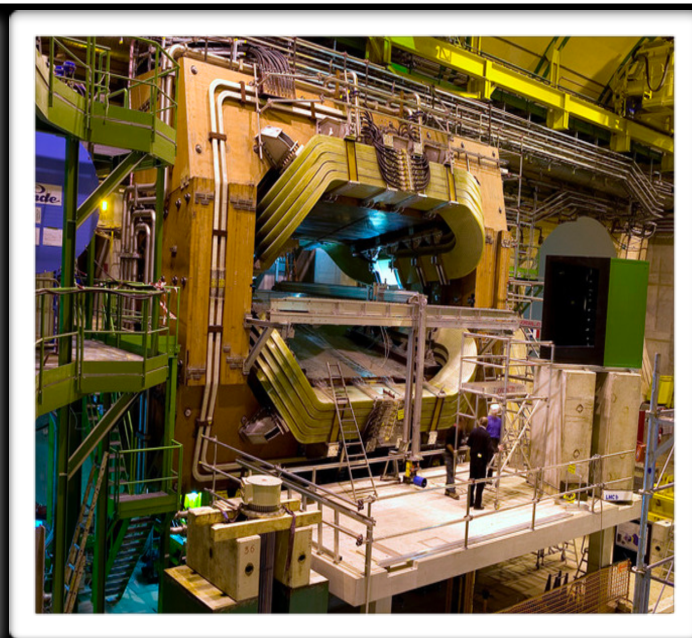
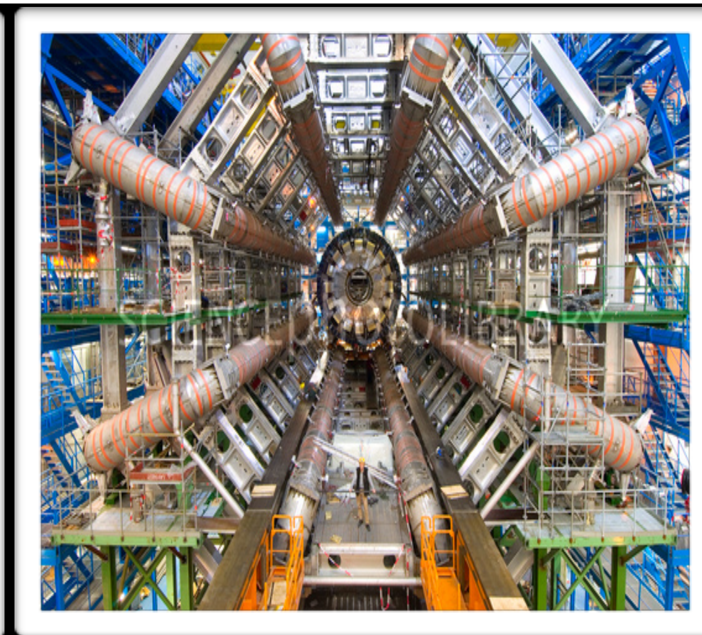
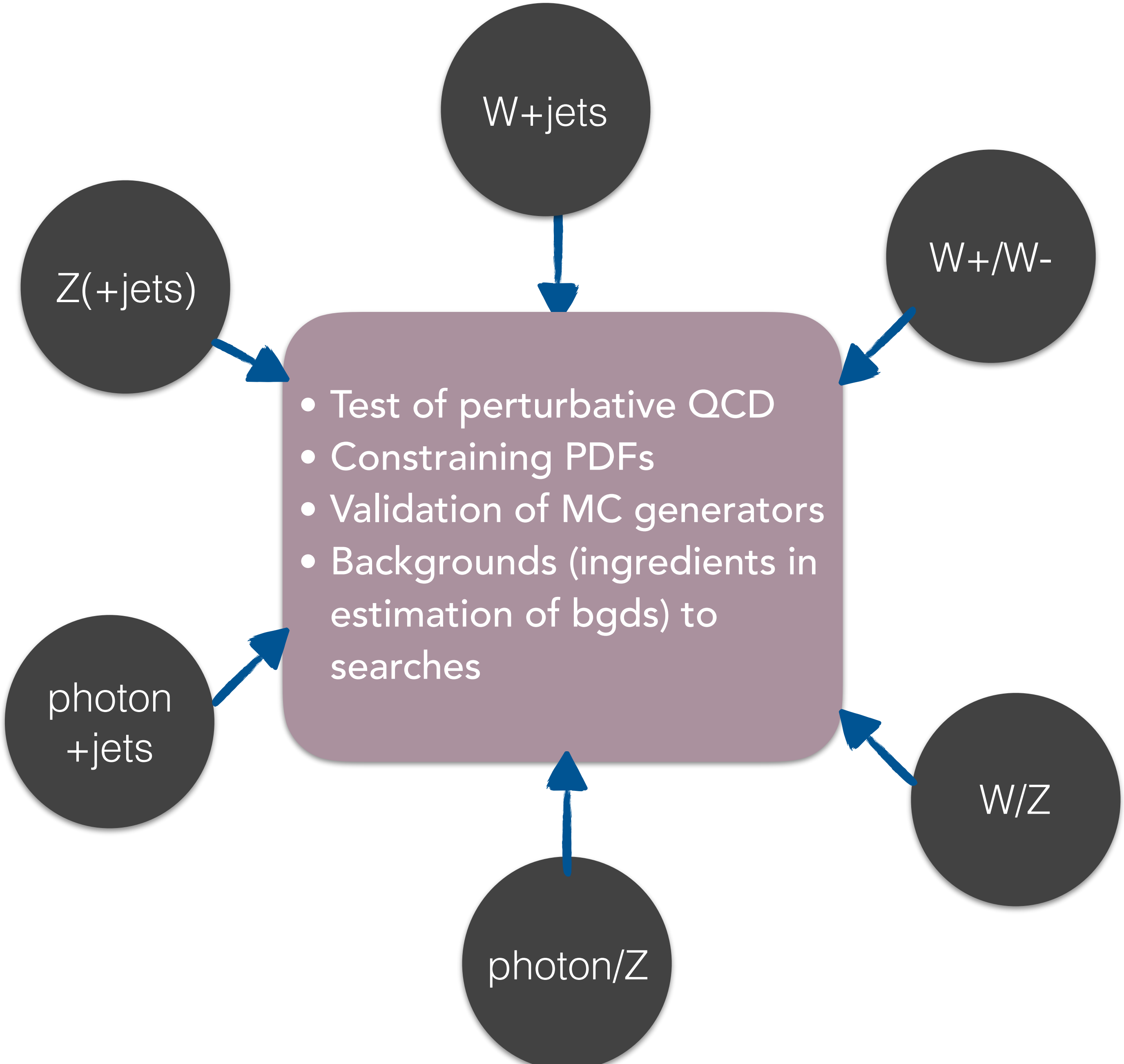




Probing QCD with EWK bosons

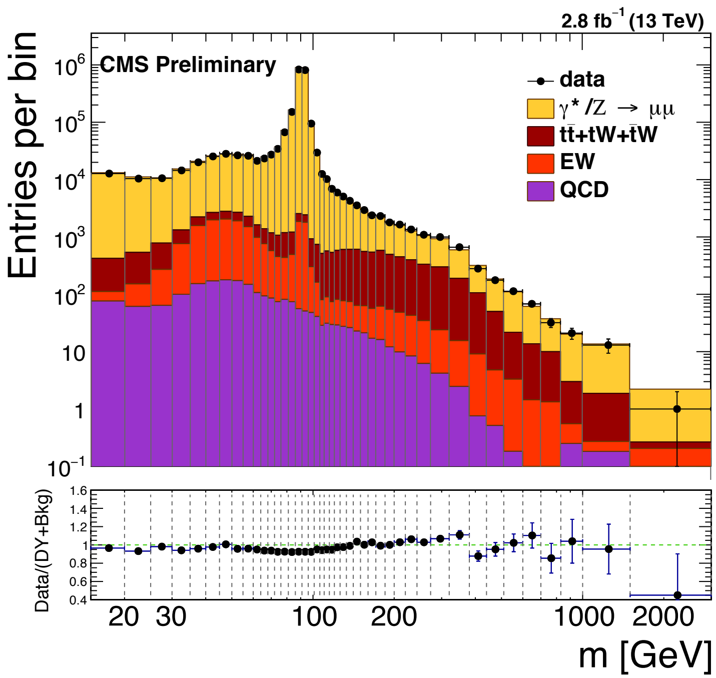
Sarah Alam Malik (Imperial College London)
on behalf of the CMS, ATLAS & LHCb collaborations

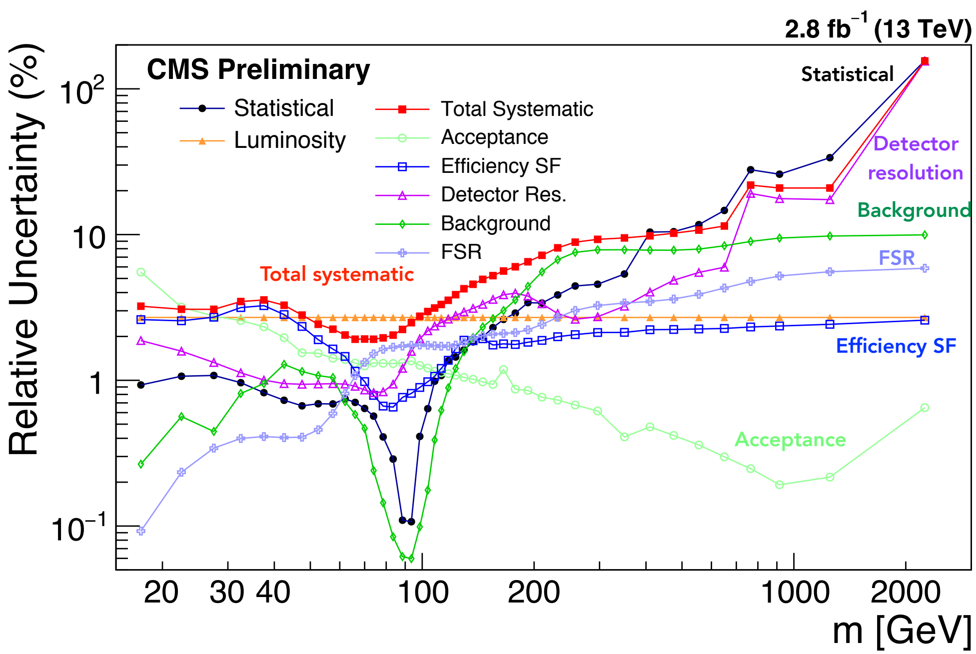
Introduction



Differential Drell Yan dσ/dm

- Using 13 TeV data from 2015, integrated luminosity of 2.8 fb^{-1}
- Muon p_T > 22 (10) GeV for leading (subleading) and $|\eta|$< 2.4
- 43 dilepton invariant mass bins, 15 - 3000 GeV
- Data driven estimations for all backgrounds except WZ, ZZ.
- Systematic uncertainties dependent on mass region



