Results on Electroweak Precision Measurements from CMS

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On behalf of the CMS Collaboration

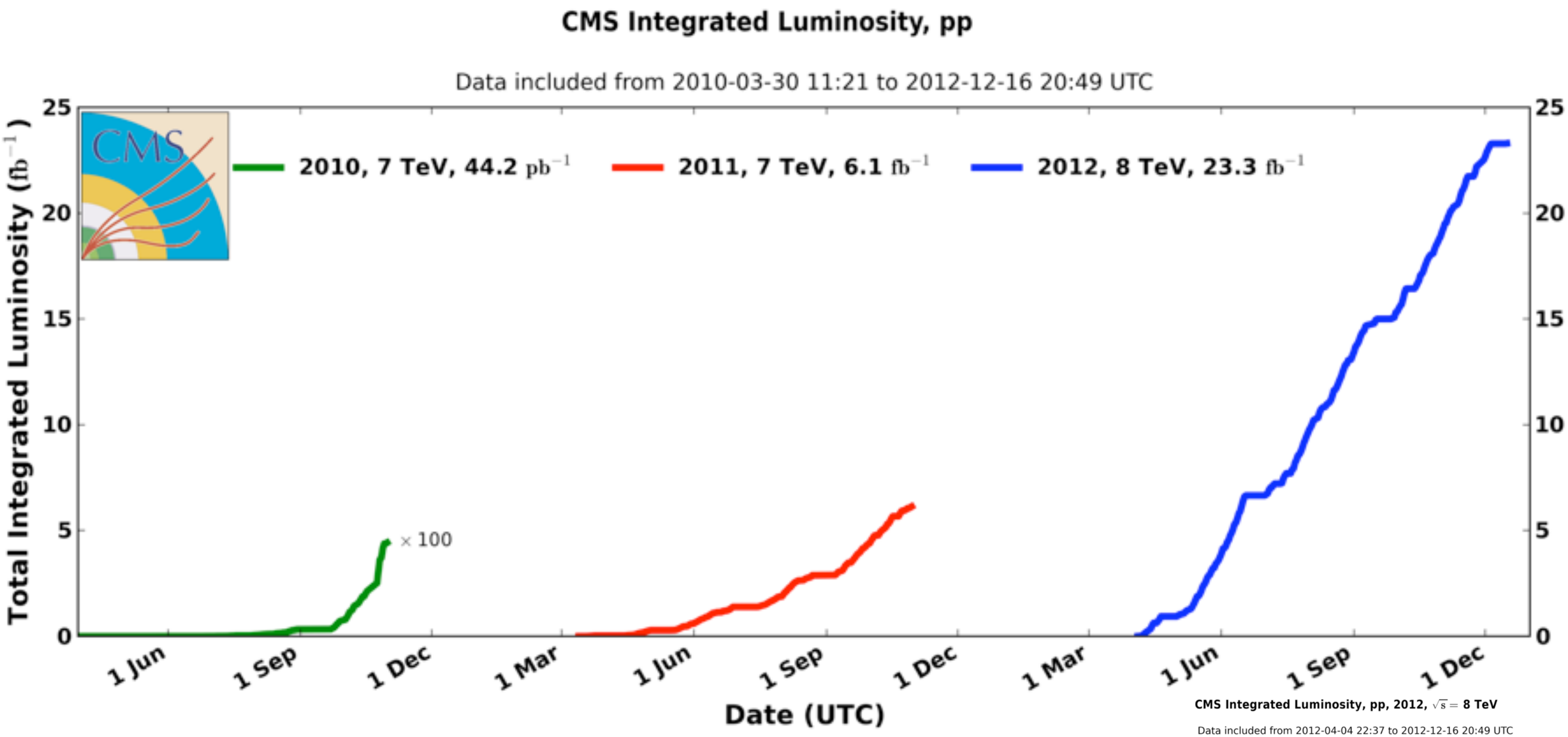
Exploring Fundamental Interactions in the Higgs Era

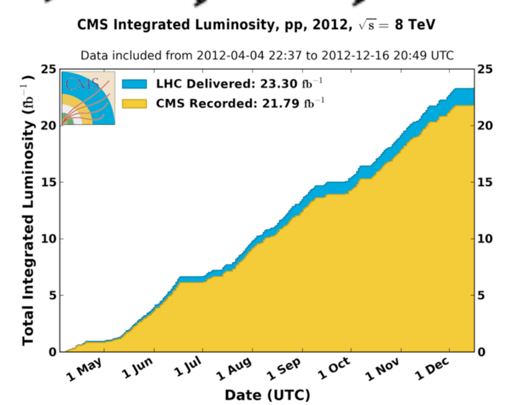
Brookhaven Forum 2013, May 1-3, 2013, Upton, NY

Outline

- Introduction
- Electroweak measurements
  - Inclusive W and Z cross section measurements
  - Cross section ratios
  - W lepton charge asymmetry
  - Drell-Yan differential and double-differential cross section
  - Z/γ^{*}+jets cross section
  - W/Z+b-jets production
  - Diboson production
  - Anomalous gauge couplings
- Summary

Data Collected

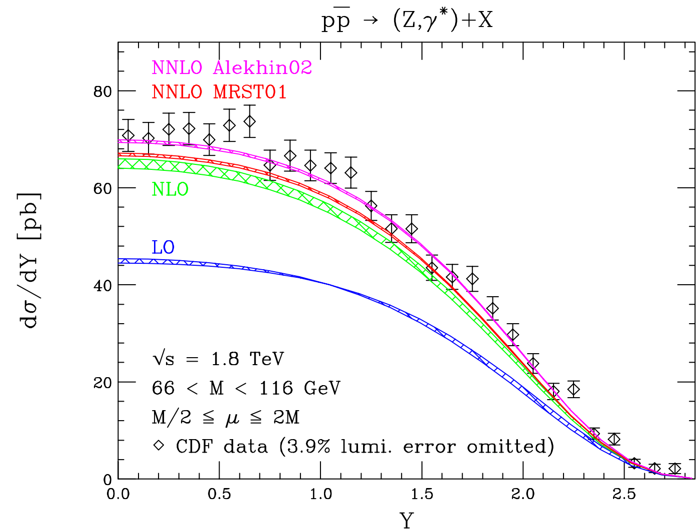




- Measurements are from 7 TeV and 8 TeV pp collisions
  - Most of the measurements are from the 7 TeV running period
  - I will highlight new results from 8 TeV running period
- All results shown can be found at:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Introduction (I)

- EWK physics plays a significant role in understanding the EWSB
  - A window to new physics
- W and Z decays are special final states:
  - They are used to understand and calibrate the detector response (trigger, identification, resolution, efficiencies)
  - They are dominant signal and/or background in many searches for new particles
- Experimentally the $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ channels are among the cleanest final states that we can exploit at hadron colliders
- We have now accurate theoretical tools at our disposal:
  - NLO MC generators (MC@NLO, POWHEG, ...). These generators should provide more accurate predictions than LO MCs for these processes (at the few percent level)
  - Integration of matrix element MCs with parton shower generators in a consistent way at NLO
  - NNLO theoretical predictions for cross section and kinematic studies are also available (FEWZ, DYNNLO, RESBOS)
  - Inclusive and differential calculation of cross sections at NNLO precision



Introduction (II)

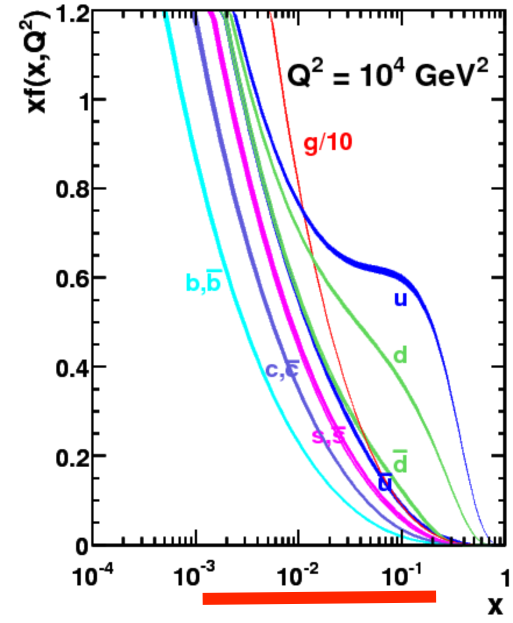
- W and Z production at LHC proceeds at the hard scattering level and first order via collisions of a valence quark (u,d) and a sea anti-quark (Q≈100 GeV):

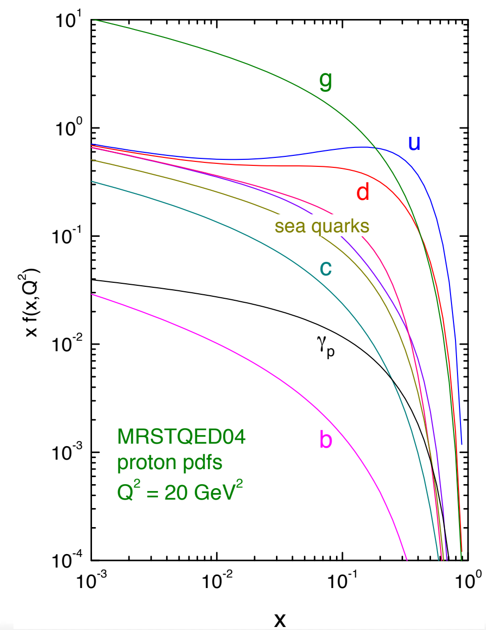
$$u + \bar{d}(\bar{s}) \rightarrow W^{+} \qquad u + \bar{u} \rightarrow Z$$

$$d + \bar{u}(\bar{c}) \rightarrow W^{-} \qquad d + \bar{d} \rightarrow Z$$

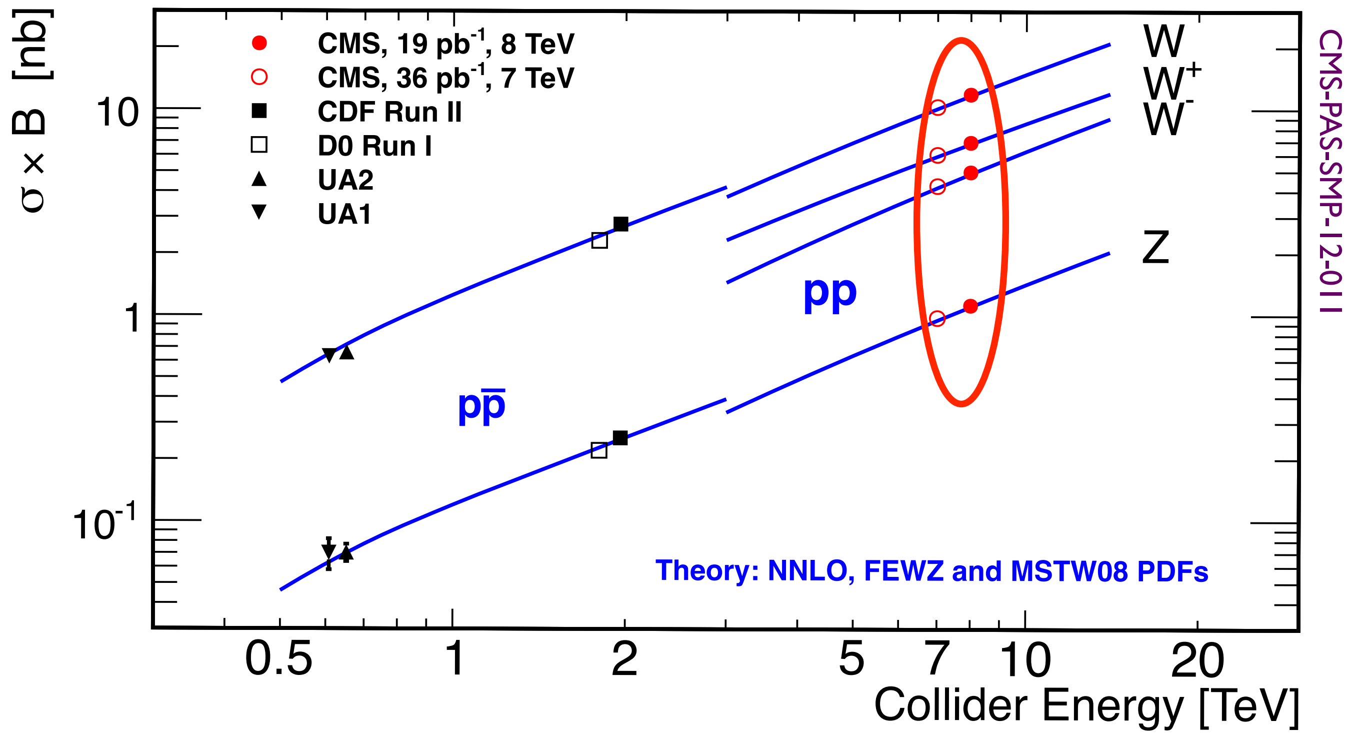
- Since parton fractions in this process are typically $10^{-3} < x < 10^{-1}$, sea-sea qq contributions are also important
- Provide access to central parameters for global EWK fit (masses, couplings, asymmetries)
- Provide powerful constraints for non-perturbative part (PDFs, tunes)

