Massachusetts Institute of Technology

Vector boson production and CMS performance at $\sqrt{s}$=13 TeV

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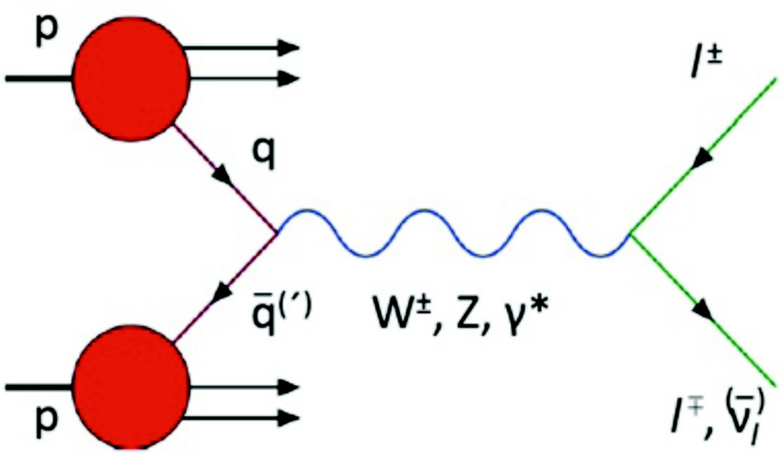
Massachusetts Institute of Technology

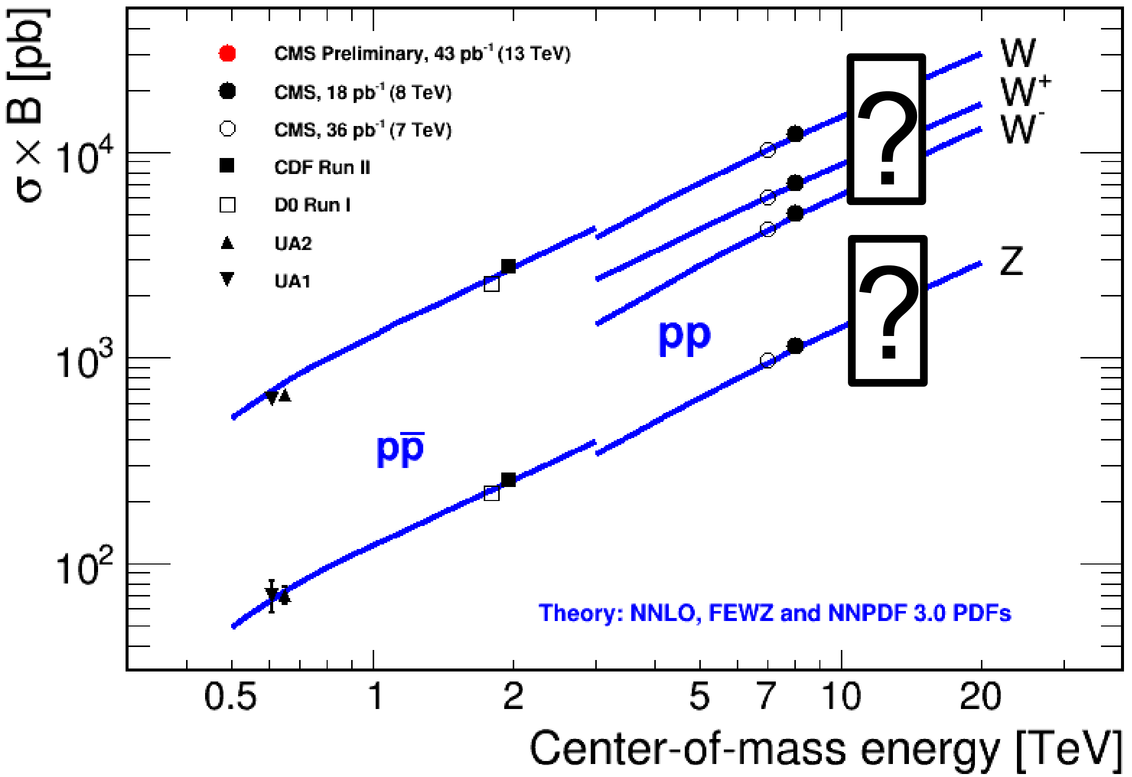
On behalf of the CMS Collaboration

LPCC Seminar

December 8, 2015

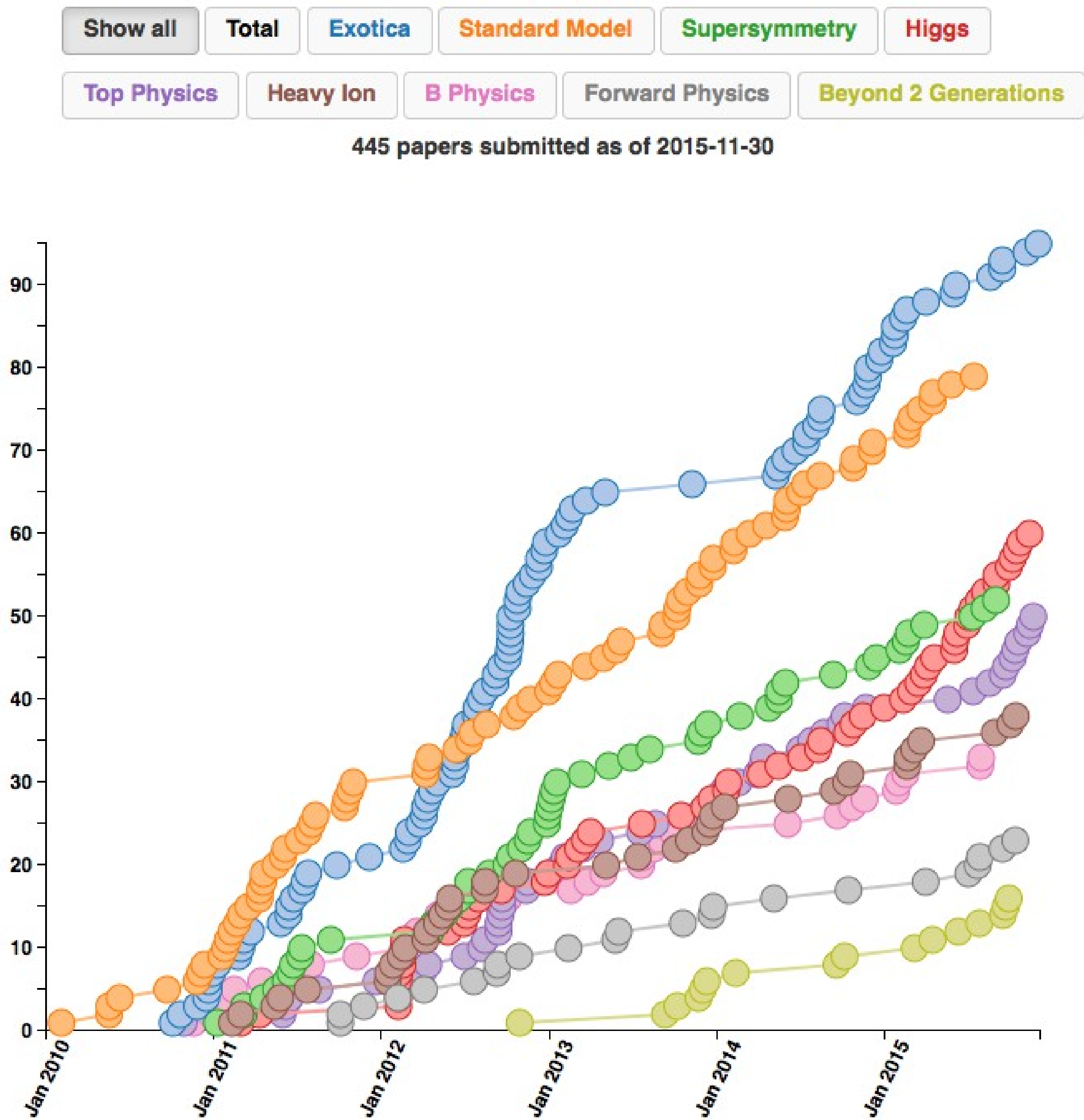
W and Z production at 13 TeV





- Serves as Standard Model precision test
- Standard candle for detector and physics commissioning
- Constrain parton distribution functions

CMS Publications



445 physics papers submitted

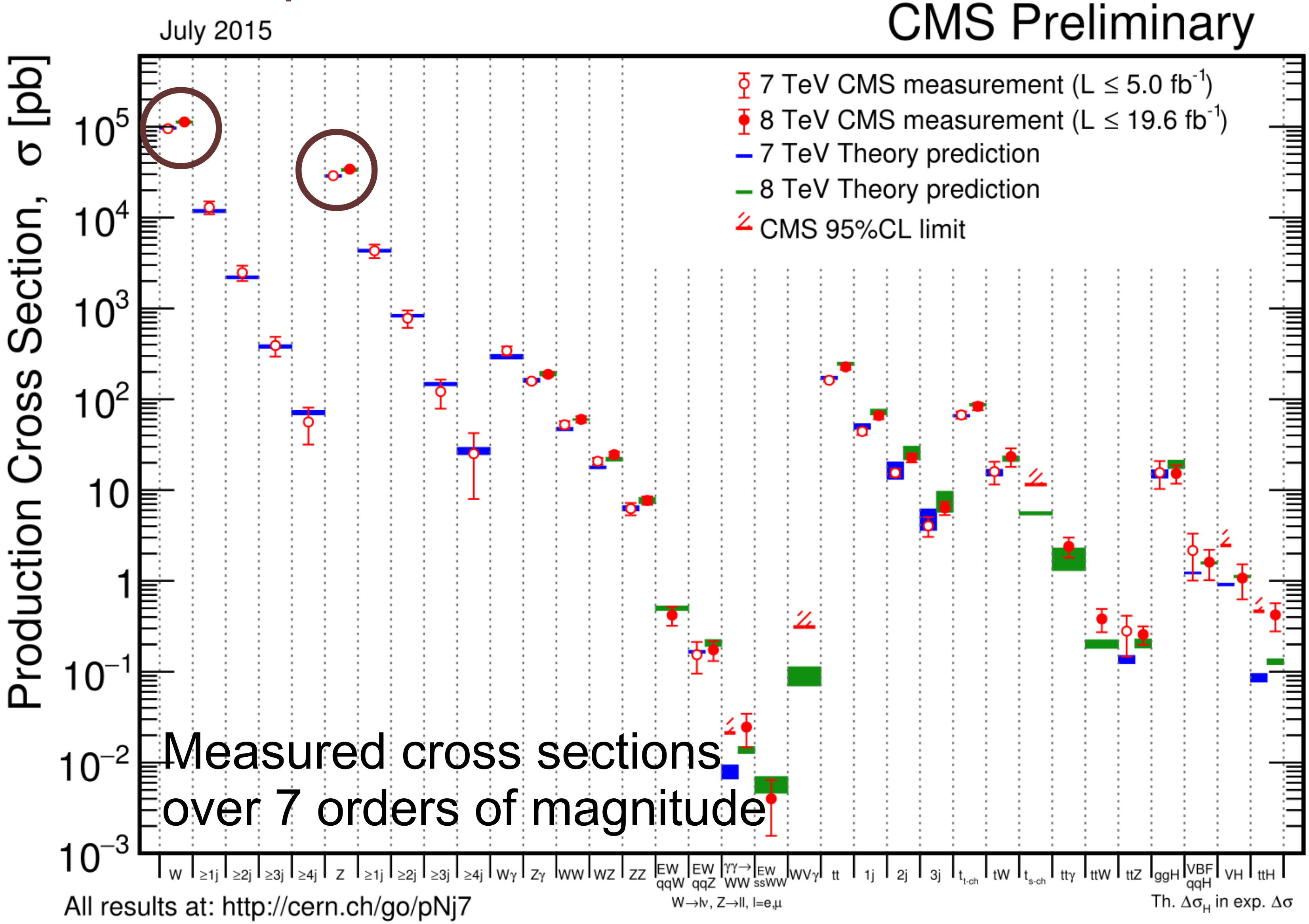
- \+ 24 papers based on cosmic rays
- \+ 15 detector performance papers
- \+ 1 CMS detector paper

79 papers dedicated to Standard Model physics

Many more in the pipeline

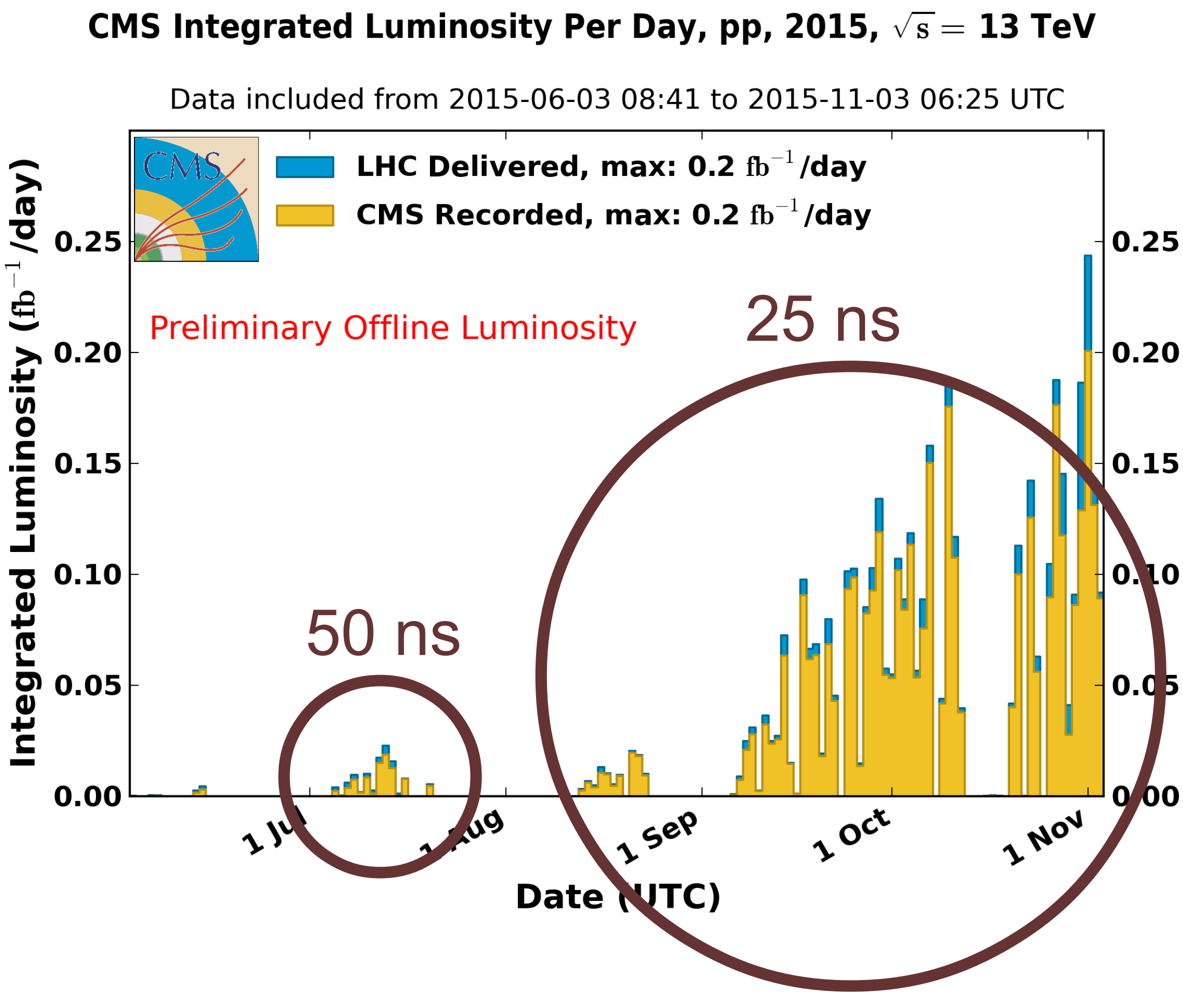
http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

W and Z production

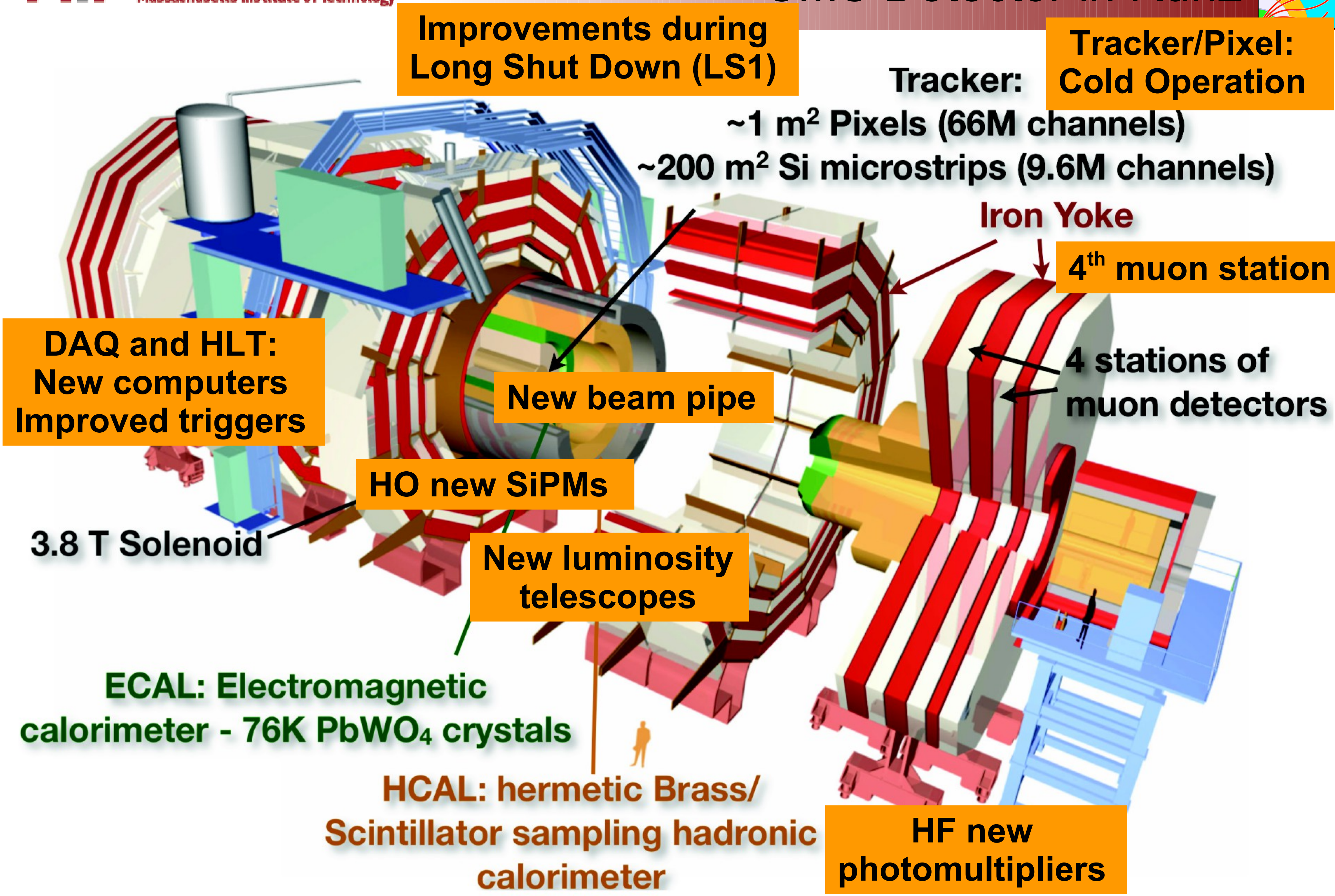


Run2 Perspective

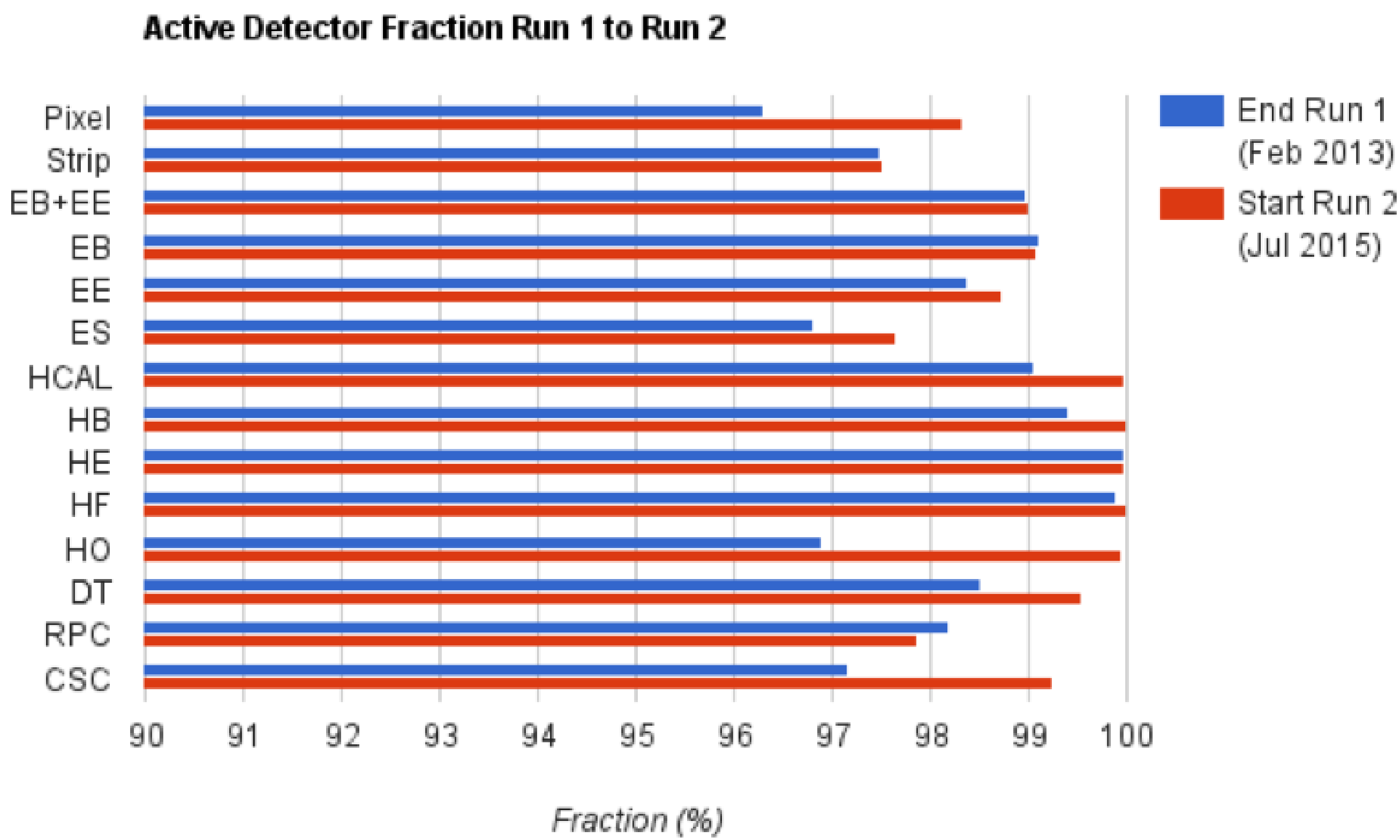
- Upgrades to detector and trigger
- Improved online/offline reconstruction
- Higher integrated luminosity expected for 2016
- Increased physics potential