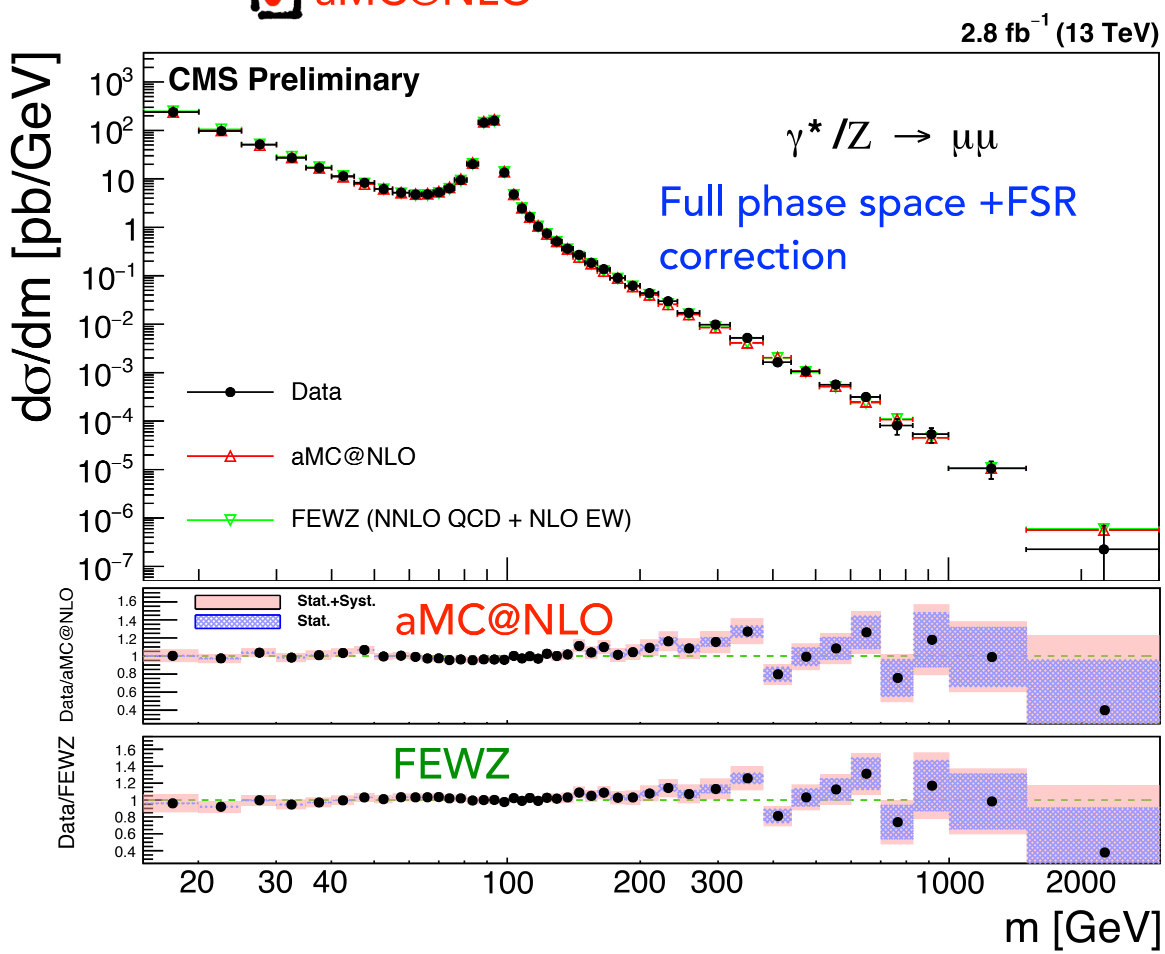


Differential Drell Yan dσ/dm

CMS PAS SMP-16-009

☑ FEWZ(NNLO QCD + NLO EW)

☑ aMC@NLO



- Good agreement within uncertainties
- FSR effects mostly under Z peak

Differential W+jets

Phys. Rev. D 96 (2017) 072005

Introduction

•Using 2.2 fb^{-1} of 13 TeV data taken at 25ns.

• Only W (—>uv)+jets considered (higher online threshold for electrons), measured vs

- inclusive, exclusive jet multiplicity
- jet p_T, rapidity of 3 leading jets
- H_T for jet multiplicity up to >= 3 jets.
- $\Delta\varphi(\mu, j_i)$
- $\Delta R(\mu$, closest jet)

Selection & Background

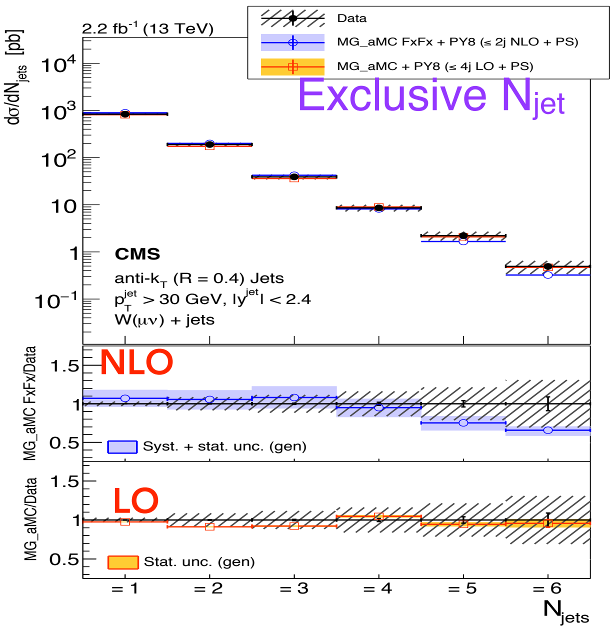
- Single muons are required to have $p_T > 25$ GeV and $|\eta| < 2.4$
- Jets with $p_T > 30$ GeV and $|y| < 2.4$
- $M_T(\mu, E_T^{miss}) > 50$ GeV
- For $\Delta R(\mu$, closest jet) distribution, jets $p_T > 100$ GeV, leading jet $p_T > 300$ GeV
- b-tag veto to reduce ttbar
- QCD background from data-driven methods, other backgrounds (diboson, ttbar, single top, DYJets) estimated from MC

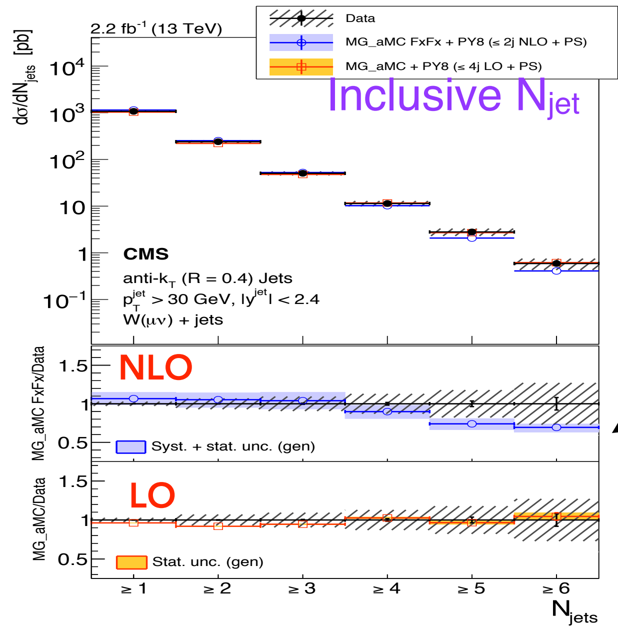
Data-MC comparison

- After unfolding, compared to particle level predictions from :
  - ☑ LO tree level calculation generated by aMC@NLO with W+0,1,2,3,4 jets
  - ☑ NLO calculation generated by aMC@NLO, NLO for W+0,1,2 jets and LO for 3,4 jets
  - ☑ N_{jetti} NNLO fixed order calculation for W+1 jet [non-perturbative effects from hadronisation and multiple interactions accounted for by corrections. Effect of FSR on NNLO at 1% level].

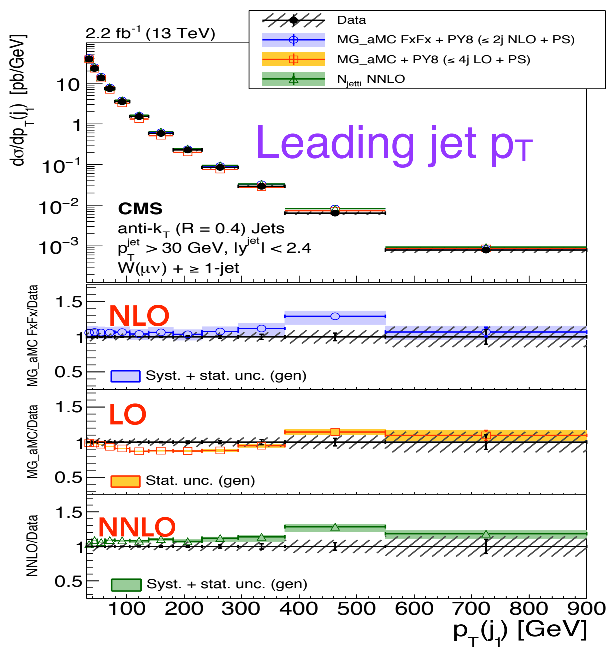
Differential W+jets

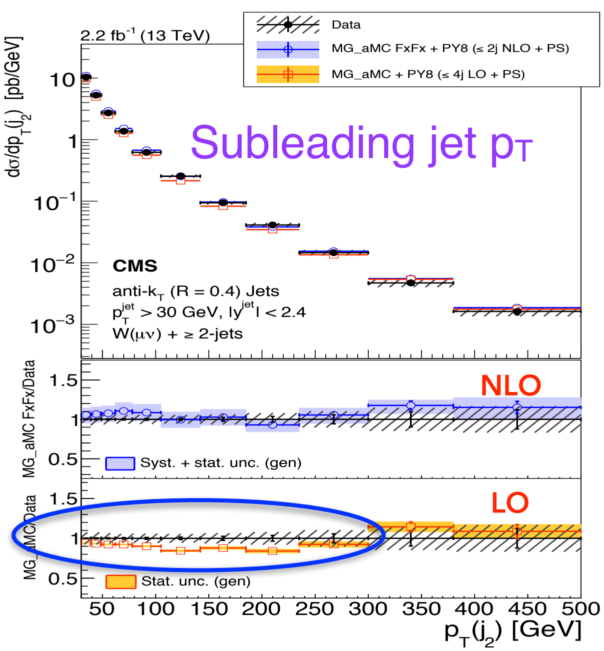
Phys. Rev. D 96 (2017) 072005





- Data and MC in agreement within uncertainty for NLO



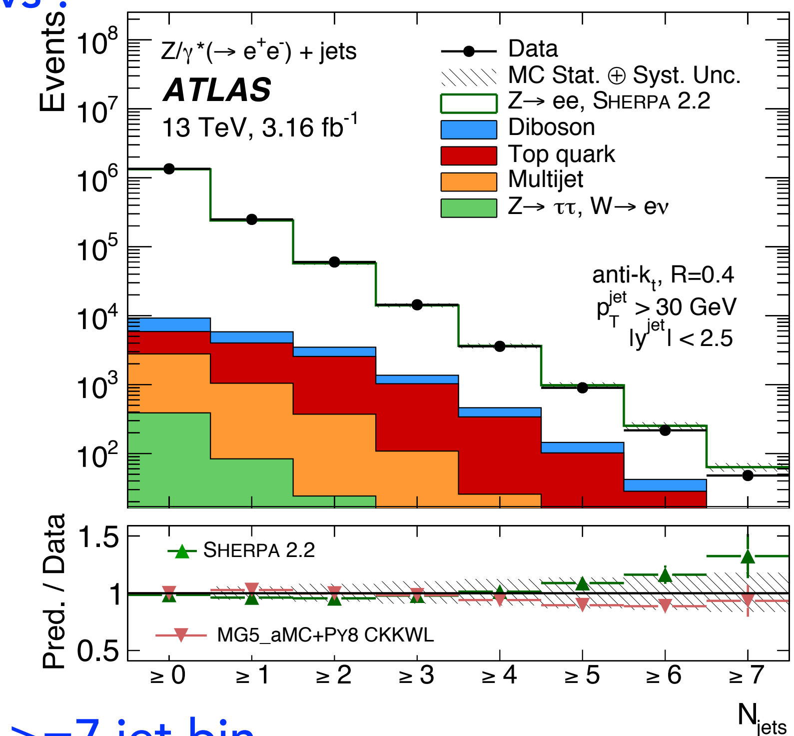


- Data and MC in agreement within uncertainty for NLO, also with NNLO W+1jet calculation
- Tree level LO calculation under predicting
- Similar conclusions for H_T, |y| dependence

Differential Z+jets

Eur. Phys. J. C77 (2017) 361

- Using 3.16 fb^{-1} of 13 TeV data
- Z decays in electron and muon channel
- Measured separately in each channel and combination vs :
    - inclusive and exclusive Njets
    - (Njets + 1)/Njets,
    - p_T of leading jet for several jet multiplicities
    - the jet rapidity y_{jet},
    - $\Delta\varphi_{jj}$ between 2 leading jets,
    - 2 leading jet invariant mass m_{jj},
    - H_T = sum p_T of all selected leptons +jets
- Purity of Z+jets 99% for inclusive region and 80-85% in >=7 jet bin



Differential Z+jets

Eur. Phys. J. C77 (2017) 361

Theoretical calculations

Unfolded data compared to :

- ☑ fixed-order calculation at NLO from BlackHat +Sherpa
- ☑ Njetti NNLO calculation Z+ ≥ 1 jet Njetti
- ☑ Sherpa 2.2, upto 2(4) partons at NLO(LO)
- ☑ Alpgen+Py6,
- ☑ MG5_aMC+Py8 CKKWL, LO, upto 4 partons
- ☑ MG5_aMC+Py8 FxFx - NLO, upto 2 partons

