Constraining QCD and electroweak physics with vector boson plus jets events

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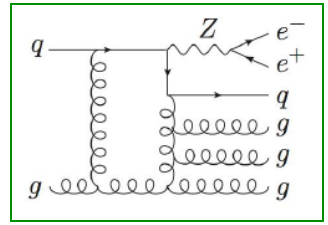
(CERN)

23rd September 2014

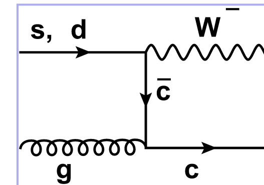
CERN EP Seminar

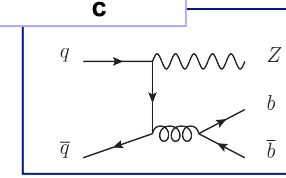
Introduction

- Constraining *QCD calculations and simulations*
  => with **Vector boson + inclusive jets**

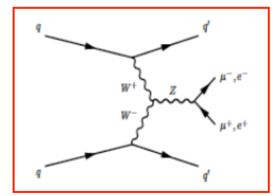


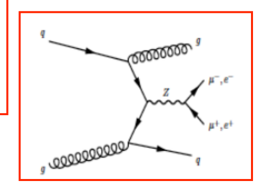
- Constraining *proton parton modelling* and *perturbative QCD modelling*
  => with **Vector boson + heavy-flavour jets**



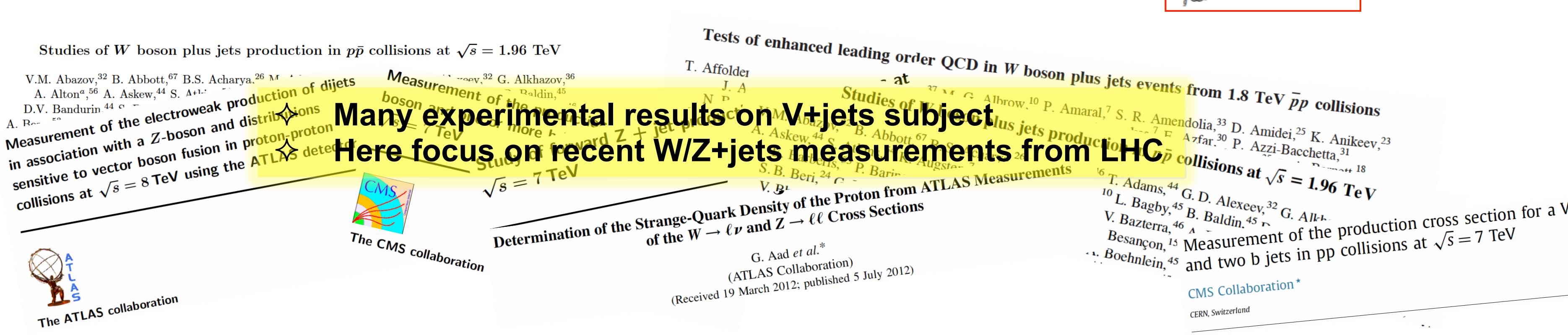


- Constraining *Electroweak and QCD physics*
  => with **Vector boson plus two forward jets**



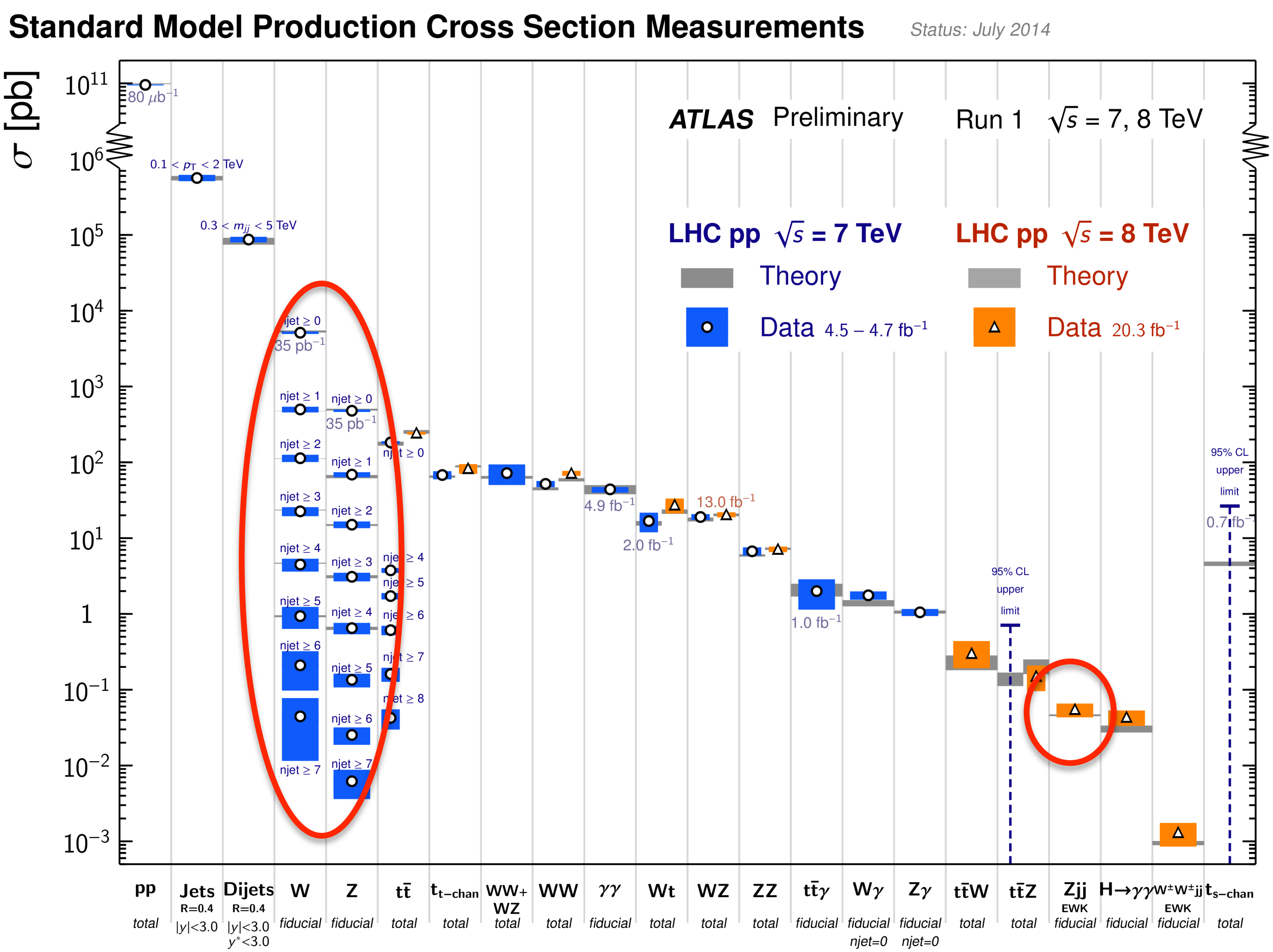


- Run 2 prospects and challenges



✧ **Many experimental results on V+jets subject**
✧ **Here focus on recent W/Z+jets measurements from LHC**

Standard Model Snapshot at LHC



σ x BR

~ 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)

V+jets physics at hadron colliders

- With V+jets we can probe different aspects of QCD calculations
- Our understanding and modeling of the QCD interactions has direct impact on the potentials for precision measurements and discoveries

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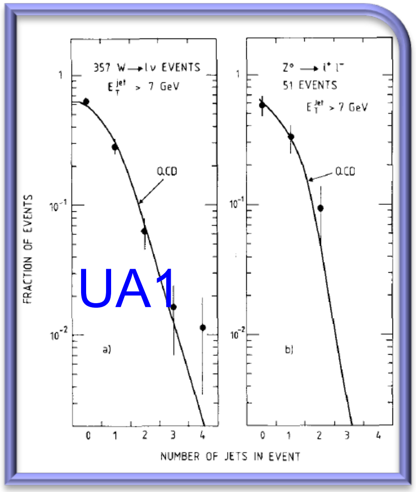

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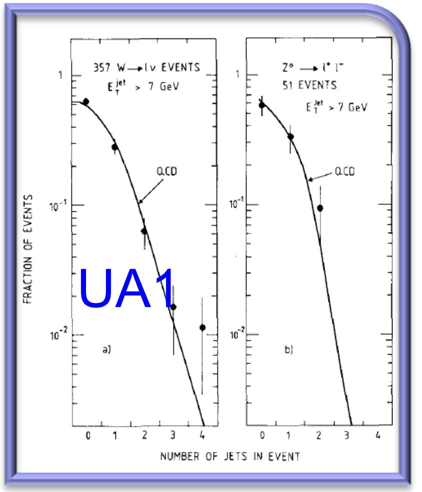
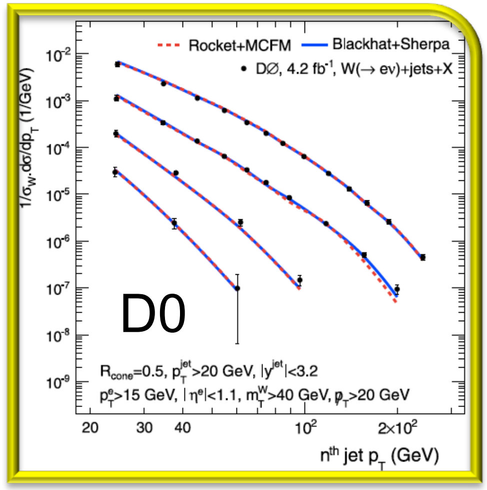
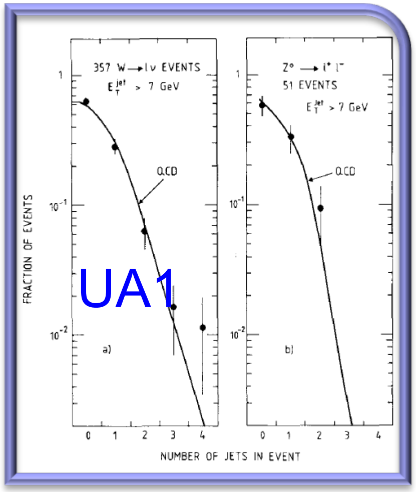
- Tevatron Legacy on LHC V+jets analyses
- Most of current theory predictions still tuned to Tevatron data





V+jets physics at hadron colliders



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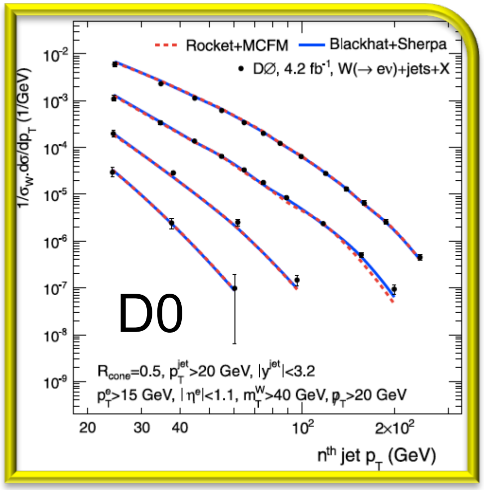
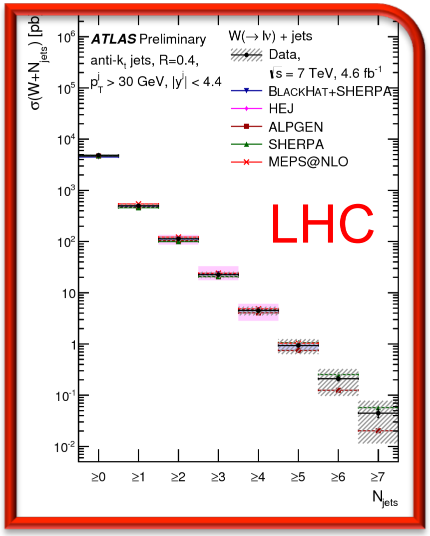
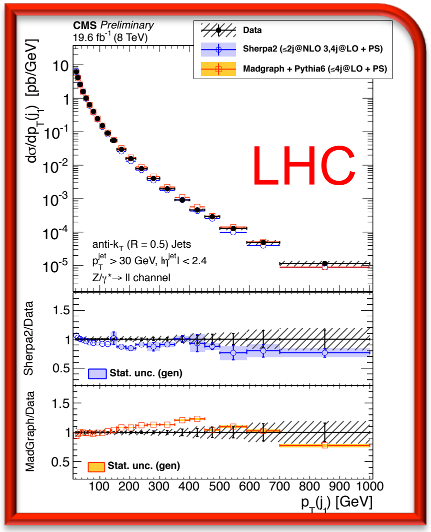
- Tevatron Legacy on LHC V+jets analyses
- Most of current theory predictions still tuned to Tevatron data
- Larger cross-sections available at LHC and larger integrated luminosity
- LHC is not a simple rescaling of Tevatron scattering
  - different Bjorken-x, parton densities and subprocesses







Further Motivations

- Accurate modeling of V+jets is of paramount importance for the success of a collider physics program
  - W/Z+jets is dominant background to Top-quark measurements

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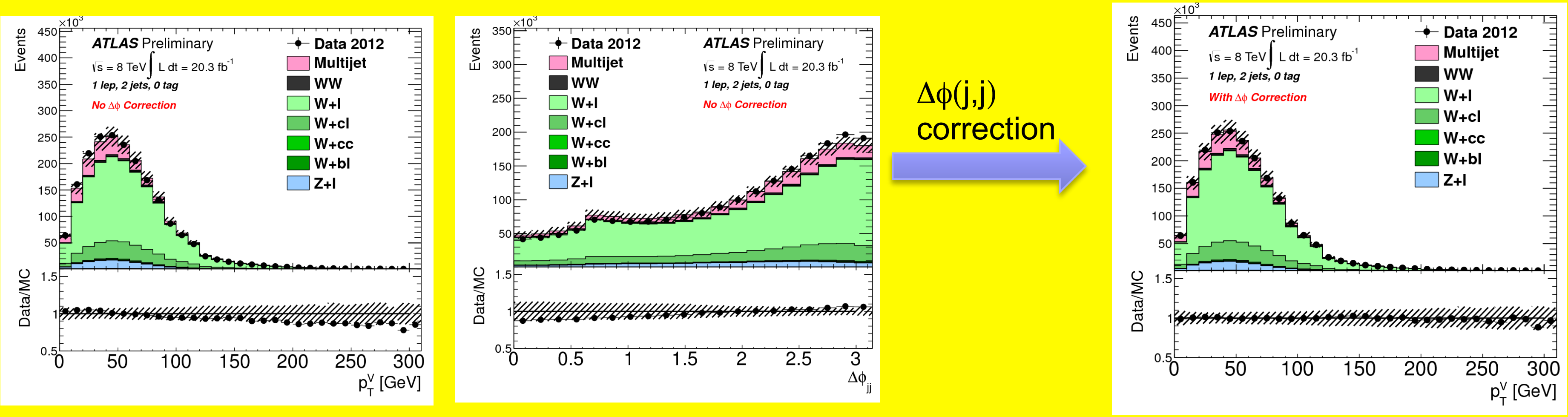
  - W/Z+jets is dominant background to Top measurements
  - Important for precision Higgs physics (background modeling)

- **VH(→ bb):** control of V+jets background is challenging
  - analysis binned in V-boson p_T to exploit varying S/B vs V-boson p_T and N_{jets}
  - mismodeling of $\Delta\phi$(jet-jet) affects V-boson p_T shape => improved V-boson p_T after correction

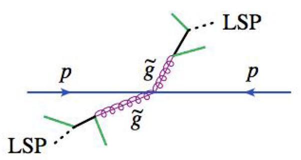


ATLAS-CONF-2013-79

Further Motivations

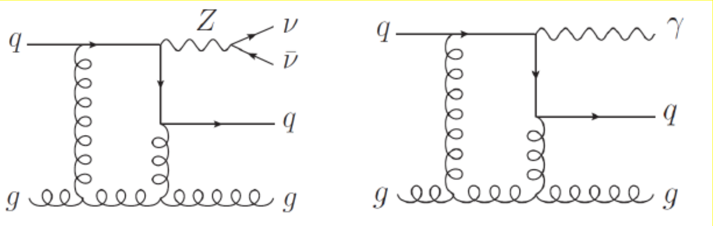
- Accurate modeling of V+jets is of paramount importance for the success of a collider physics program
  - Dominant background precision Top measurements
  - Important for precision Higgs physics (background modeling)
  - Important for modeling of SM background in searches of new particles, e.g. SUSY

MET+ 4 jets



- Z+jets as background to new physics searches
  - e.g. $Z(\rightarrow\nu\nu)$+jets in SUSY MET+jets searches
  - Exploit NLO calculations of W+jets/Z+jets or γ+jets/Z+jets ratios to calculate *Transfer Functions* from γ(or W)+jets to $Z(\rightarrow\nu\nu)$+jets
  - ➢ important to constrain theory extrapolation with data

JHEP 10 (2012) 018
PRD 90, 052008 (2014)
arXiv:1405.7875

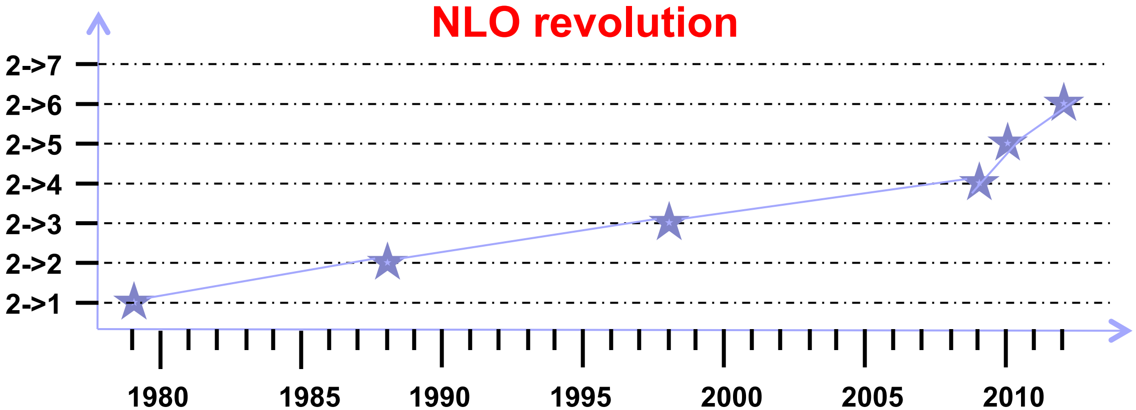


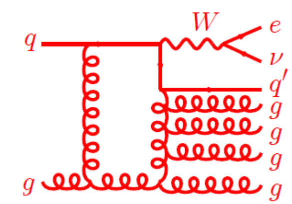
$$\sigma(pp \rightarrow Z(\rightarrow \nu\bar{\nu}) + \text{jets}) = \sigma(pp \rightarrow \gamma + \text{jets}) \times R_{Z/\gamma}$$

irreducible background — measure this — theory input

V+jets predictions: NLO Revolution

- **Steady improvement of Fixed Order pQCD predictions**
  - From LO to NLO pQCD
    - better Normalisation and Distribution Shapes, smaller Theoretical Uncertainty





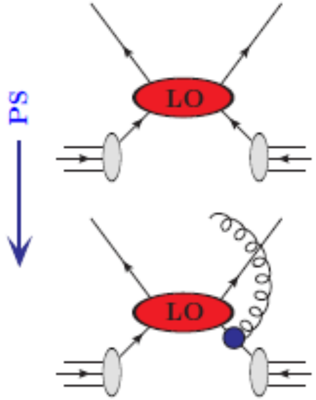
- **1979: NLO Drell-Yan** [Altarelli, Ellis & Martinelli]
- …
- **2012: NLO W+5j [BlackHat**, preliminary] [unitarity]

- Fixed-order NLO pQCD calculations: BlackHat, MCFM
- Approximate NNLO for V+1 jet: LoopSim
  - estimate NNLO corrections for processes with very large NLO K-factors

V+jets predictions: MC Evolution

- Great progress in Monte Carlo generator in past years

pQCD accuracy	MC versions
LO Matrix Element (M.E.) + Parton Shower (P.S.)	`Pythia, Herwig`



- LO M.E.
- Soft and collinear emission simulated by P.S.

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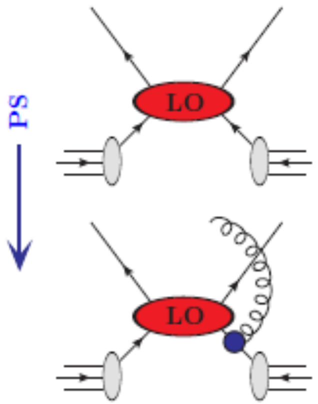
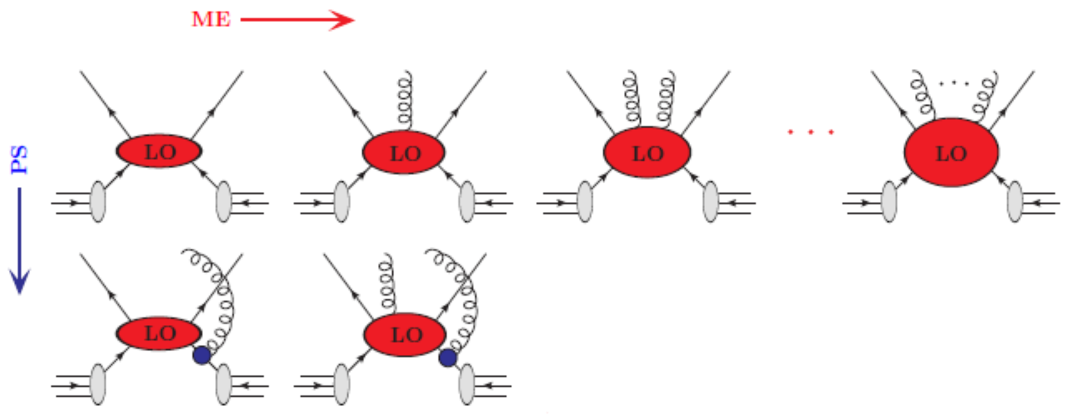
Multi-parton LO + P.S.	Alpgen, Sherpa 1.4, Madgraph





- Multiple parton emission simulated at LO in M.E
- Soft and collinear emission still done by P.S.

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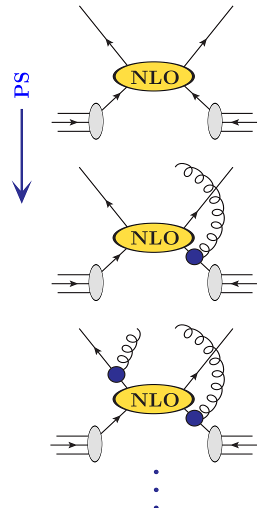
[N]NLO for lowest multiplicity M.E. + P.S.	`(a)MC@NLO, Powheg [NNLOPS], Herwig++`



➢ **M.E. accurate to NLO, matched to P.S.**

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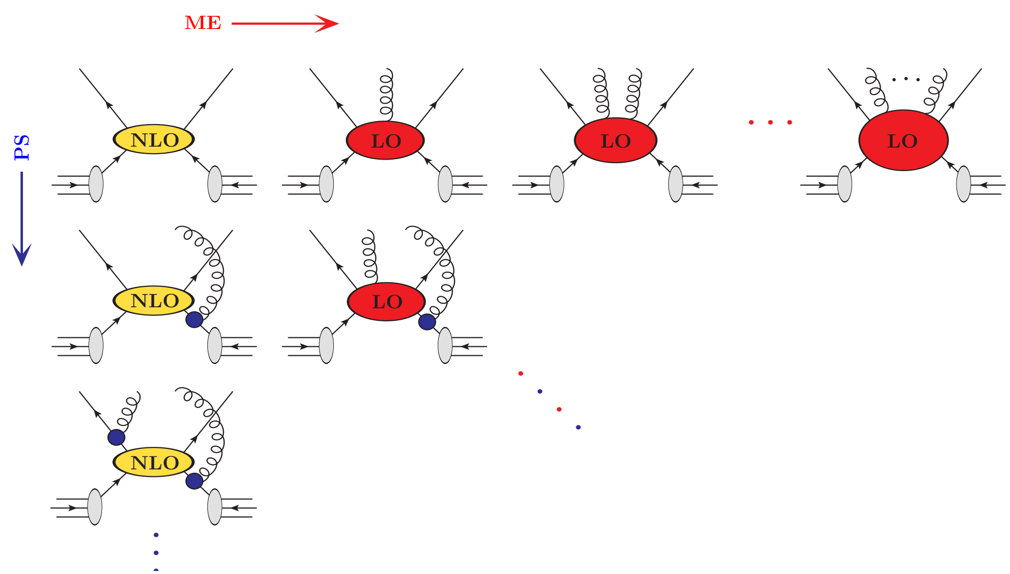
NLO for lowest multiplicity M.E., LO for other multiplicities + P.S.	`Sherpa 1.4 MEnloPS,` `(Powheg MiNLO Zjj/Wjj)`



- **Higher multiplicities simulated by LO M.E.**

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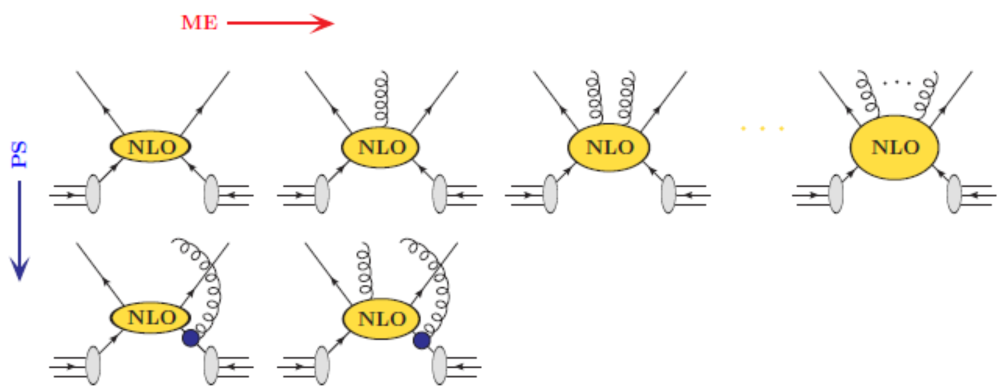
NLO for higher parton multiplicity M.E. + P.S	aMC@NLO, Sherpa 2.x MEPS@NLO



Sherpa MEPS@NLO implements BlackHat NLO calculations for 1 and 2 partons

- **NLO accuracy for each leg**
- **P.S. accuracy in collinear and soft regimes**

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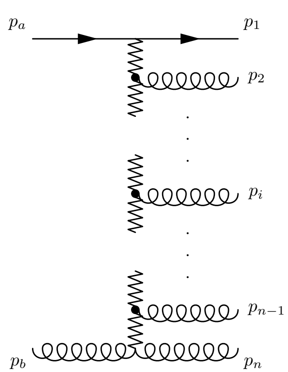
NLO for higher parton multiplicity M.E. + P.S	`aMC@NLO, Sherpa 2.x MEPS@NLO`
Resummation of all orders in α_s (parton level) – validity in the high energy limit	`HEJ`



- **"All-orders", rather than "fixed-order" calculation**
  - LL-accuracy resummation for large invariant mass between jets, matched to tree-level accuracy for multiplicities up to 4 jets
- **BFKL-inspired**
- **Approximation which captures hard wide-angle emissions**

V+jets predictions: MC Evolution

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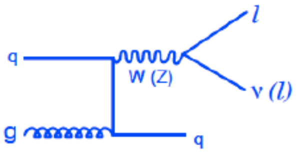
Resummation of all orders in α_s (parton level) – validity in the high energy limit	HEJ

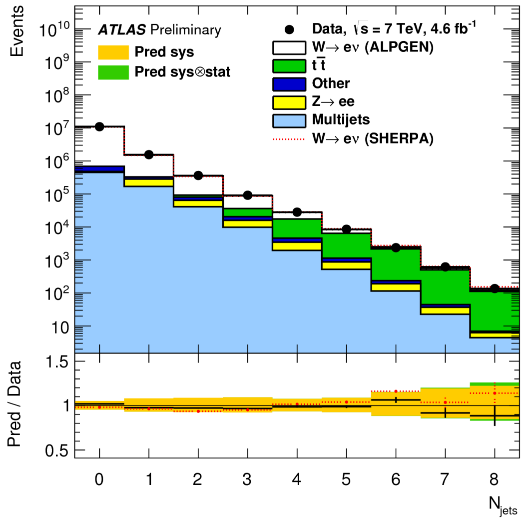
- Despite this great theoretical progress there are still theory uncertainties related to various sources which can be constrained by data
  - Higher order QCD corrections (NNLO)
  - Electroweak corrections
  - Parton Shower and its matching to Matrix Element
  - Parton Density Functions
  - Underlying Event modeling

