CMS Standard Model Results

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for the CMS Collaboration

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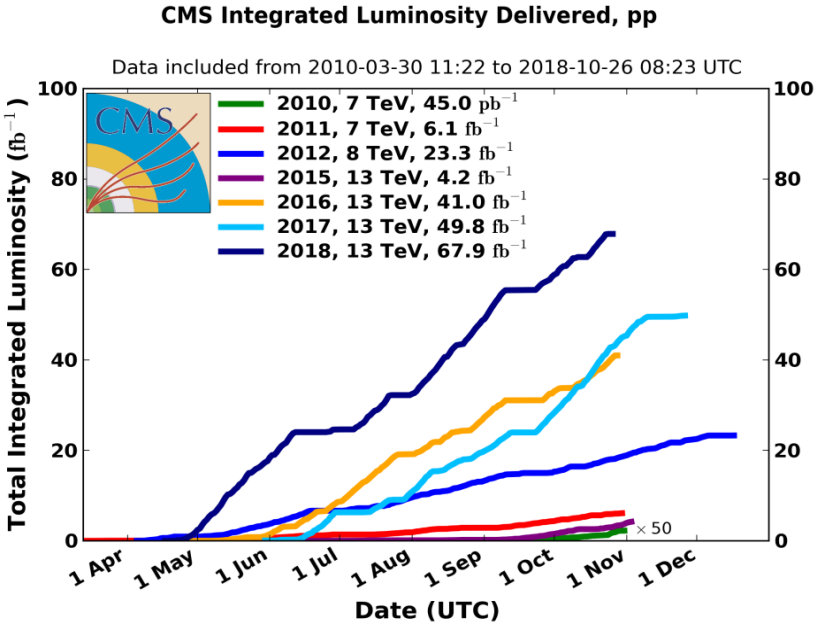
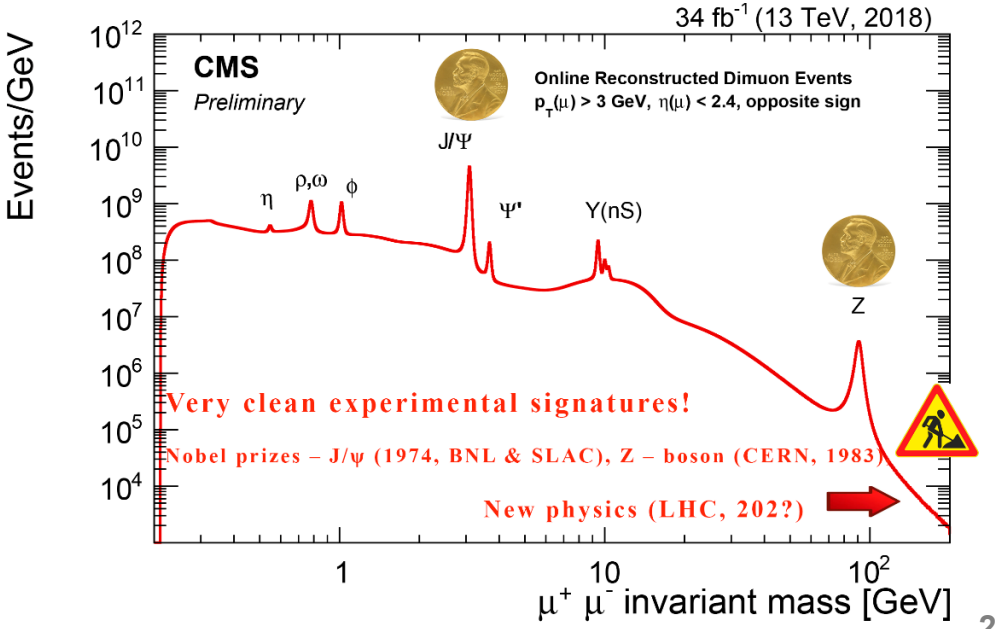
Outline

- W and Z production
  - ✓ Lepton universality
  - ✓ Z invisible decay
  - ✓ Drell-Yan differential cross sections
- Asymmetries
  - ✓ Forward-backward asymmetry and angular coefficients for Drell-Yan
  - ✓ Weak mixing angle
- Multiboson production
  - ✓ $\alpha_s(m_z)$ Measurement
  - ✓ VBS
  - ✓ Three massive boson production
  - ✓ Resonance triboson decay
- Double Parton Scattering

CMS Standard Models Physics Results
https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html





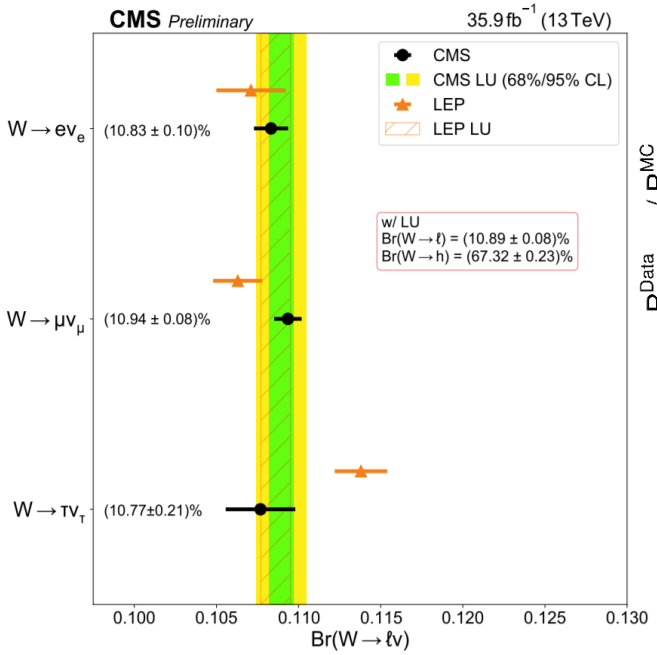
Lepton universality

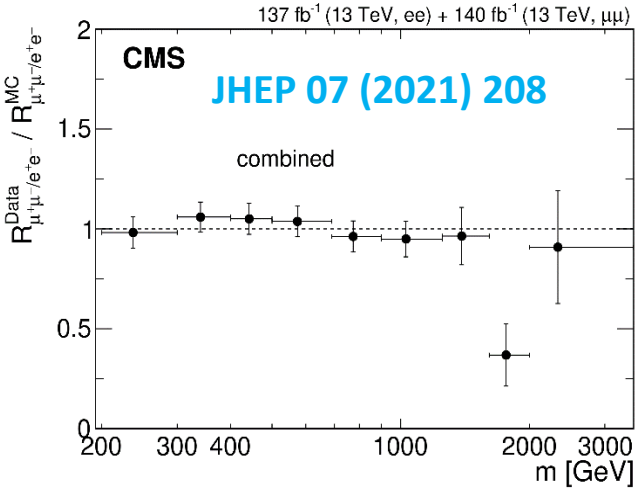
PAS SMP-18-011

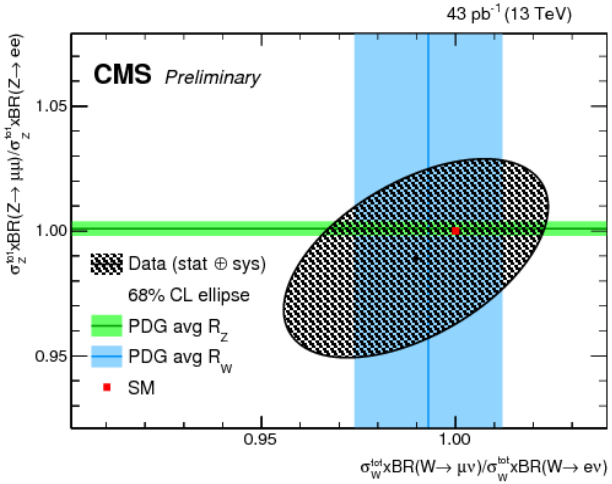
	CMS	LEP
$\mathcal{B}(W \to e\bar{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\bar{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\bar{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to h)$	$(67.46 \pm 0.04 \pm 0.28)\%$	–
with LU		
$\mathcal{B}(W \to \ell\bar{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to h)$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

CMS-PAS-SMP-15-004

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}





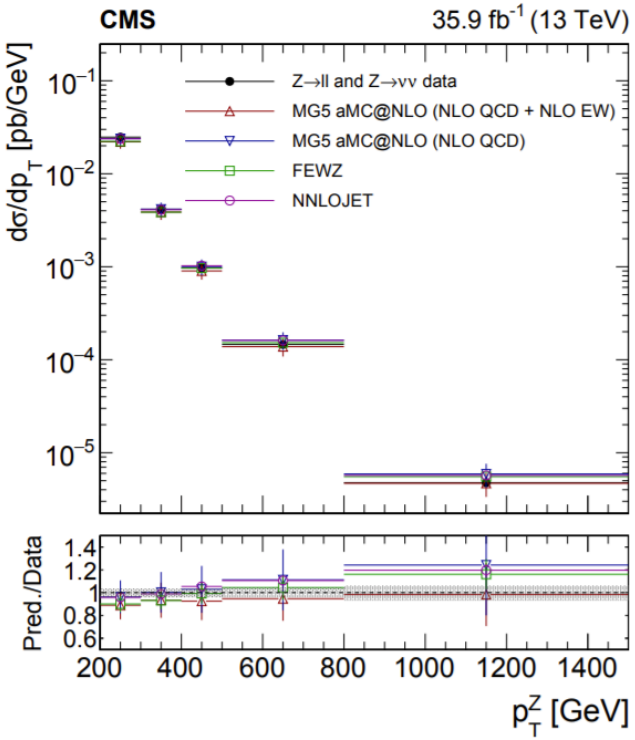


- ✓ Measured leptonic and inclusive hadronic decay branching fractions of W and Z bosons
- ✓ Precision is better than for the LEP results
- ✓ Results support the hypothesis of lepton universality for the weak interaction at new energies

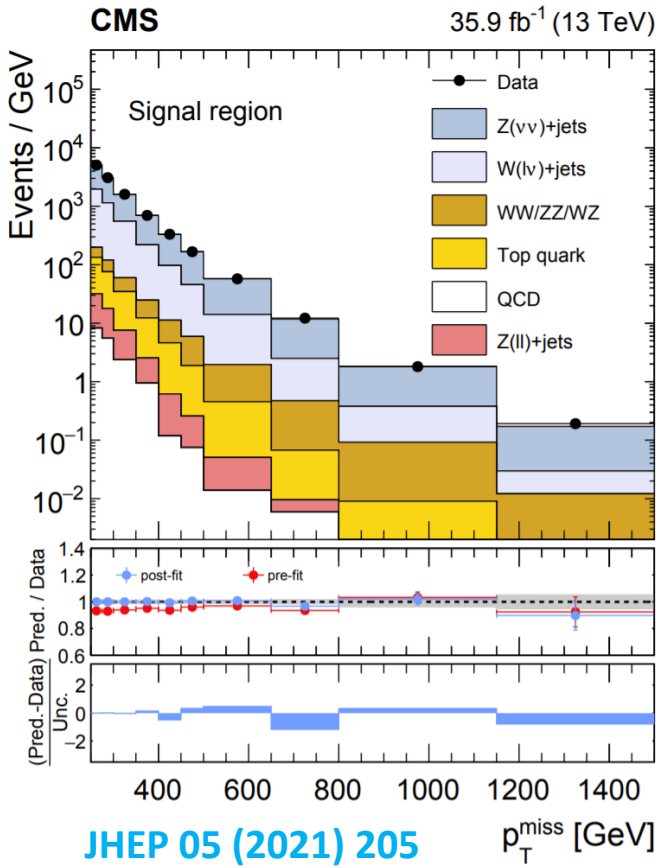
Z Invisible Decay (Z→ $\nu\bar{\nu}$)

- Important background process for BSM signals
- $Br(\mathrm{Z} \to \nu\bar{\nu}) \sim 6Br(\mathrm{Z} \to l^{+}l^{-})$ → Small statistic uncertainty
- Sensitivity at high p_T^Z region
- The precision of this result is improved by combining the cross section measured with those extracted from charged-lepton final states