Systematics

- For inclusive selection, dominated by uncertainty on unfolding
- Uncertainty from jet energy scale dominates for N_{Jet} >=1,2,3,4,5,6,7
- Statistical uncertainty for all jet multiplicities less than systematic

Relative uncertainty in $\sigma(Z(\rightarrow \ell^+\ell^-)+ \geq N_{\text{jets}})$ [%]								
	$Z \rightarrow e^+e^-$							
Systematic source	+ ≥ 0 jets	+ ≥ 1 jets	+ ≥ 2 jets	+ ≥ 3 jets	+ ≥ 4 jets	+ ≥ 5 jets	+ ≥ 6 jets	+ ≥ 7 jets
Electron trigger	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3
Electron selection	1.2	1.6	1.8	1.9	2.3	2.7	2.9	3.8
Jet energy scale	< 0.1	6.6	9.2	11.5	13.8	17.3	20.6	23.7
Jet energy resolution	< 0.1	3.7	3.7	4.4	5.3	5.2	6.2	7.3
Jet vertex tagger	< 0.1	1.3	2.1	2.8	3.6	4.5	5.5	6.3
Pile-up	0.4	0.2	0.1	0.2	0.2	0.1	0.4	0.8
Luminosity	2.1	2.1	2.2	2.3	2.4	2.5	2.6	2.8
Unfolding	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.2
Background	0.1	0.3	0.6	1.0	1.6	3.3	6.0	11.6
Total syst. uncertainty	3.9	8.7	11.0	13.4	15.9	19.5	23.6	28.7
Stat. uncertainty	0.1	0.2	0.5	0.9	1.9	3.7	7.7	15.9

Differential Z+jets

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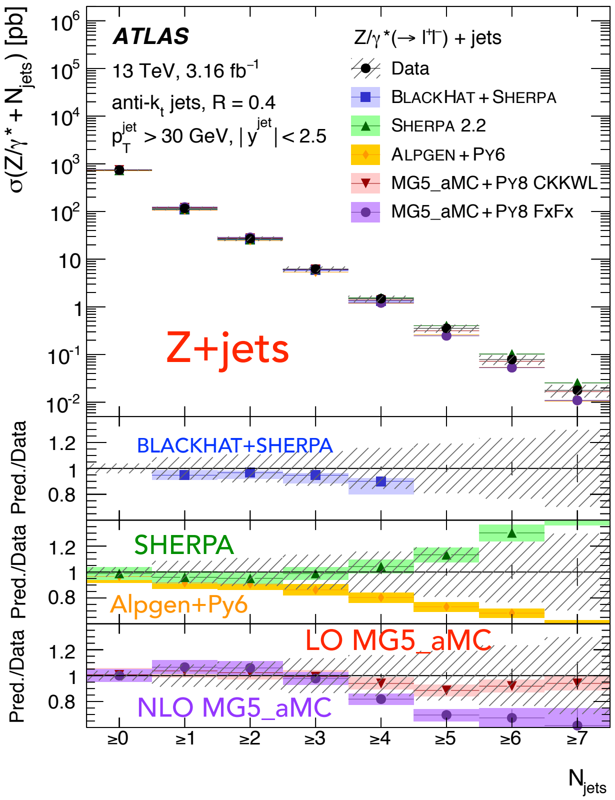
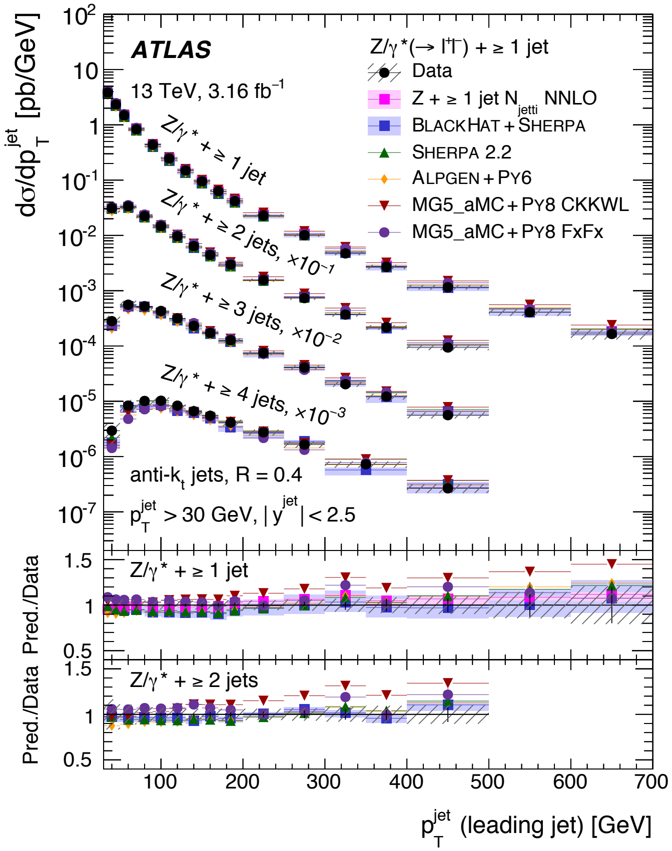
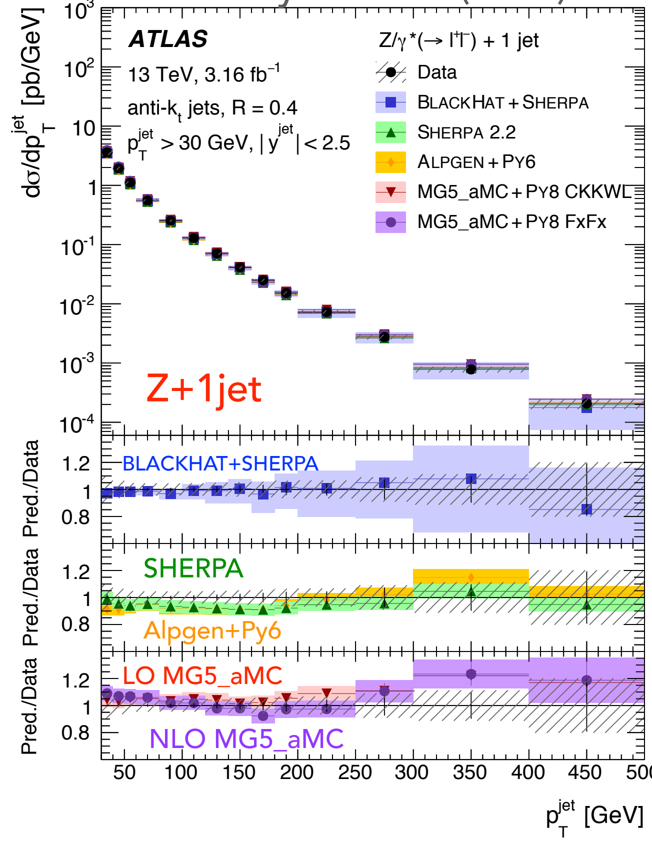






Disagreement with data for Sherpa 2.2, Alpgen+Py6 and MG5_aMC+Py8 FxFx for high jet multiplicity because higher fraction of the jets from parton shower.

Probes pQCD over a wide range of scales

LO MG5_aMC over predicts - p_T spectrum too hard (possibly due to dynamic ren/fac scale not appropriate for full p_T range)

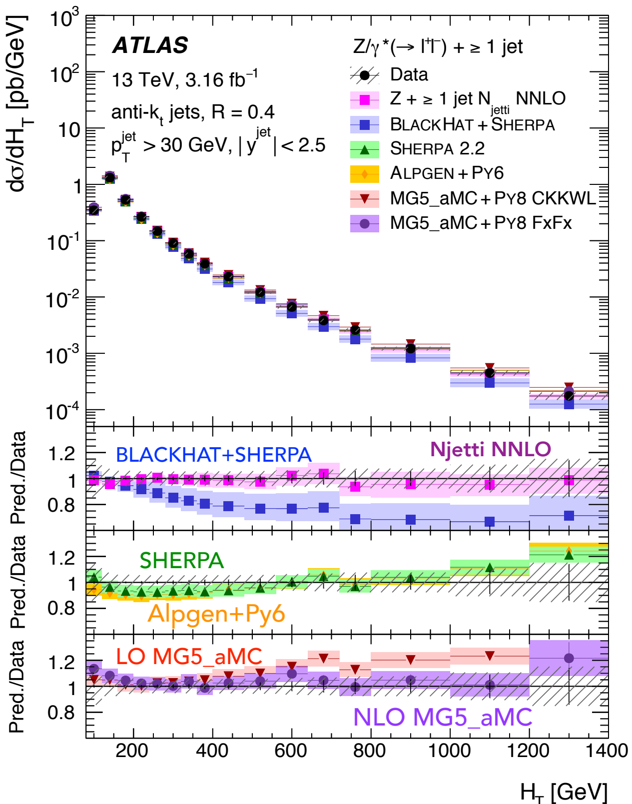
Probes validity of Z+1jet prediction at increasing QCD scale in presence of jet veto at constant low scale.

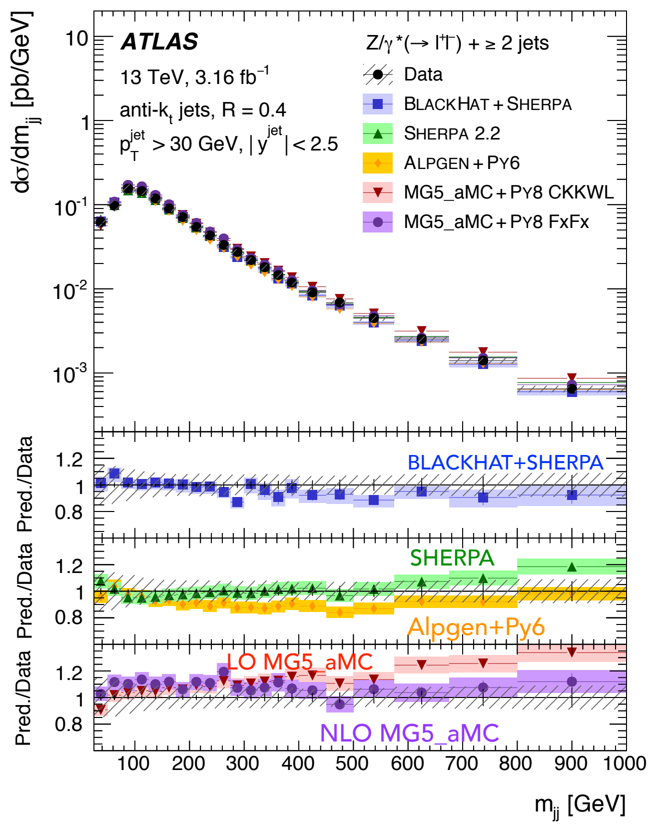
Jet scale probed ~10x larger than veto scale

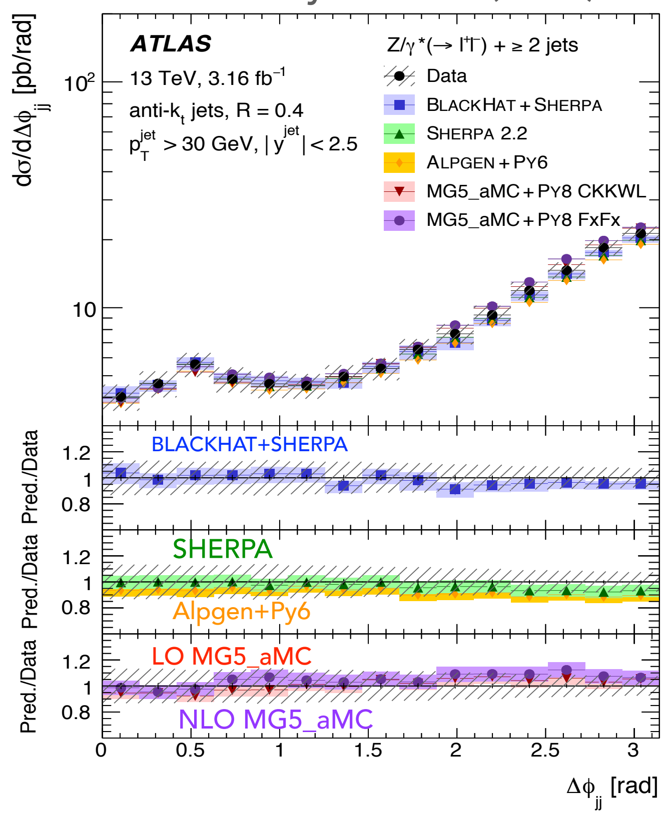
Predictions consistent within uncertainties

