SM & Higgs at the LHC

Peter Onyisi, *on behalf of ATLAS and CMS*

Pheno, 8 May 2017

TEXAS
The University of Texas at Austin

ATLAS
EXPERIMENT

CMS
Compact Muon Solenoid

Introduction

- LHC: not just an “energy frontier” machine!
  - Enormous datasets of gauge bosons, top quarks, Higgs
- What can we study?
  - Precision SM parameters
  - all the nonperturbative stuff in proton collisions: parton distribution functions, underlying event
  - can we calculate well in the SM?
  - are there hints of BSM physics in “SM-like” interactions?
  - fundamental tests
- “Beyond the Standard Model” searches require understanding the Standard Model
  - no royal road to BSM … ?

Process	2016 yield per experiment
$W \rightarrow \ell\nu$	700 x 10^6
$Z \rightarrow \ell\ell$	70 x 10^6
WZ	1.7 x 10^6
$t\bar{t}$	30 x 10^6
inclusive H	1.9 x 10^6
$t\bar{t}H$	18 x 10^3

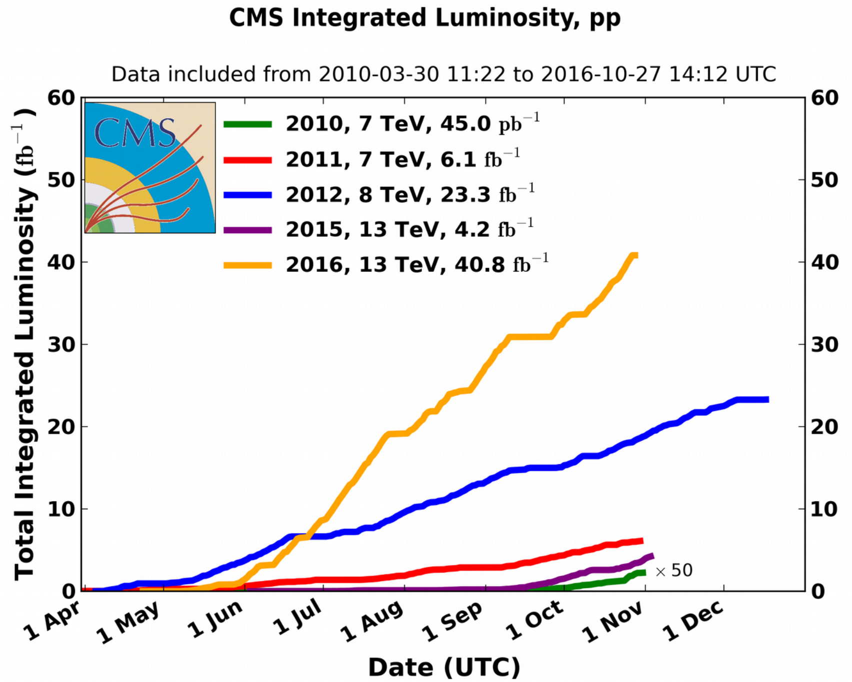
This talk: a few selected topics!

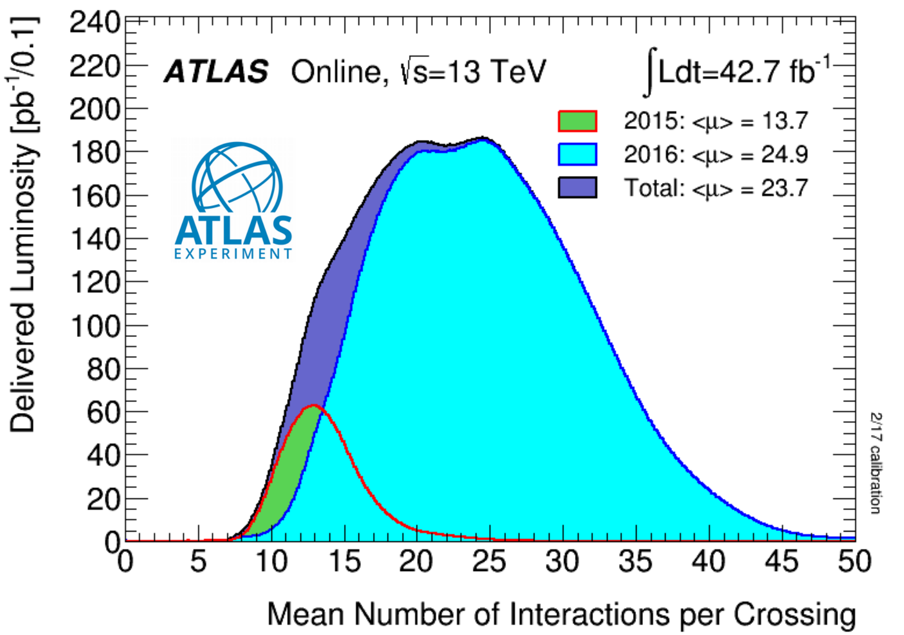
Will generally not show both experiments’ versions of an analysis…

Datasets

- 2016: superb year of LHC data delivery
  - LHC design luminosity exceeded, high uptime
  - more data than all previous years combined
  - pileup mitigation strategies in place
- Many SM & top analyses utilize lower energy/lower pileup datasets
  - may take a long time to understand systematics for a dataset at required precision

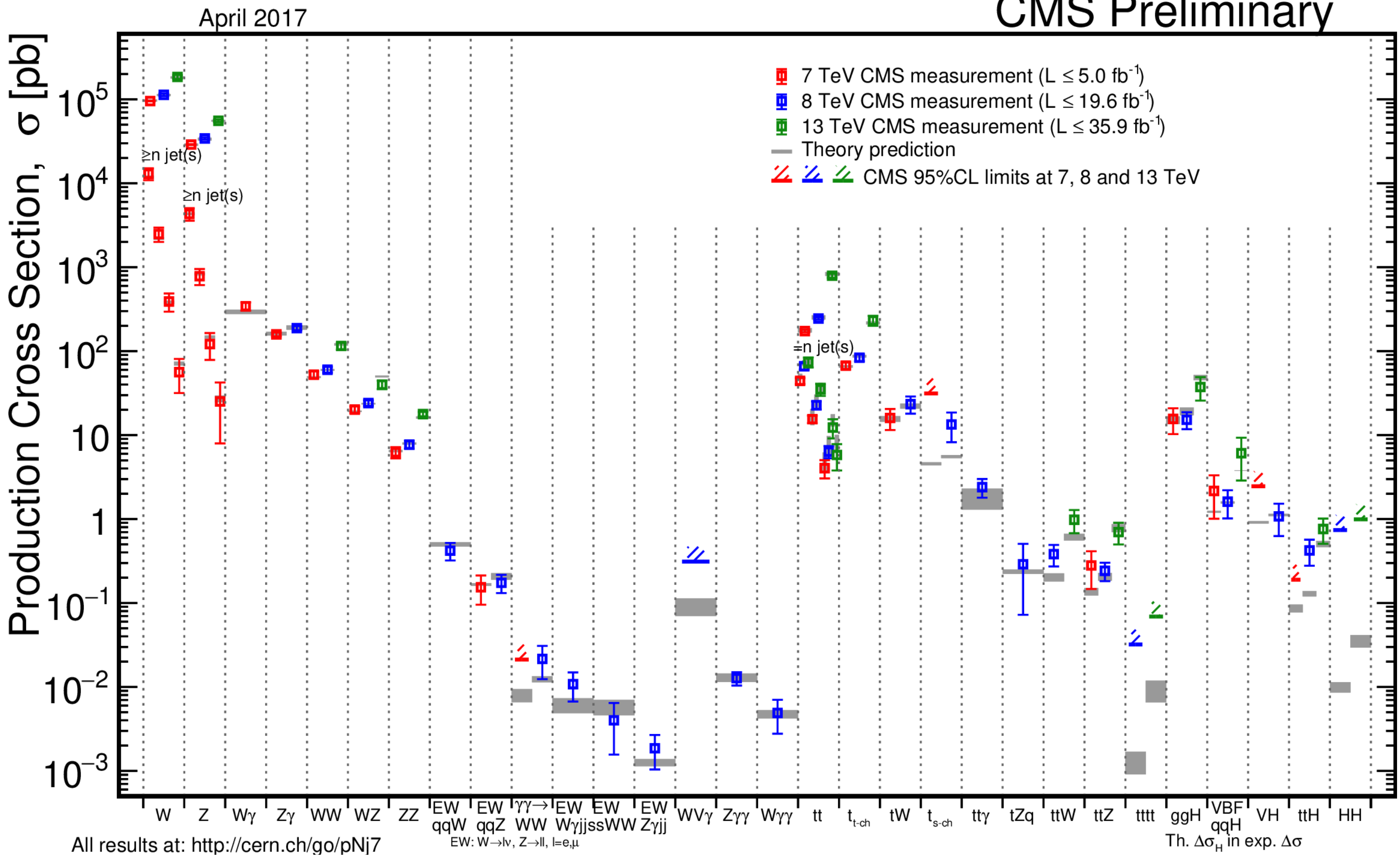
LHC 13 TeV delivered luminosity to date
~ 1.5% of HL-LHC





Cross Sections: view from 35,000 ft

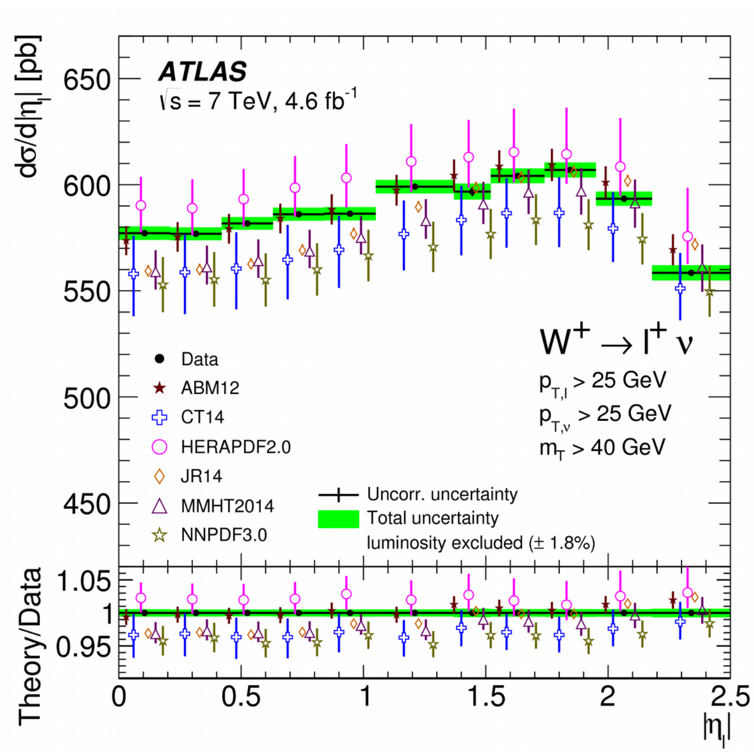
- Many measurements (many not in plot ...)
- Good agreement of theory & data

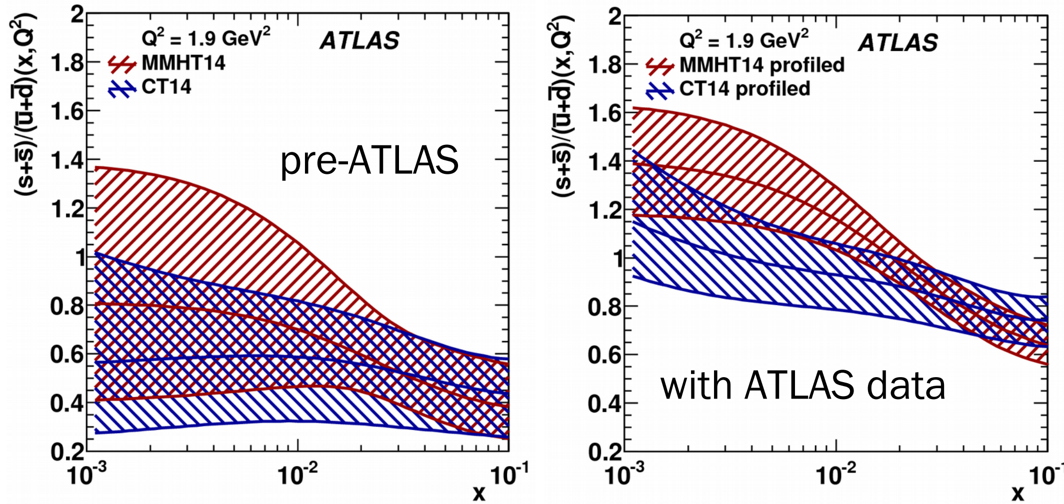


Proton Structure: PDF

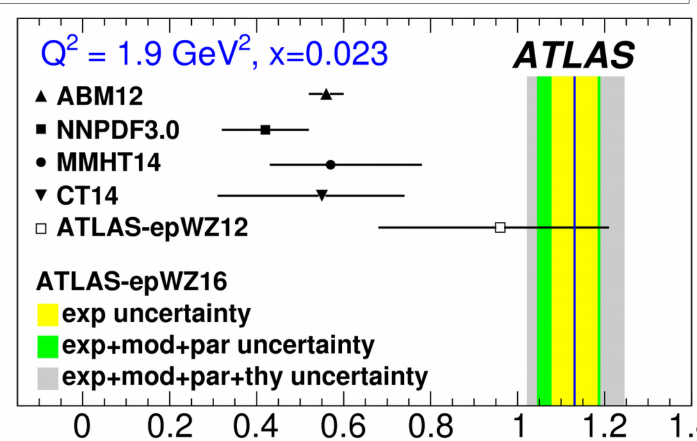
- Use high order perturbative calculations + precision data to constrain parton behavior
- e.g., W & Z differential cross sections

1612.03016, sub to EPJC





No evidence for suppression of strange sea

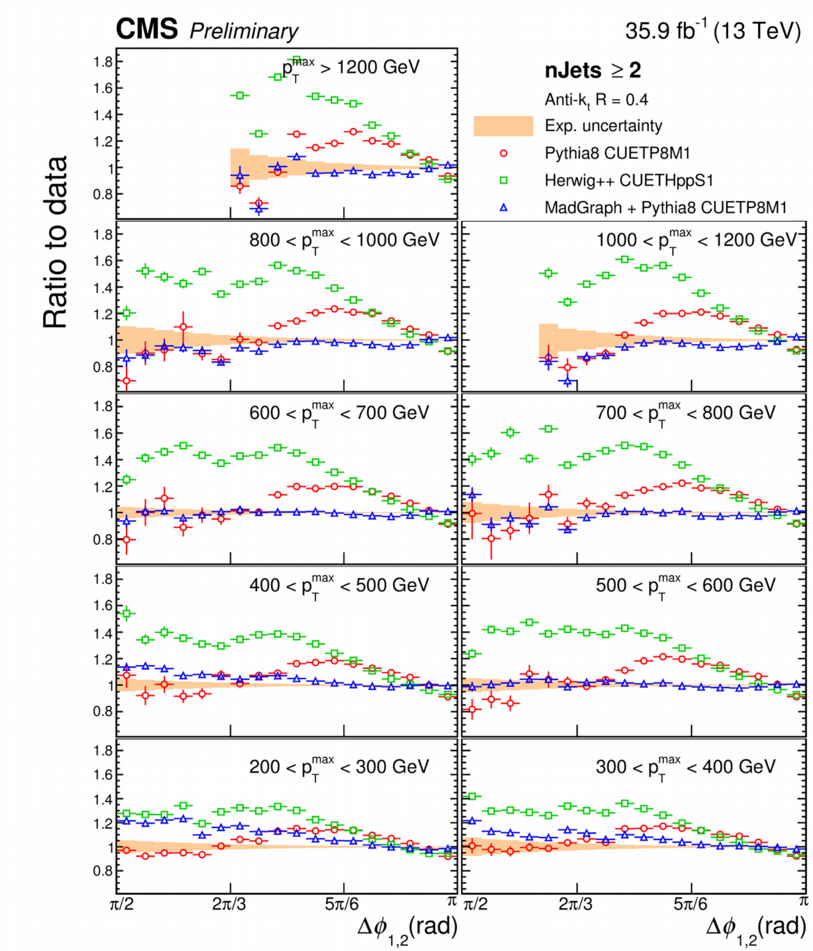


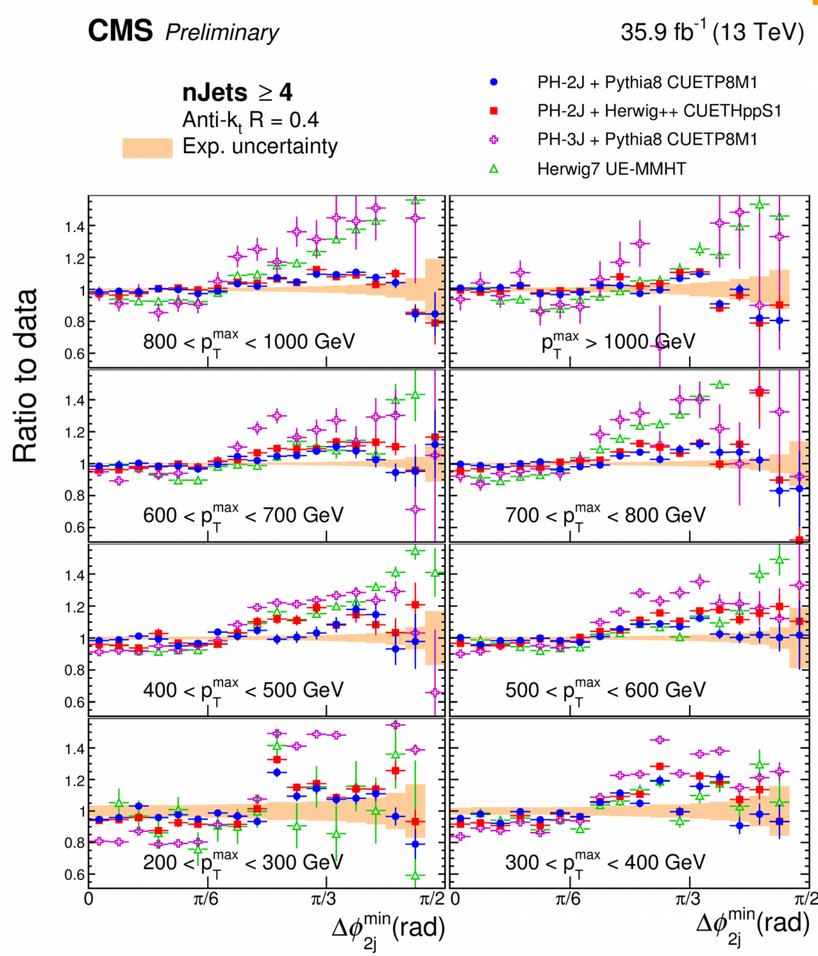
$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

