Higgs boson in the standard model and other highlights of SM measurements

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Michał Bluj

LLR/École Polytechnique – CNRS/IN2P3

Narodowe Centrum Badań Jądrowych, Świerk

on behalf of the ATLAS and CMS Collaborations

Outline

- Introduction
- Higgs at LHC
  - Production and decay
  - Clearly-seen Higgs ($H\to\gamma\gamma$, $H\to ZZ\to 4l$, $H\to WW\to 2l2\nu$)
  - Almost-seen Higgs ($H\to bb$, $H\to\tau\tau$)
  - To-be-seen Higgs ($H\to Z\gamma$, ttH, $H\to\mu\mu$)
    - Additional material

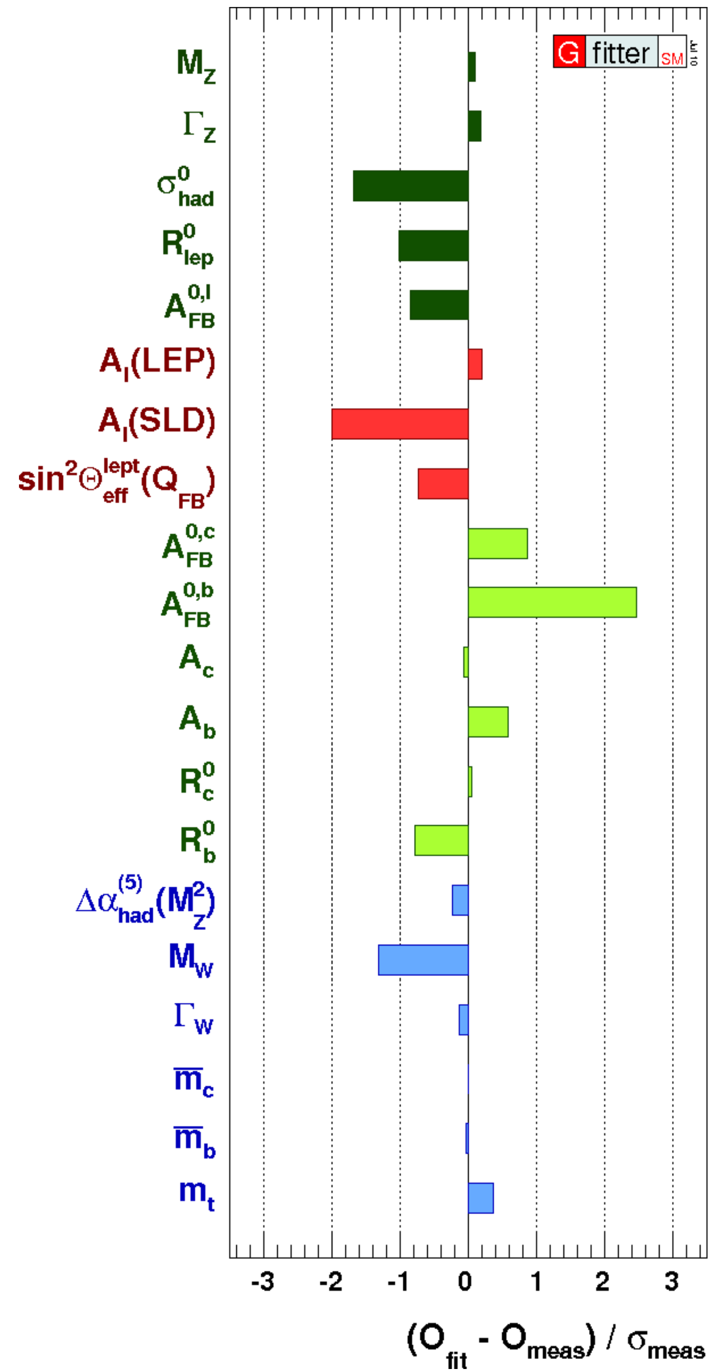
Main subject of the talk

- Electro-weak physics at LHC
  - Vector boson production
  - Multi-boson production
- Top physics
  - Single top production

Some selected standard model measurements – “highlights”

SM before LHC era (<2010)

- Standard model describes experimental data with excellent precision (*)
  - Big success of SM was e.g. discovery of top (Tevatron 1995) with mass within range favoured by precision measurements
  - Some small tensions < 3σ (e.g. FB asymmetry of b-quarks), but
  - No strong indications for physics beyond SM
  - Overall p-value of global SM fit of ~20%
- The only missing element is Higgs boson



(*) M. Goebel, "Gfitter" talk at ICHEP'2010, arXiv:1012.1331

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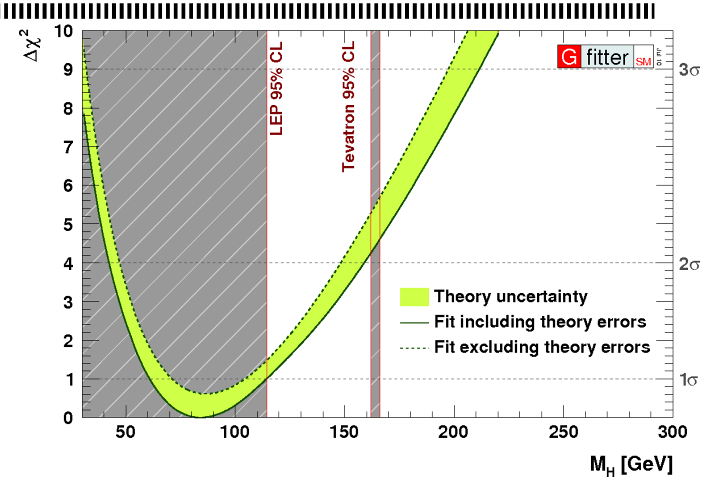
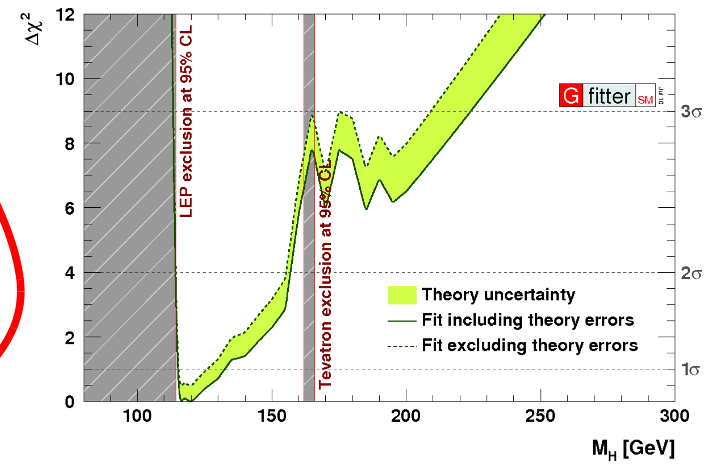
  - Constraints on m_H from direct searches
    - $m_H > 114.4 \mathrm{GeV}/c^2$ (LEP)
    - Excluded small window around $164 \mathrm{GeV}/c^2$ (Tevatron)
  - Light Higgs preferred by fit (2σ intervals)
    - $m_H \in [42, 159]\ \mathrm{GeV}/c^2$ (w/o searches)
    - $m_H \in [114, 157]\ \mathrm{GeV}/c^2$ (w/ searches, as above w/ left side cut)
    - $m_H <\sim 220\ \mathrm{GeV}/c^2$ at 3σ basically unconstrained at 5σ





- Very weak constraint due to log dependence on m_H
- Minimal Higgs sector with one doublet assumed

⇒ Only direct search (discovery) can solve the issue

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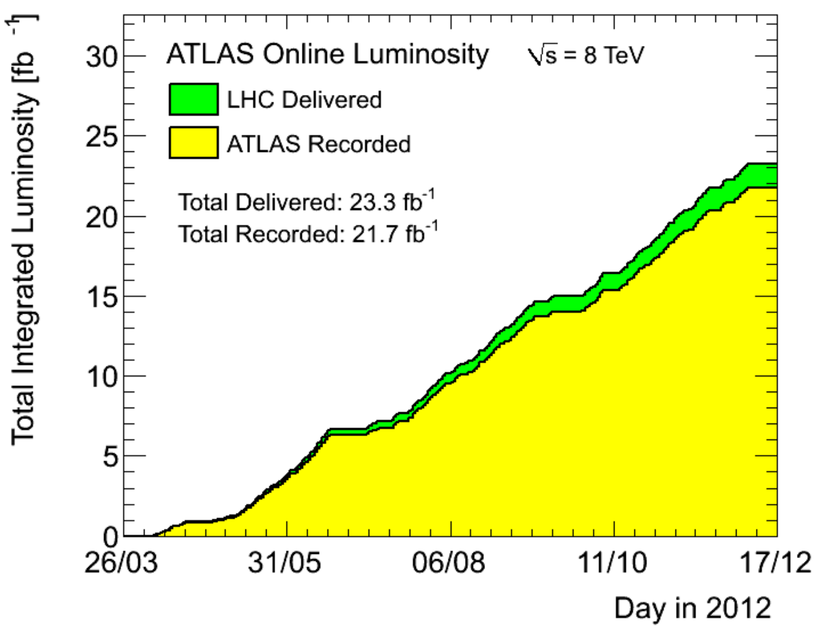
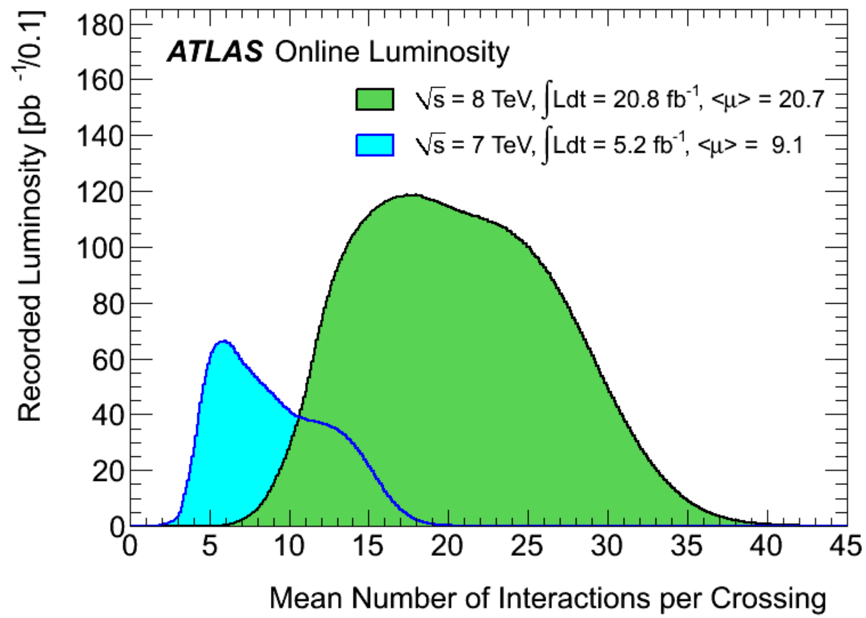
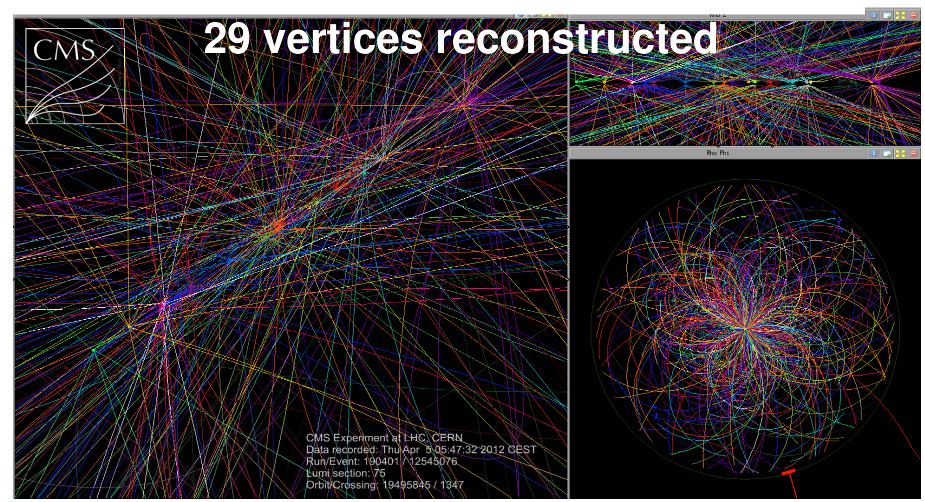
LHC data

- Excellent performance of LHC and both experiments!
  - 95% of delivered data recorded, 90% of those certified and used for analyses
  - 5/fb at 7TeV + 21/fb at 8TeV for analyses per experiment



- LHC reached nominal pileup rate
  - Inst. luminosity up to $8{\times}10^{33}$ cm^{-2}s^{-1} $\rightarrow$ <PU> up to ~30
  - Experiments cope well against pileup!





Pileup mitigation

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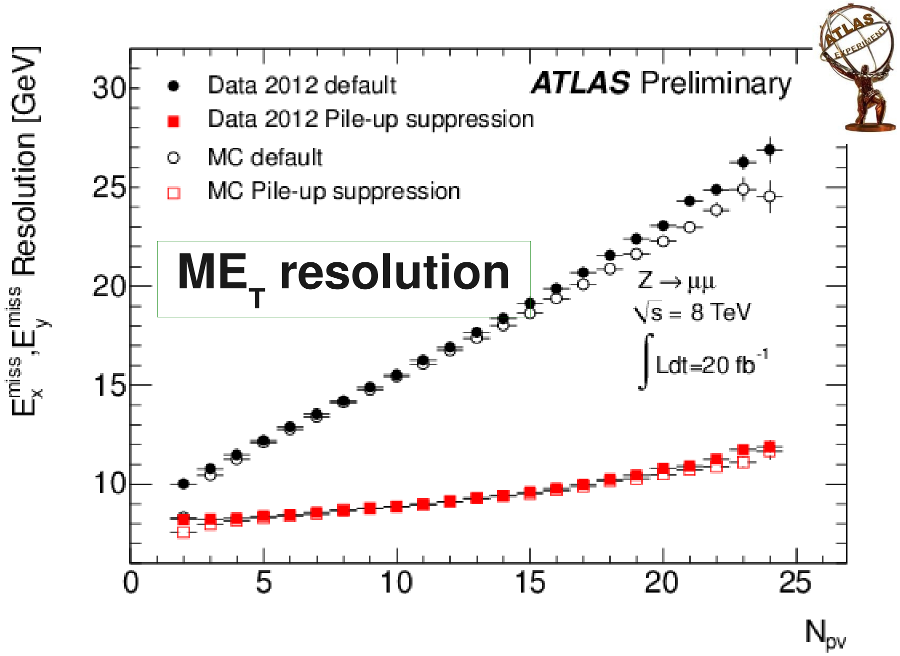
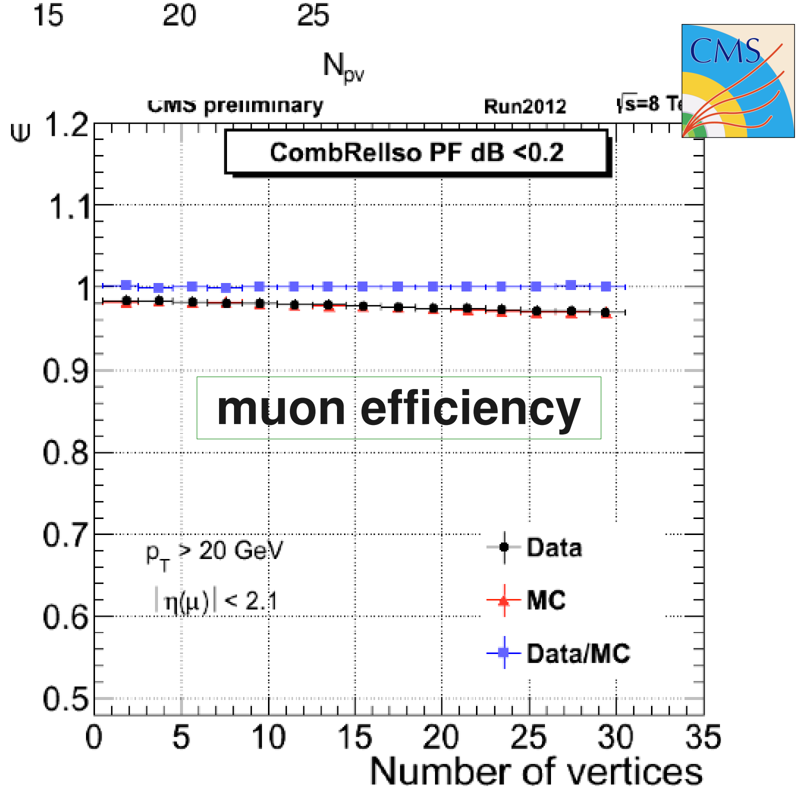
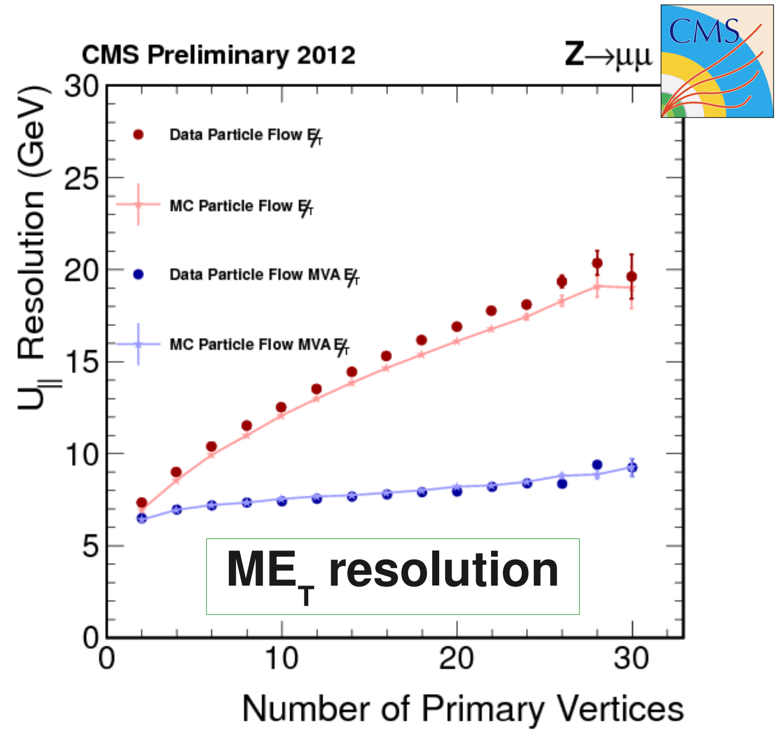




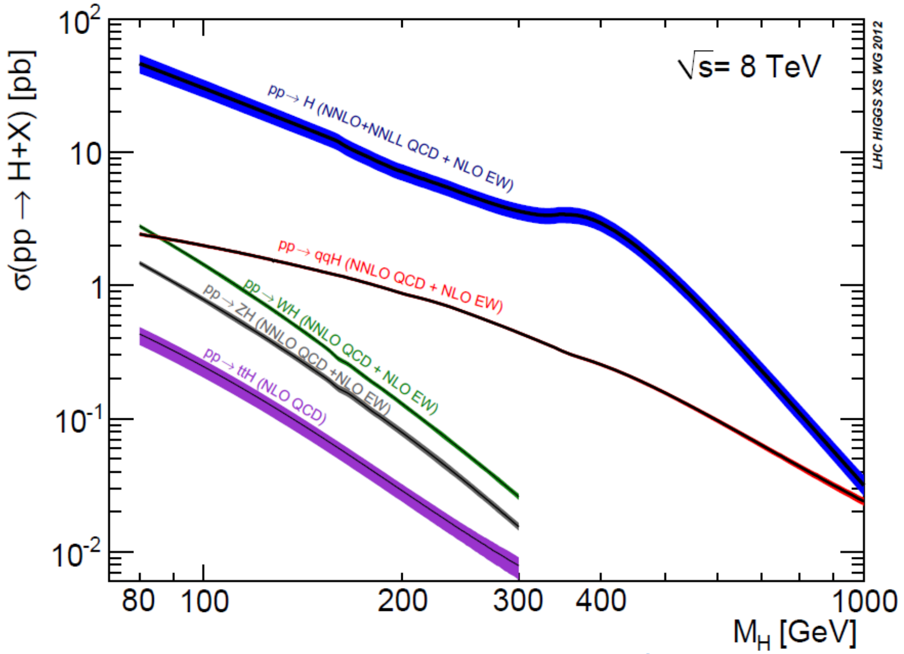


Higgs at LHC

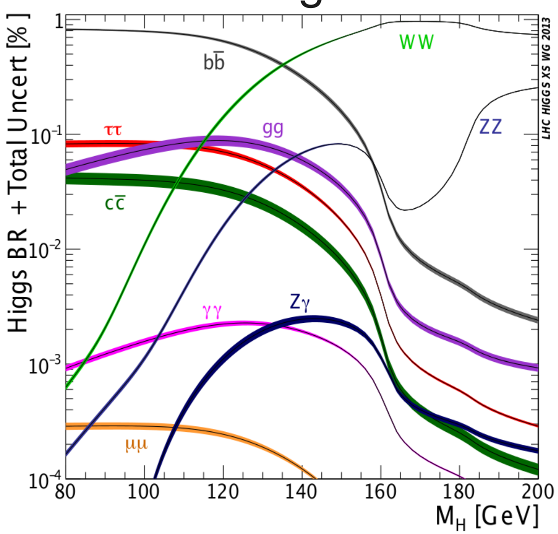

HIGGS BOSON
H
The HIGGS BOSON is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland, which collides particles at 99.99% the speed of light, will detect the elusive Higgs Boson
Higgs boson
$10.49 PLUS SHIPPING
LIGHT
HEAVY
Wool felt, fleece with gravel fill for maximum mass.
The PARTICLE ZOO

Higgs production at LHC

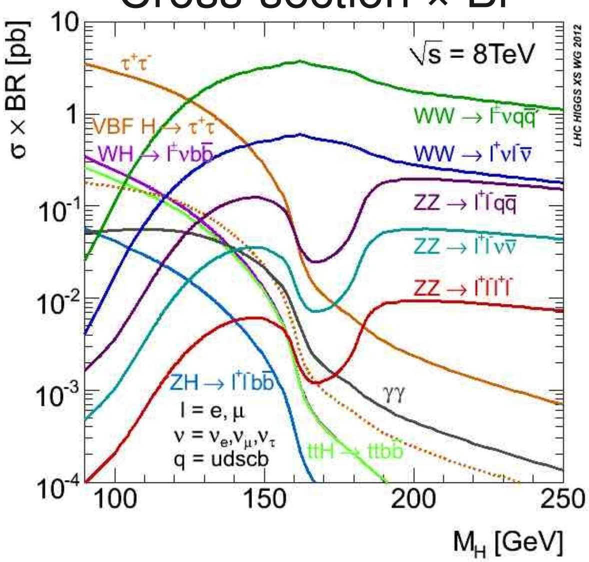
- Dominant production mode is the gg → H
  - 19(15) pb at 8(7) TeV for m_H=125 GeV/c^2, big NLO and NNLO corrections
- VBF and VH production modes
  - Cross-section smaller ~10 times than gg → H
  - Useful thanks to additional signatures (jets, leptons, ME_T)
- ttH production



Branching fraction

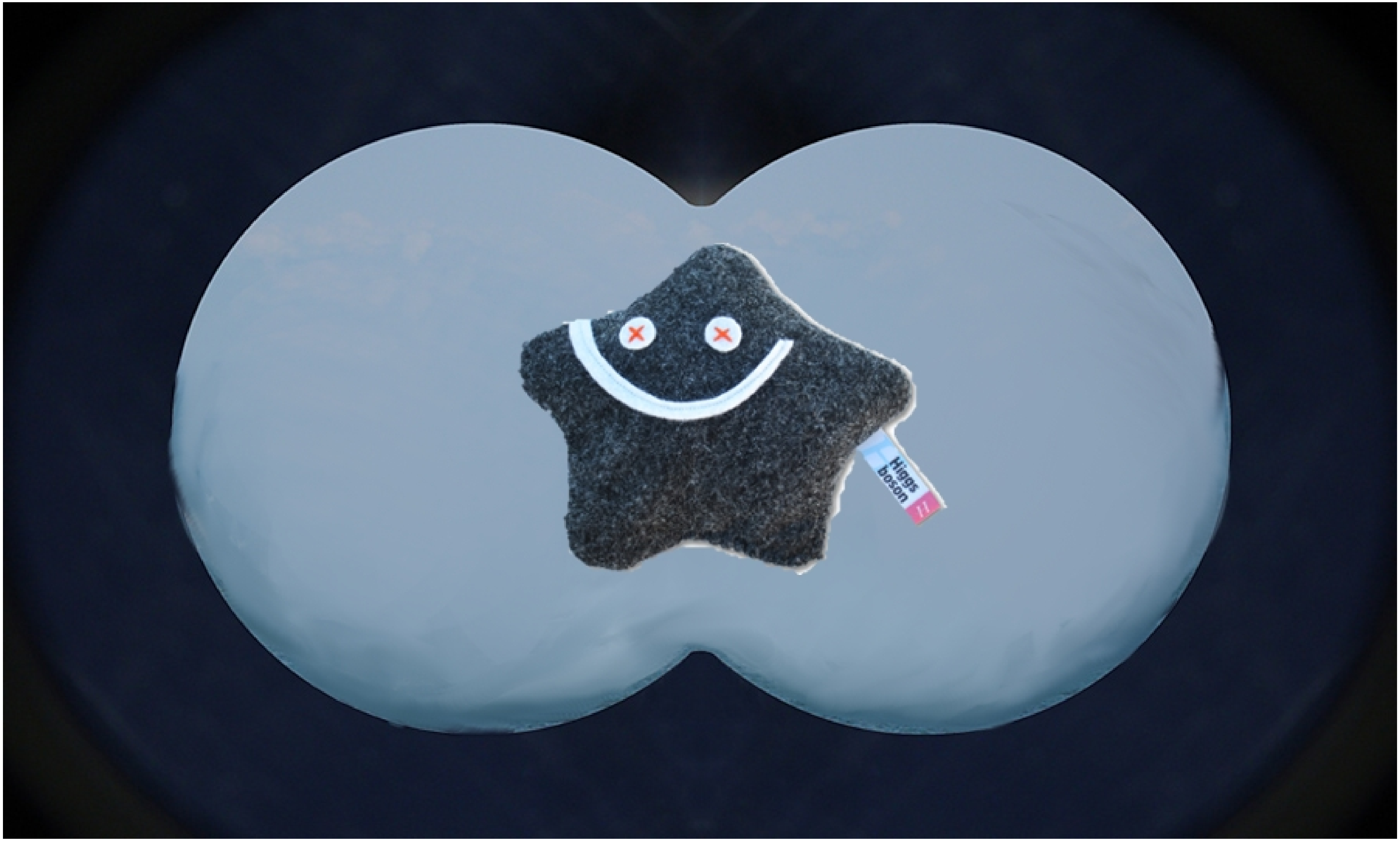


Cross-section × Br



- For m_H~125GeV/c^2 decay spectrum maximally rich,...
- but experimentally challenging
- Decay modes for search for Higgs boson determined by σ×Br and S/B:
  - H → ZZ → 4l
  - H → γγ
  - H → WW → 2l2ν
  - H → ττ
  - H → bb

Clearly-seen Higgs



Channels sensitive on H(125) with current data:

$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow 2l2\nu$

Golden-plated: $H \to ZZ \to 4l$

- **Most sensitive channel**
  - **Narrow 4l-mass peak,** resolution 1-2%
  - Low p_T lepton identification crucial
    - p_T>7(5) GeV for e(μ)
- **Signature:** 4 isolated leptons from one vertex
- **Reducible backgrounds:**
  - tt → 2l2ν2b, Z+bb, Z+jets
  - Removed by lepton isolation & impact parameter
- **Irreducible background:** ZZ*/γ*
- **Event Selection:** 2 pairs of same flavour, opposite charge leptons
  - ATLAS: FSR recovery (4μ), untagged+VBF+VH (for m_V-m_F)
  - CMS: Angular analysis (MELA), event-by-event m_{4l} uncertainty, FSR recovery, untagged + dijet (VH+VBF)
- **Significance**
  - ATLAS: **6.6σ** (exp. 4.4σ)
  - CMS: **6.7σ** (exp. 7.2σ)

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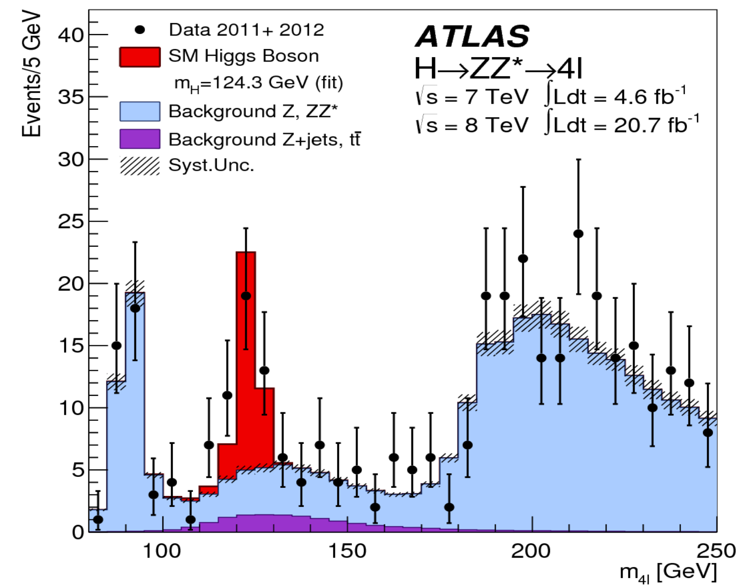
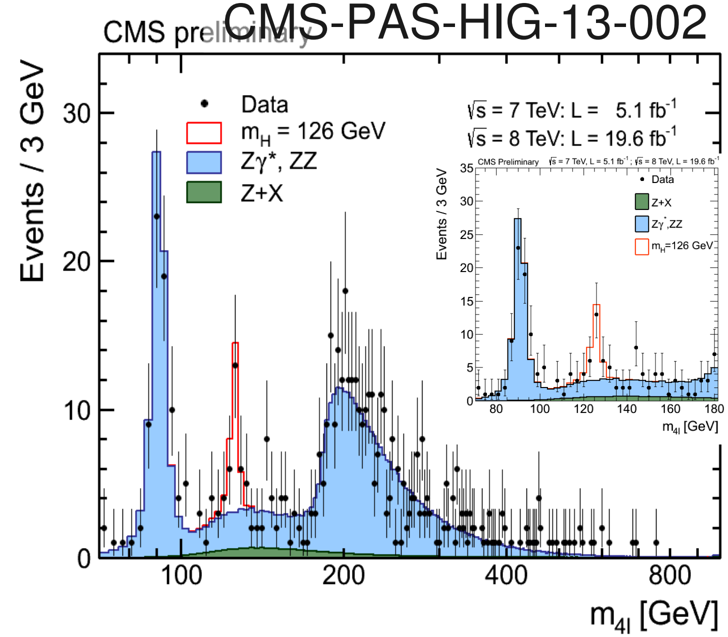


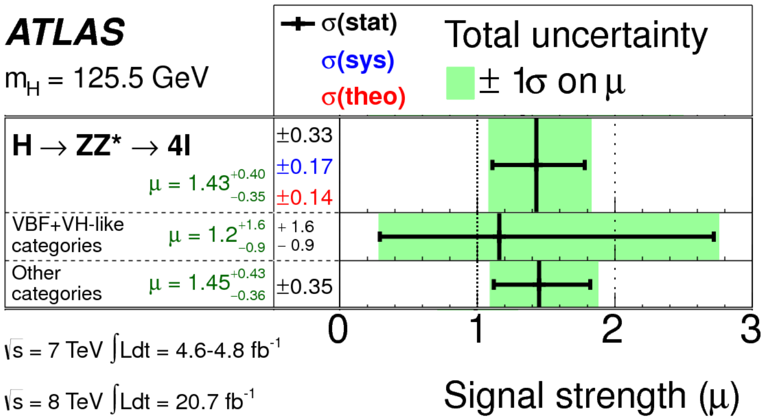
CMS-PAS-HIG-13-002



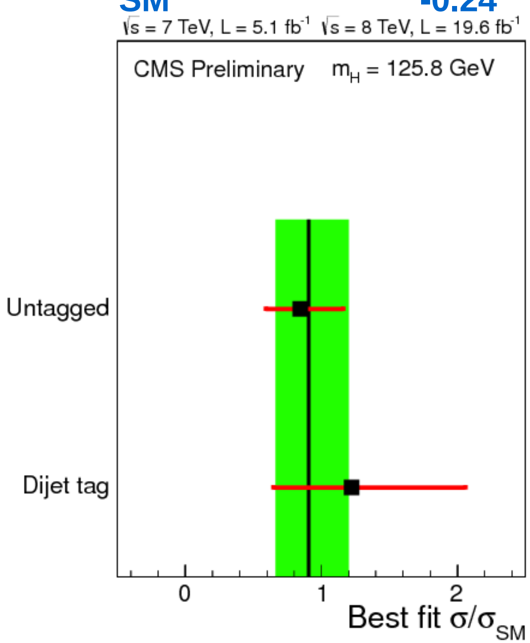
H → ZZ → 4l: results

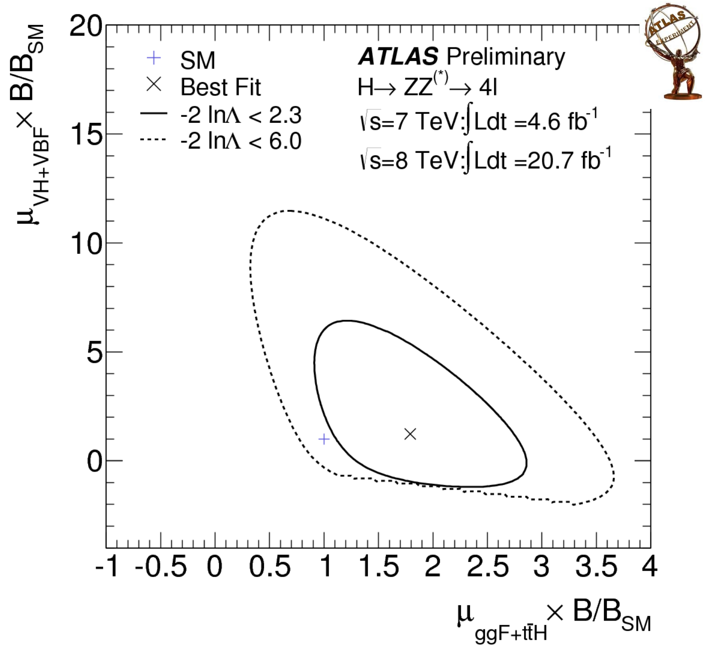
Signal strength (μ):

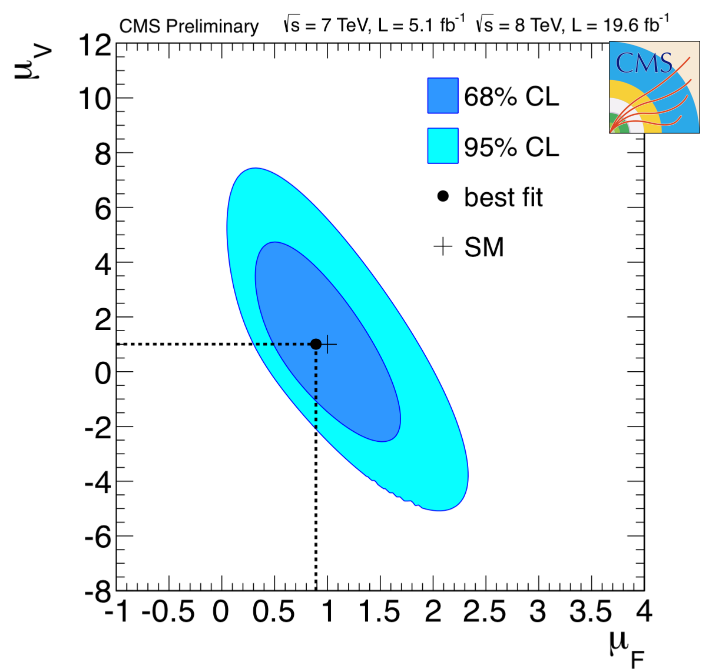
- ATLAS: $\sigma/\sigma_{SM} = 1.43^{+0.40}_{-0.35}$



- CMS: $\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$

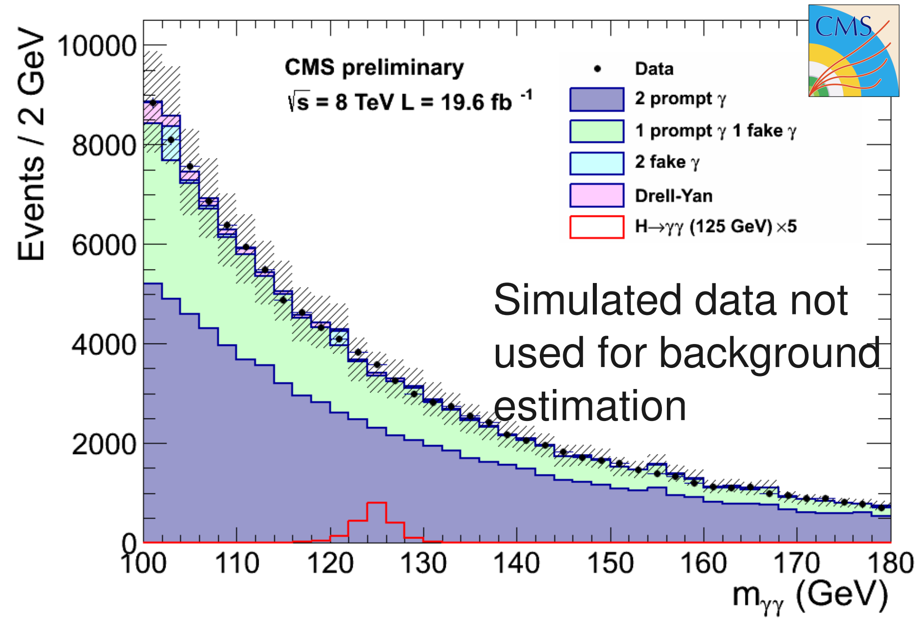


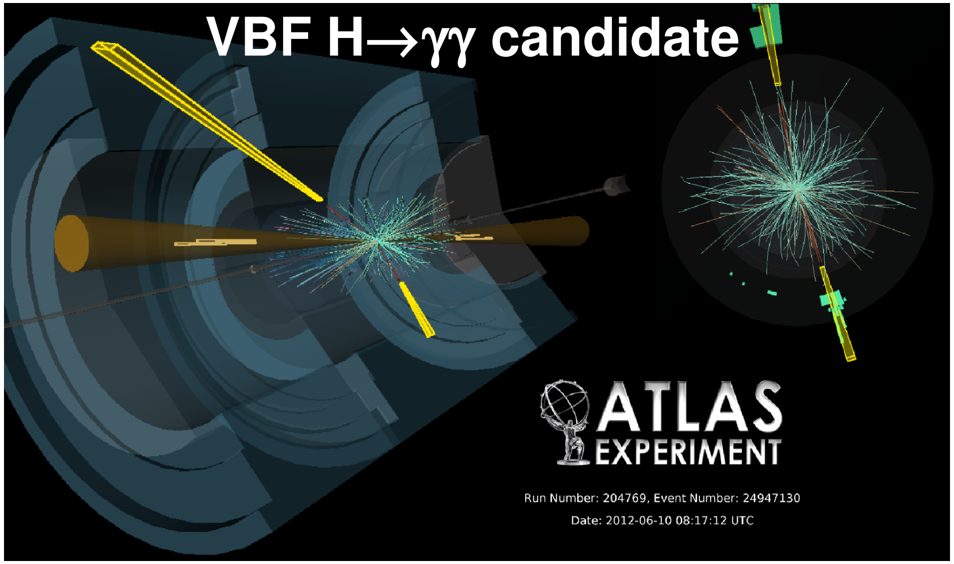




H → γγ

- **Very sensitive channel at low mass despite a small branching fraction** (Br~1-2×10^{-3})
  - **Narrow peak in di-photon mass,** resolution ~1-2%
  - Large QCD background from direct di-photon and photon+jet, jet → γ
  - Background normalisation from $m_{\gamma\gamma}$ sidebands – analytic model independent on simulation
- Ambiguity with primary vertex selection
  - dedicated MVA
- Sample divided on categories basing on additional tags and $m_{\gamma\gamma}$ resolution
  - ATLAS: untagged (9 subcategories), lepton tag (VH), ME_T tag (Z(νν)H, 8TeV), VBF (1 or 2 subcategories)
  - CMS: untagged (4 subcategories), lepton tag, ME_T tag, VBF (1 or 2 subcategories)





H→γγ: results

ATLAS

- **Significance:**
  7.4σ (4.1σ exp.)

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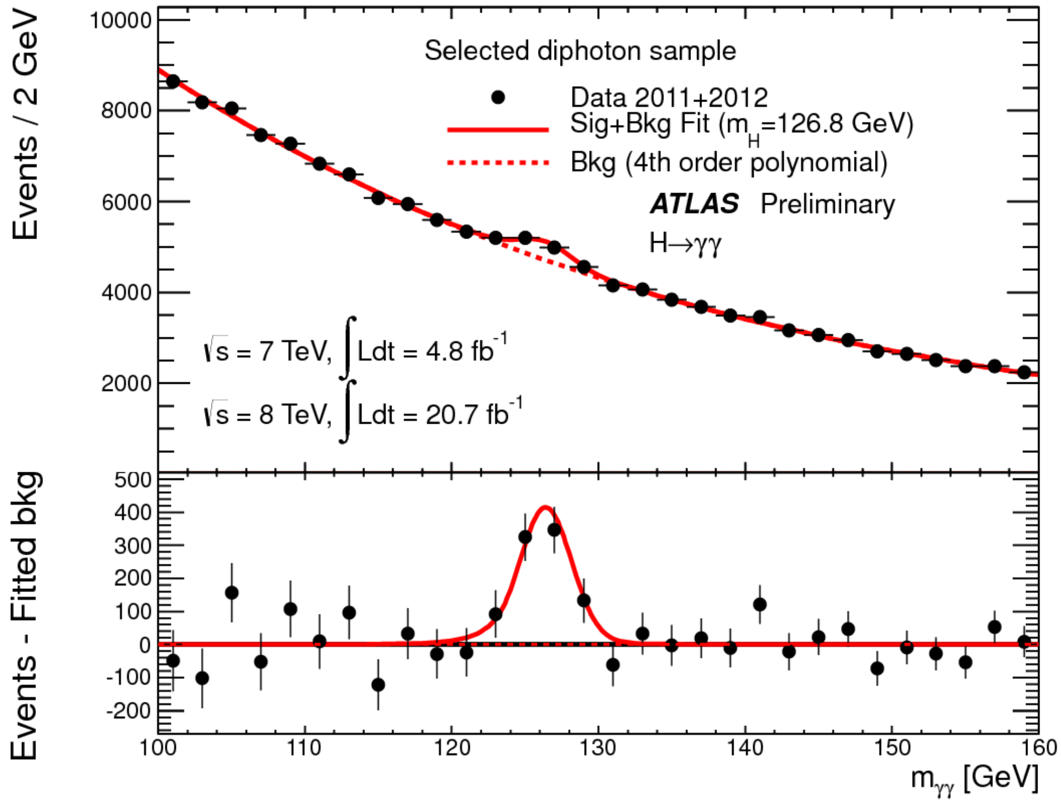
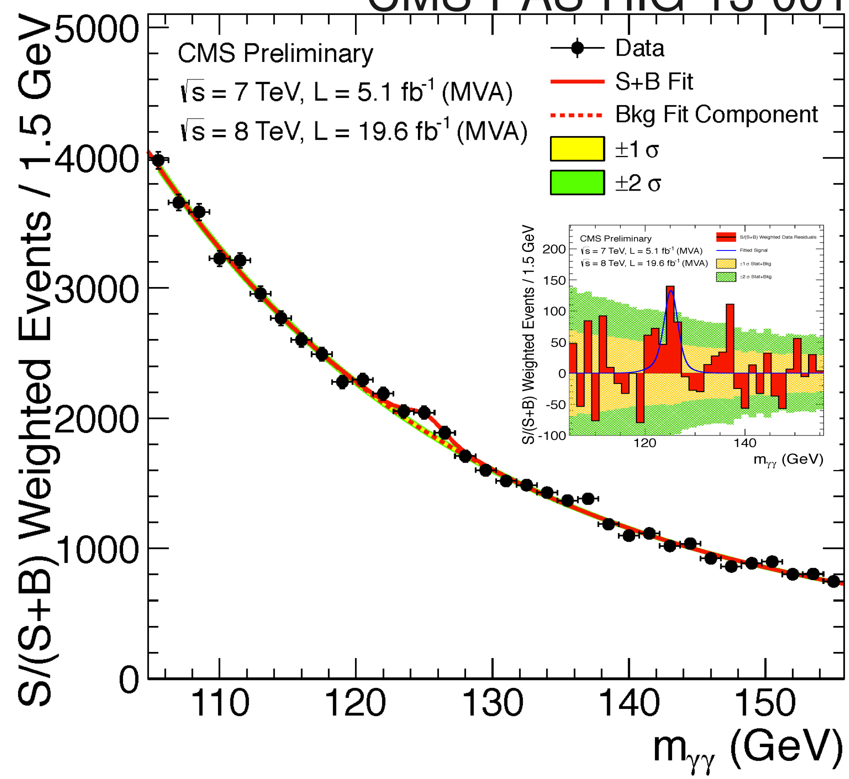


CMS

Main analysis: MVA-based;
cross check: cut-in-categories (CiC)

- **Significance**
  - MVA: **3.2σ** (4.2σ exp.)
  - CiC: 3.9σ (3.5σ exp.)
- Compatibility between two analyses within 1.5σ

CMS-PAS-HIG-13-001

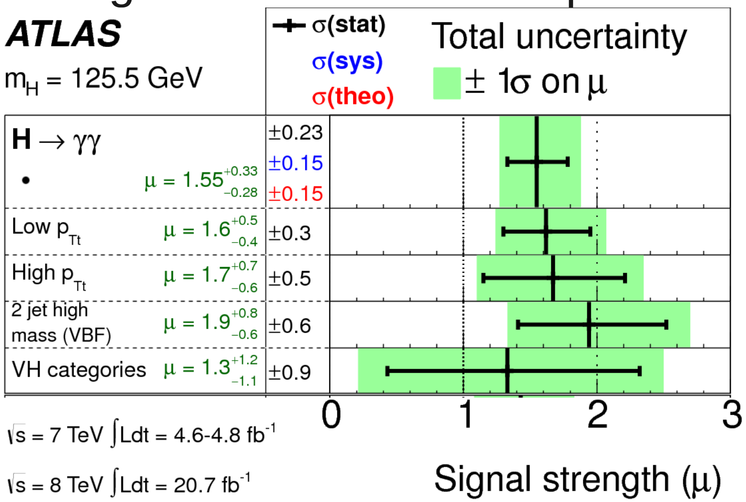


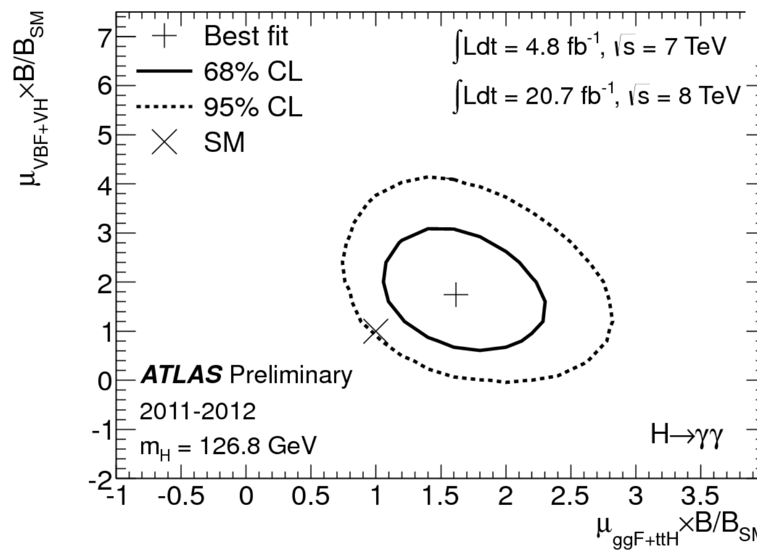
H → γγ: results

ATLAS: Signal strength (μ):

σ/σ_{SM} = 1.55 ± 0.23(stat) ± 0.15(syst) ± 0.15(th)

- Consistent across categories
- ~2σ higher than SM S+B expectation

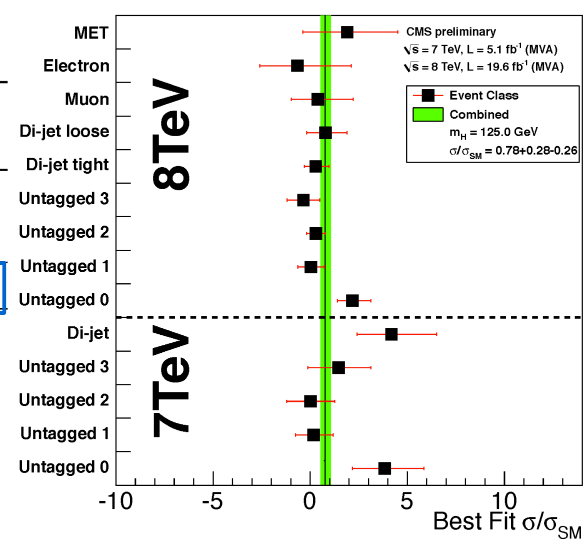


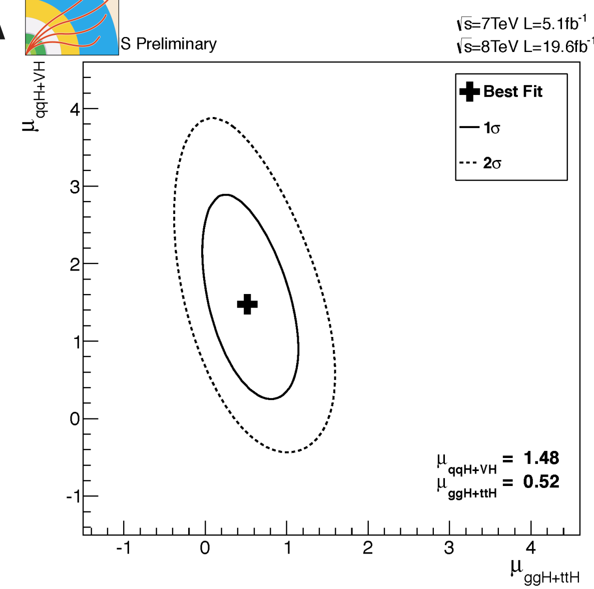


CMS: Signal strength (μ):

	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

MVA





Differential cross-sections

Thanks to high signal it is possible to determine differential distributions for $H \rightarrow \gamma\gamma$

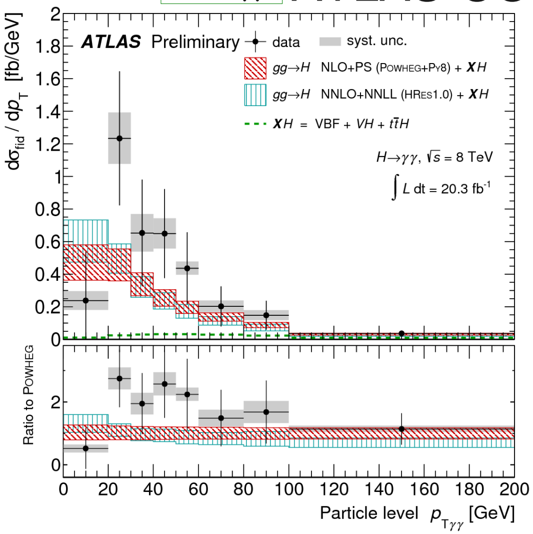
Strategy

- Define binning for studied variable
- For each bin extract yield fitting $m_{\gamma\gamma}$
- For each bin correct for acceptance, efficiency resolution => “unfolding”

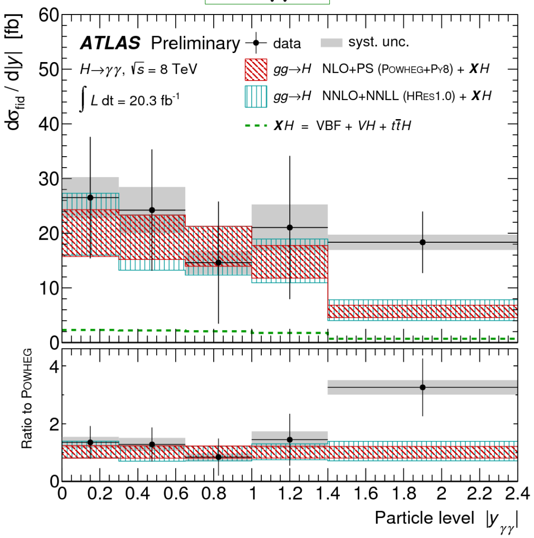
  Unfolding critical to compare with theory predictions

- Uncertainties due to JES/JER, UE, PDF, scale
- Fair agreement at current precision → No significant deviation from SM predictions (beyond overall excess),
- Also other distributions available: N_{jet}, $p_{T,j}$, $\Delta\varphi_{jj}$

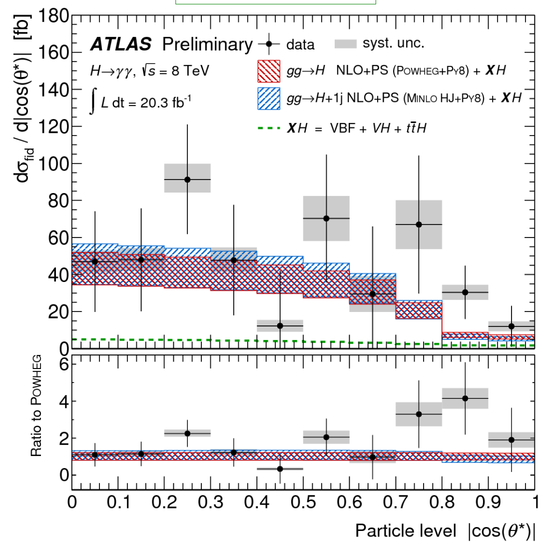
$p_{T,\gamma\gamma}$ ATLAS-CONF-2013-072



