An (Early) Experimental Profile of the Higgs Boson

Summary of LHC Run 1 Higgs Results

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Outline

Introduction — *Run 1, the discovery and its implications*

Higgs physics with the discovery channels

- *The mass of the Higgs boson*
- *Differential cross sections*
- *Its main quantum numbers JPC*

Exploring the vast LHC potential

- Discovery in the fermionic channels
- Cornering the top Yukawa
- Rare decays

The Higgs Natural Width at the LHC and the Higgs as portal to Dark Matter

- Direct measurements of the width
- Width with interference
- Off shell couplings
- Invisible Higgs channels

Coupling properties of the Higgs boson

Prospects

Disclaimer

Many subjects will not be covered in detail, for a complete list of results from the ATLAS and CMS collaboration, please see:

ATLAS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

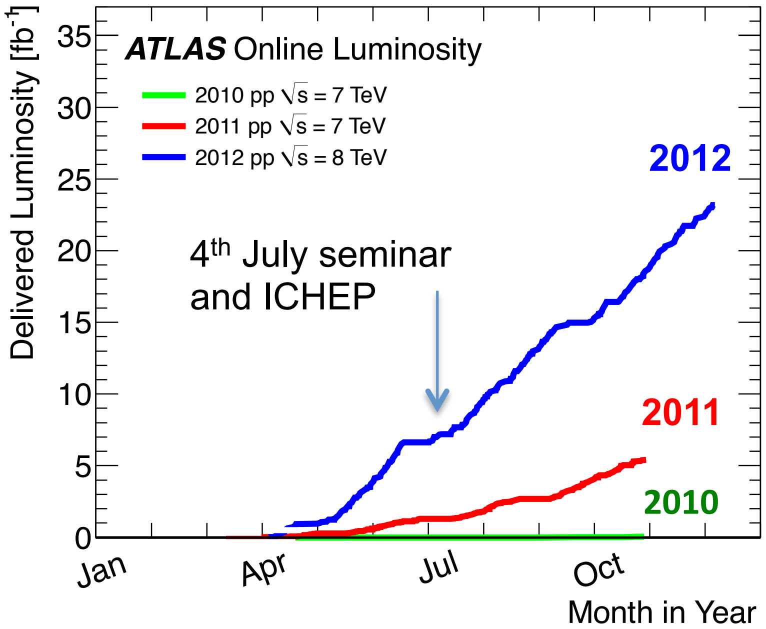
CMS

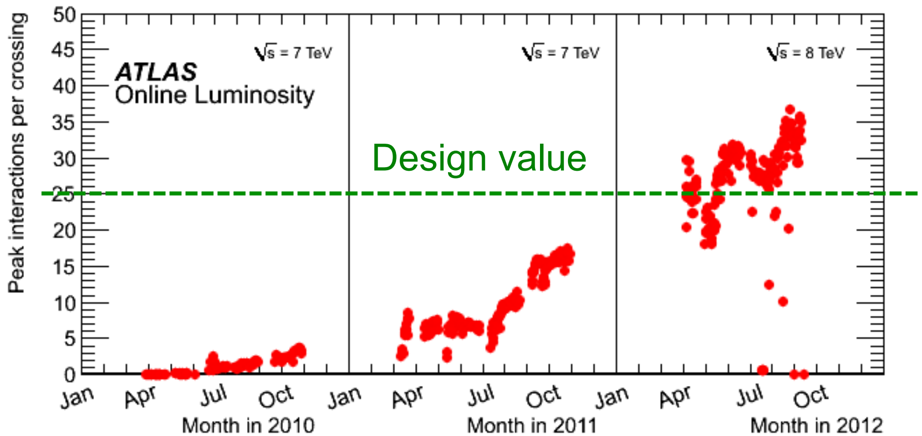
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Outline

Introduction	*Run 1, the discovery and its implications*

The LHC Run 1



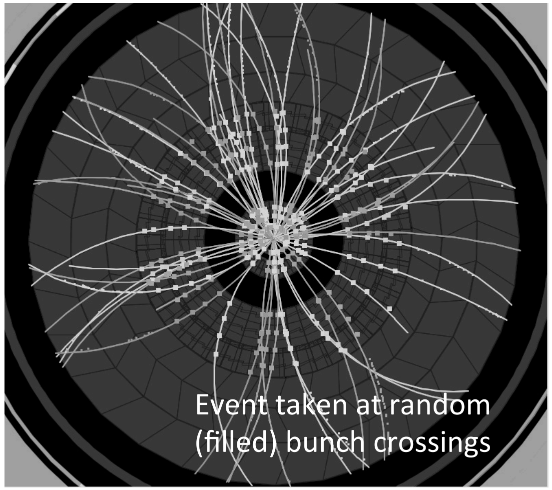


2010

0.05 fb^{-1} at 7 TeV

O(2) Pile-up events

150 ns inter-bunch spacing

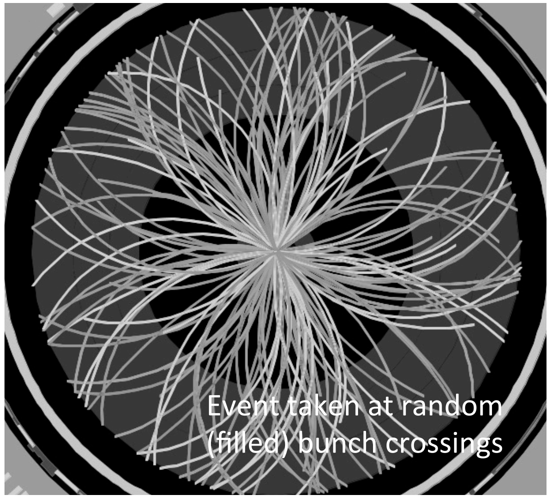


2011

~ 5 fb^{-1} at 7 TeV

O(10) Pile-up events

50 ns inter-bunch spacing

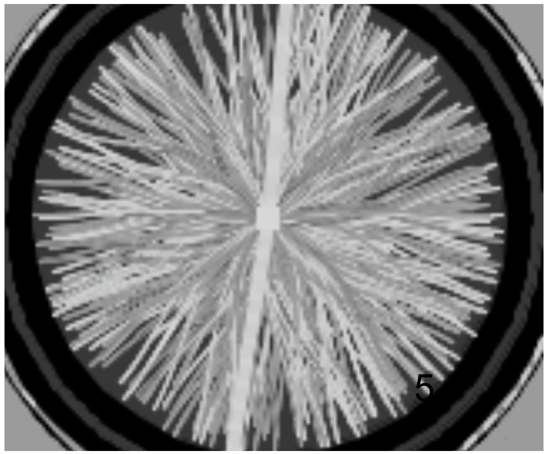


2012

~ 20 fb^{-1} at 8 TeV

O(30) Pile-up events

50 ns inter-bunch spacing



The LHC Run 1

A Textbook and Timely Discovery

Summer 2011: EPS and Lepton-Photon

First (and last) focus on limits (scrutiny of the p_0)

December 2011: CERN Council

First hints

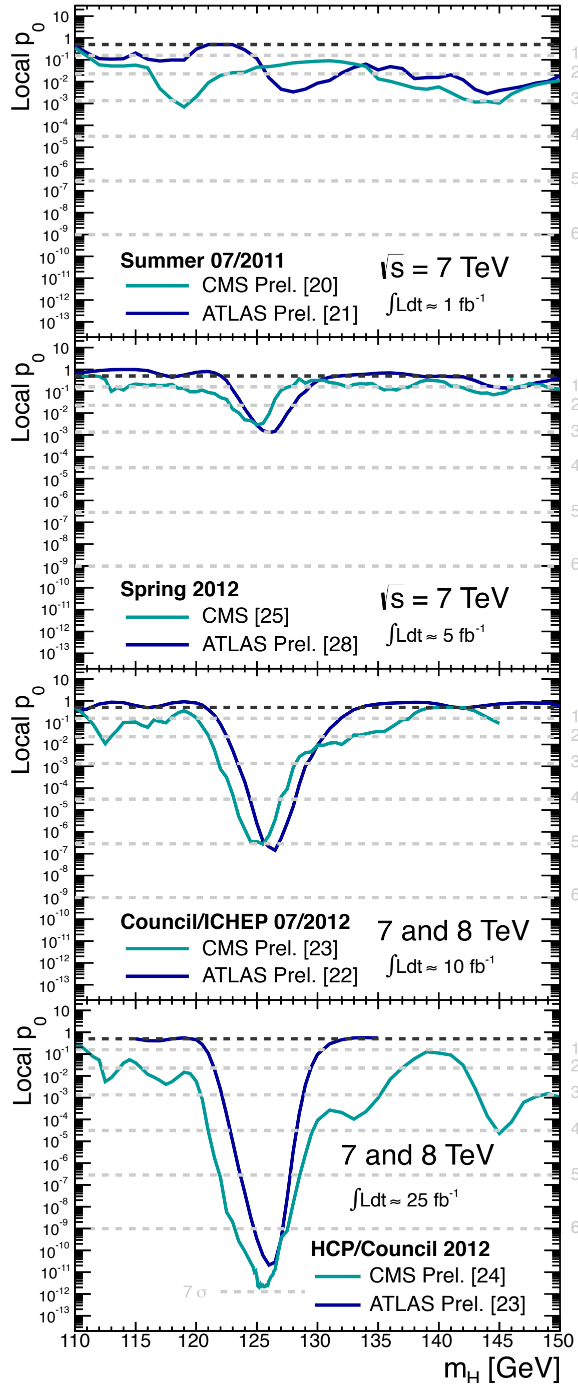
Summer 2012: CERN Council and ICHEP

Discovery!

December 2012: CERN Council

Beginning of a new era

The LHC and the experiments have worked remarkably

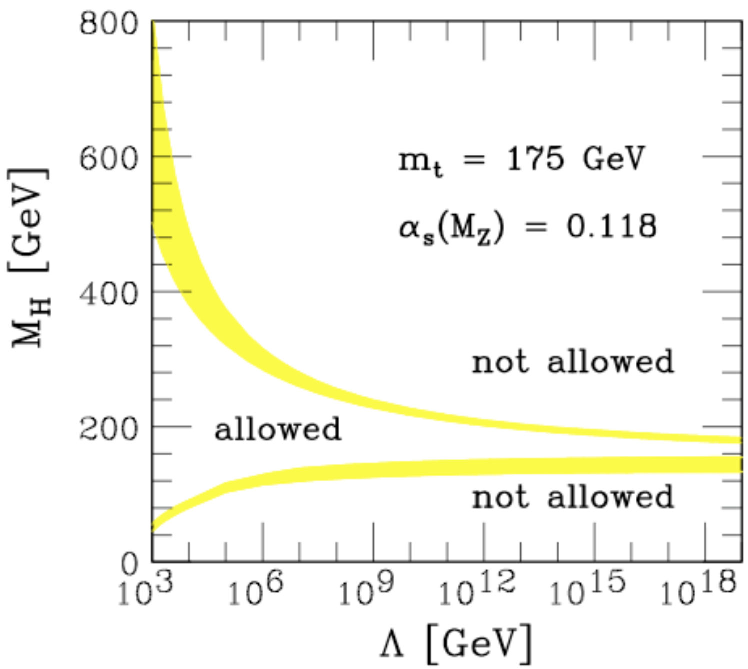


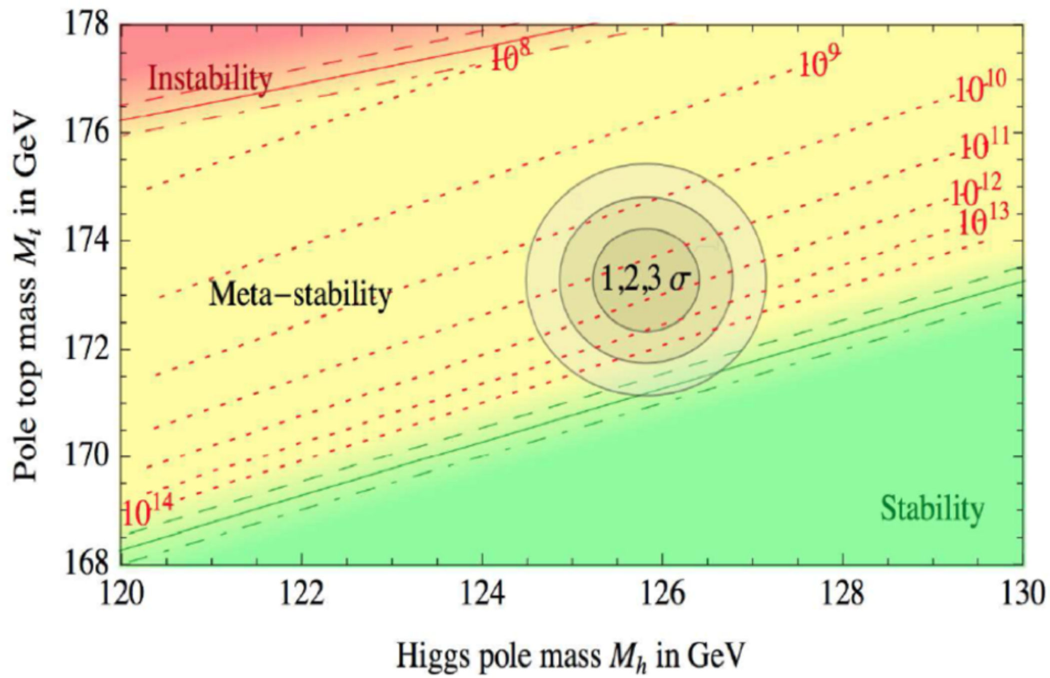
Implications (I) : *The Standard Model is Complete*

There is no need of new physics based on previously strong arguments:

- *Unitarity*
- *Vacuum stability*
- *Triviality*

A rather special value of the Higgs mass (I)

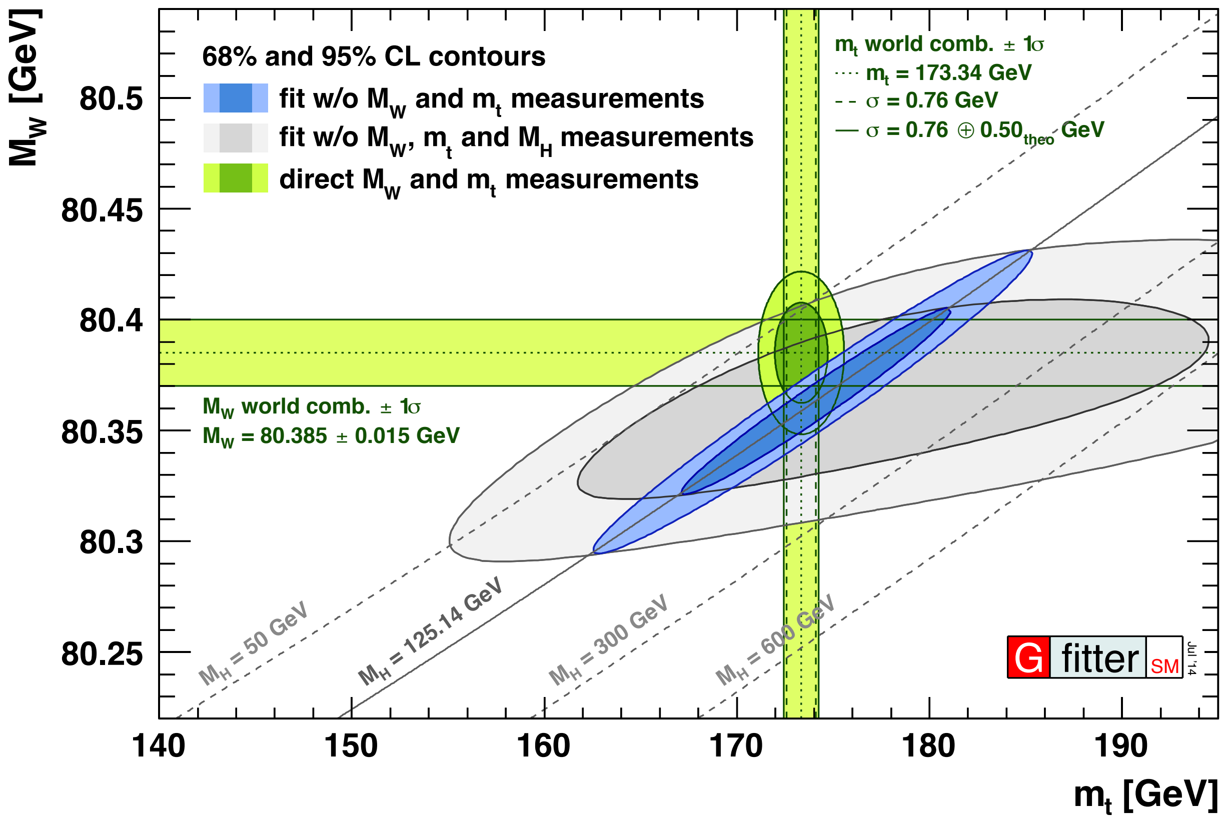




Beyond the anthropic principle: is near criticality a guiding principle?

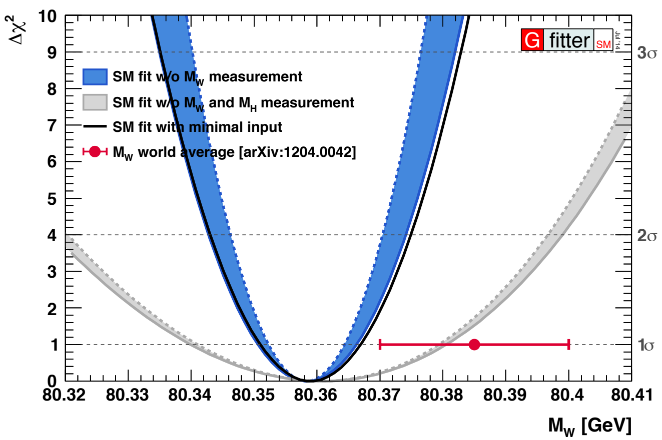
(Sand dunes effect) 1307.3536

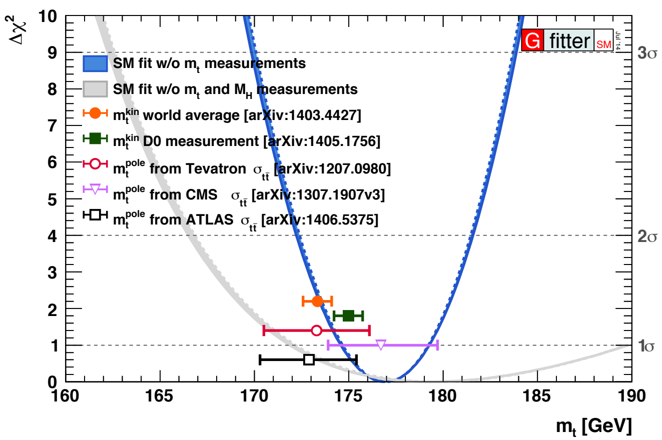
Implications (II) : *EW Precision Fit*



Important to have the Higgs mass, the current uncertainty is irrelevant in the fit

[Eur. Phys. J. C **74**, 3046 (2014)]

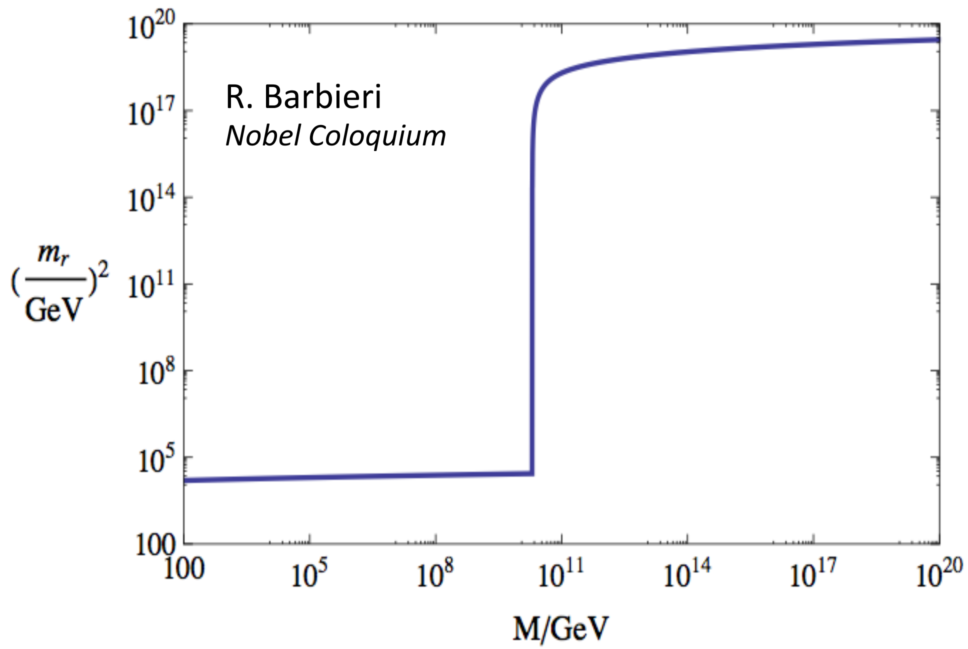




Implications (III) : *Naturalness*

No "no loose" theorem anymore…

Still Naturalness as Guiding Principle



Higgs(es) is (are) priviledged Probes of Naturalness

(Precision) H_{125} Measurements

- Weakly coupled (SUSY) → Searches for additional states
- Strongly coupled (Composite)

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…

$$H^0$$

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…

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

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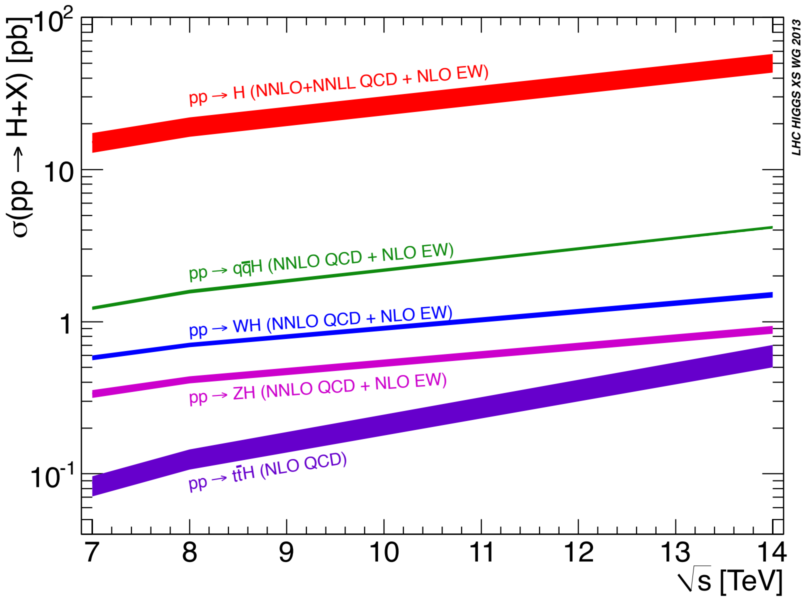
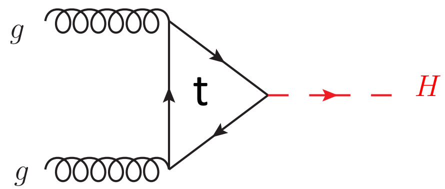
- *Differential cross sections*
- *Its main quantum numbers JPC*

Higgs Production Modes

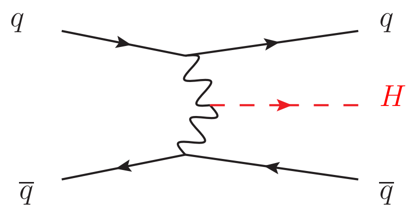




Gluon fusion process

NNnLO ~O(10%), but …

~0.5 M events produced

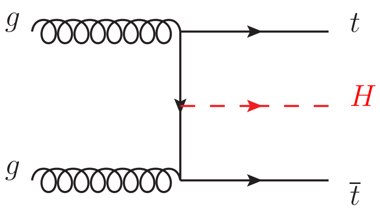


Vector Boson Fusion

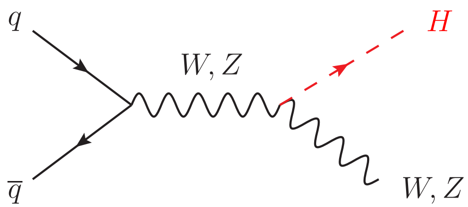
NNLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap

~40 k events produced



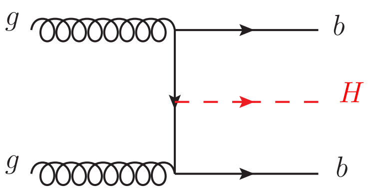
Top Assoc. Prod. ~3 k evts produced



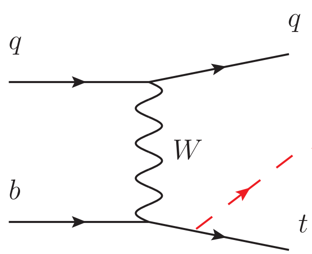
W and Z Associated Production

NNLO TH uncertainty ~O(5%)

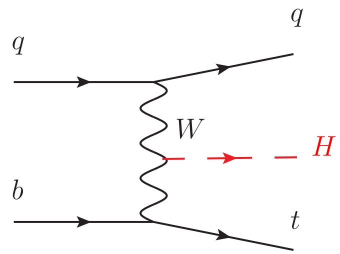
~20 k events produced



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



tH



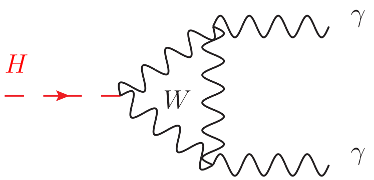
Standard Higgs Decay Modes

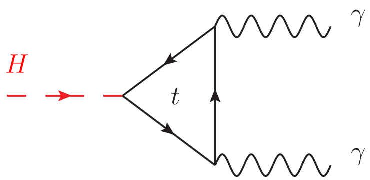
- Dominant: bb (57%)
- WW channel (22%)

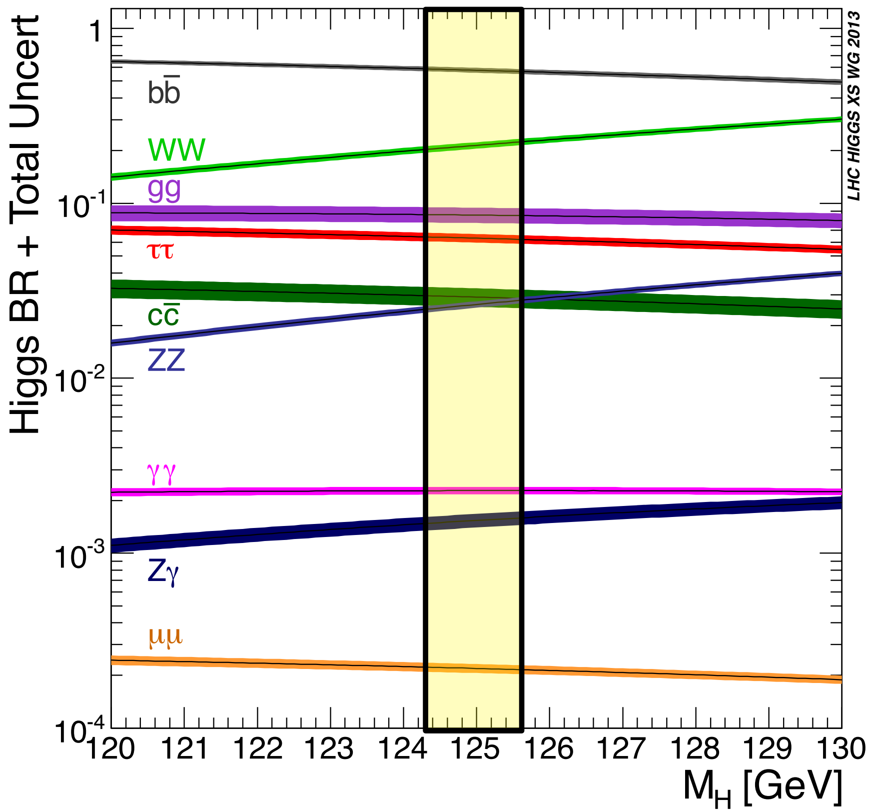
  W to e or μ (~11 %)
- ττ channel (6.3%)
- ZZ channel (3%)

  Z to e or μ (~3.4 %)
- cc channel (3%)

  Extremely difficult
- γγ channel (0.2%)

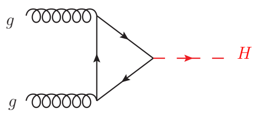
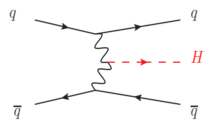
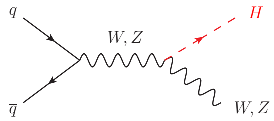
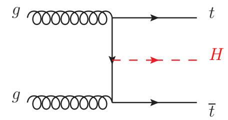






- Zγ channel (0.2%)
- μμ channel (0.02%)

Panorama of Higgs Analyses

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

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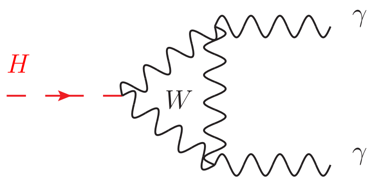
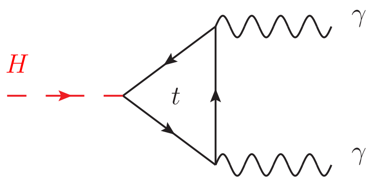
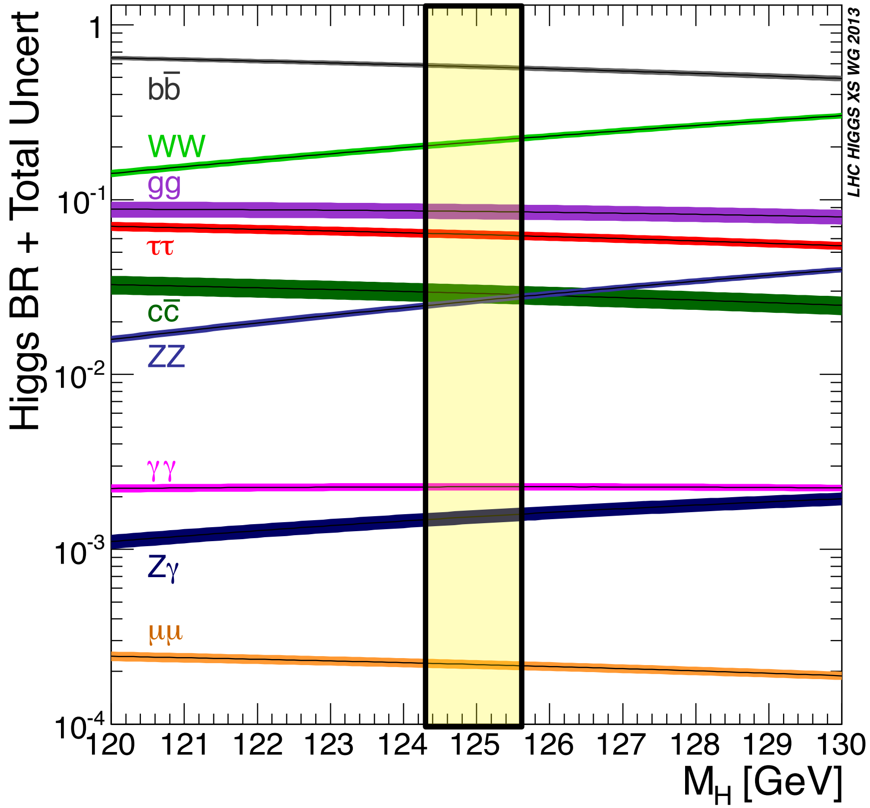




