Inclusive and differential vector boson (W, Z) measurements from CMS

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On behalf of the CMS Collaboration

Corfu2017: Workshop on the Standard Model and Beyond, 2-10 Sep. 2017, Corfu, Greece

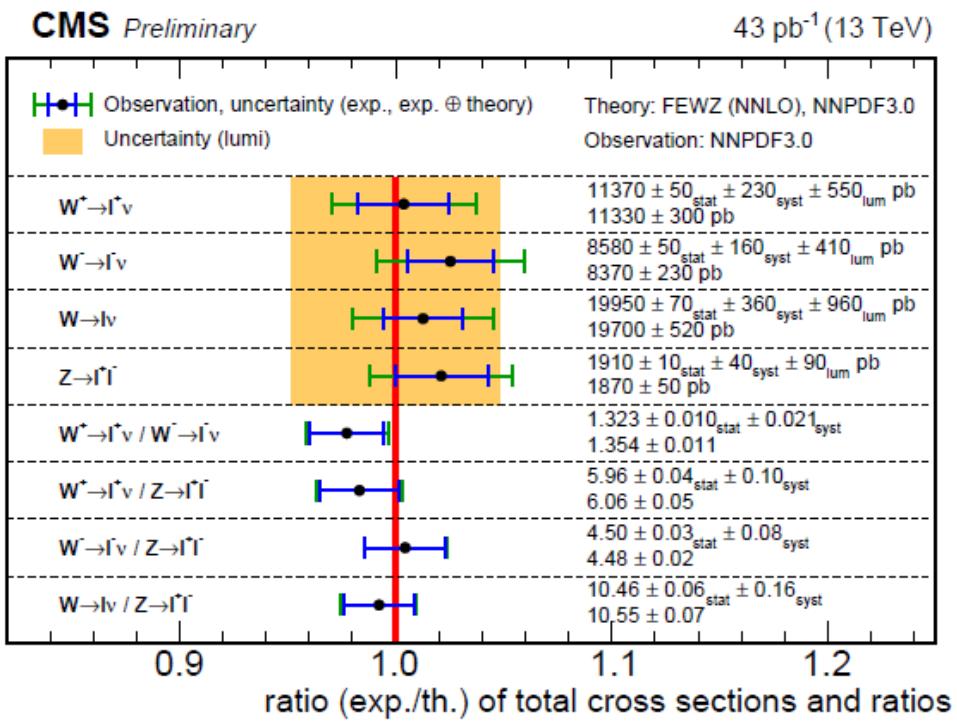
Weak vector boson (+jets) production (an overview)

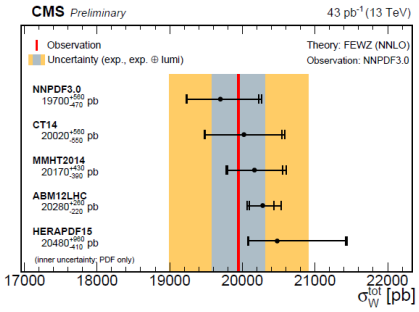
- W and Z boson (+jets) production processes play an important role at hadron colliders
- Their large production cross sections and clean experimental signatures allow for
  - precision tests of SM including substantial inputs for PDFs
  - tuning MC simulations and theoretical calculations
  - modeling backgrounds to rare SM processes and BSM signatures
  - detector calibration as a "standard candle" (lepton, missing energy, and jet performances)
- Reconstructed using leptonic final states **$Z/\gamma^* \to \ell\ell$** and **$W \to \ell\nu$**
- Jet definition by anti-k_T algorithm (R=0.4/0.5) used in W/Z+jets analyses
- Their measurements are corrected for detector effects and compared with predictions from several MC event generators and theoretical calculations where available
- **Presented here only the latest CMS W/Z (+jets) results based on 8 TeV (2012) and 13 TeV (2015, 2016) proton-proton collision data.** A complete set of all results can be found at http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

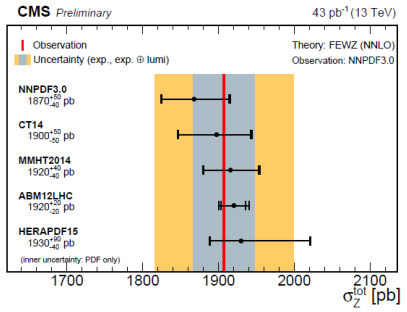
Inclusive W and Z boson cross sections at 13 TeV

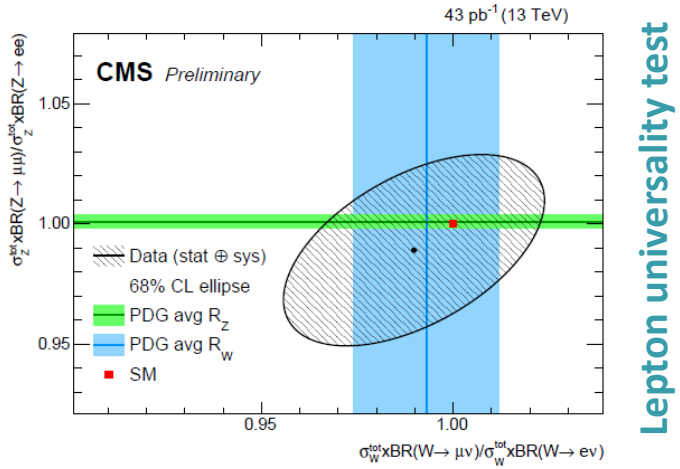
CMS-PAS-SMP-15-004

- Measurements of total (and also fiducial) inclusive W($\ell\nu$) and Z($\ell\ell$) cross sections
- Event selection with $p_T(\ell)$>25 GeV and $|\eta(e,\mu)|$<2.5(2.4). Z candidates within 60<$m_{\ell\ell}$<120 GeV
- Theory predictions by FEWZ NNLO (calculated for 5 different PDF sets)
- Ratios of cross sections $R_{W+/W-}$ and $R_{W/Z}$ with improved precision
  - Dominant systematic due to luminosity (4.8%) cancels









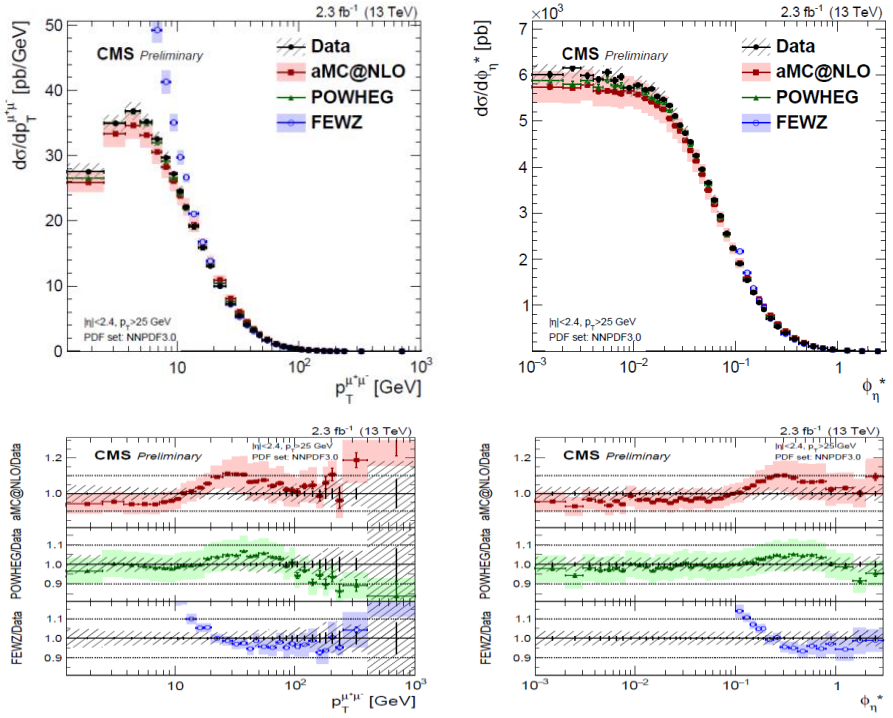
Lepton universality test

✓ **Precise measurements of cross sections and ratios only with 43 pb^{-1} data. Measured cross sections overall agree with NNLO SM calculation**

Inclusive/differential Z cross section at 13 TeV

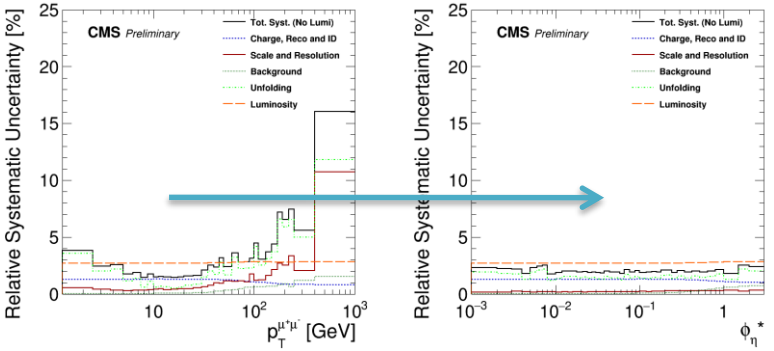
CMS-PAS-SMP-15-011

- Using Z($\mu^+\mu^-$) events with $p_T(\mu)$>25 GeV and $|\eta(\mu)|$<2.4 in 60<$m_{\mu\mu}$<120 GeV
- Measured total inclusive cross section: **$\sigma(pp\rightarrow Z+X)\times B(Z\rightarrow\mu^+\mu^-)$=1870±2(stat.)±35(syst.)±51(lumi.) pb**
  - Consistent with FEWZ NNLO QCD+NLO EW predictions using various PDF sets such as NNPDF3.0: **1870±50 pb**
- Differential cross sections are measured as functions of $p_T(Z)$ and ϕ_η^* (also for y(Z) and $p_T(\mu)$)
- Unfolded data compared to **MG5_aMC (NLO), POWHEG (normalized to NLO), FEWZ NNLO+NLO EW**



$p_T(Z)$ is a probe of strong interaction (governed by ISR at low p_T and q-g scattering at high p_T). **ϕ_η^* is correlated to $p_T(Z)$, but depends on direction of muon → smaller exp. uncertainty**

$$\phi_\eta^* = \tan\left(\frac{\pi-\Delta\phi}{2}\right)\cdot\sin(\theta_\eta^*) \text{ where, } \cos(\theta_\eta^*) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$

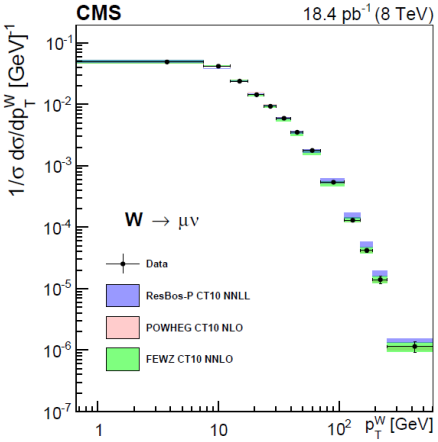


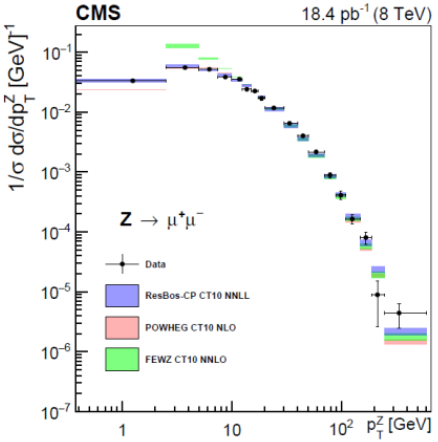
- ✓ **Overall fair agreement between data and predictions within uncertainties**
- ✓ **Discrepancy at low Z boson p_T and ϕ_η^* by FEWZ due to lack of soft gluon resummation**

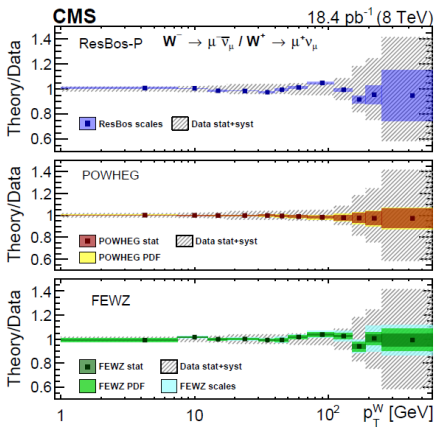
W/Z diff. cross sections (p_T spectra) at 8 TeV

JHEP 02 (2017) 096

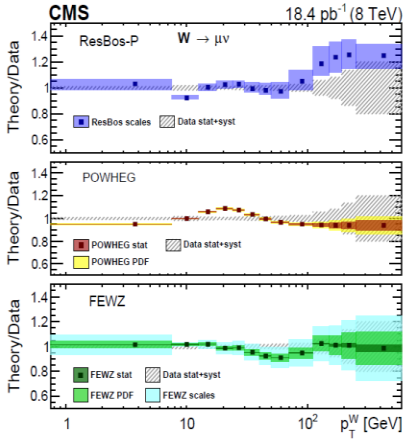
- Using low-luminosity data of 18.4 pb^{-1} (pileup:~4). W($\ell\nu$) and Z($\mu^+\mu^-$) events with p_T(e, μ)>25(20) GeV and |η(e, μ)|<2.5(2.1). Z boson selection with 60<$m_{\mu\mu}$<120 GeV
- Measurements of differential cross sections dσ/dp_T(W) and dσ/dp_T(Z) and their ratios $R_{W-/W+}$, $R_{Z/W}$
- The results are compared to the theoretical predictions: **ResBos**, **POWHEG**, and **FEWZ** using CT10

