Measurements of V+jets production in CMS

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On behalf of the CMS Collaboration

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Introduction

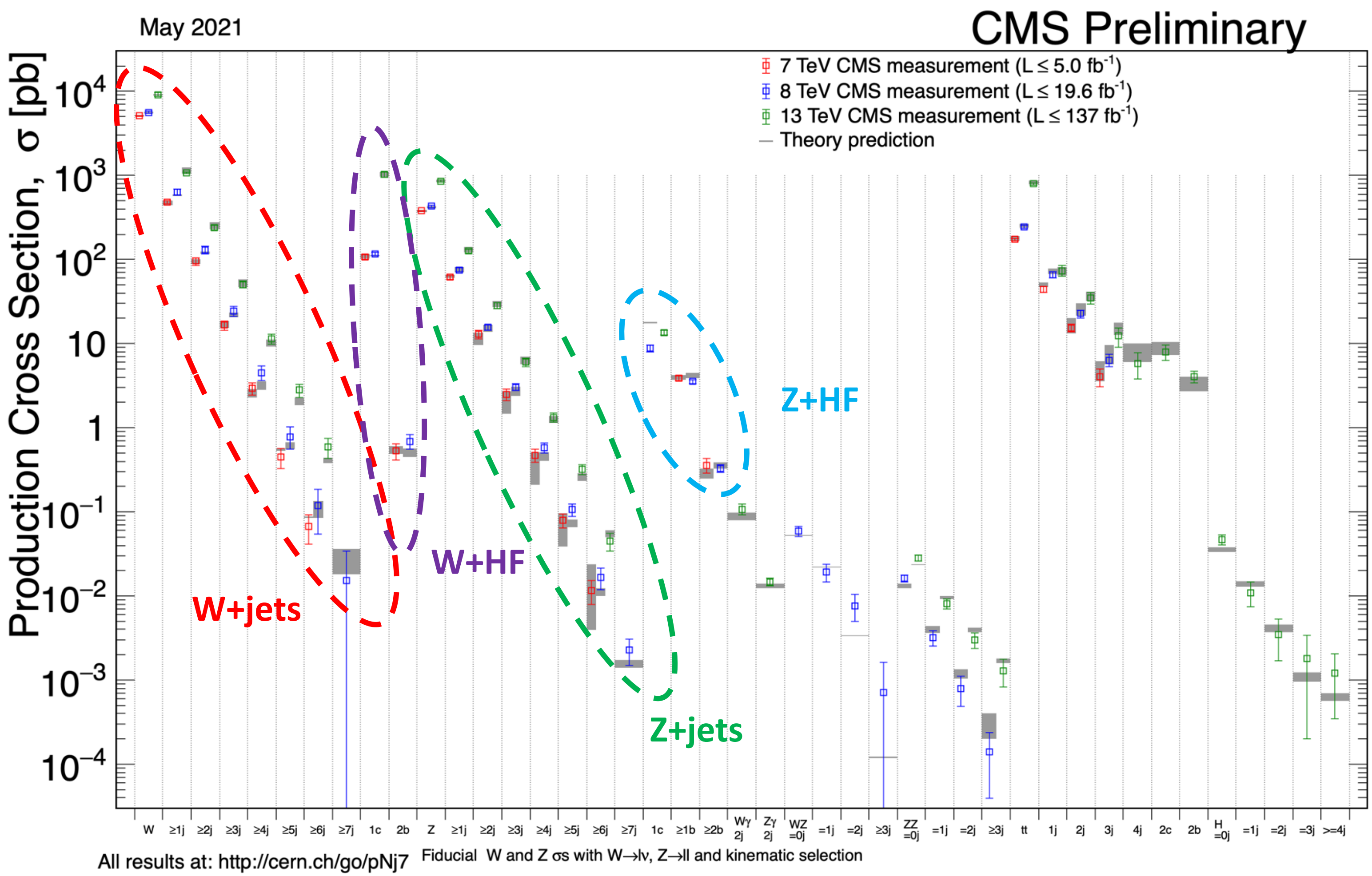
- **Electroweak vector boson (V=W, Z, and γ) plus jets at the LHC has several motivations:**
  - **copious production in pp collisions enables precision tests of the SM**
  - **stringent tests for MC event generators and perturbative QCD calculations**
  - **prominent backgrounds for SM processes and new physics searches**
  - **good probes for the quark and gluon PDFs in the proton**
  - **inputs for calibrating detector response (lepton, jet, and missing energy performances)**

- W and Z boson are reconstructed via leptonic final states: $Z/\gamma^* \to l^+ l^-$ and $W \to l\nu$ ($l = e, \mu$)
- Prompt photons are reconstructed from isolated energy deposits in the electromagnetic calorimeter (ECAL)
- Their measurements are corrected for detector effects to fiducial phase space and compared with predictions from several MC event generators and theoretical calculations, where available

- **Presented here only the more recent V+jets results mostly based on 13 TeV pp collisions**

- **A complete set of CMS V+jets (and more SM) measurements can be found at:**
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

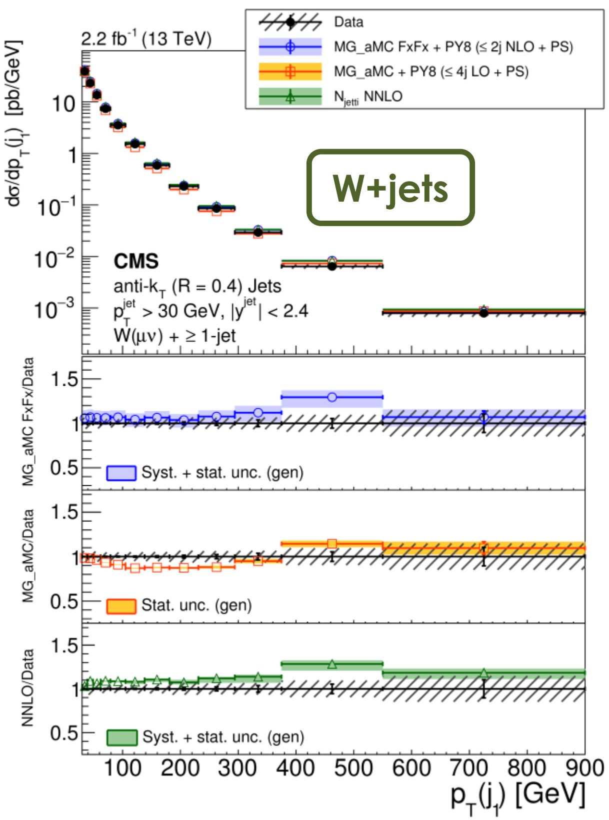
Summary of V+jets measurements

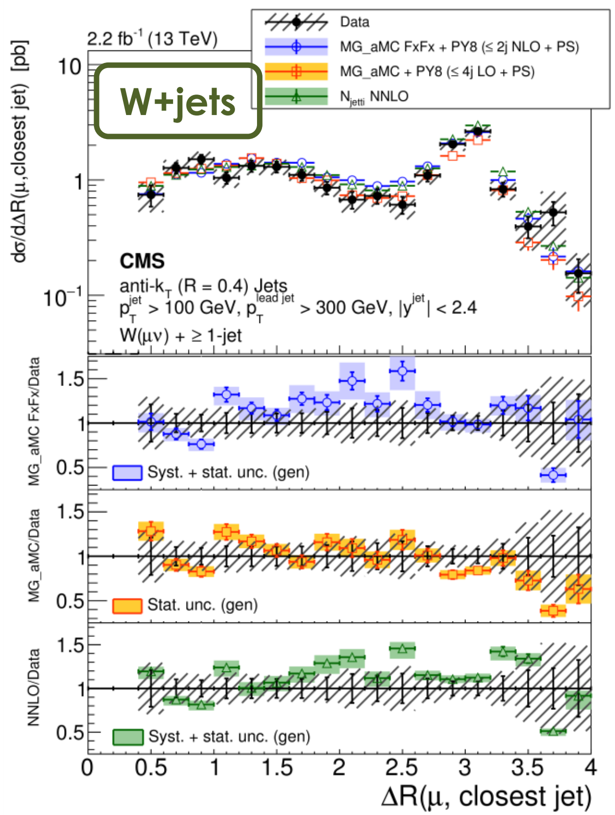


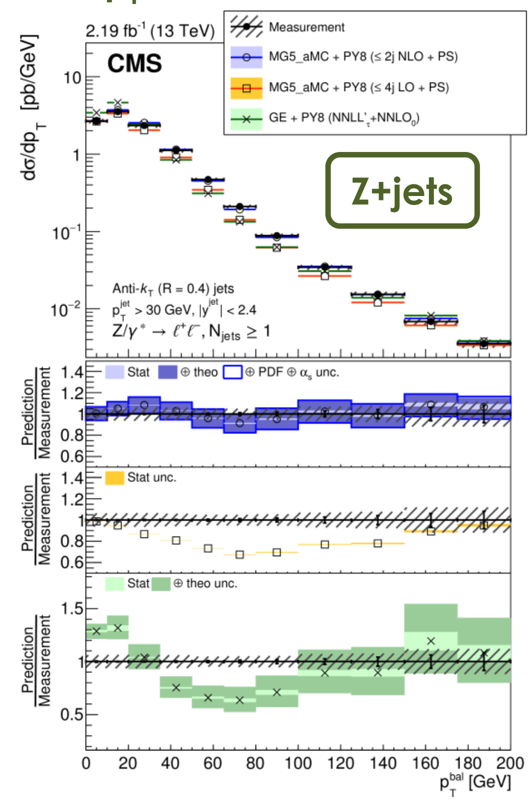
- CMS V+jets measurements at 7, 8, and 13 TeV span several orders of magnitude in cross section
- *See M. Meena's dedicated talk on V+HF measurements, presented in Monday's Flavor II session!*

W/Z+jets *(Phys. Rev. D 96 (2017) 072005, Eur. Phys. J. C 78 (2018) 965)*

- Differential cross section (xsec) measurements of several kinematical/angular variables at 13 TeV
  - W+jets: $p_T(\mu)>25$ GeV, $|\eta(\mu)|<2.4$, $p_T(j)>30$ GeV, $|y(j)|<2.4$, and $m_T(W)>50$ GeV
  - Z+jets: $p_T(l)>20$ GeV, $|\eta(l)|<2.4$, $p_T(j)>30$ GeV, $|y(j)|<2.4$, $71<m_{ll}<111$ GeV
- Comparison with (N)LO ME+PS, fixed-order NNLO, and NNLO+NNLL+PS predictions
- Generally, better agreement of the data with the (N)NLO predictions
- **Probing W collinear emission off a jet with $\Delta R(\mu, j)$ & Z+jets imbalance with p_T^{bal}**



