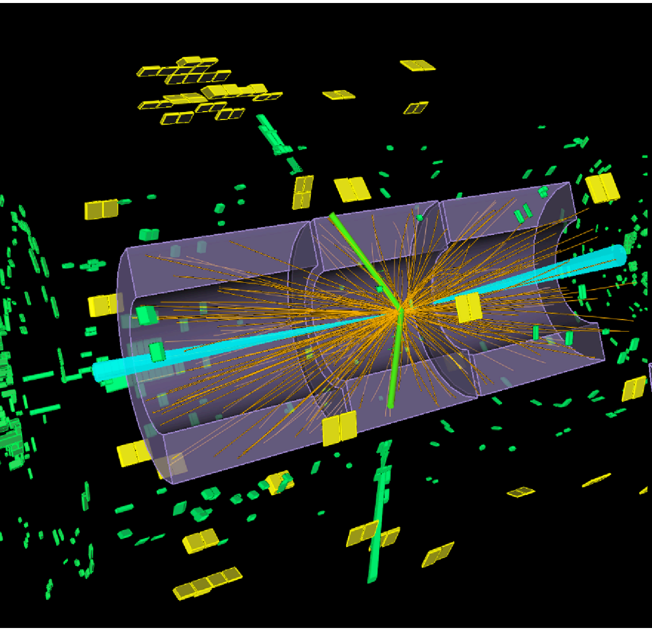
Higgs Physics at LHC

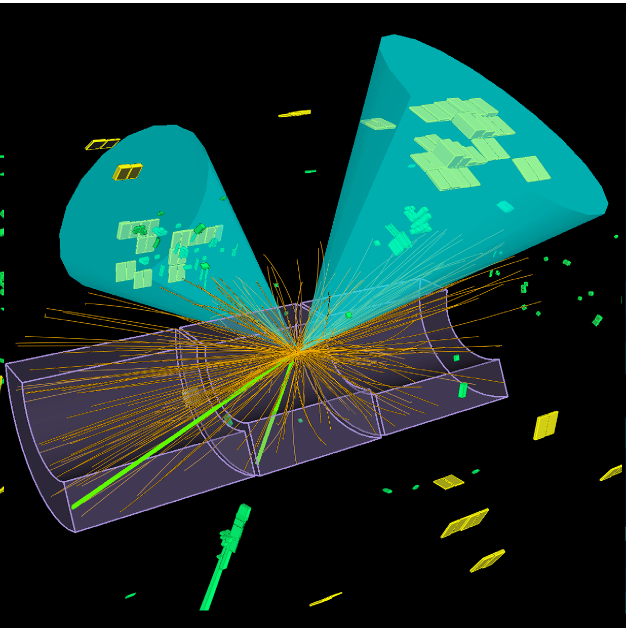
Lecture 2 –*Higgs Properties* TAE 2017

Experimental profile of the Higgs boson

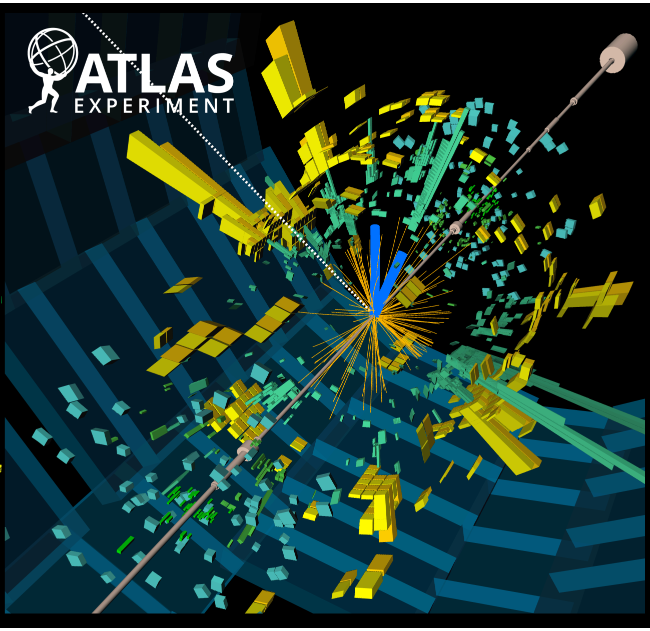
VBF H → ττ candidate



Z(ll)H → bb candidate



ttH (ML) candidate



Kado Marumi
LAL, Orsay

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September, 2017

Overall Contents

Lecture 1: Fundamentals, The beauty and overwhelming success of the Standard Model

Lecture 2: Experimental profile of the Higgs boson, current challenges

Lecture 3: Future challenges (and future machines), implications and searches for new physics beyond the Standard Model

Higgs Physics - Lecture 2

Experimental Profile of the Higgs boson

1.- A one slide panorama!

2.- Going further with « bread and butter » channels

3.- Going further with the discovery channels

4.- Intermezzo on Sources of Systematic Uncertainties (Experimental and Modelling)

5.- **Direct probes of the couplings the Higgs boson to fermions:** Highly anticipated Run 2 Analyses

6.- **Combined Measurement of properties:** Based on Run 1

Higgs physics Landscape Redefined

Flurry of new ideas !

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma$, $\gamma\gamma^*$
- Muons $\mu\mu$
- LFV $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, $Z\Upsilon$, WD etc...

$$H^0$$

Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

...and More!
- FCNC top decays
- Di-Higgs production
- Trilinear couplings prospects
- Etc...

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Further with « Bread and Butter » channels

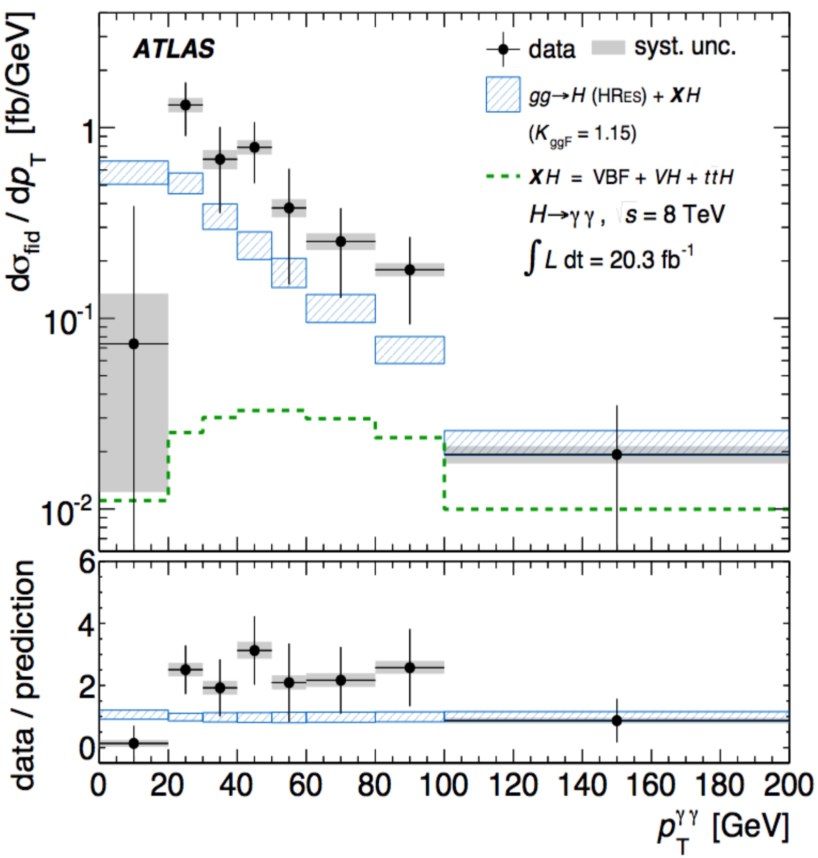
Simple channels which are mostly dominated by statistics

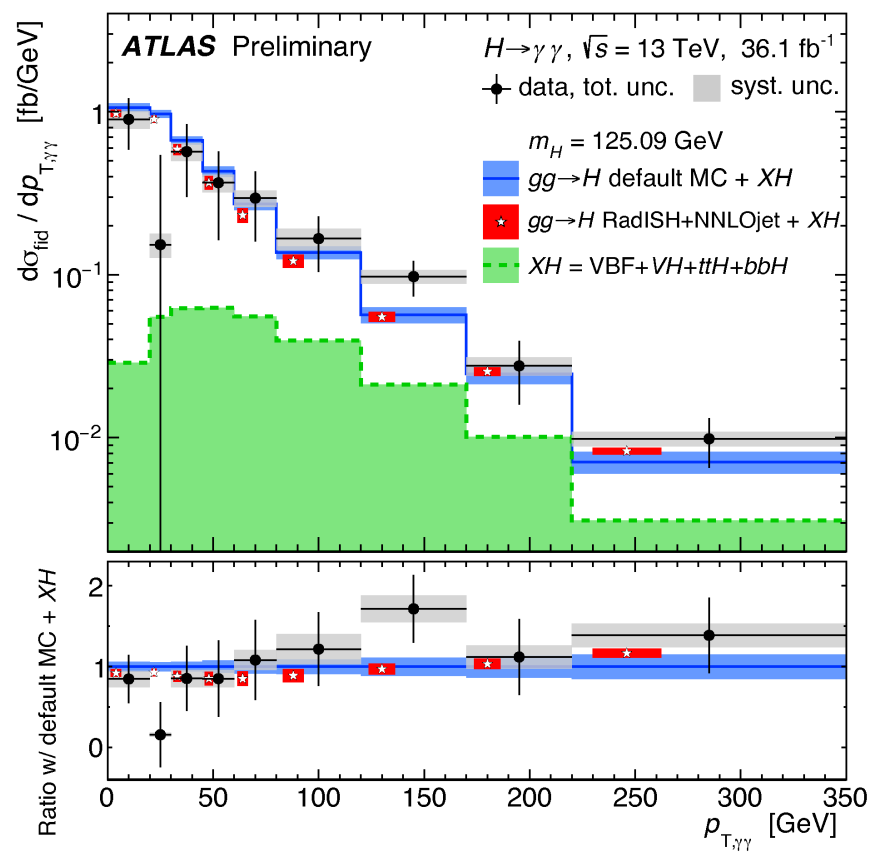
Decay channel	Mass resolution
$H \to \gamma\gamma$	1–2%
$H \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	1–2%
$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$	20%
$H \to b\bar{b}$	10%
$H \to \tau^+\tau^-$	15%

Differential, Fiducial and Unfolded cross section

- Higgs results in general rely on the prediction of Higgs transverse momentum or jet multiplicities : Important to measure it.
- Direct tests of the production (sensitive e.g. to new physics)

$H \to \gamma\gamma$

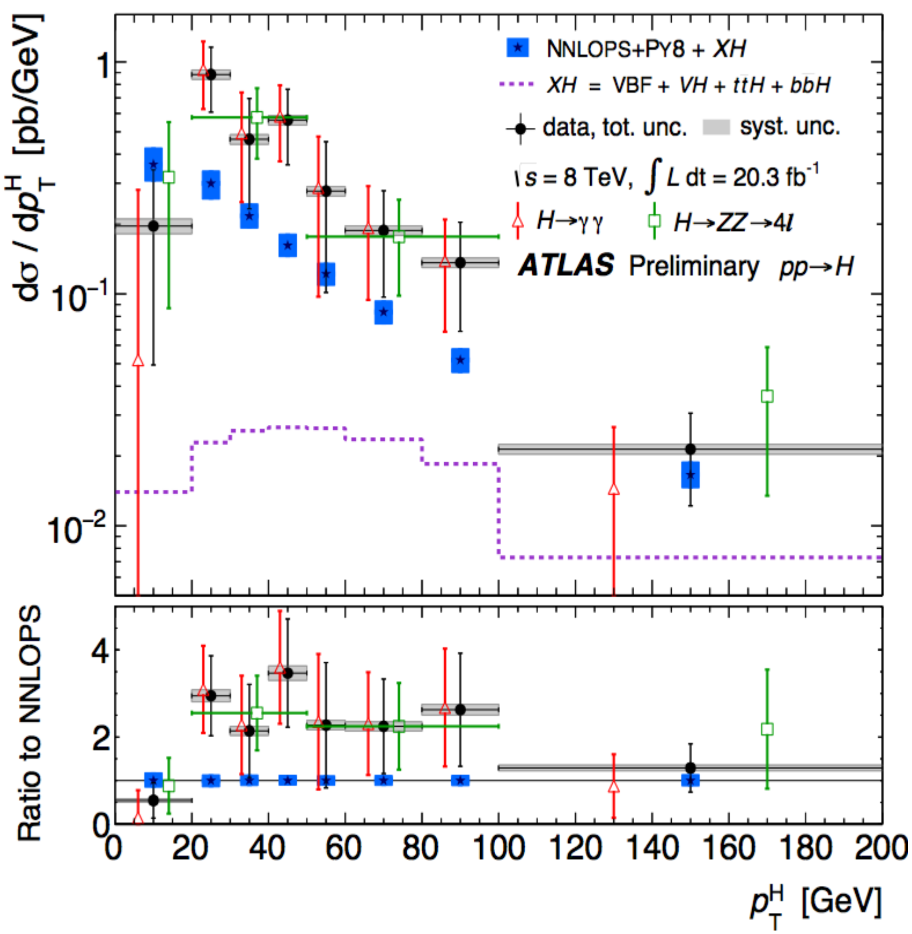


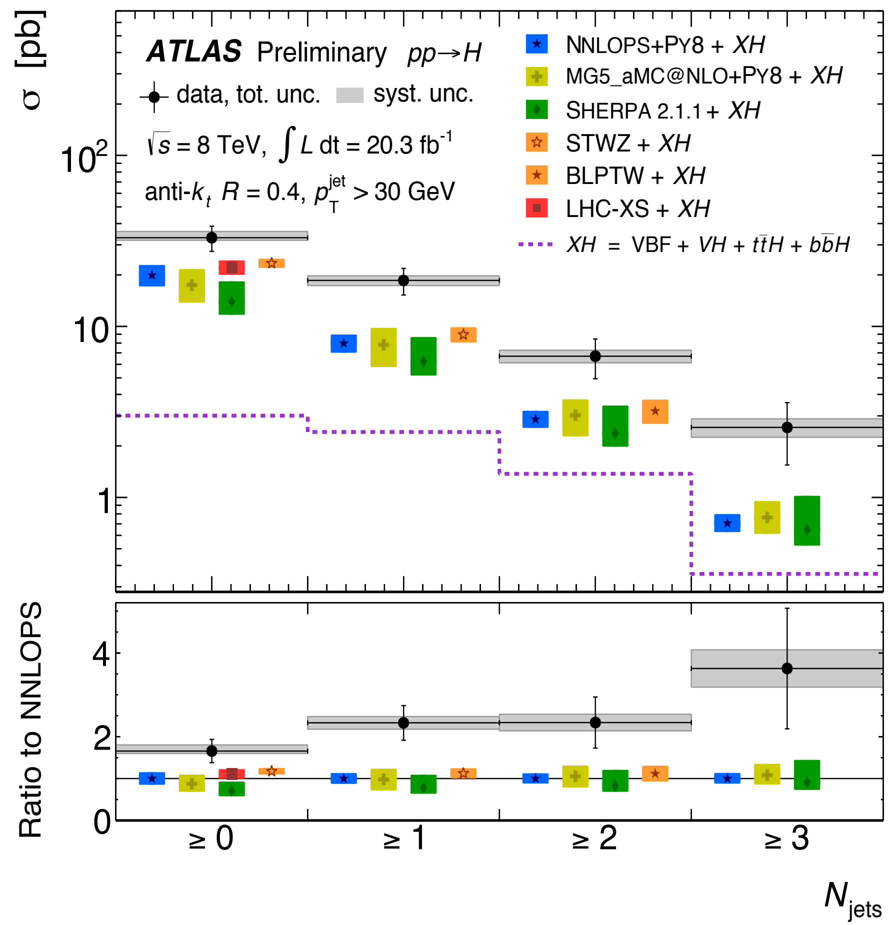


Combined Differential Cross sections

Inclusive cross section (Acceptances assume SM production) –
Absolute(Comparison with several State of the Art MCs and XS calculations)

(Publication in preparation)

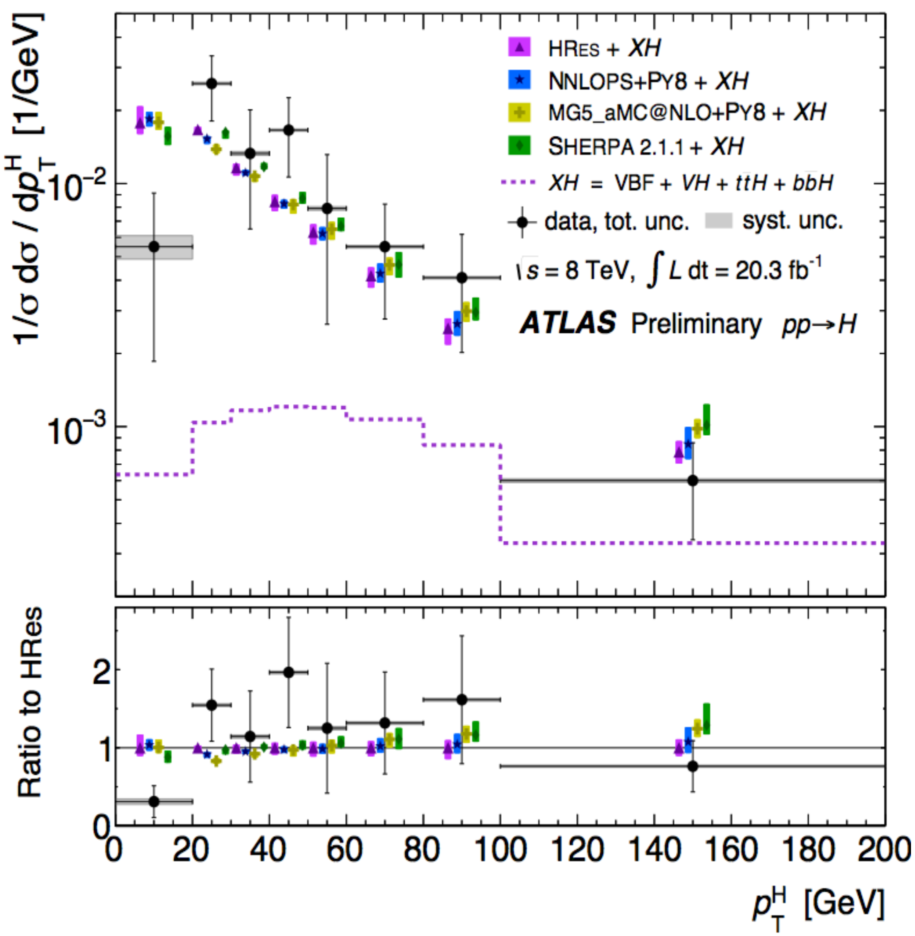


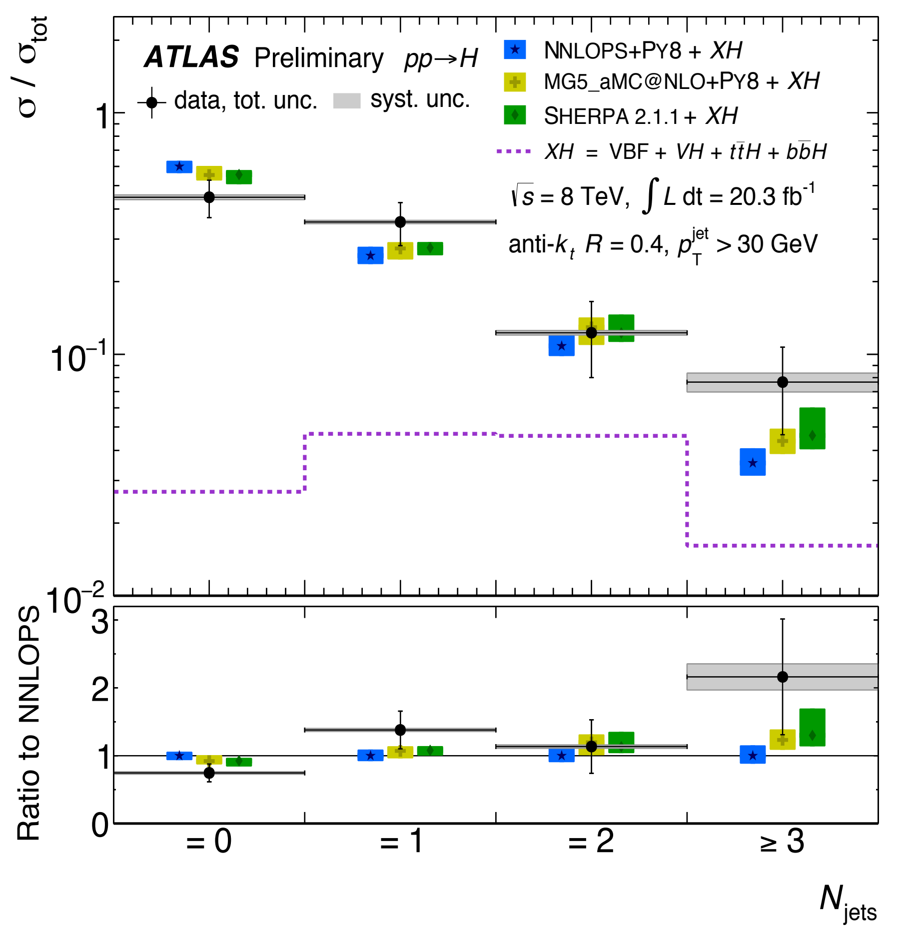


Compatibility probability ~few permil level (mostly due to the overall normalisation)

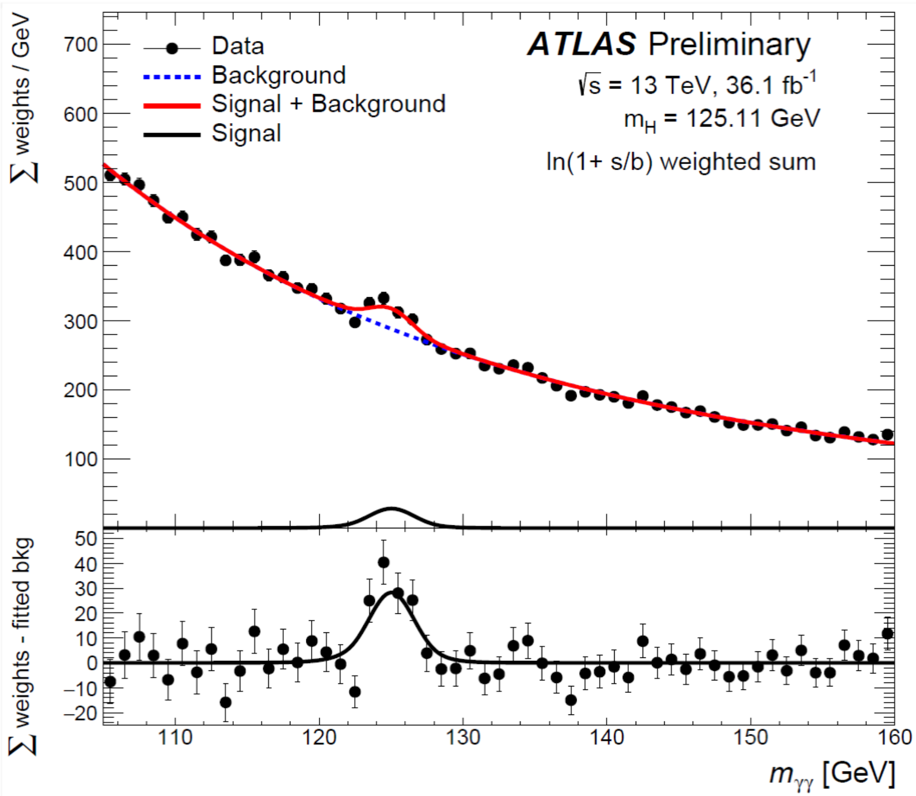
Combined Differential Cross sections

Inclusive cross section (Acceptances assume SM production) – Absolute(Comparison with several State of the Art MCs and XS calculation





Run 2 ATLAS results



Let's take a simple example with two categories:

- C1: s=12 and b=60
- C2: s=18 and b=40

Inclusively significance of 3

Separating in two categories:

- C1 2.85 σ
- C2 1.55 σ

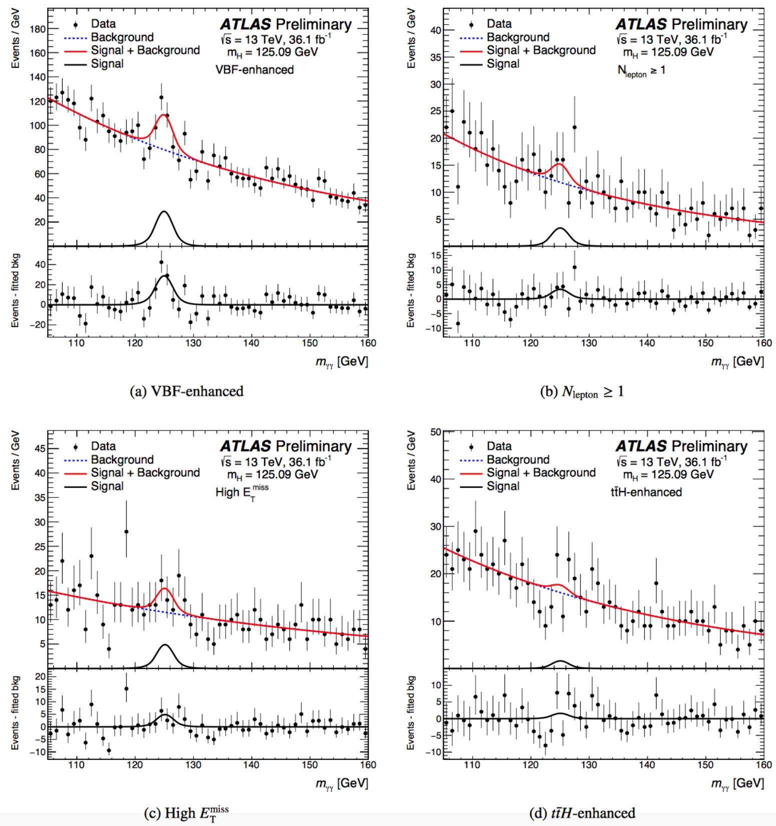
Combined significance: 3.24

Exercise: demonstrate this formula!

$$\sqrt{Z_1^2 + Z_2^2}$$

Important: does not work for observed!!

31 categories



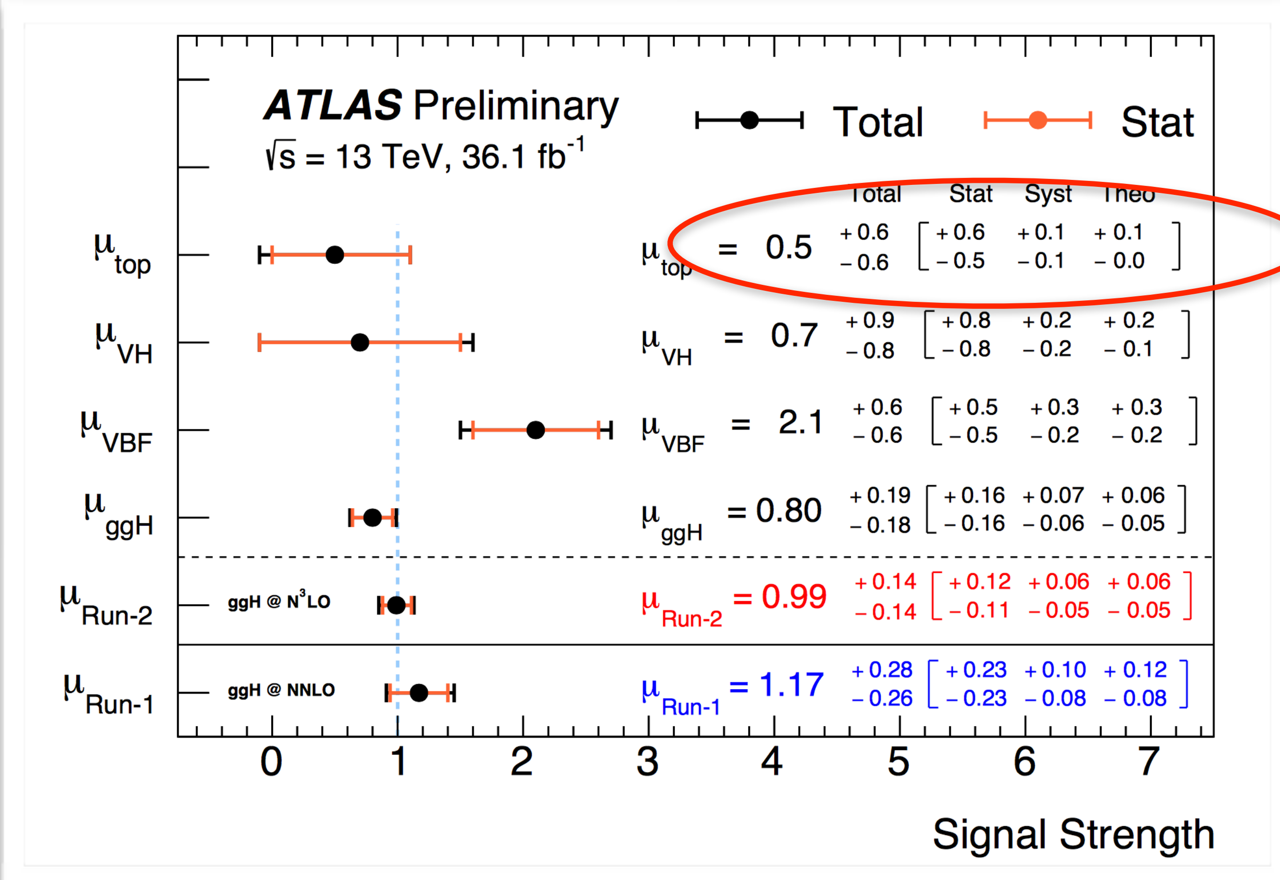
(a) VBF-enhanced

(b) $N_{\mathrm{lepton}} \geq 1$

(c) High $E_{\mathrm{T}}^{\mathrm{miss}}$

(d) $t\bar{t}H$-enhanced

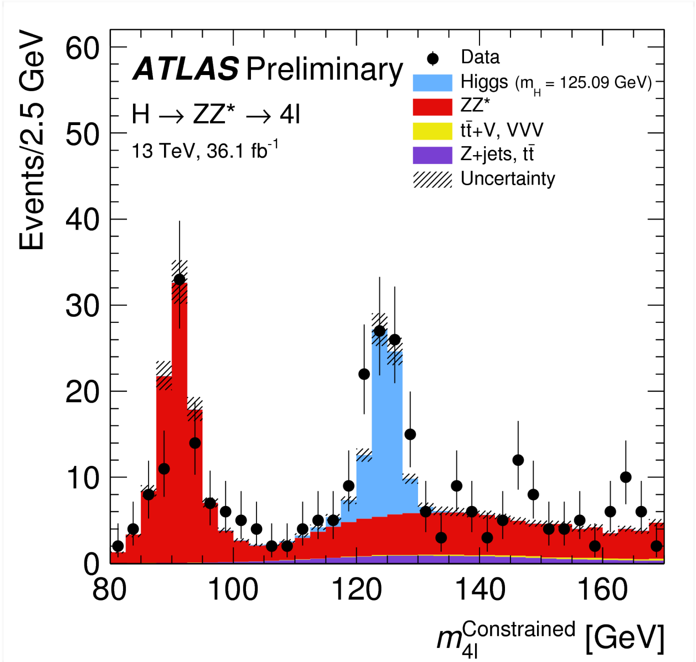
Old School

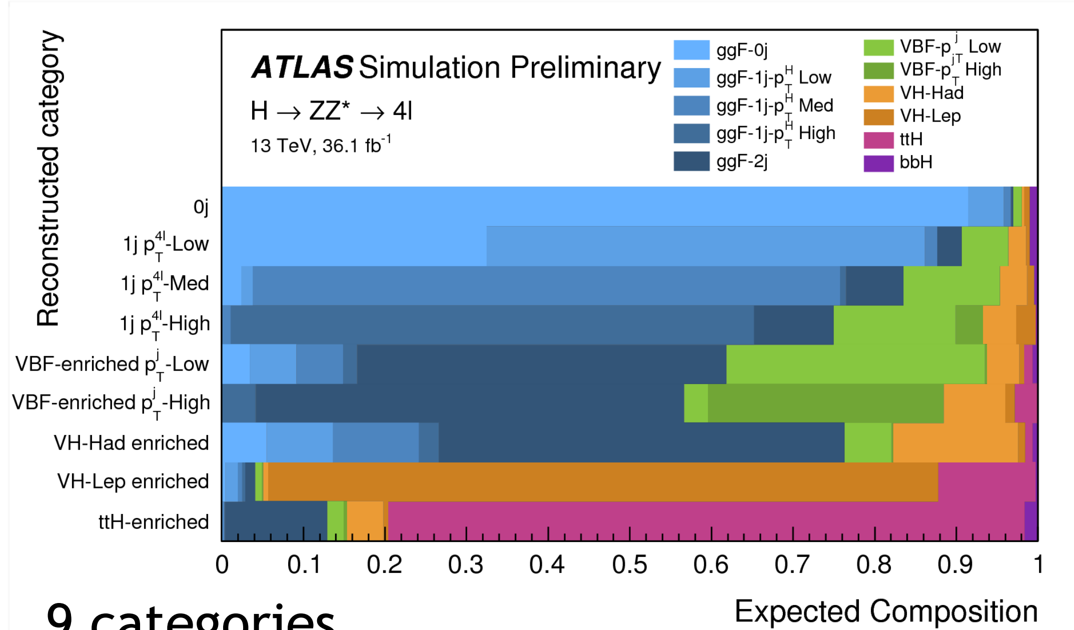


Measurement	Exp. Z_0	Obs. Z_0
μ_{VBF}	2.6 σ	4.9 σ
μ_{VH}	1.4 σ	0.8 σ
μ_{top}	1.8 σ	1.0 σ

ttH channels in semi-leptonic and hadronic top decays (with BDT)
Evidence sensitivity to ttH in ~2.8 times the current luminosity