Multijets: QCD & Parton Shower

- Can we accurately simulate production of multiple jets (pure QCD)?
- e.g. azimuthal correlations of jets in ≥2, ≥3, ≥4 jet events
  - compare to a variety of calculations (different hard scatter matrix elements, parton showers). All generators have regions of difficulty

CMS-SMP-16-014

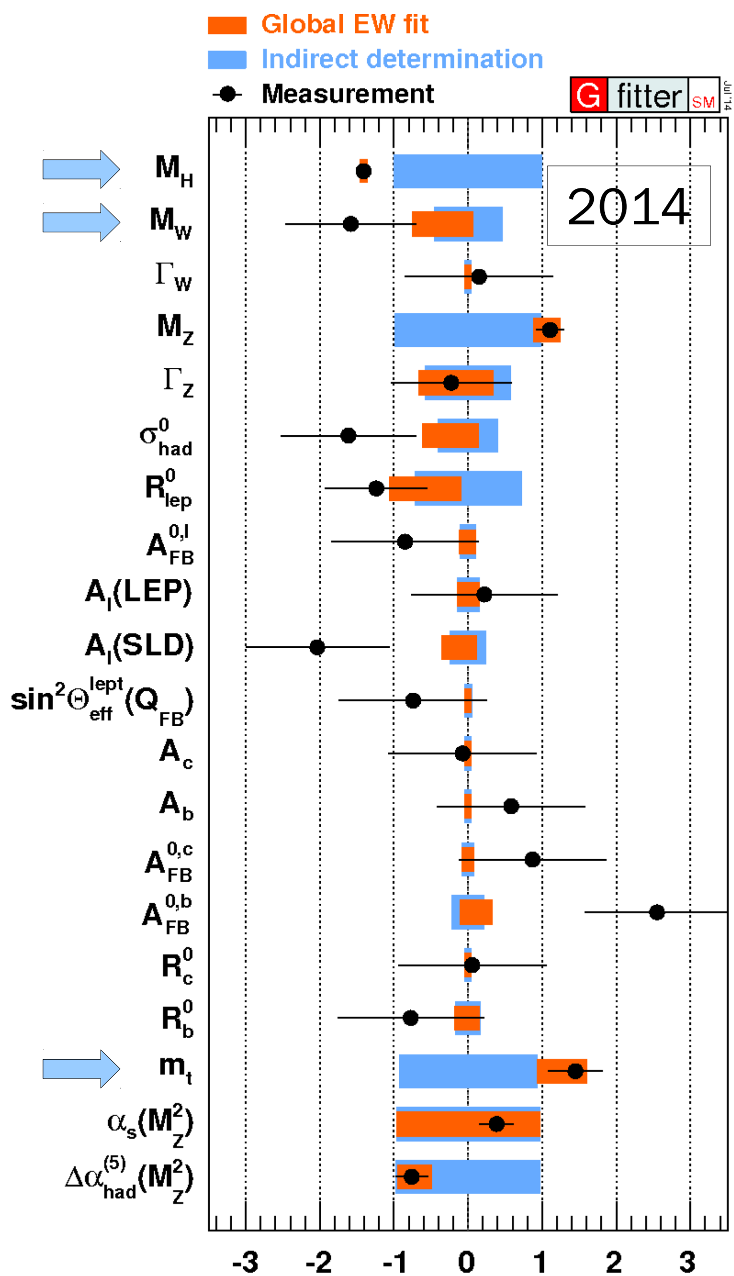




Overall, best performance from Herwig7

Electroweak Consistency

- Standard Model has many subtle dependencies between various parameters due to quantum corrections
  - on the whole good consistency seen with expectations
- LHC experiments are main game in town for improvements for several parameters



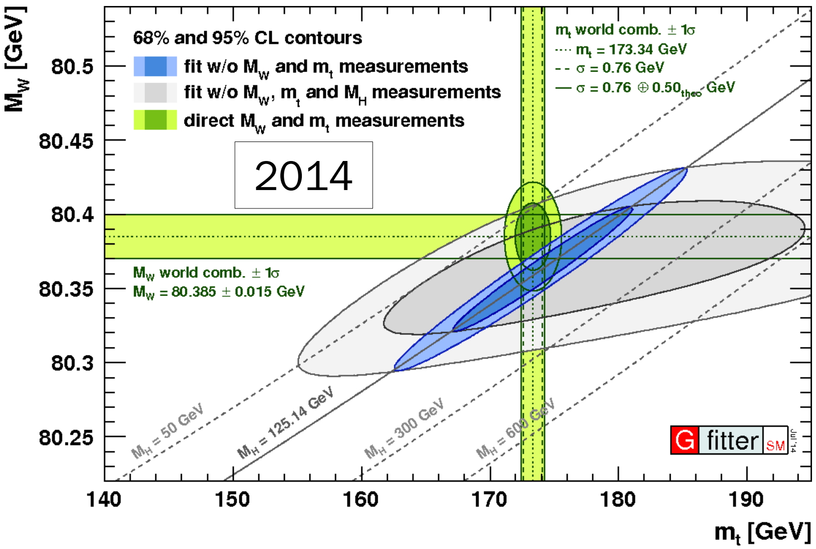
Gfitter group, EPJ C 74, 3046 (2014)

Particle Masses

More than just stamp-collecting!

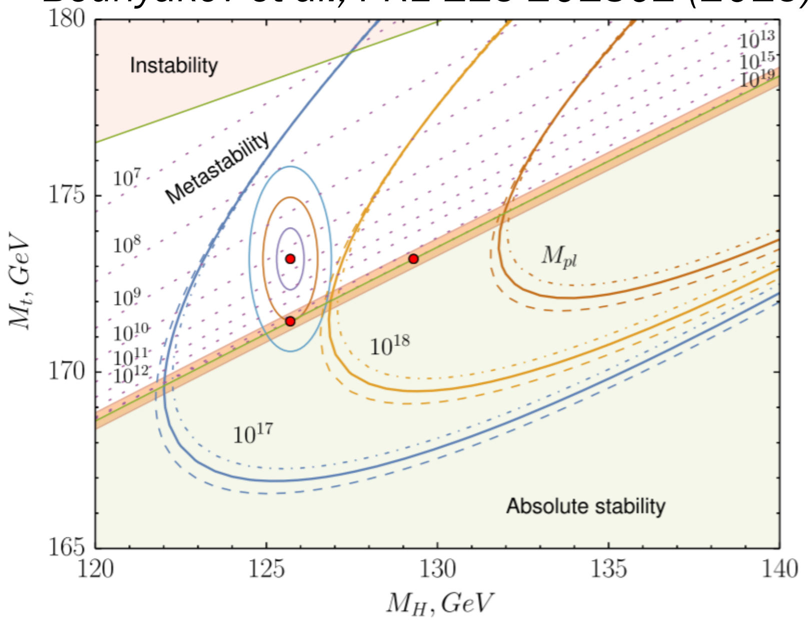
- W, H, t masses: consistent with other EW measurements?

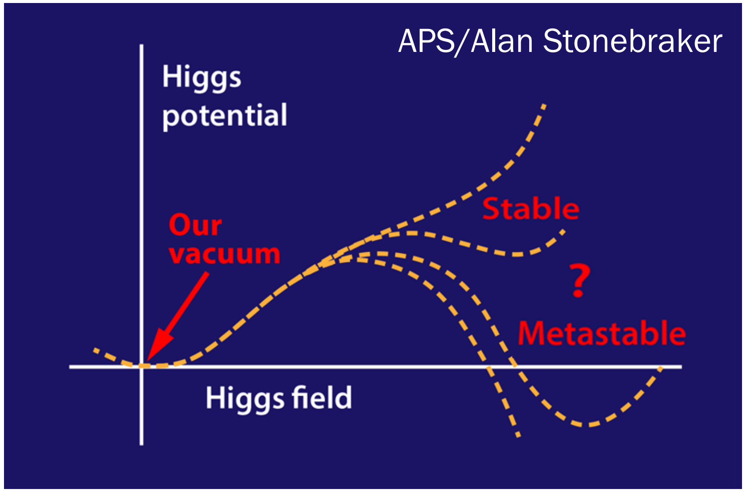
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$



- H, t masses: is there a deeper minimum of the Higgs potential? is SM EW vacuum metastable?

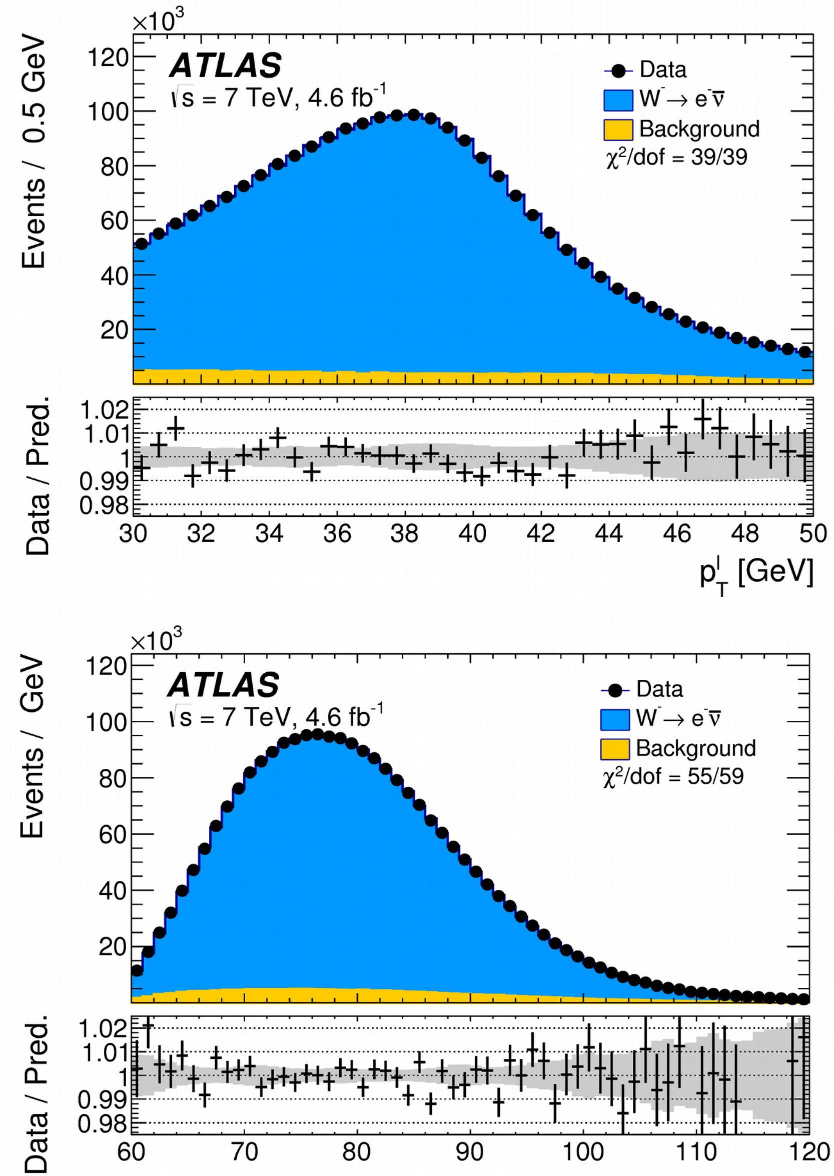
Bednyakov et al., PRL 115 201802 (2015)





W Mass

- First measurement of m_W at the LHC
- 7 TeV data alone: plenty of statistics
- Observables:
  - charged lepton p_T
  - reconstructed W m_T
- Use Z as standard candle for calibration, tuning, method validation
- Complications:
  - pp initial state: W^+ and W^- produced differently
  - large (~ 25%) contribution of $c\bar{s} \rightarrow W$: sea quarks more important than at Tevatron
  - generators don't necessarily get boson polarization right

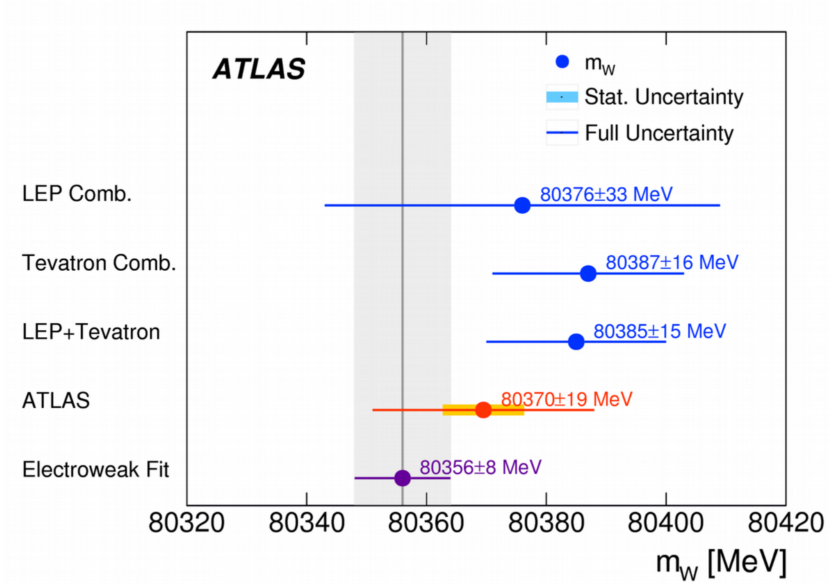


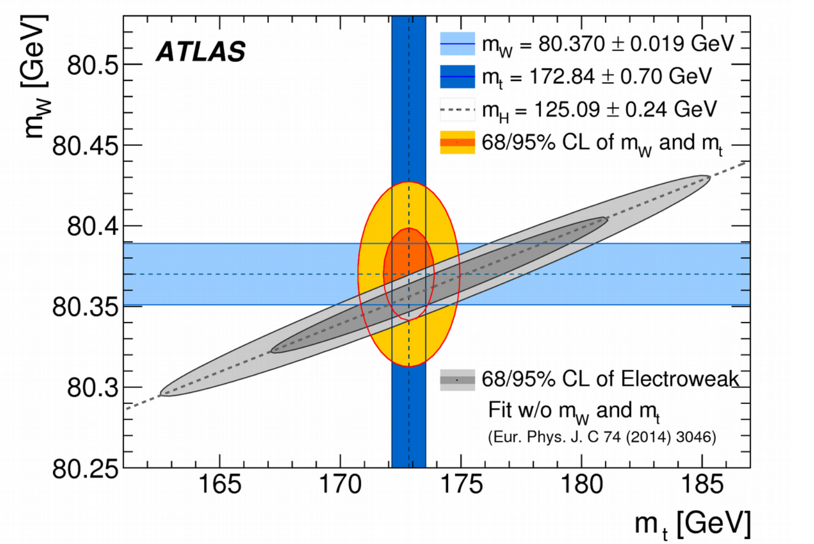
1701.07240, sub. to EPJ C

W Mass Result

$$m_W = 80370 \pm 7(\text{stat}) \pm 11(\text{exp syst}) \pm 14(\text{mod syst})\ \text{MeV}$$

- Largest experimental systematics: lepton energy/momentum scale
- Largest modeling systematics are parton distribution functions, parton showers
  - relies on correlation of higher-order QCD corrections in W & Z
- Precision better than LEP combination, not far from Tevatron combination
- Better consistency with global EW fit than before



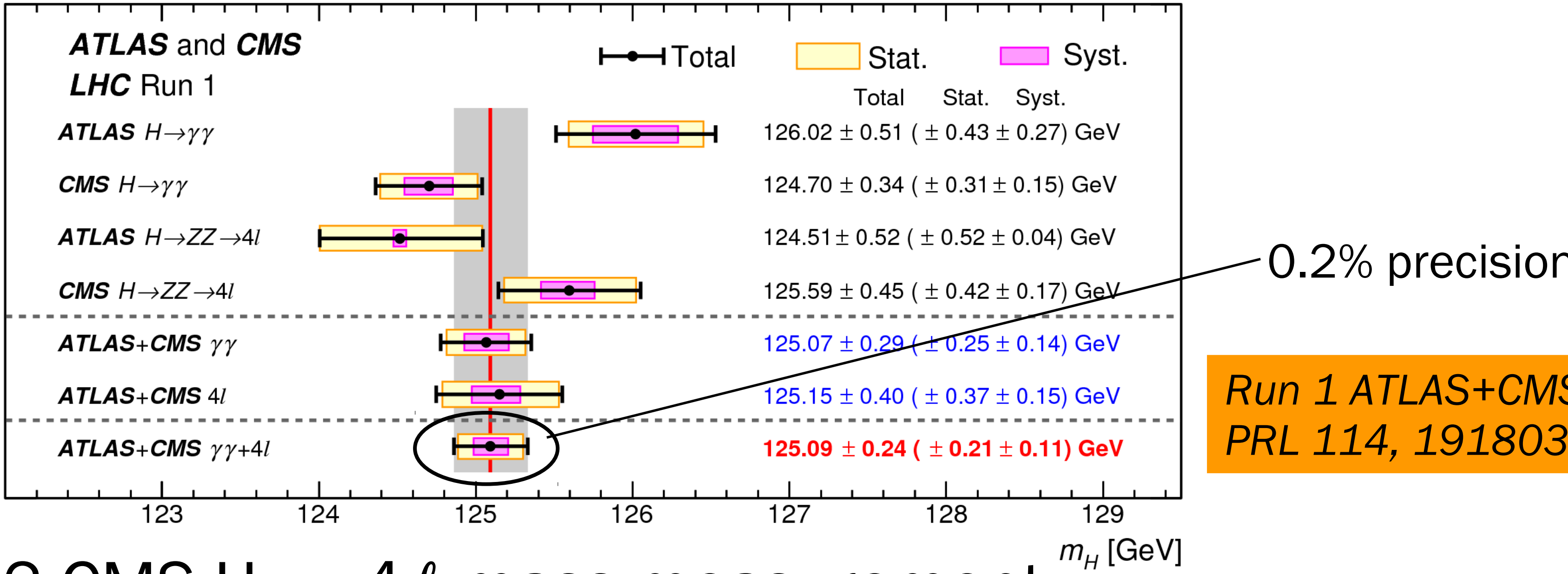


1701.07240, sub. to EPJ C

ATLAS EXPERIMENT

Higgs Mass

- Use fully-reconstructible decays $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$
  - Great potential for improvement: 4ℓ stats dominated