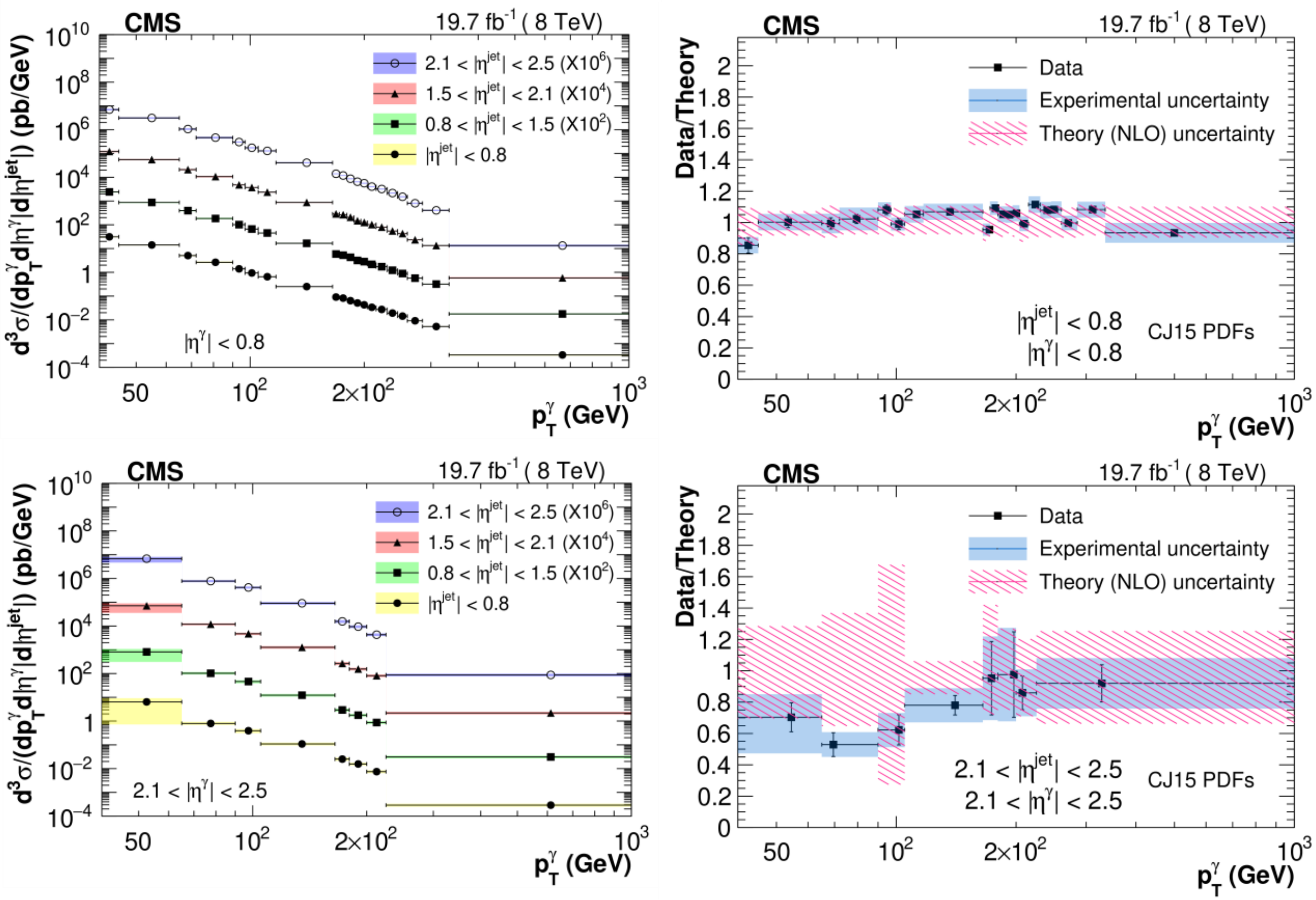




$$p_T^{bal} = \left| \vec{p}_T(Z) + \sum_{jets} \vec{p}_T(j_i) \right|$$

γ+jet at 8 TeV *(Eur. Phys. J. C 79 (2019) 969)*

- Triple differential xsecs as functions of $p_T(\gamma)$, $|\eta(\gamma)|$, and $|\eta(j)|$
  - γ isolation based on sum p_T of all particles in a cone of radius $\Delta R=0.3$ is less than 5 GeV
  - $p_T(\gamma)$=40-1000 GeV, $|\eta(\gamma)|<2.5$, $p_T(j)>25$ GeV, and $|\eta(j)|<2.5$
  - 16 different combinations of $|\eta(\gamma)|$ and $|\eta(j)|$ regions

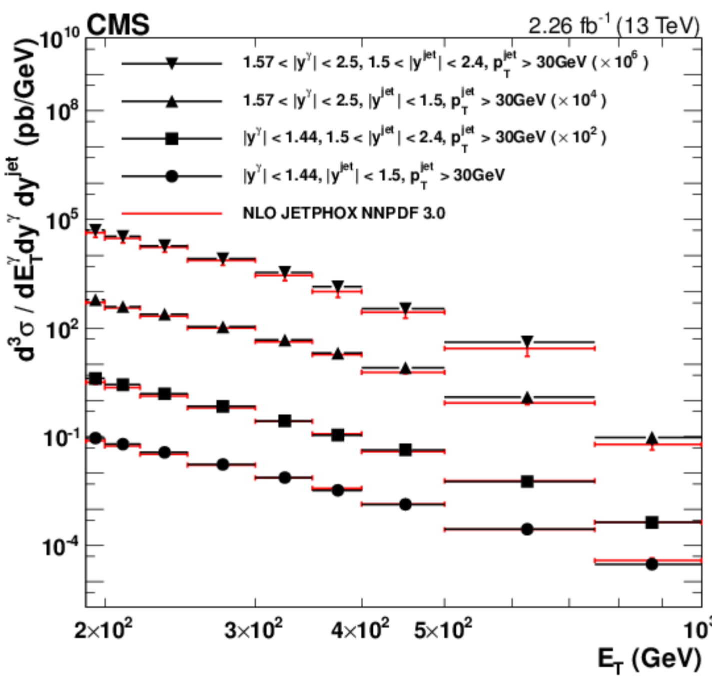


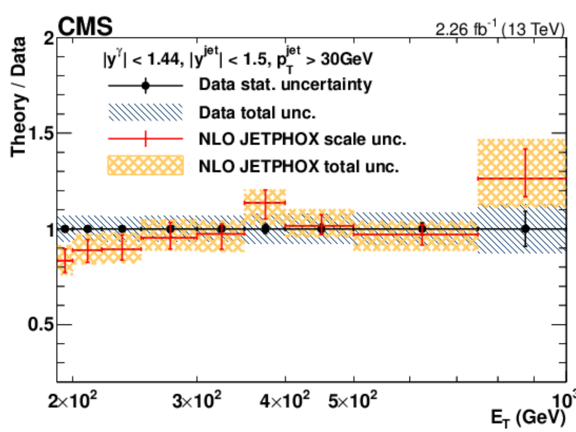
- **Good agreement between data and GamJet NLO (using CJ15 PDF set and set II BFG fragmentation functions)**
- **Probing a wide range of Q^2 and x_T with smaller experimental uncertainties compared to theory**

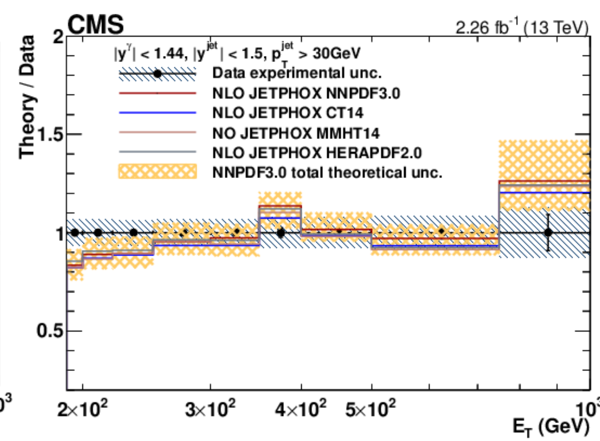
- **γ+jet measurements are potentially sensitive to gluon PDF in the proton**

γ+jet at 13 TeV *(Eur. Phys. J. C 79 (2019) 20)*

- Triple differential xsecs for γ+jet events, with γ isolation in a cone of $\Delta R=0.4$
  - several shower shape and isolation variables used in an MVA (BDT)
  - fiducial selection: $E_T(\gamma)>190$ GeV, $|y(\gamma)|<2.5$, $|y(j)|<2.4$, and $p_T(j)>30$ GeV
  - in the extended $E_T(\gamma)$ range up to 1 TeV for two photon and two jet rapidity ranges
- Compared with JETPHOX 1.3.1 NLO (using NNPDF3.0 PDF and set II BFG frag. functions)
  - reasonable agreement between data and predictions within uncertainties
  - the differences between predictions using different PDF sets are not sizable





