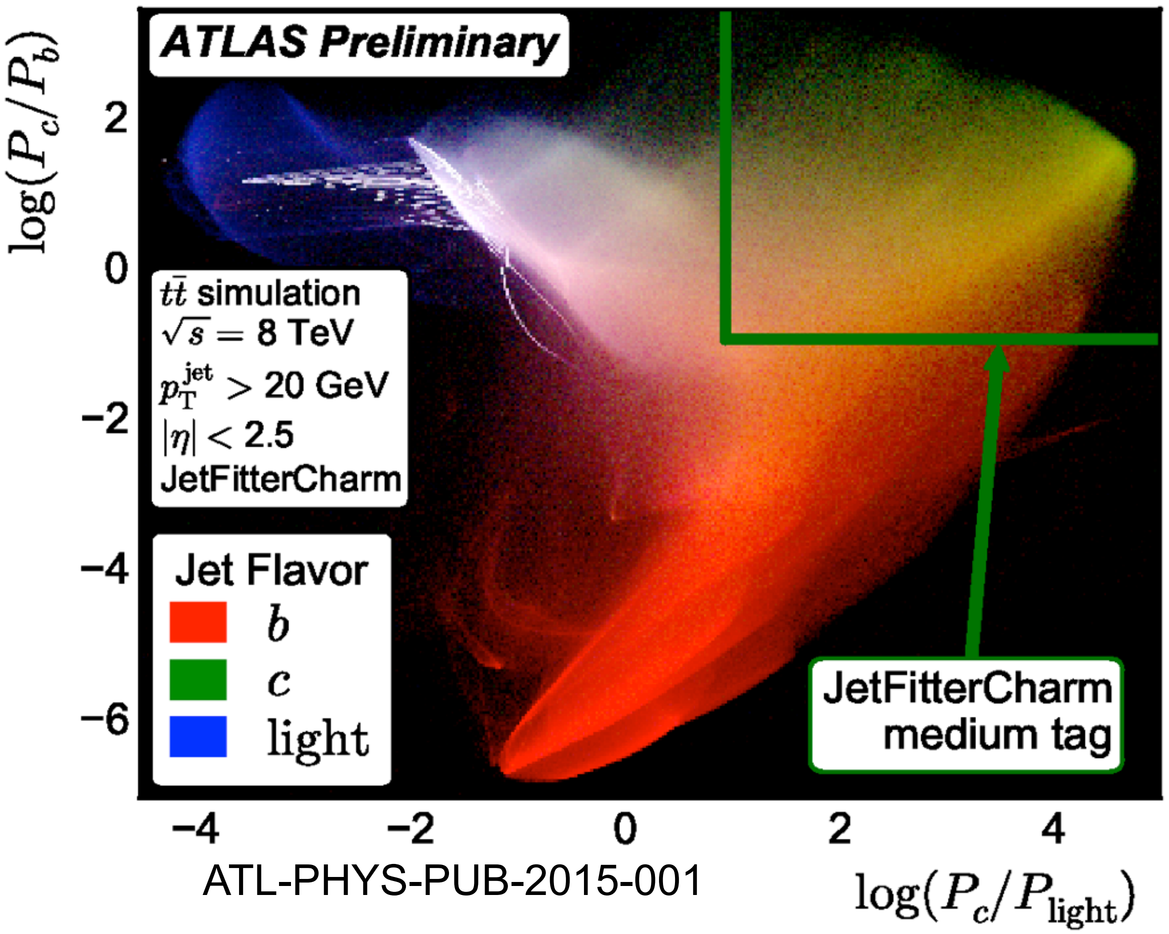
→ Extracting info about Yukawa couplings: account for new production modes

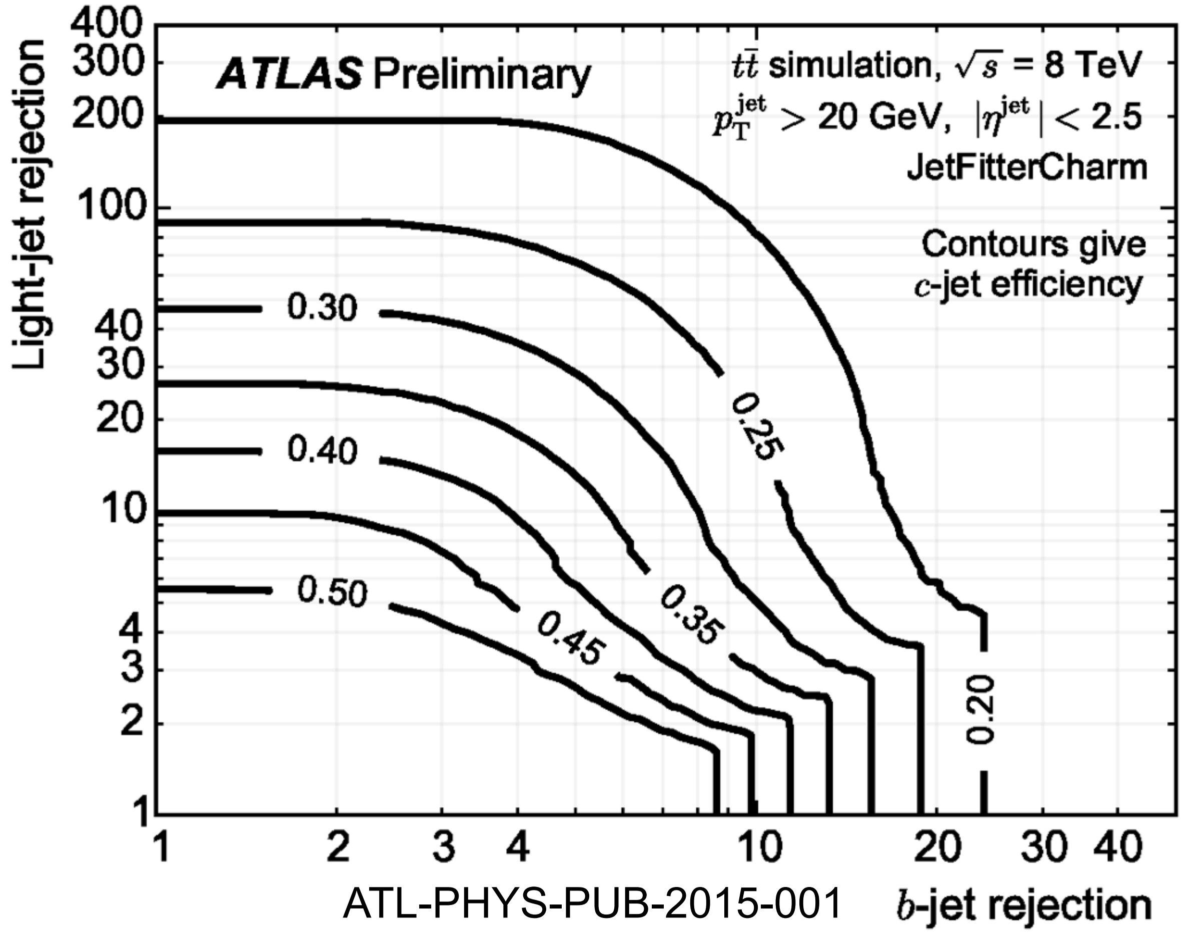


$$\kappa_c \lesssim 234 \text{ at } 95\% \text{ CL}\,,$$

→ No detailed experimental analysis performed yet!

Charm Tagging

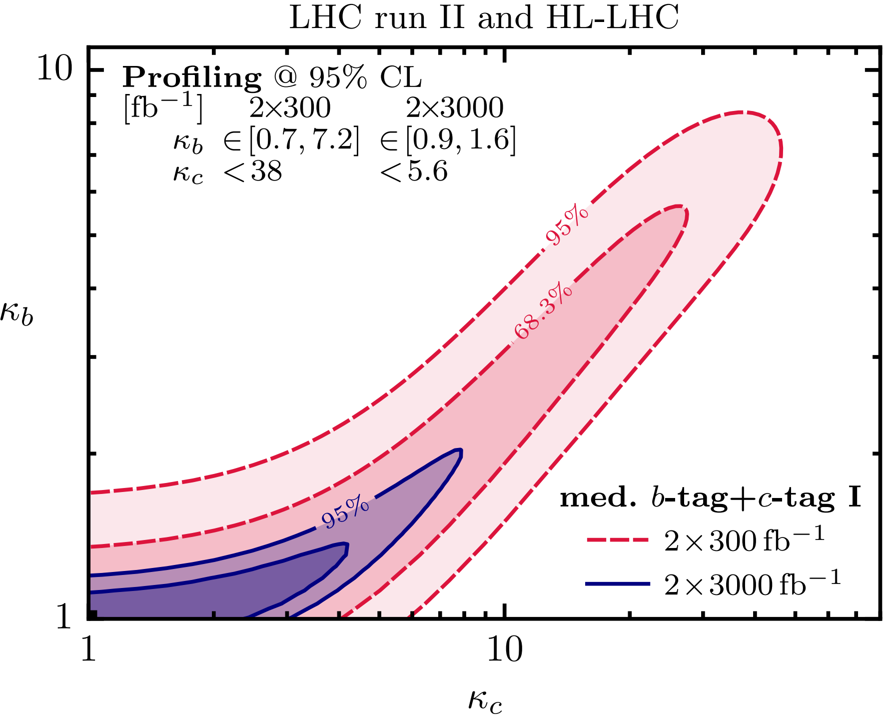


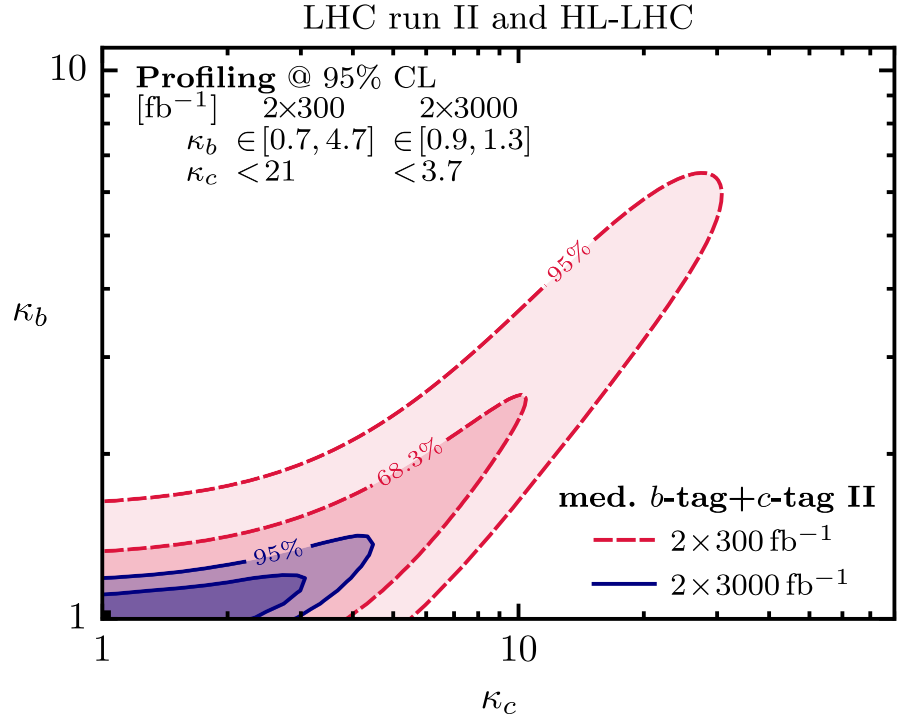


To resolve the two contributions improved c-tagging is needed
→ ideally completely separate b- and c-jets
Future H→ccbar searches will benefit from dedicated c-tagging (ATL-PHYS-PUB-2015-001), already applied in ATLAS s-charm search. [Phys.Rev.Lett. 114 (2015) 161801]

However:
- complicated analysis with large QCD backgrounds
- signal sits on top of large (×20) h→bbbar "background"
- sensitivity to systematics of b/c-tagging efficiency
- need dedicated simulations for decay and production

Charm Tagging in HL-LHC



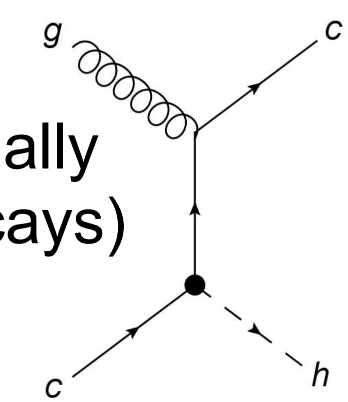


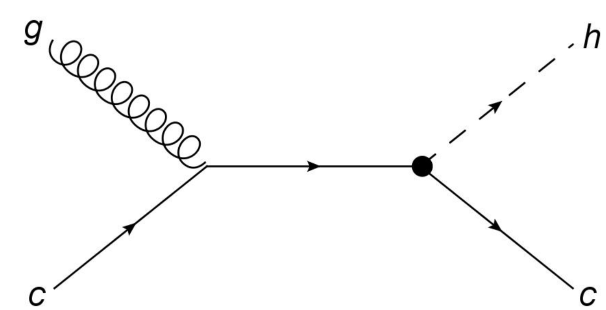
arXiv:1505.06689

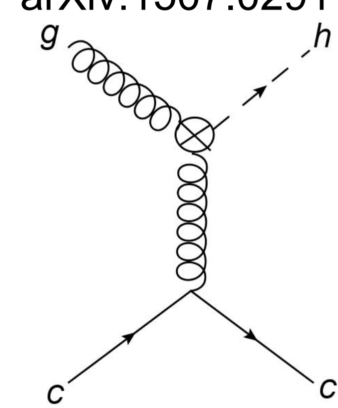
	ϵ_b	ϵ_c	ϵ_l
b-tagging	70%	20%	1.25%
c-tagging I	13%	19%	0.5%
c-tagging II	20%	30%	0.5%
c-tagging III	20%	50%	0.5%

2×3000 fb^{-1}
$|\kappa_c|\lesssim2.5$-5.5 at 95%CL
depending on the
c-tagging scenario

arXiv:1507.0291







For the HL-LHC the pp→hc could be potentially employed (using high purity Higgs boson decays) to probe the charm Yukawa coupling
SM cross section σ(pp→hc)~166 fb

Main backgrounds are
pp→hg (σ~12pb) [with g→cc (~55fb)] and
pp→hb (σ~200fb)
2×3000 fb^{-1} $|\kappa_c|\lesssim2$ at 95%CL
[p_{Tj}>20 GeV, $|\eta_j|$<5, DR(j_1,j_2)>0.4, ε_c=0.4, $\varepsilon_{g\to c}$=1%, $\varepsilon_{b\to c}$=30%]

pp→ch(→γγ) 3000 fb^{-1}

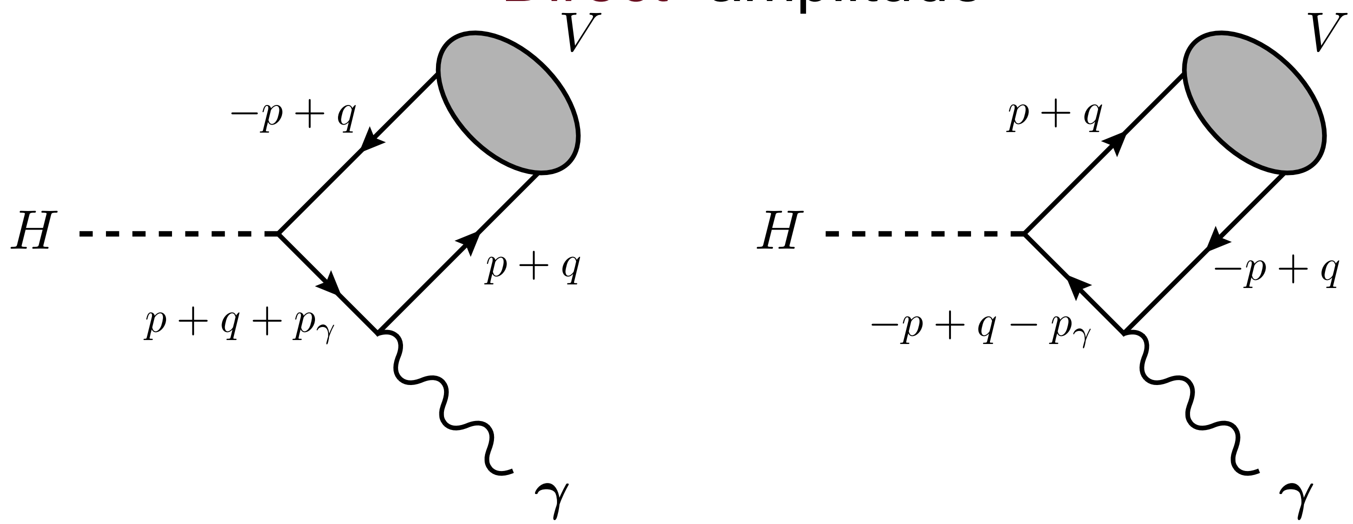
κ_c	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2
S	874	877	885	899	917	941	973	1008	1052

κ_c	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5
S	1097	1148	1206	1276	1350	1424	1504	1590	1683	1786

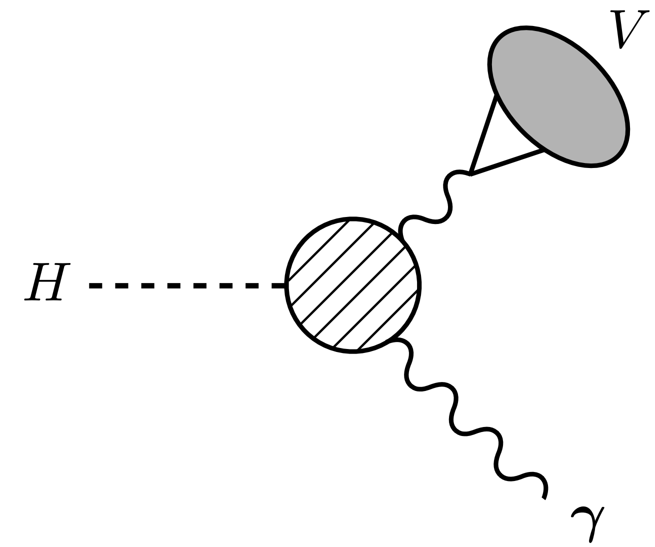
Exclusive Decays H→Qγ

Exclusive decays lead to distinct experimental signatures
→ High-pT quarkonium back-to-back with a high-pT photon.

"Direct" amplitude



"Indirect" contribution



Direct amplitude alone:
→ $BR_{SM}(H\to J/\psi\gamma) = 5.48\cdot10^{-8}$
→ $BR_{SM}(H\to \Upsilon\gamma) = 3.84\cdot10^{-7}$

Phys.Rev. D88 (2013) 5, 053003

Indirect amplitude: significant contribution, larger than direct amplitude

Destructive interference between the two:

$$\Gamma(H\to J/\psi+\gamma) = \left|(11.9\pm0.2)-(1.04\pm0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

Phys.Rev. D90 (2014) 11, 113010

$$\mathrm{Br}(h\to J/\psi\,\gamma) = (2.95\pm0.07_{f_{J/\psi}}\pm0.06_{\mathrm{direct}}\pm0.14_{h\to\gamma\gamma})\cdot10^{-6}\,,$$

$$\mathrm{Br}(h\to \Upsilon(1S)\,\gamma) = (4.61\pm0.06_{f_{\Upsilon(1S)}}\,{}^{+1.75}_{-1.21}{}_{\mathrm{direct}}\pm0.22_{h\to\gamma\gamma})\cdot10^{-9}\,,$$

$$\mathrm{Br}(h\to \Upsilon(2S)\,\gamma) = (2.34\pm0.04_{f_{\Upsilon(2S)}}\,{}^{+0.75}_{-0.99}{}_{\mathrm{direct}}\pm0.11_{h\to\gamma\gamma})\cdot10^{-9}\,,$$

$$\mathrm{Br}(h\to \Upsilon(3S)\,\gamma) = (2.13\pm0.04_{f_{\Upsilon(3S)}}\,{}^{+0.75}_{-1.12}{}_{\mathrm{direct}}\pm0.10_{h\to\gamma\gamma})\cdot10^{-9}\,.$$

JHEP 1508 (2015) 012

Exclusive Decays Z→Qγ: J/ψ and Υ

→ Analogous Z boson decays also attracting significant attention
[Nucl. Phys. B 174, 317 (1980), Theor. Math. Phys. 170, 39 (2012), Phys.Rev. D92 (2015) 014007, JHEP 1504 (2015) 101]

→ These exclusive final states are experimentally unconstrained

→ LEP has accurately measured couplings to b- and c-quarks (~1%), but couplings to light quarks less constrained

→ Sensitive to BSM contributions, e.g, FCNC processes Z→K^0γ/D^0γ/B^0γ/B_sγ (currently constrained indirectly)

Recently, a number of numerical results have appeared, for these decay rates.

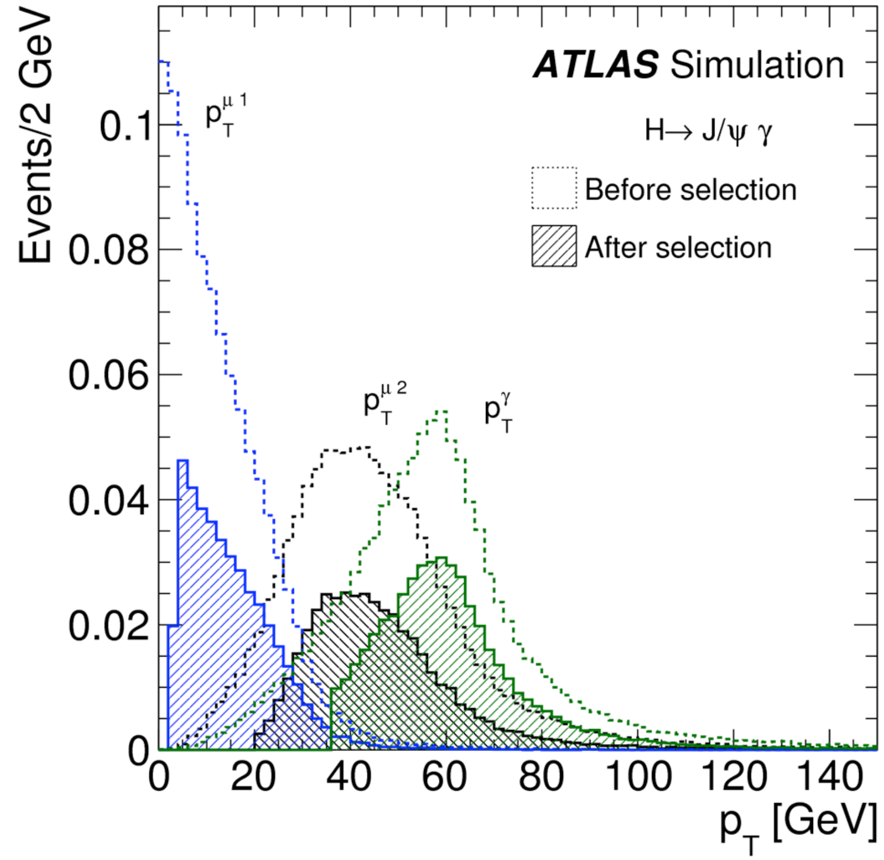
JHEP 1504 (2015) 101

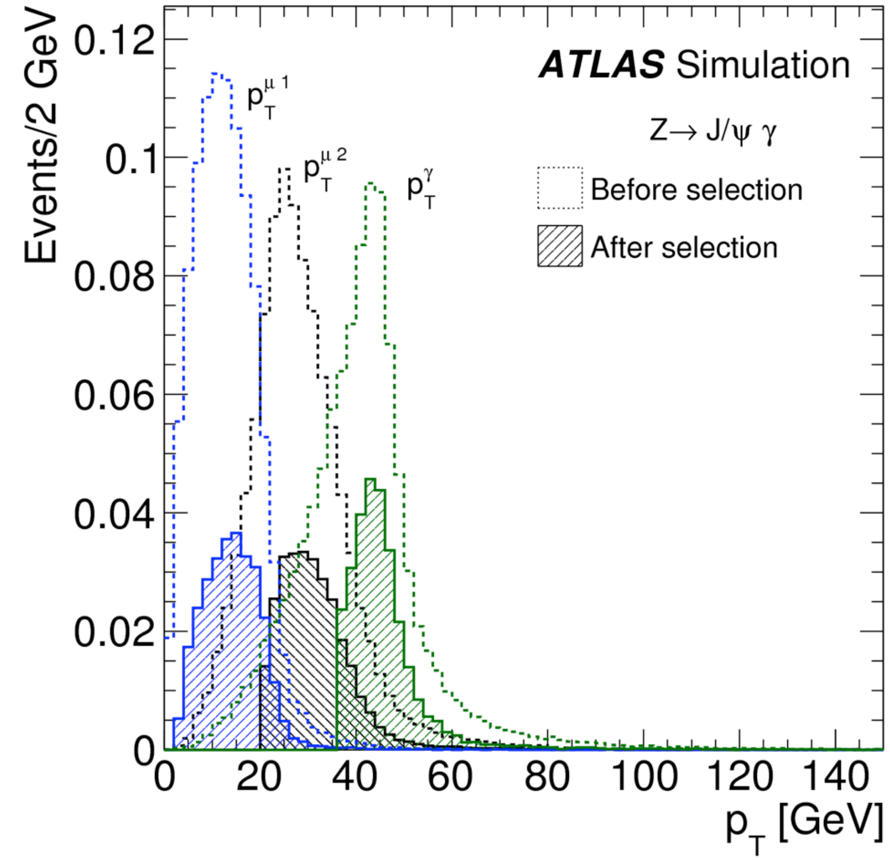
Decay mode	Branching ratio
$Z^0 \to \pi^0\gamma$	$(9.80\,^{+0.09}_{-0.14}\,{}_\mu \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$
$Z^0 \to \rho^0\gamma$	$(4.19\,^{+0.04}_{-0.06}\,{}_\mu \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$
$Z^0 \to \omega\gamma$	$(2.89\,^{+0.03}_{-0.05}\,{}_\mu \pm 0.15_f \pm 0.29_{a_2} \pm 0.25_{a_4}) \cdot 10^{-8}$
$Z^0 \to \phi\gamma$	$(8.63\,^{+0.08}_{-0.13}\,{}_\mu \pm 0.41_f \pm 0.55_{a_2} \pm 0.74_{a_4}) \cdot 10^{-9}$
$Z^0 \to J/\psi\,\gamma$	$(8.02\,^{+0.14}_{-0.15}\,{}_\mu \pm 0.20_f\,^{+0.39}_{-0.36}\,{}_\sigma) \cdot 10^{-8}$
$Z^0 \to \Upsilon(1S)\,\gamma$	$(5.39\,^{+0.10}_{-0.10}\,{}_\mu \pm 0.08_f\,^{+0.11}_{-0.08}\,{}_\sigma) \cdot 10^{-8}$
$Z^0 \to \Upsilon(4S)\,\gamma$	$(1.22\,^{+0.02}_{-0.02}\,{}_\mu \pm 0.13_f\,^{+0.02}_{-0.02}\,{}_\sigma) \cdot 10^{-8}$
$Z^0 \to \Upsilon(nS)\,\gamma$	$(9.96\,^{+0.18}_{-0.19}\,{}_\mu \pm 0.09_f\,^{+0.20}_{-0.15}\,{}_\sigma) \cdot 10^{-8}$

h→J/ψγ and h→Υ(ns)γ

Phys.Rev.Lett. 114 (2015) 121801

ATLAS performed the first search for these exclusive decays of the Higgs and Z bosons $H/Z \to Q\gamma$ where Q = J/ψ or Υ(1S,2S,3S)





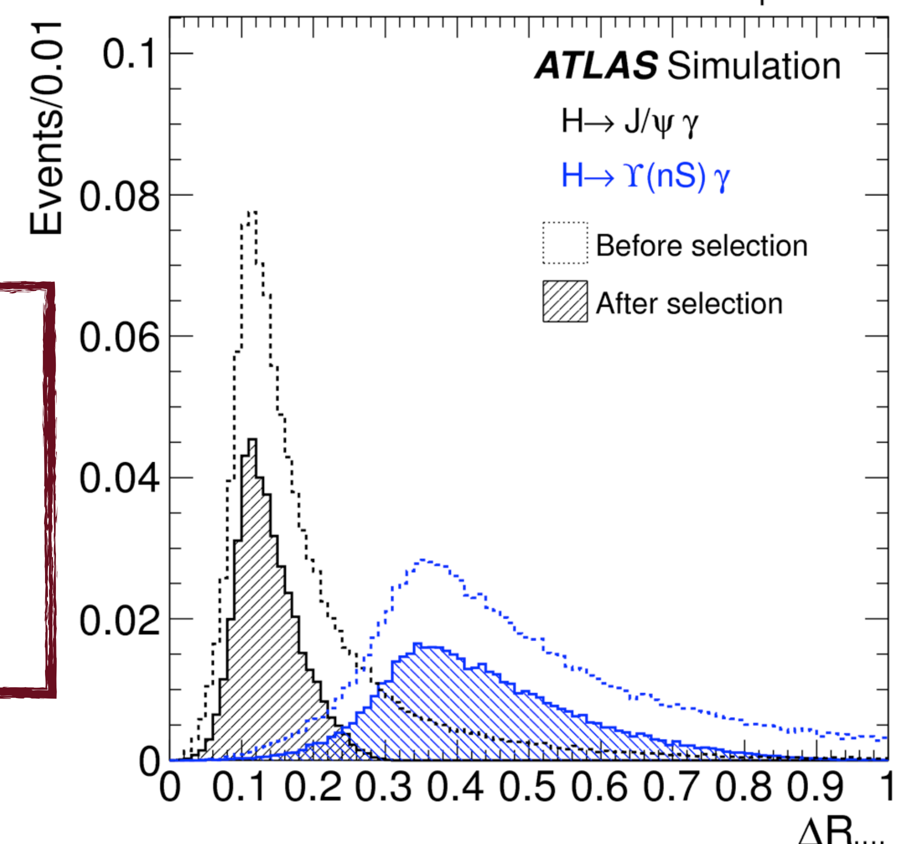
Signature: $\mu^+\mu^-+\gamma$

→ event selection:
- single(di)-muon trigger
- pT_μ>20,3 GeV,
- $pT_{\mu\mu}$>36 GeV,
- pT_γ>36 GeV
- μμ and γ isolation,
- [J/ψ mass requirement]
- L_{xy} significance,
- $\Delta\varphi(\mu\mu,\gamma)$>0.5

→ total signal acceptance/efficiency
- $H(Z)\to J/\psi\gamma\to\mu^+\mu^-+\gamma$ ~ 22% (12%)
- $H(Z)\to \Upsilon\gamma\to\mu^+\mu^-+\gamma$ ~ 28% (15%)

→ $m_{\mu\mu\gamma}$ mass resolution ~1.2-1.8%

$e^+e^-+\gamma$
experimentally more challenging
- dedicated reconstruction for nearby electrons
- poorer mass resolution/efficiency
- typically larger backgrounds



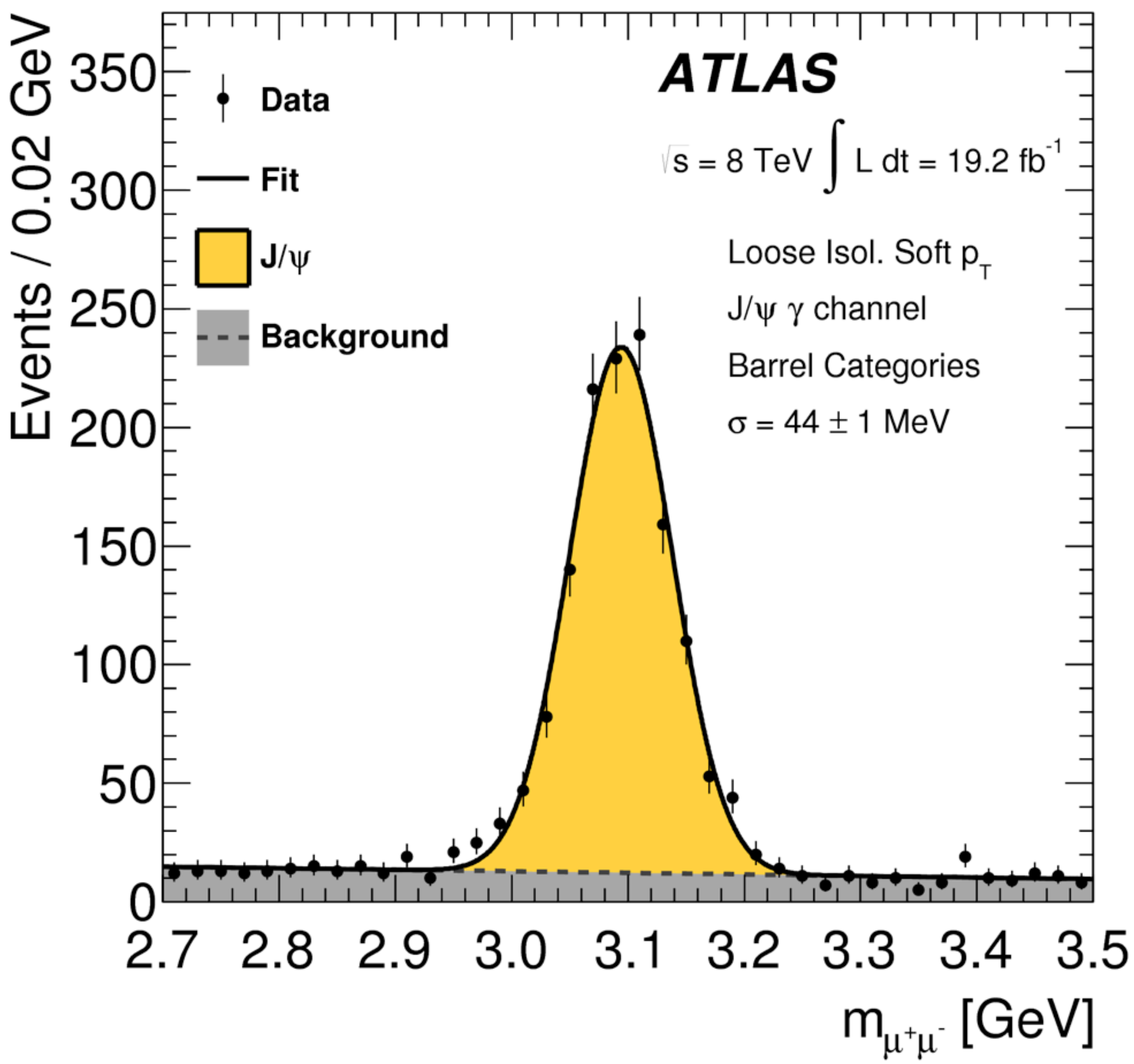
h/Z→J/ψγ and h/Z→Υ(ns)γ

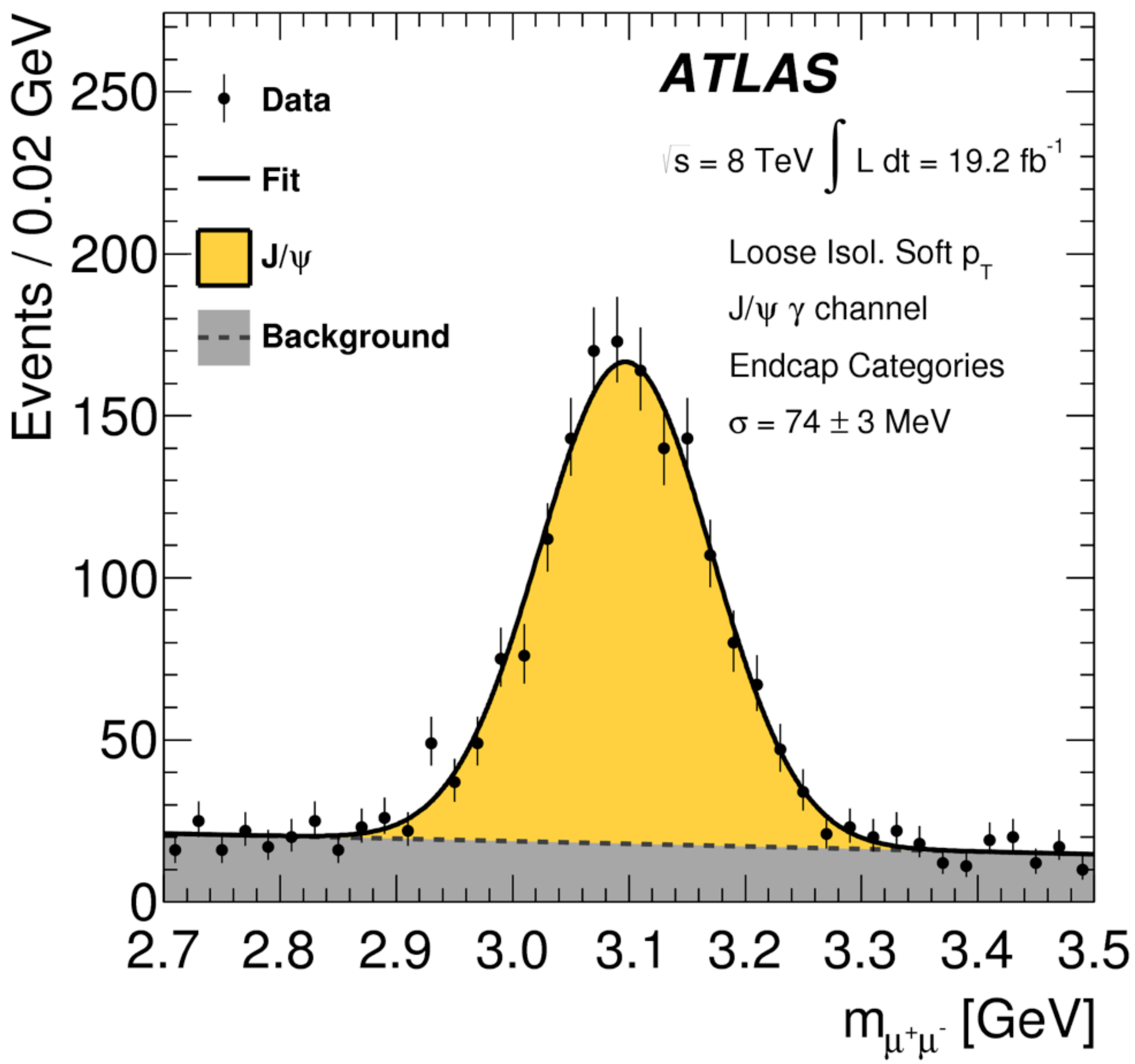
Phys.Rev.Lett. 114 (2015) 121801

Categories

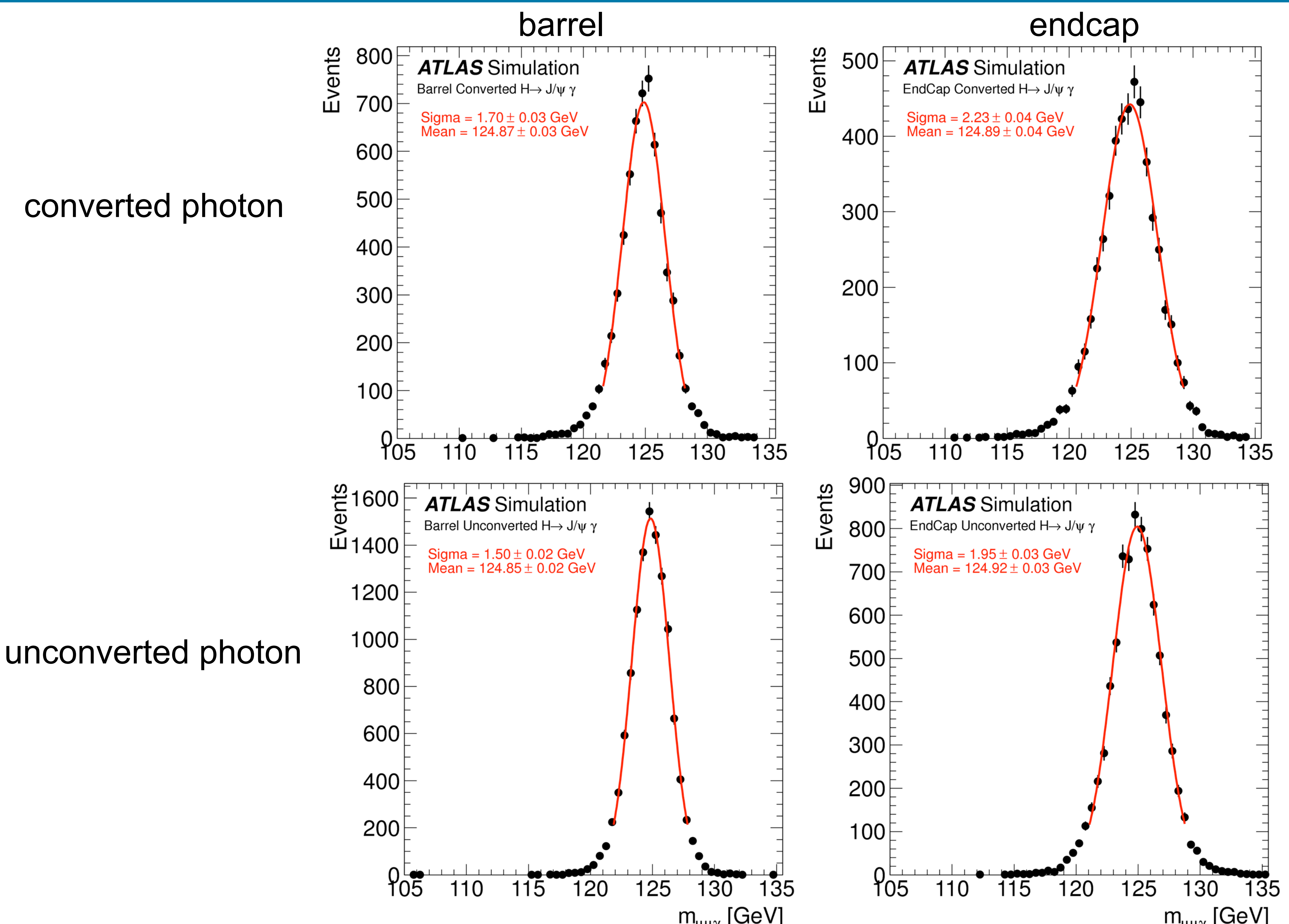
For this search simple - detector performance driven categorisation

→ Muon pseudo-rapidity
  → Both Central/One Non-Central
→ Photon Unconverted/Converted





h→J/ψγ and h→ϒ(ns)γ: Mass Resolution



h/Z→J/ψγ and h/Z→Υ(ns)γ

Phys.Rev.Lett. 114 (2015) 121801

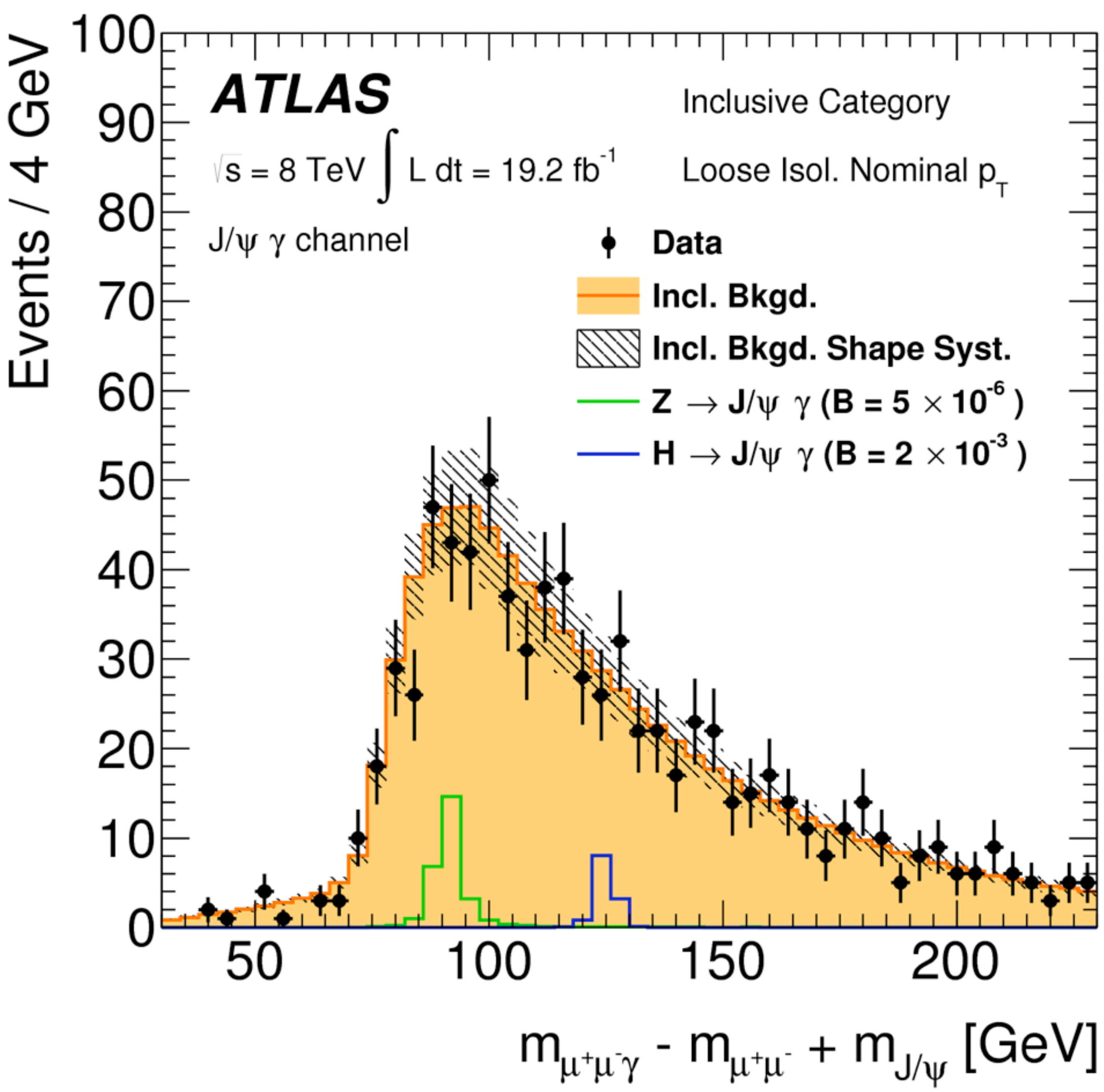
Background

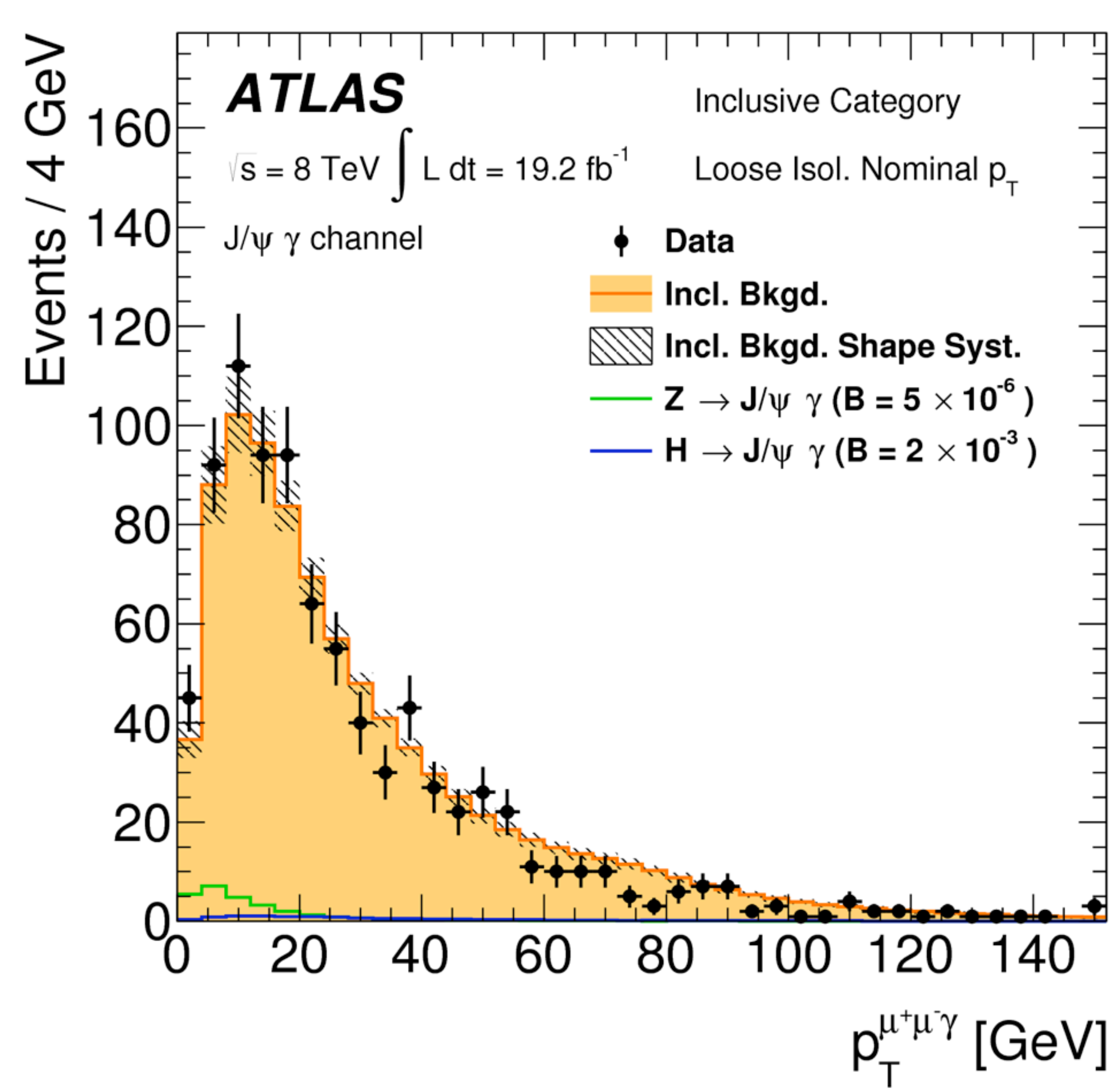
→ inclusive quarkonium with jet “seen” as γ
- → small component of combinatoric
- → contribution from Q+γ production

→ Non-parametric data-driven background estimation

→ for Υ(nS)γ also $Z \to \mu\mu\gamma_{FSR}$ from side-band fit

Category	Observed (Expected Background)					Signal	
		Mass Range [GeV]				Z	H
	All	80–100		115–135		$\mathcal{B}$ $[10^{-6}]$	$\mathcal{B}$ $[10^{-3}]$
$J/\psi\,\gamma$							
BU	30	9	(8.9±1.3)	5	(5.0±0.9)	1.29±0.07	1.96±0.24
BC	29	8	(6.0±0.7)	3	(5.5±0.6)	0.63±0.03	1.06±0.13
EU	35	8	(8.7±1.0)	10	(5.8±0.8)	1.37±0.07	1.47±0.18
EC	23	6	(5.6±0.7)	2	(3.0±0.4)	0.99±0.05	0.93±0.12
$\Upsilon(nS)\,\gamma$							
BU	93	42	(39±6)	16	(12.9±2.0)	1.67±0.09	2.6±0.3
BC	71	32	(27.7±2.4)	5	(9.7±1.2)	0.79±0.04	1.45±0.18
EU	125	49	(47±6)	16	(17.8±2.4)	2.24±0.12	2.5±0.3
EC	85	31	(31±5)	18	(12.3±1.9)	1.55±0.08	1.60±0.20

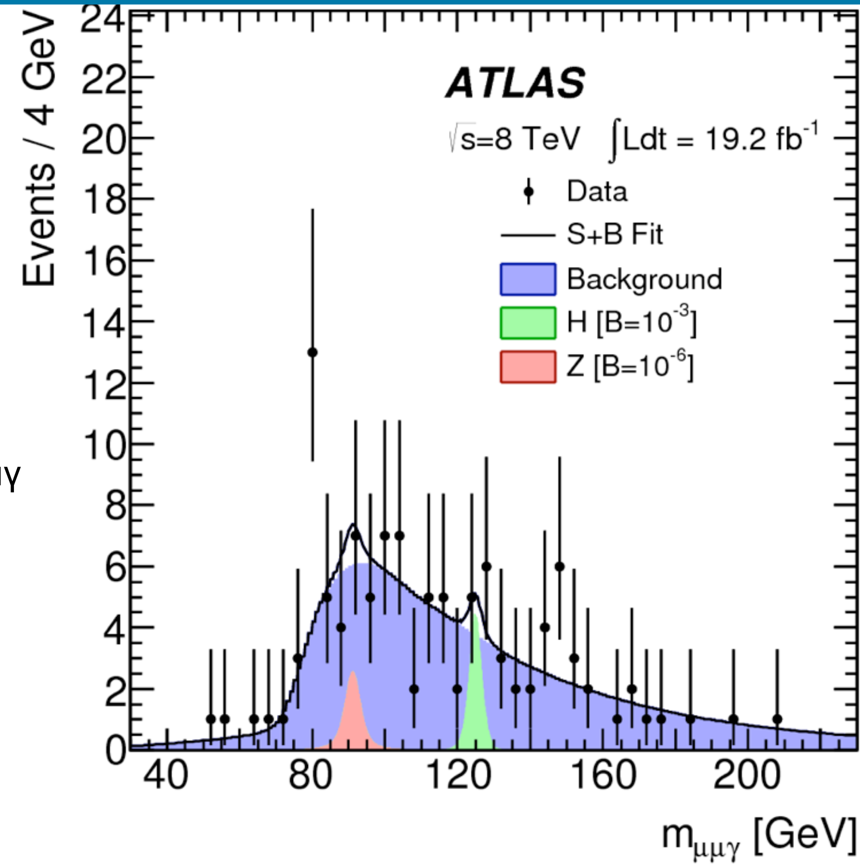


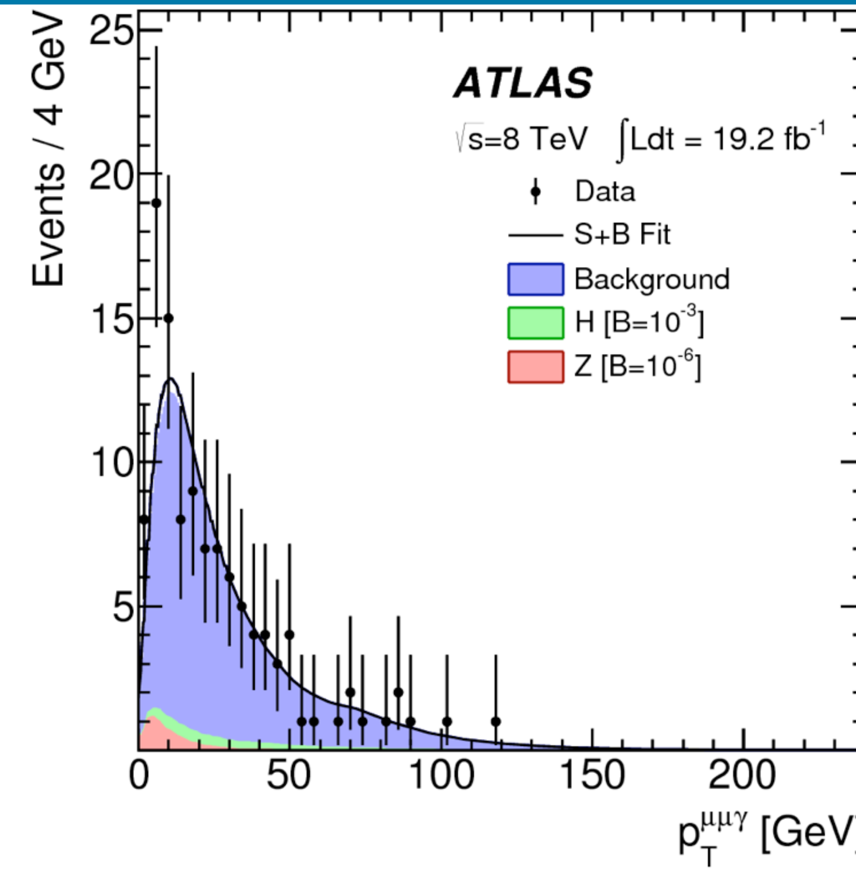


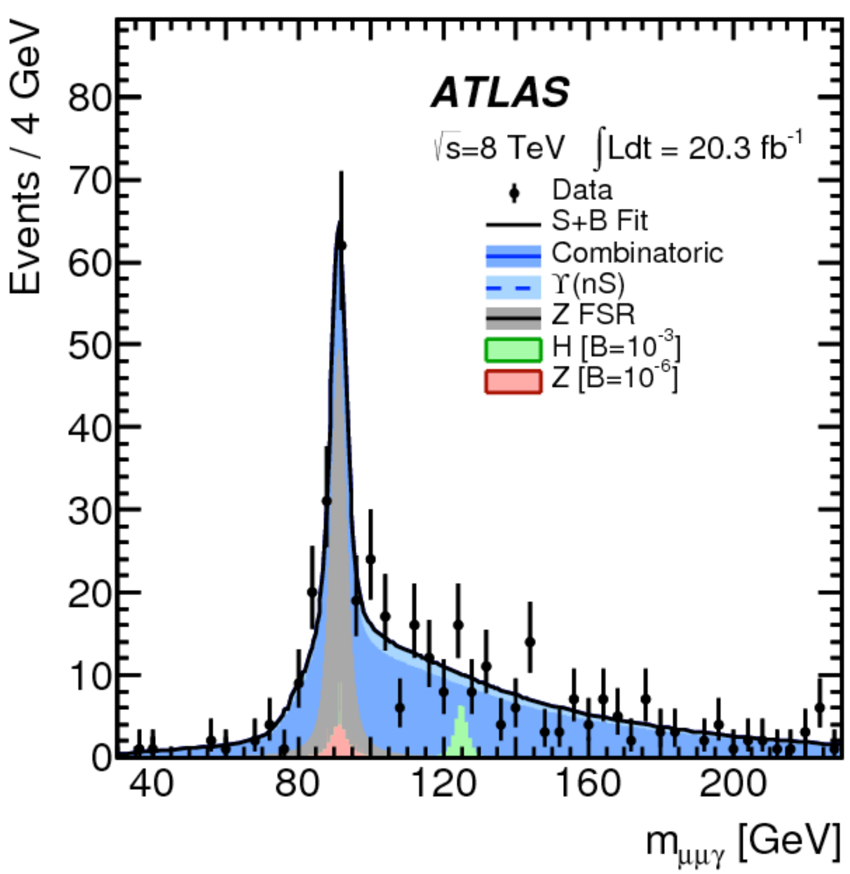
h/Z→J/ψγ and h/Z→Υ(ns)γ: Results

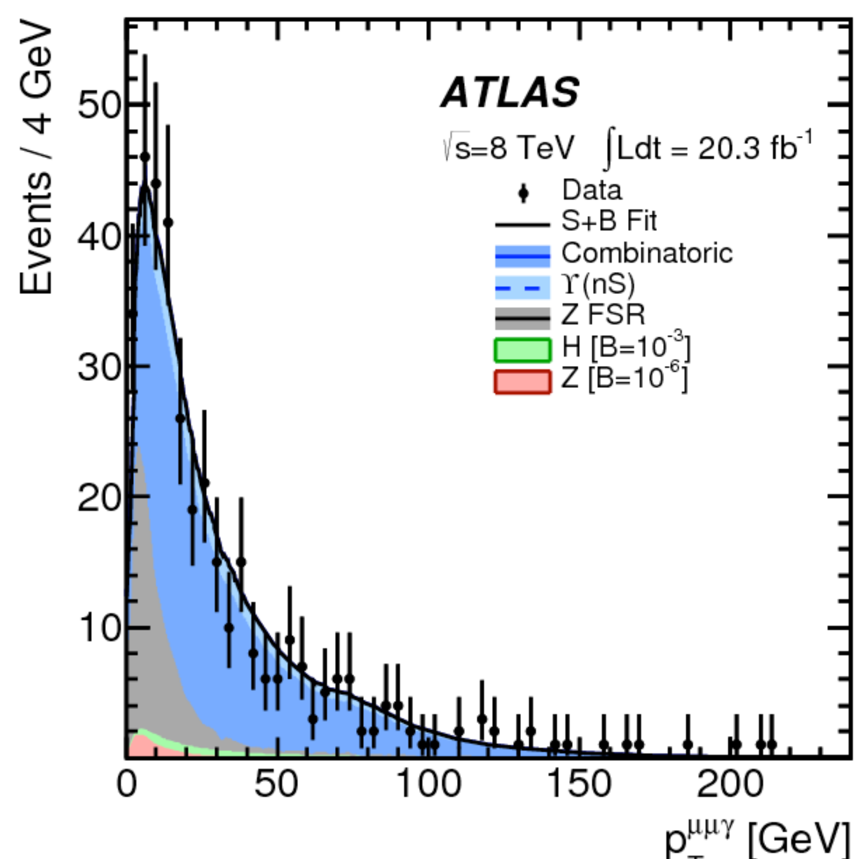
Phys.Rev.Lett. 114 (2015) 1121801

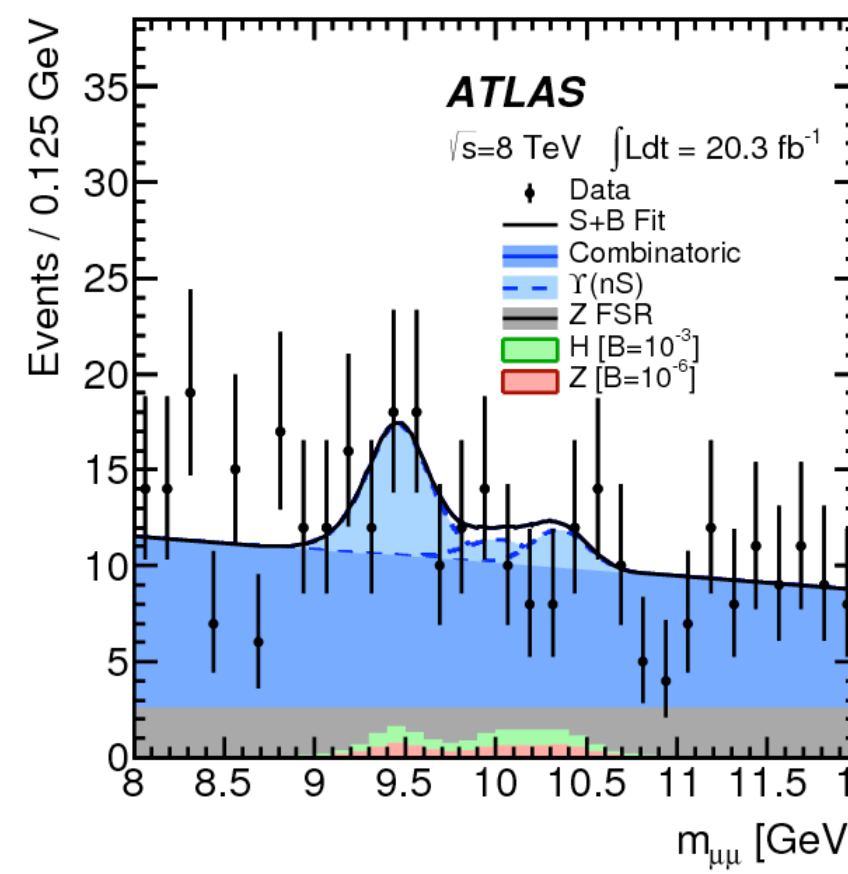
→ Multi-observable fit to $m_{\mu\mu\gamma}$, $pT_{\mu\mu\gamma}$
→ also $m_{\mu\mu}$ for Υ(nS)γ
→ No significant excess above background observed



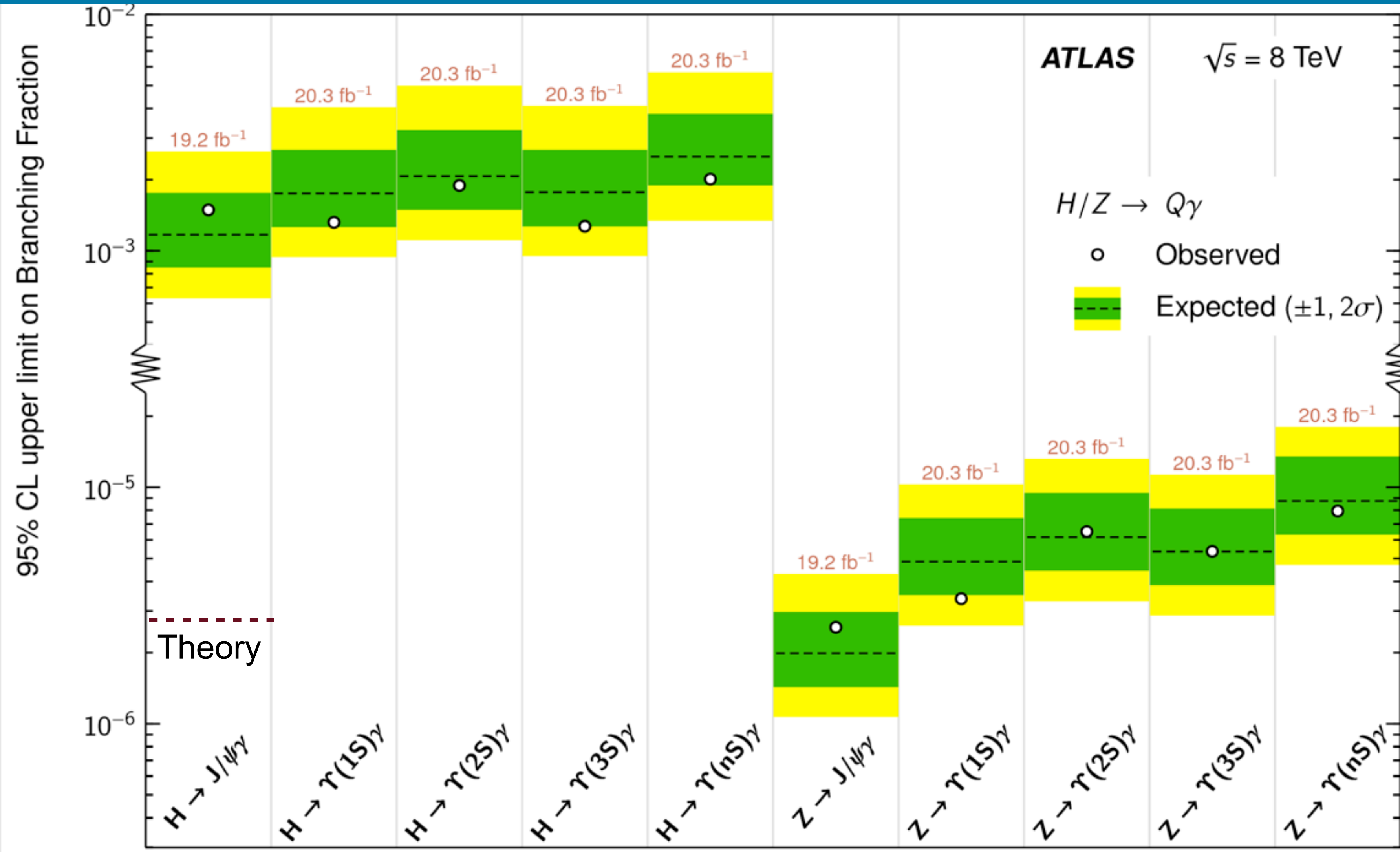








h/Z→J/ψγ and h/Z→Υ(ns)γ: Results



Phys.Rev.Lett. 114 (2015) 12, 121801

	95% CL_s Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [10^{-6}]					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H \to \mathcal{Q}\gamma)$ [10^{-3}]					
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]					
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44

First search for H/Z→Qγ, indications for non-universal Higgs boson couplings to quarks, will constitute the basis for Run 2 and HL-LHC extrapolations

BR 95% CLs upper limits:
~10^{-3} level for Higgs boson (SM production) decays and ~10^{-6} for the Z boson decays

CMS recently obtained 95% CL upper limit on BR[H→(J/ψ)γ] < 1.5x10^{-3} [arXiv:1507.03031]

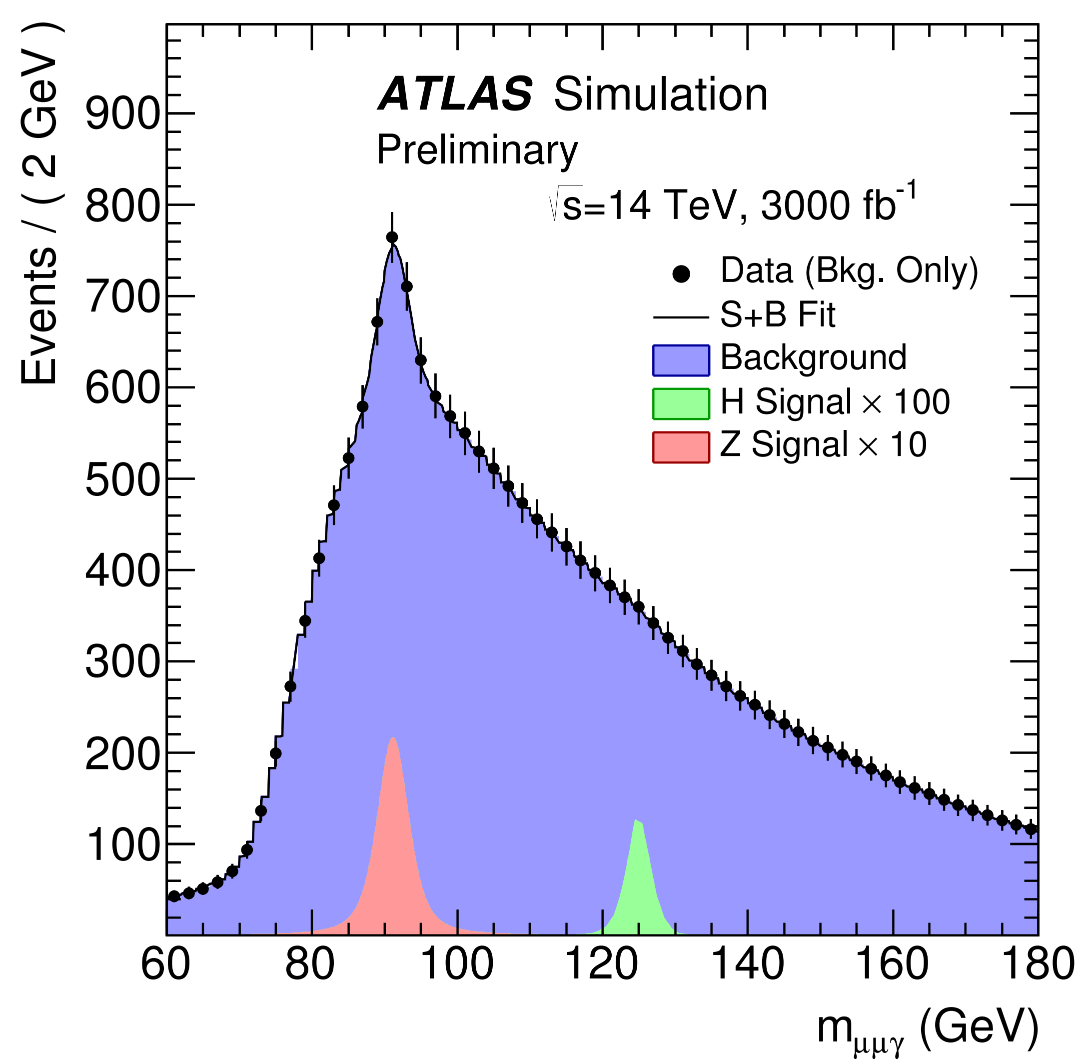
h/Z→J/ψγ and h/Z→Υ(ns)γ: in the future

This is a nice and, relatively, clean final state.
Fun and interesting thing to do!
Drawbacks:
1) Small branching ratio, a handful of events expected even at HL-LHC
2) At SM sensitivity significant contribution from non-resonant h→μμγ ~3×h→J/ψγ and Z→μμγ
3) This channel is also affected by potential "anomalies" in the h→γγ loop

3000 fb^{-1} @ 14 TeV

$J/\psi\,\gamma$ Final state

	Expected Background				Signal	
	Inclusive QCD Mass Range [GeV]		Other Backgrounds			
	80-100	115-135	$Z \to \mu^+\mu^-\gamma$	$H_{\gamma^*\gamma} \to \mu^+\mu^-\gamma$	Z	H
Cut Based Analysis	7800±500	3500±400	780 ±100	15.1 ±1.4	62±3	3.1±0.1
Multivariate Analysis		1700±200		13.7 ±1.3		2.8±0.1

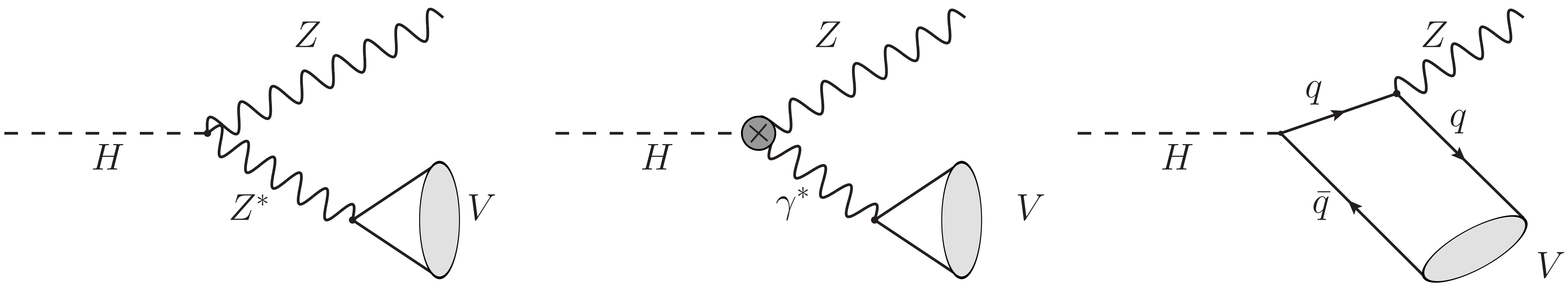


	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$		$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	Cut Based	Multivariate Analysis	Cut Based
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$

	Standard Model expectation	
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$	$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	2.9 ± 0.2	0.80 ± 0.05

H→ZJ/ψ and H→ZΥ(ns): A short note

arXiv:1411.2210



H→ZQ could be another, way to approach the charm/bottom Yukawa couplings, quite similar to the exclusive H→Qγ decays discussed earlier.