$$Q^2 = m_{W,Z}^2 = x_1 x_2 s$$





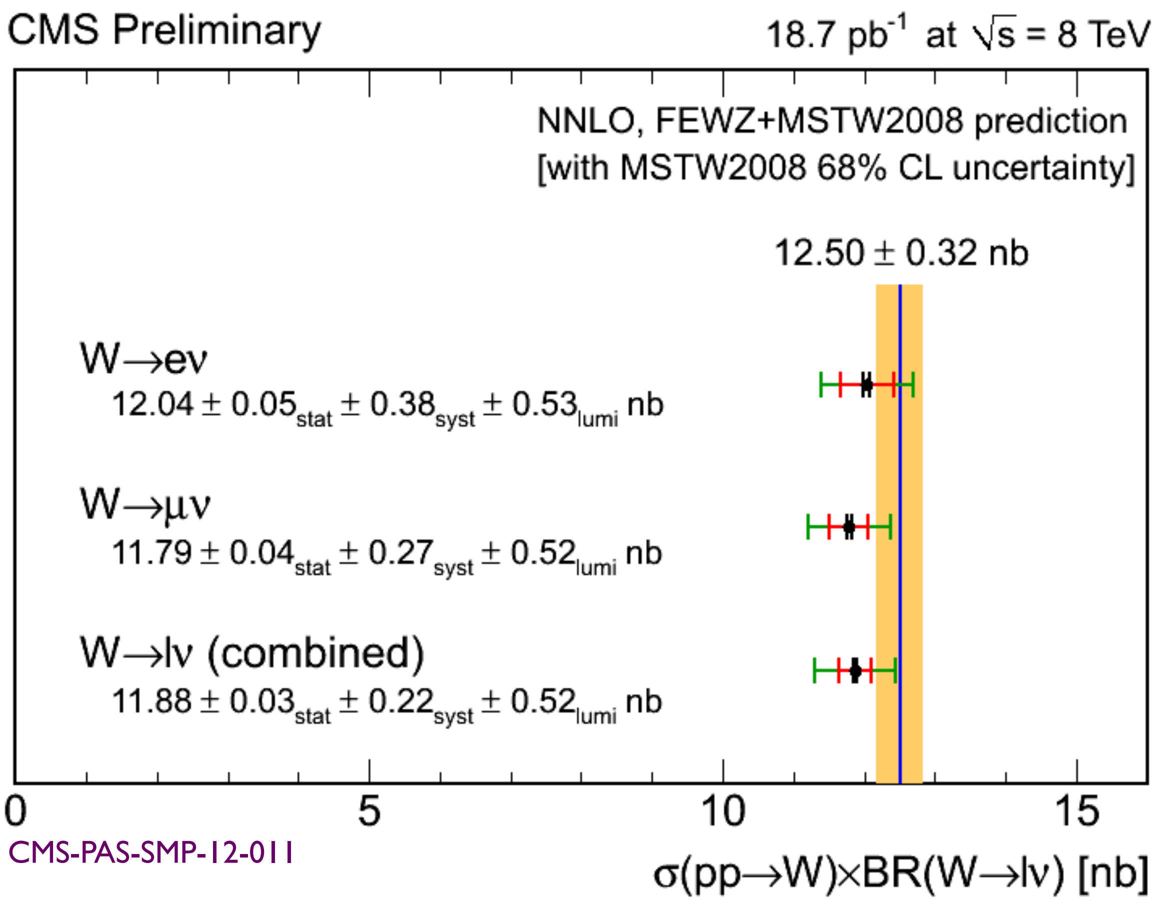
W & Z Production vs. √s



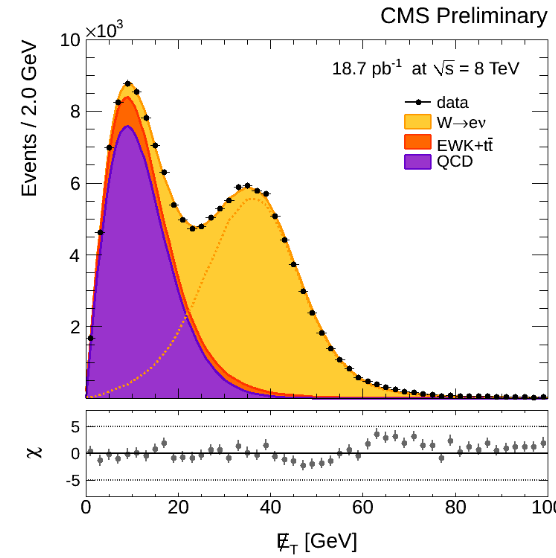
- From pQCD prediction we expect an increase of the cross section of 15 - 20 % from 7 to 8 TeV
- 7 TeV cross sections measured with 1% precision (with 36 pb^{-1})
- 8 TeV results from dedicated low pile-up run early in 2012
- Measure the W/Z, W^+/W^- ratios and the 7/8 TeV ratio to test pQCD
- Good overall agreement with theory predictions at NNLO both at 7 and 8 TeV

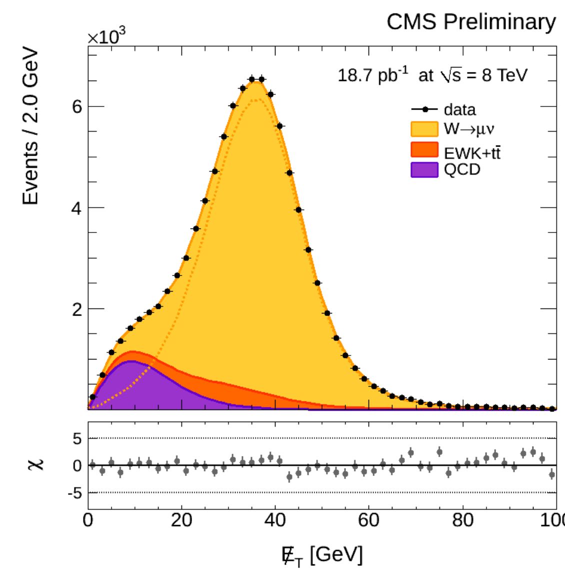
W Cross Section

- Comparable experimental and theory uncertainty
  - 2-3% systematic and 4.4% luminosity
- Comparison with FEWZ