Run 2 ATLAS 4l result



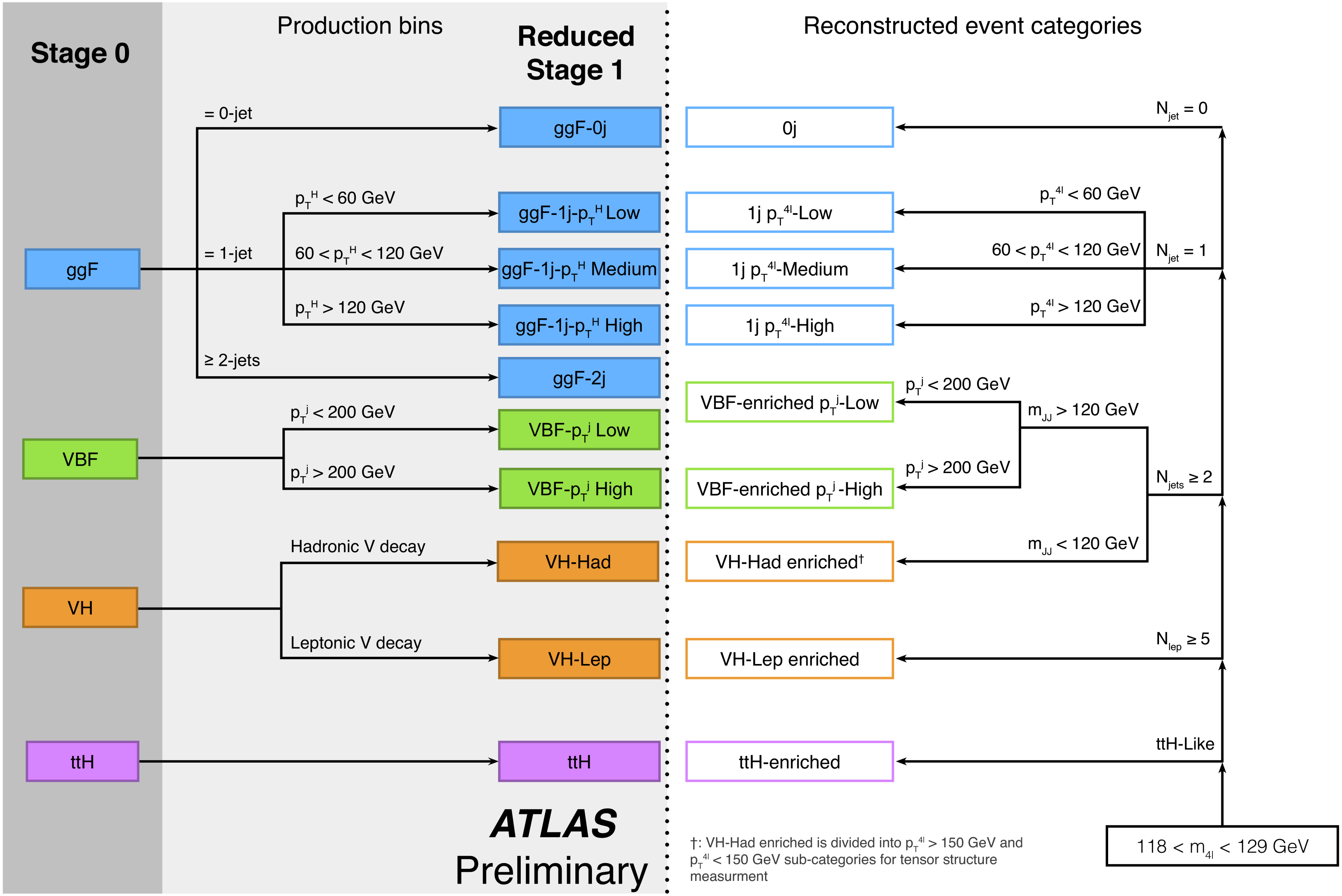


9 categories

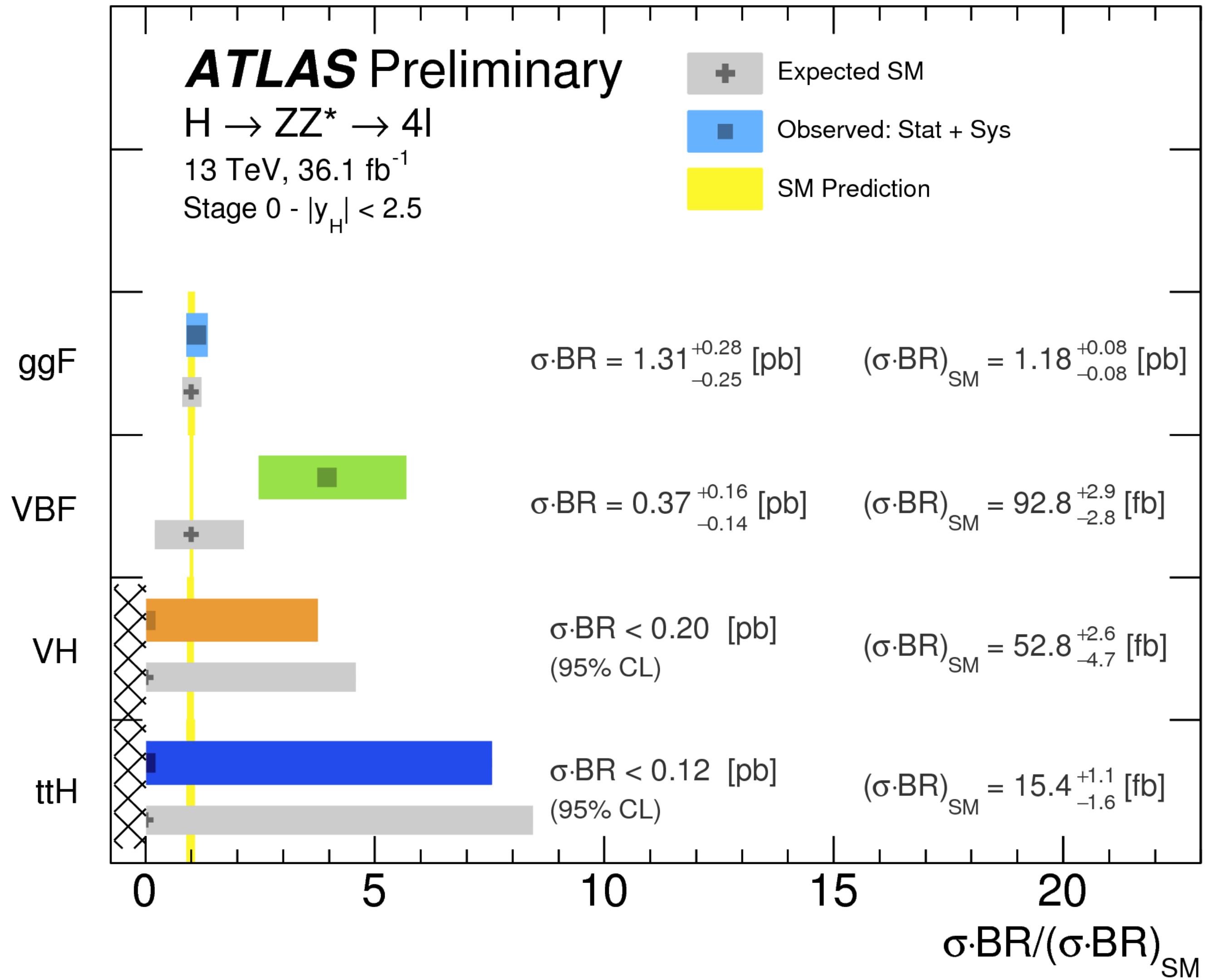
Number of events in mass [118,129] GeV

Decay channel	Signal (full mass range)	Signal	ZZ^*	Other backgrounds	Total expected	Observed
4μ	21.0 ± 1.7	19.7 ± 1.6	7.5 ± 0.6	1.00 ± 0.21	28.1 ± 1.7	32
$2e2\mu$	15.0 ± 1.2	13.5 ± 1.0	5.4 ± 0.4	0.78 ± 0.17	19.7 ± 1.1	30
$2\mu 2e$	11.4 ± 1.1	10.4 ± 1.0	3.57 ± 0.35	1.09 ± 0.19	15.1 ± 1.0	18
$4e$	11.3 ± 1.1	9.9 ± 1.0	3.35 ± 0.32	1.01 ± 0.17	14.3 ± 1.0	15
Total	59 ± 5	54 ± 4	19.7 ± 1.5	3.9 ± 0.5	77 ± 4	95

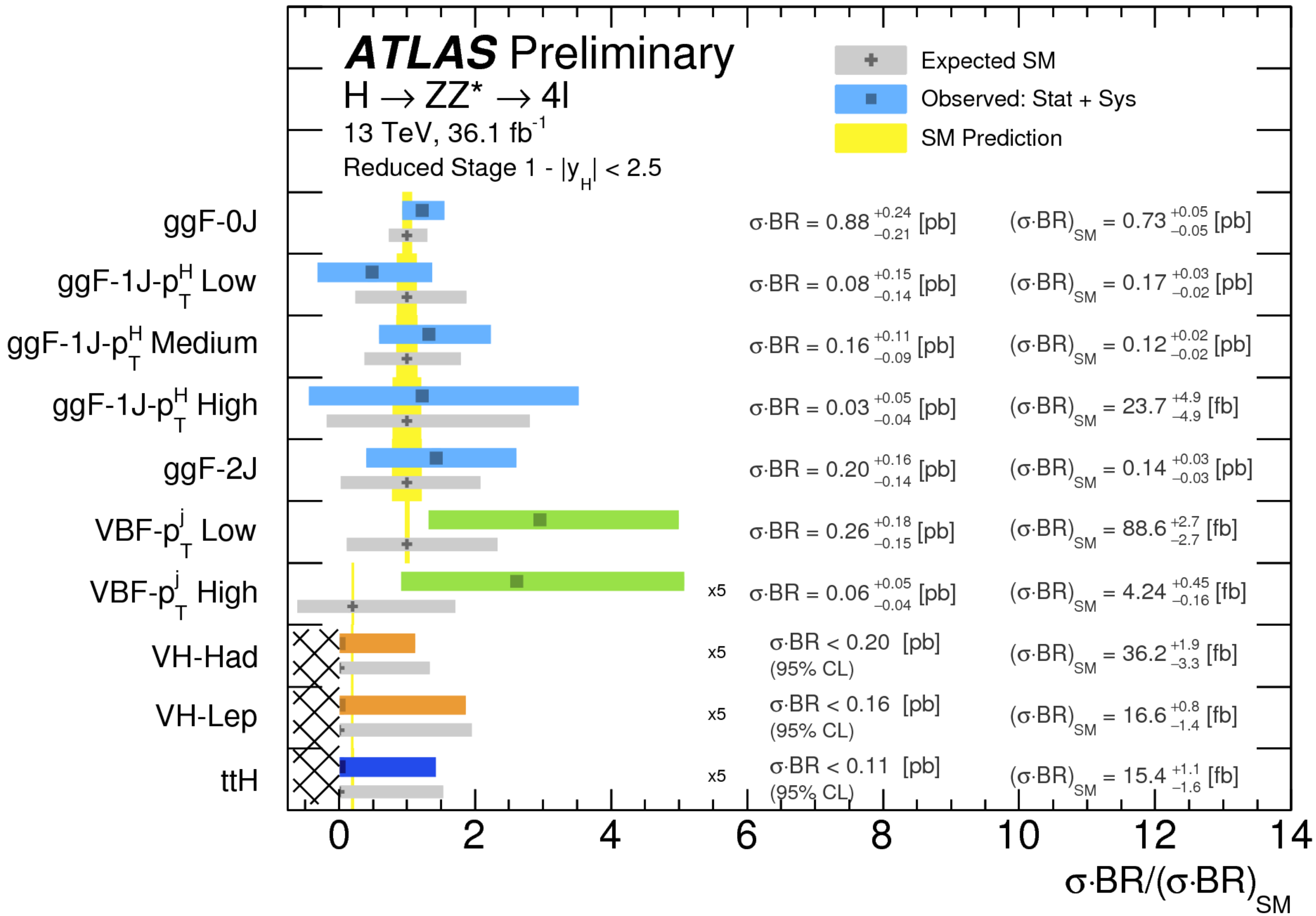
Simplified Template Cross Sections



Stage-0 Results



Stage-1 Results



Beyond « Bread and Butter » channel

But still a discovery channel

Decay channel	Mass resolution
$H \to \gamma\gamma$	1–2%
$H \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	1–2%
$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$	20%
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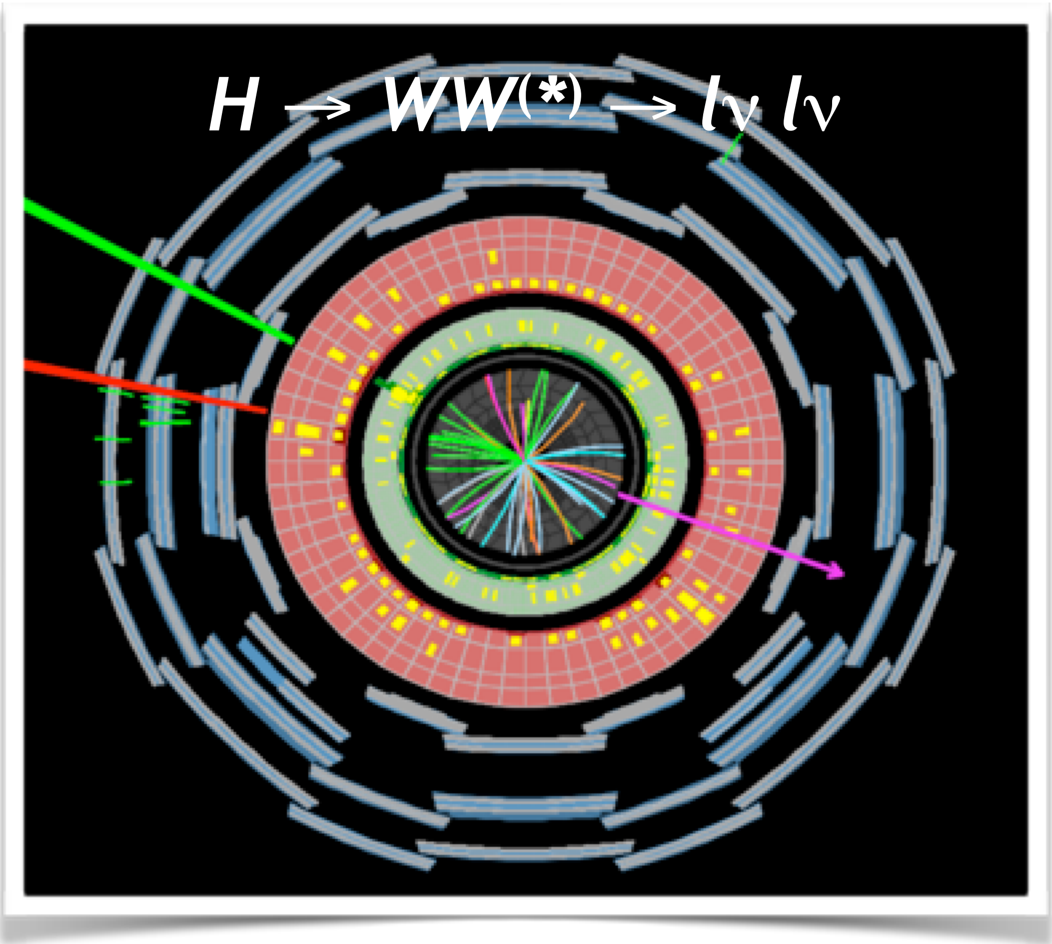
A discovery channel of a different kind...

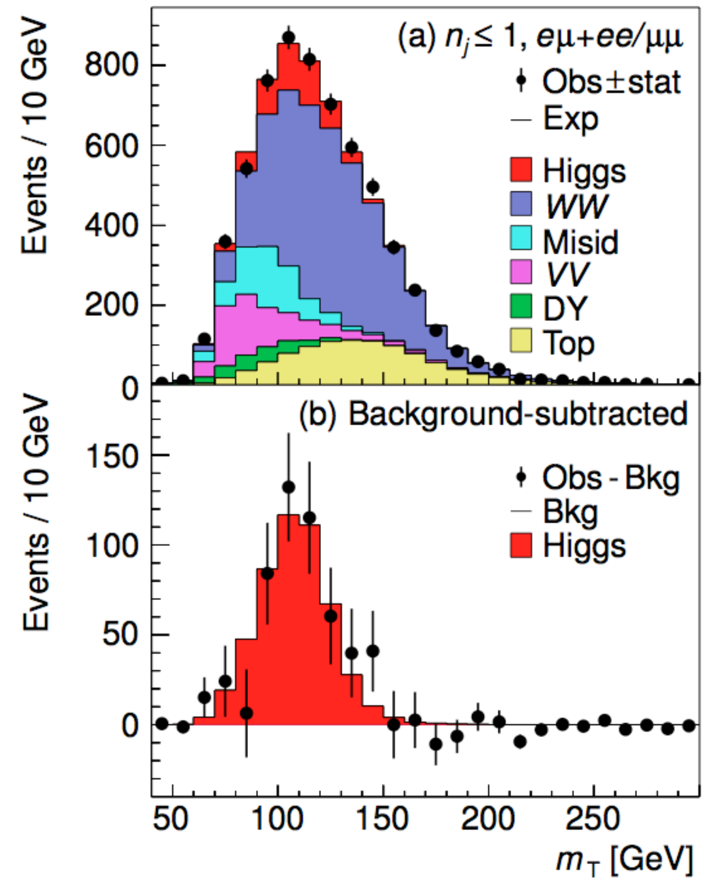


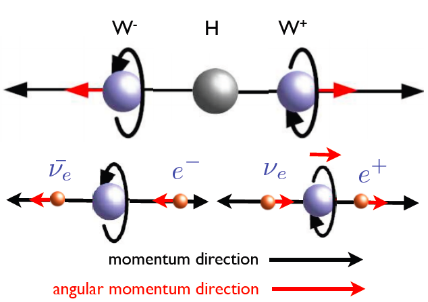
ATLAS

$Z = 6.1\ (5.8)\ \sigma$

CMS

$Z = 4.0\ (5.0)\ \sigma$





- Intricate analysis
- Moderate s/b ratio starting from approximately 1.5 and reaching more than 10
- Poor mass resolution

Background systematic uncertainties
The WW channel

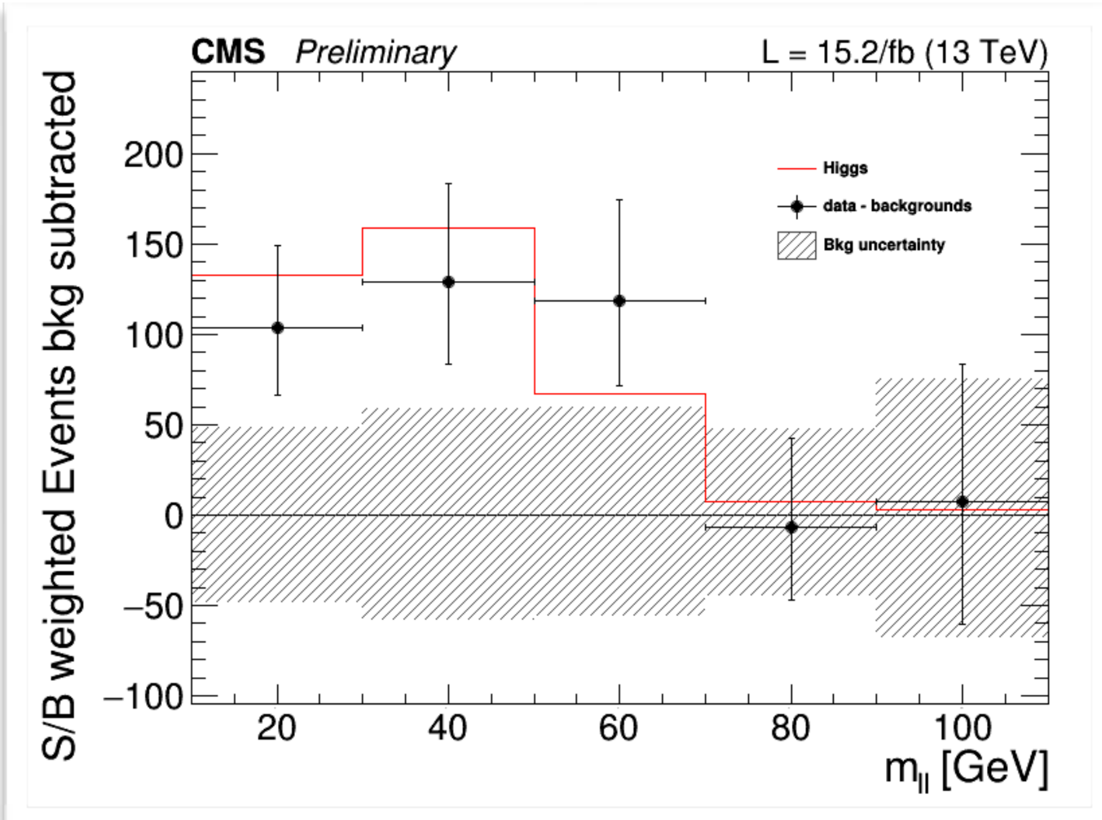
Systematic source	Impact on $\hat{\mu}$: Pre-fit $\Delta_{\hat{\mu}}$ +	Pre-fit $\Delta_{\hat{\mu}}$ −	Post-fit $\Delta_{\hat{\mu}}$ +	Post-fit $\Delta_{\hat{\mu}}$ −	Plot of post-fit $\pm\Delta_{\hat{\mu}}$
WW, generator modeling	−0.07	+0.07	−0.05	+0.05	
ggF H, QCD scale on total cross section	−0.04	+0.05	−0.04	+0.05	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
Misid. of μ, OC uncorrelated corr. factor α_{misid}, 2012	−0.03	+0.04	−0.02	+0.03	
Misid. of e, OC uncorrelated corr. factor α_{misid}, 2012	−0.03	+0.03	−0.02	+0.03	
Integrated luminosity, 2012	−0.02	+0.03	−0.02	+0.03	
ggF H, PDF variations on cross section	+0.02	−0.03	+0.02	−0.03	
ggF H, QCD scale on $n_j \geq 2$ cross section	+0.02	−0.03	+0.01	−0.03	
Muon isolation efficiency	−0.02	+0.02	−0.02	+0.02	
VBF H, UE/PS	−0.02	+0.02	−0.02	+0.02	
ggF H, PDF variations on acceptance	−0.02	+0.02	−0.02	+0.02	
Jet energy scale, η intercalibration	−0.02	+0.02	−0.02	+0.02	
VV, QCD scale on acceptance	−0.01	+0.02	−0.01	+0.02	
ggF H, UE/PS	-	−0.02	-	−0.02	
Light jets, tagging efficiency	+0.01	−0.02	+0.01	−0.02	
Misid. jj, correction on α_{misid}	+0.01	−0.02	+0.01	−0.02	
Electron isolation efficiency	−0.01	+0.02	−0.01	+0.02	
Misid. of μ, closure on α_{misid}, 2011	−0.01	+0.02	−0.01	+0.01	
Electron identification eff. on $p_T^{\ell 2} > 20\,\text{GeV}$, 2012	−0.01	+0.02	−0.01	+0.02	
ggF H, QCD scale on ϵ_1	−0.01	+0.02	−0.01	+0.02	
					-0.1 -0.05 0 0.05 0.1

NNLO fiducial was available but not used yet!

Analysis done at Run 2 by CMS

Partial 2016 dataset

CMS-PAS-HIG-2016-021



$$\mu = 1.05 \pm 0.26$$

Difficult channel, requires thorough study of systematic uncertainties

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J^{PC}

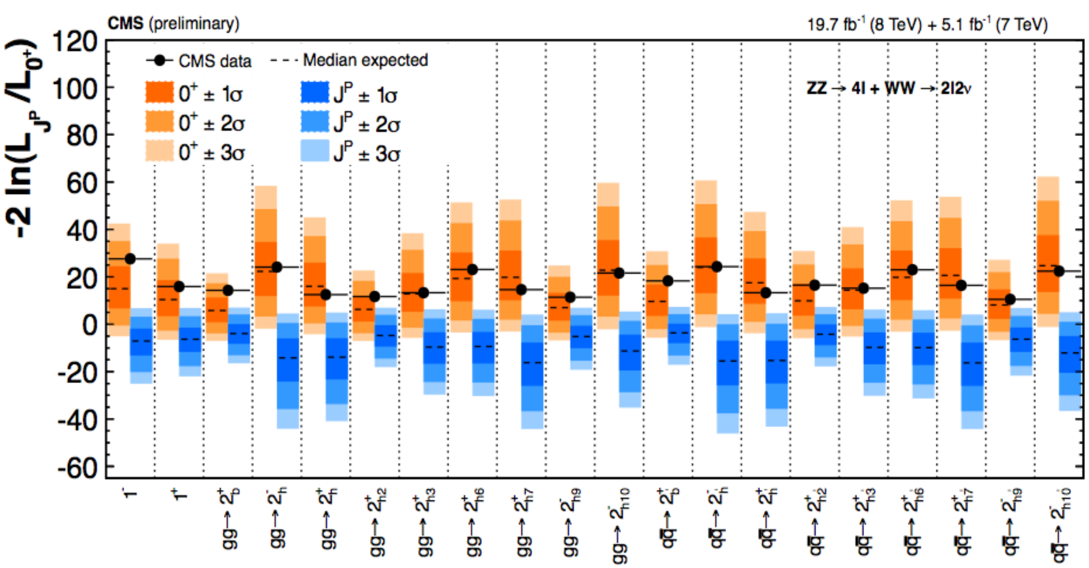
- The observed rates in the diboson channels already a lot of information:
  - Observation in the diphoton channel J != 1
  - Observation in WW and ZZ channels disfavor the CP-Odd hypothesis (can occur through loops)

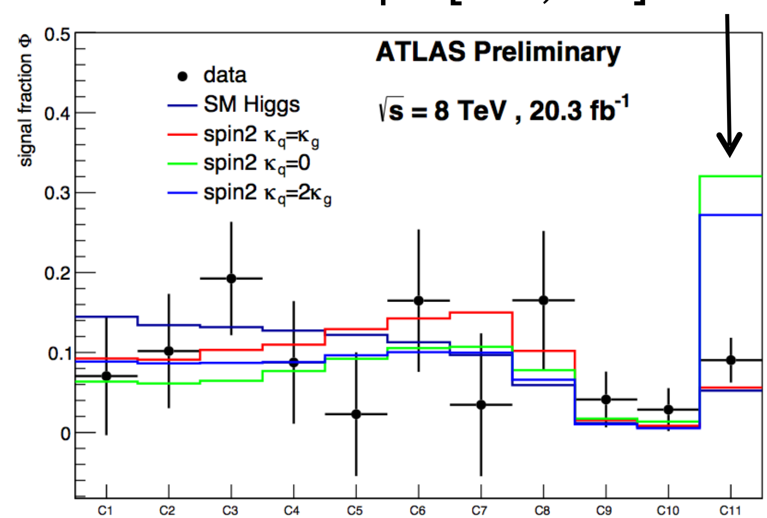
- Spin hypothesis tests (difficult model spin 2) – Combination of ZZ, WW and $\gamma\gamma$

$$\mathcal{L}_2 = \frac{1}{\Lambda}\left[\sum_V \kappa_V X^{\mu\nu}\mathcal{T}^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu}\mathcal{T}^f_{\mu\nu}\right]$$

