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21/09/2021

Experimental summary

INTRODUCTION

Thanks to the organisers for this nice opportunity
and for some sleep deprivation in the last days :)

Impossible to make justice to all the many results presented in a single talk

- focussing on some highlights and personal remarks. A poor's experimentalist view

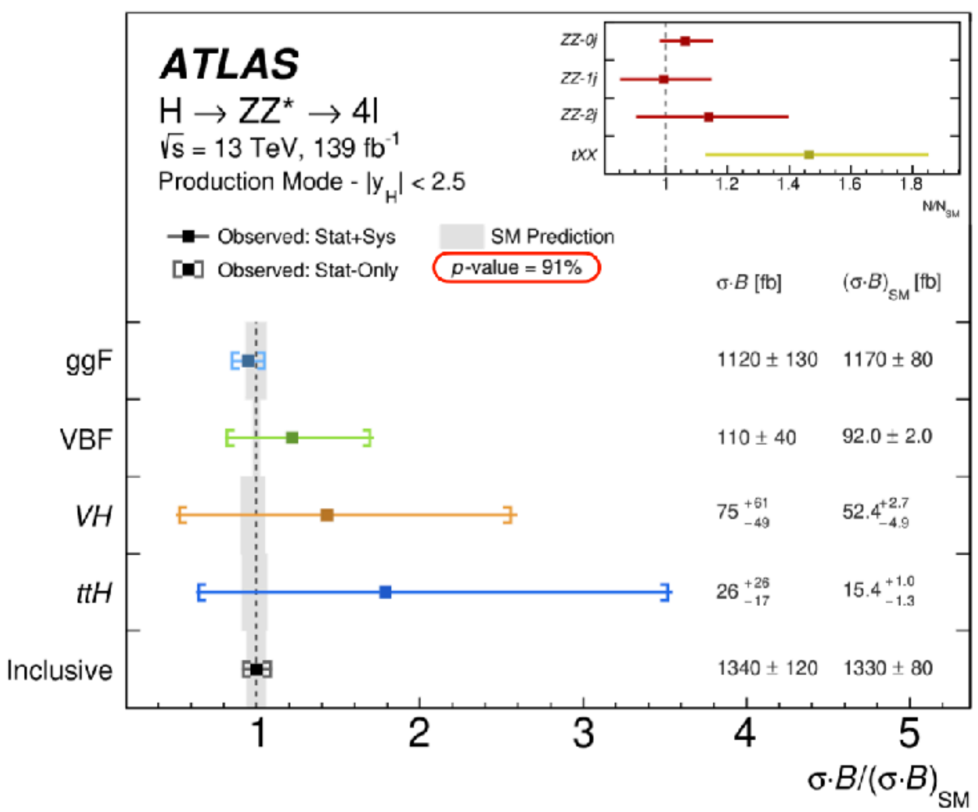
Lively discussion also with the online format, thanks to the organisers for keeping this year conference

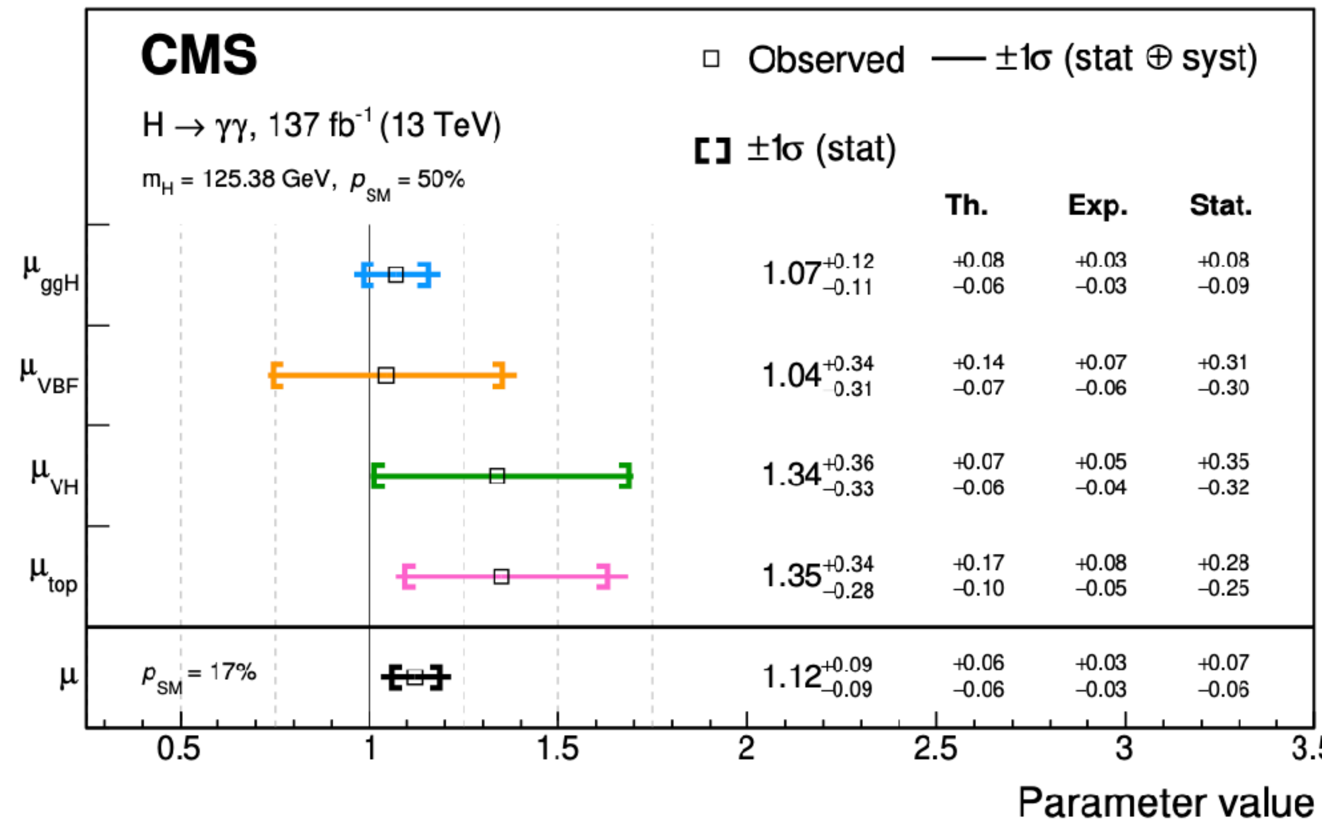
- all excellent and very investing talks, in particular congratulations to the YSF speakers
- missing coffee break discussions and Paris. Let's hope for a 2022 HH in person :)

BOSONIC CHANNELS

ZZ, γγ, WW: steady progress with more stat, full Run2 inclusive measurements with full Run2 agreeing at ~10% with SM expectation (ggF@N3LO theoretical uncertainty 5%)

Marchiori, Errico





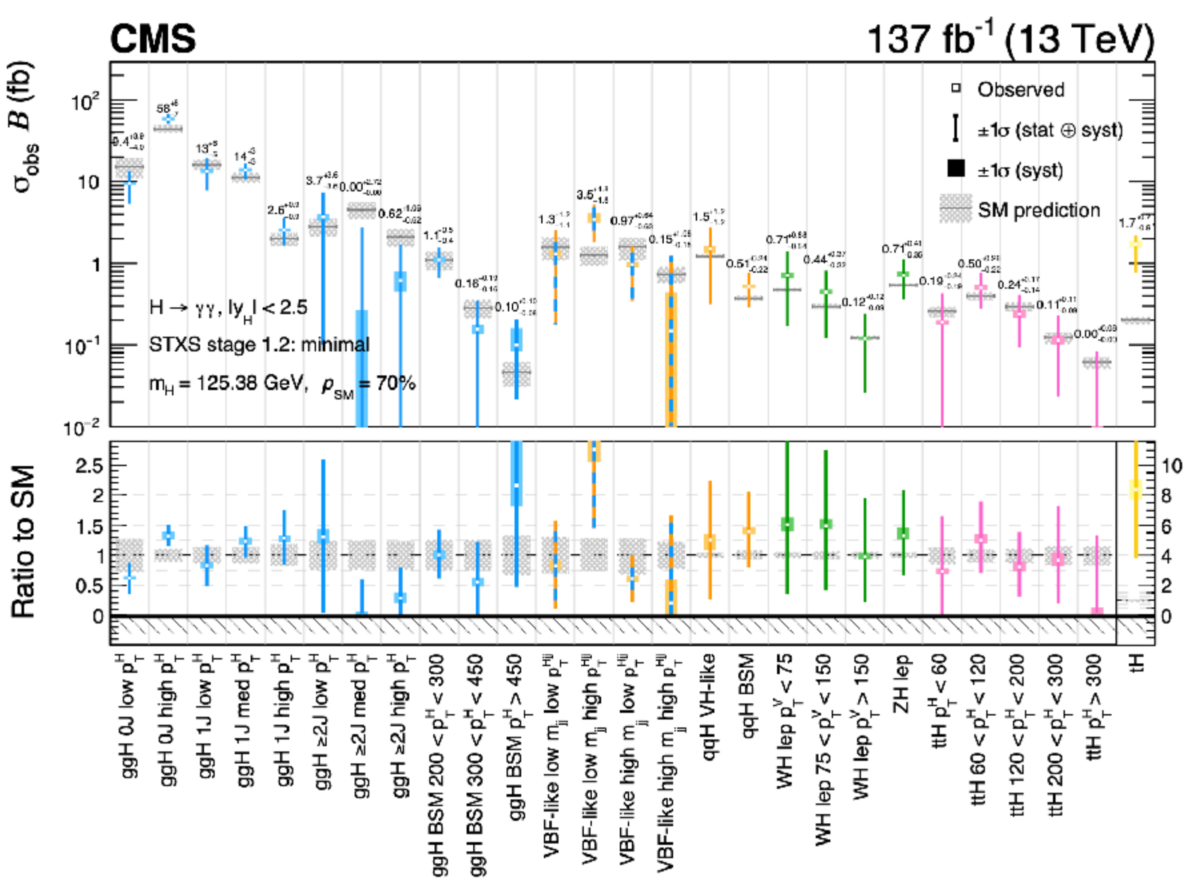
Success for experiments and theory, though these measurements are now starting to be systematically limited

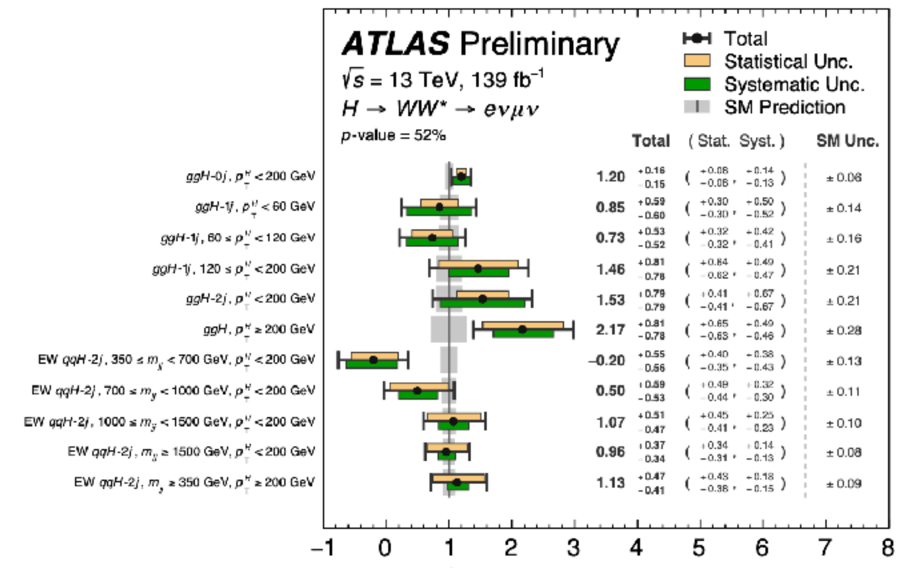
Mass measurements from γγ and ZZ at 1-2% per mille level, systematically limited for γγ. No clear evolution path for this measurement in the future

STXS: Bosonic Channels

STXS: xsec measured in several bins of phase space to reduce model dependence and allow easy interpretation to for BSM effects (EFT)

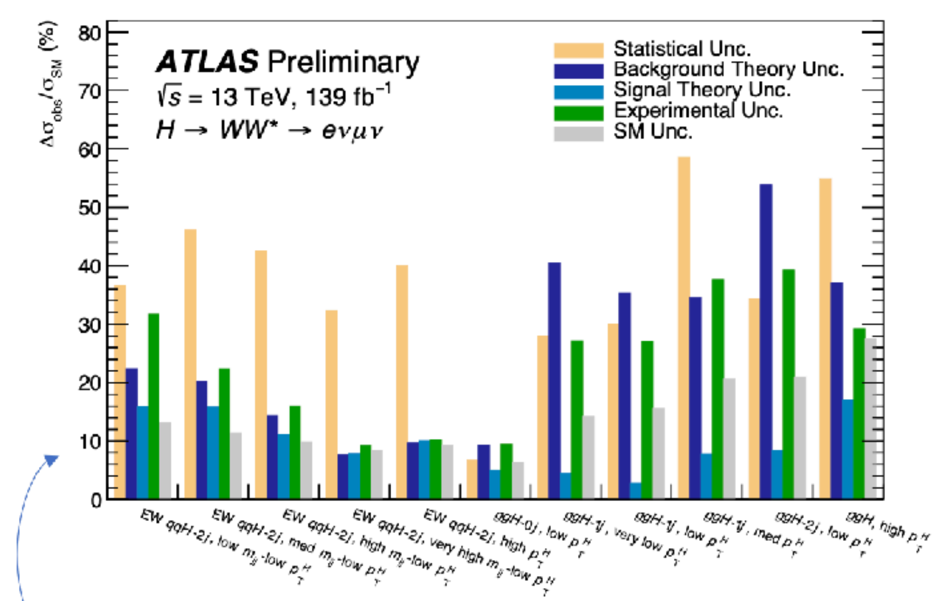
Marchiori, Errico, Hayes





WW(eνμν), competitive in particular for qqH

γγ with full Run2 already capable to make kinematic bins in several WH/ZH and ttH productions modes (STXS stage 1.2)

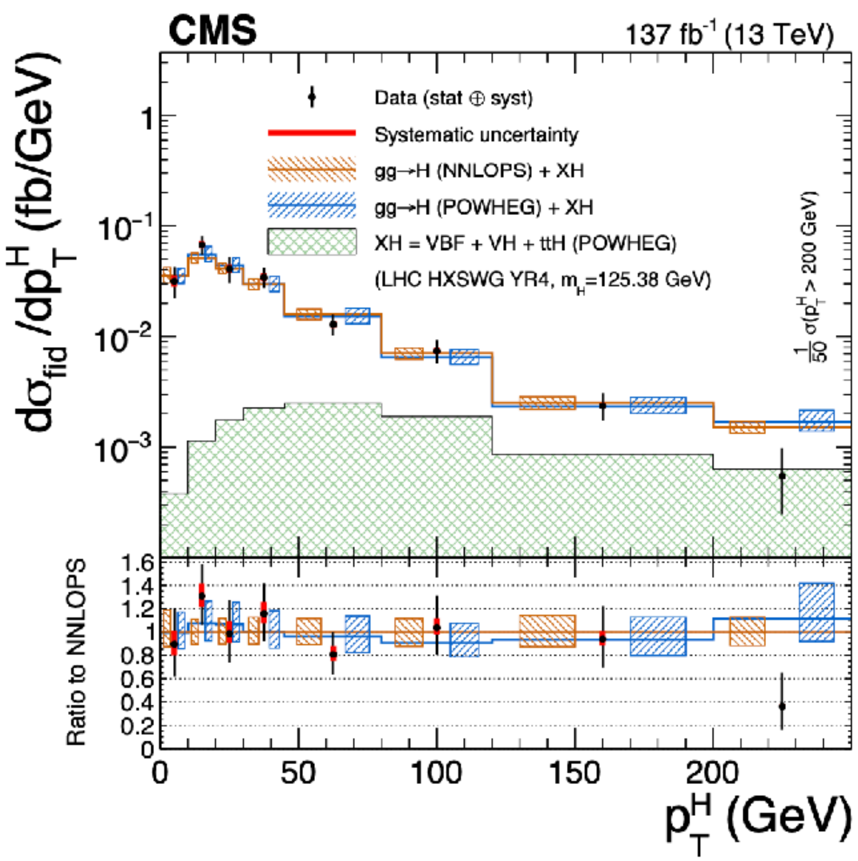


Signal theory uncertainties no longer dominate.