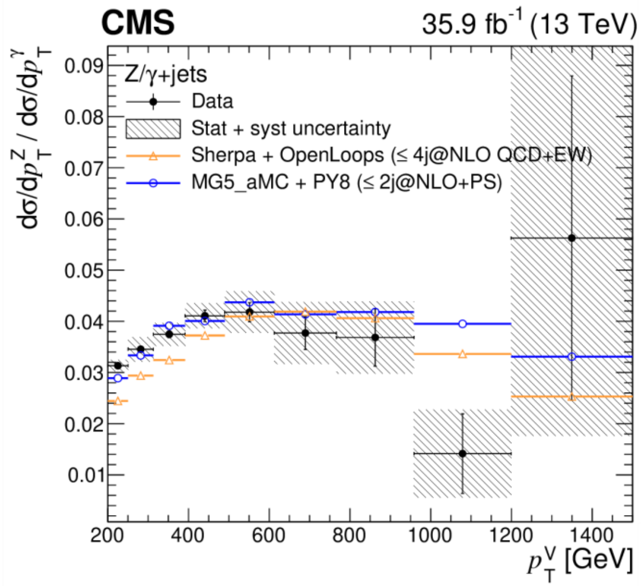


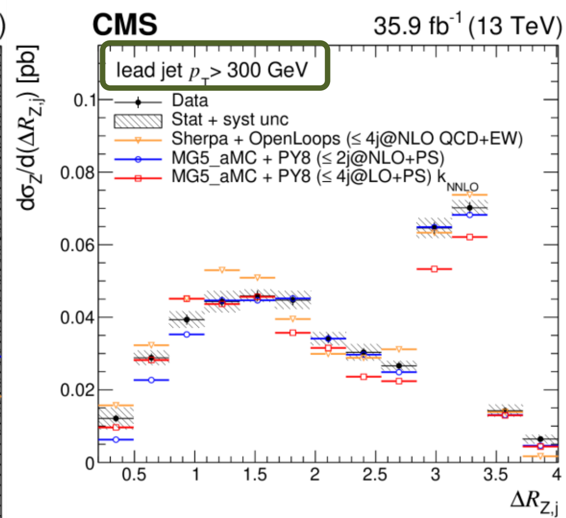
for $|y(\gamma)|<1.44$ and $|y(j)|<1.5$

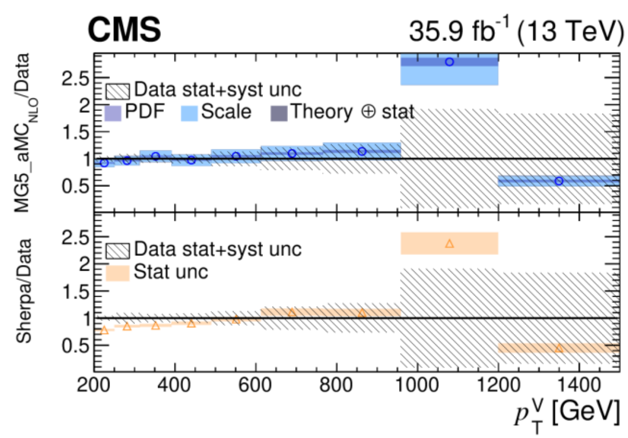
Z+jets/γ+jets at 13 TeV *(arXiv:2102.02238)*

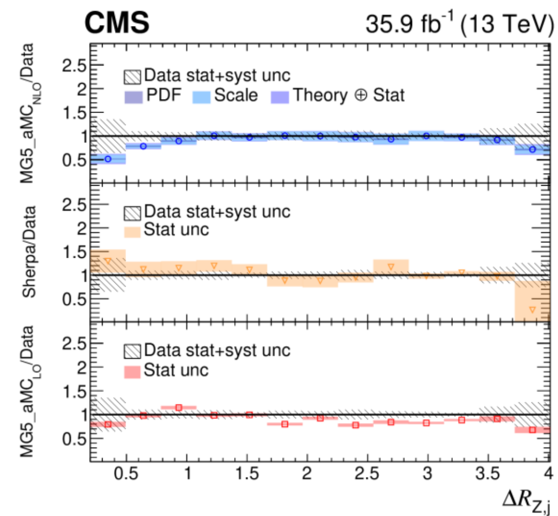
new!

- Differential xsec measurements for Z+jets, γ+jets, and their ratio
  - $p_T(V)>200$ GeV and $|y(V)|<1.4$
  - at least one jet with $p_T>100$ GeV and $|\eta|<2.4$
- First direct measurement of collinear emission of a Z boson with a jet based on the $\Delta R_{Z,j}$
  - require harder leading jet p_T thresholds (>300 and 500 GeV) to enhance collinear emission
- Predictions by MG5_aMC at (N)LO, Sherpa+OpenLoops NLO QCD+EW, JETPHOX NLO (for γ)
- Predictions are generally in agreement with the data except some deviations in a few ranges of the distributions
- **Z/γ ratio provides input to help reduce uncertainties related to the Z→νν̄ bkg. estimation in new physics searches**









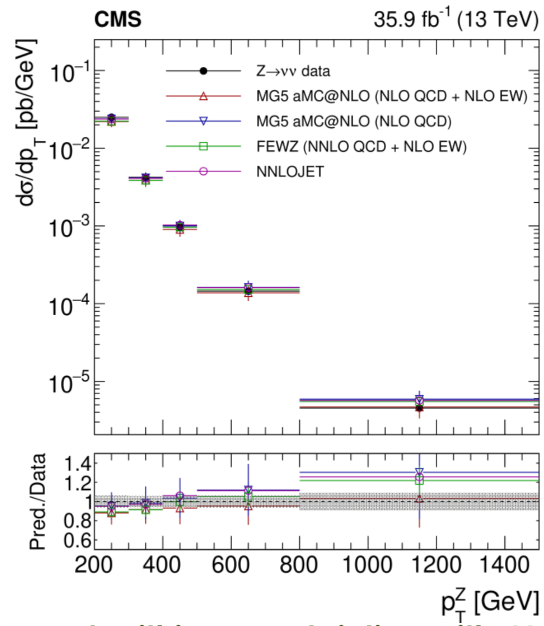
The Z/γ ratio is sensitive to higher order QCD and EW corrections at high p_T range

$\Delta R_{Z,j}$<2.5 ($\Delta R_{Z,j}$>2.5) dominated by collinear (back-to-back) production

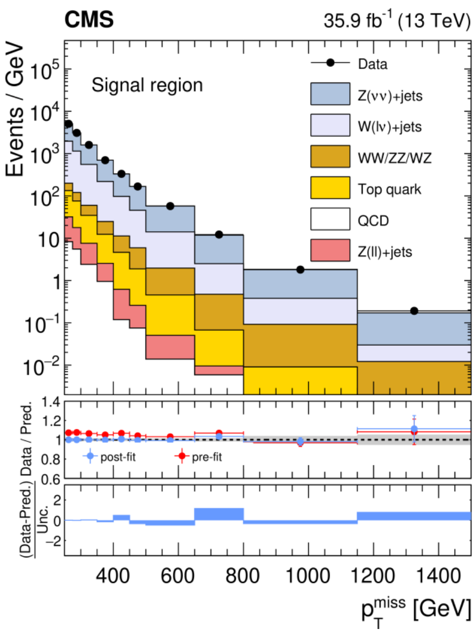
$Z(\rightarrow\nu\bar{\nu})$+jets *(arXiv:2012.09254)*

new!

- Measurements of fiducial and differential xsec of $Z\rightarrow\nu\bar{\nu}$+jets at 13 TeV
  - important background to searches with invisible decays (SUSY, dark matter, etc.)
  - neutrinos reconstructed indirectly through the p_T imbalance in the event
  - $p_T^{miss}>250$ GeV, and the leading jet $p_T>100$ GeV and $|\eta|<2.4$
- **Measured fiducial xsec for $p_T(Z)$ 200-1500 GeV: 3000^{+180}_{-170} fb**
- **Prediction by MG5_aMC (NLO QCD+NLO EW): 2700±440 fb**



Signal extracted from fits in signal region (to p_T^{miss} distribution) and in two $W\rightarrow l\nu$ control regions



- **Agreement within uncertainties with MG5_aMC, FEWZ, and NNLOJET at (N)NLO w/o NLO EW corrections**
- **Better description of data with MG5_aMC at NLO QCD+EW for $p_T(Z)>500$ GeV**

p_T^Z (GeV)	$Z\rightarrow e^+e^-$	$Z\rightarrow\mu^+\mu^-$	$Z\rightarrow\ell\ell$	$Z\rightarrow\nu\nu$	$Z\rightarrow\ell\ell+\nu\nu$	Theory
200–300	2500^{+140}_{-110}	2400^{+120}_{-120}	2500^{+100}_{-100}	2500^{+150}_{-150}	2500^{+82}_{-100}	2200 ± 350
300–400	390^{+22}_{-18}	400^{+22}_{-21}	400^{+17}_{-16}	420^{+24}_{-23}	410^{+14}_{-17}	390 ± 69
400–500	$99^{+5.7}_{-4.9}$	$97^{+6.4}_{-6.1}$	$100^{+4.4}_{-4.2}$	$97^{+5.6}_{-5.4}$	$97^{+3.3}_{-4.0}$	90 ± 18
500–800	$47^{+3.0}_{-2.5}$	$41^{+4.0}_{-3.7}$	$45^{+2.3}_{-2.2}$	$44^{+2.7}_{-2.6}$	$44^{+1.6}_{-1.9}$	41 ± 9.0
800–1500	$3.9^{+0.6}_{-0.5}$	$3.2^{+0.7}_{-0.6}$	$3.7^{+0.4}_{-0.4}$	$3.2^{+0.3}_{-0.3}$	$3.3^{+0.2}_{-0.2}$	3.3 ± 0.9
200–1500	3000^{+160}_{-130}	3000^{+150}_{-140}	3000^{+120}_{-110}	3000^{+180}_{-170}	3000^{+100}_{-120}	2700 ± 440

- **Combination with the $Z\rightarrow ll$ channel, results in improved precision for the measured differential $p_T(Z)$ xsec**

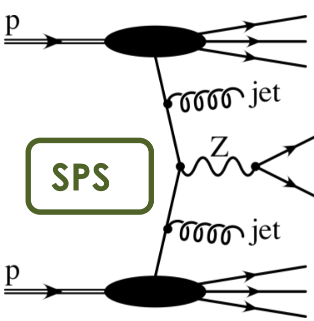
DPS with Z+jets *(CMS-PAS-SMP-20-009)*

new!

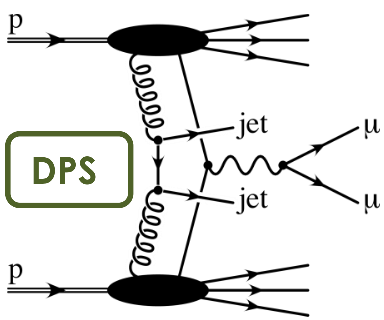
- Measurement of observables sensitive to the presence of DPS with Z+≥1-jet and Z+≥2-jet events
  - Double parton scattering (DPS): two hard parton-parton interactions in a single pp collision
  - $p_T(\mu)>27$ GeV, $|\eta(\mu)|<2.4$, $p_T(j)>20$ GeV, $|\eta(j)|<2.4$, $70 < m_{\mu\mu}<110$ GeV
- Use $\Delta\Phi(Z,j)$ and p_T imbalance Δ_{pT}^{rel} among the Z boson and jets

$$\Delta^{rel}_{p_T}(A,B) = \frac{|\vec{p}_T(A)+\vec{p}_T(B)|}{|\vec{p}_T(A)|+|\vec{p}_T(B)|}$$

