Single boson production overview

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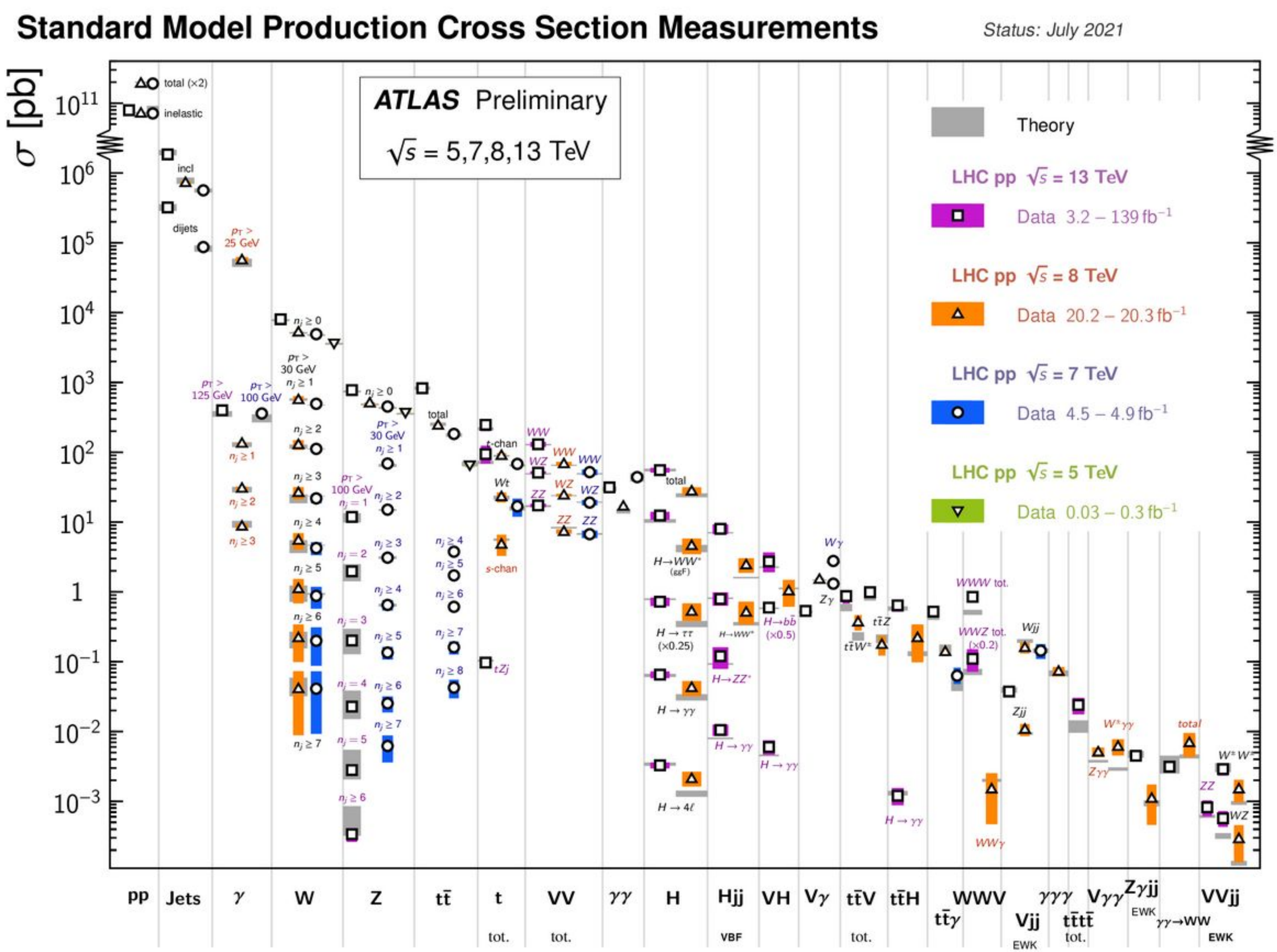
on behalf of the CMS and ATLAS collaborations

PANIC 2021

General outlook



Inclusive isolated γ

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	Phase-space region			
Requirement on E_T^γ	$E_T^\gamma > 125$ GeV			
Isolation requirement	$E_T^{iso} < 4.2 \times 10^{-3} \times E_T^\gamma + 4.8$ GeV			
Requirement on $\lvert\eta^\gamma\rvert$	$\lvert\eta^\gamma\rvert < 0.6$	$0.6 < \lvert\eta^\gamma\rvert < 1.37$	$1.56 < \lvert\eta^\gamma\rvert < 1.81$	$1.81 < \lvert\eta^\gamma\rvert < 2.37$
Number of events with $125 < E_T^\gamma < 150$ GeV	182 754	248 538	74 405	144 713
Number of events with $E_T^\gamma > 150$ GeV	2 030 144	2 696 077	814 623	1 471 953

Mainly test for pQCD

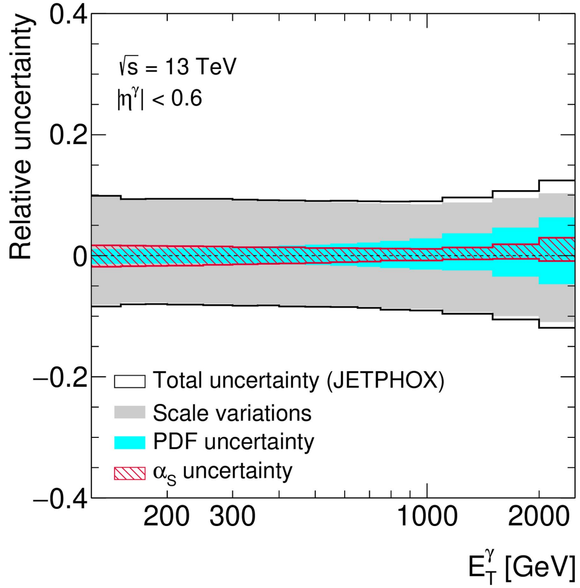
Sensitive to gluon density in proton already at LO

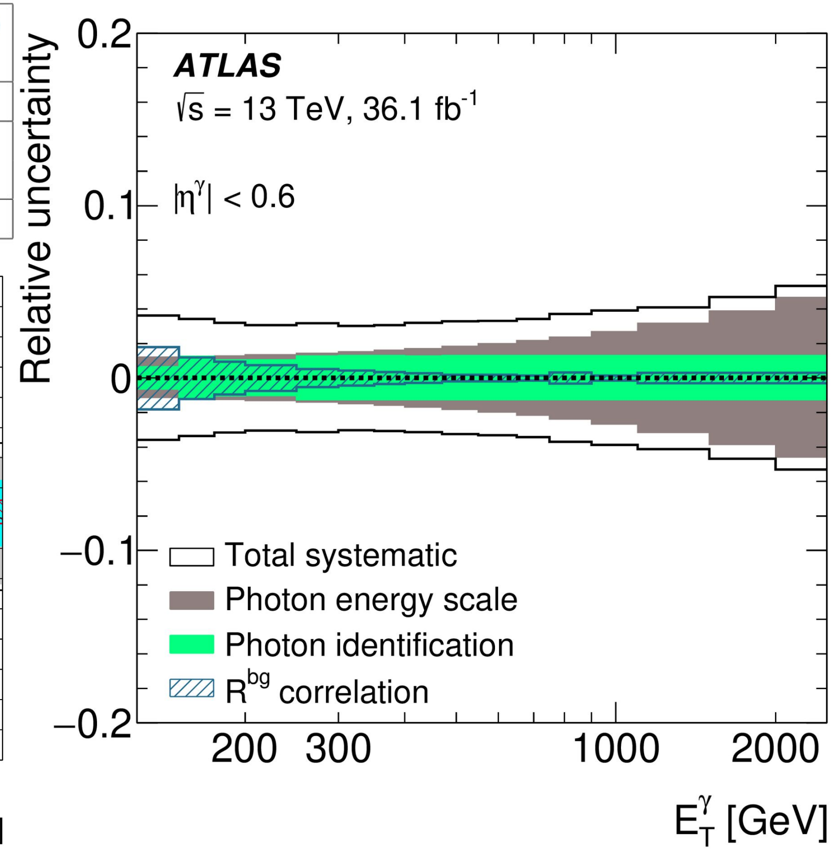
Program	Order in α_s	Fragmentation	Parton shower	Isolation	α_{EM}	Particle Level
JETPHOX	NLO	Yes	No	Fixed cone	1/137.036	No
SHERPA 2.2.2	NLO for $\gamma + (1, 2)$-jet LO for $\gamma + (3, 4)$-jet	No	Yes	Hybrid cone	1/137.036	Yes
NNLOJET	NNLO	No	No	Hybrid cone	1/132.232	No

No EWK corrections included

Likely have important role at TeV scale

Measurements help to probe this





Inclusive isolated γ

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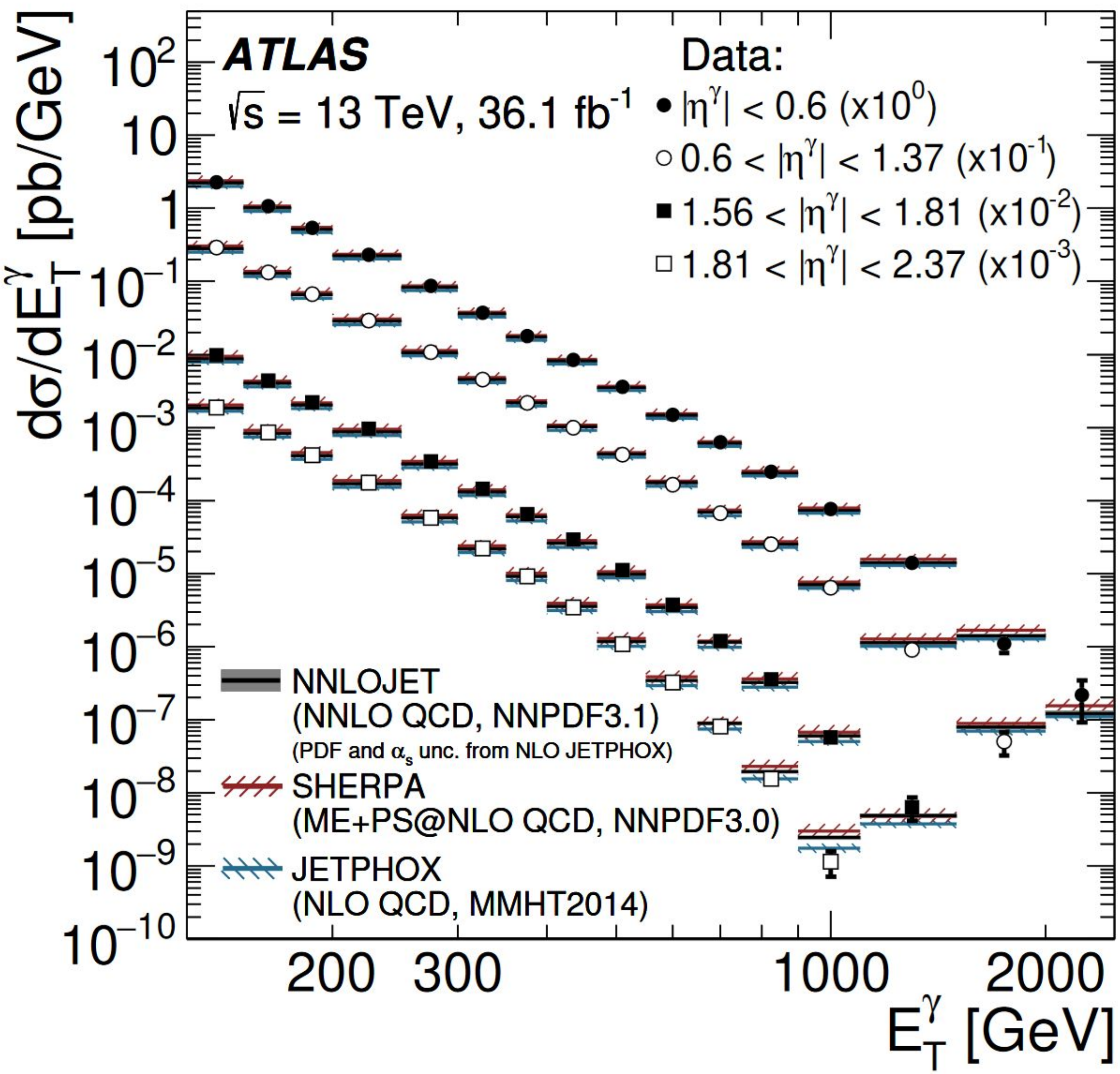
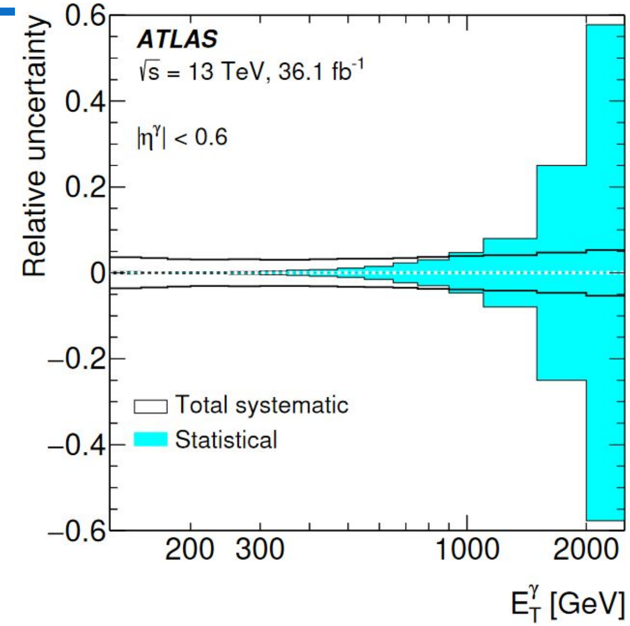
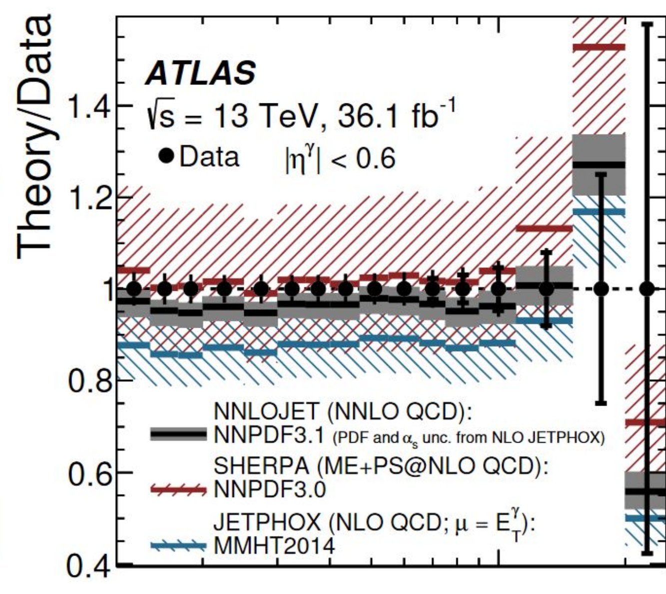
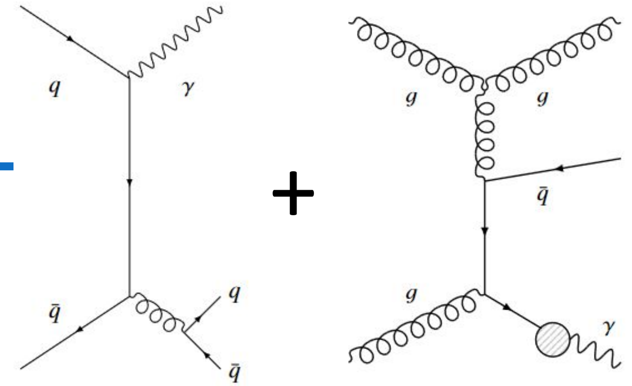