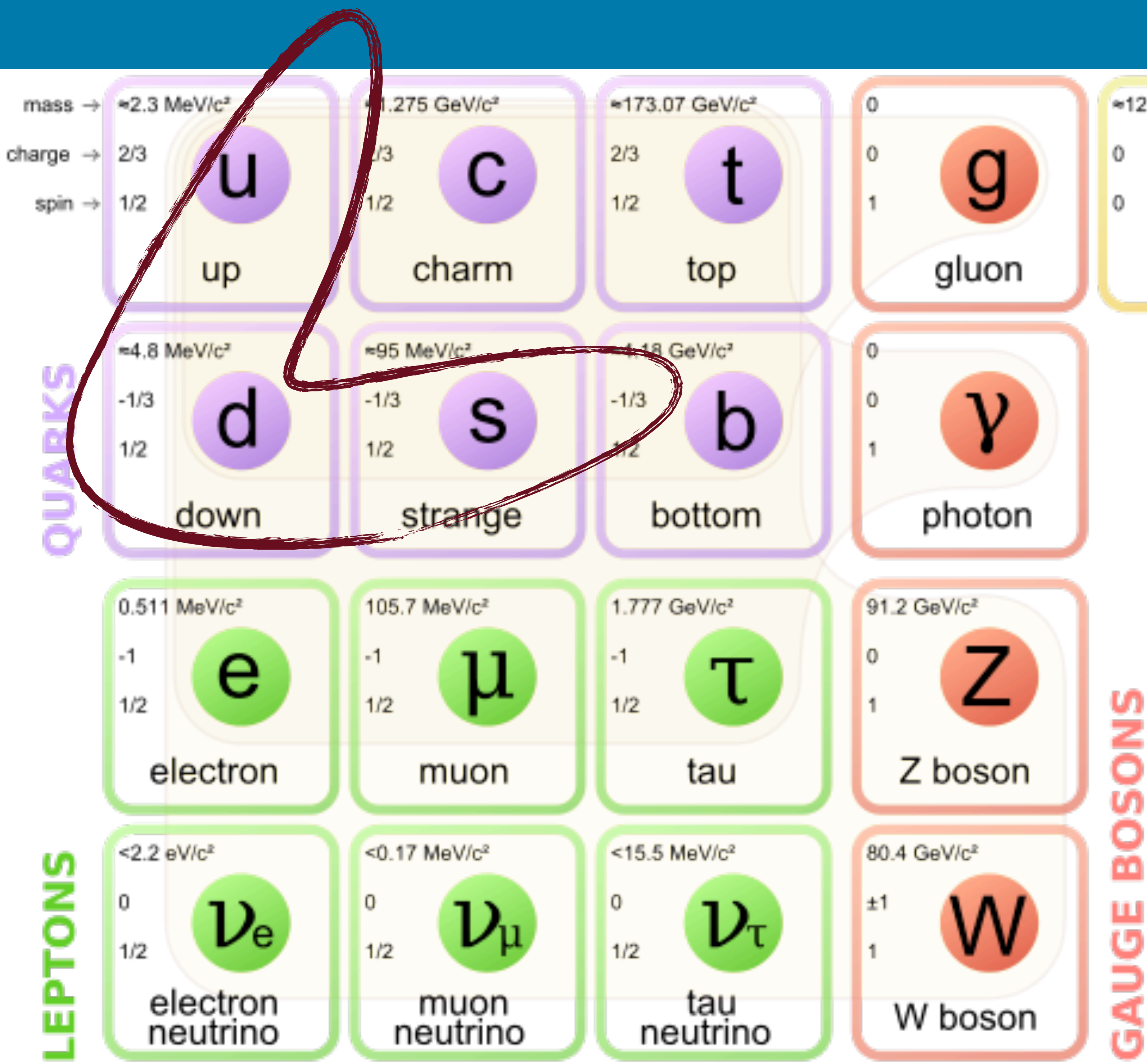
arXiv:1411.2210

$\mathcal{B}r(H \to ZV)$	$J/\psi(1S)$	$\Upsilon(1S)$
$\mathcal{B}r_{\Gamma_1}$	1.75×10^{-6}	1.68×10^{-5}
$\mathcal{B}r_{\Gamma_2}$	1.14×10^{-6}	8.33×10^{-8}
$\mathcal{B}r_{\Gamma_3}$	8.52×10^{-9}	5.80×10^{-7}
$\mathcal{B}r_{\Gamma_{12}}$	4.50×10^{-7}	1.10×10^{-6}
$\mathcal{B}r_{\Gamma_{13}}$	3.89×10^{-8}	2.89×10^{-6}
$\mathcal{B}r_{\Gamma_{23}}$	1.97×10^{-7}	4.40×10^{-7}

$$\Gamma = \Gamma_1 \kappa_V^2 + \Gamma_2 \kappa_{Z\gamma}^2 + \Gamma_3 \kappa_Q^2 + \Gamma_{12} \kappa_V \kappa_{Z\gamma} + \Gamma_{13} \kappa_V \kappa_Q + \Gamma_{23} \kappa_{Z\gamma} \kappa_Q$$

$\boxed{\mathrm{BR_{SM}}(H\to J/\psi\gamma) \simeq \mathrm{BR_{SM}}(H\to ZJ/\psi)}$

need to account for the additional
~6% BR(Z→ee/μμ)
and properly evaluate S/B



mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
1.275 GeV/c²
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
-1/3
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

Light-Quark Yukawa couplings

Initially, considered impossible at the LHC, recent activity on its feasibility:

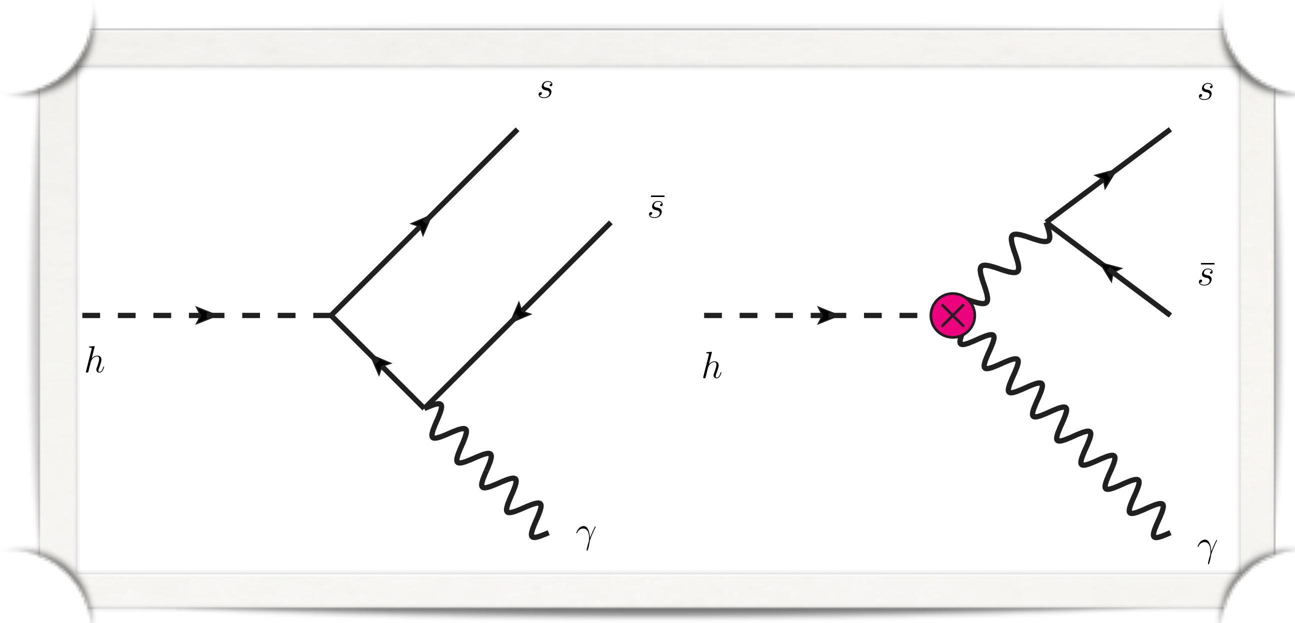
→ Exploit the exclusive decays H→Qγ as direct probe to the quark Yukawa couplings

[Phys.Rev.Lett. 114 (2015) 101802]

→ Sensitive to BSM physics [Phys. Rev. D 80, 076002, Phys. Lett. B665 (2008) 79, Phys.Rev. D90 (2014) 115022]

The idea is to benefit from the interference of the “direct” and “indirect” amplitudes!

Phys.Rev.Lett. 114 (2015) 101802



$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(3.0\pm0.3)\kappa_\gamma-0.78\bar{\kappa}_s]\times10^{-6}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(1.9\pm0.2)\kappa_\gamma-0.24\bar{\kappa}_u-0.12\bar{\kappa}_d]\times10^{-5}}{0.57\bar{\kappa}_b^2},$$

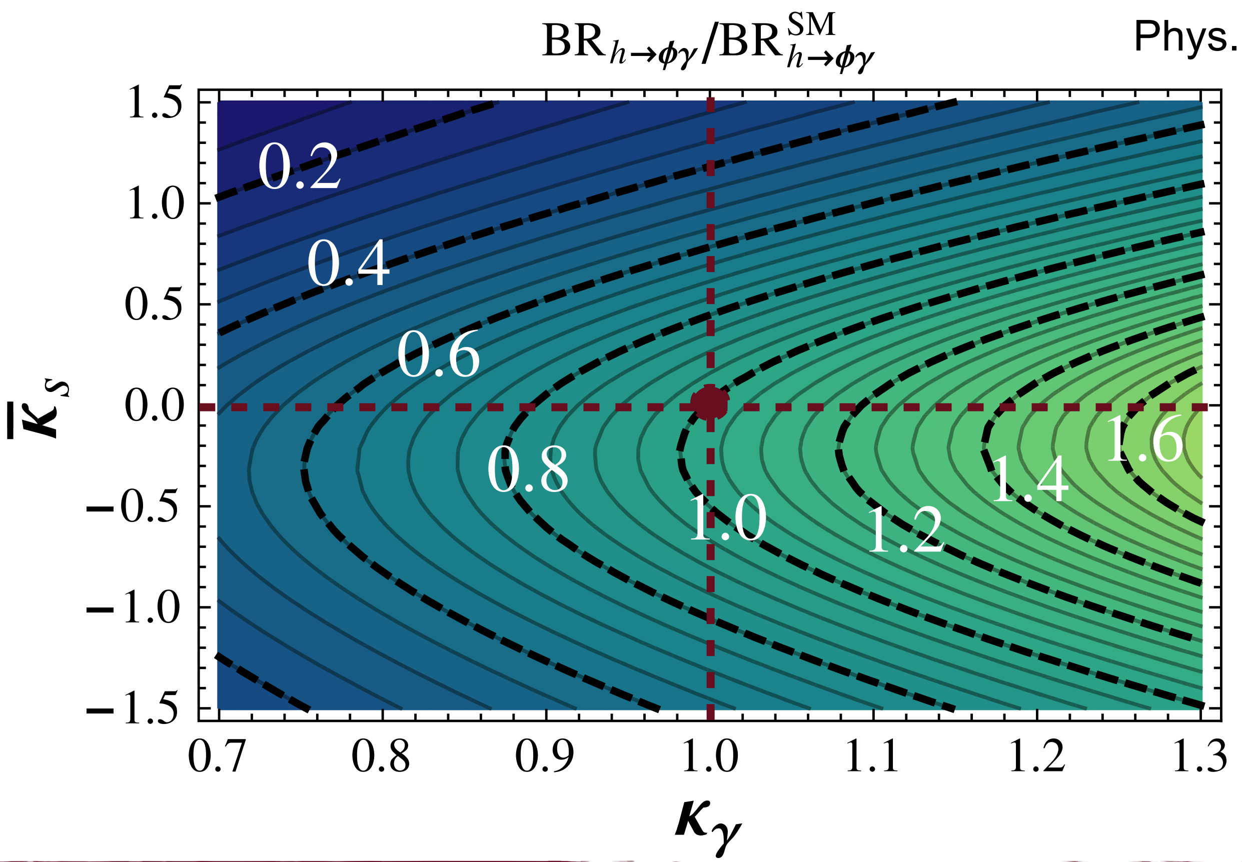
$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(1.6\pm0.2)\kappa_\gamma-0.59\bar{\kappa}_u-0.29\bar{\kappa}_d]\times10^{-6}}{0.57\bar{\kappa}_b^2},$$

$$\bar{\kappa}_s = m_s/m_b \approx 0.02$$
$$\bar{\kappa}_d = m_d/m_b \approx 1\cdot 10^{-3}$$
$$\bar{\kappa}_u = m_u/m_b \approx 4.7\cdot 10^{-4}$$

$$\mathrm{Br}(h\to\rho^0\gamma) = (1.68\pm0.02_{f_\rho}\pm0.08_{h\to\gamma\gamma})\cdot10^{-5}\,,$$
$$\mathrm{Br}(h\to\omega\gamma) = (1.48\pm0.03_{f_\omega}\pm0.07_{h\to\gamma\gamma})\cdot10^{-6}\,,$$
$$\mathrm{Br}(h\to\phi\gamma) = (2.31\pm0.03_{f_\phi}\pm0.11_{h\to\gamma\gamma})\cdot10^{-6}\,,$$

JHEP 1508 (2015) 012

Light-Quark Yukawa couplings

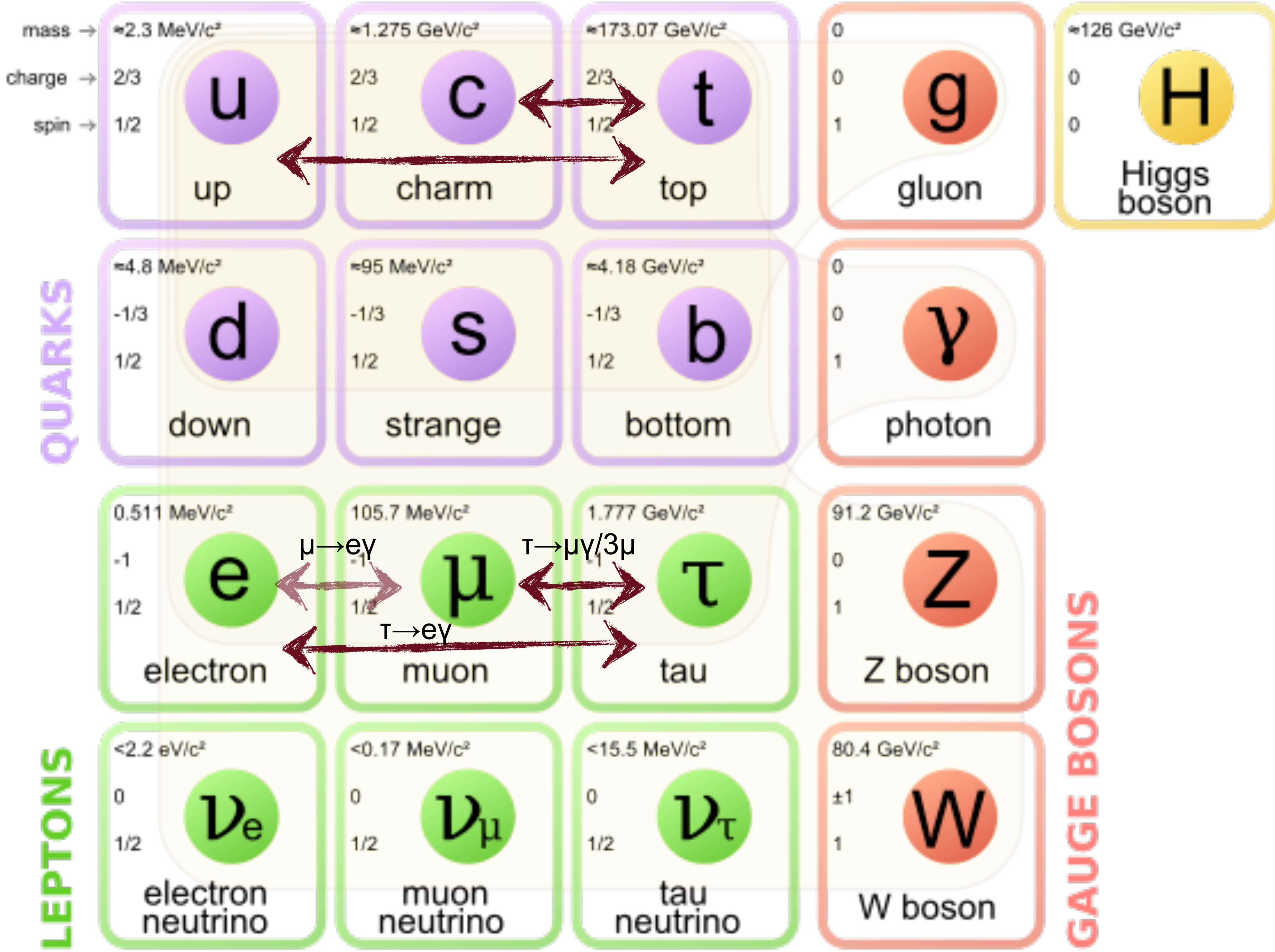


Phys.Rev.Lett. 114 (2015) 101802

$\varphi \to K^+K^-$ (BR=48.9%), ~8 events 100 fb^{-1} @14 TeV!
$\omega \to \pi^+\pi^-\pi^0$ (BR=89.2%) similar rate
$\rho \to \pi^+\pi^-$ (BR~100%) expect ~100 events!

Interesting/experimentally challenging topologies!
- triggering on a photon + narrow hadronic jet
→ will benefit from ATLAS FTK
- boosted decays but overwhelming QCD backgrounds,
- Γ_ρ and ω-ρ interference

arXiv:1505.06689
Preliminary "back-of-the-envelope" study gives pessimistic prospects of $\kappa_c < \mathcal{O}(2000)$ at the HL-LHC


mass →
charge →
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≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
QUARKS
0.511 MeV/c²
-1
1/2
e
electron
μ→eγ
105.7 MeV/c²
-1
1/2
μ
muon
τ→μγ/3μ
1.777 GeV/c²
-1
1/2
τ
tau
τ→eγ
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
ν_e
electron neutrino
<0.17 MeV/c²
0
1/2
ν_μ
muon neutrino
<15.5 MeV/c²
0
1/2
ν_τ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
LEPTONS
GAUGE BOSONS

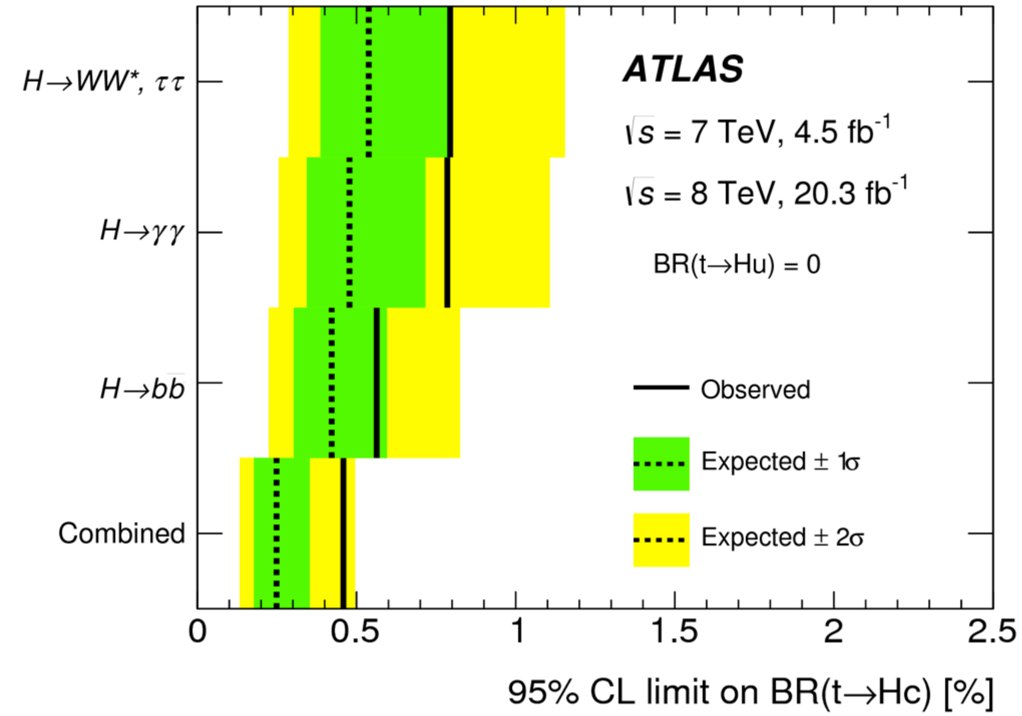
Quark/Lepton Flavor Violation

→ Indirect constraints from low-energy data; certain transitions still loosely constrained
[JHEP 03 (2013) 026; Phys.Lett. B712 (2012) 386]
→ QFV: constraints from flavor physics
→ LFV: constraints from $\mu \to e\gamma$, $\tau \to \mu/e\gamma$, μ/e g-2, EDM
$BR(H \to e\mu) < 10^{-8}$; $BR(H \to e\tau) \lesssim 10\%$; $BR(H \to \mu\tau) \lesssim 10\%$

FCNC in t→qh

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

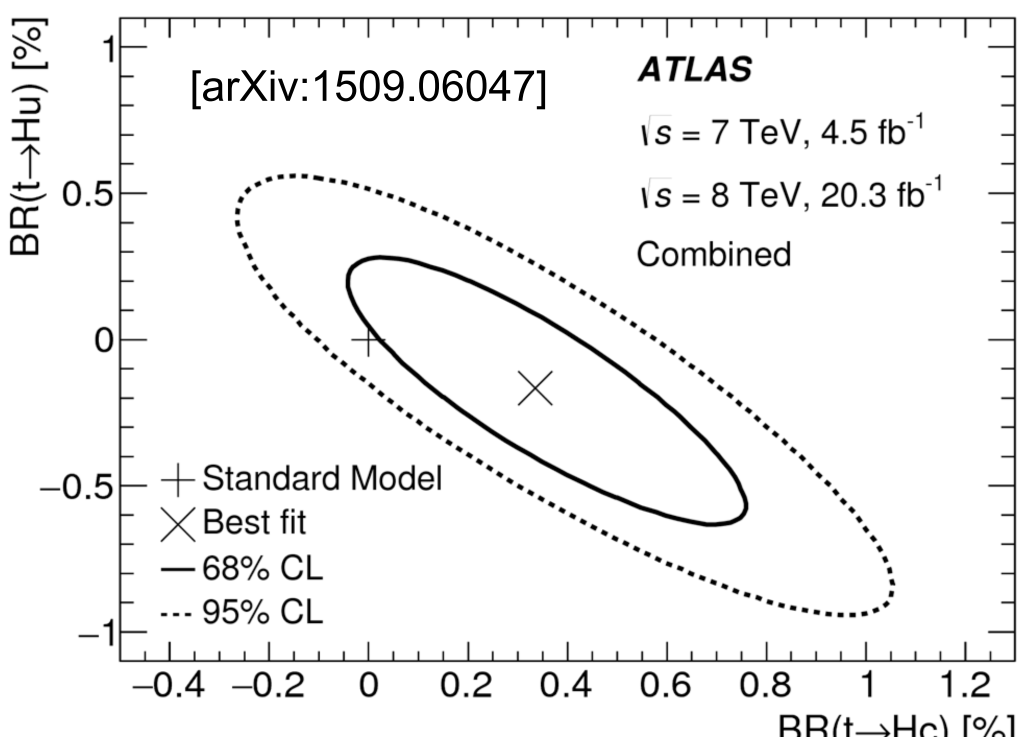
$t\bar{t} \to Wbhq \to \ell\nu bbbq$ [arXiv:1509.06047]

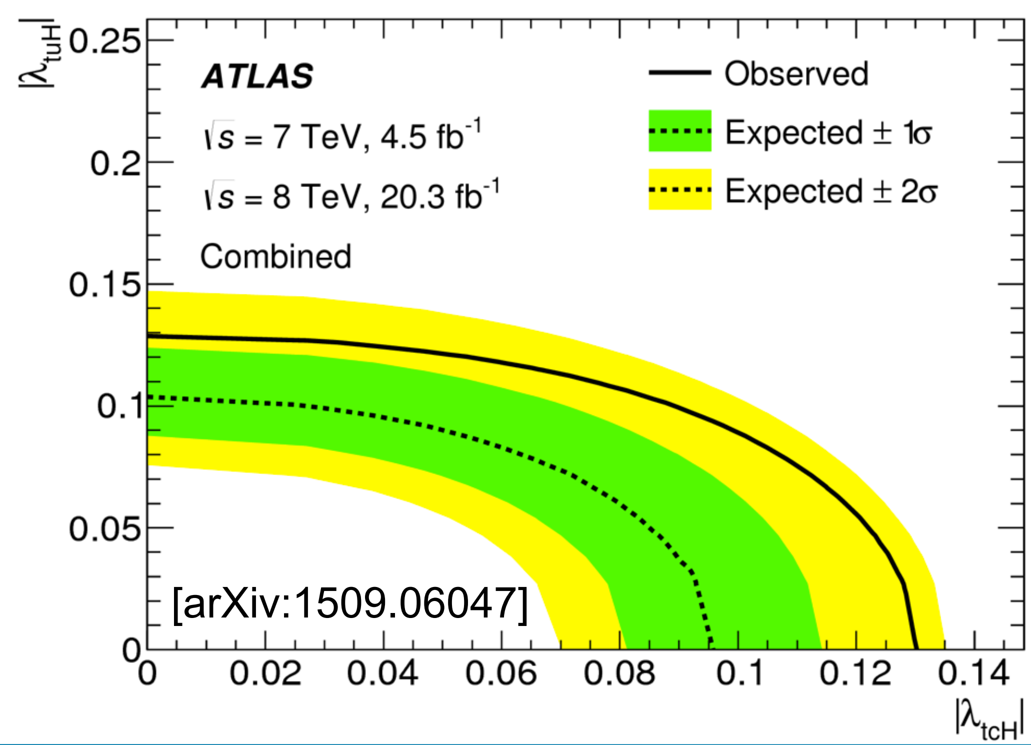


Light quarks challenging, focus is on top-quark decays in ttbar

- ATLAS comprehensive search for t→qh(→γγ, bb, WW, ττ), where q=(c,u) [h→bb discriminates c and u]
  - 95% CL upper limit on BR(t→ch): 0.46% (0.25%)
  - 95% CL upper limit on BR(t→uh): 0.45% (0.29%)
- CMS combined h→γγ and multi-lepton search.[Phys.Rev. D90 (2014) 112013]
  - 95% CL upper limit on BR(t→ch): 0.56% (0.65%)

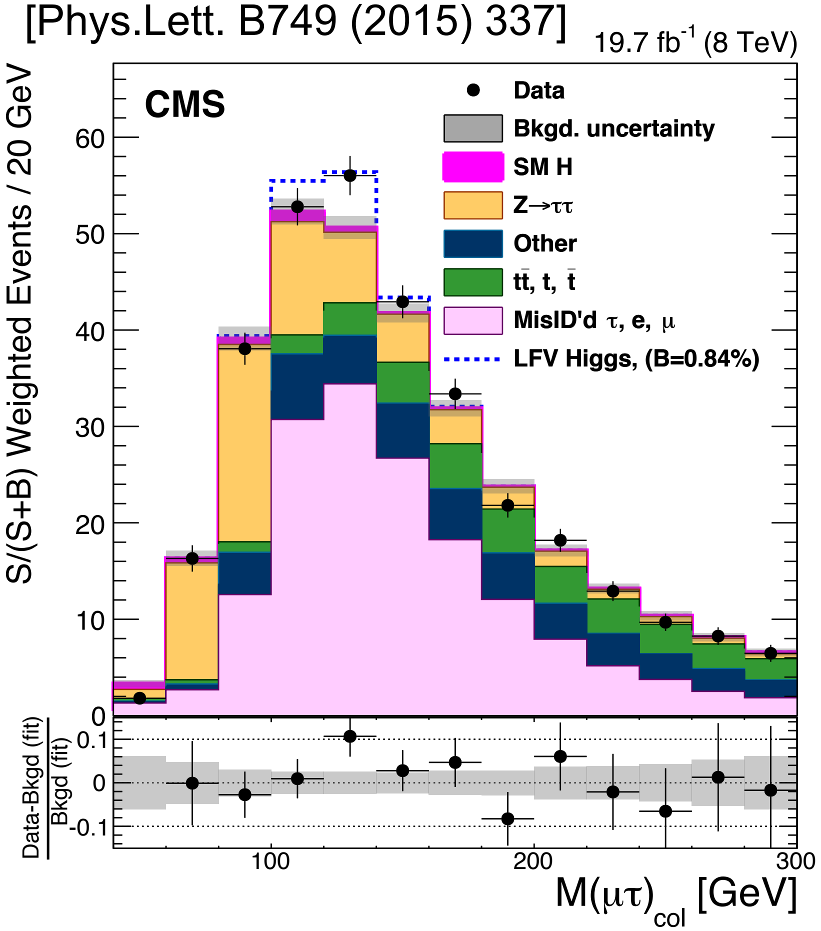
$$\mathcal{L}_{\rm FCNC} = \lambda_{tcH}\bar{t}Hc + \lambda_{tuH}\bar{t}Hu + h.c.$$

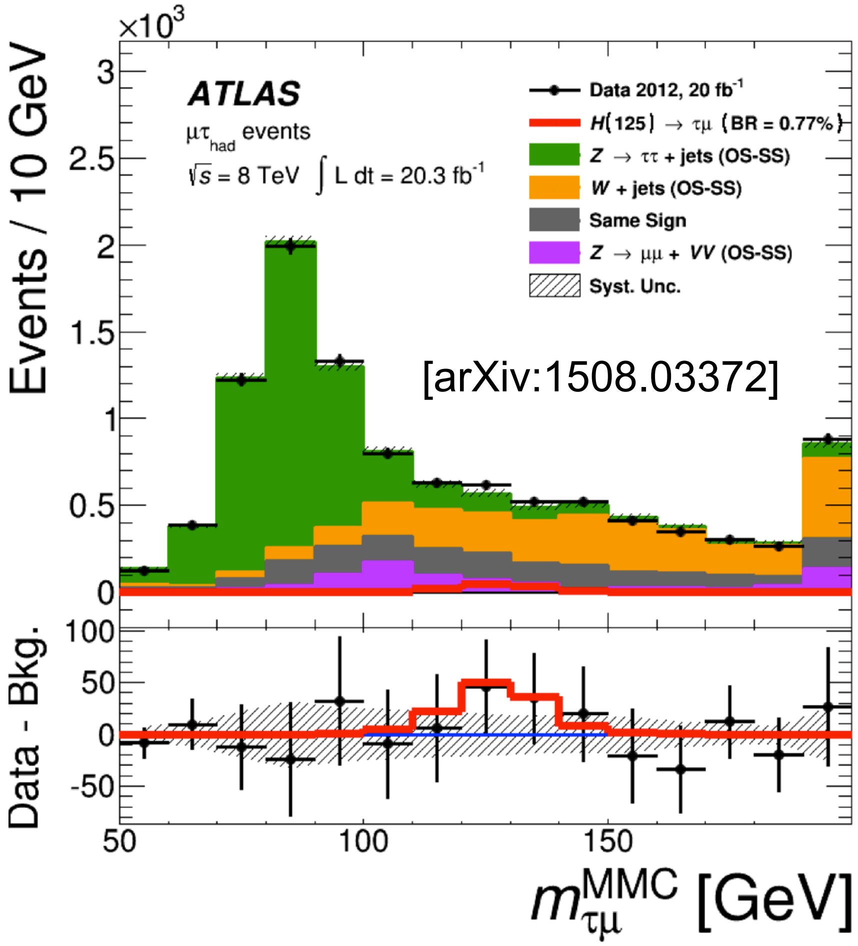




- Direct search for Lepton Flavor Violating h→τμ
  - $\tau_h\mu$ (ATLAS and CMS)
    - Background: fake τ from W+jets/QCD/ttbar, Z→ττ
  - $\tau_e\mu$ (CMS-only)
    - Background: Z→ττ
  - Small contribution from h→ττ
  - Categorize in number of jets: 0, 1, 2 jets
- Data driven background estimates
  - Z→ττ embedding
  - fake τ from side-band method
- Discriminant variable: MMC (ATLAS), collinear mass of μτ system (CMS)

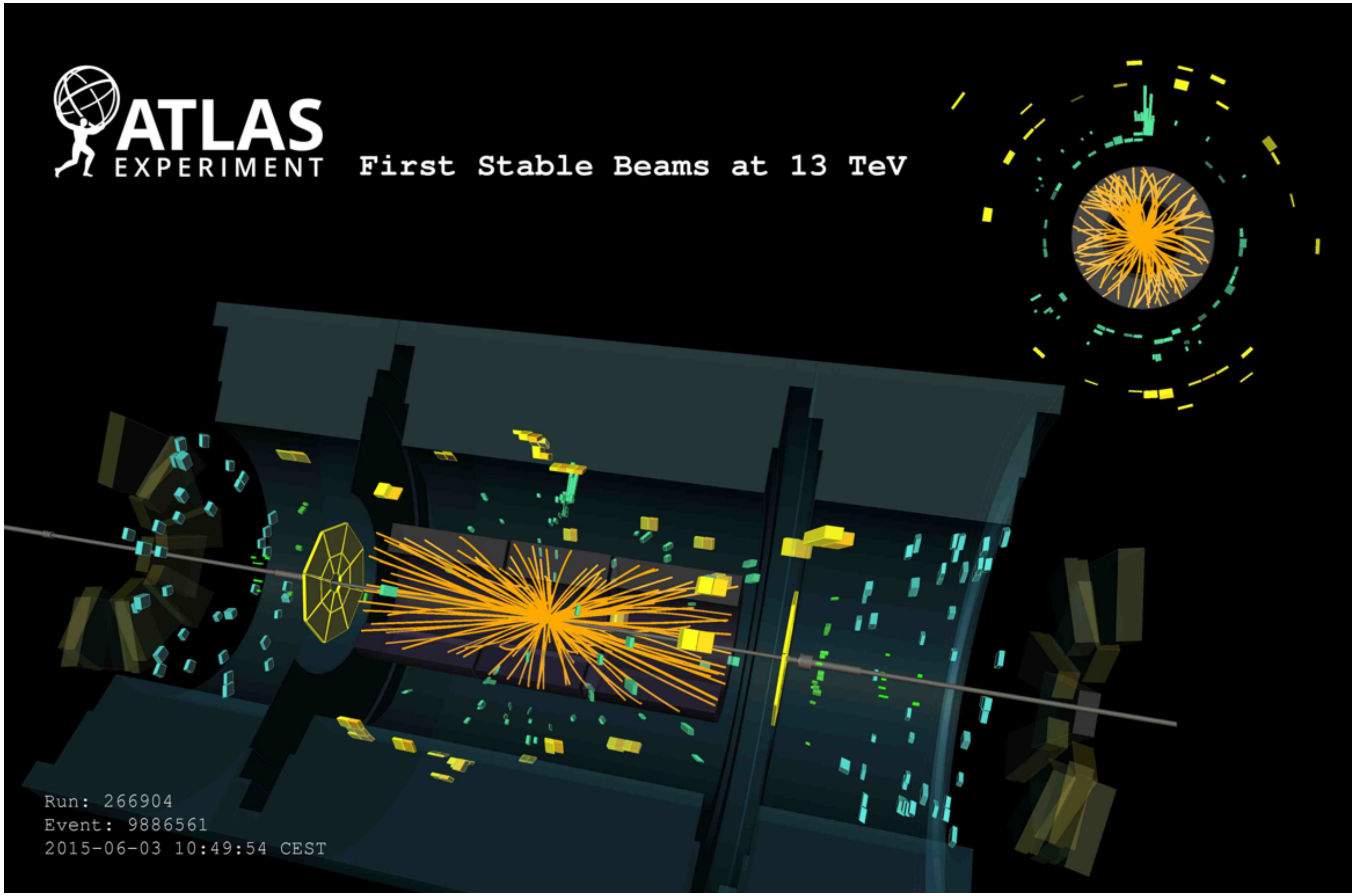
[Phys.Lett. B749 (2015) 337]





- CMS 95% CL upper limit on BR(h→μτ)<1.51% (0.75%)
  - 2.4σ excess over background
- ATLAS 95% CL upper limit on BR(h→μτ)<1.85% (1.24%)
- More stringent than indirect constraints

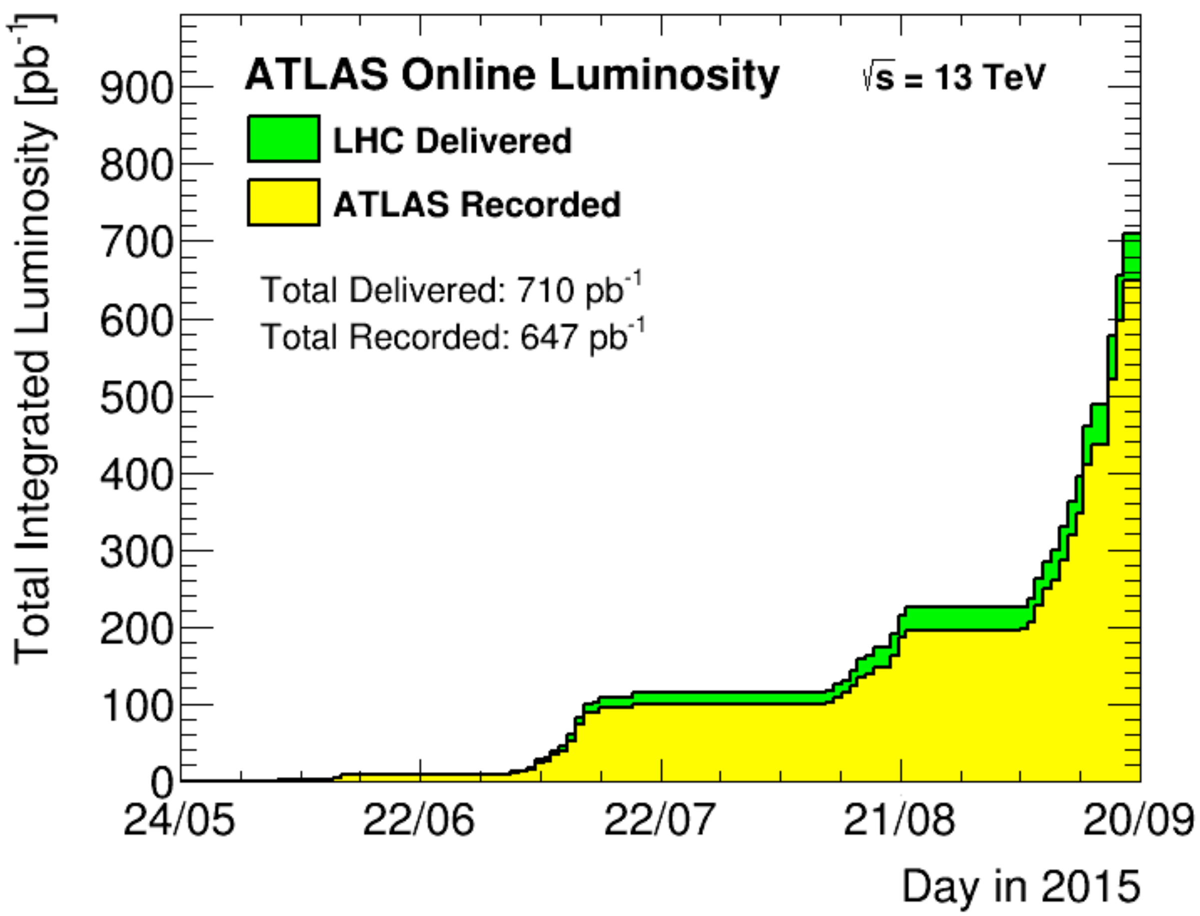
LHC Run II


ATLAS
EXPERIMENT
First Stable Beams at 13 TeV
Run: 266904
Event: 9886561
2015-06-03 10:49:54 CEST

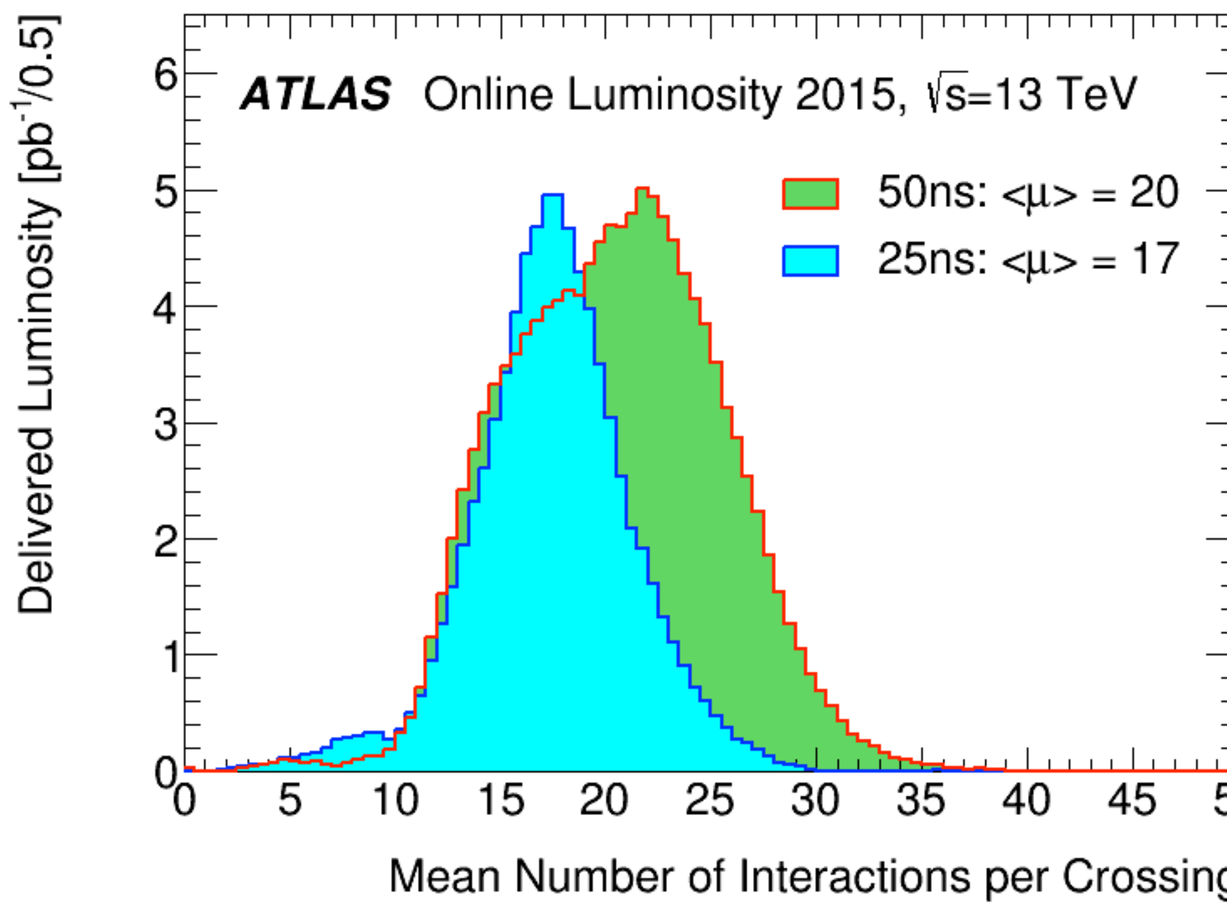

LHC Page1
Fill: 4402
E: 6500 GeV
t(SB): 00:46:54
21-09-15 21:47:16
PROTON PHYSICS: STABLE BEAMS
Energy:
6500 GeV
I(B1):
1.24e+14
I(B2):
1.23e+14

LHC Run II

LHC Page1
Fill: 4402
E: 6500 GeV
t(SB): 00:46:54
21-09-15 21:47:16
PROTON PHYSICS: STABLE BEAMS
Energy:
6500 GeV
I(B1):
1.24e+14
I(B2):
1.23e+14



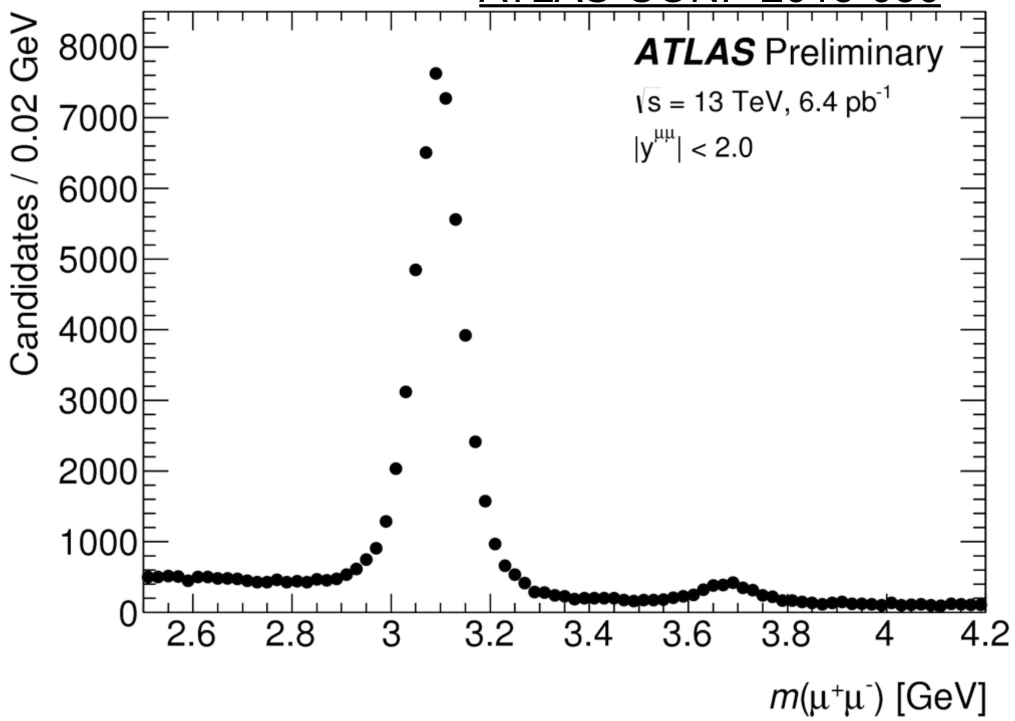
ATLAS Online Luminosity
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 710 pb-1
Total Recorded: 647 pb-1
Total Integrated Luminosity [pb-1]
0
100
200
300
400
500
600
700
800
900
24/05
22/06
22/07
21/08
20/09
Day in 2015



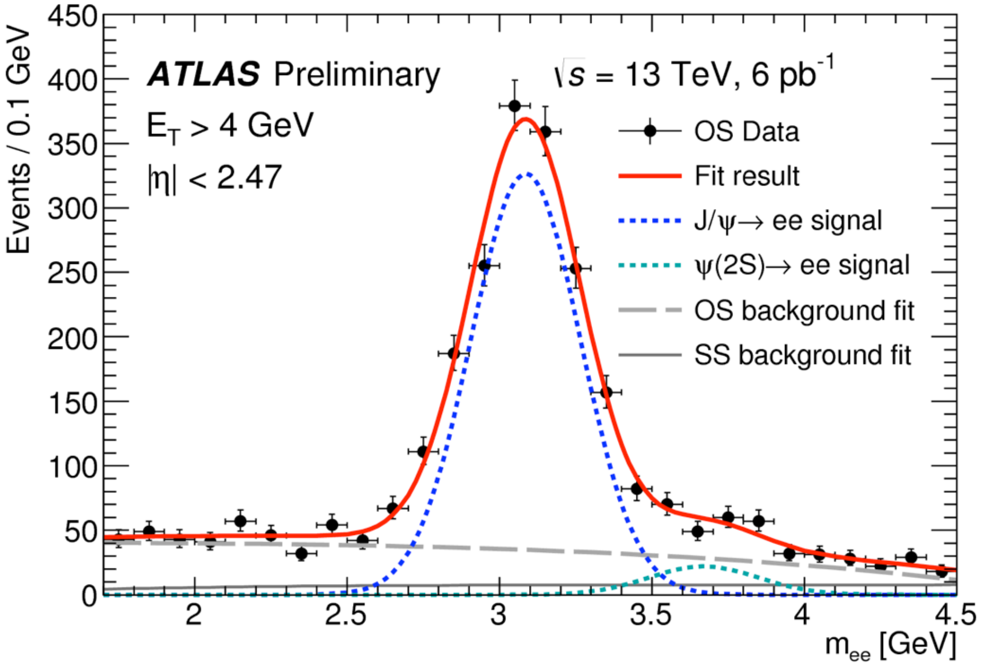
ATLAS Online Luminosity 2015, √s=13 TeV
50ns: <μ> = 20
25ns: <μ> = 17
Delivered Luminosity [pb-1/0.5]
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
50
Mean Number of Interactions per Crossing

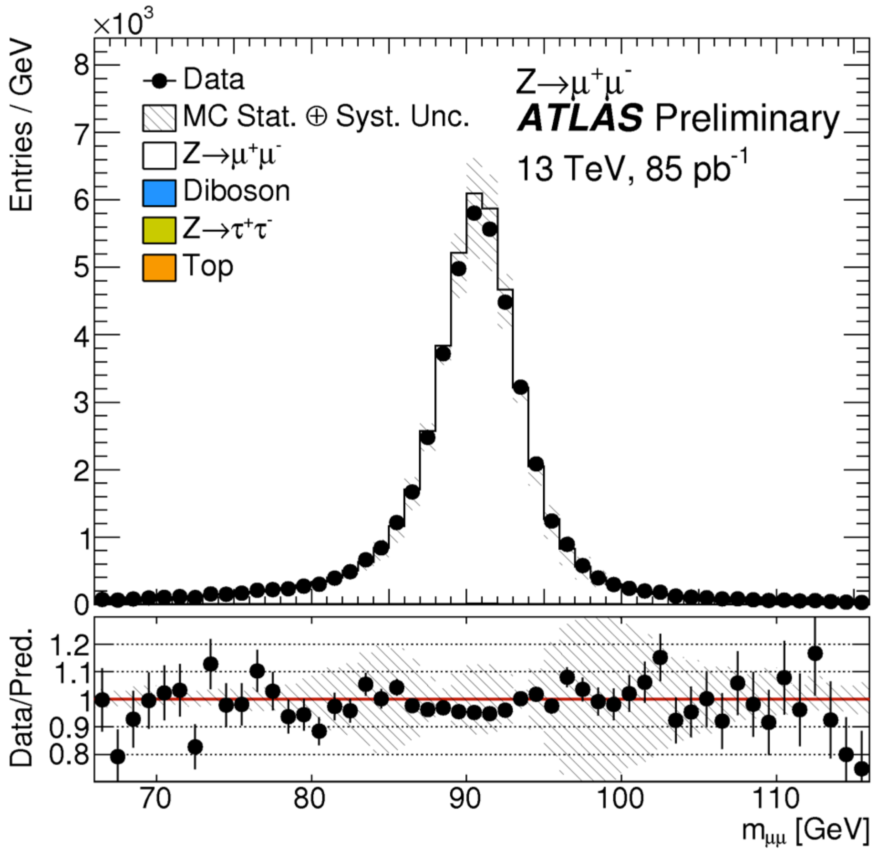
First resonances in Run II

ATLAS-CONF-2015-030

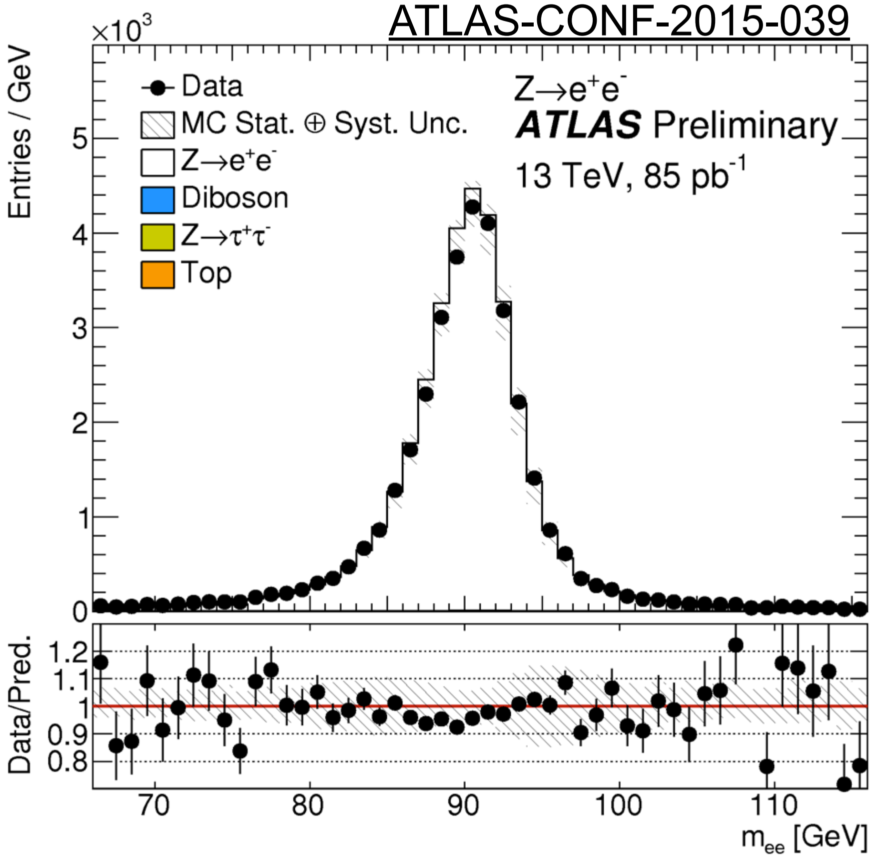


EGAM-2015-003

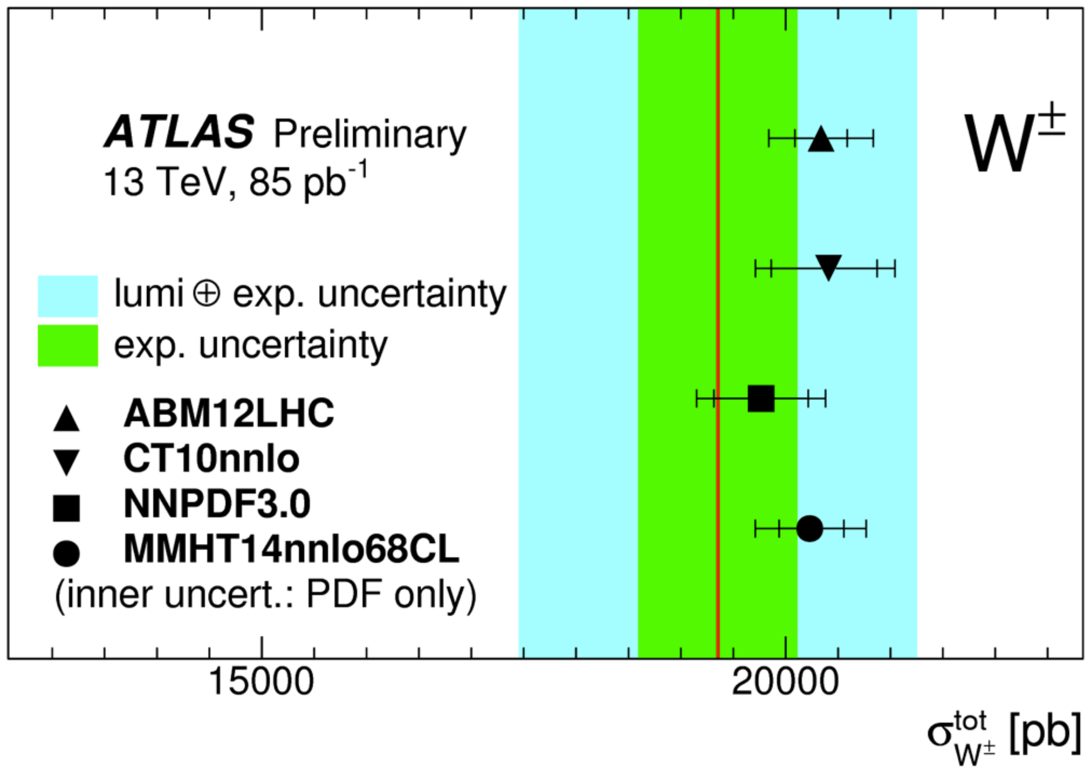


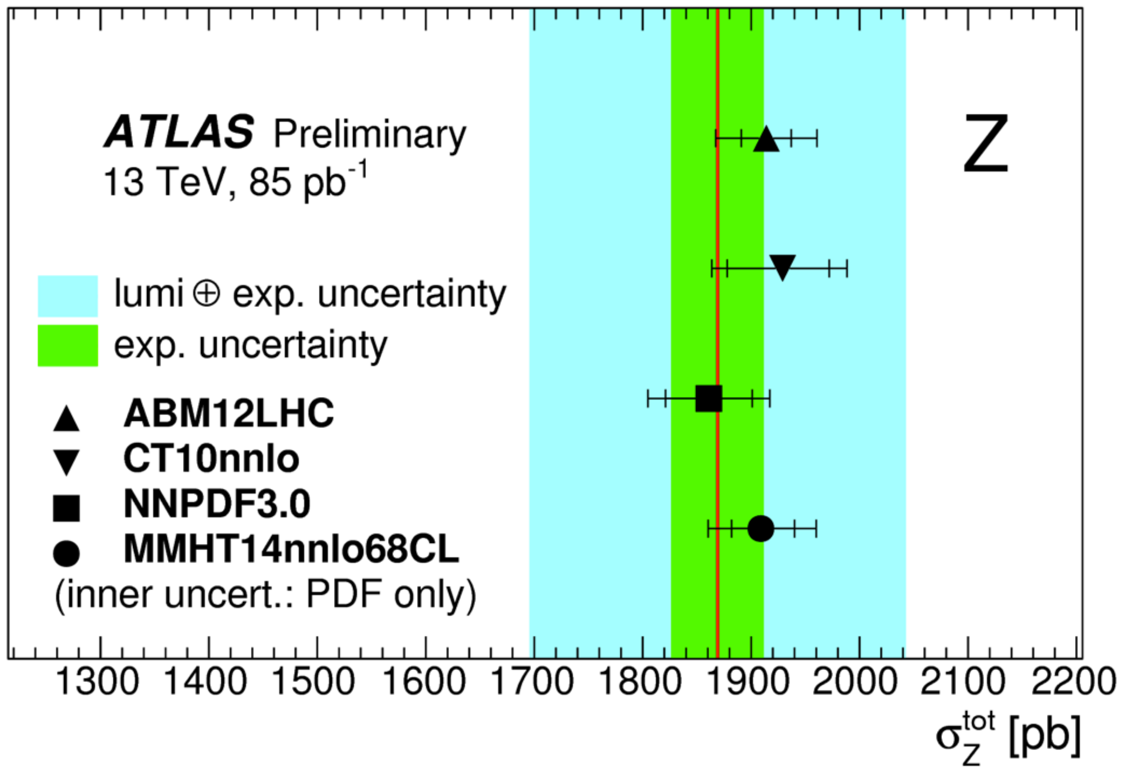


ATLAS-CONF-2015-039

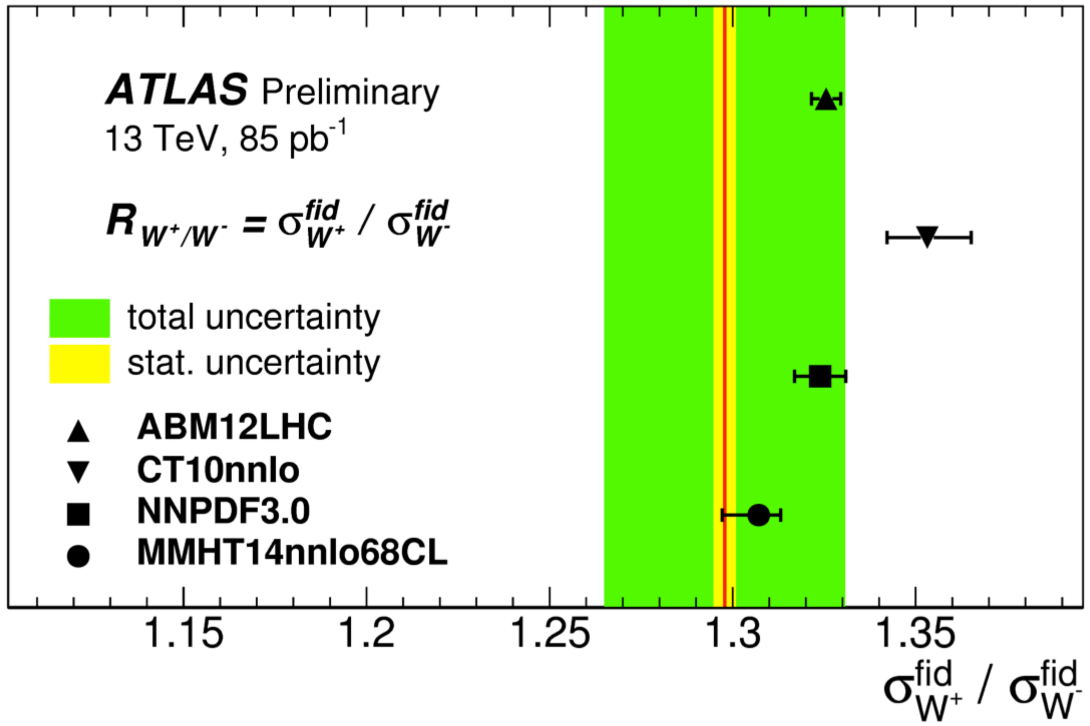


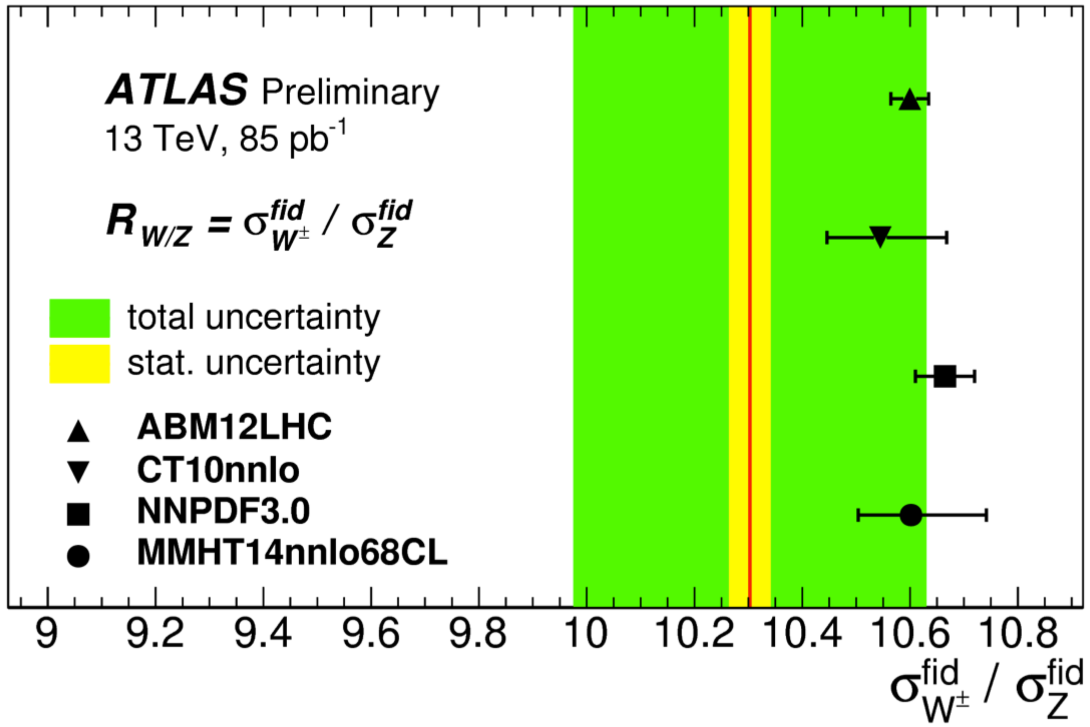
W and Z production



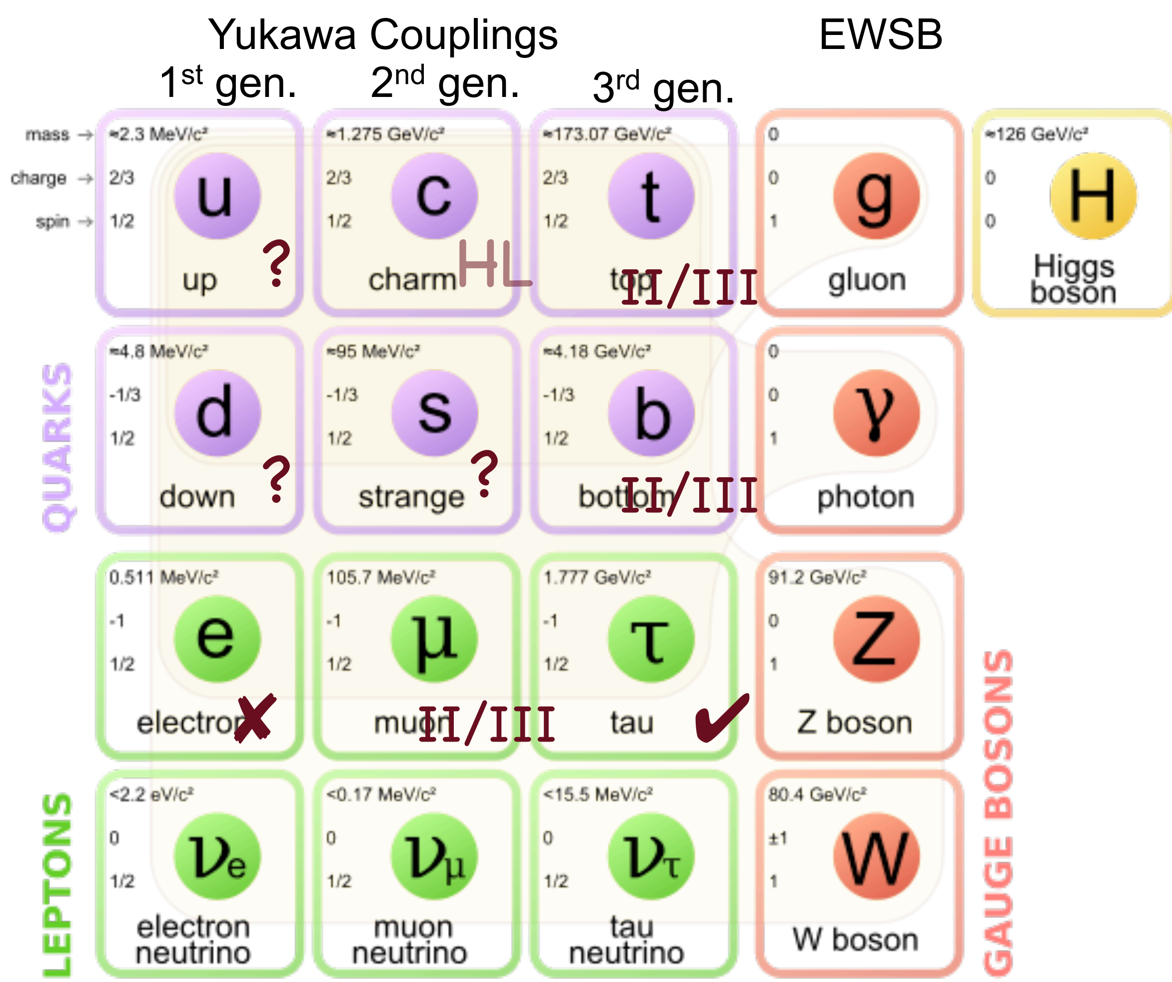


ATLAS-CONF-2015-039





Summary



Yukawa sector likely the least theoretically motivated and constrained part of the Standard Model
→ Particularly for 1st/2nd generation.

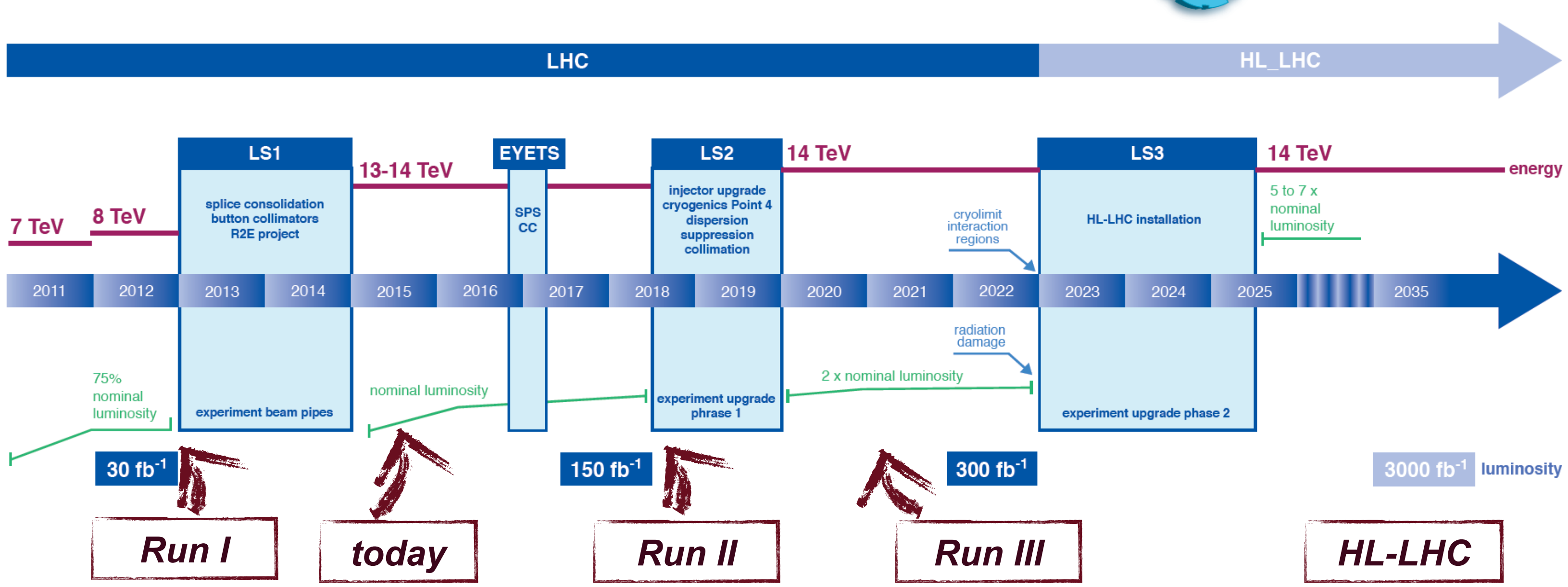
New Physics could be lurking here!

A wealth of information has been collected over the last few years on the nature of the Higgs boson
→ Yukawa sector still relatively unconstrained

Currently, under intense experimental and phenomenological focus; many new results (h→J/ψγ, h→τμ, t→hq) and new ideas/approaches to probe this sector at the LHC appear!