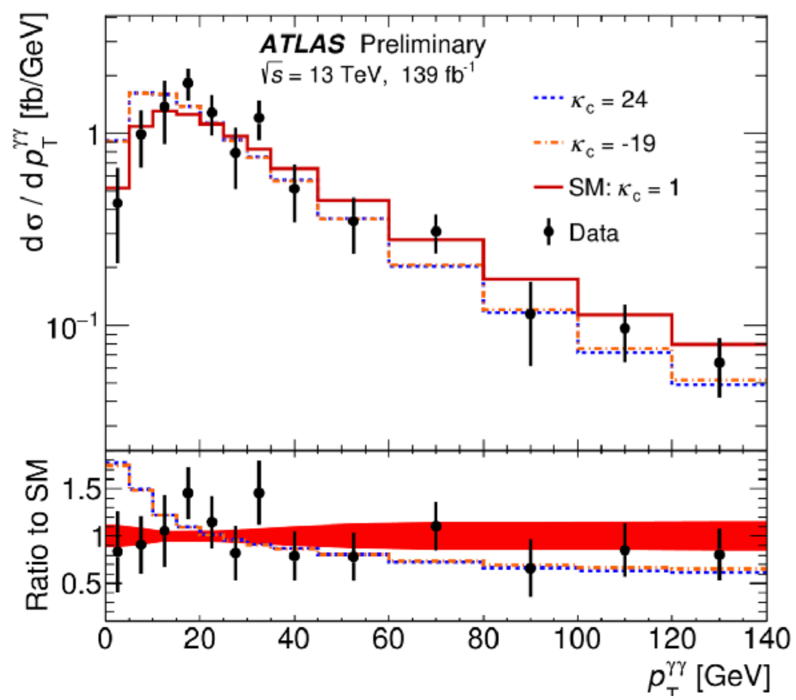
BOSONIC CHANNELS

Differential fiducial cross-sections. Higgs pT carries sensitivity to look for BSM: low p_T k_C,k_b, UV physics @ high p_T)

Marchiori, Errico



Coefficient	Observed 95% CL limit	Expected 95% CL limit
κ_c	$[-19, 24]$	$[-15, 19]$

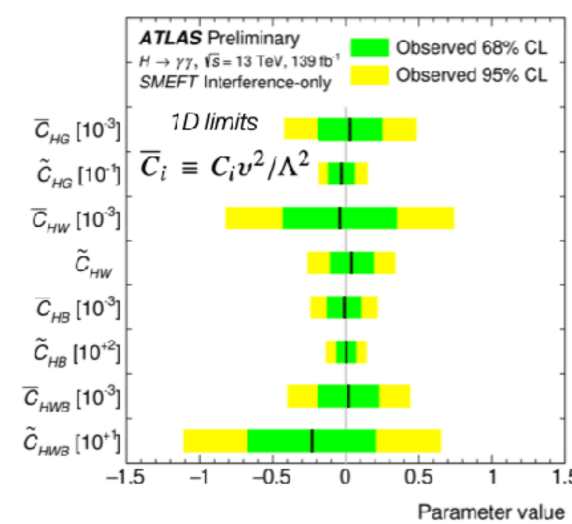


k_C bounds complementary to direct H→cc searches

CMS: full Run2 differential xsec also from WW(eνμν)

For Run3 possibility to start looking at differential fiducial xsec for specific production modes

BSM couplings to gauge bosons (EFT)



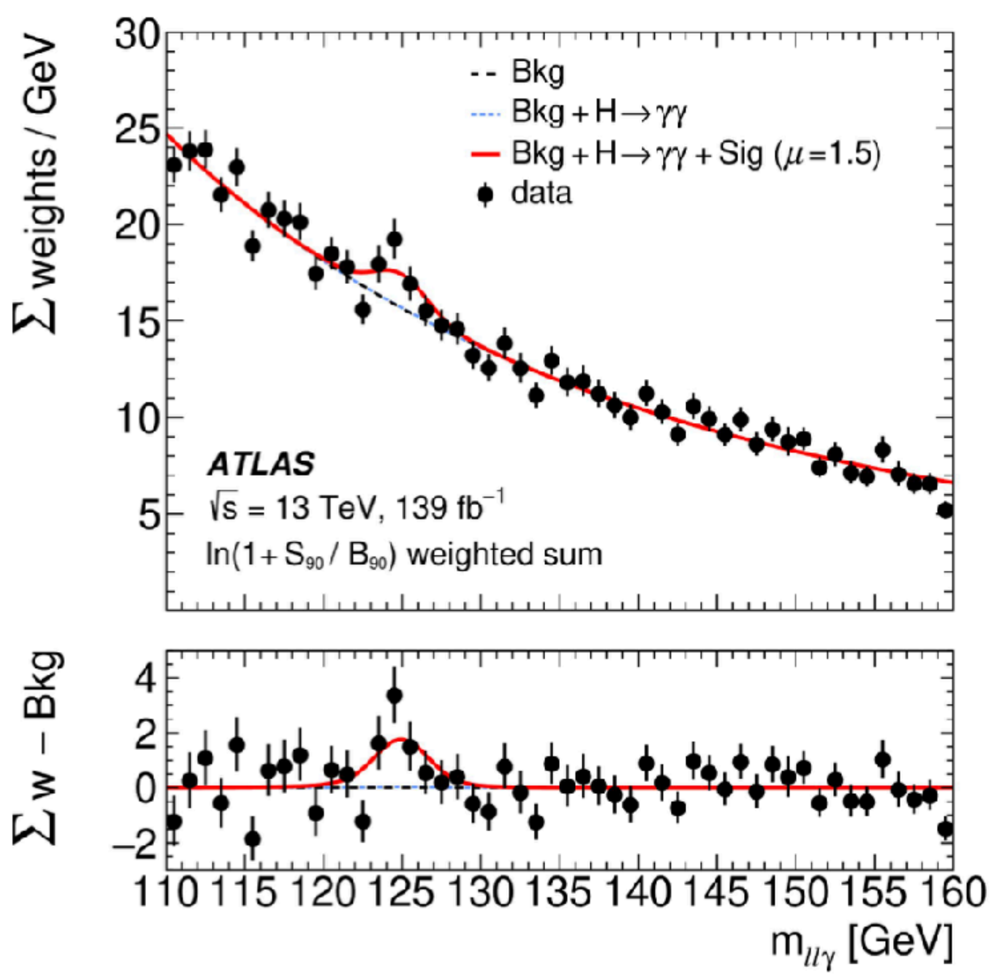
EFT (SMEFT) sensitivity from shape and normalisations

RARE CHANNELS

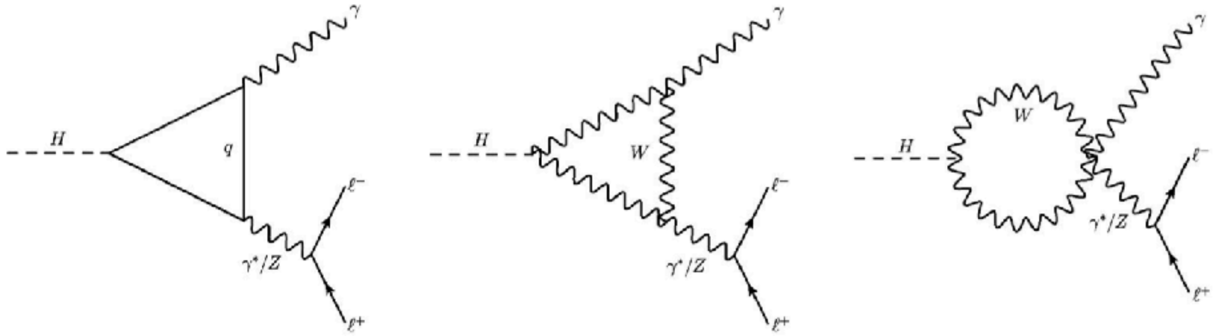
Rarer channels starting to be on-sight: H→Zɣ, H→llɣ

Evidence for H→llɣ channel

Marzocchi, Milic



- $H\rightarrow ll\gamma$ decays explored where $l = e, \mu$
- Analyses separated in
  - Low-mass $m_{ll} < 30$ GeV
  - m_{ll} close to Z peak



Phys. Lett. B 819 (2021) 136412

- First evidence for $H\rightarrow ll\gamma$!
  - 3.2 σ observed, 2.1 σ expected
  - xsec × BR = $8.7^{2.8}_{-2.7}$ fb

3RD GEN COUPLING: TTH

Run2 legacy: discovery of the Yukawa mechanism for all 3rd gen fermions (t,b,τ)

Le Bihanne, Chisholm

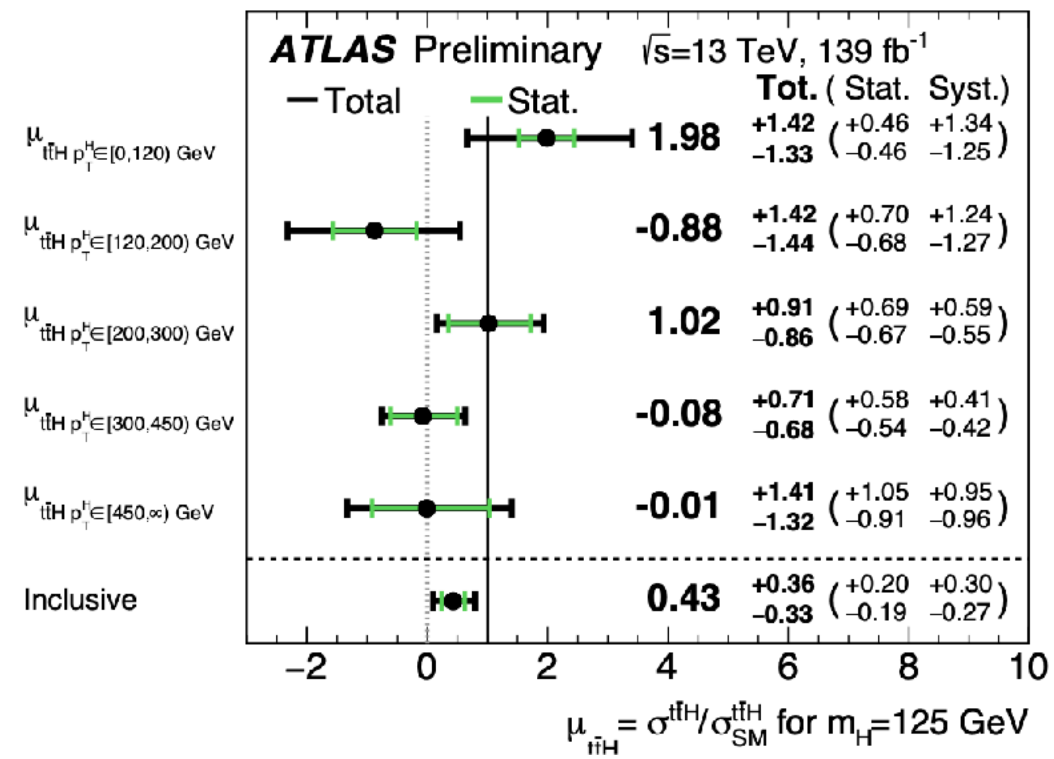
ttH: 5σ from combination in 2018, now with full Run2 probing ttH @ ~ 20-30% in single channels

CMS ttH

		Signal strength	Obs/Exp significances
Multi-leptons H→WW, ZZ, $\tau\tau$	**137 fb-1**	0.92 + 0.26 - 0.23	**4.7σ** / 5.2σ (ttH) 1.4σ / 0.3σ (tH)
$H \to b\bar{b}$	77 fb-1	1.15 + 0.32 - 0.29	3.9σ / 3.5σ
$H \to \gamma\gamma$	**137 fb-1**	1.38 + 0.36 - 0.29	**6.6σ** / 4.7σ

Last results →

First dedicated measurements for tH (multi lepton, γγ)

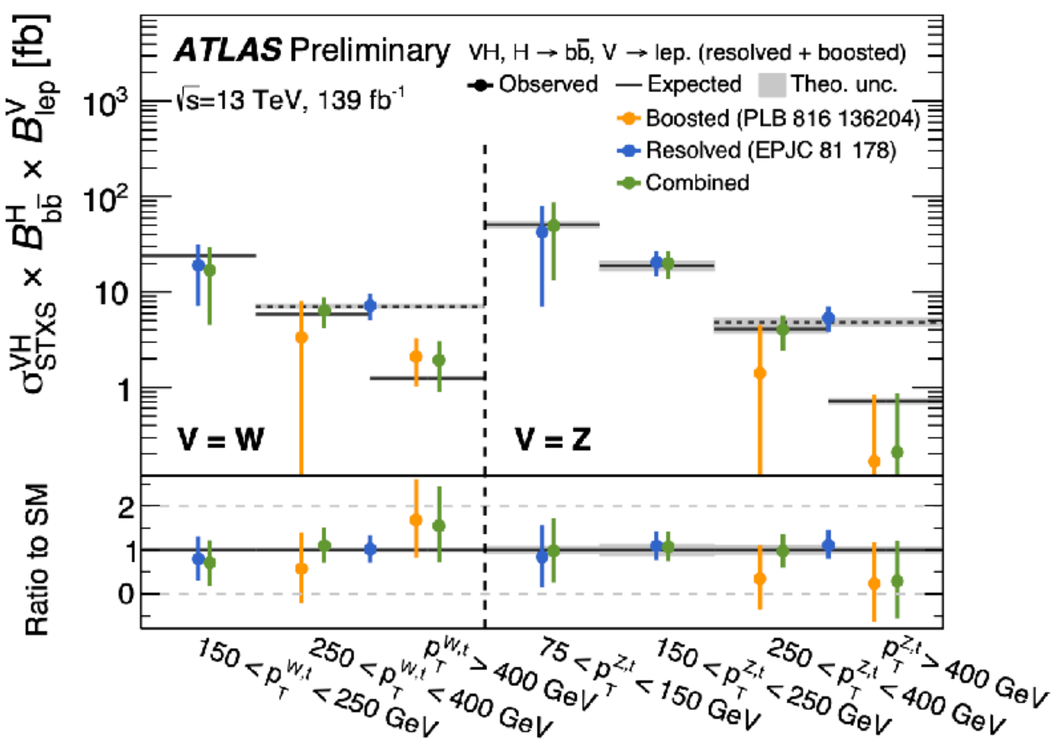


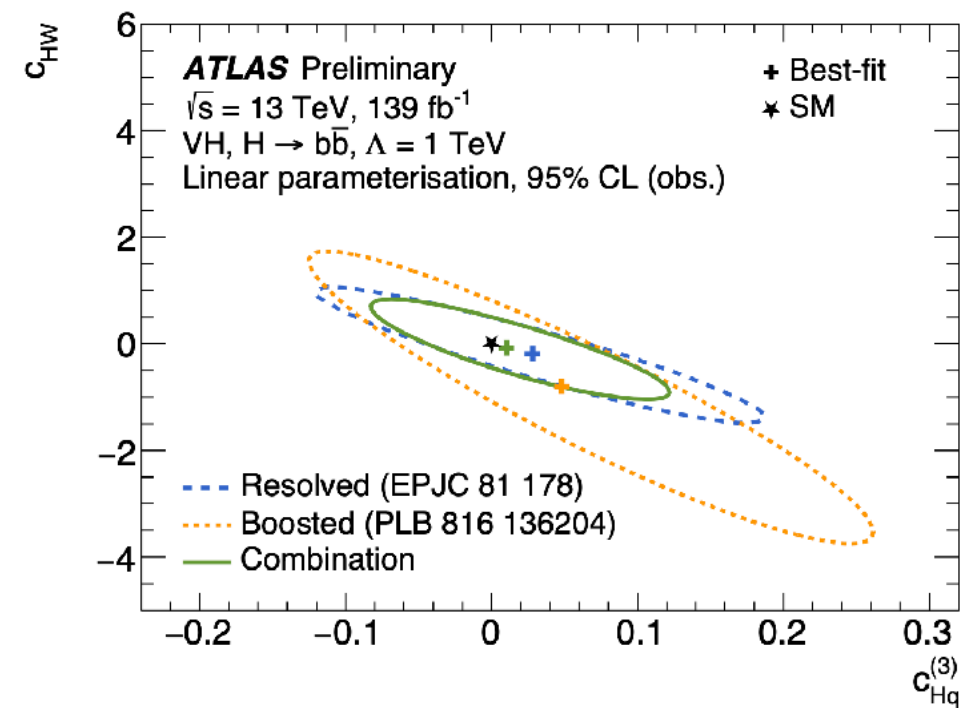
ATLAS ttH→bb: xsec also in pt(H) bins

3RD GEN COUPLING: VH(bb)

VH(→bb): new analysis from ATLAS combining resolved and boosted topology in STXS bins $p_t(V)$

Le Bihanne, Chisholm

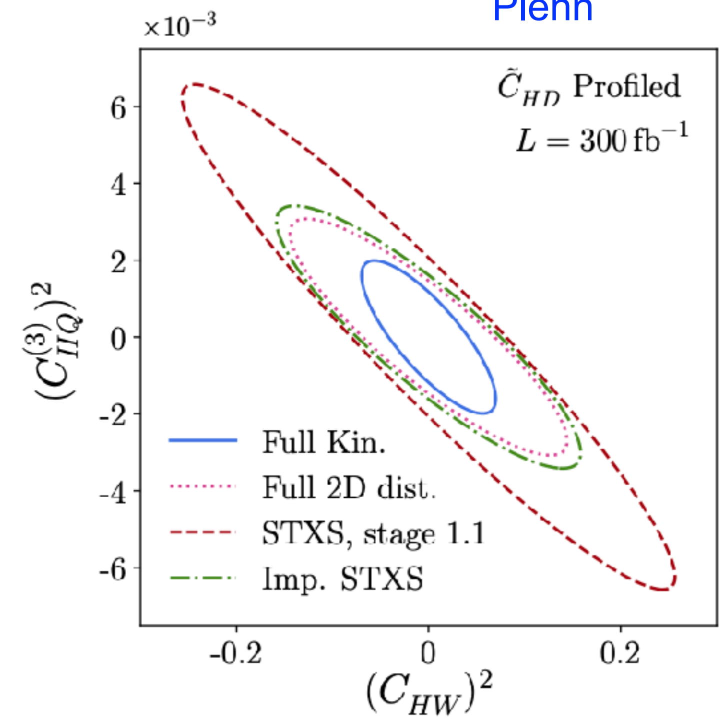




Sensitivity in EFT improved

A potential application for Run3: more granular 2D measurement (pT(W) vs mT) guarantees better EFT constraints for VH

