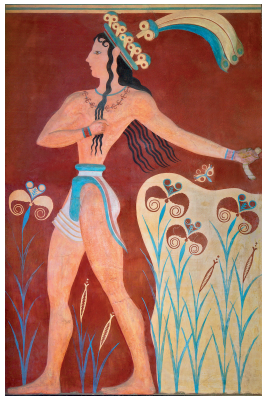

Standard Model Measurements with CMS

Norbert Neumeister

PURDUE UNIVERSITY

On behalf of the CMS Collaboration

6th International Conference on new Frontiers in Physics 2017, August 17-29, 2017, Kolymbari, Greece

Outline

- Introduction
- QCD
  - Inclusive jet cross sections
  - Di-jet cross sections
  - PDF constraints
  - Measurement of α_s
  - 2-, 3-, 4-jet azimuthal correlations
- Electroweak
  - Inclusive Z/W production
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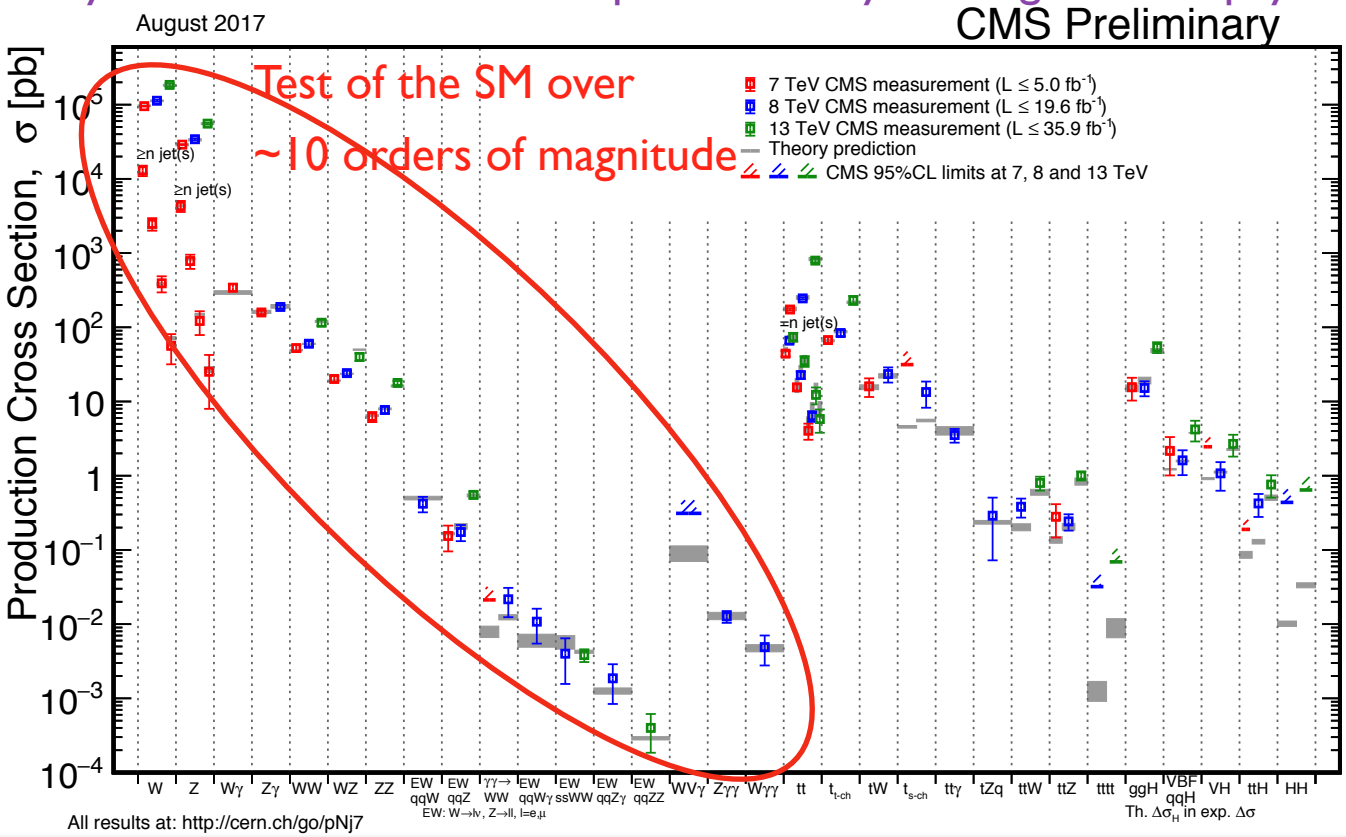
  - Differential cross sections and PDFs
  - Di-boson production
  - aTGC and aQGC
- Summary

Introduction

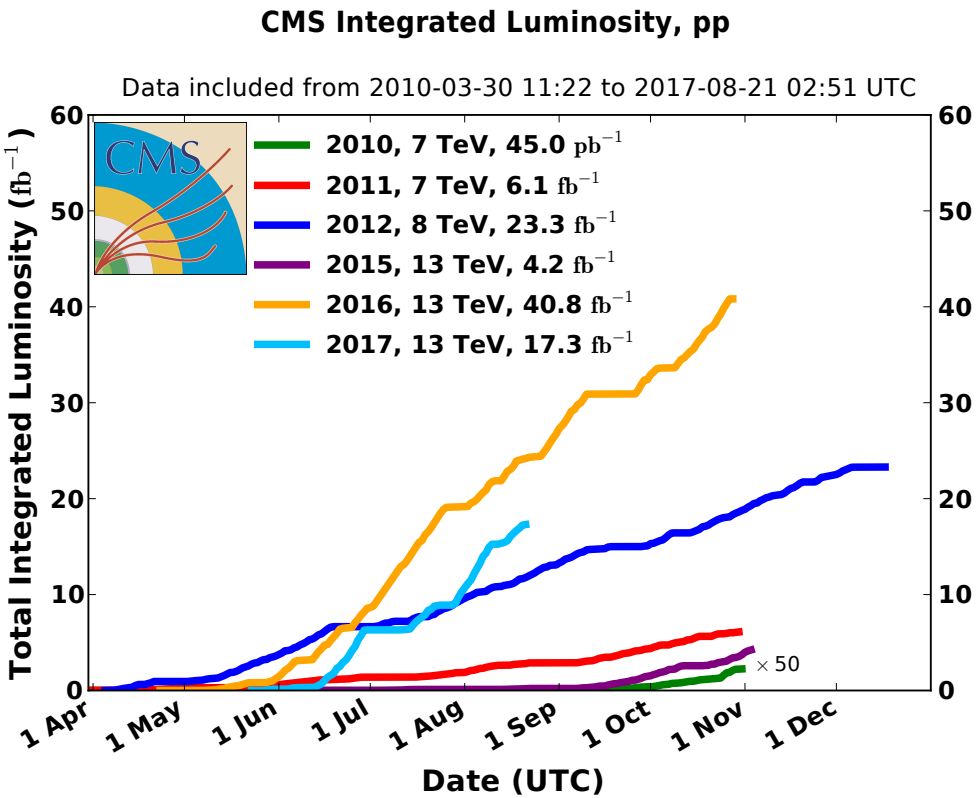
- SM precision measurements are important at the LHC
  - test a wide range of QCD and EW predictions to the highest energies available
  - tune theoretical calculations and MC generators
  - provide precise modeling of backgrounds to many searches
    - any deviation from the SM expectation may be a sign of new physics!



LHC Performance

- About 40 fb^{-1} has been delivered by the LHC in 2016, exceeding the integrated luminosity accumulated in all years before 2016 and expectations.
- The CMS detectors has been working spectacularly with virtually no degradation in performance over the 3 years of Run 1 and 2 years of Run 2.

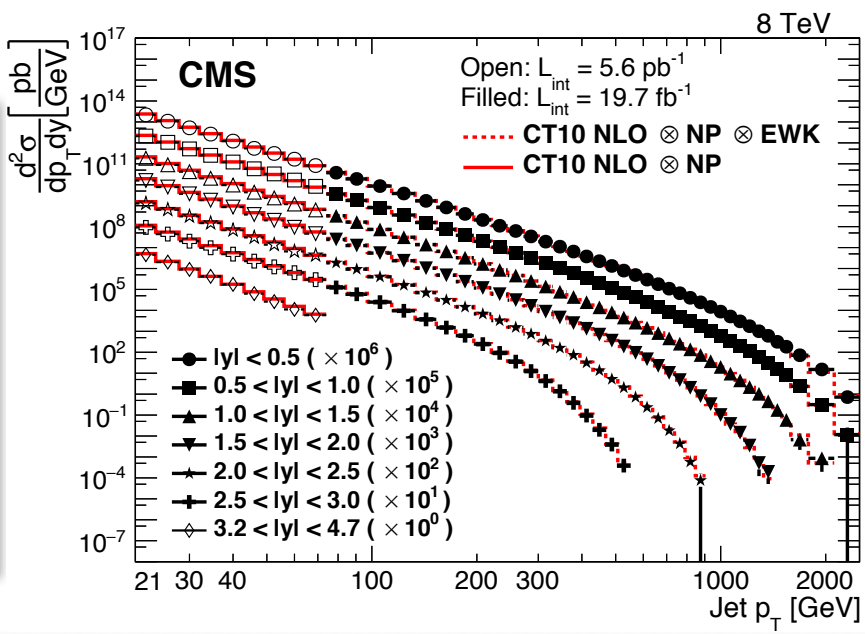
- 7 TeV: 6 fb^{-1} (2010-11)
- 8 TeV: 23 fb^{-1} (2012)
- 13 TeV: 4 fb^{-1} (2015) + 40 fb^{-1} (2016)



Inclusive Jet Production

- Double and triple-differential jet cross section measurements at 8 TeV and 13 TeV
  - Use anti-k_T clustering algorithm with R = 0.7 or 0.4 → test radiative and non-perturbative effects
  - 7 orders of magnitude, for jet p_T up to ~ 2 TeV and |y|=4.7
  - Good agreement with NLO QCD predictions + NLO EW + non-perturbative calculations

CMS-PAS-SMP-14-001
JHEP 1703 (2017) 156



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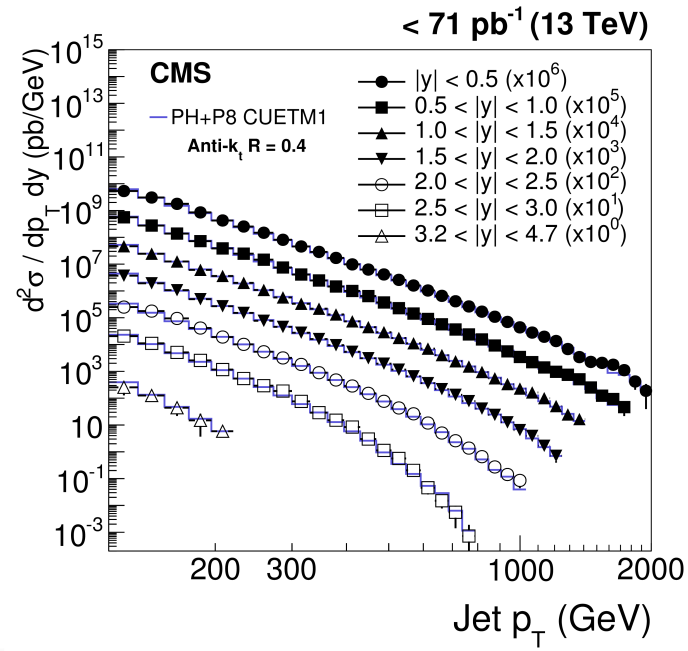
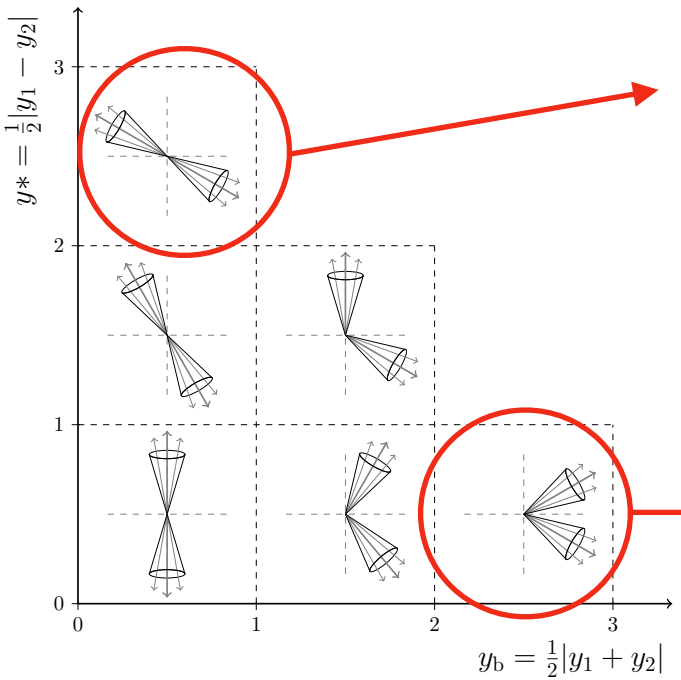
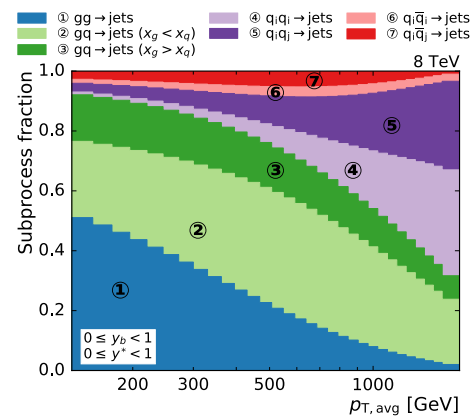


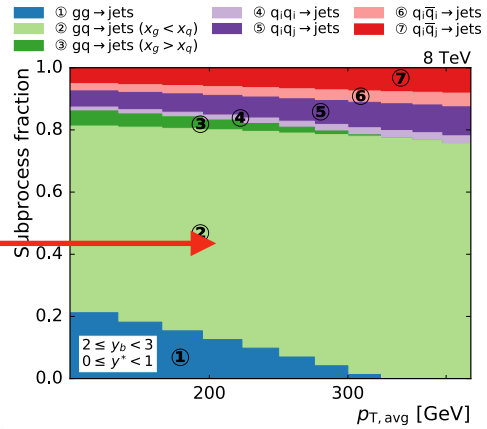
Di-Jet Production

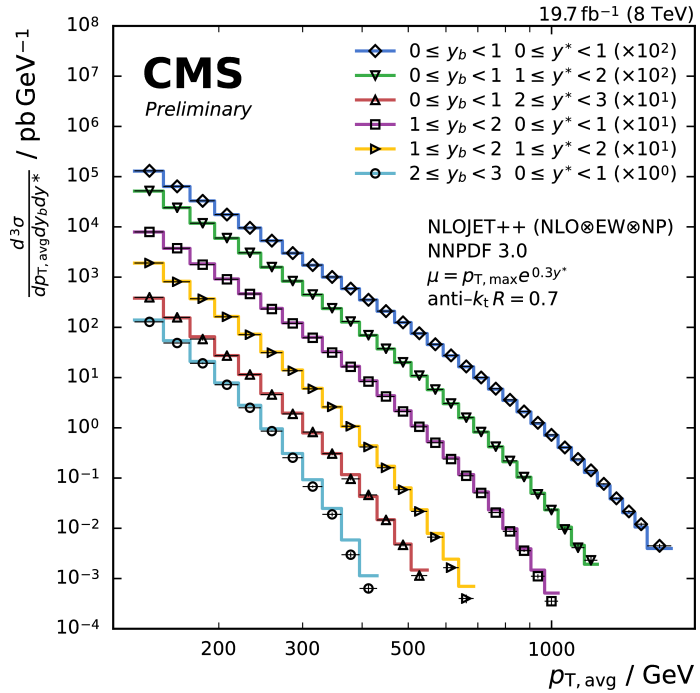
- Triple differential cross sections ($p_{T,avg}$, y^*, y_b), sensitive to different subprocesses and overlapping (x,Q) regions in PDFs
- Compared to NLOJet++ (with non-perturbative and EW effects)
  - in agreement with NLO predictions
  - used to constraint PDFs
  - used to extract α_s

CMS-PAS-SMP-16-011
arXiv:1705.02628





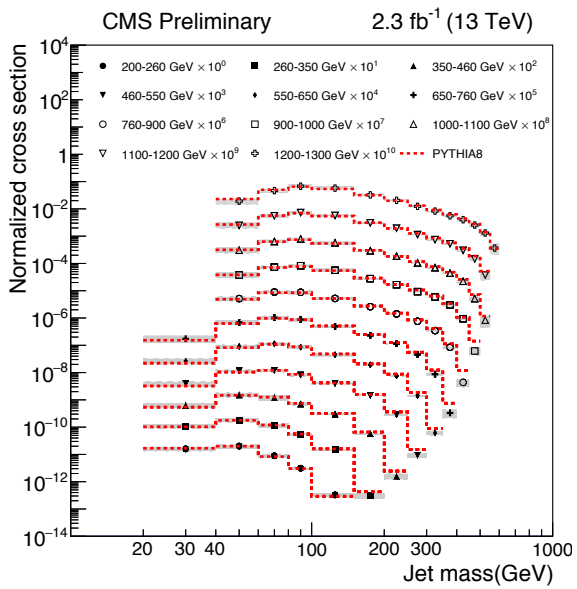


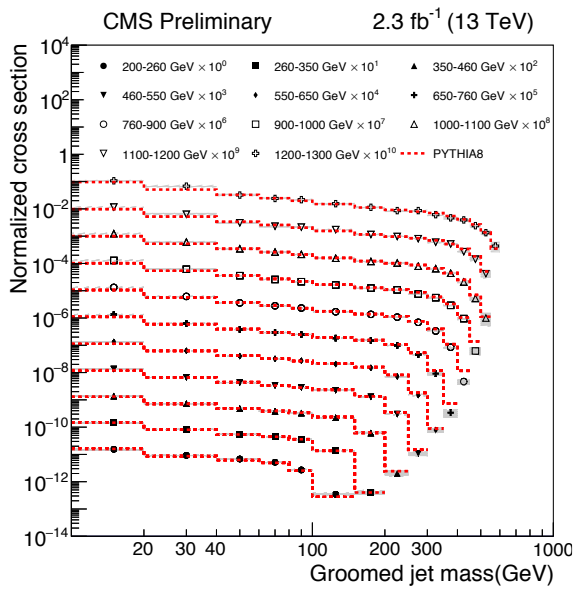


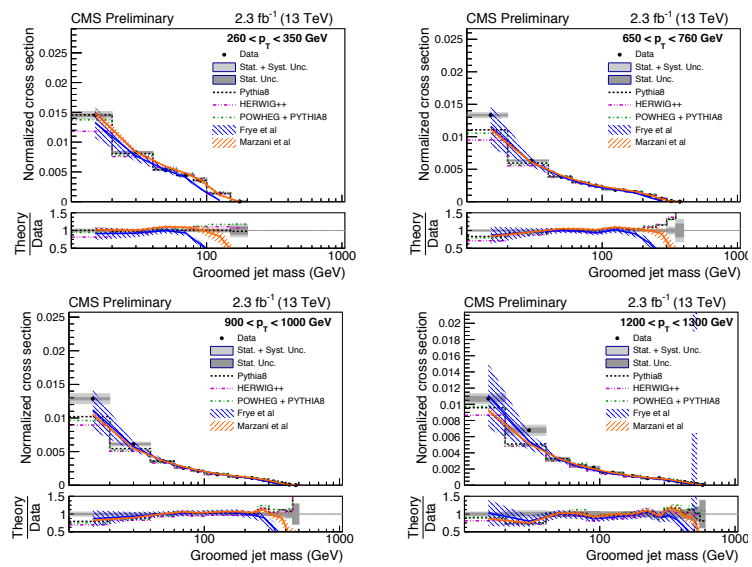
Jet Mass Measurement

CMS-PAS-SMP-16-010

- Jet mass is sensitive to internal structure of jets
- Double-differential jet cross section measured as a function of the jet mass and jet p_T in events with a dijet topology
  - with and without a jet grooming algorithm applied that removes low-energy portions from a jet.
  - for ungroomed jets, all Monte Carlo event generators are found to predict the jet mass spectrum within uncertainties in the data for intermediate masses of about 10-30% of the jet transverse momentum.







