ELECTROWEAK PRECISION PHYSICS AT THE LHC

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For the CMS and ATLAS Collaborations

Outline

- Introduction
- W, Z bosons: Production & Properties
  - Cross Sections
  - W Mass, W Charge Asymmetry
  - Z and Drell-Yan
    - Differential Cross sections
    - Kinematics
  - Weak Mixing Angle
- Multi-boson production and Gauge Couplings
- Vector Boson Scattering: First evidence
- Summary

Introduction

- The Standard Model has been a phenomenal success, especially now that a SM-like Higgs boson has been found.

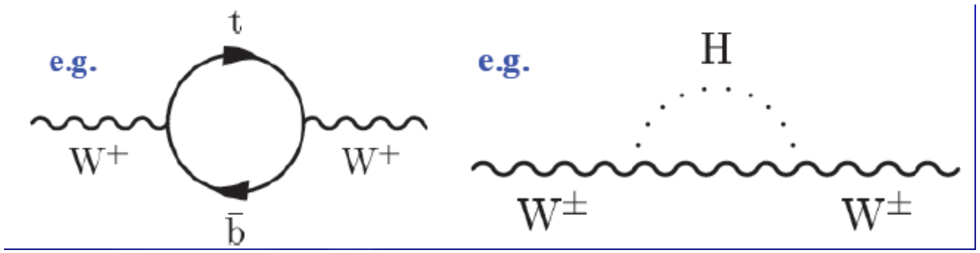
- However, it is most likely that the SM is a low energy approximation to a more fundamental theory.

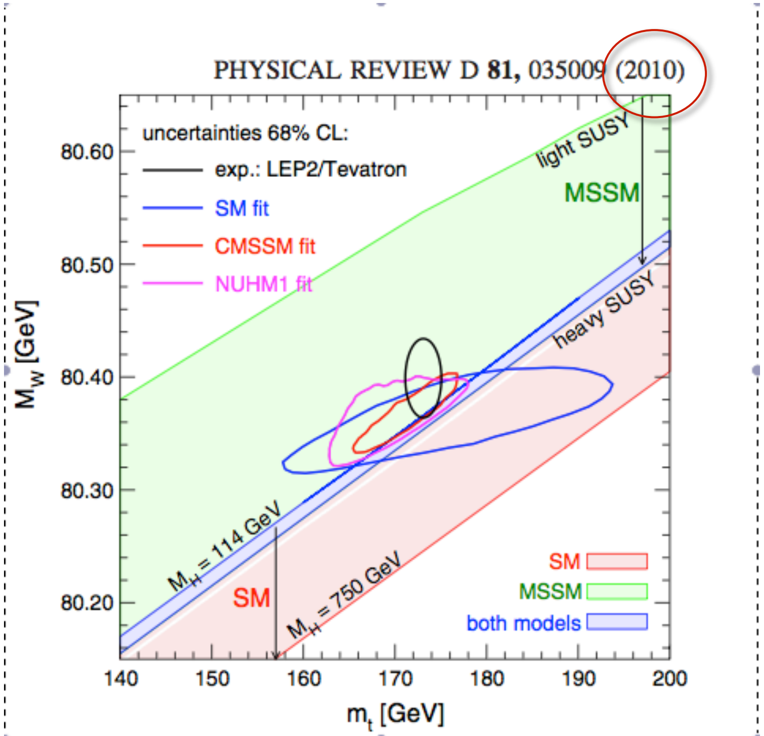
- We may directly observe particles and interactions of new physics at the LHC.

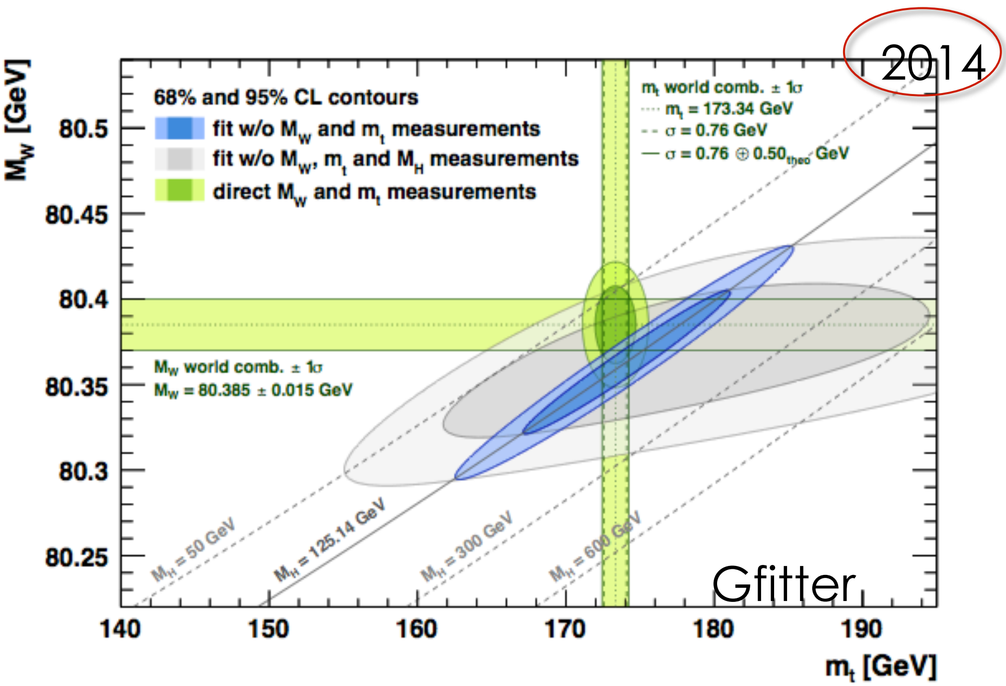
- Precision electroweak measurements can provide us indirect access to new physics beyond the SM.

The Precision Frontier with EWK Physics

- Precision electroweak measurements are sensitive to top mass m_t and Higgs mass M_H via quantum corrections.
- Global EWK fits provided estimates for m_t and M_H before the discoveries.



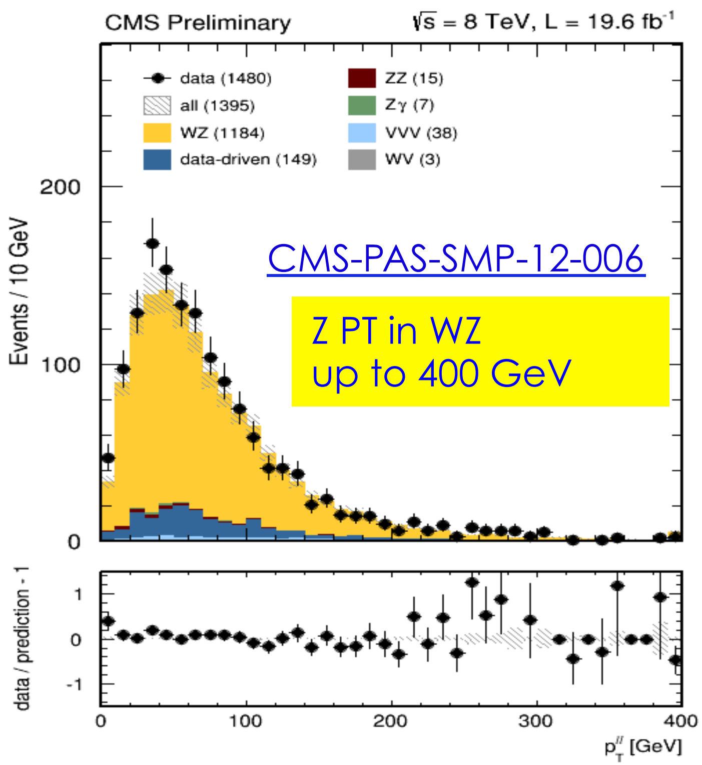




SM-like Higgs discovery at ~126 GeV is compatible with global EWK data at 1.3 sigma (p = 0.18)

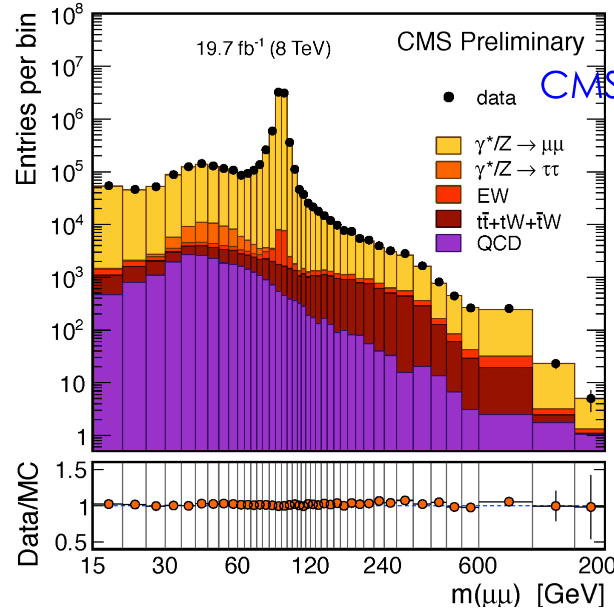
EWK Physics at the Energy Frontier

- ◆Data from the successful LHC Run 1 is providing TeV-scale tests of single and multiple electroweak boson production



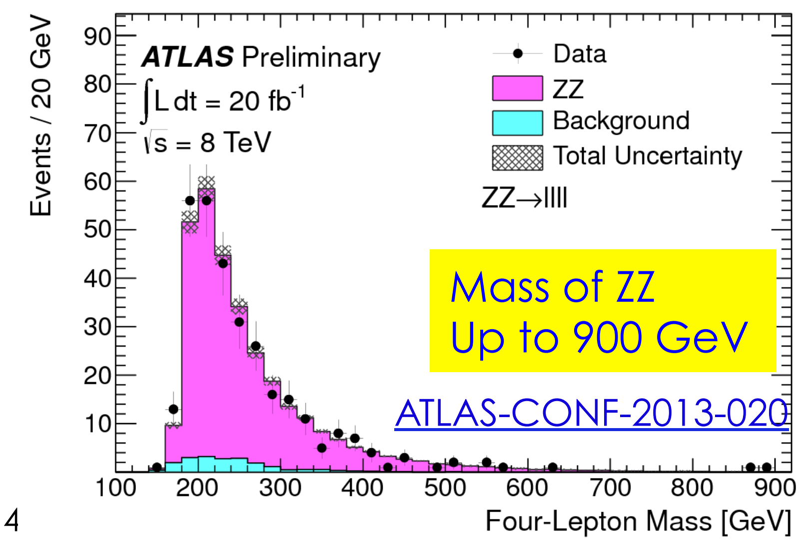
CMS-PAS-SMP-12-006

Z PT in WZ
up to 400 GeV



CMS-PAS-SMP-14-003

Mass of DY pairs up to 2000 GeV



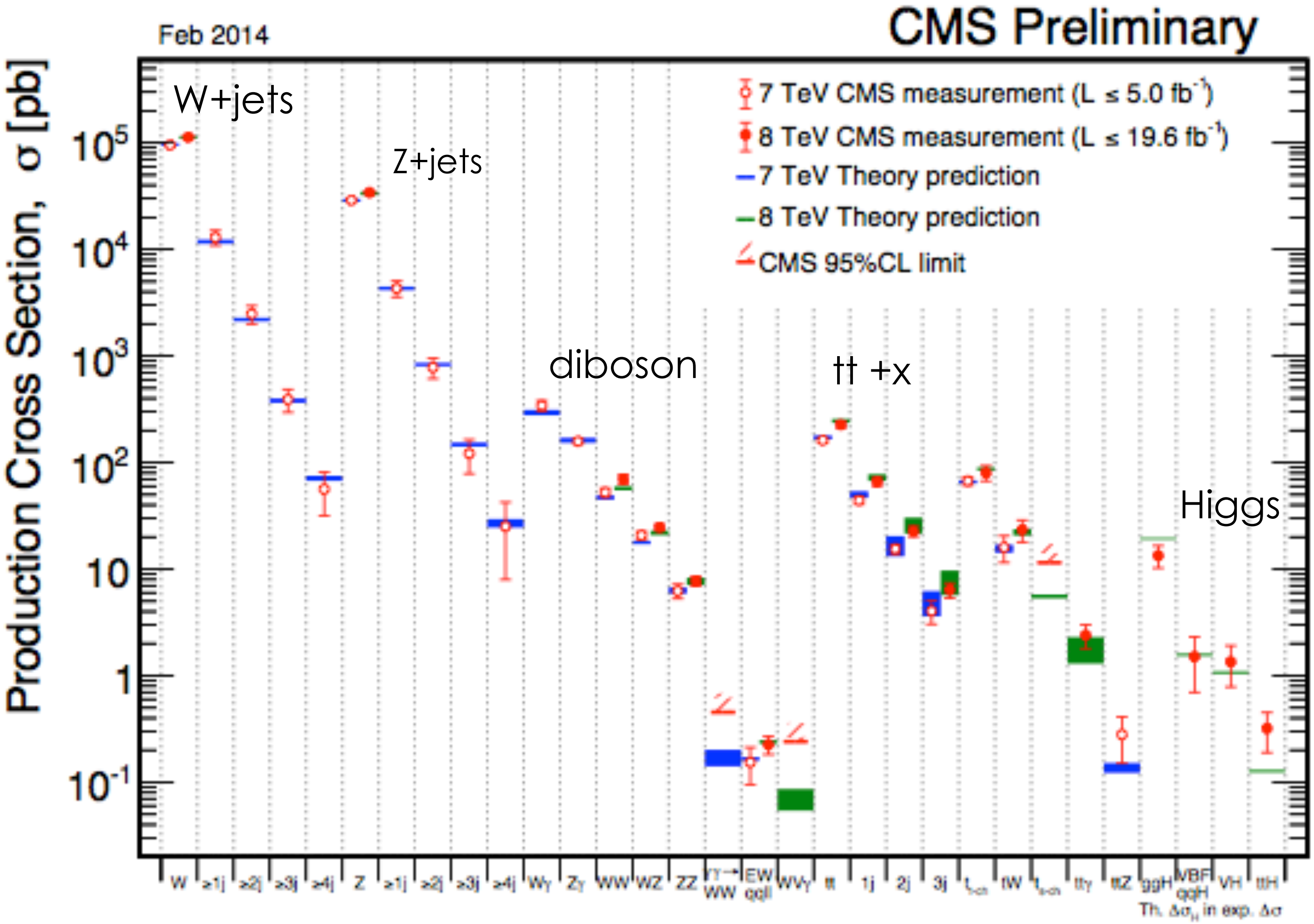
Mass of ZZ
Up to 900 GeV

ATLAS-CONF-2013-020

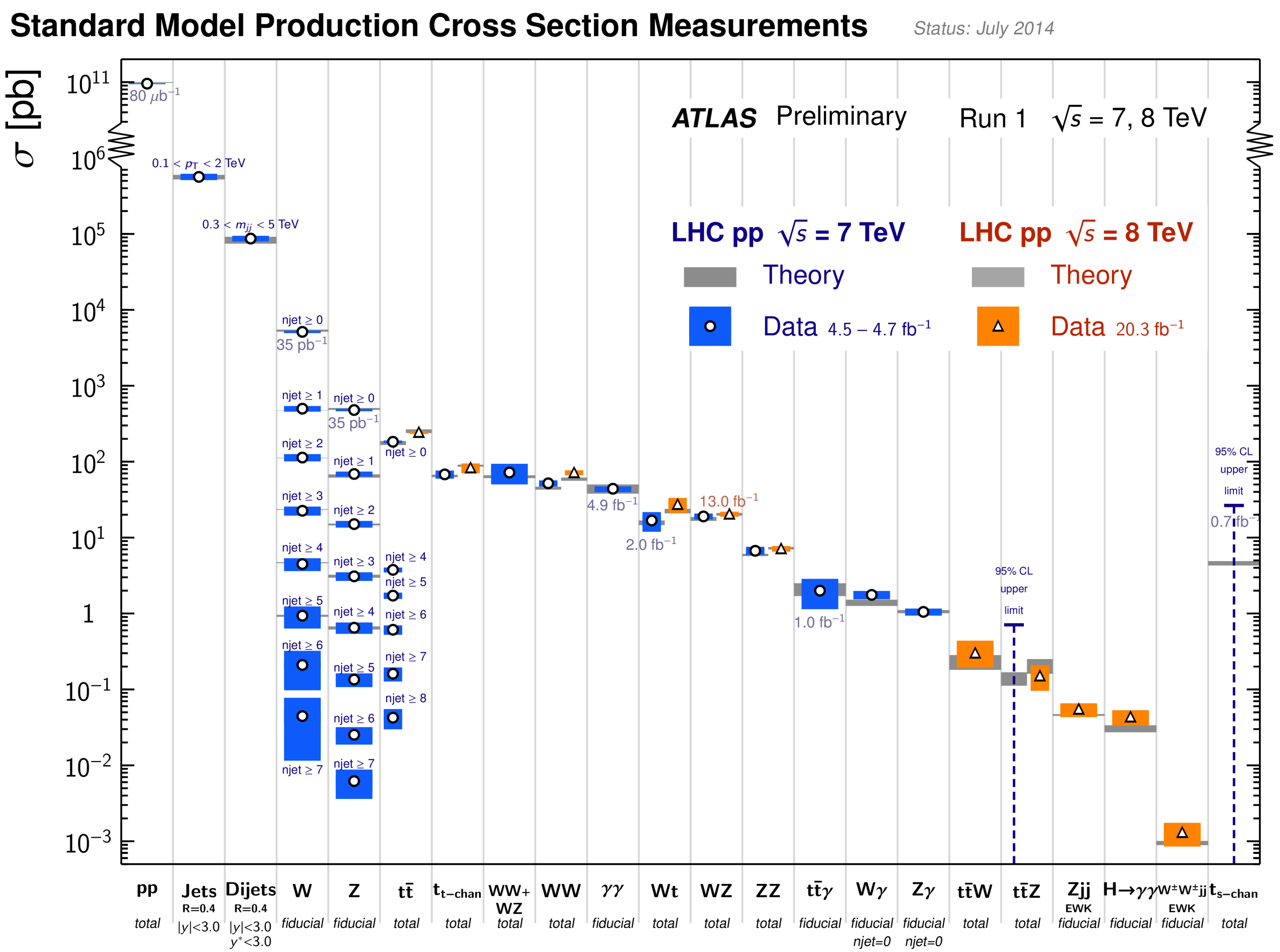
W, Z Production and Properties

- The W, Z boson production are benchmark processes for physics at the LHC.
- They provide calibration of the energy scale and the rates, and provide control samples for analyses.
- W, Z +X events also form backgrounds for many physics processes of interest, and hence need to be understood very well.
  - (top quark events become important background, e.g., for WW; they also help calibrate jet energy scale)
- Electroweak processes and properties have sensitivity to new physics beyond the SM through radiative corrections.

Cross Section Measurements (CMS)
Stairway to .. Where?



Cross section Measurements (ATLAS)



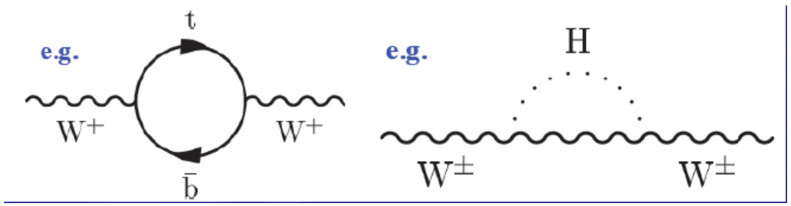
W Boson Mass

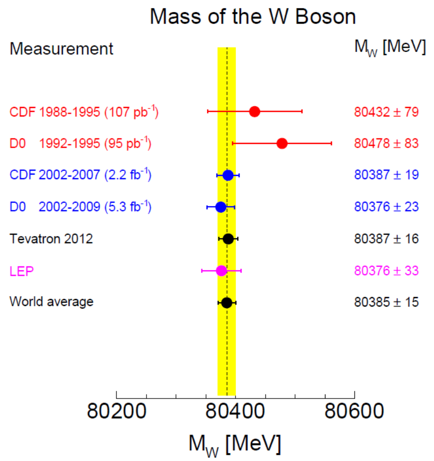
- ◆The W mass, $M_{W,}$ is a key parameter in the SM.
- ◆The world's most precise measurements of $M_{W,}$ so far, come from the Tevatron experiments.

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{\sin\theta_W \sqrt{(1-\Delta r)}}$$

θ_W is the weak mixing angle

Δr: radiative correction



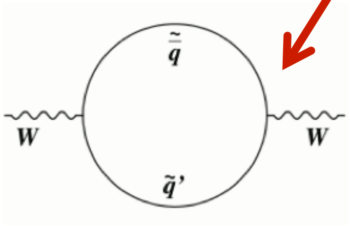


CDF: 19 MeV
D0: 23 MeV
LEP2: 33 MeV

World Average (2012): 15 MeV

Tevatron Combined Projected: 9 MeV

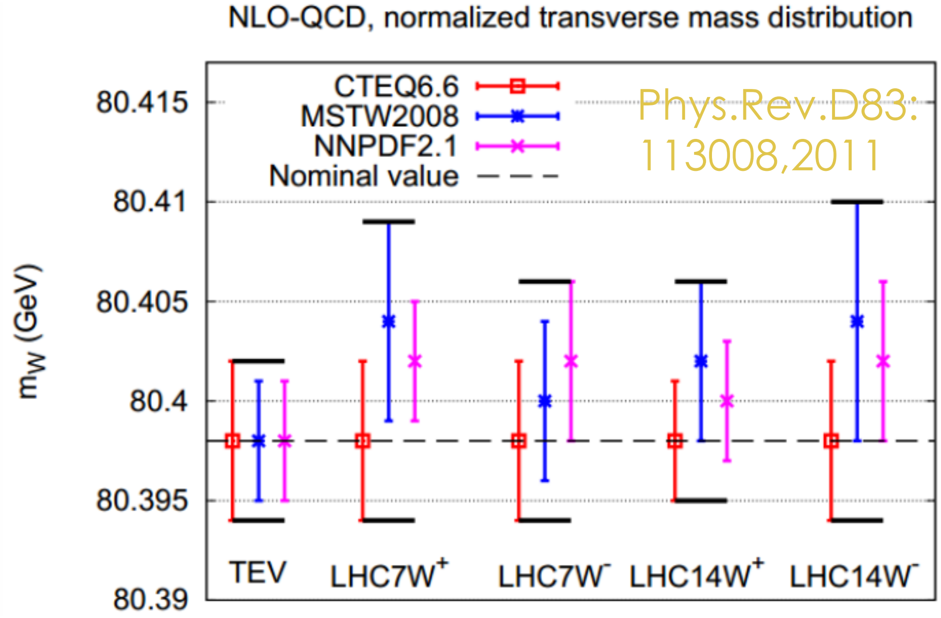
◆Additional contributions to Δr can arise from new physics beyond the SM. (such as in SUSY)



W Mass at LHC

- The LHC has excellent detectors and huge statistics
  - ~100 million W(μ ν)
  - ~10 million Z(μμ)

  (CMS in Run I)
- Good prospect for a <10-MeV measurement
- Big issues:
  - Need 2x better PDFs. Sea quarks play a strong role.
  - Momentum scale
  - Hadronic recoil/Missing ET
  - Pile-up at High Lumi?