Analysis methodology

- W/Z clean signatures in leptonic decay channels
  - Trigger events on charged leptons
  - Often measurement in both e, μ channels
    - useful cross-check and can constrain uncertainties
  - Selection by cuts on inv. Mass (Z) or M_T(W), Missing E_T(W)



- Z+jets has small background contamination
- W+jets has larger background contributions from
  - **multi-jet:** ~5-15%
    - extracted by data-driven techniques
  - **ttbar:** ~ 0% (1 jet) – 20% (Z+6jets) - 80% (W+6 jets)
    - estimated by MC or in a data-driven way or suppressed by b-jet veto



- Systematics dominated by jet energy scale and background (on W)

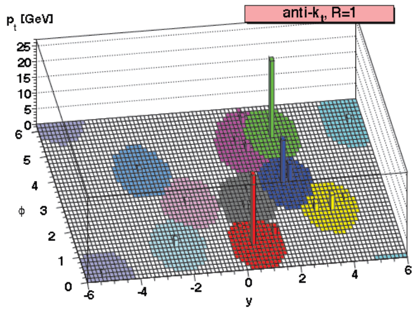
$N_{\rm jets}$	Tot. Unc. [%]	stat [%]	JEC [%]	JER [%]	PU [%]	Bgnd [%]	Lumi [%]	Unf [%]	Eff [%]
= 1	5.4	0.11	4.5	0.55	0.29	0.048	2.6	1.5	1.3
= 2	6.9	0.24	6.3	0.36	0.32	0.25	2.6	1.5	1.2
= 3	9.0	0.58	8.5	0.35	0.37	0.54	2.6	1.3	1.2
= 4	11	1.3	11	0.28	0.46	0.93	2.6	1.2	1.4
= 5	15	3.0	15	0.52	0.75	1.3	2.6	2.6	1.5
= 6	21	7.5	19	0.48	1.5	2.1	2.6	2.2	1.4
= 7	27	19	17	2.40	4.1	3.0	2.6	2.5	1.6

CMS Z+jets at 8 TeV

Analysis methodology

- Measure absolute or normalised differential cross sections in fiducial phase spaces
  - event-based observables => N_{jets}, boson p_T, W M_T , H_T, event-shapes
  - jet-based observables => n^{th}-jet p_T, y
  - Measure angular correlations (jet-jet, lepton-jet, Z-jet) => $\Delta\phi$, ΔR, Δy, m_{jj}

- Various of jet algorithms:
  - **Tevatron**: cone algorithms,
    - e.g Midpoint R=0.5
  - **LHC**: anti-k_T R=0.4 (ATLAS), 0.5 (CMS, LHCb)



Detector-Level Measurement → *unfolding* → Particle-Level Measurement/Prediction ← *non-pertur. corrections* ← Parton-Level Calculation

- MC simulations provide particle level final states
- Parton-level calculations (BlackHat, MCFM) corrected for Non-Perturbative effects
  - hadronisation and underlying event (3-4% corr.)
- Fixed order NLO uncertainties:
  - scales (renorm. and fact.): 4-13%
  - parton densities:1-3%, α_s: 1-3%

High-order pQCD corrections

ATLAS-CONF-2014-035

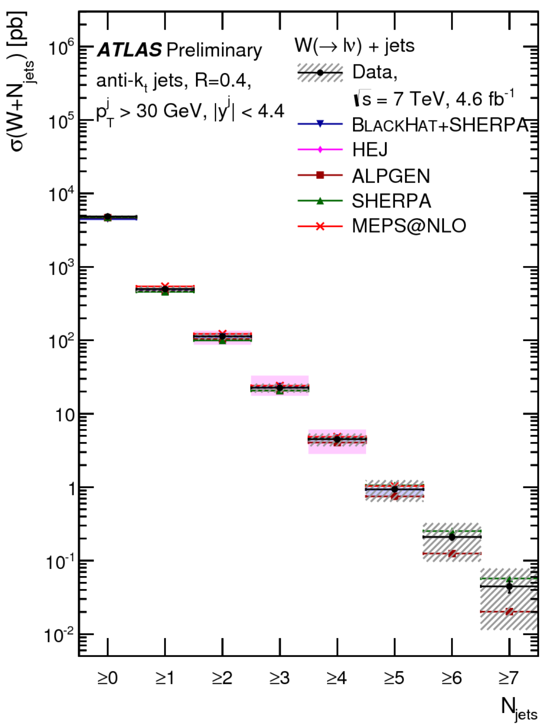
N_{jets}, jet p_T

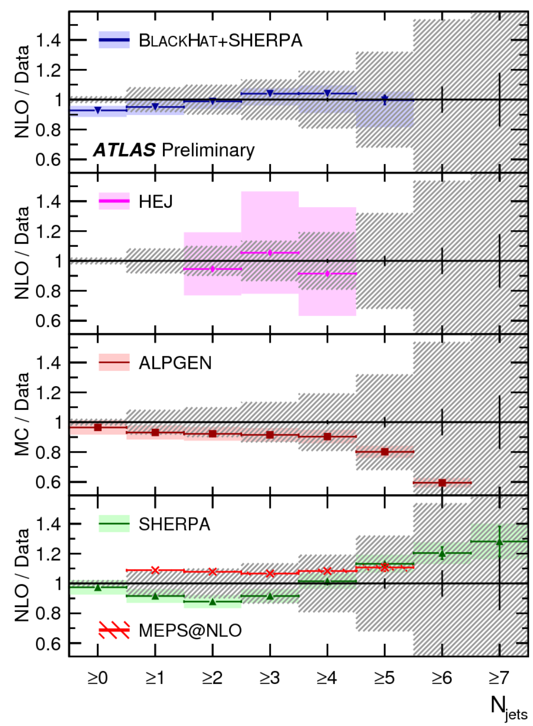
in W+jets at 7 TeV

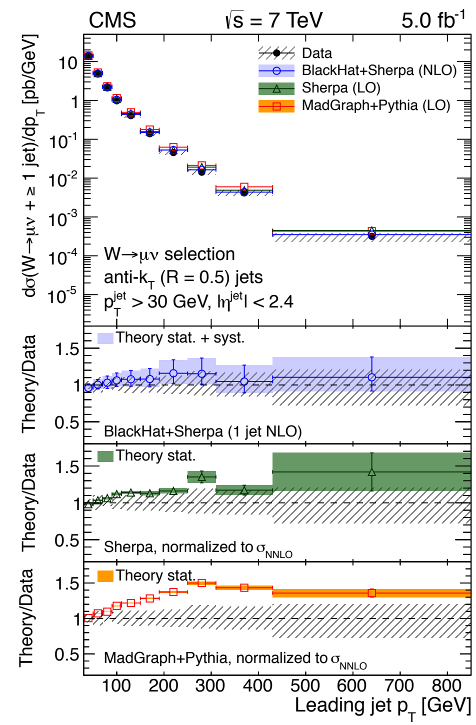
arXiv.1406.7533

ATLAS:
Lepton p_T>25 GeV, $|\eta|$<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, $|y|$<4.4
$\Delta R(l,j) > 0.5$
Missing E_T>25 GeV, M_T>40 GeV

CMS:
Muon p_T>25 GeV, $|\eta|$<2.1
Anti-k_T jets R=0.5, p_T>30 GeV, $|\eta|$<2.4
$\Delta R(\mu,j) > 0.5$
M_T>50 GeV





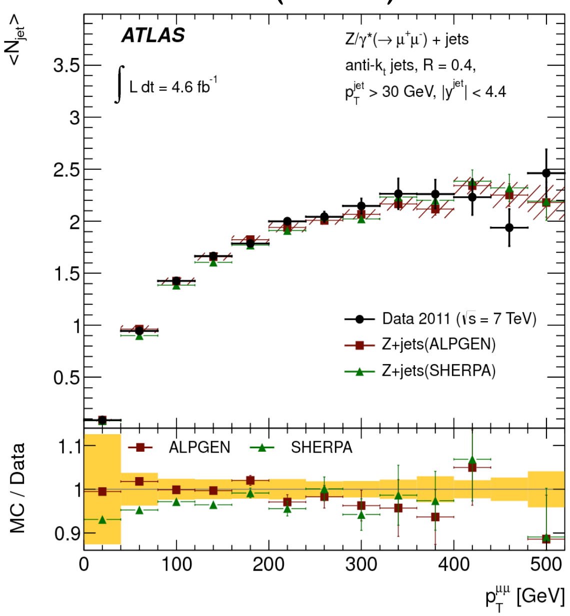


- Extraordinary agreement between experiments and theory over 5 orders of magnitude in cross-sections
- High experimental accuracy exposes discrepancies with predictions
  - LO multileg+PS overestimate data at high jet scales (jet p_T)

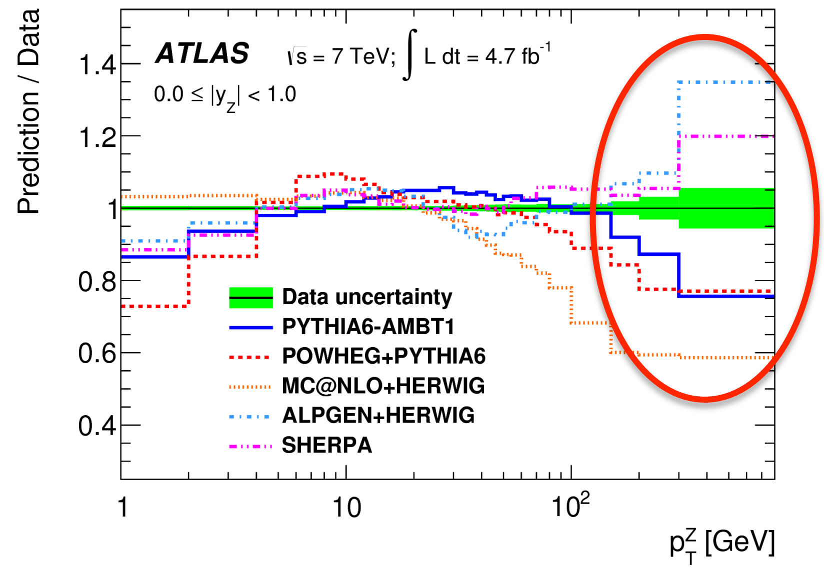
Lepton p_T>20 GeV, |η|<2.5
66 < m_{ll} < 116 GeV
Anti-k_T jets R=0.4, p_T>30 GeV, |y|<4.4
ΔR(lept,jet) > 0.5

Z p_T in Z+jets at 7 TeV

JHEP 07 (2013) 032

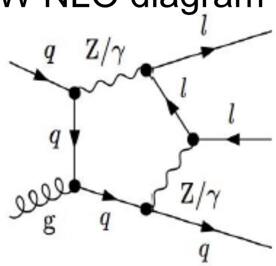


Prediction/data ratio of inclusive Z p_T distribution



Phys. Lett. B 722 (2013) 238–261

EW NLO diagram



JHEP 1106 (2011) 069

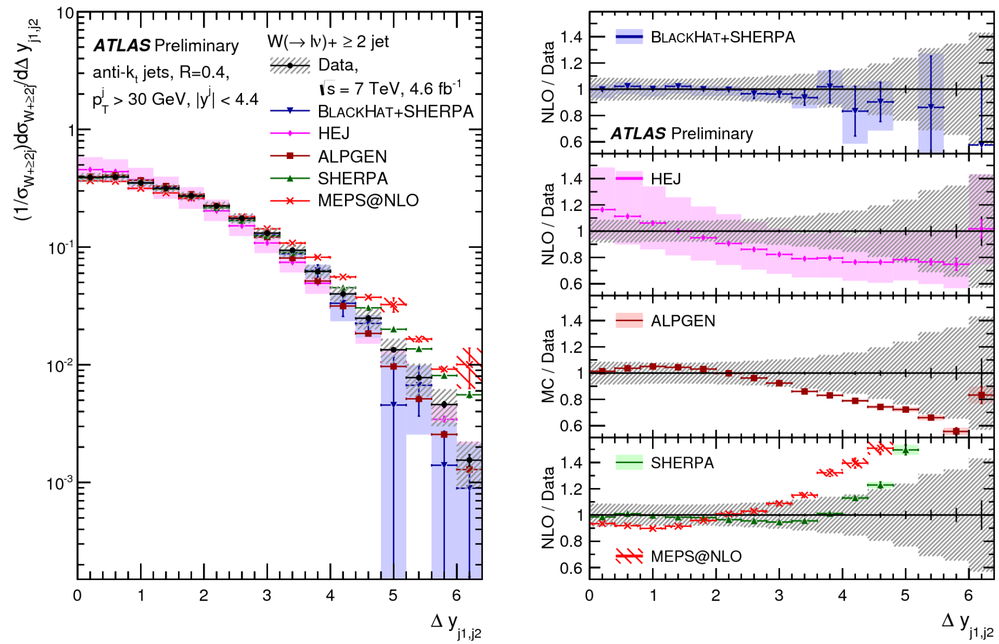
- At large p_T^Z multi-jet events contribute to inclusive Z + ≥ 1 jets
  - MC with NLO accuracy on inclusive Z production undershoot data
  - Multi-jet generator overpredict high Z p_T
- Higher-order EW corr. expected to reduce cross section by 5-20% at p_T^Z > 100 GeV (non included in main stream MC's)

ATLAS-CONF-2014-035

ATLAS:
Lepton p_T>25 GeV, $|\eta|$<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, $|y|$<4.4
$\Delta R(l,j) > 0.5$
Missing E_T>25 GeV, M_T>40 GeV

Angular distributions
in W+jets at 7 TeV

- Angular distributions provide important test of QCD modeling:
  - Hard radiation at large angles
    - Modeled by M.E.
  - Unresolved soft/collinear radiation
    - Modeled by P.S.
- Important for Higgs selection and to study VBF/VBS mechanisms



- *BlackHat* in good agreement with data on $\Delta y(j,j)$
- Higher experimental precision exposes data-predictions discrepancies

High-order pQCD corrections
Matrix Element – Parton Shower

ATLAS:
Lepton p_T>25 GeV, |η|<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, |y|<4.4
ΔR(l,j) > 0.5
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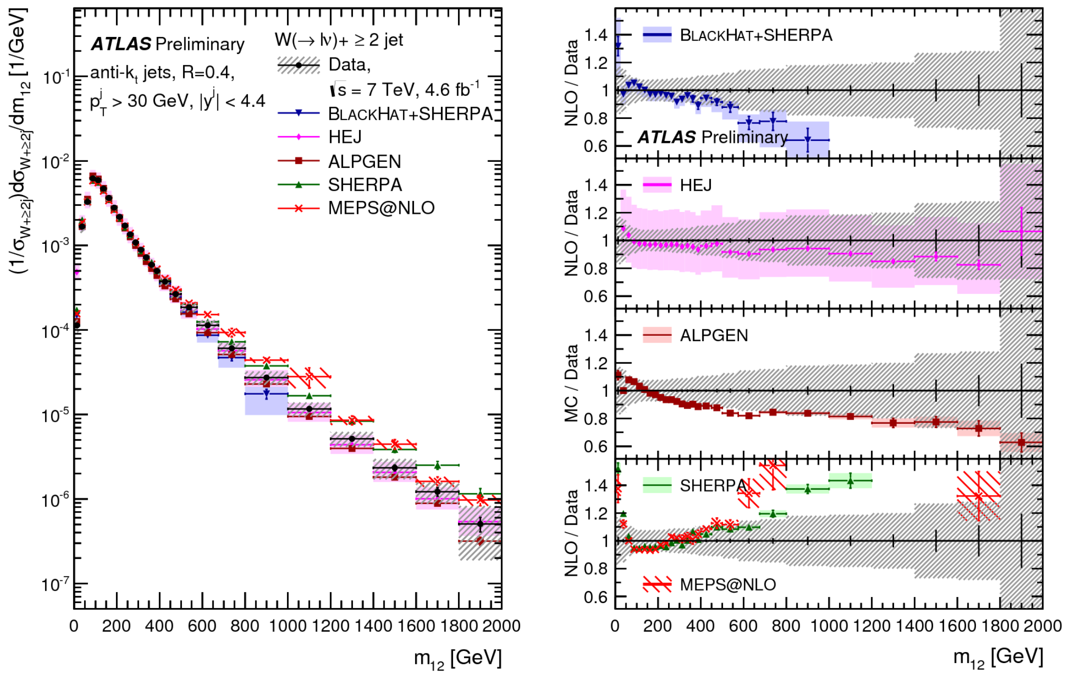
m_{jj} in W+jets at 7 TeV

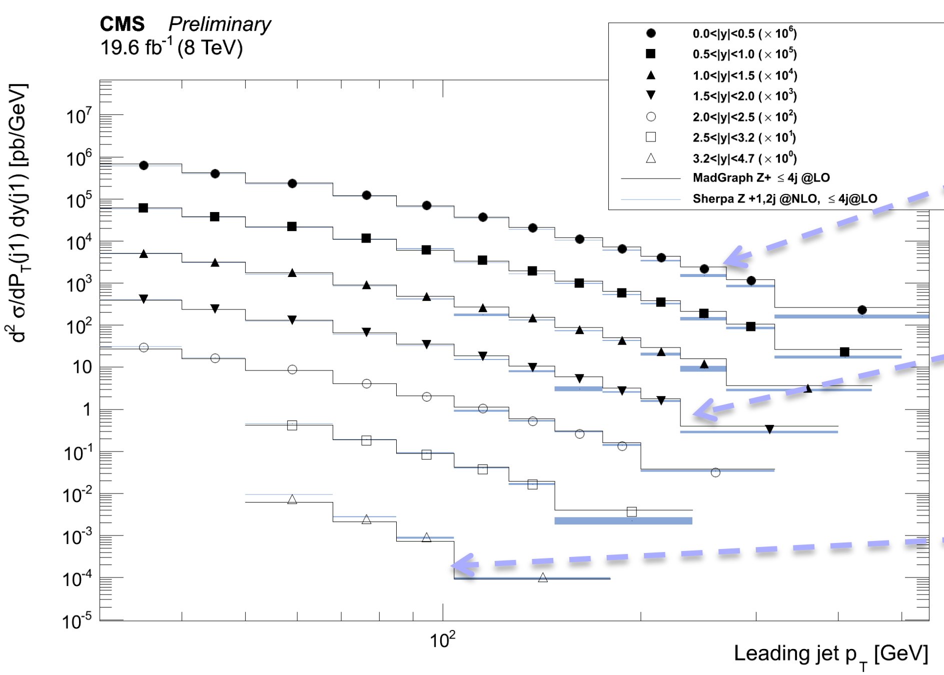


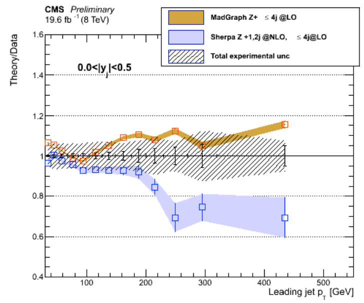
- Fixed-order NLO calculation (BlakHat) underestimate the high m_{jj} region
- BFKL-like resummation (*HEJ*) is in agreement with data on m_{jj}
- Discrepancies of LO and NLO multi-leg MC predictions
  - room for MC tuning, e.g. P.S, M.E.- P.S matching

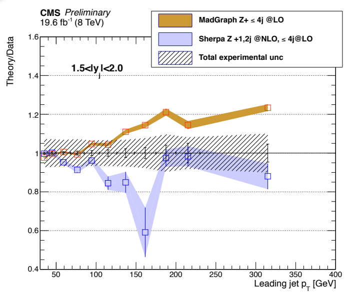
Double differential cross sections in Z+jets at 8 TeV

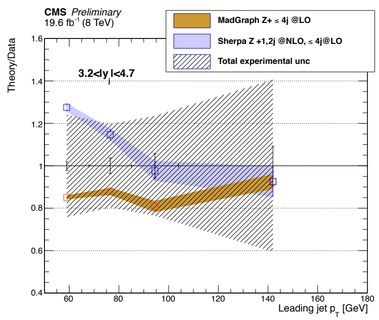
CMS:
Muon p_T>20 GeV, $|\eta|$<2.4
Anti-k_T jets R=0.5, p_T>30(50) GeV, $|\eta|$<2.5 (>2.5)
$\Delta R(\mu,j) > 0.5$
M_T>50 GeV

- First double differential measurement: leading jet p_T and rapidity (like in jet measurements)
  - also suitable for PDF fitting
- Extended jet rapidity range, up to $|\eta|$ = 4.7







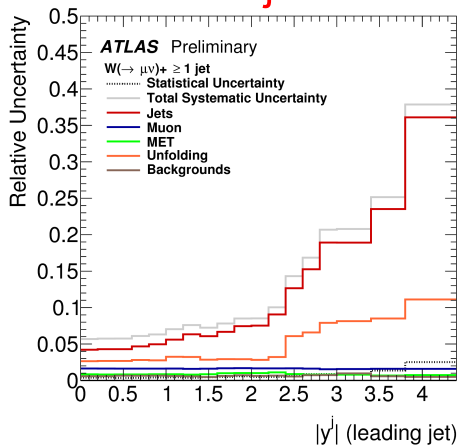


- For central jets the precision of experimental measurements is higher than prediction-to-prediction differences
  - up to ±20% data-theory discrepancies (Madgraph, Sherpa MEPS@NLO) in high p_T tails of 1st jet

Cancellation of uncertainties in ratios

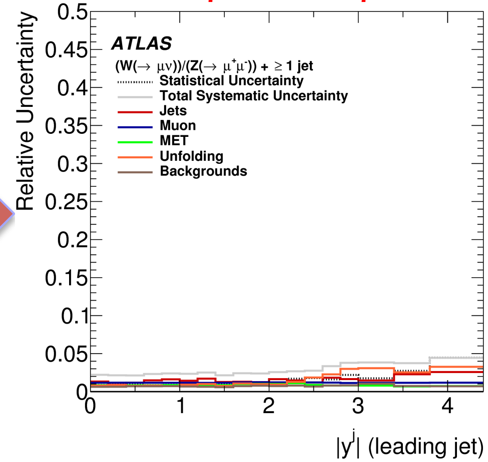
- Ratio measurements allow for cancellations of uncertainties (exp. and theory)
  - Experimental: jet calibration uncertainties, lumi etc.

W+jets



ATLAS-CONF-2014-035

W+jets / Z+jets



arXiv:1408.6510

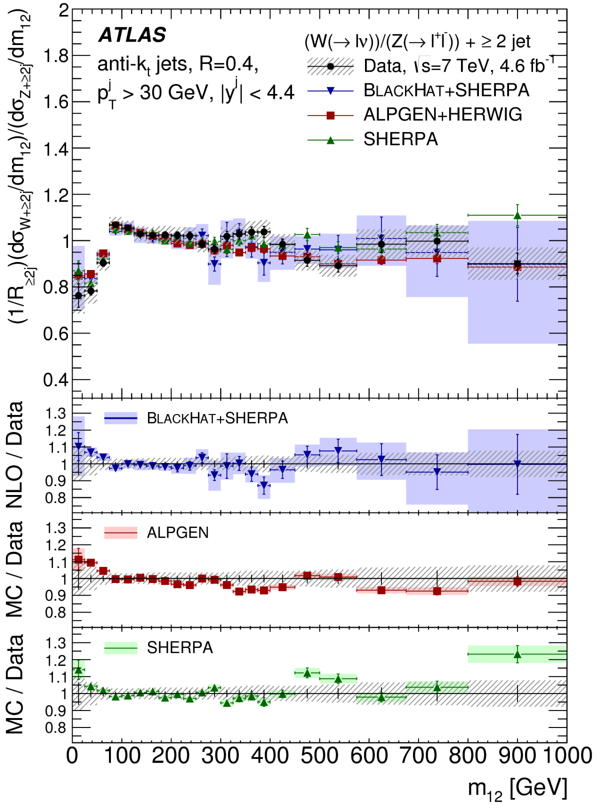
  - Theory: (if treated as correlated between numerator and denominator)
    - scale+PDF uncertainties: *20%* (W+1j) -> *2-4%* on W+1j/Z+1j at jet p_T=800 GeV

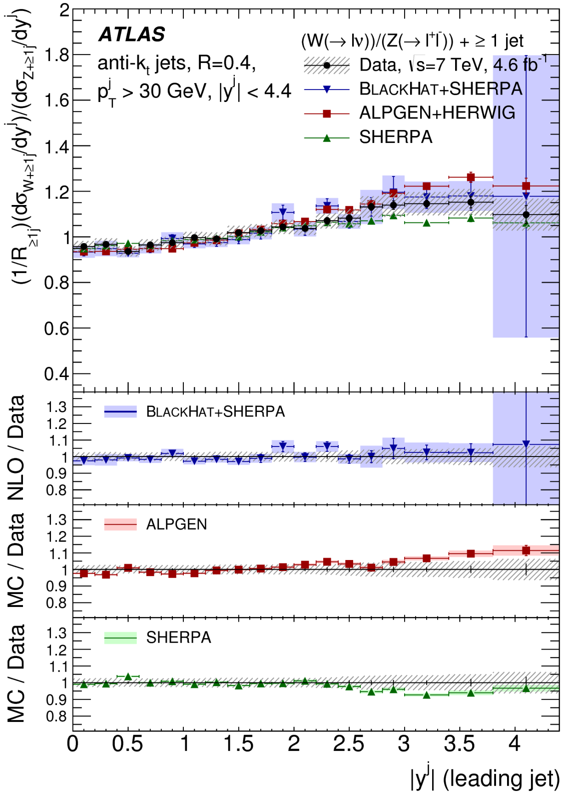
➢ Accurate test of SM predictions
➢ Important for Z(νν)+jets background estimation in searches (see transfer factor)
➢ Model-independent searches of new physics

Lepton p_T>25 GeV, $|\eta|$<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, $|y|$<4.4
$\Delta R(l,j) > 0.5$
W: Missing E_T>25 GeV, M_T>40 GeV
Z: 66<m_{ll}<116 GeV

R_{jets} = W+jets / Z+jets

- Mismodeling seen in W+jets and Z+jets separately mostly cancel in R_{jets}





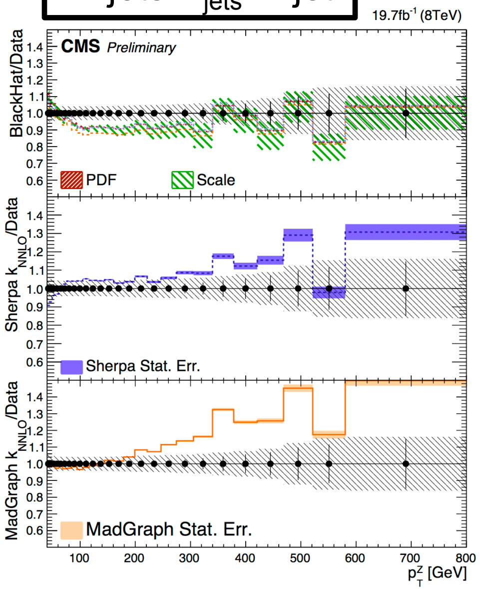
- Significant discrepancies with theory in some regions of phase space
  - e.g. high leading-jet rapidity

Z+jets / γ+jets ratio

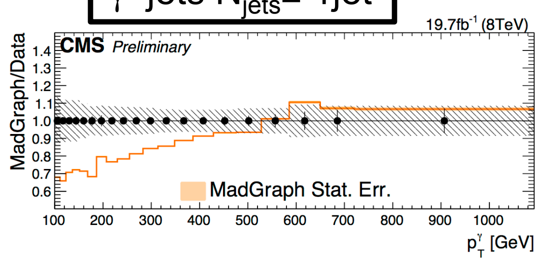
Lepton p_T>20 GeV |η|<2.4
V-boson p_T>100 GeV
V-boson |y| < 1.4
Anti-Kt R=0.5 jet p_T>30 GeV, |η|<2.4
ΔR(l,j) > 0.5

- At large V-boson p_T QCD and EW introduce large high-order corr.
  - NLO (BlakHat) underestimate data at Z p_T≥100 GeV by ~10%
  - LO multileg MC (Madgraph, Sherpa) overestimate high Z p_T
    - scaled to NNLO inclusive Z cross-section