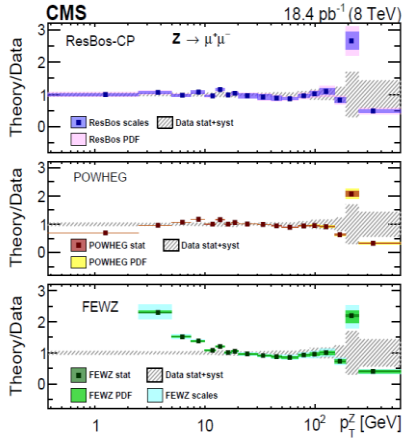


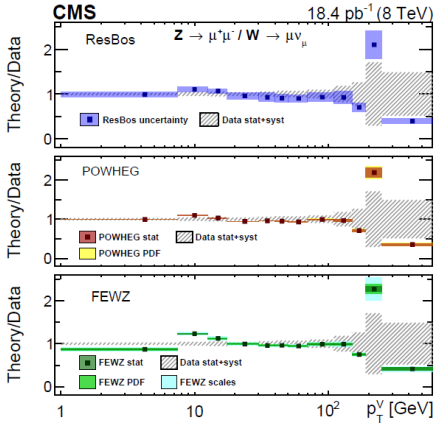




$R_{W-/W+}$ theory/data ratio







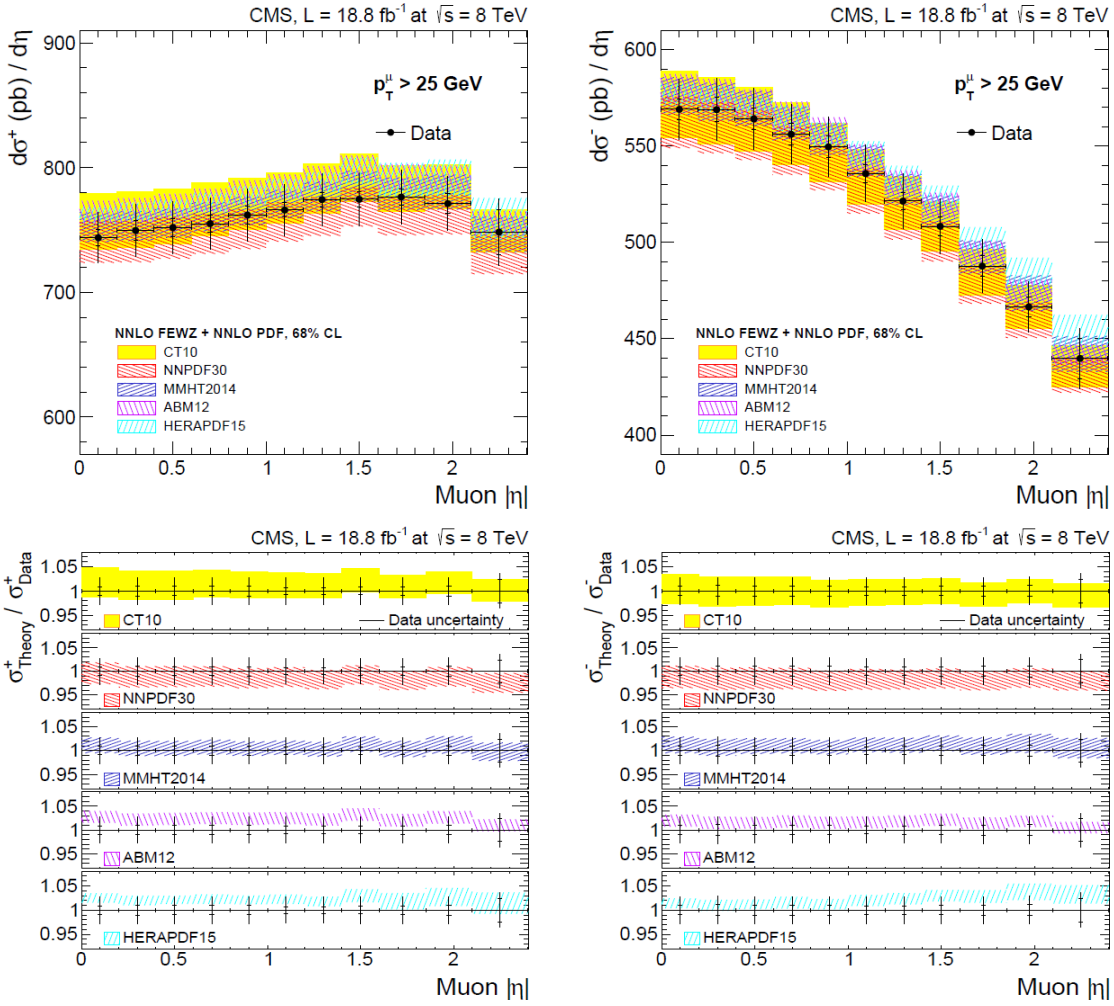
$R_{Z/W}$ theory/data ratio

✓ **Predictions reproduce the data, expected deviation by FEWZ at low p_T (Z)**

W charge asymmetry at 8 TeV

EPJC 76 (2016) 469

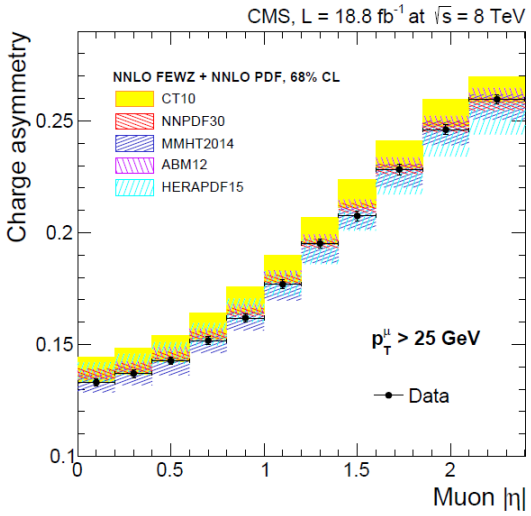
- Differential cross sections as a function of muon |η| and charge asymmetry for inclusive $W^{\pm}(\mu^{\pm}\nu)$ production. Muon selection with $p_T(\mu)>25$ GeV and $|\eta(\mu)|<2.5$
- Predictions from FEWZ 3.1 NNLO. No EW corrections are included

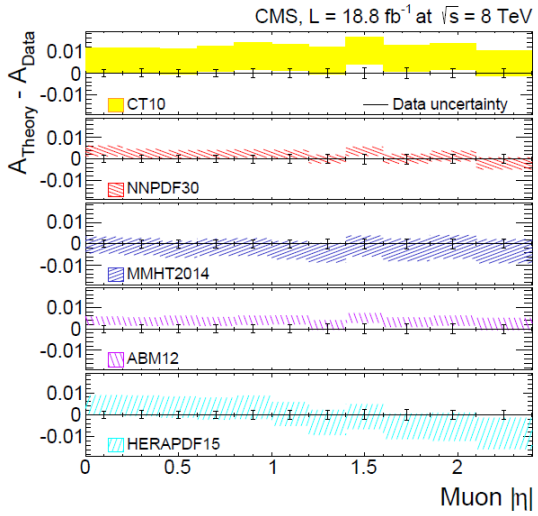


Differential cross sections are well described by all considered PDFs (CT10, NNPDF3.0, MMHT2014, ABM12, HERAPDF1.5)

W charge asymmetry at 8 TeV

EPJC 76 (2016) 469



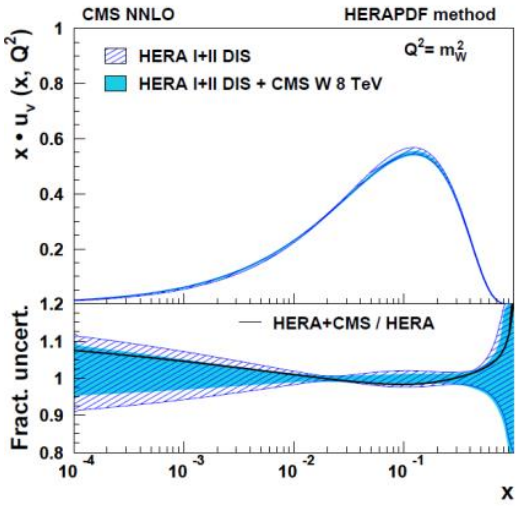


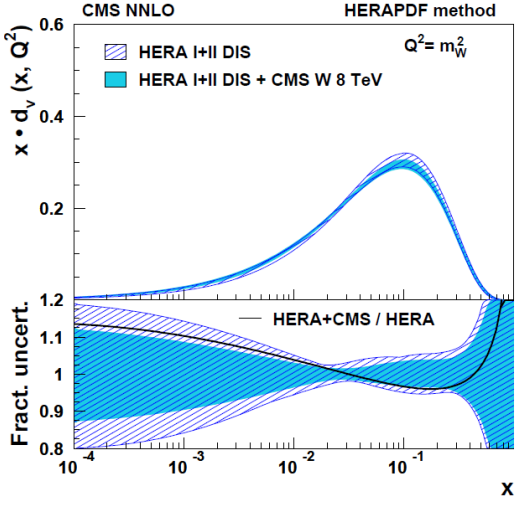
W$^+$ is more produced than W$^-$ in pp collision → strong asymmetry in the lepton decay

Measured charge asymmetry A(η) also agrees well with PDF sets

$$\sigma_\eta^\pm = \frac{d\sigma}{d\eta}(pp \to W^\pm + X \to \mu^\pm \nu + X)$$

$$A(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$$





Results incorporated into QCD NNLO analysis + HERA DIS data

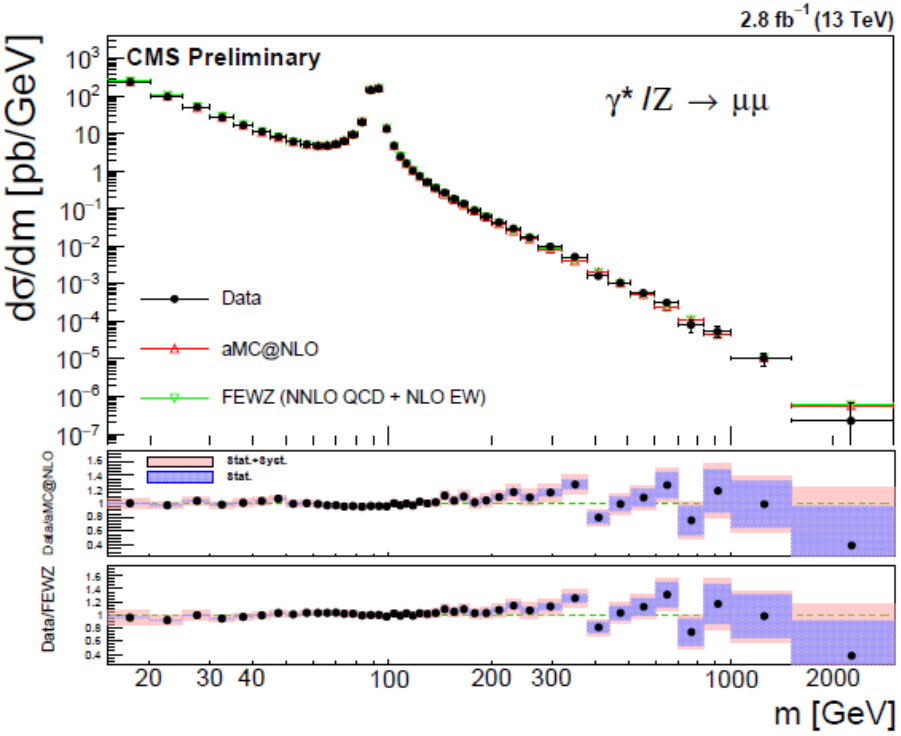
Significantly improves constraints on the valence quark distributions

W charge asymmetry is to be used in future PDF determinations

Differential Drell-Yan cross section

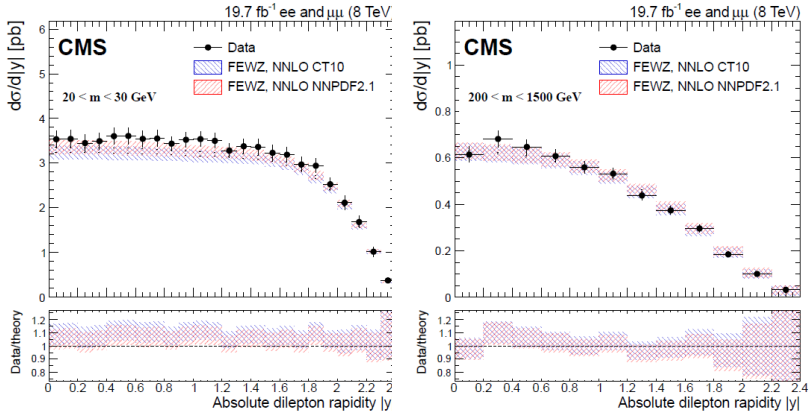
CMS-PAS-SMP-16-009

- Drell-Yan lepton pairs are produced via Z/γ* exchange in the s-channel at hadron colliders
- Cross section measurement of dσ/dm in $15<m_{\mu\mu}<3000$ GeV at 13 TeV
- The results are corrected to the full phase space (FSR effects are included)



✓ **SM predictions (FEWZ 3.1 NNLO and MG5_aMC NLO using NNPDF 3.0 PDF) are in good agreement with measurement**

EPJC 75 (2015) 147



✓ **8 TeV measurement of double differential cross section in bins of $20<m_{\ell\ell}<1500$ GeV for $|y_{\ell\ell}|<2.4$**

✓ **No acceptance correction to the full phase space**

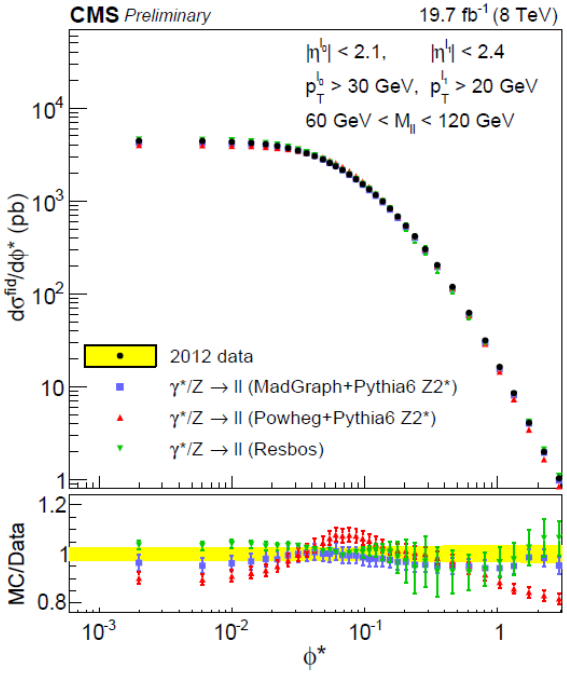
✓ **Rapidity and mass distributions of gauge bosons are sensitive to parton content of the proton (PDFs)**

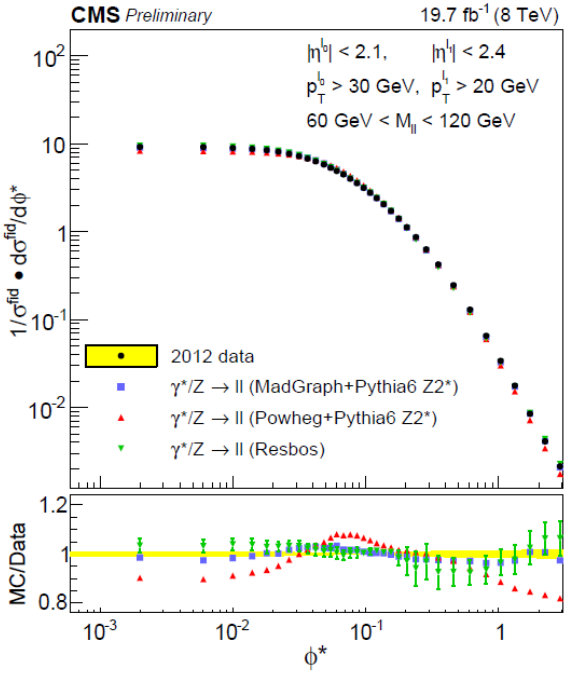
$$x_{\pm} = (m/\sqrt{s})e^{\pm y}$$

Drell-Yan ϕ* diff. cross section at 8 TeV

CMS-PAS-SMP-15-002

- dσ/dϕ* distributions have been measured with Drell-Yan events in both electron and muon channel
- Measurements are compared with predictions by MADGRAPH, POWHEG, and ResBos
- MADGRAPH and POWHEG are normalized to the total cross section at NNLO from FEWZ





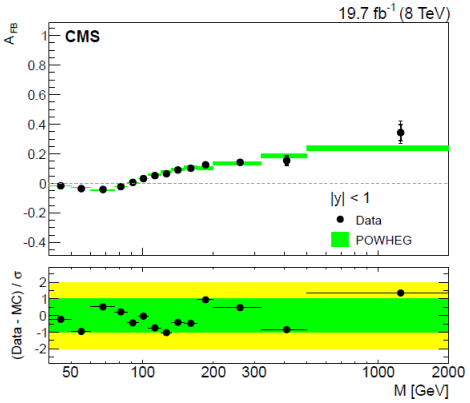
Luminosity uncertainty cancels in the normalized cross section (right), precision at 1-2% level

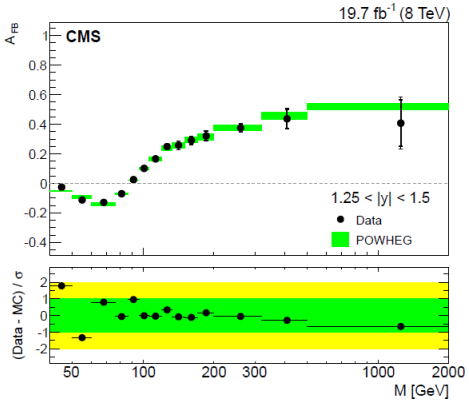
✓ **None of the theoretical calculations predict the measurements perfectly over the entire range of ϕ*. MADGRAPH shows better agreement with the data**

A_{FB} of Drell-Yan lepton pairs at 8 TeV

EPJC 76 (2016) 325

- Forward-backward asymmetry A_{FB} of $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$, measured for $40<m_{\ell\ell}<2000$ GeV, $|y_{\ell\ell}|<5$
- Sensitive to new physics, quark weak couplings, and effective weak mixing angle $\sin^2\theta^{eff}_{lept}(m_Z)$
- SM prediction by POWHEG NLO using CT10 PDFs ($\sin^2\theta^{eff}_{lept}=0.2312$ is used)
- Measurement corrected for the detector resolution, efficiency, acceptance, and FSR



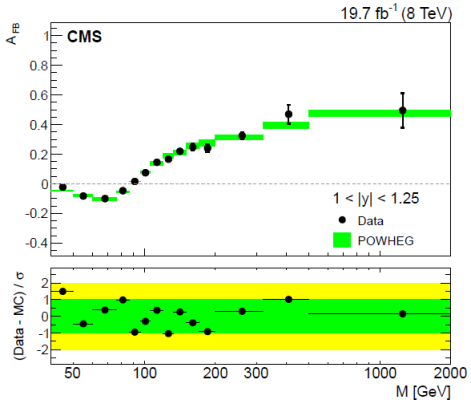


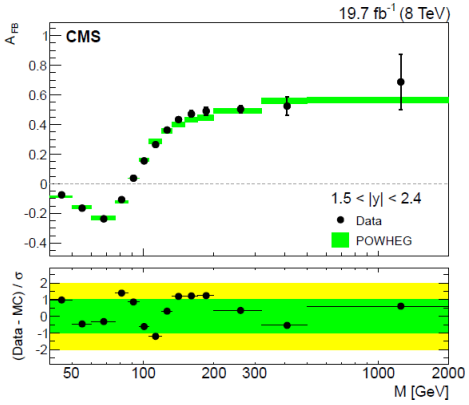
$$\frac{d\sigma}{d(\cos\theta^*)} = A(1+\cos^2\theta^*) + B\cos\theta^*$$

