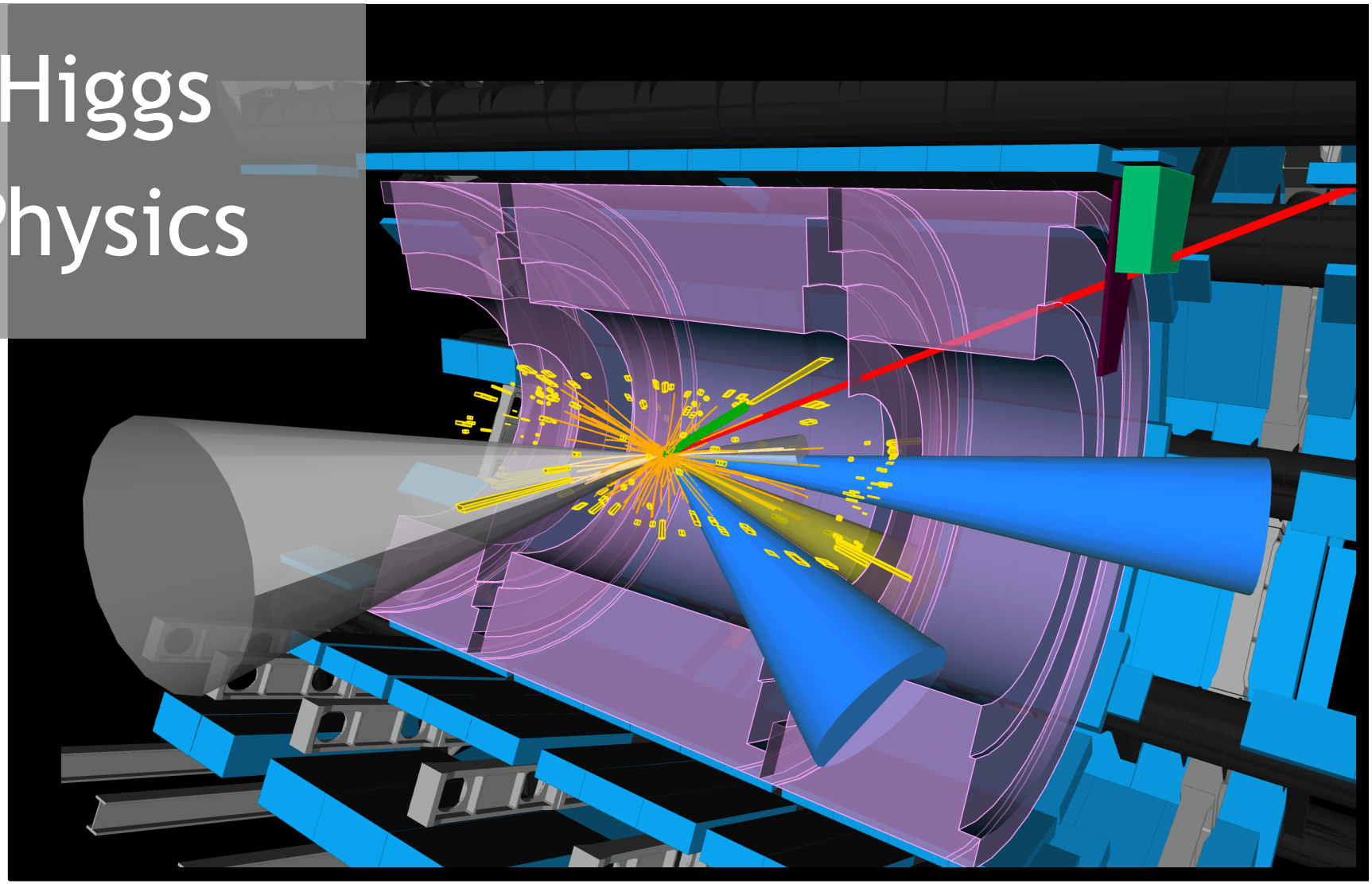
Higgs Physics



Lecture II

Exploring the new Higgs Physics Landscape

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LAL and CERN

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Outline

Lecture I

- Introduction : Elements of history
- Elements of SM Higgs theory
- Precision EW tests
- The discovery of the Higgs boson
- An (early) experimental profile of the Higgs boson: The discovery channels

Lecture II

- An (early) experimental profile of the Higgs boson: All Final States (Fermion modes)
- The Higgs width
- Rare decay modes
- Rare production modes
- Combined measurements

Lecture III

- Implications of the discovered state
- Search for BSM Higgs and extended sectors
- New trends
- Future Higgs programs

The Discovery channels beyond discovery

Differential, Fiducial and Unfolded cross section

$$n_s = \sigma \times Br \times A \times \varepsilon \times L$$

Interpretation of an observed number of events of a given signal S

"Total cross section": an estimate of the an acceptance (given by theory) is needed to perform the measurement

$$\sigma Br = \frac{n_s}{A \times \varepsilon \times L}$$

"Fiducial" : means that the measurement is given for a specific acceptance

$$\sigma Br \times A = \frac{n_s}{\varepsilon \times L}$$

To be most useful the acceptance definition should be as close as possible to the reconstructed cuts.

“Unfolded” : how to estimate the particle level **distribution** from a measured distribution “smeared” by detector effects. Typically done using MC, the subtlety is to make this estimate independent of the MC model itself and only on the detector effects.

Why bother?

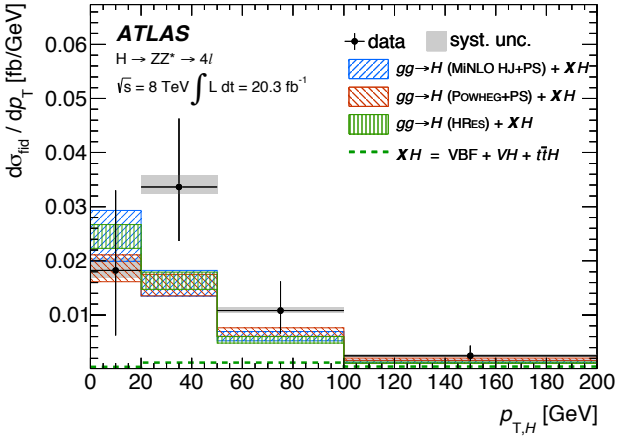
- Compare with theory
- Compare between experiments with different responses

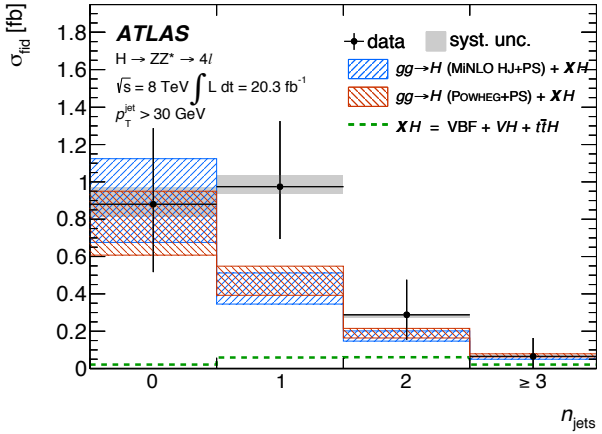
Differential, Fiducial and Unfolded cross section

- 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)

$$H \rightarrow 4l$$

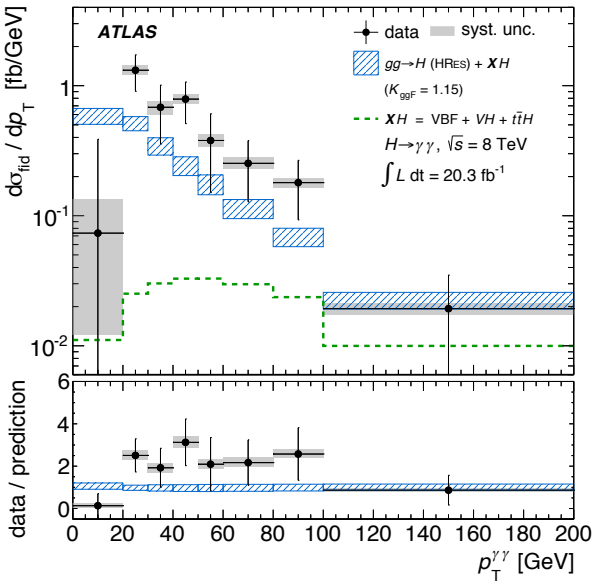
Phys. Lett. B 738 (2014)

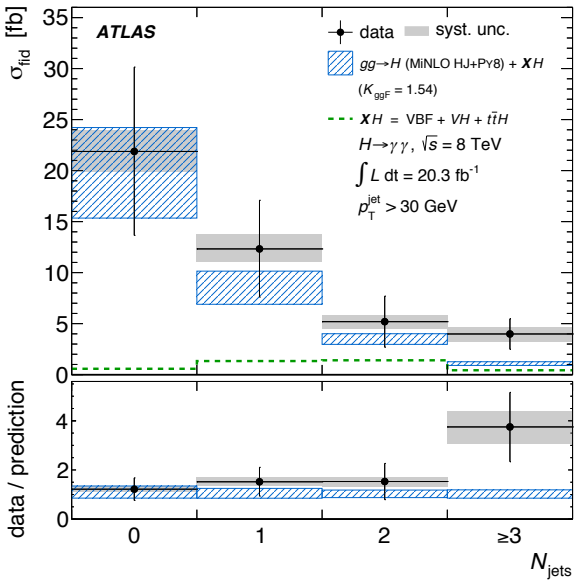




$$H \rightarrow \gamma\gamma$$

JHEP 09 (2014)

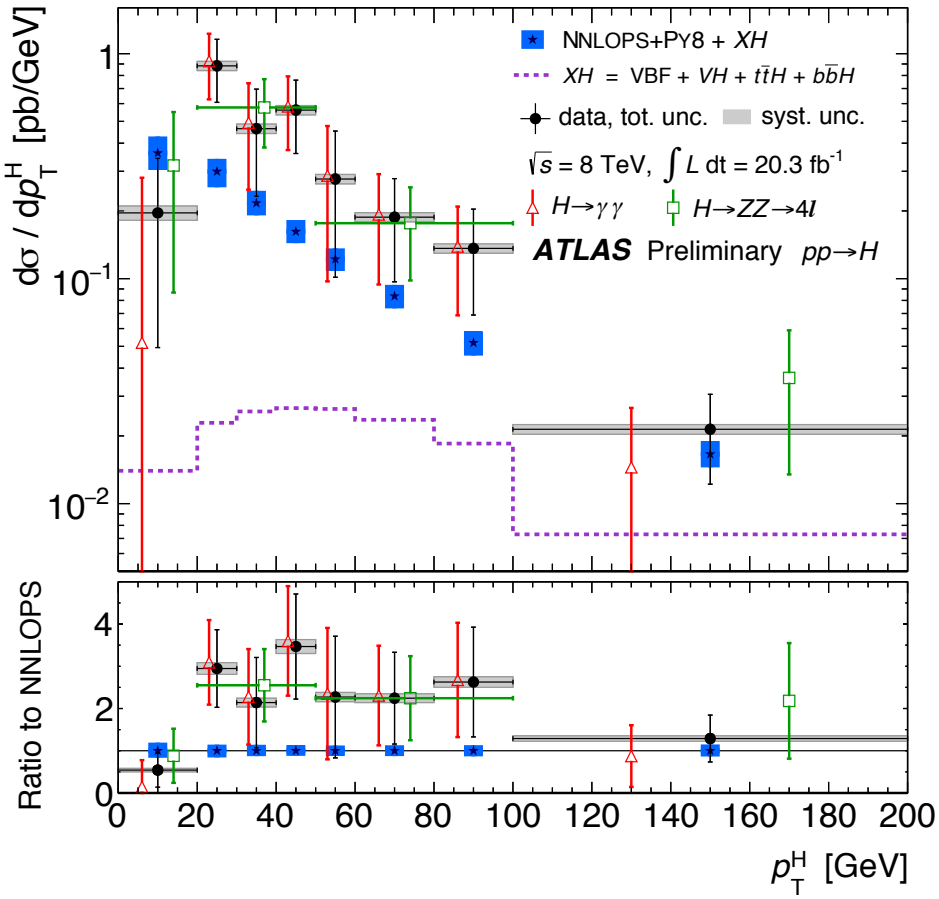


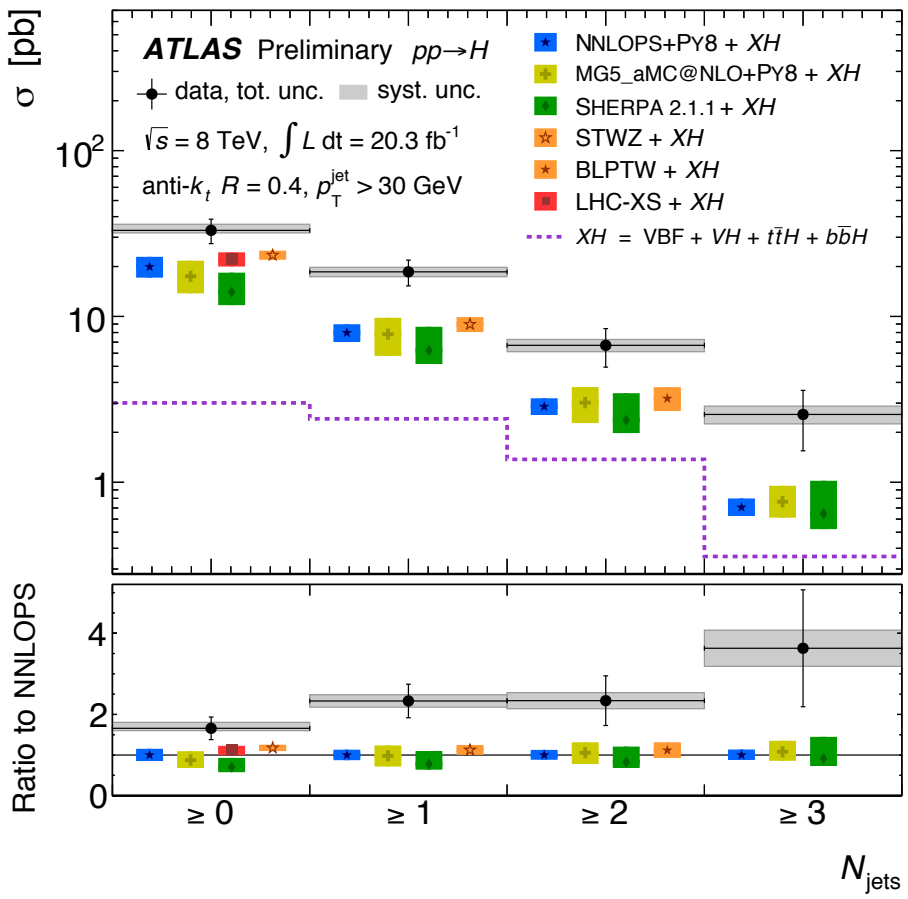


Combined Differential Cross sections

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

(Publication in preparation)



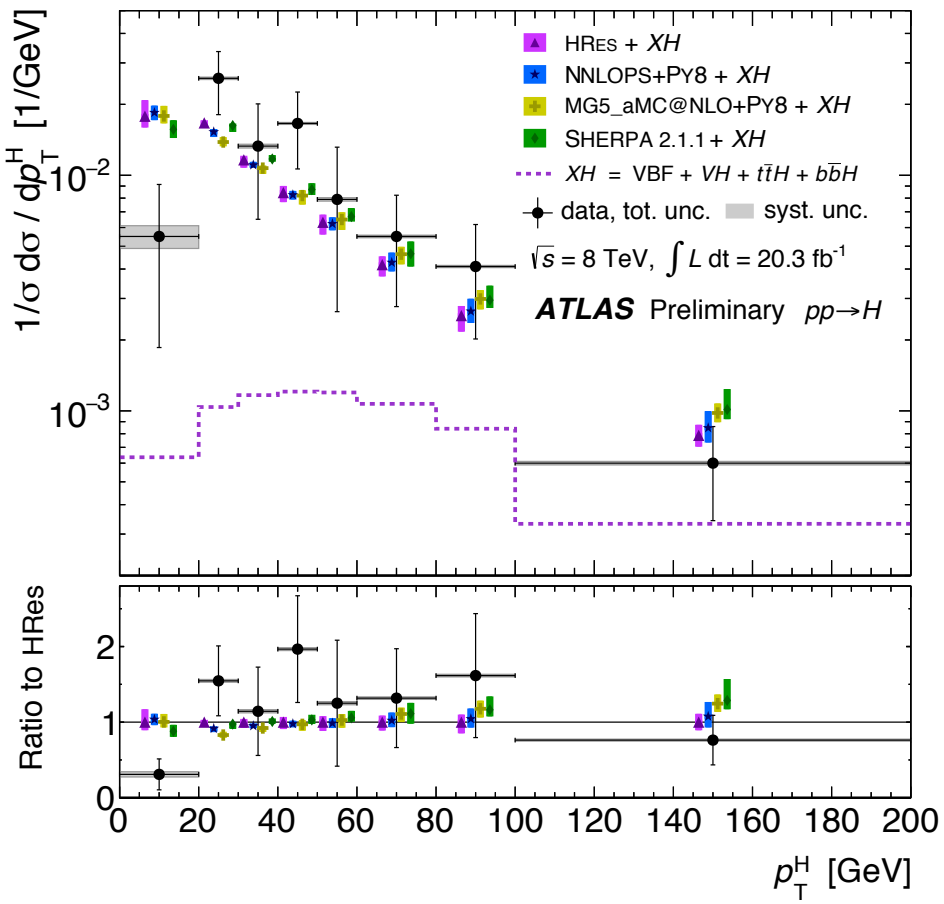


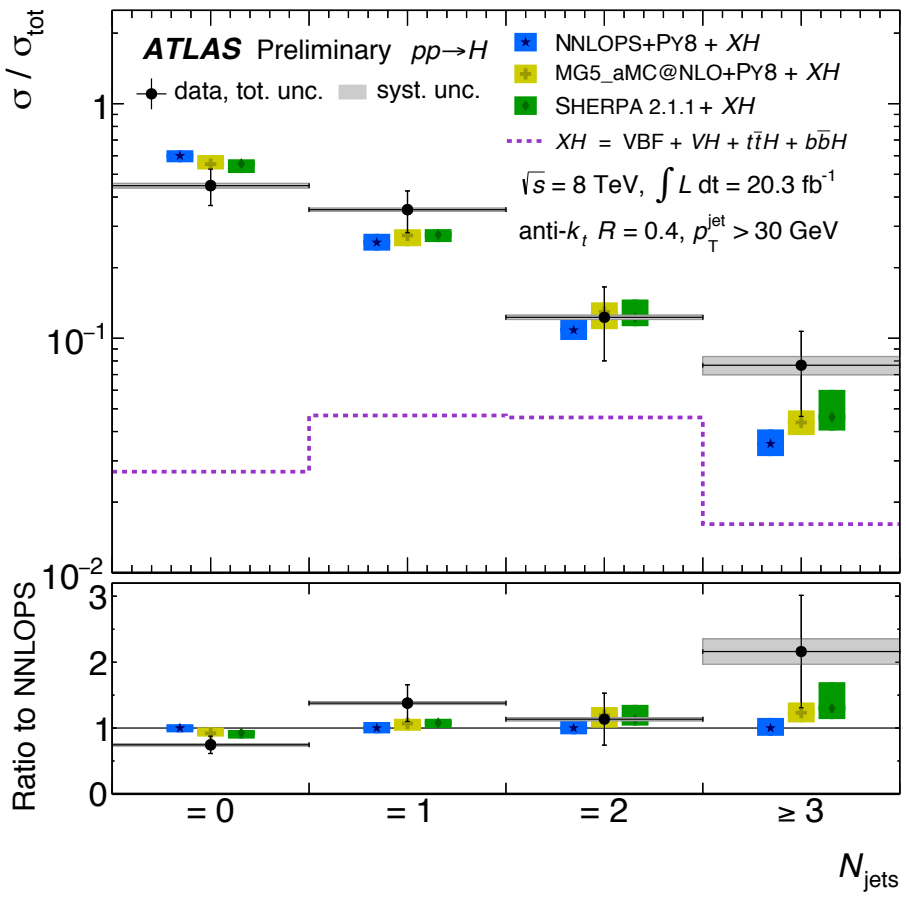
Compatibility probability ~few permil level (mostly due to the overall normalisation)

Combined Differential Cross sections

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

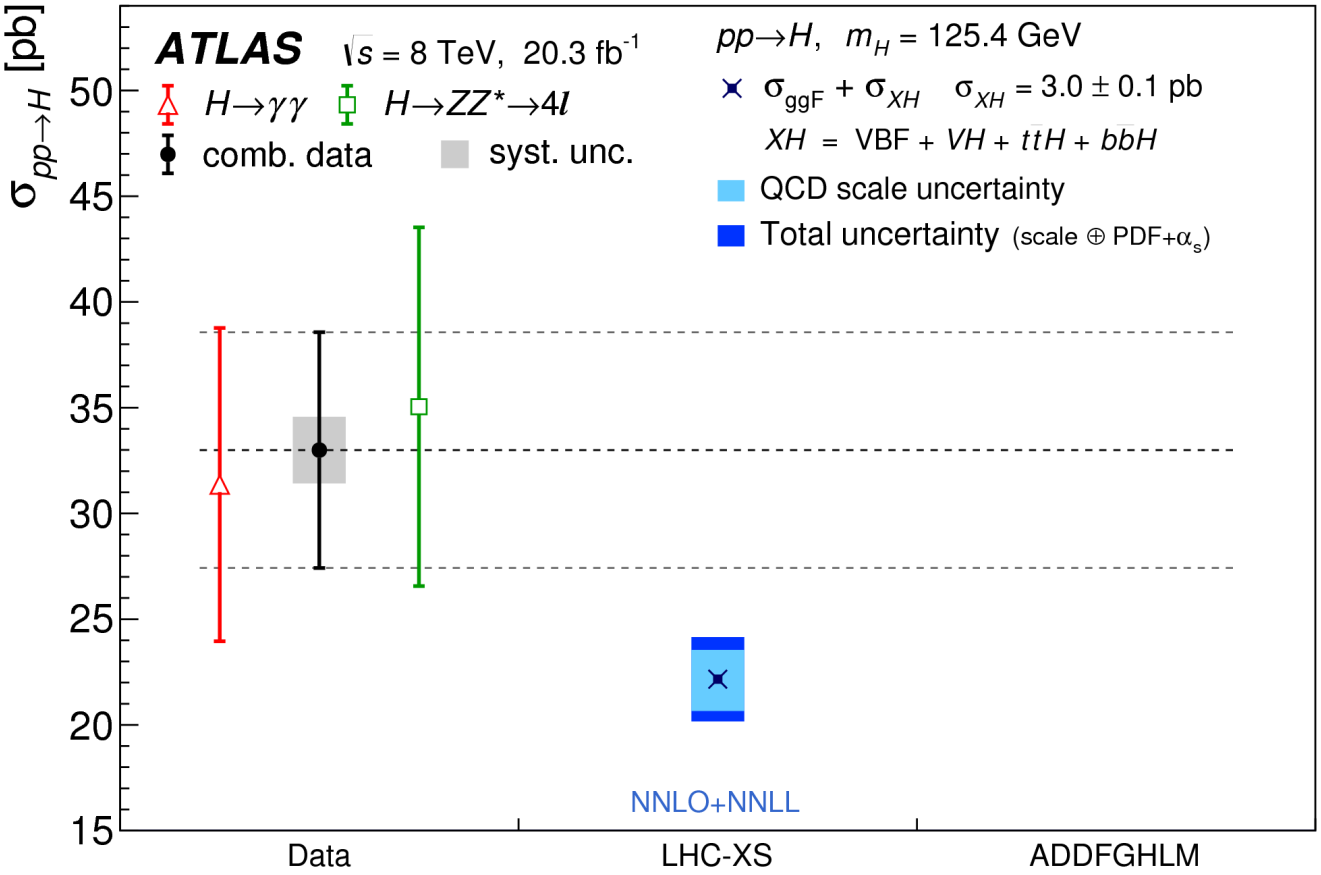
(Publication in preparation)





