V+jets/+heavy flavour production at the LHC

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On behalf of the ATLAS & CMS Collaborations

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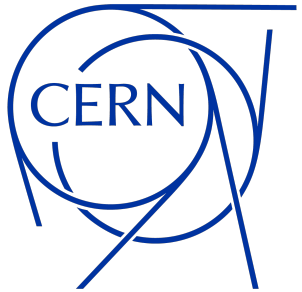
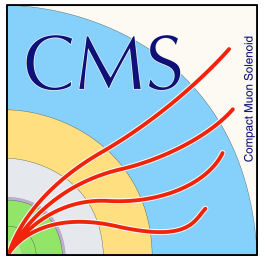


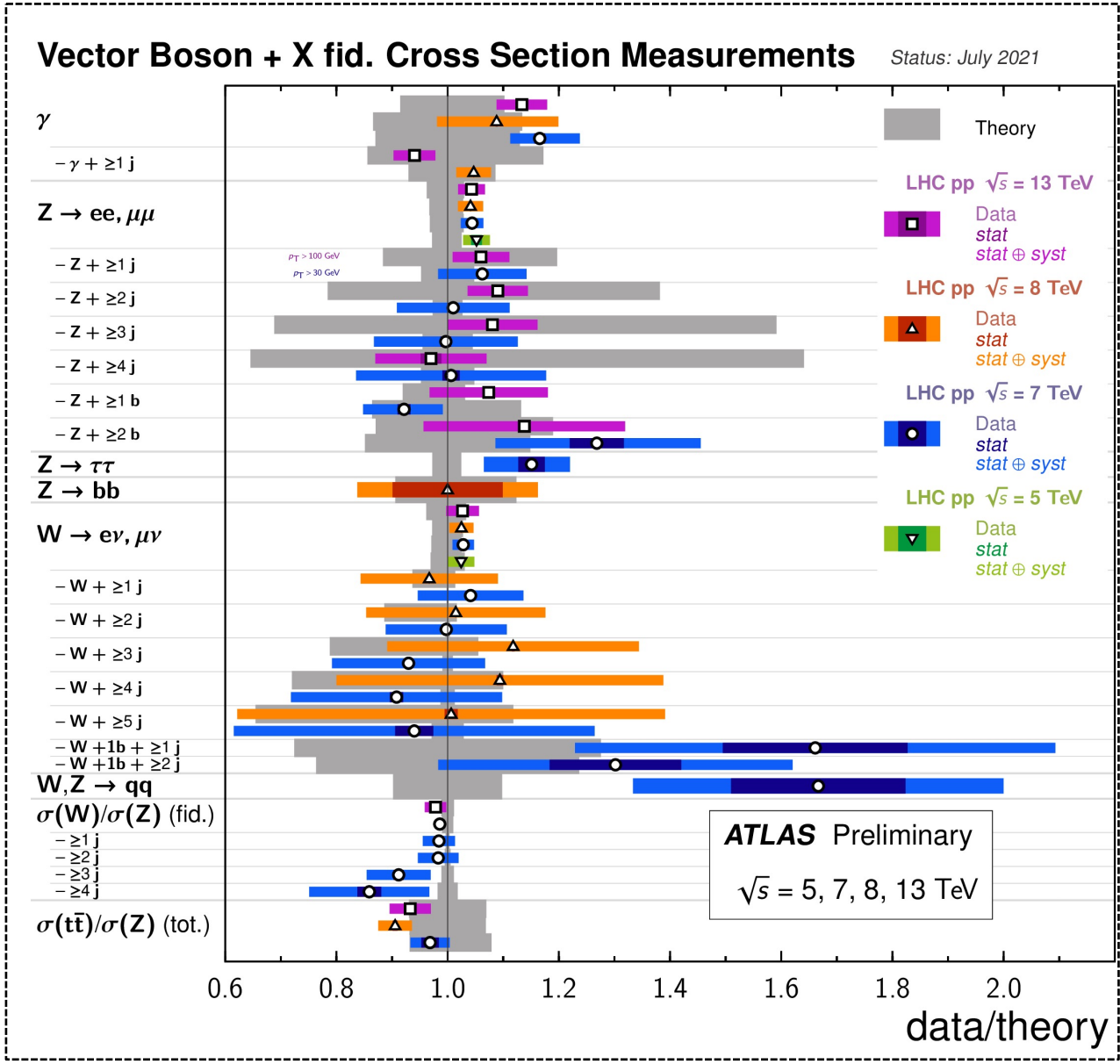


Introduction

- High rates of W, Z production at LHC
- **Clean signal with leptonic decays**
- W and Z + jets are standard candles
- Very precise measurements to test SM

- Irreducible background to BSM and Higgs analyses

- V + jets measurements test perturbative QCD (pQCD)
- Z + b/c jet sensitive to quark PDF
- Z + bb jets sensitive to gluon splitting



Recent results

* Results released in 2021

- Z + jets measurements at 13 TeV
  - ATLAS Collinear Z + jets (ATLAS-CONF-2021-033) *
  - CMS Z/ γ + jets (JHEP 05 (2021) 285) *
  - CMS Azimuthal correlations in Z + jets (CMS-PAS-SMP-21-003) *
  - CMS Z + jets (CMS-PAS-SMP-19-009) *
  - CMS Precision Z invisible width (CMS-PAS-SMP-18-014) *
  - CMS Double parton scattering using Z + jets (CMS-SMP-20-009)* – in backup

- V + heavy flavour measurements at 13 TeV
  - ATLAS Z + 1 or 2 b jets (*JHEP 07 (2020) 44*)
  - CMS Z + 1 or 2 b jets (CMS-PAS-SMP-20-015) *

Collinear Z + jets

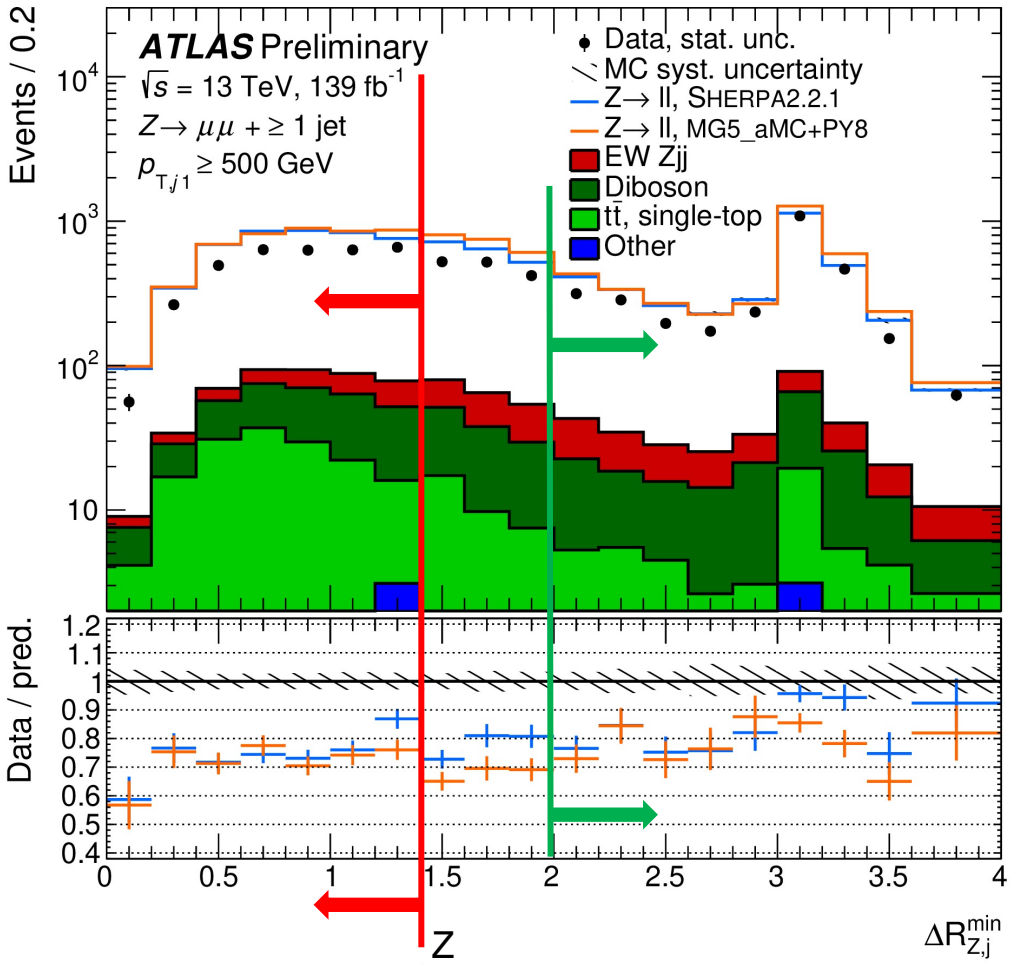
ATLAS EXPERIMENT

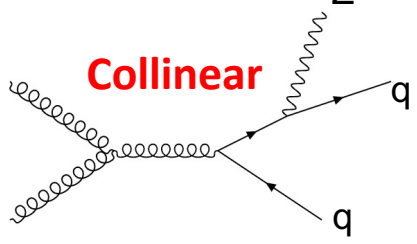
ATLAS-CONF-2021-033

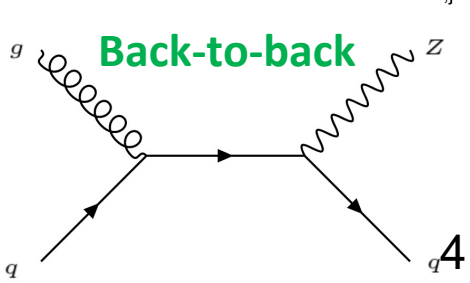
- Probing for real Z emission as FSR from quark
- Measure Z production with high p_T jets
- Study kinematics between Z and closest jet

- Full run 2 dataset: 139 fb^{-1}
- Z($\rightarrow ee,\mu\mu$) + jets
- jet p_T > 100 GeV, $|y| < 2.5$
- $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$
- Cross sections in different phase spaces:
  - High p_T : lead jet p_T > 500 GeV
  - High scalar sum p_T of jets: S_T > 600 GeV
  - **Collinear** and **back-to-back** Z emission