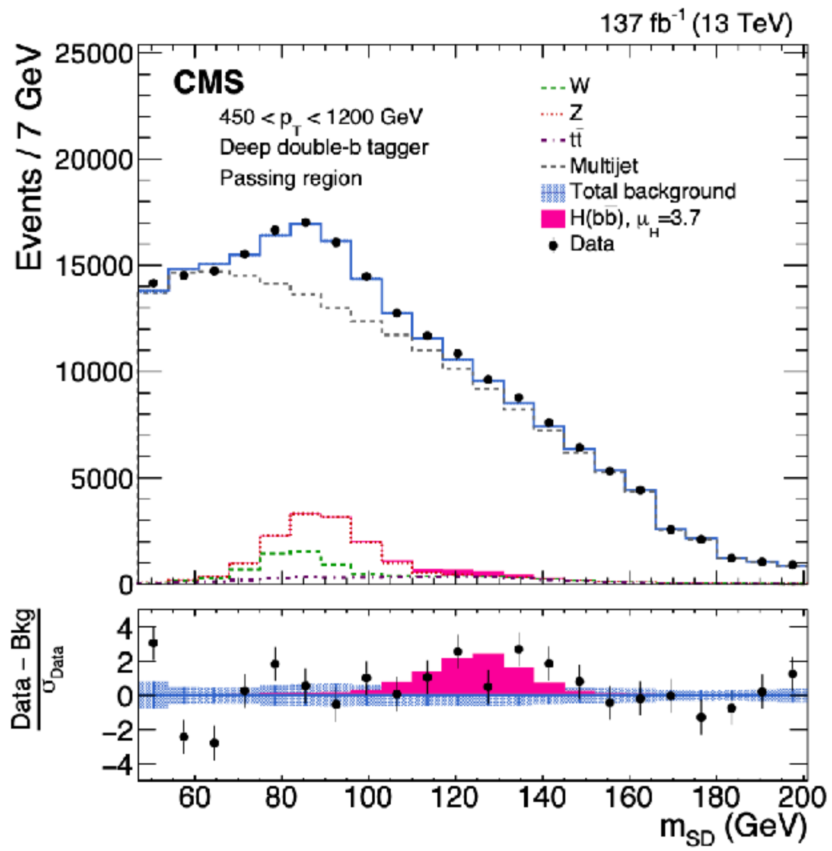
Plehn

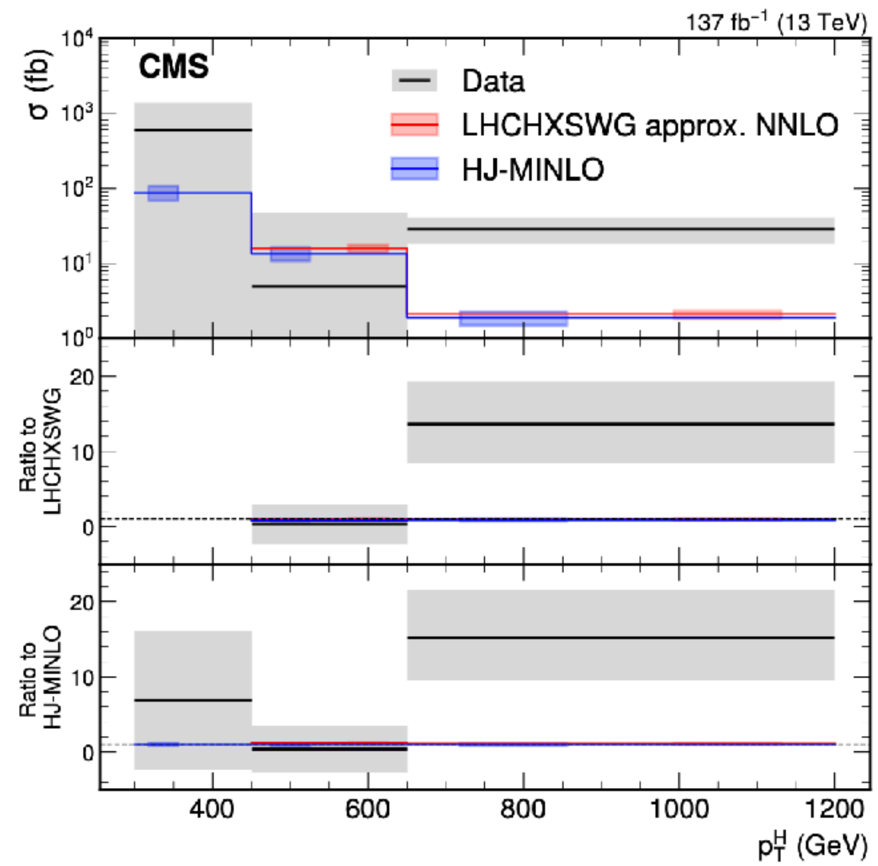


BOOSTED H(bb)

Boosted H(→bb): considered "impossible" before Run2, now continuously improving thanks to improvements to boosted topology tagging

Le Bihanne, Chisholm





2.6σ local significance

p_T^H>650 GeV

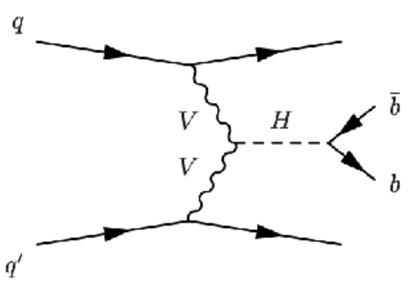
HJ-MINLO for modelling

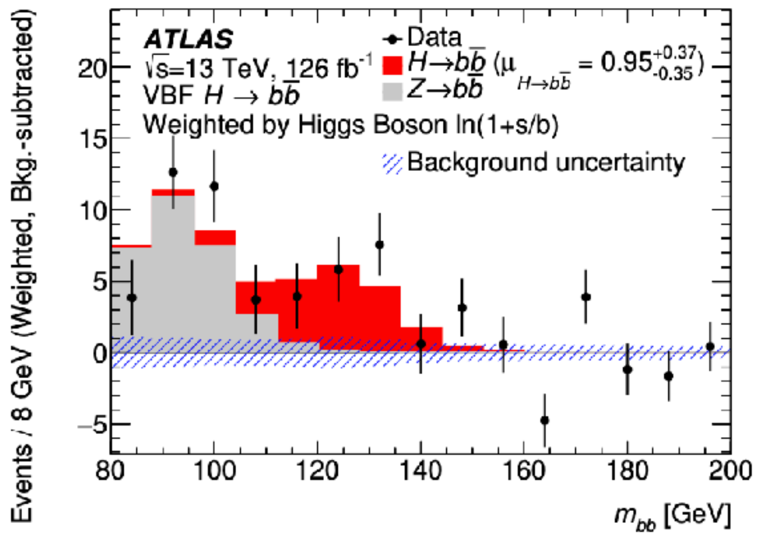
$\mu = 3.7 \pm 1.2(stat)^{+0.8}_{-0.7}(sys)^{+0.8}_{-0.5}(theo)$, **1.9σ observed w.r.t. SM (2.5σ vs background)**

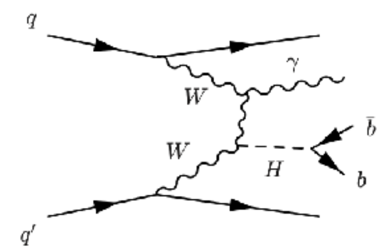
Discrepancy in the highest pT regions, some excess also for **ATLAS-CONF-2021-010**

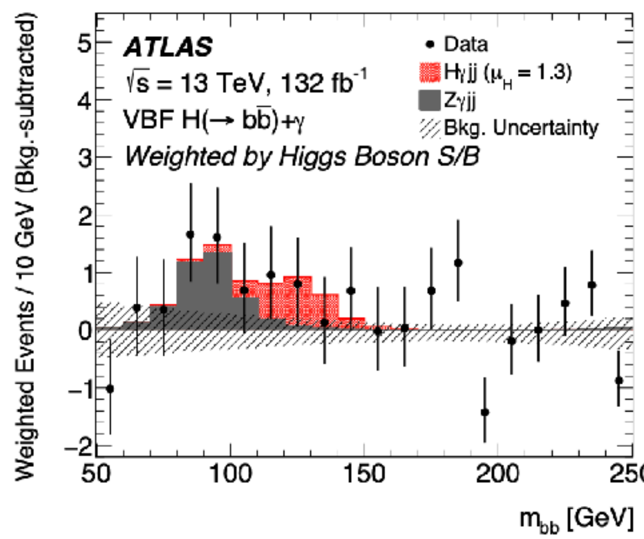
p_T^H	μ_H	σ_H [fb]	
		Best fit	95% CL upper limit
> 450 GeV	0.7 ± 3.3	13 ± 52 (stat.) ± 32 (syst.) ± 3 (theory)	144
> 1 TeV	26 ± 31	3.4 ± 3.9 (stat.) ± 1.0 (syst.) ± 0.8 (theory)	10.3

VBF H(bb)





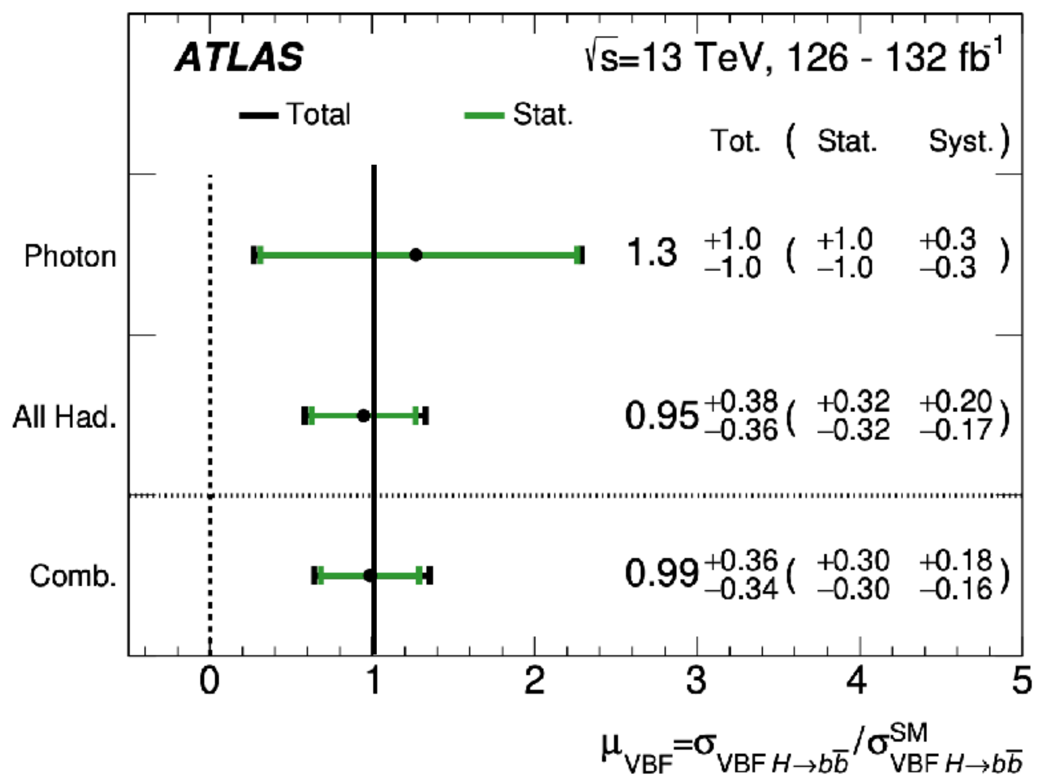




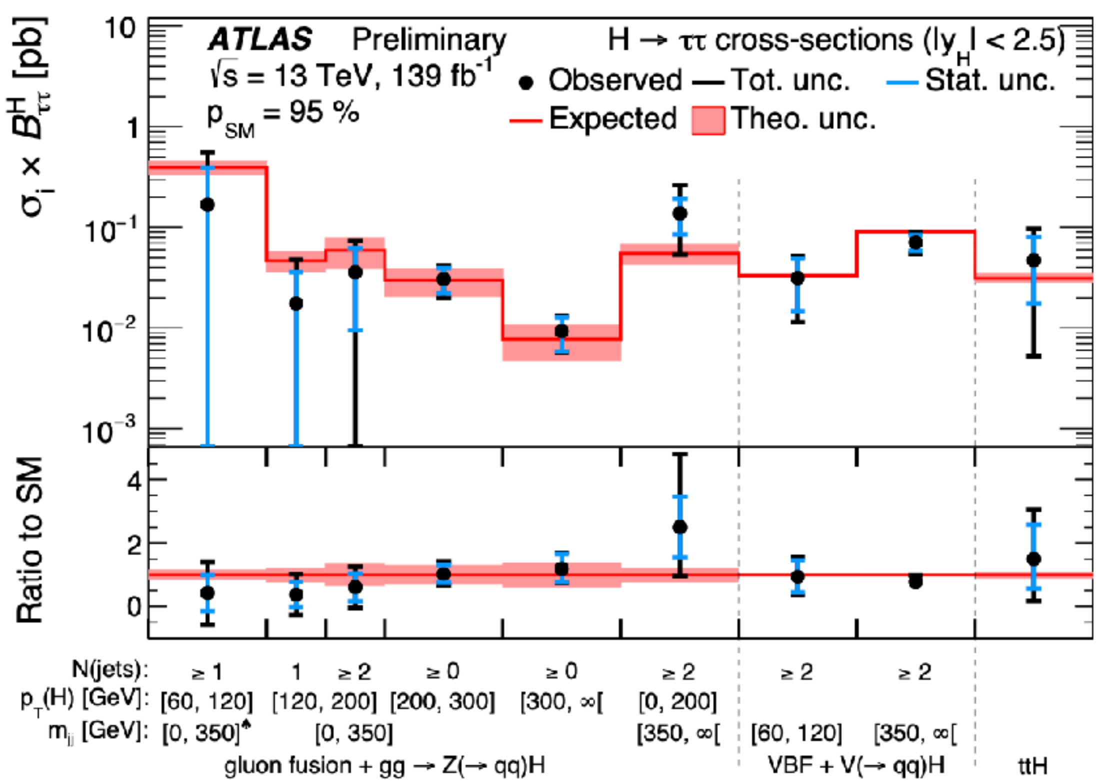
Le Bihanne, Chisholm

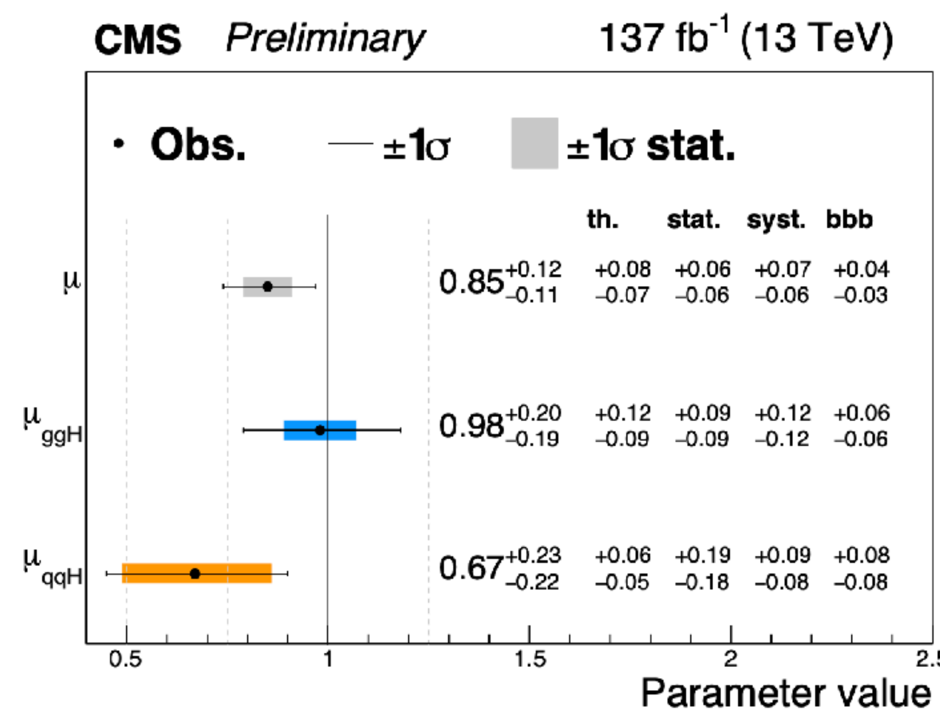
Another "unforeseen" channel. Combining 2 channels: full hadronic (bbjj) with bbjj+ɣ

3σ for VBF in H→bb alone



3RD GEN COUPLING: H($\tau\tau$)