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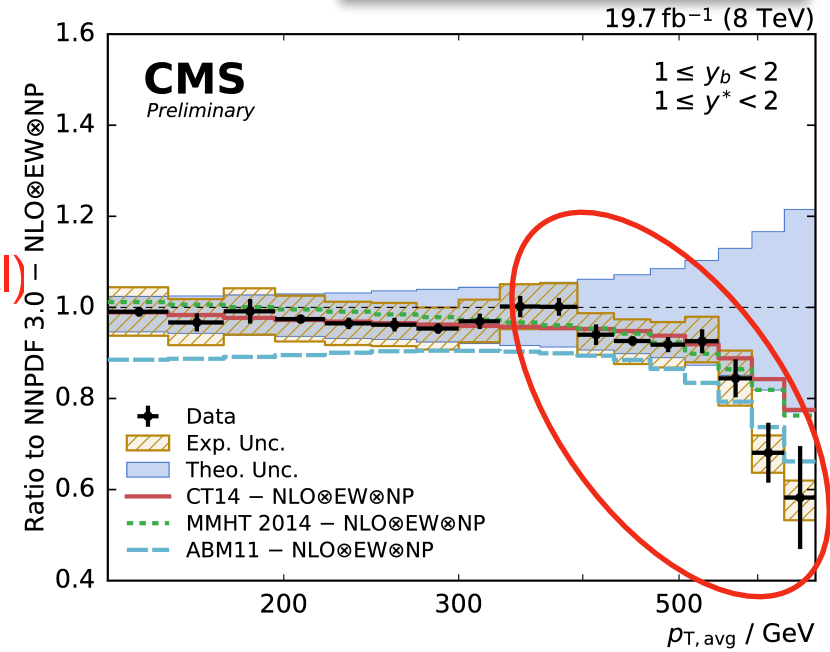
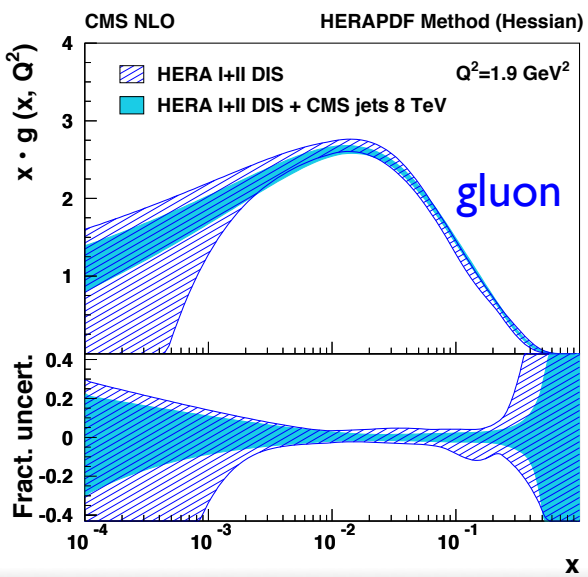
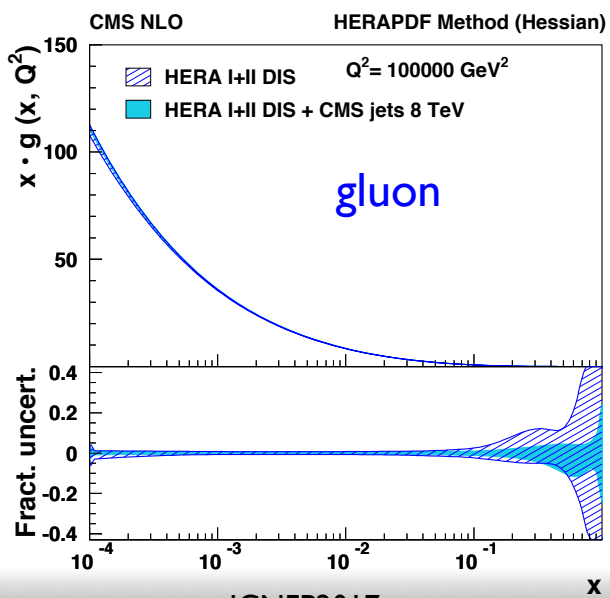
PDF Constraints

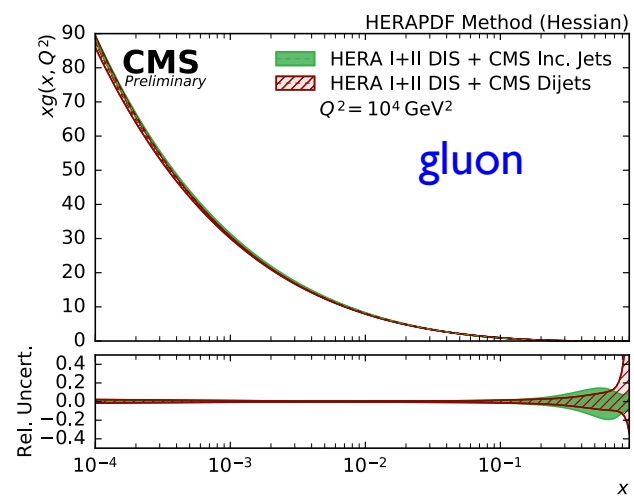
CMS-PAS-SMP-16-011
arXiv:1705.02628

- Considering high $|y_1 + y_2|$, high p_T allows access to high x values
  - Constrain PDF at high x (theory uncertainties are larger than experimental)
  - Reduces PDF uncertainties, specially the gluon PDF, in the boosted regime (high $|y_1+y_2|$, high p_T), where large x are probed
  - It also changes the gluon PDF shape for low Q^2



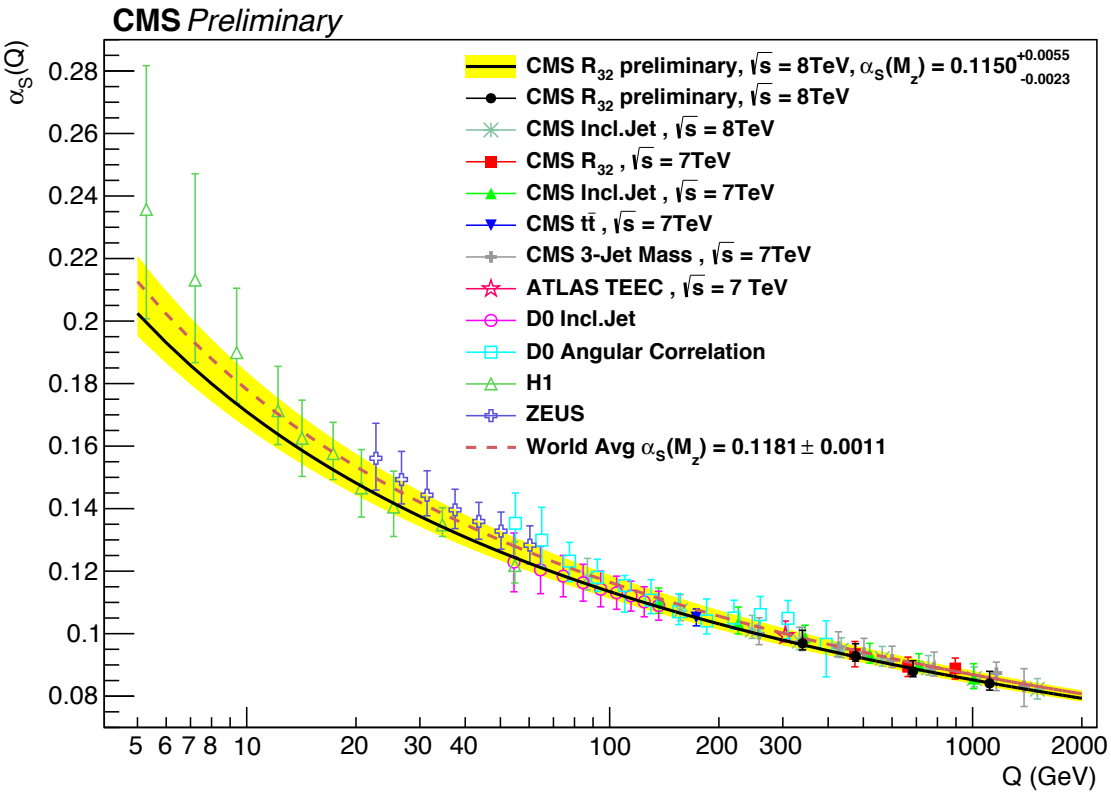


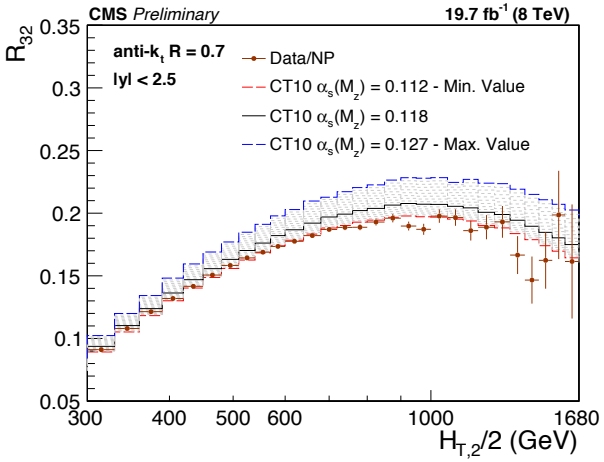




Measurement of α_s CMS-PAS-SMP-16-008

- Use ratio of inclusive two- and three-jet event cross sections (R_{32}) to extract α_s at M_Z
  - Minimize χ^2 of the fit of theoretical predictions to data





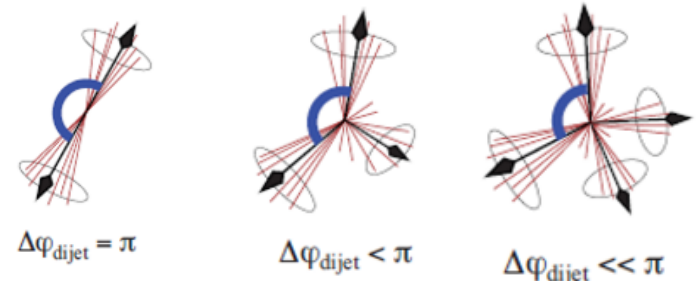
R_{32} as function of $H_T/2=1/2(p_{T1}+p_{T2})$
Compared to NLOJet++ to extract as with FastNLO framework

PDF set	2- & 3-jets $\alpha_s(M_Z)$	$\pm\Delta\alpha_s(M_Z)$	χ^2/n_{dof}	R_{32} $\alpha_s(M_Z)$	$\pm\Delta\alpha_s(M_Z)$	χ^2/n_{dof}
CT10	0.1170	0.0026	8.2/37	0.1141	0.0028	19./18
CT14	0.1161	0.0029	9.1/37	0.1139	0.0032	15./18
MSTW2008	0.1161	0.0021	11./37	0.1150	0.0023	21./18
MMHT2014	0.1168	0.0025	11./37	0.1142	0.0022	19./18
NNPDF2.3	0.1188	0.0019	15./37	0.1184	0.0021	12./18

$\alpha_s(M_Z) = 0.1150 \pm 0.0010\,(\text{exp}) \pm 0.0013\,(\text{PDF}) \pm 0.0015\,(\text{NP}) -0.0000 +0.0050\,(\text{scale})$

2-3-4-Jet Azimuthal Correlations

- Normalized differential cross-section in $\Delta\phi_{1,2}$ of the two leading p_T jets in inclusive 2-, 3-, 4- jets, and in $\Delta\phi_{2j\ min}$, the minimum azimuthal angular separation between any two jets in 3-, 4- jet topologies.
  - Sensitive to the radiation of additional jets.
  - Probes the dynamics of multijet production.
  - Results compared to LO and NLO MC generators with various PS tunes.



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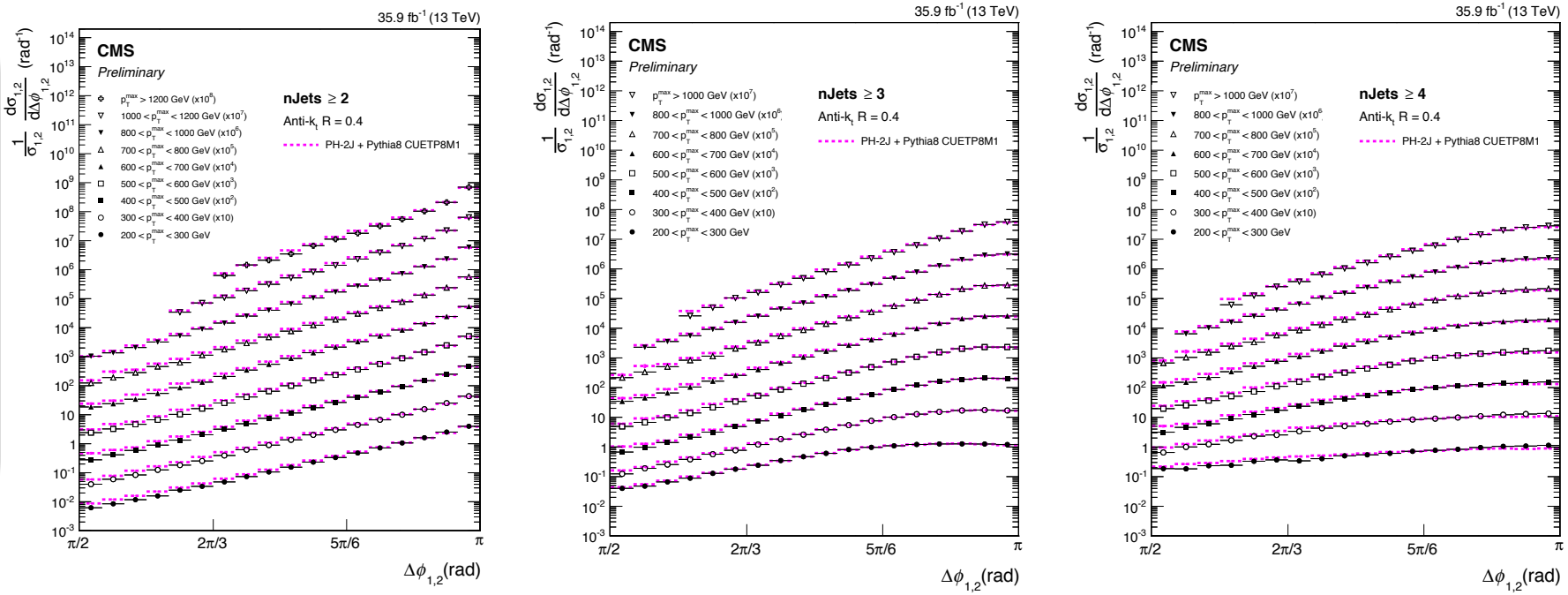
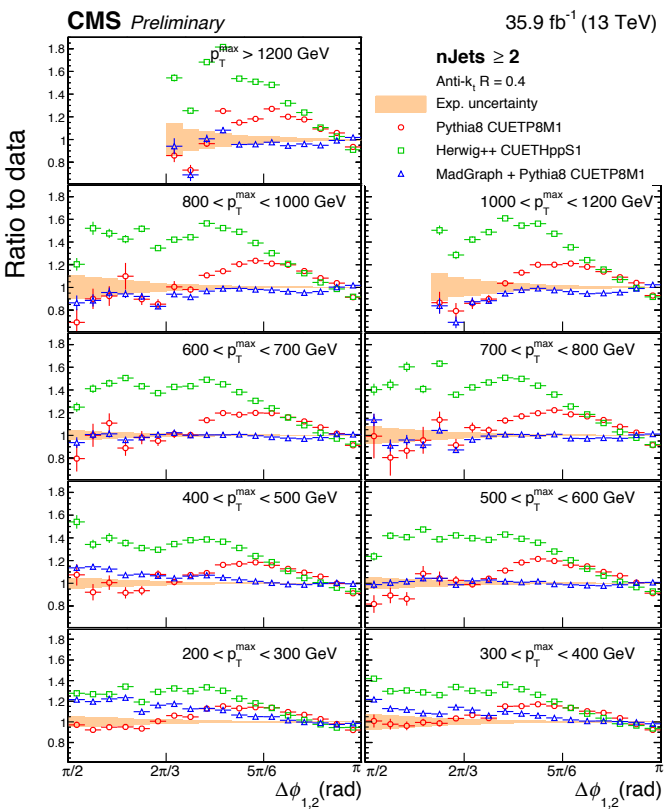


