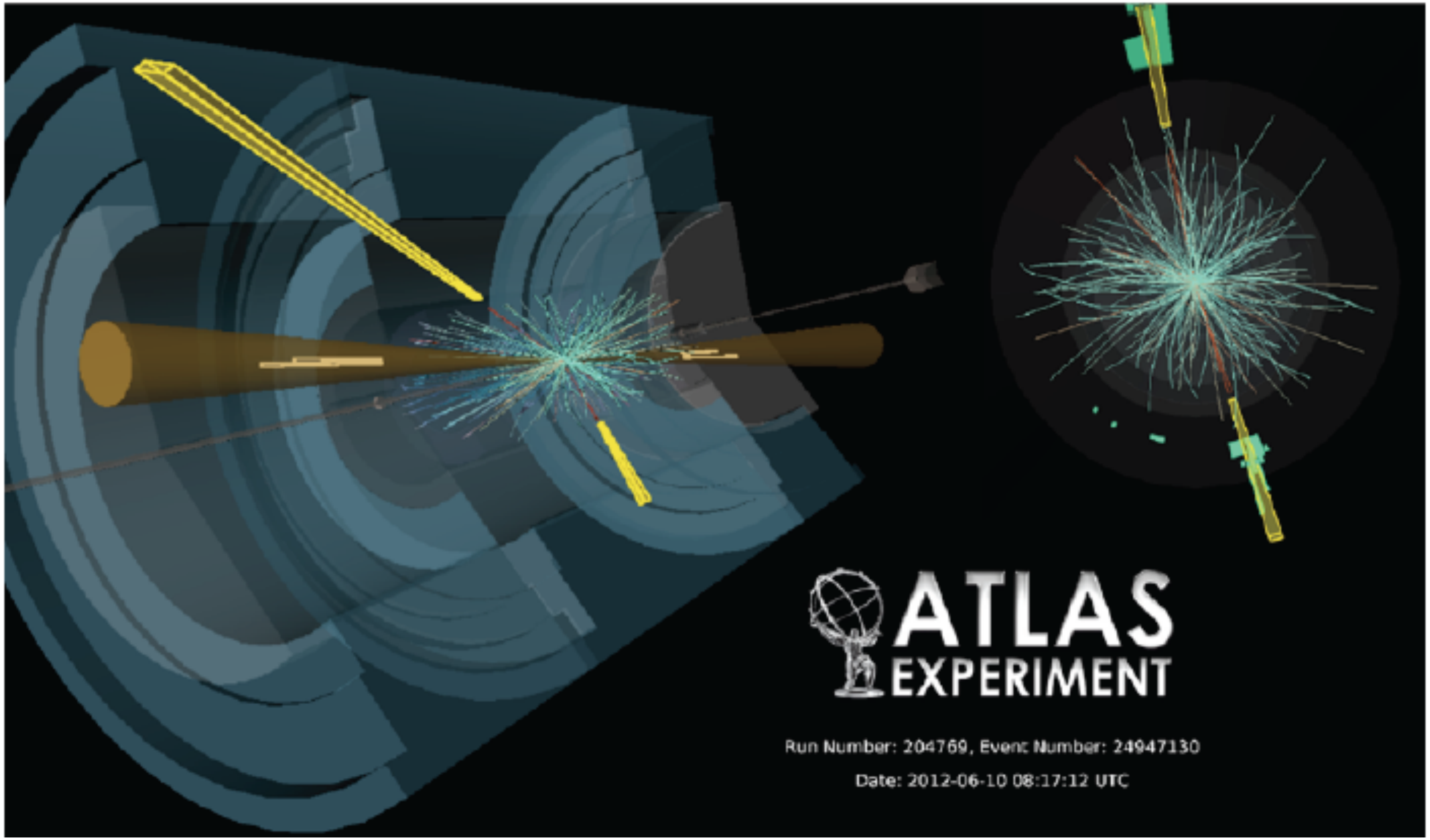
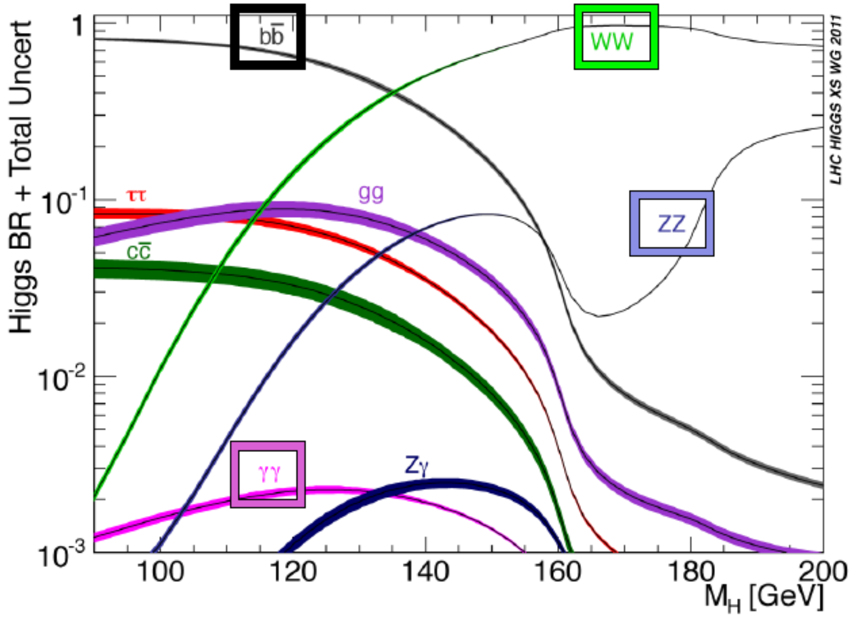
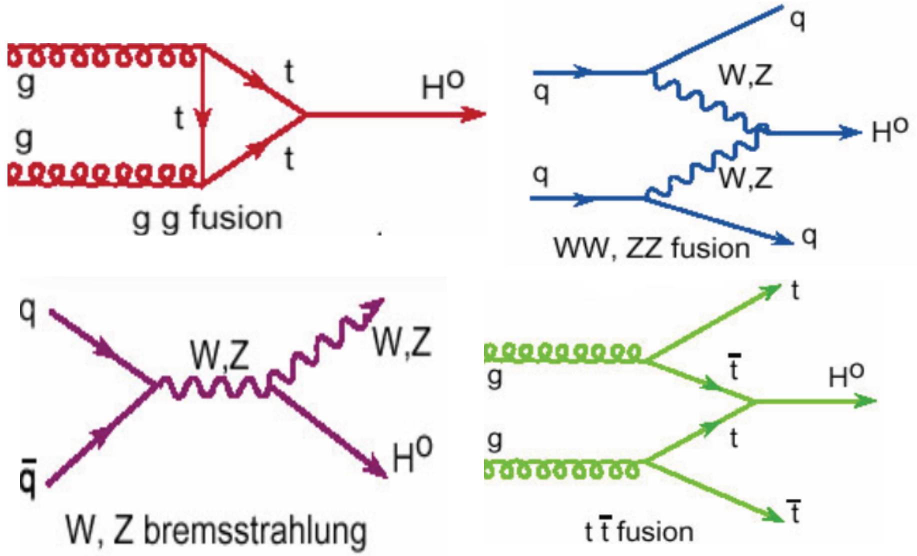
The Higgs boson in the $\gamma\gamma$ mode at ATLAS



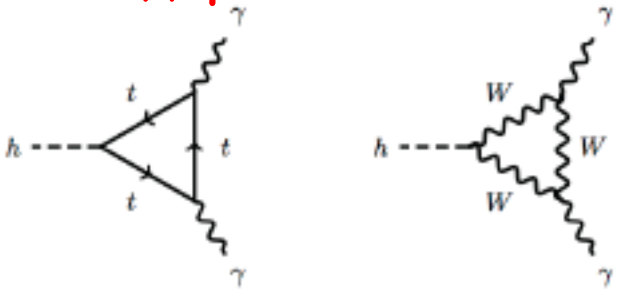
G.Calderini (LPNHE, Paris)
on behalf of the ATLAS Collaboration

The H -> γγ mode





H -> γγ proceeds through W and top loops



Sensitive to Vector boson and top couplings both in production and decay; sensitive to BSM physics

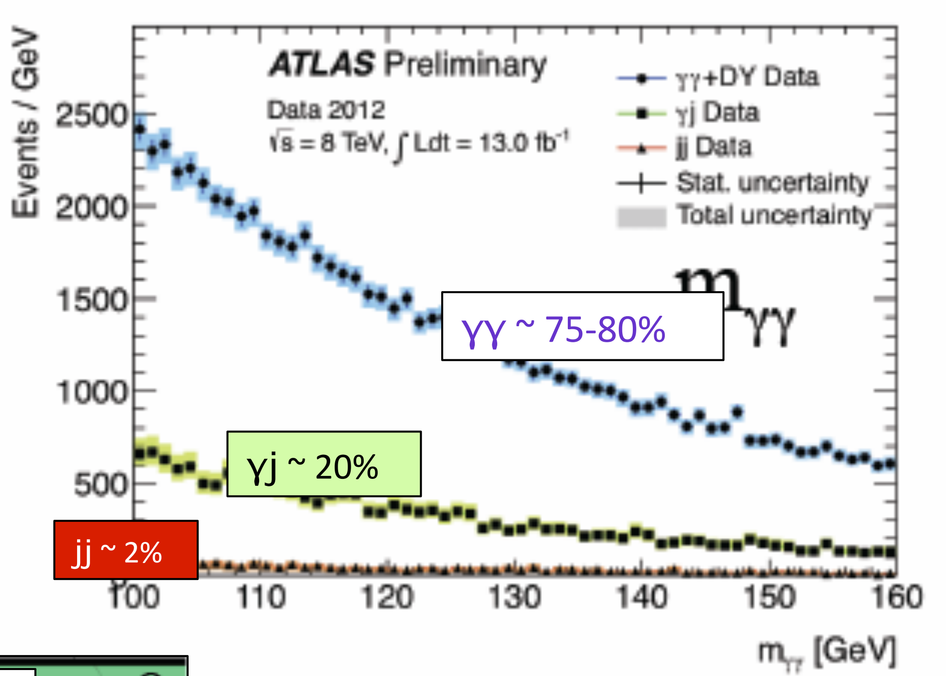
Very good mass resolution -> mass measurement
Good yield (S_{prod}~1175, S_{exp}~400 events) but S/B~3%

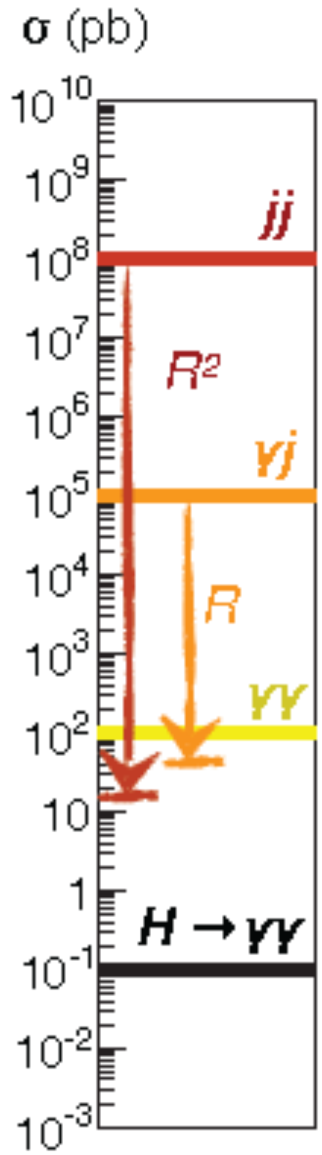
Signal: 2 high-P_T (40, 30 GeV) well identified and isolated photons

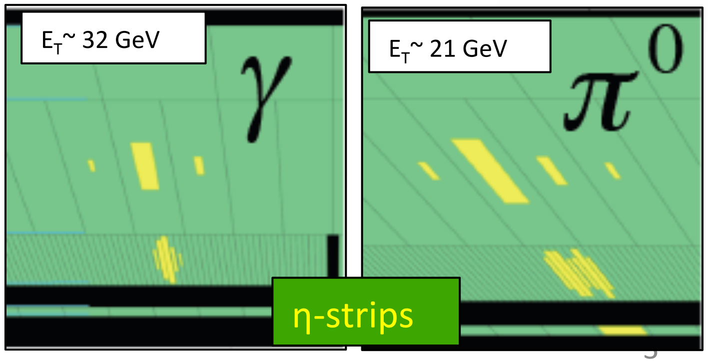
Resonance in $m_{\gamma\gamma}$ spectrum over a smooth, very large background

