Production of vector bosons in association with jets in ATLAS

E. Meoni
(UNICAL & INFN)

On behalf of the ATLAS Collaboration

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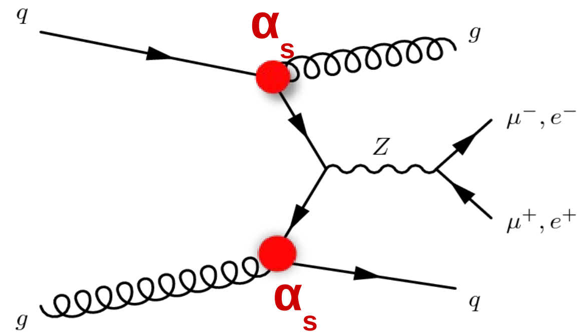
Motivations



V+jets production dominated by **strong interactions**:

- **Precision test of pQCD**:test state-of-the-art pQCD calculations
- Impact of **PDFs** understandings
- **Background** to SM measurements, Higgs and New Physics:
  important validation of the **Matrix Element (ME)+Parton Shower (PS) MCs**

V+jets cross-section measurements

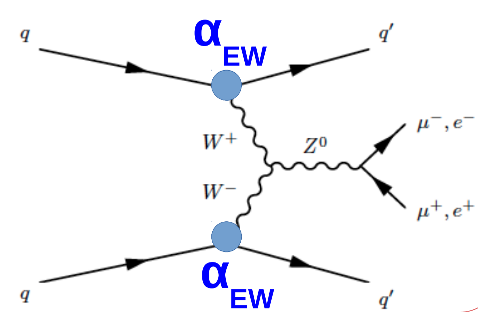
- **Study QCD quantities** with high statistics in a very clean environment

V+jets as tool for k_t splitting

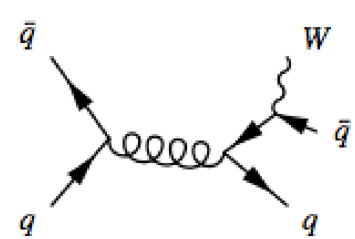
- Explore **extreme phase spaces**:

  - enhanced EW-production regions to constrain MCs in **VBF-like regions** important to understand Higgs and BSM backgrounds

  - V-jet collinear configurations enhanced with high p_T jets to study regions where predictions could not work and mimic boosted signatures sensitive to New Physics

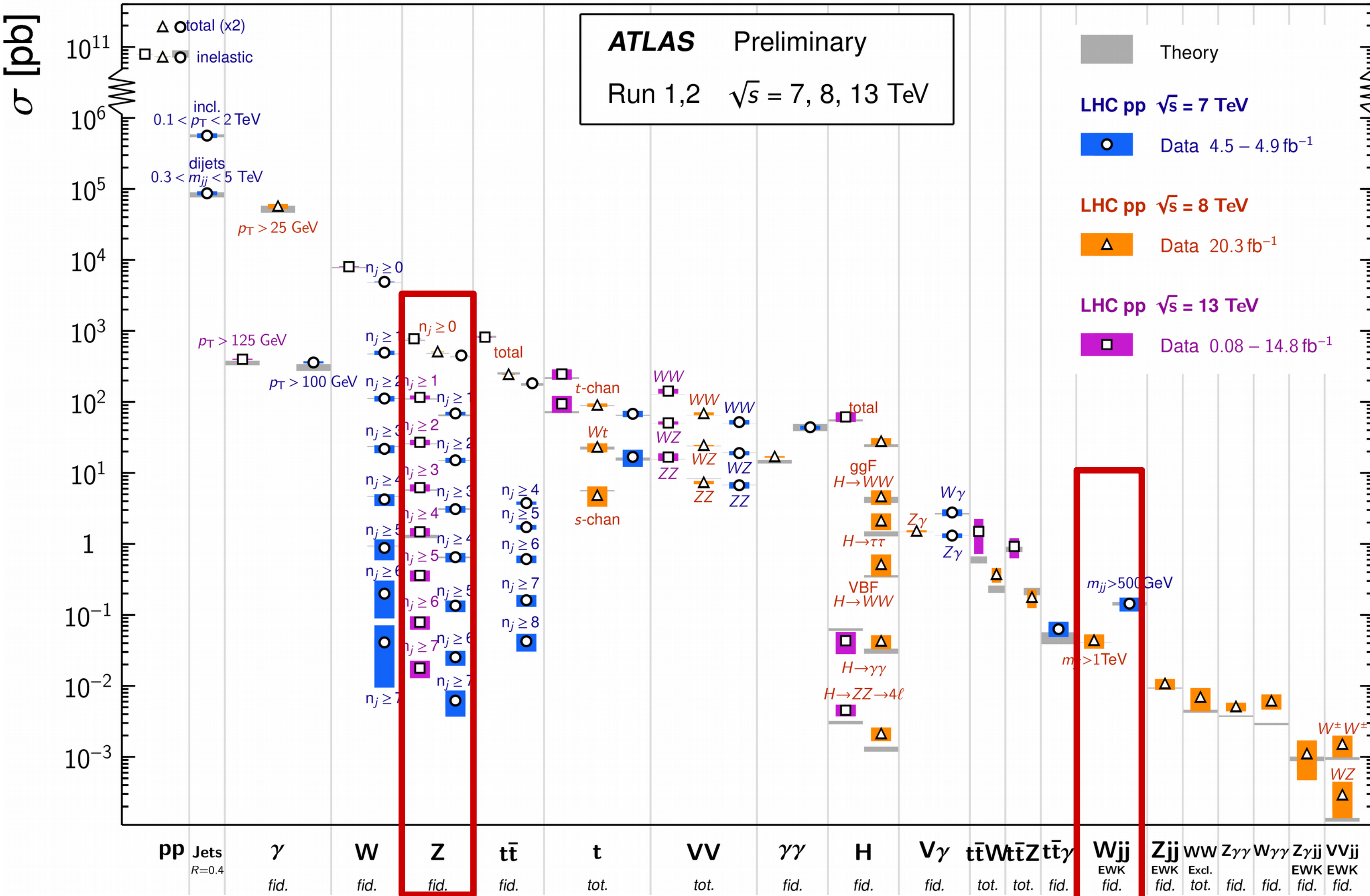


EW V+jets measurements



V+jets angular distributions for high p_T

Outline



σx BR (@13TeV)
~ 2σ x BR(@7TeV)

σx BR (@7-8TeV)

~ 1-10 nb
(W/Z inclusive)

~ 1-10⁻⁵ nb
(W/Z+1-7 jets)

~ 10⁻²-10⁻³ nb
(W/Z+ b-jets)

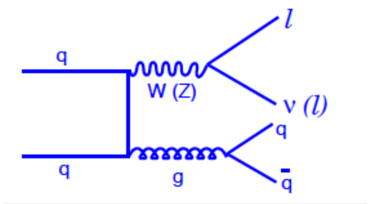
~ 10⁻⁴-10⁻⁵ nb
(EWK W/Z+ 2 jets)

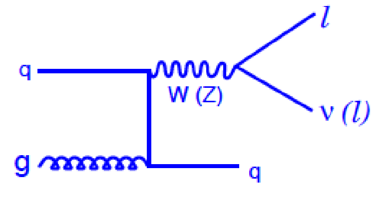
Measurements presented today:

- **“Classic” Z+jets cross-section** measurement at 13 TeV (**arXiv:1702.05725 [hep-ex]**)
- **QCD+EW W+2 jets** cross-section measurement at 8 TeV (**arXiv:1703.04362 [hep-ex]**)
- **W-jets collinear region** measurement at 8 TeV (**Phys. Lett. B 765 (2017) 132**)
- **k_T splitting measurement** in Z+jets at 8 TeV (**arXiv:1704.01530 [hep-ex]**)

Z+jets @ 13 TeV

Look at leptonic decays Z→μμ/ ee (very clear probe)





Detector Level

Kinematic region with high efficiencies, good detector performances and low backgrounds:

Leptons: p_T>25 GeV, |η|<2.4 (μ)- 2.47 (e)
Z: 71 GeV <m_{ll}<111 GeV
Jets: anti-kt R=0.4, p_T>30 GeV, |y|<2.5, ΔR (l,j)>0.4

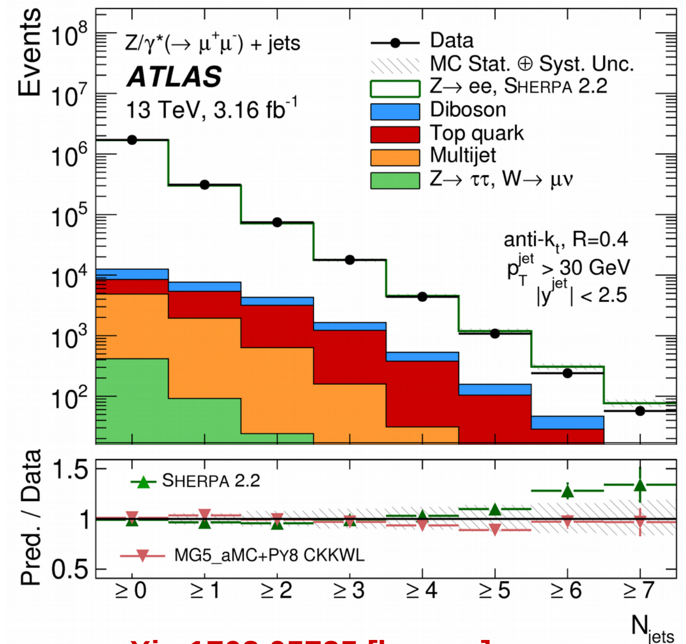
The Particle Level

Unfolding with MC: Correct for detector effects

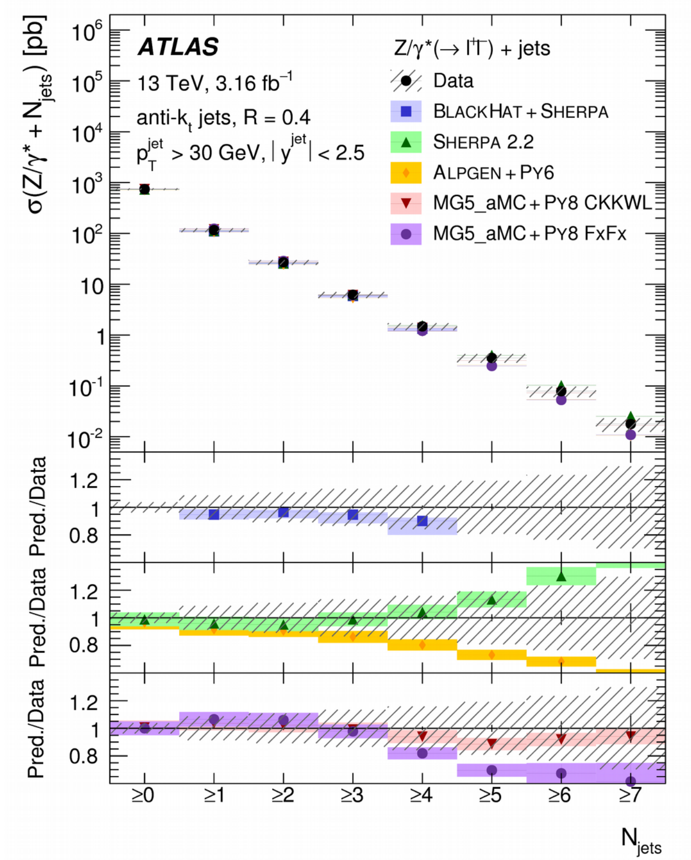
Comparisons : Data unfolded – MCs
Data unfolded – Fixed order calculations corrected for non perturbative effect