Run 1 ATLAS+CMS, PRL 114, 191803

- Run 2 CMS $H \rightarrow 4\ell$ mass measurement
  - $H \rightarrow 4\ell$: in concert with other Higgs properties measurements

$$m_H = 125.26 \pm 0.20(\mathrm{stat}) \pm 0.08(\mathrm{syst})\ \mathrm{GeV}$$

  - Better precision than LHC Run 1 combo
    (49 MeV smaller uncertainty than expected)

CMS-HIG-16-041

Top Mass

- Standard technique: test per-event compatibility of events with various mass hypotheses
  - Full/partial reconstruction, usually involving b-jets; could use J/ψ or B-hadron flight distance as proxy for b quark
  - Subject to jet and b-jet energy scale systematics, details of nonperturbative QCD in events
  - Also, what does MC generator top mass actually mean? Potentially O(GeV) shift between generator and "pole" mass
  - Top Yukawa coupling not expressed in pole scheme
- Alternative methods for pole mass:
  - measure $t\bar{t}$ cross section
  - shape of tt+1 jet total invariant mass

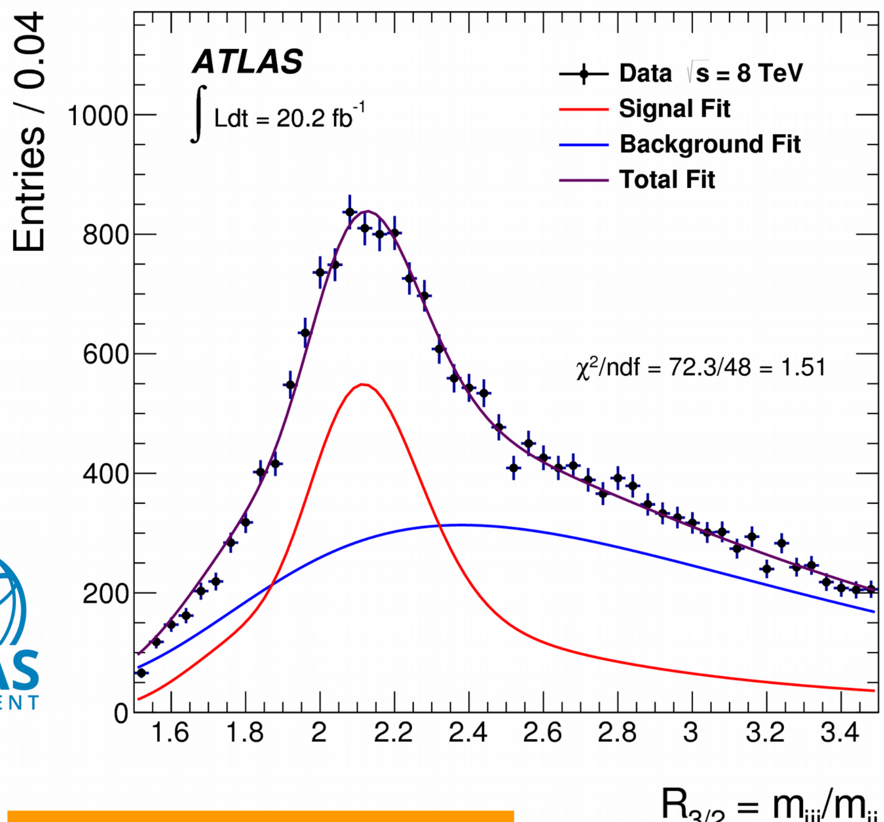
} Theoretically under better control

Top Mass Examples

"standard" analysis: all-hadronic top decays

plotted: m(t)/m(W)

m_t = 173.72 ± 0.55 (stat) ± 1.01 (syst) GeV

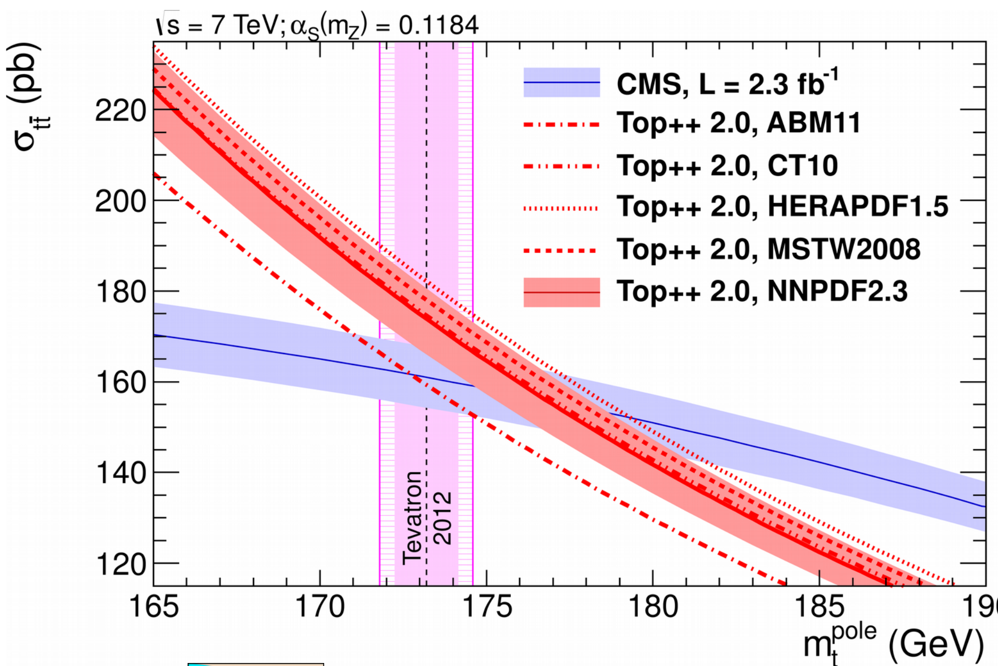


1702.07546, sub to JHEP

Interpret cross section from dileptonic decays (*pole mass*)

still depends on generator mass through acceptance

m_t = 176.7 + 3.0 – 2.8 GeV

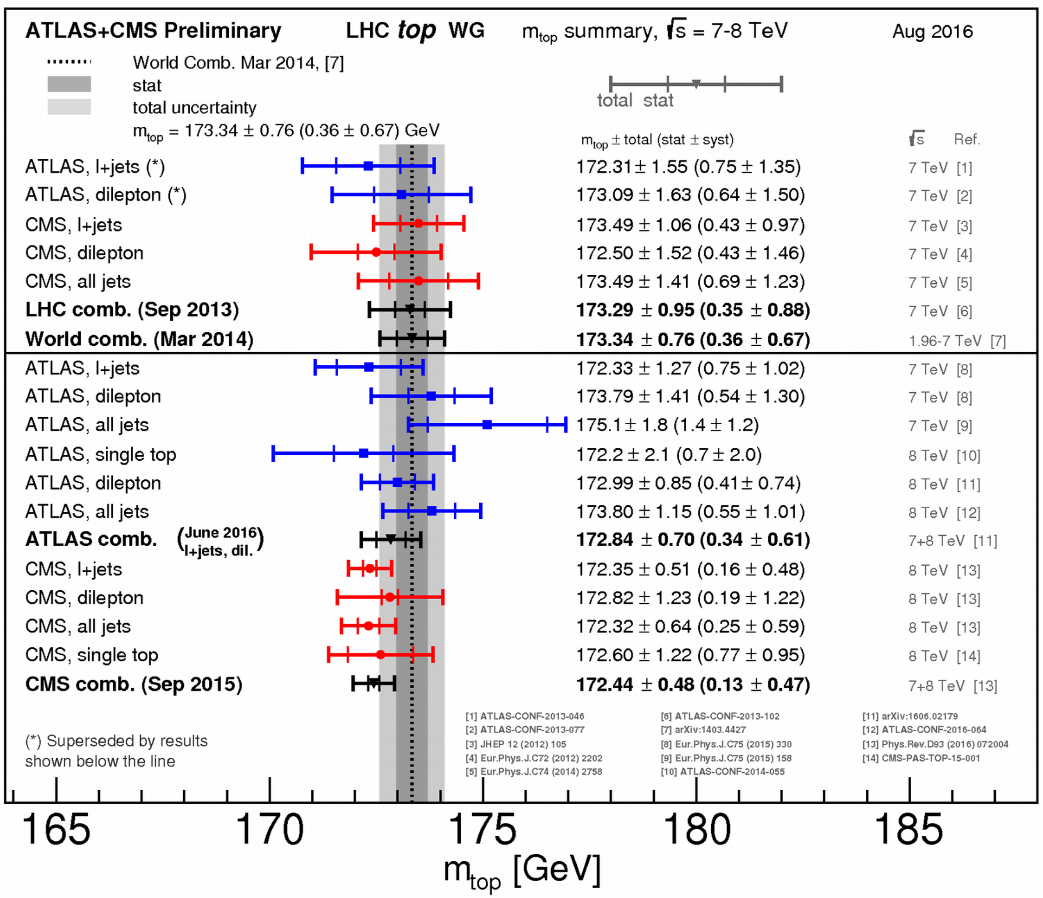


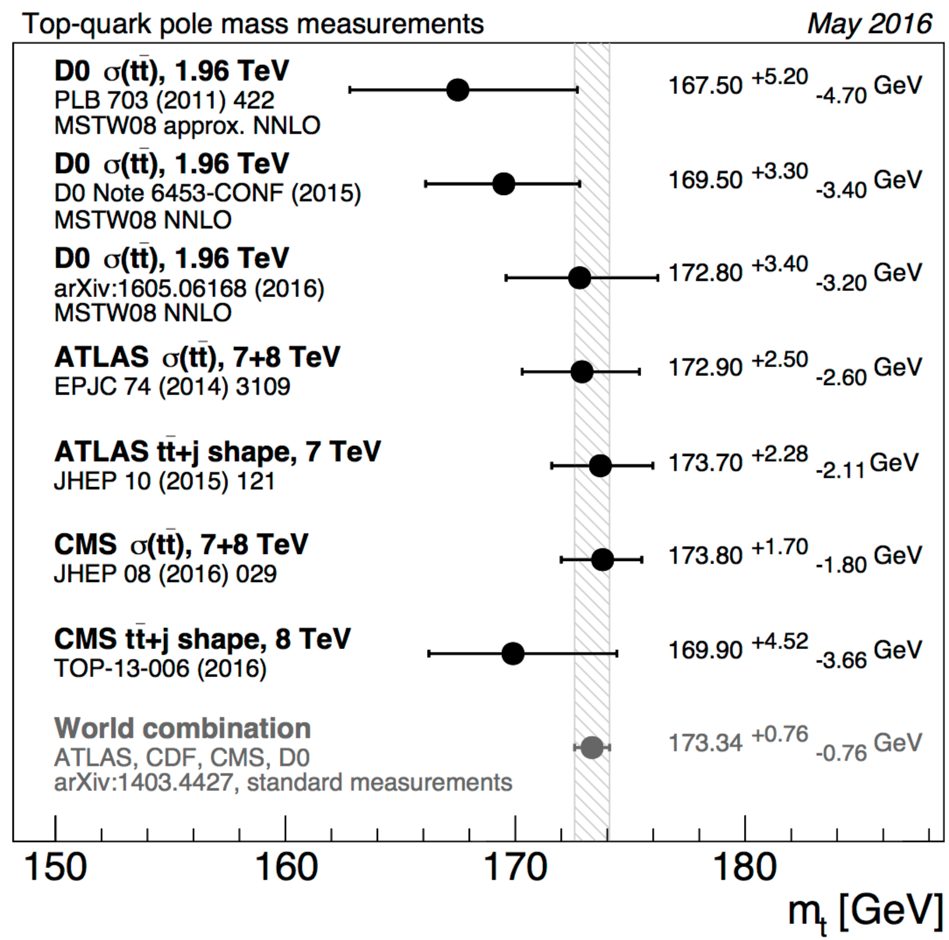
Phys Lett B 728, 496 (2014)

Top Mass Summary

- Standard methods are systematics limited at the ~ 0.5 GeV level
  - CMS projects ~ 0.2 GeV for HL-LHC
- Pole measurements at best ~ 1.8 GeV

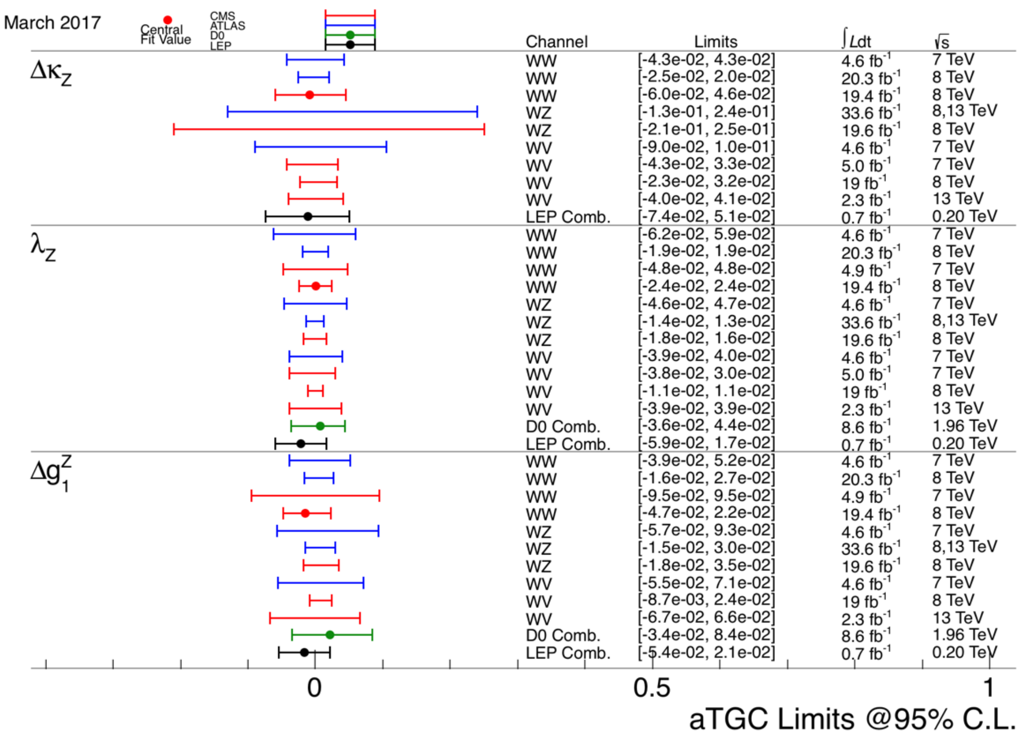
CMS-PAS-FTR-13-017



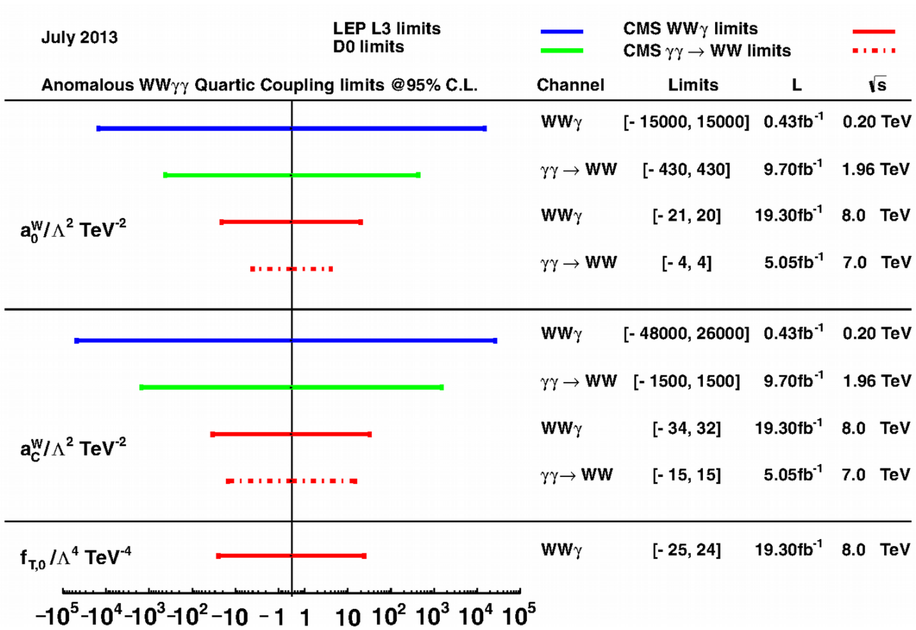


- Multiboson final states: check if rates, kinematics consistent with vertices of SM
  - e.g., γZZ, ZZZ vertices forbidden; higher-dim operators typically more important at higher momentum
  - probe anomalous *quartic* couplings with e.g. $\gamma\gamma \rightarrow WW$