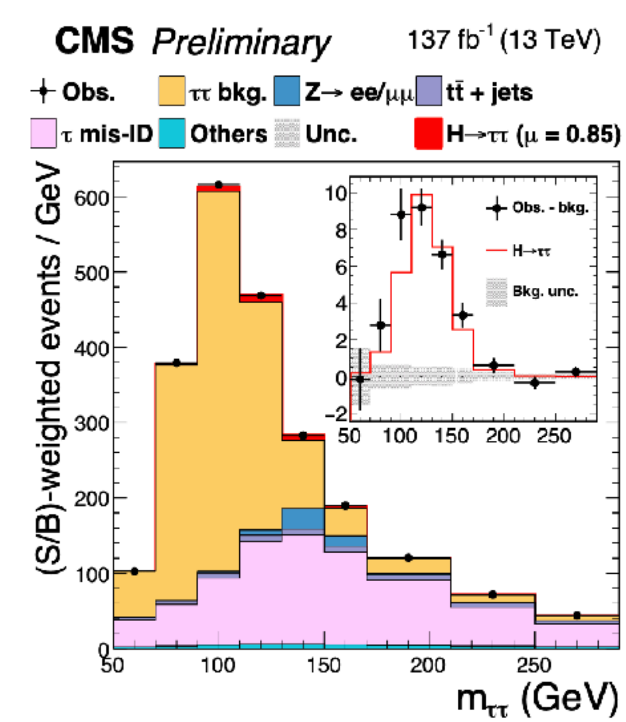




Le Bihanne, Chisholm

Probing H($\tau\tau$) coupling at ~12% level with full Run2 stat

Run2 analysis making use of improved τ tagging, mass reconstruction and data-driven Z→$\tau\tau$ techniques (embedding)



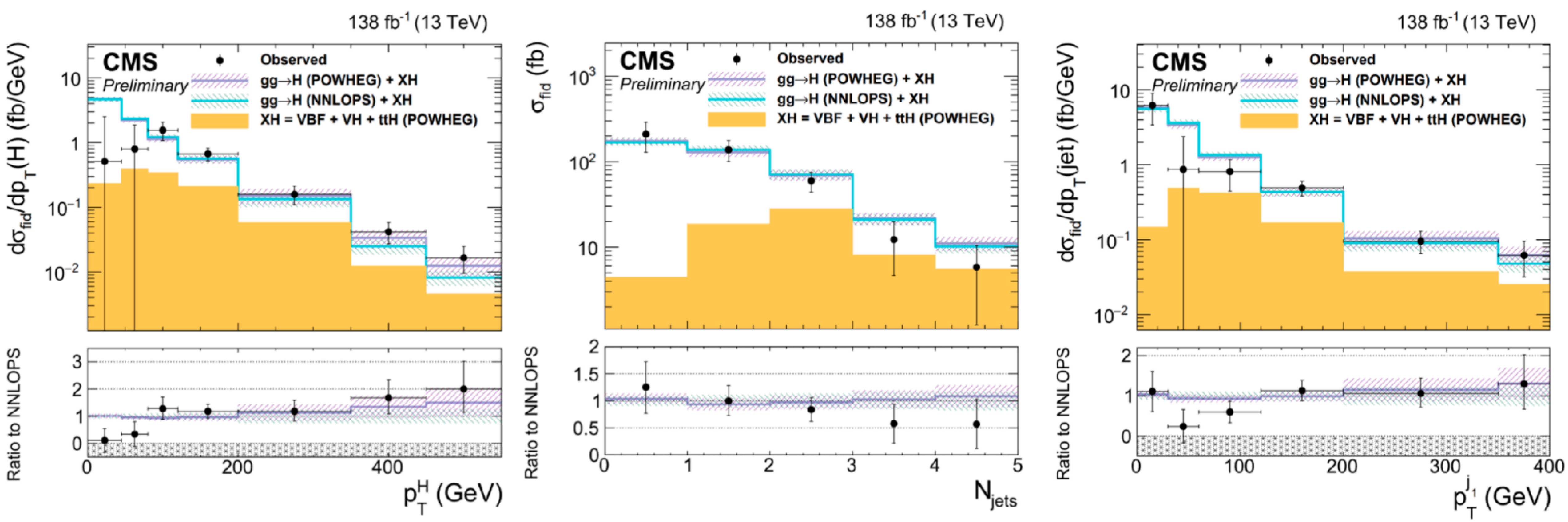
$m_{\tau\tau}$ from simplified matrix-element algorithm

3RD GEN COUPLING: H($\tau\tau$)

Le Bihanne, Chisholm, Loeliger

First differential cross section measurement at LHC in fiducial volume of tau decay products!

Check variables sensitive to new physics, measurement integrates over several production modes



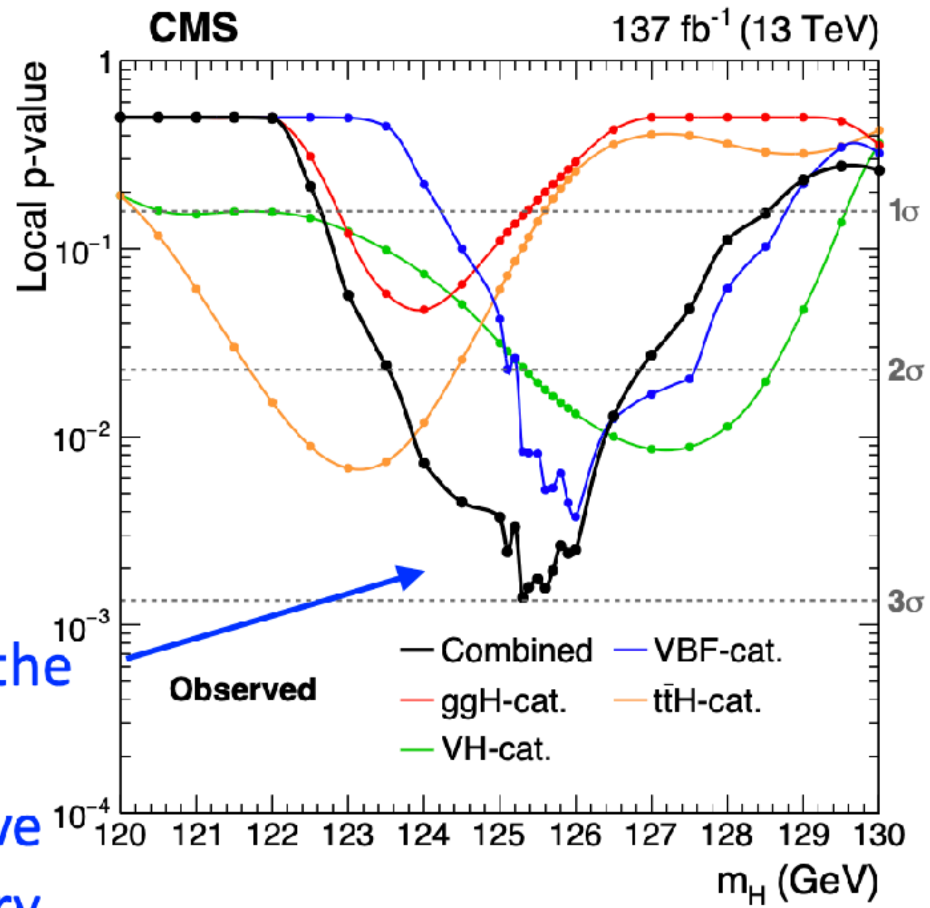
SM P-Value: 17% SM P-Value: 71% SM P-Value: 45%

Competitive precision w.r.t. other final states at high p_T^H, high jet multiplicity.

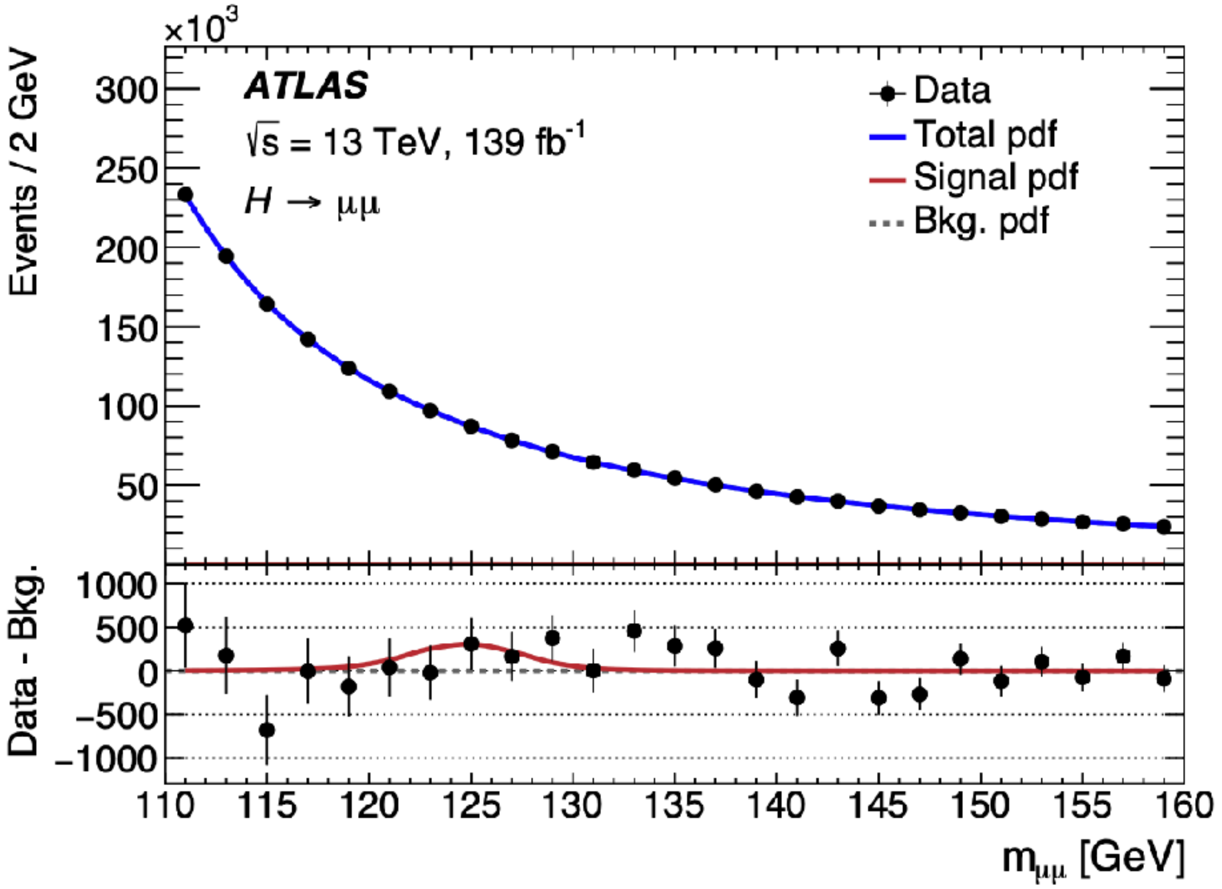
2ND GEN: H→μμ

Le Bihanne, Chisholm, Marzocchi, Milic

Another fundamental milestone for Run2: 2nd gen coupling H→μμ



VBF is the most sensitive category



CMS: evidence for H→μμ

- **3.0σ observed** (2.5σ expected)
- Signal strength μ = 1.19 ± 0.40 (stat) ± 0.15 (syst)

- Observed (expected) significance 2.0 (1.7) σ (w.r.t B only)

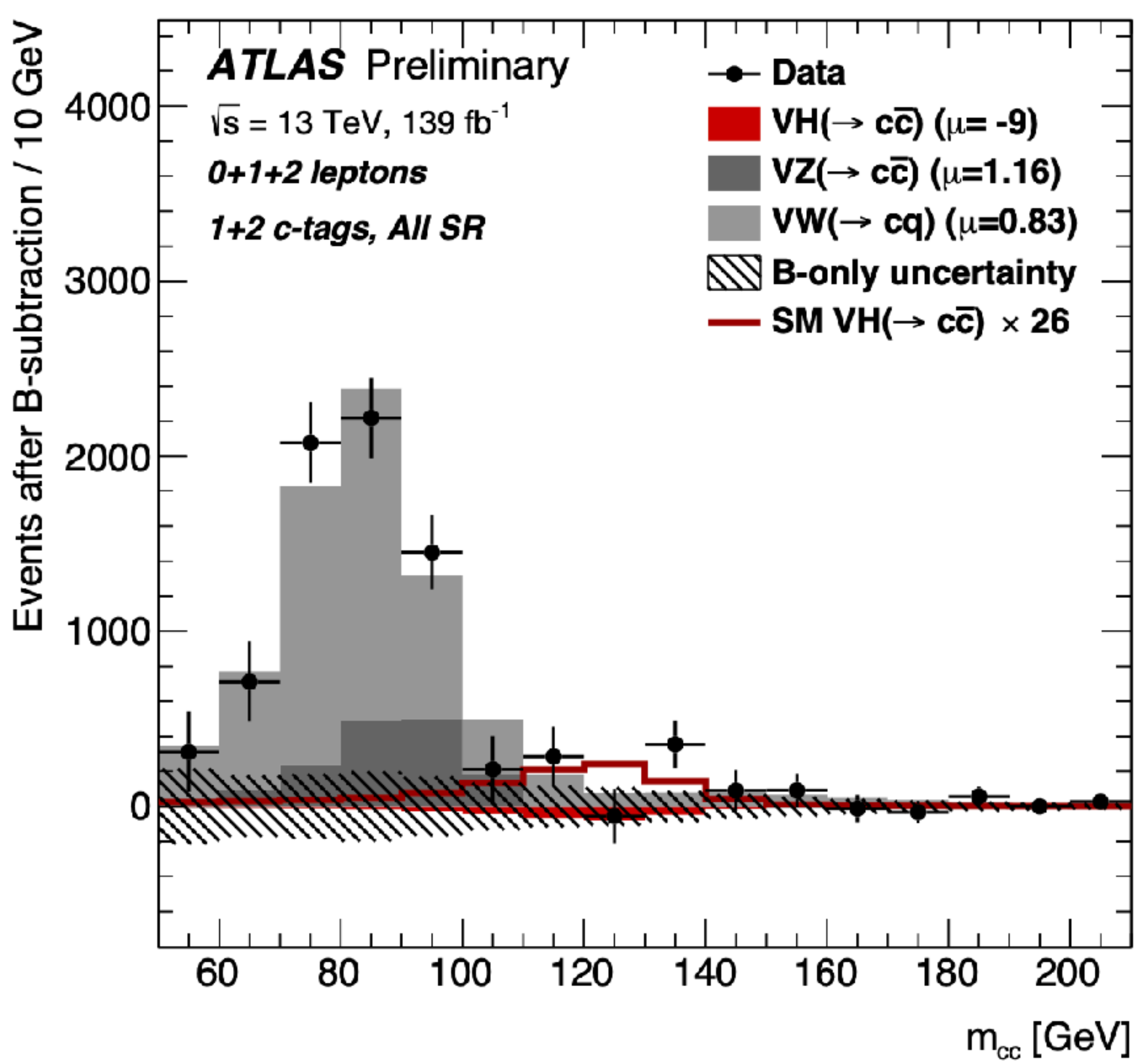
Better di-muon mass resolution for CMS: ~40% better

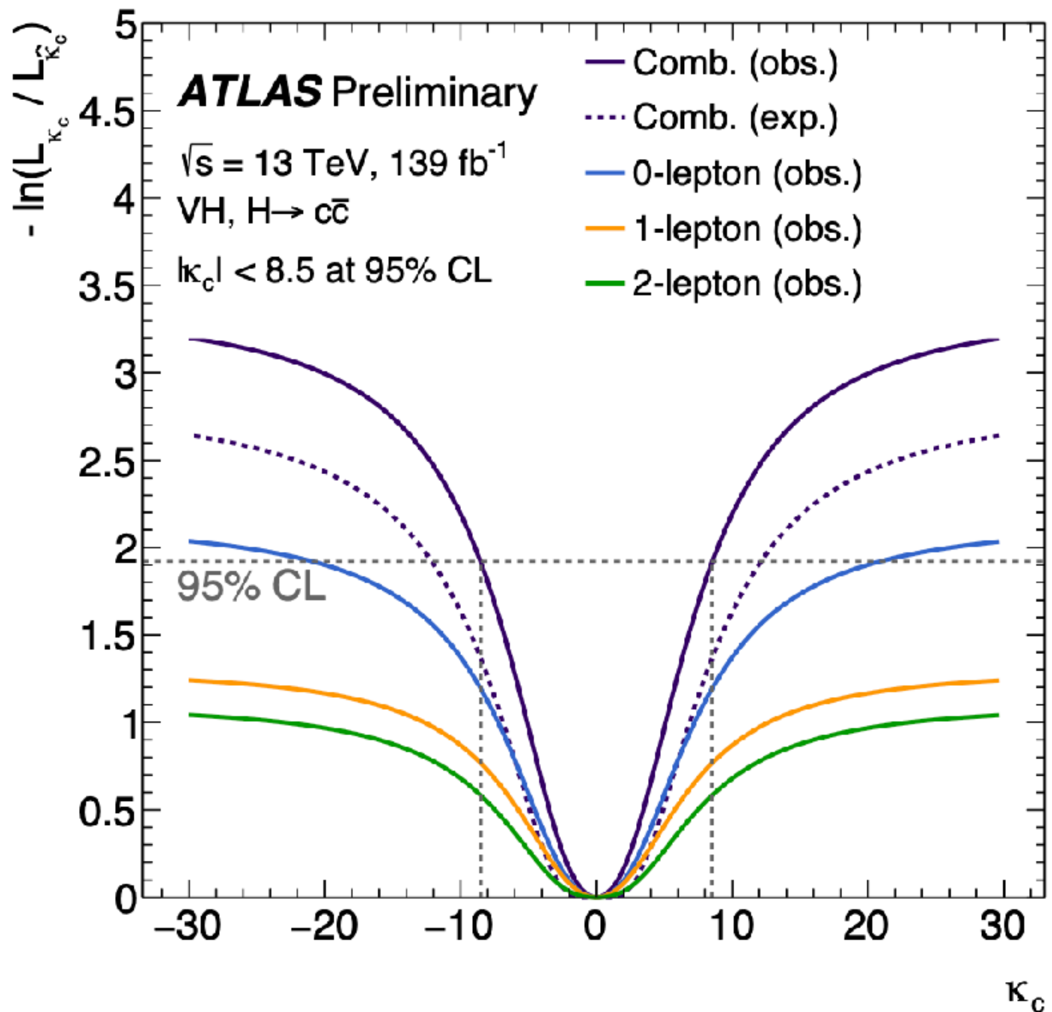
2ND GEN: H→cc

ATLAS: full Run2 search for H→cc

Mironova

Also here benefit from improved c-tagging and more event categories





$$\mu = \kappa_c^2 / \left(1 + \mathcal{B}(H \to c\bar{c}) \cdot (\kappa_c^2 - 1)\right)$$