CMS Detector in Run2



Detector Performance



All sub-detector operating with active detector fraction higher than Run1

Run2 PAS and Publication			
FSQ-15-001	Pseudorapidity distribution of charged hadrons in proton-proton collisions at $\sqrt{s}$= 13 TeV	PLB 751 (2015) 143	22nd July 2015
FSQ-15-002	Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s}$= 13 TeV	Submitted to PRL	11th October 2015
TOP-15-003	Measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s}$= 13 TeV	Submitted to PRL	18th October 2015
EXO-15-001	Search for narrow resonances decaying to dijets in pp Collisions at $\sqrt{s}$= 13 TeV	Submitted to PRL	3rd December 2015
TOP-15-010	First measurement of the differential cross section for ttbar production in the dilepton final state at $\sqrt{s}$= 13 TeV	CMS approved	August 2015
TOP-15-005	Measurement of the inclusive and differential $t\bar{t}$ production cross sections in lepton+jets final states at 13 TeV	CMS approved	September 2015
TOP-15-004	Measurement of the t-channel single top-quark cross section at 13 TeV	CMS approved	September 2015
TOP-15-013	Measurement of differential top quark pair production cross sections in a fiducial volume as a function of event variables in pp collisions at $\sqrt{s}$= 13 TeV	CMS approved	November 2015
SMP-15-004	Measurement of inclusive W and Z boson production cross sections in pp collisions at $\sqrt{s}$= 13 TeV	CMS approved	November 2015
FSQ-15-007	Underlying event measurements with leading particles and jets in pp collisions at $\sqrt{s}$= 13 TeV	CMS approved	November 2015

Cross Section Measurement

Fiducial cross section

Total cross section

$$\sigma_{tot} = \frac{N}{A \cdot \varepsilon \cdot \int L\, dt}$$

- Signal extraction

- Lepton selection
- Lepton efficiencies

- Experimental setup
- Dataset
- Luminosity Calibration

- Acceptance
- Theory uncertainties

- Measure **fiducial cross section** (within detector acceptance)
- Measure **total cross section** (extrapolated to full phase space)

Luminosity Calibration

- Luminosity estimation relies on precise rate measurements using dedicated devices (Luminometers)
- Rates converted to luminosity by means of constant calibration factor (visible cross section)

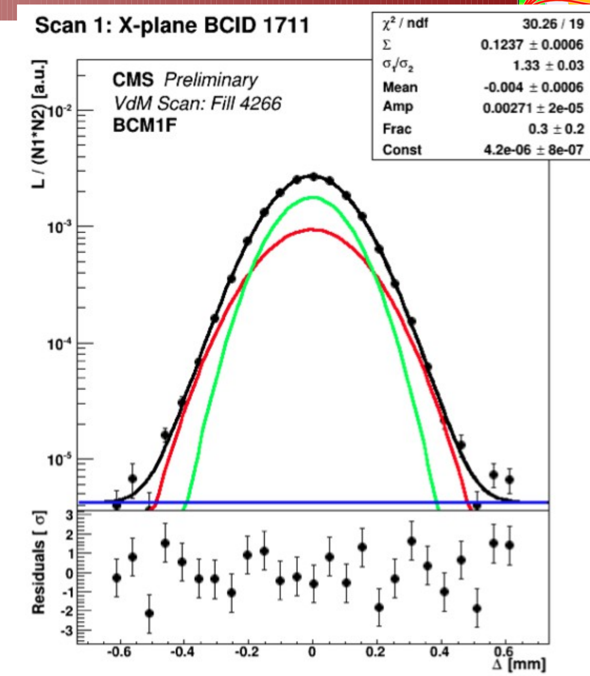
$$\mathcal{L} \cdot \sigma_{\text{vis}} = R$$

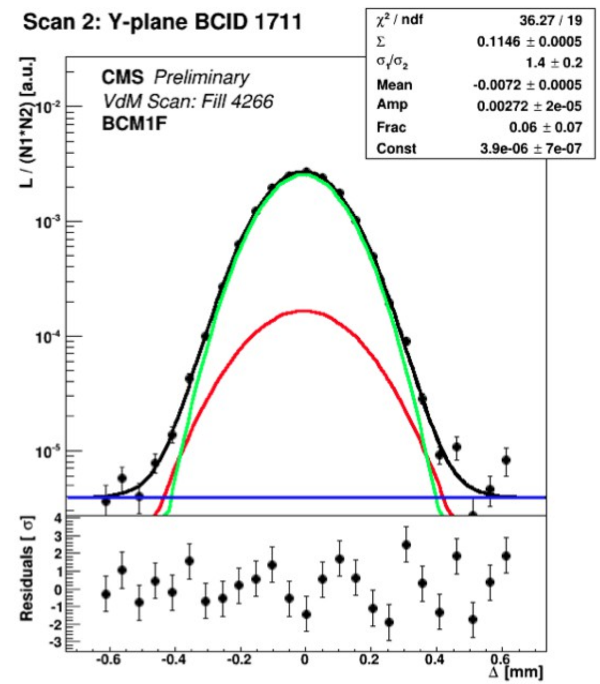
- Calibration constant determined using Van der Meer (VDM) scan technique, measuring inst. luminosity from machine parameters

$$\mathcal{L} = f \underline{N_1 N_2} \iint \underline{\rho_1(x,y)\rho_2(x,y)}\, dx\, dy$$

Bunch current measurements

Measured from scan curve





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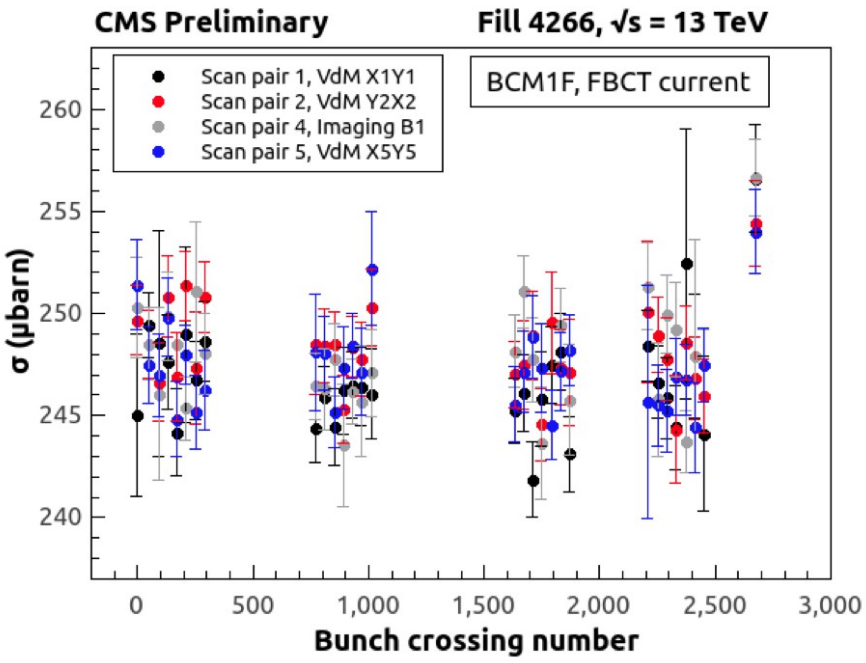
Preliminary Luminosity Calibration

- Multiple CMS sub-detectors used to understand beam and detector systematics
- CMS luminosity measurement based on 4 sub-detectors and luminosity algorithms
  - CMS Pixel Detector (offline), based on pixel cluster counting
  - Hadronic Forward Calorimeter (online), based on occupancy
  - Pixel Luminosity Telescope (online), based on occupancy
  - BCM1F diamond sensors (online), based on number of MIPs
- VDM-calibrated-BCM1F used as primary offline luminometer for physics for 2015 50 ns recorded data



Preliminary

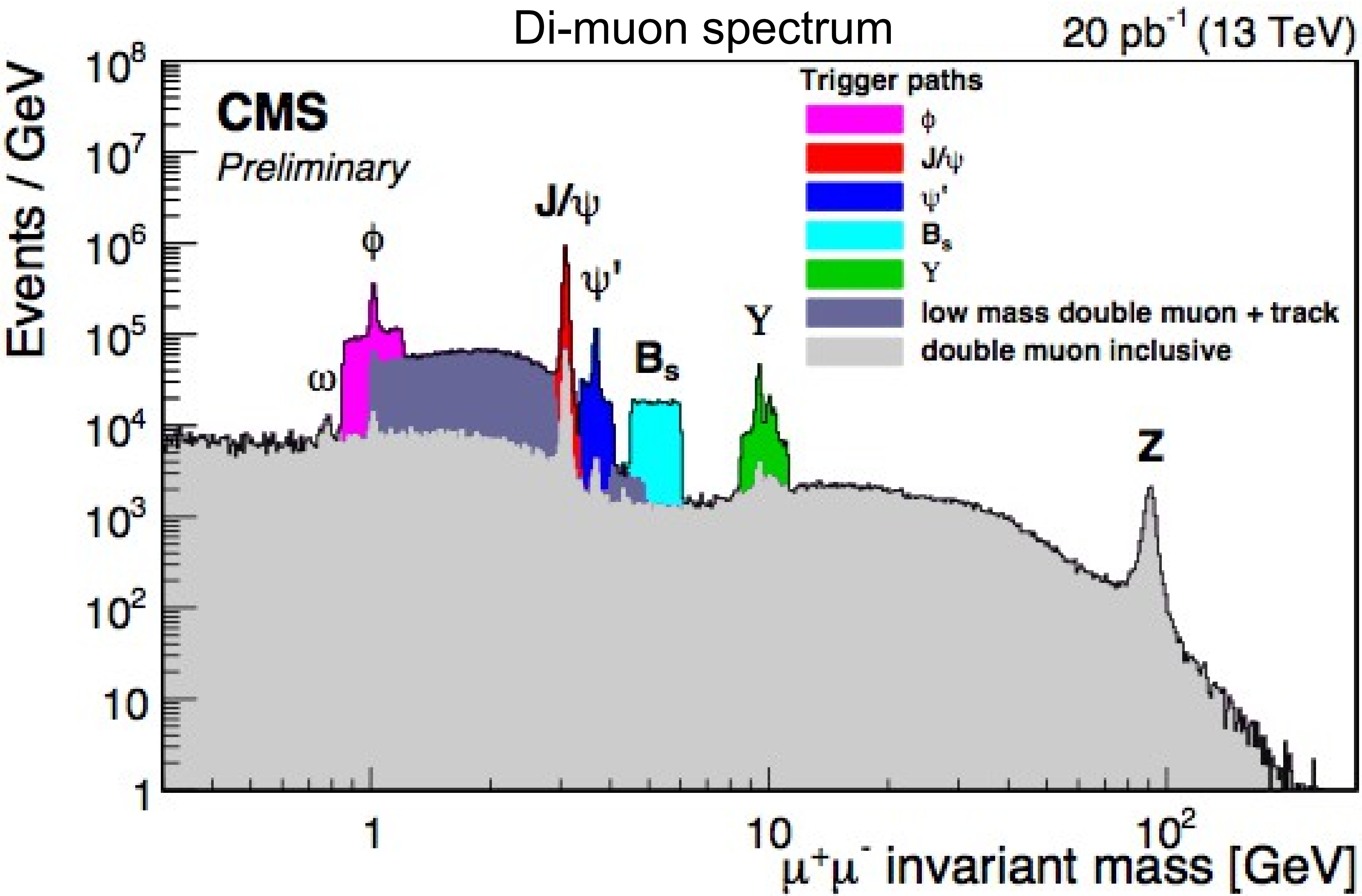
Source	Uncertainty
Uncertainty from VDM	2.6 %
Luminometer linearity and stability	4%
Total [50ns]	**4.8%**

Fiducial Region

- Muon Channel:
  - p_T>25 GeV and $|\eta|$<2.4
  - Z selection: opposite charge, 60 GeV <$M_{\mu\mu}$<120 GeV
  - W selection: reject second muon with p_T>10 GeV

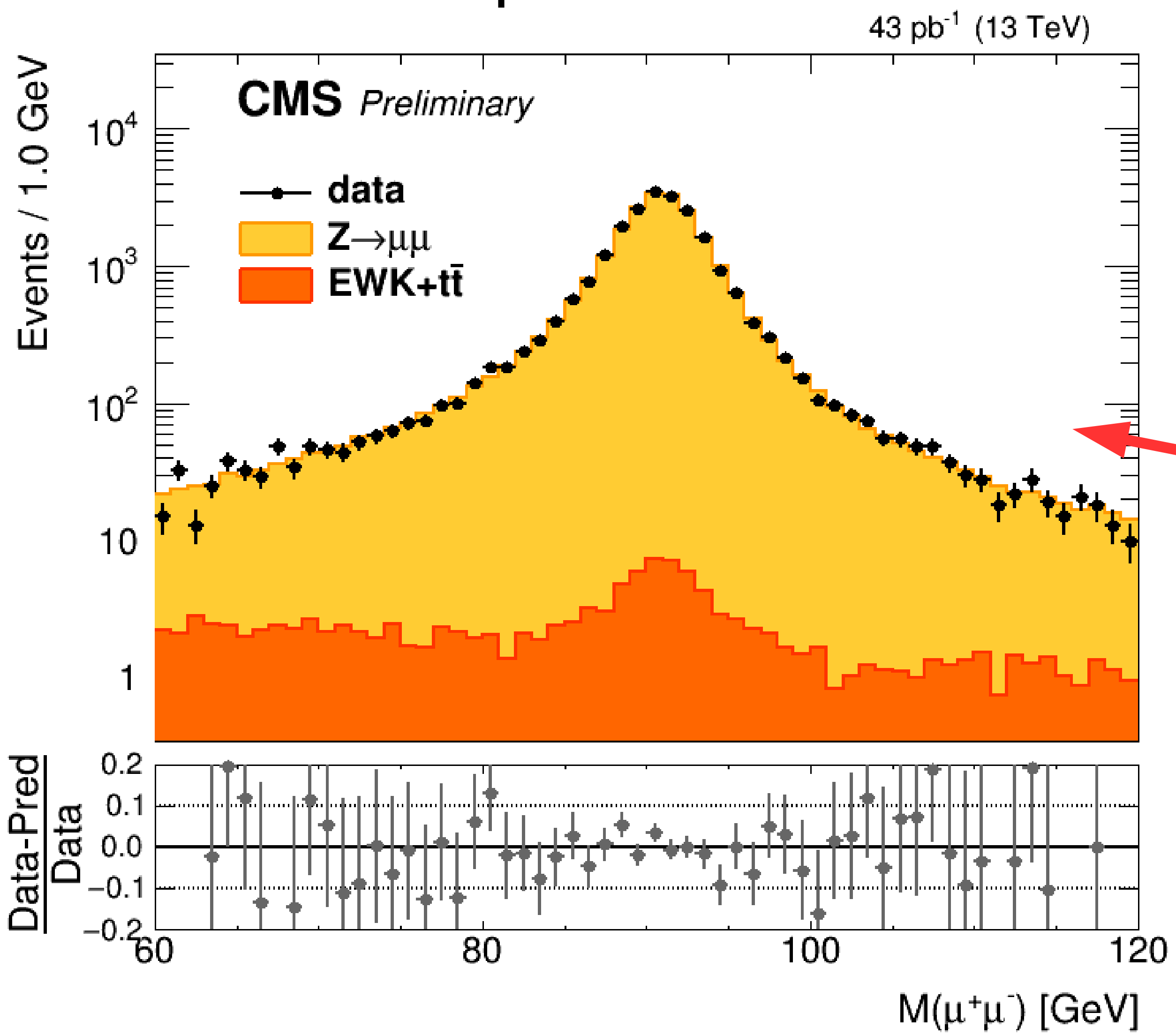
- Electron Channel:
  - E_T>25 GeV and $|\eta|$<2.5, excluding 1.44<$|\eta|$<1.5
  - Z selection: 60 GeV <M_{ee}<120 GeV
  - W selection: reject second electron with E_T>10 GeV