γ+2jets

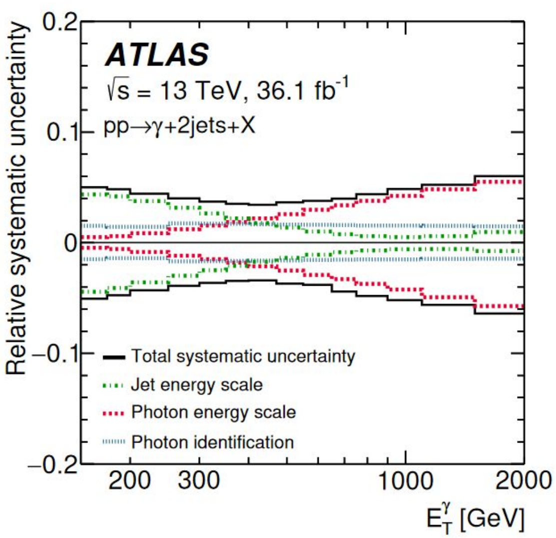


Two main production mechanisms (at LO)

- Phase space selection accounts for that

Using the 2016 dataset (36 fb^{-1})

Requirements on photon	$E_T^\gamma > 150\,\text{GeV}$, $\lvert\eta^\gamma\rvert < 2.37$ (excluding $1.37 < \lvert\eta^\gamma\rvert < 1.56$) $E_T^{\text{iso}} < 0.0042 \cdot E_T^\gamma + 4.8$ GeV (reconstruction level) $E_T^{\text{iso}} < 0.0042 \cdot E_T^\gamma + 10$ GeV (particle level)		
Requirements on jets	at least two jets using anti-k_t algorithm with $R = 0.4$ $p_T^{\text{jet}} > 100\,\text{GeV}$, $\lvert y^{\text{jet}}\rvert < 2.5$, $\Delta R^{\gamma\text{-jet}} > 0.8$		
Phase space	total	fragmentation enriched $E_T^\gamma < p_T^{\text{jet2}}$	direct enriched $E_T^\gamma > p_T^{\text{jet1}}$
Number of events	755 270	111 666	386 846



Photon and jet energy scales are the main sources of uncertainty

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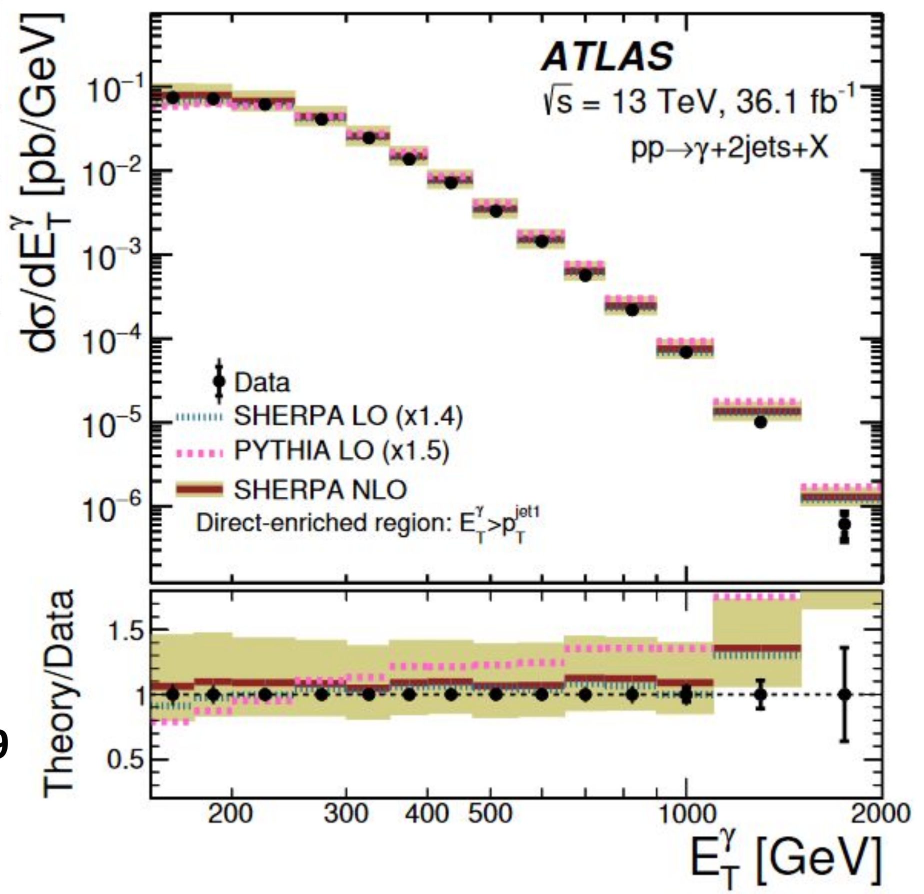
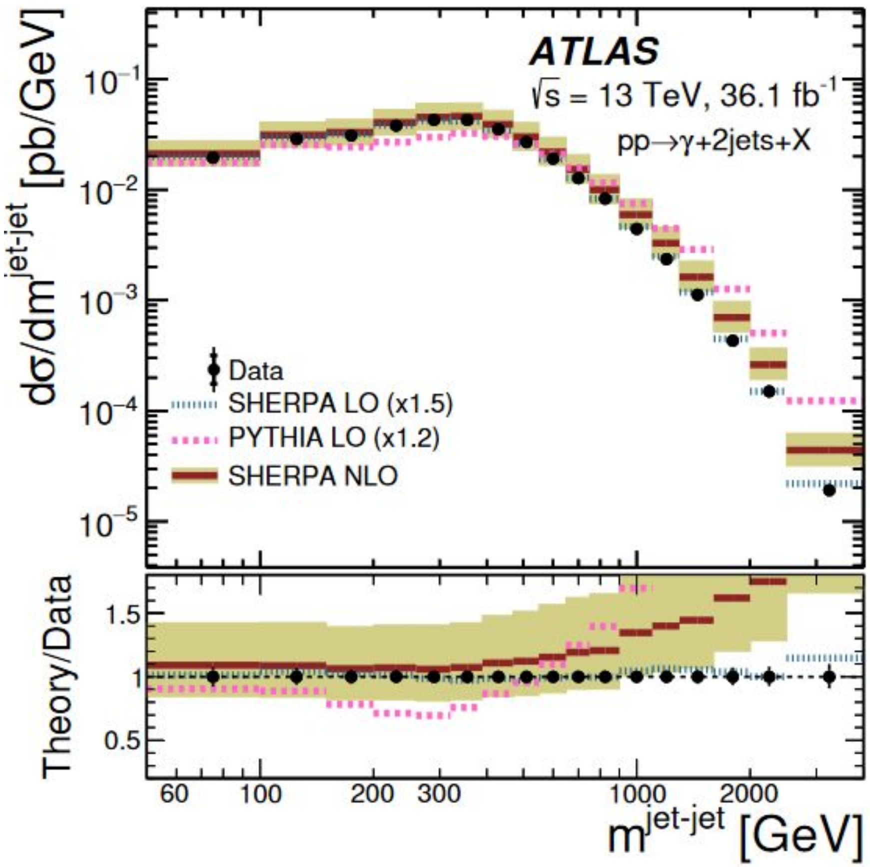
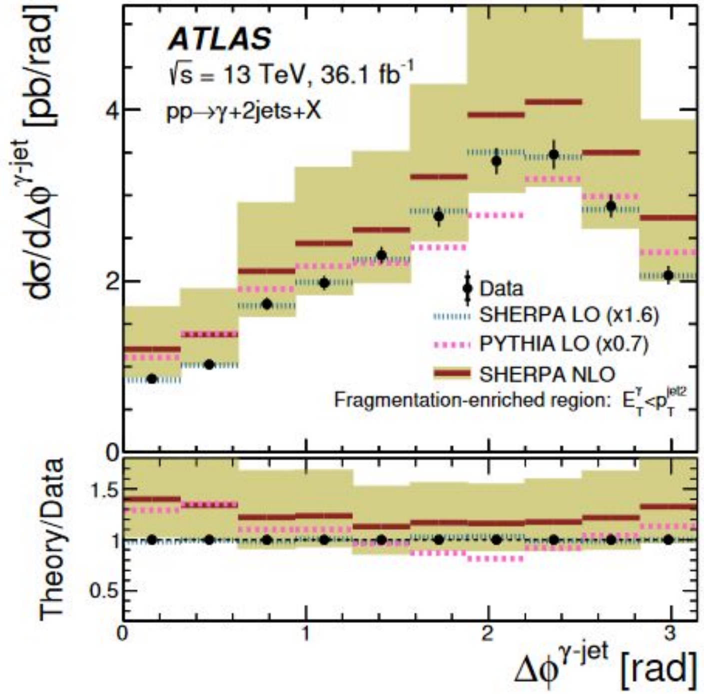
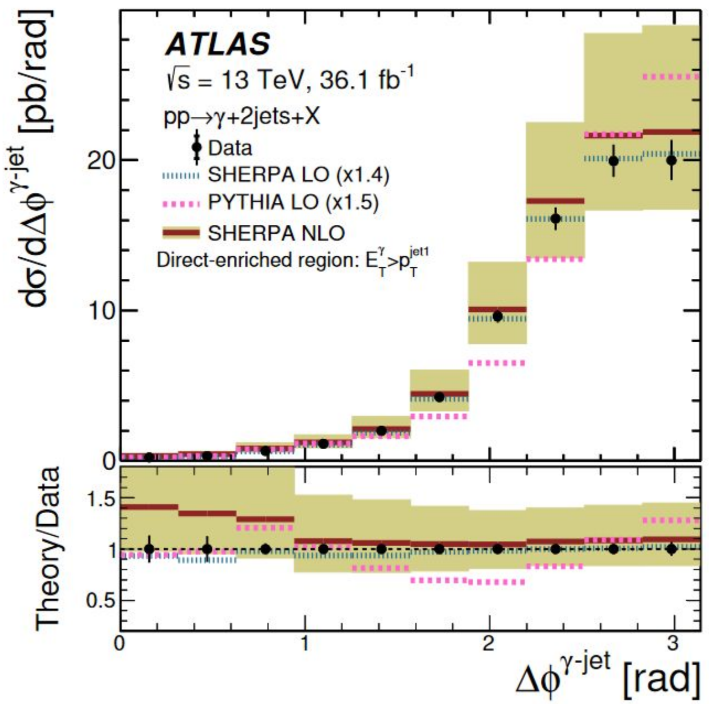


γ+2jets







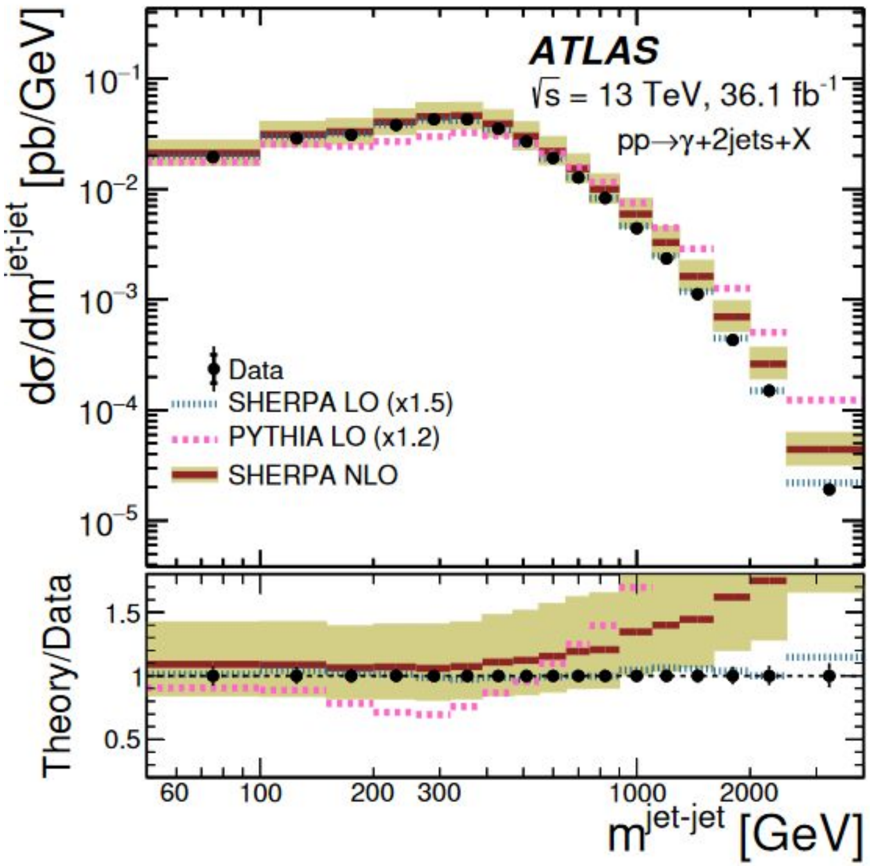
Fair description for $\Delta\phi^{\gamma\text{-jet}}$

Difficulty in the description of high m_{jj} region

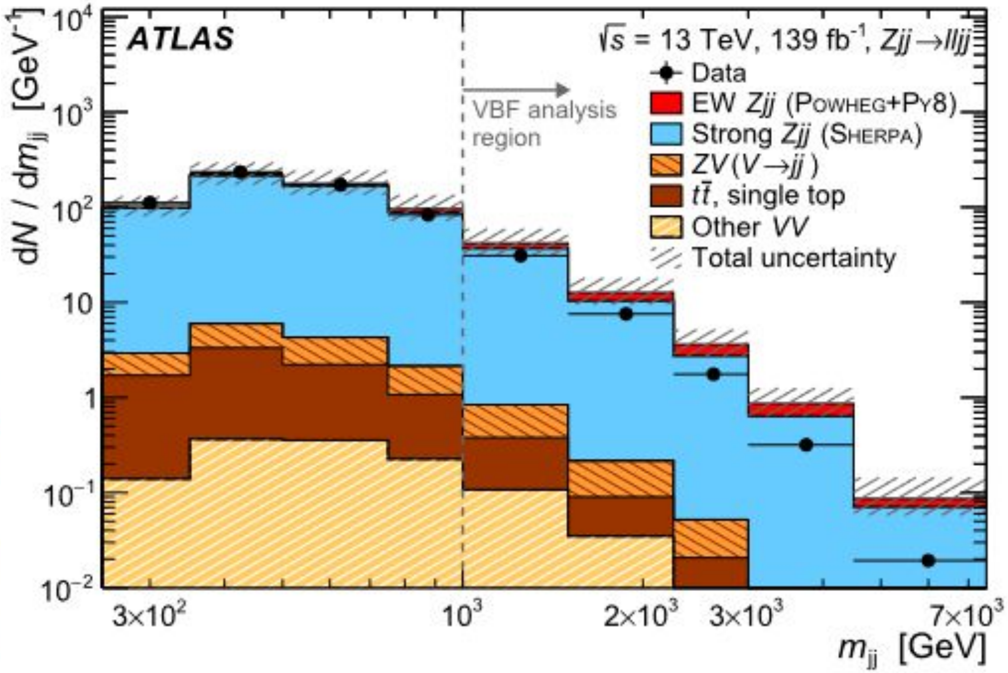
There are some interesting hints...