LHC / HL-LHC Plan

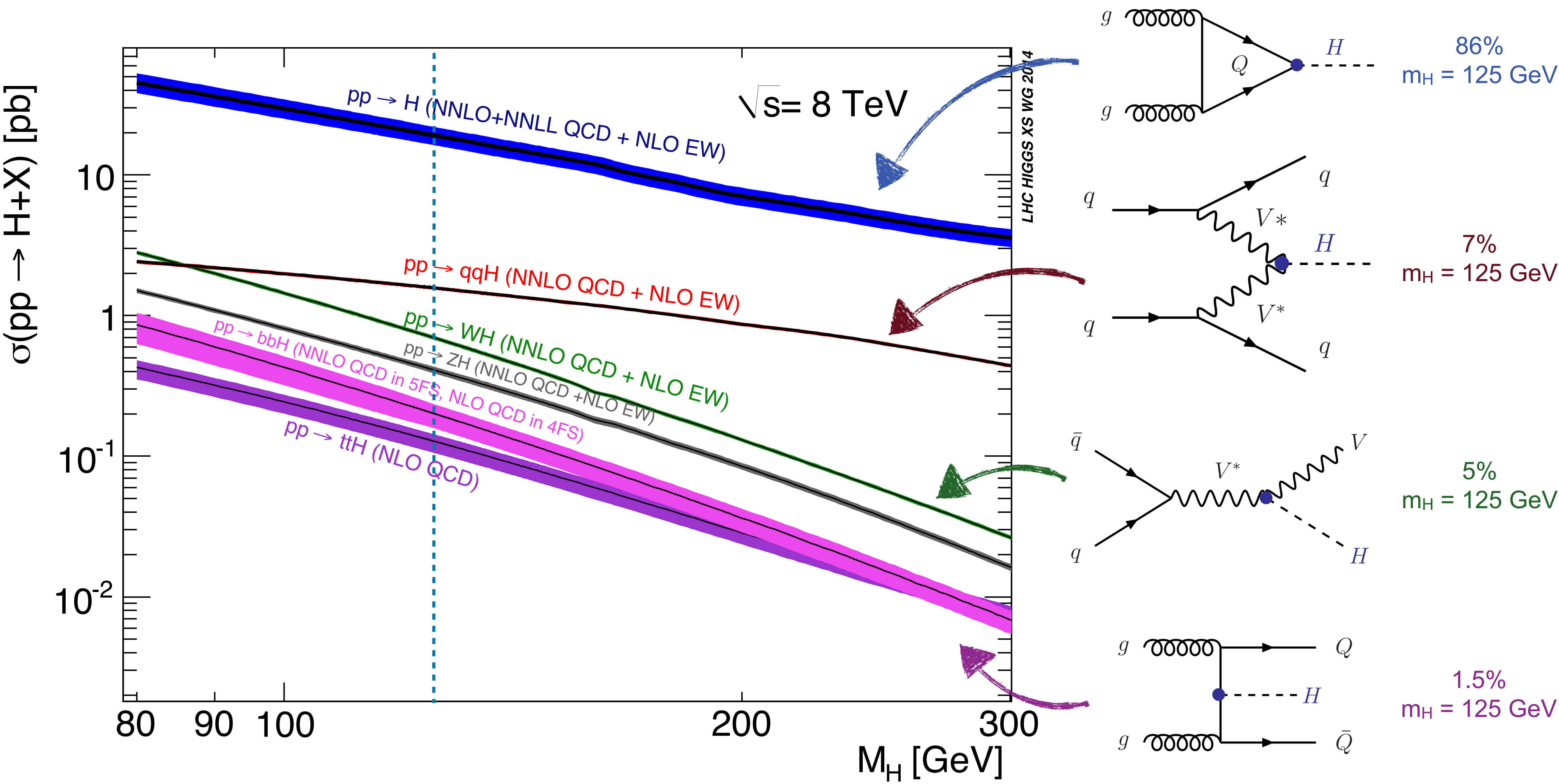
High Luminosity LHC



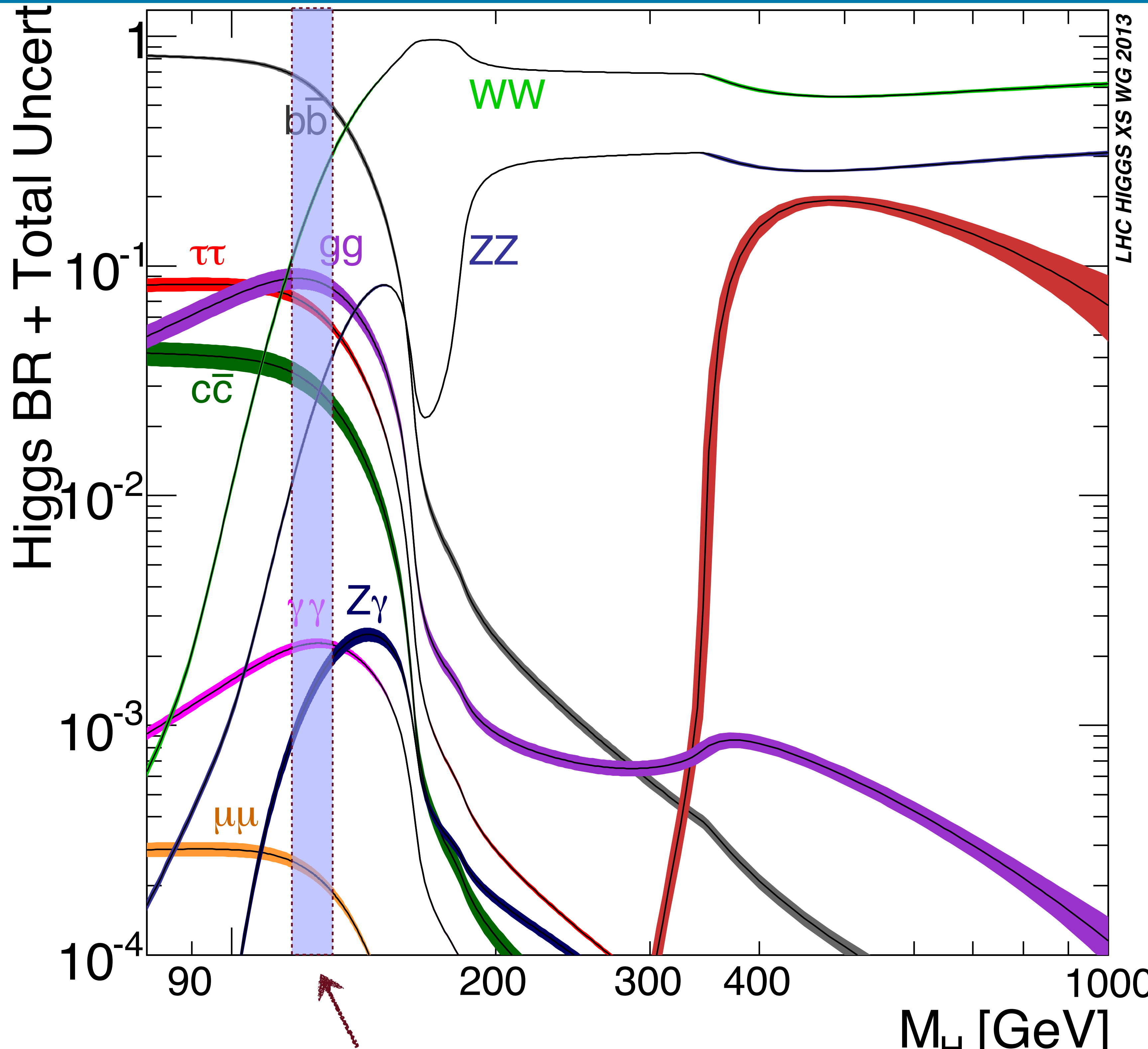
Most importantly:
ingenuity, both from both theory and experiment, will be crucial to achieve such an enhancement of the LHC physics potential

Additional Slides

SM Higgs boson production at the LHC

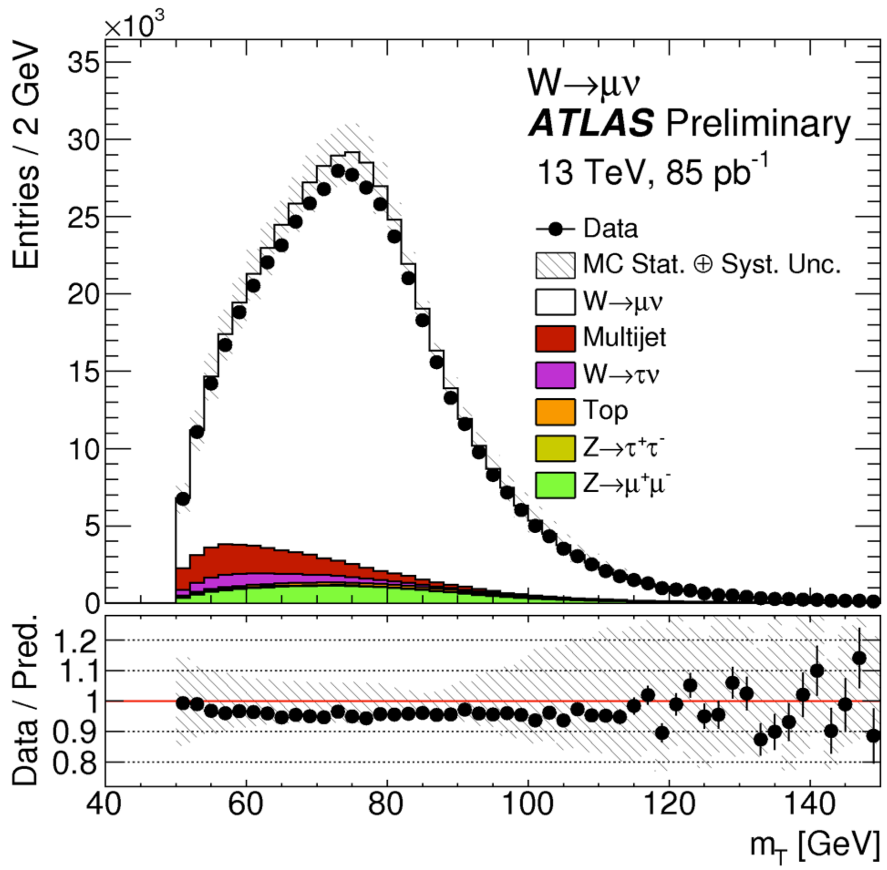


SM Higgs boson decays

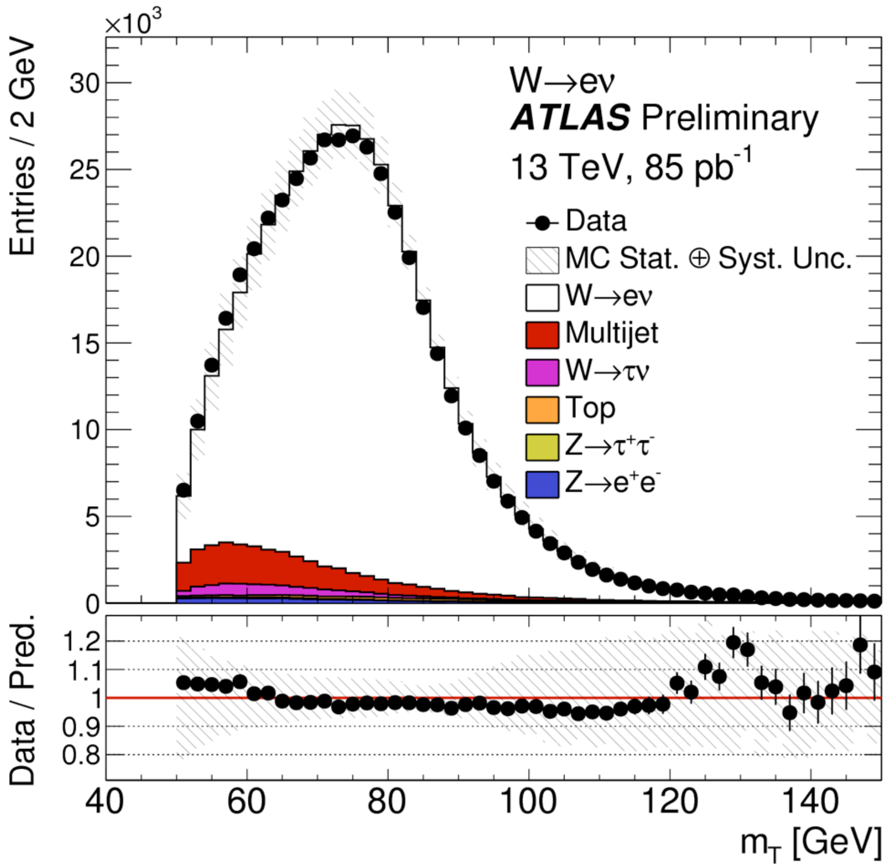


m_H~125 GeV gives access to several decay channels
Gauge bosons: γγ, ZZ*, WW*, Zγ
Fermions: bb, ττ, μμ

W→lv

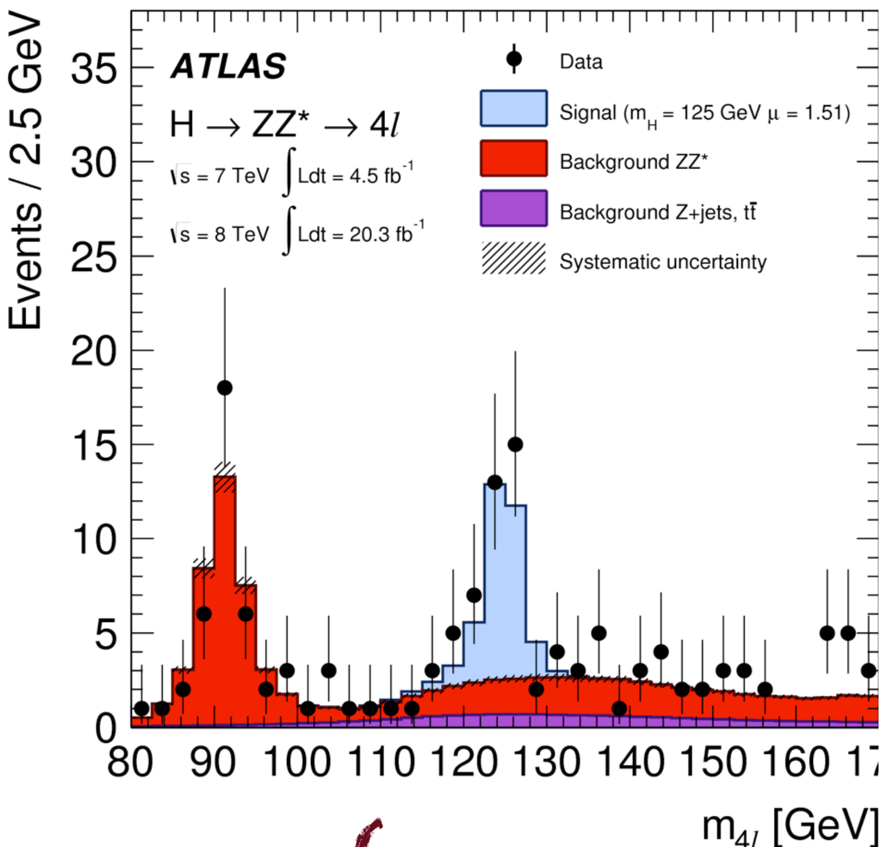


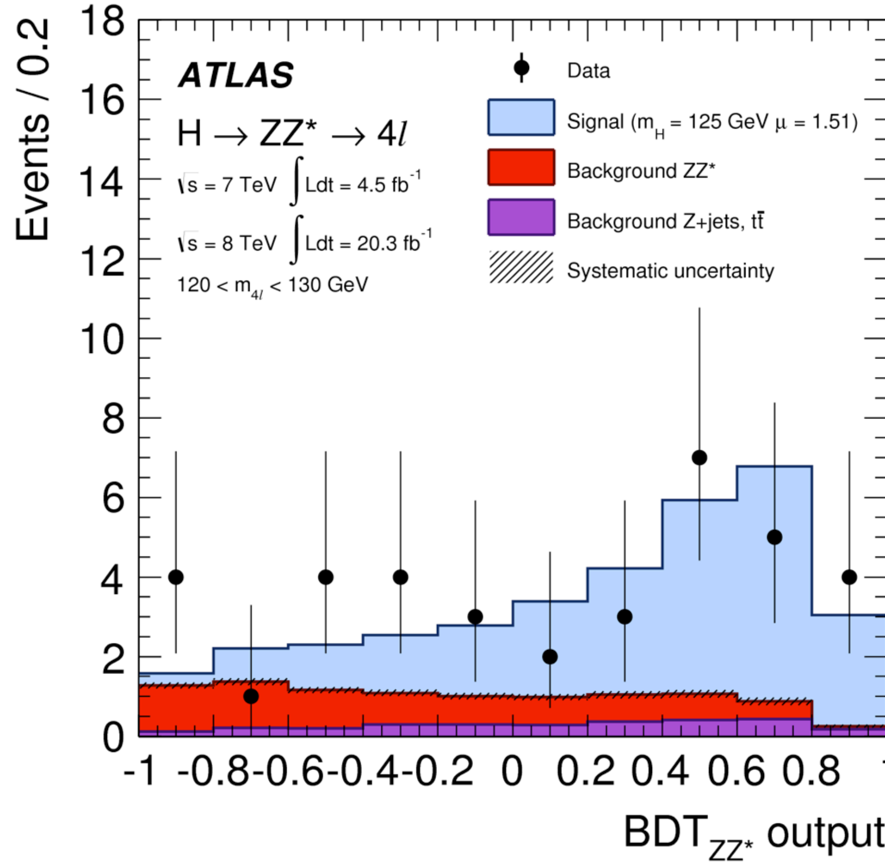
W→μν
ATLAS Preliminary
13 TeV, 85 pb^{-1}
Data
MC Stat. ⊕ Syst. Unc.
W→μν
Multijet
W→τν
Top
Z→τ$^+$τ$^-$
Z→μ$^+$μ$^-$
Entries / 2 GeV
Data / Pred.
m$_T$ [GeV]



W→eν
ATLAS Preliminary
13 TeV, 85 pb^{-1}
Data
MC Stat. ⊕ Syst. Unc.
W→eν
Multijet
W→τν
Top
Z→τ$^+$τ$^-$
Z→e$^+$e$^-$
Entries / 2 GeV
Data / Pred.
m$_T$ [GeV]

H→ZZ*→4l

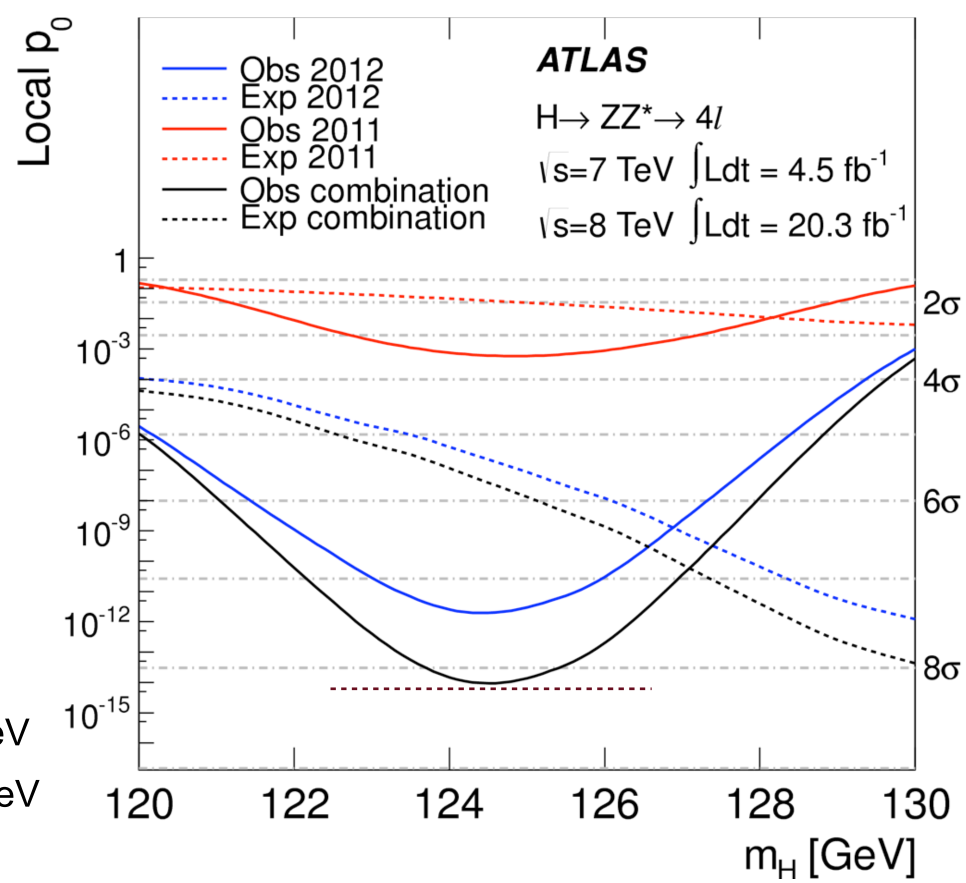




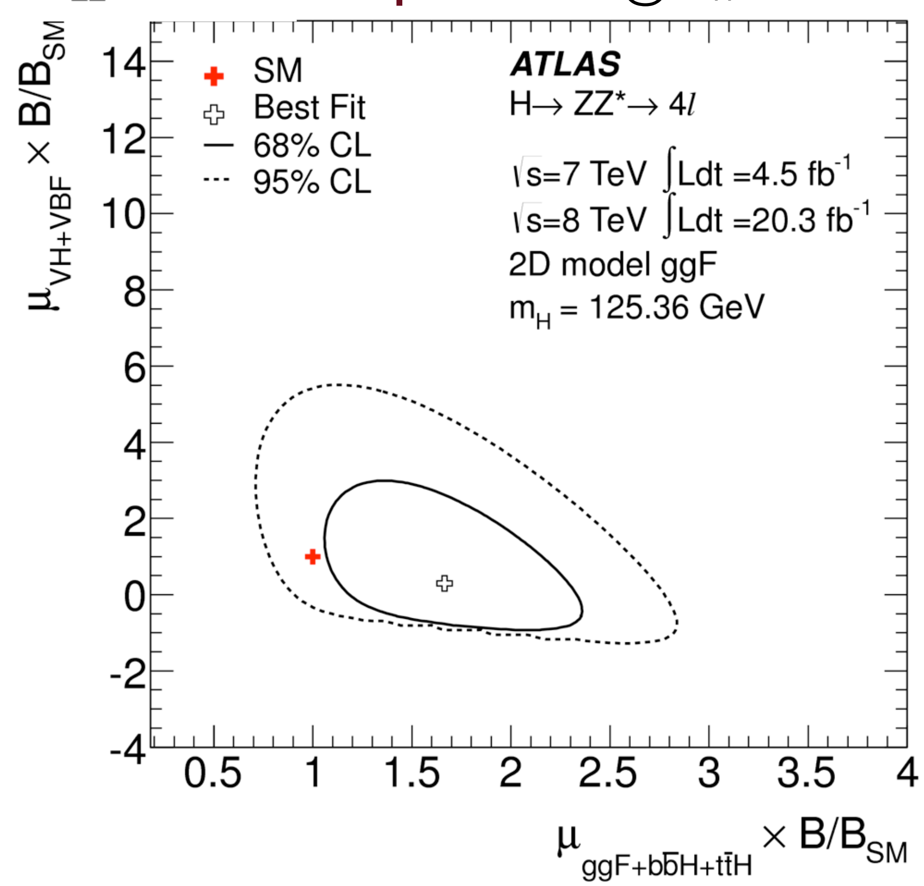
$\mu_{ggF+bbH+ttH} = 1.66^{+0.45}_{-0.41}(stat)^{+0.25}_{-0.15}(syst)$

$\mu_{VBF+VH} = 0.26^{+1.60}_{-0.91}(stat)^{+0.36}_{-0.23}(syst)$

$\mu_{VBF+VH}/\mu_{ggF+bbH+ttH} = 0.2^{+1.2}_{-0.5}$



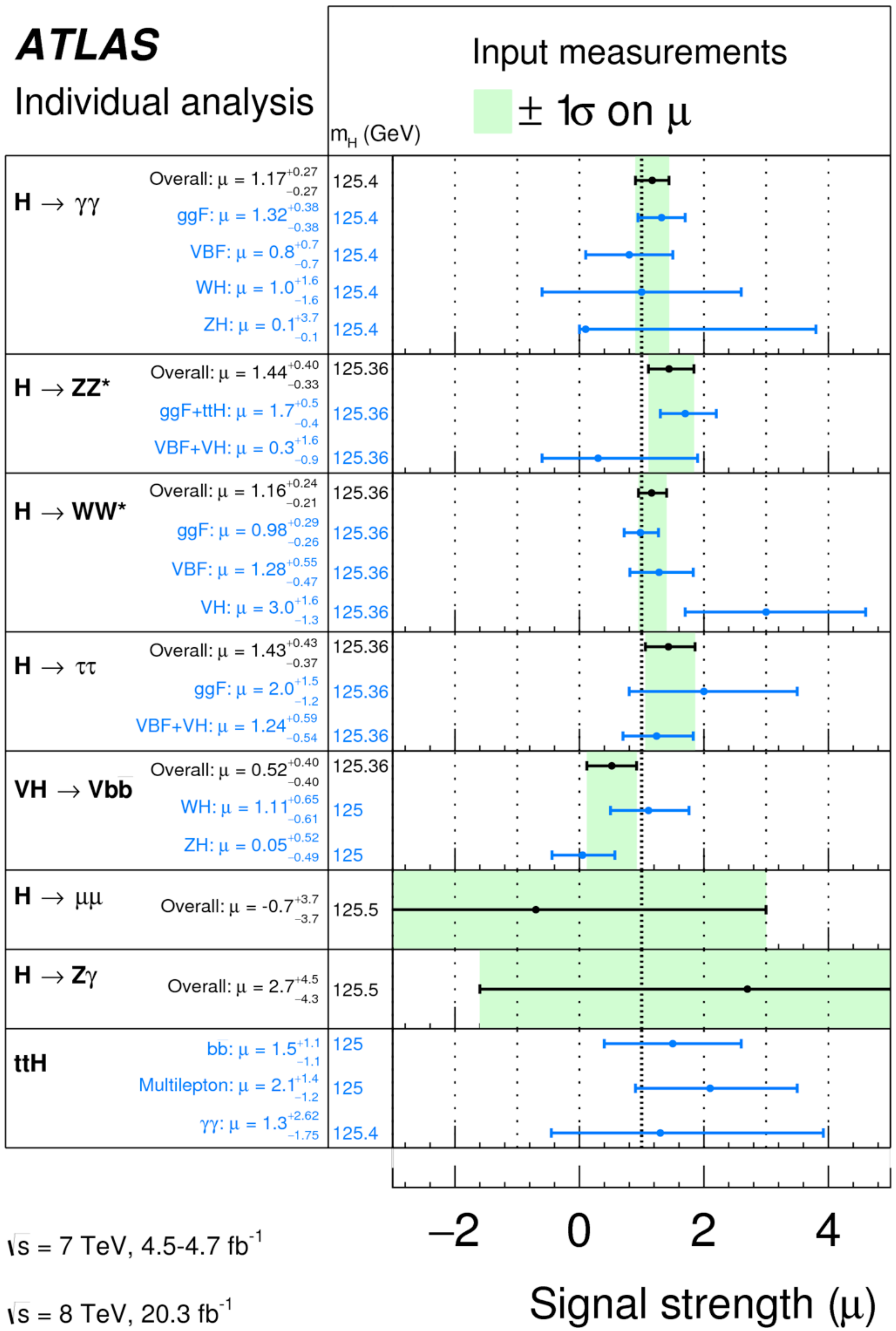
μ=1.5 ± 0.4 @ m_H = 125.36GeV



8.2σ (5.8σ) @ m_H=124.51 GeV

8.1σ (6.2σ) @ m_H = 125.36GeV

Overview of rate measurements



Overview of measurements

ATLAS-CONF-2015-044

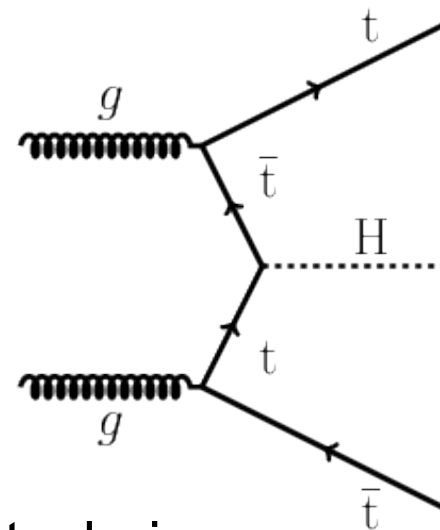
Table 5: Overview of the decay and production channels analysed in this paper. To show the relative importance of the various channels, the results from the combined analysis presented in this paper for $m_H = 125.09$ GeV (see Tables 10 and 11 in Section 5.2) are shown as observed signal strengths μ with their uncertainties (the expected uncertainties are shown in parentheses). Also shown are the observed statistical significances (the expected significances are shown in parentheses) except for the $H \to \mu\mu$ channel which has very low sensitivity. For most decay channels, only the most sensitive analyses are quoted as references, e.g. the ggF and VBF analyses for the $H \to WW$ decay channel or the VH analysis for the $H \to bb$ decay channel. The results are nevertheless close to those from the individual publications, in which, in addition, slightly different values for the Higgs boson mass were assumed and in which the signal modelling and signal uncertainties were slightly different, as discussed in the text.

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	5.0	5.6
			$\left(^{+0.26}_{-0.24}\right)$	$\left(^{+0.24}_{-0.22}\right)$	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
			$\left(^{+0.33}_{-0.27}\right)$	$\left(^{+0.31}_{-0.26}\right)$	(5.5)	(6.8)
$H \to WW$	[55, 56]	[57]	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
			$\left(^{+0.21}_{-0.20}\right)$	$\left(^{+0.23}_{-0.20}\right)$	(5.8)	(5.6)
$H \to \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
			$\left(^{+0.37}_{-0.33}\right)$	$\left(^{+0.31}_{-0.29}\right)$	(3.3)	(3.7)
$H \to bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
			$\left(^{+0.39}_{-0.37}\right)$	$\left(^{+0.45}_{-0.43}\right)$	(2.7)	(2.5)
$H \to \mu\mu$	[60]	[61]	-0.7 ± 3.6	0.8 ± 3.5		
			(± 3.6)	(± 3.5)		
ttH production	[28, 62, 63]	[65]	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
			$\left(^{+0.72}_{-0.66}\right)$	$\left(^{+0.88}_{-0.80}\right)$	(1.6)	(1.3)

top quark

The top-quark, m_t~173 GeV, has a Yukawa coupling of O(1)
→ its presence in LHC Higgs boson production ubiquitous
h→ttbar kinematically forbidden; direct information from tth
→ direct measurement to help discriminate of BSM contributions in ggH

- h→Hadrons (bb, $\tau_h\tau_h$, WW)
  - Use leptonic or l+jets decays of associated ttbar
  - Backgrounds ttbar+jets, W/Z+jets
- h→Leptons (WW/ZZ/ττ)
  - Exploit also W→lv from top decays
  - Same-sign di-leptons, tri-leptons, four-leptons
  - Backgrounds ttbar+W/Z,di-bosons, fakes
- h→γγ
  - Focus on Higgs decay, top used for event tagging
- Complex final states → Extensive use of MVA techniques

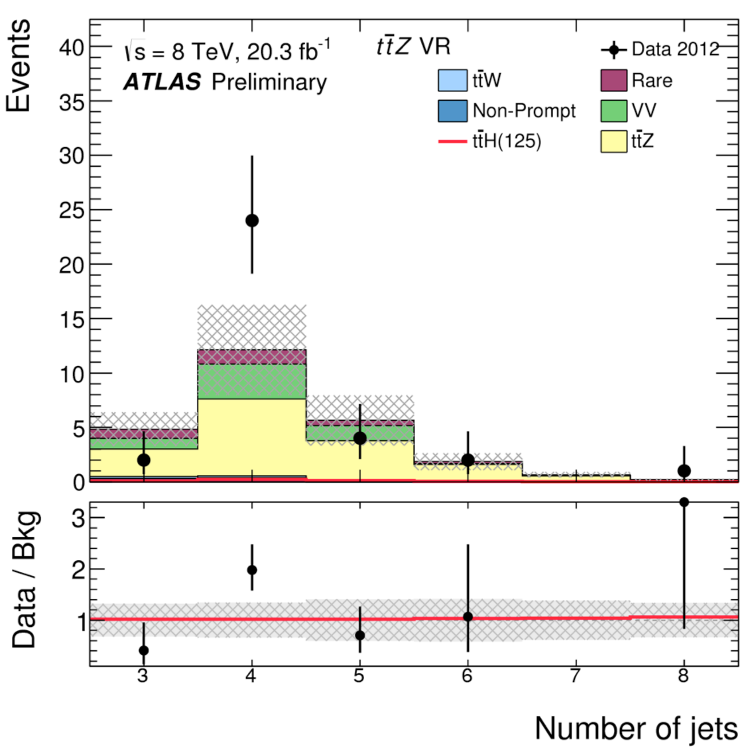


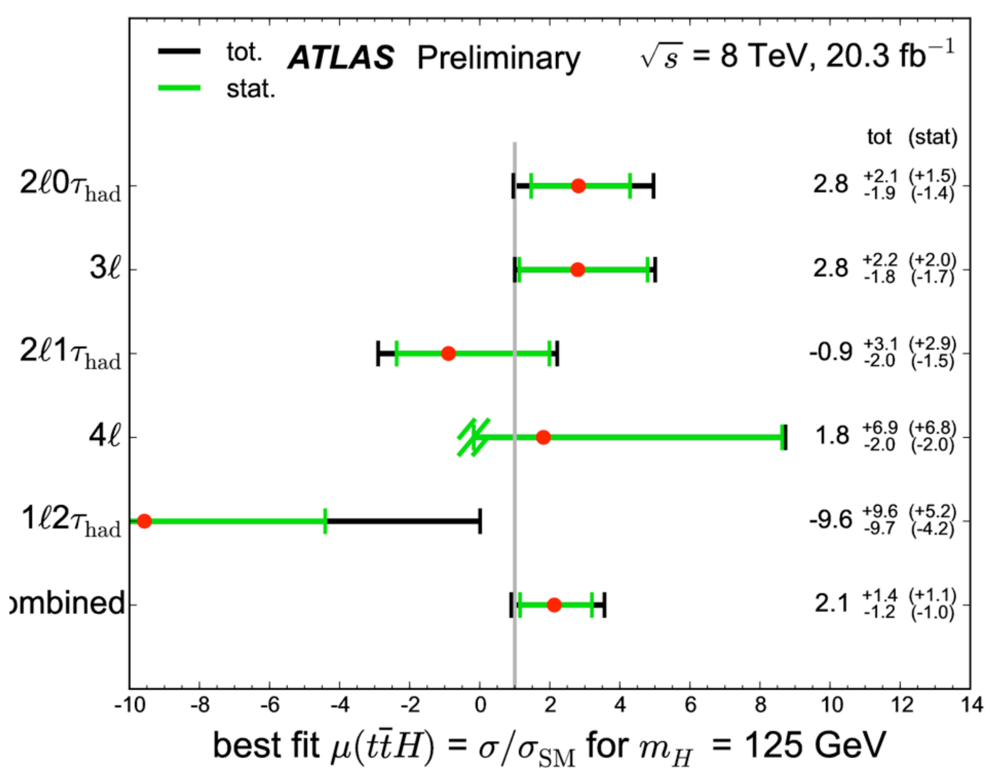
tth→Leptons

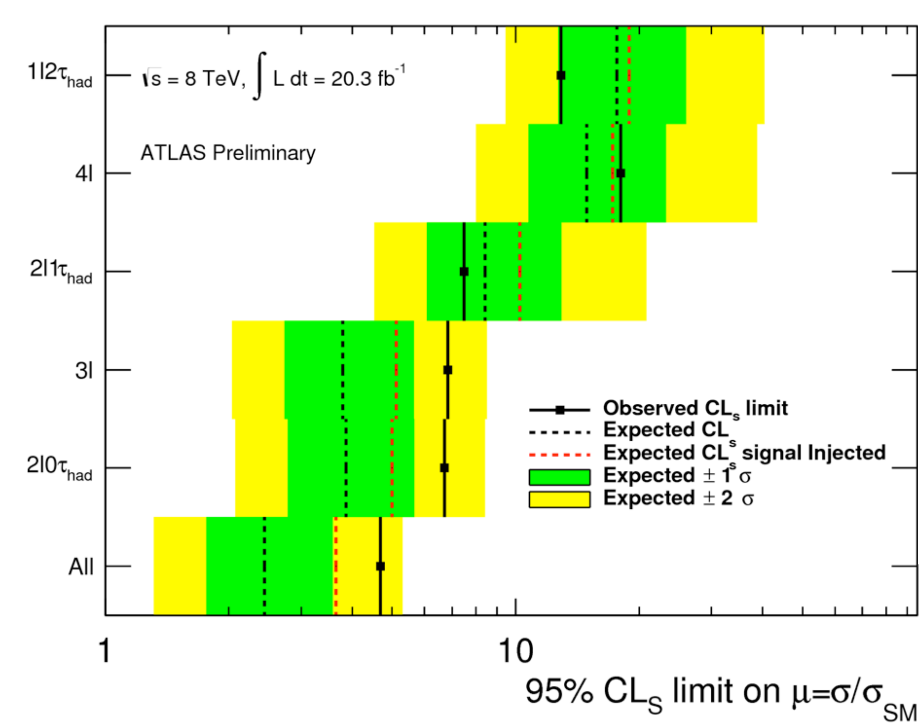
Category	Higgs boson decay mode WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{had}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{had}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{had}$	4%	93%	0%	3%

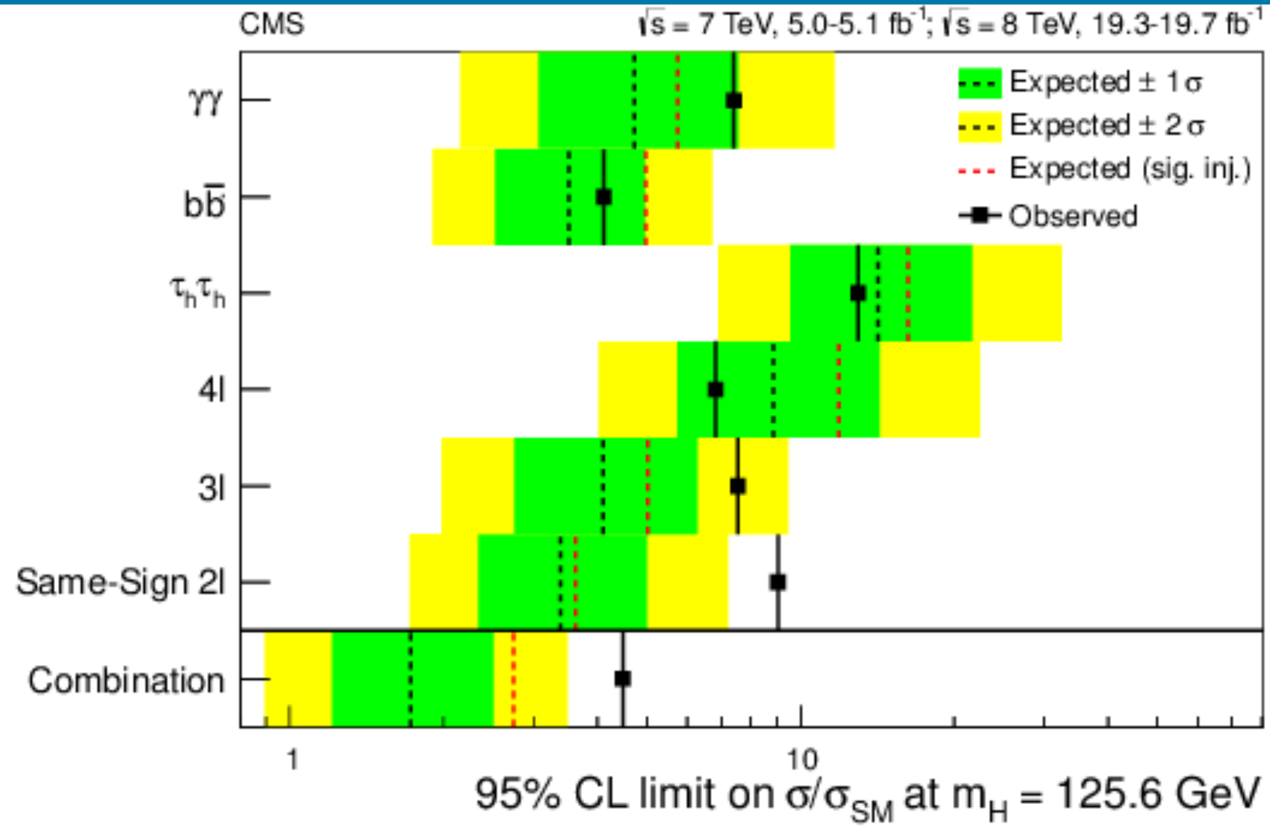
h→μμ/bb

ATLAS-CONF-2015-006





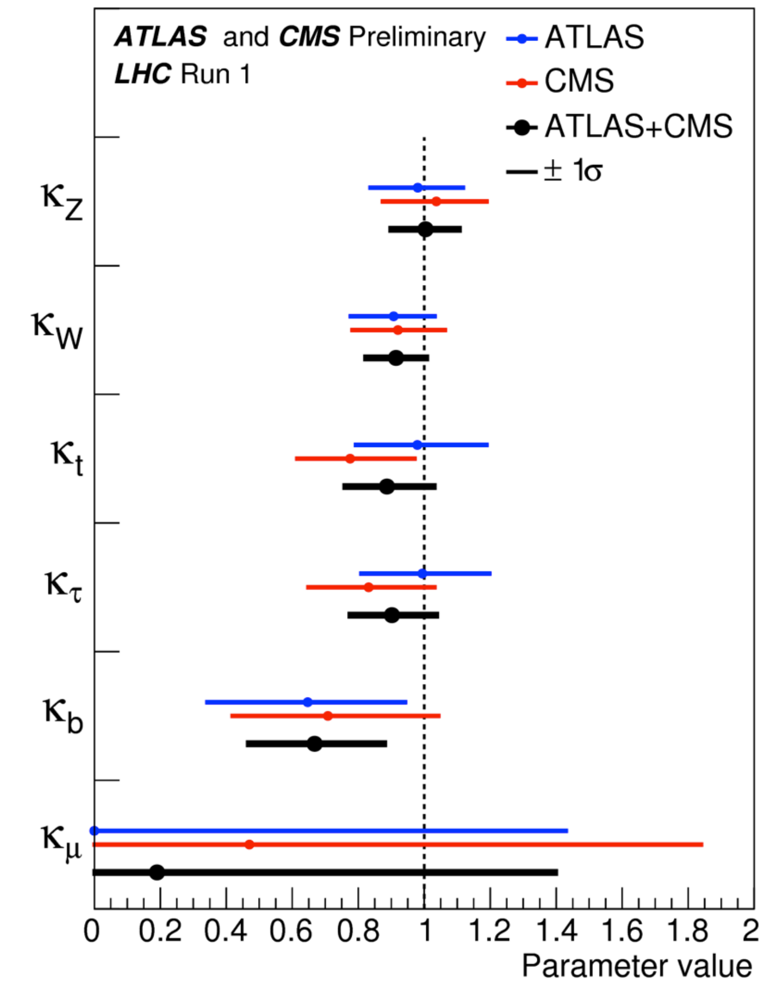




JHEP 1409 (2014) 087

CMS performed similar searches

ATLAS-CONF-2015-044



m_h=125 GeV	$\mu^{95\%}_{upper}$	Significance	Reference
CMS (125.6 GeV)	4.5 (1.7)	3.4(1.2)	JHEP 1409(2014) 087
ATLAS bb	3.4 (2.2)	1.4(1.1)	arXiv:1503.05066
ATLAS leptons	4.7 (2.4)	1.8(0.9)	ATLAS-CONF-2015-006
ATLAS γγ (125.4 GeV)	6.7 (4.9)	-	Phys.Lett. B740(2015) 222
ATLAS Couplings (125.36 GeV)	-	2.4(1.5)	ATLAS-CONF-2015-007

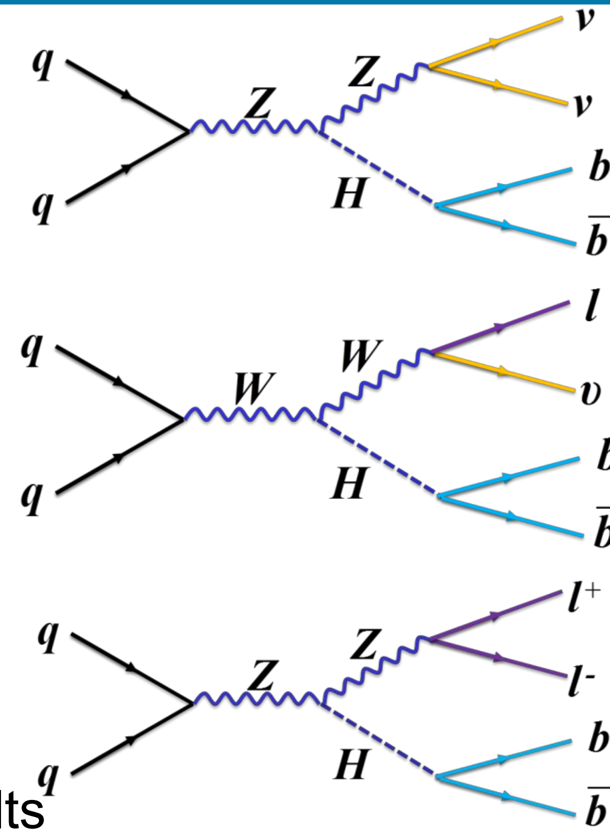
- Analyses approaching SM sensitivity
- Nevertheless, excess of events over background observed

→ No firm evidence yet

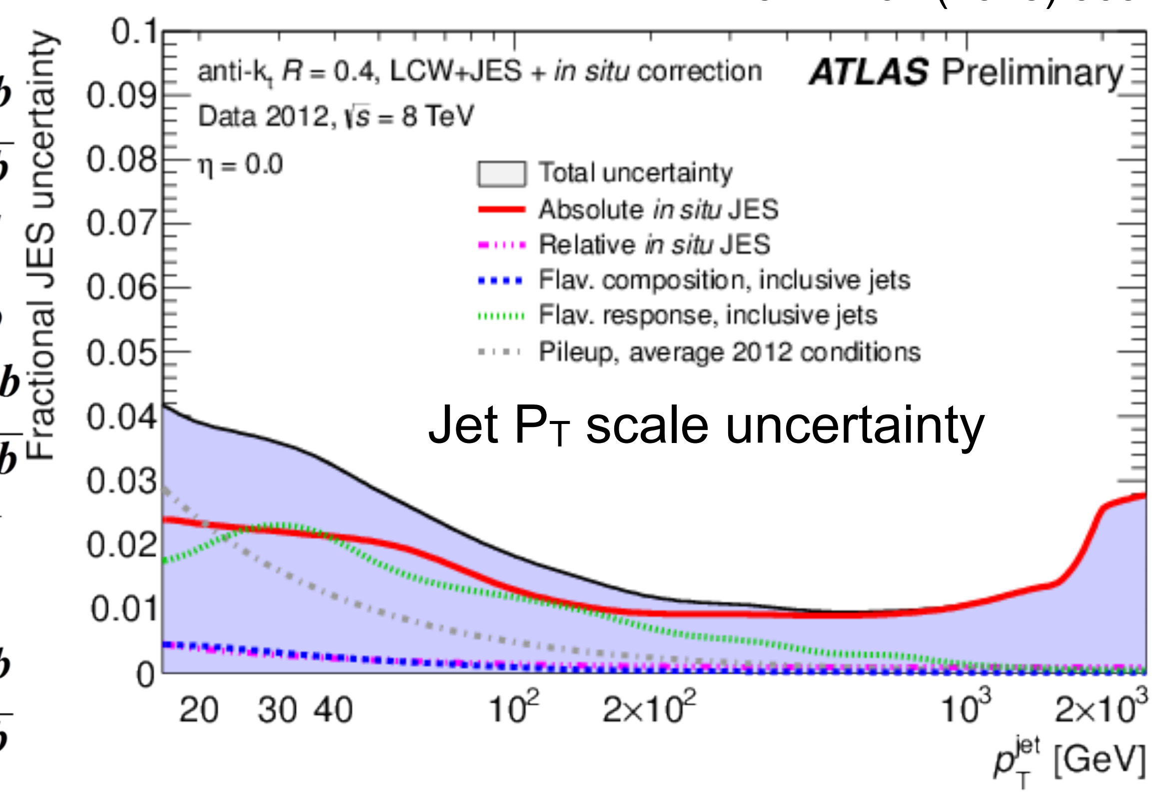
- tHq sensitive to anomalous top-Yukawa CMS $\mu^{95\%}_{up}$<6.7(5.0) [arXiv:1504.031
- ATLAS tth→γγ projection gives 8.2σ for 3000 fb^{-1} [ATL-PHYS-PUB-2014-012]
  - Naively (both leptons and γγ statistics limited) feasible in Run II/III

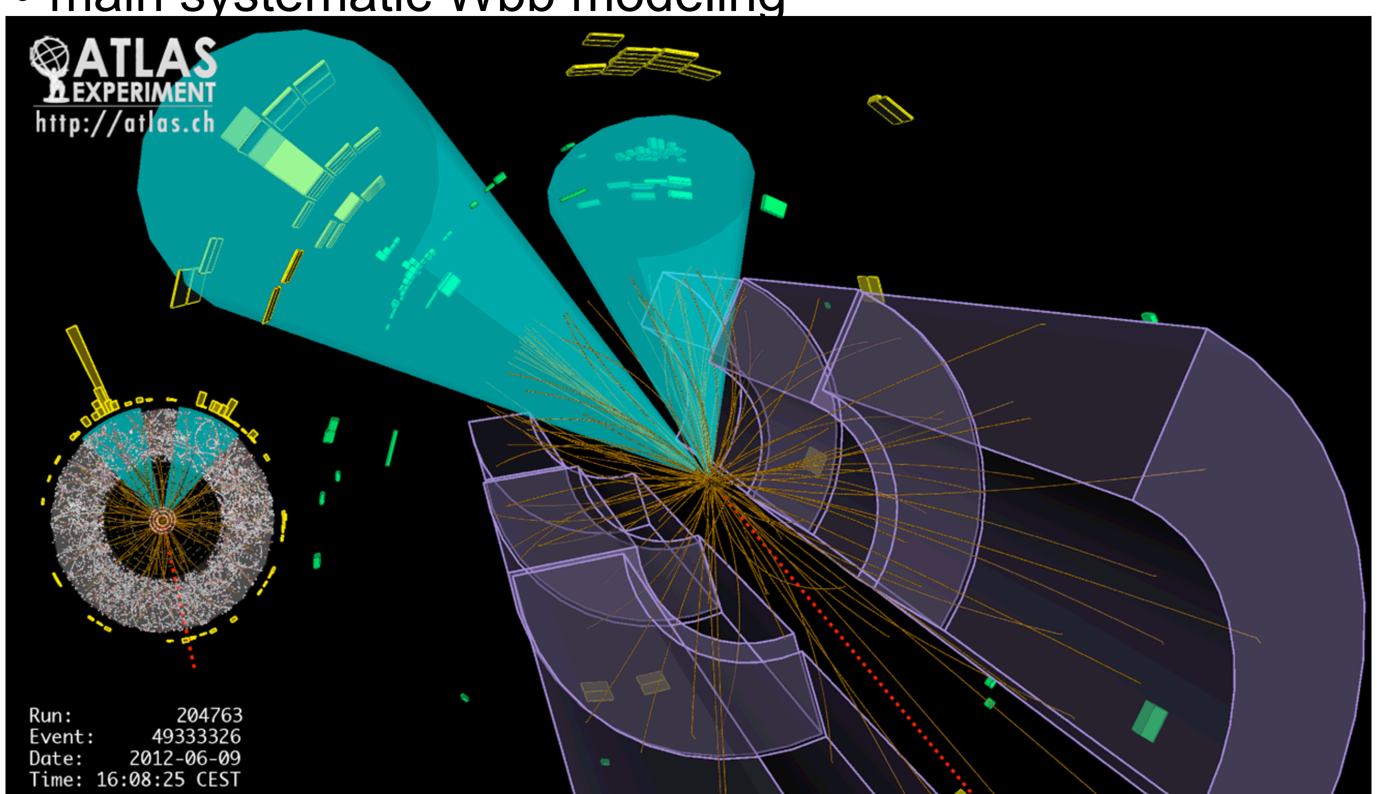
h→bb : Results

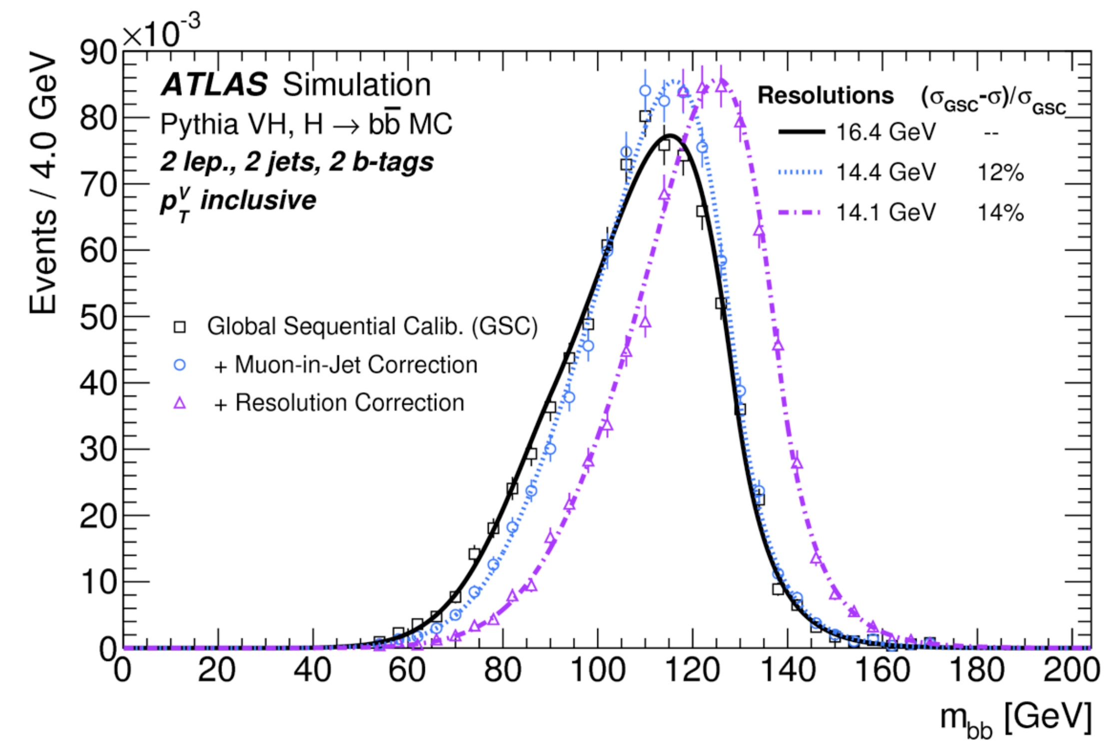
- Largest BR (58%@m_H=125 GeV) but large QCD background
- Exploit associated production with W/Z
  - Complex final states
- Backgrounds: W/Z+jets and top
- Final discriminant: BDT_{VH} including m_{bb} and up to 16 variables
- Separate final states:
  - number of leptons: 0, 1, 2
  - $P_T(V)$ or MET
  - number of jets and b-tags (MV1c)
- >50% improvement w.r.t. previous results
  - BDT_{VH}, improved b-tagging (MV1c), m_{bb},...
  - main systematic Wbb modeling



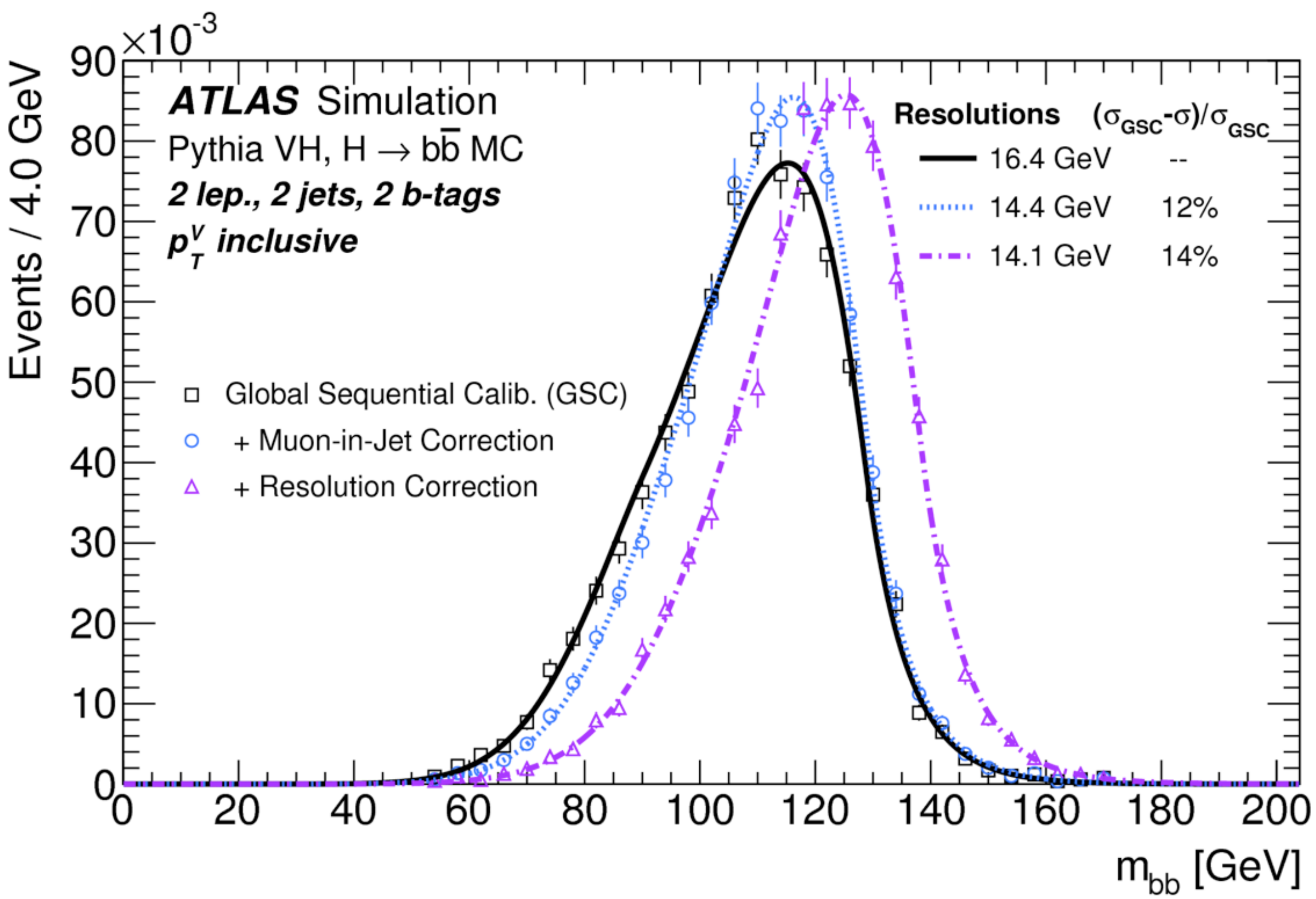
JHEP 01 (2015) 069

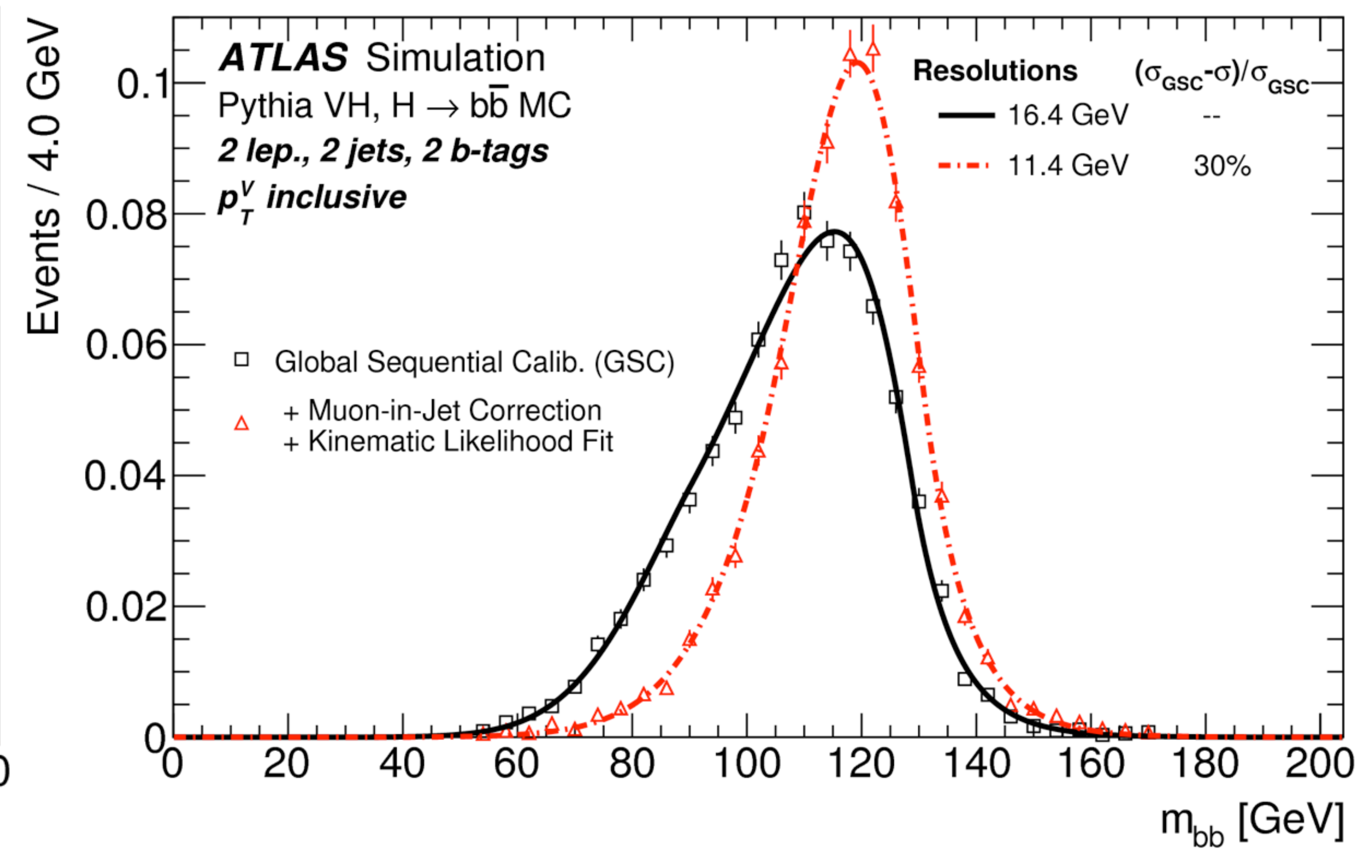


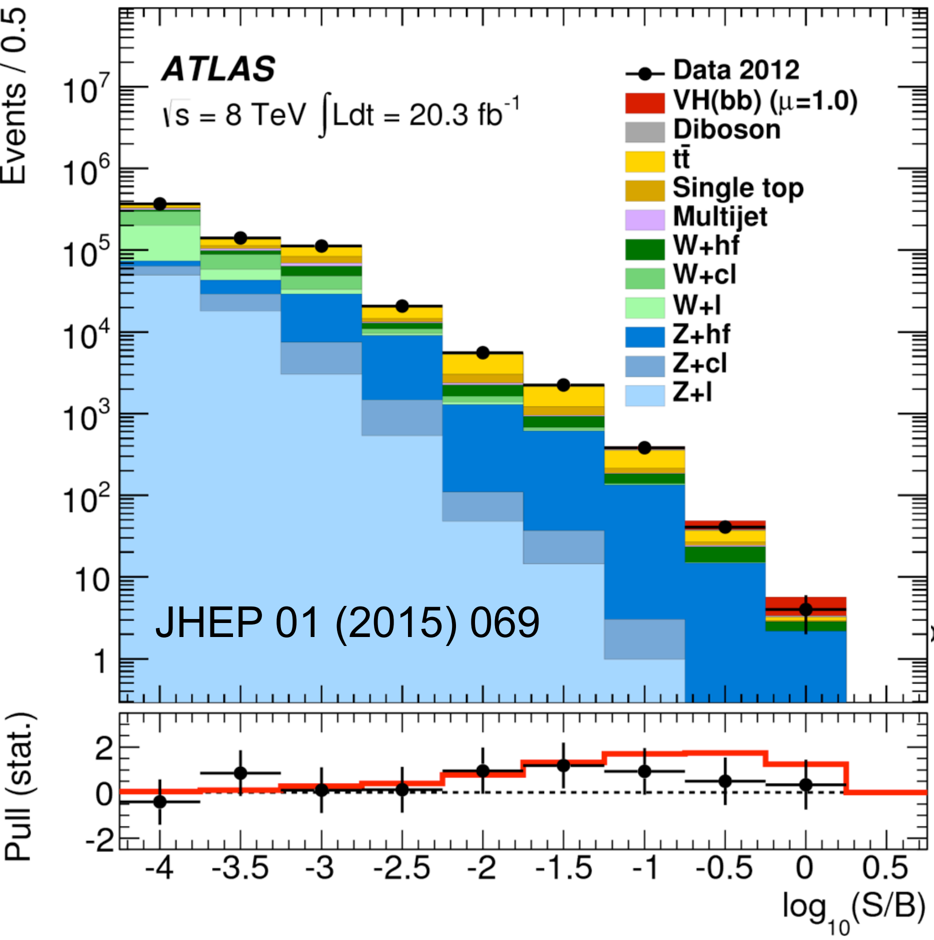




H→bb: m_{bb} resolution







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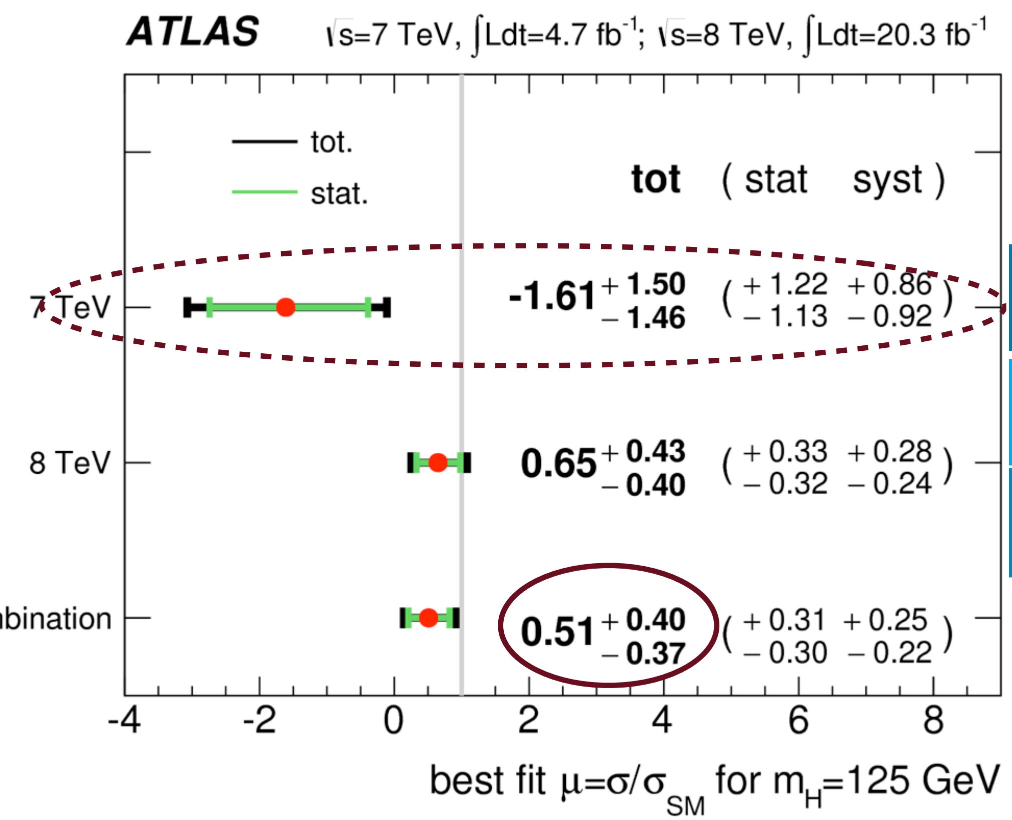
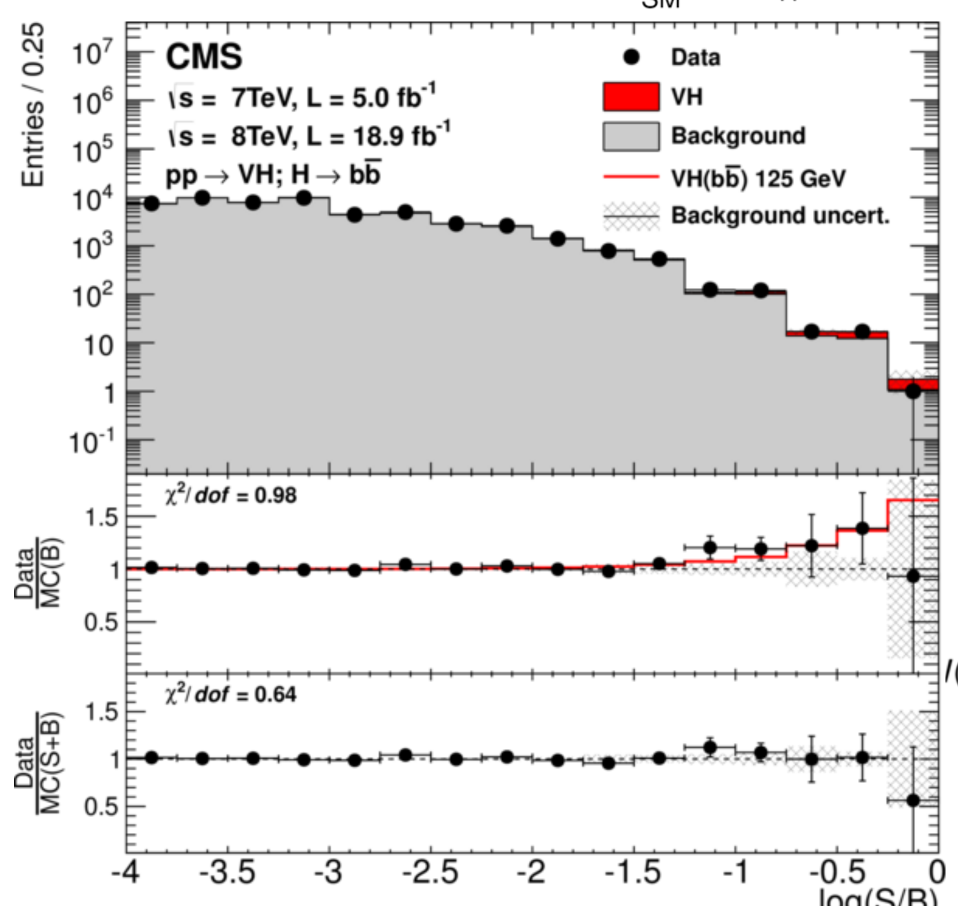


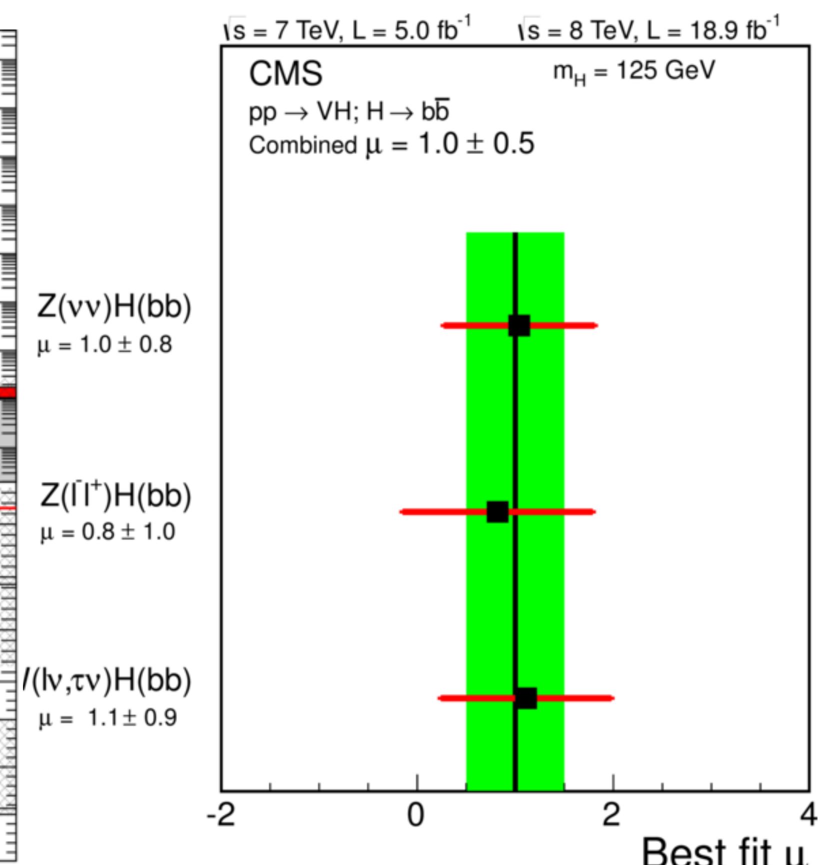
m_H= 125 GeV	Significance	$\mu^{95\%}_{upper}$
ATLAS	1.4σ (2.6σ)	1.2 (0.8)
CMS	2.1σ (2.1σ)	1.89 (0.95)

Run I dataset ~SM sensitivity
ATLAS/CMS observe excess over expected background
→ no firm evidence yet

Despite challenging pile-up conditions, evidence for SM within reach for LHC Run II

[ATLAS projections ≳3σ expected with 300fb^{-1}
ATL-PHYS-PUB-2014-011]

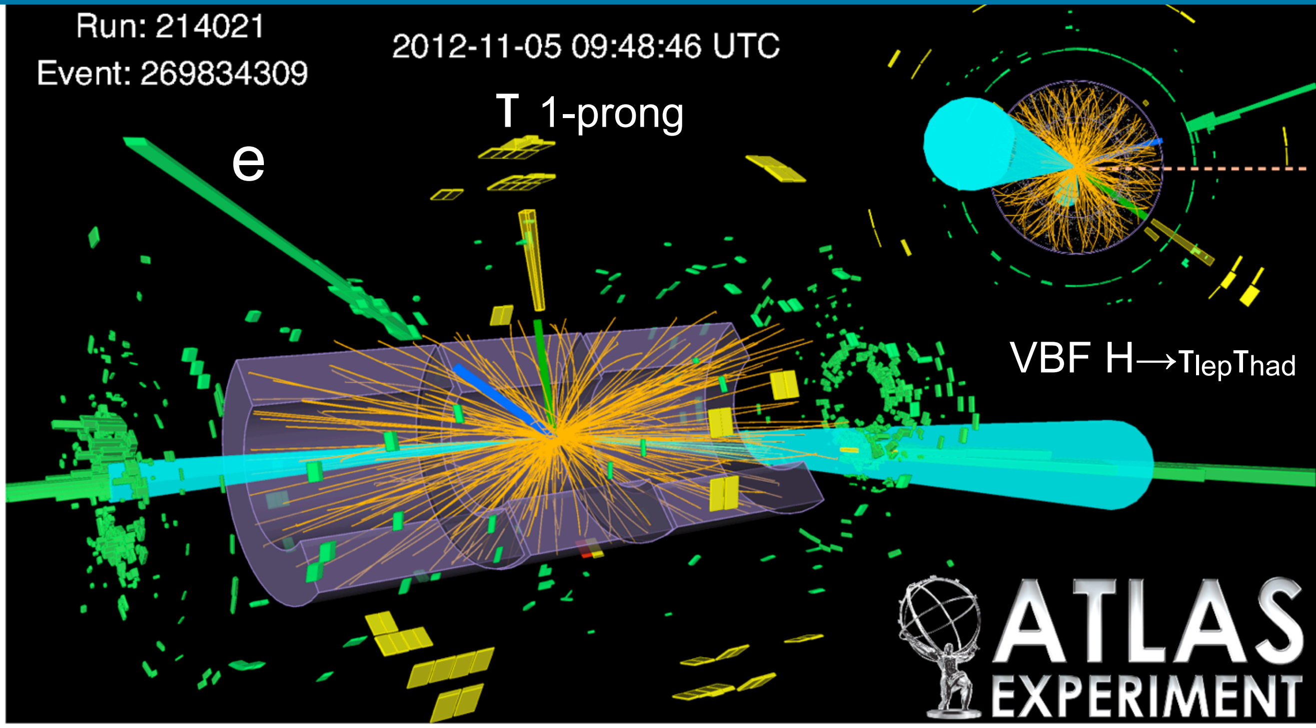




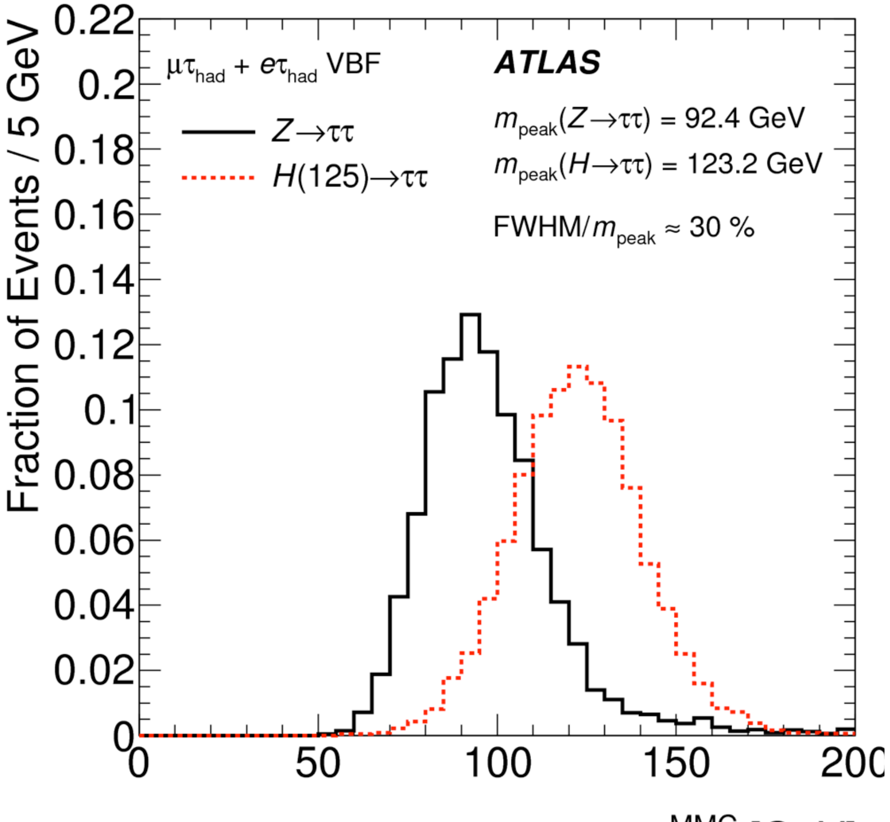
Phys.Rev. D89 (2014) 1, 012003

h→ττ

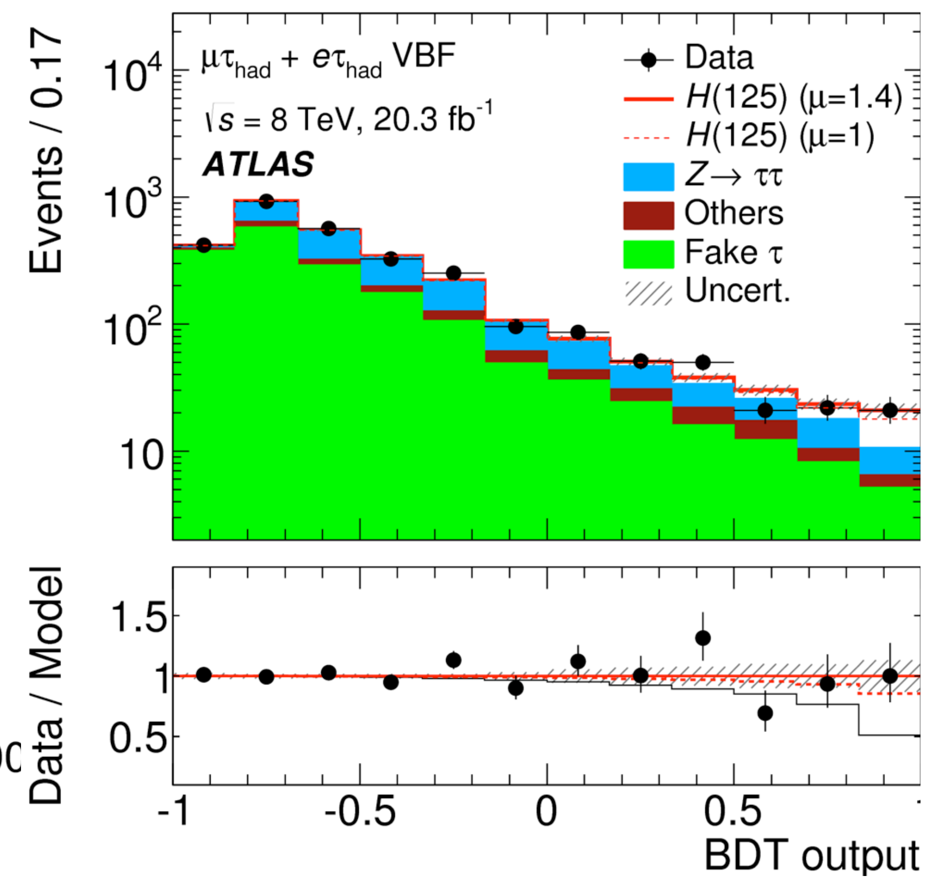
- Most promising for down-type fermion/lepton couplings
- Backgrounds
  - Z → ττ dominant [embedding]
  - “Fakes”: Multijet, W+jets, top [data-driven]
  - “Other”: Dibosons/H->WW* [MC]
- Three sub-channels: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- Two exclusive categories/final state: *VBF* (2 jets with large Δη) and *Boosted* (large di-tau pT)
- BDT for each category: *di-tau properties* ($m_{\tau\tau}$, $\Delta R_{\tau\tau}$, ...), *jet topology* (m_{jj}, $\Delta\eta_{jj}$, ...), *event activity/topology* (scalar/vector pT sum, object centralities, ...)