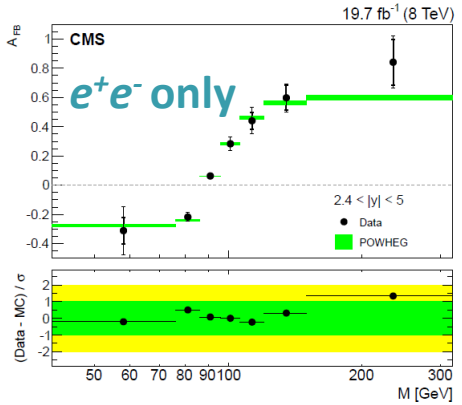
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$\sigma_{F(B)}$: the total cross section for forward (backward) events

: defined by $\cos\theta^* > 0$ $(\cos\theta^* < 0)$, evaluate $\cos\theta^*$ in Collins – Soper(CS) frame



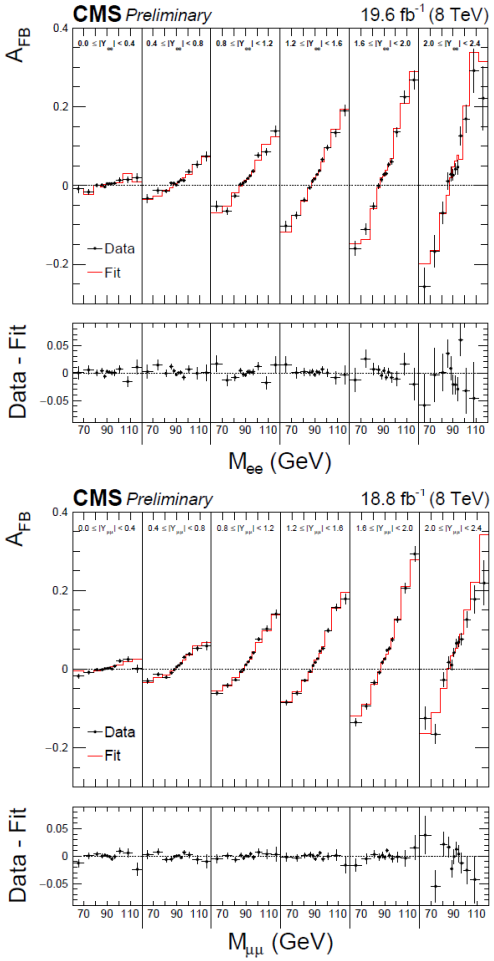




✓ **Good agreement with data in all $|y_{\ell\ell}|$ regions including $2.4<|y_{ee}|<5$ for m_{ee}: 40-320 GeV**

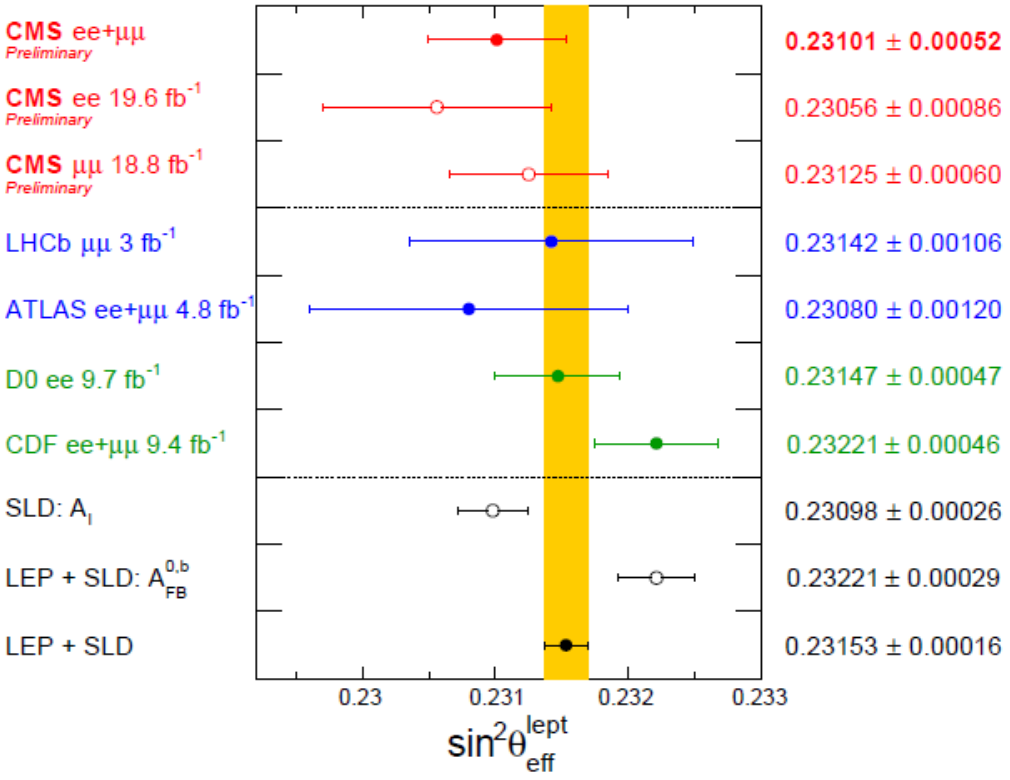
$\sin^2\theta^{eff}_{lept}$ from A_{FB} of Drell-Yan events at 8 TeV

CMS-PAS-SMP-16-007



Template fitting to A_{FB} in $m_{\ell\ell}$ and $y_{\ell\ell}$ bins to extract $\sin^2\theta^{eff}_{lept}$

$\sin^2\theta^{eff}_{lept}$ = 0.23101±0.00036(stat.)±0.00018(syst.)±0.00016(theory)±0.00030(pdf)

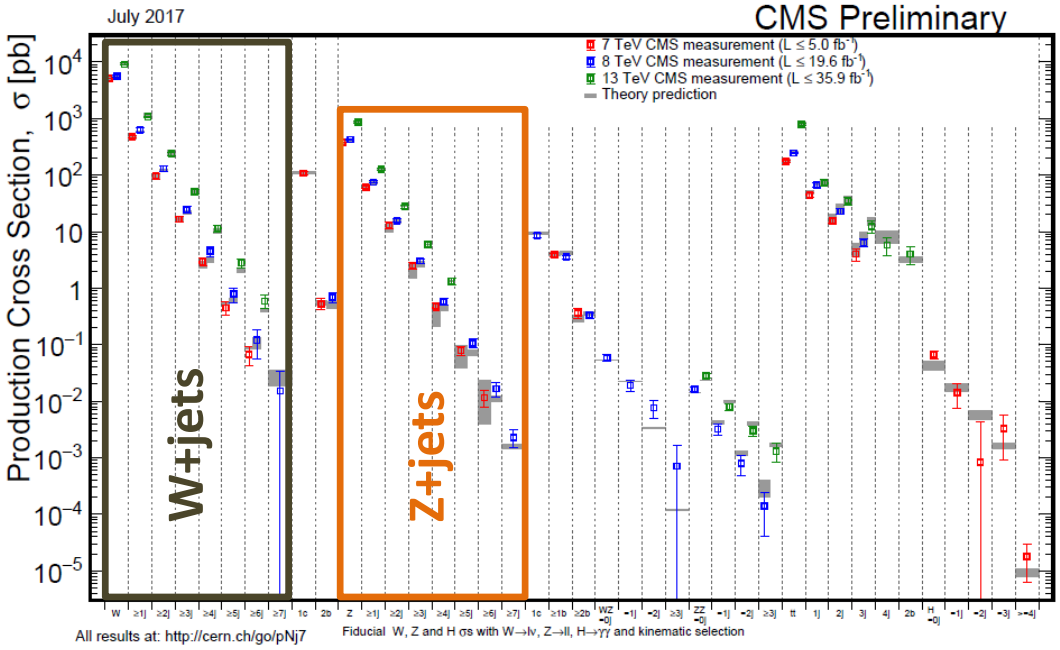


✓ **The results are consistent with the most precise LEP and SLD measurements**

W/Z+jets cross section measurements

- Important SM benchmarks providing precision tests for pQCD calculations and inputs to constrain PDFs
  - powerful tool to test modern MC event generators and theoretical calculations
  - prominent background for rare SM processes (Higgs, top pair, etc.) and BSM searches such as SUSY
- Typical fiducial phase space selections at 8 (13) TeV:
  - Z($\ell^+\ell^-$, ℓ=e, μ)+jets: isolated leptons with $p_T(\ell)$>20 GeV, $|\eta(\ell)|$<2.4, 71 < $m_{\ell\ell}$ < 111 GeV
  - W($\ell\nu$, ℓ=μ)+jets: isolated muons with $p_T(\mu)$>25 GeV, $|\eta(\mu)|$<2.1(2.4), m_T(W)>50 GeV
  - jets defined by the anti-k_T algorithm with R=0.5(0.4), p_T(j)>30 GeV, |y(j)|<2.4
- Data distributions are unfolded for detector effects to fiducial phase space at the stable-particle level and compared with ME+PS N(LO) MC simulations and to fixed order (N)NLO calculations corrected for nonperturbative effects

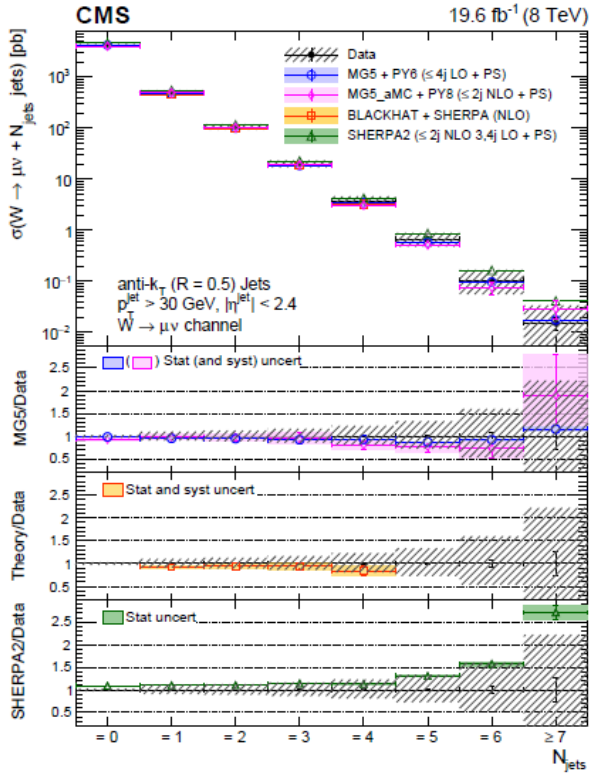
✓ **W/Z+jets measurements at 7, 8, and 13 TeV span several orders of magnitude in cross section**
✓ **Good data/theory agreements up to higher jet multiplicities**

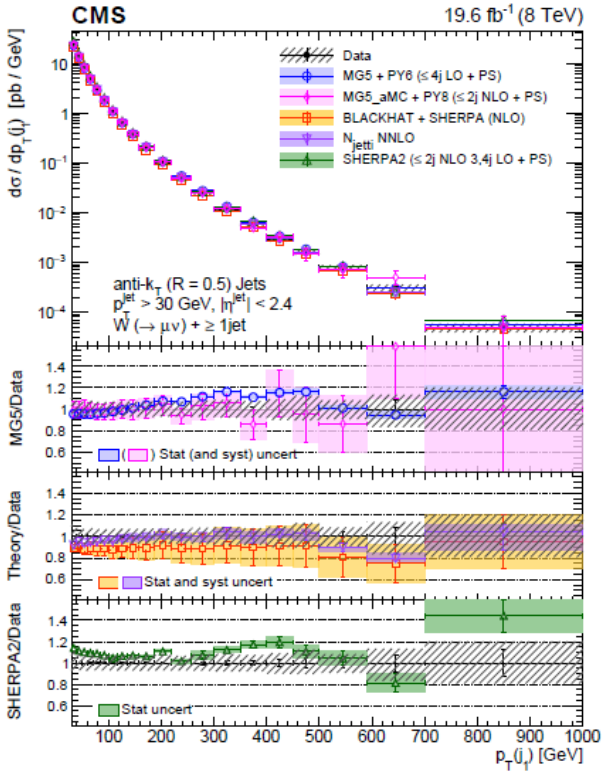


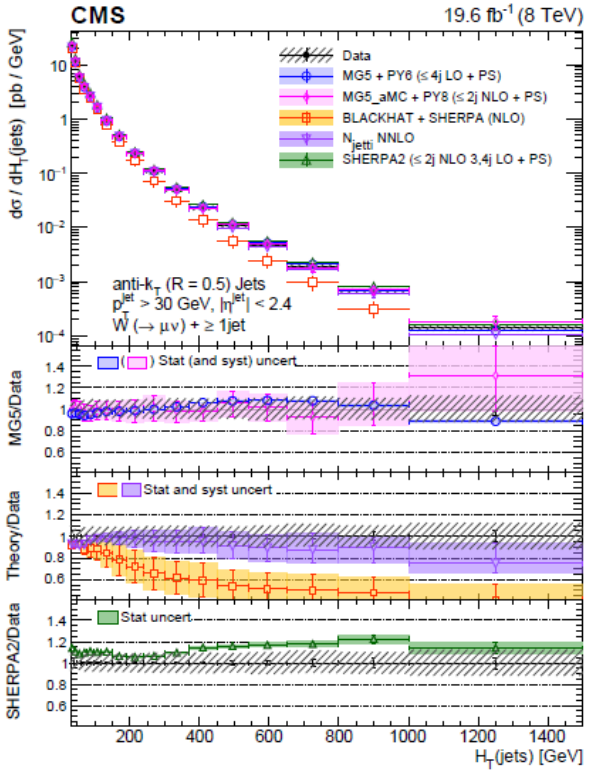
W+jets at 8 TeV

PRD 95 (2017) 052002

- Differential cross sections of W($\mu\nu$)+jets up to 7 jets and up to 4 inclusive jets on several variables
- Predictions by LO and NLO ME+PS, fixed-order NLO, and NNLO for W+≥1-jet in pQCD
- Nonperturbative effects are accounted for fixed-order calculations





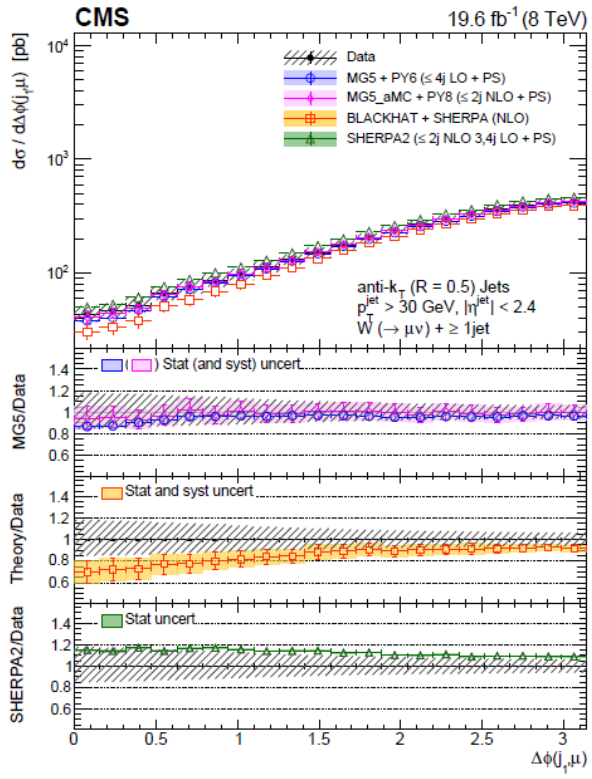


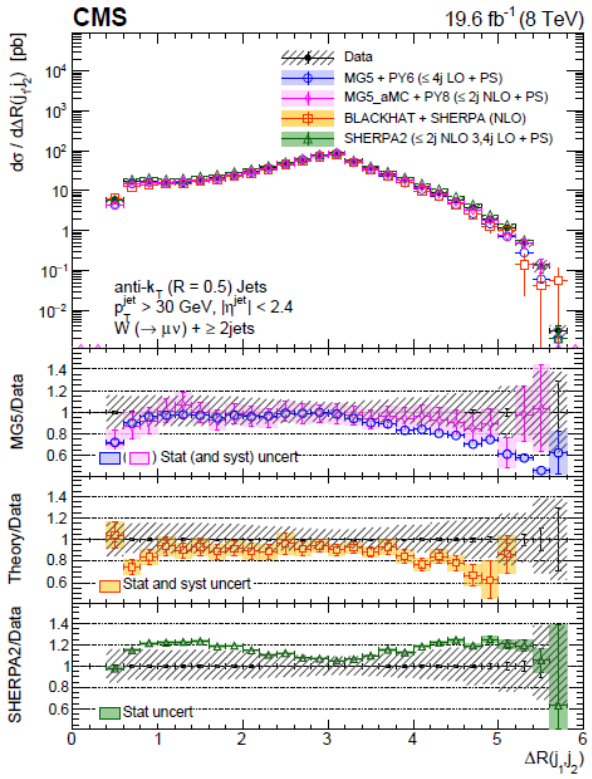
- ✓ **Measured ranges extend up to 1 TeV for the leading jet p_T and 1.5 TeV for the jets H_T ($N_{jets} \geq 1$)**
- ✓ **Good data description by MG5_aMC FxFx (NLO up to 2 jets) and N_{jetti} NNLO predictions**
- ✓ **BlackHat under predicts data at high H_T ($N_{jets} \geq 1$) as expected (max. 2 jets at NLO included)**