$|y_{\gamma\gamma}|$



$|\cos\theta^*|$



$H \rightarrow WW^* \rightarrow 2l2\nu$

- **High yield, low mass resolution**
  - Signature: exactly 2 opposite sign, isolated leptons, significant MET
  - Small $\Delta\varphi_{ll}$ (and m_{ll}) thanks to scalar nature of a Higgs boson (and A-V Wlν coupling)
  - **No signal mass peak** (presence of 2ν)
    - Transverse mass of di-lepton plus ME_T system (m_T) sensitive on m_H
- **Classes based on jet multiplicity & b-veto**
  - 0/1 jets (ggF), 2 jets (VBF)
- **Selection**
  - **ATLAS:** extract signal by fitting m_T distribution in two m_{ll} bins
  - **CMS:** 2D analysis m_{ll} vs m_T for the eμ channel, cut based for same flavour channels

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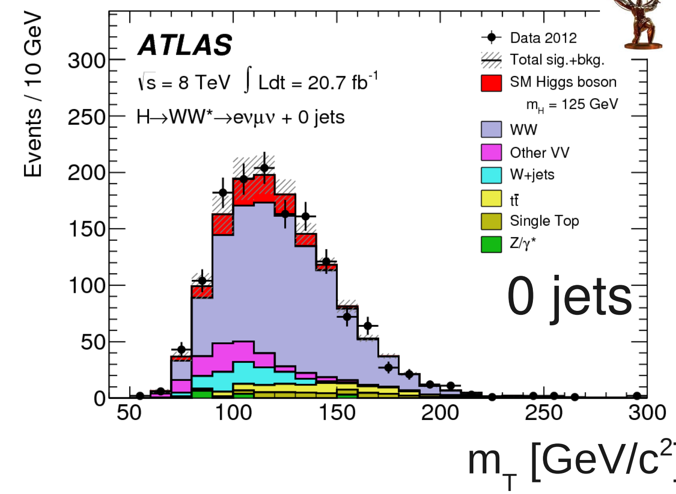
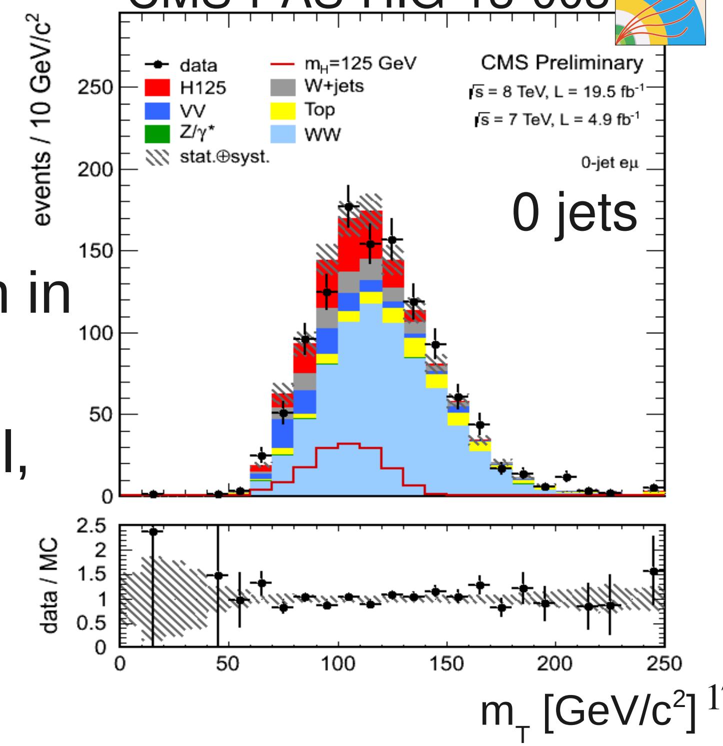


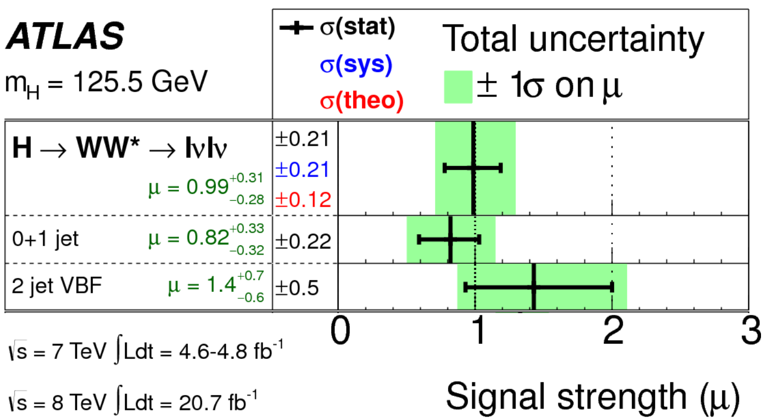
CMS-PAS-HIG-13-003

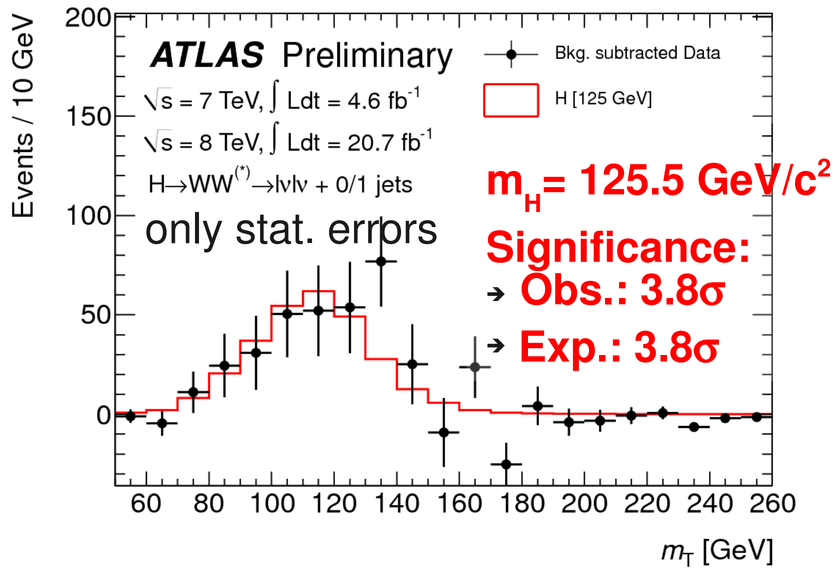


H → WW* → 2l2ν: results

Signal strength (μ):

- ATLAS: $\sigma/\sigma_{SM} = 0.99^{+0.31}_{-0.28}$

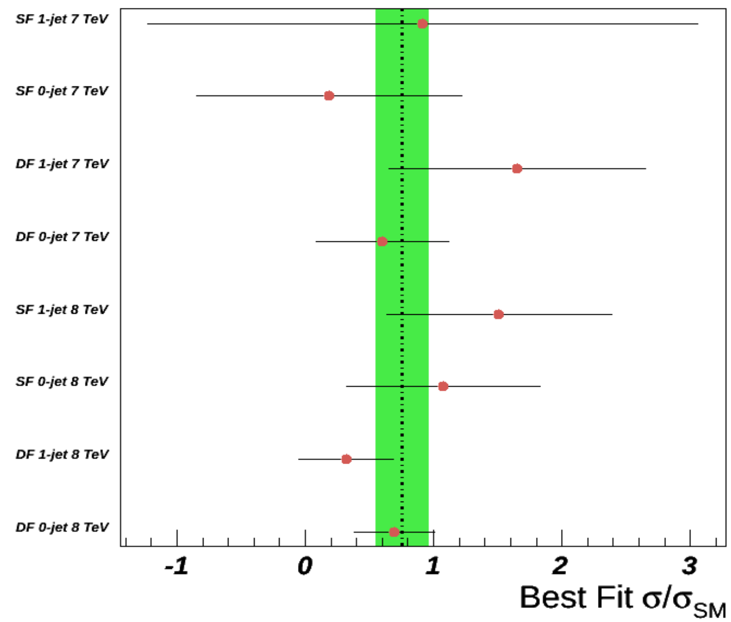


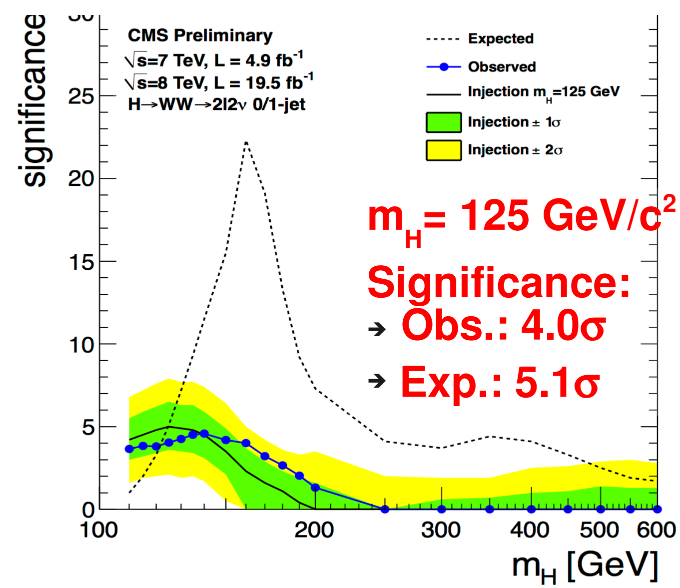


Background-subtracted m_T distribution

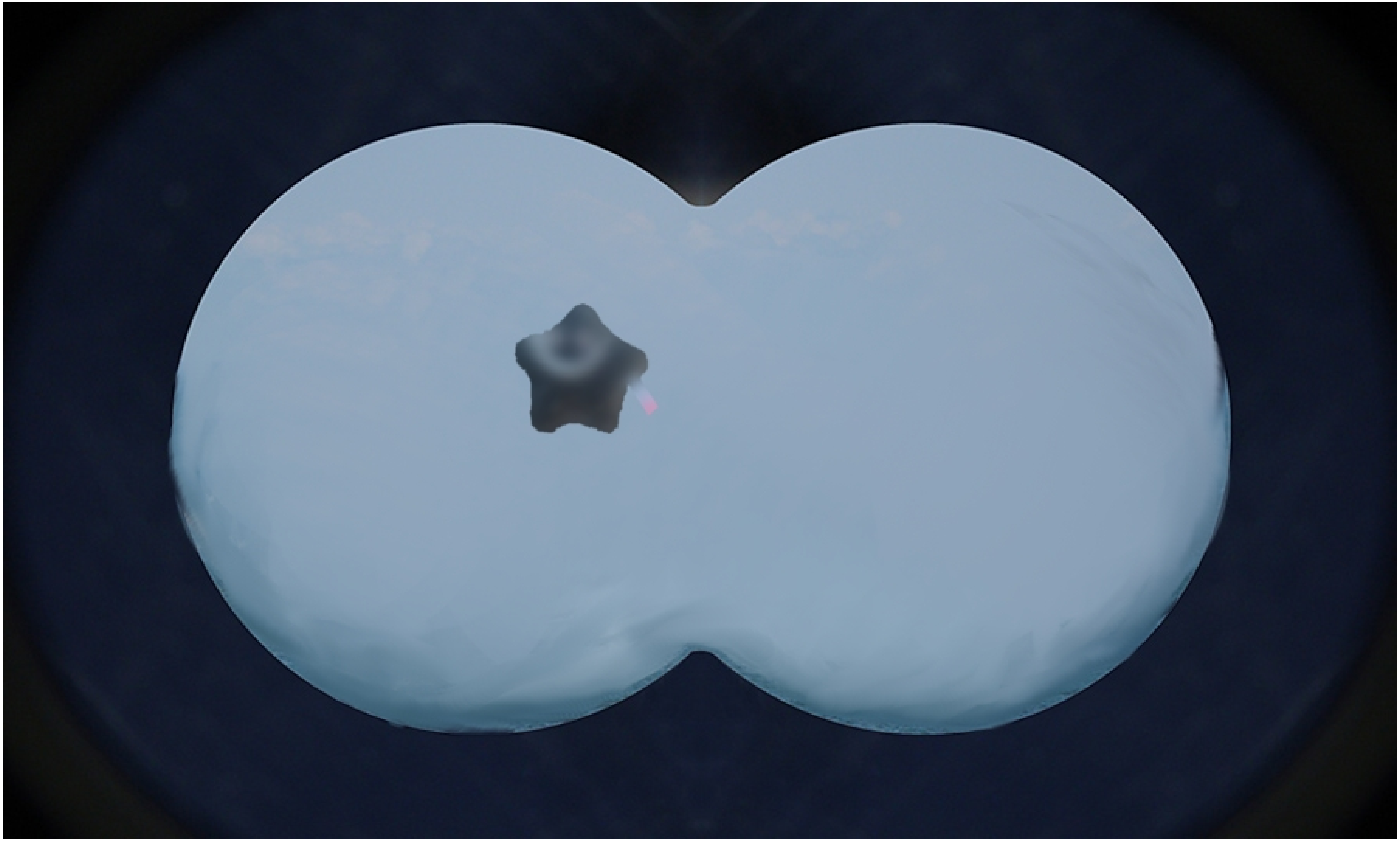
Signal strength (μ):

- CMS: $\sigma/\sigma_{SM} = 0.76 \pm 0.21$





Almost-seen Higgs



Channels becoming sensitive on H(125):

$H \rightarrow \tau\tau$, (V)$H \rightarrow bb$

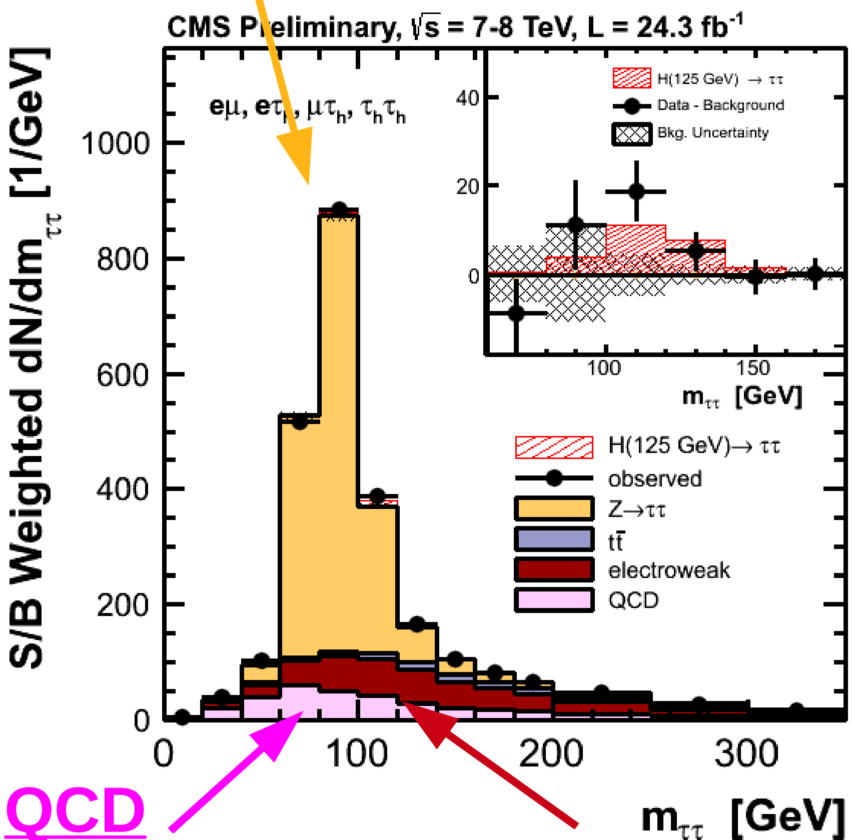
$H \rightarrow \tau\tau$ with CMS

- Based on the $\mu\tau_h$, $e\tau_h$, $e\mu$, $\mu\mu$, and $\tau_h\tau_h$ channels
- Analysis is done in 0-, 1-and 2-jet (VBF) categories
- 0/1-jet categories split in two, depending on the p_T of the τ-decay products
- $\tau_h\tau_h$ doesn't use 0-jet category and the 1-jet category not split
- VH(ττ) channels included
- Full $m_{\tau\tau}$ reconstruction (SVFit) with resolution of ~20%
- Benefits significantly from particle-flow reconstruction

→ CMS-PAS-HIG-13-004

$Z \rightarrow \tau\tau$

Embedding: $Z \rightarrow \mu\mu$ data with μ replaced by simulated τ (5% syst.)



QCD

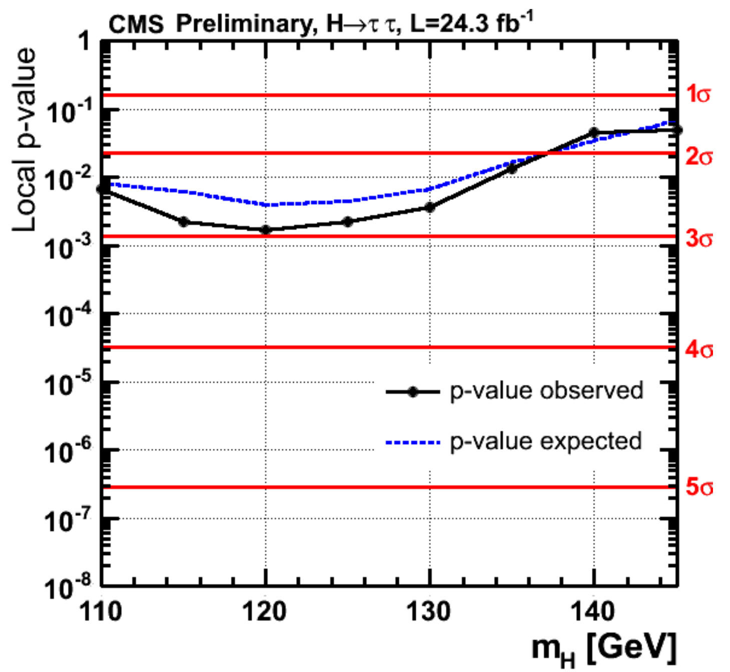
- From same-sign data (10% syst.)

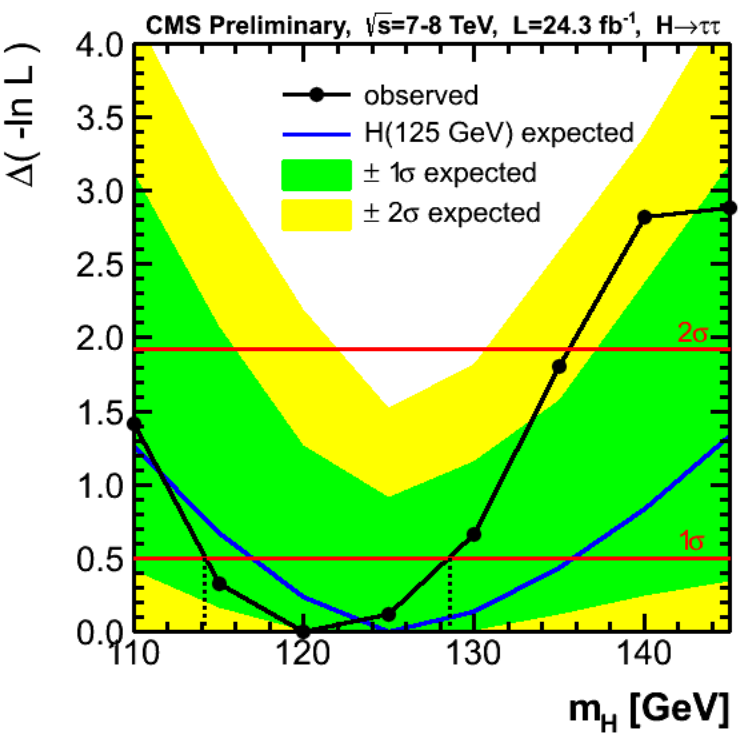
W+jets

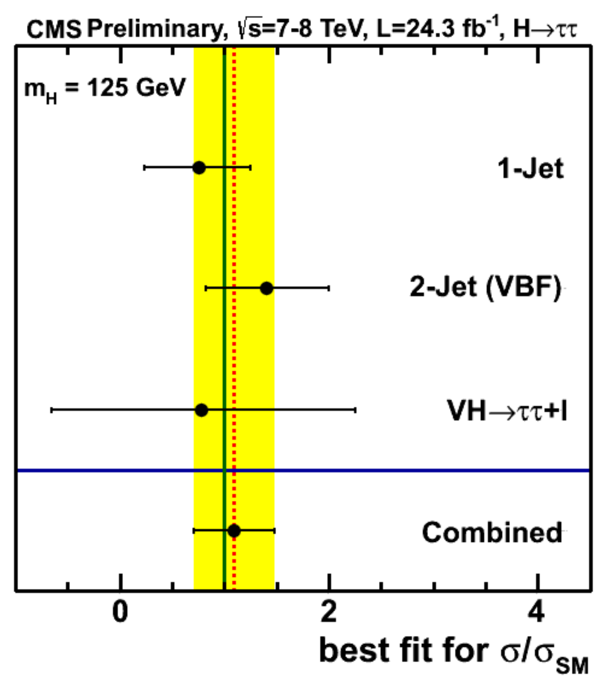
- Simulation normalized in control region (10-20% syst.)

CMS: H → ττ results

- Wide excess compatible with expectation for SM Higgs and obs. in sensitive channels
  - Significance of 2.9σ (exp. 2.6σ) at 125 GeV/c^2
  - Signal strength of $\sigma/\sigma_{SM} = 1.1 \pm 0.4$
- **Strong indication that Higgs decays to taus!**
- First mass measurement in this channel
  - $\mathbf{m_H = 120^{+9}_{-7}}$ **(stat+syst) GeV/c^2**
  - Consistent with combined $m_H(\gamma\gamma+4l) = 125.7 \pm 0.4$ (stat+syst) GeV/c^2



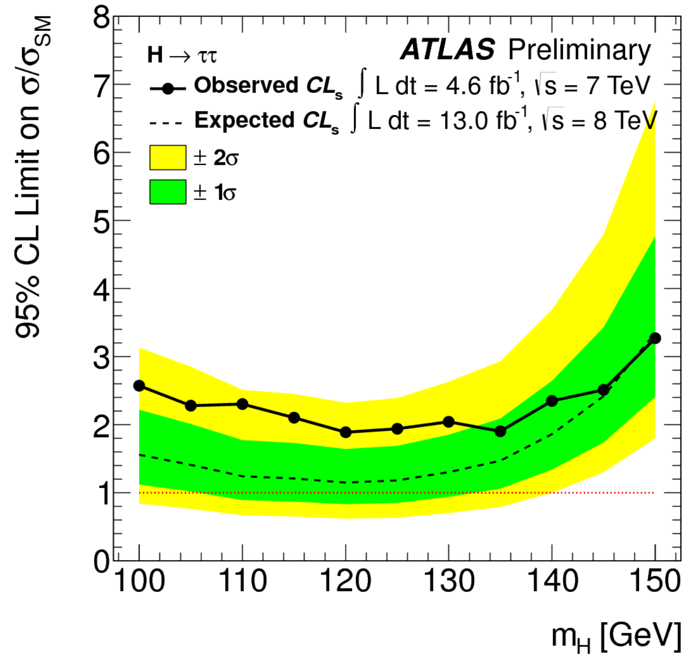


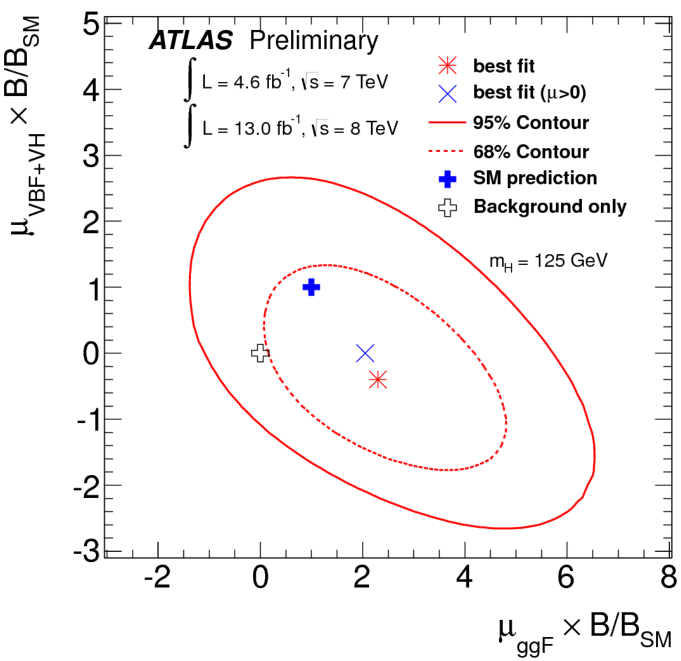


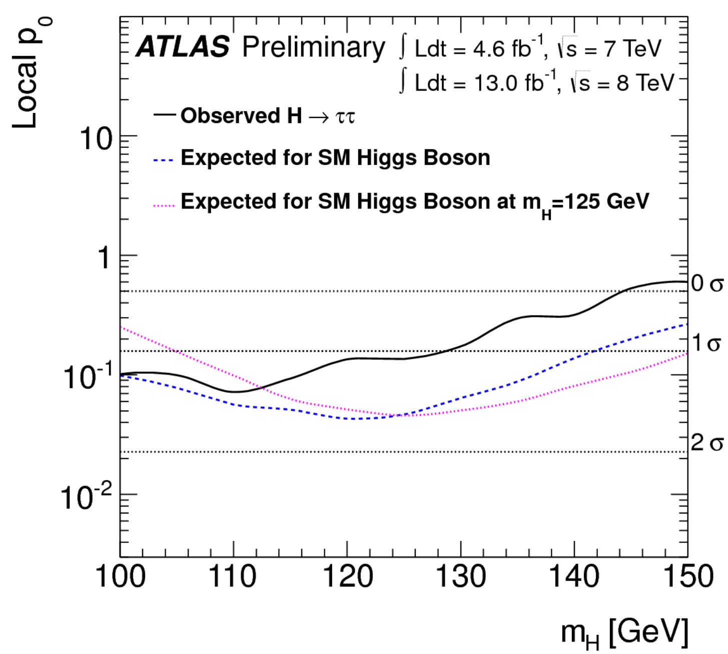
H → ττ with ATLAS

- Similar analysis strategy as used by CMS
- Not updated to full dataset yet
  - 4.6/fb+13/fb analysed
- Not yet sensitive enough
  - Analysis of full dataset with improved techniques ongoing
- **Significance**: 1.1σ (exp. 1.7σ)
- **σ/σ_{SM} = 0.7 ± 0.7**