✓ The results agree within uncertainties with the theoretical predictions from MADGRAPH5 aMC@NLO, FEWZ and Z+1 jet at next-to-next-to-leading order in perturbative quantum chromodynamics



✓ These are the most precise measurements of the p_T^Z spectrum to date (05.2021) in proton-proton collisions at 13 TeV

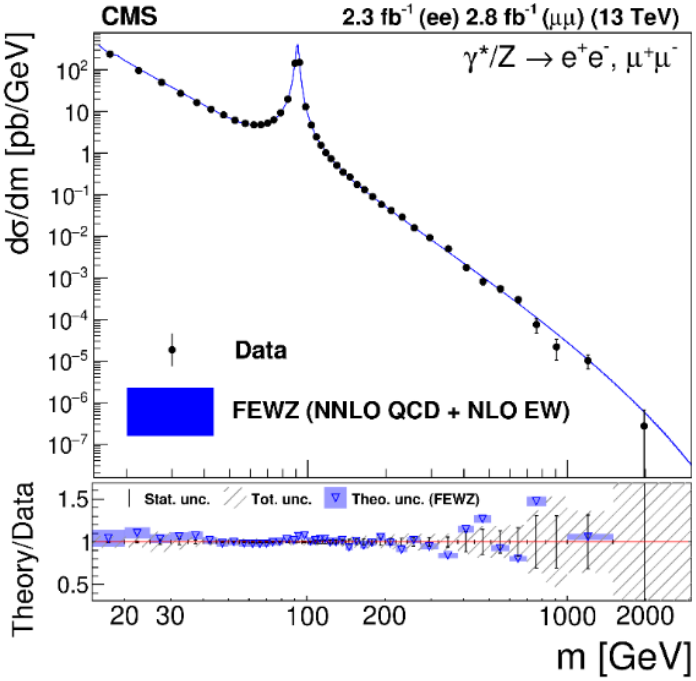


JHEP 05 (2021) 205

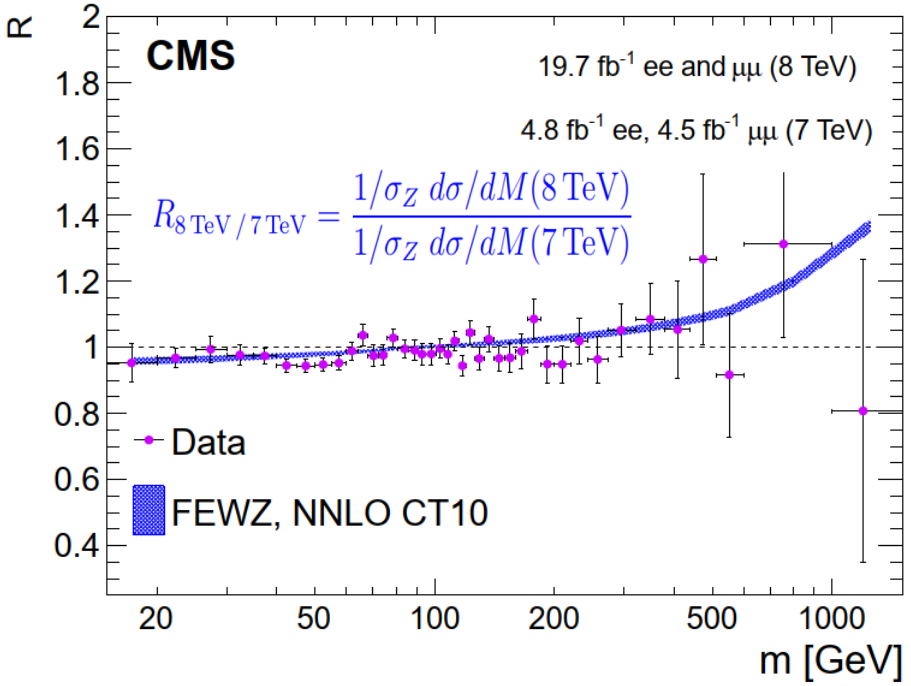
p_T^Z (GeV)	$Z \to \ell\ell$	$Z \to \nu\nu$	$Z \to \ell\ell + \nu\nu$
200–300	$1.012^{+0.006}_{-0.007}$	$1.019^{+0.009}_{-0.009}$	$1.011^{+0.004}_{-0.004}$
300–400	$0.943^{+0.025}_{-0.025}$	$0.979^{+0.015}_{-0.015}$	$0.963^{+0.015}_{-0.014}$
400–500	$1.006^{+0.031}_{-0.030}$	$0.963^{+0.019}_{-0.019}$	$0.971^{+0.017}_{-0.016}$
500–800	$0.993^{+0.036}_{-0.036}$	$0.942^{+0.024}_{-0.024}$	$0.949^{+0.021}_{-0.020}$
800–1500	$1.036^{+0.099}_{-0.095}$	$0.869^{+0.059}_{-0.057}$	$0.914^{+0.052}_{-0.051}$

Drell-Yan Differential Cross Section

JHEP 12 (2019) 059



EPJ C 75 (2015) 147, arXiv:1412.1115



✓ The total cross section measurements are presented as a function of dilepton invariant mass in the range 15 to 3000 GeV

✓ The measured differential cross sections are in good agreement with the theoretical calculations (NNLO QCD + NLO EWK)

<u>We observe agreement of the cross section(s) and double ratio measurement with the theoretical prediction within uncertainties</u>

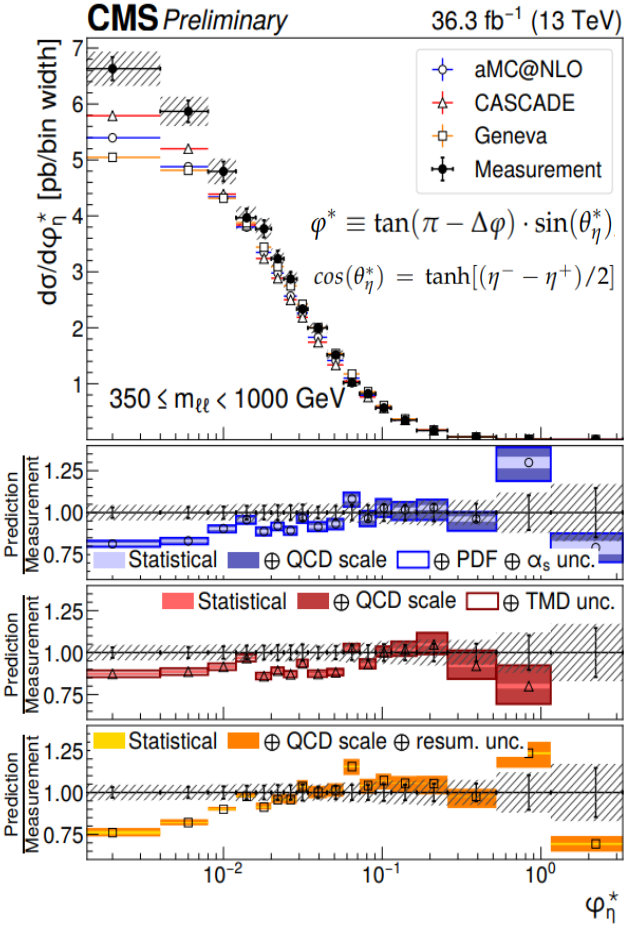
$3 \times 10^{-4} < x < 1.0$ and $6 \times 10^2 < Q^2 < 3 \times 10^6$ GeV^2

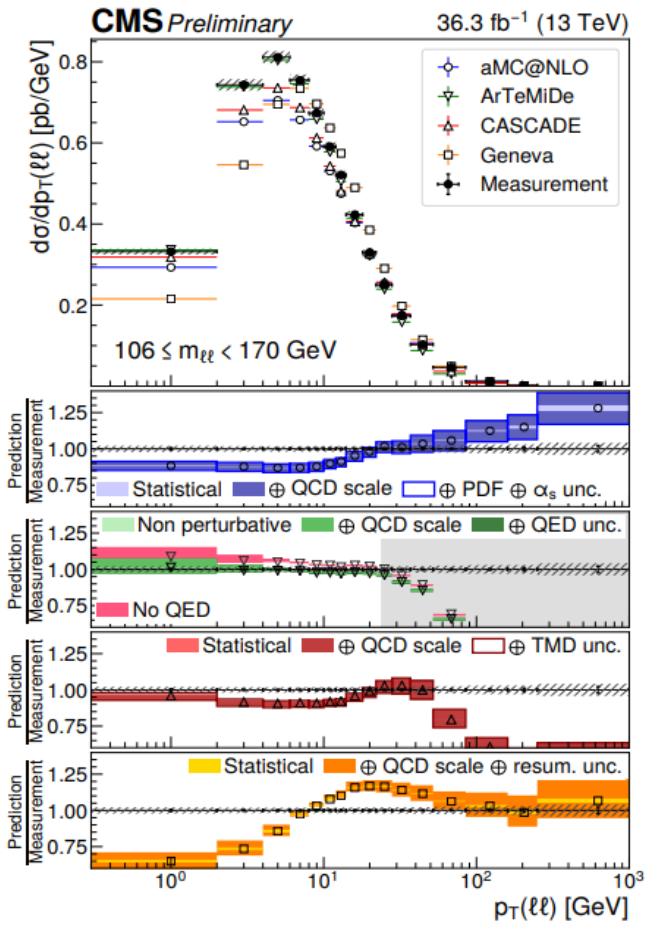
✓ The shape of the distribution is defined entirely by the √s and the Bjorken x dependencies of the PDFs, since the dependence on the hard scattering cross section is canceled out. In the Z peak region, the expected double ratio is close to 1 by definition.

Drell-Yan Differential Cross Sections vs M_{ll}

PAS-SMP-20-003

- ✓ The double differential cross sections of the Drell-Yan lepton pair production, as a function M_{ll}, p_T^{ll}, φ_η^* are measured up to M_{ll} = 1000 GeV
- ✓ Measurements are compared to state-of-the-art predictions based on perturbative quantum chromodynamics including soft gluon resummation



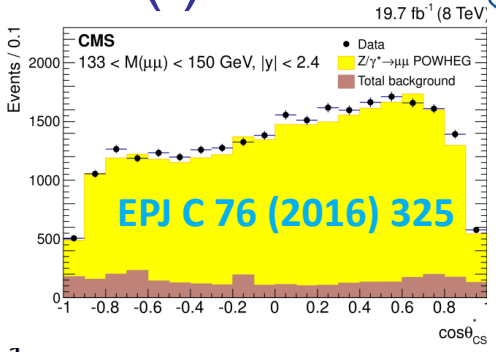


✓The DY double-differential cross sections and double ratio measurements presented here can be used to impose constraints on the quark and antiquark PDFs in a wide range of x

Different approaches for describing PDF evolution more or less successfully describe experimental data in different kinematic region. However, it is still far from perfect!

Drell-Yan Angular Coefficients (I)

The lepton angular distribution in the Drell - Yan process in the γ^*/Z rest frame is expressed by both the CMS and ATLAS Collaborations (measured at 8 TeV) as:



$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta^*\mathrm{d}\phi^*} \propto \left[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)\right.$$
$$\left. + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\right].$$

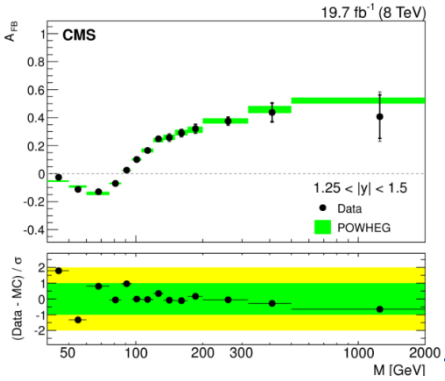
where θ and ϕ are the polar and azimuthal angles of l^- (e^- or μ^-) in the rest frame of γ^*/Z (Collins-Soper) and coefficients $A_0 - A_7$ are functions of p_T^Z, Y^Z, M^Z kinematic variables.