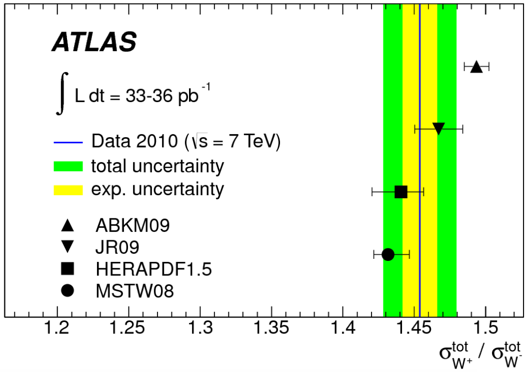


ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\mathrm{fb}^{-1}]$	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

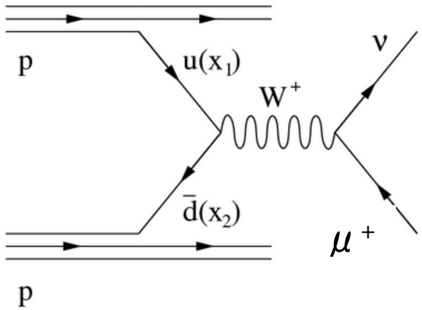
arXiv:1310.6708

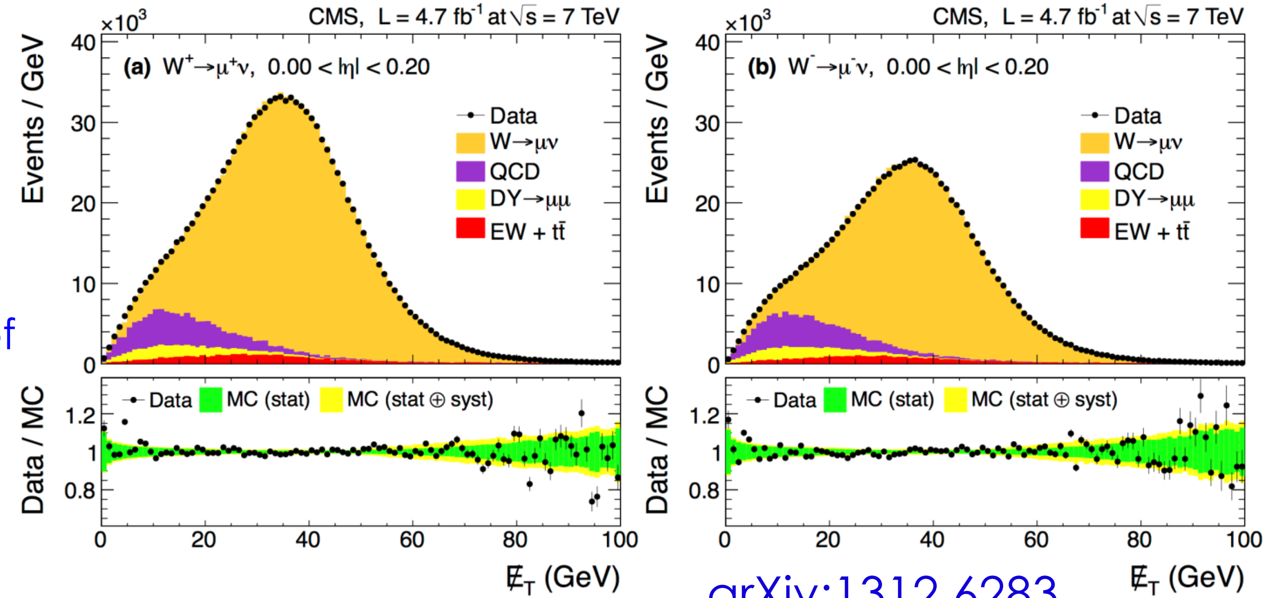
W Charge Asymmetry

- In pp collisions, more W^+ produced than W^- since u dominates over d
- Differential W charge asymmetry probes u/d ratio vs x.



$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}$$





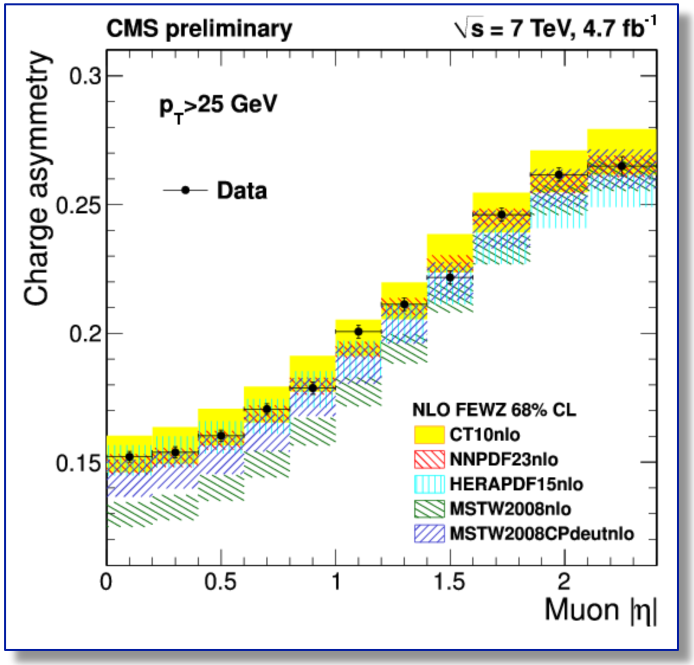
- Extract muon charge asymmetry from a sample of 12.9 M W+ and 9.1 M W- event sample
  - 8% QCD, 8% EW, 0.8% ttbar

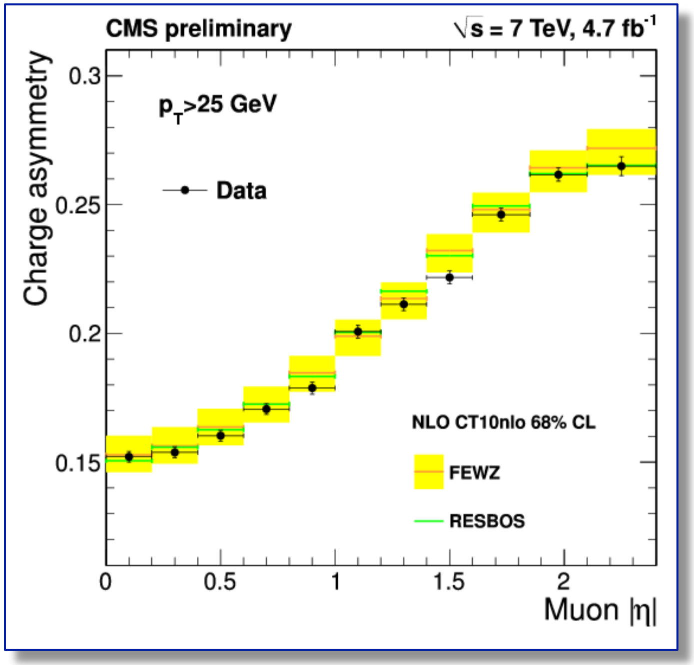
arXiv:1312.6283

W Charge Asymmetry

arXiv: 1312.6283

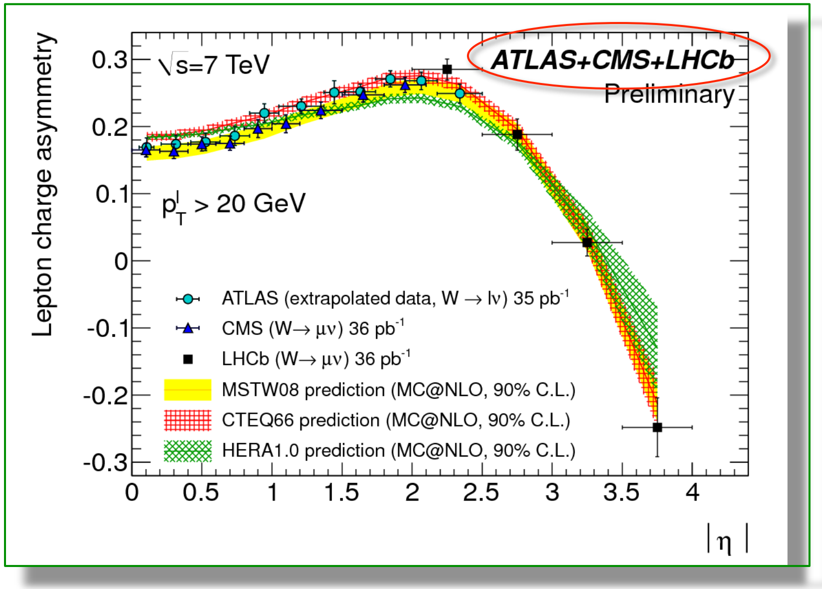
- ◆New measurement from CMS with > 20 M W events
  - ❖Measured in 11 y bins and with two p_T (25 GeV, 35 GeV) thresholds
  - ❖Exp. uncertainty per bin 0.2 -0.4%, smaller than pdf uncertainties





- ◆Power to distinguish and constrain PDFs, and improve future fits
  - ❖CT10nlo does better than others
- ◆RESBOS and FEWZ also describe data well.

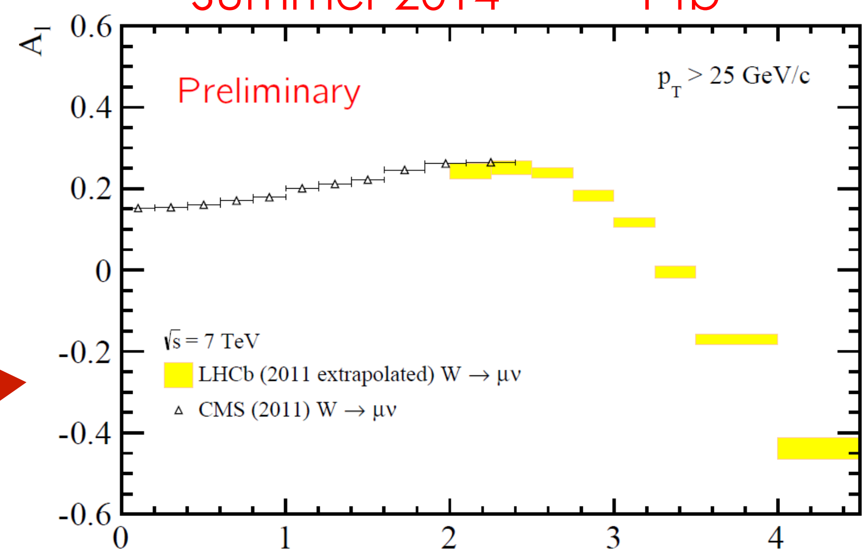
W Charge Asymmetry at the LHC



- ◆LHCb has unique access to high rapidity leptons (2< | η |<4.5)

- ◆New measurements in agreement with CMS in the overlap region.
- ◆Constrains PDFs at lower X

Summer 2014 1 fb^{-1}



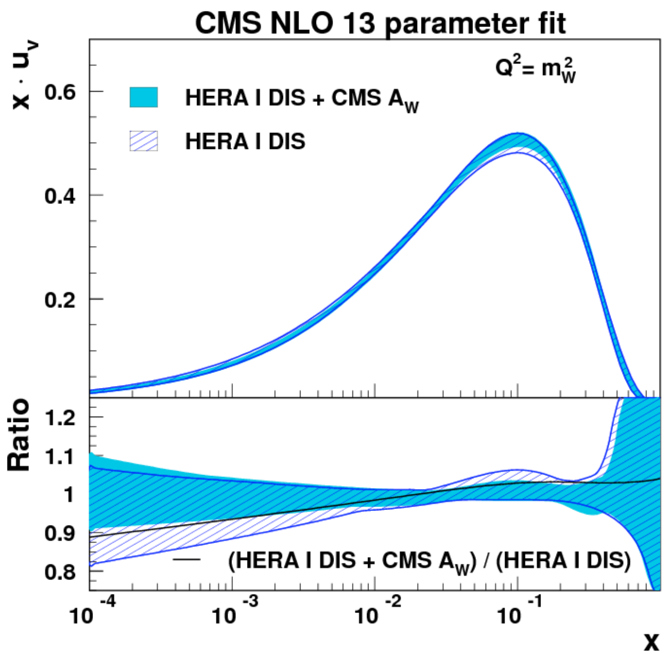
LHCb-CONF-2014-002.pdf

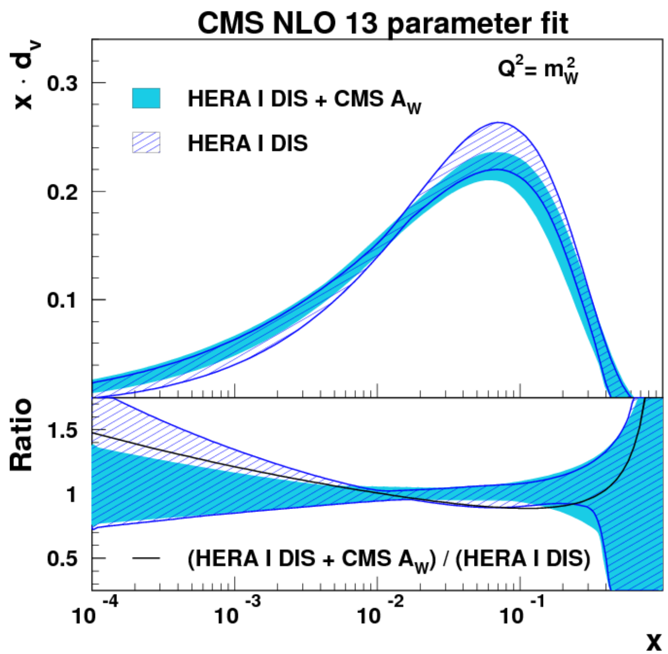
Improving PDFs

arXiv: 1312.6283

- CMS W (μ) asymmetry combined with HERA I DIS results improve precision of valence quark PDFs
  - 13 parameter fixed S-fit

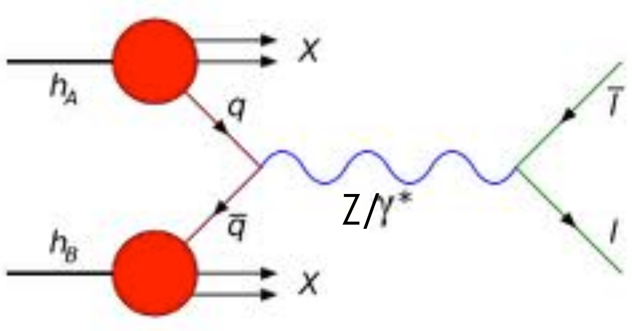
CMS data 4.7 fb^{-1}

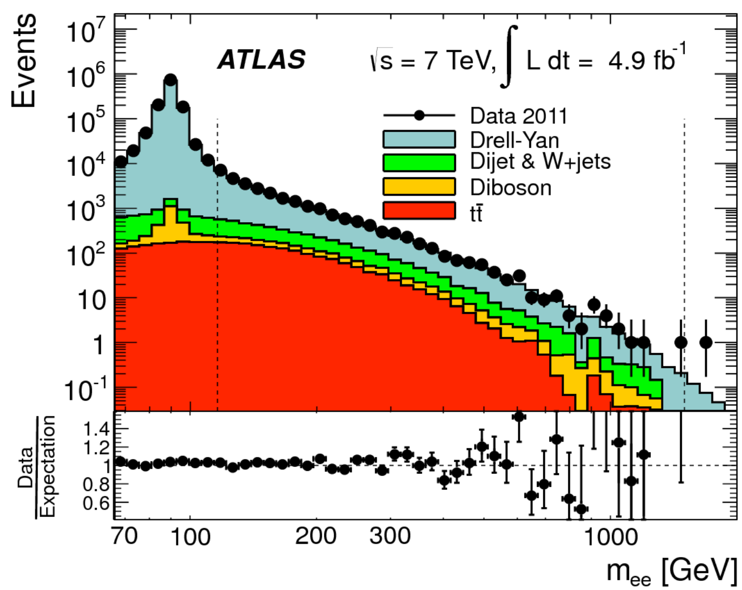




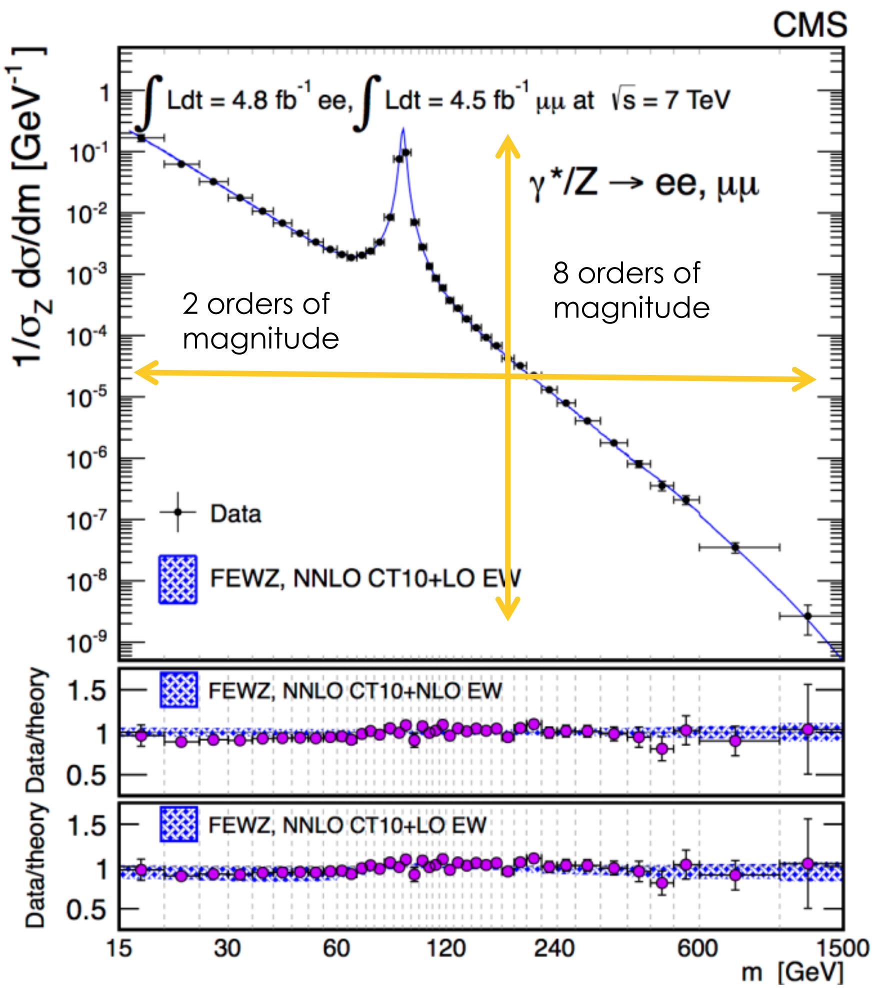
Z and Drell-Yan Measurements

Z and Drell-Yan Process



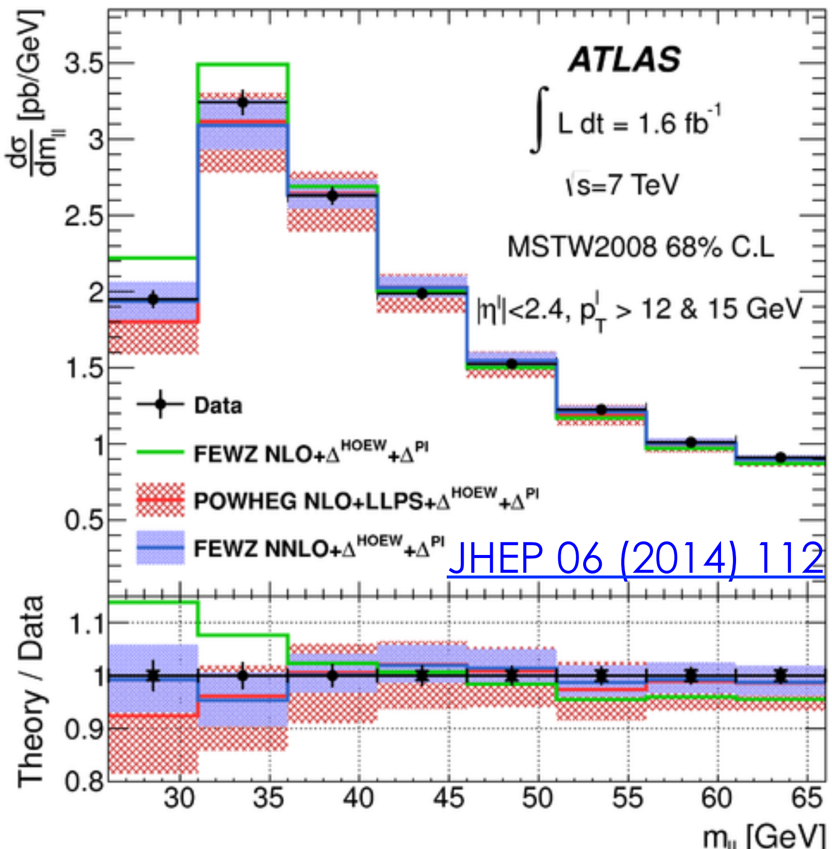


Cross section as a function of Dilepton mass

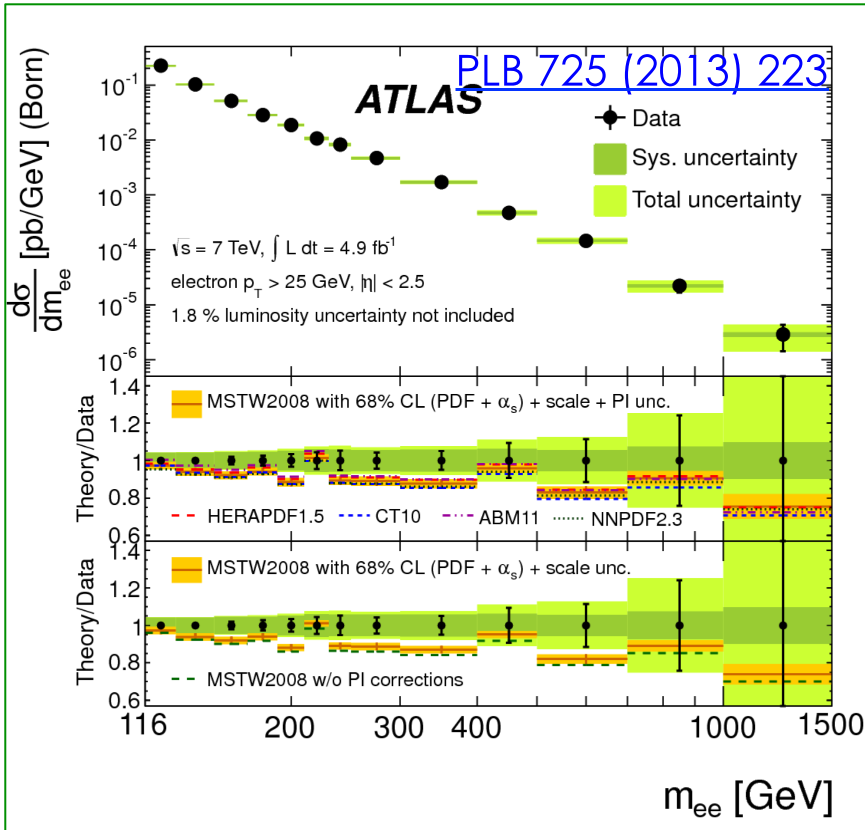


Drell-Yan (ATLAS)

Low mass



High mass



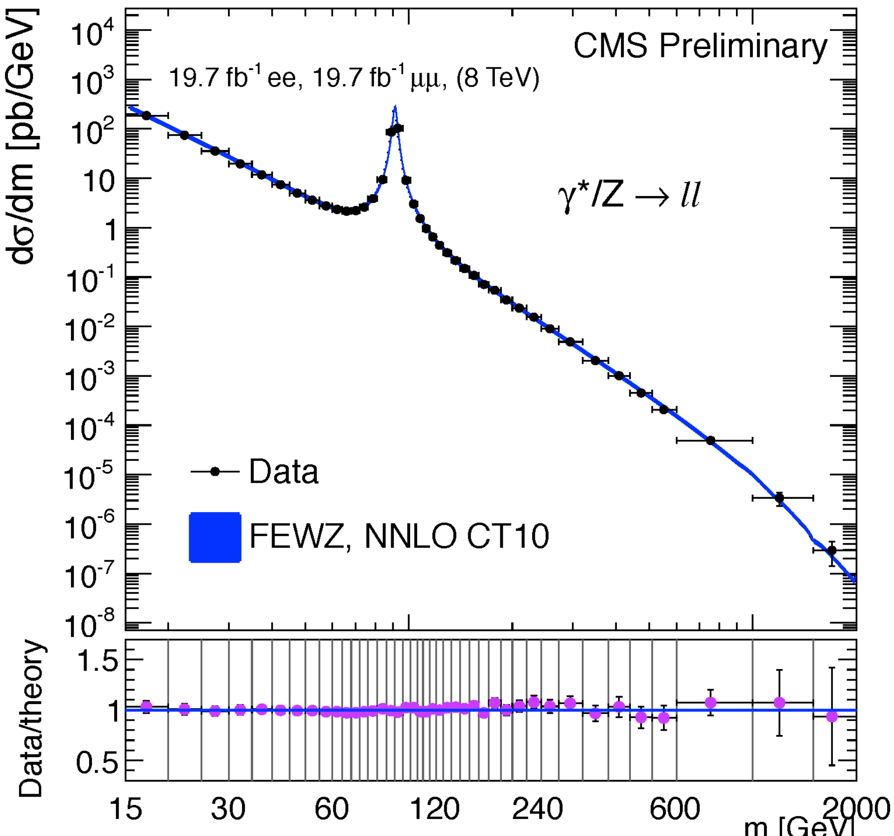
NNLO corrections seem to be important at low mass (Similar observation from CMS data)

Data above predictions for m ~ 120 -400 GeV

NLO EWK corrections and photon-induced production relevant at high mass

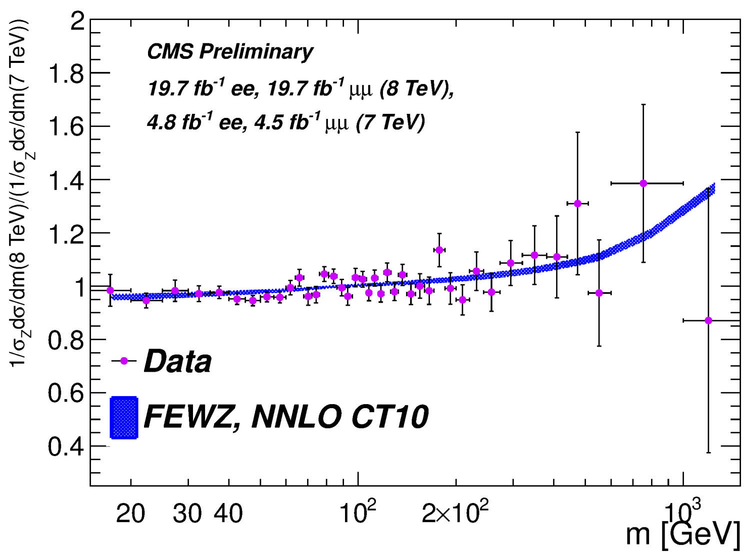
DY Cross Section at 8 TeV

- Measured from 15 to 2000 GeV!