More compatible

Combined Inclusive Total Cross Section

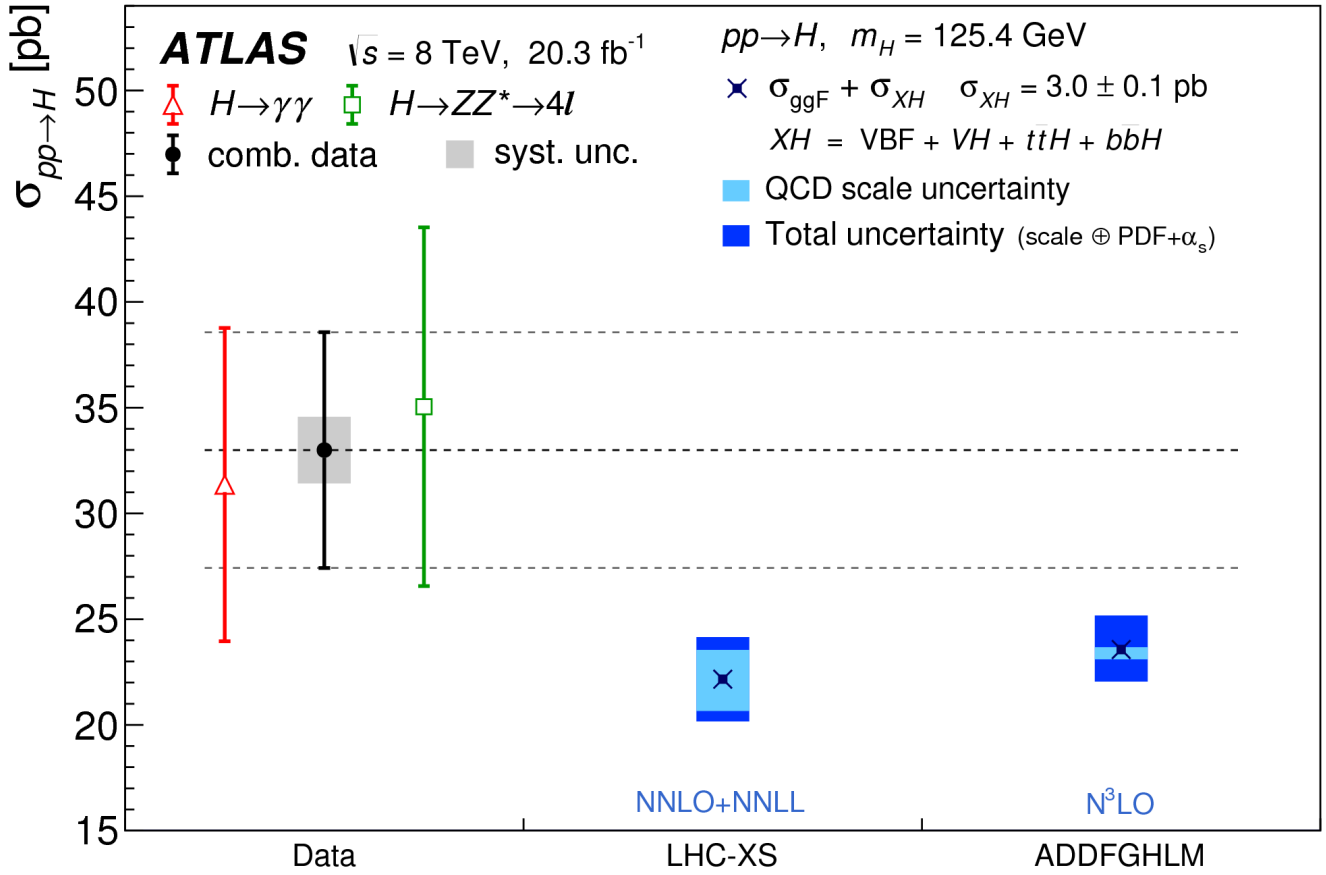


$$\sigma(\text{Data}, pp \to H) = 33.0 \pm 5.3\ (\text{stat}) \pm 1.6\ (\text{syst})\ \text{pb}$$

$$\sigma(\text{Data}, gg \to H) = 30.0 \pm 5.5\ \text{pb}$$

$$\sigma(\text{LHC Higgs XS WG}, gg \to H) = 19.1 \pm 2.0\ \text{pb}$$

Breakthrough !!



$$\sigma(\text{Data}, pp \to H) = 33.0 \pm 5.3\ (\text{stat}) \pm 1.6\ (\text{syst})\ \text{pb}$$

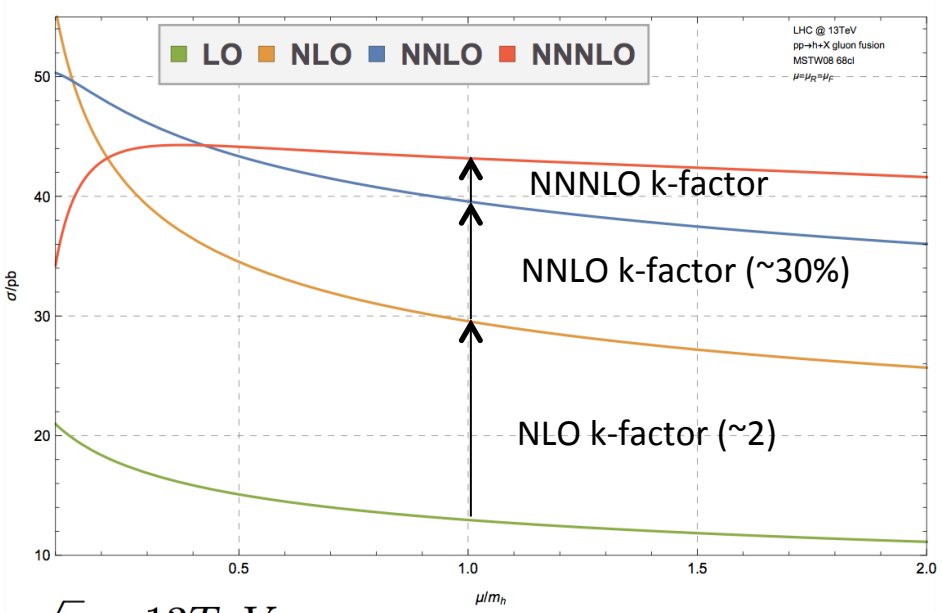
$$\sigma(\text{Data}, gg \to H) = 30.0 \pm 5.5\ \text{pb}$$

$$\sigma(\text{LHC Higgs XS WG}, gg \to H) = 19.1 \pm 2.0\ \text{pb}$$

Recent Important News

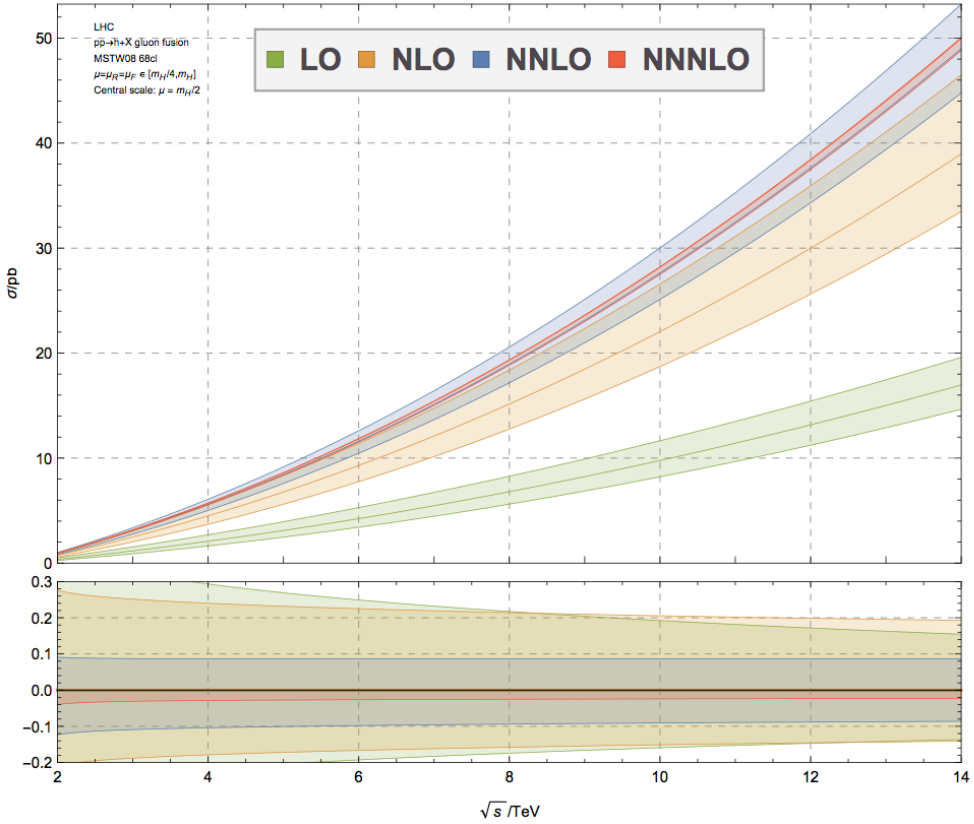
N3LO Inclusive Higgs Production Achieved

Development of sophisticated numerical/computational methods.



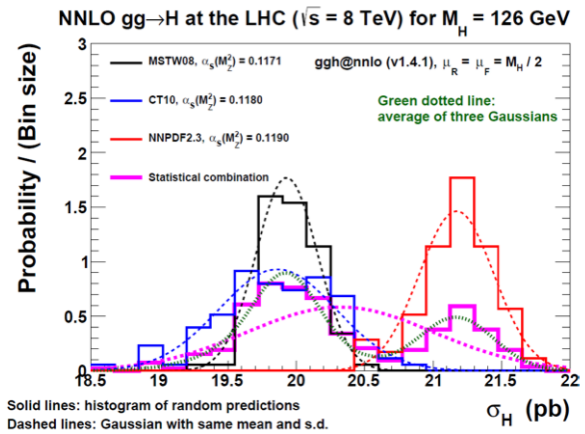
$\sqrt{s} = 13TeV$

B. Mistelberger @ Moriond QCD (2015)



Other uncertainties now become important (PDFs, treatment of EW, heavy-top approximation, top-bottom interference in loops...).

PDF Uncertainties



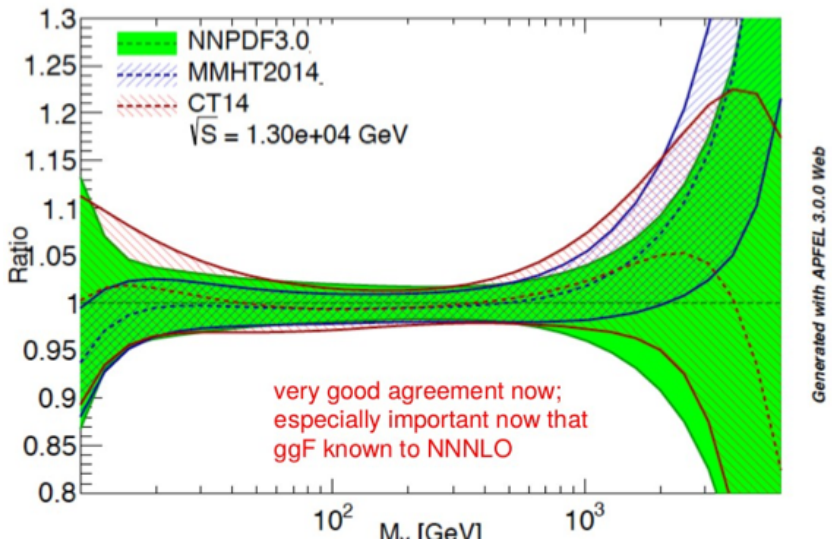
PDF (+ α_S) Uncertainties dominant in particular with recent N3LO Calculation

Situation likely to change …

Very recent developments …

CT14	MMHT2014	NNPDF3.0
42.68 pb	42.70 pb	42.97 pb
+2.0% -2.4%	+1.3% -1.8%	+1.9% -1.9%

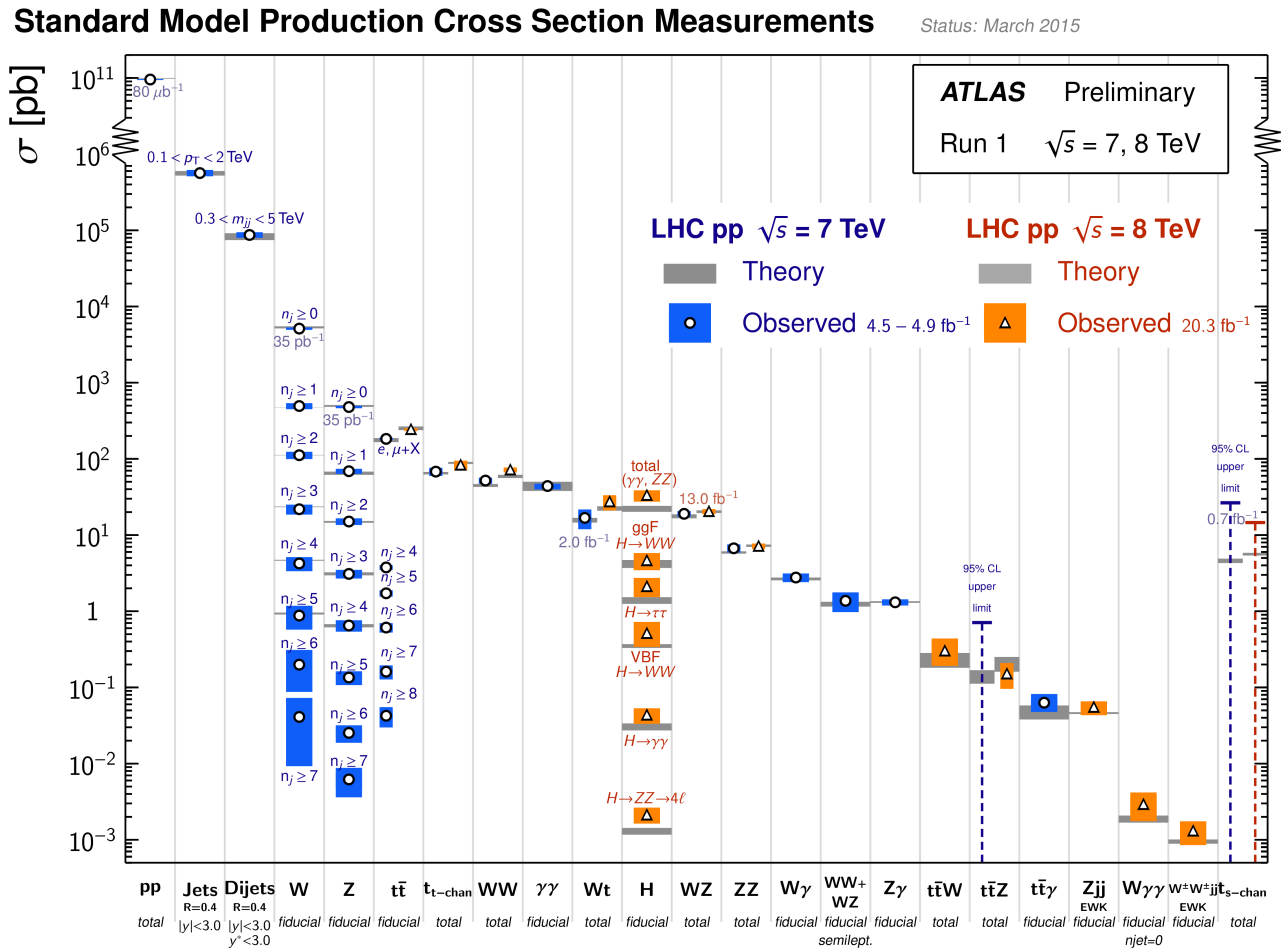
Gluon density



Wide Overview of Measurements

Past decade tremendous progresses in theory calculations and simulation "Next-to… revolution"

Processes are simulated to an unprecedented level of accuracy



Number of events selected in full 2010-2012 dataset

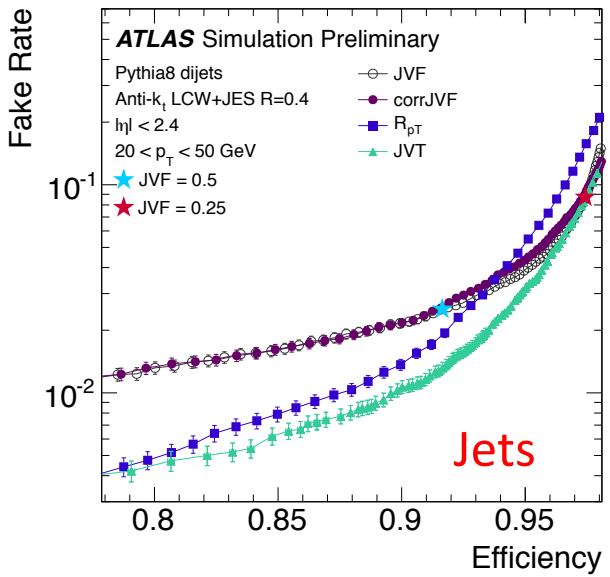
W (lν) ~ 100 M
Z (ll) ~ 10 M
tt (l+X) ~ 0.4 M
(top factory)

- Test Standard Model predictions at 7 and 8 TeV
- Calibrate the detector

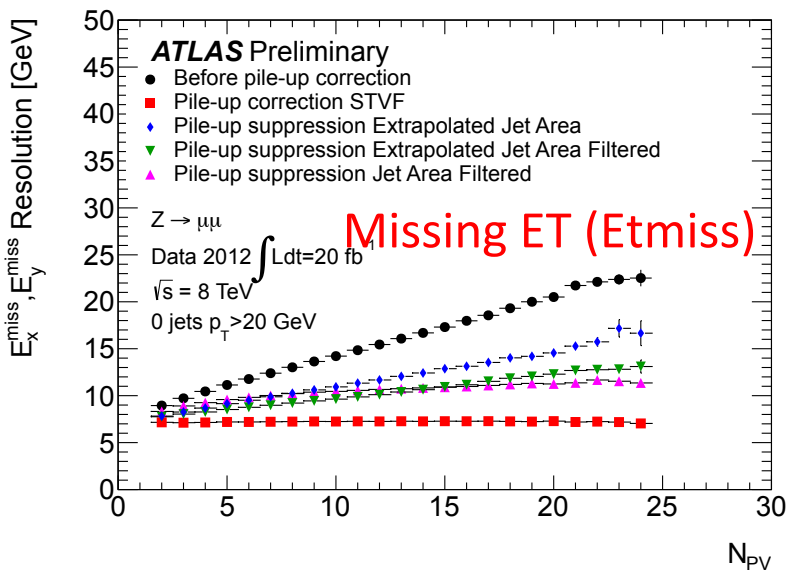
A More Complex Discovery Mode

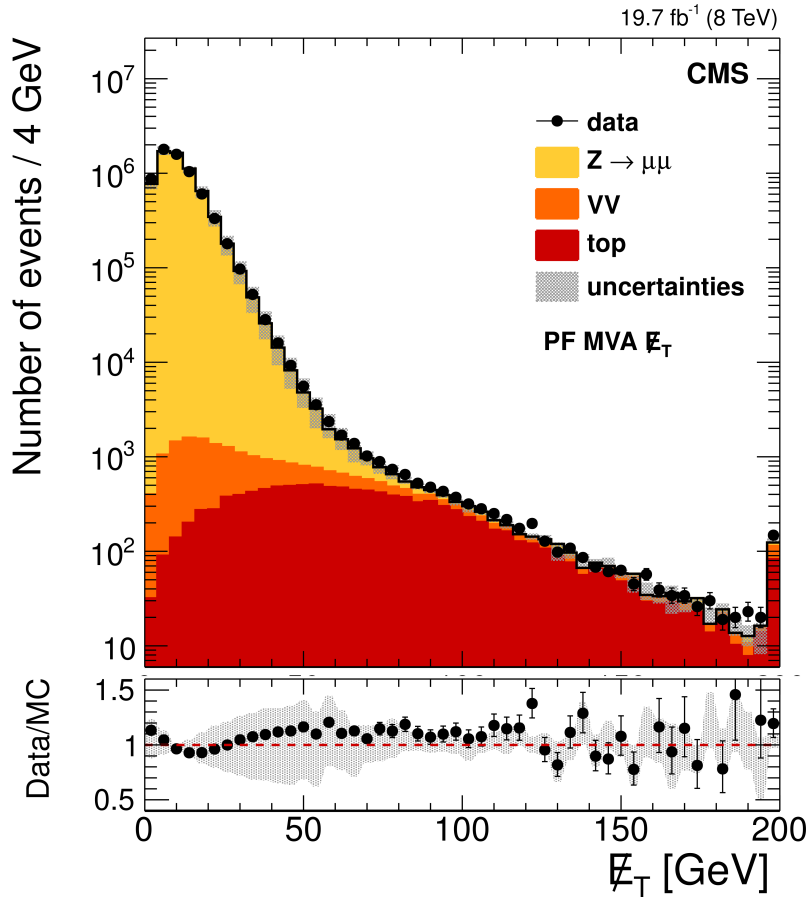
Jets and MET

Another important (r)evolution: Jet algorithms



- Fastjet: IR and collinear safe computable
- PU subtraction
- Boosted techniques (discussed in top lecture)

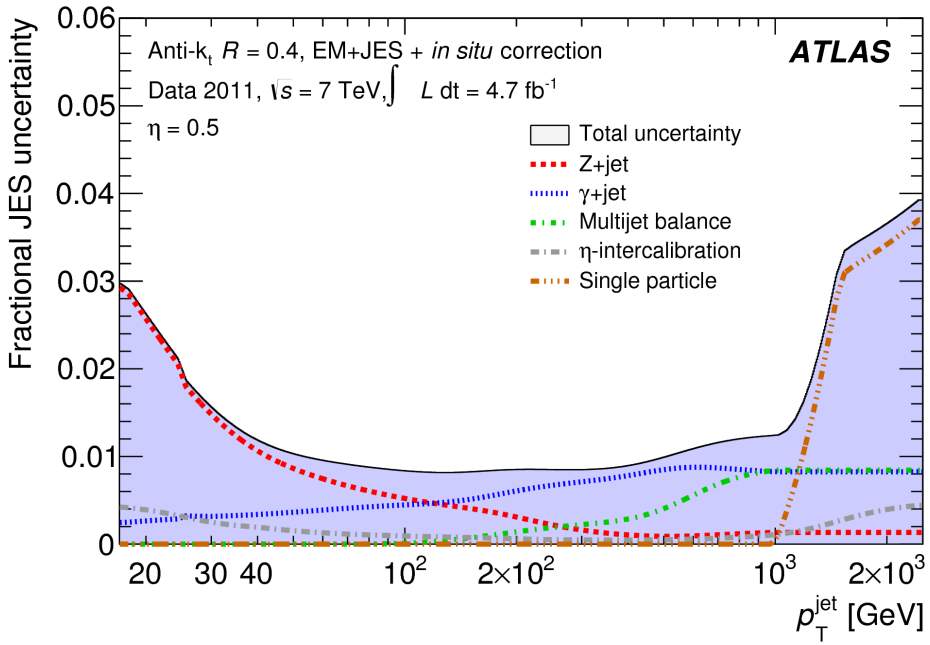


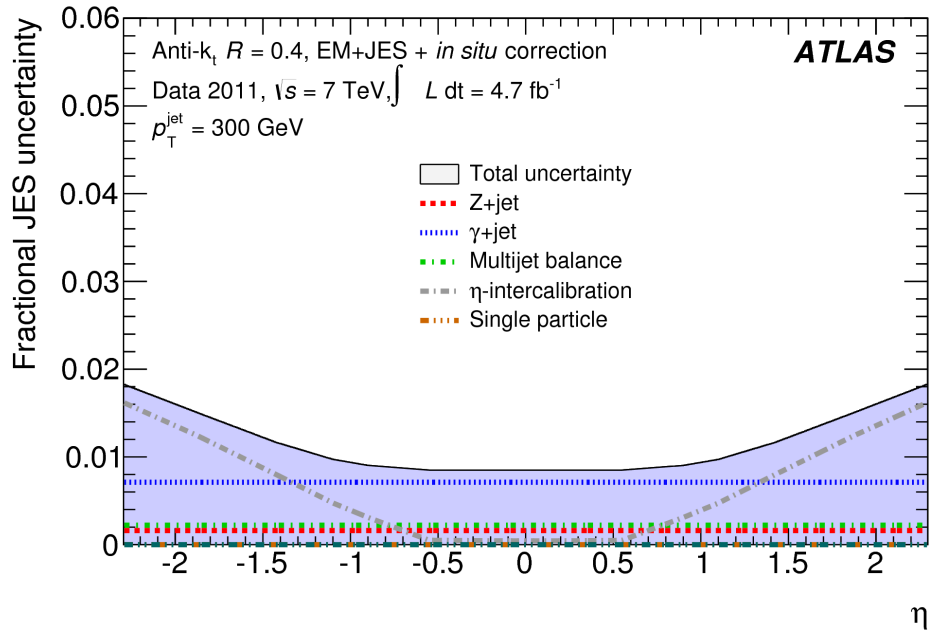


Jet Energy Scale

Jet Energy Calibration at **Percent level**

Achieved in situ

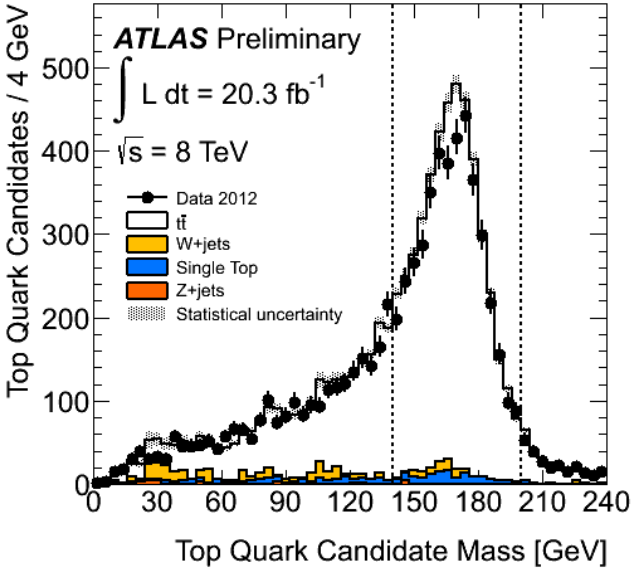




Astonishing Precision !