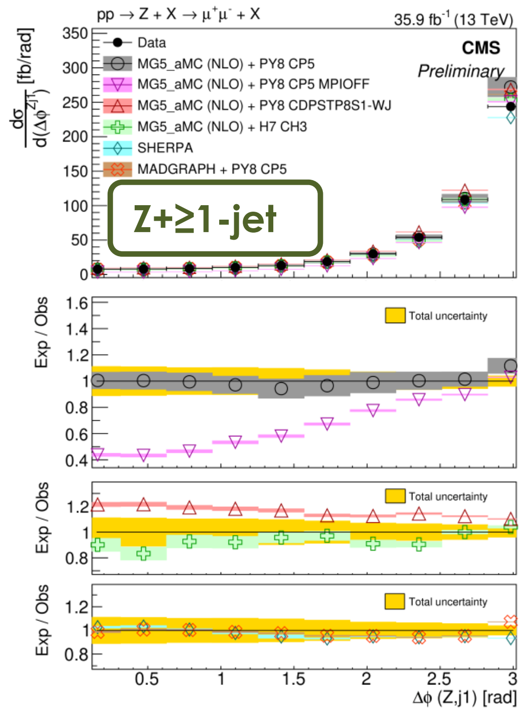
SPS



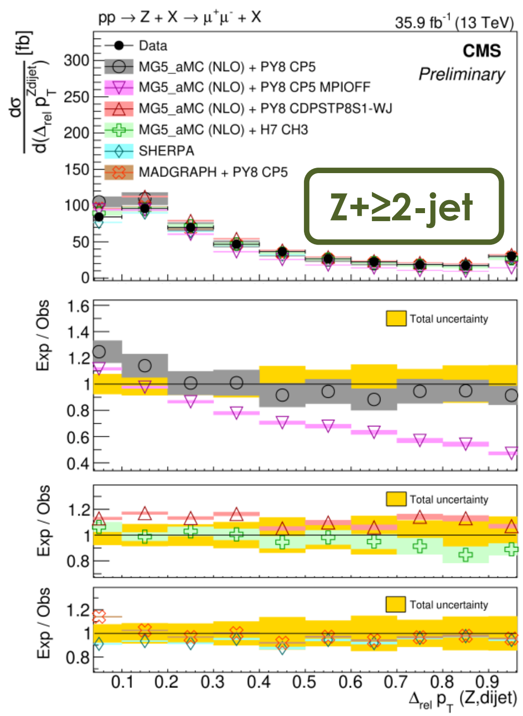
DPS



Jets balance each other in DPS production, whereas not in SPS



$\Delta\Phi(Z,j_1)$ is expected to be flat (around π) in DPS (SPS)



Δ_{pT}^{rel}(Z,dijet) is expected to be at higher values (zero) in DPS (SPS)

- **Predictions with MPI off are significantly lower than data in the DPS-sensitive regions**
- **Other predictions are overall consistent with data except for CDPSTP8S1-WJ tune which overshoots data by ~10-20%**
- **Results are important to further improve DPS modeling in MC**

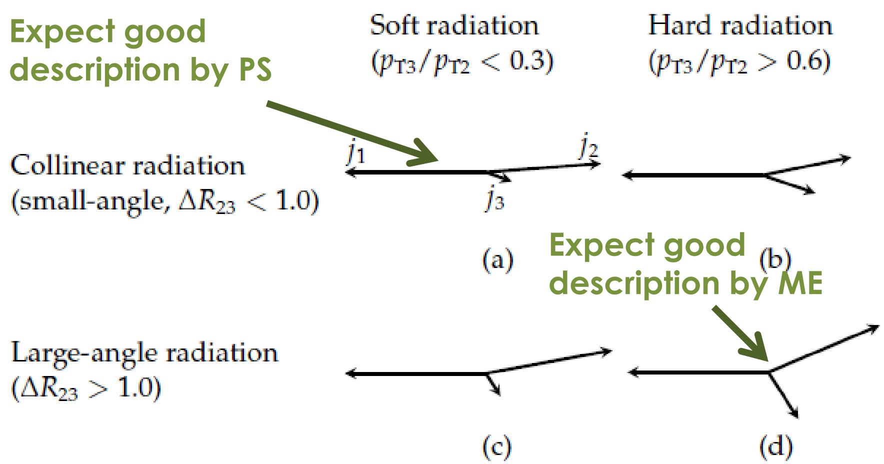
Z+2-jet at 8 TeV *(arXiv:2102.08816)*

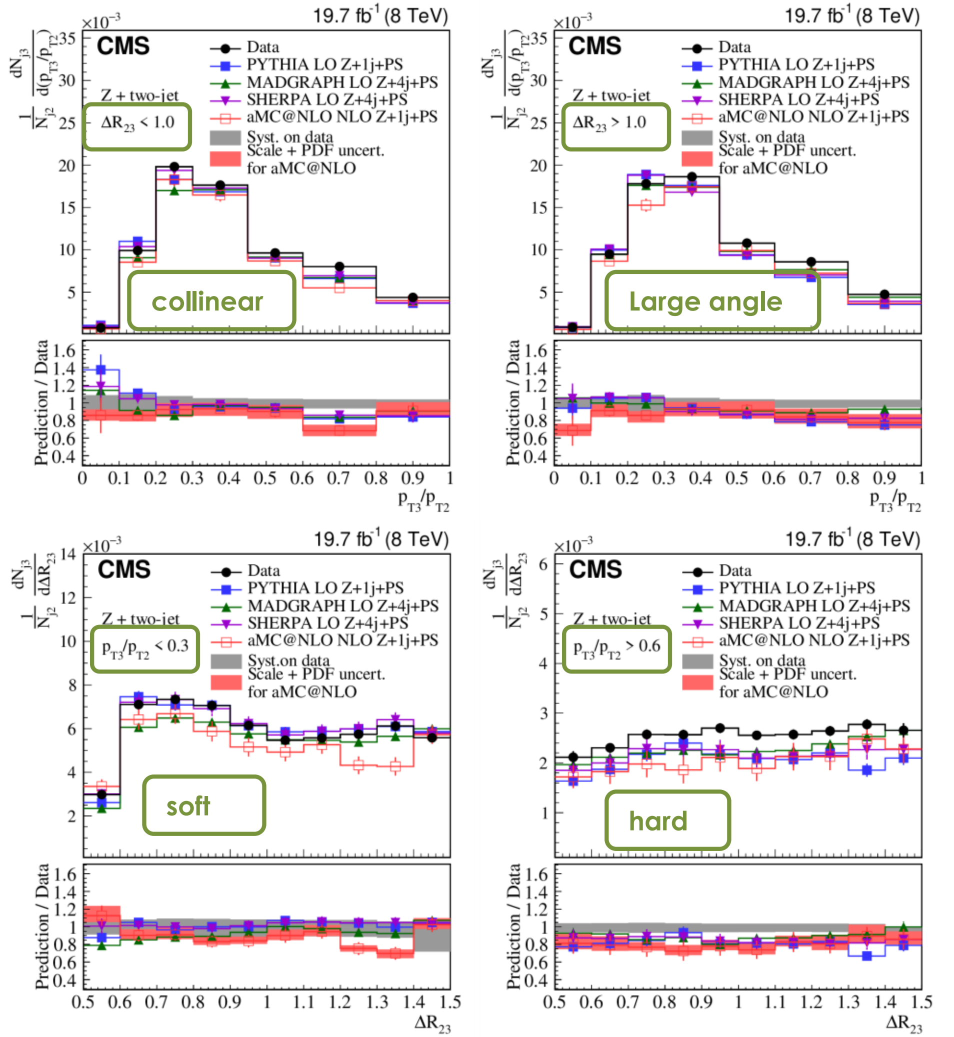
new!

- Collinear, large-angle, soft, and hard radiations in Z+2-jet (also 3-jet) events
- Select events with p_T>25 (5) GeV and |y|<2.1 (2.4) for the lead (sublead) muon, $p_T(\mu^+\mu^-)$>80 GeV and $|y(\mu^+\mu^-)|$<2, 70<$m_{\mu\mu}$<110 GeV, and p_T>80 (20) GeV and |y|<1 (2.4) for the lead (sublead) jet
- **Measure p_{T3}/p_{T2} ratio and angular distance ΔR_{23} from subleading jets**

$$\Delta R_{23} = \sqrt{(y_3 - y_2)^2 + (\varphi_3 - \varphi_2)^2}$$

- Split events into categories using the classification scheme:





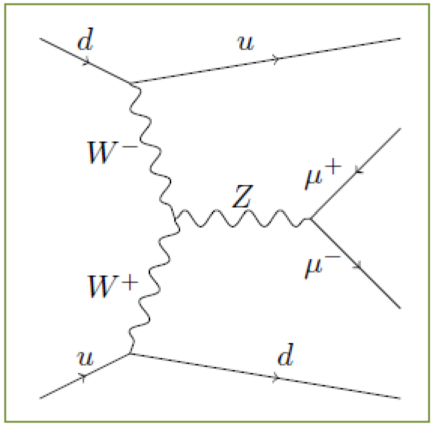
- **Overall, good data description by all the MCs**
- **Predictions tend to underestimate ΔR_{23} at large p_{T3}/p_{T2} in small- and large-angle regions**

EW V+2 jets production

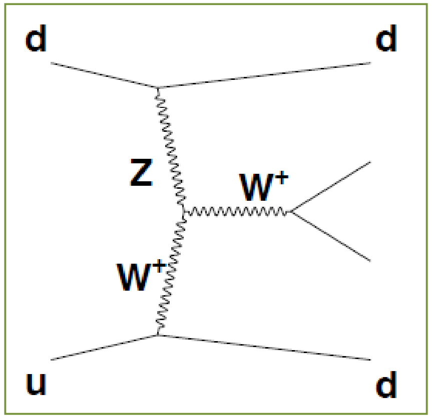
- **Characterized by the presence of two high-p_T jets with large separation in η and low hadronic activity in-between**

- **Tests of the gauge structure of the EW sector (i.e., gauge boson self interactions) → sensitive to anomalous trilinear gauge coupling (aTGC) searches**
- **Modeling of VBF processes for Higgs measurements**
- **Tests of soft QCD rapidity gap modeling**

- Main background from QCD W/Z+jets production
- Roughly ten times lower cross sections than QCD production