75% irreducible $\gamma\gamma$ QCD background

25% reducible γj, jj background







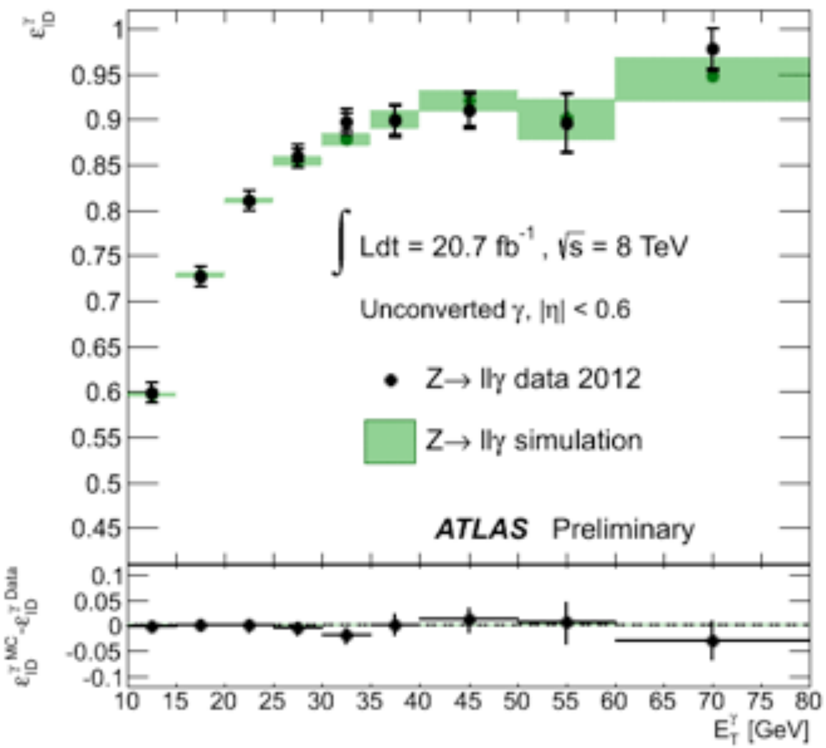
γ/π^0 discrimination

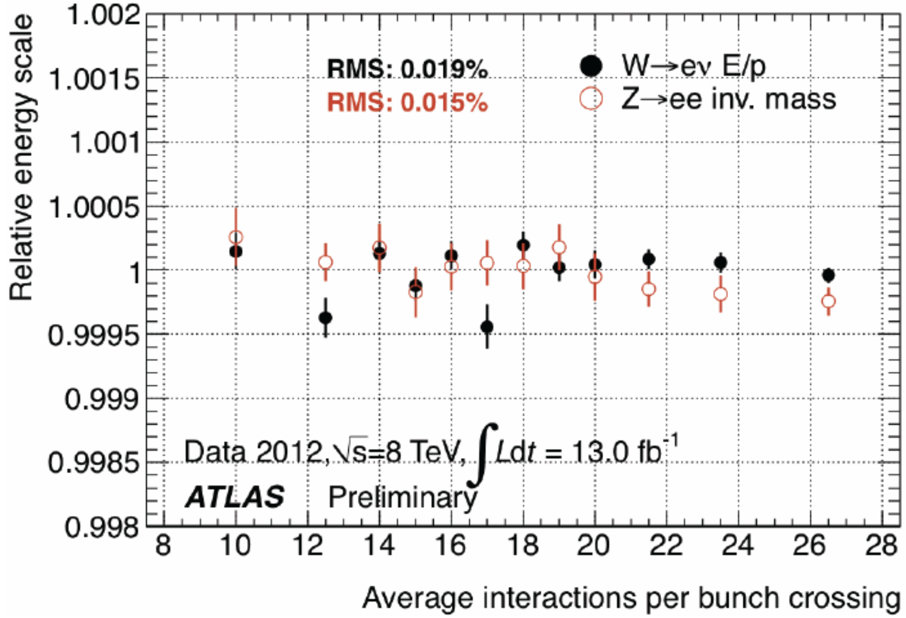
$R_j \sim 10^4$
$\varepsilon(\gamma) \sim 90\%$

- Photon identification
- Photon energy reconstruction

  Validated with Z->ee and corrected with MC for e-γ translation effects; MC material description is critical

- Energy scale robust with respect to pile-up

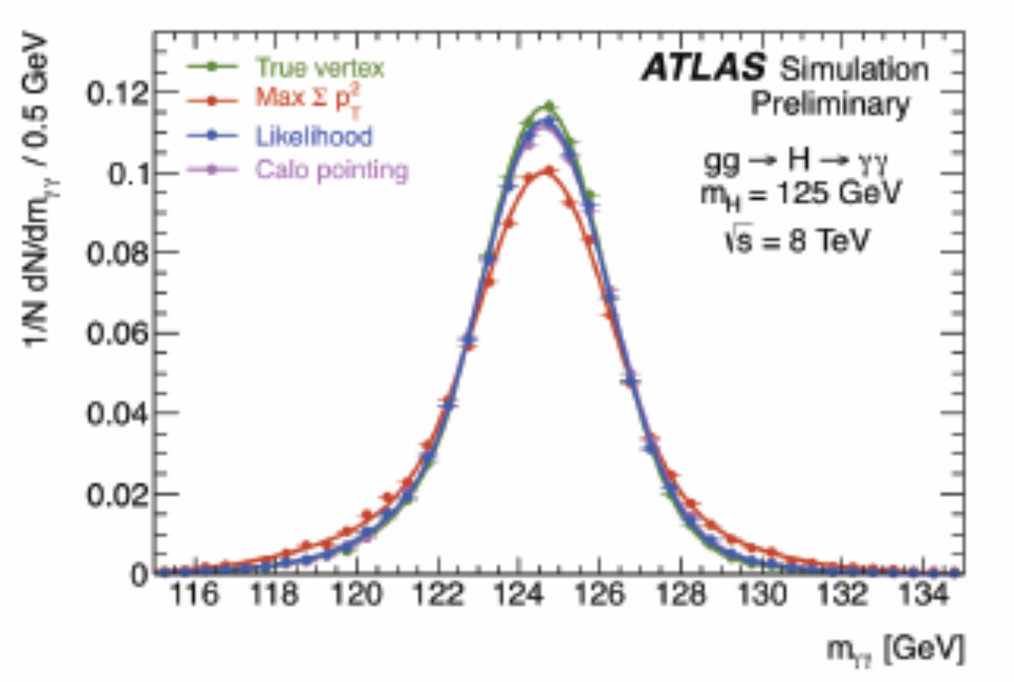




$$m_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta_{12})$$

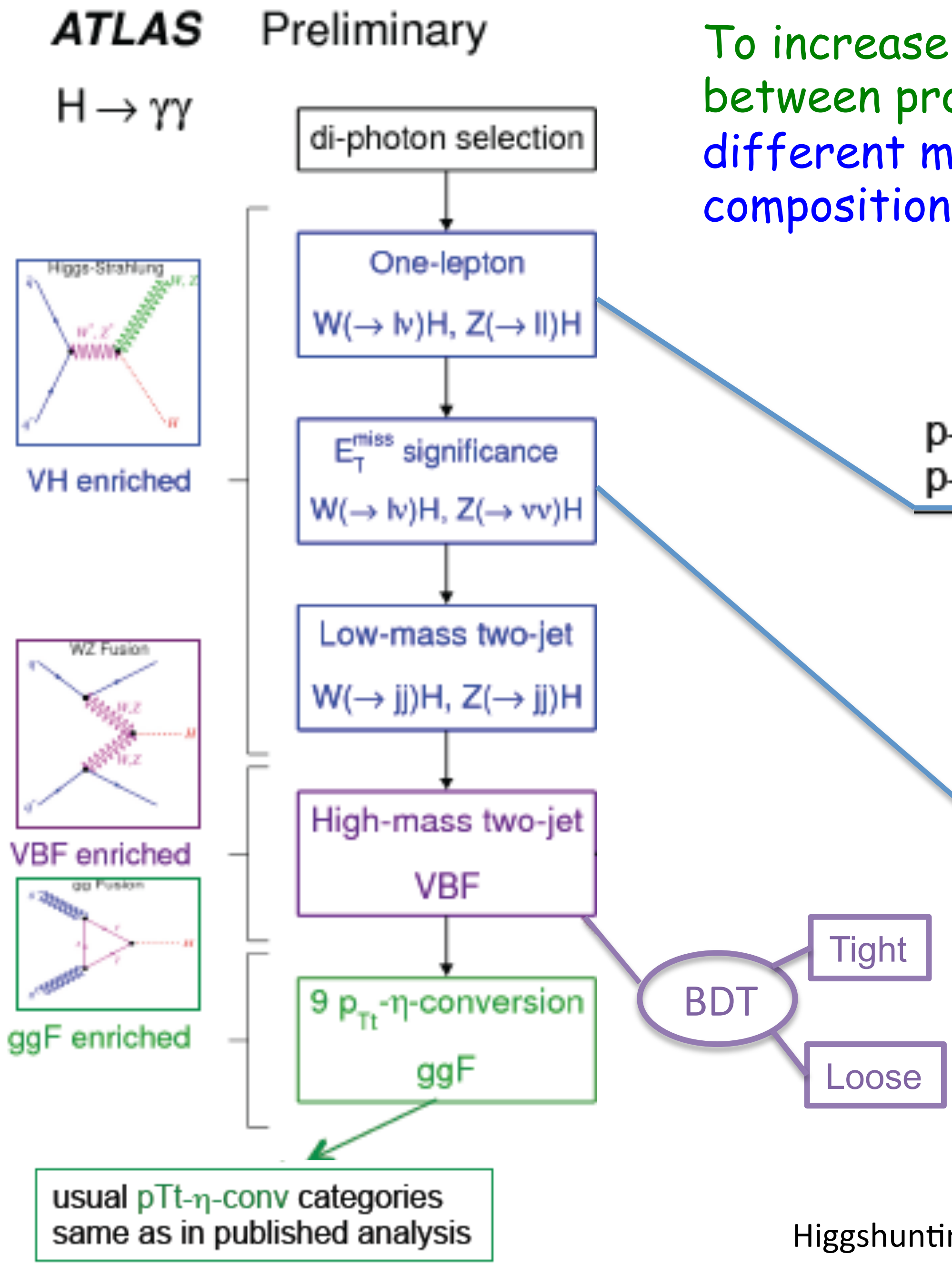
Choice of primary vertex with neural network

- Pointing from the calorimeter
- Information from conversion vertex position
- Vertex recoil

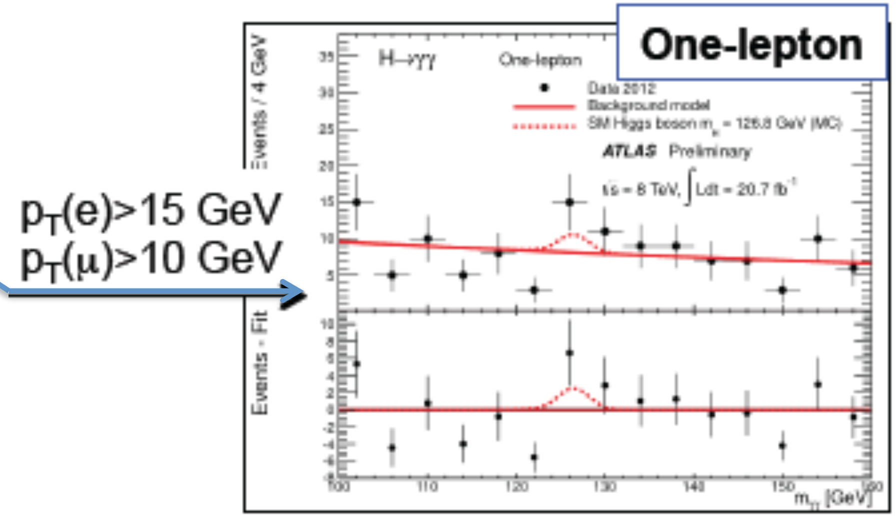


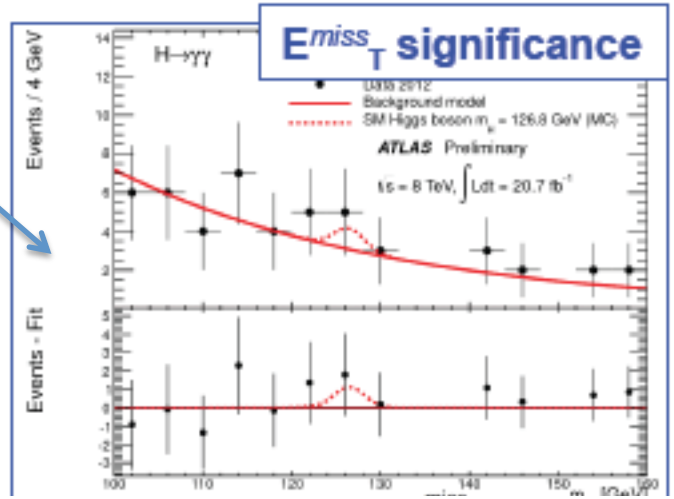
If PV not measured, this would add O(1.3 GeV) to the mass resolution.
Instead: negligible contribution to the mass resolution from direction

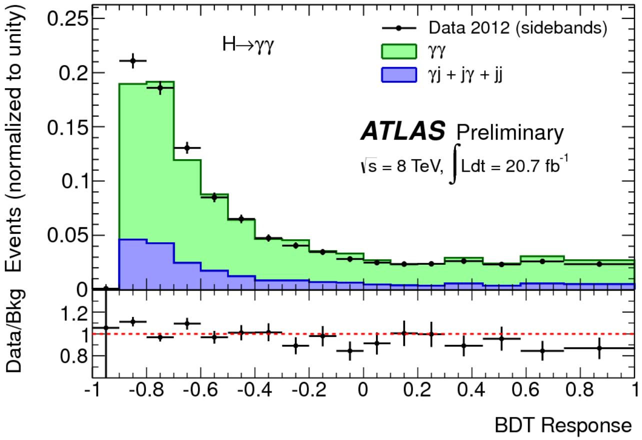
The ATLAS H -> γγ analysis: the categorization



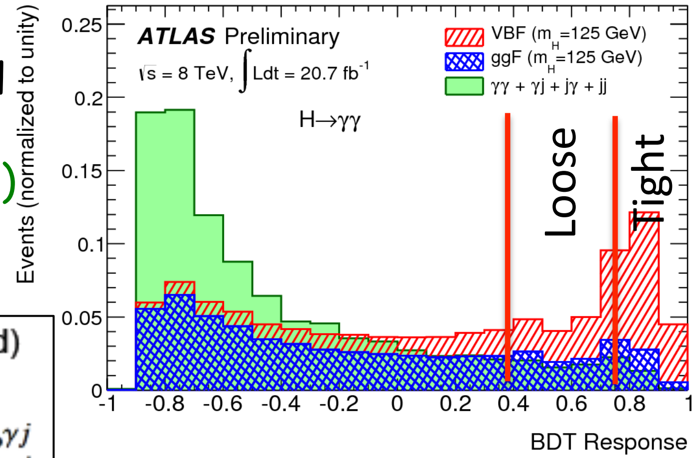
To increase the sensitivity and disentangle between production modes, 14 categories with different mass resolution, S/B and signal composition are defined







BDT trained on VBF signal MC for backgrounds:
irreducible γγ MC (Sherpa)
gj+jj from data



- **Input variables:** (mass factorized)