Multiple probes

From ɣ+jets



From Z+jets



Eur. Phys. J. C (2021) 81:163

Important area for VBF and VBS studies

Also visible in W+jets

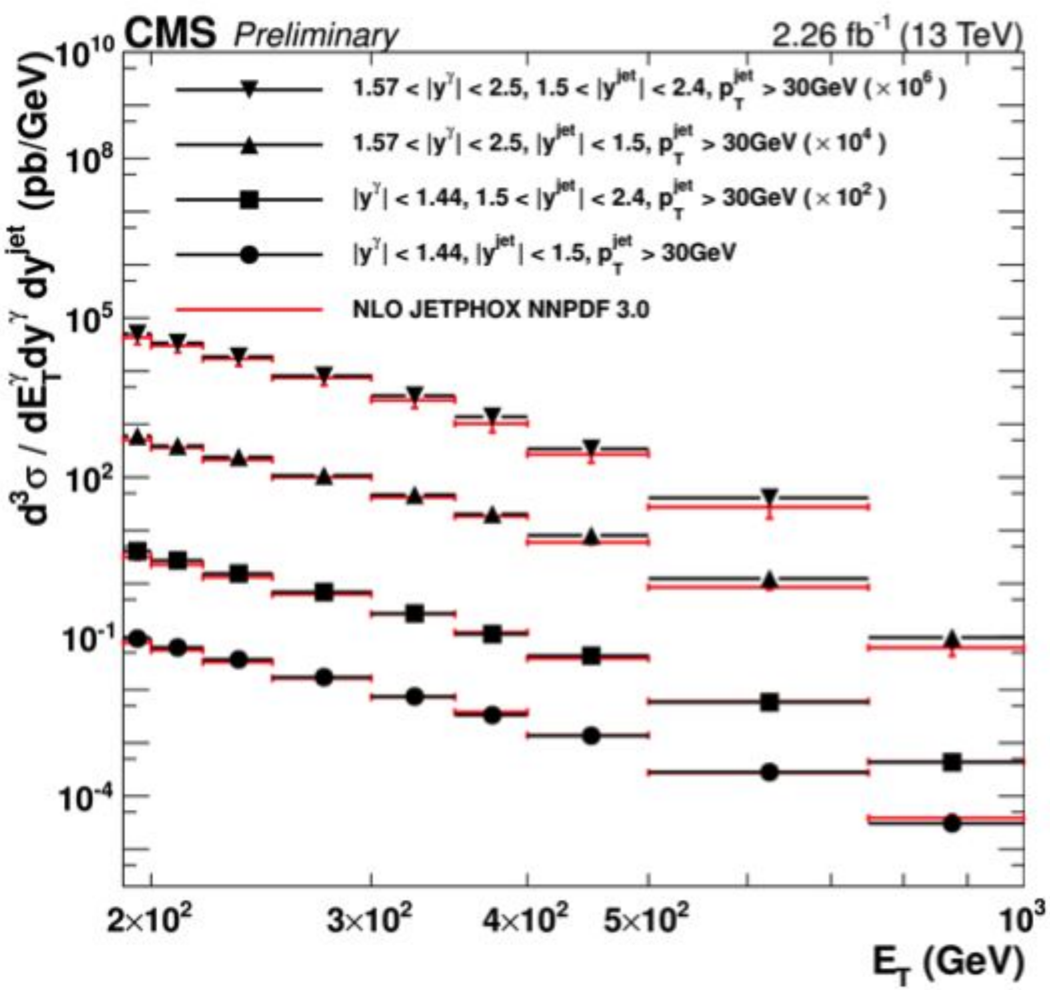
Prevalent in the fragmentation enriched sample in ɣ+jets

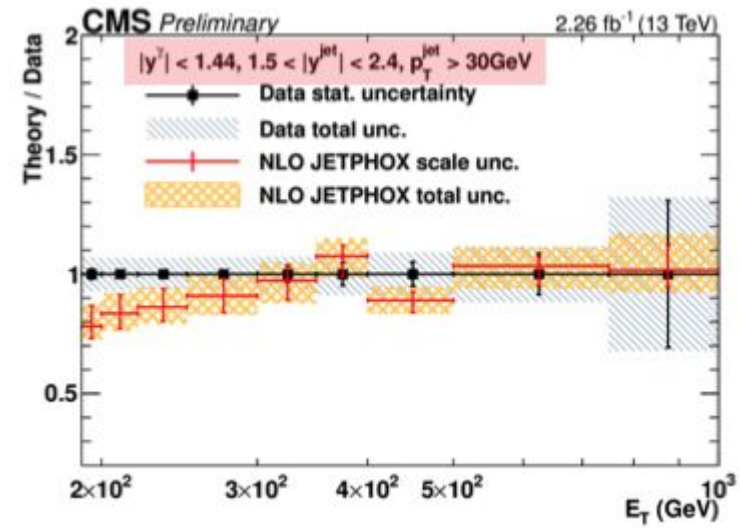
Triple differential γ+jets

Eur. Phys. J. C 79 (2019) 20

Main processes are quark-gluon Compton scattering and qq annihilation

Test of QCD and probe of gluon PDF





NLO calculations available for comparison

Data with low uncertainties in lower E_T regions, can allow to constrain/select PDF sets

Z differential cross section

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Combined measurement in $\ell^+\ell^-$ and neutrino channels

Charged channel

Single lepton triggers with p_T > 24 GeV

Tighter offline selection (usually O(GeV))

Select opposite charge same-flavor leptons within the tracking acceptance

Reject events with additional leptons with p_T > 10 GeV

Main backgrounds are tt (leptonic), WW, tW

Neutral channel

Variable	Selection	To suppress background from
Electron veto	$p_T > 10\,\text{GeV}, \lvert\eta\rvert < 2.5$	$Z \to \ell\ell + \text{jets}$, $W(\ell\nu) + \text{jets}$
Muon veto	$p_T > 10\,\text{GeV}, \lvert\eta\rvert < 2.4$	$Z \to \ell\ell + \text{jets}$, $W(\ell\nu) + \text{jets}$
τ veto	$p_T > 18\,\text{GeV}, \lvert\eta\rvert < 2.3$	$Z \to \ell\ell + \text{jets}$, $W(\ell\nu) + \text{jets}$
Photon veto	$p_T > 15\,\text{GeV}, \lvert\eta\rvert < 2.5$	$\gamma + \text{jets}$
b jet veto	CSVv2 <0.8484, $p_T > 20\,\text{GeV}$, $\lvert\eta\rvert < 2.4$	Top quark
p_T^{miss}	>250 GeV	QCD multijet, top quark, $Z \to \ell\ell + \text{jets}$
$\Delta\phi(\vec{p}_T^{\,\text{jet}}, \vec{p}_T^{\,\text{miss}})$	>0.5 radians	QCD multijet
Leading jet	$p_T > 100\,\text{GeV}$, $\lvert\eta\rvert < 2.4$	All

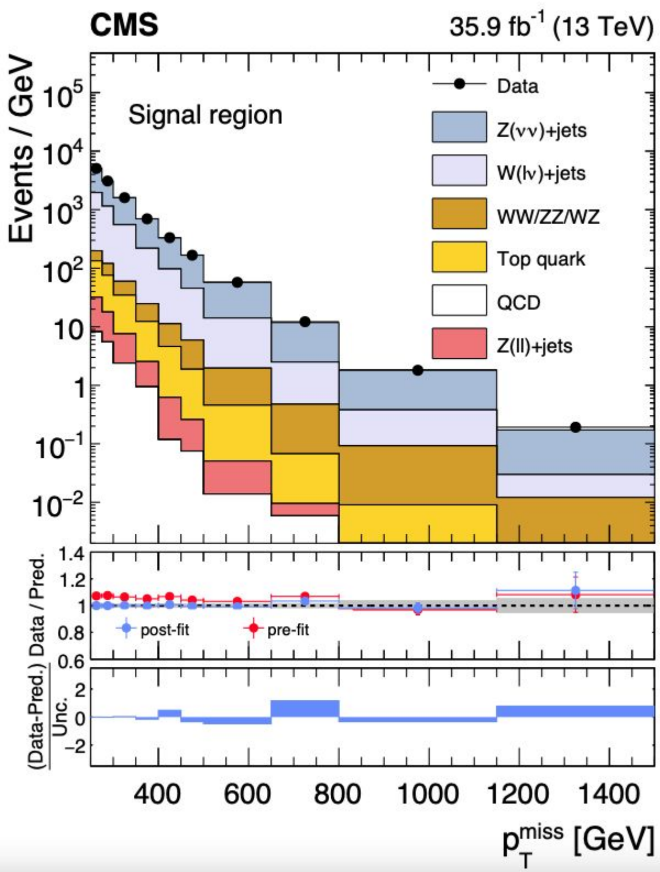
Z differential cross section

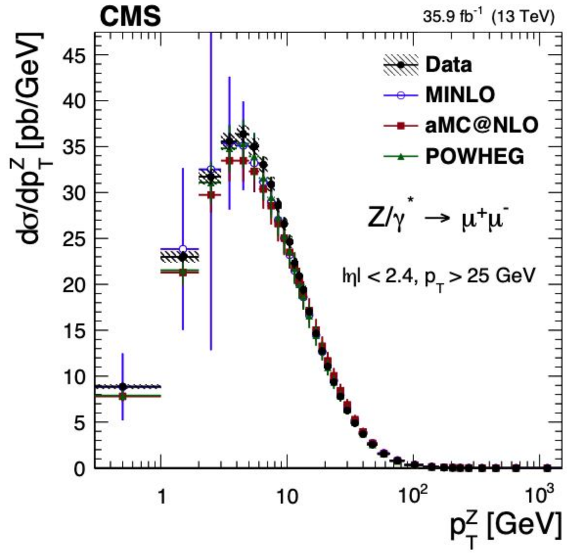
JHEP 12 (2019) 061

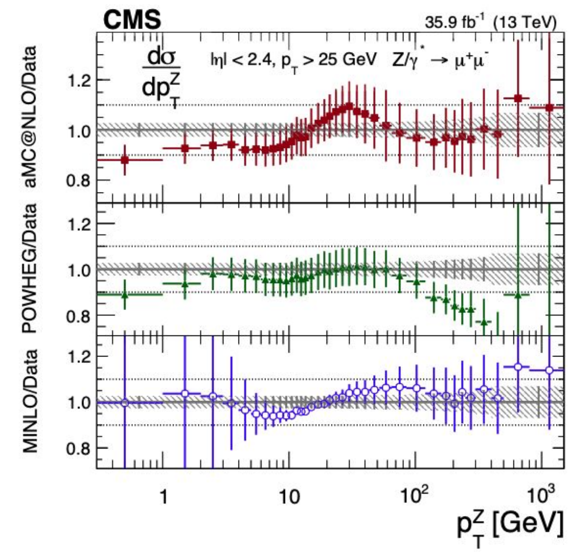
Use di-lepton + $\nu\nu$ for high p_T

Lower stat. above 300 GeV

and more precise $p_{T,miss}$







Normalized cross section measurement

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	$1.036^{+0.099}_{-0.095}$	$0.869^{+0.059}_{-0.057}$	$0.914^{+0.052}_{-0.051}$