Integrated cross section by φ^*

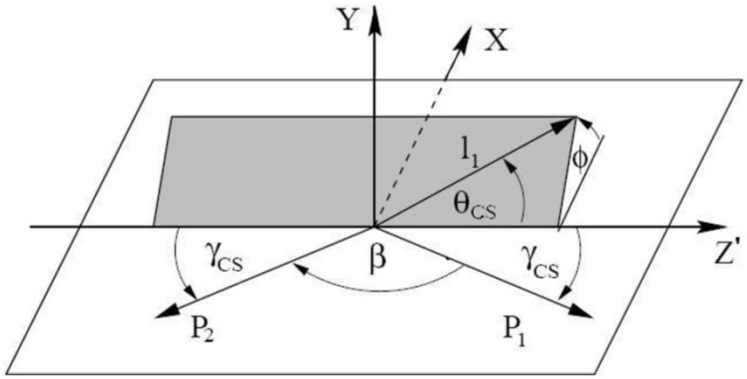
$$\frac{d^2\sigma}{dcos\theta^*} = 1 + A_4 cos\theta^* + cos^2\theta^*$$

and

$$A_{FB} = \frac{3}{8}A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B},$$

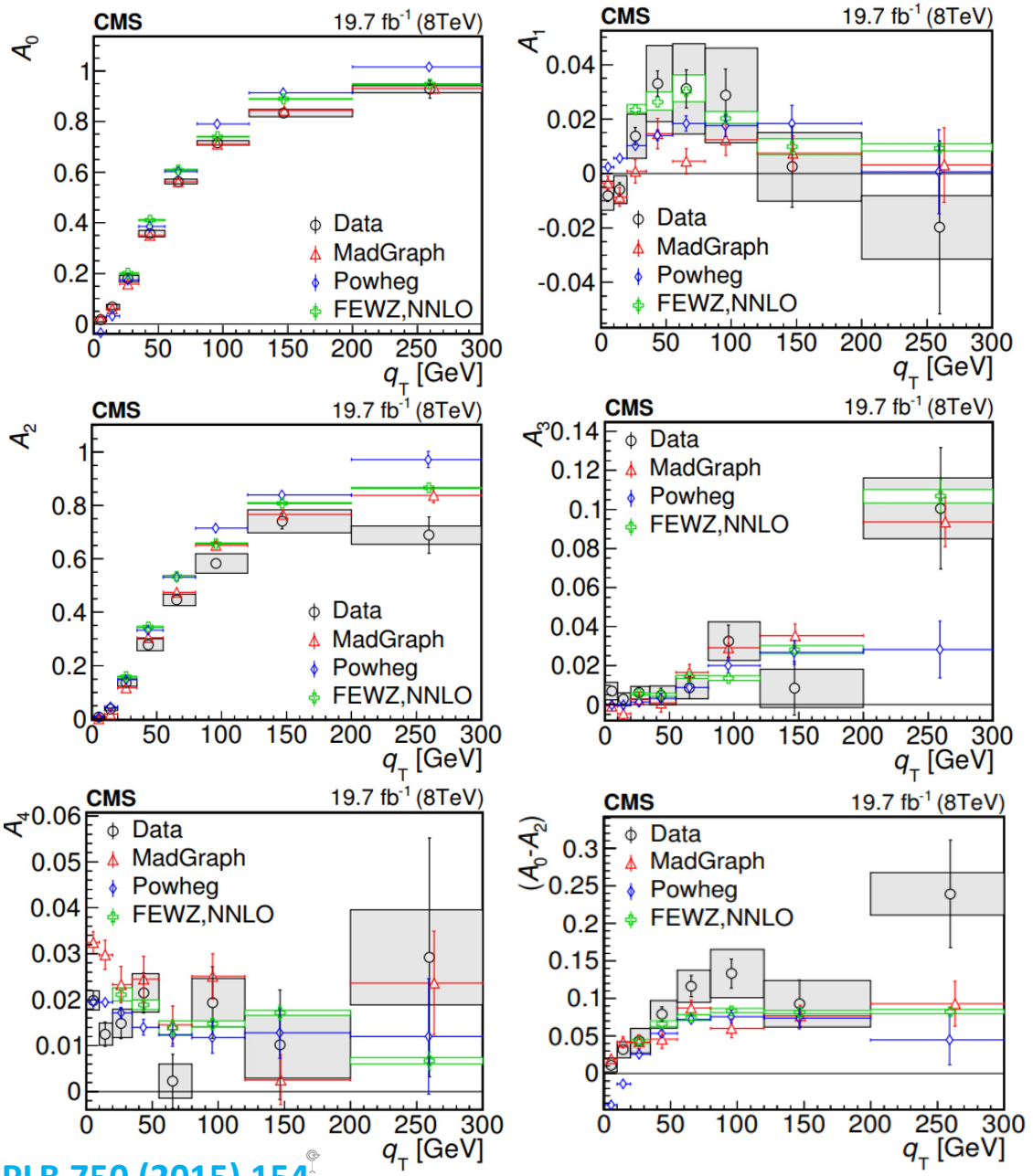


EPJ C 76 (2016) 325



The Collins-Soper coordinate system is chosen in such a way that the Z-axis bisects the angle between the interacting quarks

Drell-Yan Angular Coefficients (II)



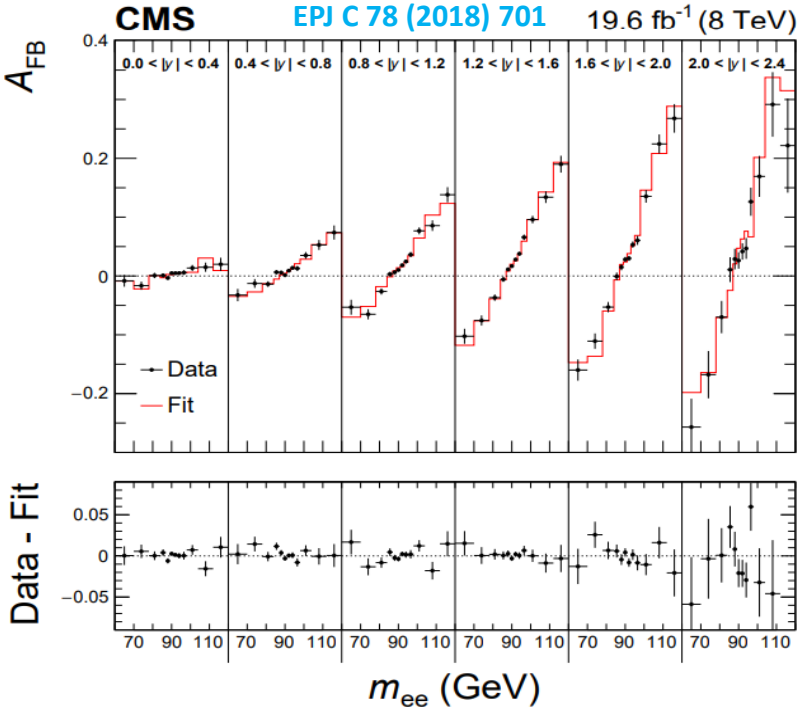
Angular coefficients A_{0-4} are obtained in bins of dimuon transverse momentum and rapidity in Z-peak mass region 80 < $M_{\mu^+\mu^-}$ < 100 GeV by CMS experiment at 8 TeV

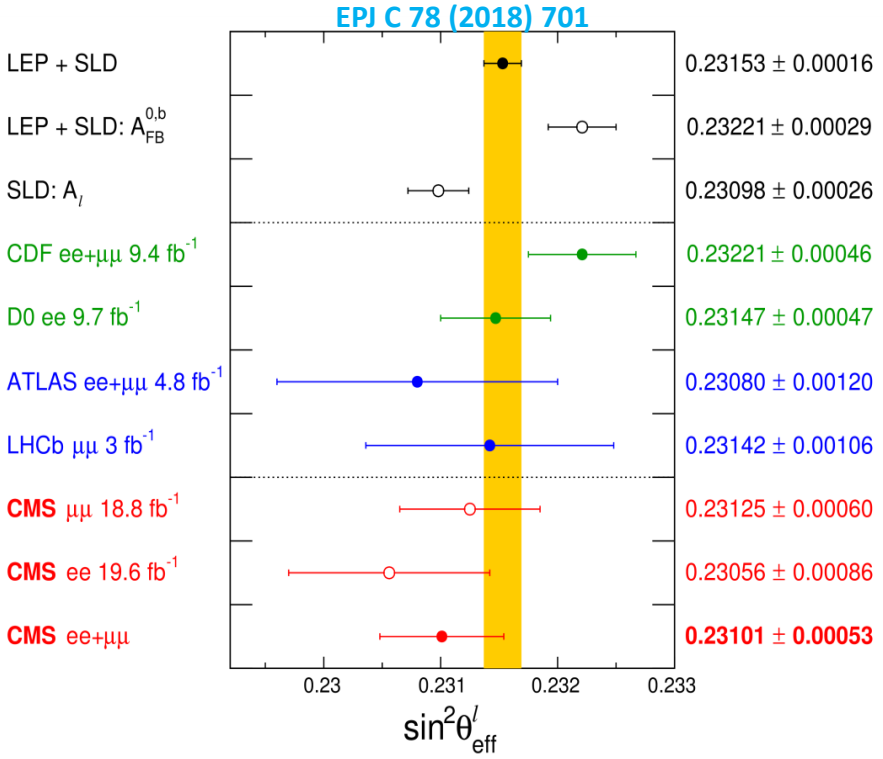
- ✓ Lam-Tung relation $A_0 = A_2$ (related with rotation invariance) violation was observed. At $p_T^Z \approx 100$ GeV it is twice more then predicted
- ✓ Non –zero coefficients A_{5-7} were measured by ATLAS collaboration
- ✓ Experimental data of CMS collaboration are in agreement with ATLAS results and with SM NNLO predictions
- ✓ A_{0-7} measurements at 13 TeV are in progress (CMS)

PLB 750 (2015) 154

Weak Mixing Angle

- A_4 $\left(\frac{3}{8}A_{FB}\right)$ sensetive to V-A structure of the couplings in parity violation terms
- Only A_4 $\left(\frac{3}{8}A_{FB}\right)$ is non-zero at LO QCD at small p_T^Z
- A_{FB} was used to extracting $sin^2\theta_{eff}^l$ value by CMS and ATLAS collaborations





EPJ C 78 (2018) 701 $sin^2\theta_{eff}^l$ (CMS):

$$0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00031\,(\text{PDF})$$

ATLAS-CONF-2018-037 $sin^2\theta_{eff}^l$ (ATLAS):

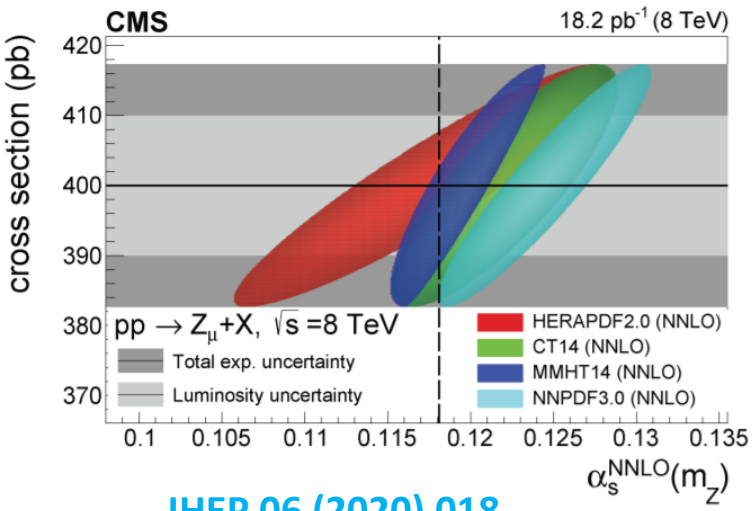
$$0.23140 \pm 0.00021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.})$$