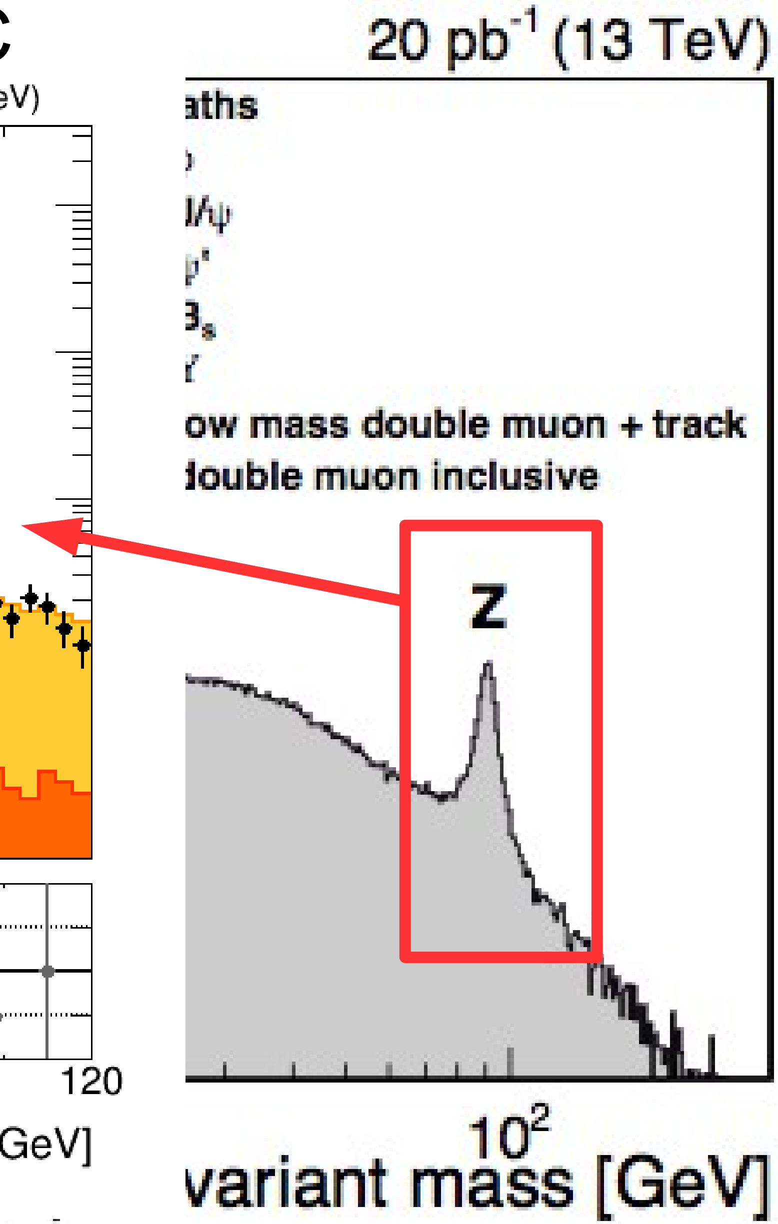
Muon Performance



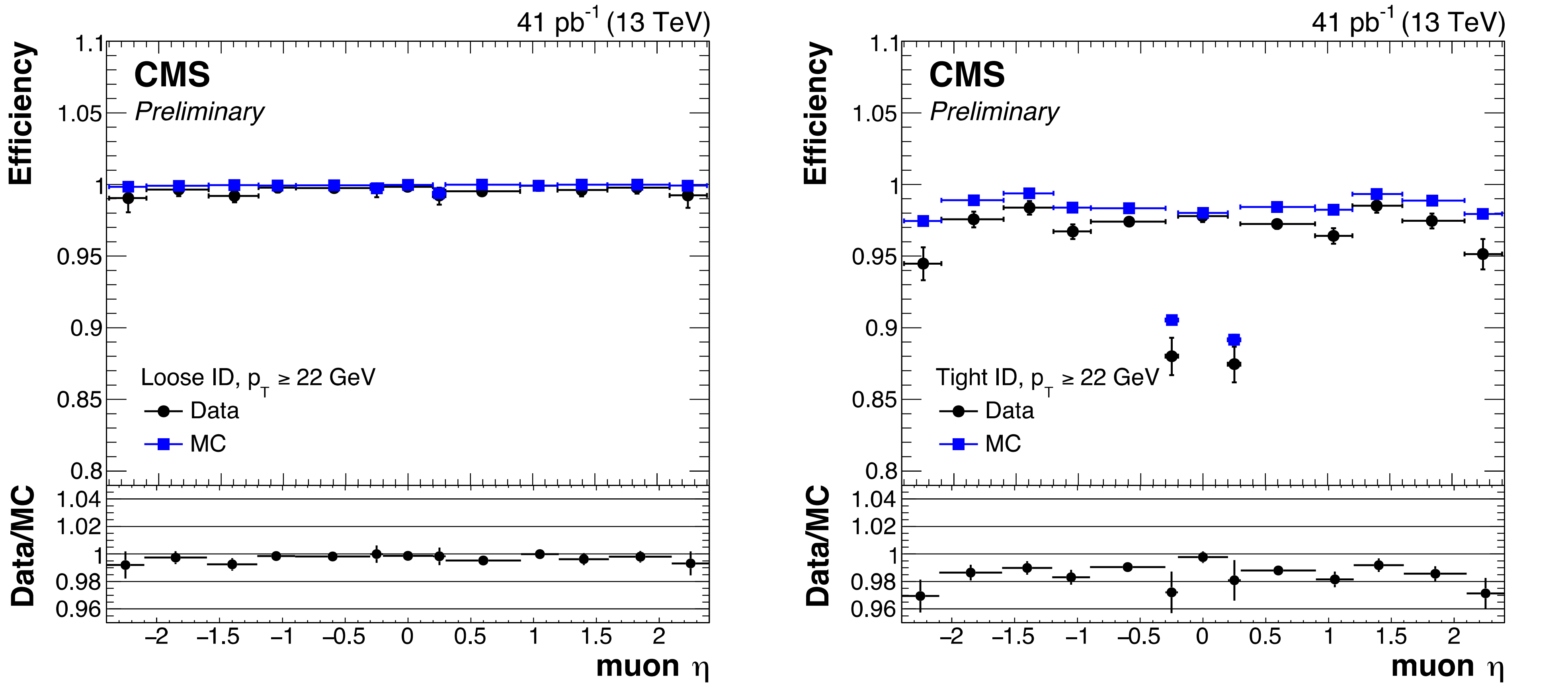
Collected with various dimuon triggers

Z line shape in data and MC



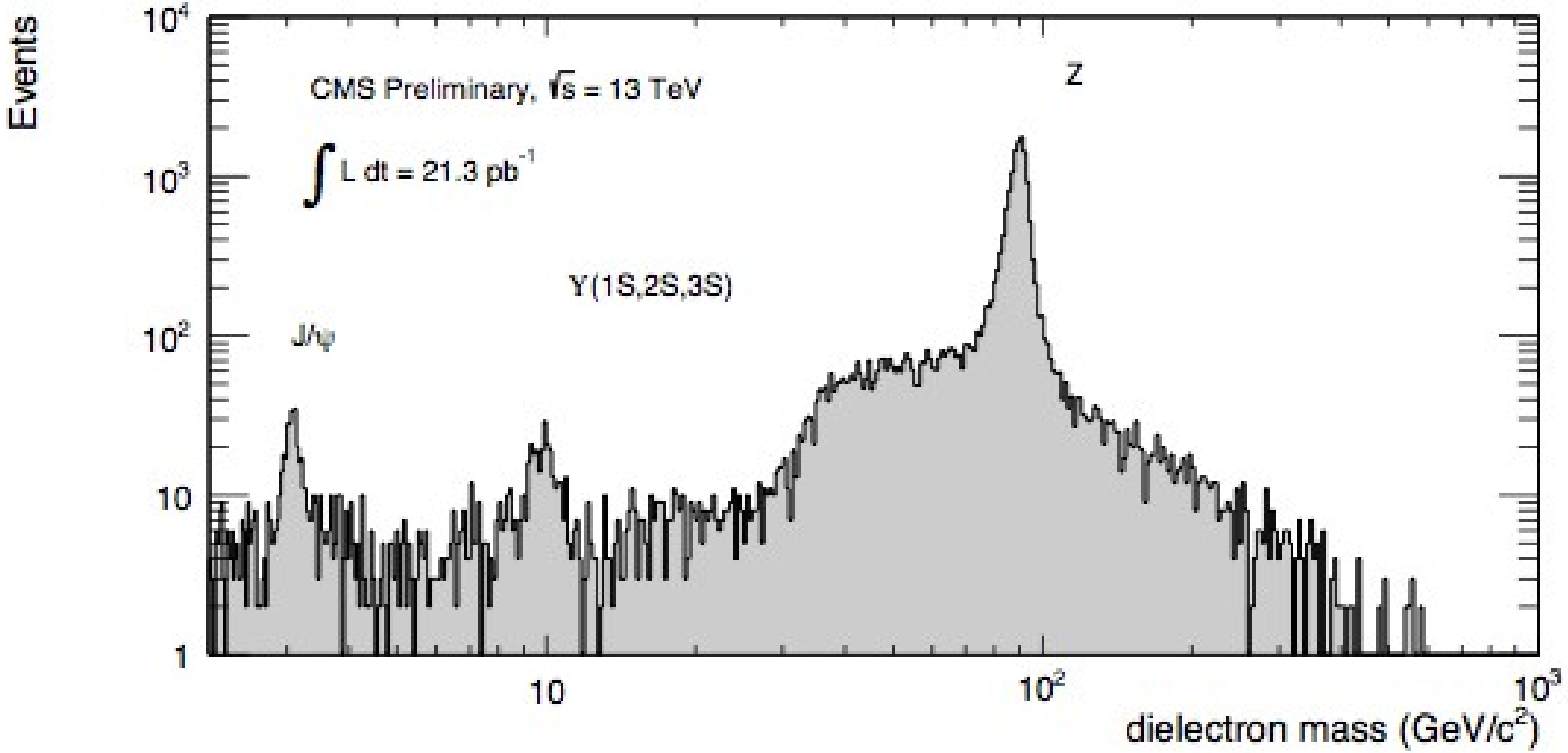


Reconstruction and Identification Efficiency



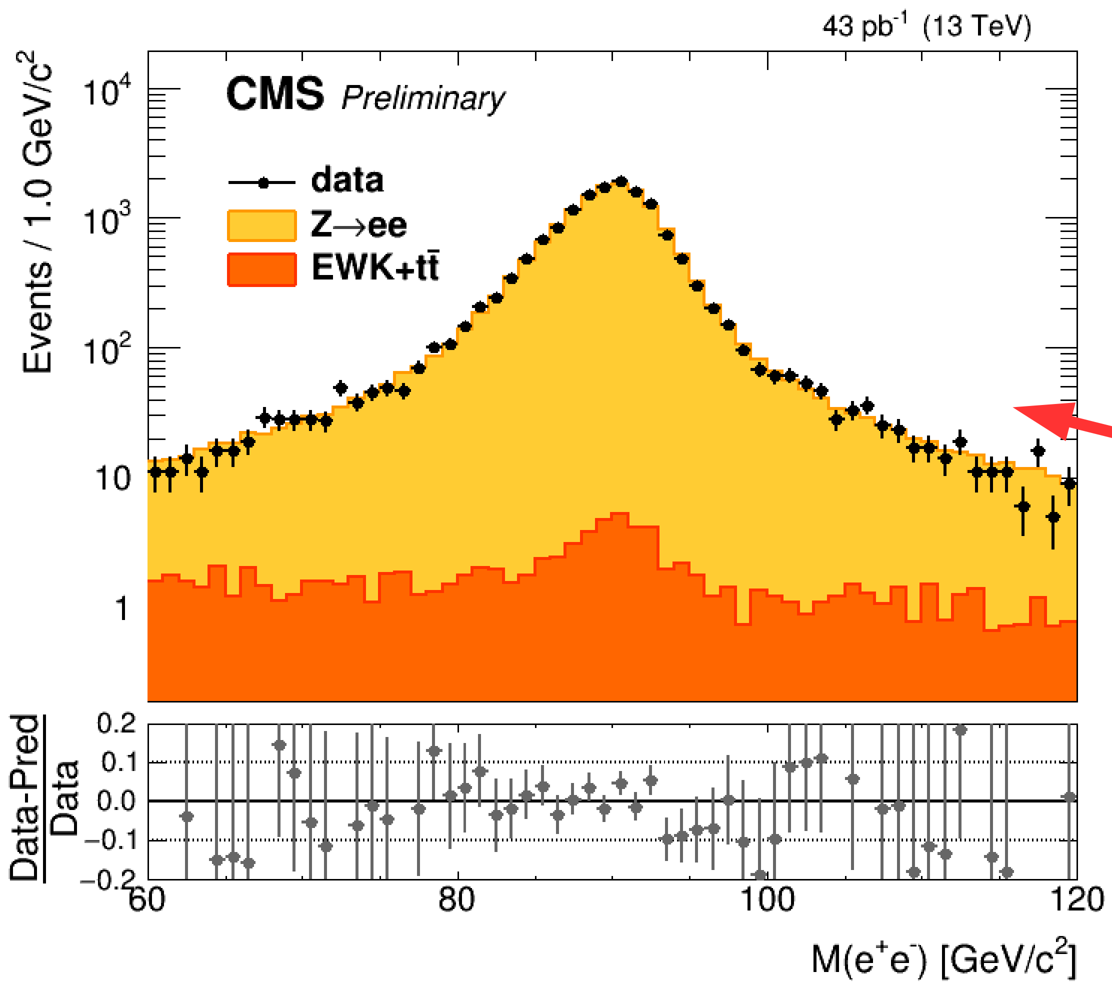
- Efficiency estimated using tag-and-probe technique
- Reconstruction efficiency in good agreement between data and MC, scale factors close to 1

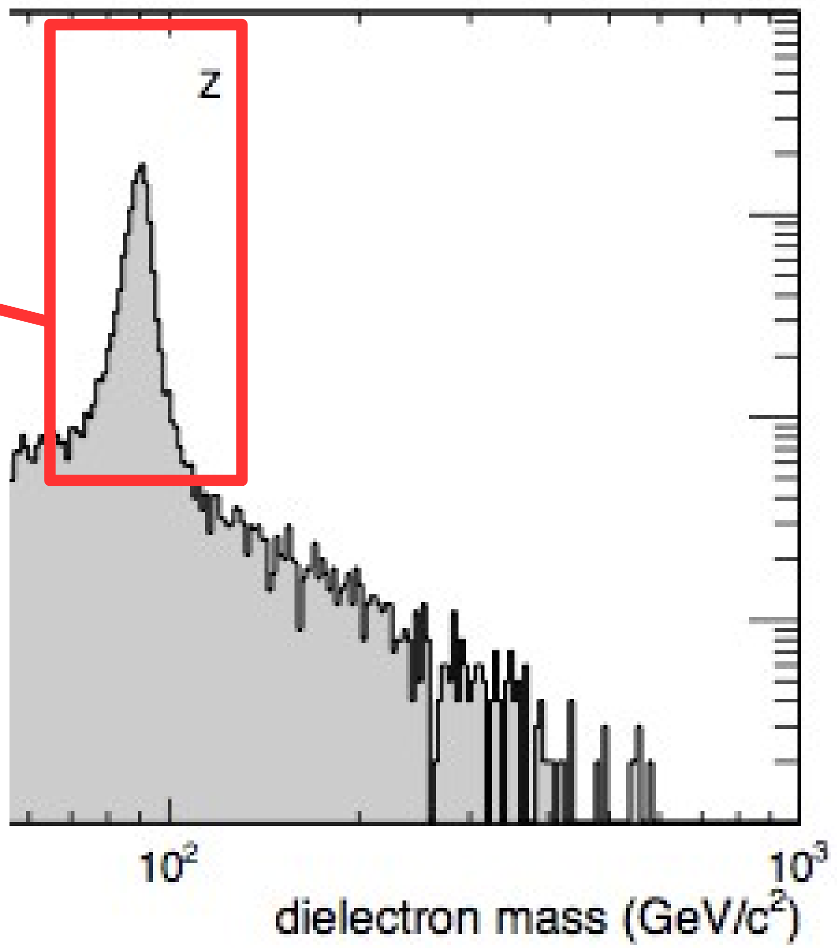
Di-electron spectrum



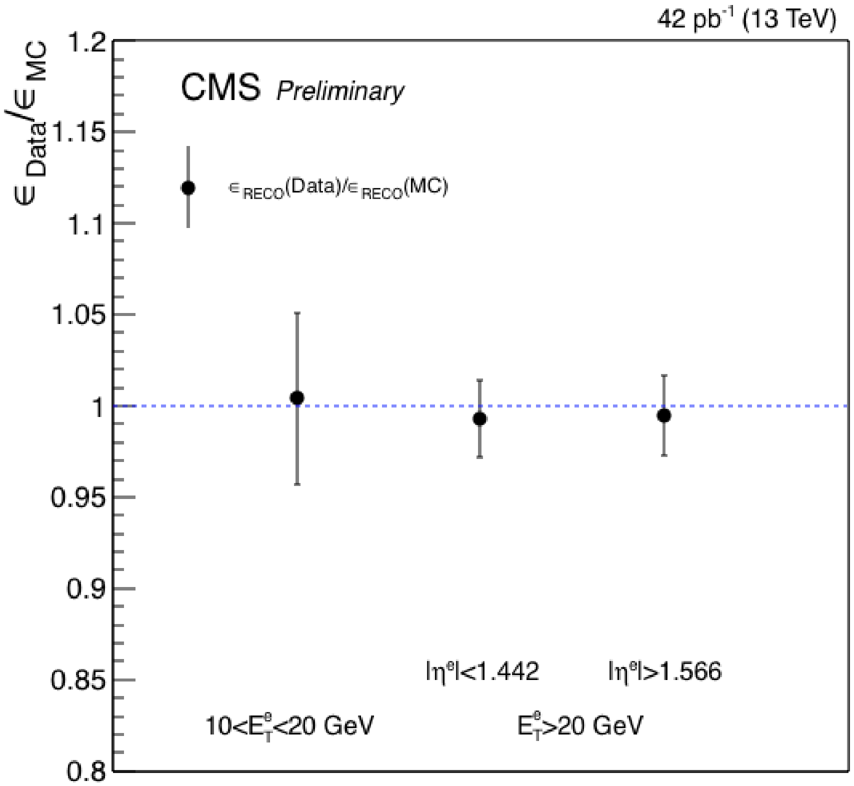
Events selected in the di-electron data sets

Z line shape in data and MC

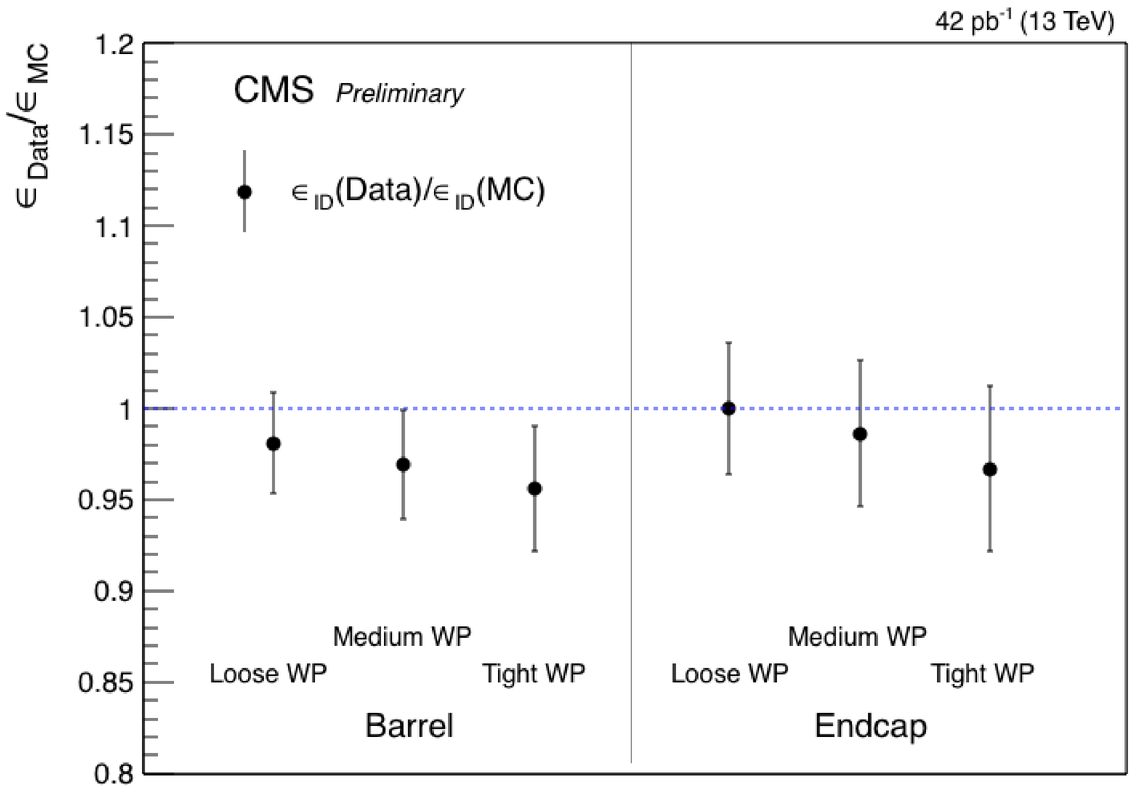




Reconstruction Efficiency



Identification Efficiency



- Efficiency estimated using tag-and-probe technique
- ID and reconstruction efficiency in good agreement between data and MC, scale factors close to 1

Efficiency

- Estimated using tag-and-probe technique
  - Tag satisfying lepton selection
  - Tag+probe mass: 60 GeV<mll<120 GeV
  - Count passing and failing probes to estimate efficiency

$$\epsilon = \frac{N_{pass}}{N_{pass} + N_{fail}}$$

  - In case of non-negligible background, simultaneous fit to mass distribution in passing and failing categories
- Efficiency factorized, each estimated wrt previous selection
- Lepton efficiencies binned in [p_T,η]
- Main systematic uncertainties
  - Choice of signal and background shape
  - Different binning
- Statistics of tag-and-probe sample affects systematic uncertainty

Acceptance

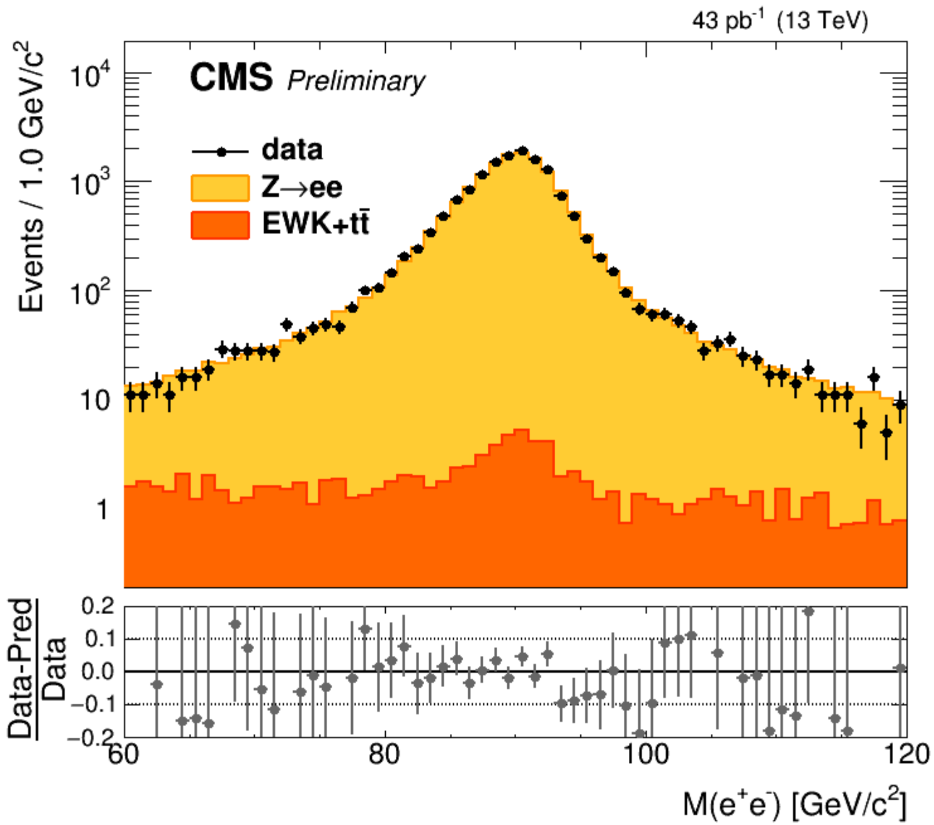
- Fraction of events passing the fiducial requirements
  - Central value estimated using aMC@NLO with NNPDF3.0
- AMC@NLO (+Pythia 8 parton shower) is accurate to NLO perturbative QCD effects
  - Parton shower to model soft, non-perturbative QCD effects
- Effect on the acceptances due to missing effects and choice of models
  - Higher order QCD corrections
  - Soft QCD corrections (resummation)
  - Higher order EWK corrections
  - PDF choice (NNPDF 3.0 used)
  - Parton shower model for FSR (Pythia 8)
- The corrections are small->no additional corrections applied
  - Differences taken as systematic uncertainties