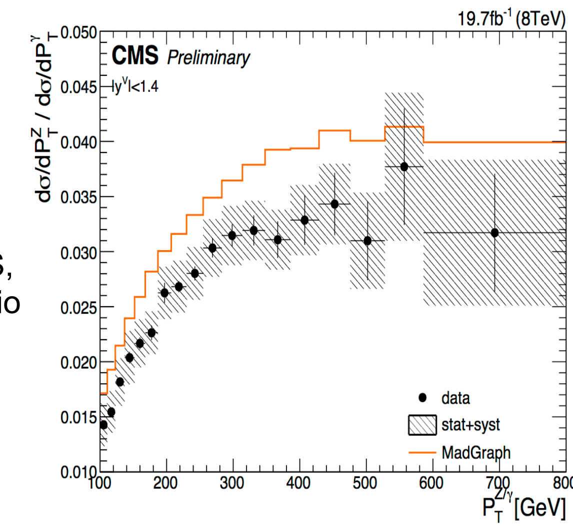
Z+jets N_{jets}≥ 1jet

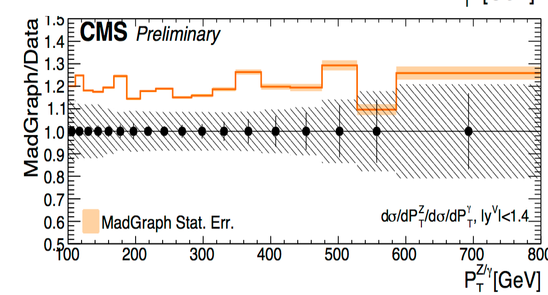


γ+jets N_{jets}≥ 1jet



Cancellation of JES, JER and lumi in ratio





- In Z/γ Ratio:
  - flattening at high Z/γ p_T
  - over-estimation of ratio by a flat 20% by LO Multi-leg MC
  - shape is well modeled (cancellation of mis-modeling of individual Z and γ p_T)

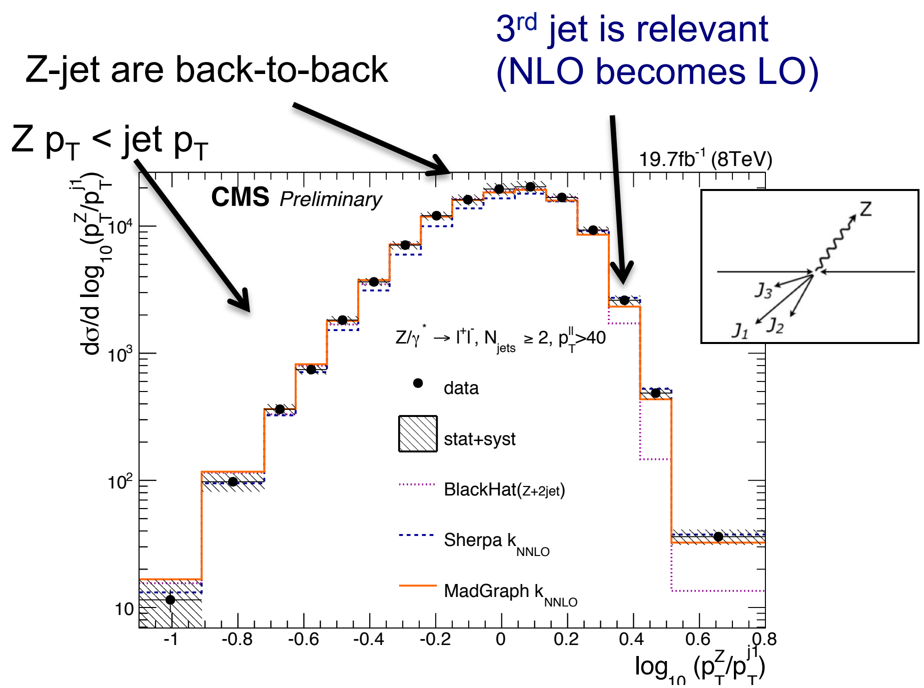
Ratios in Z+jets

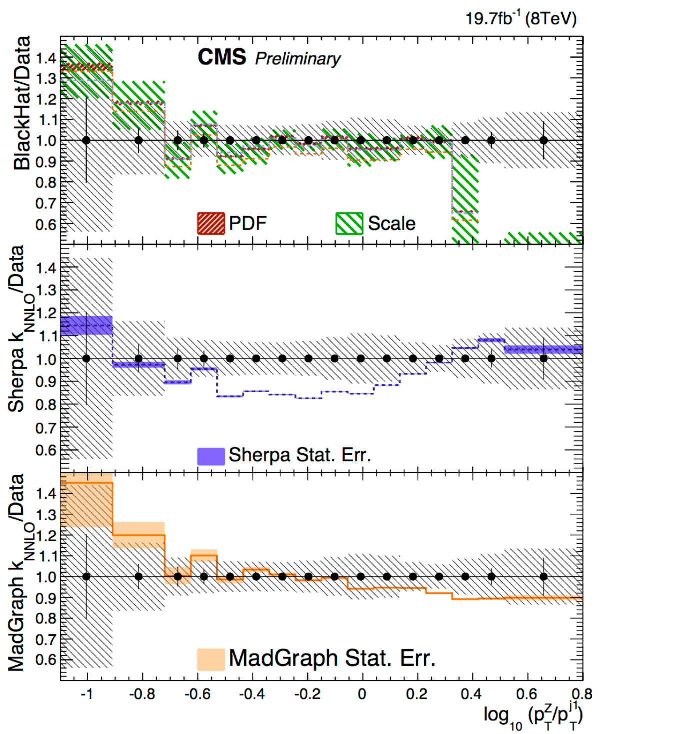
Lepton p_T>20 geV |η|<2.4
Z p_T>100 GeV
antiKt5 jet p_T>30 GeV, |η|<2.4
ΔR(l,j) > 0.5

- Test limit of validity of NLO pQCD calculation
  (where large logs are expected or missing higher orders)

- Fixed-order NLO fails at large $p_T^Z/p_T^{\text{1st jet}}$ due to missing higher predictions
  - 3-jet emission only at LO in BlackHat

- Parton shower adds soft jets and provides better description of high tails

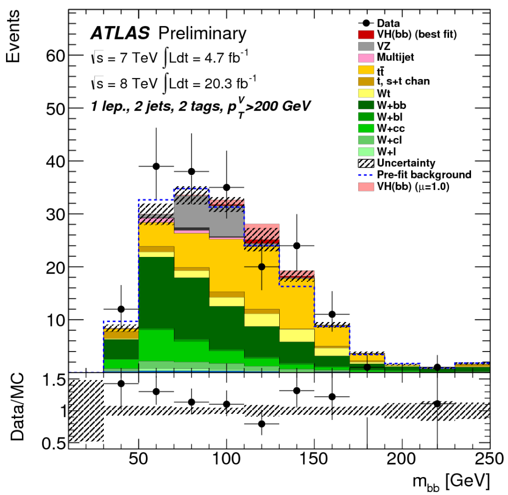


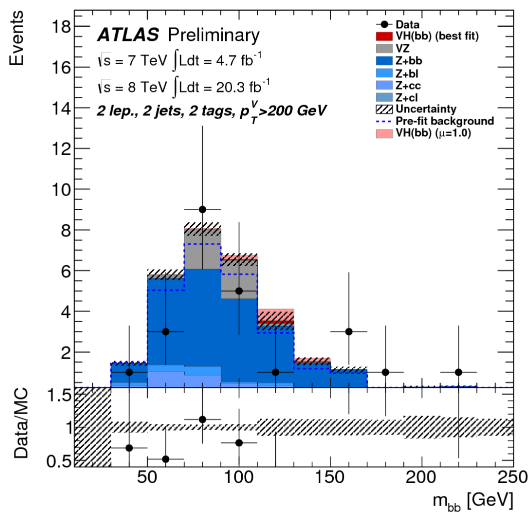


Vector Boson + heavy-favour jets

W,Z + heavy-flavour jets

- Theoretical uncertainties on W/Z+heavy flavour jets are larger than for light jets
  - heavy-quark content in the proton
  - modeling of gluon splitting (initial state, final state)
  - massive vs massless b-quark in calculations
- Test of QCD predictions with various implementations (LO multileg+PS, NLO, NLO+PS)
- Very important processes as background to Higgs and searches





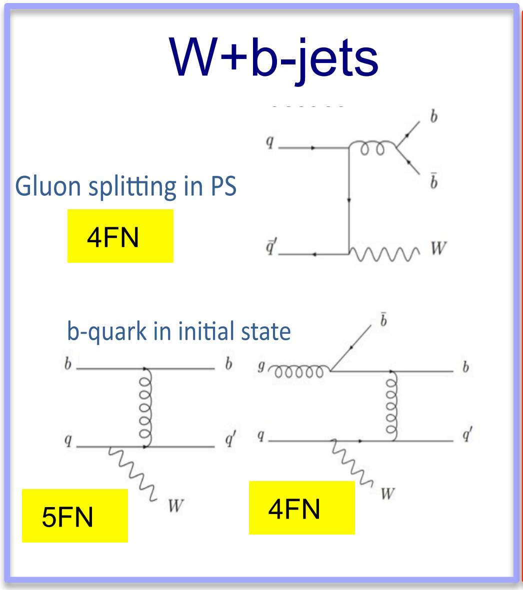
ATLAS-CONF-2013-79

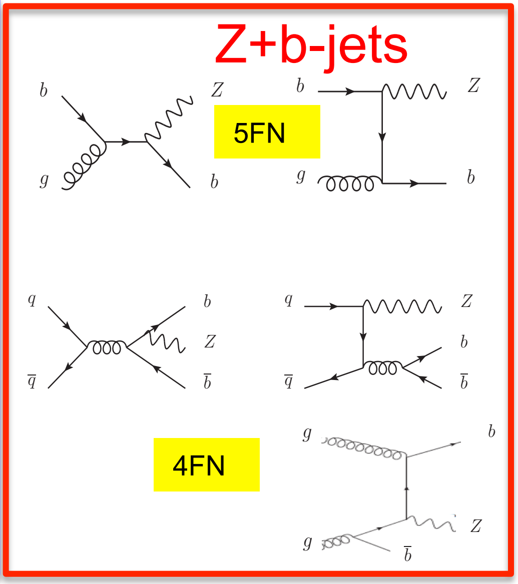
- VH(→bb) analysis
- 2 b-jet resolved topology

W,Z + b-jets processes and analysis strategy

qq→Wbb

bq→Wbq
gq→Wbbq





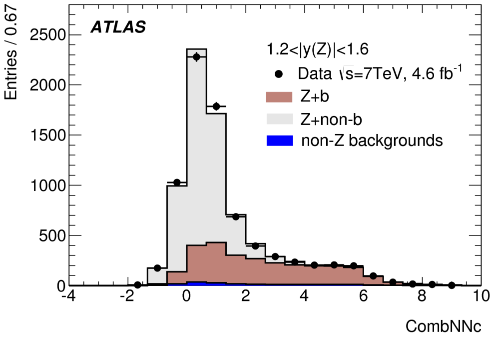
bg→Zb

qq→Zbb

gg→Zbb

- Descriptions of "b-initiated processes"
  - 4 flavors number scheme (4FNS): b-quark generated through gluon splitting
  - 5 flavors number scheme (5FNS): b-quark generated in the initial state by DGLAP evolution

- Experimental analysis strategy:
  - b-jet tagging
    - Exploit long life-time and large masses of b-hadrons (e.g. secondary vertex and large impact parameter)
  - Signal extraction based on fit to distributions sensitive jet-flavour
    - i.e. b-tagging weight distribution
    - Templates based on MC, but checked in data control regions

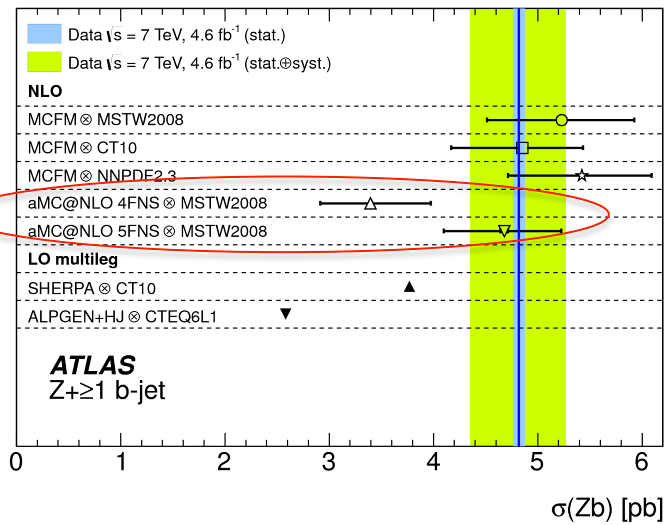


ATLAS:
Lepton p_T>20 GeV, |η|<2.5
Anti-k_T jets R=0.4, p_T>20 GeV, |y|<2.4
At least 1 or 2 b-jets

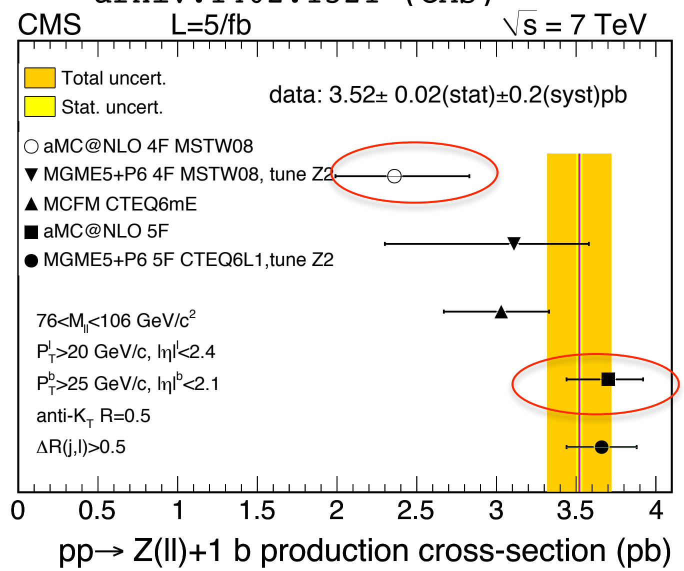
Z + ≥ 1 b-jet

CMS:
Lepton p_T>20 GeV, |η|<2.4
Anti-k_T jets R=0.5, p_T>25 GeV, |η|<2.1
Exactly 1 or at least 2 b-jets

arXiv:1407.3643 (ATLAS)



arXiv.1402.1521 (CMS)



- **MCFM:** _5FN_ NLO Z+b, Z+bb, massless b-quarks
- **aMC@NLO** _4FN_: *NLO Z+bb, and Z+b, massive b-quarks*
- **aMC@NLO** _5FN_: *NLO for Z+b, LO for Z+bb*
- **Sherpa**: _5FN_ Z+b LO+PS, massive b-quark
- **Alpgen**: _4FN_ Z+b LO+PS, massive b-quark
- **Madgraph:** _5FN_ LO+PS, massless b-quark
- **Madgraph:** _4FN_ LO+PS, massive b-quark

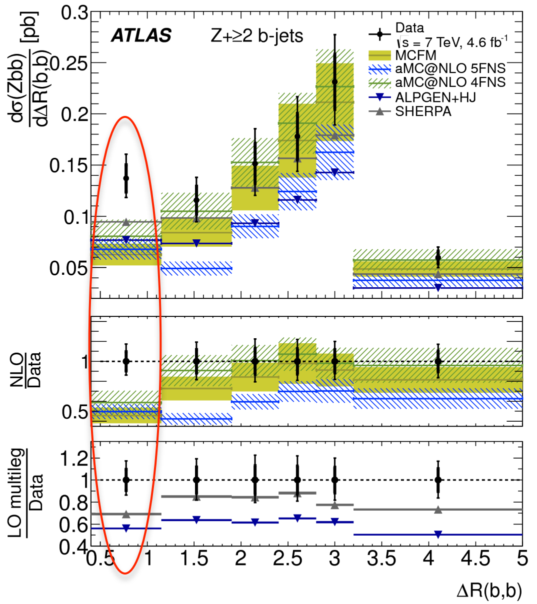
- LO+PS generators underestimate cross sections
- NLO agrees well with data
- Z+b data favor NLO 5FN
  - NLO 4FNS underestimate the measurement
- Cannot constrain b-PDF yet due to large NLO QCD scale uncertainty

Gluon splitting

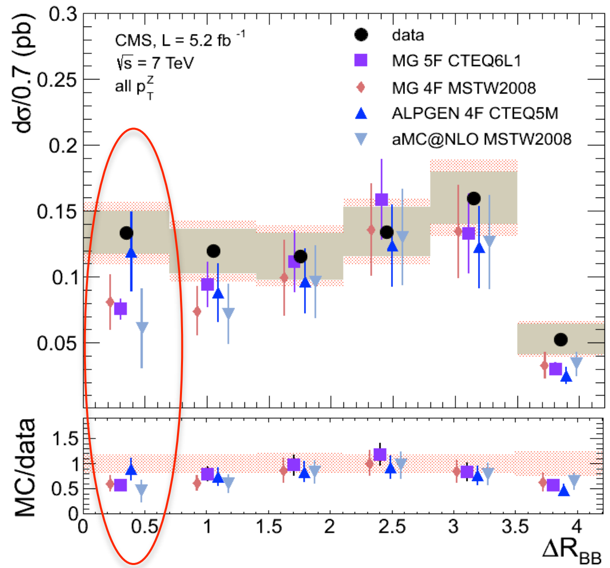
Z + ≥ 2 b's

- Z+bb cross section tends to prefer 4FN scheme instead
- Z+bb data sensitive to different underlying processes
  - Contribution from by two hard initial state or final state gluon splitting with resolved b-jets
- Distribution shapes generally well described by predictions
- Except for configurations with nearby b-jets, dominated by gluon splitting

arXiv:1407.3643 (ATLAS)



JHEP 12 (2013) 39 (CMS)



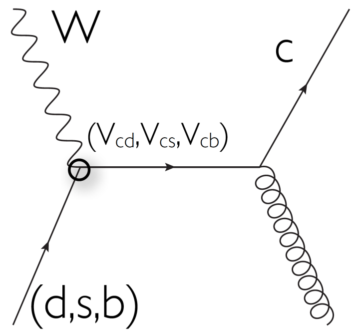
ATLAS Z+bb:
Lepton p_T>20 GeV, |η|<2.5
Anti-k_T jets R=0.4, p_T>20 GeV, |y|<2.4
At least 1 or 2 b-jets

Z+BB Fiducial phase space:
b-hadron p_T>15 GeV, |η|<2
Lepton p_T>20 GeV |η|<2.4
81< M_{ll}<101 GeV

- Exclusive reconstruction of B-hadrons in Z+ BB avoids limitation of b-jet size radius
  - B-hadrons identified from displaced secondary vertices, reconstructed from charged decay products

W + charm

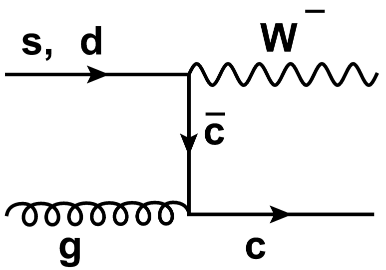
- ❑ W+c sensitive to strange quark content in proton
  - ▪ gluon splitting treated as background
- ❖ Strange-quark usually suppressed by factor ½ wrt down-quark in PDF
  - ▪ as suggested by ν-N DIS (NuTev)
- ❖ ATLAS W/Z cross section measurements favour strange-quark enhancement

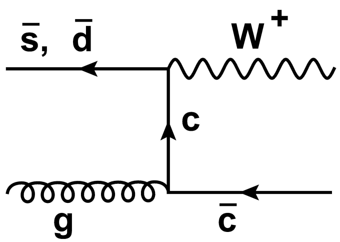


90% sg→Wc

10% dg→Wc

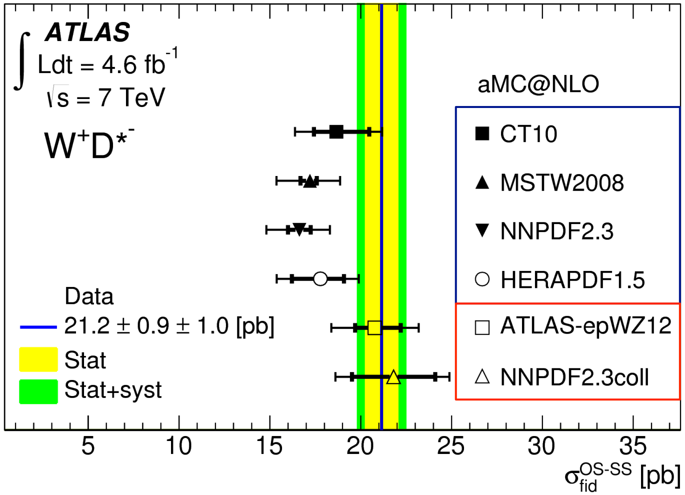
- ❑ Charm candidates identified with two strategies
  - ▪ Soft muon tagged inside a jet
  - ▪ Exclusive decays of the charmed hadrons $D^{\pm}$ and $D^{*\pm}$
- ❑ Use the W-charm charge correlation to suppress backgrounds (e.g. gluon splitting, multijet, etc..)
  - ▪ Same-sign contribution is subtracted
  - ⇒ Measuring OS-SS yields

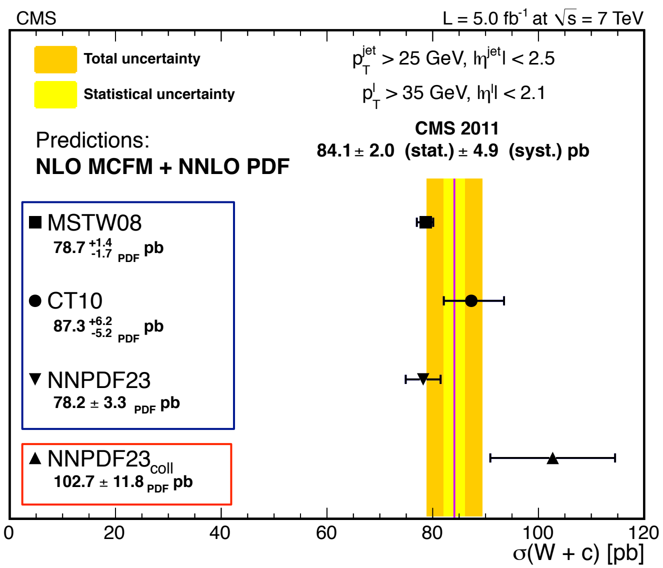




W + c

JHEP05(2014)068 (ATLAS)





JHEP02(2014)013 (CMS)

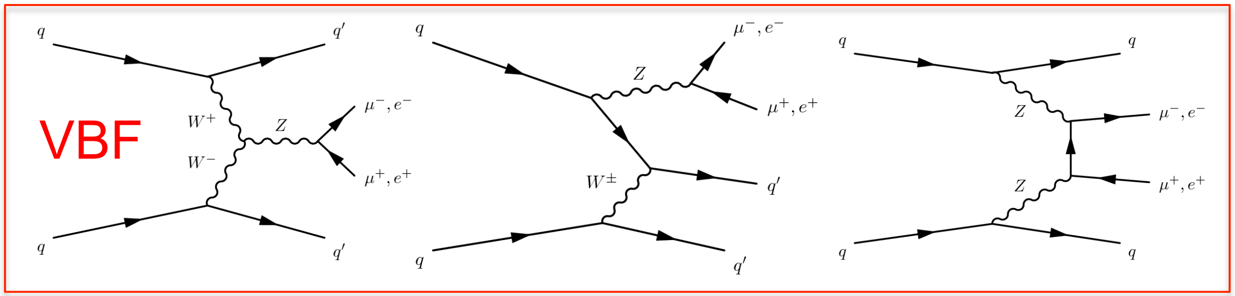
ATLAS:
W: Lepton p_T>20 GeV, |η|<2.5
Missing E_T> 25 GeV, M_T>40 GeV
c-jet: p_T>25 GeV, |η|<2.5
D:pT>25 GeV, |η|<2.5

- Overall agreement with **NLO QCD** predictions
- Cross section depends on PDF
- ATLAS data suggests s-quark enhancement
  (ATLAS-epWZ12 and NNPDF2.3coll with enhanced strange)
  - Consistently with inclusive W/Z data results
- CMS data in better agreement with suppressed strange

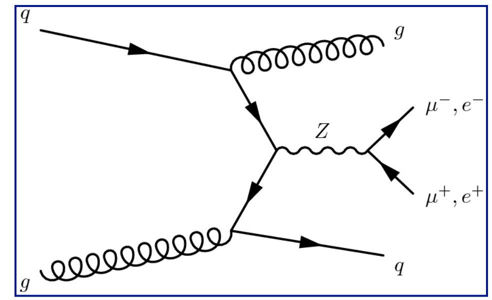
Electroweak vs QCD production of Vector Boson + 2 jets

Electroweak W/Z + 2 jets

Electroweak Z+2jets production is 1% of inclusive Z+2jets cross section

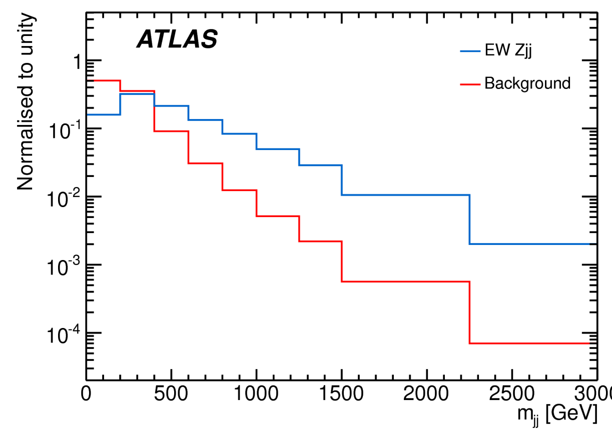


Electroweak production



Strong production

- To enhance events with VBF contribution:
  - Tag well-separated jets in rapidity with large m_{jj}
    - no color flow in region between the two quarks (low jet activity in rapidity interval)



- Measurements by ATLAS and CMS at 8 TeV

Electroweak Z + 2 jets

- ATLAS 5 phase space regions with different sensitivity to the EW Z+2j production

ATLAS

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\|\eta^\ell\| < 2.47$, $p_T^\ell > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\|y^j\| < 4.4$, $\Delta R_{j,\ell} \geq 0.3$				
	$p_T^{j_1} > 55$ GeV				$p_T^{j_1} > 85$ GeV
	$p_T^{j_2} > 45$ GeV				$p_T^{j_2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\text{jet}}^{\text{gap}} = 0$	$N_{\text{jet}}^{\text{gap}} \geq 1$	—
Zjj system	—		$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance},3} < 0.15$	—

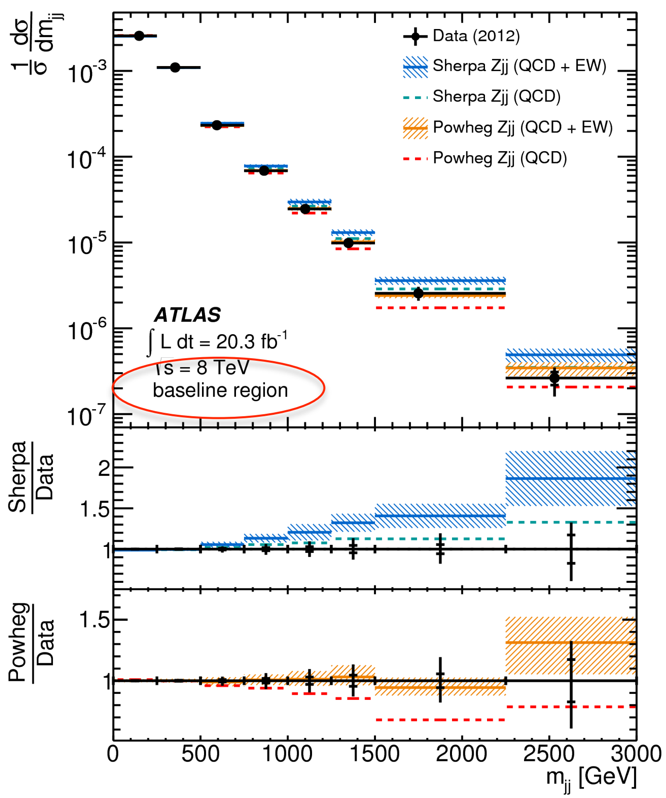
$$p_T^{balance} = \left|\sum_{\ell,j} \vec{p}_T\right| \Big/ \sum_{\ell,j} |\vec{p}_T|$$