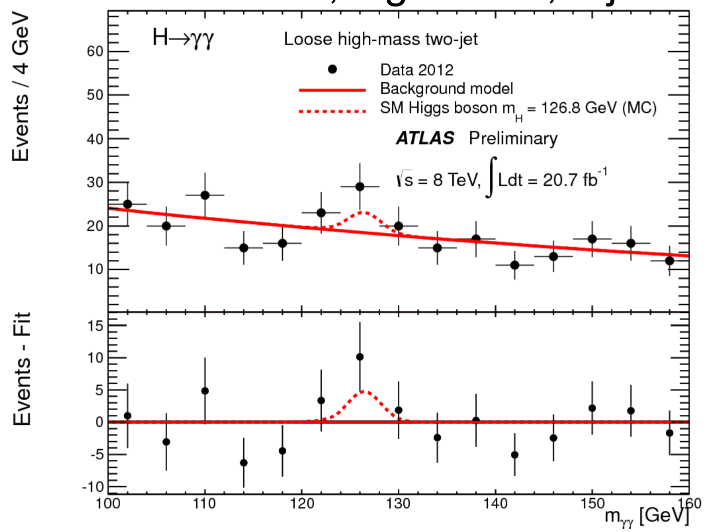
m_{jj} $\Delta\eta_{jj}$ η_{j1} η_{j2} p_{Tt}

$\Delta\phi_{\gamma\gamma;jj}$ $\eta^* = \eta_{\gamma\gamma} - \frac{\eta_{j1}+\eta_{j2}}{2}$ $\Delta R^{\gamma j}_{\min}$

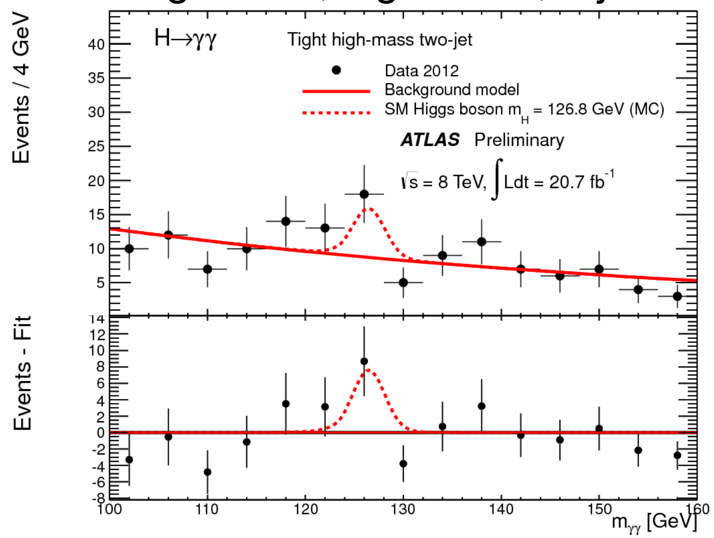
(ggH+jets leakage main systematic)

Two categories (high mass, 2 jets, loose & tight BDT) are very rich in VBF (purities ~ 54%, 76%) -> optimized to measure μ_{VBF}

Loose BDT, high mass, 2-jets



Tight BDT, high mass, 2-jets

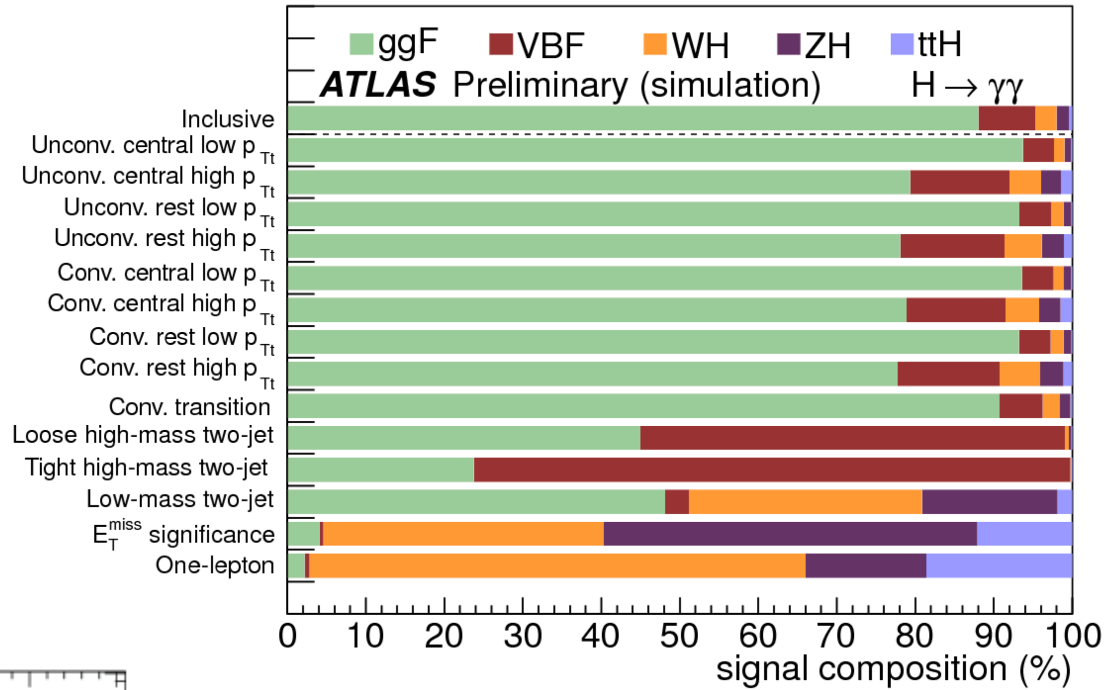


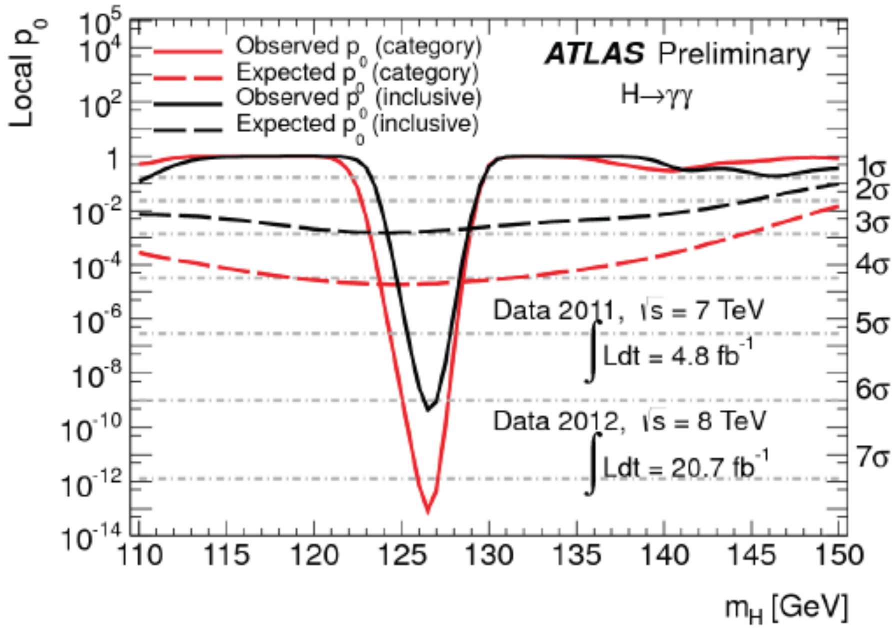
Signal composition per category

ggF

VBF

VH



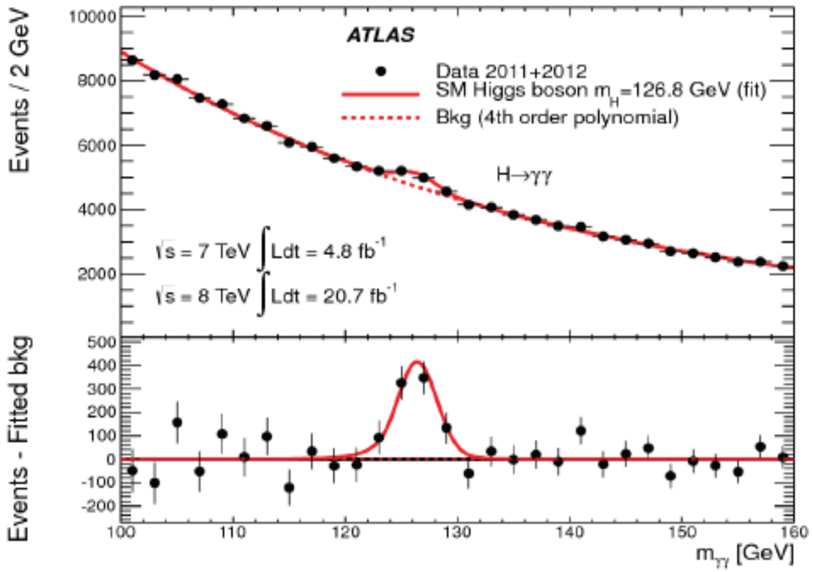


Maximum significance is reached at 126.5 GeV

7.4σ (4.1σ expected) with categories

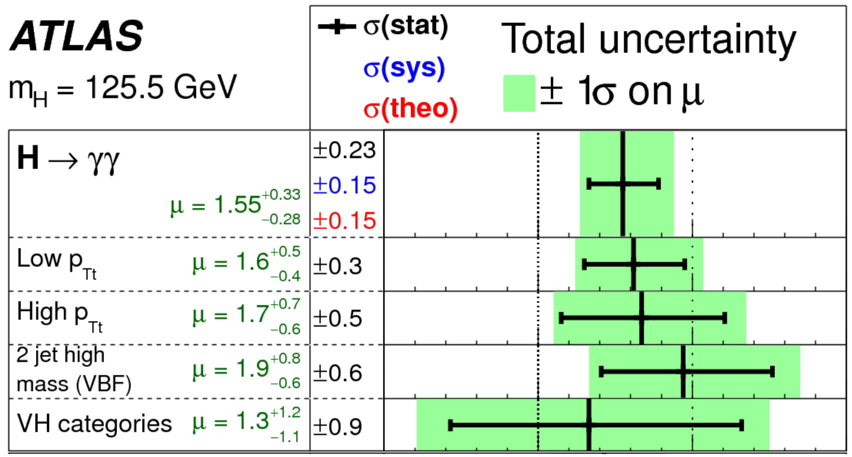
6.1σ (2.9σ expected) in inclusive analysis (no categorization)

Signal strength



Signal strength μ = 1.55 ± 0.23 (stat) ± 0.15 (syst) ± 0.15 (th)

- consistent across categories
- 2σ from SM Higgs + background hypothesis



$\sigma_{fiducial}$ x BR = 56.2 ± 12.5 fb

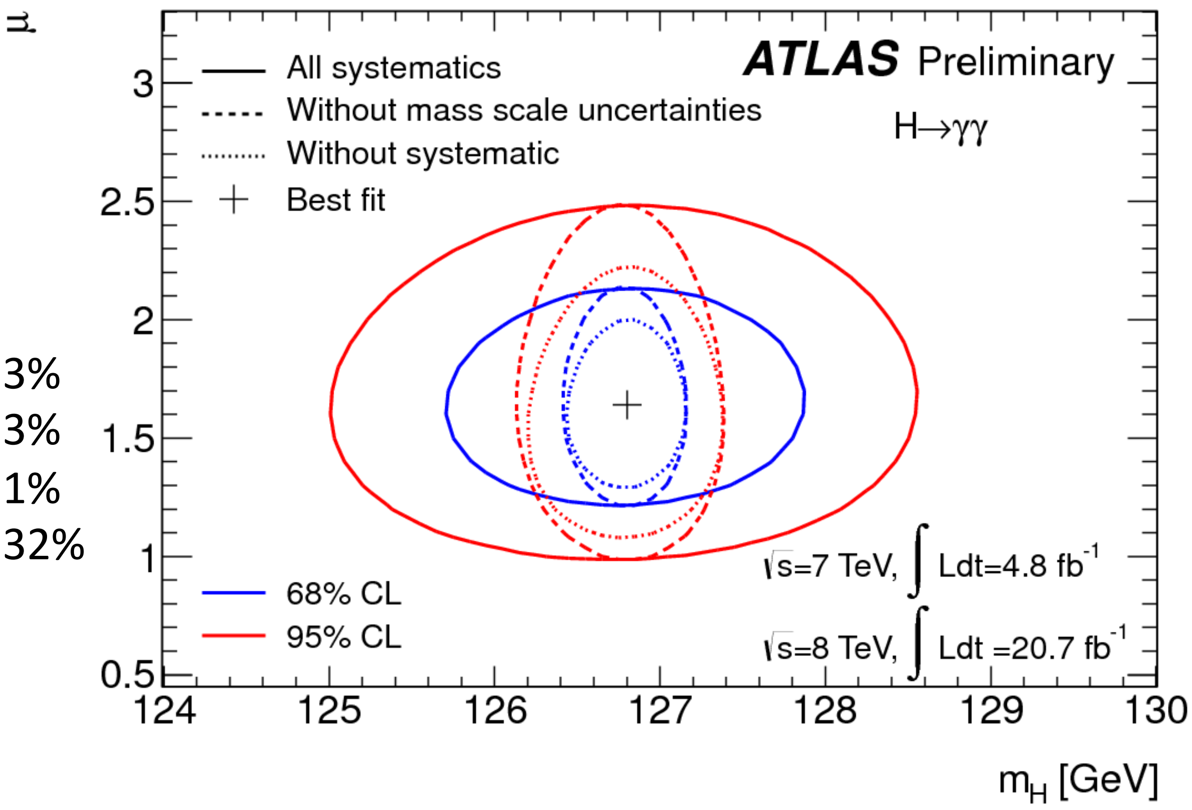
- $|\eta|$<2.37, $p_T(\gamma)$ > 30/40 GeV
- inclusive analysis to reduce model dependency

Stable across categories

Mass measurement

Photon energy scale dominant (0.55% total):