Differential Z+jets

Eur. Phys. J. C77 (2017) 361







- Fixed-order BlackHat+Sherpa under predicts for H_T > 300 GeV (missing higher parton multiplicities)
- Good description of data by Z +>=1 jet Njetti NNLO
- MG5_aMC+Py8 CKKWL over predicts at larger H_T (as observed in harder p_T spectrum)

- Useful for separating either heavier SM particles or beyond-SM physics from the Z + jets process.
- MG5_aMC+Py8 CKKWL predicts a harder spectrum

- Well modeled by all predictions

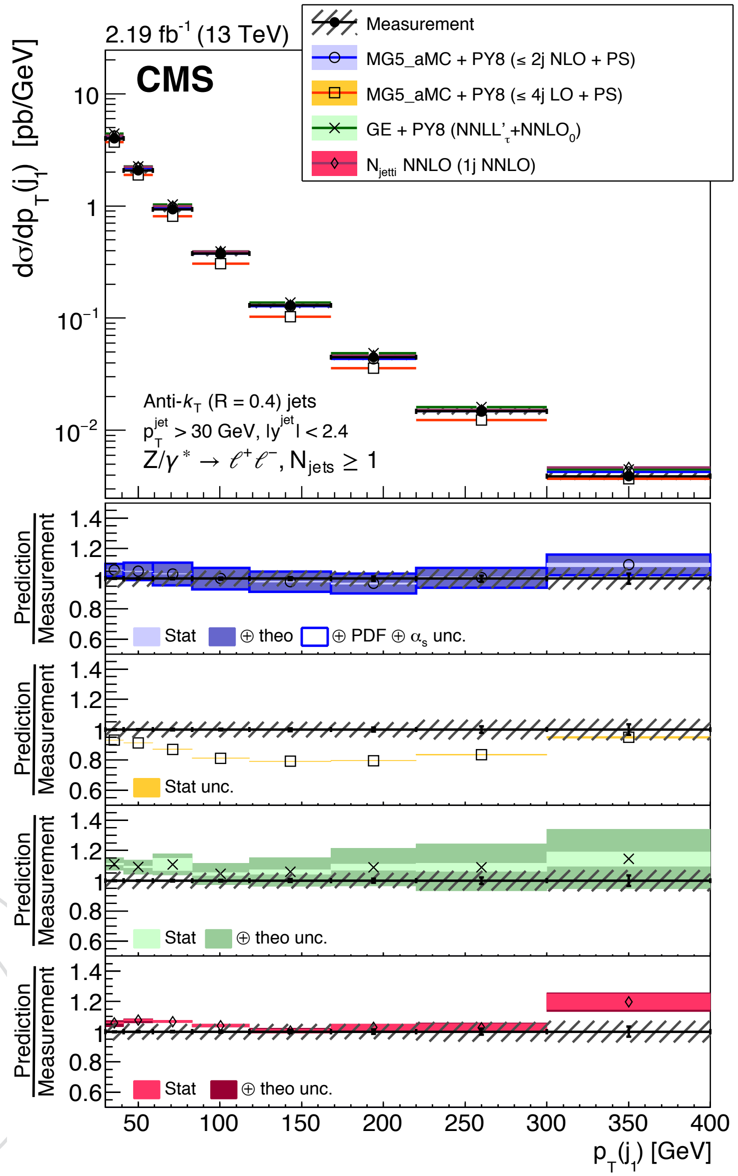
Dedicated talk on this by Louis Moureaux yesterday (slides)

SMP-16-015

13 TeV, 2.19 fb-1

Differential cross section vs

- transverse momentum of the Z boson,
- jet kinematic variables (transverse momentum and rapidity)
- scalar sum of the jet momenta,
- balance in transverse momentum between the reconstructed jet recoil and the Z boson



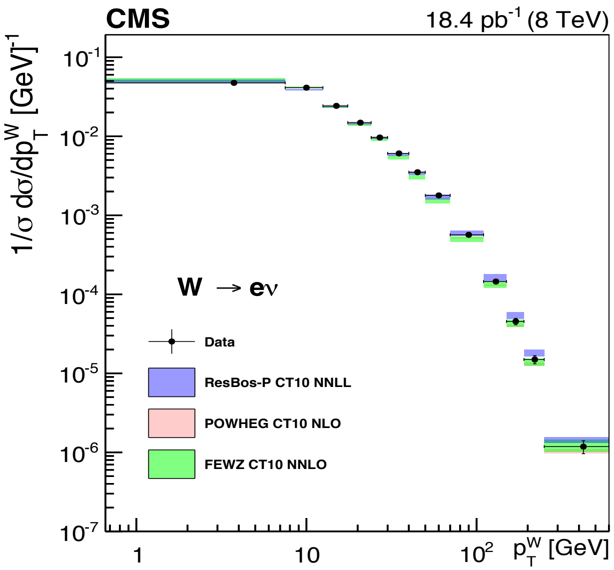
	No jet	1 jet	2 jets	3 jets	4 jets
MADGRAPH (LO*)	LO	LO	LO	LO	LO
MADGRAPH (NLO)	NLO	NLO	NLO	LO	Py
GENEVA 1.0-RC2	NNLO	NLO	LO	Py	Py
Z+1 jet at NNLO†	–	NNLO	(NLO)	(LO)	–

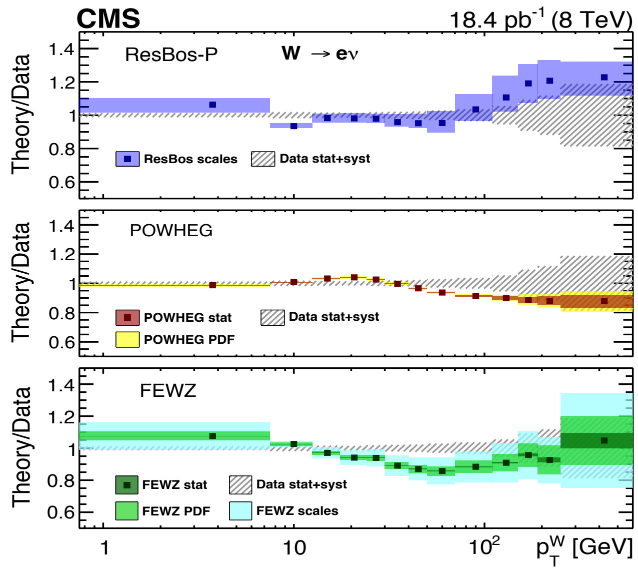
from Louis's talk

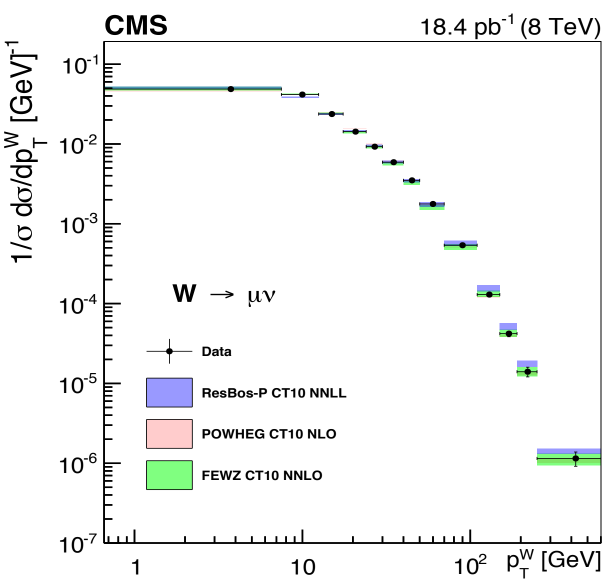
W p_T spectrum

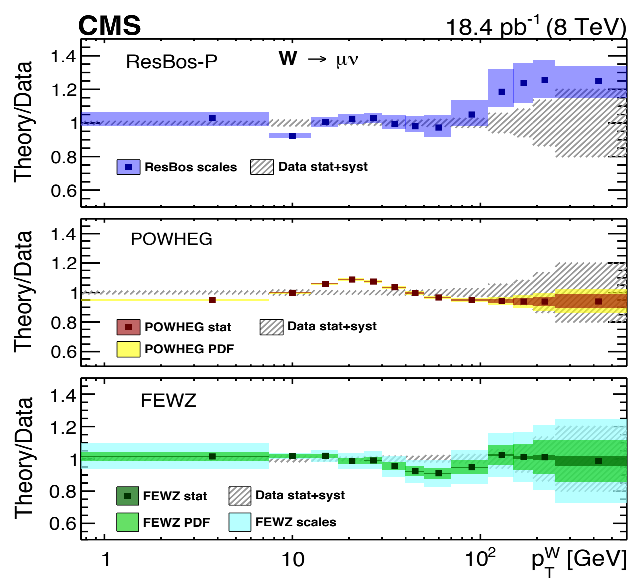
CMS-SMP-14-012

- Using 8 TeV data, special low luminosity, low pileup run, using 18.4 pb^{-1} (av. 4 collisions per bunch crossing, less background, better resolution)









Uncertainties :

- FEWZ from stats, scale, PDF
- POWHEG from stats, PDF
- RESBOS from scale
- Data from quadrature sum of stat and syst

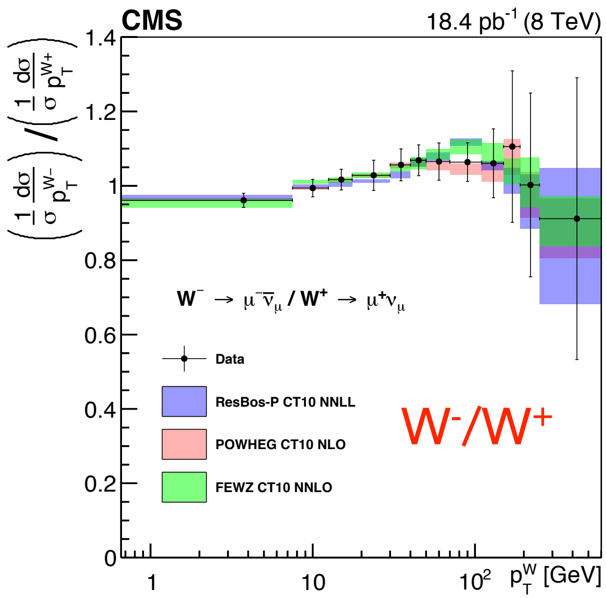
ResBos: Agree for p_T < 110 GeV (except 7.5 - 12.5 GeV) consistent over-prediction > 110 GeV by ~ 20%

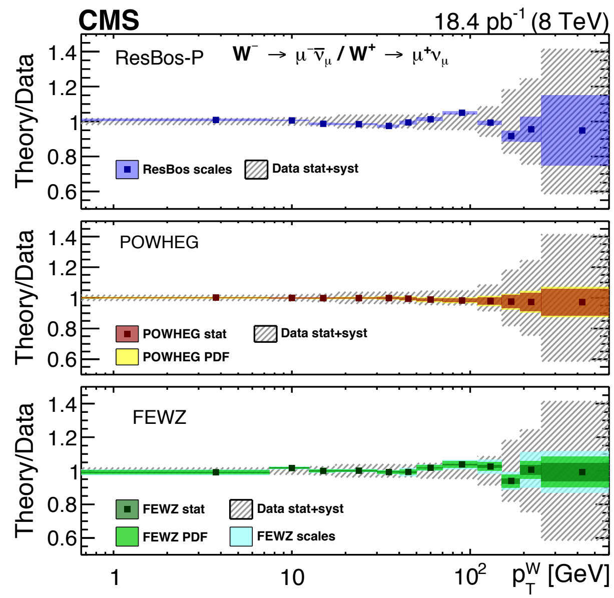
POWHEG: agrees well above 100 GeV, over predicts by ~12% in transition region 25 GeV