1st time



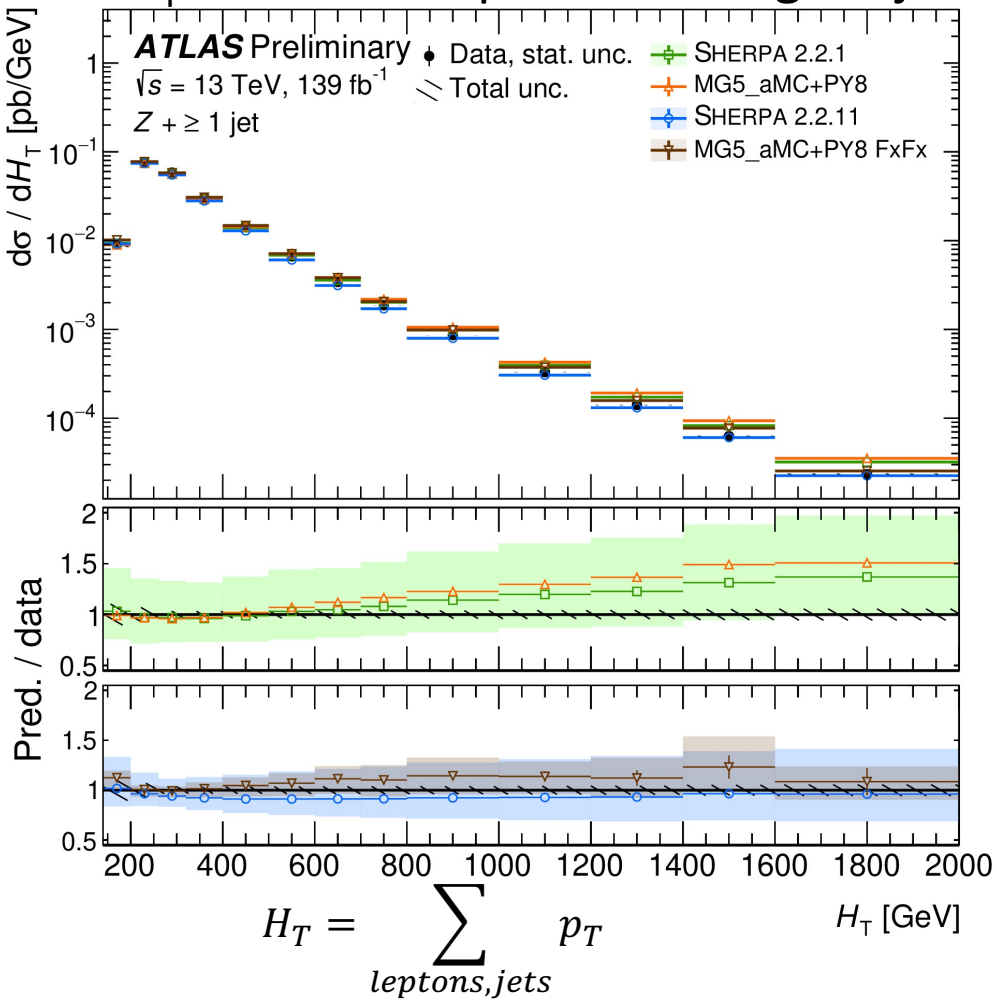


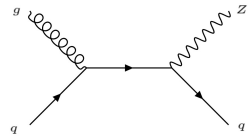


Collinear Z + jets

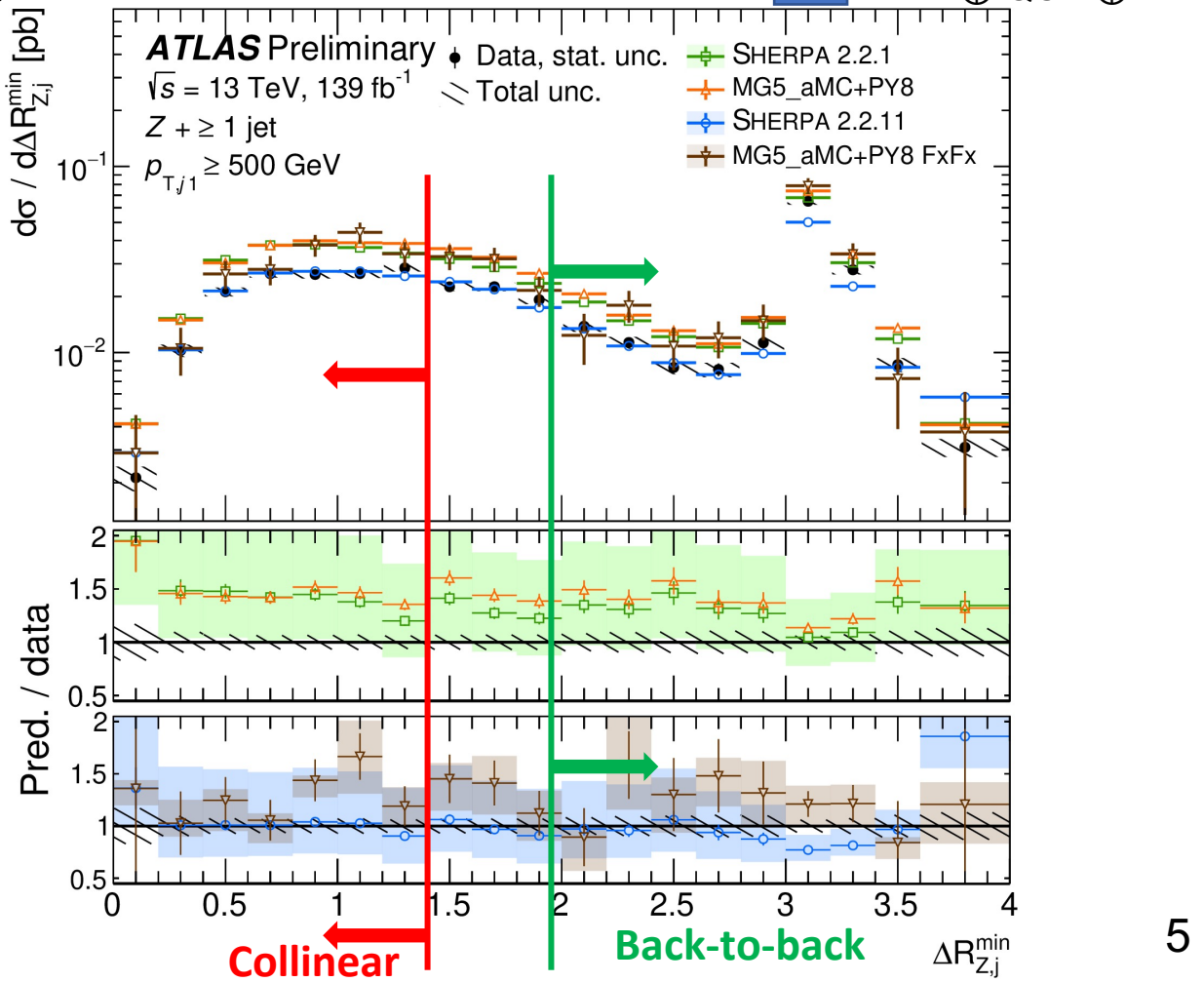
ATLAS-CONF-2021-033

- Sherpa2.2.11, MGPy8 FxFx MC show improved modelling in collinear and high p_T regions
- **Back-to-back** region well modelled: mostly Z + 1 jet events →
- H_T sensitive to pQCD and higher jet multiplicities





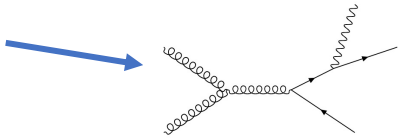
PDF ⊕ QCD ⊕ EW



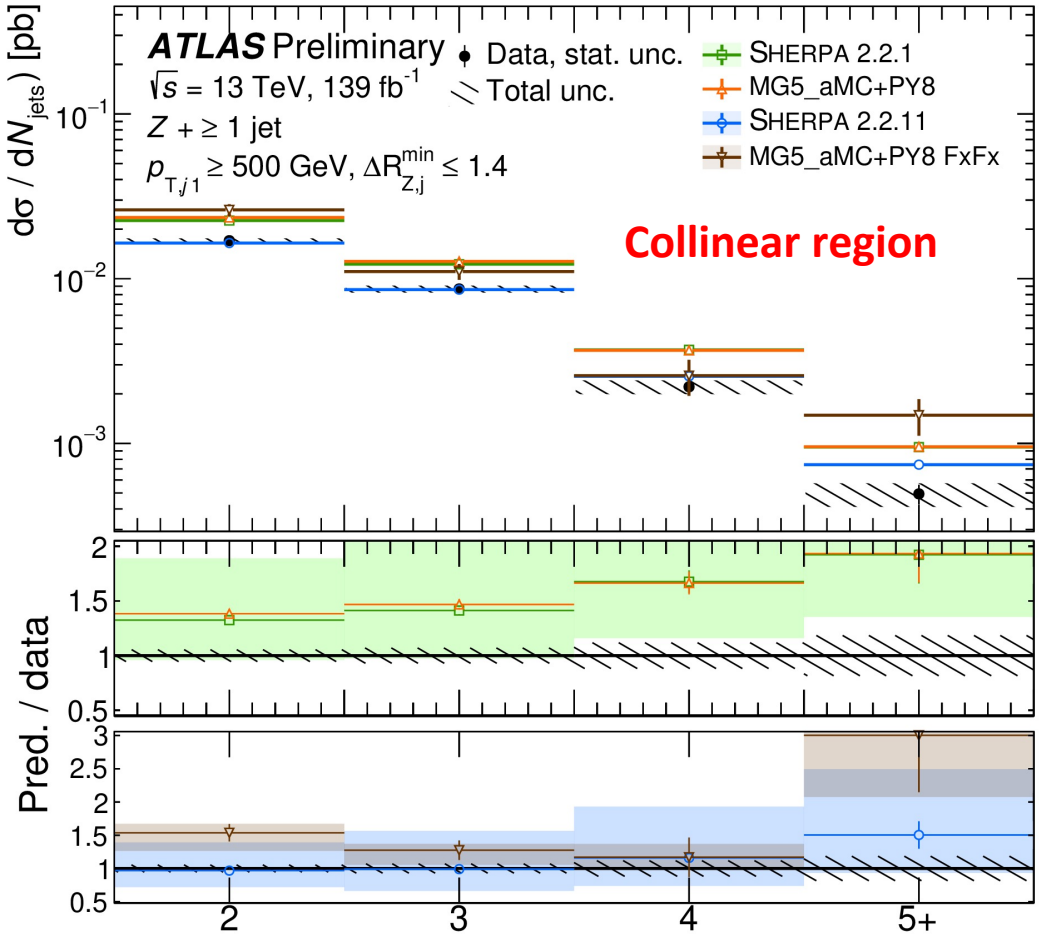
Collinear Z + jets

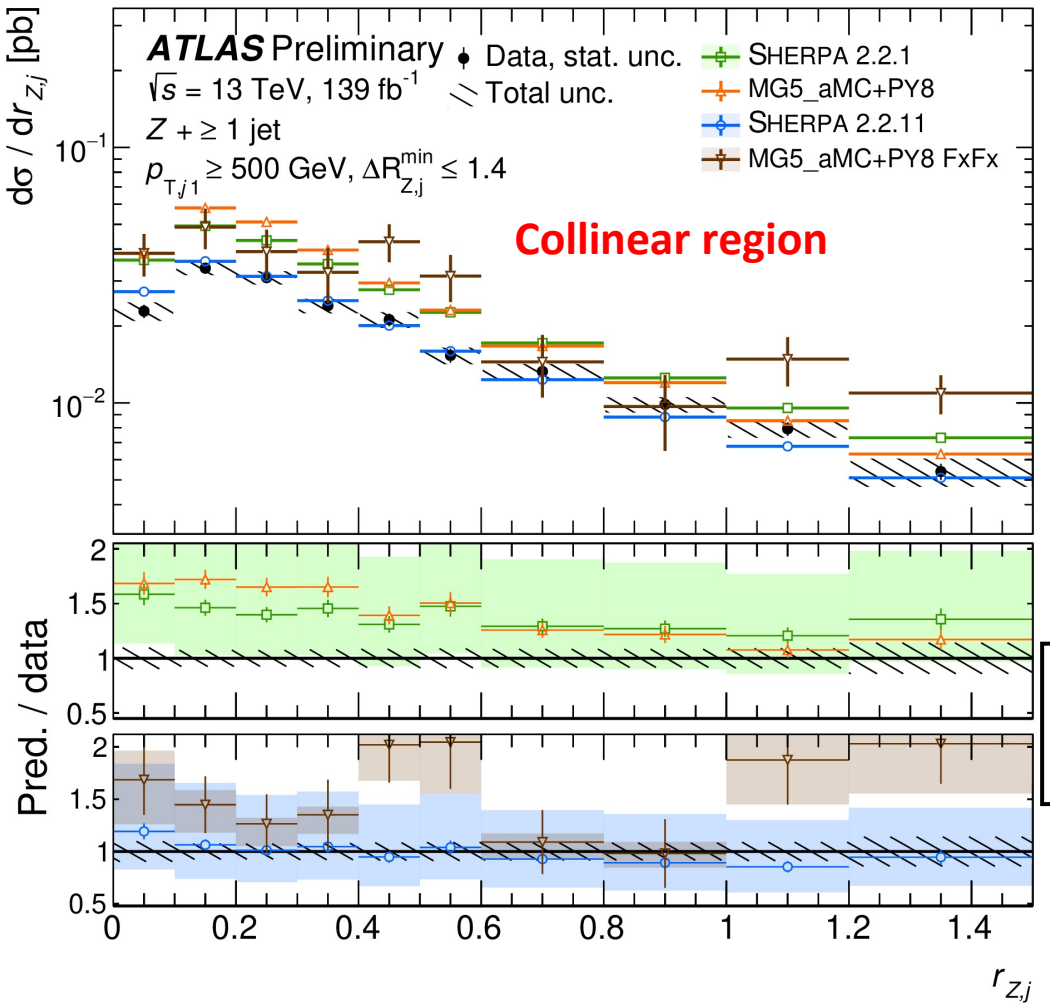
ATLAS-CONF-2021-033

- State-of-the-art Sherpa2.2.11 MC (blue), inc. virtual EW corrections, consistent with data in **collinear** region
- Large population at low $r_{Z,j}$: **collinear** emission of Z from jet
- Prediction uncertainties dominated by QCD scale uncertainties