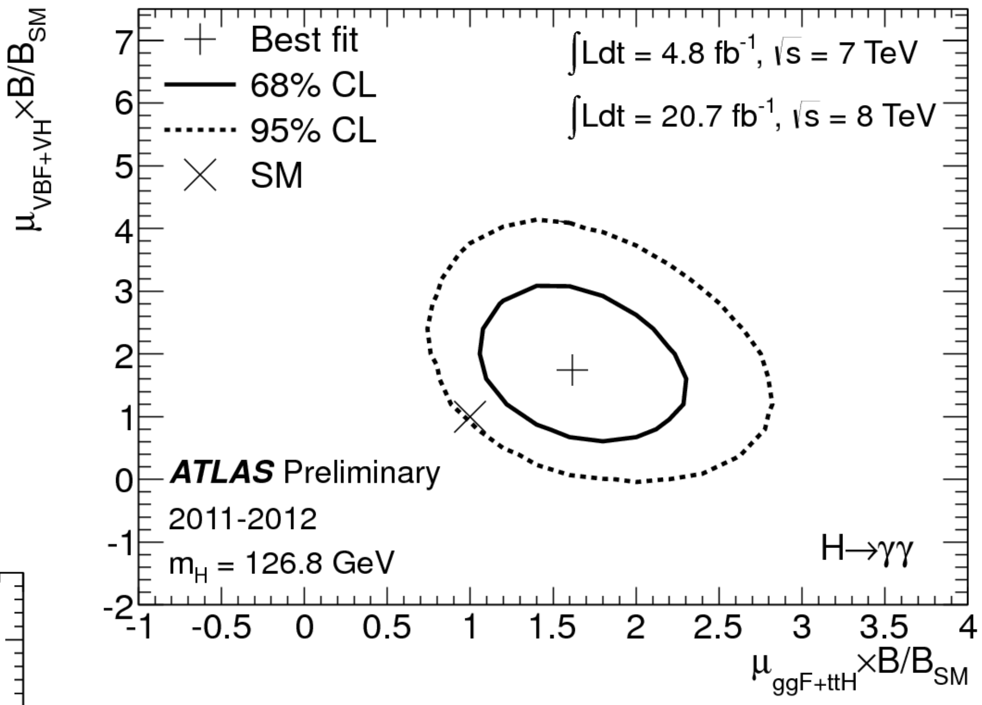
extrapolated from Z->ee:	±0.3%
material modeling:	±0.3%
presampler scale:	±0.1%
others	±0.32%

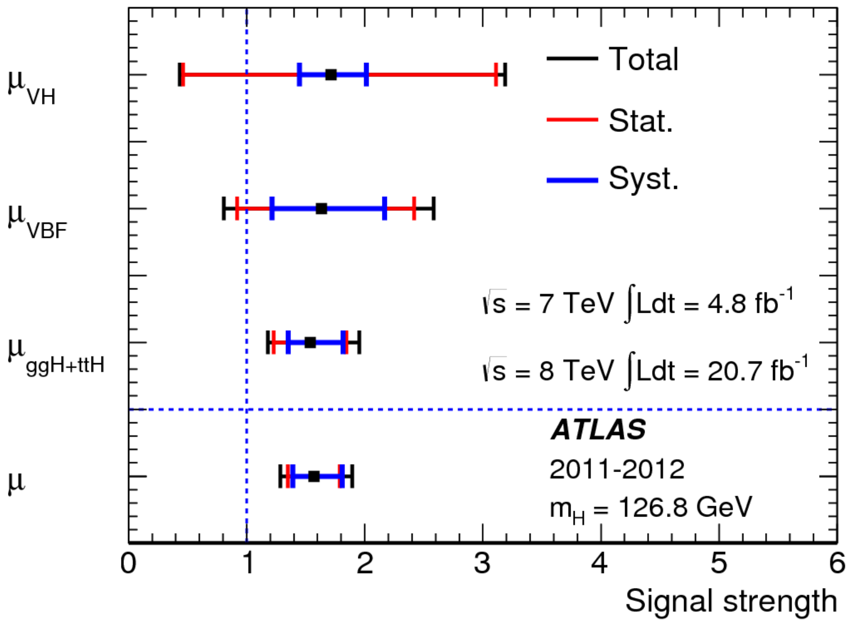


m_H= 126.8 ± 0.2 $_{stat}$ ± 0.7 $_{syst}$ GeV/c^2

Coupling measurements

The category analysis allows sensitivity to VBF and VH processes





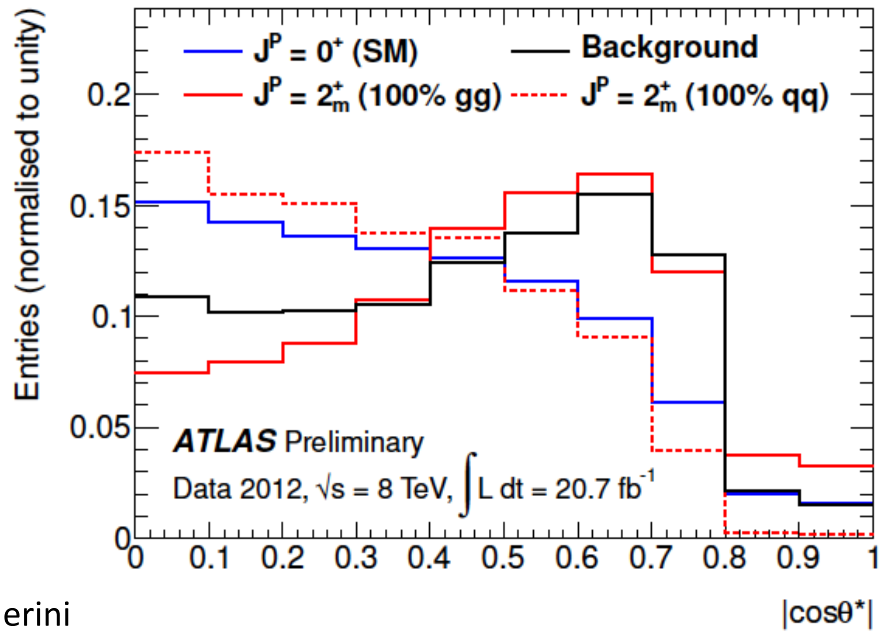
Spin studies

1Dx1D fit to $m_{\gamma\gamma}$ vs $|\cos\theta^*|$ (Collins-Soper frame)

Try to distinguish SM Higgs (0^+) from a singly-produced $J=2^+$ state
(hypothesis tested here: minimal couplings graviton-like model)

dN/d(cosθ*) distribution (before detector acceptance)

flat	for 0^+
$1 + 6\cos^2\theta^* + \cos^4\theta^*$	for gg -> X_2 state
$1 - \cos^4\theta^*$	for qq -> X_2 state

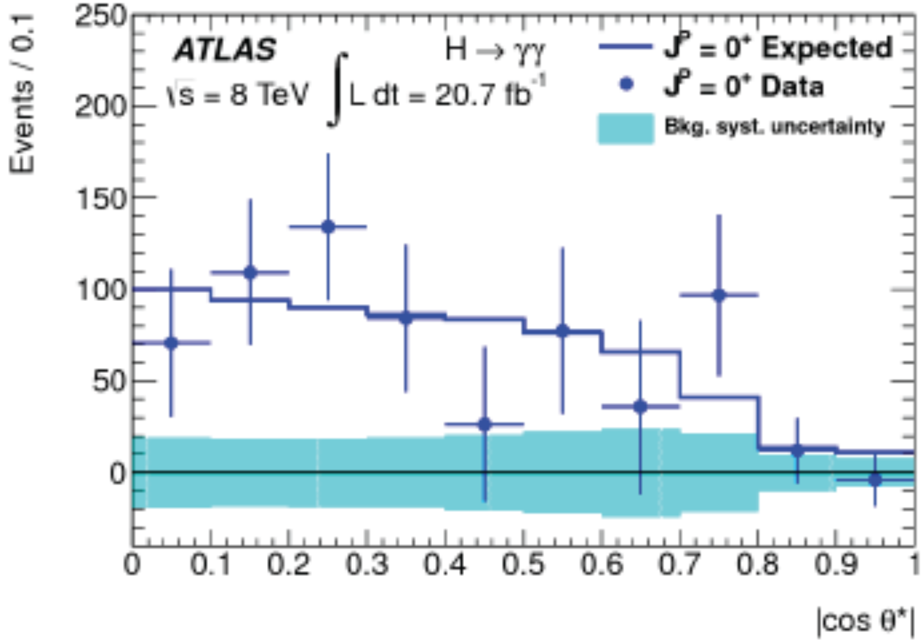


background shape from data $m_{\gamma\gamma}$ sidebands

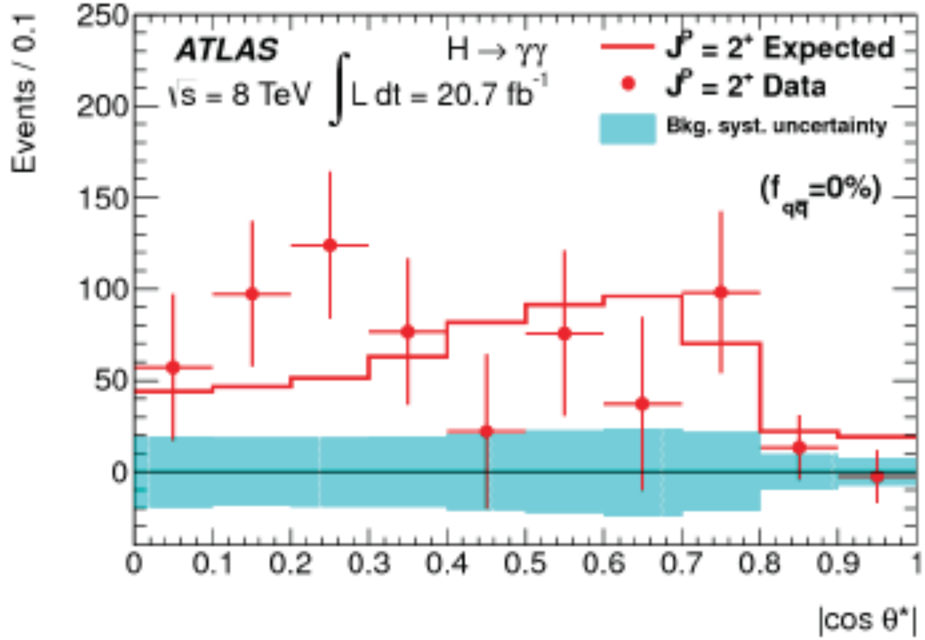
same as inclusive analysis but P_T cuts modified to remove correlation with $m_{\gamma\gamma}$ and $\cos\theta^*$ in background

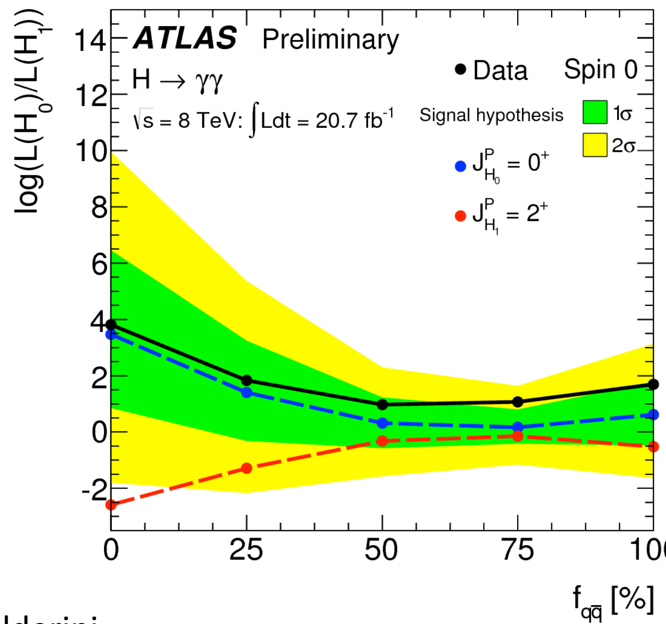
-> use $P_T/m_{\gamma\gamma}$

Standard Model



J=2⁺ and 100% gg





If we test the 100% gluon fusion hypothesis

- 58.8% compatibility with SM
- p0 for considered spin-2 model
  0.3% observed
  1.2% expected in SM hypothesis

Sensitivity strongly diluted as the qq becomes significant

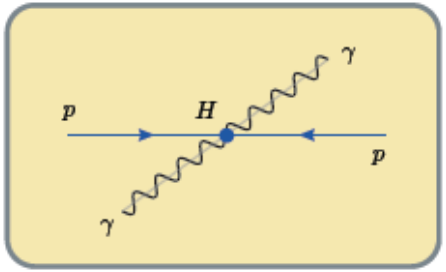
Differential cross section measurement

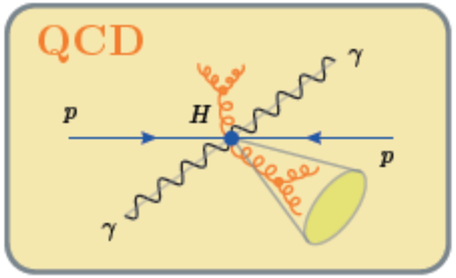
In the H-> $\gamma\gamma$ the rather abundant signal can allow to further study properties

Different variables considered

Inclusive	$p_T^{\gamma\gamma}$	Fundamental Kinematics + QCD Balance in $gg \to H$
	$\|y^{\gamma\gamma}\|$	Fundamental Kinematics + PDFs
	$\|\cos\theta^*\|$	Spin (Model Independent!)
	N_{jets}	Discriminate Prod. Modes, QCD
1-jet	leading jet p_T	Hardest parton emission and soft radiation
2-jet	$\Delta\phi_{jj}$	$gg \to H$: ME v. PS; VBF: Spin + CP
	p_T(H-jj)	Powerful VBF variable with large uncertainties