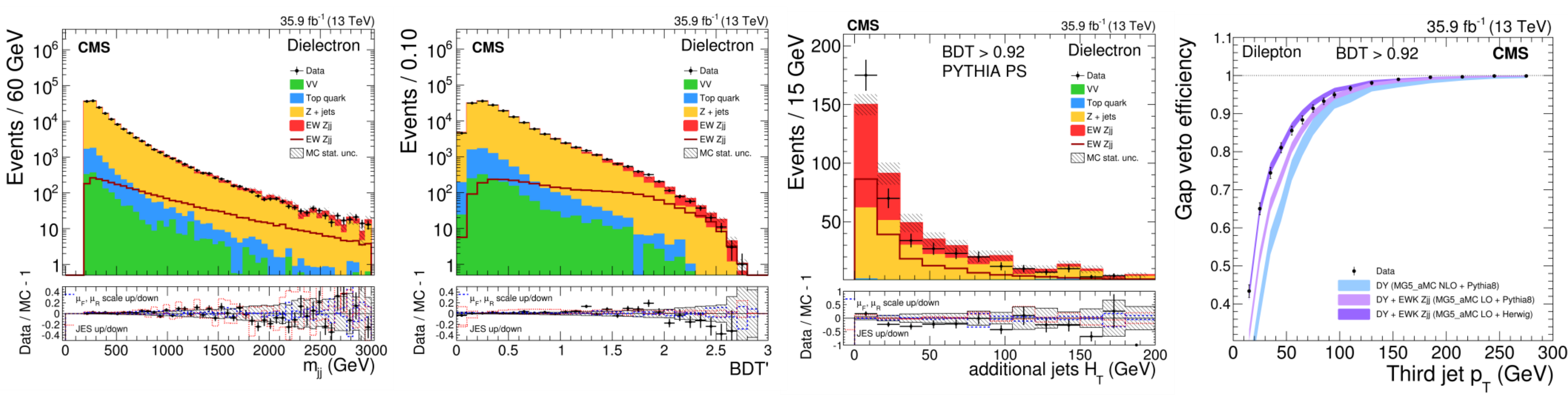
EW Z(lljj) VBF signal



EW W(lνjj) VBF signal

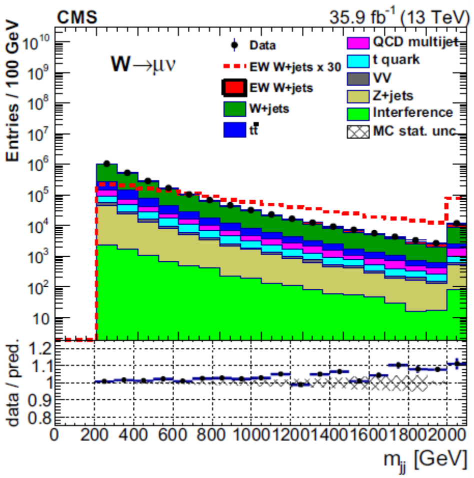
EW Z+2 jets *(Eur. Phys. J. C 78 (2018) 589)*

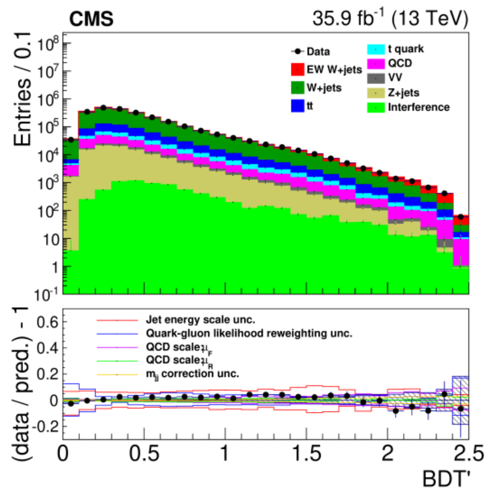
- Signal defined as m_{jj}>120 GeV, $p_T(j)$>25 GeV, and m_{ll} > 50 GeV:
  - measured σ(EW Z→lljj) = 534 ± 20(stat) ± 57(syst) fb
  - good agreement with the SM prediction σ_{LO}(EW Z→lljj)=543 ± 24 fb by MG5_aMC+PYTHIA 8
- Event selection: two OS e (μ): p_T > 30 (20) GeV, |η| < 2.4, |m_{ll} - m(Z)|<15 GeV, at least two jets with p_T > 50 (30) GeV, |η| < 4.7, m_{jj} > 200 GeV
- Several discriminating variables used to achieve the best separation between signal and DY+2 jets strong process → signal extracted from the fit to the BDT
- Additional hadronic activity in signal-enriched region (BDT > 0.92) is studied
  - consider additional jets with p_T>15 GeV jets in the gap
  - Herwig (Pythia 8) PS models data better for low and moderate (higher) gap activity

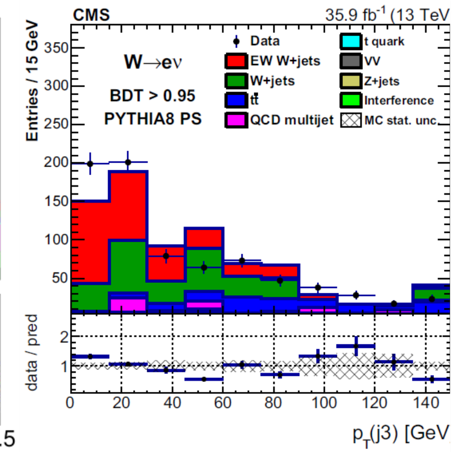


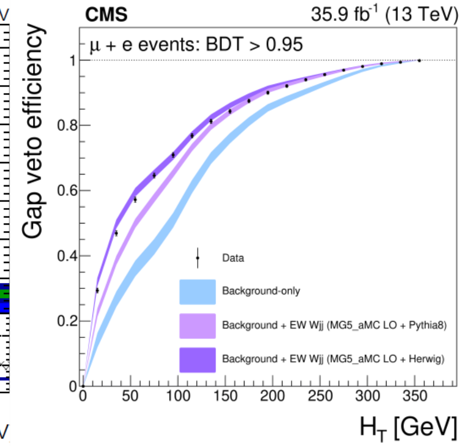
EW W+2 jets *(Eur. Phys. J. C 80 (2020) 43)*

- Signal region defined with m_{jj}>120 GeV, p_T(j)>25 GeV:
  - measured σ(EW W→lνjj) = 6.23 ± 0.12 (stat) ± 0.61 (syst) pb
  - consistent with LO SM prediction by MG5_aMC σ_{LO}(EW W→lνjj)=$6.81^{+0.03}_{-0.06}$ (scale)±0.26 (PDF) pb
- Event selection: e (μ) channel: p_T>30(25) GeV, |η| < 2.4, p_T^{miss}> 40 (20 GeV) GeV, m_T(W)>40 GeV, at least two jets with p_T > 50 (30) GeV, |η| < 4.7, m_{jj} > 200 GeV, and R(p_T) < 0.2









• Several discriminating variables (m_{jj}, $\Delta\eta_{jj}$, etc.) used to differentiate signal from W+jets strong process (DY W+2 jets)

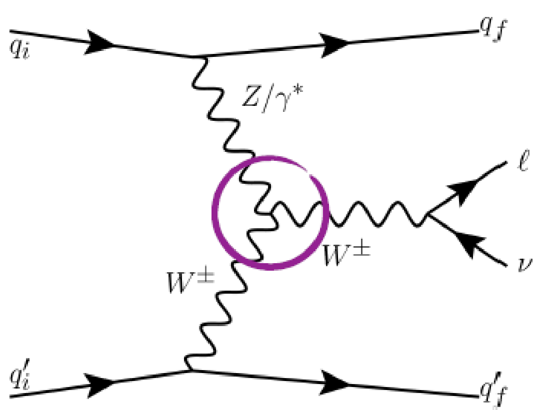
• Extraction of signal via fit to BDT → QCD W+jets dominant background, but significant contributions as well from top and QCD multijet

• Additional hadronic activity and gap veto efficiencies in the signal-enriched region (BDT>0.95)

• Good agreement between data and Herwig, while Pyhtia 8 shows greater activity in the rapidity gap between the two tagging jets

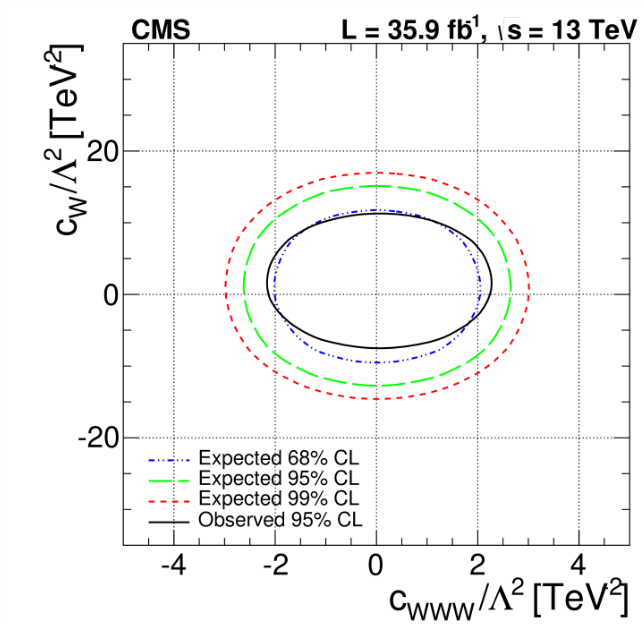
EW V+2 jets – constraints on aTGCs

- Both the EW Zjj and EW Wjj measurements are sensitive to aTGC EFT parameters: c_{WWW}/Λ^2, c_W/Λ^2, and c_B/Λ^2
- Exploit combined fit of experimentally clean $p_T(Z)$ (from VBF Z) and $p_T(l)$ (from VBF W) distributions to limit systematic uncertainties
- Constraint in VBF W channel improved by 20-25% by requiring BDT>0.5 in pre-selection
- No evidence found for aTGCs from the combined 13 TeV Wjj and Zjj results
- Suggest limits on aTGCs -> stringent limit on c_{WWW}/Λ^2: $-1.8<c_{WWW}/\Lambda^2<2.0$ TeV^{-2}



Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	[−2.3, 2.4]	[−1.8, 2.0]
c_W/Λ^2	[−11, 14]	[−5.8, 10.0]
c_B/Λ^2	[−61, 61]	[−43, 45]

One-dimensional limits on the aTGC EFT parameters from the combination of EW Wjj and EW Zjj analyses



Summary

- ✓ **V+jets measurements are an integral part of the CMS SM physics program at the LHC, deeping our understanding of QCD and EW processes and their theoretical modeling**
  - **Precise measurements compared with various MC-based and theoretical predictions, exploiting different PDF models** → ***overall good agreement with the data on several angular and kinematical observables***
  - **Valuable inputs provided for improving existing constraints on the proton PDFs** → ***b, c, and s quark PDFs from V+HF jets and gluon PDF from γ+jet***
  - **Provided wealth of results on many fronts** → ***background modeling for Higgs and new physics, perturbative and soft QCD effects, DPS modeling, collinear and large-angle radiation, QCD HF sector, EW tests including aTGCs, etc.***

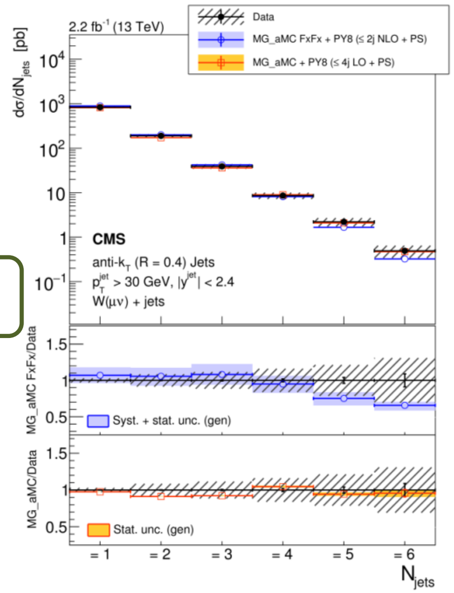
- ✓ **Stay tuned for more V+jets results with Run 2 data at 13 TeV towards Run 3!**

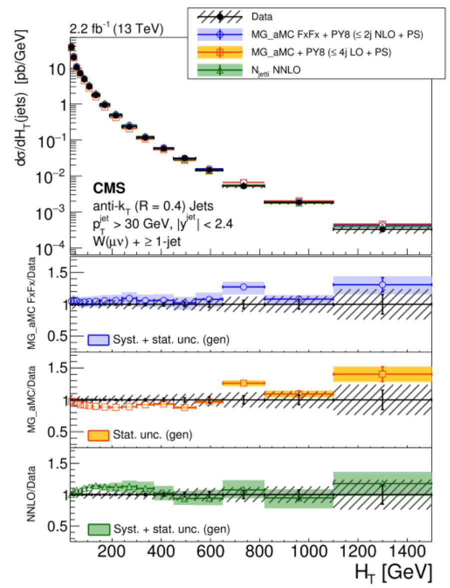
Thank you!