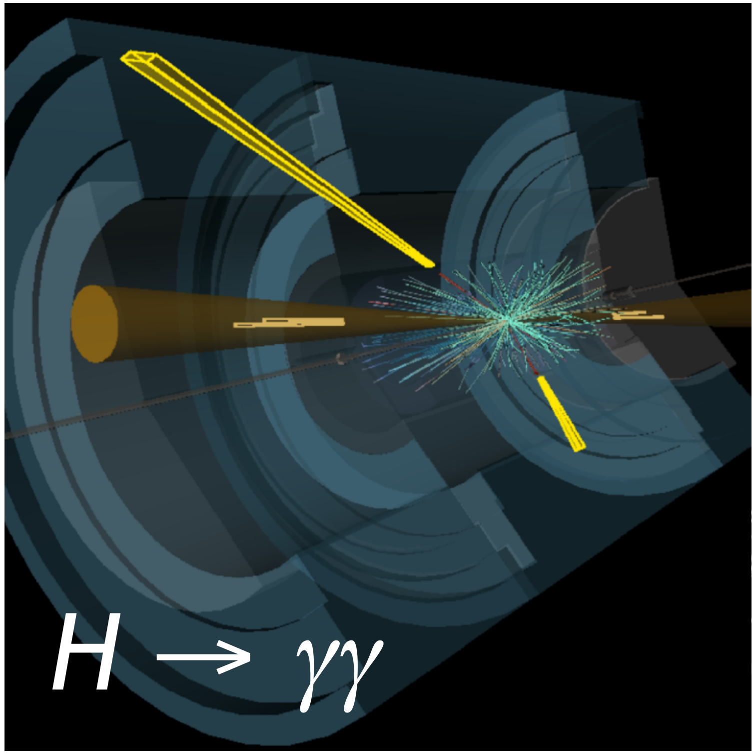


- Zγ channel (0.2%)

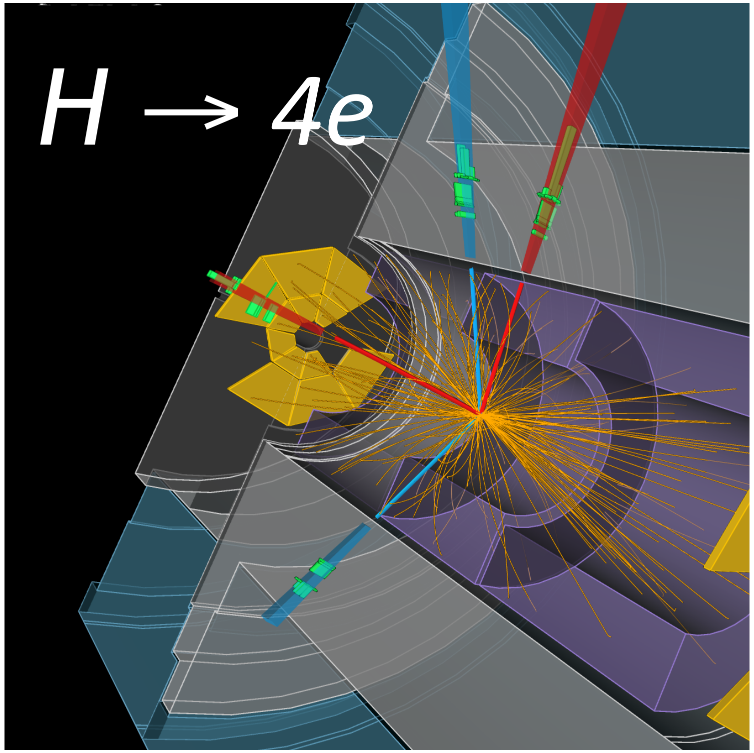
- μμ channel (0.02%)

The two Main discovery Chanels

An excellent chanel for a Higgs boson near 125 GeV

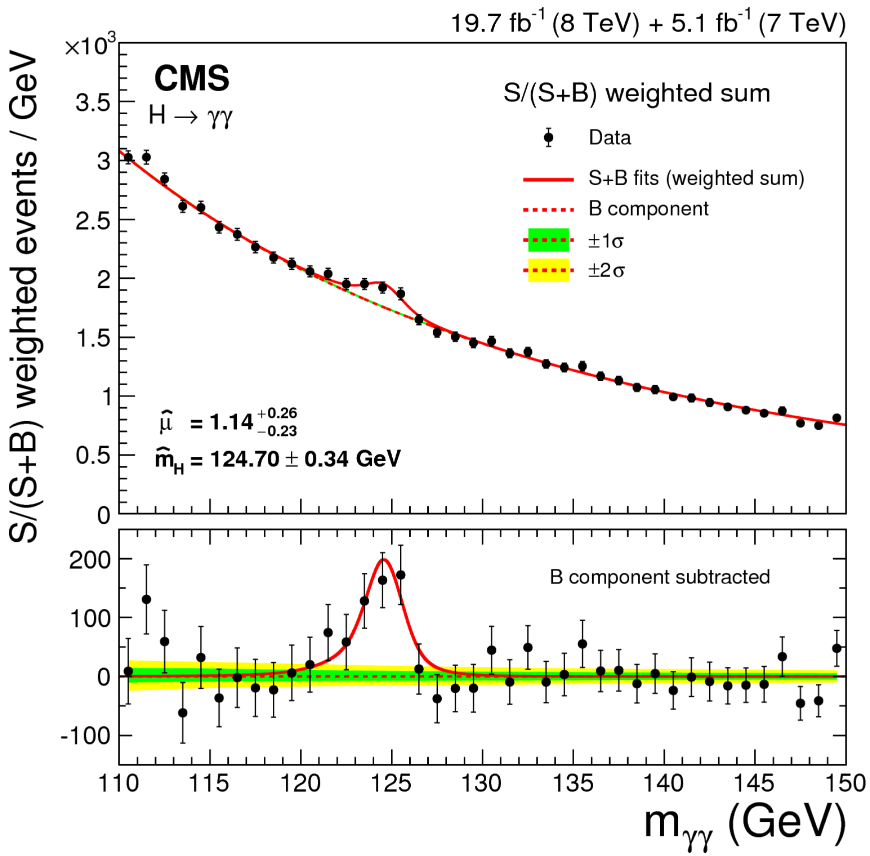


The Golden chanel over a large range in mass

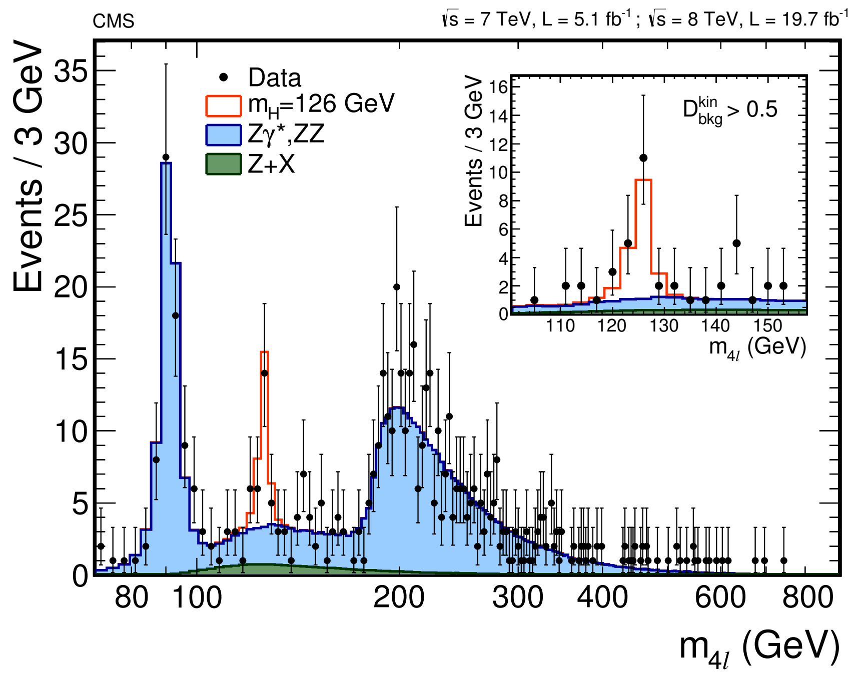


Very simple channels, with excellent mass resolution (unambiguous signatures)

The Discovery and the Measurement are fully lead by two channels

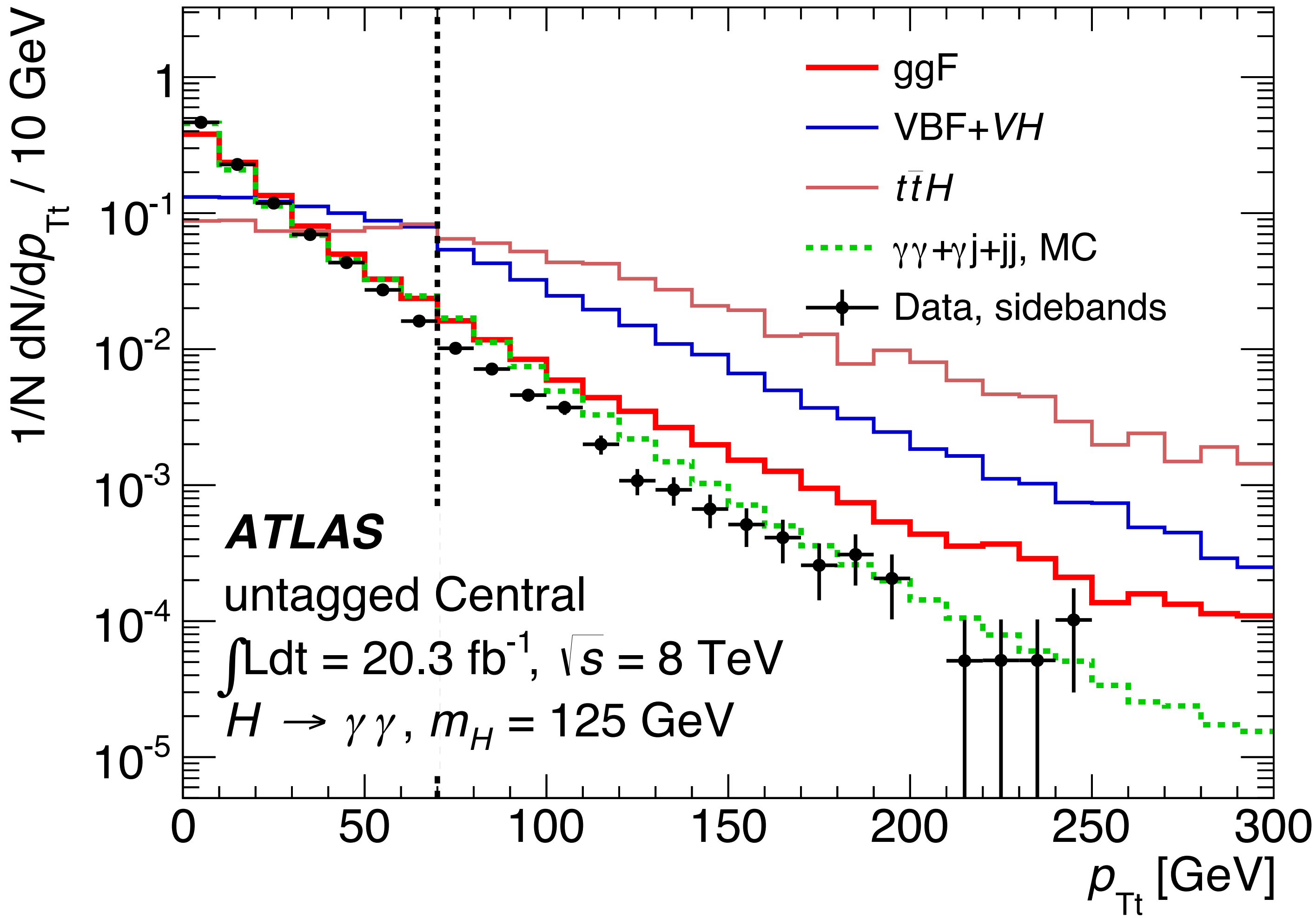


- s/b ratio ranging from few % to approximately 30%
- Uses exclusive production (VBF,VH and ttH) not for the mass measurement
- Uses Higgs pT as discriminating variable

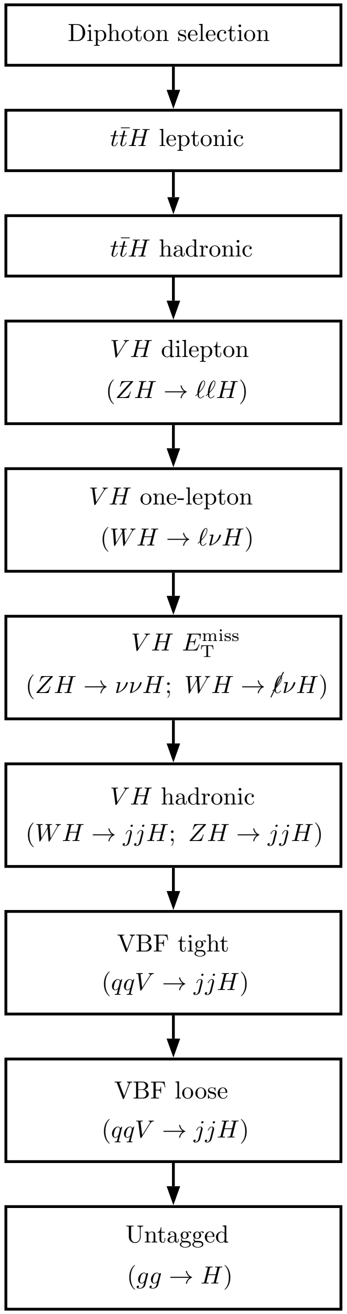


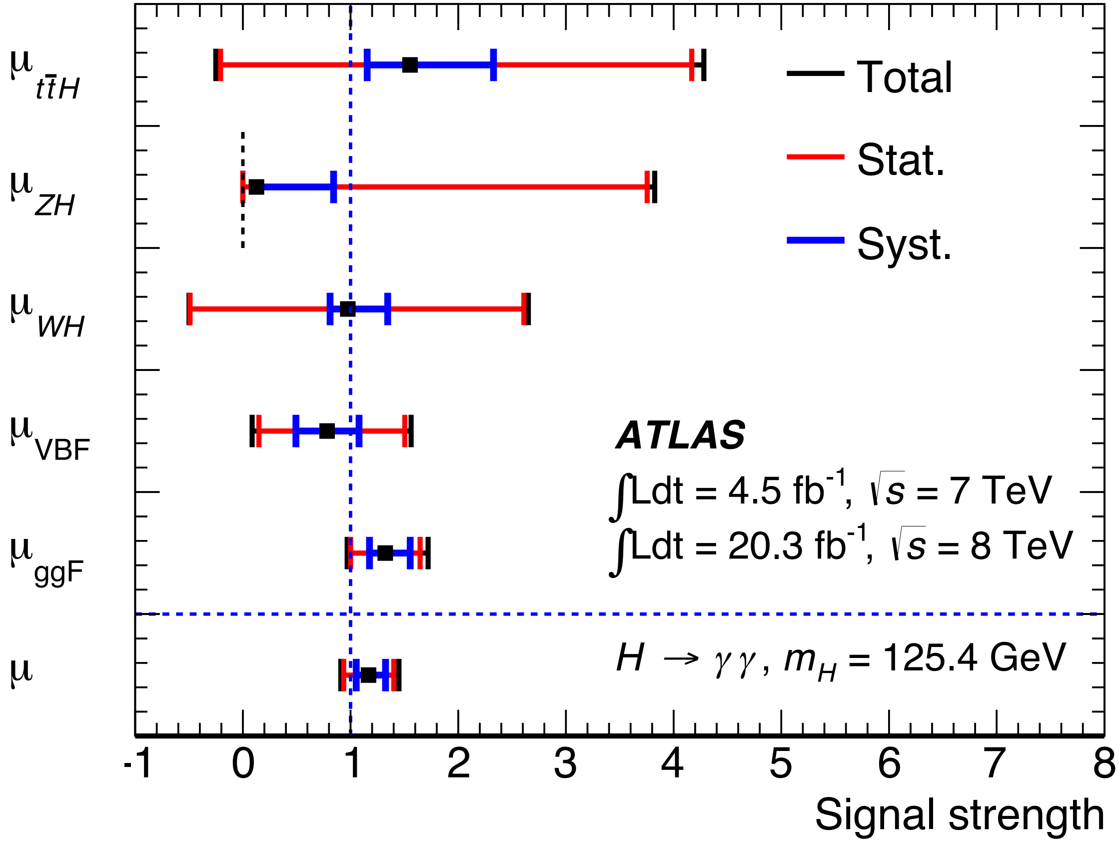
- High s/b ratio from approximately 1.5 up to more than 10.
- Uses exclusive production (VBF,VH and ttH) not for the mass measurement
- Uses Higgs pT as discriminating variable
- Uses angular variables to discriminate background

The Importance of the Higgs Boson Transverse Momentum

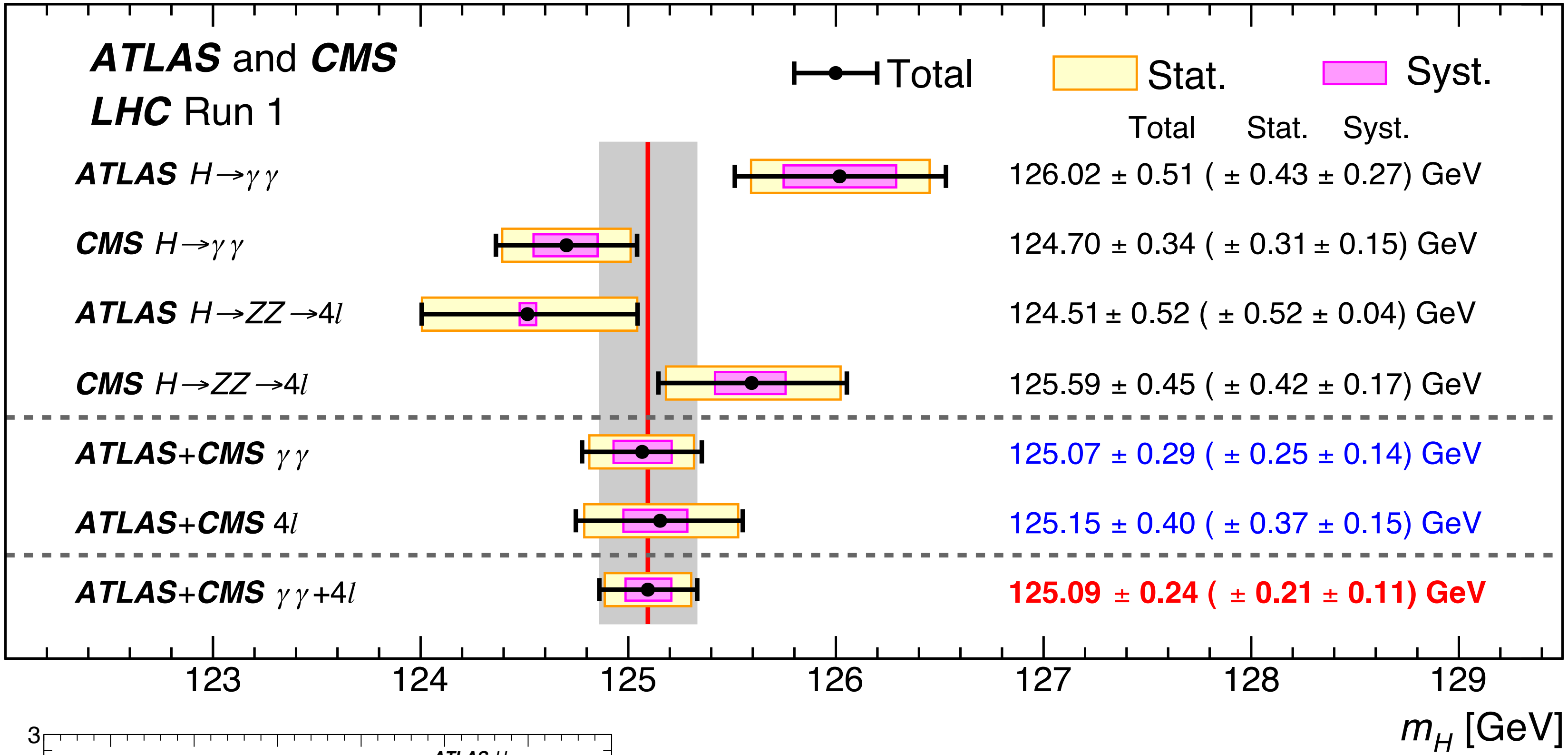


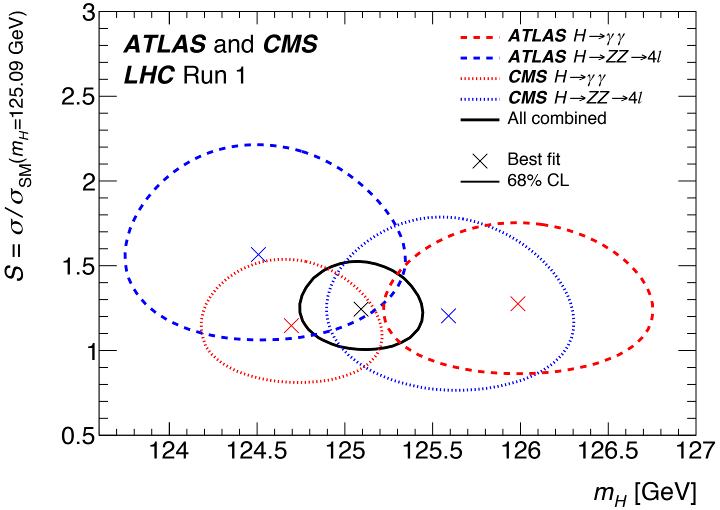
Analyses in Categories





A Precision Measurement





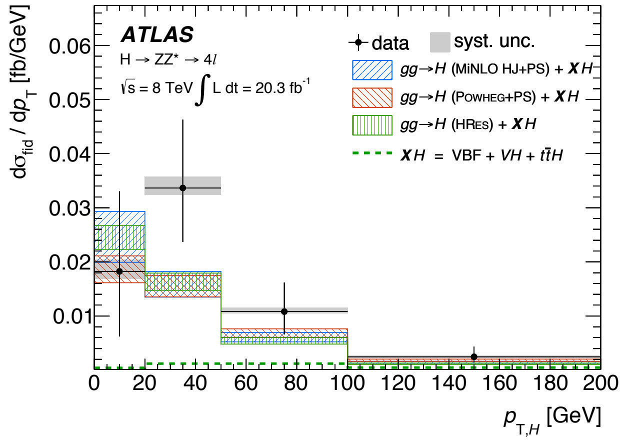
- Statistics dominated Measurement
- Systematic uncertainties completely dominated by calibration uncertainties
- Compatibility of the four measurements masses O(10%)
- Tension between ATLAS 4l and γγ ~2σ

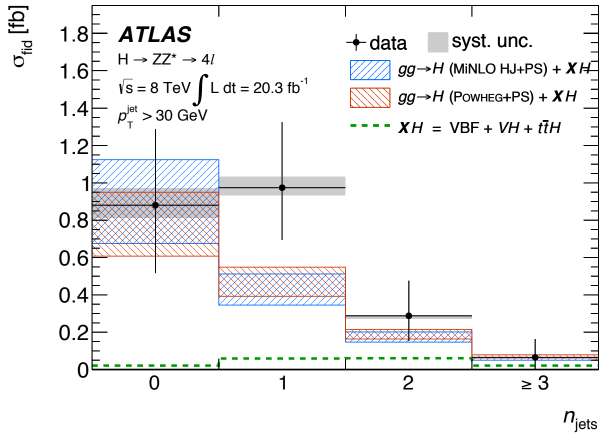
Differential, Fiducial and Unfolded cross section

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

$$H \rightarrow 4l$$

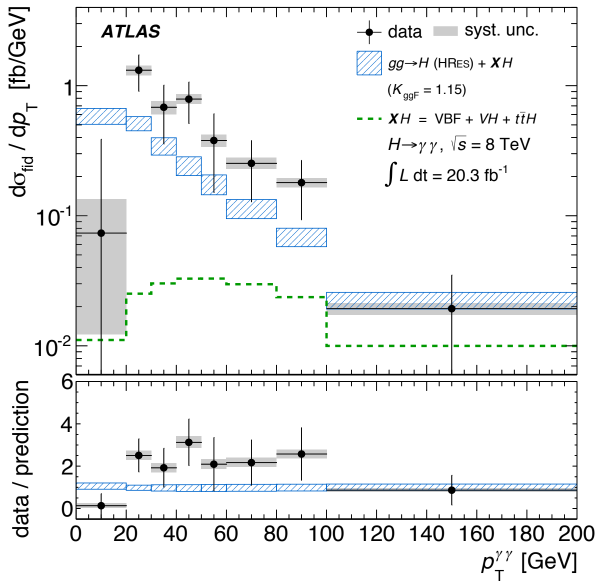
Phys. Lett. B 738 (2014)

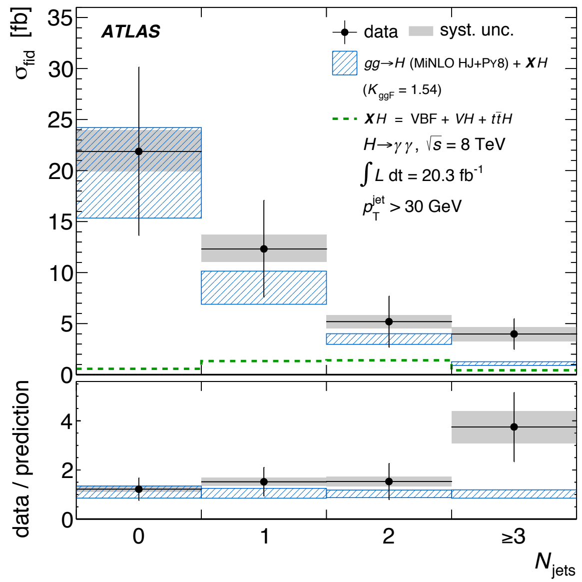




$$H \rightarrow \gamma\gamma$$

JHEP 09 (2014)

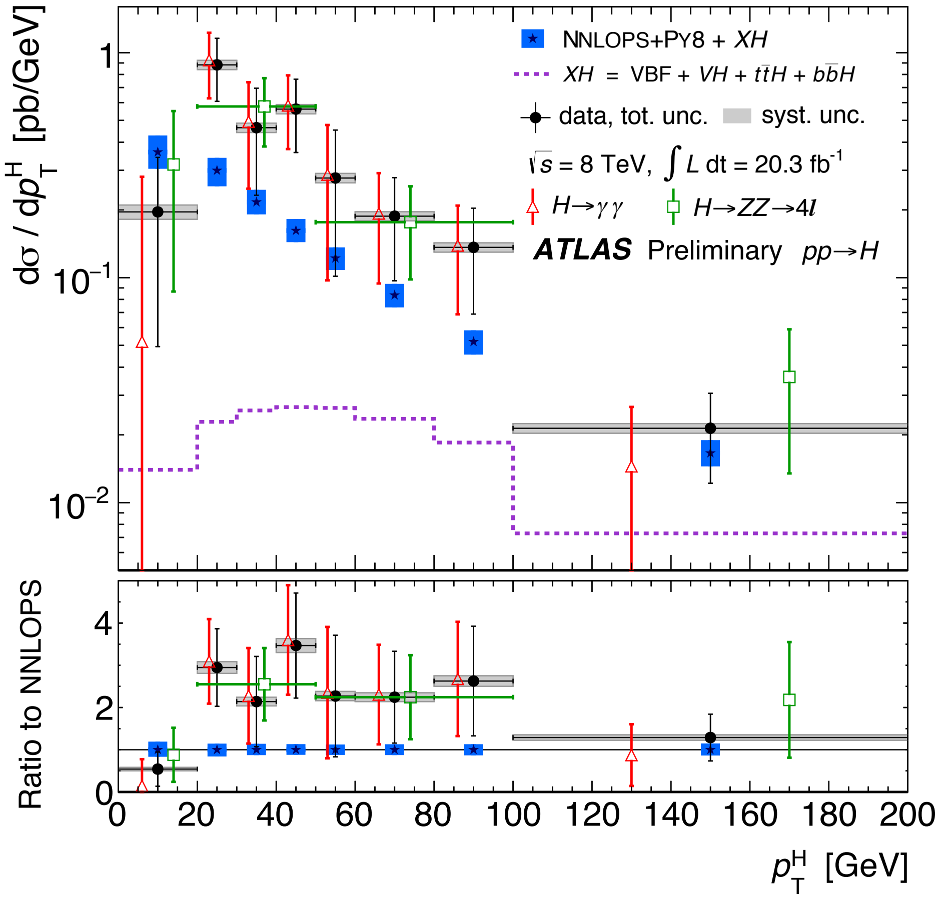


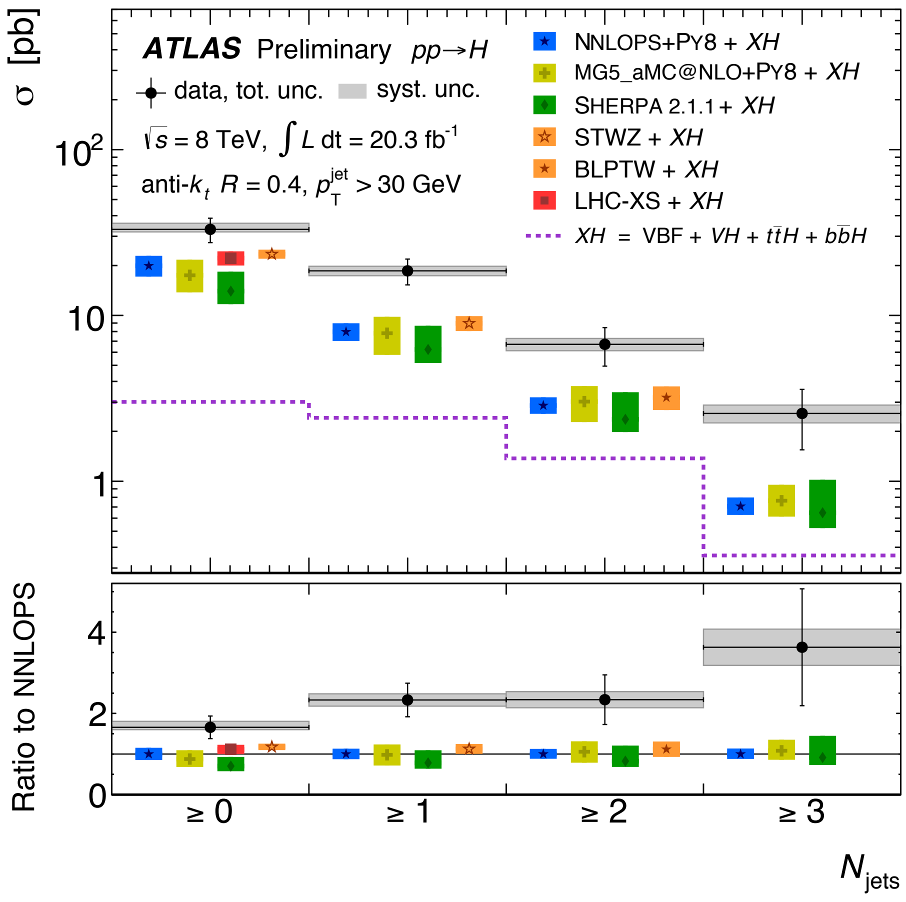


Combined Differential Cross sections

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

(Publication in preparation)