➔ ATLAS-CONF-2012-160



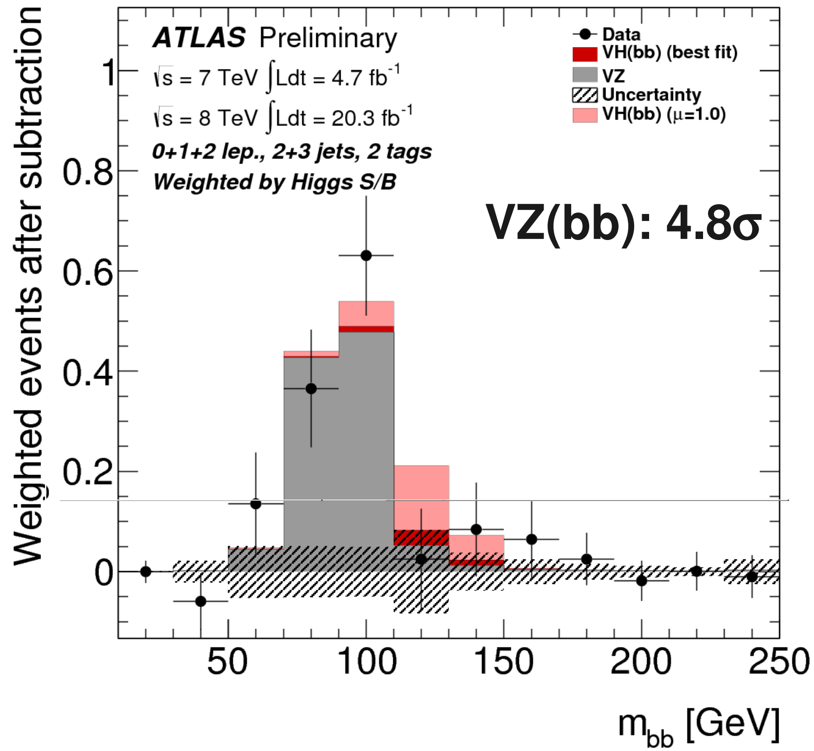


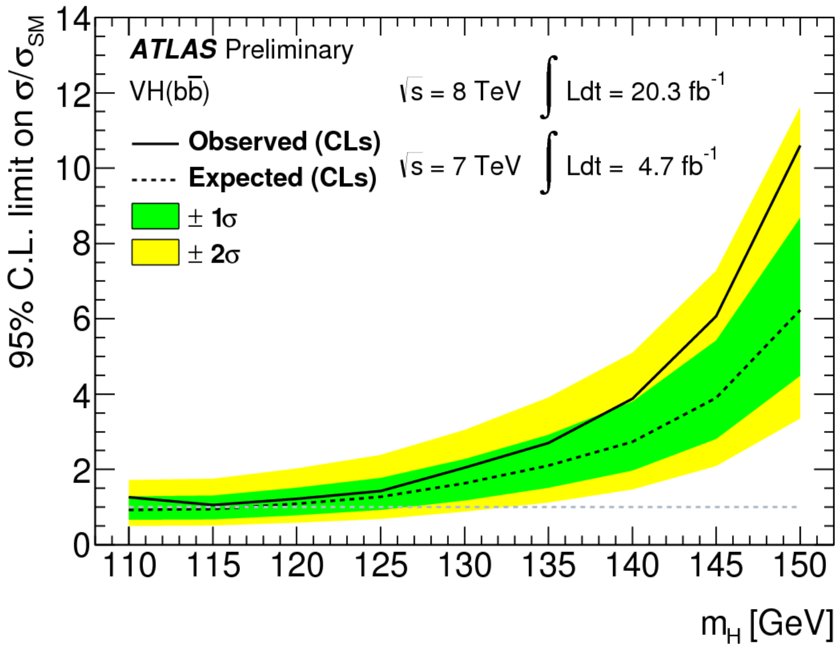


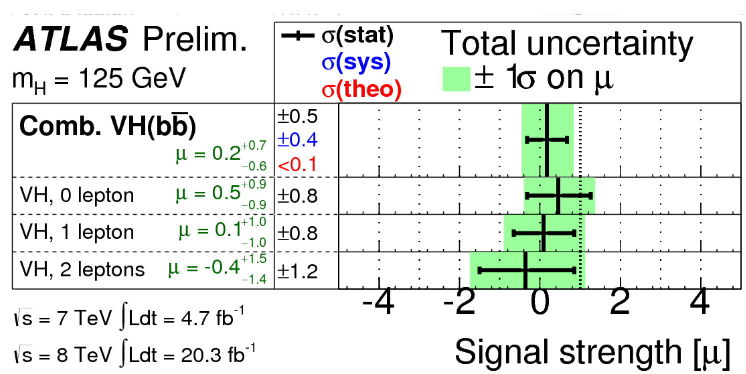
VH → bb with ATLAS

- Search performed in 0-, 1-, 2-lepton categories split further into $p_T(V)$ bins
- Signal extracted by simultaneous fit of m_{bb} in all categories
  - Cross check with VZ(bb): 4.8σ
- Limit: obs. 1.4 x SM (exp. 1.3 x SM) 95% C.L. at 125GeV/c^2
- $\sigma/\sigma_{SM} = 0.2^{+0.7}_{-0.6}$
  - Not sensitive yet, neither S+B nor B only favoured

ATLAS-CONF-2013-079



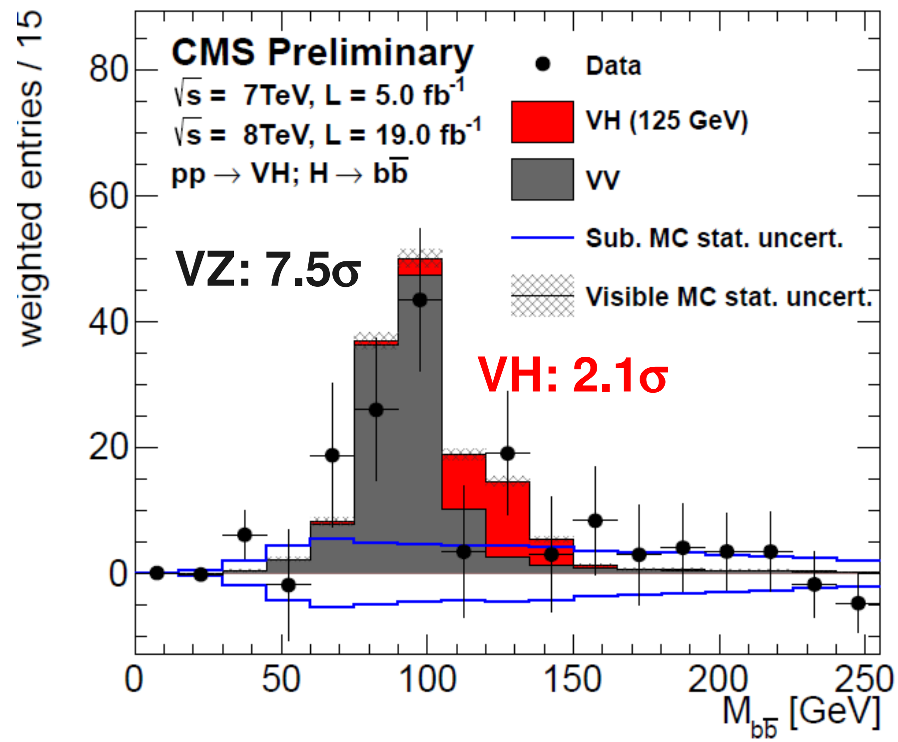




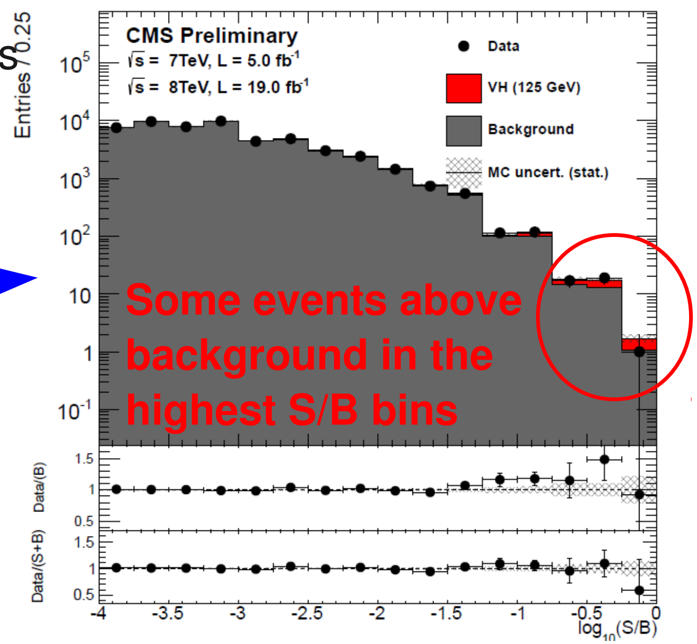
VH → bb with CMS

CMS-PAS-HIG-2013-012

- Combines the W → lν (incl. τ), Z → ee/μμ/νν channels
- m_{bb} resolution of ~10%
  - BDT regression
- Train BDT discriminates using
  - Kinematics: m_{bb}, $p_{T,bb}$, ..
  - b-tagging
  - Topology
- Extract signal from simultaneous fit of BDT's for all channels

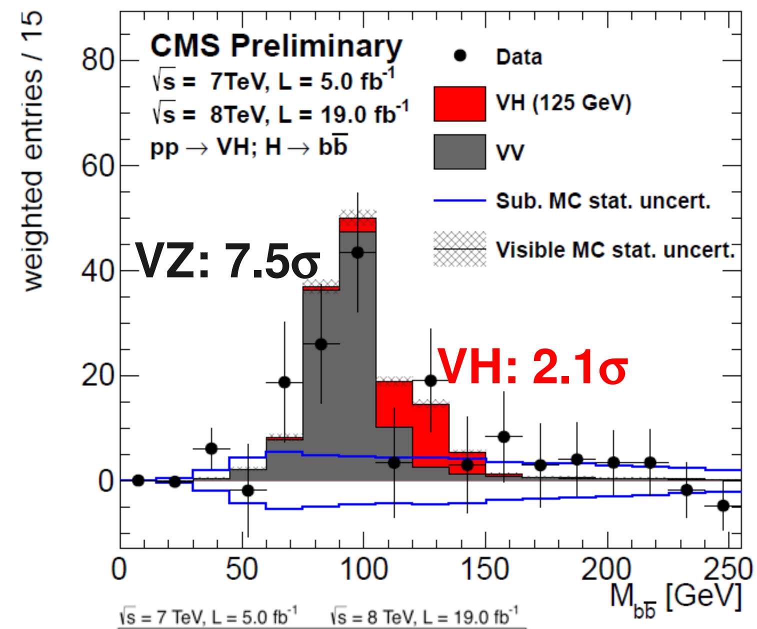


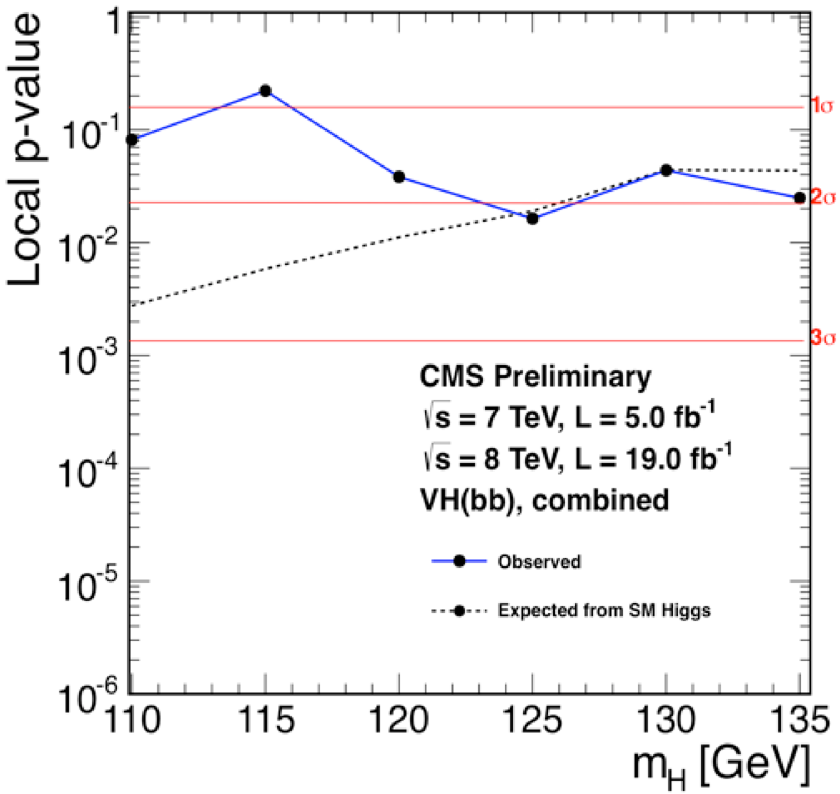
Summarise all BDT's by sorting bins with same S/B

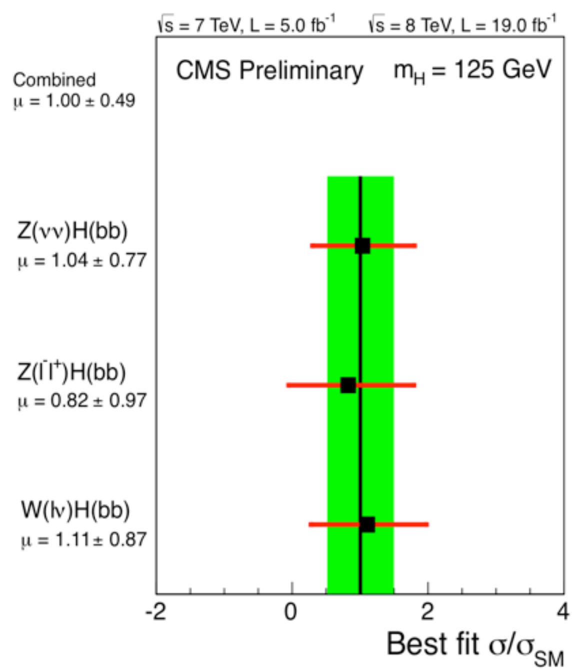


CMS: VH→bb results

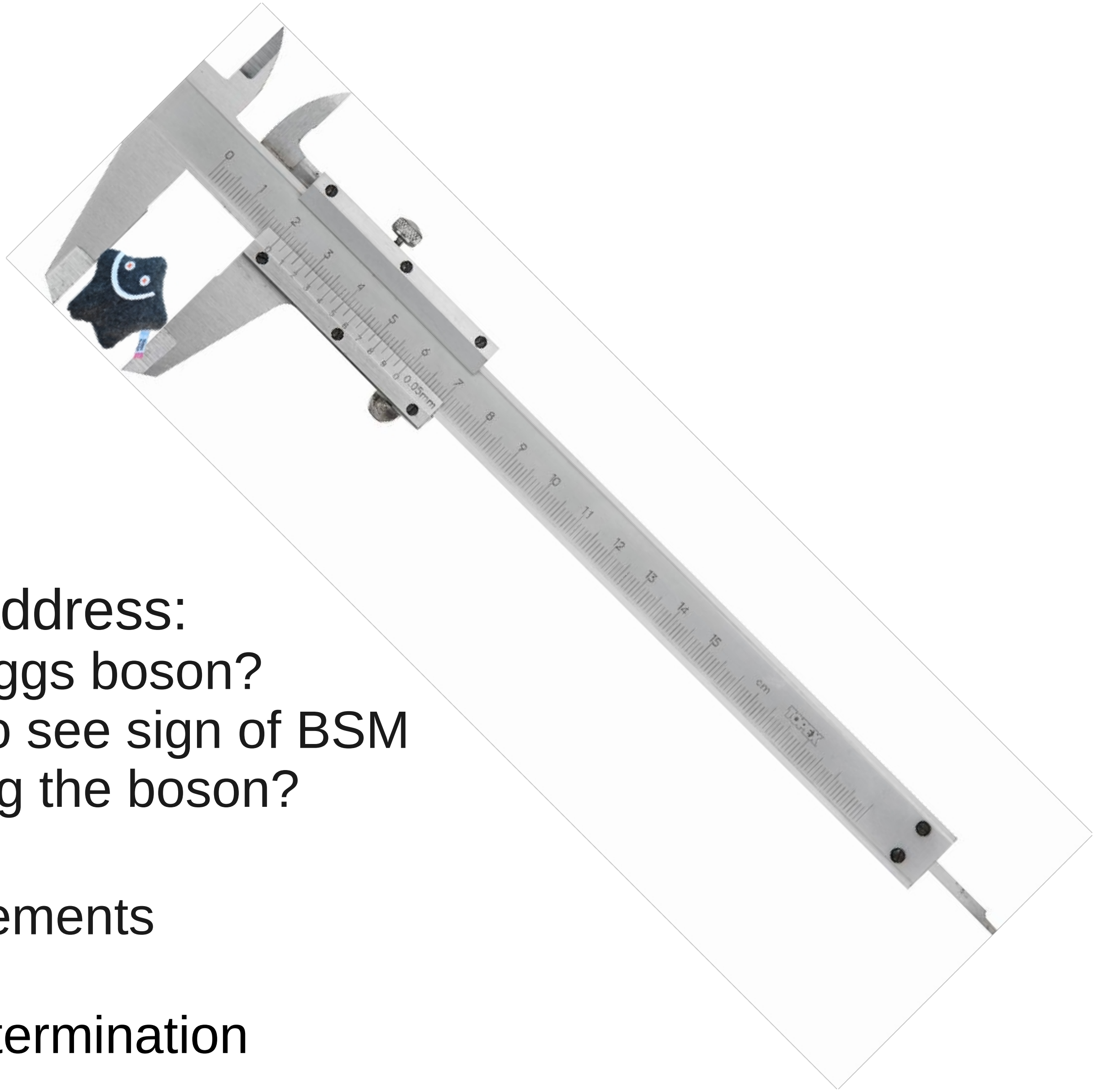
- **Observed excess of 2.1σ (exp. 2.1σ)**
  - >7σ for VZ(bb) observation
- **σ/σ_{SM} = 1.00 + 0.49** at m_H=125 GeV/c^2
  - **Combined with H→ττ gives an evidence for the Hff coupling to the 3rd generation down fermions at 3.4σ (exp. 3.4σ)**







Higgs properties



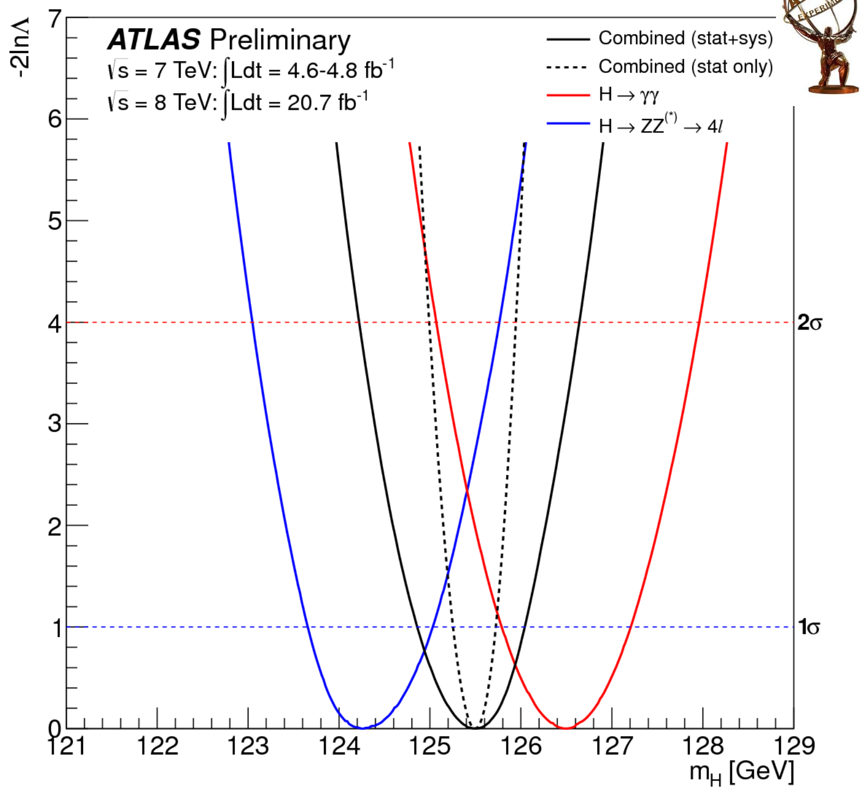
Questions to address:
- Is it the SM Higgs boson?
- Is it possible to see sign of BSM physic studying the boson?

Properties:
- Mass measurements
- Couplings
- Spin-parity determination

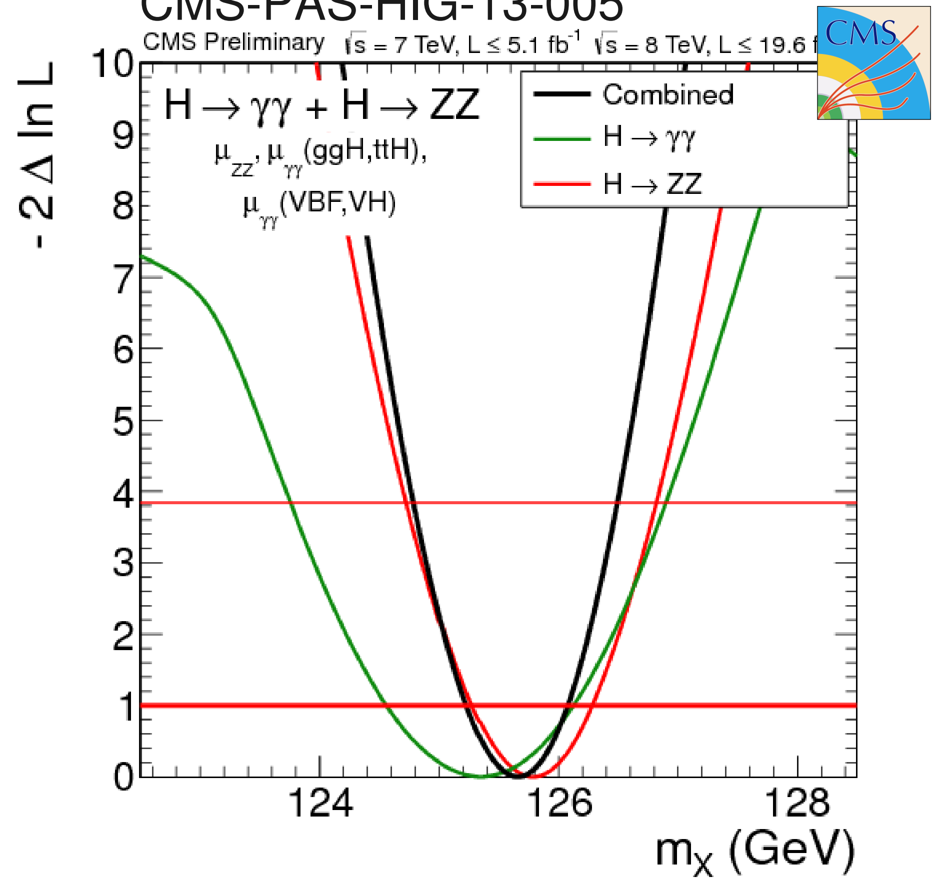
Higgs mass

Measured from $m_{\gamma\gamma}$ and m_{4l} distributions together with signal strength μ

ATLAS-CONF-2013-014



CMS-PAS-HIG-13-005



ATLAS:

m_H= 125.5 ± 0.2(stat) ± 0.6(syst) GeV/c^2

CMS:

m_H= 125.7 ± 0.3(stat) ± 0.3(syst) GeV/c^2

Couplings

- Studies following recommendation of LHC Higgs-XS-WG
  - 1 resonance, zero-width approx., SM tensor structure ($J^P=0^+$)

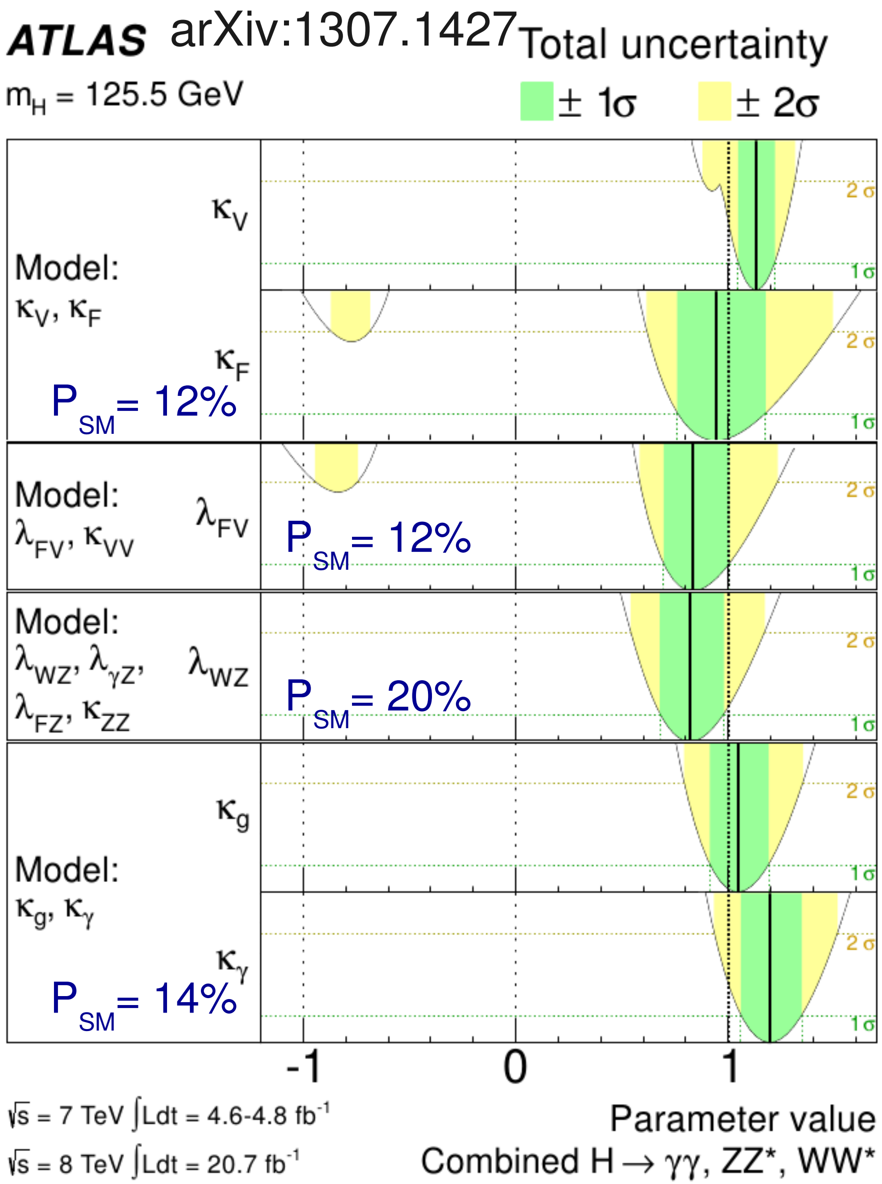
$$\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