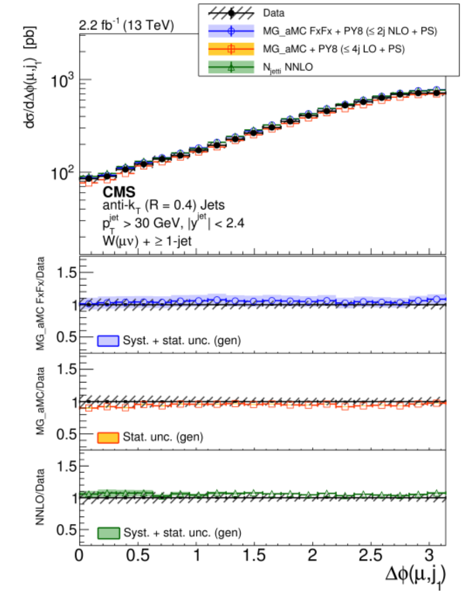
Back-up slides

W/Z+jets at 13 TeV (more distributions)

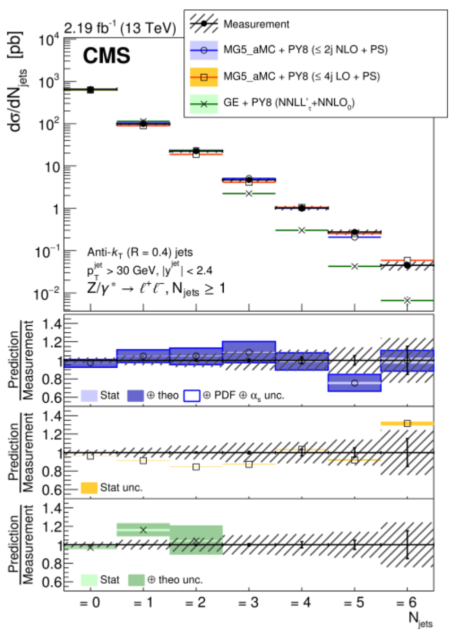
W+jets

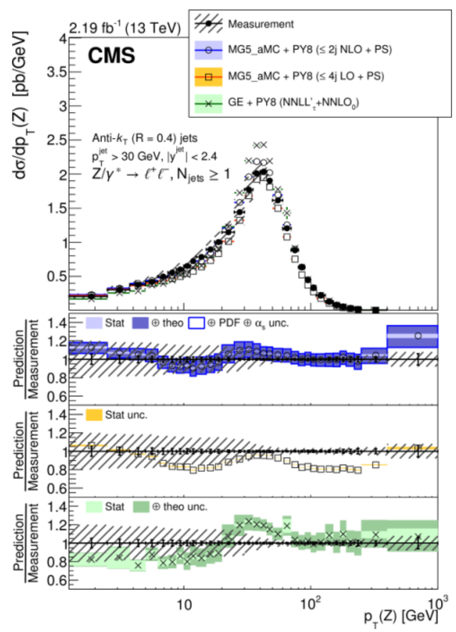


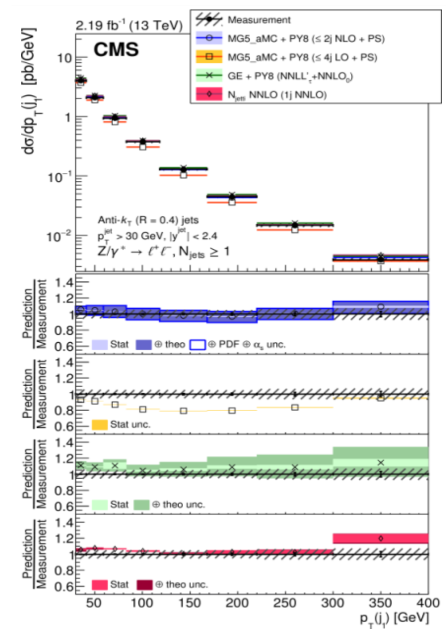




Z+jets

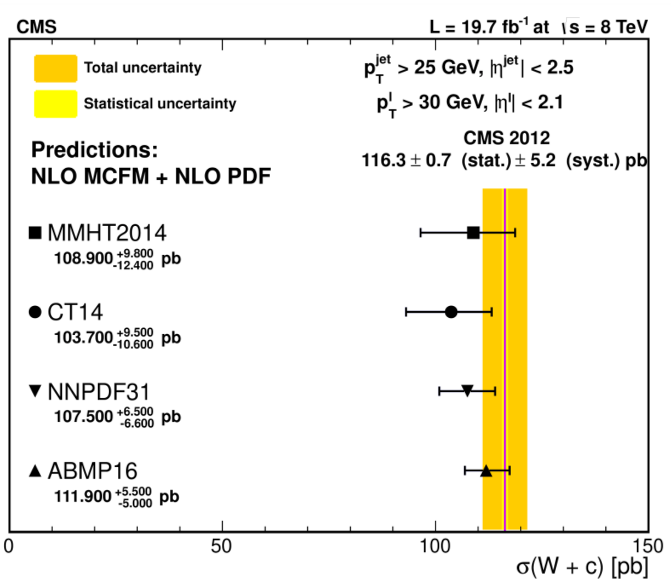


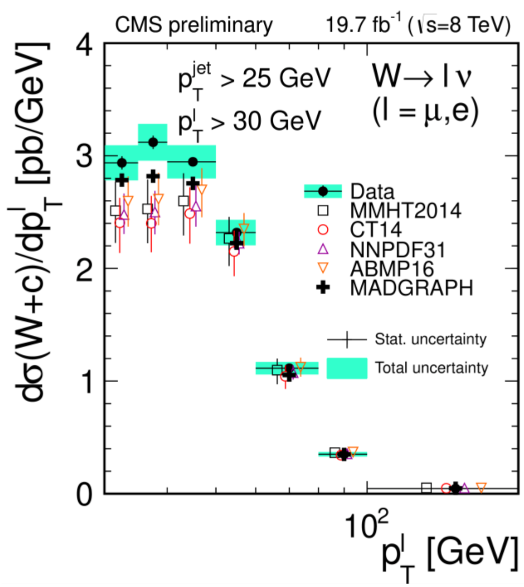


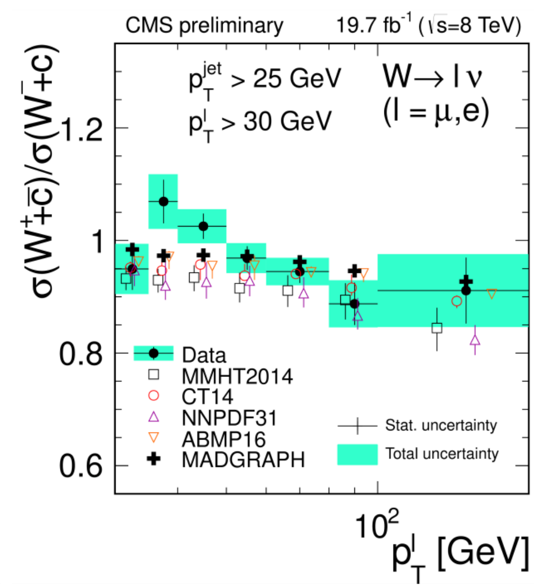


W+c-jet at 8 TeV *(CMS-PAS-SMP-18-013)*

- Charm jets identified through:
  - a semileptonic decay of a c hadron leading to a well identified μ inside a jet (SL)
  - a reconstructed displaced secondary vertex inside a jet (SV)
- Selection: $p_T(l)>30$ GeV, $|\eta(l)|<2.1$, and $m_T(W)>55$ GeV, $p_T(j)>25$ GeV, $|\eta(j)|<2.5$
- Measured W+c cross section and $W^{+}+\bar{c}/W^{-}+c$ ratio inclusively
  - good agreement with MCFM NLO predictions with various PDFs
- Measured W+c cross section and $W^{+}+\bar{c}/W^{-}+c$ ratio differentially for $p_T(l)$ and $|\eta(l)|$
  - slight discrepancies with MCFM NLO at low-$p_T(l)$ region