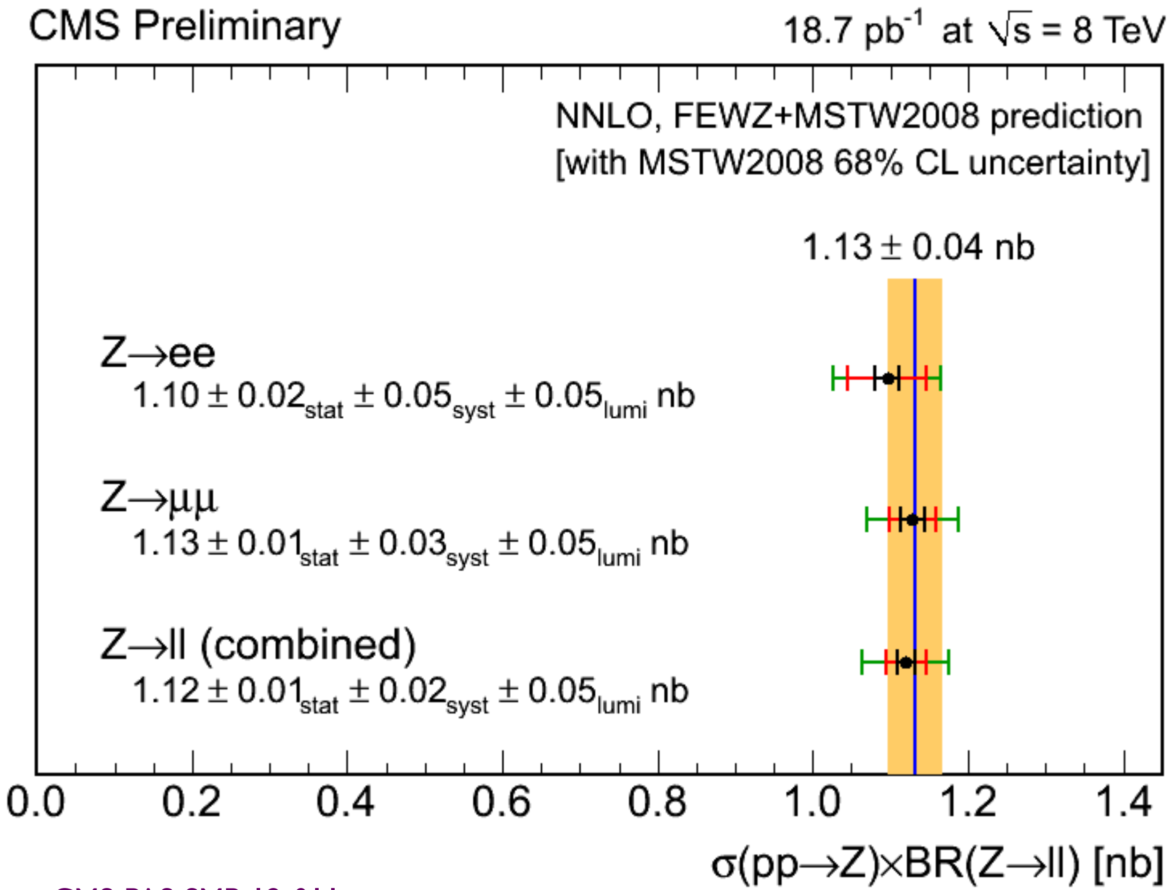
CMS-PAS-SMP-12-011

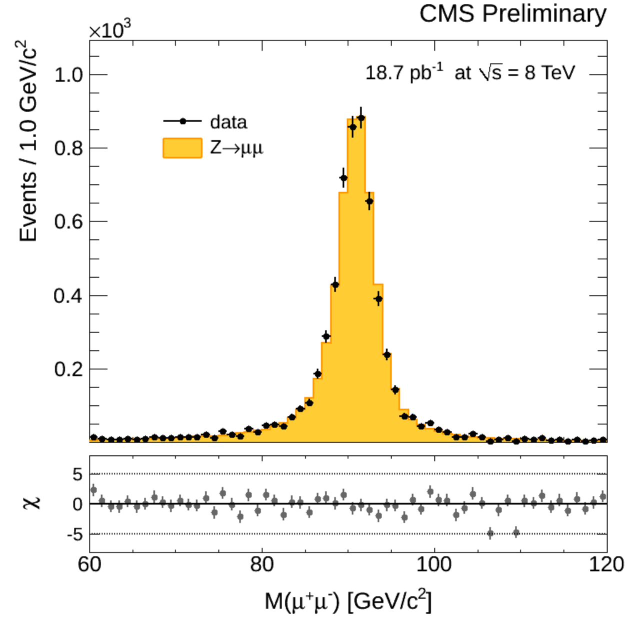


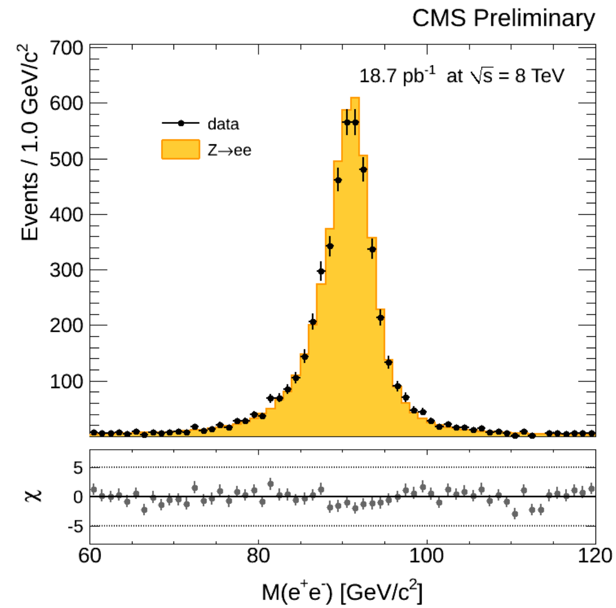


Z Cross Section

- 7 TeV and 8 TeV measurement
- Comparison with FEWZ

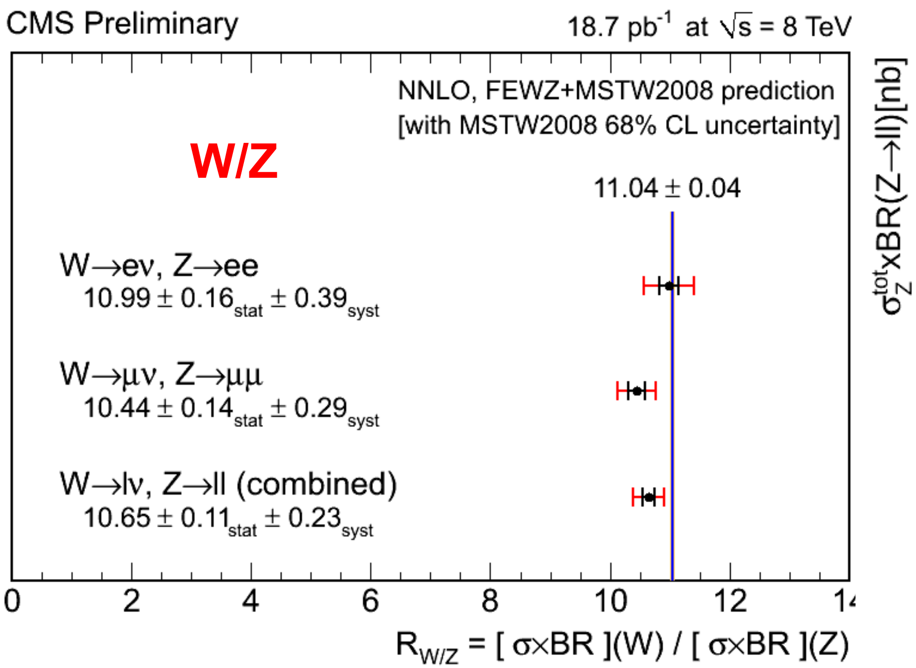


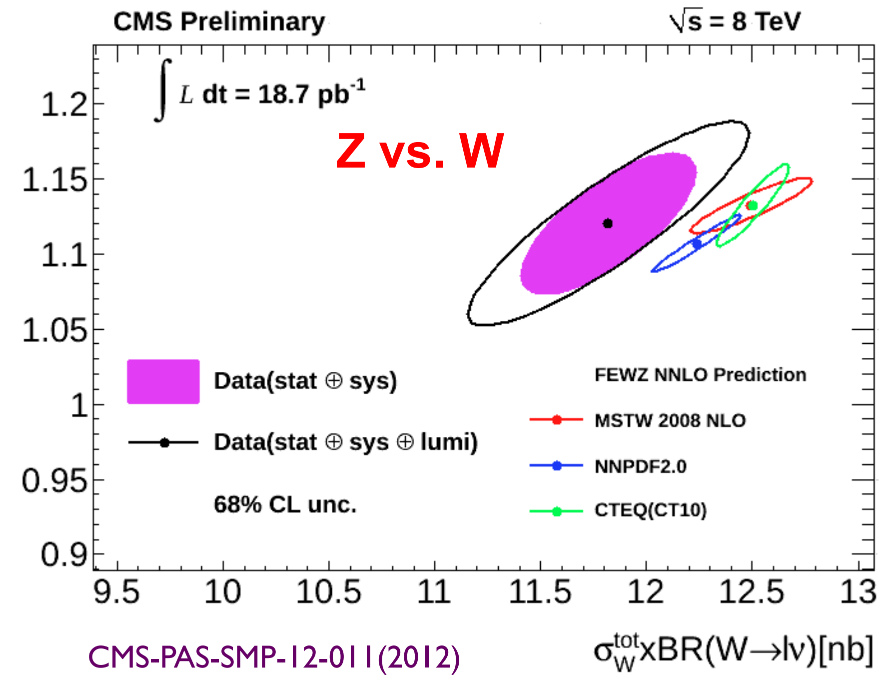




CMS-PAS-SMP-12-011

Ratio of W and Z Cross Sections

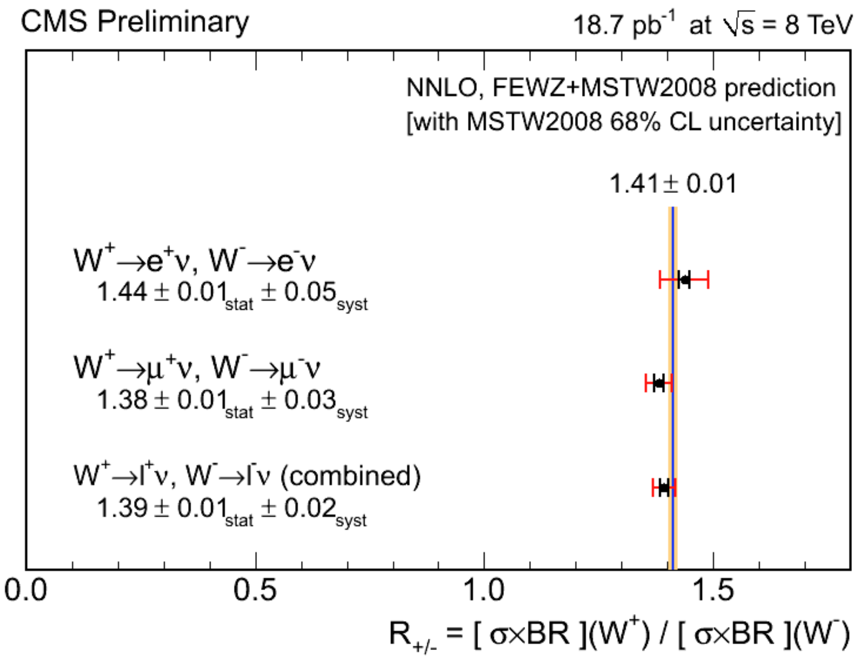


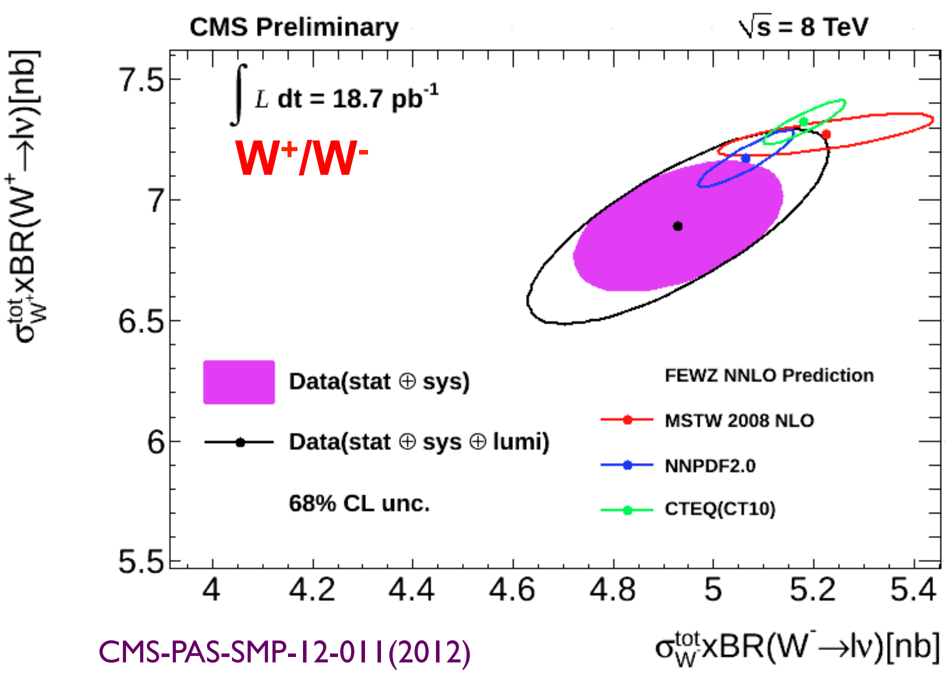


CMS-PAS-SMP-12-011(2012)

- Cancelation of systematic errors in ratio
  - both experimental and theoretical
- W/Z ratio at 8 TeV: 1.5 sigma difference with most PDFs
- 2% experimental systematic uncertainty
- Milder tension is present in the 7 TeV measurement

Ratio of W^+ and W^- Cross Sections



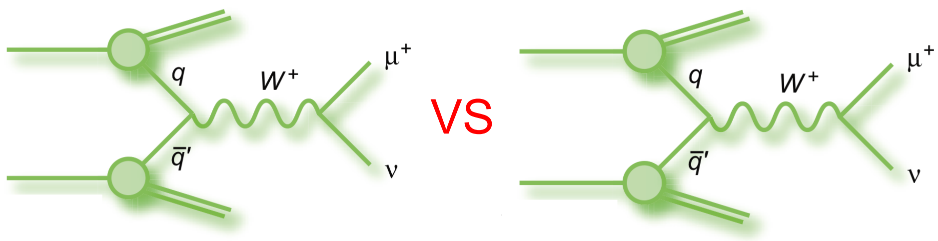


CMS-PAS-SMP-12-011(2012)

- Expect 2:1 ratio from valence quarks in valance-sea annihilation, diluted by sea-sea
- Ratios are not affected by luminosity uncertainty
- W^+/W^- potentially sensitive to PDF
- Agrees with theory predictions
- Tested at 2% level driven by experimental systematic uncertainty

W Charge Asymmetry

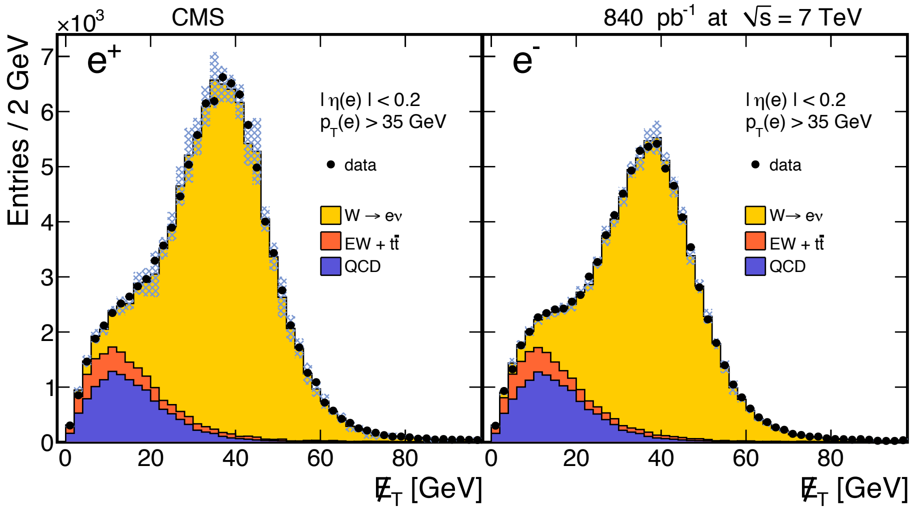
- A natural extension of the inclusive measurement is the study of the W^+/W^- ratio R_W, as a function of different kinematic variables
- An experimentally clean way to do it is to study the charge asymmetry as a function of the lepton pseudorapidity
- This measurement is very sensitive to PDFs as most uncertainties cancel in the ratio
  - more u-dbar than d-ubar in pp collisions: expect charge asymmetry!
- Apply similar selection as for the inclusive measurement and divide the sample in different rapidity bins



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

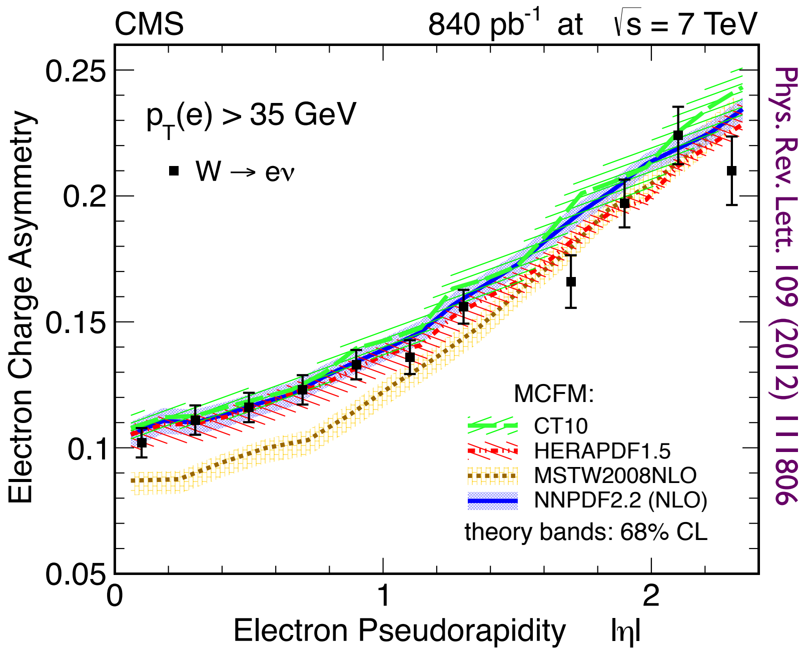
Phys. Rev. Lett. 109 (2012) 111806

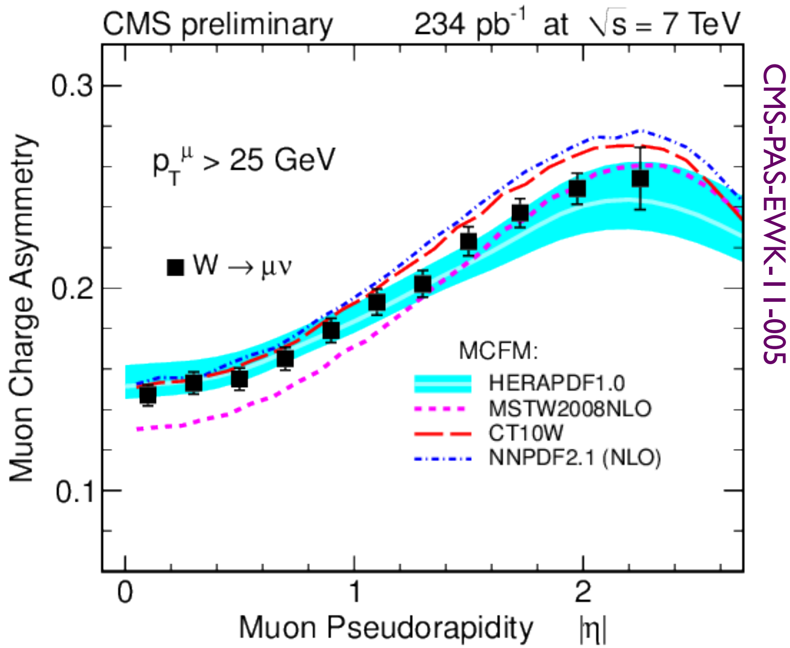
First η bin in electron channel



W Charge Asymmetry

- Background contribution increases with η
- The main uncertainties are from signal/ background shape variations and energy scale
- This measurement is very sensitive to PDFs as most uncertainties cancel in the ratio
- Good agreement with NLO predictions *except* MSTW

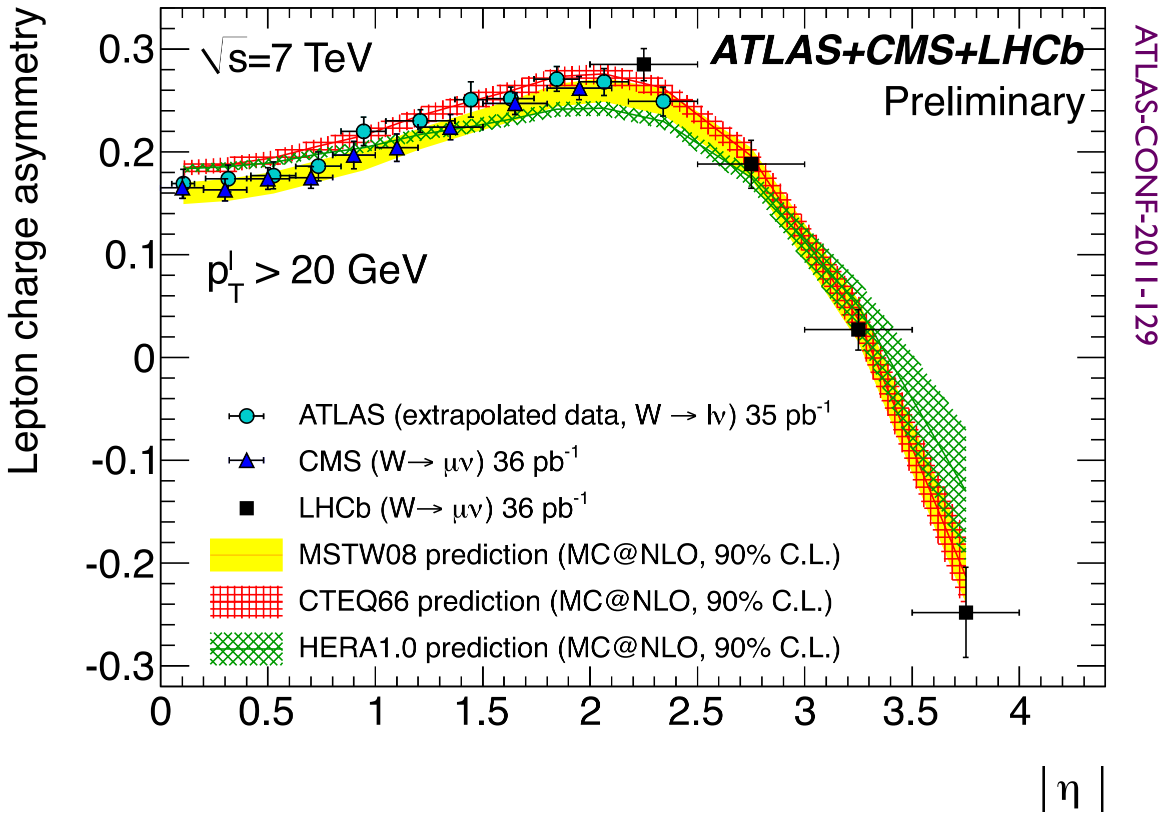


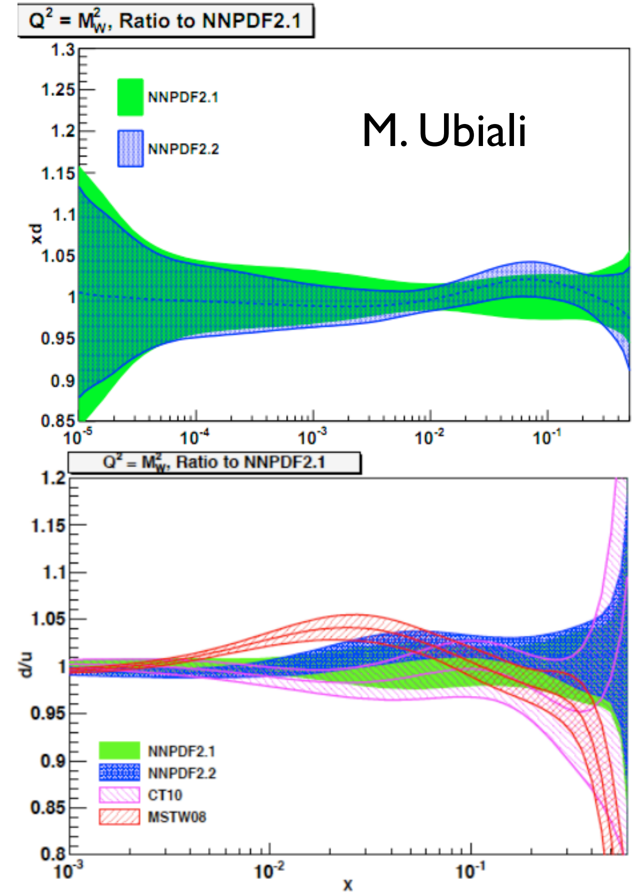


- Provides significant constraint on PDF global fits

PDF model	χ^2
MSTW2008NLO	5.3
CT10W	2.1
NNPDF2.1	4.1
HERAPDF1.0	0.9

W Charge Asymmetry





ATLAS and CMS results complementary to LHCb measurements

- ATLAS, CMS: Medium, small-x region, light quarks/antiquarks
- LHCb: high rapidity data: small-x region