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DY transverse momentum

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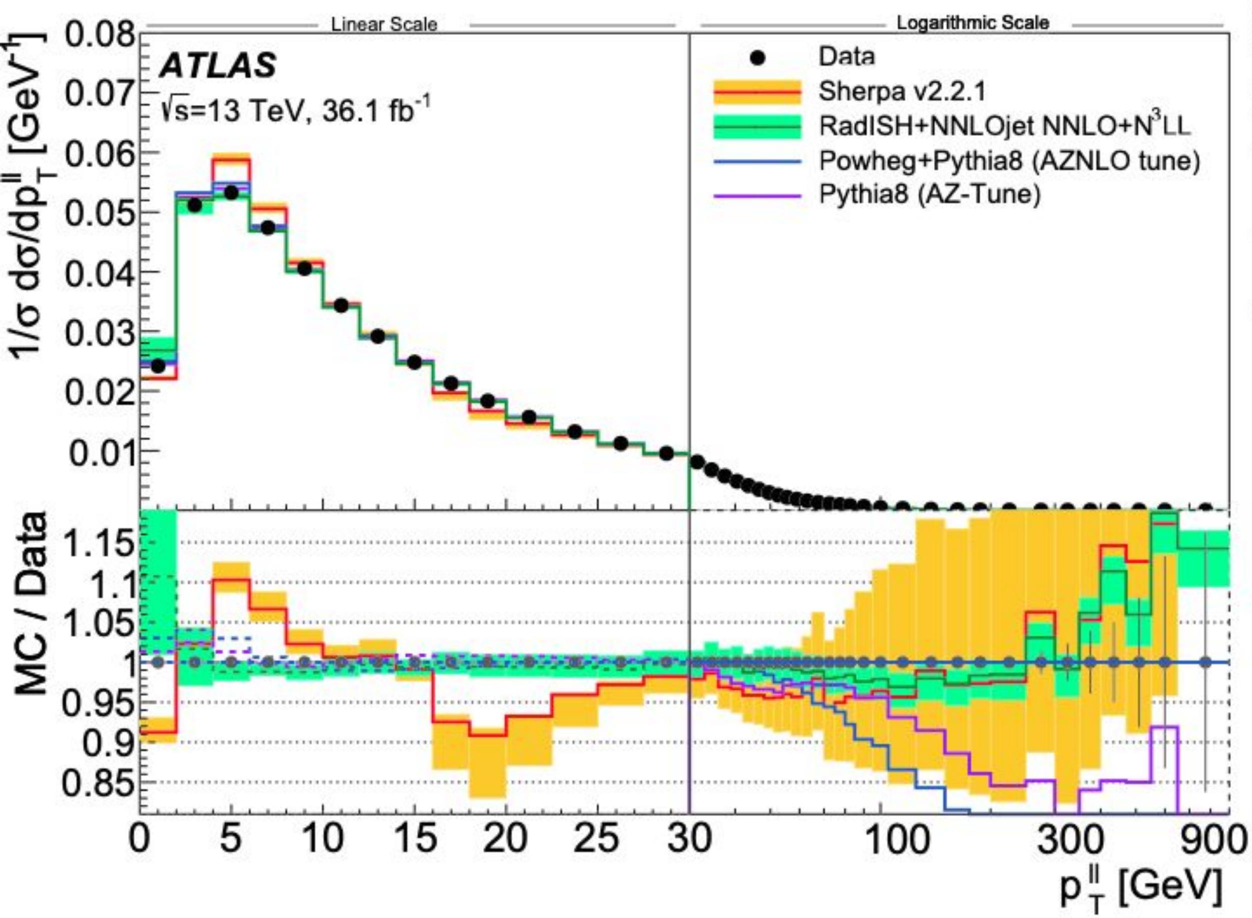
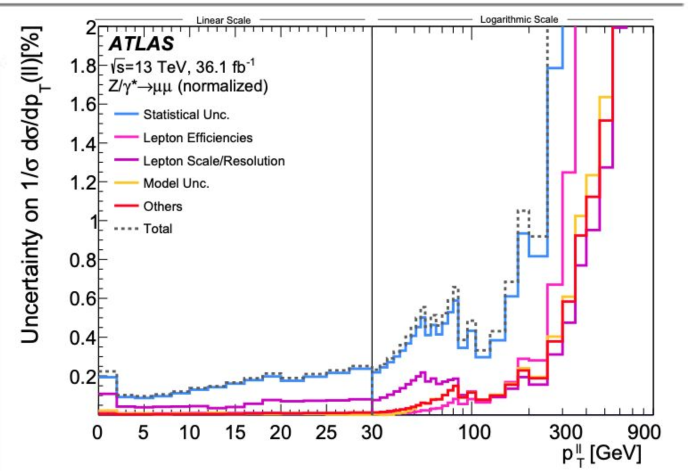
Another important test of QCD because of production mechanism

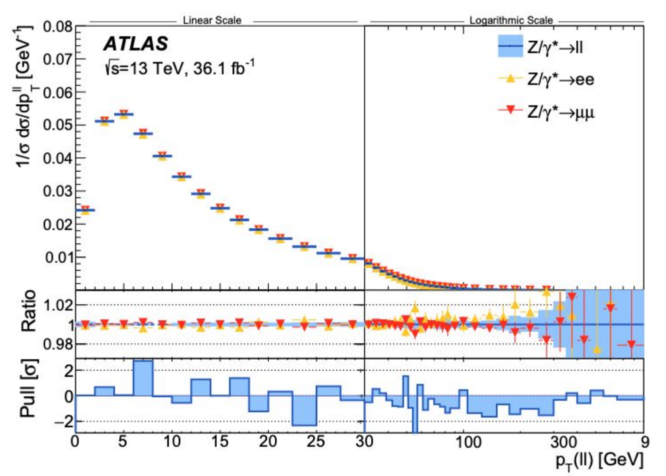
Precision at the permille level in lower end of the spectrum

Favours predictions based on resummation approaches

	$Z/\gamma^* \to ee$	$Z/\gamma^* \to \mu\mu$
Two reconstructed leptons within fiducial volume	13 649 239	18 162 641
Electroweak background ($Z \to \tau\tau, WW, WZ, ZZ$)	40 000 ± 2000	50 000 ± 2500
Photon-induced background	2900 ± 140	4100 ± 200
Top-quark background	38 000 ± 1900	45 400 ± 2200
Multijet background	8500 ± 4900	1000 ± 200
Total background	89 400 ± 5600	100 500 ± 3300







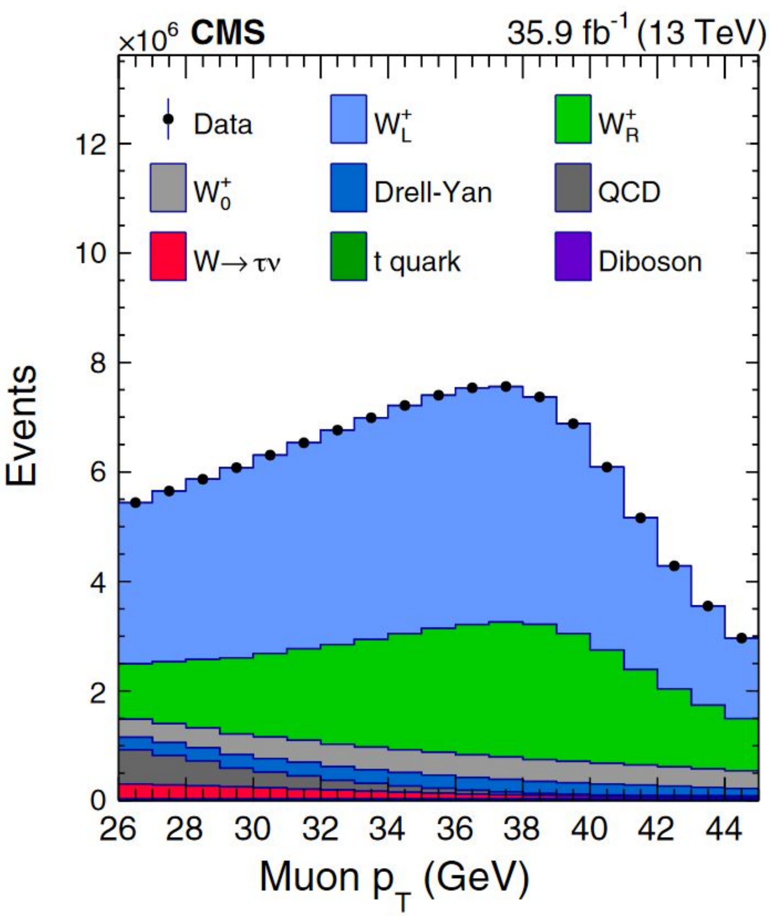
W boson production

PRD 102 (2020) 092012

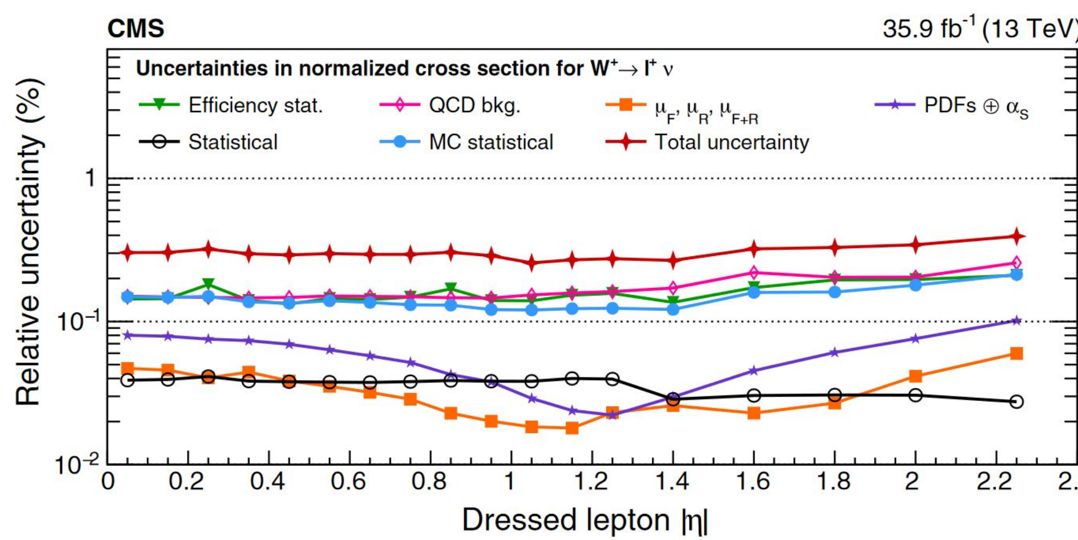
Interest in rapidity, helicity, charge asymmetry, cross section

- Test of QCD, PDF, V-A structure of EWK

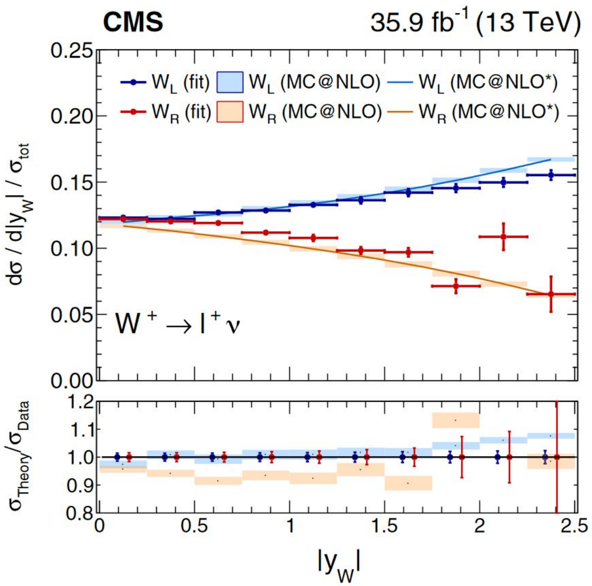
Analysis in the leptonic channel with 2016 data

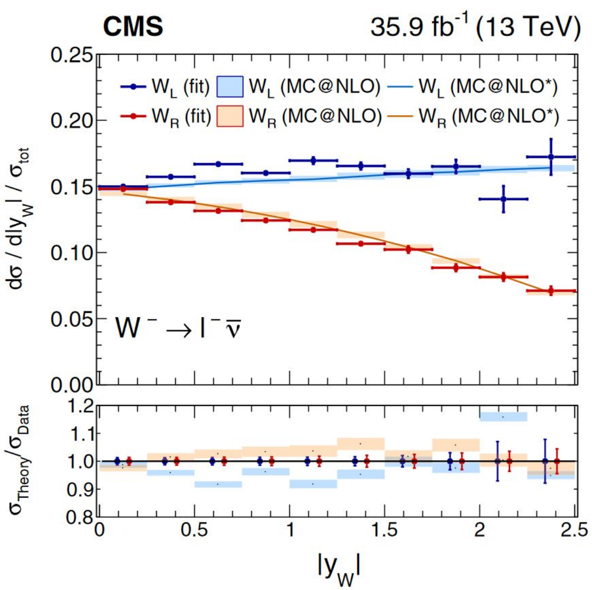


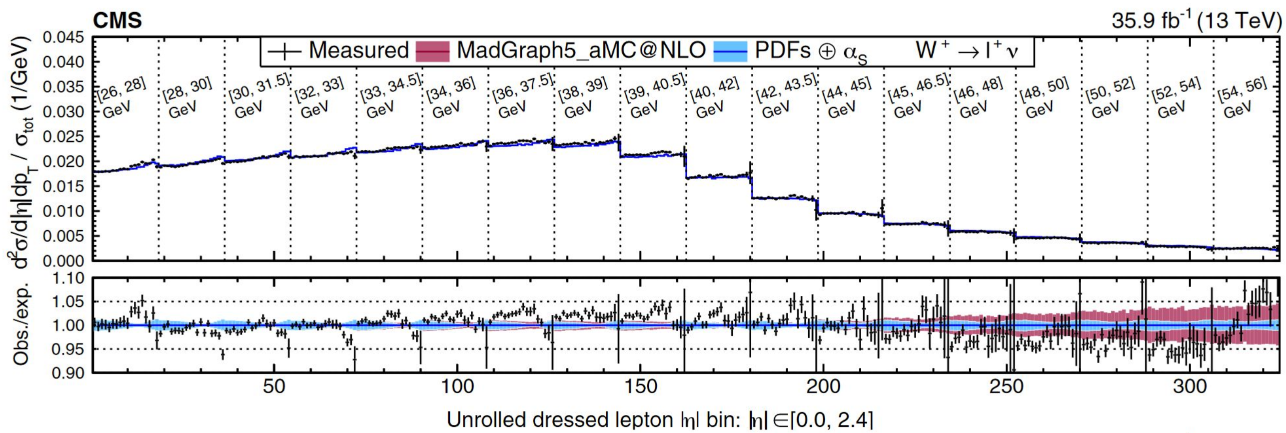
Processes	Bkg. to sig. ratio $W \to \mu\nu$	$W \to e\nu$
$Z \to \ell\ell$ (DY)	5.2%	3.9%
$W \to \tau\nu$	3.2%	1.3%
$WW + WZ + ZZ$	0.1%	0.1%
Top	0.5%	0.5%
Wrong charge	...	0.02%
QCD	5.5%	8.2%