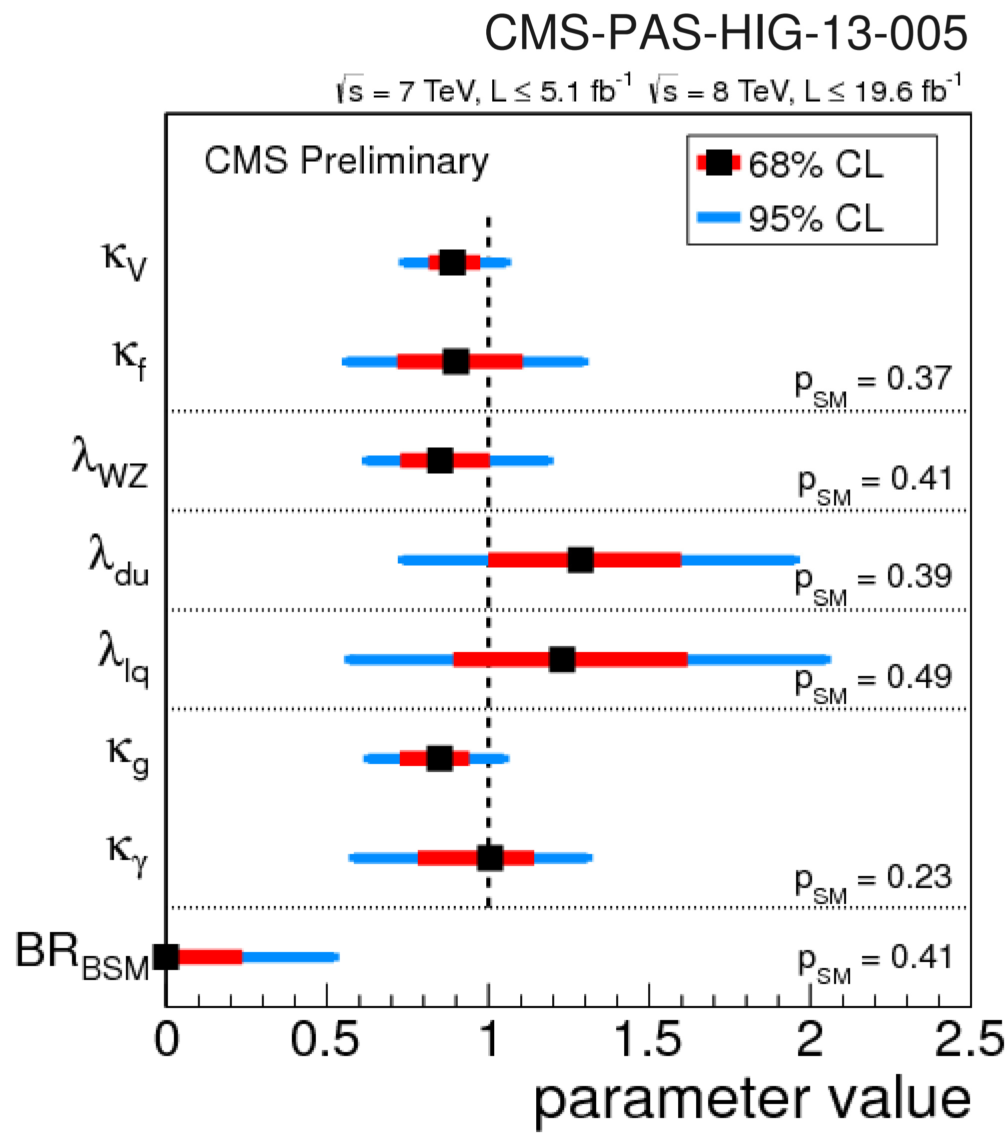
  - Allows to exploit correlations between production and decay modes to test SM predictions
  - Measured yield can be parametrised in terms of *coupling strength scaling factors* $\kappa = g/g_{SM}$, e.g. for ZV→bb:

$$\mu_{ZH\to bb} = [\sigma_{ZH} \times Br(H\to bb)]/[\sigma_{ZH} \times Br(H\to bb)]_{SM} = (\kappa_Z^2 \times \kappa_b^2)/\kappa_H^2$$

    - In SM all μ's and κ's are equal to 1
  - Loop scaling factors (κ_g, κ_{γ}.) can be
    - expressed in terms SM coupling scaling factors
    - treated as free parameters → effective couplings sensitive on BSM
  - Γ_H requires assumptions: $\kappa_H = \kappa_H(\kappa_W, \kappa_Z, \ldots)$

Couplings summary

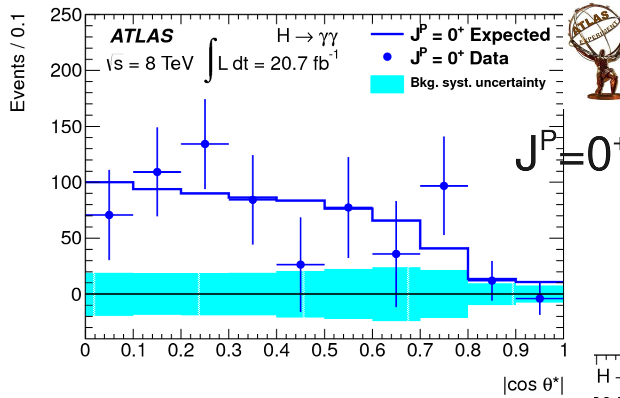


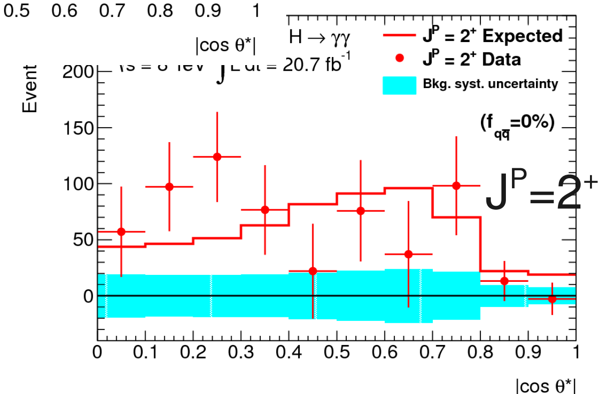


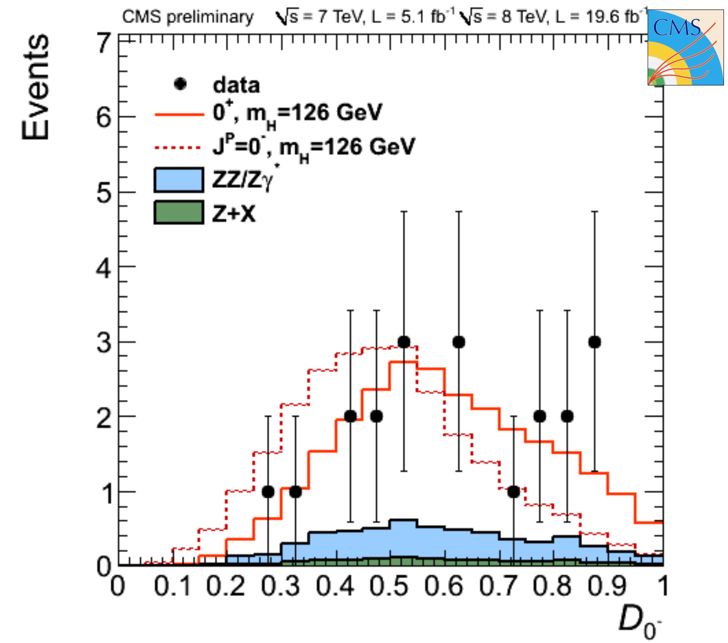
- All results consistent with SM Higgs boson

Spin-parity determination

- Experimental approach:
  - Use observables sensitive to spin and parity of Higgs boson **independent on the signal (coupling) strengths**
- Several alternative hypotheses ($J^P=0^-$, 1^+, 1^-, 2^+) tested against the SM Higgs ($J^P=0^+$)
  - On shell $X(J=1)\rightarrow\gamma\gamma$ decay forbidden (Landau-Yang theorem)
- Analysed decay modes
  - **$H\rightarrow\gamma\gamma$**: decay angle $\cos(\theta^*)$ sensitive to J
  - **$H\rightarrow WW\rightarrow l\nu l\nu$**: several variables sensitive to J^P ($\Delta\varphi_{ll}$, m_{ll},...) combined with BDT (ATLAS) or 2D fit (CMS)
  - **$H\rightarrow ZZ\rightarrow 4l$**: full final state kinematics sensitive to J^P: 5 angles, 2 masses ($m_{ll,1}$, $m_{ll,2}$) combined with BDT or Matrix-element based variable D_{JP}
- Test statistics
  - $$q = \log \frac{\mathcal{L}(J^P=0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})}$$

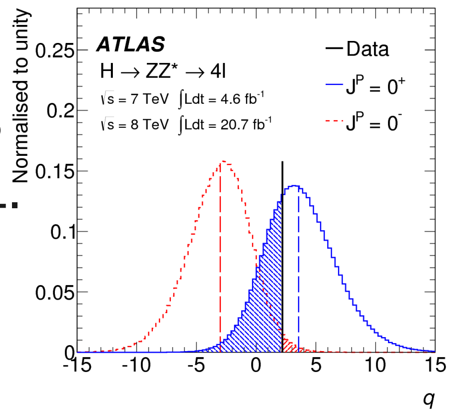


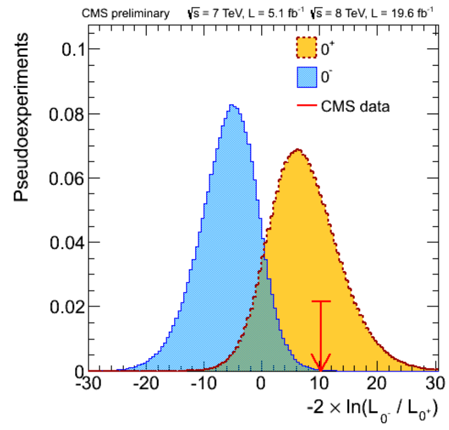




Spin-parity: 0^- results

- **0^+ vs 0^-**
  - $H \to ZZ \to 4l$ used by both ATLAS and CMS
  - **$J^P=0^-$** excluded at **97.8%** (exp. 99.6%) C.L. and **99.8%** (exp. 99.5%)
    by ATLAS and CMS, respectively



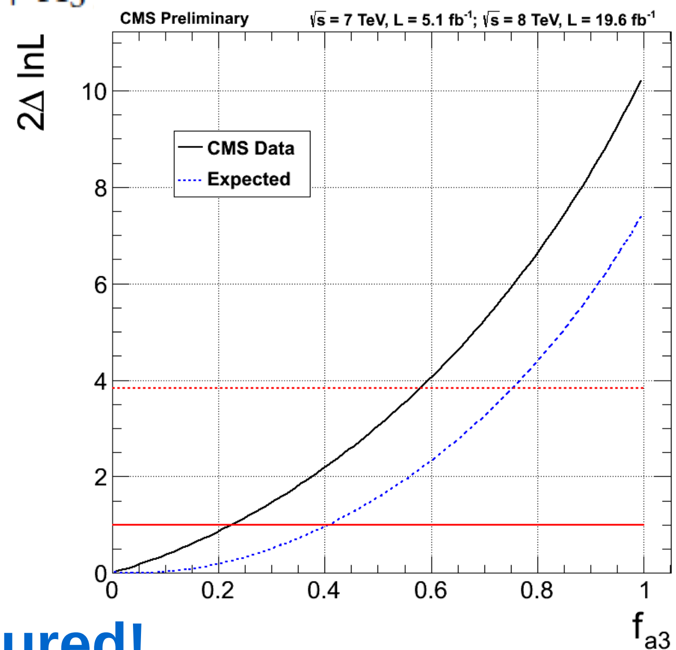


CMS investigated also sensitivity to different CP amplitudes in $H \to ZZ \to 4l$

- $A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$
  - $a_1=2$, $a_2=a_3=0$ in SM at tree level
- Check for presence of a 0^- component fitting (assuming $a_2=0$)

  $$\mathbf{f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)}$$

  $f_{a3} = 0^{+0.23}_{-0.00}$
  $f_{a3} < 0.56$ at 95% C.L (exp. < 0.76)



- **SM quantum numbers ($J^P=0^+$) strongly favoured!**

Spin-parity summary

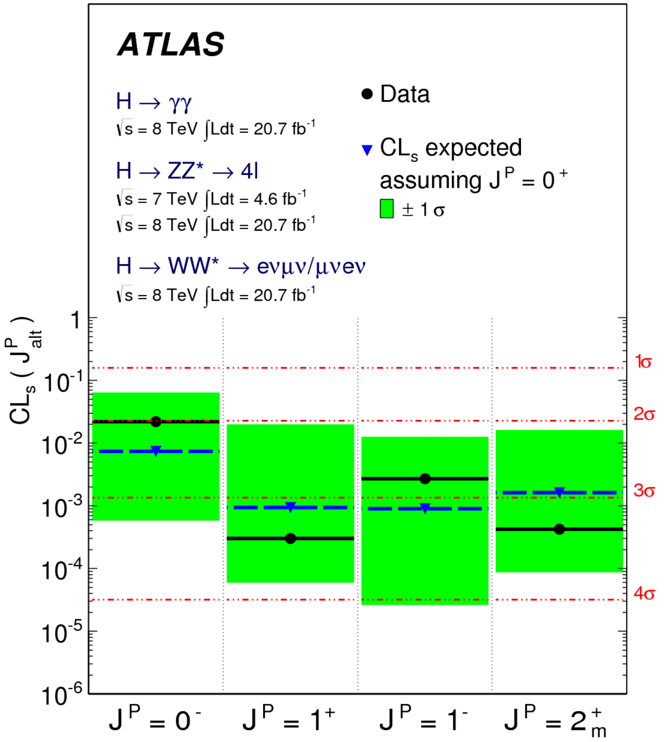
CMS: $H \to ZZ \to 4l$

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

- CMS-PAS-HIG-13-002
- CMS-PAS-HIG-13-005

ATLAS: $H \to \gamma\gamma$, $H \to ZZ \to 4l$, $H \to WW \to l\nu l\nu$

- ATLAS-CONF-2013-040



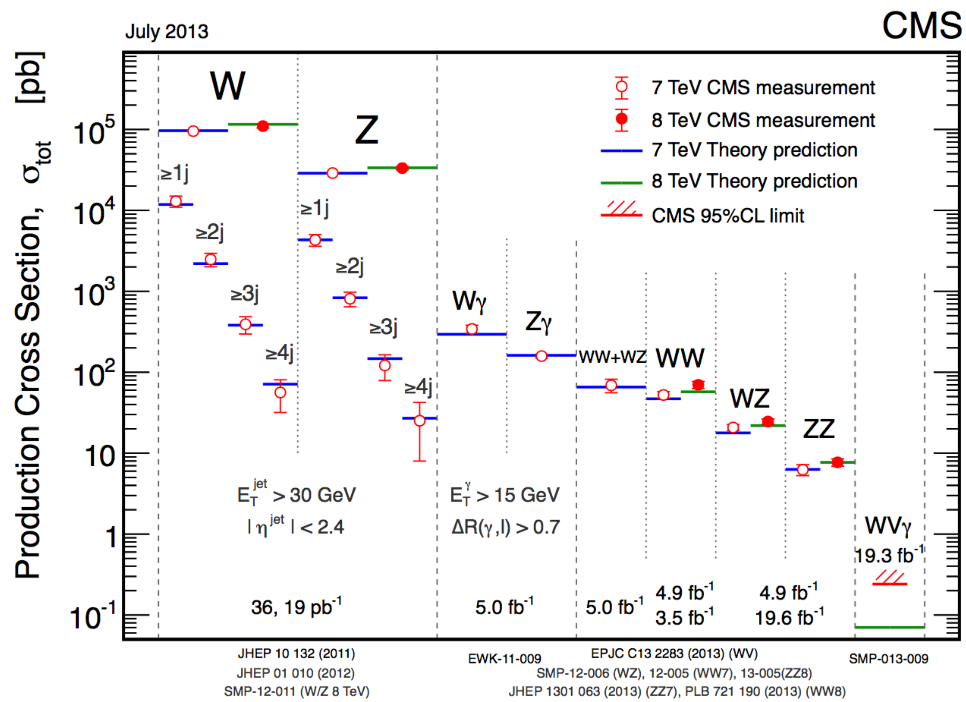
SM quantum numbers ($J^P=0^+$) strongly favoured!

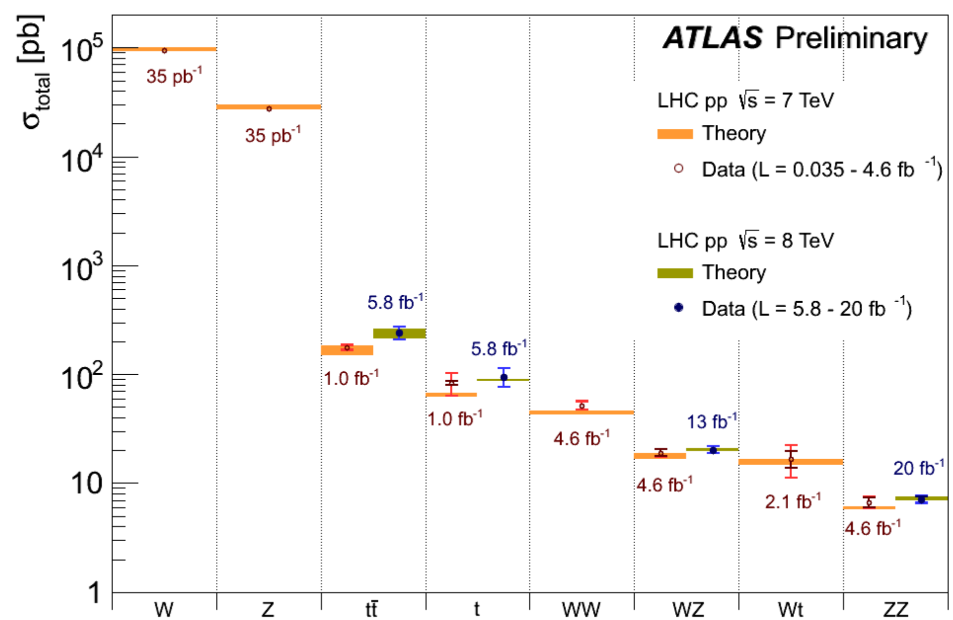
- All other studied alternative J^P models excluded at > 95% C.L.

Electro-weak physics

Introduction

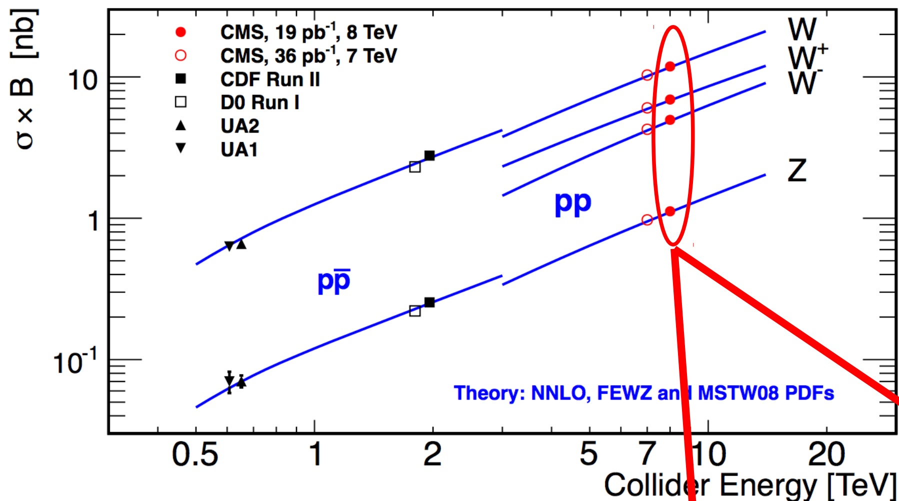
- Standard model was "rediscovered" at LHC!
- At lot of electro-weak studies at LHC
  - Detailed study of W and Z production
    - To confront with precise theory predictions
    - To constrain PDF's
    - …
  - Electro-weak interactions at TeV scale
    - Multi-boson production
    - aTGC's, QGC's
    - …
- Some examples will be presented

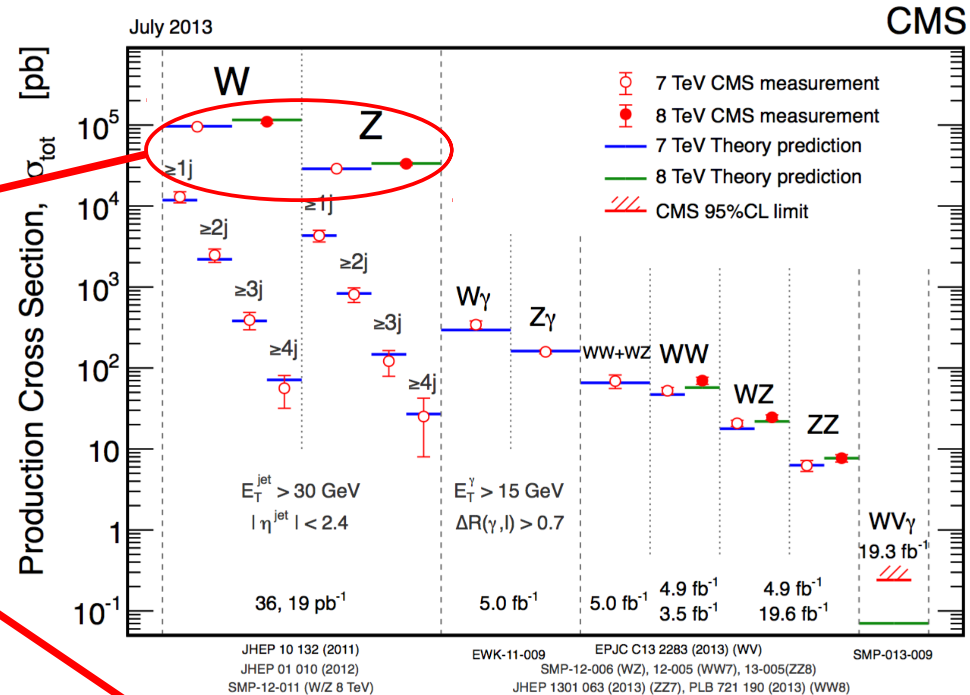




W & Z production

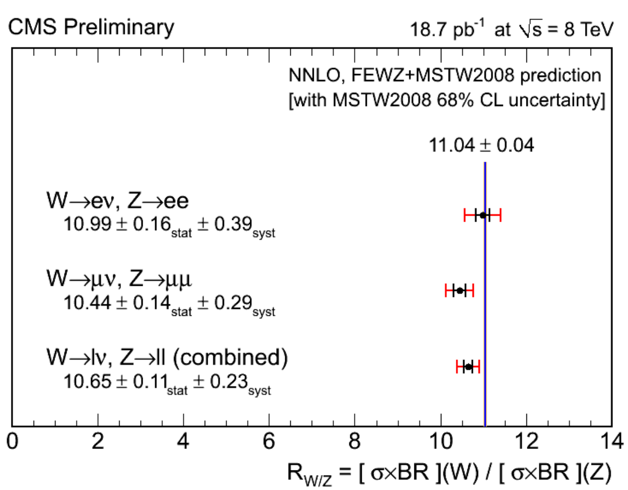
- Inclusive cross-sections

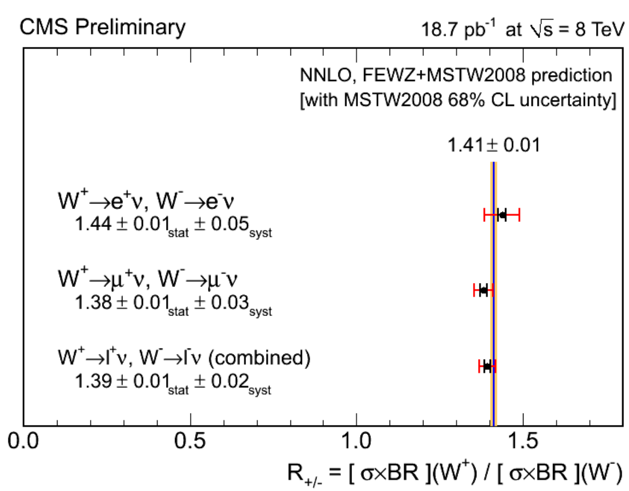




CMS: 8TeV measurement
based on 18.7/pb
of low pileup data

CMS-PAS-SMP-12-011



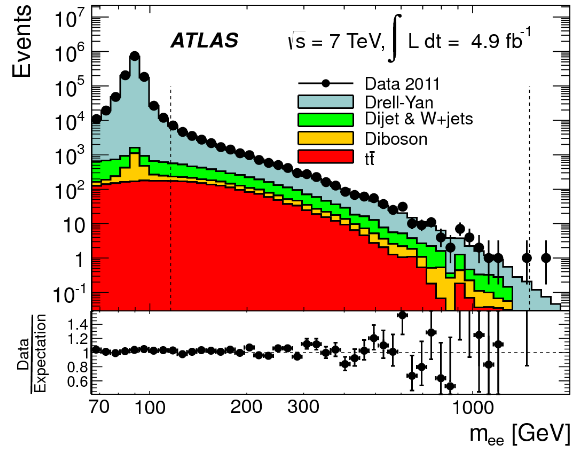


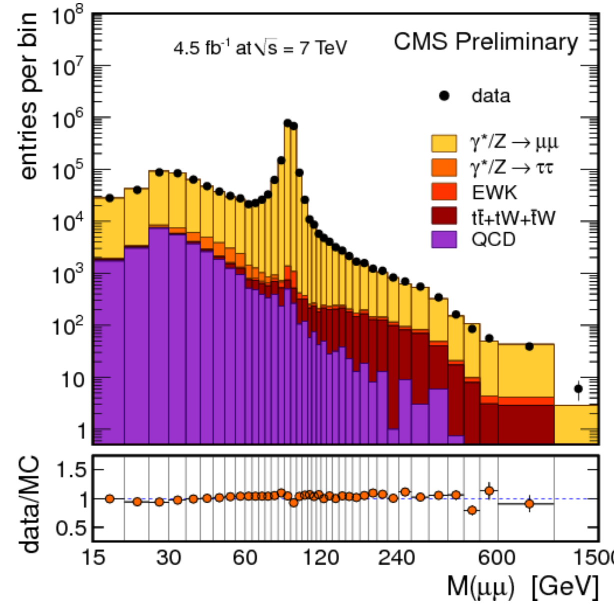
W & Z production

- (Some) Differential measurements

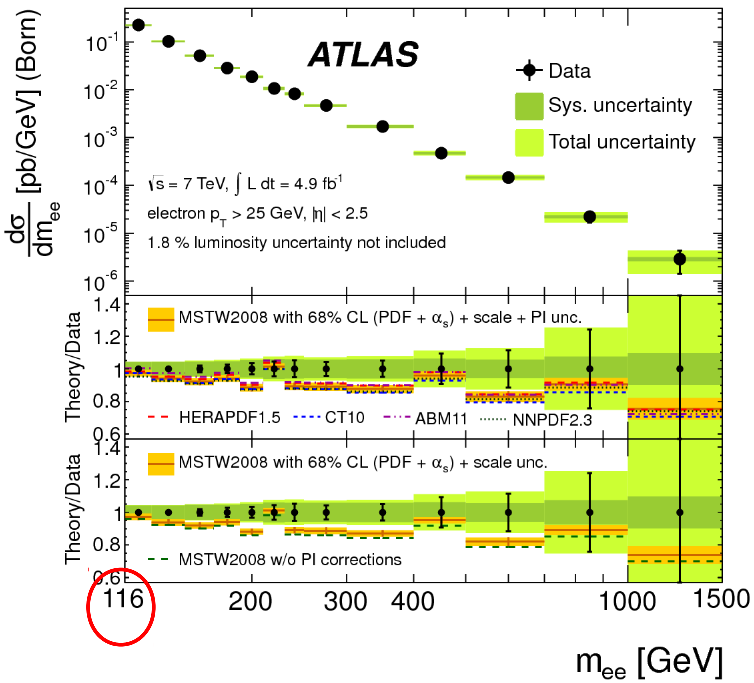
MC/data at reconstruction level

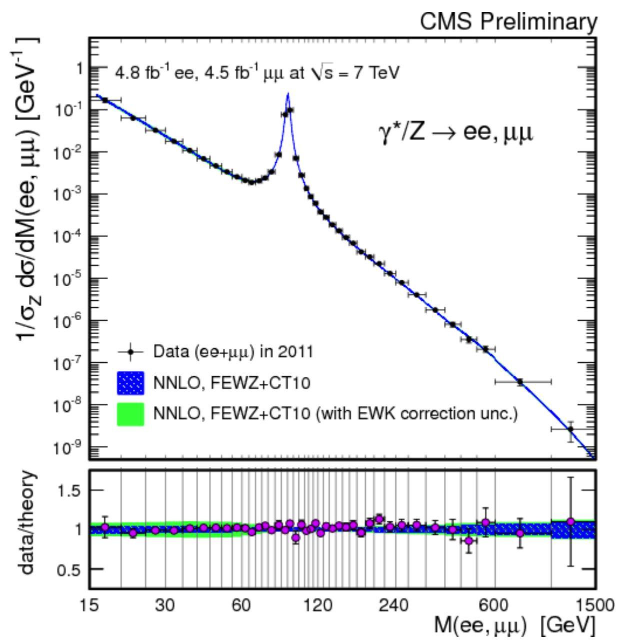
ATLAS: arXiv:1305.4192
CMS-PAS-SMP-13-003