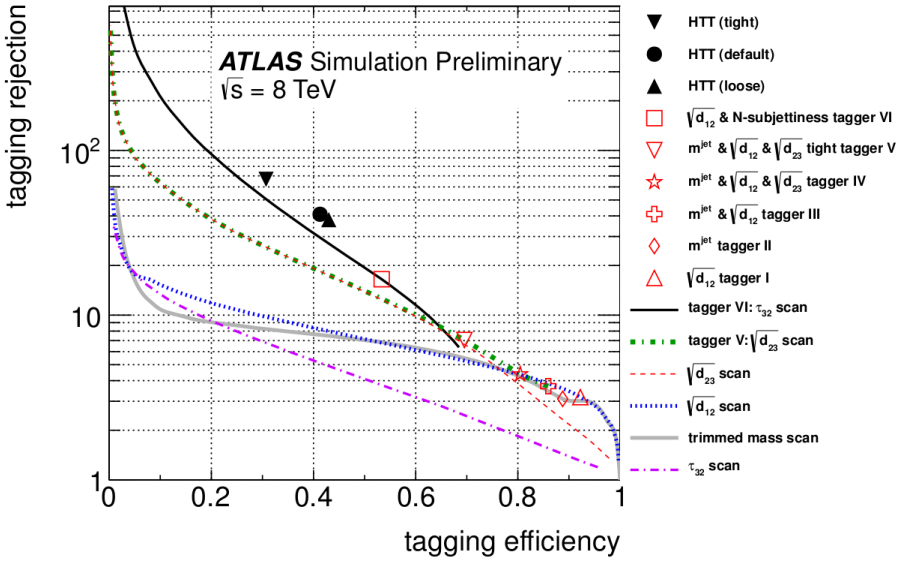
Boosted Jets

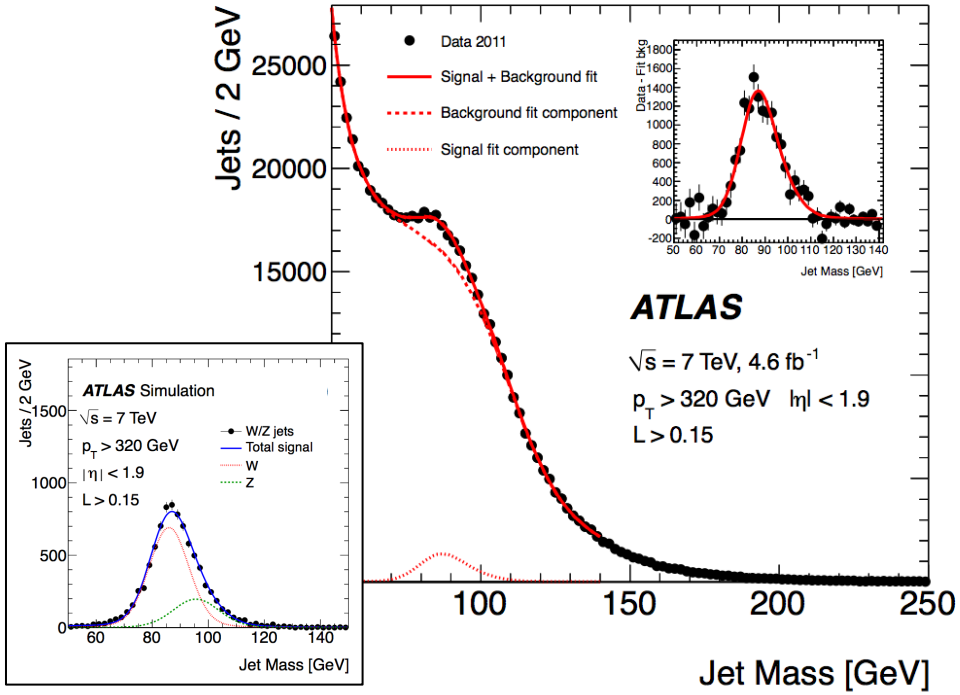
Important developments used extensively at Run 1, increasingly important at Run 2



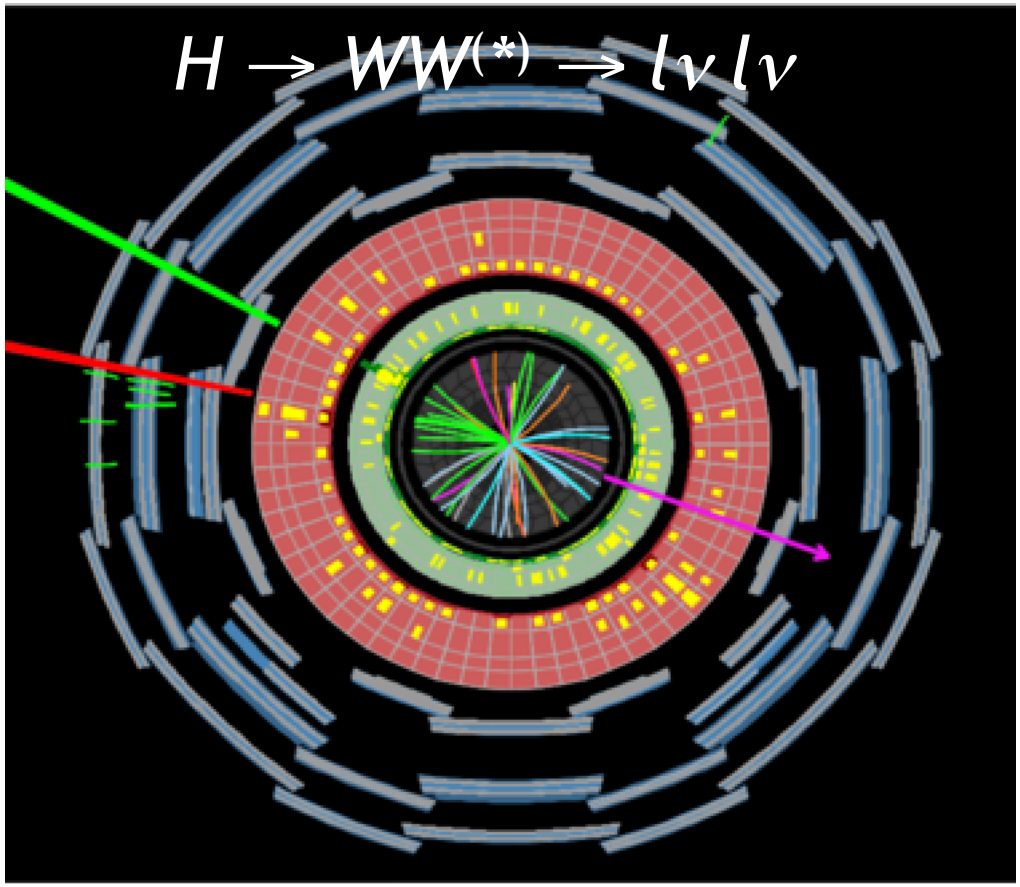
HEP Top Tagger: Reconstruction of the top jets in tt events

High pT W and Z cross section: Measurement of the W and Z production cross sections in a boosted regim





A discovery channel of a different kind…

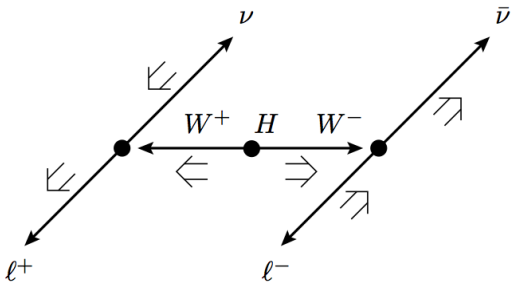


ATLAS

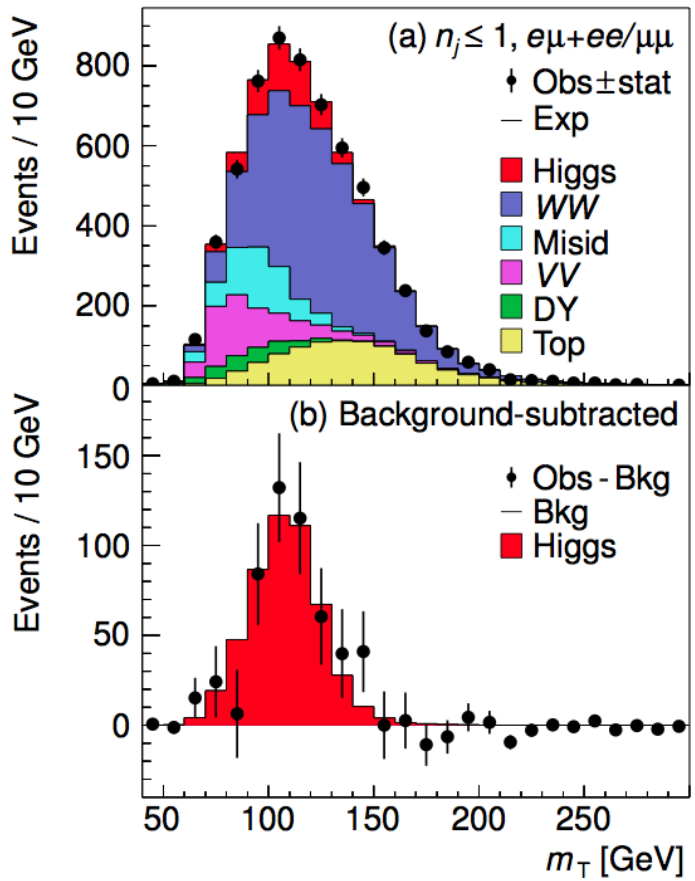
$$Z = 6.1\ (5.8)\ \sigma$$

CMS

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

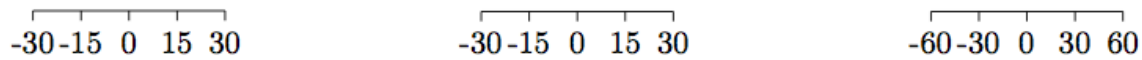


- Intricate analysis
- Moderate s/b ratio starting from approximately 1.5 and reaching more than 10.
- Poor mass resolution



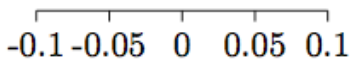
Systematics (in particular TH systematics) play a very important role

Source	Observed $\mu = 1.08$ Error +	Observed $\mu = 1.08$ Error −	Observed $\mu = 1.08$ Plot of error (scaled by 100)	Observed $\mu_{ggF} = 1.01$ Error +	Observed $\mu_{ggF} = 1.01$ Error −	Observed $\mu_{ggF} = 1.01$ Plot of error (scaled by 100)	Observed $\mu_{VBF} = 1.27$ Error +	Observed $\mu_{VBF} = 1.27$ Error −	Observed $\mu_{VBF} = 1.27$ Plot of error (scaled by 100)
Data statistics	0.16	0.15		0.19	0.19		0.44	0.40	
Signal regions	0.12	0.12		0.14	0.14		0.38	0.35	
Profiled control regions	0.10	0.10		0.12	0.12		0.21	0.18	
Profiled signal regions	-	-	-	0.03	0.03		0.09	0.08	
MC statistics	0.04	0.04		0.05	0.06		0.05	0.05	
Theoretical systematics	0.13	0.11		0.17	0.14		0.22	0.16	
Signal $H \to WW^*$ $\mathcal{B}$	0.05	0.04		0.05	0.03		0.07	0.04	
Signal ggF normalization	0.06	0.05		0.09	0.06		0.03	0.03	
Signal ggF acceptance	0.05	0.04		0.06	0.05		0.07	0.07	
Signal VBF normalization	0.01	0.01		-	-	-	0.07	0.04	
Signal VBF acceptance	0.02	0.01		-	-	-	0.15	0.08	
Background WW	0.06	0.06		0.08	0.08		0.07	0.07	
Background top quark	0.03	0.03		0.04	0.04		0.06	0.06	
Background misid. factor	0.05	0.05		0.06	0.06		0.02	0.02	
Others	0.02	0.02		0.02	0.02		0.03	0.02	
Experimental systematics	0.07	0.06		0.08	0.07		0.18	0.14	
Background misid. factor	0.03	0.03		0.04	0.04		0.02	0.01	
Bkg. $Z/\gamma^* \to ee$, $\mu\mu$	0.02	0.02		0.03	0.03		0.01	0.01	
Muons and electrons	0.04	0.04		0.05	0.04		0.03	0.02	
Missing transv. momentum	0.02	0.02		0.02	0.01		0.05	0.05	
Jets	0.03	0.02		0.04	0.03		0.14	0.11	
Others	0.03	0.02		0.03	0.03		0.06	0.06	
Integrated luminosity	0.03	0.03		0.03	0.02		0.05	0.03	
Total	0.22	0.20		0.27	0.25		0.53	0.45	



In particular background systematic uncertainties play an important role *(which affect the significances* described above)*

Systematic source	Impact on $\hat{\mu}$				
	Pre-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	
Top quarks, generator modeling on α_{top}	+0.03	−0.04	+0.03	−0.03	
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 $p_{\text{T}}^{\ell 2} > 20\,\text{GeV}$, 2012	−0.01	+0.02	−0.01	+0.02	
ggF H, QCD scale on ϵ_1	−0.01	+0.02	−0.01	+0.02	



NNLO Done (need fiducial and differential) !

*Discovery with help from Theory

Combining Bosonic Modes to Measure Higgs Properties

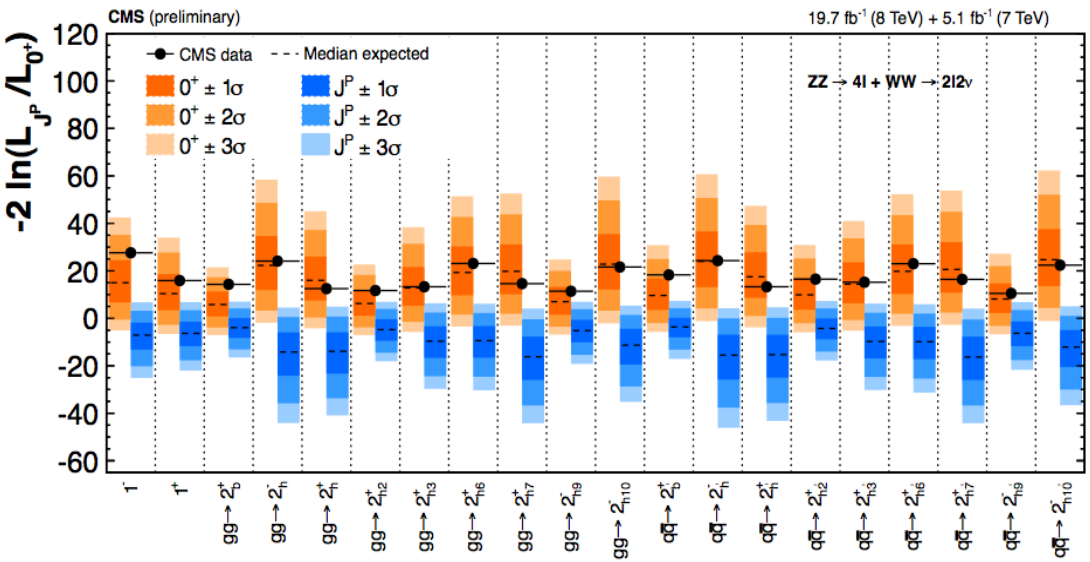
J^{PC}

- 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)

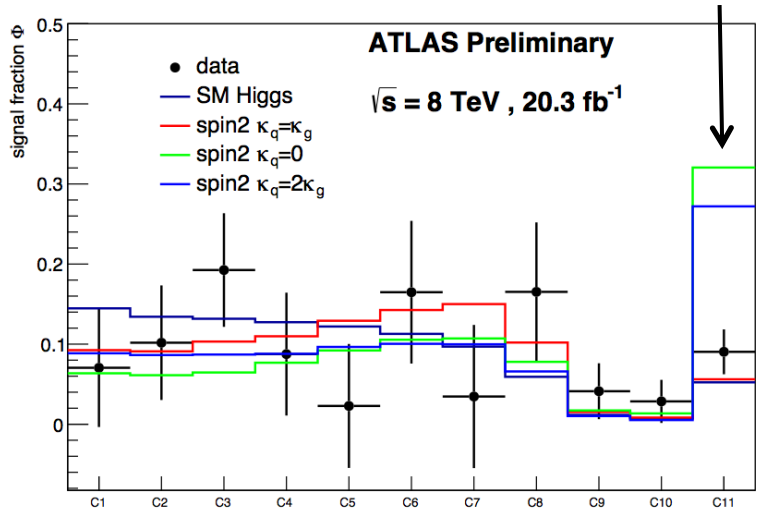
- Spin hypothesis tests (difficult model spin 2) – Combination of ZZ, WW and $\gamma\gamma$

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

Coupling to energy-momentum tensor



pT [125,300] GeV



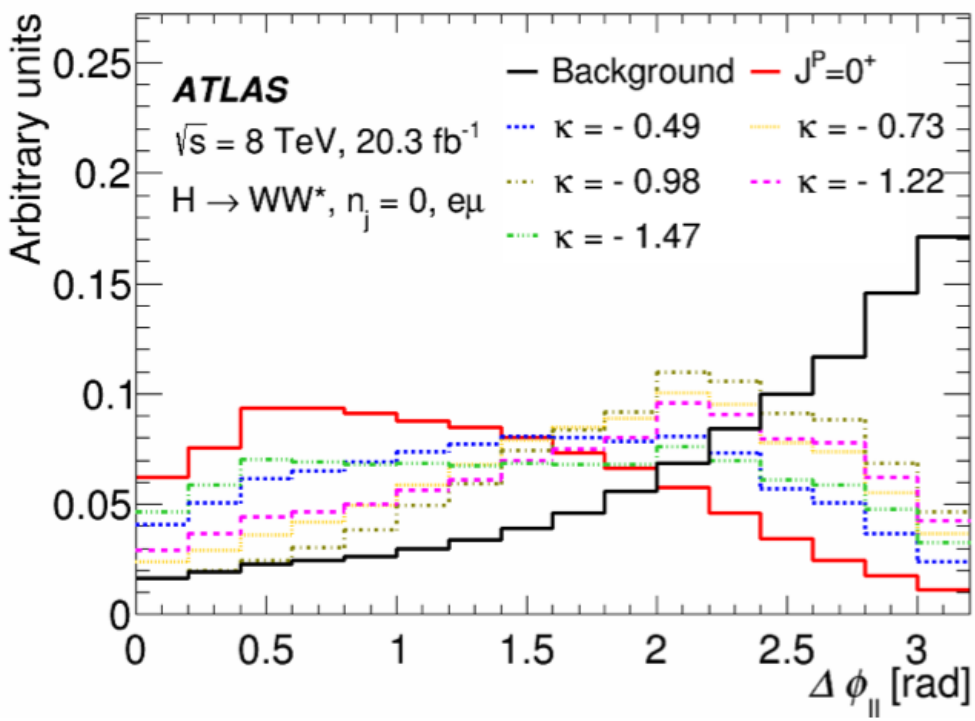
cos θ*

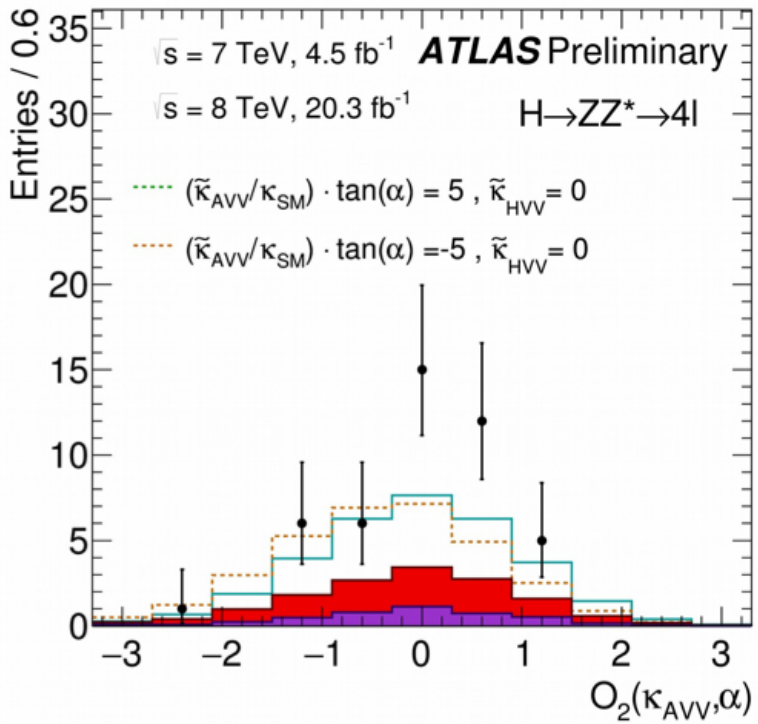
CP Mixing

- Spin 0 effective model

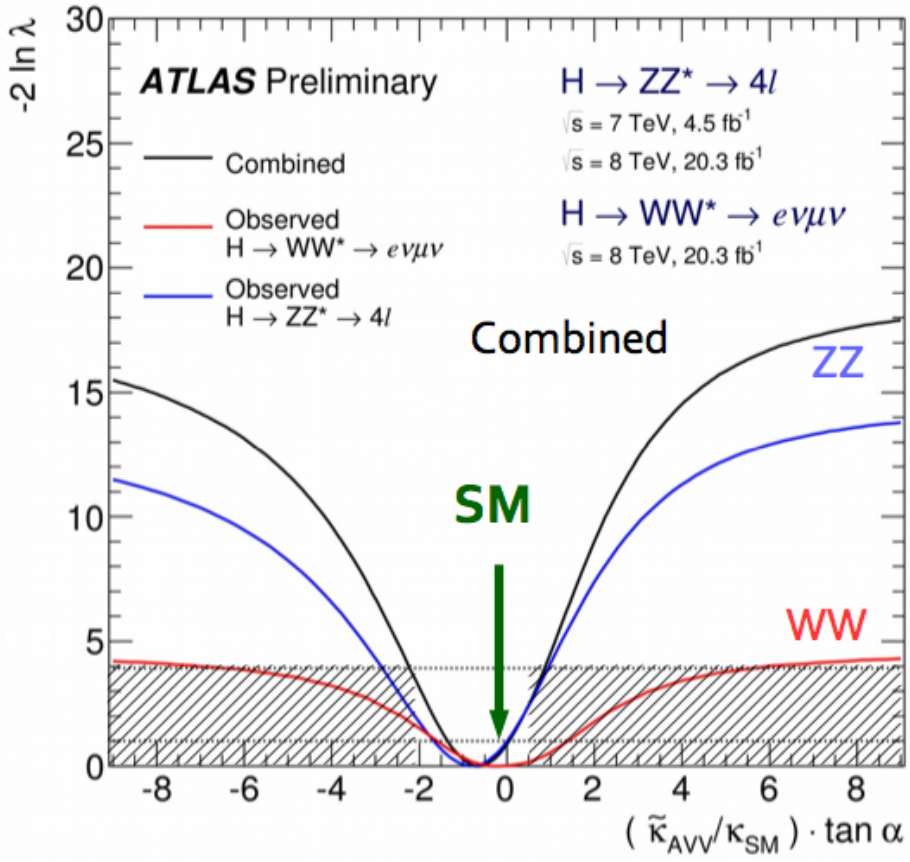
$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu} \right] - \tfrac{1}{4}\tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \tfrac{1}{2}\tfrac{1}{\Lambda}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

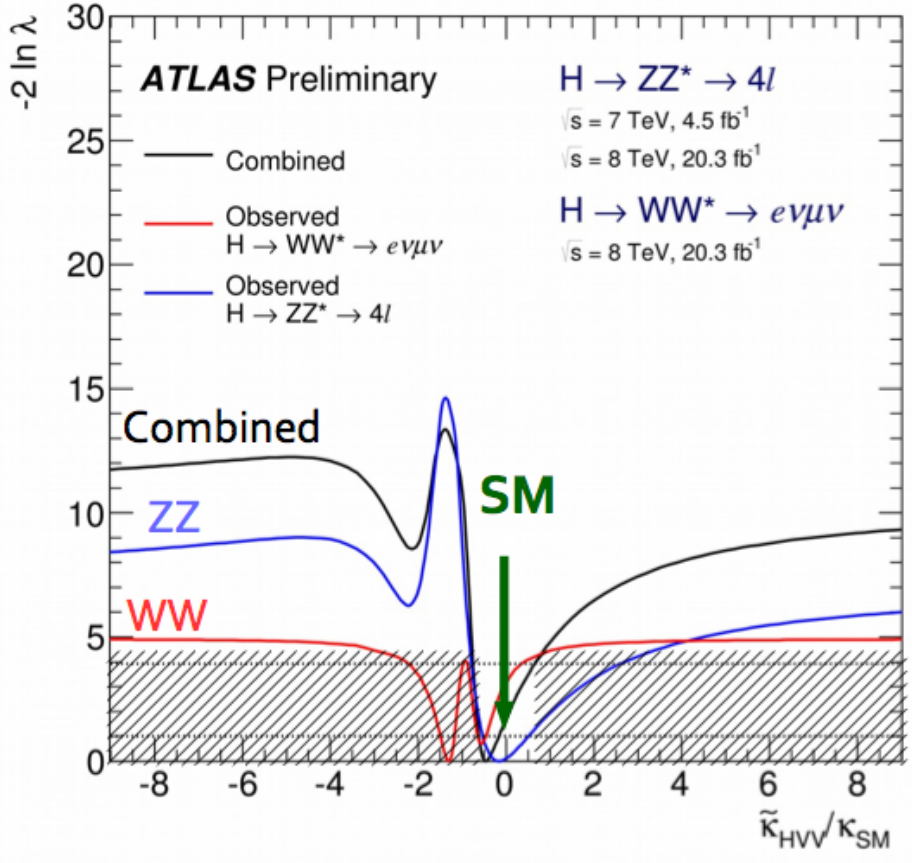
(Use e.g. optimal observables in 4l channel)





CP Mixing





Both ATLAS and CMS find that the observed Higgs boson is compatible with a standard CP-even

The Higgs Natural Width

Problem at the LHC: Measure only cross sections times branching fractions in specific modes !!