WWZ aTGC



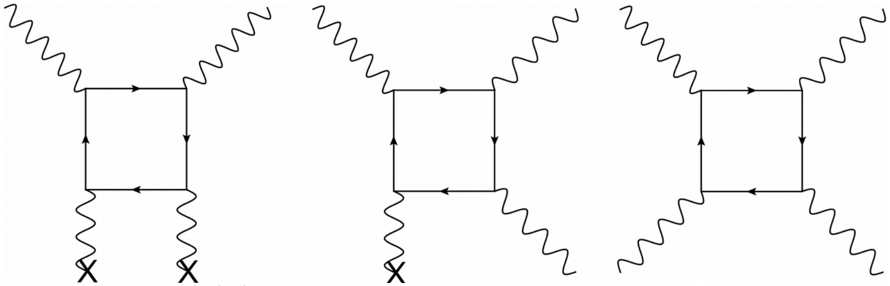
γγWW aQGC

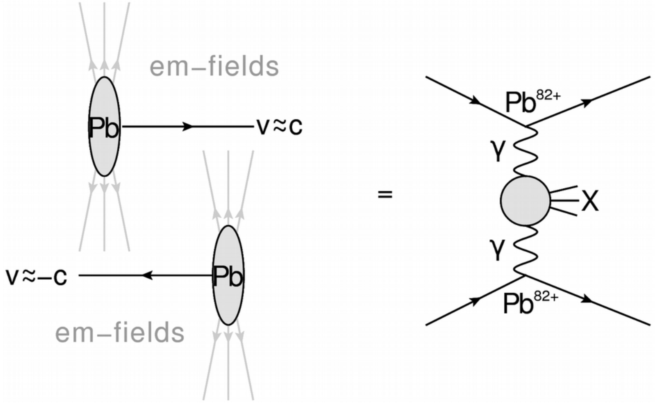


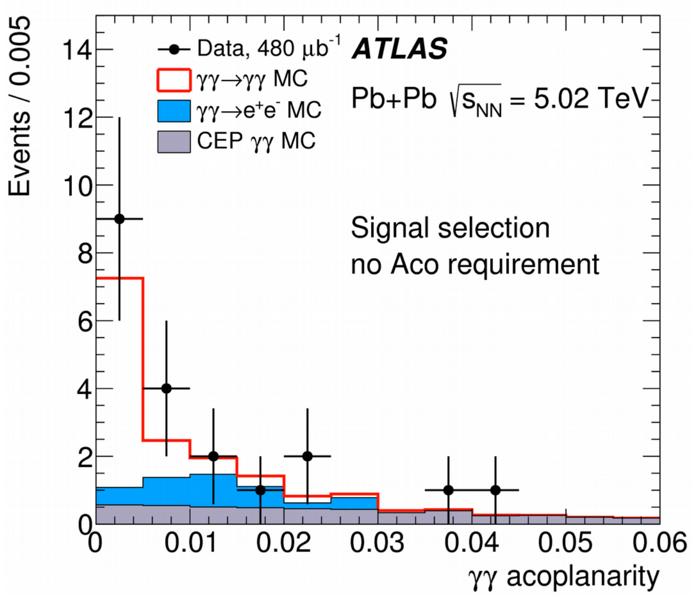
Light-by-Light Scattering

- Process γγ → γγ is predicted in QED
  - completely non-classical (nonlinearity in E, B fields – superposition fails)
  - lasers not yet intense enough
- At LHC: Collide the electric fields of relativistic lead nuclei
  - equivalent to colliding intense photon beam
  - signature: two photons + nothing; Pb ions vanish down beampipe
  - first evidence (4.4 σ) for γγ → γγ

1702.01625 (sub. to Nature Physics)



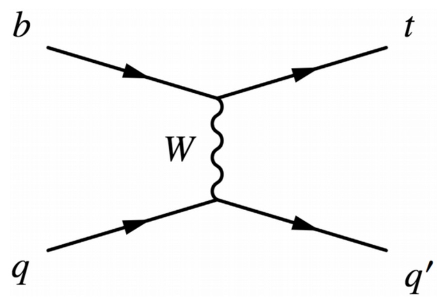


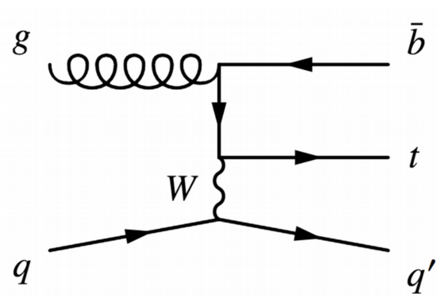


Observed rate ~ (1.6 ± 0.7) × theory

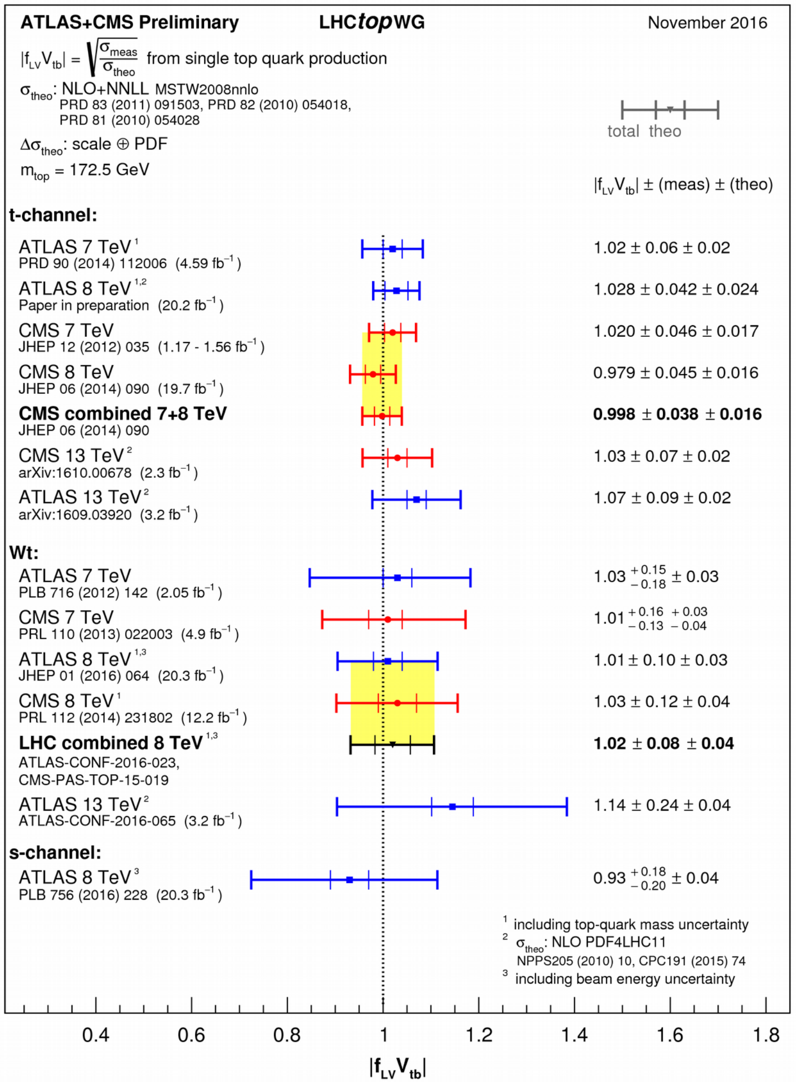
Top Quark Interactions: tWb Vertex

- Probe strength of vertex with single top (electroweak) production

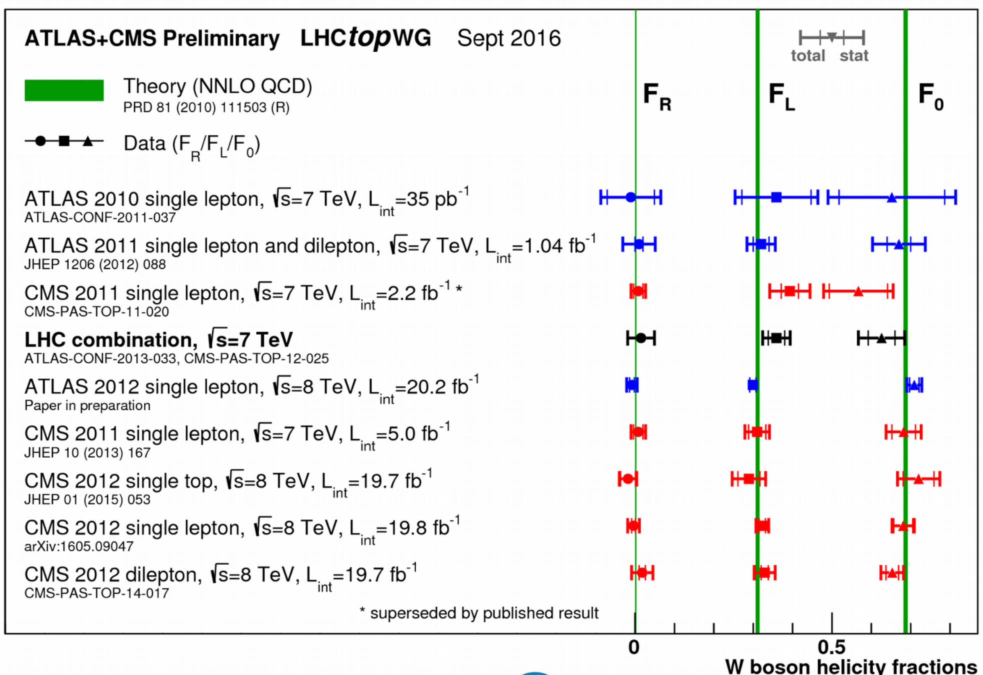




$|f_{Lv}V_{tb}|$ (= $|V_{tb}|$ in SM)



Polarization of W in $t\bar{t}$ events

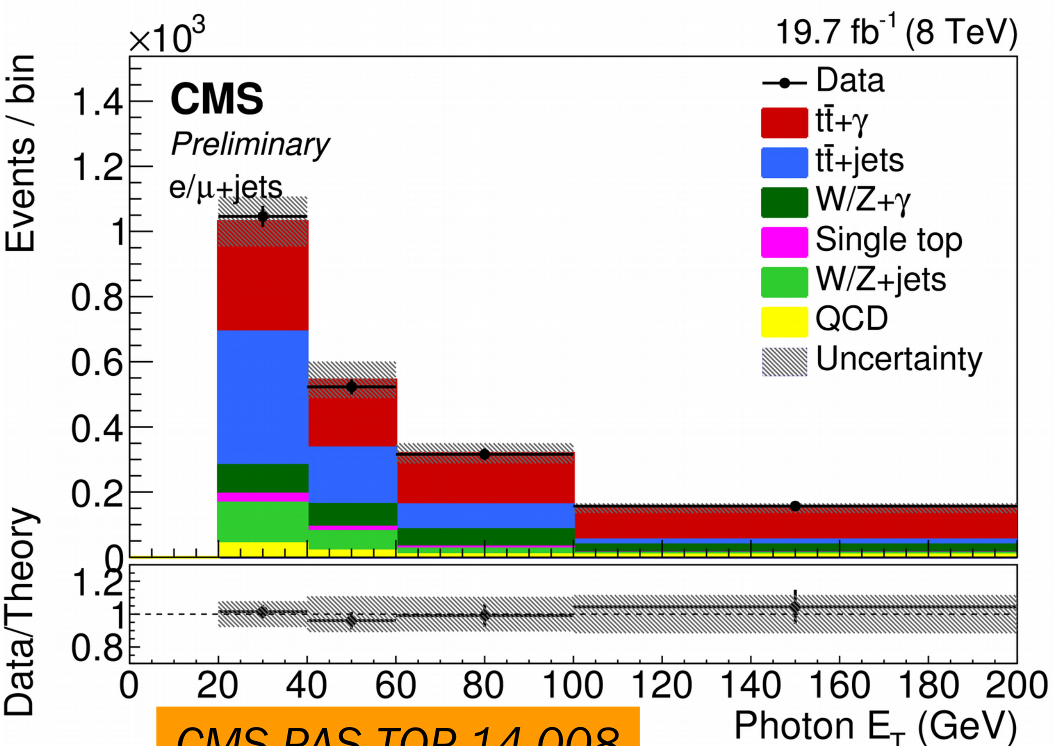


see also EPJ C 77, 264 (2017)

$t\bar{t}$+vector boson

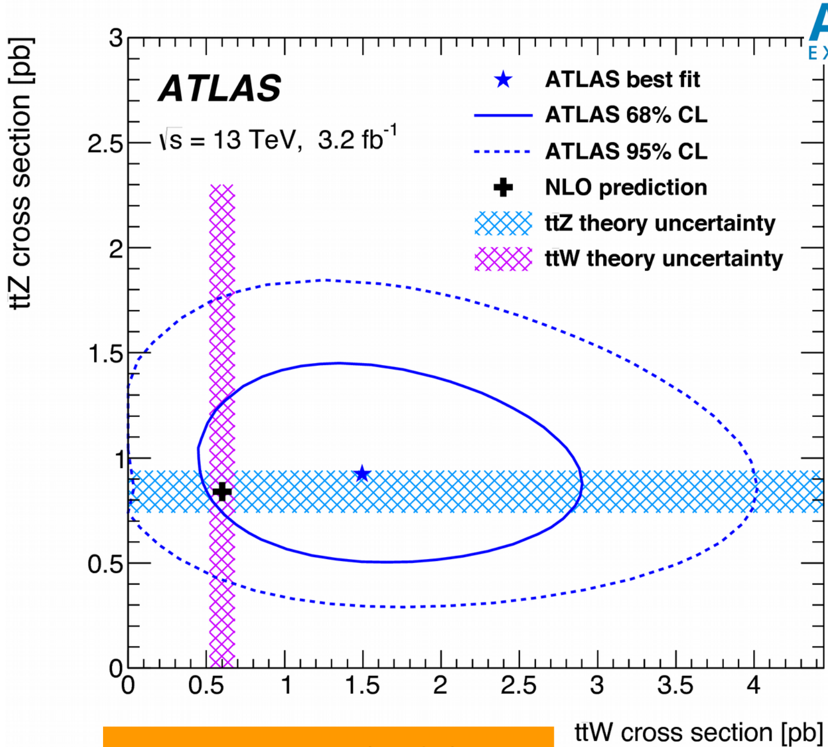
- Probe tZ, tγ couplings; measure backgrounds for new physics searches

$\sigma(t\bar{t}\gamma)$ x BR:
Exp: 515 ± 108
Theo: 592 ± 71 (scale) ±30 (PDF)



CMS-PAS-TOP-14-008

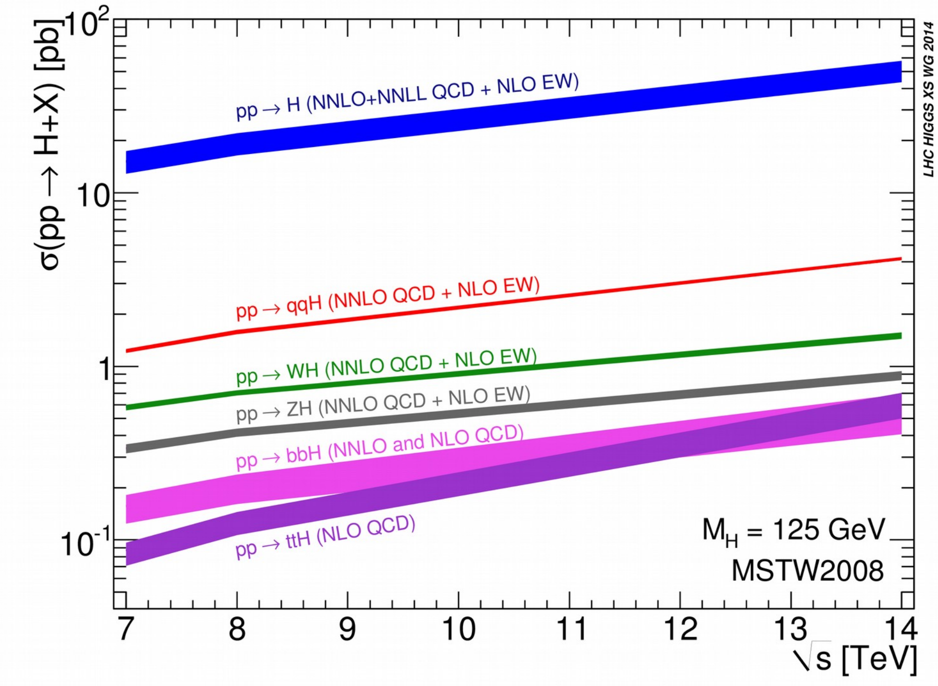
Simultaneous measurement of $\sigma(t\bar{t}Z)$, $\sigma(t\bar{t}W)$



EPJ C 77, 40 (2017)

SM Higgs: Plan

- First phase of h(125) characterization "done"
  - no O(1) departures from SM
- Next phase:
  - precision gauge boson interactions; offshell couplings
  - confirm + precisely measure third generation fermion couplings
  - explore 2nd gen fermion couplings
  - further use of kinematic distributions to probe new physics (and SM) – EFT, simplified template cross sections, pseudo-observables…
  - high[er] precision mass



13 vs 8 TeV: σ(H) up x2 (ttH up x4)

Matched by progress in theory:
→ N³LO inclusive ggF cross section
→ NNLO differential ggF
→ NLO interference between offshell H and gg → VV
→ Updated generators