$sin^2\theta_{eff}^l$ (Global EWK fit):

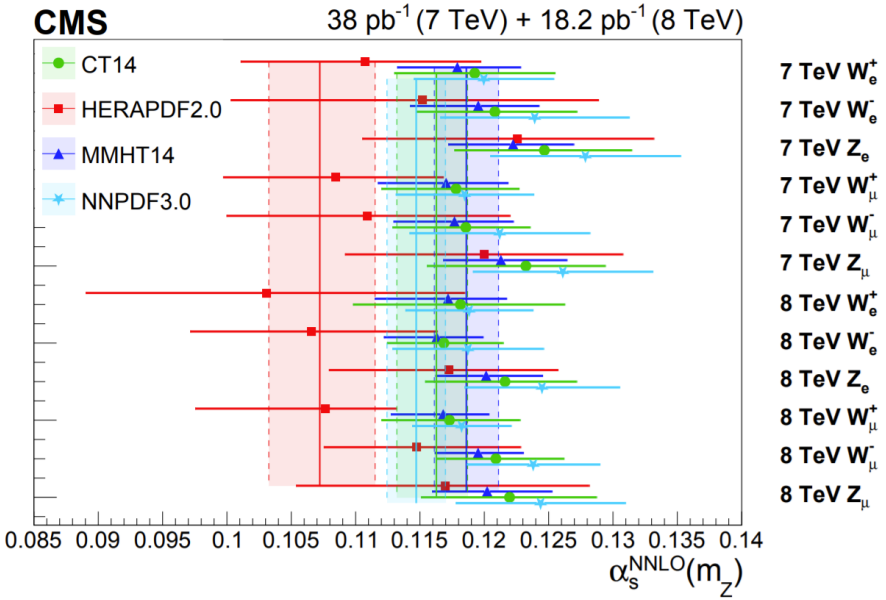
$$0.23150 \pm 0.00006$$

$\alpha_s(m_z)$ Measurement with $W^{\pm}, Z$ Production

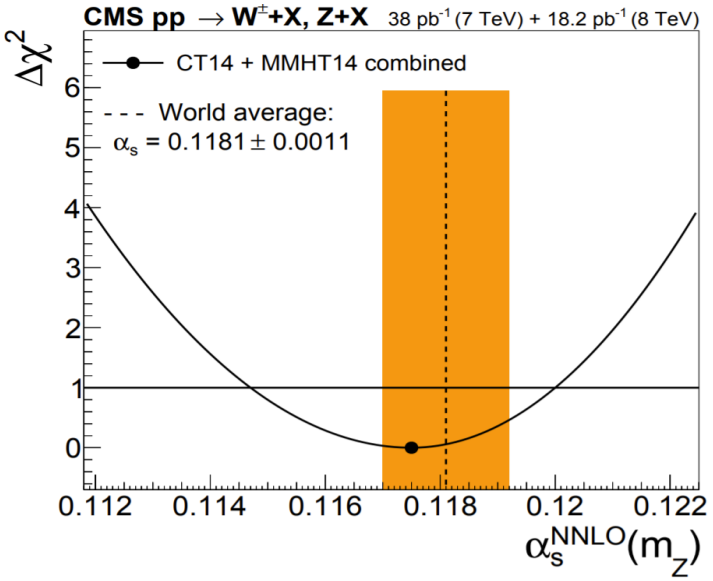
The main idea: Calculate V-production cross-section at NNLO level for varying $\alpha_S(m_Z)$ and PDFs compare theoretical predictions to experimental data



JHEP 06 (2020) 018



- ✓ Inclusion into the world average of new independent observables sensitive to α_s
- ✓ $W^{\pm}, Z$ cross sections are known at NNLO pQCD and can be measured with high accuracy
- ✓ About 25% of V-production come from partonic processes



Fully Compatible!

$\alpha_s(m_z)$ (JHEP 06 (2020) 018):

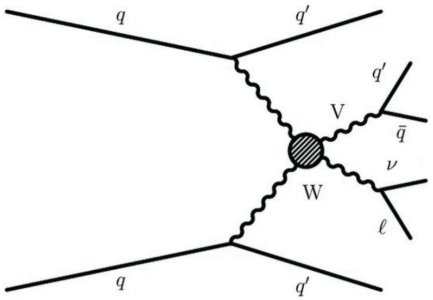
$$\alpha_S(m_Z) = 0.1175^{+0.0025}_{-0.0028}$$

$\alpha_s(m_z)$ (World average):

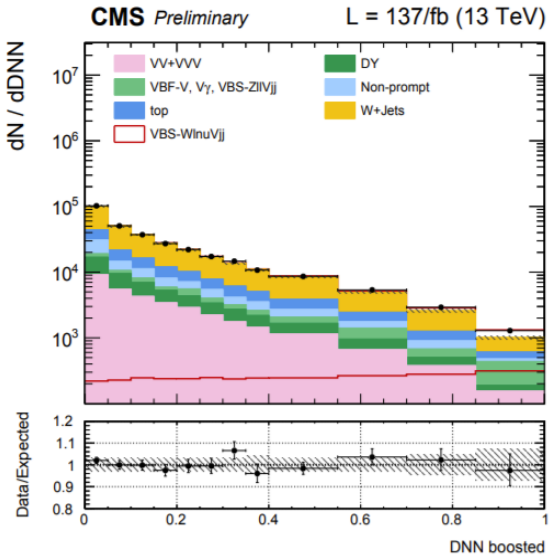
$$\alpha_s = 0.1181 \pm 0.0011$$

Search for EW Vector Boson Scattering (VBS) in $lvqq$

- Purely EW process. Very rare! High background contamination
- Differential cross sections are model-independent test of the Higgs couplings to vector bosons
- An additional confirmation of EW symmetry breaking
- Sensitive to BSM effects



✓ The first evidence for the EW vector boson scattering of a WV pair plus two jets in the semileptonic channel is obtained!



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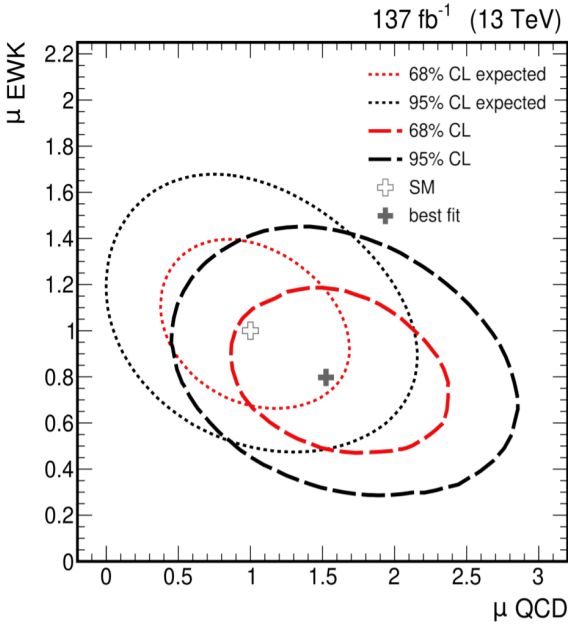


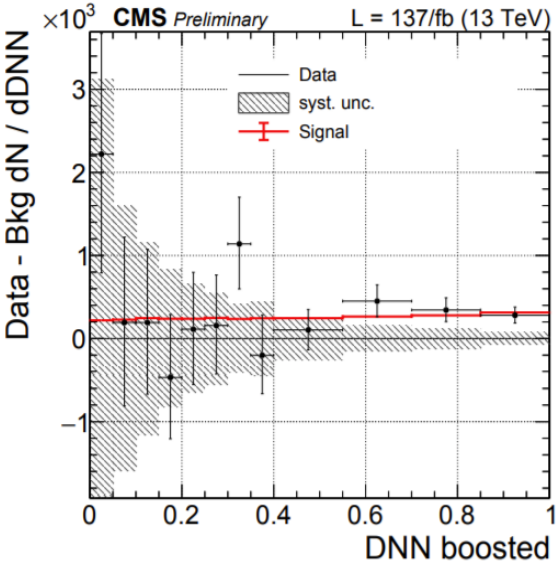
EW signal strength (4.4 σ):

$$0.85^{+0.24}_{-0.20} = 0.85^{+0.21}_{-0.17}(\text{syst})\ ^{+0.12}_{-0.12}(\text{stat}),$$

EW+QCD signal strength:

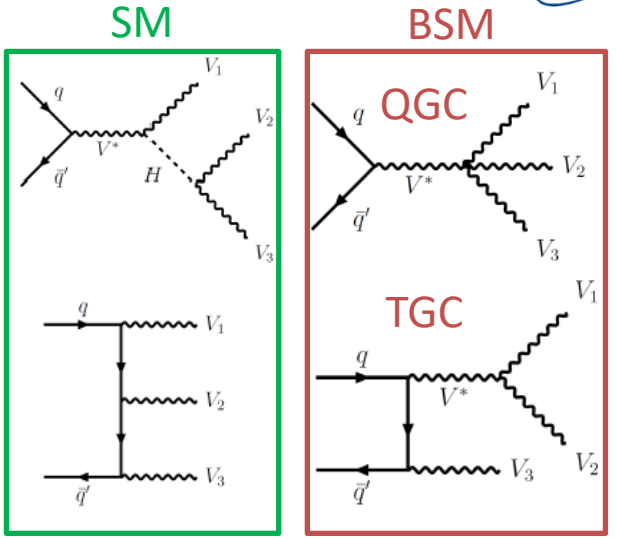
$$0.98^{+0.20}_{-0.17} = 0.98^{+0.19}_{-0.16}(\text{syst})\ ^{+0.07}_{-0.07}(\text{stat})$$

Simultaneous two-dimensional fit of the EW and QCD WV production is performed. It is in agreement with the SM predictions within the 68% confidence interval



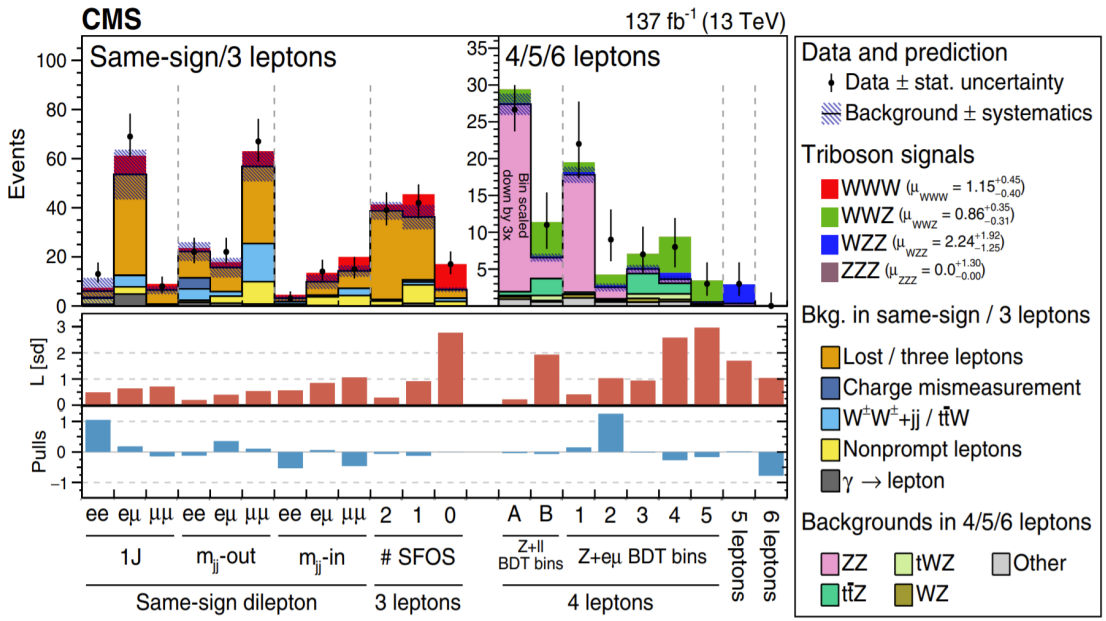
Production of Three Massive Gauge Bosons