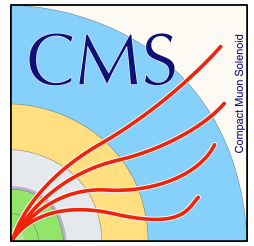
PDF ⊕ QCD ⊕ EW





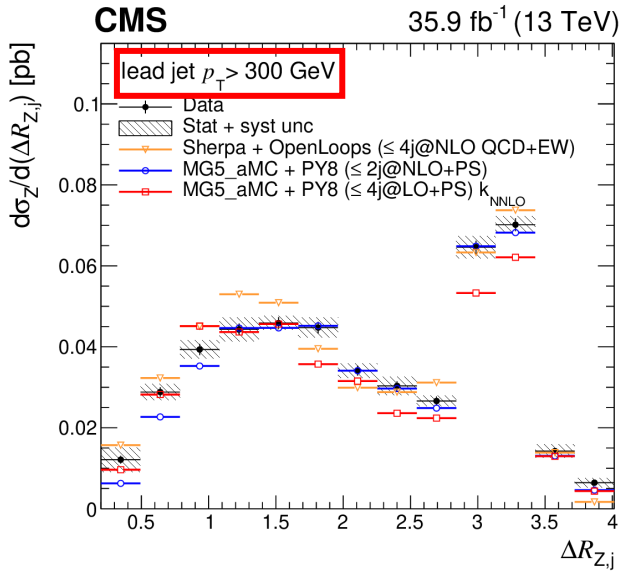
$$r_{Z,j} = \frac{pT(Z)}{pT(jet)}$$

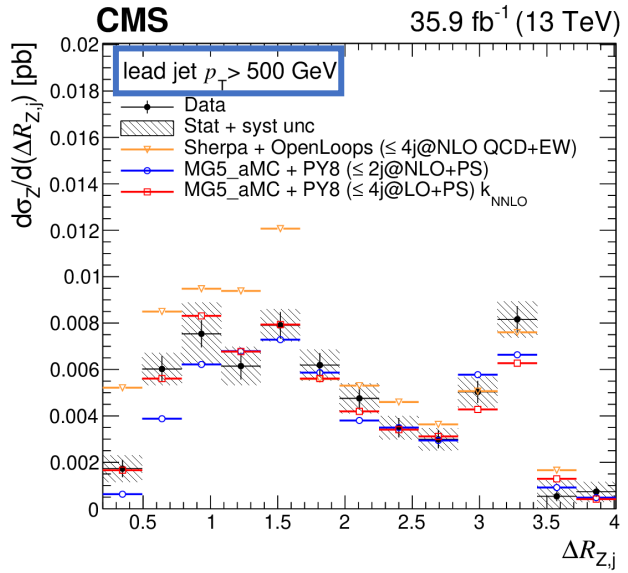
Collinear Z + jets

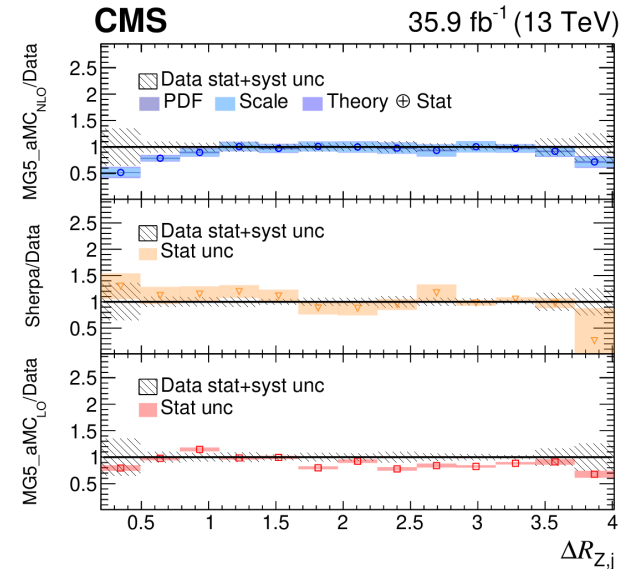


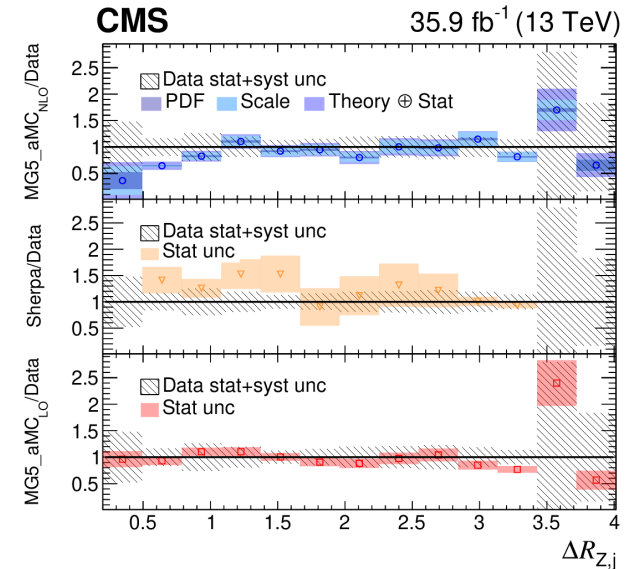
[JHEP 05 (2021) 285]

- Measure real collinear Z emission from jets
- Different lead jet p_T regions:
  - p_T(jet) > 300 GeV
  - p_T(jet) > 500 GeV
- Partial run 2 dataset: 35.9 fb^{-1}
- Z($\rightarrow \mu\mu$) + jets
- jet p_T > 40 GeV, $|\eta| < 2.4$
- $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$
- 2 distinct populations:
  - Back-to-back near $\Delta R \approx \pi$
  - Collinear emission $\Delta R \leq 2.5$
- **MC agreement w/ data**

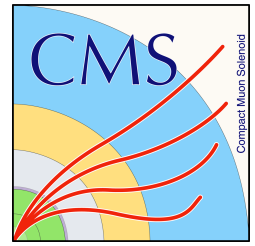








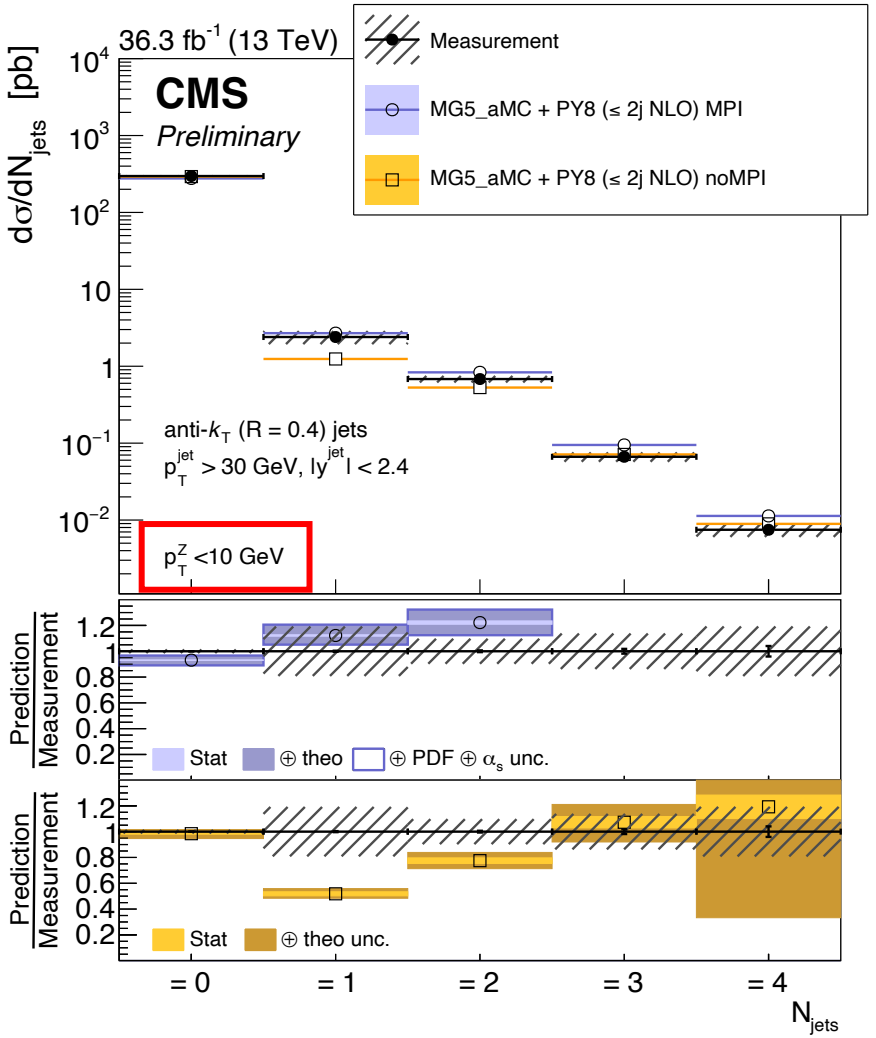
Z + jets azimuthal correlations

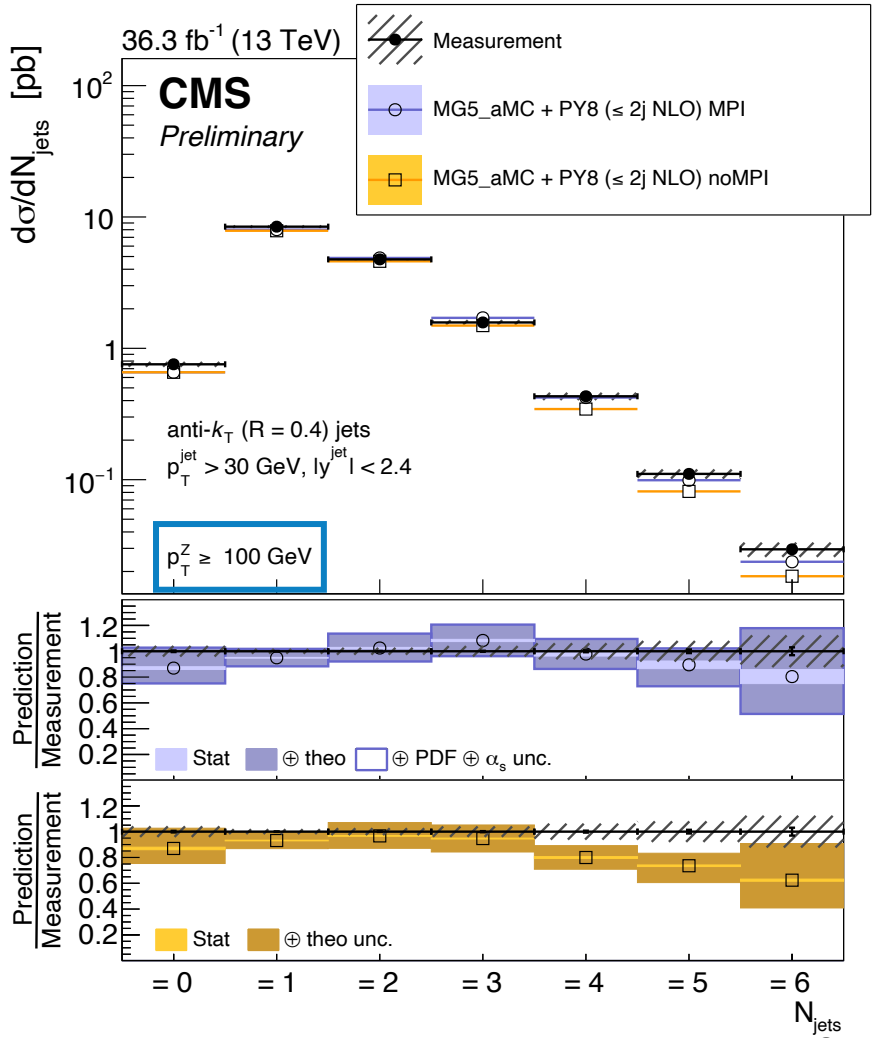


- Measure $\Delta\phi(Z, j_1)$ and $\Delta\phi(j_1, j_2)$

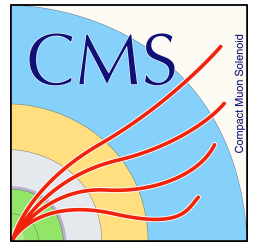
CMS-PAS-SMP-21-003

- Study effect of multi-parton interactions (MPI)
- Different Z p_T regions:
  - $p_T(Z) < 10$ GeV
  - $30 < p_T(Z) < 50$ GeV
  - $p_T(Z) > 100$ GeV
- Partial run 2 dataset: 36.3 fb^{-1}
- Z($\rightarrow ee,\mu\mu$) + jets
- jet $p_T > 30$ GeV, $|\eta| < 2.4$
- Very large effect of MPI at low Z p_T