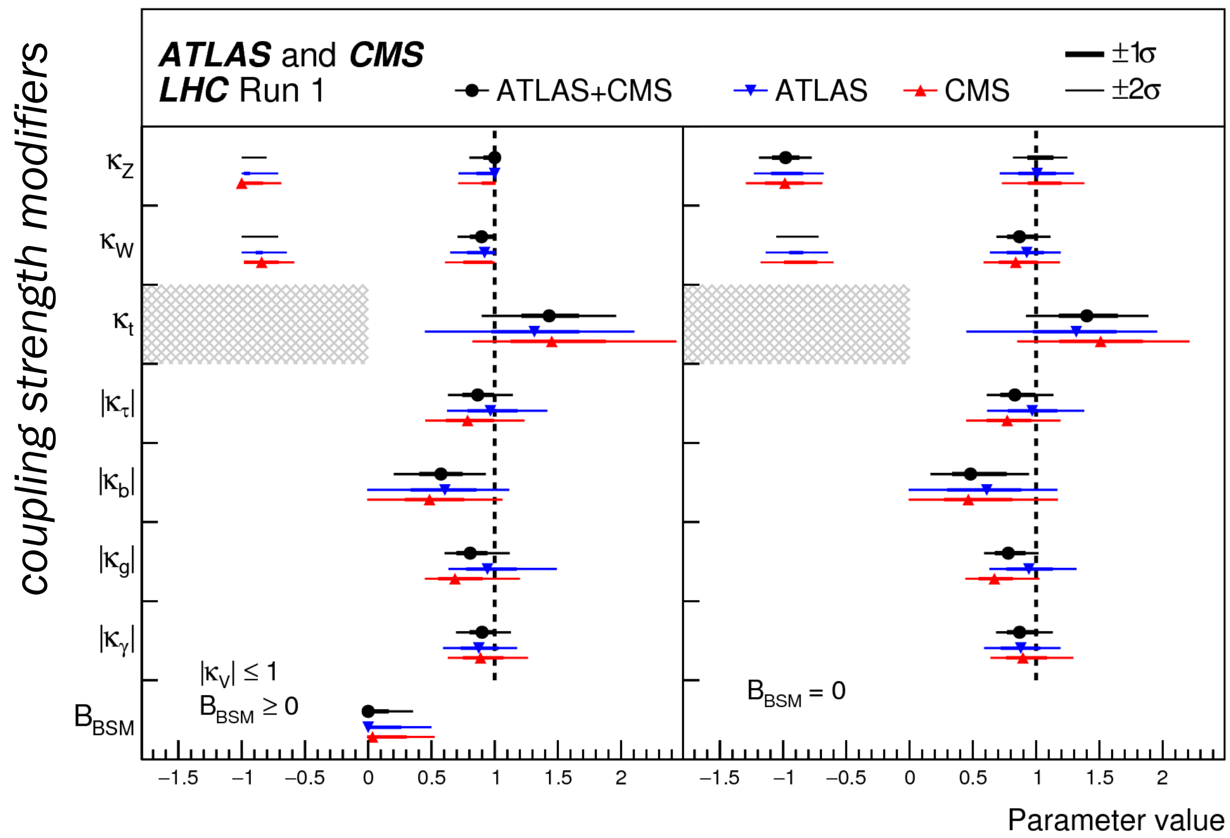
State of Play after Run 1

ATLAS + CMS
JHEP 08(2016) 045

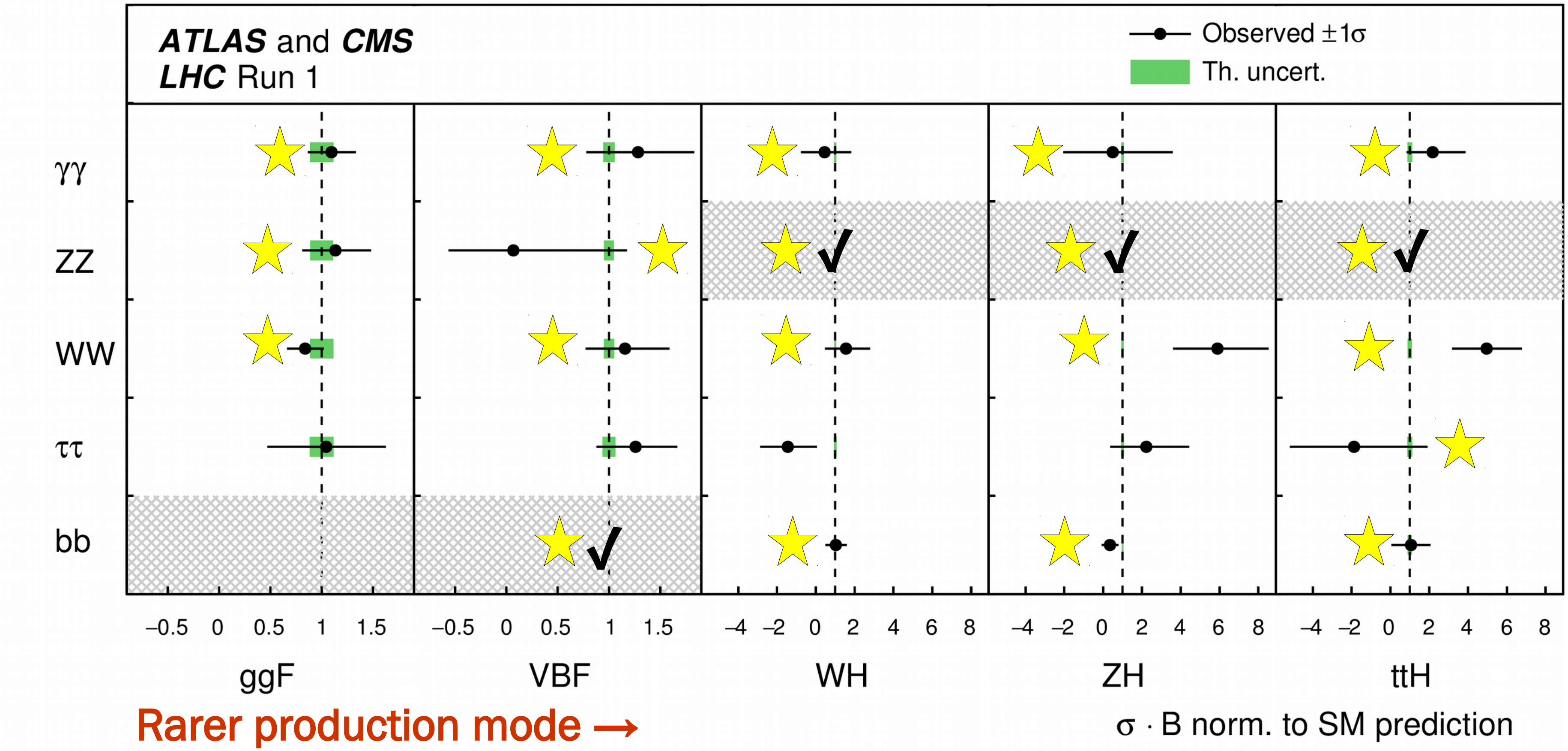
h(125) in ZZ, WW decays: compatible with $J^P = 0^+$

From experiment combo:
Observation of ggF, VBF
Evidence for VH
Evidence for ttH (!)

Observation of $H \rightarrow \tau\tau$
Significance of $H \rightarrow bb$ still < 3σ!



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



Comprehensive set of measurements/searches for "standard" production/decay modes

✔ = done since Run 1 combination

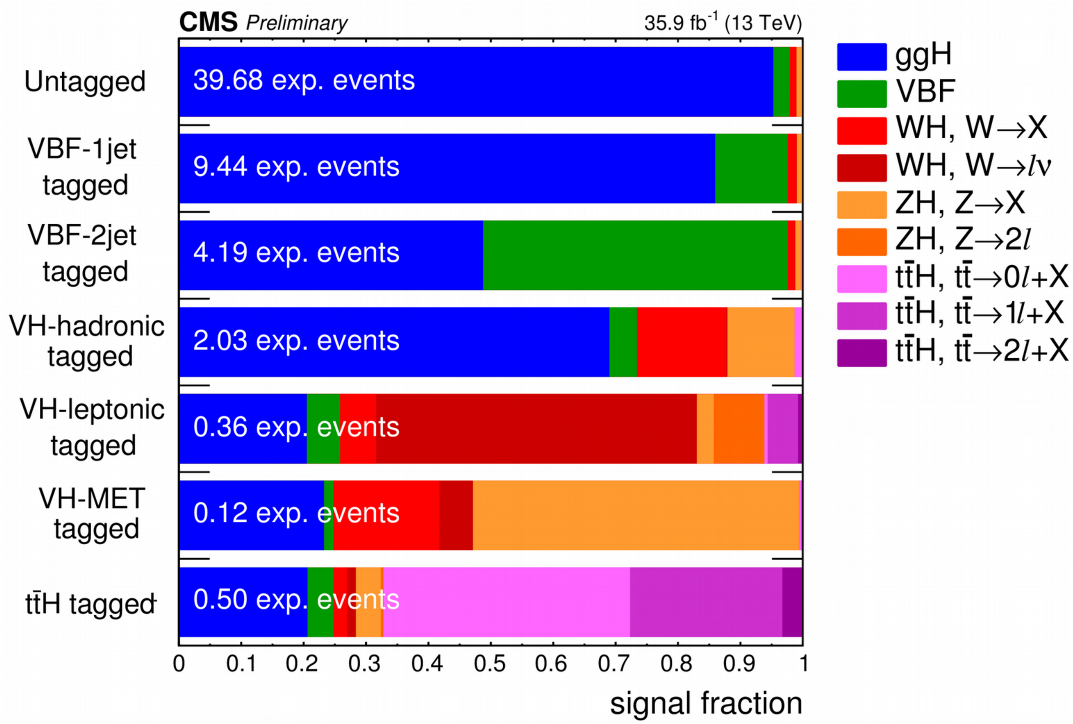
Also searches for rare decays e.g. H ⟶ μμ, Zγ, γJ/ψ, γφ

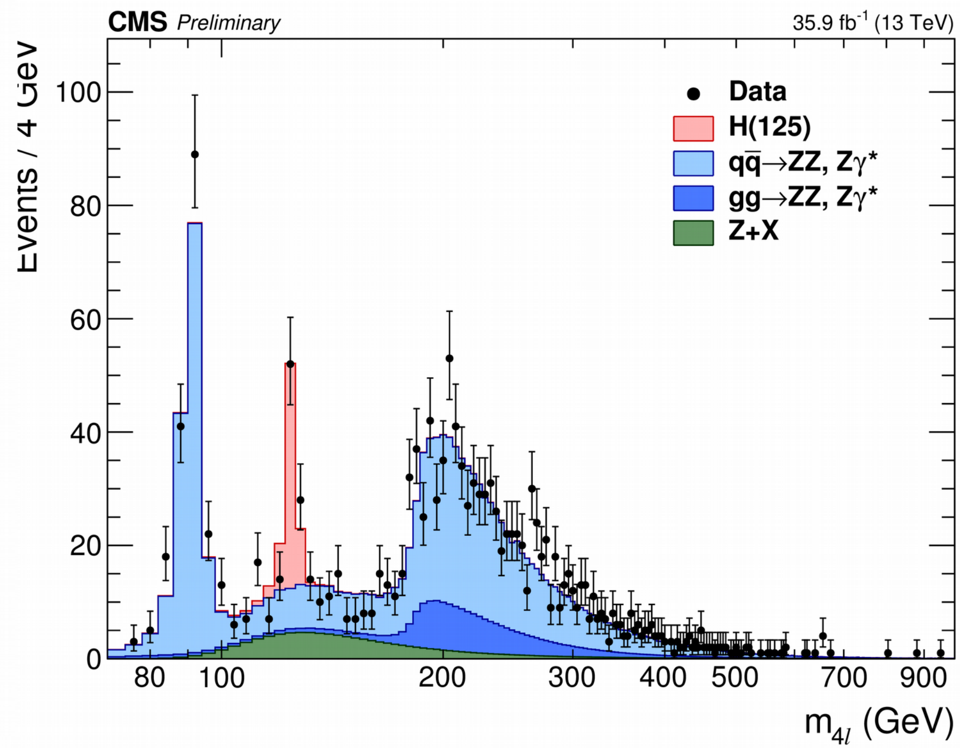
★ = 13 TeV results

$H \rightarrow 4\ell$

- High resolution channel, good S/B
- probe production mechanisms by kinematics of other objects in event
- Lepton angles give access to Higgs spin, parity
- Low stats limit reach for rare production modes

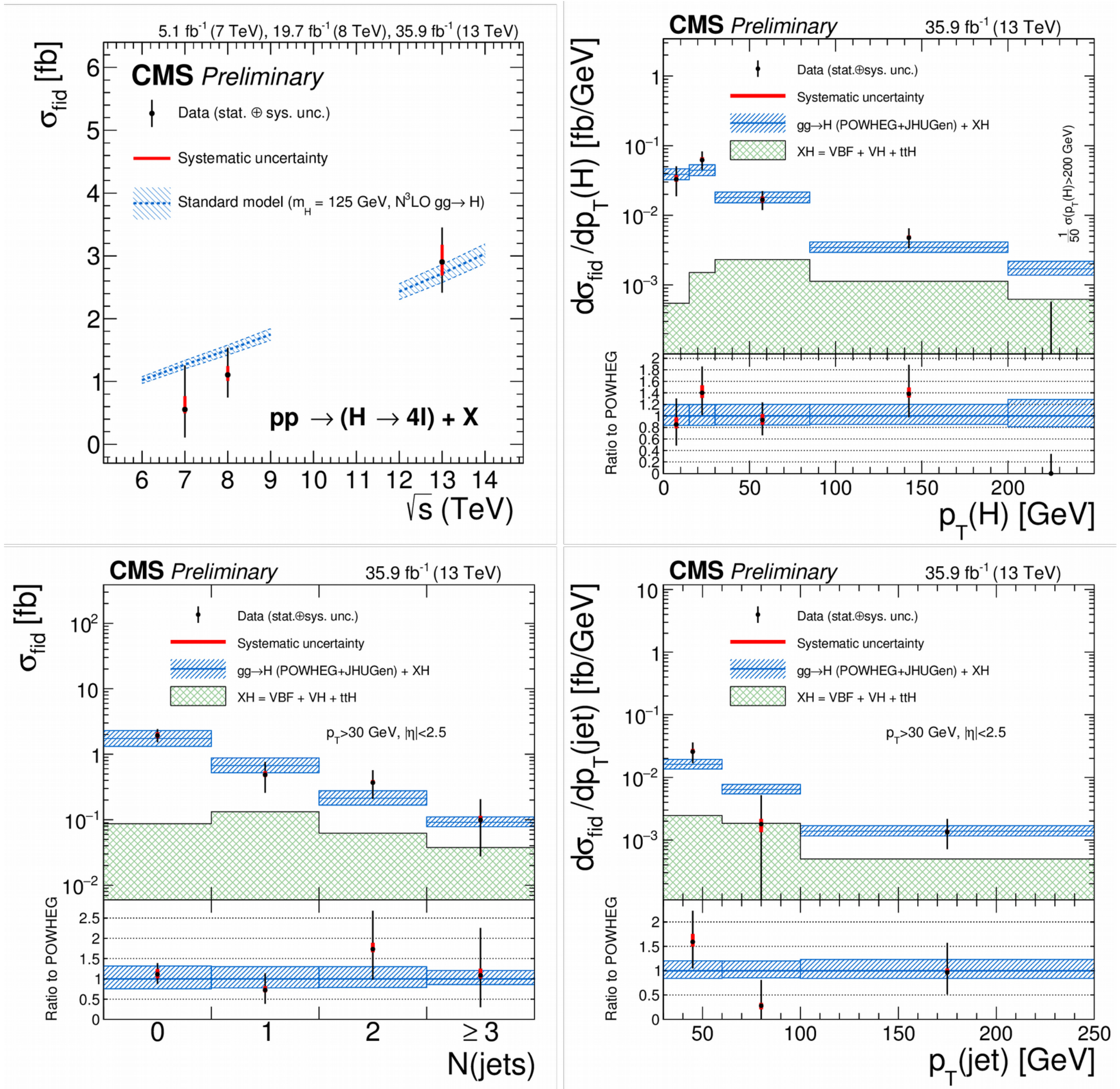
CMS-PAS-HIG-16-041

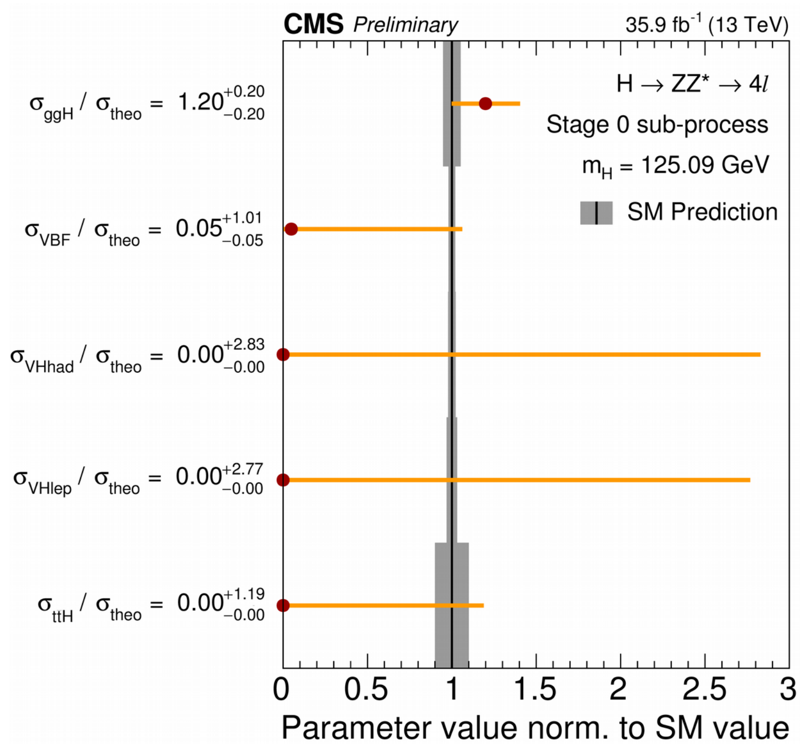




H → 4 ℓ Cross Sections

- Report a cross section, not just a ratio to expectation
- Also differential cross sections