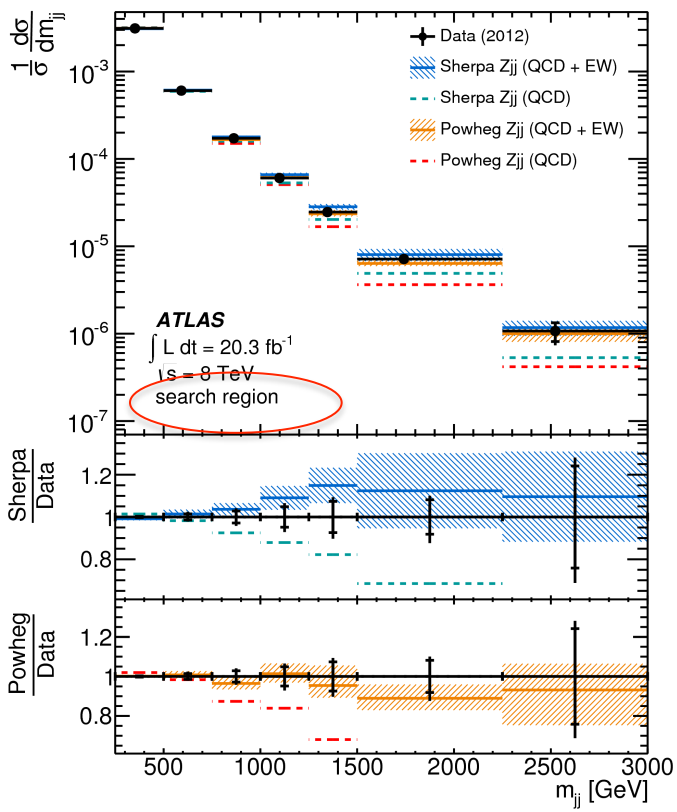
- Z-boson selection
- Baseline jet selection
- Search/control cuts for electroweak extraction and modeling of Strong Z+2j production
- Probe impact of EWK Z+2j on high-p_T or high-mass

➢ Laboratory for studying generator behavior in VBF/VBS context

Electroweak Z + 2 jets

- normalized differential cross section as a function of m_{jj} in different regions



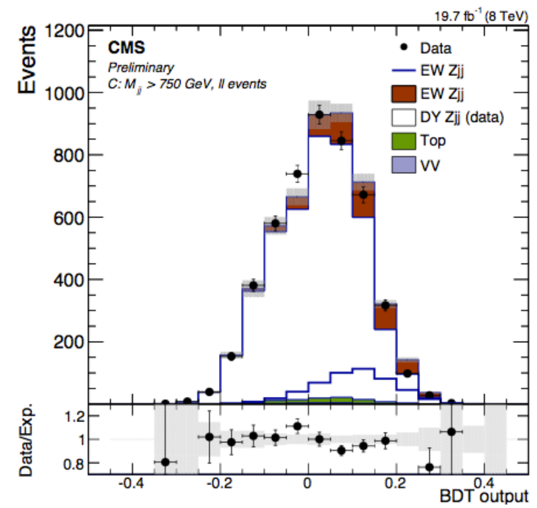


- Powheg accurate to NLO in QCD for Z+2j production
- Sherpa accurate only to LO in QCD for Z+2j production

- Strong Z+2j prediction undershoots m_{jj} in search region

Electroweak Z + 2 jets

- EW Zjj component extracted by a 2-template fit to the m_{jj} spectrum (or discriminator output - CMS) in *search region*
- Strong Zjj production model constrained from data
  - ATLAS: *control region* has reverted jet veto
    - Correct the simulation in *search region* using the data/MC ratio in *control region*, to better model jet dynamics and constrain experimental systematics
  - CMS: strong Z+2j model built from γ+2j data reweighting γ-p_T



➢ background-only hypothesis excluded with significance above 5σ for both ATLAS and CMS

❖ EW Zjj production cross section measured in signal fiducial regions in agreement with theory prediction:

ATLAS: mjj > 250 GeV: $\sigma_{EW} = 54.7 \pm 4.6\,(\text{stat})\,^{+9.8}_{-10.4}\,(\text{syst}) \pm 1.5\,(\text{lumi})\,\text{fb}$

$\sigma_{Powheg} = 46.1 \pm 0.2\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{scale}) \pm 0.8\,(\text{PDF}) \pm 0.5\,(\text{model})\,\text{fb}$

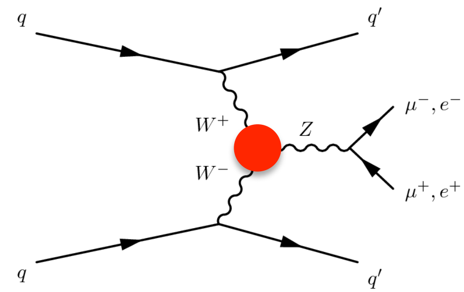
CMS: : mjj > 120 GeV: σ_{EW}= 174 ± 15 (stat) ± 40 (syst) fb σ_{VBFNLO} = 208±11 fb

Electroweak Z + 2 jets

- Constrain new physics in a model independent approach (complementary to direct searches)
  - SM: a low-energy effective theory of a more complete but unknown theory
  - Modification of gauge boson self-interactions

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_{\text{dimension } d} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- Constrain anomalous Triple Gauge Coupling (aTGC) on VBF vertex



- 95% confidence intervals on aTGC parameters from counting the number of events in search region with m_{jj}>1 TeV
  - Not as stringent as limits set in di-boson production but complementary, as two of vector bosons have space-like four-momentum-transfer

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	[−0.65, 0.33]	[−0.58, 0.27]	[−0.50, 0.26]	[−0.45, 0.22]
λ_Z	[−0.22, 0.19]	[−0.19, 0.16]	[−0.15, 0.13]	[−0.14, 0.11]

$$\frac{\mathcal{L}}{g_{WWZ}} = i\left[g_{1,Z}\left(W^\dagger_{\mu\nu}W^\mu Z^\nu - W_{\mu\nu}W^{\dagger\mu}Z^\nu\right) + \kappa_Z W^\dagger_\mu W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} W^\dagger_{\rho\mu} W^\mu_\nu Z^{\nu\rho}\right]$$

Unitarisation of couplings by dipole form factor

$$a(\hat{s}) = \frac{a_0}{(1+\hat{s}/\Lambda^2)^2}$$

Λ = unitarisation scale

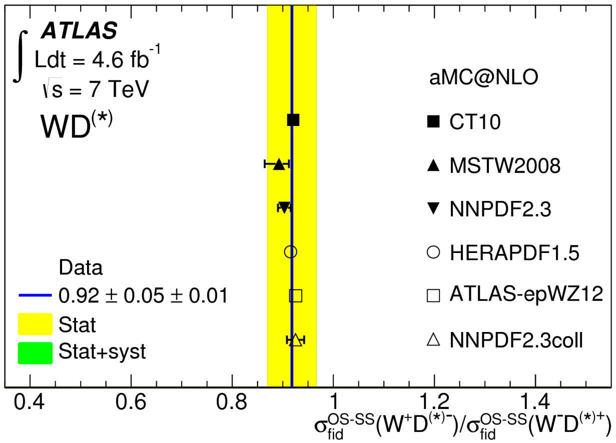
Future prospects

Lesson from Run 1, prospects for Run 2

- Many W/Z+jets experimental results performed with Run 1 data
  - W/Z+jets physics will still be critical in LHC Run 2 with higher $\sqrt{s}$ and larger integrated luminosity
- LHC measurements have already reached sensitivity to QCD effects beyond the NLO accuracy of differential calculations and are approaching sensitivity to EW corrections
- Full NNLO QCD corrections will reduce scale uncertainties and can improve sensitivity to PDF, e.g. high-x gluon
- A variety of measurements already available for *re-tuning of Monte Carlo's* and *constrain PDF*
- Accuracy of the theoretical tools (MC and PDF) need re-assessment at higher $\sqrt{s}$ in new regions of phase space
- New measurements possible: ratios of cross-sections at different $\sqrt{s}$ (cancellations of uncertainties)

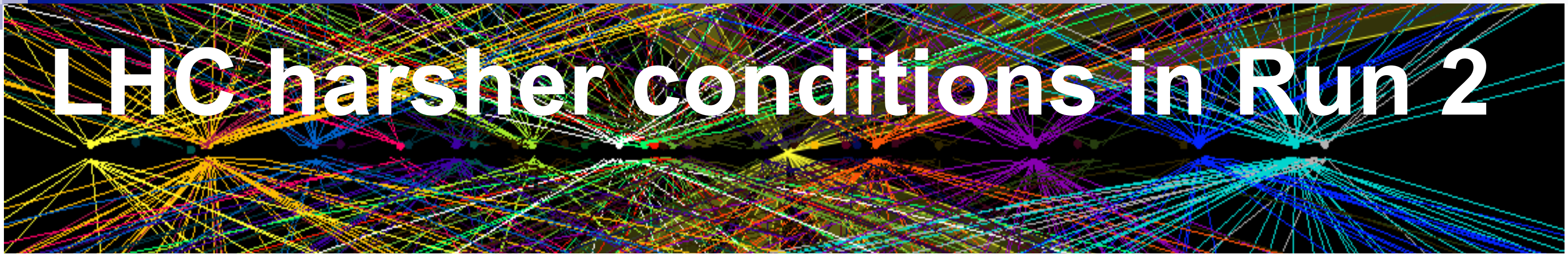
Run 2 Prospects

❖ Examples of W/Z+jets analyses limited by statistics in Run 1



- W+D analysis still statistically limited in Run 1
- Study of **s / $\bar{s}$** asymmetry by Ratio $R_c^{\pm} = \frac{\sigma(W^+D^{(*)-})}{\sigma(W^-D^{(*)+})}$
- NuTeV data suggests asymmetric strange sea
  - LHC data consistent with all PDFs
    - CT10 and NNPDF2.3 with s=/≈$\bar{s}$
    - MSTW2008 with s-$\bar{s}$ asymmetry
  - Run 2 can discriminate between the two assumptions

- High N_{jets} , jet p_T distributions in W/Z+jets
- Z+BB statistically limited in Run 1
- High mjj in Z+2j in EWK search region



LHC harsher conditions in Run 2

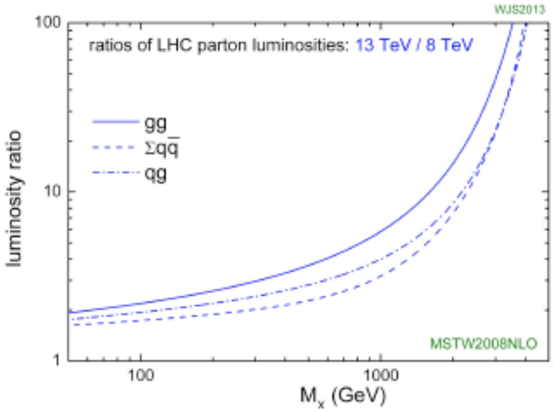
- Run 2 will open new possibilities for discoveries of new physics, rediscovery of SM processes with higher centre-of-mass energy and luminosities
  - Increase of production cross-sections at 13 TeV
- However experimental environment will be harsher
  - higher pileup
  - larger trigger rate
  - larger data volume
- LHC detectors upgrades in various subsystems, e.g. tracker, muon system, calorimeters, trigger
  - to complete/extend coverage and detector consolidation
  - to improve efficiencies and allow further rejection in high pileup conditions
- Detector subsystems will be put under stress, in particular the Trigger system

LHC Run 1 conditions:

- $\sqrt{s}$=900 GeV, 7 TeV, 8TeV
- Luminosity: up to 7×10^{33} cm^{-2} s^{-1}
- Pileup up to 35
- Integrated luminosity ~30 fb^{-1}

Expected LHC Run 2 conditions:

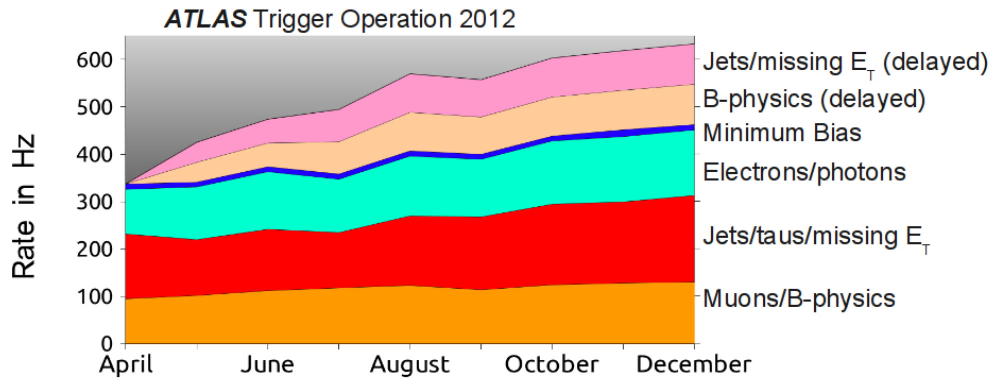
- **$\sqrt{s}$=13 TeV**
- **Luminosity: up to 1.6×10^{34} cm^{-2} s^{-1}**
- **Pileup up to ~50**
- **Integrated luminosity ~150 fb^{-1}**



Triggering at LHC in Run 1

- ATLAS and CMS have a three-level trigger system
  - **Level-1**: hardware-based, synchronous at 40MHz, with reduced detector granularity
  - **High Level Trigger:** Level-2 and Level-3 software based
    - handles complexity with custom fast software, accessing the full resolution of all the detectors

- Trigger challenges towards Run 2
  - Simple extrapolation of rates from Run 1 to Run 2 will exceed trigger and DAQ resources available in Run 1
  - Reduced rejection power of the algorithms due to pileup

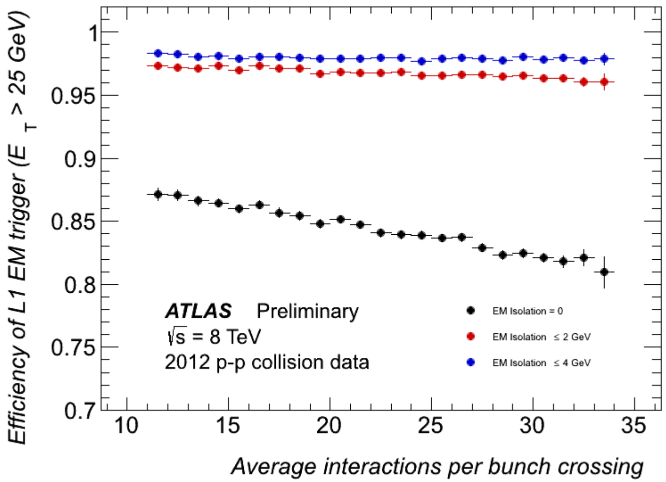


- Trigger strategy for Run 2 in ATLAS:
  1) Efficient triggering over the full physics coverage
  2) Maintain sensitivity to Electroweak scale
     - Inclusive single lepton triggers (both electrons & muons)
     - Exclusive / multi-object triggers

- **Increased L1 and HLT output rate budget:**
  - L1: nominal 75 kHz (Run 1) → *100 kHz (Run 2):* effort of the whole detector
  - HLT: 600 Hz (Run 1) → *1 kHz (Run 2)*: need software improvements and speed up

Triggering on W/Z+jets in Run 2

- Standard Model physics of W and W+jets set tight constraints on trigger strategy
  - W cross section, W mass, W+c, W+b(b) etc.
- Compromise between high rates and efficient selection of W(+jets)
- Various options being debated within collaborations
  - Low-p_T lepton trigger threshold required for efficient selection (p_T~20-30 GeV)
    $\Rightarrow$ High rates ($\mathcal{O}$(400 Hz) of W/Z->lν/ll)
  - Tightening of lepton identification requirements (e.g. isolation of leptons from surrounding particles) to reject high-rate jet background and minimise increase of lepton trigger p_T threshold
  - Reduce acceptance of single lepton triggers (e.g. exclude high-rate high |η| regions)
  - Prescaling of single lepton triggers (reduction of statistics)
  - Additional requirements to single lepton threshold (e.g. missing E_T, M_T, jets, b-jets etc.)
    $\Rightarrow$ bias on kinematics and efficiency and acceptance losses



Conclusions

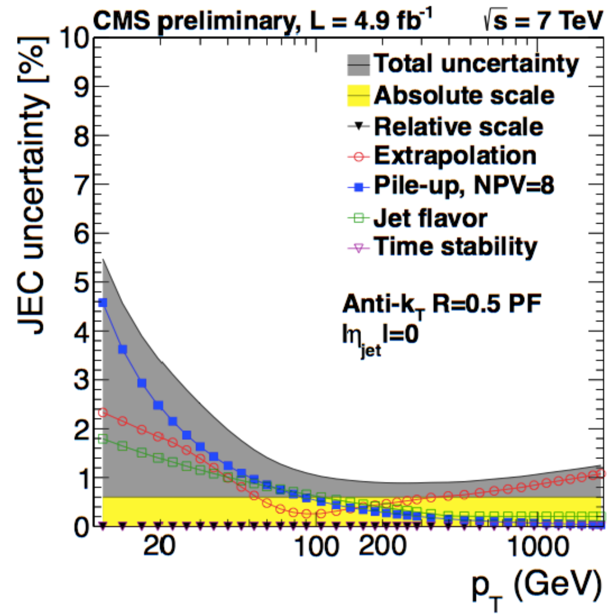
- Vector boson + jets is a thriving and fast moving field of research, at the basis of the hadron colliders programmes
  - deepens our knowledge of QCD and EW dynamics
  - improves modeling of backgrounds for searches
- Progress in understanding of W/Z+jets driven by both theory and experiments
- Theoretical predictions provide good description of data in many regions of phase space over many orders of magnitudes
- Latest results show that experimental uncertainties are often at the level or smaller than theoretical uncertainty
  - more and more data-theory discrepancies are not exposed
  - It is time re-tune the QCD models, e.g. MC generators and PDF fits, to improve theory reliability in preparation for Run 2
- Run 2 data will increase experimental sensitivity of W/Z+jets processes, and allow more measurements to be carried out
- The challenges of harsher LHC conditions are being met by experiments
  - Upgrade of trigger hardware and software
  - Re-optimisation of trigger selection

➢ Looking forward to a Run 2 as successful as Run 1!

EXTRA SLIDES

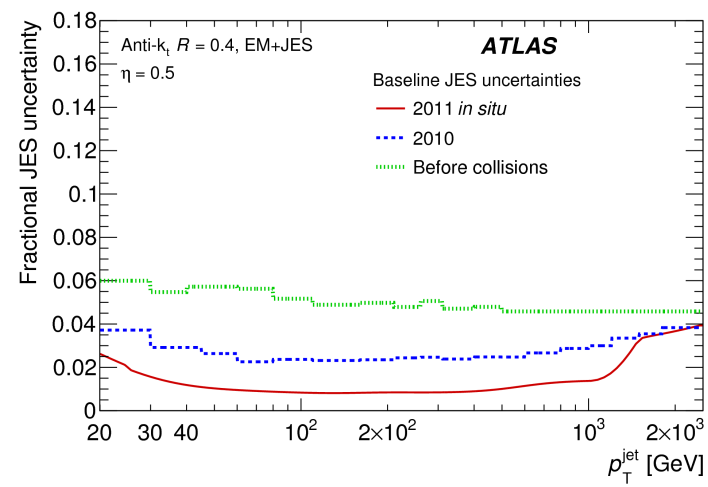
Jet Calibration

- ATLAS: calorimeter-cluster based jets (topological clusters)
- CMS: *particle flow* jets are most used
  - Particles are reconstructed from all subdetectors information, and then clustered to form jets.



- Pileup correction on jet p_T
  - offset correction or jet area subtraction
- Jet calibrated based on MC jet p_T response, plus residual in-situ calibration
  - compensate for the non-linear response of the calorimeters vs p_T and variations of the response in η

$$\frac{\mathrm{Response_{MC}}}{\mathrm{Response_{Data}}} = \frac{\left\langle p_T^{\mathrm{jet}}/p_T^{\mathrm{ref}} \right\rangle_{\mathrm{MC}}}{\left\langle p_T^{\mathrm{jet}}/p_T^{\mathrm{ref}} \right\rangle_{\mathrm{Data}}}$$

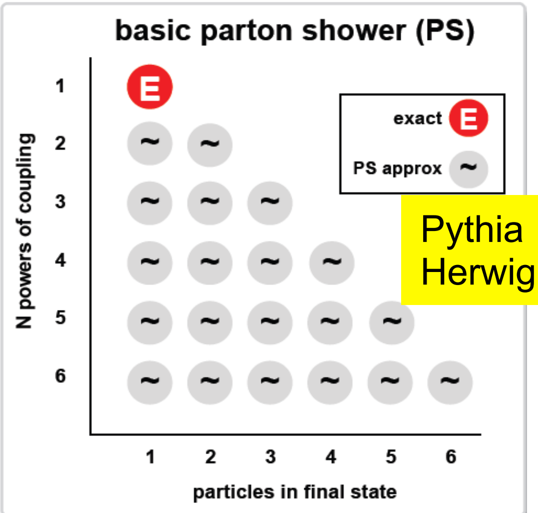


- Several in-situ methods to cover large kinematic phase space
  - dijet η-intercalibration
  - γ+jet balance,
  - Z+jet balance
  - multijet balance

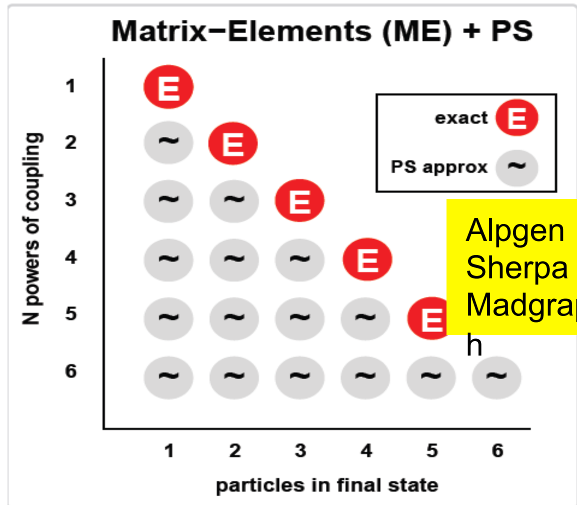
W+jets prediction accuracy

Program	Max. number of partons at approx. NNLO ($\alpha_s^{N_{\rm jets}+2}$)	NLO ($\alpha_s^{N_{\rm jets}+1}$)	LO ($\alpha_s^{N_{\rm jets}}$)	Parton/Particle level
LoopSim	1	2	3	parton level with corrections
BlackHat+SHERPA	–	5	6	parton level with corrections
BlackHat+SHERPA exclusive sums	1	2	3	parton level with corrections
HEJ	all orders, resummation			parton level
MEPS@NLO	–	2	4	particle level
ALPGEN	–	–	5	particle level
SHERPA	–	–	4	particle level

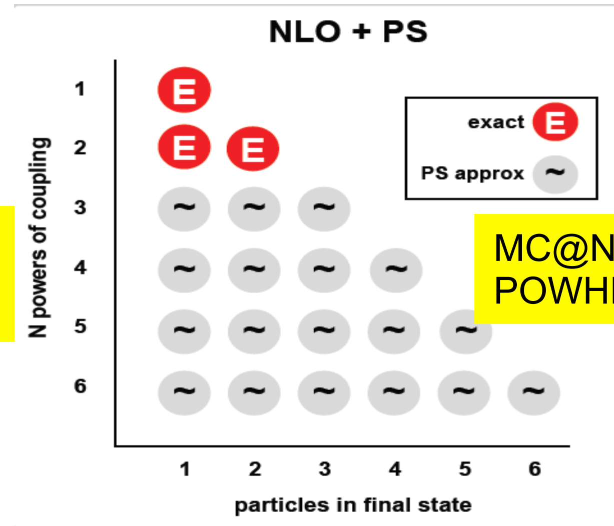
PS, ME+PS, NLO+PS



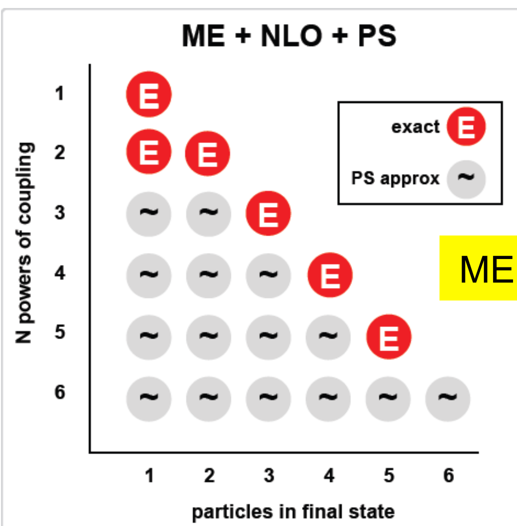
Pythia
Herwig



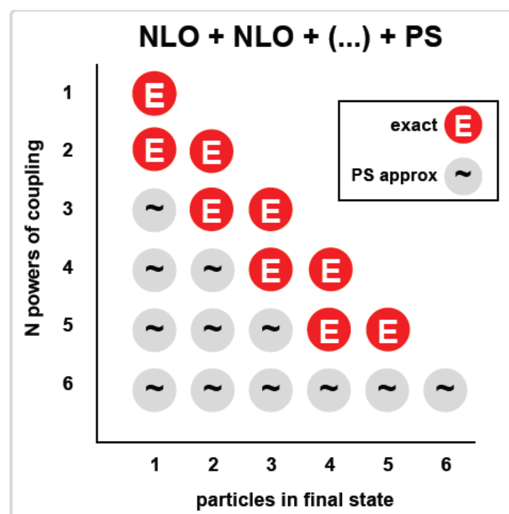
Alpgen
Sherpa
Madgraph



MC@NLO
POWHEG



MENLOPS



MEPS@NLO

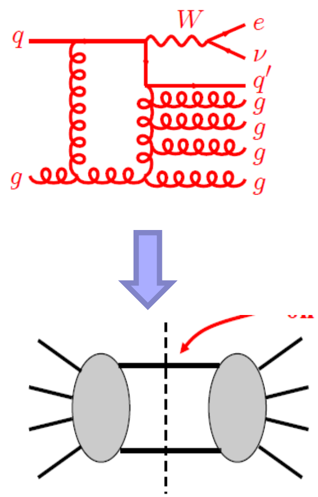
Theoretical Revolution – NLO

- Steep curve in achievements of NLO calculations in recent years thanks to a novel technique in pQFT calculations

- Feynmann diagrams clumsy for high multiplicity processes
  - Origin of complexity is that vertices and propagators involve gauge-dependent off-shell states ($p^2 \neq m^2$)

- Recent years breakthrough based on Unitarity Principle
  - Only gauge invariant on-shell quantities appear in intermediate step
  - ⇒ On-shell formalism reduces problem to tree-like calculation
    - no more need for calculating hundreds of loop diagrams

  - On-shell methods applied on variety of problems
    - N=4 Super Yan-Mills problems
    - UV properties of gravity



- Main programs for Fixed Order NLO W/Z+jets:
  - MCFM/Rocket
  - Blackhat Z+4 jets and W+5 jets
    - **NB: Parton Level** i.e. no hadronisation nor simulation of multi-parton interaction (underlying event)