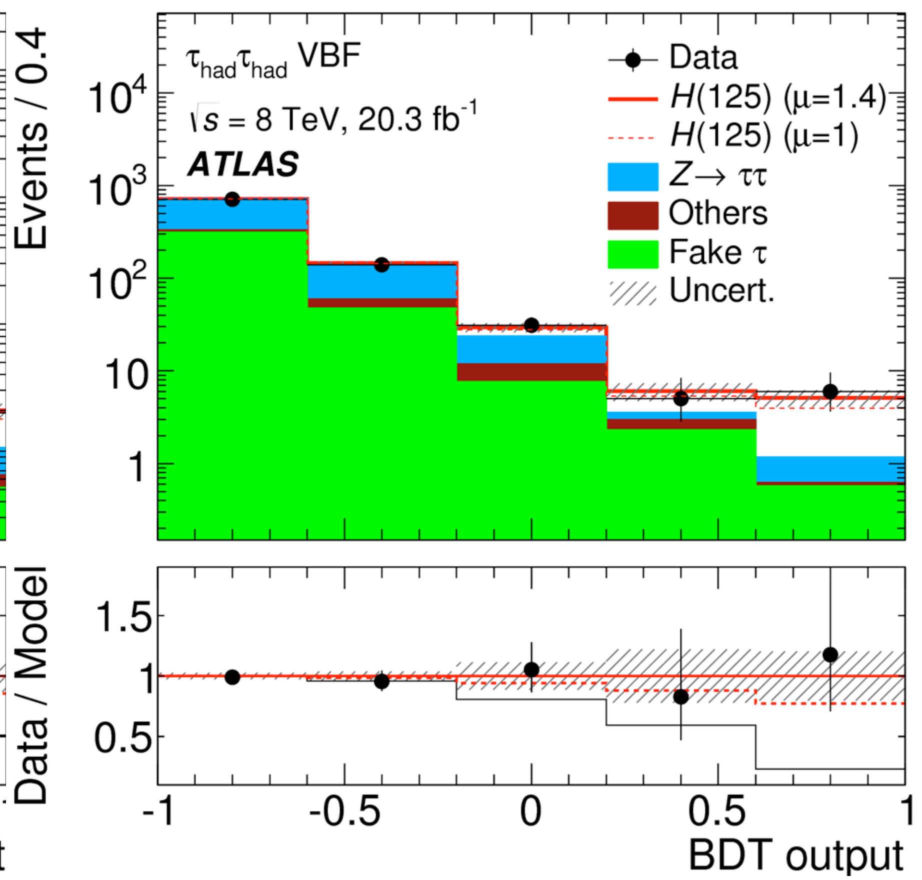


e p_T = 56 GeV, τ_{had} p_T = 27 GeV, MET=113 GeV, $m_{j1,j2}$=1.53 TeV, $m_{\tau\tau}^{MMC}$=129 GeV, BDT score = 0.99. S/B ratio of this bin 1.0



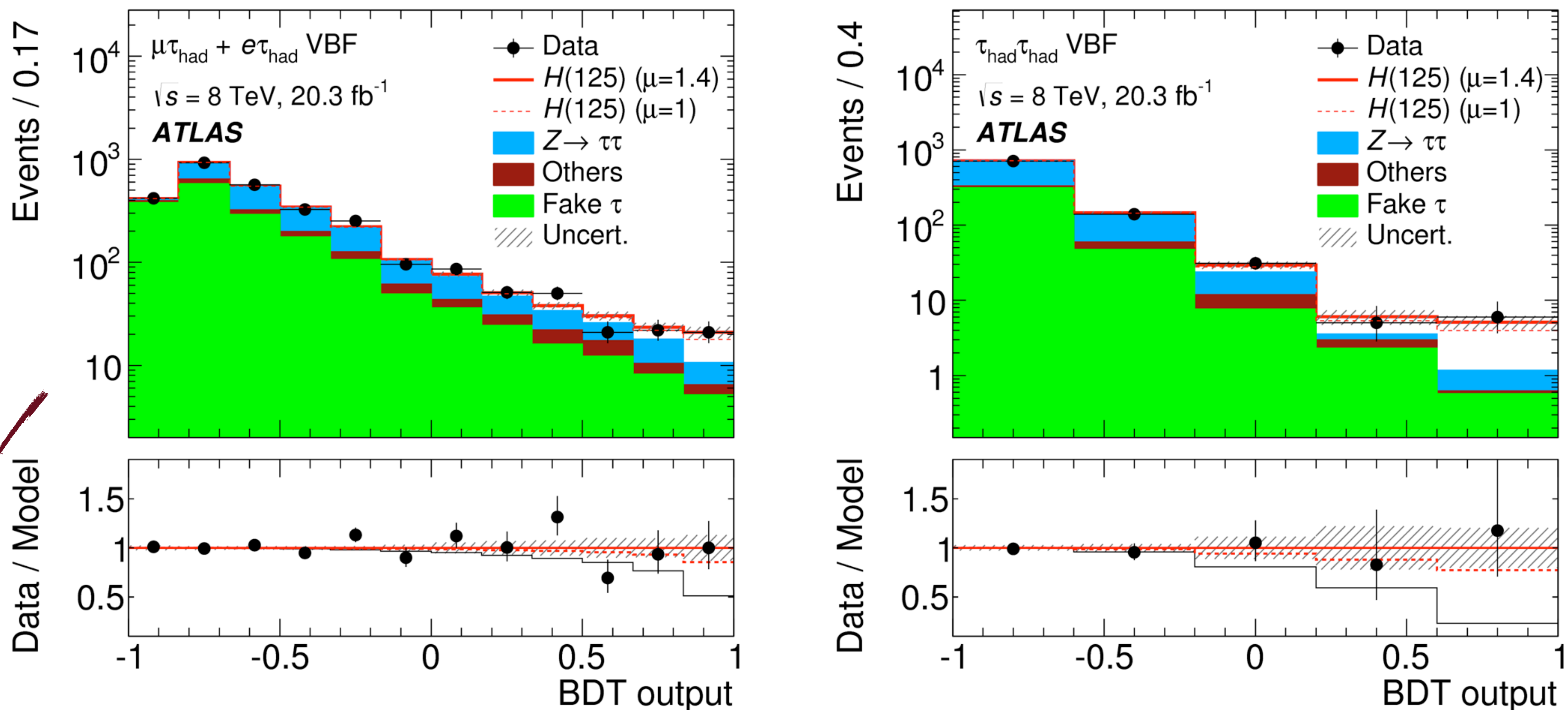
JHEP 1504 (2015) 117





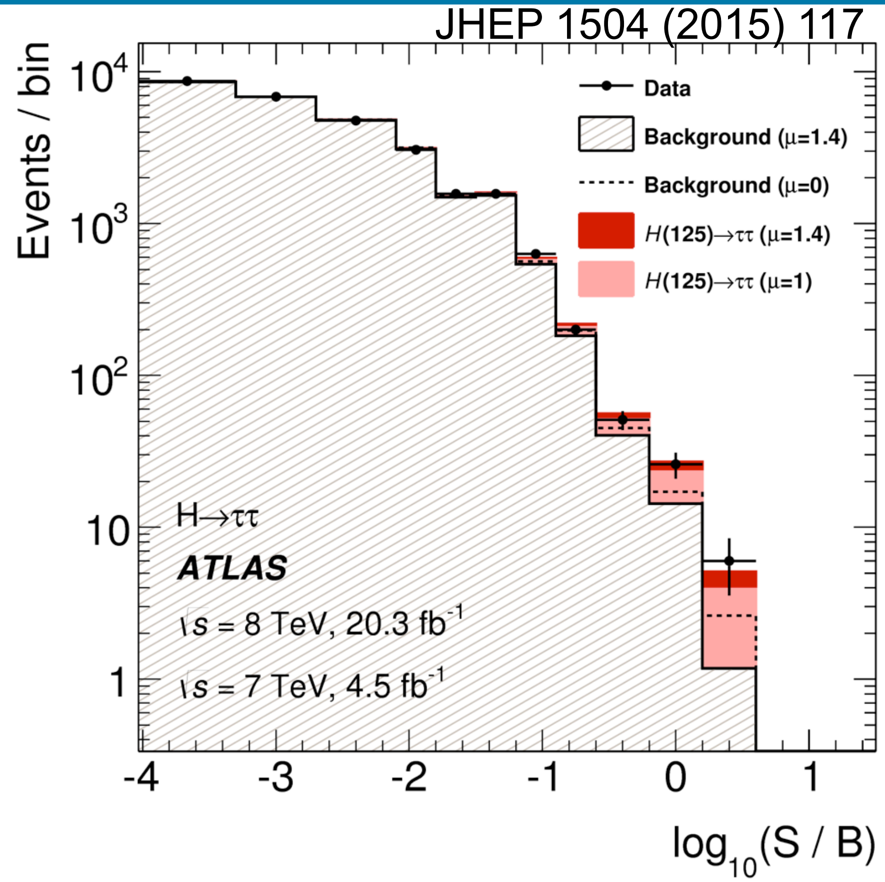
H→ττ: Results

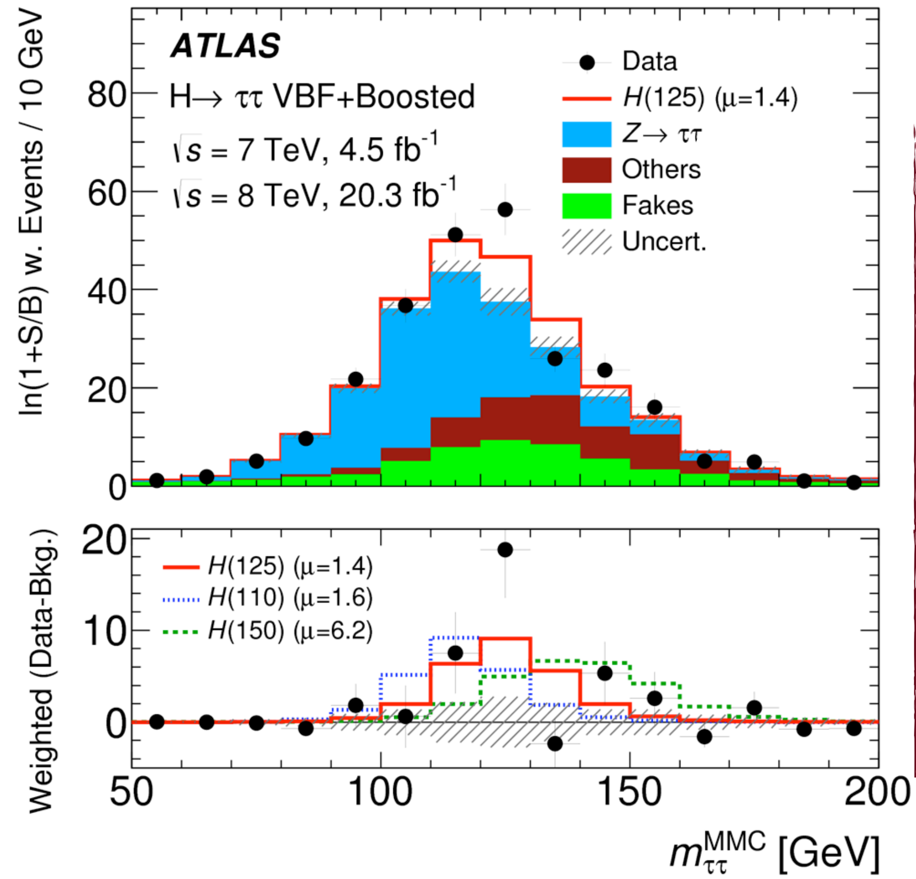
arXiv:1501.04943



Channel and Category	Expected Significance (σ)	Observed Significance (σ)
$\tau_{lep}\tau_{lep}$ VBF	1.15	1.88
$\tau_{lep}\tau_{lep}$ Boosted	0.57	1.72
$\tau_{lep}\tau_{lep}$ Total	1.25	2.40
$\tau_{lep}\tau_{had}$ VBF	2.11	2.23
$\tau_{lep}\tau_{had}$ Boosted	1.11	1.01
$\tau_{lep}\tau_{had}$ Total	2.33	2.33
$\tau_{had}\tau_{had}$ VBF	1.70	2.23
$\tau_{had}\tau_{had}$ Boosted	0.82	2.56
$\tau_{had}\tau_{had}$ Total	1.99	3.25
Combined	3.43	4.54

$h \to \tau\tau$: Results





Evidence observed for Higgs boson decays to τ-leptons

<u>significance at 125 GeV</u>

ATLAS: 4.5σ (3.4σ)

CMS: 3.2σ (3.5σ)

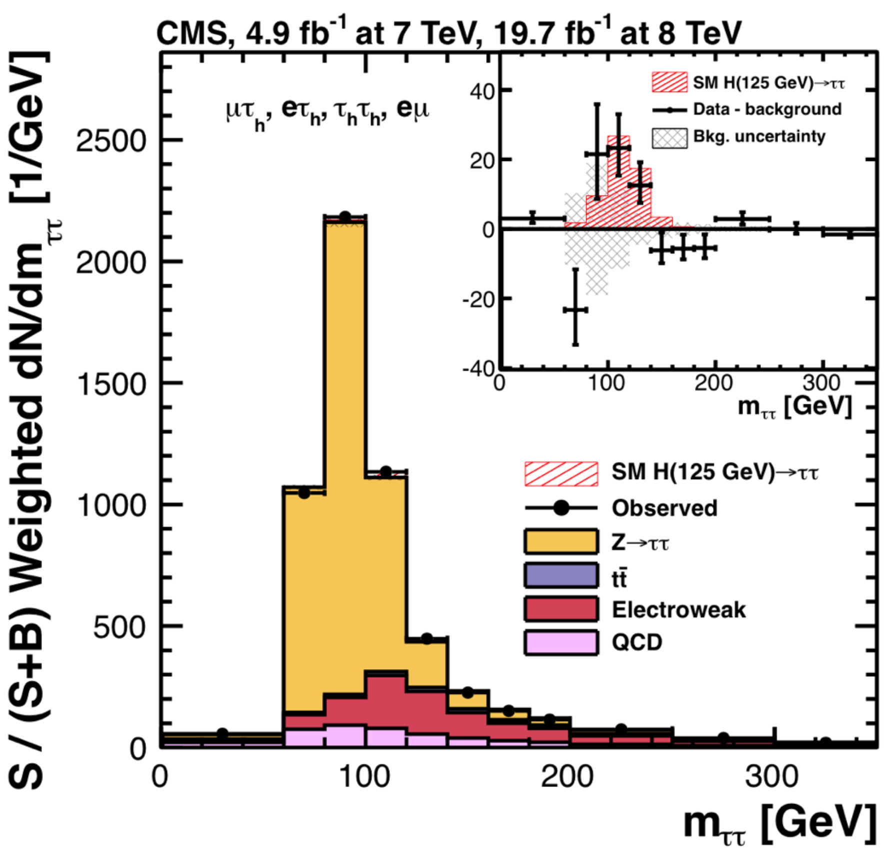
<u>Rate measurement</u>

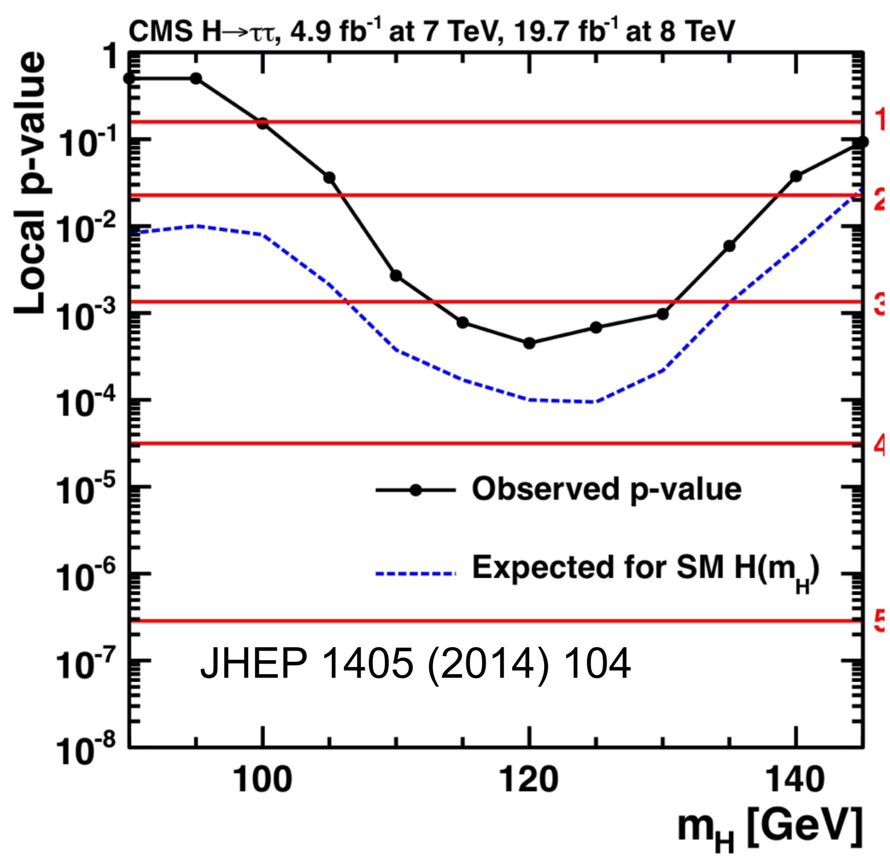
ATLAS $\mu=1.43^{+0.27}_{-0.26}$(stat) $^{+0.32}_{-0.25}$(syst) ± 0.09 (theo syst)

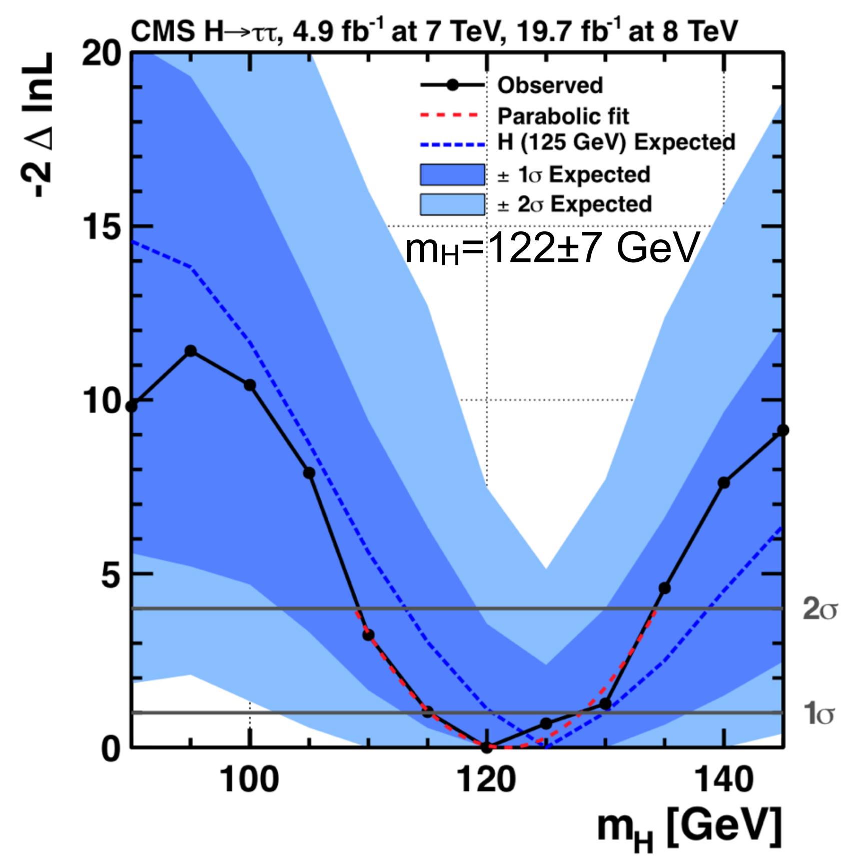
[@ m_H=125.36 GeV]

CMS μ=0.78 ± 0.27

[@ m_H=125.00 GeV]







Significances for Production mechanisms

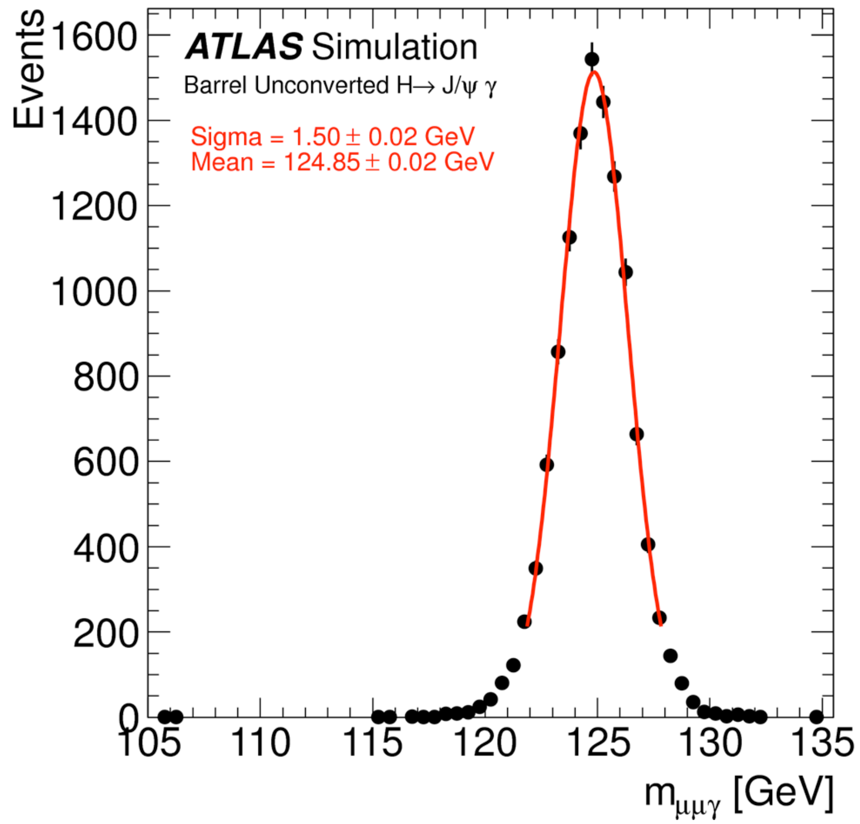
arXiv:1507.04548

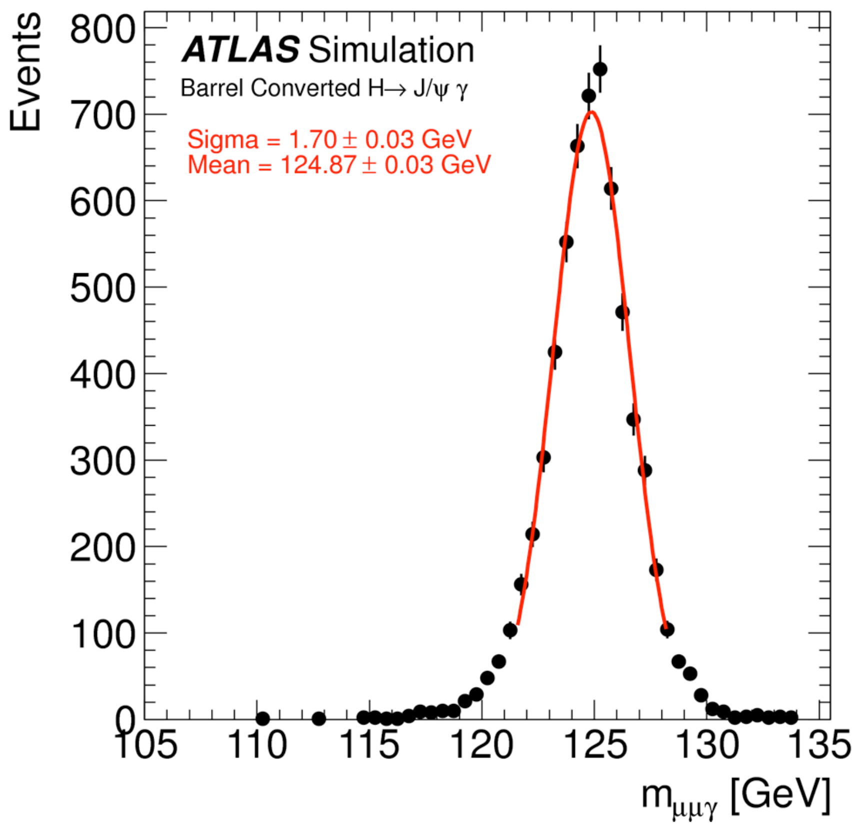
Table 8: The observed and expected significances in units of standard deviations for different Higgs boson production processes except ggF production which is well established (see text). The significances of VH production are obtained by combining the WH and ZH processes, assuming the SM value for their relative cross sections. All significances are calculated under the asymptotic approximation [65].

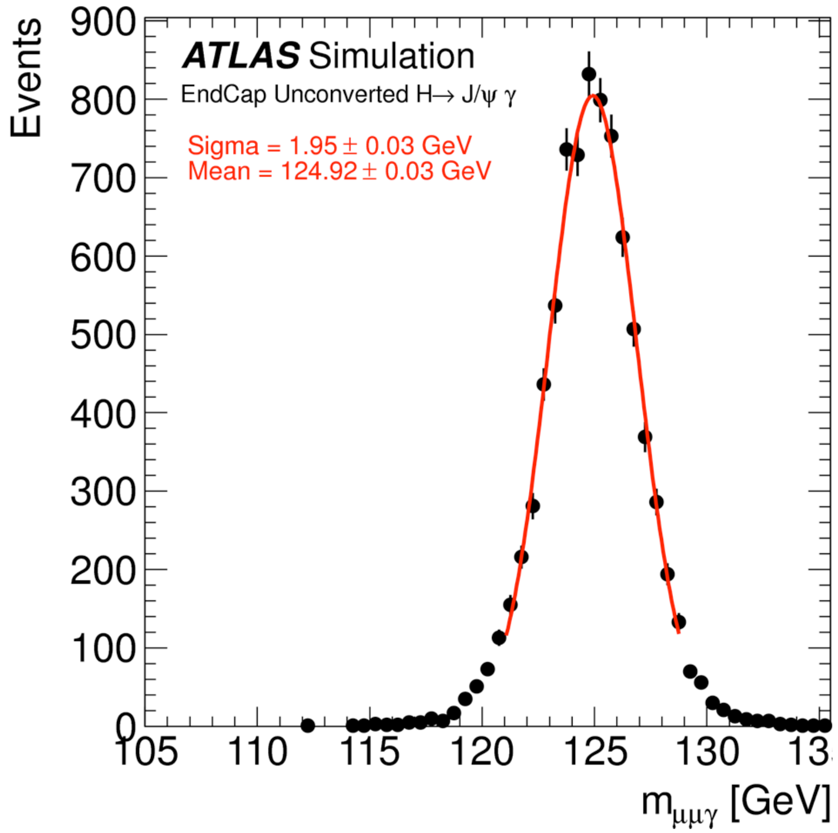
Process	VBF	ttH	WH	ZH	VH
Observed	4.3	2.5	2.1	0.9	2.6
Expected	3.8	1.5	2.0	2.1	3.1

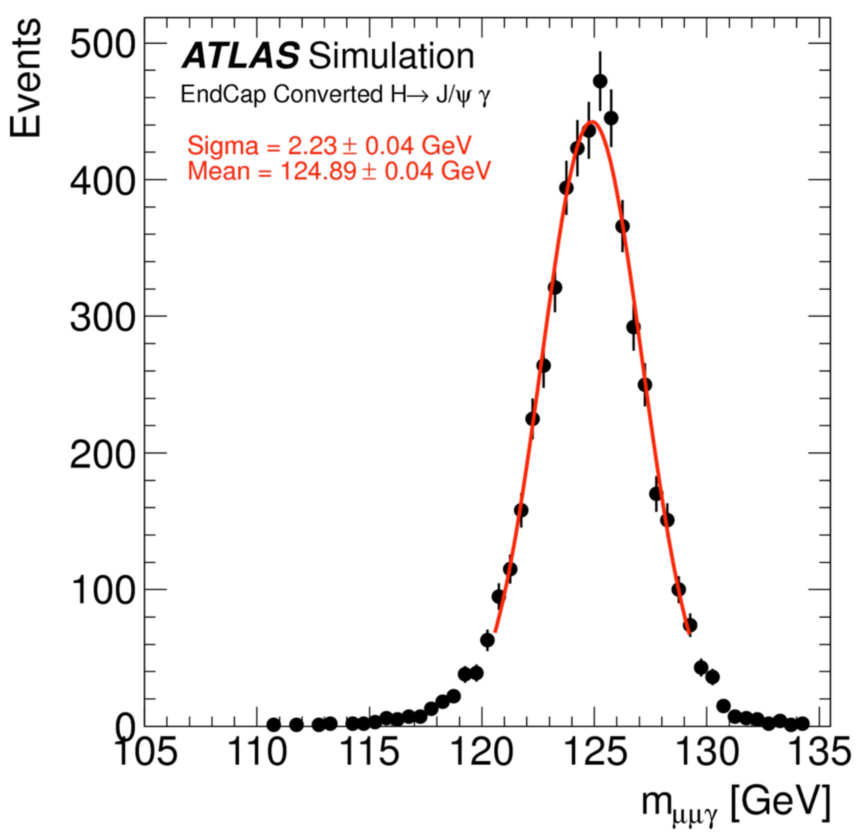
H→J/ψγ and H→Υ(ns)γ

Phys.Rev.Lett. 114 (2015) 12, 121801

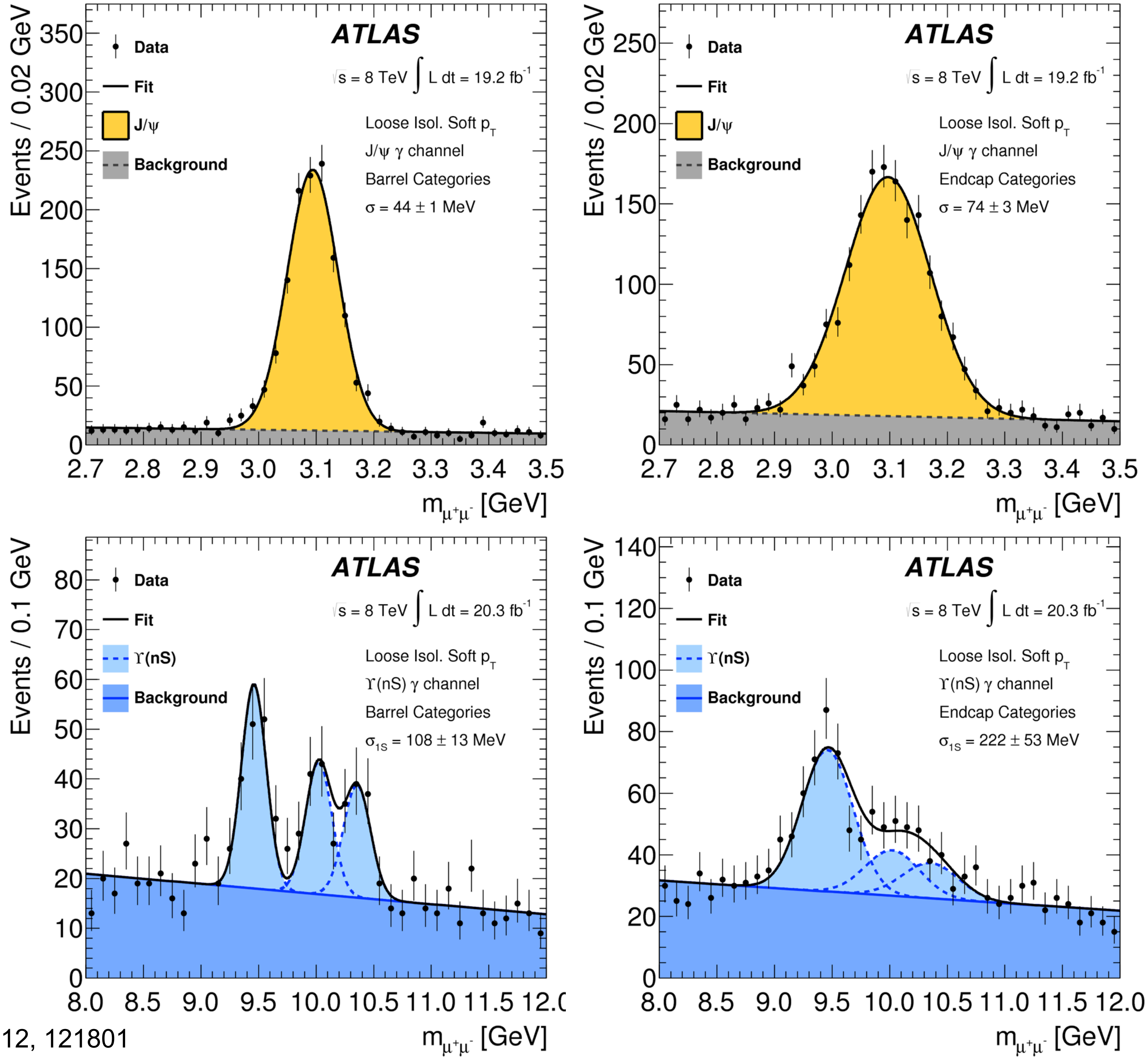








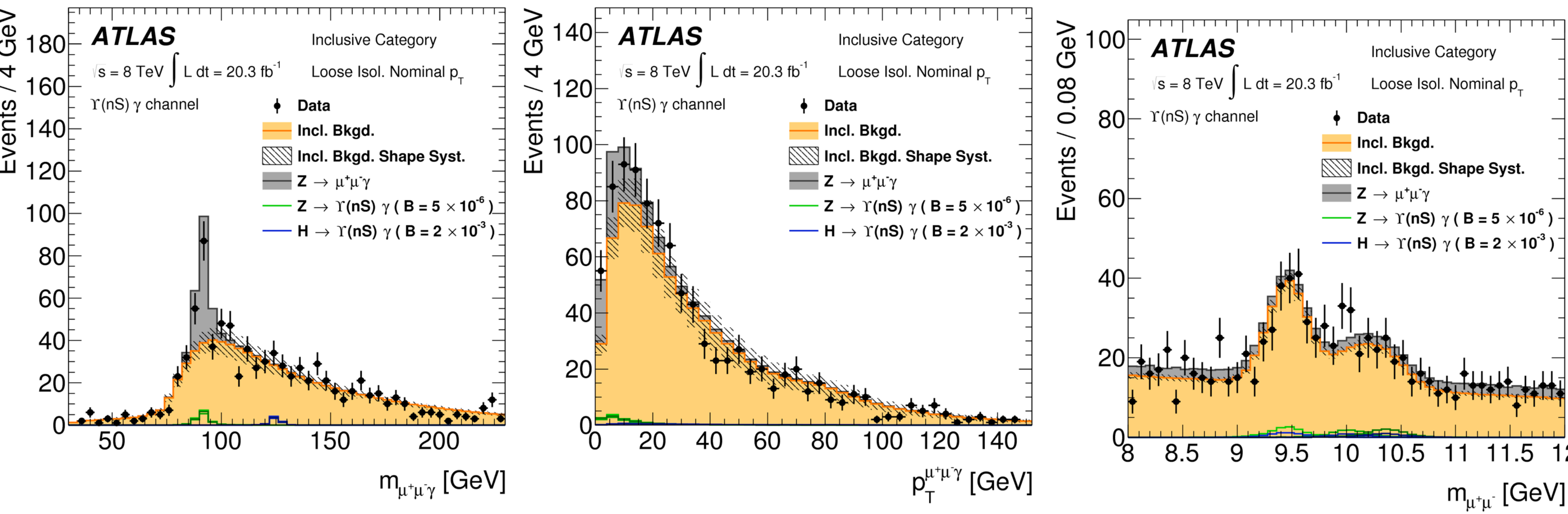
H→J/ψγ and H→Υ(ns)γ



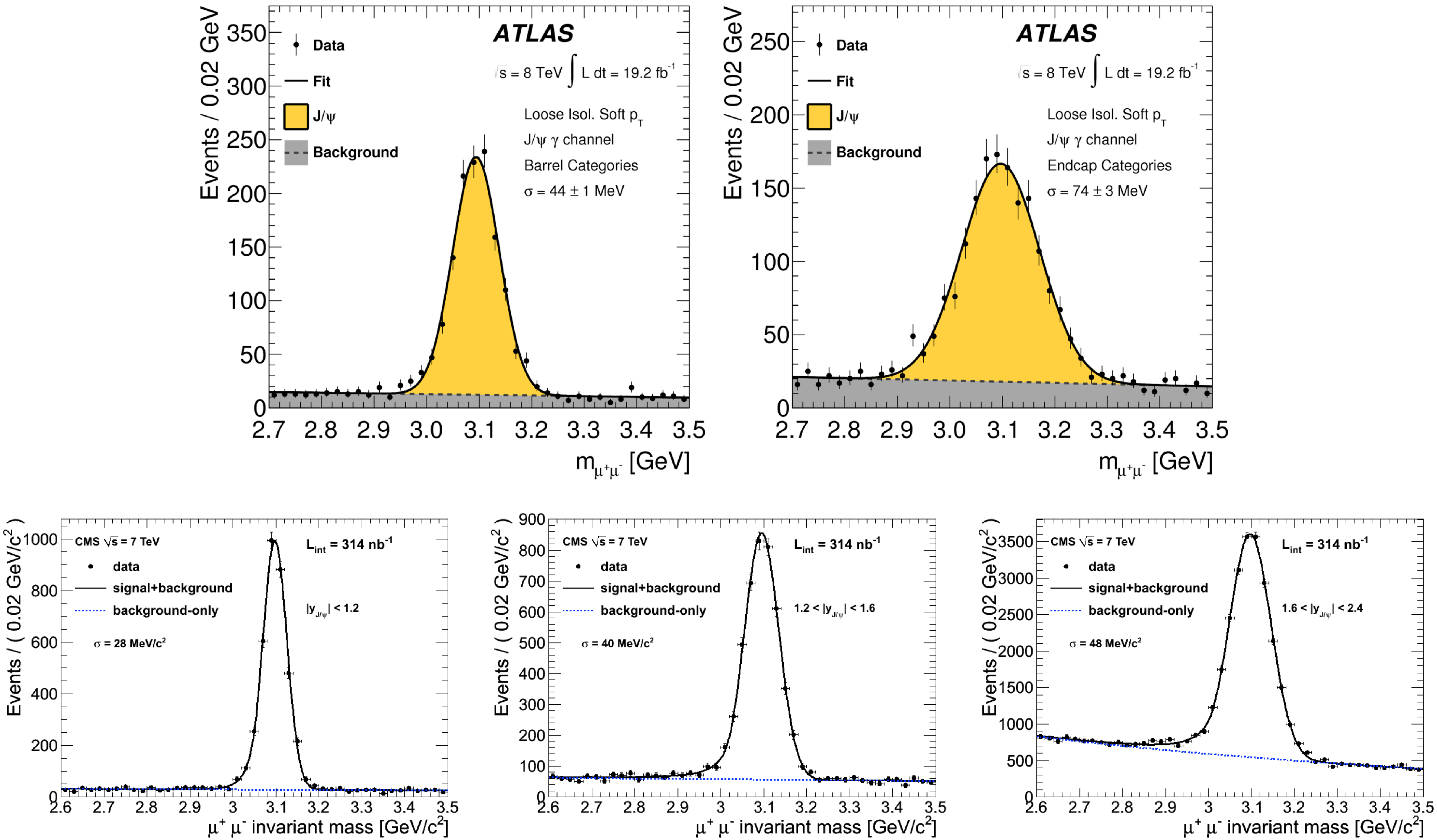
Phys.Rev.Lett. 114 (2015) 12, 121801

H→J/ψγ and H→Υ(ns)γ

Phys.Rev.Lett. 114 (2015) 12, 121801



H→J/ψγ and H→Υ(ns)γ



Light-Quark Yukawa couplings

This was also considered impossible for the LHC. Recent activity on its feasibility:

→ Exploit the exclusive decays H→Qγ as direct probe to the quark Yukawa couplings

[Phys.Rev.Lett. 114 (2015) 10, 101802]

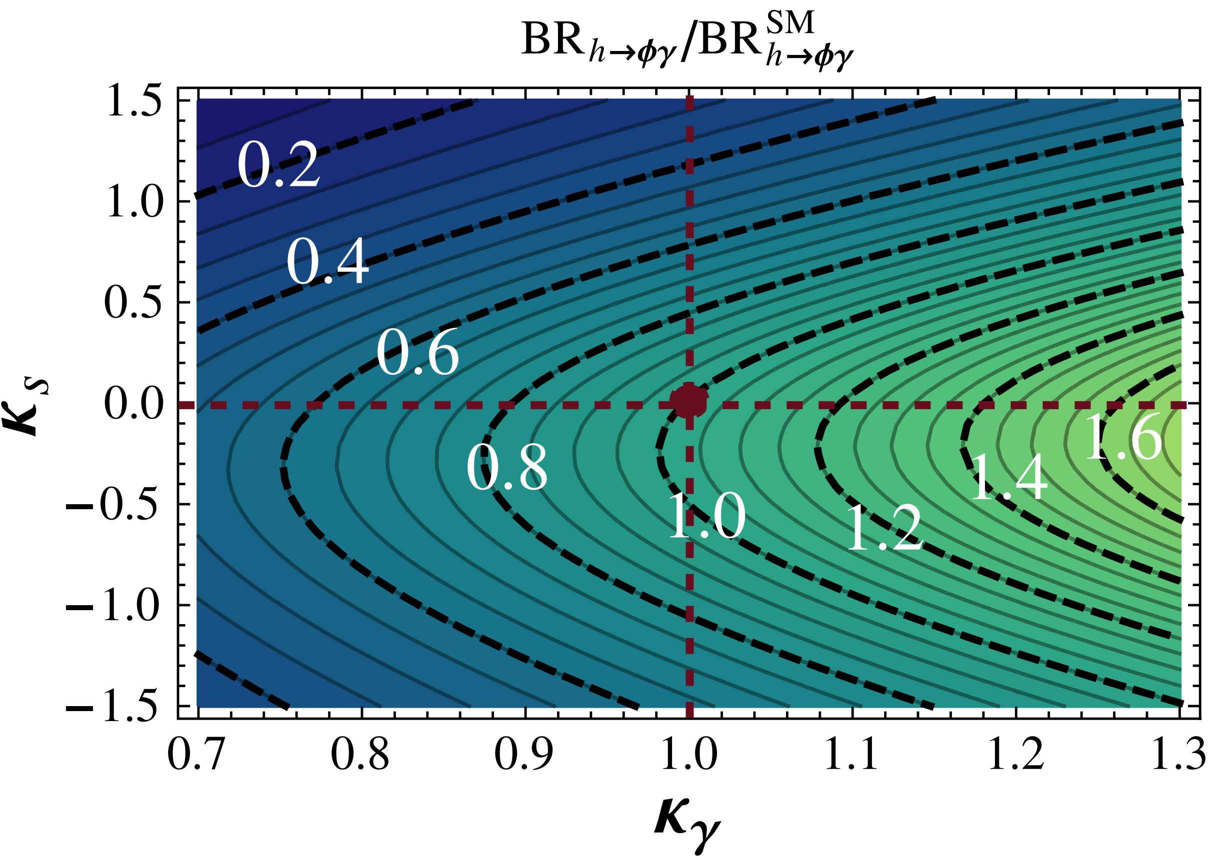
→ Sensitive to BSM physics [Phys. Rev. D 80, 076002, Phys. Lett. B665 (2008) 79, Phys.Rev. D90 (2014) 115022]

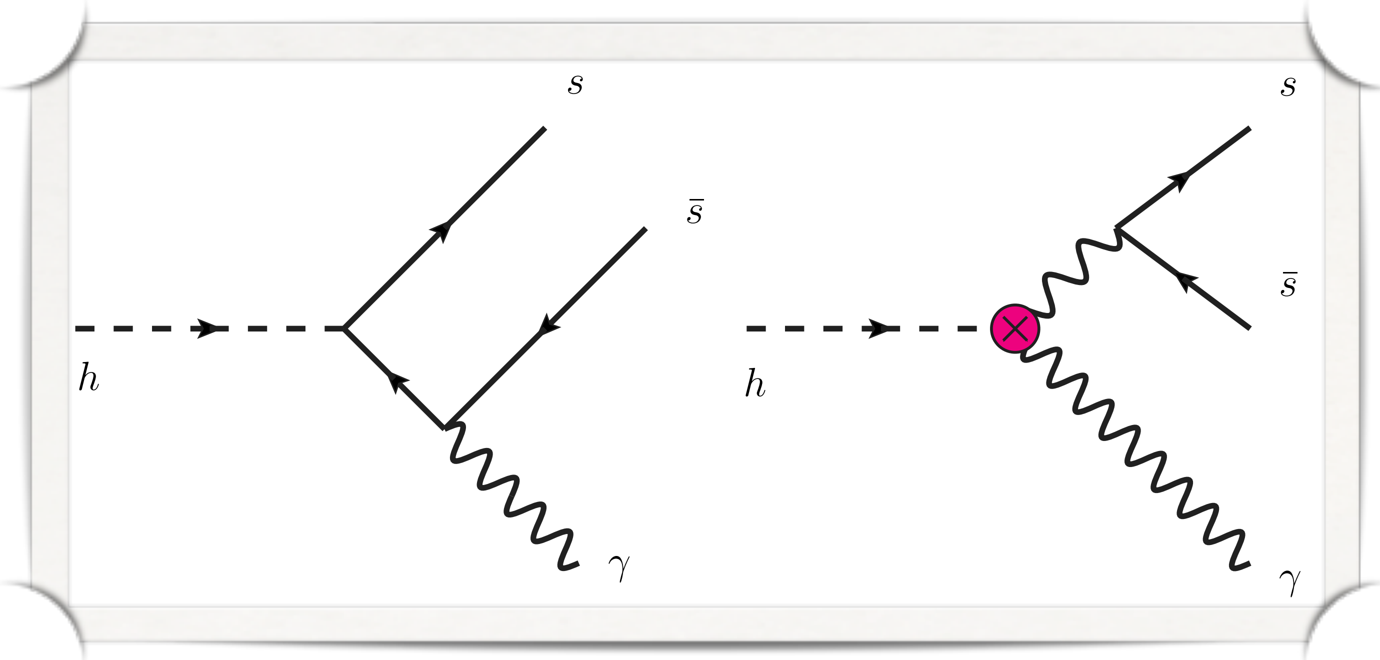
The idea is to benefit from the interference of the "direct" and "indirect" amplitudes!

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(3.0\pm0.3)\kappa_\gamma-0.78\bar{\kappa}_s]\times10^{-6}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(1.9\pm0.2)\kappa_\gamma-0.24\bar{\kappa}_u-0.12\bar{\kappa}_d]\times10^{-5}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(1.6\pm0.2)\kappa_\gamma-0.59\bar{\kappa}_u-0.29\bar{\kappa}_d]\times10^{-6}}{0.57\bar{\kappa}_b^2},$$





Phys.Rev.Lett. 114 (2015) 10, 101802

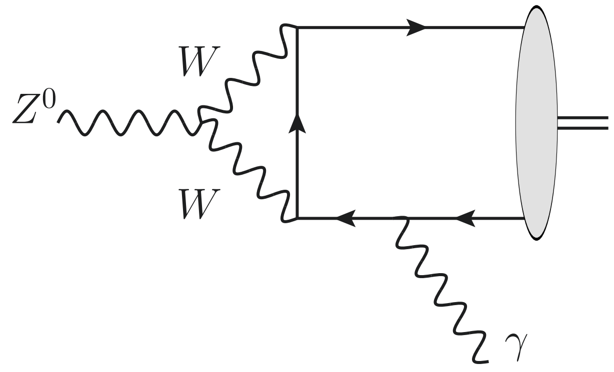
$$\bar{\kappa}_s = m_s/m_b \approx 0.02$$
$$\bar{\kappa}_d = m_d/m_b \approx 1\cdot10^{-3}$$
$$\bar{\kappa}_u = m_u/m_b \approx 4.7\cdot10^{-4}$$

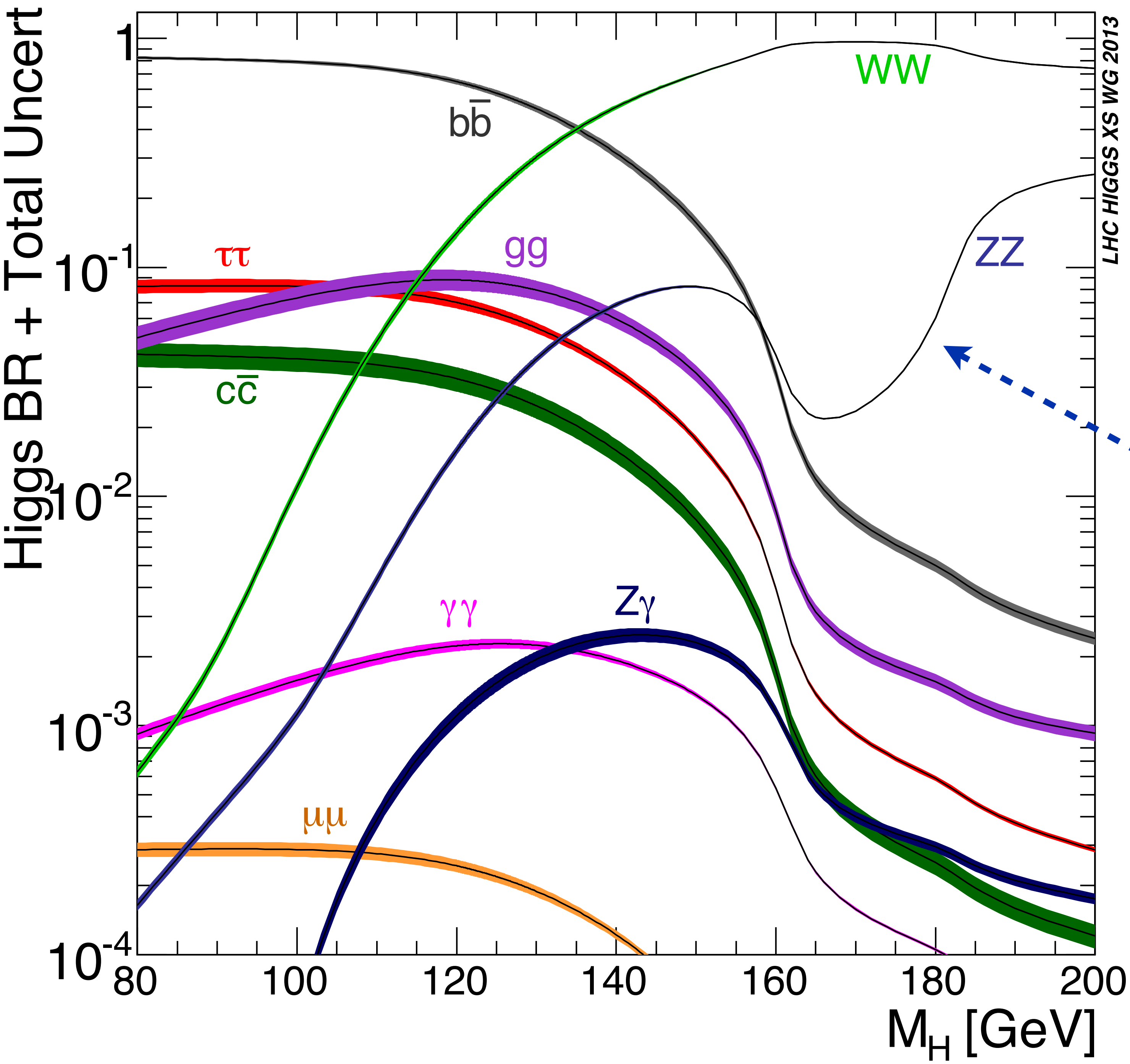
$$BR^{SM}_{h\to\phi\gamma}\approx 3\cdot10^{-6}$$
$$BR^{SM}_{h\to\rho\gamma}\approx 1.9\cdot10^{-5}$$
$$BR^{SM}_{h\to\omega\gamma}\approx 1.6\cdot10^{-6}$$

FCNC Z→Qγ decays

relative to new physics contributions

Decay mode	Branching ratio	SM background
$Z^0 \to K^0\gamma$	$\left[(7.70 \pm 0.83)\,\lvert v_{sd}\rvert^2 + (0.01 \pm 0.01)\,\lvert a_{sd}\rvert^2\right] \cdot 10^{-8}$	$\frac{\lambda}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 2 \cdot 10^{-3}$
$Z^0 \to D^0\gamma$	$\left[(5.30\,^{+0.67}_{-0.43})\,\lvert v_{cu}\rvert^2 + (0.62\,^{+0.36}_{-0.23})\,\lvert a_{cu}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 2 \cdot 10^{-3}$
$Z^0 \to B^0\gamma$	$\left[(2.08\,^{+0.59}_{-0.41})\,\lvert v_{bd}\rvert^2 + (0.77\,^{+0.38}_{-0.26})\,\lvert a_{bd}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda^3}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 8 \cdot 10^{-5}$
$Z^0 \to B_s\gamma$	$\left[(2.64\,^{+0.82}_{-0.52})\,\lvert v_{bs}\rvert^2 + (0.87\,^{+0.51}_{-0.33})\,\lvert a_{bs}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda^2}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 4 \cdot 10^{-4}$





$H \rightarrow ZZ \rightarrow 4l$

Mass Measurement: Phys. Rev. D. 90, 052004 (2014)

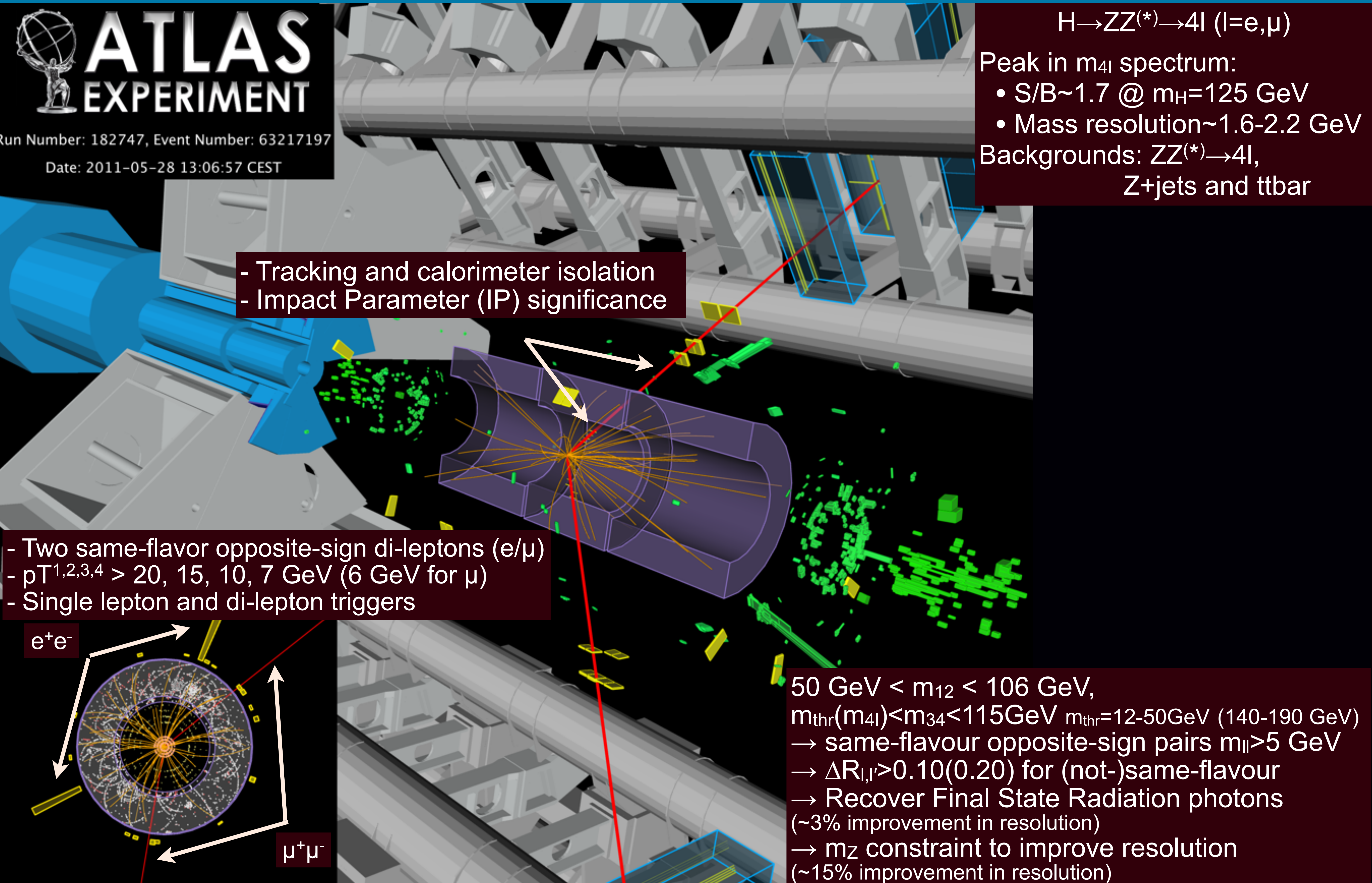
Couplings: Phys. Rev. D 91, 012006 (2015)

Differential Cross-Sections: PLB 738 (2014) 234-253

Spin/CP: Phys. Lett. B726 (2013) 120

Indirect Γ_H measurement: ATLAS-CONF-2014-042

$H \rightarrow ZZ^{(*)} \rightarrow 4l$



$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (l=e,μ)

Peak in m_{4l} spectrum:

- S/B~1.7 @ m_H=125 GeV
- Mass resolution~1.6-2.2 GeV

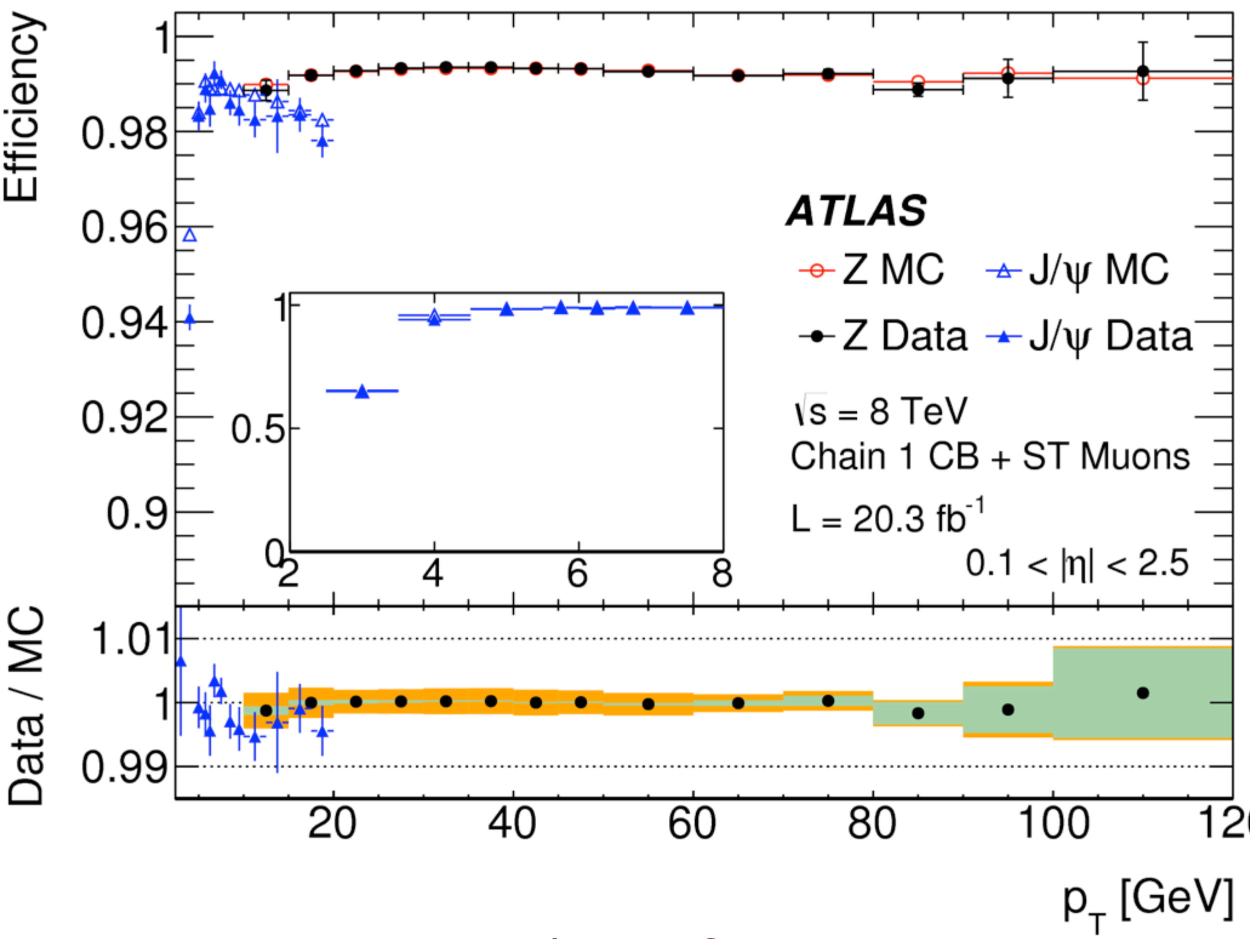
Backgrounds: $ZZ^{(*)} \rightarrow 4l$, Z+jets and ttbar

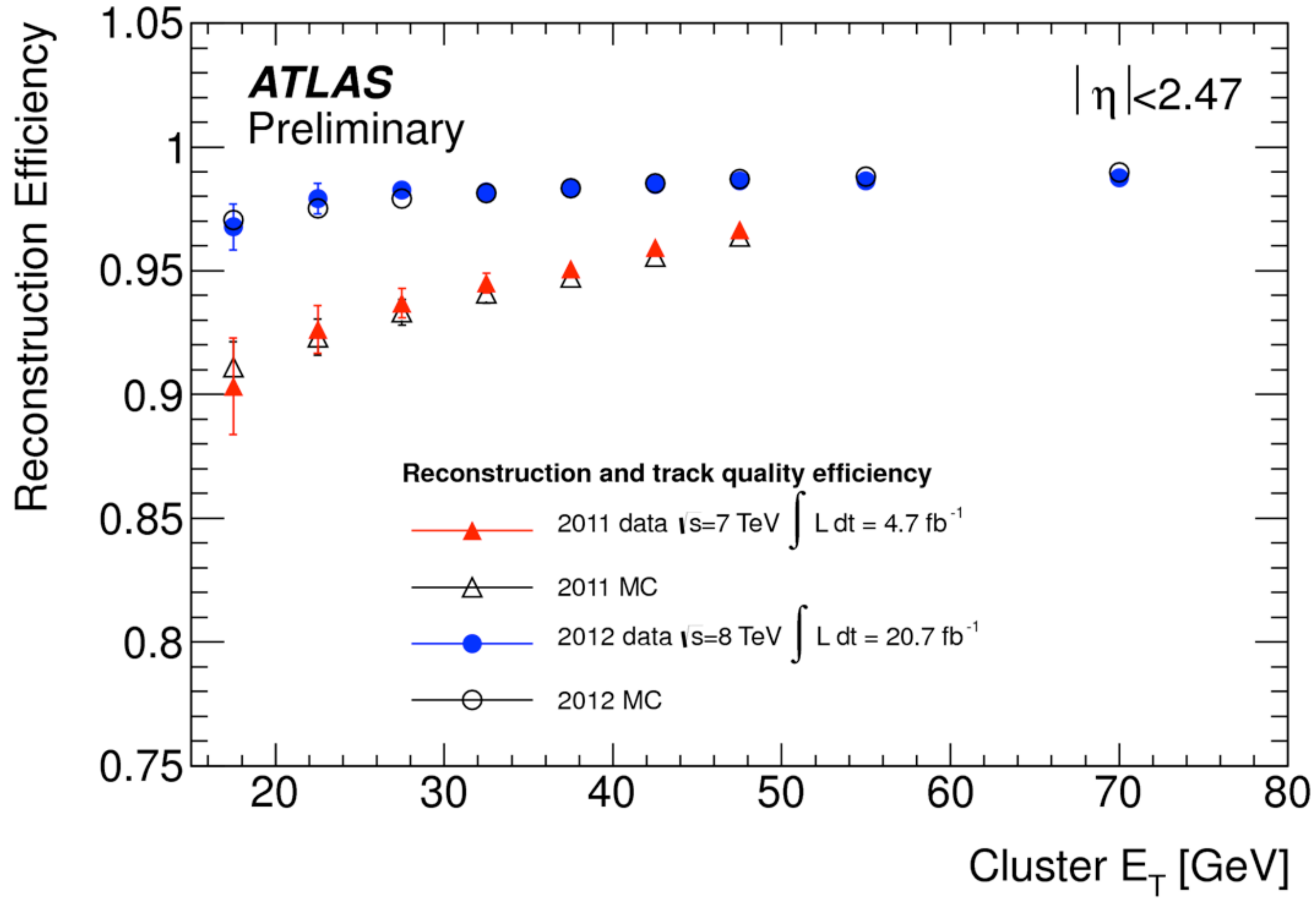
- Tracking and calorimeter isolation
- Impact Parameter (IP) significance

- Two same-flavor opposite-sign di-leptons (e/μ)
- $pT^{1,2,3,4}$ > 20, 15, 10, 7 GeV (6 GeV for μ)
- Single lepton and di-lepton triggers

50 GeV < m_{12} < 106 GeV,
$m_{thr}(m_{4l})<m_{34}<115$GeV m_{thr}=12-50GeV (140-190 GeV)
→ same-flavour opposite-sign pairs m_{ll}>5 GeV
→ $\Delta R_{l,l'}$>0.10(0.20) for (not-)same-flavour
→ Recover Final State Radiation photons
(~3% improvement in resolution)
→ m_Z constraint to improve resolution
(~15% improvement in resolution)

H→ZZ(*)→4l: Muon and Electron reconstruction





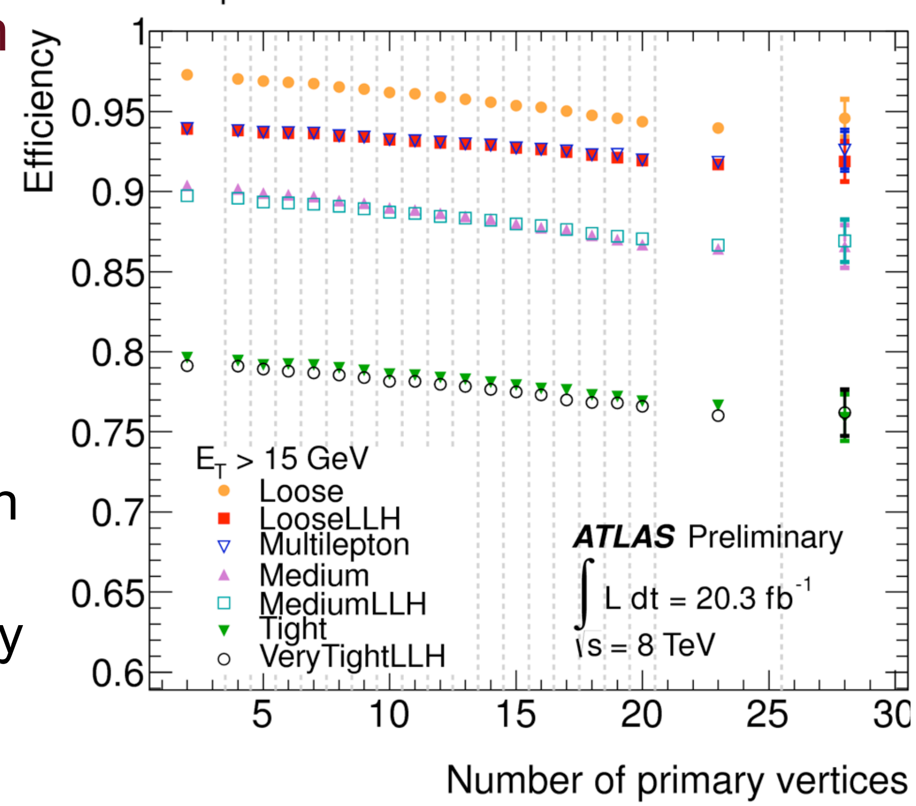
High reconstruction/identification efficiency to very low pT/ET

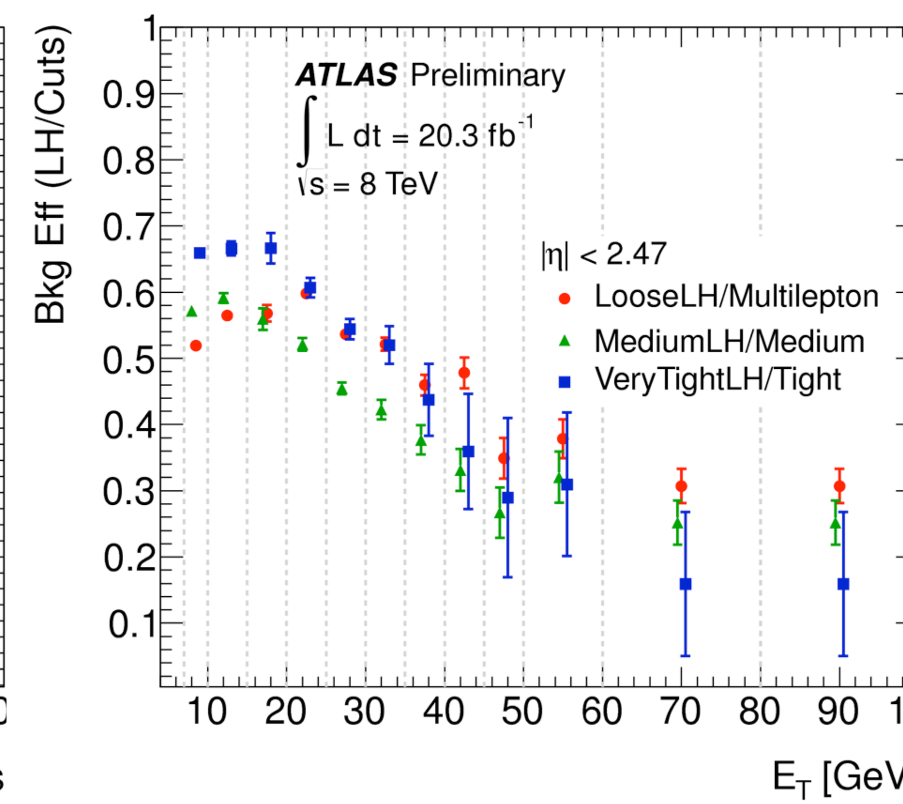
Muons

Systematic uncertainty at few ‰

Electrons

- GSF track reconstruction and improved track/cluster matching → substantially improved low ET region
- Likelihood based discriminant → -50% background for same efficiency
- Systematic uncertainty between few ‰ and few %



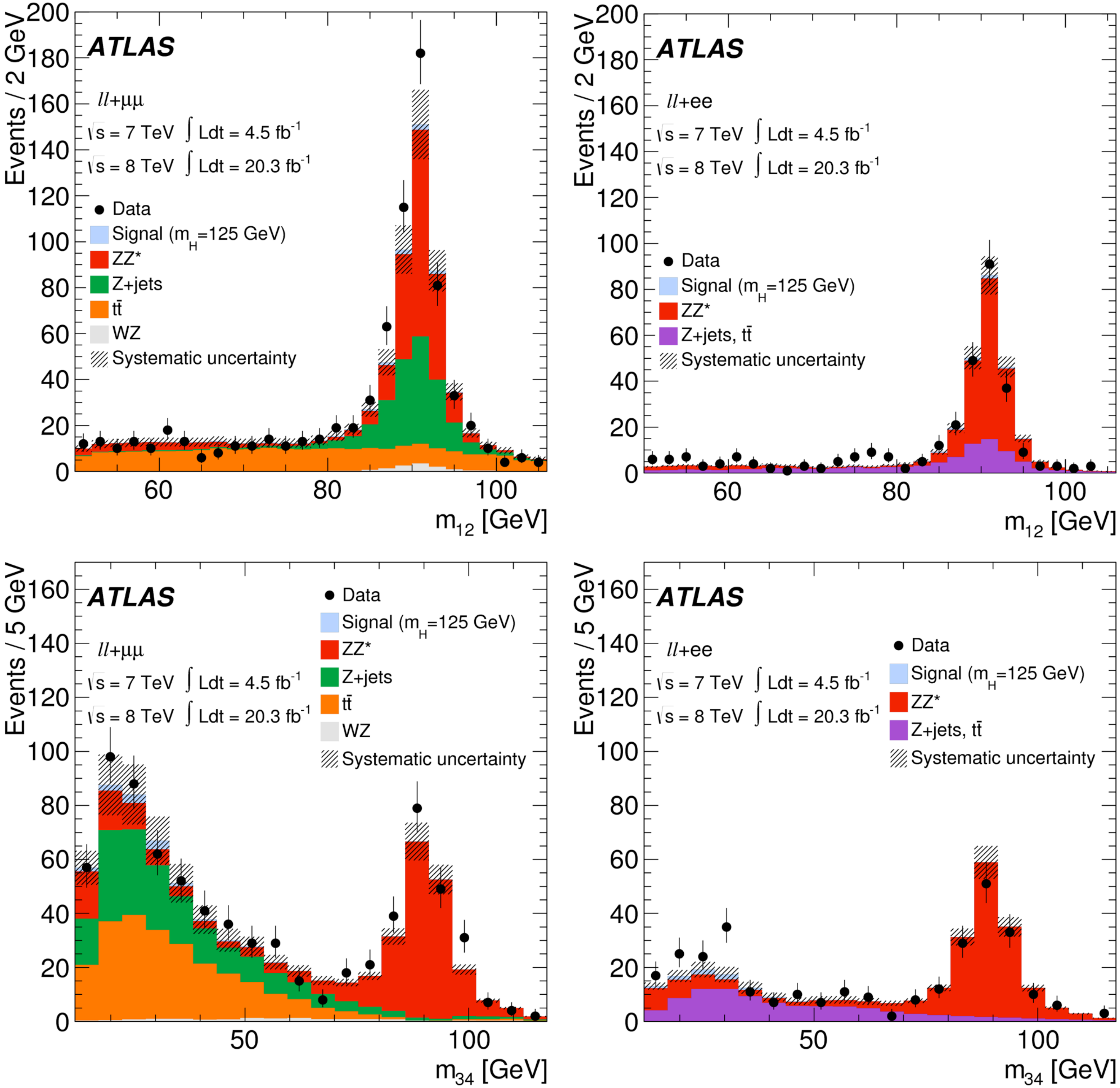


H→ZZ$^{(*)}$→4l: Updated Analysis

120-130 GeV

Final state	Signal full mass range	Signal	ZZ^*	$Z+$jets, $t\bar{t}$	S/B	Expected	Observed
			$\sqrt{s}=7$ TeV				
4μ	1.00 ± 0.10	0.91 ± 0.09	0.46 ± 0.02	0.10 ± 0.04	1.7	1.47 ± 0.10	2
$2e2\mu$	0.66 ± 0.06	0.58 ± 0.06	0.32 ± 0.02	0.09 ± 0.03	1.5	0.99 ± 0.07	2
$2\mu 2e$	0.50 ± 0.05	0.44 ± 0.04	0.21 ± 0.01	0.36 ± 0.08	0.8	1.01 ± 0.09	1
$4e$	0.46 ± 0.05	0.39 ± 0.04	0.19 ± 0.01	0.40 ± 0.09	0.7	0.98 ± 0.10	1
Total	2.62 ± 0.26	2.32 ± 0.23	1.17 ± 0.06	0.96 ± 0.18	1.1	4.45 ± 0.30	6
			$\sqrt{s}=8$ TeV				
4μ	5.80 ± 0.57	5.28 ± 0.52	2.36 ± 0.12	0.69 ± 0.13	1.7	8.33 ± 0.6	12
$2e2\mu$	3.92 ± 0.39	3.45 ± 0.34	1.67 ± 0.08	0.60 ± 0.10	1.5	5.72 ± 0.37	7
$2\mu 2e$	3.06 ± 0.31	2.71 ± 0.28	1.17 ± 0.07	0.36 ± 0.08	1.8	4.23 ± 0.30	5
$4e$	2.79 ± 0.29	2.38 ± 0.25	1.03 ± 0.07	0.35 ± 0.07	1.7	3.77 ± 0.27	7
Total	15.6 ± 1.6	13.8 ± 1.4	6.24 ± 0.34	2.00 ± 0.28	1.7	22.1 ± 1.5	31

$H \to ZZ^{(*)} \to 4l$: Backgrounds



ZZ background estimated using MC simulation and NLO cross section

Backgrounds with fake/non-prompt leptons (ttbar, Z+heavy flavour, Z+jet, WZ) estimated from data:

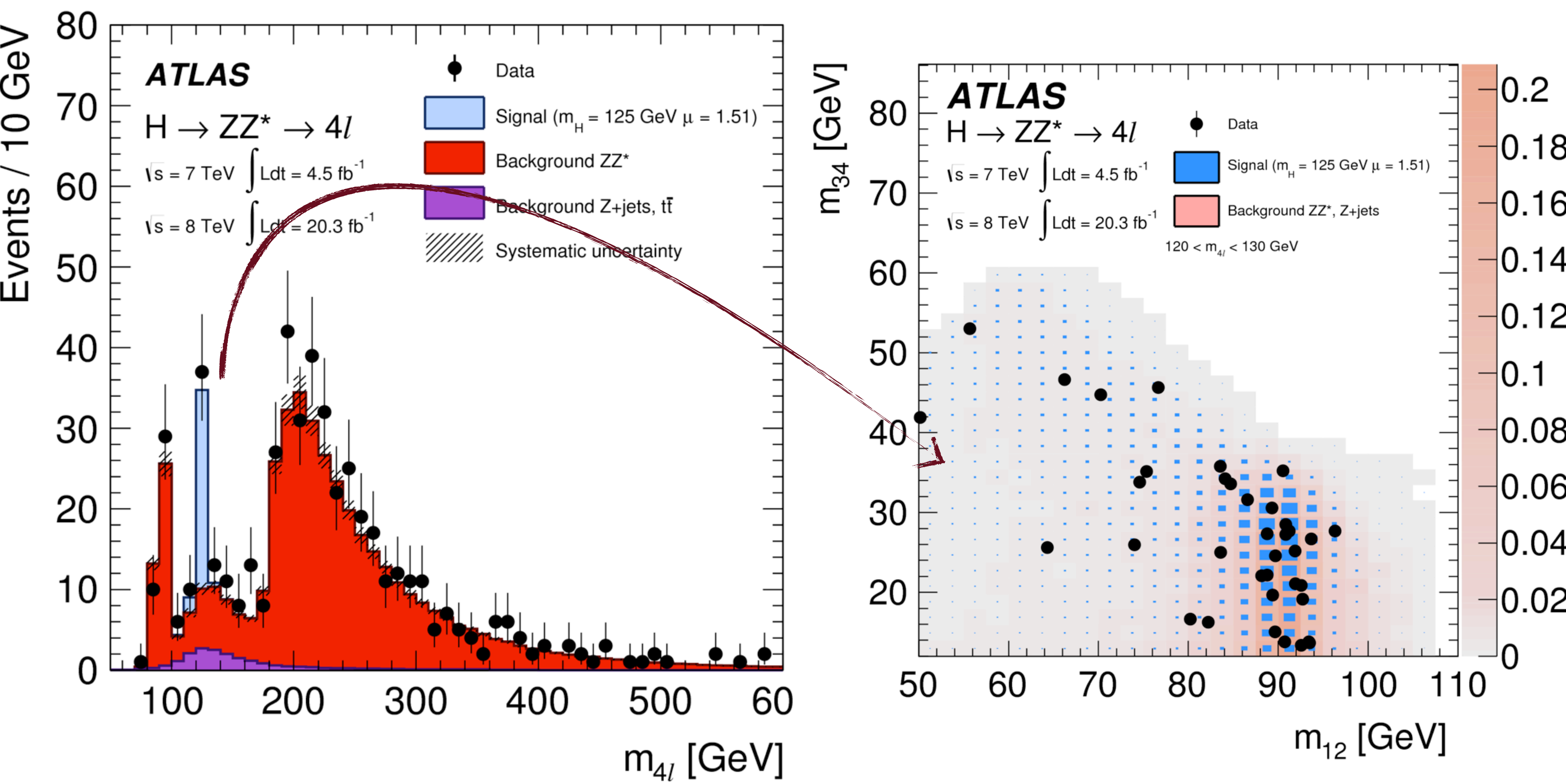
ll+μμ : Simultaneous fit using 4 exclusive Control Regions
- inverted d_0 significance
- inverted isolation
- eμ+μμ
- Same-sign sub-leading

ll+ee : 3 data-driven methods
- 3l+X
- transfer factors
- truth/reco categories

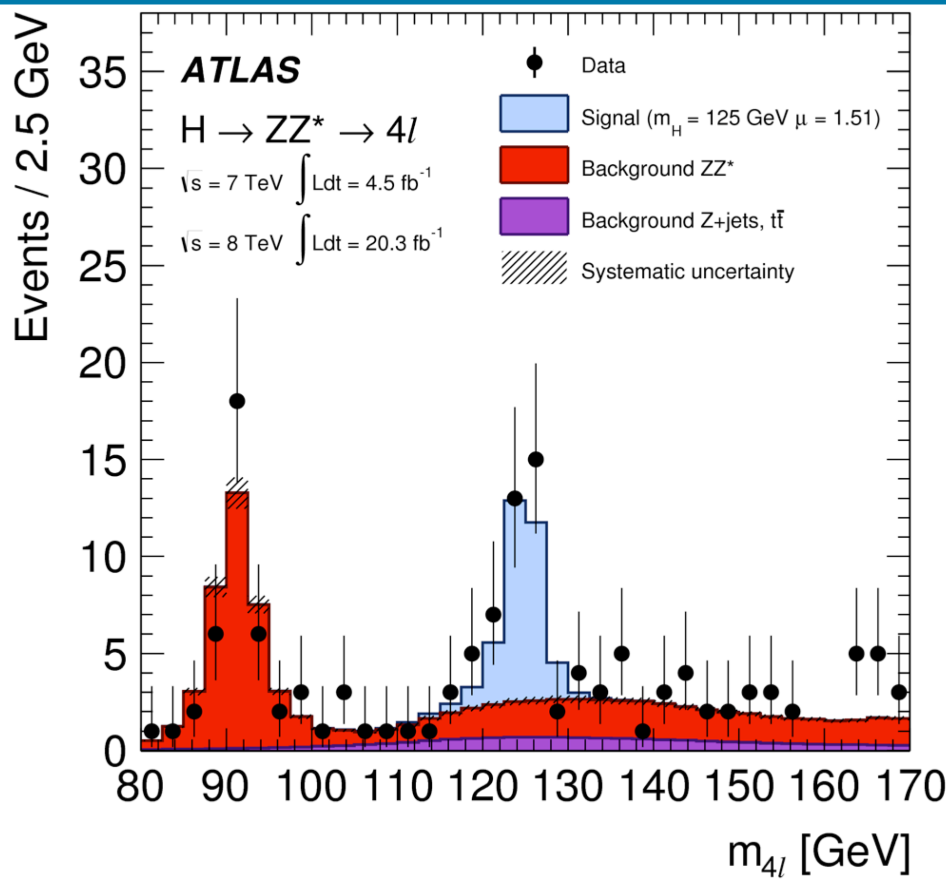
Overall uncertainties ~20%

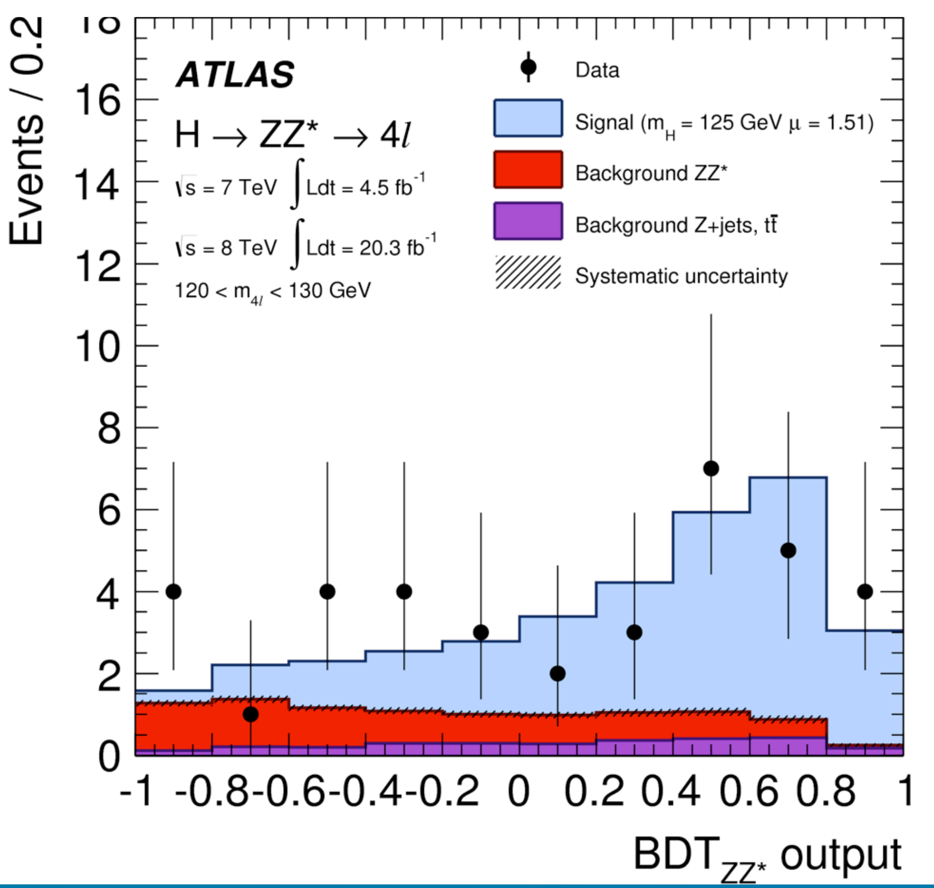
Background-dominated Control Region
[Remove isolation/impact parameter requirements on sub-leading di-lepton]