FEWZ in agreement with data within uncertainties in full range except ~ 60 GeV

W⁻/W⁺ and W/Z ratio measurement

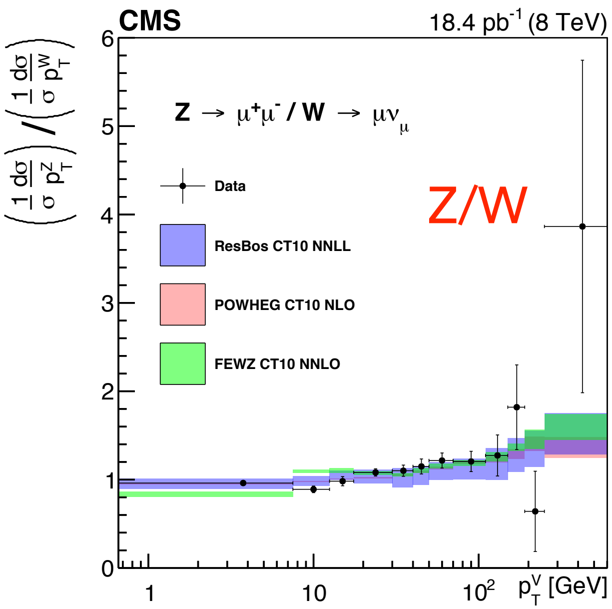
CMS-SMP-14-012

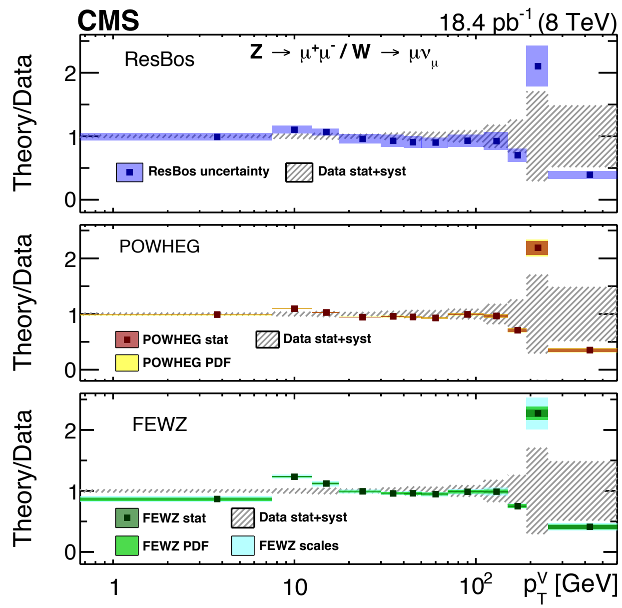




Ratios reasonably well described by the different theoretical predictions

Larger uncertainties for RESBOS because the way scale and PDFs varied gives no cancellation in ratio.





Ratios reasonably well described by the different theoretical predictions

Z/gamma ratio

CMS-SMP-14-005

- In limit of high $p_T(V)$ and at LO in QCD effects from mass of Z are small, cross-section ratio of Z/gamma expected to become constant, plateau at ~300 GeV
- At higher p_T, corrections from higher order QCD and EWK processes can lead to dependence of cross section on logarithmic terms of the form $\ln(p_T^Z/m_Z)$ that can become large.
- A precise measurement constrains the higher order effects of logarithmic corrections.

Detector-corrected data compared with predictions from :

- ☑ Sherpa,
- ☑ LO MadGraph with up to 4 partons, corrected to NNLO cross-section from FEWZ. (k-factor = 1.197). For photon+jets LO cross-section used as no NNLO calculation available.
- ☑ NLO calculation from BlackHat for upto 3 jets. Corrected for non-perturbative effects using MG+Pythia,

Systematics

Z channel
JES and lepton SF dominant

Process	JES ($n_{\text{jets}} \geq 1$)	JES (otherwise)	JER	Lep SFs	UF	PU, BG LRES	LS	Lumi
$Z \to e^+e^-$	1–3%	5–10%	<1%	3–4%	2–3%	<1%	1–5%	2.6%
$Z \to \mu^+\mu^-$	1–3%	5–10%	<1%	2.5–5.5%	2–3%	<1%	<1%	2.6%

photon channel
JES and photon purity

Process	JES ($n_{\text{jets}} \geq 1$)	JES (otherwise)	JER	UF	PU	γ Pur	γ ES	Lumi
γ	1–3%	5–10%	0.5–1.5%	2%	<0.5%	4–10%	3%	2.6%

Z/gamma ratio

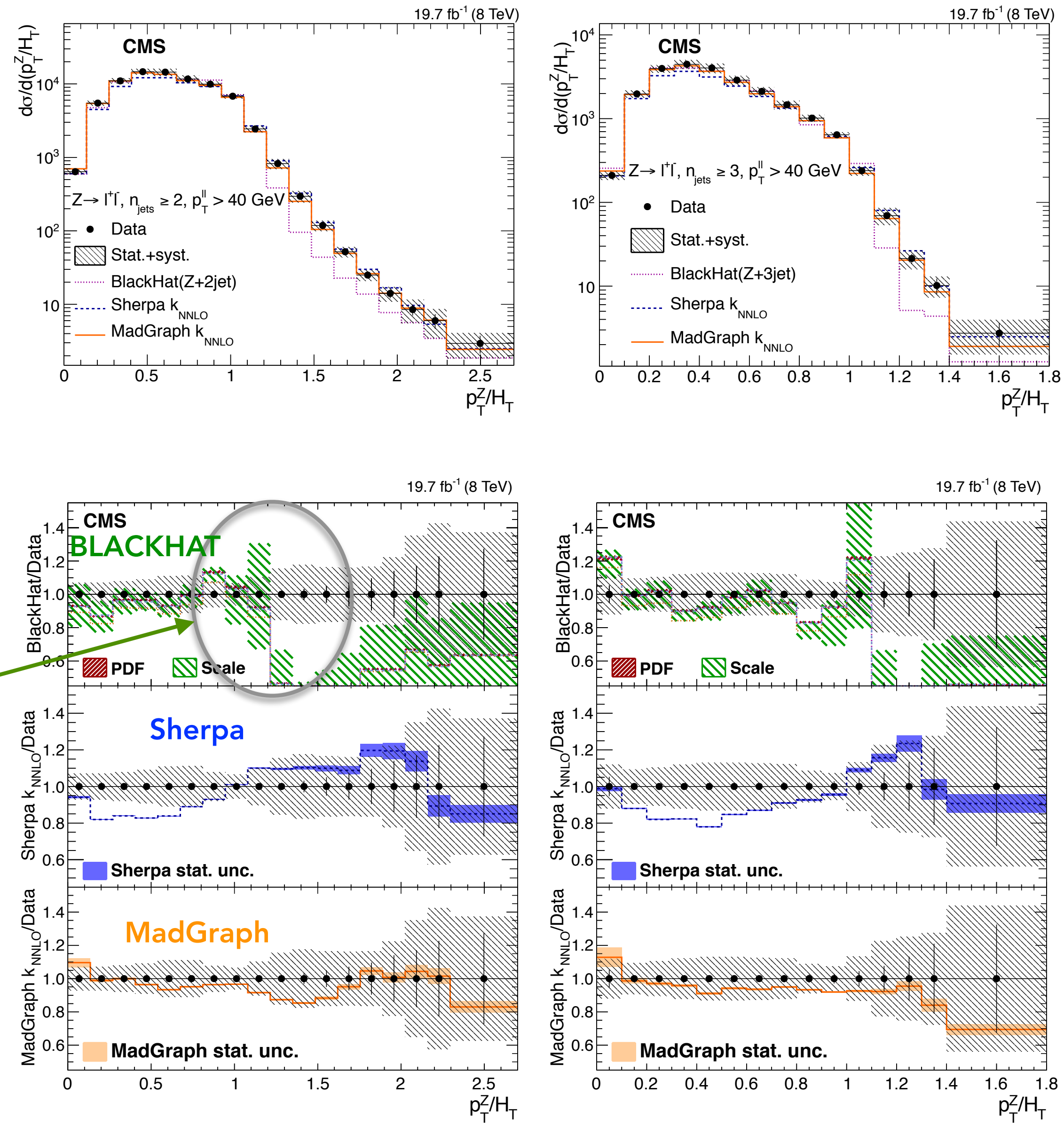
THE ROYAL SOCIETY

Imperial College London

CMS-SMP-14-005

- Most events with $p_T^Z/H_T < 1$.
- Events in tail from jets outside acceptance in forward region, or additional unclustered hadronic radiation.
- MG describes best the rate and shape of distribution
- Blackhat ok in bulk but not describing the tails well

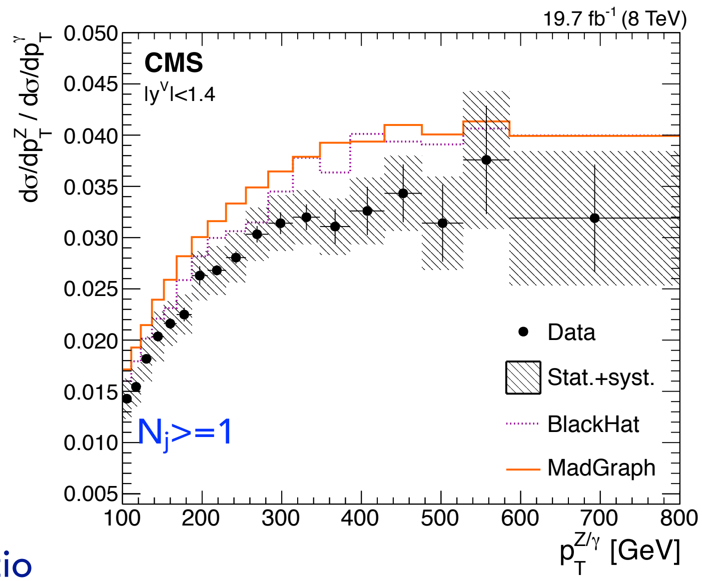
Sharp drop in BLACKHAT ~ 1, need the parton showering for the soft jets or jets in forward region to get $p_T^Z/HT > 1$

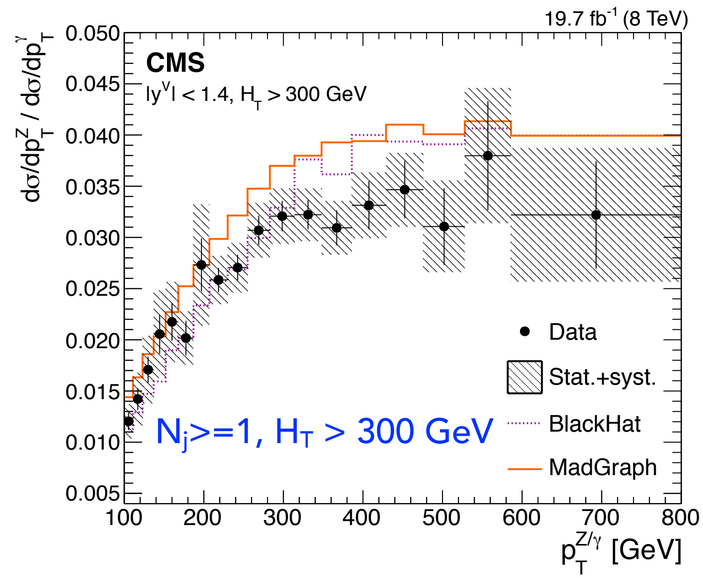


Z/gamma ratio

CMS-SMP-14-005

- Z/gamma ratio
- Ratio measured in 4 regions $N_{jets}>=1,2,3$, HT > 300,
- Systematics from JES, JER, lumi correlated between Z and gamma, cancel in the ratio

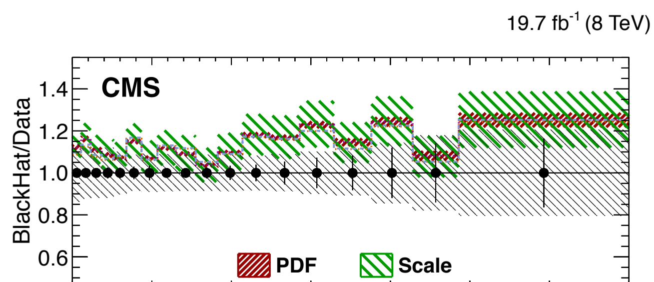


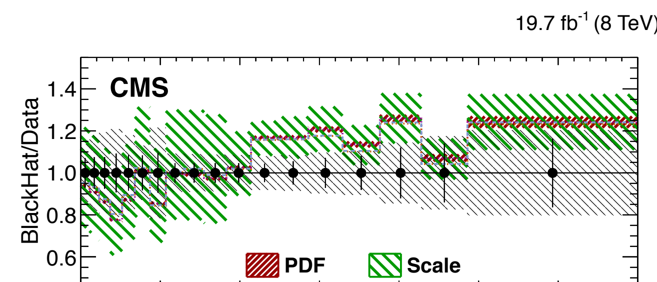


- Ratio plateaus at cross-section ratio of:

0.0322 +/- 0.0008(stat) +/- 0.0020(sys)

- Divide by leptonic branching fraction, Ratio of total cross-sections = 0.957 +/- 0.066





✦ MadGraph consistently ~20% higher than data

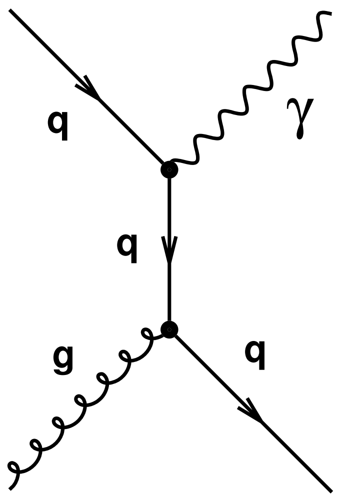
✦ BLACKHAT also overestimates at high p_T by ~20%.

