



# Standard Model and Electroweak Measurements at ATLAS and CMS

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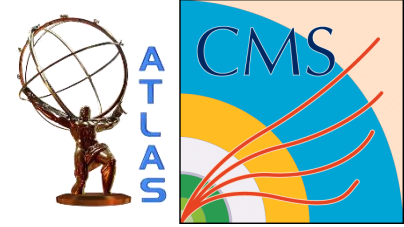
PASCOS 2016

10-16 July 2016

ICISE, Vinh Quy Nhon (Viet Nam)



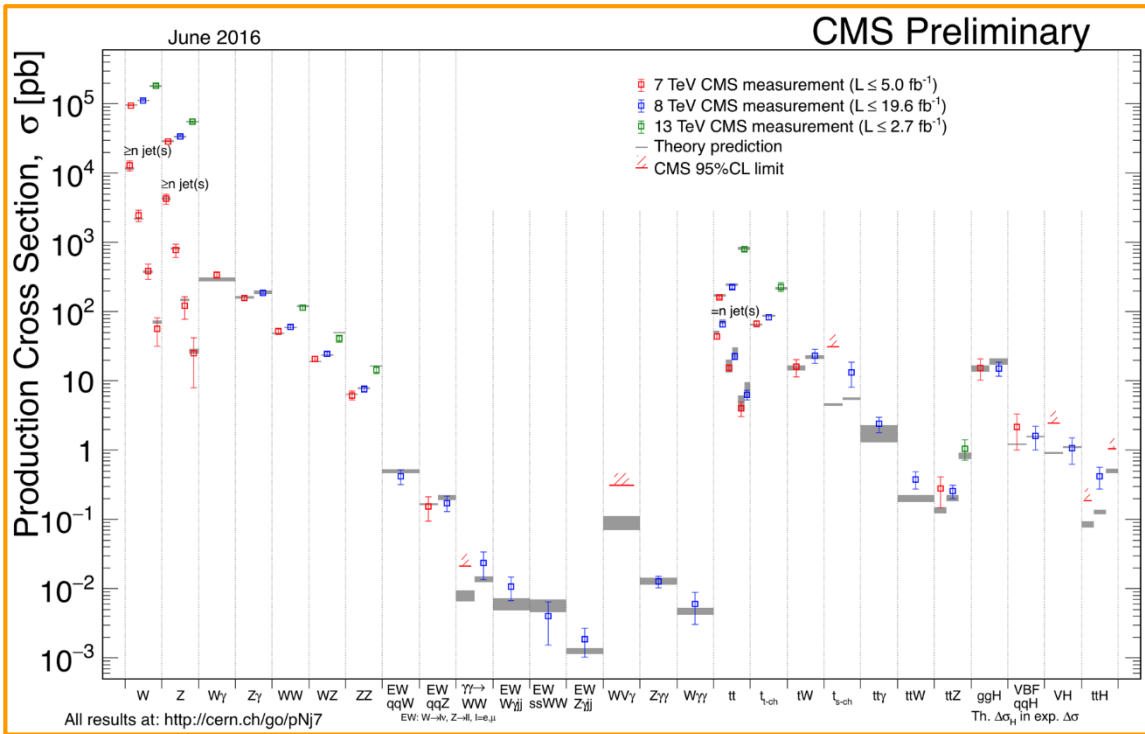
# A Quick Snapshot



- Following the 8TeV run, an extremely successful run at 13TeV
  - LHC reached nominal luminosity, and keeps delivering ( $\sim 2/\text{fb}/\text{week!}$ )
  - Outstanding detector performance allows for exploitation of data sample
- Pushing the frontier of precision measurements
  - Recent work on calculations and generators increased precision in theory predictions
    - The “precision revolution” (G. Salam): explosion of calculations in last 1.5yr
- Still some open questions in SM
  - Higgs: naturalness, no explanation of observed masses and mixing of fermions
  - No Dark Matter in SM

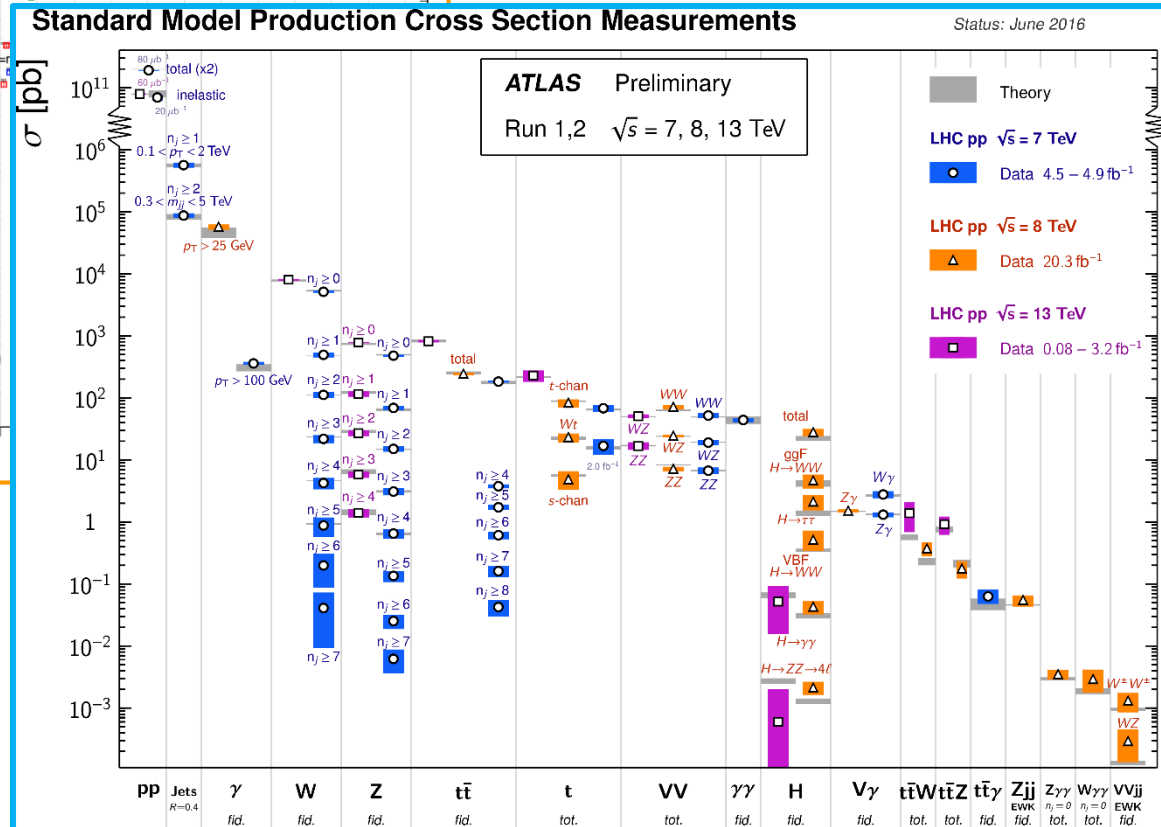
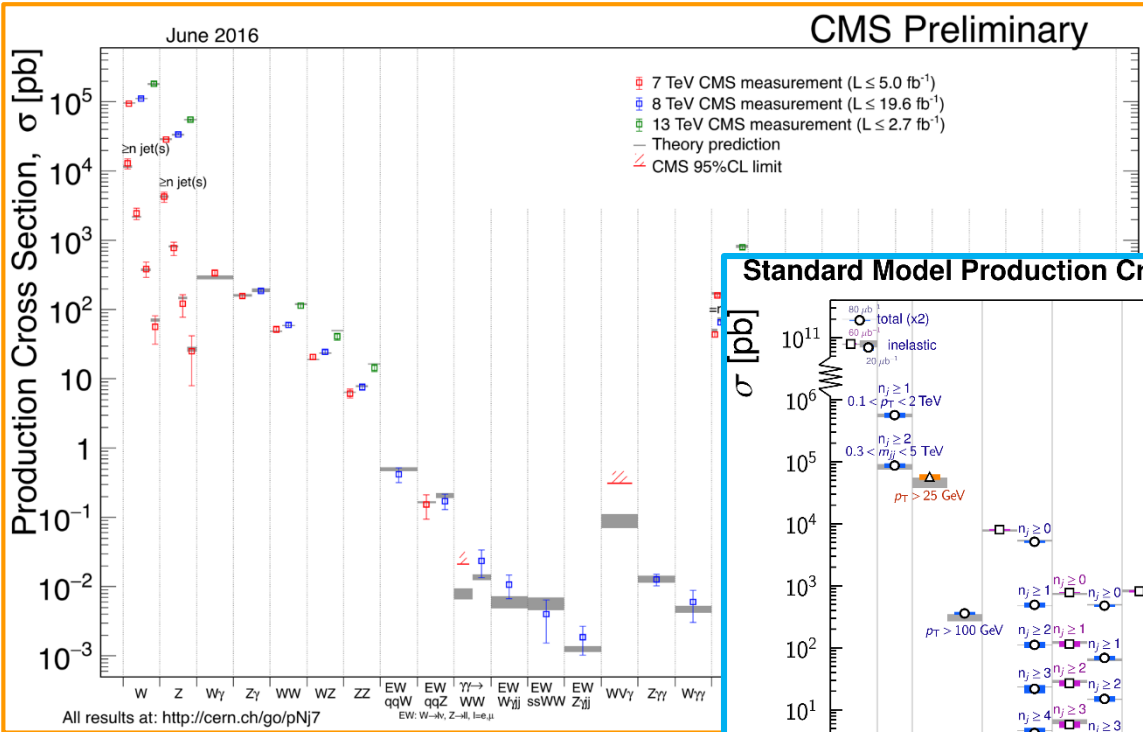
# SM: a Success Story

From inelastic  $pp$  to multi-boson, Higgs, associated boson production, VBF and electroweak production