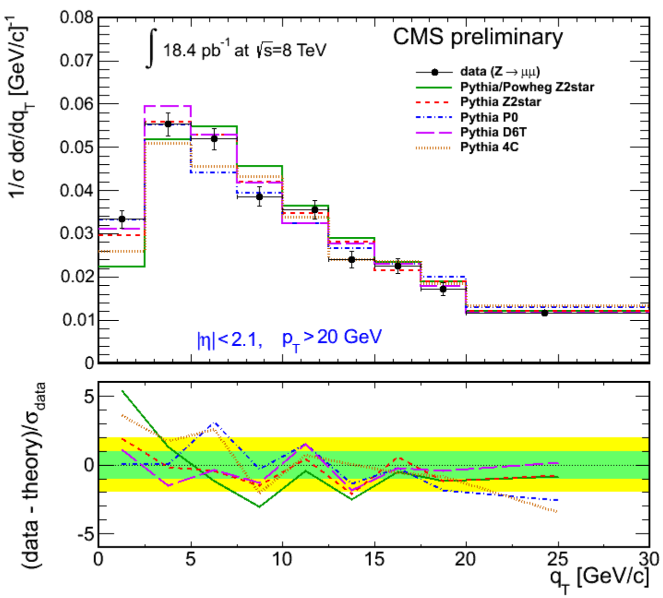
- NNPDF2.2: Added ATLAS and CMS W lepton asymmetry data
- Their inclusion reduces uncertainty and moves central values
- Total uncertainty reduction is significant

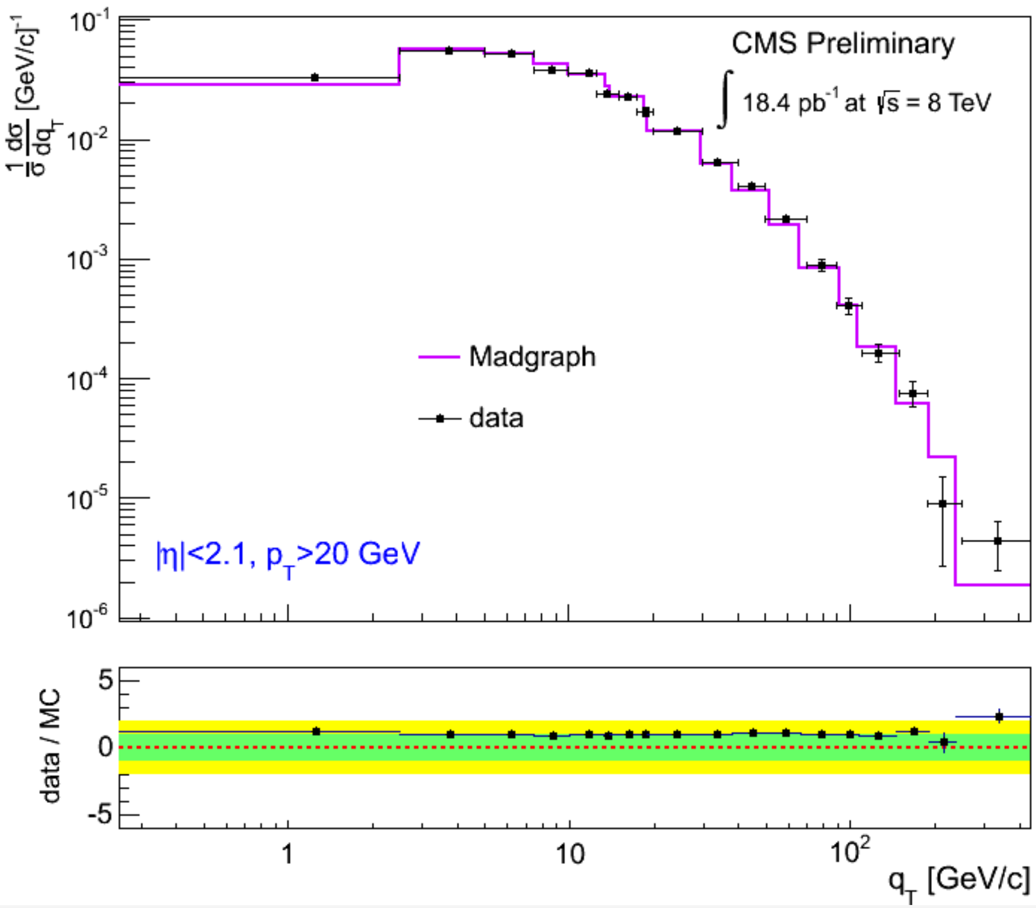
Z/γ* Transverse Momentum

- W and Z bosons are produced with a non-zero p_T because of quark/gluon radiation from the initial-sate partons. Probe modeling of p_T of Z boson in MC.
- Low-p_T dominated by multiple soft gluon radiation (includes perturbative effects) / intermediate p_T is dominated by first higher order corrections / high-p_T dominated by hard single gluon radiation (matrix element)

CMS-PAS-SMP-12-025

- $\sqrt{s}$ = 8 TeV, L = 18.4/pb
- Muon channel only
- PYTHIA (Z2star) is good at low p_T^Z
- Madgraph is slightly better at high p_T^Z





Drell-Yan Cross Section

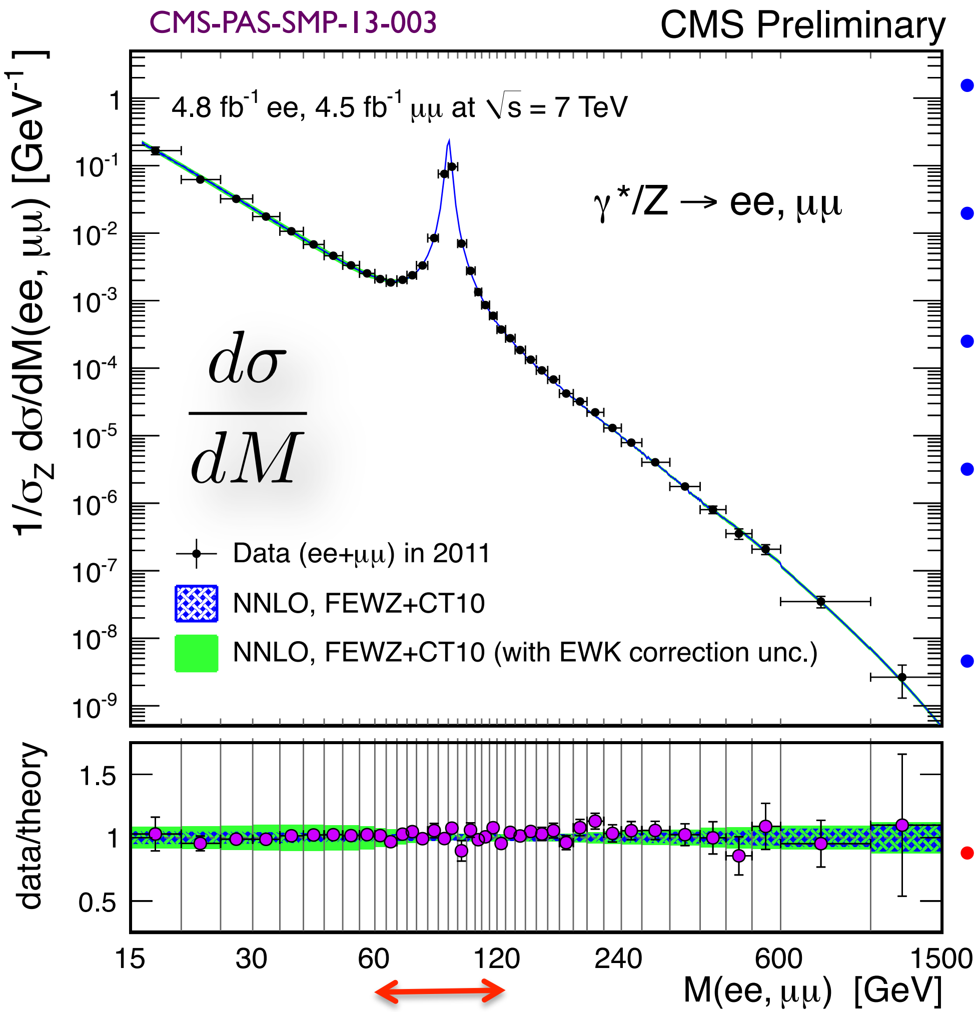
- Full 7 TeV dataset is used; both dimuon and dielectron channel
- Measure the differential cross section $(1/\sigma_Z)d\sigma/dM$
  - normalize differential cross sections to the cross section at the Z peak
  - performed in muon and electron channel
- Measure the double differential cross section $(1/\sigma_Z)d^2\sigma/dMdY$
  - measurement directly usable to constraint PDFs
  - performed in muon channel $|Y| < 2.4$
- Drell-Yan samples are produced with POWHEG MC generator
  - rescaled to NNLO cross section from FEWZ
- Cross section measurement per bin:

$$\sigma_{i,j} = \frac{N^u_{i,j}}{A_{i,j} \cdot \varepsilon_{i,j} \cdot C_{i,j} \cdot L_{\text{int}}} \qquad R_i = \frac{1}{\sigma_Z}\frac{d\sigma}{dM}$$

- Note: the acceptance correction is not applied for the 2D measurement

Take advantage of the CMS detector's capabilities to measure very low mass DY

Drell-Yan Cross Section

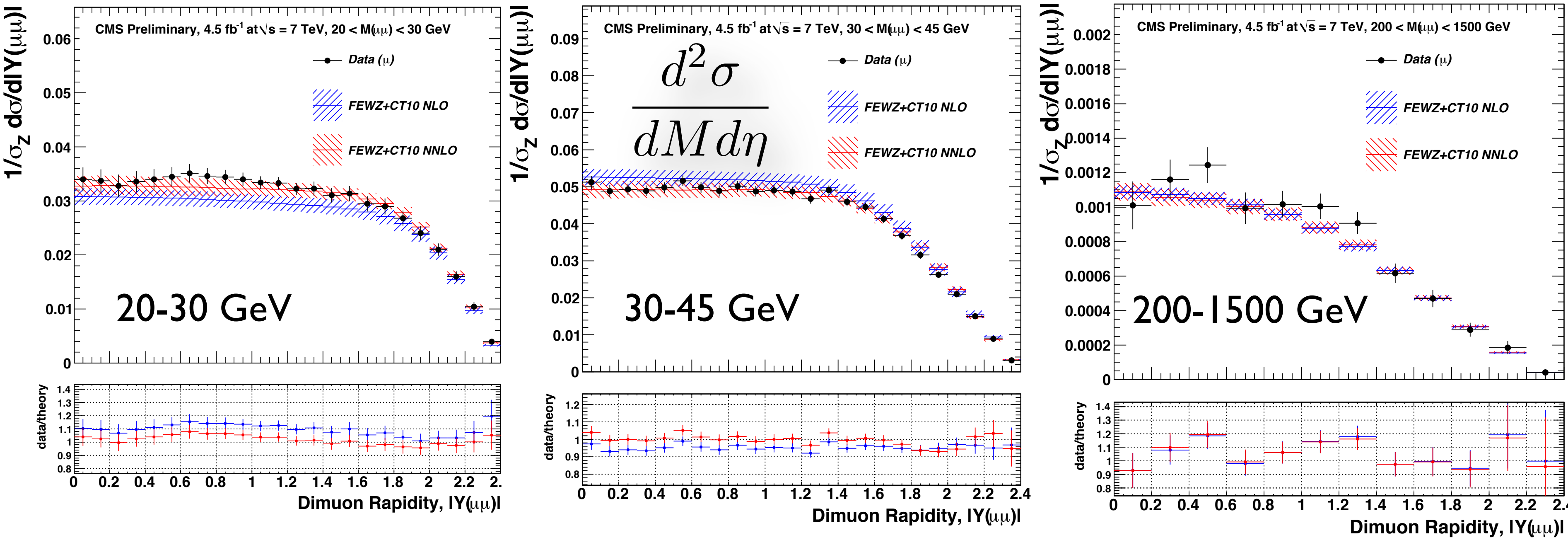


- dσ/dM is measured in 40 mass bins covering the range from 15 to 1500 GeV
- Normalized to Z peak: 60 < M < 120 GeV
- Pre-FSR full acceptance normalizated cross section in dimuon and dielectron
- The uncertainty in the dimuon channel is dominated by efficiency corrections (1%), and FSR systematics (0.3%)
- The uncertainty in the dielectron channel is dominated by the energy scale corrections (0.7%)
- Very good agreement over several orders of magnitude

The blue error band for the theory calculation includes the statistical error from the FEWZ calculation and 68% confidence limit (CL) PDF uncertainty combined in quadrature. The uncertainty of EWK correction including γγ initiated processes effect is added in the green error band.

