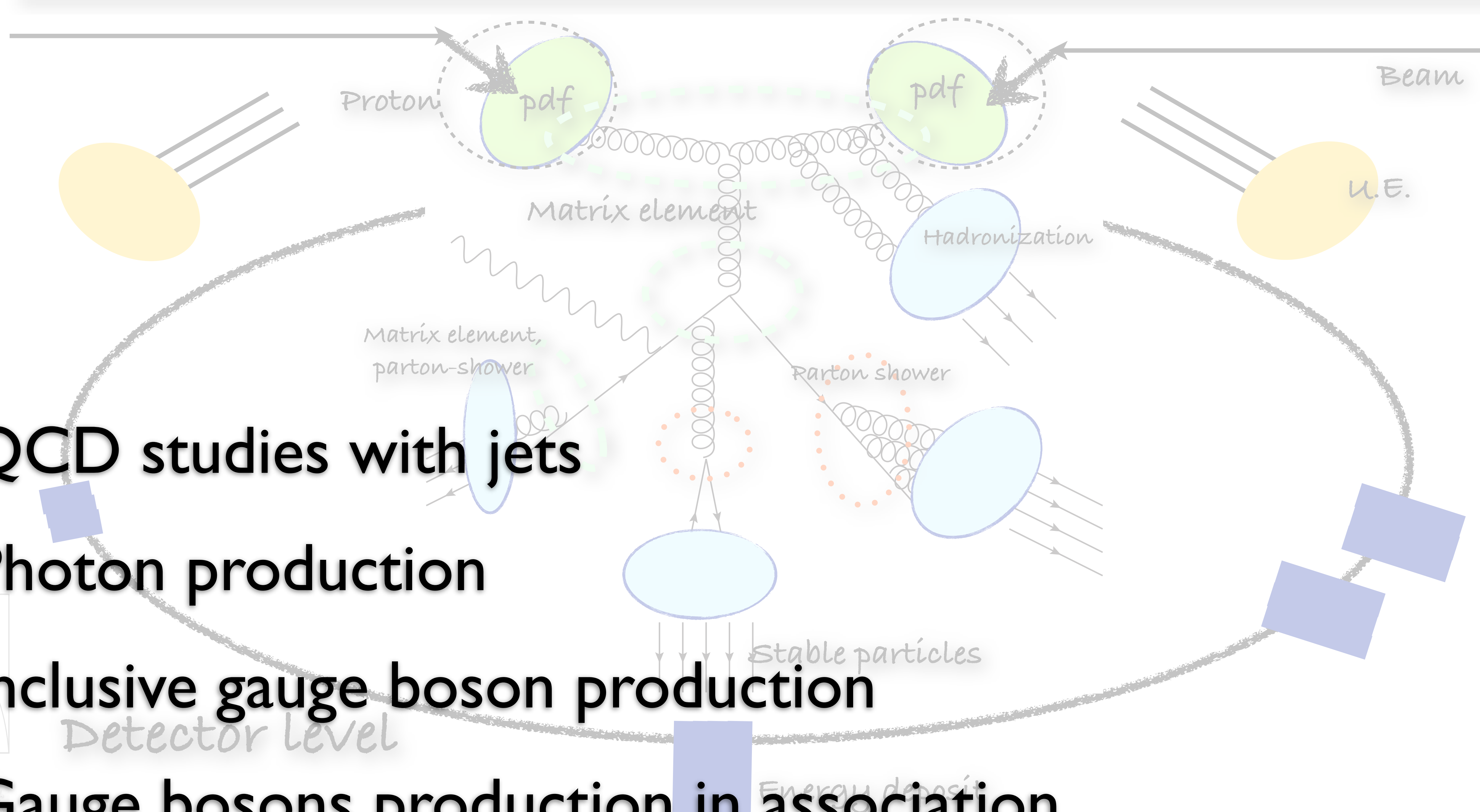
QCD results from ATLAS and CMS

LC13 Workshop
16-20 September, Villa Tambosi, Villazzano (Italy)

N. Orlando for the ATLAS and CMS Collaborations

INFN Lecce and Dipartimento di Matematica e Fisica "Ennio De Giorgi", Universita' del Salento