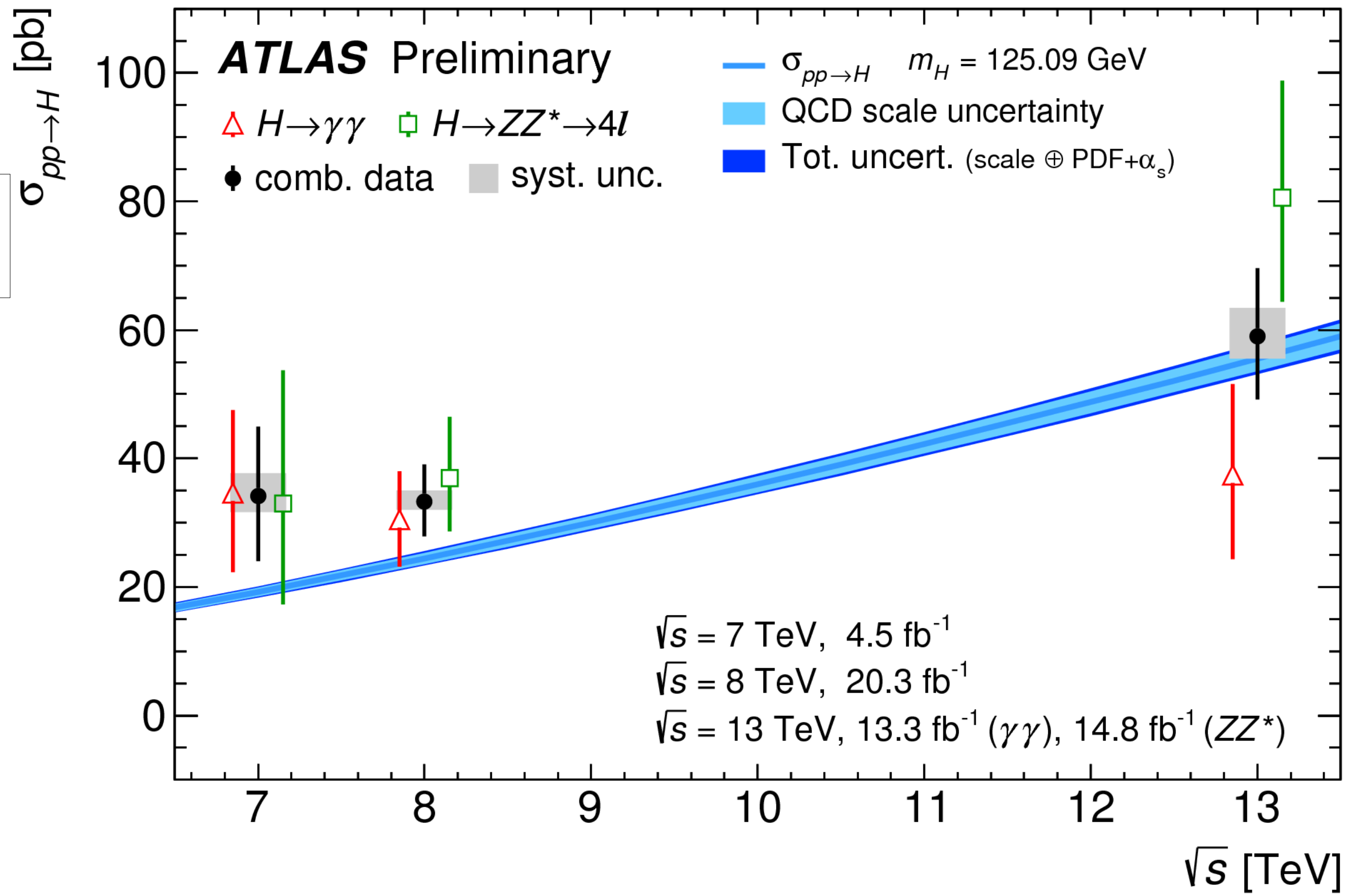
"simplified template cross sections" ratio to SM ($|y_H| < 2.5$)

ATLAS 4 ℓ, γγ Combination

γγ: better sensitivity for rarer production modes

ATLAS-CONF-2016-081

Total σ, extrap. from fiducial σ



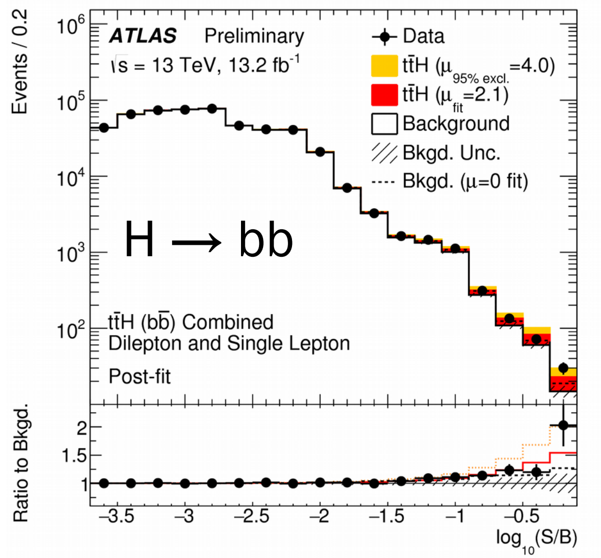
$$\sigma(pp \to H + X) = 59.0^{+9.7}_{-9.2}(\text{stat})^{+4.4}_{-3.5}(\text{syst})\ \text{pb}$$ (ATLAS)

$$\sigma(pp \to H + X) = 55.5^{+2.4}_{-3.4}\ \text{pb}$$ (N^3LO theo)

ttH

- Follow up excesses in Run 1
- Combine searches in γγ, bb, WW/ττ
- Both experiments exceed Run 1 sensitivity
- Proper handling of systematics increasingly important

ATLAS-CONF-2016-080



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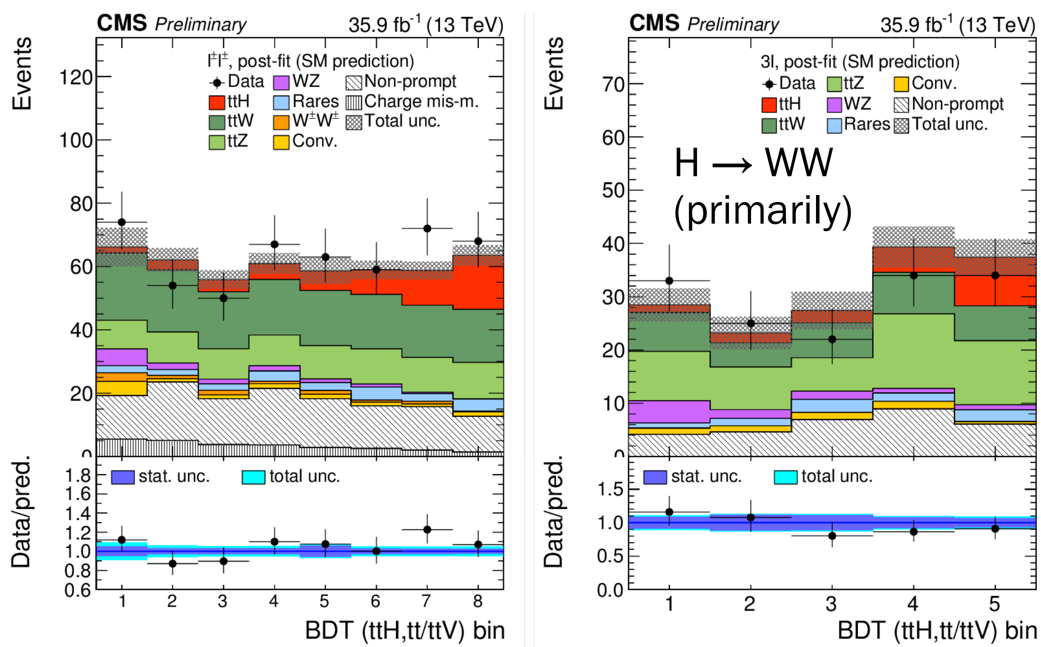
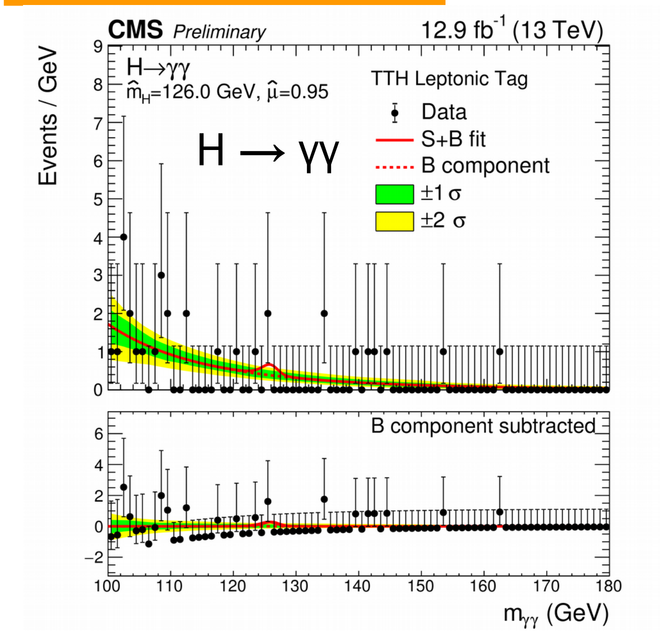
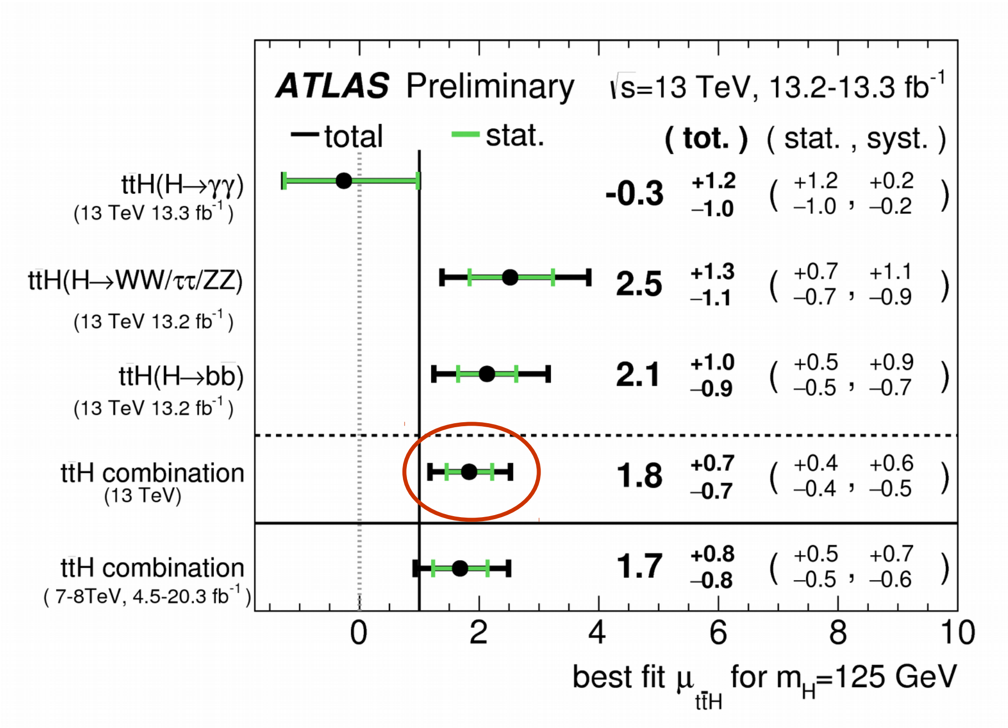


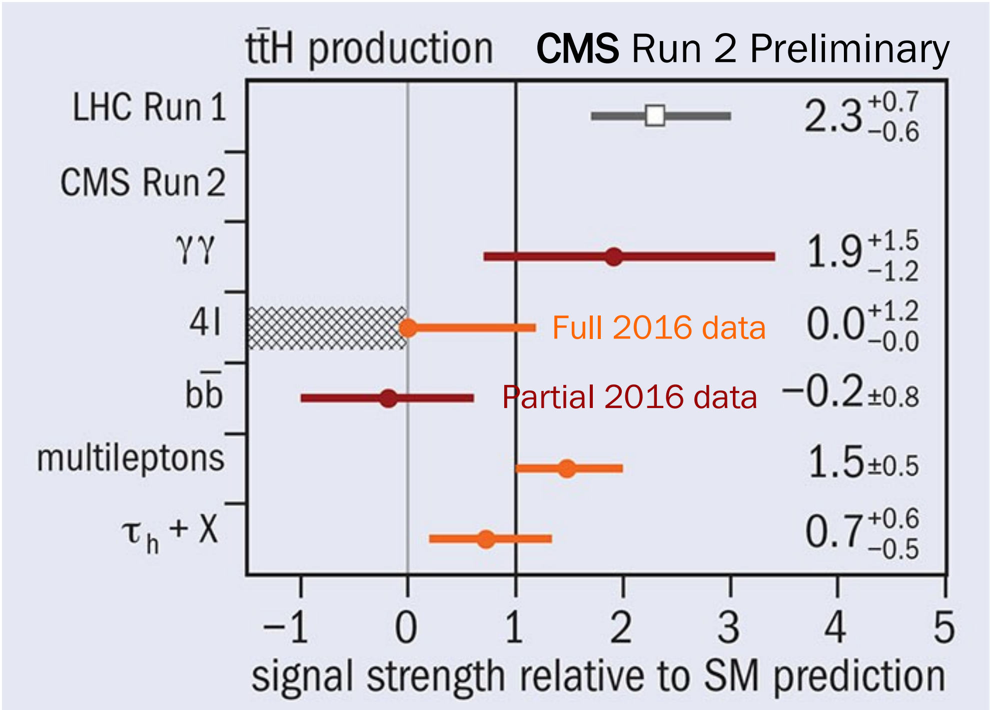
CMS-PAS-HIG-16-020



ttH Status

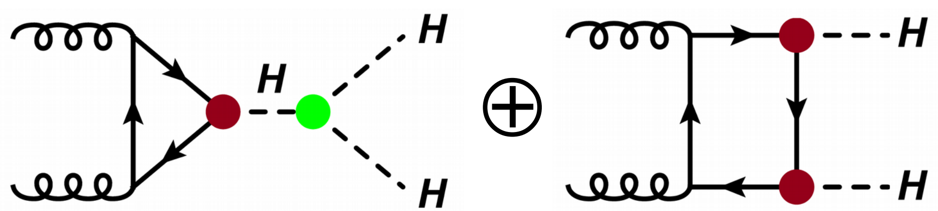
- Creeping up on 3σ significance per experiment
  - observed significance > expected [best fit σ higher than SM]
- No single dominant channel
- Can we say we have "evidence" already?





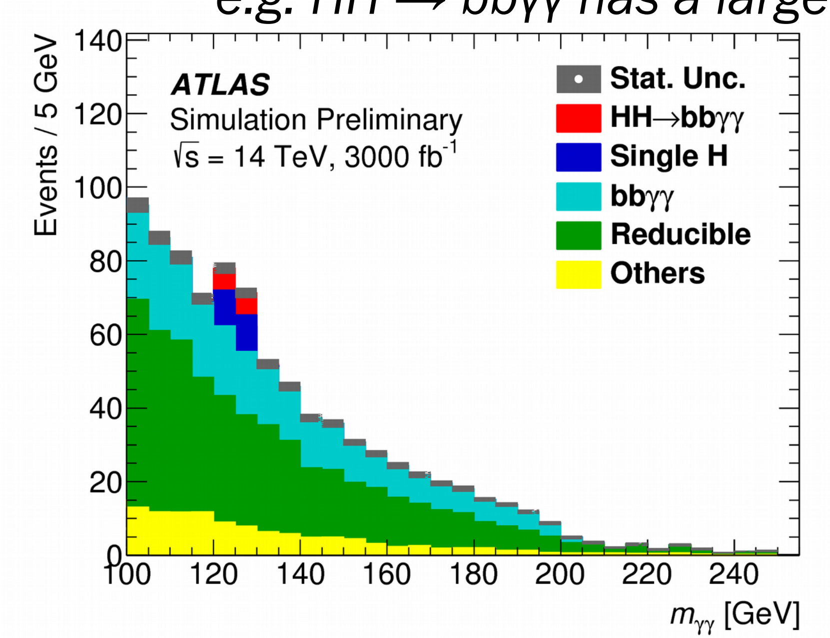
Future

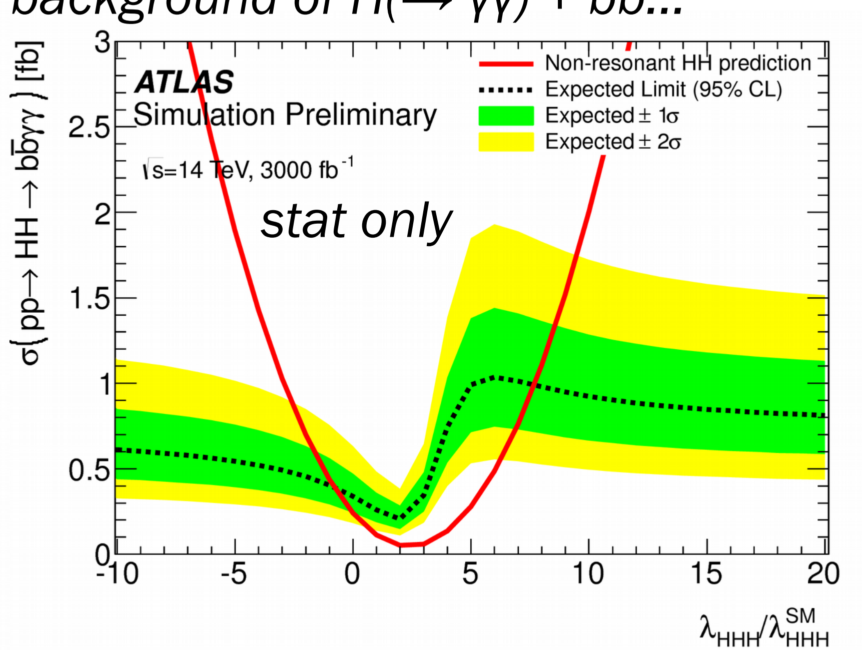
- Many studies done to probe requirements for HL-LHC
  - Precision physics a main driver for HL-LHC
- Example: many studies focused on HH prospects
  - SM sensitivity still a challenge…



ATL-PHYS-PUB-2017-001

e.g. HH → bbγγ has a large background of H(→ γγ) + bb…





Summary

- Probing the Standard Model in great detail is mandatory
  - Test the consistency of the electroweak sector
  - Show we can calculate complex processes
  - Understand backgrounds for difficult new physics searches
- LHC is a factory for W, Z, top, Higgs
  - with large datasets, able to do exquisite precision and rare process searches
  - so far good consistency with SM
- Can make important improvements with additional integrated luminosity
- Future is bright!