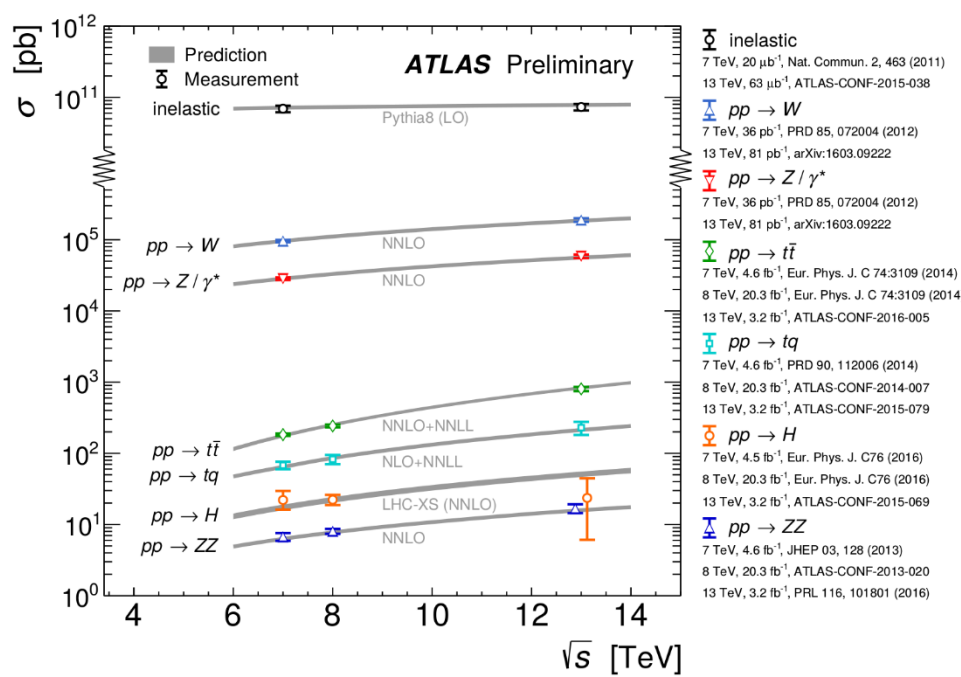
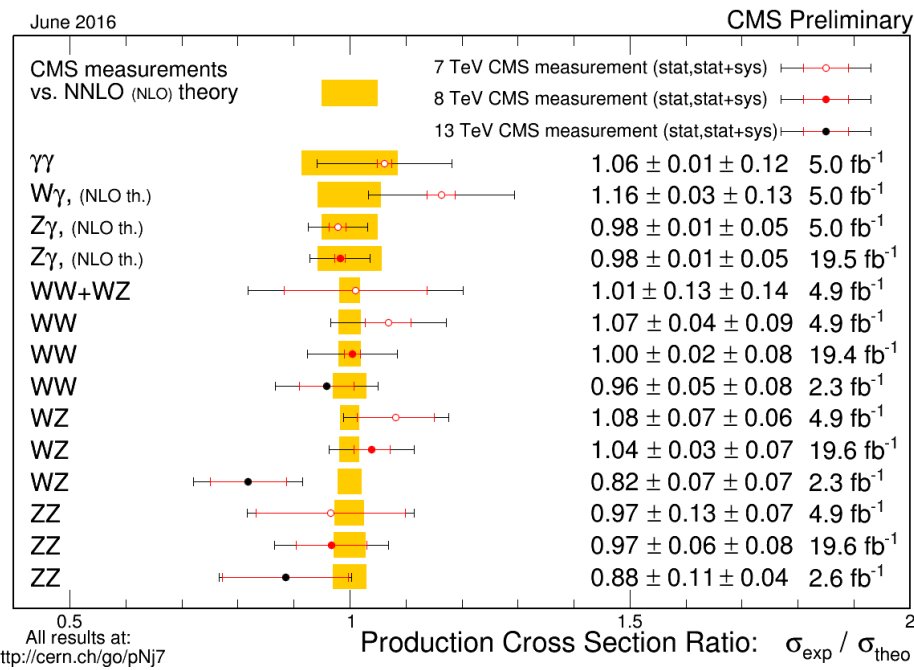
# SM: a Success Story

From inelastic  $pp$  to multi-boson, Higgs, associated boson production, VBF and electroweak production



Cross-section measurements span more than 10 orders of magnitude

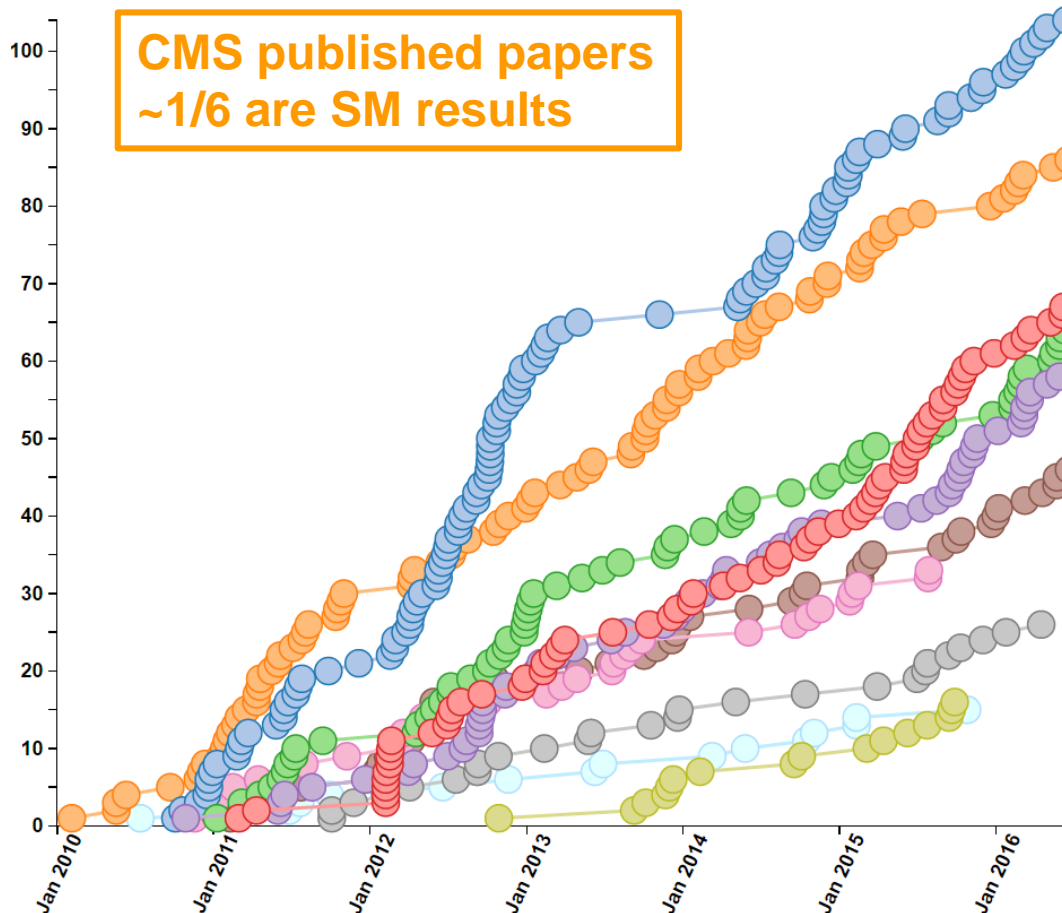
# Comparison with Theory



- So far, no smoking-gun indicating disagreement between SM predictions and experimental measurements
  - Improvement in experimental accuracy and prediction precision makes tests more and more stringent
- Must keep looking in all possible paths
  - Currently, the  $\gamma\gamma$  direction seems interesting...

# An Active Field!

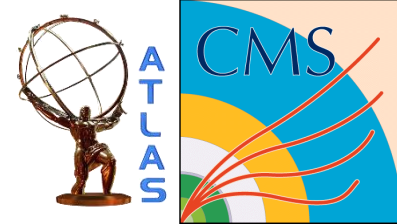
514 collider data papers submitted as of 2016-06-21




# Outline

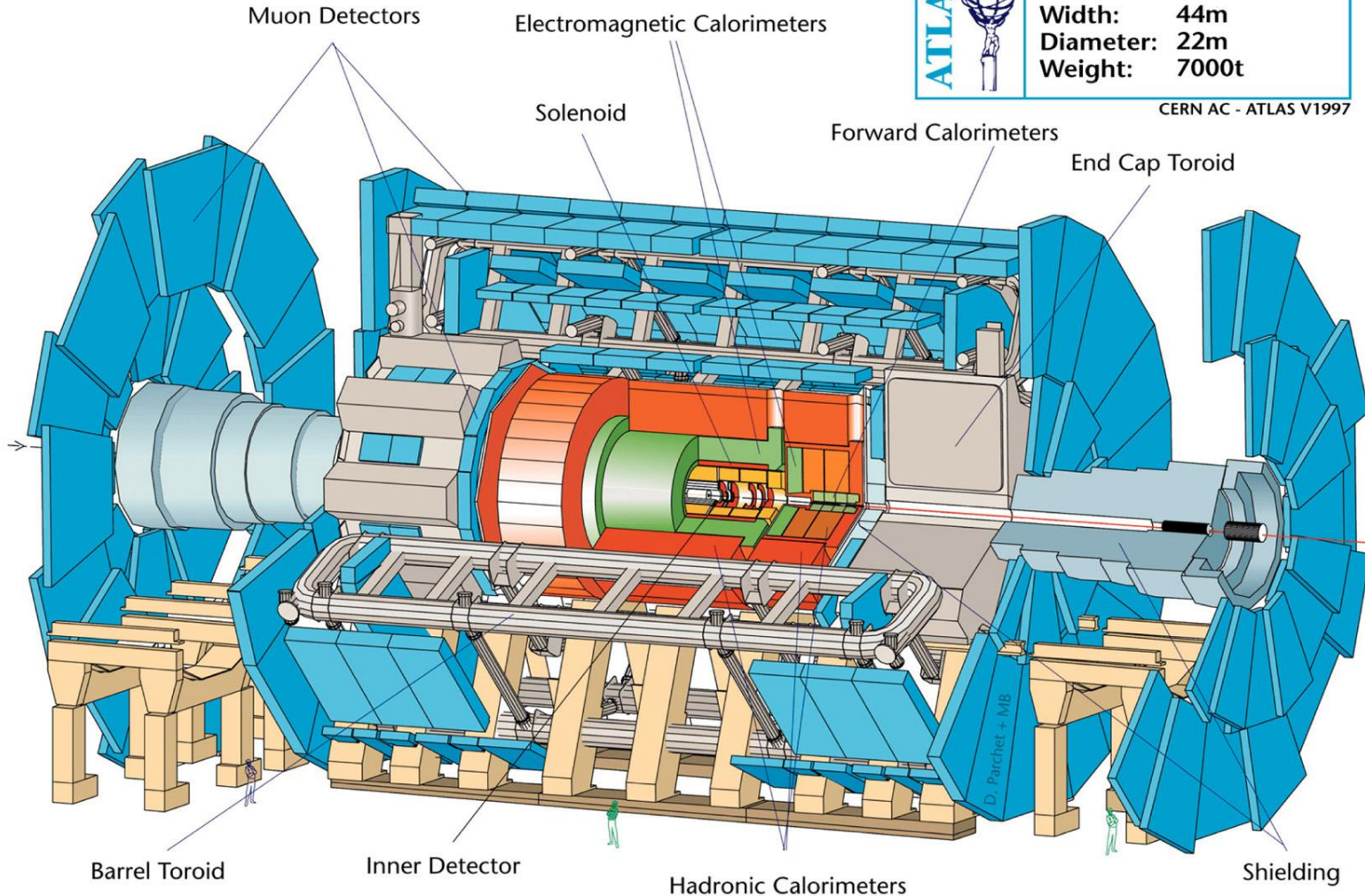
- **Preliminaries**
  - Detectors, data samples
- **QCD Physics**
  - Jets, vector bosons: cross sections, asymmetries, ratios
- **Electroweak Physics**
  - Multi-boson final states: cross sections, limits on anomalous couplings
- **Summary and prospects**