2-3-4-Jet Azimuthal Correlations

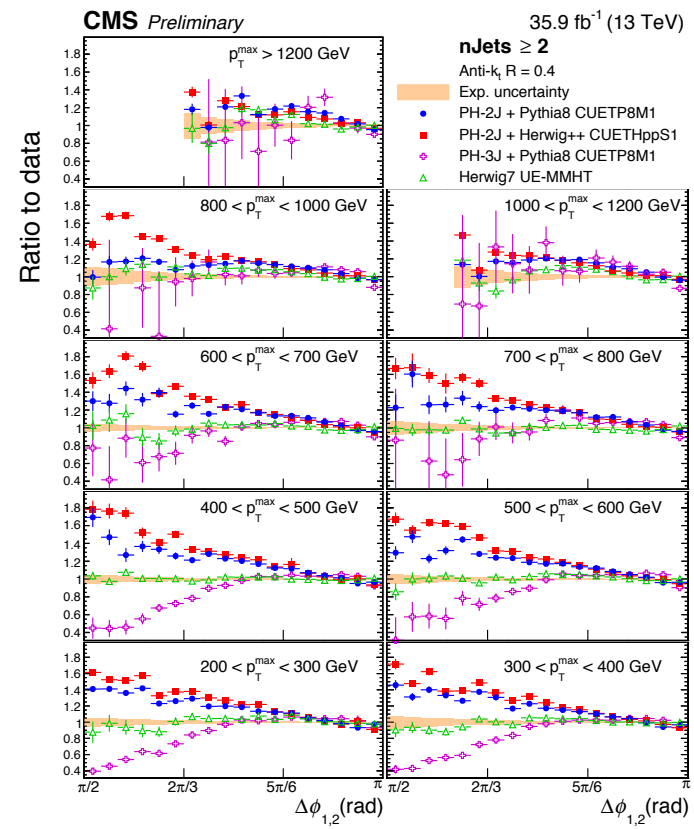
- Improved description from NLO
- Herwig7 describes the $\Delta\phi_{1,2}$ cross sections best, while PH2J (POWHEG matched to Herwig++ or Pythia8) describes the $\Delta\phi_{2j}^{min}$ data best

CMS-PAS-SMP-16-014



LO

NLO



Inclusive W/Z Production

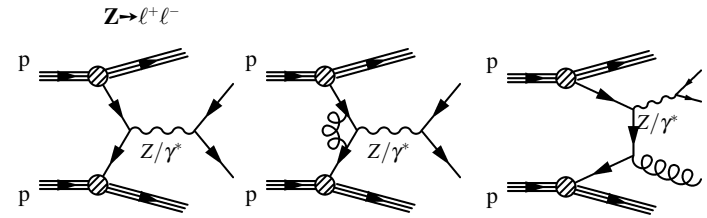
- W and Z decays are special final states:
  - They are theoretically well understood, unique signatures and have high rate
  - Experimentally the $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ channels are among the cleanest final states that we can exploit at hadron colliders
  - They are used to understand and calibrate the detector response (trigger, identification, resolution, efficiencies)
  - They are dominant signal and/or background in many searches for new particles
- Constraints for Parton Distribution Functions
  - Key ingredient to make theoretical predictions at hadron colliders
  - LHC probes gluons and sea quarks
- With W/Z we can probe different aspects of QCD calculations
  - Tests of perturbative QCD and parton emission in a new energy regime
  - Tune Monte Carlo generators in order to better describe the data

Inclusive W/Z Production

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

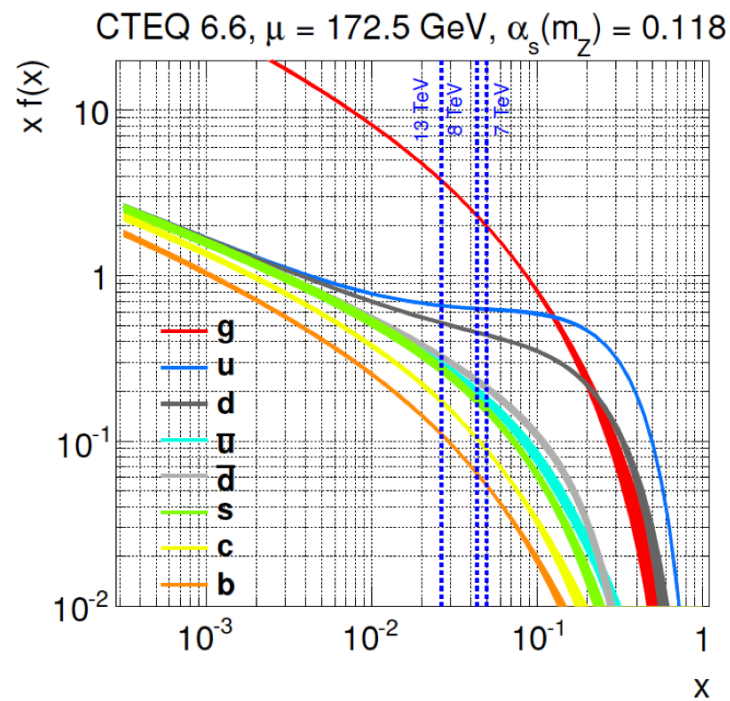
$$u + \bar{d}(\bar{s}) \rightarrow W^{+} \qquad u + \bar{u} \rightarrow Z$$

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



LO (Drell-Yan) + NLO

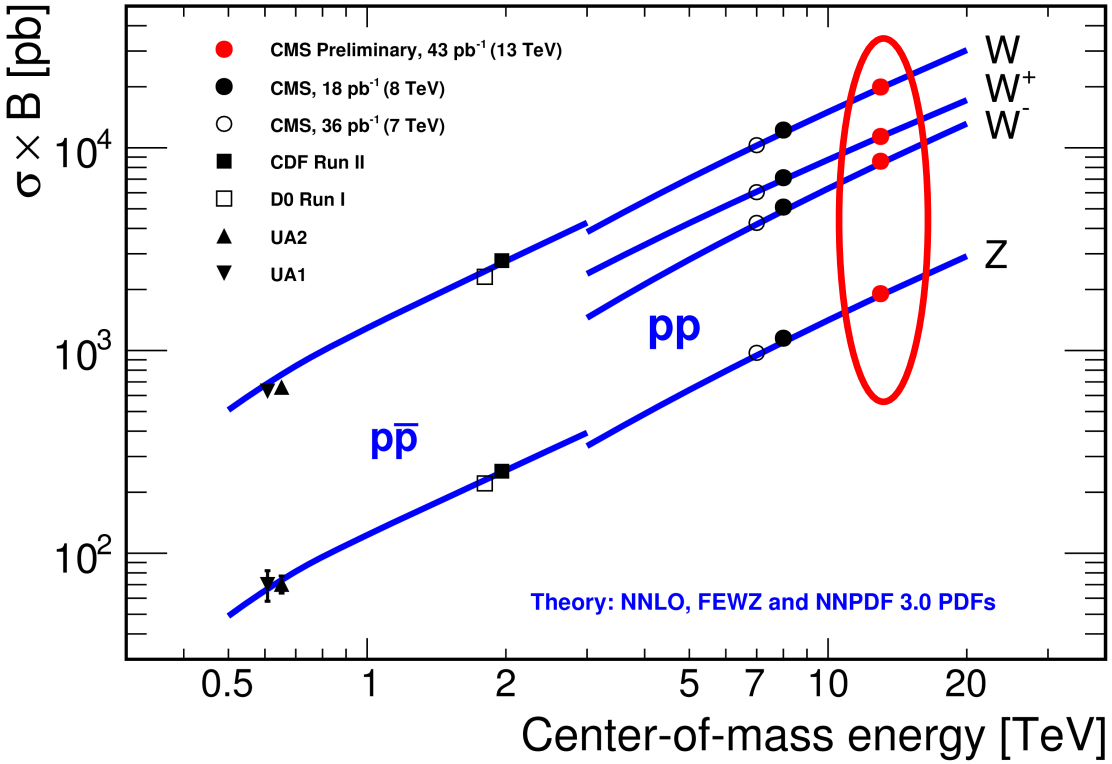
- Since parton fractions in this process are typically $10^{-3} < x < 10^{-1}$, sea-sea qq contributions are also important
- Provide access to central parameters for global EWK fit (masses, couplings, asymmetries)
- Provide powerful constraints for non-perturbative part (PDFs, tunes)



W and Z Production

- Inclusive W and Z cross section measurements at 7, 8, and 13 TeV
  - Good agreement with NNLO
- Building blocks for a number of physics analyses
  - V+b/c, differential cross sections and many others

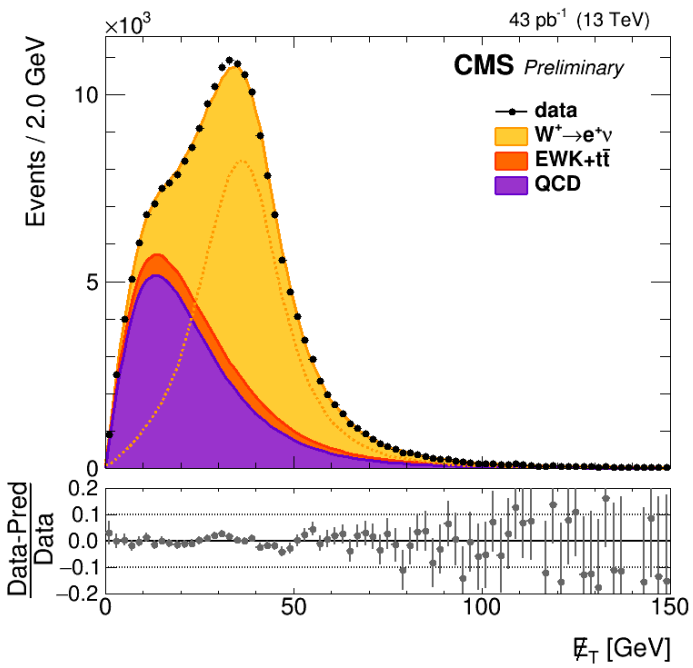
CMS-PAS-SMP-15-004
arXiv:1612.03016

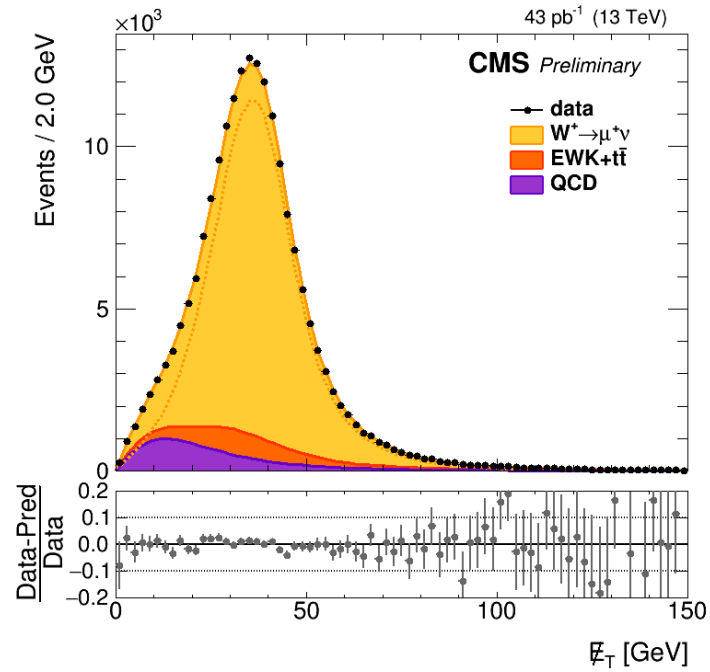


Inclusive W Cross Section

- Inclusive W/Z cross sections are measured at $\sqrt{s}$ = 13 TeV, $\int L$ = 43 pb^{-1}
- Electron (E_T>25 GeV, |η|<2.5) and muon (p_T>25 GeV, |η|<2.4) used
- MET fit is used for W^+ and W^- signal extraction, respectively
  - Main background is QCD
  - $W \to \tau\nu$, Drell-Yan, diboson and top-pair production

CMS-PAS-SMP-15-004
arXiv:1612.03016





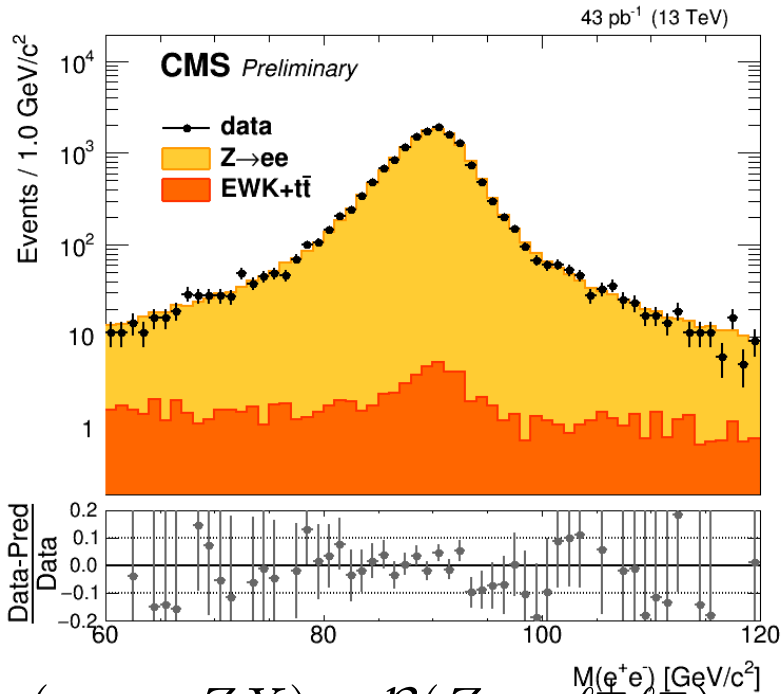
$$\sigma(pp \to W^+X) \times \mathcal{B}(W^+ \to \ell^+\nu) = 11370 \pm 50(\text{stat}) \pm 230(\text{syst}) \pm 550(\text{lumi})\ \text{pb}$$

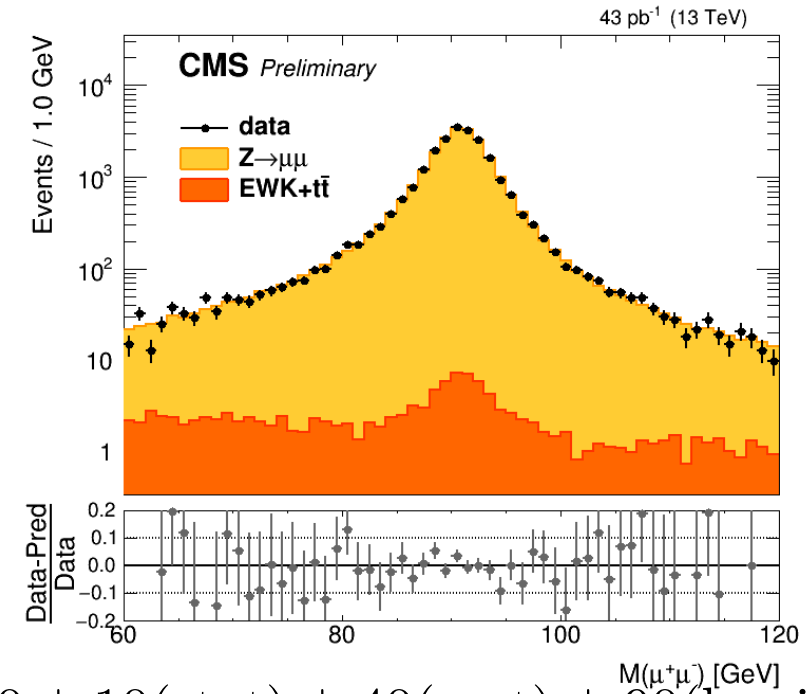
$$\sigma(pp \to W^-X) \times \mathcal{B}(W^- \to \ell^-\bar{\nu}) = 8580 \pm 50(\text{stat}) \pm 160(\text{syst}) \pm 410(\text{lumi})\ \text{pb}$$

Inclusive Z Cross Section

- Z signal extraction is estimated using counting method in 60<M(Z)<120 GeV
- Almost background free
- Both total and fiducial cross sections

CMS-PAS-SMP-15-004
arXiv:1612.03016





$$\sigma(pp \to ZX) \times \mathcal{B}(Z \to \ell^+\ell^-) = 1910 \pm 10(\text{stat}) \pm 40(\text{syst}) \pm 90(\text{lumi})\ \text{pb}$$

CMS-PAS-SMP-15-011

- Updated result Z →μμ with full dataset and new luminosity:

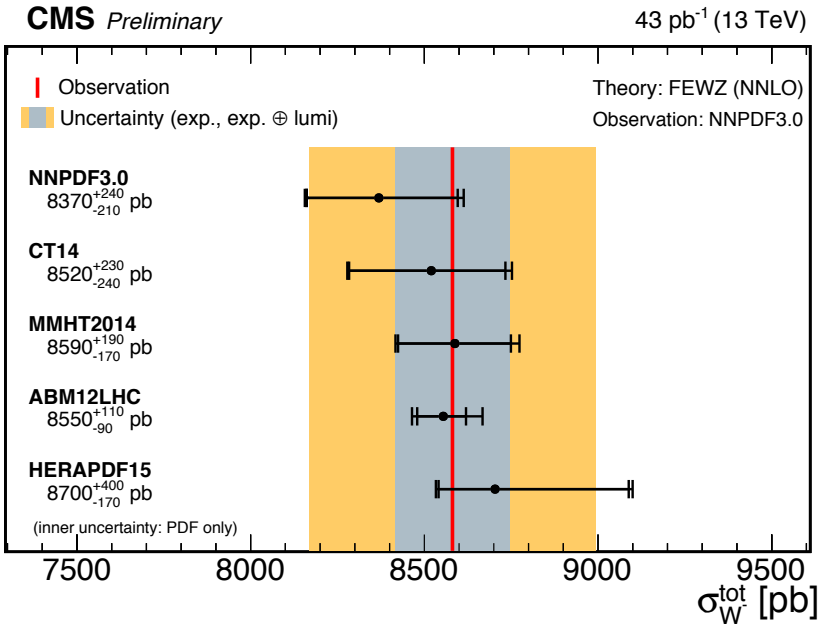
$$\sigma(pp \to ZX) \times \mathcal{B}(Z \to \mu^+\mu^-) = 1870 \pm 2(\text{stat}) \pm 35(\text{syst}) \pm 51(\text{lumi})\ \text{pb}$$

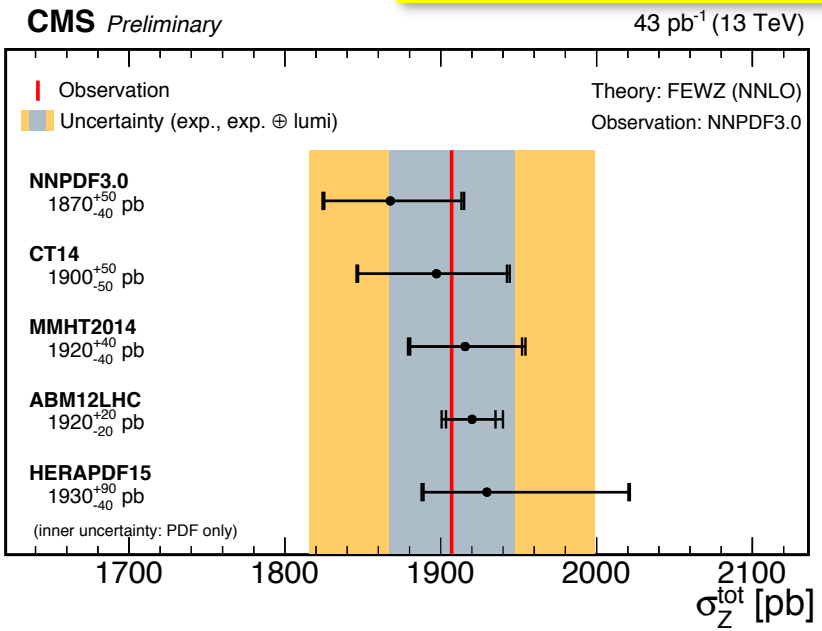
FEWZ (NNLO, NNPDF3.0) = 1870 ± 50 pb

Inclusive W/Z Cross Section

- Measured cross sections agree with next-to-next-to-leading order QCD and next-to-leading order EW calculations.