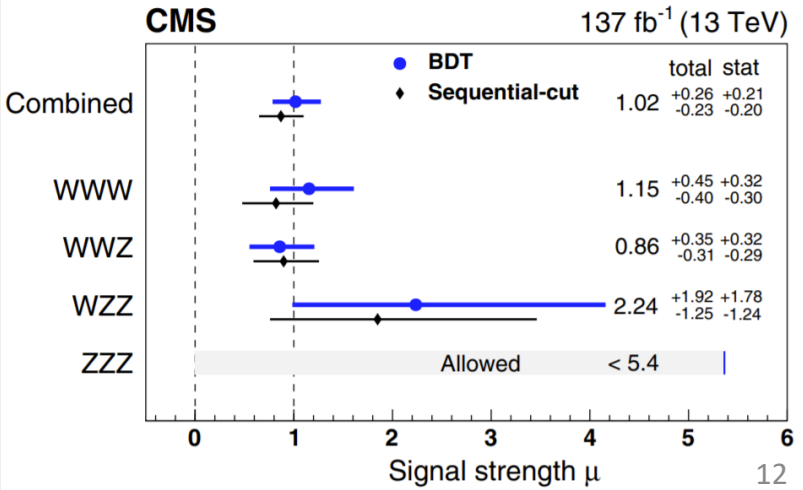
- Triboson final states are among the least-known SM processes due to their small production cross sections
- The presence of quadruple gauge boson interactions can be probed through VVV production
- ✓ First observation by CMS with significance:
  - VVV (Combined) - 5.7 s.d. (with 5.9 expected)
  - WWW – 3.3 (3.4) s.d.
  - WWZ – 3.1 (4.1) s.d.
- Observed by ATLAS as well with significance 8.3 (PLB 798 (2019) 134913)



Five final states are considered (where $\ell = e$ or μ): $W^\pm W^\pm W^\mp \to \ell^\pm\ell^\pm 2\nu q\bar{q}'$, $W^\pm W^\pm W^\mp \to \ell^\pm\ell^\pm\ell^\mp 3\nu$, $W^\pm W^\mp Z \to \ell^\pm\ell^\mp 2\nu\ell^\pm\ell^\mp$, $W^\pm ZZ \to \ell^\pm\nu 2(\ell^\pm\ell^\mp)$, and $ZZZ \to 3(\ell^\pm\ell^\mp)$.

PRL 125, 151802 (2020)

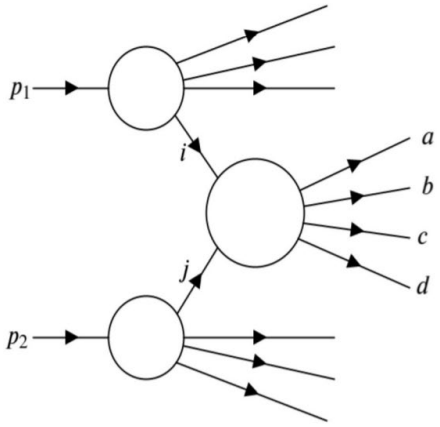




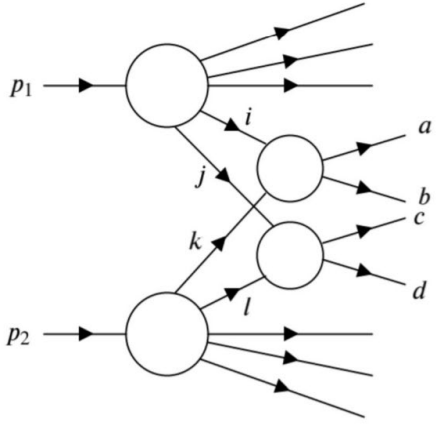
Double Parton Scattering (DPS)

DPS - Events where two hard parton-parton interactions occur in single proton-proton collisions

SPS



DPS

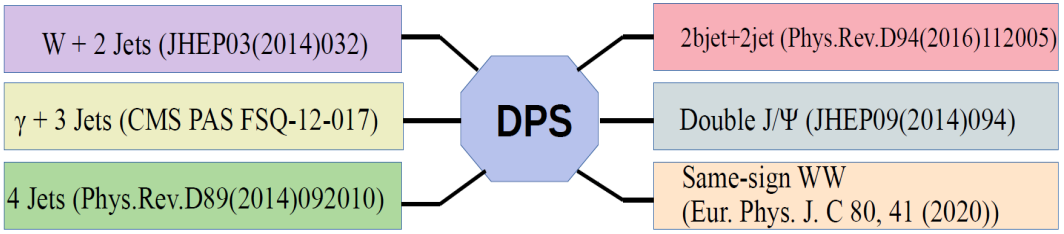


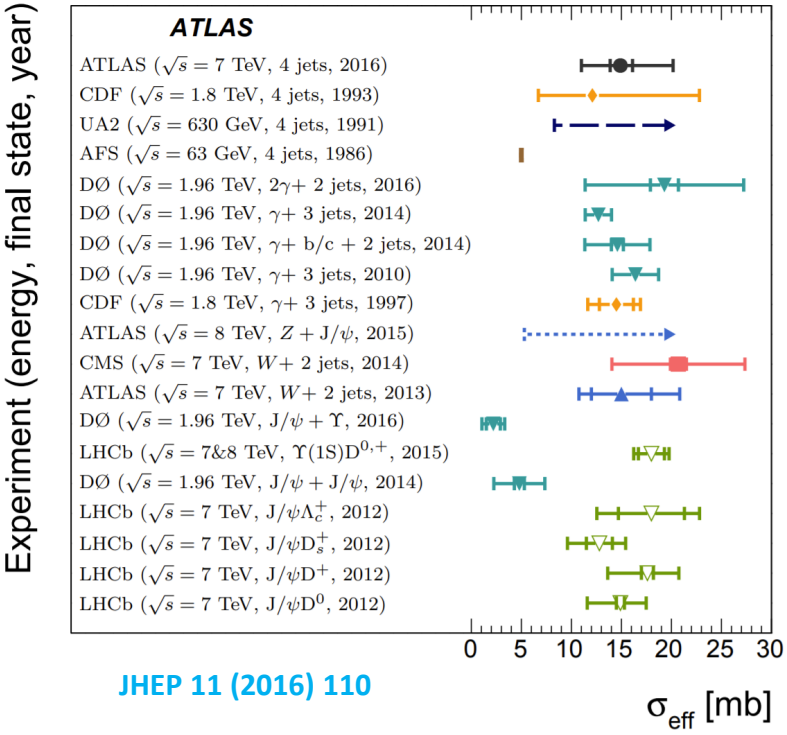
$$\sigma^{\mathrm{DPS}}_{\mathrm{A,B}} = \frac{m}{2}\frac{\sigma_{\mathrm{A}} \cdot \sigma_{\mathrm{B}}}{\sigma_{\mathrm{eff}}}$$

m = 1 when A=B
m = 2 when A≠B

σ_{eff} reflects how strongly the occurrence of A and B is correlated

- Background for rare SM processes
- Provides information on transverse partonic distribution of hadrons
- Is σ_{eff} independent on the process and interaction energy?





JHEP 11 (2016) 110

Double Parton Scattering. 4 jets

Observables:

$$\Delta\phi_{\text{soft}} = |\phi_3 - \phi_4|$$

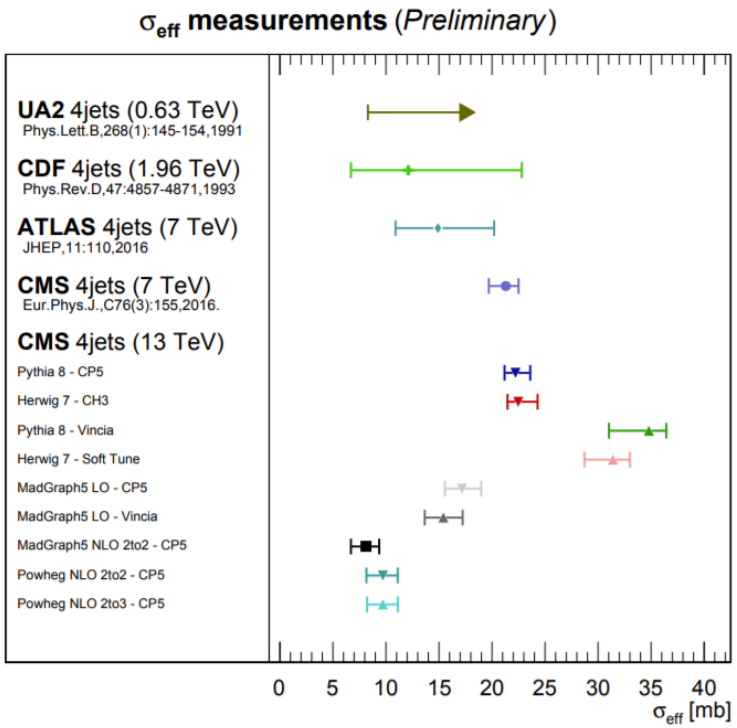
$$\Delta\phi_{3j}^{\min} = \min\left\{|\phi_i - \phi_j| + |\phi_j - \phi_k| \,\middle|\, i,j,k \in [1,2,3,4], i \neq j \neq k\right\}$$

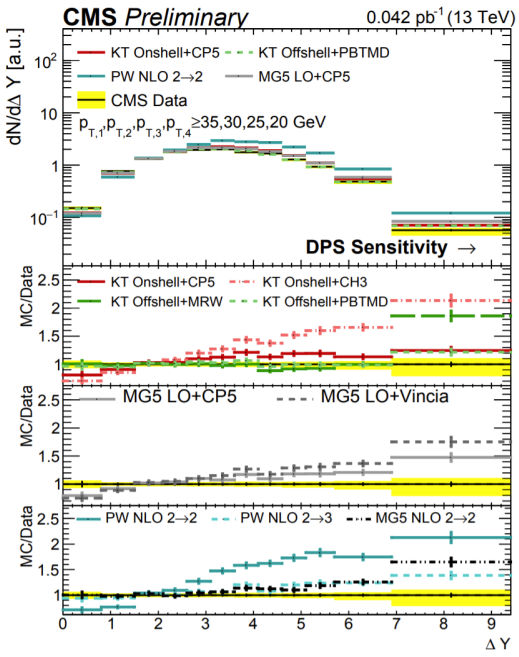
$$\Delta Y = \max\left\{|\eta_i - \eta_j| \,\middle|\, i,j \in [1,2,3,4], i \neq j\right\}$$

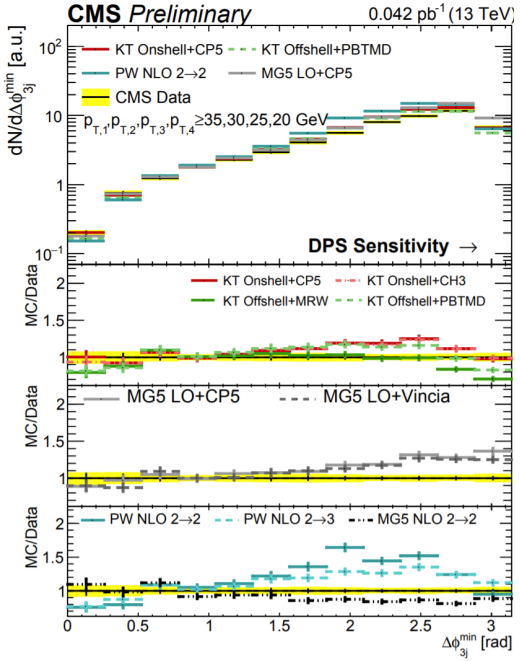
$$\phi_{ij} = |\phi_i - \phi_j| \quad \text{for} \quad \Delta Y = |\eta_i - \eta_j|$$

$$\Delta p_{\text{T,soft}} = \frac{|\vec{p}_{\text{T},3} + \vec{p}_{\text{T},4}|}{|\vec{p}_{\text{T},3}| + |\vec{p}_{\text{T},4}|}$$

$$\Delta S = \arccos\left(\frac{(\vec{p}_{\text{T},1} + \vec{p}_{\text{T},2}) \cdot (\vec{p}_{\text{T},3} + \vec{p}_{\text{T},4})}{|\vec{p}_{\text{T},1} + \vec{p}_{\text{T},2}|\,|\vec{p}_{\text{T},3} + \vec{p}_{\text{T},4}|}\right)$$