# The ATLAS Detector



	<b>Detector characteristics</b>	
	<b>Width:</b>	<b>44m</b>
	<b>Diameter:</b>	<b>22m</b>
	<b>Weight:</b>	<b>7000t</b>

CERN AC - ATLAS V1997





# The CMS Detector

## CMS DETECTOR

Total weight : 14,000 tonnes  
 Overall diameter : 15.0 m  
 Overall length : 28.7 m  
 Magnetic field : 3.8 T

STEEL RETURN YOKE  
 12,500 tonnes

SILICON TRACKERS  
 Pixel ( $100 \times 150 \mu\text{m}$ )  $\sim 16\text{m}^2 \sim 66\text{M}$  channels  
 Microstrips ( $80 \times 180 \mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
 Niobium titanium coil carrying  $\sim 18,000\text{A}$

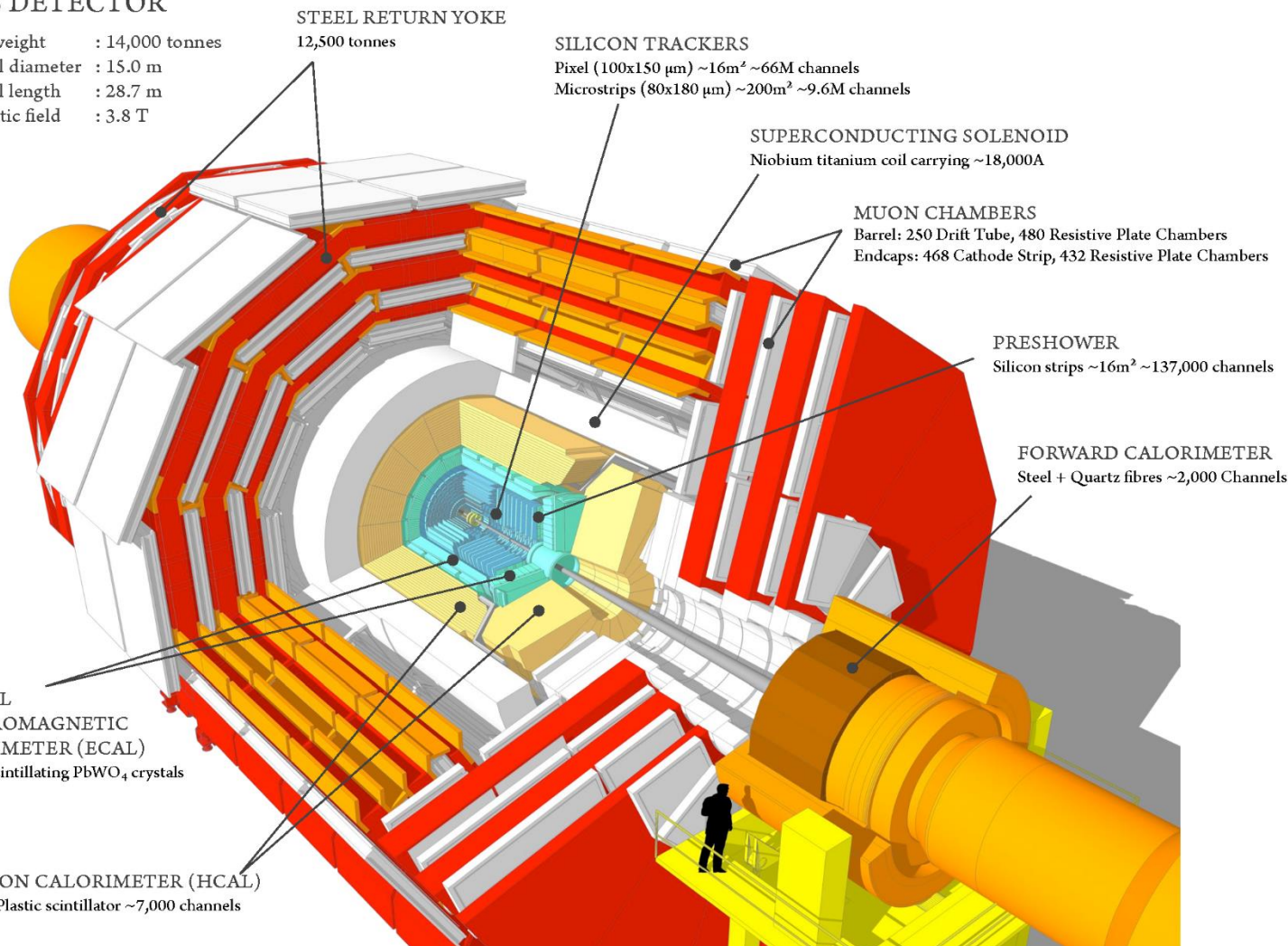
MUON CHAMBERS  
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
 Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER  
 Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER  
 Steel + Quartz fibres  $\sim 2,000$  Channels

CRYSTAL  
 ELECTROMAGNETIC  
 CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

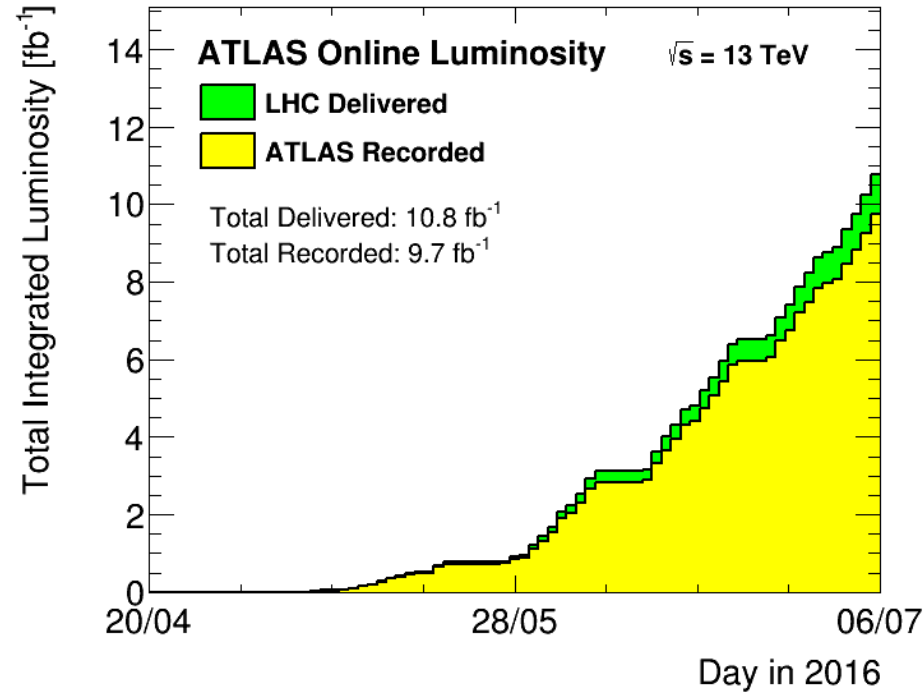
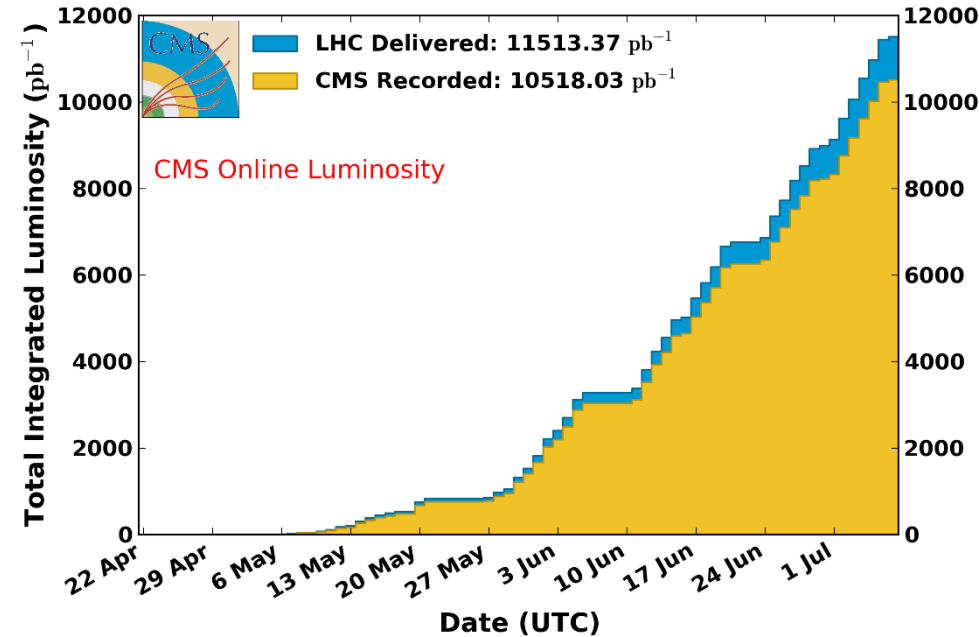
HADRON CALORIMETER (HCAL)  
 Brass + Plastic scintillator  $\sim 7,000$  channels



# 2016 Collisions

**CMS Integrated Luminosity, pp, 2016,  $\sqrt{s} = 13$  TeV**

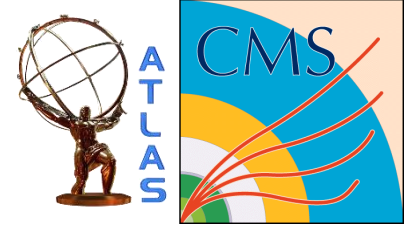
Data included from 2016-04-22 22:48 to 2016-07-07 04:17 UTC



- About 20/fb collected at 8TeV in 2012
  - Completing analysis of data sample, some new result presented today
- Collected about 4/fb at 13TeV in 2015
- Record instantaneous luminosity reached design in 2016:  $10^{34}/\text{cm}^2/\text{s}$ 
  - Congratulations to the beam division for reaching this milestone