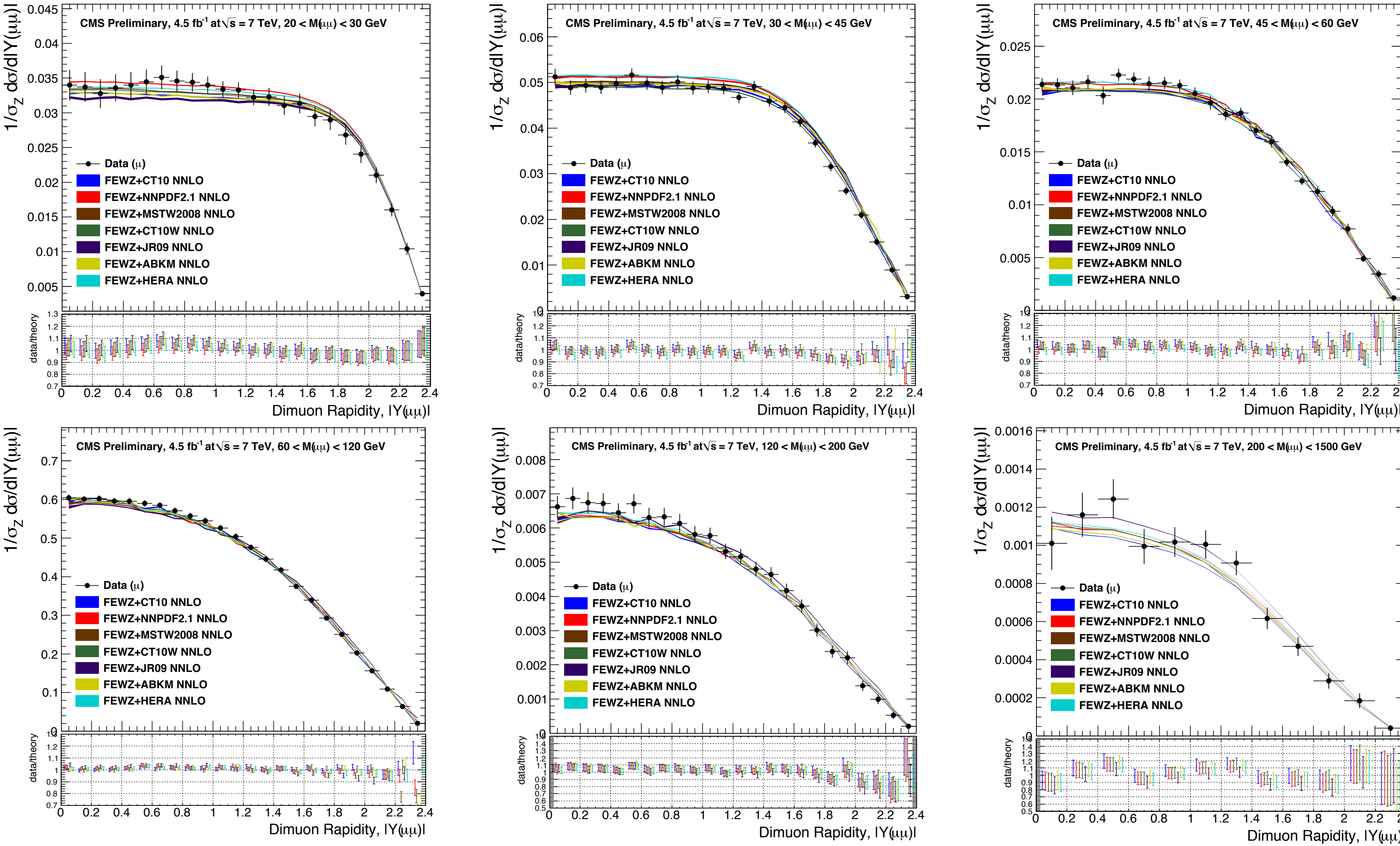
Double Differential Drell-Yan Cross Section

CMS-PAS-SMP-13-003



- Measurement within the detector acceptance, to reduce the model dependence
- Performed in 24 rapidity bins between 0 and 2.4 (12 Y-bins for the highest mass bin) and 6 mass ranges: (20-30), (30,45), (45,60), **(60,120)**, (120, 200), (200,1500) GeV
- Low mass very sensitive to PDF uncertainties
- Comparing to FEWZ + CT10 NLO and FEWZ + CT10 NNLO

Double Differential Drell-Yan Cross Section

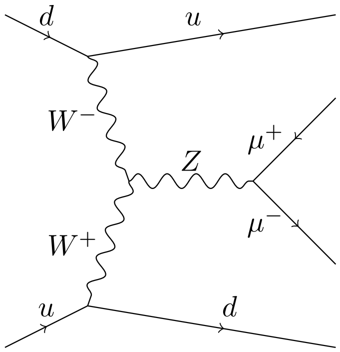


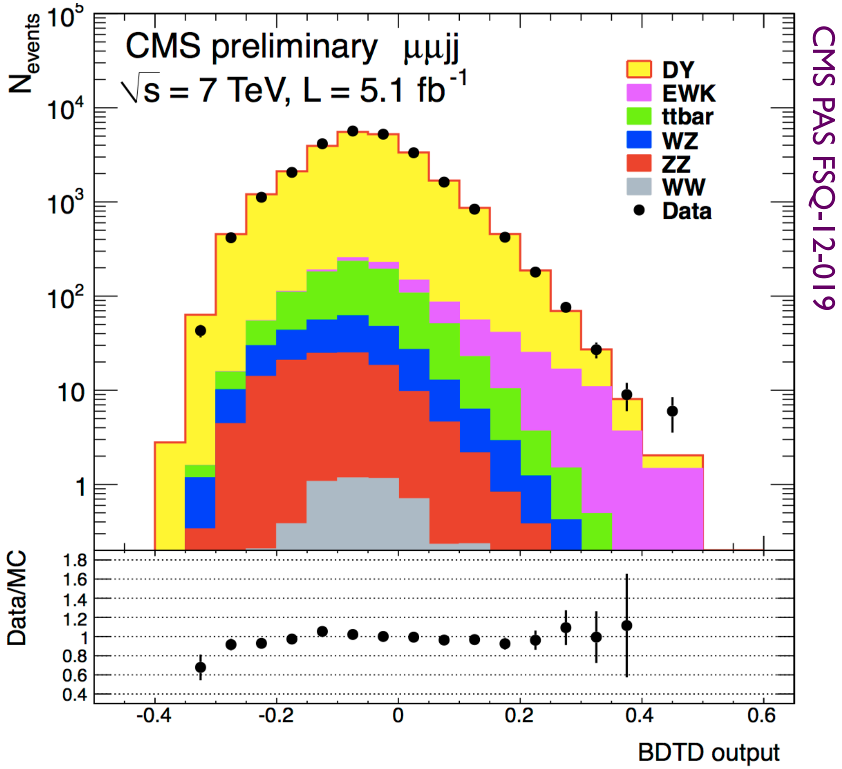
- Comparison with various NNLO PDF sets:
  ABKM, CT10, CT10W, HERA, JR09, MSTW2008, NNPDF

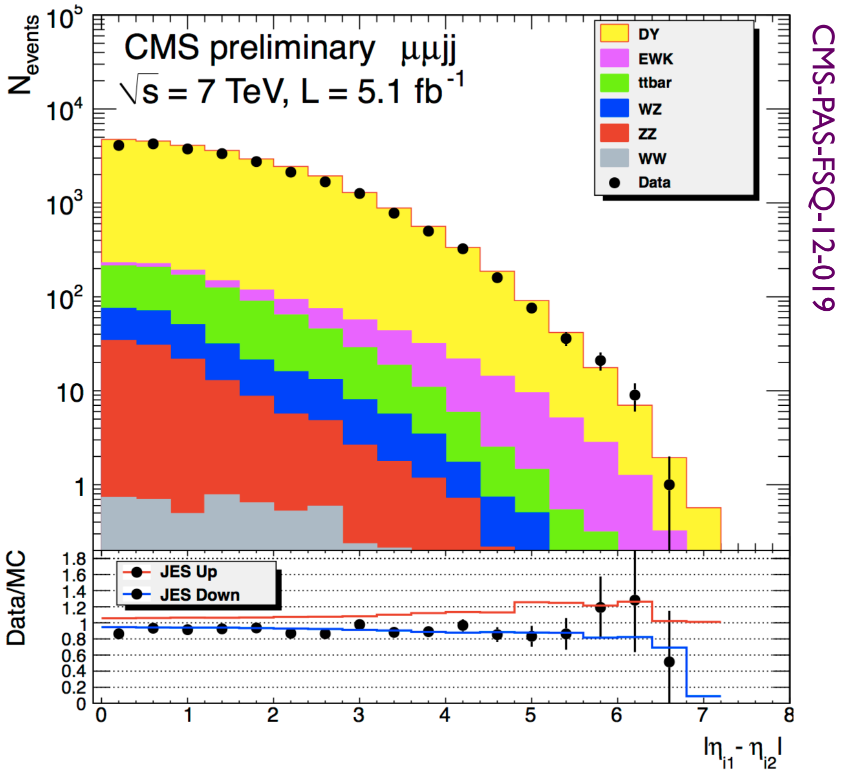
CMS-PAS-SMP-13-003

Evidence for VBF Z Production

- EW production of Z + jets – with the two jets well separated in rapidity – important benchmark in the searches for VBF Higgs
- Very hard due to dominant DY production, uses advanced multivariate techniques (BDT) to extract signal





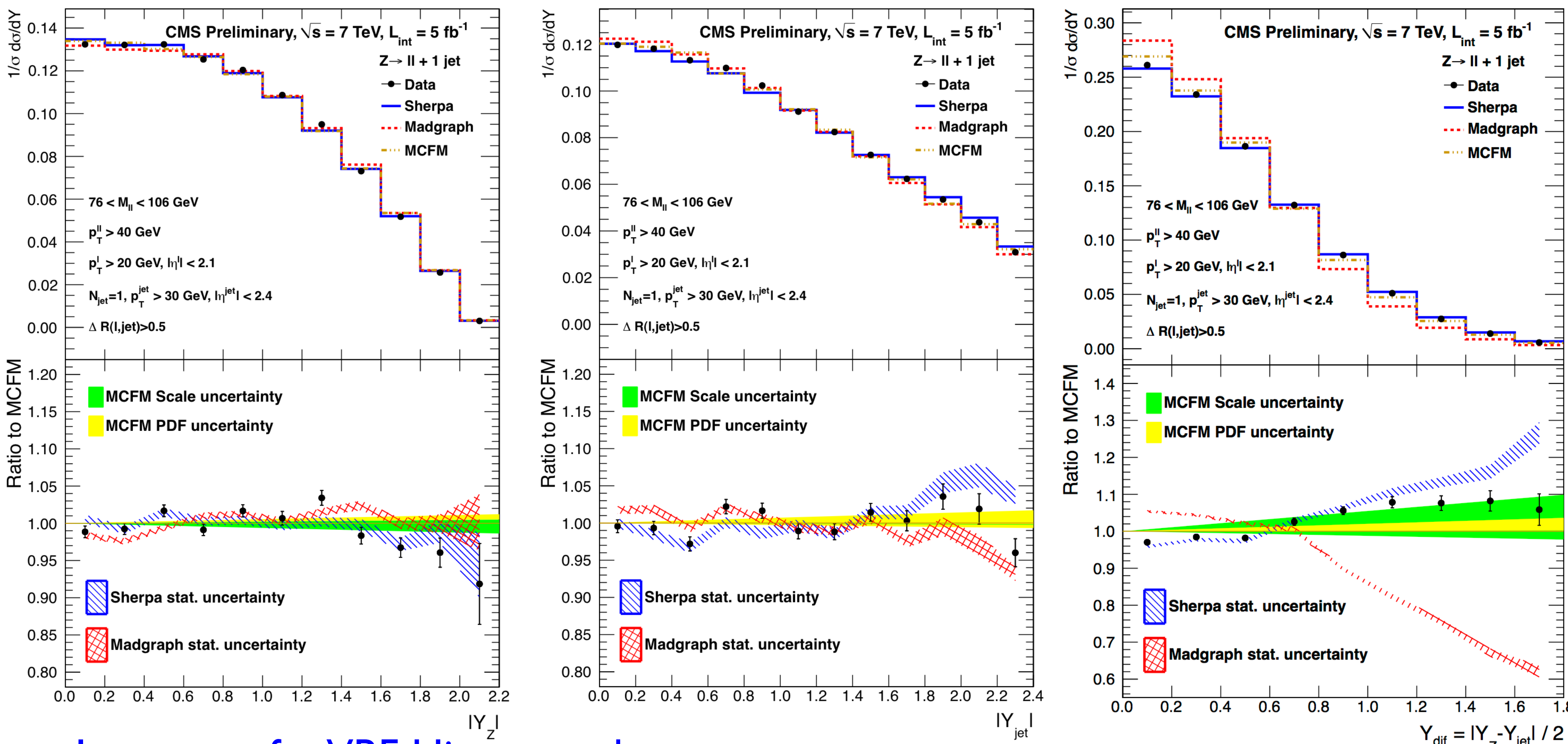


σ(μμ+ee) = 154 ± 24 (stat.) ± 46 (syst.) ± 27 (th.) ± 3 (lum.)fb

(Theory: 166 fb)

Differential Z/γ* + Jets Cross Section

Z rapidity CMS-PAS-SMP-12-004 Jet rapidity Rapidity difference



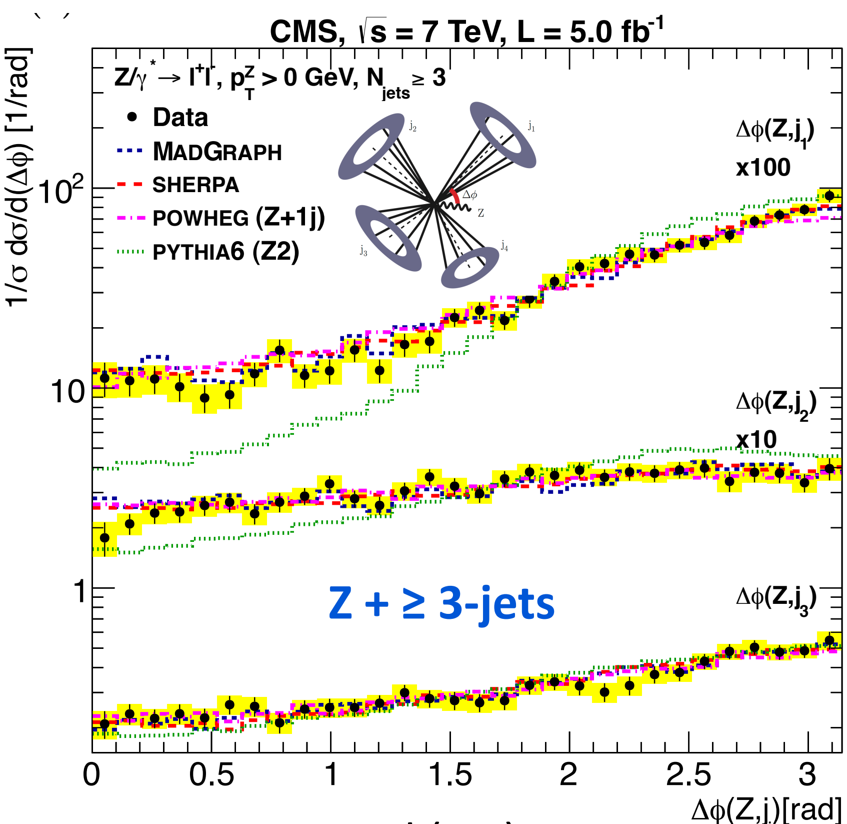
- Important for VBF Higgs searches
- Data compared to MadGraph and Sherpa (ME+PS) generators and to MCFM:
  - good agreement in the rapidity range!
  - differences in rapidity difference are probably due to jet matching in ME+PS