The total width can be scaled at will (with an undetected part) and be compensated by the scaling of the couplings in the observed modes.

$$\Gamma_{SM} = 4.2 \text{ MeV}$$

Is small therefore small couplings to the Higgs can be easily visible: tool for discovery!

Exploring the far Off-Shell signal strength And constraints on the Higgs boson width

Probing the Higgs boson as a propagator:

- N. Kauer and G. Passarino, Inadequacy of zero-width approximation for a light Higgs boson signal, JHEP 1208 (2012) 116, arXiv:1206.4803.

- F. Caola and K. Melnikov, Constraining the Higgs boson width with ZZ production at the LHC, Phys.Rev. D88 (2013) 054024, arXiv:1307.4935.

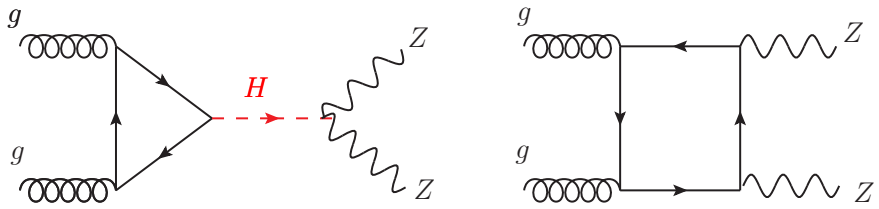
- J. M. Campbell, R. K. Ellis, and C. Williams, Bounding the Higgs width at the LHC, JHEP 1404 (2014) 060, arXiv:1311.3589.

- J. M. Campbell, R. K. Ellis, and C. Williams, Bounding the Higgs width at the LHC, Phys.Rev. D89 (2014) 053011, arXiv:1312.1628.

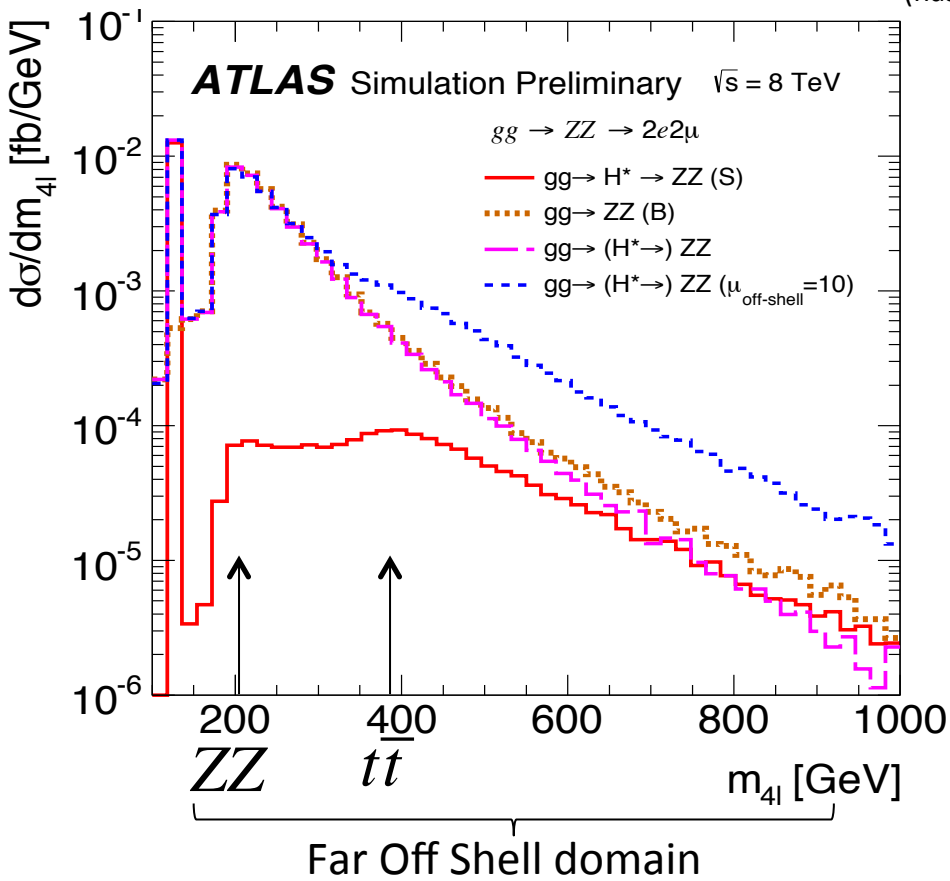
- A. Azatov, C. Grojean, A. Paul and E. Salvioni, Taming the Off-Shell Higgs boson, CERN-PH-TH-2014-108, arXiv:1406:6338

Off Shell Higgs coupling properties Measurement

Study the Higgs boson as a propagator



(has been done also in the WW channel as well but less sensitive)



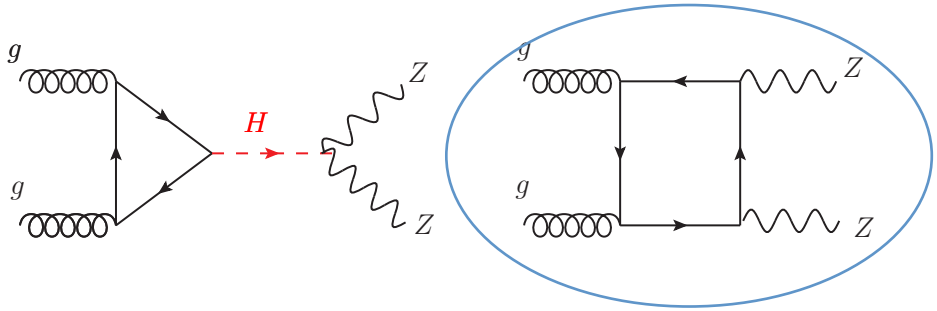
Why is it interesting?

- If the coupling properties of the Higgs boson are known on mass shell (in particular the width of the Higgs: Probe e.g. the running of the Higgs coupling to gluons.

- If we assume that the running does not have large contributions from new physics at higher mass scales: Probe of the width.

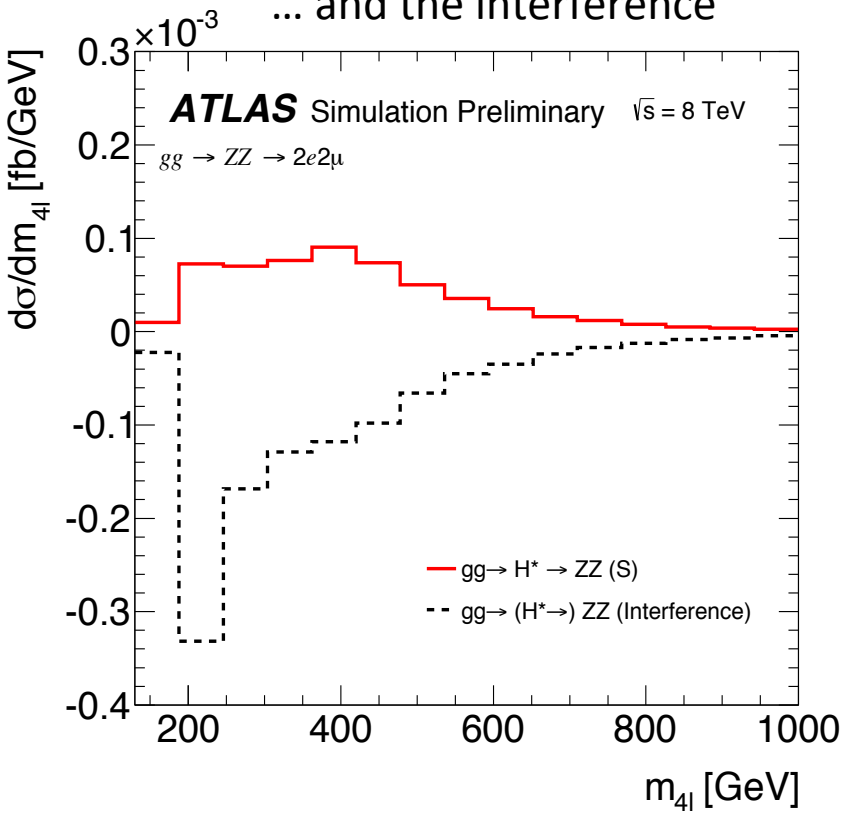
Intricacies…

Study the Higgs boson as a propagator

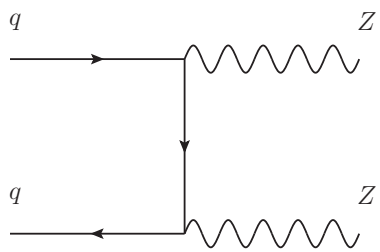


Needs to be known to a high precision level. Latest NLO estimate (Melnikov and Dowling TTP-15-009)

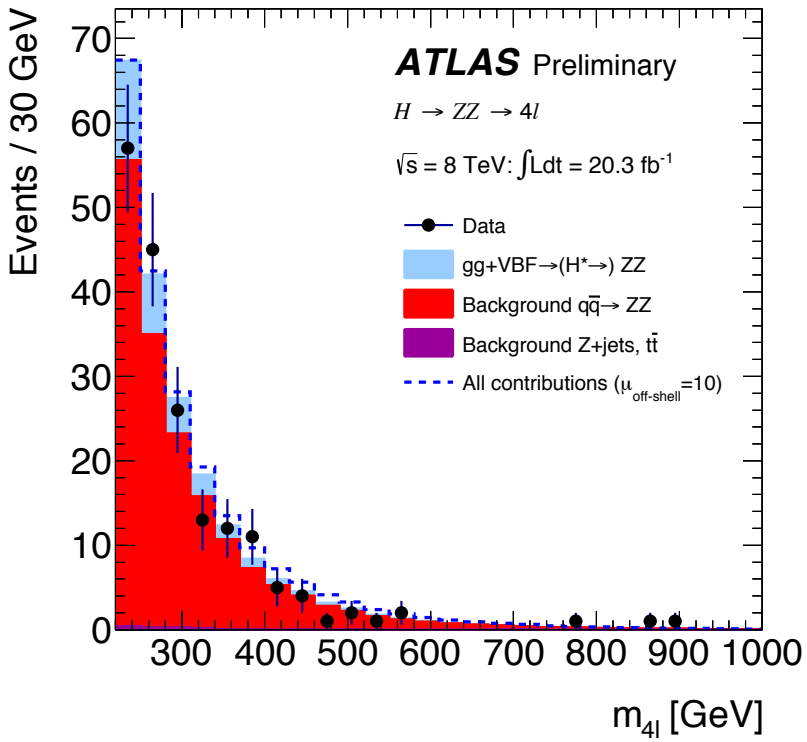
… and the interference

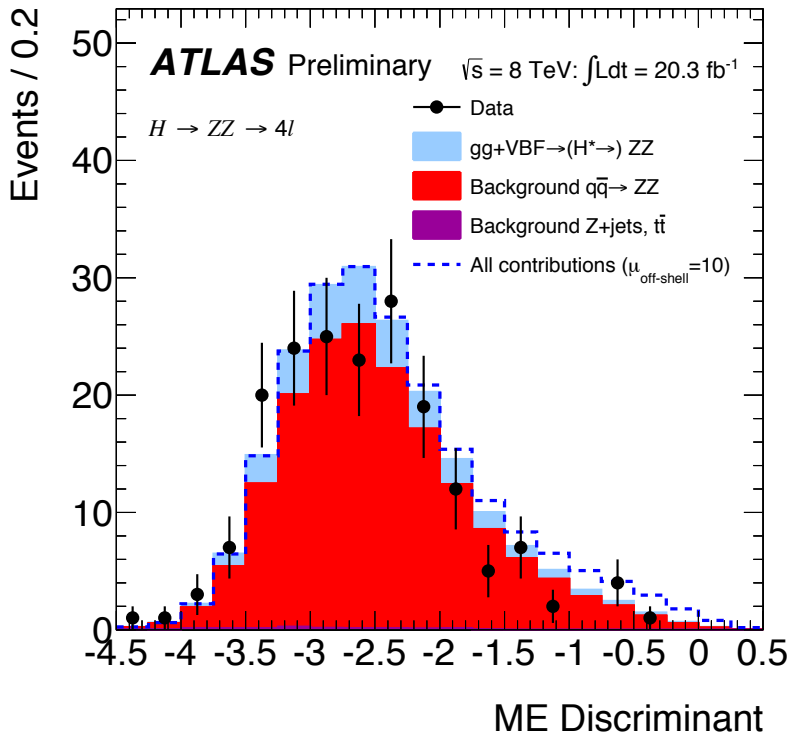


… but wait there is a way larger background (also needing to be accuratly, in particular with EW corrections)!



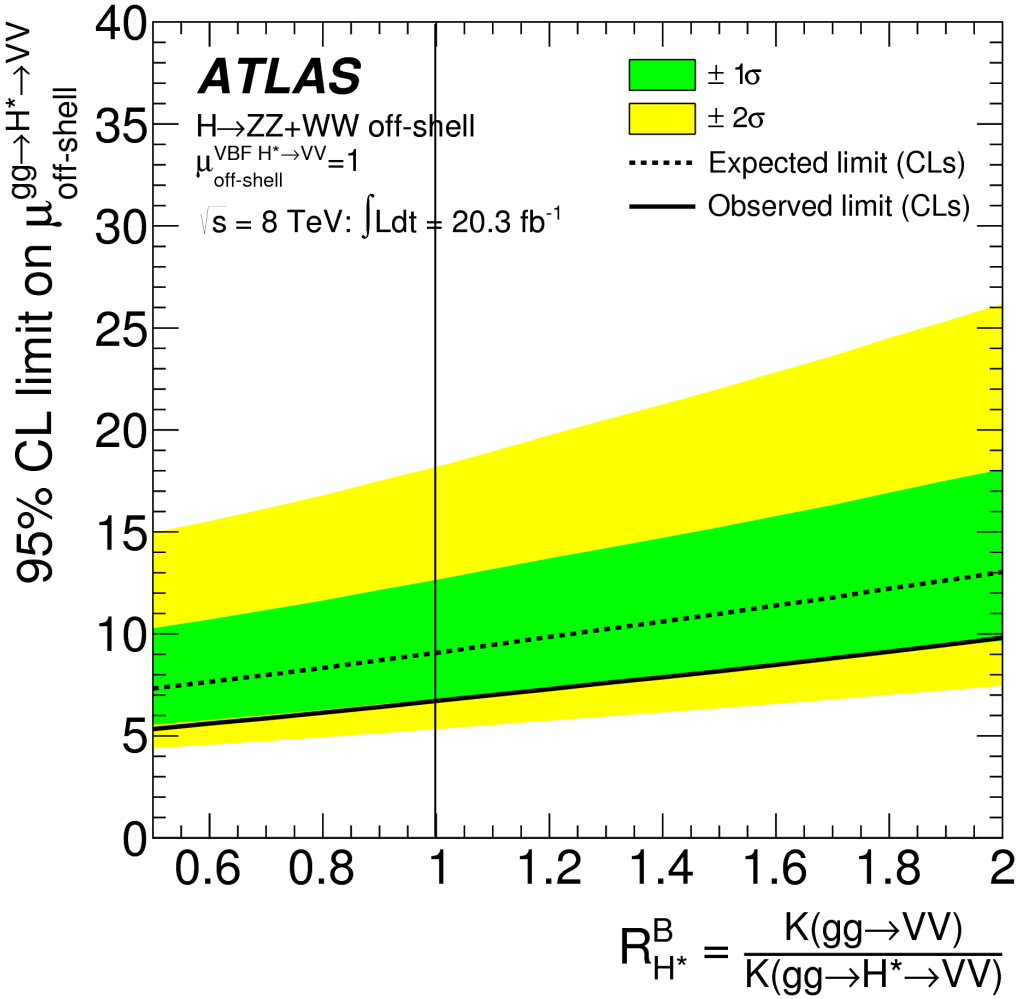
Exploring the High mass region in 4l and 2l2v





Need to use as much information as possible e.g. Matrix Element

CLs limits on Off-Shell signal strength

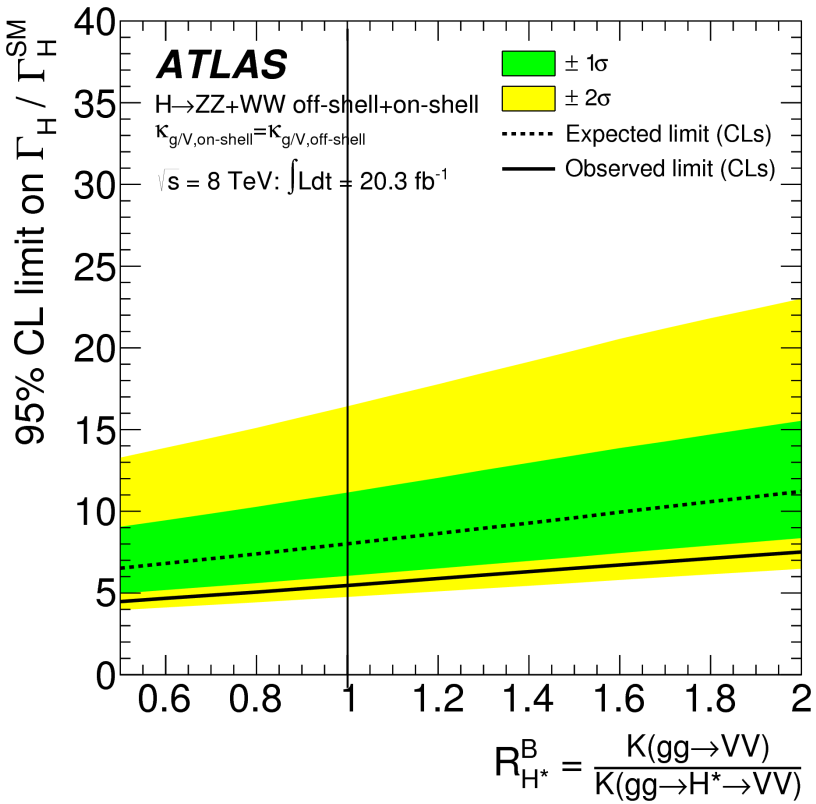


Agnostic to k-factor!

R=1 Approximately verified in the soft collinear approximation and latest calculations

95% CL limit obs. (exp.)
$\mu_{OffShell} < 6.7\ (8.1)$

Natural Width



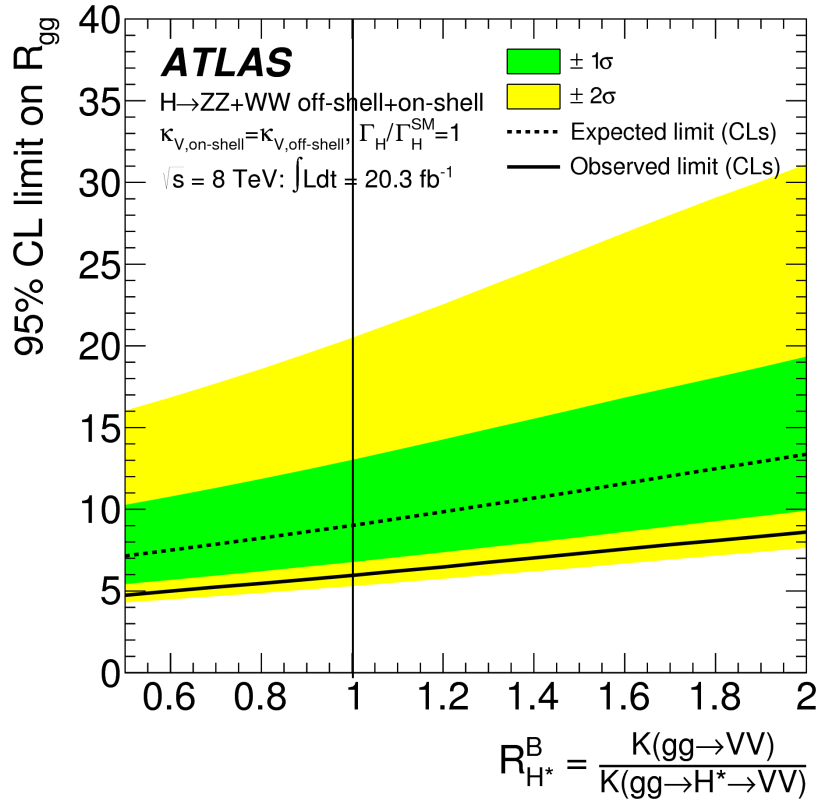
$$\mu_{OnShell} \equiv \frac{(\kappa_g^2 \kappa_V^2)_{OnShell}}{\Gamma_H / \Gamma_H^{SM}}$$

Assuming: $(\kappa_g^2 \kappa_V^2)_{OnShell} = (\kappa_g^2 \kappa_V^2)_{OffShell}$

95% CL limit obs. (exp.)
$\Gamma_H / \Gamma_H^{SM} < 5.5\ (8.0)$

~23 MeV

Running

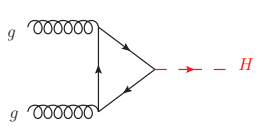
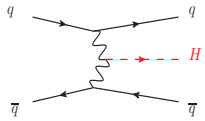
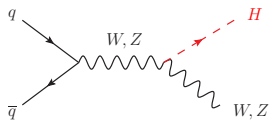
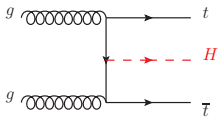


95% CL limit obs. (exp.)
R < 6.0 (9.0)

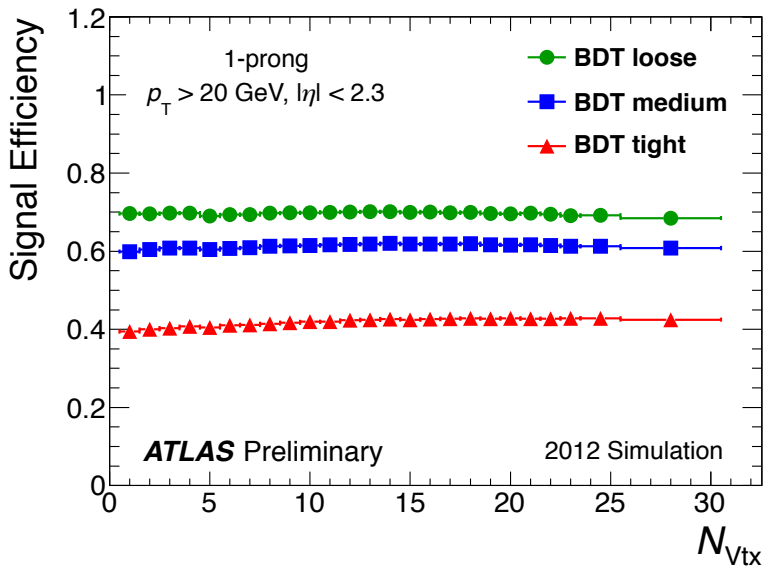
Precision curently statistically limited

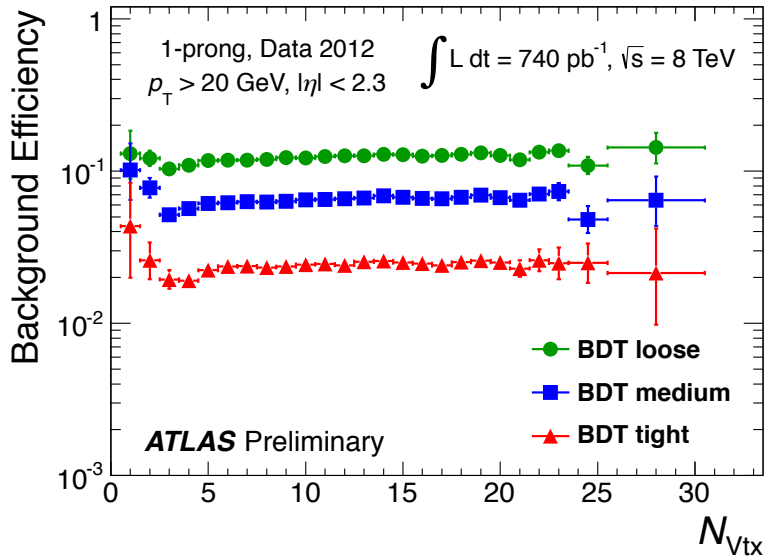
Exploring the Fermion Sector in Complex Final States