Unfolded cross-section



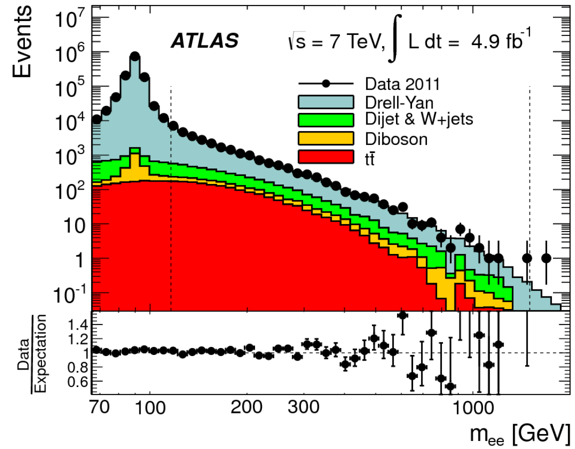


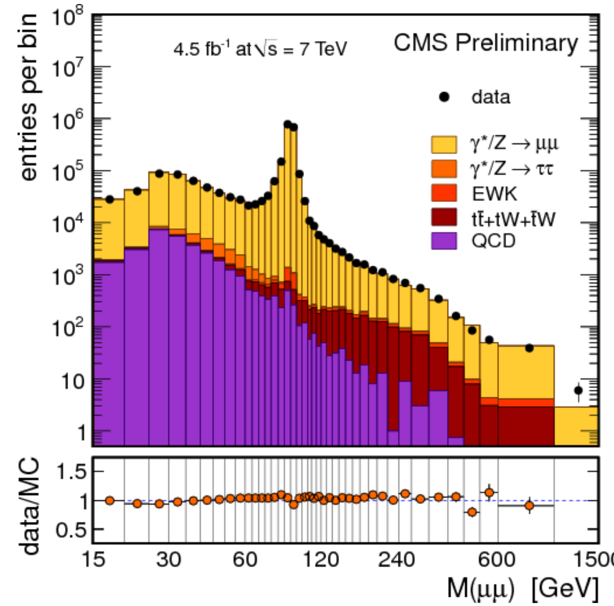
EWK corrections incl. photon-initiated production (PI: $\gamma\gamma \to ll$) – 10% effect at high m_{ll} comparable to PDF uncertainties

W & Z production

- (Some) Differential measurements

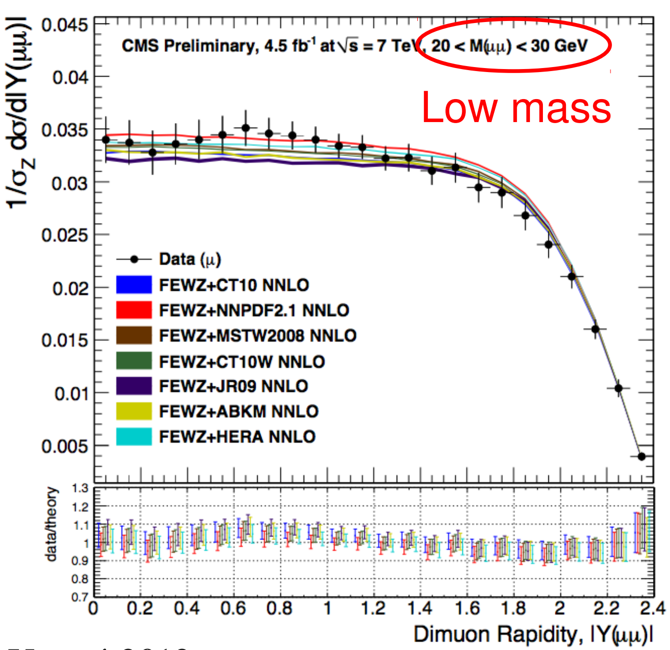
MC/data at reconstruction level

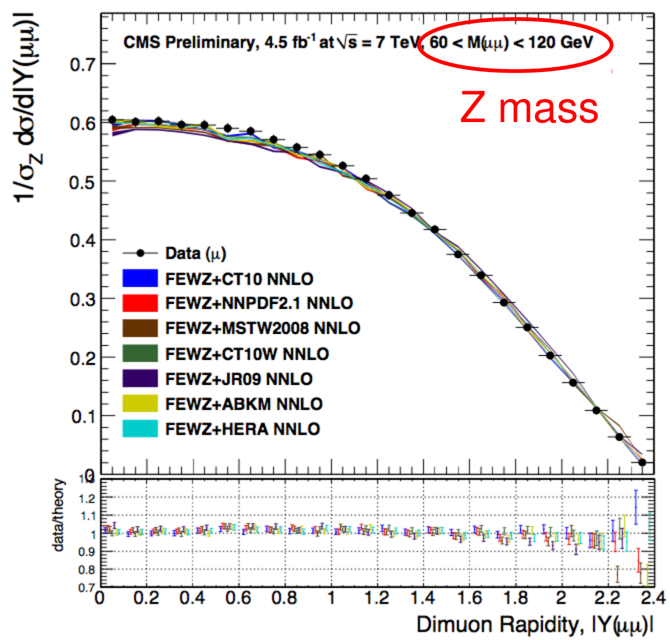


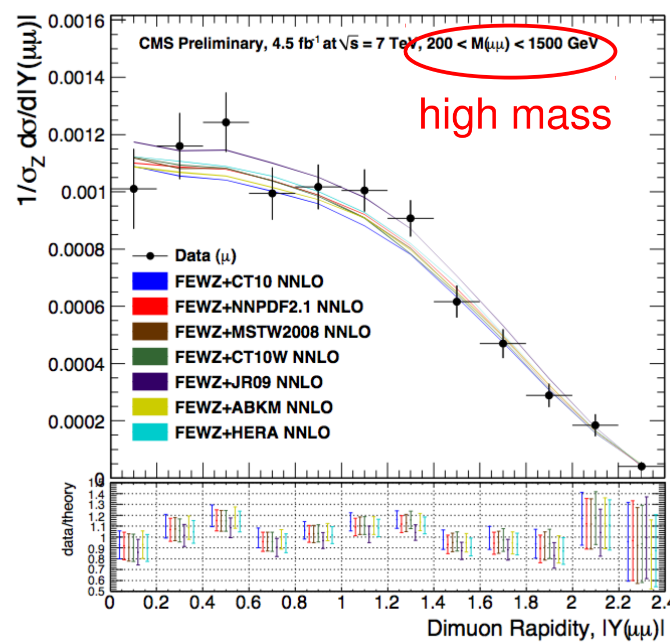


Unfolded cross-section

Double differential cross-section



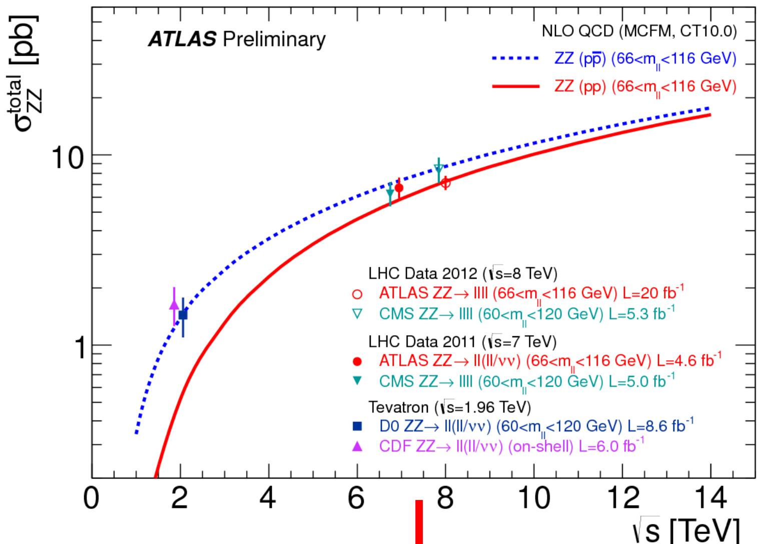


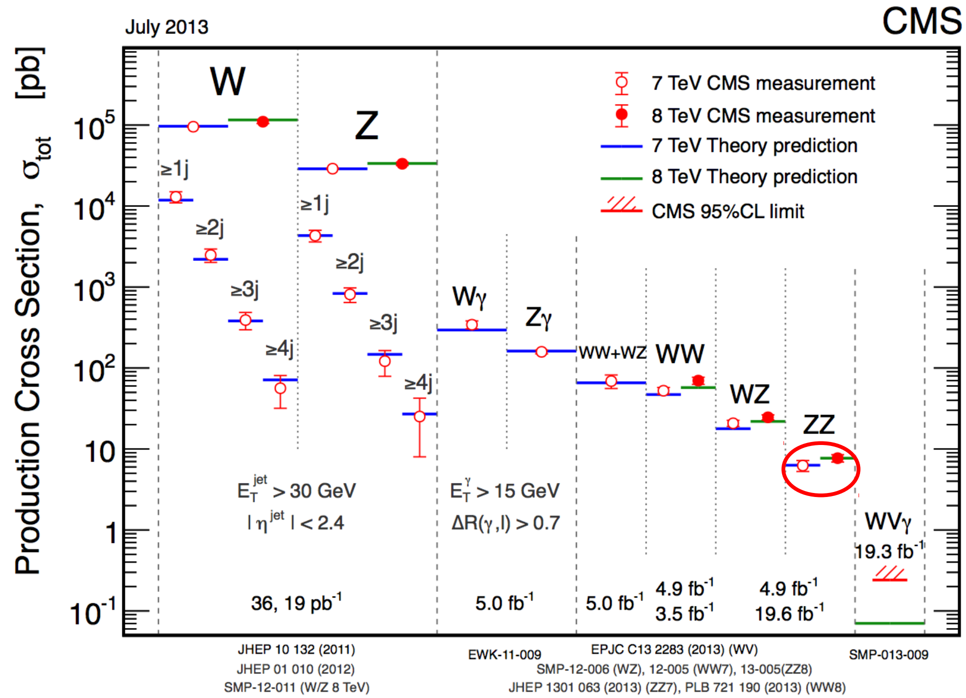


Multi-boson production

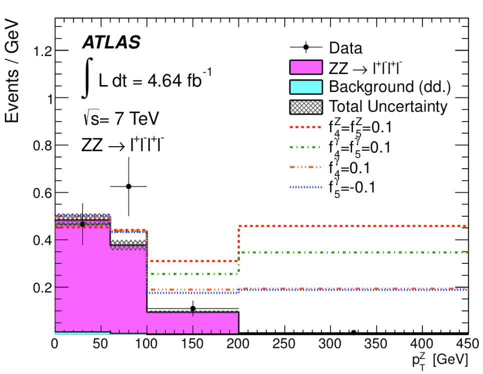
◎ Example: the ZZ production

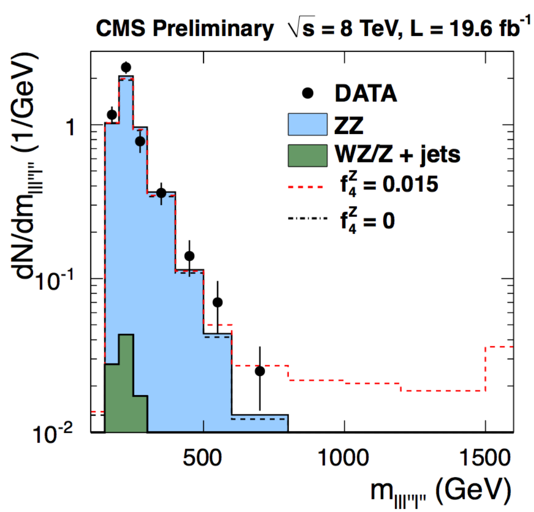
Inclusive cross-section

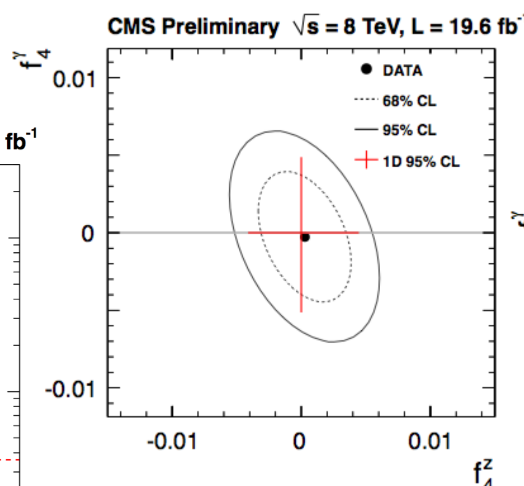


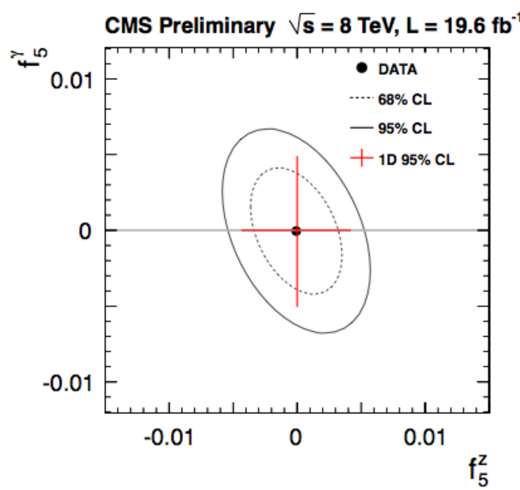


Measure aTGC's from kinematic distributions



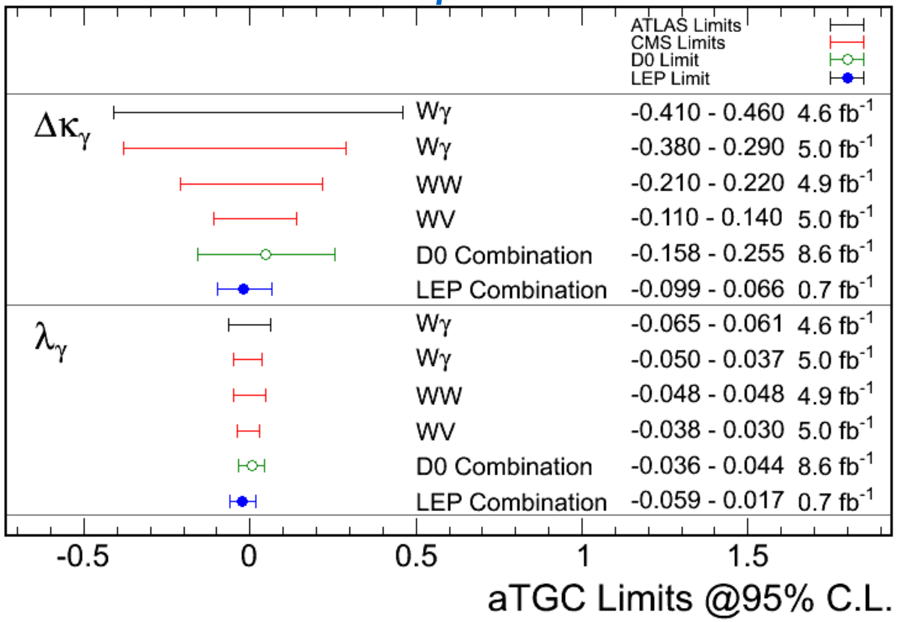




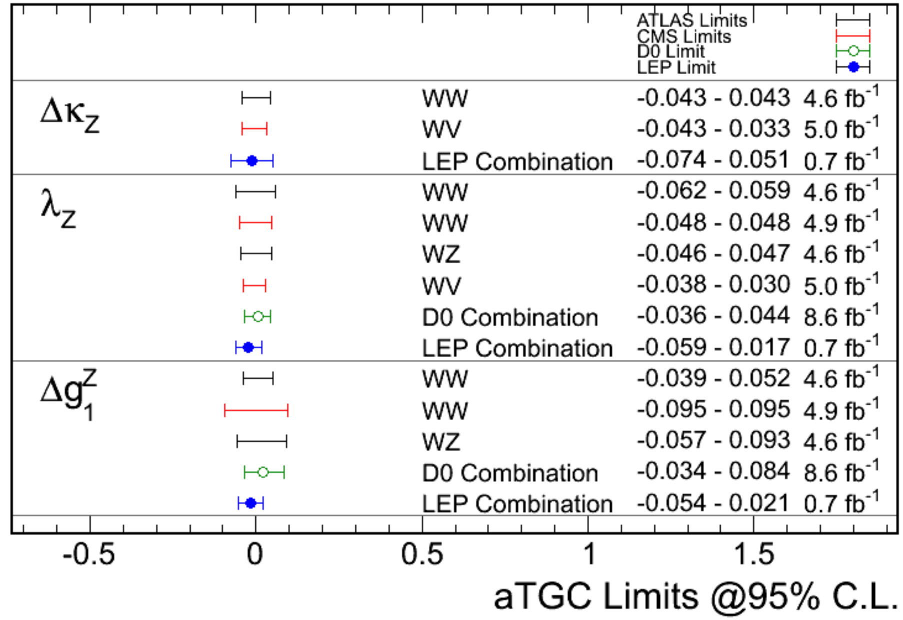


aTGC summary

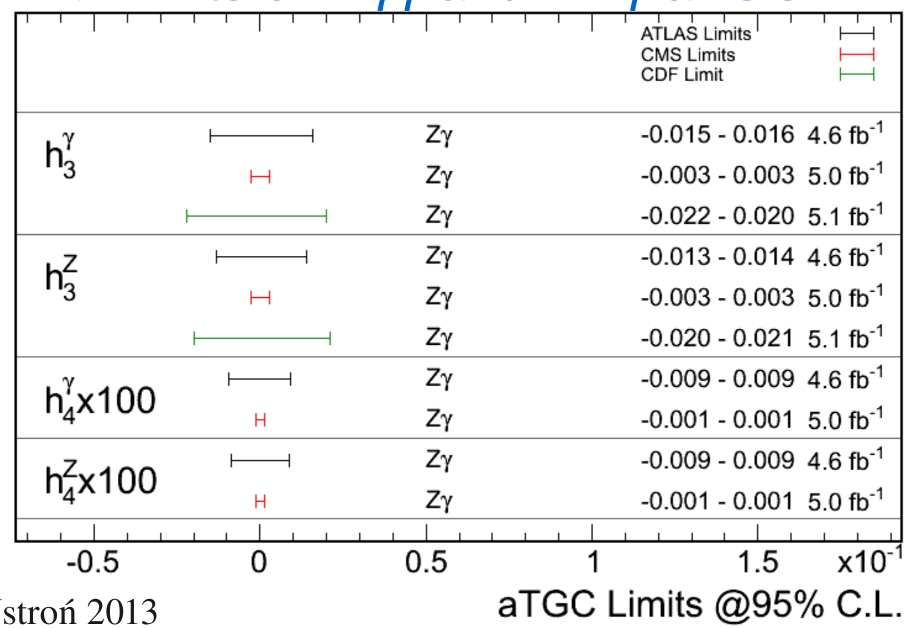
Feb 2013 **Limits on WWγ aTGC**



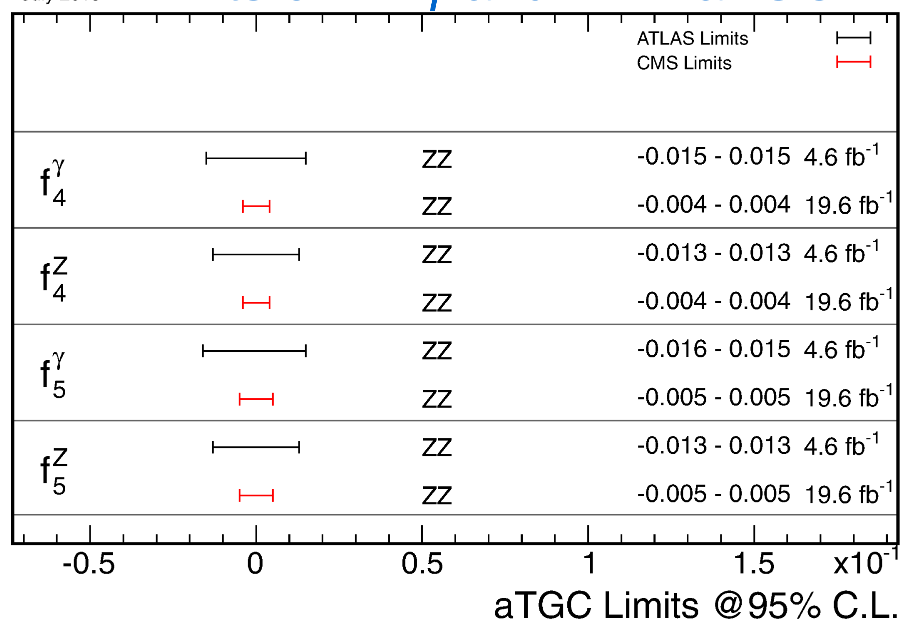
Feb 2013 **Limits on WWZ aTGC**



Feb 2013 **Limits on Zγγ and ZZγ aTGC**

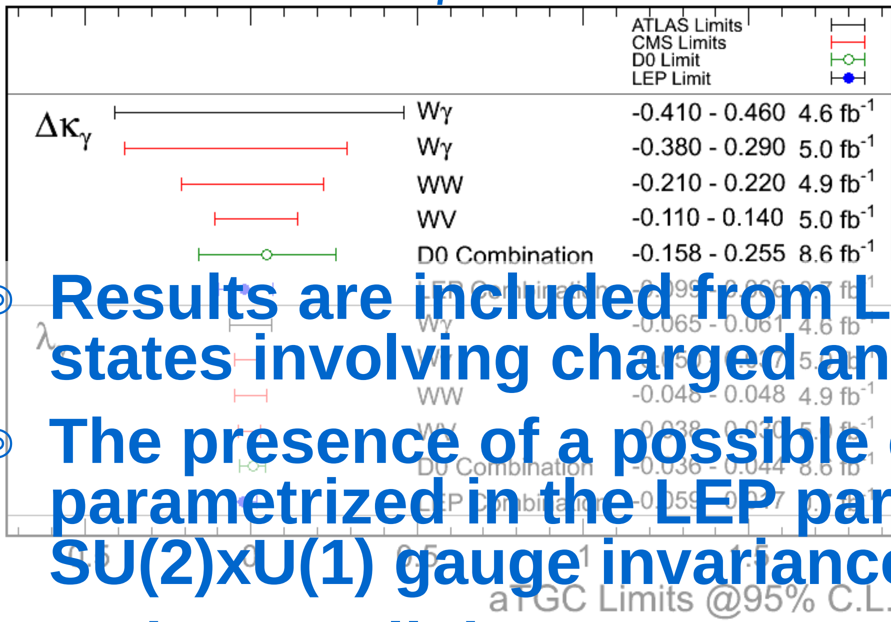


July 2013 **Limits on ZZγ and ZZZ aTGC**

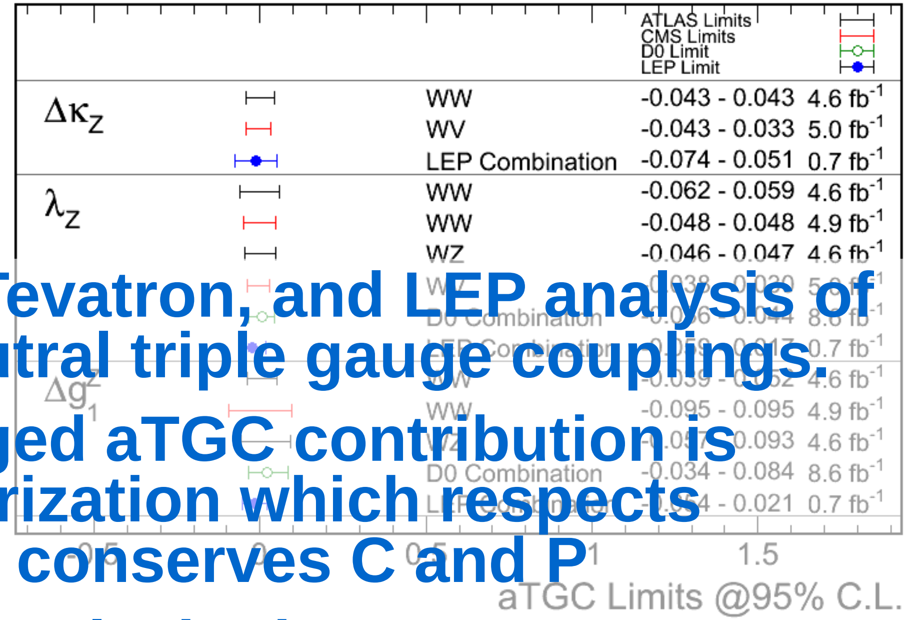


aTGC summary

Feb 2013 Limits on WWγ aTGC

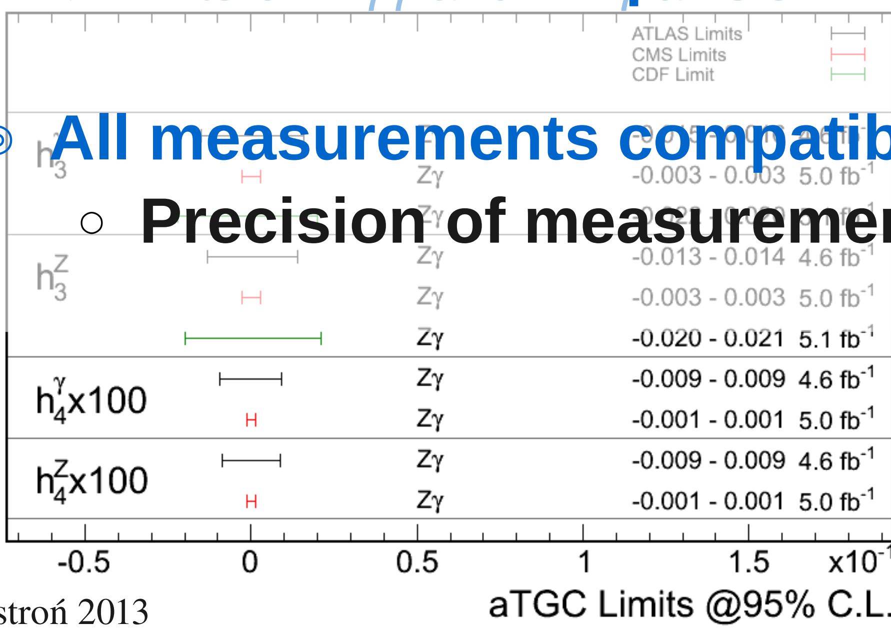


Feb 2013 Limits on WWZ aTGC

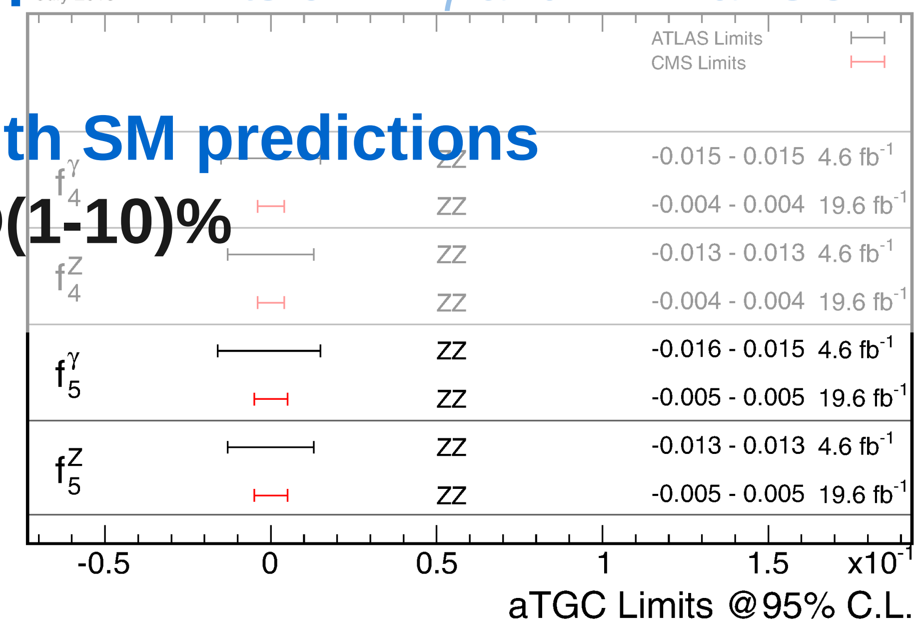


- **Results are included from LHC, Tevatron, and LEP analysis of states involving charged and neutral triple gauge couplings.**
- **The presence of a possible charged aTGC contribution is parametrized in the LEP parametrization which respects SU(2)xU(1) gauge invariance and conserves C and P**
- **In the SM all these parameters equal 0 in the SM**