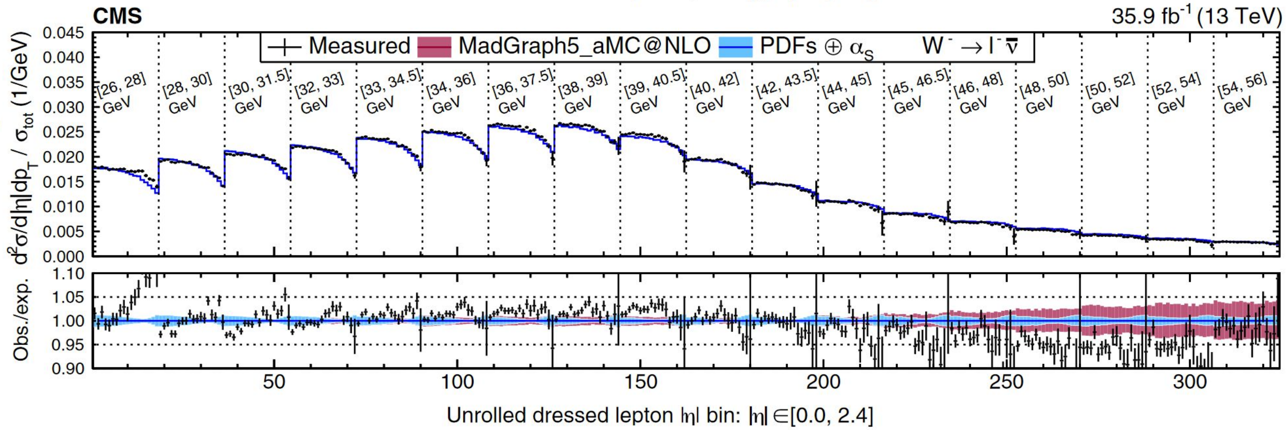


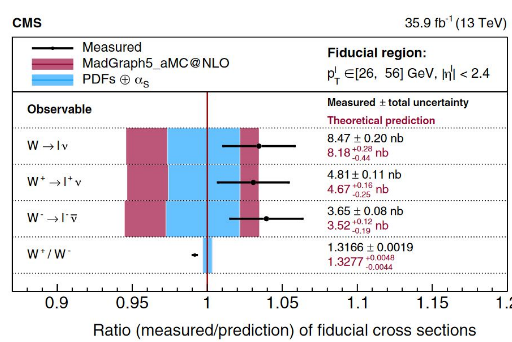
W boson production





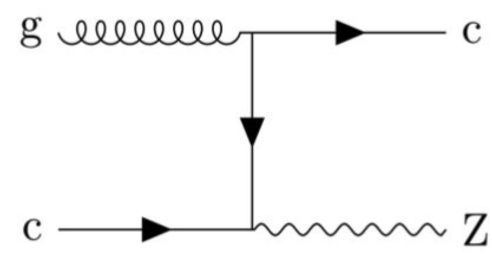


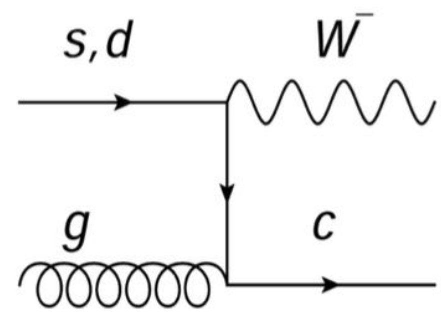




PRD 102 (2020) 092012

V+heavy flavor





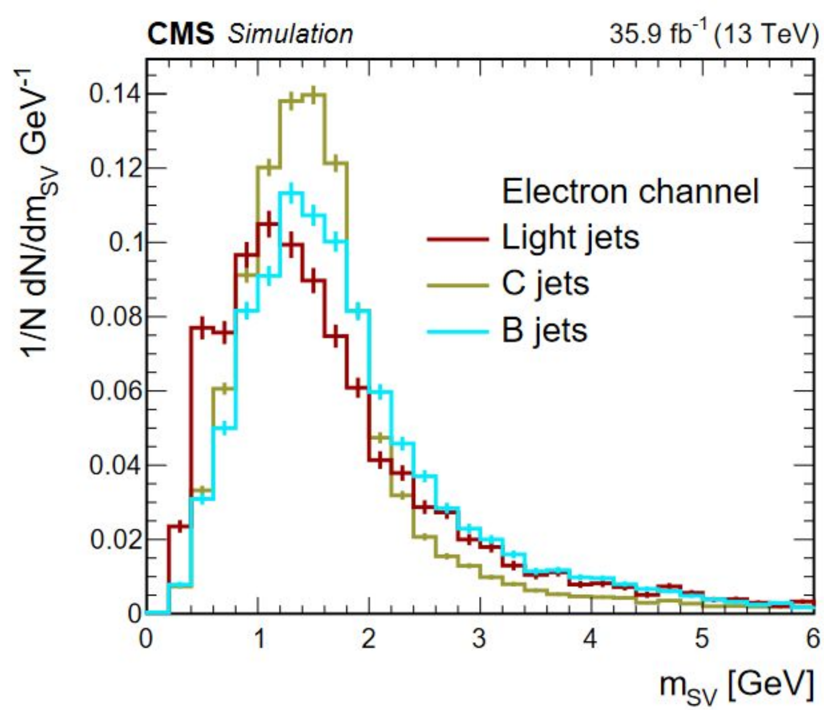
Important for MC tuning

Major background in many BSM searches

Probe of heavy quark PDF

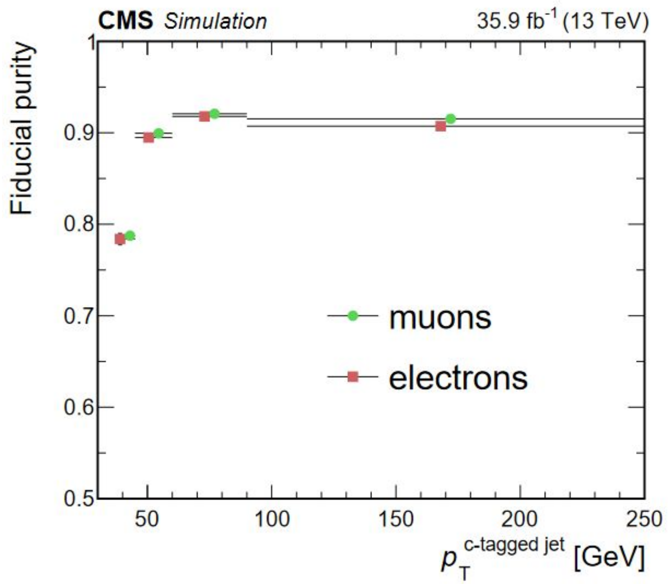
Case study: **Z+charm** **JHEP 04 (2021) 109**

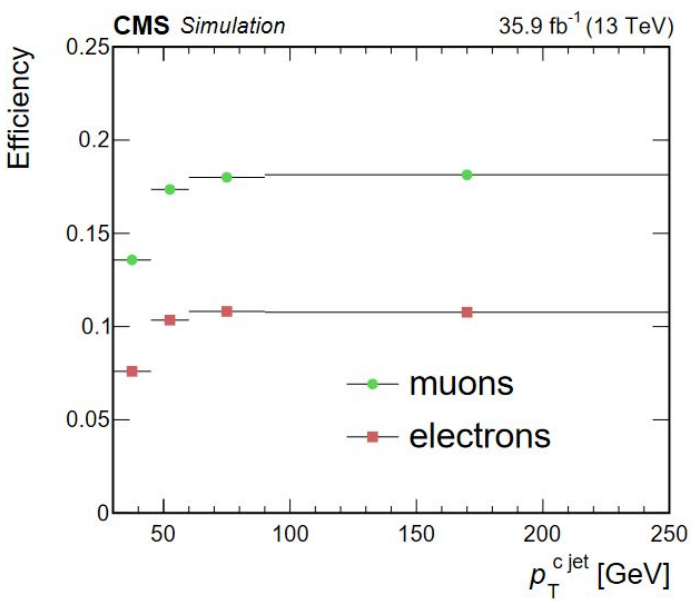
- Reconstruct Z in leptonic final states
- $p_{T,jet} > 30$ GeV, $|\eta(\text{jet})| < 2.4$
- Measure using m_{SV} and c-tagger
- c-ID with hadronic decays of charm

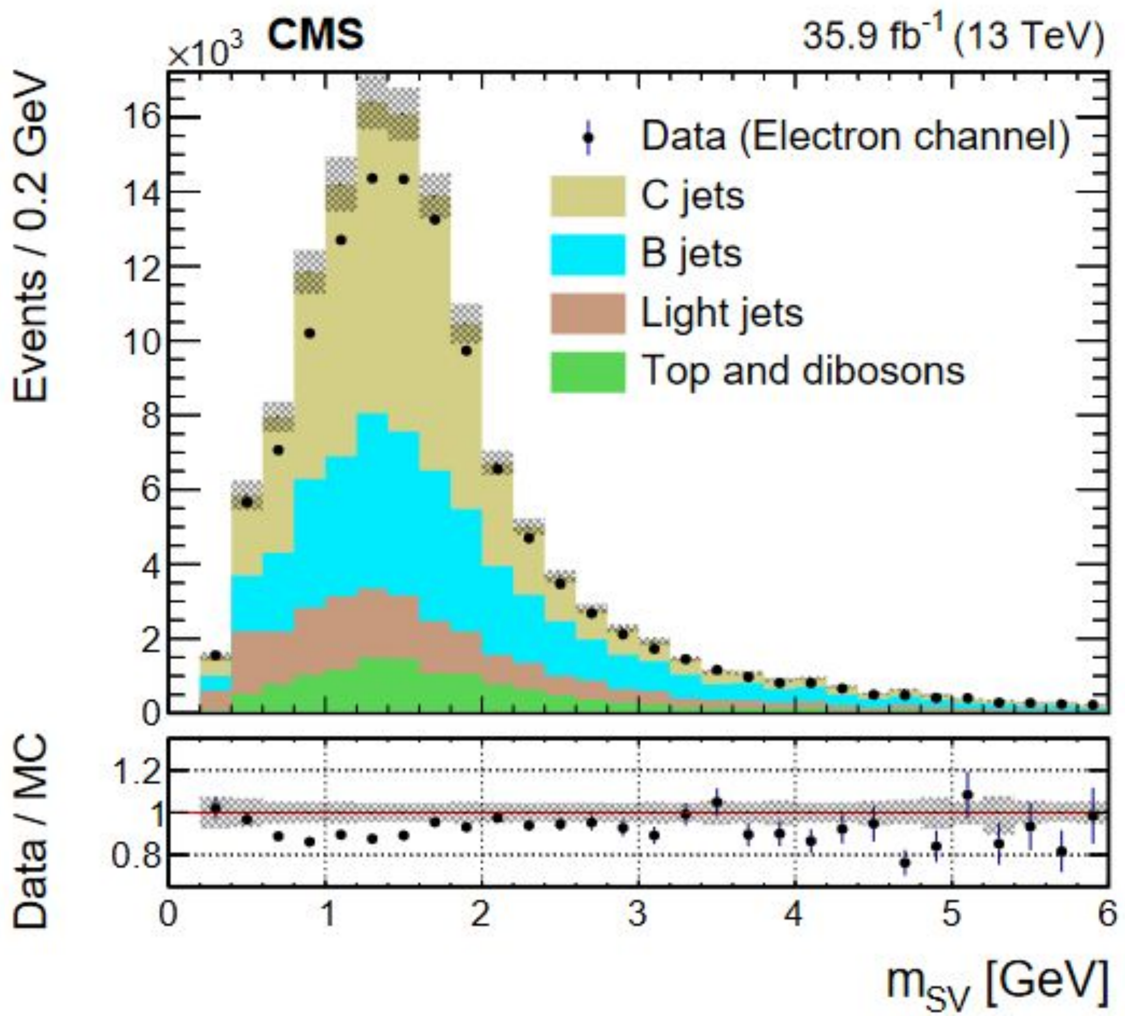


See Alexander Laurier's talk for more details!

Z+charm







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Z+charm

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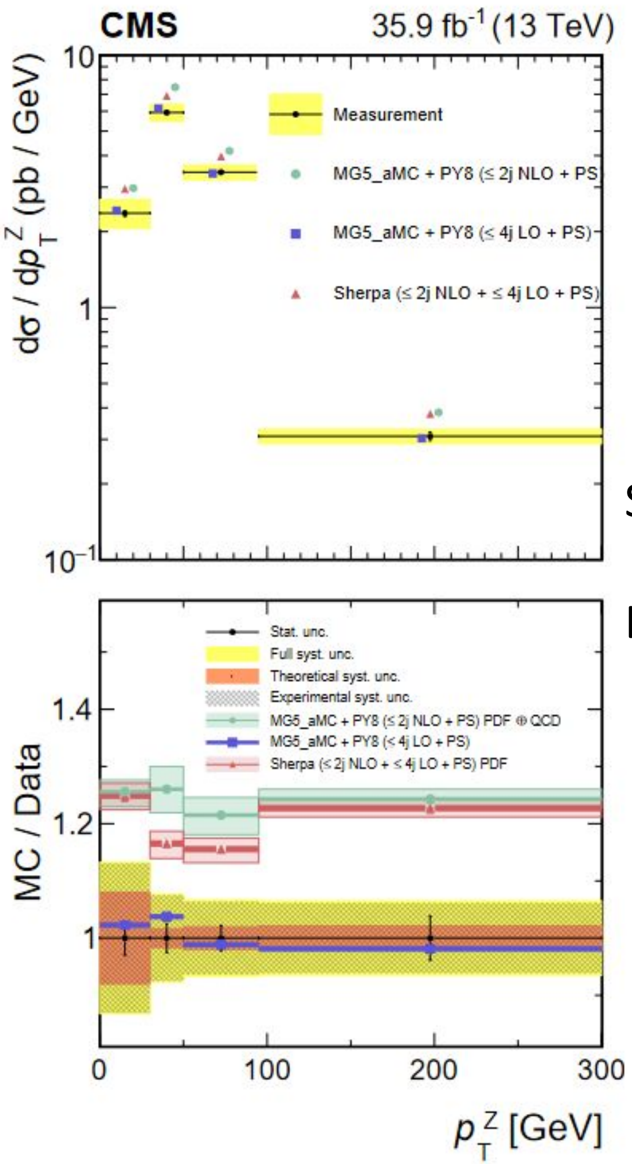


Systematic uncertainties, integrated over p_T

Channel	QCD (%)	PDF (%)	c tag/mistag (%)	JER (%)	JES (%)	Pileup (%)	Top Pair (%)	ID\Iso (%)	$\mathcal{L}$ (%)	MC stat. (%)
$\mu\mu, p_T^{c\ jet}$	5.5	0.5	4.2	3.9	4.8	1.5	0.6	1.0	2.5	4.2
$\mu\mu, p_T^{Z}$	1.9	0.5	4.2	1.1	3.9	1.6	0.8	1.0	2.5	3.1
$ee, p_T^{c\ jet}$	6.4	0.6	4.2	3.1	6.4	3.0	0.7	2.6	2.5	6.3
ee, p_T^{Z}	2.6	0.5	4.1	1.1	4.8	1.8	0.6	2.6	2.5	3.8

Signal extracted from m_{SV} template fits

Differential cross section measured in p_T of c-jet or Z

$$\sigma_{fid.meas} = 405.4 \pm 5.6(\text{stat}) \pm 24.3(\text{exp}) \pm 3.7(\text{theo})\ \text{pb}$$

$$\sigma_{theo} = 524.9 \pm 11.7(\text{theo})\ \text{pb}$$

Hint at charm content of proton overestimate?