Panorama of Main Higgs Analyses

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

Reconstructing Taus

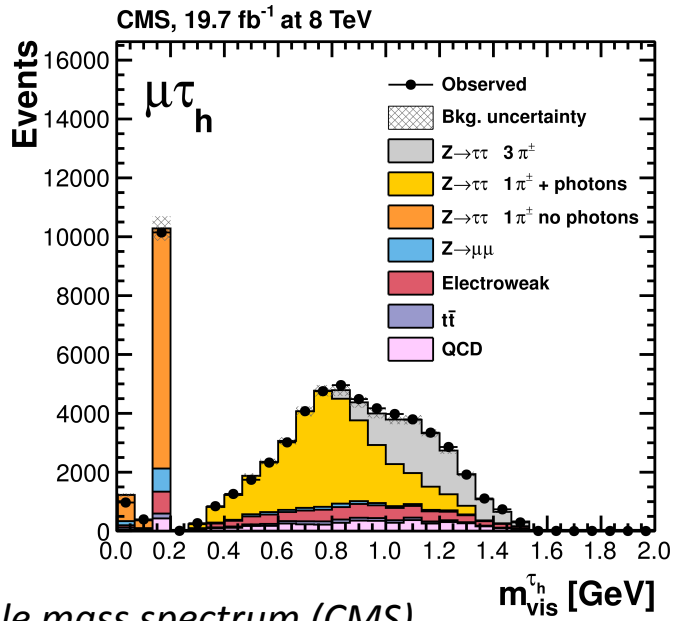




Tau reconstruction

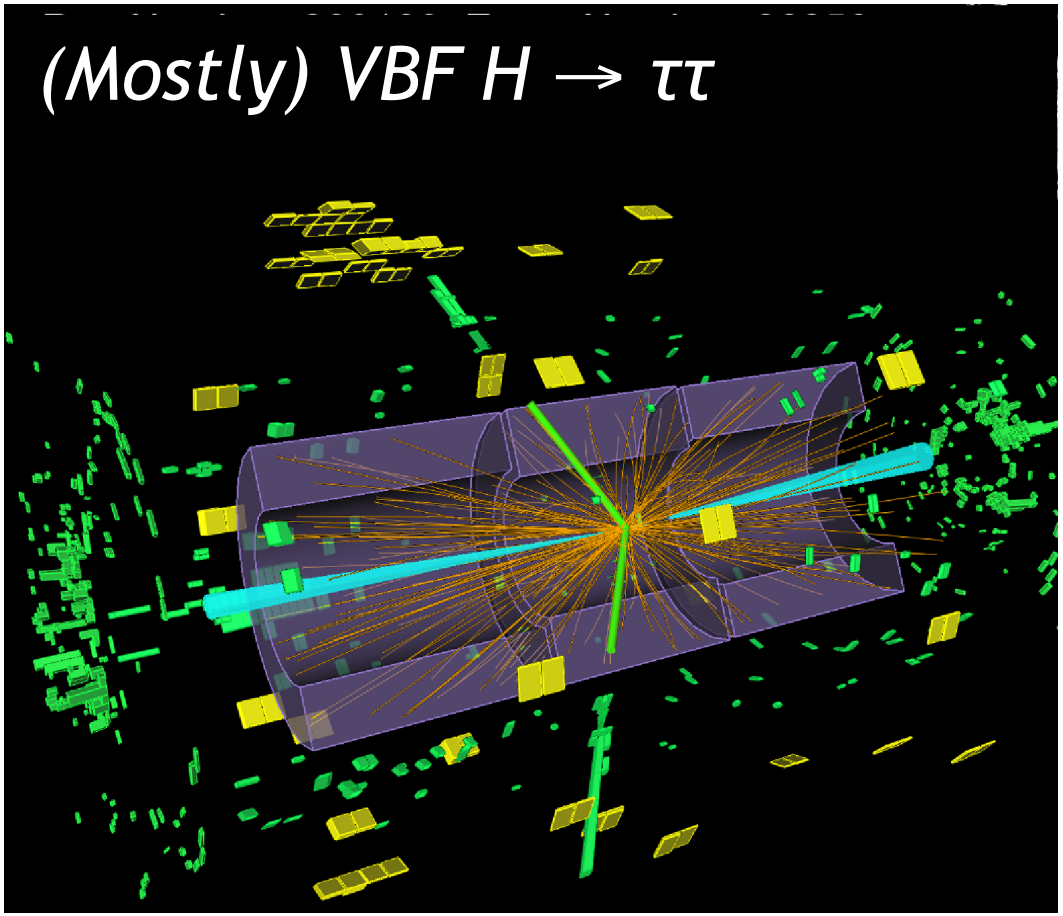
Typical numbers:

- Efficiency ~50%
- Background efficiency ~2%



Splendid visible mass spectrum (CMS)

A Very Important Observation…

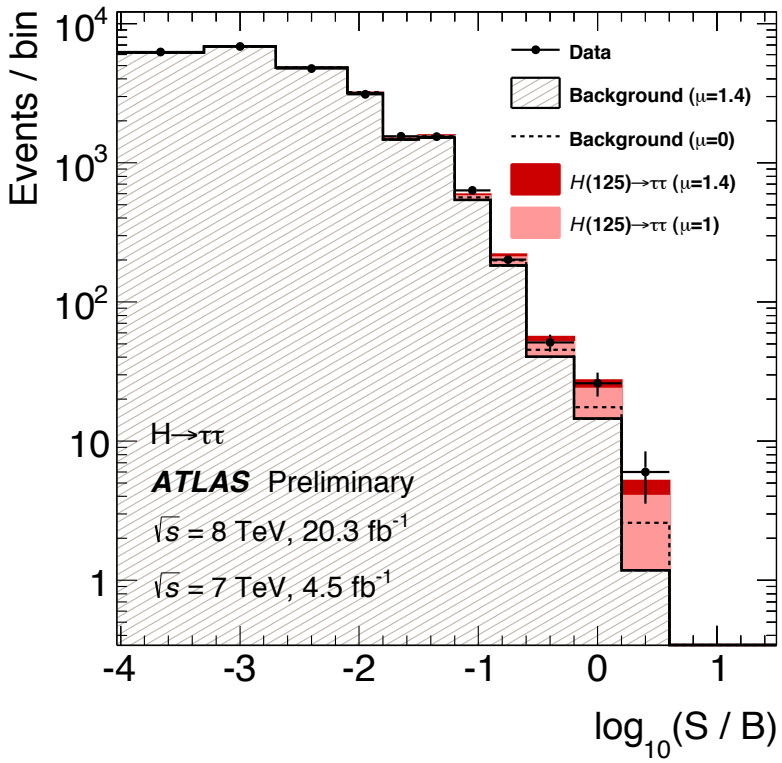


ATLAS

$$Z = 4.5\ (3.5)\ \sigma$$

CMS

$$Z = 3.2\ (3.7)\ \sigma$$

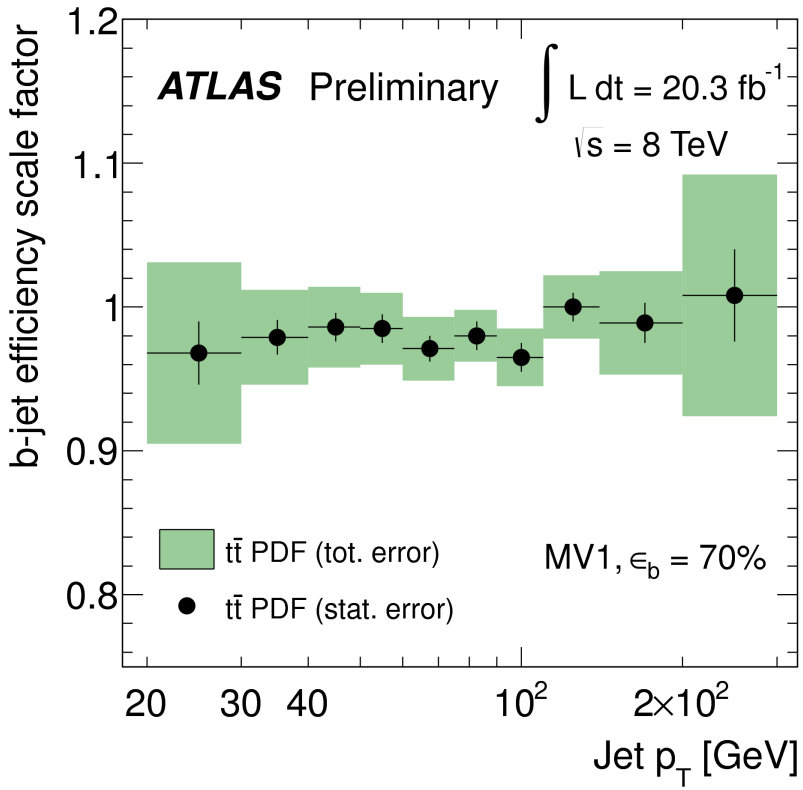


- Control of background through embedding (of taus in dimuon data events)
- Moderate s/b ratio starting from a few percent to approximately 1

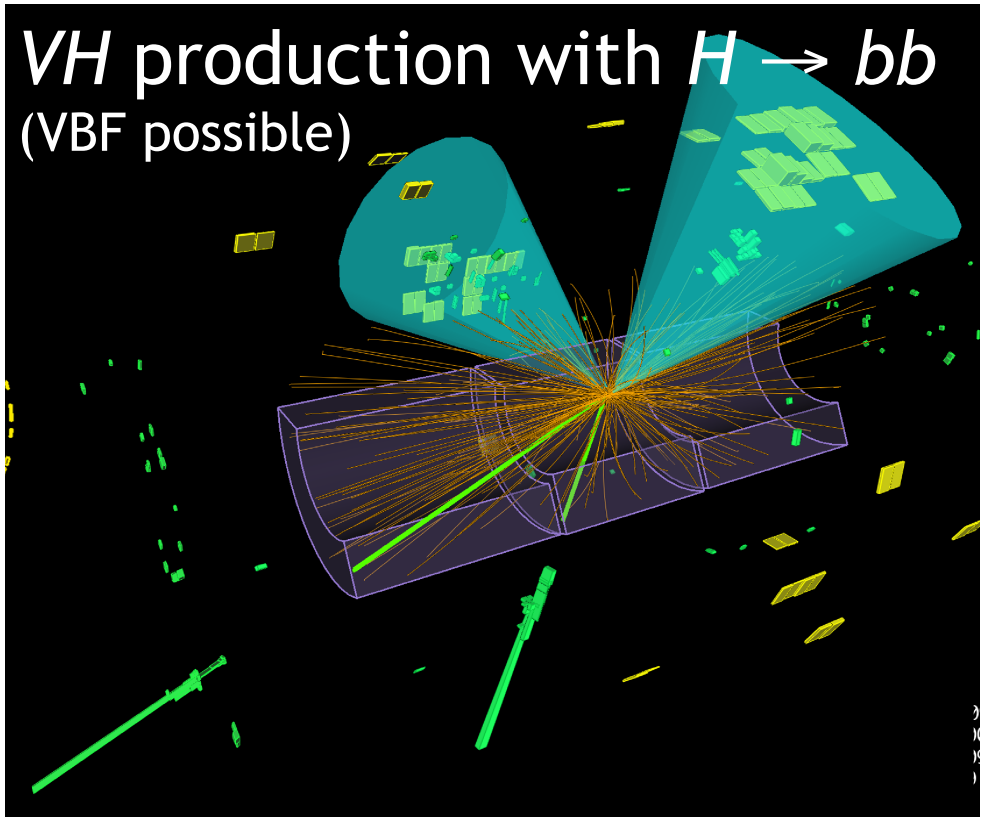
Tagging b-jets

Performant tagging algorithms using the impact parameter andreconstructed secondary vertex information. Only one quick (important) comment:

Challenge : Controlling the efficiency in data at high transverse momentum !



Cornering the b Yukawa Coupling

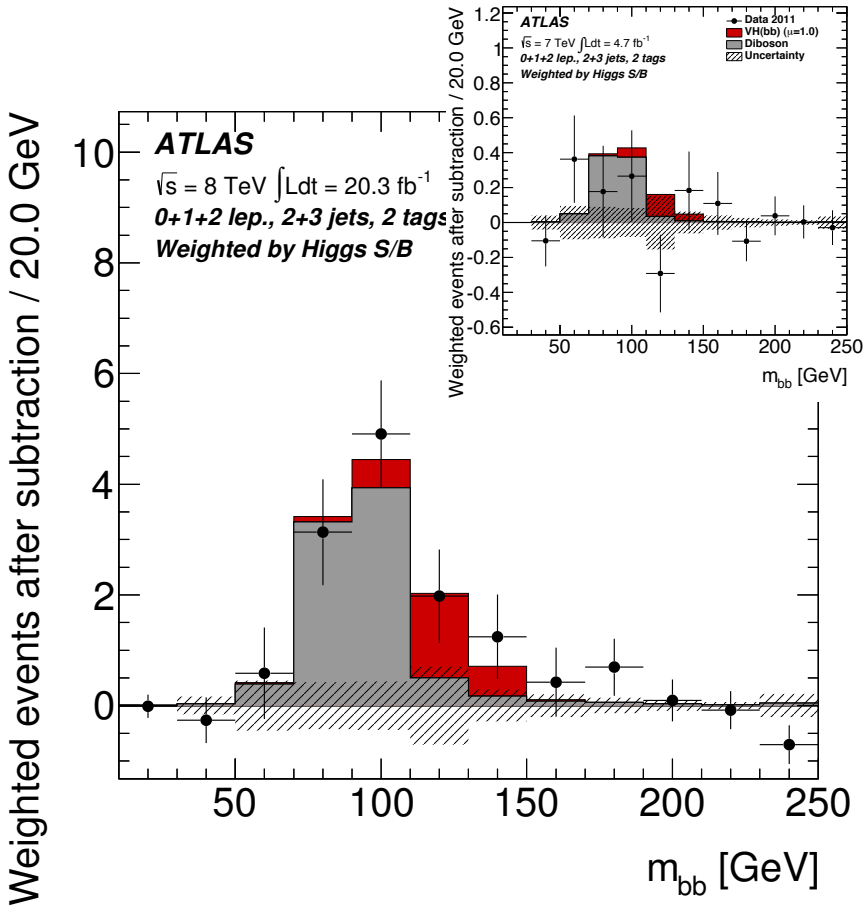


ATLAS

$$Z = 1.4\ (2.6)\ \sigma$$

CMS

$$Z = 2.1\ (2.1)\ \sigma$$

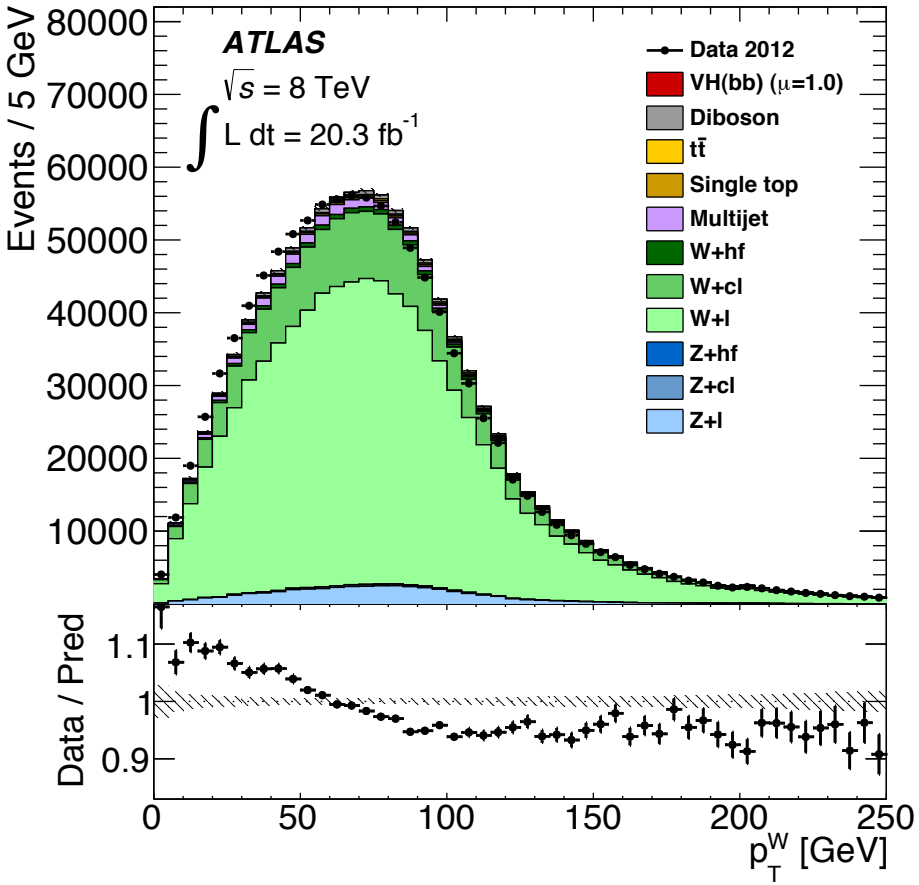


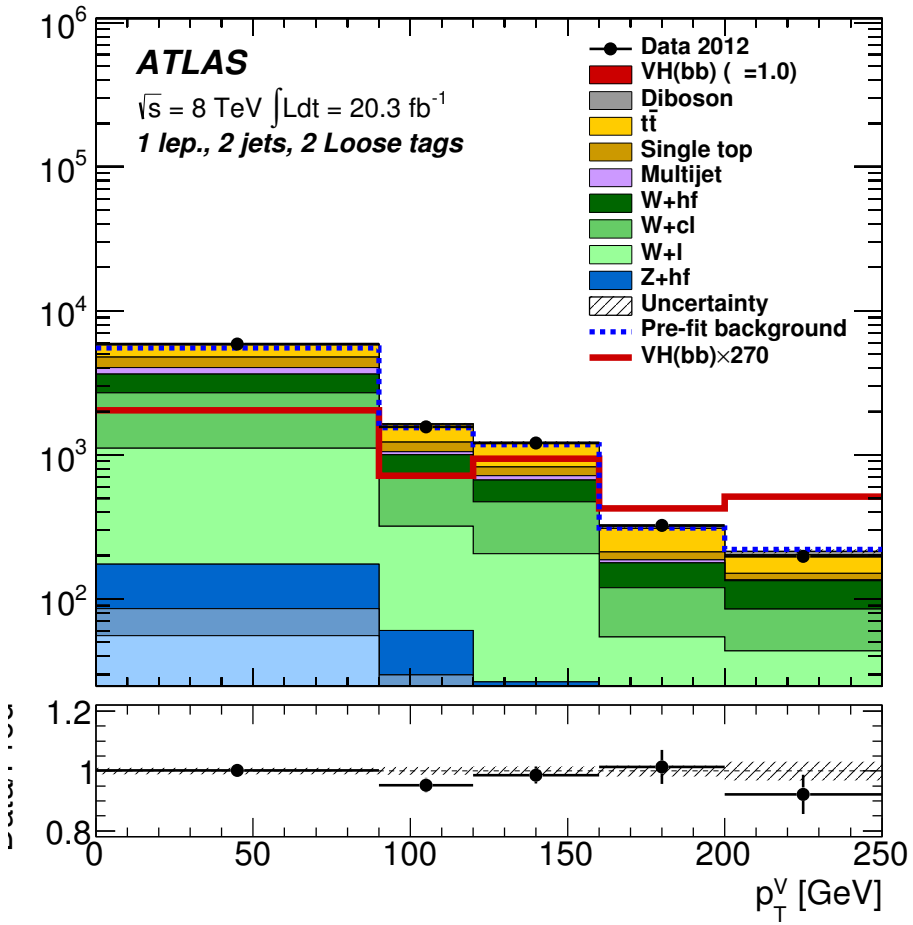
- Analysis using the boost (without substructure)
- Moderate s/b ratio starting from approximately few percent to approximately 30%

Tevatron: $\mu = 1.6 \pm 0.7$ (~2.3 sigma)

Boosted Analyses (without substructure)

Simulation of pT (V) is critical





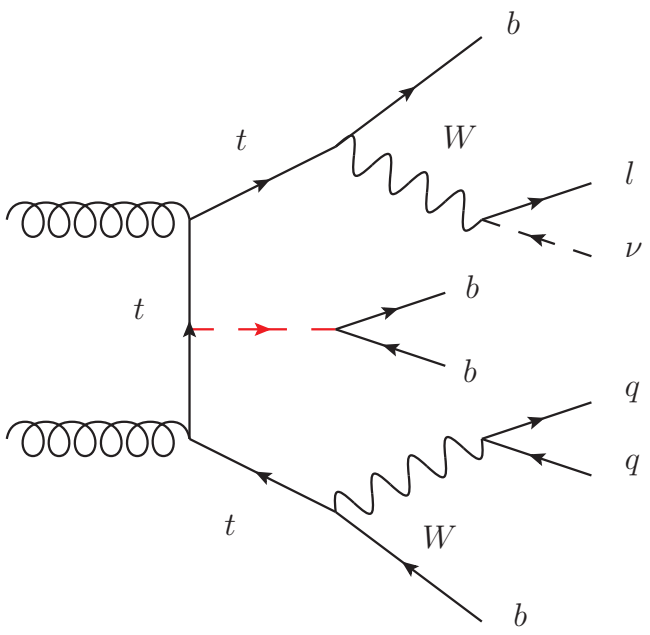
Our precision will initially rely significantly on the simulation,
will move to state-of-the-art MC for Run-2

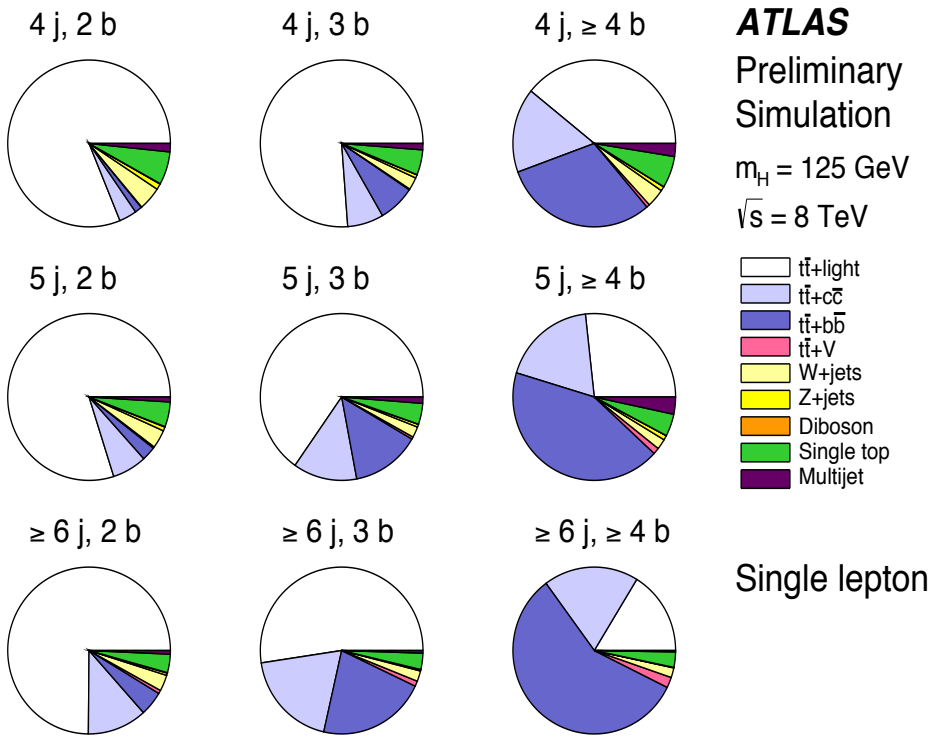
Cornering (directly) the top Yukawa coupling

Analysis strategy

- 2 channels t(lvb)t(qqb)H(bb) and t(lvb)t(lvb)H(bb)
- Challenging tt+jets background…
- tt+jets and tt+HF tamed

$$ttH(bb)$$





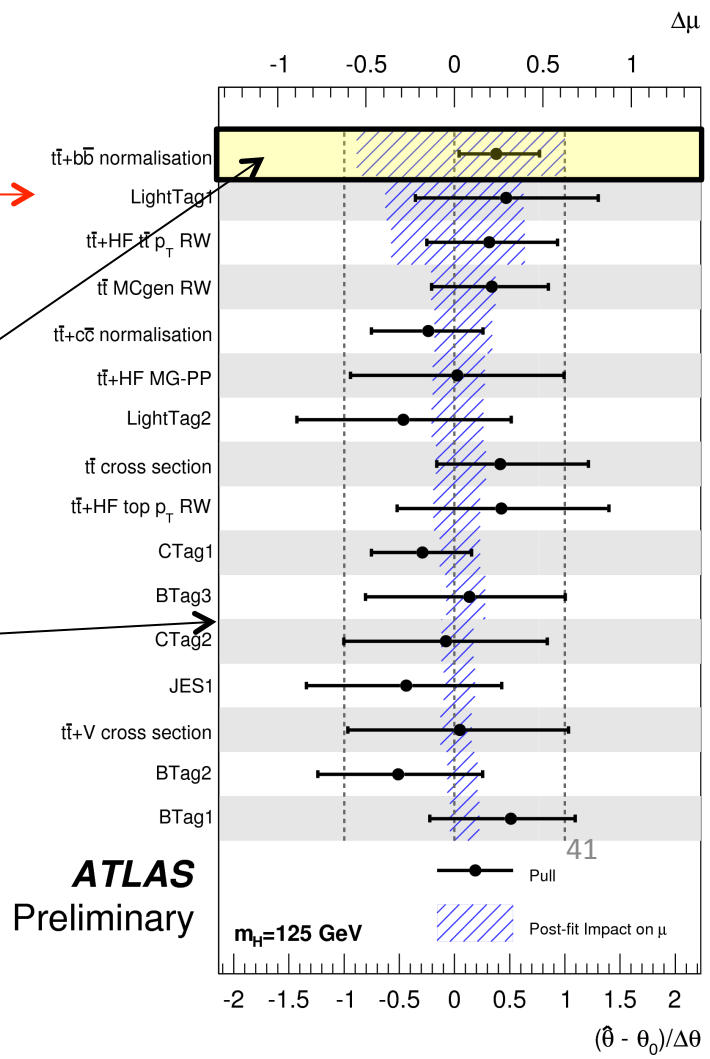
Profiling Paradigm: why it matters ?