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

Combined Differential Cross sections

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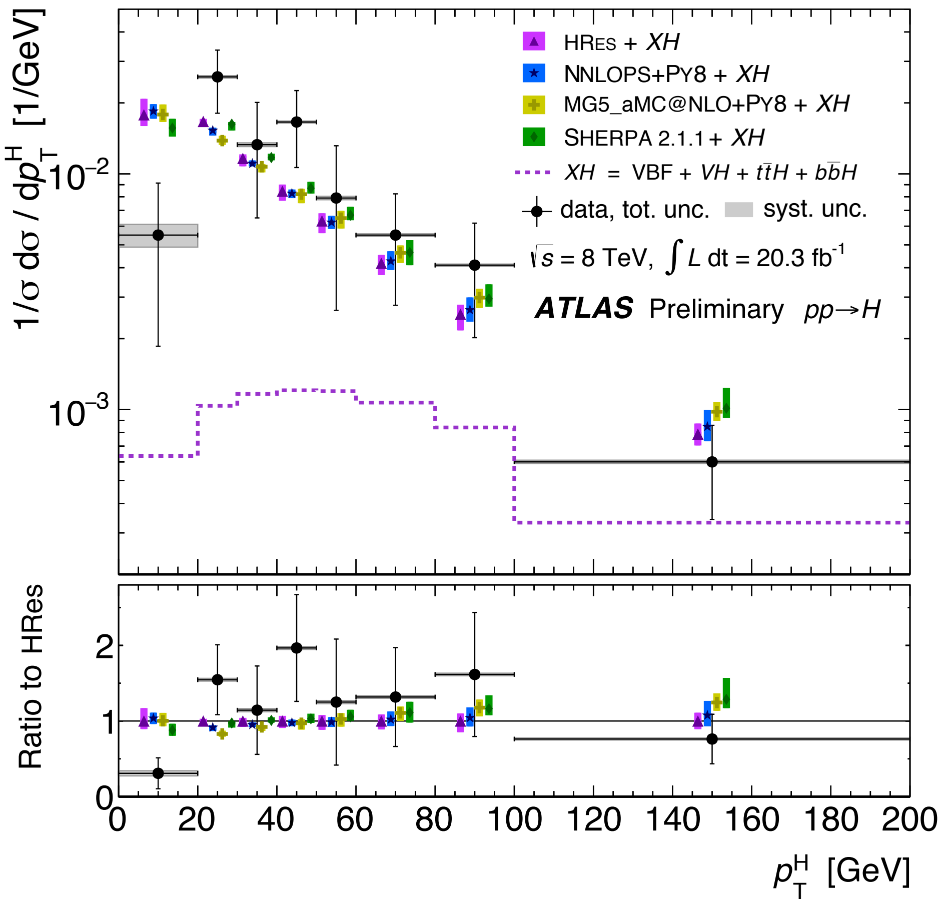
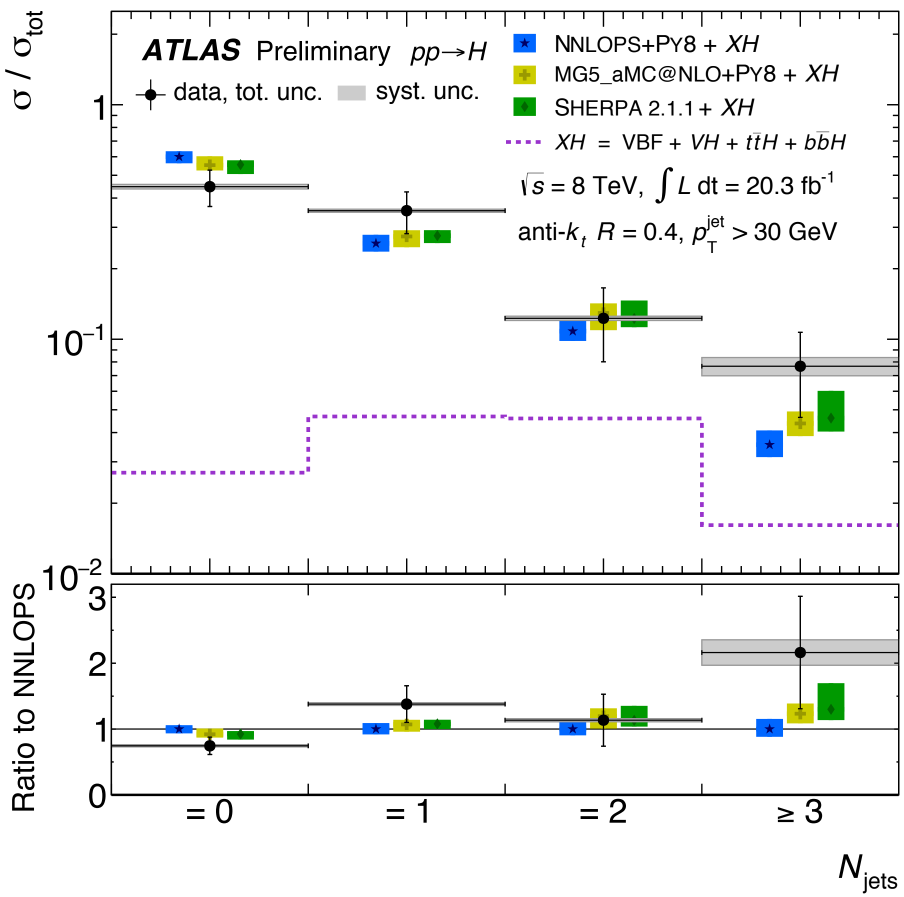
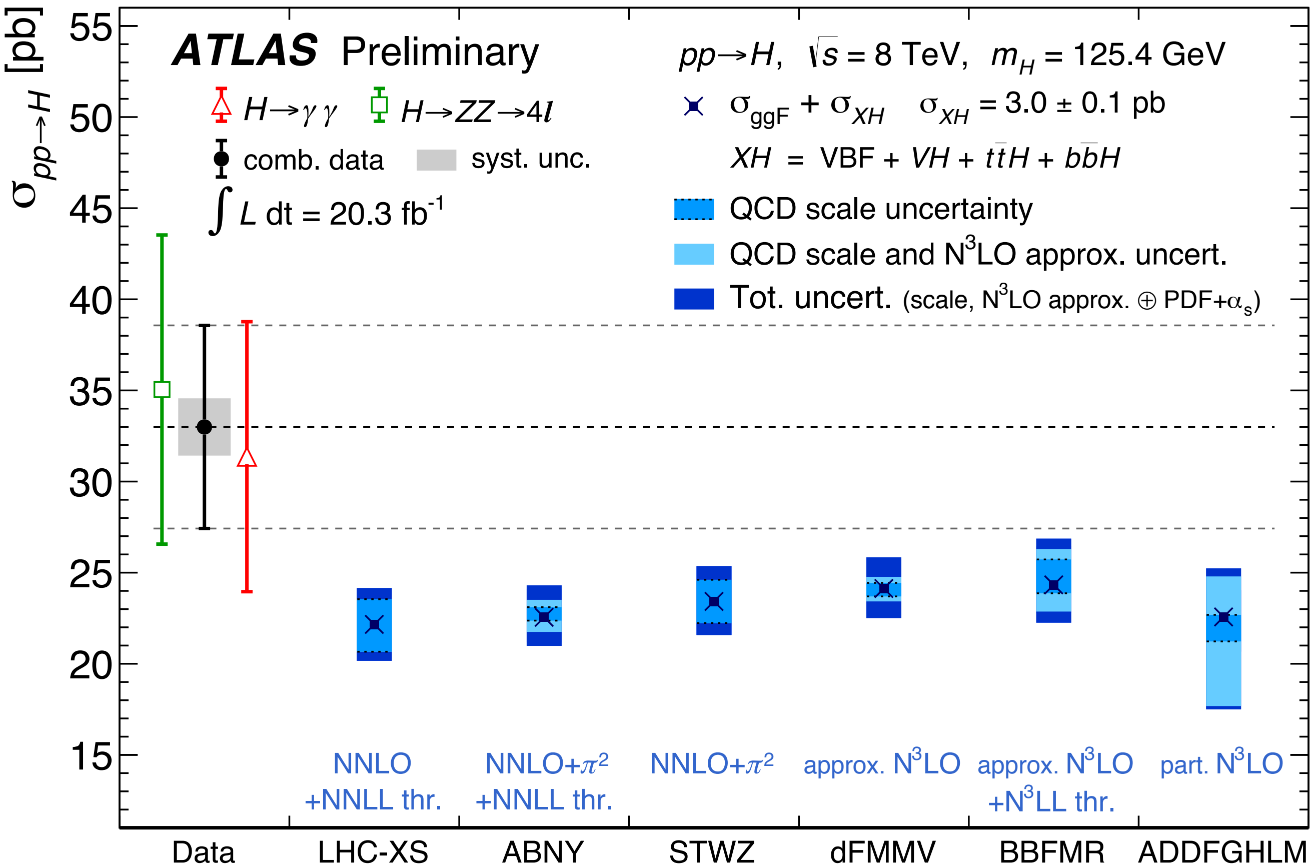




More compatible

Combined Inclusive Total Cross Section



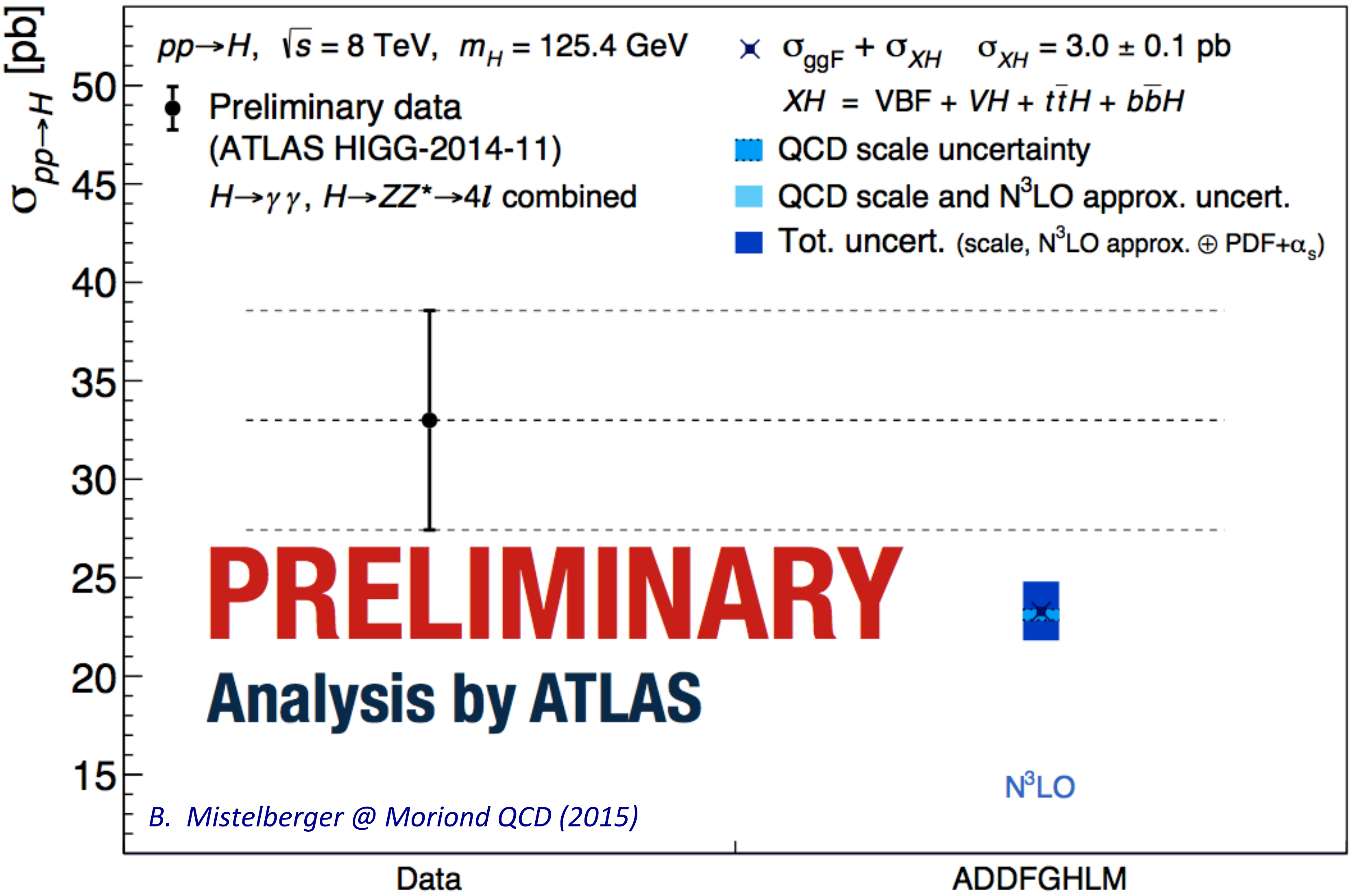
$$\sigma(\mathrm{Data}, pp \to H) = 33.0 \pm 5.3\ (\mathrm{stat}) \pm 1.6\ (\mathrm{syst})\ \mathrm{pb}$$

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

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

Breaking News

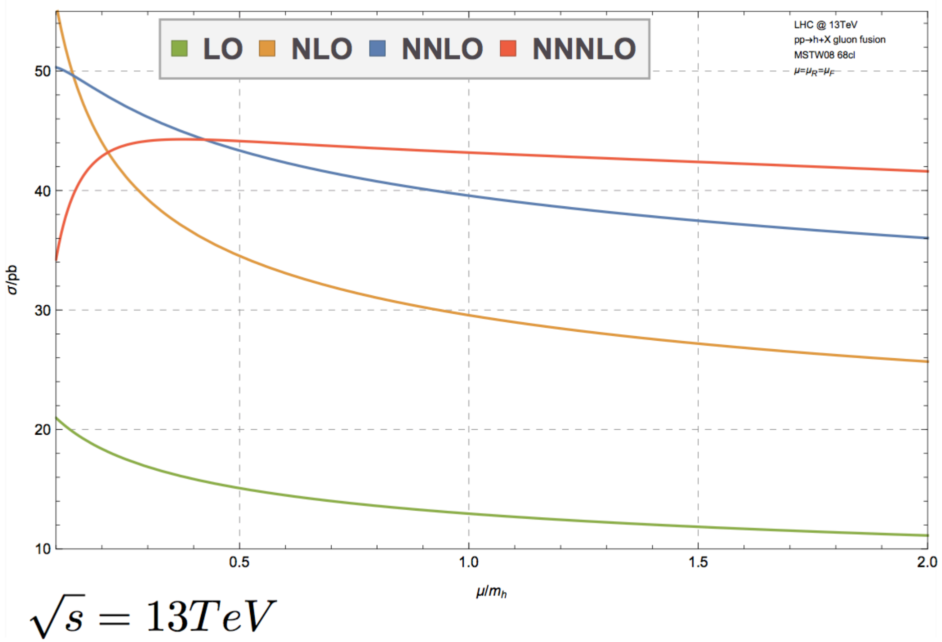
N3LO Inclusive Higgs Production Achieved



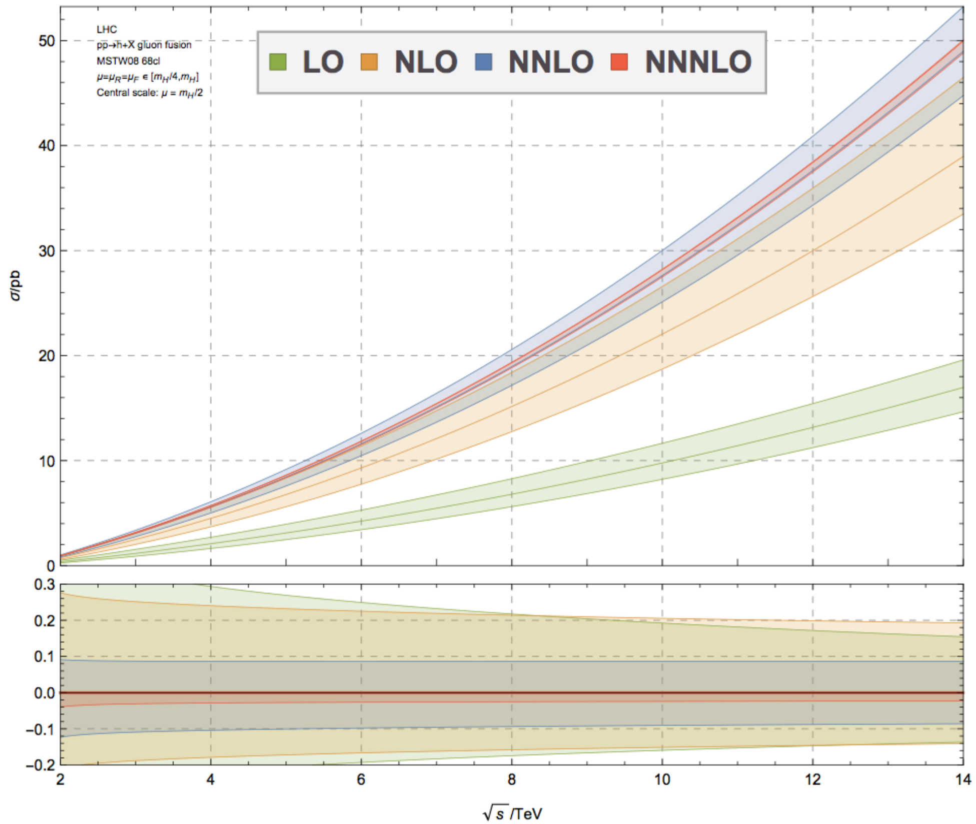
Breaking News

N3LO Inclusive Higgs Production Achieved

Development of sophisticated numerical/computational methods.

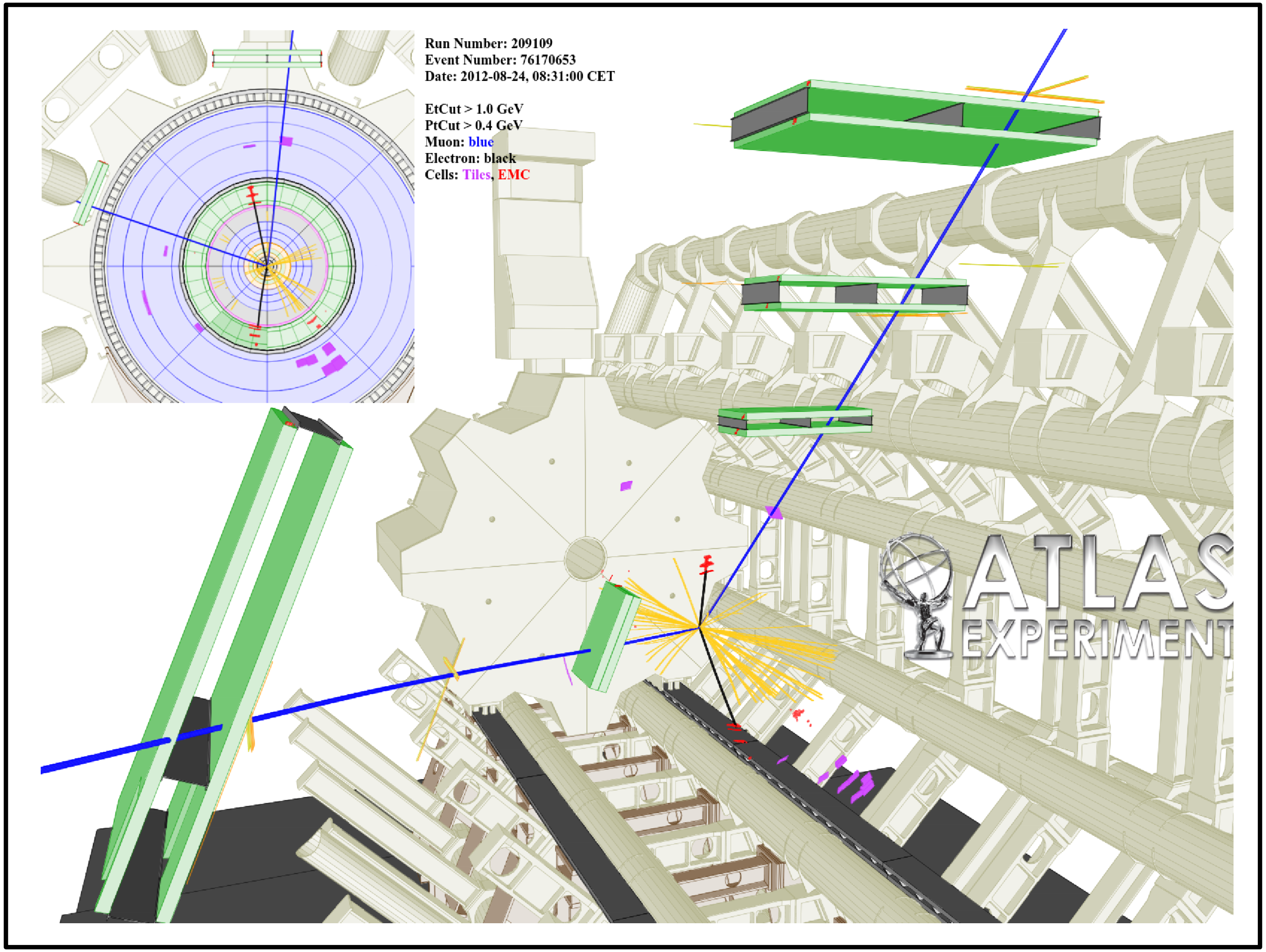


B. Mistelberger @ Moriond QCD (2015)

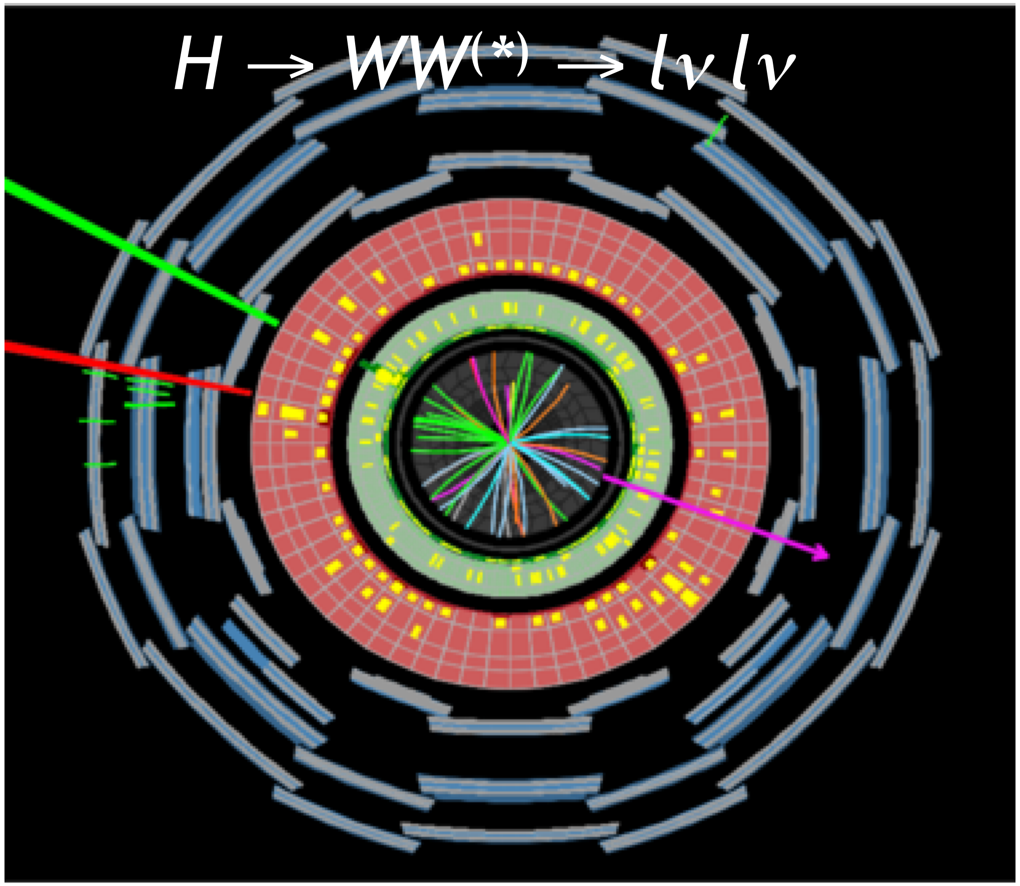


Other uncertainties now become important (PDFs, treatment of EW, heavy-top approximation, top-bottom interference in loops...).

Bright Future for the 4-lepton Analysis



A discovery channel of a different kind…

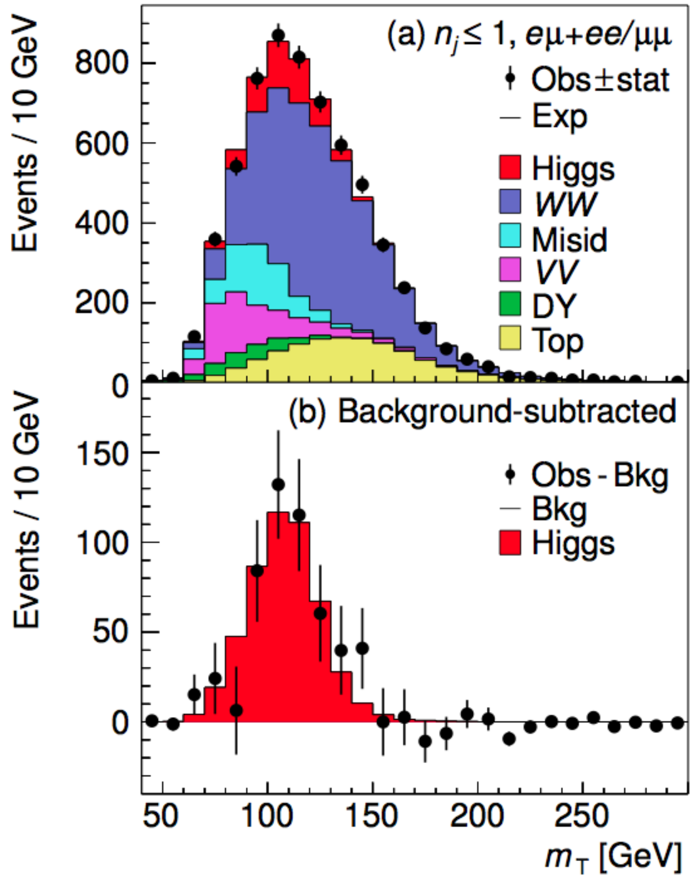


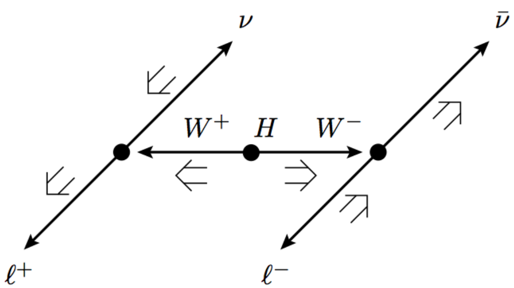
ATLAS

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

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 +	Error −	Plot of error (scaled by 100)	Observed $\mu_{\mathrm{ggF}} = 1.01$ Error +	Error −	Plot of error (scaled by 100)	Observed $\mu_{\mathrm{VBF}} = 1.27$ Error +	Error −	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	
			-30 -15 0 15 30			-30 -15 0 15 30			-60 -30 0 30 60

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

Systematic source	Impact on $\hat{\mu}$: Pre-fit $\Delta_{\hat{\mu}}$ +	Pre-fit $\Delta_{\hat{\mu}}$ −	Post-fit $\Delta_{\hat{\mu}}$ +	Post-fit $\Delta_{\hat{\mu}}$ −
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 $\alpha_{\rm top}$	+0.03	−0.04	+0.03	−0.03
Misid. of μ, OC uncorrelated corr. factor $\alpha_{\rm misid}$, 2012	−0.03	+0.04	−0.02	+0.03
Misid. of e, OC uncorrelated corr. factor $\alpha_{\rm misid}$, 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 $\alpha_{\rm misid}$	+0.01	−0.02	+0.01	−0.02
Electron isolation efficiency	−0.01	+0.02	−0.01	+0.02
Misid. of μ, closure on $\alpha_{\rm misid}$, 2011	−0.01	+0.02	−0.01	+0.01
Electron identification eff. on $p_{\rm T}^{\ell 2} > 20\,{\rm GeV}$, 2012	−0.01	+0.02	−0.01	+0.02
ggF H, QCD scale on ϵ_1	−0.01	+0.02	−0.01	+0.02

Plot of post-fit $\pm\Delta_{\hat{\mu}}$

NNLO Done (need fiducial and differential) !