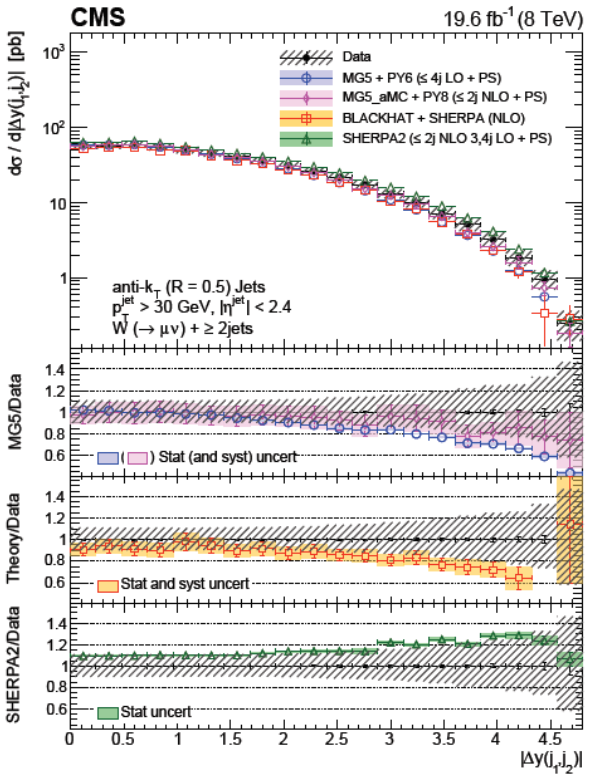
W+jets angular correlations at 8 TeV

PRD 95 (2017) 052002

- Testing accuracy of modeling using W(μν)+jets cross sections differential in angular variables and rapidity separation among jets (and muon)





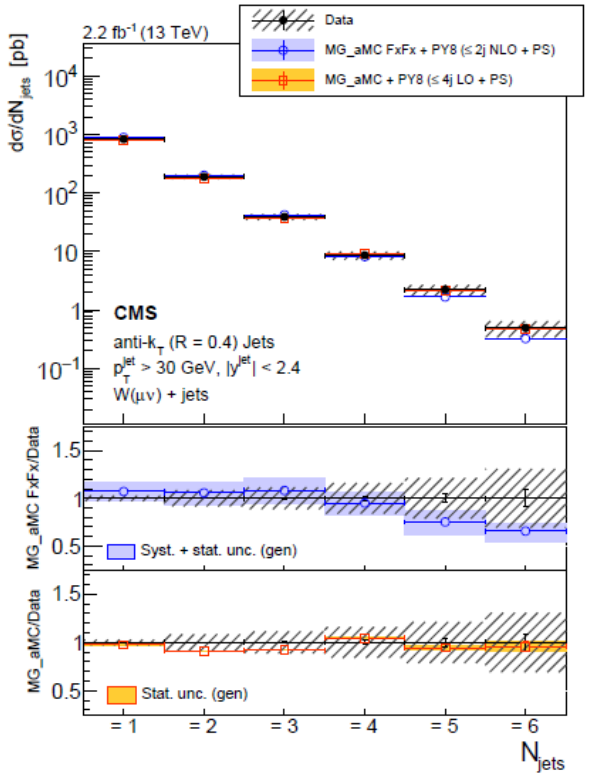


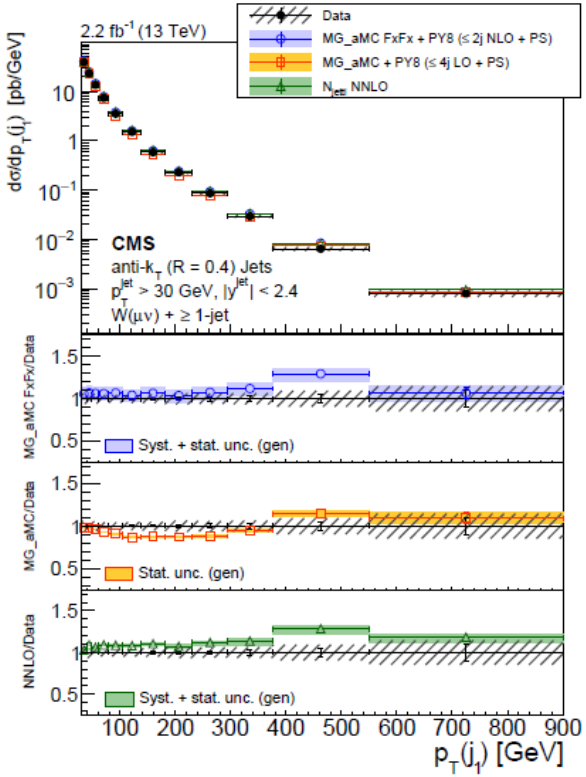
- ✓ **Best description of data by MG5_aMC FxFx NLO (improved prediction w.r.t. MG5_aMC LO)**
- ✓ **Fixed-order NLO shows some more deviations from data at low Δϕ between muon and jets and at high Δy between jets. Sherpa 2 shows higher trend over almost the entire ranges**

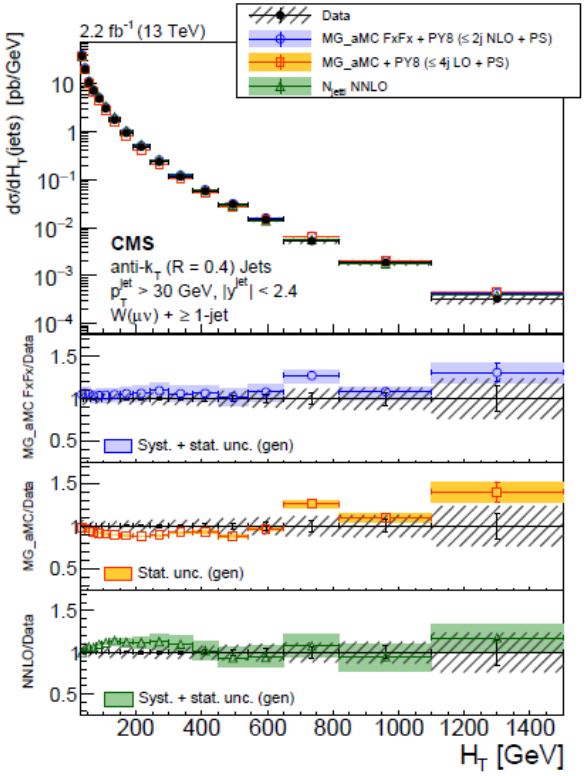
W+jets at 13 TeV

arXiv:1707.05979

- **First W+jets differential cross sections measurement at 13 TeV!**
- Measured distributions up to 4 inclusive jets in muon decay channel
- Data comparison to MG5_aMC LO+PS, MG5_aMC merged NLO+PS, and N_{jetti} NNLO predictions





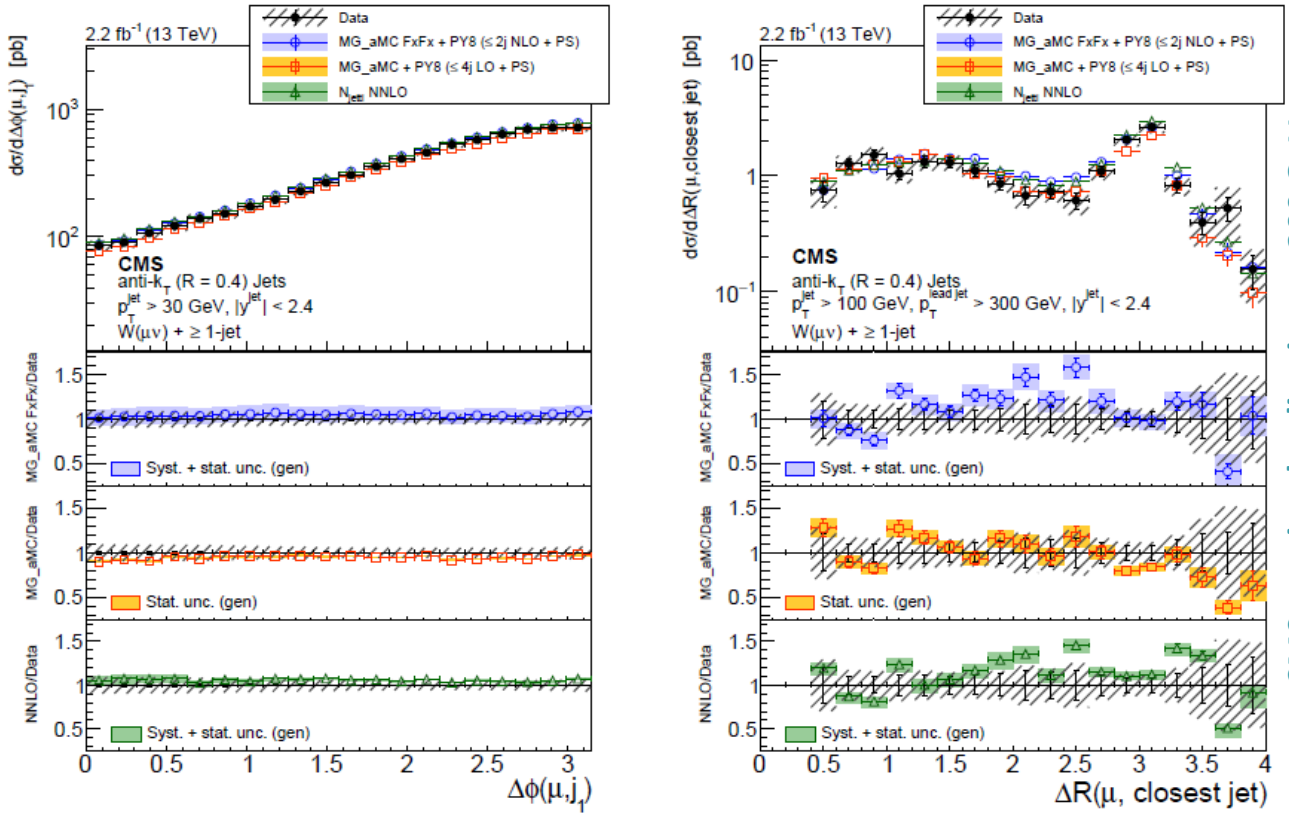


- ✓ **MG5_aMC N(LO) agrees well with the jet multiplicity data within uncertainty**
- ✓ **The leading jet p_T and the jets H_T measurements well reproduced by (N)NLO predictions**

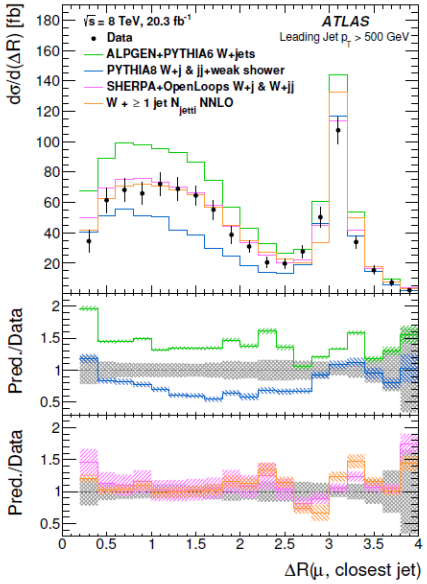
W+jets angular variables at 13 TeV

arXiv:1707.05979

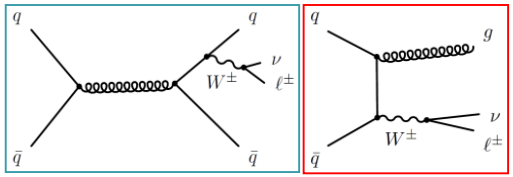
- Measured cross sections differential in angular correlation variables Δϕ(μ,jet) and ΔR(μ, closest jet)
- Δϕ(μ,jet) is sensitive to particle emissions and other nonperturbative effects in event generators
- ΔR(μ, closest jet) probes contribution of electroweak radiative processes to W+jets



CMS requires leading jet p_T>300 GeV



ATLAS 8 TeV measurement with leading jet p_T>500 GeV (Phys. Lett. B 765 (2017) 132)



Left: ΔR<2.4 - collinear W emission

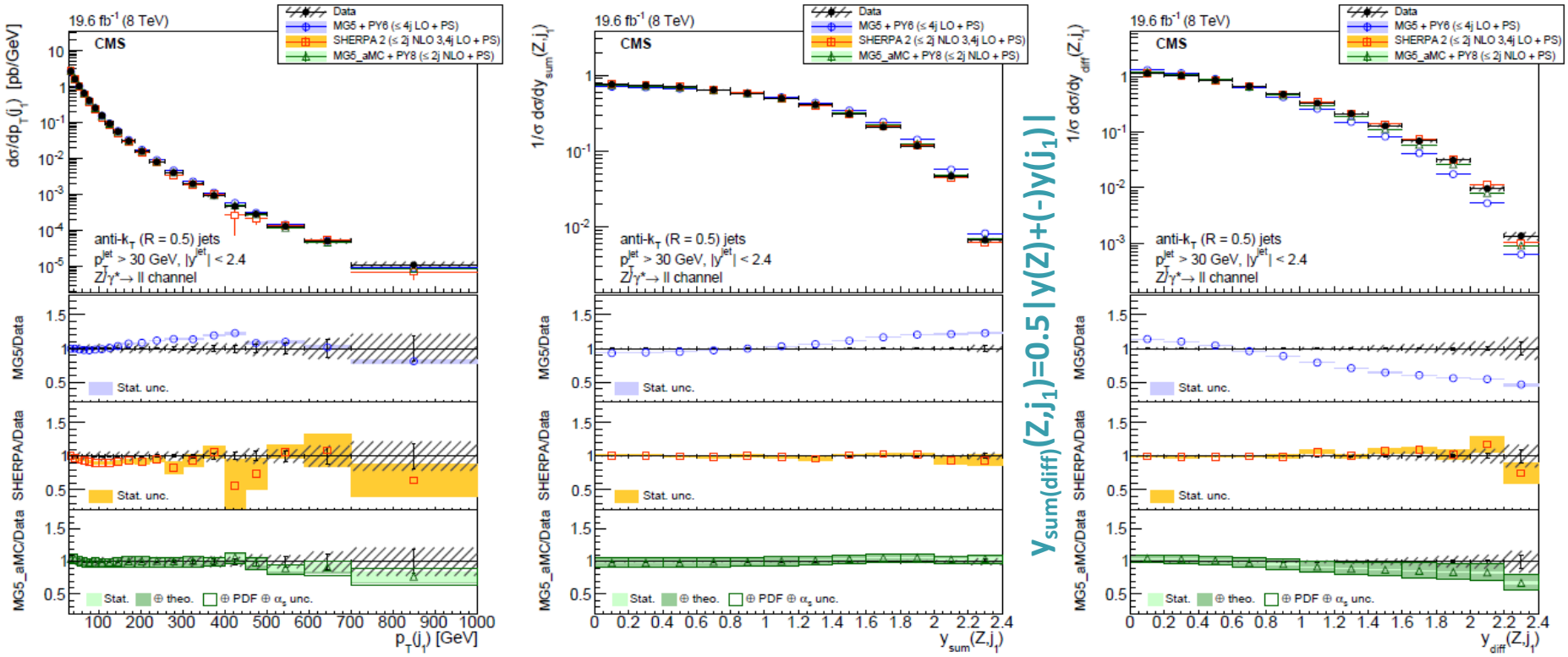
Right: ΔR>2.4 - W balanced by a hadronic recoil

- ✓ **All predictions accurately describe data for Δϕ(μ,jet)**
- ✓ **Best agreement with data by N$_{jetti}$ NNLO for ΔR(μ, closest jet)**