Coupling to energy-momentum tensor

pT [125,300] GeV





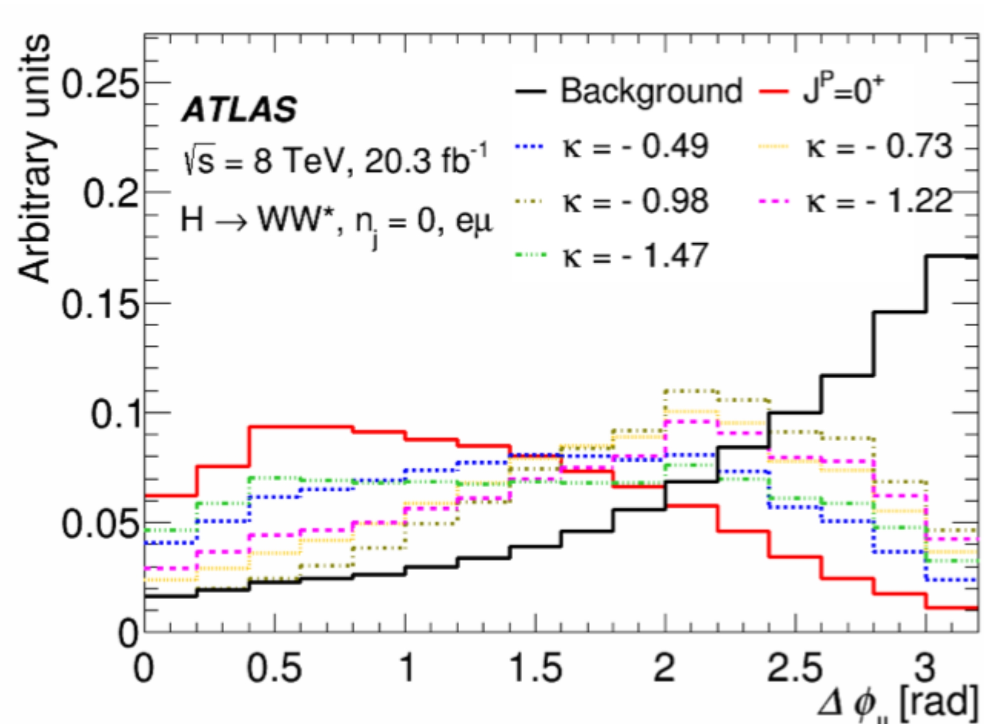
cos θ*

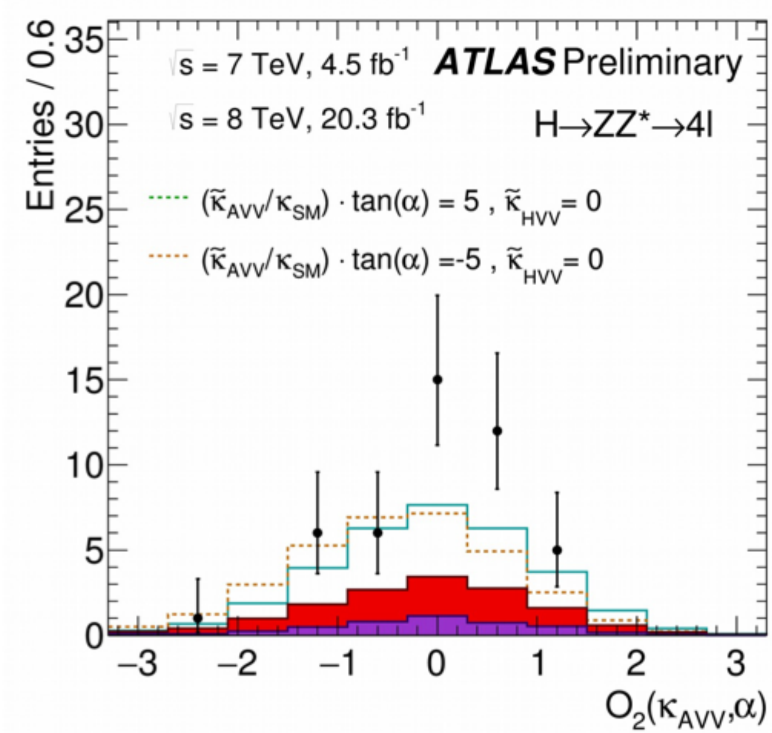
CP Mixing

Using effect model of general spin 0 couplings, Run 1 style analysis using specific optimal observables

$$
\begin{aligned}
\mathcal{L}_0^V = \quad & \Big\{ c_\alpha \kappa_{\mathrm{SM}} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \\
& - \tfrac{1}{4} \tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
& - \tfrac{1}{2} \tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \Big\} X_0
\end{aligned}
$$

(Use e.g. optimal observables in 4l channel)

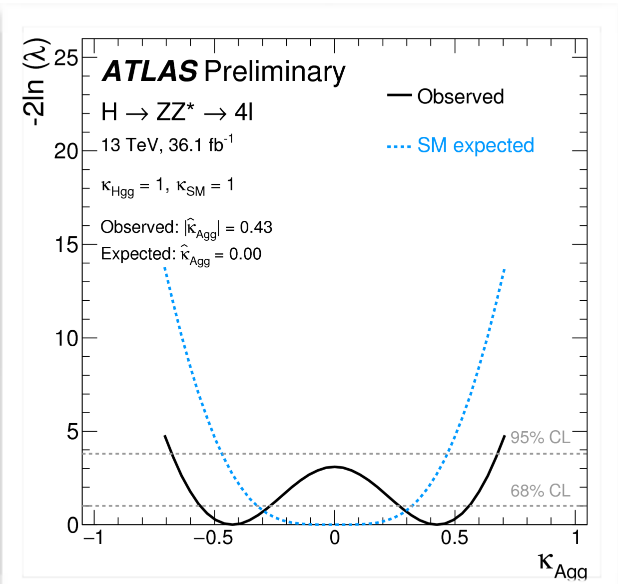


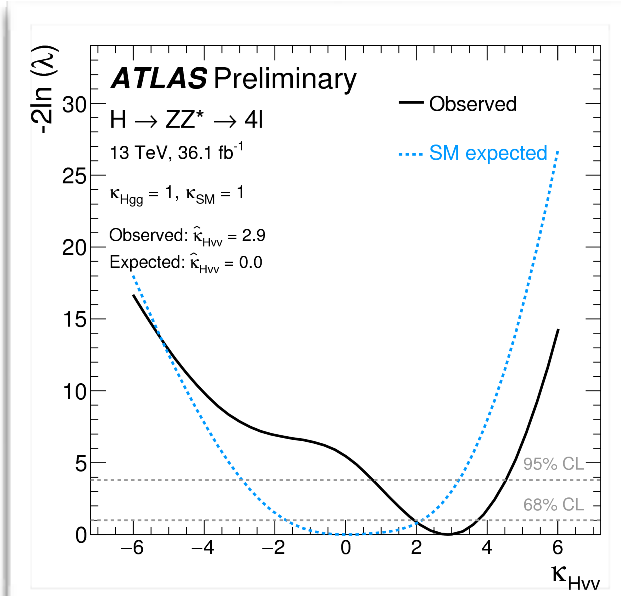


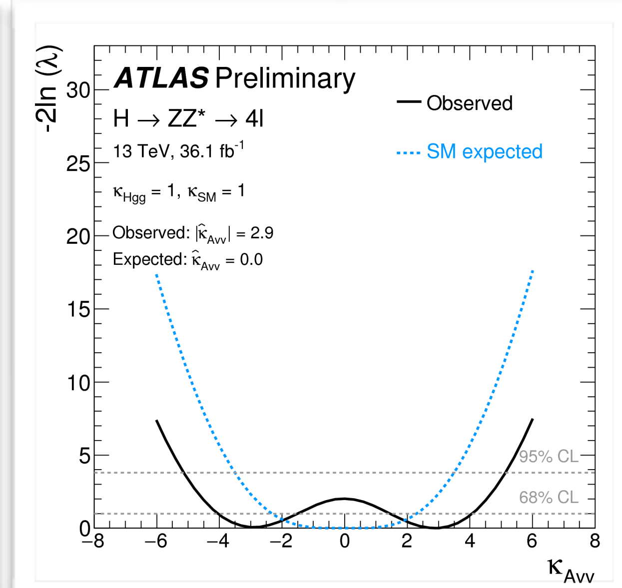
CP Mixing at Run 2

Fitting categories from the nominal ZZ ATLAS analysis

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu} \right] - \tfrac{1}{4}\tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \tfrac{1}{2}\tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right] \Big\} X_0$$

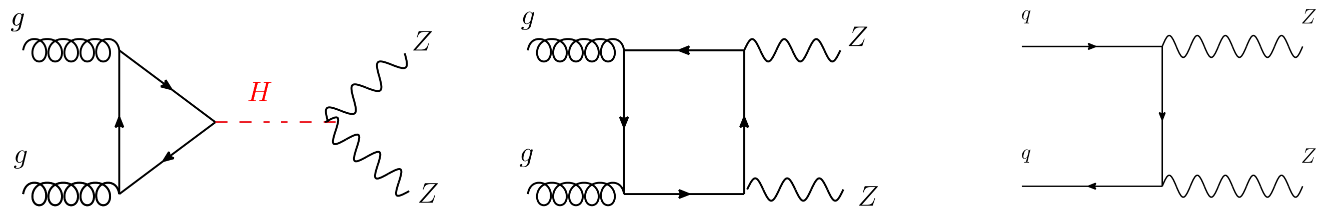


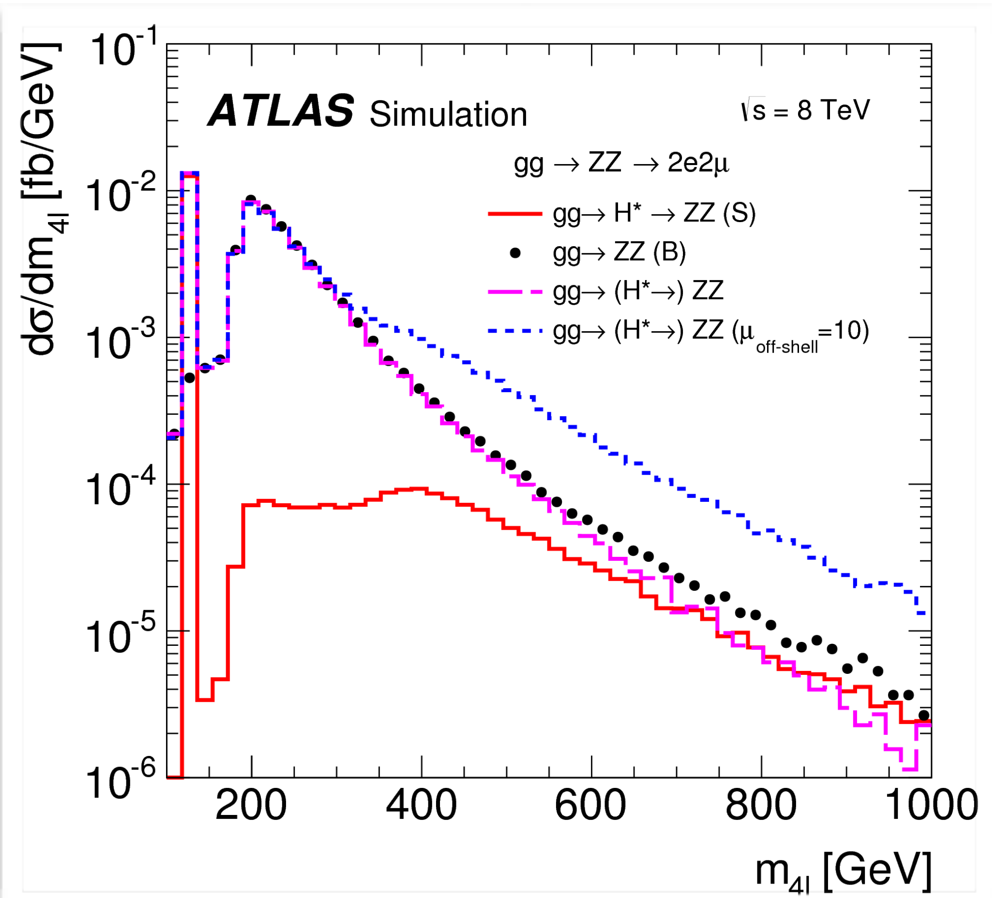




Off Shell Higgs

Study the Higgs boson as a propagator





Constrain the width through the assumption that the running of the gluon and the Z couplings of the Higgs are those of the Standard Model:

$$\mu_{off\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

$$\mu_{on\ shell} = \frac{(\kappa_t^2 \kappa_V^2)_{on\ shell}}{\Gamma_H / \Gamma_H^{SM}}$$

$$(\kappa_t^2 \kappa_V^2)_{on\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

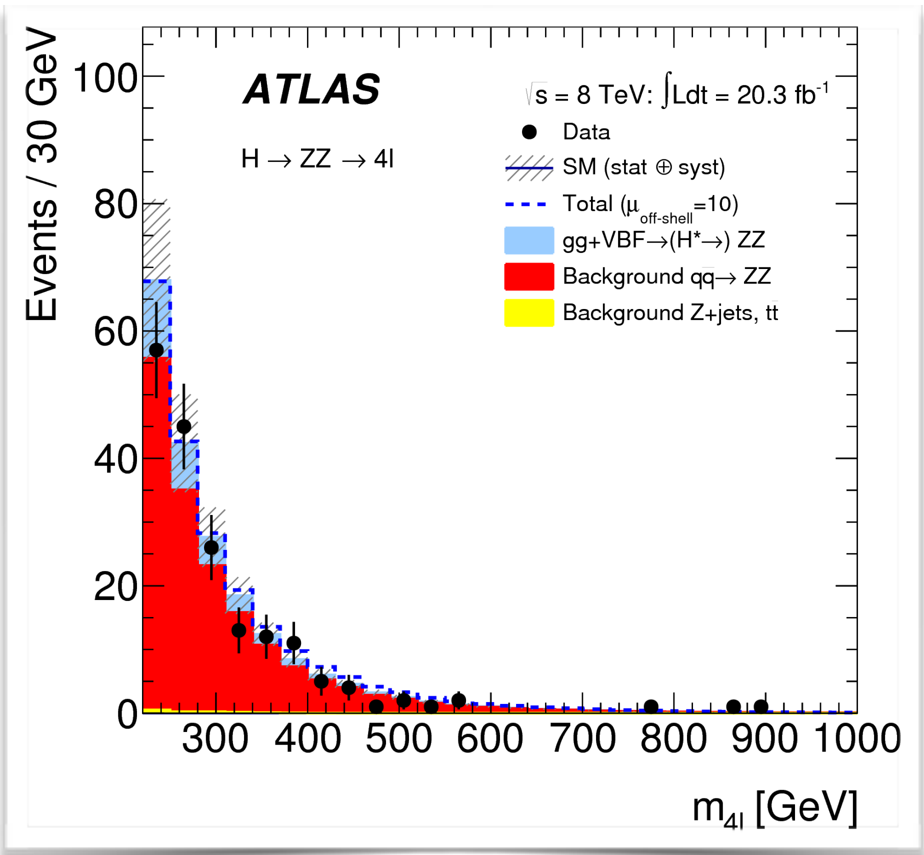
$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM}$$

Off Shell Higgs

Study the Higgs boson as a propagator

Results obtained at Run 1 are already impressive (experimental limits at 30 MeV per experiment level on total width of the Higgs boson), challenges:

- Importance of gg to VV at NLO
- Importance of the qq to VV background and EW corrections
- How to best estimate/parametrise error on interference



Off Shell Higgs

Study the Higgs boson as a propagator

Run 1 combining the ZZ and WW channels

$$ZZ \to 4\ell,\ 2\ell 2\nu$$

$$WW \to e\nu\mu\nu$$

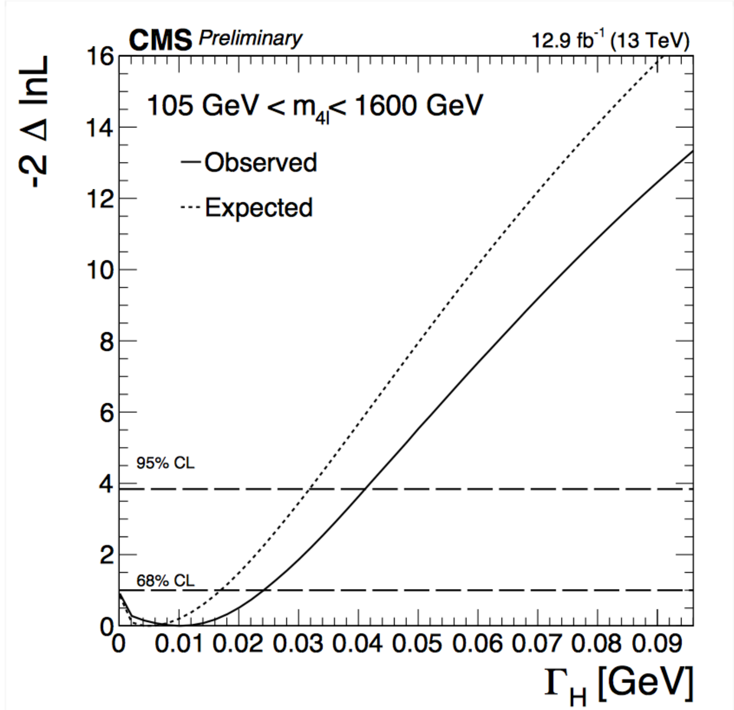
$$\Gamma_H < 26\,MeV\ (Obs.\ 95\%\,CL)$$

$$\Gamma_H < 66\,MeV\ (Exp.\ 95\%\,CL)$$

First Run 2 results from CMS with 12.9 fb-1

$$\Gamma_H < 41\,MeV$$

Expected at around 30 MeV

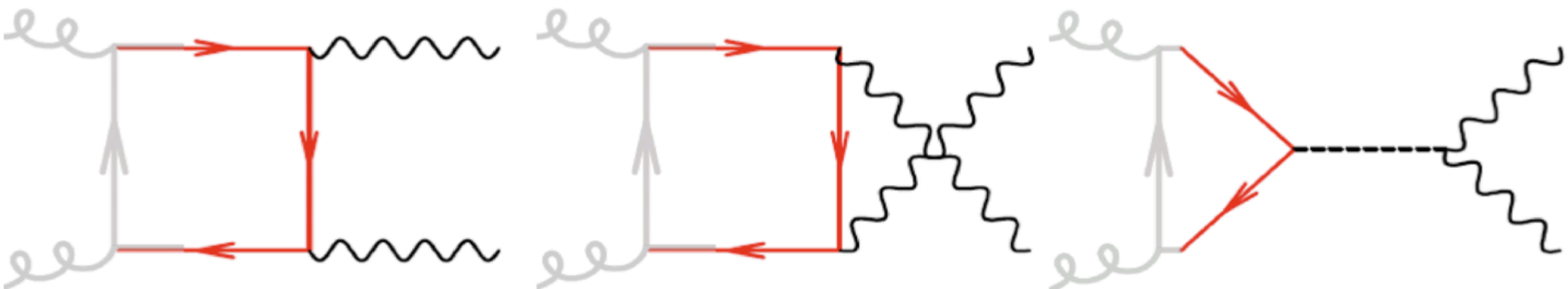


Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab-1:

$$\Gamma_H = 4.2^{+1.5}_{-2.1}\,MeV$$

Off Shell Higgs

Study the Higgs boson as a propagator



$aE^2 + (b+c)m_tE$ $\quad$ $-aE^2 + (d-c)m_tE$ $\quad$ $-(b+d)m_tE$

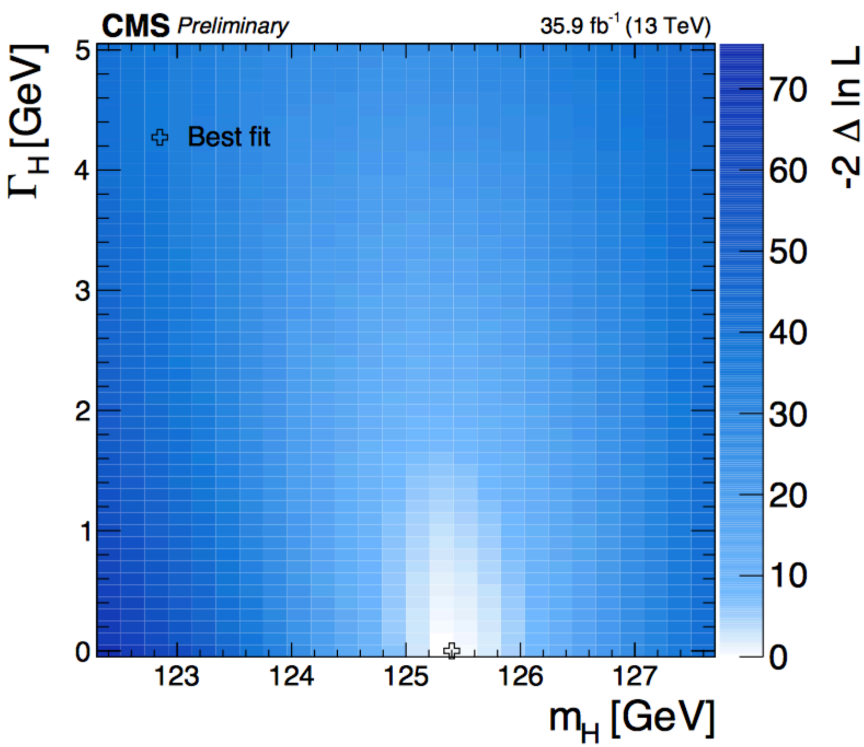
From J. Campbell

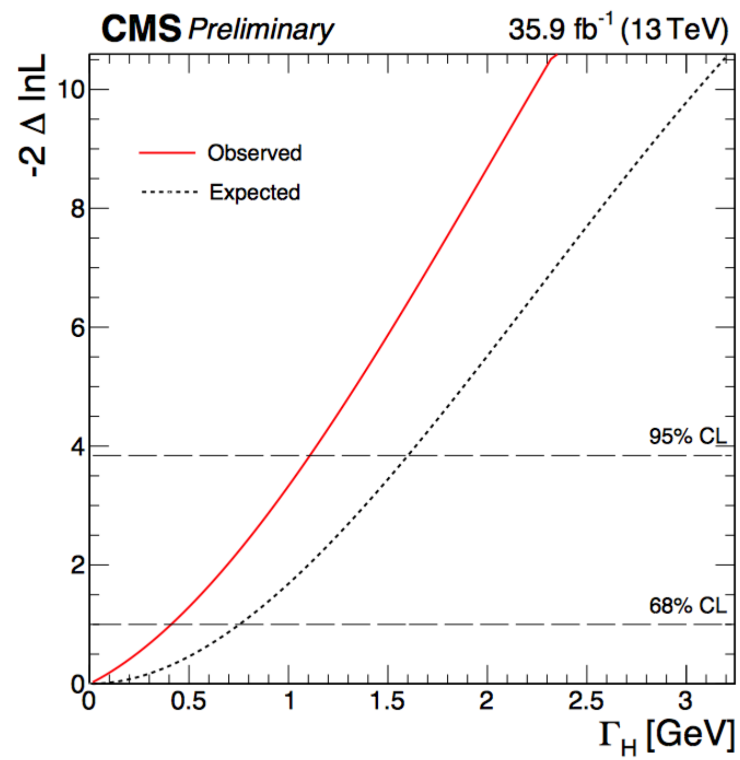
Understanding the negative interference to cancel the high energy behaviour of the gg to ZZ process.

On Shell width measurement

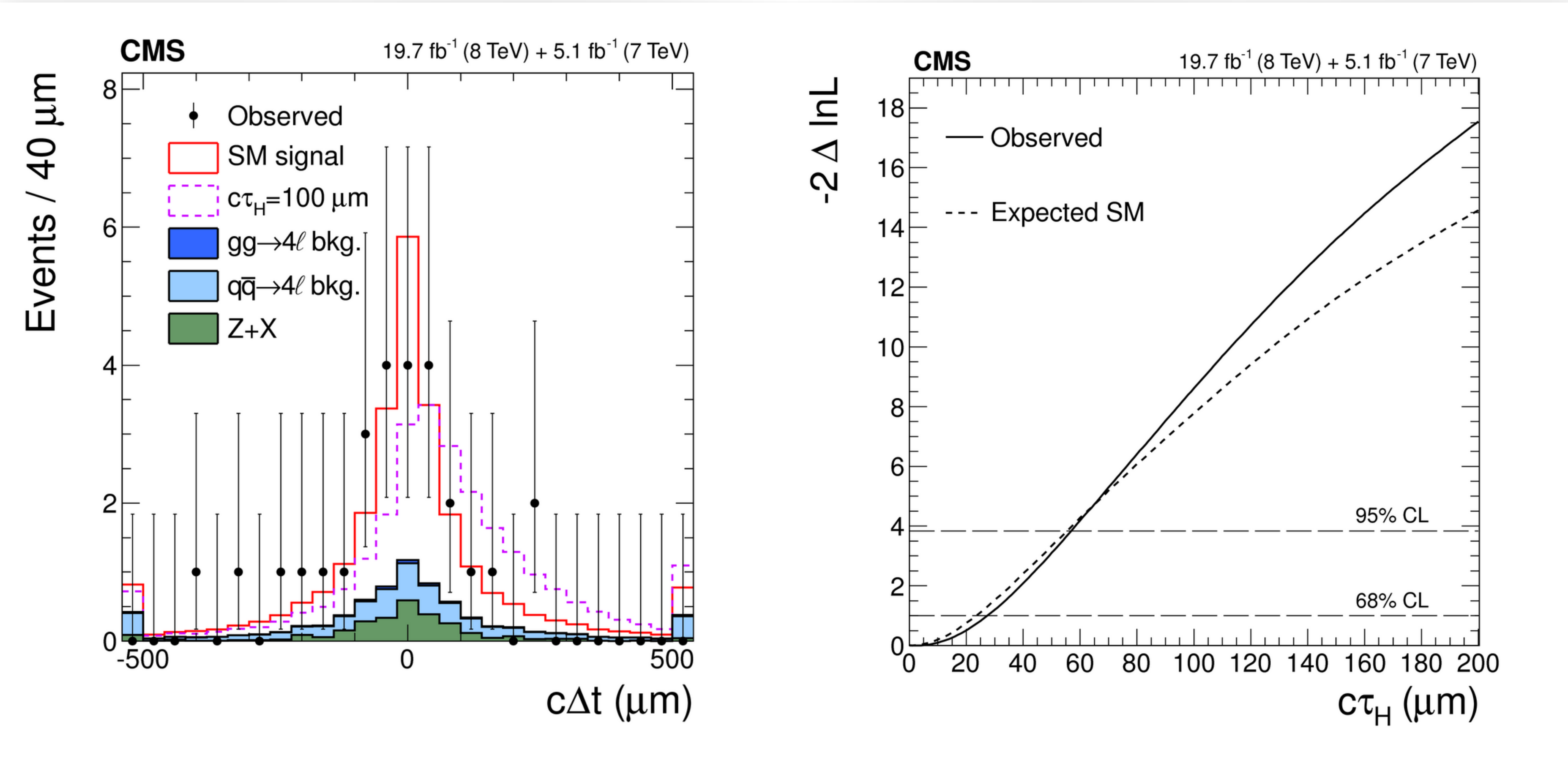
Done both in the diphoton and the 4 leptons channels, intricate in particular to describe very accurately the mass line shape

Parameter	$m_{4\ell}$ range	Expected	Observed
Γ_H (GeV)	[105, 140]	$0.00^{+0.75}_{-0.00}$ [0.00, 1.60]	$0.00^{+0.41}_{-0.00}$ [0.00, 1.10]





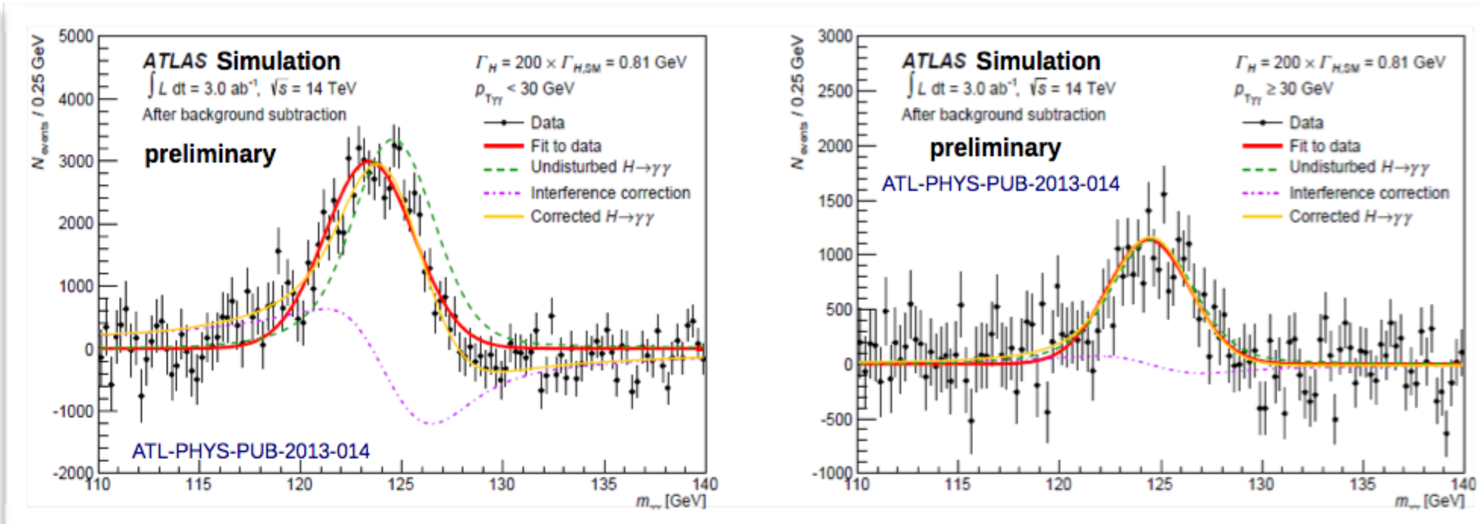
Constraints from the Higgs Lifetime

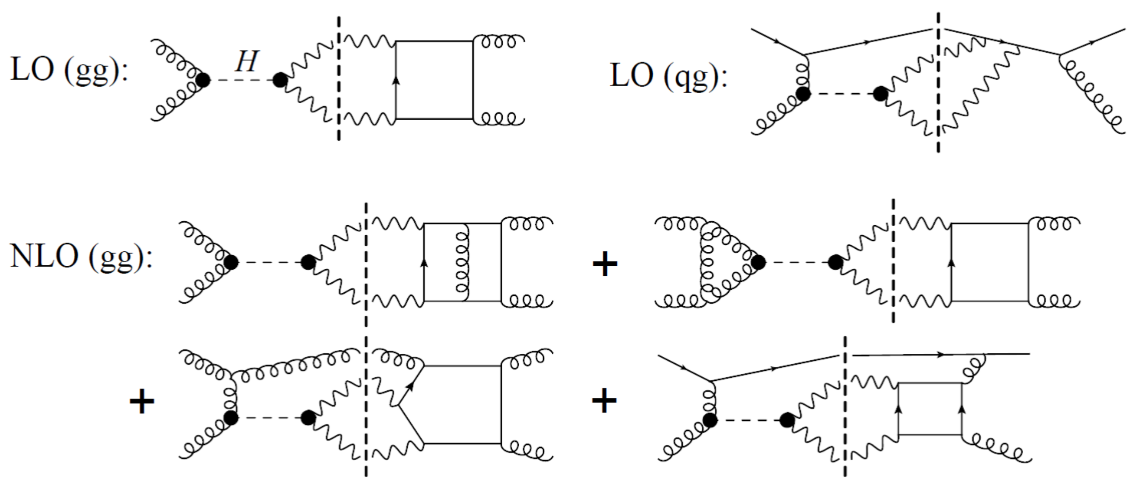


$$\tau_H < 1.9 \times 10^{-13}\, s$$

$$\Gamma_H > 3.5 \times 10^{-9}\, MeV$$

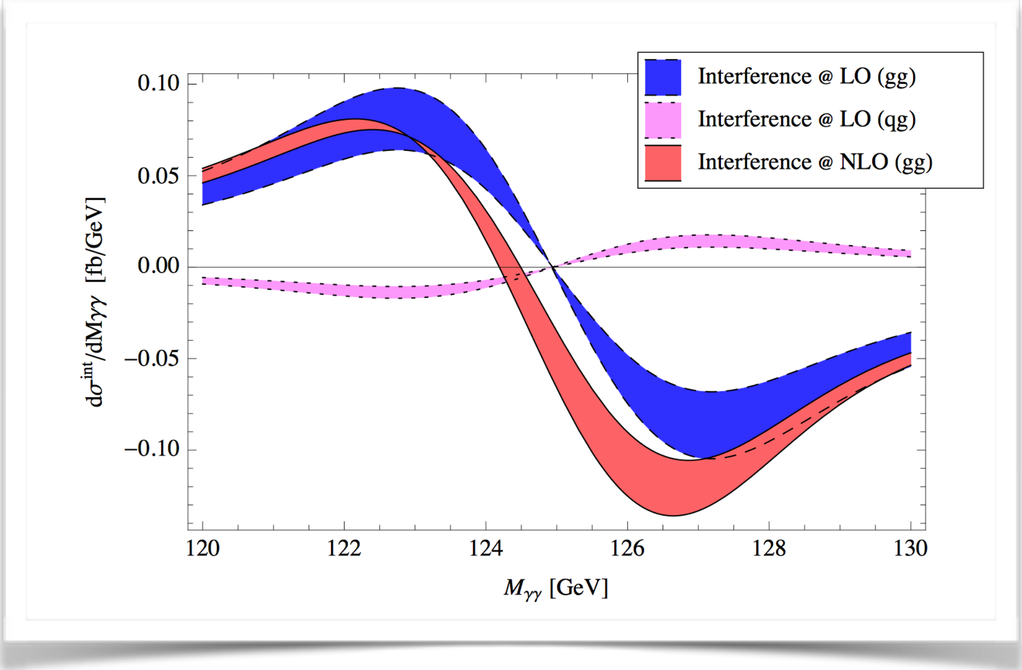
Mass shift from interference in γγ events





Martin, Dixon and Li Phys.Rev.Lett. 111 (2013) 11180

Width from mass shift



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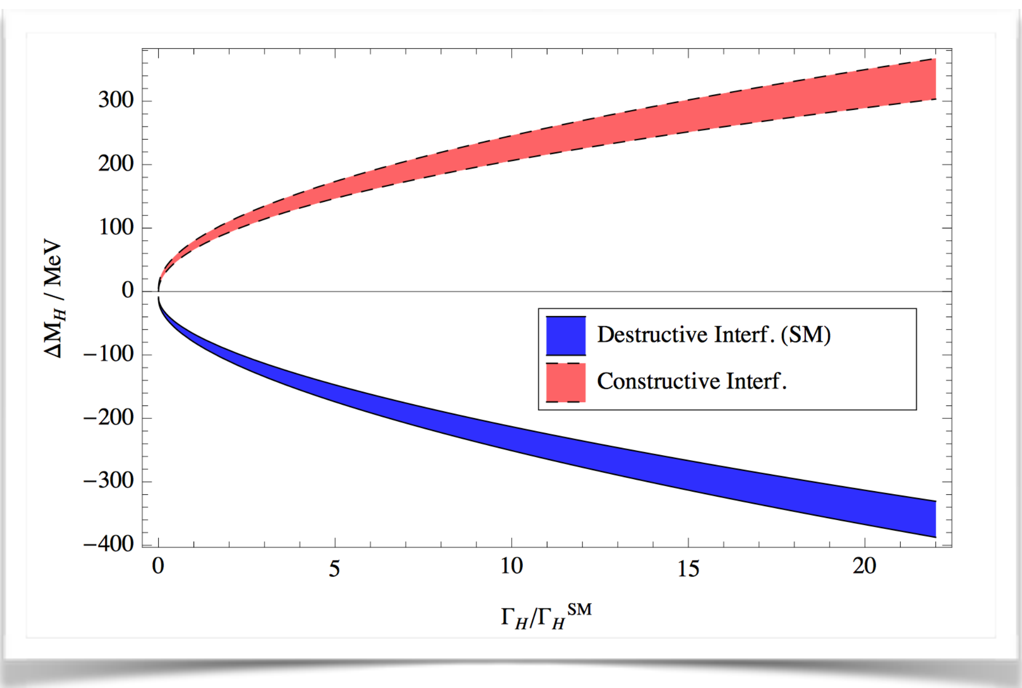
$$\Delta m_H = -35 \pm 9\, MeV$$

Assuming the SM width



Shift grows with the width

$$\Delta m_H < 200\, MeV$$

at HL-LHC (3 ab^{-1})

Higgs Physics - Lecture 2

Experimental Profile of the Higgs boson

1.- A one slide panorama!