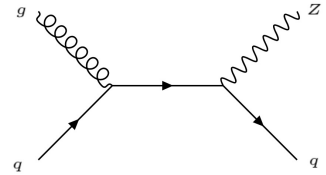


Z + jets azimuthal correlations

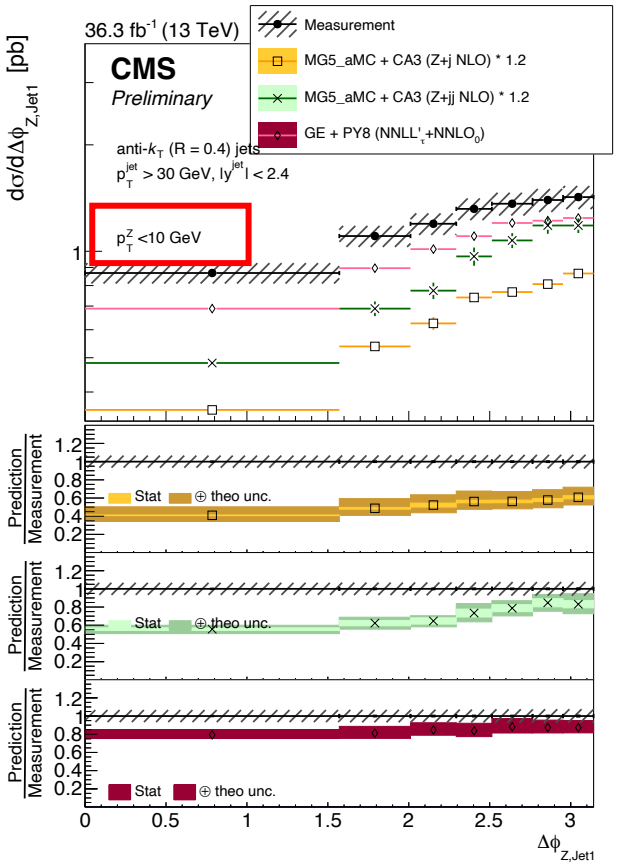


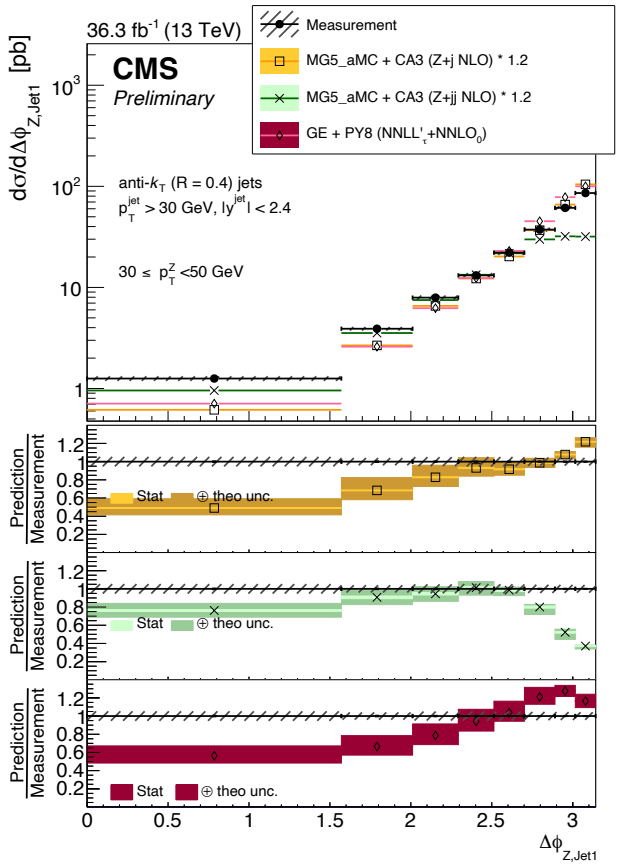
CMS-PAS-SMP-21-003

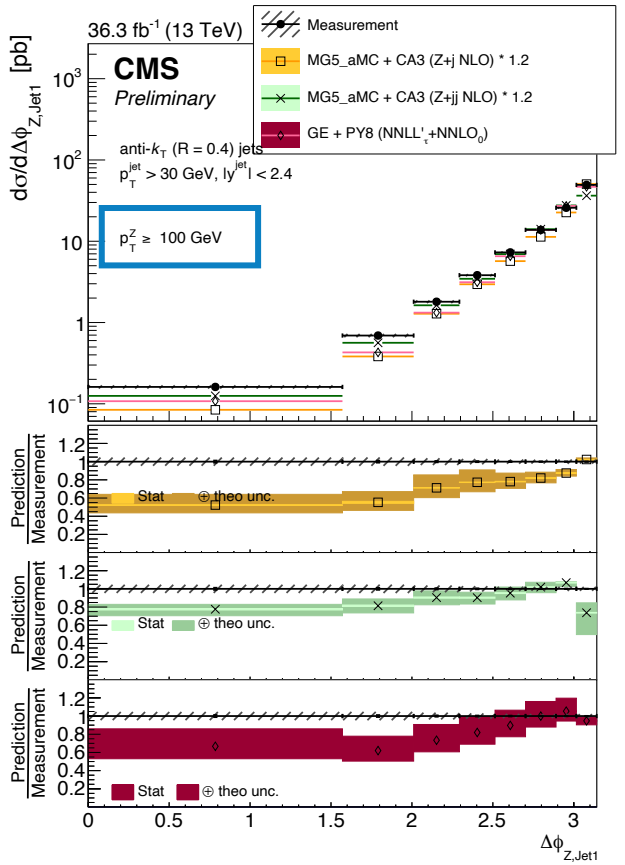
- $\Delta\phi(Z, j_1)$ Mostly flat for **p_T(Z) < 10 GeV**: no correlation
- For **p_T(Z) > 100 GeV**: Z and jet back-to-back



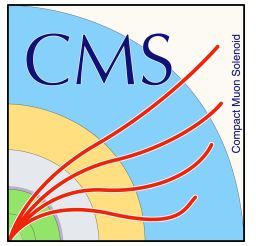
- Important higher order ME contributions at low $\Delta\phi_{Z,jet1}$
- Z+2 jet @NLO generally performs better over Z+1jet @NLO
- Geneva includes MPI, helping agreement at low Z p_T
- MG5_aMC Z+2 jet @NLO (no MPI) agrees with Geneva at high Z p_T where MPI has little effect





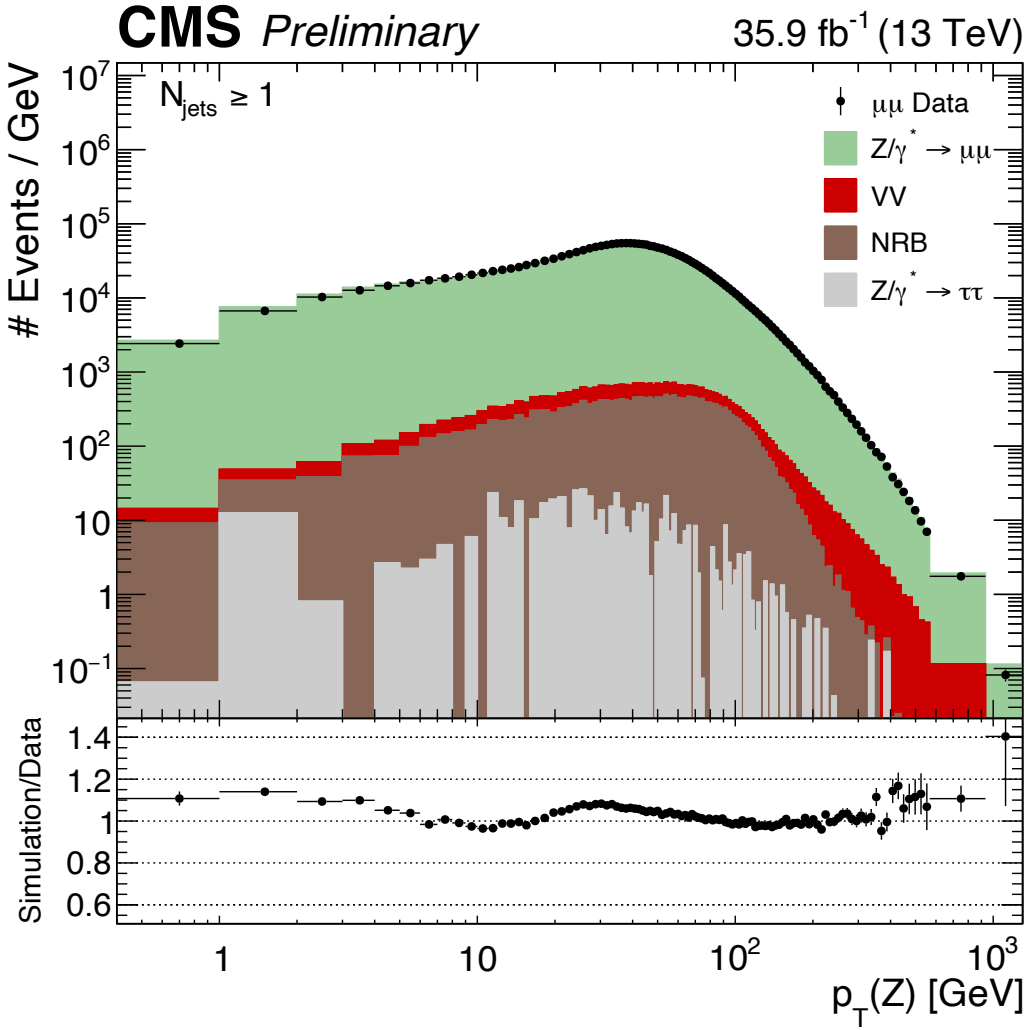


Z + jets differential measurements



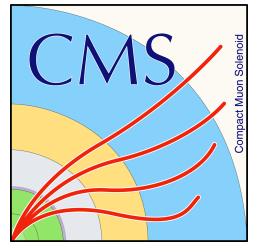
CMS-PAS-SMP-19-009

- Precise measurements of several observables of Z + jets
- Differential cross section:
  - **Double differential p_T and |y| of Z and jets**
  - Jet multiplicity
  - **p_T and |y| of 5 leading jets**
  - Angular variables
- Partial run 2 dataset: 35.9 fb^{-1}
- Z($\rightarrow ee,\mu\mu$) + jets
- jet p_T > 30 GeV, $|\eta| < 2.4$
- Backgrounds: 1-10% of event yield
  - Higher background in tails of p_T distributions
  - NRB = non-resonant background e.g $t\bar{t}$



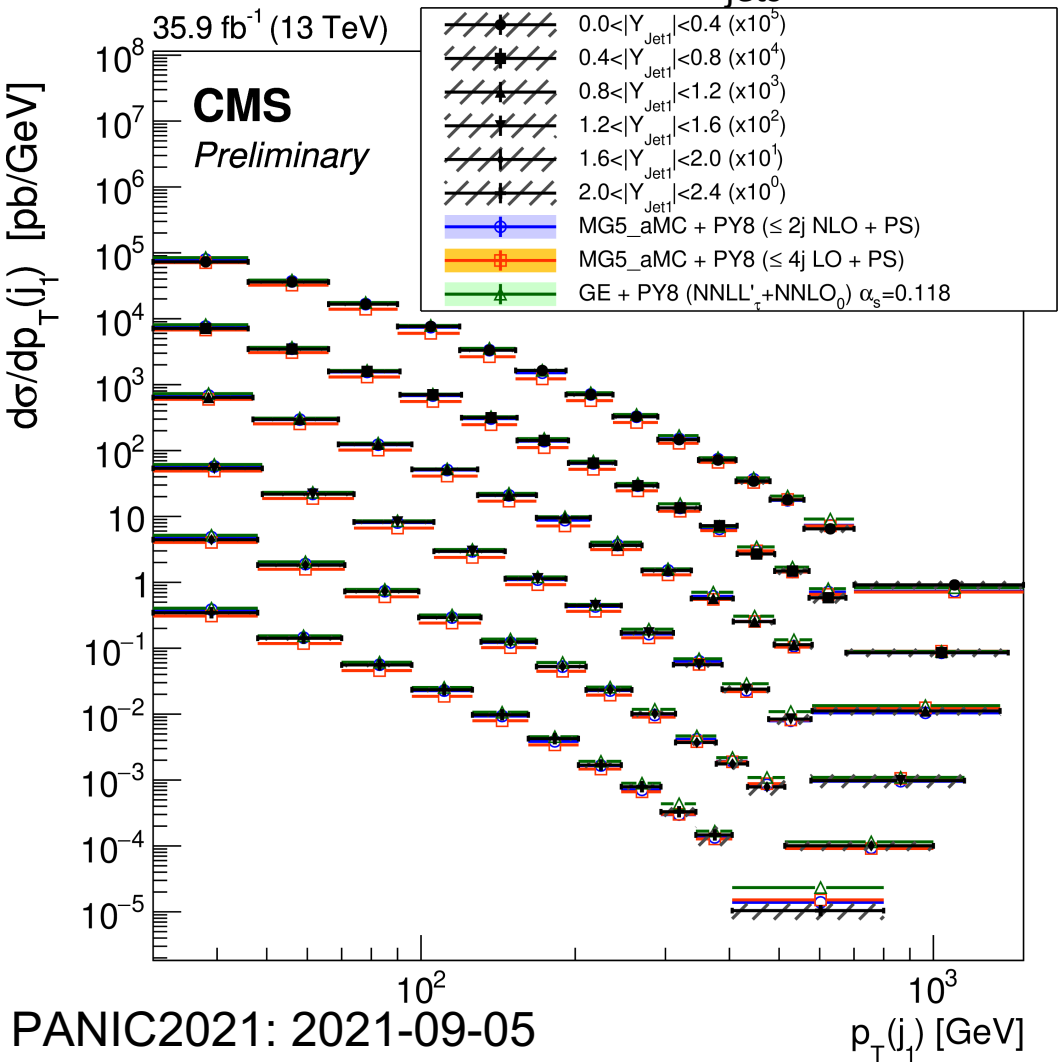
Detector-level plot. MC and data statistical uncertainties only.

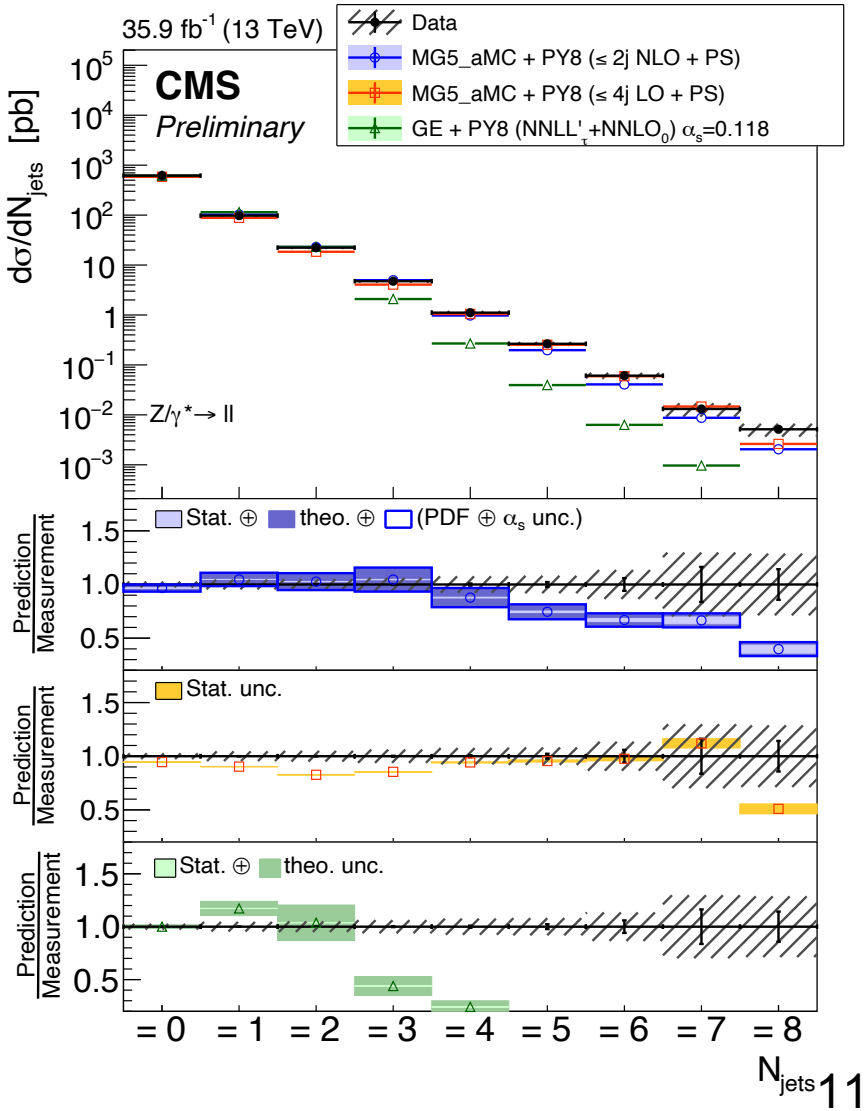
Z + jets differential measurements



CMS-PAS-SMP-19-009

- Double differential cross section: lead jet p_T against |y|
- Good agreement with N_{jets} up to 4 jets, due to matrix element