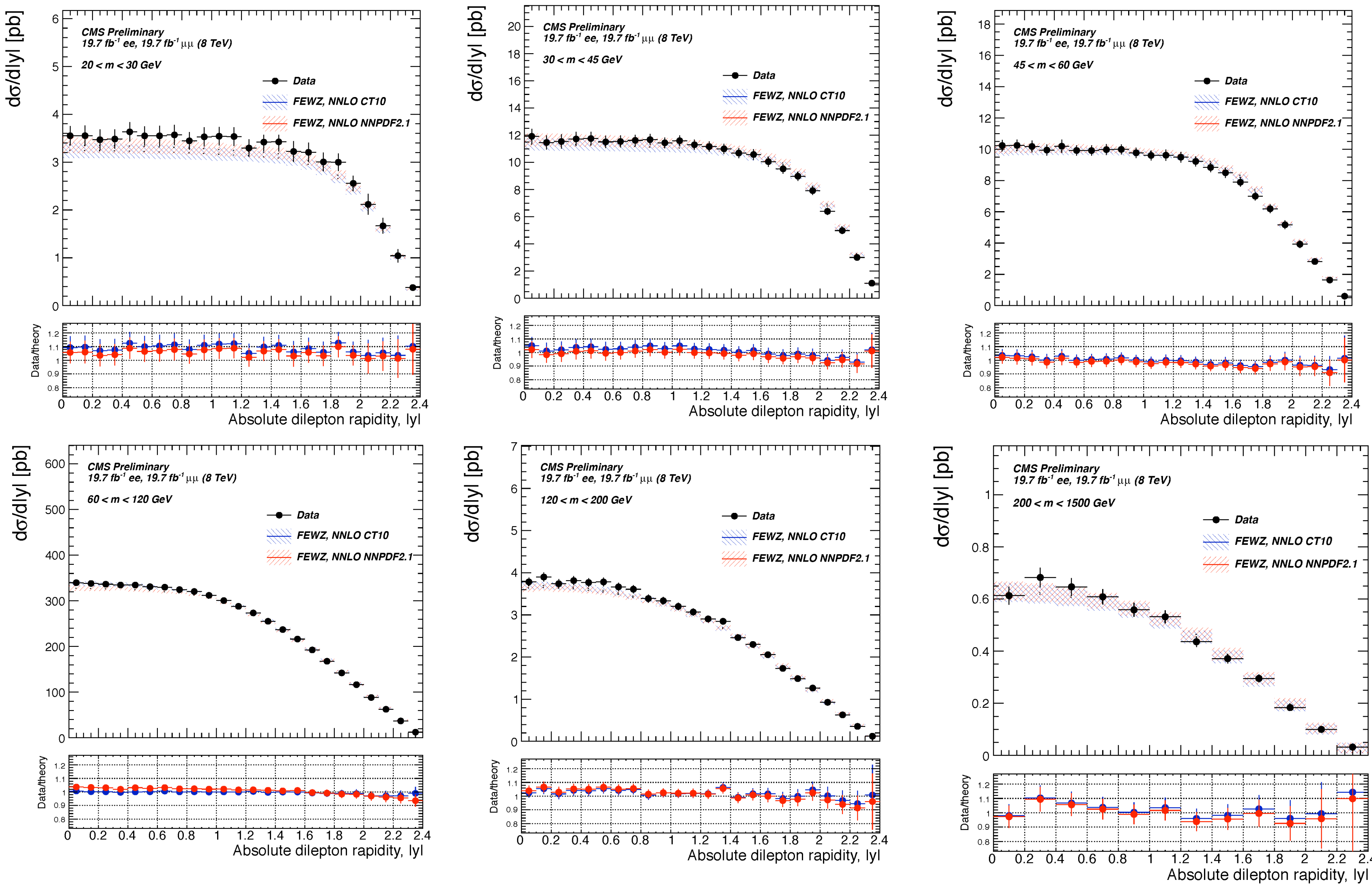
CMS-PAS-SMP-14-003

- Differential Cross section ratios for the two energies measured for the first time!



Differential Cross section at 8 TeV

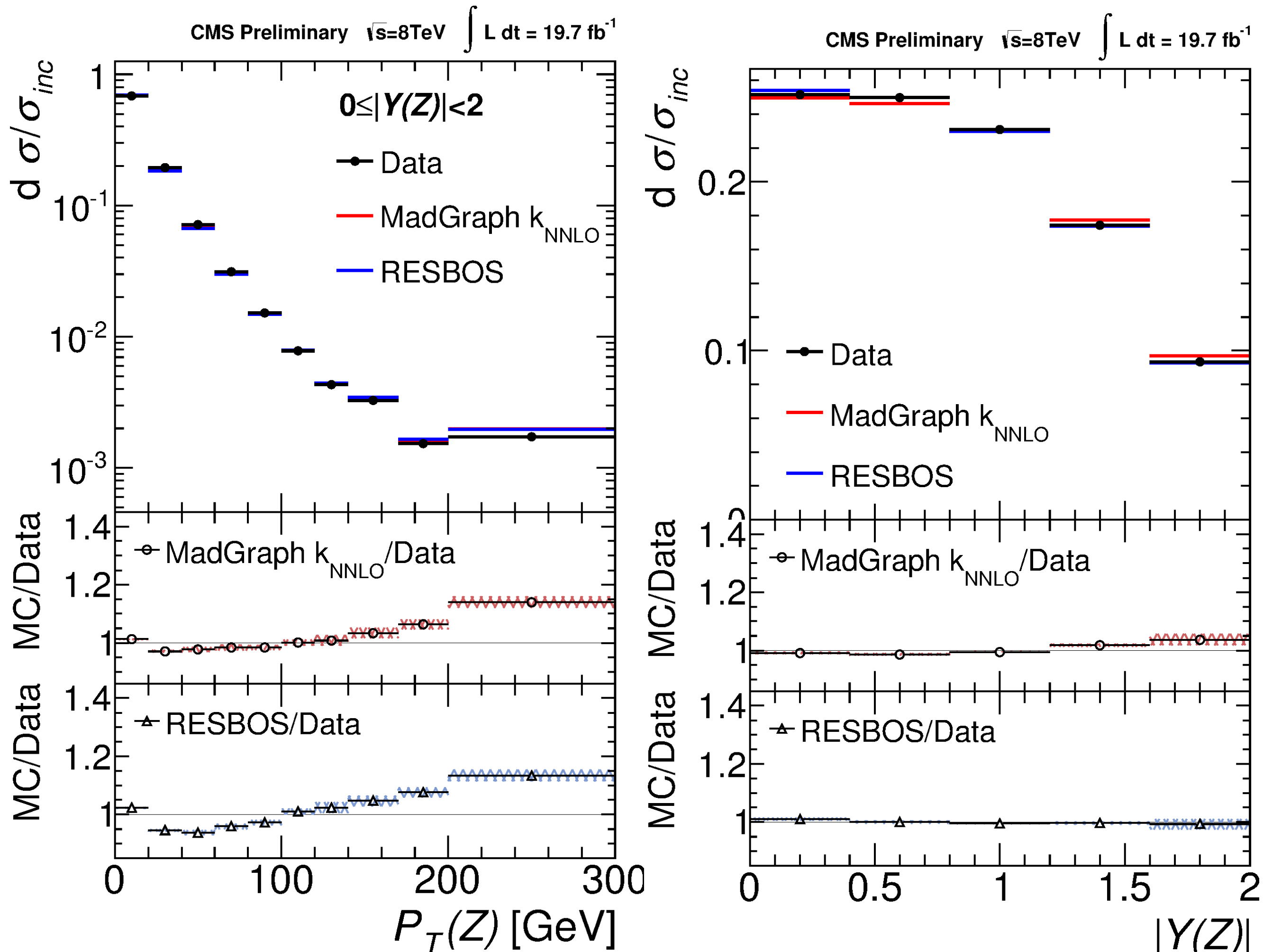
- dσ/dy for Drell-Yan in six different mass bins (CMS)



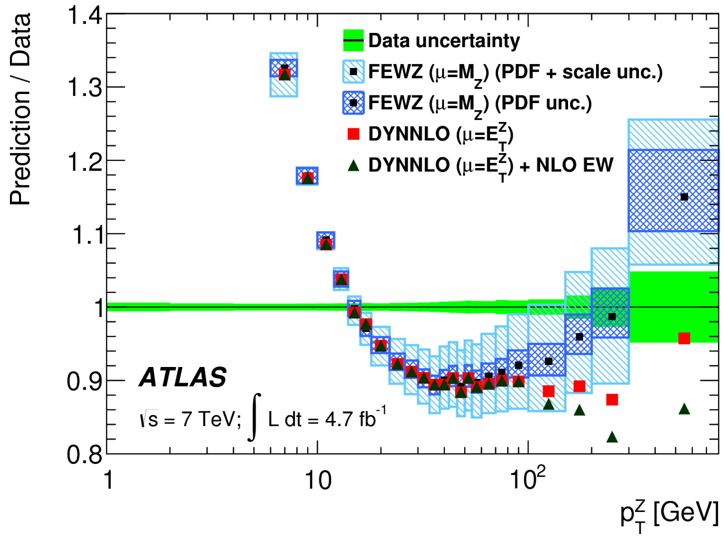
Kinematic Properties of the Z (CMS)

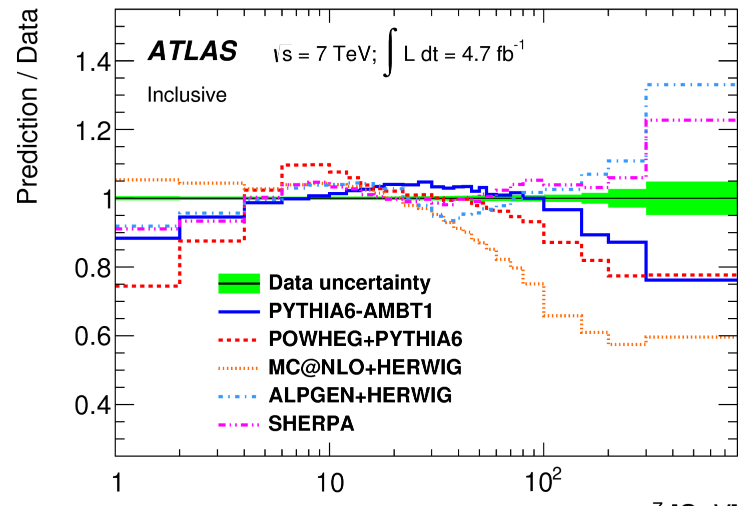
- Z boson p_T and Z rapidity measured and compared with predictions
- Measured doubly differentially
- Data spectrum softer at higher p_T than MC
- Discrepancy at lower p_T as well.

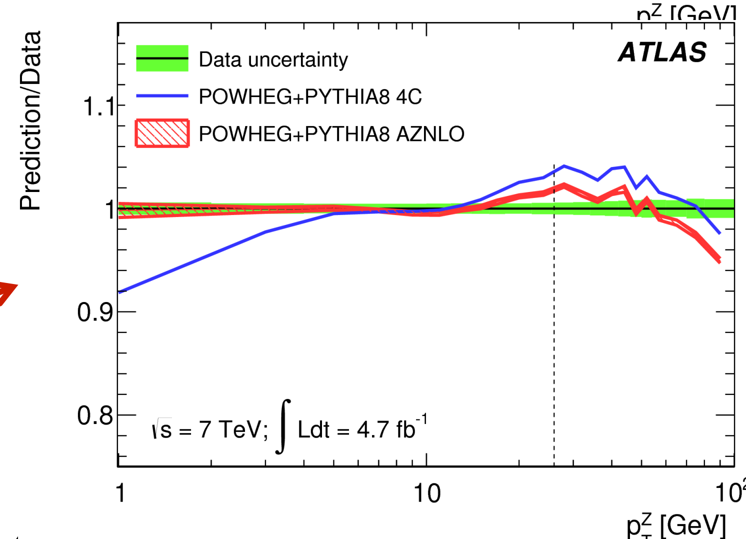
CMS-PAS-SMP-13-013



Kinematic Properties of the Z (ATLAS)







- ◆Disagreement with predictions at low and high p_T
- ◆New tune for PYTHIA8 which gives good agreement at low p_T with AZNLO

arxiv:1406.3660

Weak Mixing Angle

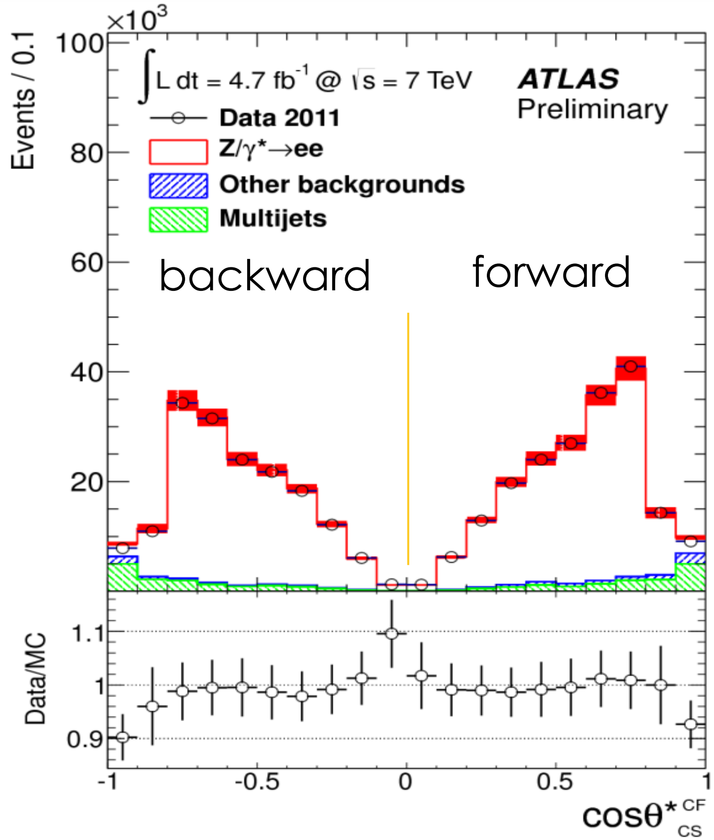
Weak Mixing Angle (CMS)

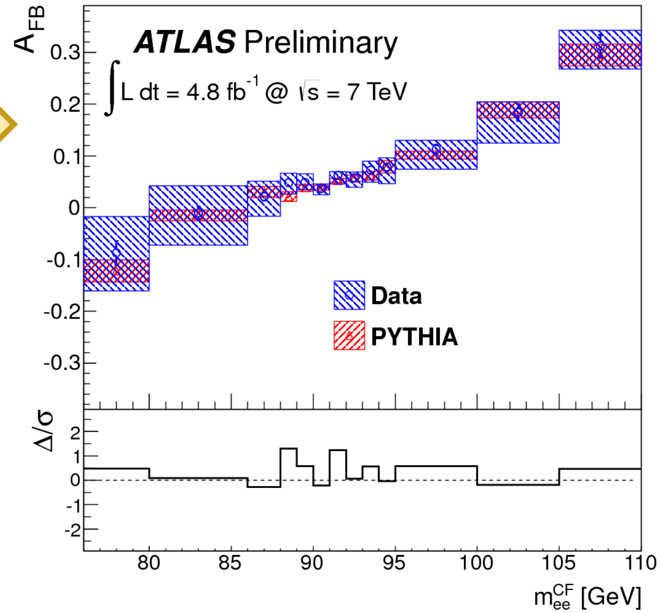
- The "forward-backward" asymmetry in the distribution of the polar angle of the lepton w.r.t. the direction of the quark from the incoming proton is used to extract $\sin^2\theta_W$.
- In pp collisions, the direction of the quark is not known and can be deduced only on a statistical basis.
- CMS performed a multivariate likelihood analysis where the quark direction is statistically modeled using the correlation between the dilepton rapidity, invariant mass and decay angle observables.
- With 1.1 fb^{-1}, CMS measured

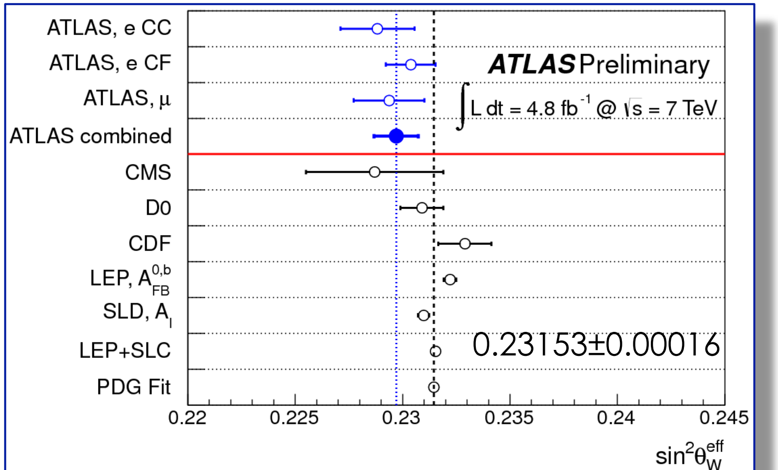
$$\boxed{\sin^2\theta_{eff} = 0.2287 \pm 0.0020(stat) \pm 0.0025(syst)}$$

Phys. Rev. D 84, 112002 (2011)

A_{FB} and $\sin^2\theta_{eff}$ from ATLAS







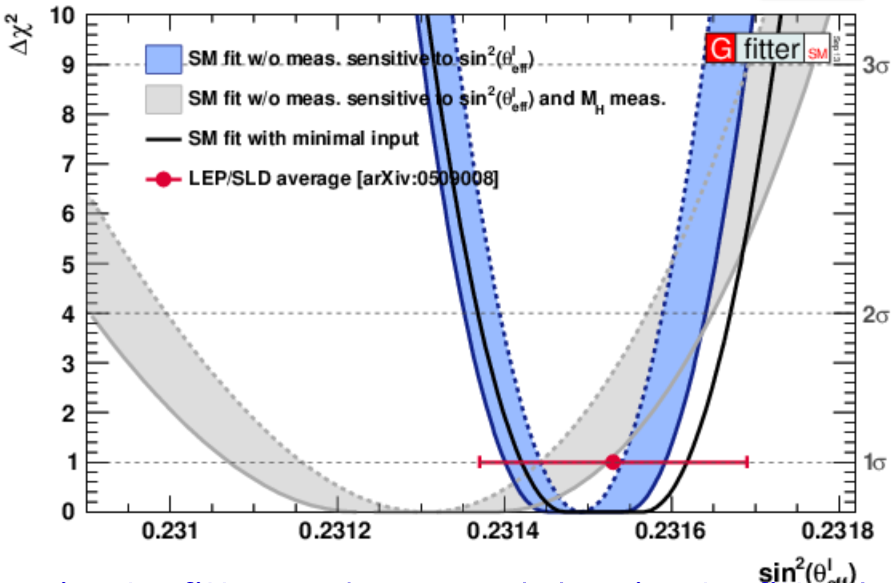
$\sin^2\theta_{eff}$ = 0.2297±0.0004(stat)±0.0009(syst)

ATLAS-CONF-2013-043

Prospects for $\sin^2\theta_{eff}$ at the LHC

- ◆Need a 6x better measurement to achieve current world-average precision
- ◆Requires
  - ❖20 fb^{-1} at 13-14 TeV for target statistical error
  - ❖Lepton energy scale by 5x
  - ❖PDF uncertainty to improve by 5-10x