Photon+jets

arXiv:1801.00112

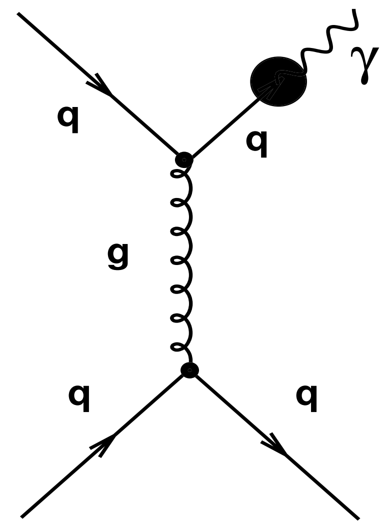
- Angular correlations between photon and jet can be used to probe the dynamics of hard scattering process
- Useful for tuning MC and testing t-channel quark exchange

prompt process
(photon originates from hard process)



For t-channel quark exchange, cross section expected to have a $(1 - |\cos\theta^*|)^{-1}$ dependence as $|\cos\theta^*| \rightarrow 1$ (similar to W/Z+jet production)

fragmentation process
(photon from fragmentation of colored high p_T parton)

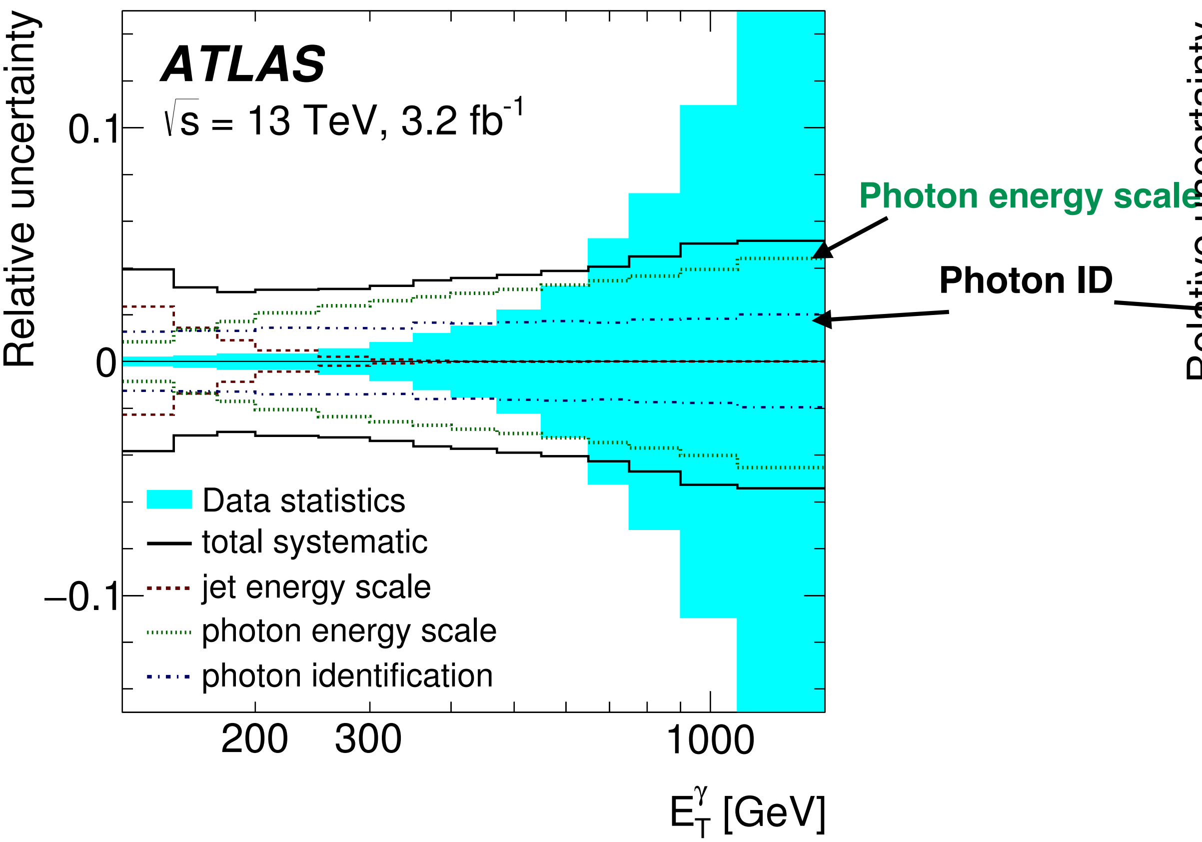


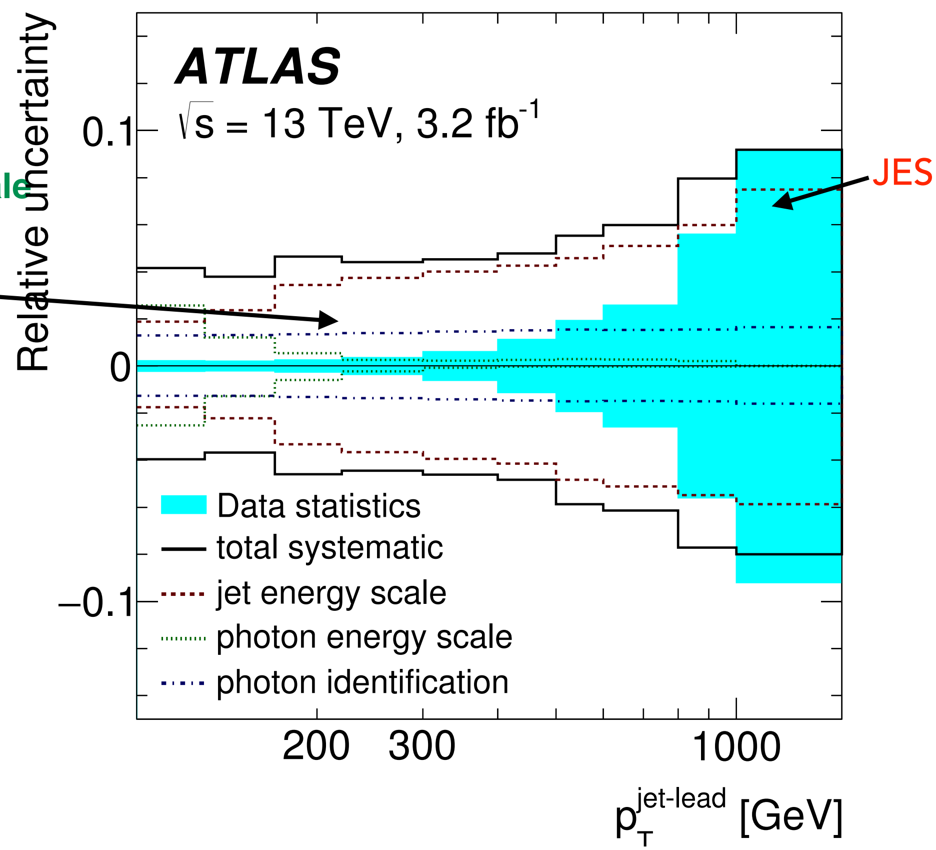
For t-channel gluon exchange, cross section expected to exhibit a $(1 - |\cos\theta^*|)^{-2}$ (as in dijet production)

Precise measurement of the cross section sensitive interplay between direct and fragmentation components

arXiv:1801.00112

Requirements on photons
$E_T^{\gamma} > 125$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$ (excluding $1.37 < \lvert\eta^{\gamma}\rvert < 1.56$)
$E_T^{\rm iso} < 4.2 \cdot 10^{-3} \cdot E_T^{\gamma} + 10$ GeV
Requirements on jets
anti-k_t algorithm with $R = 0.4$
the leading jet within $\lvert y^{\rm jet}\rvert < 2.37$ and $\Delta R^{\gamma-{\rm jet}} > 0.8$ is selected
$p_T^{\rm jet\text{-}lead} > 100$ GeV
UE subtraction using $k_\perp$ algorithm with $R = 0.5$ (cf. Section 4)
Additional requirements for $d\sigma/dm^{\gamma-{\rm jet}}$ and $d\sigma/d\lvert\cos\theta^*\rvert$
$\lvert\eta^{\gamma} + y^{\rm jet\text{-}lead}\rvert < 2.37$, $\lvert\cos\theta^*\rvert < 0.83$ and $m^{\gamma-{\rm jet}} > 450$ GeV



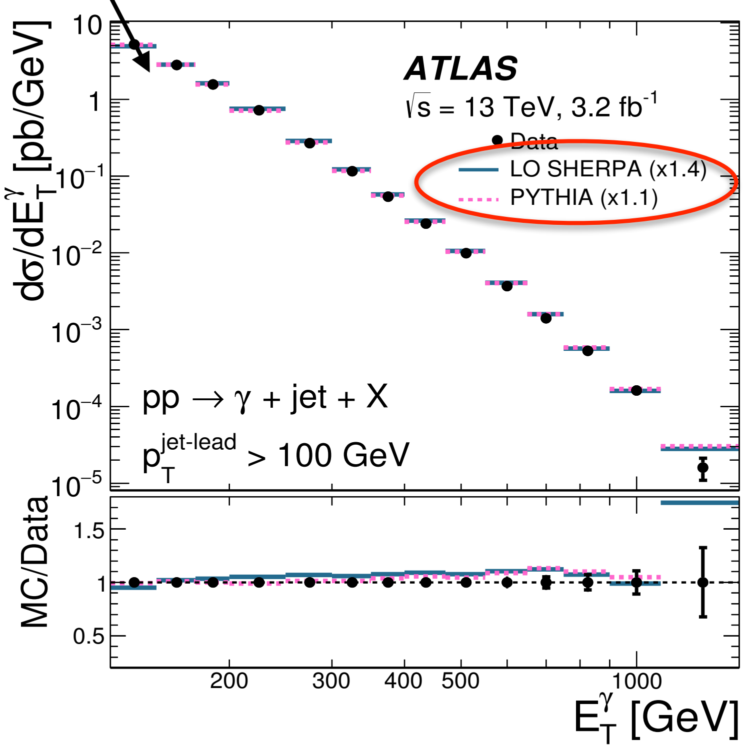


Photon+jets

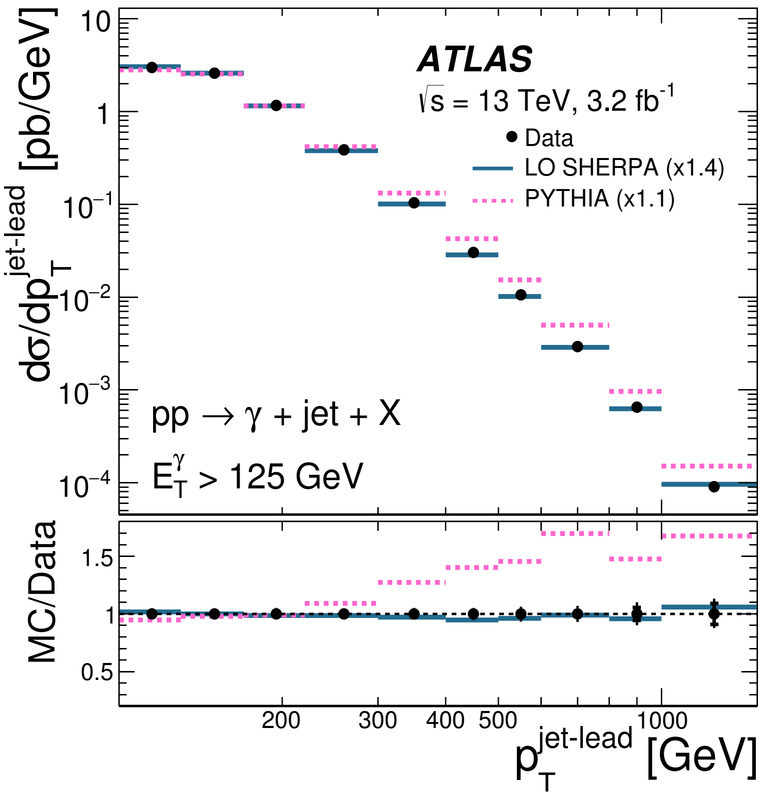
arXiv:1801.00112

☑ Pythia
☑ LO Sherpa

6 orders of magnitude studied



diff. in normalisation of 10% (Pythia) and 40%(Sherpa) - missing higher order terms