Z+jets at 8 TeV

JHEP 04 (2017) 022

- Differential cross sections of Z($\ell\ell$)+jets as functions of numerous observables up to 5 inclusive jets
- Two opposite-sign same-flavor leptons with $m_{\ell\ell}$ window around m_Z: 71 < $m_{\ell\ell}$ < 111 GeV
- Predictions by LO and NLO ME+PS event generators, employing different PS algorithms

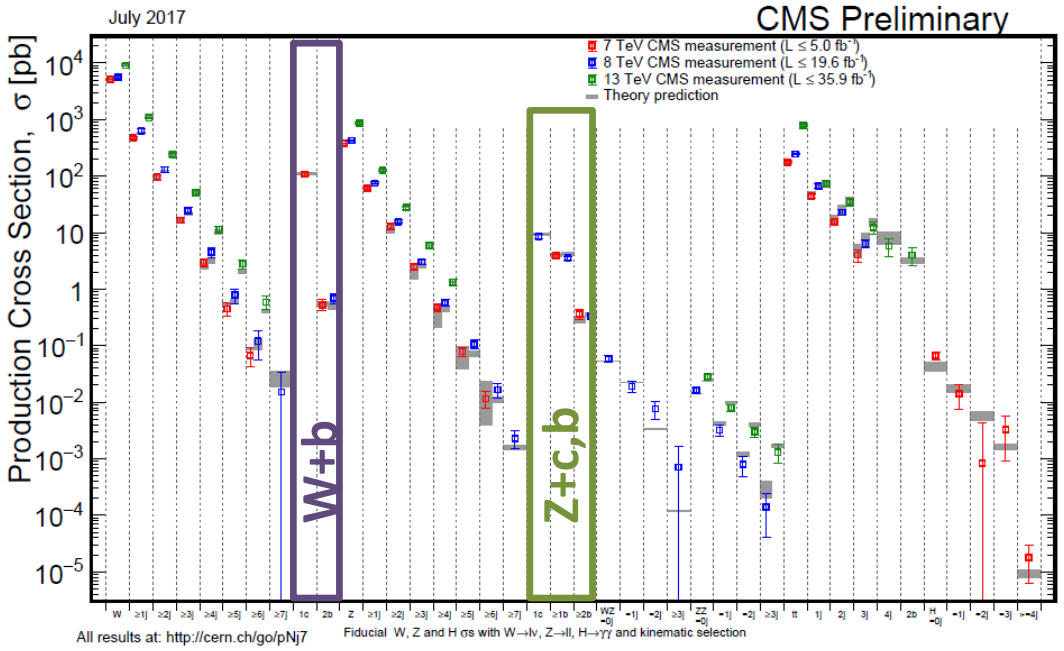


- ✓ **Improved data description for the leading jet p_T when NLO terms included in MG5_aMC**
- ✓ **Discrepancy by MG5_aMC LO for the $y_{sum(diff)}$, confirmation of CMS 7 TeV paper, Phys. Rev. D 88 (2013) 112009**
- ✓ **MG5_aMC/Sherpa 2 NLO predictions reproduce the $y_{sum(diff)}$ measurement, using different PS algorithms and jet merging schemes (FxFx vs. MEPS@NLO)**

W/Z+HF-jets

- Experimentally challenging analyses but are of paramount importance
  - Precisions tests of QCD heavy flavor (HF) sector
  - Background processes to Higgs and BSM searches
  - Sensitivity to probe strange and HF quark (b, c) content in the proton
  - b quark flavor content of the PDFs: 4 flavor vs. 5 flavor scheme
- HF-jets identified using multivariate analysis techniques (information about secondary vertices and impact parameters) or explicitly requiring b, c hadrons or soft muons in jets

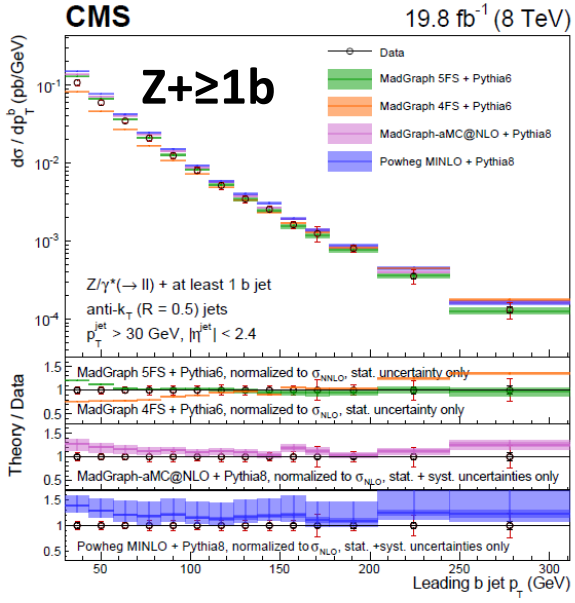
✓ **CMS HF-jets cross section measurements at 7 and 8 TeV**

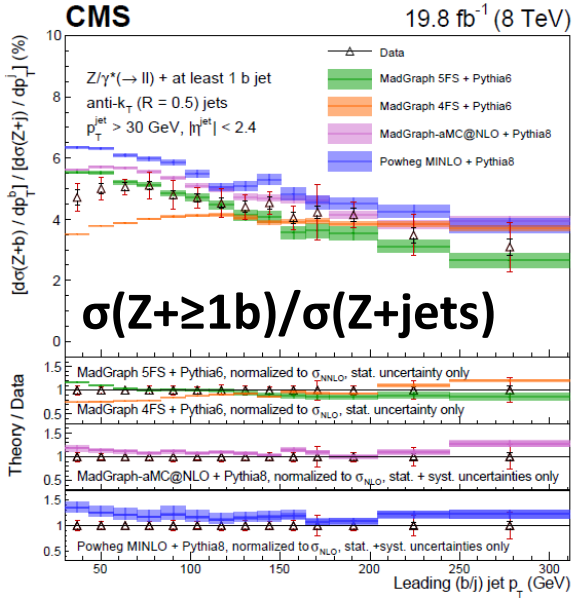


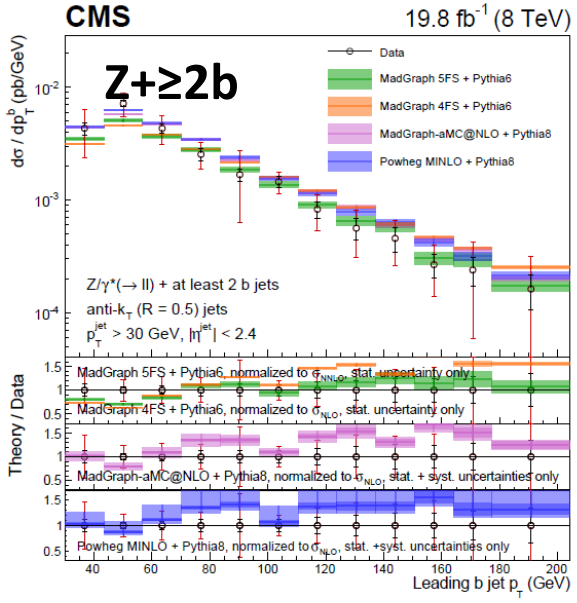
Z+b-jets at 8 TeV

arXiv:1611.06507

- Z($\ell\ell$)+≥1b, ≥2b productions. Select isolated leptons with $p_T(\ell)$>20 GeV, $|\eta(\ell)|$<2.4, 71 < $m_{\ell\ell}$ < 111 GeV and b-tagged jets with p_T(j)>30 GeV, $|\eta(j)|$<2.4
- Measured fiducial cross sections for Z+≥1b and Z+≥2b in combined lepton channel:
  - **σ(Z+≥1b)=3.55±0.12(stat.)±0.21(syst.) pb and σ(Z+≥2b)=0.331±0.011(stat.)±0.035(syst.) pb**
  - **σ(Z+≥2b)/σ(Z+≥1b)=0.093±0.004(stat.)±0.007(syst.)**
- MG5 using CTEQL1 (MSTW2008) PDF set in 5FS (4FS)+PYTHIA 6, MG5_aMC merged NLO and POWHEG MiNLO predictions using NNPDF 3.0 PDF set and 5FS+PYTHIA 8





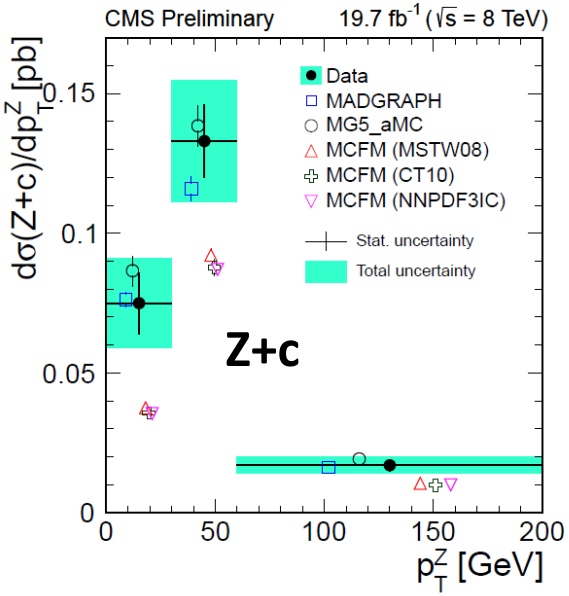


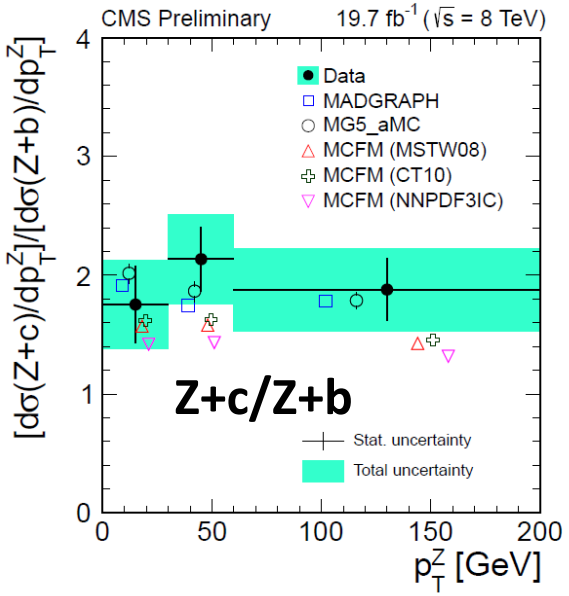
- ✓ **Observed discrepancy from all predictions at low jet p_T for Z+≥1b. Normalization effect in MG5 4FS.**
- ✓ **Measurements do not strongly discriminate between the theoretical predictions**

Z+c-jets at 8 TeV

CMS-PAS-SMP-15-009

- Z($\ell\ell$)+≥1c associated production, selections for isolated leptons with $p_T(\ell)$>20 GeV, $|\eta(\ell)|$<2.1, 71 < $m_{\ell\ell}$ < 111 GeV and at least one c or b jet with p_T(j)>25 GeV, $|\eta(j)|$<2.5
- HF-quark jets identified using three signatures: semileptonic decay modes and hadronic decays of charm hadrons $D^{\pm}\rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$ and $D^{*\pm}\rightarrow D^0(\bar{D}^0)\pi^{\pm}$ (where $D^0(\bar{D}^0)\rightarrow K^{\mp}\pi^{\pm}$)
- Fiducial inclusive cross section (ratio of Z+c/Z+b) measured in combined lepton channel:
  - **$\sigma(pp\rightarrow Z+c+X)\times\mathcal{B}(Z\rightarrow\ell^+\ell^-)$=8.6±0.5(stat.)±0.7(syst.) pb, $\sigma(pp\rightarrow Z+c+X)/\sigma(pp\rightarrow Z+b+X)$=2.0±0.2(stat.)±0.2(syst.)**
- Differential cross sections measured in semileptonic mode as a function of Z boson p_T

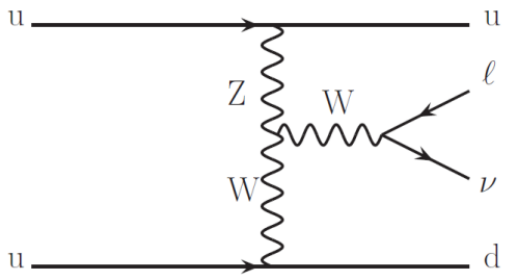


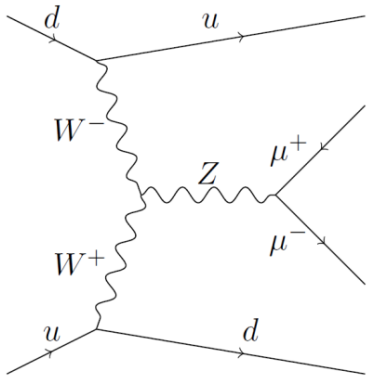


- ✓ **MG5_aMC LO(NLO)+PYTHIA 6(8) describe well the measurement. MCFM fixed order NLO (using different PDF sets) predicts smaller cross section both inclusively and differentially**
- ✓ **All predictions reproduce the data in Z+c/Z+b cross section ratio better**

EW W/Z+2-jet production

- **Characterized by the presence of two high-p_T jets with**
  - **large pseudorapidity separation**
  - **low hadronic activity in-between**



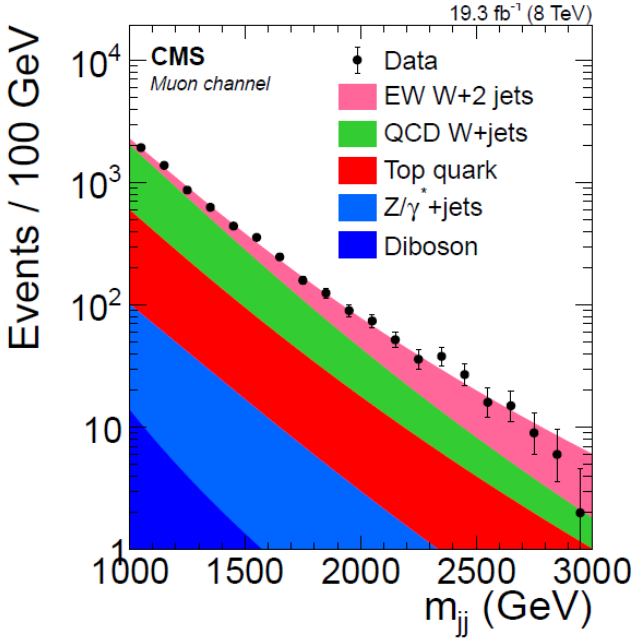


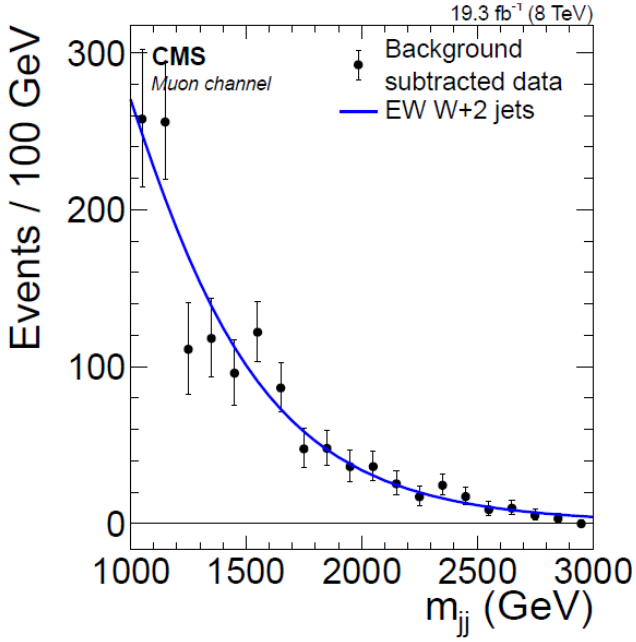
- Roughly ten times lower cross sections than QCD production
- Tests of the gauge structure of the EW sector (i.e. gauge boson self interactions)
- Important for VBF production studies for Higgs boson
- Main background from QCD W/Z+jets

EW W+2-jets production at 8 TeV

JHEP 11 (2016) 147

- Cross section measurement of the EW W($\ell\nu$)+2-jets final state in the kinematic region defined as $p_T(j_1)>60$ GeV, $p_T(j_2)>50$ GeV, and $|\eta(j)|<4.7$ with high dijet mass $m_{jj} > 1000$ GeV and small hadronic activity in the central region of the detector
  - probes triple gauge couplings and background to Higgs boson production in VBF channel
  - fiducial cross section from fits to m_{jj} distributions, using parametric models for all processes