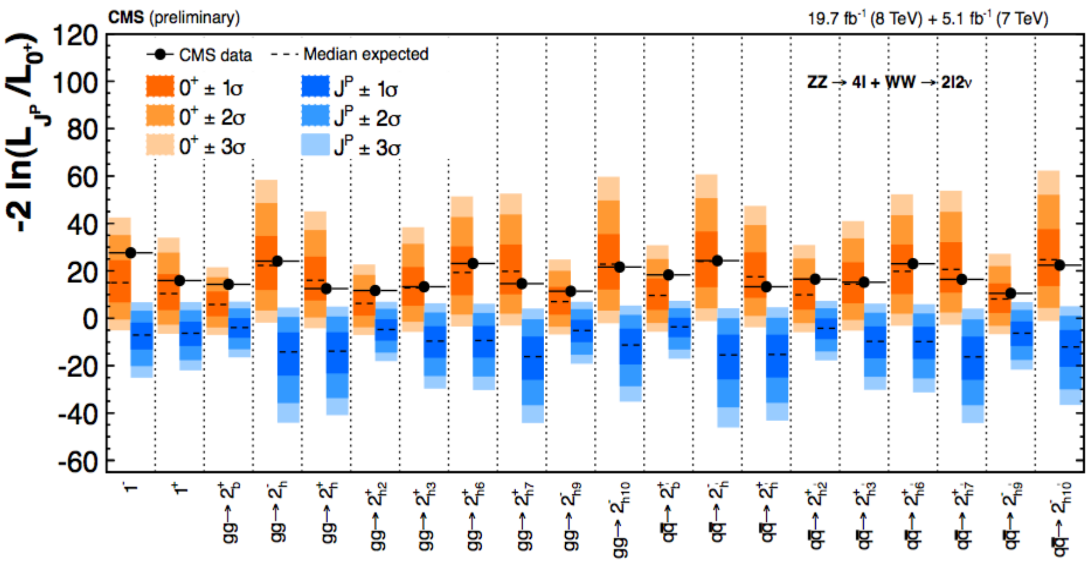
*Discovery with help from Theory

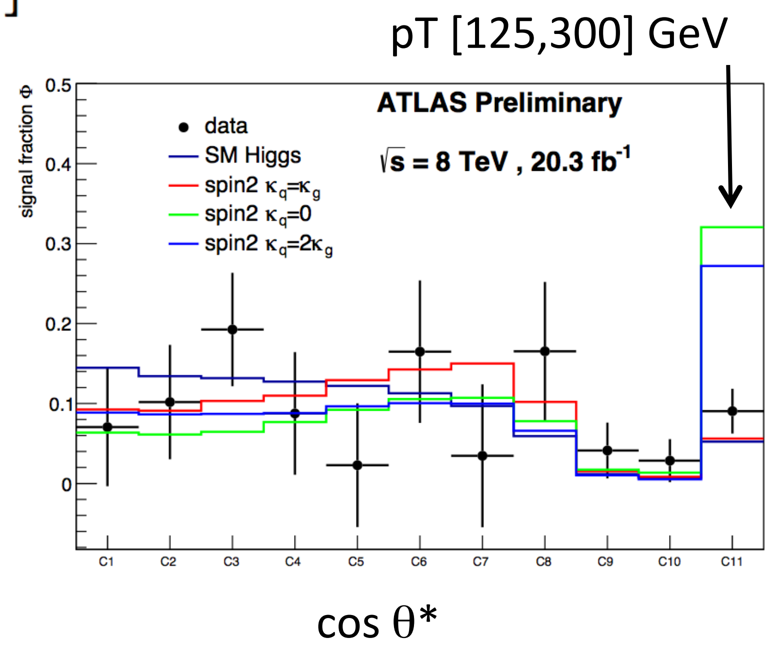
J^{PC}

- 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 γγ

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

Coupling to energy-momentum tensor



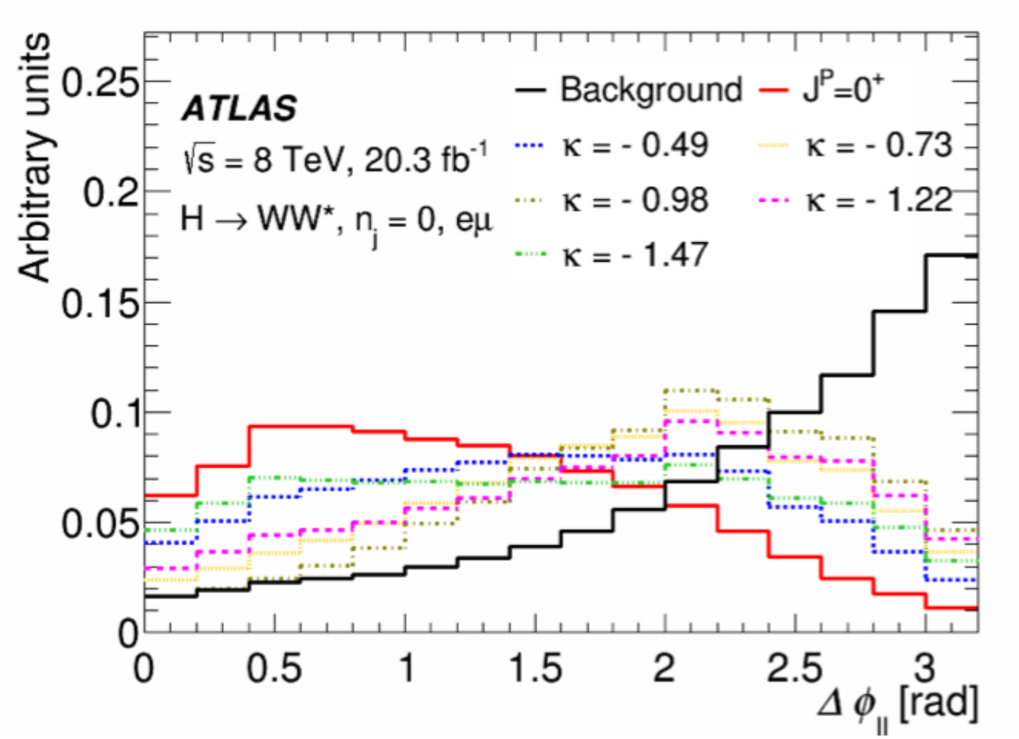


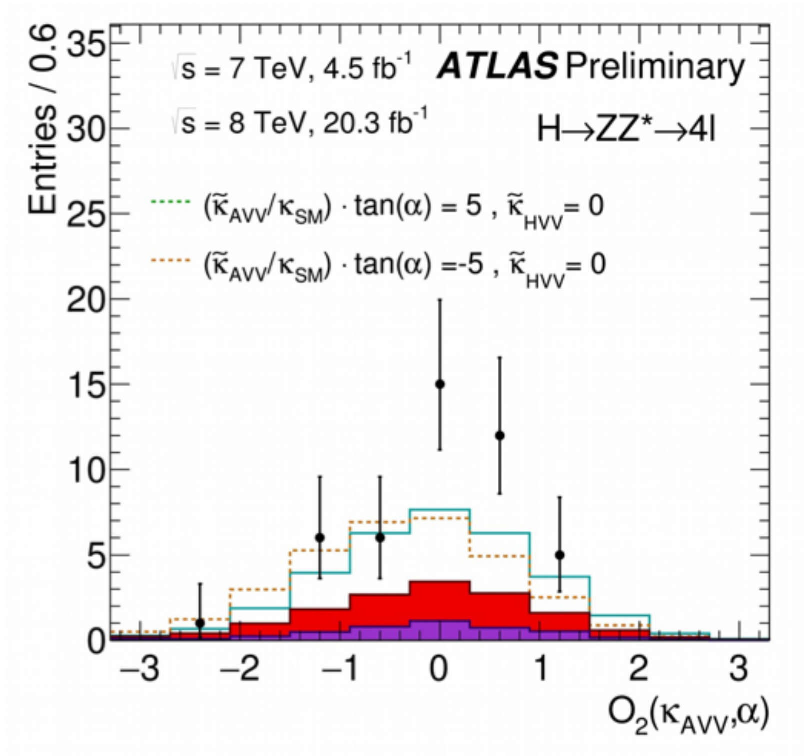
CP Mixing

- Spin 0 effective model

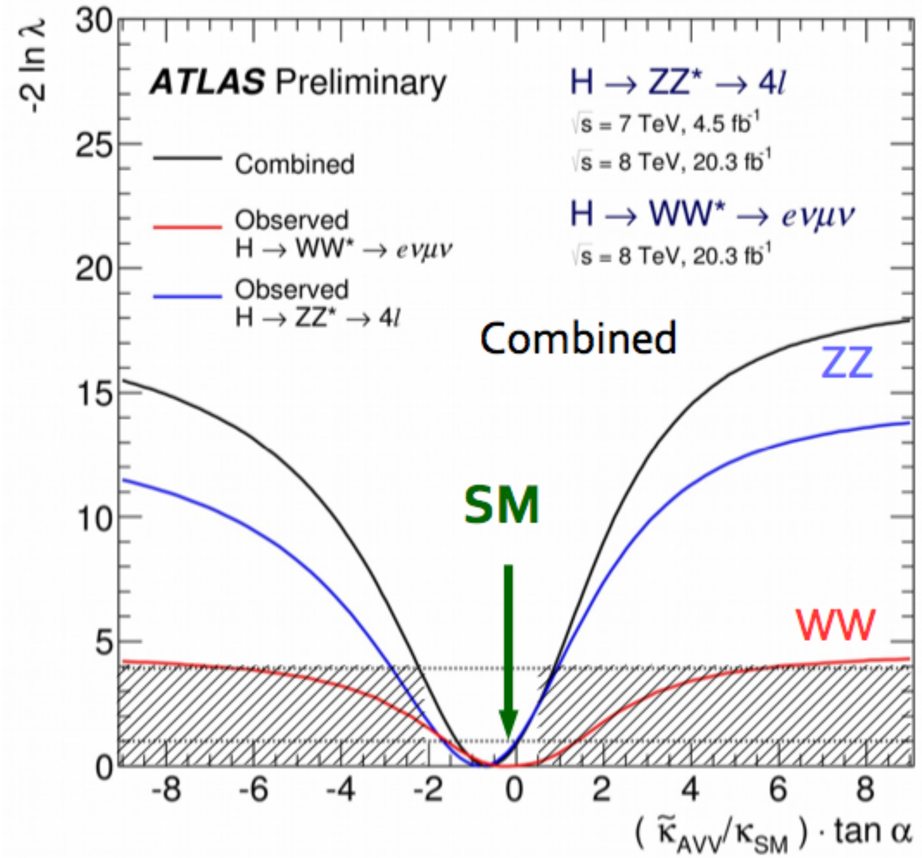
$$\mathcal{L}_0^V = \left\{ c_\alpha \kappa_{\rm SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] - \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha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

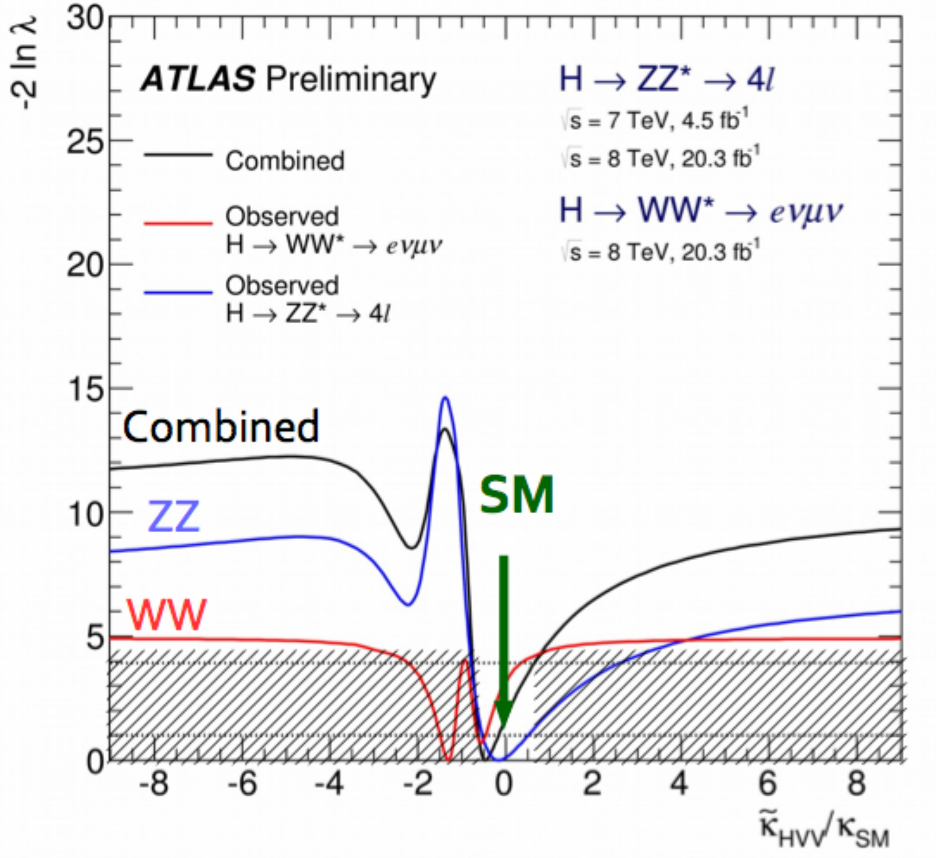
(ATLAS uses optimal observables in 4l channel)





CP Mixing





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

Outline

Introduction — *Run 1, the discovery and its implications*

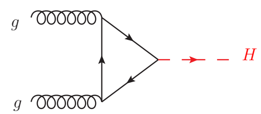
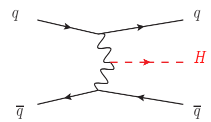
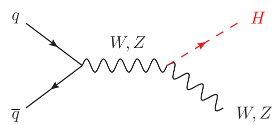
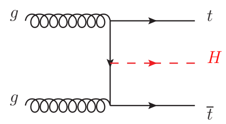
Higgs physics with the discovery channels

- *The mass of the Higgs boson*
- *Differential cross sections*
- *Its main quantum numbers JPC*

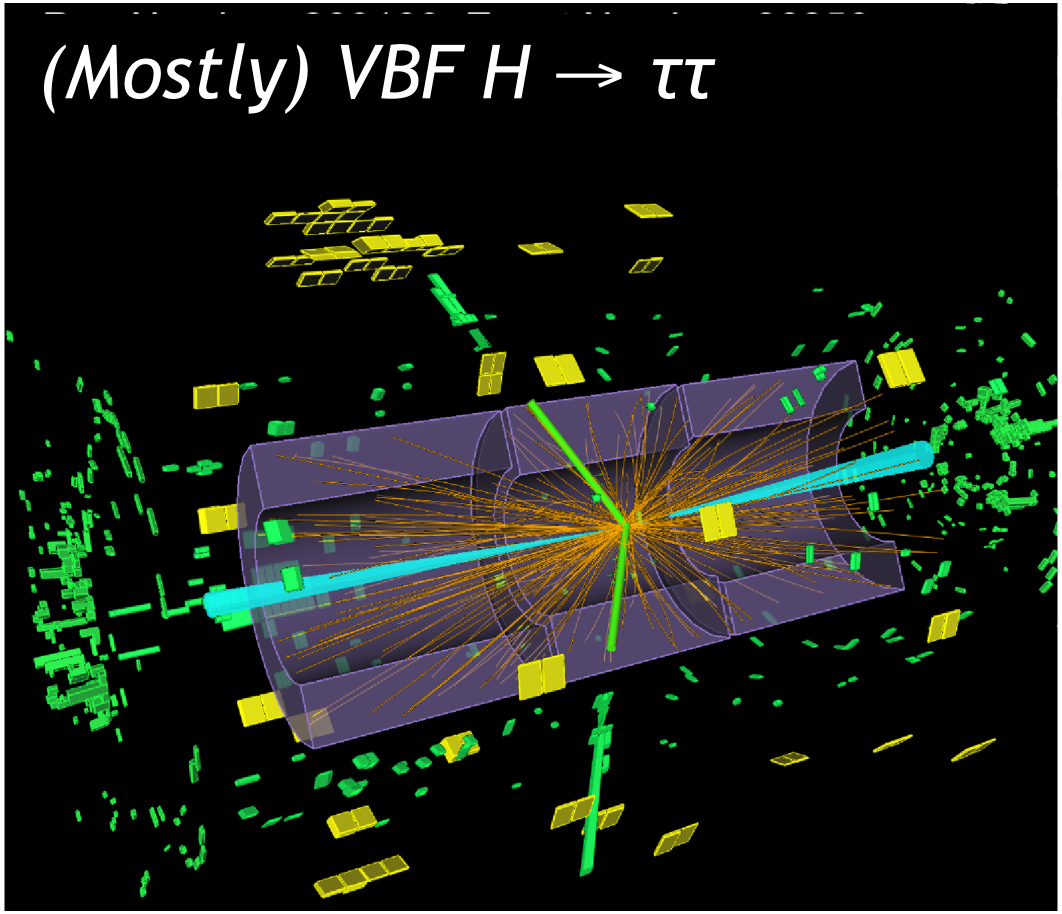
Exploring the vast LHC potential

- Discovery in the fermionic channels
- Cornering the top Yukawa
- Rare decays

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)	✓	✓	

An Important Observation…

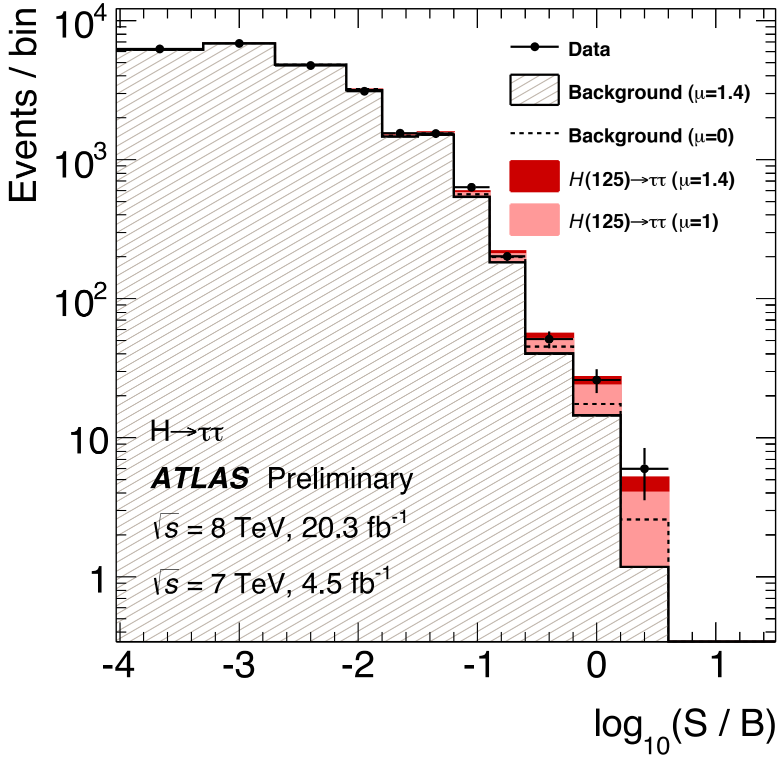


ATLAS

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

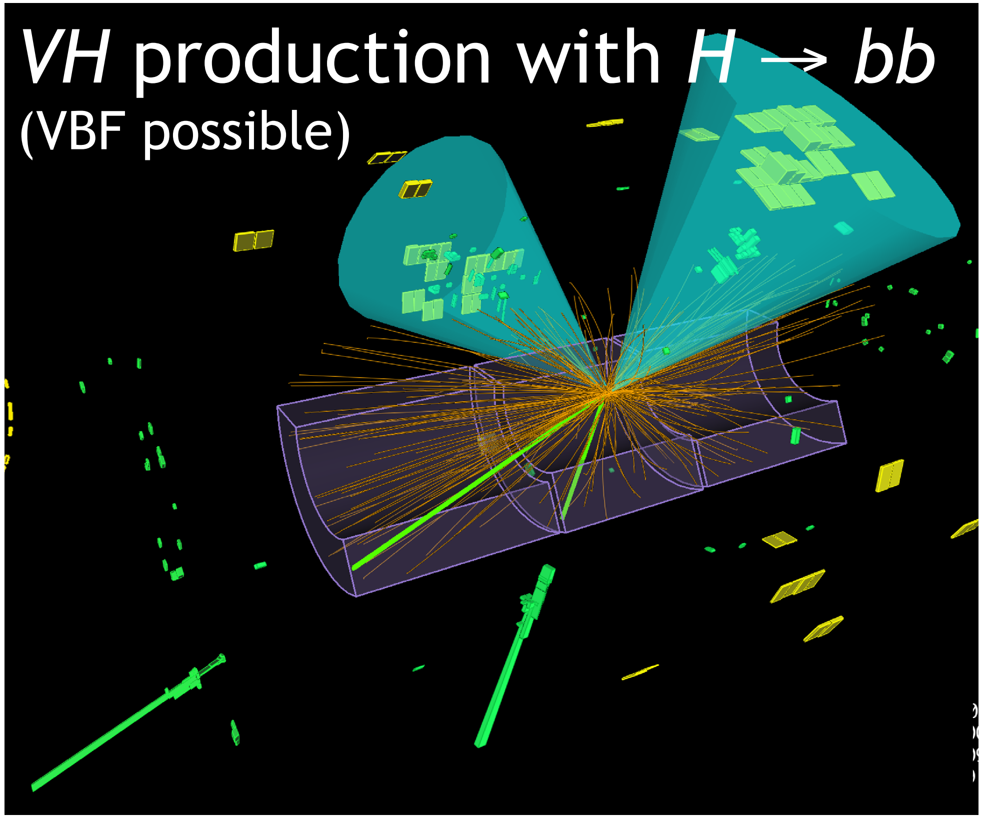
CMS

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



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

Cornering the b Yukawa Coupling

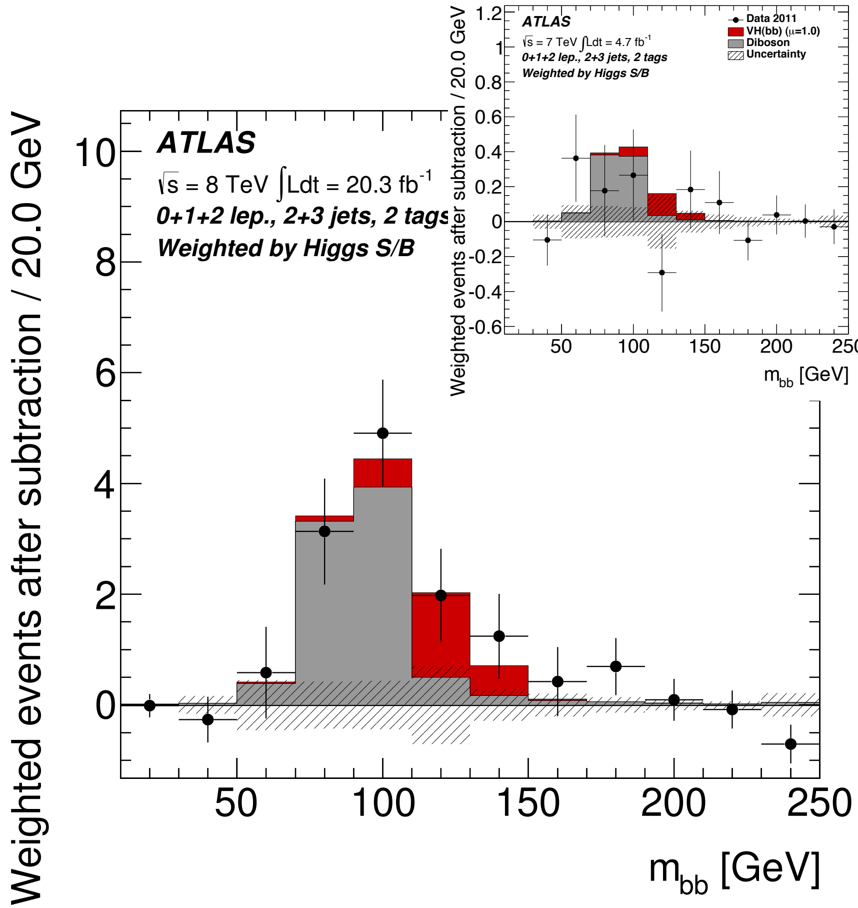


ATLAS

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

CMS

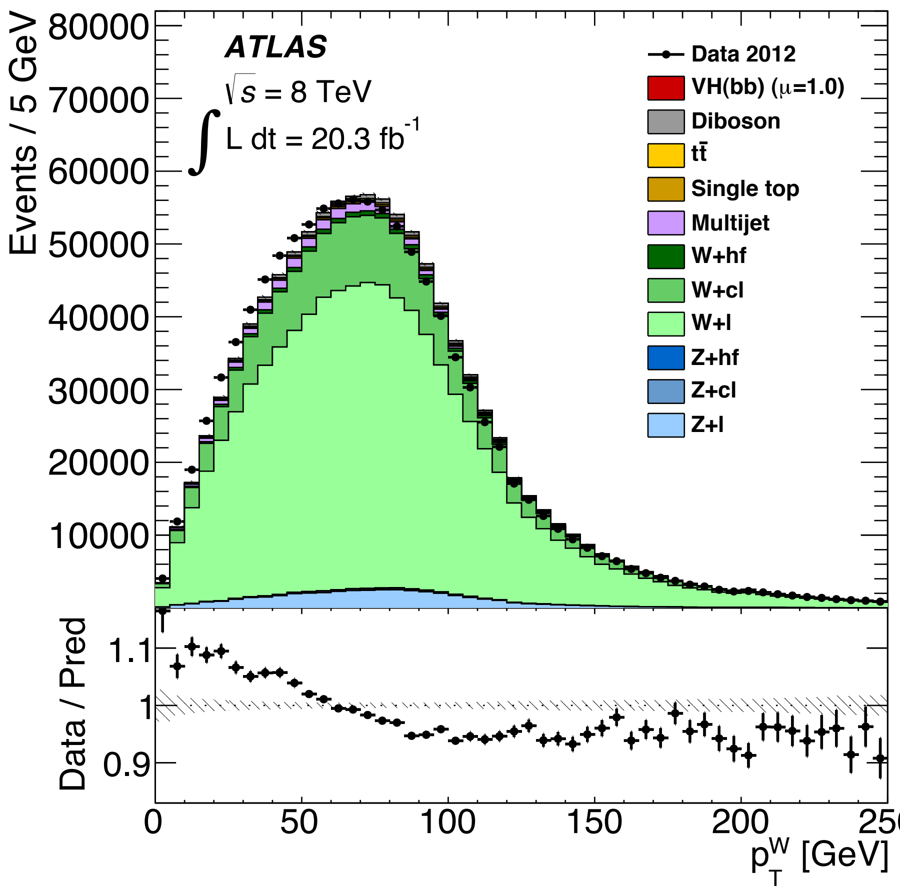
$$Z = 2.1\ (2.1)\ \sigma$$

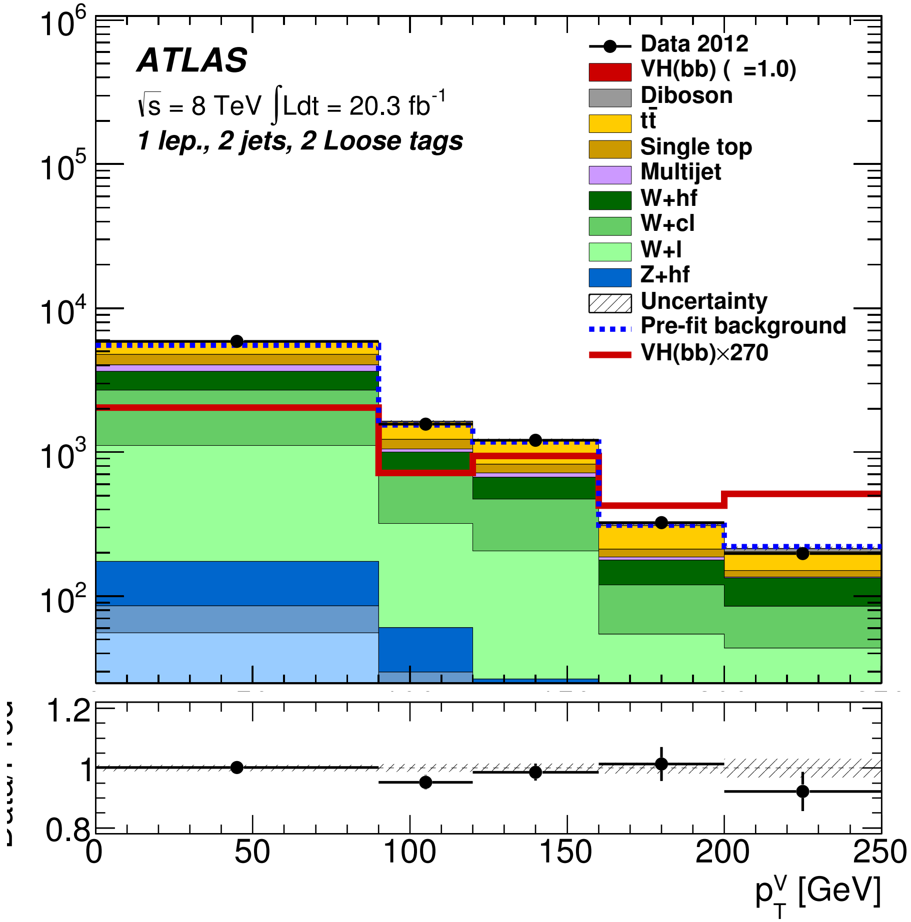


- Analysis using the boost (without substructure)
- Moderate s/b ratio starting from approximately few percent to approximately 30%

Boosted Analyses (without substructure)

Simulation of pT (V) is critical

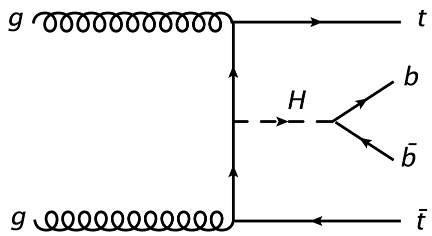


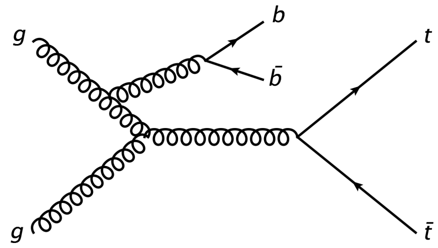


Our precision will depend a lot on the simulation, will move to state-of-the-art MC for Run-2

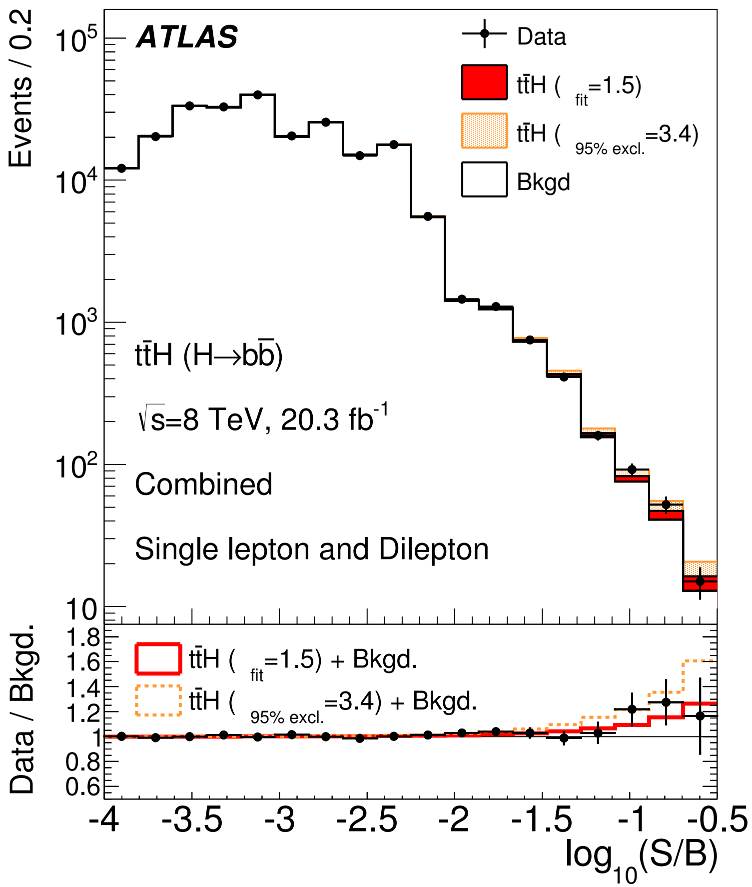
Cornering (directly) the top Yukawa coupling