Non-perturbative corrections

on parton-level pQCD Z+jets calculations at 7 TeV

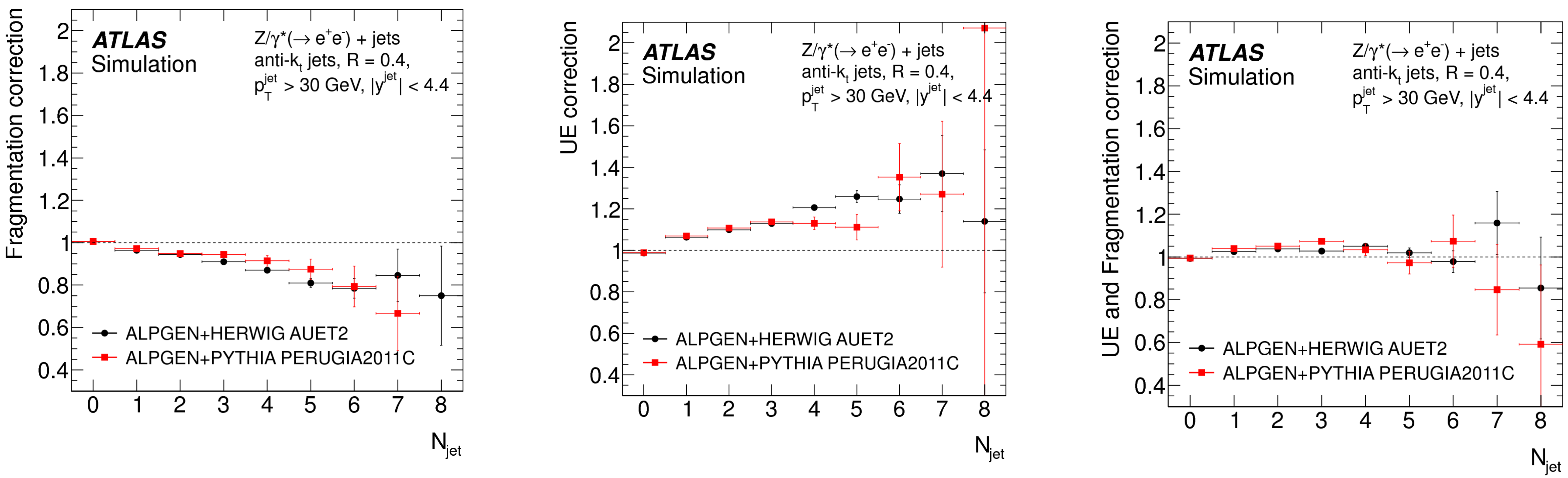
Non-perturbative contributions

- **UE: δ_{UE}**

$$\delta_{\text{UE}} = \frac{\text{hadron level, UE on, born leptons}}{\text{hadron level, UE off, born leptons}}$$

- **Fragmentation: δ_{had}**

$$\delta_{\text{had}} = \frac{\text{hadron level, UE off, born leptons}}{\text{parton level, UE off, born leptons}}$$



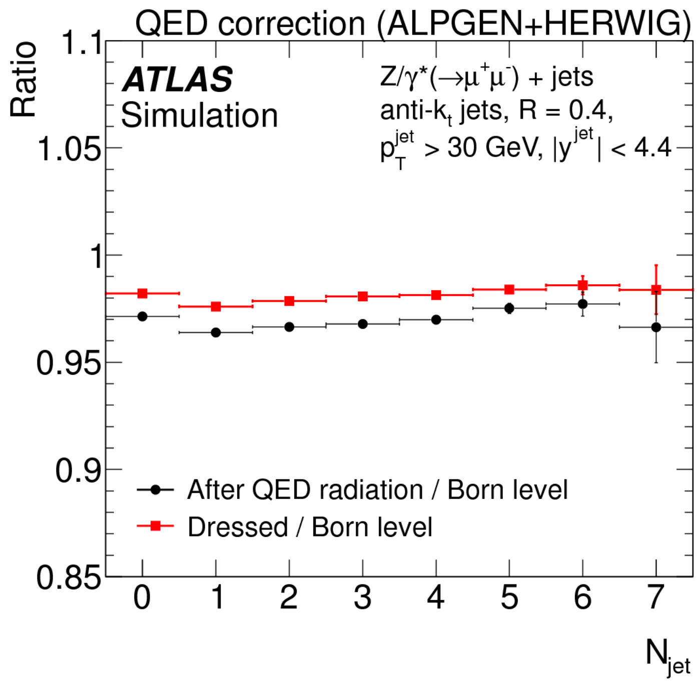
➢ Non-perturbative corrections mainly cancel: *~3%-4% correction*

QED FSR corrections

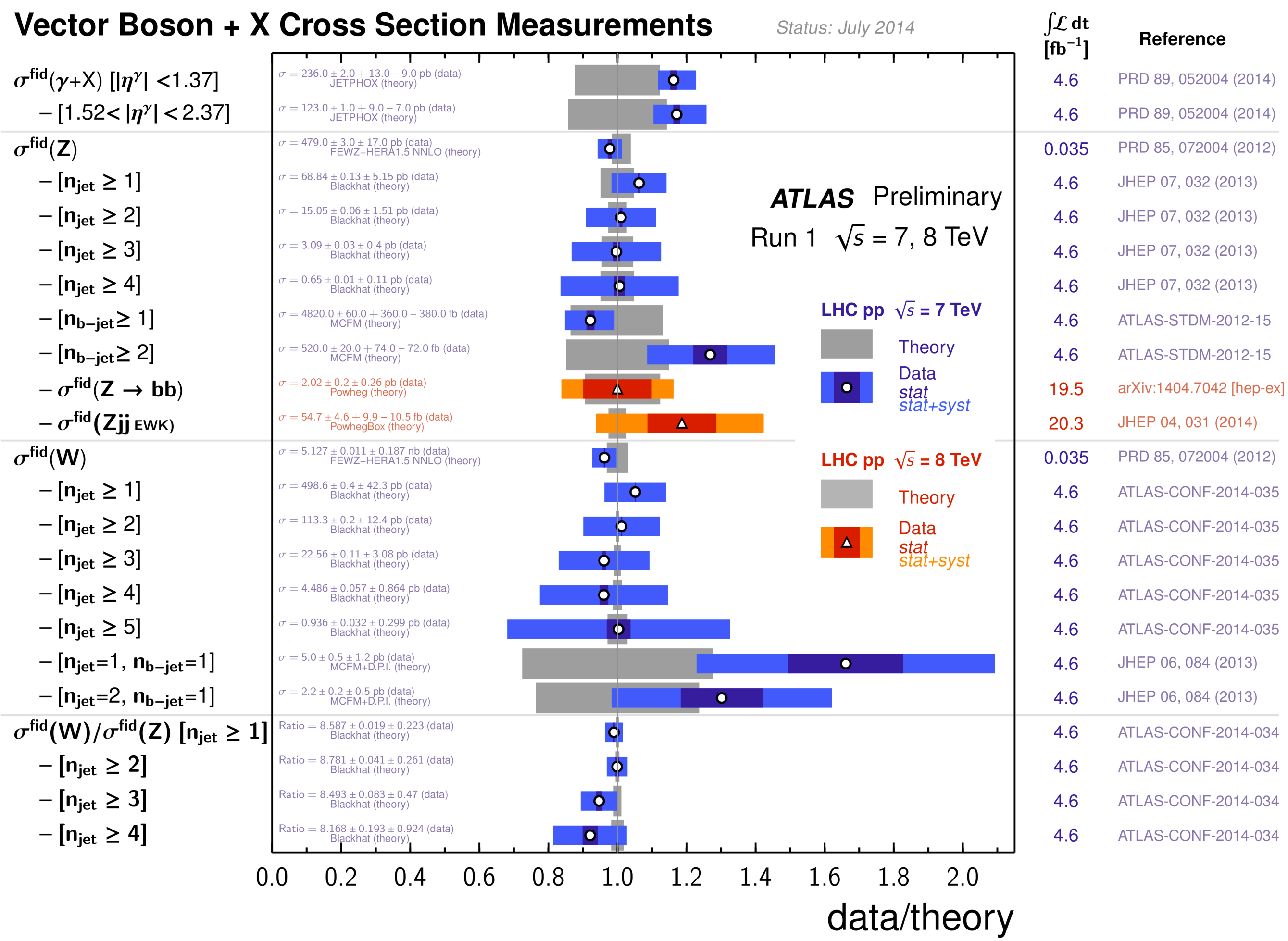
on pQCD Z+jets calculations at 7 TeV

QED corrections:

- Born → dressed (add γ in $\Delta R<0.1$) : 1% per lepton
- Bare (after QED radiation) → Born (before QED radiation): 3% per lepton



LHC Snapshot of V+jets



ATLAS W+jets at 7 TeV

Signal yield and background fractions

N_{jet}	0	1	2	3	4	5	6	7
				$W \to e\nu$				
$W \to e\nu$	94%	78%	74%	59%	37%	24%	14%	11%
Multijet	4%	11%	12%	11%	7%	6%	5%	4%
$t\bar{t}$	<1%	<1%	3%	18%	46%	63%	77%	81%
Single top	<1%	<1%	1%	2%	2%	2%	1%	1%
$W \to \tau\nu$, diboson	2%	3%	3%	3%	2%	1%	1%	1%
$Z \to ee$	<1%	8%	7%	7%	5%	4%	3%	3%
Total Predicted	11 100 000 ± 640 000	1 510 000 ± 99 000	352 000 ± 23 000	88 300 ± 5600	27 700 ± 1400	8420 ± 430	2510 ± 200	567 ± 61
Data Observed	10 878 398	1 548 000	361 957	91 212	28 076	8514	2358	618
				$W \to \mu\nu$				
$W \to \mu\nu$	93%	82%	79%	63%	40%	26%	17%	11%
Multijet	2%	11%	10%	10%	7%	5%	4%	3%
$t\bar{t}$	<1%	<1%	3%	20%	47%	65%	76%	84%
Single top	<1%	<1%	1%	2%	2%	2%	1%	1%
$W \to \tau\nu$, diboson	2%	3%	3%	3%	2%	1%	1%	<1%
$Z \to \mu\mu$	3%	4%	3%	3%	2%	1%	1%	1%
Total Predicted	13 300 000 ± 770 000	1 700 000 ± 100 000	383 000 ± 24 000	95 400 ± 5700	29 600 ± 1300	8860 ± 420	2370 ± 180	622 ± 66
Data Observed	13 414 400	1 758 239	403 146	99 749	30 400	9325	2637	663

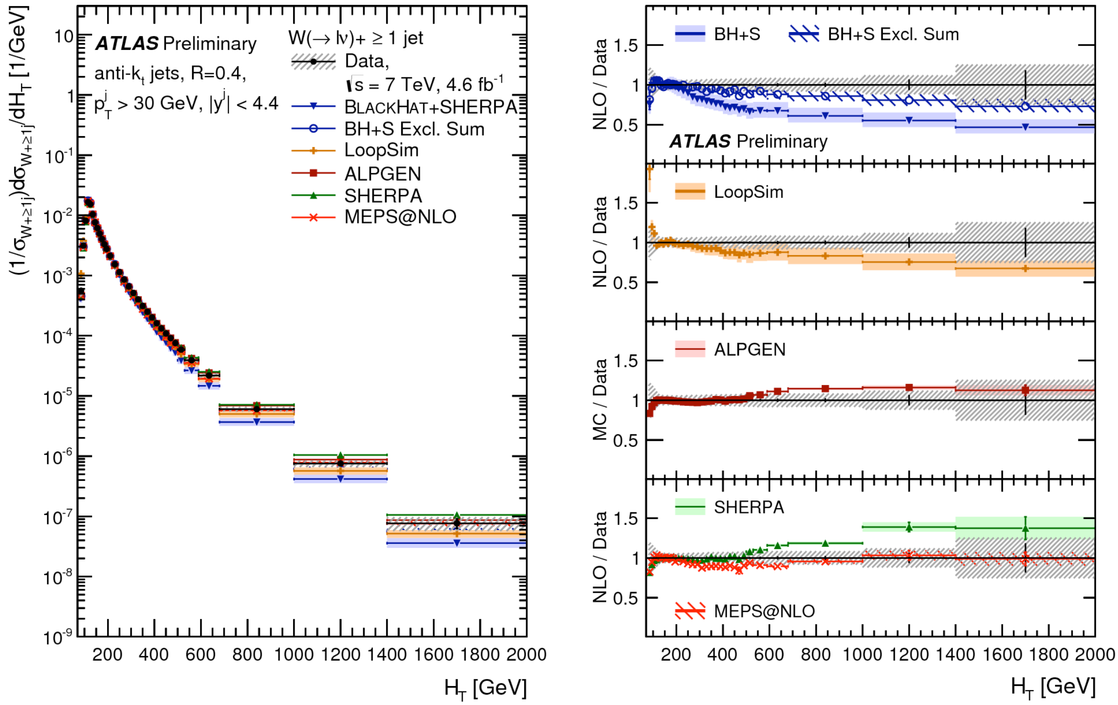
ATLAS-CONF-2014-035

H_T in W+jets at 7 TeV

ATLAS:
Lepton p_T>25 GeV, |η|<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, |y|<4.4
ΔR(l,j) > 0.5
Missing E_T>25 GeV, M_T>40 GeV

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

- used to discriminate SM from New Physics (e.g. SUSY)
- used to set scales in multi-scale processes (e.g. W/Z+jets)



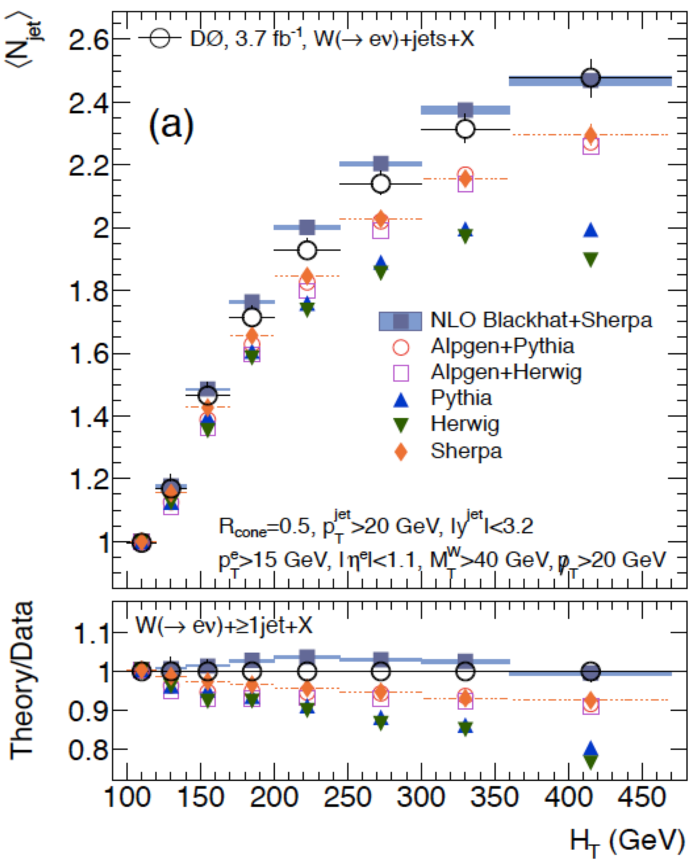
- Discrepancies on H_T with NLO calculations (BlackHat):
  - Mean N_{jets} >2 at large H_T
  - Agreement improved on H_T with BlackHat by replacing NLO W+ ≥ 1 jet with *exclusive sum*:

$$W + \geq 1 = (W + 1) + (W + 2) + (W + 3) + (W + \geq 4)$$

- LO multileg generators over-predict H_T at high scales
- MEPS@NLO does very well up to high H_T

Tevatron results - W+jets

Phys. Rev. D 88 (2013) 092001

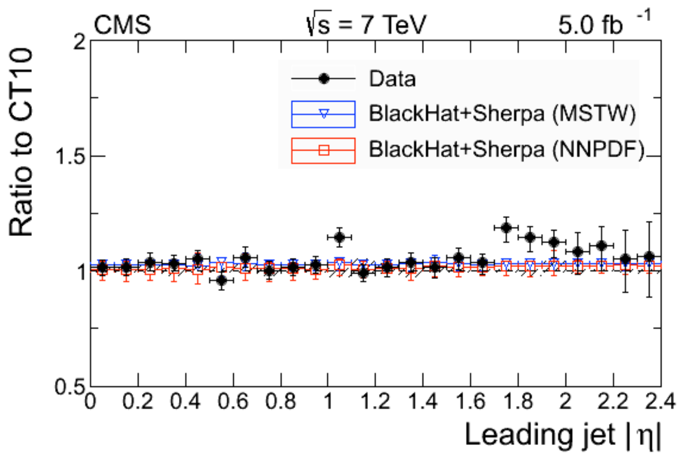


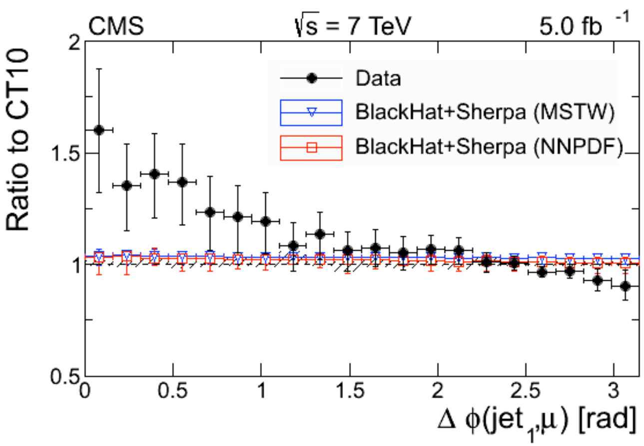
- ❑ H_T is important observable
  - used to discriminate SM from New Physics
  - used to set scales in multi-scale processes
- ❑ Average number grows as function of H_T
  - Exceeds 2 for H_T~250 GeV
- ➢ NLO pQCD calculation agrees with data over all H_T range
- ➢ LO M.E. + P.S. simulation underestimate <N_{jets}> at high H_T

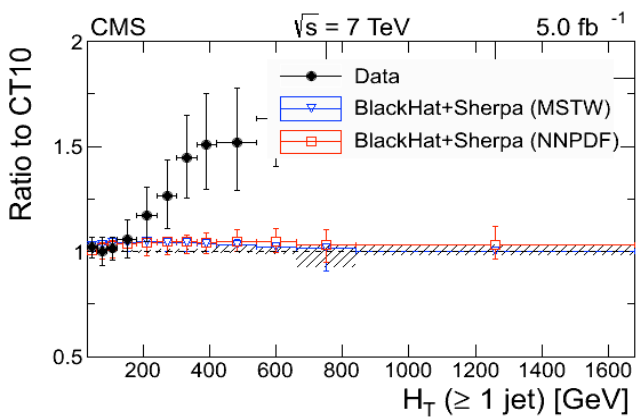
Angular distributions

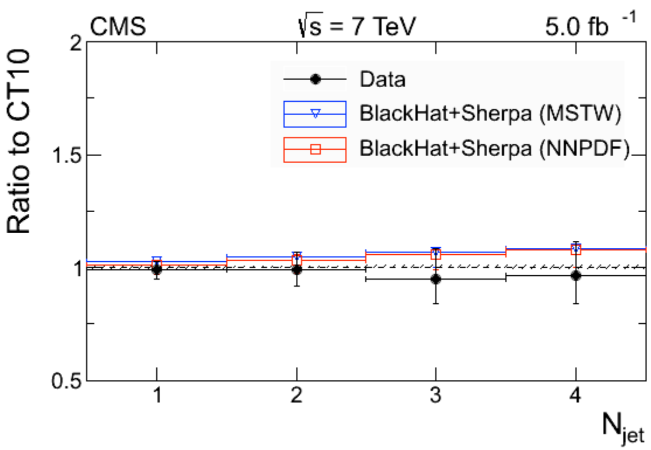
in W+jets at 7 TeV

PDF study by CMS



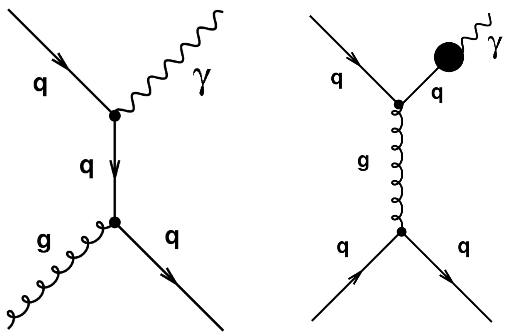


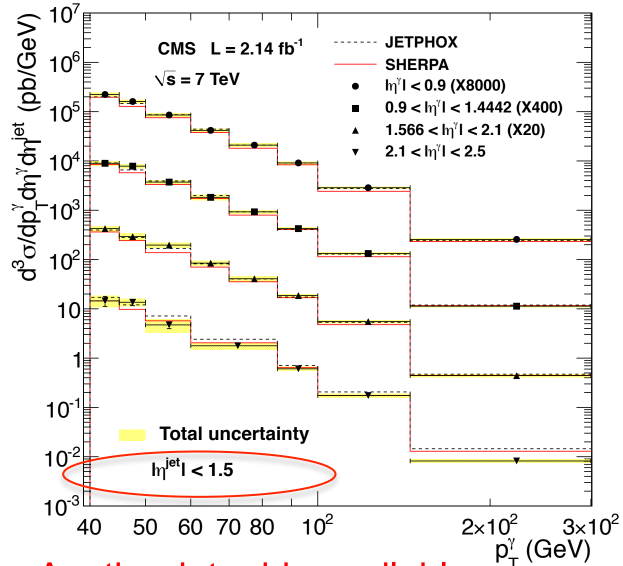




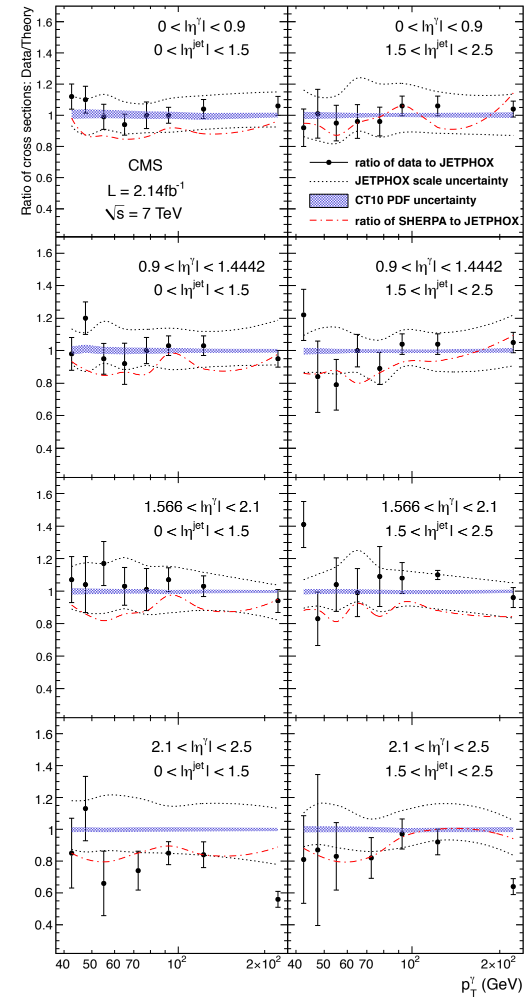
γ+jets at LHC at 7 TeV

- Triple differential cross-section: γ p_T, γ rapidity and jet p_T
- Comparison with predictions by NLO pQCD (JETPHOX) and LO MC (Sherpa)



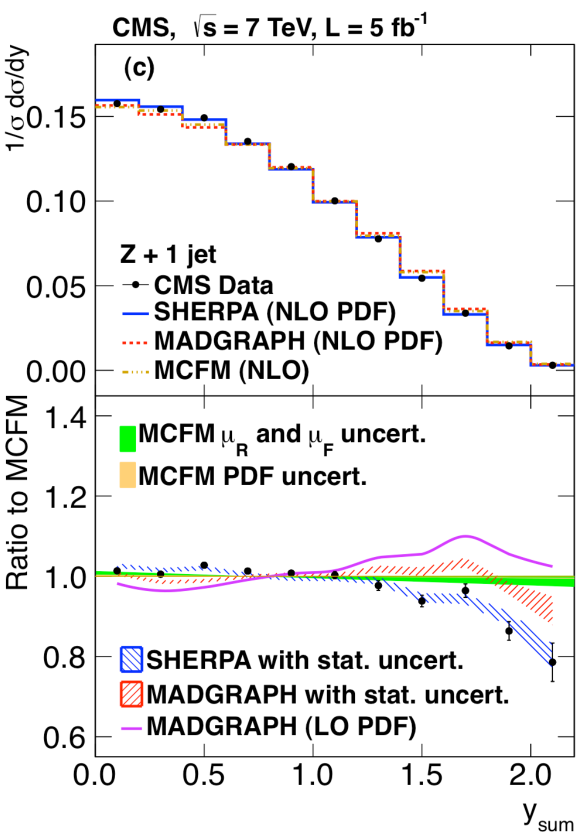


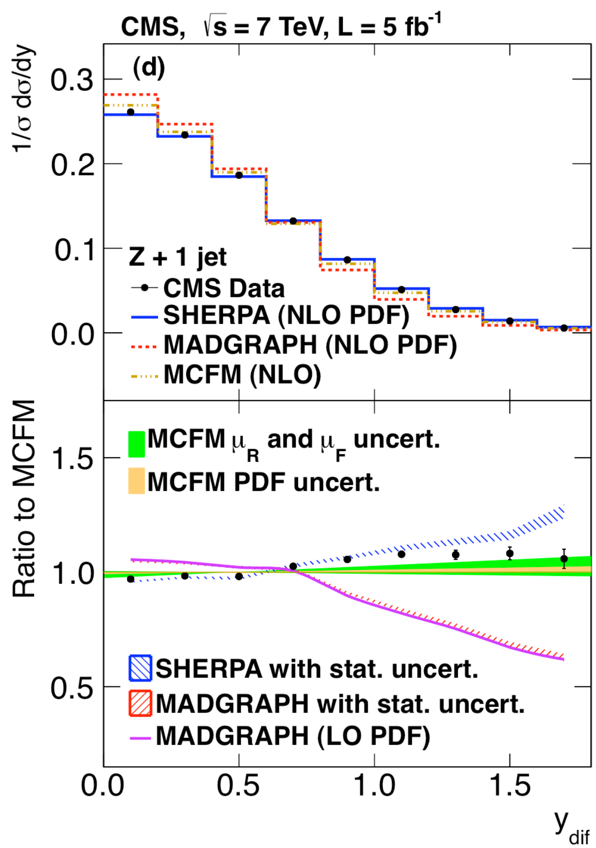
Another jet η bin available
$1.5 < |\eta^{jet}| < 2.5$



➢ Sherpa and JETPHOX are consistent with data except for cases of photons in the largest η and p_T regions

Z/γ+jets rapidity distributions at 7 TeV





$$y_{\mathrm{sum}} = |y_V + y_{\mathrm{jet}}|/2$$

$$y_{\mathrm{dif}} = |y_V - y_{\mathrm{jet}}|/2$$

- ❑ y_{sum} sensitive to PDF
- ❑ y_{diff} sensitive to MC modeling of jet radiation
  - i.e. M.E.-P.S. matching

➢ Striking divergence of MADGRAPH predictions on y_{diff}

❑ similar findings in same analysis with γ + jet events

W/Z+jets at Tevatron and LHC

- LHC is not a simple rescaling of Tevatron scattering

- Probe different Bjorken-x, parton densities and processes
  - Tevatron has significant valence quark contribution
  - LHC has significant gluon and sea contribution
    - x at Tevatron typically larger than at LHC

  - Z+2jets: qg →Zqg fraction ~75% (LHC), ~25% (Tevatron)
  - qq initiated processes relative smaller contribution at LHC than Tevatron (e.g. qq→Zbb vs gb →Zb)

- LHC provided larger cross sections than Tevatron
  - W+4jets cross section at LHC 500x larger (with same kinematic cuts)
  - Inclusive Zb cross section at LHC 50x larger [Phys. Rev. D 69, 074021]

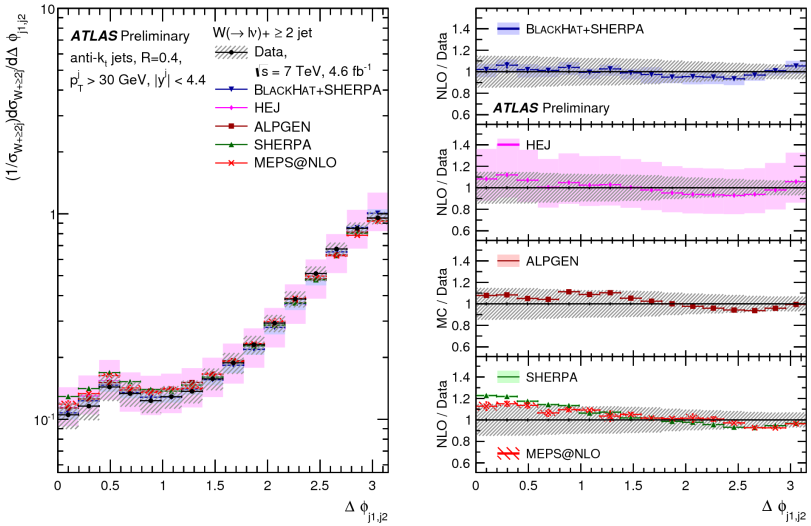
W+N-jets at LHC

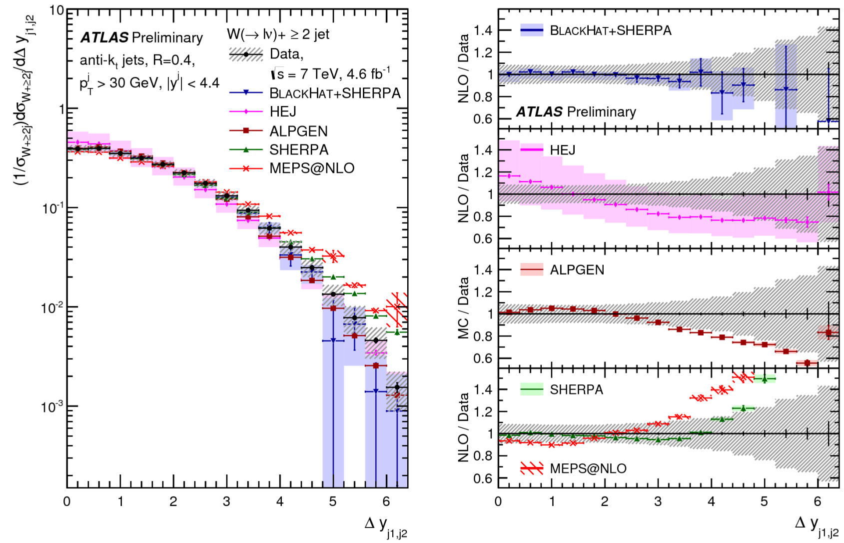
N	QQ (%)	Qg (%)	gg (%)
0	100	-	-
1	18	82	-
2	21	73	6
3	23	70	7
4	25	67	8