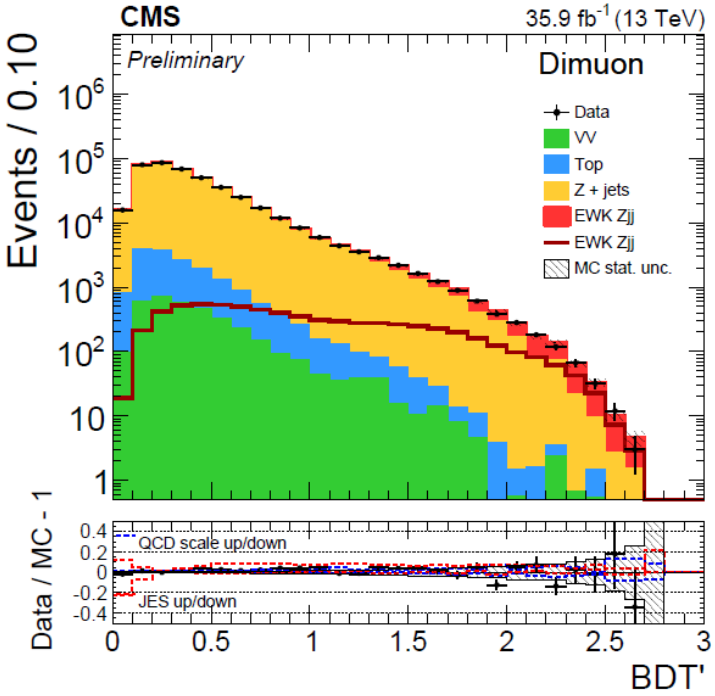


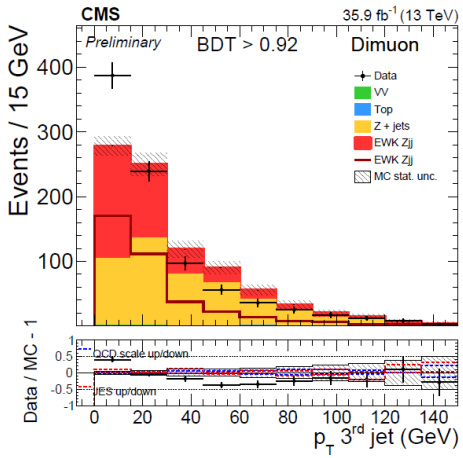
- ✓ **First cross section measurement for this process. Measured fiducial cross section in agreement with SM LO prediction by MG5_aMC+PYTHIA 6:**
  - ✓ **σ(EW W($\ell\nu$)+2-jets)=0.42±0.04(stat.)±0.09(syst.)±0.01(lumi) pb**
  - ✓ **σ(SM LO EW W($\ell\nu$)+2-jets)= 0.50±0.02(scale)±0.02(PDF) pb**

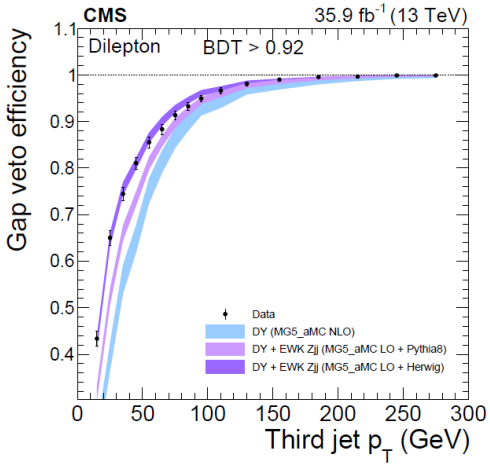
EW Z+2-jets production at 13 TeV

CMS-PAS-SMP-16-018

- The pure EW Z($\ell\ell$)+2-jets final state. Measurement with 2016 data (L=35.9 fb^{-1})
- Several discriminating variables used to achieve the best separation between EW Z+2-jets signal and Drell-Yan+jets strong processes. Signal extracted from the fit to the BDT output distribution







- **Studied jet and hadronic activity in the signal-enriched region (BDT>0.92)**
- **Efficiencies of a gap activity veto for the third jet p_T (representative)**
- **Herwig (Pythia 8) PS does better for low and moderate (higher) gap activity**

✓ **The first cross section measurement for this process at 13 TeV.** Cross section measured in the kinematic region defined as $p_T(j)>25$ GeV, $m_{jj}>120$ GeV, $m_{\ell\ell}>50$ GeV

✓ **Measured fiducial cross section in agreement with SM LO prediction by MG5_aMC+PYTHIA 8:**

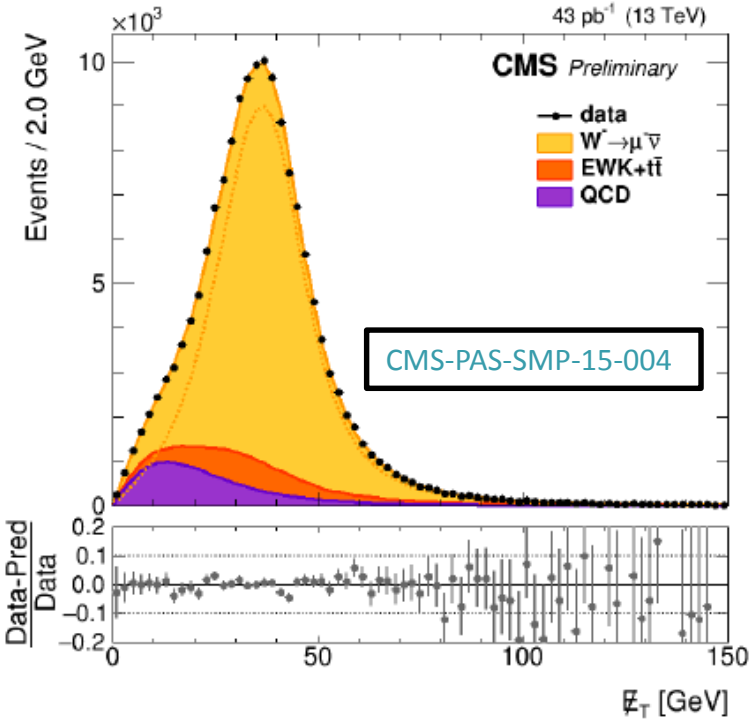
✓ **σ(EW Z($\ell\ell$)+2-jets)=552±19(stat.)±55(syst.) fb, σ(SM LO EW Z($\ell\ell$)+2-jets)=543±24 fb**

Conclusion

- **CMS has provided a comprehensive set of measurements on W/Z (+jets) production from 8 and 13 TeV pp collision data at the LHC**
  - High precision has been achieved on measurements of inclusive and differential cross sections and ratios of cross sections
  - Generally good agreement with predictions comprising ME calculations, PS models, NLO and NNLO fixed order calculations
  - Provided tests of QCD and EW sector with wealth of information (perturbative and soft QCD effects, PDF constraints, Drell-Yan forward-backward asymmetry, W charge asymmetry, weak mixing angle, background modeling for Higgs and new physics, HF sector of QCD, etc.)
  - Still need to improve modeling and precisions for the remained discrepancies and larger uncertainties
- **More results from 2016 data to come! 2017 run already started!**

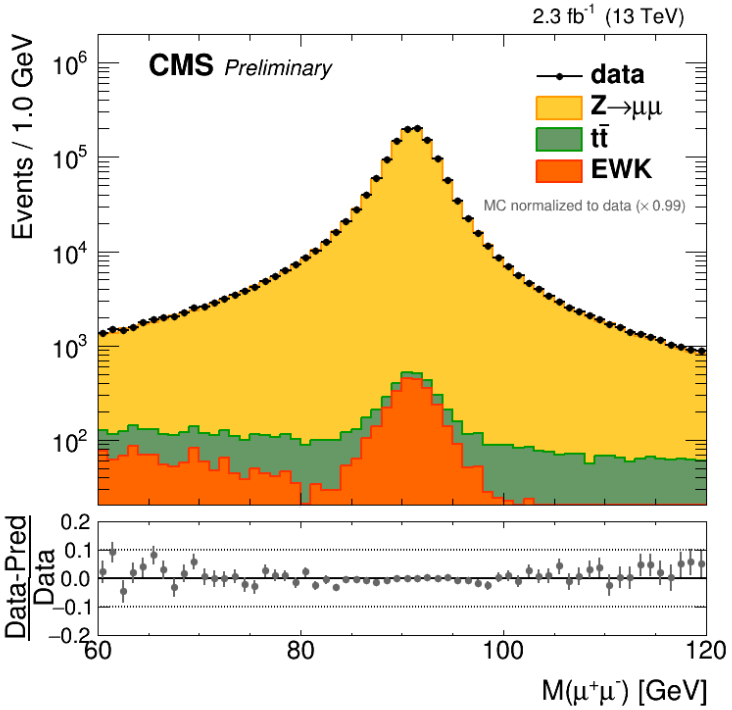
Back-up slides

W and Z yields



CMS-PAS-SMP-15-004

W boson: signal extracted by fitting to MET, where MET is associated with an undetected neutrino
Background: EWK+ttbar from simulation
QCD multijet is major background and estimated from data



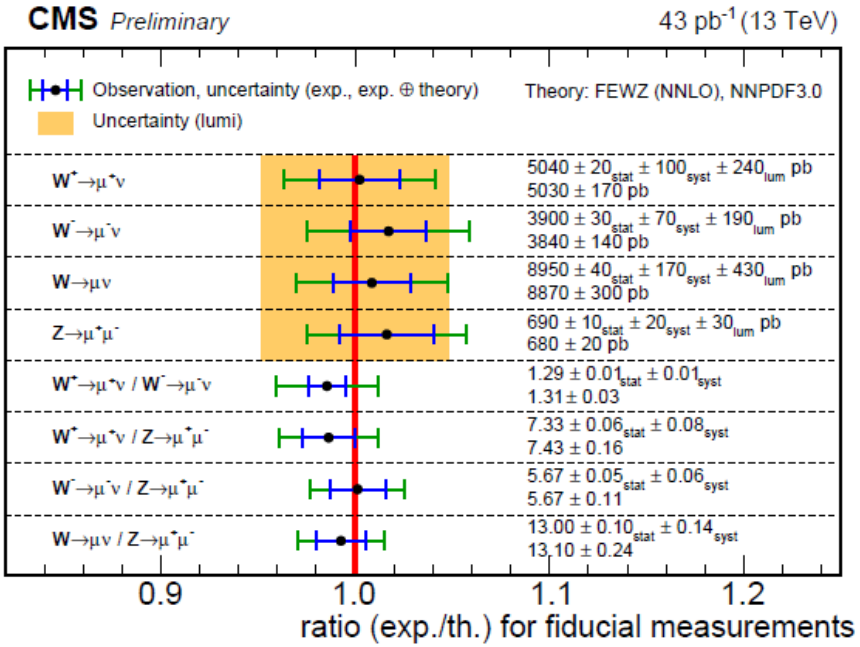
CMS-PAS-SMP-15-011

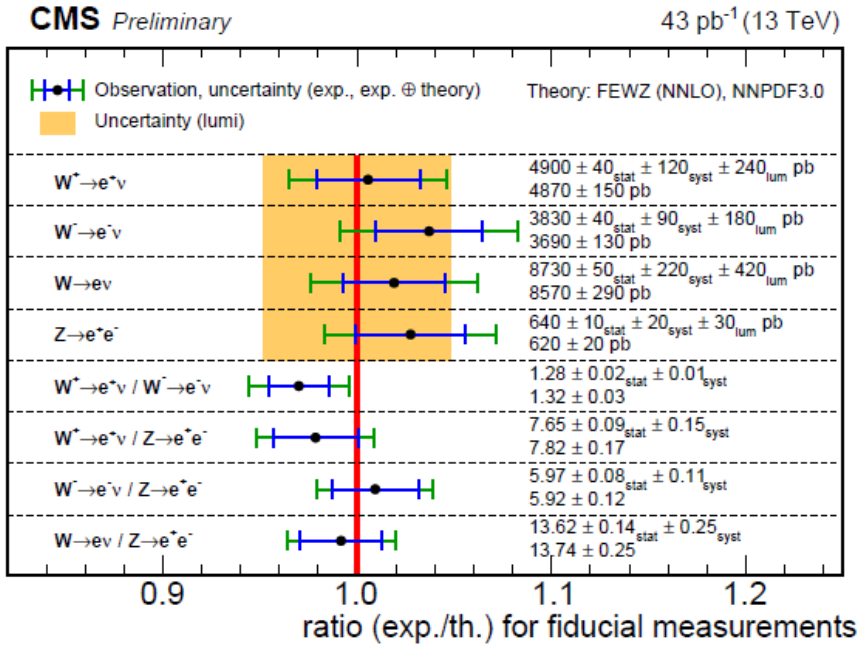
Z boson: signal events counted in dilepton invariant mass window 60-120 GeV
Background: EWK+ttbar from simulation

W and Z fiducial cross sections and ratios

CMS-PAS-SMP-15-004

- Event selection with $p_T(\ell)$>25 GeV, $|\eta(e,\mu)|$<2.5(2.4). Z candidates within 60<$m_{\ell\ell}$<120 GeV
- No acceptance correction. The systematic uncertainties are reduced





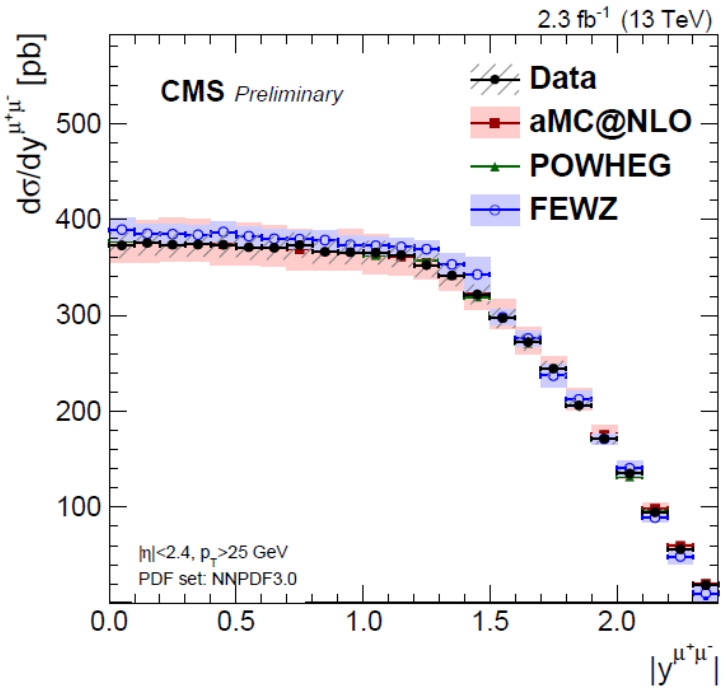
Muons

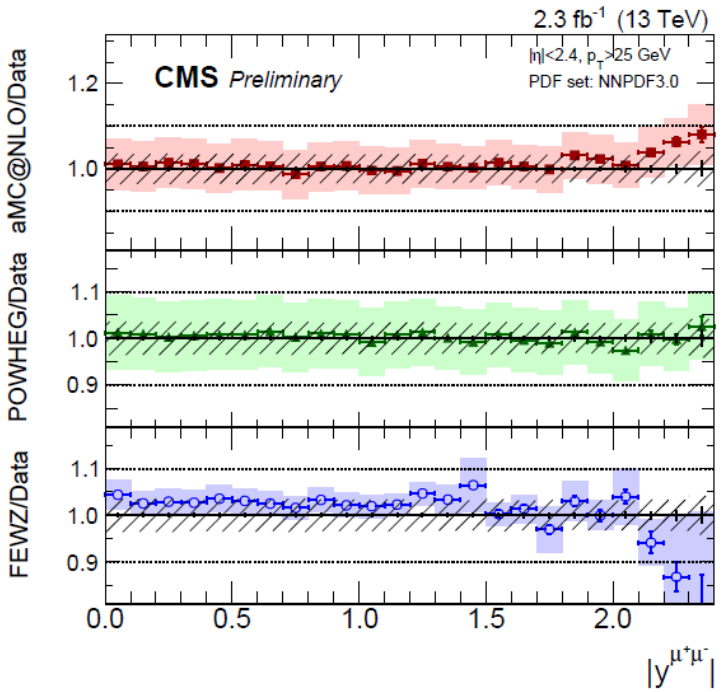
Electrons

dσ/dy(Z)

CMS-PAS-SMP-15-011

- Z rapidity gives useful input for the global fit to the PDFs
- Unfolded data compared to MG5_aMC (NLO), POWHEG (normalized to NLO), FEWZ NNLO+NLO EW