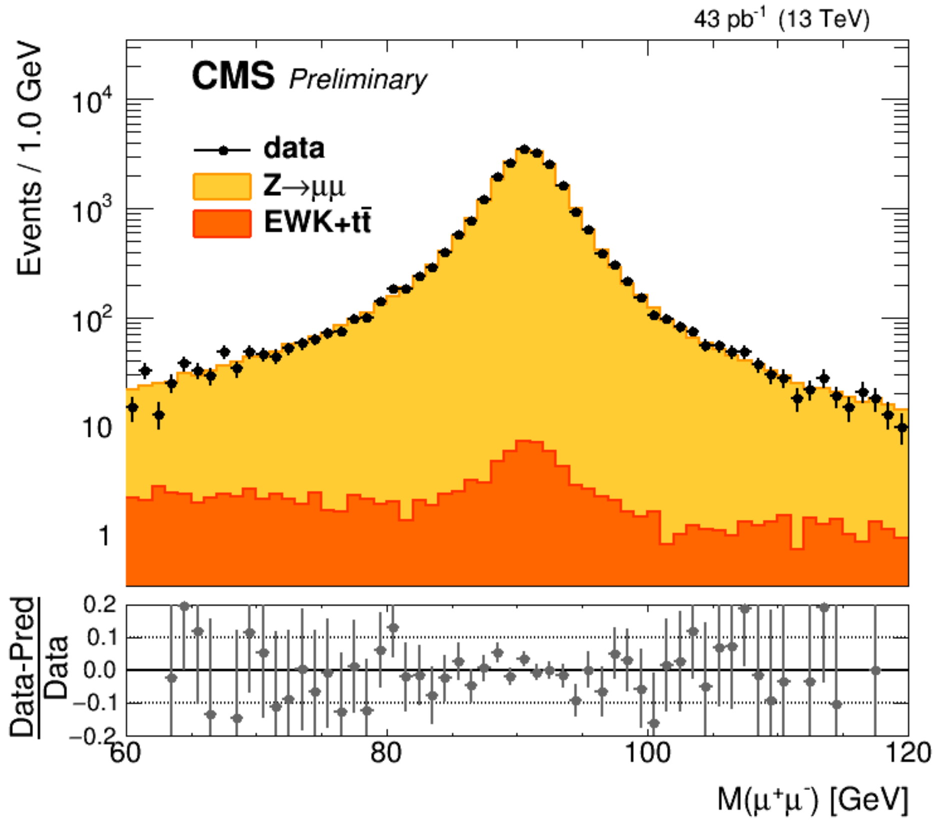
Theory Uncertainties

- Higher order QCD corrections [NNLO] and resummation
  - Compare ResBos/DYRES [NNLO and NNLL] with the baseline acceptance
- PDF uncertainties
  - Uncertainties due to error PDF sets and α_s
- Missing QCD corrections beyond NNLO
  - Use FEWZ 3.1 to estimate the uncertainty by varying the factorization and renormalization scales: $\mu_R=\mu_F=\{M,2M,M/2\}$
- FSR modeling and higher order EWK corrections
  - Use Horace for FSR modeling and compare to Pythia 8 FSR modeling
  - Compare Horace with full NLO EWK corrections to Horace with just FSR correction

Z Signal Extraction

- Z events yields computed by counting events in mass window
- Very small background contribution, estimated from simulation





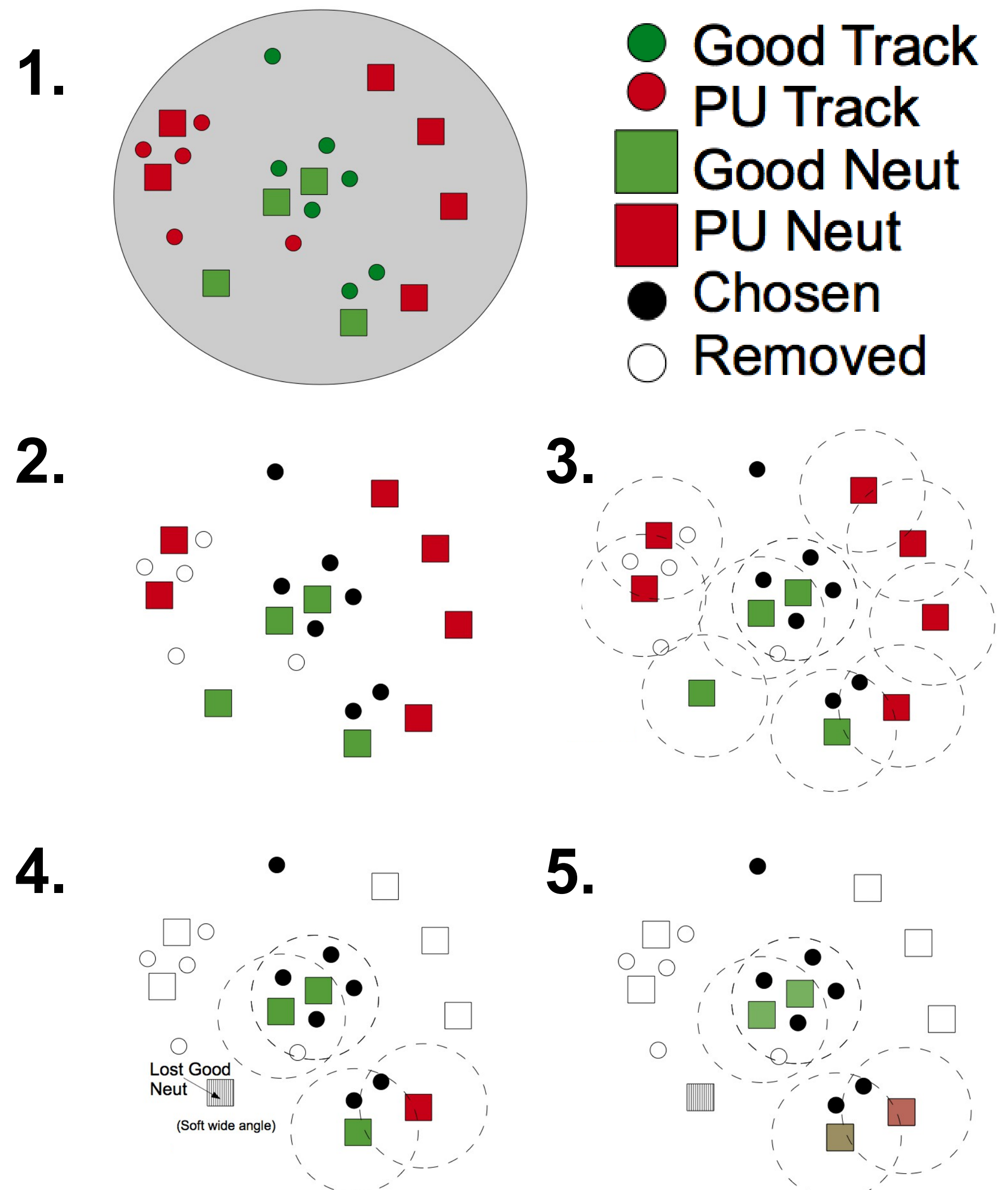
Signal Yield: 15290±120
Acceptance: 0.33±0.01
Efficiency: 0.56±0.04

Signal Yield: 23670±150
Acceptance: 0.36±0.01
Efficiency: 0.80±0.02

W Signal Extraction

- W signal yield estimated from fit to MET distribution
- Accurate MET measurement essential to distinguish signal from background
- New method for pile-up mitigation at single particle level (PUPPI)
- Compute weight per particle to discriminate PU
- Discard small-weight or small-E_T particles
- Calculate E_T^{miss} as negative weighted vector sum of particles

PUPPI algorithm

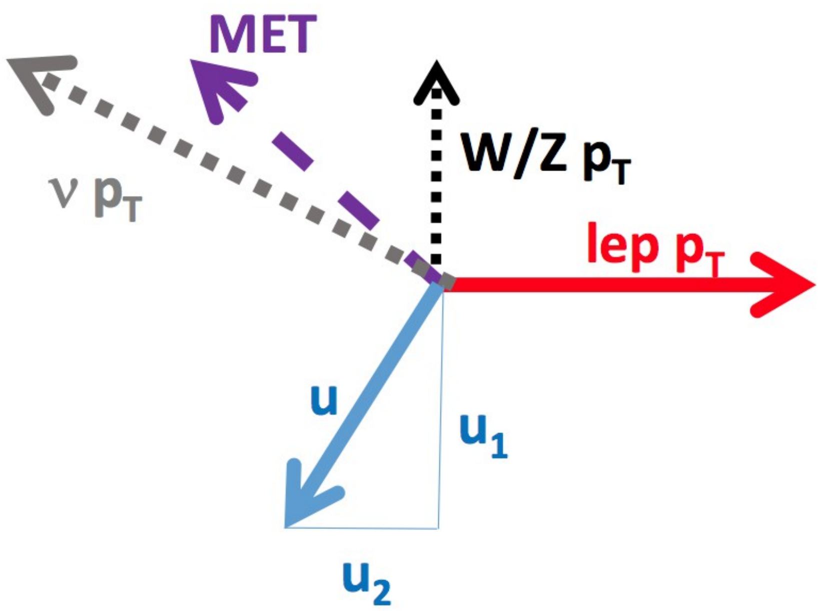


JHEP 10 (2014) 59, arXiv:1407.6013

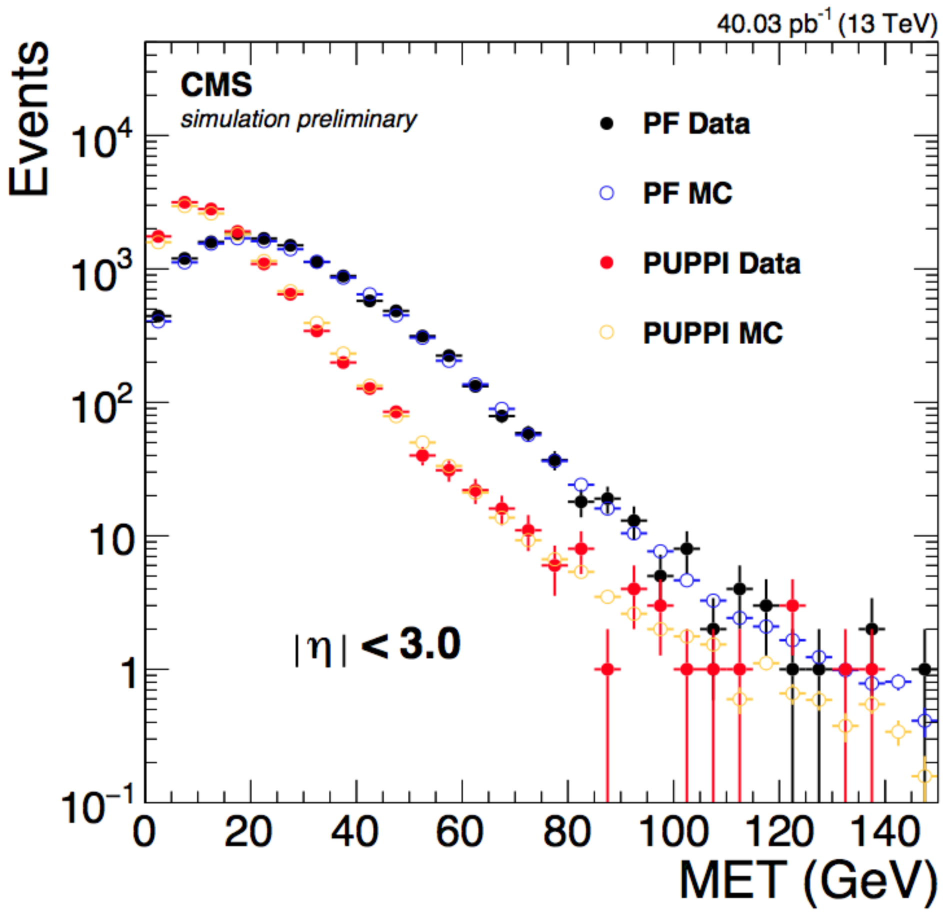
Courtesy of P. Harris

Missing Energy Performance

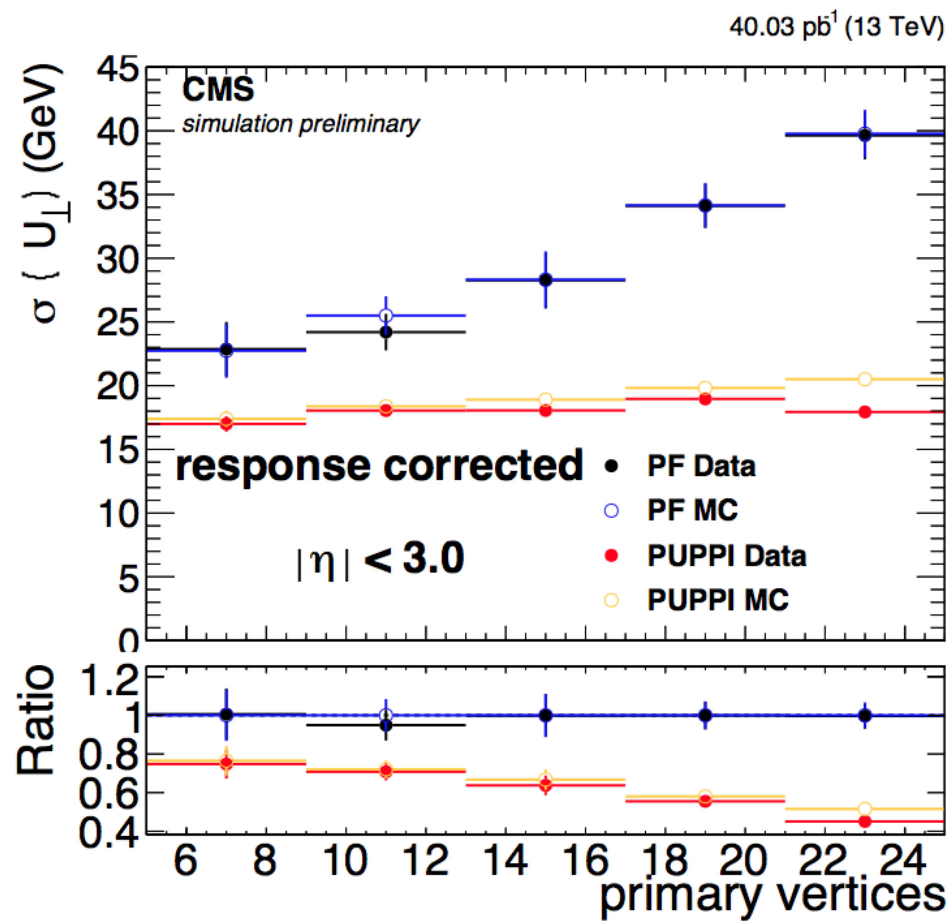
- Evaluate MET performance
- Obtained accurate MET model by recoil calibration
  - Parametrize parallel (u_1) and perpendicular (u_2) components of recoil as function of boson p_T
  - Correct recoil in W simulation using data/MC corrections obtained in Z events



Missing Energy Performance



MET from PF and PF PUPPI inputs for data and simulation

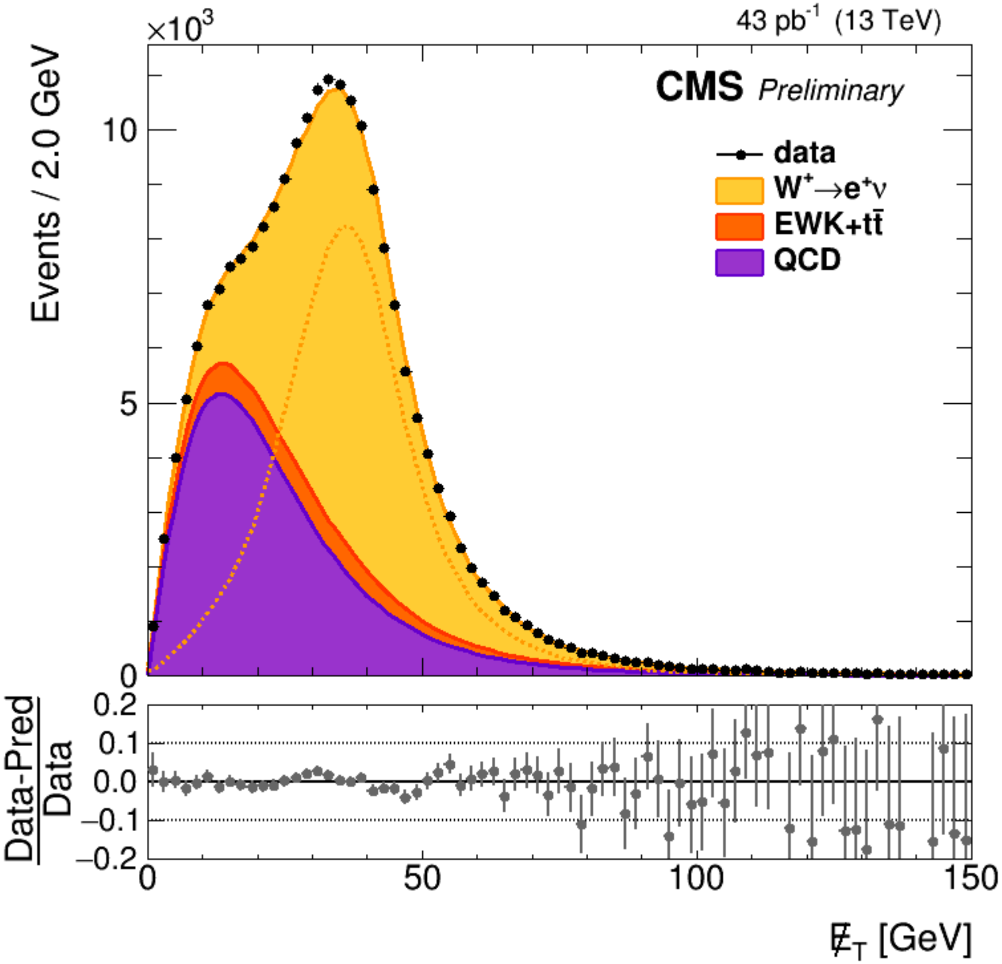


Resolution of perpendicular recoil $U_\perp$ for PF and PF PUPPI inputs versus number of reconstructed primary vertices

CMS-DP-2015-034

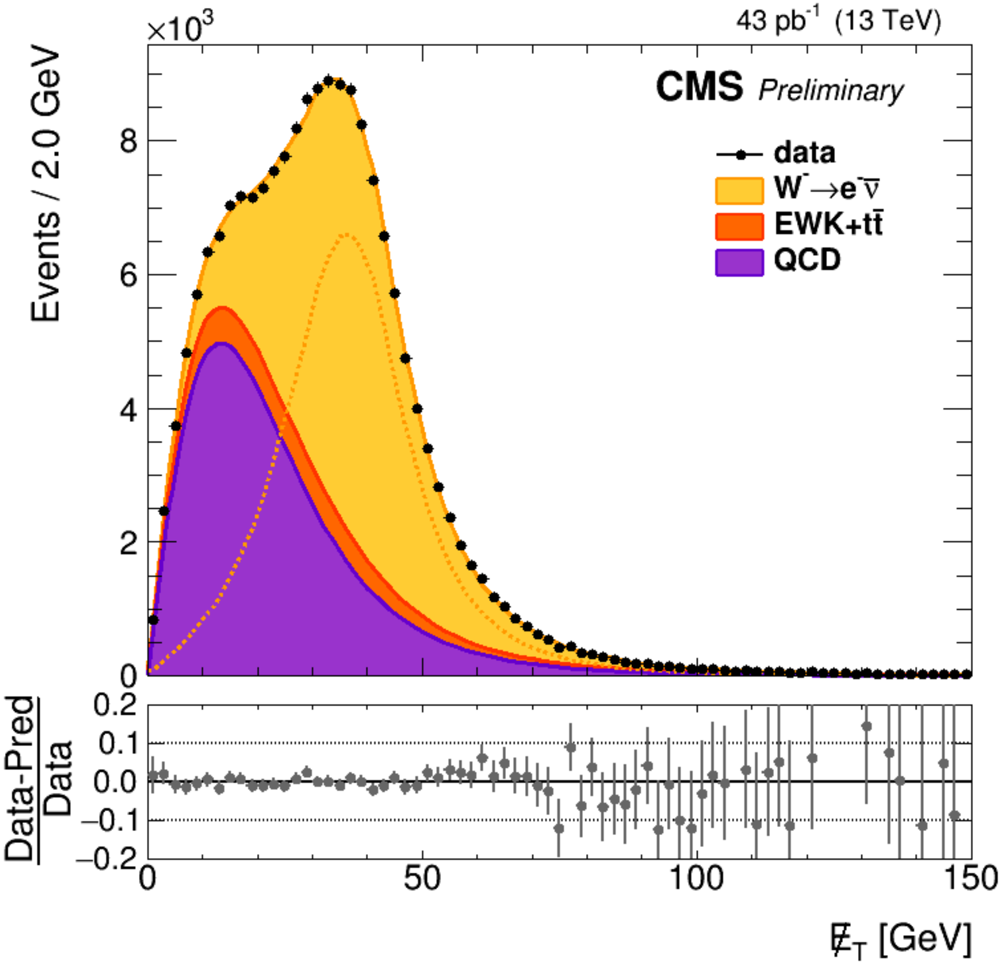
W→eν Signal Extraction

$W^+ \rightarrow e^+\nu$



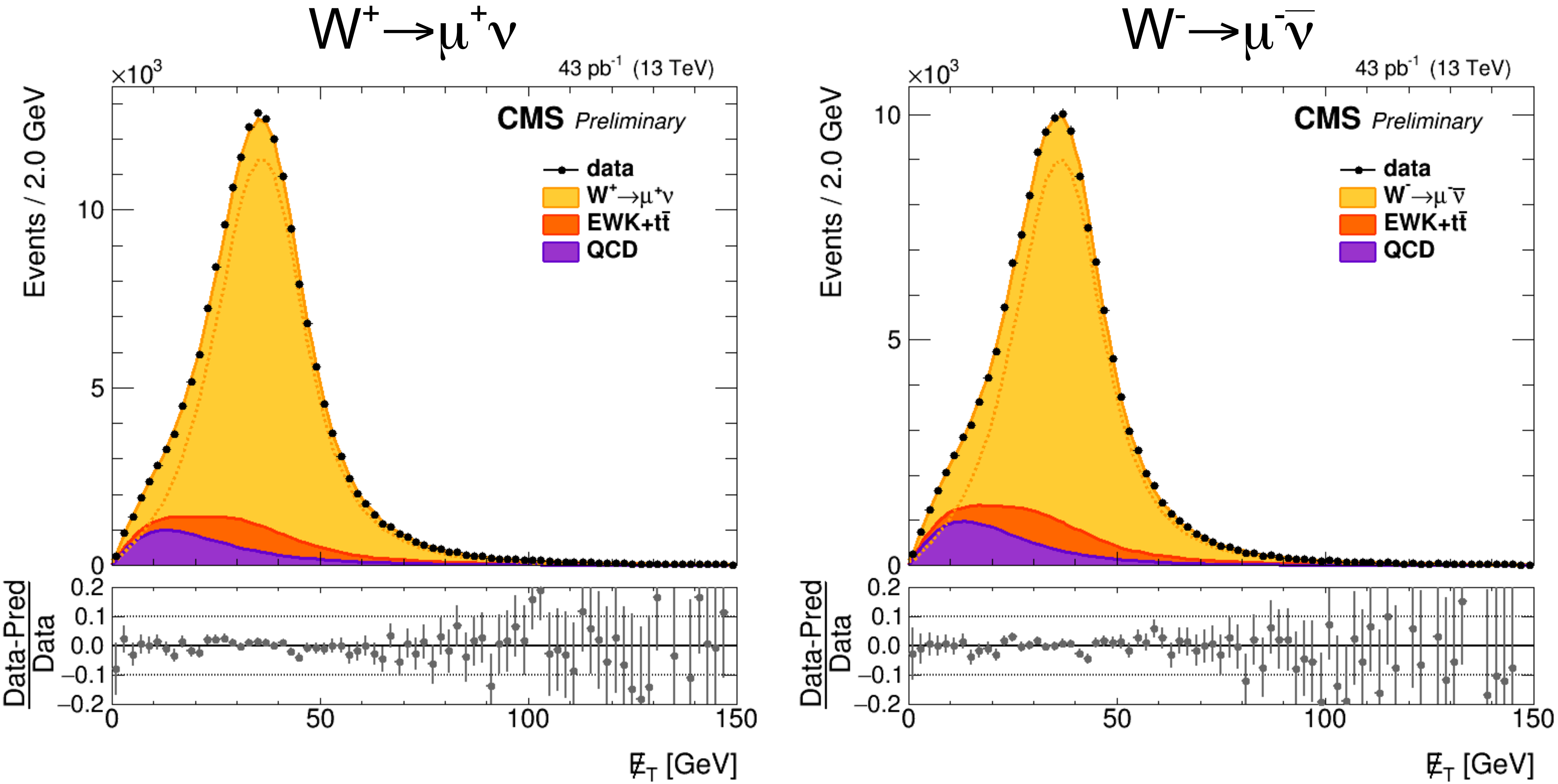
Signal Yield: 122320±980
Acceptance: 0.43±0.01
Efficiency: 0.58±0.02