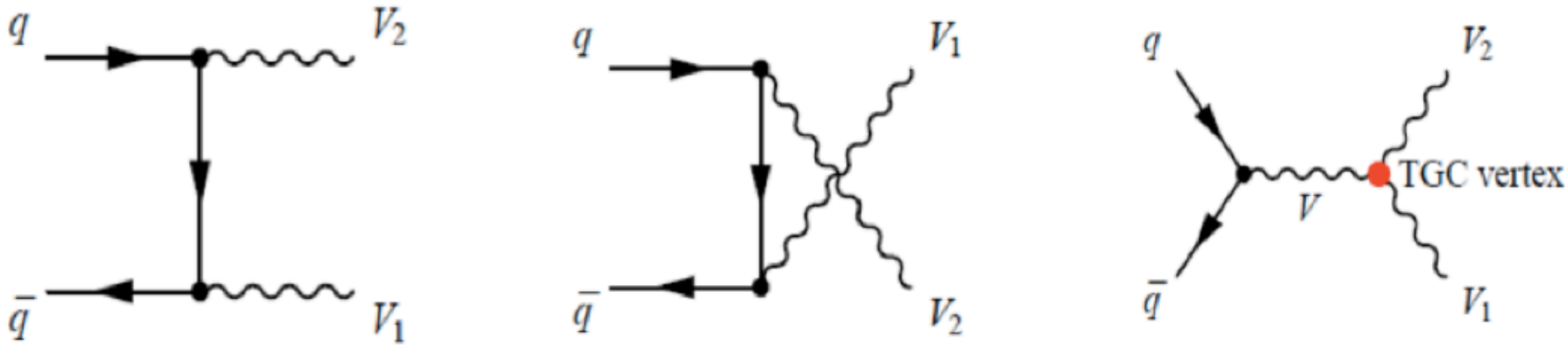
Uncertainty source	CC electrons (10^{-4})	CF electrons (10^{-4})	Muons (10^{-4})	Combined (10^{-4})
PDF	9	5	9	7
MC statistics	9	5	9	4
Electron energy scale	4	6	–	4
Electron energy smearing	4	5	–	3
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2



http://project-gfitter.web.cern.ch/project-gfitter/

Multi-boson Production and Anomalous Gauge Boson Couplings

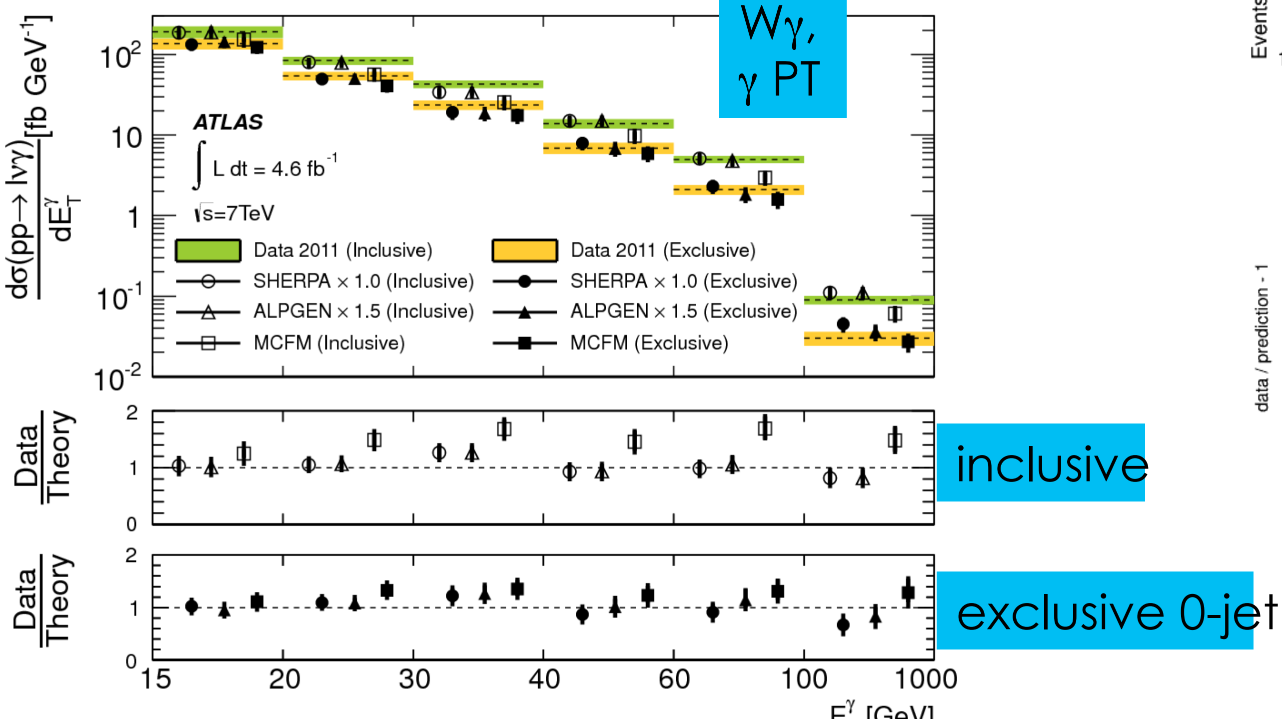
Diboson Production

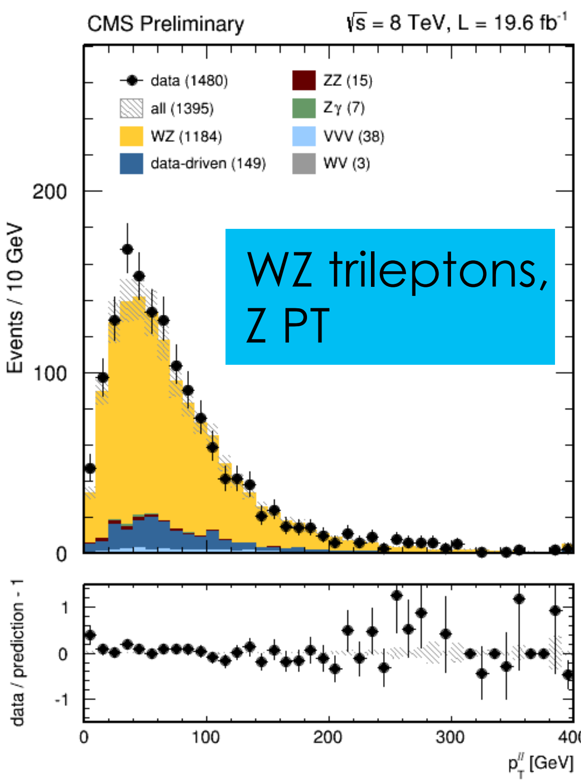


- Measurement of diboson production ($W\gamma$, $Z\gamma$, WW, WZ, ZZ) test the gauge structure of the SM.
  - Vector boson self-couplings are fundamental predictions
  - Deviations from SM i.e., anomalous triple gauge couplings (aTGC) would indicate new physics
  - Sensitive to new particles decaying into boson pairs
  - Non-resonant diboson production is an irreducible background to Higgs production processes
    - Critical to understand to study properties of the Higgs boson

WZ and Wγ Production

- ◆Thousands of high purity trilepton WZ candidates and tens of thousands of Wγ
- ◆Main background from photon and lepton fakes
- ◆No evidence of new physics in high p_T tails



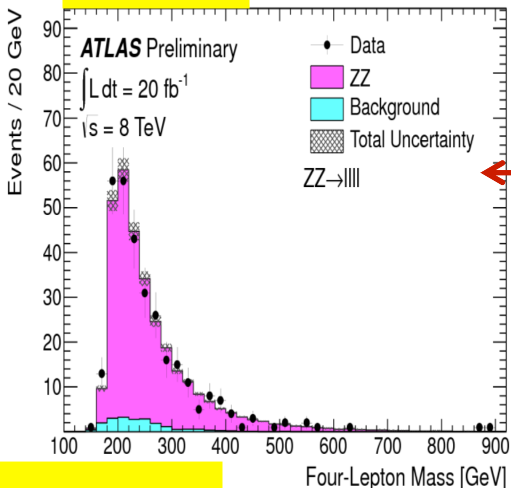


[PRD 87, 112003 (2013)]

[CMS-PAS-SMP-12-006]

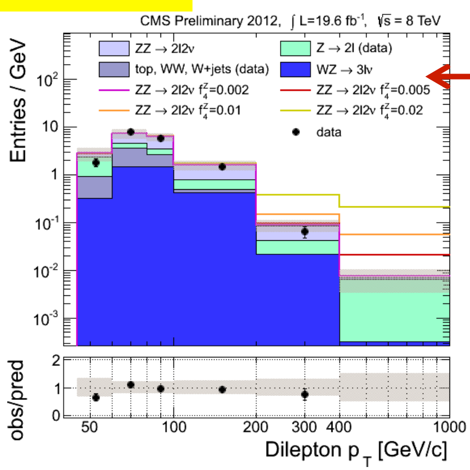
ZZ and Zγ Production

ZZ →4ℓ



- ~300 ZZ → 4ℓ at 8 TeV with SM rates

ZZ → 2ℓ2ν



- 200 ZZ → 2ℓ2ν at 8 TeV

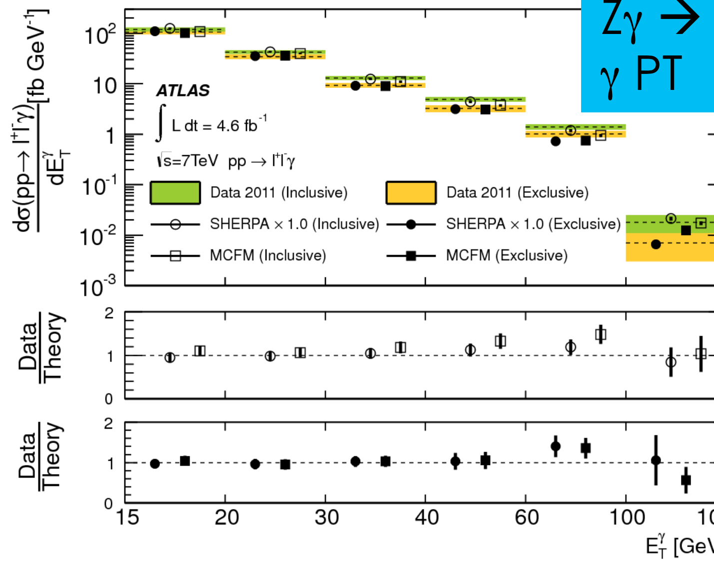
[JHEP 10 (2013) 164](#)

[PRD 89 (2014) 092005](#)

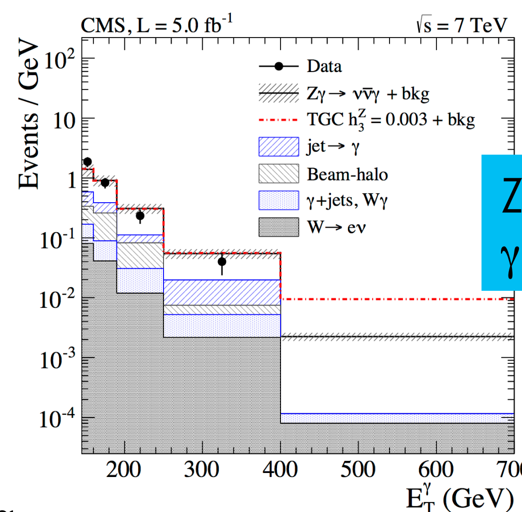
[PRD 87 (2013) 112003](#)

Good statistics at 7 TeV

Zγ → ℓℓγ
γ PT



Low background at high p_T

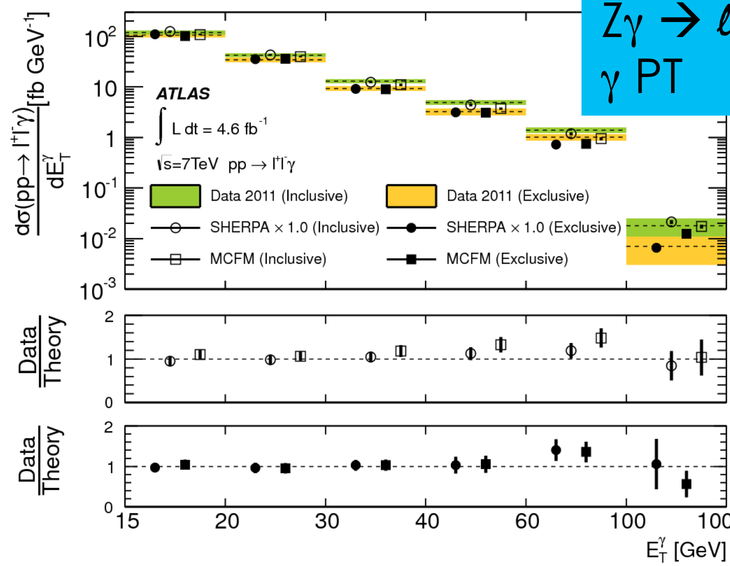


Zγ →MET+γ
γ PT

ZZ and Zγ Production

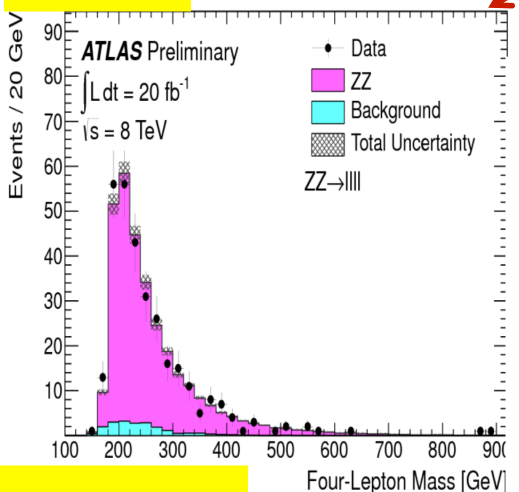
Good statistics at 7 TeV

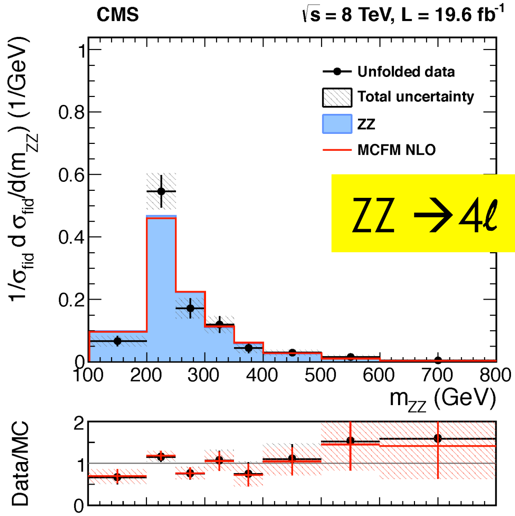
$Z\gamma \rightarrow \ell\ell\gamma$
γ PT



$ZZ \rightarrow 4\ell$

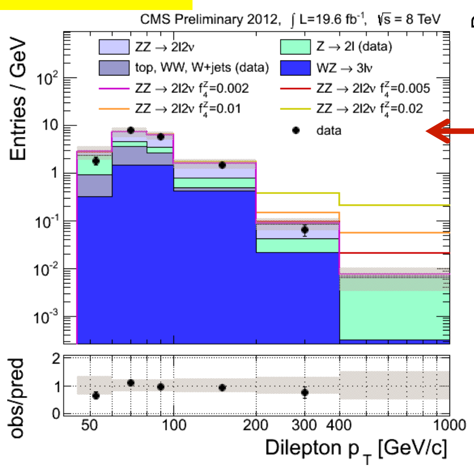
~300 $ZZ \rightarrow 4\ell$ at
8 TeV with SM rates





$ZZ \rightarrow 4\ell$

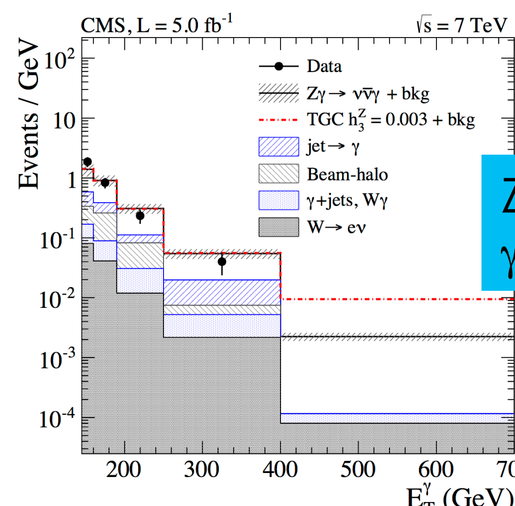
$ZZ \rightarrow 2\ell 2\nu$



~200 $ZZ \rightarrow 2\ell 2\nu$
at 8 TeV

JHEP 10 (2013) 164
PRD 89 (2014) 092005
PRD 87 (2013) 112003

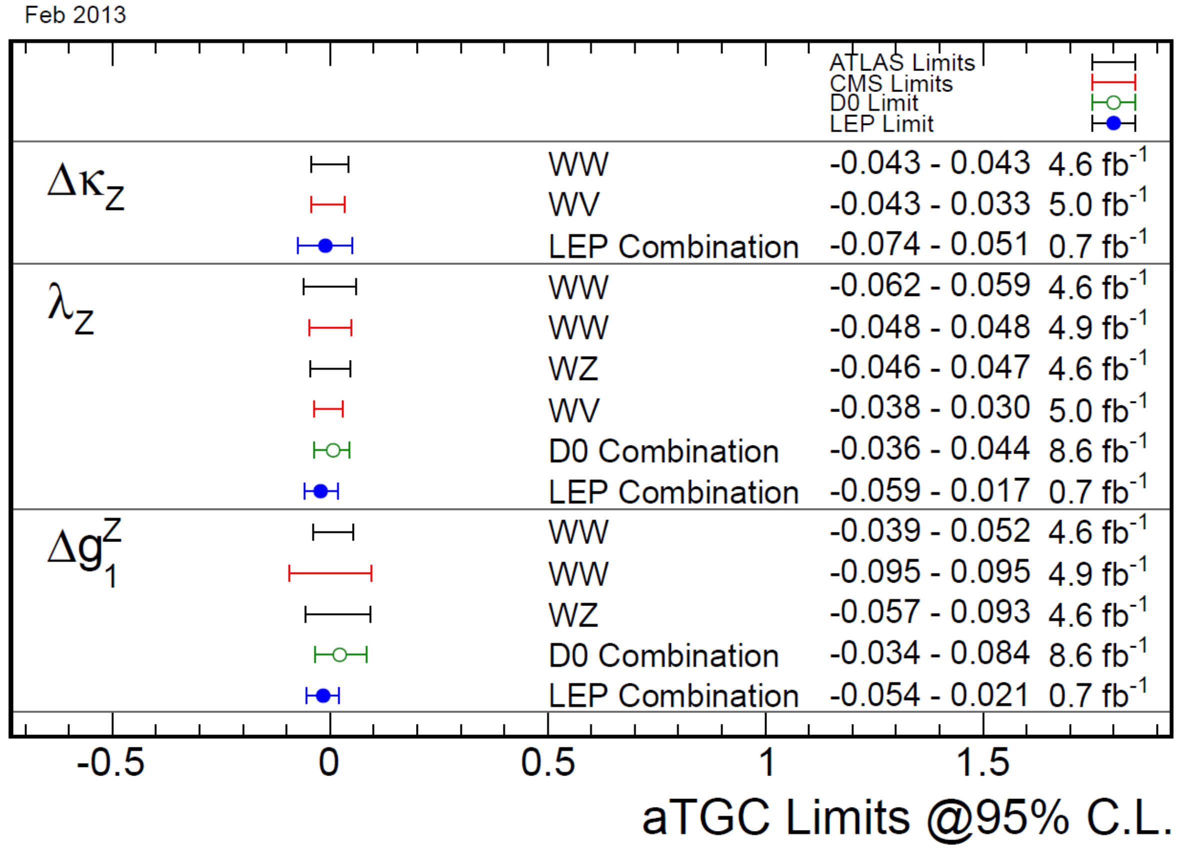
Low background at high p_T



$Z\gamma \rightarrow$MET+γ
γ PT

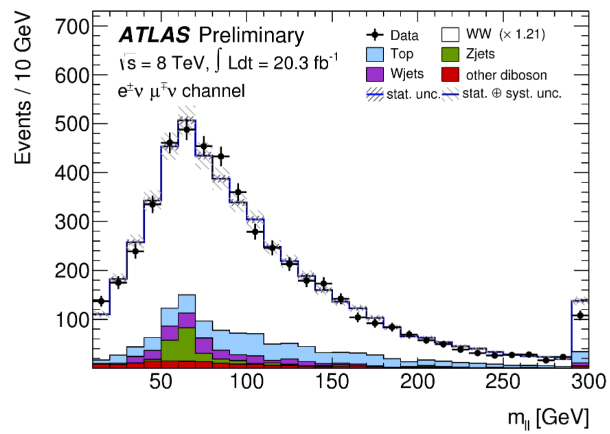
aTGC Results Summary

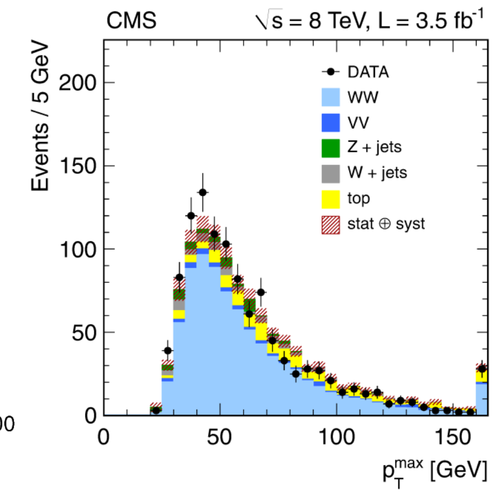
- ◆Best LHC 7 TeV measurements as good as LEP2 +Tevatron combinations
- ◆Semileptonic WW gives the best info on κ and λ, leptonic WW and WZ better for g.
- ◆Probing Λ ~ 200-500 GeV for c=1.



WW Production (8 TeV)

PLB 721 (2013) 190
ATLAS-CONF-2014-033





- Kinematic shapes agree with prediction but cross section higher by ~20% in both CMS and ATLAS

CMS 69.9±2.8 (stat.)±5.6 (syst.)±3.1 (lum.) pb (1.8σ)

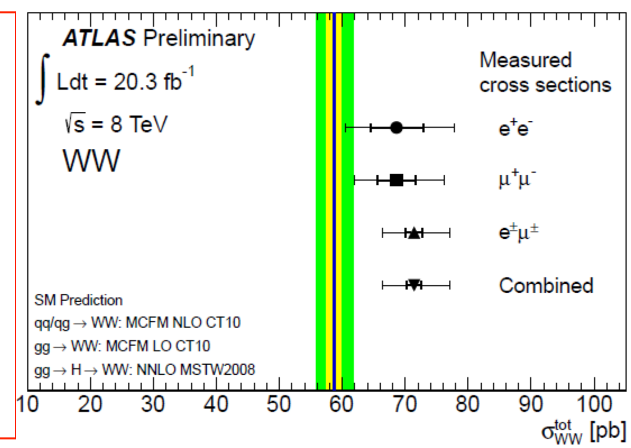
ATLAS 71.4±1.2 (stat.)±5.0 (syst.)±2.2 (lum.) pb (2.1σ)

- ~5000 eμ candidates in ATLAS with 20 fb $^{-1}$

MCFM 58.7±3.0 (syst.) pb

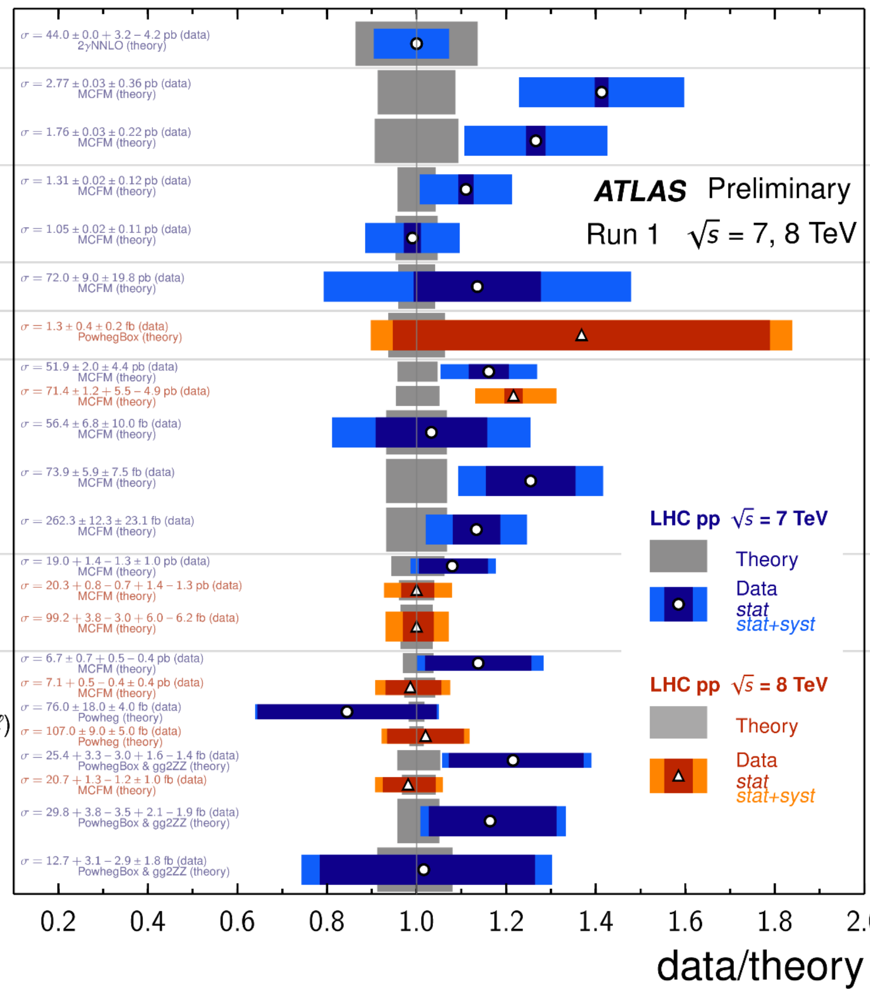
=qq,qg 53.2 MCFM NLO
+gg 1.4 MCFM LO
+HWW 4.1 NNLO+NNLL

Higher order/other≈ 3-4pb?