Selection similar to the H-> $\gamma\gamma$ analysis

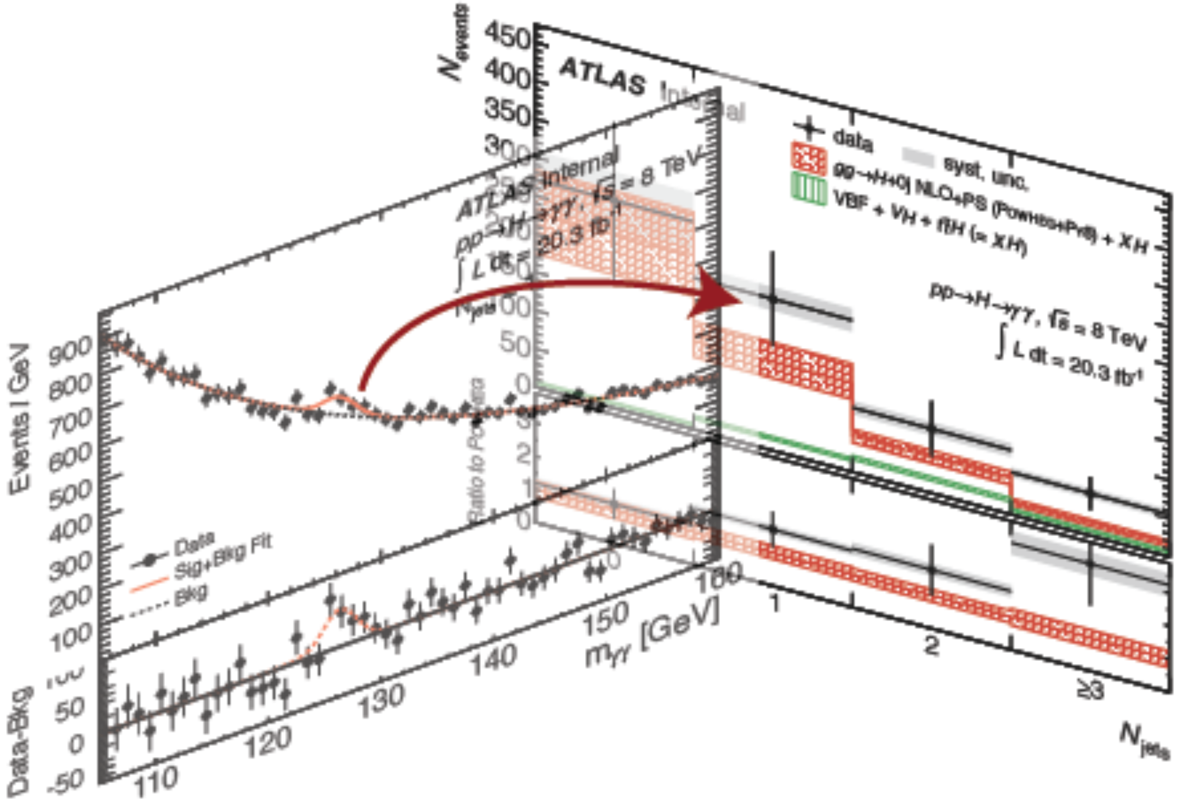




2 Isolated Photons
105 < $m_{\gamma\gamma}$ < 160 GeV;
$p_T/m_{\gamma\gamma}$ > 0.35(0.25) for leading/subleading γ
$|\eta|$ < 2.37 excluding region [1.37-1.56]

Jets
anti-KT, R = 0.4
p_T > 30 GeV, $|\eta|$ < 4.4
Cuts for pile-up suppression (JVF)

Strategy



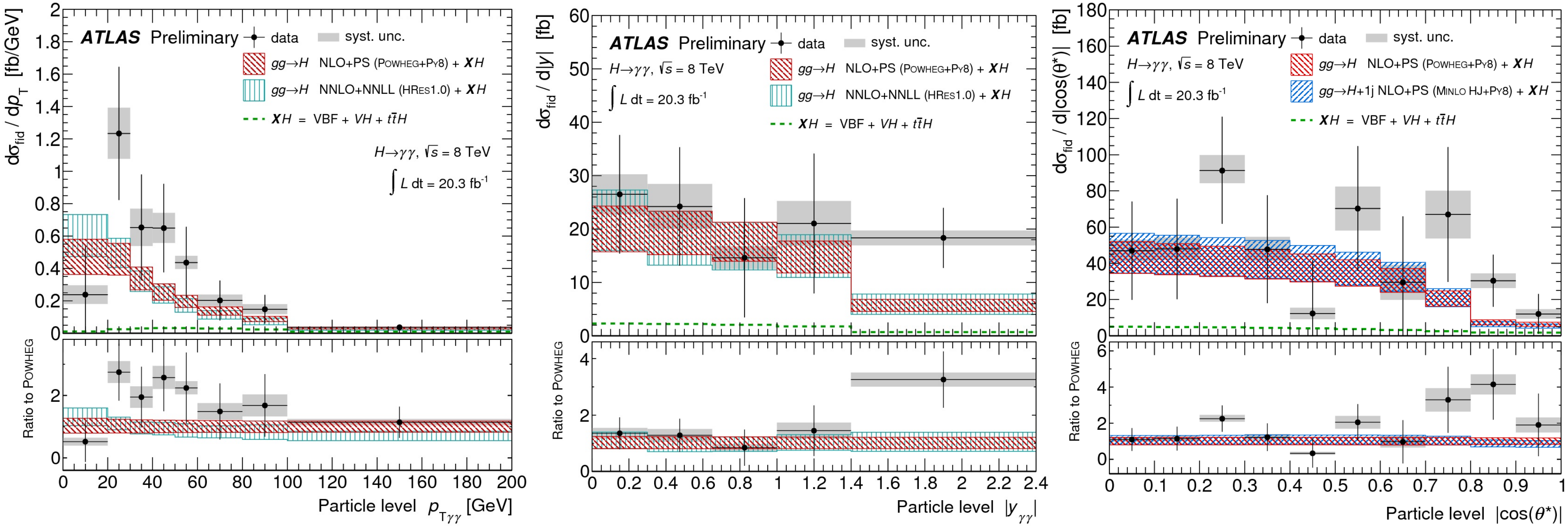
Define a binning for a variable

For each bin extract yield from fit to $m_{\gamma\gamma}$

For each bin, correct for acceptance, efficiency, resolution:
"*unfolding*"

Unfolding procedure becomes critical to compare with theoretical predictions

$P_{T\gamma\gamma}$ $\eta_{\gamma\gamma}$ $\cos\theta^*$



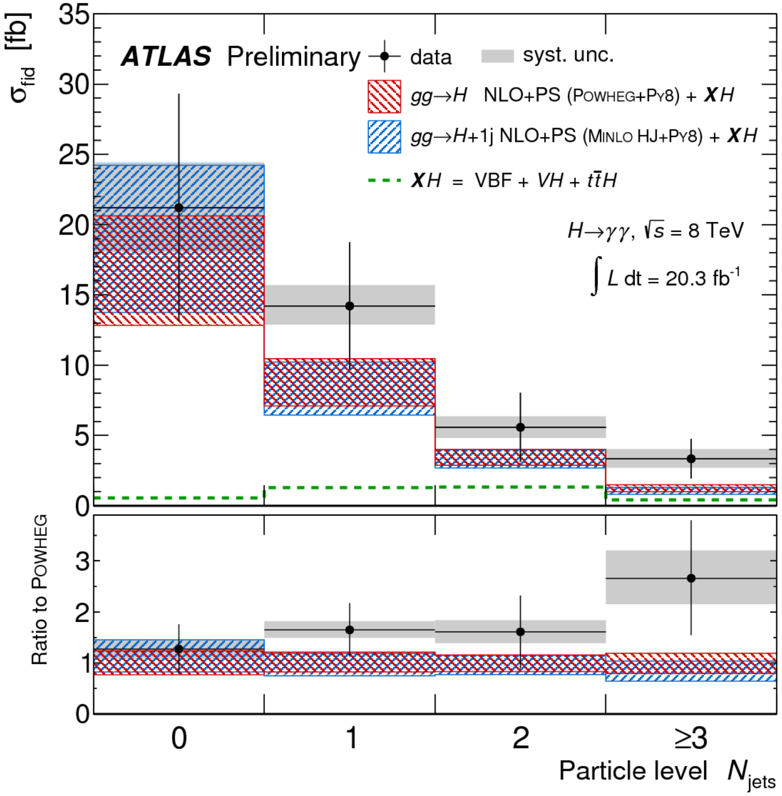
MC: Powheg + Pythia8 full simulation @ m=125 GeV

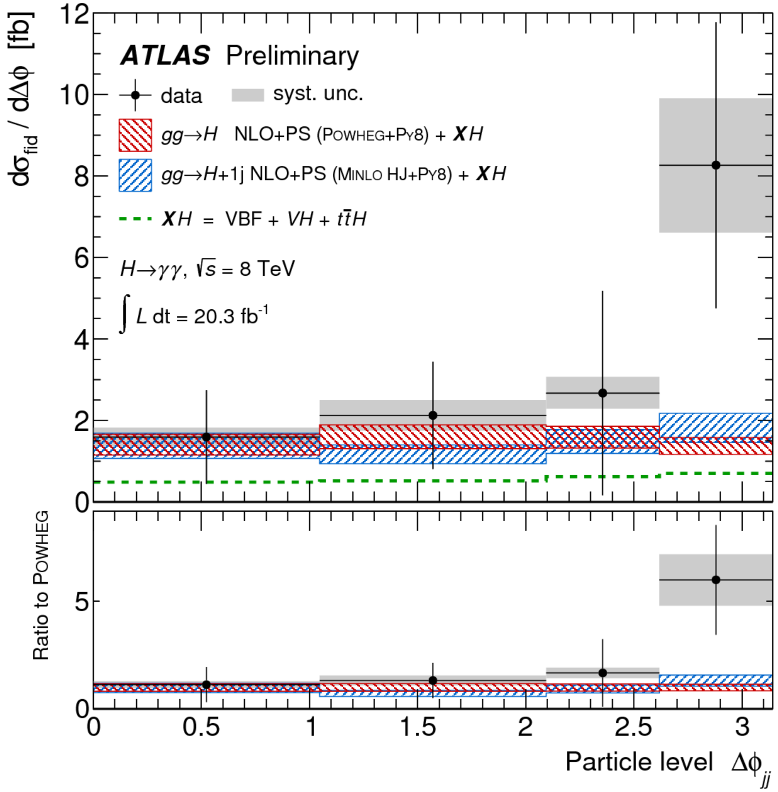
Uncertainties: JES/JER, UE, PDF, Scale

Compatibility test: χ^2 & Kolmogorov-Smirnov

	χ^2 / ndf	P-Value
p_T	6.9 / 8	0.55
$\lvert y \rvert$	5.3 / 5	0.38
$\lvert \cos\theta^* \rvert$	7.9 / 10	0.64

N_{Jet} $\Delta\phi_{JJ}$



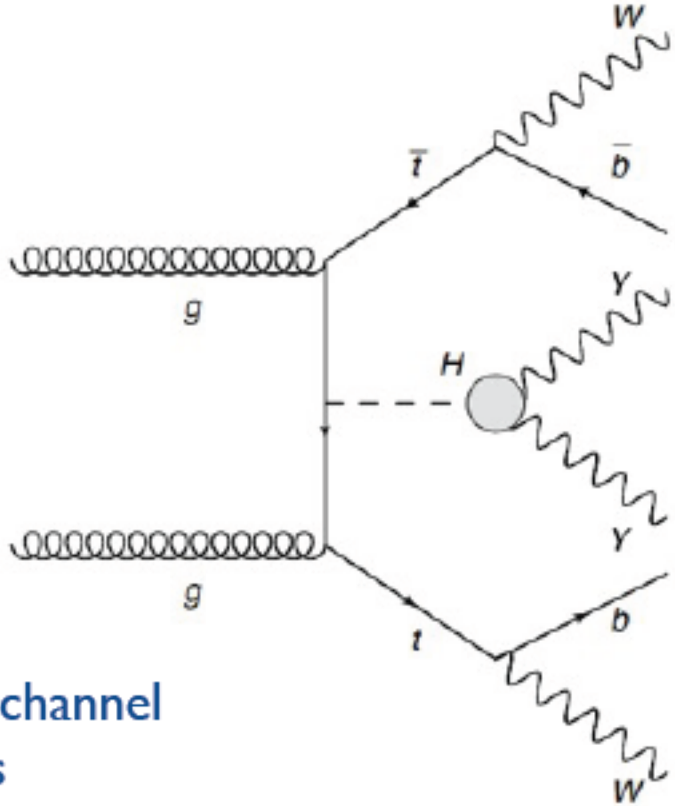


	χ^2 / ndf	P-Value
N_{jets}	4.6 / 4	0.33
$\Delta\phi_{jj}$	4.6 / 4	0.33

At the precision we have the agreement looks fair

ttH(γγ)

A possibility to measure directly the coupling to the top is offered by the ttH process



The good mass resolution and event yield of the H->γγ mode is a good laboratory to investigate this process

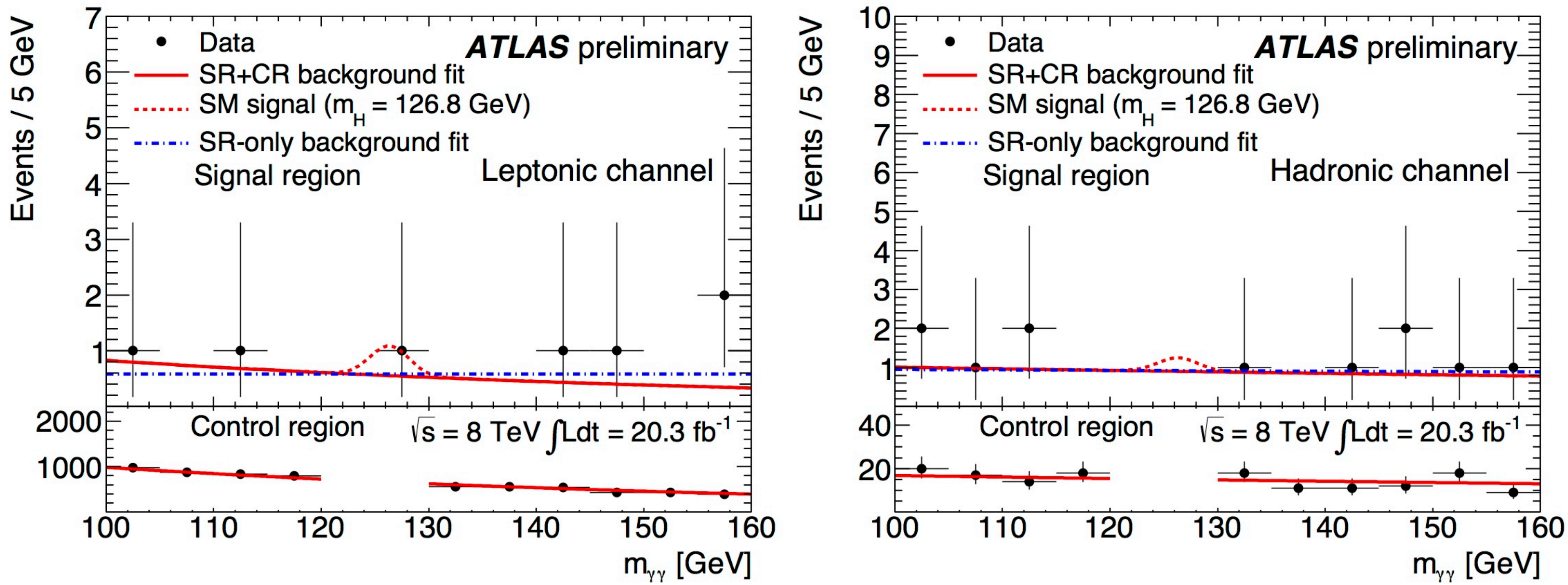
Higgs selection similar to the γγ analysis