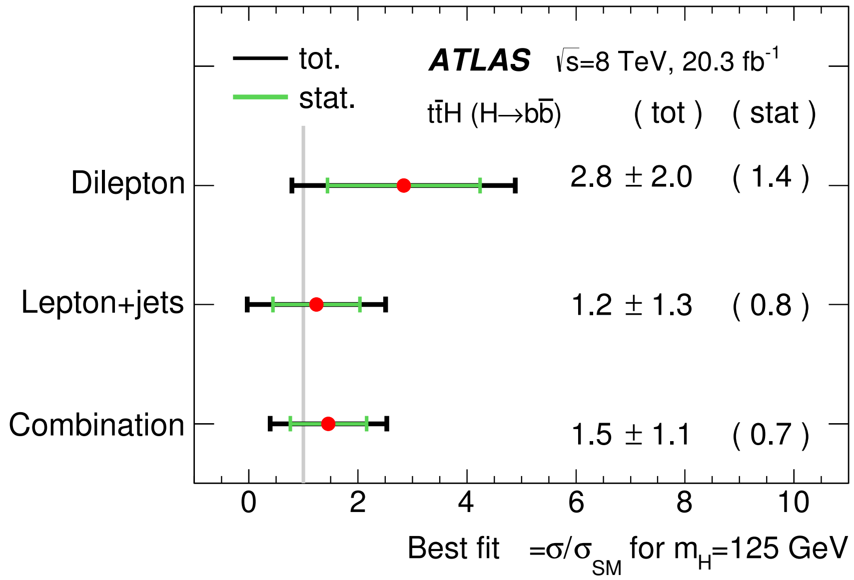
$ttH(bb)$





Very complex final state that requires a thorough control of the background

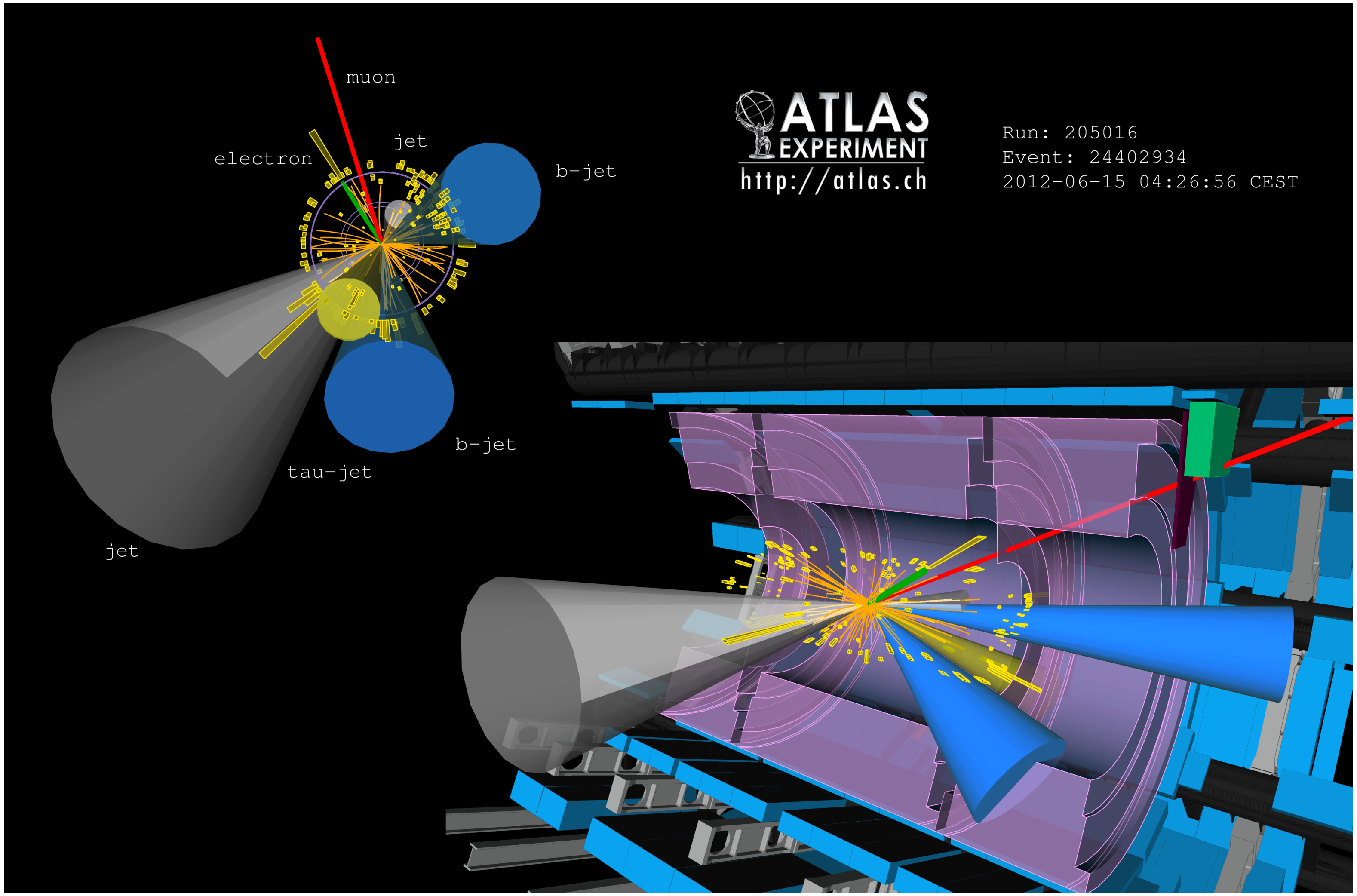




Cornering (directly) the top Yukawa coupling

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

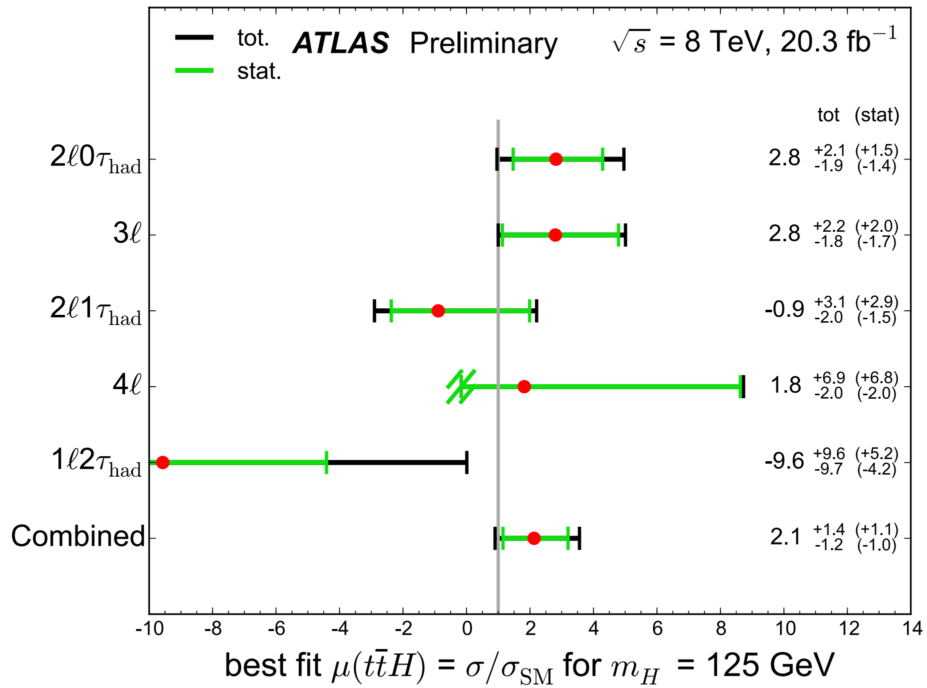
$$ttH\,(ML)$$

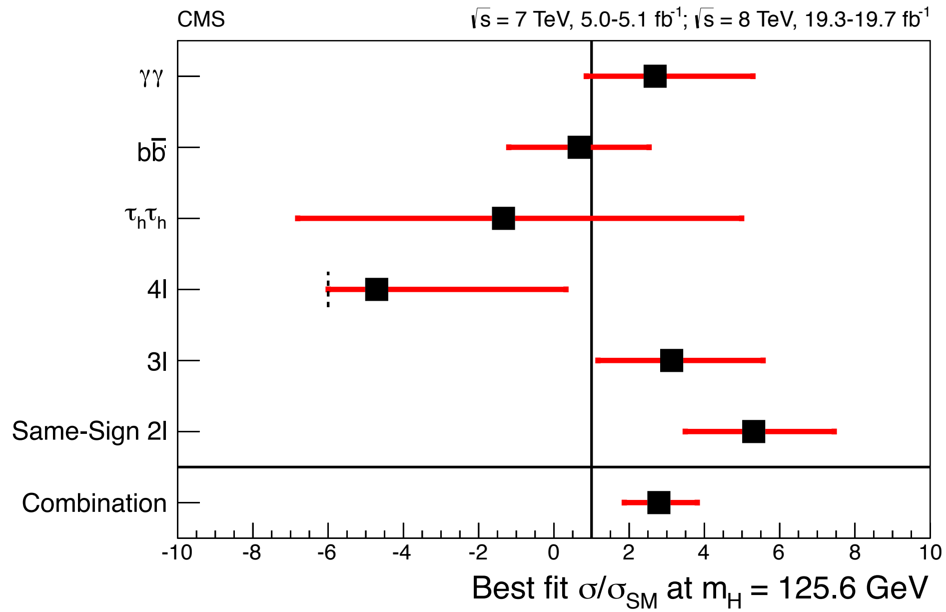


Cornering (directly) the top Yukawa coupling

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

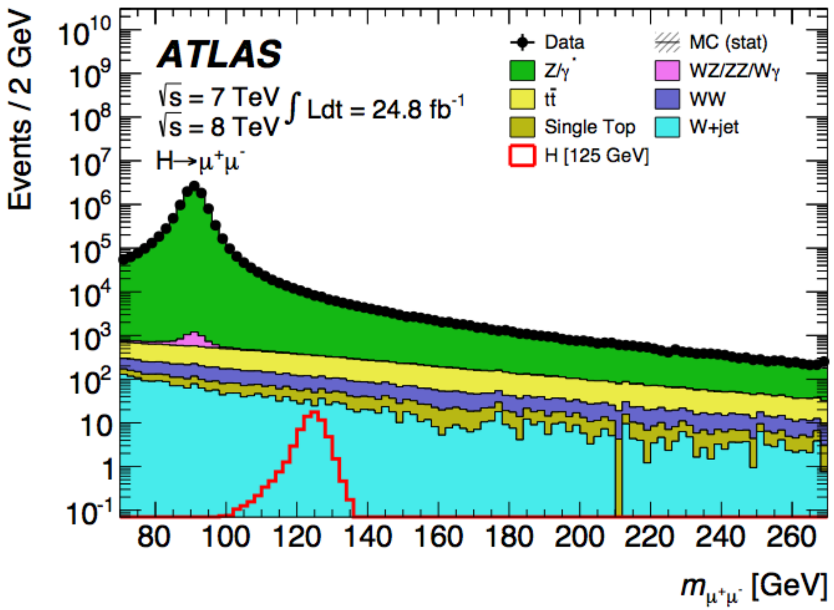
$$ttH(ML)$$





Hints of a signal emerging, a combination of ATLAS and CMS would be of course very interesting… Naive combination yields approximately 2 with an uncertainty of 0.7.

Rare Decays



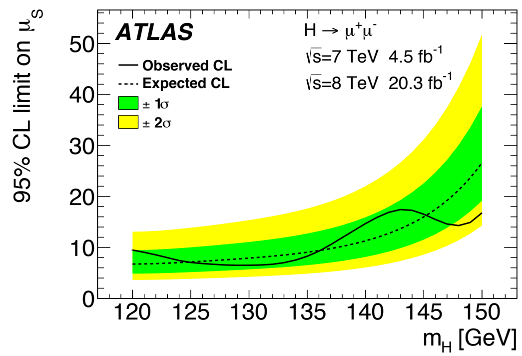
$\mu^+\mu^-$ Analysis strategy

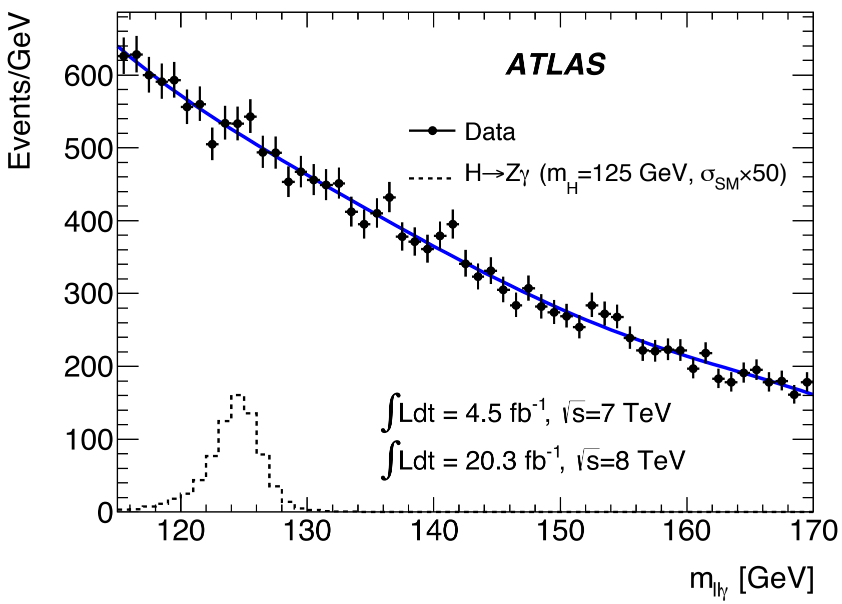
- 2 analysis channels (ggF and VBF)
- Analytic background model (similarly to γγ)

Results at 95% CL:

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

Universal couplings
~260 times SM





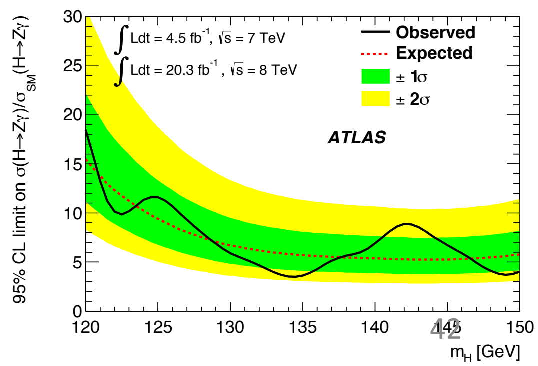
$Z\gamma$ Analysis strategy

PLB 732 (2014)

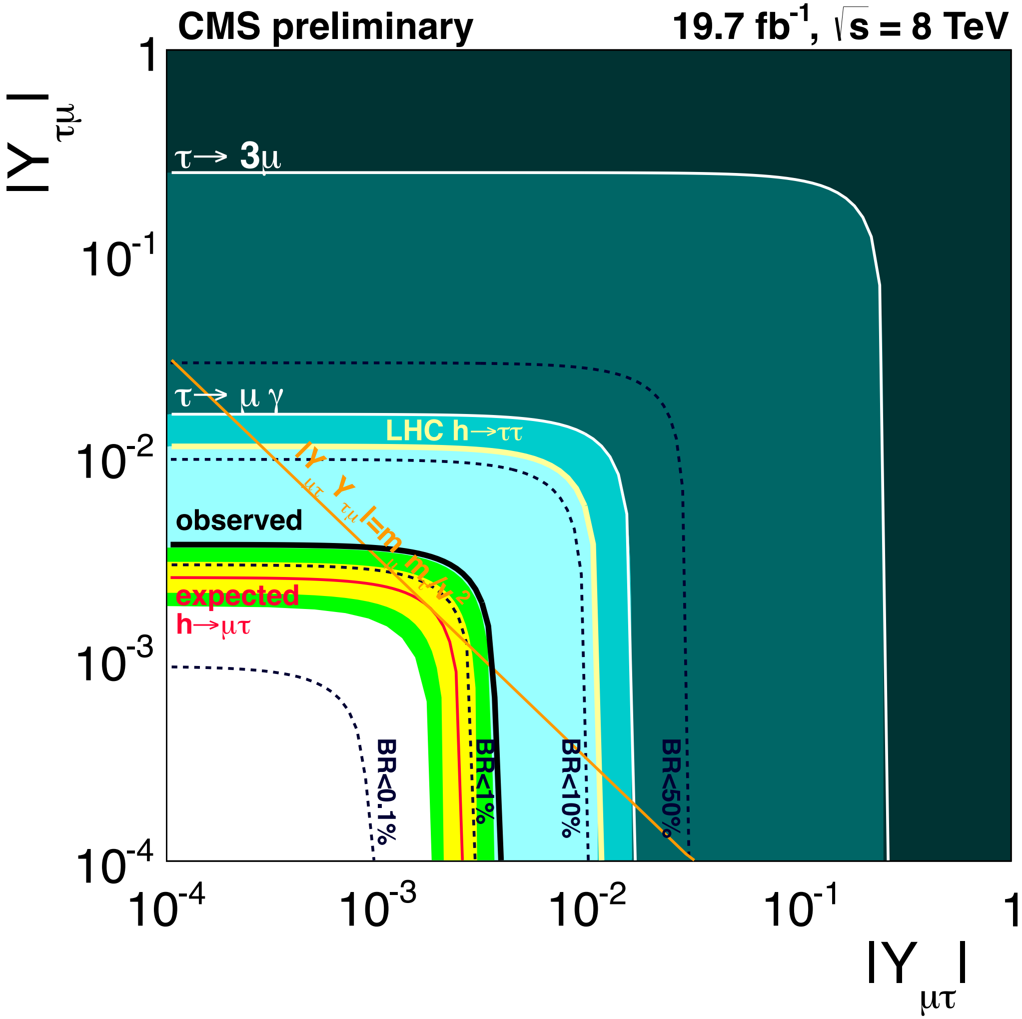
- Detector and pT Categories
- Analytic background model (similarly to γγ)

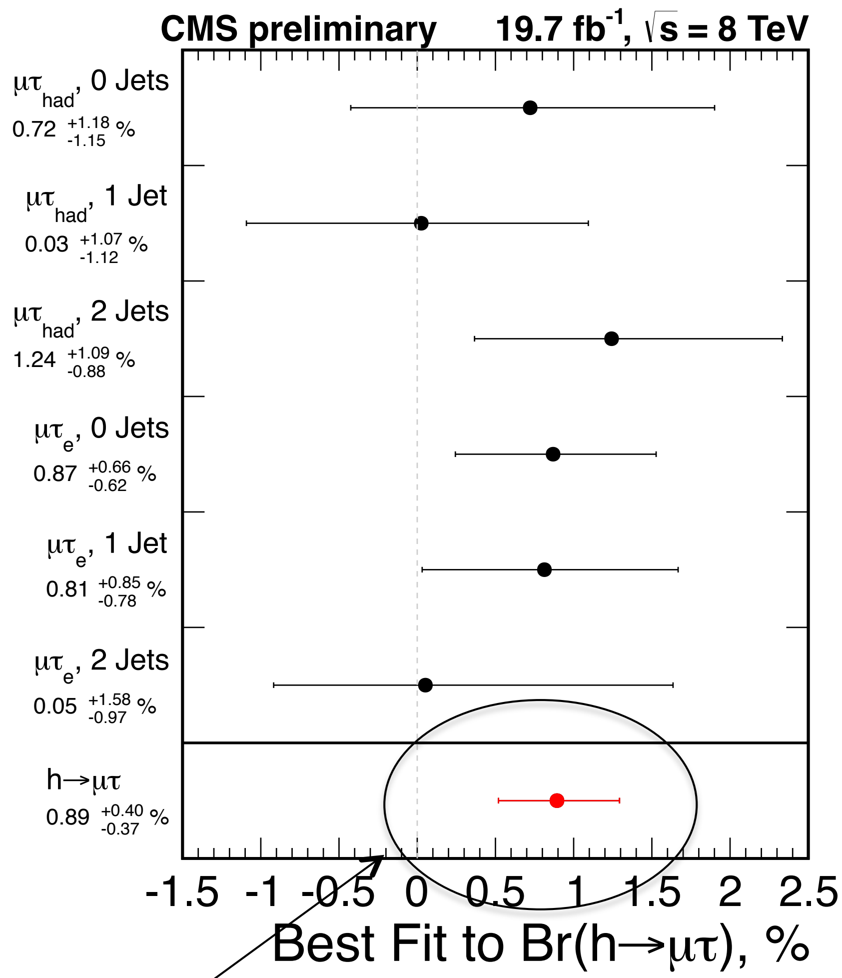
Results at 95% CL:

$\sigma.Br < 11\ (9)(\sigma.Br)_{SM}$



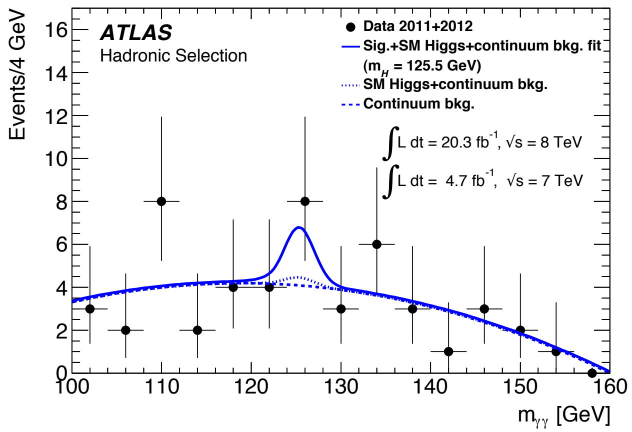
LFV Decays of the Higgs boson





~2.5σ Deviation…

Rare production modes



$FCNC\ t \rightarrow H(\gamma\gamma)\ q(u,c)$

In 2HDM type III (without flavor conservation)
The c(u)H coupling is present at tree level

95% CL upper limit

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

JHEP 06 (2014) 08

$HH \rightarrow bb\gamma\gamma$

CERN-PH-EP-2014-113

Non resonant 95%CL limit:

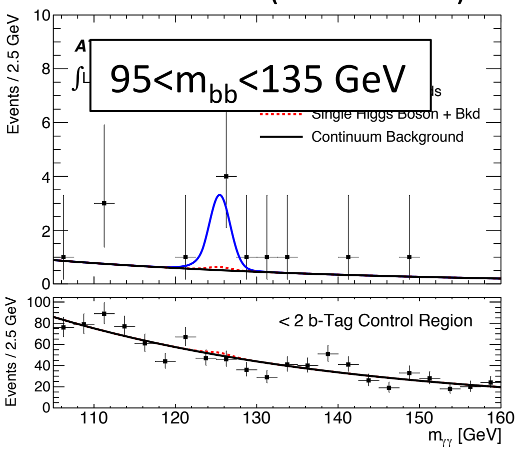
$\sigma_{HH}\ Br_{bb,\gamma\gamma} < 2.2\ (1.0)$ pb

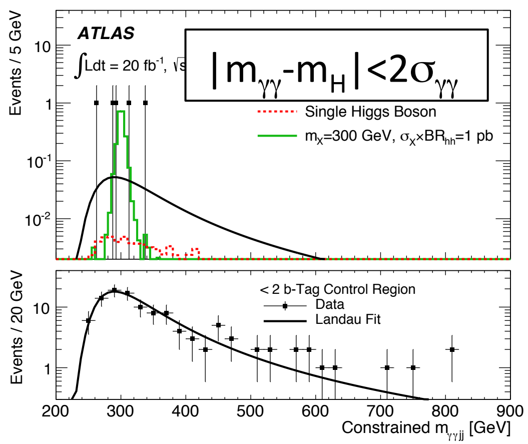
(2.4σ excess)

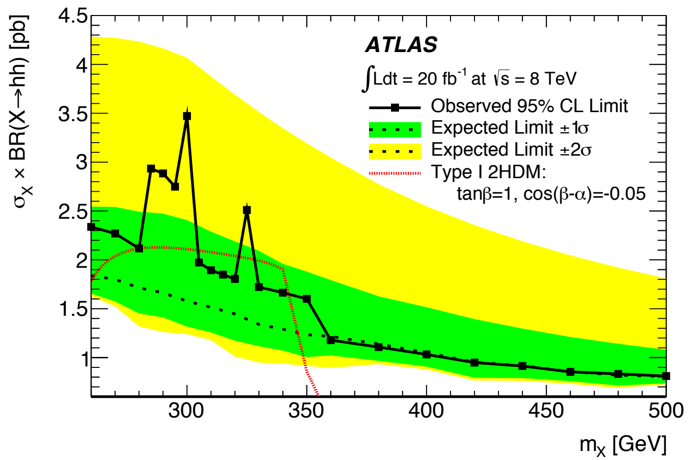
$X \rightarrow HH \rightarrow bb\gamma\gamma$

Search for a resonance
(Heavy Higgs, radion, stoponium, etc…)

(Counting in smallest window containing 95% signal)







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The Higgs Natural Width at the LHC and the Higgs as portal to Dark Matter

- Direct measurements of the width
- Width with interference
- Off shell couplings
- Invisible Higgs channels

The Natural Width of the Higgs Boson

$\Gamma_{SM} = 4.2\ \text{MeV}$ Is small therefore small couplings to the Higgs can be easily visible: tool for discovery!

At LHC total width not simply accessible…

- Direct measurement (on-shell) with the ZZ(4l) and $\gamma\gamma$ channels [obs. (exp.)]:

  Γ_{4l} < 2.6 (3.5) GeV *[exp. 6.5 for μ=1]* and $\Gamma_{\gamma\gamma}$ <5.0 (6.2) GeV

- Only measure ratio of couplings or coupling modifiers with specific assumptions

- Constraints from invisible (and exotic decays)

Total width: Interference in diphoton

(SM shift of approximately 50 MeV)

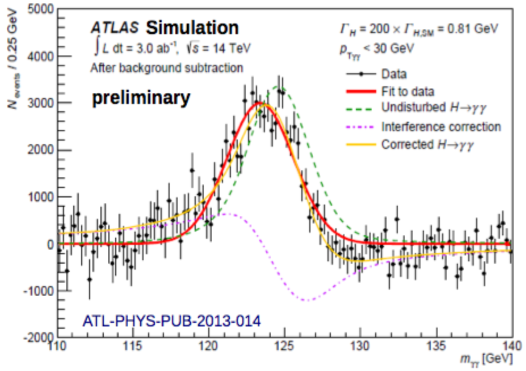
Use pT dependence of shift

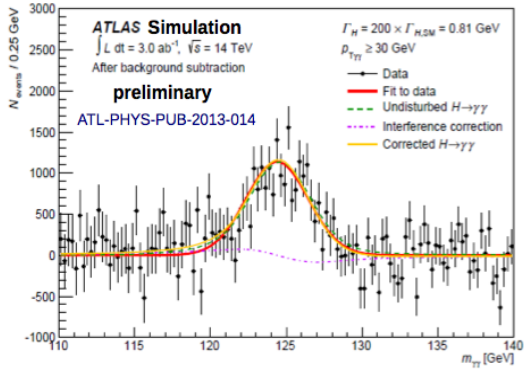
(~200 MeV limit expected for 3 ab^{-1})

Total width:

Through off shell couplings

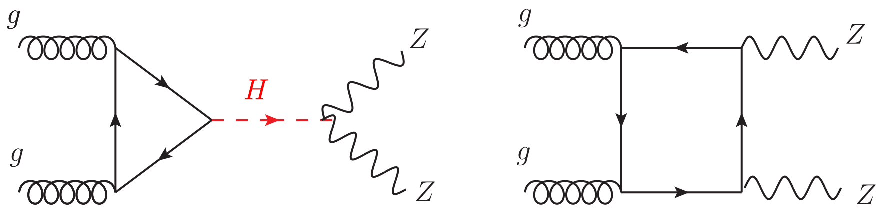
ATL-PHYS-PUB-2013-014





Off Shell Higgs Couplings

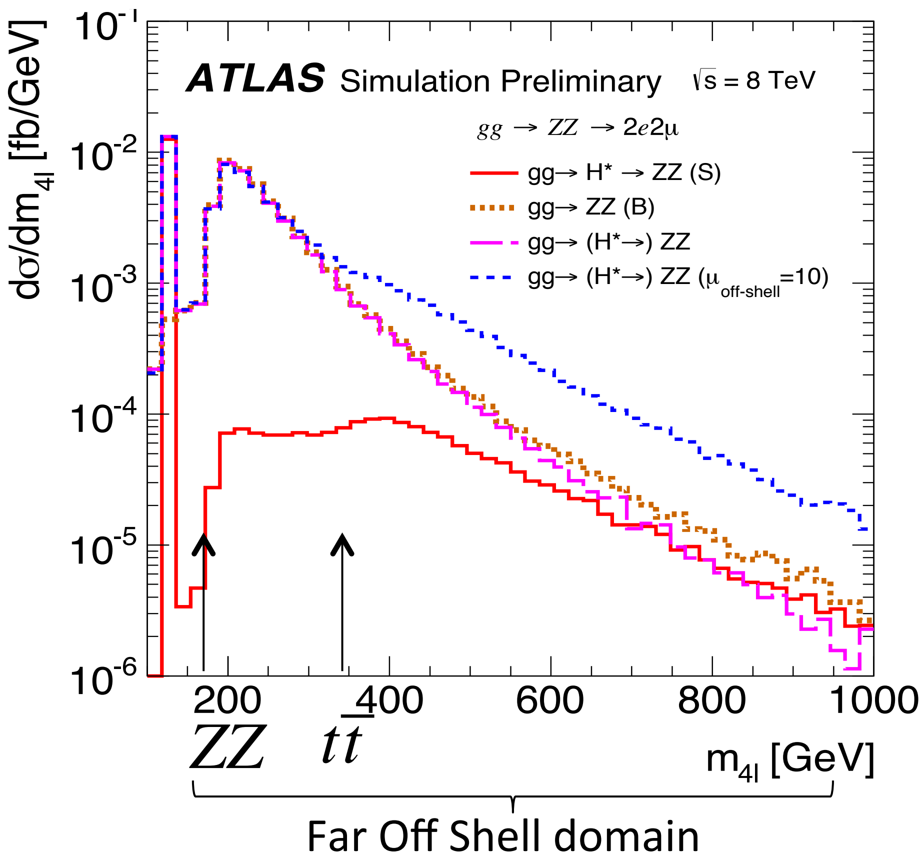
What are the limitations?



$$\mu_{OffShell} \equiv \frac{\sigma^{gg \to H^* \to ZZ}_{OffShell}}{(\sigma^{gg \to H^* \to ZZ}_{OffShell})_{SM}} = (\kappa_g^2 \kappa_V^2)_{OffShell}$$

Higgs boson as a propagator

ATLAS-CONF-2014-042



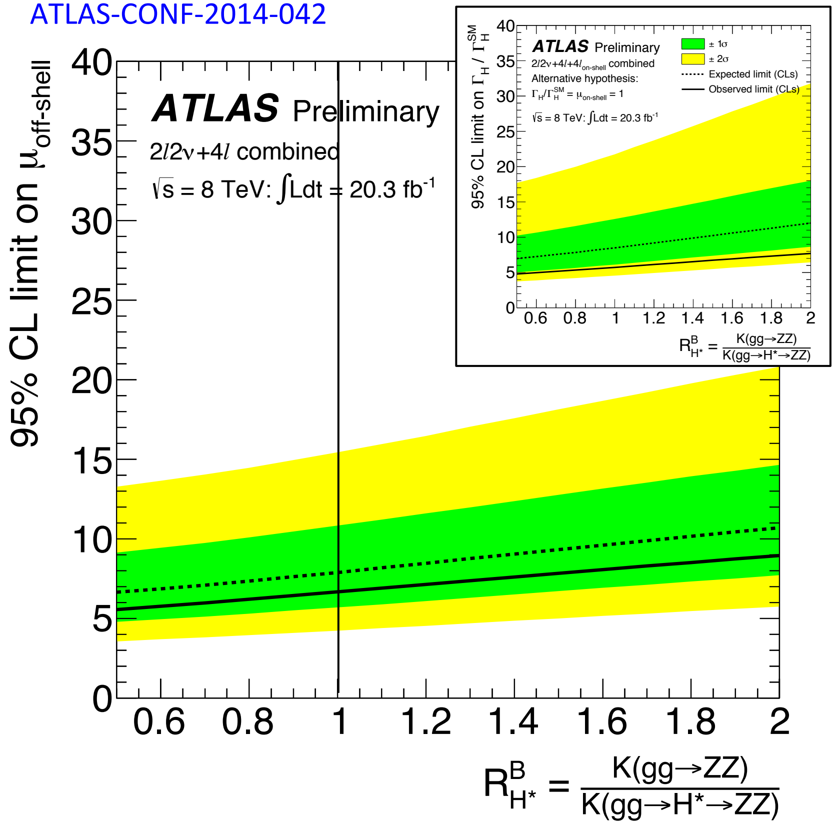
- LO description of the continuum (gg2VV), use of k-factor: no assumption made on bkg k-factor

$$R^b_{H^*} = \frac{k_{gg \to ZZ}}{k_{gg \to H^* \to ZZ}}$$

- Uncertainty of 30% on the interference term w.r.t. to chosen continuum k-factor

CLs limits on Off-Shell signal strength

ATLAS-CONF-2014-042



Agnostic to k-factor!