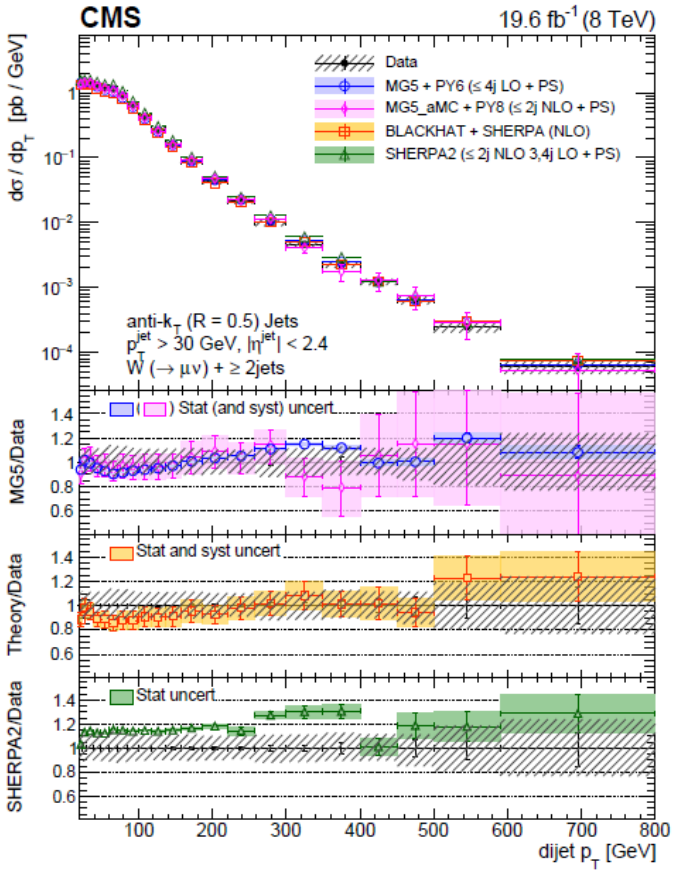


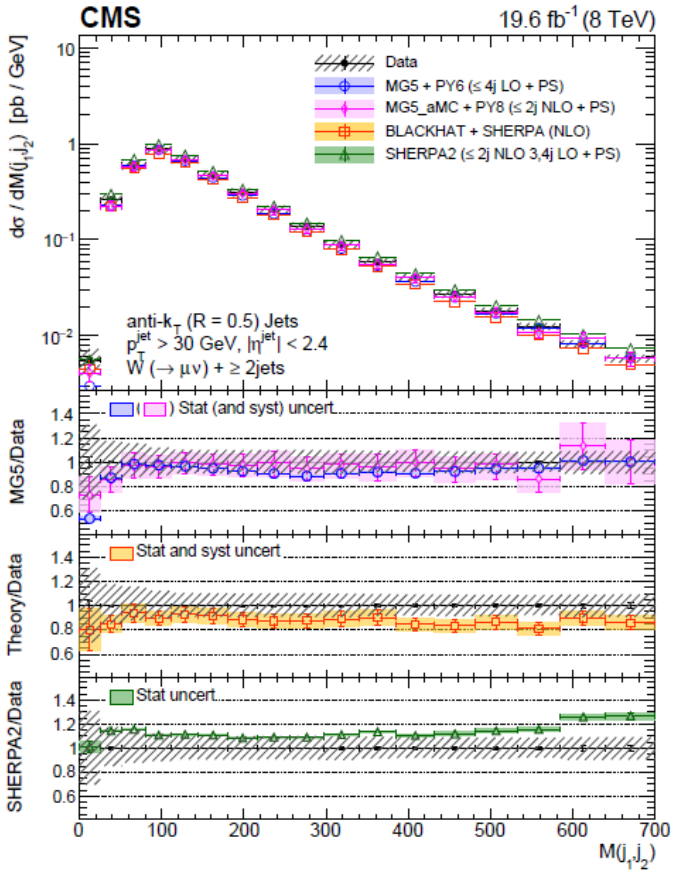
✓ **Good agreement between data and predicted distributions**

W + dijet at 8 TeV

PRD 95 (2017) 052002

- Dependence of the measured cross sections on the dijet transverse momentum and invariant mass. Sensitivity to the presence of physics beyond the SM in dijet final states



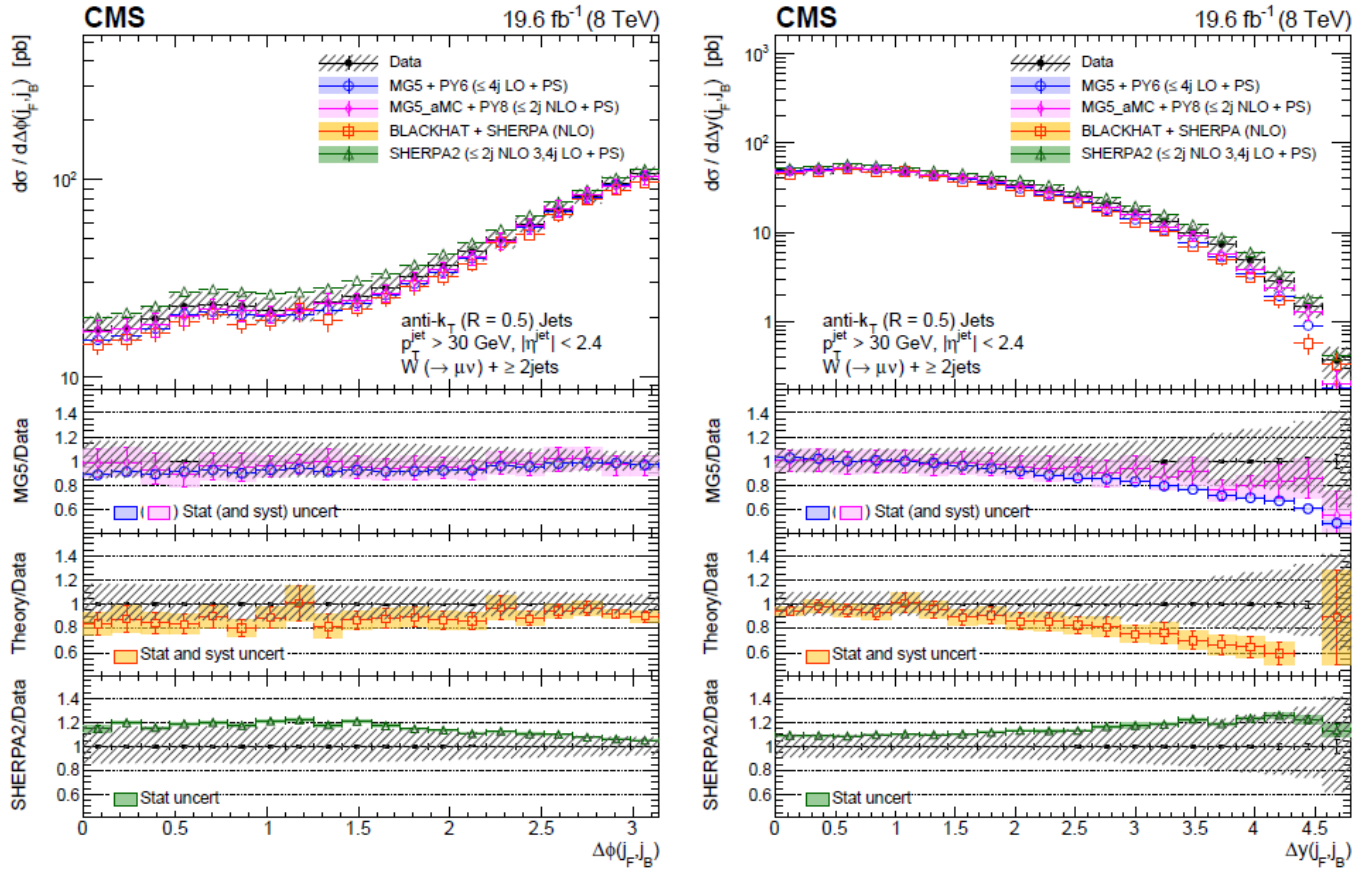


✓ **For dijet p_T and $M_{j1,j2}$, different generators give similar prediction, apart from Sherpa 2**

W + jets at 8 TeV: $\Delta\phi(j_F, j_B)$ and $\Delta y(j_F, j_B)$

PRD 95 (2017) 052002

- $\Delta\phi(j_F, j_B)$: A sensitive test of modeling of higher-order corrections in theoretical calculations
- $\Delta y(j_F, j_B)$: A test of wide-angle parton radiation and ME+PS matching schemes



$\Delta\phi(j_1, j_2)$ is a test of QCD and MC modeling:

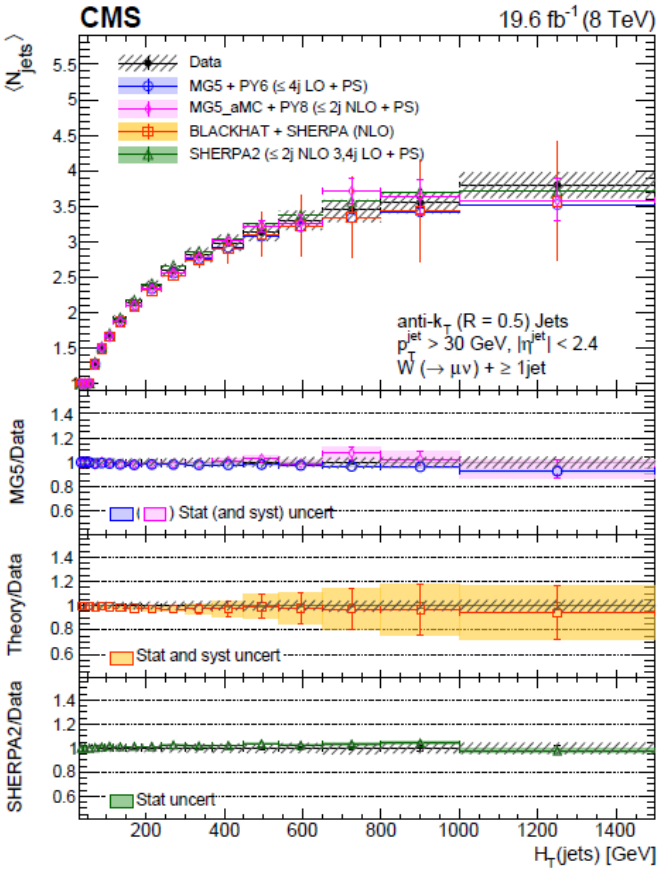
- **Hard radiation at large angles from ME**
- **Soft collinear radiation from PS**

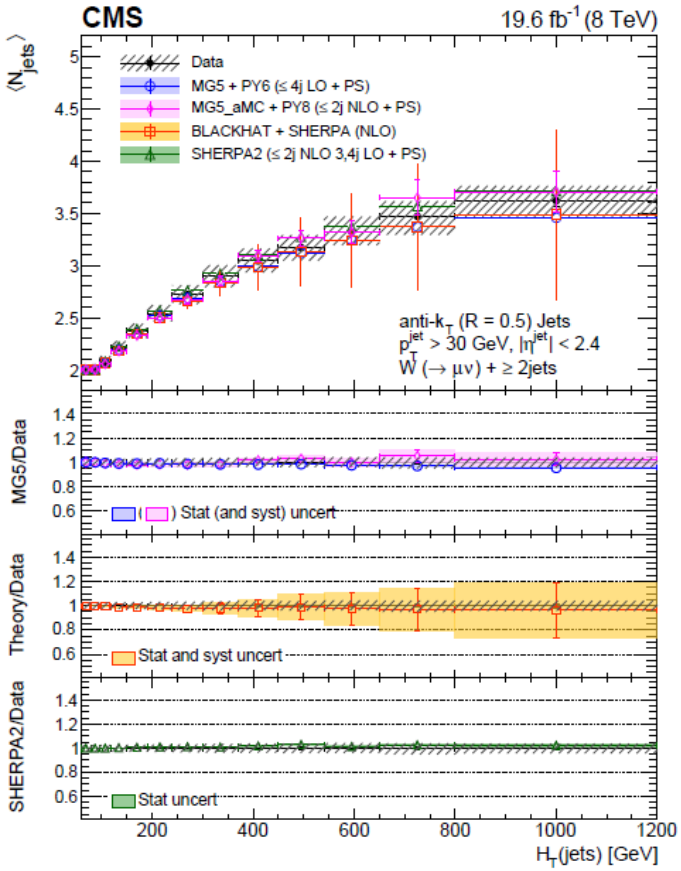
✓ **Predictions tend to undershoot data at high rapidity separation of jets, except Sherpa 2**

W + jets at 8 TeV: Average number of jets <N_{jets}>

PRD 95 (2017) 052002

- **Sensitivity to the effects of the higher-order processes**



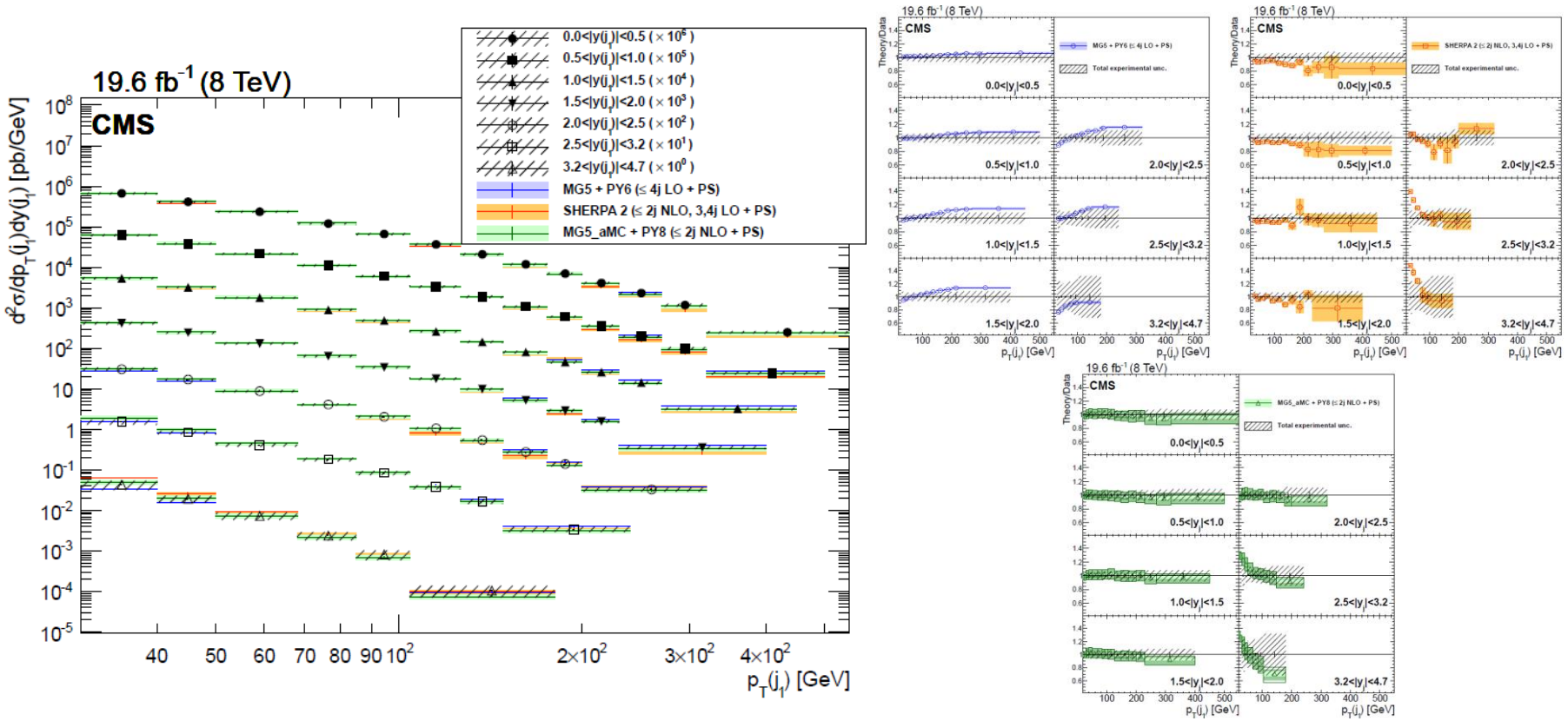


✓ **Excellent description of data over the entire ranges of H_T for N_{jets} ≥ 1 (2) jet left (right)**

Z+jets double diff. cross section at 8 TeV

JHEP 04 (2017) 022

- Double differential cross section in an extended jet rapidity acceptance to |y| < 4.7, where Z+jets events constitute background for VBF (e.g., Higgs boson production)