Outline

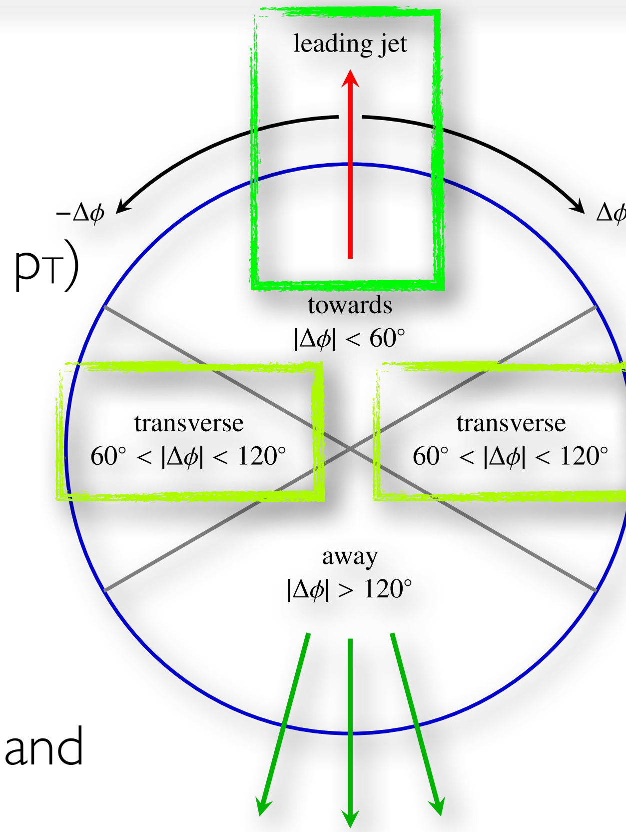


- QCD studies with jets
- Photon production
- Inclusive gauge boson production
- Gauge bosons production in association with jets

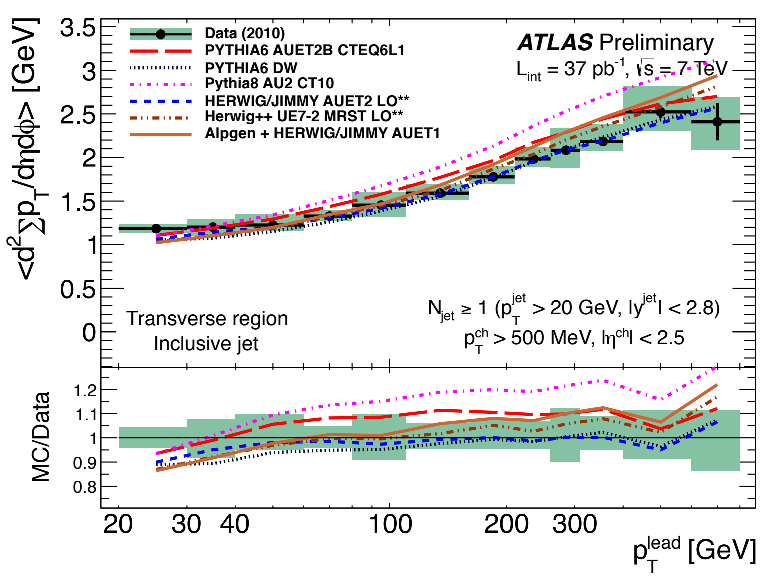
Charged tracks multiplicity studies at 7TeV