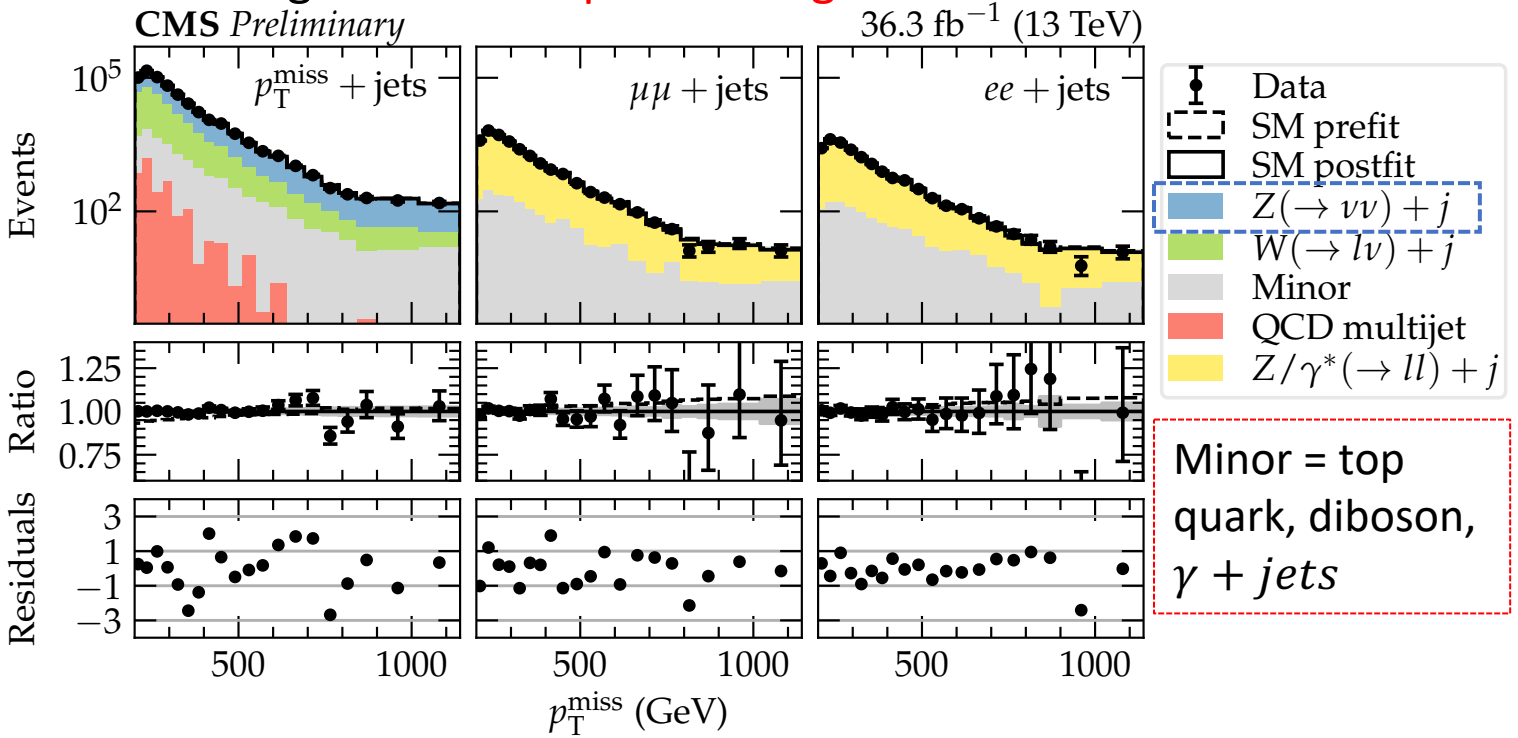


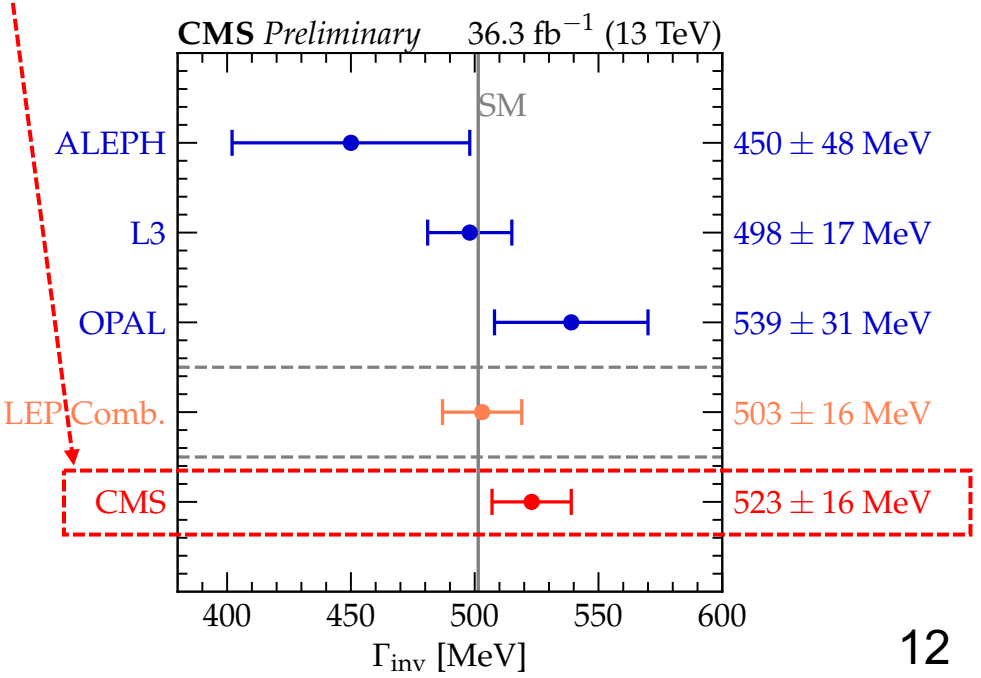
Precision Z invisible width: $Z \to \nu\nu$

- Precision measurement of Z invisible decay width **CMS-PAS-SMP-18-014**

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z + jets)\, B(Z \to \nu\bar{\nu})}{\sigma(Z + jets)\, B(Z \to l\bar{l})} \Gamma(Z \to l\bar{l})$$

- First direct measurement of Z invisible width at hadron collider
- Partial run 2 dataset: 36.3 fb^{-1}
- Invisible width extracted from **simultaneous likelihood fit** to the jets + MET, ll + jets and l + jets regions
- Resulting in the most precise single direct measurement in the world, competing with combined LEP





Z + b jets - ATLAS & CMS

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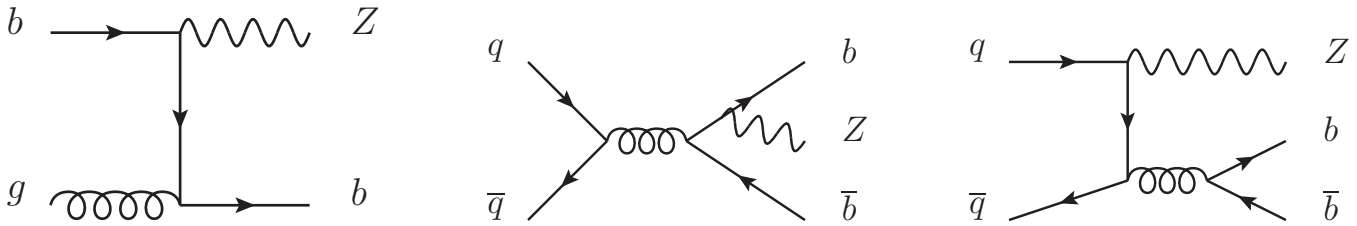
CMS-PAS-SMP-20-015

- Test pCQD predictions and quark PDF in presence of heavy flavour jets
- Z (→ *ee*,*μμ*) + b jets measurements
- Sensitive to gluon splitting and b quark parton distribution function (PDF)
- MC predictions sensitive to flavour number scheme (FNS) in PDF



ATLAS

- Partial run 2 dataset: 35.6 fb^{-1}
- Z + ≥ 1 or ≥ 2 b jets, b-jet p_T > 20 GeV, |y| < 2.5
- b-jet tagger: ≈ 70% efficiency
- Testing several MC predictions with 4 and 5 FNS: 5FNS includes b quark in PDF

CMS

- Full run 2 dataset: 137 fb^{-1}
- Z + ≥ 1 or ≥ 2 b jets, b-jet p_T > 30 GeV $|\eta| < 2.4$
- b-jet tagger: ≈ 50% efficiency (tight WP)

Z + b jets - ATLAS & CMS

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ATLAS

Kinematic variable	Acceptance cut
Lepton p_{T}	$p_{\mathrm{T}} > 27$ GeV
Lepton η	$\lvert\eta\rvert < 2.5$
$m_{\ell\ell}$	$m_{\ell\ell} = 91 \pm 15$ GeV
b-jet p_{T}	$p_{\mathrm{T}} > 20$ GeV
b-jet rapidity	$\lvert y\rvert < 2.5$
b-jet–lepton angular distance	$\Delta R(b\text{-jet}, \ell) > 0.4$

CMS

CMS-PAS-SMP-20-015

Object	Selection
Dressed leptons	p_{T} (leading) > 35 GeV, p_{T} (subleading) > 25 GeV, $\lvert\eta\rvert < 2.4$
Z boson	$71 < M_{\ell\ell} < 111$
Particle-level bjet	bhadron jet, $p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 2.4$

Fiducial selections

- Differences in fiducial selections will lead to different results and MC modelling
- See backup for details about the different MC generators used in both analysis