H→ZZ$^{(*)}$→4l: Selected Events



H→ZZ$^{(*)}$→4l: ZZ* suppression

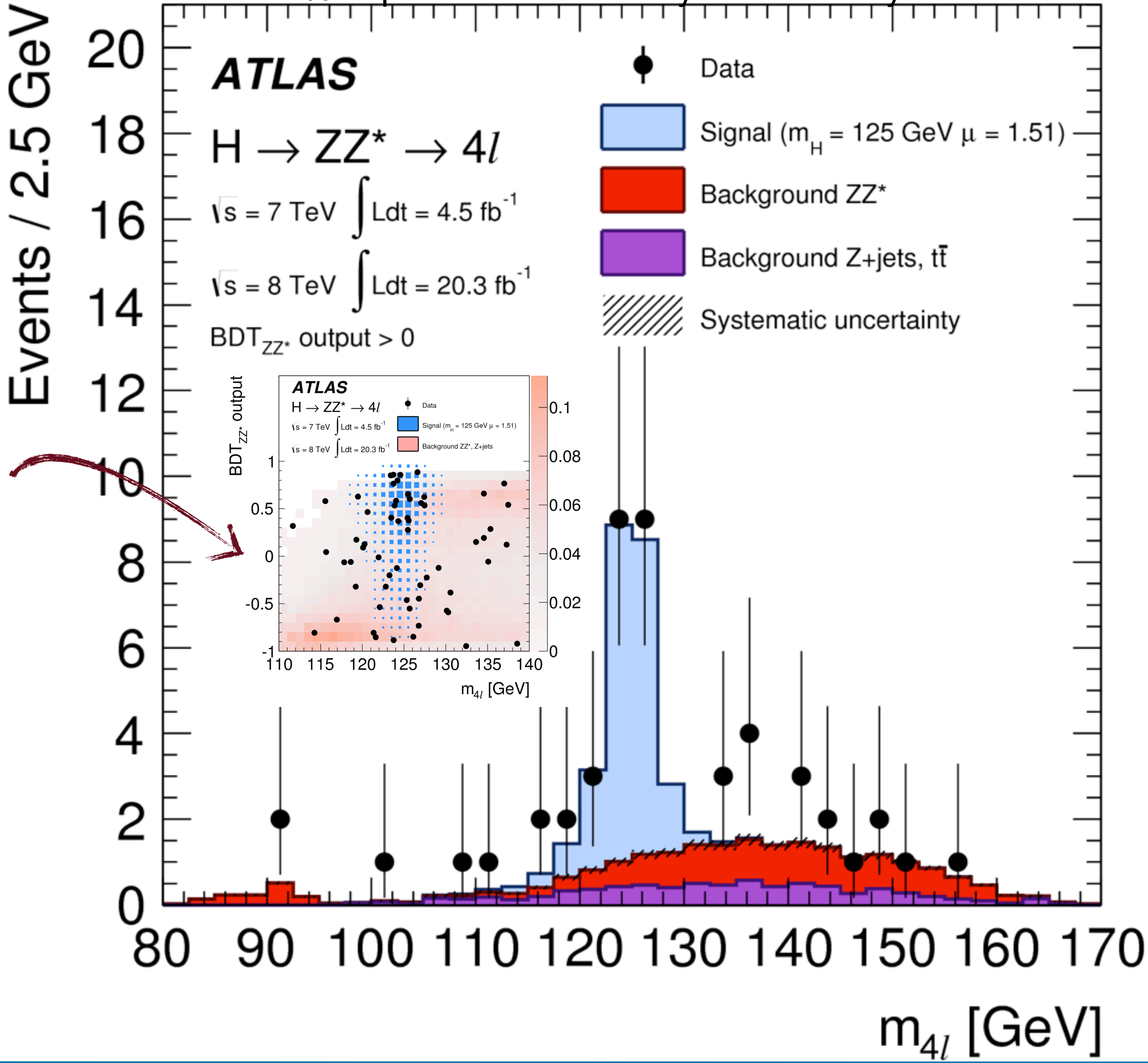




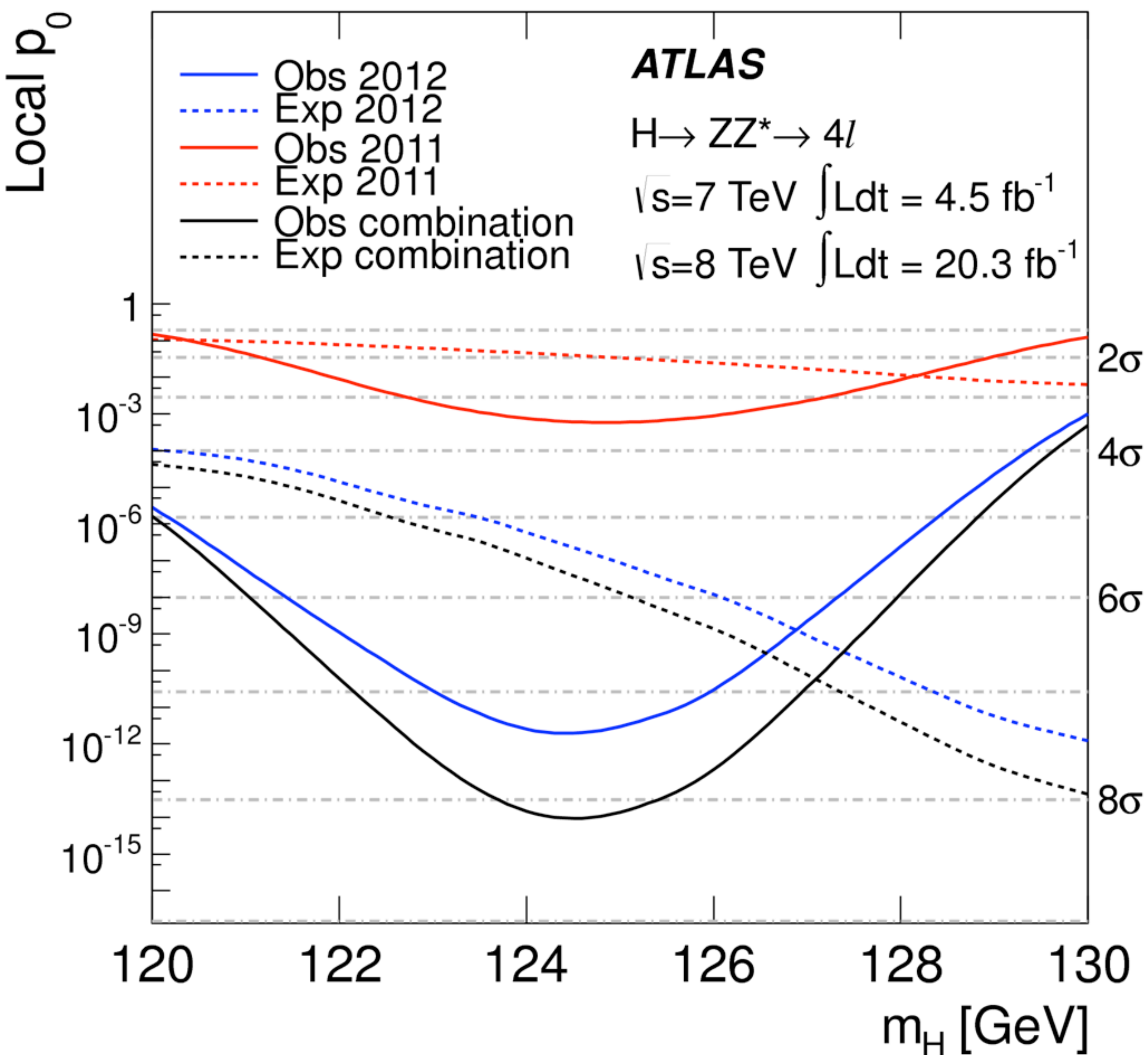
Introduced BDT discriminant to suppress ZZ* contribution

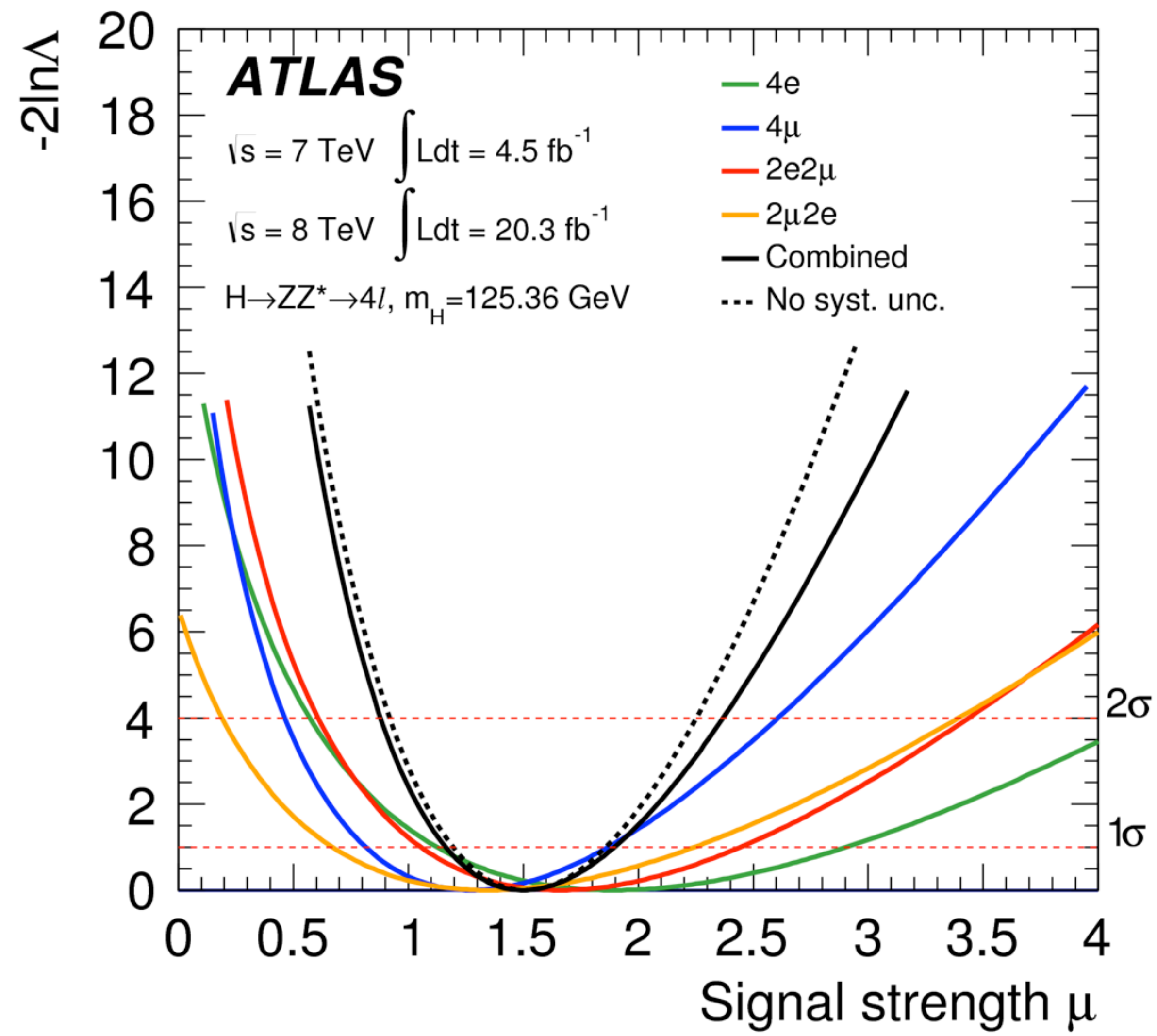
using Matrix Element Kinematic Discriminant, pT_{4l}, η_{4l}

~20% improvement on analysis sensitivity



H→ZZ(*)→4l: Inclusive Results





Maximum local significance: **8.2σ** (5.8σ)@ m_H=124.51 GeV

For m_H = 125.36GeV

local significance: **8.1σ** (6.2σ)

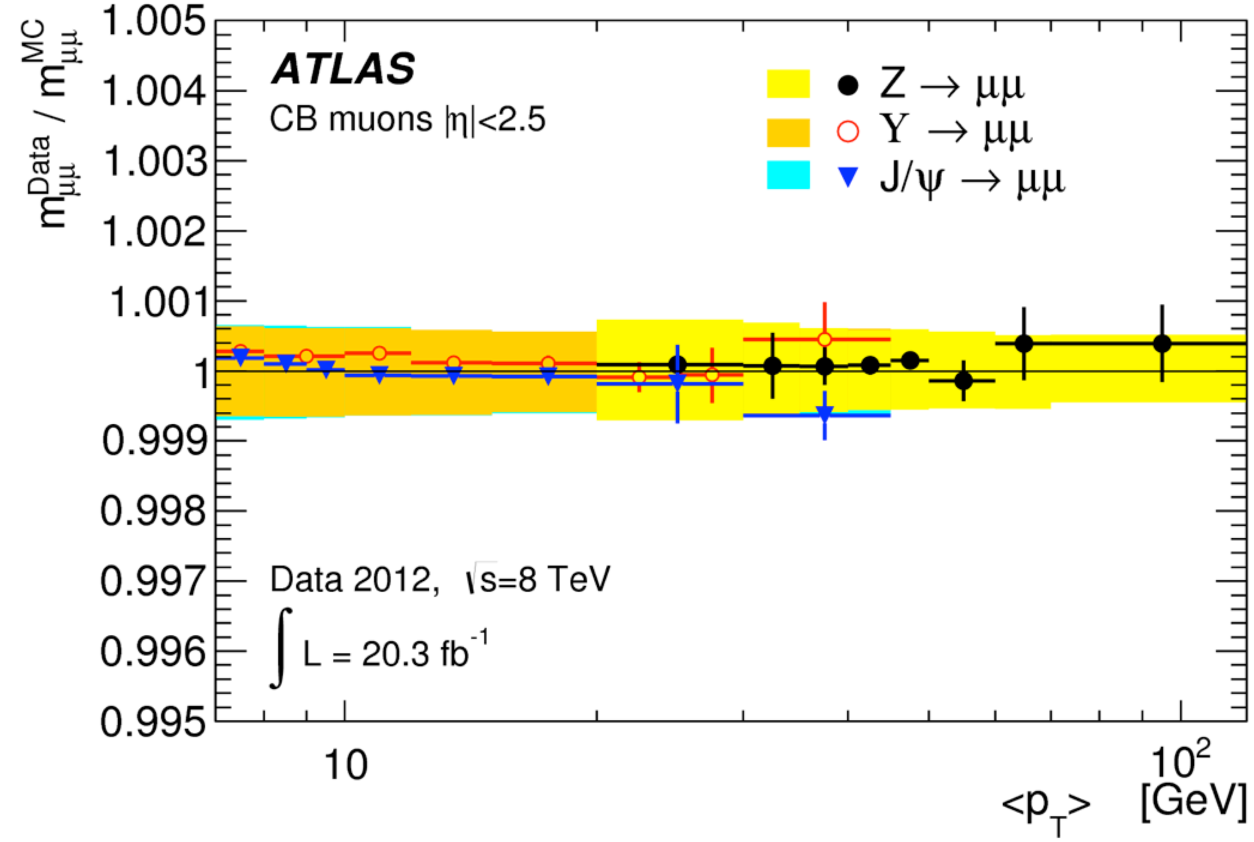
inclusive rate with respect to SM: **1.5 ± 0.4**

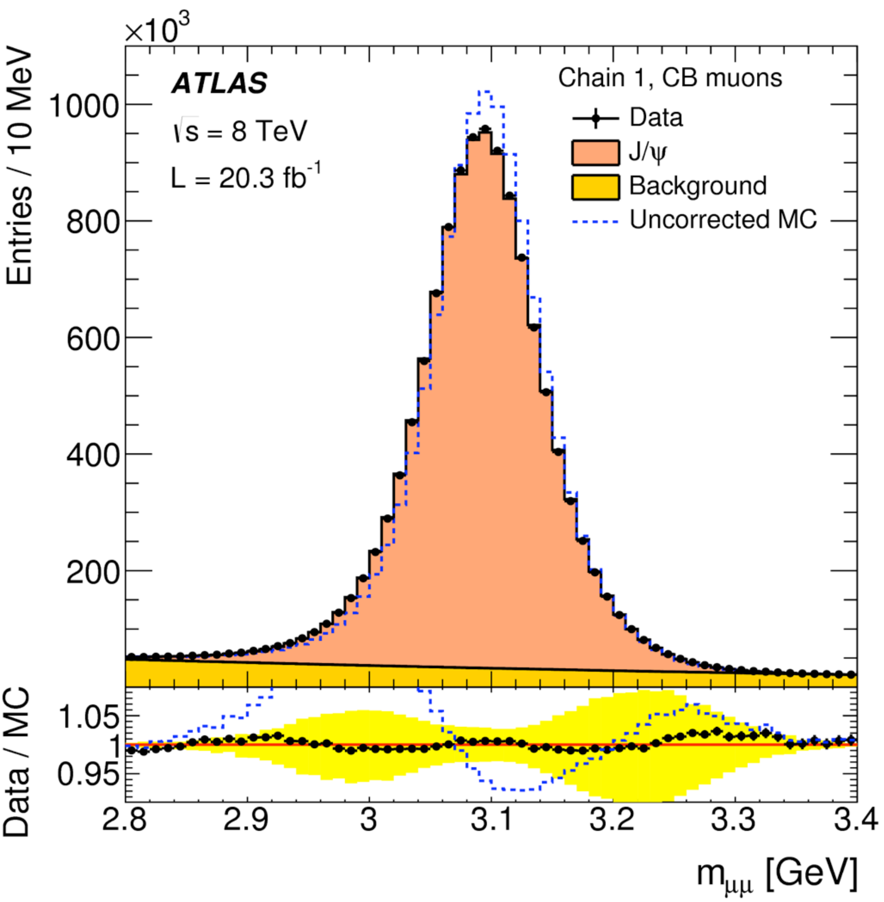
H→ZZ(*)→4l: Muon momentum scale

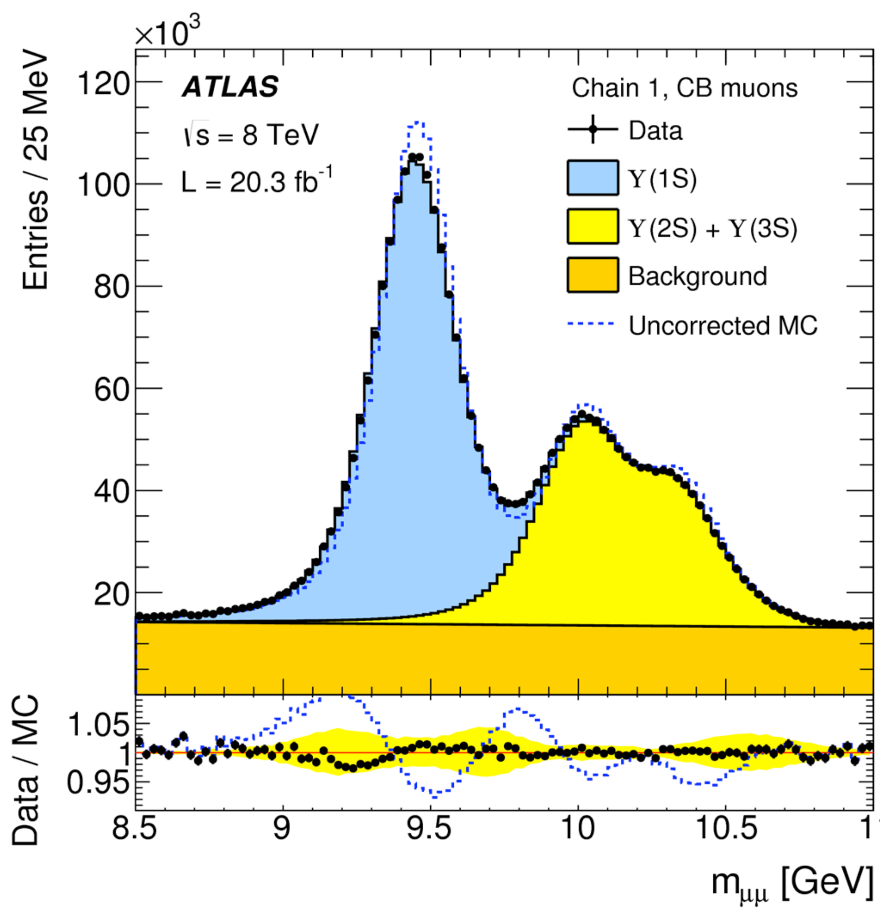
Major improvement in muon calibration:

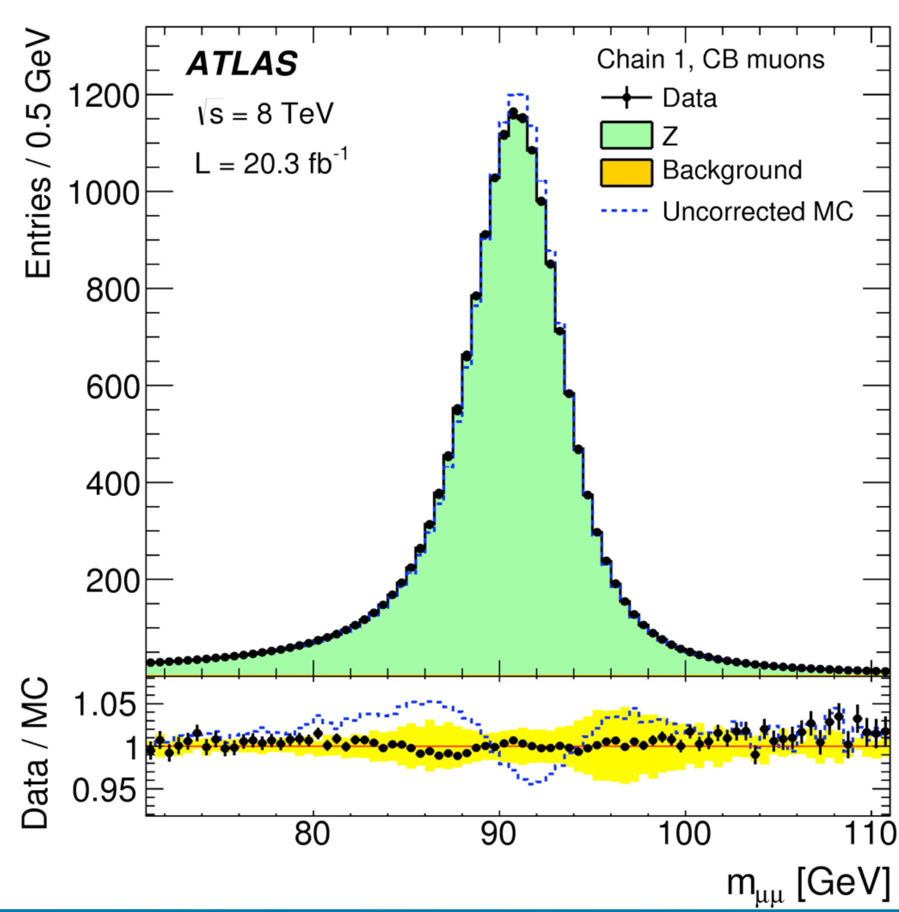
combine J/ψ→μμ and Z→ μμ samples

- Simulation corrected to match resolution and momentum scale in data
- Corrections determined from fits to $m_{\mu\mu}$
  - Inclusion of J/ψ improves H→4l pT region
  - Also cross-checked with ϒ→μμ
- Momentum scale corrections ~0.04 - 0.2%
  - η-dependent
  - Uncertainty is of the same order



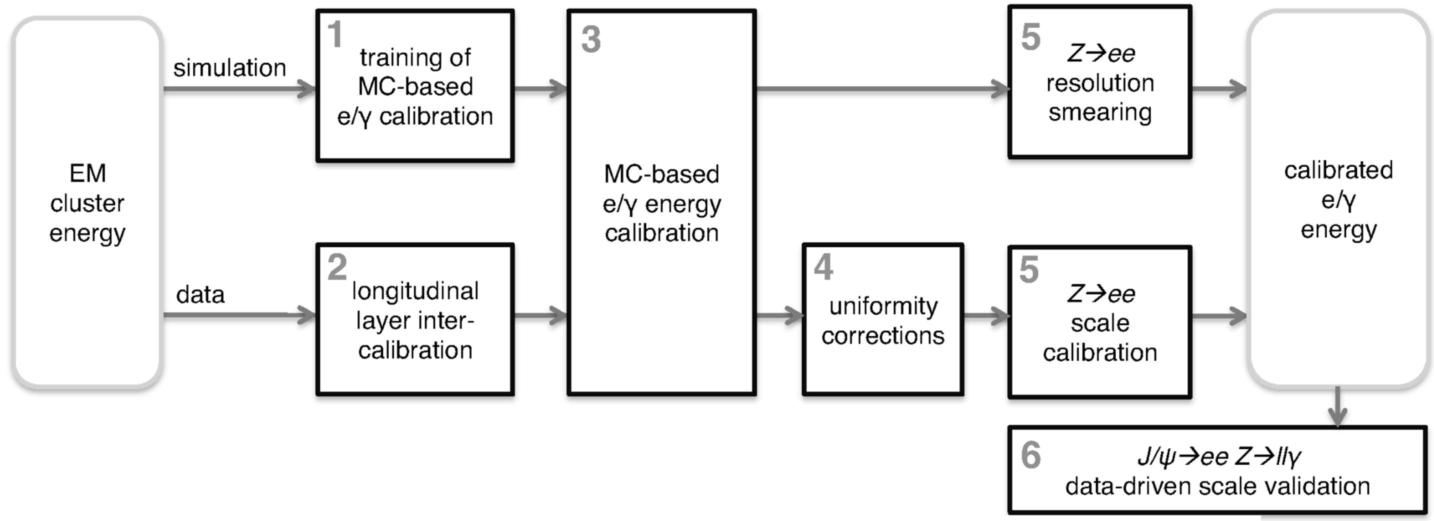






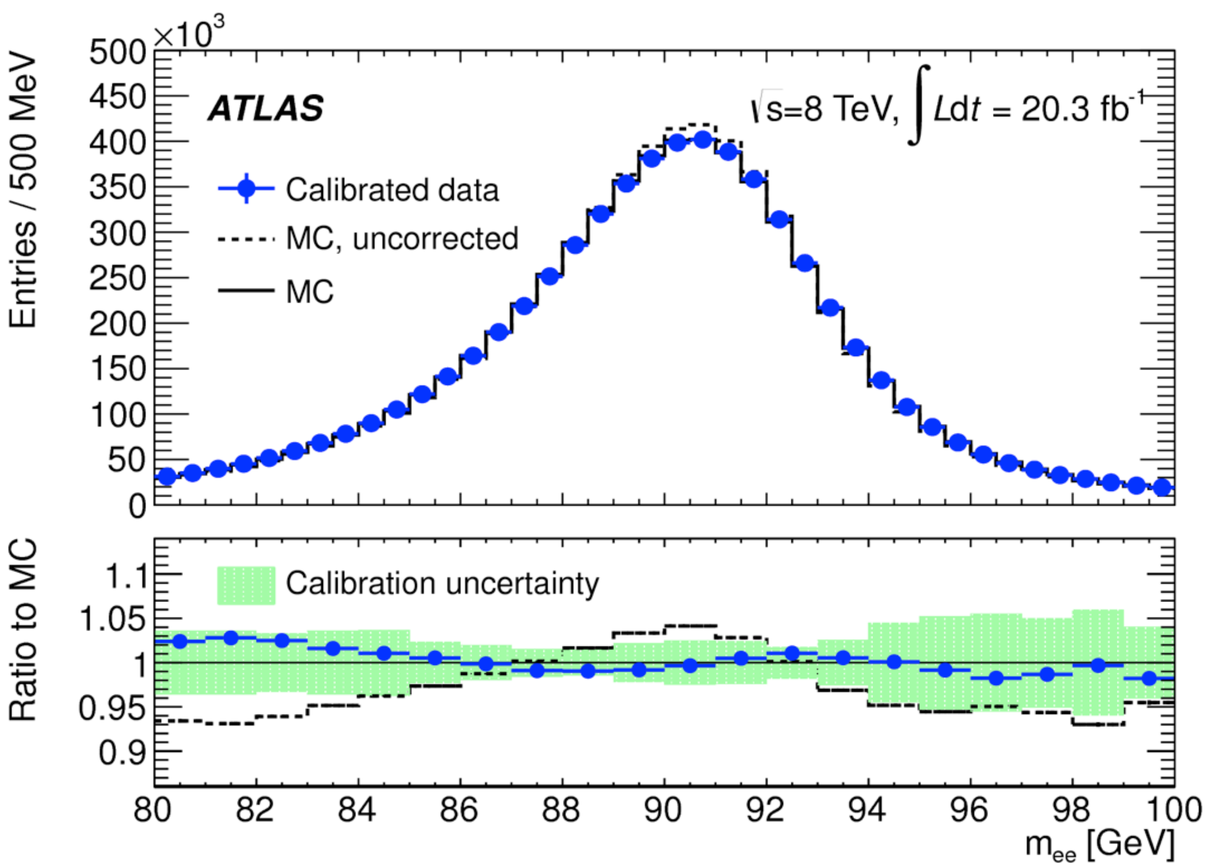
H→ZZ$^{(*)}$→4l: Electron energy scale

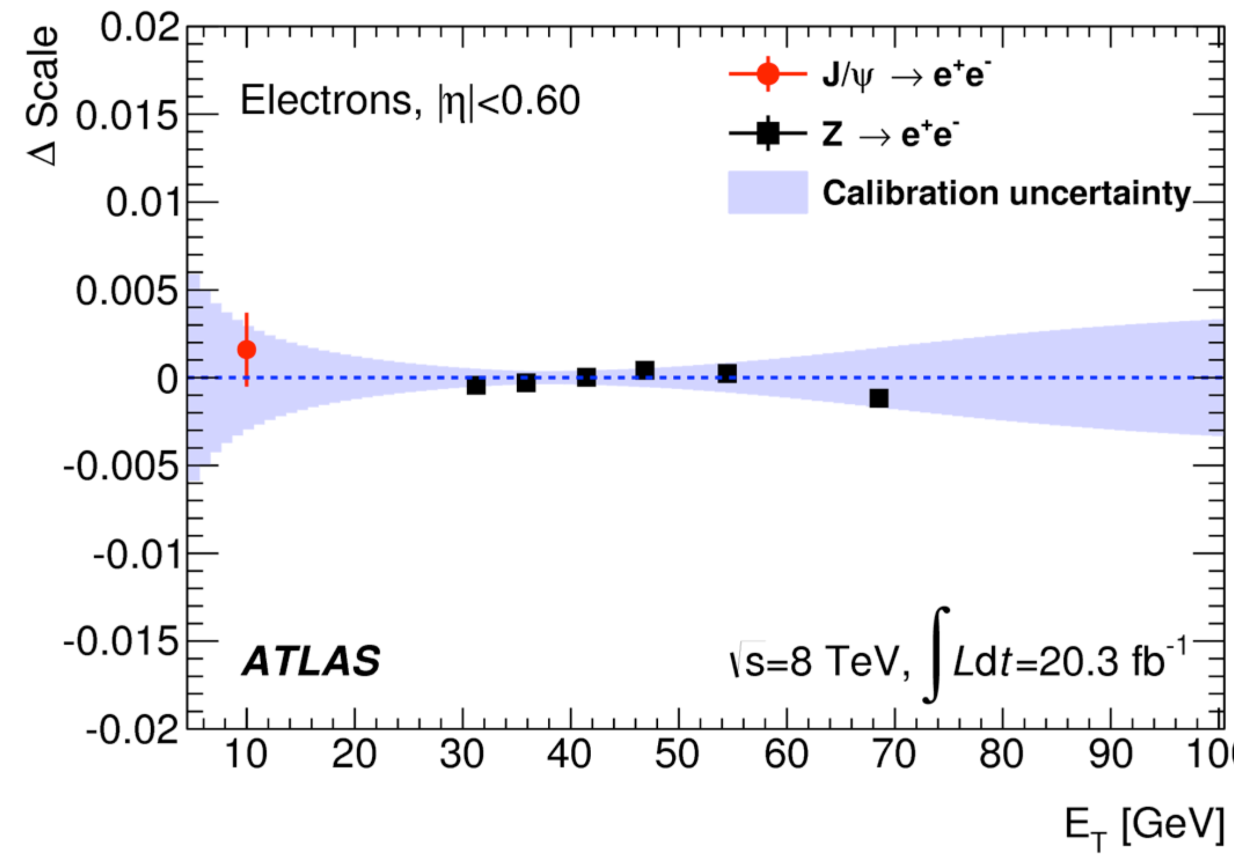
- Improved electron ET reconstruction:
  - combined tracker and calorimeter information
  - ~4%improvement in resolution for 4e/2μ2e
- New MVA calibration procedure
  - Correlation between E_{true} and reconstruction-level variables (E0...E3, η, φ, shower depth...) optimized using BDT
  - |η| < 1.37 the uncertainty is reduced from 0.4% to 0.04% for electrons of ET = 40 GeV



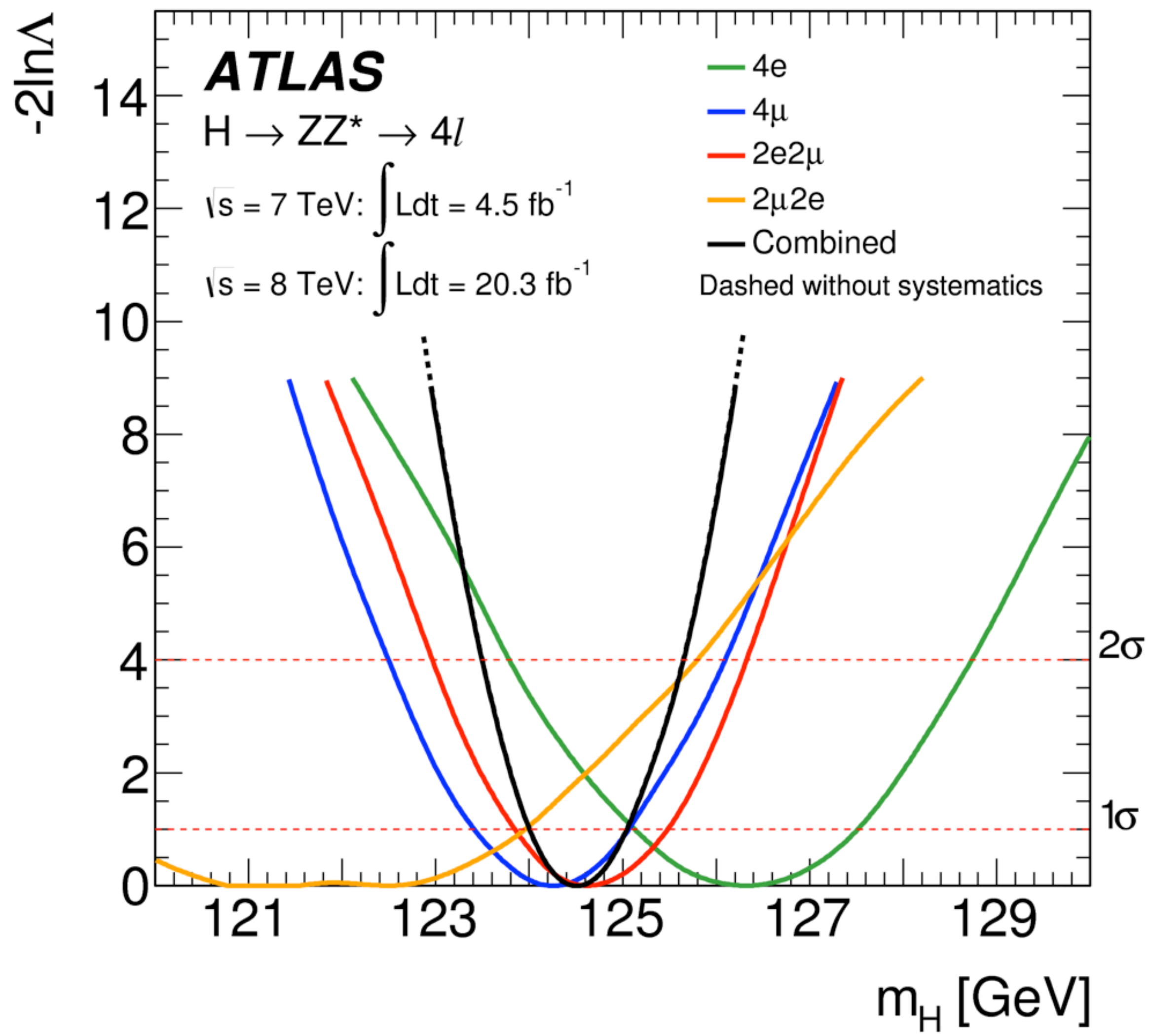
① ATLAS calibration relies on MC → need accurate geometry:
- More material = earlier shower
- Benefiting from the longitudinal segmentation to study material in front of the calorimeter

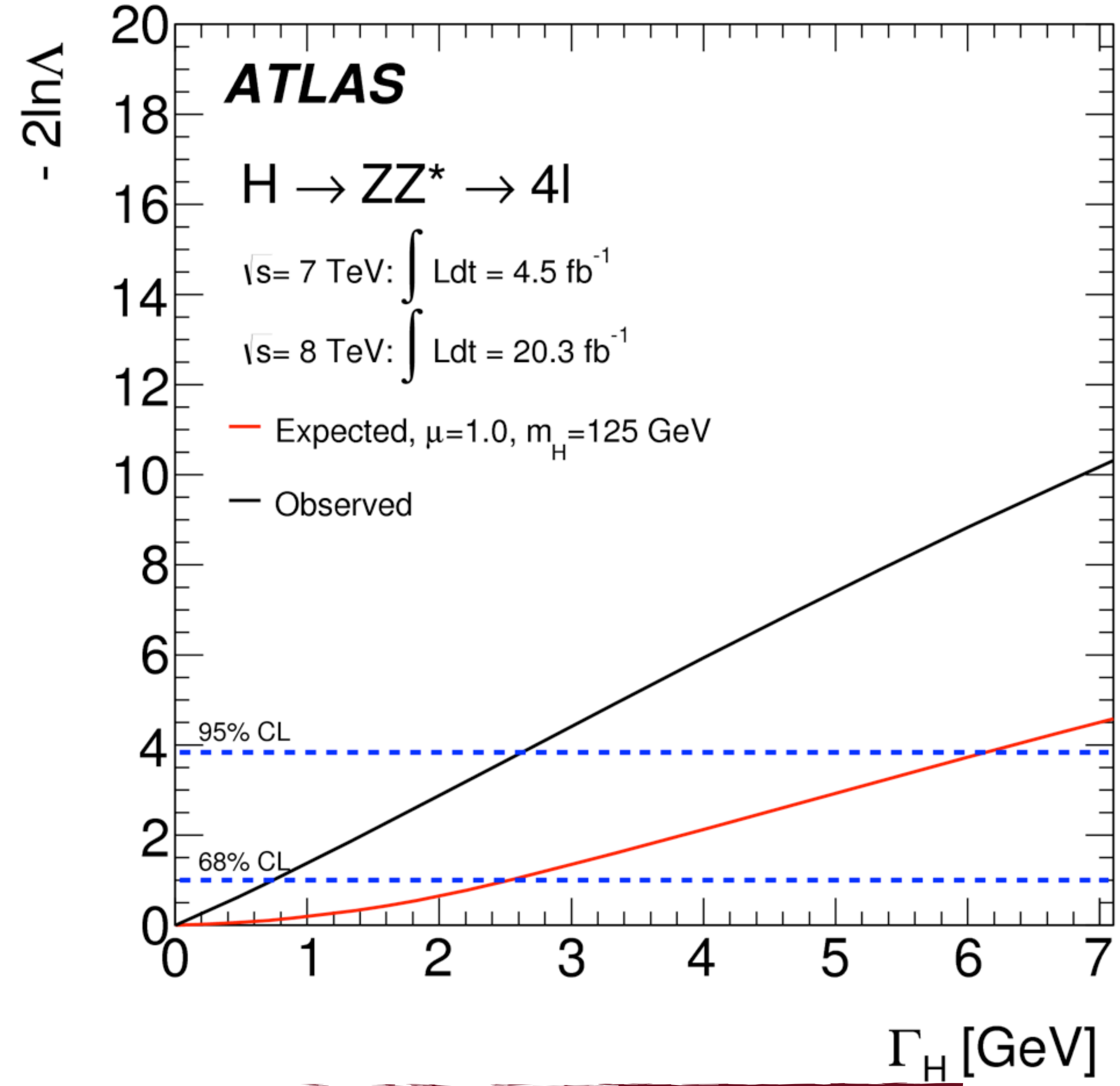
② Calorimeter non-uniformities and layer inter-calibration corrected using e/γ/μ in data:
- Response stable at ~0.05% vs. time and pileup
- 1-2% precision on $E_{1/2}$, 5% on E_{PS}
- Constrain inactive material (2-5 X_0) to ~2-10% X_0





H→ZZ$^{(*)}$→4l: Mass and width measurement





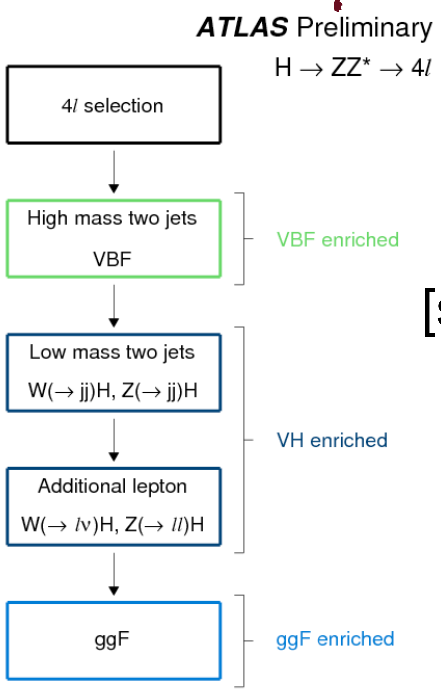
Mass and width measurement

- **124.51 ± 0.52 (stat) ± 0.06 (syst) GeV**
  - 2D fit including BDT_{ZZ}
  - energy scale uncertainty negligible with respect to total uncertainty
    - electrons: 0.04-0.2% (40 GeV) 0.2-1% (10 GeV)
    - muons: ~0.07% (central) - 0.2-0.3% (large η)
  - previous measurement: **124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV**
- Γ_H<2.6 (6.2@SM rate) GeV @ 95% CLs
  - Event-by-event (detector response)⊗(H line-shape)

H→ZZ(*)→4l: Event Categorization

Event Categorization

-> probe production mechanisms

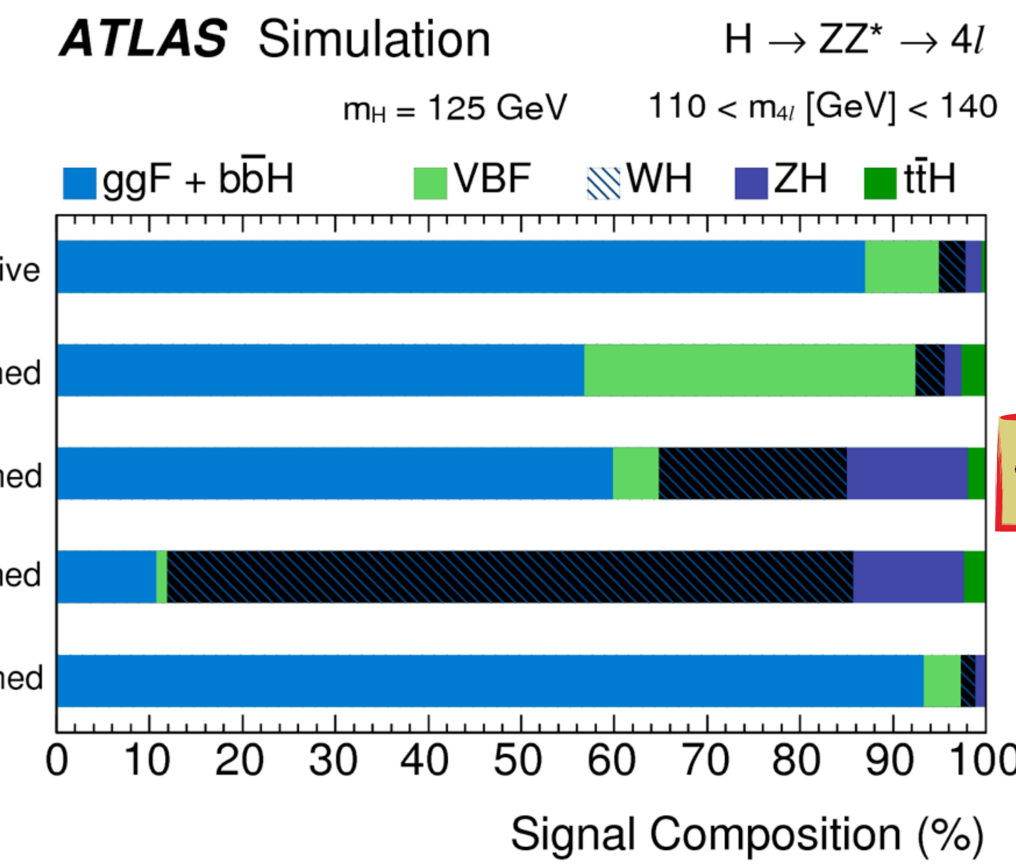


2D fit: (m_{4l},BDT_{VBF})

1D fit: m_{4l}
[selection using BDT_{VH}]

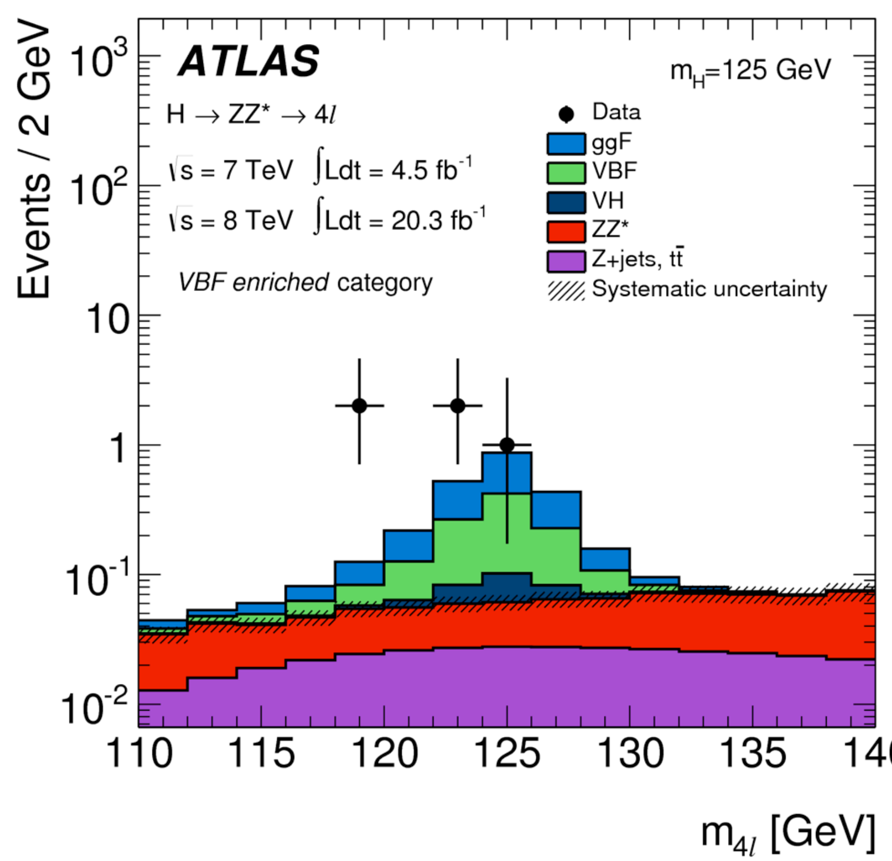
1D fit: m_{4l}

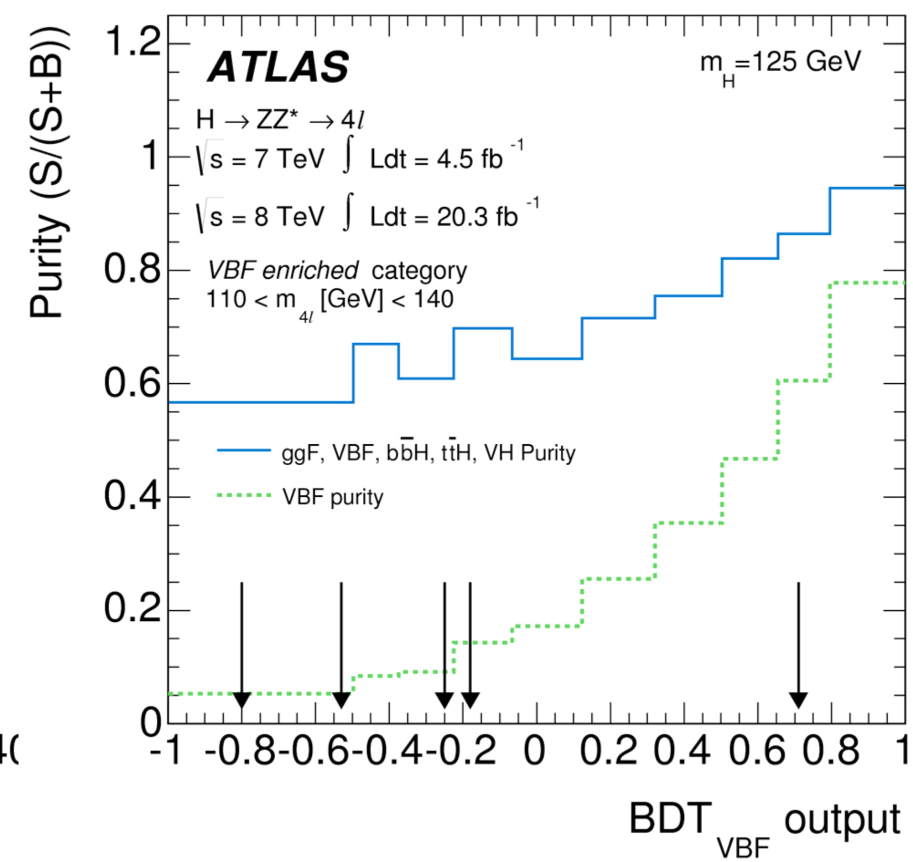
2D fit: (m_{4l},BDT_{ZZ})



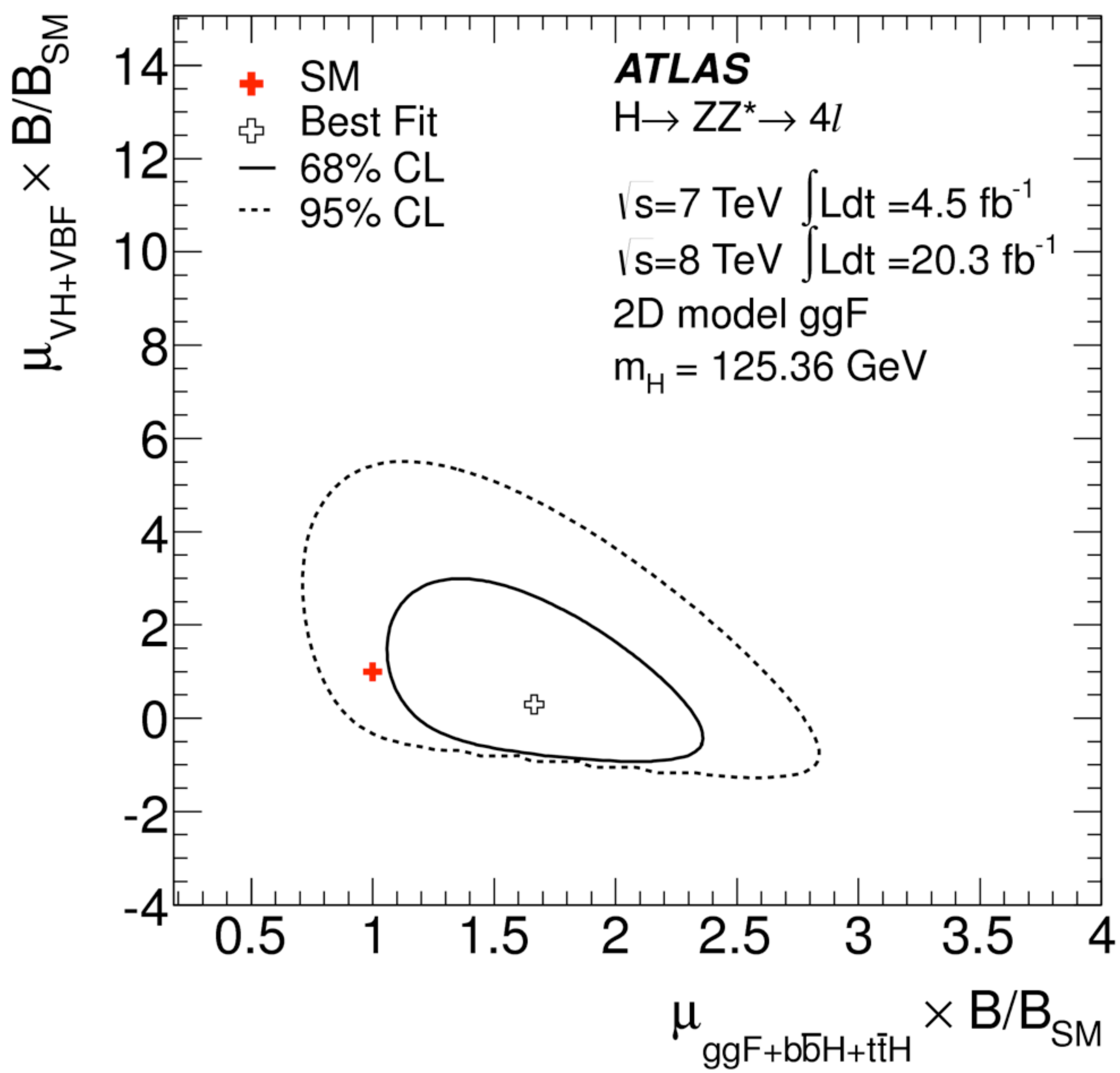
NEW!

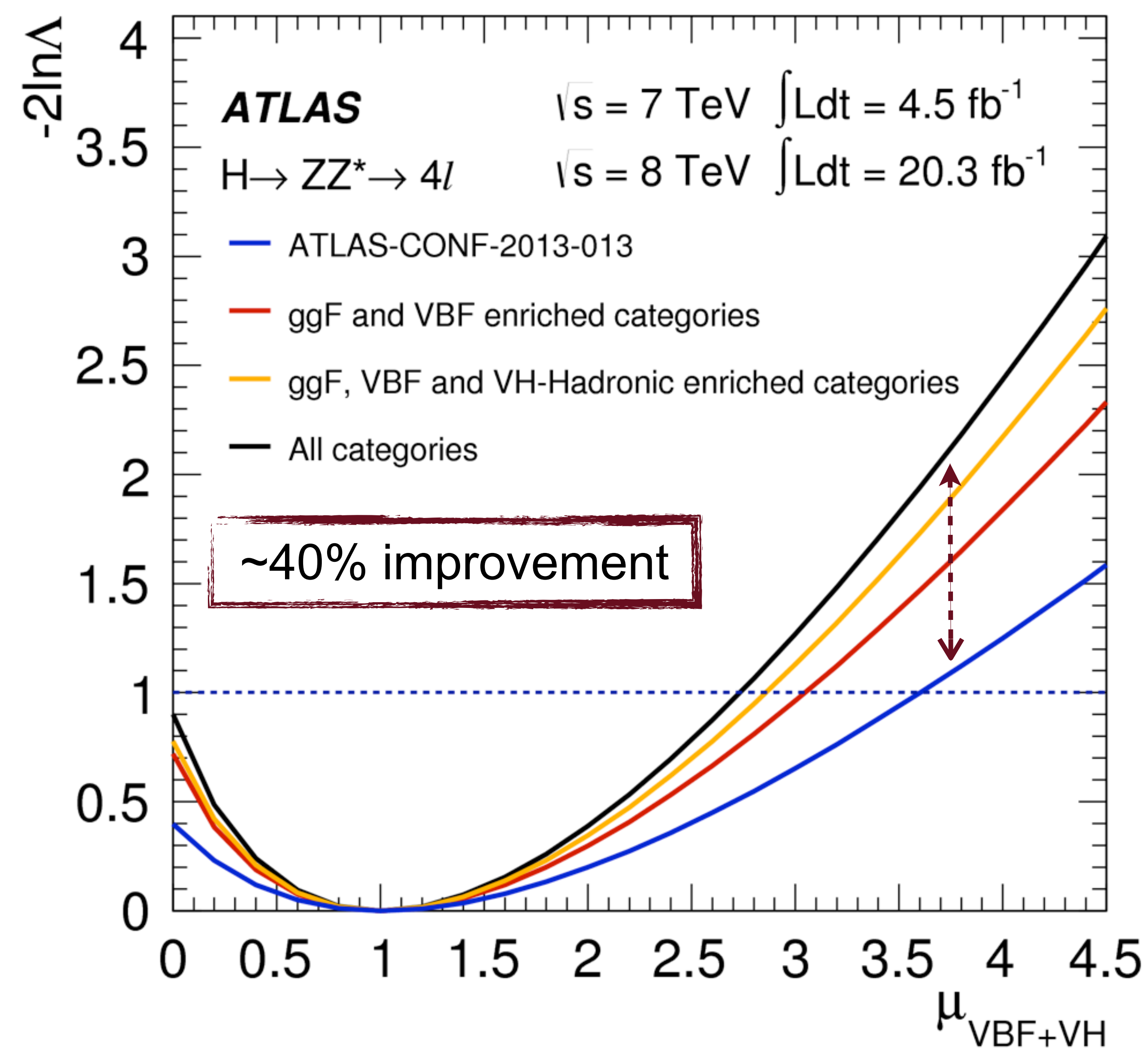
110 < m_{4l} < 140 GeV
event yields
VBF-enriched: 5
VH-hadronic: 0
VH-leptonic: 0





$H \to ZZ^{(*)} \to 4l$: Coupling Results

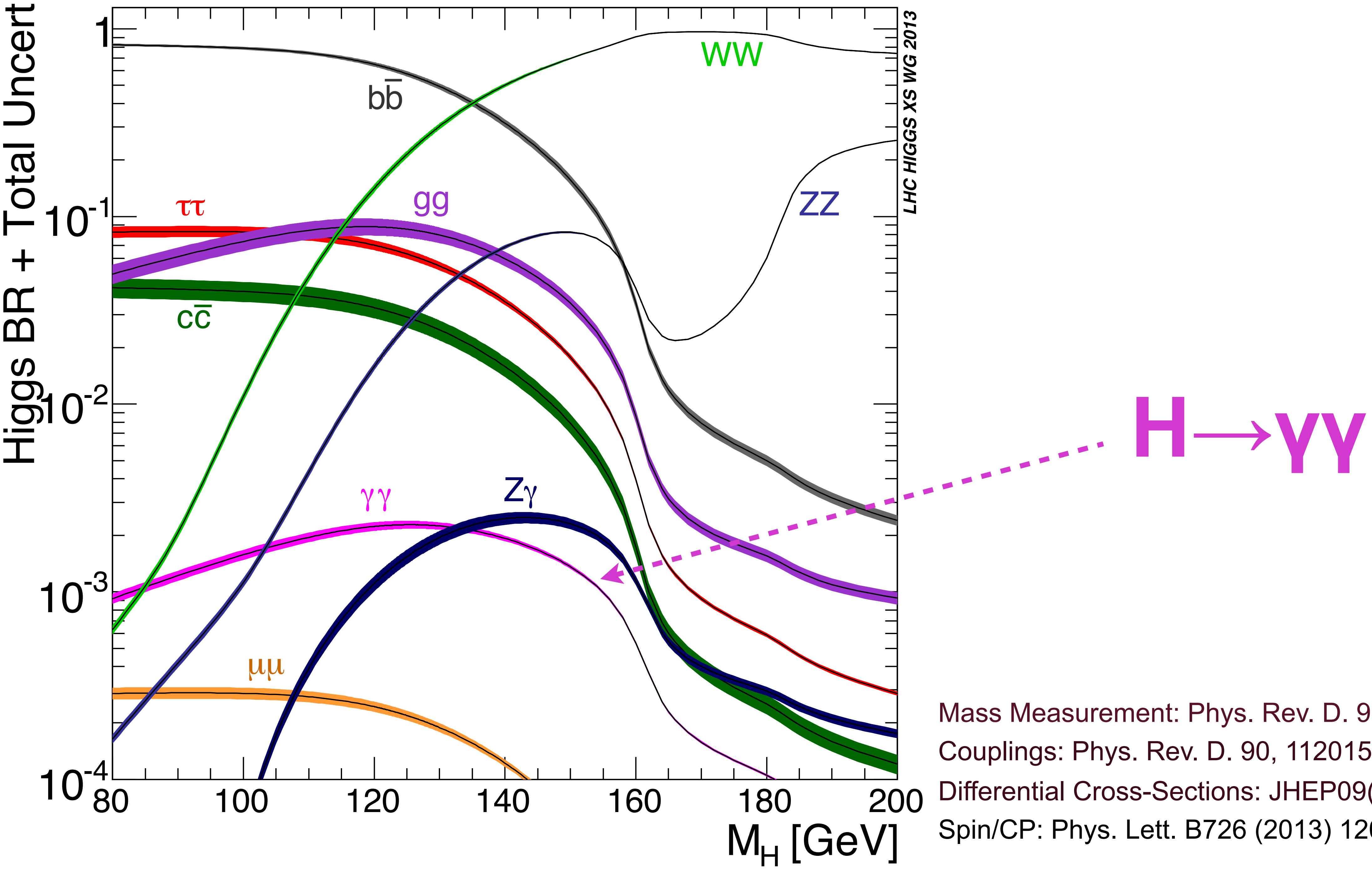




$\mu_{ggF+bbH+ttH} = 1.66^{+0.45}_{-0.41}(\text{stat})^{+0.25}_{-0.15}(\text{syst})$

$\mu_{VBF+VH} = 0.26^{+1.60}_{-0.91}(\text{stat})^{+0.36}_{-0.23}(\text{syst})$

$\mu_{VBF+VH}/\mu_{ggF+bbH+ttH} = 0.2^{+1.2}_{-0.5}$



Mass Measurement: Phys. Rev. D. 90, 052004 (2014)

Couplings: Phys. Rev. D. 90, 112015 (2014)

Differential Cross-Sections: JHEP09(2014)112

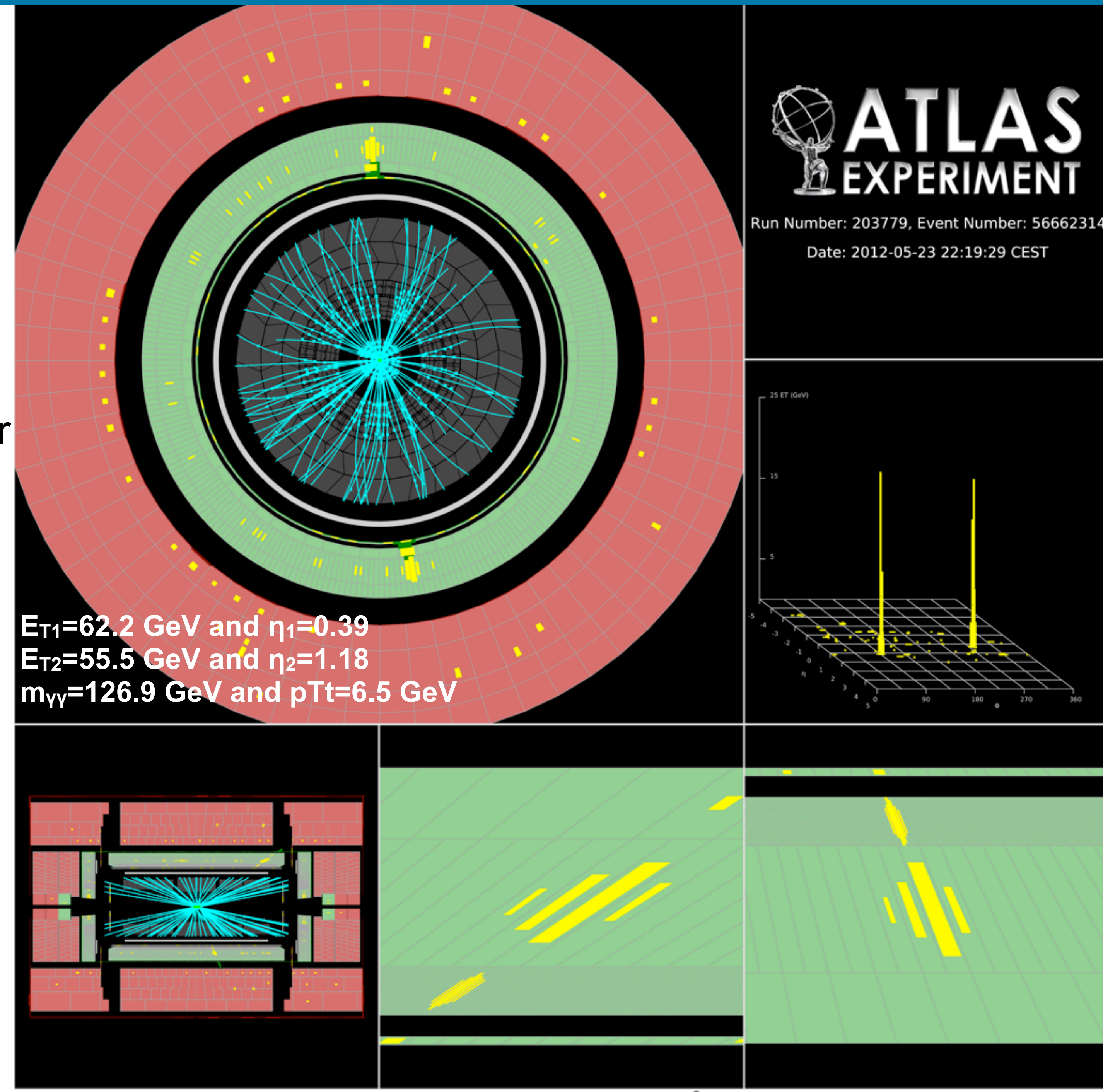
Spin/CP: Phys. Lett. B726 (2013) 120

H→γγ

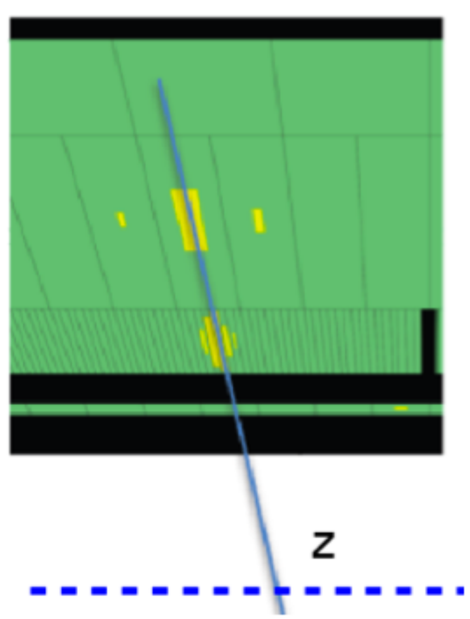
- Narrow peak in $m_{\gamma\gamma}$ spectrum
  - inclusive S/B ~ 3-4%
- Main Backgrounds:
  ~80% di-photon → $m_{\gamma\gamma}$ resolution [~1.7 GeV]
  ~20% γj and jj → photon-ID
- Background from data side-bands
- Build likelihood to identify the primary vertex using
  - longitudinal/lateral segmentation of EM calorimeter
  - use beam-spot constraint/converted photon tracks
  - reconstructed vertex $\Sigma(pT)^2$

•Event Selection:

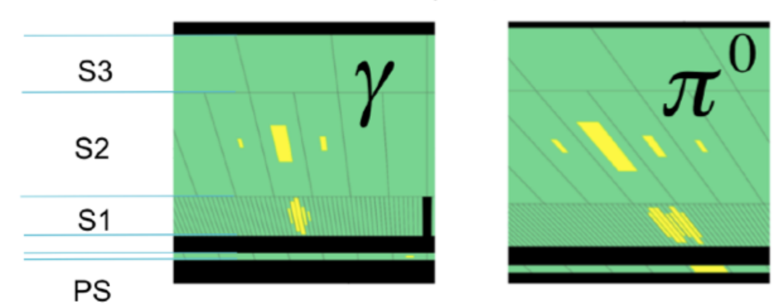
→ Two isolated photons ($|\eta|<2.47$)
with $E_T>0.35(0.25)*m_{\gamma\gamma}$



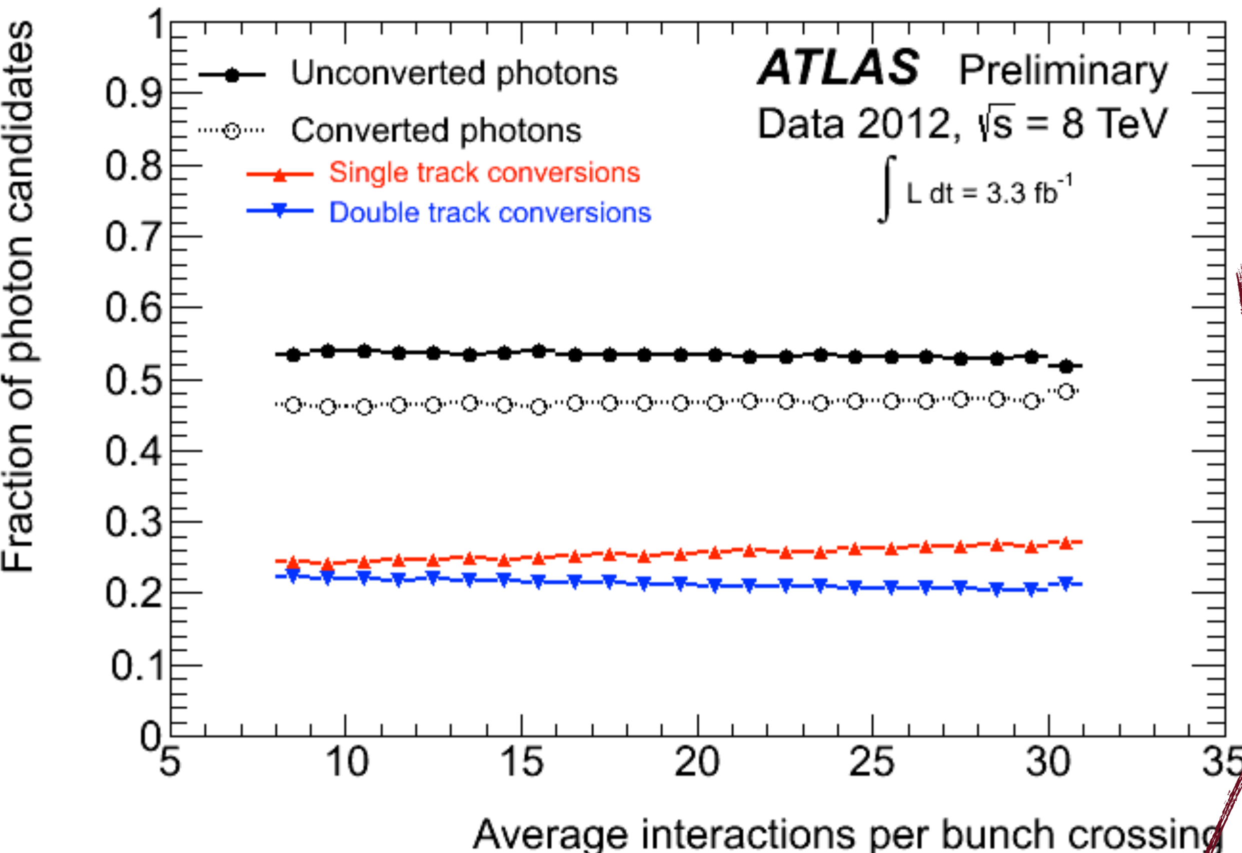
$$\boxed{m^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)}$$



π^0-γ Rejection



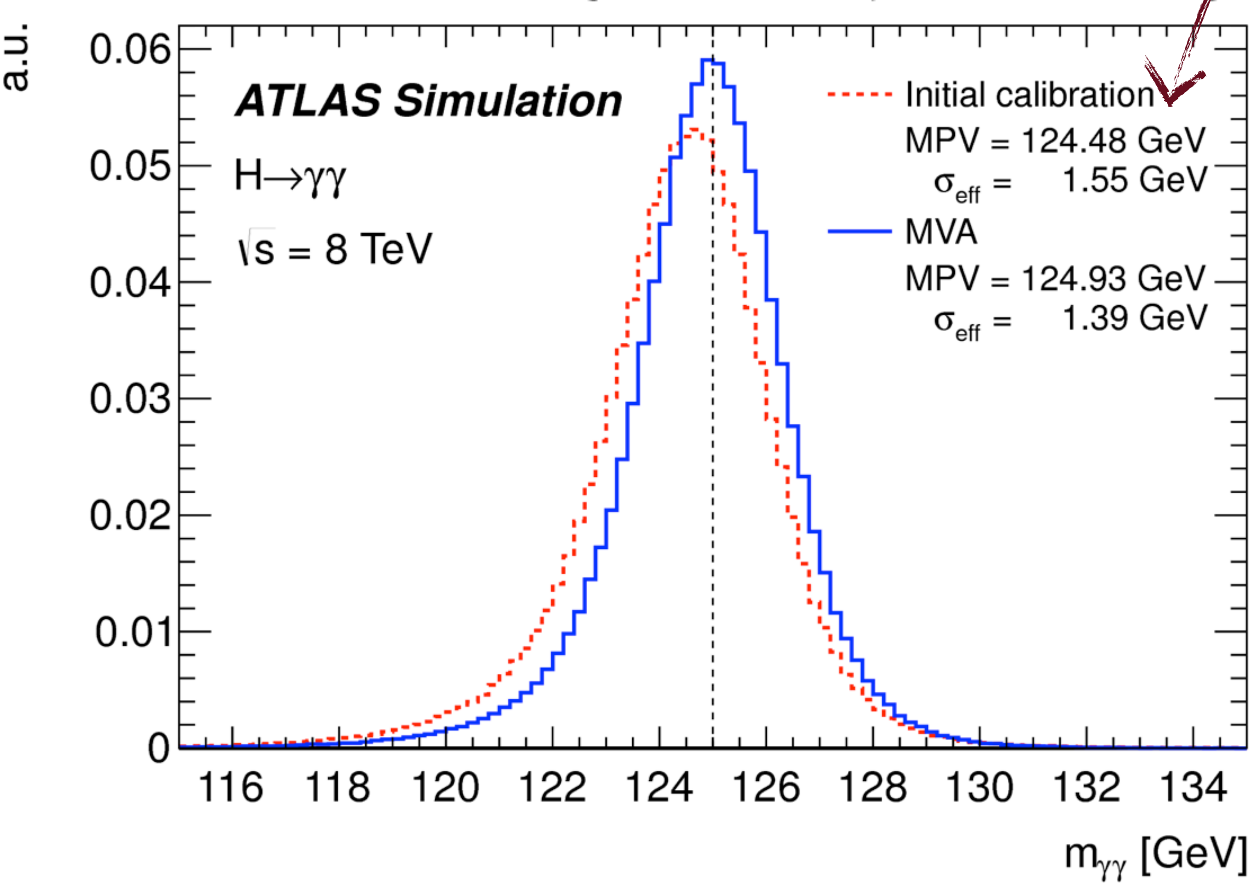
H→γγ: Photon Reconstrution and Energy Resolution