$W^- \rightarrow e^-\bar{\nu}$



Signal Yield: 98200±950
Acceptance: 0.44±0.01
Efficiency: 0.60±0.02

W→μν Signal Extraction



Signal Yield: 167710±830
Acceptance: 0.44±0.01
Efficiency: 0.78±0.01

Signal Yield: 131250±910
Acceptance: 0.46±0.01
Efficiency: 0.79±0.01

Systematic Uncertainties

Electron Channel

Source	W^+	W^-	W	W^+/W^-	Z	W^+/Z	W^-/Z	W/Z
Lepton charge, reco. & id. [%]	2.1	2.0	2.1	0.6	2.5	1.2	1.0	1.0
Bkg. subtraction / modeling [%]	1.4	1.4	1.4	0.9	0.6	1.5	1.5	1.5
E_T^{miss} scale and resolution			shape		NA		shape	
Electron scale and resolution			shape		NA		shape	
Total experimental [%]	2.5	2.5	2.5	1.1	2.6	1.9	1.8	1.8
Theoretical uncertainty [%]	1.6	1.4	1.4	1.9	1.6	1.9	1.9	1.7
Lumi [%]	4.8	4.8	4.8	NA	4.8	NA	NA	NA
Total [%]	5.6	5.6	5.6	2.1	5.7	2.7	2.6	2.5

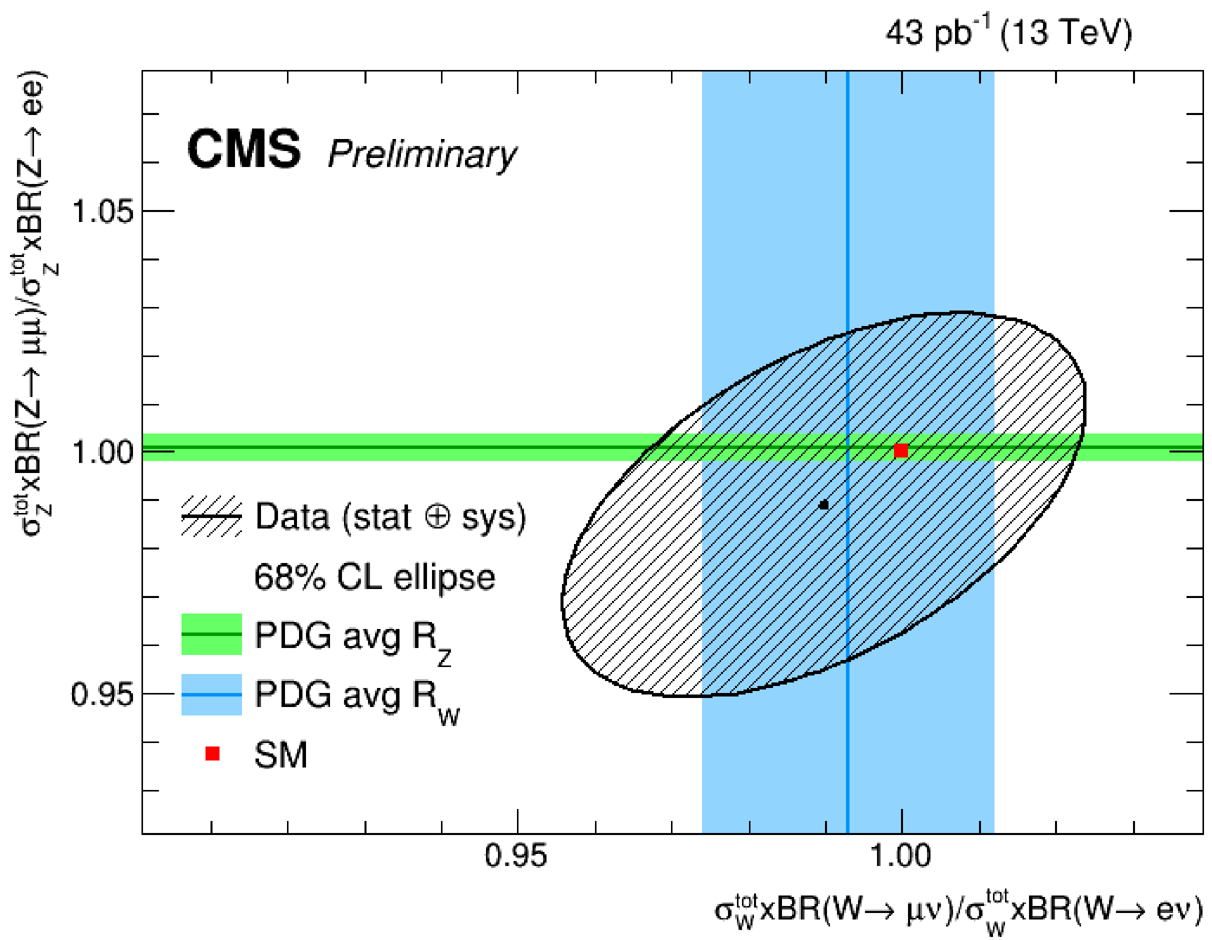
Muon Channel

Source	W^+	W^-	W	W^+/W^-	Z	W^+/Z	W^-/Z	W/Z
Lepton charge, reco. & id. [%]	1.9	1.7	1.8	0.3	2.2	0.6	0.6	0.6
Bkg. subtraction / modeling [%]	0.6	0.6	0.6	0.4	0.6	0.8	0.8	0.8
E_T^{miss} scale and resolution			shape		NA		shape	
Muon scale and resolution			shape		NA		shape	
Total experimental [%]	2.0	1.8	1.9	0.5	2.3	1.1	1.1	1.1
Theoretical Uncertainty [%]	2.0	1.7	1.3	2.3	1.5	2.0	1.9	1.6
Lumi [%]	4.8	4.8	4.8	NA	4.8	NA	NA	NA
Total [%]	5.6	5.4	5.3	2.3	5.5	2.3	2.2	1.9

- Experimental precision comparable with theoretical uncertainties
- Uncertainty on preliminary luminosity calibration dominates, cancels in the ratios

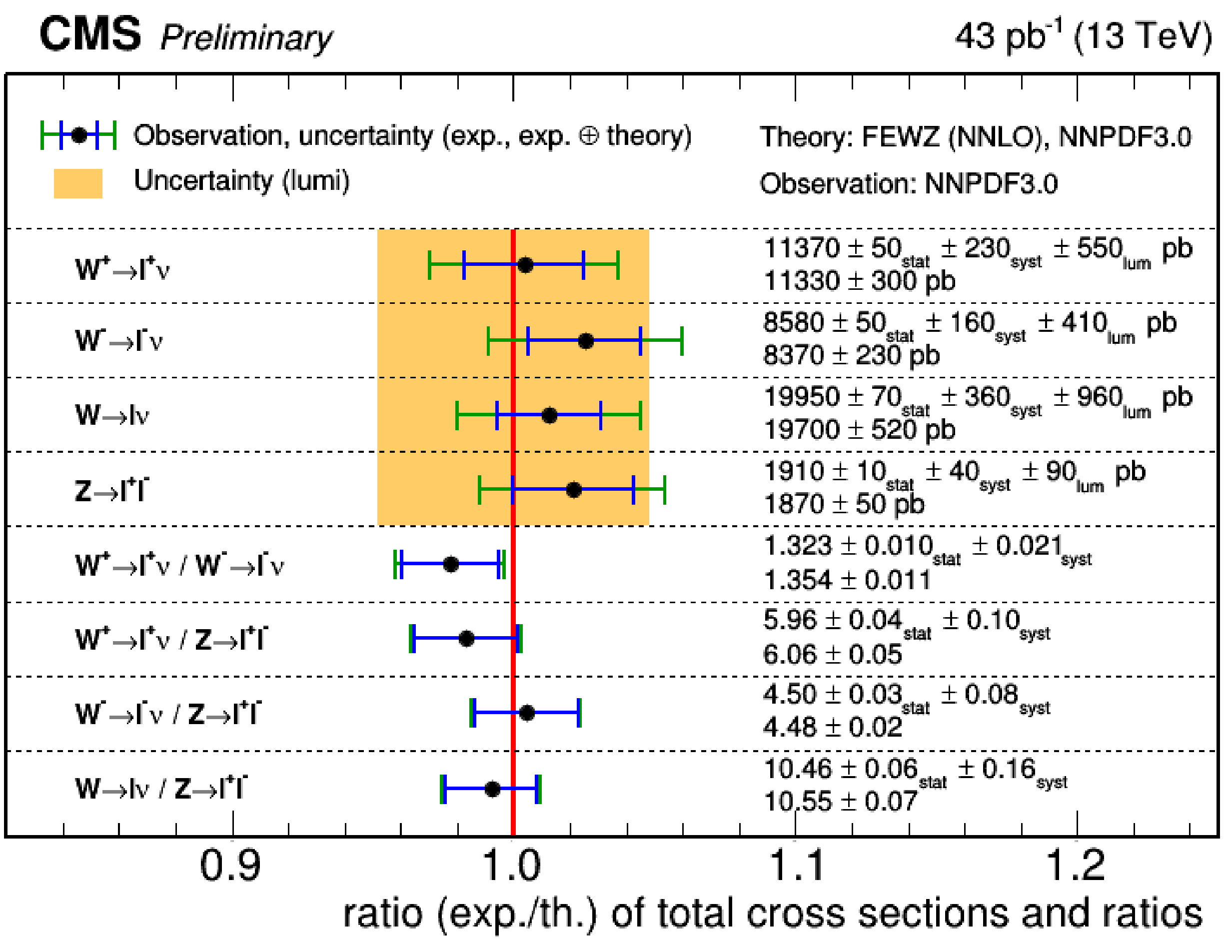
Results

- Measurement of W and Z cross sections in electron and muon channel yield a test of lepton universality
- Results in muon and electron decay channel compatible



Results

Total inclusive cross sections



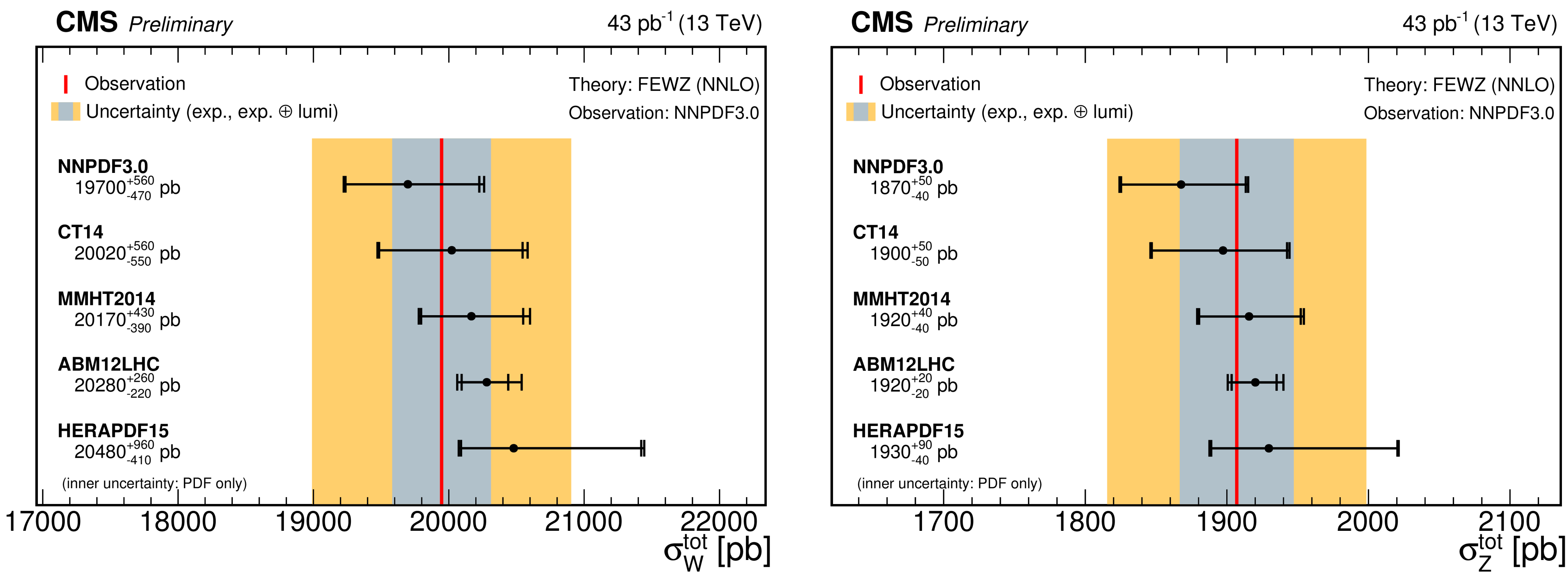
- Theoretical predictions at NNLO from FEWZ using NNPDF3.0 PDF set
  - Uncertainties include contributions from α_s, heavy quark masses, and missing higher orders
- Results have been combined assuming lepton universality
- Ratios are particular interesting as several uncertainties cancel
- Very good agreement with NNLO SM predictions

Total inclusive cross sections

Channel		$\sigma \times \mathcal{B}$ [pb] (total)	NNLO [pb]
W^+	$e^+\nu$	$11390 \pm 90\,(\text{stat}) \pm 340\,(\text{syst}) \pm 550\,(\text{lumi})$	11330^{+320}_{-270}
	$\mu^+\nu$	$11350 \pm 60\,(\text{stat}) \pm 320\,(\text{syst}) \pm 550\,(\text{lumi})$	
	$\ell^+\nu$	$11370 \pm 50\,(\text{stat}) \pm 230\,(\text{syst}) \pm 550\,(\text{lumi})$	
W^-	$e^-\nu$	$8680 \pm 80\,(\text{stat}) \pm 250\,(\text{syst}) \pm 420\,(\text{lumi})$	8370^{+240}_{-210}
	$\mu^-\nu$	$8510 \pm 60\,(\text{stat}) \pm 210\,(\text{syst}) \pm 410\,(\text{lumi})$	
	$\ell^-\nu$	$8580 \pm 50\,(\text{stat}) \pm 160\,(\text{syst}) \pm 410\,(\text{lumi})$	
W	$e\nu$	$20070 \pm 120\,(\text{stat}) \pm 570\,(\text{syst}) \pm 960\,(\text{lumi})$	19700^{+560}_{-470}
	$\mu\nu$	$19870 \pm 80\,(\text{stat}) \pm 460\,(\text{syst}) \pm 950\,(\text{lumi})$	
	$\ell\nu$	$19950 \pm 70\,(\text{stat}) \pm 360\,(\text{syst}) \pm 960\,(\text{lumi})$	
Z	e^+e^-	$1920 \pm 20\,(\text{stat}) \pm 60\,(\text{syst}) \pm 90\,(\text{lumi})$	1870^{+50}_{-40}
	$\mu^+\mu^-$	$1900 \pm 10\,(\text{stat}) \pm 50\,(\text{syst}) \pm 90\,(\text{lumi})$	
	$\ell^+\ell^-$	$1910 \pm 10\,(\text{stat}) \pm 40\,(\text{syst}) \pm 90\,(\text{lumi})$	
Quantity		**Ratio (total)**	**NNLO**
R_{W^+/W^-}	e	$1.313 \pm 0.016\,(\text{stat}) \pm 0.028\,(\text{syst})$	$1.354^{+0.011}_{-0.012}$
	μ	$1.334 \pm 0.011\,(\text{stat}) \pm 0.031\,(\text{syst})$	
	ℓ	$1.323 \pm 0.010\,(\text{stat}) \pm 0.021\,(\text{syst})$	
$R_{W^+/Z}$	e	$5.94 \pm 0.07\,(\text{stat}) \pm 0.16\,(\text{syst})$	$6.06^{+0.04}_{-0.05}$
	μ	$5.98 \pm 0.05\,(\text{stat}) \pm 0.14\,(\text{syst})$	
	ℓ	$5.96 \pm 0.04\,(\text{stat}) \pm 0.10\,(\text{syst})$	
$R_{W^-/Z}$	e	$4.52 \pm 0.06\,(\text{stat}) \pm 0.12\,(\text{syst})$	$4.48^{+0.03}_{-0.02}$
	μ	$4.49 \pm 0.04\,(\text{stat}) \pm 0.10\,(\text{syst})$	
	ℓ	$4.50 \pm 0.03\,(\text{stat}) \pm 0.08\,(\text{syst})$	
$R_{W/Z}$	e	$10.46 \pm 0.11\,(\text{stat}) \pm 0.26\,(\text{syst})$	$10.55^{+0.07}_{-0.06}$
	μ	$10.47 \pm 0.08\,(\text{stat}) \pm 0.20\,(\text{syst})$	
	ℓ	$10.46 \pm 0.06\,(\text{stat}) \pm 0.16\,(\text{syst})$	

- Theoretical predictions at NNLO from FEWZ using NNPDF3.0 PDF set
  - Uncertainties include contributions from α_s, heavy quark masses, and missing higher orders
- Results have been combined assuming lepton universality
- Ratios are particular interesting as several uncertainties cancel
- Very good agreement with NNLO SM predictions