Z + Jets: Angular Correlations

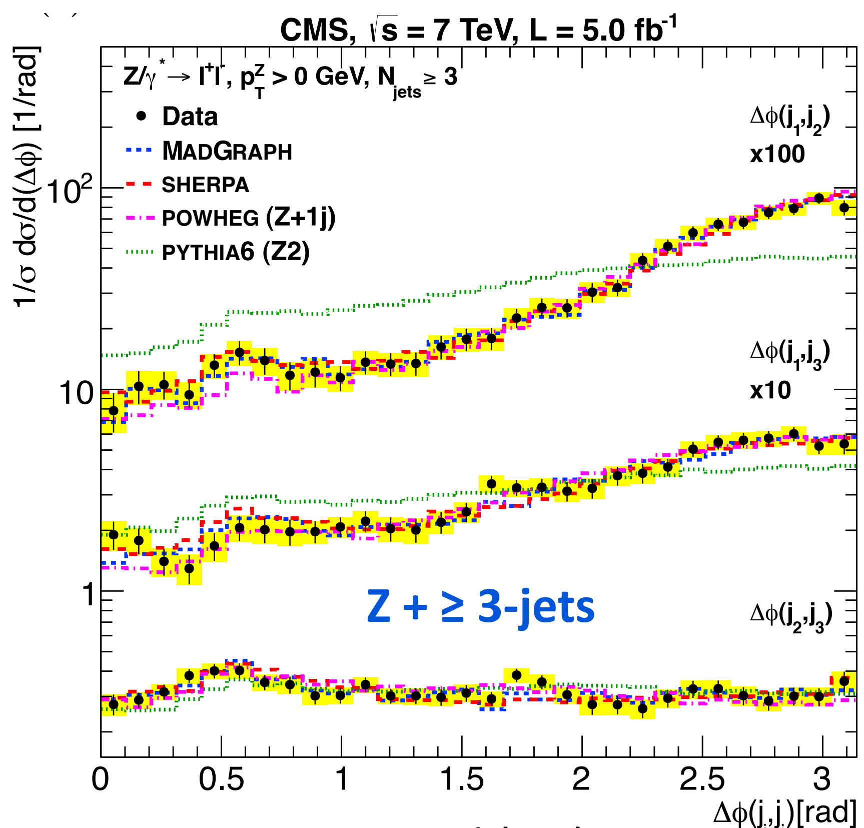
- Data with Z + ≥ 3 jets
- Leptons with p_T>20 GeV, |η|<2.4
- Anti-kt (R=0.5) jets with p_T>50 GeV, |η|<2.5
- ΔΦ between Z and J_i, between J_i, J_l (i,l≤3)

- Compatible results between ME+PS and NLO(Z+1j)+PS generators
- PYTHIA: only PS
- Sherpa and MadGraph: ME + PS
- POWHEG: NLO (Z+1jet) + PS

arXiv:1301.1646

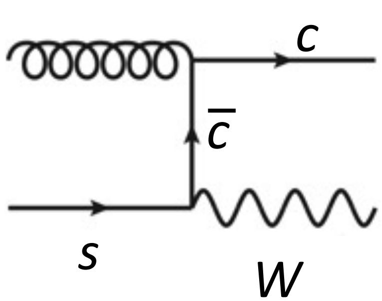


$\Delta\phi(Z, J_i)$



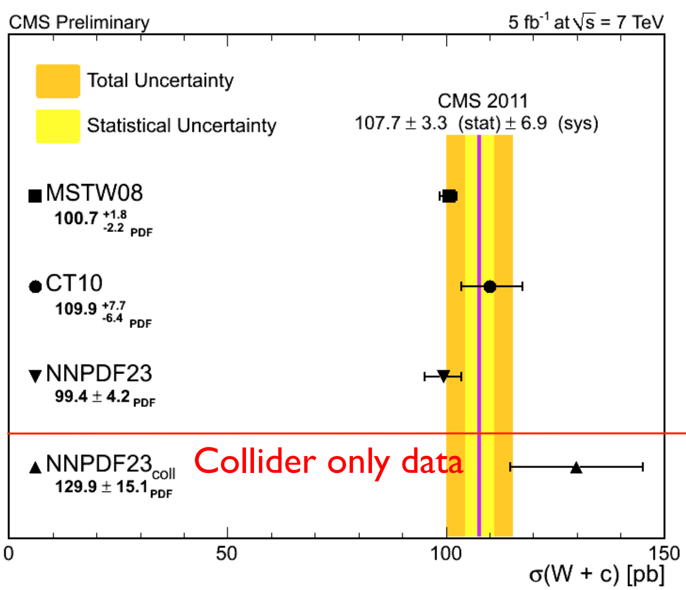
$\Delta\phi(J_i, J_j)$

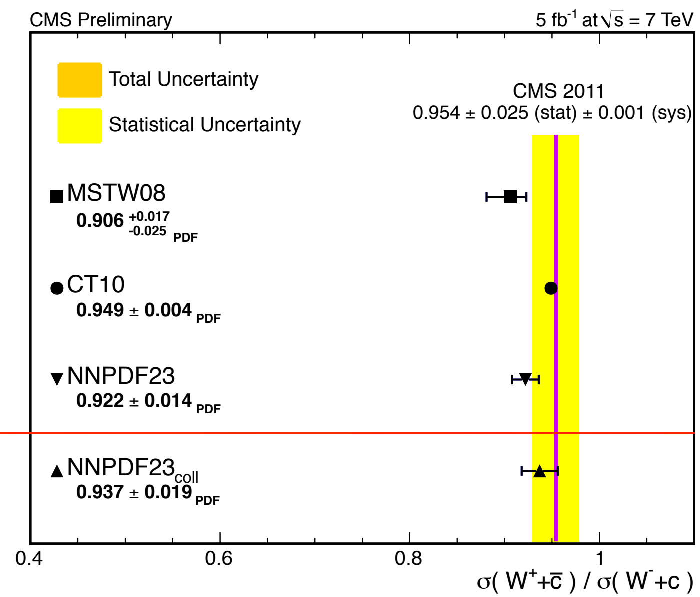
W + c-Jet

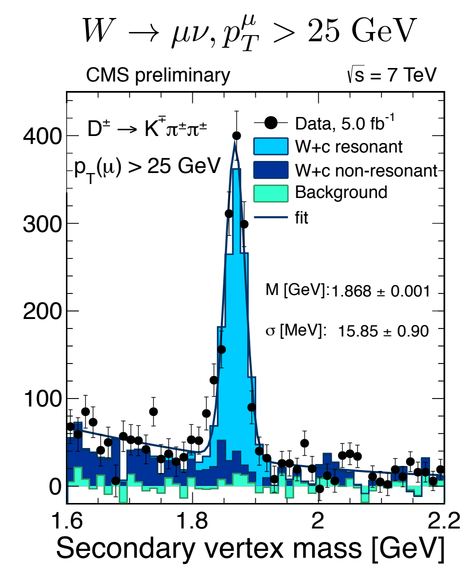


- In W+c events the charge of the W (and the lepton) and the charge of the c quark are of opposite sign
- Analysis uses charm hadron reconstruction to identify charm jets
  - W→lν + a leading jet with charm content, identified through reconstruction of D±, D0, D* decays

CMS-PAS-SMP-12-002

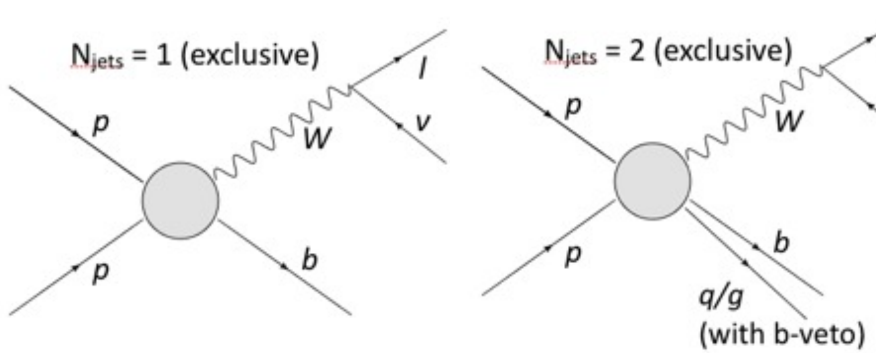






- σ(W+c−jet) sensitive to strange content of the proton
- c−jet viable through charm mesons reconstruction
- PDF with collider data only predict a symmetric light sea, but with large uncertainty
  - In agreement with data within 1σ

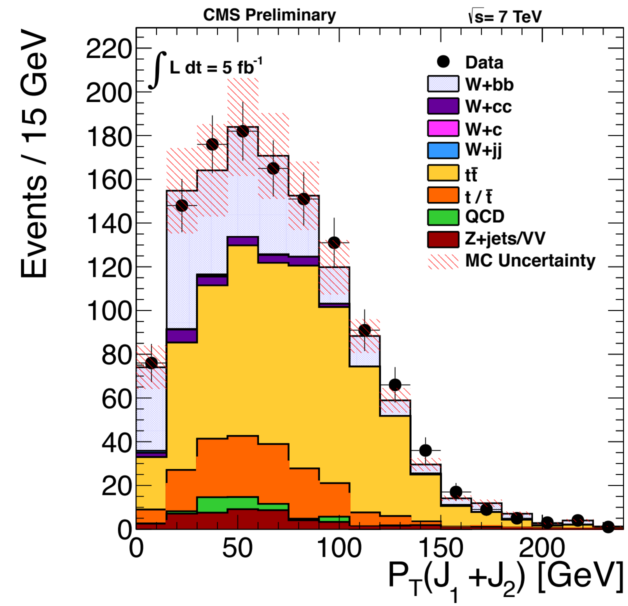
W + 2b-Jets

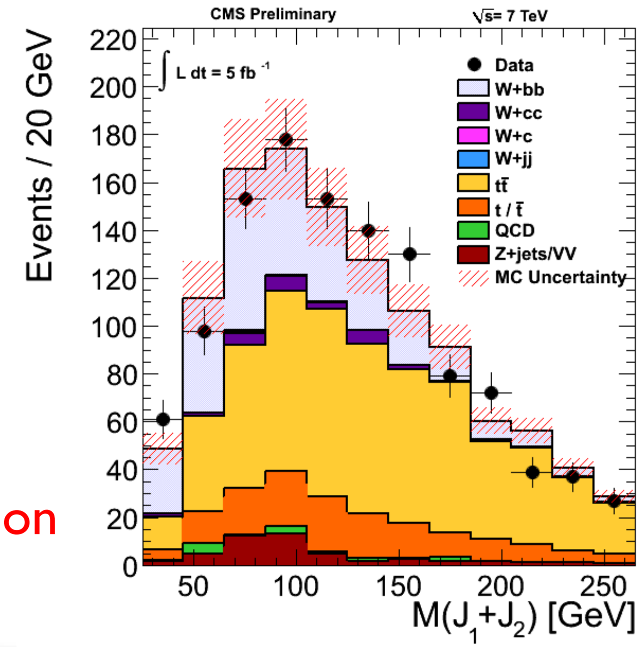


	σ(W→bb)
Data (CMS)	0.53 ± 0.05 stat ± 0.1 sys [pb]
MCFM (MSTW08NNLO)	0.52 ± 0.03 [pb]

CMS-PAS-SMP-12-026

- Exclusive W+bb cross section measured
- Complementary phase space wrt W+b
- Major background to H→bb analysis
- Measurement is in agreement with the MCFM prediction within uncertainties

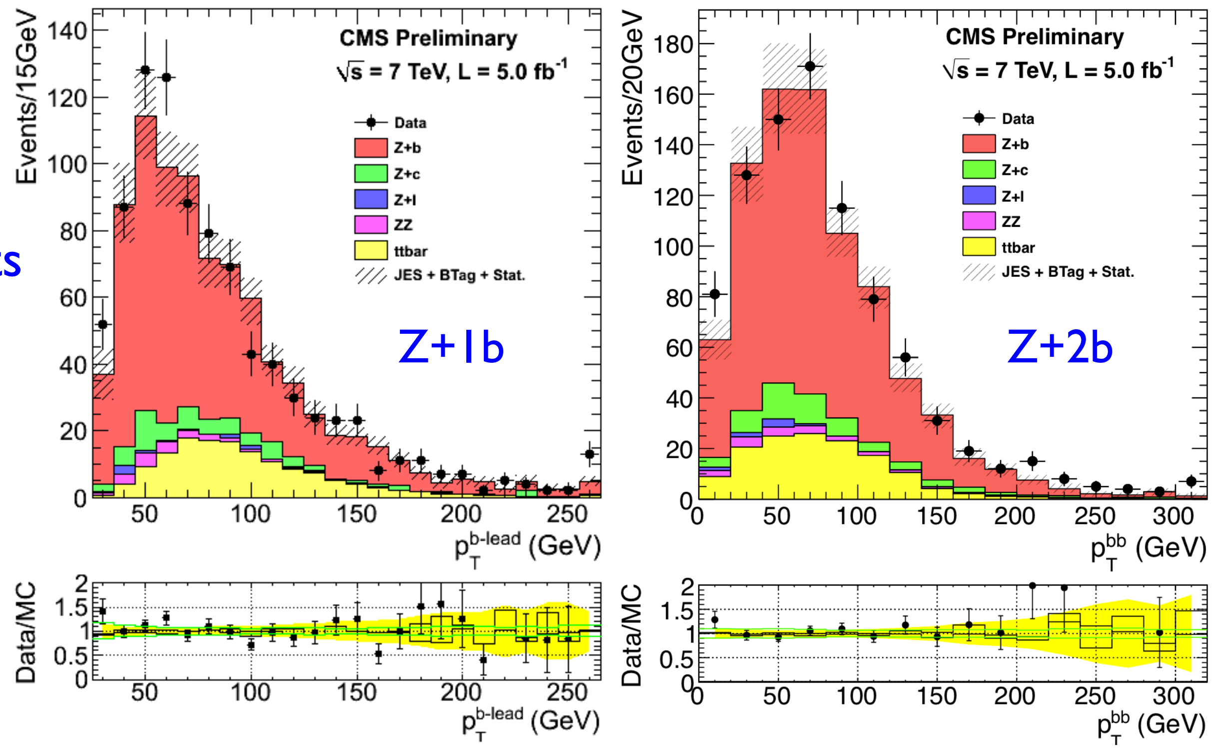




Z + b-Jets

CMS-PAS-SMP-13-004

- 2011 dataset (~5 fb^{-1})
- b-tagged Jets with p_T>25 GeV, |η|<2.4 in Z events
- Most important kinematical observables compared to ME+PS generator (MadGraph)