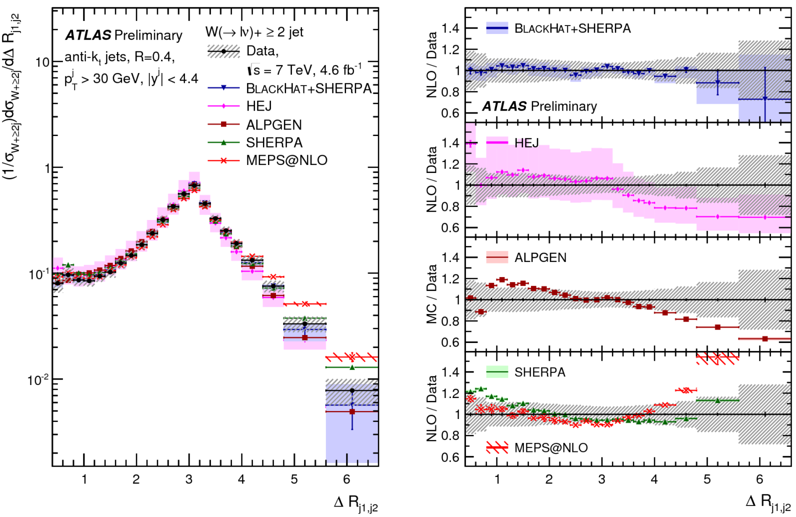
arXiv:1004.3404

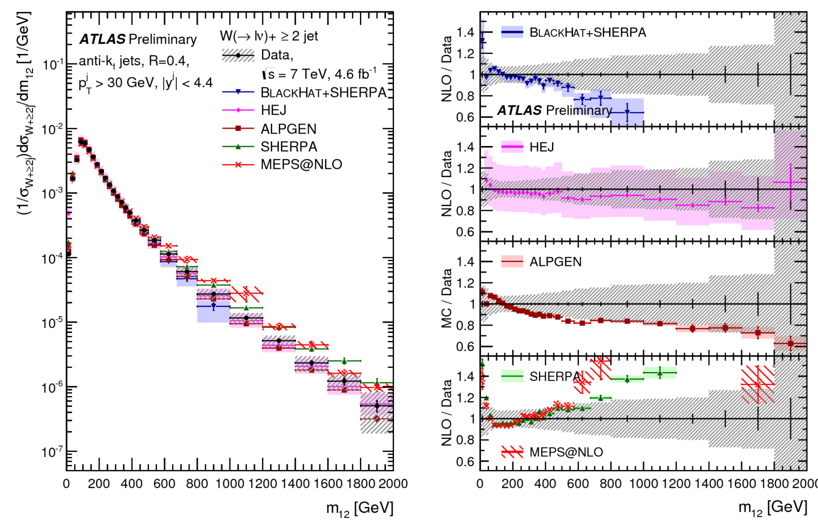
Angular distributions and m_{jj}

in W+jets at 7 TeV



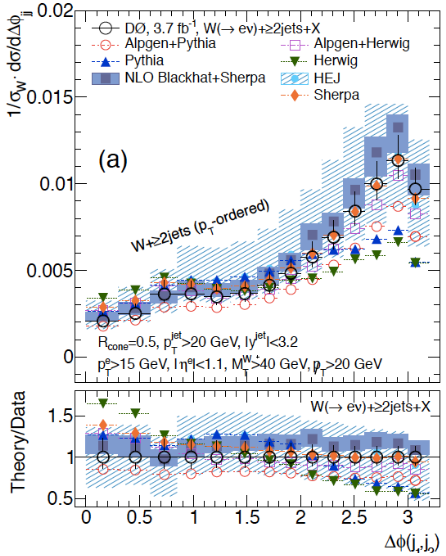


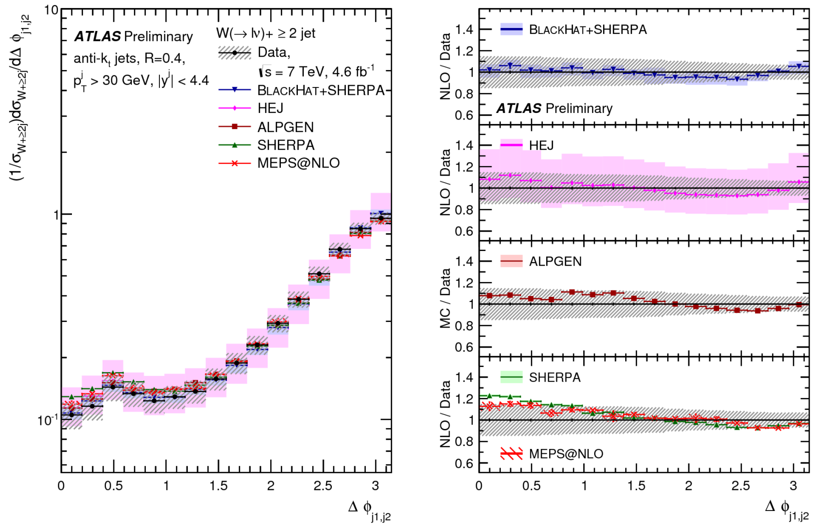


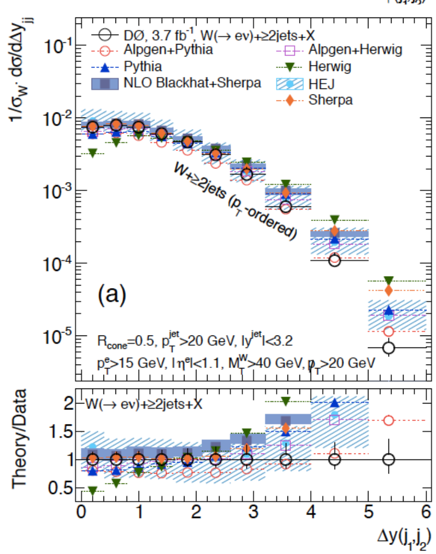


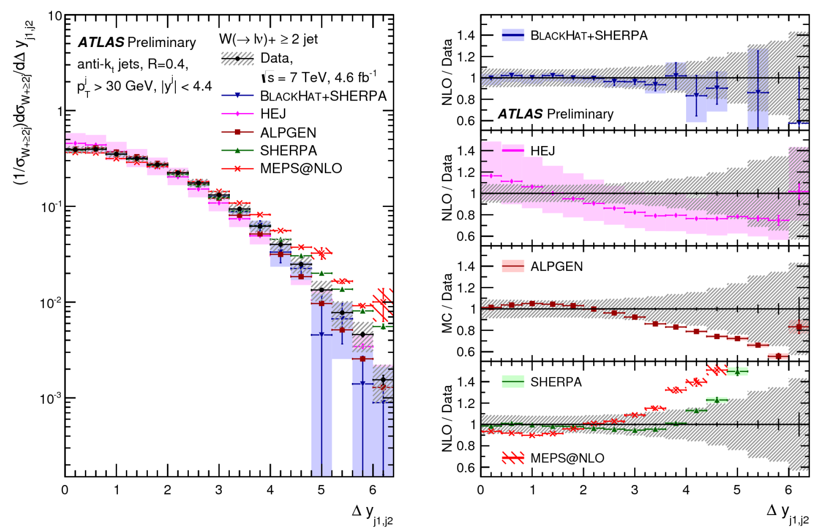
Angular distributions

in W+jets at 1.96 and 7 TeV







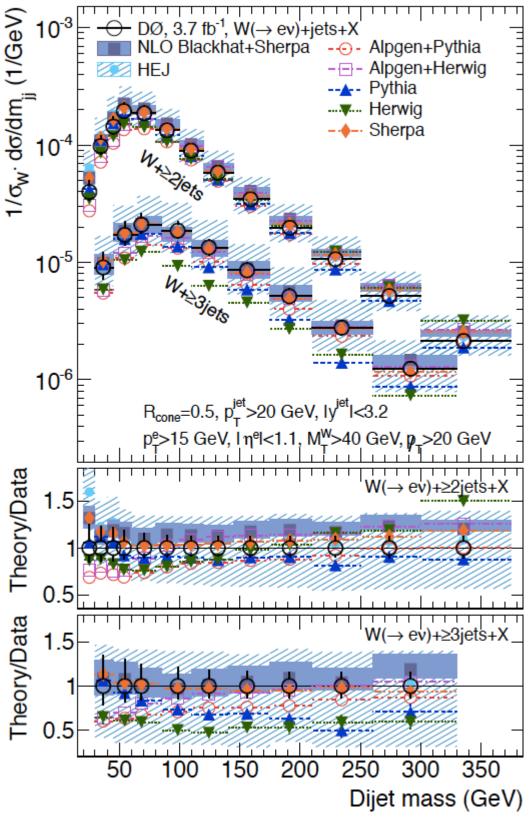


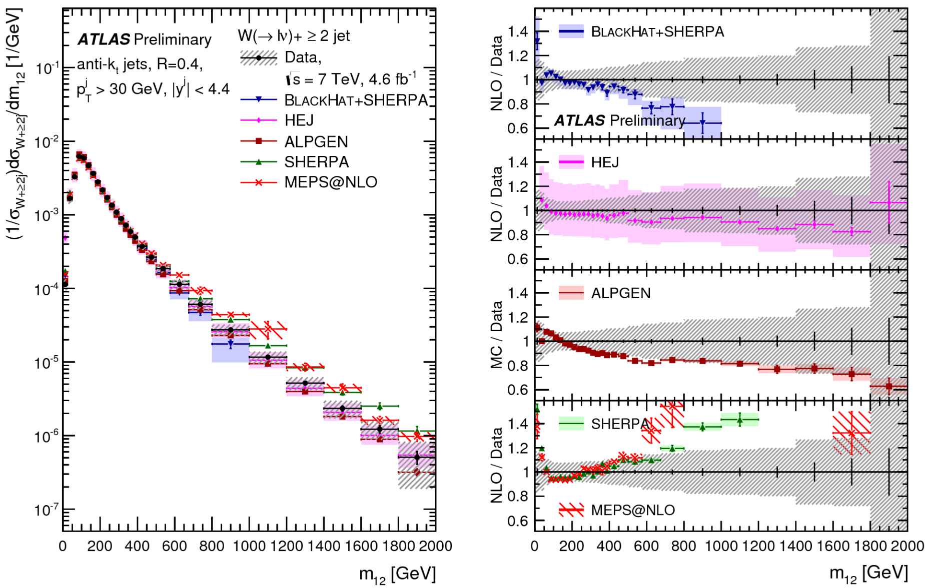
Similar discrepancies on angular distributions at Tevatron and LHC

- e.g. Sherpa and Alpgen mismodeling of $\Delta\phi$(j1,j2)

m_{jj}

in W+jets at 1.96 and 7 TeV

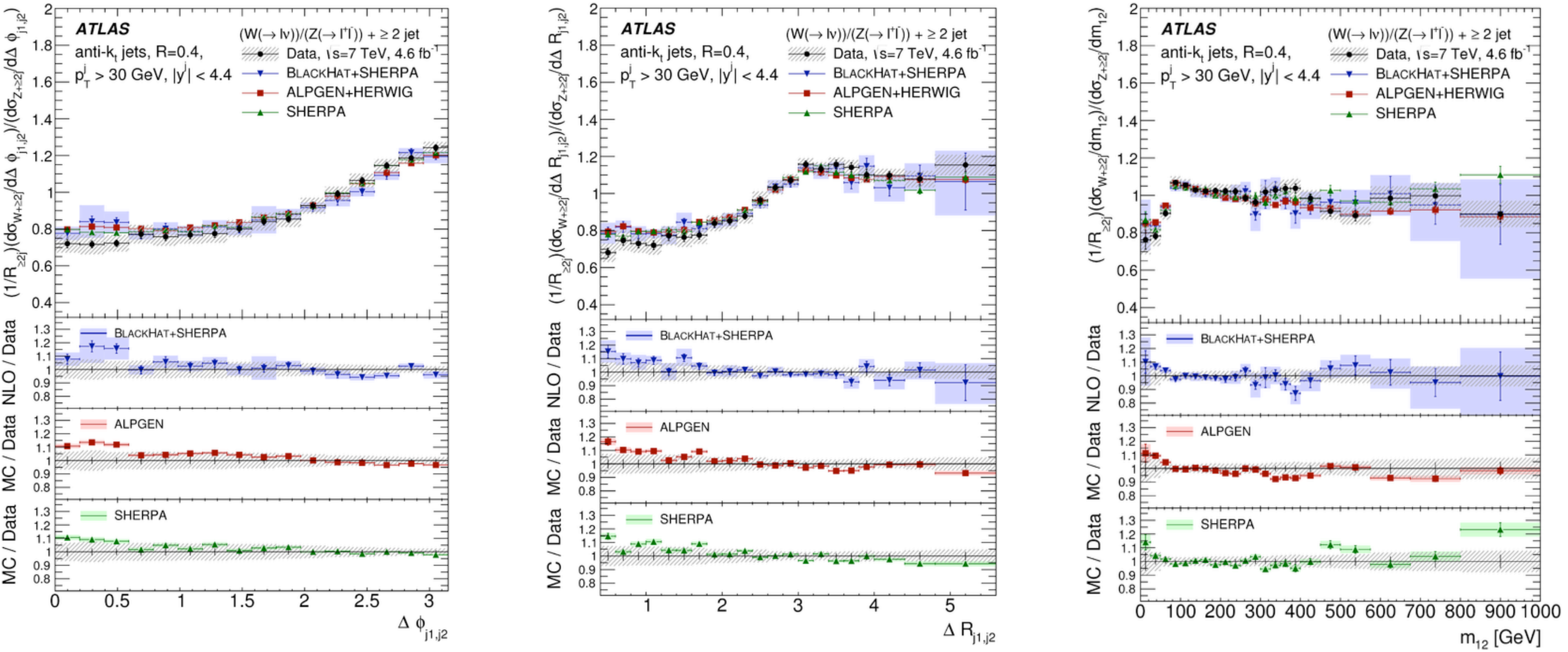




- Smaller m_{jj} range at Tevatron than LHC
- Discrepancies seen at LHC are less evident at Tevatron

Angular distributions

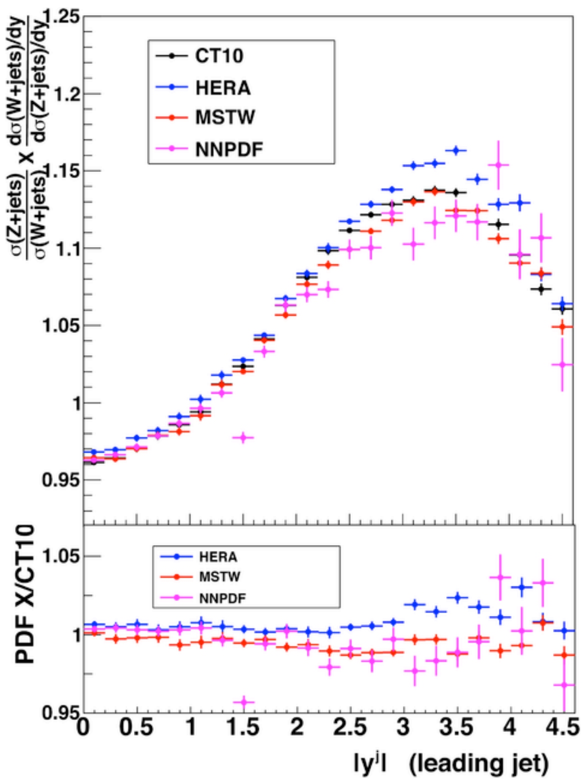
In Rjets at 7 TeV

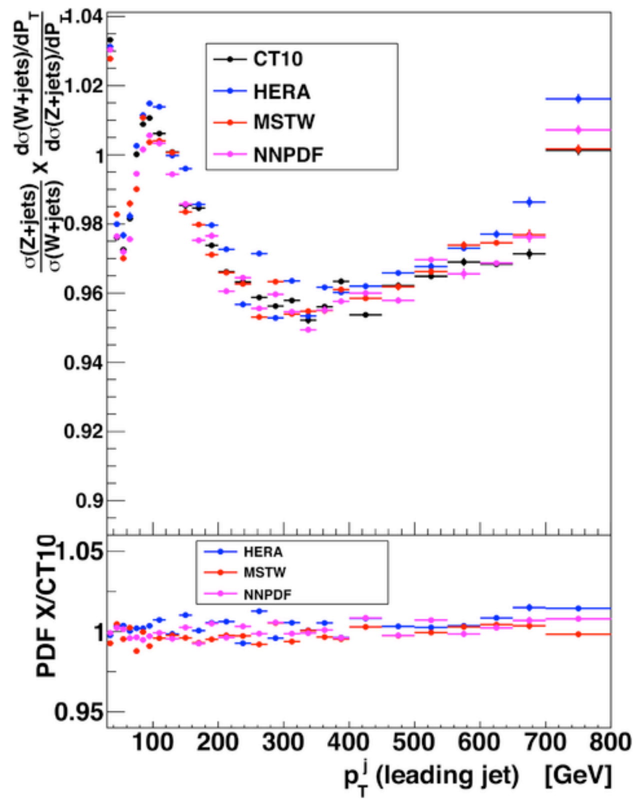


Jet Rapidity

In Rjets at 7 TeV

PDF study by ATLAS

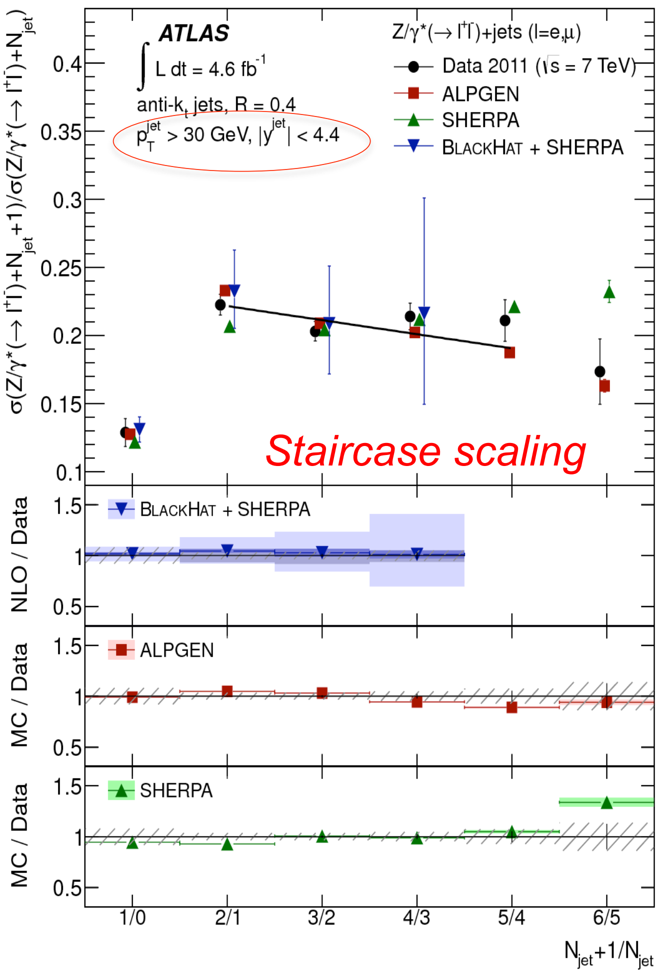


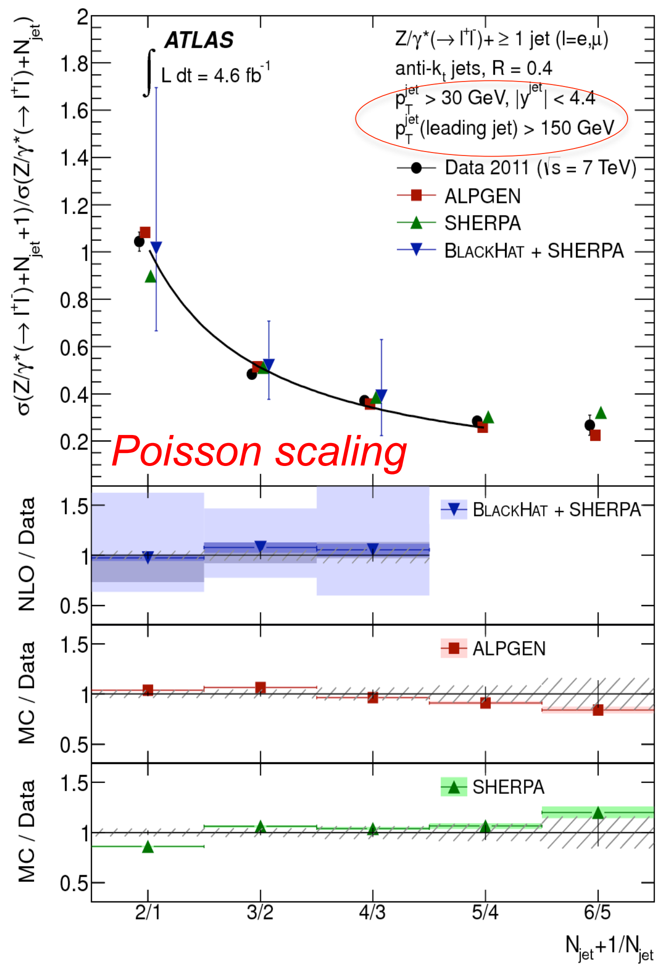


➢ Experimental uncertainty still too large to be sensitive to PDF with Rjets

Z+jets at 7 TeV - Scaling

- QCD scaling properties useful in analyses that employ jet vetoes to separate signal from W/Z+jets backgrounds





Exclusive Ratios:

$$R_{(n+1)/n} = N_{Z+(n+1)} / N_{Z+n}$$

- Staircase scaling:
  - with *Symmetric* jet p_T
  - => $R_{(n+1)/n}$ constant
- Poisson scaling:
  - with *Asymmetric* jet p_T
  - =>

➢ Scaling properties are well modeled by theory

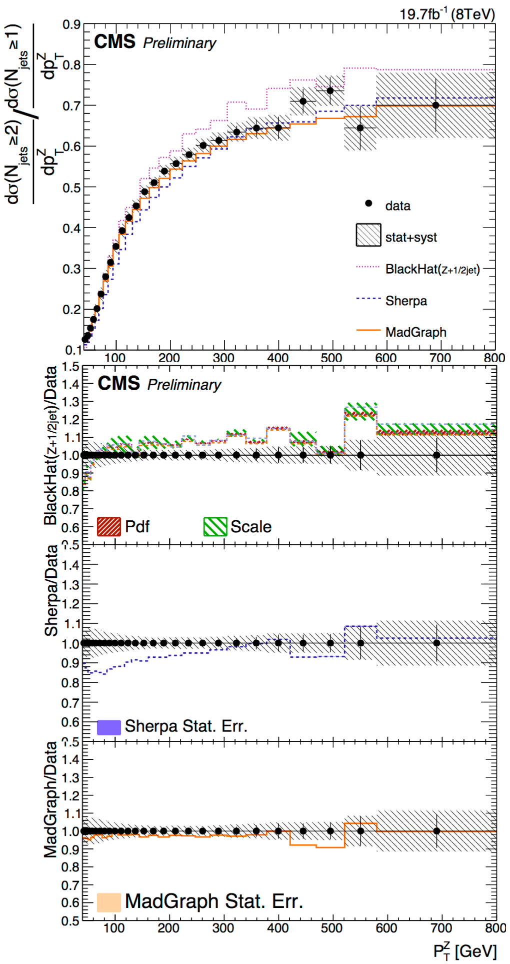
Z+jets - Scaling

- Poisson scaling (known in FSR QED at e+e- colliders) when large difference between the scale of the process Q and the radiation cut-off scale Q0.
  - For Q>>Q0 each emission is independent from the previous one (primary emission, i.e. off the hard parton leg)
  - For Q~Q0 emissions are correlated (secondary emissions, i.e. from newly produced quark line)
- At hadron colliders:
  1. **Poisson Scaling** ($R_{(n+1)/n} = \langle n\rangle/n+1 \Leftarrow P_n = \langle n\rangle^n e^{-\langle n\rangle} / n!$) – Abelian
     - With asymmetric selection, with hierarchy of jet scales
     - Large difference between the core-process scale and the jet acceptance cut
       - 1st jet pT >150 GeV, all other jet pT>30 GeV, in Exclusive Ratios only
     - At large N_{jets} Staircase will dominate
  2. **Staircase Scaling** ($R_{(n+1)/n} = R = e^{-b} \Leftarrow \sigma_n = \sigma_0 e^{-bn}$) – Non-Abelian
     - With democratic jet selection and no major scale separations
       - E.g. All jet pT>30 GeV, in Exclusive and Inclusive Ratios
     - $R_{1/0}$ suppressed by PDF (by 60%), otherwise would be very large value

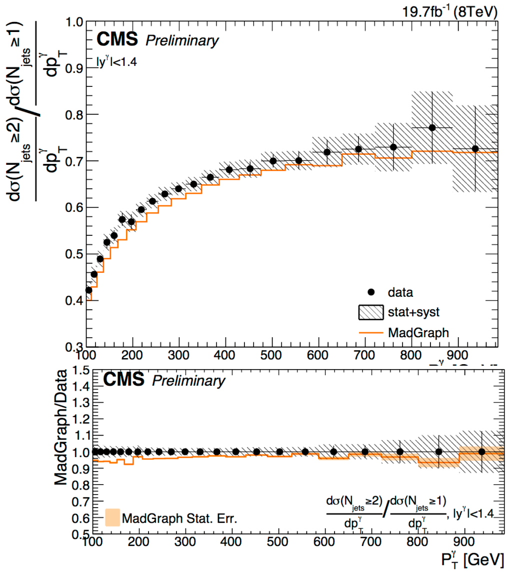
jet rates in γ/Z+jets at 8 TeV

Lepton p_T>20 geV |η|<2.4
V-boson p_T>100 GeV
γ-boson |y| < 1.4
antiKt5 jet p_T>30 GeV, |η|<2.4
ΔR(l,j) > 0.5

Z+jets



γ+jets



- Inclusive 2-over-1 ratio vs boson p_T
  - Systematics correlated in ratio

- BlackHat for Z+1,2,3 Partons
- Particle-level comparison with LO ME Z +≤4 jets
  - Magraph+Pythia6, Sherpa

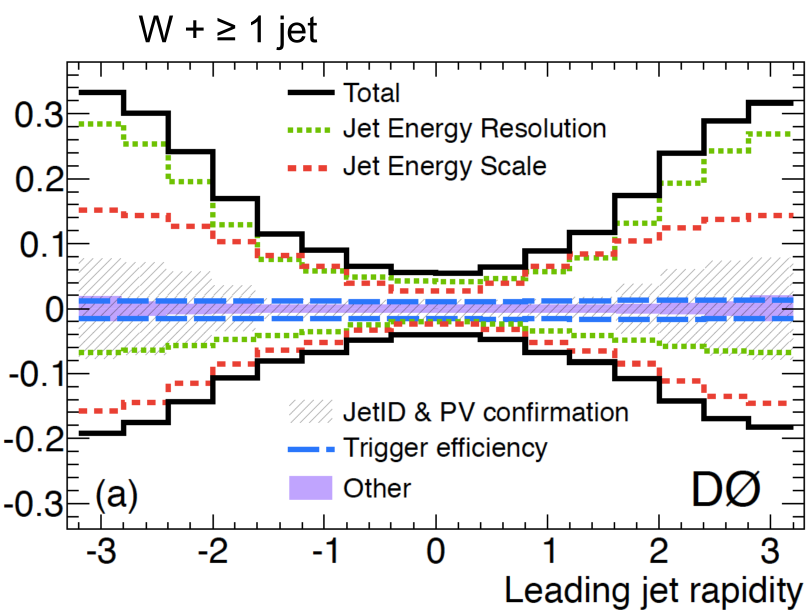
- Madgraph's discrepancies in N_{jets} ≥1 and ≥2 jet samples cancel in ≥2 / ≥1 ratio
- Discrepancies with NLO and Sherpa by ~ ±10%