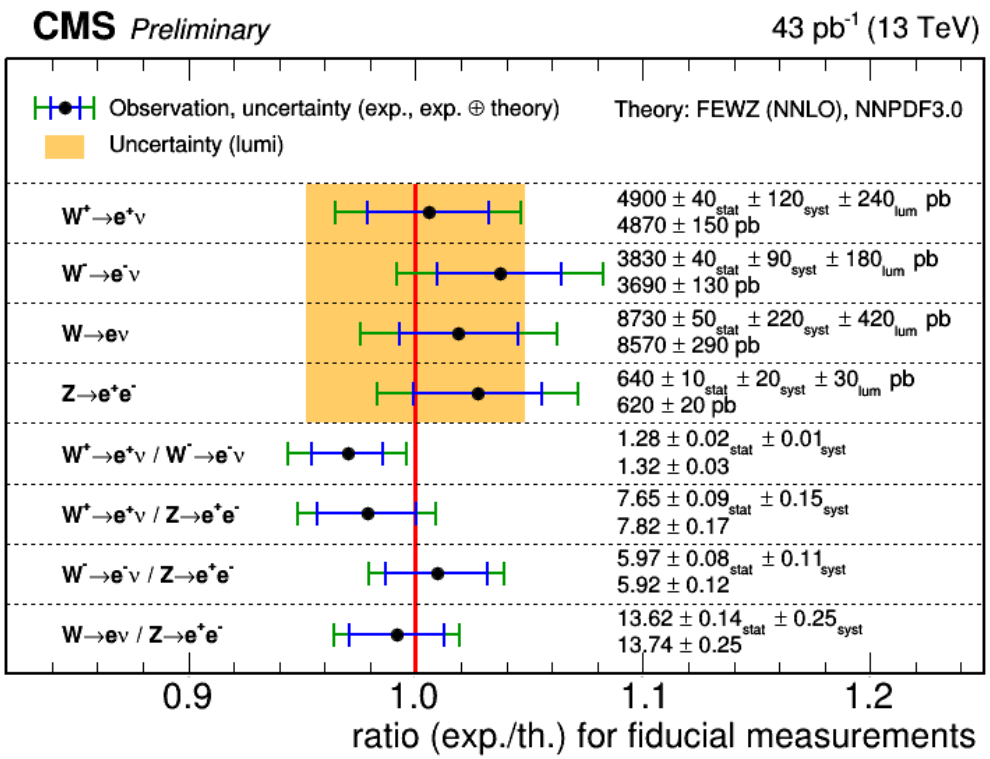
Total inclusive cross sections



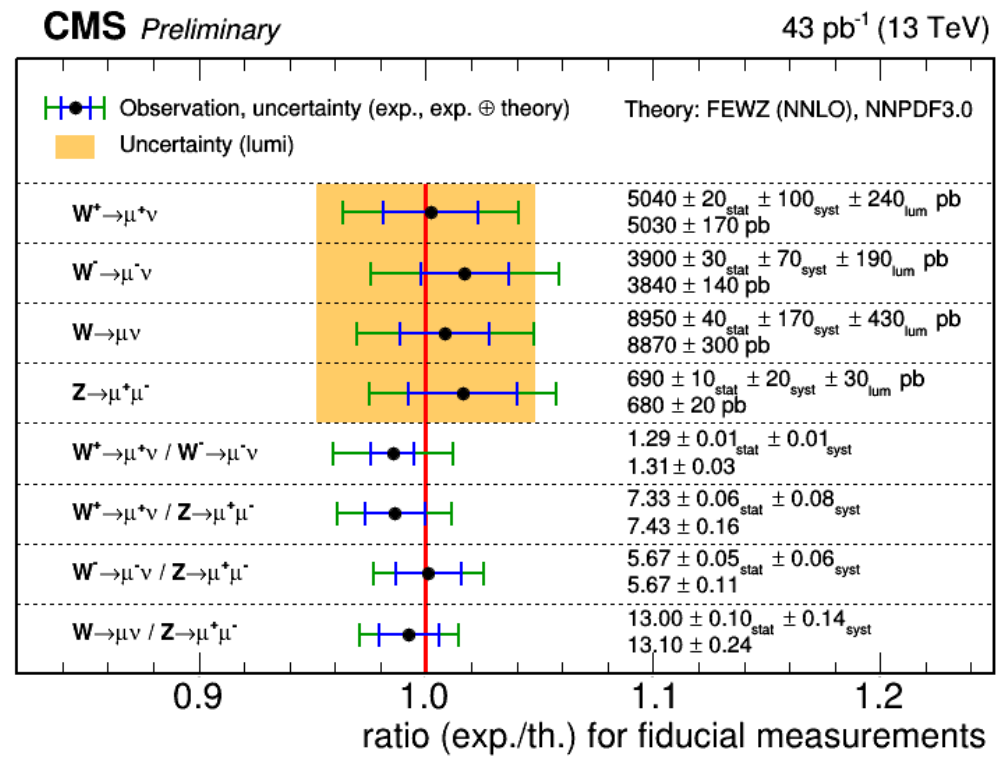
- Handle to constrain PDFs
- Measurement agrees with different PDF predictions within uncertainties

Fiducial inclusive cross sections

Electron Channel

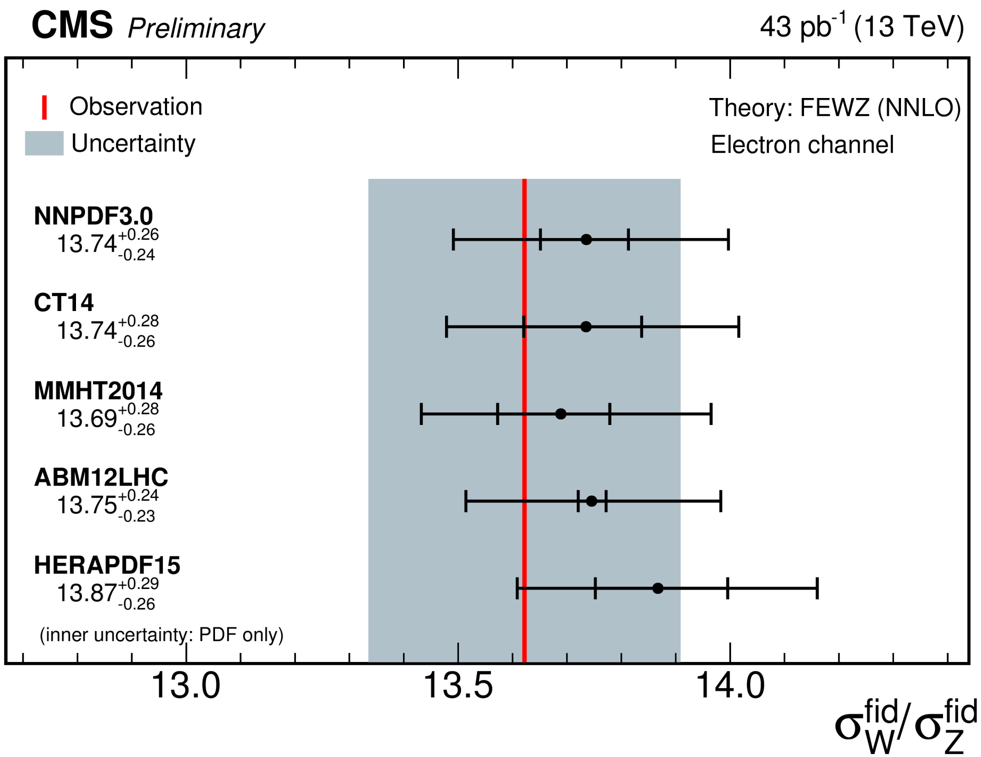


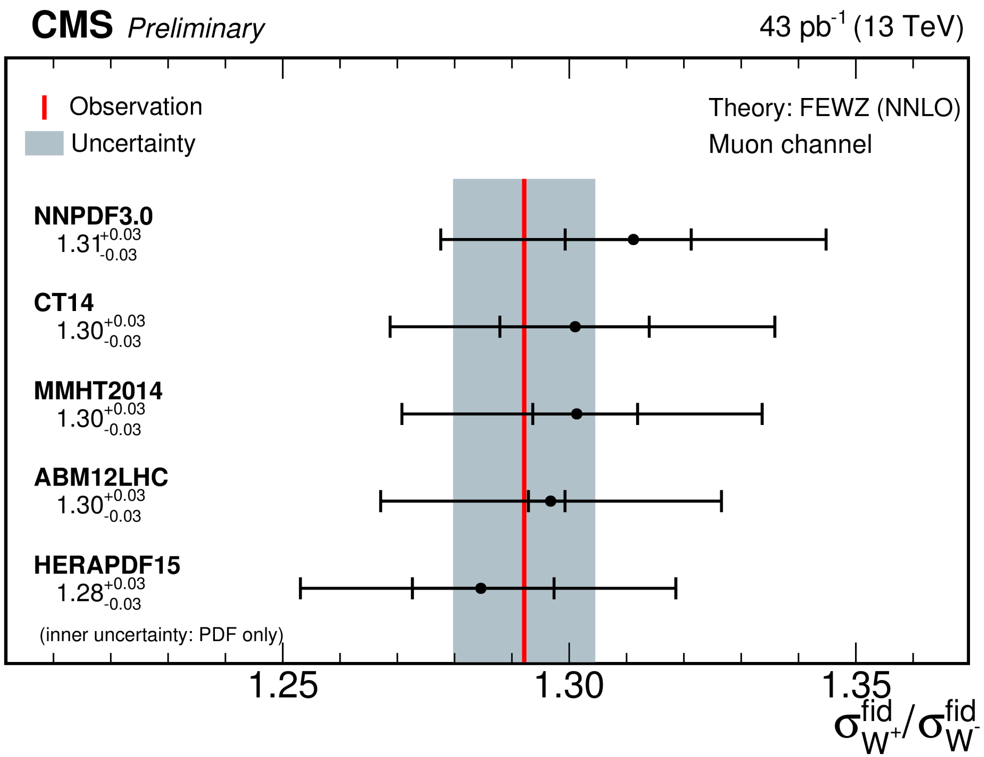
Muon Channel



- Fiducial cross sections disentangle experimental and theoretical effects
- Very good agreement with NNLO SM predictions

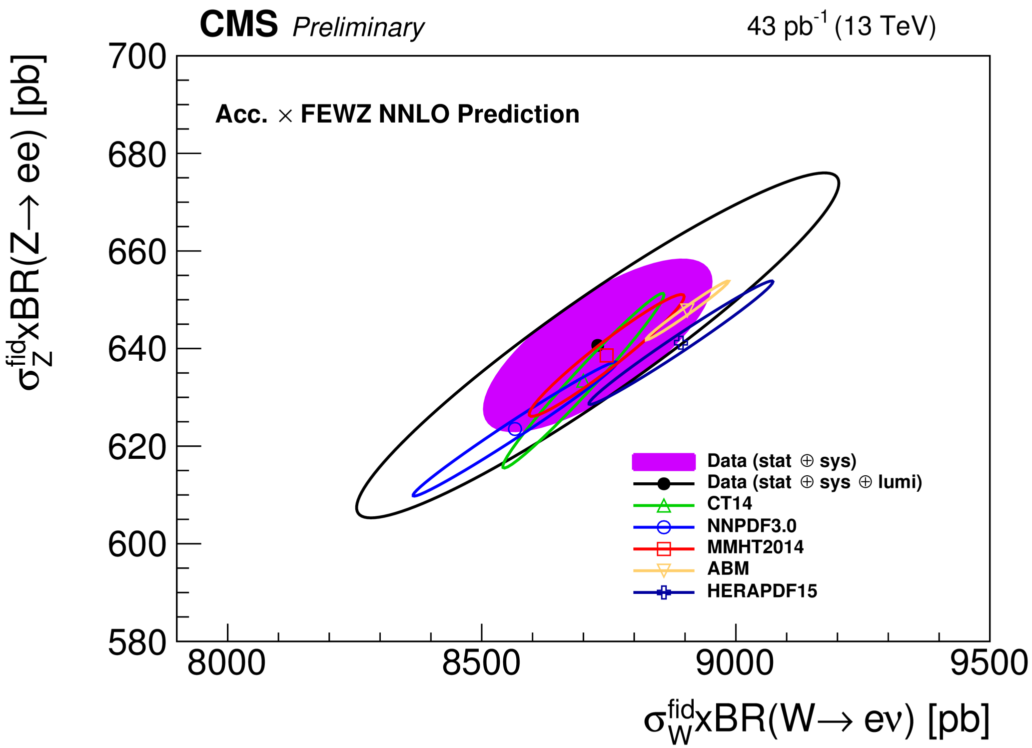
Fiducial inclusive cross section ratios

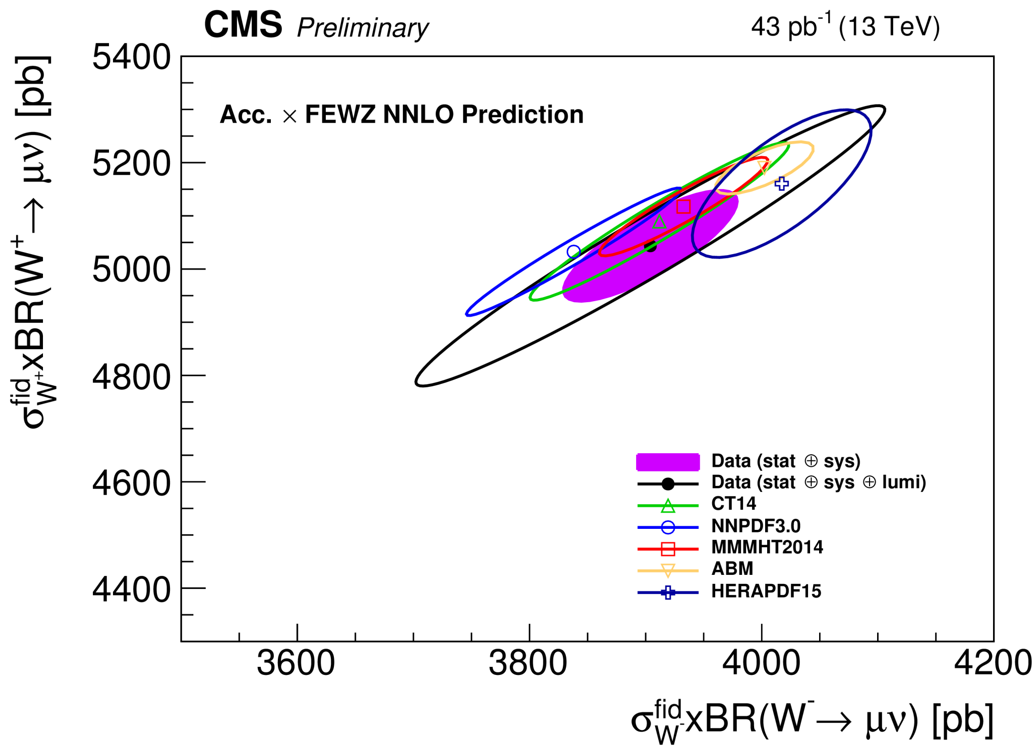




- Fiducial cross sections provides more stringent comparisons between measurement and predictions using different PDF sets
- Measurement in good agreement with different PDF predictions

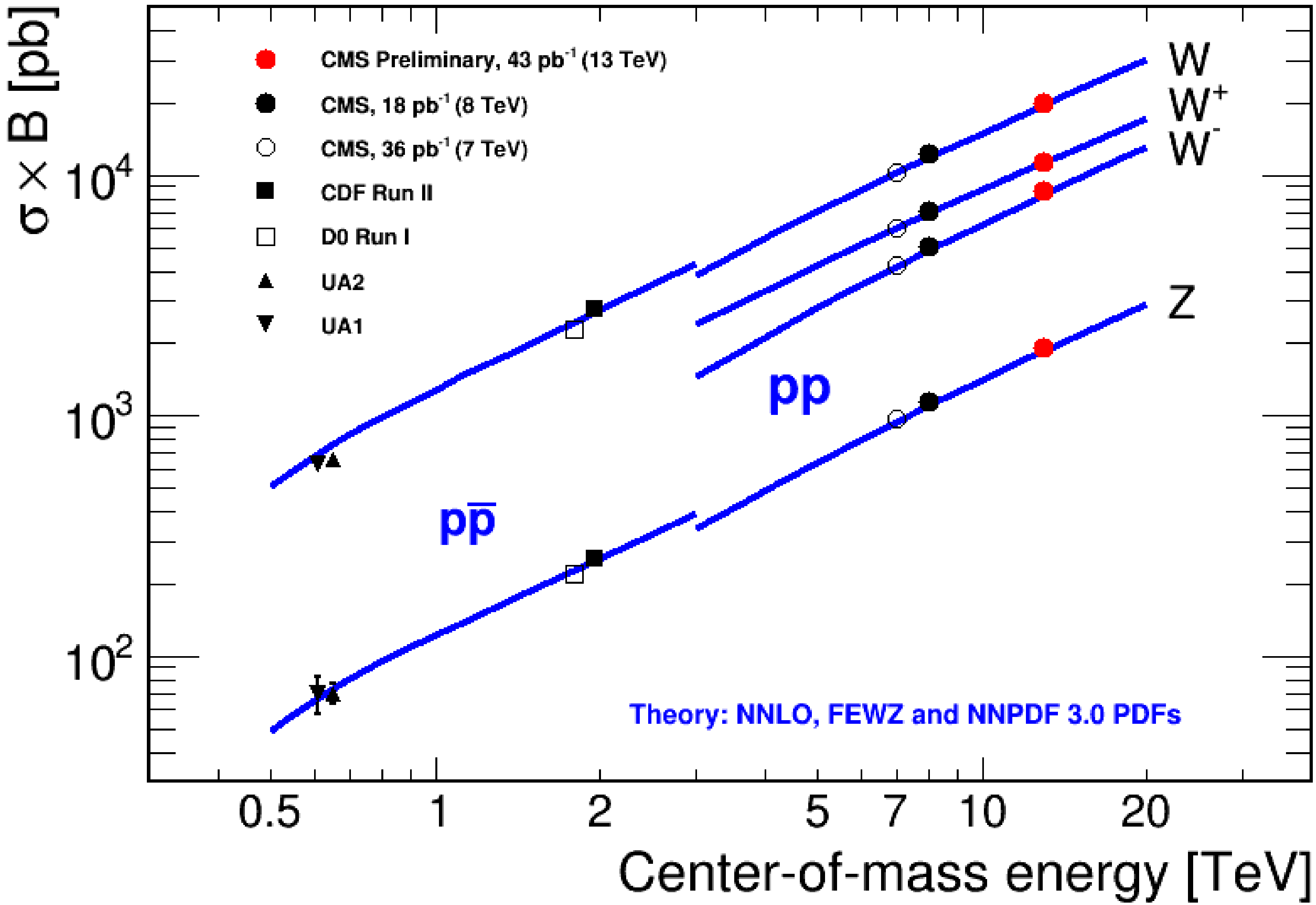
Fiducial inclusive cross sections





Measurement in good agreement with different PDF predictions

Results



Predicted increase of cross sections with centre-of-mass energy confirmed by measurements

Conclusion

- New opportunities with CMS at 13 TeV
- All sub-detectors calibrated and commissioned
- Good data quality allows for precision measurements already with first data
- First 13 TeV results published and many more in the pipeline
- Already achieved excellent accuracy for measurement of W and Z boson production
  - Measurement limited by preliminary luminosity calibration

Back-Up

Selection

- Both W and Z analysis rely on single lepton triggers
- Offline Selection:
  - Electrons:
    - p_T>25 GeV, $|\eta|$<2.5, excluding 1.44<$|\eta|$<1.5
    - Isolation: $\Sigma p_T^i < 0.15 p_T^{el}$ (sum over particle flow candidates within cone of ΔR=0.3)
  - Muons:
    - p_T>25 GeV, $|\eta|$<2.4
    - Isolation: $\Sigma p_T^i < 0.12 p_T^{mu}$ (sum over particle flow candidates within cone of ΔR=0.4)
  - W selection:
    - Veto against 2nd lepton
    - No MET cut, use MET to discriminate signal from background
  - Z selection:
    - 60 GeV<m_{ll}<120 GeV