Reasonable description of shape of distribution by both predictions

- Sherpa is OK
- Pythia overestimated above 200 GeV - due to large contribution from photon bremsstrahlung predicted by tune used in Pythia

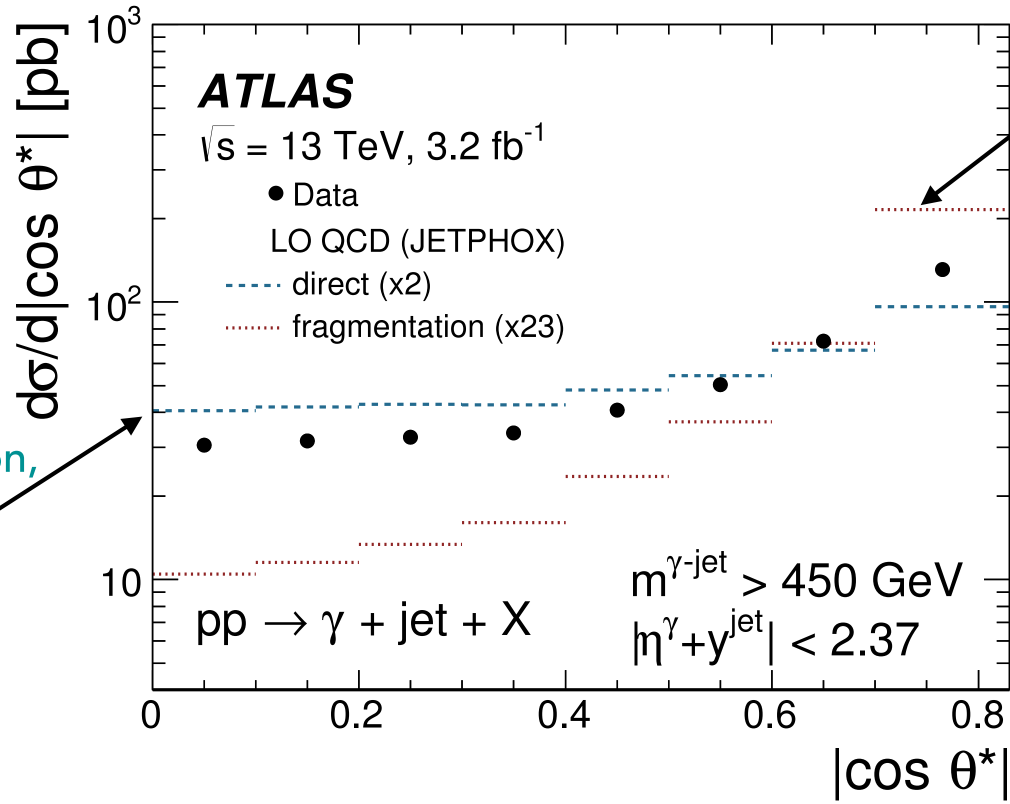
arXiv:1801.00112

Use LO JETPHOX to show sensitivity to t-channel quark or gluon exchange

LO JETPHOX
☑ direct
☑ fragmentation

Fragmentation process, dominated by gluon exchange, shows steeper increase as |cosθ*|→1

Direct production, dominated by quark exchange

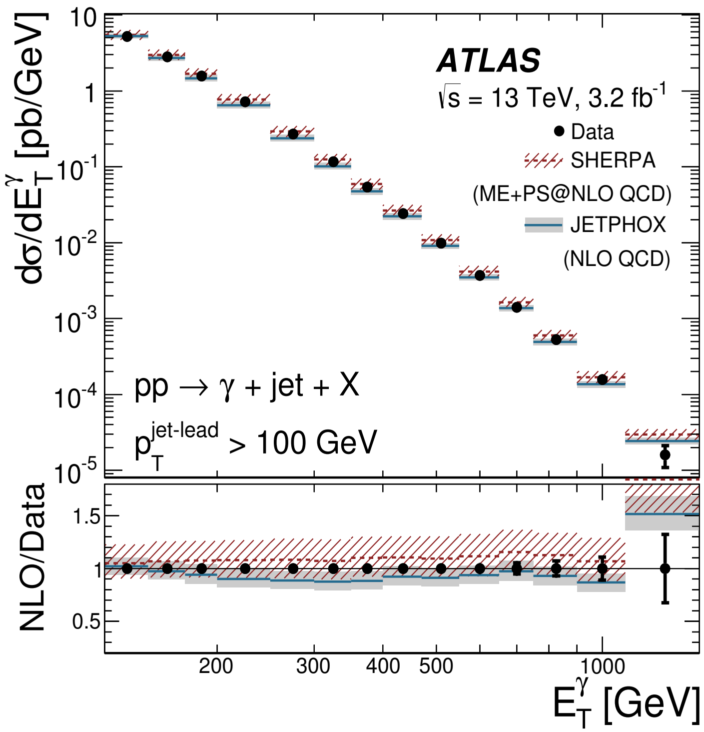


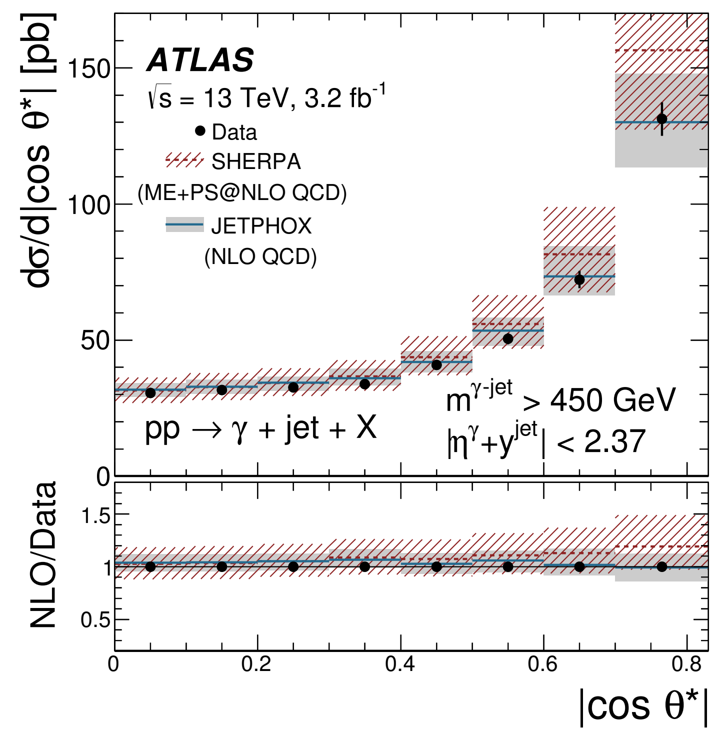
Shape of measured differential cross section closer to direct process than fragmentation, consistent with dominance of t-channel quark exchange

Photon+jets

arXiv:1801.00112

- SHERPA ME+PS [γ+(1,2) jet @ NLO, γ+(3,4) jet @LO]
- JETPHOX NLO QCD





Both predictions within experimental/theoretical uncertainties, theory uncertainties dominating

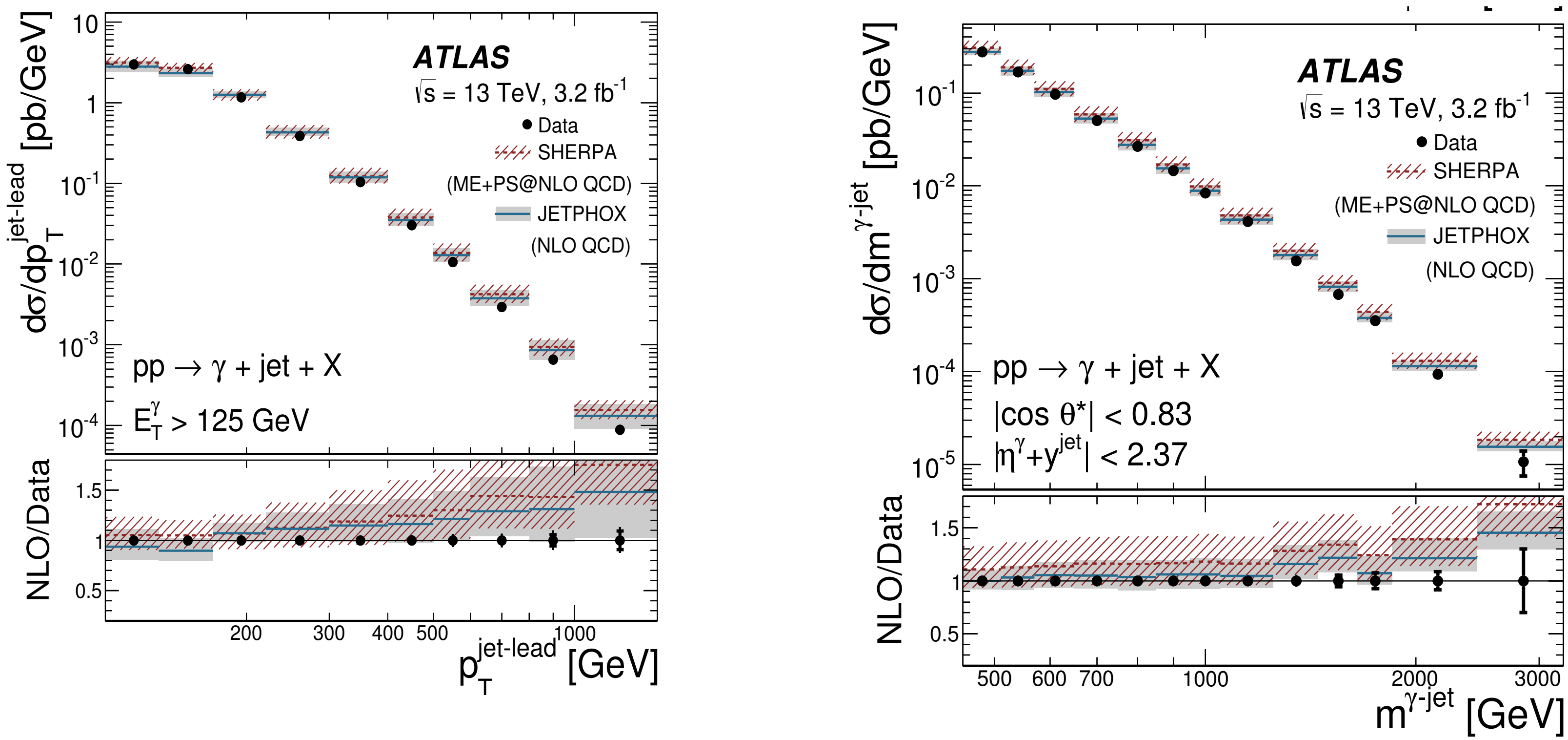
Total theory uncertainty (dominated by missing higher orders beyond NLO)

	SHERPA	JETPHOX
E_T^{γ}, $m^{\gamma\text{-jet}}$ $|\cos\theta^*|$	15–25%	10–15%
$p_T^{jet-lead}$	15–30%	10–40%
$\Delta\varphi^{\gamma-jet}$	10–40%	-

Photon+jets

arXiv:1801.00112

- ☑ SHERPA ME+PS [γ+(1,2) jet @ NLO, γ+(3,4) jet @LO]
- ☑ JETPHOX NLO QCD



Total theory uncertainty (dominated by missing higher orders beyond NLO)

	SHERPA	JETPHOX
E_T^γ, $m^{\gamma\text{-jet}}$ $\|\cos\theta^*\|$	15–25%	10–15%
$p_T^{\text{jet-lead}}$	15–30%	10–40%
$\Delta\varphi^{\gamma-\text{jet}}$	10–40%	-