N_{jets}: figure of merit of goodness of QCD predictions and important discriminator with respect to the background in Higgs and searches

LO MG5_aMC+Py8 CKKWL shows good agreement with data, while **LO Alpgen+Py6, NLO Sherpa 2.2** and **NLO MG5_aMC+Py8 FxFx** show a systematic trend deviating from data at high jet multiplicities, where large jet fraction comes from PS

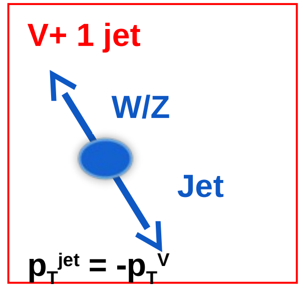


arXiv:1702.05725 [hep-ex]

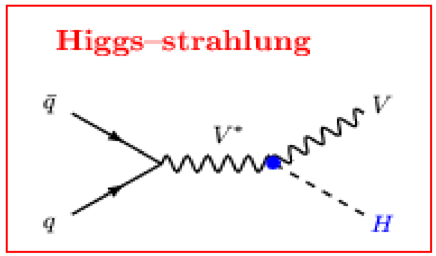


Z+jets @ 13 TeV

- Highly correlated to p_T of V boson



- Modeling important for VH and some BMS searches: analysis done in different p_T^V ranges

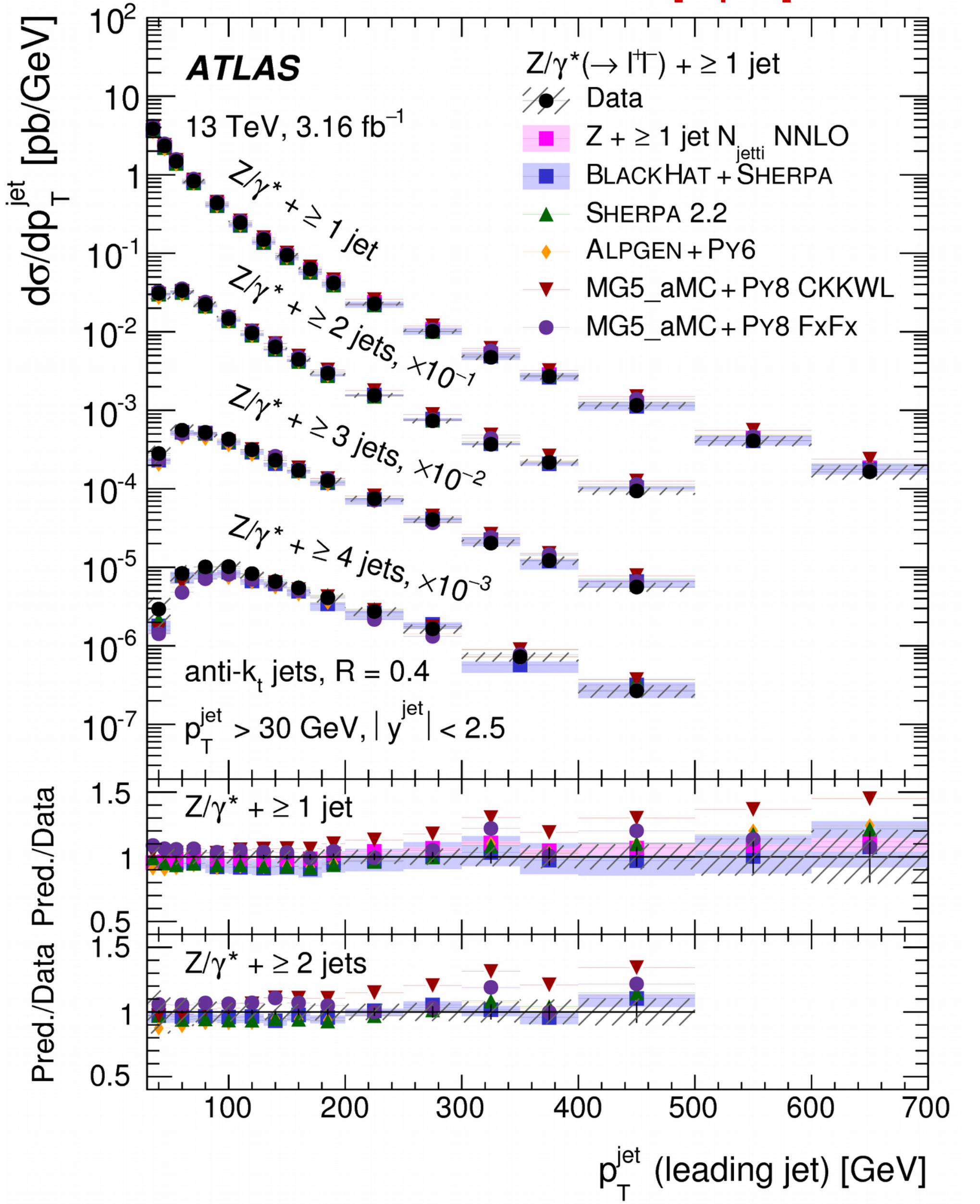


LO Alpgen+Py6 and **NLO Sherpa 2.2** and **NLO calculation from BlackHat+Sherpa** in agreement with data within systematics over the full jet p_T range and at different jet multiplicities

N_{jetti}NNLO models well the jet p_T spectrum

LO MG5_aMC+Py8 CKKWL models too hard jet p_T spectrum for high p_T

arXiv:1702.05725 [hep-ex]

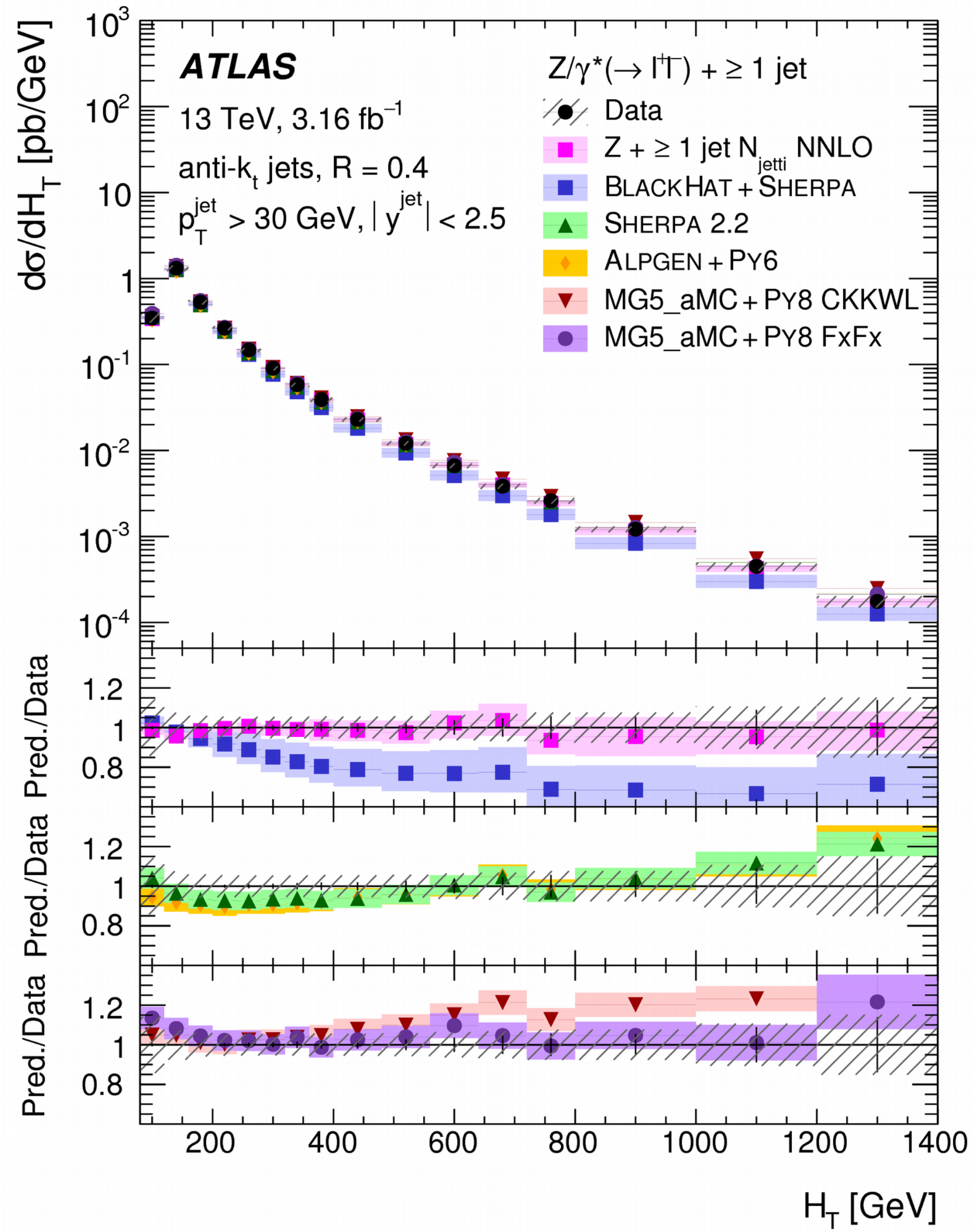


Z+jets @ 13 TeV

arXiv:1702.05725 [hep-ex]

$$H_T = \sum_{leptons,jets} |p_T|$$

- Usual QCD scale
- Important for searches: signal topologies with large jet activity (discriminant with respect to SM background)



NLO calculations from BlackHat+Sherpa underestimates data in H_T>300GeV (missing higher orders)