R=1 (Verified in the soft colinear approximation)
(G. Passarino)

95% CL limit obs. (exp.)
$\mu_{OffShell} < 6.7$ (7.9)

...and on the total width

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

Using:

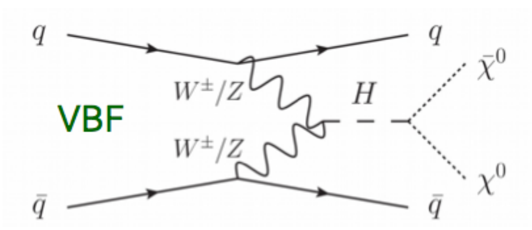
$$(\kappa_g^2 \kappa_V^2)_{OnShell} = (\kappa_g^2 \kappa_V^2)_{OffShell}$$

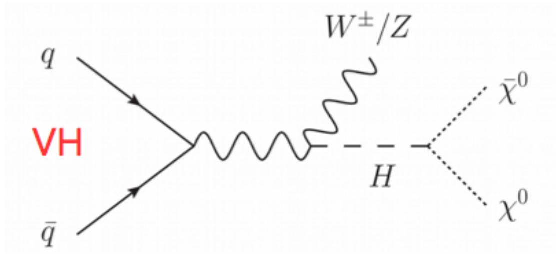
*Particularly sensitive to running of the effective coupling κ_g in the production (through loop)

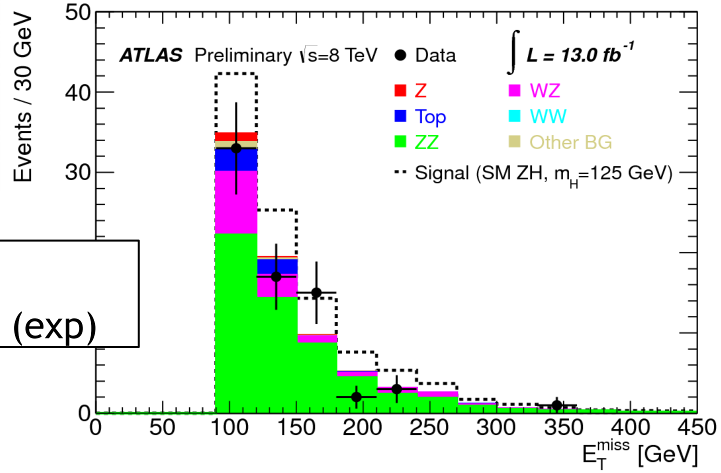
Source of systematic uncertainties	95% CL on $\mu_{\mathrm{off-shell}}$
QCD scale for $gg \to ZZ$	6.7
QCD scale for the $gg \to (H^* \to) ZZ$ interference	6.7
QCD scale for $q\bar{q} \to ZZ$	6.4
Z BG systematic	6.2
Luminosity	6.2
PDF for $pp \to ZZ$	6.1
Sum of remaining systematic uncertainties	6.2
No systematic	6.0
All systematic	7.9

Statistically limited
dominant systematic is TH

Search for Invisible Higgs Decays

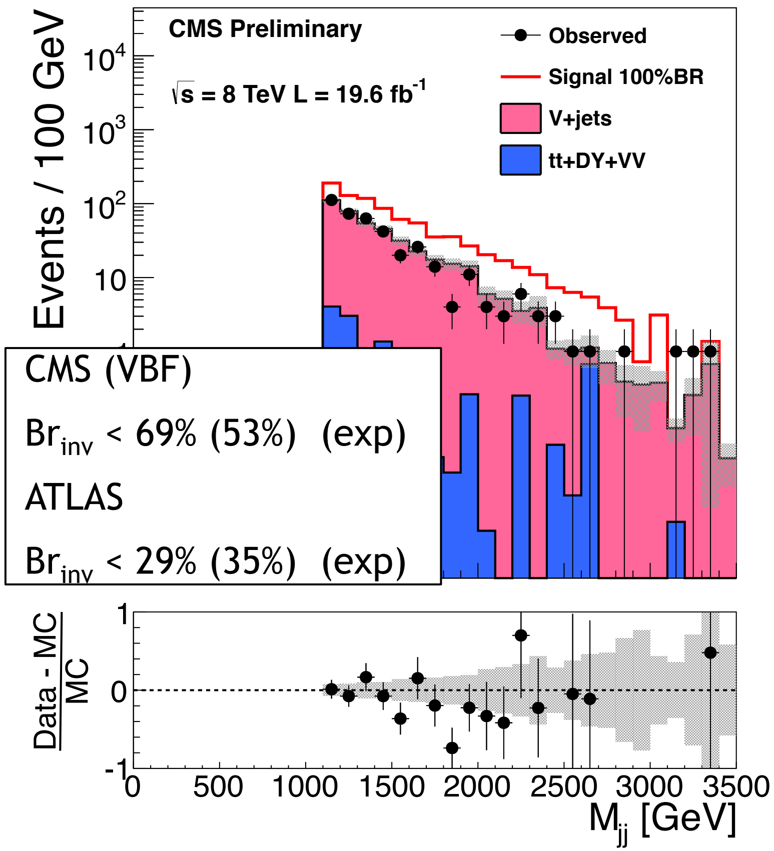






ATLAS (ll MET)

Br_{inv} < 75% (62%) (exp)

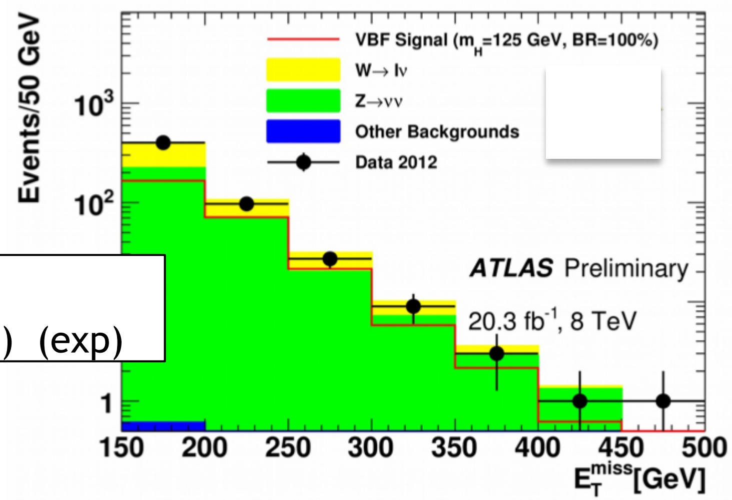


CMS (VBF)

Br_{inv} < 69% (53%) (exp)

ATLAS

Br_{inv} < 29% (35%) (exp)

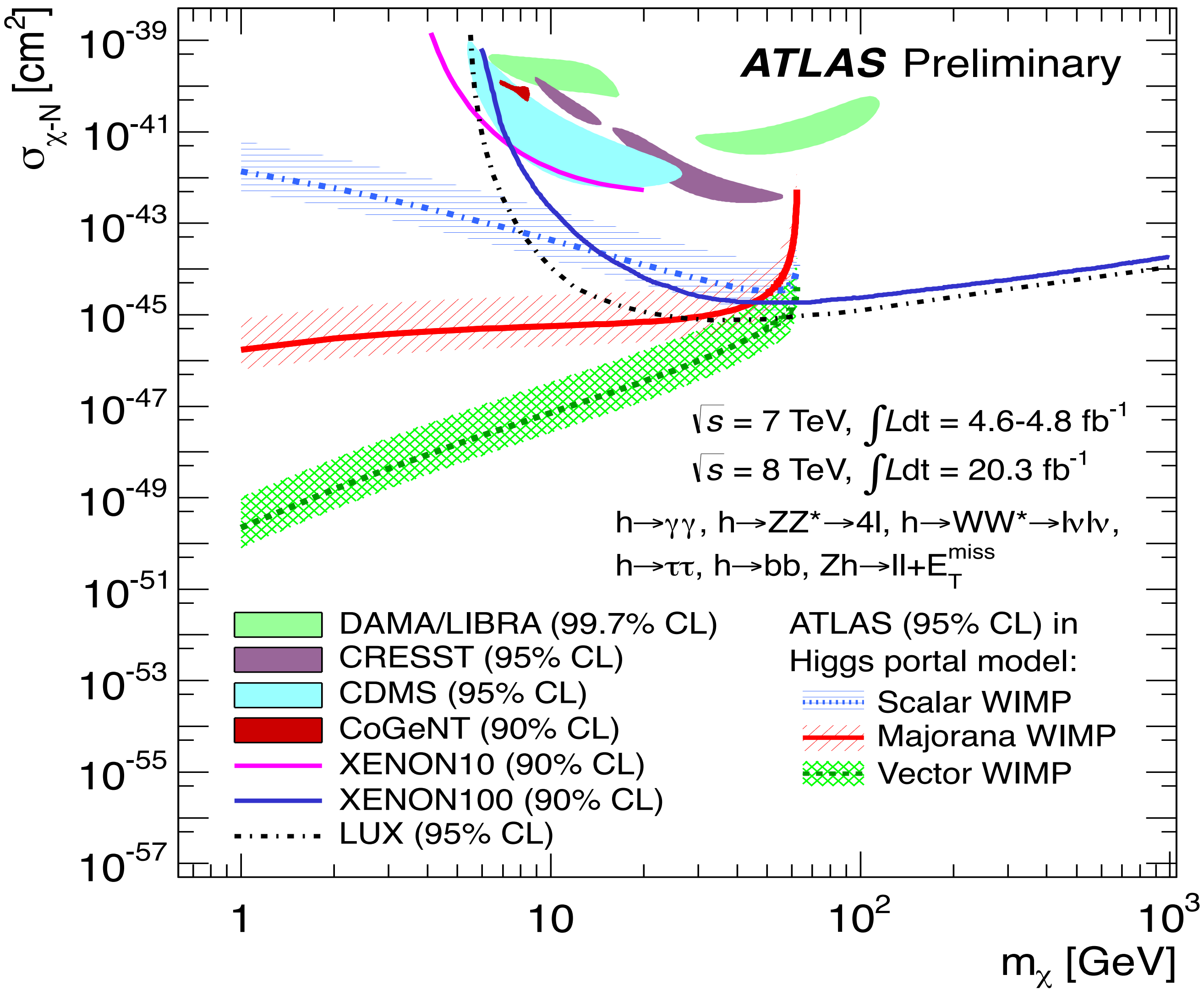


ATLAS (jj MET)

Br_{inv} < 78% (86%) (exp)

Inivisible branching constrained at the level of ~30%

Higgs Portal Interpretation



Outline

Introduction — *Run 1, the discovery and its implications*

Higgs physics with the discovery channels

- *The mass of the Higgs boson*
- *Differential cross sections*
- *Its main quantum numbers JPC*

Exploring the vast LHC potential

- Discovery in the fermionic channels
- Cornering the top Yukawa
- Rare decays

The Higgs Natural Width at the LHC and the Higgs as portal to Dark Matter

- Direct measurements of the width
- Width with interference
- Off shell couplings
- Invisible Higgs channels

Coupling properties of the Higgs boson

$$\mu$$

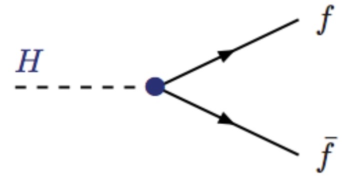
Combination Master Formula

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

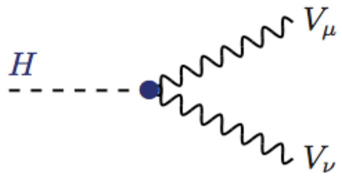
$$n_s^c = \mu \sum_{i \in \{productions\}} \sum_{f \in \{decays\}} \mu^i \sigma_{SM}^i \times \mathrm{A}^{ifc} \times \varepsilon^{ifc} \times \mu^f Br^f \times L^c$$

The Higgs Sector and κ Framework

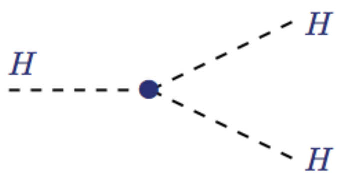
A Predictive Sector of non Universal Couplings



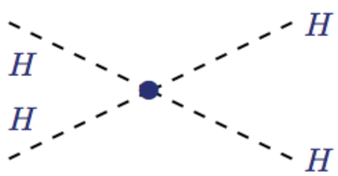
$$g_{Hff} = m_f/v \quad \propto \kappa_F$$



$$g_{HVV} = 2M_V^2/v \quad \propto \kappa_V$$



$$g_{HHH} = 3M_H^2/v$$

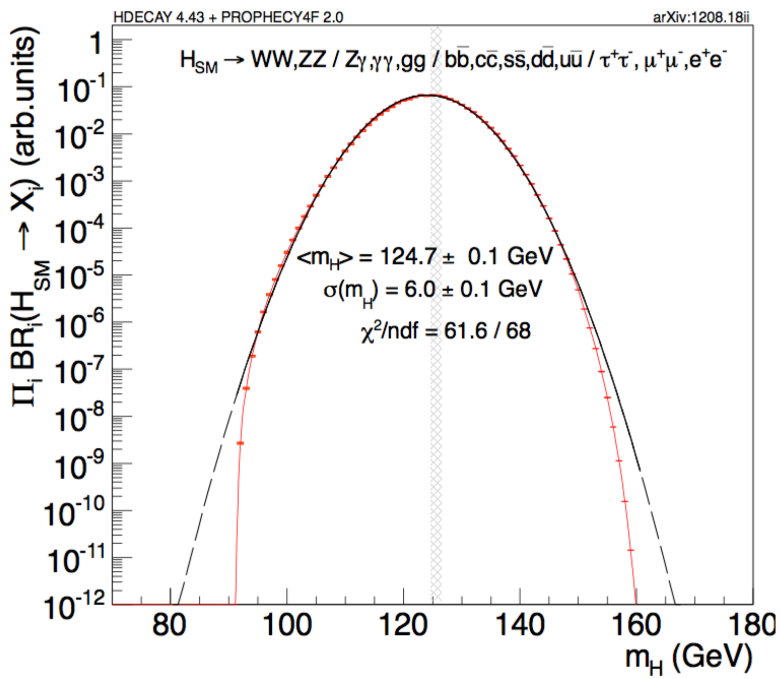


$$g_{HHHH} = 3M_H^2/v^2$$

A rather special value of the Higgs mass (II)

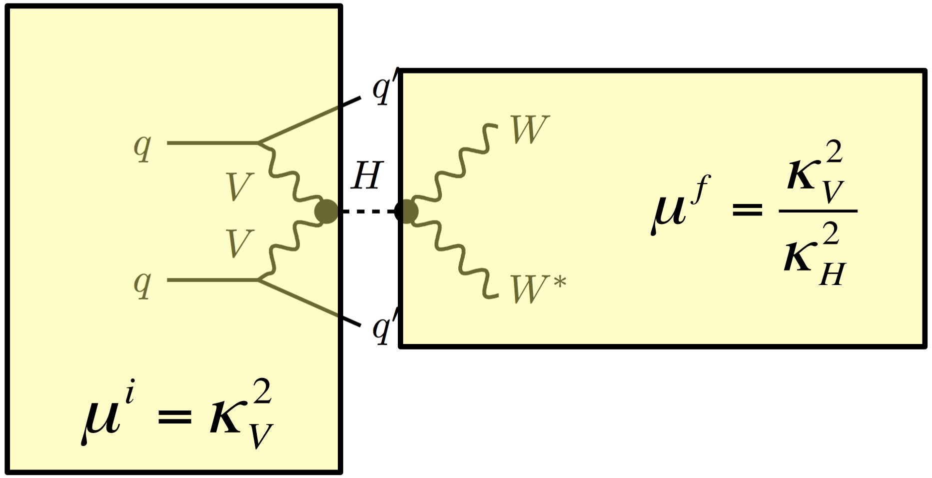
"A Gift of Nature"

Fabiola Gianotti (July 4, 2012 CERN)



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

$$\kappa$$

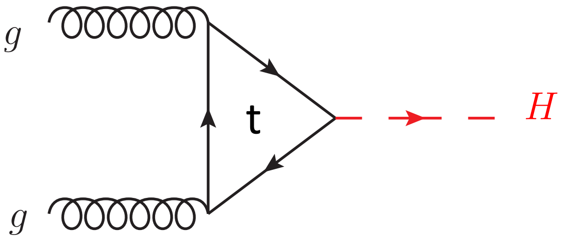


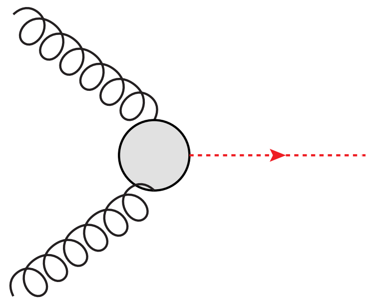
$$\kappa_H^2 = \frac{\sum_f \Gamma_f}{\Gamma_{SM}} = \underbrace{0.75 \times \kappa_F^2 + 0.25 \times \kappa_V^2}_{\text{Assuming no BSM width}}$$

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



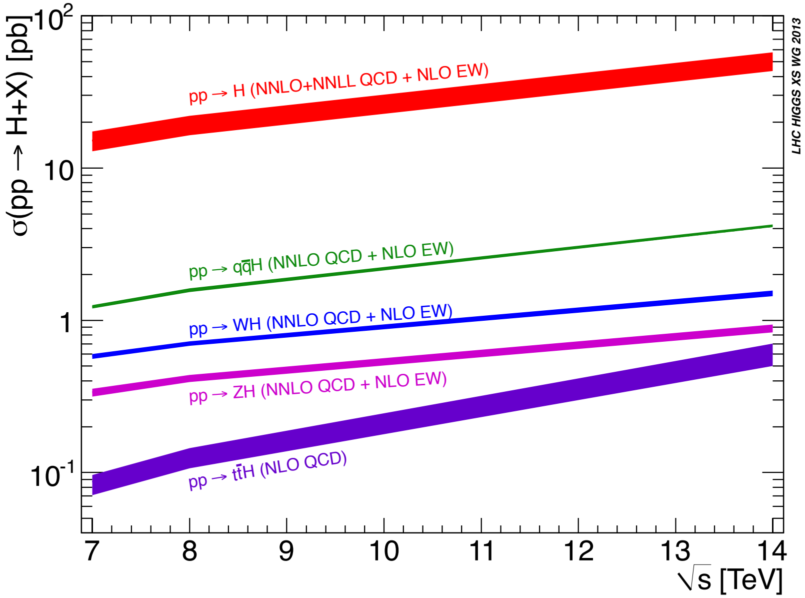


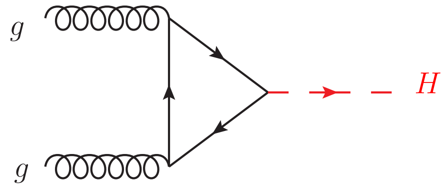
$$\kappa_g^2 \propto 1.\times 06\kappa_t^2 - 0.07 \times \kappa_t \kappa_b + 0.01 \times \kappa_b^2$$

$$\kappa_g^2$$

Higgs Production Modes

κ for m_H = 125.5 GeV



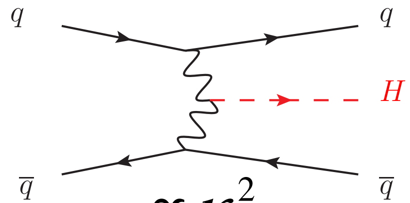


Gluon fusion process

NNnLO ~O(10%)

~0.5 M events produced

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



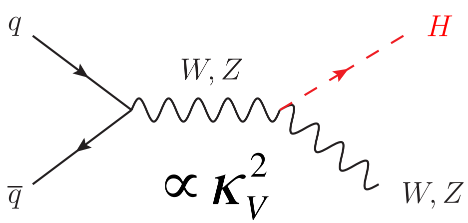
$\propto \kappa_V^2$

Vector Boson Fusion

NNLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap

~40 k events produced

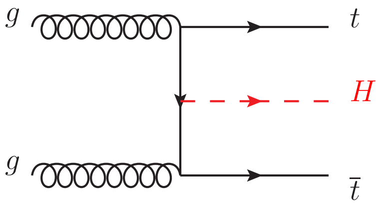


$\propto \kappa_V^2$

W and Z Associated Production

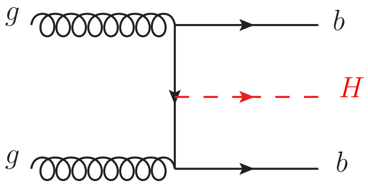
NNLO TH uncertainty ~O(5%)

~20 k events produced



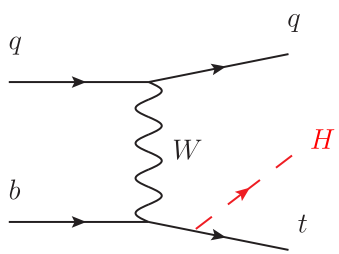
$\propto \kappa_t^2$

Top Assoc. Prod. ~3 k evts produced

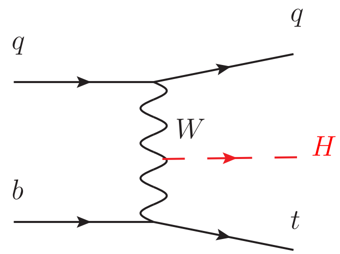


$\propto \kappa_b^2$

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



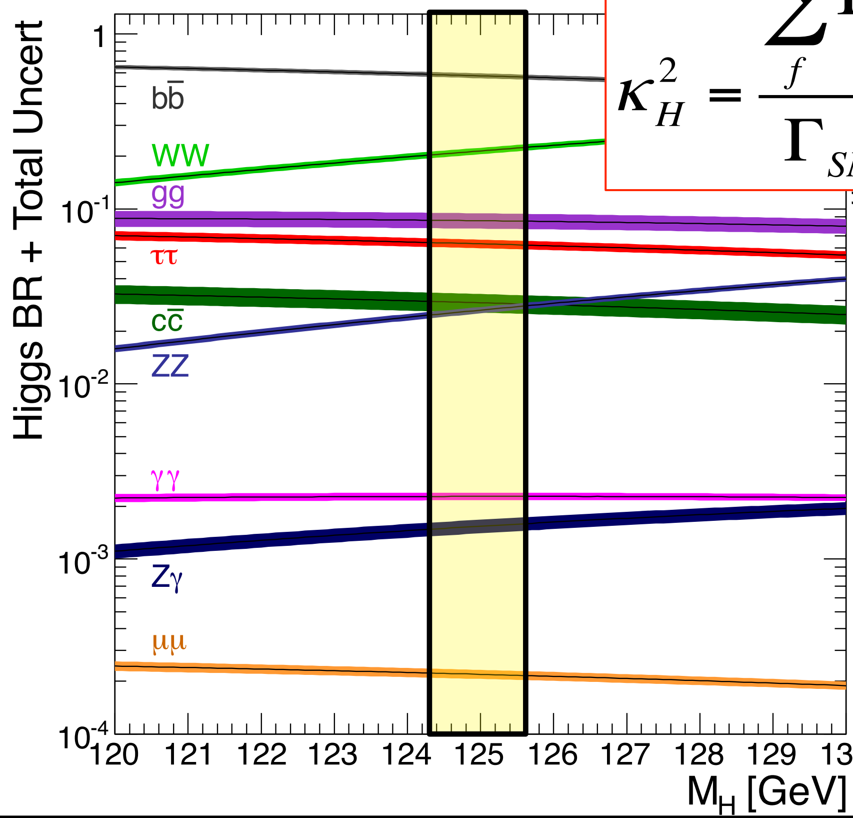
tH



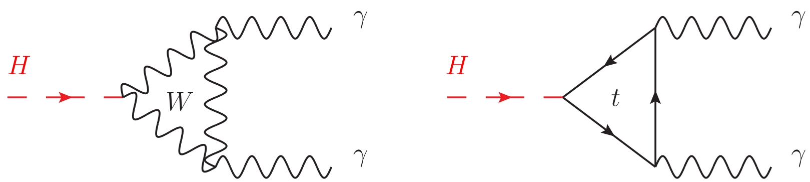
$$\propto 3.3\times\kappa_W^2 - 5.1\times\kappa_t\kappa_W + 2.8\times\kappa_t^2$$

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%) $\propto \kappa_\tau^2 / \kappa_H^2$
- 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%) $\propto \kappa_\gamma^2 / \kappa_H^2$



$$\kappa_H^2 = \frac{\sum_f \Gamma_f}{\Gamma_{SM}}$$



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

(when assuming no BSM charged in the loop)

- The Zγ (0.2%) $\kappa_{Z\gamma} \propto 1.12 \times \kappa_W^2 - 0.15 \times \kappa_t \kappa_W + 0.03 \times \kappa_t^2$
- The μμ channel (0.02%) $\propto \kappa_\mu^2 / \kappa_H^2$

Overall Signal Strength

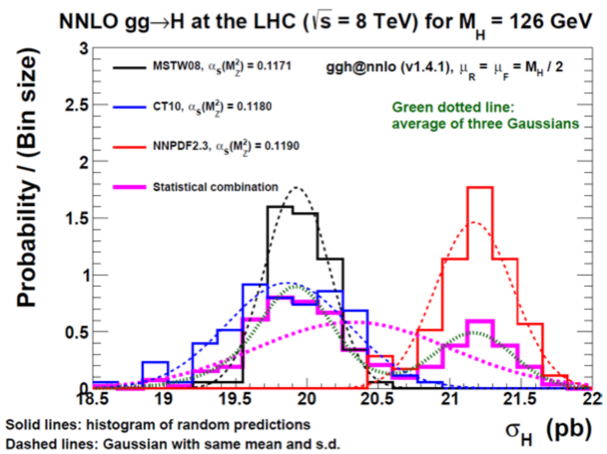
$$n_s^c = \mu \left(\sum_{i \in \{processes\}} \mu^i \sigma_{SM}^i \times A^{ic} \times \varepsilon^{ic} \right) \times \mu^f Br^f \times L^c$$

ATLAS

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

CMS

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



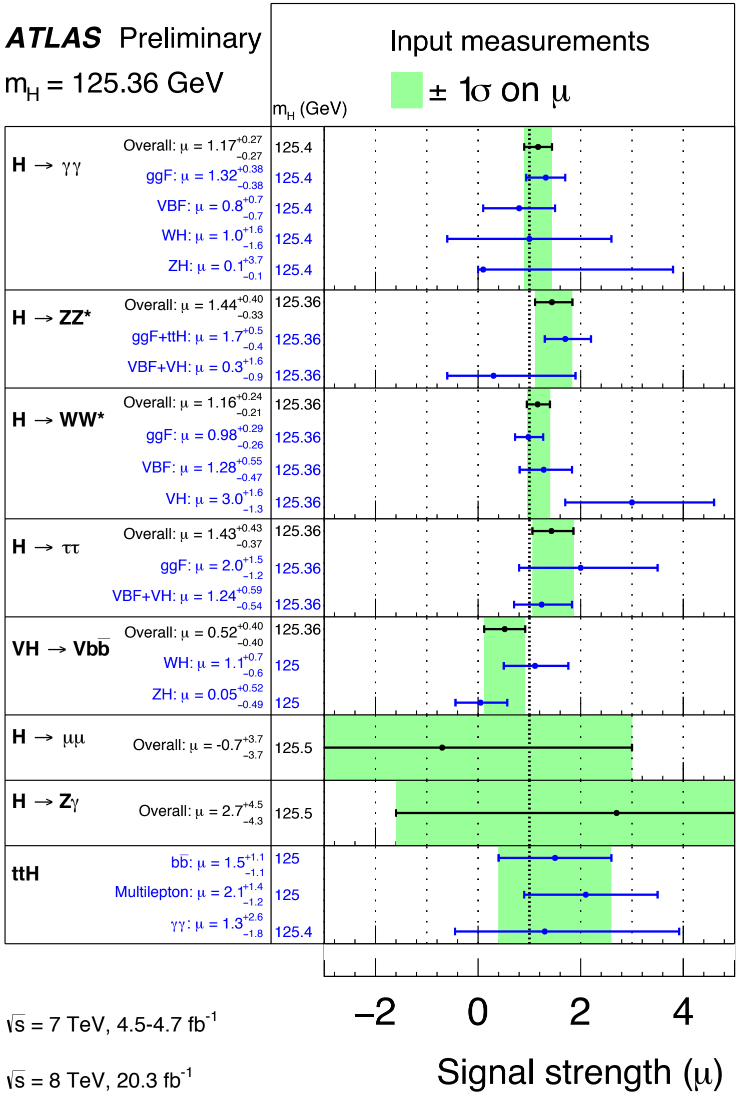
PDF (+ α_S) Uncertainties will very soon dominate the TH systematic

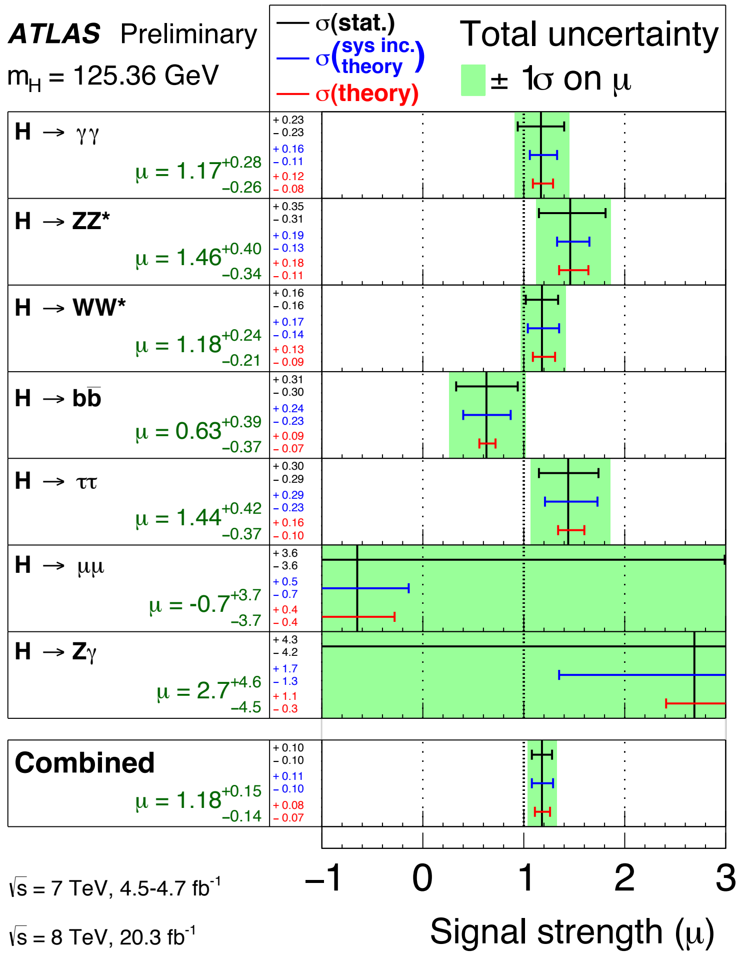
Strengths in the Main Categories

Independent fit of each channel

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

Combination of all channels assuming SM production

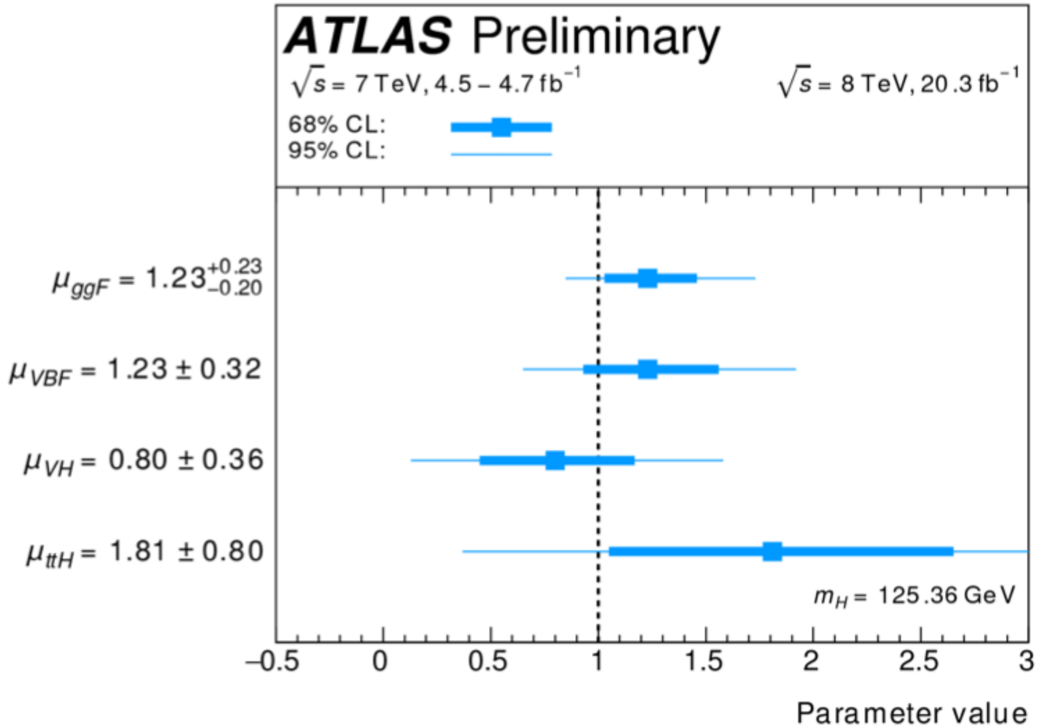


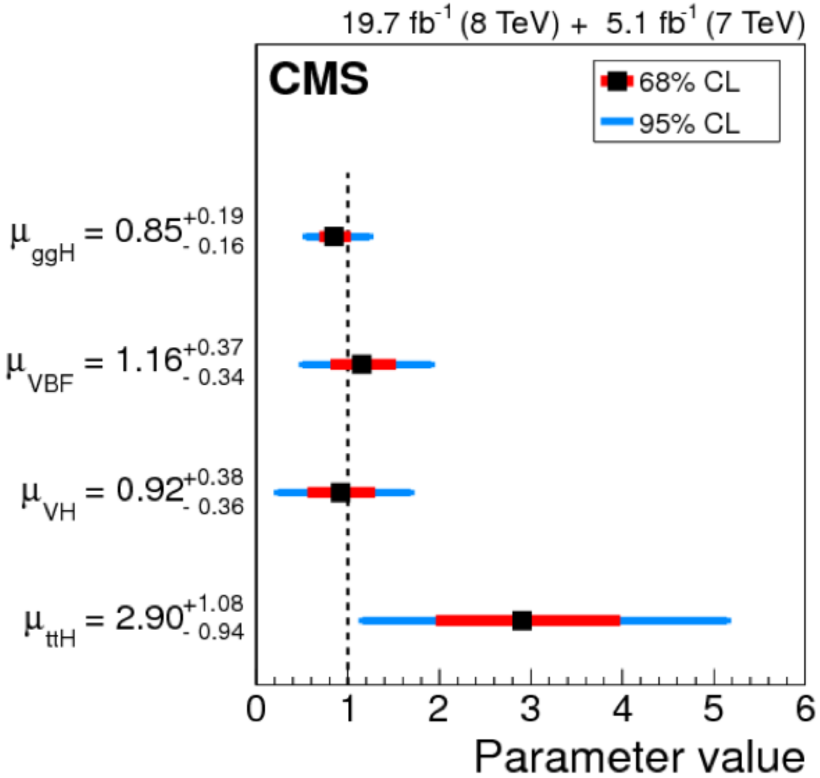


Production Strengths or Cross Sections

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

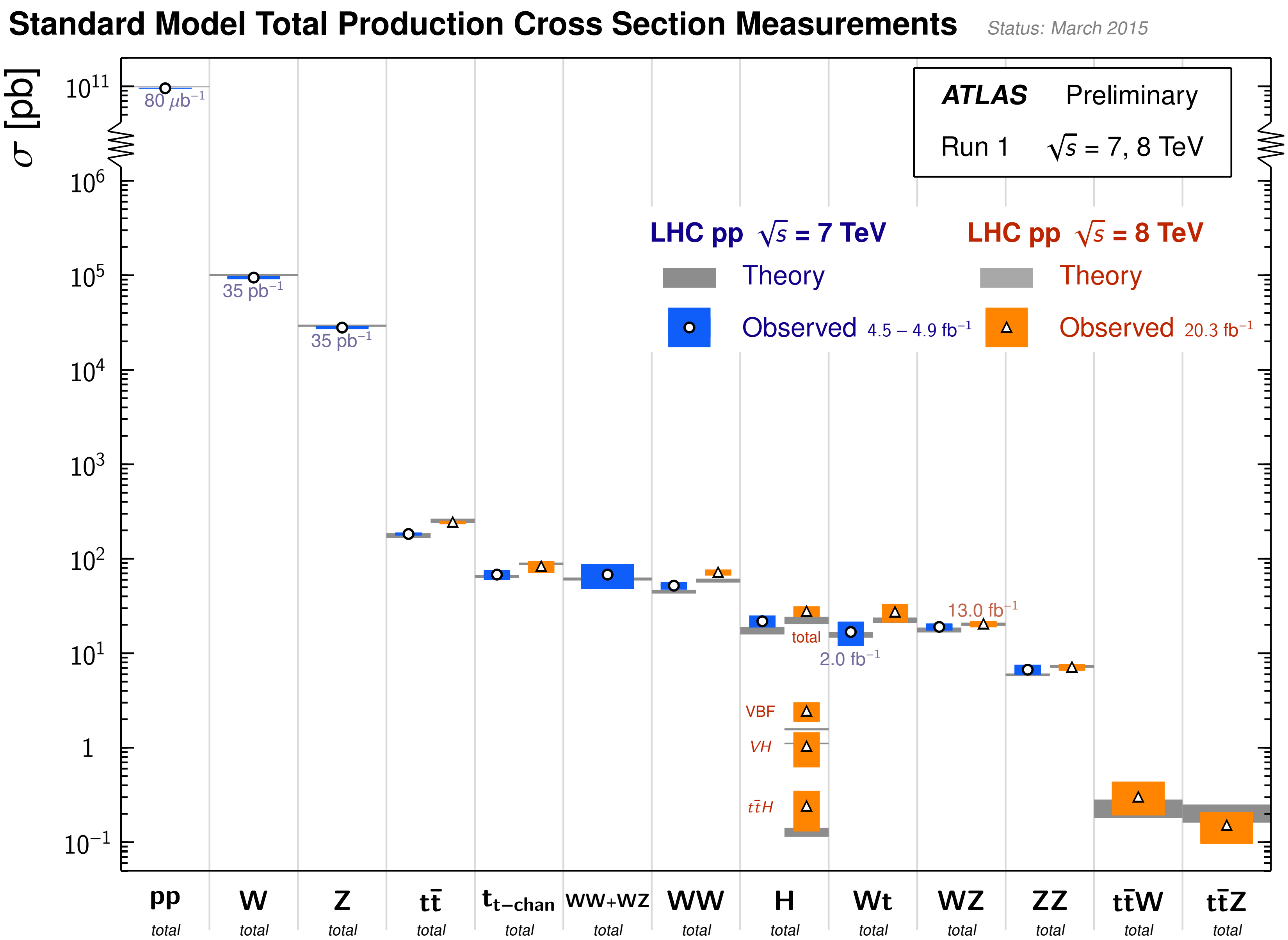
Combination of all channels assuming SM branchings