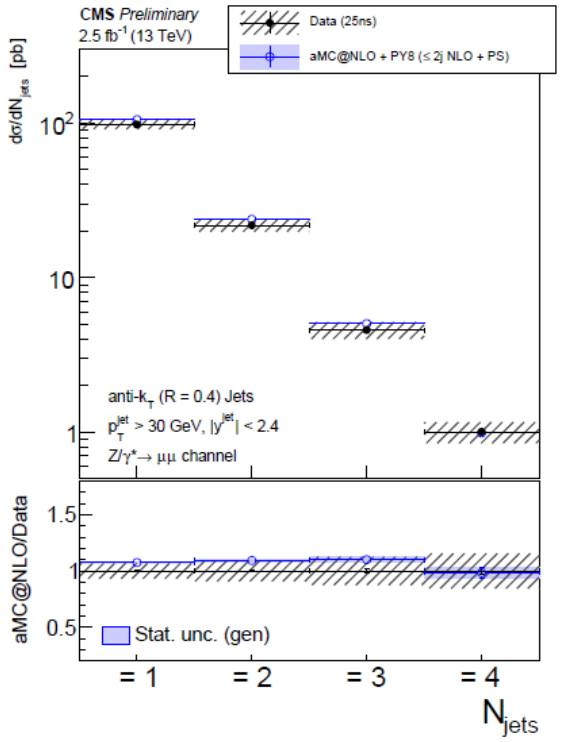


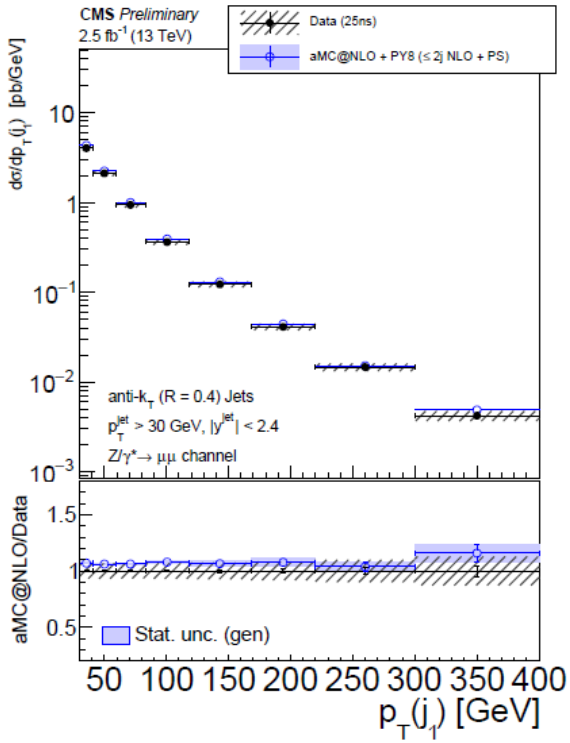
- ✓ **Predictions challenge to fairly reproduce data distributions in forward rapidity regions as well**

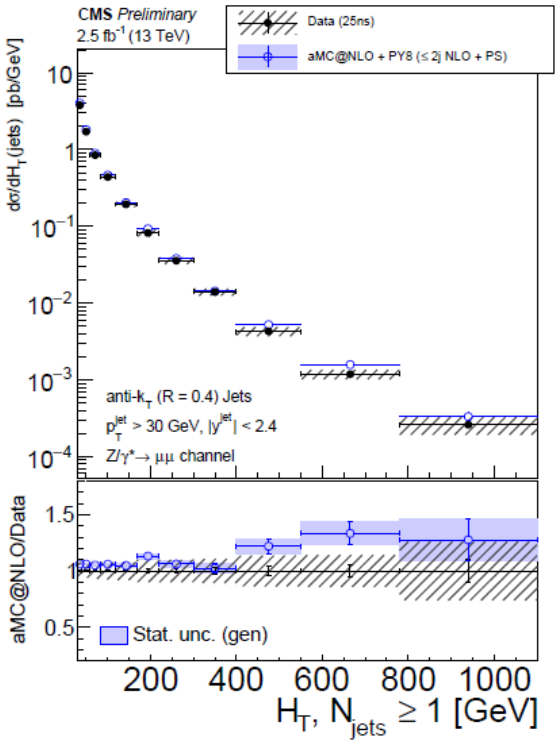
Z+jets diff. cross sections at 13 TeV

CMS-PAS-SMP-15-010

- Measurement using Z($\mu\mu$)+jets events with $p_T(\mu)$>20 GeV, $|\eta(\mu)|$<2.4 and jets with p_T(jet)>30 GeV, |y(jet)|<2.4. Require $m_{\ell\ell}$: 71-111 GeV
- Comparisons by MG5_aMC+PYTHIA 8 (NLO accuracy up to 2 additional partons merged using FxFx scheme)
- ✓ **Good data description by MG5_AMC@NLO**



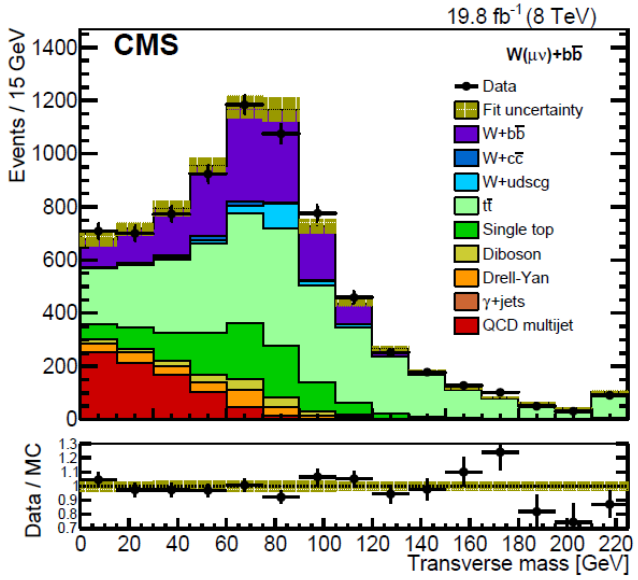




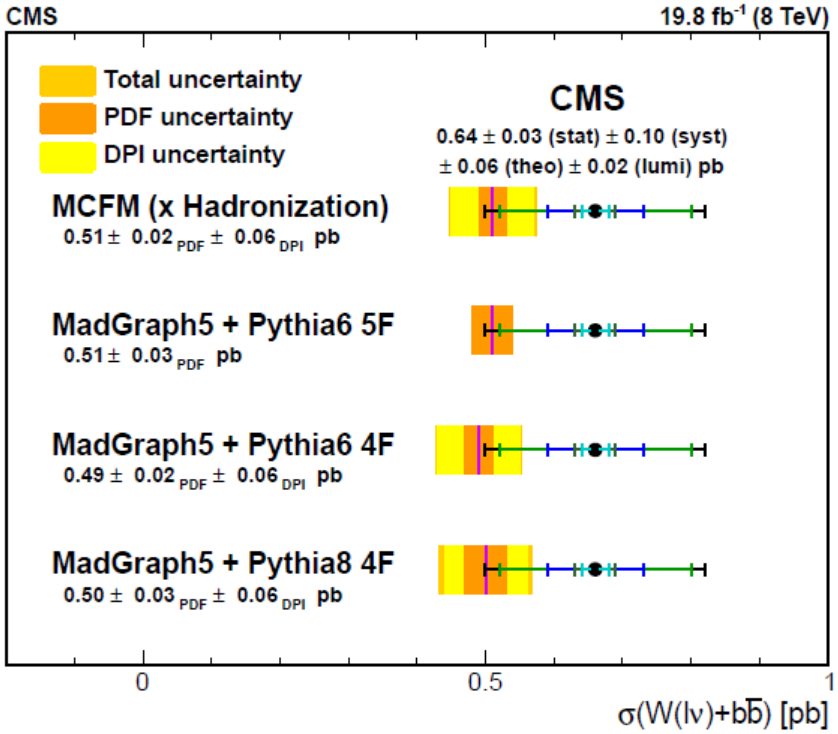
W+2b-jets at 8 TeV

EPJC 77 (2017) 92

- Measurement of the cross section for W($\ell\nu$)+2b-jets. Require isolated e or μ with $p_T(\ell)$>30 GeV, $|\eta(\ell)|$<2.1 and exactly 2 b-tagged jets with p_T(j)>30 GeV, $|\eta(j)|$<2.4
- Dominant background in W+H($b\bar{b}$) and in several BSM scenarios
- Theoretical predictions by MCFM NLO (corrected for hadronization), LO MG5+PYTHIA 6/PYTHIA 8 in 4FS/5FS approaches. MCFM and MG5+PYTHIA 6/8 using 4FS are corrected for DPI effects



✓ **The simulation is tuned to better describe the tt̄ control samples and used to extract the signal yield in the signal region**



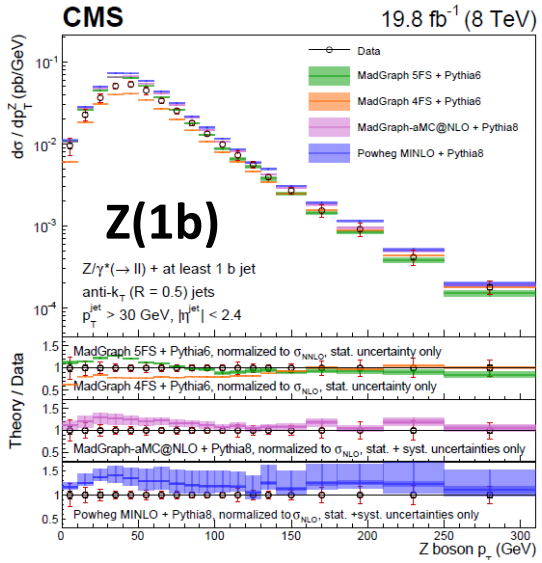
✓ **Important test of pQCD with heavy flavors: 4FS (b massive) and 5FS (b massless)**

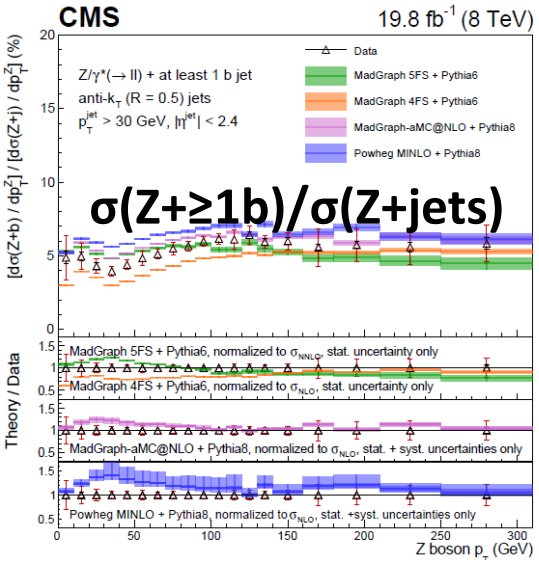
✓ **Predictions agree with each other and are consistent with CMS data within their uncertainties**

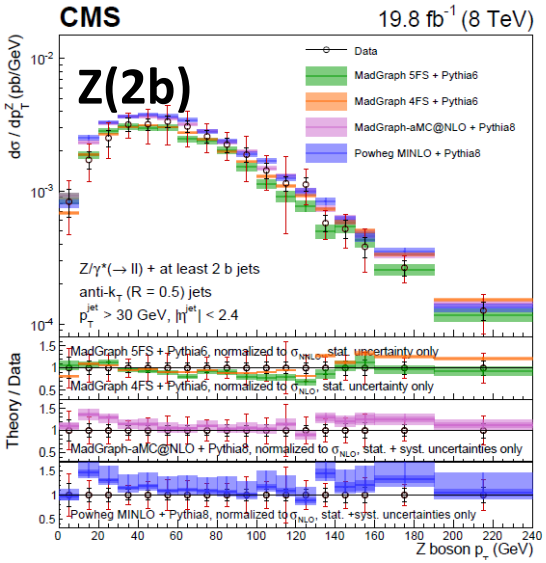
Z+b-jets at 8 TeV (more differential distributions)

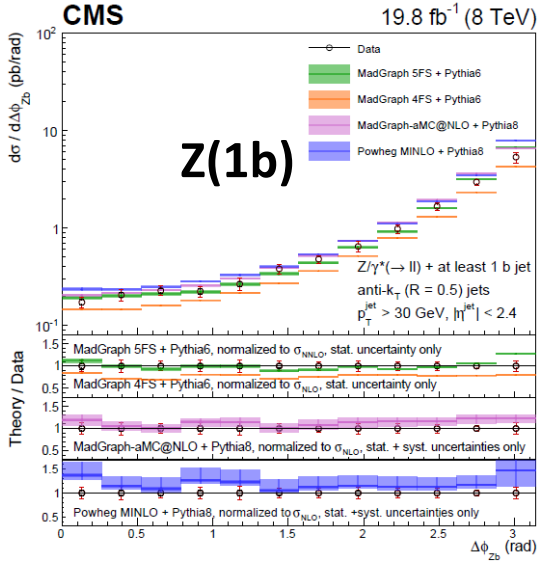
arXiv:1611.06507

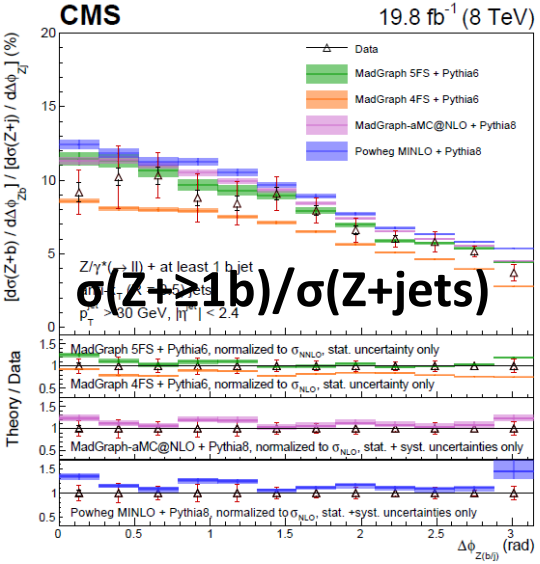
- Z bozon p_T (top), Δϕ and asymmetry variable A_{Zbb} (bottom)

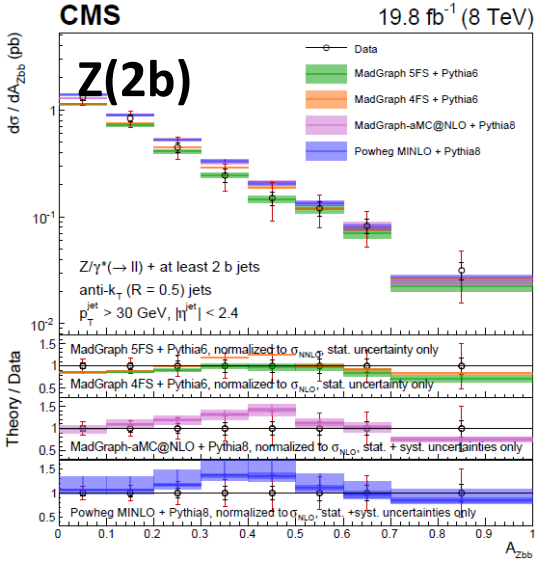








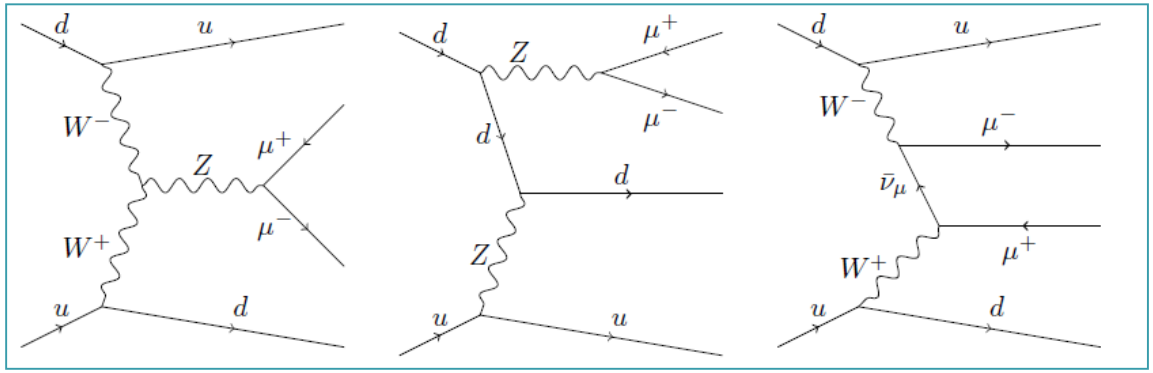




EW Z+2-jets production

- Representative Feynman diagrams for EW $\ell\ell jj$ final states

Pure EW $\ell\ell jj$ production (α_{EW}^4): VBF (left), bremsstrahlung-like (middle), and multiperipheral (right)



QCD Drell-Yan $\ell\ell jj$ production is the main background ($\alpha_{EW}^2\alpha_S^2$)