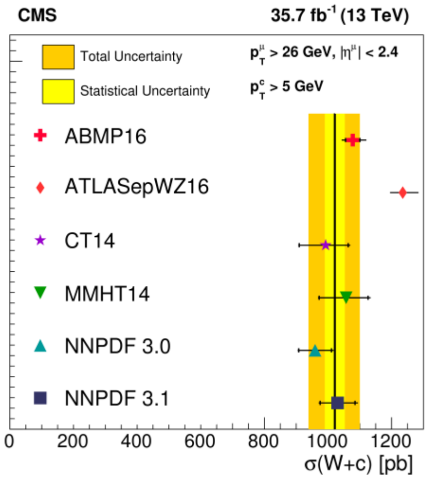


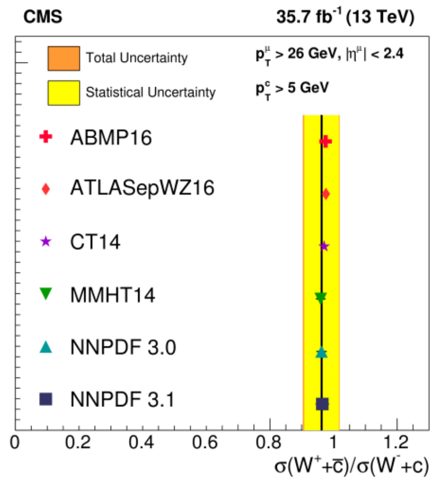




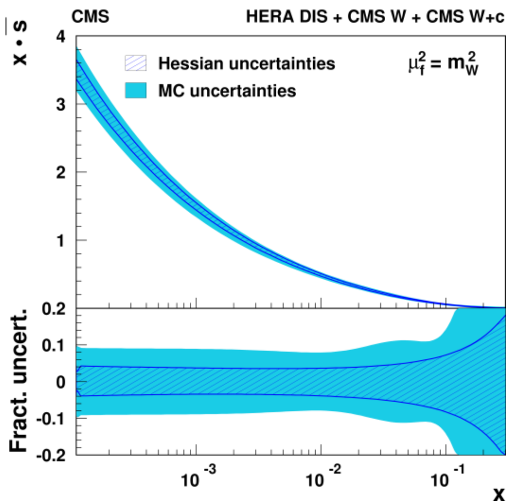
W+c-jet at 13 TeV *(Eur. Phys. J. C 79 (2019) 269)*

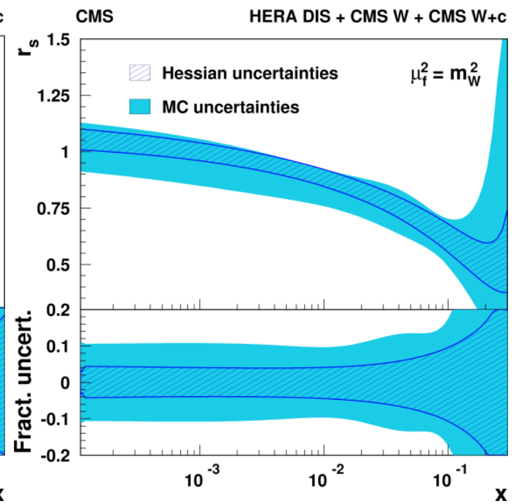
- W+c-jet can test s quark PDF
- Fiducial acceptance: $p_T(c)>5$ GeV, $|\eta(c)|<2.4$, $p_T(\mu)>26$ GeV, $|\eta(\mu)|<2.4$, and $m_T(W)>50$ GeV
- Charm quarks are tagged via full reconstruction chain of $D^*(2010)^{\pm}\rightarrow D^0+\pi^{\pm}_{slow}\rightarrow K^{\mp}+\pi^{\pm}+\pi^{\pm}_{slow}$





- σ(W+c) and $\sigma(W^+ + \bar{c})/\sigma(W^- + c)$ inclusive measurements compared to MCFM NLO
- good agreement with various predictions except for the ATLASSepWZ16nnlo PDF set for σ(W+c)

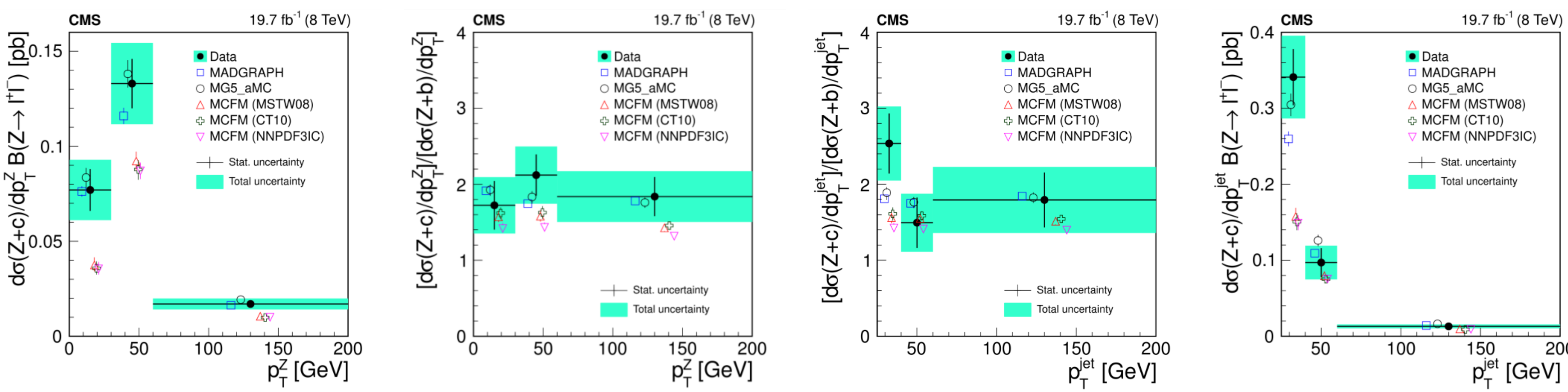




- measurements used in a QCD analysis at NLO studying s quark distribution and the strangeness suppression factor $r_s(x,\mu^2_f)=(s+\bar{s})/(\bar{u}+\bar{d})$
- analysis probes s quark distribution at $x \leq 0.01$ depending on the scale
- agreement with earlier results from neutrino scattering experiments

Z+c-jets at 8 TeV *(Eur. Phys. J. C 78 (2018) 287)*

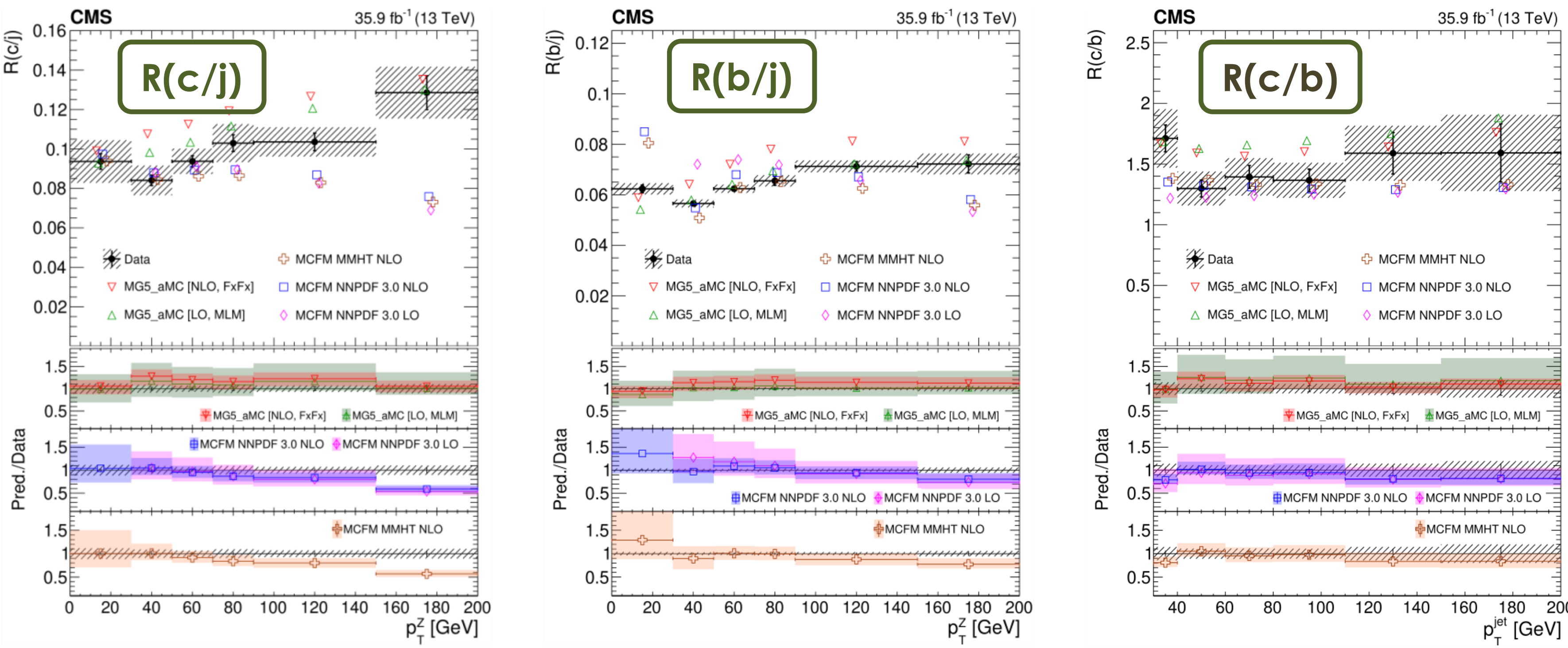
- $Z(ll)+\geq 1c(1b)$ event selection for isolated leptons with $p_T(l)>20$ GeV, $|\eta(l)|<2.1$, $71 < m_{ll} < 111$ GeV and at least one c or b jet with $p_T(j)>25$ GeV, $|\eta(j)|<2.5$
- HF jets identified through (1) the semileptonic decay of c or b flavoured hadrons with a muon in the final state, and (2) using exclusive decay channels of charm hadrons through D± and D∗(2010)± mesons
- Inclusive and differential Z+c cross section and (Z+c)/(Z+b) cross section ratio measurements
- $\sigma(pp \rightarrow Z+c+X)B(Z \rightarrow l^+l^-) = 8.8 \pm 0.5$ (stat) ± 0.6 (syst) pb and $\sigma(pp \rightarrow Z+c+X)/\sigma(pp \rightarrow Z+b+X) = 2.0 \pm 0.2$ (stat) ± 0.2 (syst).
- Differential results are presented using only semileptonic selection
- MCFM underestimates data due to absence of inclusion of parton shower development and nonperturbative effects



- **MG5_aMC LO(NLO)+PYTHIA 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**

Z+c-jets/Z+b-jets at 13 TeV *(Phys. Rev. D 102 (2020) 032007)*

- Inclusive and differential measurements of σ(Z+c)/σ(Z+j), σ(Z+b)/σ(Z+j), and σ(Z+c)/σ(Z+b) in the associated production of a Z boson with at least one c or b quark jet
  - differentially as functions of $p_T(j)$ and $p_T(Z)$ in both e^+e^- and $\mu^+\mu^-$ channels
  - $p_T(j)>30$ GeV and $|\eta(j)|<2.4$, $p_T(l)>25$ GeV and $|\eta(l)|<2.4$, $71 < m_{ll} < 111$ GeV
- Measured ratios: σ(Z+c)/σ(Z+j)=0.102±0.002(stat)±0.009(syst), σ(Z+b)/σ(Z+j)=0.0633±0.0004(stat) ±0.0015(syst), and σ(Z+c)/σ(Z+b)=1.62 ±0.03 ±0.15
- Compared to MG5_aMC and MCFM both at LO and NLO
  - MG5_aMC (N)LO predictions are higher but compatible with data within uncertainties