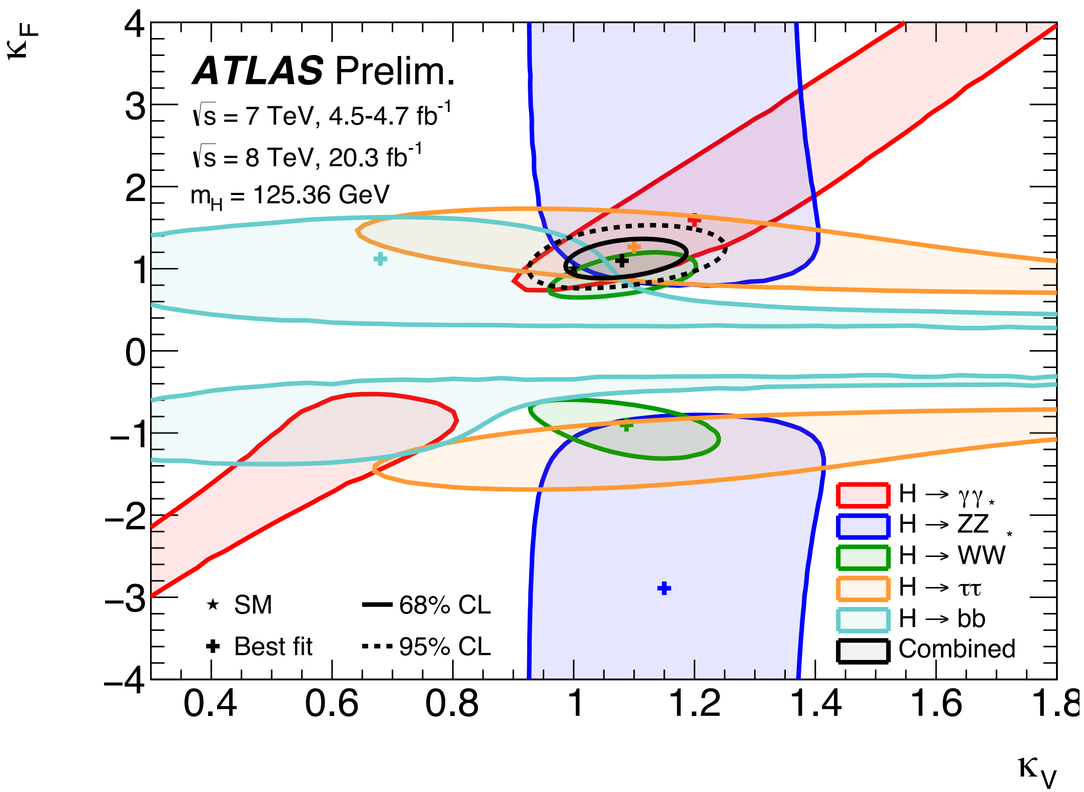
Clear evidence of production in the two main modes

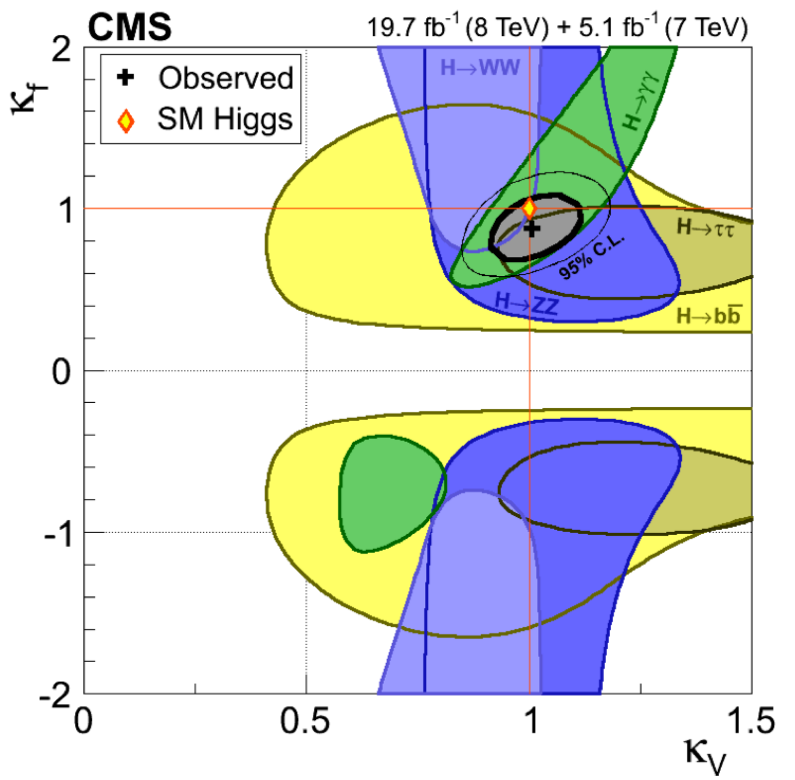
Overview of Cross Sections



Coupling to SM Spectra with Assumptions

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

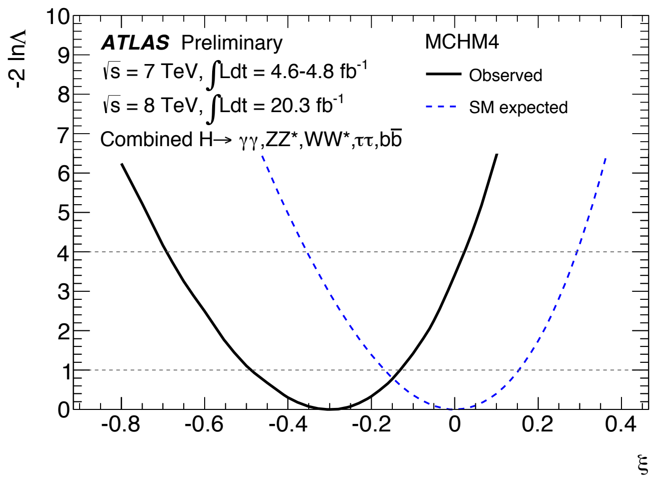




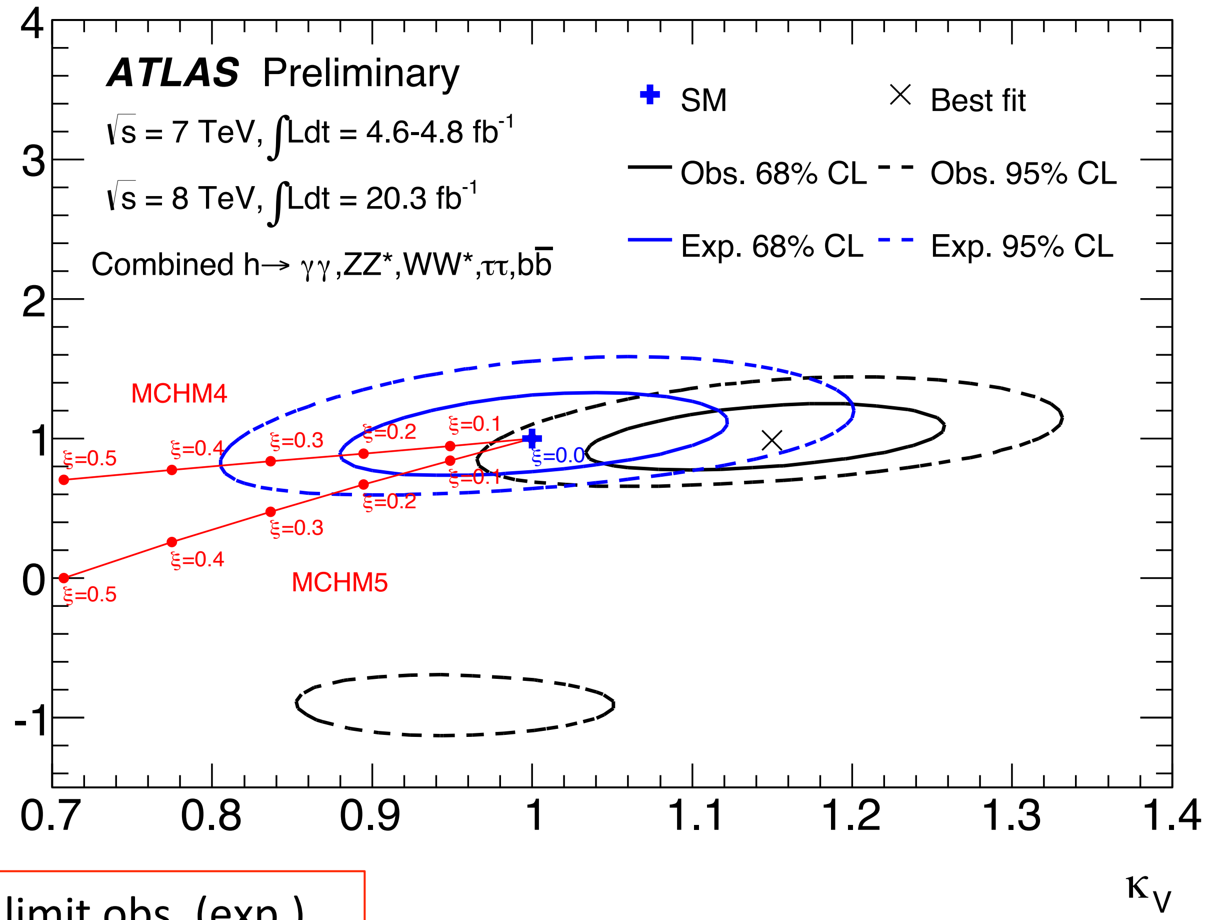
Measurements very compatible with SM hypothesis

Probing the coupling to SM particles

- BSM particles neither in the decay nor in the loops
- Fermion couplings constrained mainly through ggF production
- Interpreration in Composite Higgs models (MCHM4 and MCHM5)



ATLAS-CONF-2014-010



$$\xi = v^2/f^2$$

$$\kappa_V = \sqrt{1-\xi}$$

$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

f compositness scale:

95% CL limit obs. (exp.)
f > 710 (460) GeV

Coupling to SM Spectra with Assumptions

Assuming no BSM in the loops or in the decay,
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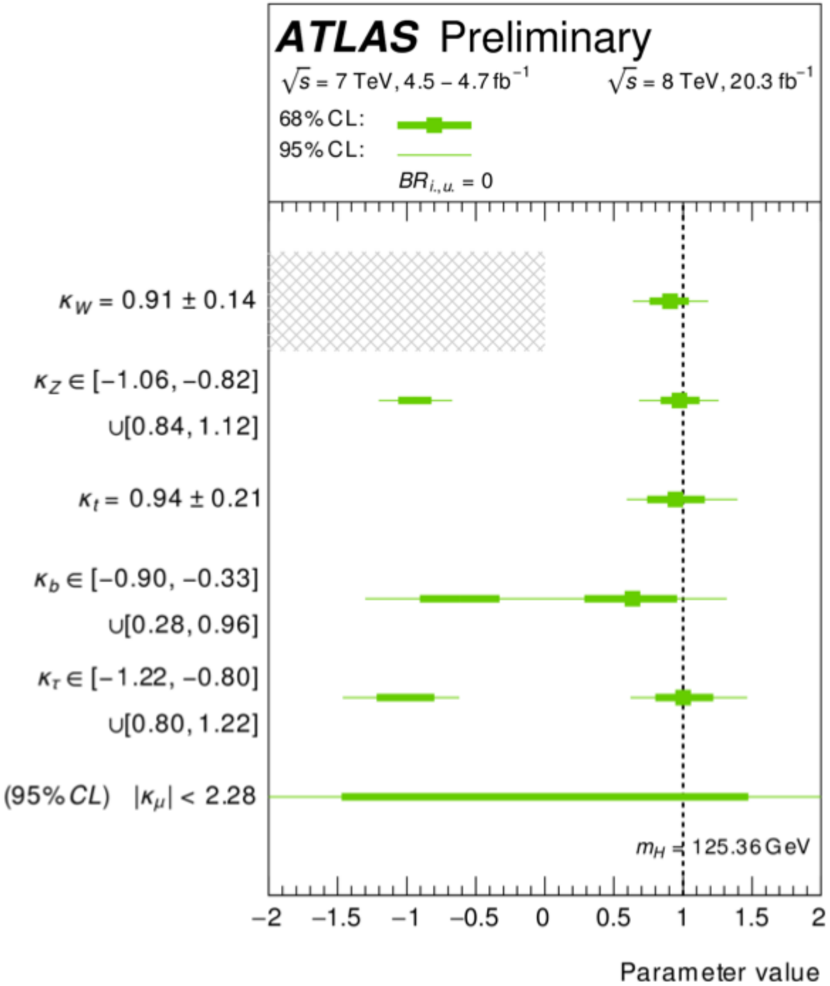

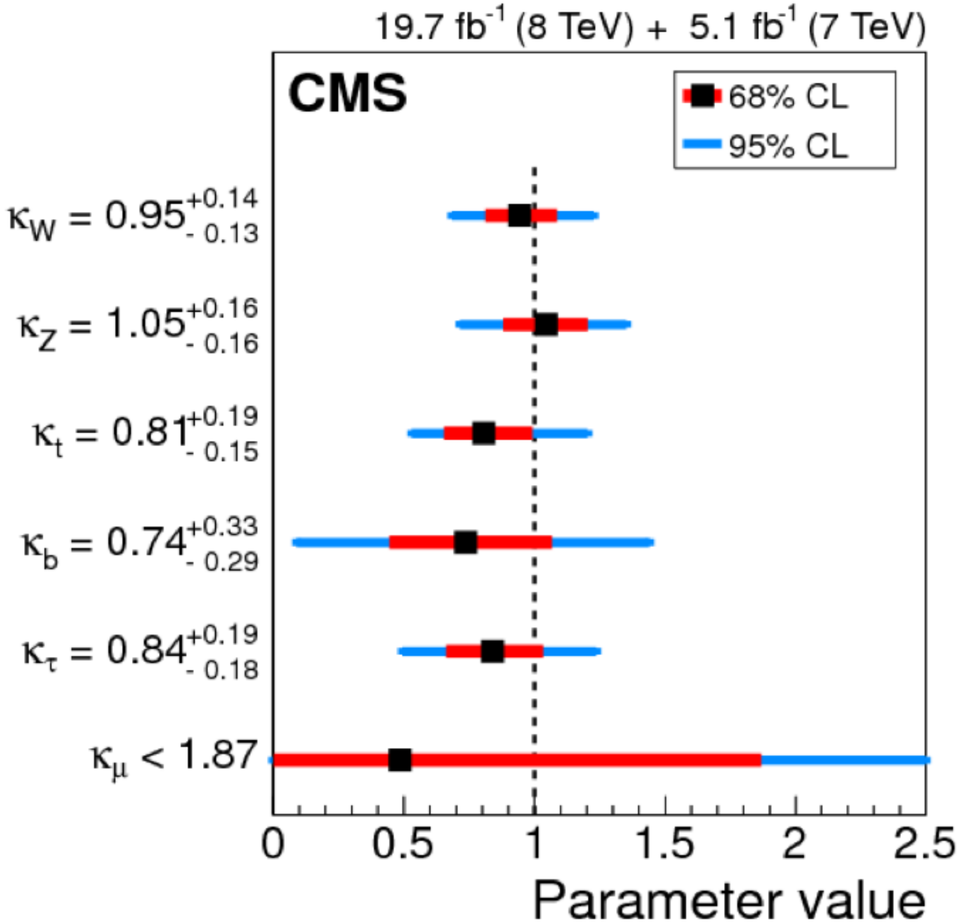

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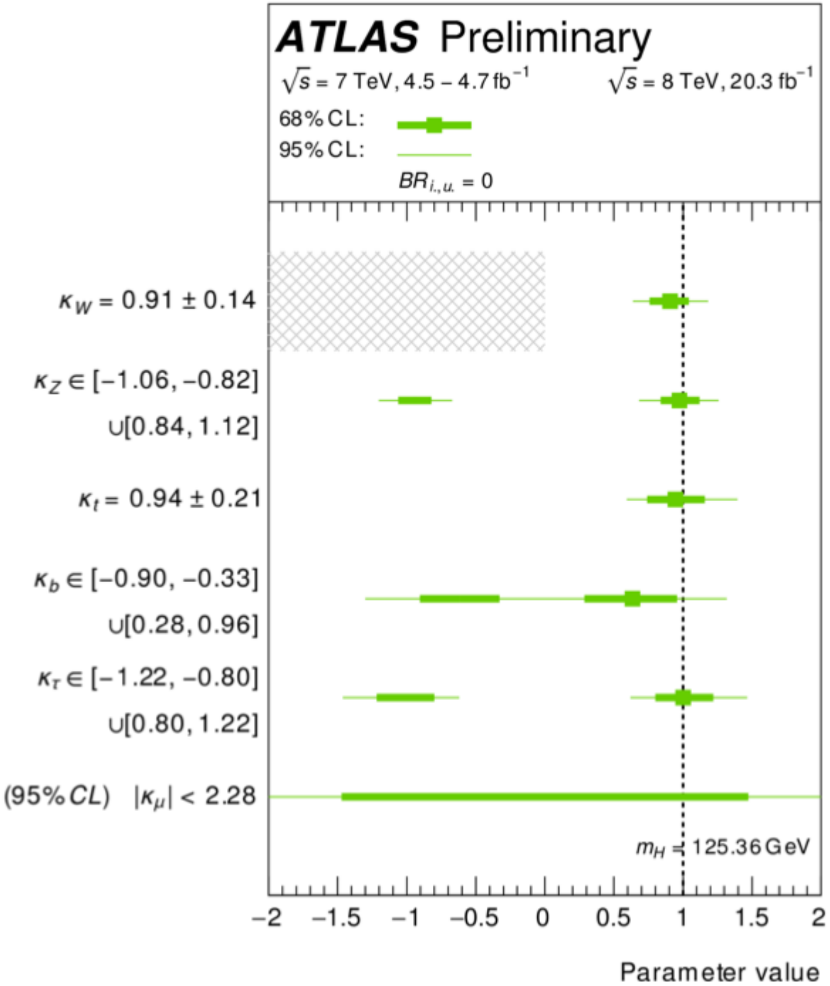
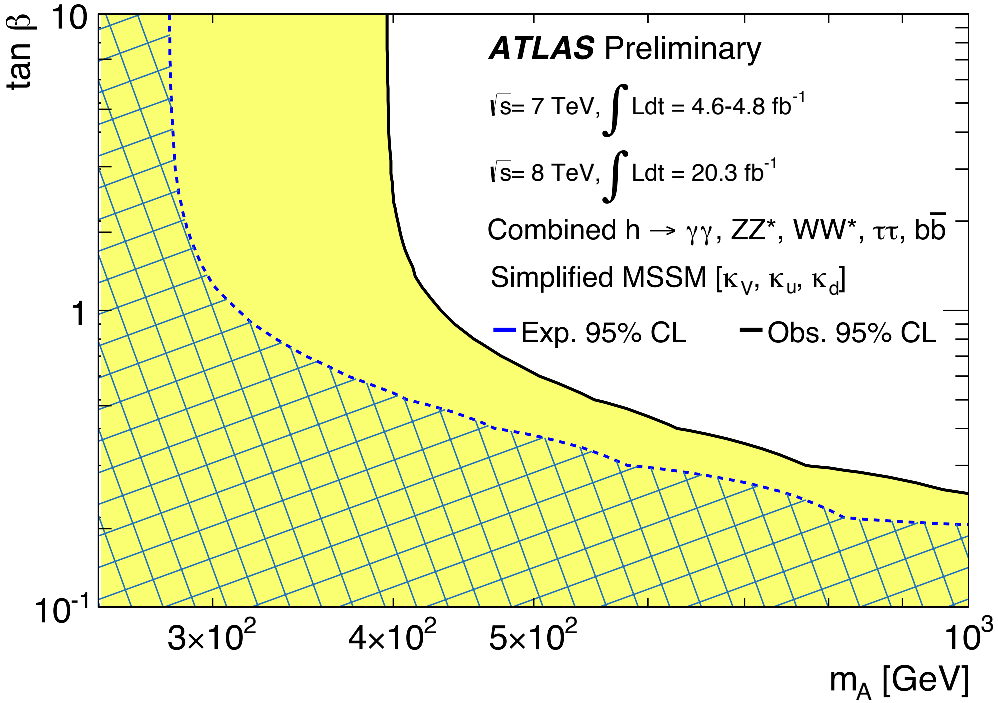
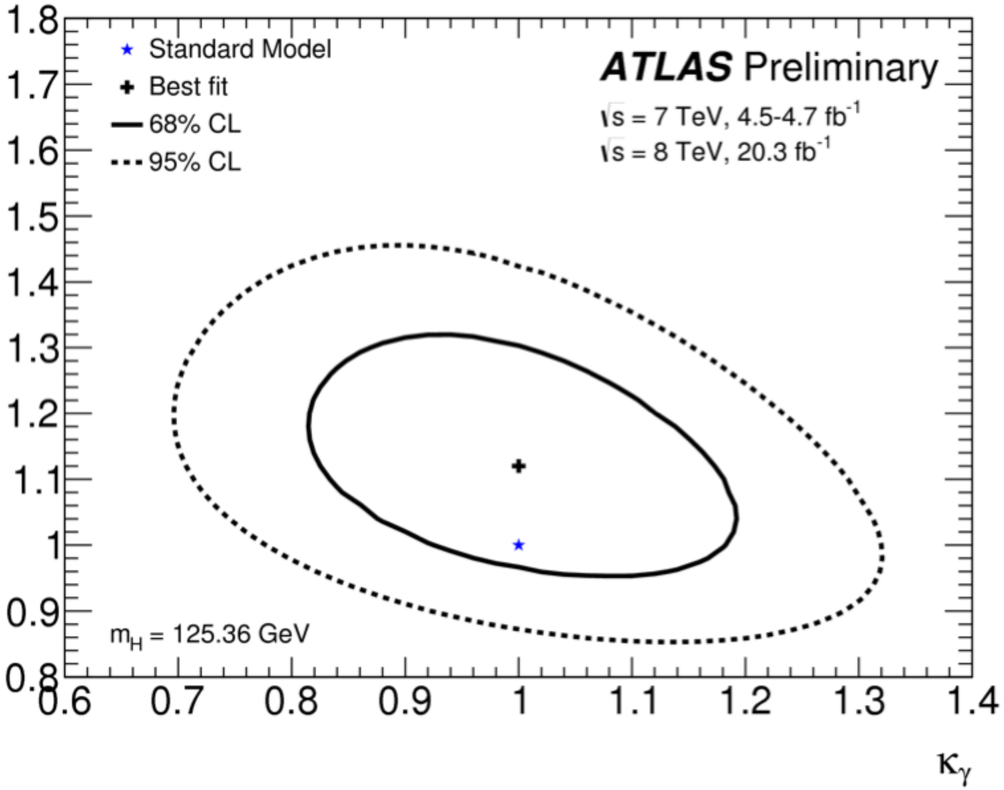


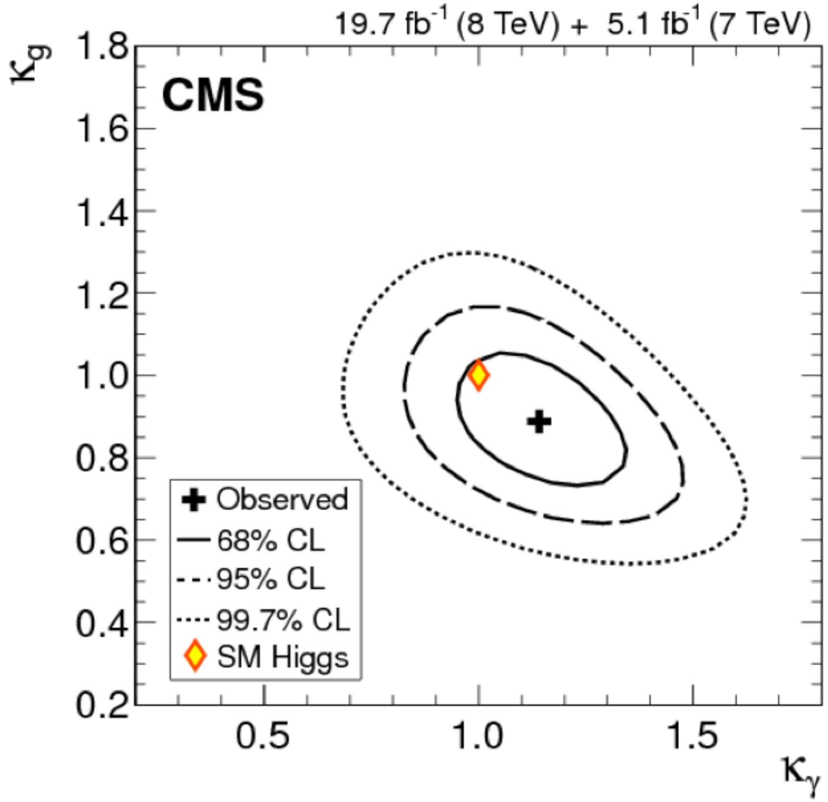


Measurements very compatible with SM hypothesis

Coupling to SM Spectra with Assumptions

Assuming SM couplings to SM particles but no assumptions on the loops or width





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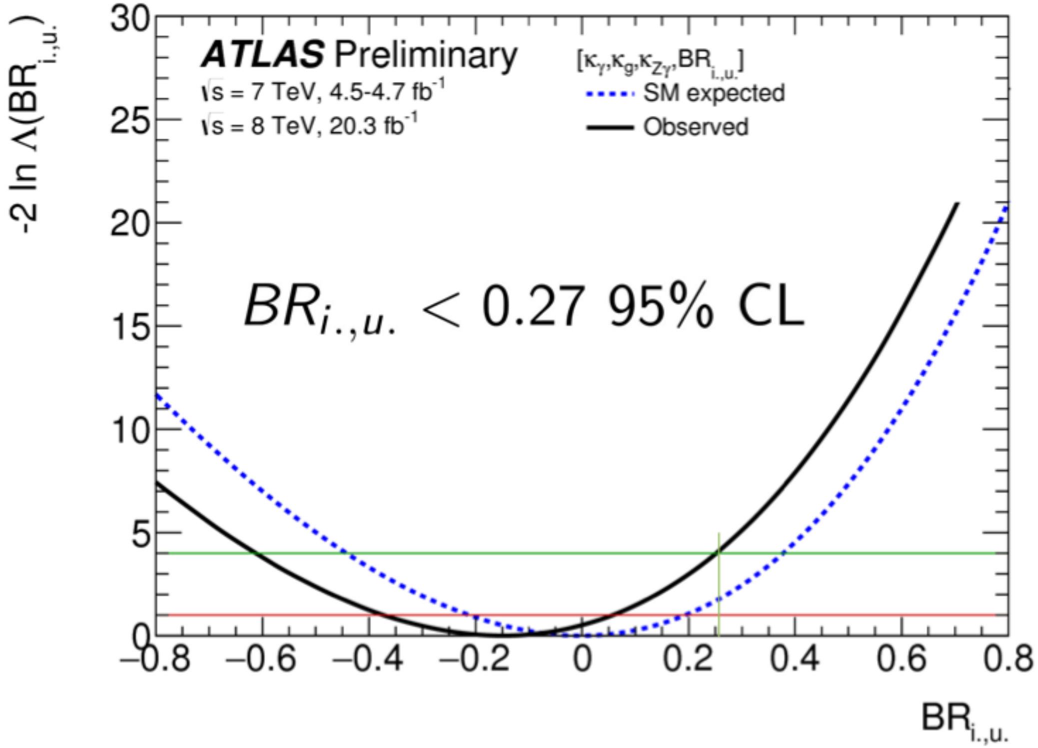
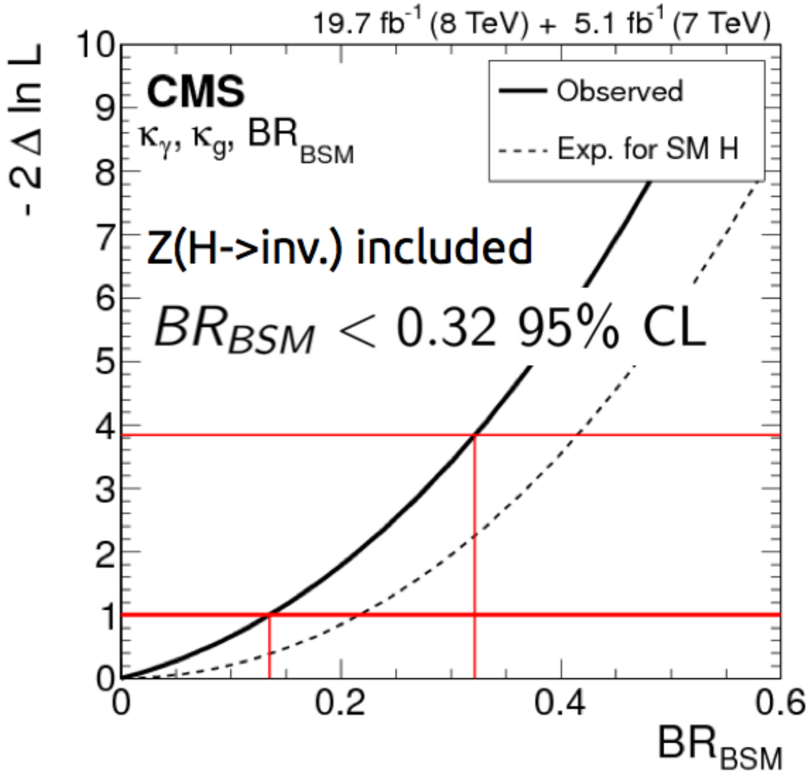
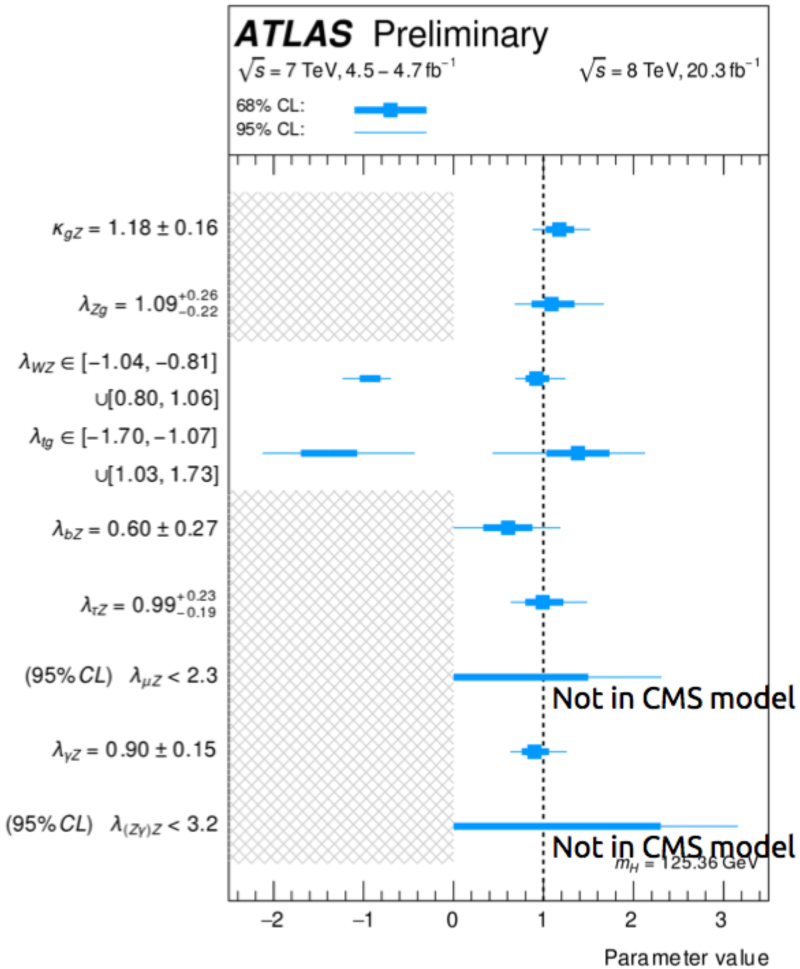