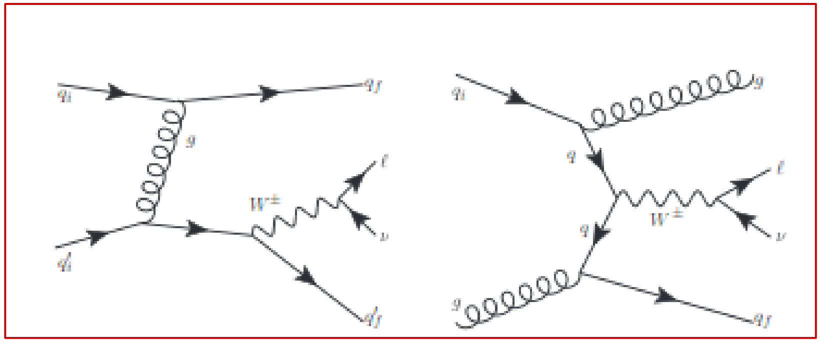
N_{jetti} NNLO recovers agreement by adding higher orders in pQCD

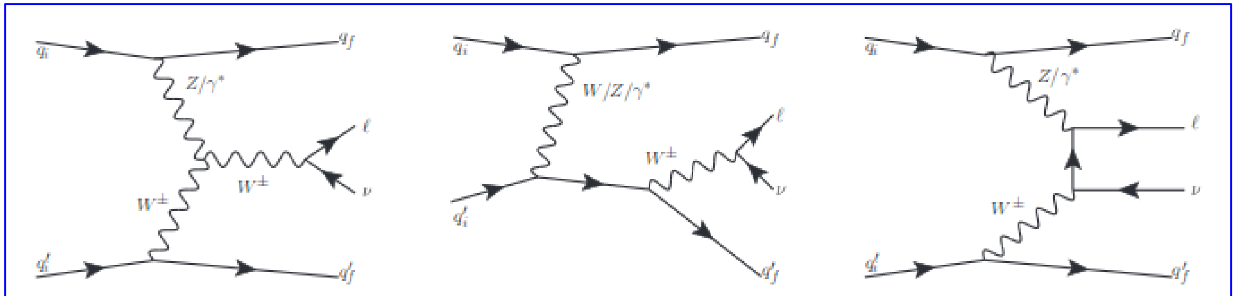
LO MG5_aMC+Py8 CKKWL over-predicts large H_T (consistently with what observed in the p_T spectra)

QCD+EW W+2 jets@ 8 TeV

EW W+2 jets production is roughly 10 times smaller than QCD W+2 jets

arXiv:1703.04362 [hep-ex]

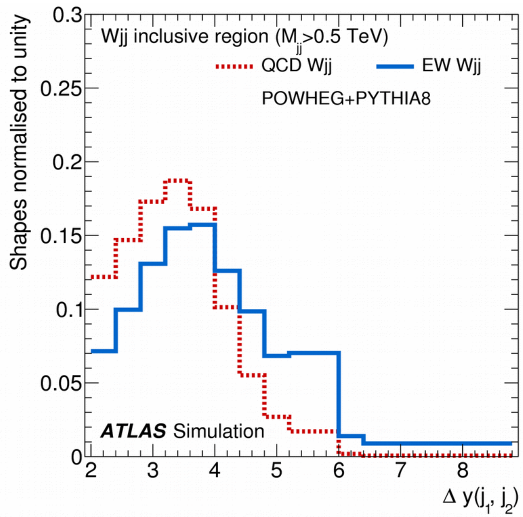


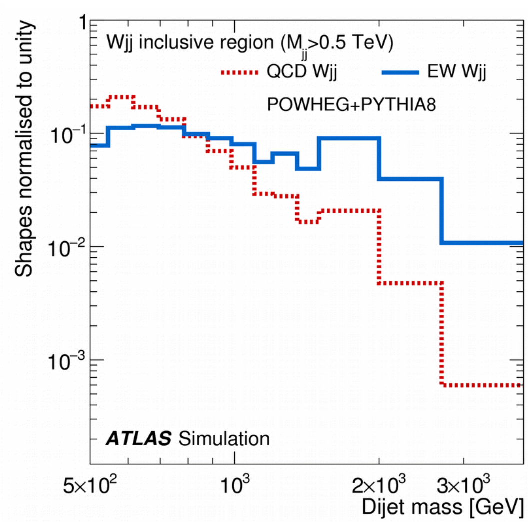


(a) Vector boson fusion (b) W bremsstrahlung (c) Non-resonant

Phase space of the measurement

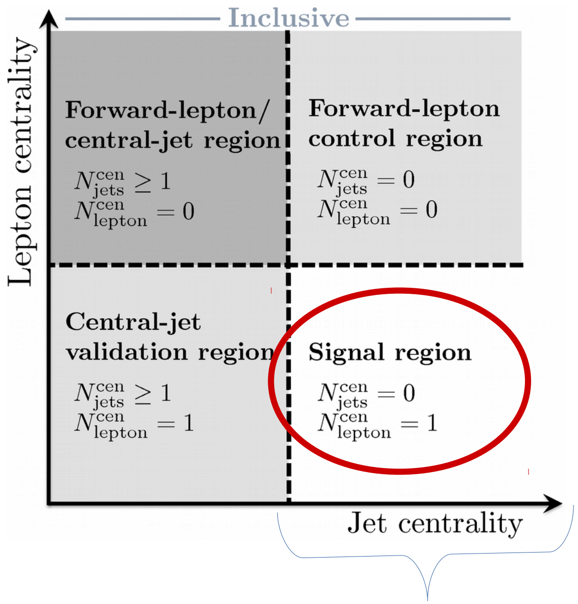
Select W via leptonic decay	Lepton $p_T > 25$ GeV Lepton $\|\eta\| < 2.5$ $E_T^{miss} > 20$ GeV $m_T > 40$ GeV
Select jets enhancing EW production with a simple selection	$p_T^{j_1} > 80$ GeV $p_T^{j_2} > 60$ GeV Jet $\|y\| < 4.4$ $M_{jj} > 500$ GeV $\Delta y(j_1, j_2) > 2$ $\Delta R(j, \ell) > 0.3$



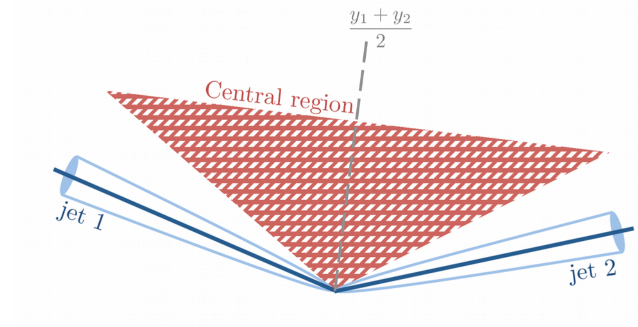


QCD+EW W+2 jets@ 8 TeV

arXiv:1703.04362 [hep-ex]

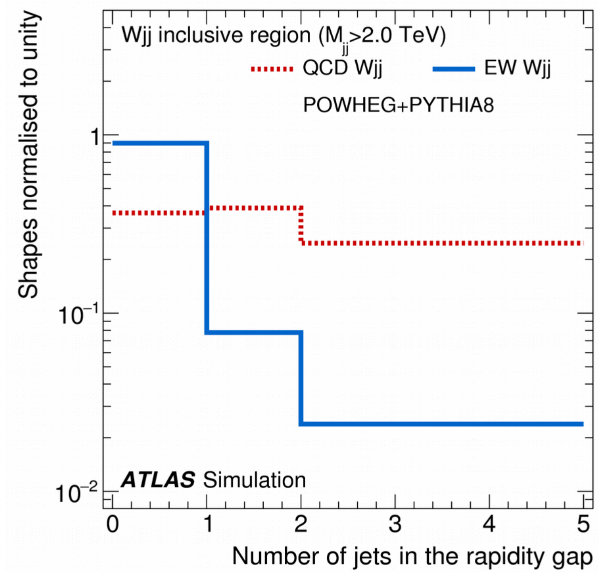


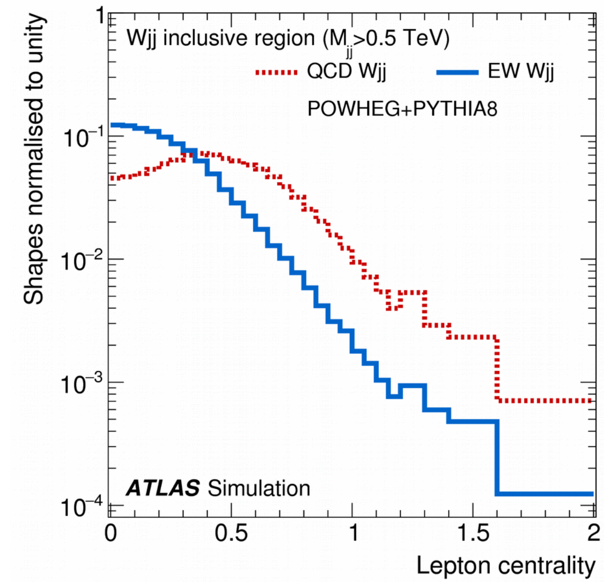
Enhanced EW component
15-20%



Lepton (jet) centrality

$$C_{\ell\,(j)} \equiv \left| \frac{y_{\ell\,(j)} - \frac{y_1+y_2}{2}}{y_1 - y_2} \right| ,$$