CMS-PAS-SMP-15-004



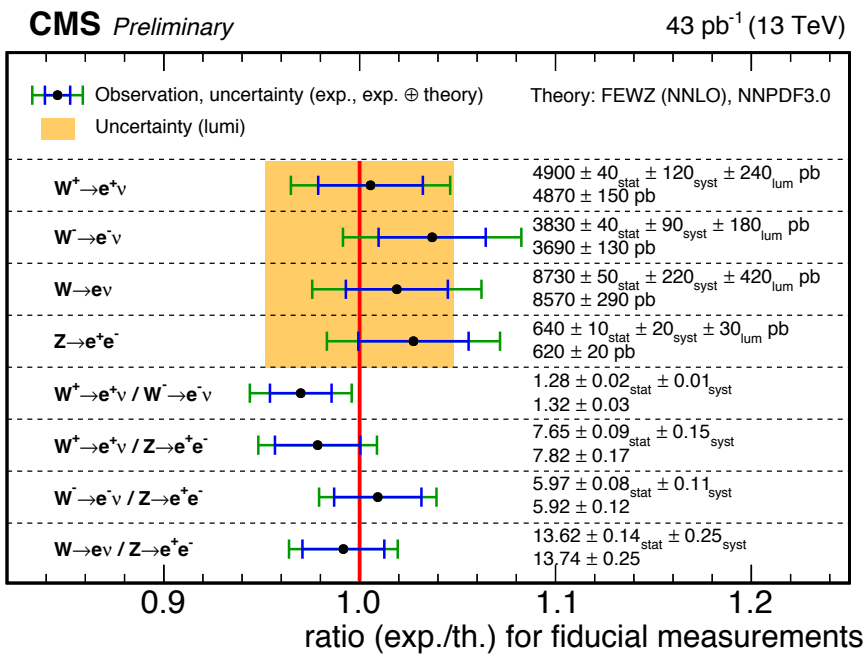


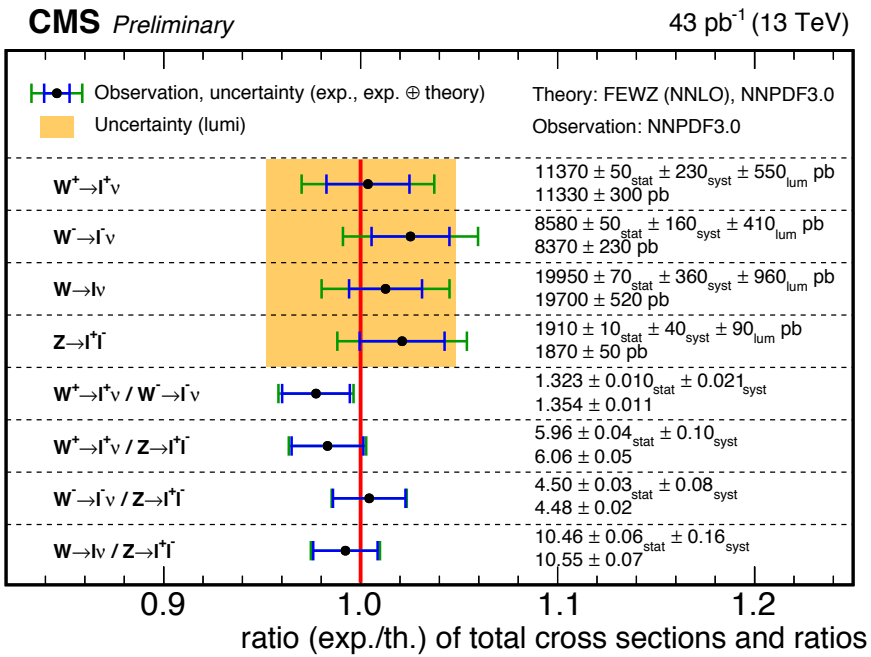
- Predictions of cross sections calculated for 5 PDF sets:
  - PDFs show differences depending on which data are used in the fit
- Systematic uncertainties:
  - Dominant uncertainty: luminosity (significantly reduced with full statistics)

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

Inclusive W & Z Production

CMS-PAS-SMP-15-004



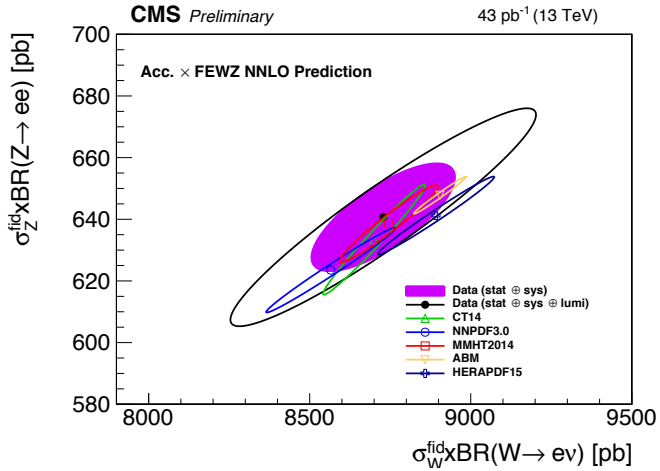


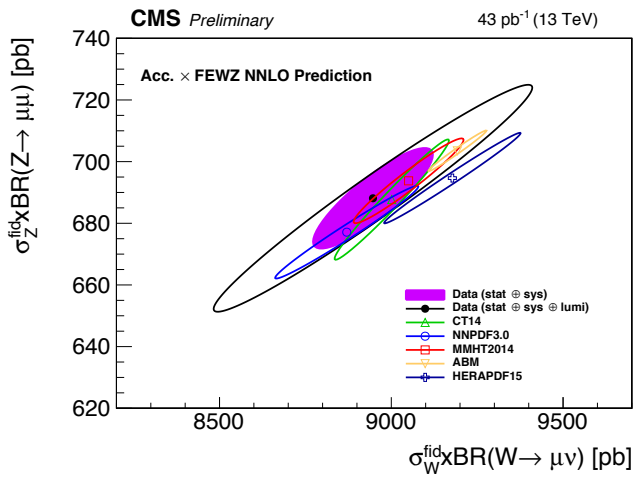
- The experimental precision is already comparable with theoretical uncertainties
  - With current statistics can challenge state-of-the-art theoretical predictions: <1% scale variation at NNLO
- Measure the W/Z, W^+/W^- ratios test pQCD
- Good overall agreement with theory predictions at NNLO

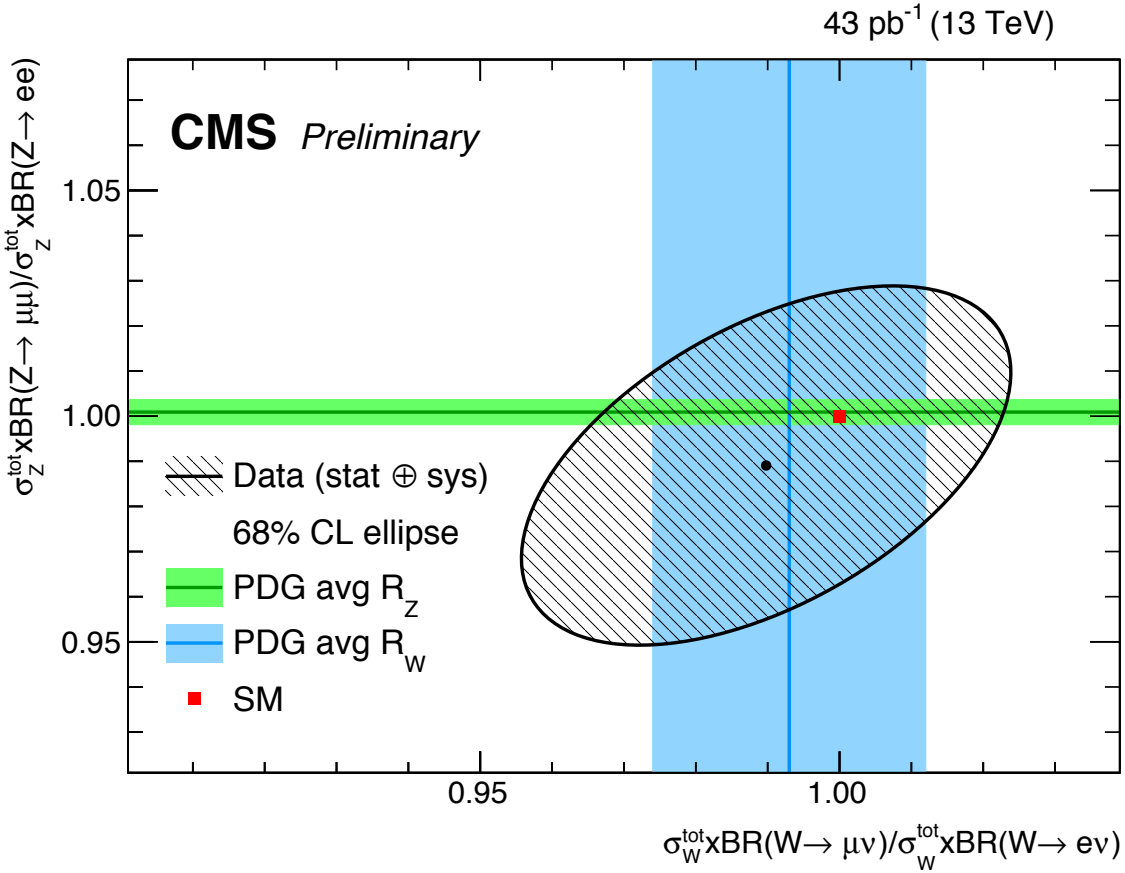
Lepton Universality

CMS-PAS-SMP-15-004

- Ratio of electron- and muon channel $W^{\pm}$ and Z boson production fiducial cross sections
- R_Z fully dominated by LEP result 0.9991 ± 0.0024



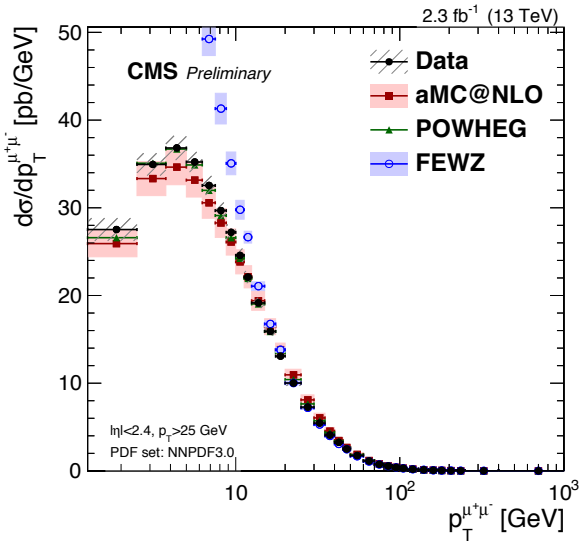


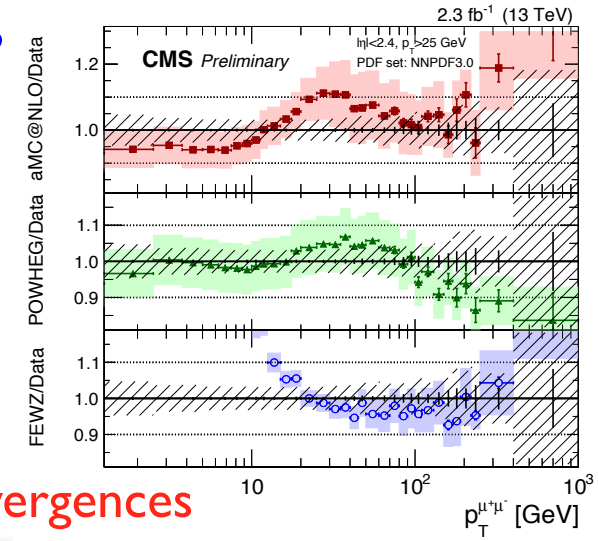


Differential Z Cross Section

CMS-PAS-SMP-15-011

- Differential $Z \rightarrow \mu\mu$ cross sections measured at $\sqrt{s}$ = 13 TeV, $\int L = 2.3\ fb^{-1}$ (full 2015 dataset)
- Differential cross sections as function of: $p_T(Z)$, $y(Z)$, $p_T(\text{lepton})$, ϕ^*
- **Low p_T:** governed by initial-state radiation and intrinsic p_T of initial-state parton inside proton
  - Modeled using soft gluon resummation or parton shower models
- **High p_T:** dominated by quark-gluon scattering, described by perturbative QCD
- Comparison with aMC@NLO, POWHEG (NLO) and FEWZ (NNLO)
  - FEWZ gives good agreement for p_T > 25 GeV
  - POWHEG and aMC@NLO show small deviations
  - Soft gluon resummation is needed to overcome divergences

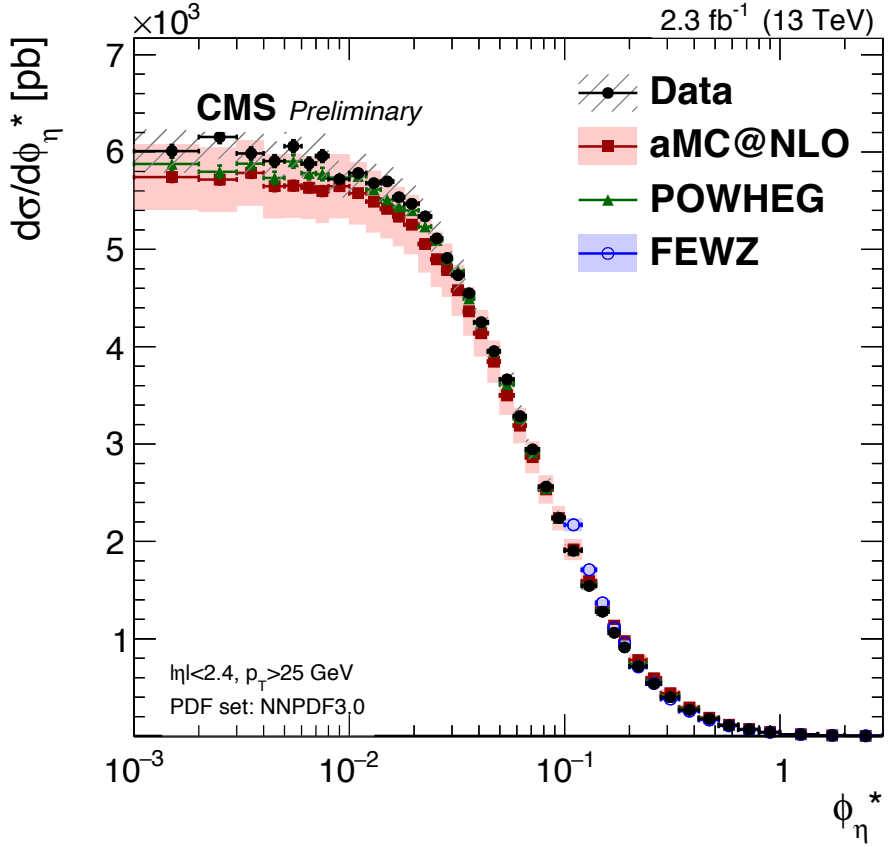


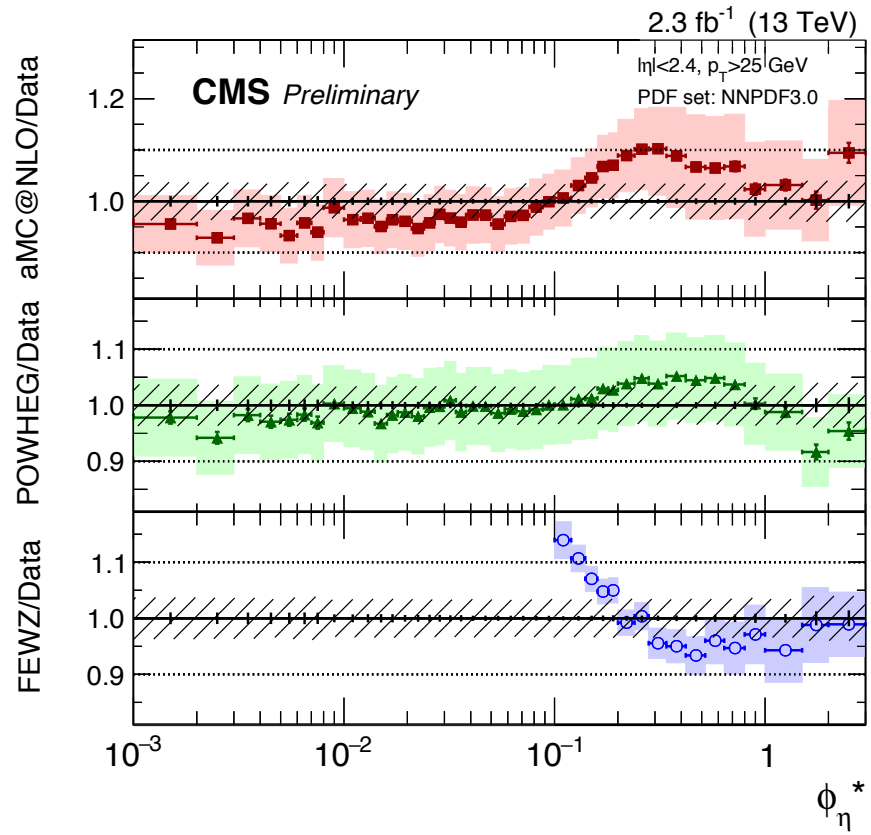


dσ/dϕ*

CMS-PAS-SMP-15-011

- Define $\phi^*_\eta = \tan(\frac{\pi - \Delta\phi}{2}) \cdot \sin(\theta^*_\eta)$ where $\cos(\theta^*_\eta) = \tanh(\frac{\eta^- - \eta^+}{2})$
- Probes Z boson P_T, but depends on direction of muon → smaller exp. uncertainty
- POWHEG shows good agreement in very low ϕ^* region