2.- Going further with « bread and butter » channels

3.- Going further with the discovery channels

4.- Intermezzo on Sources of Systematic Uncertainties (Experimental and Modelling)

5.- **Direct probes of the couplings the Higgs boson to fermions:** Highly anticipated Run 2 Analyses

6.- **Combined Measurement of properties:** Based on Run 1

Reconstruction Performance

Electrons and photons

- Likelihood (cut) based ID for electrons (γ) and MVA-based calibration
- In-situ calibration using Z, W and J/Psi

Muons

- Excellent performance (with few sporadic muon chamber failures)
- In-situ calibration of energy and ID efficiency with Z (and J/Psi)

Jets

- Anti-kT algorithm from 0.4 to 0.7 used with detector noise cleaning cuts and track based variable to mitigate PU effect.
- JES in situ uncertainty reach ~1% level already (central and intermediate pT range) – using Z, γ and multi-jets.

MET

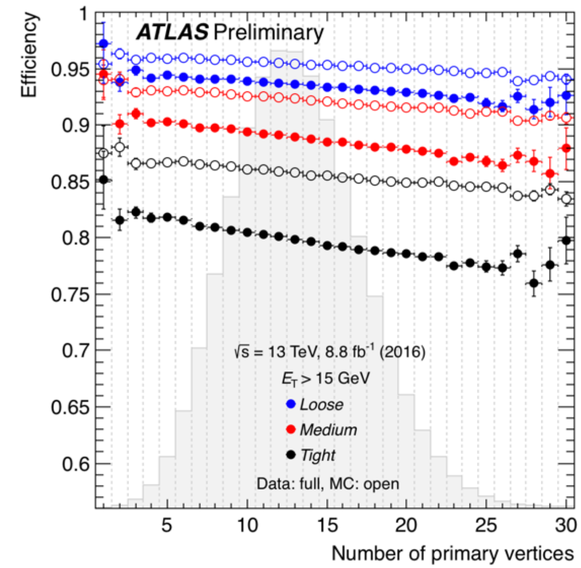
- Reconstruction use all calibrated objects and a track-based soft term

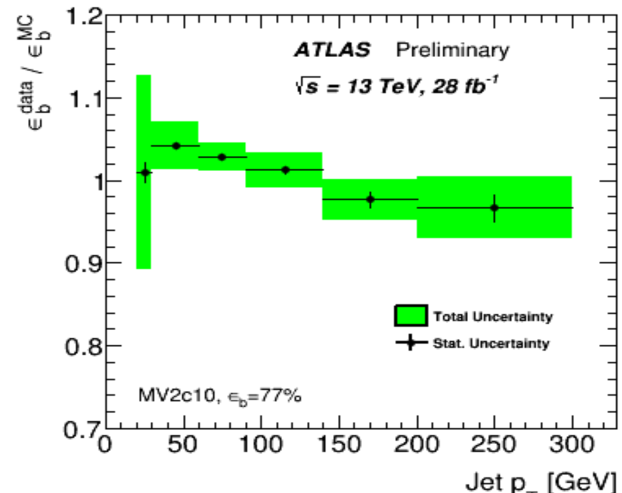
Taus

- BDT based identification (70% eff. and ~50 rej.)
- In-situ calibration based on Z events

B-jets

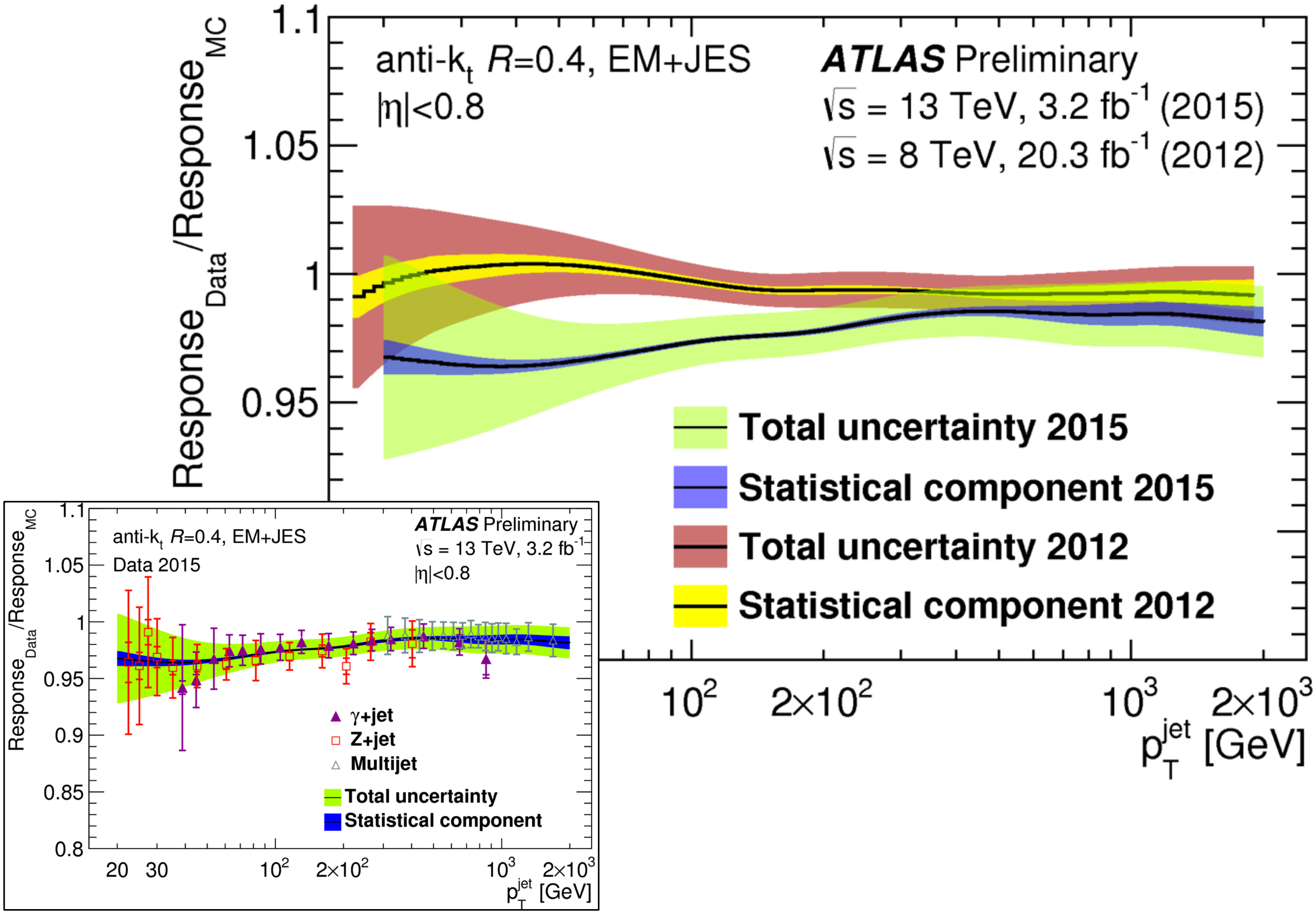
- MVA based algorithm (77% eff., ~250 l-rej. and ~8 c-rej.)
- Improvement w.r.t Run 1 pT dependent but typically ~4 in rej.
- In-situ calibration of b-tag efficiency (using top events)





Reconstruction performance so far robust to PU

Jet Energy Scale



Online typical Performance

HLT algorithms are typically asclose as possible to reconstruction level algorithms. Trigger menus are extremely complex including support items the ATLAS Run 2 menu has ~2000 items.

Photons

- Single photon threshold 140 GeV — 20 Hz
- Two photon thresholds at 25 and 35 GeV — 12 Hz

Electrons

- Single electron threshold 25 GeV — 140 Hz
- Two electrons at 12 GeV — 20 Hz

Muons

- Single muon trigger threshold 24-25 GeV (2 muons 6-6 GeV) — 130 Hz
- Two muons 10 GeV — 20 Hz

Jets

- Single jet trigger threshold 380 GeV — 20 Hz

MET — 60 Hz

- MET trigger threshold 90-110 GeV

Taus

- BDT based identification (70% eff. and ~50 rej.) similar to reconstruction level.
- Single tau 80 GeV

40 Hz

B-jets

- HLT only, but allows to lower the trigger thresholds.
- MVA based algorithm similar to reconstruction level.
- Tracking is not precisely the same (take into account updates of conditions, in particular the alignment.
- One loose b threshold 225 GeV

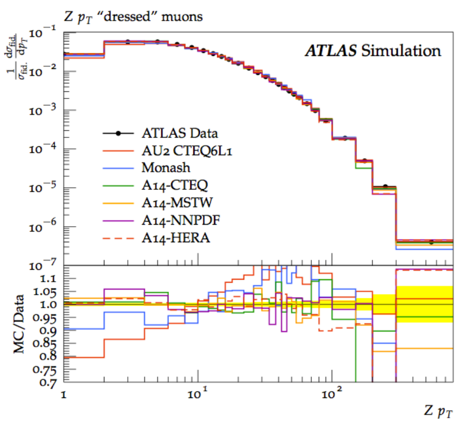
35 Hz

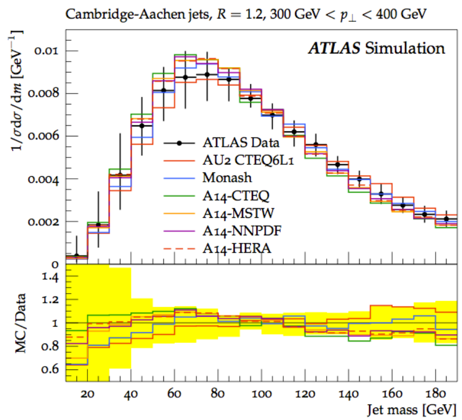
Typical HLT unique rates

Physics Modelling

A14 Minbias tune (for PU)

Pythia 6 and 8 (using 7 TeV ATLAS data only)

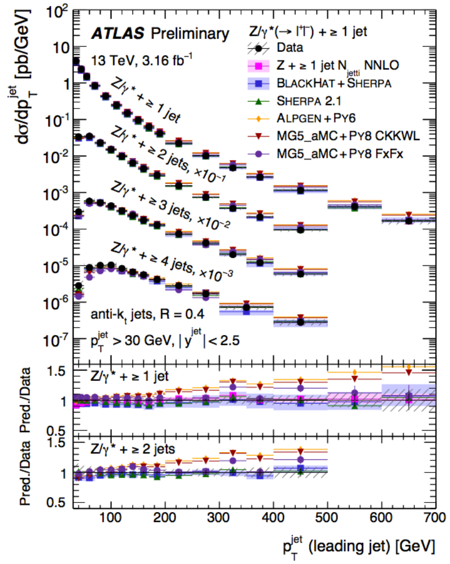


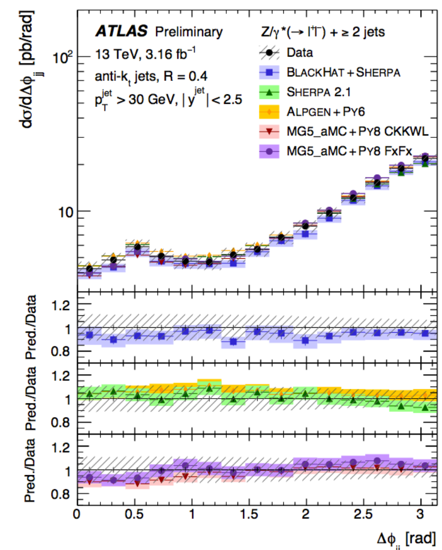


ATL-PHYS-PUB-2014-021

V+Jets , Dibosons, Tribosons

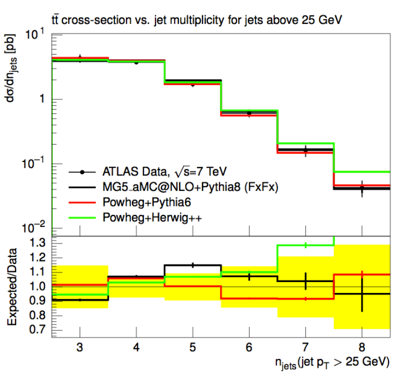
Sherpa NLO (2partons) and LO (up to 4 partons) 2.1.1

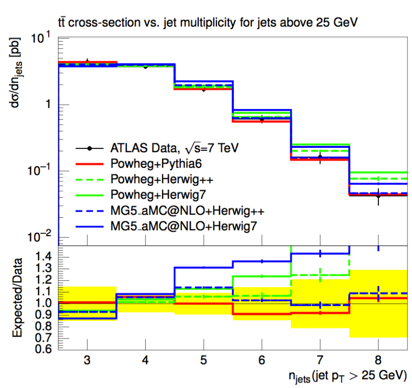




Top pair production

Powheg-Box v2 (hdamp =m_t) – Pythia 6.428 – EvtGen (HF decays) - CT10 PDFs – Perugia 2012 tune





Additional samples (main backgrounds and signals)

e.g. Pythia 8, Sherpa LO, MG5_aMC@NLO

PDFs: CT10, CTEQ6L1, NNPDF3.0

Higher order cross sections used where calculations available

Very fruitful and very efficient interactions with theory Community

Higgs Physics - Lecture 2

Experimental Profile of the Higgs boson

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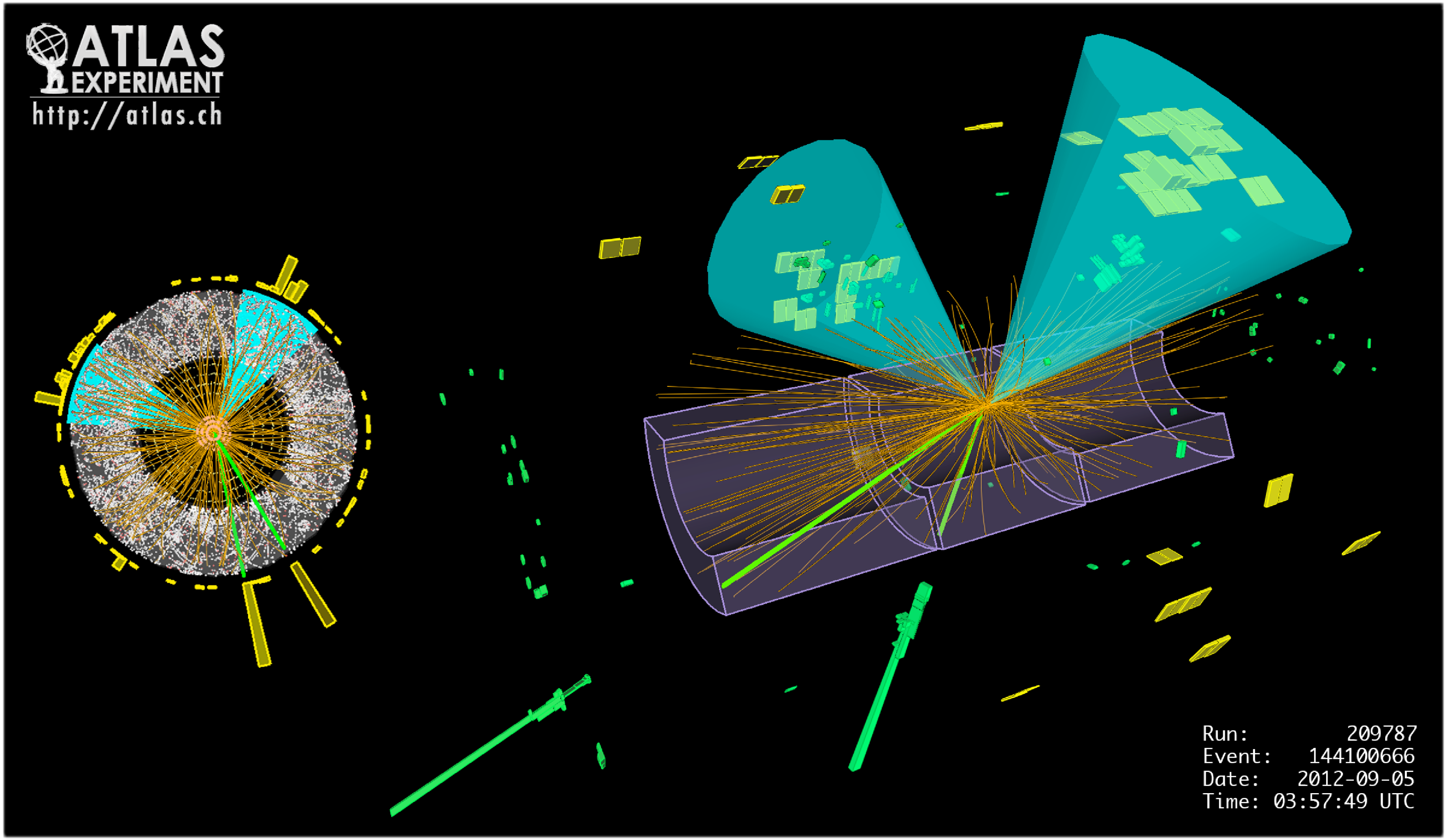
VH(bb)

Z(ll)H → bb candidate

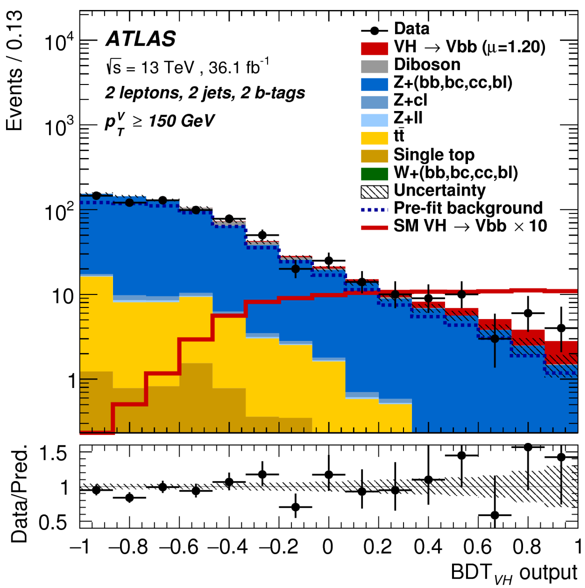


VH(bb)

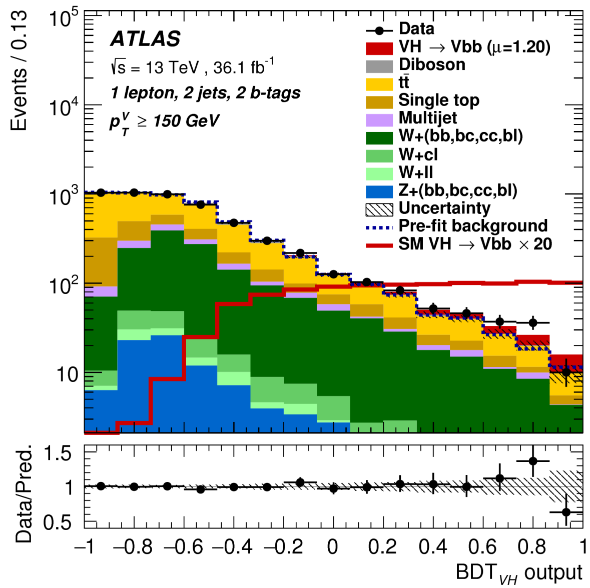
Analysis strategy done in three channels 0L, 1L, 2L done in two jet categories (2 and 3 jets), important aspects:

- Relies on high pT (boost) without “boosted” techniques to reduce background V-jets (and top for the 1L channel).
- Use MVA analysis with m_{bb} and $\Delta R(b_1,b_2)$ most discriminating variables
- Slightly simplified analysis w.r.t. Run 1 at the price of some sensitivity.
- VZ(bb) production is an important standard candle, but does note that it does not have precisely he same pT sensitivity pattern as VH(bb)
- **Critical aspect: Modelling of the V-jets process**