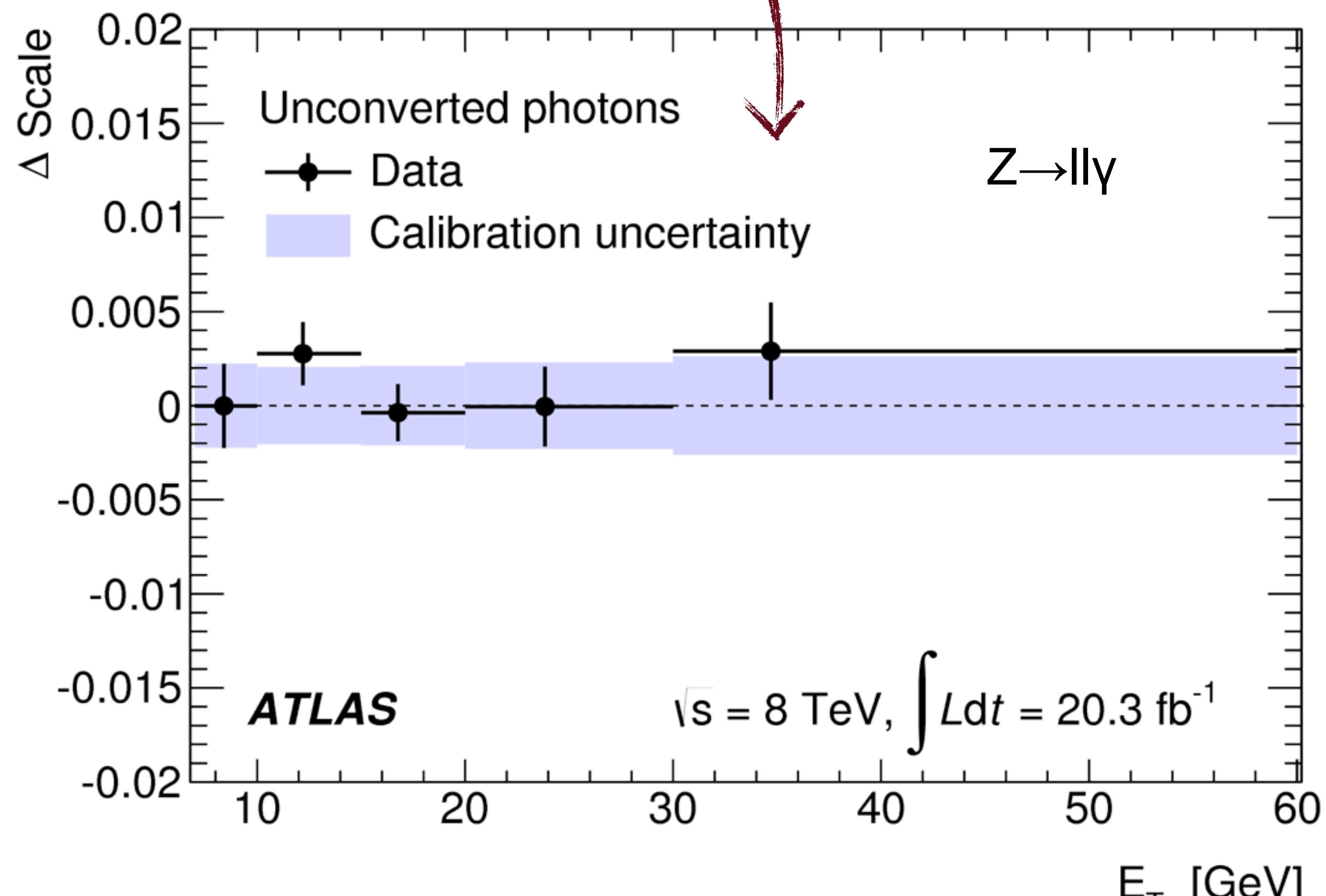


Stable photon reconstruction vs pile-up (within 1%)
Efficiency measurements using Z→ee, Z→llγ and Matrix Method on inclusive photon candidates

New MVA photon calibration
- improves by 10% the $m_{\gamma\gamma}$ resolution

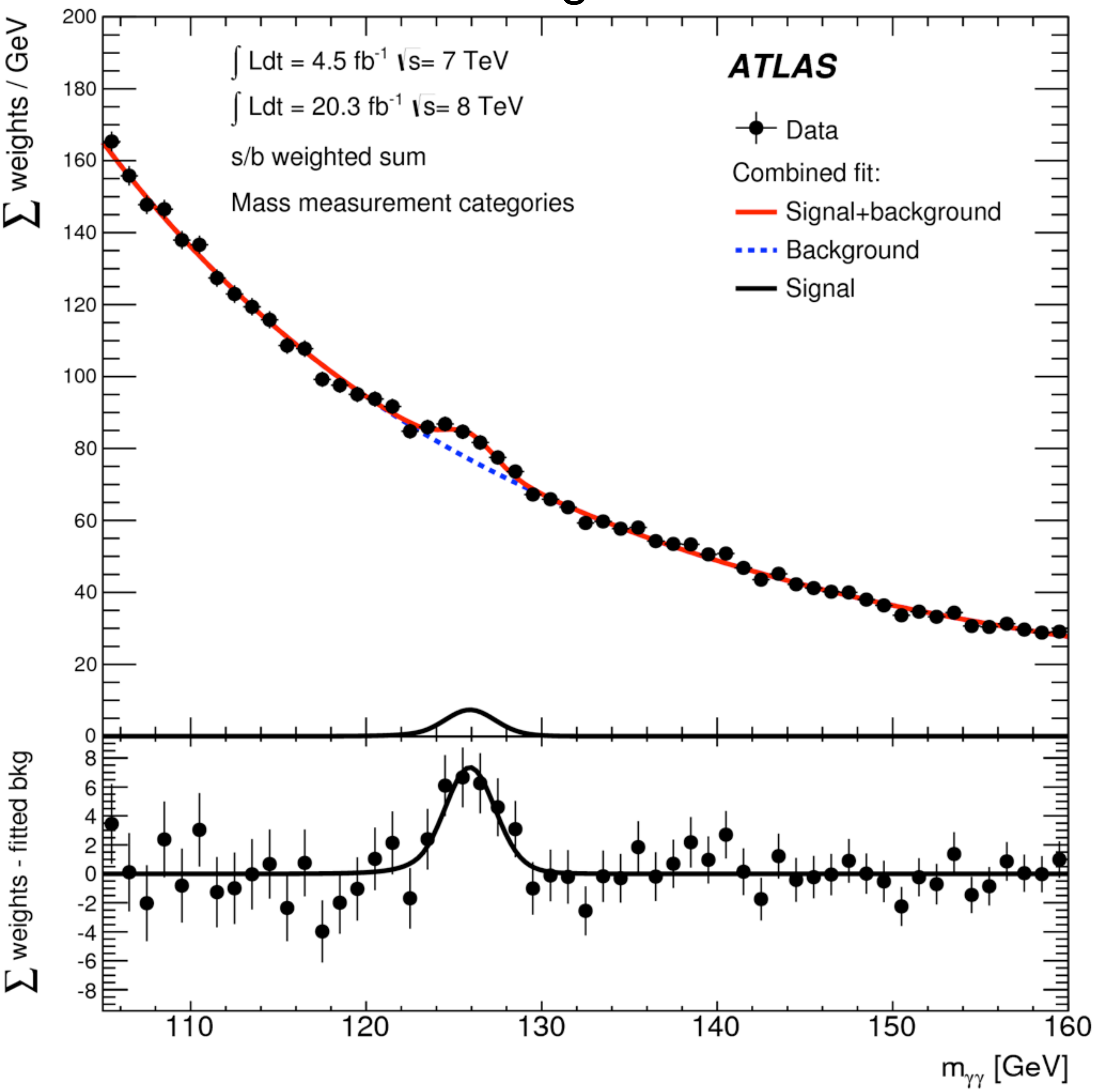
Photon energy scale transfer from Z→ee
- 0.2-0.5% uncertainty
- cross-check with Z→llγ

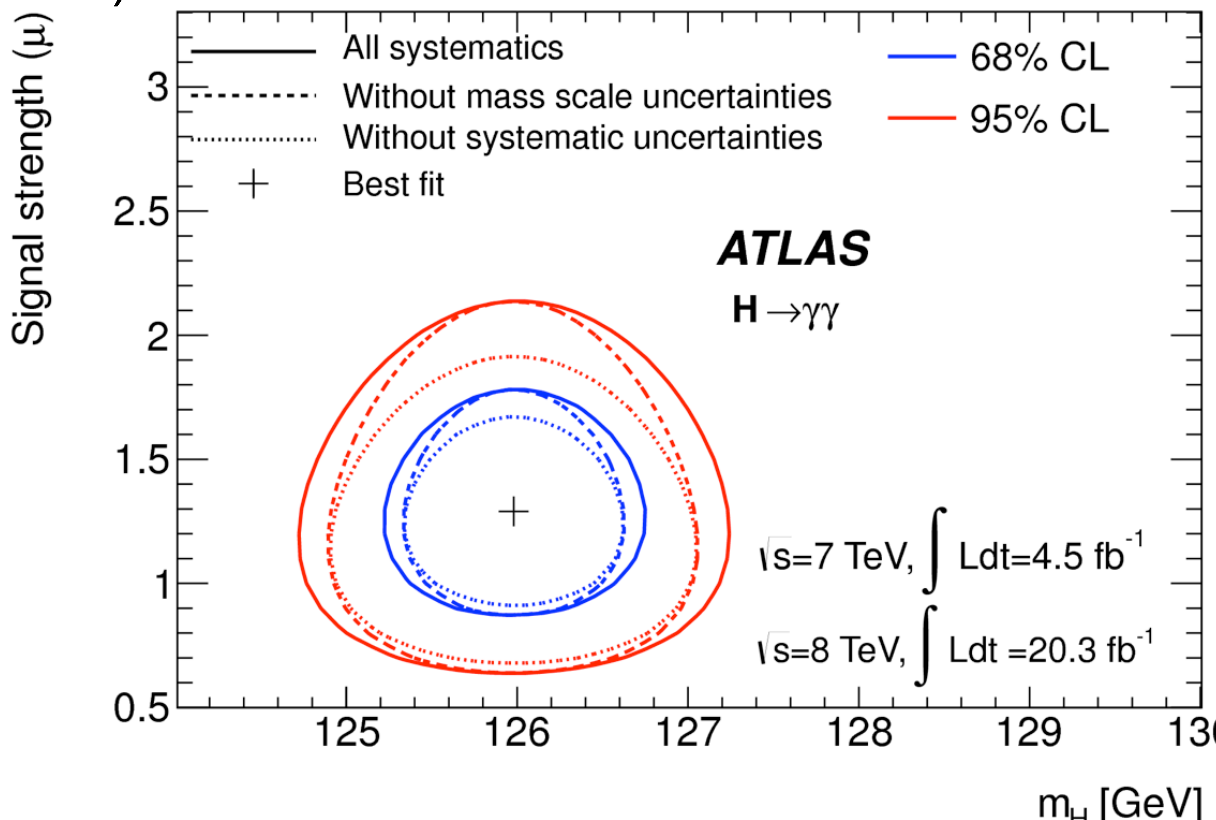




H→γγ: Mass measurement

- Analysis sensitivity optimisation
  - → Different categorization strategy for different measurements
  - → Separate between 7 and 8 TeV datasets
- m_H optimized categories [min expected δm_H for SM Higgs inc. systematics]
  - → New e/γ calibration (~10% resolution improvement)
  - → Photon quality, detector region and p_{Tt}
  - → 10 exclusive categories

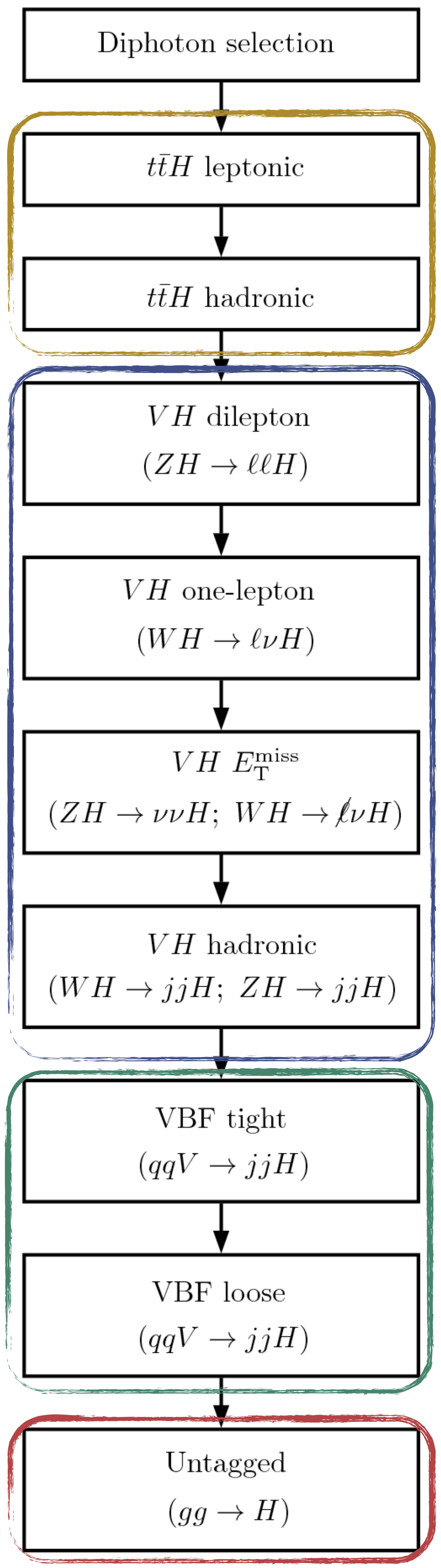




Mass measurement
- **125.98 ± 0.42(stat) ± 0.28(syst) GeV**
  - μ = 1.29 ± 0.30
  - previous: **126.8 ± 0.2 (stat) ± 0.7 (syst) GeV**

Width measurement
- Non-relativistic Breit-Wigner ⊗ detector resolution
- Γ_H<5.0 (6.2@SM rate) GeV @ 95% CLs

H→γγ: Couplings



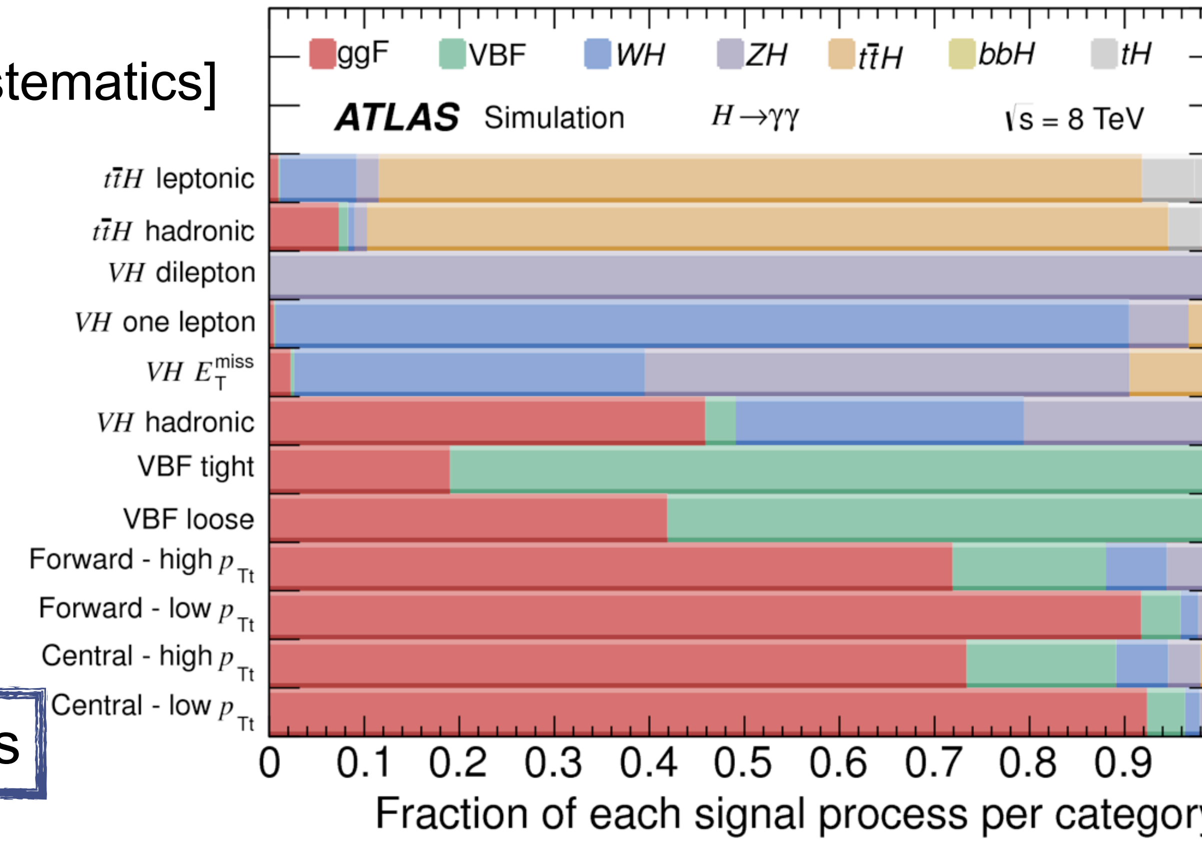
couplings optimized categories
[min expected $\delta\mu_{prod}$ for SM Higgs inc. systematics]

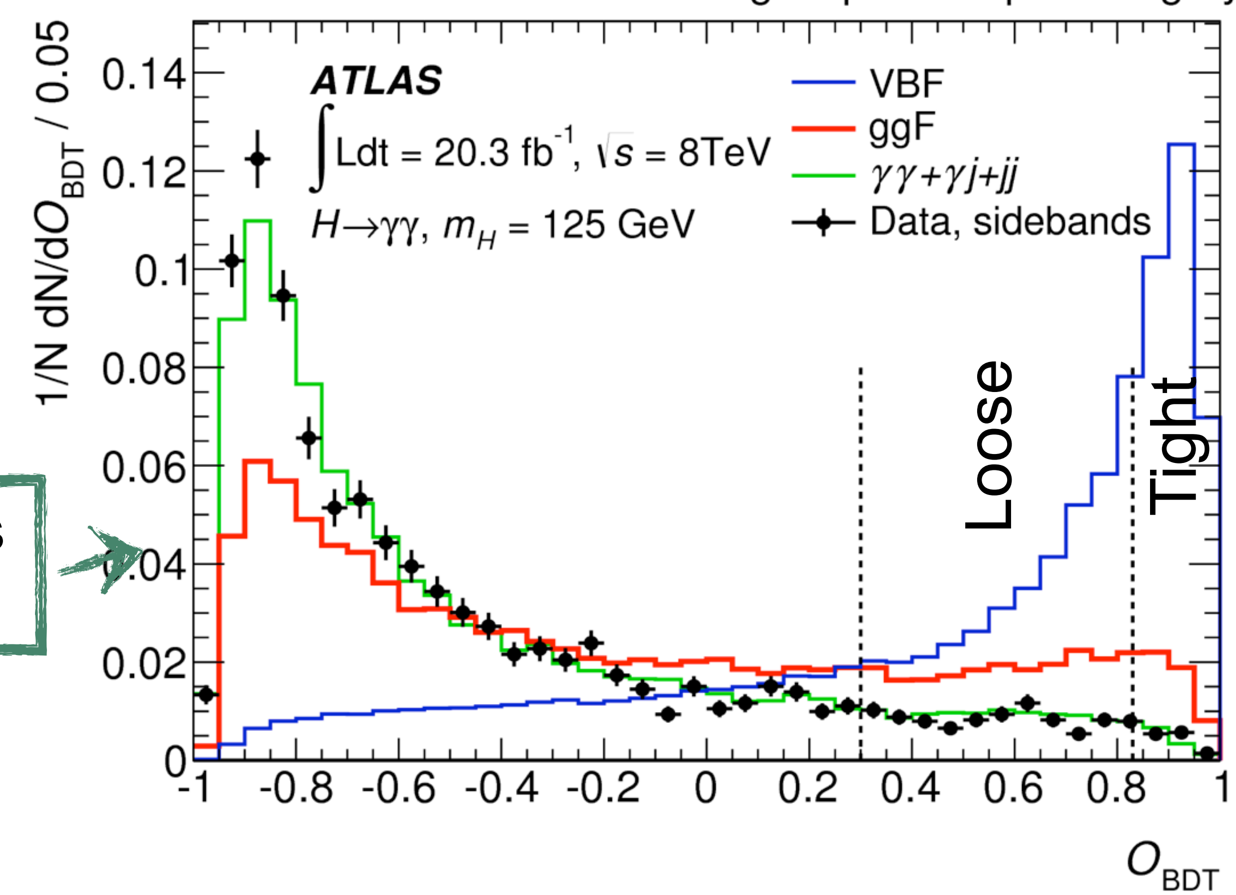
2 × ttH enriched categories

4 × WH/ZH enriched categories

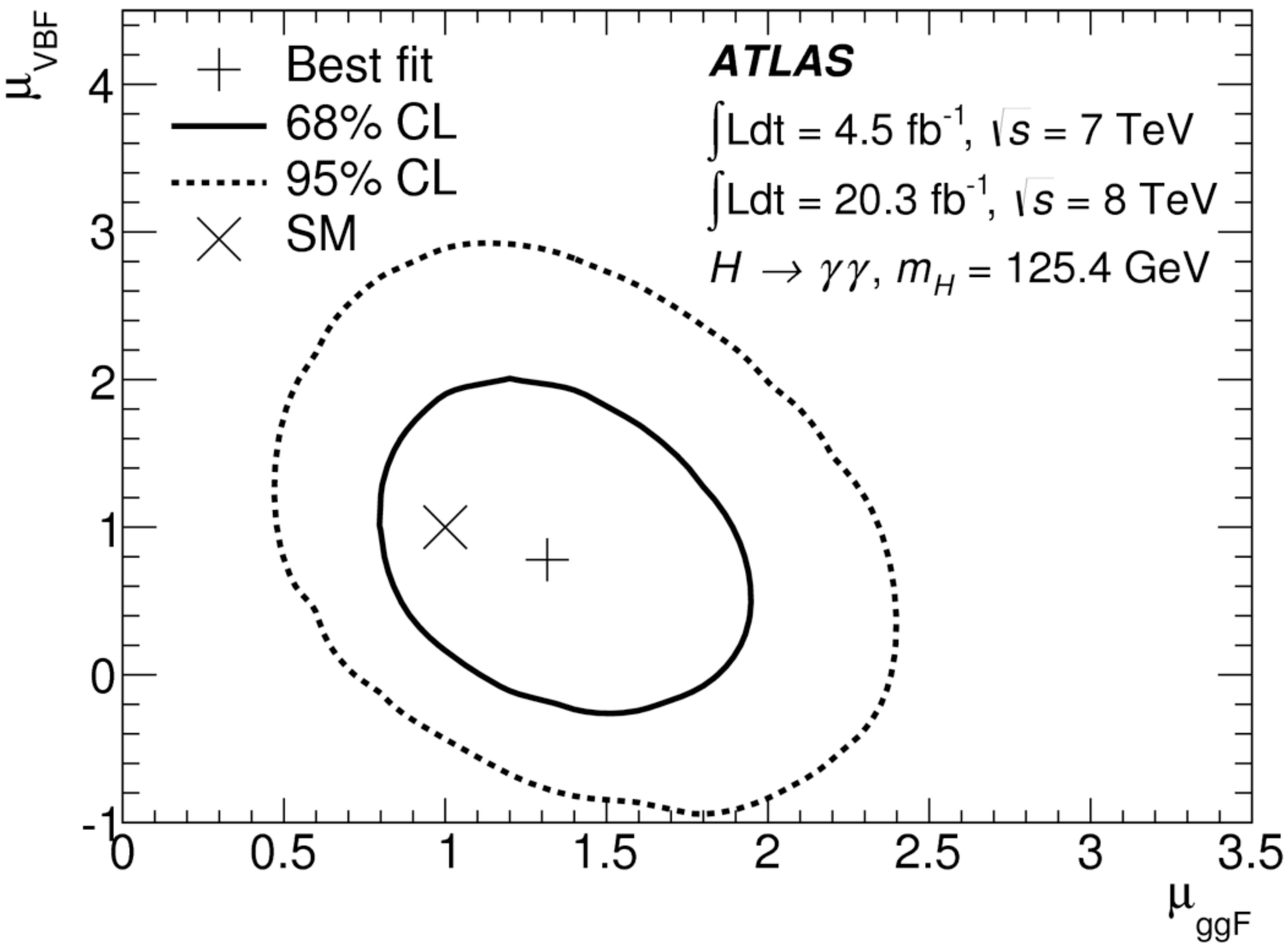
2 × VBF enriched categories
Employing a BDT selection

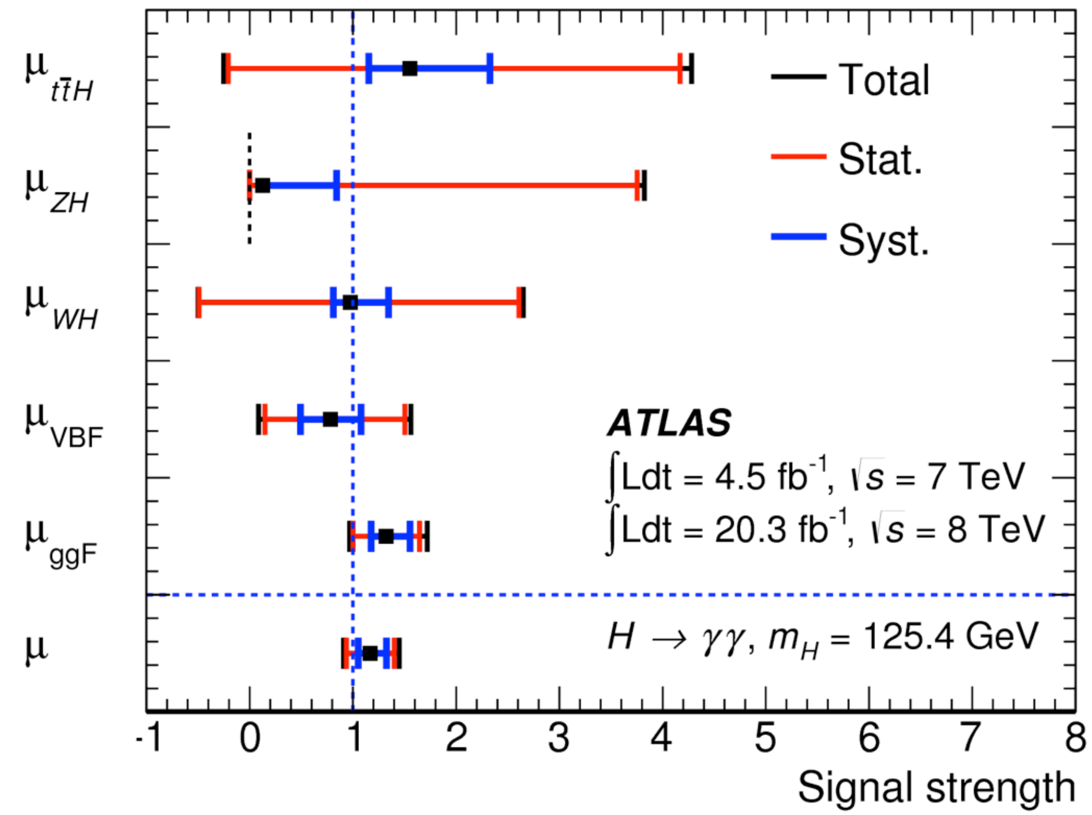
4 × untagged (pT and η)





H→γγ: Couplings





$$\mu = 1.17 \pm 0.23\ (\text{stat.})\ ^{+0.10}_{-0.08}\ (\text{syst.})\ ^{+0.12}_{-0.08}\ (\text{theory}) = 1.17 \pm 0.27,$$

$$\mu_{\text{ggF}} = 1.32\ \pm 0.32\ (\text{stat.})\ ^{+0.13}_{-0.09}\ (\text{syst.})\ ^{+0.19}_{-0.11}\ (\text{theory}) = 1.32 \pm 0.38,$$

$$\mu_{\text{VBF}} = 0.8\ \pm 0.7\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})\ ^{+0.2}_{-0.3}\ (\text{theory}) = 0.8 \pm 0.7,$$

$$\mu_{WH} = 1.0 \pm 1.5\ (\text{stat.})\ ^{+0.3}_{-0.1}\ (\text{syst.})\ ^{+0.2}_{-0.1}\ (\text{theory}) = 1.0 \pm 1.6,$$

$$\mu_{ZH} = 0.1\ ^{+3.6}_{-0.1}\ (\text{stat.})\ ^{+0.7}_{-0.0}\ (\text{syst.})\ ^{+0.1}_{-0.0}\ (\text{theory}) = 0.1\ ^{+3.7}_{-0.1},$$

$$\mu_{t\bar{t}H} = 1.6\ ^{+2.6}_{-1.8}\ (\text{stat.})\ ^{+0.6}_{-0.4}\ (\text{syst.})\ ^{+0.5}_{-0.2}\ (\text{theory}) = 1.6\ ^{+2.7}_{-1.8}.$$

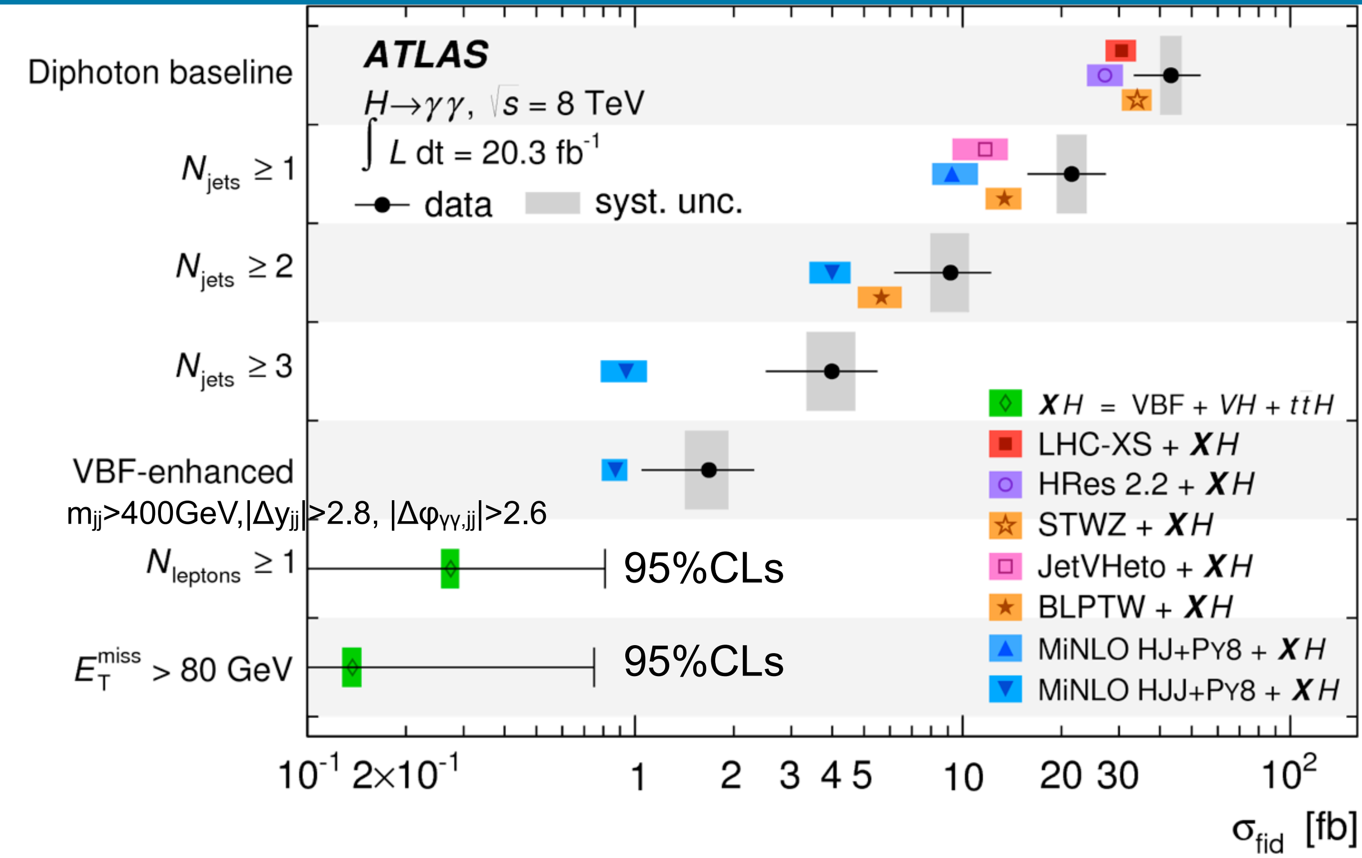
Local significance: **5.2σ** (4.6σ) @ m_H=125.4 GeV

- analysis sensitivity improved by 10%
- results lower than previous ($\mu=1.55^{+0.33}_{-0.28}$, 7.4σ)
- results compatible at 2.3σ level (74% correlation)

H→γγ: Fiducial/Differential cross sections

5 measurements + 2 upper limits
on fiducial cross sections

12 differential cross sections
a) kinematics ($pT_{\gamma\gamma}$,$|y_{\gamma\gamma}|$)
b) associated jet activity (Nj, $|y_j|$, ...)
c) spin-CP-sensitive (|cosθ*|, ...)
d) VBF-sensitive ($|\Delta y_{jj}|$,...)

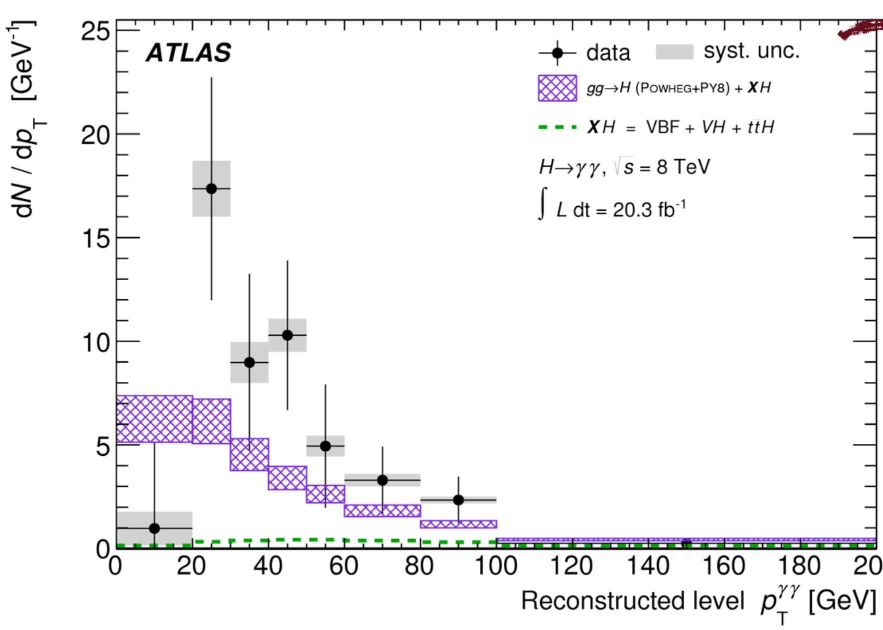


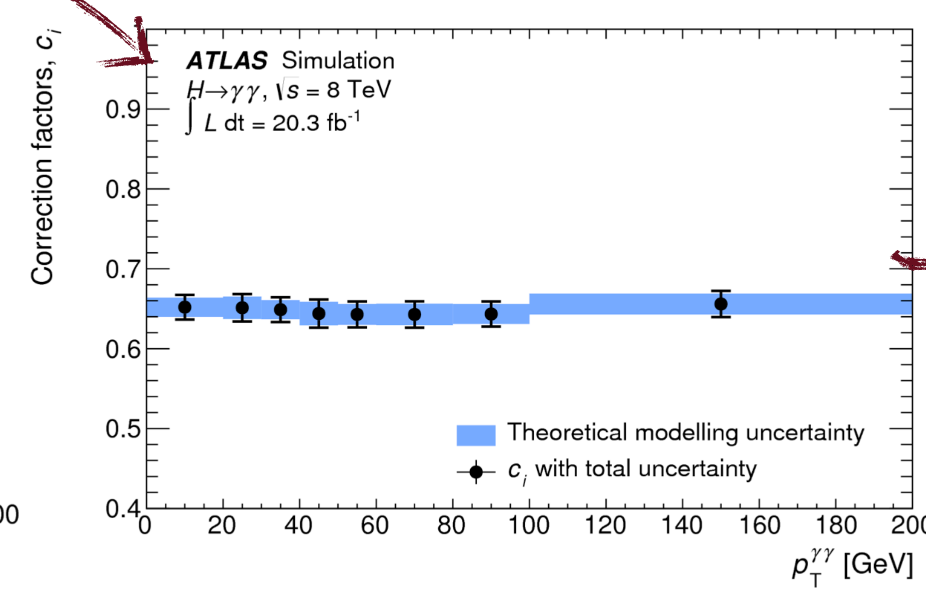
Extraction procedure

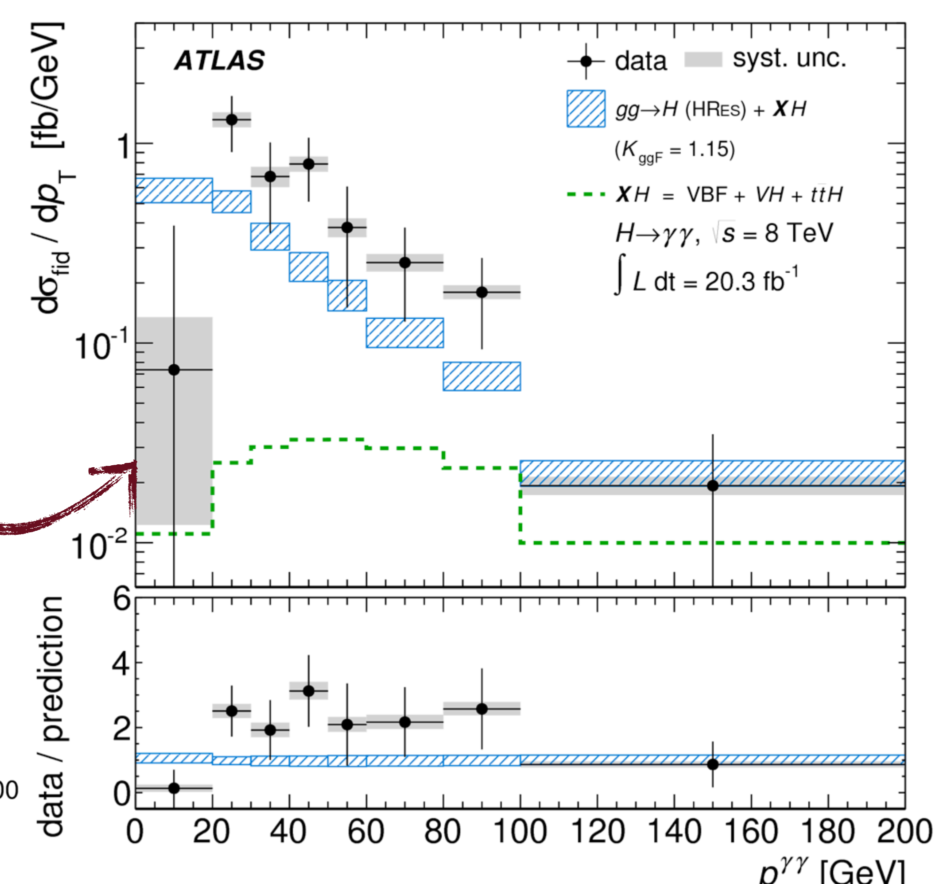
γγ dataset binned in variable of interest

Simultaneous unbinned maximum likelihood fit of $m_{\gamma\gamma}$ in each bin

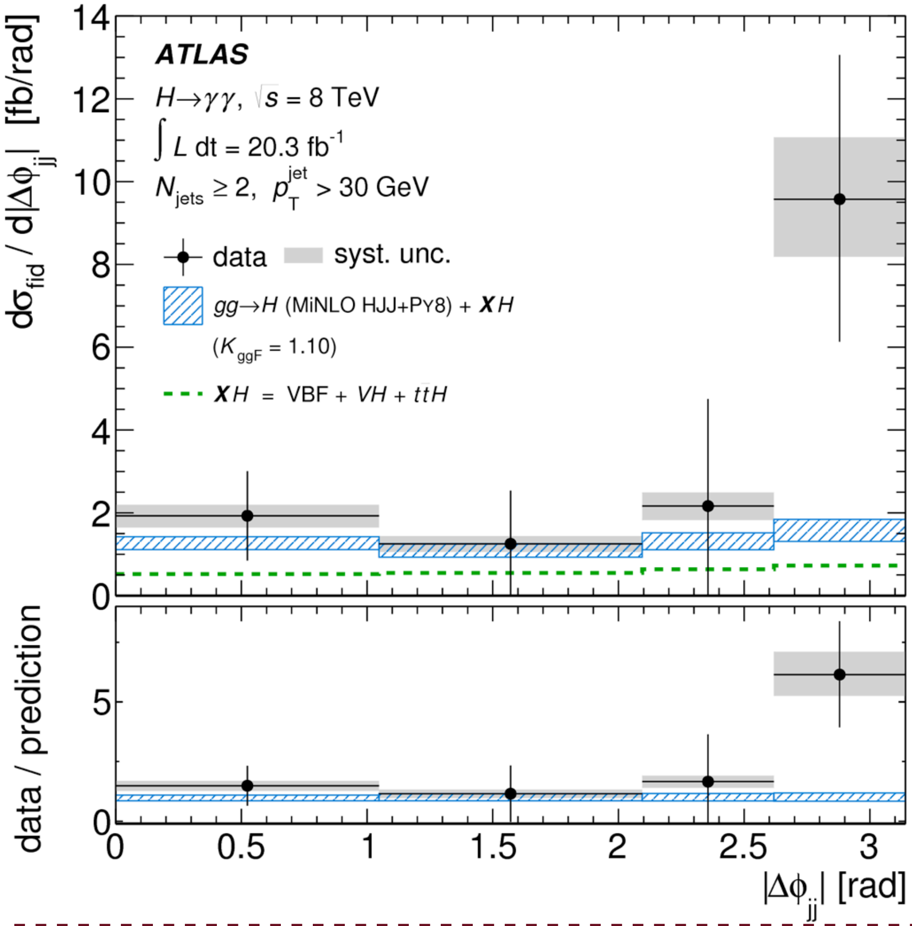
Bin-by-bin acceptance, efficiency and resolution correction("unfolding")

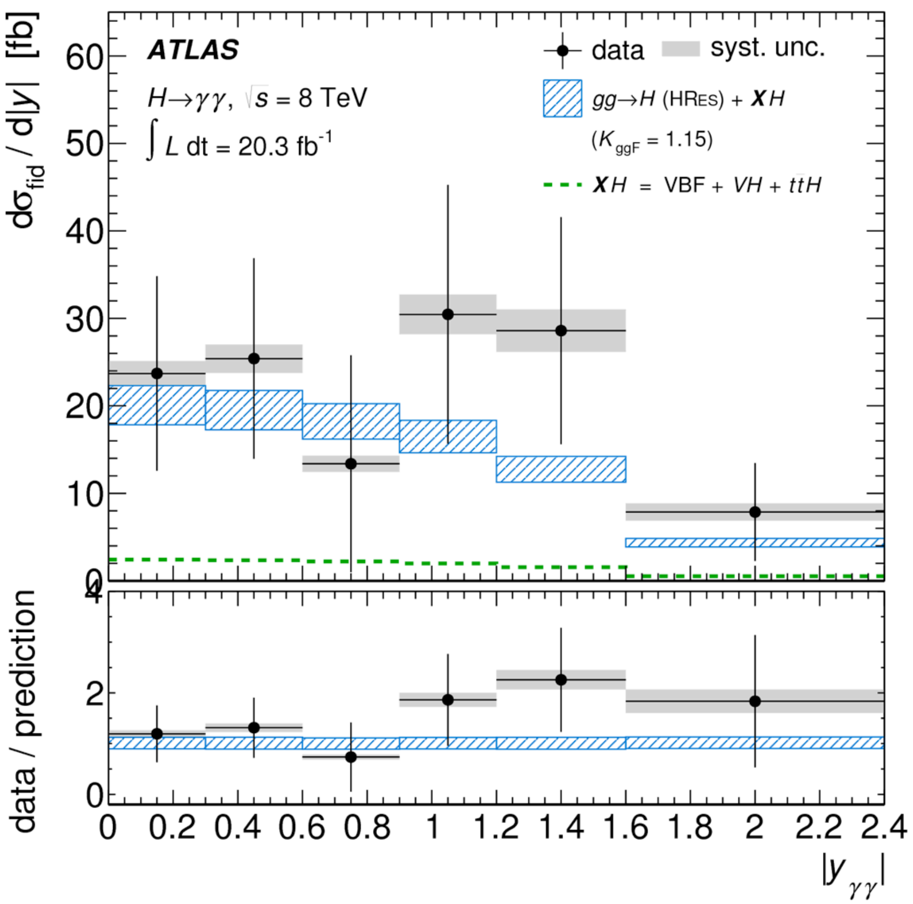


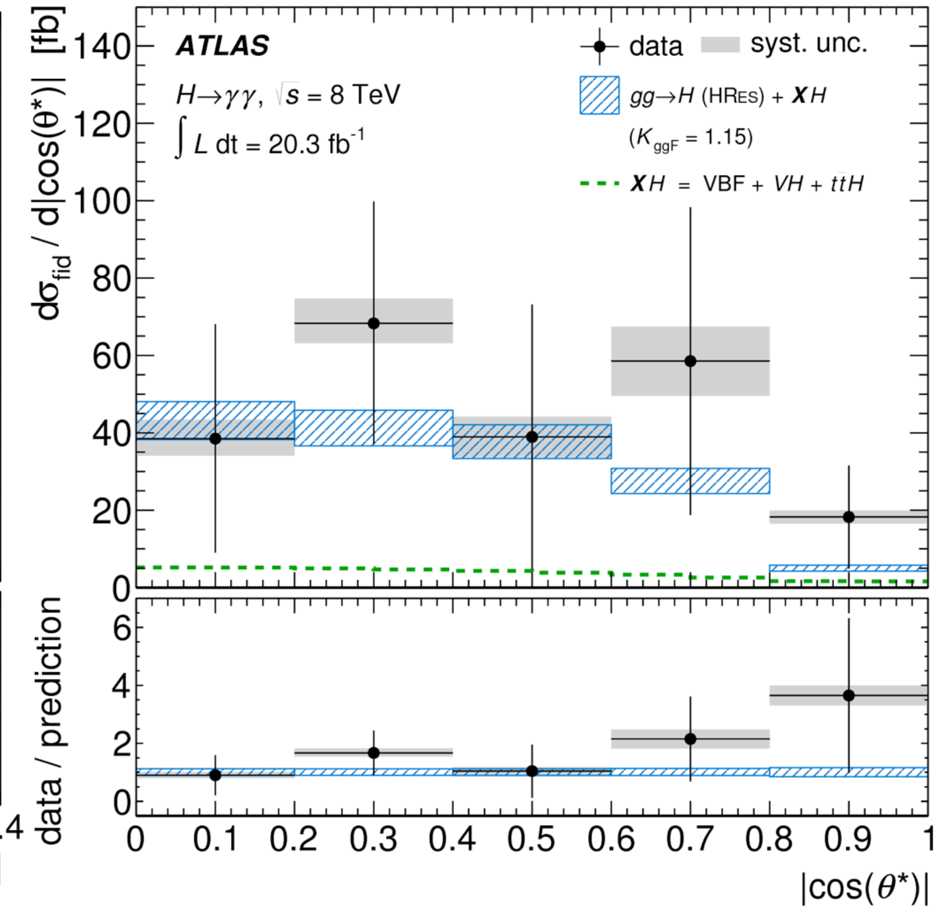


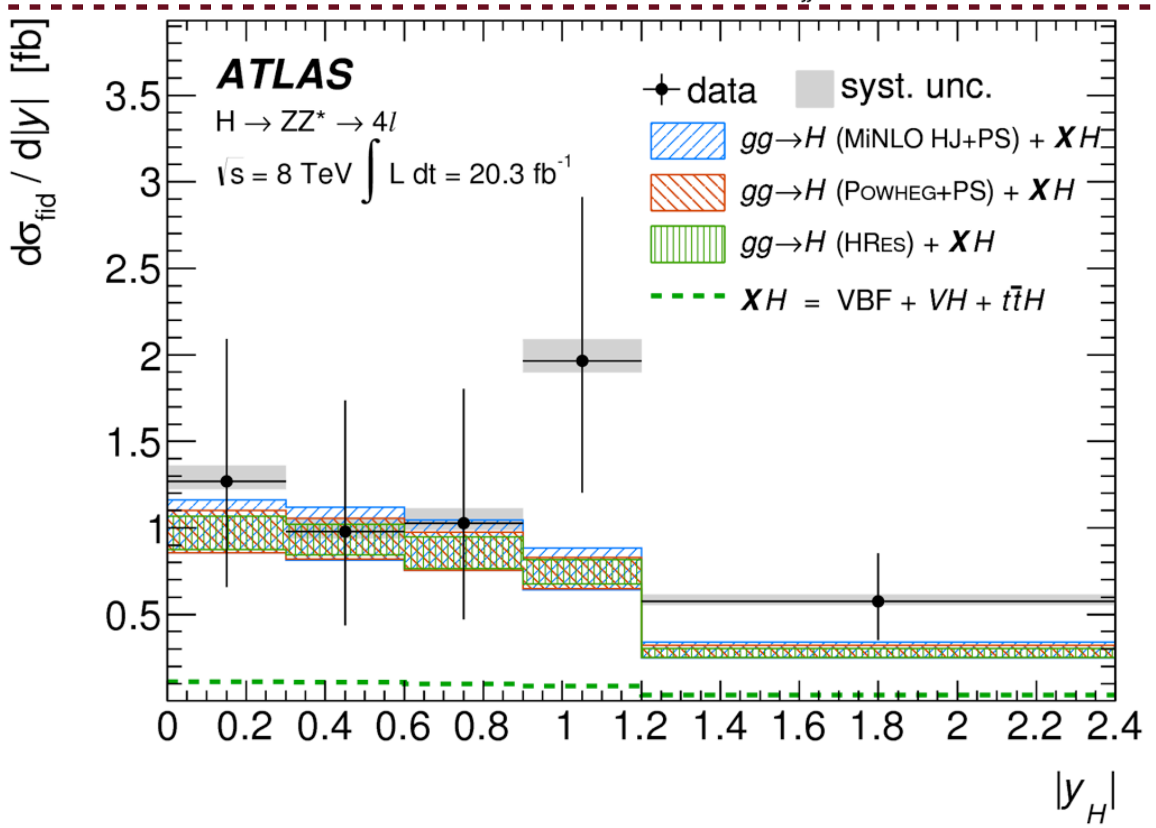


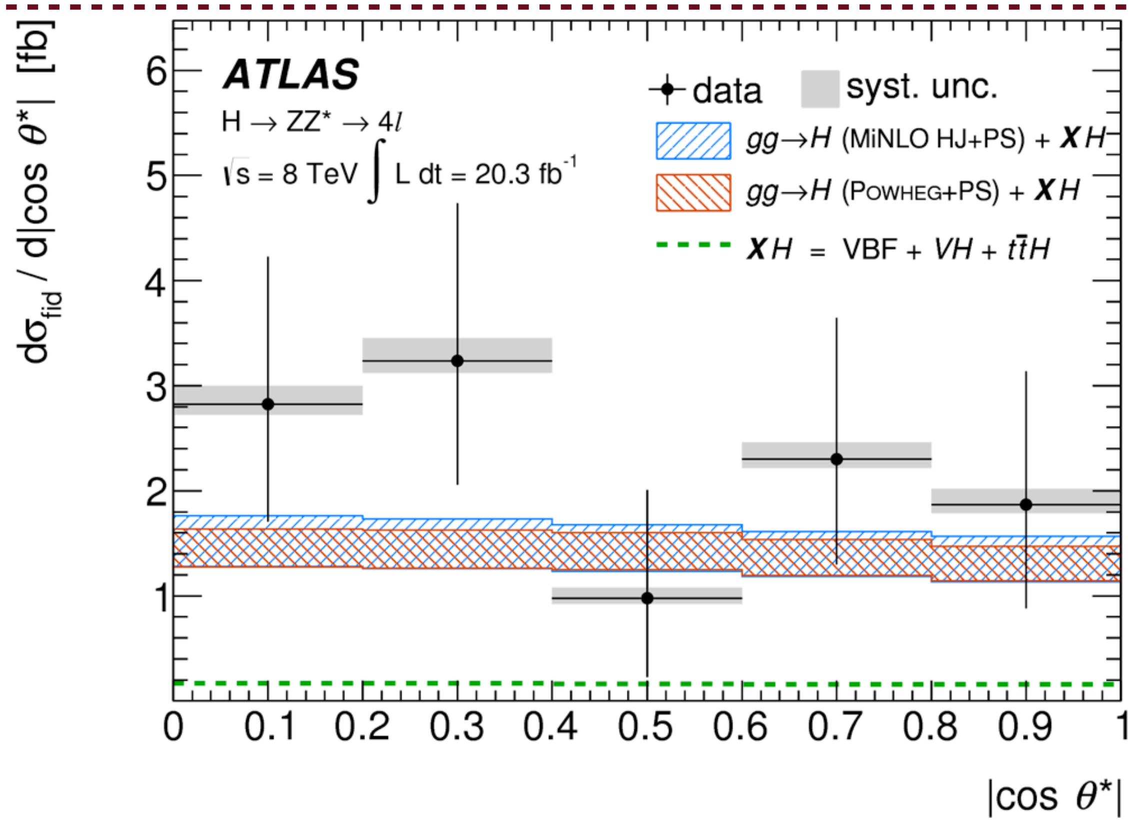
H→γγ: Fiducial/Differential cross sections





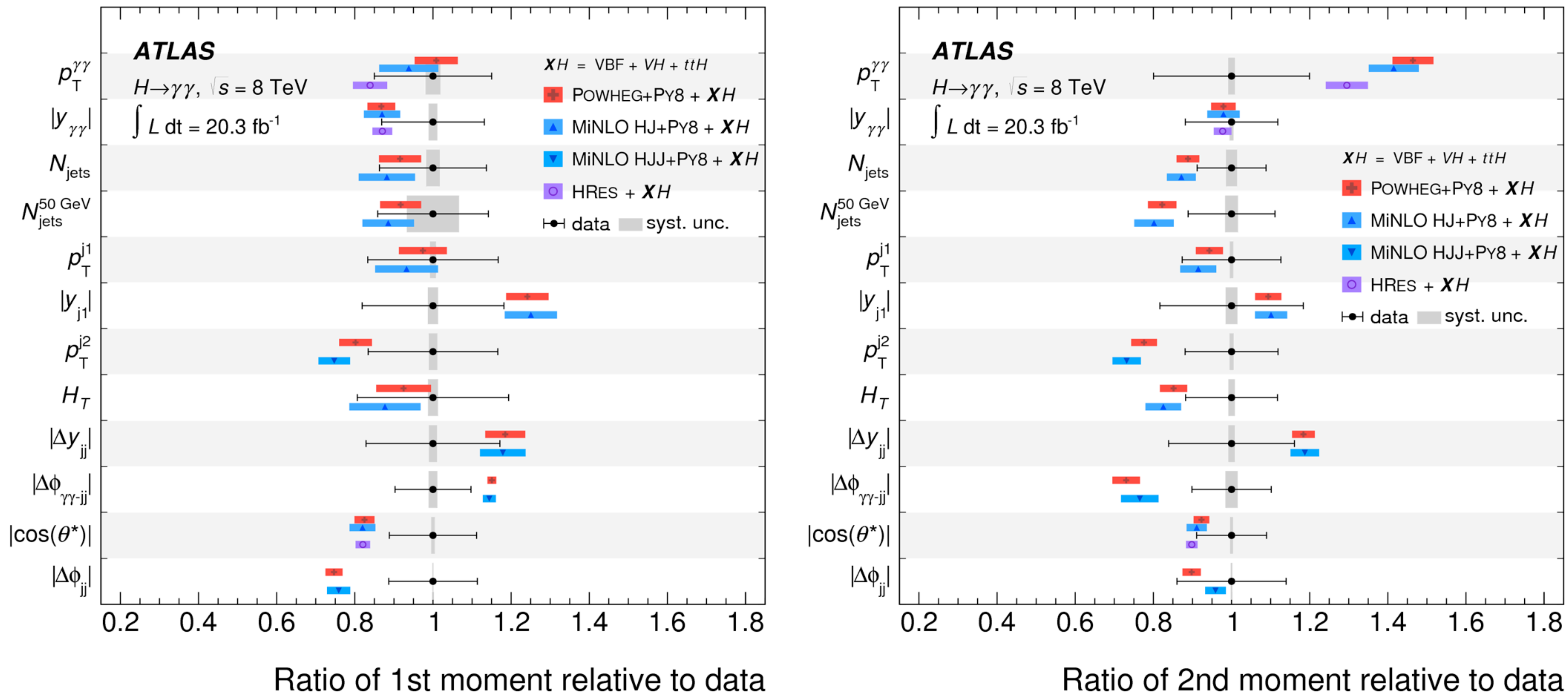






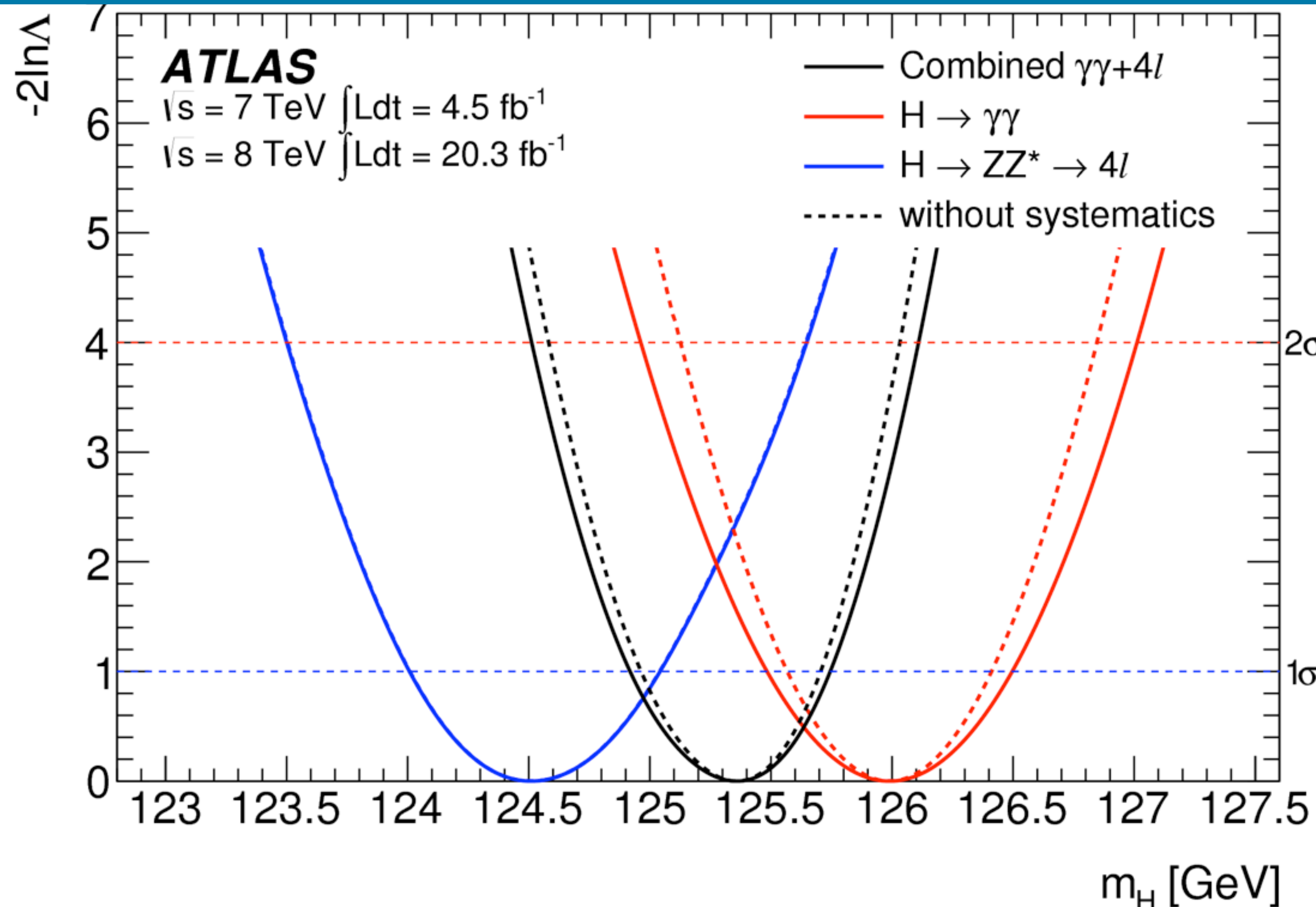
H→ZZ*→4l

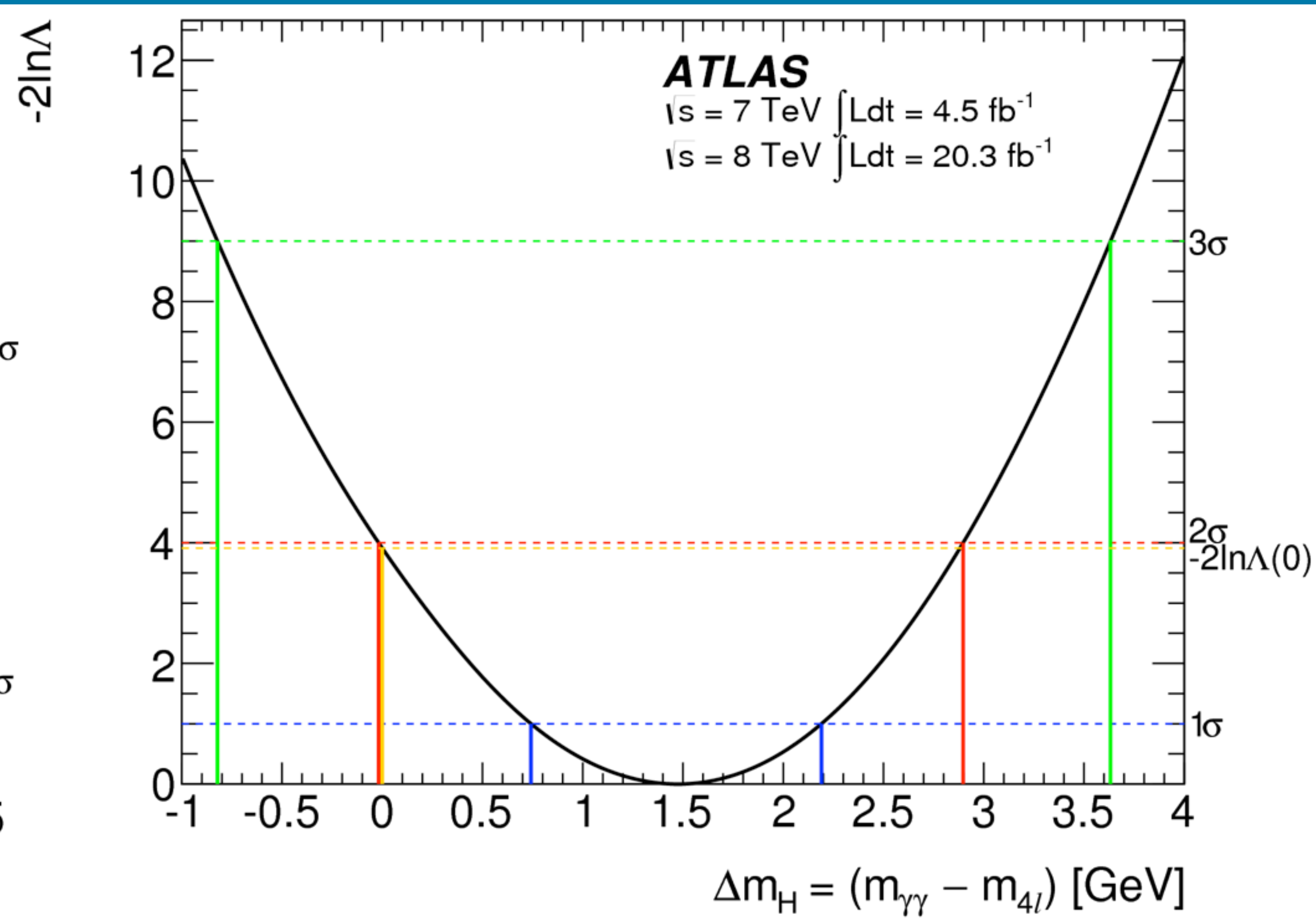
H→γγ: Fiducial/Differential cross sections



Overall good data/theory agreement
Somewhat higher jet activity data

$H \to ZZ^{(*)} \to 4l / H \to \gamma\gamma$: m_H measurement

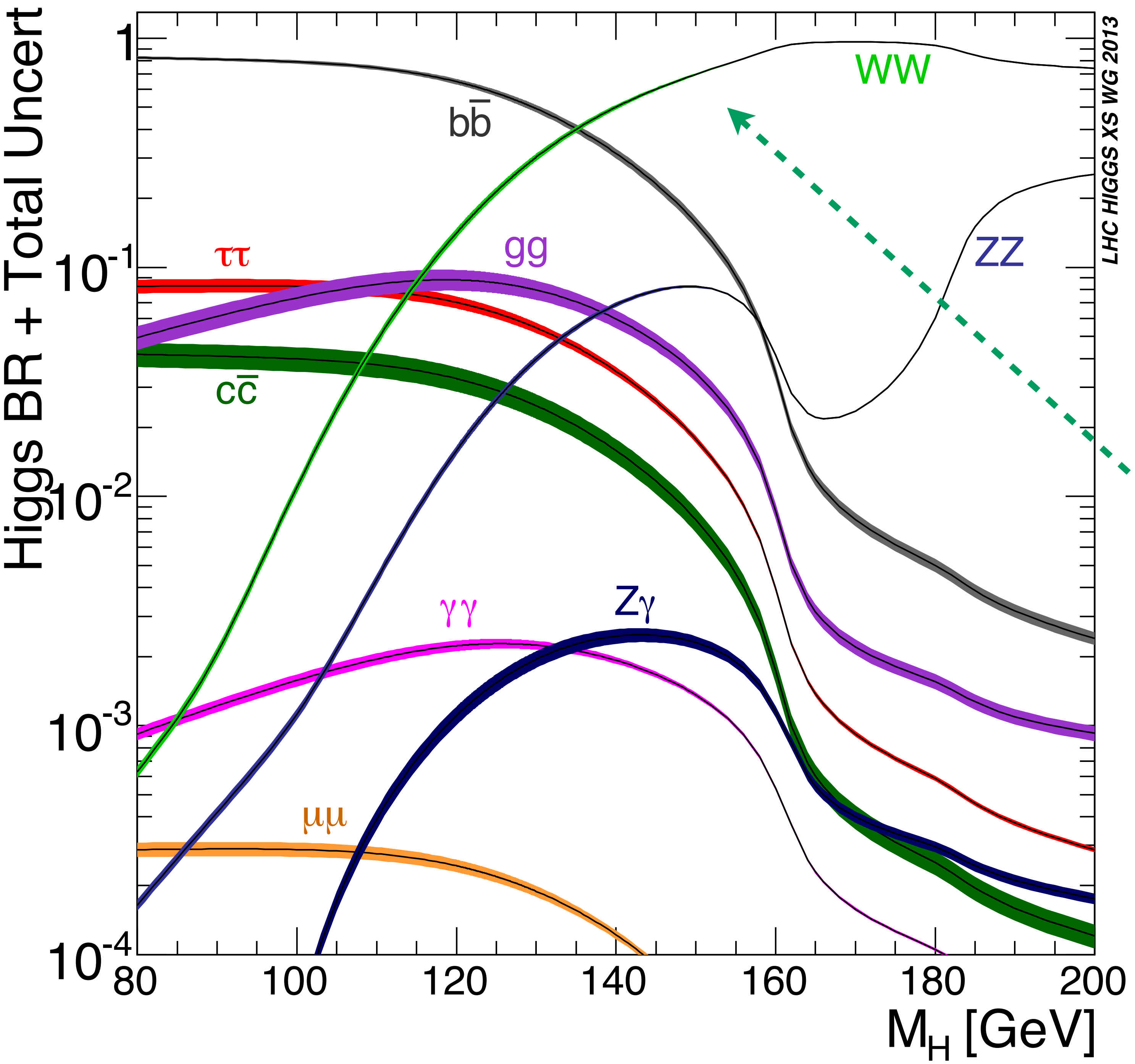




Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

H→4l/H→γγ compatibility: **1.97σ** (p-value 4.9%)

- rates independent free parameters in the fit
- fixing rates to SM expectation →1.6σ
- γ systematics as box →1.8σ
- previous measurement: **125.5 ± 0.2 (stat)$^{+0.5}_{-0.6}$ (syst) GeV**
- CMS measurement: **$125.02\,^{+0.26}_{-0.27}$ (stat) $^{+0.14}_{-0.15}$ (syst) GeV**
- increased statistical uncertainty [lower signal rate in H→γγ]



H→WW→lνlν

Couplings: arXiv:1412.2641 submitted to Phys. Rev. D

Spin/CP: Phys. Lett. B726 (2013) 120

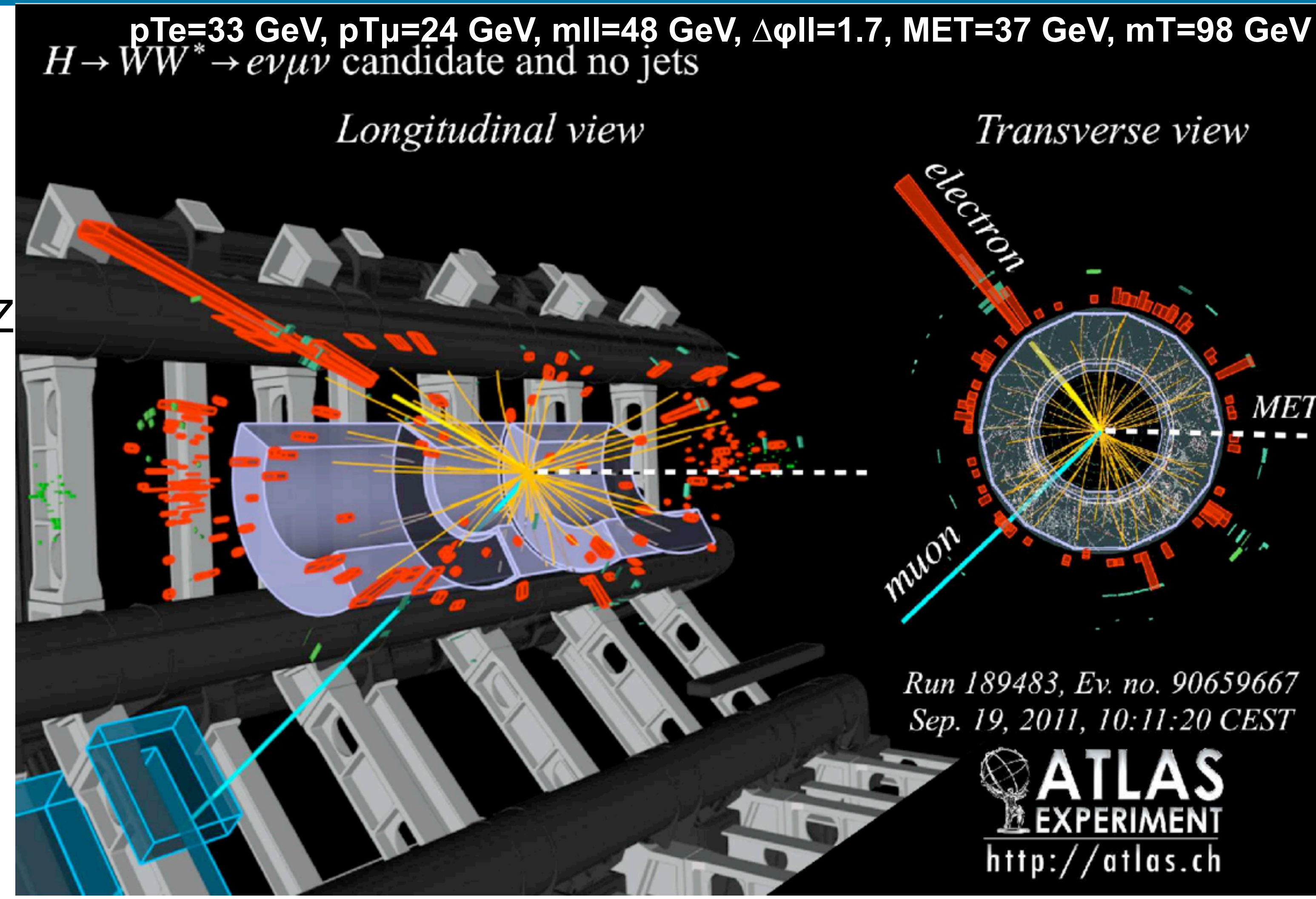
VH(→WW): ATLAS-CONF-2013-075

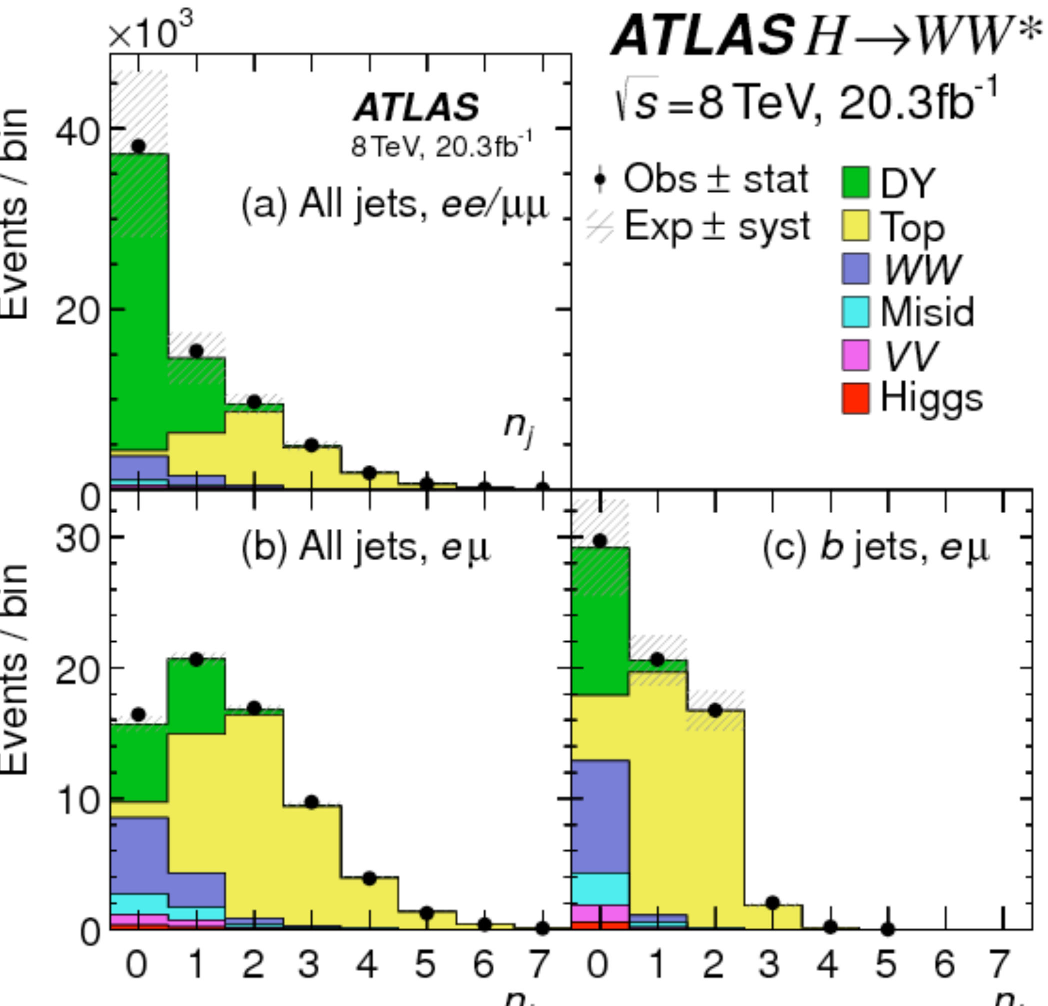
H→WW$^{(*)}$→lνlν

- Complex final state without mass peak
- Signature: l^+l^- + MET
- Observables: m_T (but also BDT in VBF)

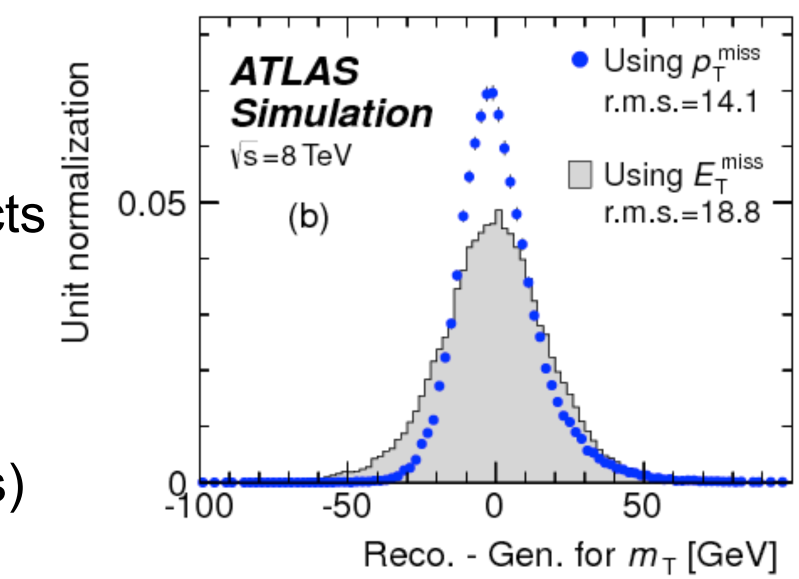
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