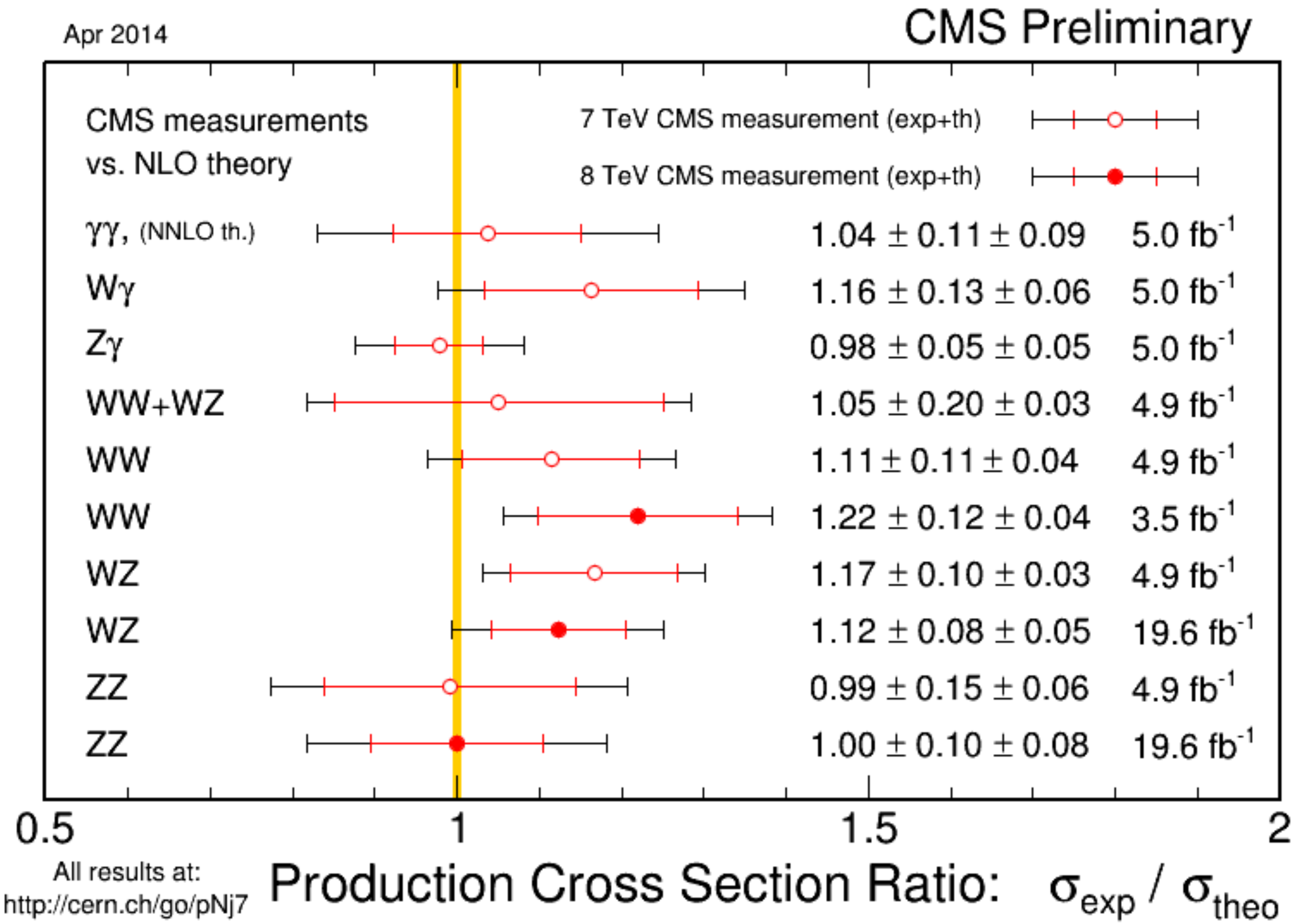
- Yet to come
  - CMS lνlν 20 fb $^{-1}$
  - lνjj 20 fb $^{-1}$

ATLAS Diboson Summary



Measurement	∫L dt [fb^{-1}]	Reference
$\sigma^{fid}(\gamma\gamma)[\Delta R_{\gamma\gamma} > 0.4]$	4.9	JHEP 01, 086 (2013)
$\sigma^{fid}(W\gamma \to \ell\nu\gamma)$	4.6	PRD 87, 112003 (2013)
$-[n_{jet} = 0]$	4.6	PRD 87, 112003 (2013)
$\sigma^{fid}(Z\gamma \to \ell\ell\gamma)$	4.6	PRD 87, 112003 (2013)
$-[n_{jet} = 0]$	4.6	PRD 87, 112003 (2013)
$\sigma^{total}(pp\to WW+WZ)$	4.7	ATLAS-CONF-2012-157
$\sigma^{fid}(W^\pm W^\pm jj)$ EWK	20.3	arXiv:1405.6241 [hep-ex]
$\sigma^{total}(pp\to WW)$	4.6	PRD 87, 112001 (2013)
	20.3	ATLAS-CONF-2014-033
$-\sigma^{fid}(WW \to ee)$	4.6	PRD 87, 112001 (2013)
$-\sigma^{fid}(WW \to \mu\mu)$	4.6	PRD 87, 112001 (2013)
$-\sigma^{fid}(WW \to e\mu)$	4.6	PRD 87, 112001 (2013)
$\sigma^{total}(pp\to WZ)$	4.6	EPJC 72, 2173 (2012)
	13.0	ATLAS-CONF-2013-021
$-\sigma^{fid}(WZ \to \ell\nu\ell\ell)$	13.0	ATLAS-CONF-2013-021
$\sigma^{total}(pp\to ZZ)$	4.6	JHEP 03, 128 (2013)
	20.3	ATLAS-CONF-2013-020
$-\sigma^{total}(pp\to ZZ\to 4\ell)$	4.5	arXiv:1403.5657 [hep-ex]
	20.3	arXiv:1403.5657 [hep-ex]
$-\sigma^{fid}(ZZ \to 4\ell)$	4.6	JHEP 03, 128 (2013)
	20.3	ATLAS-CONF-2013-020
$-\sigma^{fid}(ZZ^* \to 4\ell)$	4.6	JHEP 03, 128 (2013)
$-\sigma^{fid}(ZZ^* \to \ell\ell\nu\nu)$	4.6	JHEP 03, 128 (2013)

CMS Diboson Summary

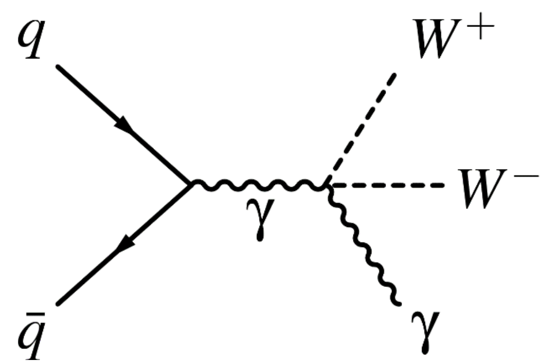


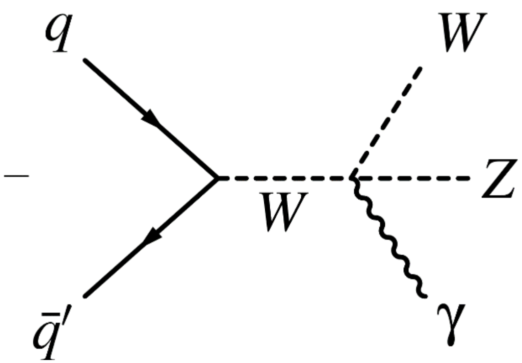
Triboson Search in WWγ and WZγ

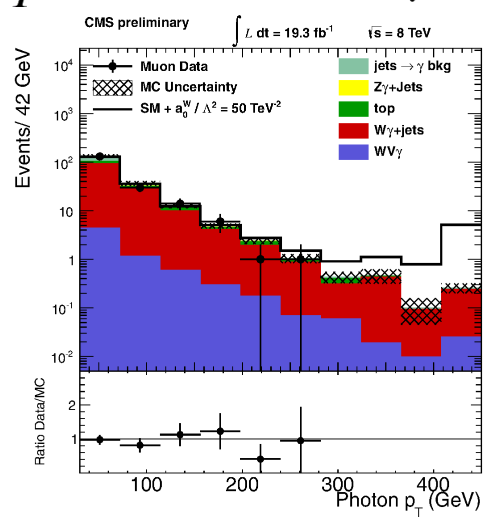
arxiv:1404.4619

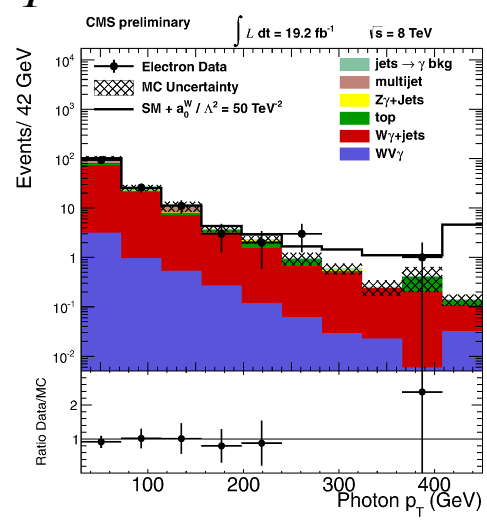
- ◆Studied in lν+jj+γ final state for best aQGC sensitivity
- ◆No anomalous high p_T tail in photon p_T
- ◆Cross section Upper Limit on SM triboson rate is 3.4xSM (<311 fb)
- ◆First limits ever on several aQGCs

$$-21 < a_0^W/\Lambda^2 < 20\,\mathrm{TeV}^{-2},$$
$$-34 < a_C^W/\Lambda^2 < 32\,\mathrm{TeV}^{-2},$$
$$-25 < f_{T,0}/\Lambda^4 < 24\,\mathrm{TeV}^{-4},$$
$$-12 < \kappa_0^W/\Lambda^2 < 10\,\mathrm{TeV}^{-2}, \text{ and}$$
$$-18 < \kappa_C^W/\Lambda^2 < 17\,\mathrm{TeV}^{-2}.$$





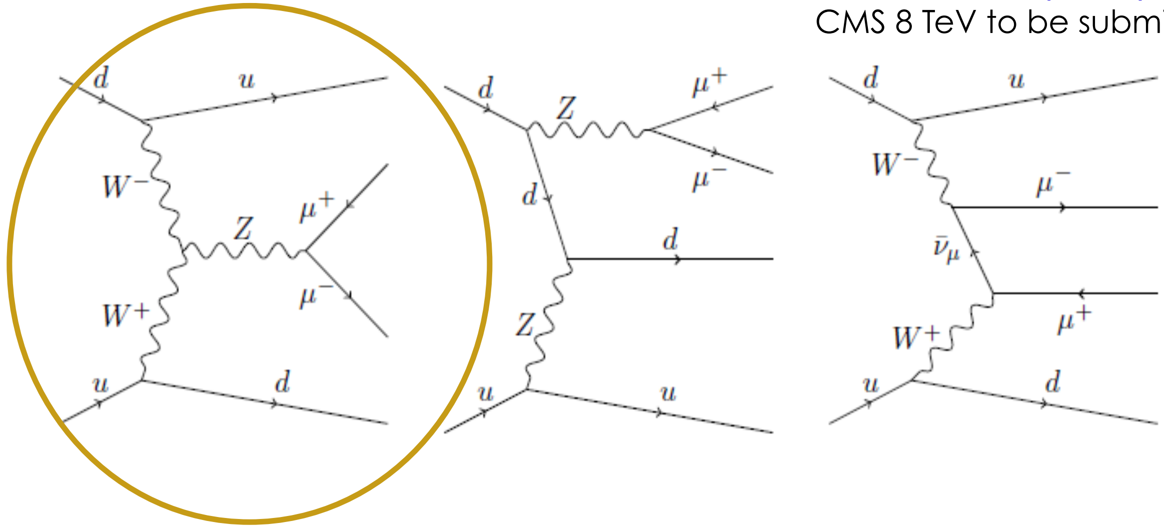


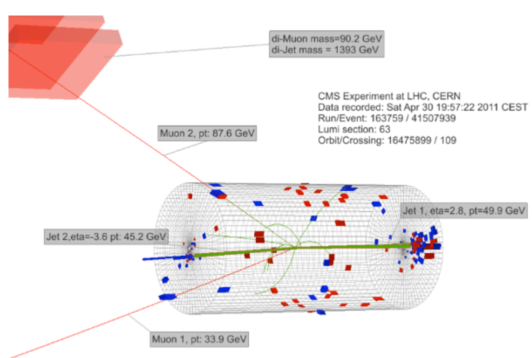


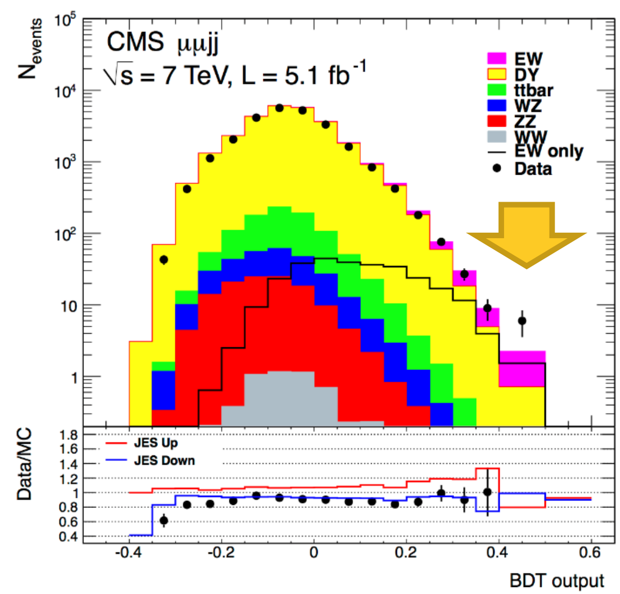
Electroweak Z + 2 jet production

JHEP 04 (2014) 031
JHEP 10 (2013) 062
CMS 8 TeV to be submitted

- Unique process for studying rapidity gaps and VBF jet dynamics
- Require dijet "VBF topology":
  - large dijet mass (250-1000 GeV)
  - Large dijet Δy (or rapidity gap)
  - other kinematic information to separate from QCD Z+ 2 jet
- CMS observed a 2.6σ signal in the 7 TeV data after a BDT selection





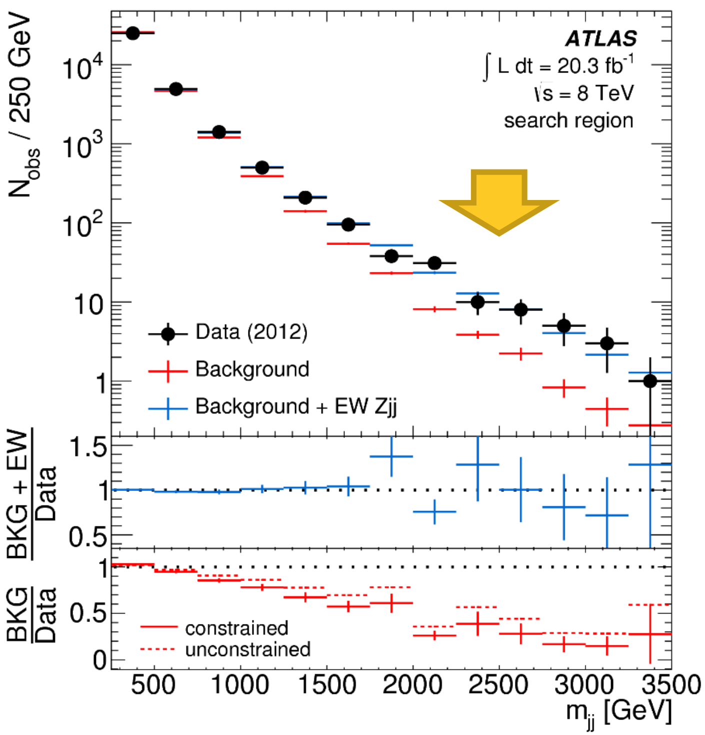


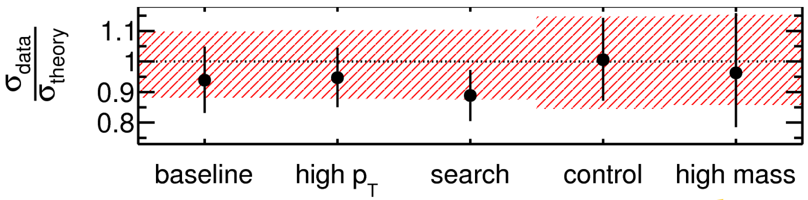
Electroweak Z + 2 jet production

JHEP 04 (2014) 031
JHEP 10 (2013) 062
CMS 8 TeV to be submitted

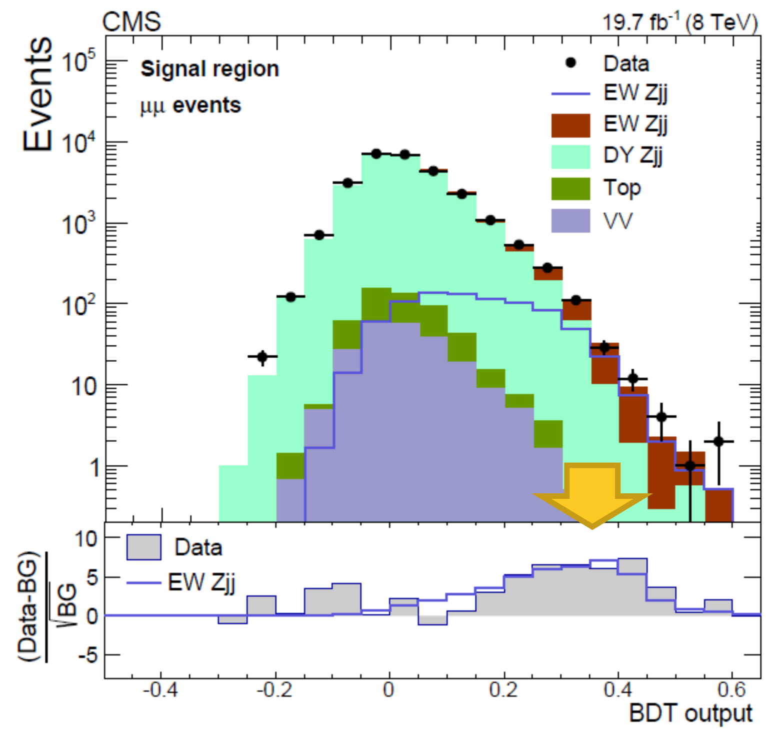
σ_{EWK} = 226 ± 44 fb
σ_{VBFNLO} = 239 fb

- **>5 σ evidence** has been reported by both experiments at 8 TeV, first published by ATLAS. Cross sections are consistent with SM predictions.





σ_{EWK} = 10.7 ± 2.1 fb
σ_{POWHEG} = 9.4 fb



- After reweighting QCD Z+2 jets in sidebands, jet dynamics well-modeled in and around search regions

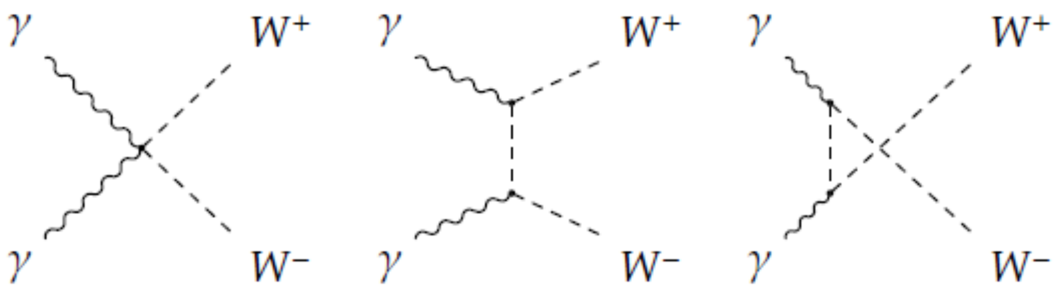
First VV→VV search at the LHC

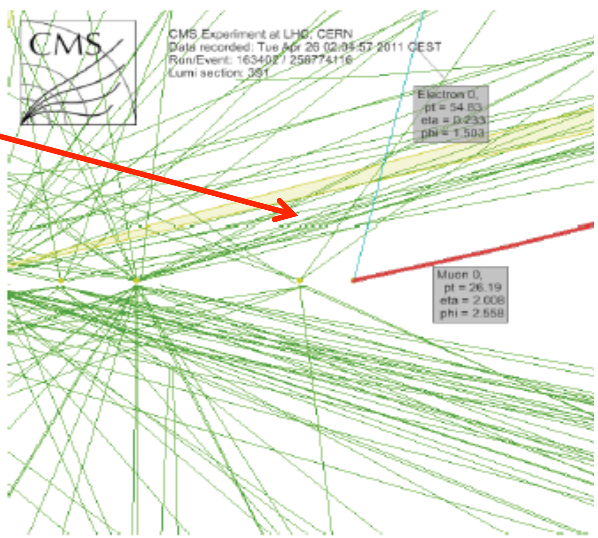
WWγγ QGC

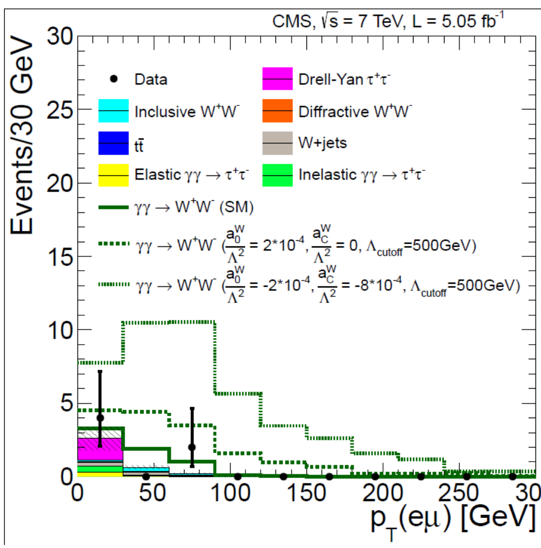
- First search for photon-photon scattering production of WW
- WWγγ quartic gauge coupling one of the amplitudes
- Two eμ events observed **with no UE present**
- First quartic gauge coupling limits at LHC; WWγγ limit two orders better than LEP or Tevatron!