	5 jets, ≥ 4 b-tags	≥ 6 jets, 3 b-tags	≥ 6 jets, ≥ 4 b-tags
$t\bar{t}H$ (125)	$11 \pm 1 \pm 9$	$69 \pm 3 \pm 57$	$28 \pm 2 \pm 23$
$t\bar{t}$+ light	78 ± 9	2380 ± 130	78 ± 11
$t\bar{t} + c\bar{c}$	45 ± 12	750 ± 190	75 ± 19
$t\bar{t} + b\bar{b}$	149 ± 20	1160 ± 170	300 ± 40
$t\bar{t} + V$	3.3 ± 1.0	44 ± 13	8.9 ± 2.7
non-$t\bar{t}$	23.2 ± 2.5	218 ± 23	18.8 ± 2.2
Total	309 ± 11	4620 ± 80	507 ± 27
Data	283	4671	516

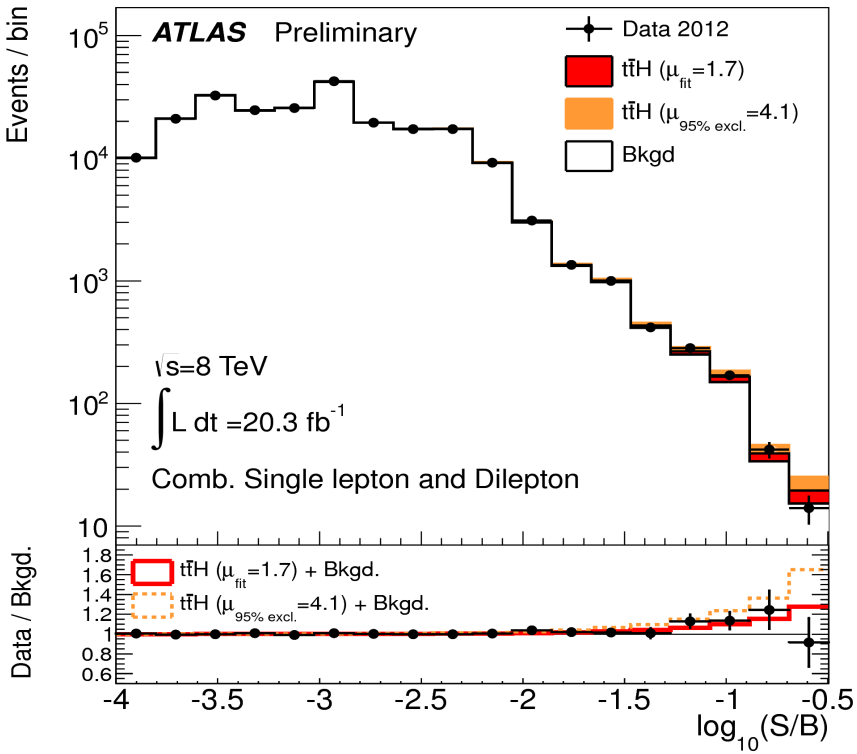
Light rejection crucial

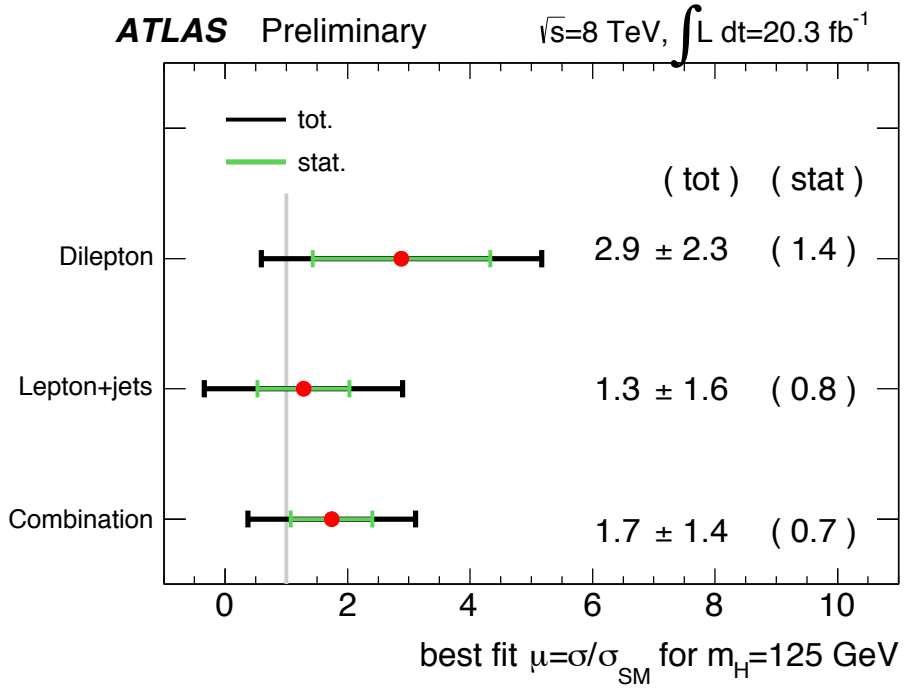
13%

Irreducible not critical



Cornering (directly) the top Yukawa coupling





$ttH(bb)$

Cornering the top Yukawa coupling

$t(t)H(\gamma\gamma)$

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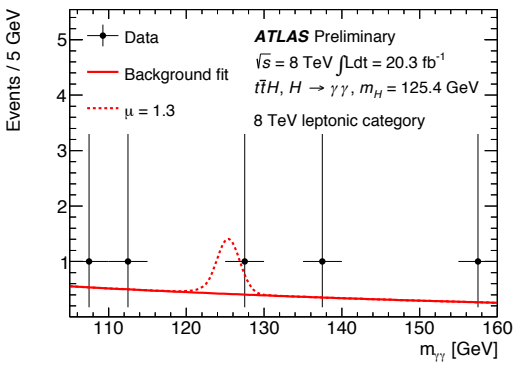
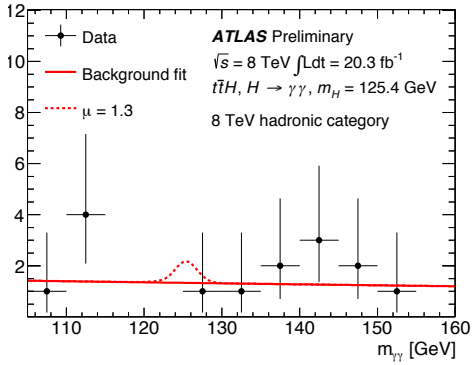
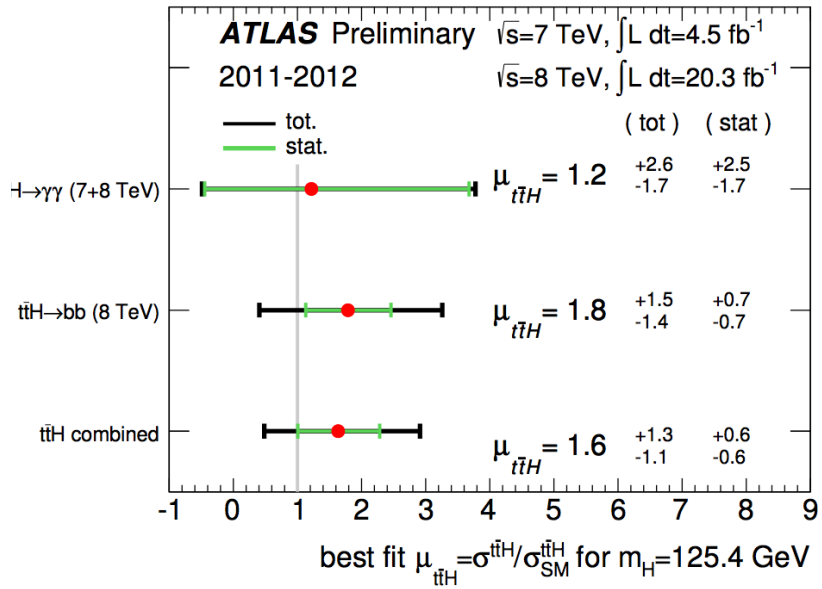
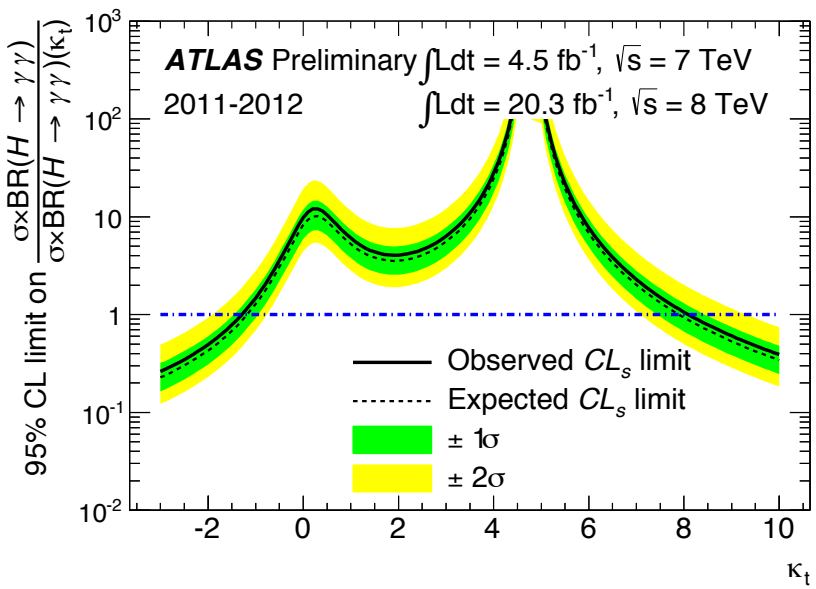
Leptonic channel



Hadronic channel



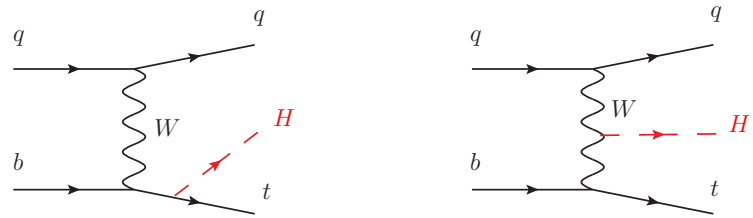




Analysis reinterpretation

Inclusive γγ limit from process assuming $\kappa_W = 1$

tH contribution at negative κ_t



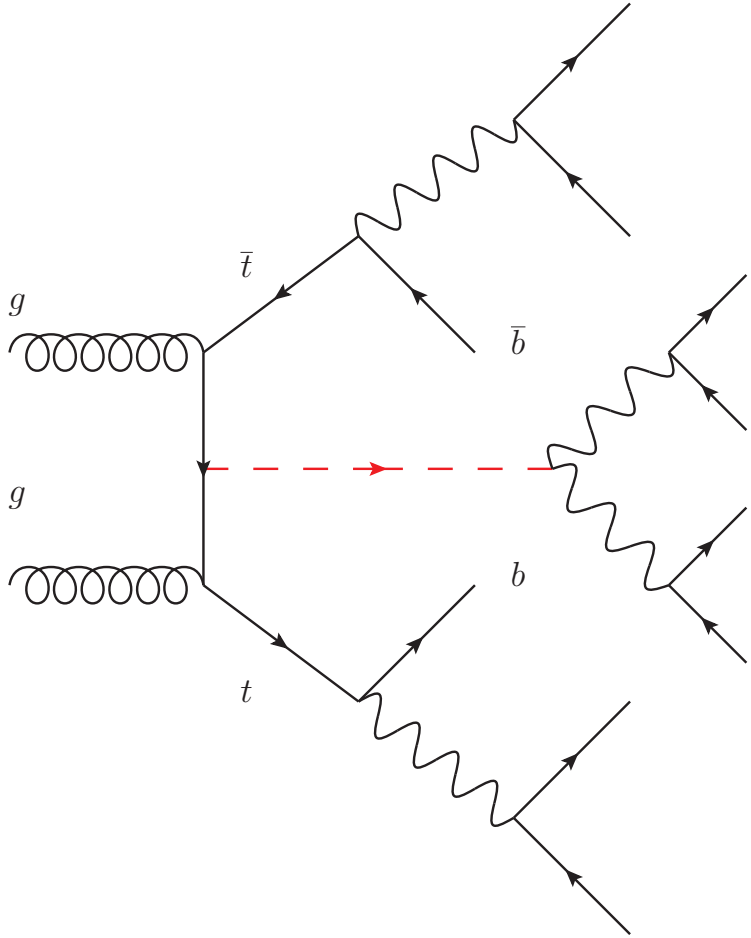
$$\propto 3.3\times\kappa_W^2 - 5.1\times\kappa_t\kappa_W + 2.8\times\kappa_t^2$$

95% CL exclusion $]-\infty,1.3]\cup[8.1,+\infty[$ $(]-\infty,1.2]\cup[7.9,+\infty[)$

Cornering (directly) the top Yukawa coupling

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

$$ttH(ML)$$

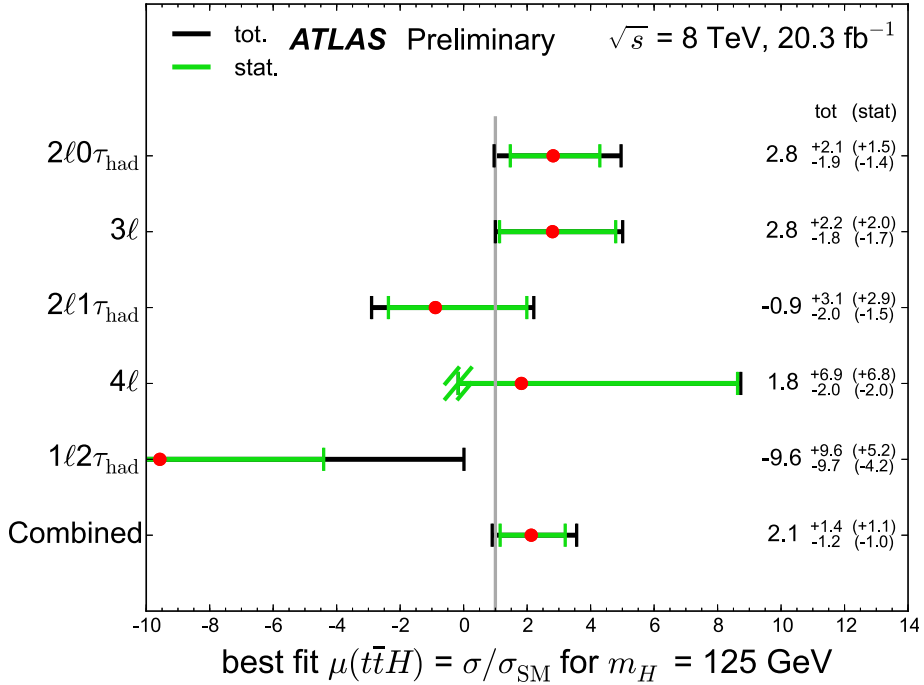


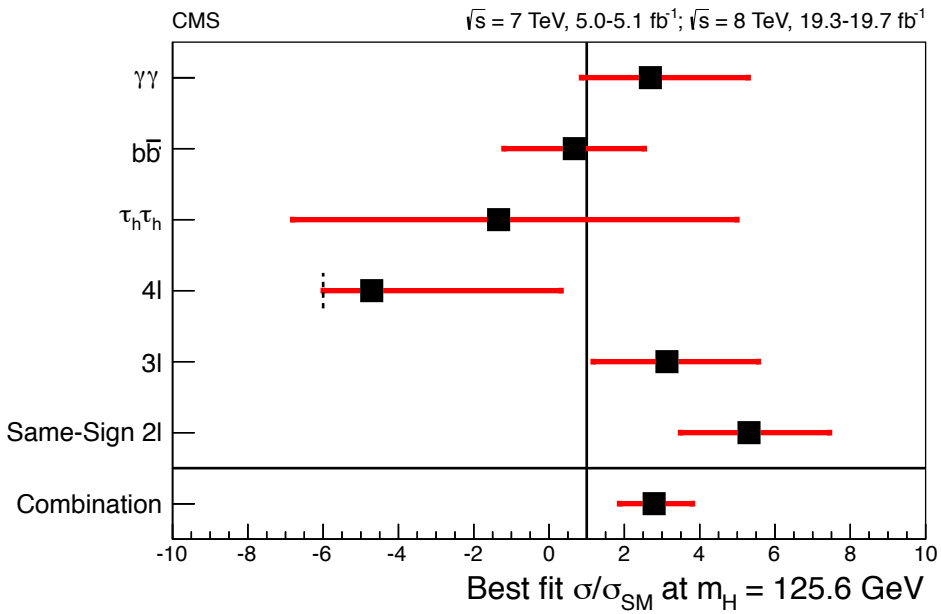
- Uses decays of W's and taus
- Essentially 4W's and 2b's in the final state
- All possible combinations

Cornering (directly) the top Yukawa coupling

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

$$ttH(ML)$$





$$2.9^{+1.1}_{-0.9} \qquad Z = 2.1\sigma$$

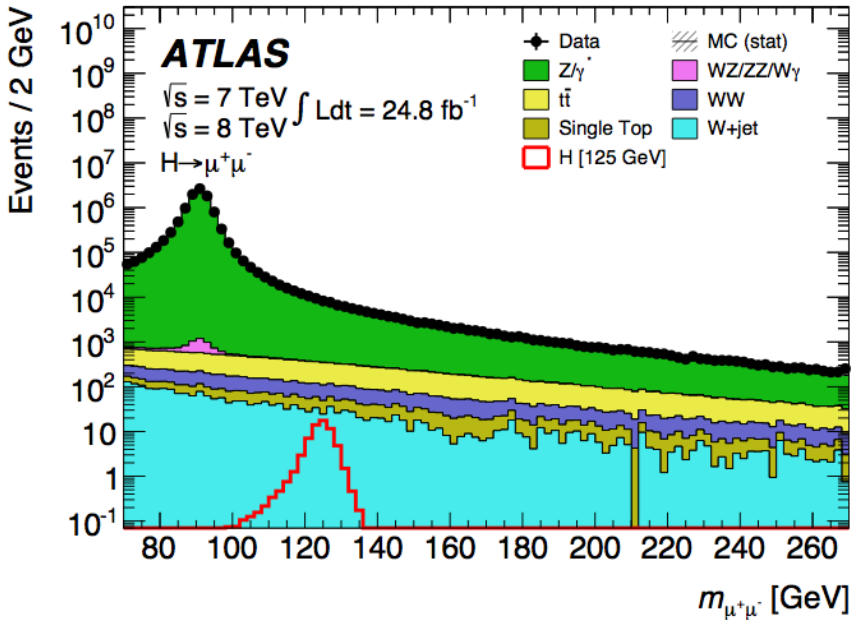
From SM

- Analysis much more vulnerable to irreducible ttV background
- Determination of fakes is delicate and important
- An excess is observed in both experiments in the SS 2-leptons channel

Back of the enveloppe: $2.3^{+0.7}_{-0.6}$ (Still roughly 2 sigma high)