Prospects for sensitivity @ ~ 2xSM with LHCb at HL-LHC

Zuliani

CP Violation In Fermion Coupling

Le Bihanne, Chisholm, Gori

Generalised Yukawa coupling, CP violation can occur at tree level e.g. 2HDM

$$L_Y = \frac{m_f}{v} H(\kappa_f \bar{f} f + \tilde{\kappa}_f \bar{f} i \gamma_5 f)$$ **CP violating angle** $$\phi_{ff} = \frac{\kappa_f}{\tilde{\kappa}_f}, \quad \phi_{ff} = 0 \text{ in SM}$$

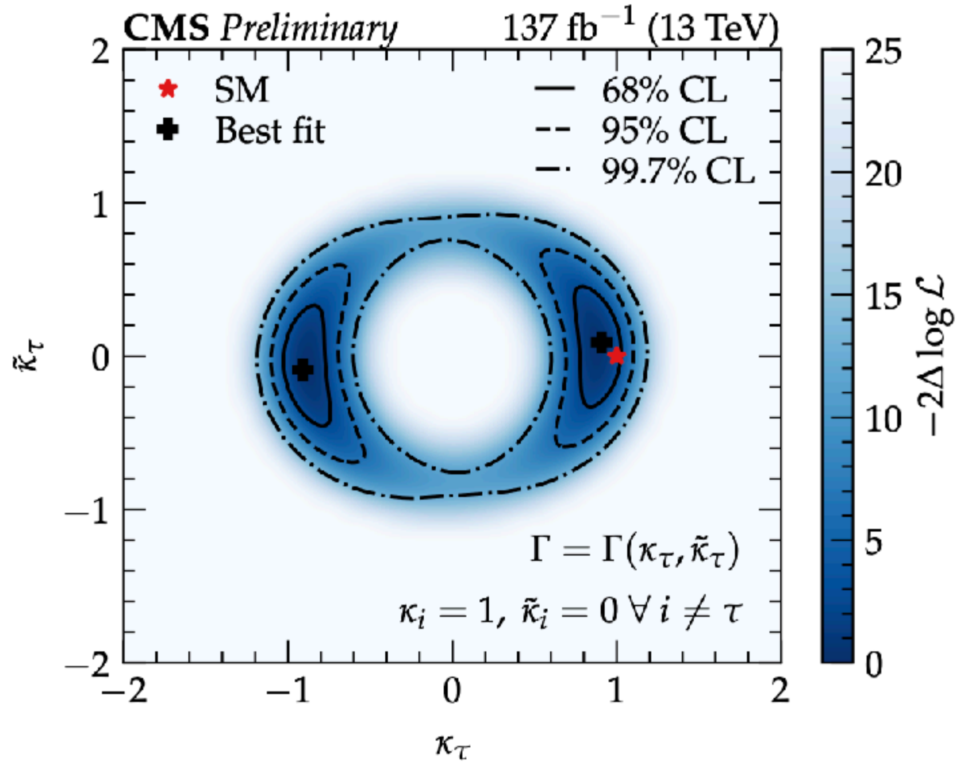
Search for CPV in H$\tau\tau$: impressive experimental result

Angle between tau decay planes allows to reconstruct $\phi_{\tau\tau}$

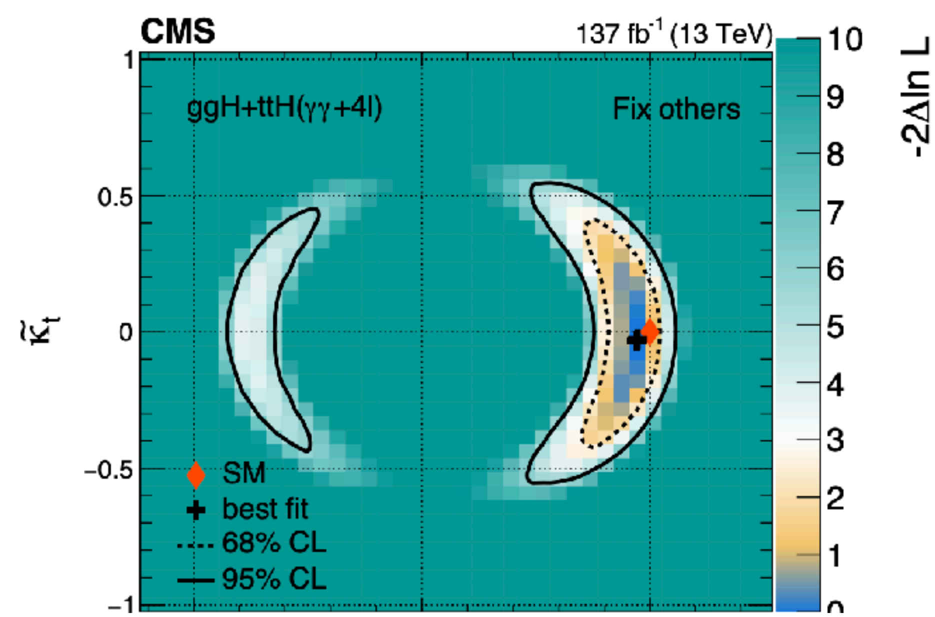
Several techniques depending on τ decay mode $\mu^{\pm}, \pi^{\pm}, \rho^{\pm}, a_1^{1pr,3pr}$

→pure CP-odd hypothesis excluded at 3.2σ

$\phi_{\tau\tau} = 4 \pm 17^{\circ}$ @ 68% CL



CPV in ttH: combination of γγ and 4l (also taking into account rate change for ggH)



$$f_{CP}^{ttH} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} sign(\tilde{\kappa}_t/\kappa_t) = 0.00 \pm 0.33$$

→ pure CP-odd hypothesis excluded at 3.2σ

Also ATLAS excluding pure CP-odd @3.9σ

HIGGS COMBINATION

Full Run2 combinations not finalised yet

Bonanomi, Zhou

Decay channel	ggF		VBF		VH		ttH+tH	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	139	77 ⟳	139	77 ⟳	139	⟳	139	77 ⟳
$H \to ZZ^* \to 4\ell$	139	137 ⟳	139	137 ⟳	139	137 ⟳	139	137 ⟳
$H \to WW^*$	36[1] ⟳	36	36[1] ⟳	36		36 ⟳		
$H \to bb$	⟳	36 ⟳	<31[1] ⟳		139	77	36[1] ⟳	77
$H \to \tau\tau$	36[1] ⟳	77 ⟳	36[1] ⟳	77 ⟳	⟳	77	⟳	
ttH multilepton							36[1] ⟳	77 ⟳
$H \to \mu\mu$	139[1]	36 ⟳	139[1]	36 ⟳	139[1]	⟳	139[1]	⟳
$H \to$ invisible		⟳	139[1]		⟳	⟳	⟳	

Full Run 2

⟳ Updated result available; not yet in main public combination

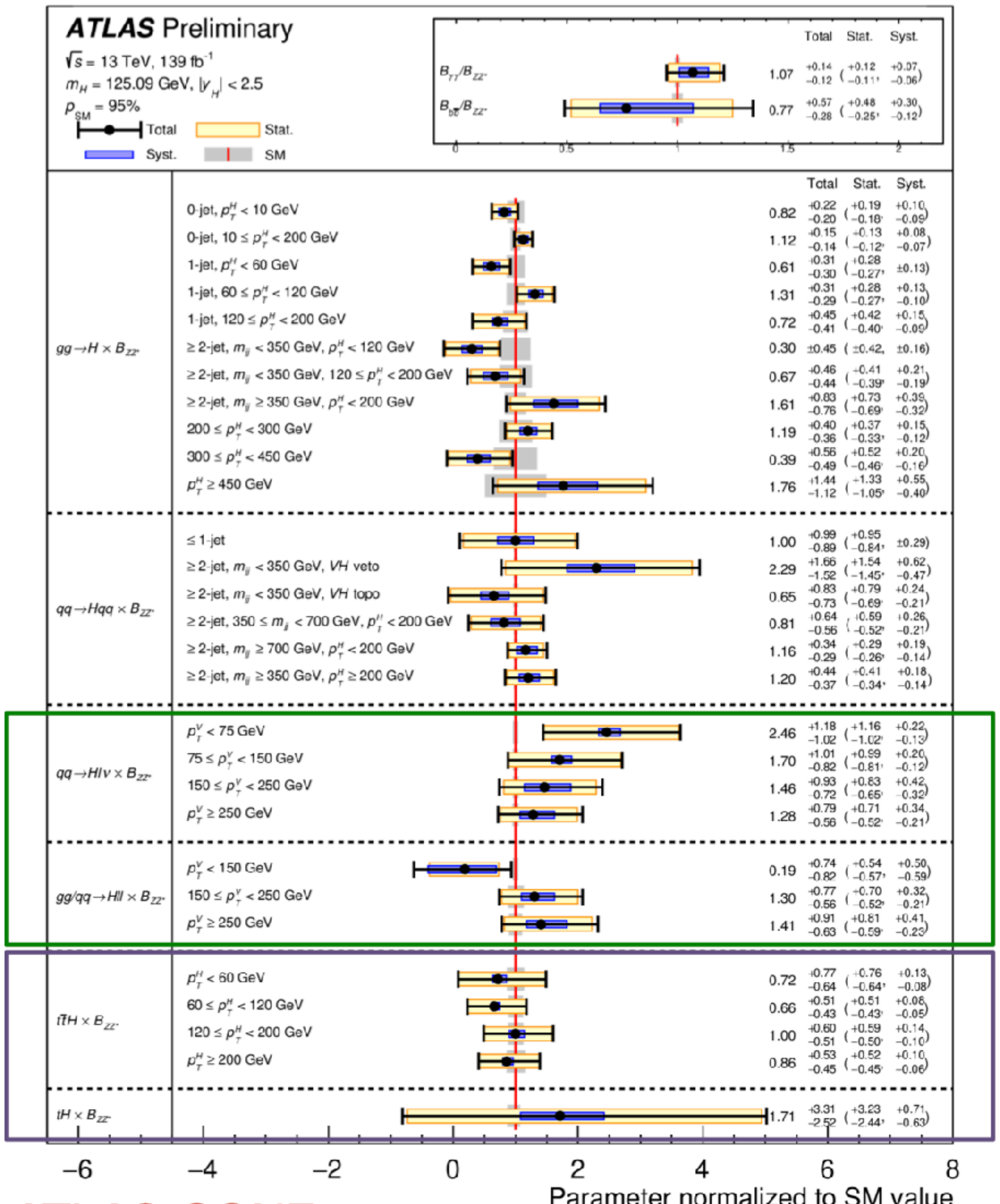
[1] Not used in STXS fit

Global signal strength:

- ATLAS: $\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(\text{stat.}) \pm 0.03(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$
- CMS: $\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\text{stat}) \pm 0.04(\text{exp}) \pm 0.04(\text{theo})$

Higgs Combination: STXS

Bonanomi, Zhou



ATLAS-CONF-2020-027

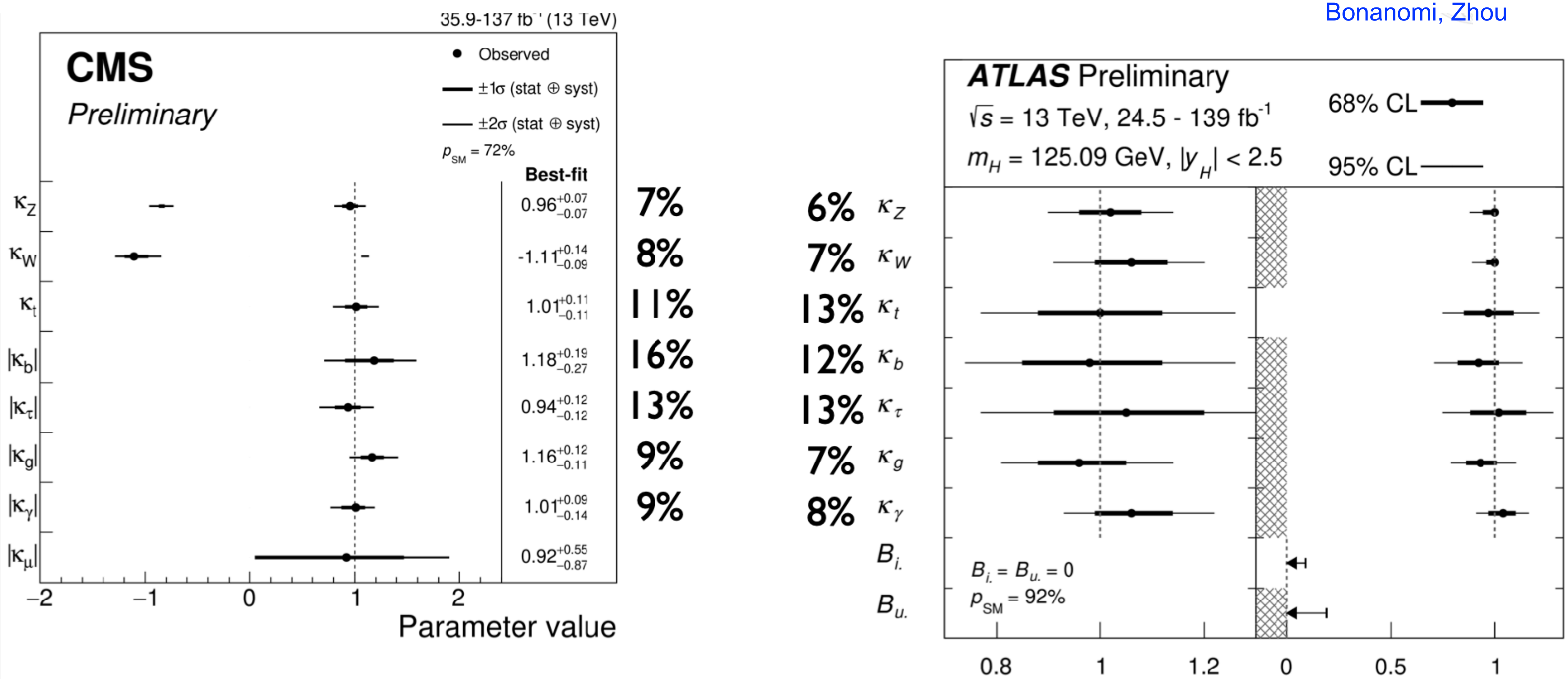
The actual measurements: xsec in several kinematics bins, as much as possible model independent