JHEP 1307 (2013) 116

Two photon production of WW (s, t, and u channel)



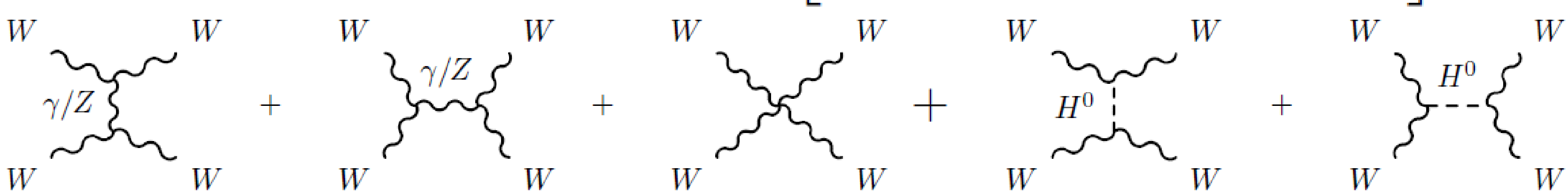


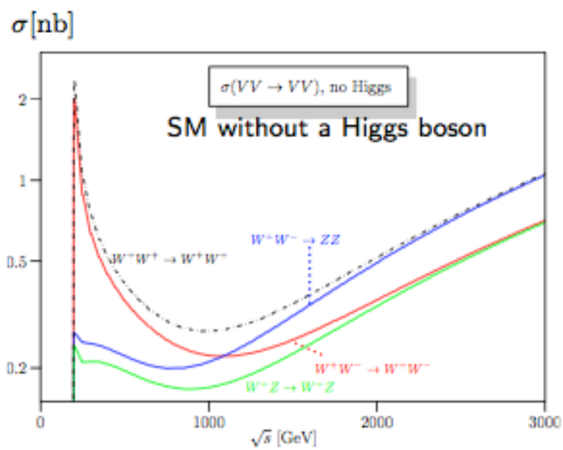


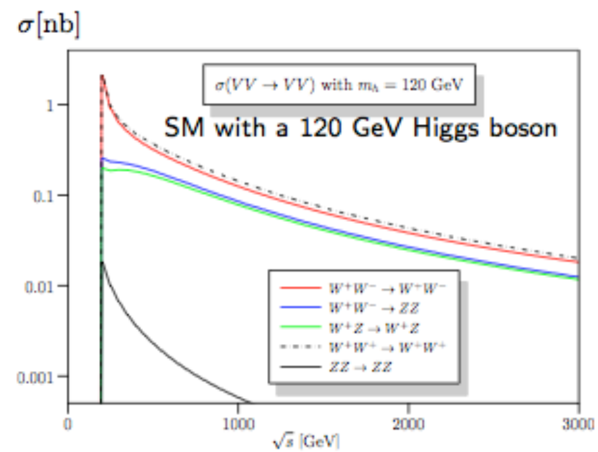
Vector Boson Scattering and EWSB

- Vector Boson scattering is an important process to study in order to probe the nature of electroweak symmetry breaking (EWSB).
- EWSB in SM with Higgs essential to preserve VV scattering cross section unitarity

$$\mathcal{A}(W_L W_L \to W_L W_L) \propto \frac{g_W^2}{v^2}\left[-s - t + \frac{s^2}{s-m_H^2} + \frac{t^2}{t-m_H^2}\right]$$



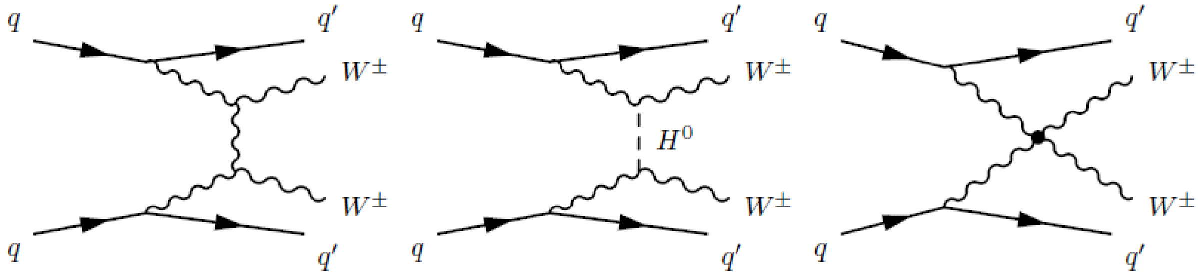




arXiv:0806.4145

VV jj Production via VBS

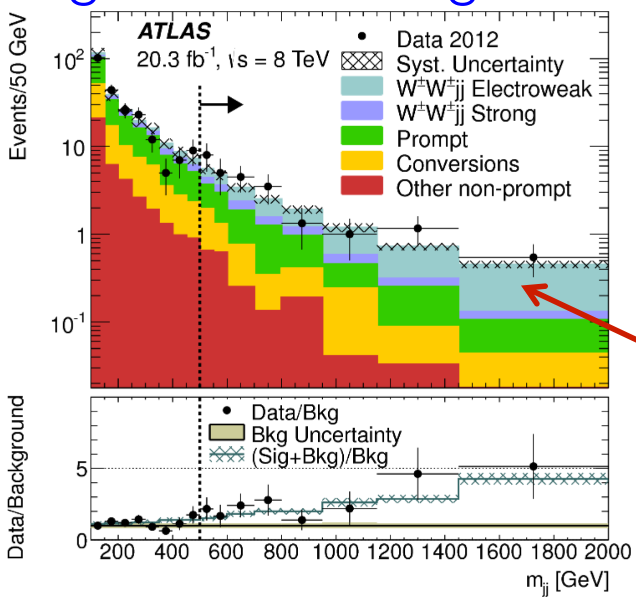
- At hadron colliders VBS can be seen as an interaction of gauge bosons radiated from initial state quarks, yielding two vector bosons (VV) and two jets (jj) in the final state.

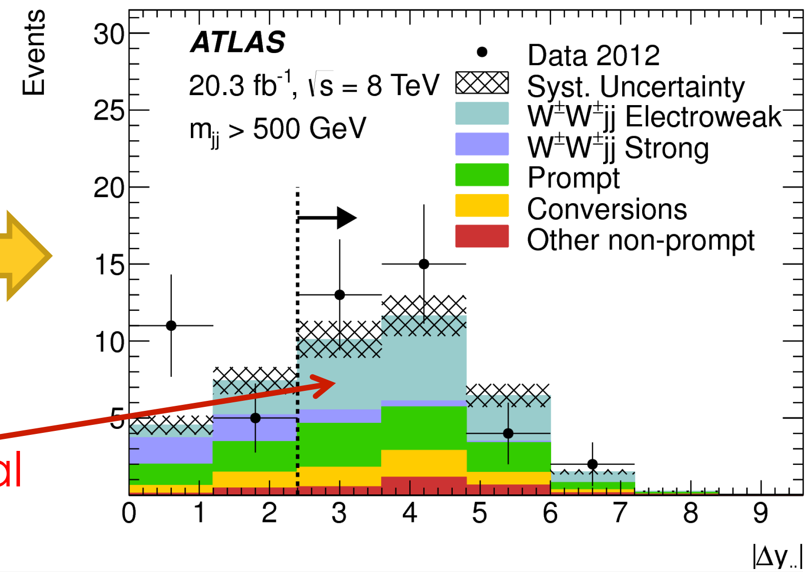


- The VVjj final state can have contributions from strong production processes as well
- In case of same-sign WW +jj, the strong production background is small enough to make this channel attractive at the LHC

W±W± jj Production (ATLAS)

- Both CMS and ATLAS have searched 8 TeV data for same sign WW + 2 jets
- ATLAS analysis defines dijet_mass>500 GeV, rapidity-gap> 2.4 as the signal rich VBS region





signal

VBS Signal Region	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	Total
$W^\pm W^\pm$jj Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^\pm W^\pm$jj Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
$WZ/\gamma^*, ZZ, t\bar{t} + W/Z$	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W + \gamma$	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	6	18	10	34

- Good agreement with SM in signal and control region.
- Background mainly from real multi-lepton processes

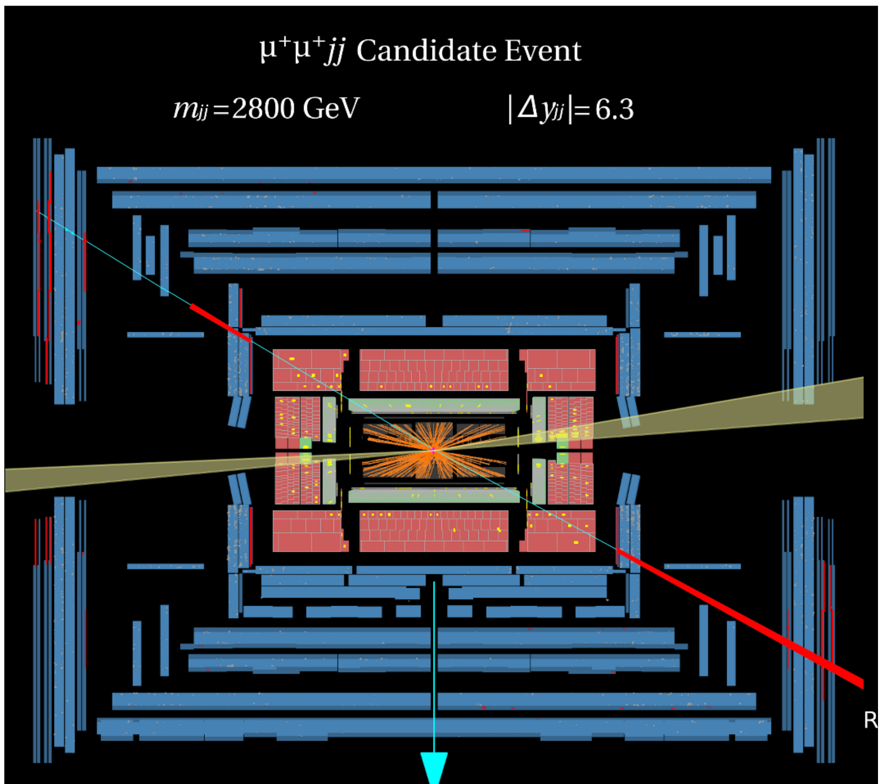
Evidence for EWK $W^{\pm}W^{\pm}jj$ Scattering

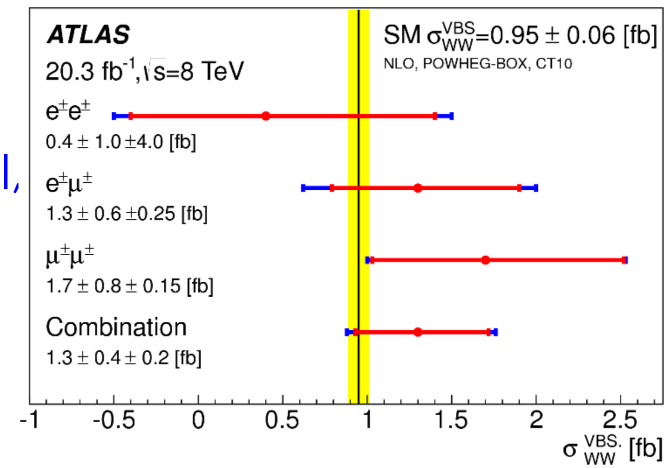
arxiv:1405.6241

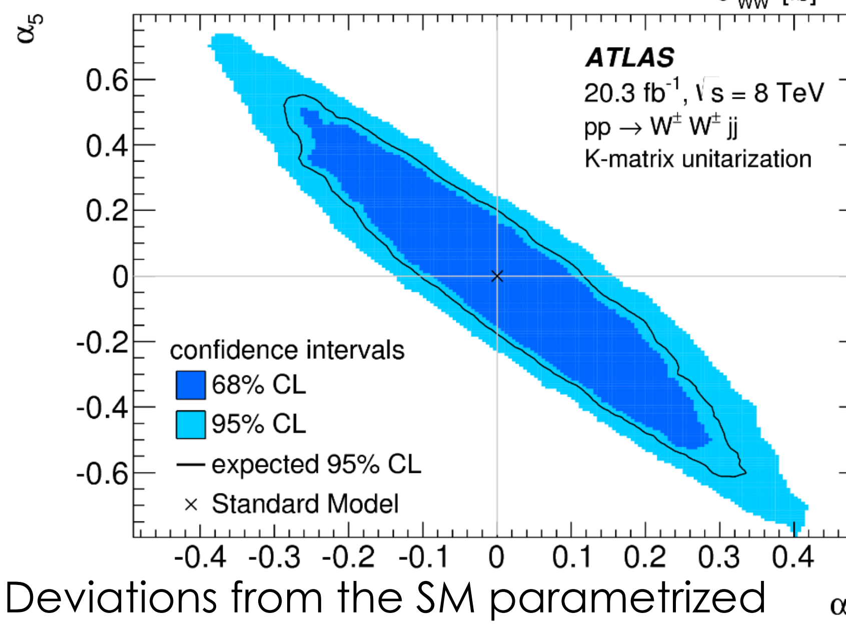
SM-like cross section with **3.6 σ significance (2.8 expected)**

First evidence for vector boson scattering!

Limits obtained on aQGCs in a unitarized model, $\Lambda \approx 650$ GeV for $c \approx 1$







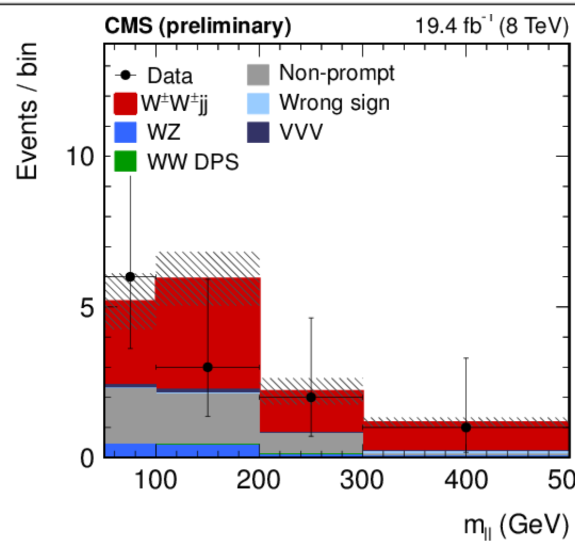
Deviations from the SM parametrized

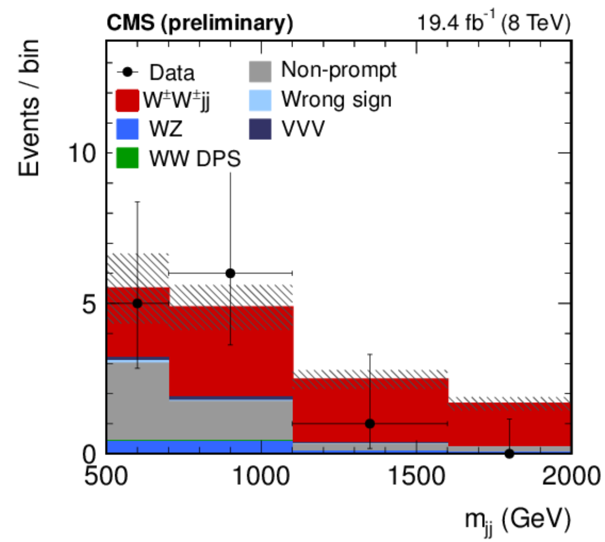
$W^{\pm}W^{\pm}jj$ Production (CMS)

◆ CMS Analysis (19.4 fb^{-1}): CMS-PAS-SMP-13-015

- > 500 GeV dijet mass and 2.5 dijet rapidity gap, with top veto, Z veto, and dilepton mass > 50 GeV defined as VBS signal region
- Most remaining background is fake/non-prompt leptons
- Observed events agree with SM predictions

	Data	$W^{\pm}W^{\pm}jj$	Total bkg.	Non-prompt	WZ	VVV	Wrong sign	WW DPS
$W^{\pm}W^{\pm}$	12	8.8 ± 0.2	5.7 ± 0.8	4.2 ± 0.8	1.0 ± 0.1	0.3 ± 0.1	0.1 ± 0.08	0.1 ± 0.1
$W^{+}W^{+}$	10	7.0 ± 0.2	3.1 ± 0.6	2.1 ± 0.6	0.6 ± 0.1	0.2 ± 0.1	0.1 ± 0.08	0.1 ± 0.1
$W^{-}W^{-}$	2	1.8 ± 0.1	2.6 ± 0.6	2.1 ± 0.5	0.4 ± 0.1	0.1 ± 0.1	—	—





2.0σ excess from VBS (3.1 expected)

4.0+2.4−2.0 (stat) +1.1−1.0 (syst) fb

(p_T^{ℓ}>10 GeV, $|\eta_\ell|$<2.5
p_T^{j}>20 GeV, $|\eta j|$<5.0
M_{jj}>300 GeV, $|\Delta\eta_{jj}|$>2.5)

VBFNLO: 5.8 ± 1.2 fb

Summary

- ◆Precision electroweak measurements at the LHC can provide indirect access to new physics beyond the SM
- ◆Many impressive results on single- and multi- vector boson production and properties obtained by ATLAS and CMS from data at 7 TeV and 8 TeV LHC runs
- ◆First evidence for EWK vector boson scattering (VBS) seen by ATLAS in $W^{\pm}W^{\pm}jj$ production
- ◆LHC poised to directly test electroweak symmetry breaking. Exploring VBS at higher energies is complementary to studying Higgs properties in order to understand EWSB.

CMS, ATLAS public results:

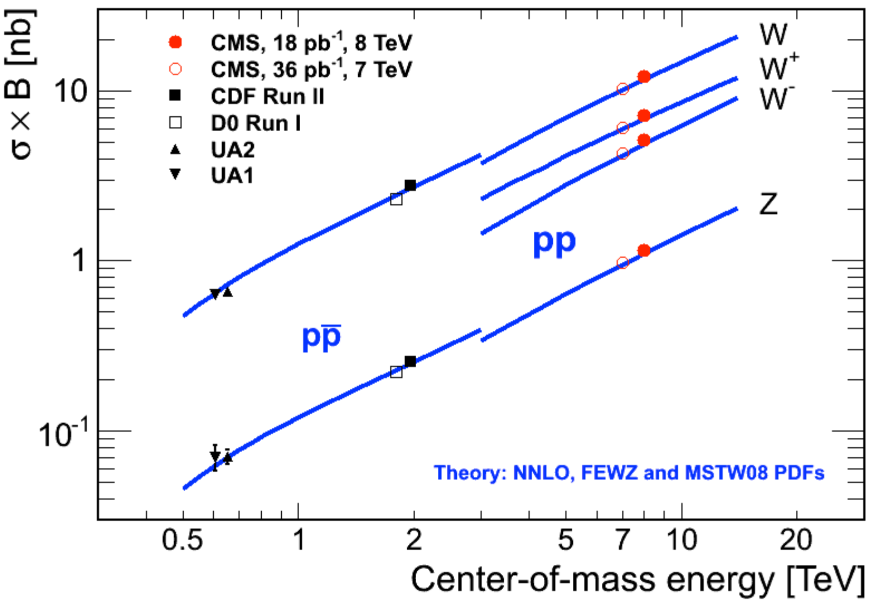
- ❖ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- ❖ https://twiki.cern.ch/twiki/bin/view/AtlasPublic