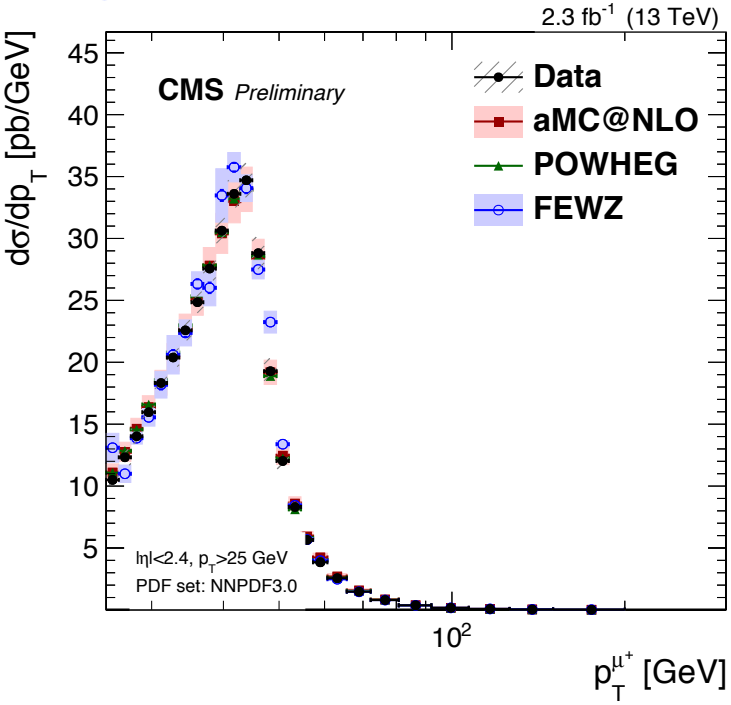


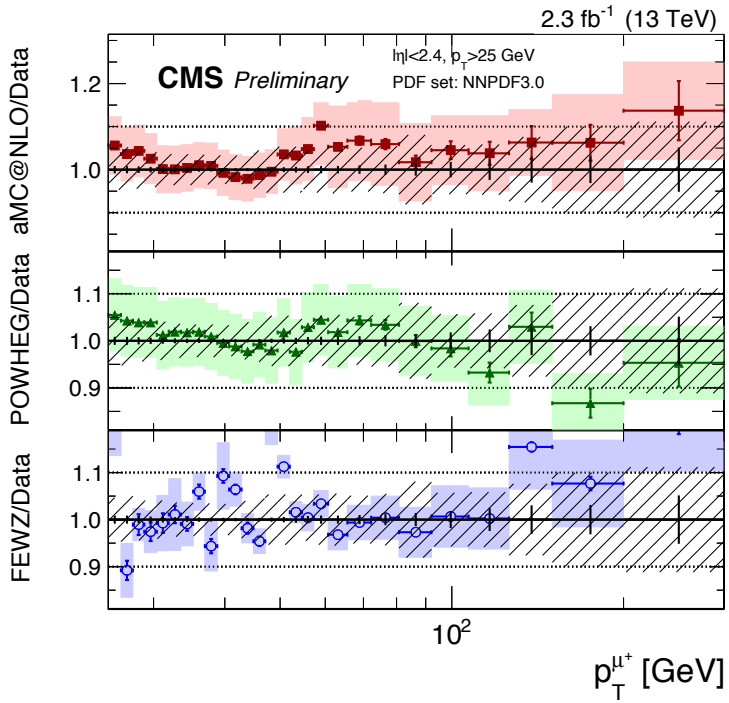


$d\sigma/dp_T^{\mu}$

CMS-PAS-SMP-15-011

- p_T distribution of Z boson
  - Muons with $p_T > 25$ GeV and $|\eta| < 2.4$
  - Relative isolation in a cone of radius $\Delta R = 0.4$ with an isolation selection requirement of less than 15%
  - 60 GeV < M_Z < 120 GeV
- No generator is able to describe the data in all of the studied phase-space

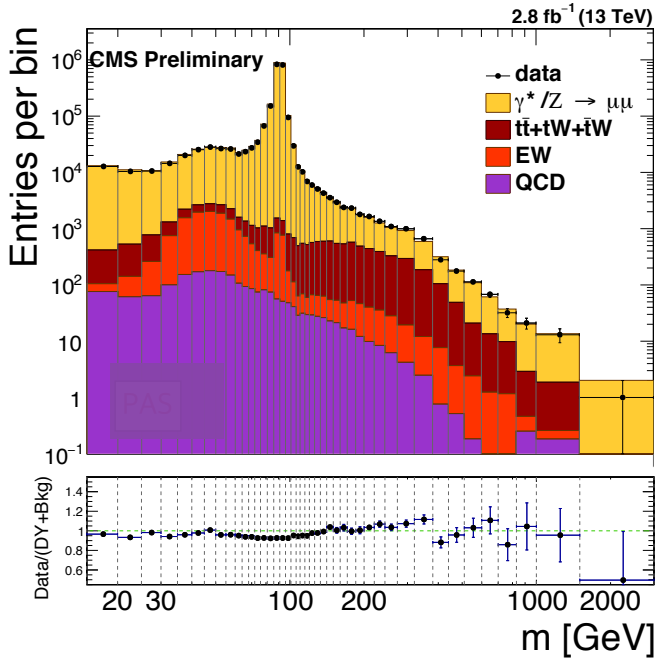


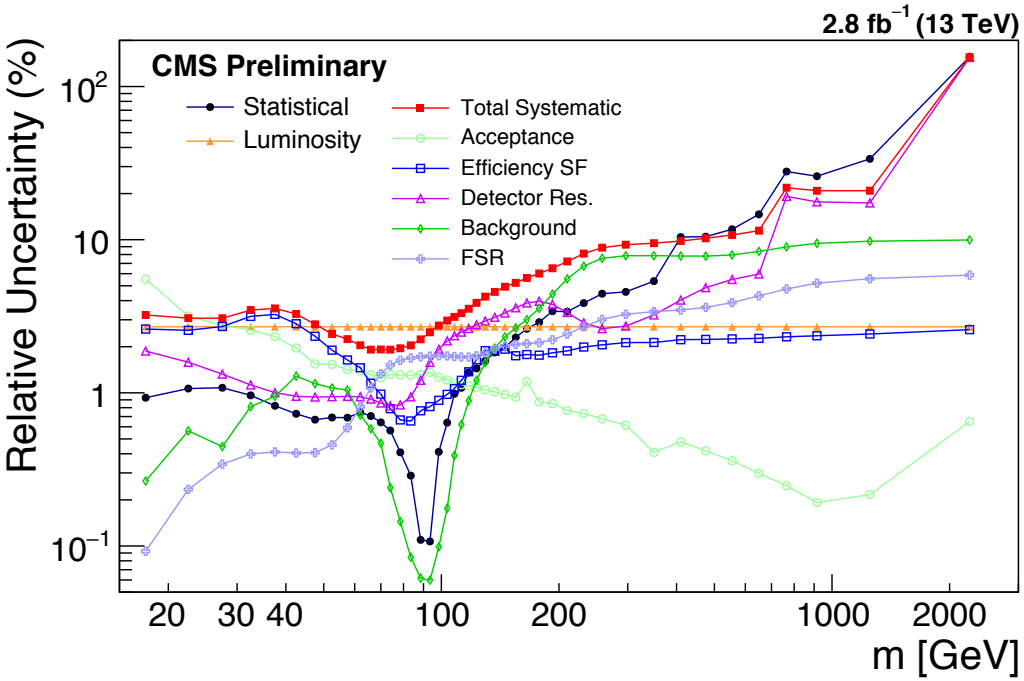


Drell-Yan dσ/dm

CMS-PAS-SMP-16-009

- Differential Drell-Yan cross section measured at $\sqrt{s}$ = 13 TeV with $\int L$ = 2.8 fb^{-1} of data
- Only μμ final states; Muons with p_T > 22 (10) GeV and |η| < 2.4
- dσ/dm in range 15 < M < 3000 GeV (43 bins)
- Apply all corrections to get FSR-corrected results in full acceptance
- Data-driven background estimation for $t\bar{t}$, tW, ττ, W+jets, QCD djets



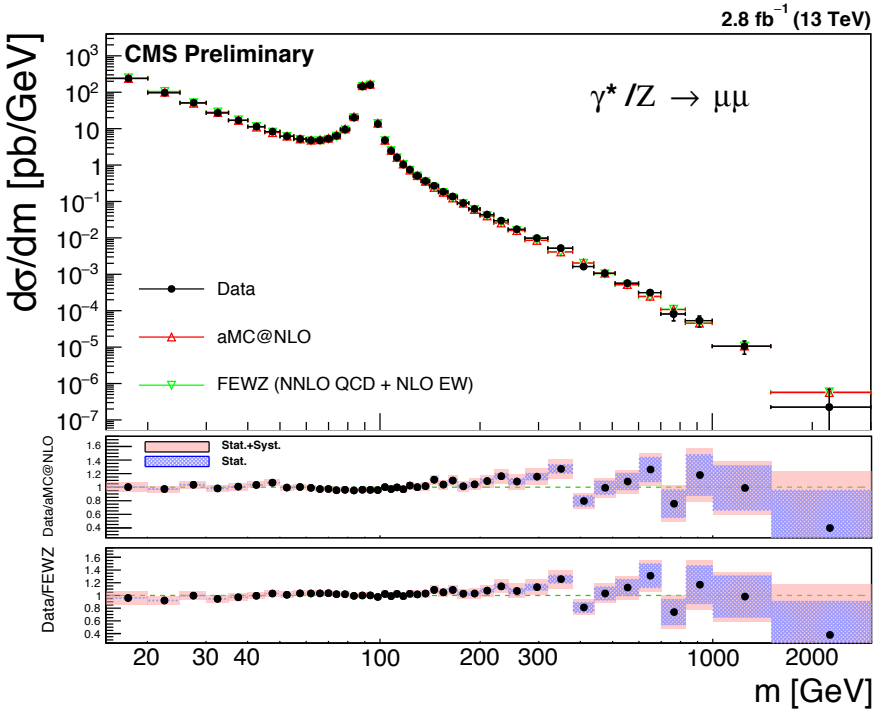


Drell-Yan dσ/dm

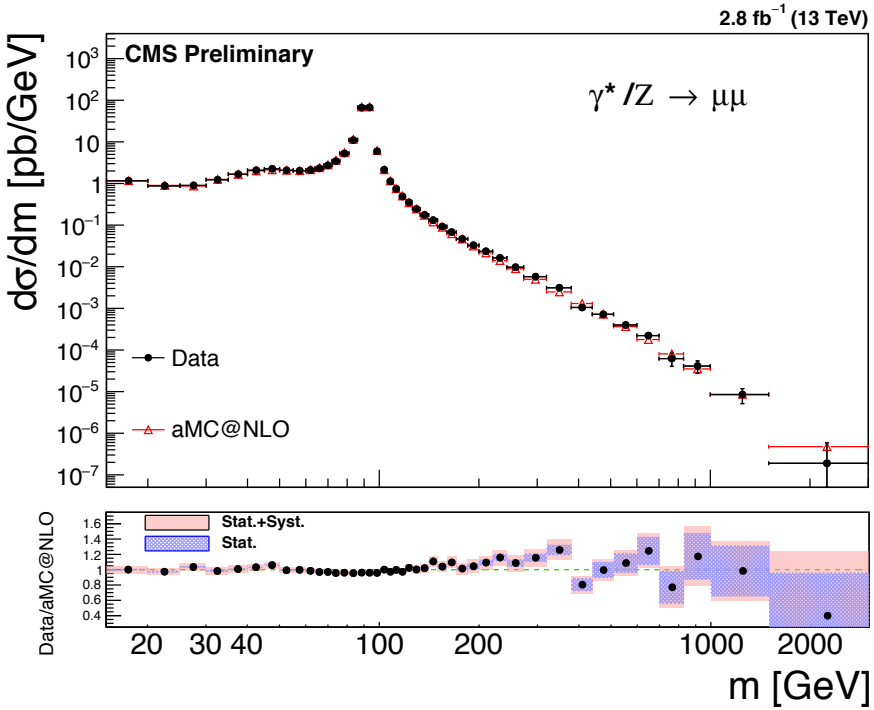
CMS-PAS-SMP-16-009

- Measured differential cross section compared with aMC@NLO and FEWZ predictions
  - FEWZ prediction is NNLO theoretical values calculated with NNPDF3.0 PDF
  - Generally good agreement with the prediction within uncertainties

pre-FSR, full phase space



post-FSR, detector acceptance



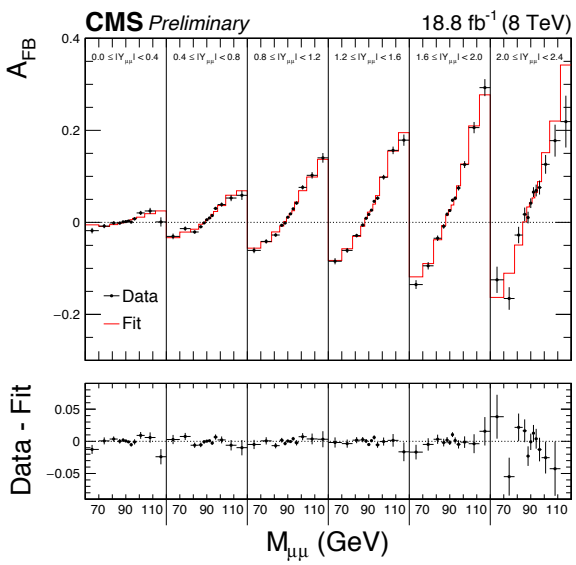
Electroweak Mixing Angle

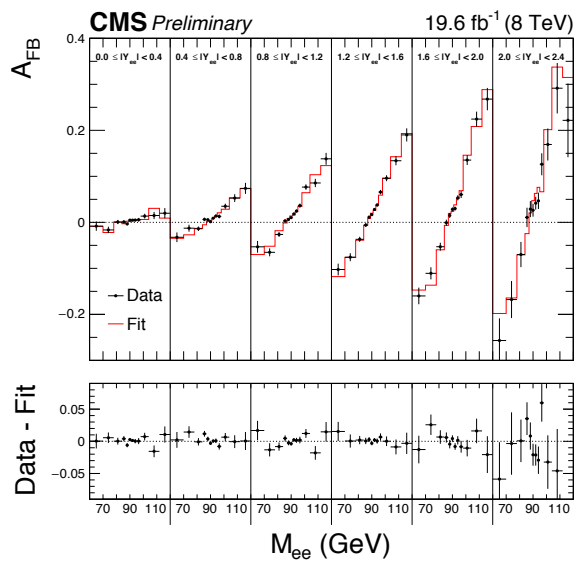
- Forward-backward asymmetry near Z peak is sensitive to leptonic $\sin^2\theta_{eff}$

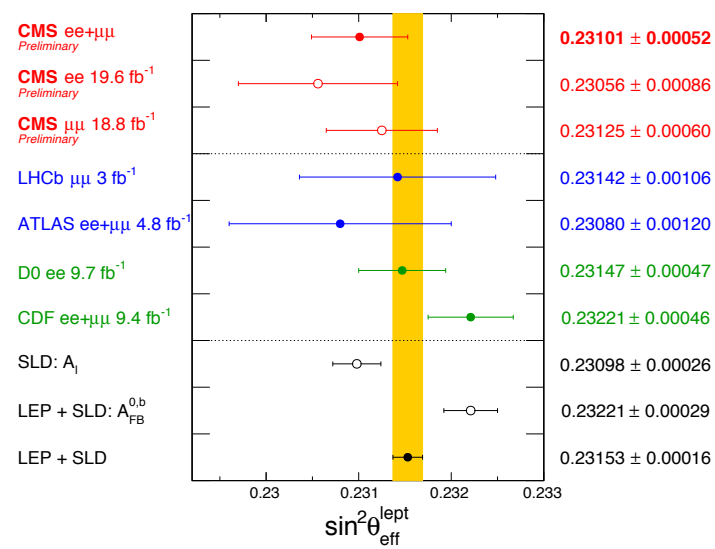
CMS-PAS-SMP-16-007

- Use combined ee and μμ data samples
- Fit A_{FB} distribution in 12 bins of m and 6 bins in |y| with different $\sin^2\theta_{eff}$ templates

$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00036({\rm stat}) \pm 0.00018({\rm syst}) \pm 0.00016({\rm theory}) \pm 0.00030({\rm pdf})$$
$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00052.$$