Rare Decays and Rare Production modes

Rare Decays

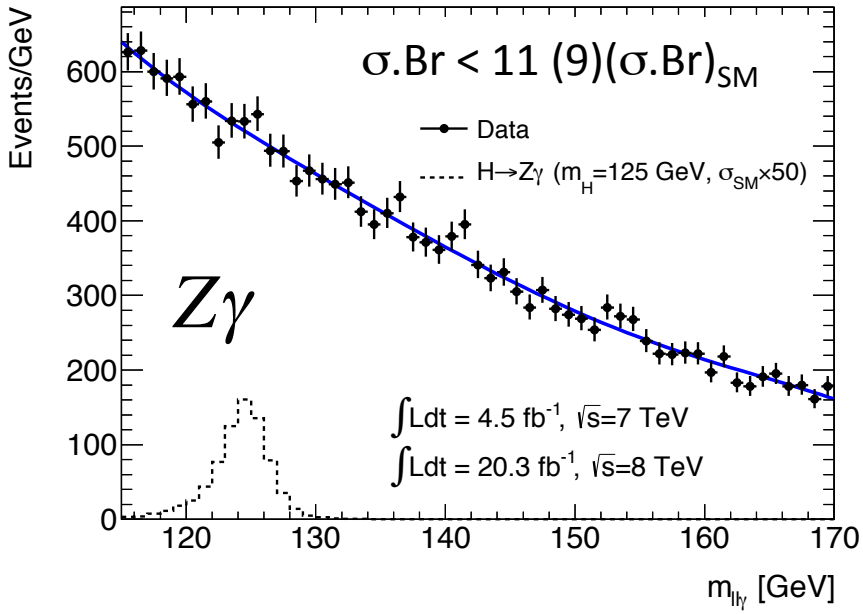


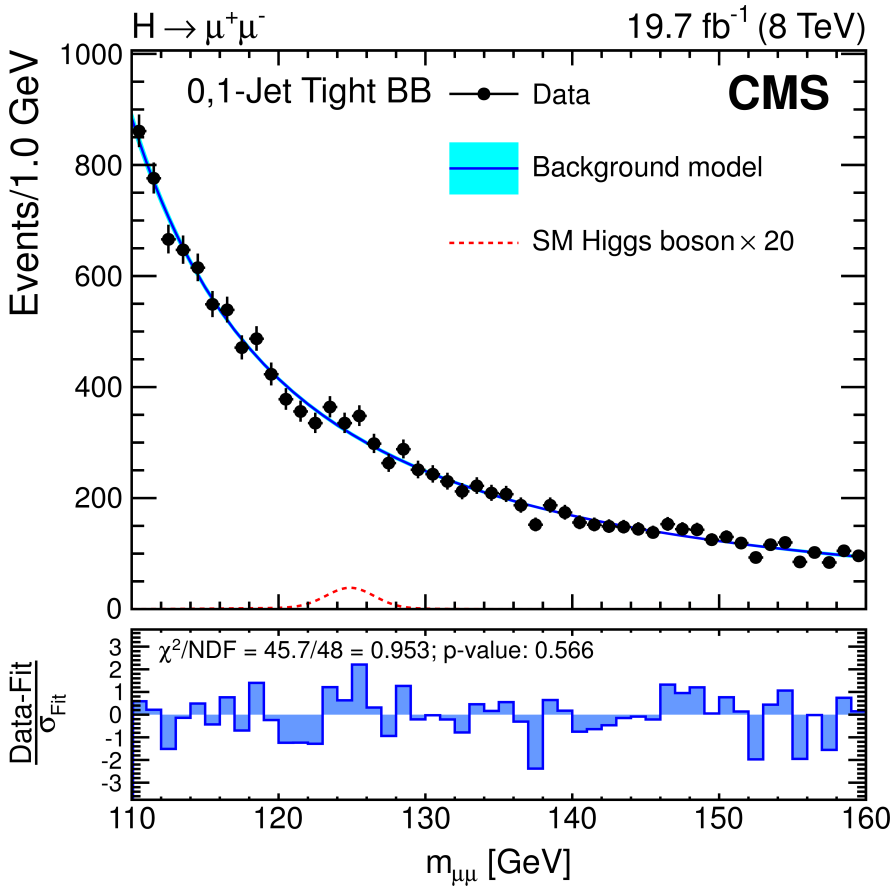
$\mu^+\mu^-$

$\sigma.Br < 7.0\ (7.2)(\sigma.Br)_{SM}$

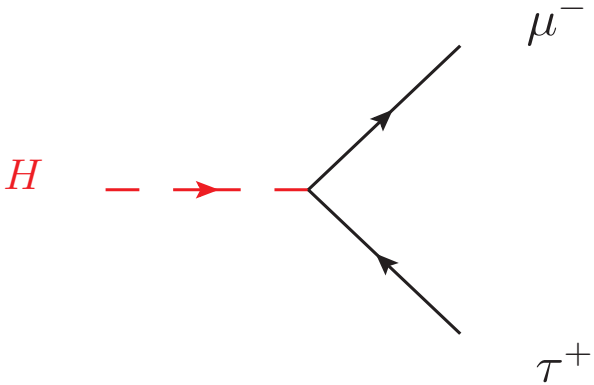
Universal couplings
~260 times SM

e^+e^- $\sigma.Br < 3.7\ 10^5\ (\sigma.Br)_{SM}$





LFV Decays of the Higgs boson

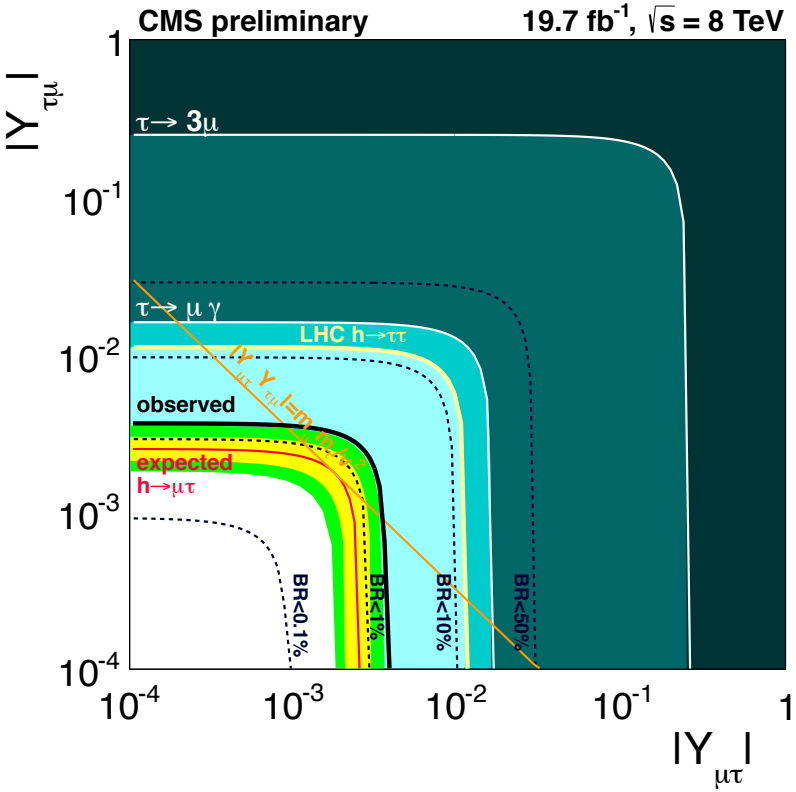


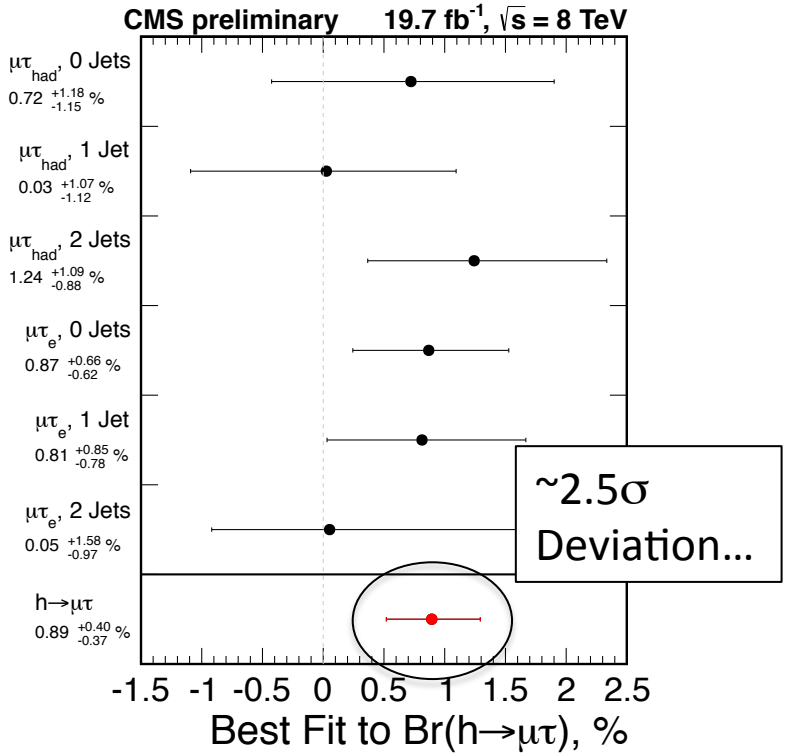
Strong Constraints on $Br(H \to e\mu) < O(10^{-8})$

from $\mu \to e\gamma$

Less on $Br(H \to \tau\mu)$

Observed limit: 1.6% (0.7% expected)

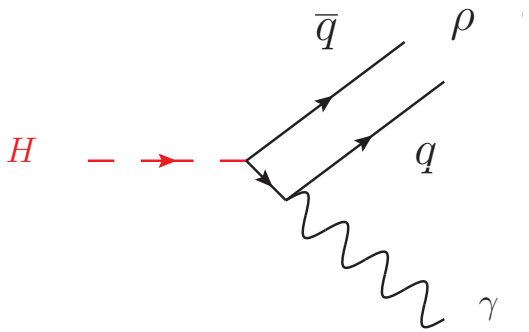




~2.5σ Deviation…

Sensitivity to Light Quark Modes?

Decays to a Meson and a photon



Final State

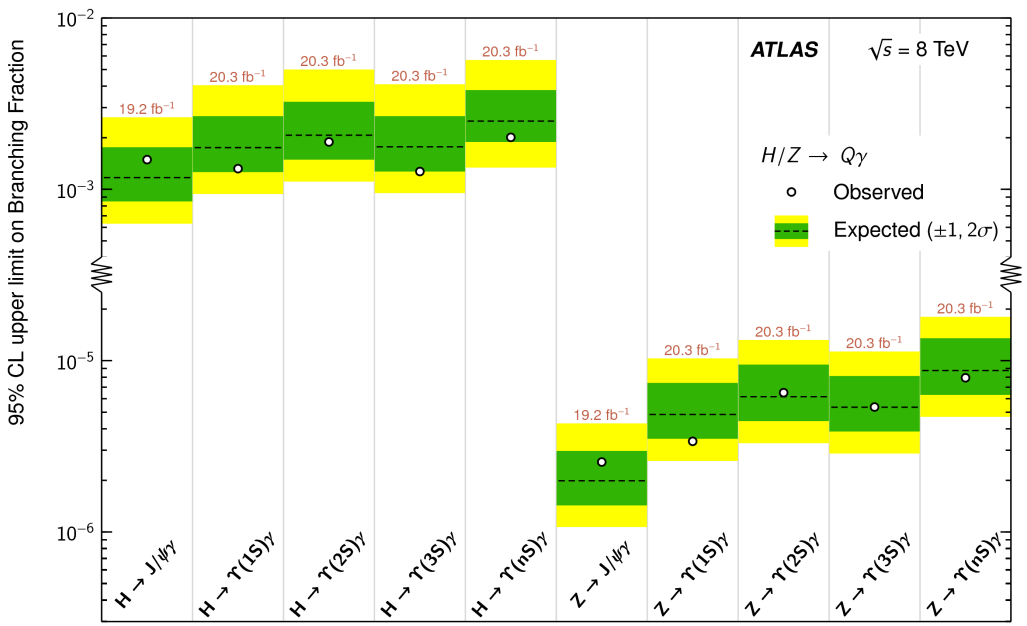
$$\pi^+\pi^-\gamma$$

Potentially sensitive to strange Yukawa

$$\Gamma \sim \left|11.9 - 1.04\kappa_c\right|^2$$

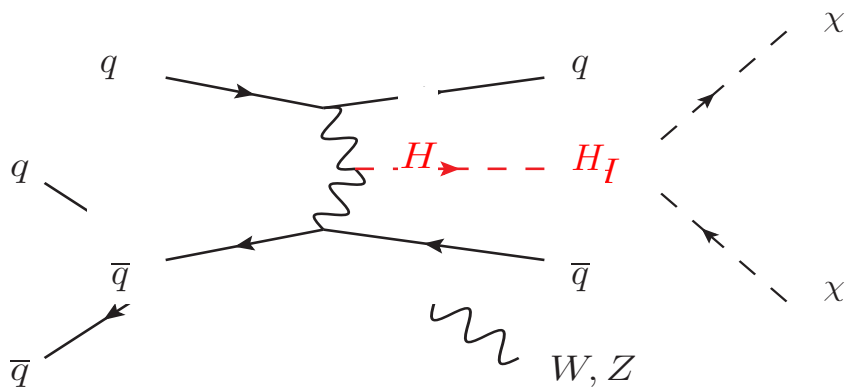
Current limit more than one order of magnitude away.

Current limit more than one order of magnitude away.



Invisible Decays

Very small expected SM signal

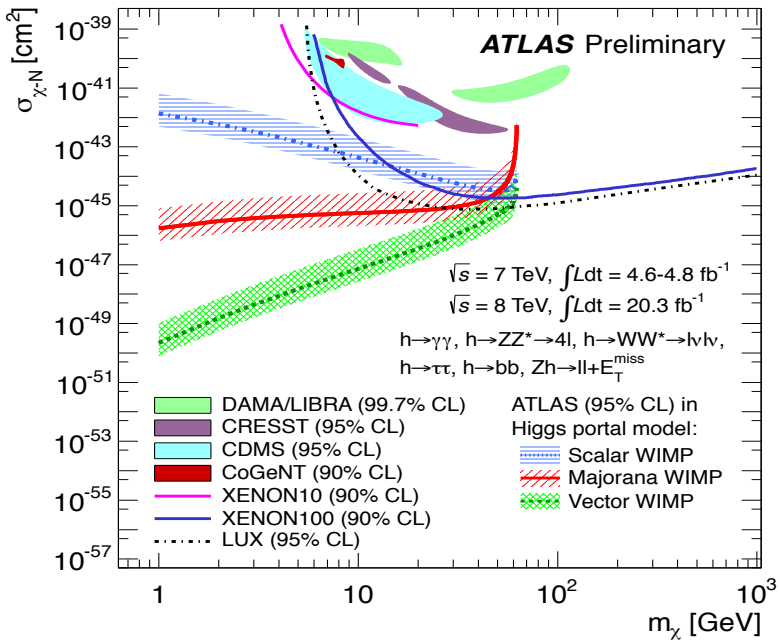


$$Br(H \rightarrow invisible)$$

VH Production
Observed limit 95% CL: approximately **60%**

VBF Production
Observed limit 95% CL: approximately **30%**

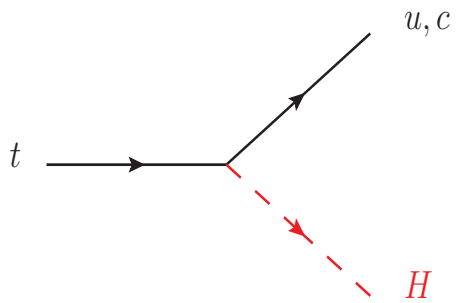
Indirect limit from standard combination (assuming Standard couplings to Standard fields)
Observed limit 95% CL: approximately **30%**



Searches sensitive to Dark Matter
(if it couples to the Higgs boson
and if it is light enough)

Rare Production Modes

Flavor changing neutral curent decays of the top quark



Various decay channels of the Higgs boson (gg, bb)

Limits on $Br(t \to Hq)$

SM Branching ~10^{-15}

$$Br(t \to cH) < 0.79\ (0.51)\%$$

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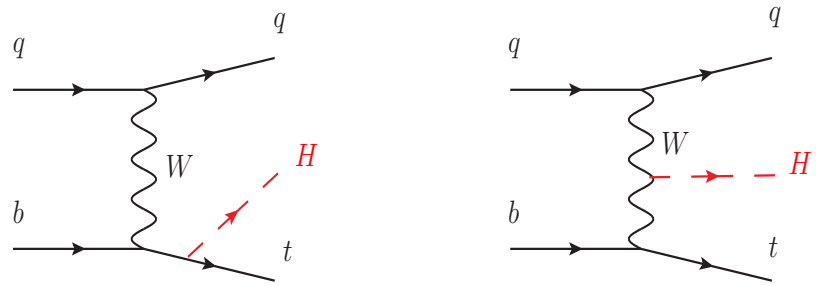
Single top associated production

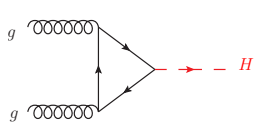
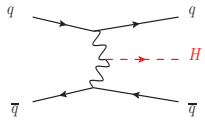
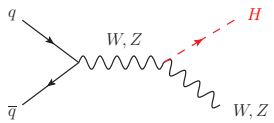
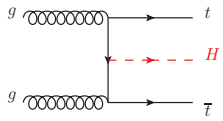
Tree level interference between W and top



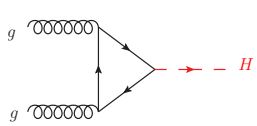
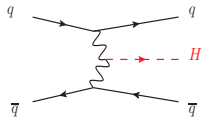
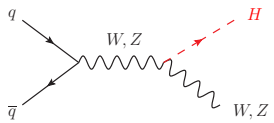
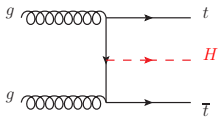
$$\propto 3.3 \times \kappa_W^2 - 5.1 \times \kappa_t \kappa_W + 2.8 \times \kappa_t^2$$

Allows to further constrain the top Yukawa coupling, in particular to exclude a negative relative sign

Putting All Channels Together

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

The Observed Part of the Landscape

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
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ττ	✓	✓	✓	✓
bb		✓	✓	✓
Zγ and γγ*	✓	✓		
μμ and ee	✓	✓		
Invisible	✓ (monojet)	✓	✓	

μ

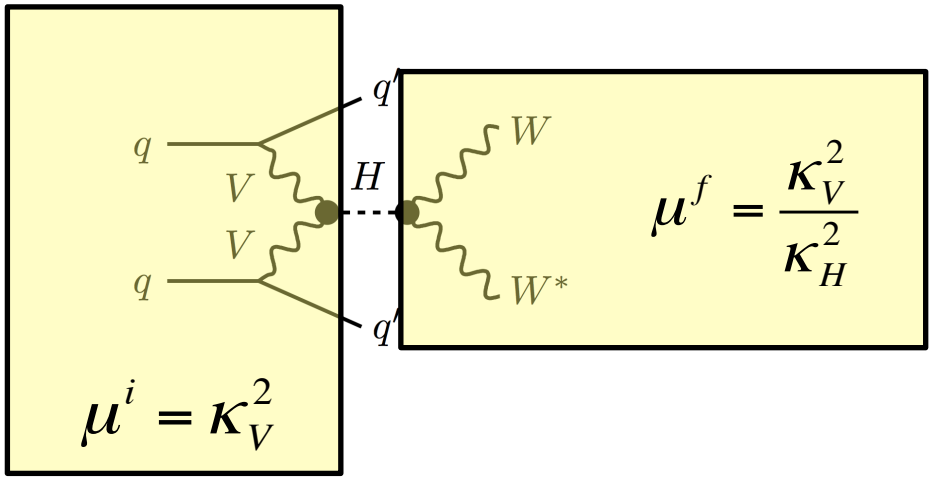
Combination Master Formula

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

$$n_s^c = \mu \sum_{i \in \{productions\}} \sum_{f \in \{decays\}} \mu^i \sigma_{SM}^i \times \mathrm{A}^{ifc} \times \varepsilon^{ifc} \times \mu^f Br^f \times L^c$$

Naïve interpretation, simple example, VBF production in the WW decay channel:

κ

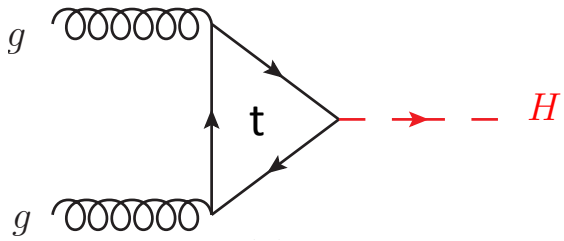


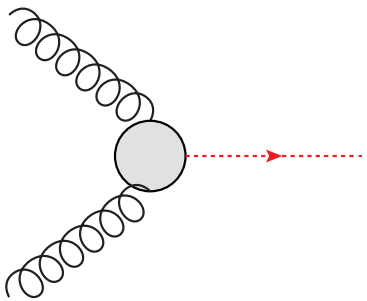
$$\kappa_H^2 = \frac{\sum_f \Gamma_f}{\Gamma_{SM}} = \underbrace{0.75 \times \kappa_F^2 + 0.25 \times \kappa_V^2}_{\text{Assuming no BSM width}}$$

Two fundamental options:

1.- Allow BSM fields in the decay: κ_H free parameter (typically cannot constrain the couplings to SM particles in this case)

2.- Allow BSM particles in the loops or resolve the loops assuming SM fields only



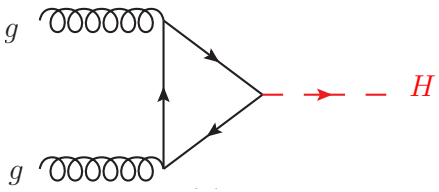


$$\kappa_g^2 \propto 1.\times 06\kappa_t^2 - 0.07 \times \kappa_t \kappa_b + 0.01 \times \kappa_b^2$$

$$\kappa_g^2$$

Higgs Production Modes

κ for m_H = 125.5 GeV

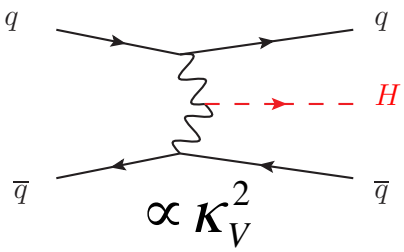


Gluon fusion process

NNnLO ~O(10%)

~0.5 M events produced

$$\kappa_g^2 \propto 1.\times 06\kappa_t^2 - 0.07\times\kappa_t\kappa_b + 0.01\times\kappa_b^2$$

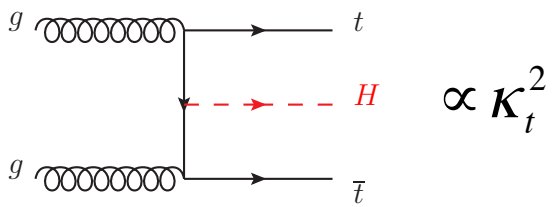


Vector Boson Fusion

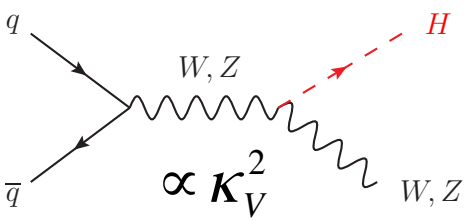
NNLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap

~40 k events produced



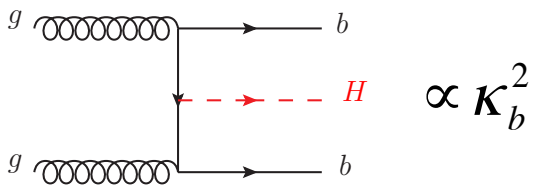
Top Assoc. Prod. ~3 k evts produced



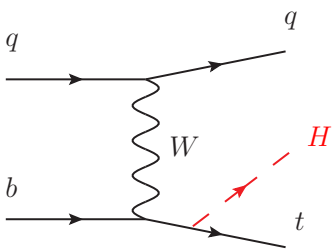
W and Z Associated Production

NNLO TH uncertainty ~O(5%)

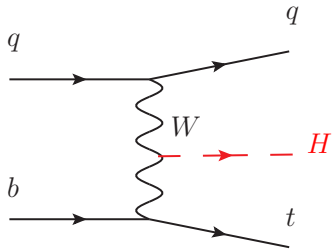
~20 k events produced



B-quark Assoc. Prod. ~5 k evts produced



tH

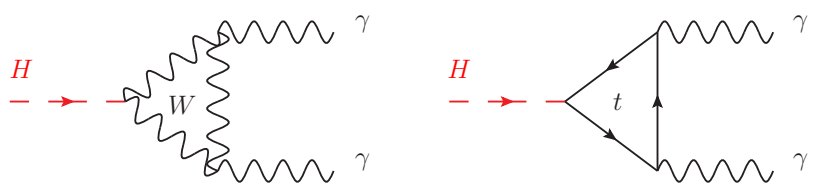


$$\propto 3.3\times\kappa_W^2 - 5.1\times\kappa_t\kappa_W + 2.8\times\kappa_t^2$$

And more e.g. gg to VH…

Higgs Decay Channels

- Dominant: bb (57%) $\propto \kappa_b^2 / \kappa_H^2$
- WW channel (22%) $\propto \kappa_W^2 / \kappa_H^2$
- ττ channel (6.3%) $\propto \kappa_\tau^2 / \kappa_H^2$
- The μμ channel (0.02%) $\propto \kappa_\mu^2 / \kappa_H^2$
- ZZ channel (3%) $\propto \kappa_Z^2 / \kappa_H^2$
- cc channel (3%) $\propto \kappa_c^2 / \kappa_H^2$
  Extremely difficult
- The γγ channel (0.2%) $\propto \kappa_\gamma^2 / \kappa_H^2$



$$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

(when assuming no BSM charged in the loop)

- The Zg (0.2%) $\kappa_{Z\gamma} \propto 1.12 \times \kappa_W^2 - 0.15 \times \kappa_t \kappa_W + 0.03 \times \kappa_t^2$

Overall Signal Strengths

Probing Consistency with Standard Model Higgs

ATLAS

$$\mu = 1.18 \pm 0.10\,(stat)\,^{+0.08}_{-0.07}\,(th) \pm 0.07\,(syst)$$

CMS

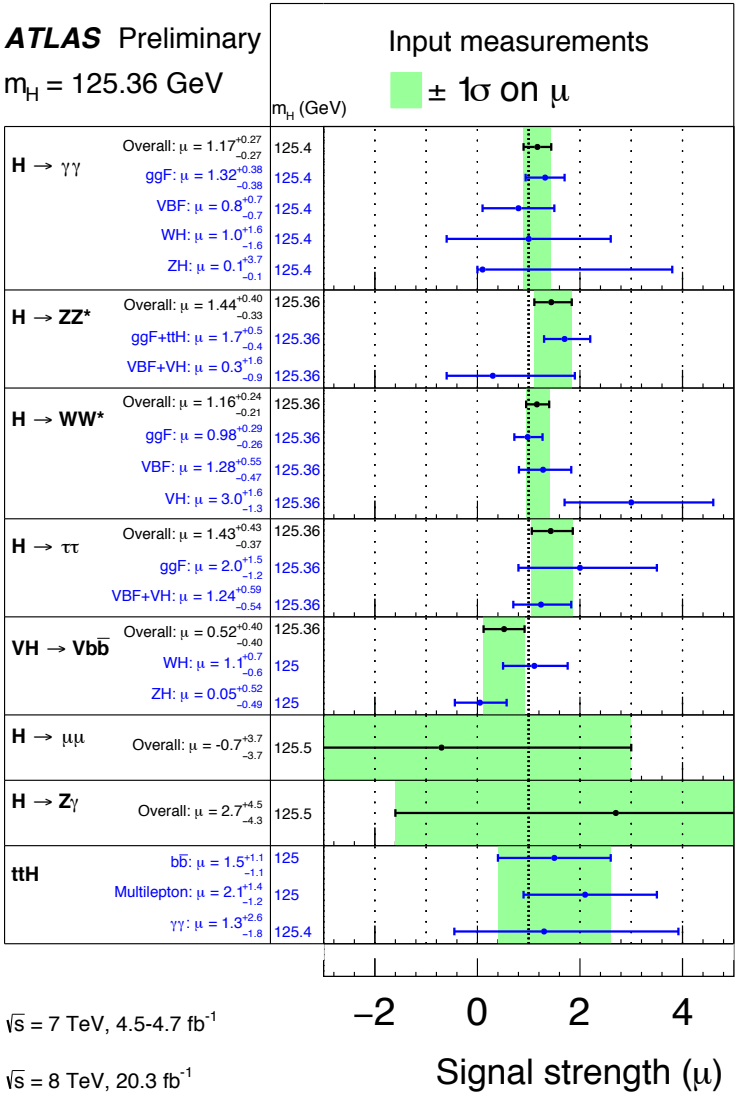
$$\mu = 1.00 \pm 0.09\,(stat)\,^{+0.08}_{-0.07}\,(th) \pm 0.07\,(syst)$$