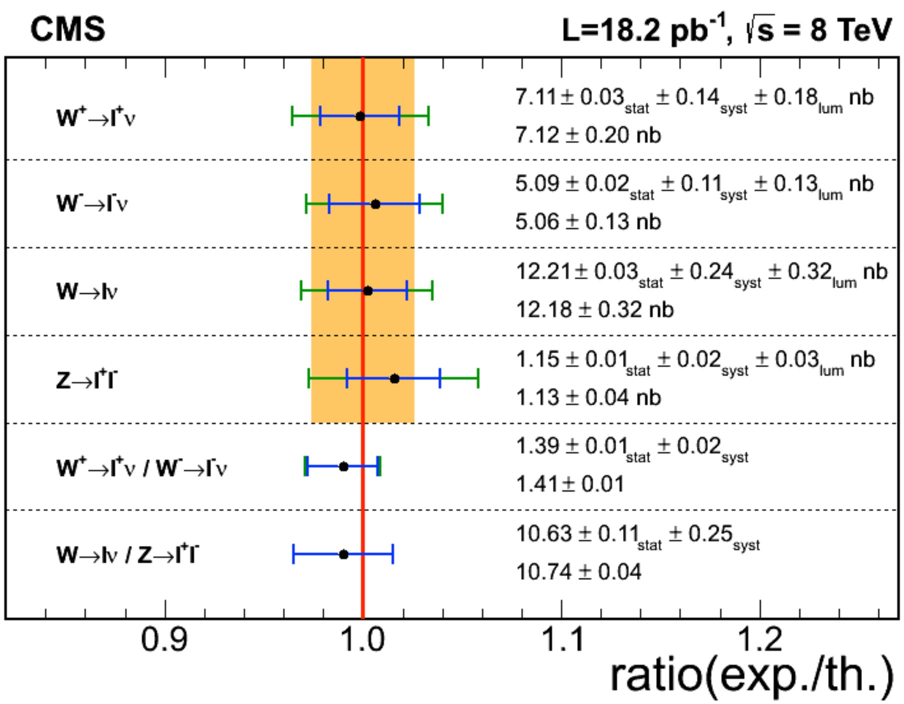
BACK-UP SLIDES

W, Z Cross Sections

CMS-SMP-12-011

arXiv:1402.0923





<u>Systematic uncertainties:</u>

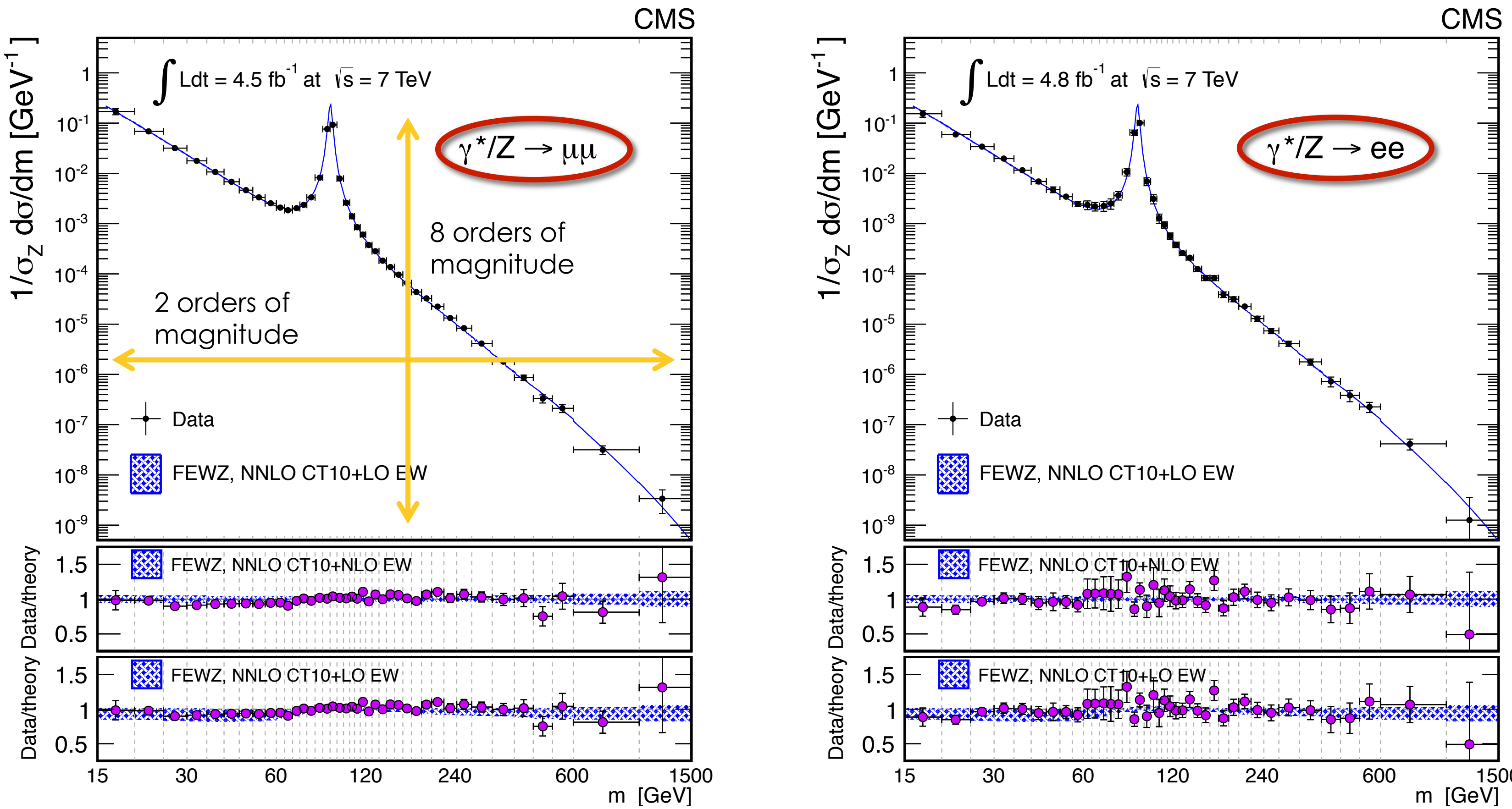
lepton efficiency (1-3%), momentum (energy) scale (0.3-0.7%), MET modeling (0.5-0.8%), background subtraction (0.2-0.3%)

theoretical uncertainty (acceptance): ~2 -2.5 %

luminosity: 2.6%

Drell-Yan Cross Section at 7 TeV (CMS)

ee and μμ channels

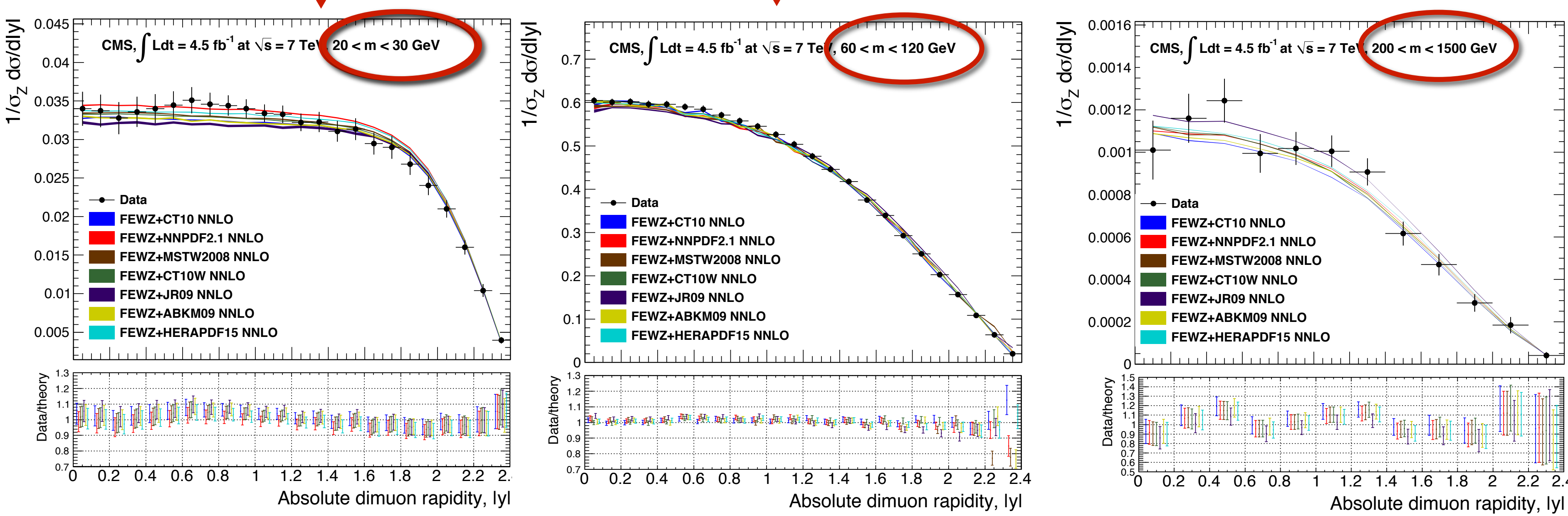


Differential Cross-section at 7 TeV

- $d\sigma/dy$ for Drell-Yan in different mass bins from CMS

In the low mass bin, data errors similar to spread from PDFs

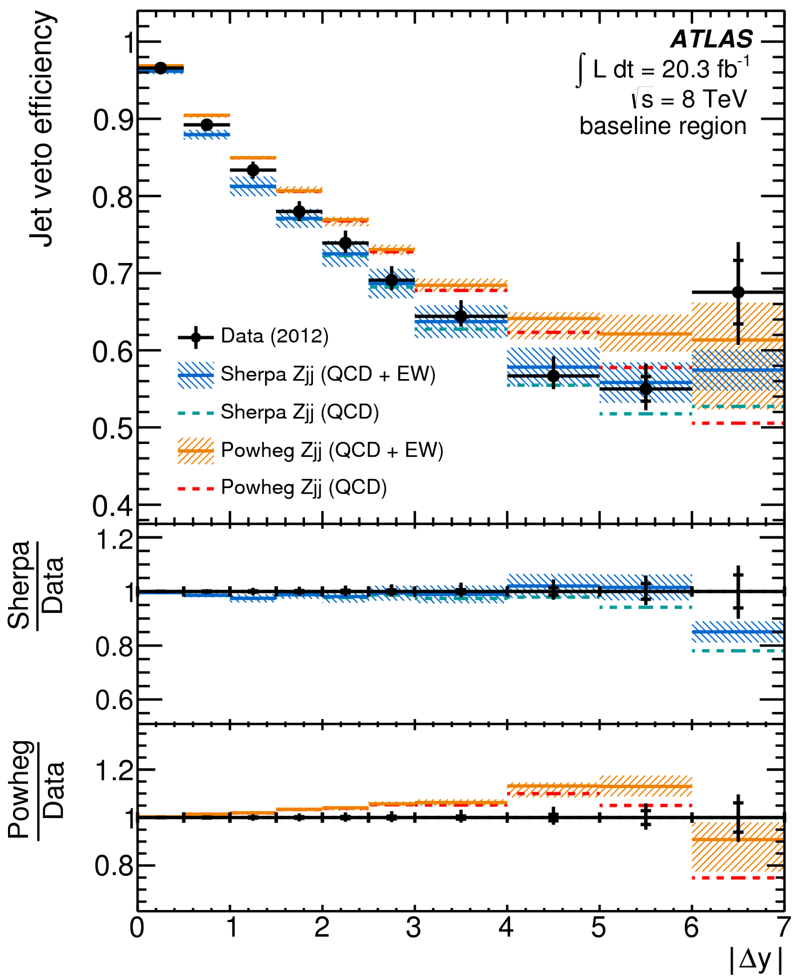
Very small errors in the Z peak bin

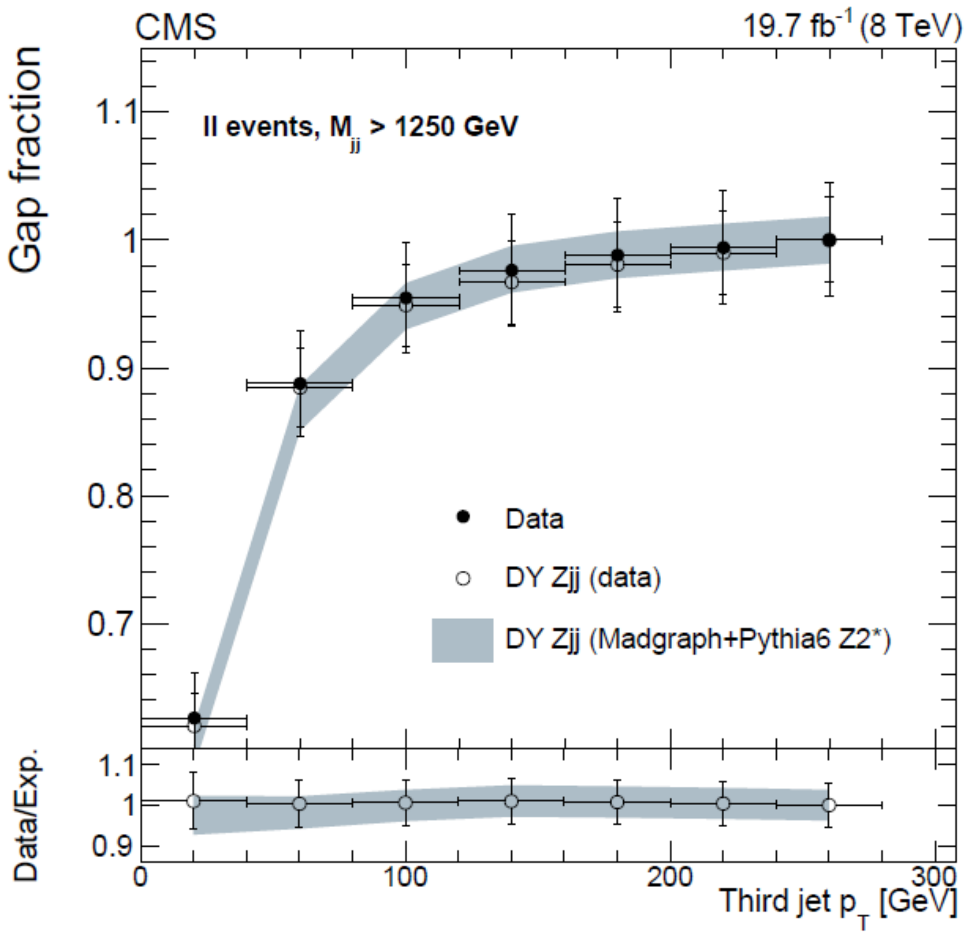


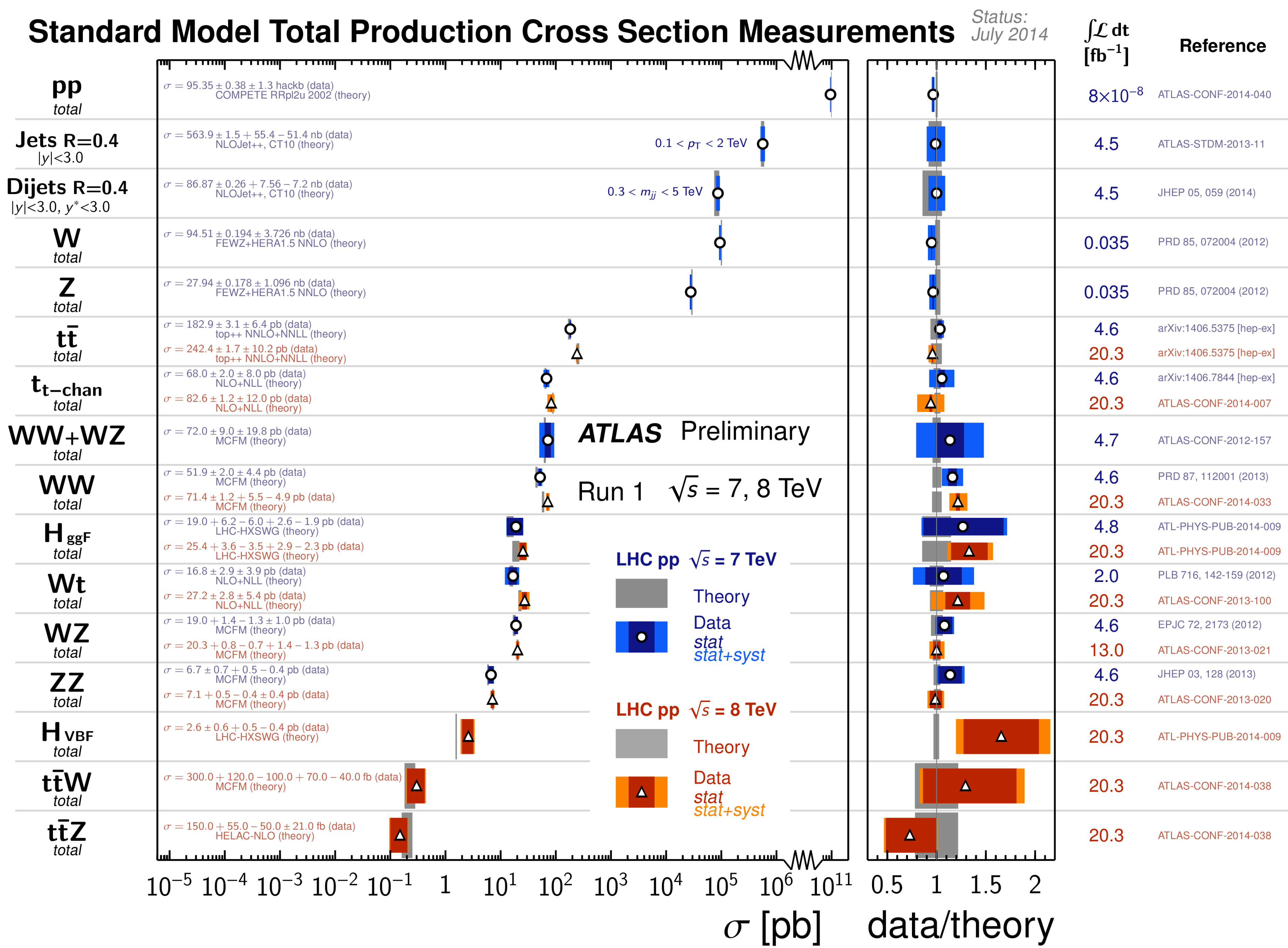
Electroweak Z + 2 jet production

JHEP 04 (2014) 031
JHEP 10 (2013) 062
CMS 8 TeV to be submitted

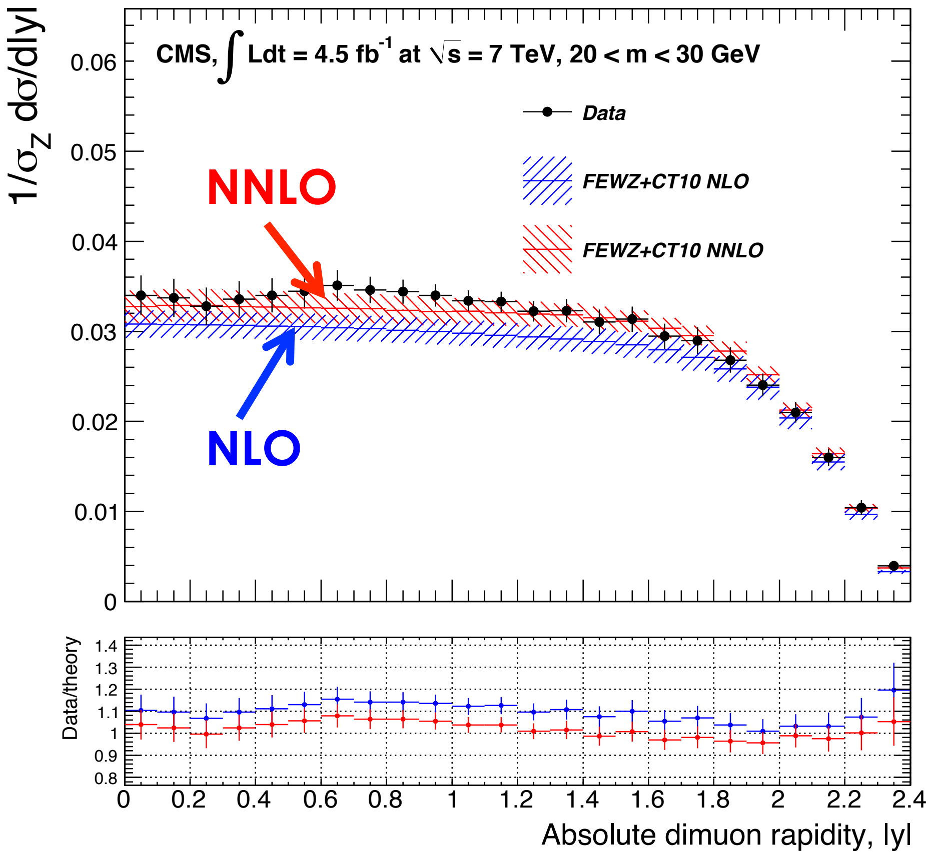
- **Now a laboratory for studying generator behavior in VBF/VBS context!**
- TGC limits obtained from ATLAS less stringent than diboson

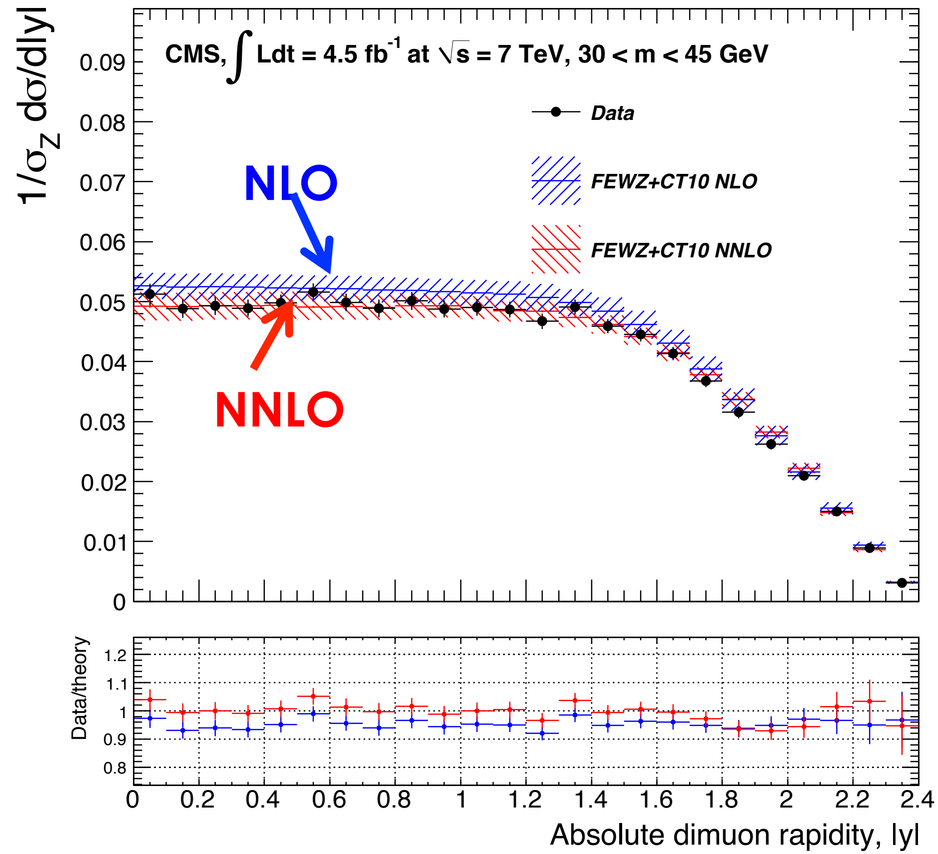





Standard Model Total Production Cross Section Measurements
Status: July 2014
∫ℒ dt [fb⁻¹]
Reference
pp total
σ = 95.35 ± 0.38 ± 1.3 hackb (data)
COMPETE RRpl2u 2002 (theory)
8×10⁻⁸
ATLAS-CONF-2014-040
Jets R=0.4 |y|<3.0
σ = 563.9 ± 1.5 + 55.4 − 51.4 nb (data)
NLOJet++, CT10 (theory)
0.1 < pT < 2 TeV
4.5
ATLAS-STDM-2013-11
Dijets R=0.4 |y|<3.0, y*<3.0
σ = 86.87 ± 0.26 + 7.56 − 7.2 nb (data)
NLOJet++, CT10 (theory)
0.3 < mjj < 5 TeV
4.5
JHEP 05, 059 (2014)
W total
σ = 94.51 ± 0.194 ± 3.726 nb (data)
FEWZ+HERA1.5 NNLO (theory)
0.035
PRD 85, 072004 (2012)
Z total
σ = 27.94 ± 0.178 ± 1.096 nb (data)
FEWZ+HERA1.5 NNLO (theory)
0.035
PRD 85, 072004 (2012)
tt̄ total
σ = 182.9 ± 3.1 ± 6.4 pb (data)
top++ NNLO+NNLL (theory)
4.6
arXiv:1406.5375 [hep-ex]
σ = 242.4 ± 1.7 ± 10.2 pb (data)
top++ NNLO+NNLL (theory)
20.3
arXiv:1406.5375 [hep-ex]
tt−chan total
σ = 68.0 ± 2.0 ± 8.0 pb (data)
NLO+NLL (theory)
4.6
arXiv:1406.7844 [hep-ex]
σ = 82.6 ± 1.2 ± 12.0 pb (data)
NLO+NLL (theory)
20.3
ATLAS-CONF-2014-007
WW+WZ total
σ = 72.0 ± 9.0 ± 19.8 pb (data)
MCFM (theory)
4.7
ATLAS-CONF-2012-157
WW total
σ = 51.9 ± 2.0 ± 4.4 pb (data)
MCFM (theory)
4.6
PRD 87, 112001 (2013)
σ = 71.4 ± 1.2 + 5.5 − 4.9 pb (data)
MCFM (theory)
20.3
ATLAS-CONF-2014-033
H ggF total
σ = 19.0 + 6.2 − 6.0 + 2.6 − 1.9 pb (data)
LHC-HXSWG (theory)
4.8
ATL-PHYS-PUB-2014-009
σ = 25.4 + 3.6 − 3.5 + 2.9 − 2.3 pb (data)
LHC-HXSWG (theory)
20.3
ATL-PHYS-PUB-2014-009
Wt total
σ = 16.8 ± 2.9 ± 3.9 pb (data)
NLO+NLL (theory)
2.0
PLB 716, 142-159 (2012)
σ = 27.2 ± 2.8 ± 5.4 pb (data)
NLO+NLL (theory)
20.3
ATLAS-CONF-2013-100
WZ total
σ = 19.0 + 1.4 − 1.3 ± 1.0 pb (data)
MCFM (theory)
4.6
EPJC 72, 2173 (2012)
σ = 20.3 + 0.8 − 0.7 + 1.4 − 1.3 pb (data)
MCFM (theory)
13.0
ATLAS-CONF-2013-021
ZZ total
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data)
MCFM (theory)
4.6
JHEP 03, 128 (2013)
σ = 7.1 + 0.5 − 0.4 ± 0.4 pb (data)
MCFM (theory)
20.3
ATLAS-CONF-2013-020
H VBF total
σ = 2.6 ± 0.6 + 0.5 − 0.4 pb (data)
LHC-HXSWG (theory)
20.3
ATL-PHYS-PUB-2014-009
tt̄W total
σ = 300.0 + 120.0 − 100.0 + 70.0 − 40.0 fb (data)
MCFM (theory)
20.3
ATLAS-CONF-2014-038
tt̄Z total
σ = 150.0 + 55.0 − 50.0 ± 21.0 fb (data)
HELAC-NLO (theory)
20.3
ATLAS-CONF-2014-038
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Data
stat
stat+syst
LHC pp √s = 8 TeV
Theory
Data
stat
stat+syst
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1 1.5 2
data/theory