Conclusions

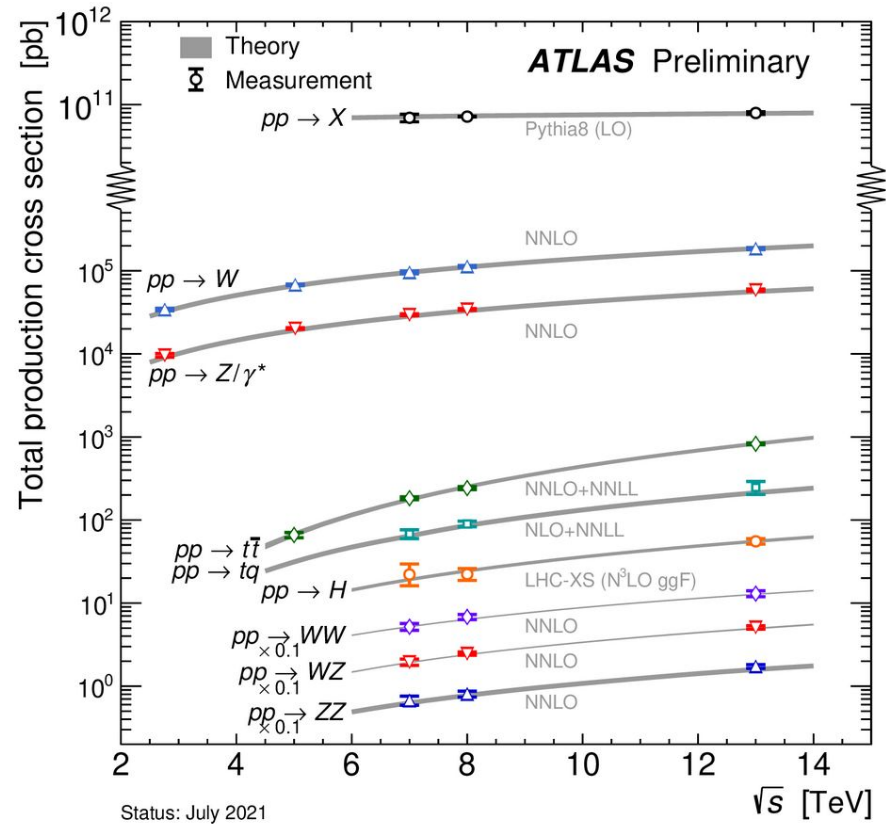
Single vector boson production remains

an important test field for EWK and

QCD at LHC

- Test of high oder predictions
  - And in general MC tuning
- Better understanding of backgrounds

  for other areas



High statistics and clean final states

$\longrightarrow$ important probes in the foreseeable future

In general, predictions have reached an impressive agreement with data,

with a few areas where deeper understanding is needed

Backup

Z+jets

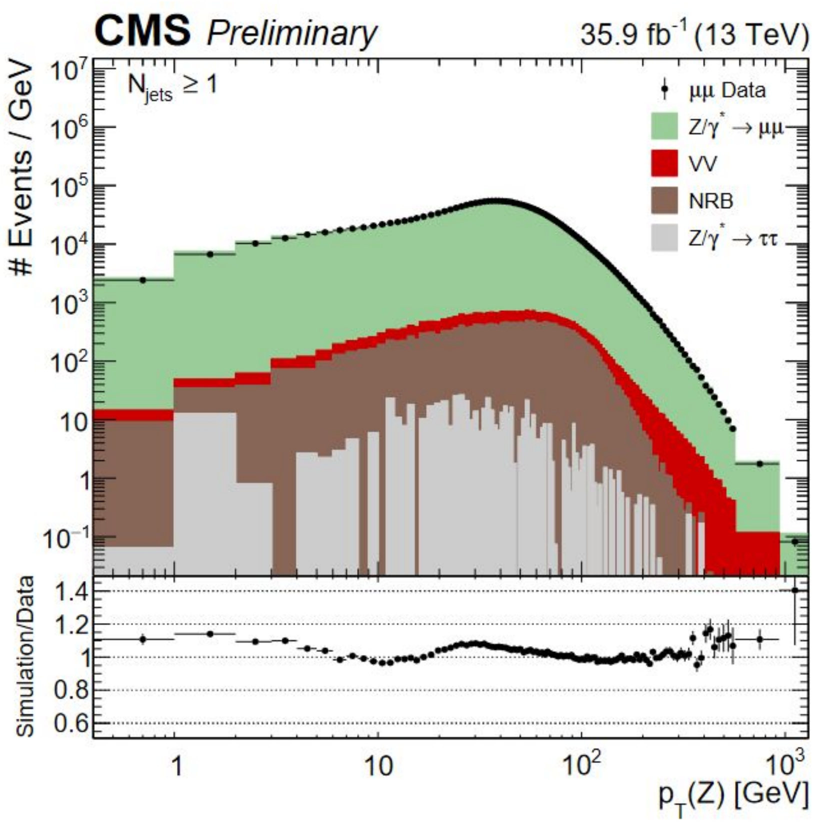
Great interest for many reasons:

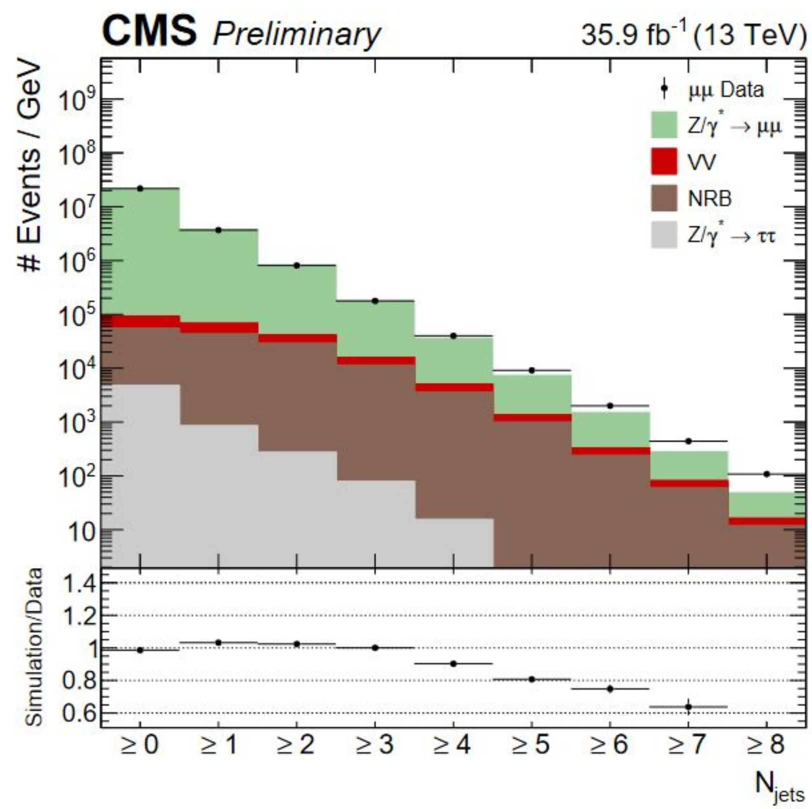
- QCD testing, Higgs physics, BSM searches

Leptonic final state with $p_{T,1/2} > 30/20$ GeV

CMS-SMP-19-009

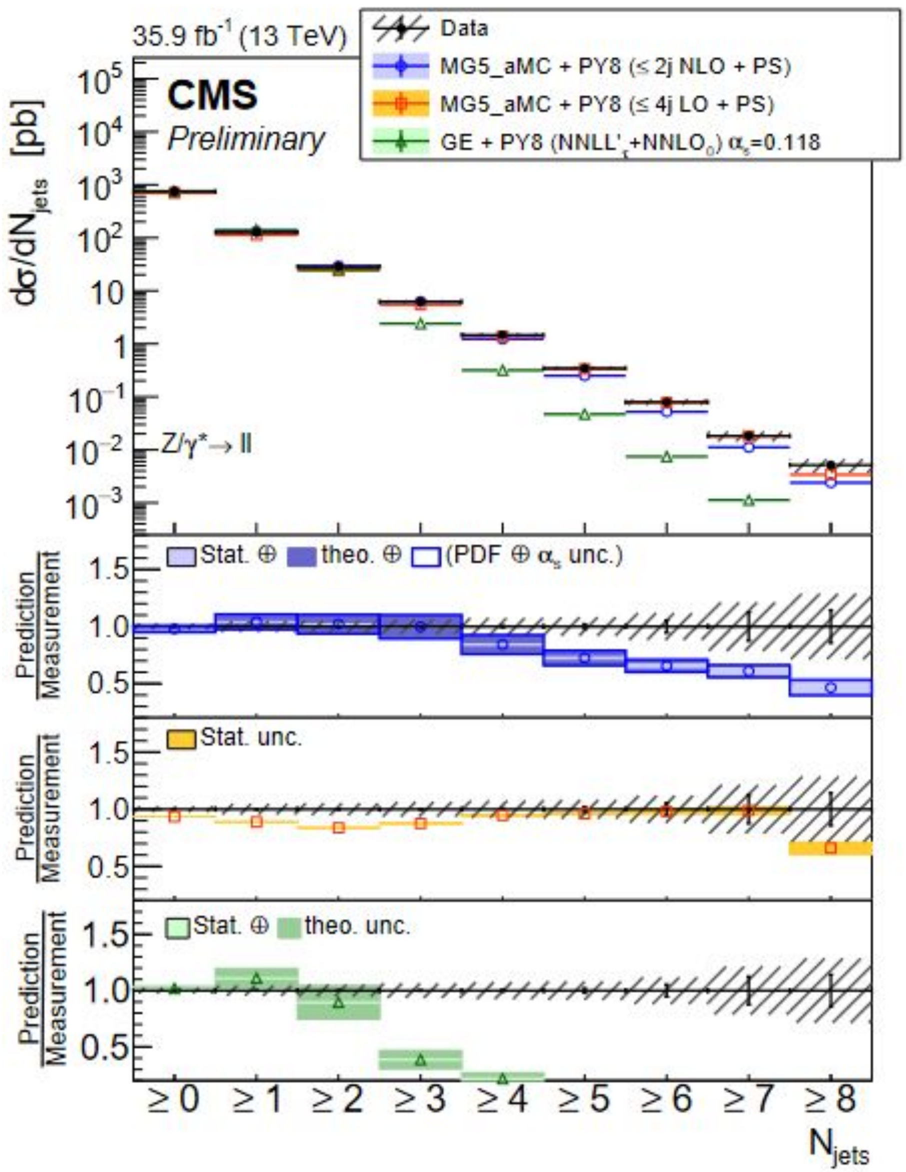
Used for properties, (differential) cross section, angular correlations