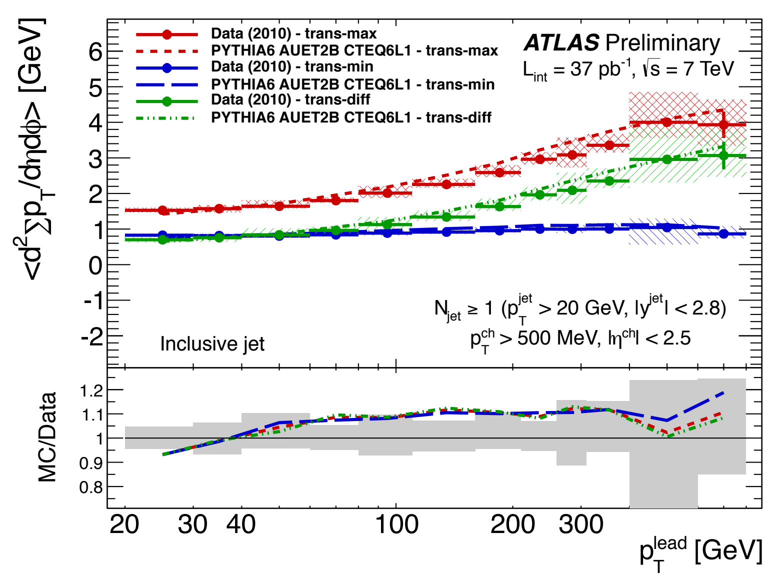
ATLAS ATLAS-CONF-2012-164

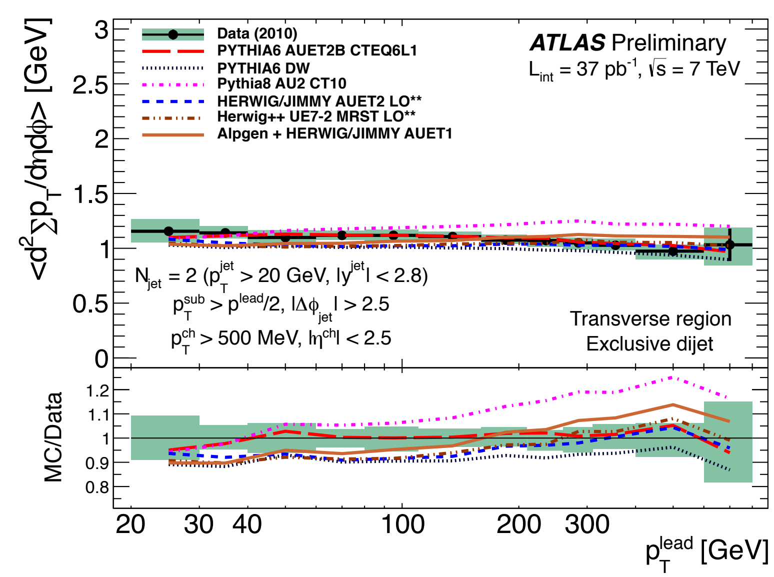
- Look at events with **hard jets**
- Characterize the underlying event (UE) using track multiplicity and transverse momentum density as function of the event hard scale (jet p_T)
- Study the topologies sensitive to the UE
  - ☑ **Transverse regions**
    - more active transverse region "transv-max"
    - less active transverse region "transv-min"
    - "transv-diff": difference between observables in "transv-max" and "transv-min"