Overall picture very consistent with SM

All measurements statistically limited

HIGGS COMBINATION: K FRAMEWORK

Bonanomi, Zhou



The infamous 1D scaling…. very well serving Run1 needs

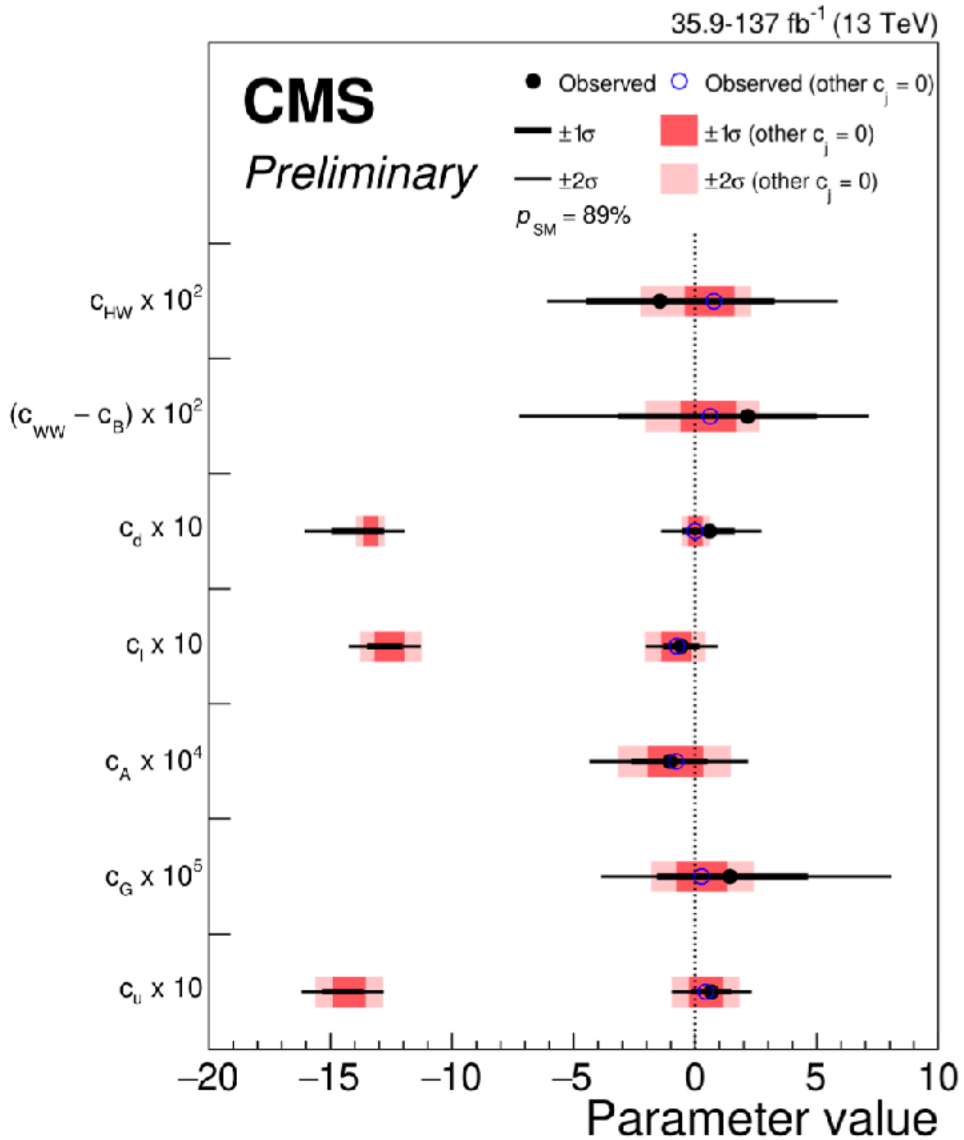
Also here very good agreement with precision <~10% on most couplings.
ATLAS: limit on B_{inv}<9% (invisible searches in the dataset) and $B_{undetected}$<19% @95%CL

Combination

EFT needed for proper interpretation of kinematics (shape) and normalisation in signal and background, however a very large space to be constrained (a global effort)

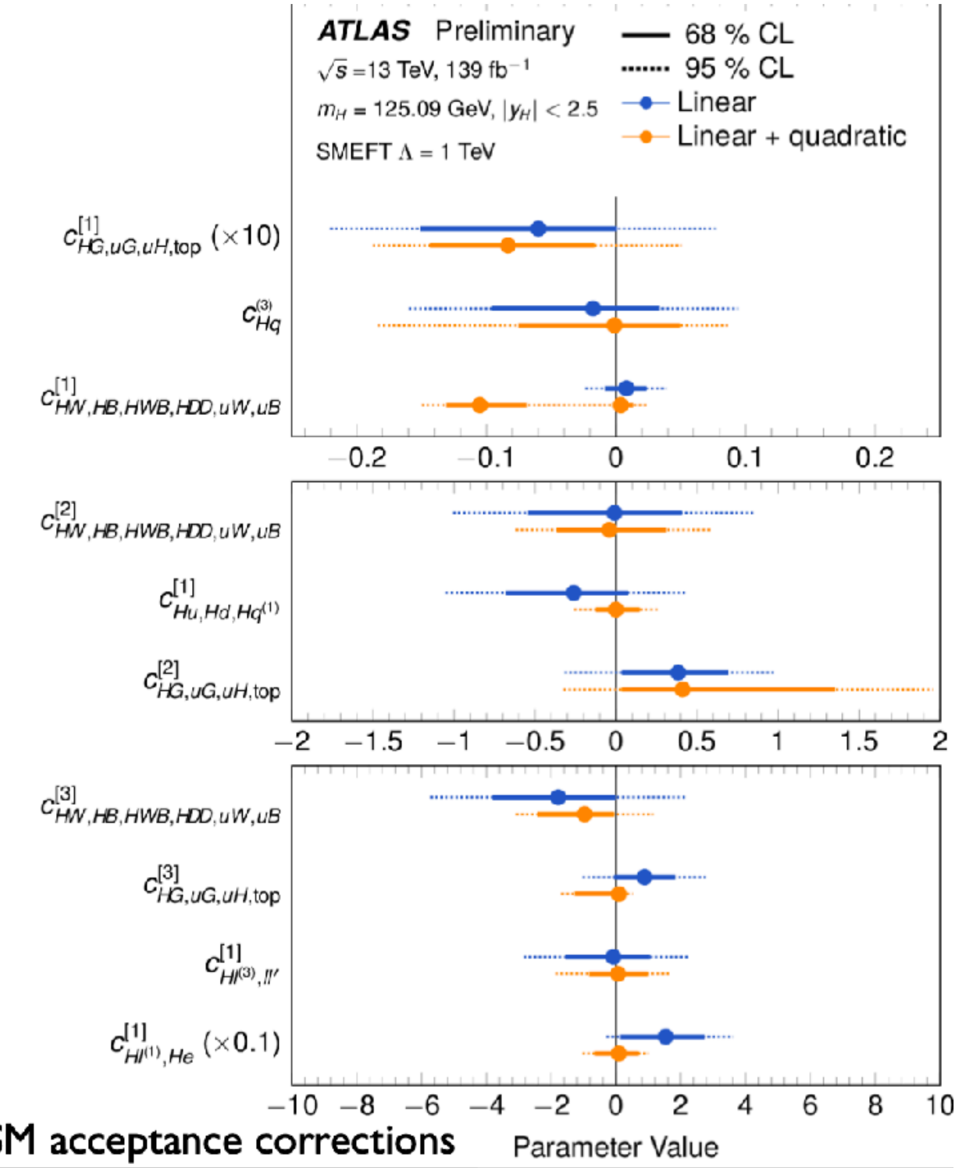
CMS+ATLAS combination will surely be a good occasion to harmonise treatment

Bonanomi, Zhou



No BSM acceptance corrections

- Leading D=6 CP-even EFT operators
- Different EFT bases:
  - HEL vs SMEFT
- Different procedures
  - Finding (non-) sensitive directions
  - Acceptance corrections



BSM acceptance corrections for $H \rightarrow ZZ^* \rightarrow 4\ell$

Karsten Köneke 6

Global Fits

Theory

- **(N)NLO QCD + NLO EW** SM XS
- **NLO-QCD, linear and quadratic,** EFT (**SMEFT@NLO**)
- **PDFs,** avoid redundancy (no top)

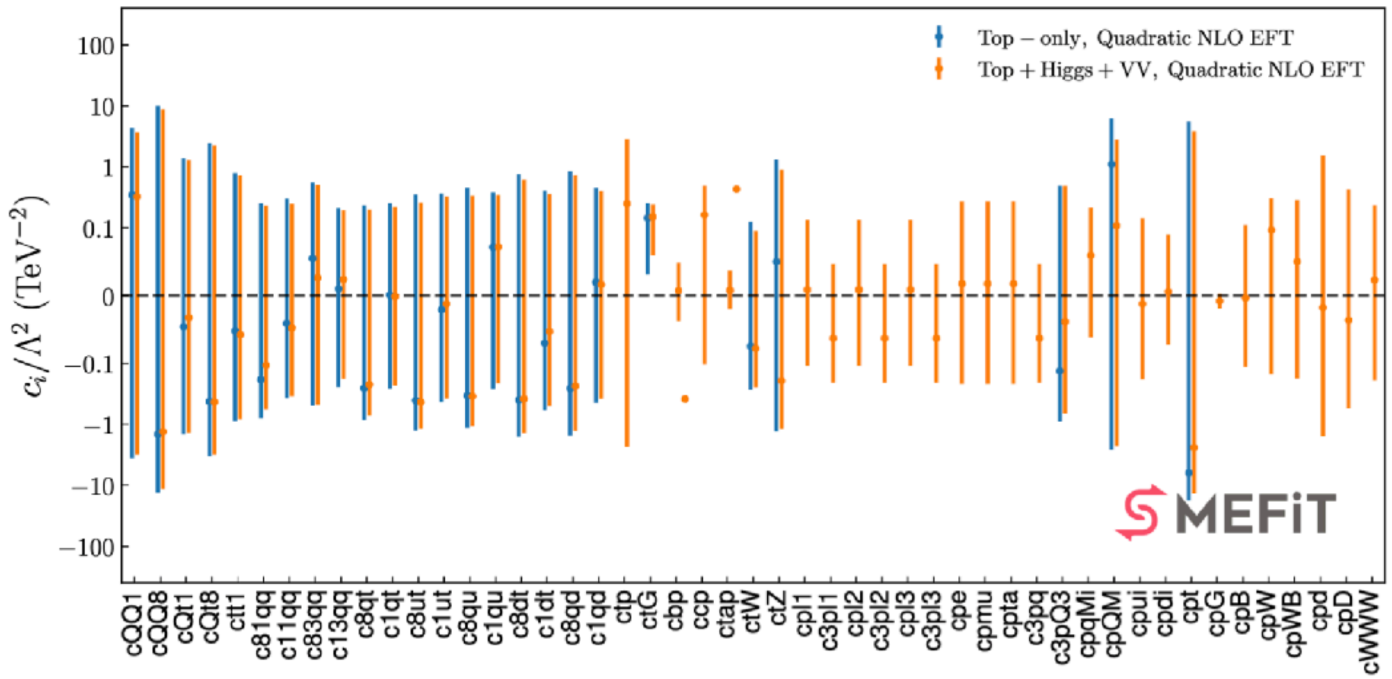
Data

- **Higgs data** (inclusive, diff, STXS)
- **Top quark data**
- **Diboson production** (LEP + LHC)

Mantani

SMEFiT

$$\mathcal{O} = \mathcal{O}_{SM} + \frac{C_i}{\Lambda^2}\,\mathcal{O}_i^{INT} + \frac{C_i\,C_j}{\Lambda^4}\,\mathcal{O}_{ij}^{SQ}$$



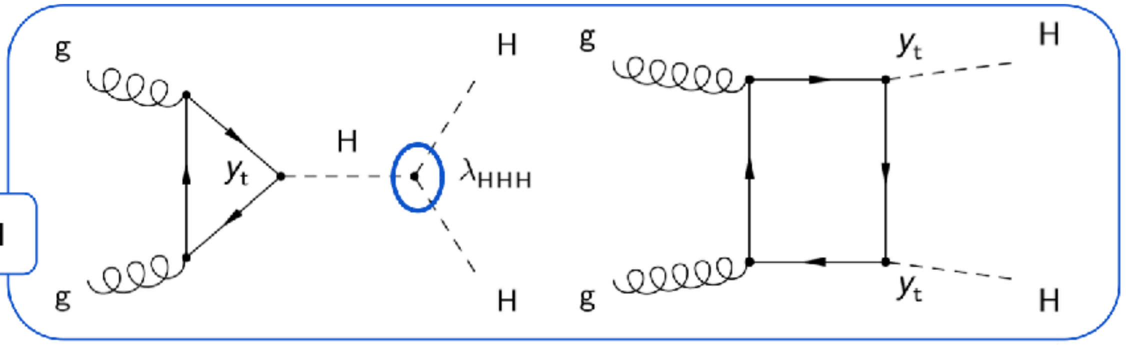
First results trying to coherently use of measurements from different sectors

A dedicated WG at LHC: LHC EFT group https://lpcc.web.cern.ch/lhc-eft-wg

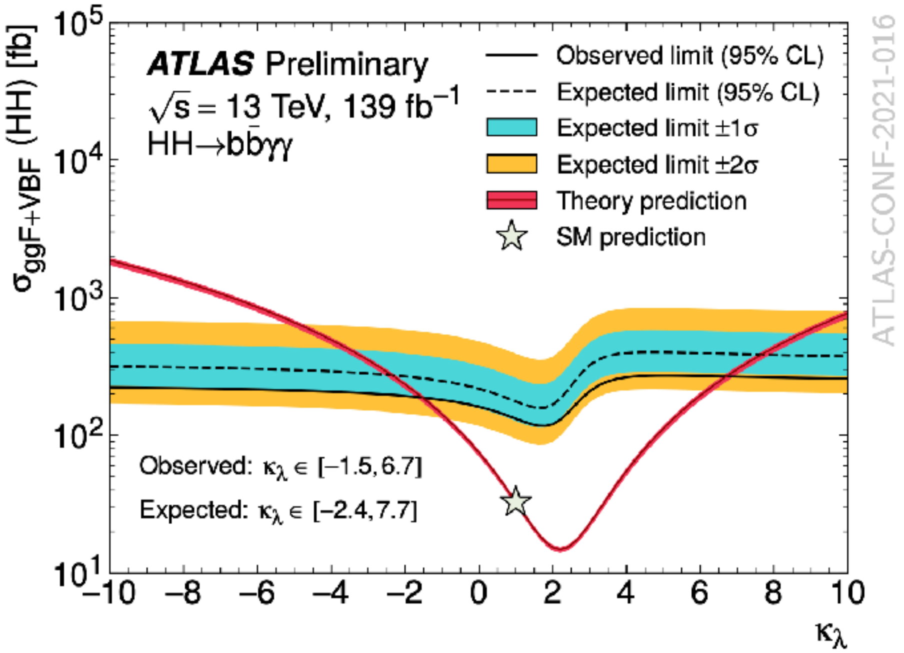
NON RESONANT HH

Bokan, Cappati, Guerrero Ibarra, Lenz, Hulsker

ggHH

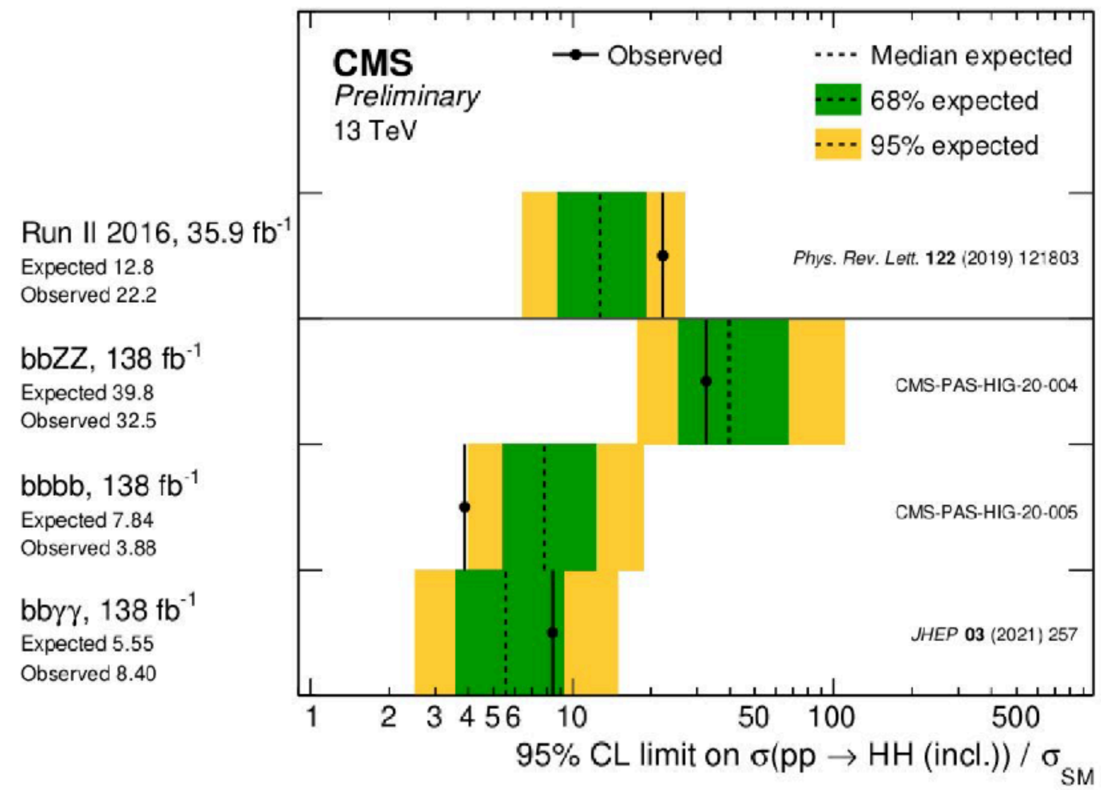


The golden mode to probe directly Higgs self-interaction at LHC



	Expected	Observed
$bb\gamma\gamma$ 139 fb^{-1} $(ggF+VBF)$	$\kappa_\lambda \in [-2.4, 7.7]$	$\kappa_\lambda \in [-1.5, 6.7]$

at 95% CL

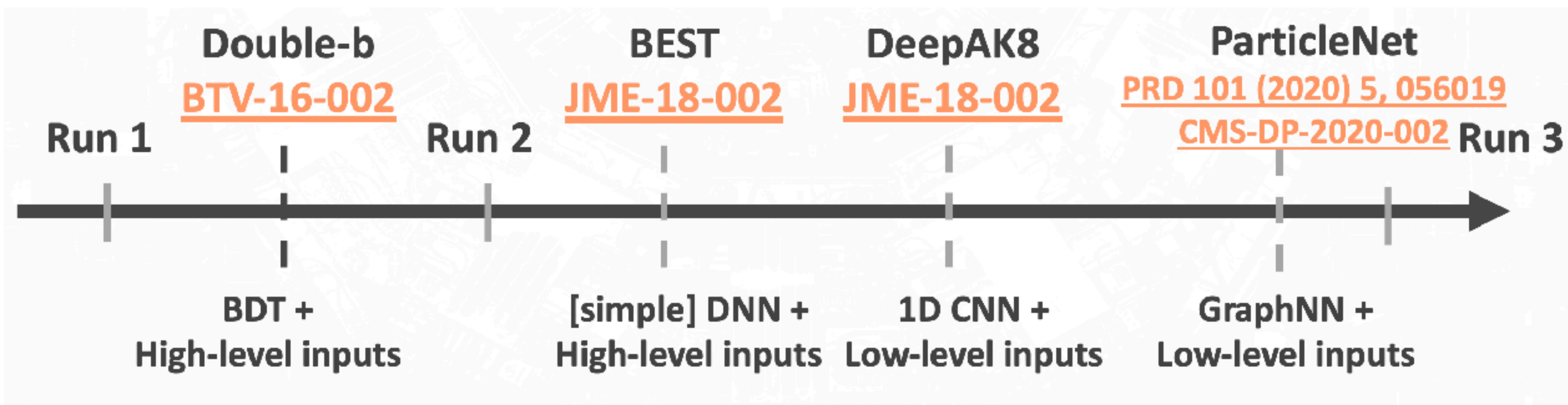


- Improvements in analysis strategy, categorisation and event reconstruction are bringing improvements >x2 beyond lumi scaling compared to 2016
- Starting to target also VBFHH (1.72fb) sensitive to VVHH: new boosted HH->4b excludes k_{2V}=0 @ 95% CL
- Full Run2+Run3 combination may start getting into the ~x2 SM territory (NB single Higgs production constraint (should) also be combined)
- Wishful thinking: HL-LHC target most-likely (hopefully) underestimated (also considering additional potential gains from new triggers, detectors)