# QCD Status



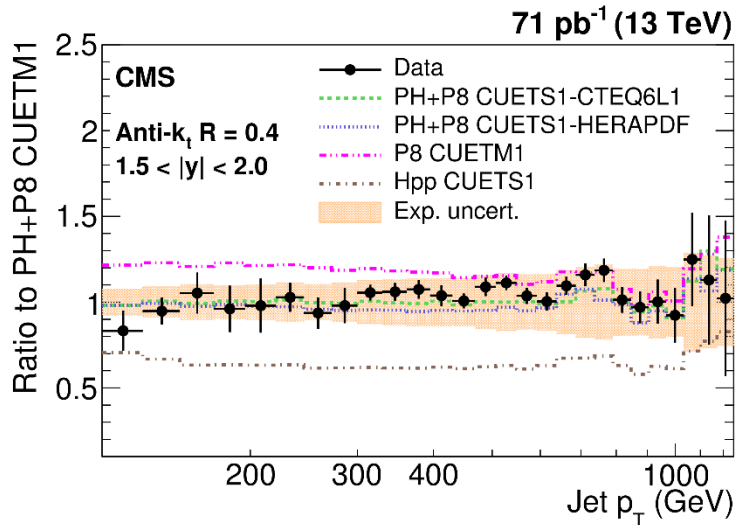
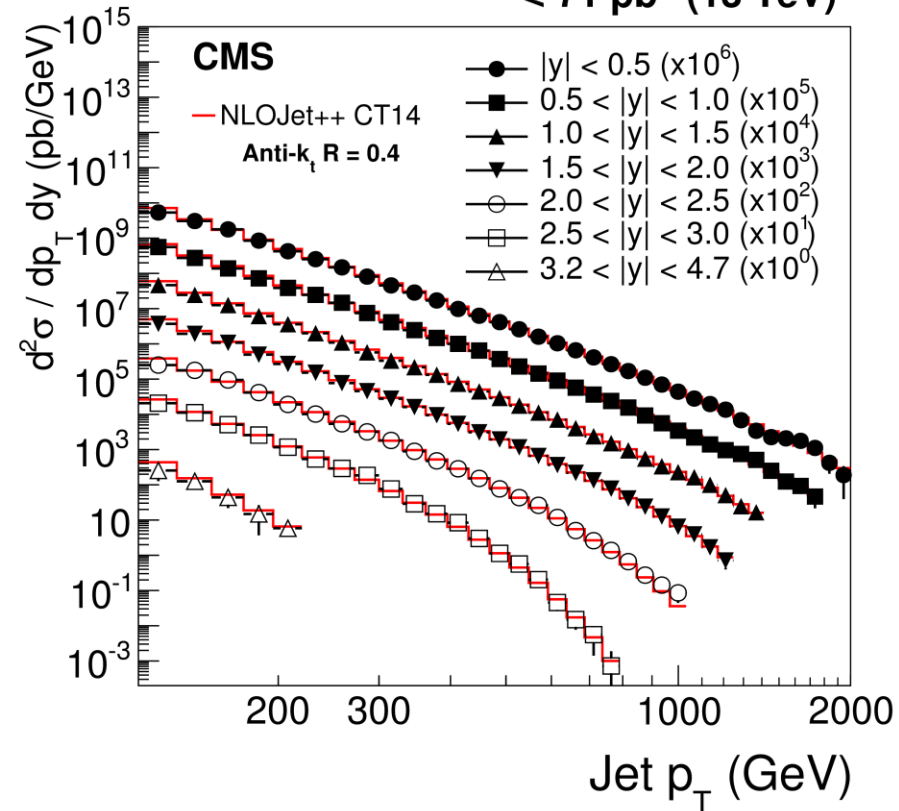
- Important updates in calculations
  - First N3LO calculations are promising; on-going work on inclusion of EWK corrections to QCD ones
- New precision measurements at 8TeV and first ones at 13TeV
  - CMS double-differential jet cross sections, ATLAS isolated photon
  - ATLAS inelastic  $pp$  cross section (backup)
  - $W$  and  $Z$  measurements: differential cross sections, associated production
- Challenging continuously improving MC predictions
  - Measurements are sensitive to NNLO, NNLL, and EWK corrections

# 13TeV QCD: Jets

- Double-differential production cross section
  - Transverse momentum up to 2TeV; rapidity up to 4.7
  - Anti- $k_T$  jets, radius: 0.4 and 0.7
- NLO predictions matched to parton showers describe data properly
  - Best match: Powheg + Pythia-8
- First indication that 13TeV jet physics is well understood

[arXiv:1605.04436](https://arxiv.org/abs/1605.04436)

$< 71 \text{ pb}^{-1} (13 \text{ TeV})$

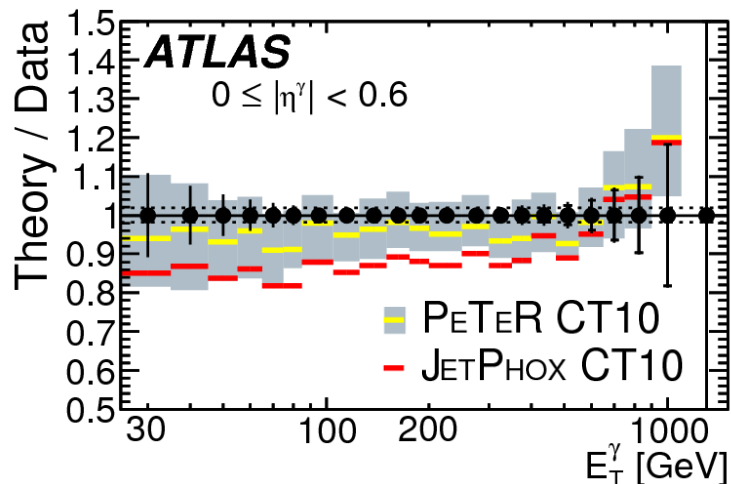
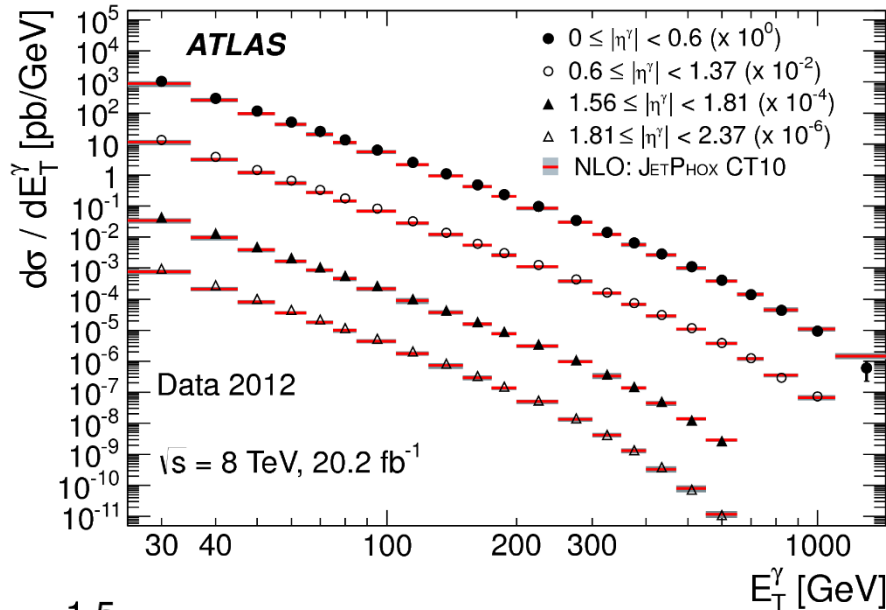


[ATLAS:  \$|y| < 0.5\$ ; comparison with NLOJet++ w/ NP and EWK corrections](#)

[ATLAS-CONF-2015-034](#)

# 8TeV QCD: $\gamma$

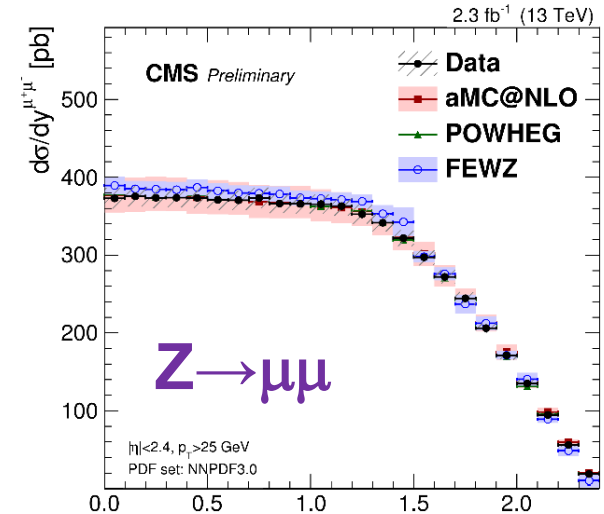
[arXiv:1605.03495](https://arxiv.org/abs/1605.03495)



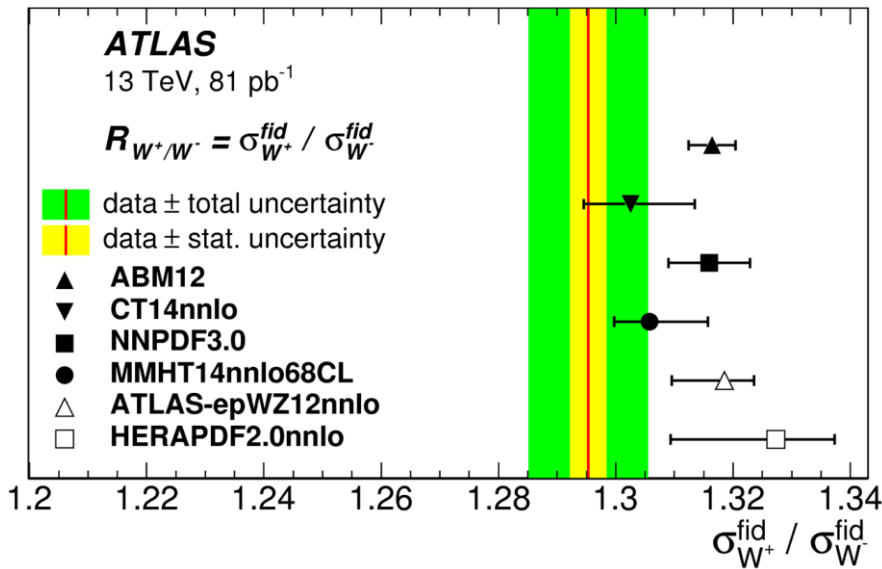
- Inclusive photon analysis
  - Fiducial cross section, bin-by-bin unfolded
  - Small experimental uncertainties
- Comparison with multiple MC samples
  - Best match: PeTer, NLO+N3LL
  - Sherpa, Pythia work in limited phase space; JetPhox shape ok, normalization off
- Preliminary results at 13TeV
  - [ATL-PHYS-PUB-2015-016](#)