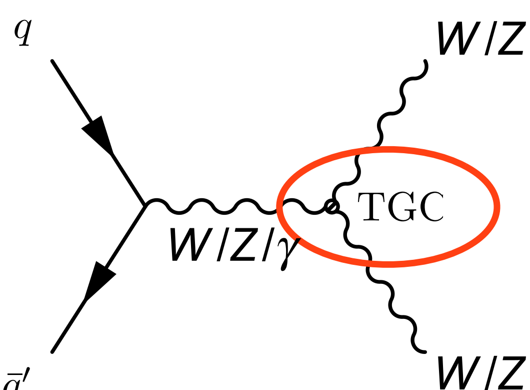


- Z + bb cross section 10% higher than tree-level prediction by Madgraph 5F rescaled by k = 1.23
- Some tensions in the description of the event dynamics

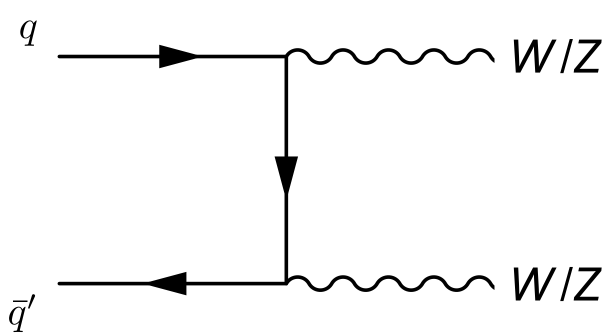
Multiplicity bin	$\mu\mu$	ee
$\sigma(Z(\ell\ell)+1b)$ (pb)	$3.52 \pm 0.03 \pm 0.22$	$3.51 \pm 0.04 \pm 0.23$
$\sigma(Z(\ell\ell)+2b)$ (pb)	$0.38 \pm 0.02 \pm 0.07$	$0.32 \pm 0.02 \pm 0.06$
$\sigma(Z(\ell\ell)+b)$ (pb)	$3.91 \pm 0.04 \pm 0.23$	$3.84 \pm 0.04 \pm 0.24$
$\sigma(Z(\ell\ell)+b)/\sigma(Z(\ell\ell)+j)$ (%)	$5.23 \pm 0.04 \pm 0.24$	$5.08 \pm 0.05 \pm 0.24$

Diboson Production

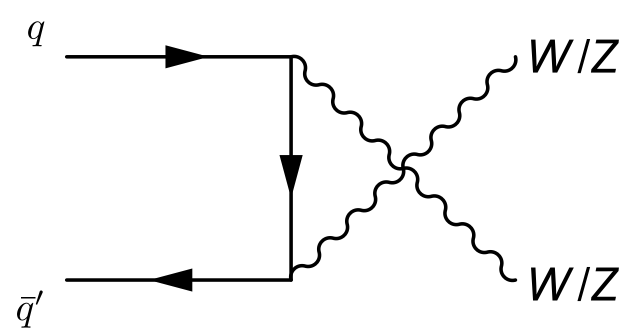
- Fundamental test of Standard Model
  - Test of gauge structure of the Standard Model
- Probe for new physics
  - Indirect search for tree or loop effect of massive new particles
  - Anomalous Triple Gauge Couplings (TGC) and Quartic Gauge Coupling (QGC)
  - Resonances
- Irreducible background for Higgs searches
  - Precise knowledge of cross sections and kinematical distributions are important
- LO diagrams for WW, WZ and ZZ production are:



s-channel

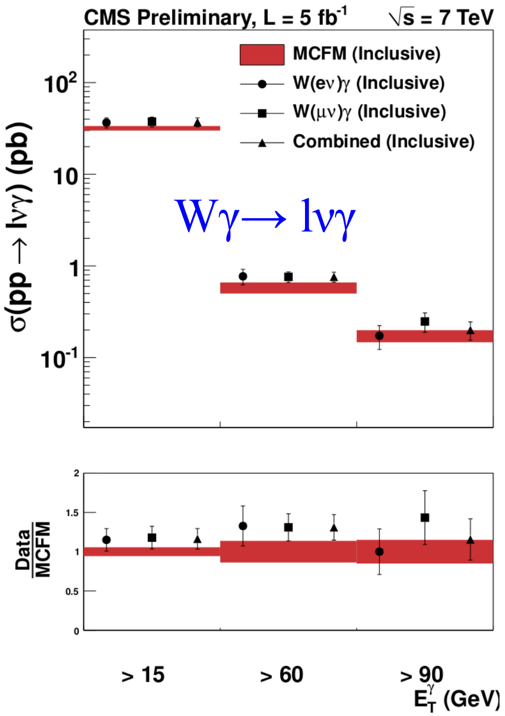


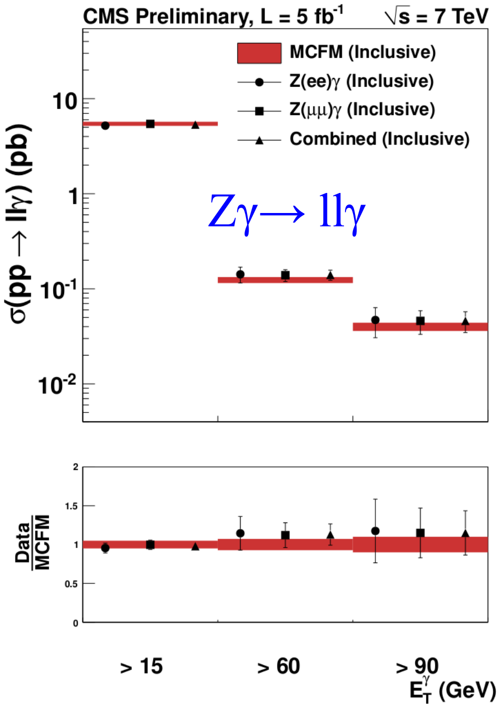
t-channel



u-channel

Wγ, Zγ Production

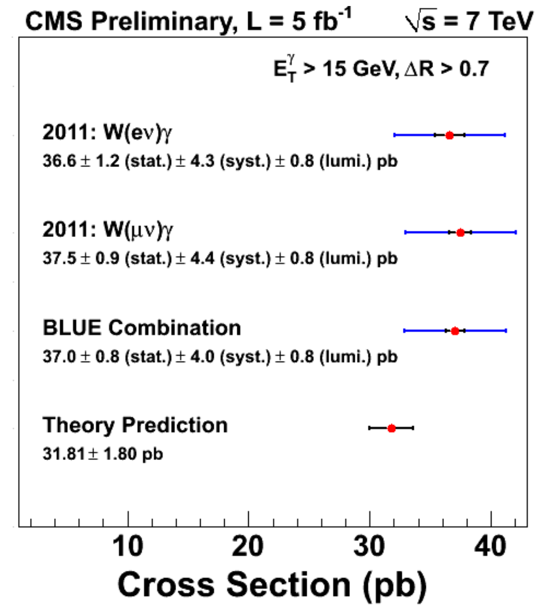


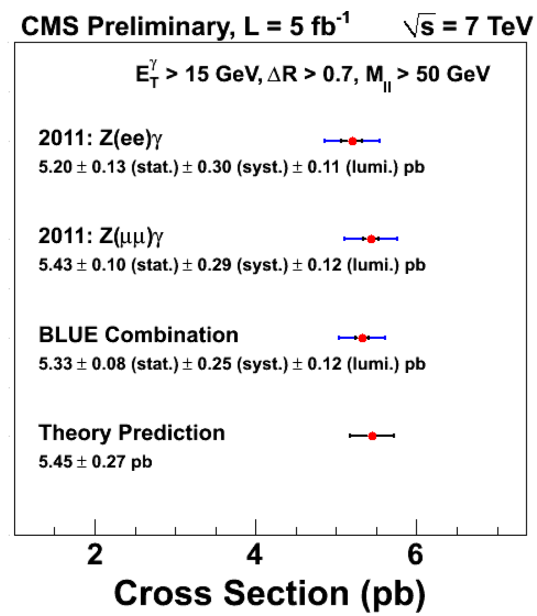


Inclusive Wγ cross sections above theory (MCFM NLO)

Fair agreement for Zγ

CMS-PAS-EWK-11-009





Analyses of lνγ, llγ, and ννγ final states

- γ with high E_T (>15 GeV)
- Large ΔR(ℓ, γ) (suppress FSR)
- Isolated lepton with high p_T
- Missing E_T if ννγ

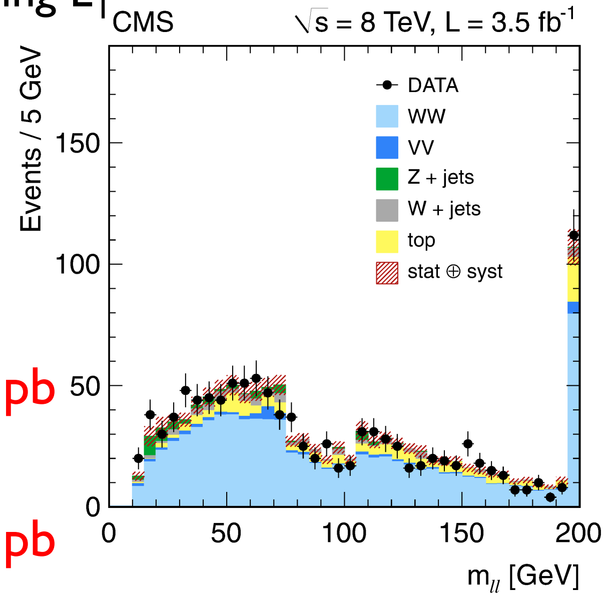
Good agreement with theory (MCFM NLO, BAUR)

- σ(Zγ→ννγ) = 21.3 ± 4.2 (stat.) ± 4.3 (syst.) ± 0.5 (lumi.) fb
- BAUR: 21.9 ±1.1 fb

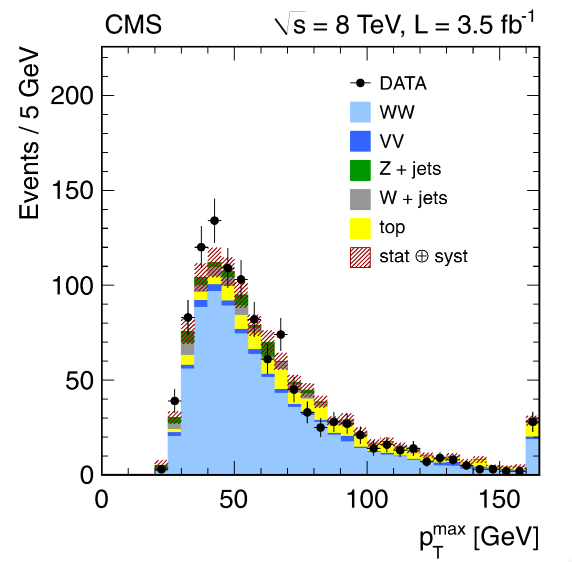
WW Production

Phys. Lett. B 721 (2013) 190–211
CMS-PAS-SMP-12-005

- Signal: two isolated opposite-sign leptons (e and μ) and missing E_T
- Main Backgrounds:
  - $Z \rightarrow \ell\ell$ + fake missing E_T → Z-veto in ee and μμ channels
  - W+jets (jet faking a lepton)
  - tW and tt use only the 0-jet events
    - apply jet veto to reduce top background



- σ(WW 7 TeV) = 52.4 ± 2.0 (stat) ± 4.5 (sys) ± 1.2 (lum) pb
- MCFM NLO : 47.0 ± 2.0 pb
- σ(WW 8 TeV) = 69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lum) pb
- MCFM NLO : 57.3 + 2.4 - 1.6 pb

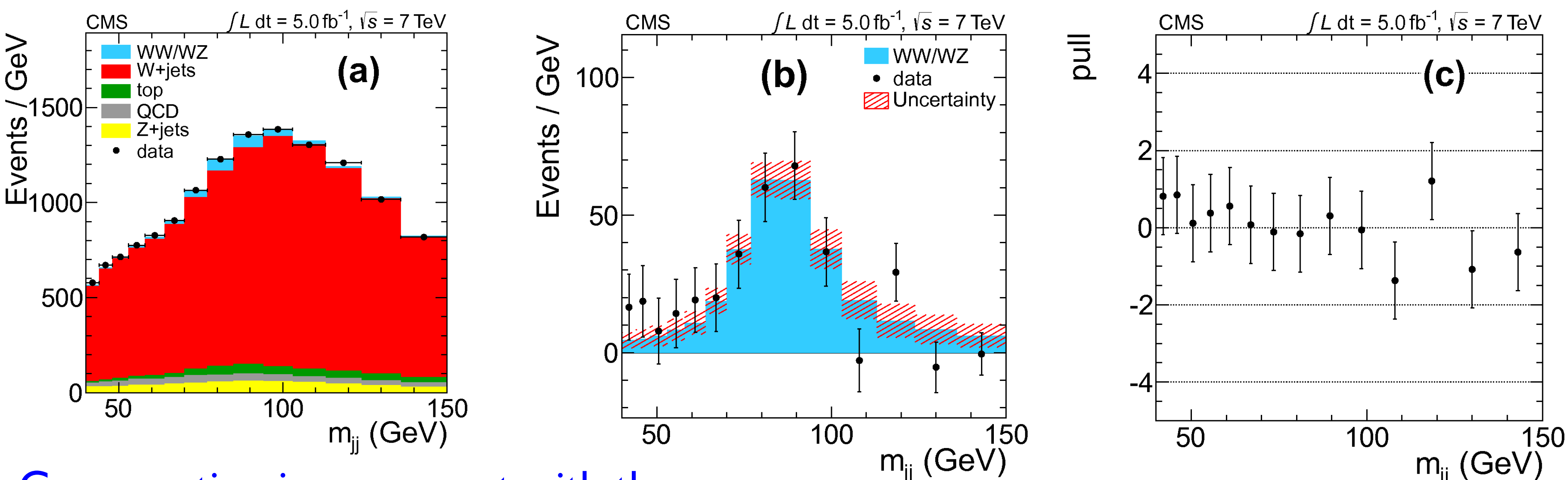


- Measured cross sections are slightly larger than SM predictions (1-1.5σ level)
  - Are the NLO calculations sufficiently precise?
- Measurement precision are systematics limited
- Higgs contribution of the order of 5% (not considered in this plot)