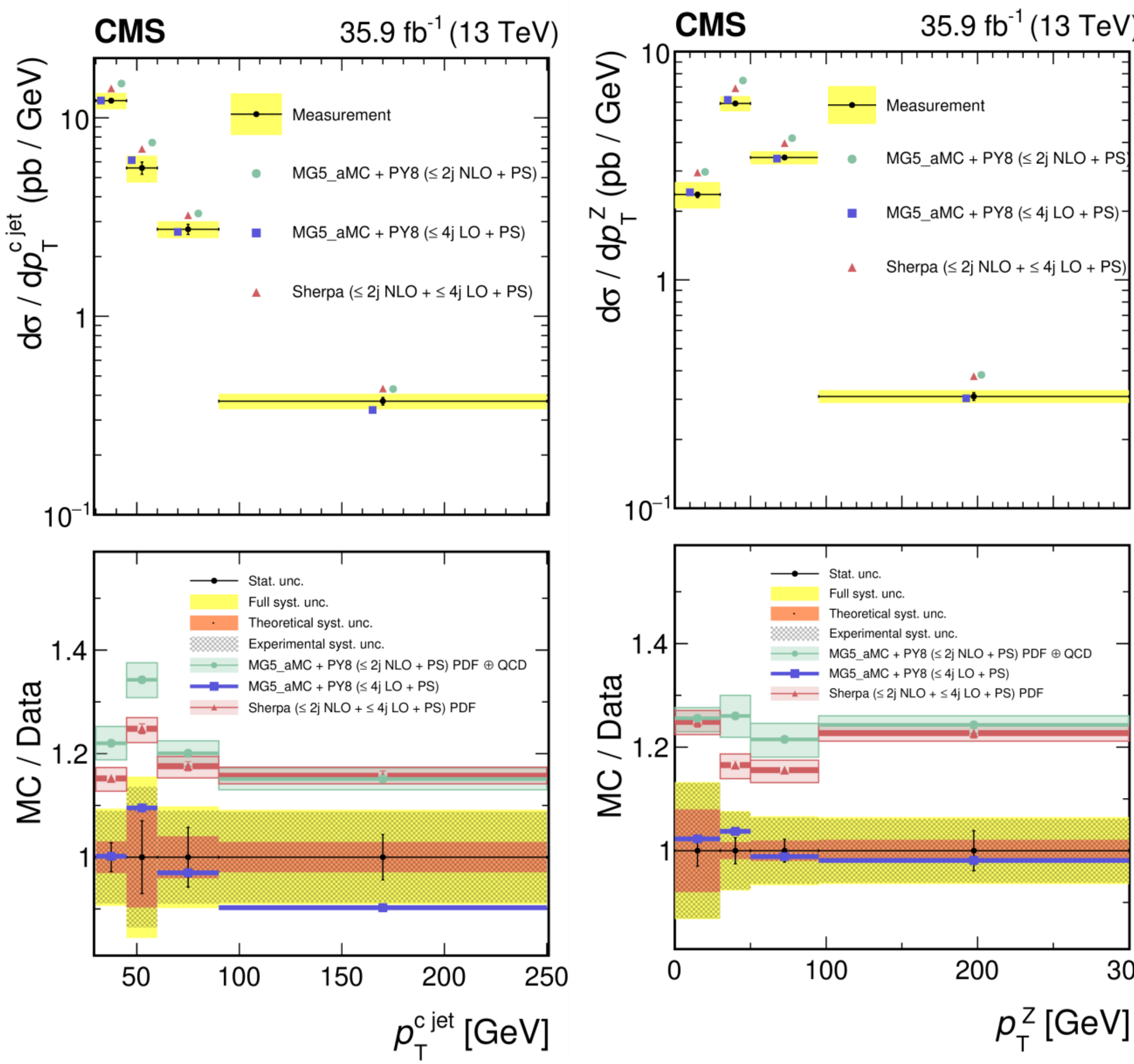


Z+c-jets at 13 TeV *(JHEP 04 (2021) 109)*

new!

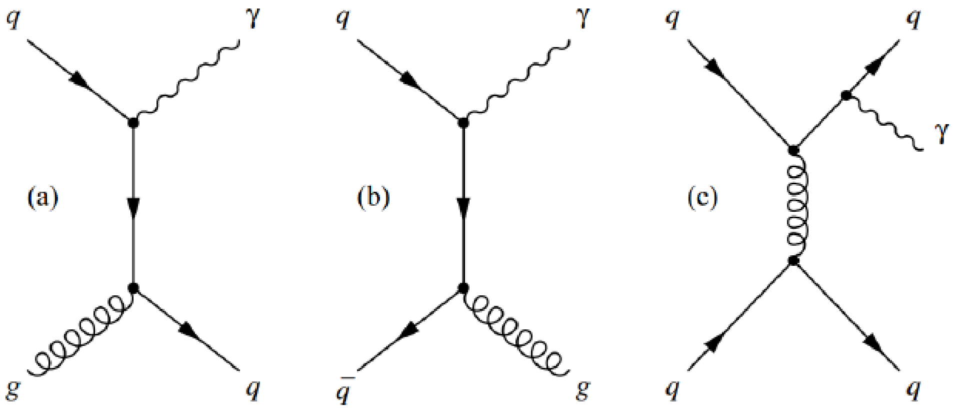
- Both incl. and diff. x-secs of Z boson production with at least one c-jet
  - differentially as functions of $p_T(j)$ and $p_T(Z)$ in the combined (e^+e^- and $\mu^+\mu^-$) channel
  - $p_T(l)>10$ GeV (at least one e (μ) with $p_T(l)>29(26)$ GeV), $|\eta(l)|<2.4$, $71 < m_{ll} < 111$ GeV , $p_T(j)>30$ GeV, $|\eta(j)|<2.4$,

- Comparisons with MG5_aMC and Sherpa (N)LO interfaced with PS
  - Predictions normalized to FEWZ NNLO
  - MG5_aMC LO is in good agreement with the data
  - NLO predictions tend to overestimate the data



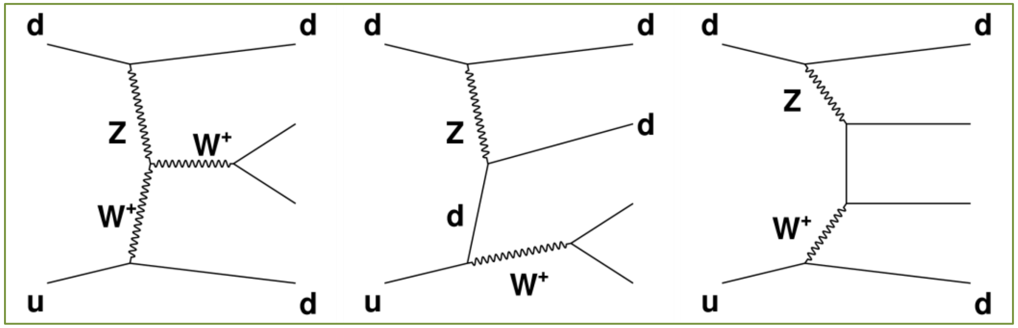
γ+jets production

- Prompt photons are produced via three main mechanisms: a) quark-gluon Compton scattering, b) quark-anti-quark annihilation, and c) bremsstrahlung radiation from an outgoing quark

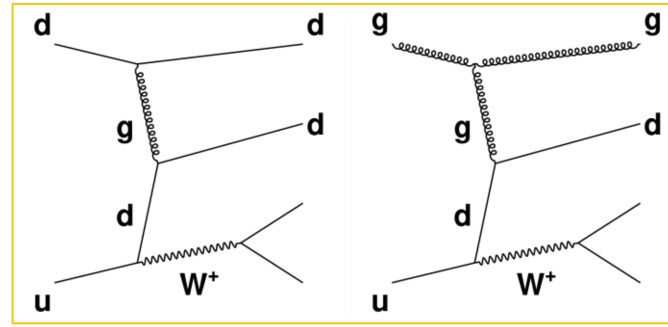


- Non-prompt photons (main background) are π^0 and η from hadronic jets, discriminated from signal photons based on isolation and shower shape properties

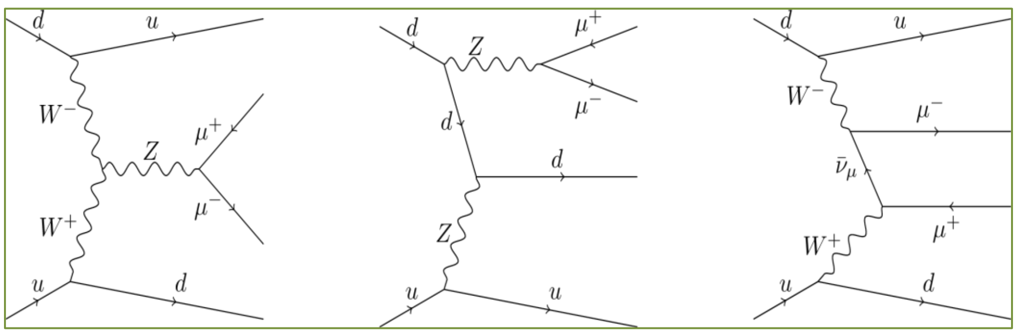
- **Measurements are sensitive to gluon PDF over a wide range of Q^2-x**
- **Main background to SM processes such as H→γγ and new physics searches**
- **Provides means for testing pQCD predictions**
- **Valuable for jet energy calibration and modeling of missing energy**



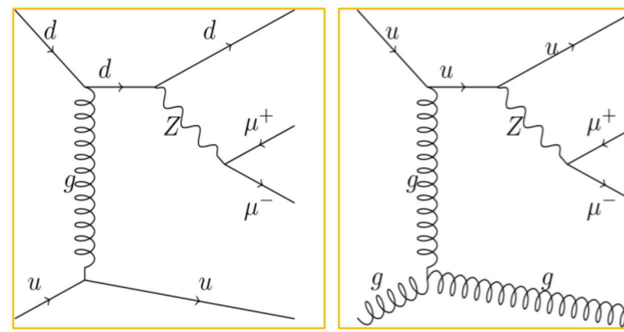
Pure EW $W \to l\nu jj$ production: VBF (left), bremsstrahlung-like (middle), and multiperipheral (right)



Main background QCD Drell-Yan $W \to l\nu jj$ production



Pure EW $Z \to lljj$ production: VBF (left), bremsstrahlung-like (middle), and multiperipheral (right)



Main background QCD Drell-Yan $Z \to lljj$ production