# Vector Boson Highlights

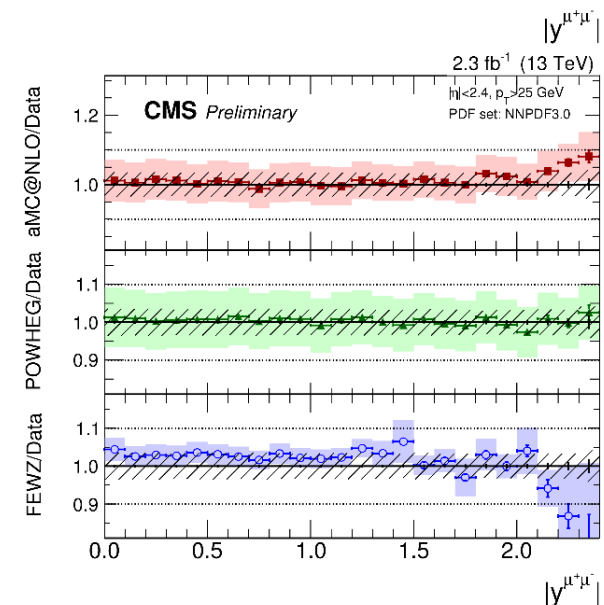
- W and Z cross sections and ratios at 13TeV
  - Sub-percent precision
- Updated differential cross-section measurements
  - $Z \rightarrow \mu\mu$  vs.  $p_T^Z, y^Z, \phi^*, p_T^\mu$
- General good agreement with NNLO predictions



arXiv:1603.09222



CMS-PAS-SMP-15-011

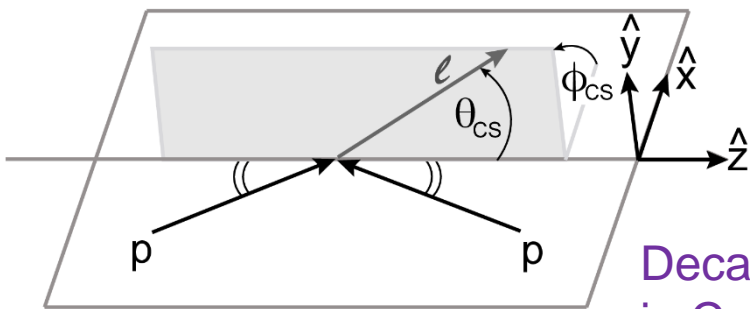
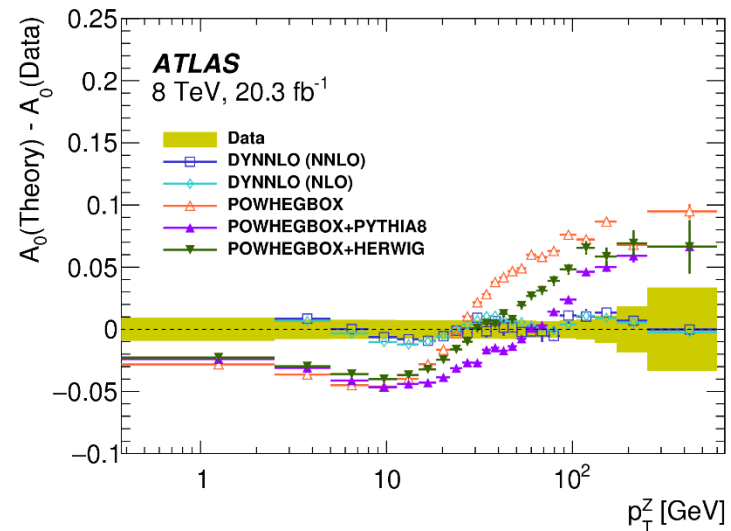
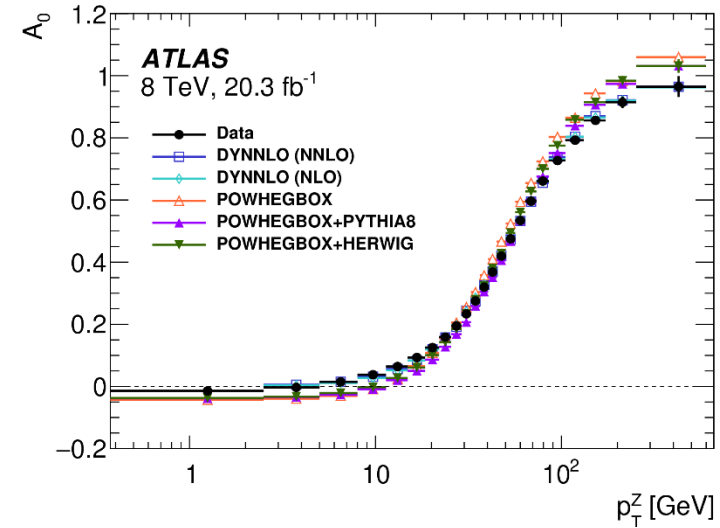


# Z Angular Coefficients

[arXiv:1606.00689](https://arxiv.org/abs/1606.00689)



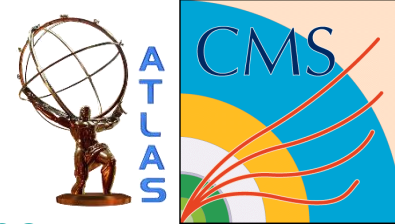
- Angular distributions of charged lepton pairs produced via Drell-Yan allow for precise measurement of production dynamics
  - Spin-correlation effects described by nine coefficients in helicity density matrix
- Inclusive measurement of angular coefficients is performed, as a function of  $p_T^Z$  and in bins of  $y^Z$ 
  - Stringent test of perturbative QCD predictions for Z-boson production provided by high granularity and precision of measurement



Decay angles defined in Collins-Soper frame



# Drell-Yan $\sigma$ vs. $\phi^*$ – 8TeV

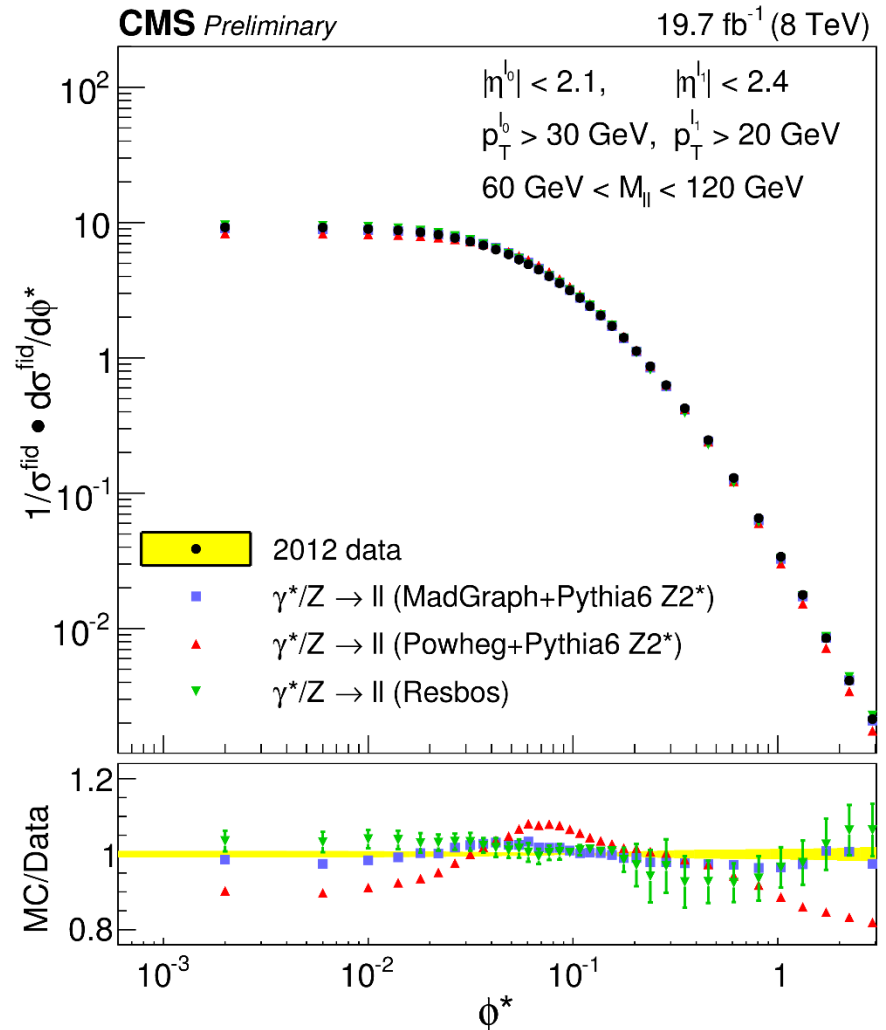


CMS-PAS-SMP-15-002

- Kinematic variable  $\phi^*$  correlated with di-lepton  $p_T$ , but smaller uncertainties
  - Based on measurement of angles
- Normalized cross sections precise at 1-2% level
  - Stringent constraint on theoretical predictions
- Comparison with various MC generators
  - MadGraph seems to show best agreement

$$\phi^* = \tan\left(\frac{\phi_{\text{acop}}}{2}\right) \sin(\theta_{\eta}^*)$$

ATLAS: [Eur. Phys. J. C 76\(5\), 1-61 \(2016\)](#)







# EW Physics Overview

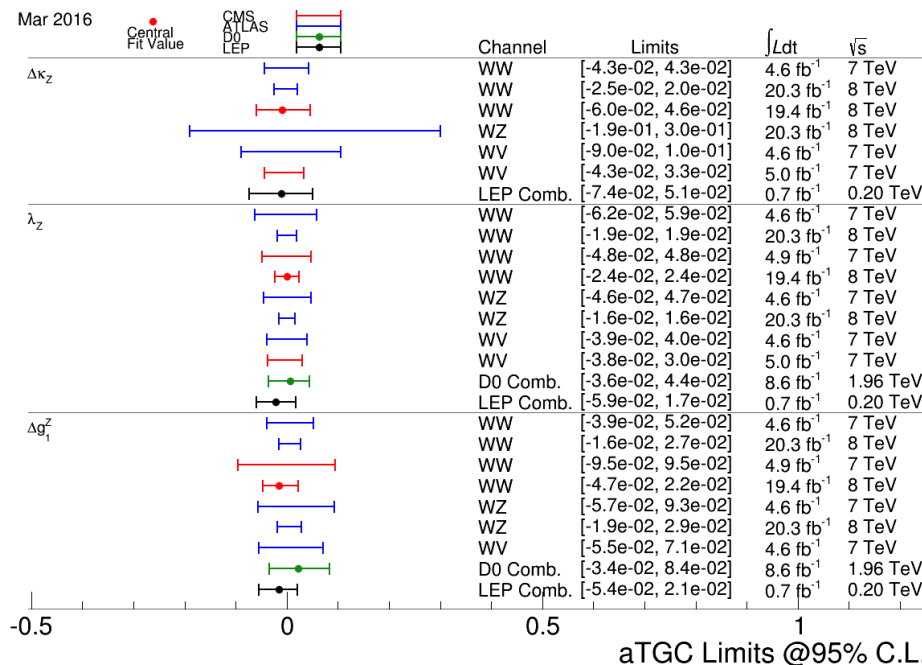
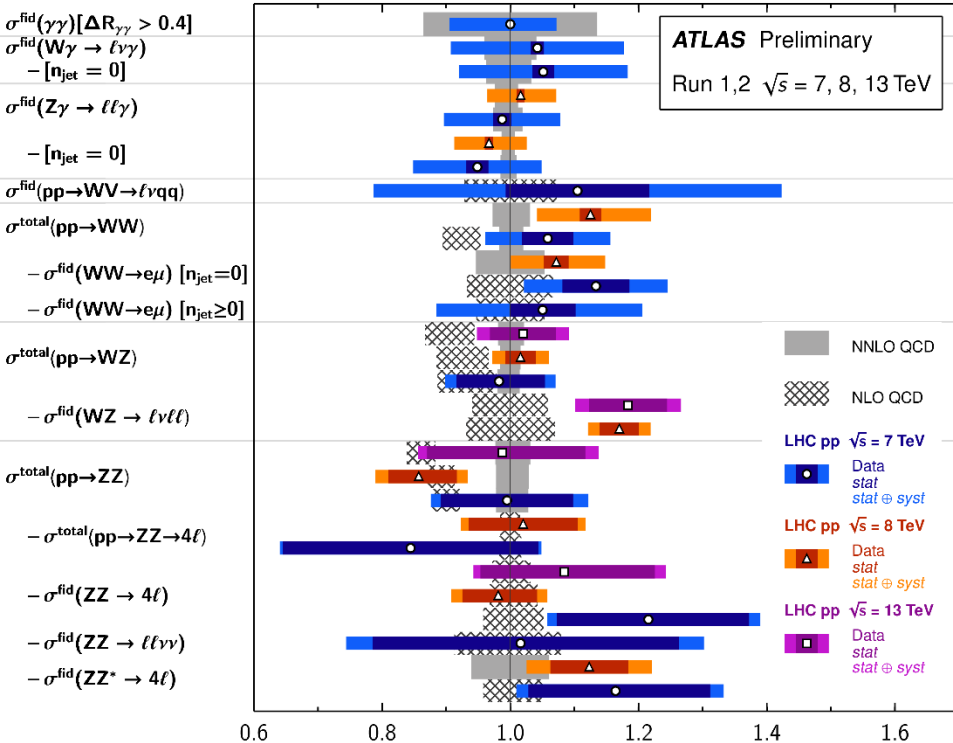