WW+WZ Production

- WW + WZ production in semileptonic decays
- Signal: leptons (e and μ) and missing E_T and two jets consistent with a W or Z
- Cross sections at 7
- Reconstruct W candidate in one lepton + missing E_T
- Fit the di-jet invariant mass distribution
- Apply jet veto to reduce top backgrounds

arXiv:1210.7544



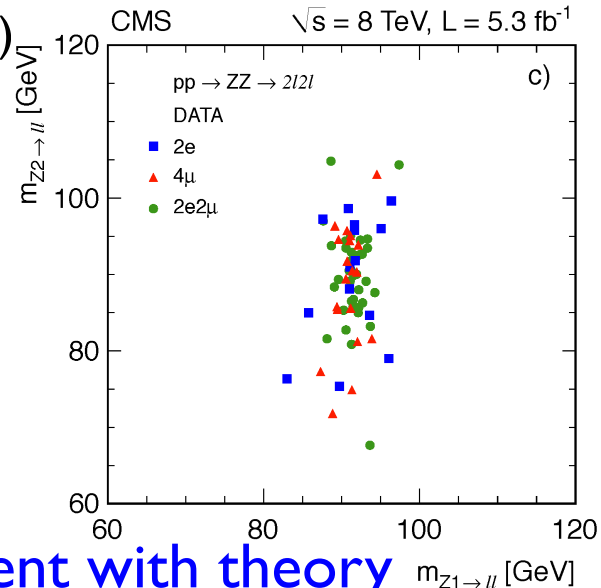
Cross section in agreement with theory

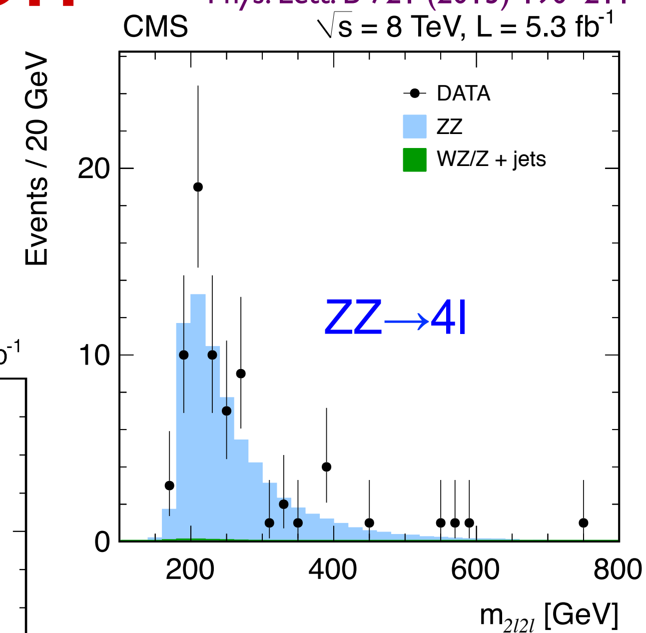
- σ(WV 7 TeV) = 68.89 ± 8.71 (stat) ± 9.70 (syst) ± 1.52 (lumi) pb
- MCFM NLO : 65.6 ± 2.2 pb

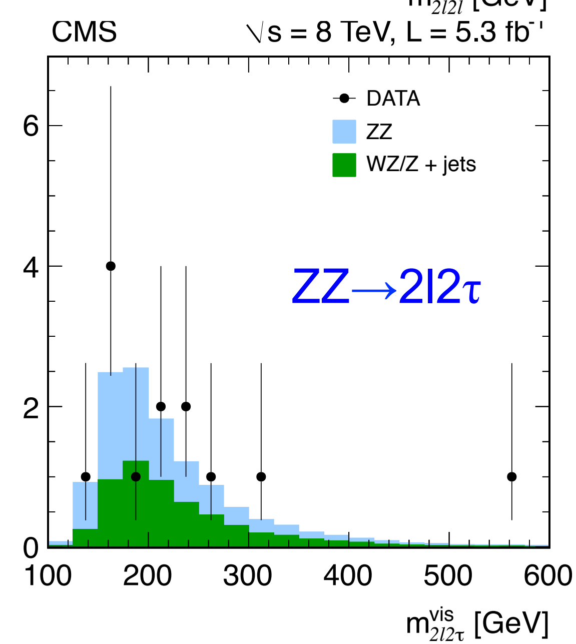
ZZ Production

J. High Energy Phys. 1301 (2013) 063
Phys. Lett. B 721 (2013) 190–211

- Signal: either 4-leptons (making two Z) or 2 leptons (Z) + missing E_T ($\ell\ell\nu\nu$)
- One Z allowed to decay to taus: $Z\to\tau\tau$
- Very small background from *WZ* and *Z* + jets
- Main backgrounds (significant only in $\ell\ell\tau\tau$ and $\ell\ell\nu\nu$)
  - Z+jets (jet faking a lepton)
  - Other dibosons





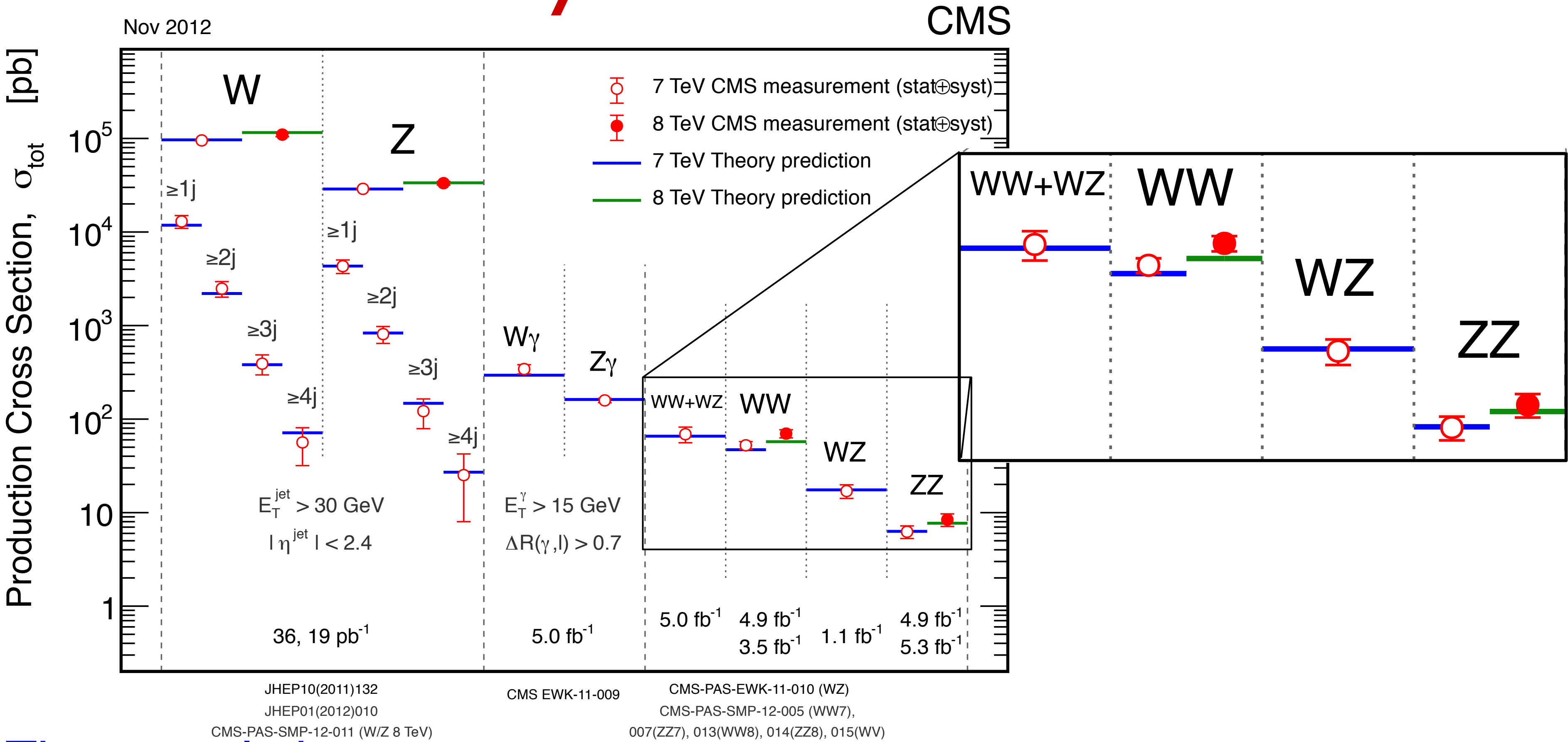


Cross sections in agreement with theory

- σ(ZZ 7 TeV) = 6.2 ± 0.8 (stat) ± 0.4 (sys.) ± 0.1 (lum) pb
- MCFM NLO : 6.3 ± 0.4 pb

- σ(ZZ 8 TeV) = 8.4 ± 1.0 (stat) ± 0.7 (sys) ± 0.4 (lum) pb
- MCFM NLO : 7.7 ± 0.4 pb

Summary of Cross Sections

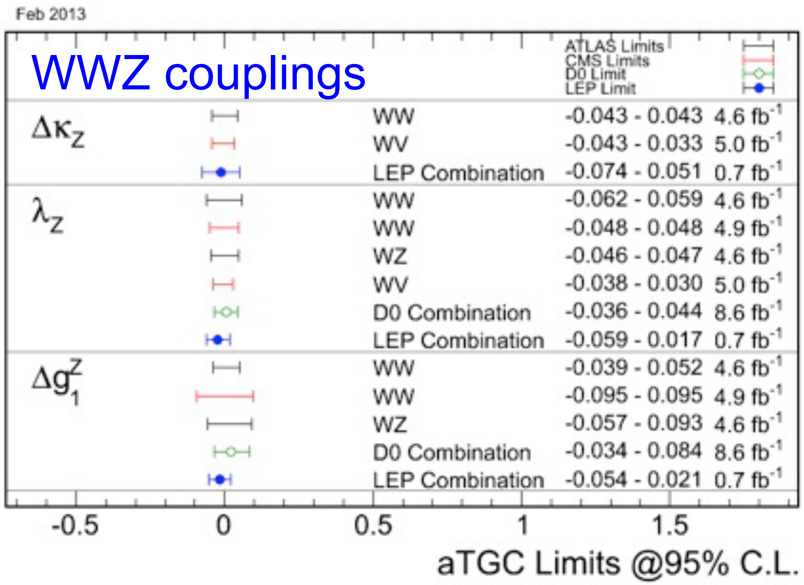


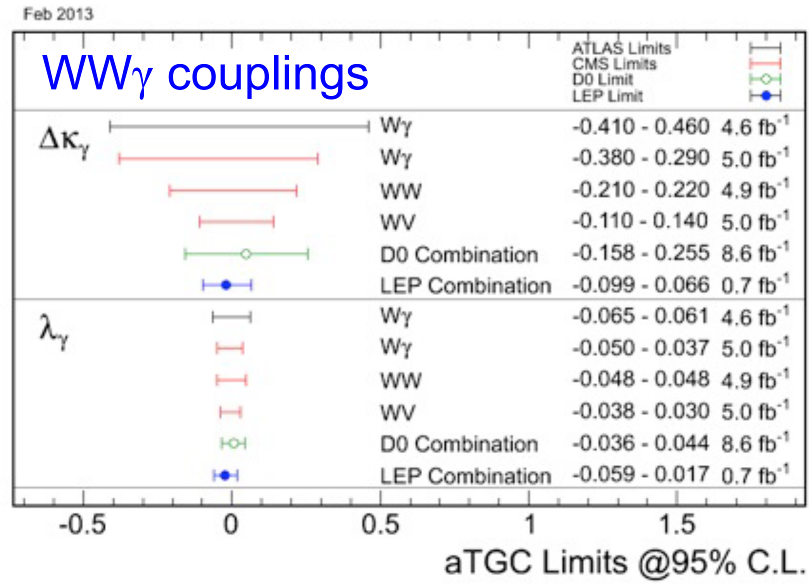
Theory includes:

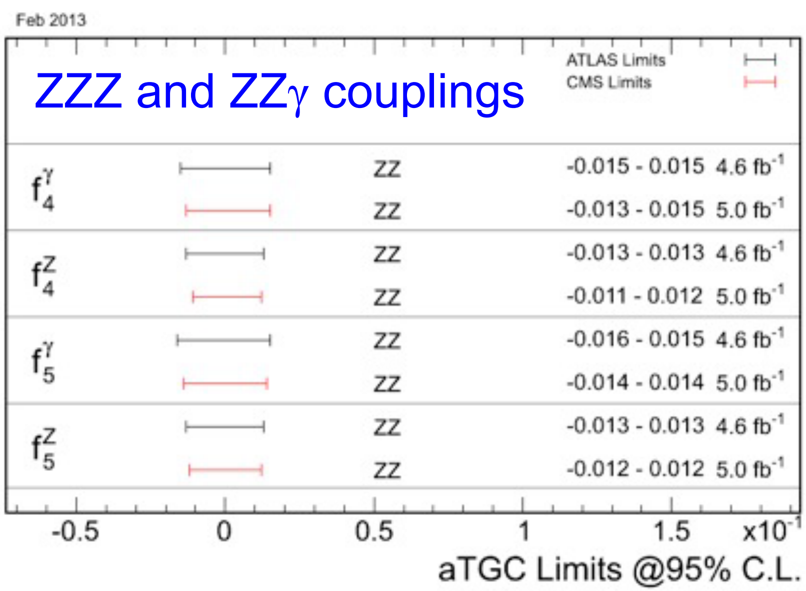
- NLO for single boson production
- gg' → Zγ, WW or ZZ (few%)

CMS have measured the production cross sections of Wγ, Zγ, WW, WZ and ZZ at $\sqrt{s}$ = 7 and 8 TeV

Triple Gauge Couplings







TGCs consistent with the SM

- Four of the WWZ and WWγ couplings are constrained to O(0.05)
  - Caveat: LEP scenario is used
  - $\Delta\kappa_\gamma$ remains less precise
- ZZZ and ZZγ couplings are constrained by the LHC results to O(0.01)

8 TeV data not included yet

Summary

- Impressive amount of EWK results from the CMS experiment
  - Precise test of the Standard Model at TeV scale
  - Agreement with theory across orders of magnitude
  - Starting to set serious constraints on electroweak parameters and PDFs
  - Measurements are challenging NLO and NNLO predictions
  - TGCs show no deviation from the SM

- Still most of the LHC data at 8 TeV to be analyzed
  - More results with improved precision expected soon, stay tuned!