W and Z in the forward region

arXiv:1605.00951

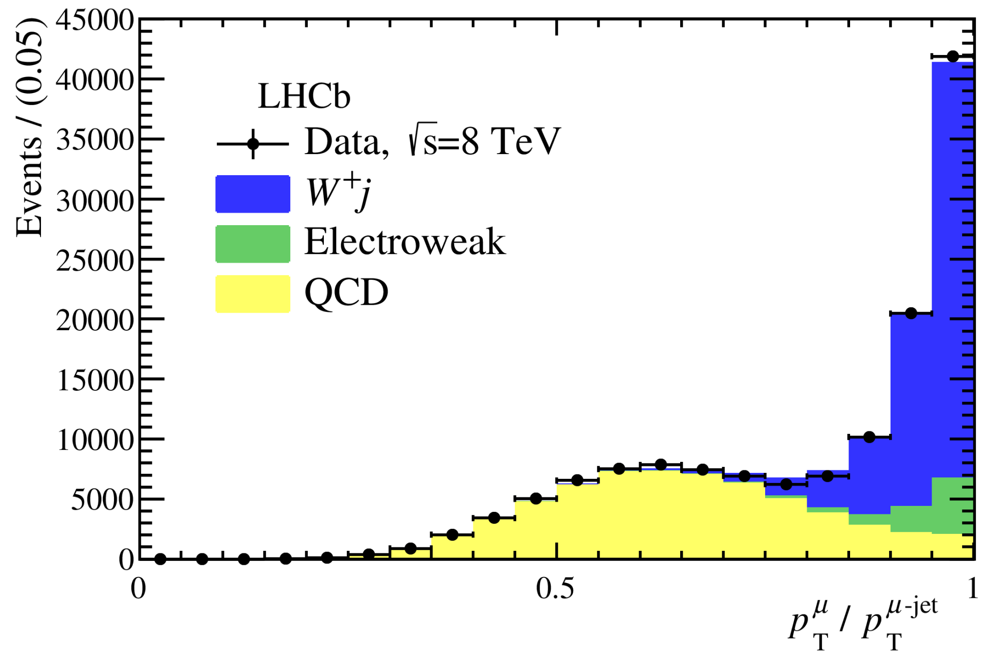
8 TeV, 1.98 fb^{-1}

- LHCb only detector with precision tracking coverage in forward region
- Sensitive to PDFs at different Bjorken-x than CMS and ATLAS
- Probes low-x down to 10^{-4} and high *x*

Selection

- Muon p_T^{μ} > 20 GeV, 2.0 < η^{μ} < 4.5
- Jet p_T^{jet} > 20 GeV, 2.2 < η^{jet} < 4.2
- Z—>μμ:: 60 < $M_{\mu\mu}$ < 120 GeV
- W—>μν: $p_T^{\mu+j}$ > 20 GeV
- p_T^{jet} > 20 GeV, 2.2 < η^{jet} < 4.2

Source	σ_{W^+j}	σ_{W^-j}	σ_{Zj}	R_{WZ}	$R_{W^\pm}$
Statistical	0.4	0.5	1.1	1.2	0.7
Muon reconstruction	1.3	1.3	0.6	0.9	0.0
Jet reconstruction	1.9	1.9	1.9	0.0	0.0
Selection	1.0	1.0	0.0	1.0	0.0
GEC	0.5	0.5	0.4	0.2	0.1
Purity	5.5	7.0	0.4	6.0	2.5
Acceptance	0.6	0.6	0.0	0.6	0.0
Unfolding	0.8	0.8	0.8	0.0	0.2
Jet energy	6.5	7.7	4.3	3.4	1.2
Total Systematic	8.9	10.7	4.8	7.0	3.3
Luminosity	1.2	1.2	1.2	–	–



- Purity of W(μν) +jets : W^+j= 46.7%, W^-j = 36.5%
- Purity of Z(μμ)+jets : 97.8%

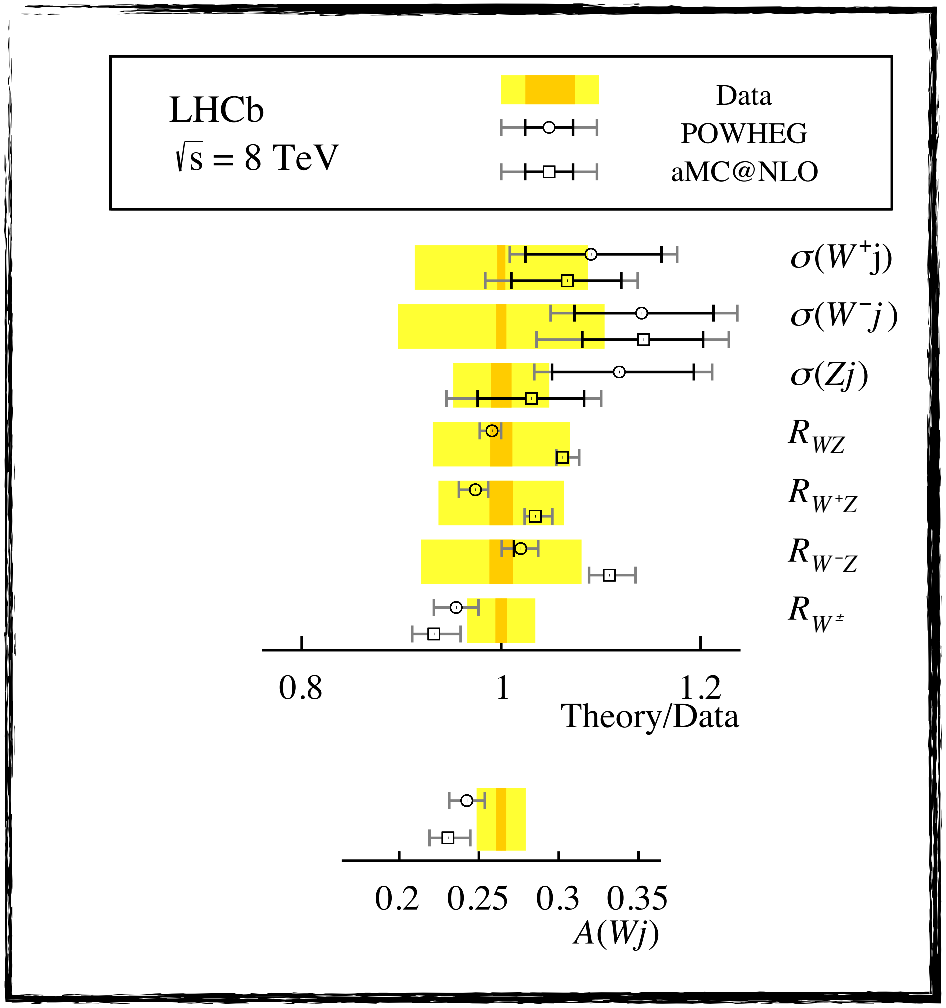
Systematic uncertainties dominate :jet energy, purity (W)

arXiv:1605.00951

		stat.	sys.	lumi.
σ_{W^+j}	=	56.9 ± 0.2	± 5.1	$\pm 0.7\,\text{pb}$,
σ_{W^-j}	=	33.1 ± 0.2	± 3.5	$\pm 0.4\,\text{pb}$,
σ_{Zj}	=	5.71 ± 0.06	± 0.27	$\pm 0.07\,\text{pb}$,

		stat.	sys.
R_{WZ}	=	15.8 ± 0.2	± 1.1,
R_{W^+Z}	=	10.0 ± 0.1	± 0.6,
R_{W^-Z}	=	5.8 ± 0.1	± 0.5,
$R_{W^\pm}$	=	1.72 ± 0.01	± 0.06,

$$A(Wj) \equiv (\sigma_{W^+j} - \sigma_{W^-j})/(\sigma_{W^+j} + \sigma_{W^-j}) = 0.264 \pm 0.003 \pm 0.015$$

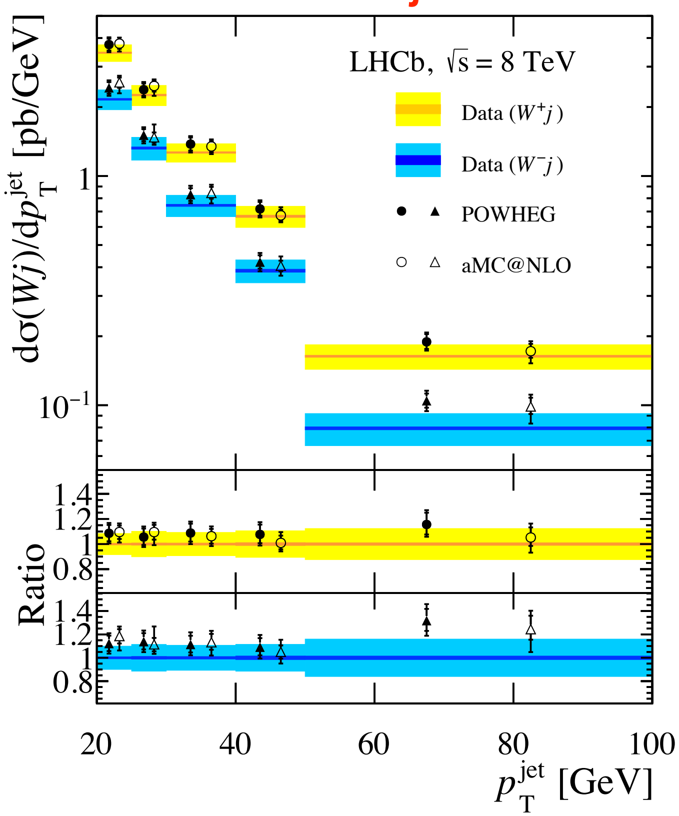


Reasonable agreement between data and predictions

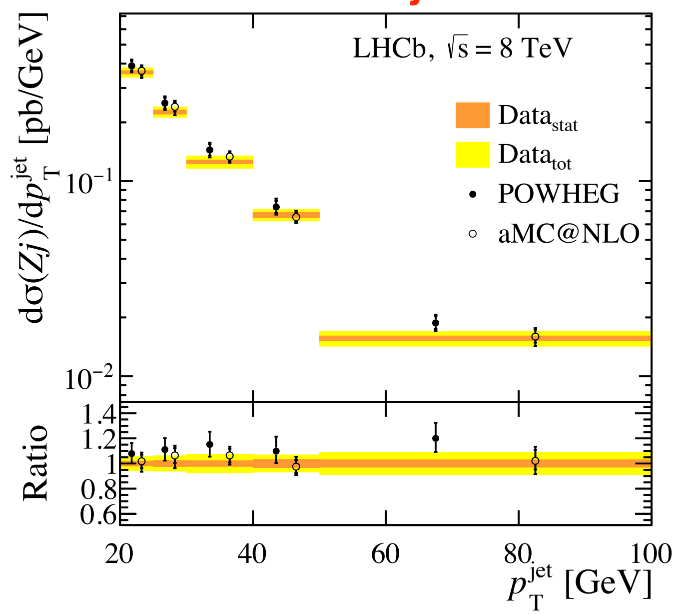
arXiv:1605.00951

POWHEG
aMC@NLO

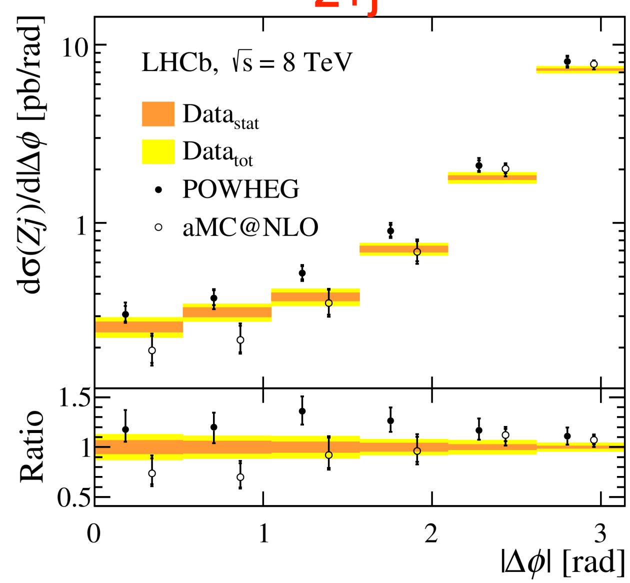
W+j



Z+j



Z+j



Reasonable agreement between data and predictions

Summary

- Precision measurements of processes with EWK bosons are fundamental tests of the Standard Model
- They probe pQCD, constrain PDFs and also dominant backgrounds to new physics searches.
- Theoretical modeling of these processes entering a new era : provision of NNLO QCD and NLO QCD+NLO EWK calculations
- Precision measurements from LHC experiments also entering an era of big data - expect reduced uncertainties and higher sensitivity to pQCD and the difference between various theoretical calculations.