- Improvements in di-boson calculations
  - Practically all channels available at NNLO QCD and NLO EWK
- Some really hard measurements under consideration
  - $\sin^2\theta_{\text{eff}}$ : much harder at LHC due to lack of valence anti-quark; dominated by PDF uncertainty
  - $W$  mass: world average uncertainty 15MeV, should aim for 5MeV; difficult measurements at LHC: pile-up effect on recoil, vector-boson  $p_T$  modeling; PDF effects
- Good news: huge number of measurements
  - Limits on anomalies in electroweak couplings now similar or better than LEP
  - Observation of VBF (electroweak production of single  $W$  and  $Z$ ) and evidence for VBS (same-sign  $WW$ ,  $Z\gamma$ )
  - Observation and evidence of tri-boson final states, e.g.  $Z\gamma\gamma$  and  $W\gamma\gamma$

# Di-Boson Summary

## Diboson Cross Section Measurements

Status: June 2016



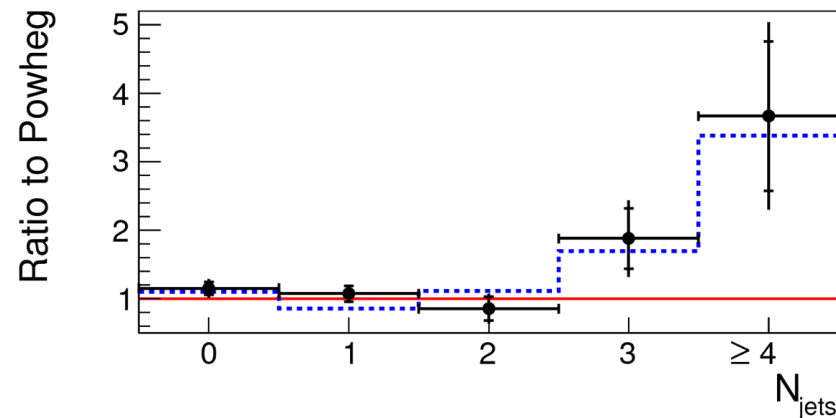
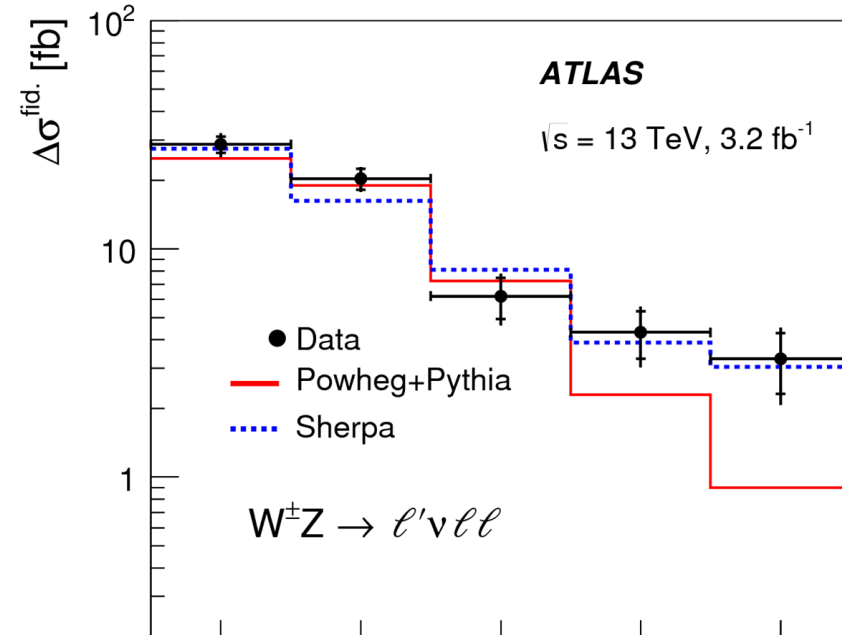
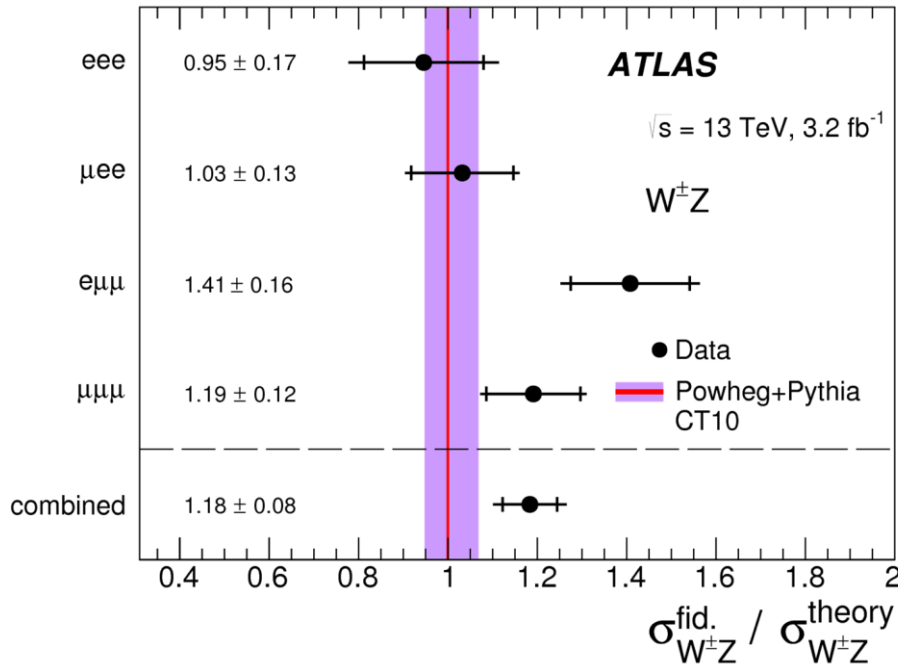
slide 5 for CMS measurements

ratio to best theory

- General good agreement between data and NLO/NNLO predictions
- Limits on anomalous TGC reached LEP sensitivity
  - Big help from increase of center-of-mass energy

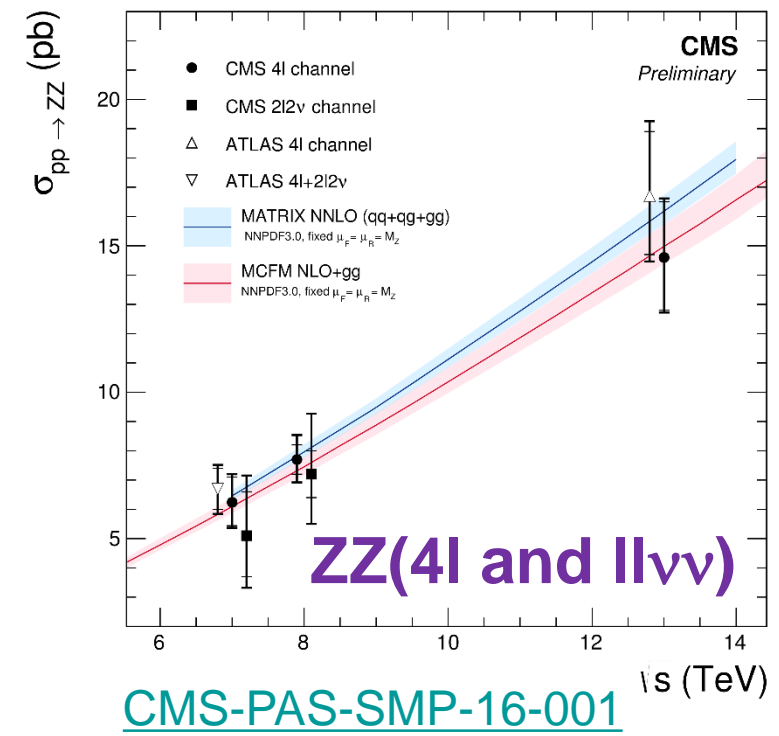
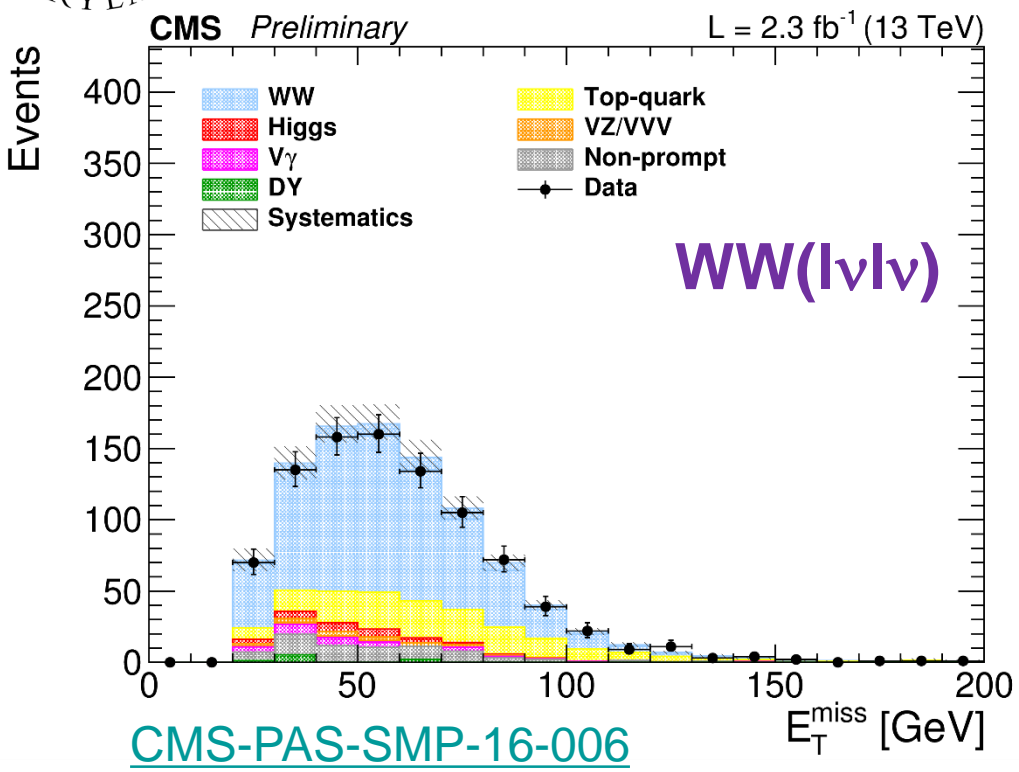
# Di-Boson Highlights: WZ