- Leptonic channel
  - ≥ 1 e or μ
  - ≥ 1 b-jet
  - MET > 20 GeV
  - m(eγ) ∉ [84 GeV, 94 GeV]
- Hadronic channel
  - ≥ 6 jets
  - ≥ 2 b-jets
  - Lepton veto

Analysis on 20.3 fb-1 (2012)

ε ~ 12.1 %

Background modeled from H -> γγ sidebands



Control regions with relaxed cuts used to constrain the background shape

Channel	N_S	$ggF(\%)$	$VBF(\%)$	$WH(\%)$	$ZH(\%)$	$tH(\%)$	$t\bar{t}H(\%)$
Leptonic	0.55	0.6	0.3	7.7	2.4	6.1	82.8
Hadronic	0.36	5.3	1.1	1.1	1.3	—	91.2

Channel	N_S	N_B	N_S/N_B
Leptonic	0.55	$1.2^{+0.6}_{-0.5}$	0.45
Hadronic	0.36	$1.9^{+0.7}_{-0.5}$	0.19

Effect of systematics on the limit on signal strength

(for 126.8 GeV)

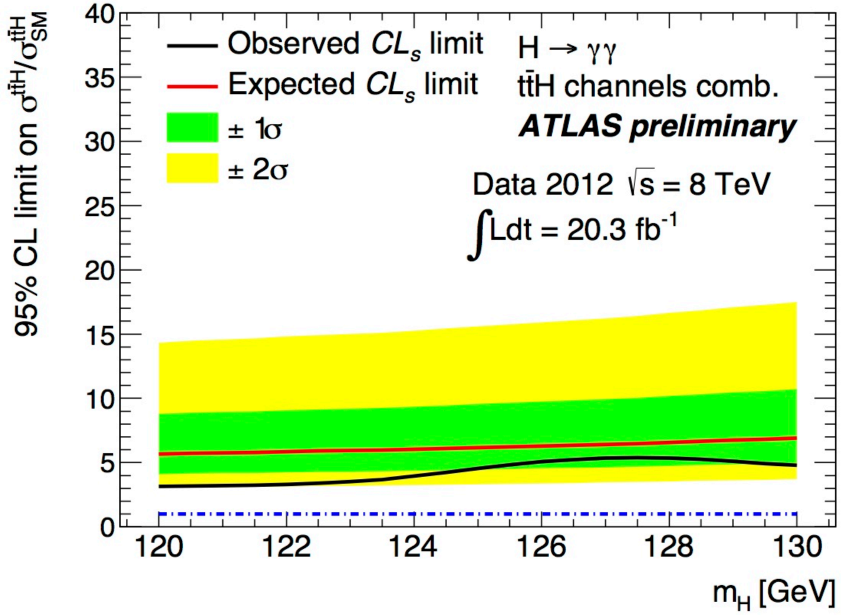
Systematic effect	Systematic uncertainty [%] Leptonic	Hadronic
Luminosity	±2.8	
Cross section	$^{+8.7}_{-12.1}$	
Branching ratio	$^{+5.0}_{-4.9}$	
QCD scale (acceptance only)	±3	±10
Trigger	±0.5	
Photon related	±13.1	
Electron related	±0.8	< ±0.1
Muon related	±0.2	< ±0.1
Jet energy scale	±0.4	±9.8
Jet energy resolution	±0.2	±3.4
Jet vertex fraction	±0.1	±1.0
b-jet energy scale	±0.2	±0.7
b-tagging	±2.1	±5.5

Still statistically limited

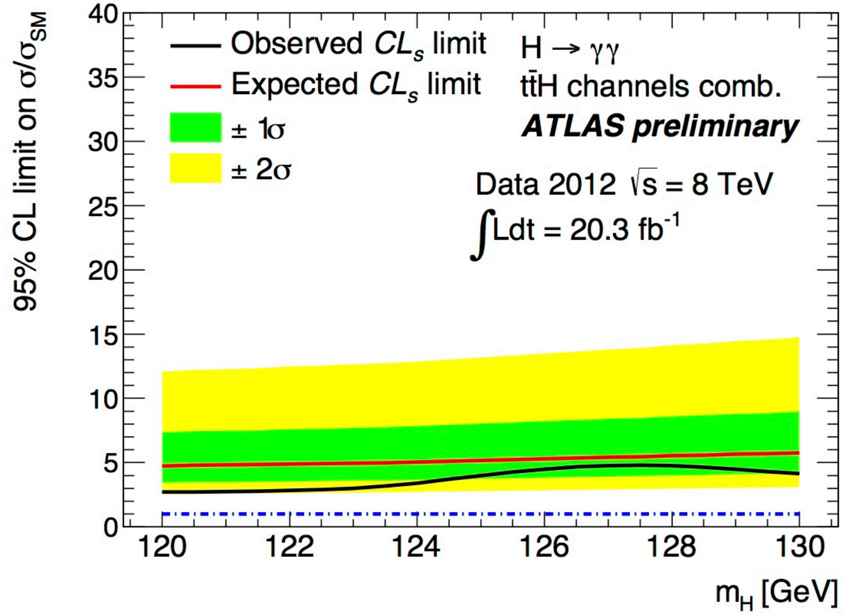
	Observed limit	Expected limit	$+2\sigma$	$+1\sigma$	-1σ	-2σ
Combined (with systematics)	5.3	6.4	16.2	9.9	4.6	3.4
Combined (statistics only)	5.0	6.0	13.5	8.9	4.3	3.2
Leptonic (with systematics)	9.0	8.4	21.9	13.2	6.1	4.5
Leptonic (statistics only)	8.5	8.0	18.8	12.1	5.7	4.3
Hadronic (with systematics)	8.4	13.6	36.4	21.5	9.8	7.3
Hadronic (statistics only)	7.9	12.6	29.1	18.9	9.1	6.8

Limit extraction

ttH



inclusive Higgs



- Observed (expected) limit on ttH signal strength 5.3 (6.4)

(@M_H = 126.8 GeV)

Still needs statistics to reach the sensitivity for SM expectation !

Search for FCNC in t -> cH($\gamma\gamma$)

FCNC involving light quarks (c,u) strongly suppressed in the SM
They are less constrained than the ones in the down sector

	SM expectation	Max expect. in some exotics (*)	Limits on Br, % (95% CL)
$t \to c(u)\, g$	$\sim 5.\ 10^{-12}$ $(4.\ 10^{-14})$	$\sim 2.\ 10^{-4}$ $(2.\ 10^{-4})$	Direct : very hard at LHC Search for single top strong production instead : $7.6\ 10^{-5}$ $(1.5\ 10^{-5})$, ATLAS 8TeV, 14.2 fb^{-1}
$t \to c(u)\, \gamma$	$\sim 5.\ 10^{-14}$ $(4.\ 10^{-16})$	$\sim 2.\ 10^{-6}$ $(2.\ 10^{-6})$	Very hard
$t \to c(u)\, Z$	$\sim 10^{-14}$ (10^{-16})	$\sim 10^{-4}$ (10^{-4})	0.07 / 0.73 (8 TeV CMS 19.5 fb^{-1}/ 7 TeV ATLAS 2.1 fb^{-1})
$t \to c(u)\, H$	$\sim 3.\ 10^{-15}$ $(2.\ 10^{-17})$	$\sim 10^{-3}$ (10^{-5})	-

Any observation would be unambiguous sign of new physics

Some model predicts enhancement by several orders of magnitude
(cfr ex. 2HDM models, J.A. Aguilar-Saavedra, hep-ph/0409342)

Strategy

Select tt events with one top in had/lept channel
Higgs reconstruction with the standard $\gamma\gamma$ selection

- Hadronic channel

At least 4 jets
At least 1 btag
no lepton
$156 < m_{\gamma\gamma j} < 191$ and $130 < m_{jjj} < 210$

- Lepton channel

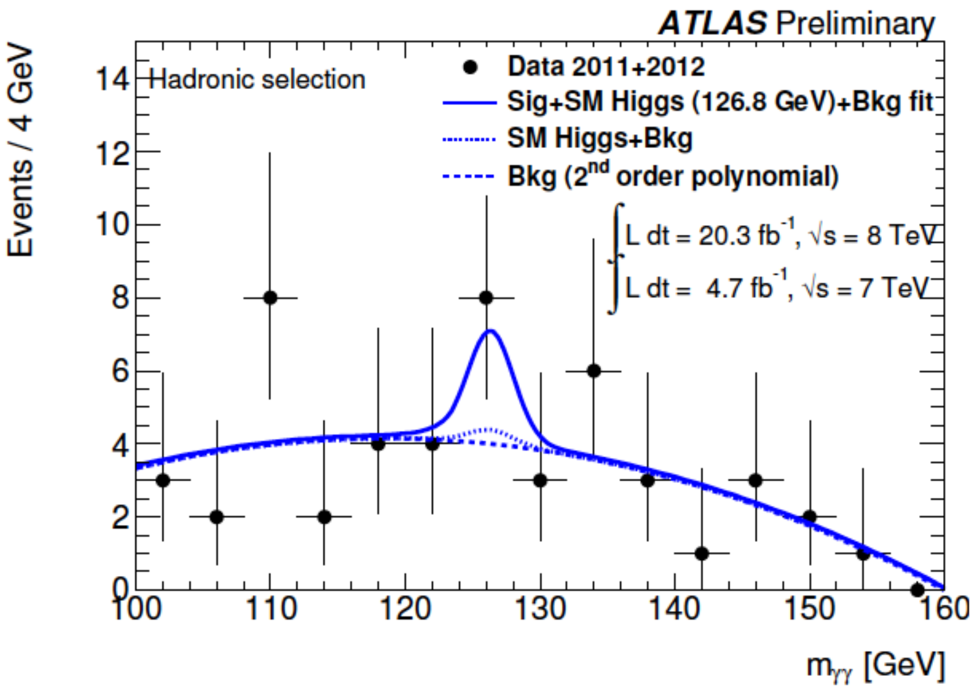
1 lepton, $m_T(\text{lepton}, E_T^{miss}) > 30$ GeV
At least 2 jets
At least 1 btag
no other lepton
$156 < m_{\gamma\gamma j} < 191$ and $135 < m_{l\nu j} < 205$

Hadronic channel (7+8 TeV combined)

N_{obs} (full range) = 50

$N^{SM}_{H} = 0.275 \pm 0.100$ (theory+lumi)

N_{FCNC} [B(t->cH)=1%] =
$(1.58 \pm 0.12)_{(7TeV)} + (9.30^{+0.65}_{-0.72})_{(8TeV)}$



Lepton channel (8 TeV)

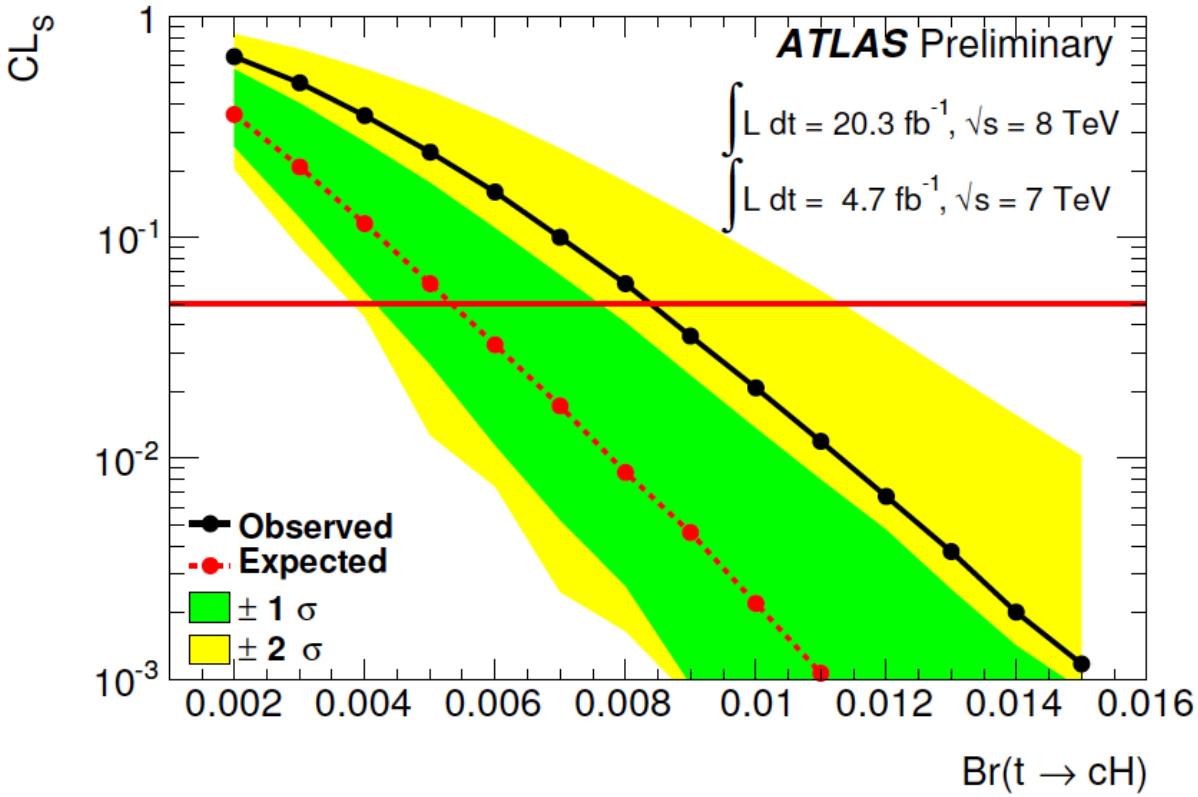
N_{obs} (full range) = 1

$N^{SM}_{H} = 0.053 \pm 0.008$ (theory+lumi)