Z + ≥ 1 b jet

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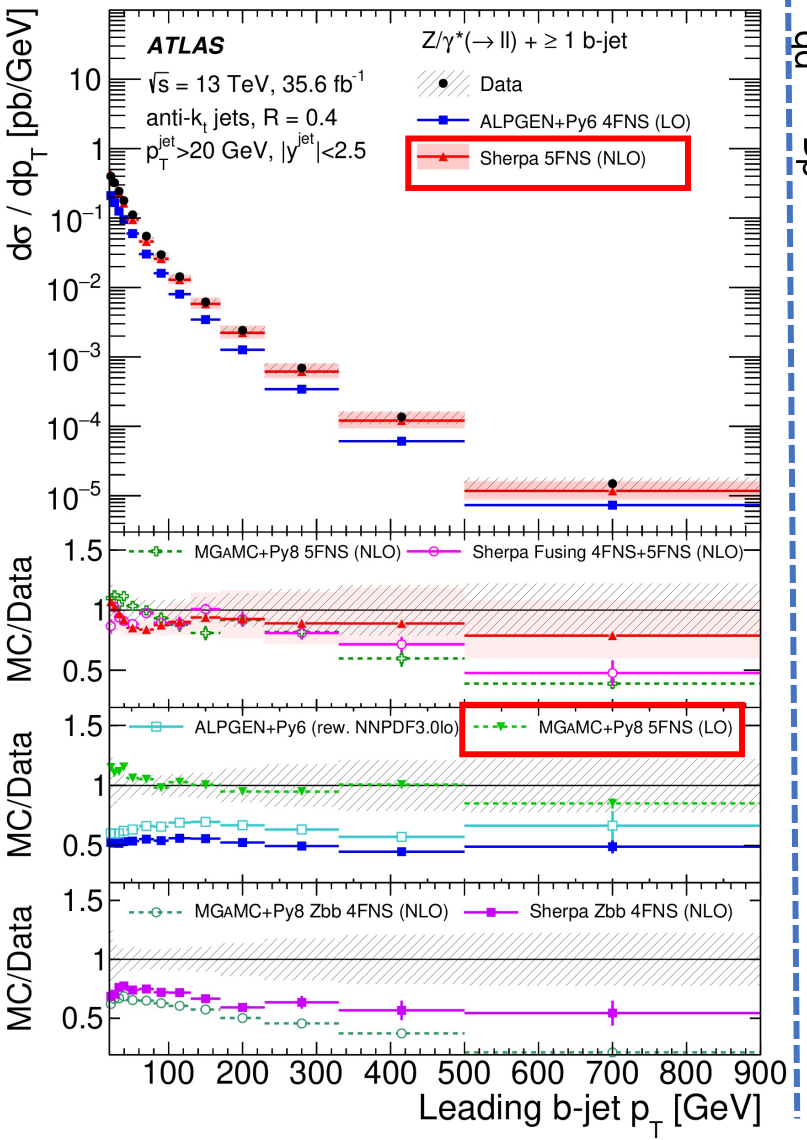
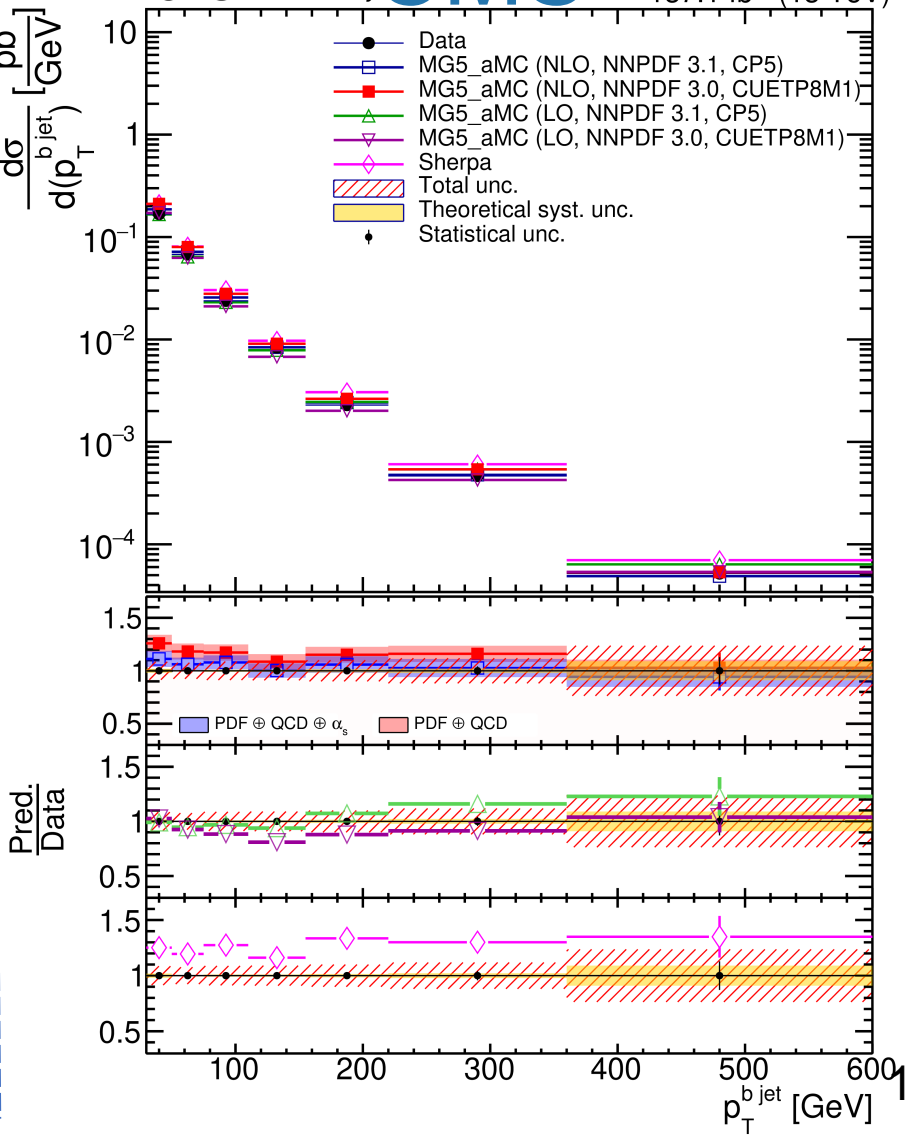
CMS-PAS-SMP-20-015

- ATLAS:
  - 5FNS MC describes data better than 4FNS
- CMS:
  - Sherpa overestimates normalization by 20%
  - Well modelled other than tail of MG5 LO

ATLAS



CMS



Z + ≥ 1 b jet

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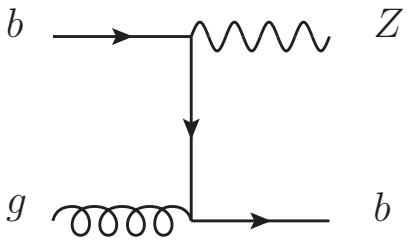
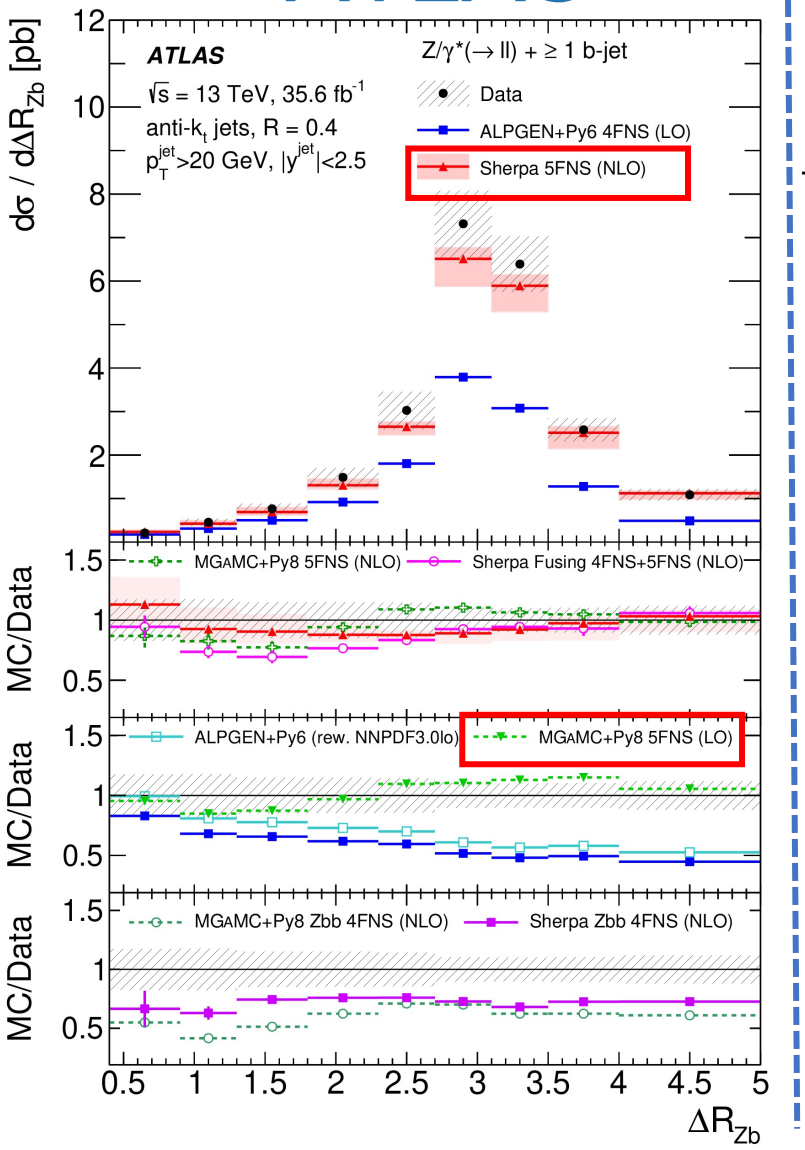
CMS-PAS-SMP-20-015



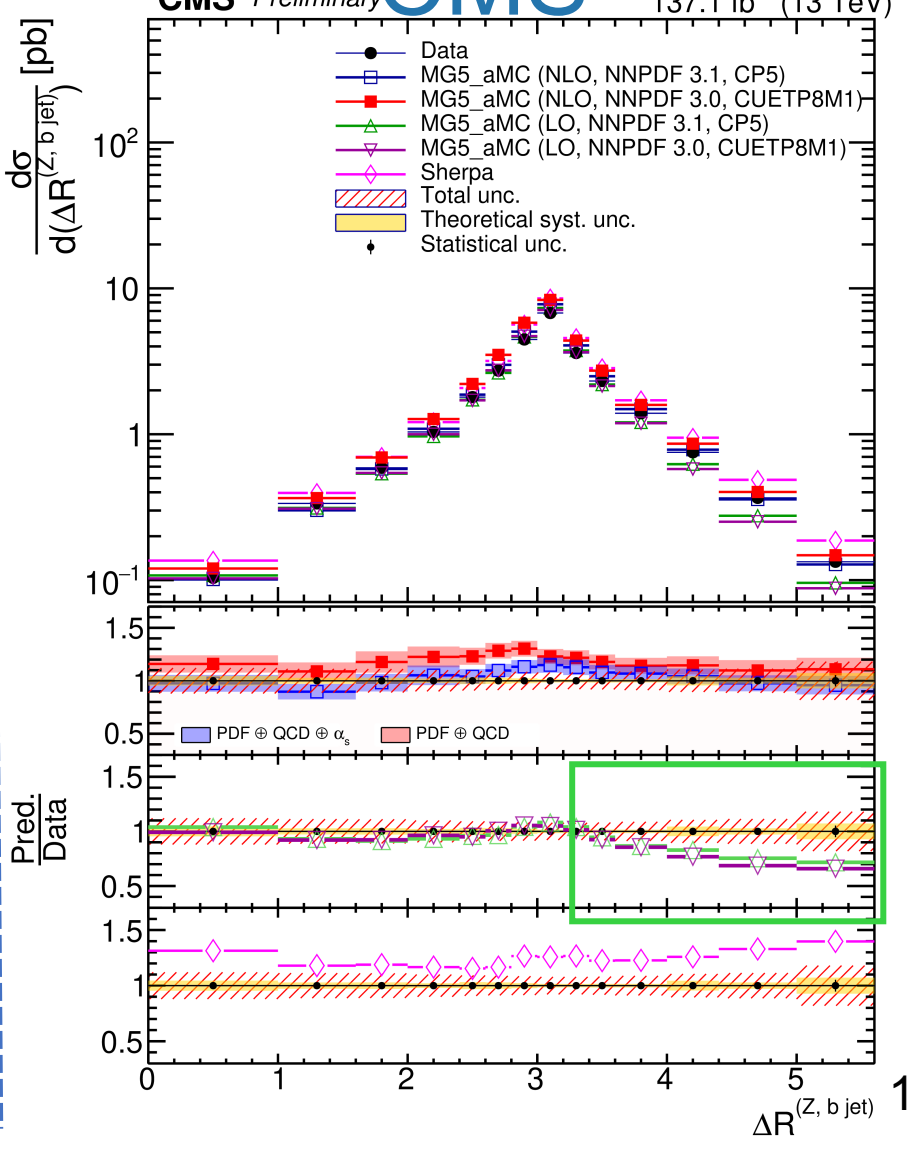
- ATLAS:
  - 5FNS MC describes data better than 4FNS
- CMS:
  - Well modelled by MC, other than LO tail at $\Delta R_{Zb} > 3$

Back-to-back peak $\Delta R_{Zb} \approx \pi$ well modelled

ATLAS



CMS



Z + ≥ 2 b jets

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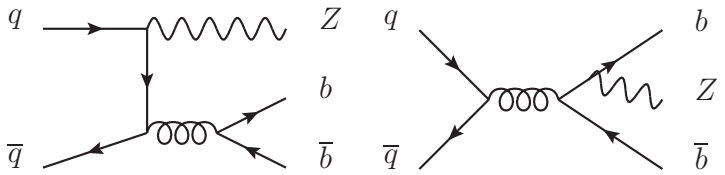
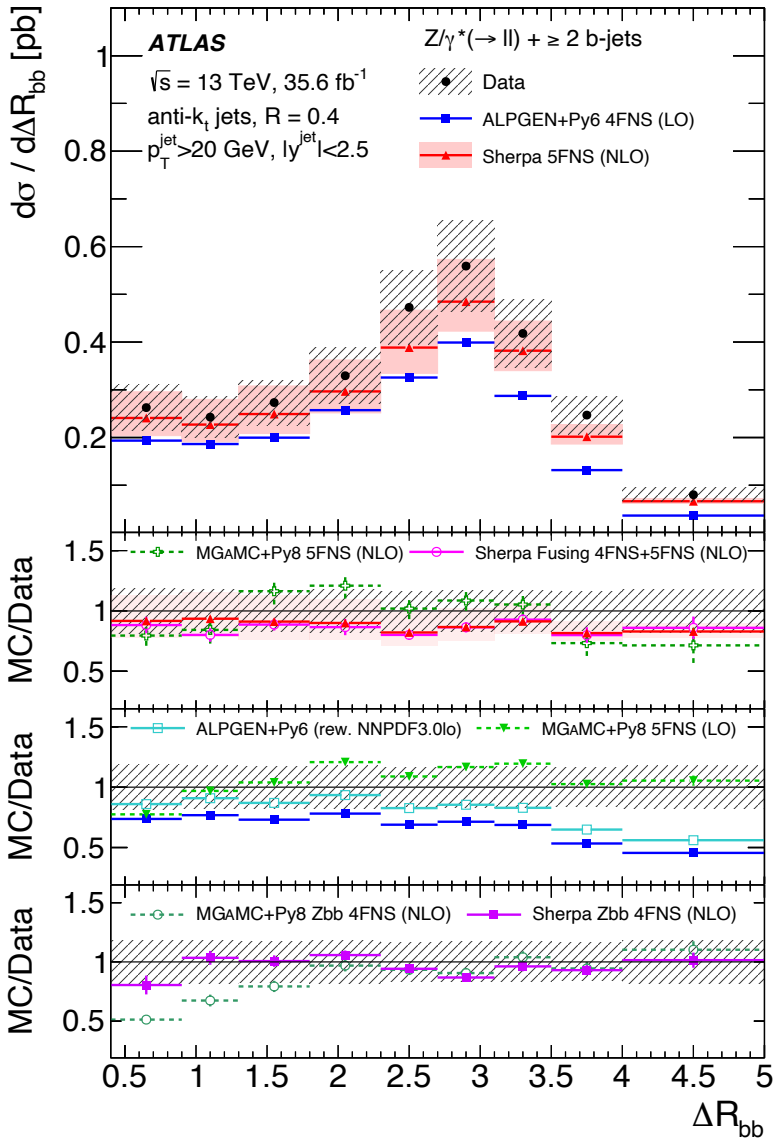
CMS-PAS-SMP-20-015