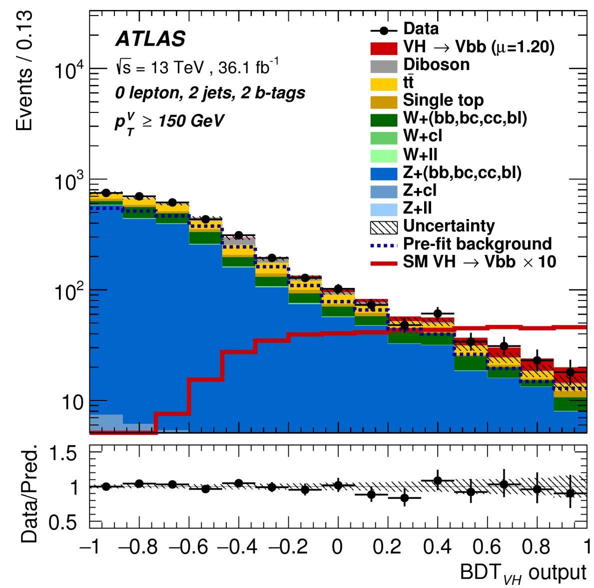
0 lepton



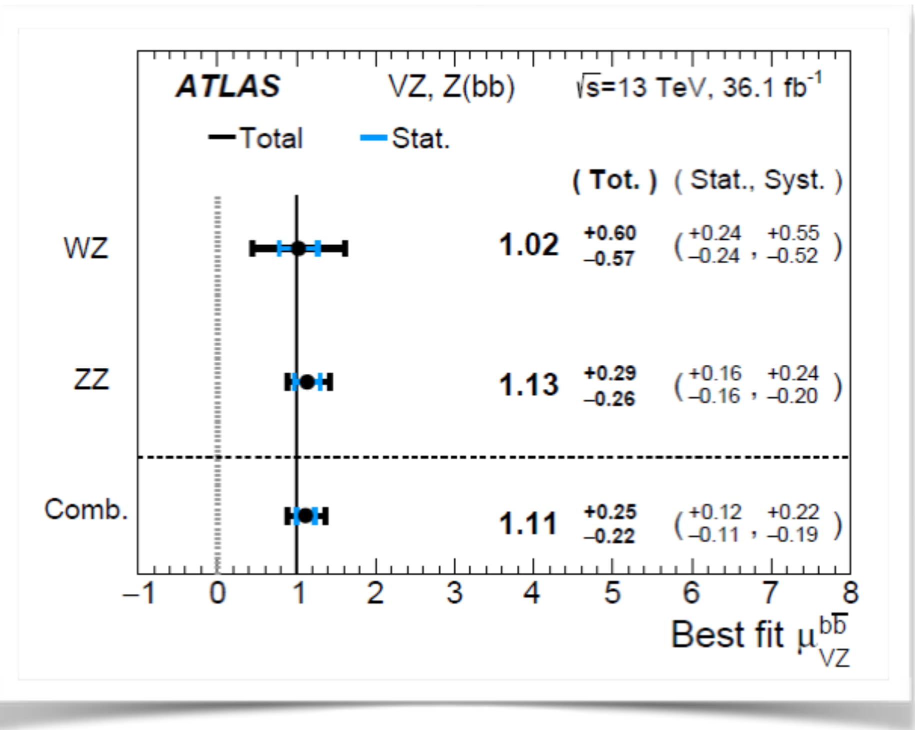
1 lepton

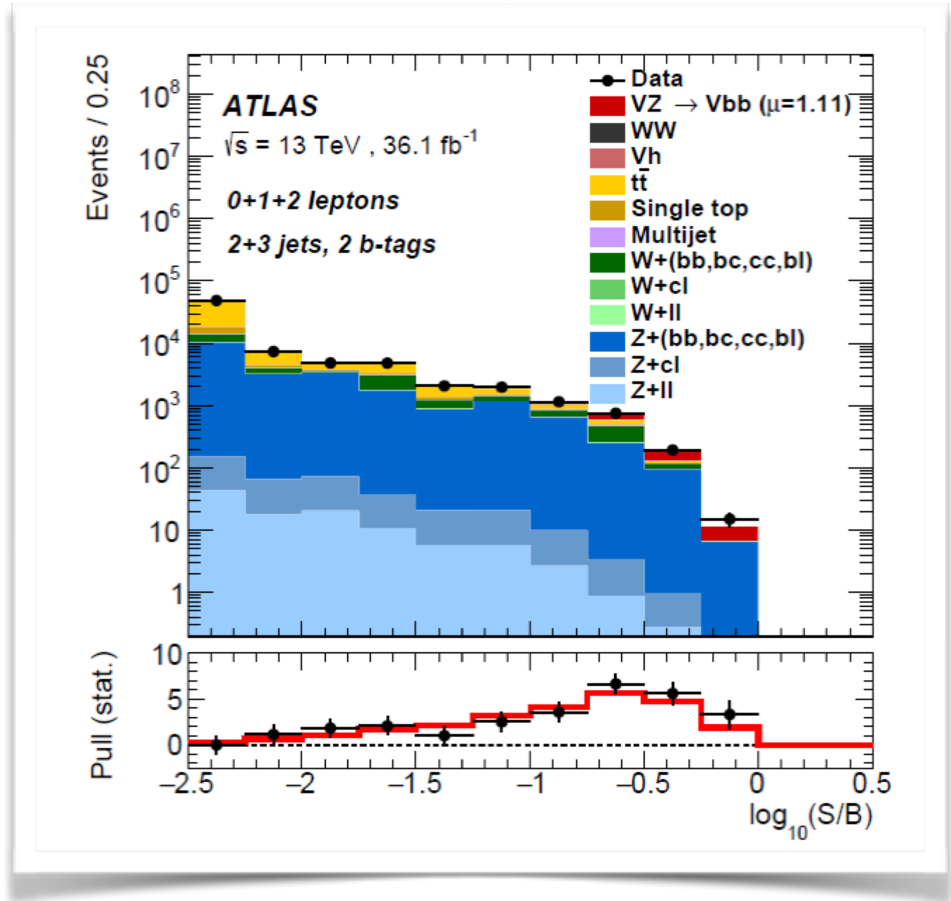


2 leptons



VZ(bb) Observation

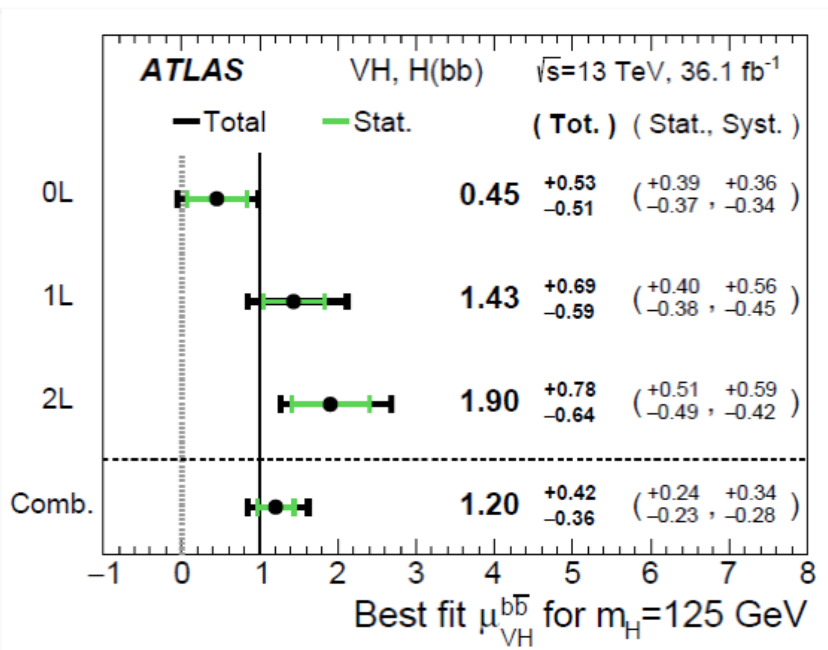


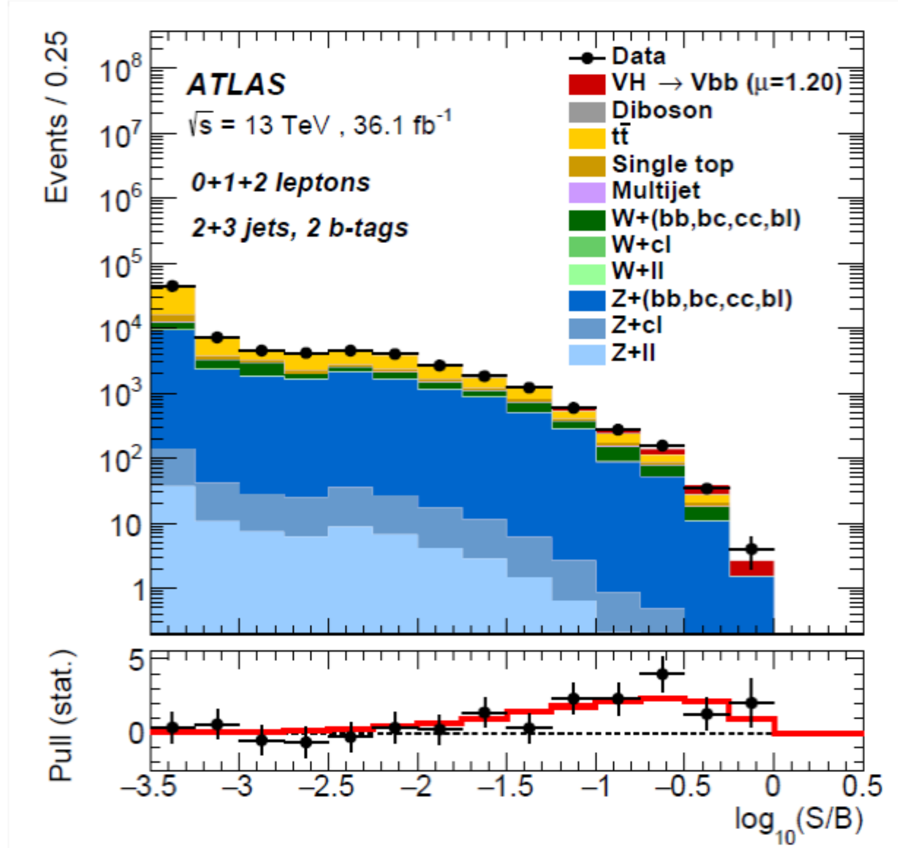


Significances $5.8\sigma\ (obs)$

$5.3\sigma\ (exp)$

VH(bb) Evidence

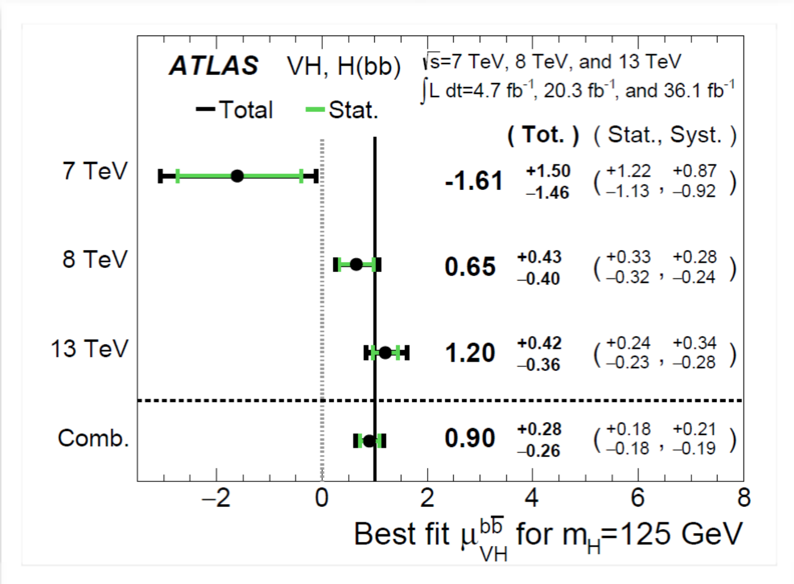


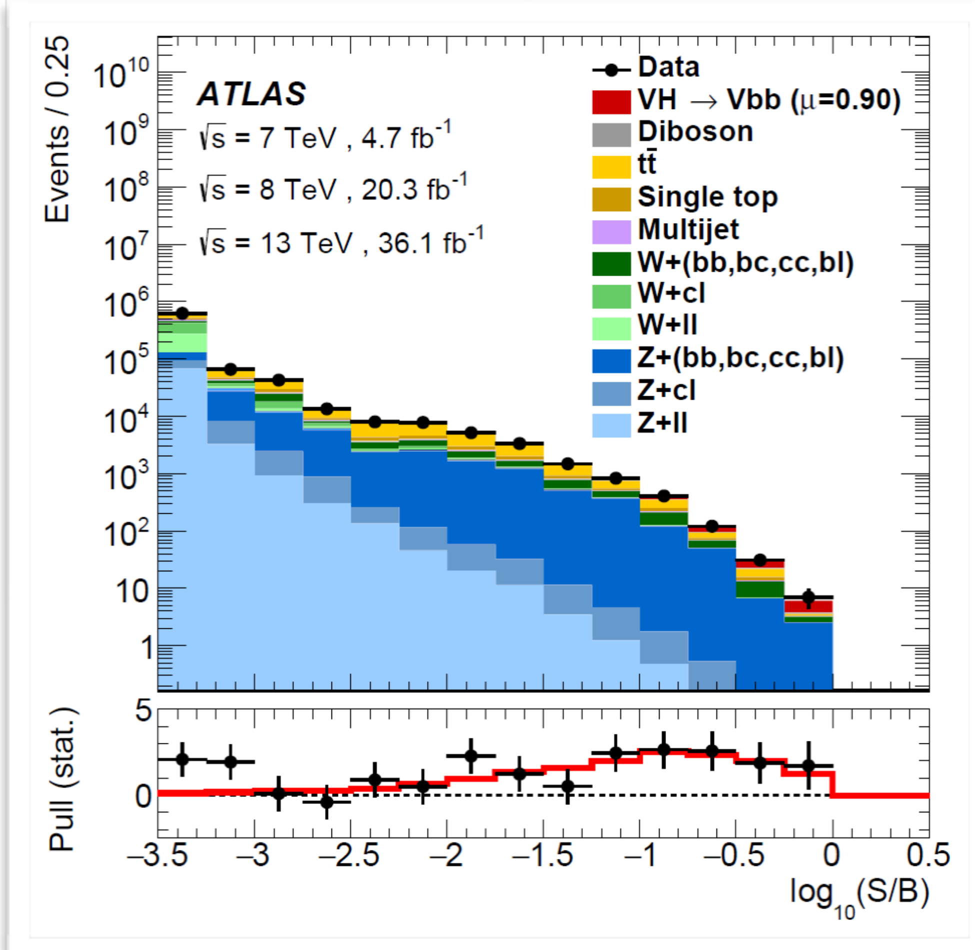


Significances $3.5\sigma\ (obs)$

$3.0\sigma\ (exp)$

Run 1 and Run 2 Combination

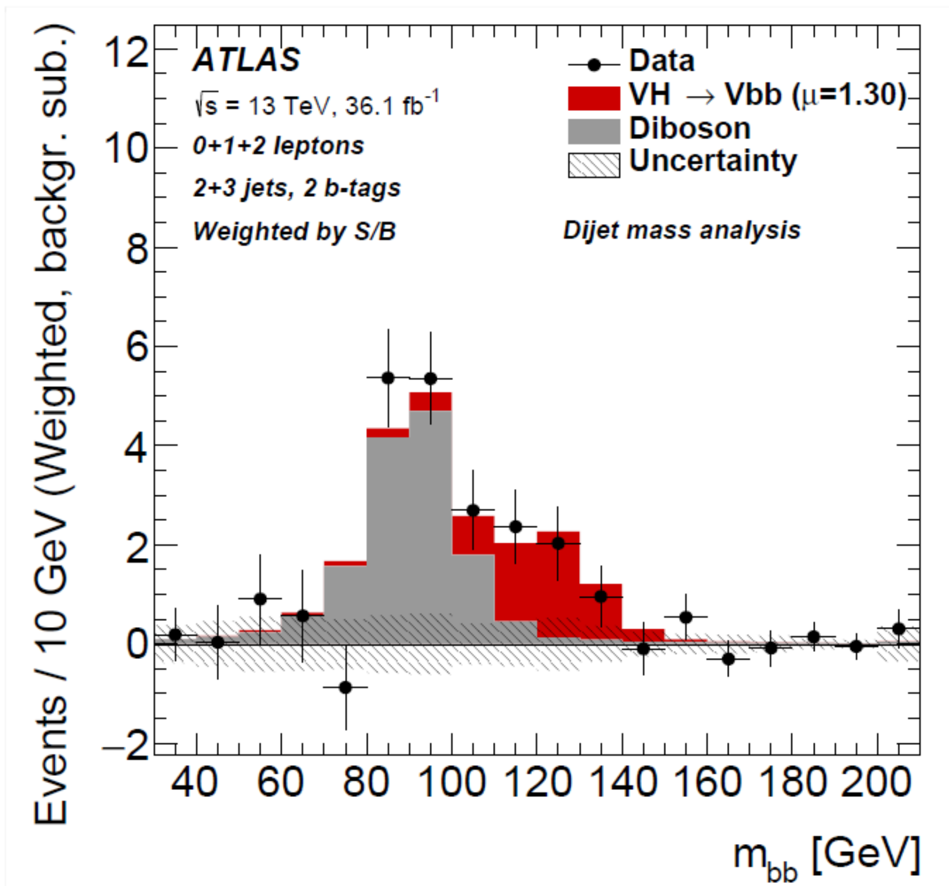




Significances

$$3.6\sigma\ (obs)$$
$$4.0\sigma\ (exp)$$

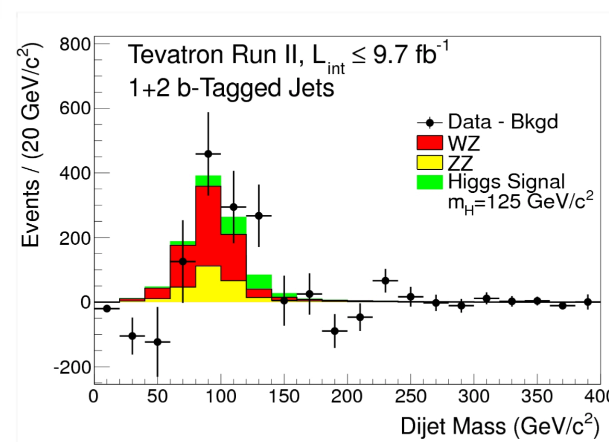
Cuts Based Cross Check



Significances

$$3.5\sigma\ (obs)$$

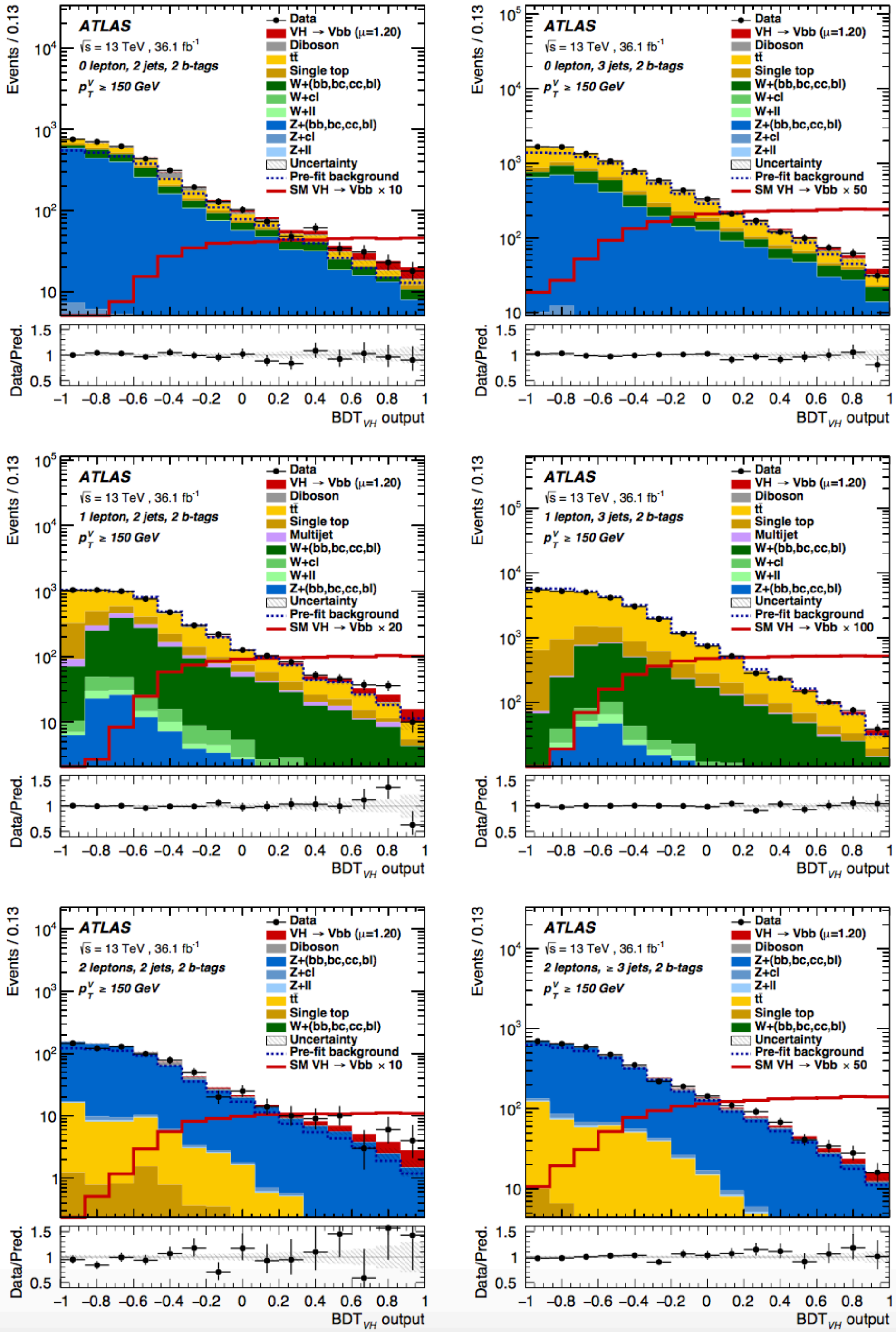
$$2.8\sigma\ (exp)$$

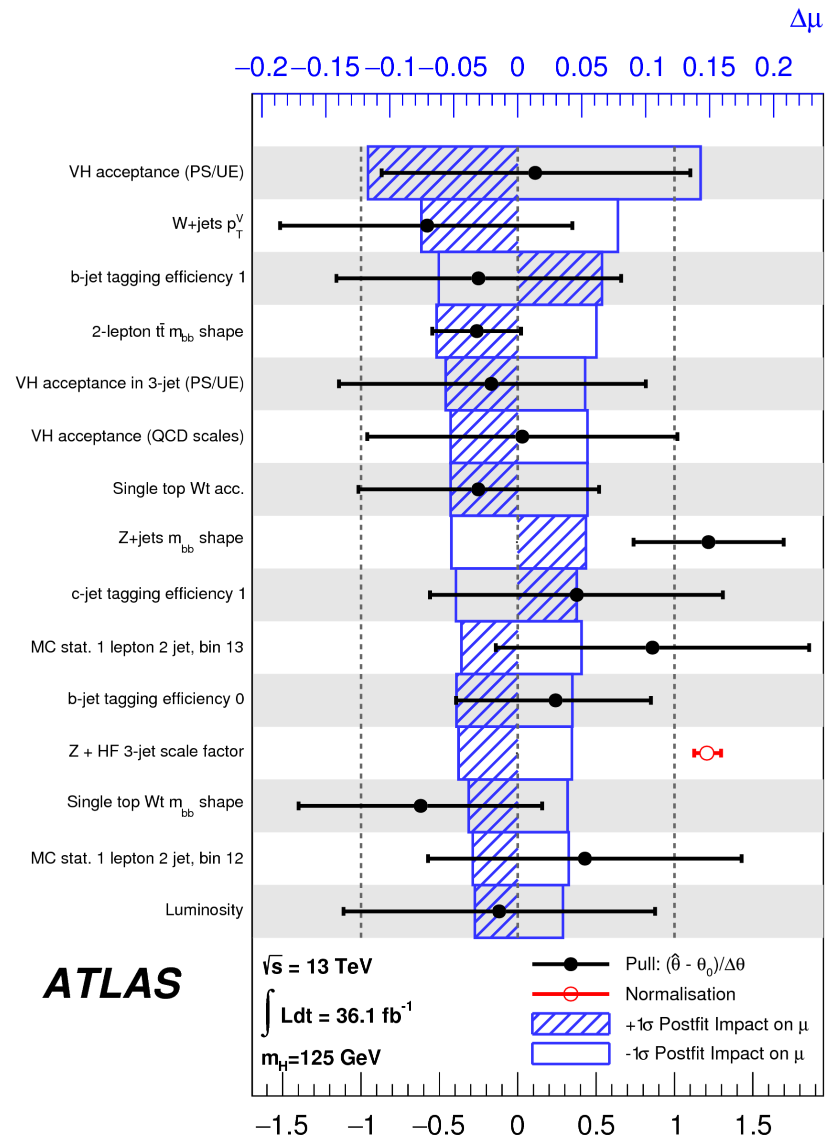


Note that this type of plot is not new, it was done at TeVatron where an excess with a significance of 2.8 std. dev. (sensitivity of approximately 1.6 std. dev. from plot) was observed at a mass near 125 GeV.

Profiling Paradigm

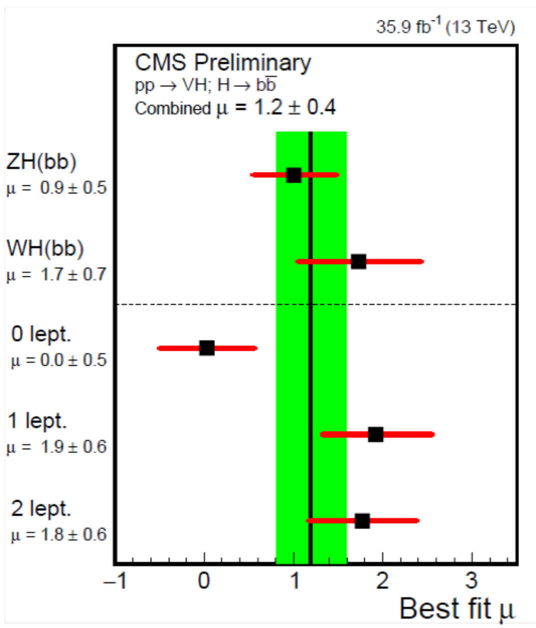
At work

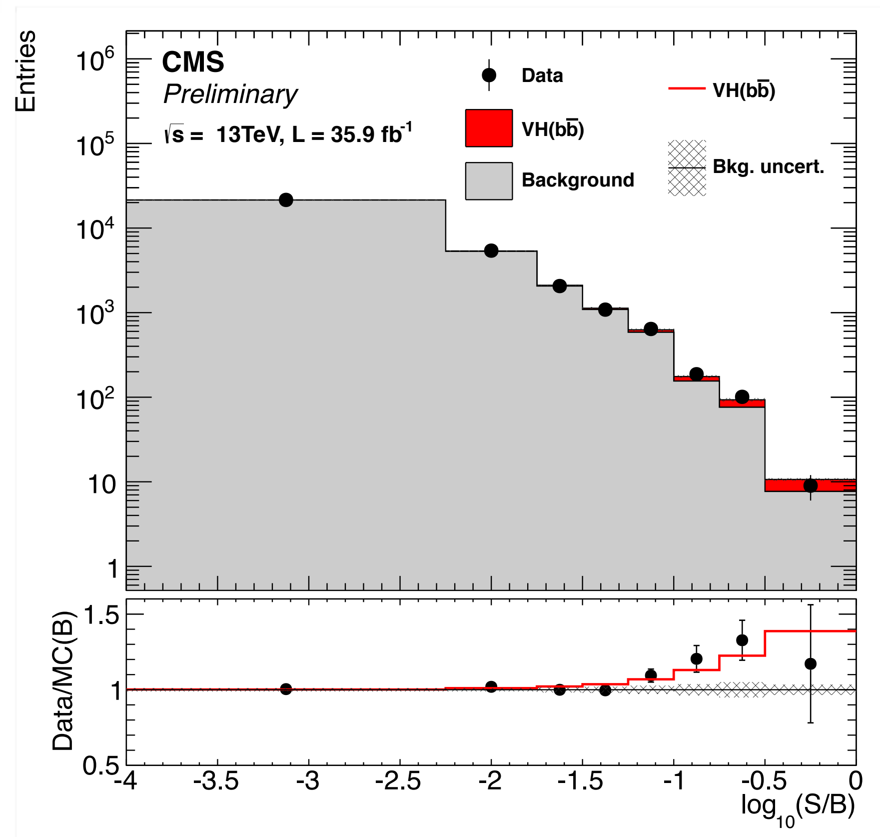




CMS Results

CMS-PAS-HIG-16-044



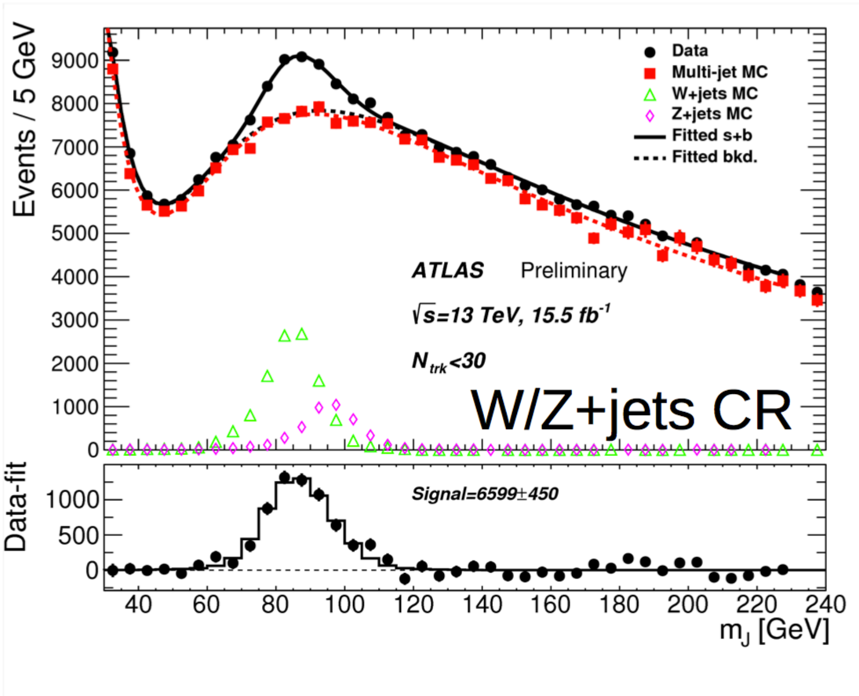


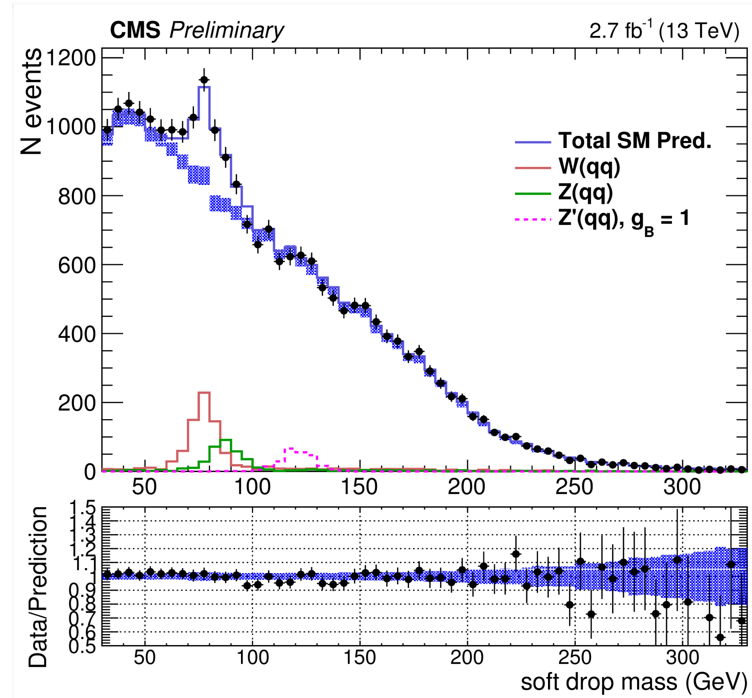
0L low both in ATLAS and CMS

Significances

$$3.8\sigma\ (obs)$$
$$3.8\sigma\ (exp)$$

Jet Substructure



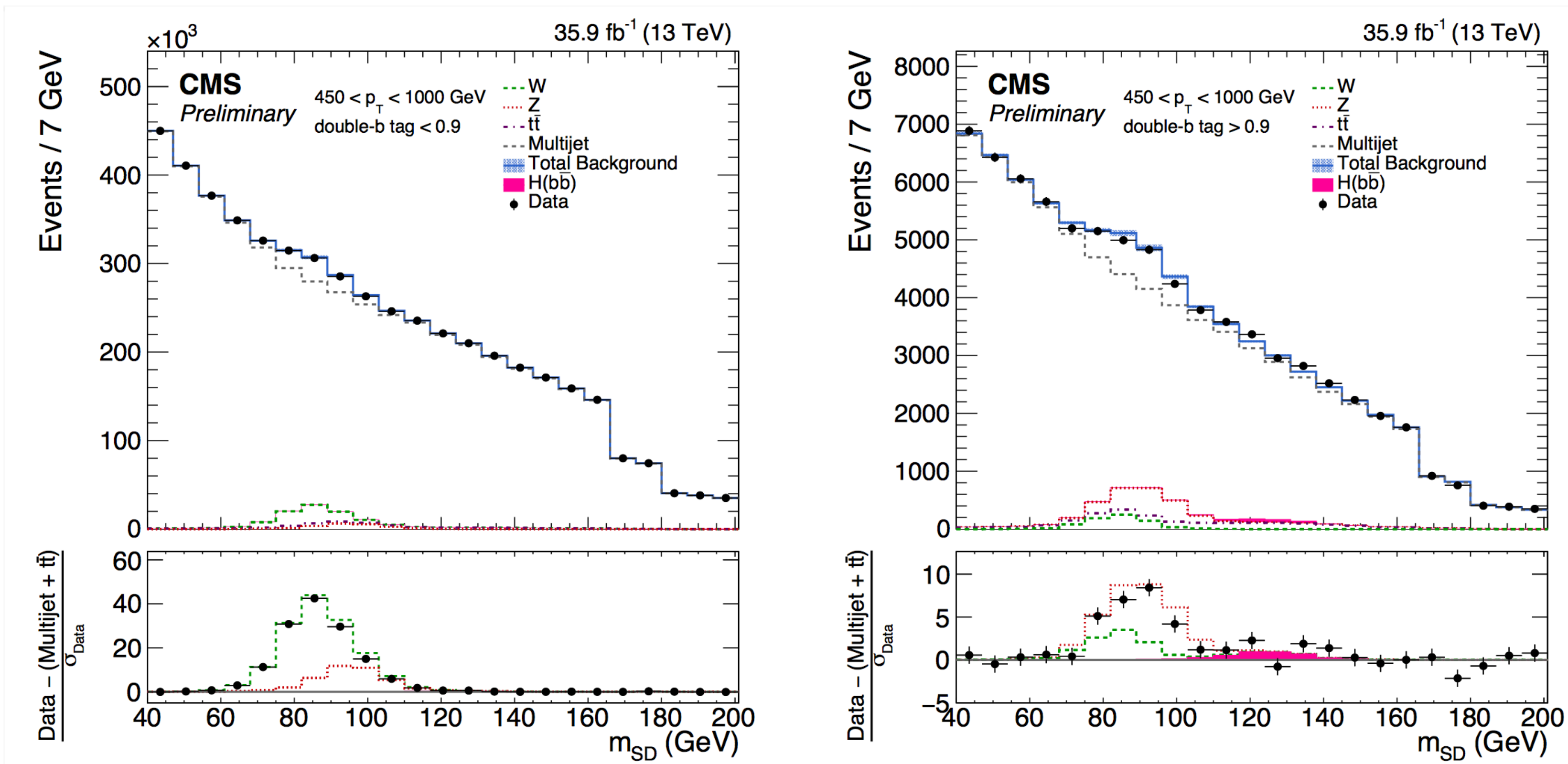


Nominal boson tagging algorithm

- Large R-jet algorithms used for hadronic decays of particles: W, Z, Higgs and the top.
- Algorithms use substructure of jets.
- Pileup subtraction very important, and a large number algorithms have been developed.
- Overall performance is very impressive!

Inclusive H(bb)

CMS-PAS-HIG-17-010



- At least one AK8 jet of 450 GeV
- One or two b-tags (double b-tagging efficiency pT dependent)

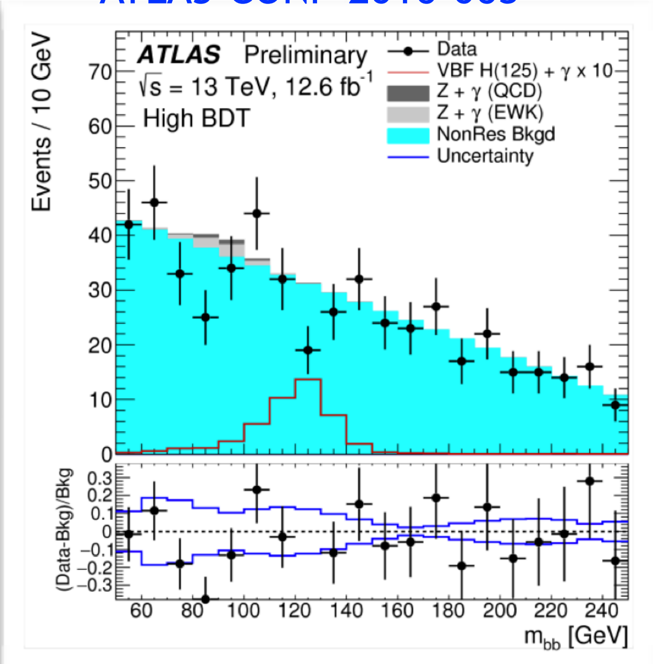
Significances

$$1.5\sigma\ (obs)$$

$$0.7\sigma\ (exp)$$

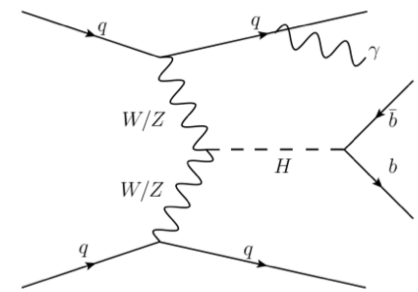
Completing the b-Yukawa Picture

ATLAS-CONF-2016-063



Analysis strategy New analysis strategy with many interesting advantages:

- Photon useful for triggering.
- Useful for distinguishing from gluon induced background processes.
- Most importantly: reduces QCD background greatly due to negative interference.