Feb 2013 Limits on Zγγ and ZZγ aTGC



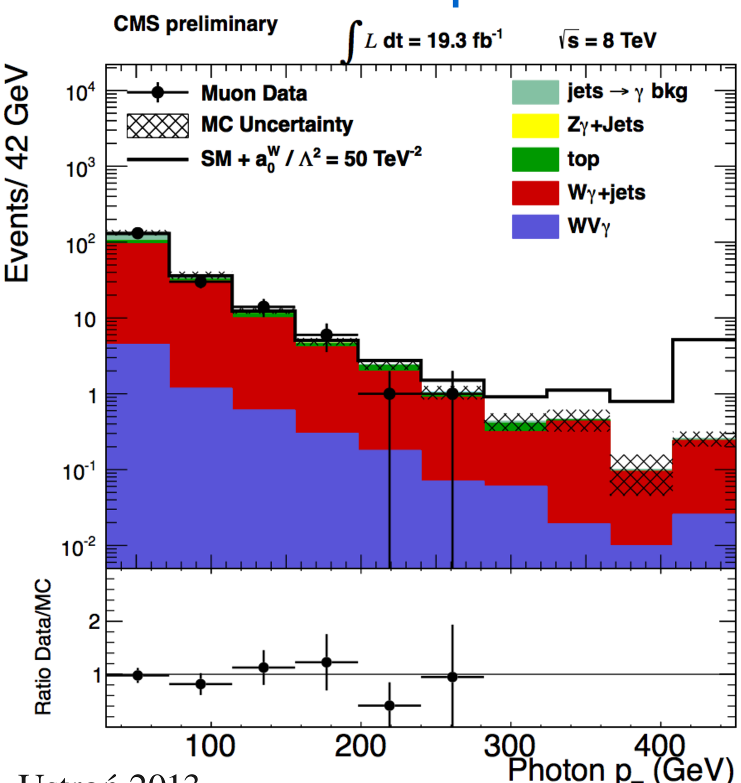
July 2013 Limits on ZZγ and ZZZ aTGC



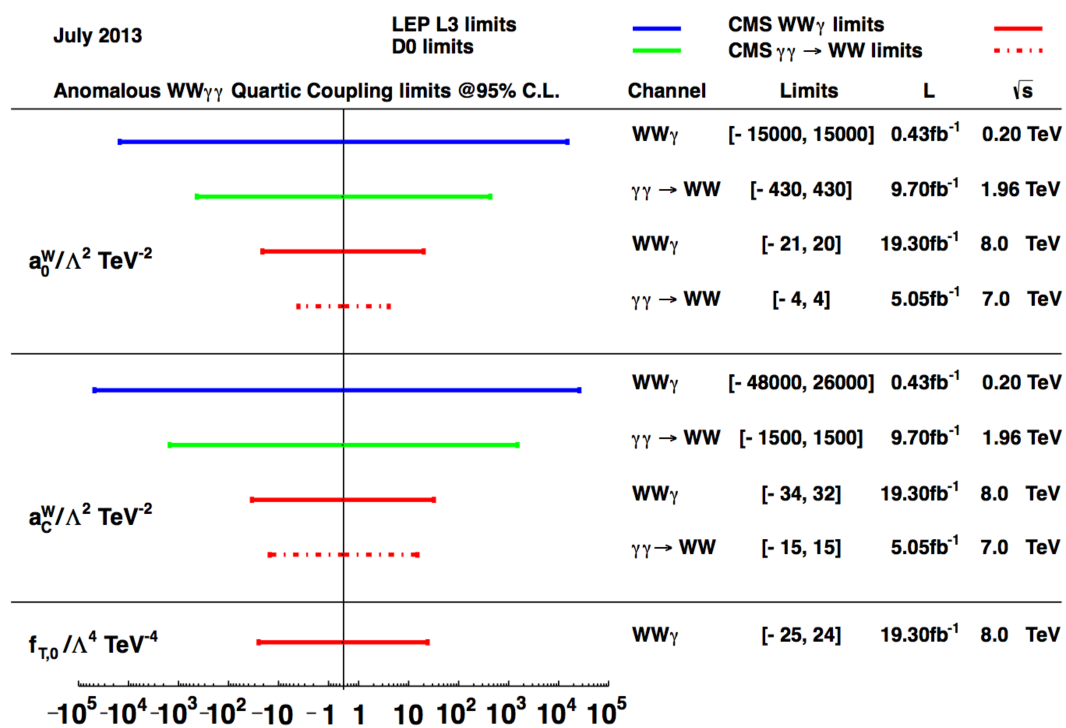
- **All measurements compatible with SM predictions**
  - **Precision of measurements O(1-10)%**

Triple-boson production

- CMS search for WVγ, V=W,Z   CMS-PAS-SMP-13-009
  - $W \to l\nu$
  - $V \to jj$
- Main background: Wγ+jets
- σ < 241 fb (3.4xSM) / exp. < 309 fb (4.4xSM) at 95% C.L.
  - $p_T(\gamma) > 10$ GeV
- Can be interpreted as a limit on aQGC



Limits on WWγγ aQGC



Top physics

Very rich top physic program at LHC
- Most analysis limited by systematics

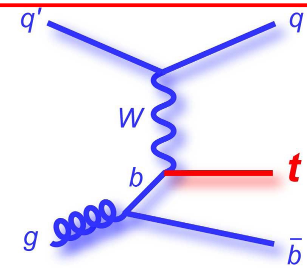
Production
- Top pair production cross-section with ~5% uncertainty
- **Single top**
  - **t-channel cross-section with ~20% precision**
  - **observation of tW process**

Properties:
- Mass measurement (>1% at LHC)
- Polarisation, asymmetry, couplings
- ...

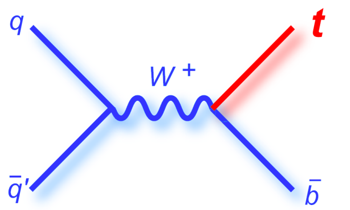
Single top production

- Single top production through electroweak interaction
  - Direct probe of Wtb coupling and V_{tb} in CKM matrix
- Challenging, mainly due to the background from W/Z+jets, tt
  - Use MVA techniques

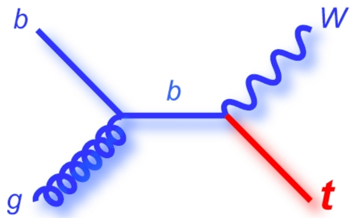
→ ATLAS-CONF-2012-056, ATLAS-CONF-2012-132
→ CMS-PAS-TOP-12-011

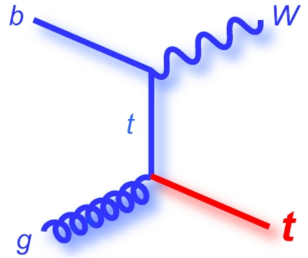


t-channel
65/87pb at 7/8TeV



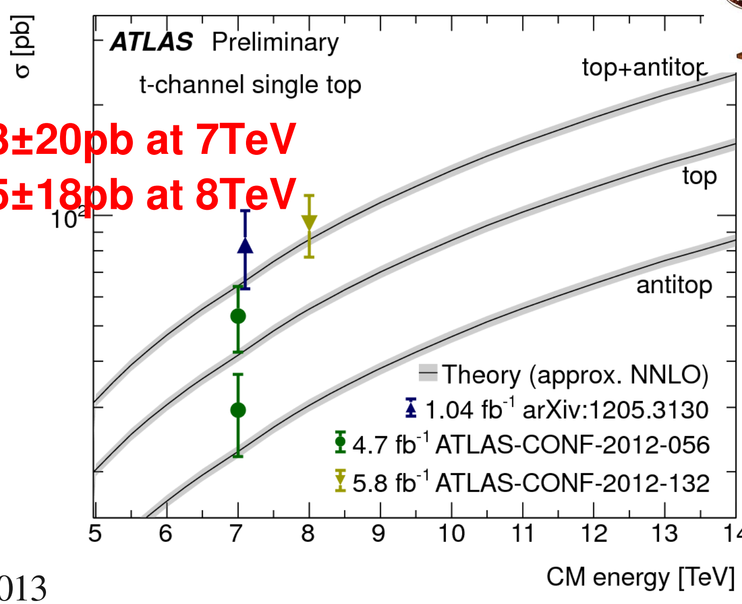
s-channel
5/6pb at 7/8TeV



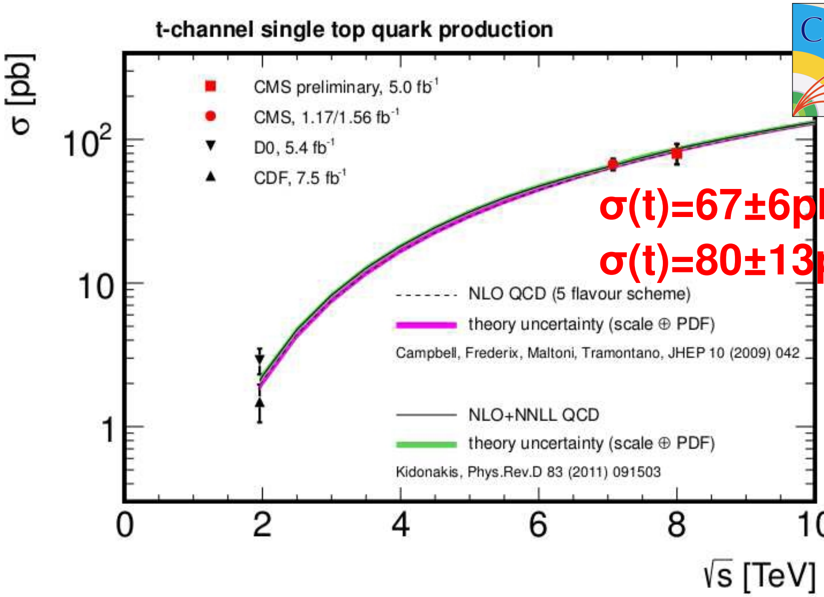


Wt-channel
16/22pb at 7/8TeV

σ(t)=83±20pb at 7TeV
σ(t)=95±18pb at 8TeV

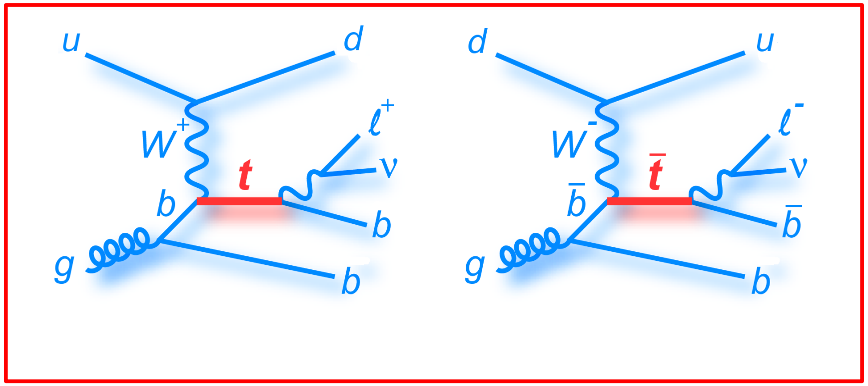


σ(t)=67±6pb at 7TeV
σ(t)=80±13pb at 8TeV

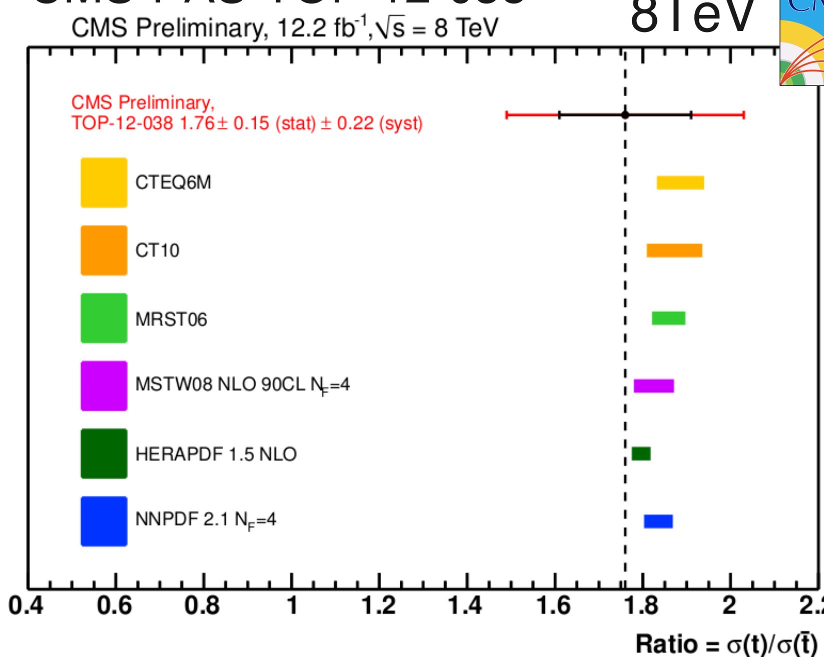


Single top production

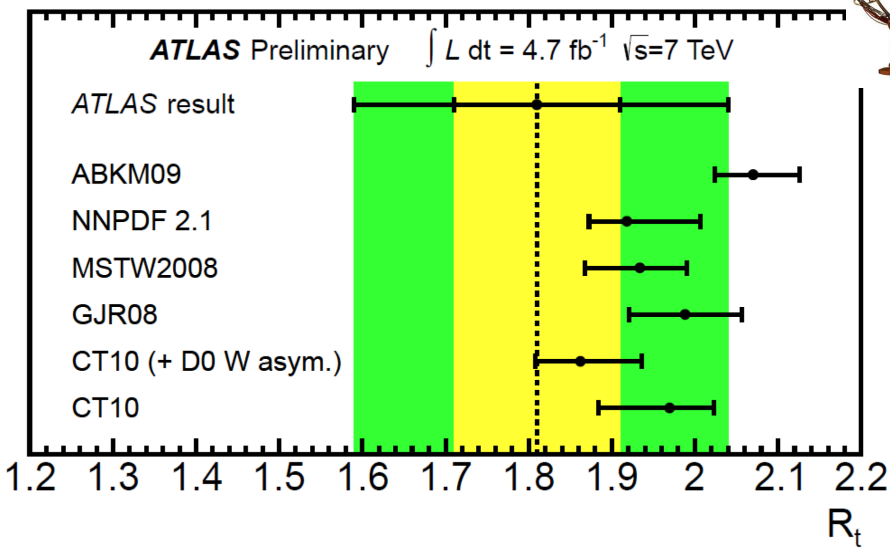
- Ratio $R_t = \sigma_t/\sigma_{\bar{t}}$ is sensitive to u/d content of proton



CMS-PAS-TOP-12-038 8TeV



ATLAS-CONF-2012-056 7TeV

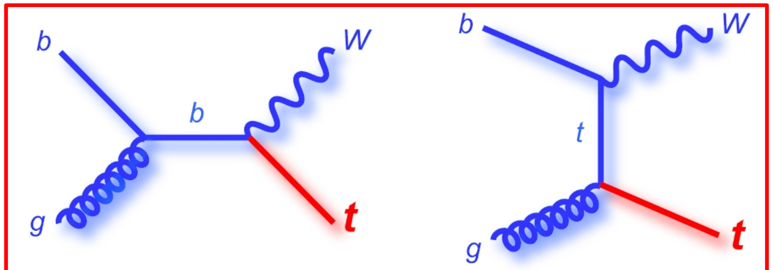


$R_t = 1.81 \pm 0.1(\mathrm{stat}) \pm 0.21(\mathrm{syst})$

$R_t = 1.76 \pm 0.14(\mathrm{stat}) \pm 0.21(\mathrm{syst})$

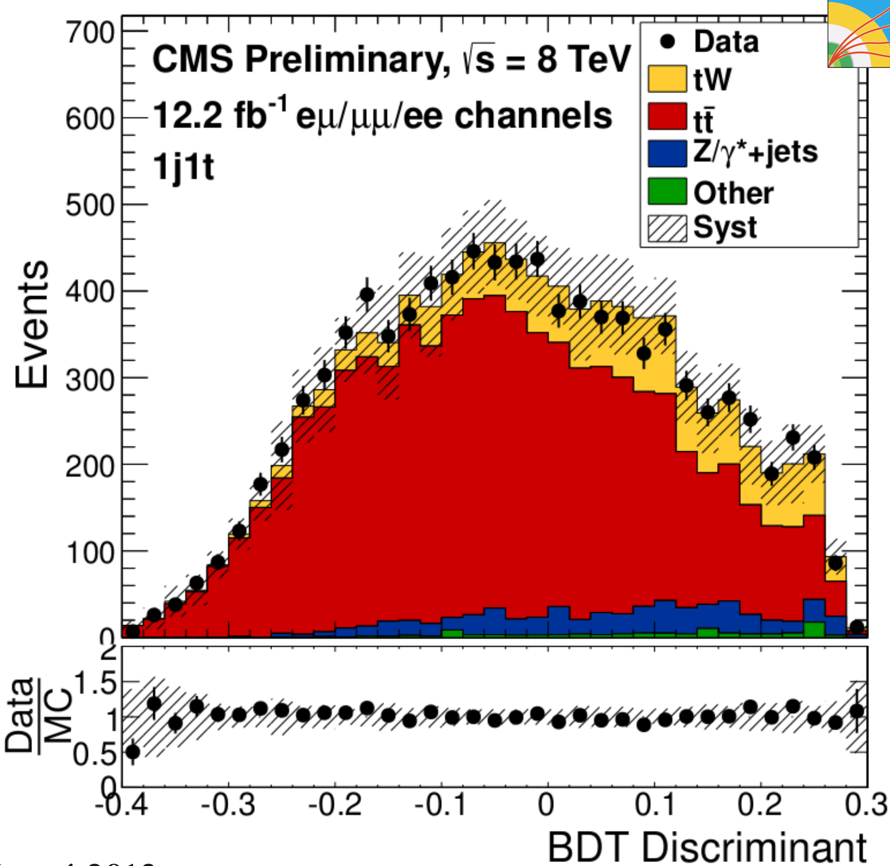
Wt production

- First observation of the Wt production by CMS (8TeV)
  - Significance 6σ
  - σ = 23.5 ± 5.5 pb at 8TeV



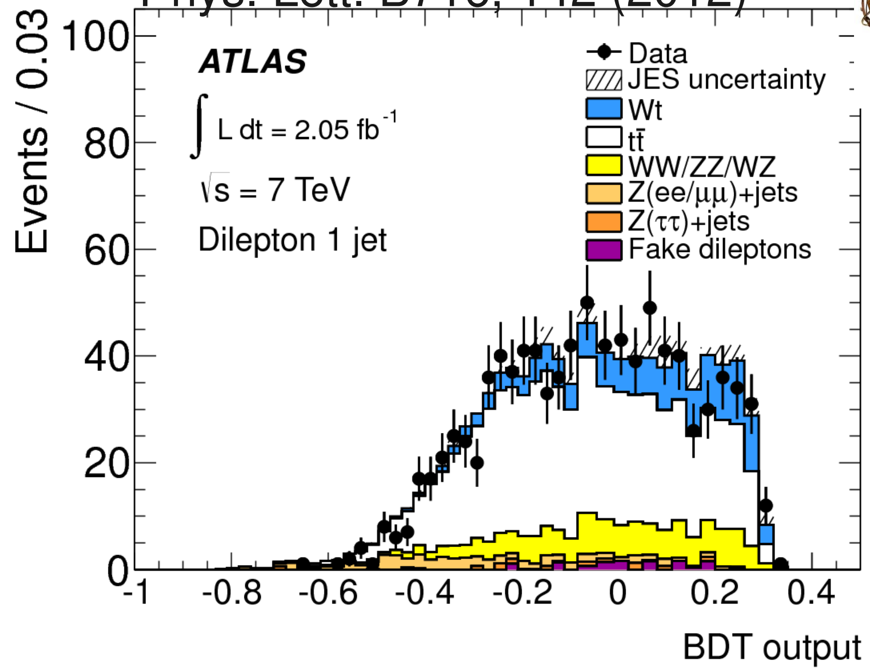
Wt-channel
16/22pb at 7/8TeV

CMS-PAS-TOP-12-040



- Evidence by ATLAS (7TeV)
  - Significance 3.3σ
  - σ=16.8±2.9(stat)±4.9(syst) pb

Phys. Lett. B716, 142 (2012)



Conclusions

- Big progress since the discovery of a Higgs boson just a year ago!
    - Observation bosonic decay modes with high significance
    - Evidence of fermonic decays
    - Precision mass measurement
    - Constraints on couplings and tensor structure

  => It looks more and more like **the** (minimal) **SM Higgs boson**
- There is a very rich SM physics program
  - Some results shown
    - W/Z cross-sections
    - Double and triple boson production and constraints on aTSG's & aQGC's
    - Single top production discussed

  => Very good agreement with SM predictions

Standard model complete after the Higgs boson discovery!

It looks very standard... with current precision

  - Still many things remain to be seen/measured/clarified
    - Is observed Higgs boson responsible for the $V_L V_L$ scattering unitarisation?
    - What is a nature of Higgs potential (⇒double H production)
    - New physics in rare decays?

THANK YOU!

Is there BSM physics?
SUSY? New strong interaction?
...?

Bibliography

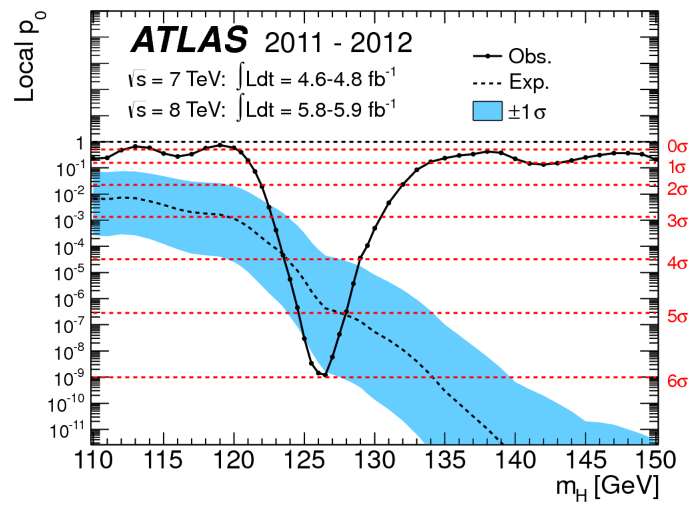
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

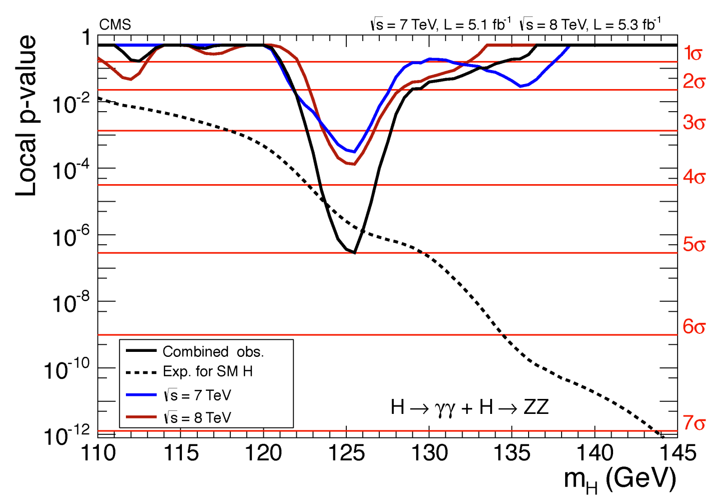
- **Higgs at LHC**
  - **LHC-XS-Higgs-WG**: x-sec, Br, and couplings and spin-parity models: arXiv:1307.1347
  - **$H \to \gamma\gamma$**: ATLAS-CONF-2013-029, ATLAS-CONF-2013-072 (diff. x-sec.), CMS-PAS-HIG-13-001
  - **$H \to ZZ \to 4l$**: ATLAS-CONF-2013-013, CMS-PAS-HIG-13-002
  - **$H \to WW \to 2l2\nu$**: ATLAS-CONF-2013-030, CMS-PAS-HIG-13-003, CMS-PAS-HIG-13-022 (VBF)
  - **$H \to bb$**: ATLAS-CONF-2013-079, CMS-PAS-HIG-13-012, CMS-PAS-HIG-13-011 (VBF)
  - **$H \to \tau\tau$:** ATLAS-CONF-2012-160, CMS-PAS-HIG-13-004, CMS-PAS-HIG-12-053 (VH)
  - **$H \to Z\gamma$:** ATLAS-CONF-2013-009, CMS-PAS-HIG-13-006 (arXiv:1307.5515)
  - **ttH**: ATLAS-CONF-2012-135 ($H \to bb$), ATLAS-CONF-2013-080 ($H \to \gamma\gamma$), CMS-PAS-HIG-13-019 ($H \to bb+\tau\tau$), CMS-PAS-HIG-13-015 ($H \to \gamma\gamma$)
  - **$H \to \mu\mu$**: ATLAS-CONF-2013-010
  - **Couplings & spin-parity**: ALTAS: arXiv:1307.1427, arXiv:1307.1432, CMS-PAS-HIG-13-005
- **Electro-weak physics at LHC**
  - **Vector boson prod.**: e.g. ATLAS: arXiv:1305.4192, CMS-PAS-SMP-12-011, CMS-PAS-SMP-13-003
  - **Multi-boson prod. and aTGC, aQGC** (summary): https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC
- **Top physics**
  - **Single top prod.**: t-channel: ATLAS-CONF-2012-056, ATLAS-CONF-2012-132, CMS-PAS-TOP-12-011, CMS-PAS-TOP-12-038
    tW channel: ATLAS: Phys. Lett. B 716, 142 (2012), CMS-PAS-TOP-12-040