[arXiv:1606.04017](https://arxiv.org/abs/1606.04017)



- Important test of SM EW sector
  - Measured fiducial and total cross sections
  - Test of QCD too: differential cross section vs. number of jets
- Slight excess over NLO prediction
  - ...but agreement with NNLO: sensitive enough to see difference

# More Highlights: WW/ZZ



- Interesting channels for a wide set of reasons
  - Test of EW sector of SM (TGC); test of QCD via  $gg$  production; backgrounds to Higgs measurements
- Excess in  $\gamma\gamma$  final state casts a new light
  - Important to see how new particle would couple to massive vector bosons

# Electroweak Production

- **Vector-Boson Fusion**
  - Observed EW production of  $W$  and  $Z$  bosons, background-only hypothesis rejected at  $>5\sigma$
- **Vector-Boson Scattering**
  - Observed same-sign  $WW$  production, limits on  $WZ$
  - Observed EW production of  $W\gamma$  and  $Z\gamma$
- **Exclusive production**
  - Measured  $\gamma\gamma \rightarrow WW$  cross section, and QGC limits

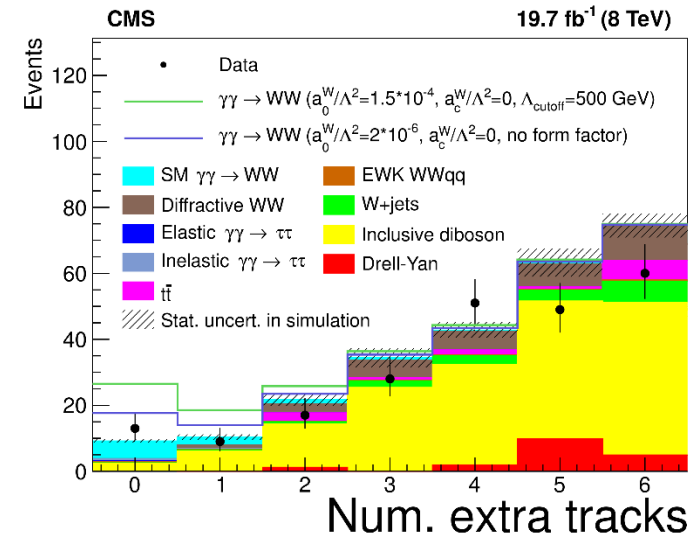
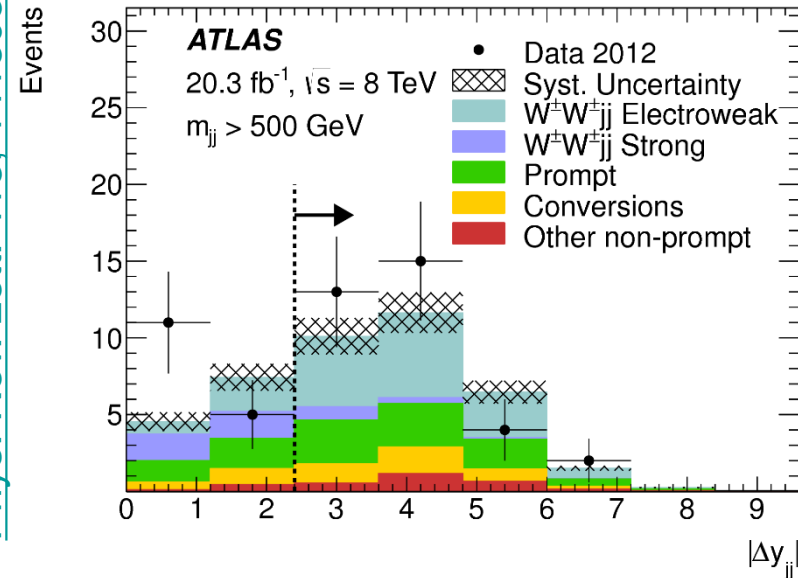
Current results use 8TeV samples  
Ready to update with 13TeV data

EWK  $W^\pm W^\pm$

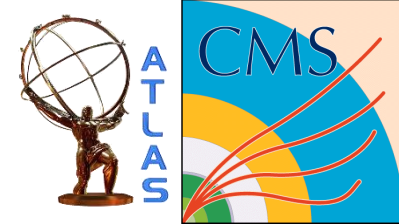
$\gamma\gamma \rightarrow WW$

Phys. Rev. Lett. 113, 141803

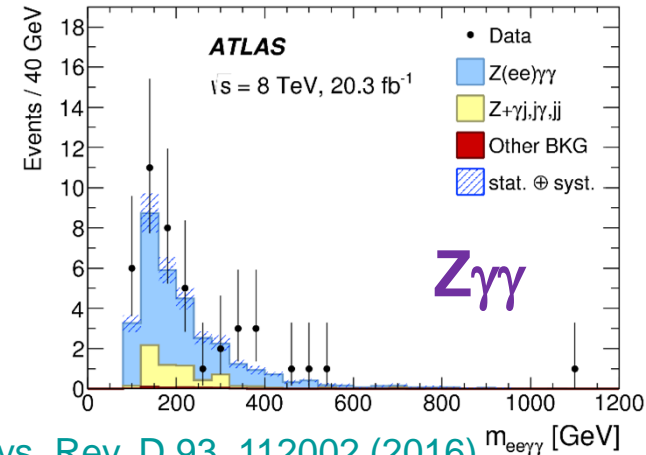
arXiv:1604.04464



# Tri-Boson Production

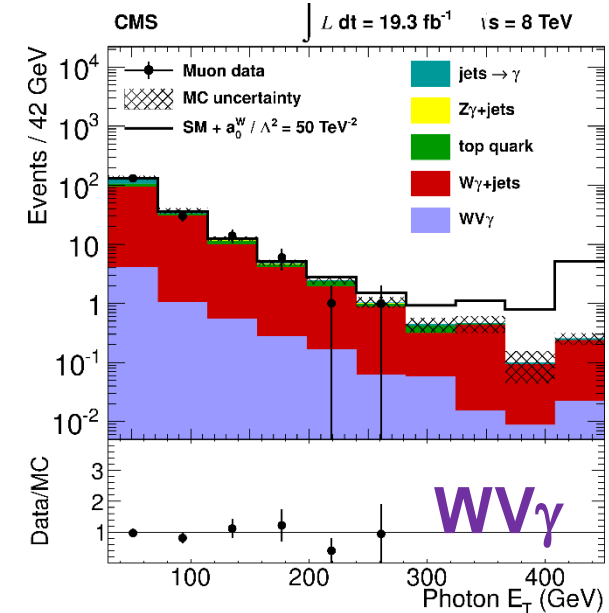
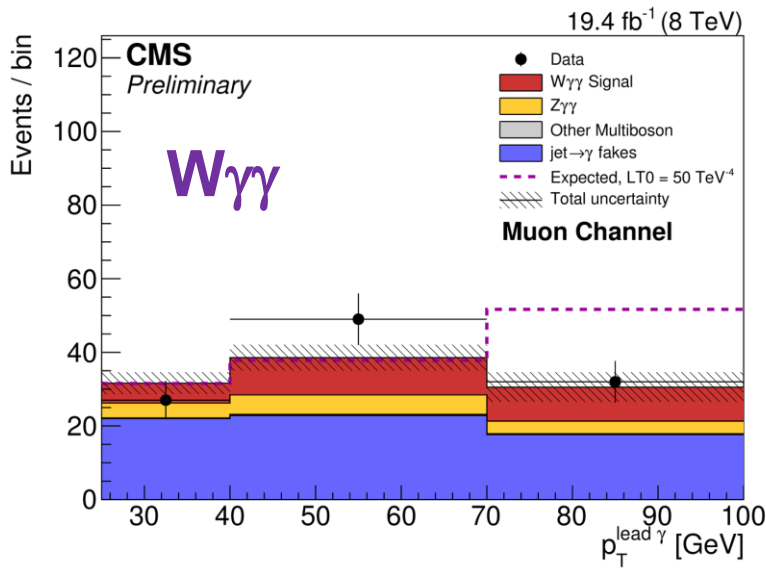


- Observed production of  $W\gamma\gamma$  and  $Z\gamma\gamma$  final states, limits on  $WV\gamma$  cross section
  - Final states include contribution from final and initial state radiation
- Natural channels to use to set limits on anomalous QGC
  - Framework: dimension-8 EFT operators
  - Anom. QGC have stronger effect at high  $Q^2$



[Phys. Rev. D 93, 112002 \(2016\)](#)  $m_{ee\gamma\gamma} [\text{GeV}]$

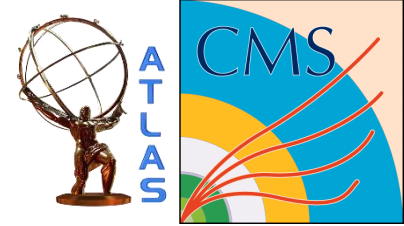
CMS-PAS-SMP-15-008



[Phys. Rev. D 90 \(2014\) 032008](#)



# Conclusion / Remarks



- The LHC reached design luminosity, Run-2 is up to speed
  - Potential to reach 2/fb/week; already delivered about 10/fb
- By the end of 2018 expect  $O(100/\text{fb})$ , increase statistical power by nearly a factor of 10
  - Similar increase will not be seen until early 2030
- Extraordinary progress in precision of both theoretical predictions and experimental measurements
  - Expect new round of stringent tests on the precision frontier by the end of Run-2: N3LO calculations of vector-boson production, exact QCD-EW corrections, NNLO+PS di-boson production