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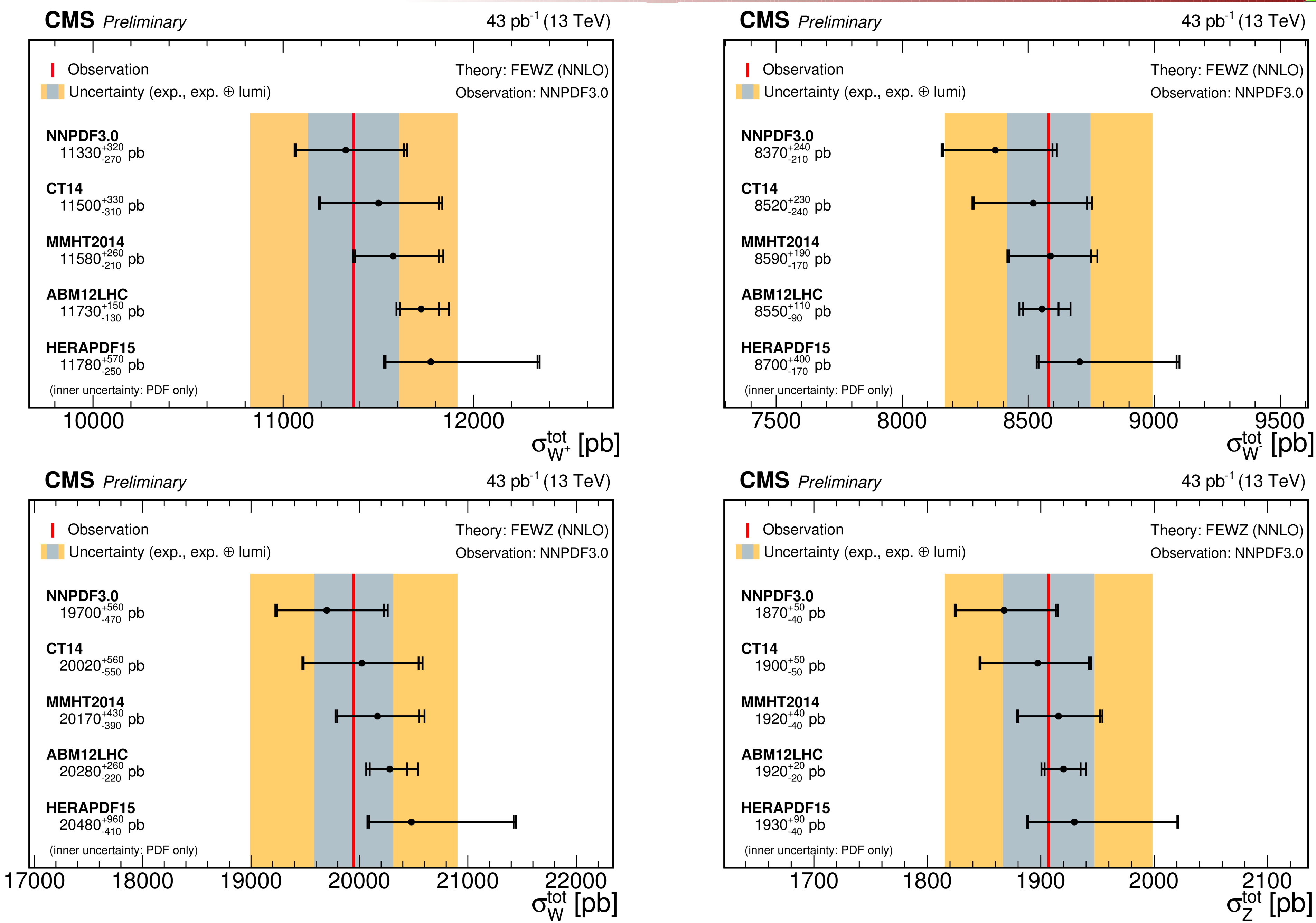
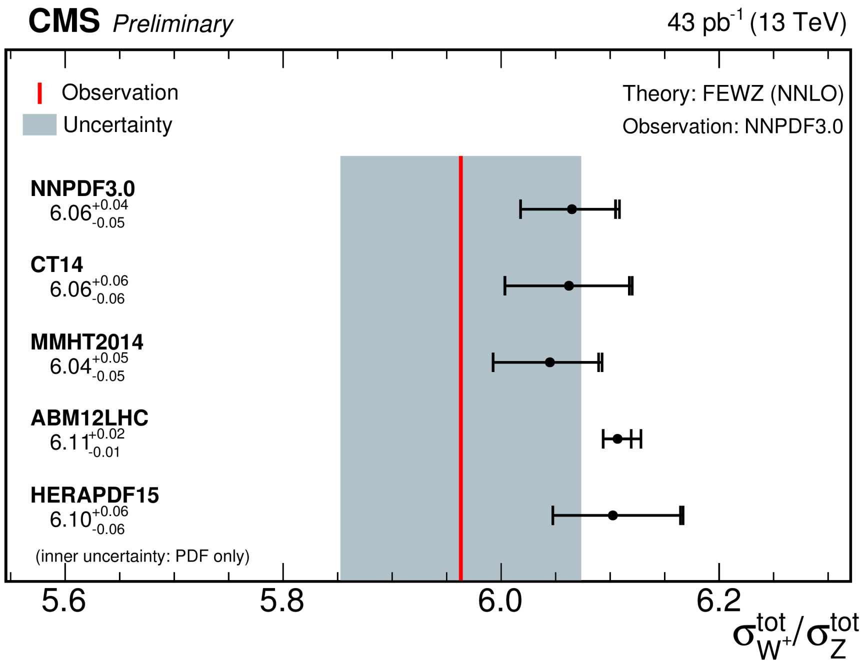
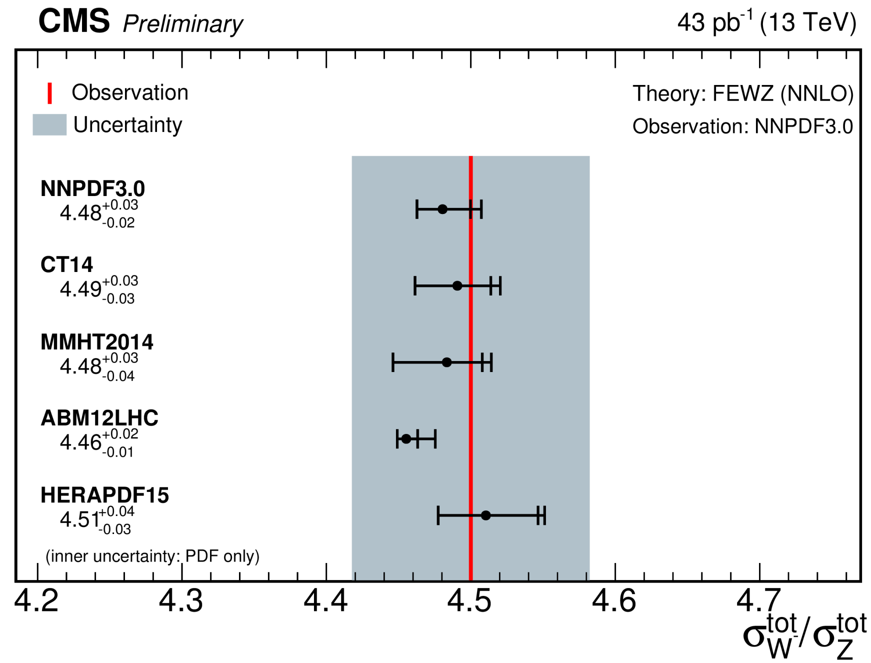
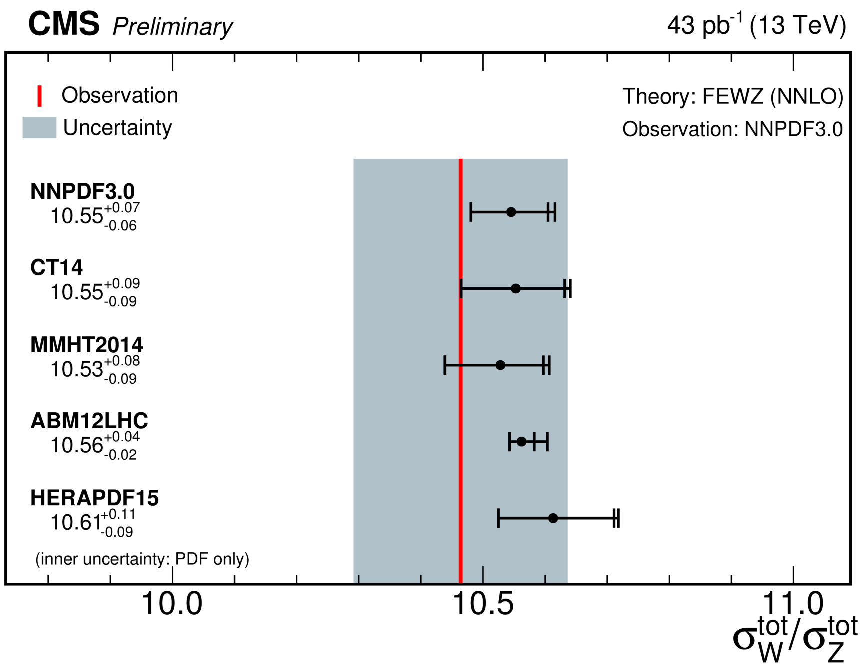
Total Inclusive Cross Section

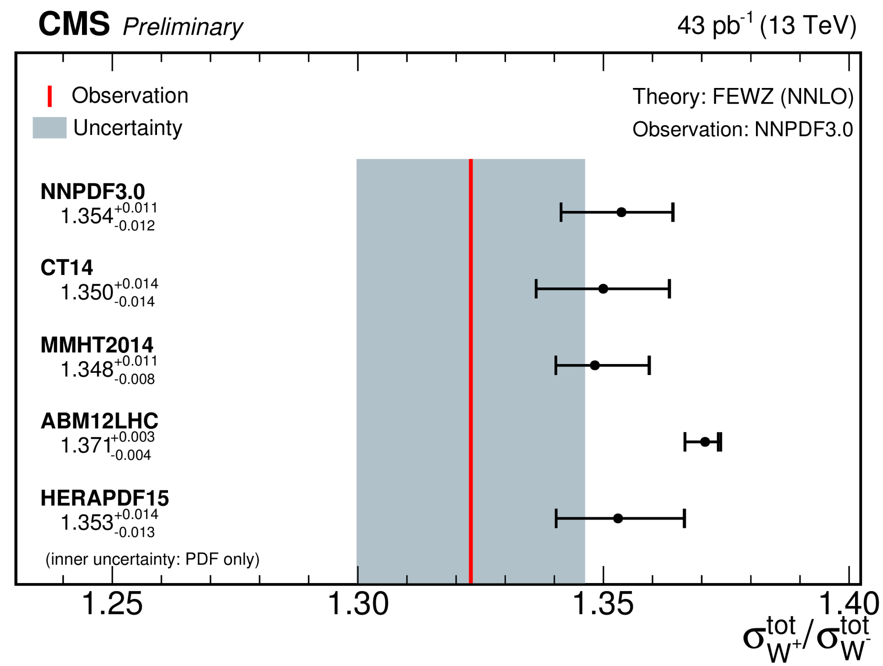


Total Inclusive Cross Section Ratios







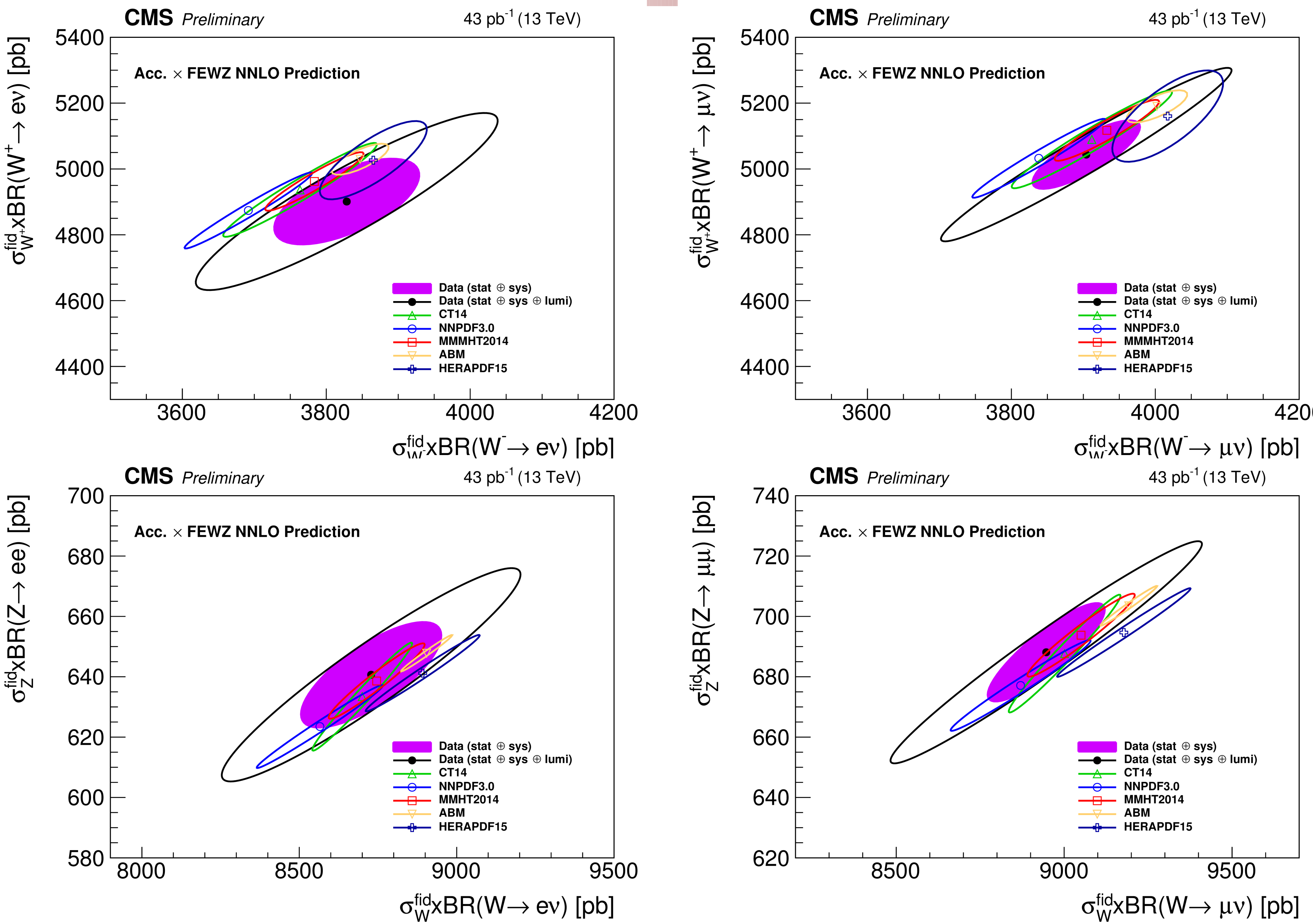


Fiducial inclusive cross sections

Channel		$\sigma \times \mathcal{B}$ [pb] (fiducial)	NNLO [pb]
W^+	$e^+\nu$	$4900 \pm 40\,(\text{stat}) \pm 120\,(\text{syst}) \pm 240\,(\text{lumi})$	4870^{+160}_{-140}
	$\mu^+\nu$	$5040 \pm 20\,(\text{stat}) \pm 100\,(\text{syst}) \pm 240\,(\text{lumi})$	5030^{+180}_{-160}
W^-	$e^-\nu$	$3830 \pm 40\,(\text{stat}) \pm 90\,(\text{syst}) \pm 180\,(\text{lumi})$	3690^{+150}_{-110}
	$\mu^-\nu$	$3900 \pm 30\,(\text{stat}) \pm 70\,(\text{syst}) \pm 190\,(\text{lumi})$	3840^{+160}_{-120}
W	$e\nu$	$8730 \pm 50\,(\text{stat}) \pm 220\,(\text{syst}) \pm 420\,(\text{lumi})$	8570^{+340}_{-240}
	$\mu\nu$	$8950 \pm 40\,(\text{stat}) \pm 170\,(\text{syst}) \pm 430\,(\text{lumi})$	8870^{+350}_{-240}
Z	e^+e^-	$640 \pm 10\,(\text{stat}) \pm 20\,(\text{syst}) \pm 30\,(\text{lumi})$	620^{+20}_{-20}
	$\mu^+\mu^-$	$690 \pm 10\,(\text{stat}) \pm 20\,(\text{syst}) \pm 30\,(\text{lumi})$	680^{+30}_{-20}
Quantity		Ratio (fiducial)	NNLO
R_{W^+/W^-}	e	$1.28 \pm 0.02\,(\text{stat}) \pm 0.01\,(\text{syst})$	$1.32^{+0.03}_{-0.03}$
	μ	$1.29 \pm 0.01\,(\text{stat}) \pm 0.01\,(\text{syst})$	$1.31^{+0.03}_{-0.03}$
$R_{W^+/Z}$	e	$7.65 \pm 0.09\,(\text{stat}) \pm 0.15\,(\text{syst})$	$7.82^{+0.17}_{-0.16}$
	μ	$7.33 \pm 0.06\,(\text{stat}) \pm 0.08\,(\text{syst})$	$7.43^{+0.17}_{-0.16}$
$R_{W^-/Z}$	e	$5.97 \pm 0.08\,(\text{stat}) \pm 0.11\,(\text{syst})$	$5.92^{+0.12}_{-0.11}$
	μ	$5.67 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})$	$5.67^{+0.11}_{-0.11}$
$R_{W/Z}$	e	$13.62 \pm 0.14\,(\text{stat}) \pm 0.25\,(\text{syst})$	$13.74^{+0.26}_{-0.25}$
	μ	$13.00 \pm 0.10\,(\text{stat}) \pm 0.14\,(\text{syst})$	$13.10^{+0.24}_{-0.23}$

- Fiducial cross sections disentangle experimental and theoretical effects
- Very good agreement with NNLO SM predictions

Fiducial Inclusive Cross Sections



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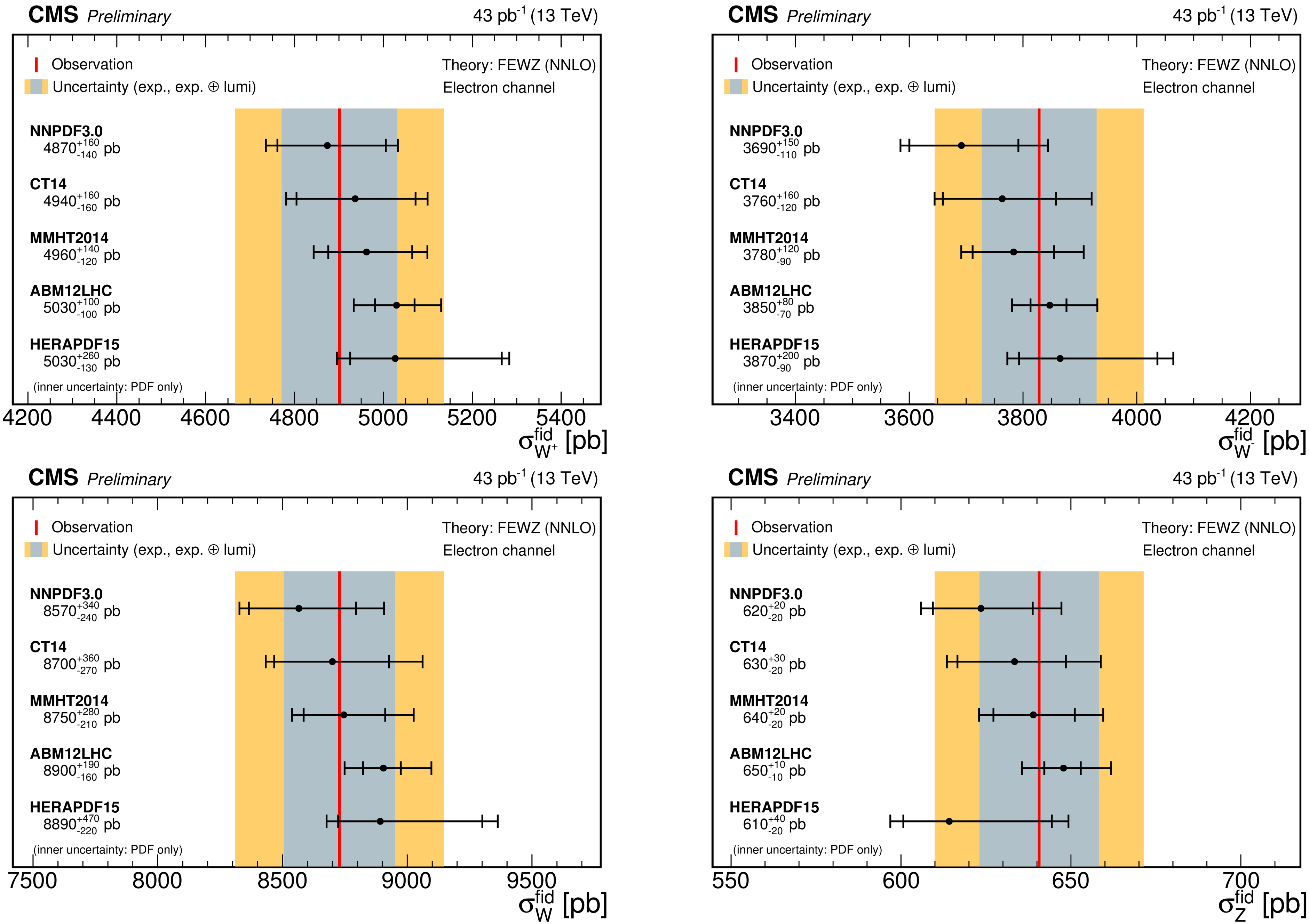
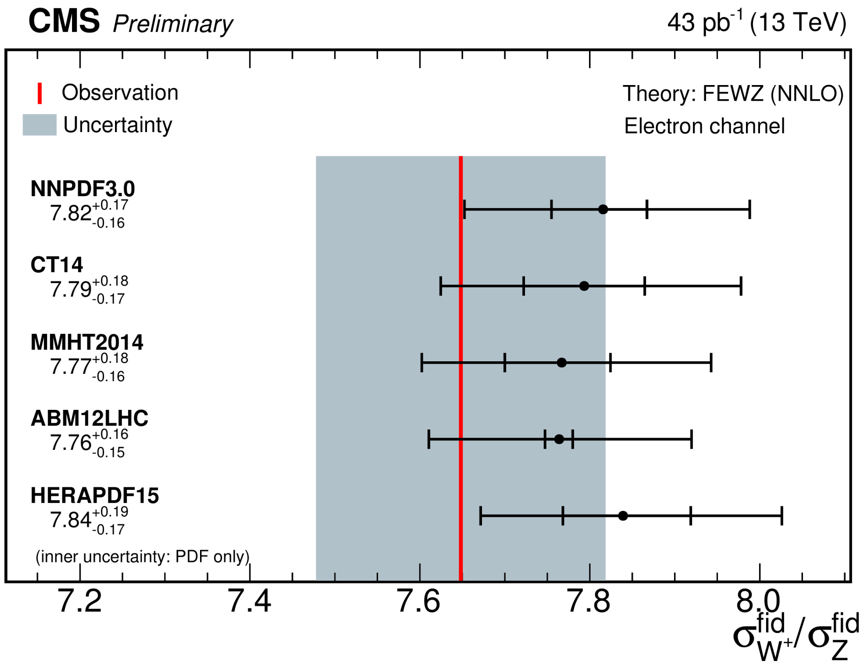
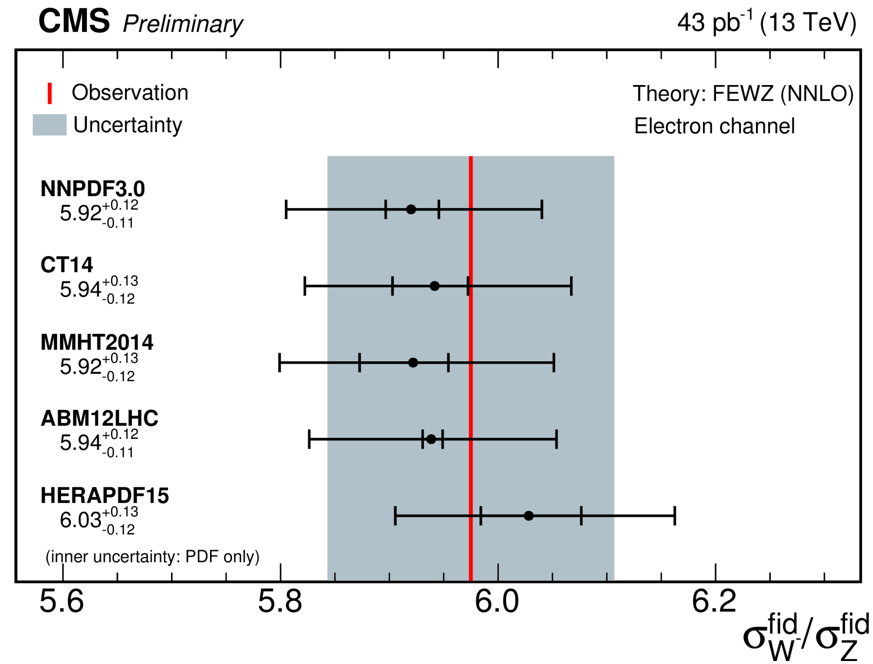
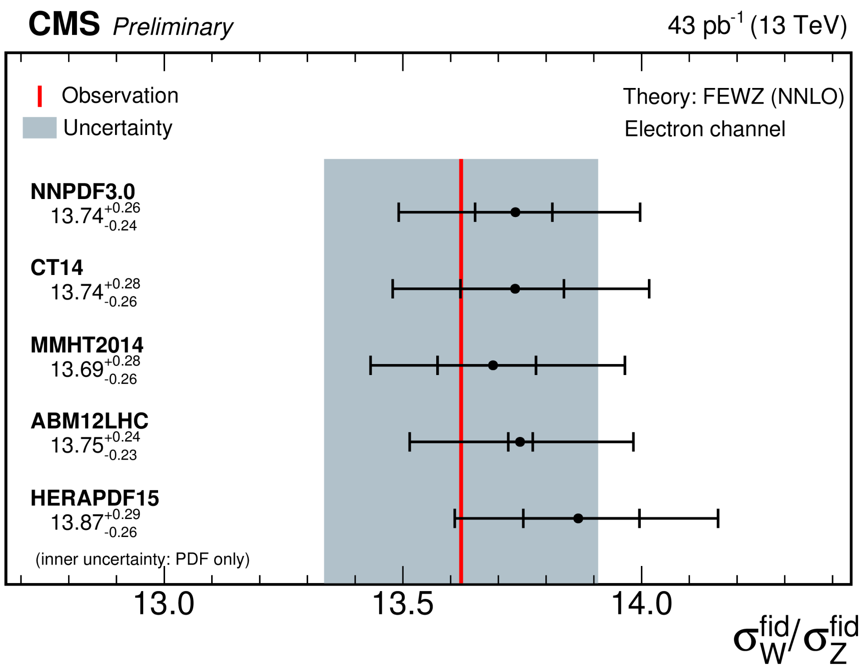
Fiducial Inclusive Cross Sections