Data distributions compared with:

1. PYTHIA8 and HERWIG
2. Multijet Models
3. SPS+DPS Models

- ✓ Models based on NLO and/or higher-multiplicity matrix elements good describes ΔY separation but are inferior to LO models in $\Delta\varphi_{3j}^{min}$ distribution description
- ✓ Strong dependence of extracted value of σ_{eff} on the model to describe SPS contribution

Double Parton Scattering. Z+jets

Cross section (pb)		Z+ ≥1 Jets	Z+ ≥2 Jets
Measured in data		158.5 ± 0.3 (stat) ±7.0 (syst) ±1.2 (theo) ±4.0 (lumi) pb	44.8 ± 0.4 (stat) ±3.7 (syst) ±0.5 (theo) ±1.1 (lumi) pb
Predicted by MC			
MG5_aMC (NLO)	PYTHIA8, CP5 tune	167.4 ± 9.7	47.0 ± 3.9
	PYTHIA8, CP5 tune MPIOFF	143.8 ± 0.3	37.7 ± 0.2
	PYTHIA8, CDPSTP8S1-WJ tune	178.4 ± 0.3	50.5 ± 0.2
	HERWIG7, CH3 tune	158.3 ± 1.1	44.4 ± 0.6
MG5_aMC (LO) + PYTHIA8, CP5 tune		161.2 ± 0.1	45.3 ± 0.1
SHERPA (NLO+LO)		149.8 ± 0.2	41.6 ± 0.1

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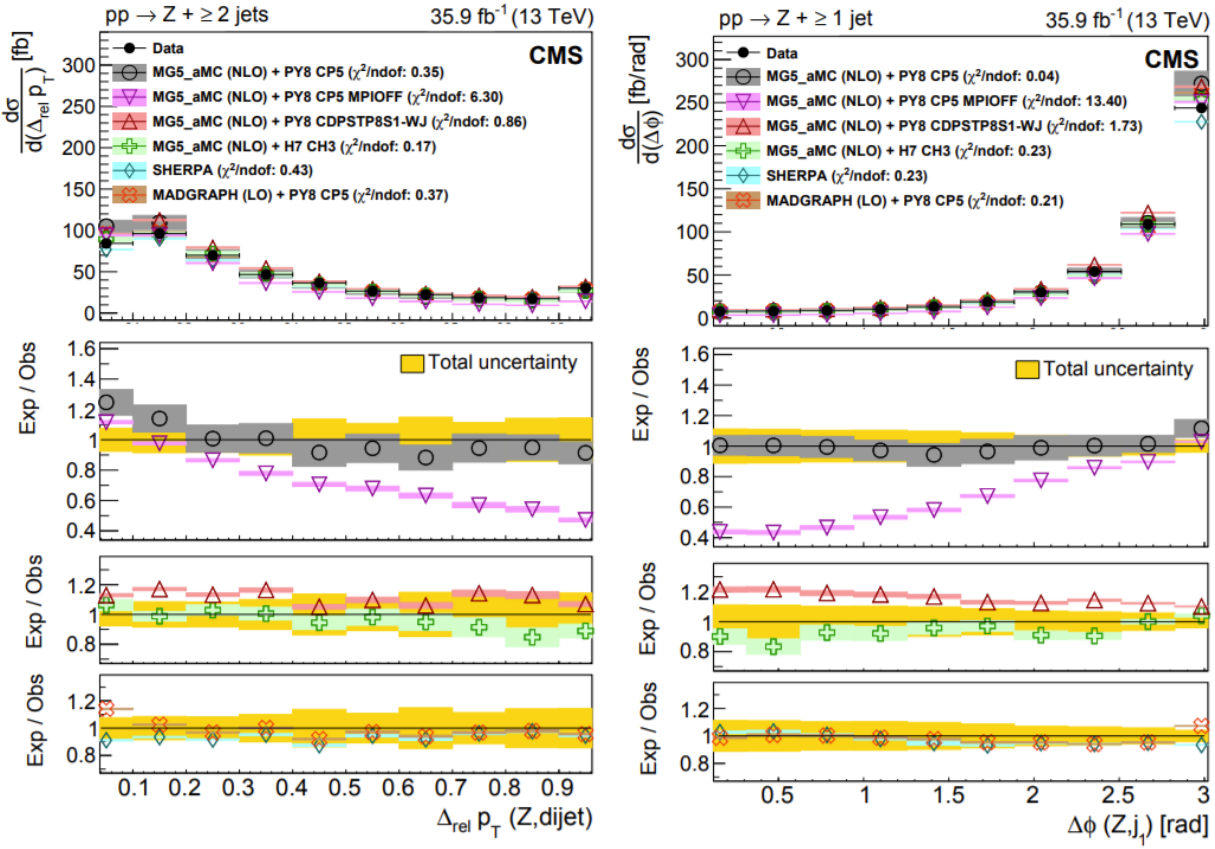


Observables:

- Z+1 jet:

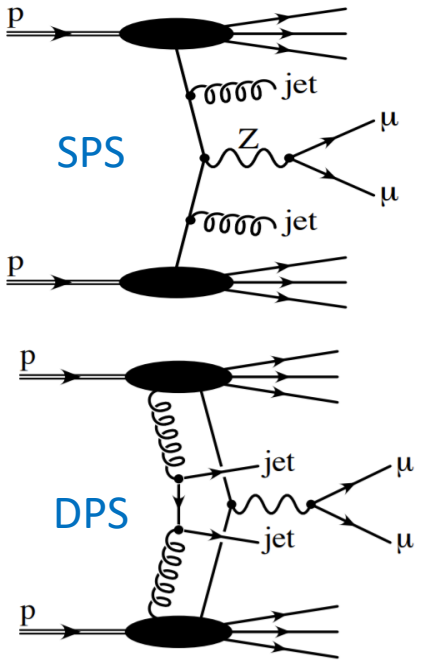
$$\Delta\phi(Z, j_1)$$

$$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(Z, j_1) = \frac{|\vec{p}_{\mathrm{T}}(Z) + \vec{p}_{\mathrm{T}}(j_1)|}{|\vec{p}_{\mathrm{T}}(Z)| + |\vec{p}_{\mathrm{T}}(j_1)|}$$

- Z+≥2 jet:

$$\Delta\phi(Z, \mathrm{dijet})$$

$$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(Z, \mathrm{dijet}) = \frac{|\vec{p}_{\mathrm{T}}(Z) + \vec{p}_{\mathrm{T}}(\mathrm{dijet})|}{|\vec{p}_{\mathrm{T}}(Z)| + |\vec{p}_{\mathrm{T}}(\mathrm{dijet})|}$$



Double Parton Scattering. Z+jets

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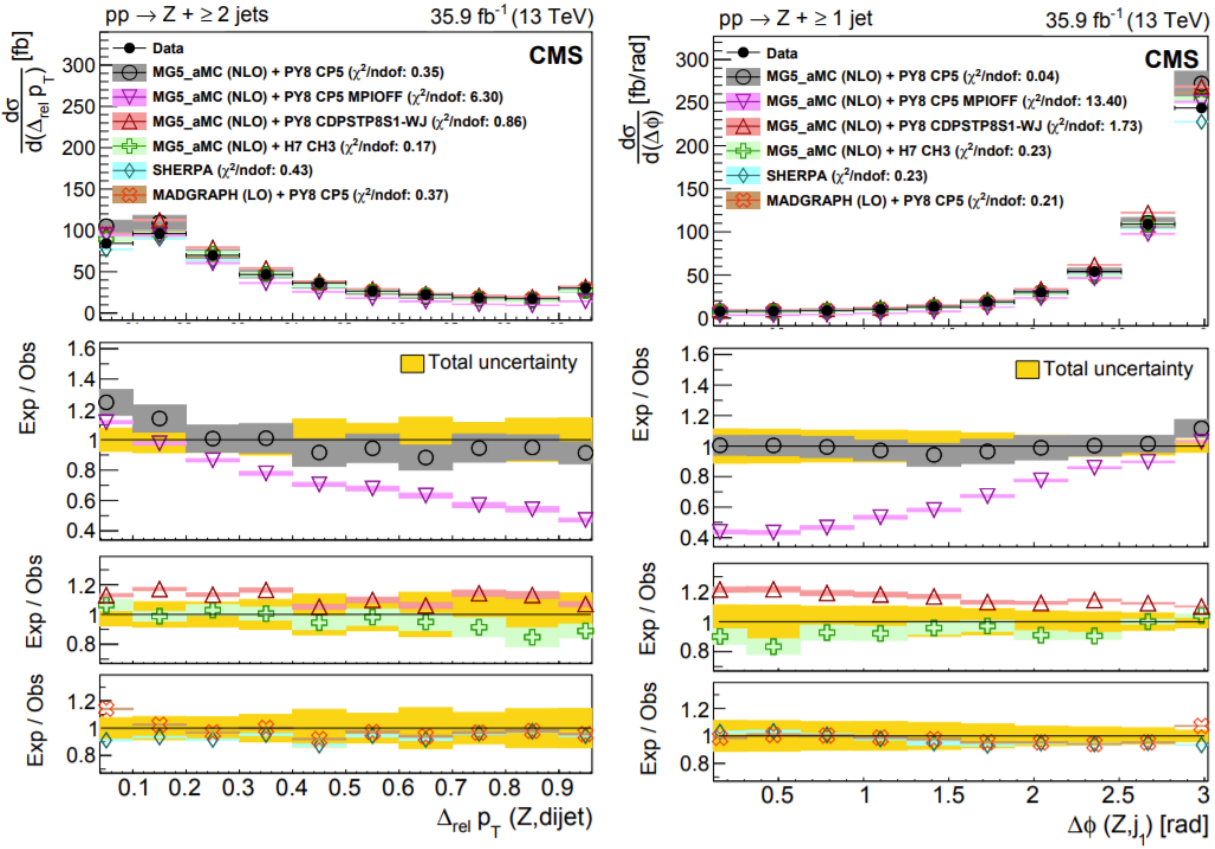
SMP-20-009



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- Z+≥2 jet:

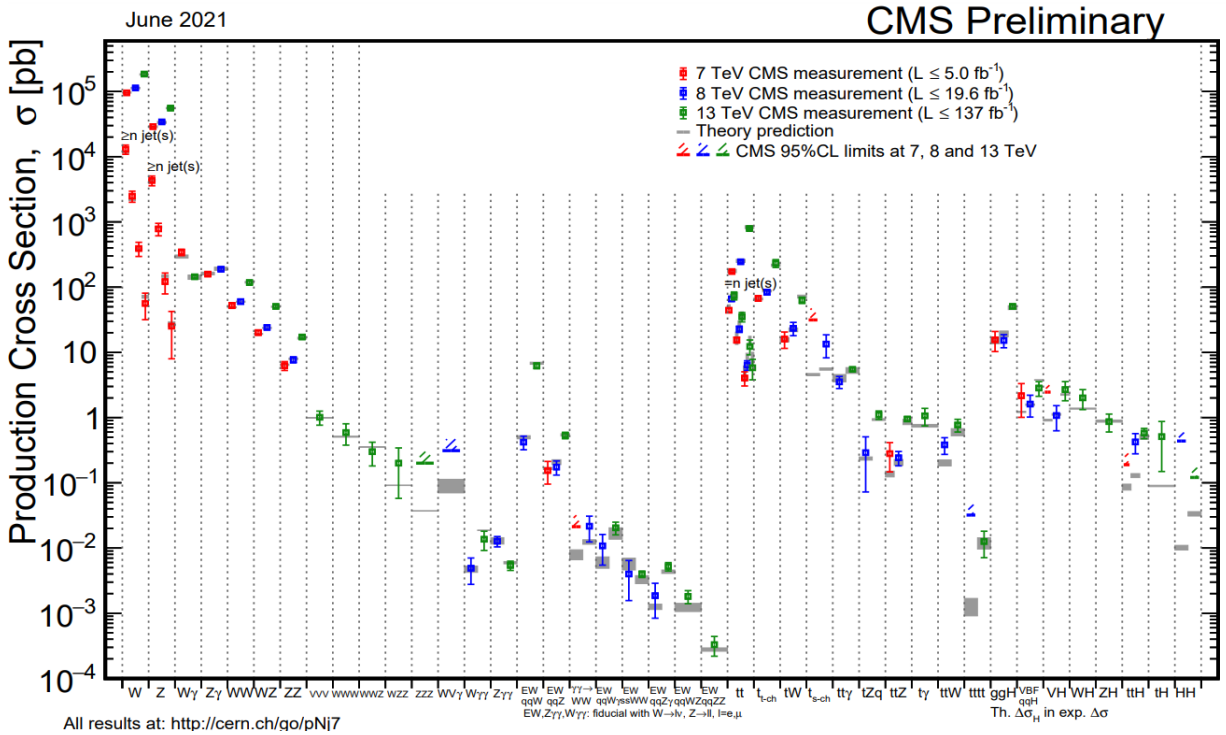
$$\Delta\phi(Z, \mathrm{dijet})$$

$$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(Z, \mathrm{dijet}) = \frac{|\vec{p}_{\mathrm{T}}(Z) + \vec{p}_{\mathrm{T}}(\mathrm{dijet})|}{|\vec{p}_{\mathrm{T}}(Z)| + |\vec{p}_{\mathrm{T}}(\mathrm{dijet})|}$$

- ✓ The first DPS observation with Z+jets topology at the LHC
- ✓ The different approaches for predictions were tried. MPI (MG5 aMC + HERWIG7, SHEPRA) models reasonably well describe measurements, However, there are parts of the distributions that are not well described. A proper simulation of MPI is essential!

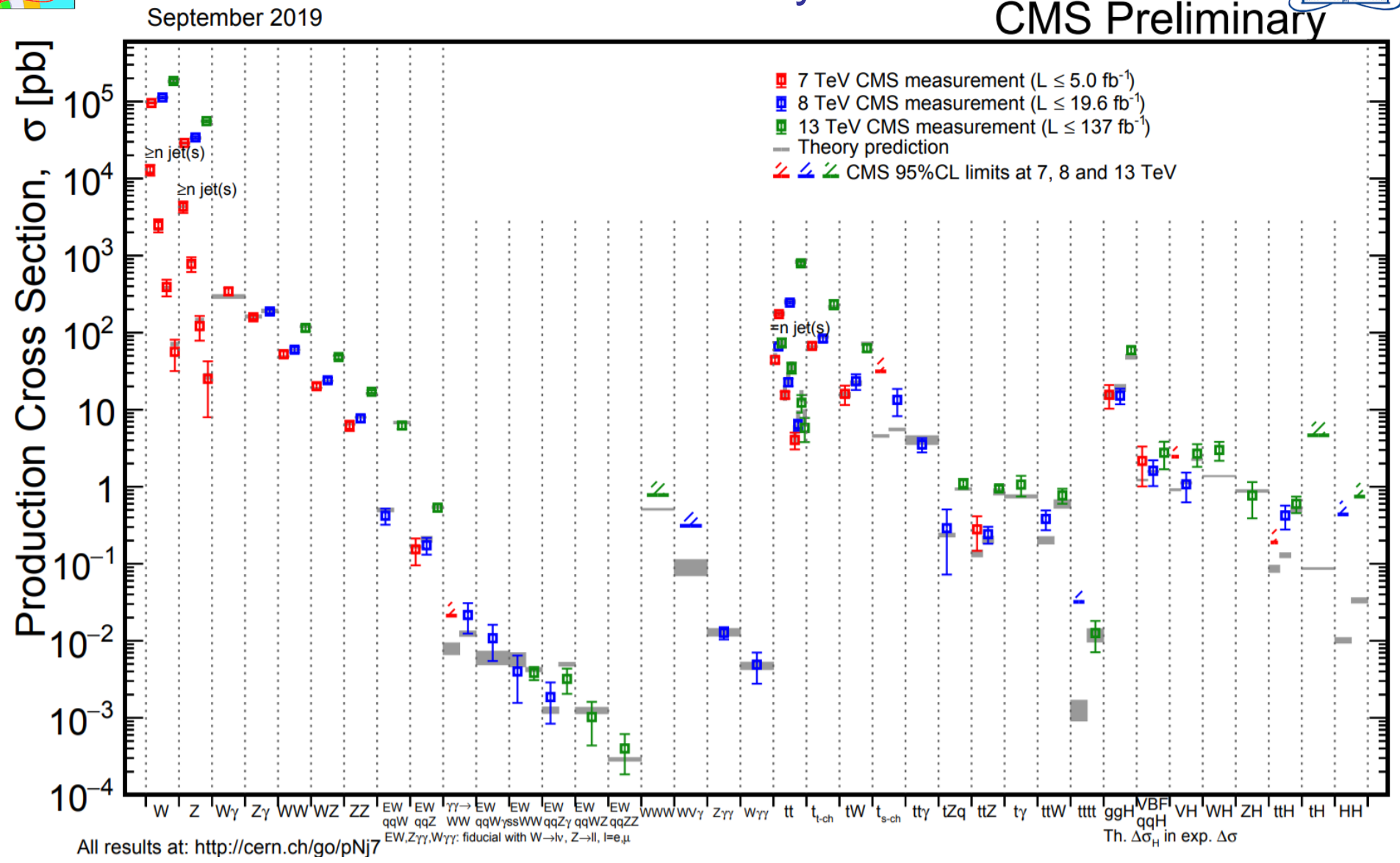
Conclusions

- ✓ CMS show an excellent performance to detect different signals and produced many EWK and QCD measurements at 7, 8 and 13 TeV
- ✓ Precision measurements of inclusive W and Z and di-boson production cross section with large statistic
- ✓ Detailed studies of differential cross sections and many observables, like asymmetries and angular coefficients
- ✓ W and Z production associated to jets, including Z plus b-jets, studied W polarisation in W+jets
- ✓ All measurements are so far in agreement with theoretical predictions from the Standard model and results of another experiments. No new physic is observed



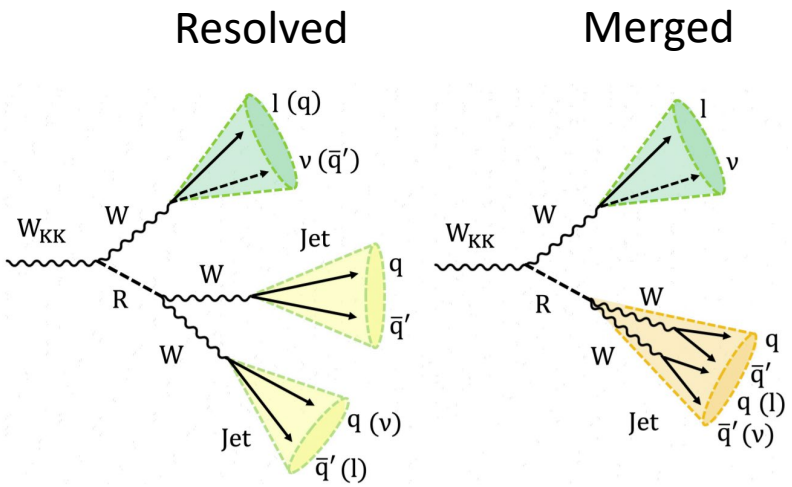
Thanks for your attention!

Summary



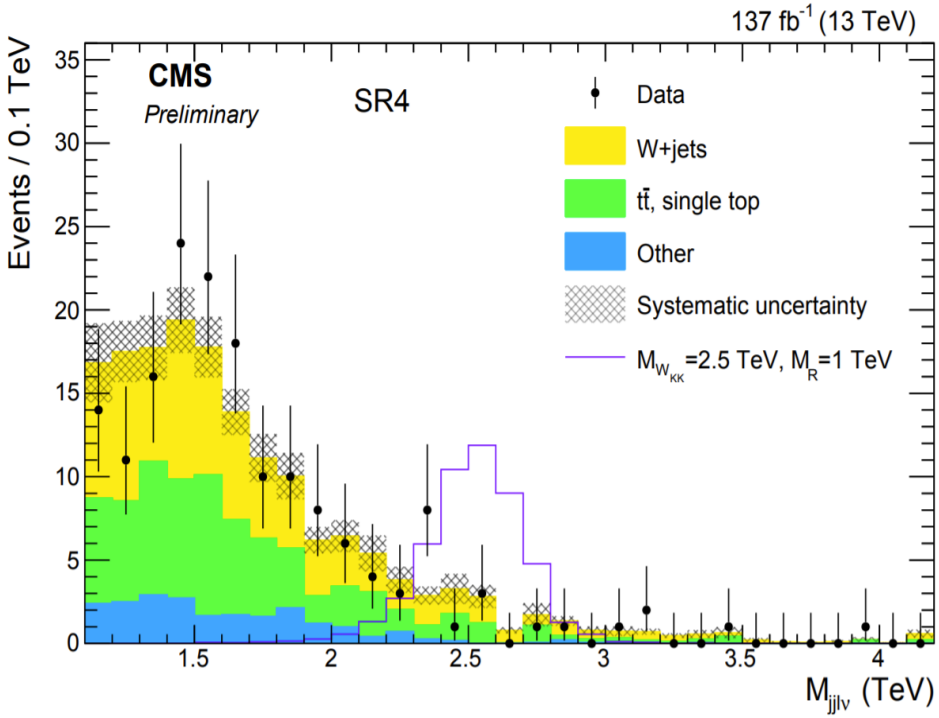
CMS shows a excellent performance to detect different signals!

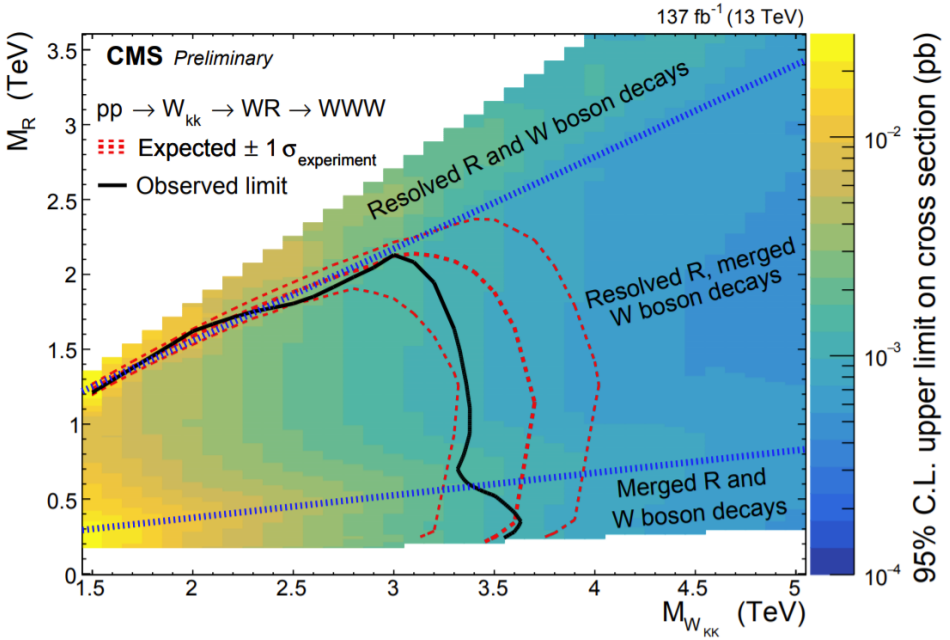
Search for resonances decaying to triple W-boson final states



- Some benchmark BSM models predict contribution in this channel
- Firs direct search for resonance triboson decay
- First search for $W_{KK} \rightarrow WR$ with $R \rightarrow WW$ decay

CMS PAS B2G-20-001





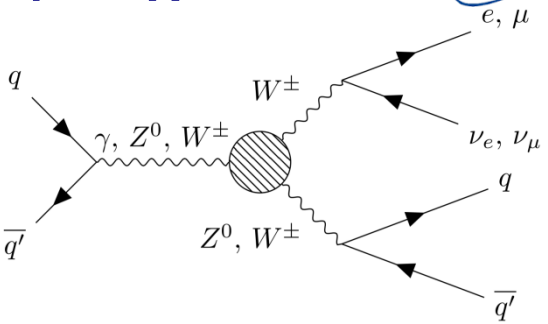
No deviations from Standard model predictions are observed!