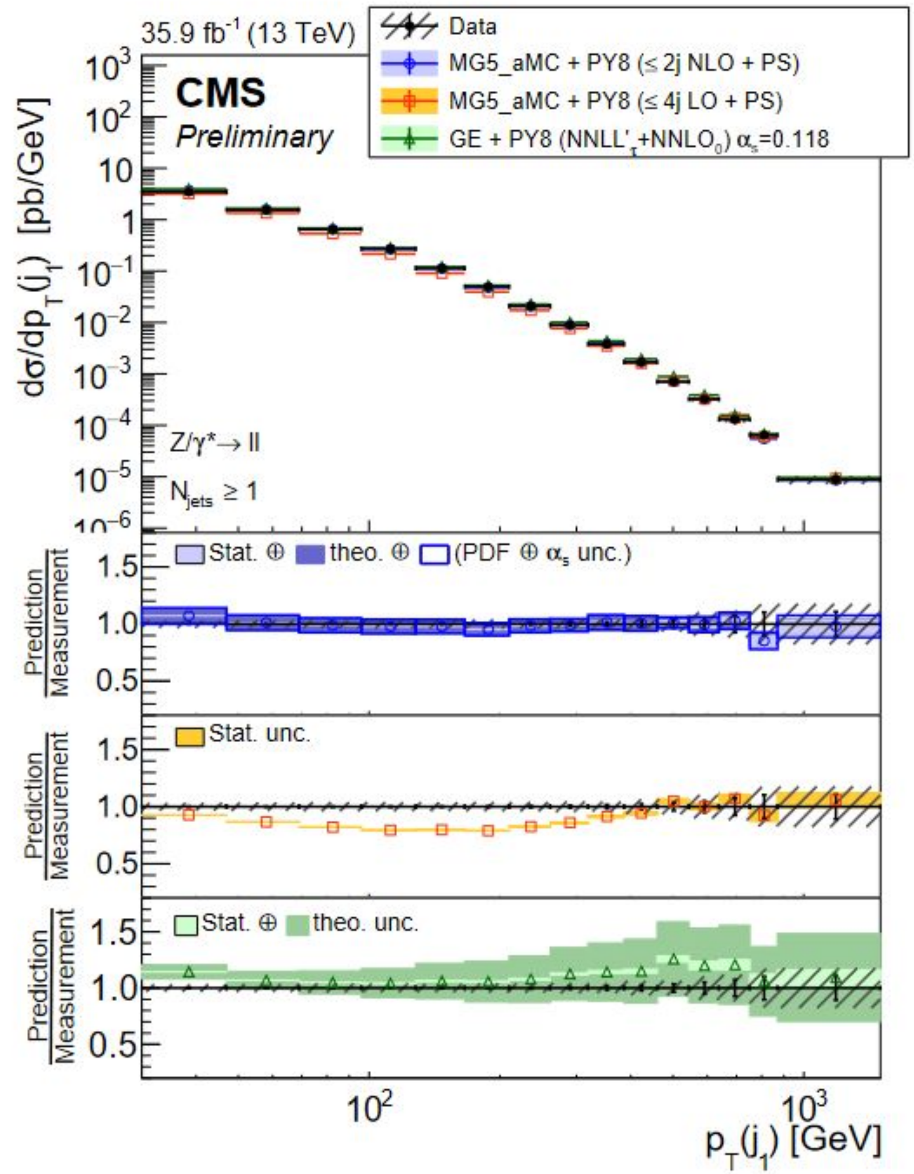




Multidifferential Z+jets cross section

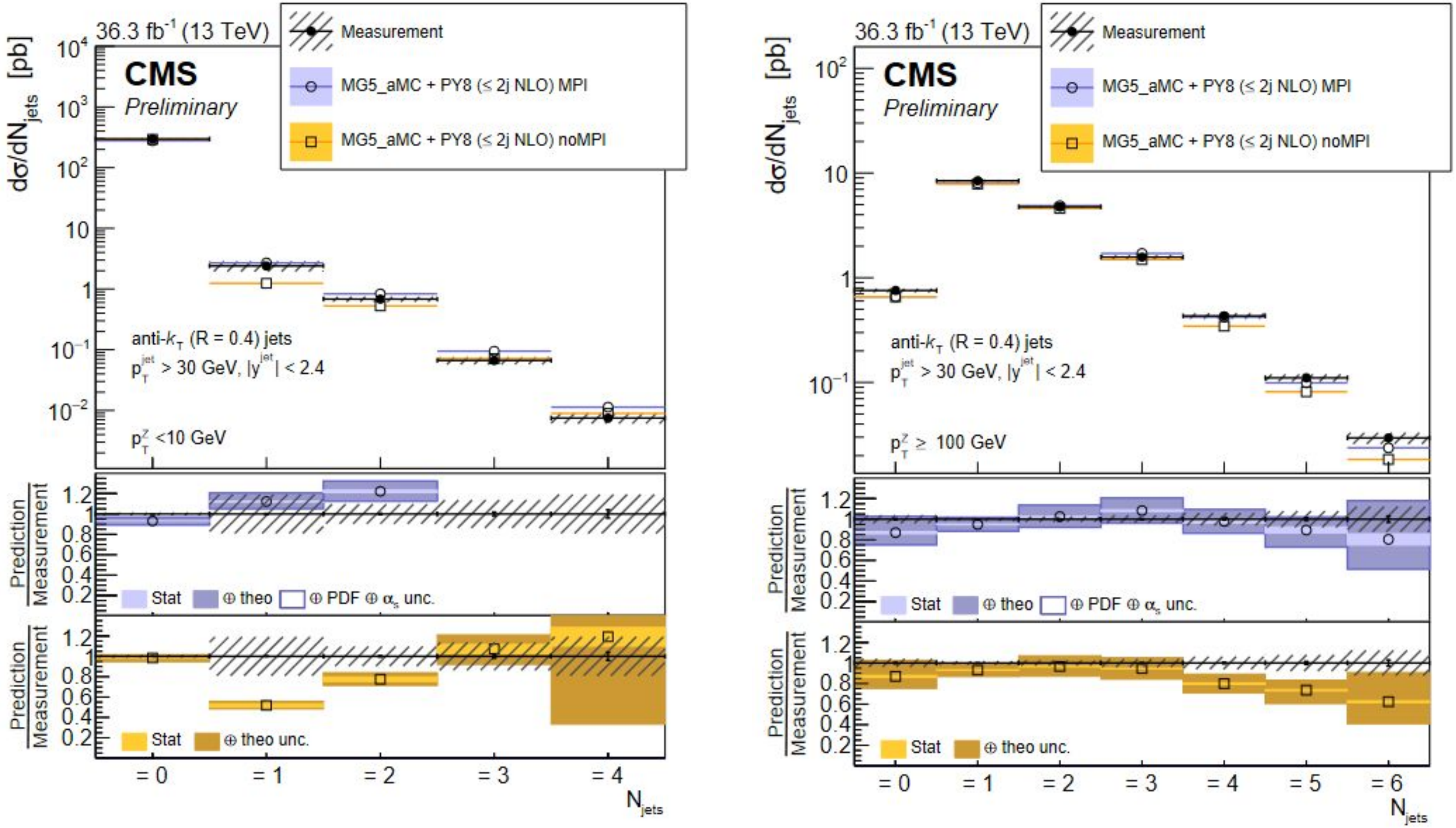
CMS-SMP-19-009





Z+jets: multiplicity

CMS-SMP-21-003



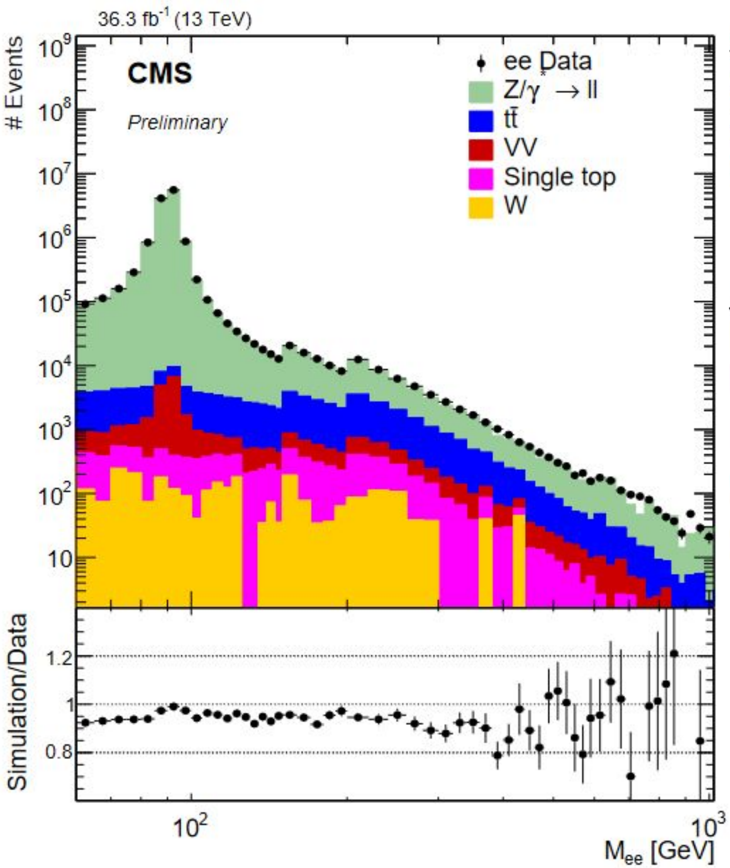
Low p_T: low multiplicity with EWK Z emission tail
High p_T: larger multiplicity, jets from higher QCD corrections

Z+jets: azimuthal correlations

CMS-SMP-21-003

Probe to QCD in Z production

- Small $p_{T,Z}$: soft gluon radiation and non-perturbativity
- High $p_{T,Z}$: Z+jets full QCD contributions



generator	PDF	matrix element
MG5_AMC+PY8 ($\leq 2j$ NLO) [33]	NNPDF 3.0 (NLO) [37]	NLO ($2 \to Z + 0, 1, 2$)
MG5AMC+CA3 (Z + 1) NLO [33]	PB-NLO-set2 (NLO) [19]	NLO ($2 \to Z + 1$)
MG5AMC+CA3 (Z + 2) NLO [33]	PB-NLO-set2 (NLO) [19]	NLO ($2 \to Z + 2$)
GENEVA NNLO [21–24]	NNPDF 3.1 (NLO) [39]	NNLO ($2 \to Z$)

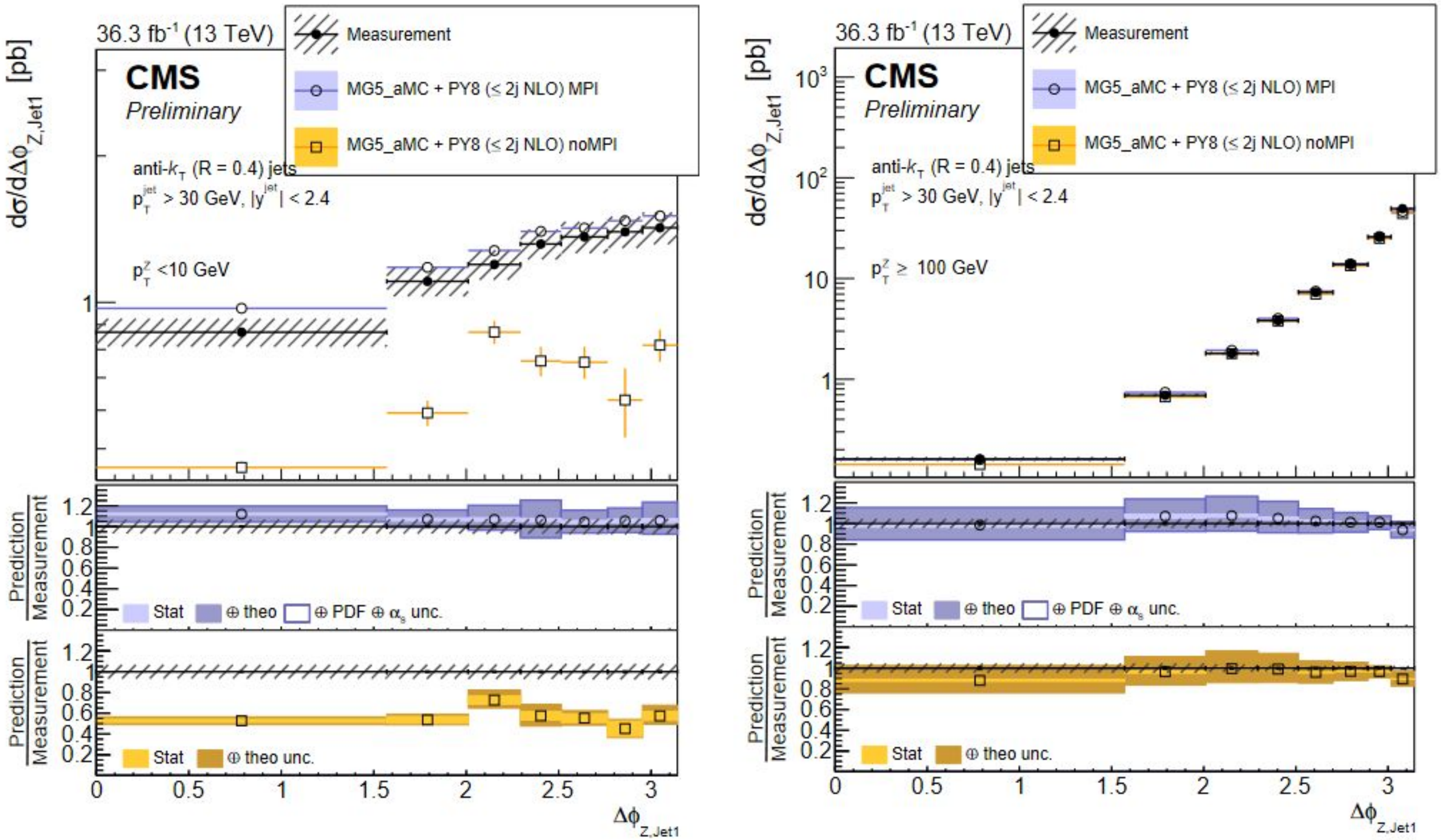
selection	cut	
electron: leading (subleading)	$p_T > 25(20)$ GeV	$\lvert\eta_e\rvert < 2.4$
muon: leading (subleading)	$p_T > 25(20)$ GeV	$\lvert\eta_\mu\rvert < 2.4$
lepton-jet isolation	$\Delta R_{l,j} > 0.4$	
$m_{l^+l^-}$	$76 < m_{l^+l^-} < 106$ GeV	
jet	$p_T > 30$ GeV	$\lvert\eta_{jet}\rvert < 2.4$

Used to study

- Z-leading jet correlation
- 2 leading jets correlation
- Jet multiplicity

Z+jets: azimuthal correlations

CMS-SMP-21-003



Correlation strongly dependent on Z p_T

Good agreement with prediction accounting for MPI

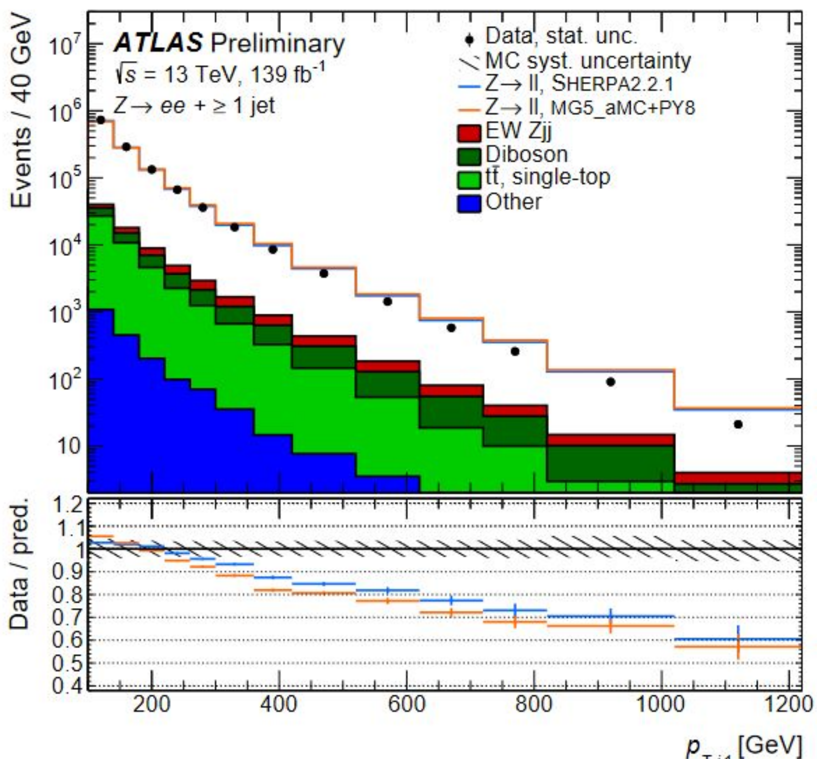
Z+collinear jet

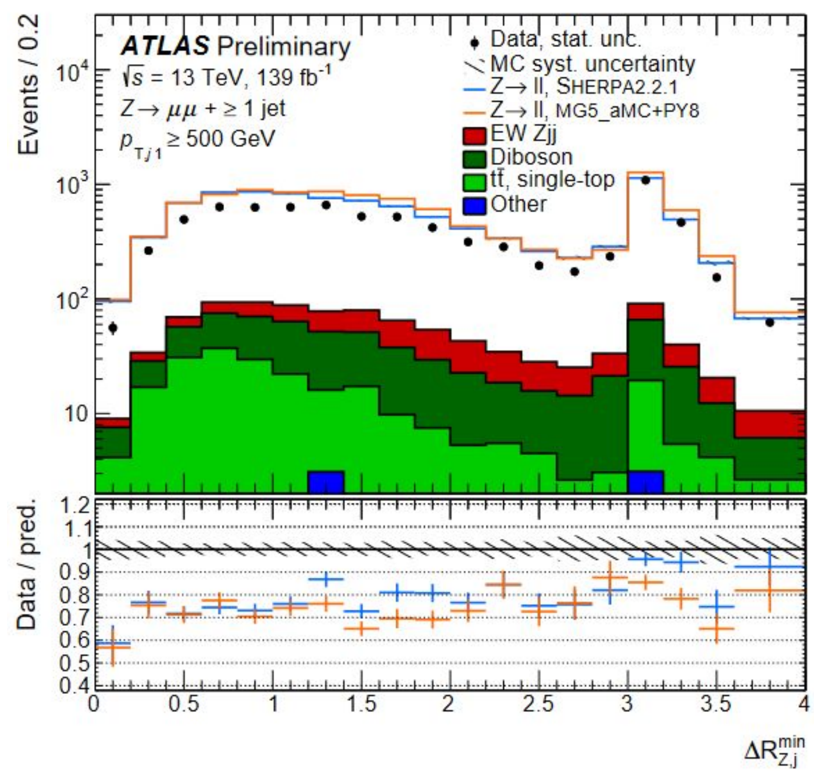
ATLAS-CONF-2021-033

Z emission from quark at NLO proportional to $\alpha_S \ln^2 \frac{p_{\mathrm{T},j}}{(m_Z)}$

Large production for small angles

- Z leptonic decays
- high-p_T region with $p_{T,jet}$ > 500 GeV
- Discriminant through jet-Z angular separation