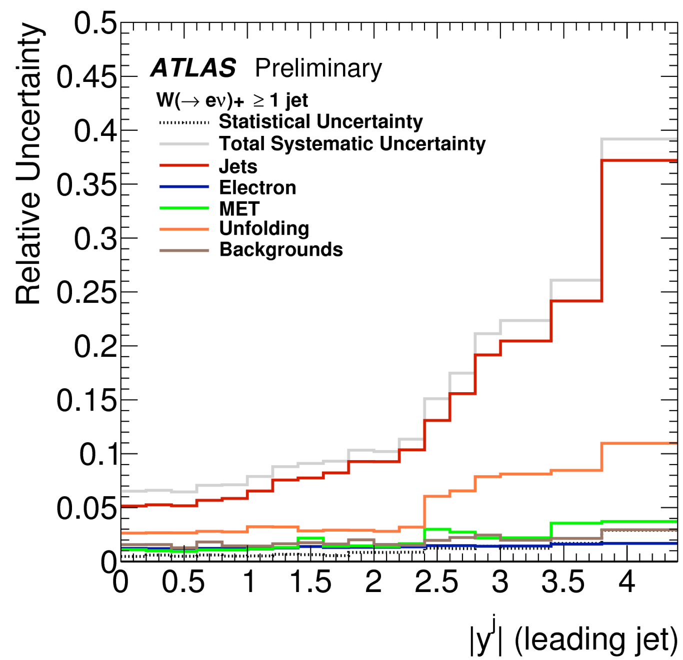
D0:
electron p_T>15 GeV $|\eta|$<1.1
Missing E_T > 20 GeV, M_T>40 GeV
Midpoint R=0.5, Jet p_T > 20 GeV, $|y|$<3.2
ΔR(ele, jet)>0.5

ATLAS:
Lepton p_T>25 GeV, $|\eta|$<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, $|y|$<4.4
ΔR(l,j) > 0.5
Missing E_T>25 GeV, M_T>40 GeV

W+jets

Tevatron vs LHC uncertainties





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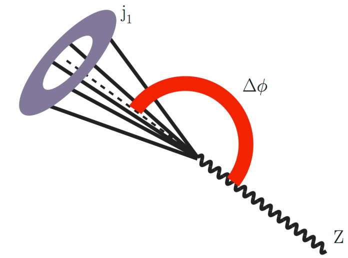
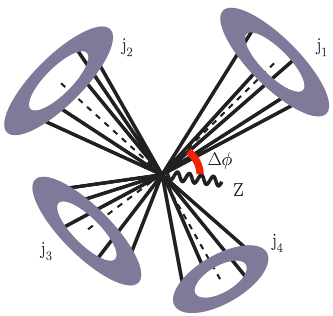
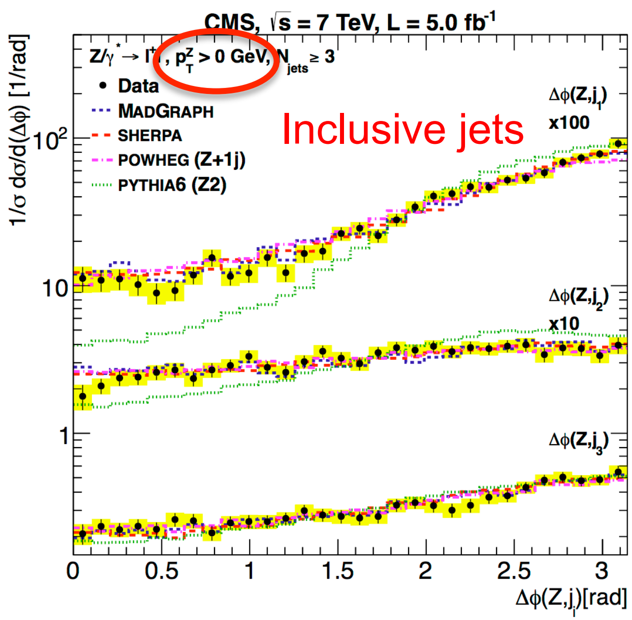
Matrix Element vs Parton shower

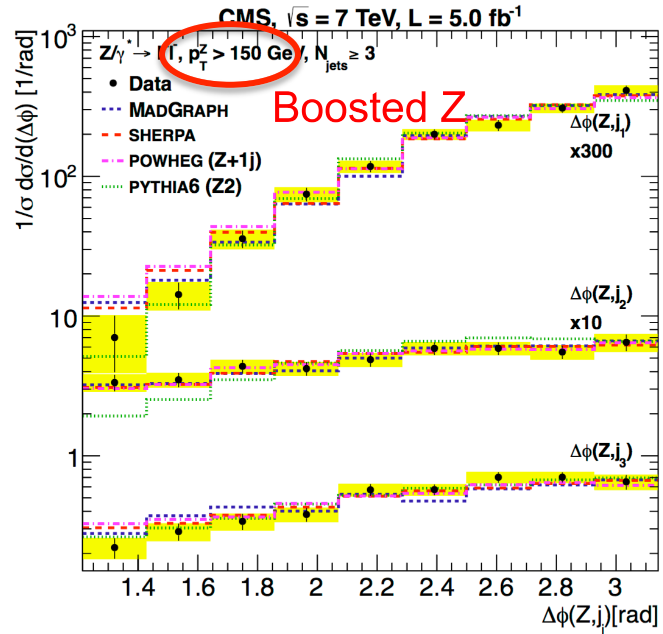
Azimuthal Correlations

In Z+jets at 7 TeV









- large correlation between Z and leading jet
- smaller correlation between Z and subleading jets
- with boosted Z the correlarion Z-1st jet is enhanced

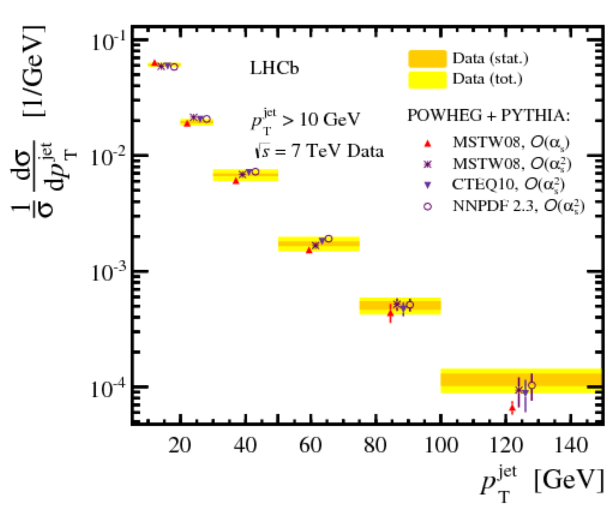
- Boosted Z topology important as background for searches with missing ET

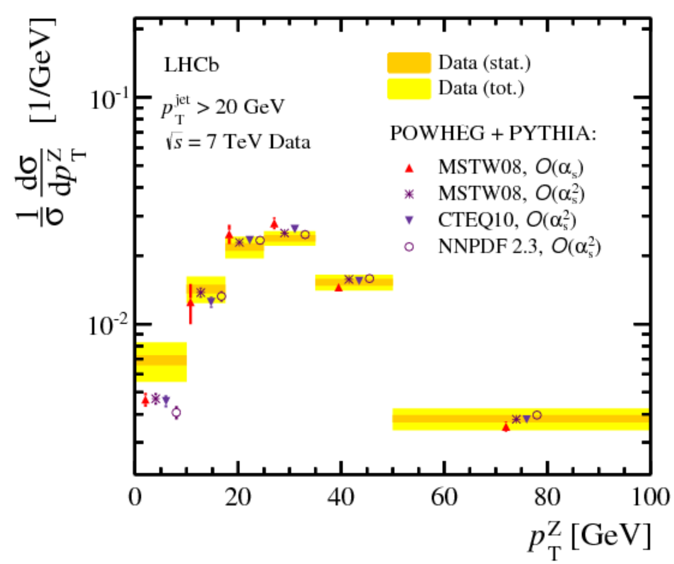
- Good modeling by LO multi-leg (Sherpa, MadGraph) and NLO Z+1 (Powheg) generators
- PS prediction (Pythia6) at small $\Delta\phi$ better modeling at high Z p_T

MC simulation, PDF

PDF sensitivity in Z+jets at 7 TeV with LHCb

- Forward Z+jets study with LHCb detector, muons from Z decay and jets in 2.0< |η| <4.5 with 1fb^{-1}
  - Two jet selections: jet p_T>10, 20 GeV, with anti-kt R=0.5 and $\Delta R(\mu,jet)$>0.4
  - MC generator and PDF studies



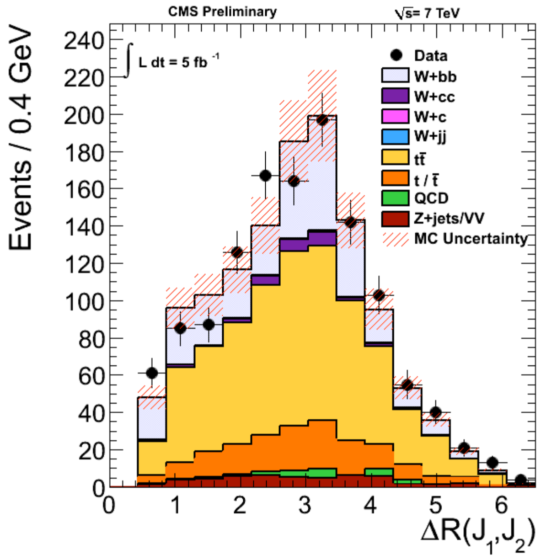


- NLO PDF agree better with data than LO
  - e.g. Z p_T and jet p_T spectra are steeper for LO than NLO and data

W + bb

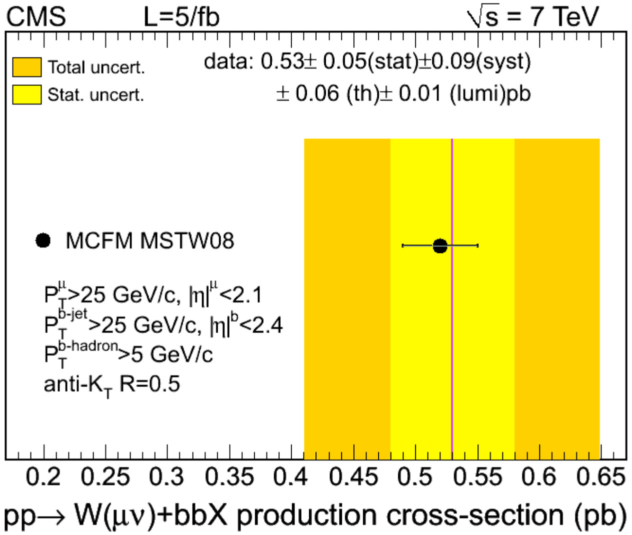
arXiv.1312.6608

CMS – muon channel only
- $p_{T\mu}$ > 25 GeV, $|\eta_\mu|$ < 2.1
- AntikT5, Jet p_T > 25 GeV, $|\eta|$ < 2.4
- m_T > 45 GeV
- **Exactly two b-jets**



- W+bb probes gluon splitting into b-quark pair
- Analysis reconstructs 2 well-separated b-jets
- Top-quark pair is largest background
  - Top control samples used to constrain bkg normalisation

- Simultaneous fit of W+bb and ttbar background in signal (p_T^{J1}) and control region ($m_{j3,j4}$)

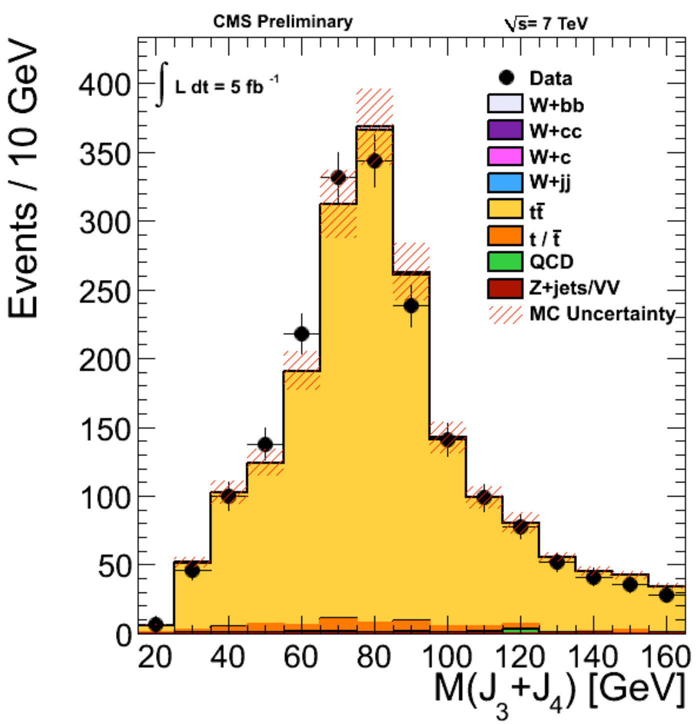


➢ agreement data and NLO prediction

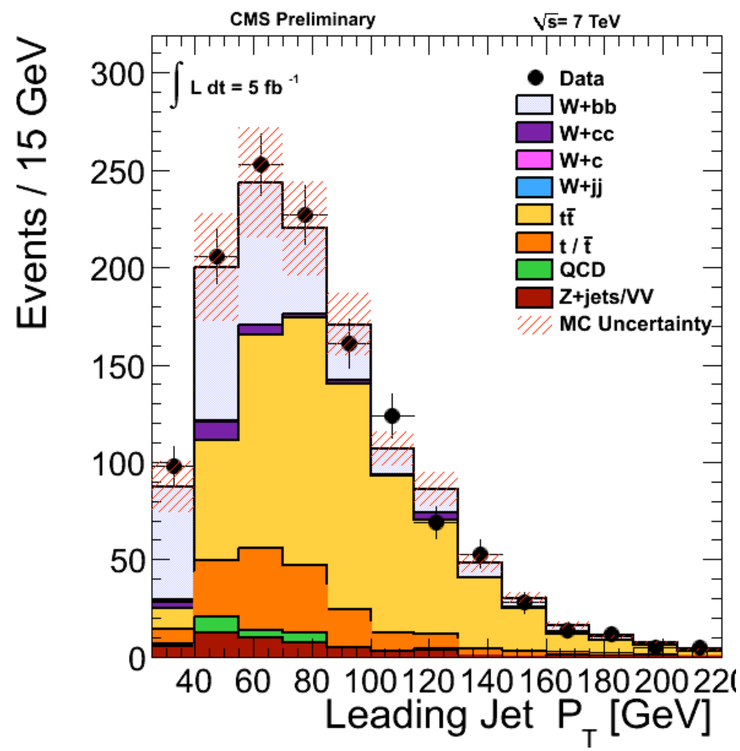
CMS – muon channel only

- $p_{T\mu} > 25$ GeV, $|\eta_\mu| < 2.1$
- AntikT5, Jet $p_T > 25$ GeV, $|\eta| < 2.4$
- $m_T > 45$ GeV
- **Exactly two b-jets**

W + bb



ttbar control region:
2 jets in addition to the 2 b-tagged jets



signal region

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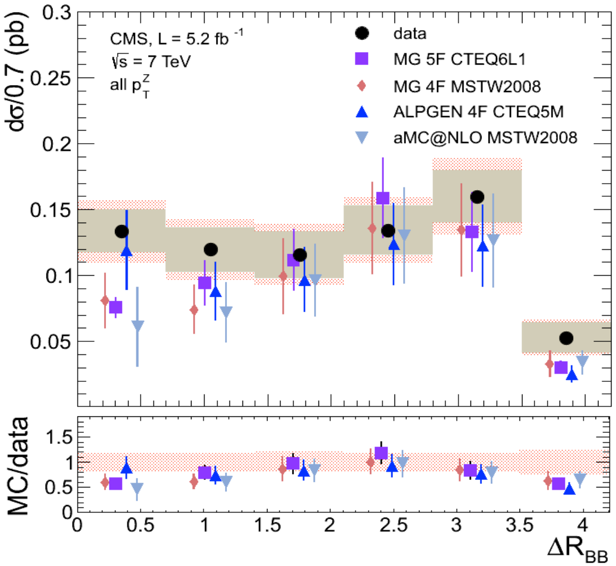
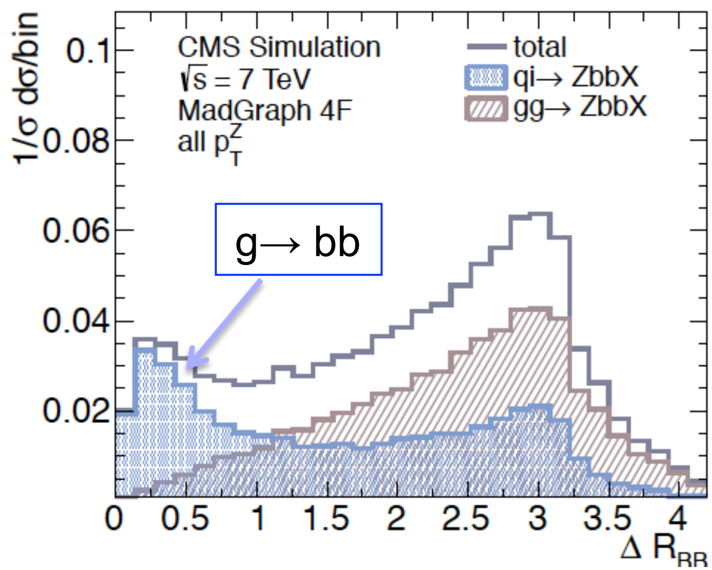
Z + BB

Z+BB Fiducial phase space:
b-hadron p_T>15 GeV, $|\eta|$<2
Lepton p_T>20 GeV $|\eta|$<2.4
81< M_{ll}<101 GeV



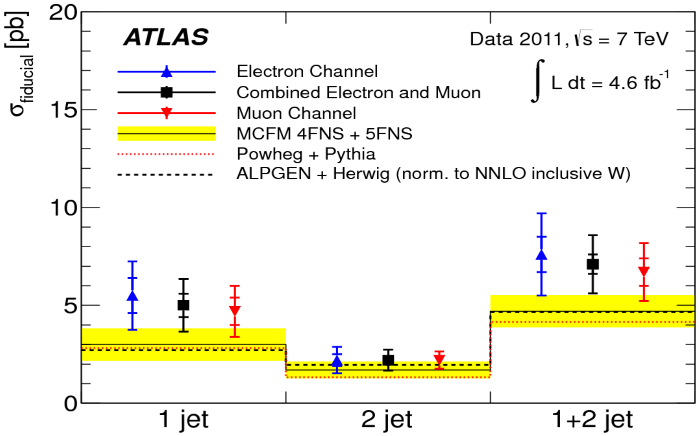


- MG4 scaled to NNLO Z cross-section (x1.23)
- MG5 and ALPGEN scaled to aMC@NLO cross-section
- Theory uncertainties:
  - b-quark mass (MG4)
  - renorm., fact. Scales
  - matching scale
  - normalisation uncertainties
  - parton shower Herwig vs Pythia (aMC@NLO)

- b-hadron pair identification efficiency: 8-10%
- ttbar bkg ~30% subtracted after fit to M_{ll} distribution
- 3-track requirement on secondary vertex is most effective at cutting Zcc bkg

W + b

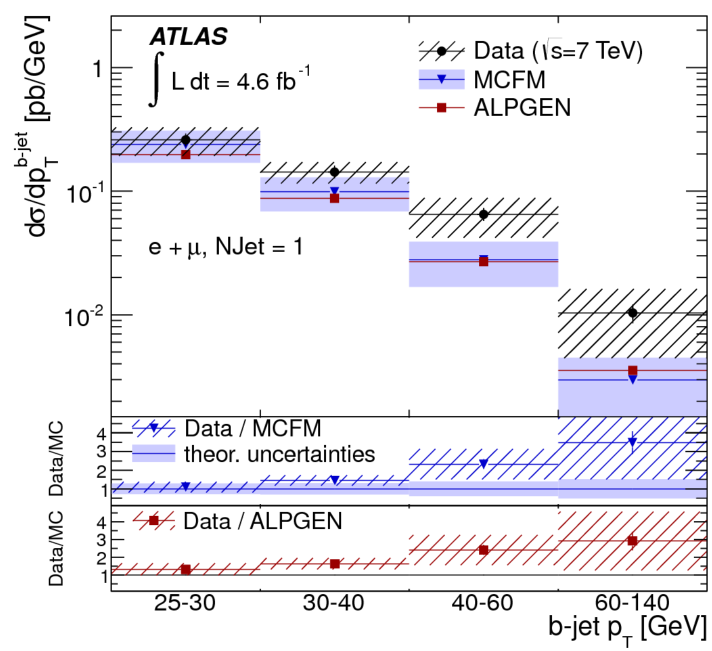
ATLAS
- $p_{T\mu}$, p_{Te} > 25 GeV, $|\eta|$ < 2.47 (e), 2.4 (μ)
- AntikT4, Jet p_T > 25 GeV, $|y|$ < 2.1
- E_{Tmiss} > 25 GeV, m_T > 60 GeV
- **Only one b-jet**



One b-jet

Two jets,
at least one b-jet

- ➢ Theory underestimate the data in the 1 jet bin

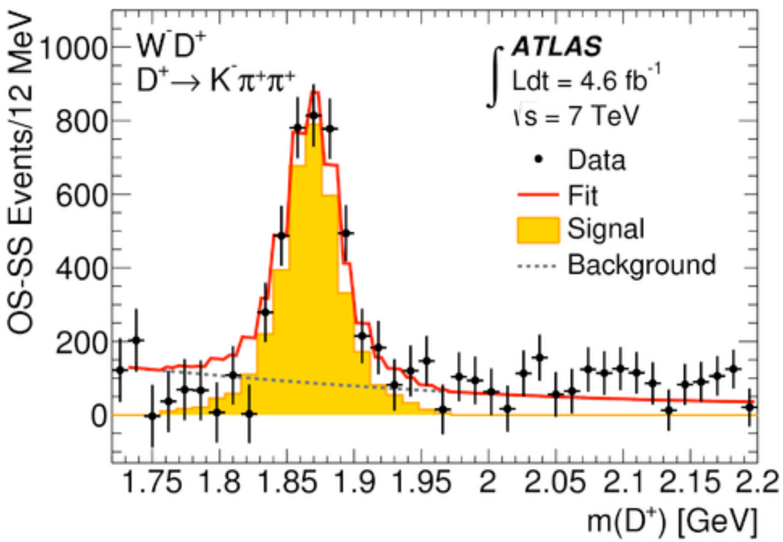


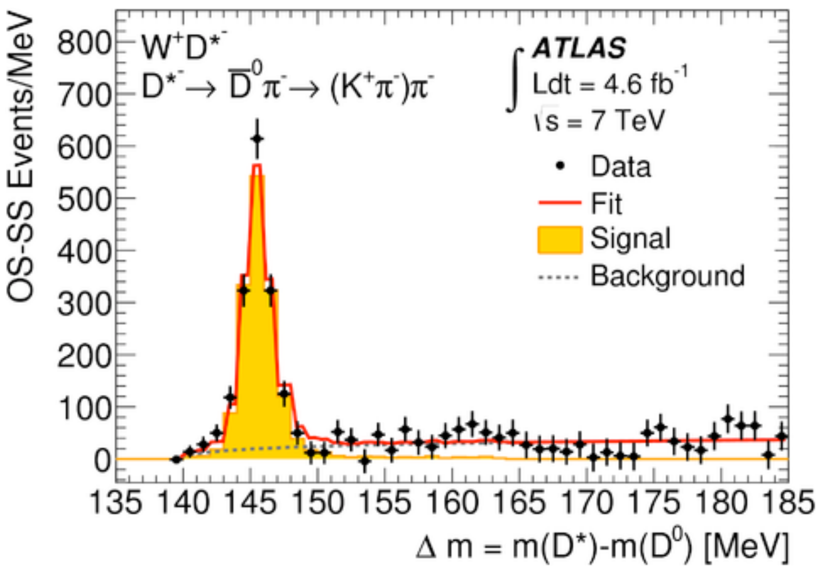
- ➢ Predictions at NLO (**MCFM, Powheg**) and LO (**Alpgen**)
  - MCFM corrected for hadronisation
  - MCFM and Powheg are corrected for DPI
- ➢ Data about 1.5 σ above predictions
  - Disagreement larger at high b-jet p_T

ATLAS W + c

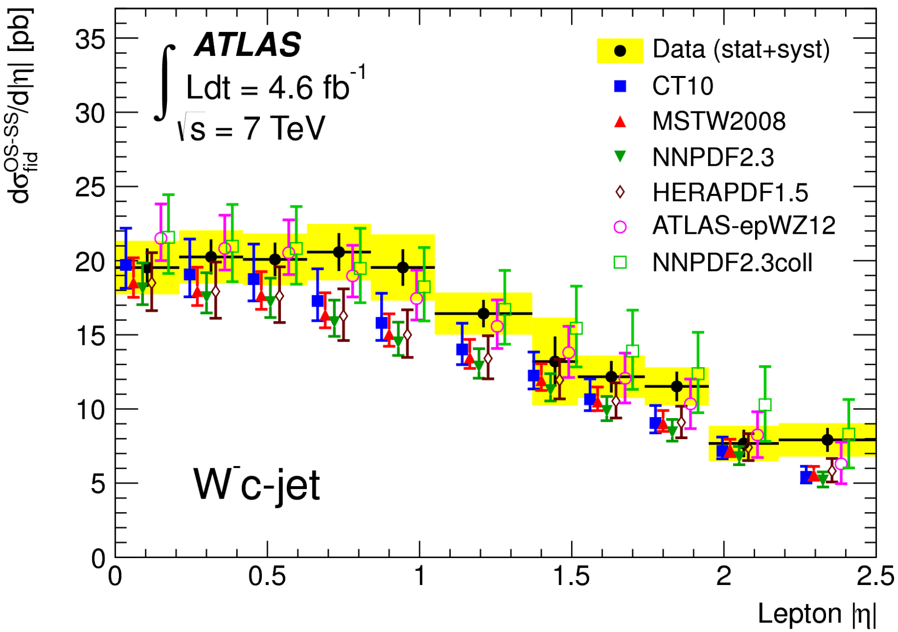
- D-mesons reconstructed in Inner Detector
  - no jet reconstruction
  - 3 or more jets vetoed to reduce top background

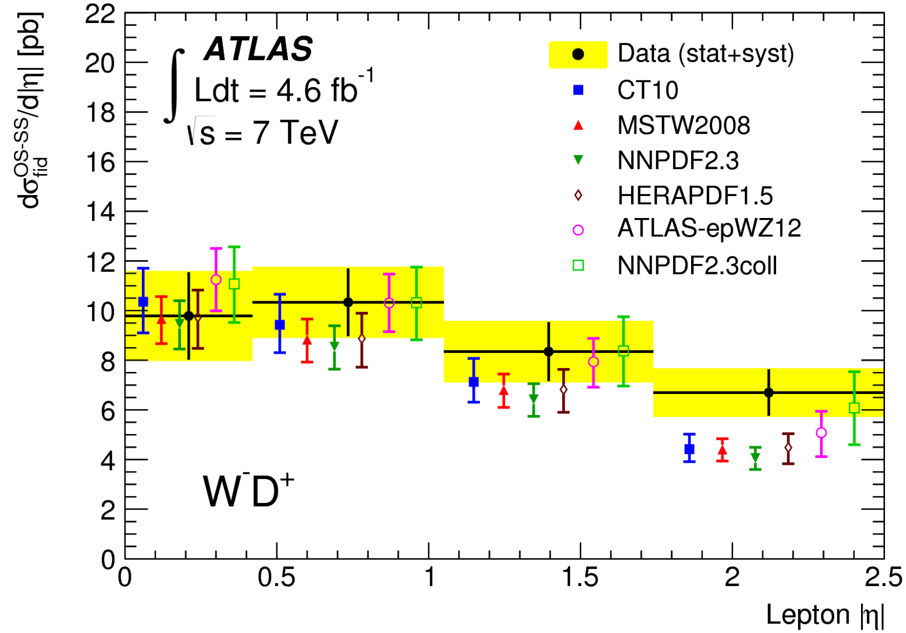
- Fit OS-SS distributions of m(Kππ) for $D^{+/-}$ and $\Delta m = m(D^*) - m(D^0)$
  - Largest background **W+jets** (smaller contribution from semi-leptonic **cc,bb** events)