N_{FCNC} [B(t->cH)=1%] = $(2.91^{+0.24}_{-0.27})$

N (had+lept) = $3.7^{+4.4}_{-3.7}$ events

Limits



$B(t \rightarrow cH) < 0.83\%$ (0.53% expected) @ 95 % CL

corresponding to a limit on the tcH coupling of :

$\lambda_{tcH} \sim 1.91\ B^{0.5} < 0.17$ (0.14 expected)

Conclusions

Some updates in H -> $\gamma\gamma$ analysis have been presented

Some change since Moriond results (strength)

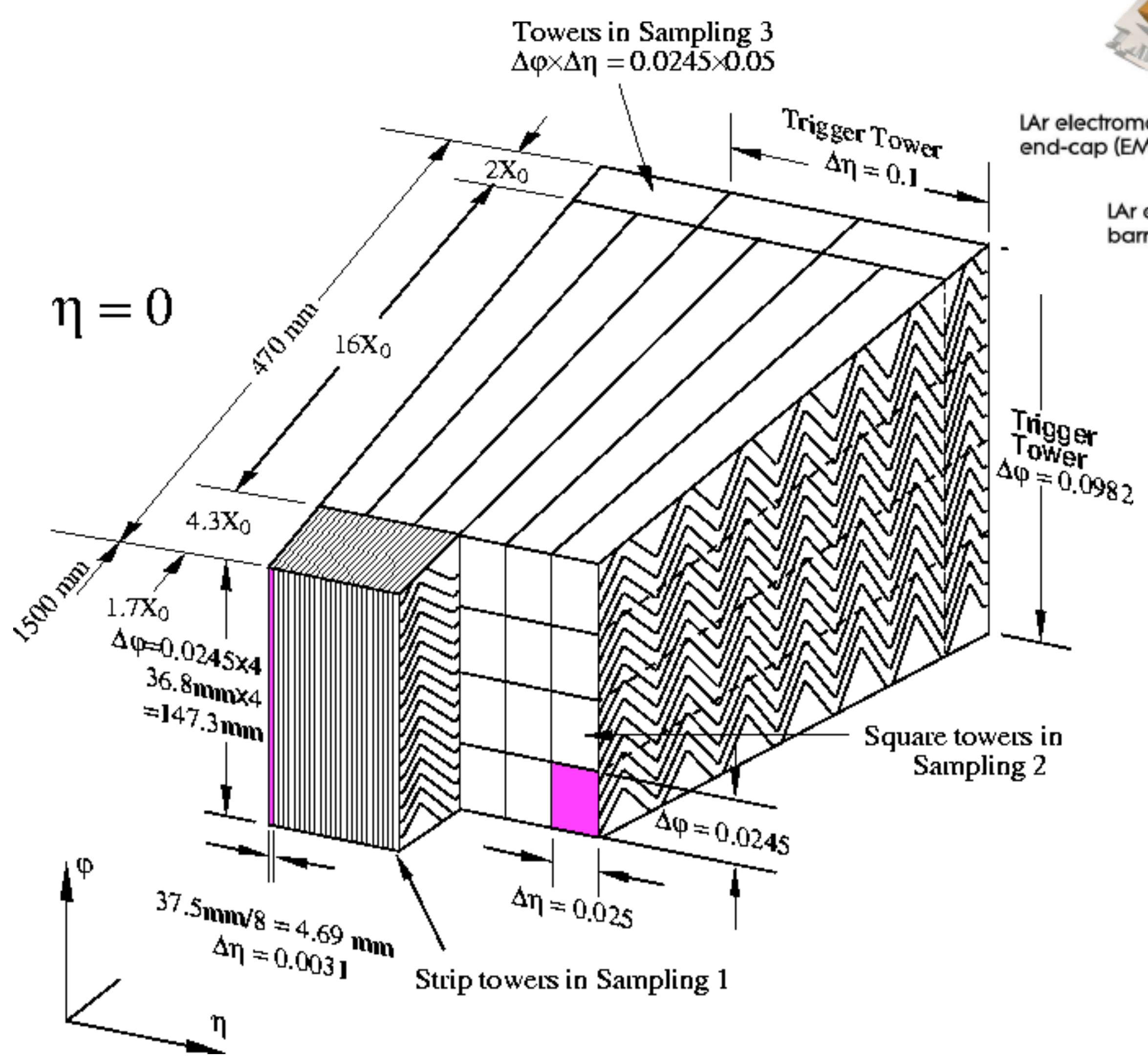
New analyses shown

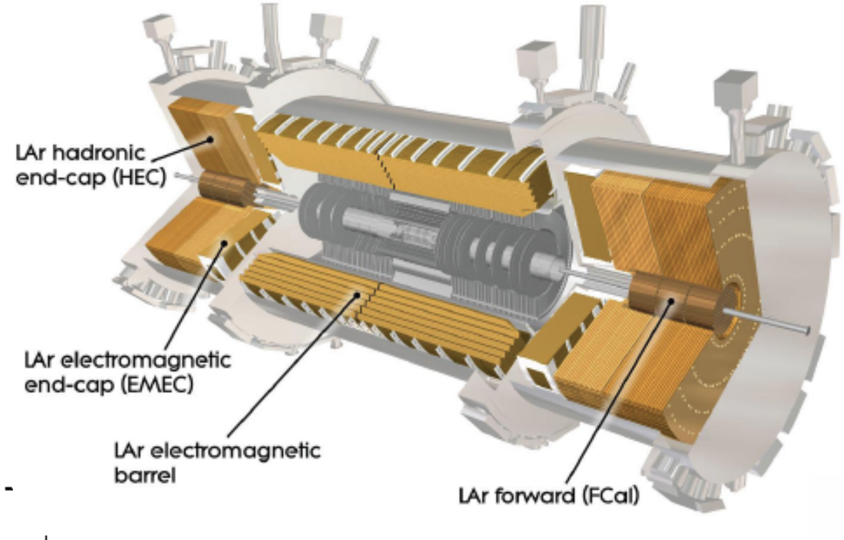
Differential cross section measurements (presented first at EPS last week)

ttH mode (flashed at EPS plenary)

Search for FCNC in the t->cH mode

Additional material





- Crack-less accordion geometry
- Uniform by construction
- Very stable operation

- ~ 200K channels

$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 0.007$$

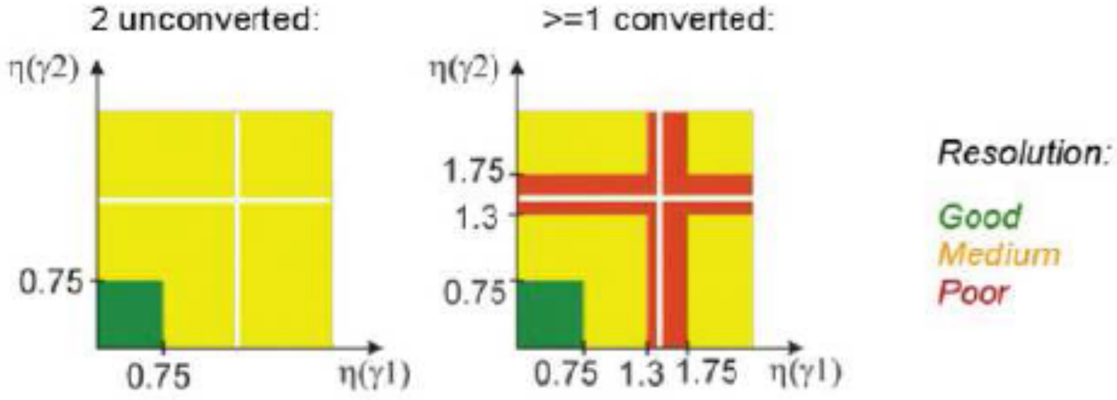
(0.7% nominal constant term : not there yet)

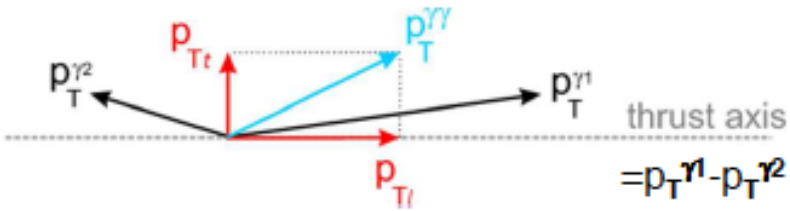
Both unconverted:

- Central
- Rest

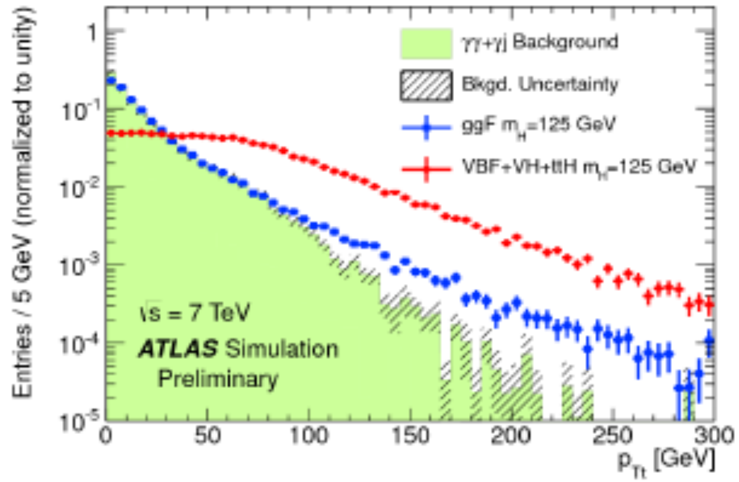
At least one converted:

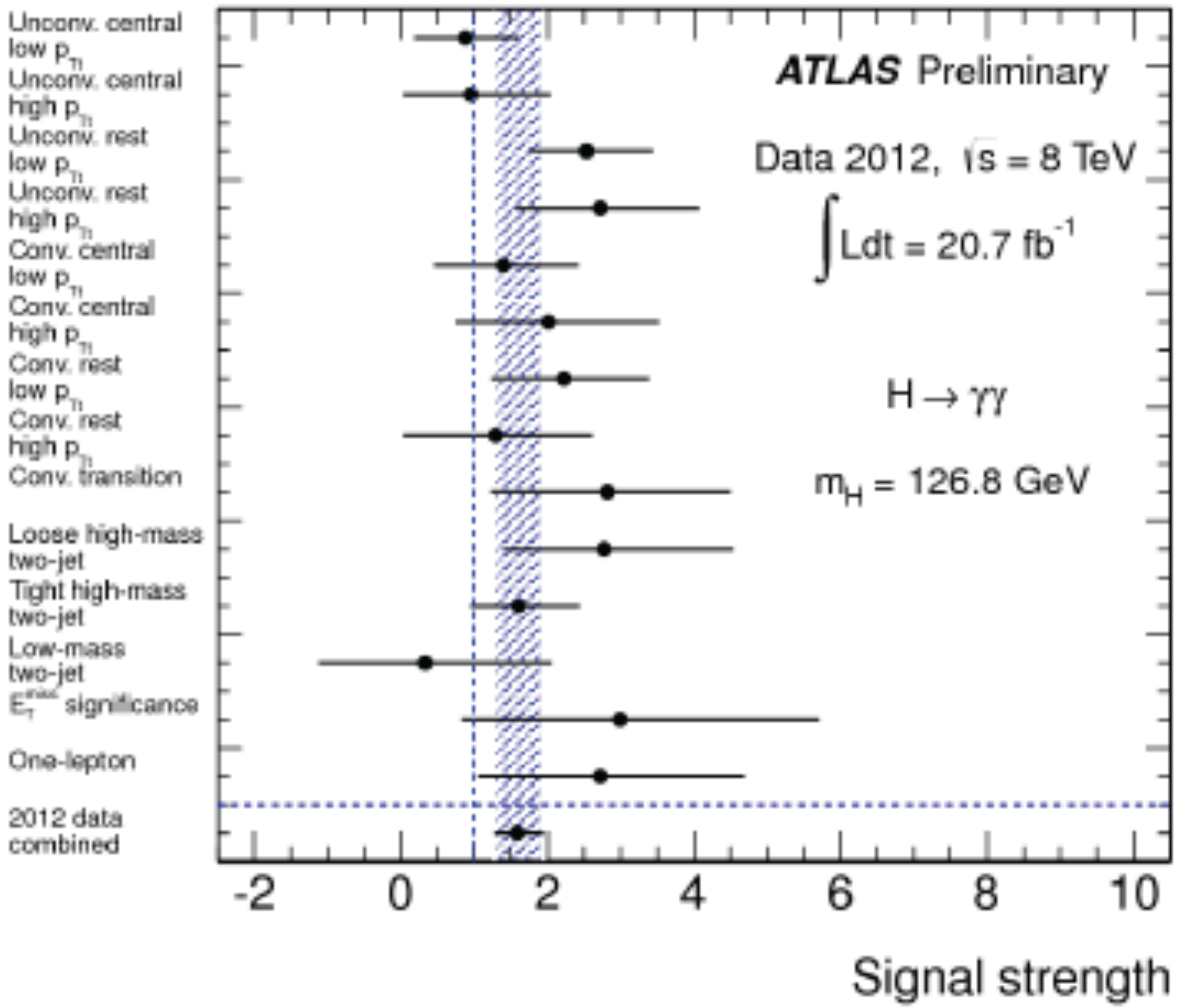
- Central
- Transition
- Rest



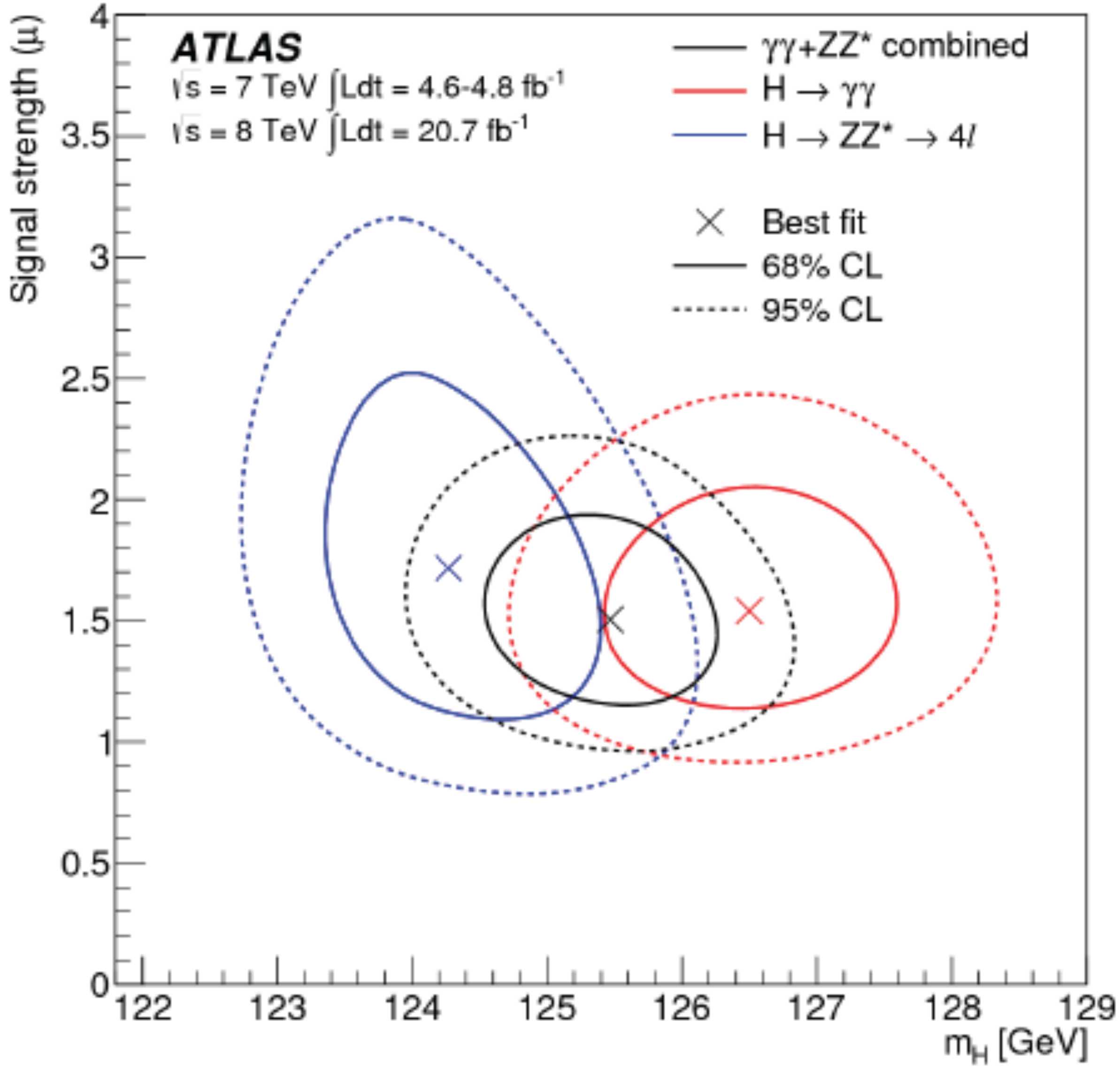


Variable p_{Tt} is strongly correlated with diphoton p_T but has better detector resolution and retains a monotically falling invariant mass for background

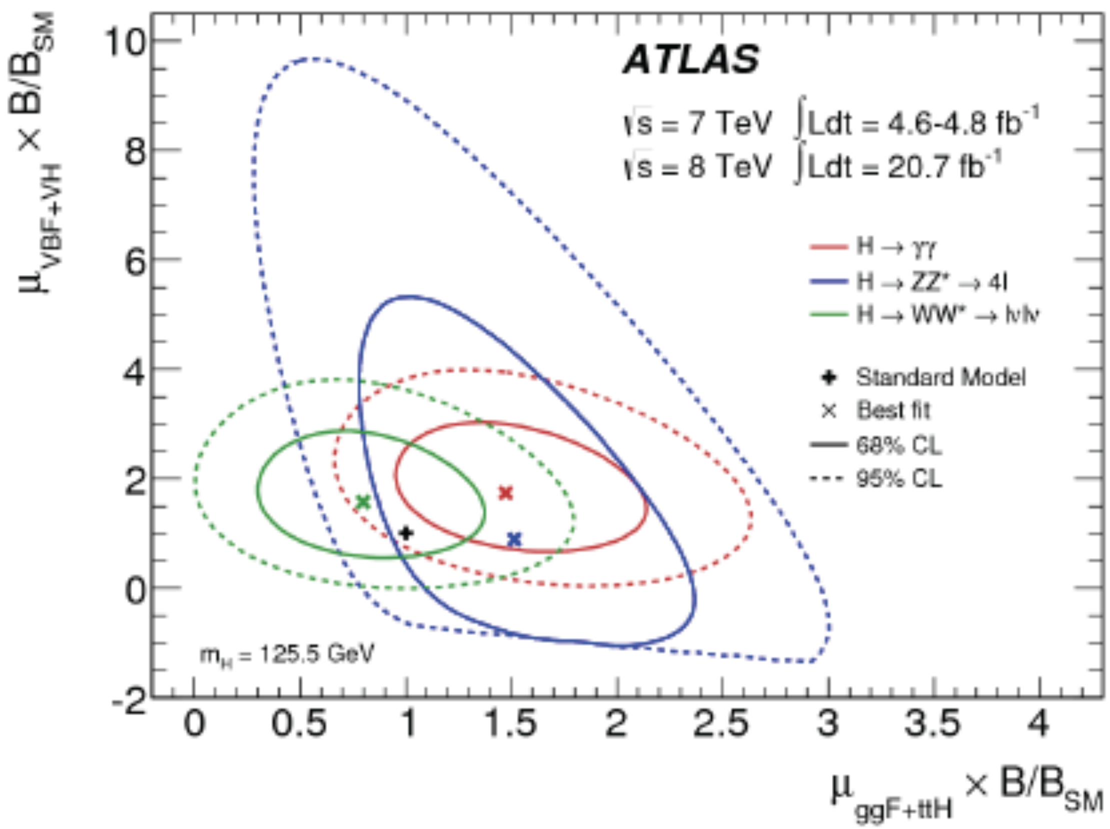




Unconv. central low p_{Tt}
Unconv. central high p_{Tt}
Unconv. rest low p_{Tt}
Unconv. rest high p_{Tt}
Conv. central low p_{Tt}
Conv. central high p_{Tt}
Conv. rest low p_{Tt}
Conv. rest high p_{Tt}
Conv. transition
Loose high-mass two-jet
Tight high-mass two-jet
Low-mass two-jet
E_T^{miss} significance
One-lepton
2012 data combined
ATLAS Preliminary
Data 2012, $\sqrt{s}$ = 8 TeV
$\int Ldt = 20.7\ fb^{-1}$
$H \rightarrow \gamma\gamma$
m_H = 126.8 GeV
-2
0
2
4
6
8
10
Signal strength



ATLAS
√s = 7 TeV ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
γγ+ZZ* combined
H → γγ
H → ZZ* → 4l
Best fit
68% CL
95% CL
Signal strength (μ)
m_H [GeV]

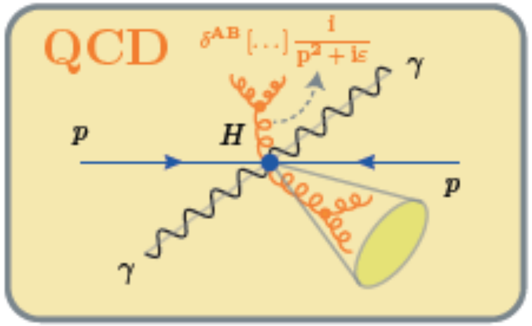


ATLAS
√s = 7 TeV ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
H → γγ
H → ZZ* → 4l
H → WW* → lνlν
Standard Model
Best fit
68% CL
95% CL
m_H = 125.5 GeV
μ_VBF+VH × B/B_SM
μ_ggF+ttH × B/B_SM

Unfolding

- Unfolding yields from detector effects into *cross sections* is an important part of this measurement:
  - Can compare with **all kinds** of theory predictions
  - Can compare with **future measurements** from CMS

Particle level definition: impacts model dependence of unfolded cross sections



Photon particle level definition:

- $\mathbf{m}_{\gamma\gamma} \in [105, 160)$ GeV
- $\mathbf{p_T}/\mathbf{m}_{\gamma\gamma} > 0.35(0.25)$ and $|\eta| < 2.37$ for (sub)leading photon
- Isolation of $\mathbf{E_T^{iso}} < 14$ GeV, mirrors the reco. iso. of < 6 GeV.
  E_T^{iso} is the E_T of the 4-momentum of the sum of stable particles within $\Delta R < 0.1$, excluding all μ and ν

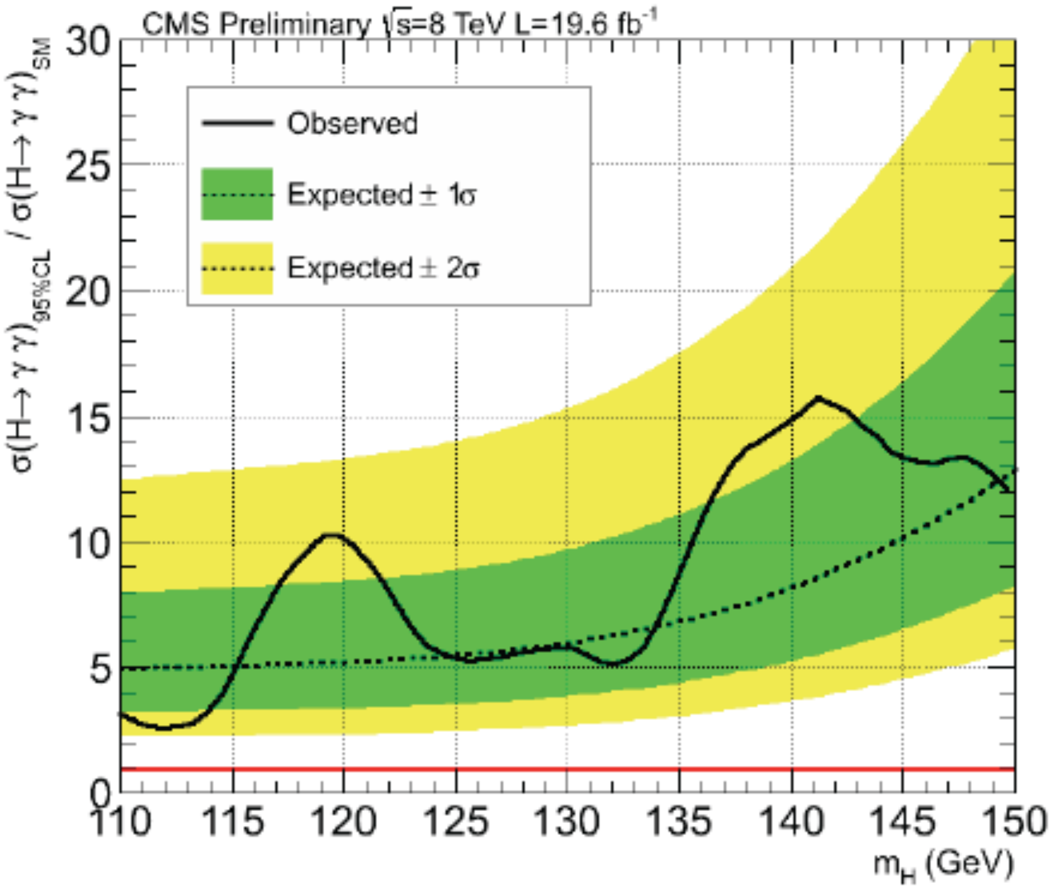
Jet particle level definition: analog to reco, no JVF

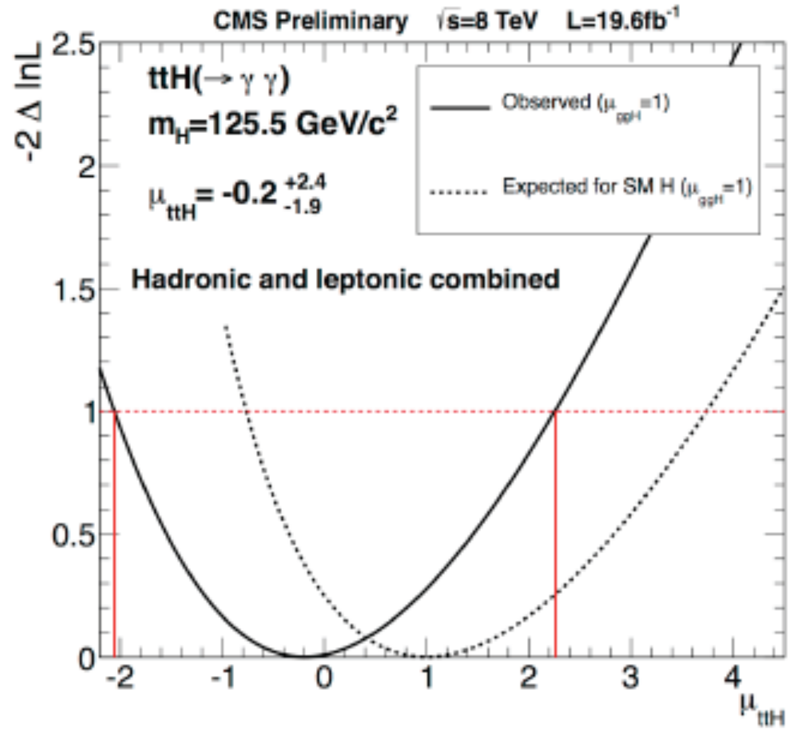
- Unfold extracted yields with correction factors: $c_i = {}^{\text{MC}}n_i^{\text{part}} / {}^{\text{MC}}n_i^{\text{det}}$

Robust method used by many SM analyses; unbiased as long as: ${}^{\text{MC}}n_i^{\text{part}} / {}^{\text{MC}}n_i^{\text{det}} = {}^{\text{Data}}n_i^{\text{part}} / {}^{\text{Data}}n_i^{\text{det}}$

Bias must be carefully studied and evaluated.

CMS ttH





$$\mu_{ttH} = -0.2^{+2.4}_{-1.9}$$

Here still some more data needed before observation can be at reach