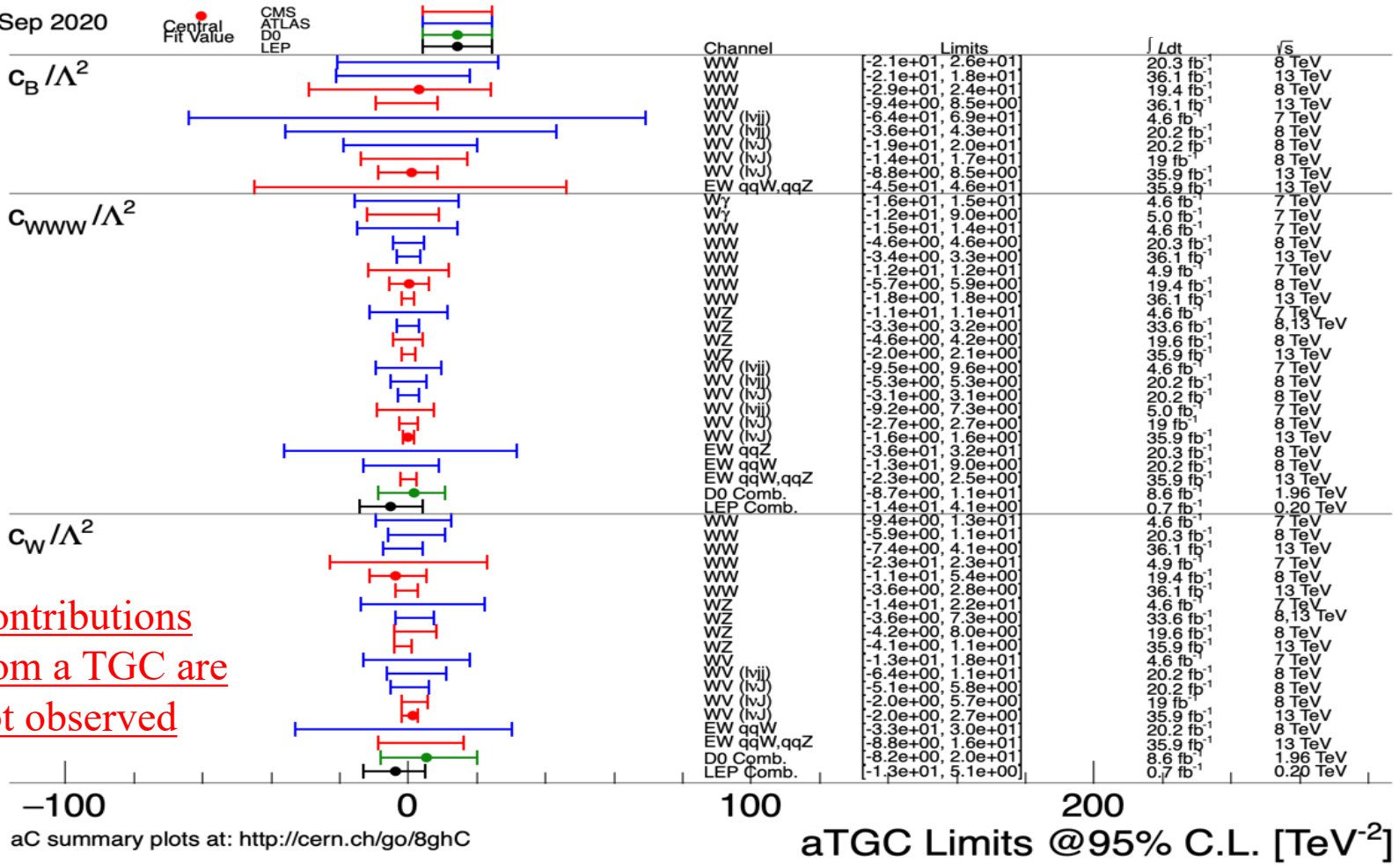
Upper limit are set on $M_{W_{KK}}$ and M_R model parameters!

Anomalous Triple Gouge Couplings

Standard model predictions: $c_W = c_{WWW} = c_B = 0$

Non-zero c-coefficients could indicate a new physics!

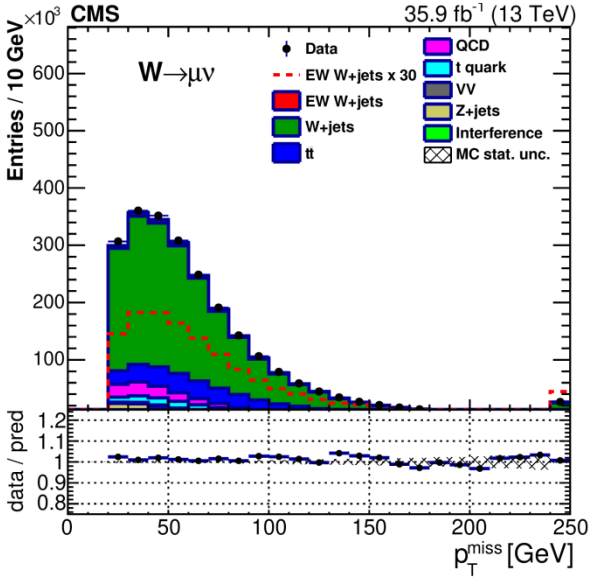


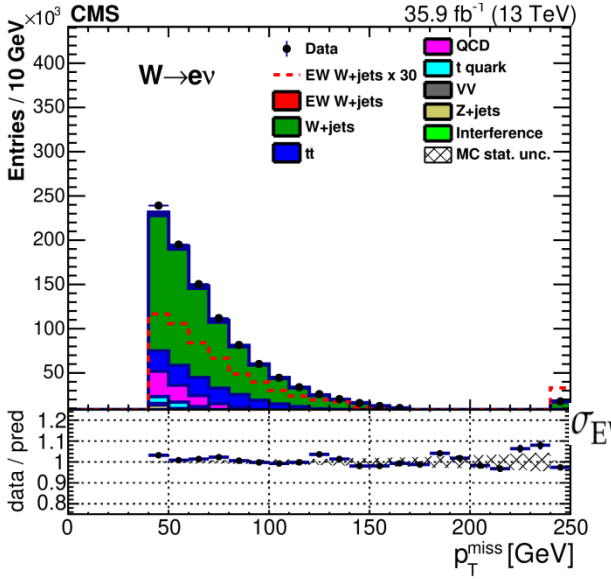


Contributions from a TGC are not observed

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

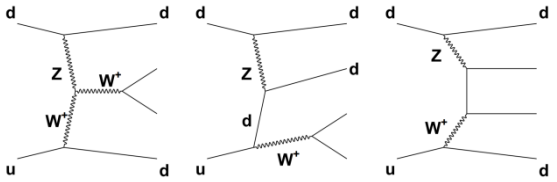
NLO pQCD Stringent Tests: V + jets, VV+jets





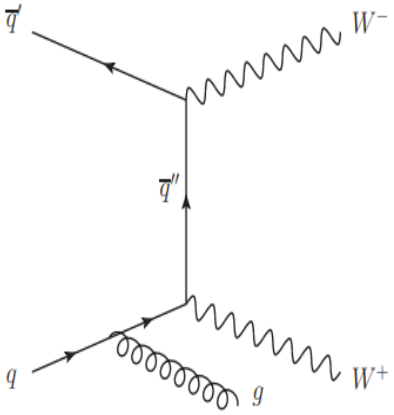
EPJ C 80 (2020) 43

W + 2jets

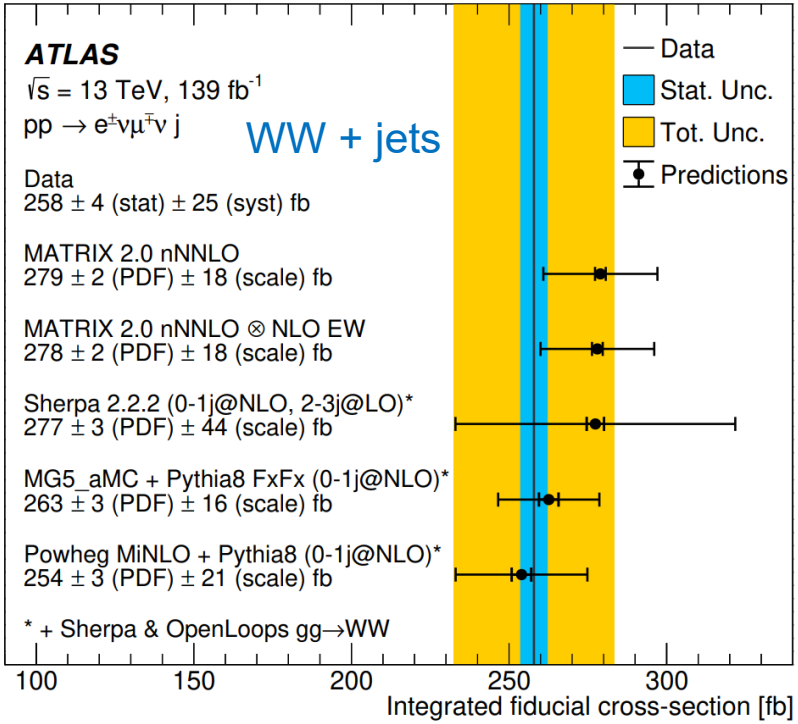


$$\sigma_{EW}(Wjj) = 6.23 \pm 0.12\,(stat) \pm 0.61\,(syst)$$

JHEP 06 (2021) 003

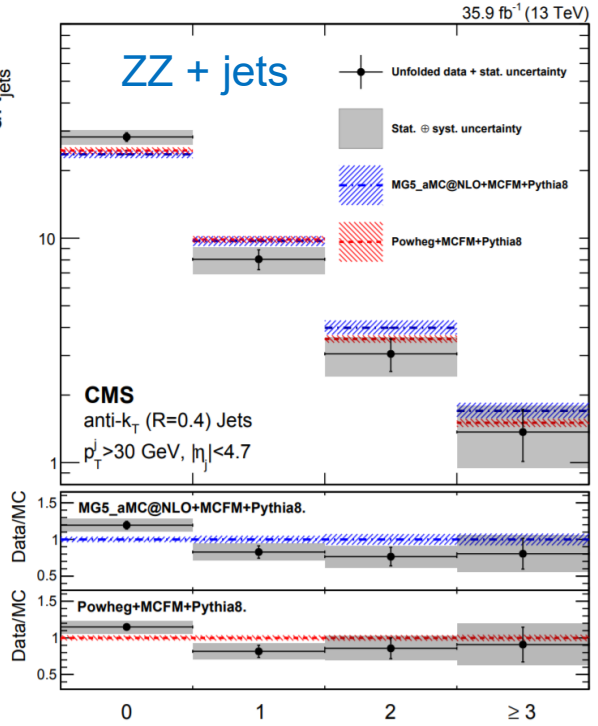


WW + jets



Agrees with the NLO and NNLO standard model prediction!

ZZ + jets



PLB 789 (2019) 19-44