- Backgrounds: WW, tt/Wt, W/Z+jets, Wγ/Wγ*/WZ
- Separate final states:
  - lepton flavors: μe, eμ, μμ, ee
    - sub-leading lepton pT
  - jet multiplicities: 0, 1, ≥2
  - aim to identify ggF and VBF production

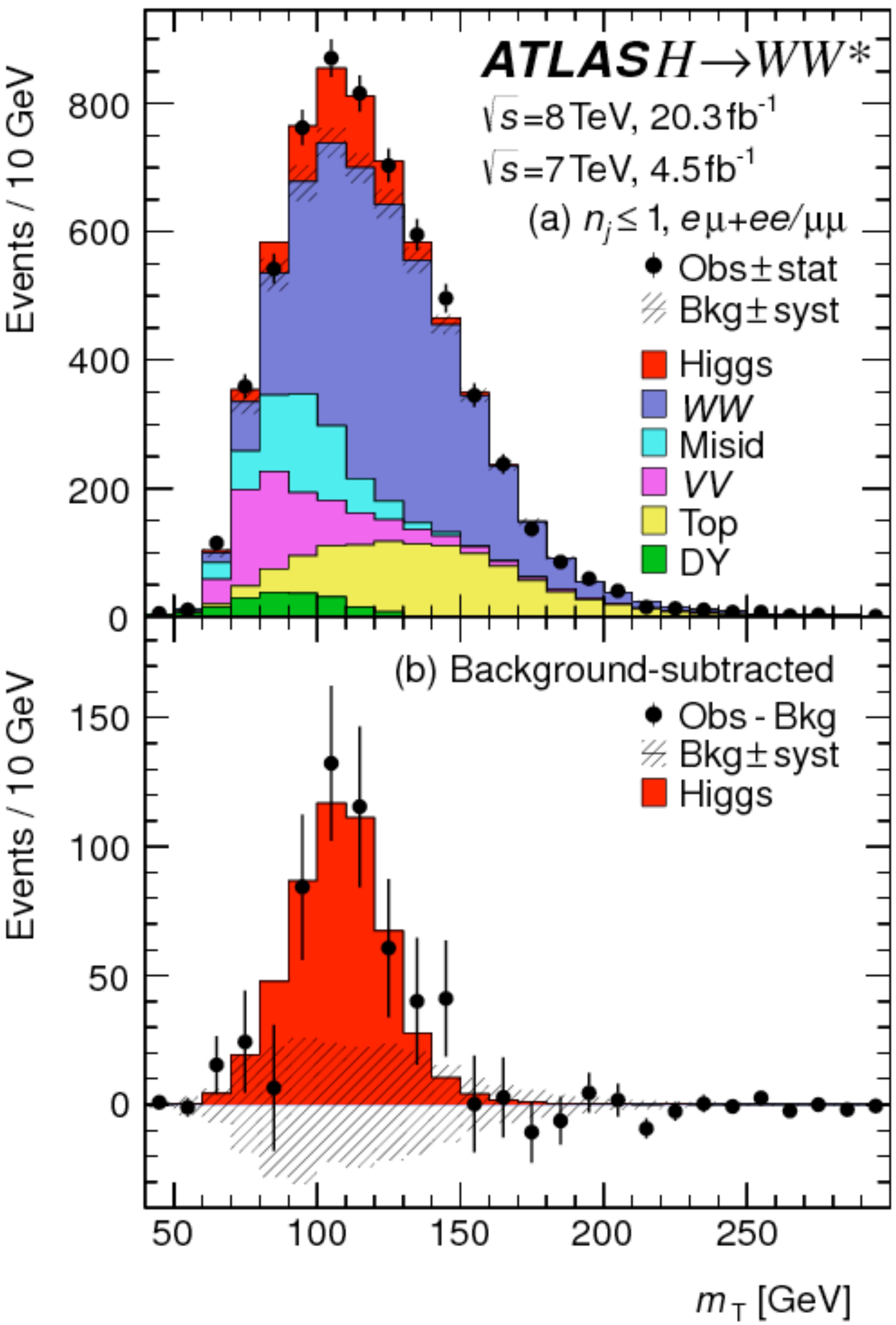


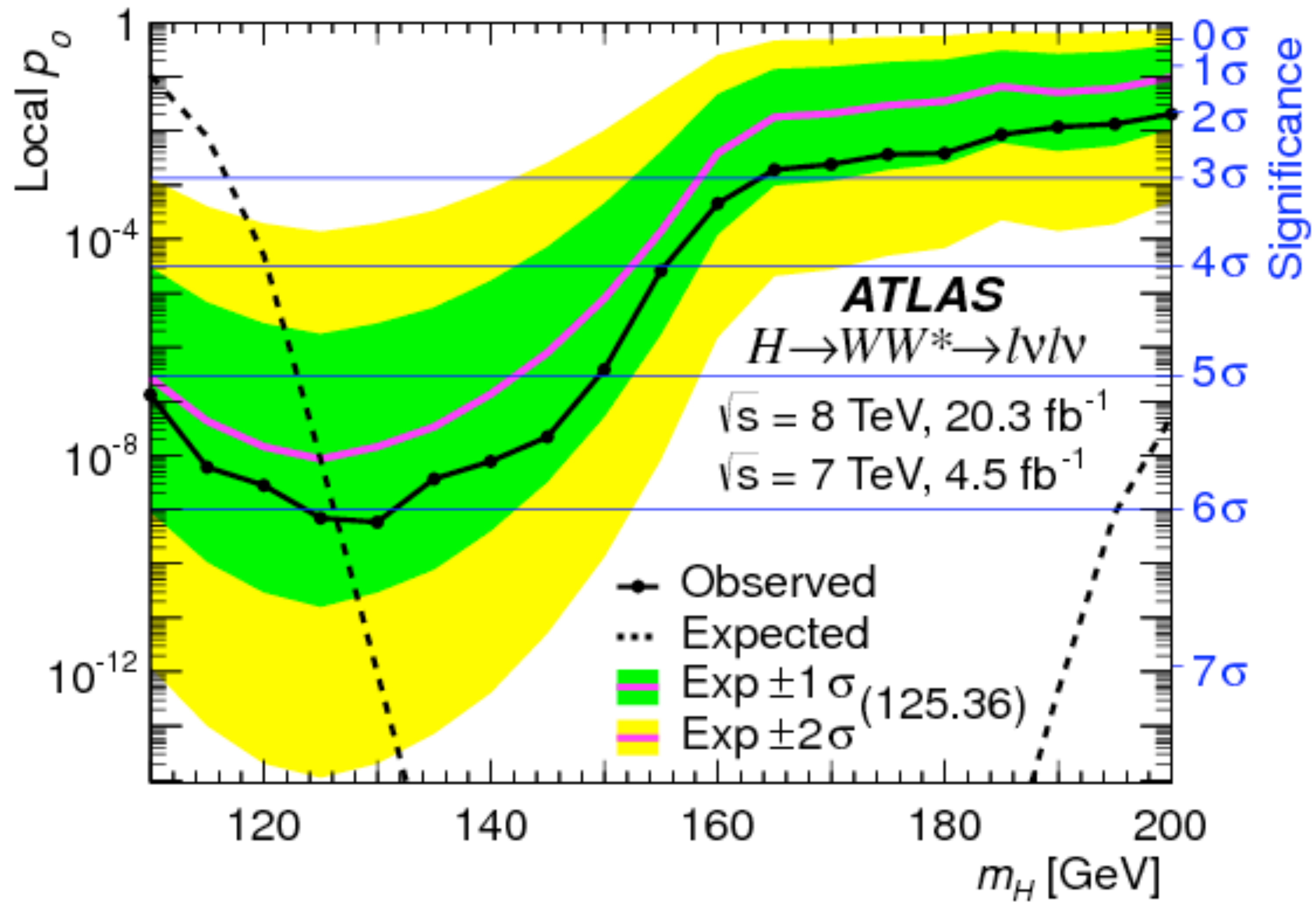


Performance improvements include:
- Track based missing momentum
  - Use track from PV for soft objects
  - ~25% improvement on mT resolution
- Likelihood based electron-ID
- Di-lepton triggers (lower thresholds)



$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$





Local significance at m_H=125.36GeV is 6.1σ (5.8σ)

Rate with respect to SM @ m_H=125.36 GeV:

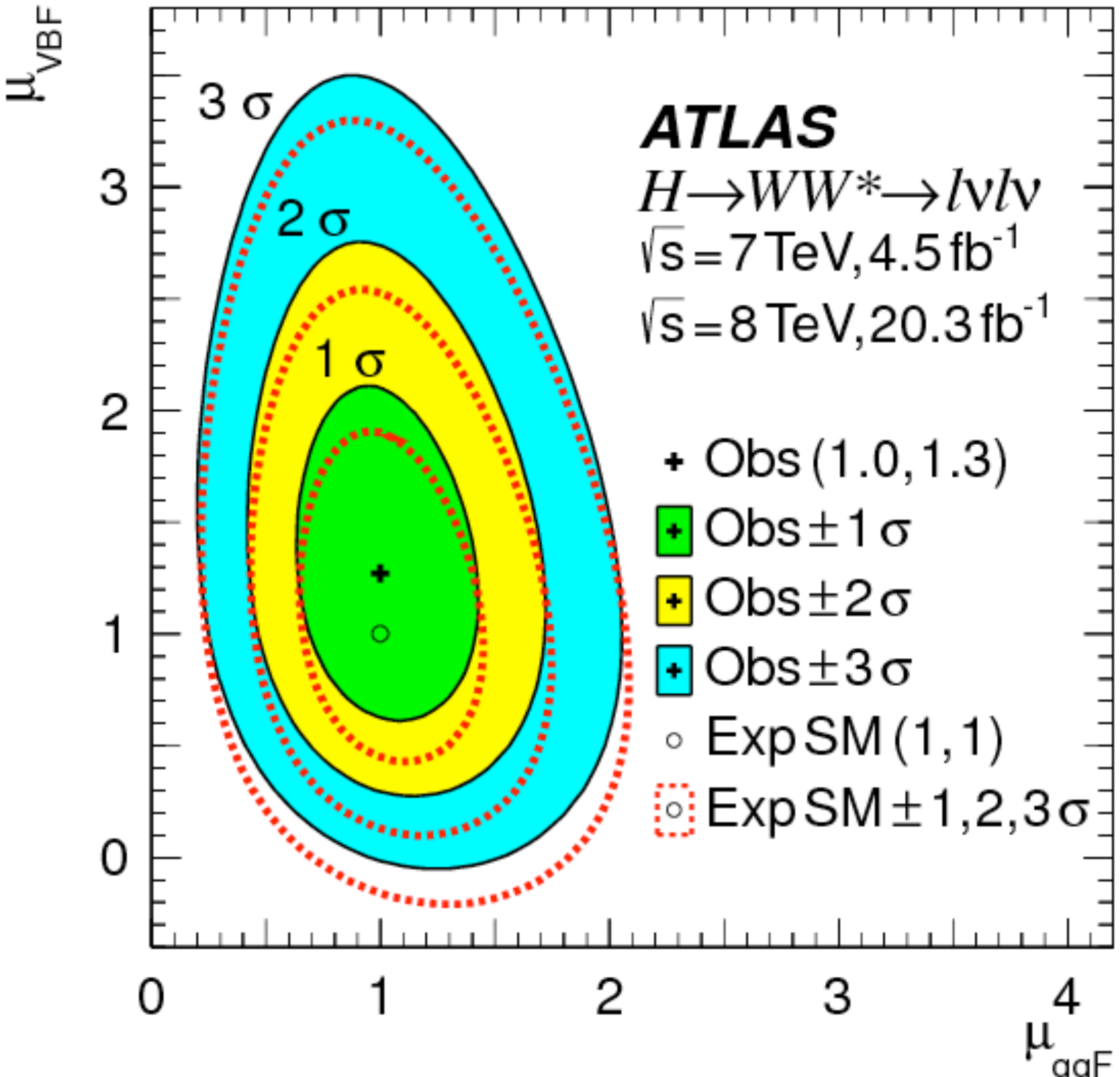
$$\mu = 1.08 \; {}^{+0.16}_{-0.15}\,(\text{stat.}) \; {}^{+0.08}_{-0.07}\left(\begin{matrix}\text{expt.}\\ \text{syst.}\end{matrix}\right) \; {}^{+0.13}_{-0.11}\left(\begin{matrix}\text{theo.}\\ \text{syst.}\end{matrix}\right) \; \pm 0.03 \left(\begin{matrix}\text{lumi.}\\ \text{syst.}\end{matrix}\right)$$

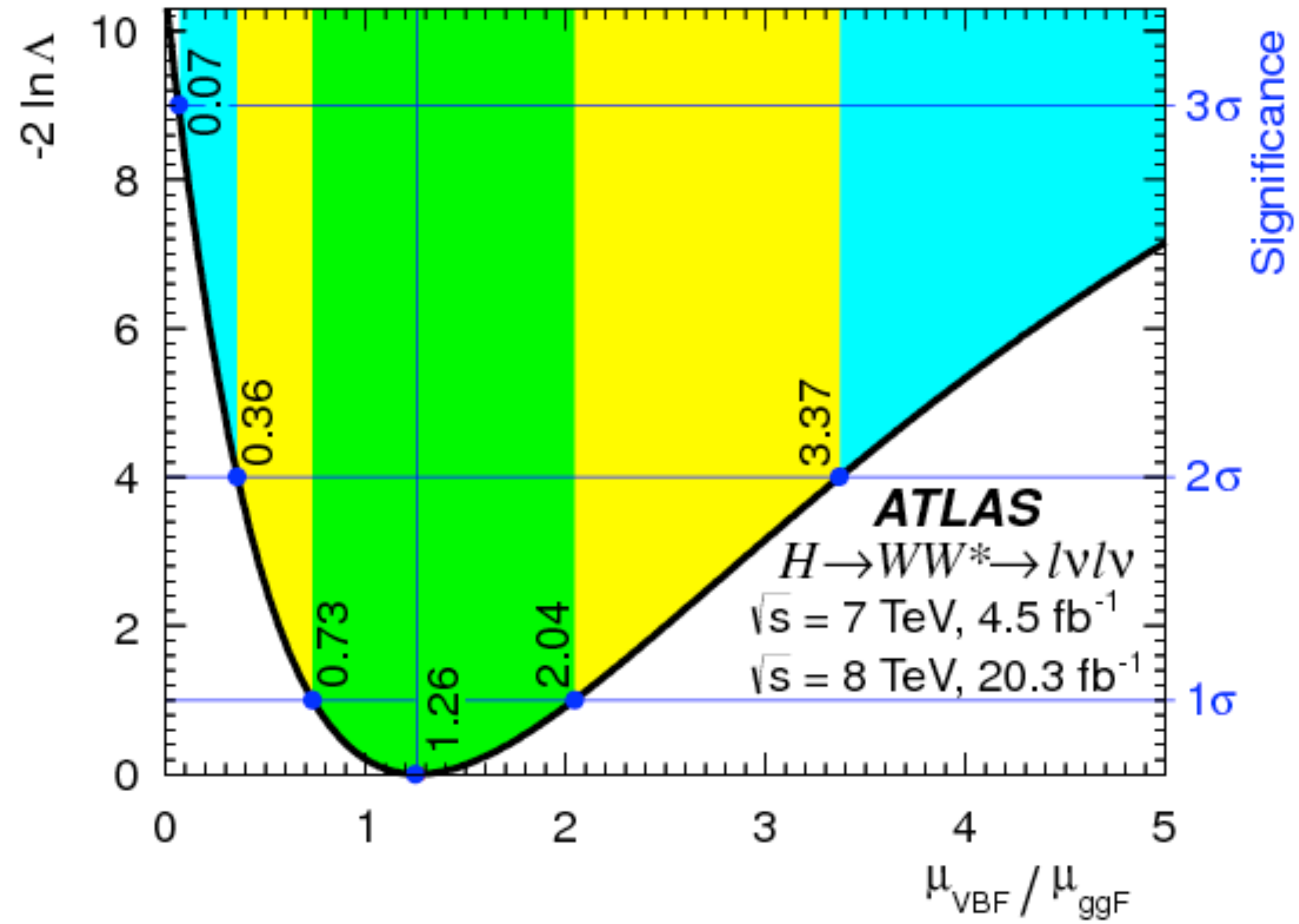
30% improvement with respect to earlier results

Dominant systematic sources on μ:

ggF signal theory uncertainty ~0.1,
WW background modeling ~0.06,
Fake lepton background modeling ~0.06

$H \to WW^{(*)} \to l\nu l\nu$





Observed significance for VBF production at m_H=125.36GeV is 3.2σ (2.7σ)

Inclusive cross section (8 TeV)

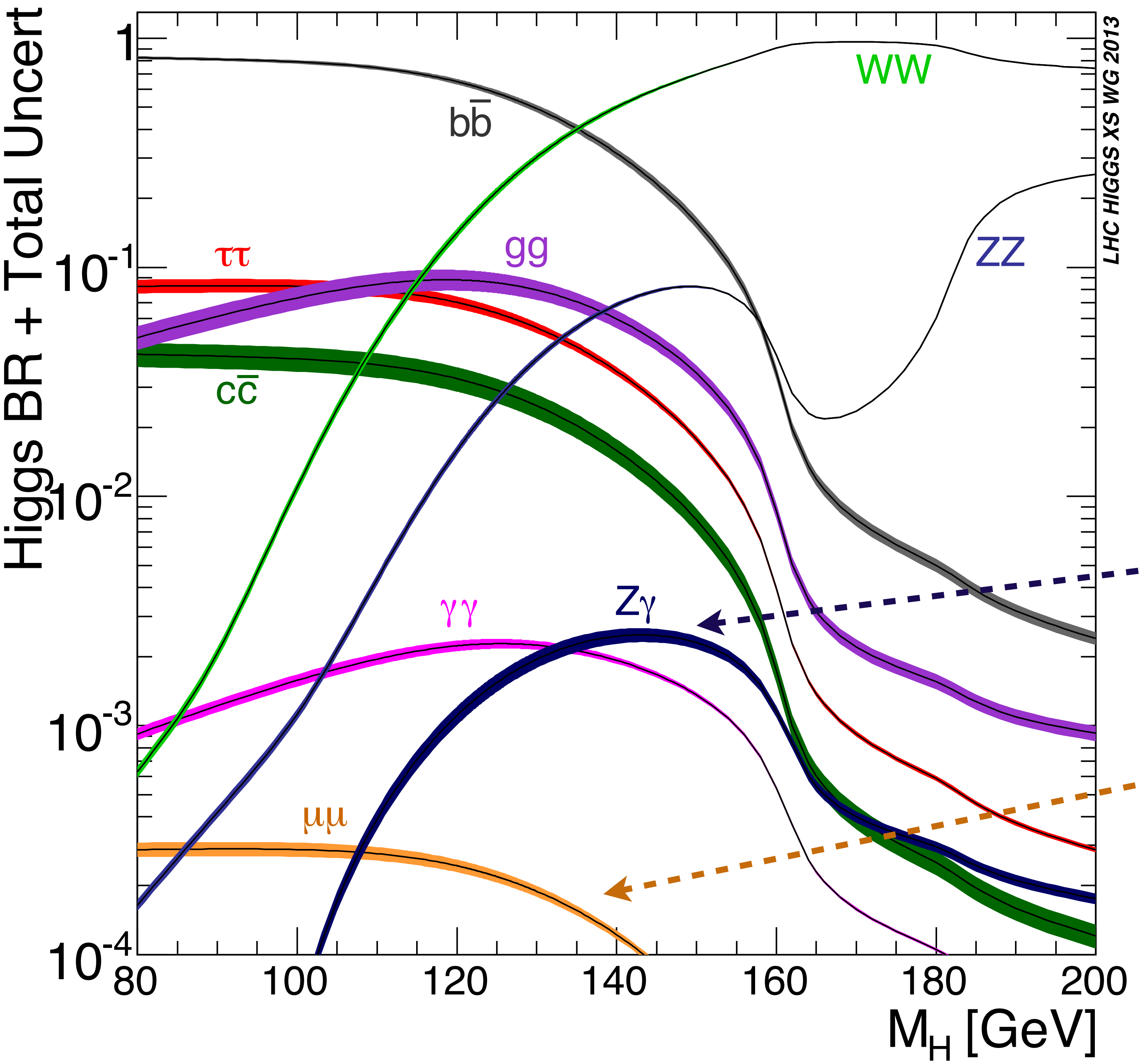
σ_{ggF} BR = 4.6±1.1 pb (SM: 4.2±0.5 pb)

σ_{VBF} BR = $0.51^{+0.22}_{-0.17}$ pb (SM: 0.35±0.02 pb)

Fiducial cross section (8 TeV, eμ)

$\sigma_{ggF}^{0j} = 27.5^{+6.9}_{-6.5}$ fb (SM: 19.9±3.3 fb)

σ_{ggF}^{1j} = 8.4±3.6 fb (SM: 7.3±1.8 fb)



$H \rightarrow Z\gamma$

Phys. Lett. B732 (2014) 8

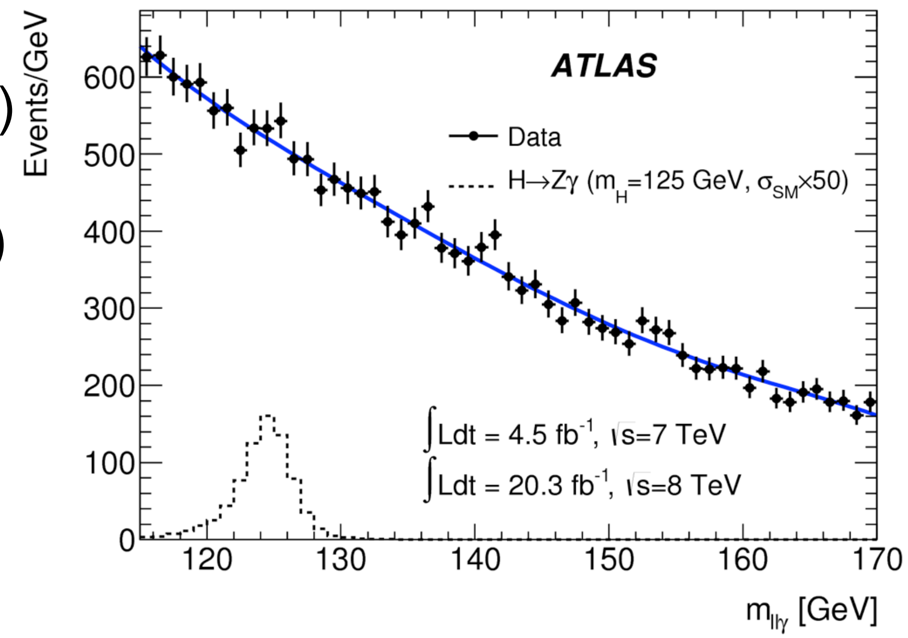
$H \rightarrow \mu\mu$

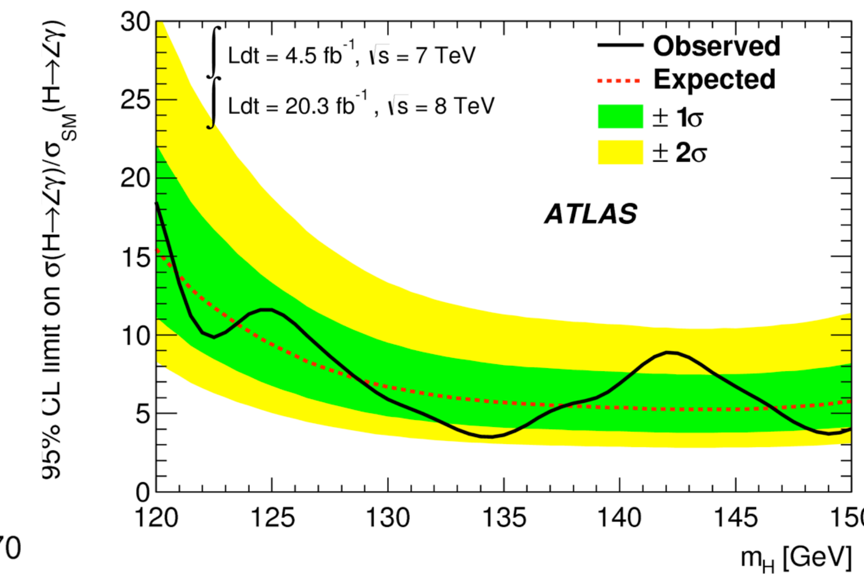
Phys. Lett B738 (2014) 68

"Rare" Higgs boson decays

H→Zγ

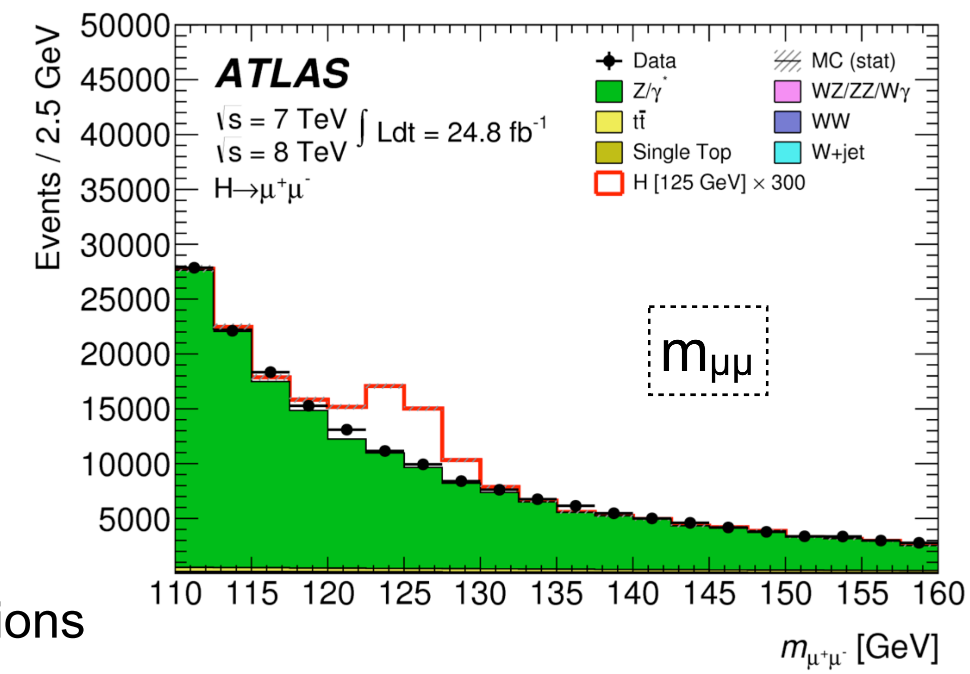
Loop mediated Higgs decay
→ BR~10^{-4}(m_H=125GeV)
Signature: $e^+e^-/\mu^+\mu^-+\gamma$
→ signal efficiency eeγ (μμγ):27% (33%)
Background
→ Z→llγ$_{FSR}$ an Z+γ continuum (82%)
→ Z+jets (17%), ttbar, WZ (~1%)
Event categories
→ ee/μμ,$\Delta\eta_{\gamma Z}$,p_{Tt}
→ S/B~3-13%
For mH=125.5 GeV,
95% CLs upper limit: 11 (9) x SM

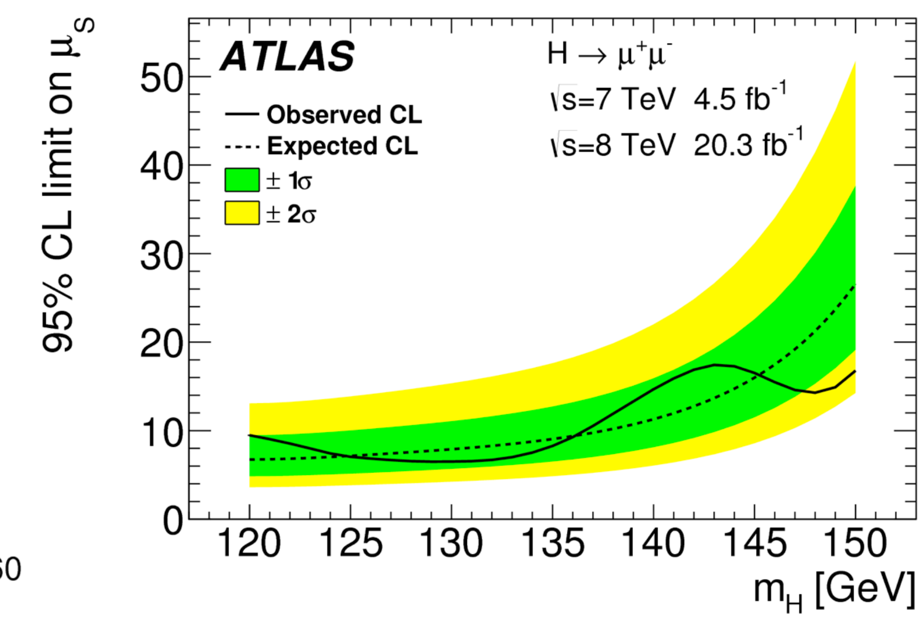


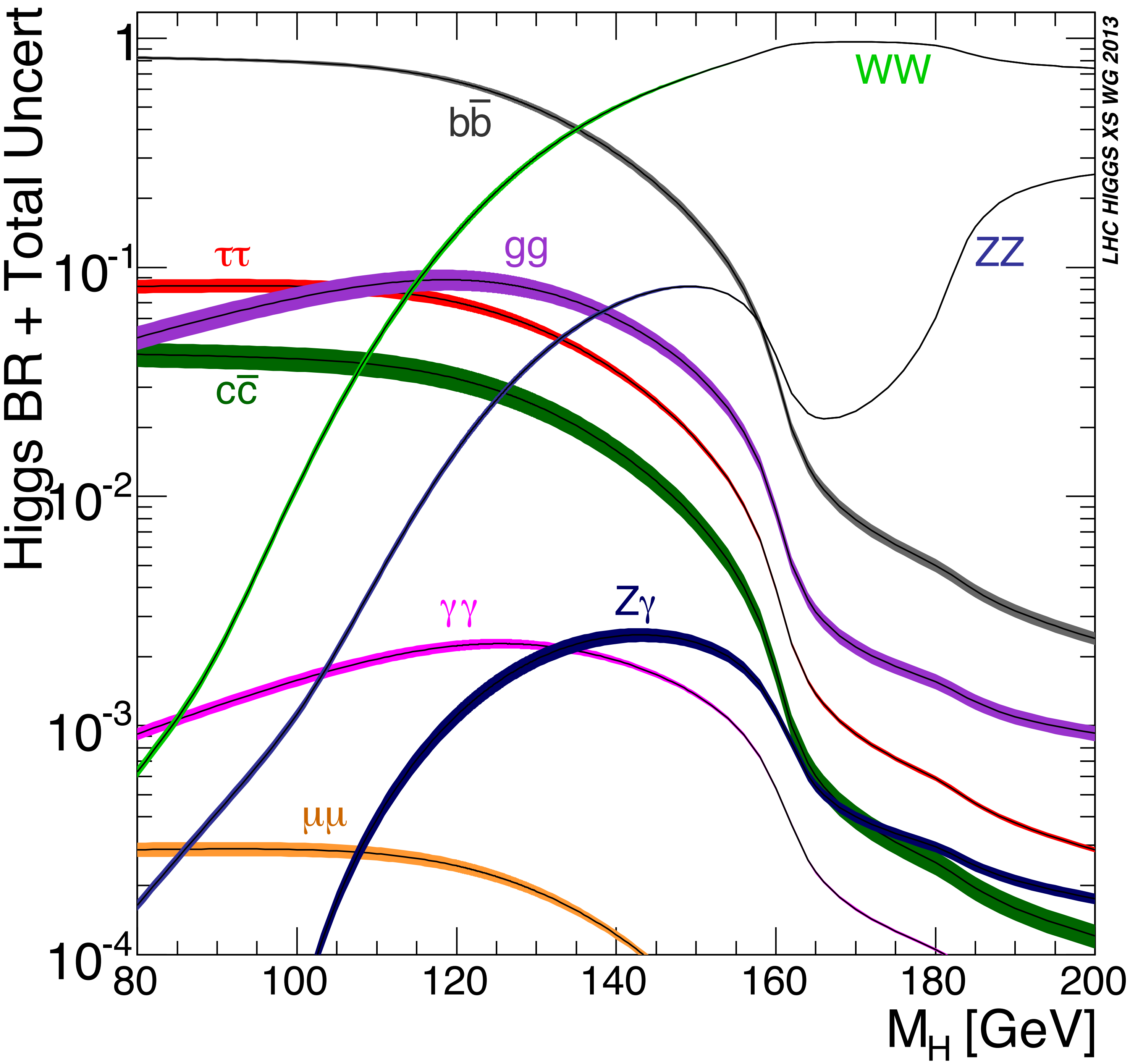


H→μμ

- probe coupling to 2nd generation fermions
- BR ~2·10^{-4}(125GeV);S/B ~0.2%
- two opposite-charge muons (pT>25,15 GeV, $pT_{\mu\mu}$>15 GeV)
- backgrounds: Z/γ*→μμ, top, dibosons
- Categorization: central/non-central muons
- Background Model: BW+Expo
- 95% CL upper limit @m_H=125 GeV: 9.8 (8.2)xSM
- no universal Higgs couplings to fermions







Anomalous Decays

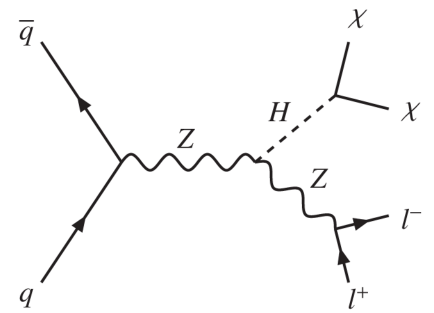
H→inv

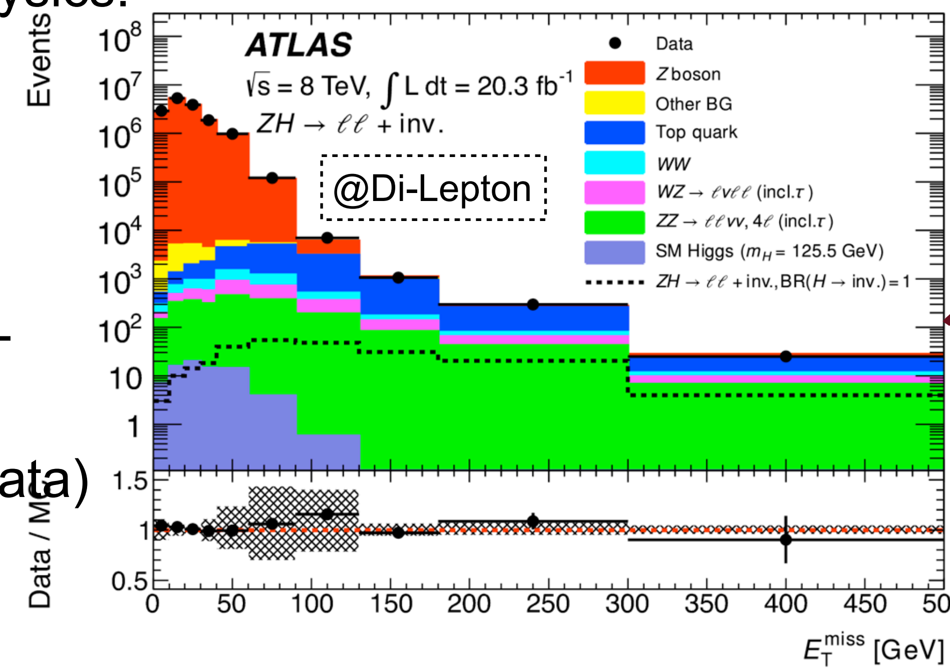
????

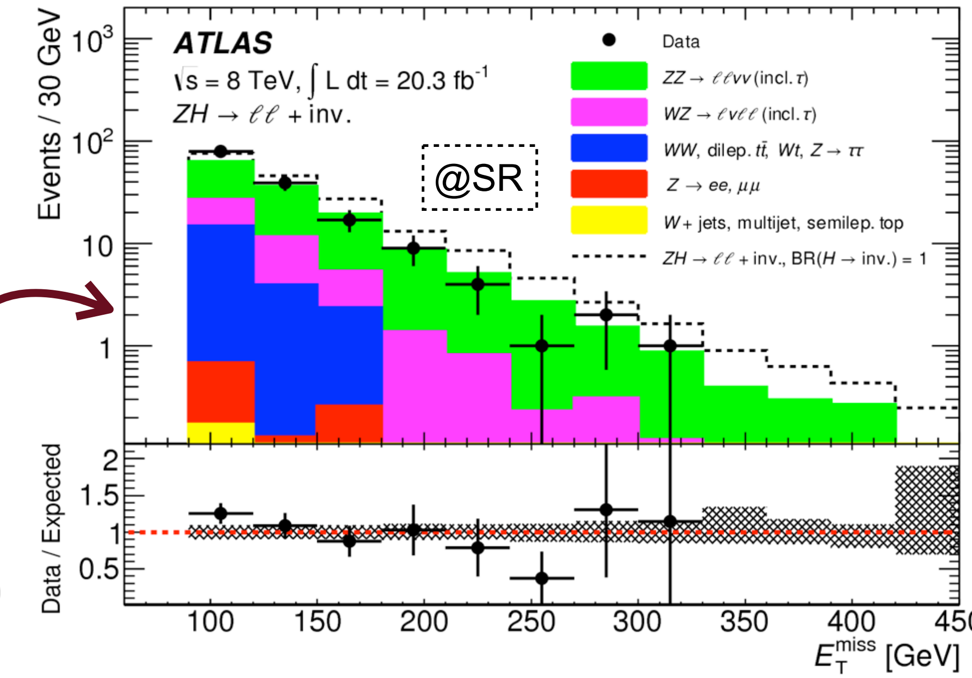
ZH(→inv)

Phys. Rev. Lett. 112, 201802 (2014)

- SM "Invisible" decays suppressed; BR(H→ZZ*→4v)=$1.2\cdot10^{-3}$
  - Observation means New Physics!

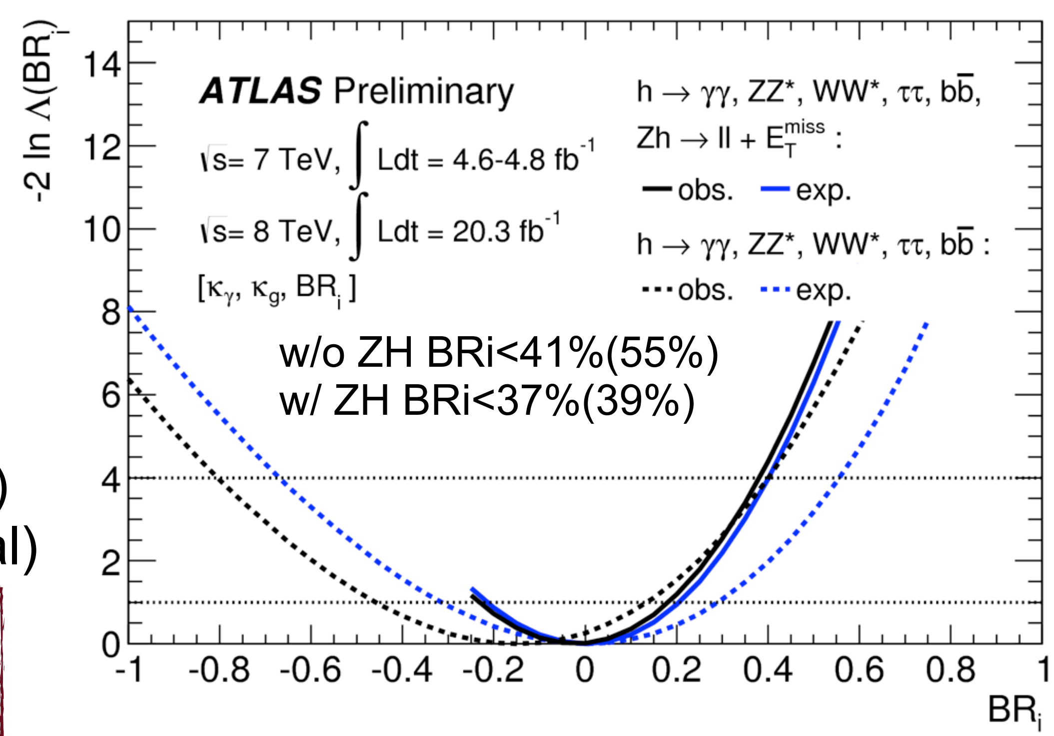


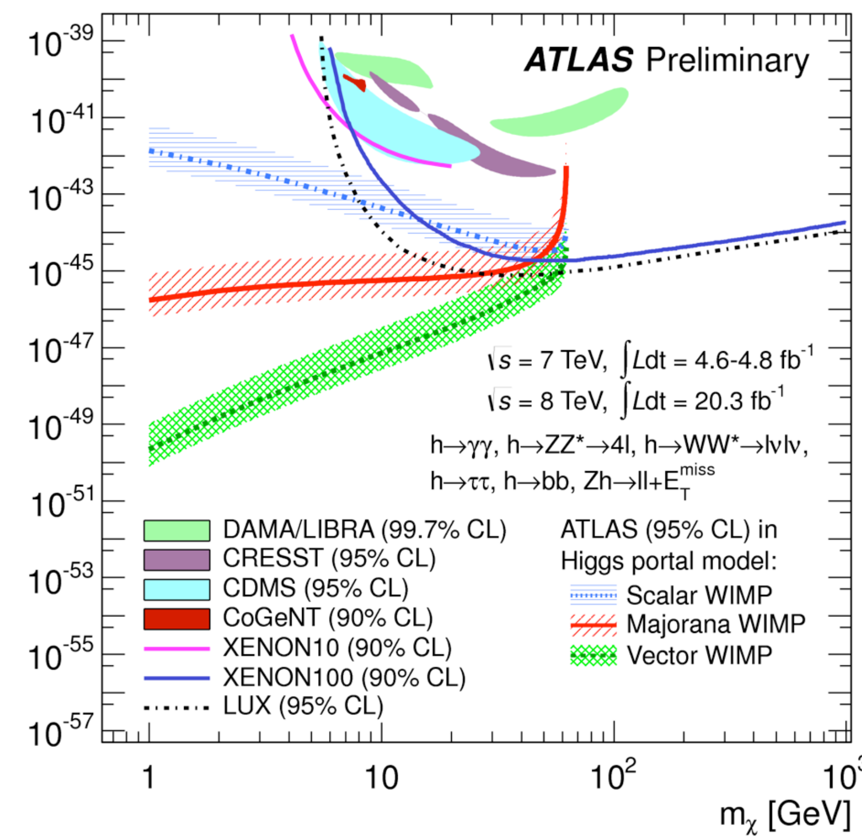




- Signature:Z→ e+e-/μ+μ- + MET
- Backgrounds
  - WW→lvlv, tt,Wt, Z→ττ (eμ-data)
  - Z→ll (double side-bands)
  - W,single-top (lepton quality)
  - ZZ→llvv, WZ→lvll (MC)
- Selection
  - Di-Lepton consistent with Z
  - ETmiss>90 GeV
  - Δφ(ETmiss,pTmiss)<0.2
  - Δφ(pTll,ETmiss)>2.6
  - Δφ(l,l)<1.7
  - |ETmiss-pTll|/pTll<0.2
  - 3rd lepton veto/jet veto
- Direct limits on the BR(H→inv)
- Constrain WIMPs (Higgs-portal)

m_H=125.5 GeV; 95% CL
BR(H→invisible) <75%(<62%)





Result based on mono-jet signature just appeared. Not as sensitive yet. [arXiv:1502.01518 submitted to EPJC]

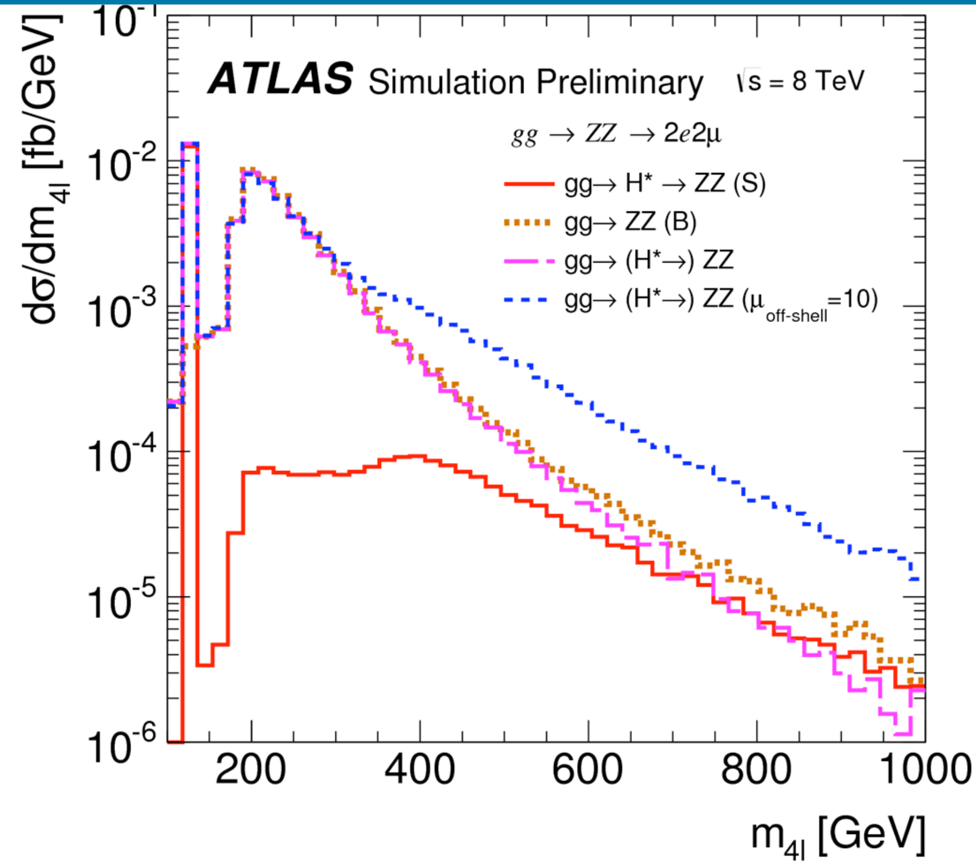
Indirect Γ_H measurement: Introduction

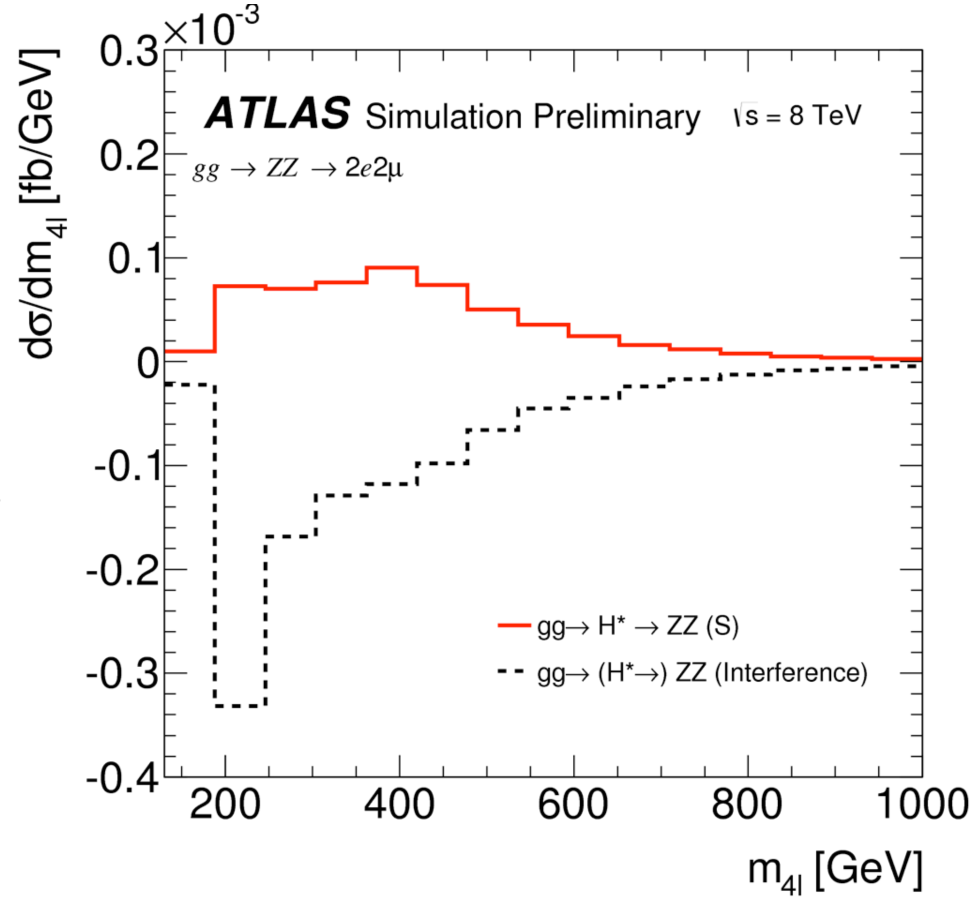
Off-shell production of Higgs boson provides indirect constraint to Γ_H

[based on Phys.Rev. D88 (2013) 05402]

$$\frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

$$\frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{V,\text{off-shell}}$$





Implemented using H→ZZ→4l with the assumptions:

→ Backgrounds insensitive to new physics modifying off-shell couplings

→ Running of couplings similar for on-shell/off-shell region

[but sensitive to new physics arXiv:1410.5440, arXiv:1406.6338,arXiv:1412.7577,...]

→ Use inclusive selections [where HO corrections available]

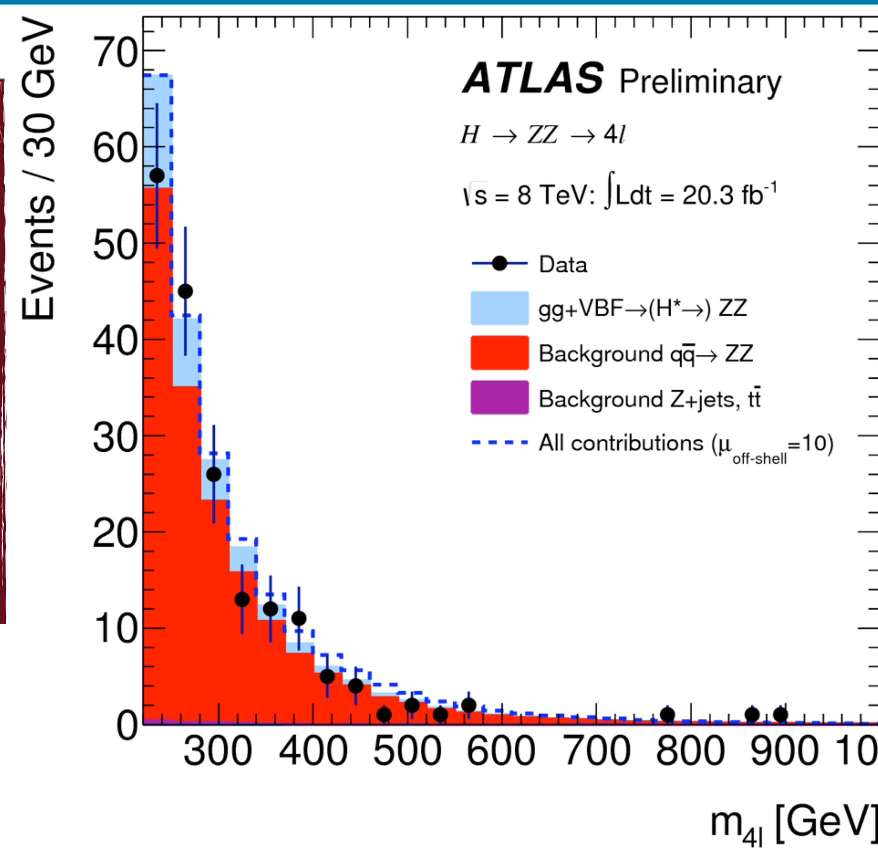
→ gg→ZZ K-factors in off-shell region unknown

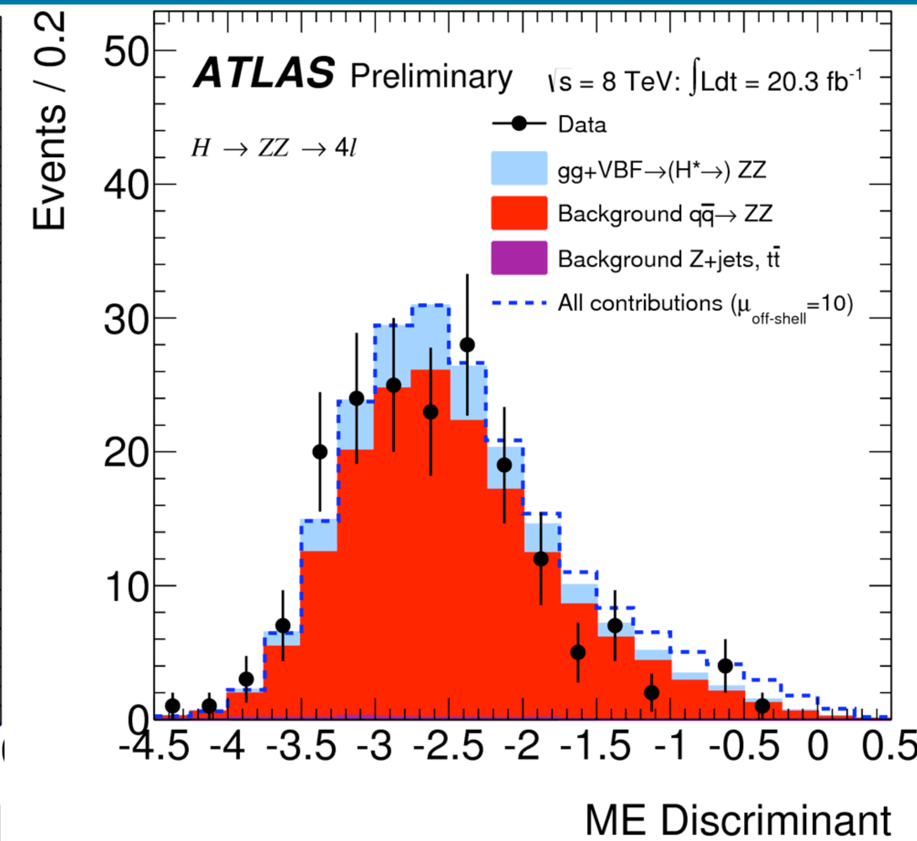
[for signal known to NNLO, gg→WW at NLO indicates that K-factors may be of similar magnitude]

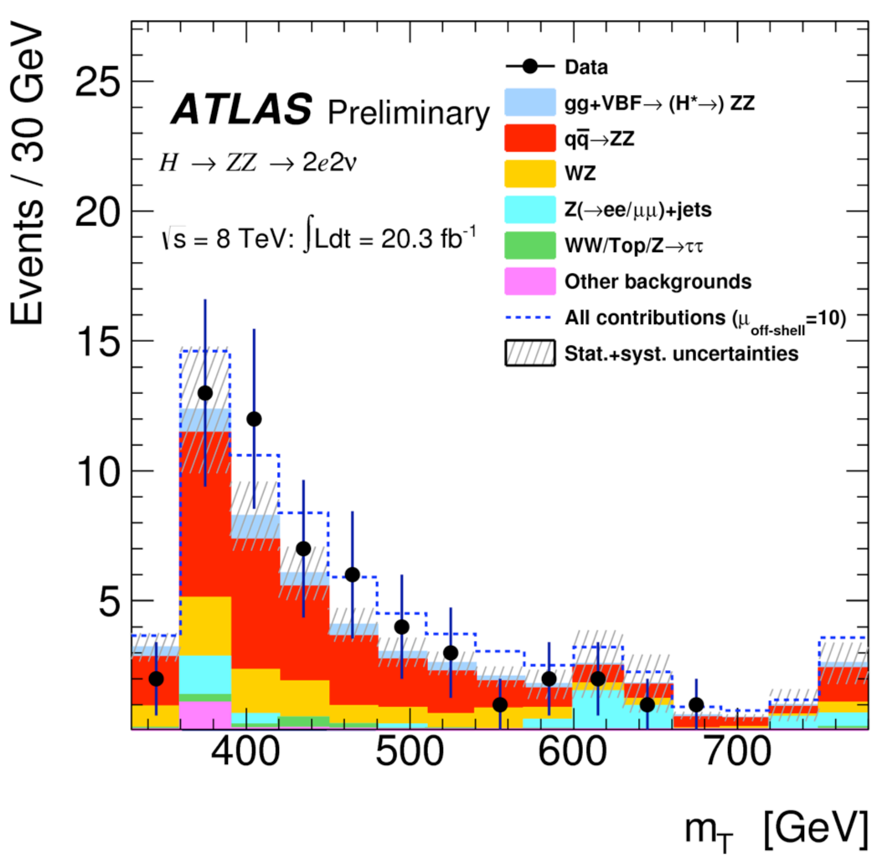
Similar assumptions to the one used for the coupling studies with the κ-factor framework

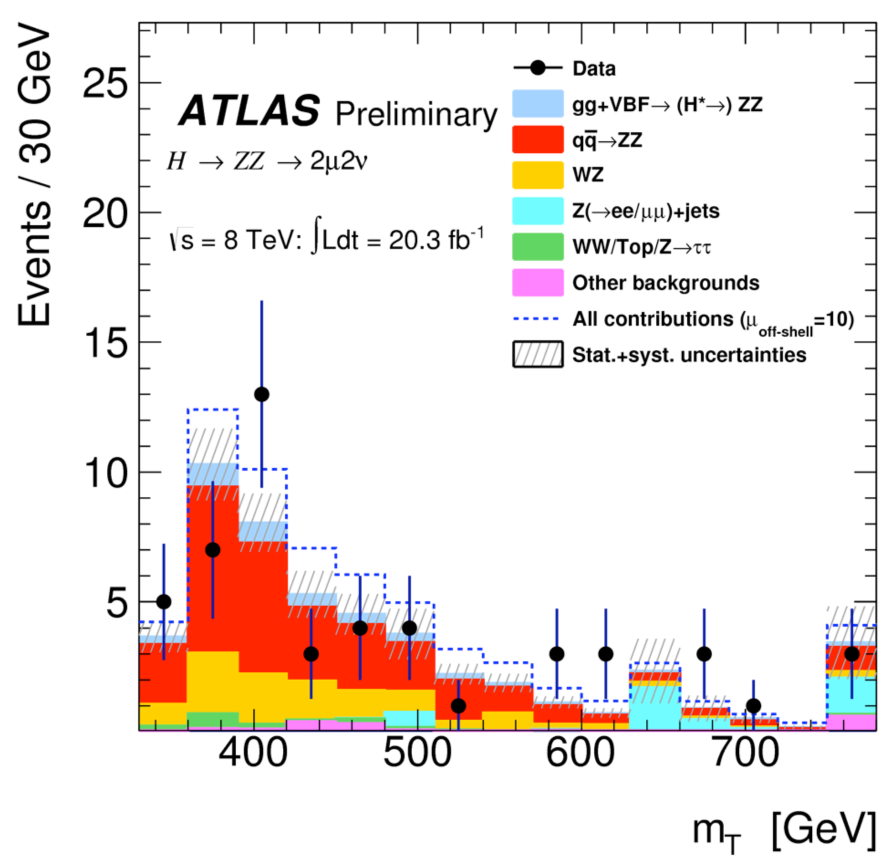
Indirect Γ_H measurement: Analysis

ZZ→4l
- Off-peak region [220 GeV, 1TeV]
- Matrix Element Kinematic Discriminant to separate gg→H*→ZZ→4l from qq→ZZ→4l/ gg→(H*)→ZZ→4l
- Limit on off-shell rate based on fit on MEKD shape



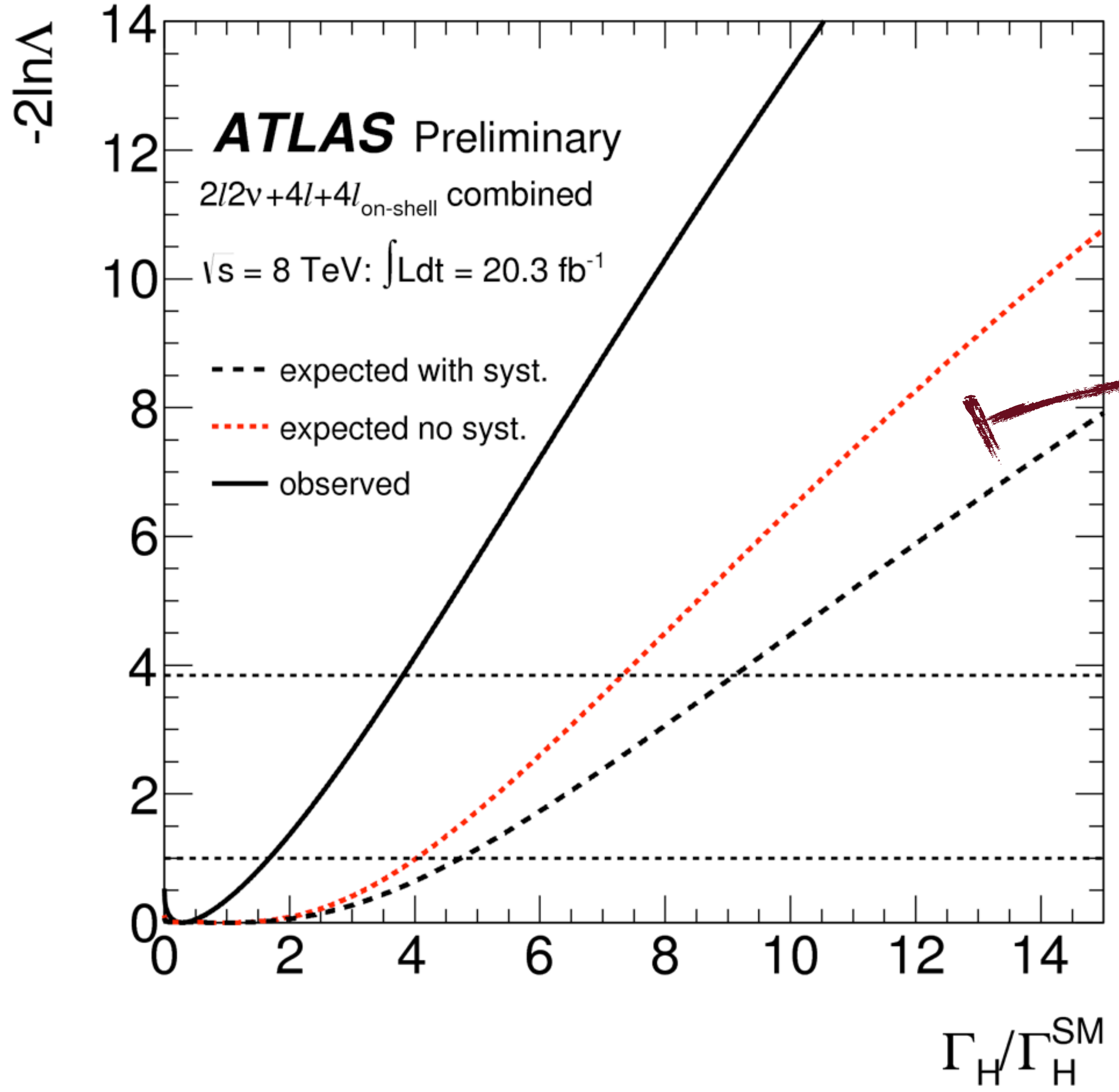


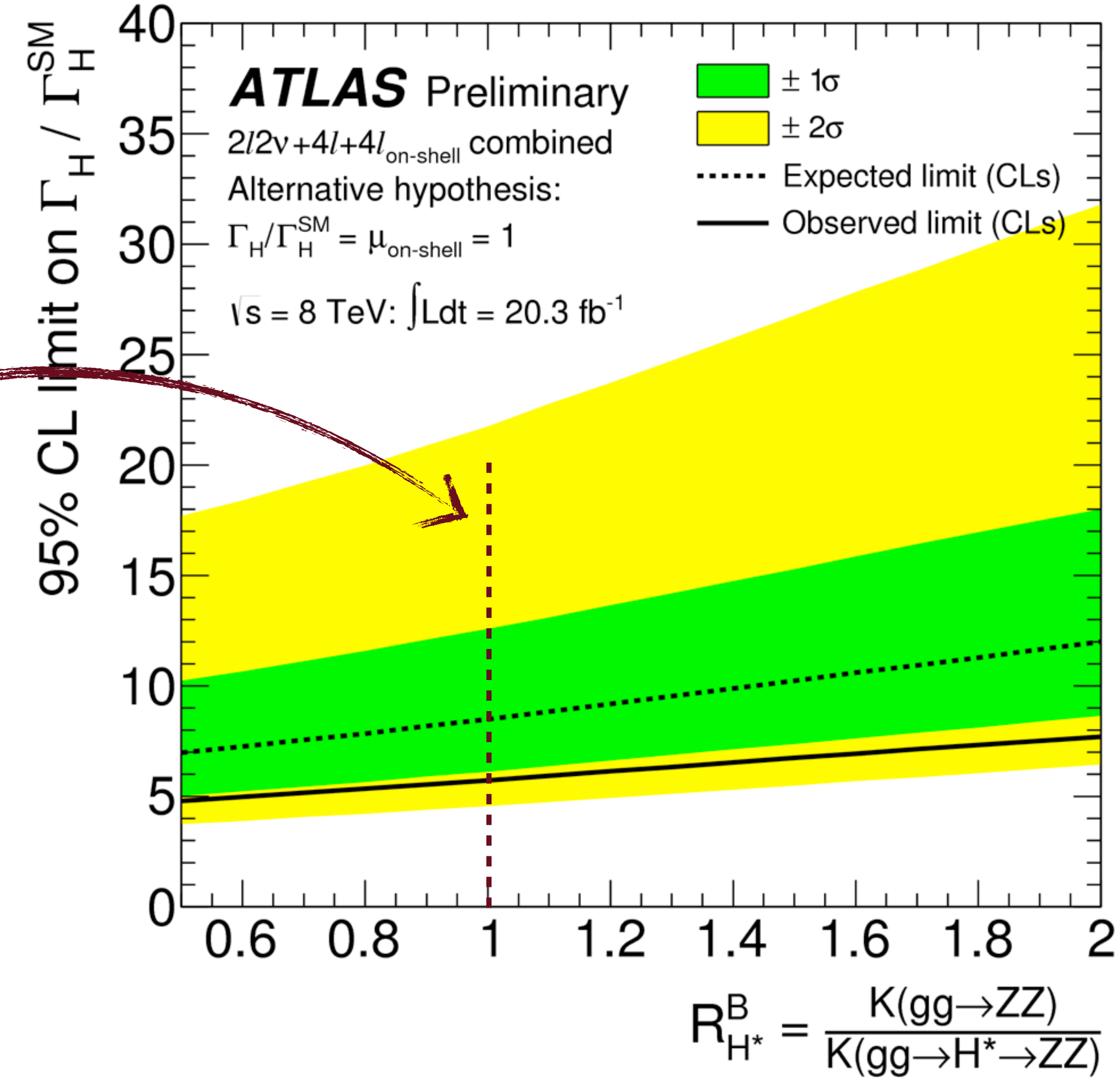




ZZ→llνν
- ETmiss>150 GeV and 76 GeV<m_{ll}<106
- Main backgrounds: qq→ZZ and WZ/WW, Z+jets and top
- Off-peak region m_{TZZ}>350 GeV
- Limit on off-shell rate based on event counting

Indirect Γ_H measurement: Results





Results are expressed as a function of the unknown K-factor for the gg→ZZ background.