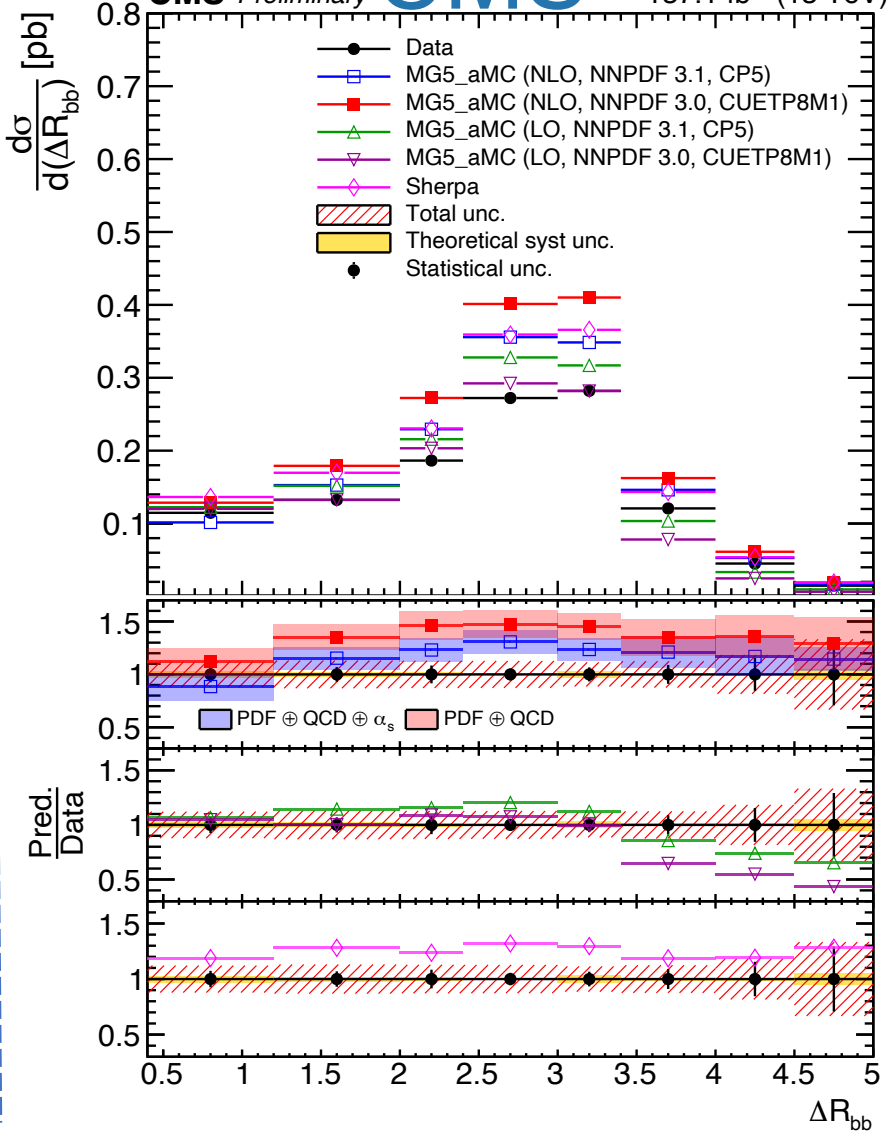


- Small values of ΔR_{bb} sensitive to gluon splitting.
- Back-to-back peak $\Delta R_{bb} \approx \pi$ well modelled
- LO tail mismodeled

ATLAS



CMS



Z + ≥ 2 b jets

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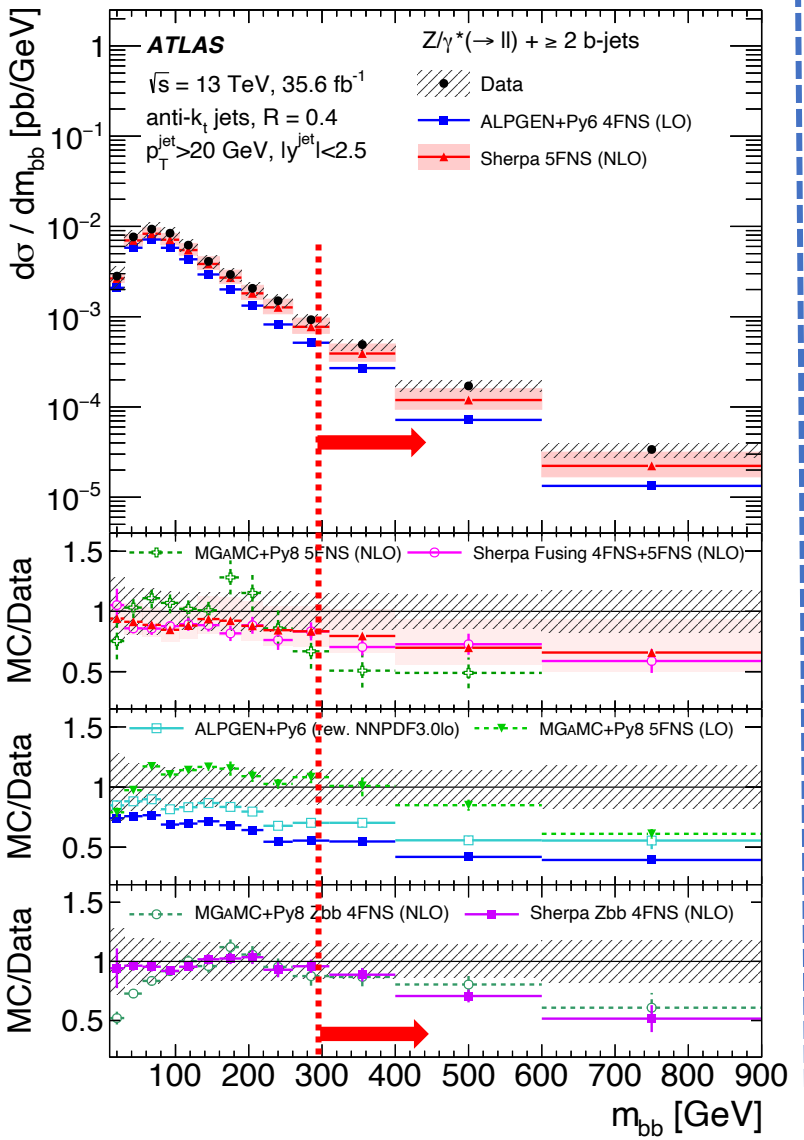
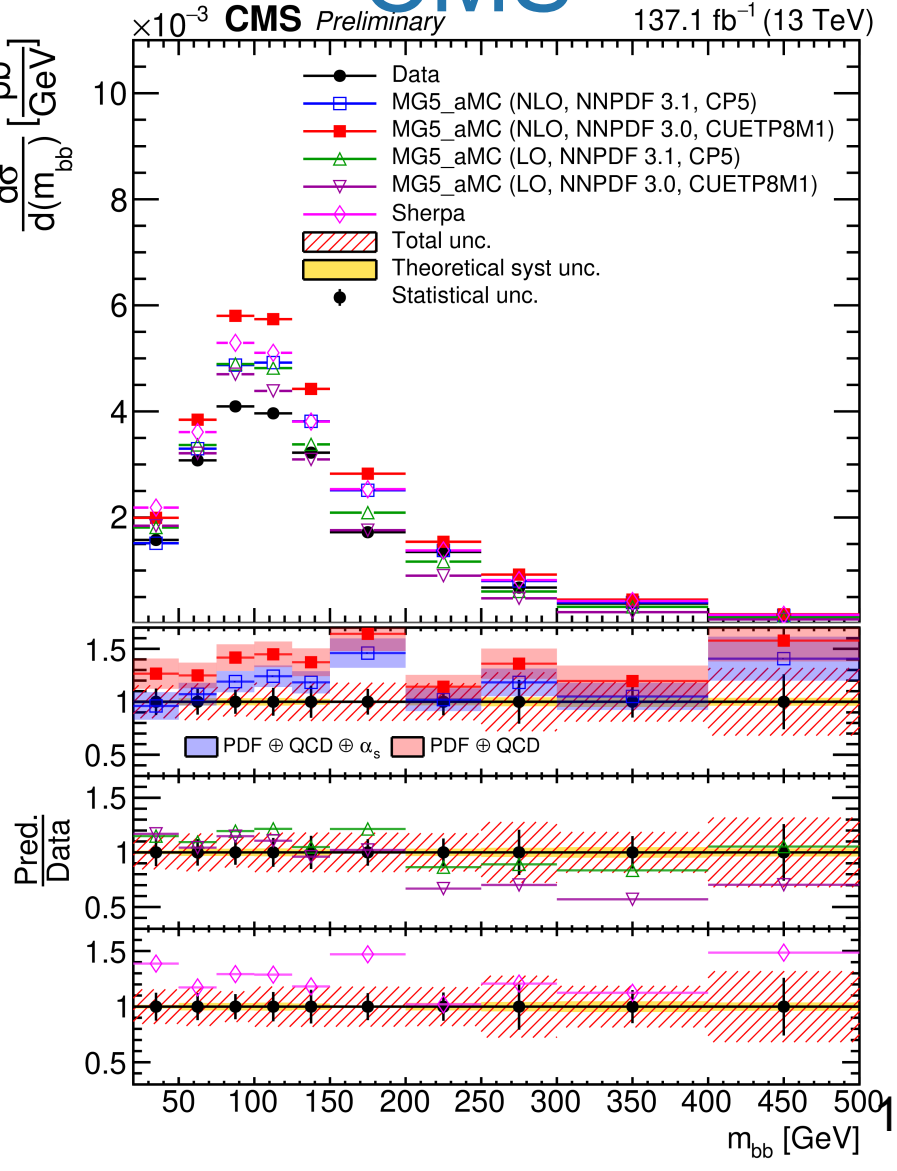
CMS-PAS-SMP-20-015

- ATLAS:
  - No MC in agreement with data for **m_{bb} > 300 GeV**
- CMS:
  - Shapes best described by MG5 NLO over LO

ATLAS



CMS



Conclusion

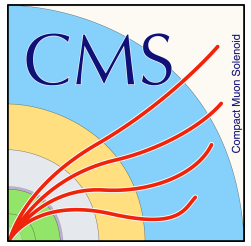
- Presented wide range of latest results of V+jets/+heavy flavour @ 13 TeV
- Several precision and extreme phase space measurements

- Run 2 statistics allows for extremely precise measurements allowing to better probe MC generator performances
- Generally, NLO generators in best agreement with data within uncertainties and Run 2 statistics

- LHC Run 3 will open the way for higher statistics, more precise measurements and new extreme phase spaces.

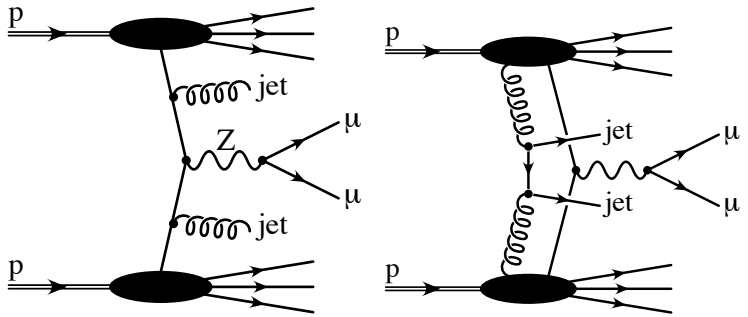
Backup

Double parton scattering Z + jets

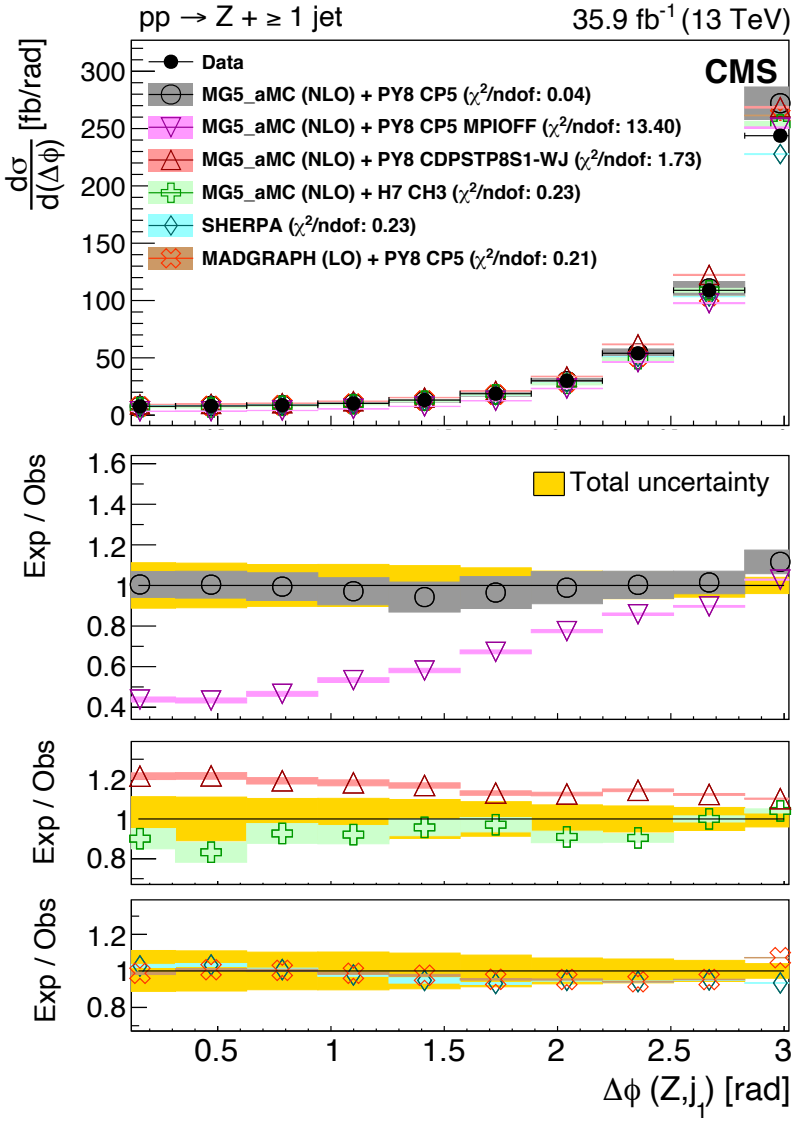


CMS-SMP-20-009

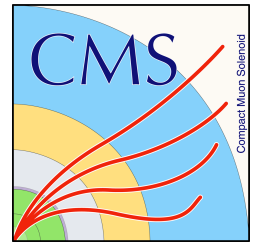
- Investigate double parton scattering
- Observables sensitive to double parton scattering
- Test various ISR, FSR and MPI models