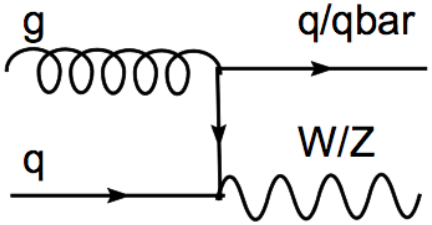


W/Z + Jets

- W/Z + jet production is sensitive to gluon content of the proton:

$$u + g \rightarrow W^{+} + q - jet$$

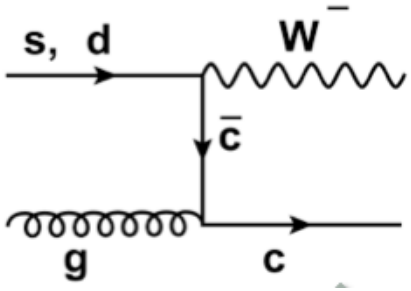
$$d + g \rightarrow W^{-} + q - jet$$



- When associated to specific jet flavors, there is sensitivity to other PDFs too:

$$s + g \rightarrow W^{-} + c$$

$$b + g \rightarrow Z^{0} + b$$



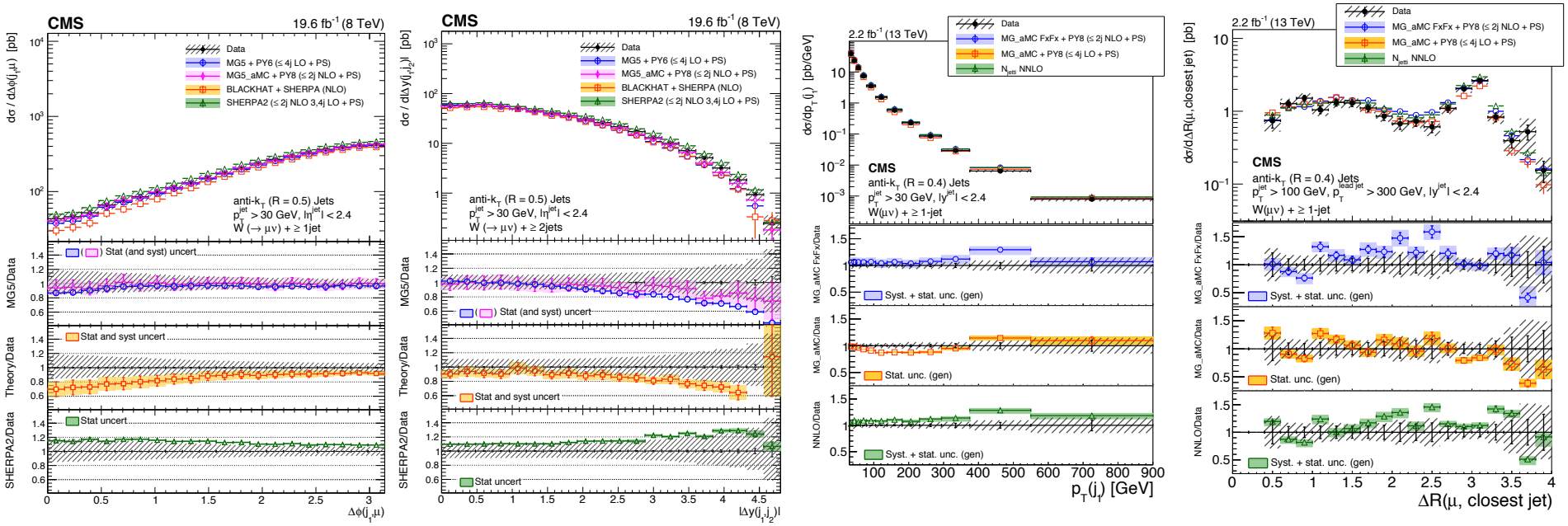
- Accurate modeling of V+jets is importance for many measurements at the LHC
  - W/Z+jets is dominant background for precision top quark measurements
  - Important for precision Higgs physics (background modeling)
  - Important for modeling of SM background in searches of new physics
- With W/Z+jets we can probe different aspects of QCD calculations

8 TeV
PRD 95 (2017) 052002

W + Jets

13 TeV
arXiv:1707.05979

- Test QCD fixed-order calculations and MCs, sensitive to higher order effects but also soft QCD effects (particle emission, PS).
  - Compared to predictions: LO(≤4j) and NLO(≤2j) MadGraph5_aMC@NLO; NNLO for one inclusive jet
  - Measured: Excl./Incl. jet multiplicities, jet p_T, jet η, and H_T up to ≥ 3 jets
  - Good agreement with predictions, but overall LO MadGraph5_aMC@NLO slightly underestimates data on the observables

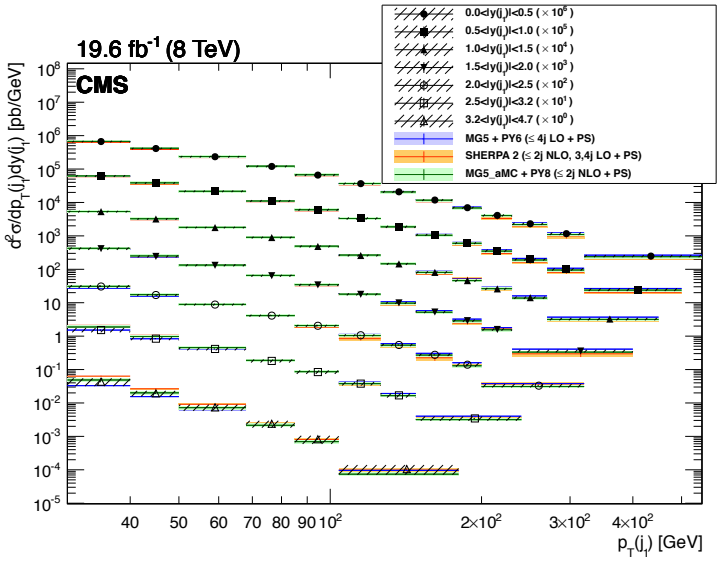


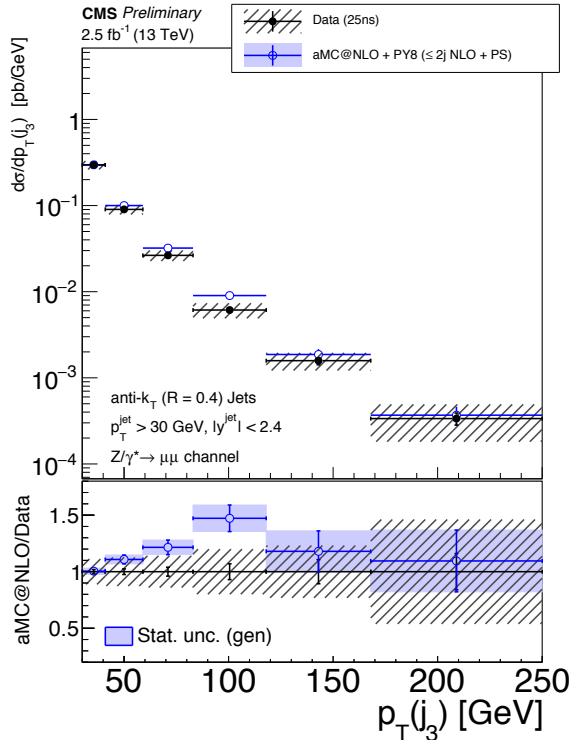
8 TeV
JHEP 04 (2017) 022

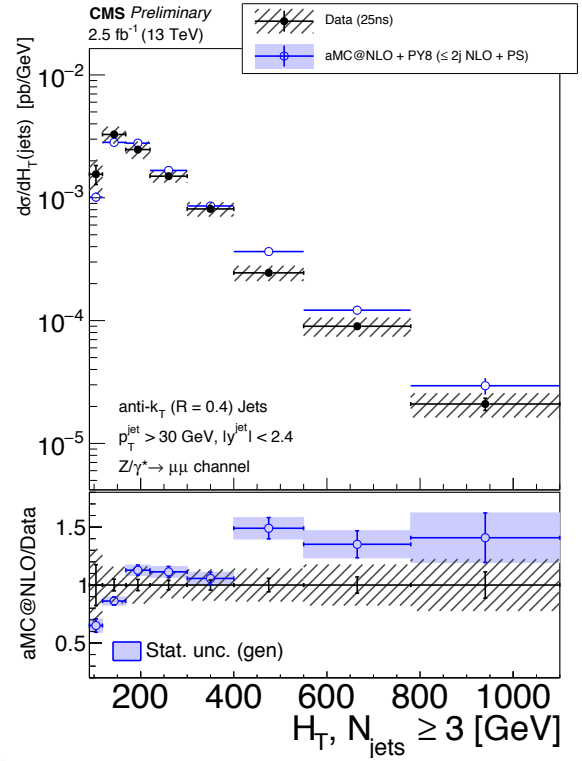
Z + Jets

13 TeV
CMS-PAS-SMP-15-010

- Similarly to W+jets, the measurements are sensitive to higher order corrections and radiative effects
- Compared to predictions: MadGraph5_aMC@NLO with NLO for 0, 1 and 2 jets
  - Good agreement although the third jet p_T is decreasing more rapidly in simulation than data



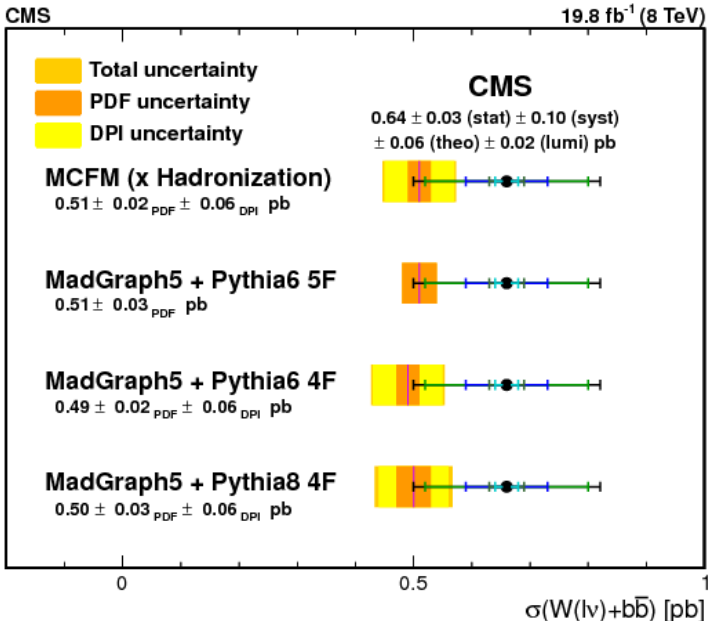




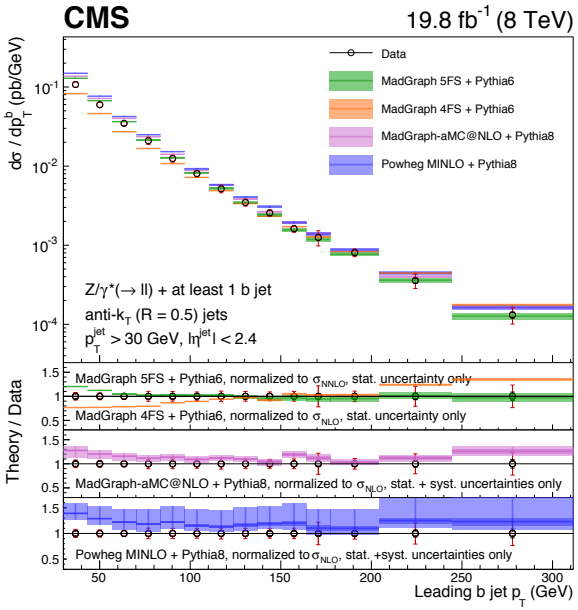
W/Z + b Jets

- Sensitive to gluon splitting, can probe b-quark PDF, important background to Higgs and BSM searches.
- W+bb
  - Cross section obtained by fitting M_T
  - Compared to LO (4FS/5FS) and NLO
  - In agreement with predictions
- Z+(b)b
  - Fiducial Z+≥1b,≥ 2b cross sections and ratio
  - Differential in jet p_T and Z p_T
  - Compared to LO (4FS/5FS) and NLO
  - 20% discrepancy for 4FS LO
  - 5FS LO overestimates data at low b-jet p_T

EPJC (2017) 77:92



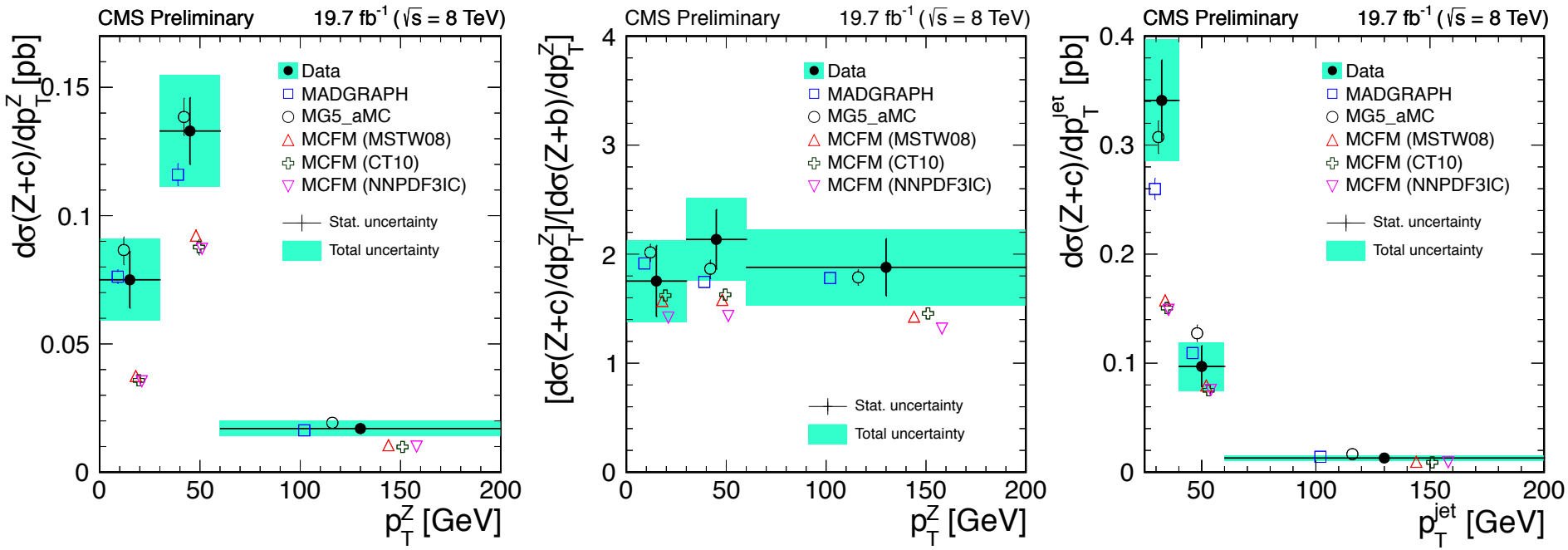
arXiv:1611.06507 submitted to EPJC



Z + c Production

CMS-PAS-SMP-15-009

- Test of QCD predictions, sensitive to charm content in the proton. Test modeling of Z+HF in searches (e.g. FCNC top decays).
- Signal isolated with:
  - Selection with a muon from decay of a HF quark, participating in a displaced vertex
  - Selection of exclusive final states from D meson resonant peaks (either $D^{\pm}$ or $D^{*\pm}$)



EW Z + 2 Jets

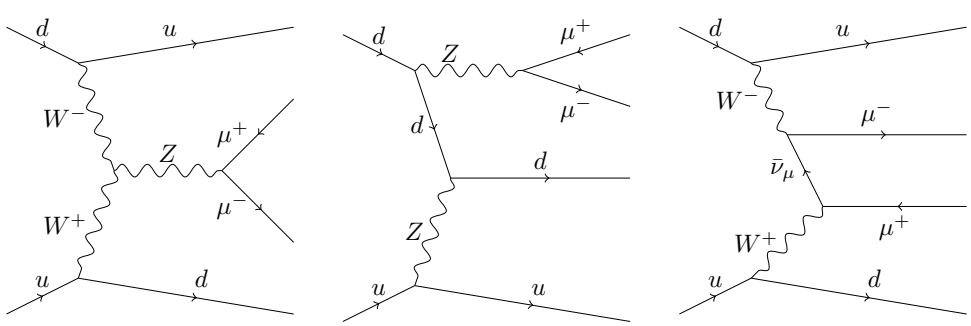
CMS-PAS-SMP-16-018
JHEP (2016) 2016: 147

- Signal is defined as $\ell\ell jj$ final state with $p_T(j)>25$ GeV, $m(jj)>120$ GeV, $m(\ell\ell)>50$ GeV

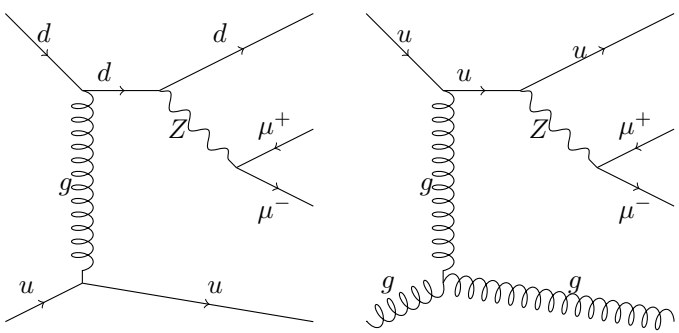
$$\sigma_{LO}(\text{EW } \ell\ell jj) = 0.50 \pm 0.02 \text{ (QCDscale)} \pm 0.02 \text{ (PDF)}$$

- Pure EW:
  - non-VBF diagrams that lead to identical final states and cannot be neglected
  - these diagrams have important negative interferences with the VBF productions

Signal:



Background:
DY + 2 jets

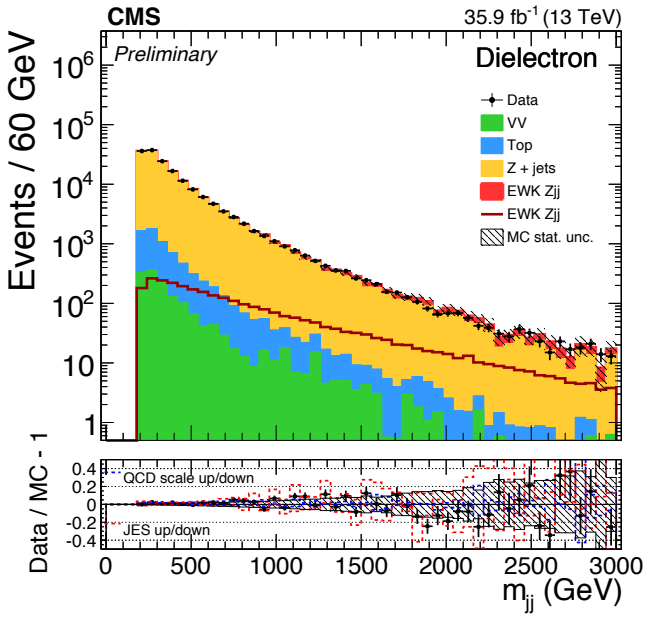


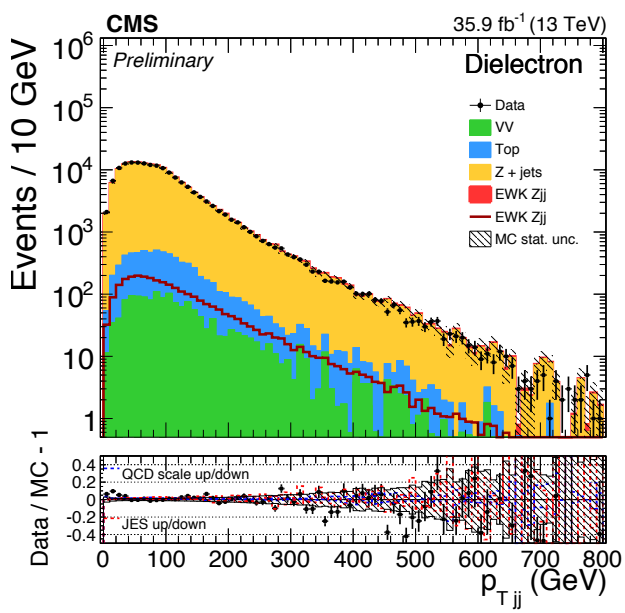
EW Z + 2 Jets

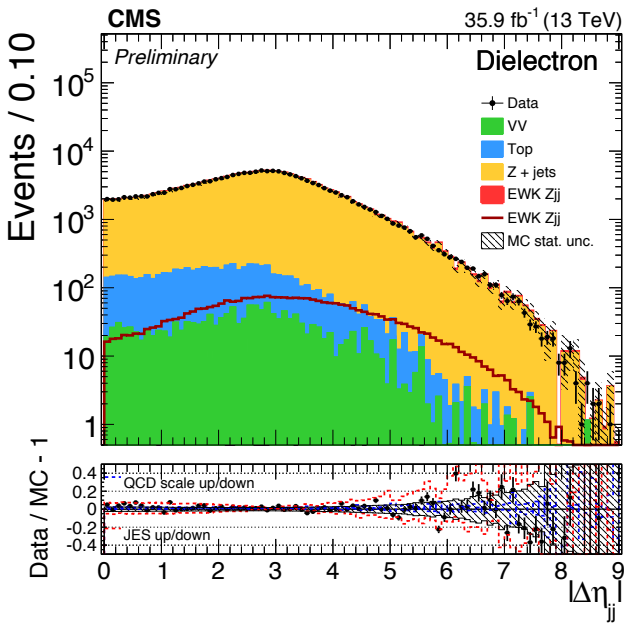
CMS-PAS-SMP-16-018
JHEP (2016) 2016: 147

- Multivariate analysis techniques are used to optimize S/B
- Binned maximum likelihood fit with strength modifiers for all MC components
- 10% precision:

combined :
$$\sigma(EW\ lljj) = 552 \pm 19(stat) \pm 55(syst) = 552 \pm 58(total)fb$$

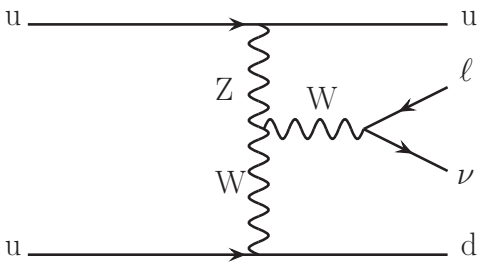






Electroweak W Production

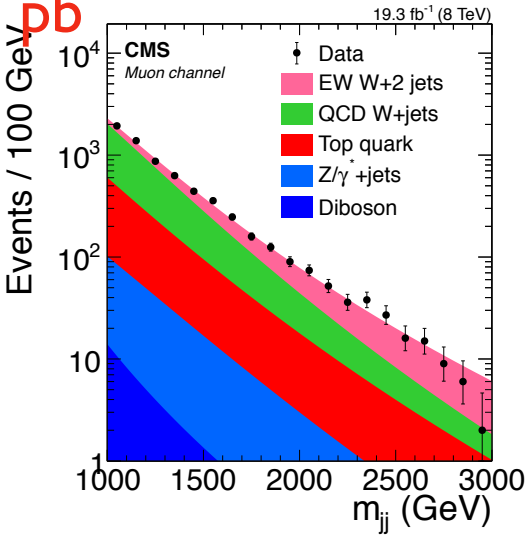
CMS-PAS-SMP-13-012



- Vector boson fusion (VBF) characteristic signature
  - 2 jets at high $|\eta|$
  - high dijet invariant mass m_{jj}
  - large rapidity separation $\Delta\eta$
  - little hadronic activity in the central part of the detector
  - multivariate analysis to increase background discrimination
- Fiducial cross section from fits to m_{jj} distributions, using parametric models for all processes

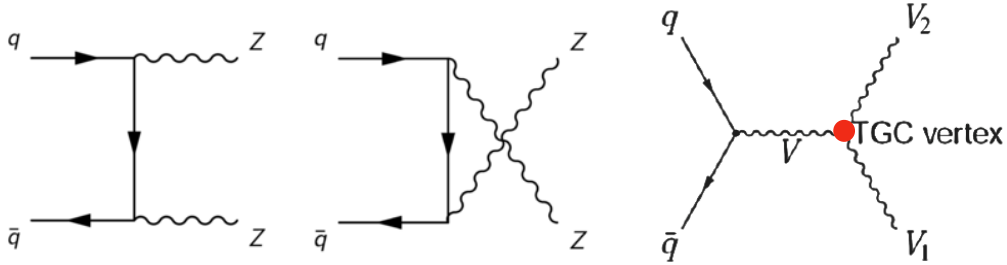
  $\sigma_{fid} = 0.42 \pm 0.04$ (stat) ± 0.09 (syst) ± 0.01 (lumi) pb
- Consistent with LO prediction

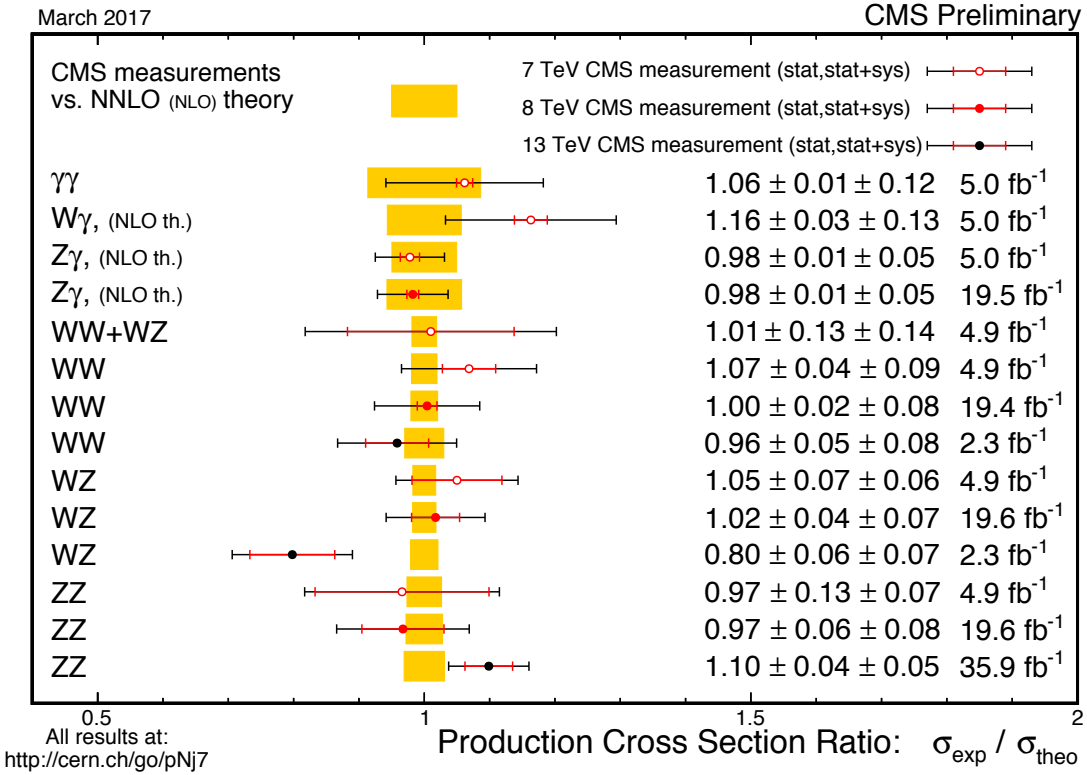
  $\sigma_{LO} = 0.50$ v 0.02 (scale) ± 0.02 (PDF) pb



Di-Boson Production

- Important test of EWSB
- Large amount of measurement variety of final states
- Sensitive to BSM contributions
- Good agreement with the SM

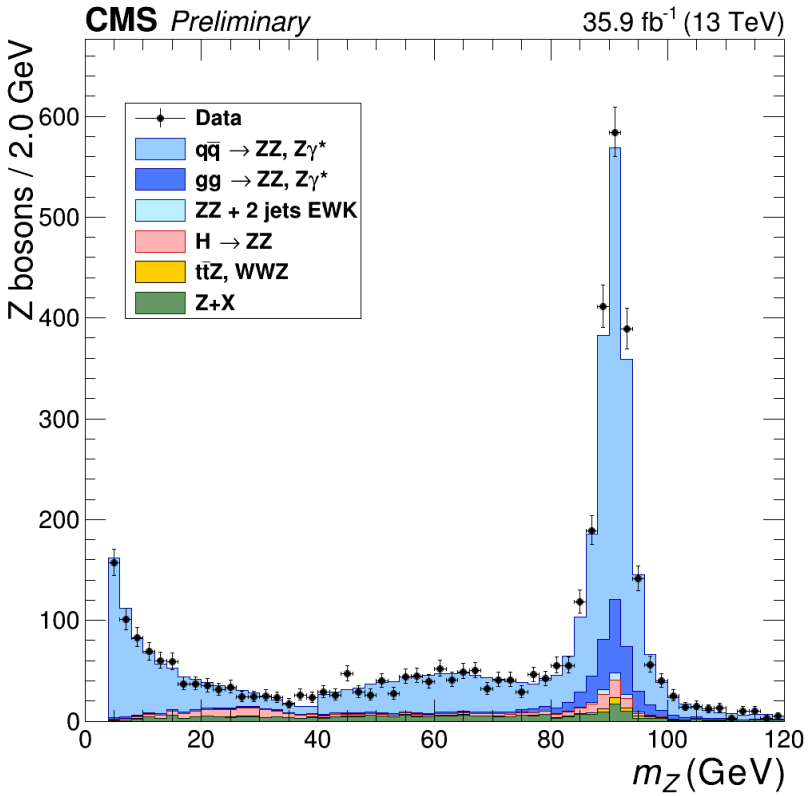


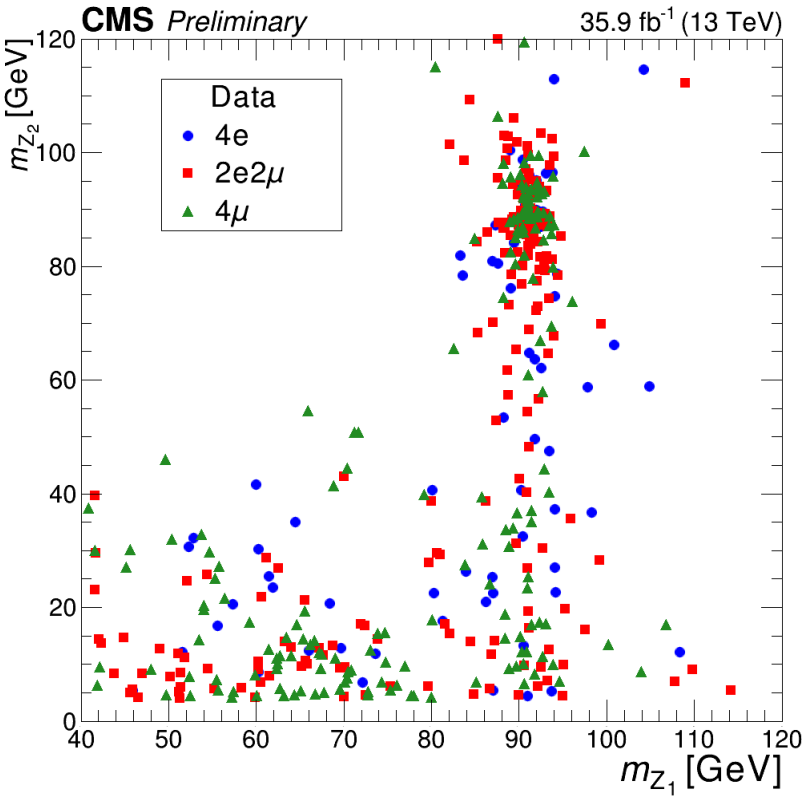


ZZ Production

CMS-PAS-SMP-16-017

- First diboson measurement with 13 TeV data
- Main channel: ZZ→ 4ℓ, clean signature and background to H → 4ℓ
- Differential cross sections (with and w/o jets) to test higher order effects (NNLO QCD and NLO QED)

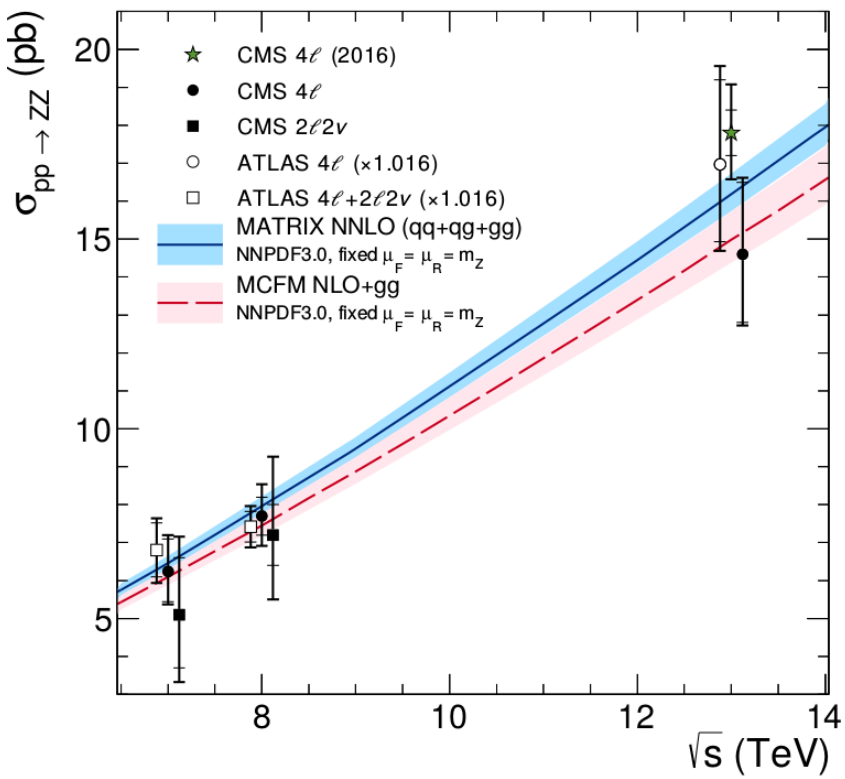


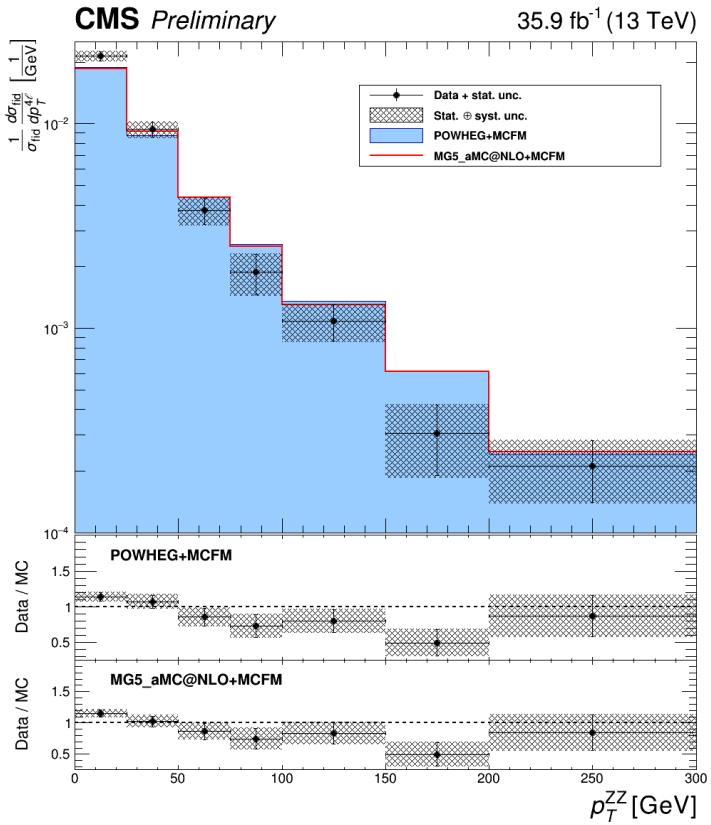


ZZ Production

CMS-PAS-SMP-16-017

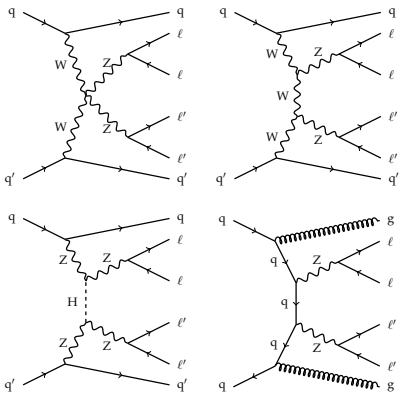
- Cross section agrees well with NNLO prediction
- Measure differential cross section as function of $p_T(ZZ)$
- Possible indication for a softer p_T^{ZZ} than what is predicted by both POWHEG+MCFM and MG+MCFM