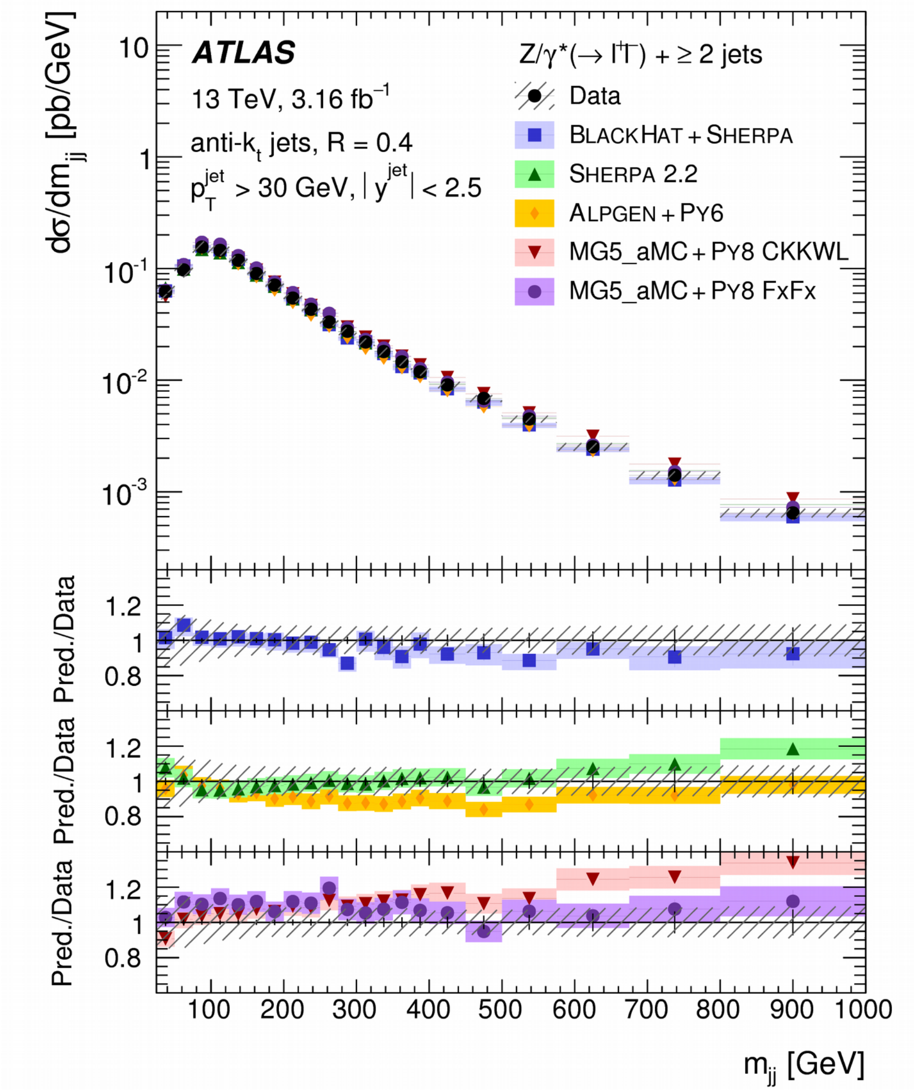




Signal region employed to extract EW component **(see talk of Narei Lorenzo Martinez at this conference)** and to explore modelling and interplay between QCD and EW production (shown in this talk)

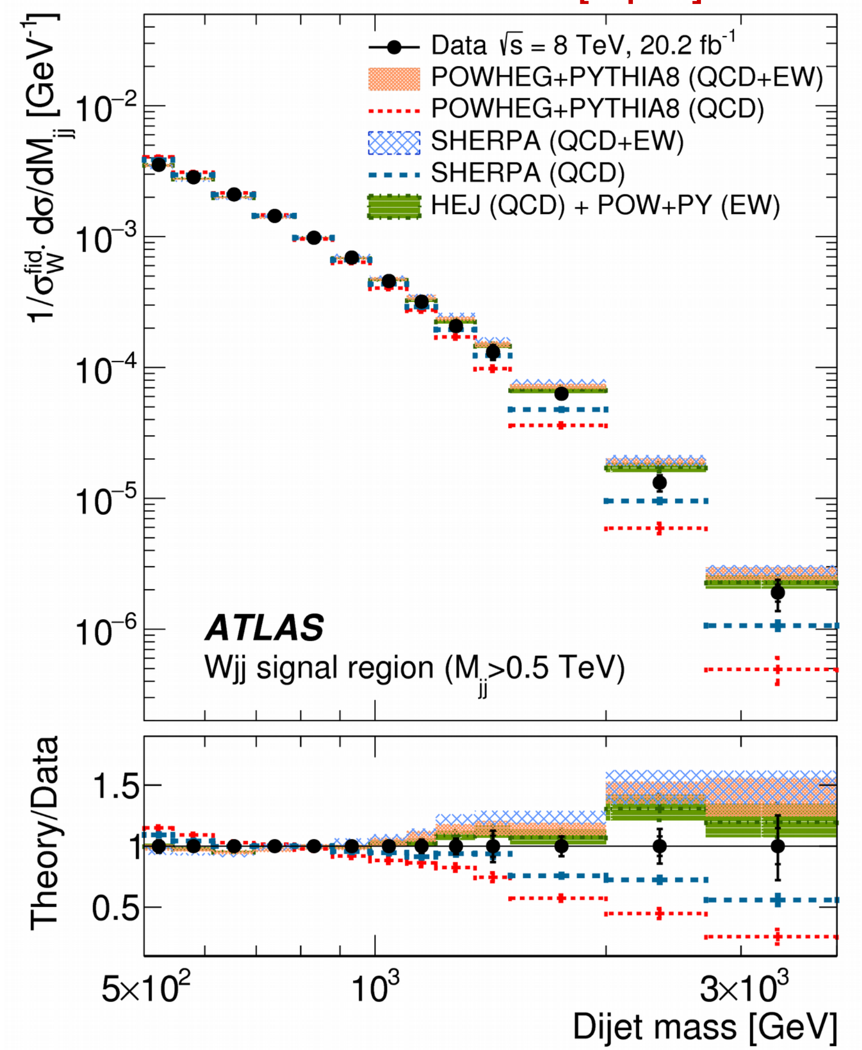
M_{jj}: QCD Z+jets & QCD+EW W+jets

arXiv:1702.05725 [hep-ex]



Very good modelling observed for all predictions, apart from a harder m_{jj} predicted by **LO MG5 CKKWL**

arXiv:1703.04362 [hep-ex]

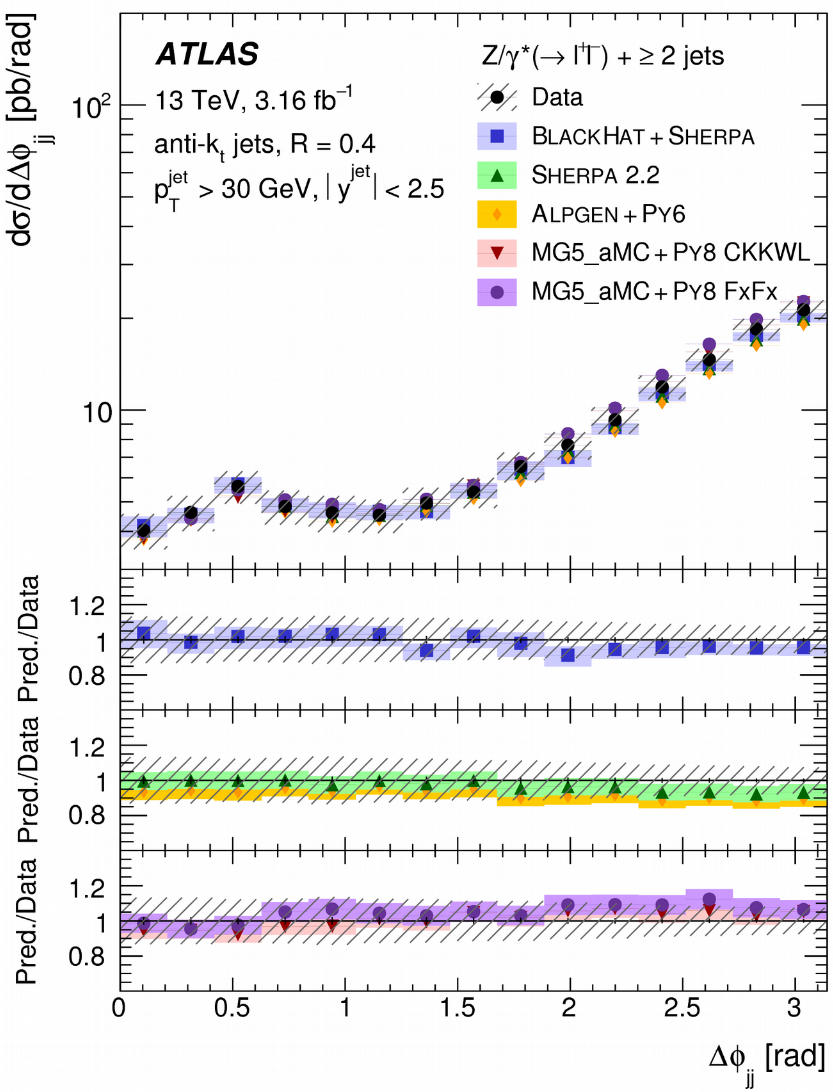


LO Sherpa and **NLO Powheg+Pythia** give a satisfactory description of data when both QCD and EW processes are included

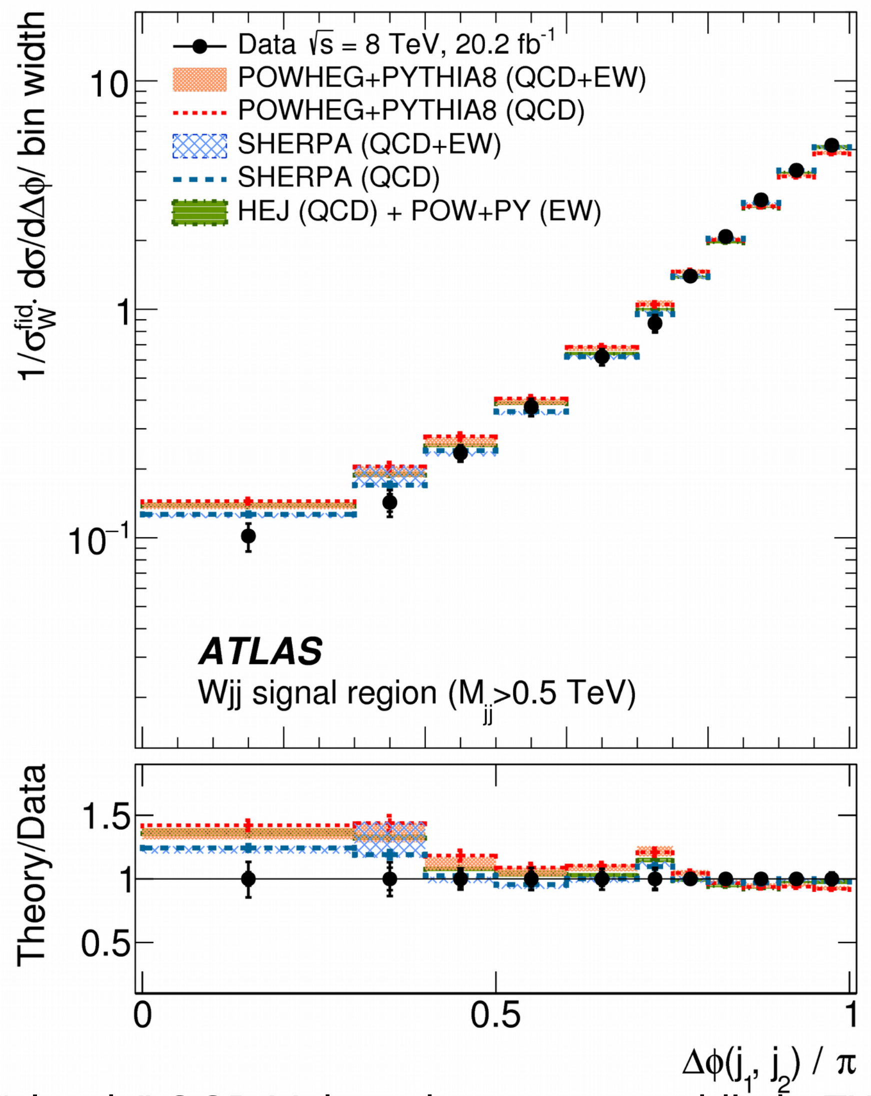
$\Delta\phi_{jj}$: QCD Z+jets & QCD+EW W+jets