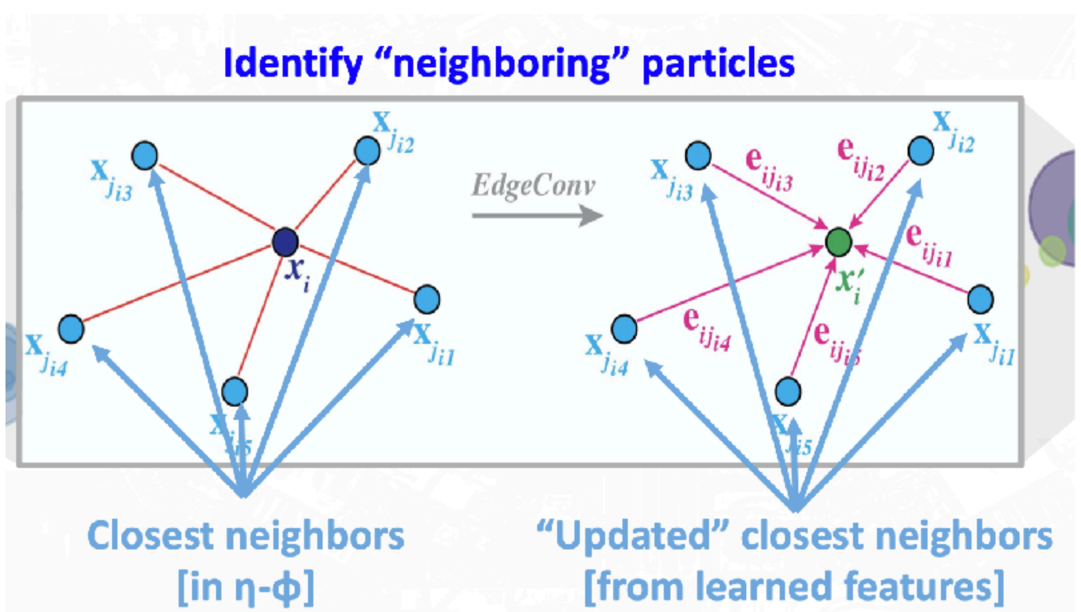
ML IMPROVEMENTS

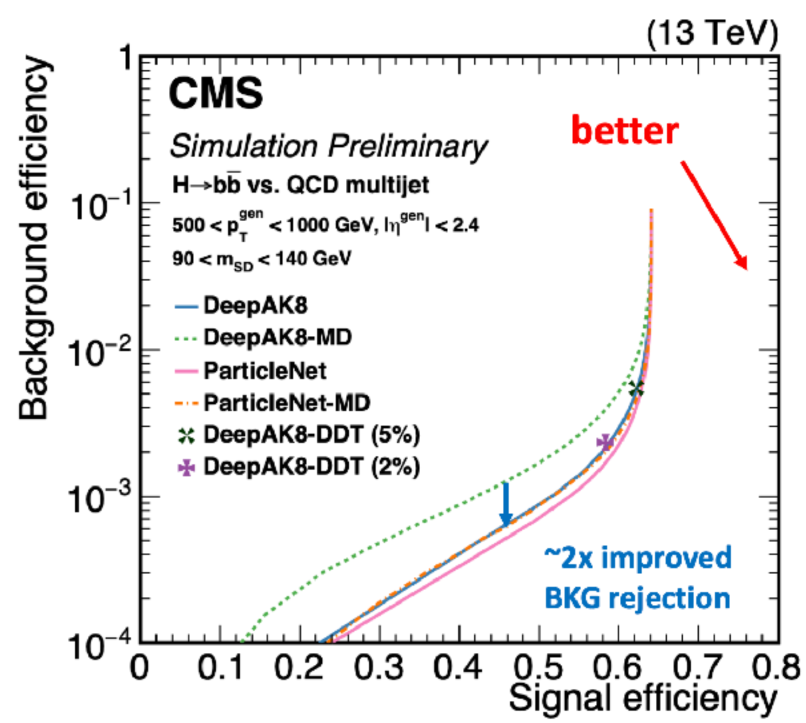
Use of advanced machine learning techniques is producing a large impact on our current analysis, and more could be expected in the future.

Improvements seen in particular for event categorisation (eg DNN with parametric training), lavour tagging (DeepTau, DeepJet, ..) and boosted topology



Example: ParticleNet, Deep Graph Neural Network, allowing to treat particle cloud as a graph, significant improvements seen in reconstruction of boosted H→bb (can be applied to several channels and searches)

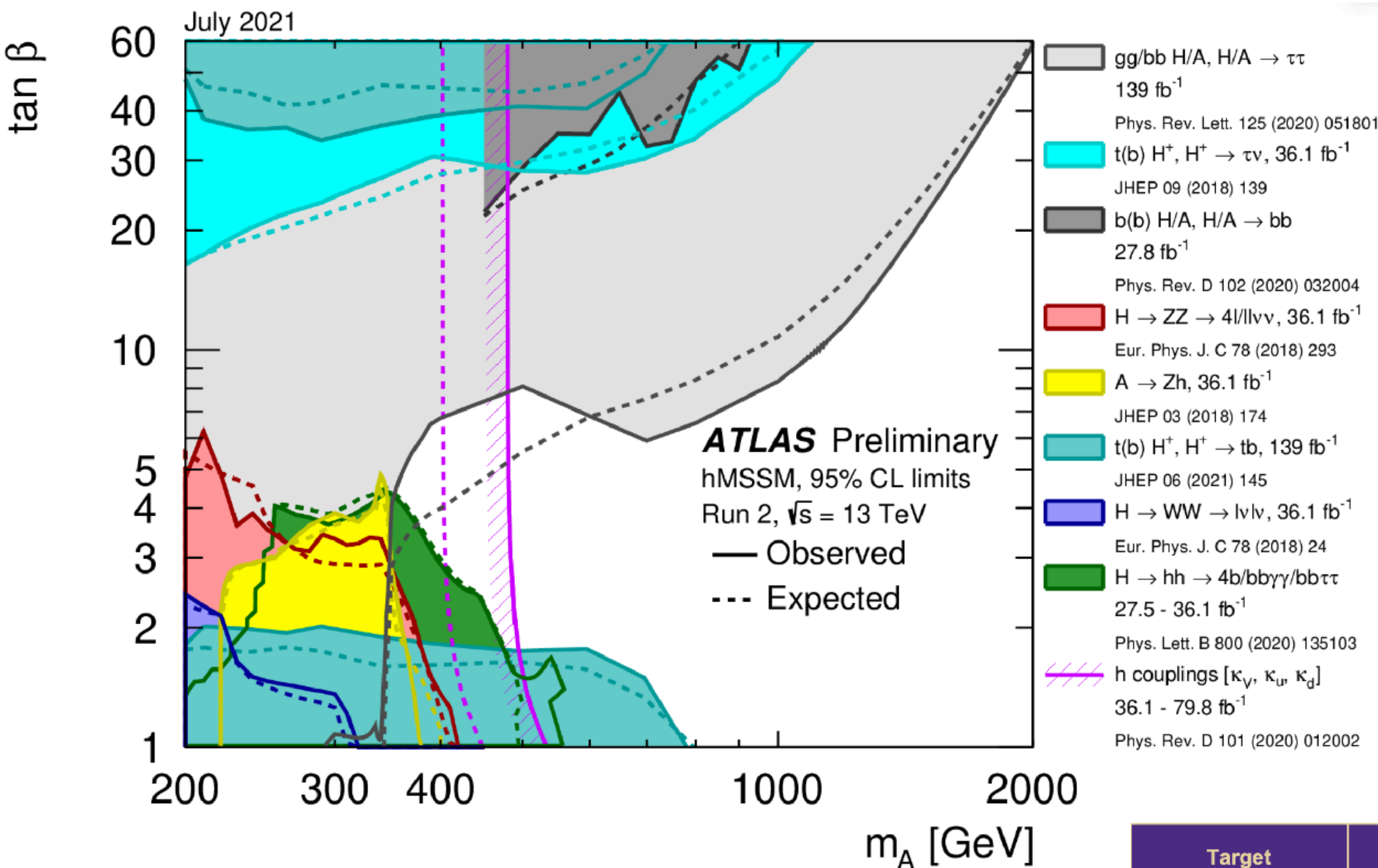




Gouskos

BSM HIGGS(ES)

Search for other scalars (neutral or charged, low and high mass) and non-SM H(125) decays still very active (theorists, please be patient 😉)



Attikis, Li, Marzocchi, Milic, Salvador, Schmieder

New search for $\phi \to \tau\tau$ (excess ~2σ local @ 400 GeV)

Also new search for charged H→tb nicely covering low tanβ region

Other several new searches presented by ATLAS and CMS, no really significant

Target	Channels	Luminosity (fb^{-1})	Reference
Heavy neutral H/A	A→Zh (h = 125 GeV Higgs)	139	ATLAS-CONF-2020-043/
	A → ZH (H ≠ 125 GeV Higgs)	139	EPJC 81 (2021) 396
	$H \to ZZ$	139	EPJC 81 (2021) 332
	$A/H \to \gamma\gamma$	139	arXiv:2102.13405
	$A/H \to \tau\tau$	139	PRL 125 (2020) 051801
Charged $H^{\pm}/H^{\pm\pm}$	$H^{\pm}$→cb	139	ATLAS-CONF-2021-037
	$t \to H^{\pm} b, H^{\pm} \to AW^{\pm}, A \to \mu\mu$	139	ATLAS-CONF-2021-047
	$H^{\pm\pm} \to W^{\pm}W^{\pm}$ and $H^{\pm} \to W^{\pm}Z$	139	JHEP 06 (2021) 146

LOW MASS H→γγ

Sven reminds us: still waiting for an answer here. Hopefully not much to be awaited :)

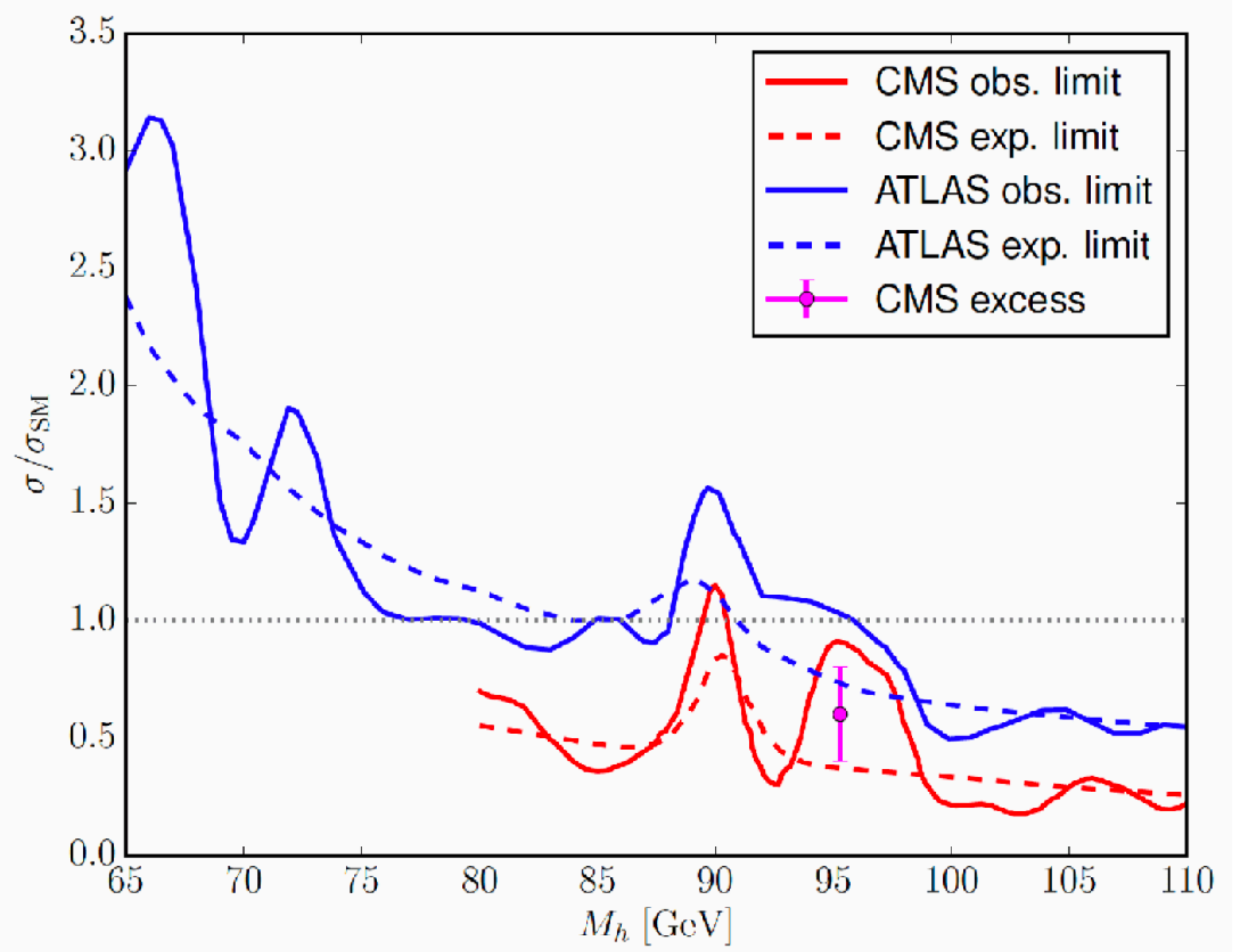
CMS excess around 95 GeV with 8TeV + 13TeV ($36fb^{-1}$)

- Expected and observed **local p-values**:

  → **8 TeV**: Excess with $\sim$2.0σ local significance at m_H = **97.6 GeV**

  → **13 TeV**: Excess with $\sim$ 2.9σ local (1.47σ global) significance at m_H = **95.3 GeV**

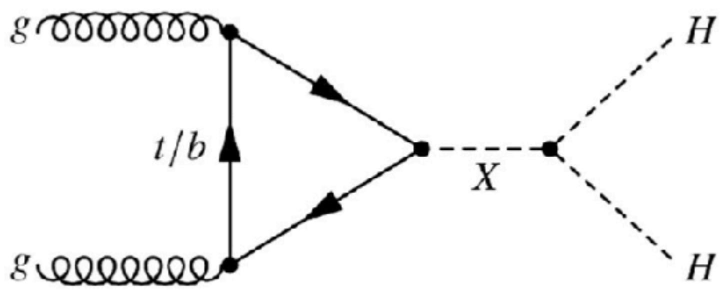
  → **8TeV+13 TeV**: Excess with $\sim$ 2.8σ local (1.3σ global) significance at m_H = **95.3 GeV**