# Extra Material





# Bibliography & Recent Results



- **Hard and soft QCD**

- [Measurement of the inclusive isolated prompt photon cross section in pp collisions at  \$\sqrt{s}=8\$  TeV with the ATLAS detector](#)
- [Measurement of the double-differential inclusive jet cross section in proton-proton collisions at  \$\sqrt{s}=13\$  TeV - CMS](#)
- [Measurement of the inclusive-jet cross section in proton-proton collisions at 13 TeV centre-of-mass energy with the ATLAS detector](#)
- [Measurement of the angular coefficients in Z-boson events using electron and muon pairs from data taken at  \$\sqrt{s}=8\$  TeV with the ATLAS detector](#)
- [Measurements of  \$\phi^\*\$  differential cross sections for Drell-Yan events in pp collisions at  \$\sqrt{s}=8\$  TeV - CMS](#)
- [Measurement of  \$W^\pm\$  and Z-boson production cross sections in pp collisions at  \$\sqrt{s}=13\$  TeV with the ATLAS detector](#)
- [Measurement of the transverse momentum spectra of weak vector bosons produced in proton-proton collisions at  \$\sqrt{s}=8\$  TeV – CMS](#)
- [Measurements of inclusive and differential Z boson production cross sections in pp collisions at  \$\sqrt{s}=13\$  TeV - CMS](#)
- [Measurement of the double-differential high-mass Drell-Yan cross section in pp collisions at  \$\sqrt{s}=8\$  TeV with the ATLAS detector](#)
- [Measurement of the differential cross section of Z boson production in association with jets in proton-proton collisions at  \$\sqrt{s}=13\$  TeV – CMS](#)
- [Measurement of the Production Cross Sections of a Z boson Boson in Association with Jets in collisions at  \$\sqrt{s}=13\$  TeV with the ATLAS Detector](#)
- [Measurement of the Inelastic Proton-Proton Cross Section at  \$\sqrt{s}=13\$  TeV with the ATLAS Detector at the LHC](#)

- Electroweak Physics

- Evidence of electroweak production of  $WWjj$  in pp collisions at  $\sqrt{s}=8$  TeV with the ATLAS detector
- Evidence for exclusive  $\gamma\gamma\rightarrow W^+W^-$  production and constraints on anomalous quartic gauge couplings in pp collisions at  $\sqrt{s}=7$  and  $\sqrt{s}=8$  TeV - CMS
- Measurement of the WZ boson pair-production cross section in pp collisions at  $\sqrt{s}=13$  TeV with the ATLAS Detector
- Measurement of the  $W^+W^-$  cross section in pp collisions at  $\sqrt{s}=13$  TeV – CMS
- Measurement of the ZZ production cross section and  $Z\rightarrow\ell\ell'\ell'$  branching fraction in pp collisions at  $\sqrt{s}=13$  TeV - CMS
- Measurements of  $Z\gamma$  and  $Z\gamma\gamma$  production in pp collisions at  $\sqrt{s}=8$  TeV with the ATLAS detector
- Measurements of the  $pp\rightarrow W^\pm\gamma\gamma$  and  $pp\rightarrow Z\gamma\gamma$  cross sections and limits on dimension-8 effective anomalous gauge couplings at  $\sqrt{s}=8$  TeV – CMS
- A search for electroweak-induced production of  $W\gamma$  with two jets and constraints on anomalous quartic gauge couplings in pp collisions at  $\sqrt{s}=8$  TeV - CMS

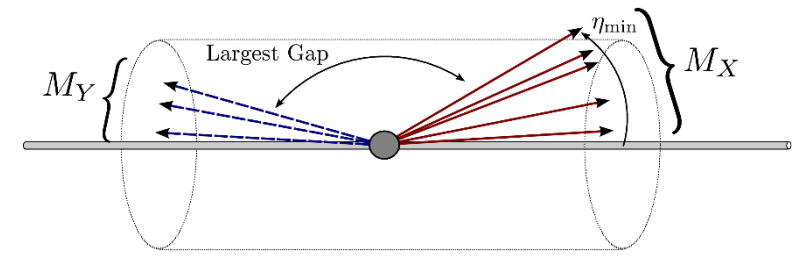
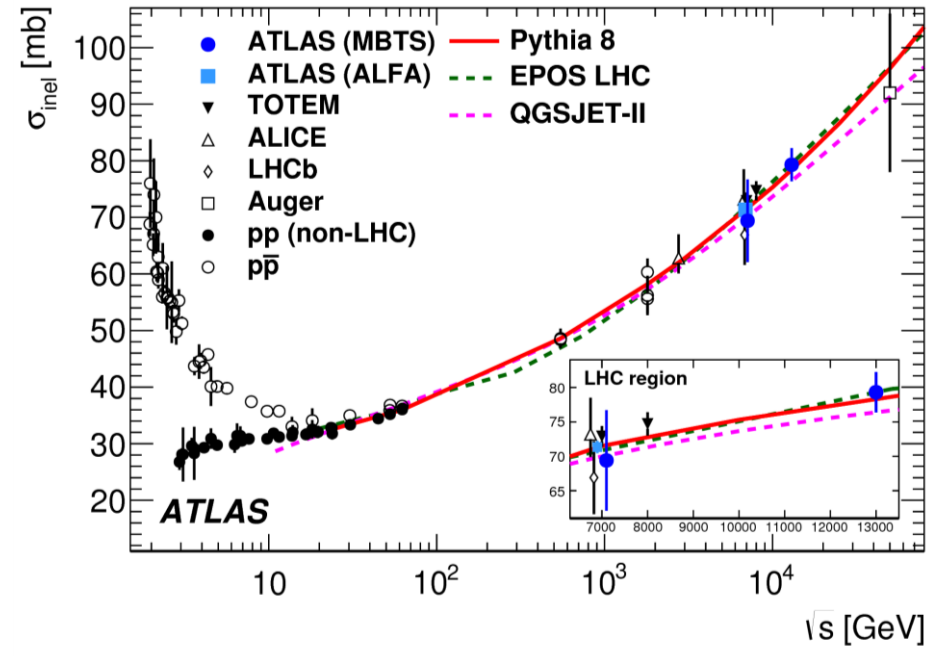


# pp Inelastic Cross Section



[arXiv:1606.02625](https://arxiv.org/abs/1606.02625)

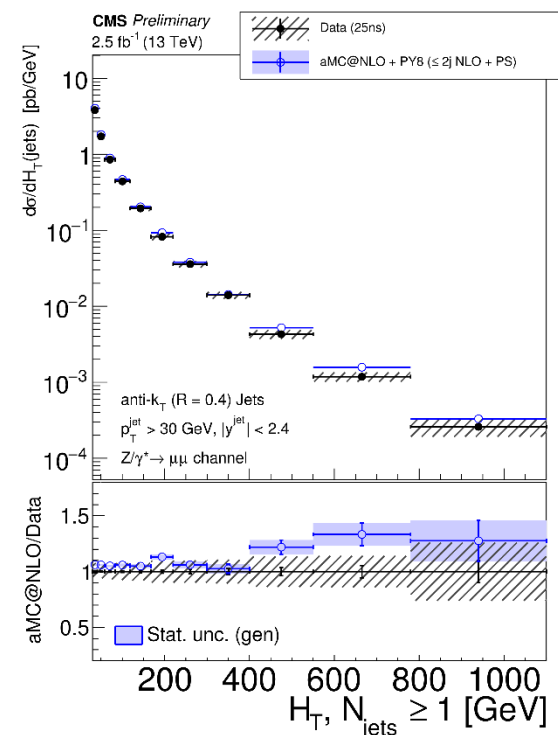
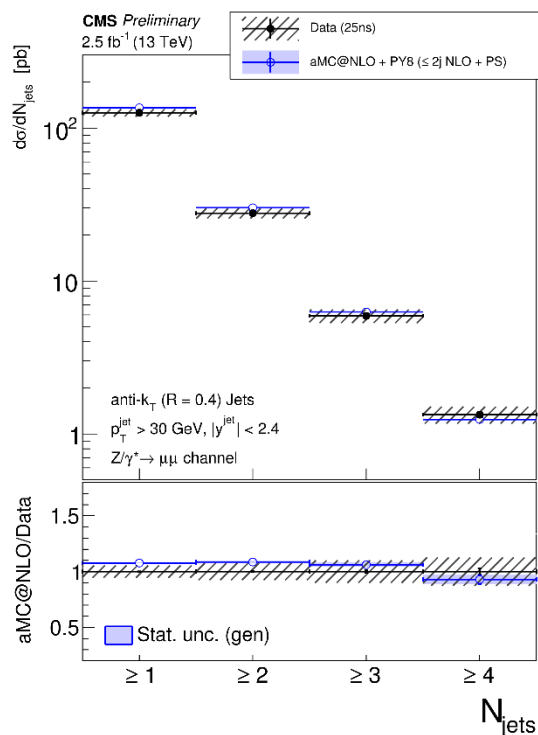
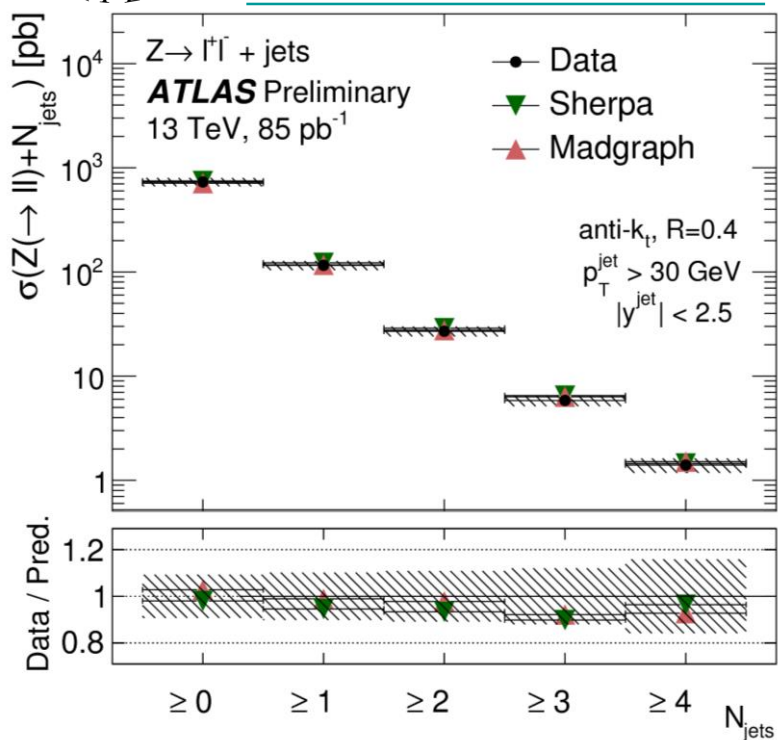
- Measurement probes non-perturbative QCD
  - Predicted to grow with center-of-mass energy, not faster than  $\ln^2(s)$
- Fiducial region identified by mass of dissociated proton
  - Measurement extrapolated to total inelastic cross section
- Results compared to several MC generators
  - Best agreement with Pythia-8 and EPOS LHC



# Z+jets @ 13TeV

ATLAS-CONF-2015-041

CMS-PAS-SMP-15-010



- V+jets measurements important testing tools
  - Perturbative and non-perturbative QCD; constraint to PDF
  - Backgrounds to search analyses

- Impressive amount of results already with 13TeV samples
  - General agreement with NLO predictions
  - Precision enough to test NNLO corrections