$\Delta\phi$ not sensitive to EW and QCD separation but discriminant variable in Higgs measurements, moreover it tests interplay between ME (radiation at large angles) and PS (soft collinear radiation)

arXiv:1702.05725 [hep-ex]



arXiv:1703.04362 [hep-ex]



Very good agreement between data and predictions in "classic" QCD V+jets phase space, while in EW enhanced phase space slight tendency for predictions to overestimate data at small angles

Collinear W+jets @ 8 TeV

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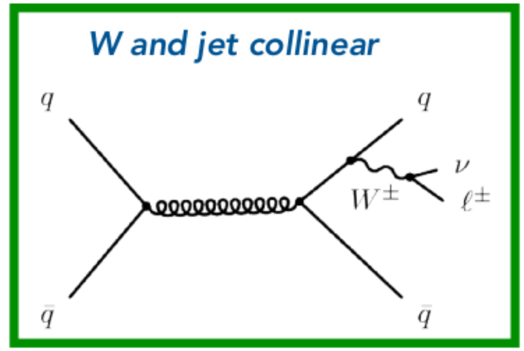
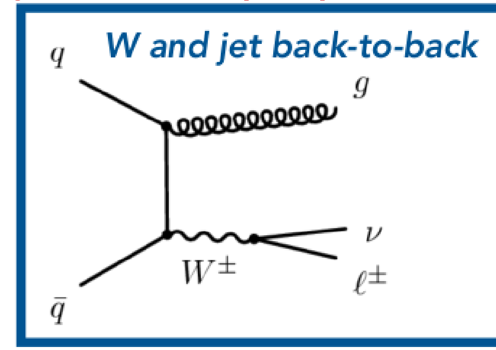




At high energy real W emission can contribute significantly to W+jets.

Probe real W emission by studying the region of small angular separation between W and jets.

Use muon from W decay as a proxy

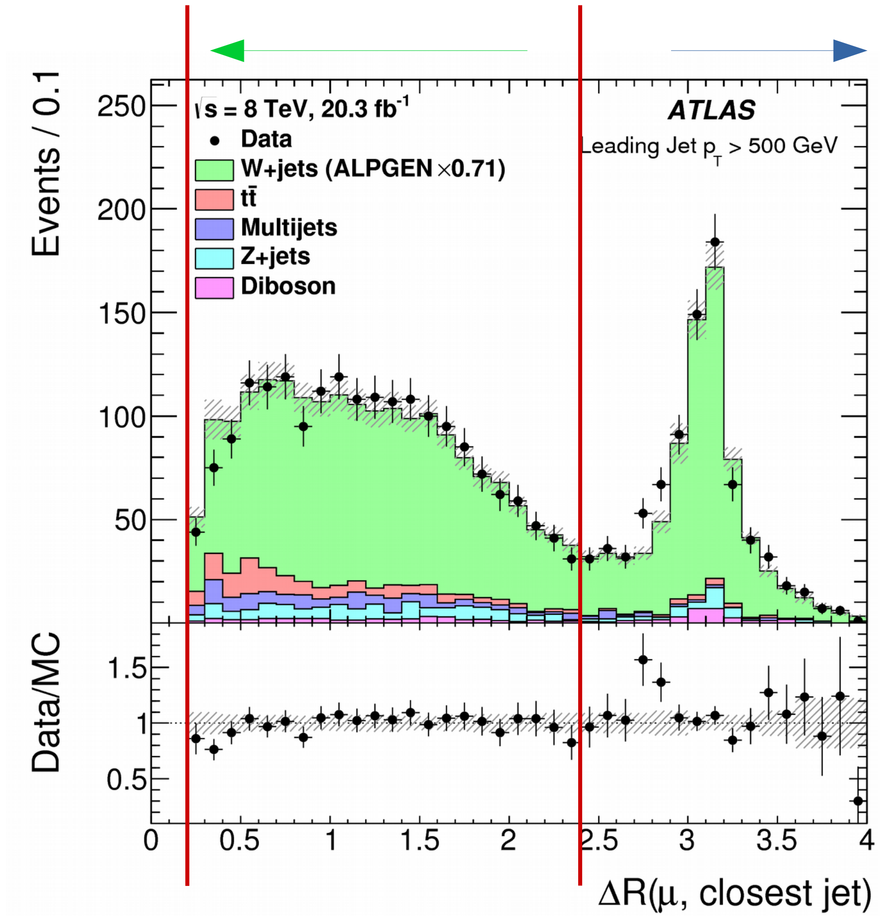
→ Muon and initial W directions highly correlated

→ Key observable: ΔR(μ-closest jet)

Use events with leading jet p_T>500 GeV

→ enriched collinear production of W+jets

Testing 2 inclusive regions: 0.2<ΔR<2.4 and ΔR>2.4



Collinear W+jets @ 8 TeV

NLO QCD+EW Sherpa and **N_{jetti}NNLO** agree with data within uncertainties

LO Alpgen describes shape well expect at very low ΔR but overestimates total cross section

Pythia8 (W+jet and dijet+weak shower) well describes back-to-back region while underestimates data at low ΔR

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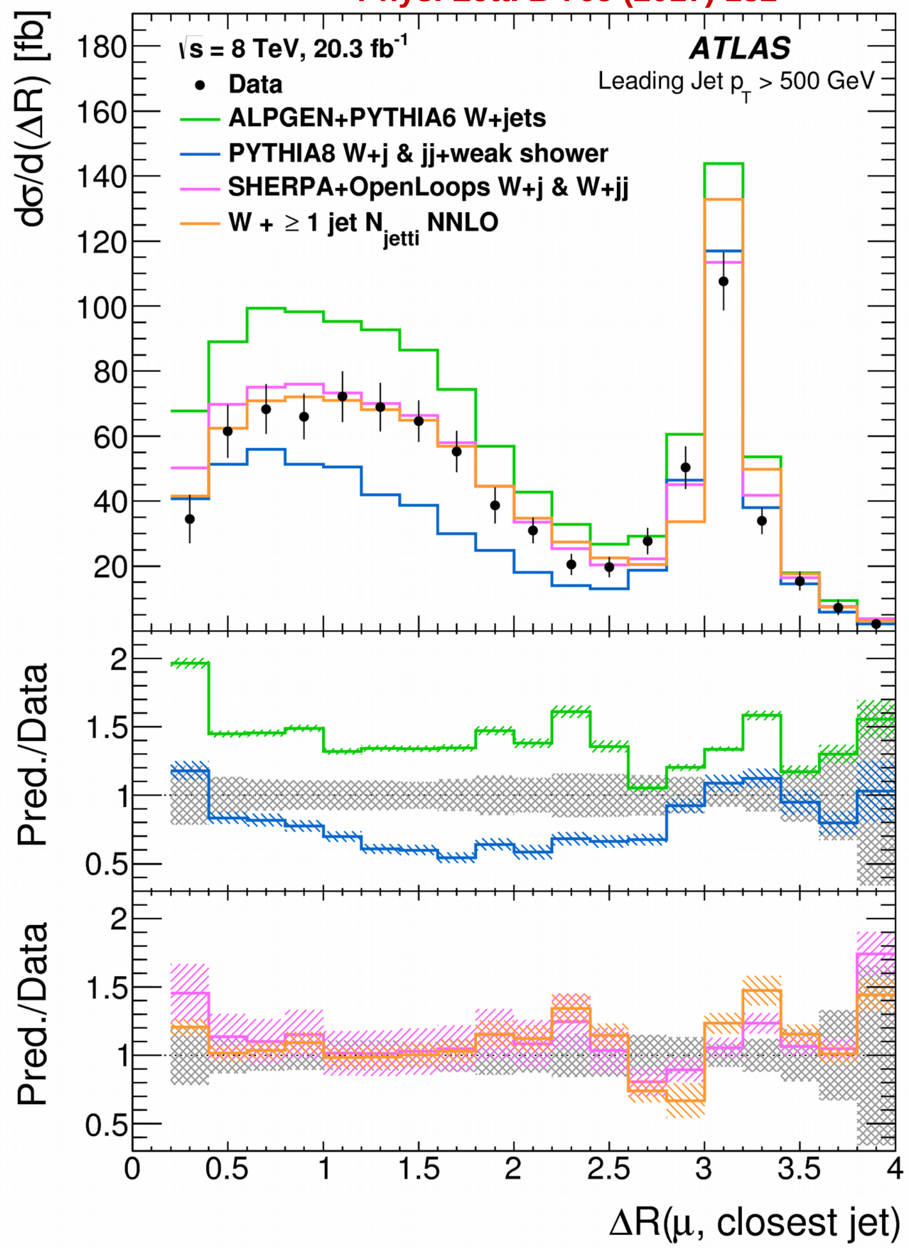


k_t splitting in Z+jets @ 8 TeV

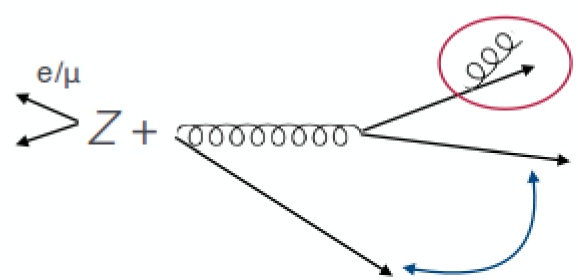
Use Z as a trigger and study jet production at different splitting scales in k_T clustering of jets (resolution scales)

arXiv:1704.01530 [hep-ex]