- Partial run 2 dataset: 35.9 fb^{-1}
- Z($\rightarrow ee,\mu\mu$) + jets, jet p_T > 20 GeV, $|\eta| < 2.4$
- MG5Py8 without MPI disagrees with data for low $\Delta\phi(Z, j_1)$, where MPI contributions are largest



Z + jets differential measurements



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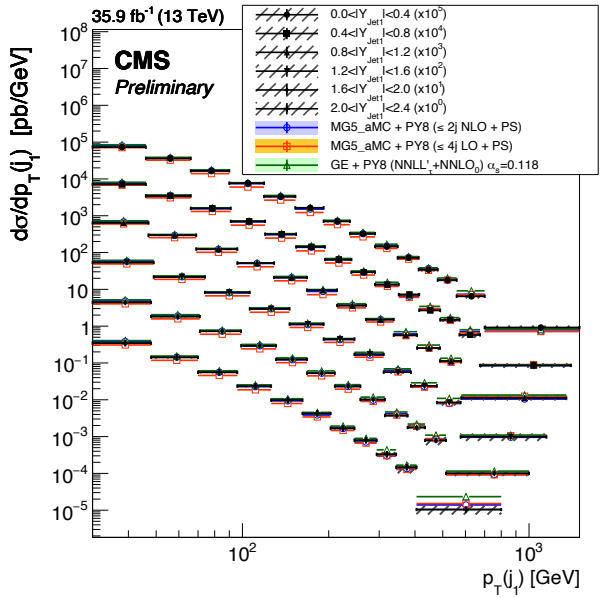

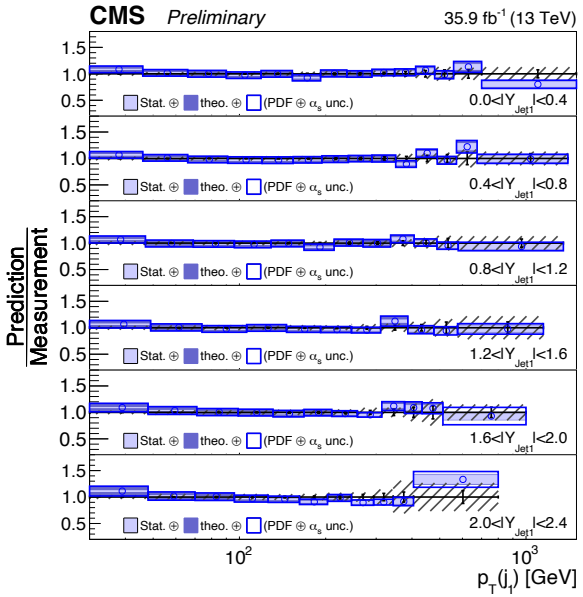

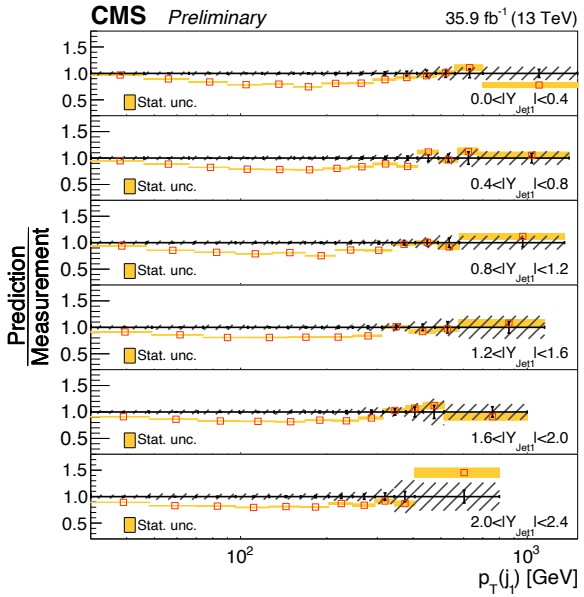

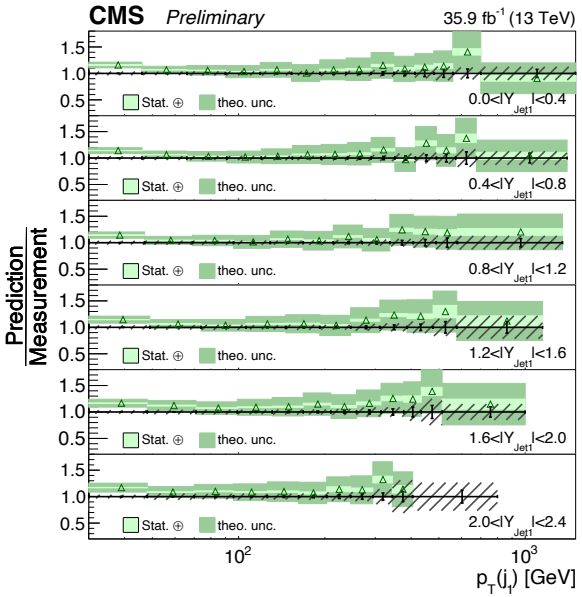

- MC Generators in agreement with data.
- MG @ NLO (Blue) performs better than LO and GENEVA

Z + b jets - ATLAS & CMS

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ATLAS

MC Generators:

- ALPGEN+Py8 4FNS: v2.14, 5p@LO, 4FNS
- Sherpa 5FNS, v2.2.1, 2p@NLO, 4p@LO
- MG5_aMC (NLO): v2.6.2, 5FNS, 1p@NLO
- Sherpa 4FNS+5FNS: v2.2.7, 5FNS 2p@NLO, 3p@LO, combined with the Z+bb events from Sherpa Zbb
- ALPGEN+Py8, ALPGEN4FNS reweighed to NNPDF3.0lo PDF set
- MG5_aMC 5FNS (LO): v2.2.2, 4p@LO
- MG5_aMC Zbb 4FNS: v2.6.2, Z+2 (massive) b jets @NLO
- Sherpa Zbb: v2.2.7, 4FNS, Z + 2 (massive) b jets @ NLO in the ME

CMS

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MC Generators (5FNS):

- MG5_aMC v2.3 NLO NNPDF 3.1, 2p@NLO w/ FxFx matching, CP5 event tune
- MG5_aMC v2.6 NLO NNPDF 3.0, 2p@NLO w/ FxFx matching, CUET8PM1 event tune
- MG5_aMC v2.2LO, NNPDF 3.1, 4p @ LO, CP5 event tune
- MG5_aMC v2.4 LO, NNPDF 3.0, 4p @ LO, CUET8PM1 event tune
- Sherpa v2.2 : 2p@NLO, 4p@LO

Z + b jets

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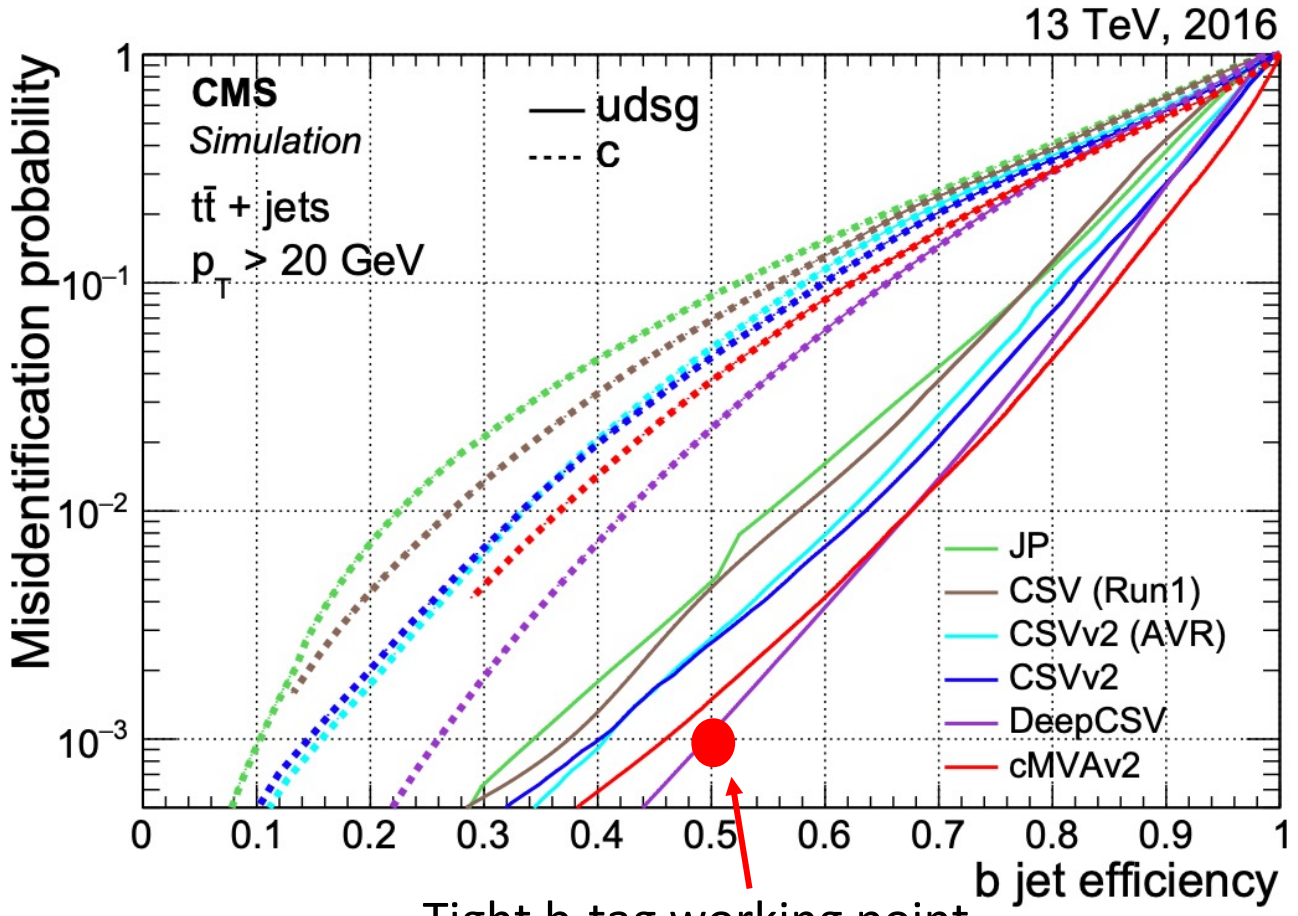
- Testing several MC predictions with 4 and 5 FNS

Generator	$N_{\text{max}}^{\text{partons}}$ NLO	$N_{\text{max}}^{\text{partons}}$ LO	FNS	PDF set	Parton Shower
Z+jets (including Z+b and Z+bb)					
Sherpa 5FNS (NLO)	2	4	5	NNPDF3.0nnlo	Sherpa
Sherpa Fusing 4FNS+5FNS (NLO)	2	3	5 (*)	NNPDF3.0nnlo	Sherpa
Alpgen + Py6 4FNS (LO)	-	5	4	CTEQ6L1	Pythia v6.426
Alpgen + Py6 (rew. NNPDF3.0lo)	-	5	4	NNPDF3.0lo	Pythia v6.426
MGaMC + Py8 5FNS (LO)	-	4	5	NNPDF3.0nlo	Pythia v8.186
MGaMC + Py8 5FNS (NLO)	1	-	5	NNPDF3.0nnlo	Pythia v8.186
Z+bb					
Sherpa Zbb 4FNS (NLO)	2	-	4	NNPDF3.0nnlo	Sherpa
MGaMC + Py8 Zbb 4FNS (NLO)	2	-	4	NNPDF3.0nnlo	Pythia v8.186

Z + b jets

CMS-PAS-SMP-20-015



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