Z+collinear jet

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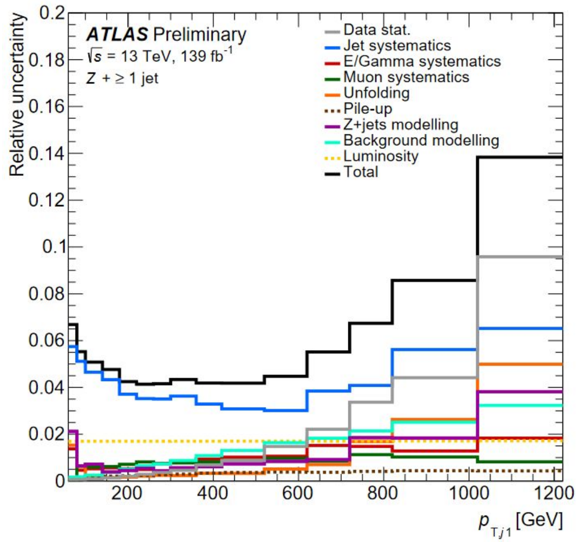
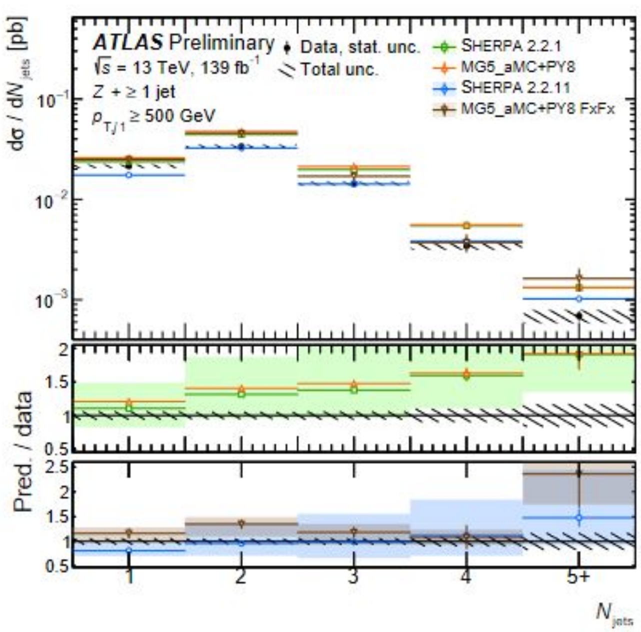
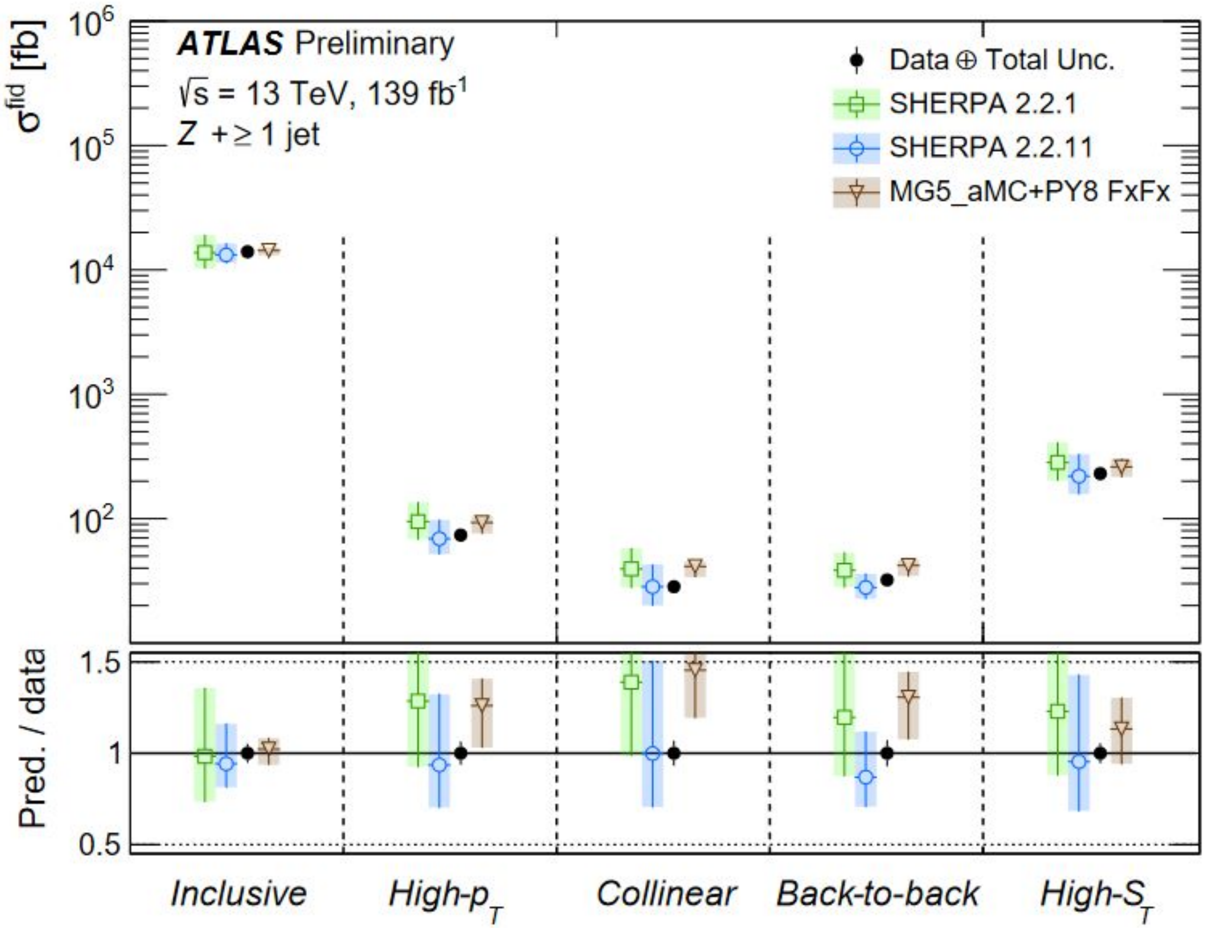
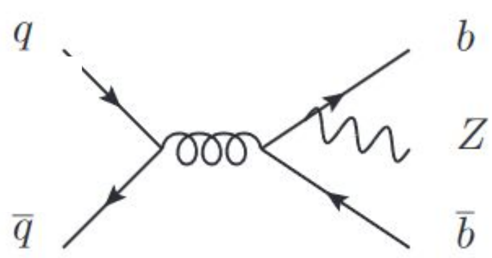






Z + b-jets

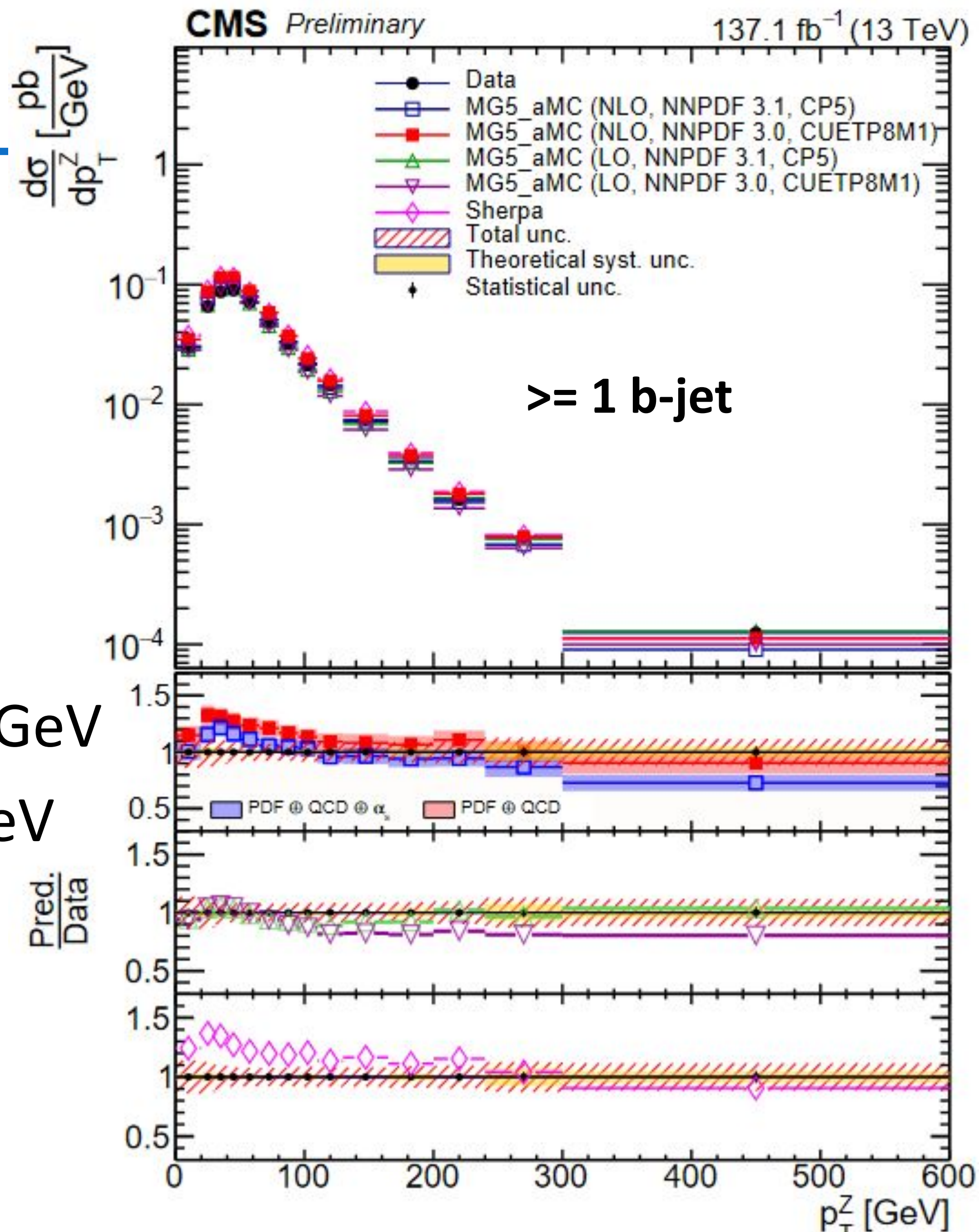
... + 

Full Run-2 analysis

Dimuons with $p_{T,1/2}$ > 35/25 GeV

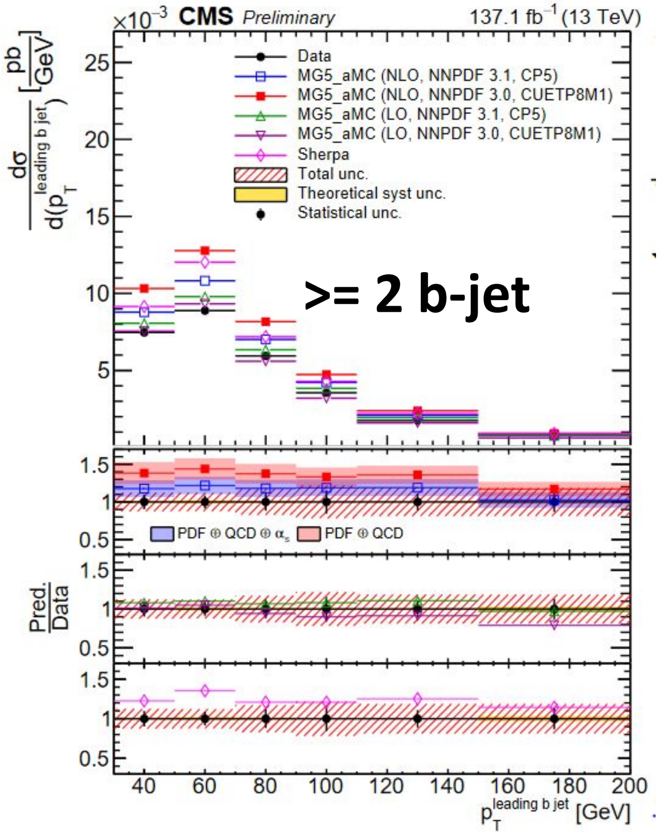
b-tagged jets with p_T > 30 GeV

CMS-SMP-20-015



Z + b-jets

CMS-SMP-20-015



Uncertainty (%)	Z + ≥ 1 b jet ee	Z + ≥ 1 b jet $\mu\mu$	Z + ≥ 1 b jet $\ell\ell$	Z + ≥ 2 b jets ee	Z + ≥ 2 b jets $\mu\mu$	Z + ≥ 2 b jets $\ell\ell$
Statistical	1.0	0.7	0.6	7.7	5.9	4.6
JES, JER	2.7	3.0	2.9	6.9	5.4	5.8
b tagging/mistagging	3.0	2.9	2.9	5.4	6.0	5.8
Unclustered energy of p_T^{miss}	2.8	2.8	2.8	3.5	3.7	3.6
Background estimation	2.2	2.0	2.1	2.3	2.4	2.4
Pileup reweighting	2.4	1.7	1.9	2.9	2.1	2.4
Electron selection	4.6	–	1.5	4.3	–	1.4
Luminosity	1.6	1.6	1.6	1.6	1.6	1.6
Muon selection	–	0.6	0.4	–	1.0	0.7
Pileup jet identification	0.3	0.3	0.3	0.6	0.7	0.7
L1 prefiring	0.3	0.2	0.2	0.3	0.2	0.3
Model dependency	0.3	0.2	0.2	0.3	0.2	0.2
μ_R and μ_F scales	2.6	2.9	2.1	2.5	2.3	2.5
PDF	0.4	0.3	0.3	0.3	0.3	0.3
α_s	0.3	0.2	0.2	0.1	0.1	0.1

	Channel	Measured	MG5_aMC LO NNPDF 3.0 CUETP8M1	MG5_aMC LO NNPDF 3.1 CP5	MG5_aMC NLO NNPDF 3.0 CUETP8M1	MG5_aMC NLO NNPDF 3.1 CP5	SHERPA
Z + ≥ 1 b jet	ee	6.45 ± 0.06 ± 0.49 ± 0.17	6.25	6.33	7.86 ± 0.52	7.05 ± 0.48	8.05
	$\mu\mu$	6.55 ± 0.05 ± 0.39 ± 0.19	6.26	6.34	7.86 ± 0.51	7.02 ± 0.47	7.98
	$\ell\ell$	6.52 ± 0.04 ± 0.40 ± 0.14	6.25	6.34	7.86 ± 0.51	7.03 ± 0.47	8.02
Z + ≥ 2 b jets	ee	0.66 ± 0.05 ± 0.07 ± 0.02	0.62	0.72	0.89 ± 0.08	0.77 ± 0.07	0.84
	$\mu\mu$	0.65 ± 0.04 ± 0.06 ± 0.02	0.64	0.71	0.91 ± 0.09	0.77 ± 0.07	0.84
	$\ell\ell$	0.65 ± 0.03 ± 0.07 ± 0.02	0.63	0.71	0.90 ± 0.09	0.77 ± 0.07	0.84