The **k_t algorithm** iteratively combines charged-particle momenta, removing particles at each iteration (in which number of input momenta goes from k+1 to k) by minimizing distance

$$d_k = \min_{i,j}(d_{ij}, d_{ib}) \quad \text{where} \quad \begin{aligned} d_{ij} &= \min\left(p^2_{\mathrm{T},i}, p^2_{\mathrm{T},j}\right) \times \frac{\Delta R^2_{ij}}{R^2} \\ d_{ib} &= p^2_{\mathrm{T},i}, \end{aligned}$$

k_t algorithm combines soft radiation first, working backwards through showering and perturbative radiation



Soft emissions clustered first = large k, small $\sqrt{d_k}$

Hardest emissions clustered last = small k, large $\sqrt{d_k}$

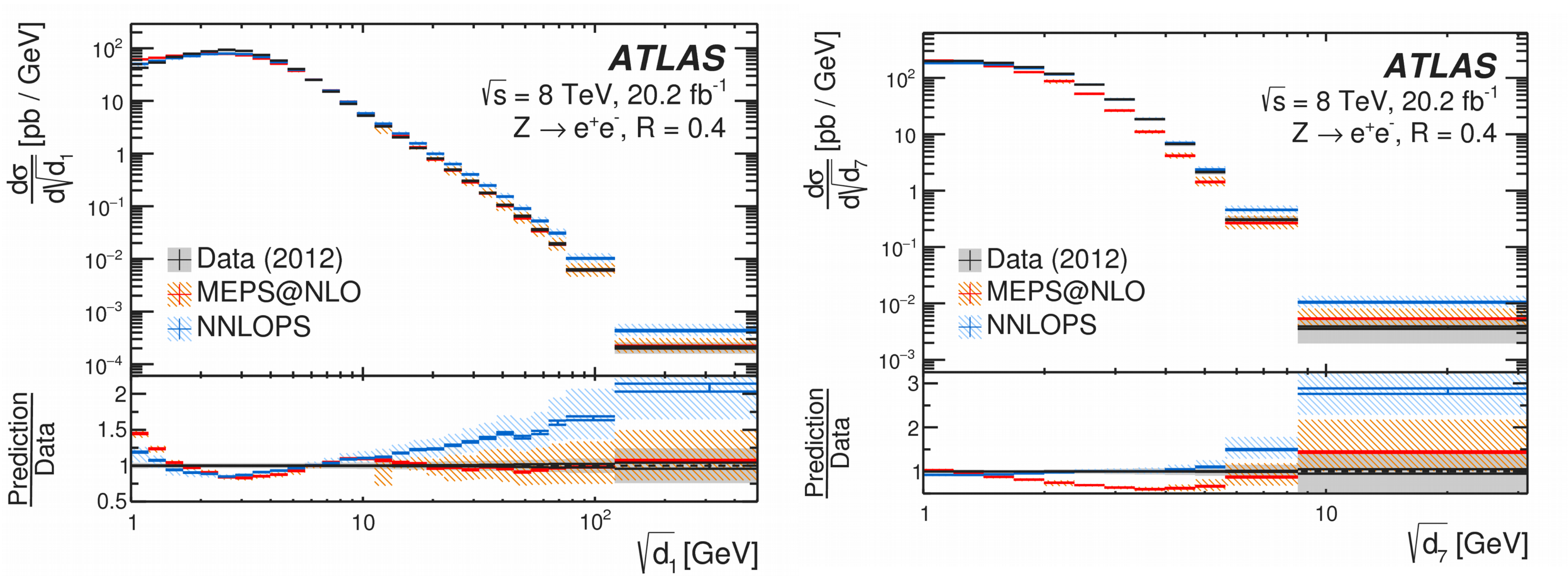
- $\sqrt{d_0}$ is the p_T of the leading k_t-jet
- **$\sqrt{d_k}$ is the distance scale at which a k-jet event is resolved as a (k + 1)-jet event → main observable**

Allows to understand region of transition between hard and soft hadronic activity, not directly probed by jet-based measurements ➡ sensitivity to PS (and matching and merging)

k_t splitting in Z+jets @ 8 TeV

Testing splitting scales (k) from 0 up to 7

arXiv:1704.01530 [hep-ex]



General underestimate of the bulk, and overestimates of the low region and tail

MEPS@NLO (equivalent to NLO Sherpa 2.2) best at high $\sqrt{d_k}$,

NNLOPS (equivalent to DY@NNLO+Powheg+Pythia 8) best at large k

Conclusions

Measurements of jet production in association with a V boson allow us to:

-Improve understanding of pQCD

-Improve understanding of MCs modelling in different kinematic regions important for many measurements and for searches:

- explored not only “classical V+jets phase space”, also “EW enhanced regions” and “collinear regions” investigated

ATLAS published a vast set of results in this contest with Run1 (7, 8 TeV) and Run2 (13 TeV) data

A lot of new exiting results are coming soon with Run-1 and Run-2 data

→ **Stay tuned!**

BACKUP

MCs & Fixed Order Calculations

Main Features	MC & Calculations	Details	PDFs
LO + PS	Alpgen (+ Pythia6)	LO up to 5 partons	CTEQ6L1
	MG5_aMC+Py8 CKKWL	LO up to 4 partons	NNPDF30NLO
	Sherpa (1.4)	LO up to 4 partons Note: EW production is LO up to 2 partons (via EW) + to up 1 parton (via QCD)	CT10
NLO+PS	Sherpa 2.2 (or MEPS@NLO)	NLO up to 2 partons and LO up to 4 partons (with Comix and OpenLoops ME)	NNPDF30NLO
	MG5_aMC+Py8 FxFx	NLO up to 2 partons	NNPDF2.3nlo
	Powheg (+ Pythia8)	NLO up to 2 partons	CT10
NNLO +PS	DY@ NNLO (+Powheg+Pythia8)	NNLO	PDF4LHC15nnlo
Fixed Order NLO Calc	BlackHat+Sherpa	NLO up to 5 jets	CT14
Fixed Order NNLO Calc	N_{jetti}NNLO	NNLO V+>=1 jets	CT14
Higher orders (with approx)	HEJ	approx. to all orders for W+>=2 jets	

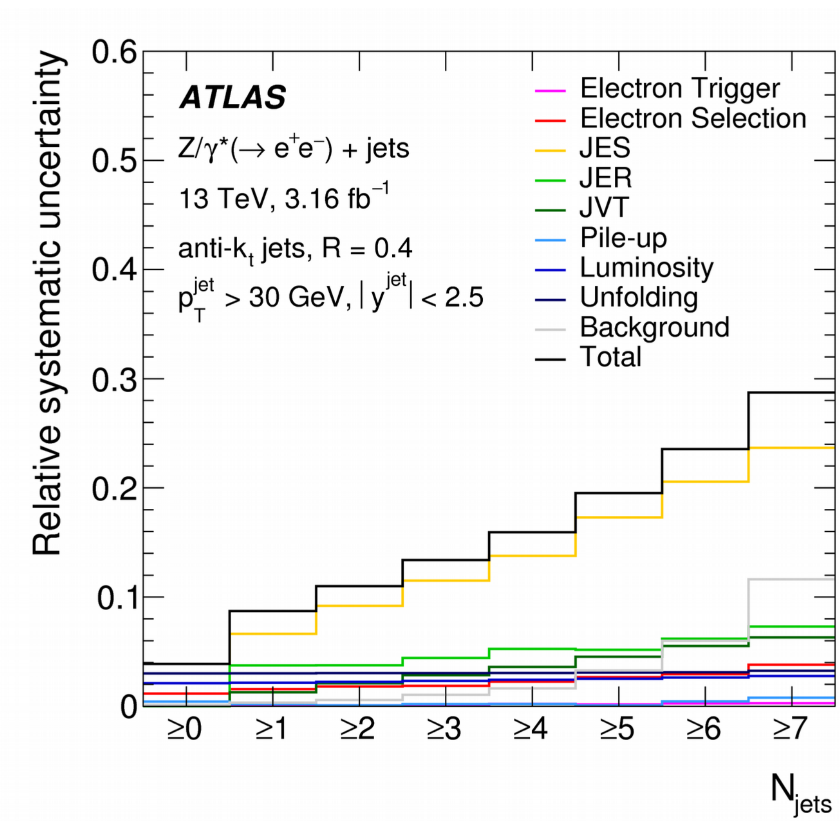
Z+jets@13 TeV

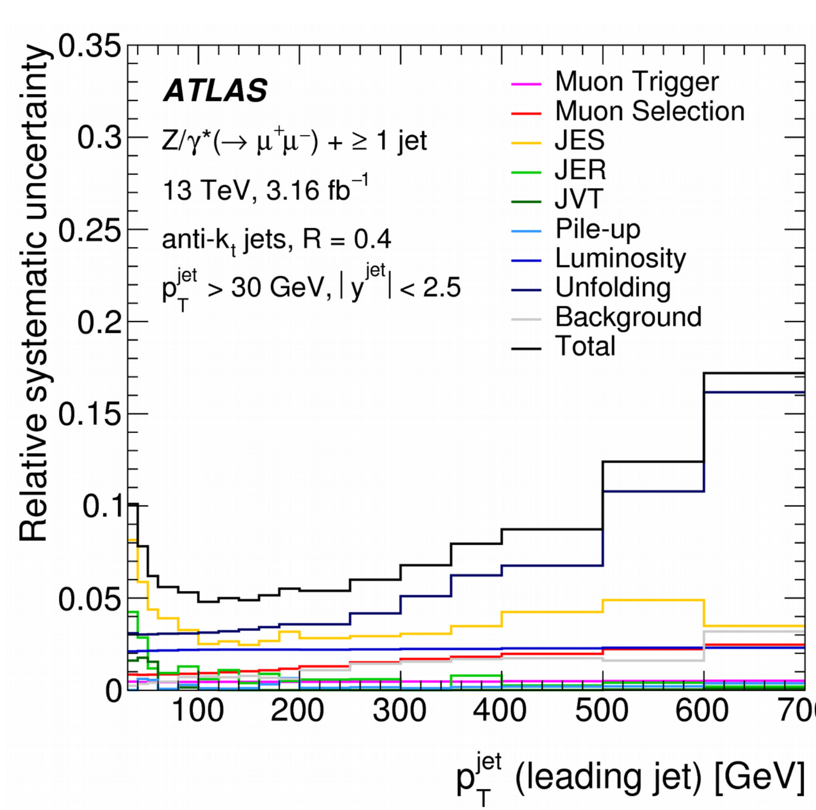
	Electron channel							
	$+\geq 0$ jets	$+\geq 1$ jet	$+\geq 2$ jets	$+\geq 3$ jets	$+\geq 4$ jets	$+\geq 5$ jets	$+\geq 6$ jets	$+\geq 7$ jets
$Z \to e^+e^-$ [%]	99.3	97.6	93.9	90.3	87.3	85.2	83.3	81.2
Top quark [%]	0.2	1.2	3.8	6.5	8.6	9.7	10.5	11.6
Diboson [%]	0.2	0.8	1.6	2.4	3.4	4.4	5.5	6.6
$Z \to \tau^+\tau^-$ [%]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$W \to e\nu$ [%]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Multijet [%]	0.2	0.4	0.6	0.7	0.7	0.7	0.7	0.7
Expected	1,327,900	239,500	57,310	14,080	3637	978	252	63
Observed	1,347,900	248,816	59,998	14,377	3587	898	217	48