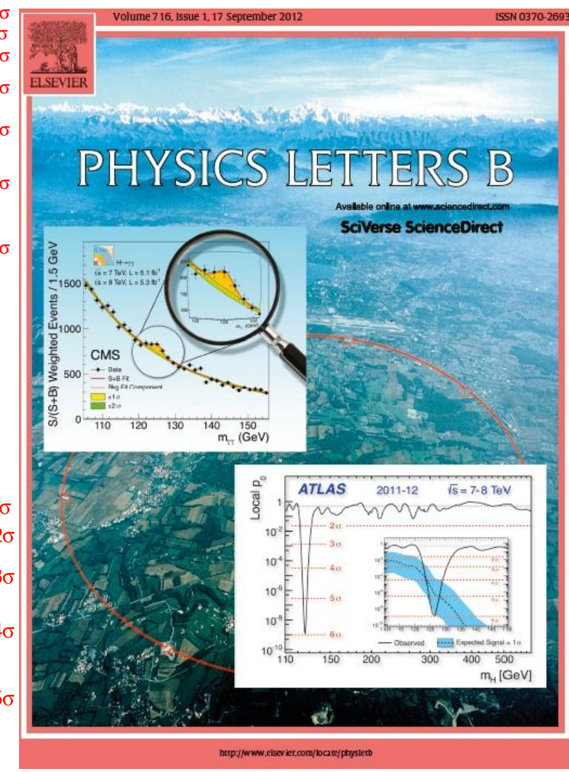
Additional material

One year ago

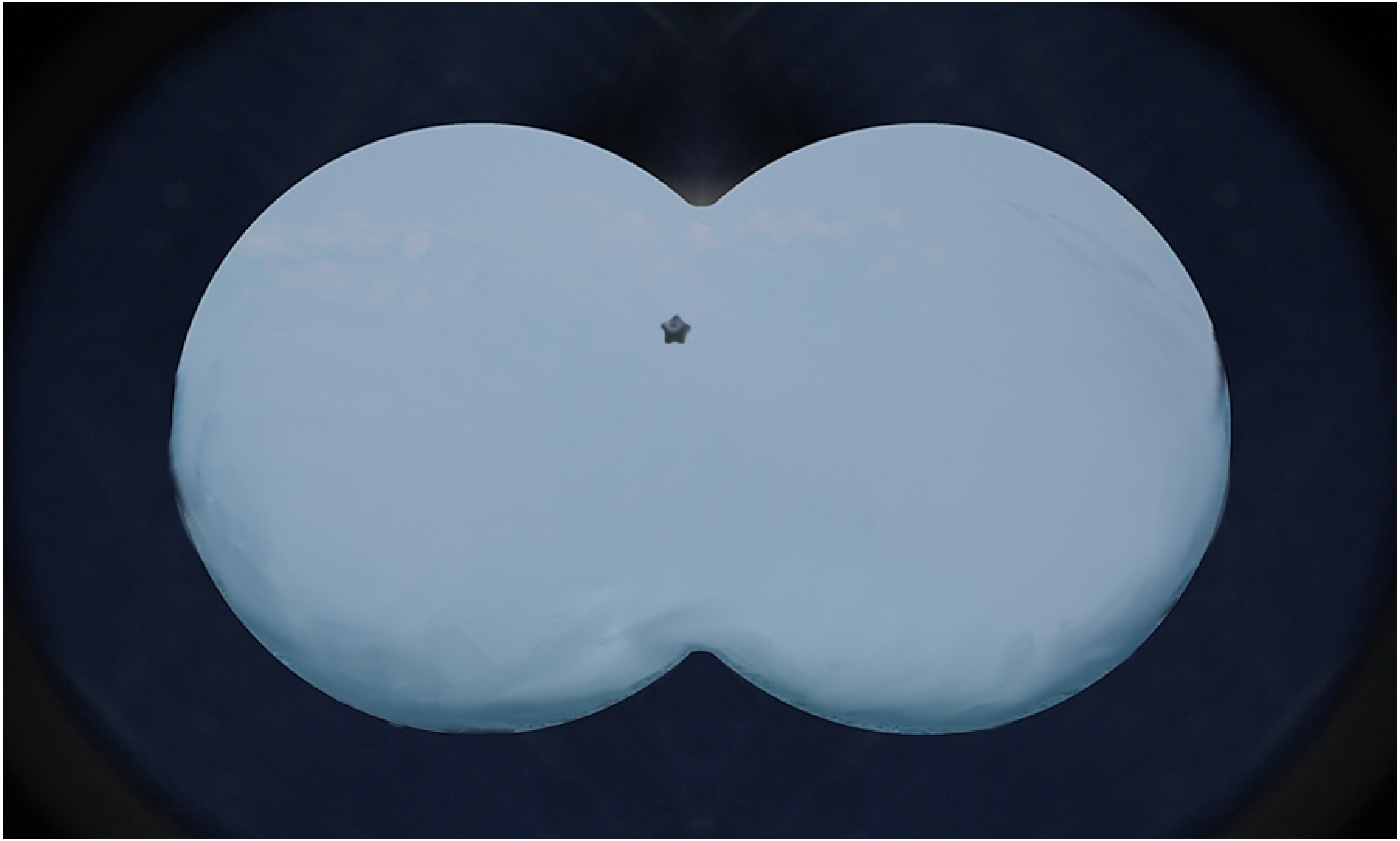
- Higgs boson discovery announced in July 4th 2012
  - m_H~125GeV/c^2
  - Driven by high resolution channels:
    $H \rightarrow \gamma\gamma$ & $H \rightarrow ZZ \rightarrow 4l$
  - Supported by the “high rate” channel $H \rightarrow WW \rightarrow l\nu l\nu$







To-be-seen Higgs

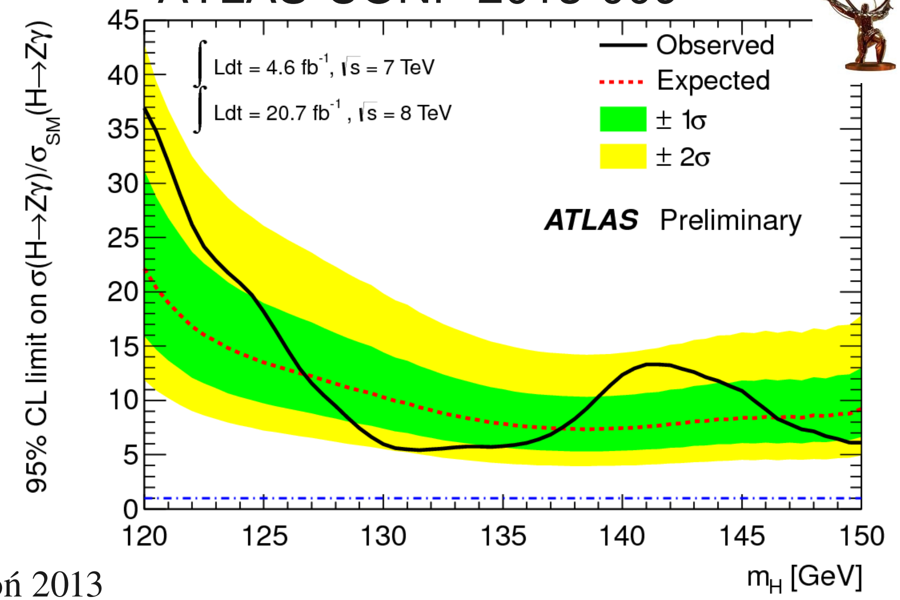


Rare channels (more data needed to reach sensitivity):
H → Zγ, H → μμ, ttH

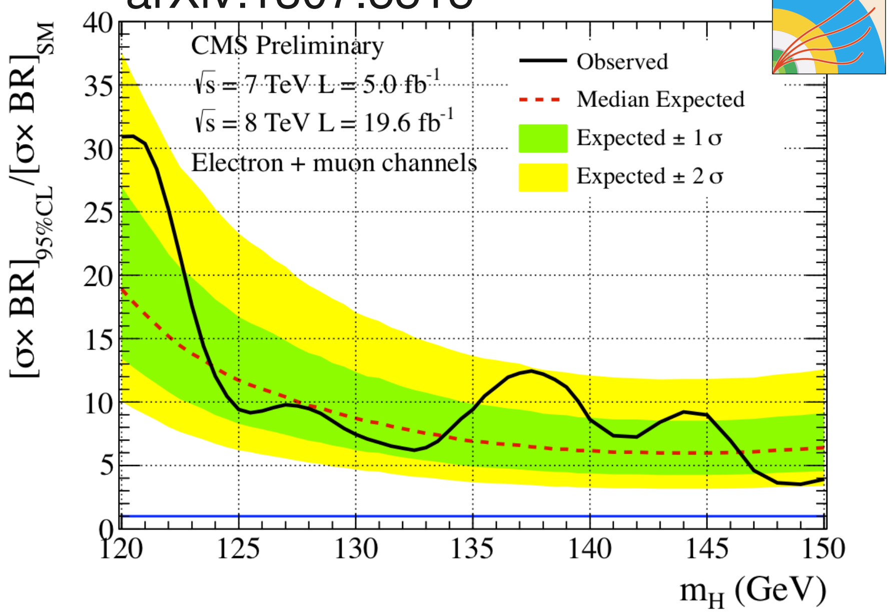
H→Zγ search

- Similar branching fraction to H→γγ, further suppressed by the Z→ll decay
- Enhanced/suppressed independently on H→γγ
  - Sensitive to deviations from SM
- Main background: Z+γ (ISR, FSR), Z+jets
- Signal from fit of Δm = $m_{ll\gamma}$ - m_Z (ATLAS) or $m_{ll\gamma}$ (CMS)
- Not sensitive on SM yet, limits (95% C.L. at m_H=125 GeV/c^2)
  - ATLAS: 18.2 x SM (exp. 13.5 x SM)
  - CMS: 10 x SM (exp. 10 x SM)

ATLAS-CONF-2013-009

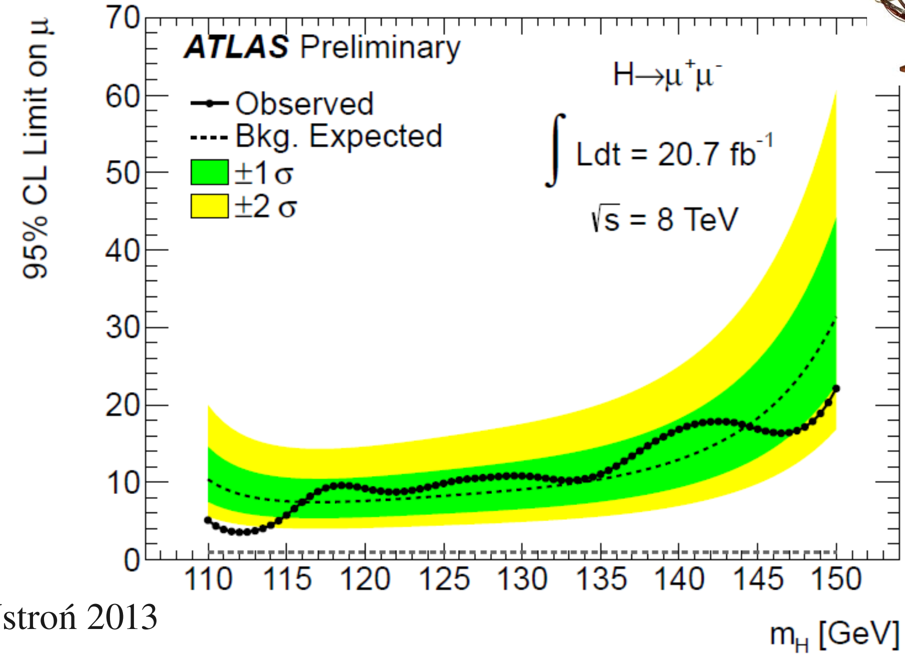


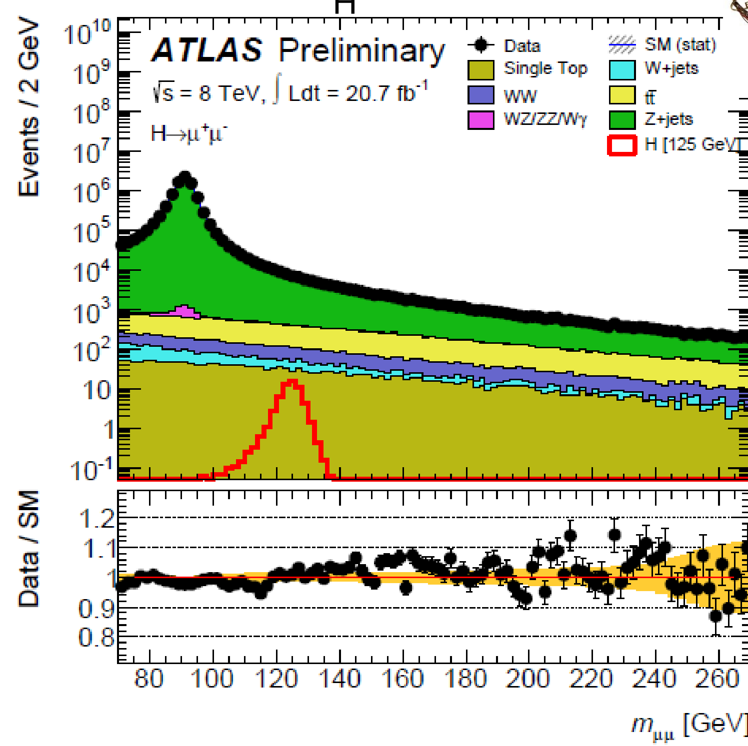
arXiv:1307.5515



H → μμ search

- Probes coupling to 2nd generation fermions
- Very small Br ~10^{-4}
  - Very high statistic required (~3/ab for >5σ) – case for HL-LHC
- Search for small bump in $m_{\mu\mu}$ on top of continuum background
  - Parametric fit of $m_{\mu\mu}$ distribution
- Main background: Z/γ* → μμ
- First results obtained by ATLAS (ATLAS-CONF-2013-010)
  - 9.8 x SM (exp. 8.2 x SM) excluded at 95% C.L. at m_H=125 GeV/c^2
  - CMS analysis ongoing





ttH search with CMS

- Very challenging mode:
  - Low cross-section
  - Backgrounds from tt+X
- The only mode that offers direct probe of the Htt coupling at tree level

ttH(bb+ττ) CMS-PAS-HIG-13-019

- Signal extracted with BDT's separate for several event classes with different jet and b-jet multiplicities
- **Limit** (95% C.L., m_H= 125 GeV/c^2)

  5.2 x SM (exp. 4.1 x SM)

ttH(γγ) CMS-PAS-HIG-13-015

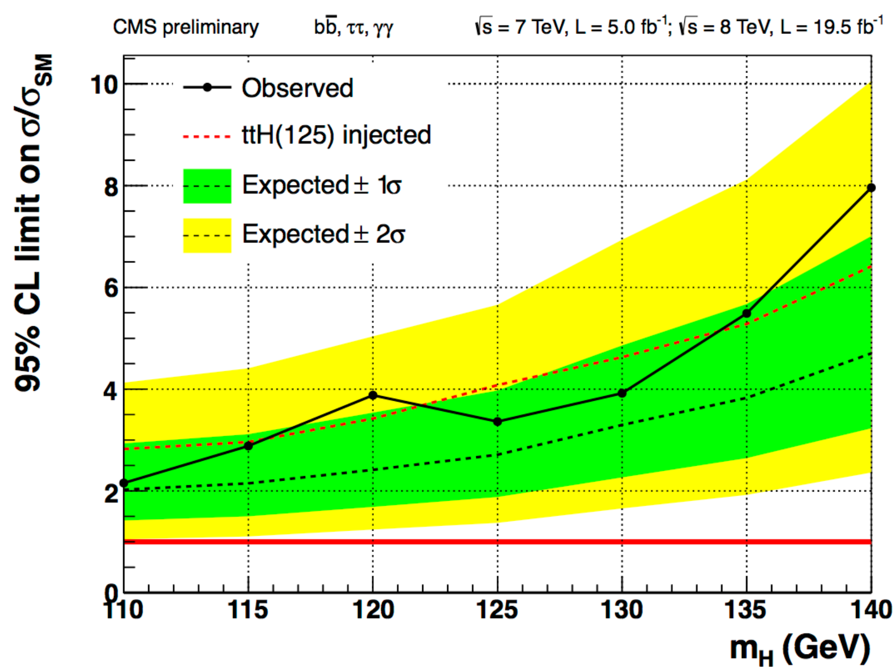
- Parametric fit to the di-photon mass in all-hadronic and semi-leptonic tt events with loose selection and ≥1 b-jet
- **Limit** (95% C.L., m_H= 125 GeV/c^2)

  5.4 x SM (exp. 5.3 x SM)

Combined result

- **Limit** (m_H= 125 GeV/c^2)

  3.4 x SM (exp. 2.7 x SM)



ttH with ATLAS

ttH(bb) 7TeV ATLAS-CONF-2012-135

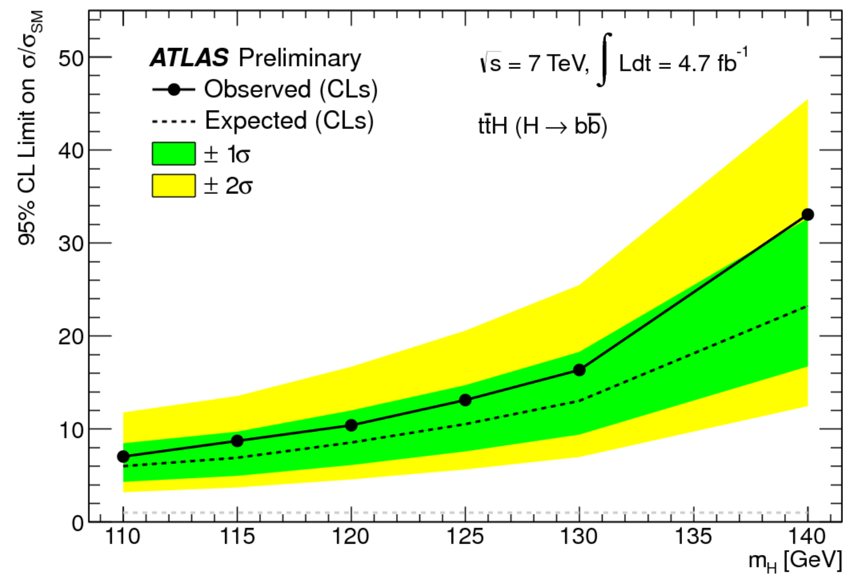
- Signal extracted by fit to H_T^{had} distribution for several event classes with different jet and b-jet multiplicities
- **Limit** (95% C.L., m_H= 125 GeV/c^2)

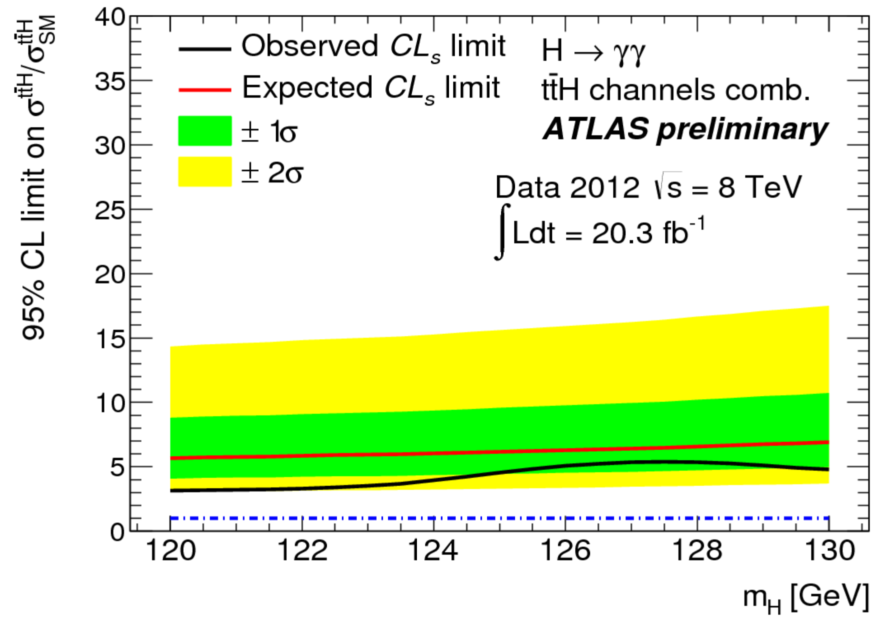
  13.1 x SM (exp. 10.5 x SM)

ttH(γγ) ATLAS-CONF-2013-080

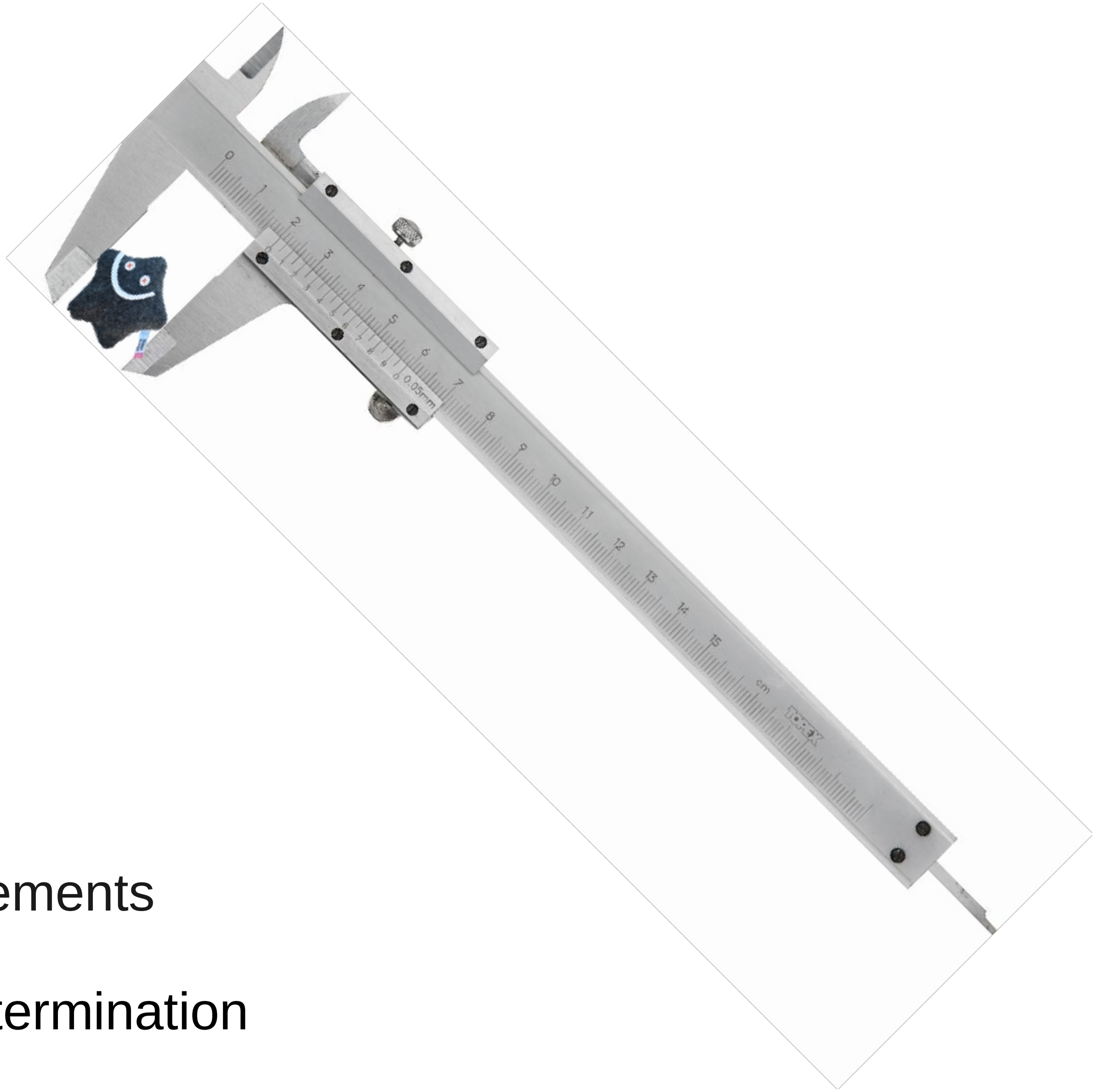
- Parametric fit to the di-photon mass in events passing loose leptonic (≥1 lepton) or hadronic tt selection
- **Limit** (95% C.L., m_H= 126.8 GeV/c^2)

  5.3 x SM (exp. 6.4 x SM)





Higgs properties

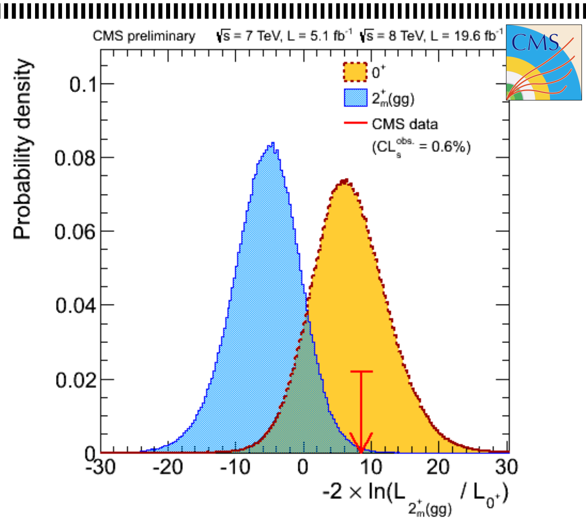


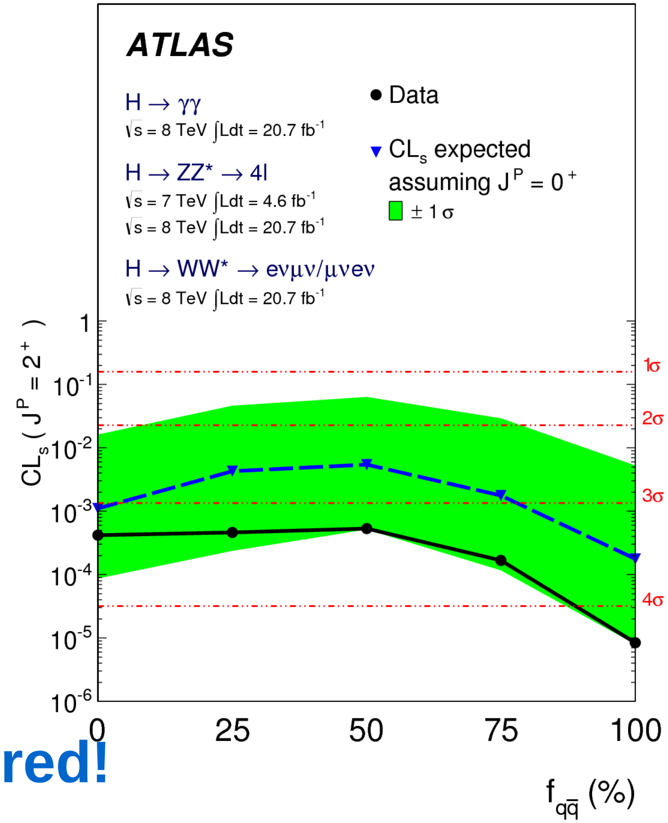
Properties:

- Mass measurements
- Couplings
- Spin-parity determination

Spin-parity: 2^+

- **0^+ vs 2^+**: Graviton inspired
  - Can be produced by qq or gg annihilation
    - f_{qq} – fraction of qq/gg produced signal (in minimal 2^+_m f_{qq}=4%)
  - ATLAS ($H \to \gamma\gamma$, $H \to ZZ \to 4l$, $H \to WW \to l\nu l\nu$)
    - **2^+** (100% gg) excluded at > **99.9%** (exp. >99.9%) C.L.
    - **2^+** (100% qq) excluded at > **99.9%** (exp. >99.9%) C.L.
  - CMS ($H \to ZZ \to 4l$, $H \to WW \to l\nu l\nu$)
    - **2^+** (100% qq) excluded at > **99.4%** (exp. >98.8%) C.L.





- **SM quantum numbers ($J^P=0^+$) strongly favoured!**