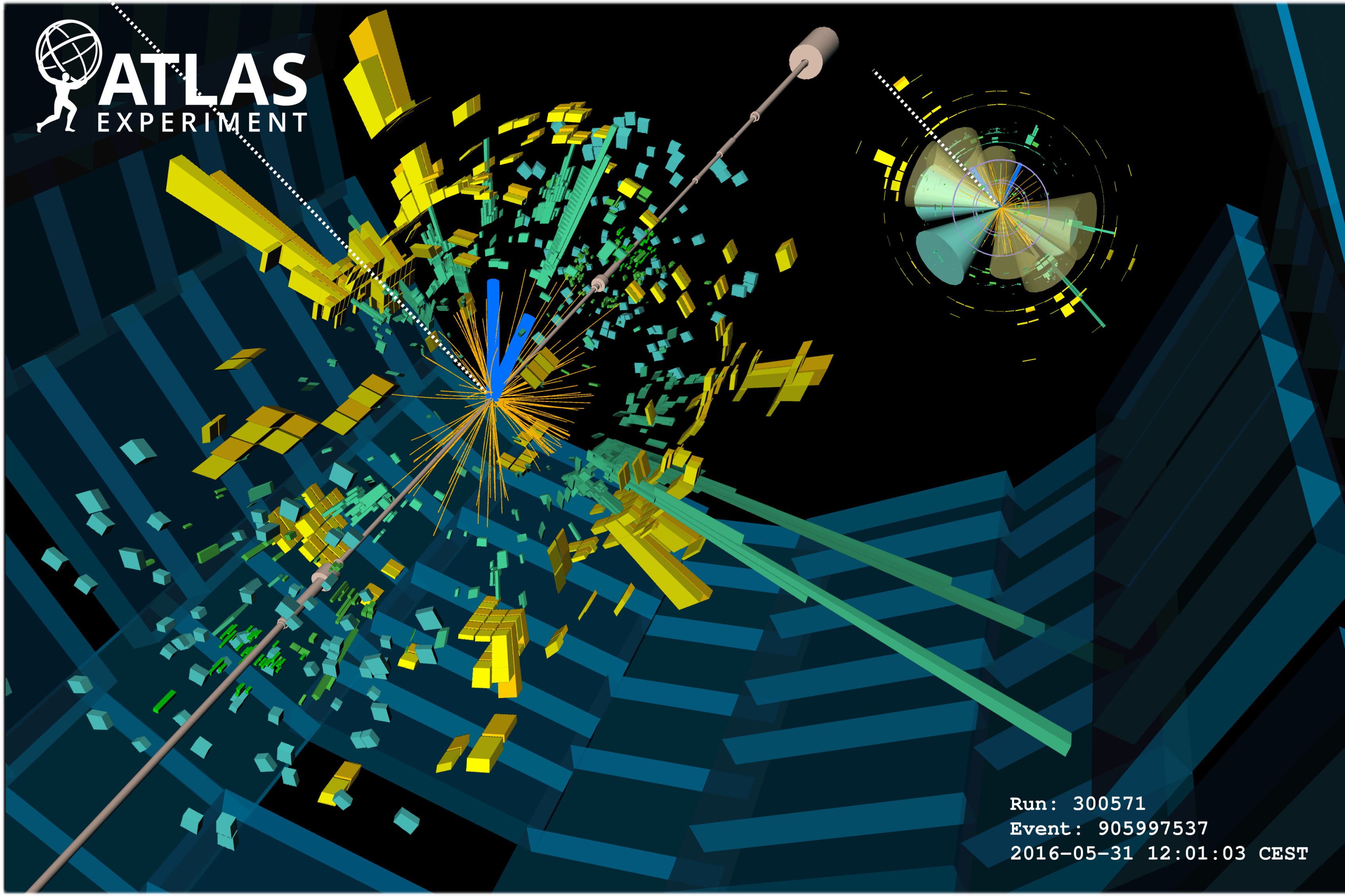
No significant excess

	VH	ttH	VBF	ggH
ATLAS Run 1	0.52 ± 0.32 (stat) ± 0.24 (syst)	1.4 ± 0.6 (stat) ± 0.8 (syst)	-	-
CMS Run 1	1.0 ± 0.5	0.7 ± 1.9	2.8 ± 1.4	-
ATLAS Run 2	1.20 ± 0.24 (stat) ± 0.28 (syst)	2.1 ± 0.5 (stat) ± 0.9 (syst)	-3.9 ± 2.8	-
CMS Run 2	1.2 ± 0.4	1.19 ± 0.5 (stat) ± 0.7 (syst)	-3.7 ± 2.7	2.3 ± 1.7

LHCb-CONF-2016-006 performed a search for VH(bb) and (cc) with limits at 50 and 7900 times the SM prediction respectively.

ttH Channels

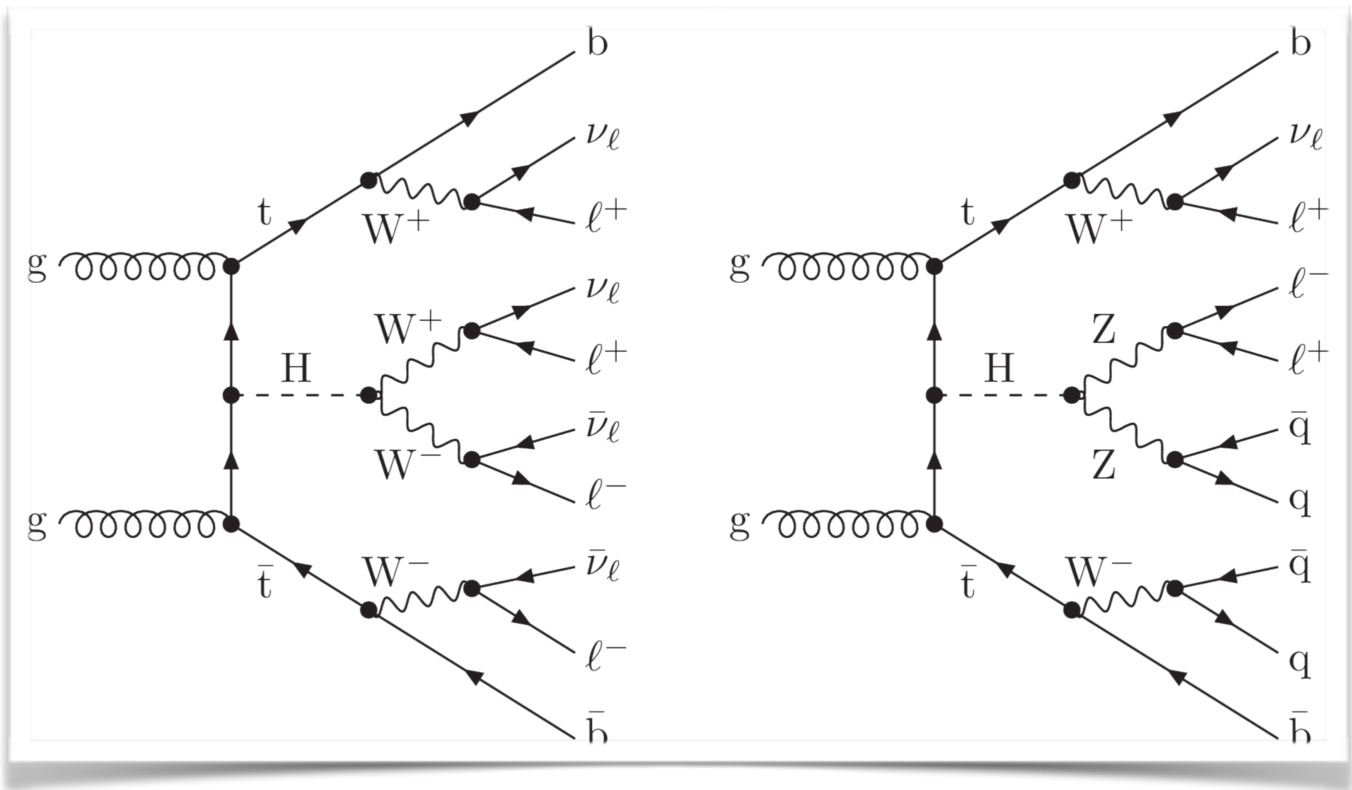
ttH (ML) candidate



Cornering (directly) the top Yukawa coupling

In addition to the diphoton and 4l channel there are two main channels H(bb) and H(WW, ZZ and $\tau\tau$).

$ttH(ML)$ Very complex final state that requires a thorough control of the background (as well)

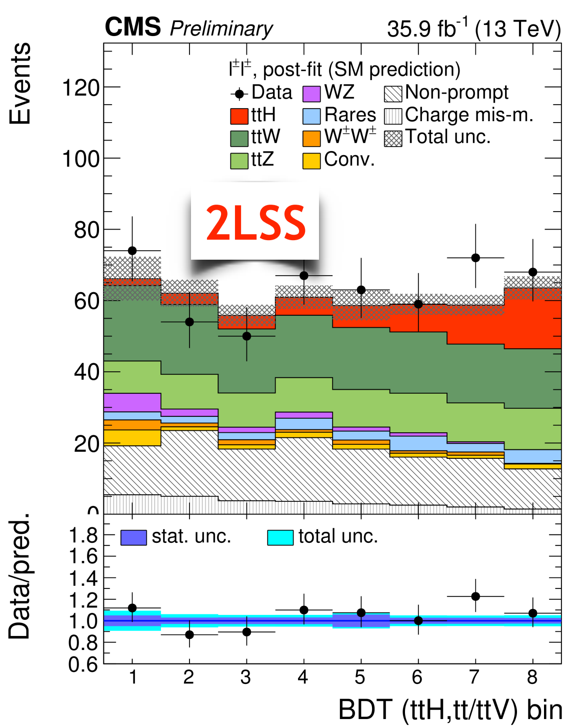


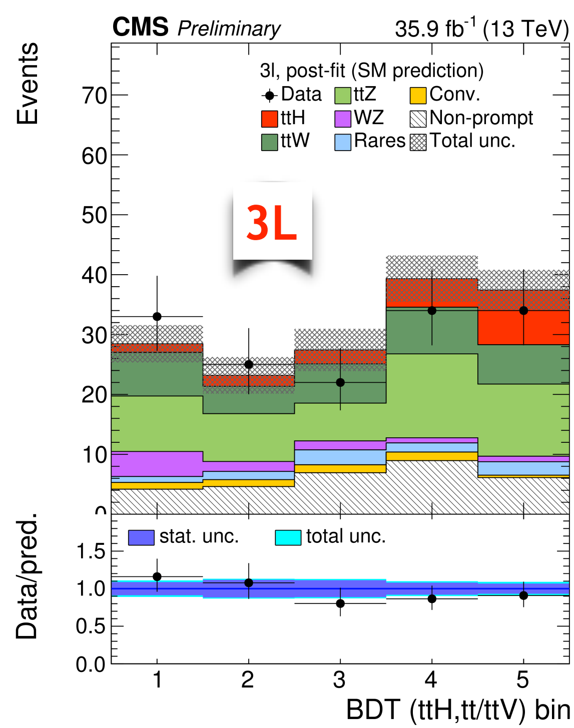
Uses decays of W(lvlv), Z(llvv, llqq) and taus

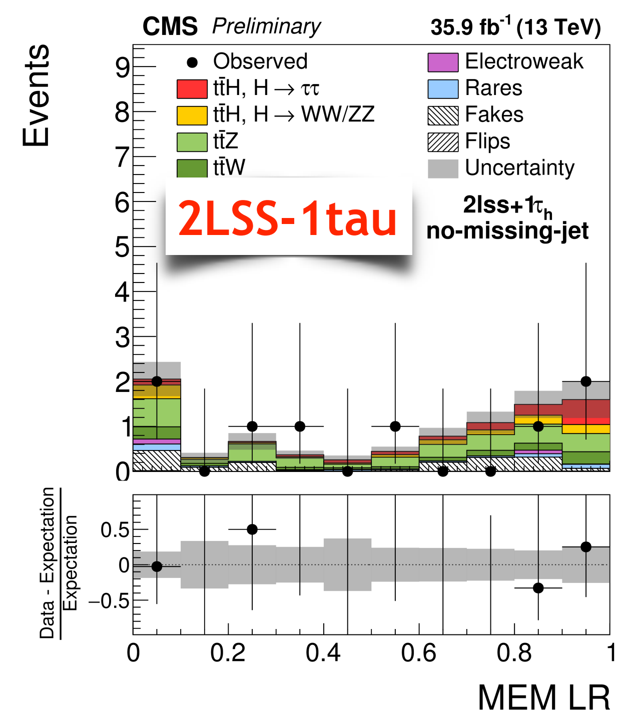
ttH Multilepton Channel

Versatile signature: 2SS, 3 and 4 leptons, 2SSL-1-tau, 2LOS-1tau, 1L-2taus, 3L-1tau and typically 3 or more jets, and at least 1 b-tagged jet, inclusively accessing WW, ZZ and TauTau decays.

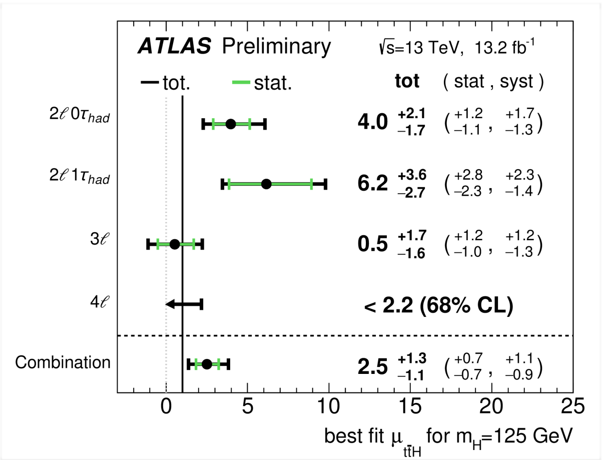
Dominant systematic uncertainty: fake-rate measurements and non-prompt background estimates from top pair production



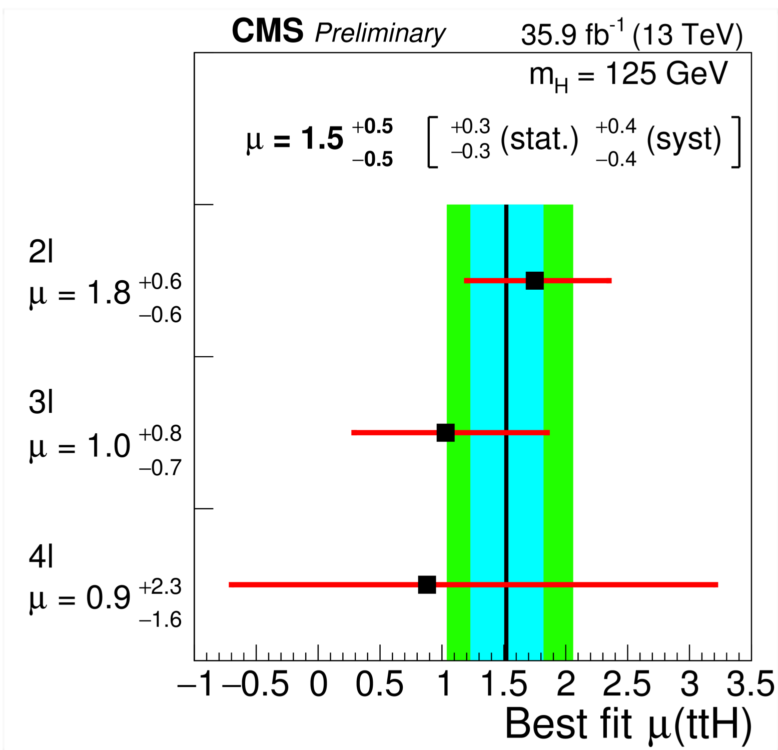


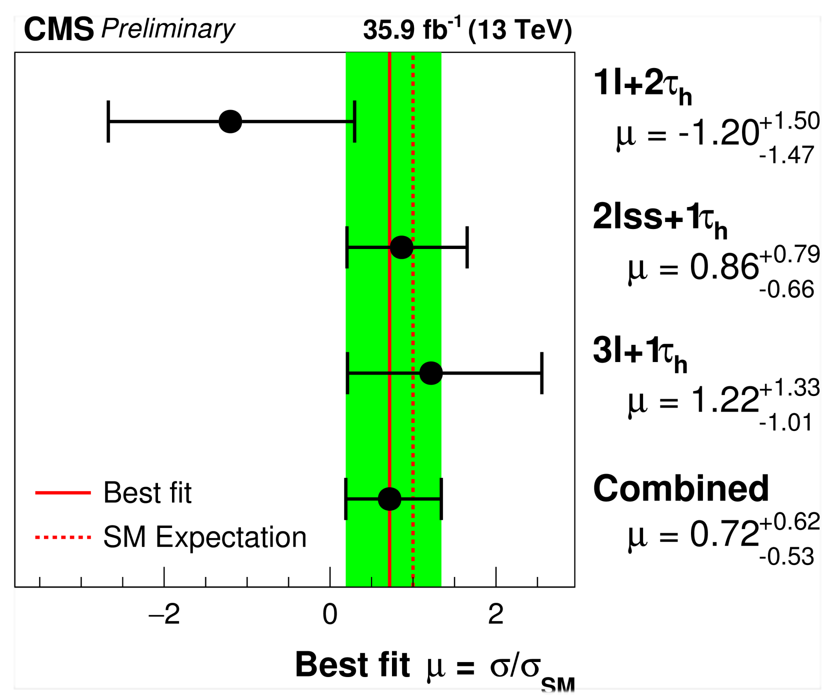


ttH Multilepton Channel



Full 2016 data update from CMS and partial update from ATLAS

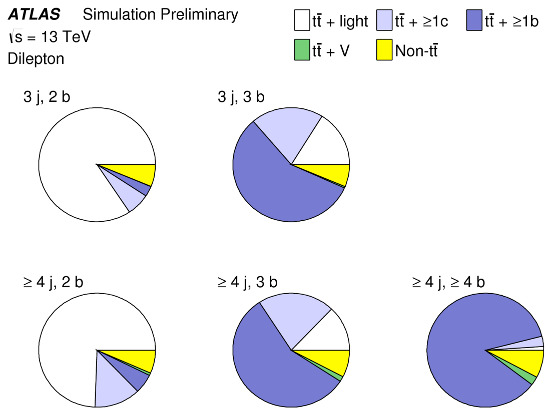


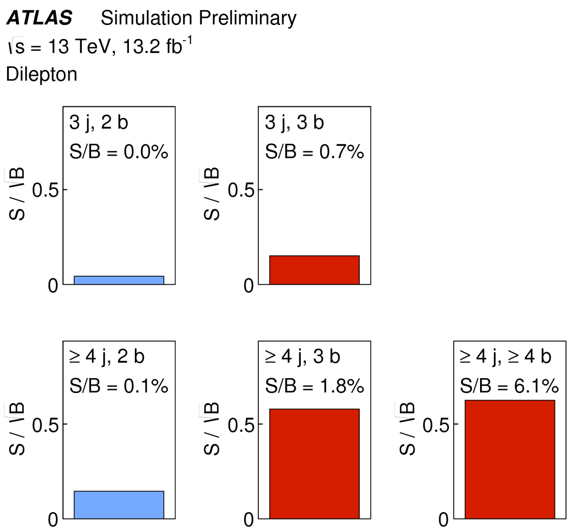


Challenging ttH(bb) Channel

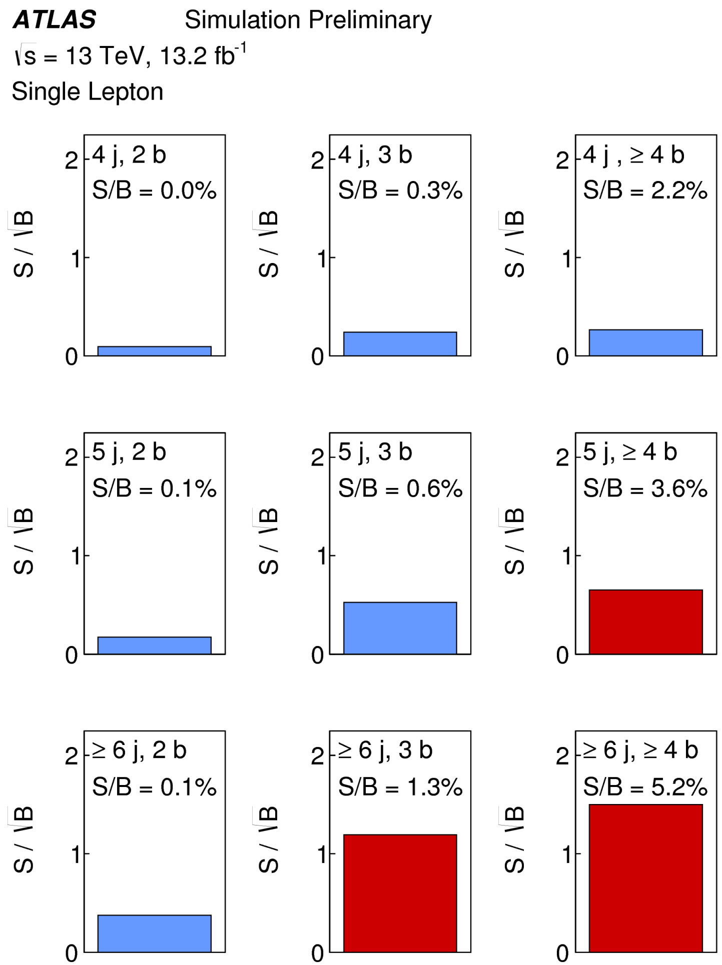
Analysis strategy: Events according to number of leptons, jets, b-jets

Dilepton



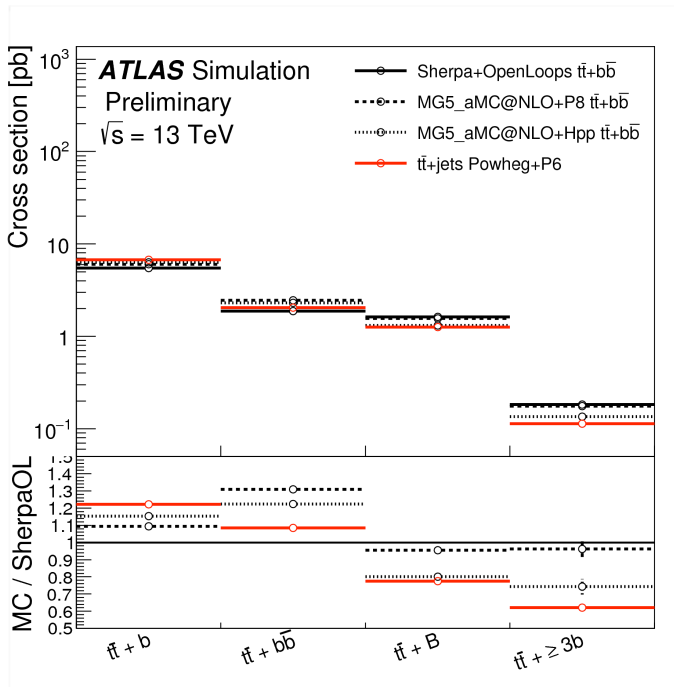


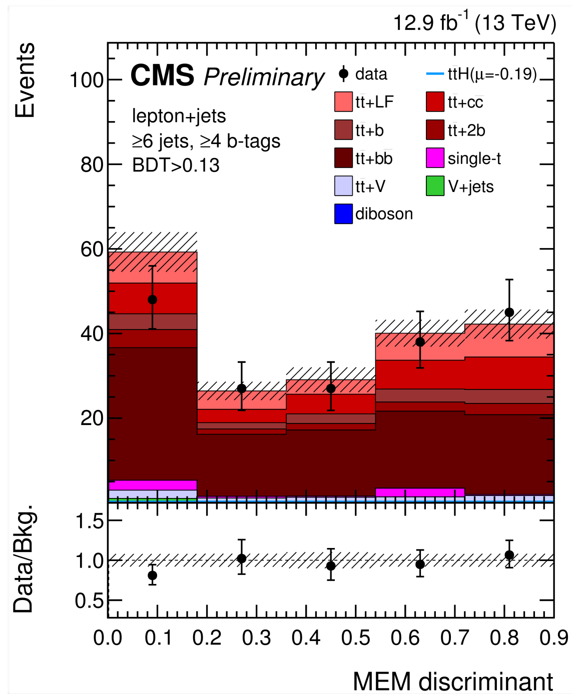
Lepton-jet

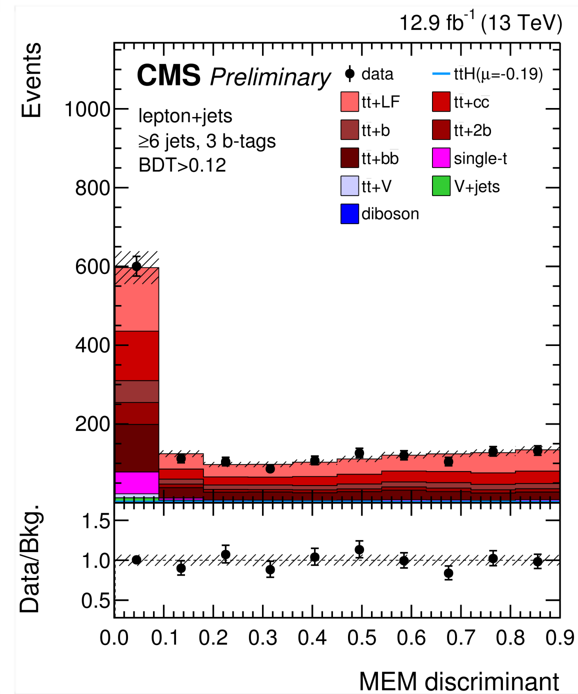


Then combine kinematic variables in BDT

Challenging ttH(bb) Channel



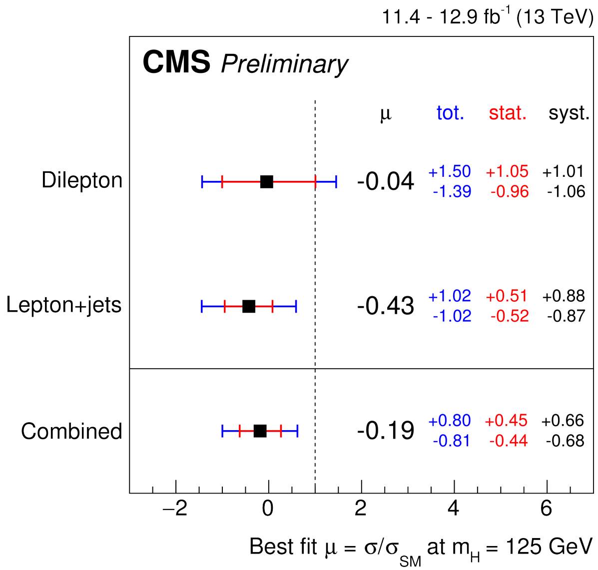




Crucial systematic uncertainty tt+HF background modelling (using state-of-the-art MC).

Challenging ttH(bb) Channel

CMS-PAS-HIG-16-038



ttH Most recent update from CMS in the ttH(bb) channel.

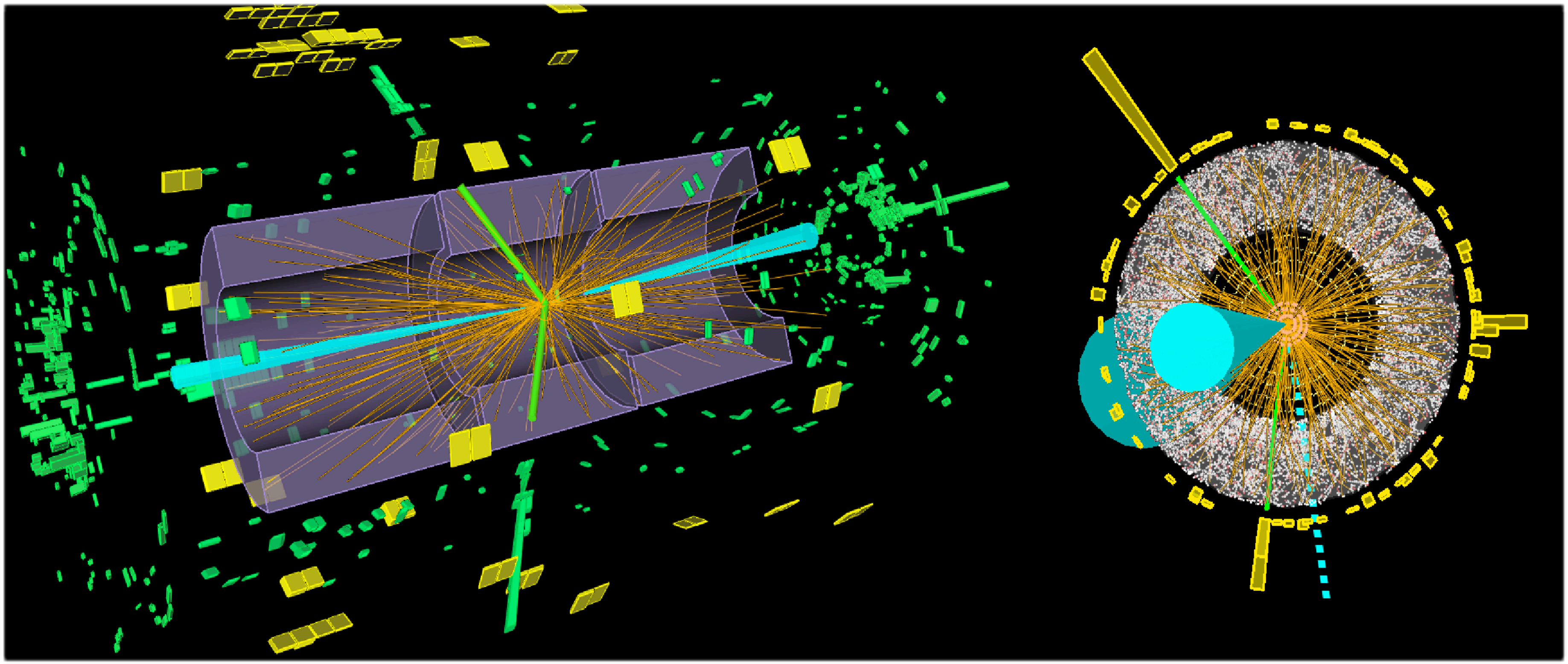
In ttH channels (as expected) sensitivity surpassed the Run 1 analyses.