	Muon channel							
	$+\geq 0$ jets	$+\geq 1$ jet	$+\geq 2$ jets	$+\geq 3$ jets	$+\geq 4$ jets	$+\geq 5$ jets	$+\geq 6$ jets	$+\geq 7$ jets
$Z \to \mu^+\mu^-$ [%]	99.3	97.5	94.0	90.7	88.3	86.7	84.8	84.6
Top quark [%]	0.2	1.1	3.6	6.0	7.7	8.1	8.7	7.7
Diboson [%]	0.2	0.7	1.6	2.4	3.4	4.5	5.9	7.0
$Z \to \tau^+\tau^-$ [%]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$W \to \mu\nu$ [%]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Multijet [%]	0.3	0.6	0.9	0.9	0.7	0.7	0.7	0.7

Backgrounds from MCs expect multijets estimated with data-driven technique: template build loosening the lepton identification and isolation requirements, normalization established with a fit on m_{ll}

arXiv:1702.05725 [hep-ex]





QCD+EW W+2 jets@ 8 TeV: background

arXiv:1703.04362 [hep-ex]

Process	7 TeV	8 TeV
Wjj (EW)	920	5600
Wjj (QCD)	3020	19600
Multijets	500	2350
$t\bar{t}$	430	1960
Single top	244	1470
Zjj (QCD)	470	1140
Dibosons	126	272
Zjj (EW)	5	79
Total SM	5700	32500
Data	6063	33719

Background estimated with MC expect multijets estimated with data-driven technique: template built inverting certain lepton identification criteria, normalization established with a fit on E_T^{miss}

W+jets collinear@8TeV: background

Process	$0.2 < \Delta R < 2.4$	$\Delta R > 2.4$	Inclusive
Dijets	5%	2%	4%
$t\bar{t}$	7%	2%	5%
Z + jets	6%	4%	5%
Dibosons	2%	4%	3%
W + jets	80%	88%	82%
Data	1907	833	2740

Main backgrounds (QCD jet, tt, Z+jets) estimated with MC but normalisation corrected with data in CR

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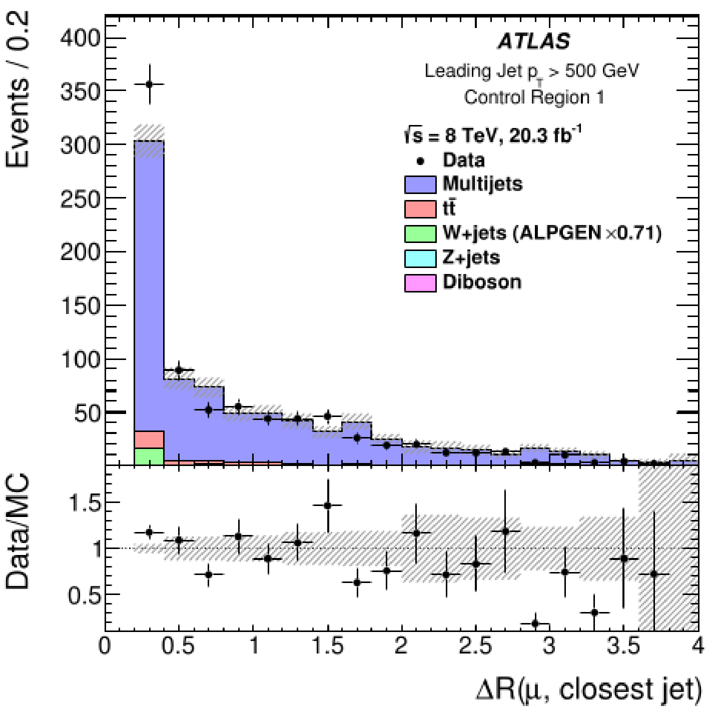
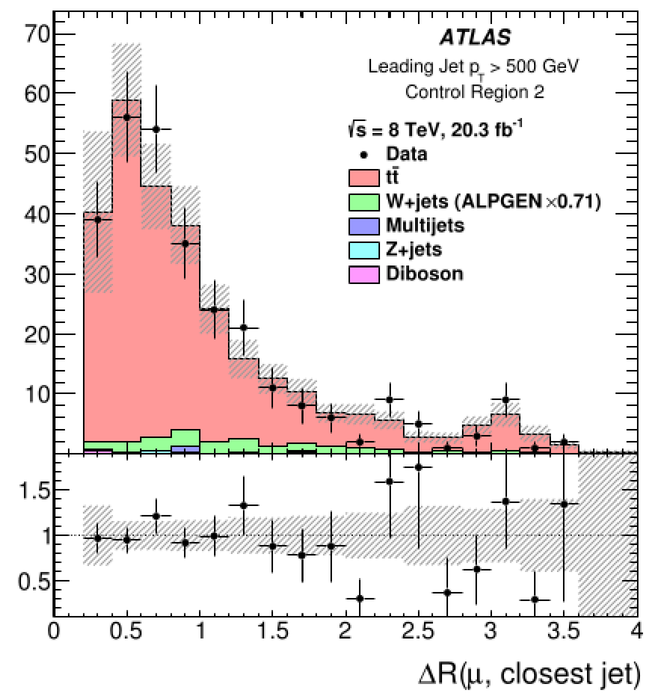
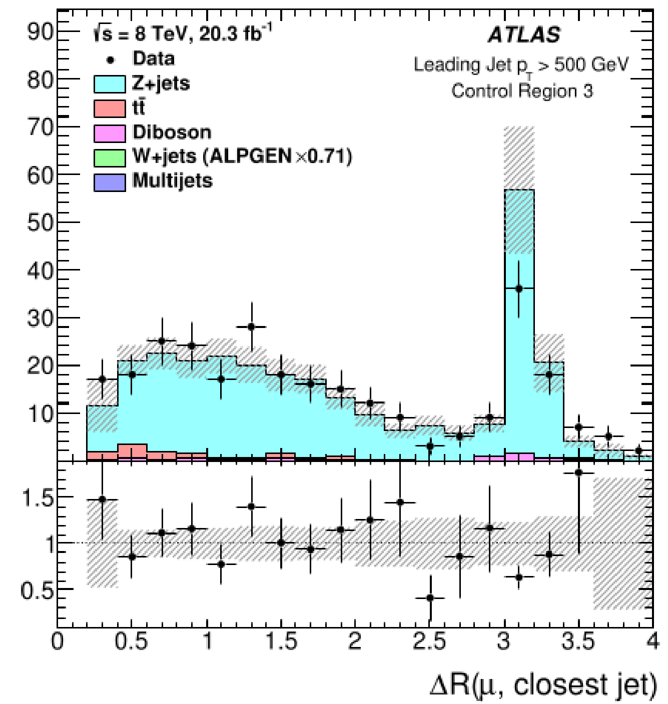
CR1: enriched in QCD (93% pure), inverting isolation requirement on signal muon

CR2: enriched in tt (91% pure), requiring at least 2 b-tagged jets

CR3: enriched in Z+jets (94% pure), requiring two signal muons within 60<mμμ/GeV<120