Sensitivity to higher order corrections



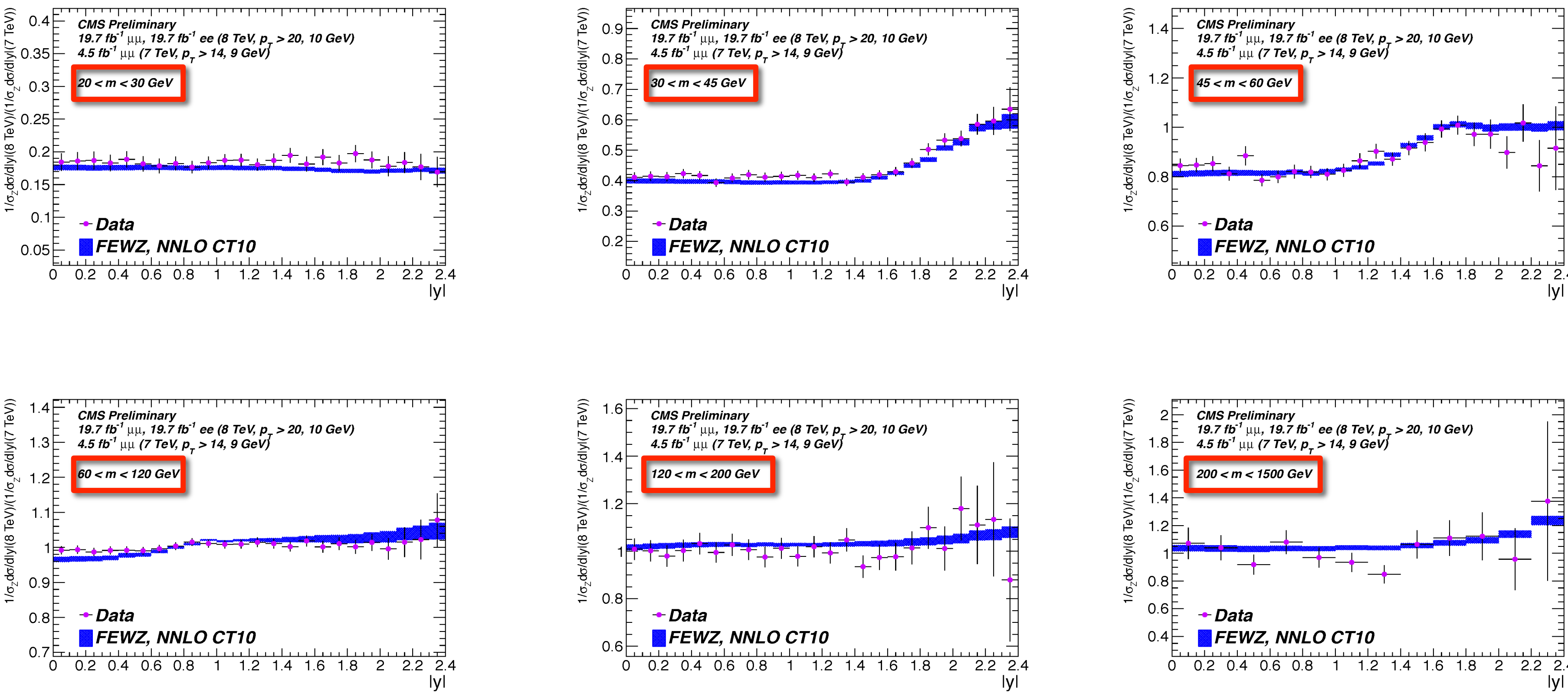


As in ATLAS, better agreement with NNLO in lower mass range

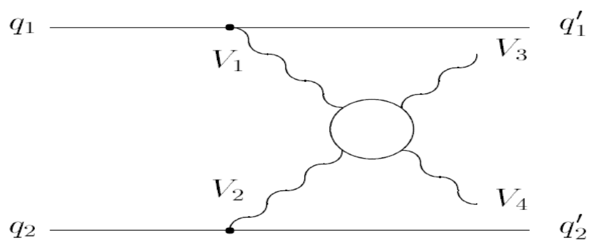
Double Differential Cross Section Ratio

$$R_{8TeV/7TeV}(pp \rightarrow \gamma^* / Z \rightarrow ll) = \frac{1/\sigma_Z d\sigma / dMdY(8TeV, p_T > 20{,}10GeV)}{1/\sigma_Z d\sigma / dMdY(7TeV, p_T > 14{,}9GeV)}$$

Good agreement with predictions, in general



VV scattering: future prospects

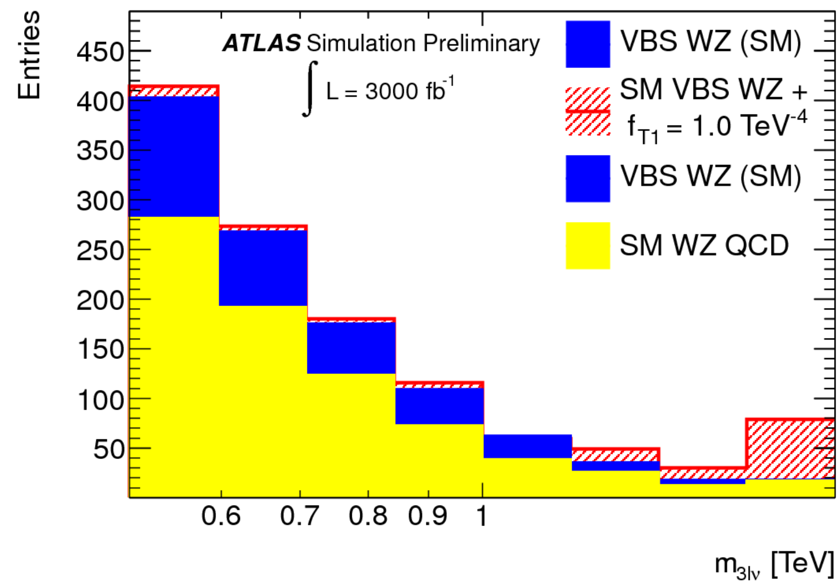


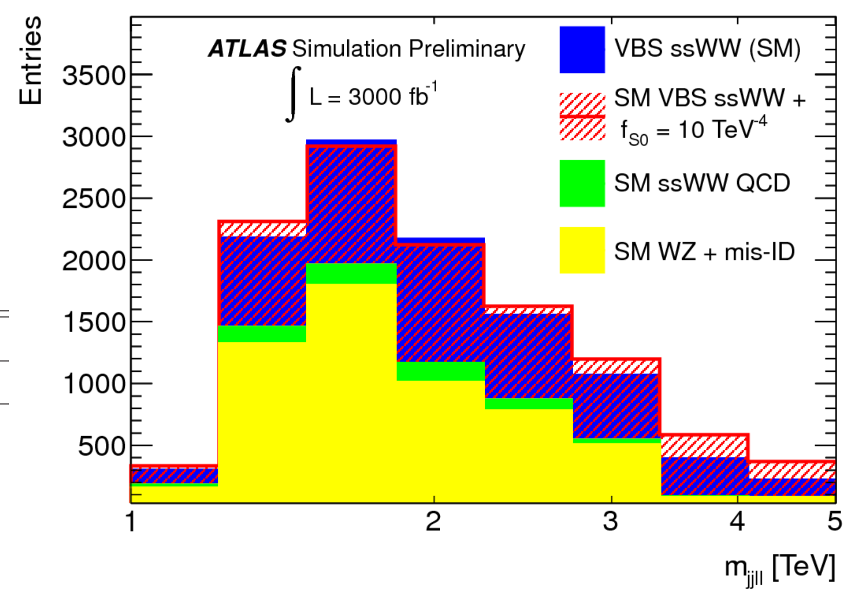
Snowmass study to understand VBS potential of LHC Run2+

Select 3 lepton or same-sign dilepton events with "VBF dijet" (dijet mass > 1 TeV)

Several modes expected to be observed with < 300/fb

5 sigma anomalous dim 8 production





Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}	
				5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}

Effective Field Theory and Boson Interactions

- For generic new physics effects descended from some high energy scale Λ, explore **operator product expansion with Wilson coefficients c_i**

- Before EWSB, 5 gauge boson interaction terms respect gauge invariance (3 CP even + 2 CP odd)

- After EWSB, induces **trilinear VVV', VV'H, and quartic interactions** with correlated coefficients.

- At dim 6, expect WWγ, WWZ interactions with **3 CP-even parameters (g_1, κ, λ)**

- **Manifested as high mass/momentum production tails**

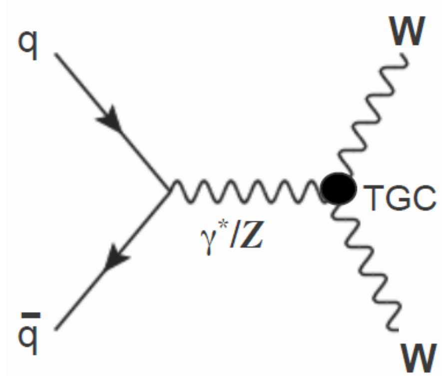
UNBROKEN

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

$$\left[\begin{aligned} \mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu] \\ \mathcal{O}_W &= (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \\ \mathcal{O}_B &= (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) \\ \mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu} W^{\nu\rho} W_\rho^\mu] \\ \mathcal{O}_{\tilde{W}} &= (D_\mu \Phi)^\dagger \tilde{W}^{\mu\nu} (D_\nu \Phi) \end{aligned}\right]$$

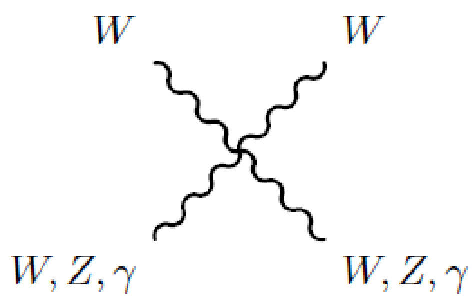
BROKEN

$$\begin{aligned} \mathcal{L} = i g_{WWV} \Big(& g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \\ & \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho \\ & + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \Big) \end{aligned}$$



Quartic Gauge Boson Couplings

- SM has four quartic interactions at tree level
  - WWWW, WWZZ, WW$\gamma\gamma$, WWZγ



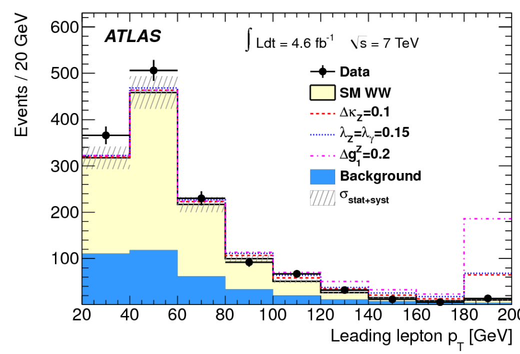
- Neutral 4 boson vertices can be nonzero, though not predicted in the SM at tree level.
  - ZZZZ, ZZZγ, ZZ$\gamma\gamma$, Z$\gamma\gamma\gamma$

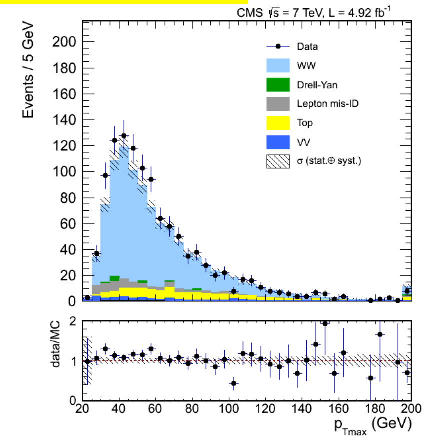
- Manifested as triboson or vector-boson scattering

WW Production (7 TeV)

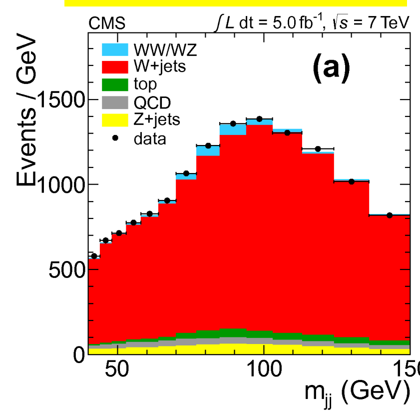
- Thousands of candidates in dilepton channel
- Leading p_T shows no anomalous contribution
- Signficant diboson signal in semileptonic channel

WW @7 TeV
leading lepton PT

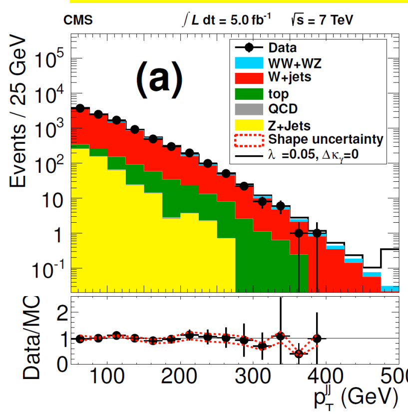




W dijet
dijet mass, 7 TeV



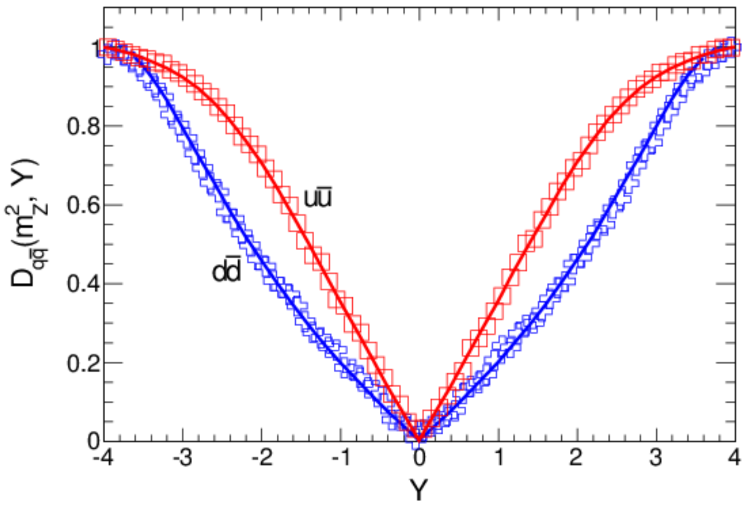
W dijet 7 TeV
PT



Weak Mixing Angle at the LHC

◆The parton-level cross section for $q\bar{q} \to Z \to \ell\ell$

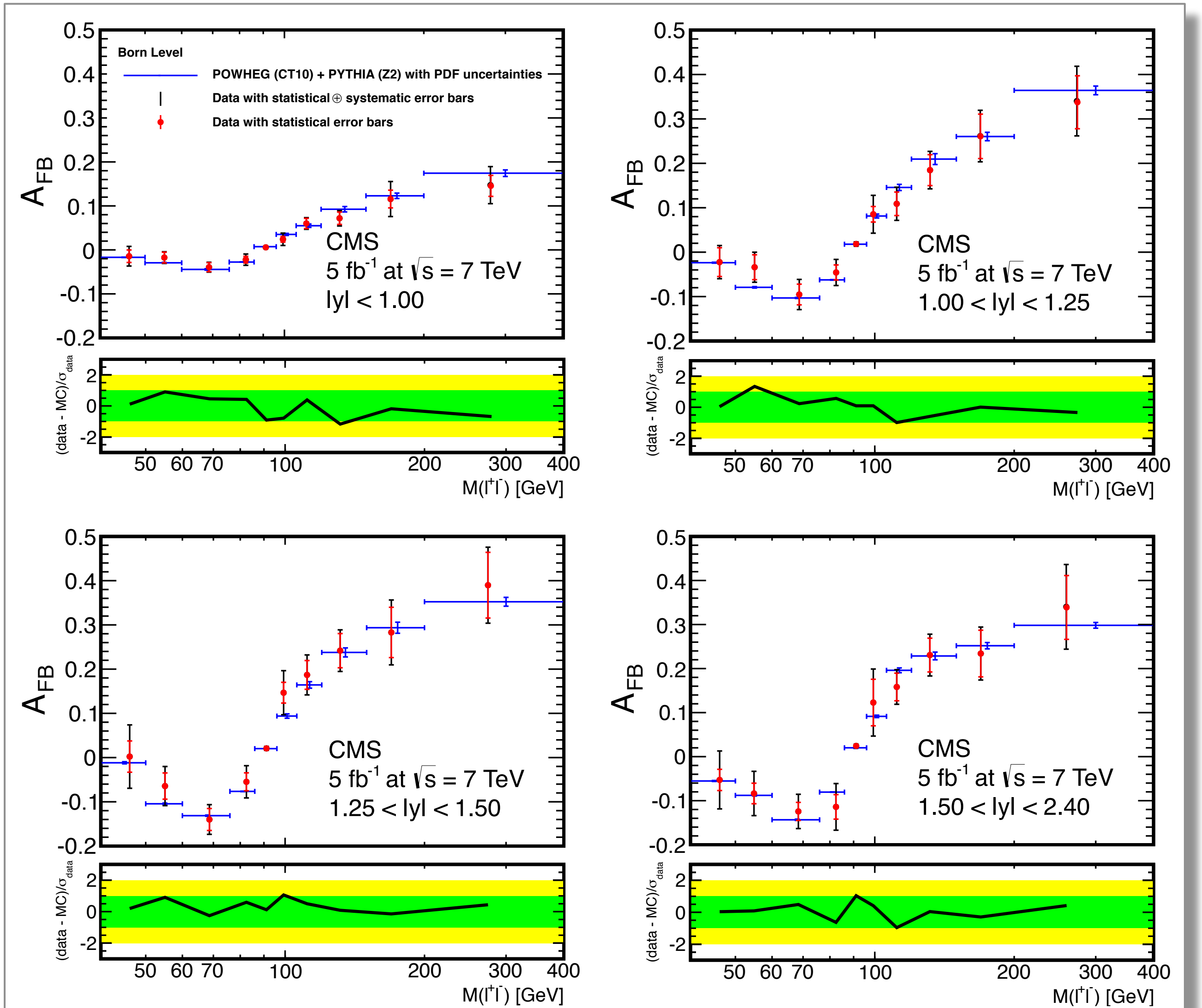
$$\hat{\sigma}_{q\bar{q}}(\hat{s}, \cos\theta^*; \theta_W) \propto \frac{3(\rho_V^{q\bar{q}\to\gamma})^2(\rho_V^{\gamma\to\ell\ell})^2}{2\hat{s}} \times (1+\cos^2\theta^*) + \frac{3}{2}\frac{\hat{s}}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$
$$\times [((\rho_V^{q\bar{q}\to Z})^2 + (\rho_A^{q\bar{q}\to Z})^2)((\rho_V^{Z\to\ell\ell})^2 + (\rho_A^{Z\to\ell\ell})^2)(1+\cos^2\theta^*) + 8\rho_V^{q\bar{q}\to Z}\rho_A^{q\bar{q}\to Z}\rho_V^{Z\to\ell\ell}\rho_A^{Z\to\ell\ell}\cos\theta^*]$$
$$+ \frac{3(\hat{s}-m_Z^2)\rho_V^{q\bar{q}\to\gamma}\rho_V^{\gamma\to\ell\ell}}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \times [\rho_V^{q\bar{q}\to Z}\rho_V^{Z\to\ell\ell}(1+\cos^2\theta^*) + 2\rho_A^{q\bar{q}\to Z}\rho_A^{Z\to\ell\ell}\cos\theta^*]. \quad (\!$$



The odd Cosθ* terms give rise to dilution in pp

Forward-Backward Asymmetry

- CMS did measure A_{FB} in an independent analysis.
- 5 fb^{-1}, 7 TeV
  >1 M events
  4 rapidity bins
- Subtract backgrounds, unfold F and B separately, correct for dilution, ..



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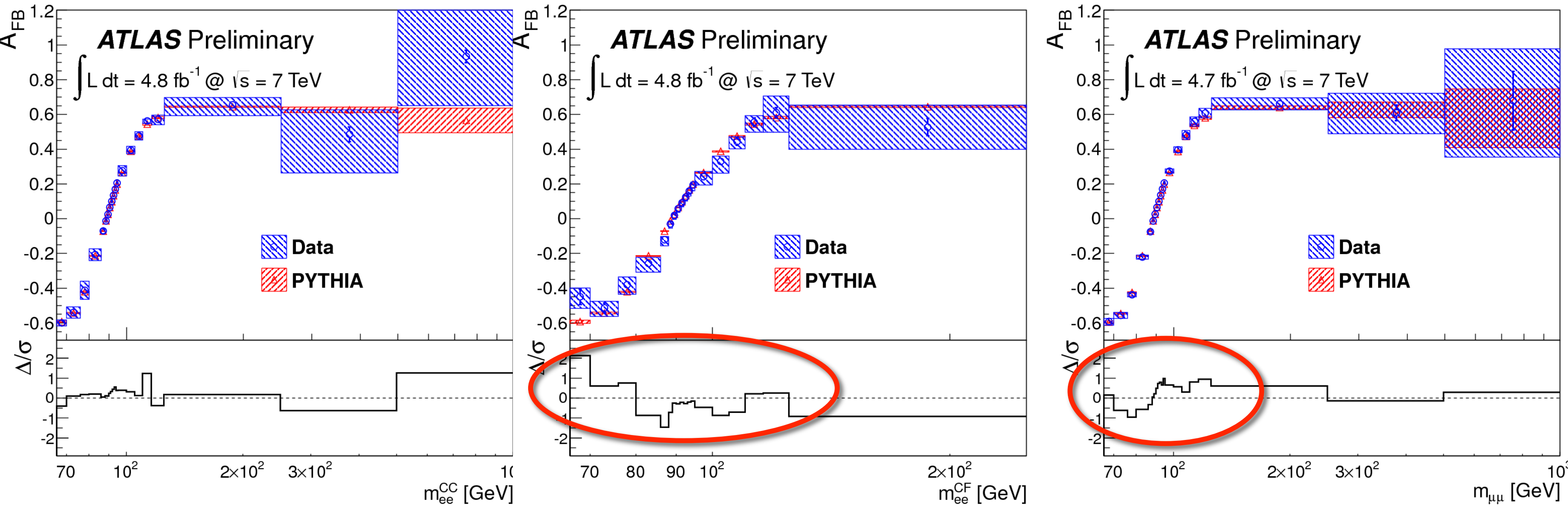
A_{FB} and $\sin^2\theta_W$ from ATLAS

- 5 fb^{-1} at $\sqrt{s}$ =7 TeV, both ee, $\mu\mu$
  central-central ee, $\mu\mu$ and central-forward ee pairs
- Unfold and correct for detector effects, QED FSR and dilution



ATLAS-CONF-2013-043

Discrepancies at low mass