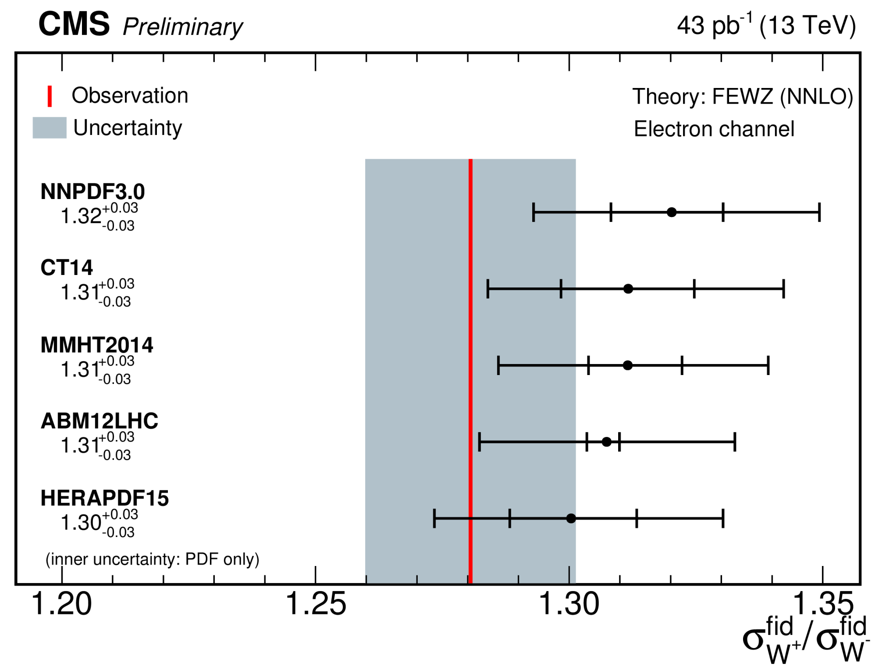


Fiducial Inclusive Cross Section Ratios

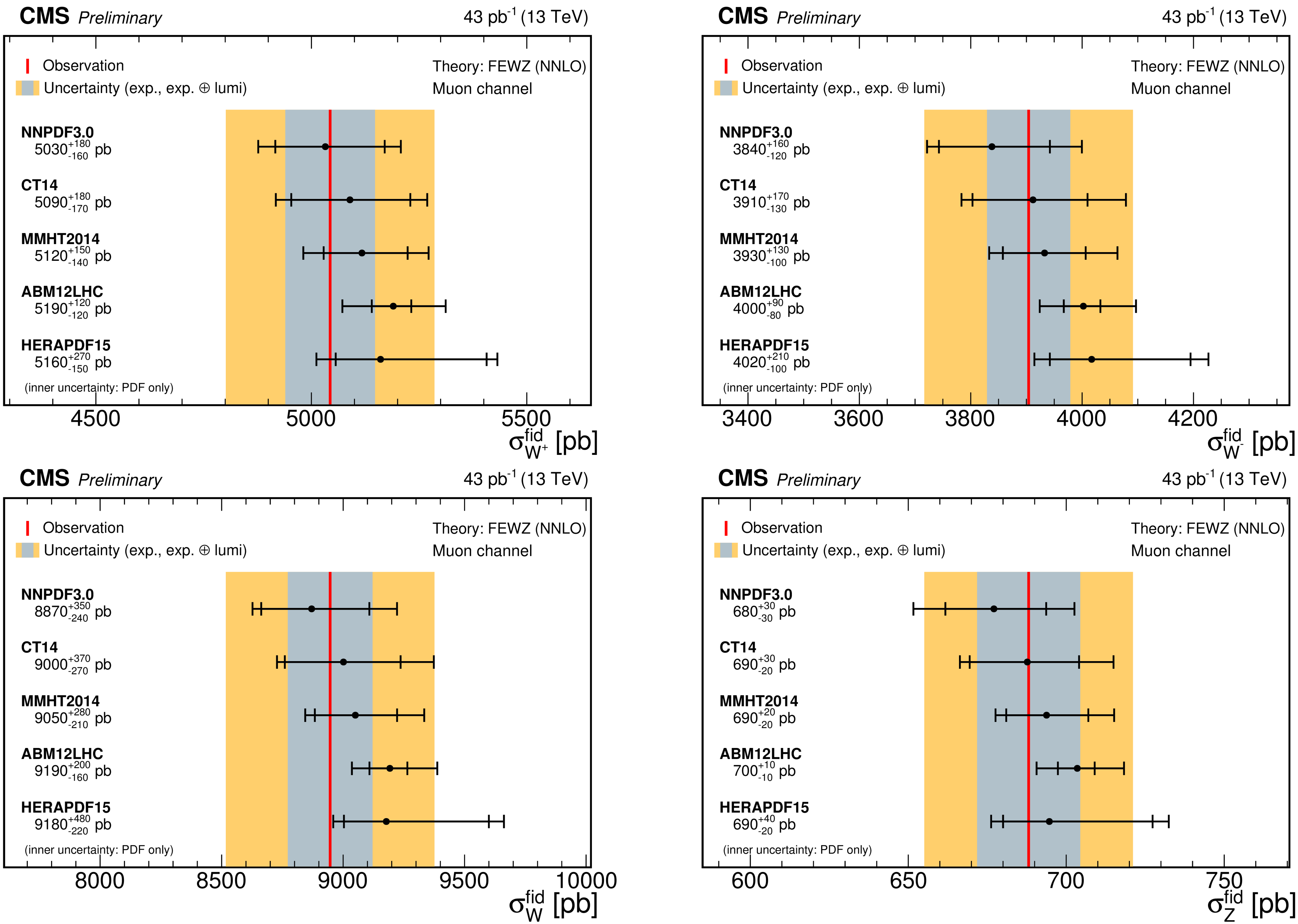




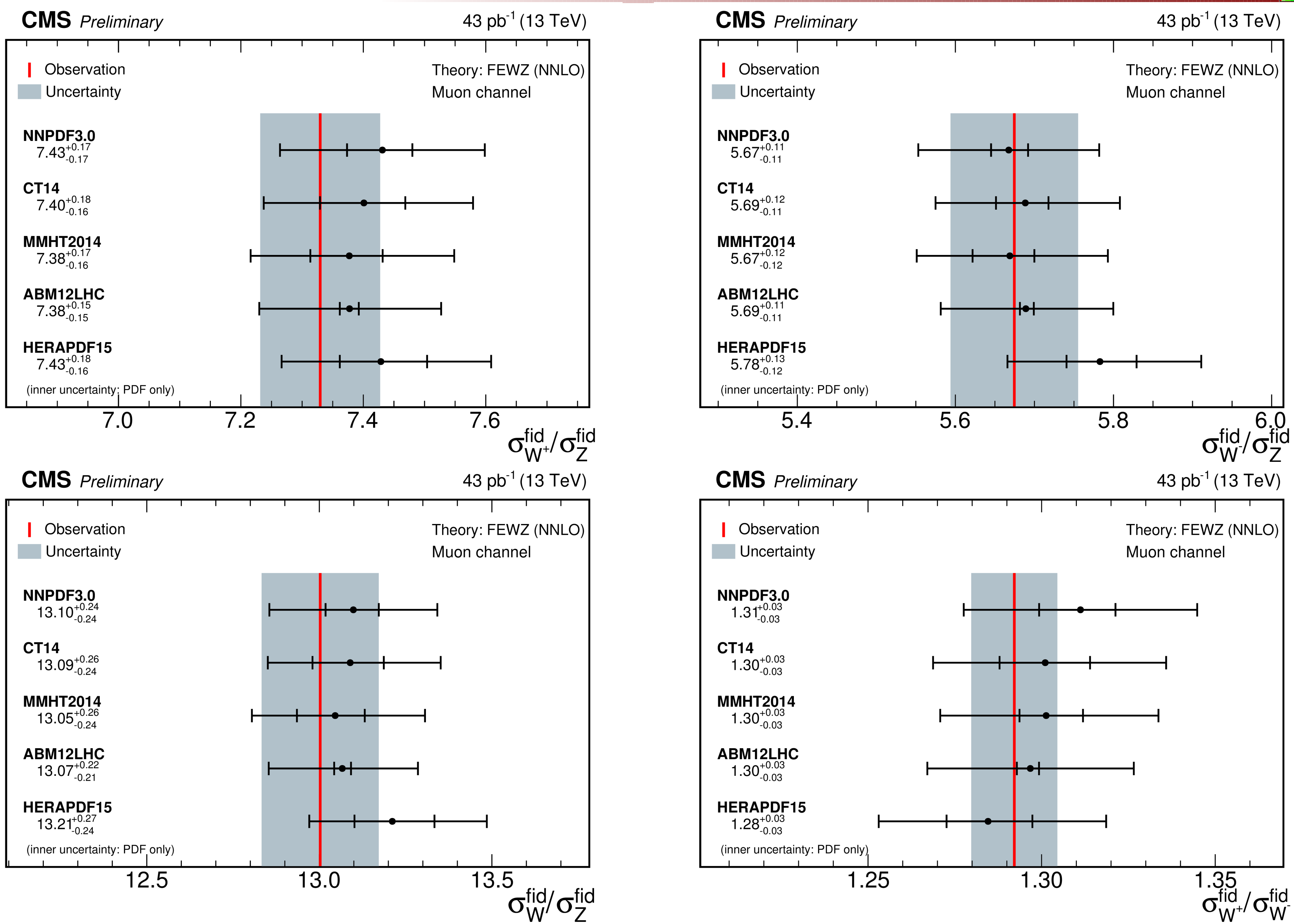




Fiducial Inclusive Cross Sections

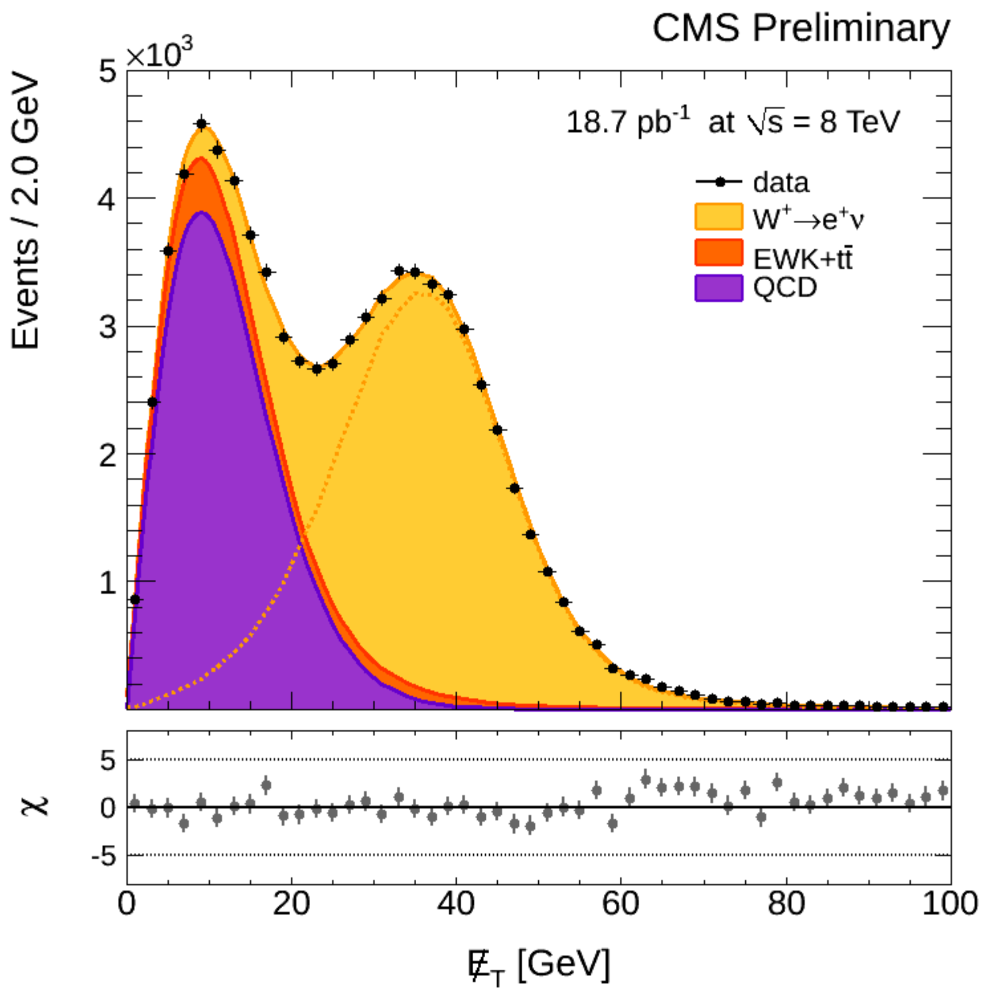


Fiducial Inclusive Cross Section Ratios

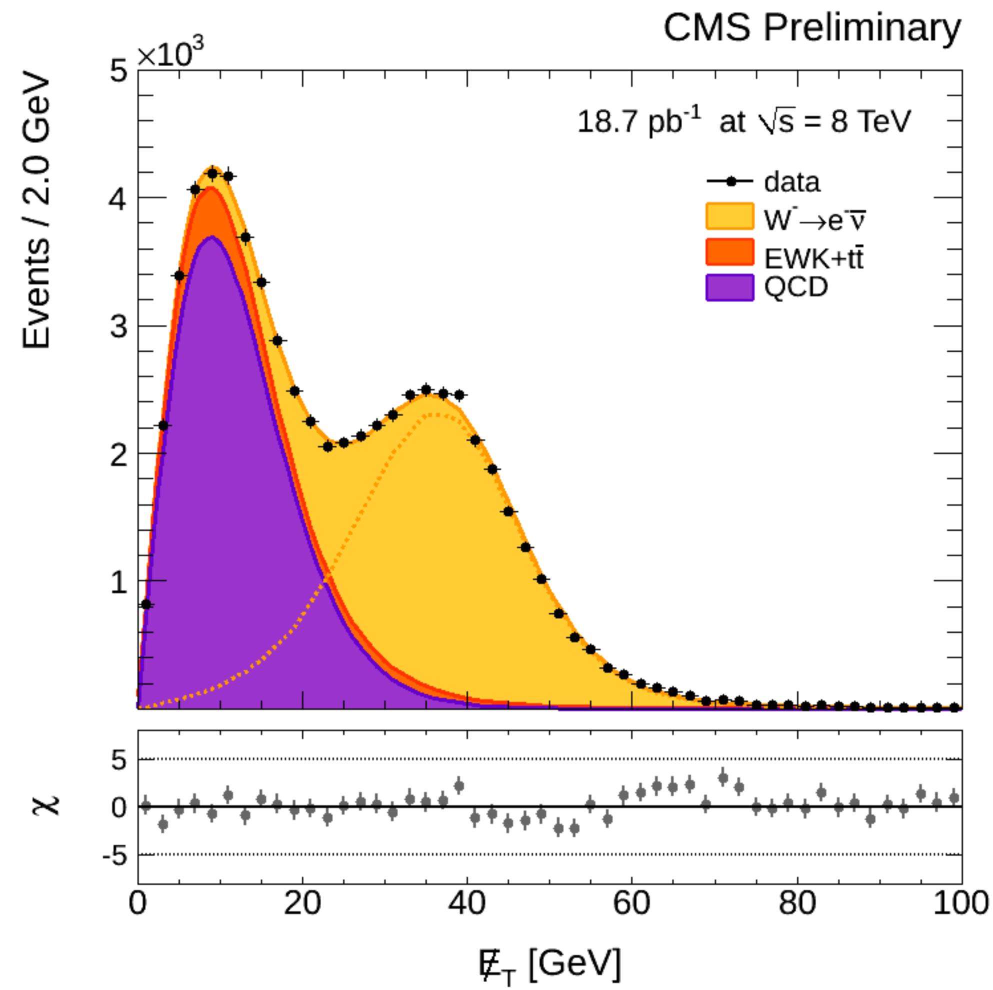


W→eν Signal Extraction (8TeV)

$W^+ \to e^+\nu$

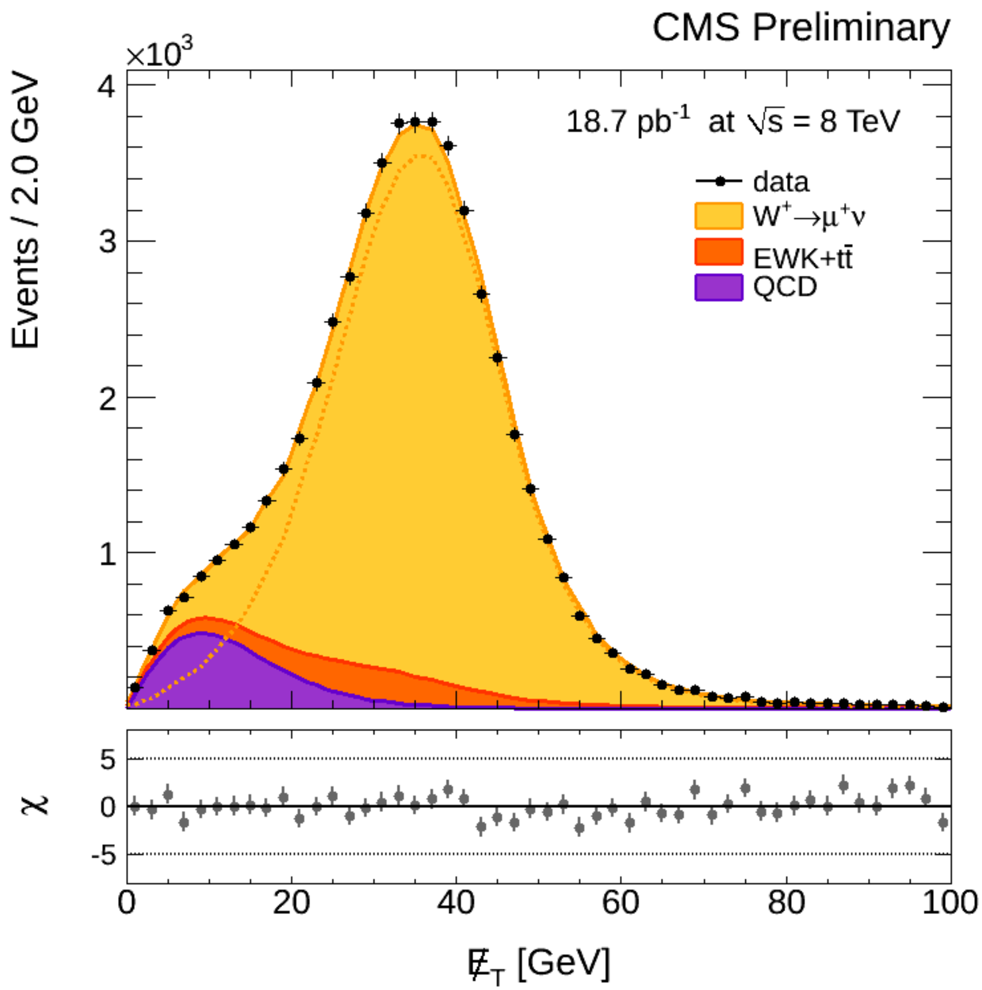


$W^- \to e^-\bar{\nu}$



$W \to \mu\nu$ Signal Extraction (8 TeV)

$W^+ \to \mu^+\nu$



$W^- \to \mu^-\bar{\nu}$