W+jets collinear@8TeV: uncertainty

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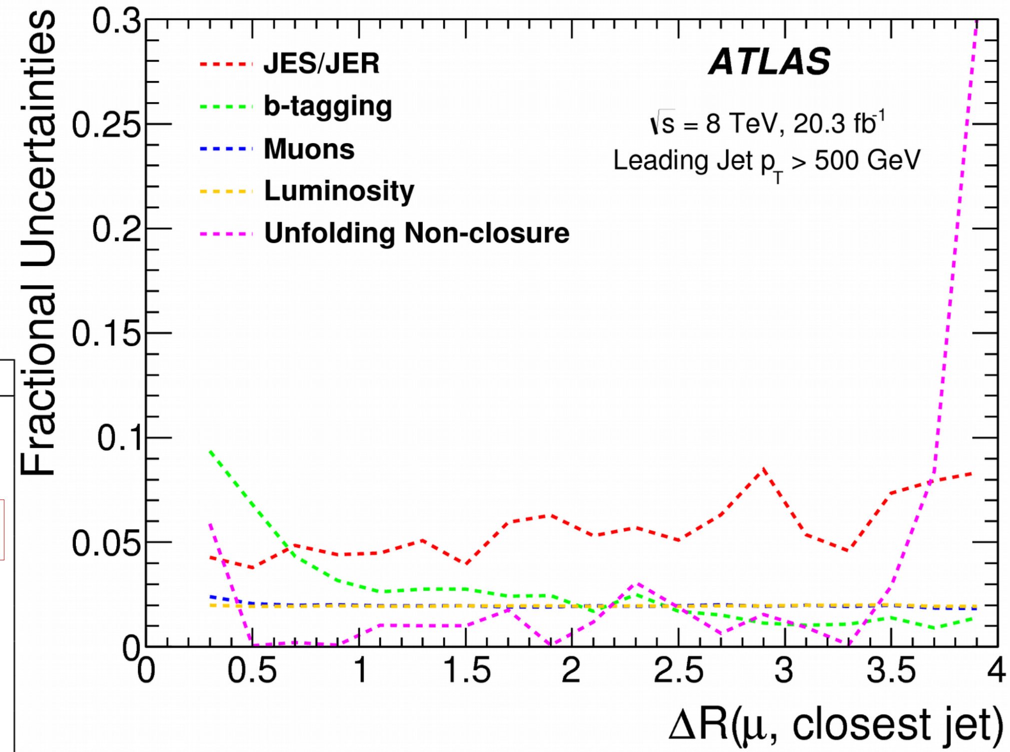
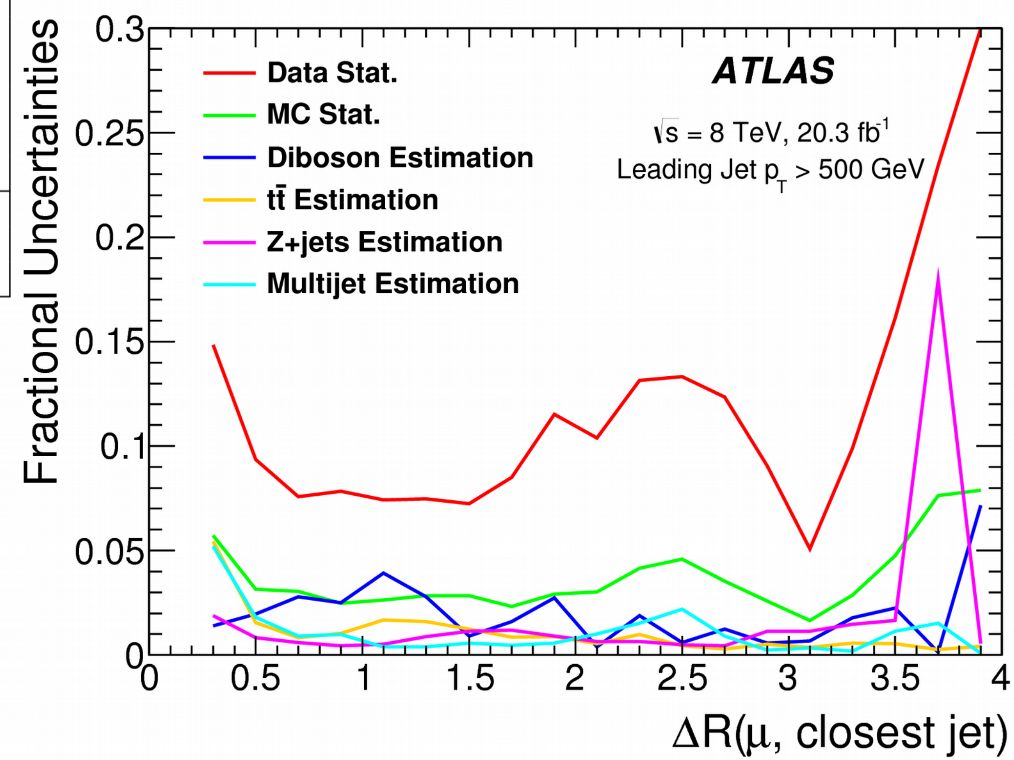
Systematic Source	$0.2 < \Delta R < 2.4$	$\Delta R > 2.4$	Inclusive
Scaling of dijets to data	0.4%	0.1%	0.3%
Scaling of $t\bar{t}$ to data	0.6%	0.2%	0.5%
Scaling of Z + jets to data	0.6%	0.3%	0.5%
Jet energy scale	4.6%	5.8%	5.0%
b-tagging efficiency	3.7%	1.2%	2.9%
Data/MC disagreement for dijets	0.9%	0.6%	0.8%
Data/MC disagreement for $t\bar{t}$	1.2%	0.4%	1.0%
Data/MC disagreement for Z + jets	0.6%	1.5%	0.9%
Diboson background estimate	2.2%	0.1%	1.5%
Unfolding dependence on prior	1.1%	1.8%	1.3%
Muon momentum scale and resolution	0.0%	0.1%	0.1%
Muon reconstruction efficiency	0.4%	0.4%	0.4%
Muon trigger efficiency	2.0%	1.9%	1.9%
Jet energy resolution	0.6%	0.8%	0.6%
MC background statistical	2.4%	1.8%	2.3%
MC response statistical	1.7%	2.2%	1.9%
Total systematic (excluding luminosity)	7.6%	7.4%	7.3%
Luminosity	1.9%	2.0%	2.0%
Data statistical	2.7%	3.6%	2.2%





k_t splitting: the algorithm

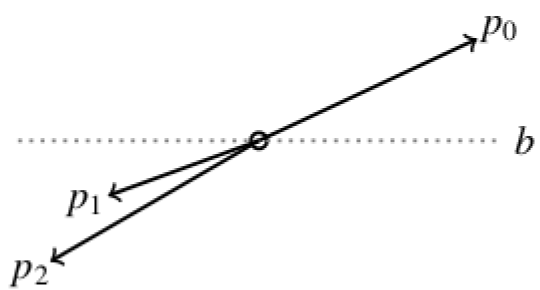
If d_{ij} is the minimum, i[th] and j[th] momenta are combined. If d_{ib} is the minimum , i[th] momentum is declared as jet and removed from the procedure

$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

where

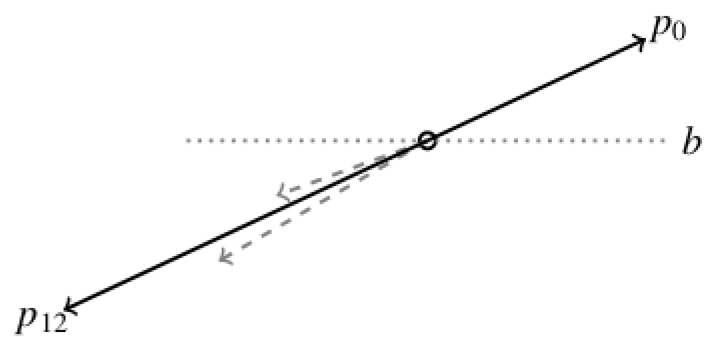
$$d_{ij} = \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{ib} = p_{\mathrm{T},i}^2,$$



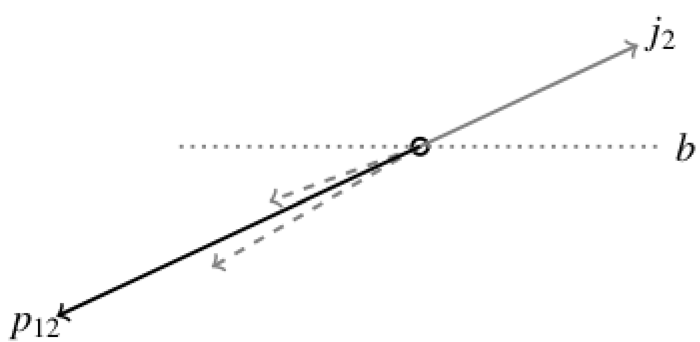
(a) Step 1.

3 inputs (p_0,p_1,p_2)



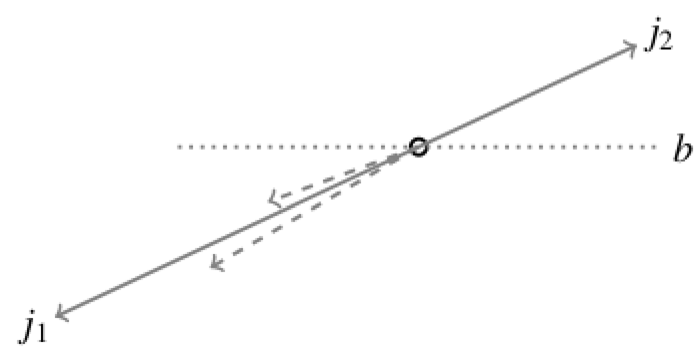
(b) Step 2.

Minimum distance is between p_1 and p_2 that are than merged



(c) Step 3.

Minimum distance is between p_0 and the beam line → p_0 is declared j_2 jet and removed from the list



(d) Step 4.

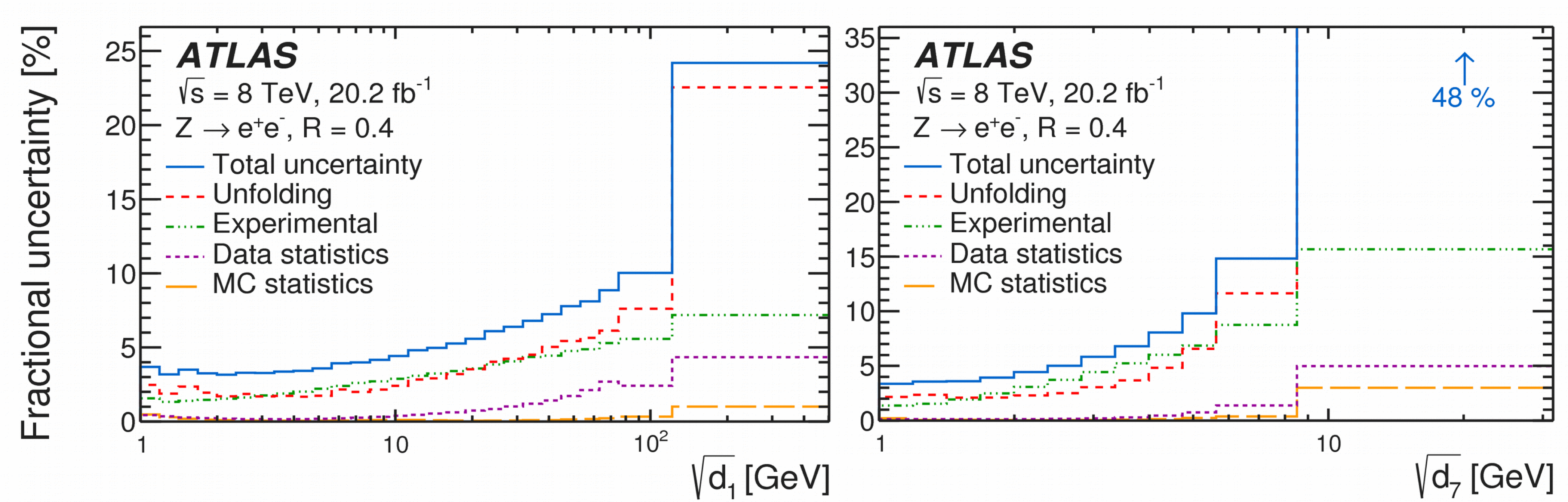
Only a combined input left (p_{12}) that is declared j_1

k_t splitting: background and uncertainty

	$Z \to e^+e^-$		$Z \to \mu^+\mu^-$	
Process	Events	Contribution [%]	Events	Contribution [%]
QCD Z + jets	5 090 000	98.93 %	7 220 000	99.40 %
Multijet	42 000	0.81 %	25 000	0.34 %
Electroweak Z + jets	5 350	0.10 %	7 340	0.10 %
Top quarks	6 190	0.12 %	8 440	0.12 %
$W(W)$	1 100	0.02 %	1 460	0.02 %
$Z \to \tau^+\tau^-$	1 100	0.02 %	1 700	0.02 %
Total expected	5 150 000	100.00 %	7 260 000	100.00 %
Total observed	5 196 858		7 349 195	

Background from MC expect multijets estimated with data-driven technique: fit on data with 2 templates one for signal+other background (from MC) and one for multijet (from data reversing some of the lepton criteria)

arXiv:1704.01530 [hep-ex]



Total uncertainty (including 1.9% luminosity) ranging typically between 5 and 30%