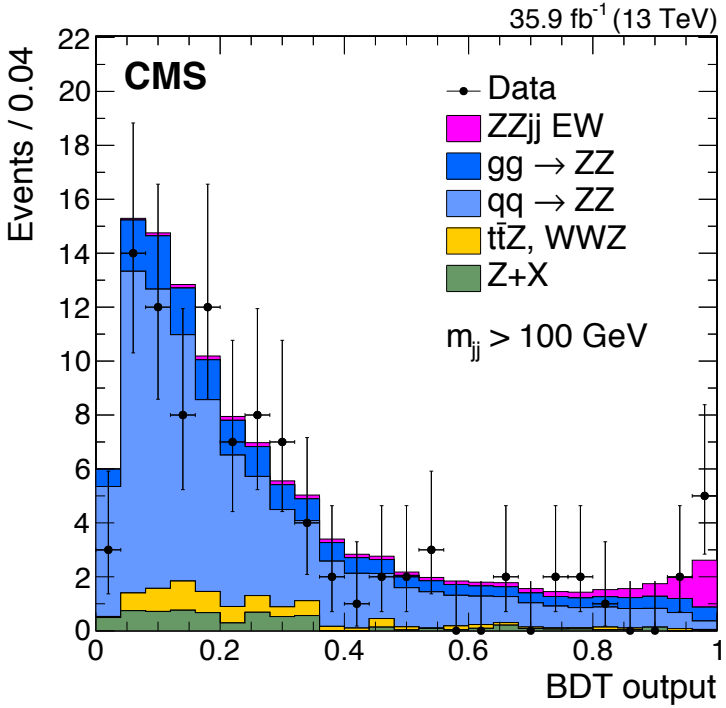


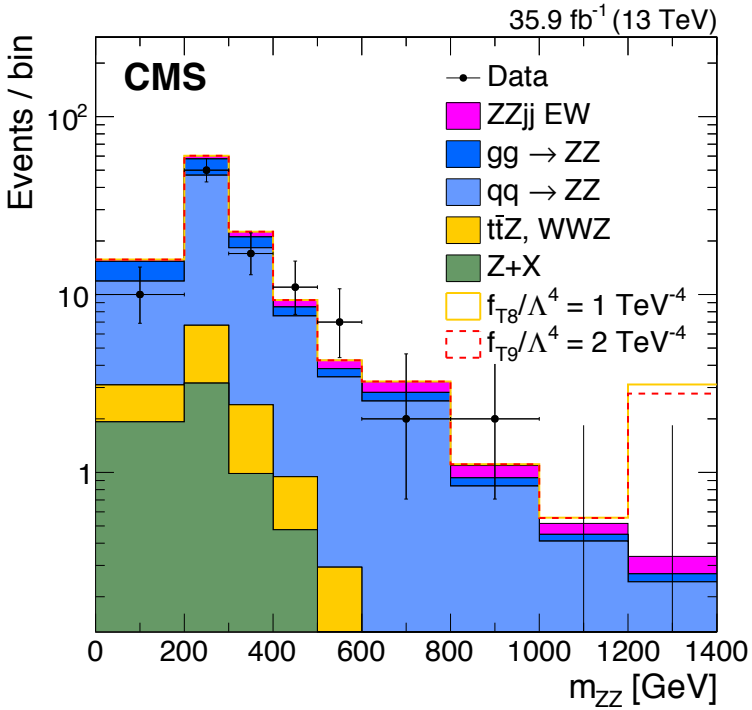
ZZ + 2 Jets

CMS-PAS-SMP-17-006
arXiv:1708.02812



- Vector boson scattering and constraints on anomalous quartic gauge couplings from events with two Z bosons and two jets
- The electroweak production of two Z bosons in association with two jets is measured with an observed (expected) significance of 2.7 (1.6) standard deviations

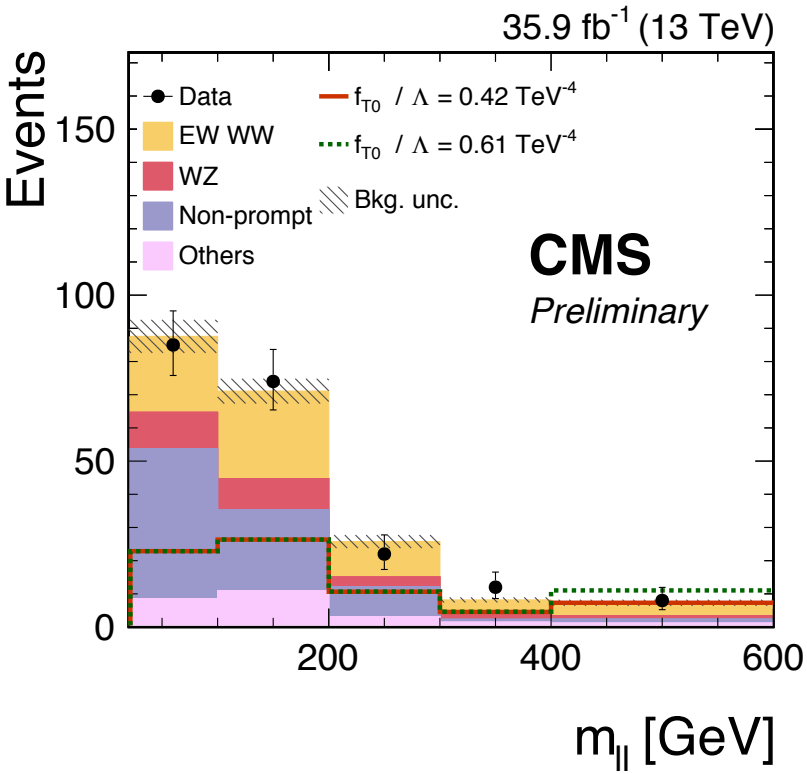


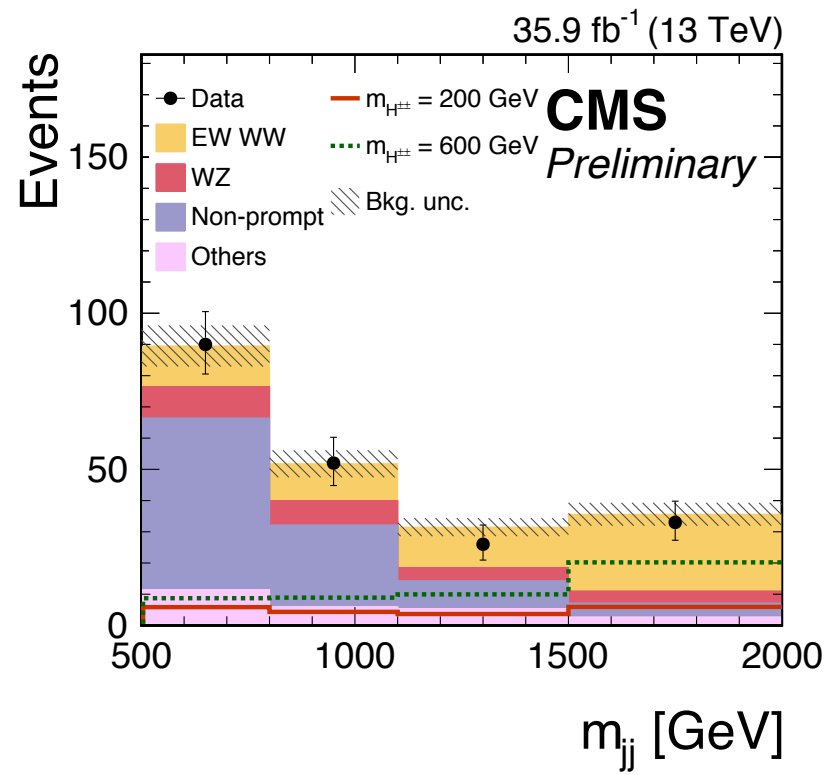


WW + 2 Jets

CMS-PAS-SMP-17-004
submitted to PLB

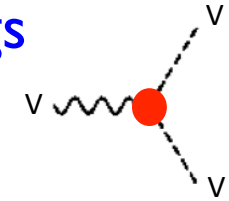
- EW VV+2 jets production (VBS) probes EWSB
- Characterized by 2 forward jets separated in rapidity, with low hadronic activity in between
- $W^{\pm}W^{\pm}$ same sign lepton selection, two jets with large y separation and m_{jj} leads to first observation of EW VV at 13 TeV (5.5σ)

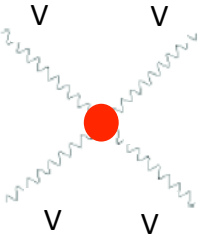




Anomalous Vector Boson Couplings

- New physics at higher scales can lead to modified couplings
  → probe for increase in cross section
  - aTGC constrained with inclusive diboson (WWZ vertex)
  - aQGC constrained with EW VVjj and triboson



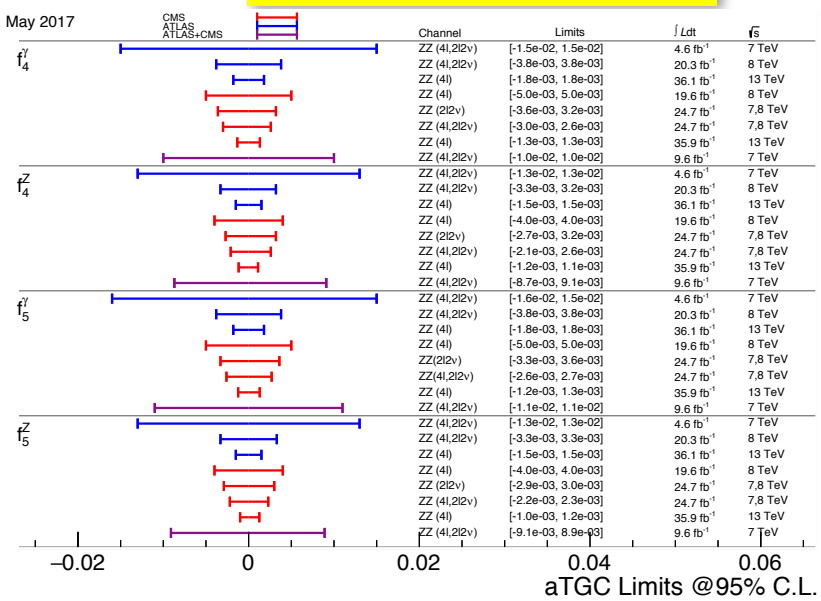


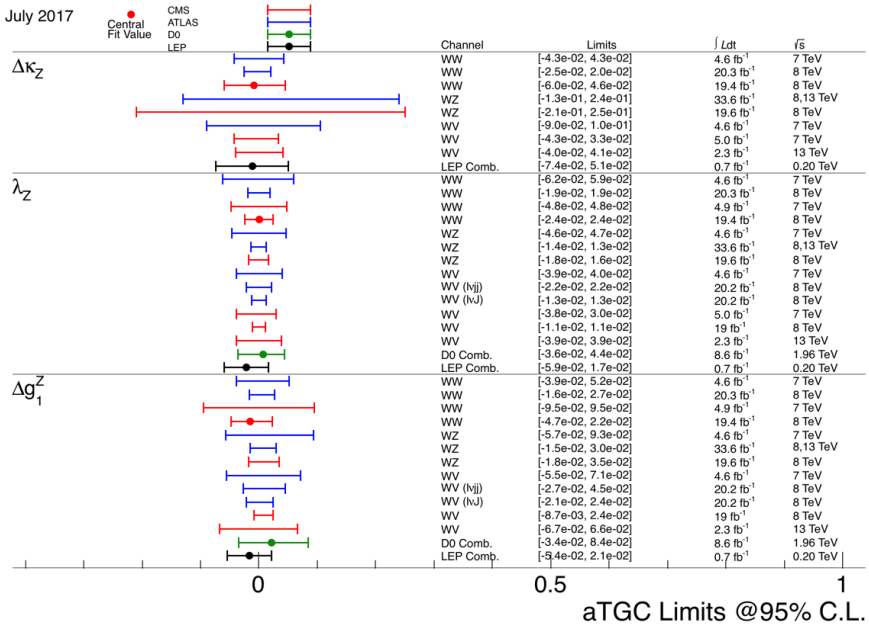
CMS-PAS-SMP-16-002
PLB 766 (2017) 268

CMS-PAS-SMP-17-006
arXiv:1708.02812

CMS-PAS-SMP-16-017

CMS-PAS-SMP-13-008
PLB 772 (2017) 21

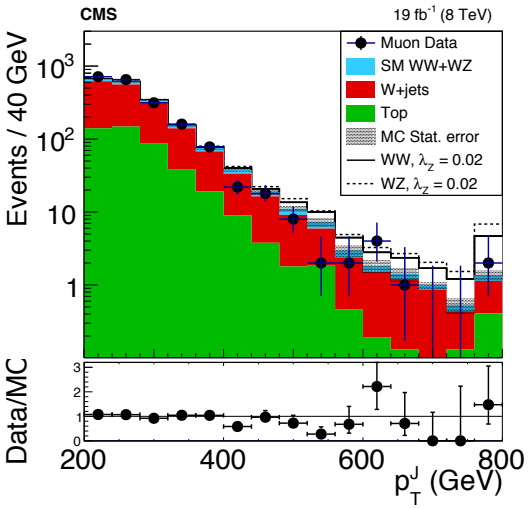




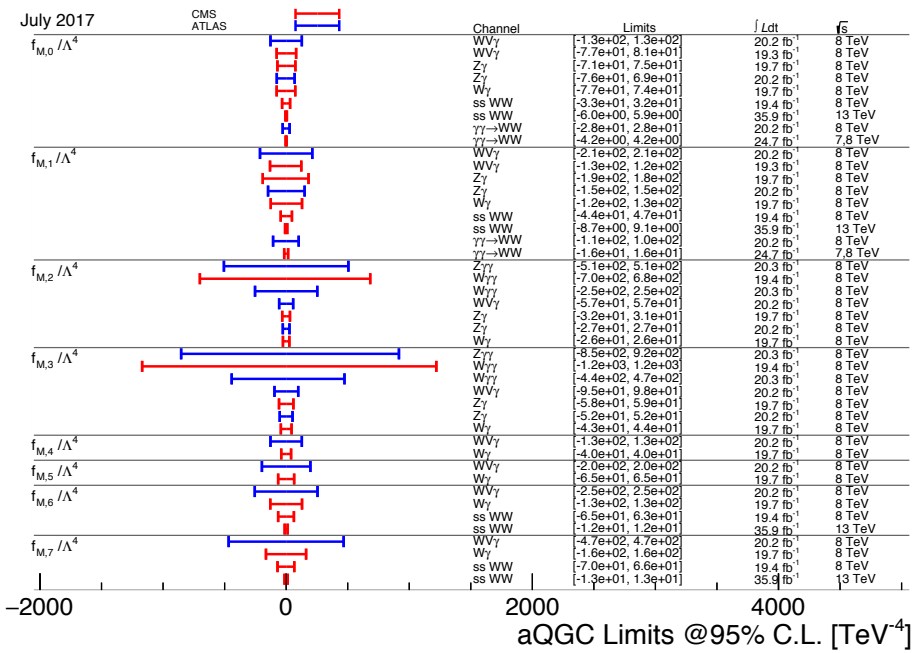
Anomalous Vector Boson Couplings

- Sensitivity depends on the channel
  - Boosted topology with hadronic final states usually has best sensitivity
  - Large gain in sensitivity with $\sqrt{s}$
- Limits on aQGC

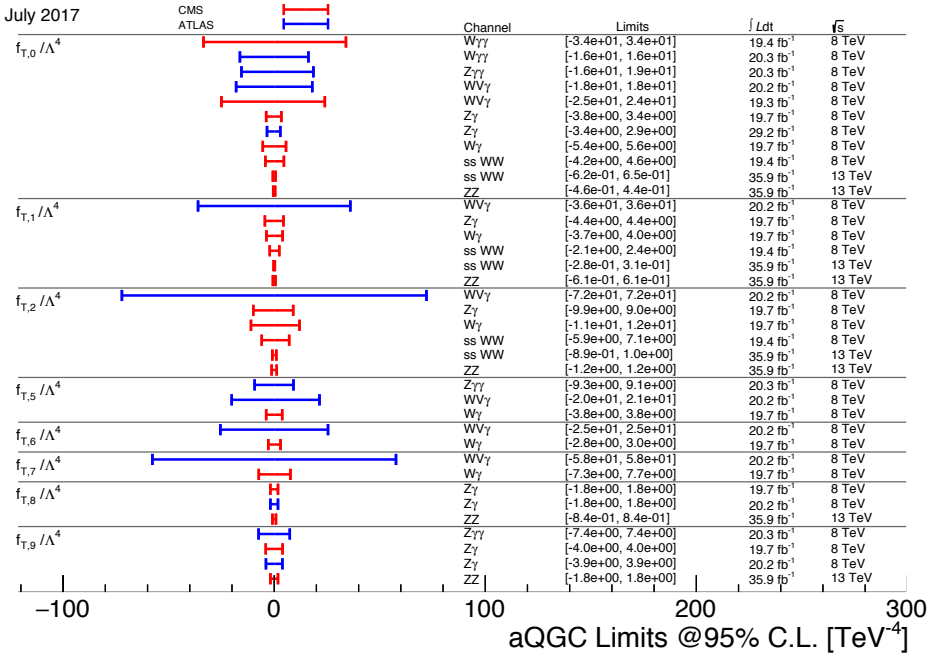
CMS-PAS-SMP-13-008
PLB 772 (2017) 21



Dimension-8 transverse parameters $f_{M,i}$



Dimension-8 mixed transverse and longitudinal parameters $f_{M,i}$



Summary

- Known QCD and EW processes continue to be studied in greater detail
  - Results benefit from (and drive) the advancements in theoretical calculations and MC generators
  - Differential measurements with uncertainties below 1%
- Enough statistics to see EW production of diboson processes: path toward $W_L W_L$ scattering
  - Development of data analysis tools (boosted techniques, using jet substructure for hadronic W and Z decays etc.)
- Expect a significant increase in sensitivity to anomalous gauge boson self-interaction couplings
  - Await for a suite of new results
- No significant deviations from the SM observed to date
  - Increasingly more precise and complex SM measurements will continue to play a complementary role to direct searches in probing for new physics