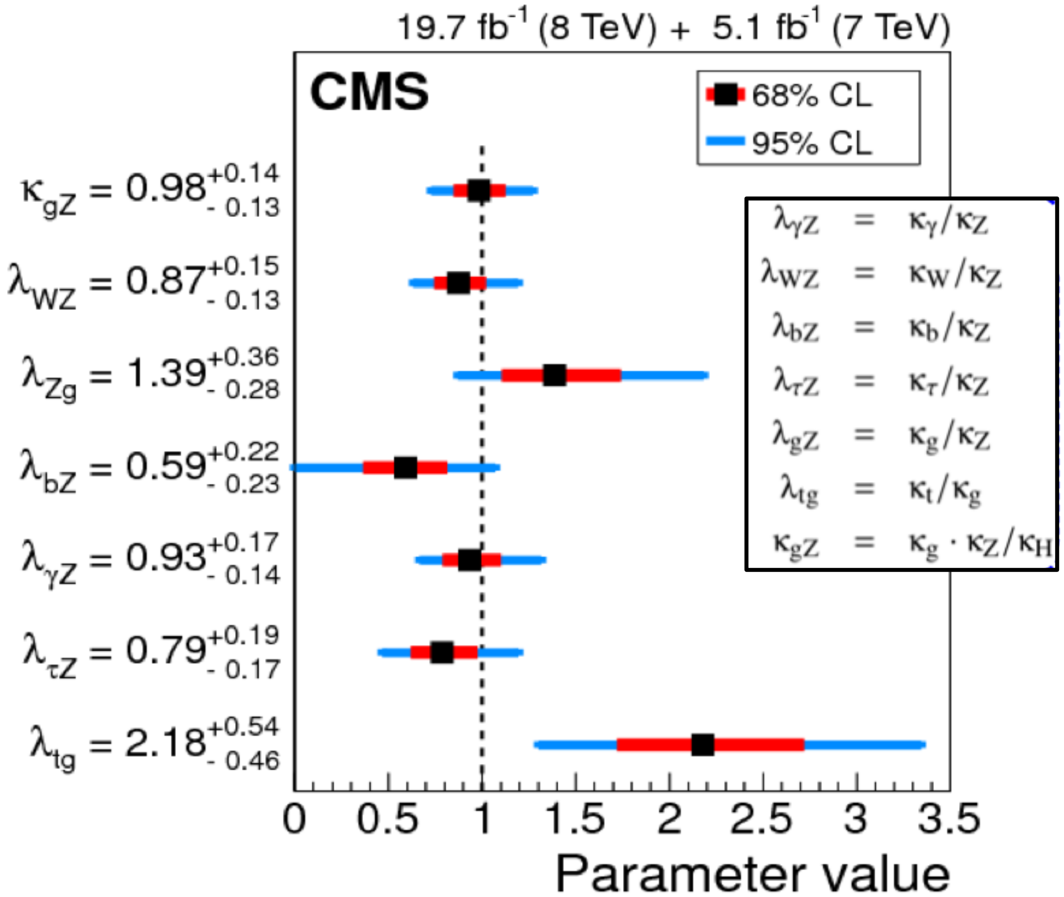


Measurements very compatible with SM hypothesis
Indirect constraint on the invisible branching

Coupling to SM Spectra with Assumptions

Assuming no assumptions on the loops or the natural width of the Higgs boson: measure ratios of couplings





Measurements very compatible with SM hypothesis

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Coupling to SM Spectra with Assumptions

Absolute Couplings Measurements with several assumptions:

1.- Unitarity inspired kV<1

2.- Using the Off Shell constraint

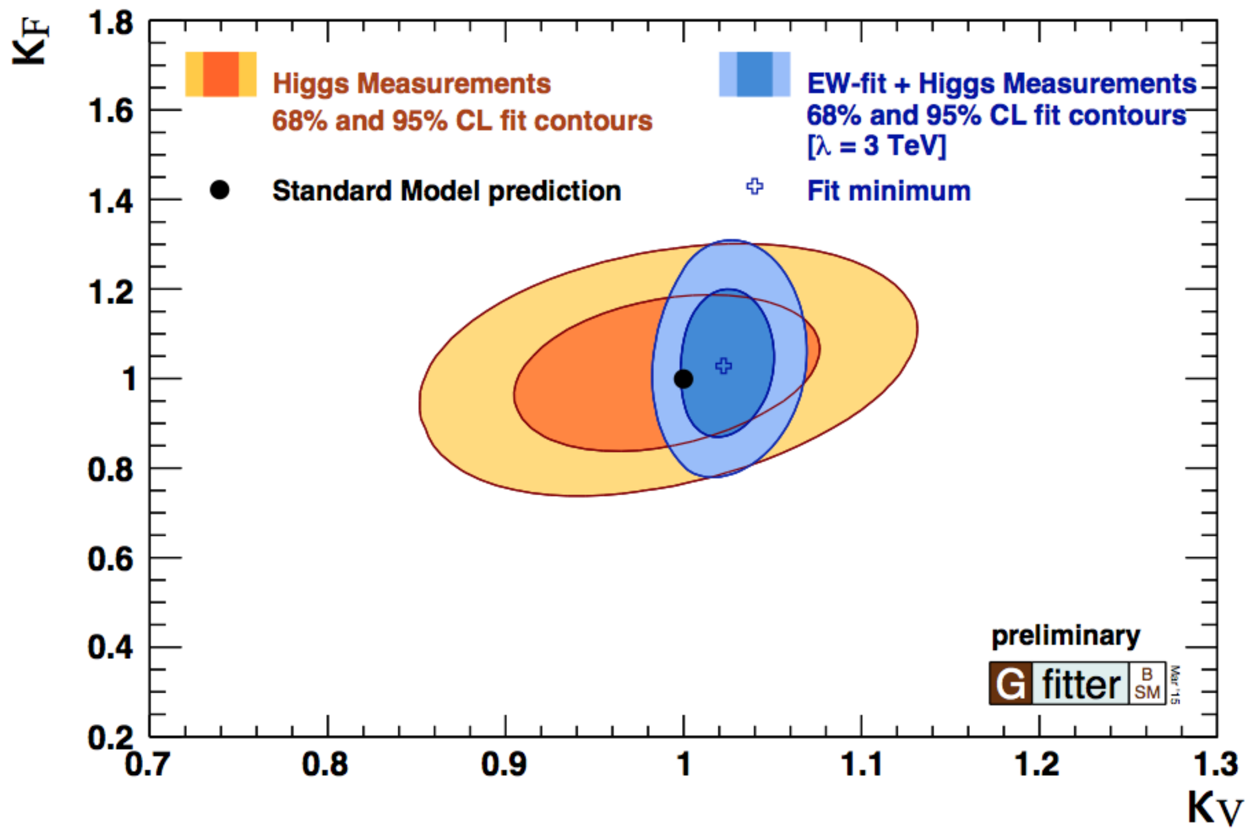
Taste of Combination (and More)

R. Kogler @ Moriond EW

Higgs coupling measurements:

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

- **Combined result:**
- $\kappa_V = 1.03 \pm 0.02$ (λ = 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…

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The Higgs Natural Width at the LHC and the Higgs as portal to Dark Matter

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- Width with interference
- Off shell couplings
- Invisible Higgs channels

Coupling properties of the Higgs boson

Prospects

The LHC timeline

LS1 Machine Consolidation

LS2 Machine upgrades for high Luminosity

- Collimation
- Cryogenics
- Injector upgrade for high intensity (lower emittance)
- Phase I for ATLAS : Pixel upgrade, FTK, and new small wheel

LS3 Machine upgrades for high Luminosity

- Upgrade interaction region
- Crab cavities?
- Phase II: full replacement of tracker, new trigger scheme (add L0), readout electronics.

European Strategy Update

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

High Luminosity LHC

LHC timeline

2009 Start of LHC

Run 1, 7+8 TeV, ~25 fb^{-1} int. lumi

2013/14 Prepare LHC for design *E* & lumi **LS1**

Collect ~30 fb^{-1} per year at 13/14 TeV

2018 Phase-1 upgrade ultimate lumi **LS2**

Twice nominal lumi at 14 TeV, ~100 fb^{-1} per year

~2022 Phase-2 upgrade to HL-LHC **LS3**

~300 fb^{-1} per year, run up to > 3 ab^{-1} collected

~2035

ATLAS Upgrades

Phase 0 Upgrade

- Additionnal insertable b-layer (Pixels)
- New beam pipe
- Complete muon coverage
- Repairs (TRT, LAr, Tile)
- FTK

Phase 1 Upgrade

- New Small Wheel (Forward muons) for L1 muon trigger
- Topological L1 trigger processors
- High granularity L1 Calorimeter trigger

Phase 2 Upgrade

- Completely new tracker (large eta?)
- Calorimeter eletronics upgrade
- Possible L1 track trigger
- Possible change to the forward calorimeters

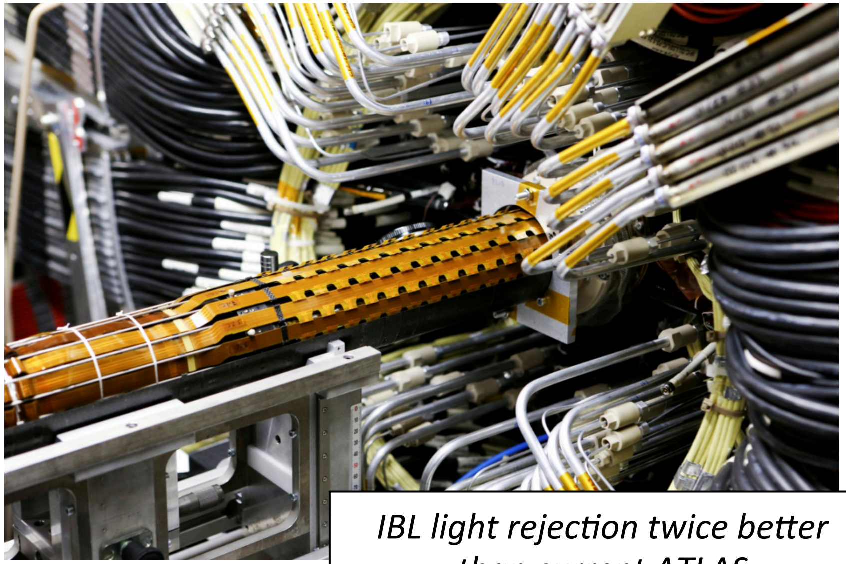
CMS Upgrades

Phase 0 Upgrade

- Complete muon coverage
- Replace HCAL photodetectors (forward and outer)

Phase 1 Upgrade

- New pixel detector
- New beam pipe
- L1 trigger upgrade
- HCAL electronics



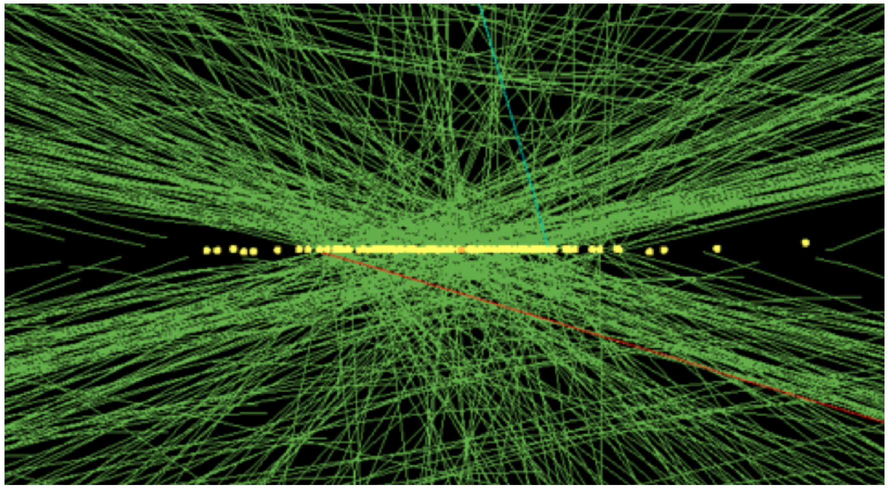
IBL light rejection twice better than current ATLAS

HL-LHC Beam Parameters

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Two HL-LHC scenarios

Parameter	2012	Nominal	HL-LHC (25 ns)	HL-LHC (50 ns)
C.O.M Energy	8 TeV	13-14 TeV	14 TeV	14 TeV
N_p	$1.2\ 10^{11}$	$1.15\ 10^{11}$	$2.0\ 10^{11}$	$3.3\ 10^{11}$
Bunch spacing / k	50 ns /1380	25 ns /2808	25 ns /2808	50ns /1404
ε (mm rad)	2.5	3.75	2.5	3.0
β* (m)	0.6	0.55	0.15	0.15
L ($cm^{-2}s^{-1}$)	$\sim 7 \times 10^{33}$	10^{34}	$7.4\ 10^{34}$	$8.4\ 10^{34}$
Pile up	~25	~20	~140	~260

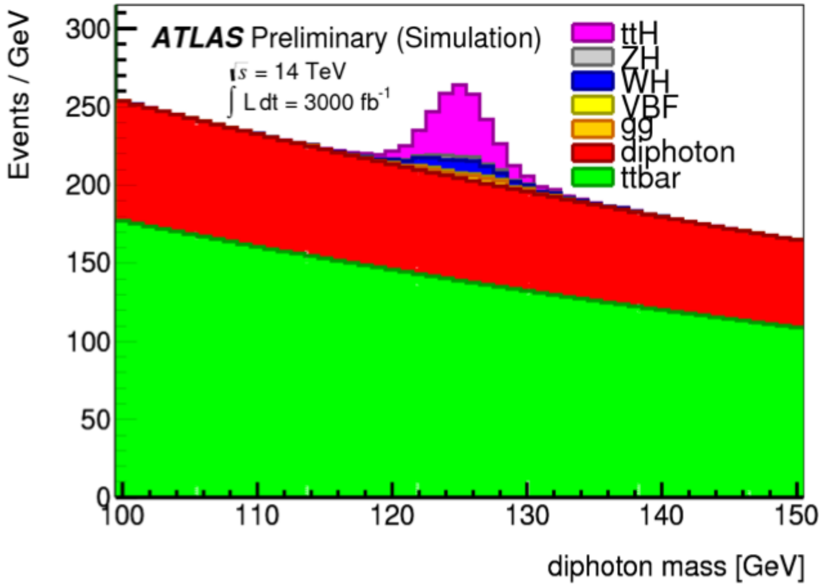


Pile up is a crucial issue!

CMS event with 78 reconstructed vertices

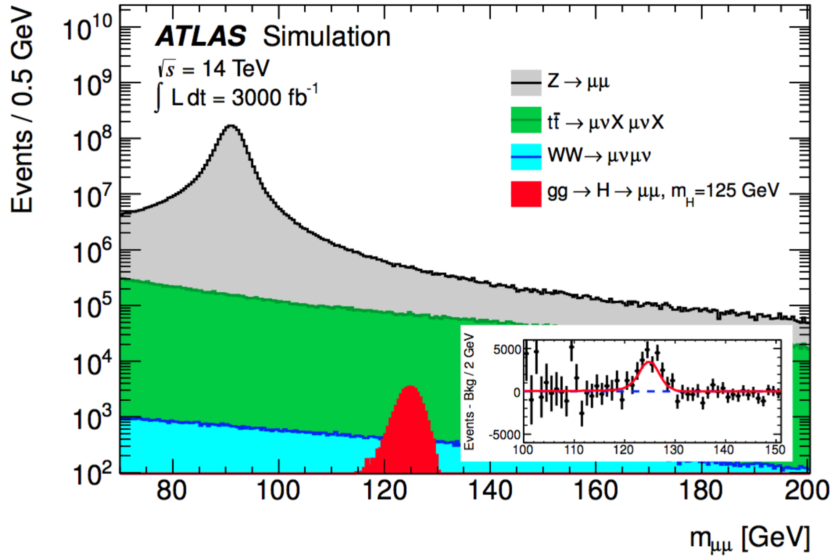
Rare and (robust) modes

Analyses not relying on more intricate decay channels (bb, ττ and WW)



- γγ channel: more than 100 Events expected with s/b~1/5
- μμ channel: approximately 30 Events expected with s/b~1

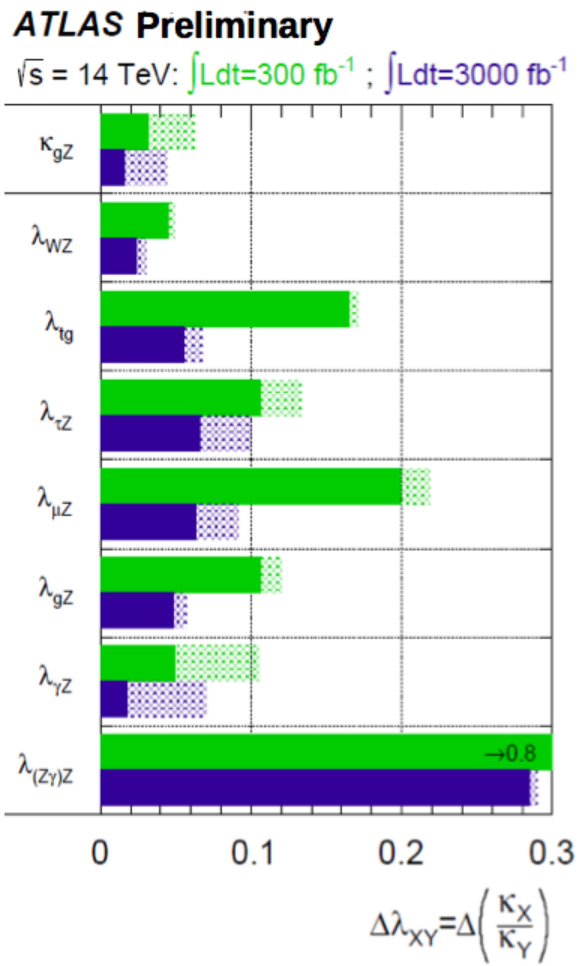
Analyses (rather) robust to PU

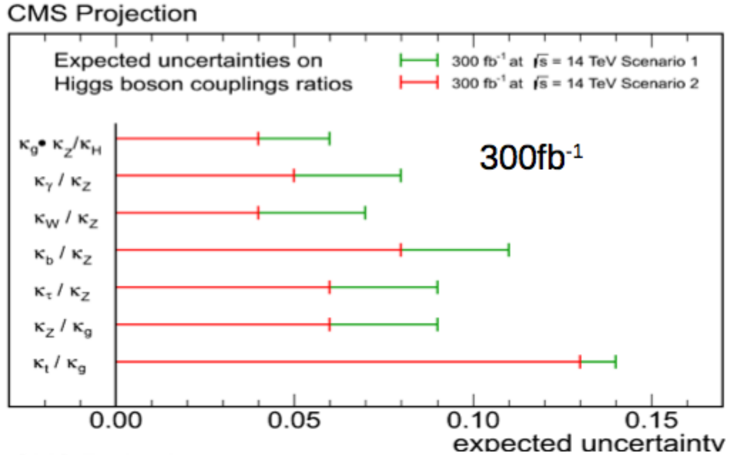


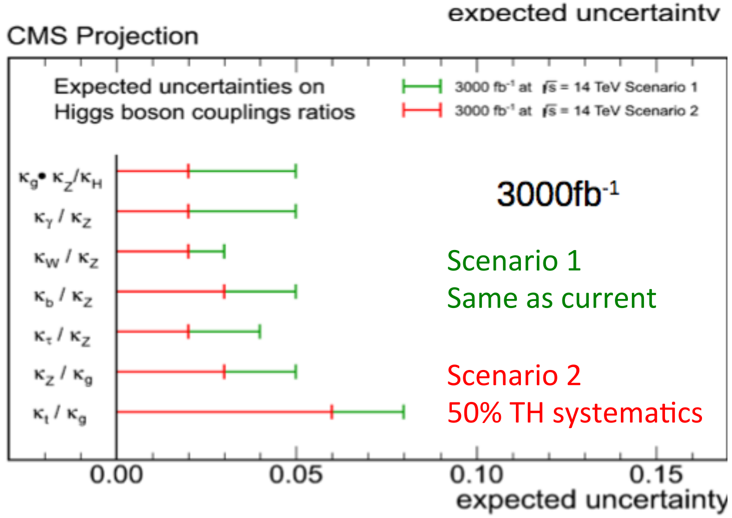
μμ decay mode should reach more than 5 standard deviation

LHC Higgs Physics Program: Main Couplings

Couplings Projections recently reappraised with a sample of analyses







Only indirect (however not negligible) constraint on the total width

Necessary to use assumptions or measure ratios: Precision down to ~5% level

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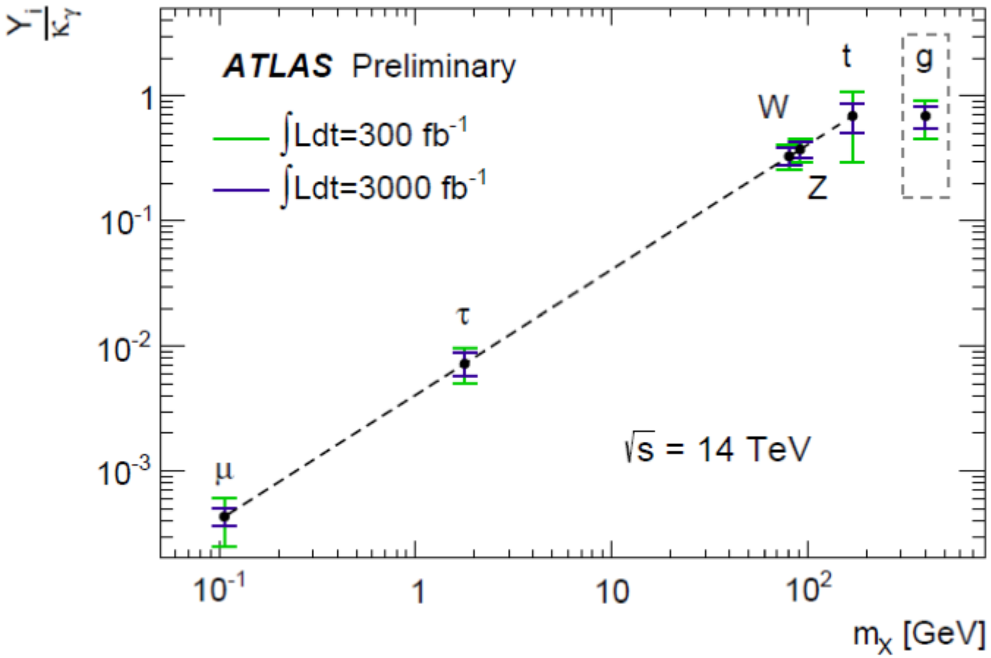

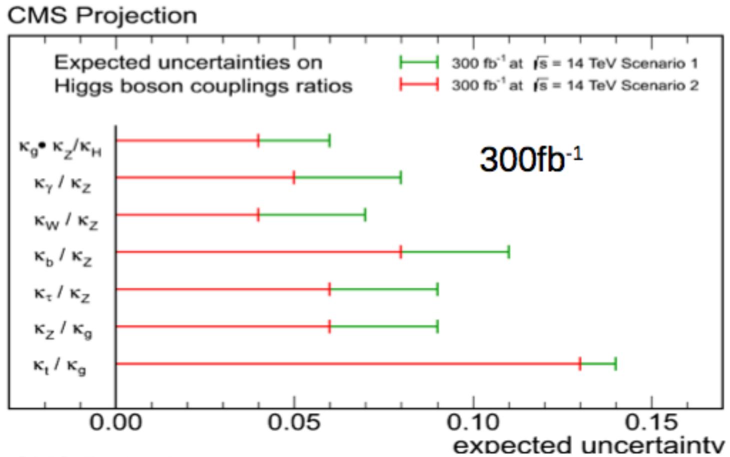

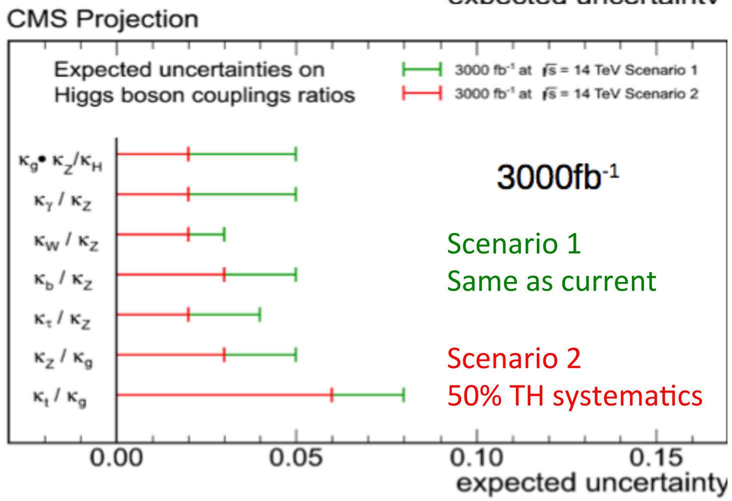

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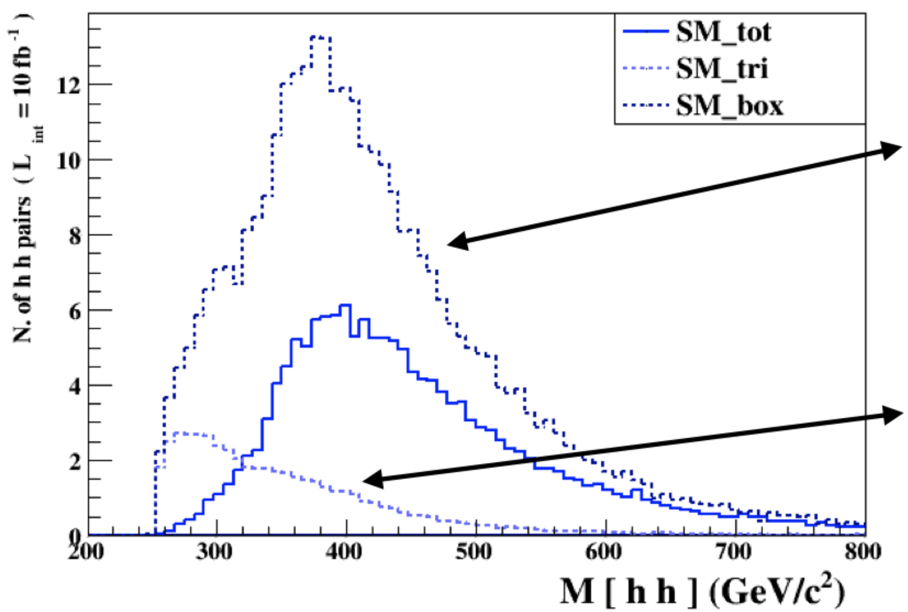
Inspiring … For self couplings

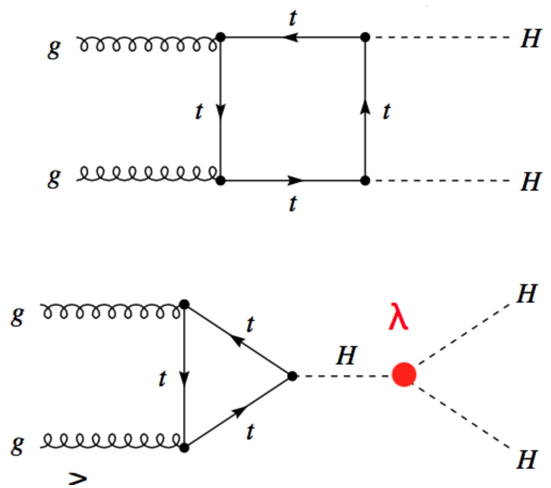
- Determination of the scalar potential, essential missing ingredient : **self couplings** $\lambda_3 \sim m_H^2/(2v)$, $\lambda_4 \sim m_H^2/(8v^2)$!

- Very similar analysis as the off shell couplings!

λ_4 : hopeless in any planed experiment (?)

λ_3 : very very hard in particular due to the double H production, which also interferes with the signal…





pp → HH → bbγγ has been studied

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ATL-PHYS-PUB-2014-019

At HL-LHC Projected sensitivity
to SM HH production

$1.3\ \sigma$

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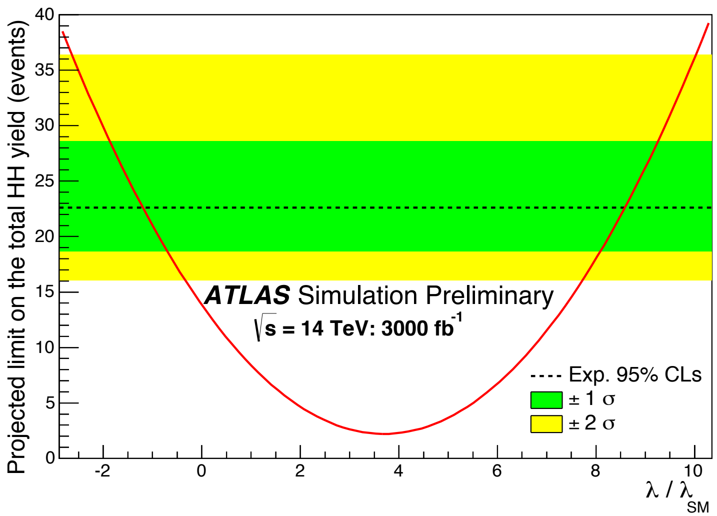

HL-LHC

Sensitivity to trilinear coupling

Need to investigate more channels

Conclusion and Discussion

- LHC Run 1 has been extremely successful
- Since the discovery of the Higgs boson, entire new field emerged with a very large number of interesting analyses (this was only part of the story and there is many more to come)
- The Higgs boson observed is compatible to a good precision with the SM Higgs boson
  - Direct evidence of coupling to W and Z
  - Direct evidence of coupling to taus (and therefore to fermions)
  - Direct evidence for non-universal couplings
  - Evidence for VBF production
  - Indirect evidence of couplings to top quark
  - Evidence of the scalar nature
- Establishing the properties of the Higgs boson has been possible and will be, through the collaboration with the Theory community
- LHC Run 2 is imminent, more results to come hopefuly very soon!