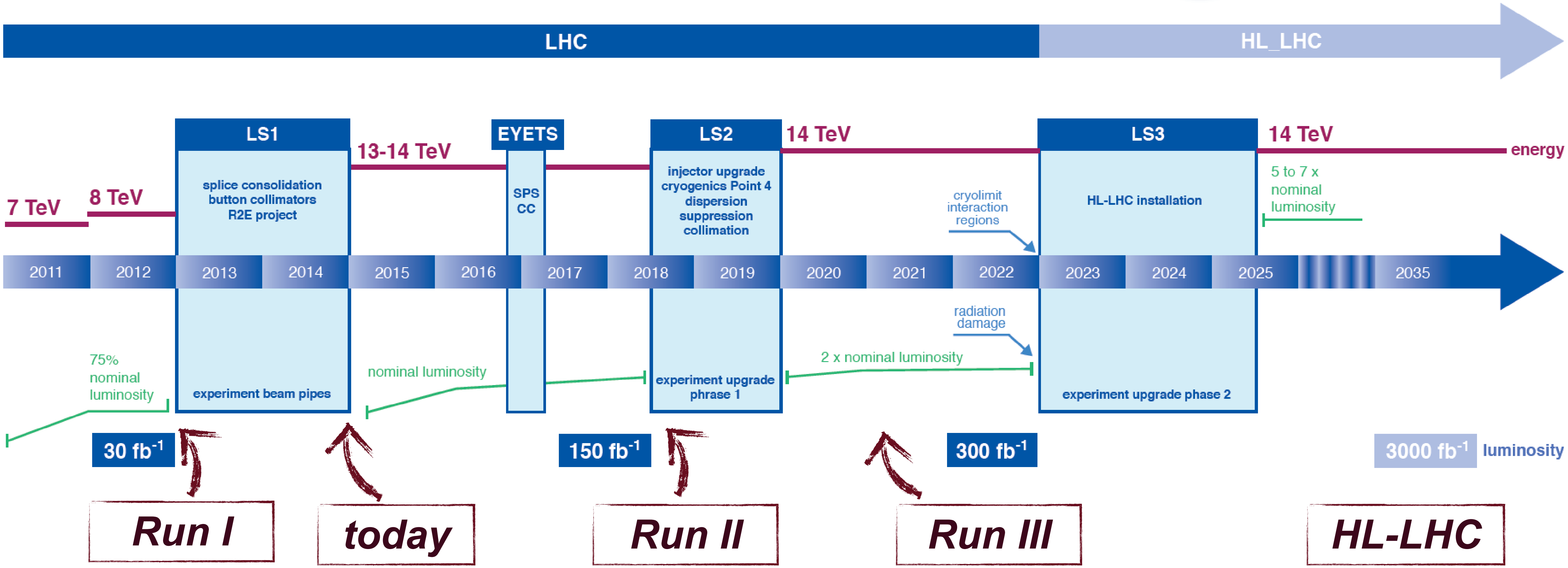
Assuming background K-factors same as for signal:

- Γ_H/Γ_{SM} < 4.8 (5.8) at 95% CLs with alternative hypothesis $R^B_{H^*}$=1, Γ_H/Γ_{SM}=1 and $\mu_{on\text{-}shell}$=1.51
- Γ_H/Γ_{SM} < 5.7 (8.5) at 95% CLs with alternative hypothesis $R^B_{H^*}$=1, Γ_H/Γ_{SM}=1 and $\mu_{on\text{-}shell}$=1.00

LHC/HL-LHC Plan

LHC / HL-LHC Plan

High Luminosity LHC



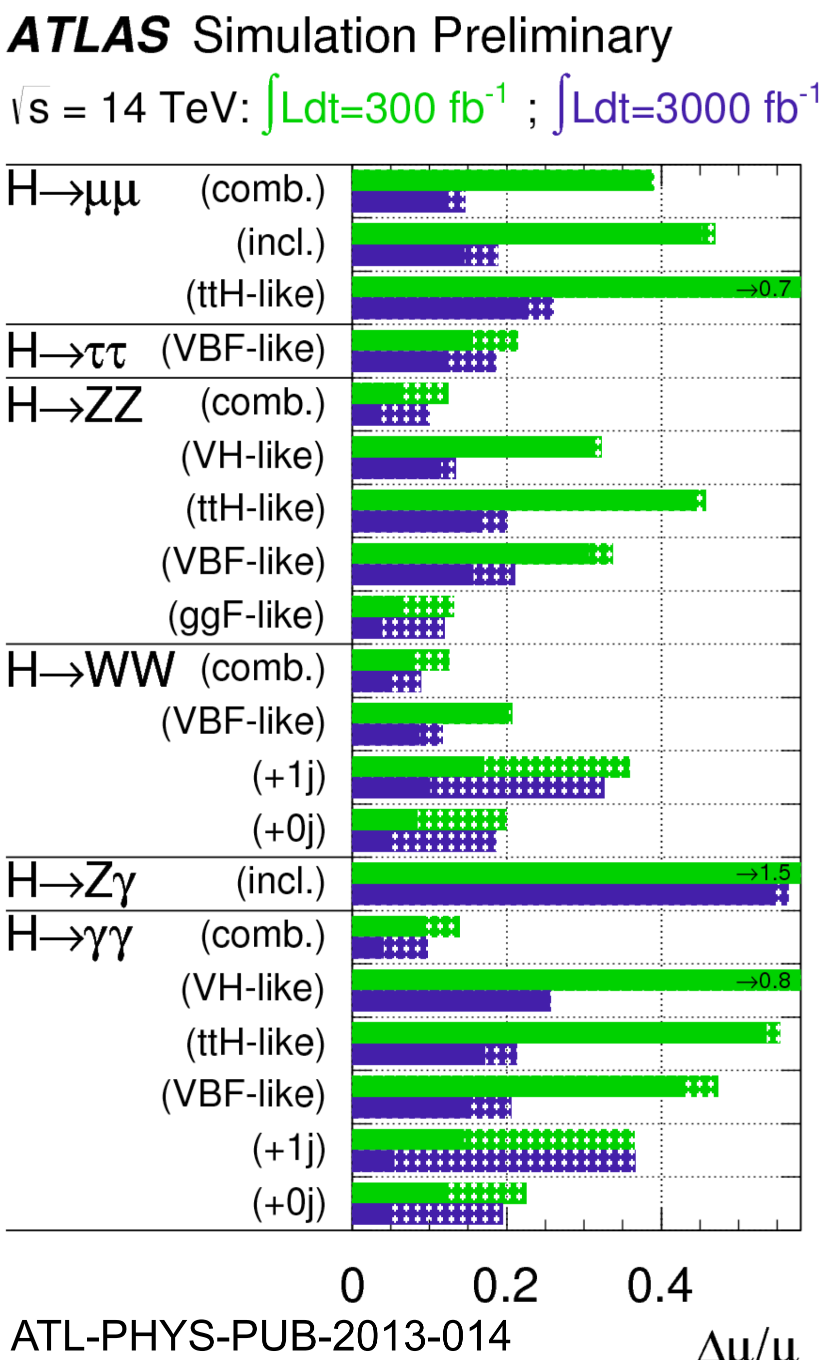
• Run II will provide ×5-6 more integrated luminosity compared to Run I
• Aiming for 3000 fb^{-1} by 2035
• Experiments will be upgraded ATLAS to go for an new all Si tracker

Higgs in Run II and beyond

The LHC is a Higgs Factory

- Run II ×5-6 more integrated luminosity compared to Run I
- ×2.3 - 3.9 increase in Higgs production cross section from 8TeV to 13TeV
- ×3.4-5 improvement in statistical sensitivity

In Run II several Higgs analysis may become systematics limited
need to work on reducing those



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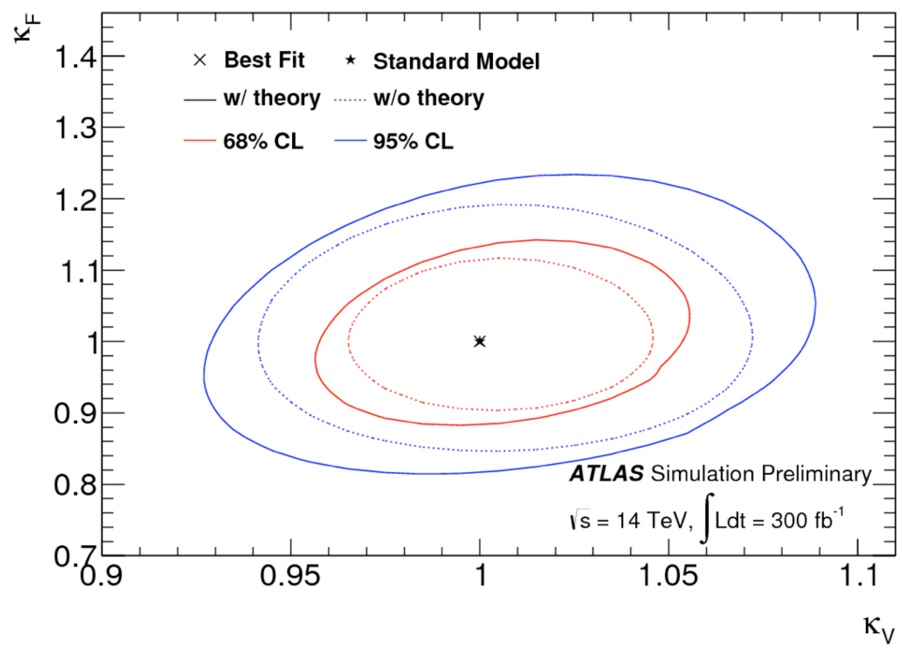
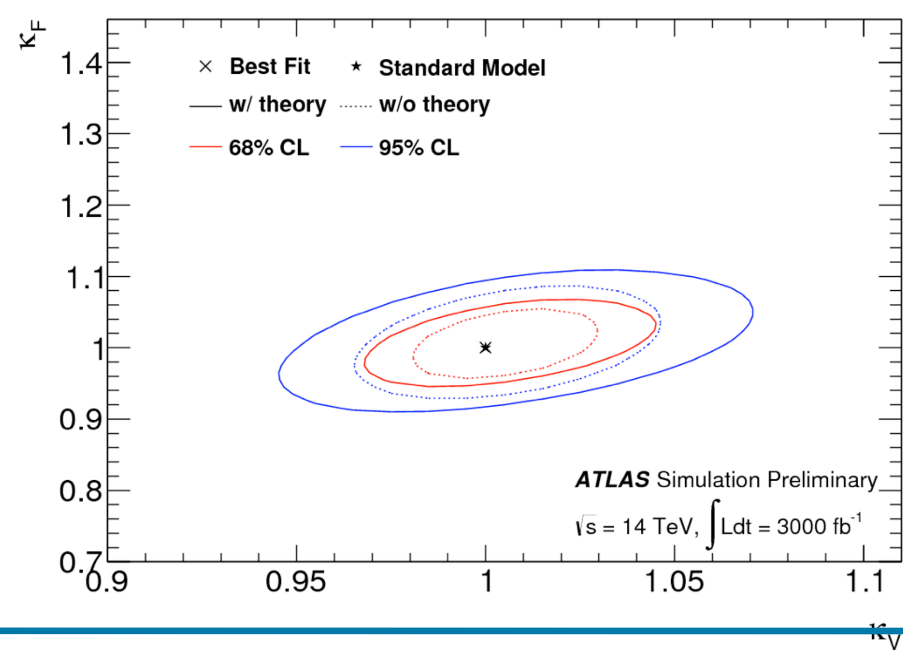
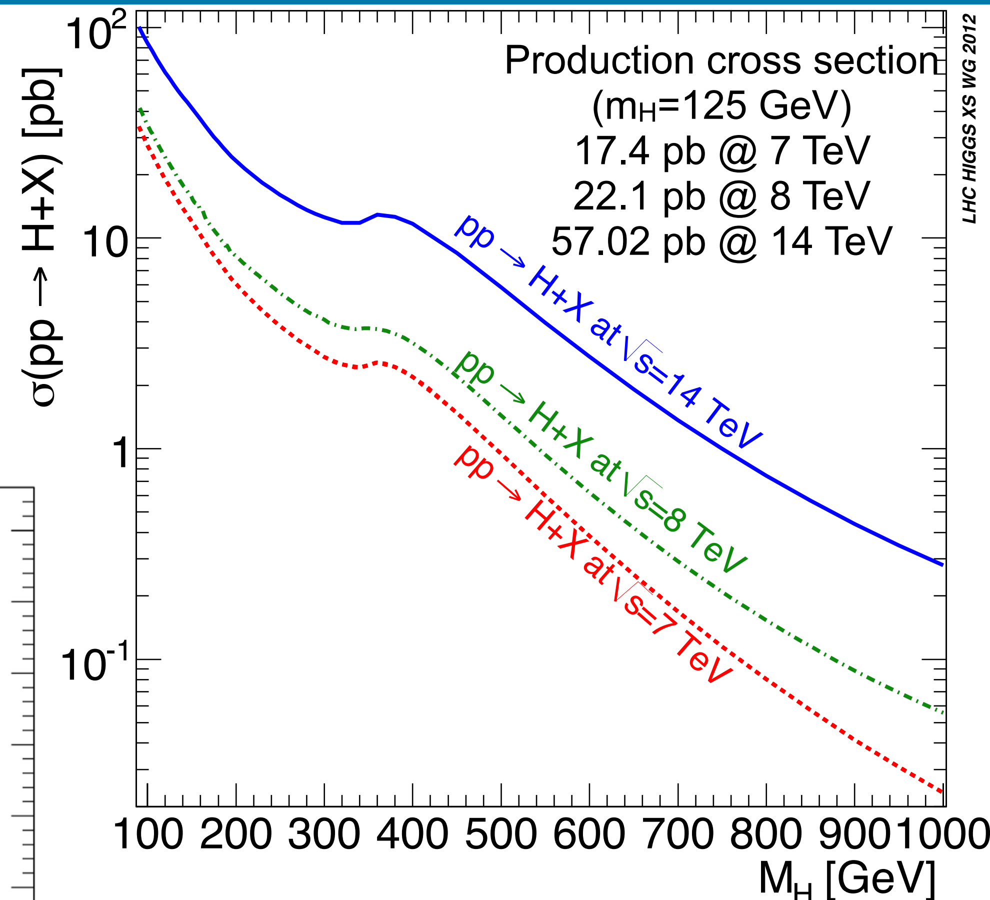






Several open topics in the Higgs sector for future studies:
- Rare decays & Couplings
- CP studies
- BSM Higgs boson searches
- Higgs boson pair production

H→ZZ(*)→4l: Fiducial/Differential cross sections

fiducial cross-section

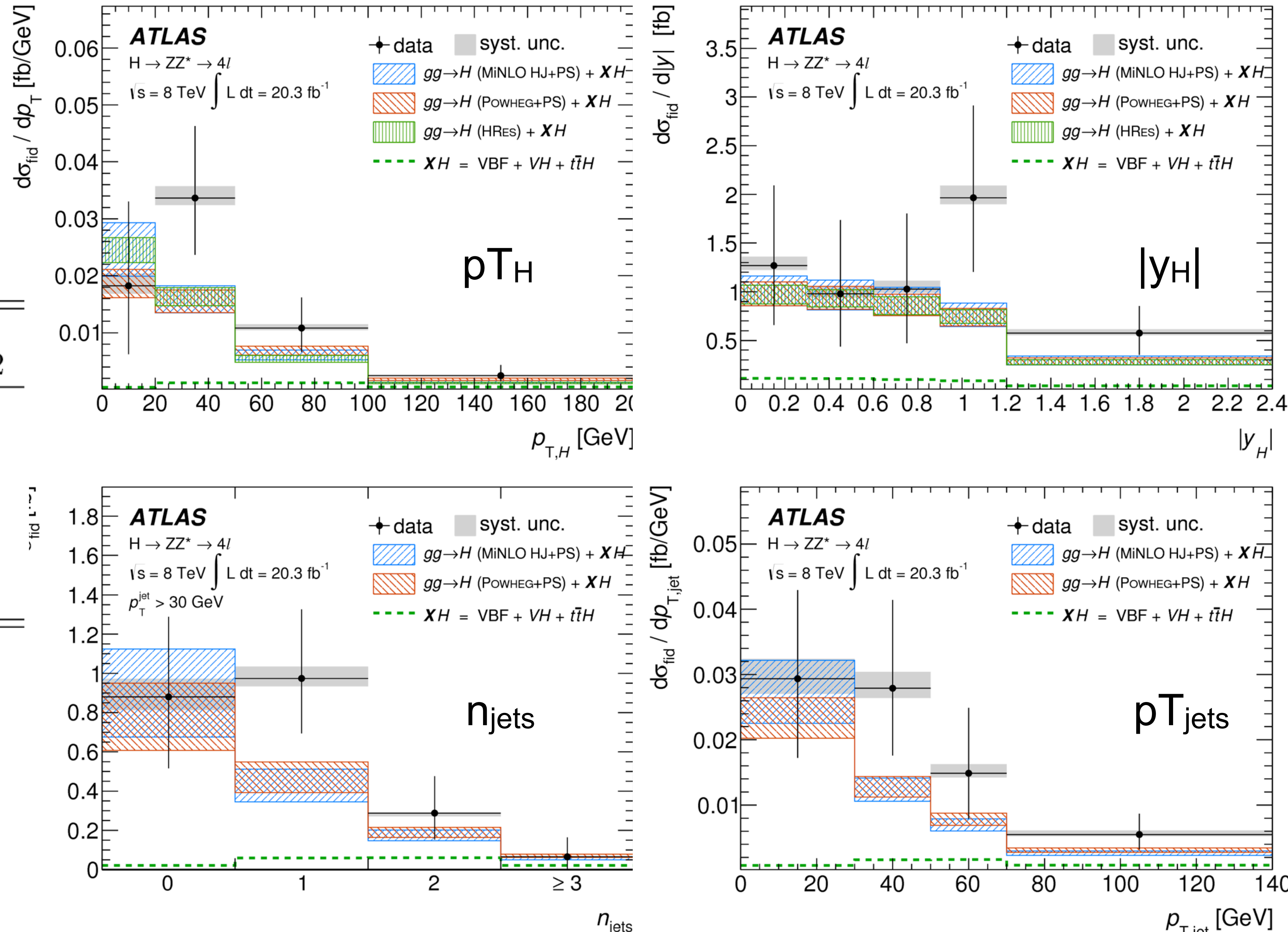
$$\sigma^{\mathrm{fid}}_{\mathrm{tot}} = 2.11^{+0.53}_{-0.47}(\mathrm{stat})^{+0.08}_{-0.08}(\mathrm{syst})\ \mathrm{fb}$$

6 differential cross sections

SM prediction at 125.4GeV = 1.30±0.13 fb

Procedure (120<m_{4l}<130 GeV):
- expected background subtracted from observed events in bins of interesting variable
- bin-by-bin unfolding

	p-values		
Variable	Powheg	Minlo	HRes2
$p_{\mathrm{T},H}$	0.30	0.23	0.16
$\lvert y_H \rvert$	0.37	0.45	0.36
m_{34}	0.48	0.60	-
$\lvert \cos\theta^* \rvert$	0.35	0.45	-
n_{jets}	0.37	0.28	-
$p_{\mathrm{T,jet}}$	0.33	0.26	-



First result/statistics limited →No large surprise

BSM examples

The properties of the observed Higgs boson already constraint BSM contributions

ATLAS-CONF-2014-010

Additional EW singlet field

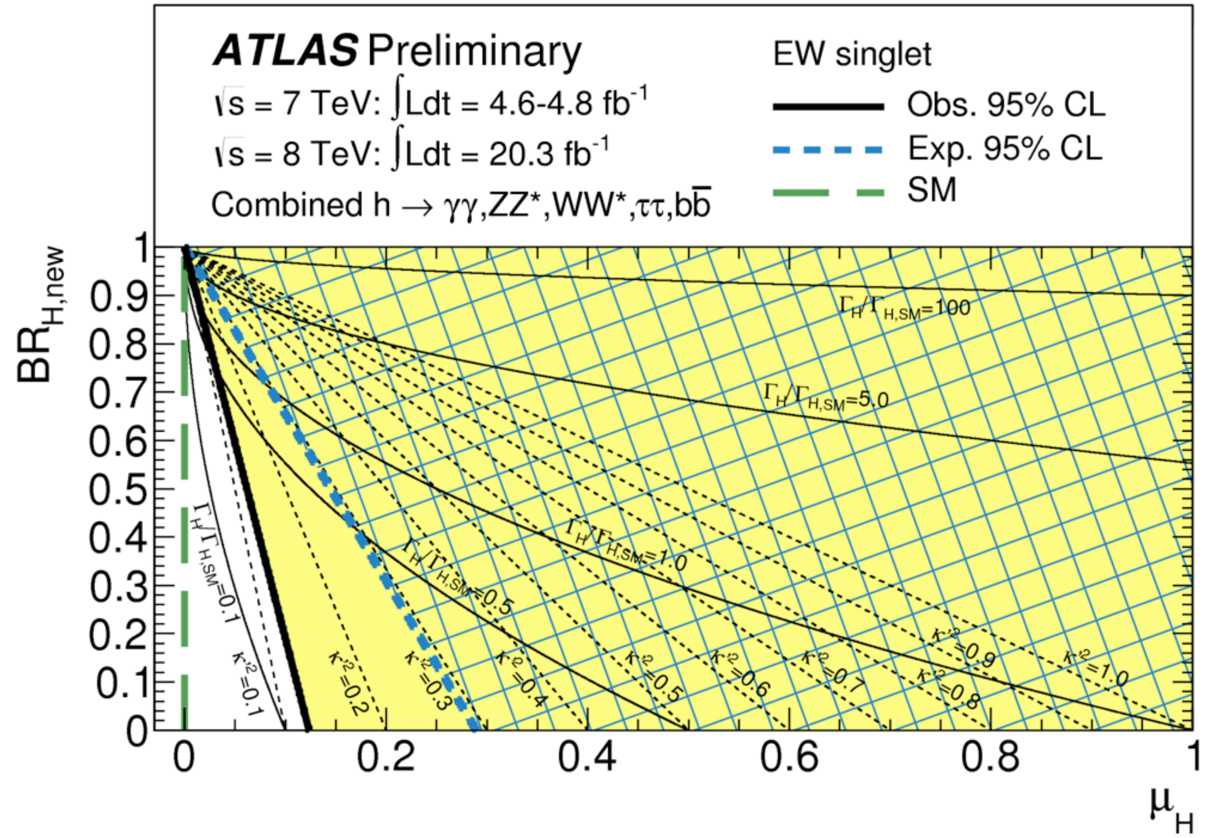
Simplest extension of SM Higgs sector

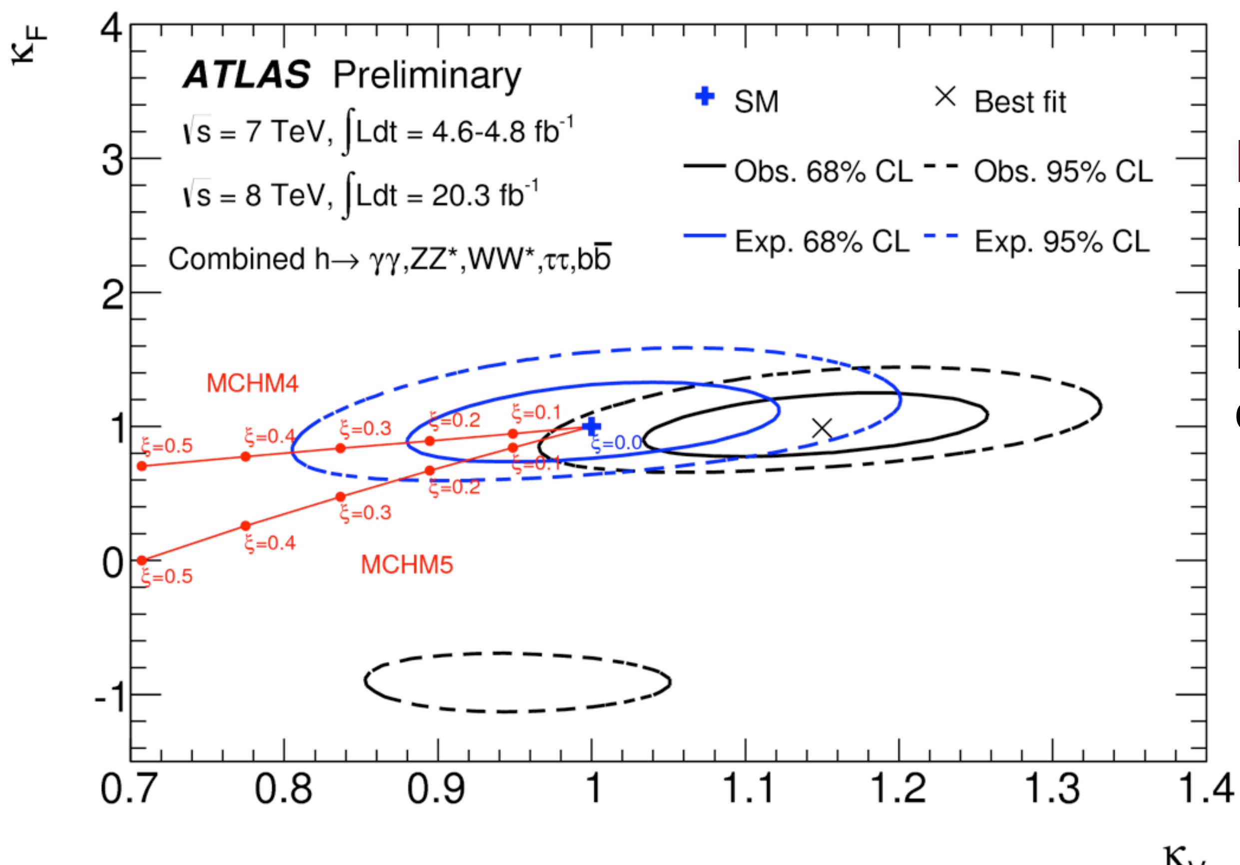
Results in two CP-even Higgs bosons: h, H (assumed non degenerate)

Couplings similar to SM Higgs boson, but each scaled by common factor, denoted as κ (κ') for h(H).
From unitarity: $\kappa^2+\kappa'^2=1$

$$\mu_h = \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2$$

$$\mu_H = \frac{\sigma_H \times \mathrm{BR}_H}{(\sigma_H \times \mathrm{BR}_H)_{\mathrm{SM}}} = \kappa'^2\,(1 - \mathrm{BR}_{H,\mathrm{new}})$$





Minimal Composite Higgs Model

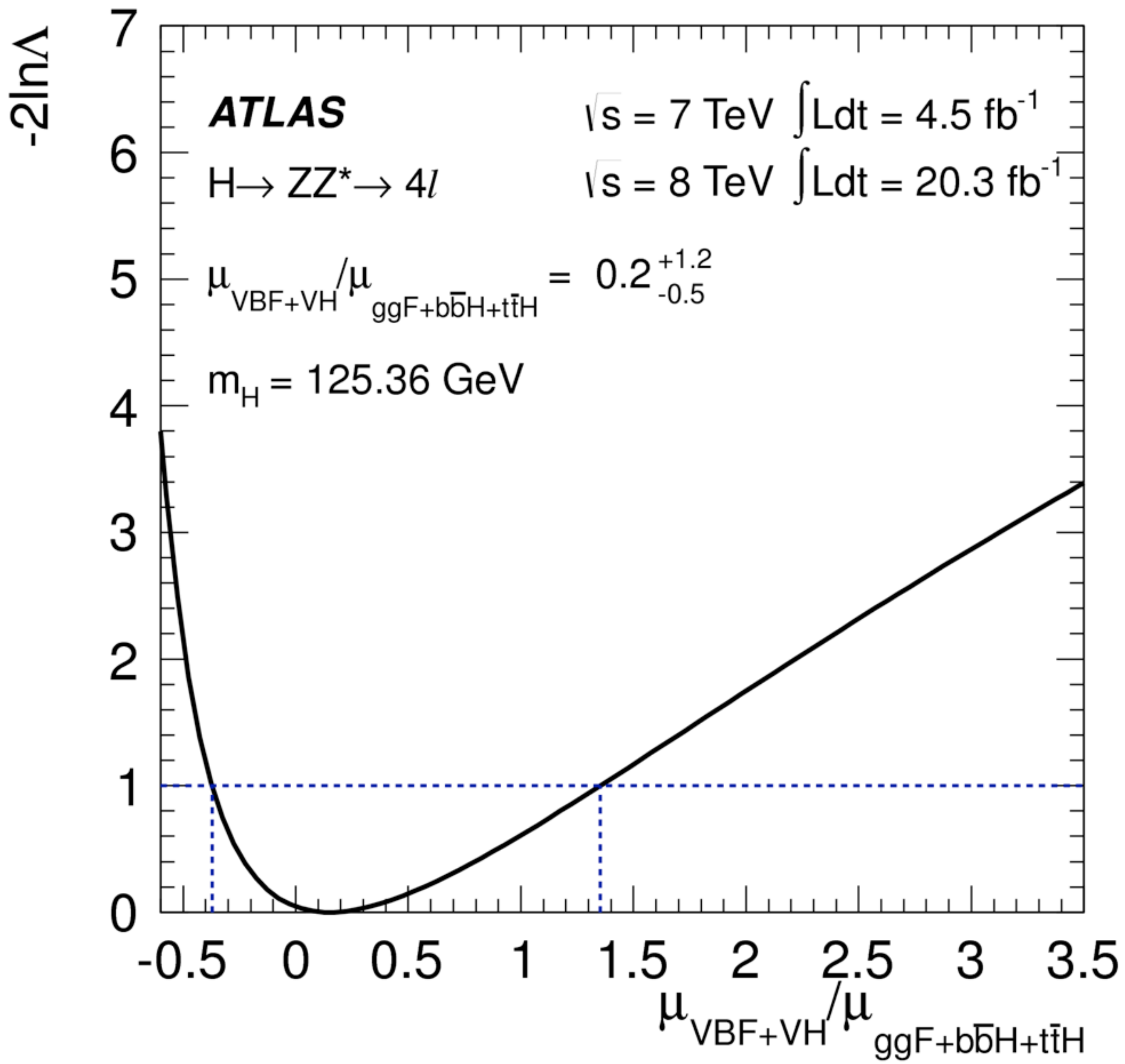
Higgs is pseudo Nambu-Goldstone boson

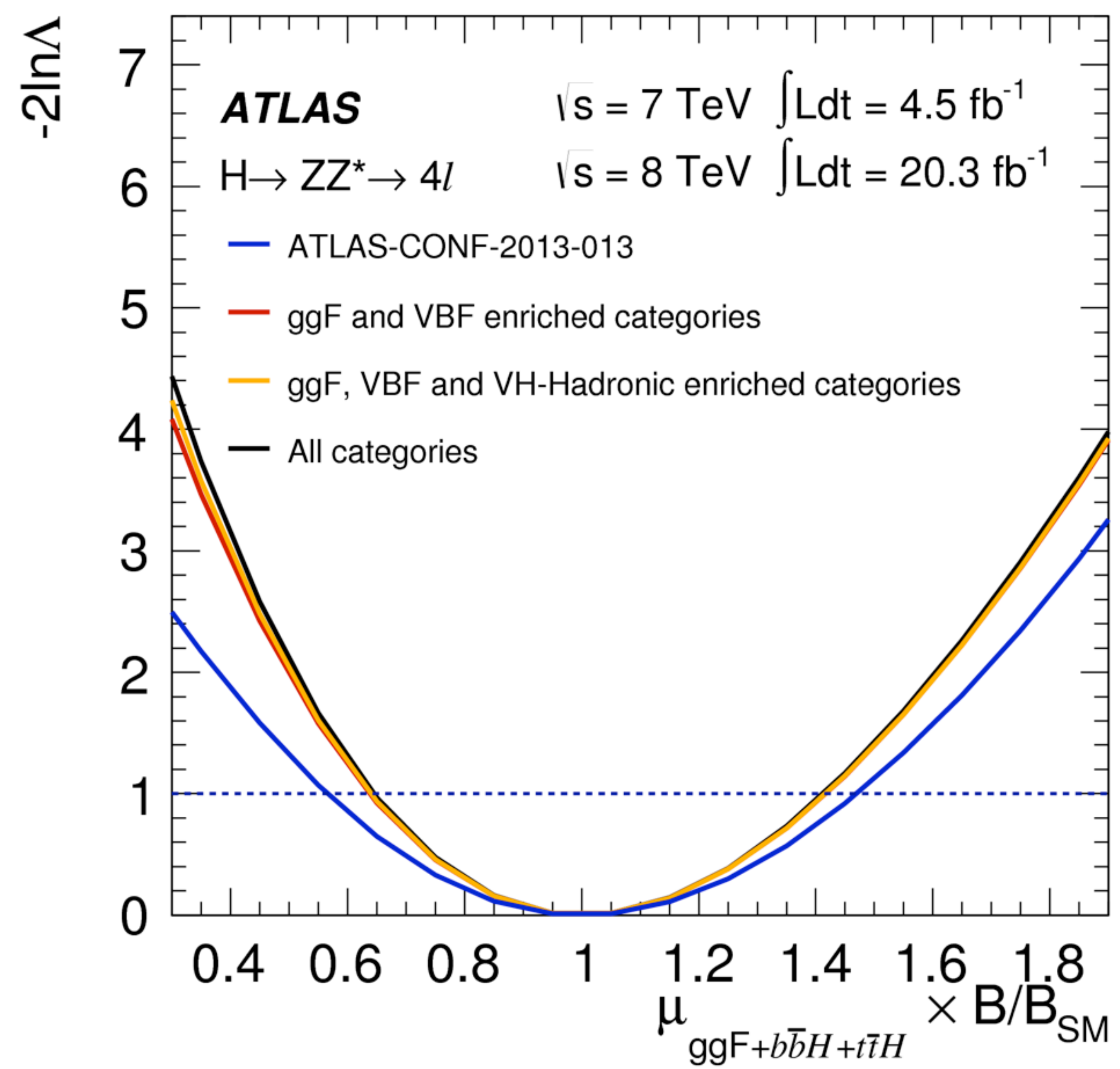
Neglecting contributions from new heavy resonances the Higgs couplings modified wrt SM as a function of compositeness scale: $\xi = v^2/f^2$

MCHM4: $\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$ f>710 (460) GeV at 95%CL

MCHM5: $\kappa_V = \sqrt{1-\xi}$, $\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$. f>640 (550) GeV at 95%CL

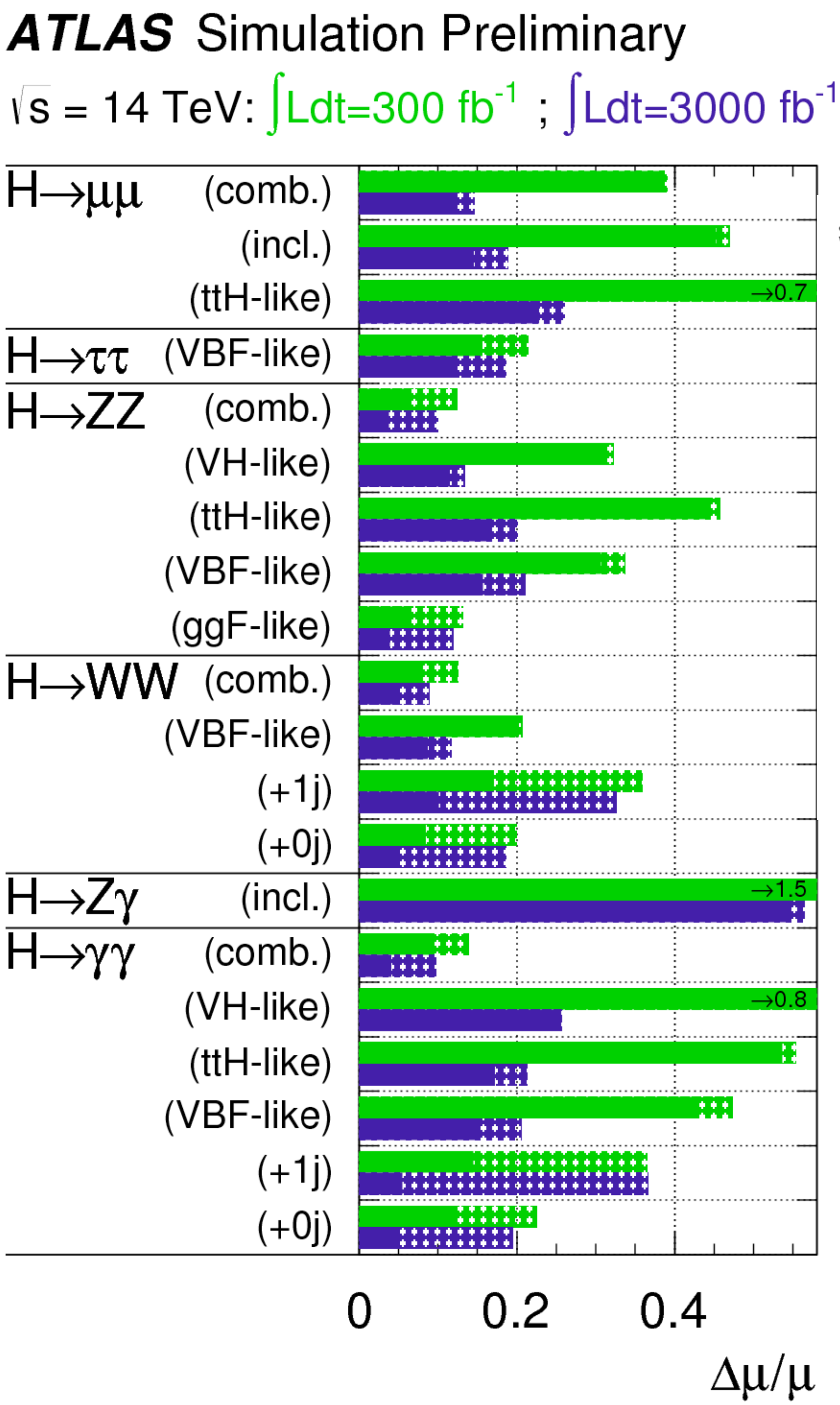
H→ZZ$^{(*)}$→4l: Coupling Results





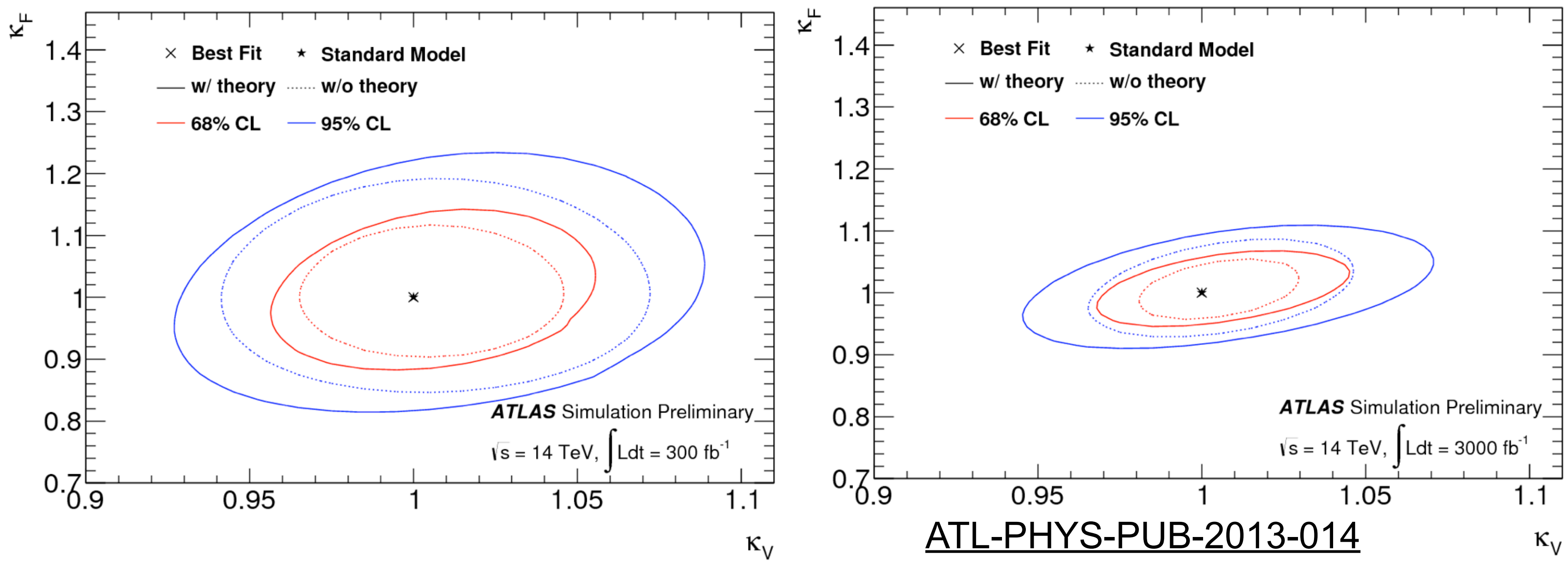
Prospects for Run II/III and HL-LHC

ATL-PHYS-PUB-2013-014



Several open topics in the Higgs sector for future studies:

- Rare decays & Couplings
- CP studies
- BSM Higgs boson searches
- Higgs boson pair production



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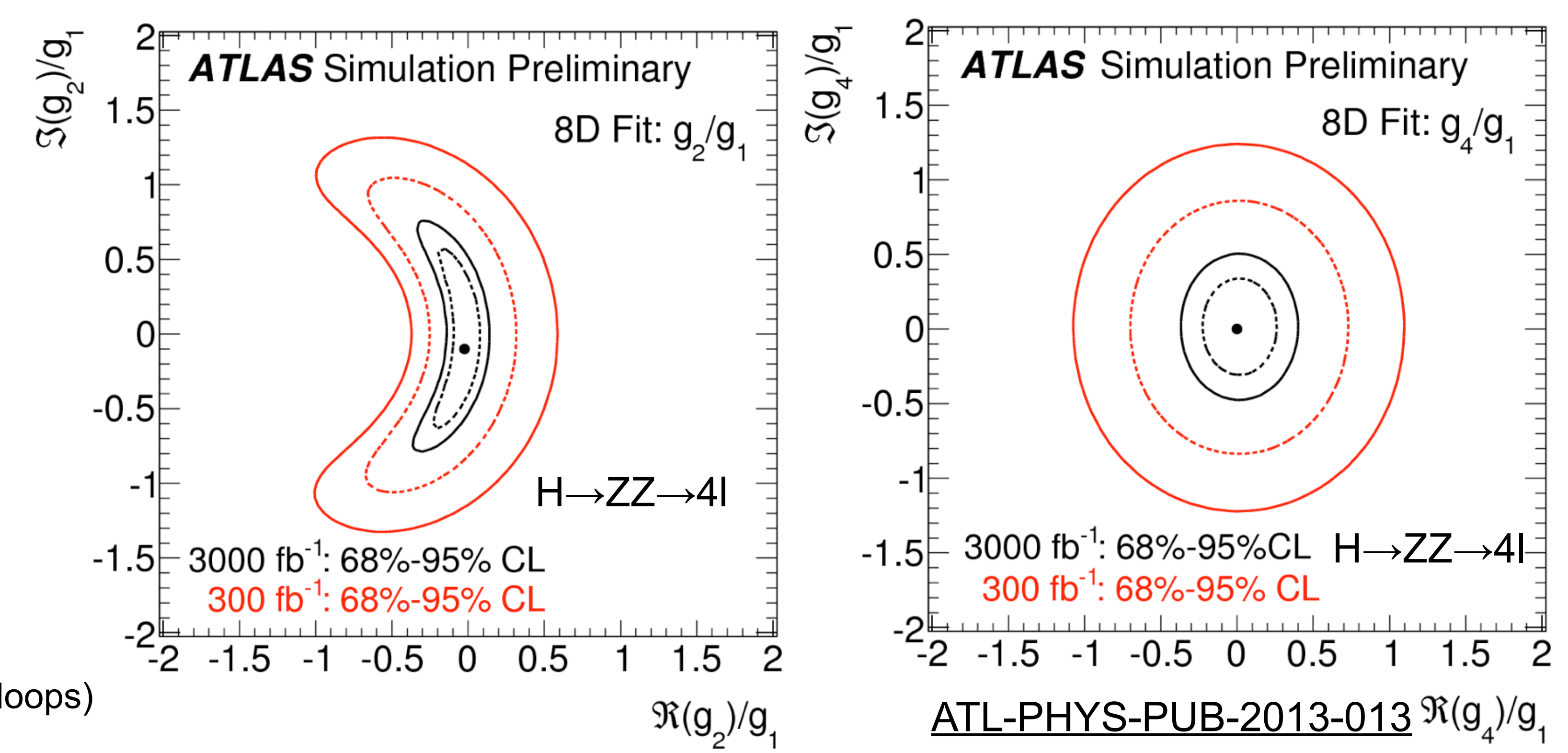

ATL-PHYS-PUB-2013-013

g_1 CP-even HZZ coupling

g_2 CP-even HZZ coupling (loops)

g_4 CP-odd HZZ coupling

FCNC in t→qH

Flavor Violation among light-quarks challenging.
Focus is on the top.
ATLAS performed a search in ttbar events for t→qH (→γγ), where q=(c,u):

→ Leptonic: 1 lep, ≥2 jets, ≥1 b-tags, MET
→ Hadronic: 0 lep, ≥4 jets, ≥1 b-tags

- Mass requirements for top candidates
- Analysis procedure similar to H→γγ
  - Leptonic :BKG shape from CR
  - Hadronic: BKG shape from MC
  - Include SM Higgs background
  - Similar sensitivity for q=u or c
- 50 (1) events in the Hadronic (Leptonic) channel
- 95% CL upper limit on BR(t→qH): 0.79% (0.51%)

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

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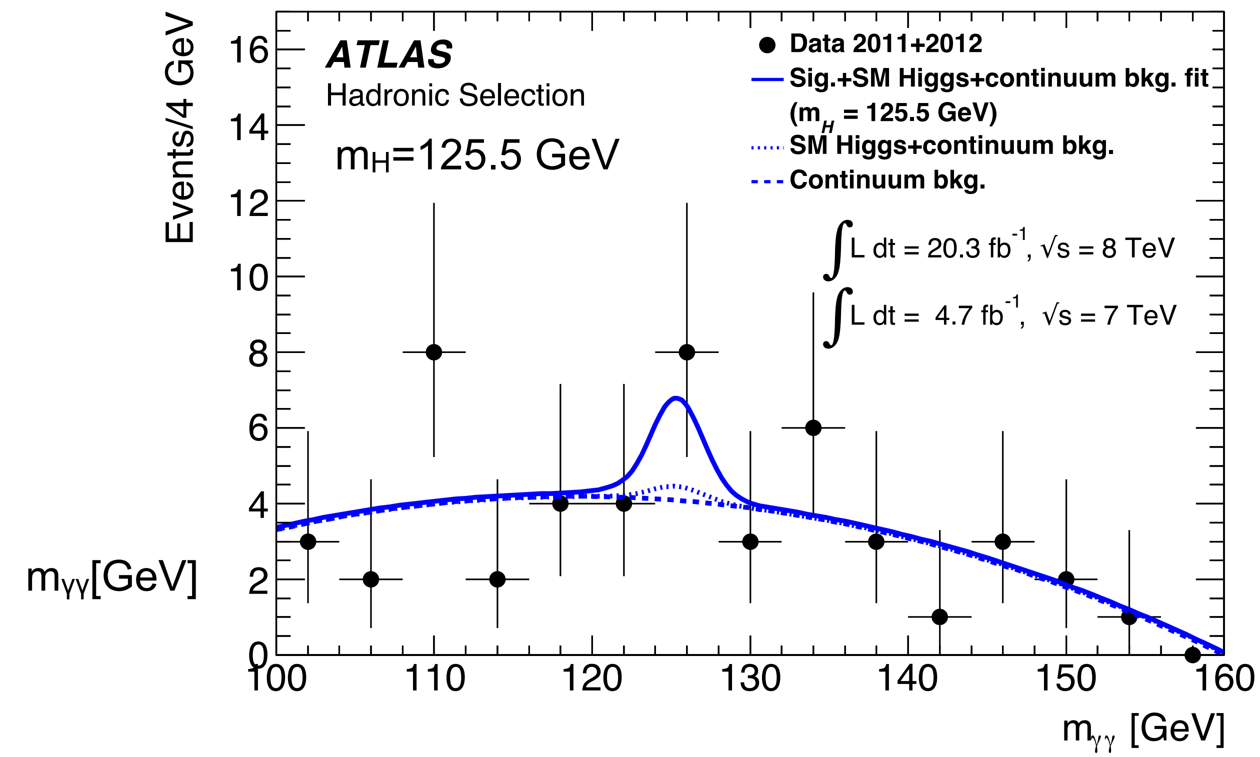

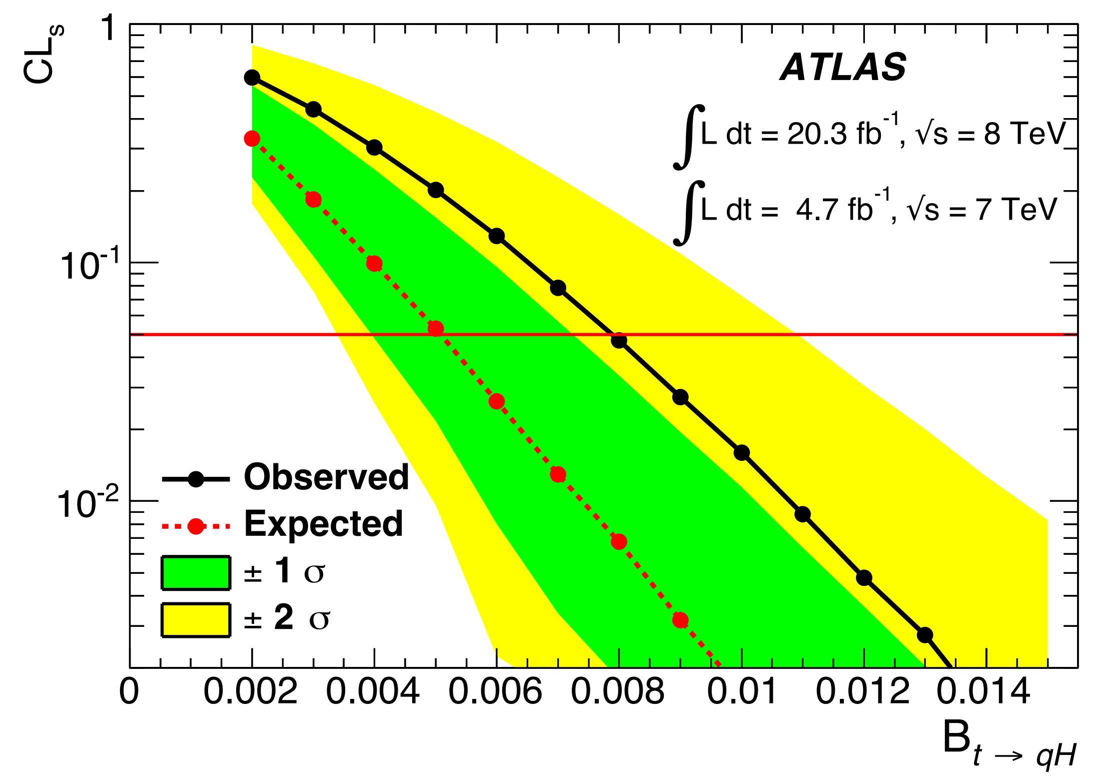

FCNC in t→qH

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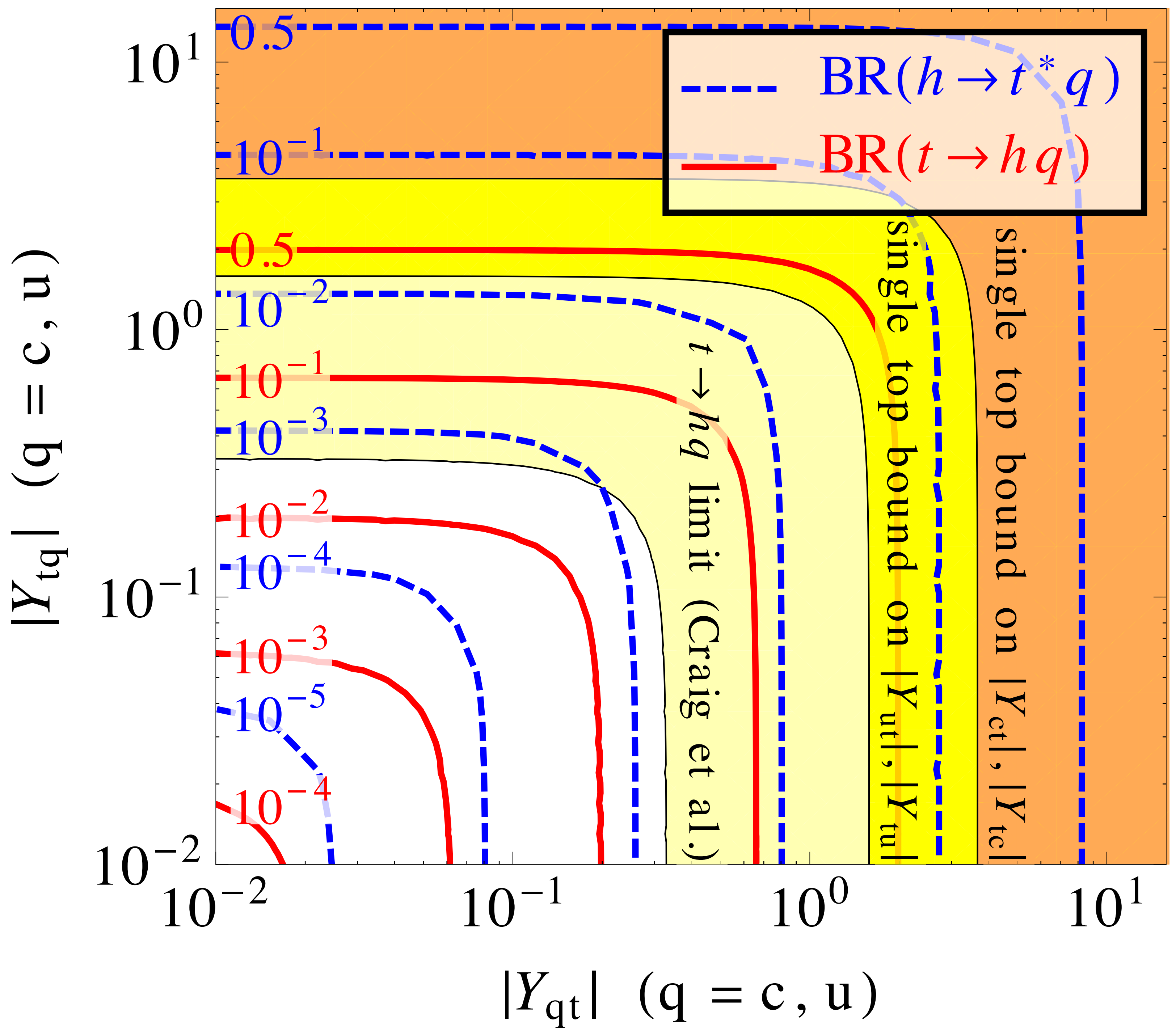
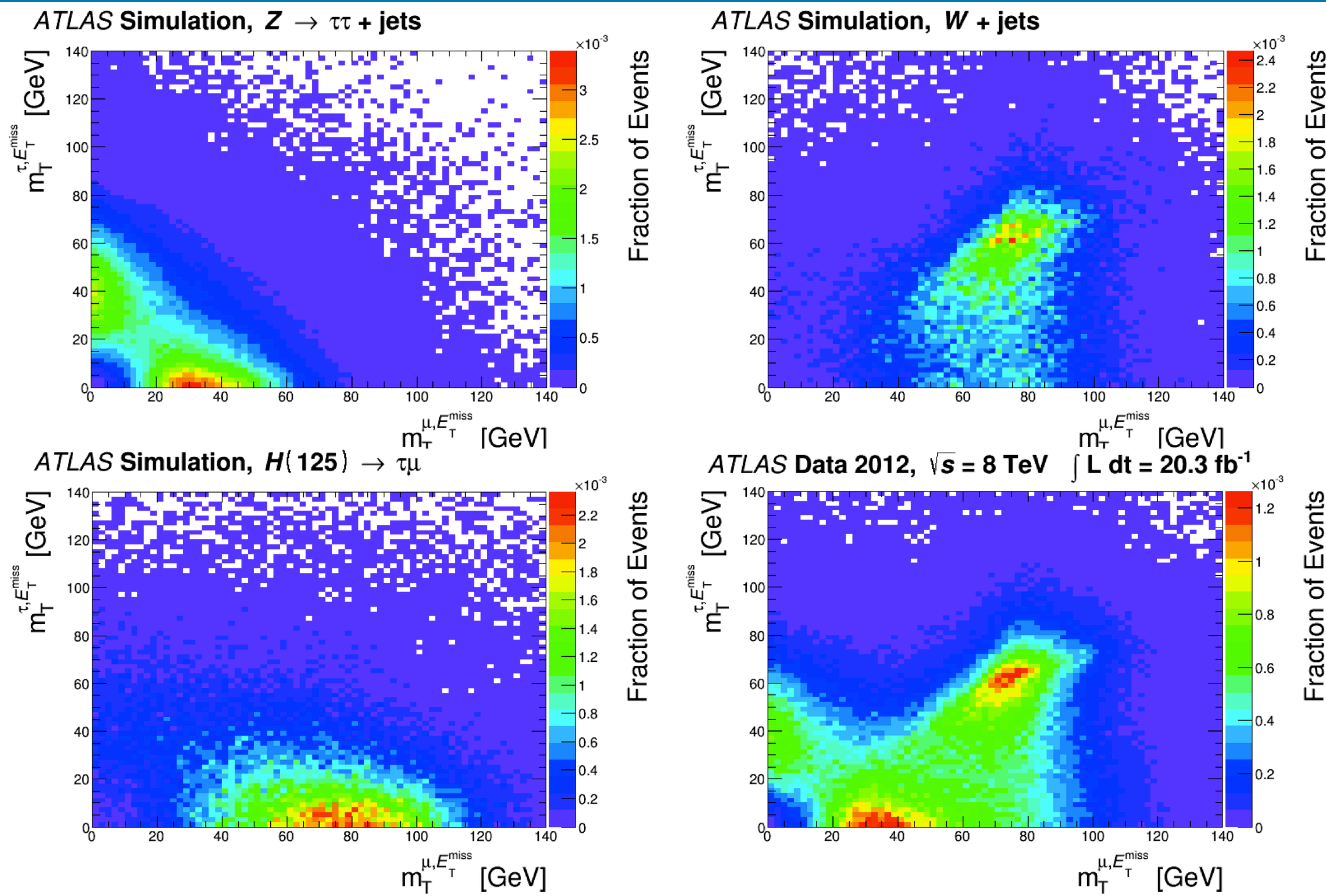
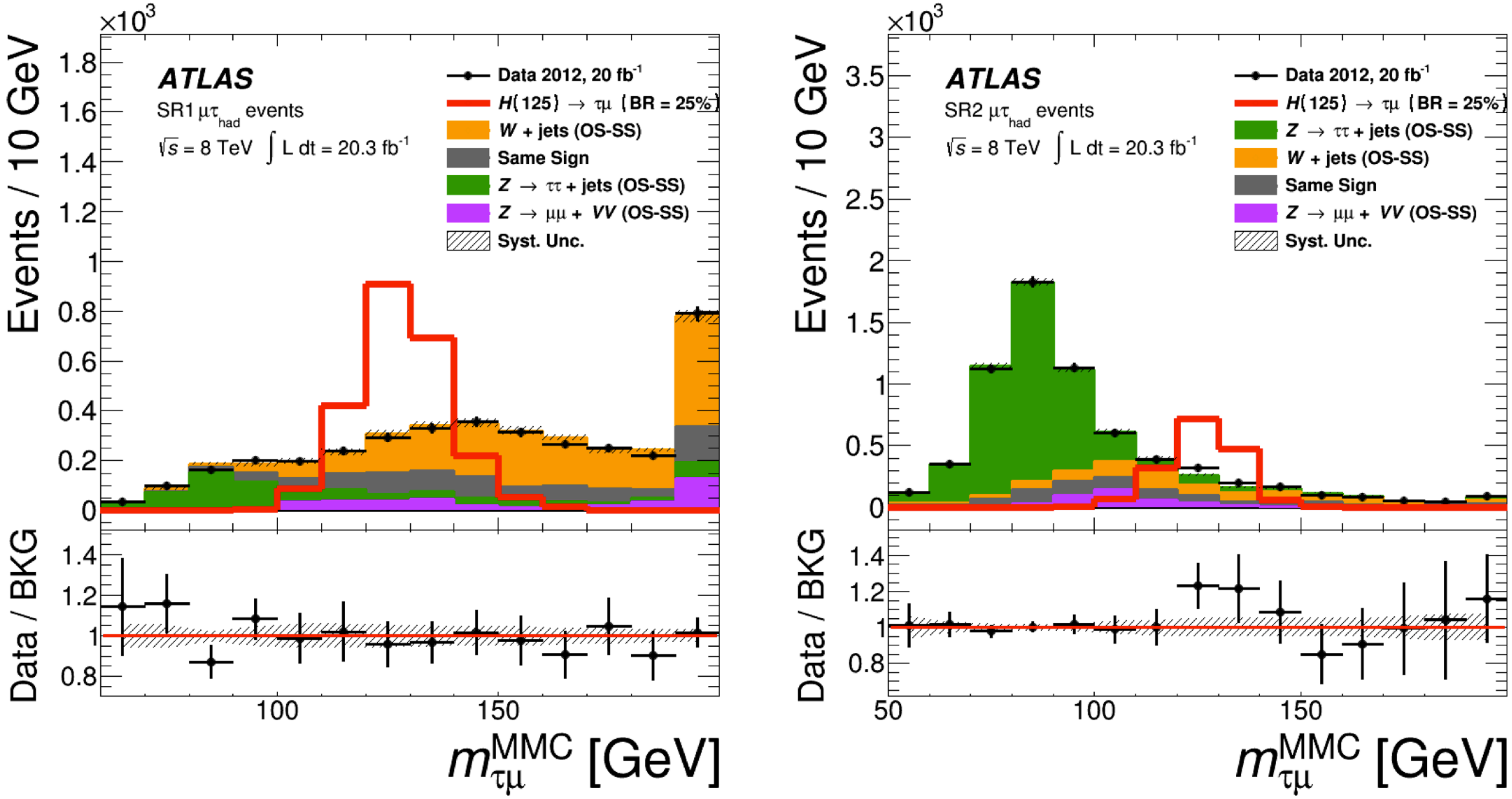


h→τμ



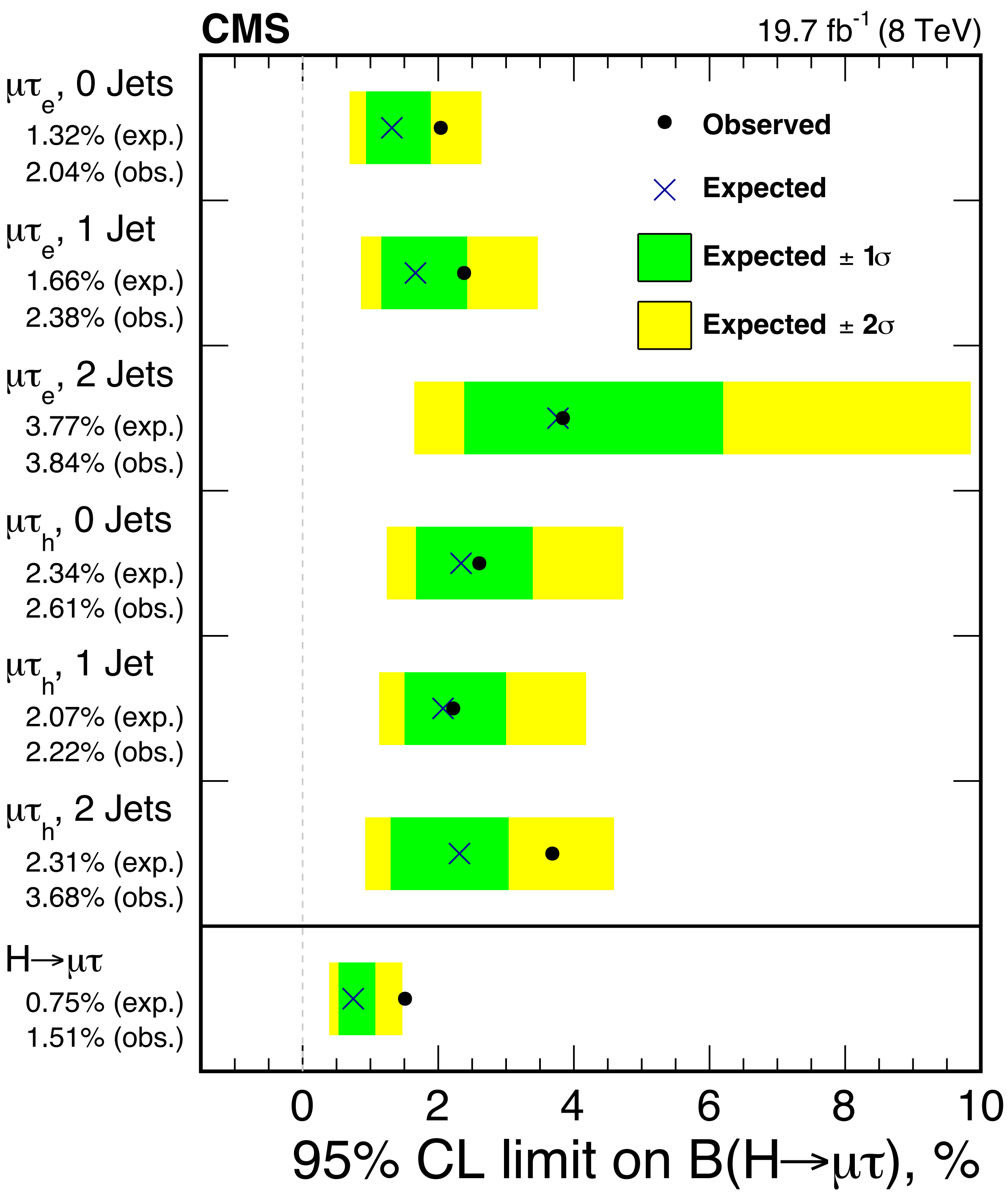
ATLAS Simulation, Z → ττ + jets
ATLAS Simulation, W + jets
ATLAS Simulation, H(125) → τμ
ATLAS Data 2012, √s = 8 TeV ∫L dt = 20.3 fb-1
m_T^{τ,E_T^miss} [GeV]
m_T^{μ,E_T^miss} [GeV]
Fraction of Events
×10-3

h→τμ



	SR1	SR2
Signal	69.1 ± 0.8 ± 9.2	48.5 ± 0.8 ± 7.5
$Z \to \tau\tau$	133.4 ± 6.9 ± 9.1	262.6 ± 9.7 ± 18.6
W+jets	619 ± 54 ± 55	406 ± 42 ± 34
Top	39.5 ± 5.3 ± 4.7	19.6 ± 3.1 ± 3.3
Same–Sign events	335 ± 19 ± 47	238 ± 16 ± 34
$VV + Z \to \mu\mu$	90 ± 21 ± 16	81 ± 22 ± 17
$H \to \tau\tau$	6.82 ± 0.21 ± 0.97	13.7 ± 0.3 ± 1.9
Total background	1224 ± 62 ± 63	1021 ± 51 ± 49
Data	1217	1075

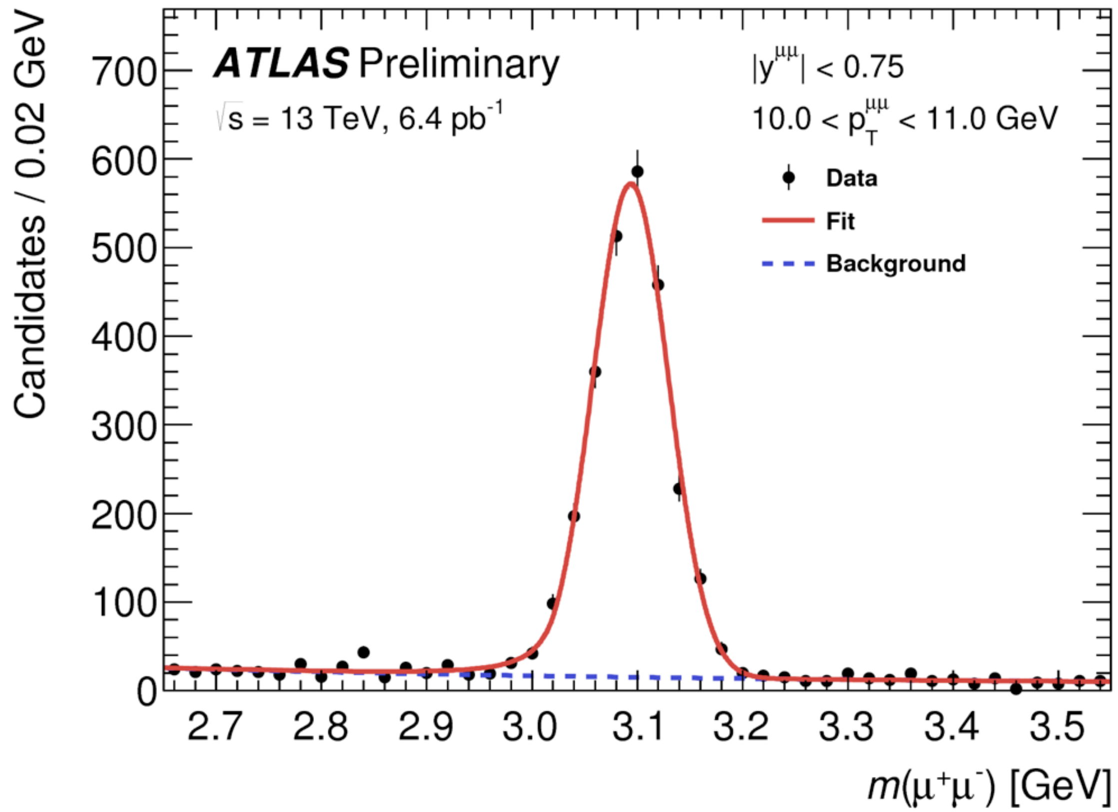
BR=0.77%

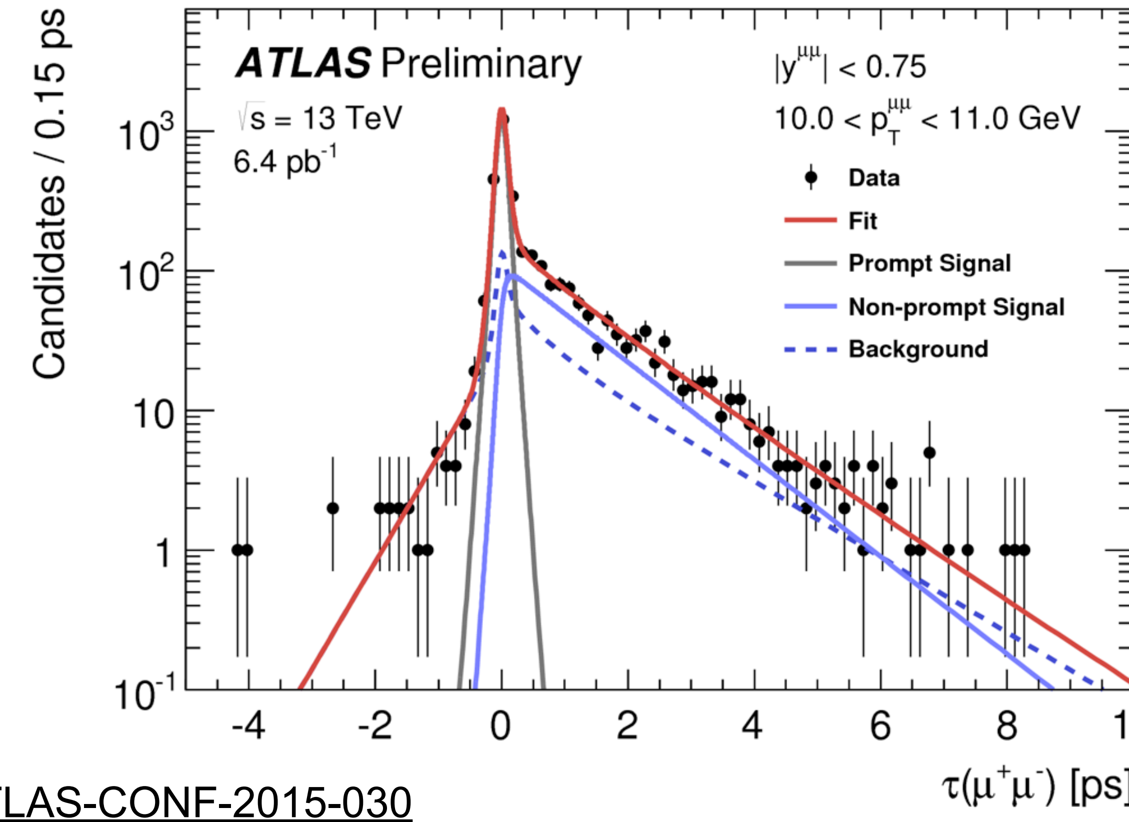


Sample	$H \to \mu\tau_h$ 0-Jet	$H \to \mu\tau_h$ 1-Jet	$H \to \mu\tau_h$ 2-Jets	$H \to \mu\tau_e$ 0-Jet	$H \to \mu\tau_e$ 1-Jet	$H \to \mu\tau_e$ 2-Jets
misidentified leptons	1770 ± 530	377 ± 114	1.8 ± 1.0	42 ± 17	16 ± 7	1.1 ± 0.7
$Z \to \tau\tau$	187 ± 10	59 ± 4	0.4 ± 0.2	65 ± 3	39 ± 2	1.3 ± 0.2
ZZ, WW	46 ± 8	15 ± 3	0.2 ± 0.2	41 ± 7	22 ± 4	0.7 ± 0.2
$W\gamma$	—	—	—	2 ± 2	2 ± 2	—
$Z \to$ ee or $\mu\mu$	110 ± 23	20 ± 7	0.1 ± 0.1	1.6 ± 0.7	1.8 ± 0.8	—
$t\bar{t}$	2.2 ± 0.6	24 ± 3	0.9 ± 0.5	4.8 ± 0.7	30 ± 3	1.8 ± 0.4
$t\bar{t}$	2.2 ± 1.1	13 ± 3	0.5 ± 0.5	1.9 ± 0.2	6.8 ± 0.8	0.2 ± 0.1
SM H background	7.1 ± 1.3	5.3 ± 0.8	1.6 ± 0.5	1.9 ± 0.3	1.6 ± 0.2	0.6 ± 0.1
sum of backgrounds	2125 ± 530	513 ± 114	5.4 ± 1.4	160 ± 19	118 ± 9	5.6 ± 0.9
LFV Higgs boson signal	66 ± 18	30 ± 8	2.9 ± 1.1	23 ± 6	13 ± 3	1.2 ± 0.3
data	2147	511	10	180	128	6

BR=0.84%

J/ψ production at 13 TeV: prompt vs non-prompt fraction





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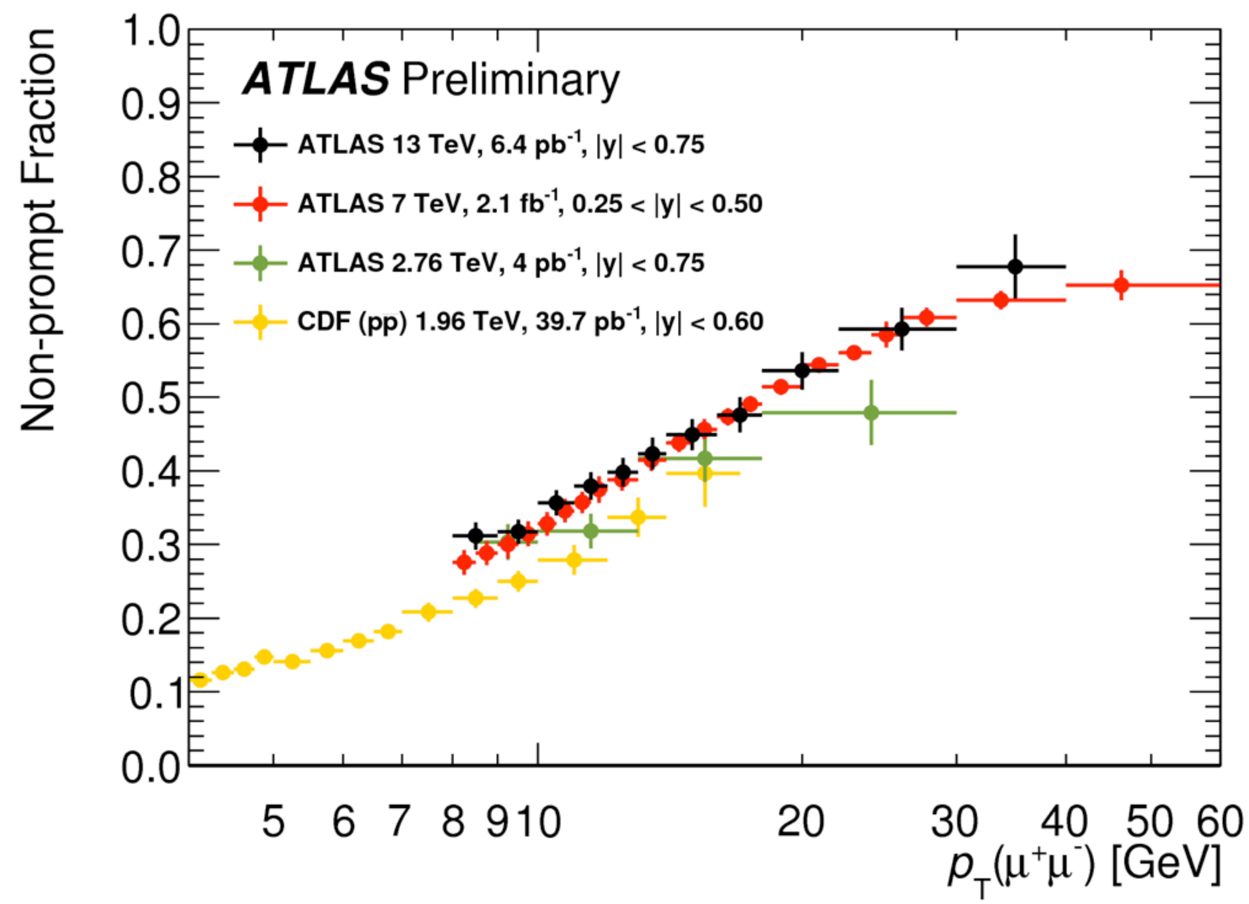
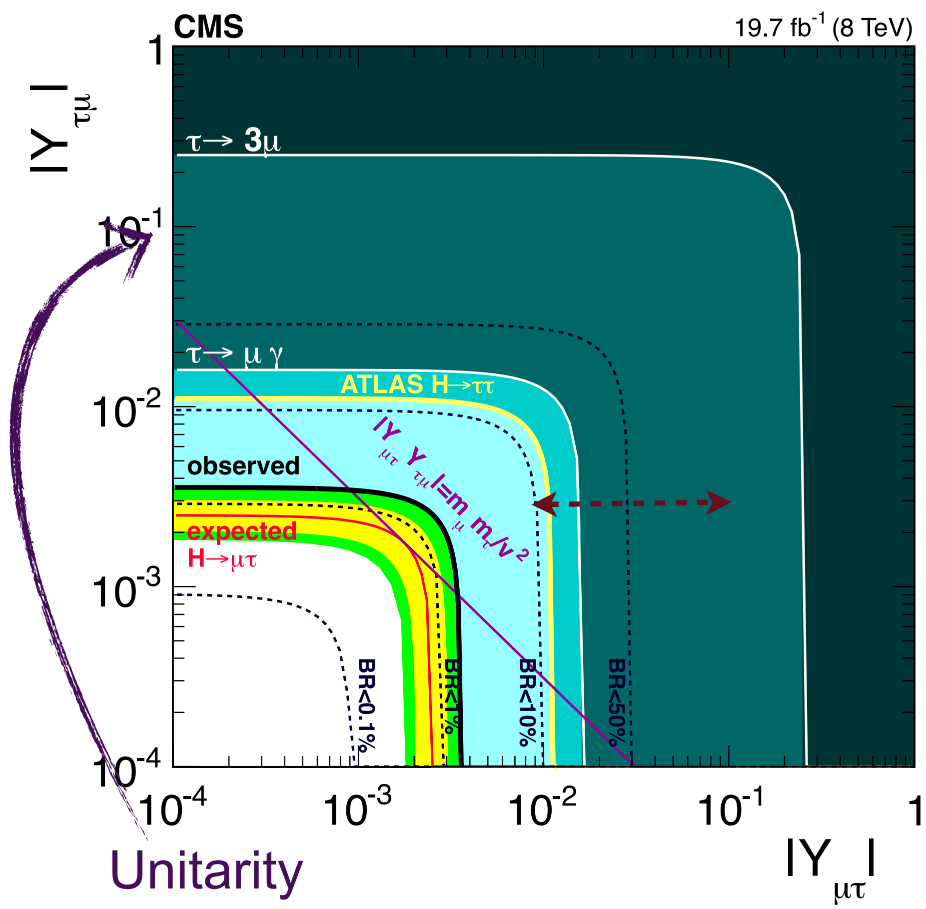


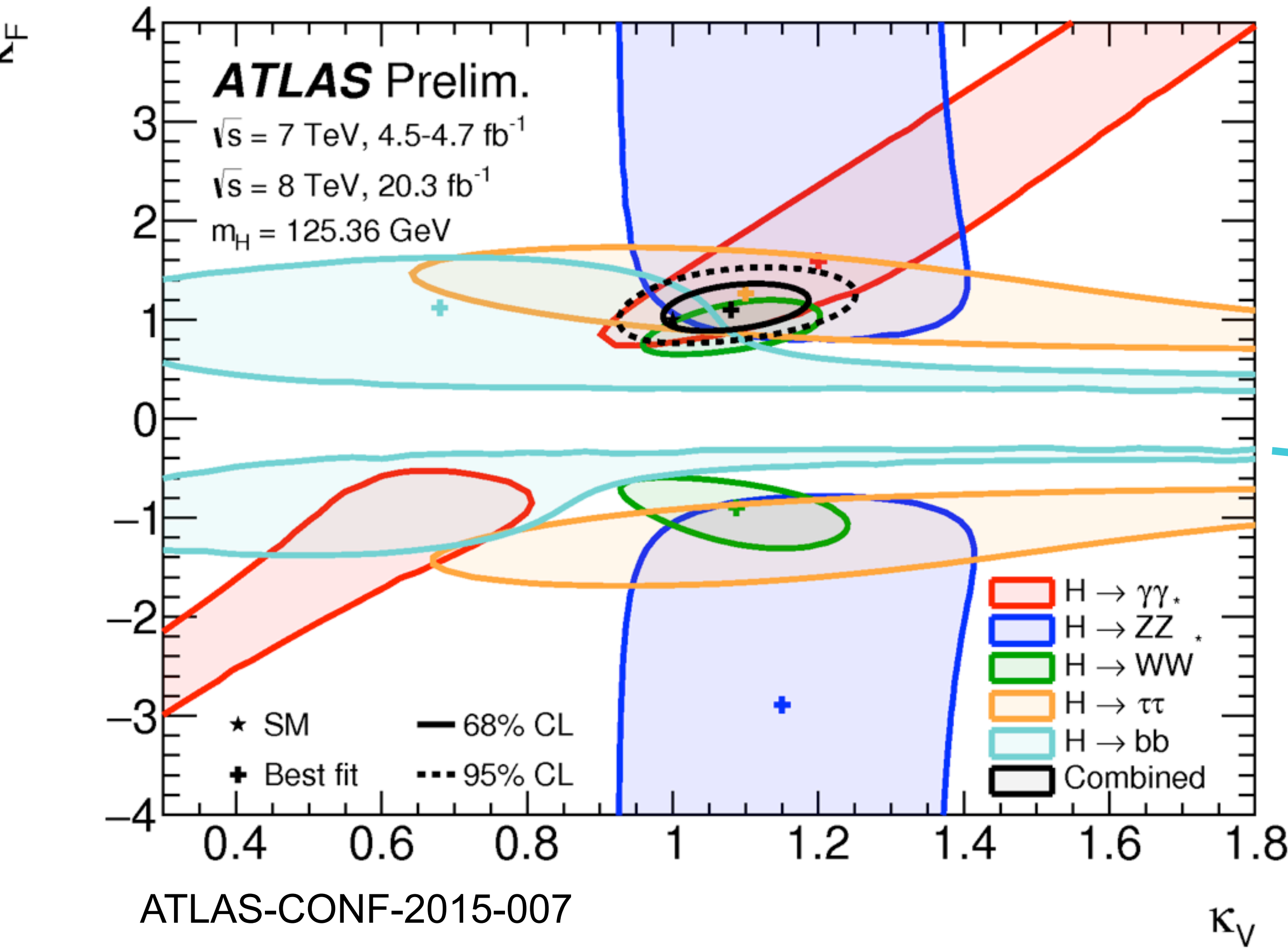
h⟶τμ



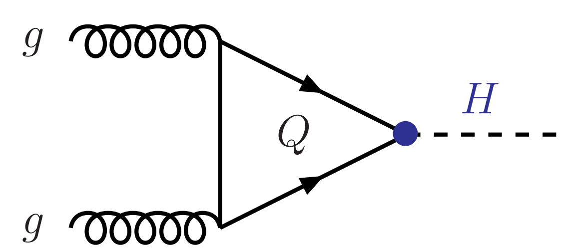
CMS
19.7 fb^{-1} (8 TeV)
$|Y_{\tau\mu}|$
$\tau \to 3\mu$
$\tau \to \mu\gamma$
ATLAS $H\to\tau\tau$
observed
expected
$H\to\mu\tau$
$|Y_{\mu\tau}Y_{\tau\mu}| = m_\mu m_\tau / v^2$
BR<0.1%
BR<1%
BR<10%
BR<50%
$|Y_{\mu\tau}|$
Unitarity

top quark

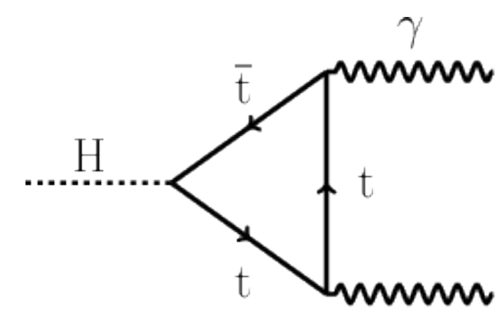
The top-quark, m_t~173 GeV, has a Yukawa coupling of O(1)
→ its presence in LHC Higgs boson production ubiquitous

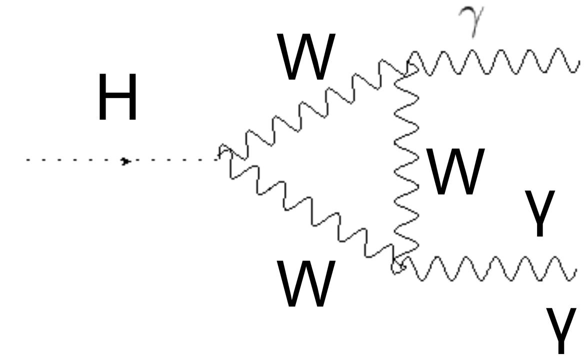


ATLAS-CONF-2015-007



H→γγ





H→bb