Parallel "SM" (Experiment) Talks

Top (Mon 2 – 4 pm)
Yao: *ATLAS $t\bar{t}$+X, σ($t\bar{t}$)*
Suster: *ATLAS single top*
Zhu: *ATLAS top mass, properties*

Higgs (Mon 2 – 4 pm)
Bortolotto, *ATLAS Higgs → diboson*
Bethani, *ATLAS Higgs → fermions, ttH*
Rossin, *CMS HH*

BSM Higgs I (Mon 4:30 – 6:30 pm)
Veatch, *ATLAS rare + exotic Higgs decays*

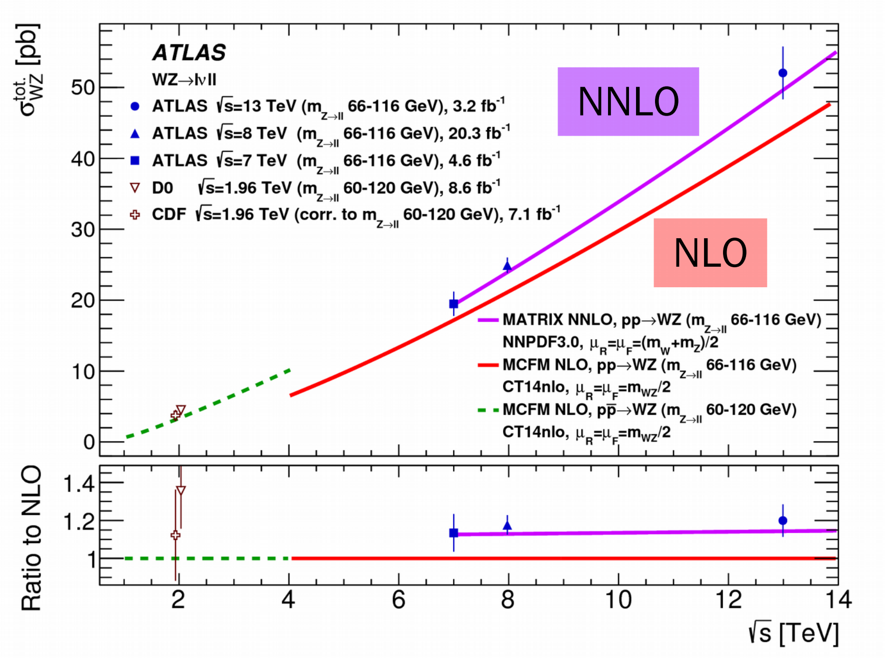
QCD & EW (Tue 2 – 4 pm)
Vachon, *ATLAS γ+jets*
Staroba, *ATLAS vector boson production*
Becker, *ATLAS multiboson production*

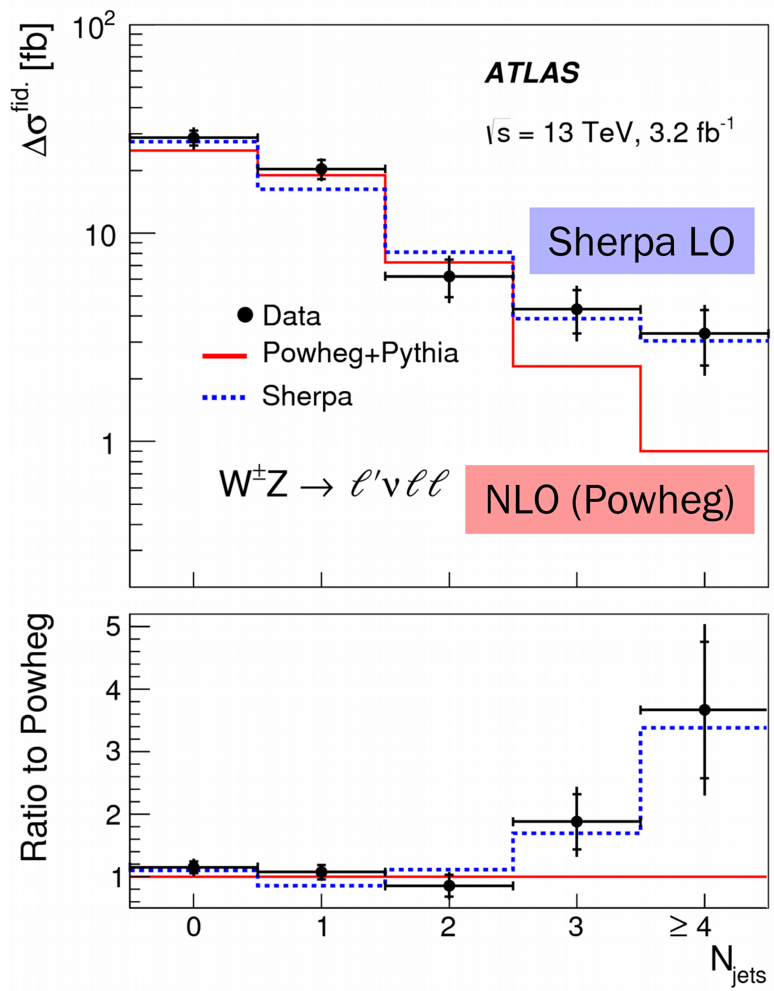
Still a long road ahead…
and a lot to learn

Inks Lake SP, Burnet, TX

Validating Calculations

- Acceptable prediction for pp → WZ rate requires NNLO calculation
- But WZ+jets multiplicity shape better modeled by merged multileg LO than NLO at high # jets

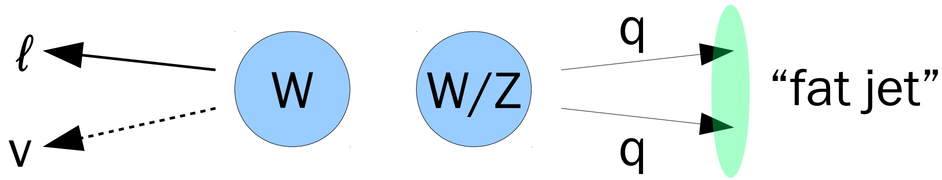




Phys. Lett. B 762 1 (2016)

WV ℓvjj search

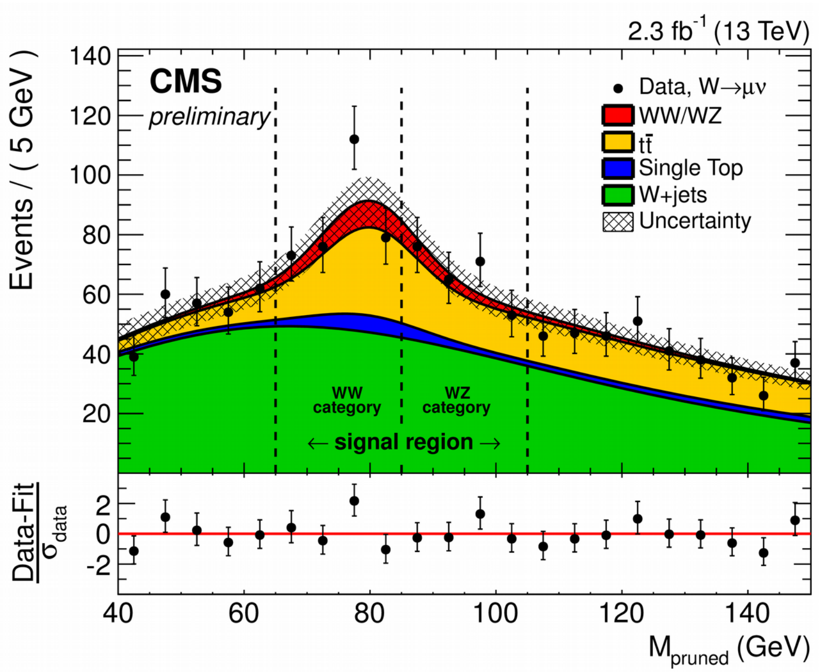
- aTGC effects most relevant at high momenta → use "boosted" techniques to search for high-momentum vector boson pairs

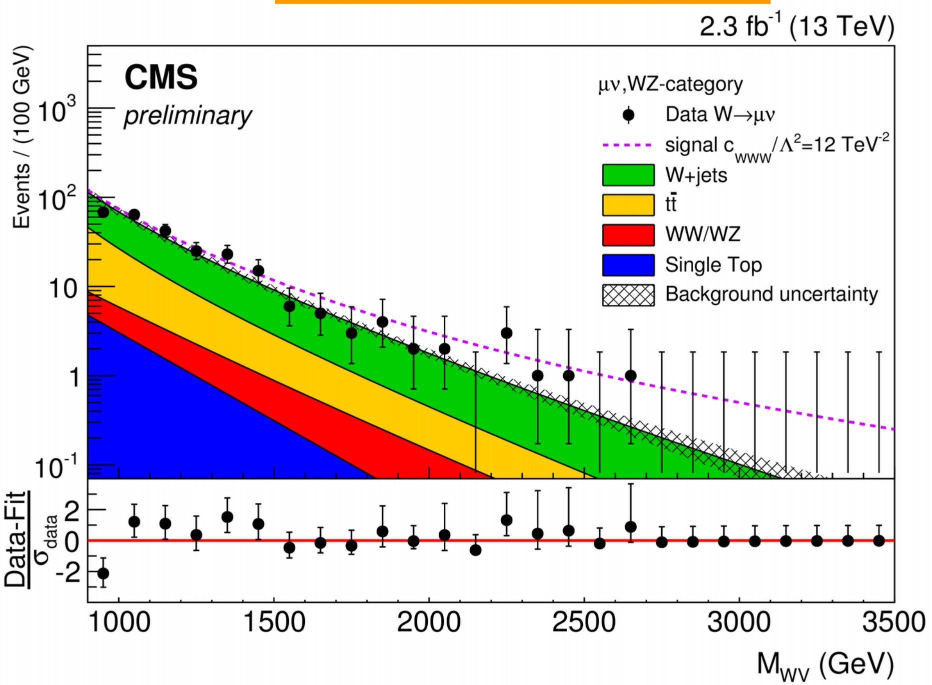


Require M_{WV} > 900 GeV

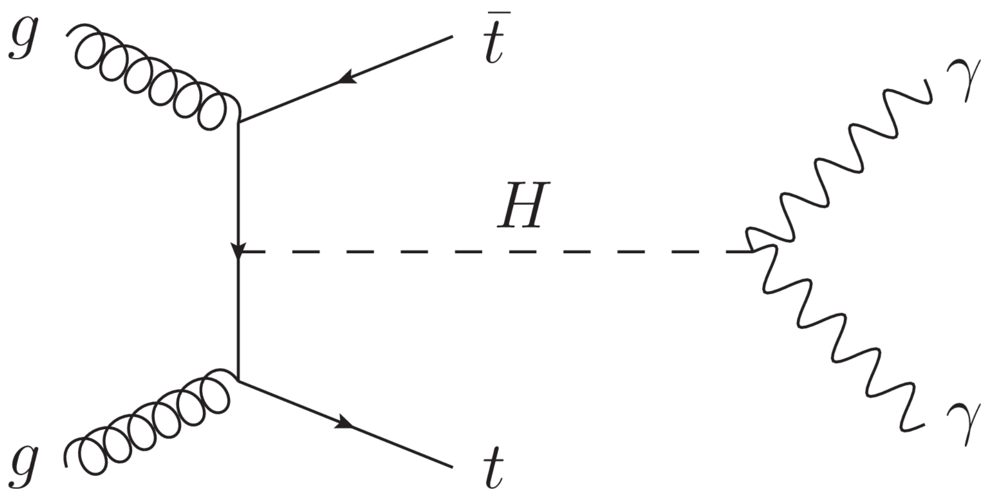
- Peaking bkg: top, SM WV

CMS-PAS-SMP-16-012





Example of κ-formalism



$\frac{\Gamma_{\gamma\gamma}/\Gamma_H}{\Gamma_{\gamma\gamma,SM}/\Gamma_{H,SM}}$

On-shell!

$$\mu = \frac{\text{Rate}}{\text{SM Rate}} = \kappa_t^2 \times \frac{\mathcal{B}(H \to \gamma\gamma)}{\mathcal{B}(H \to \gamma\gamma)_{\text{SM}}}$$

unresolved $$\kappa_t^2 \times \kappa_\gamma^2 \times \frac{\Gamma_{H,SM}}{\Gamma_H}$$

resolved $$\kappa_t^2 \times \left(1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.66\kappa_W\kappa_t\right) \times \frac{\Gamma_{H,SM}}{\Gamma_H}$$

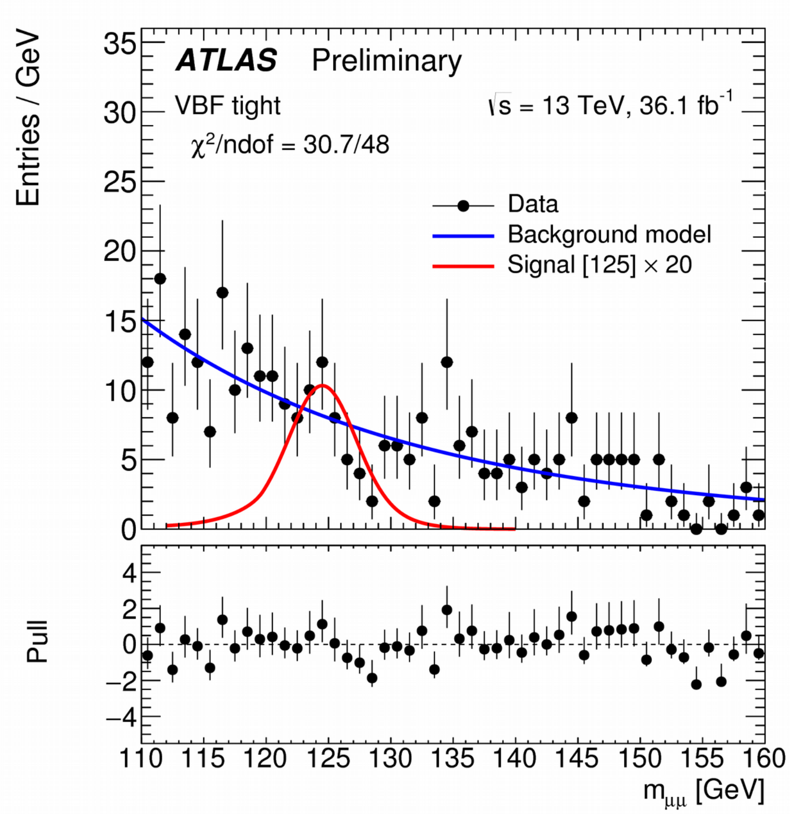
Can increase all κ coherently and keep same on-shell μ
if increase Γ_H to compensate (invisible/undetected decays)

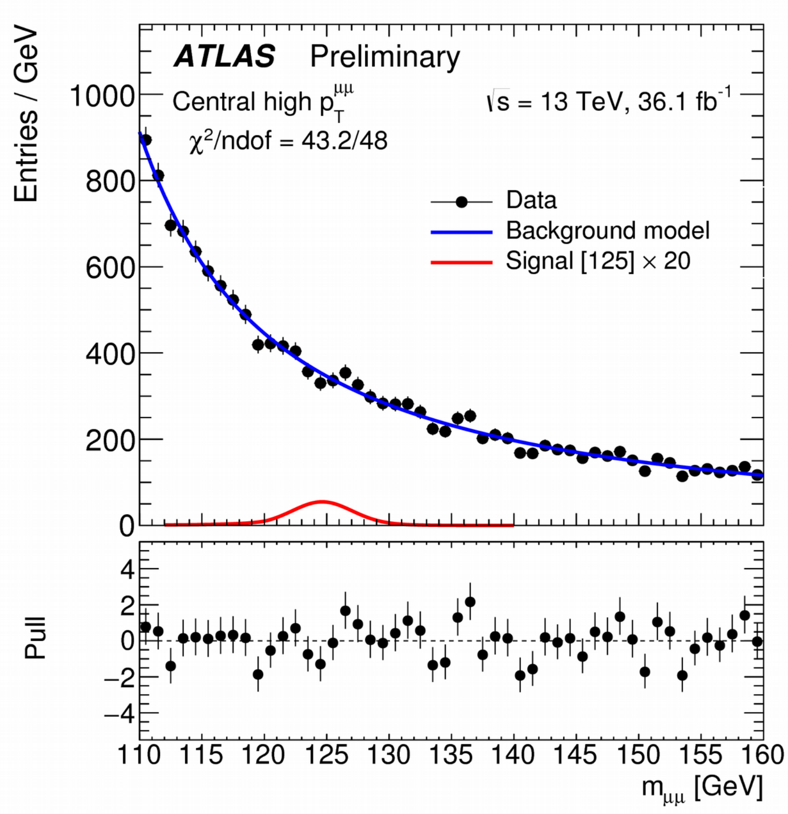
$H \longrightarrow \mu\mu$

- Search for resonant dimuon events in ggF and VBF production (separated by BDT), additional kinematics
- Fit dimuon mass spectra