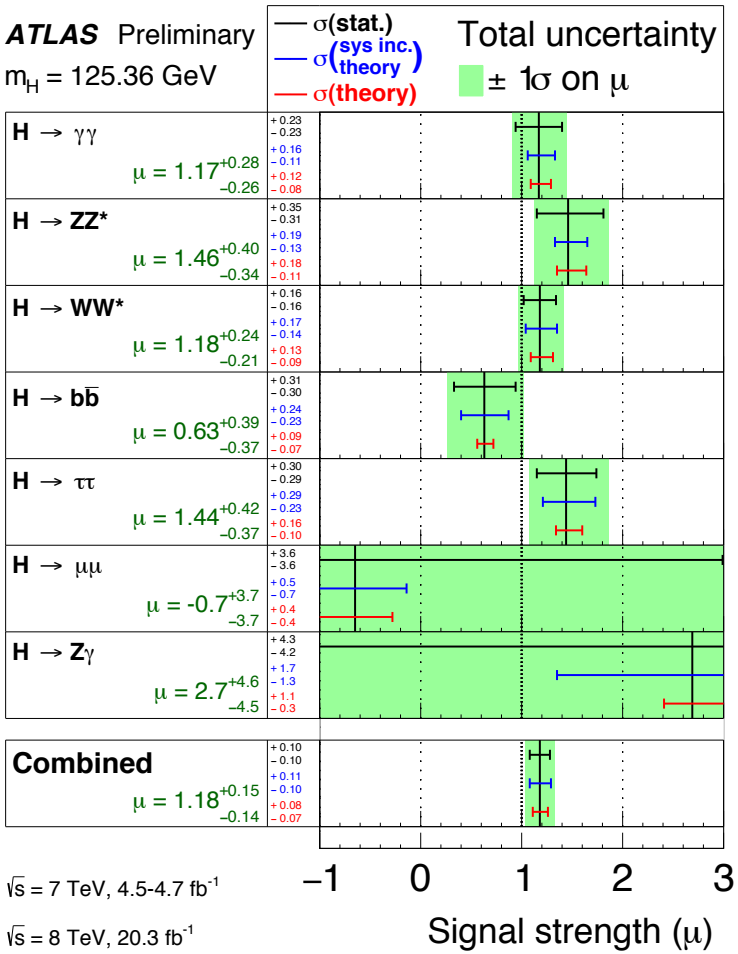
Strengths in the Main Categories

Independent fit of each channel

$$n_s^c = \mu\left(\sum_{i\in\{processes\}} \mu^i \sigma^i_{SM} \times A^{ic} \times \varepsilon^{ic}\right) \times \mu^f Br^f \times L^c$$

Combination of all channels assuming SM production

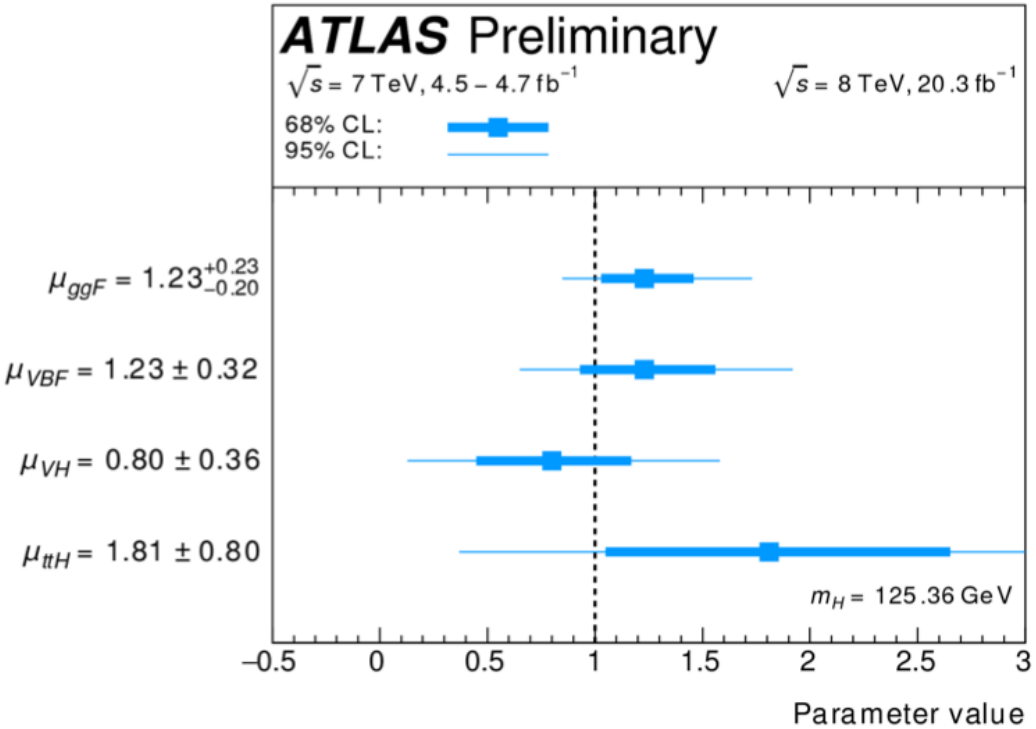


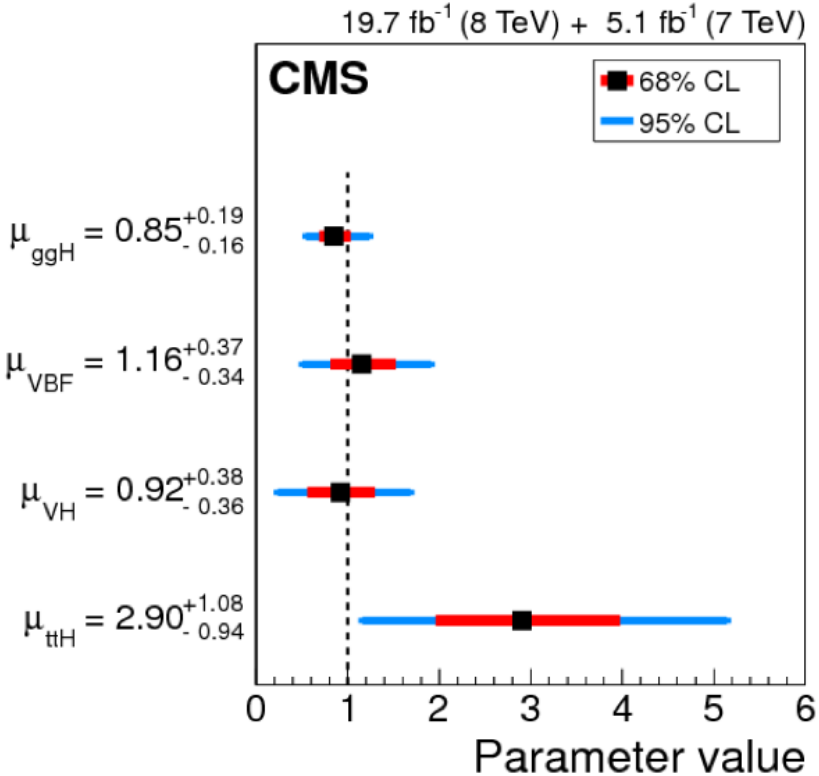


Production Strengths or Cross Sections

$$n_s^c = \mu\left(\sum_{i\in\{processes\}} \mu^i \sigma_{SM}^i \times \mathrm{A}^{ic} \times \varepsilon^{ic}\right) \times \mu^f Br^f \times L^c$$

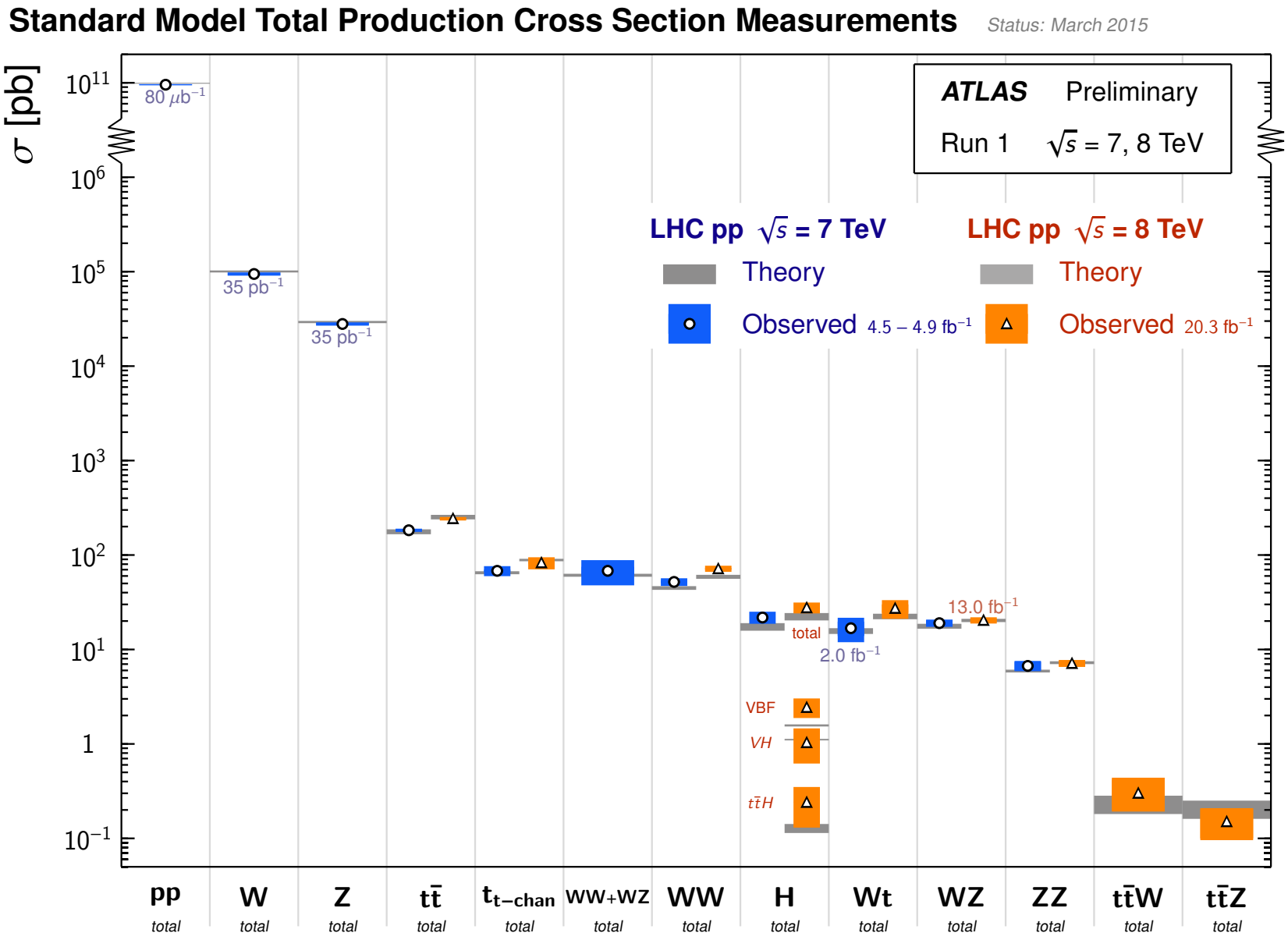
Combination of all channels assuming SM branchings





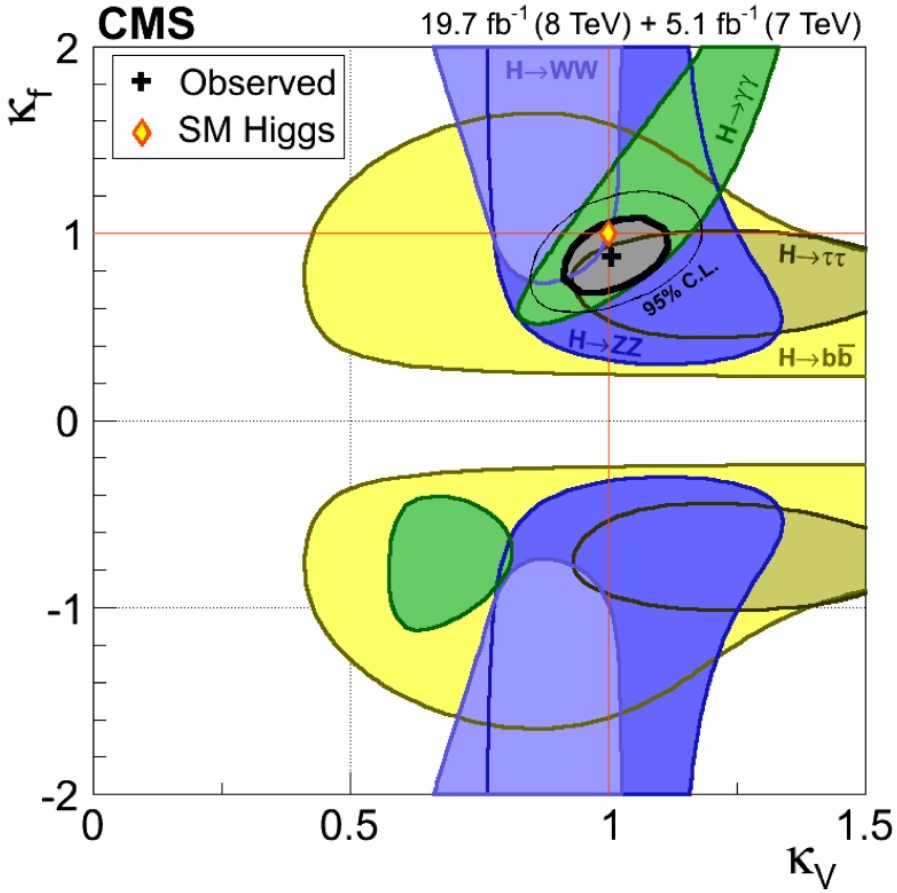
Clear evidence of production in the two main modes

Overview of Cross Sections



Coupling to SM Spectra with Assumptions

Assuming no BSM in the loops or in the decay,
testing couplings to SM particles



What are the assumptions?

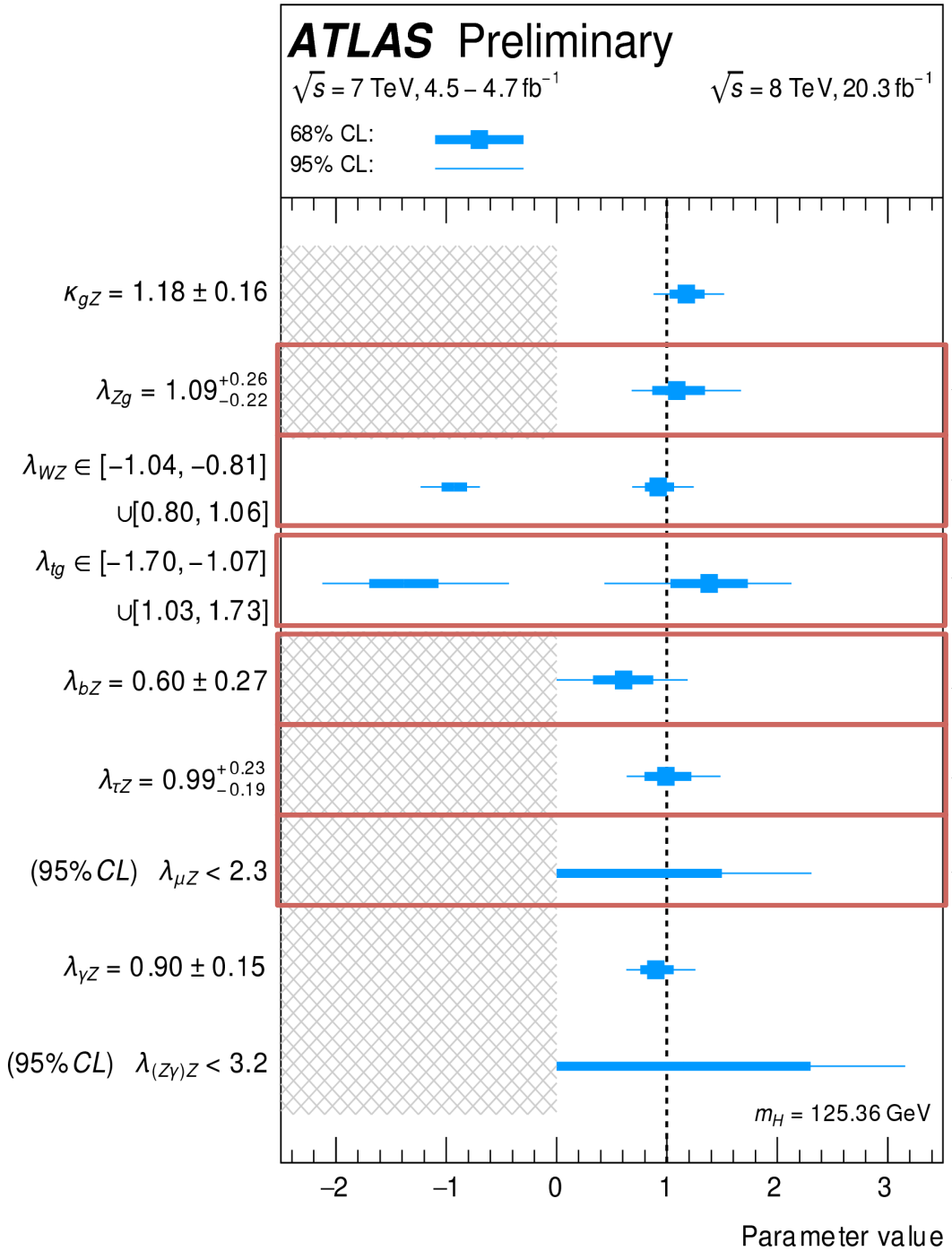
- No BSM width
- No BSM in the loops
- All boson couplings scaled equally
- All fermion couplings scaled equally

Measurements very compatible with SM hypothesis

Higgs Couplings

Most General Fit

(By definition independent of width and no assumption on the loops)



Direct coupling to the Z

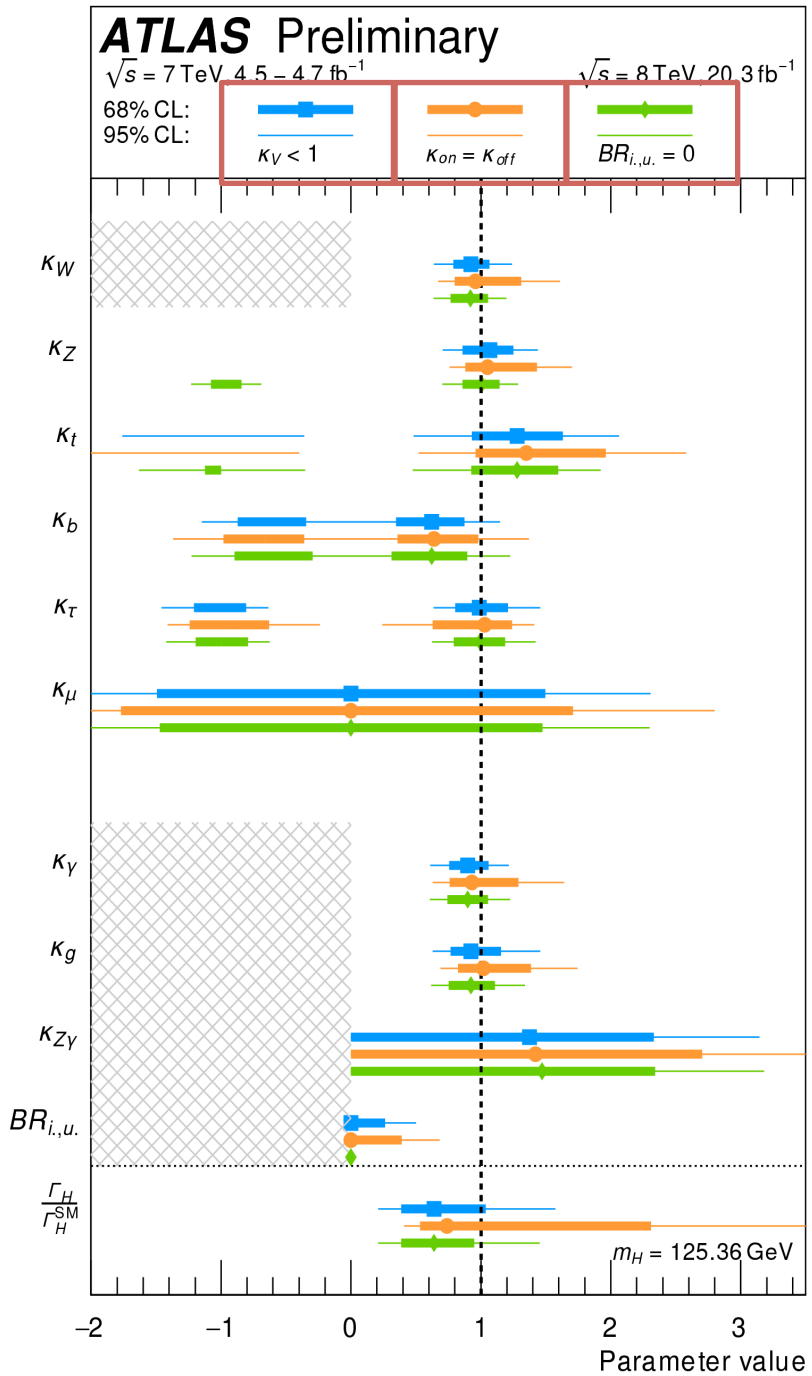
Custodial Symmetry

Direct coupling to the top
(through ttH production channels)

Direct coupling to b quarks
(Through mainly VH channels)

Direct copling to τ
(through VBF production)

Non-universality of Yukawa couplings



Higgs boson couplings

Absolute couplings measurements under specific conditions:

- Standard only width

- Unitarity constraint on the coupling to vector bosons

- Use of Off-shell couplings measurements*

*Requires constraint of equal OffShell and OnShell Higgs couplings

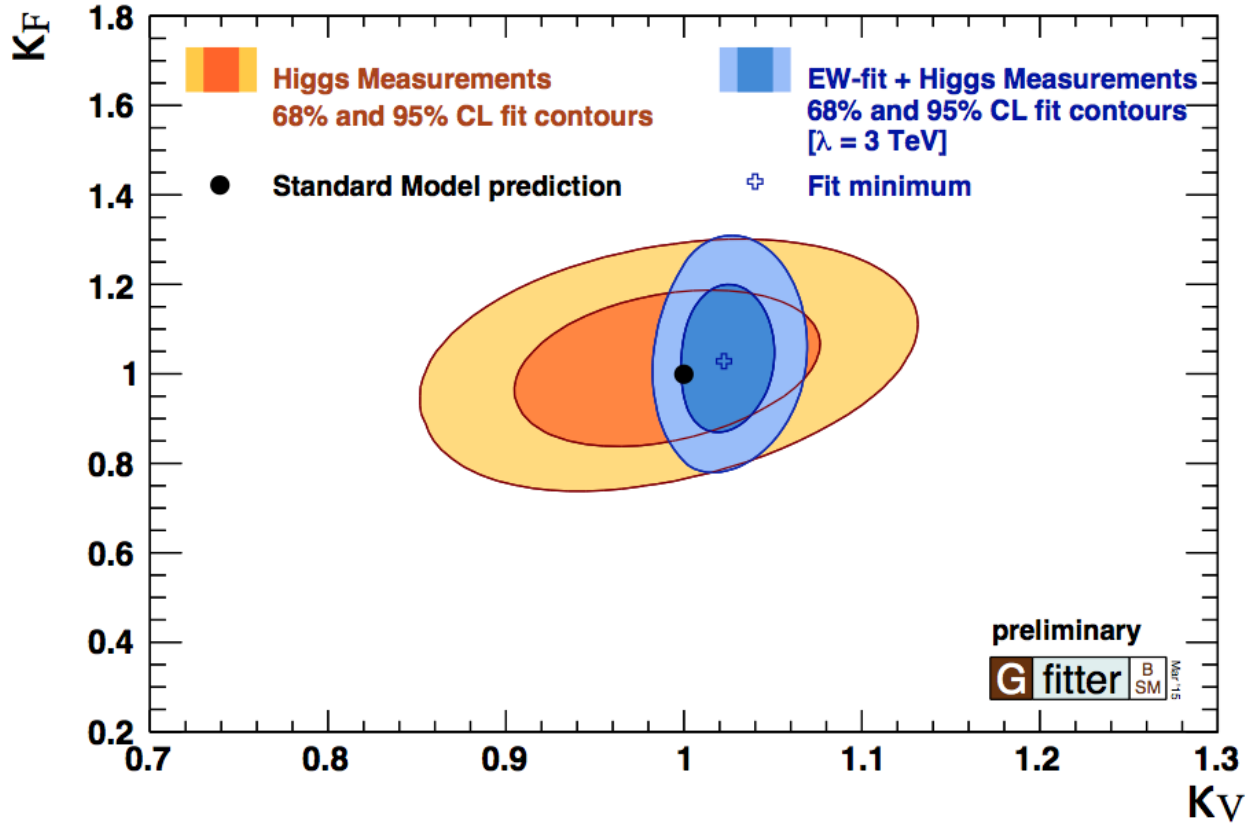
Taste of Combination (and More)

R. Kogler @ Moriond EW

Higgs coupling measurements:

- $\kappa_V = 0.99 \pm 0.08$
- $\kappa_F = 1.01 \pm 0.17$

- **Combined result:**
- $\kappa_V = 1.03 \pm 0.02$ ($\lambda = 3$ TeV) *1303.1812*
- implies NP-scale of $\Lambda \geq 13$ TeV



Taste of future programs using EFT (Still to be defined) to combine EW measurements, Higgs, top, dibosons, etc…

Summary

- A very vast new Higgs landscape
- A large amount of it already started to be investigated
- Still completely open for future investigation in quest for precision
- Emphasis: importance of theory input (for both the background and the signal predictions)
- All results very compatible with the Standard Model expectation…

But Where Is Everybody?

Nima Arkani Hamed