Overview of channels Run 1 and Run 2

	$\gamma\gamma$	bb	ML	ZZ
ATLAS Run 1	1.2 ± 2.6	1.4 ± 0.6 (stat) ± 0.8 (syst)	2.1 ± 1.1 (stat) ± 0.9 (syst)	-
CMS Run 1	2.7 ± 2.6	0.7 ± 1.9	3.3 ± 1.4	-
ATLAS Run 2	0.5 ± 0.6	2.1 ± 0.5 (stat) ± 0.9 (syst)	2.5 ± 0.7 (stat) ± 1.1 (syst)	<7.5 (95% CL)
CMS Run 2	$1.9^{+1.5}_{-1.2}$	-0.19 ± 0.8	1.10 ± 0.35	0.0 ± 1.2

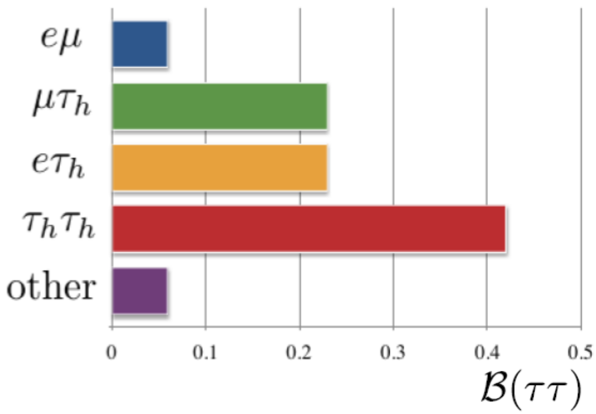
VBF and ggF H($\tau\tau$)

VBF H $\rightarrow$ $\tau\tau$ candidate



VBF and ggH H(ττ)

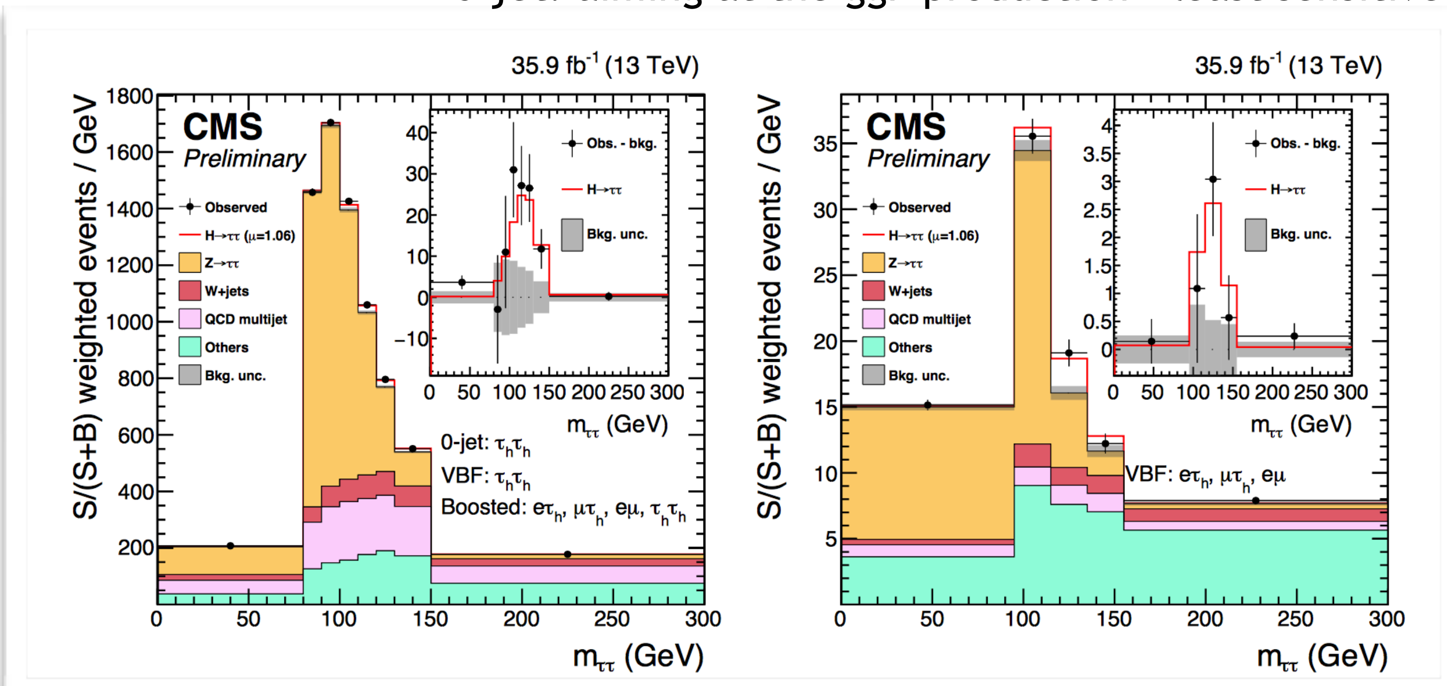
CMS-PAS-HIG-2016-043



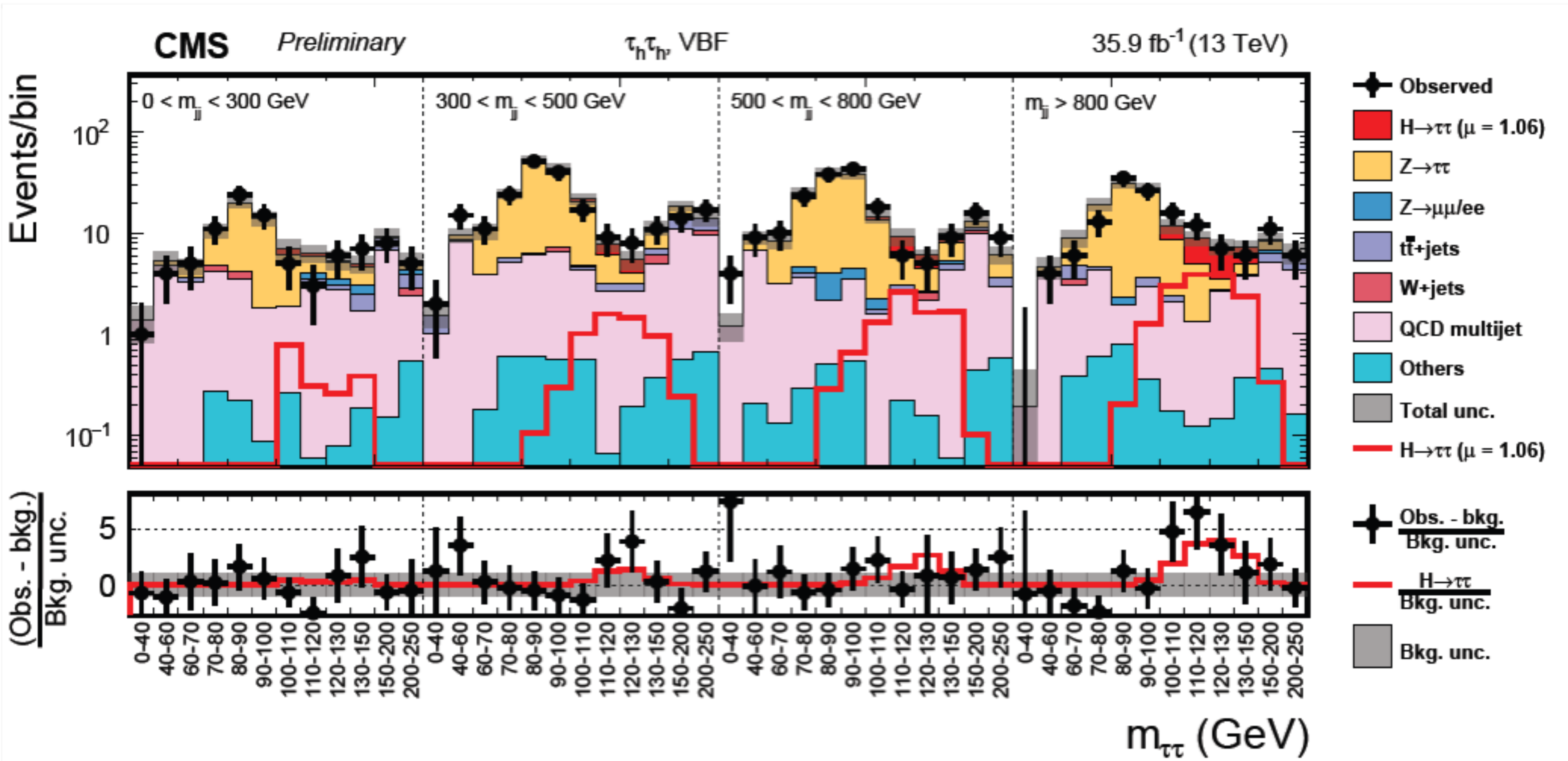
Channel using all combinations of subsequent decays of taus (94% of all possible tau decays)

Using 3 main channels:

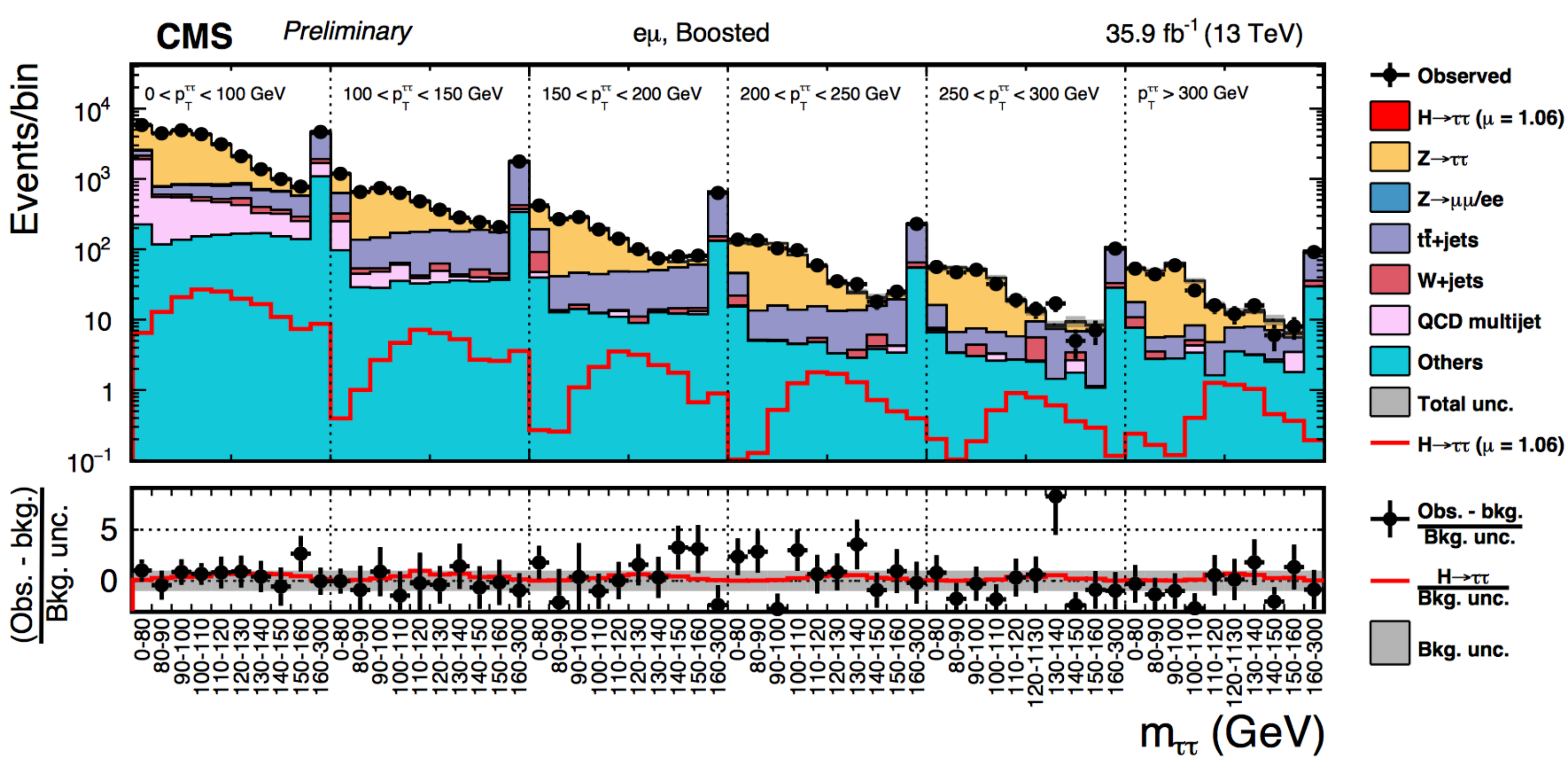
- VBF analysis: using reconstructed/fitted mass and categories in dijet mass.
- Boosted analysis: aiming mostly at ggF (in the low mjj) with boost, uses fitted mass and categorised in pT of the taus.
- 0-jet: aiming at the ggF production - least sensitive.



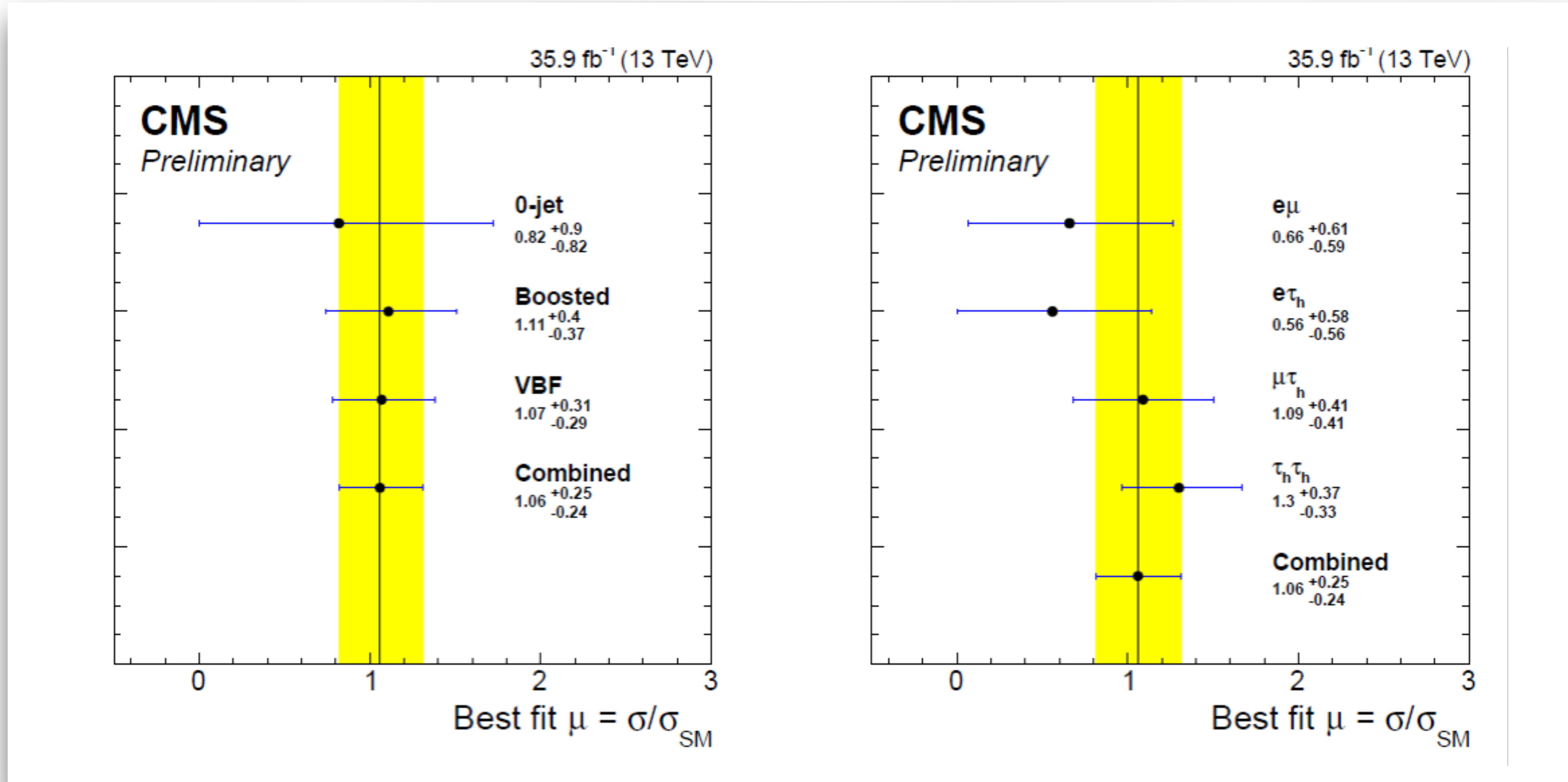
Main VBF Categories



Main ggF Categories



Observation of H(ττ)



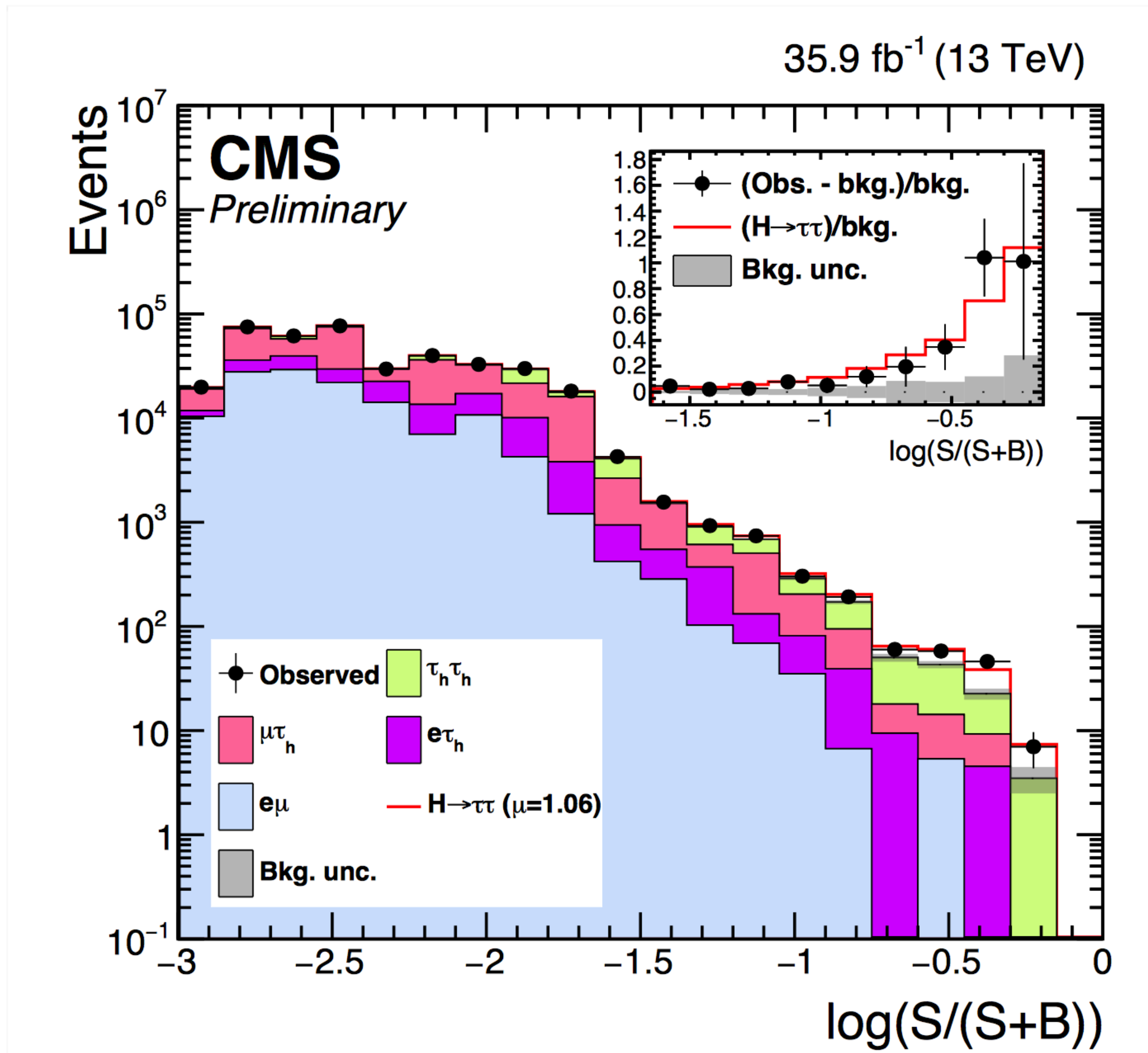
Run 2 (full 2016) analysis significances:

$$4.9\sigma\ (obs.)$$
$$4.7\sigma\ (exp.)$$

Run 1 an Run 2 combined:

$$5.9\sigma\ (obs.)$$
$$5.9\sigma\ (exp.)$$

Observation of H(ττ)



Higgs Physics - Lecture 2

Experimental Profile of the Higgs boson

1.- A one slide panorama!

2.- Going further with « bread and butter » channels

3.- Going further with the discovery channels

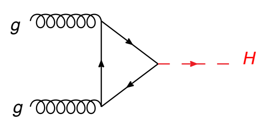
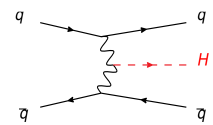
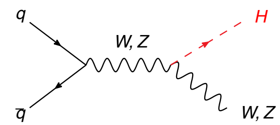
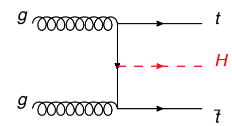
4.- Intermezzo on Sources of Systematic Uncertainties (Experimental and Modelling)

5.- **Direct probes of the couplings the Higgs boson to fermions:** Highly anticipated Run 2 Analyses

6.- **Combined Measurement of properties:** Based on Run 1

Panorama of Main Higgs Analyses

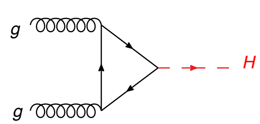
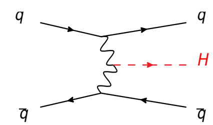
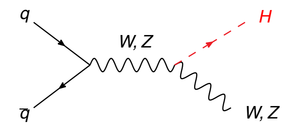
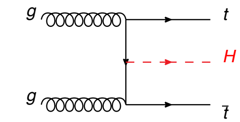
Already impressive harvest of results

Channel categories	ggF 	VBF 	VH 	ttH 
$\gamma\gamma$	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW ($l\nu l\nu$)	✓	✓	✓	✓
$\tau\tau$	✓	✓	✓	✓
bb		✓	✓	✓
Zγ and $\gamma\gamma^*$	✓	✓		
$\mu\mu$ and ee	✓	✓		
Invisible	✓ (monojet)	✓	✓	

✓ Run 1 results

Panorama of Main Higgs Analyses

Already impressive harvest of results

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✔	✔	✔	✔
ZZ (llll)	✔	✔	✓	✔
WW (lνlν)	✓	✓	✓	✔
ττ	✓	✓	✓	✔
bb		✔	✔	✔
Zγ and γγ*	✓	✓		
μμ and ee	✔	✓		
Invisible	✓ (monojet)	✔	✔	

✓ Run 1 results ✔ Run 2 results

Combination Master Formula

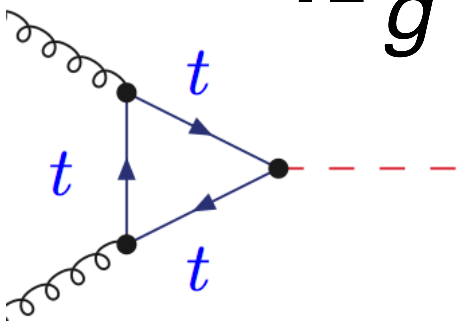
Parameterise the signal yields as a function of these parameters
(assuming narrow width approximation)

$$n_s^c = \mu \sum_i \sum_f \mu^i \sigma_{SM}^i \times A^{ifc} \times \varepsilon^{ifc} \times \mu^f Br^f \times \mathcal{L}^c$$

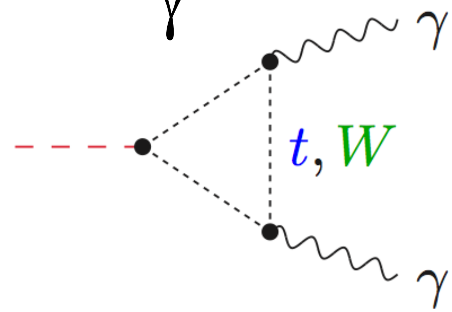
Back to the κ framework

Various possible approaches, e.g.:

κ_g



κ_γ



Couplings to gluons and photons taken as effective and fitted

$$\mu_i = \kappa_g^2 \qquad\qquad \mu_f = \frac{\kappa_\gamma^2}{\kappa_H^2}$$

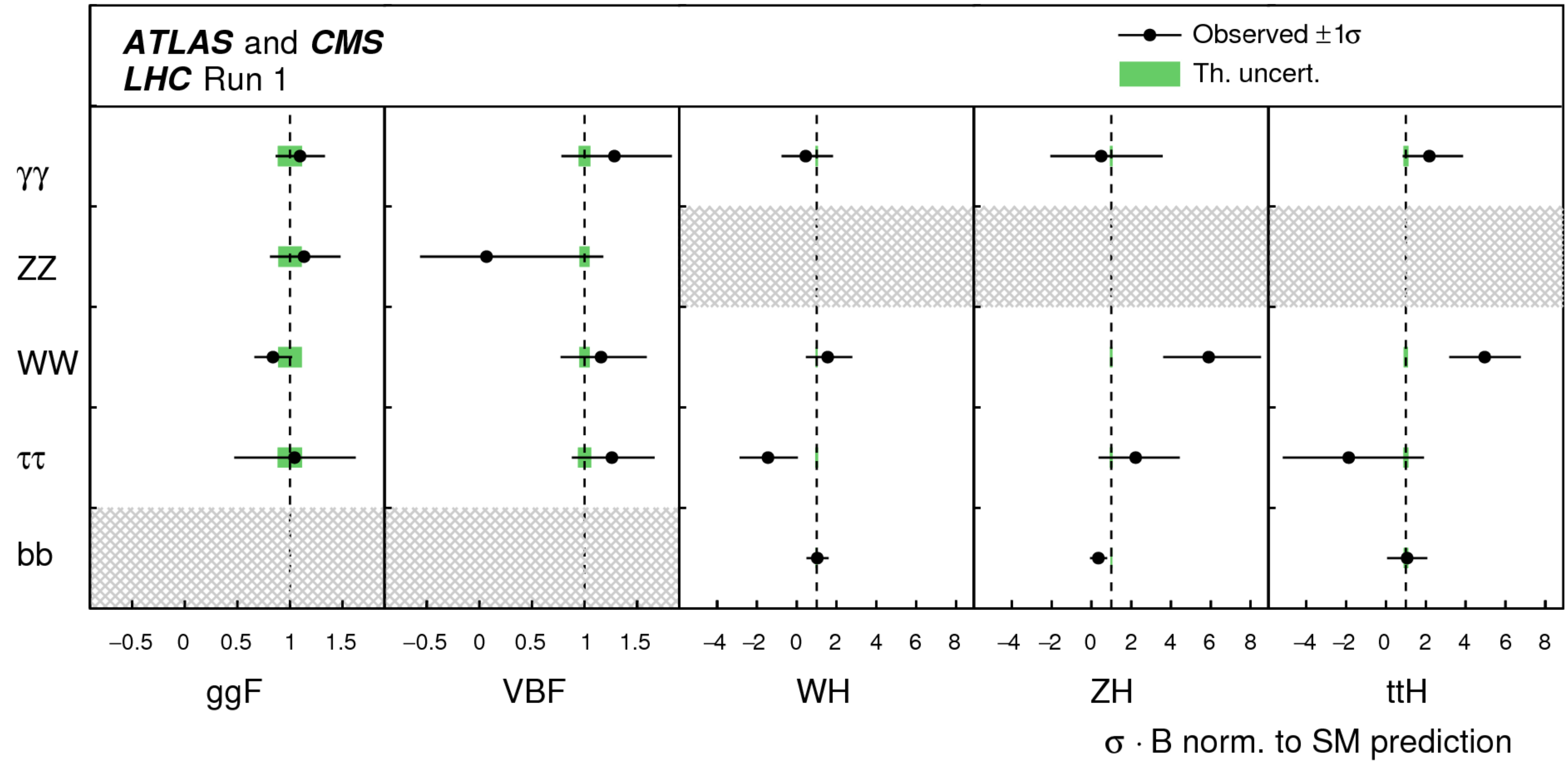
Parametrise the loop

$$\mu_i = \kappa_t^2 \qquad\qquad \mu_f = \frac{1.6\kappa_W^2 - 0.7\kappa_t\kappa_W + 0.1\kappa_t^2}{\kappa_H^2}$$

Many more possible!