ATLAS-CONF-2017-014

$\mu = -0.11^{+1.49}_{-1.51}$ *Run 2*
< 3.0 (3.1 exp) *Run 2*
< 2.7 (2.8 exp) *Run 1+2*

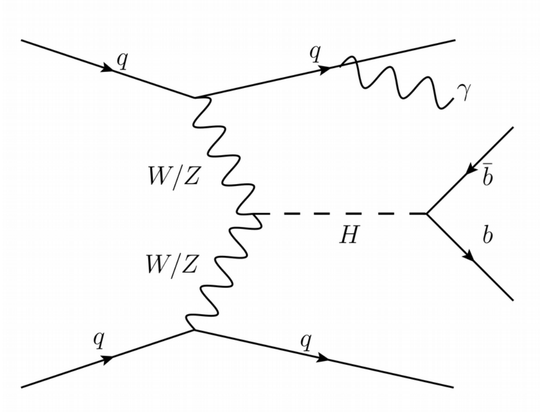


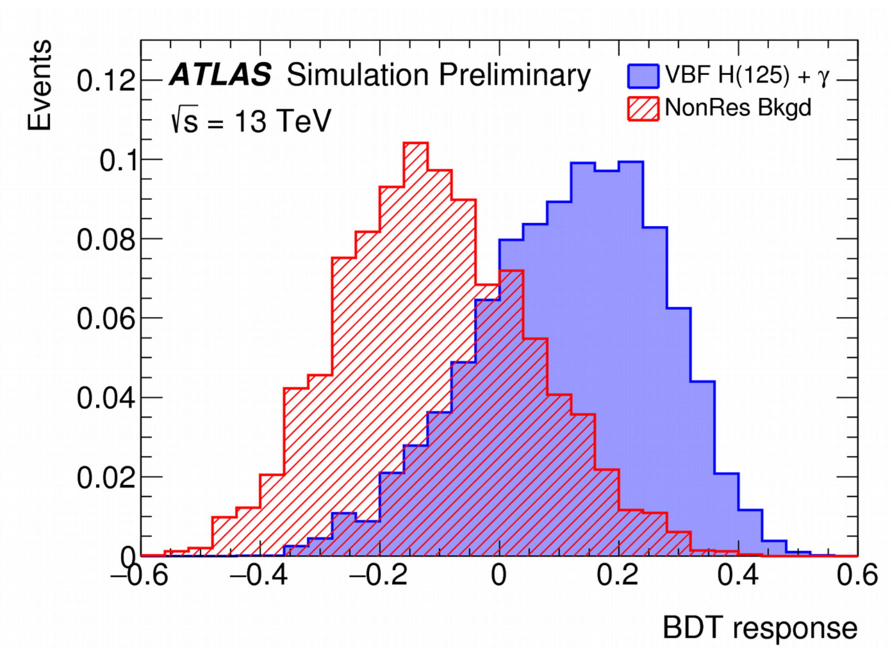


VBF γ + H, H ⟶ bb

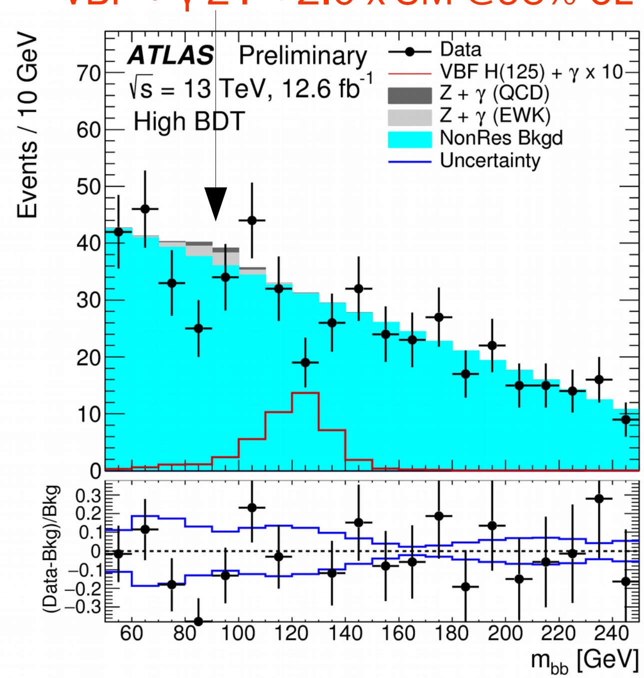
- Roundabout method to access VBF Higgs production: use radiated high-p_T photon for triggering
  - better S/B as gg-initiated bkg suppressed
- Sensitivity similar to direct VBF search, but much smaller systematics

ATLAS-CONF-2016-063



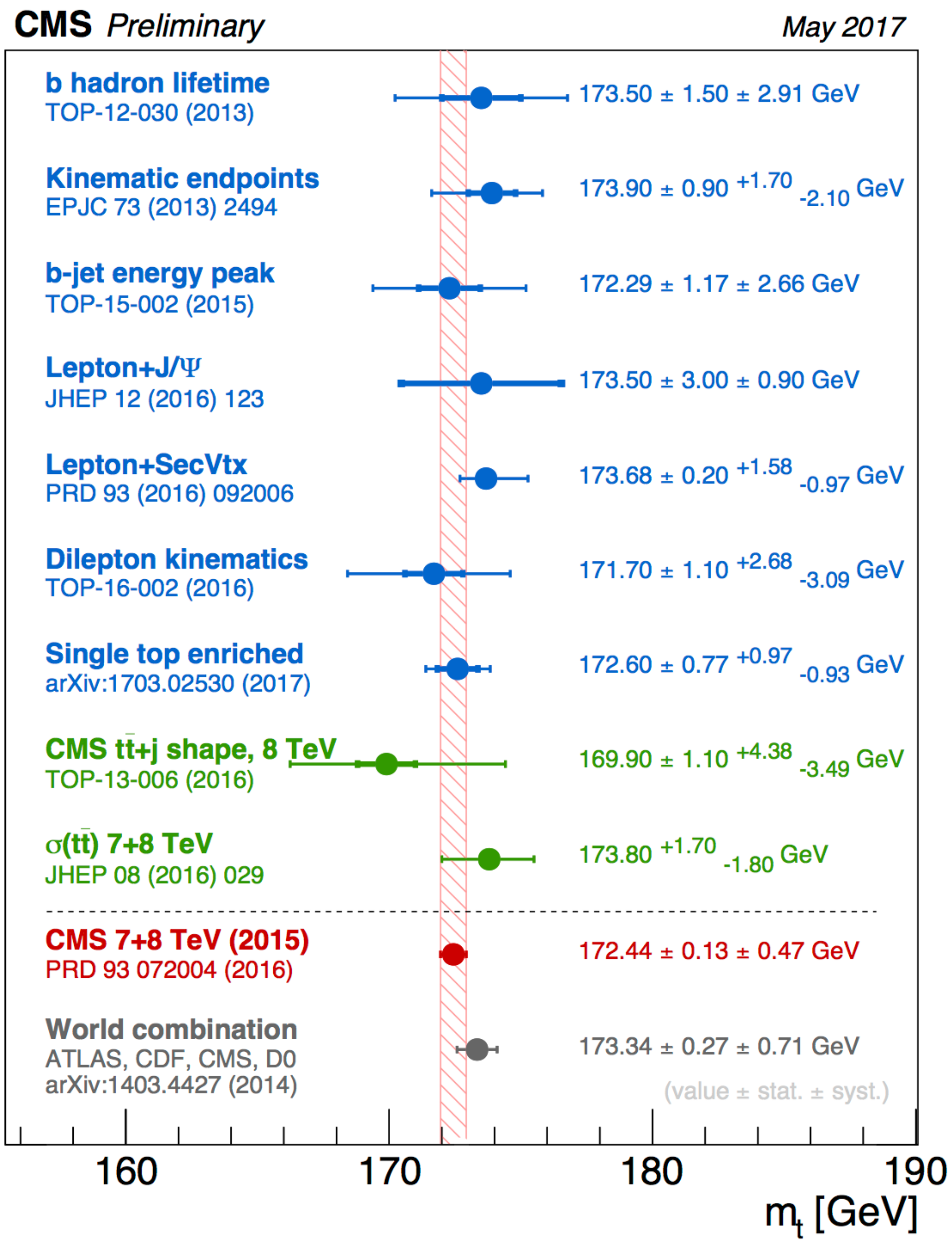


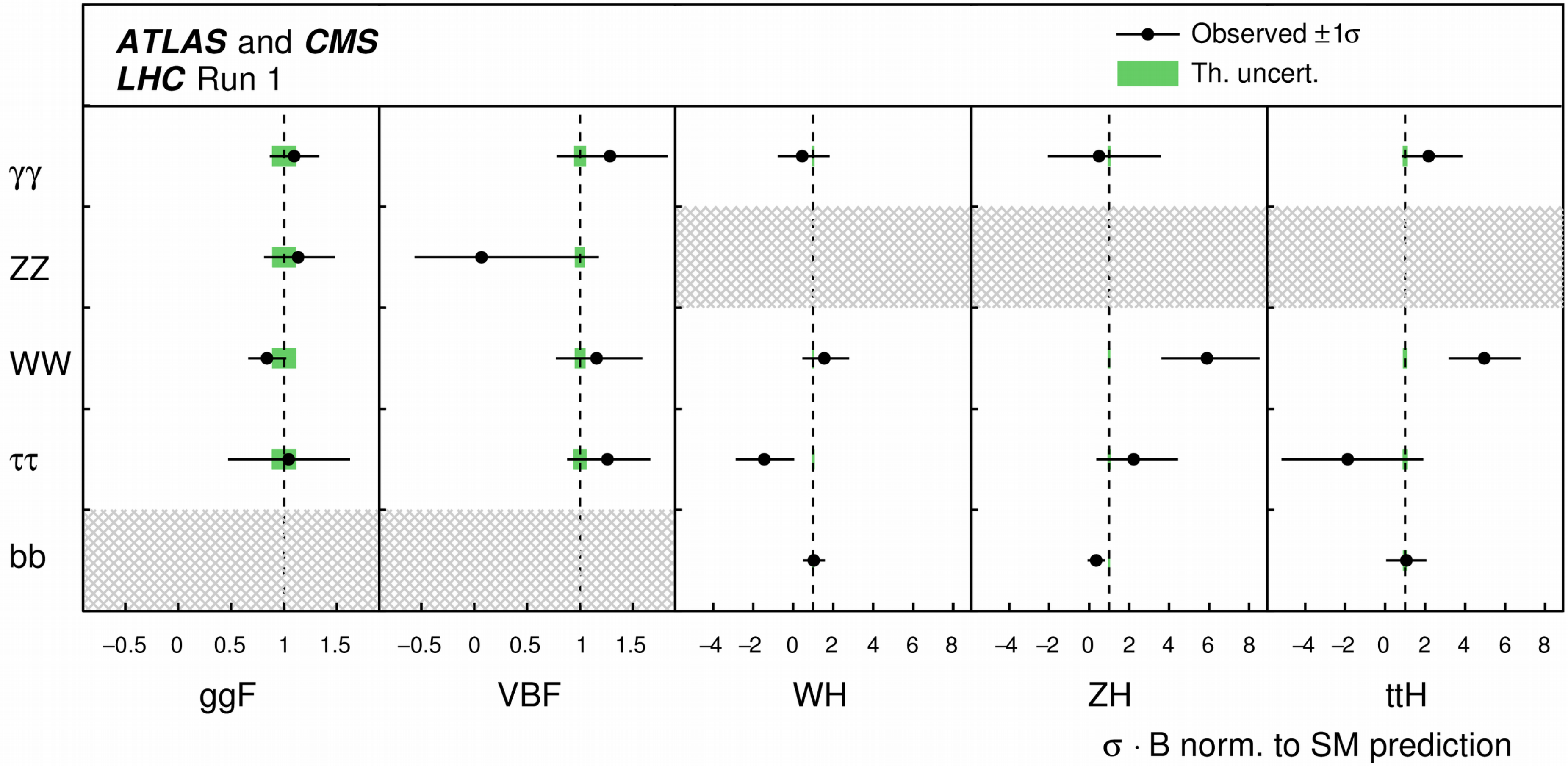
VBF + γ Z : < 2.0 x SM @95% CL



$\mu = -3.9^{+2.8}_{-2.7}$
< 4.0 (6.0 exp)

Alternative "generator mass" methods

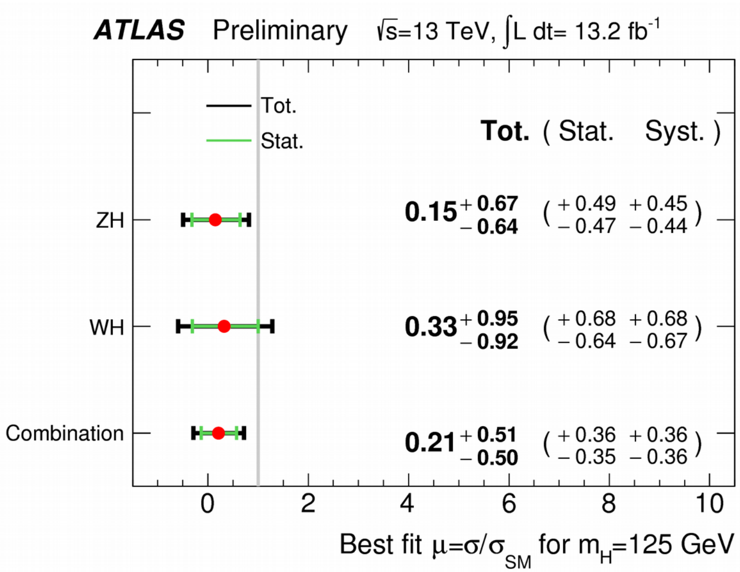




ATLAS and CMS
LHC Run 1
Observed ±1σ
Th. uncert.
γγ
ZZ
WW
ττ
bb
ggF
VBF
WH
ZH
ttH
σ · B norm. to SM prediction

VH, H ⟶ bb

- Most powerful H ⟶ bb search mode (though ttH not far behind)
  - large SM backgrounds from V+jets, VV, $t\bar{t}$
  - search in channels with 0, 1, 2 e/μ
  - aggressive use of BDT & profile likelihood fits to isolate signal & measure background parameters in data

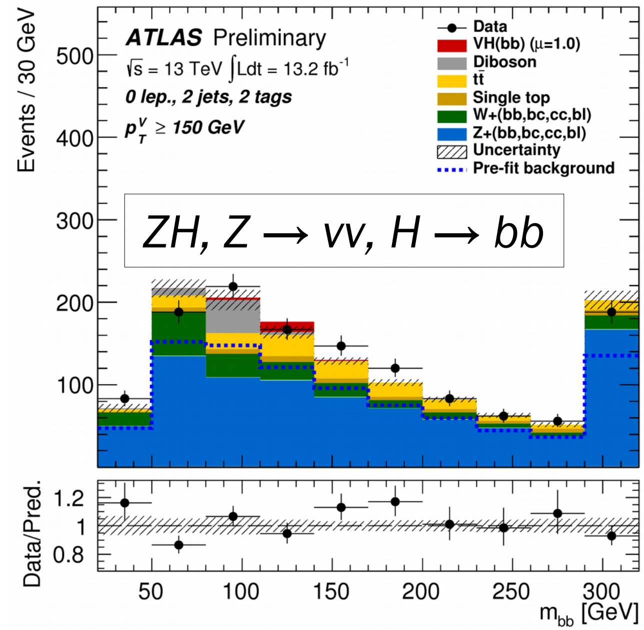


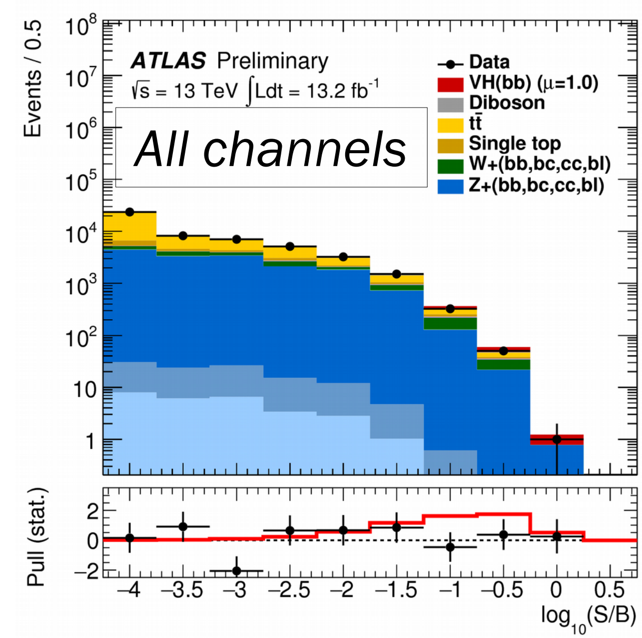
ATLAS-CONF-2016-091

H ⟶ bb significance:
0.42σ (1.94σ exp)

3.0σ (3.2σ exp)
evidence for *(W/Z)Z, Z ⟶ bb*

$$\mu_{\text{diboson}} = 0.91 \pm 0.17\ (\text{stat})^{+0.32}_{-0.27}\ (\text{syst})$$





	gluon-gluon fusion	vector boson fusion	VH	$t\bar{t}H$
$H \rightarrow \gamma\gamma$	✔	✔	✔	✔
$H \rightarrow ZZ$	✔	✔	✔	✔
$H \rightarrow \tau\tau$	✔	✔	✔	✔
$H \rightarrow WW$	✔	✔	✔	✔
$H \rightarrow bb$		✔	✔	✔
$H \rightarrow \mu\mu$	✔	✔		