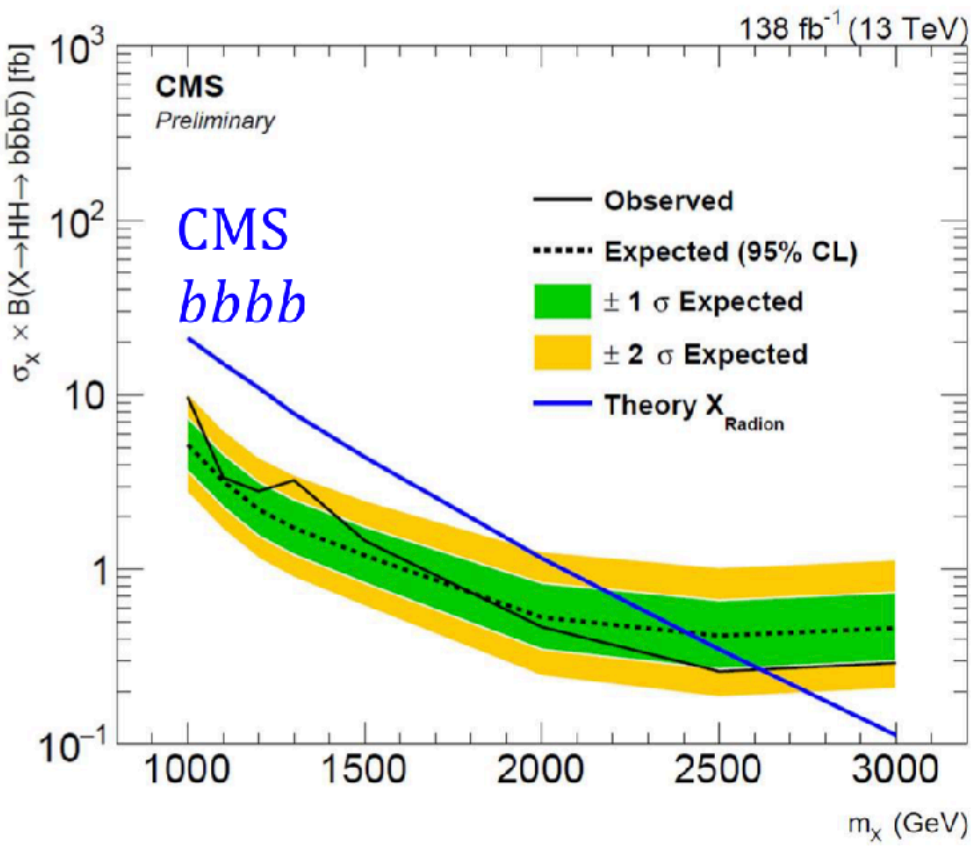
Heinemeyer

Cappati, Hulsken

Resonant Di-Higgs Searches



Benchmark Models for X
- Radion (spin-0)
- Bulk graviton (spin-2)



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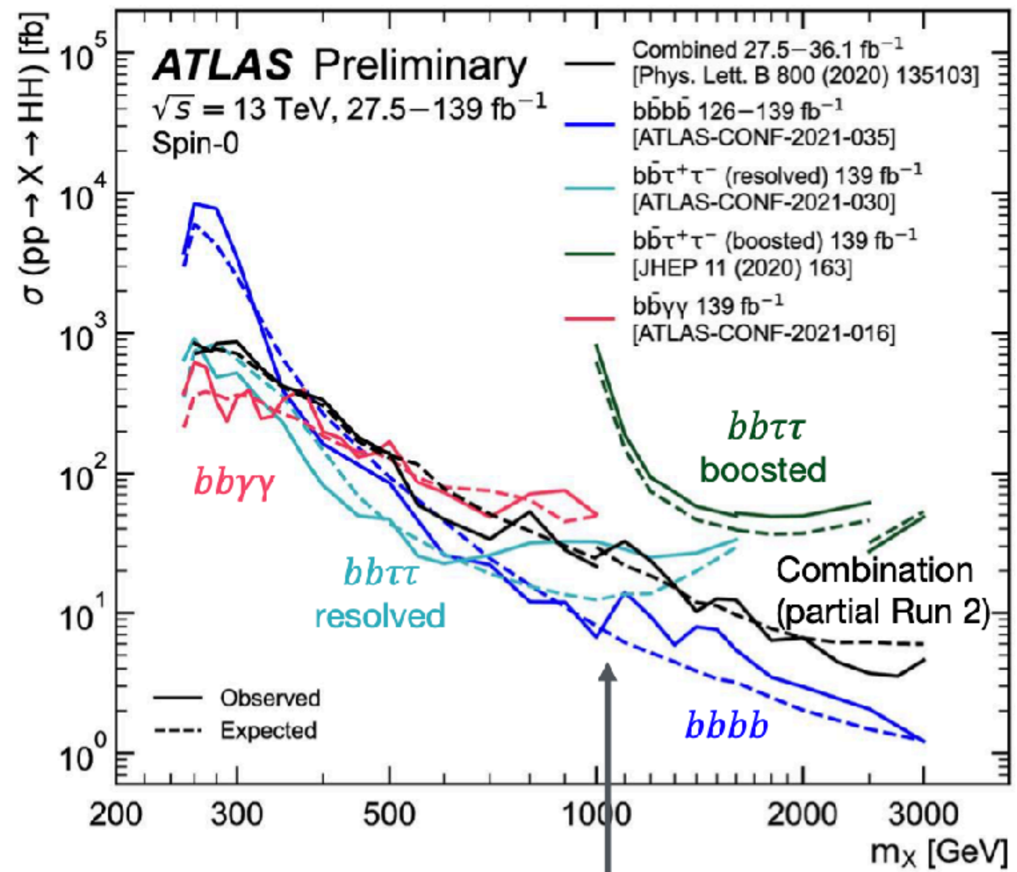
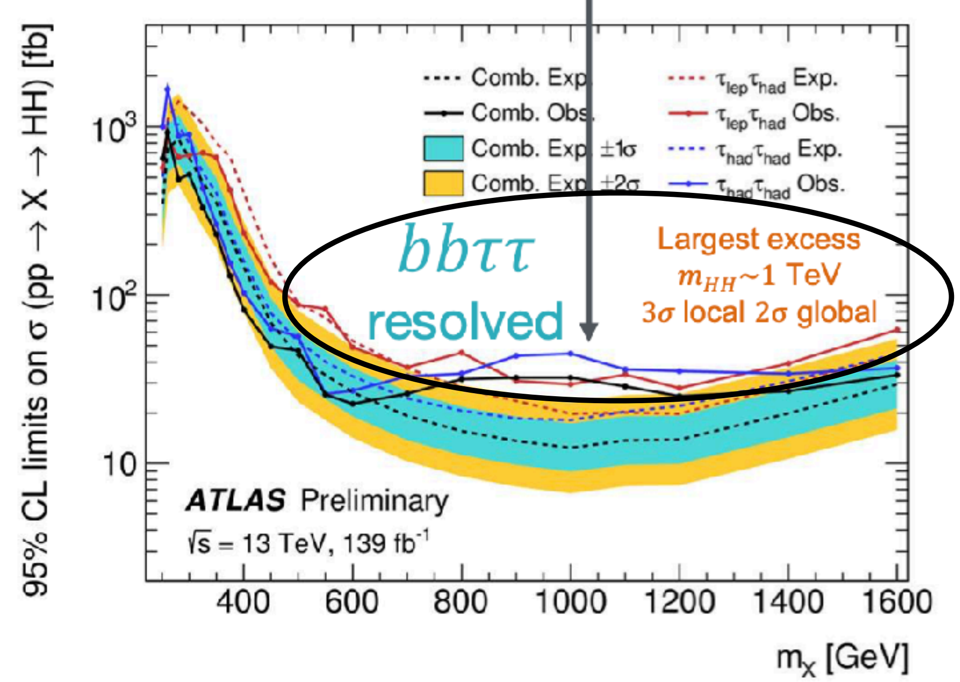


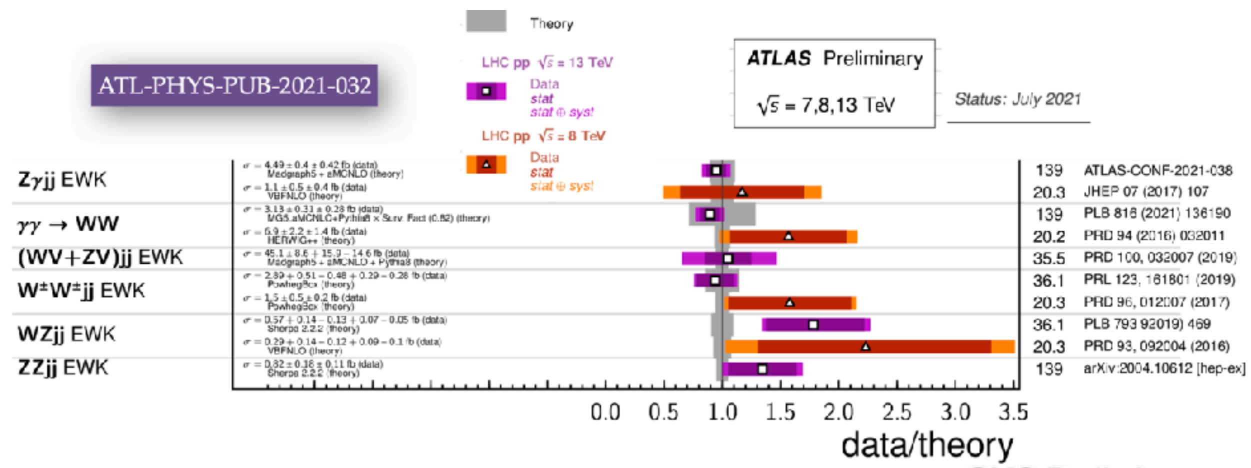


VBS

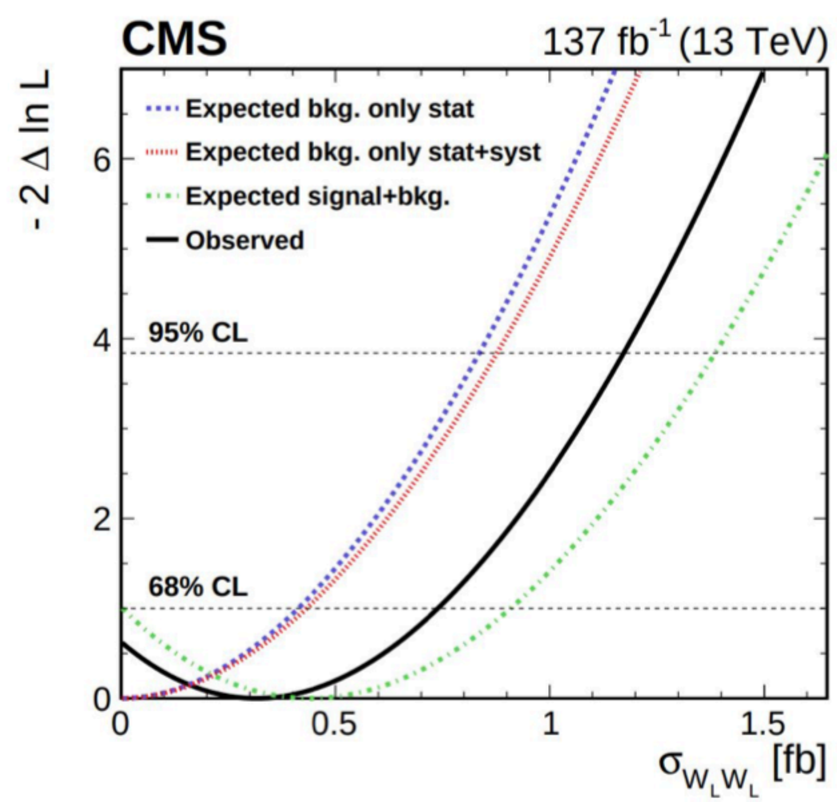
- VBS **powerful tool** to explore BSM physics in "**UV-agnostic**" way

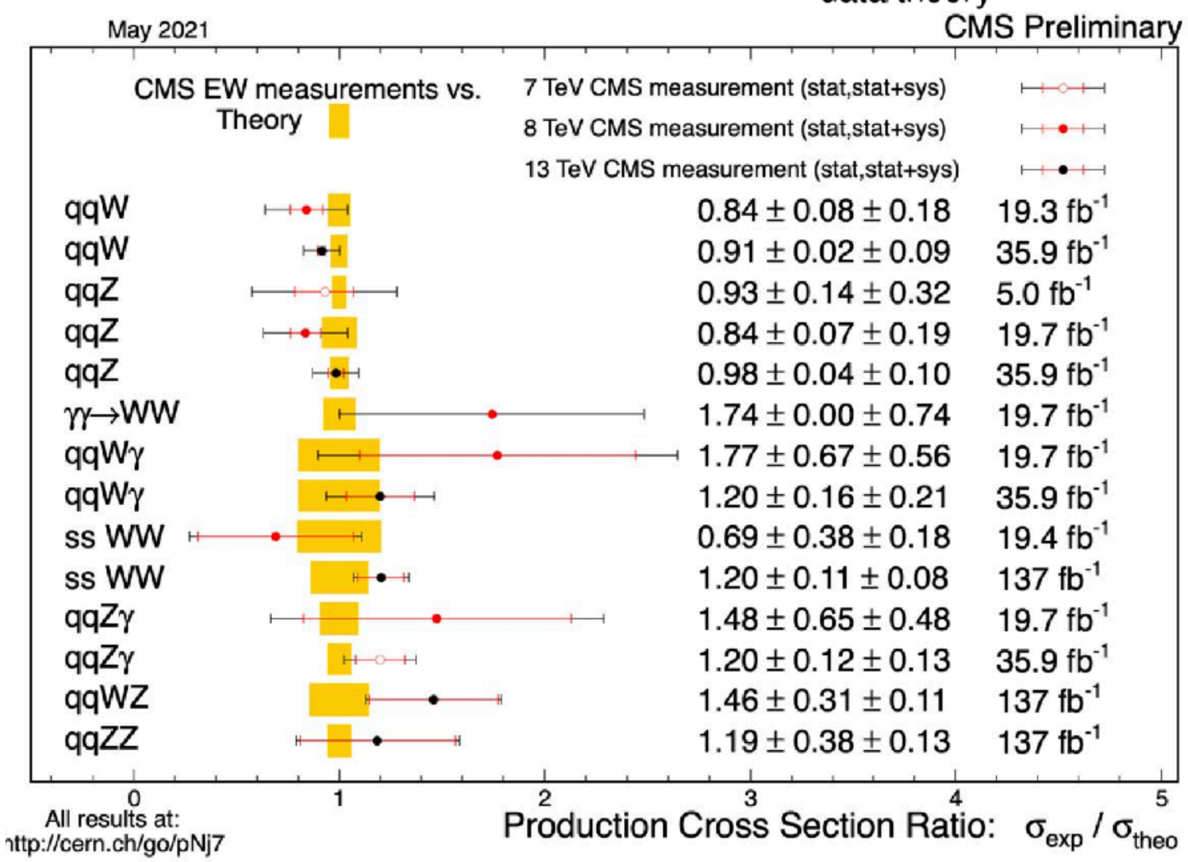
- **Extremely challenging** measurement:
  - very low yields as among **rarest processes** ever measured
  - require very accurate **modelling** of **QCD-induced background**

Martinez, Vagnerini



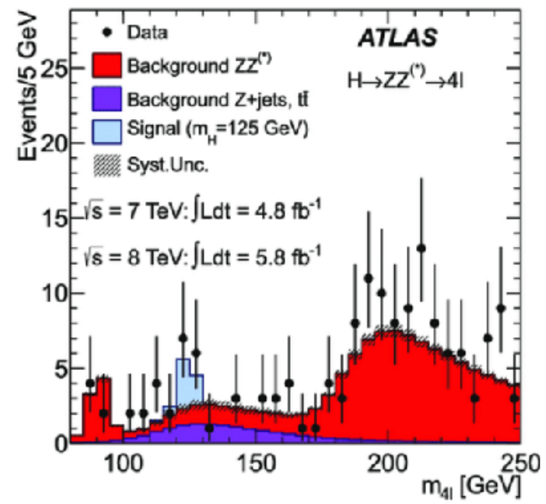
First measurement of **polarization states** in VBS **W±W±**

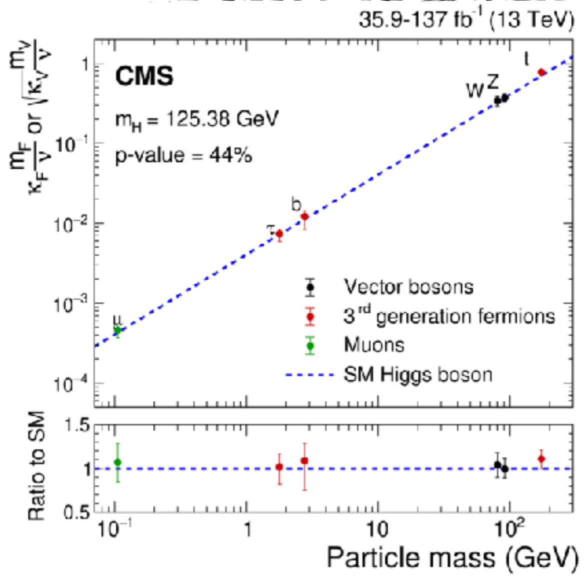




Obs (exp) **2.6(2.9)σ** significance for EW **$W_L W_X$** productior and 95% U.L. of **1.17(0.88) fb** for **$W_L W_L$**

A LONG ROAD FOR H(125)…





Almost 10 years (and x 10 statistics) have passed…

The "short executive" summary:

- fantastic measurements presented for many production and decay modes.
- moved from a "new scalar with mass around 125 GeV", to what seems in all aspects "THE SM Higgs". Systematically looking for "an anomaly" in the Higgs sector, LHC now into the "precision"/"EFT" era
- trying to answer several still un-answered questions: 2nd gen coupling, self-interaction, other scalars, BSM decays…

Prospects:

- Improvements seen for several analysis beyond lumi scaling thanks to ML. Next stop Run3 and then HL-LHC: new detectors and improved triggers, I'm sure the best is yet to come (however do not forget that we are running a >10 year long marathon…)

See you next year..