Run 1 Status of the Higgs Couplings Measurements

(Simplified or combined*) panorama of higgs channels used (many more categories are used in each case and two experiments)

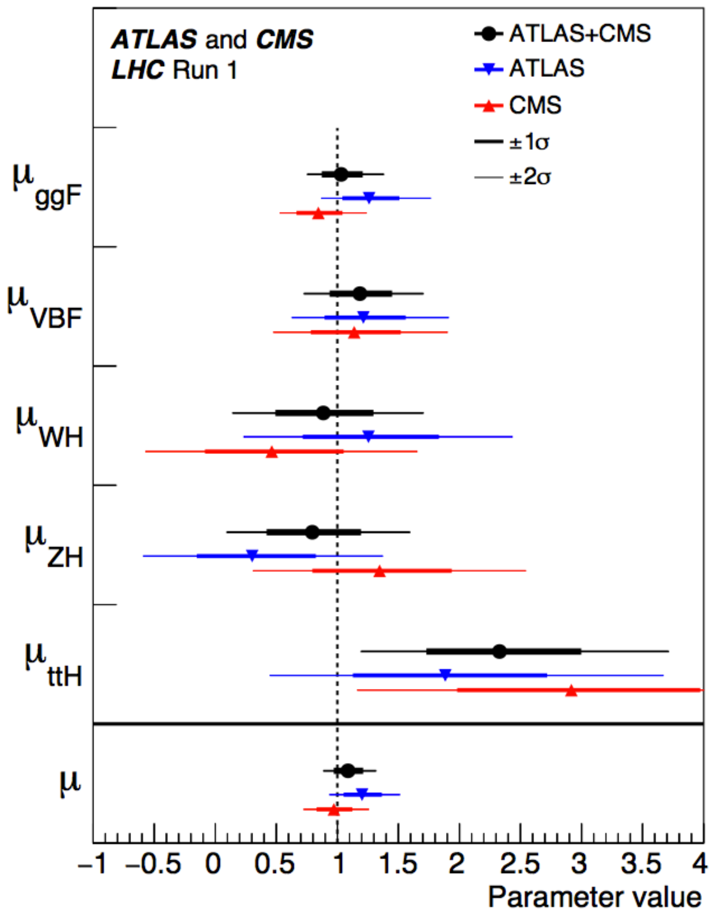


JHEP 08 (2016) 045

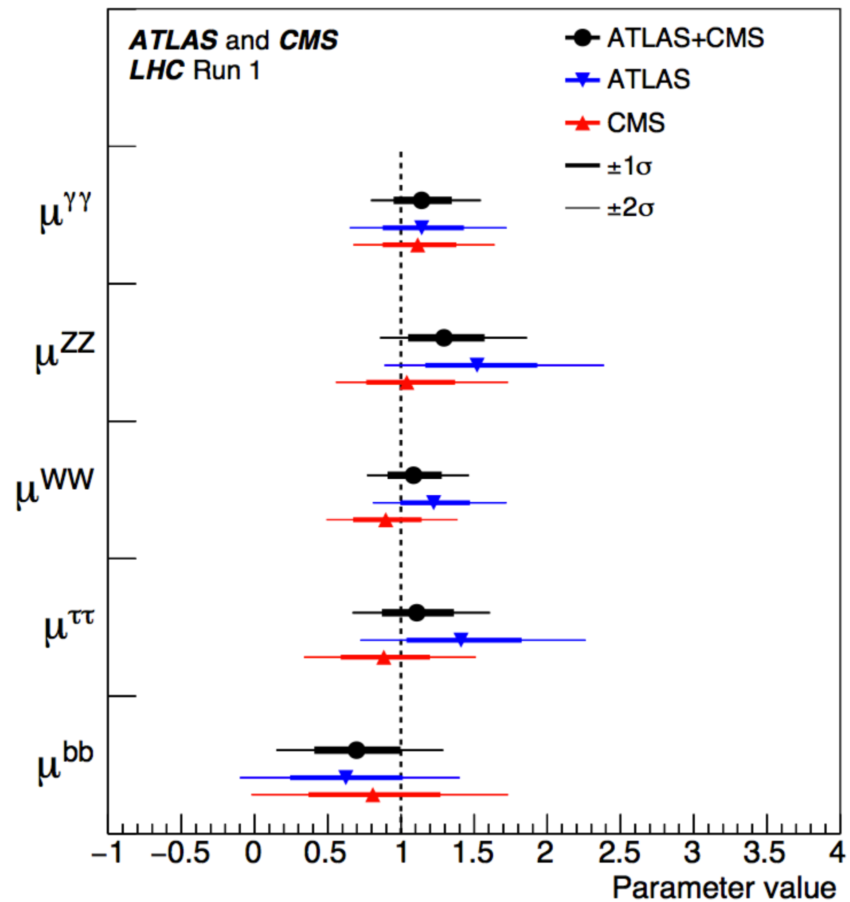
*Combination assumes narrow width approximatio

Cross Sections and Branching Ratios

Combined Measurements assuming SM branchings



Combined Measurements assuming SM Cross Sections

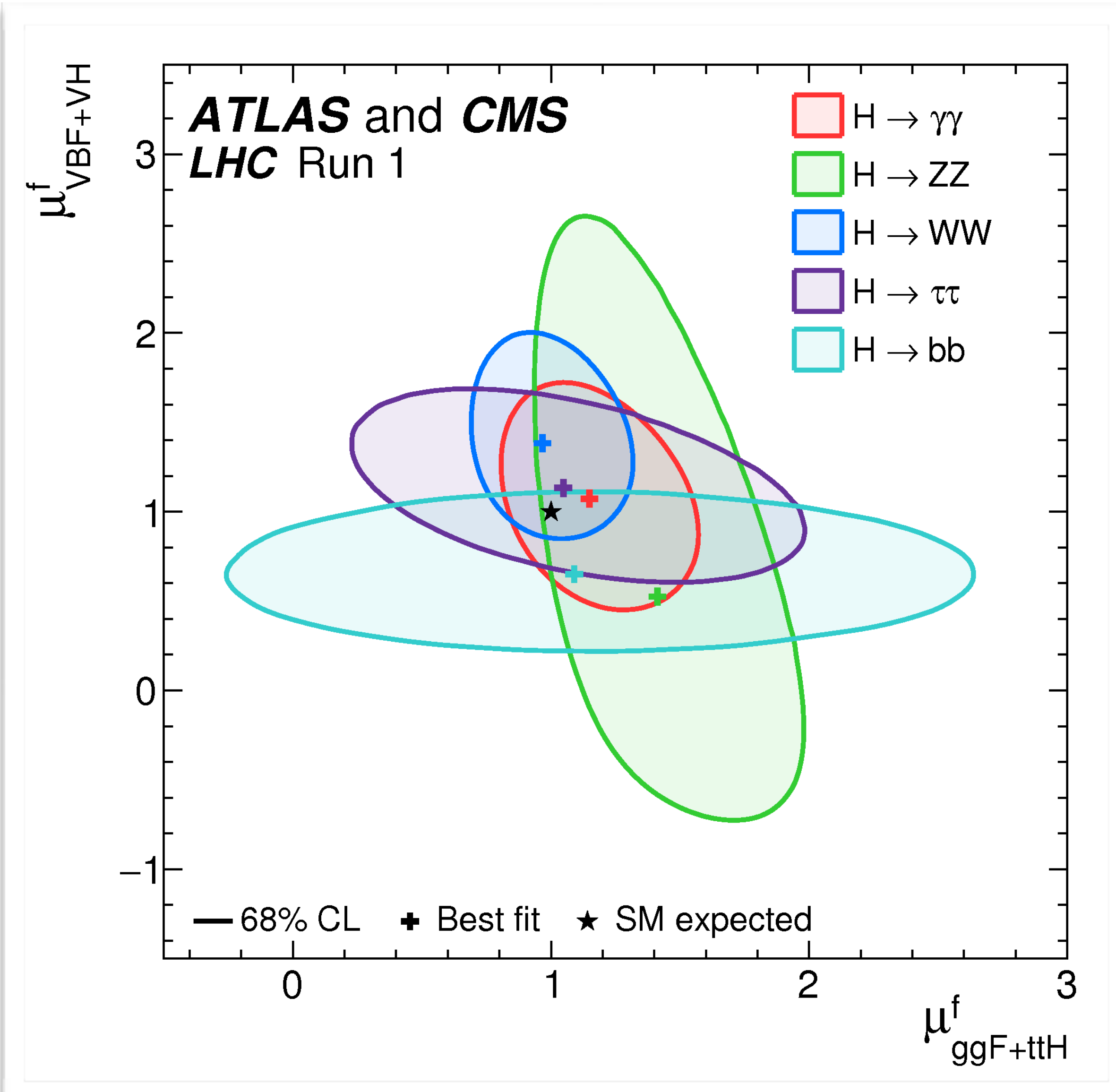


Cross Sections and Branching Ratios

Summary Table

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Channel by channel - Production comparison



Run 1 Status of the Higgs Couplings Measurements

$$\mu = 1.09 \quad \pm 0.11 \; (\pm 0.07\,(Stat) \; \pm 0.04\,(Exp) \; \pm 0.03\,(Th.\,bkg) \; \pm 0.07\,(Th.\,sig)\,)$$

Signal strength illustrates the agreement of measurements with the SM and the importance of the TH input.

Very illustrative, but not transparent on the underlying assumptions and relies on the TH input at a given time.

$\Delta\kappa/\kappa$ ~ 11%

$\Delta\lambda/\lambda$ ~ 23%

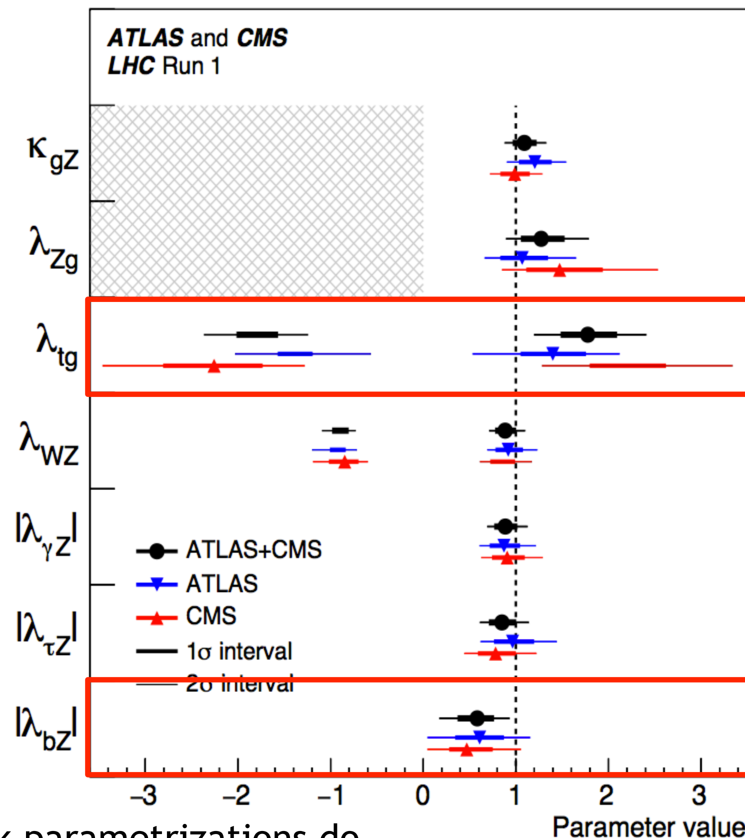
$\Delta\lambda/\lambda$ ~ 30%

$\Delta\lambda/\lambda$ ~ 11%

$\Delta\lambda/\lambda$ ~ 12%

$\Delta\lambda/\lambda$ ~ 16%

$\Delta\lambda/\lambda$ ~ 34%



Direct coupling to the Z

Direct coupling to the top*
(through ttH production channels)

Custodial Symmetry

Direct copling to τ
(through VBF production)

Direct coupling to b quarks*
(Through mainly VH channels)

*κ and λ framework parametrizations do not take into account the higher order.

JHEP 08 (2016) 045

A few comments on the next steps in precision

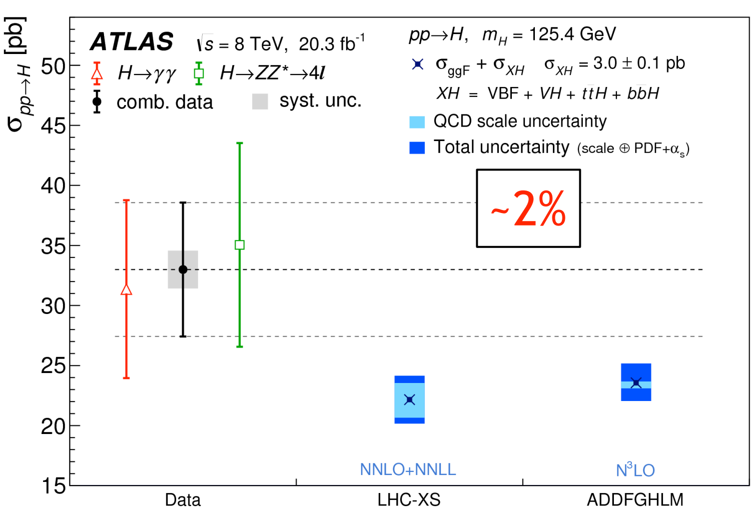
$$\mu = 1.09 \quad \pm 0.11$$
$$(\pm 0.07\,(Stat)$$
$$\pm 0.04\,(Exp)$$
$$\pm 0.03\,(Th.\,bkg)$$
$$\pm 0.07\,(Th.\,sig)\;)$$

See Run 2: typically x2 in cross section (x4 for ttH) and much much more data (and more PU).

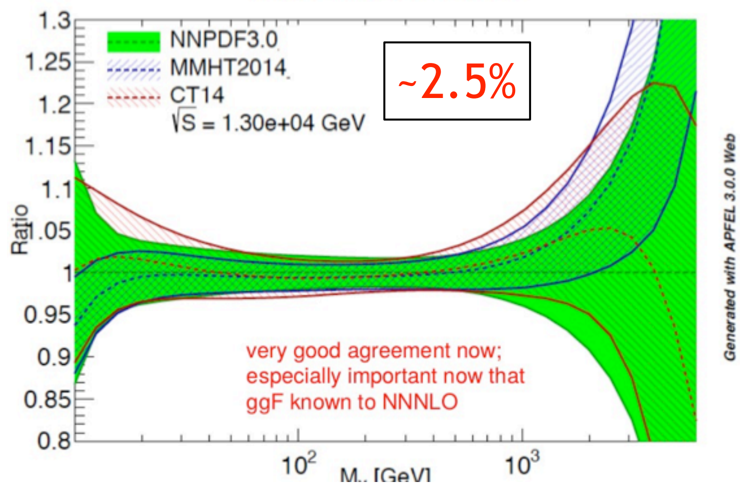
Most Exp. Uncertainties are estimated from the data, and should also reduced with more statistics (of course real life case will be more complicated – again e.g. PU).

See next slides.

Breakthrough!



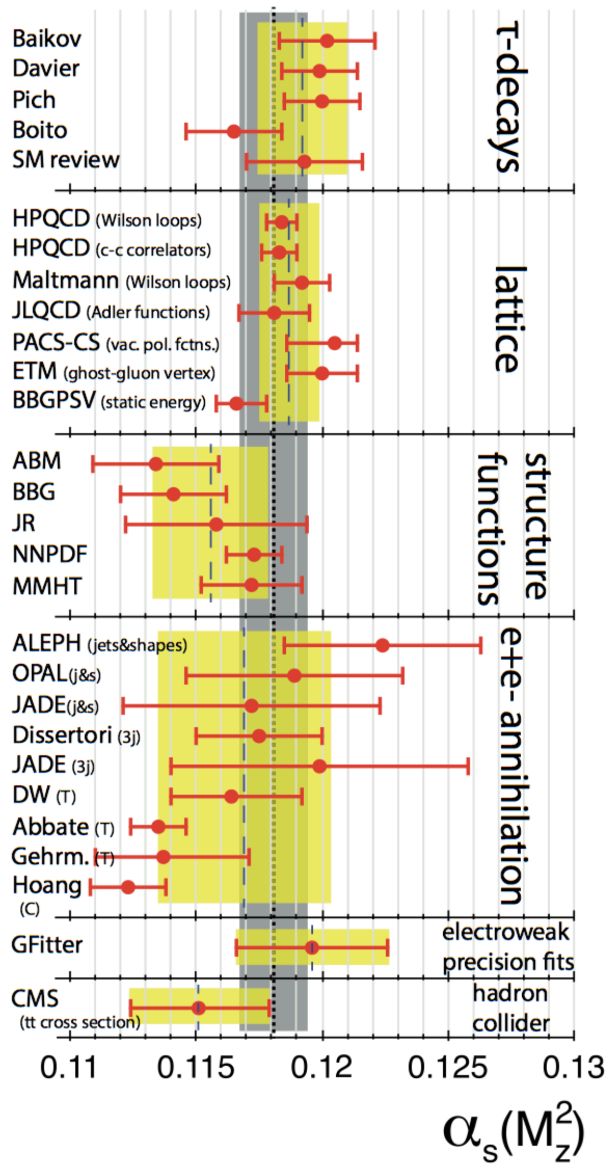
Important convergence



Uncertainty on α_s will require attention: probably underestimated currently.

~1.5%

A parameter of fundamental importance α_s



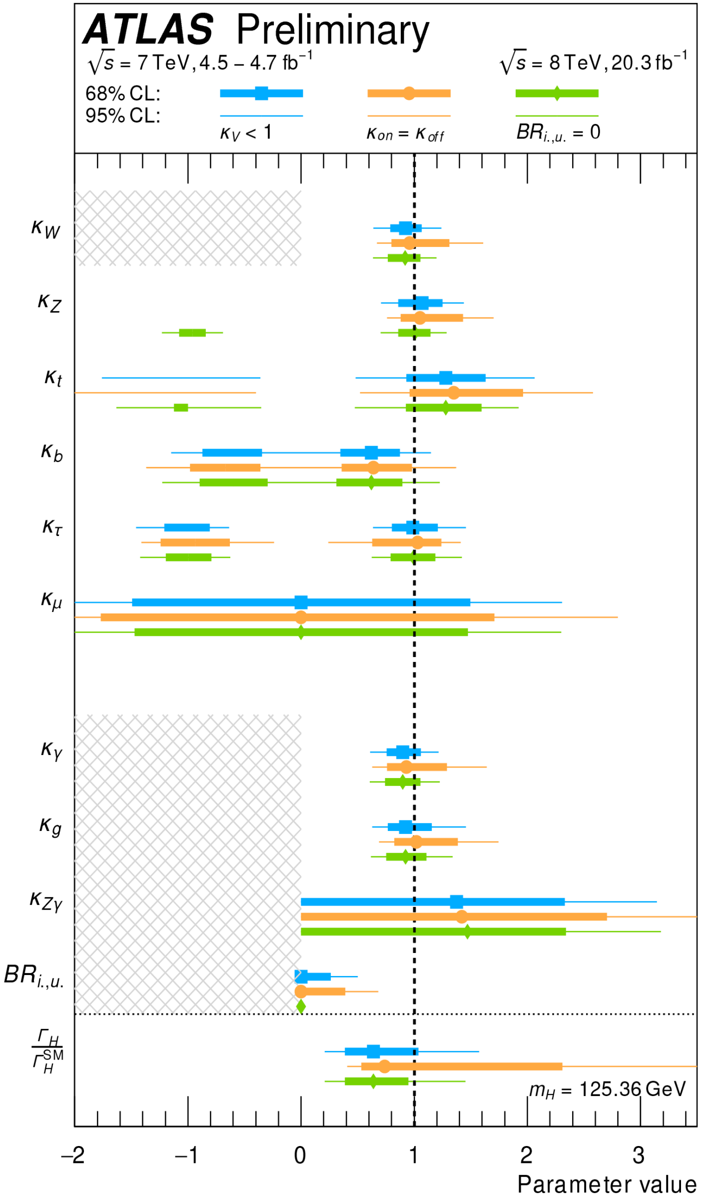
- Tension between lattice and (event shape) experimental measurement

- Event shape measurements are very difficult due to interplay between non-perturbative effects and the strong coupling constant.s

- Overall uncertainty underestimated?

- Lattice QCD increasingly confident in giving the correct value. Could it then be used for PDFs, etc… ?

Comments on the Absolute Measurement of Couplings

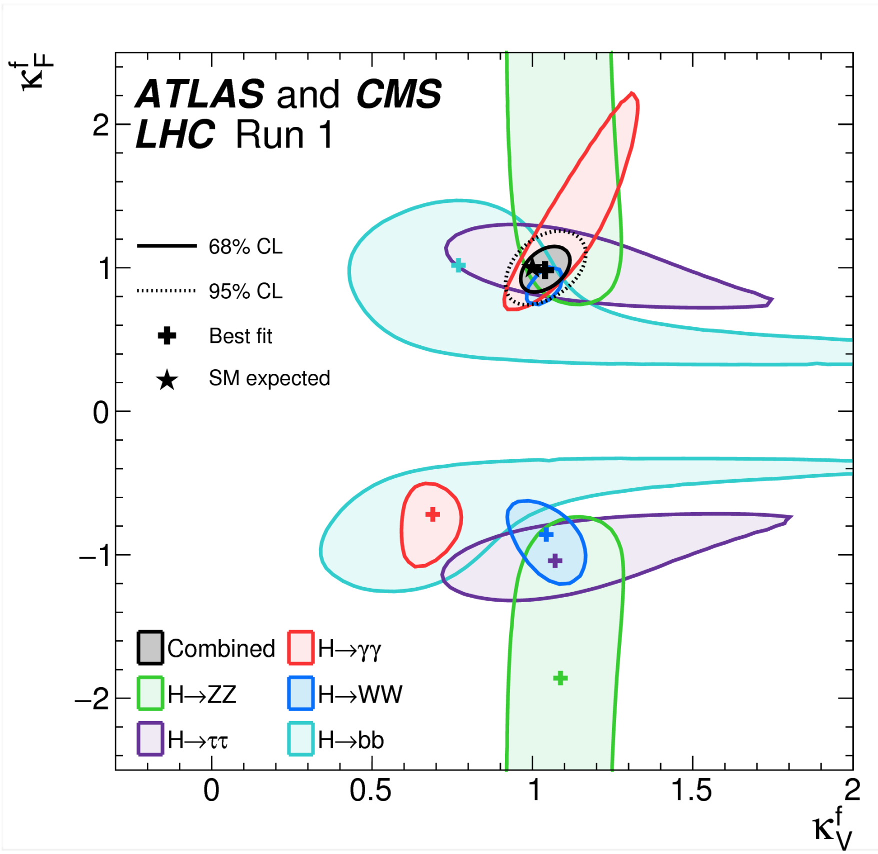


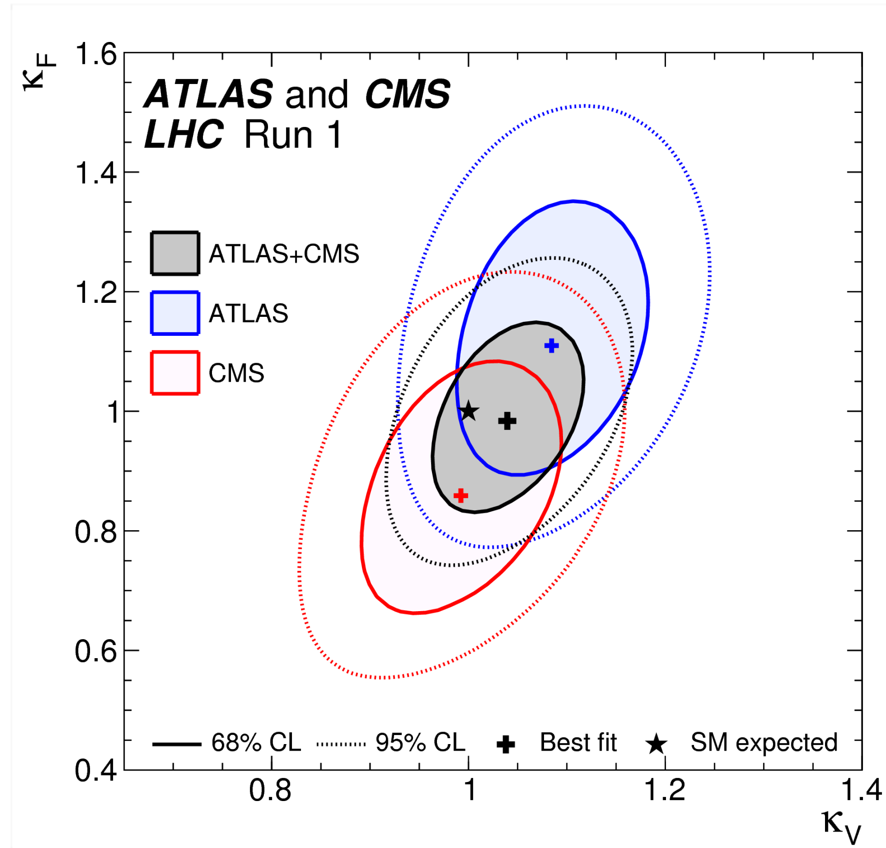
Absolute couplings measurements under specific conditions:

- **Green**: Constrain the width to SM field content only.
- **Blue**: Unitarity inspired constraint $k_V < 1$
- **Orange**: Use measurement from Off-Shell coupling*

*Requires constraint of equal OffShell and OnShell Higgs couplin

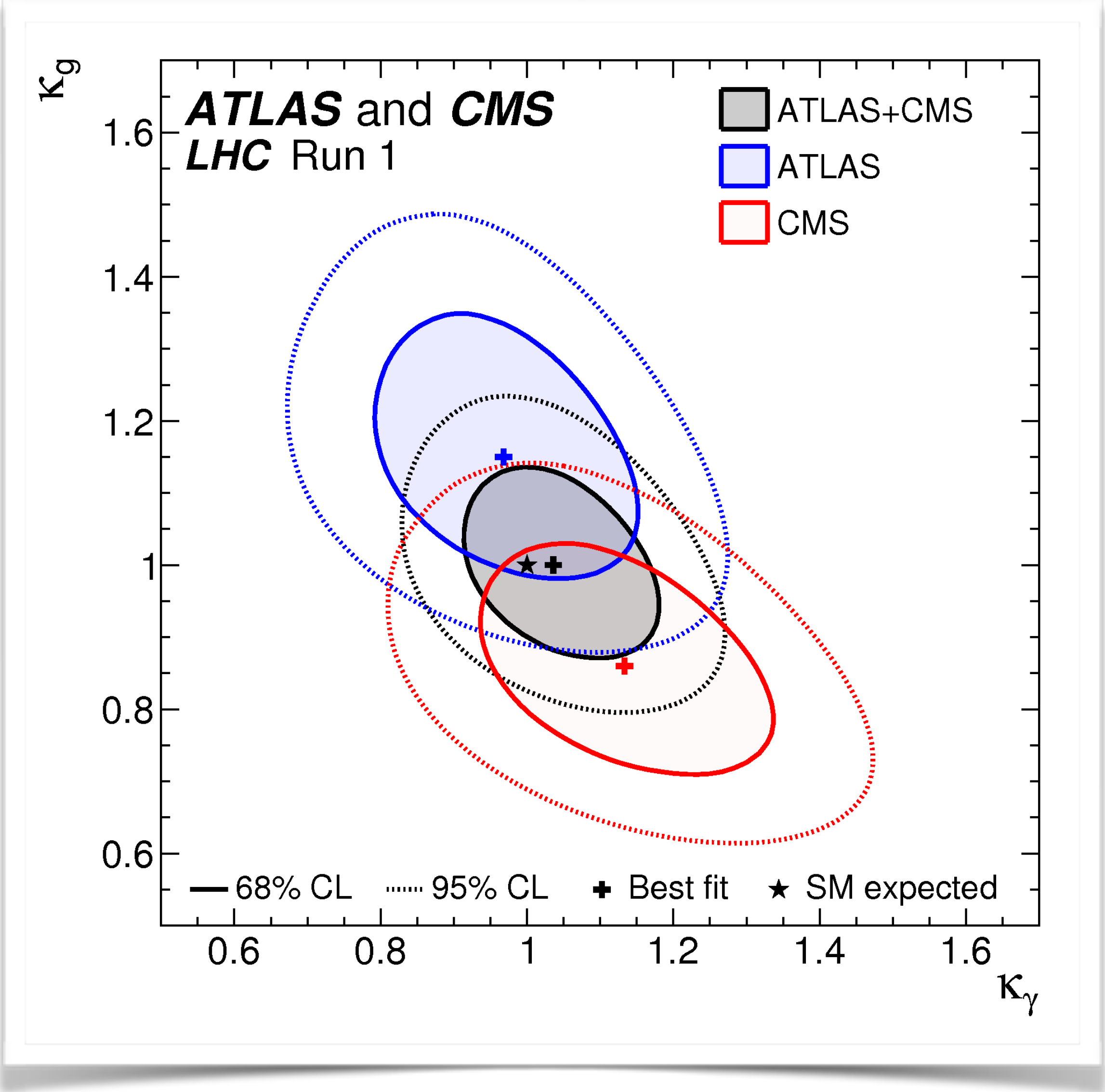
Fermions vs. Vector boson couplings

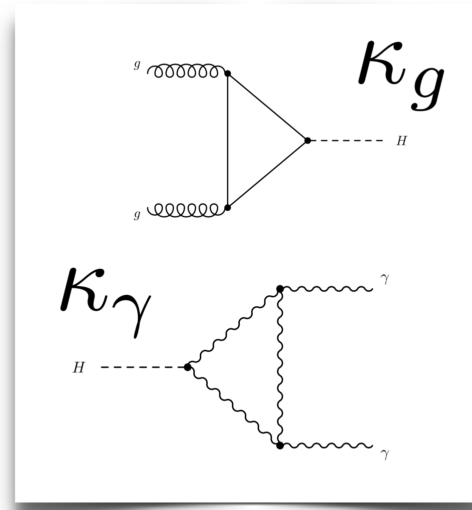




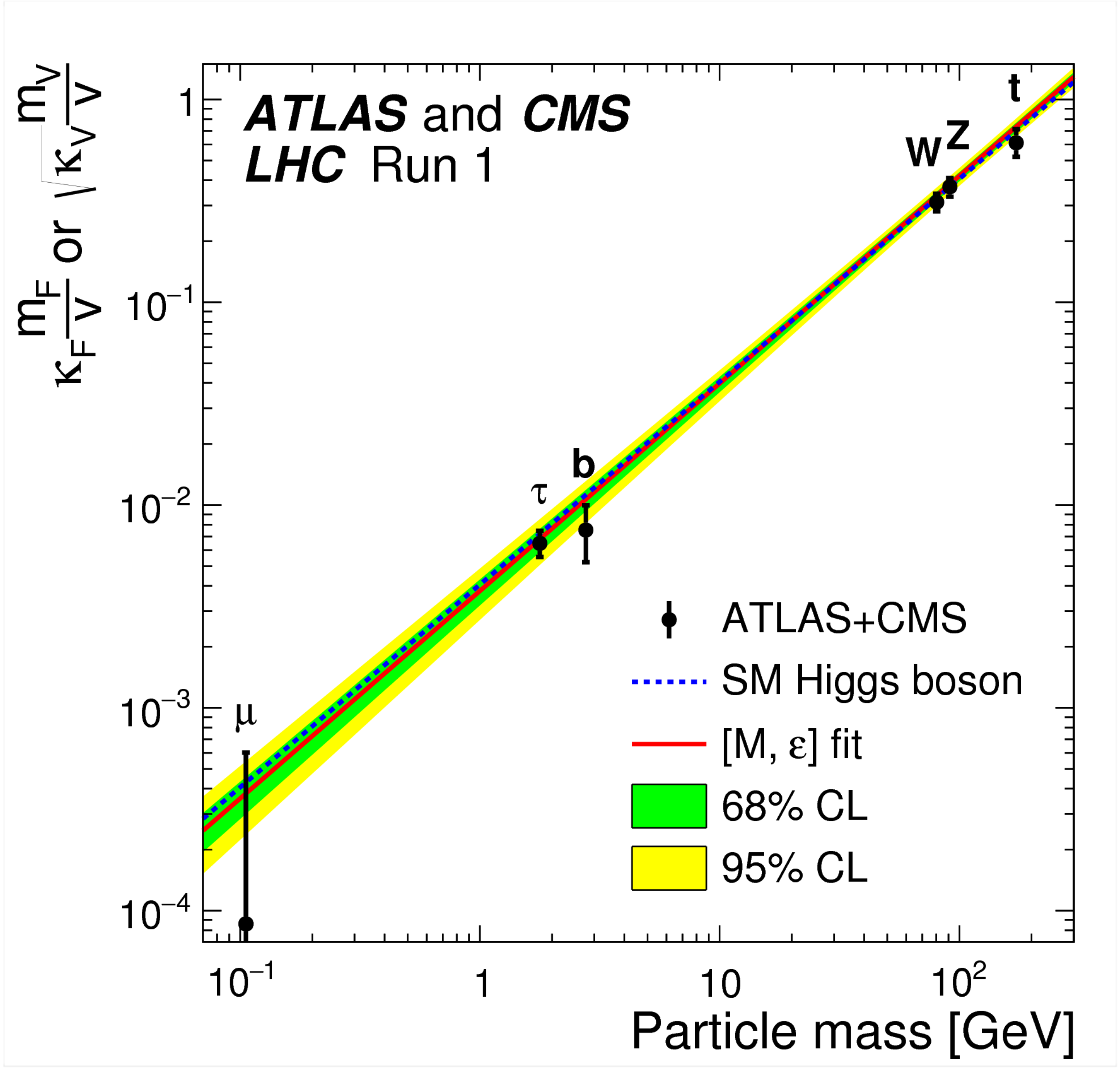
Channels and experiments yield very consistent picture

New Physics in the Loops?





Two experiments consistent and precision at 10% level



Higgs boson very Standard Model like