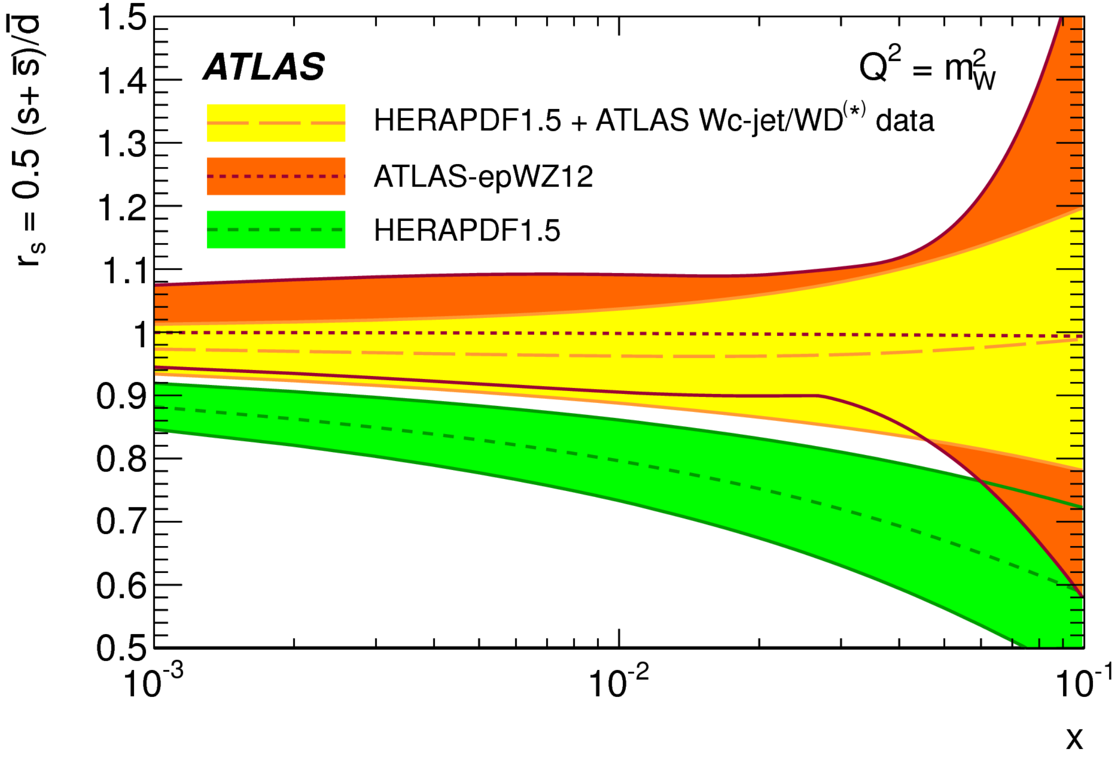
ATLAS W + c





- NNPDF2.3coll in better agreement with data

W + c



- Fit s-quark PDF with HERA data including ATLAS W+c data

Z + D at LHCb

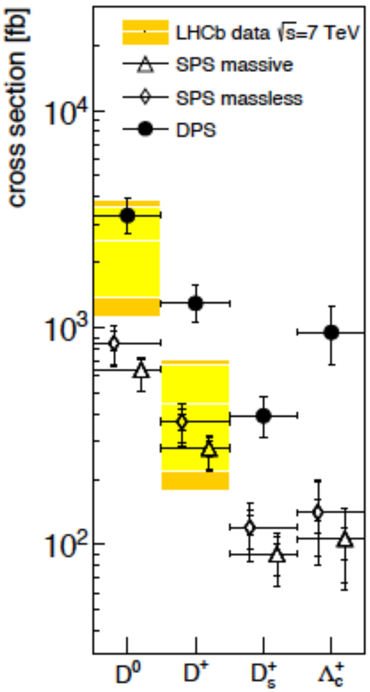
- LHCb: exclusive reconstruction of $Z(\rightarrow\mu\mu)+D^{0,+}$
  - 7 events in $Z+D^0$, 4 events in $Z+D^+$

$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+\pi^+$

$p_T(\mu^\pm) > 20\,\text{GeV},\ 2 < \eta(\mu^\pm) < 4.5\ \ 2 < p_T(D) < 12\,\text{GeV}\ \text{and}\ 2 < y(D) < 4.$

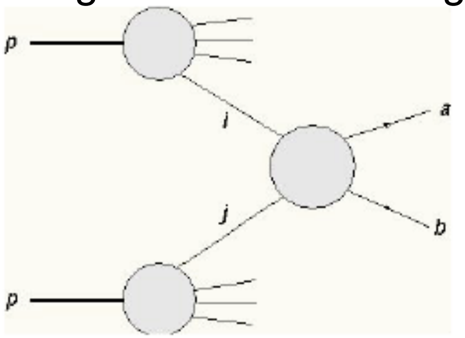
- Z+D provides information about
  - charm PDF
  - charm production mechanism
  - double parton scattering
- Z+D found by D0 Coll. in disagreement with NLO pQCD calculations
- Measurement compared to Single Parton Scattering and Double parton scattering predictions
  - Data-predictions agreement for $Z+D^0$
  - Data lies below expectations for $Z+D^+$



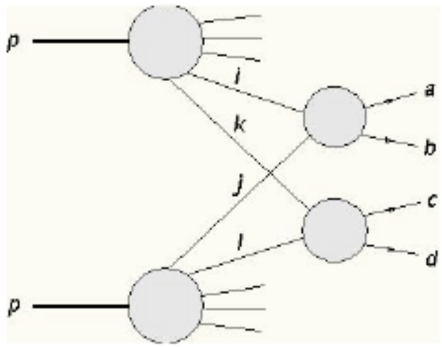
The measured cross-section is expected to be the sum of SPS and DPS (MCFM).

Experimental Results - MPI

Single Parton scattering



Double Parton scattering



- ❑ Independent scatterings in a pp collision
- ❑ Multi Parton Interactions necessary ingredient of simulations
  - Description of particle multiplicities and energy flow

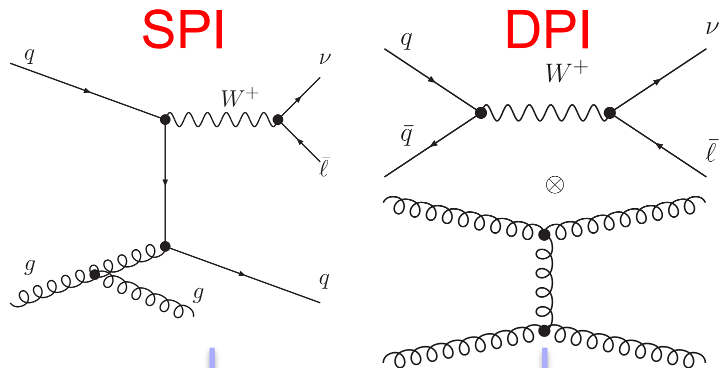
- ❑ Important contribution to precision measurements (e.g. Higgs, WW) and new physics searches
- ❑ Higher $\sqrt{s}$ and Luminosity implies bigger impact of DPI and at higher p_T
- ❑ Rapid increase in MPI with rising $\sqrt{s}$
  - Number of small-x partons increases dramatically

➢ Non negligible (~10%) at low x (< 0.2) at LHC energies

- ❑ Difficult to measure as buried in other signal
  - Co-exists with ISR, FSR, beam remnants and the hard interaction (pileup makes all of this far worse)

Experimental Results - MPI

- Double Parton Interactions are characterised by the effective area parameter σ_{eff}
  - assumed to be independent of phase space and process
- Large Uncertainties from previous measurements:
  - 5mb at low energies up to 15mb at Tevatron energies



$$\hat{\sigma}^{(DPI)}_{Y+Z} = \frac{\hat{\sigma}_Y \cdot \hat{\sigma}_Z}{\sigma_{eff}}$$

$$\hat{\sigma}^{(tot)}_{Y+Z}(s) = \hat{\sigma}^{(SPI)}_{Y+Z}(s) + \hat{\sigma}^{(DPI)}_{Y+Z}(s) = \hat{\sigma}^{(SPI)}_{Y+Z}(s) + \frac{\hat{\sigma}_Y(s)\cdot\hat{\sigma}_Z(s)}{\sigma_{eff}(s)}$$

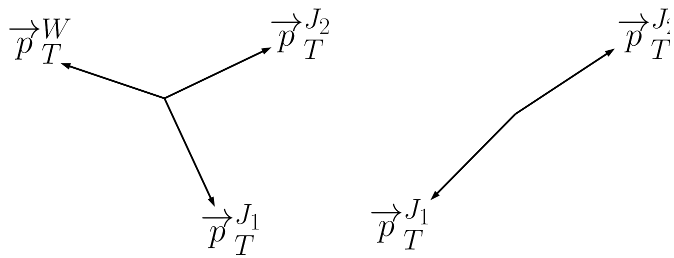
$$\sigma_{eff}(s) = \frac{\hat{\sigma}_Y(s)\cdot\hat{\sigma}_Z(s)}{\hat{\sigma}^{(tot)}_{Y+Z}(s) - \hat{\sigma}^{(SPI)}_{Y+Z}(s)} = \frac{\hat{\sigma}_Y(s)\cdot\hat{\sigma}_Z(s)}{f^{(D)}_{DP}\cdot\hat{\sigma}^{(tot)}_{Y+Z}(s)} = \frac{\sigma_{W_{0j}}\cdot\sigma_{2j}}{f^{(D)}_{DP}\ \sigma_{W+2j}}$$

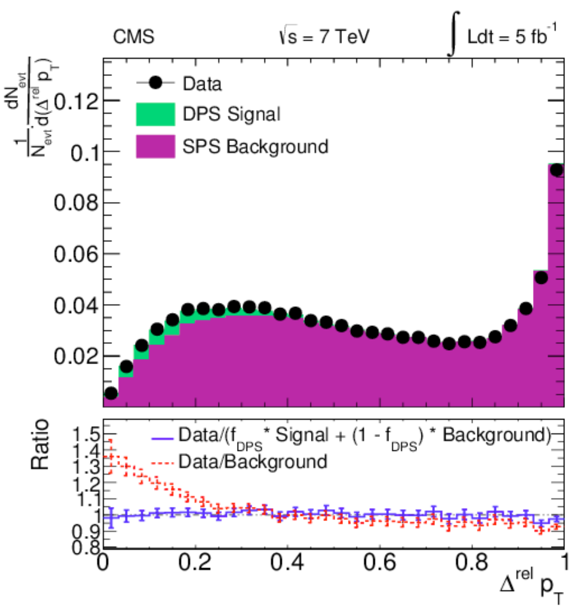
$f_{DP}^{(D)}$: Fraction of DPI in W+2j events at detector level

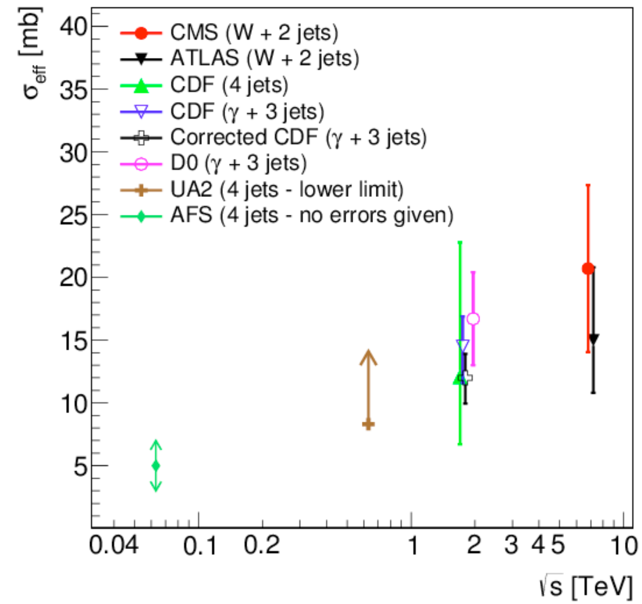
Experimental Results – MPI

- Fraction of DPI events in W+2jets data extracted from template fit to normalized transverse momentum balance

$$\Delta^{n}_{jets} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$$







Fraction of DPI in W+2j events:

$$f_{DP}^{(D)} = 0.08 \pm 0.01\ (\text{stat.}) \pm 0.02\ (\text{sys.})$$

ATLAS

$$\rightarrow \sigma_{eff}(7\ \text{TeV}) = 15 \pm 3\ (\text{stat.})\ ^{+5}_{-3}\ (\text{sys.})\ \text{mb}$$

PRD 88 (2013) 092001

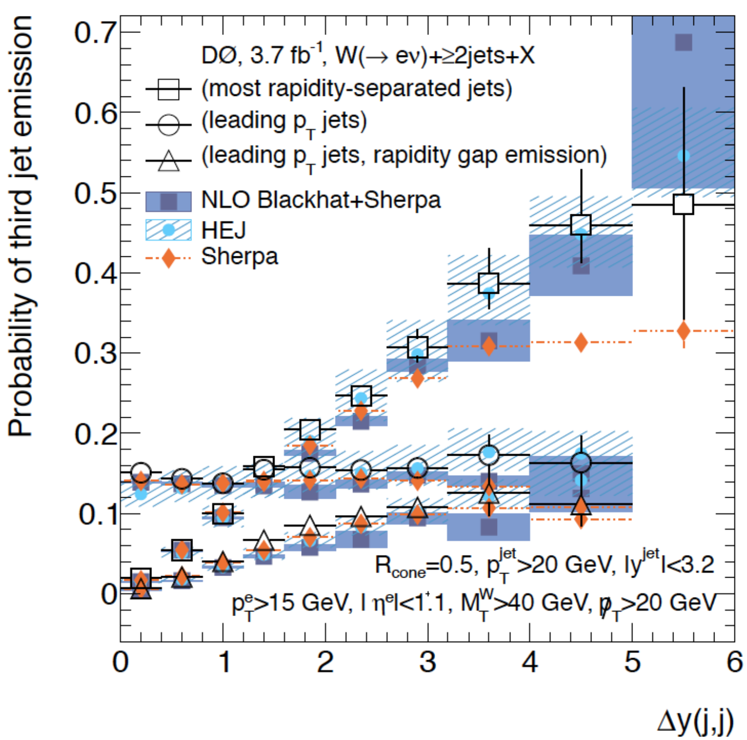
Tevatron

electron p_T>15 GeV |η|<1.1
Missing E_T > 20 GeV, M_T>40 GeV
Midpoint R=0.5, Jet p_T > 20 GeV, |y|<3.2
ΔR(ele, jet)>0.5

- Study of 3rd jet emission probability in W + ≥ 2jets vs rapidity separation between jets Δy(j,j)
  - **$\Delta y(j_F, j_R)$:** two most-rapidity-separated jets in W + ≥2j events
  - **$\Delta y(j_1,j_2)$:** two highest-p_T jets in W + ≥2j events
  - **$\Delta y(j_1,j_2)$:** two highest-p_T jets with 3rd jet in j_1-j_2 y-gap in W + ≥2j events

- Laboratory for rapidity gaps, central jet vetoes and VBF jet dynamics
  - Test of high-p_T jet emission
  - Test of wide-angle gluon emission
  - Complementary to studies in dijet events

$P_{3rd\ jet} = N^{evt}_{3jets} / N^{evt}_{\geq 2jets}$



- Weak (*strong*) dependence of 3rd jet emission probability vs jet rapidity separation in p_T-ordered (*rapidity-ordered*) configuration
  - Competing effects of increasing phase space for jet emission and decreasing PDF at at large x

- HEJ (resummation) describes best the data in all configurations

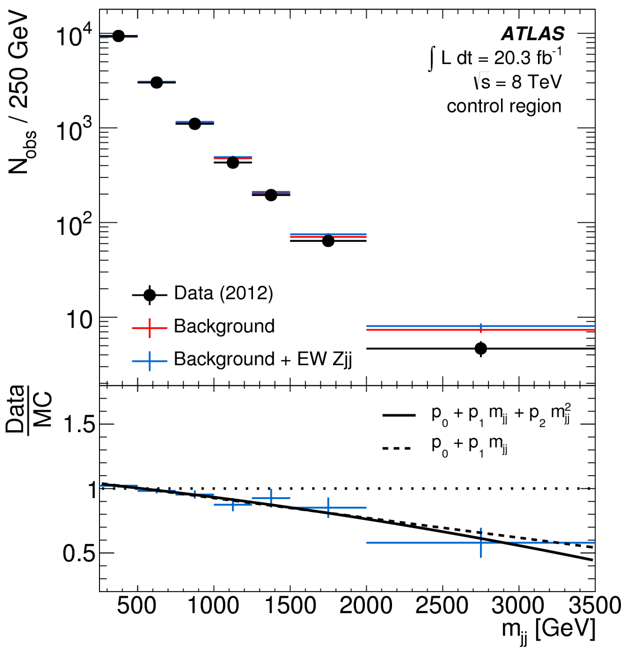
ATLAS Electroweak Z + 2 jets

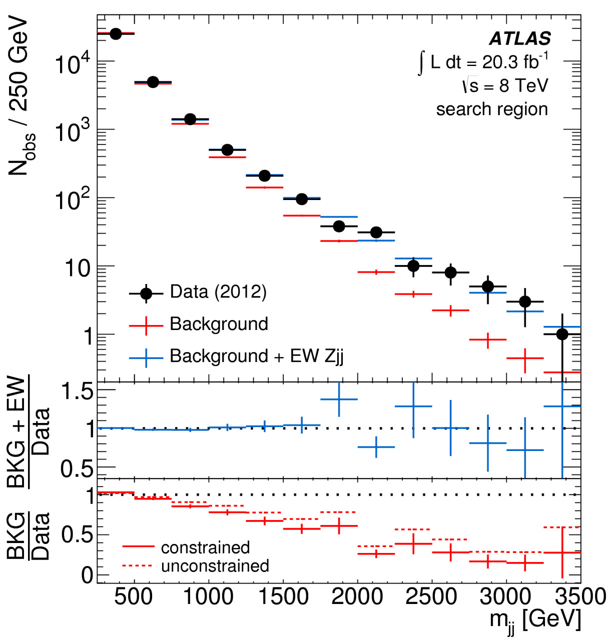
Breakdown of the electroweak cross section systematics

Source	ΔN_{EW} Electrons	ΔN_{EW} Muons	$\Delta \mathcal{C}_{\mathrm{EW}}$ Electrons	$\Delta \mathcal{C}_{\mathrm{EW}}$ Muons
Lepton systematics	—	—	± 3.2 %	± 2.5%
Control region statistics	± 8.9 %	± 11.2 %	—	—
JES	± 5.6 %		$^{+2.7}_{-3.4}$ %	
JER	± 0.4 %		± 0.8 %	
Pileup jet modelling	± 0.3 %		± 0.3 %	
JVF	± 1.1 %		$^{+0.4}_{-1.0}$ %	
Signal modelling	± 8.9 %		$^{+0.6}_{-1.0}$ %	
Background modelling	± 7.5 %		—	
Signal/background interference	± 6.2 %		—	
PDF	$^{+1.5}_{-3.9}$ %		± 0.1 %	

ATLAS Electroweak Z + 2 jets

- EW Zjj component extracted by a fit to the mjj spectrum
- Strong Zjj production constrained from events with ≥1 jet within tag jets
  - correct simulation in search region using data/MC ratio in control region
  - improves the modelling by Sherpa and limits systematic uncertainties

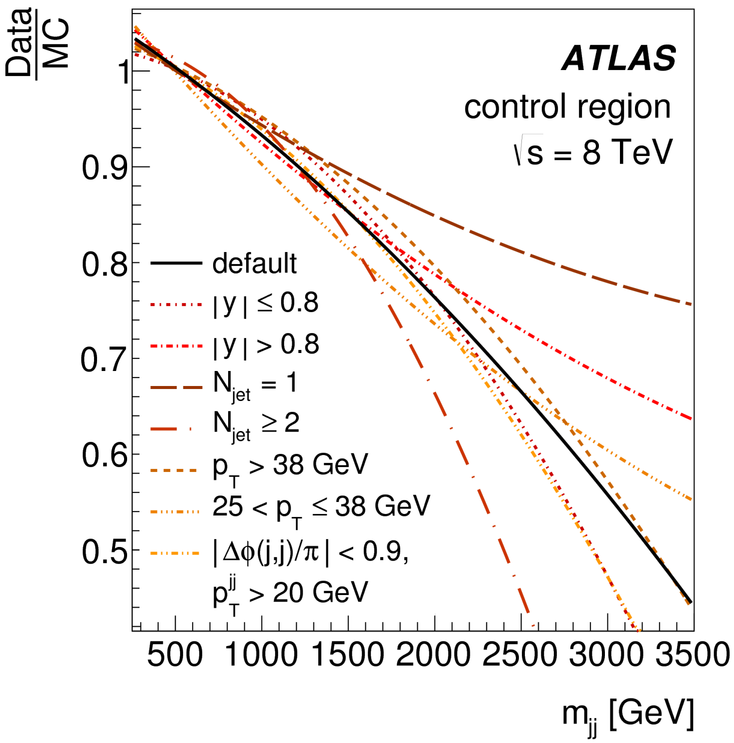




- Correction derived from Sherpa

ATLAS Electroweak Z + 2 jets

- Choice of generator checked by using POWHEG (instead of SHERPA) and repeating full analysis chain
  - Extracted signal yields agree to 0.8%
- Choice of control region validated by splitting it into 7 sub-regions
  - deriving new constraints,
  - repeating full analysis chain
  - extracted signal yields agree within 5%
    - background modelling at high mjj region has small impact on the extracted number of electroweak Zjj events

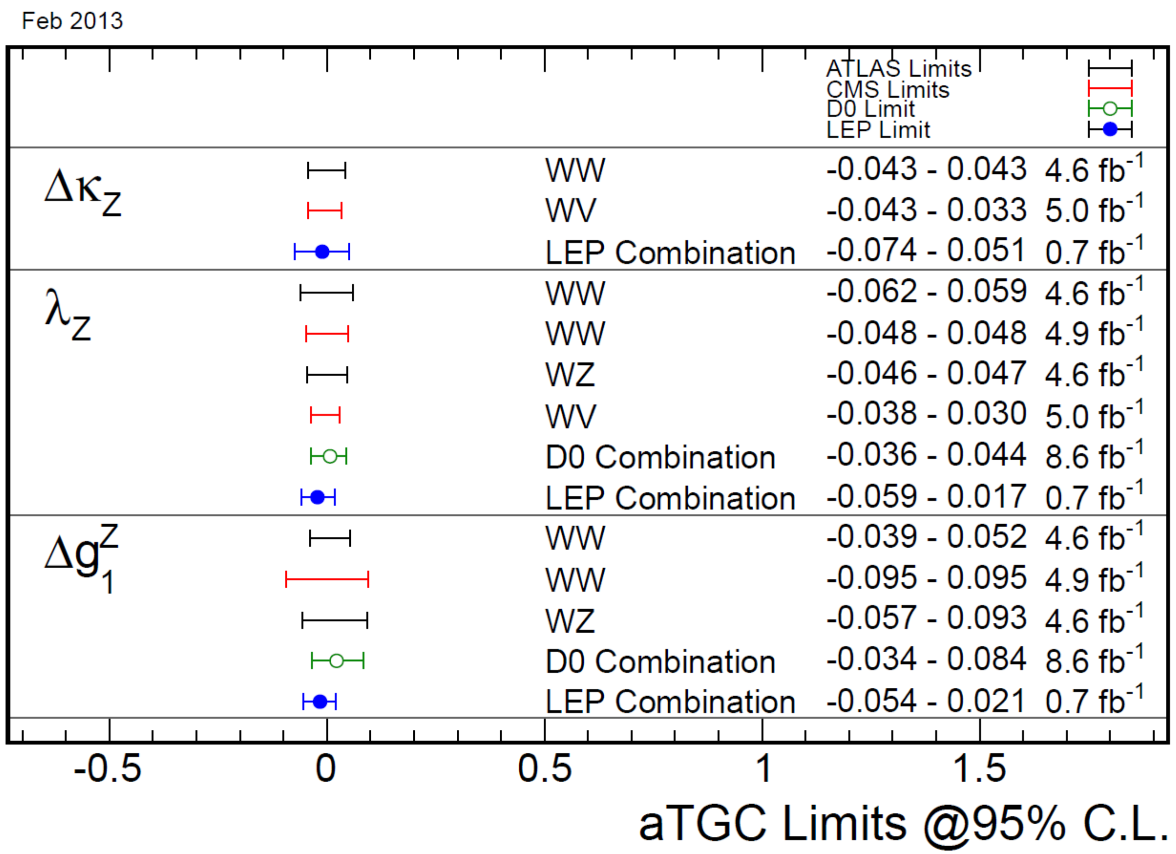


ATLAS Electroweak Z + 2 jets

Process composition in each fiducial region

	Composition (%)				
Process	*baseline*	*high-p_T*	*search*	*control*	*high-mass*
Strong Zjj	95.8	94.0	94.7	96.0	85
Electroweak Zjj	1.1	2.1	4.0	1.4	12
WZ and ZZ	1.0	1.3	0.7	1.4	1
$t\bar{t}$	1.8	2.2	0.6	1.0	2
Single top	0.1	0.1	< 0.1	< 0.1	< 0.1
Multijet	0.1	0.2	< 0.1	0.2	< 0.1
WW, W+jets	< 0.1	< 0.1	< 0.1	< 1.1	< 0.1

Charged aTGCs: World Summary



LHC detector upgrades

CMS

- LS1
  - Complete Muon coverage
  - Replace HCAL photo-detectors in Forward and Outer
- LS2 :
  - New 4-layer Pixel detector
    - improves tracking eff. with lower fake rate
  - L1-Trigger upgrade
    - allows much improved algorithm for PU mitigation
  - HCAL electronics
- LS3, considered upgrade
  - Replace detectors due to radiation damage
    - Pixel, strip and endcap calorimeters
  - Enhanced coverage up to $\eta=4$
    - Forward: tracker, calorimeter and muon detectors
  - Track trigger

ATLAS

- LS1
  - New beam pipe
  - New Insertable pixel b-layer and pixel services
  - Complete installation of muon chambers
  - L1 Topological triggers
- LS2
  - New Small Wheel for the forward muon Spectrometer
  - Trigger upgrade
    - Higher granularity Calorimeter L1-Trigger
    - Fast TracKing for L2-Trigger
- LS3, considered upgrade
  - New tracking detectors
  - Calorimeter electronics and muon system upgrades
  - Two stage L0/L1 system from the present L1-Trigger

Trigger strategy for Run 2

Run 1	Offline p_T Threshold [GeV]	Rate [kHz]	Run 2	Offline p_T Threshold [GeV]	Rate [kHz]
EM18VH	25	130	EM30VHI	38	14
EM30	37	61	EM80	100	2.5
2EM10	2x17	168	2EM15VHI	2x22	2.9
EM total		**270**			**18**
MU15	25	150	MU20	25	28
2MU10	2x12	14	2MU11	2x12	4.0
Muon total		**164**			**32**
EM10VH_MU6	17,6	22	EM15VH_MU10	22,12	3.0
			EM10H_2MU6	17,2x6	2.5
TAU40	100	52	TAU80V	180	4.7
			2TAU50V	2x110	3.8
2TAU11I_TAU15	30,40	147	2TAU20VI_3J20	2x50,60	5.2
2TAU11I_EM14VH	30,21	60	2TAU20VI_ EM18VHI_3J18	50,25,60	2.8
			TAU15VI_MU15	40,20	3.8
TAU15_XE35	40,80	63	TAU20VI_ XE40_3J20	50,90,60	4.4
Tau total		**238**			**20**
J75	200	34	J100	200	7.0
4J15	4x55	87	4J25	4x60	3.3
			J75_XE40	150,150	8.3
XE40	120	157	XE90	250	10
Jet/E_T^{miss} total[a]		**306**			**25**
Topological triggers		**-**			**~5**
Total		**~800**			**~100**

ATLAS:
Rates extrapolated to luminosity of 3×10^{34} cm^{-2} s^{-1}