- Data well described by most of the generators



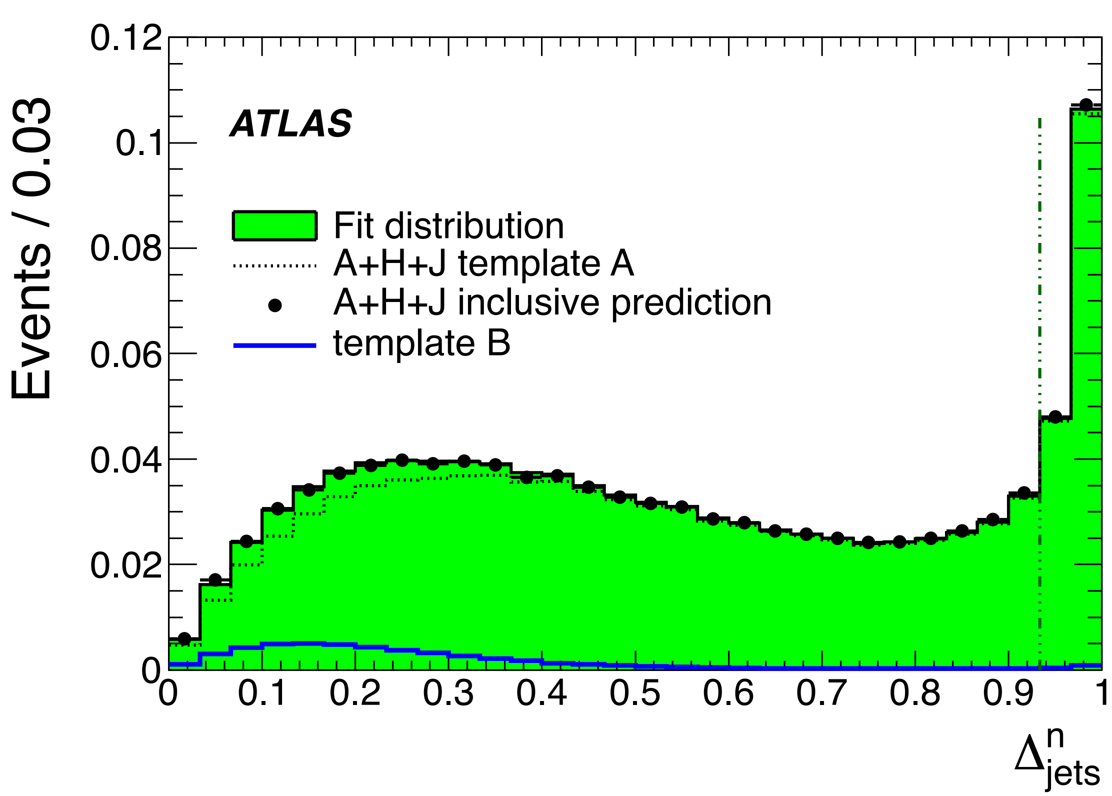




Double parton interactions

ATLAS New J. Phys. 15 (2013) 033038

- Poorly understood process
  - And possibly not negligible in several searches and measurements
- ATLAS and CMS measure the double parton interactions (DPI) in events with W+2jets
  - Use peculiar kinematics of a 2→2 process to distinguish DPI in W+2jets

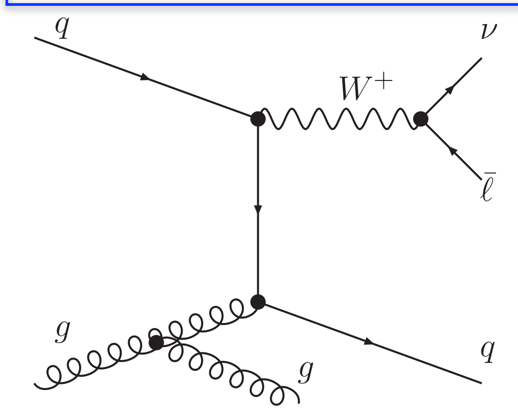


$$\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{\,J_1} + \vec{p}_{\mathrm{T}}^{\,J_2}|}{|\vec{p}_{\mathrm{T}}^{\,J_1}| + |\vec{p}_{\mathrm{T}}^{\,J_2}|}$$

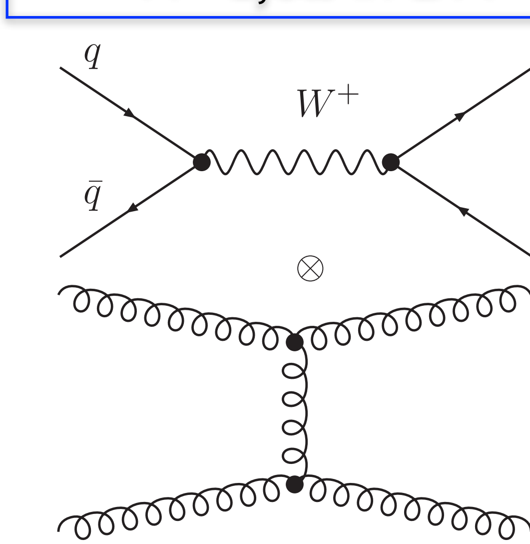
↓

Small dependence on the energy scale

W+2jets in single parton interaction



W+2jets in DPI



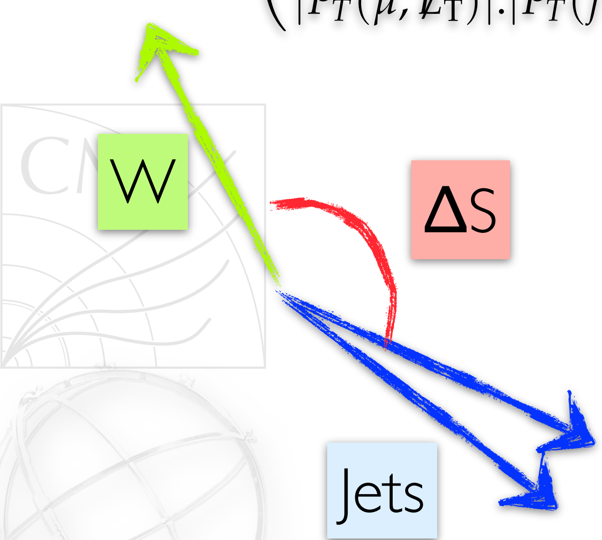
Double parton interactions

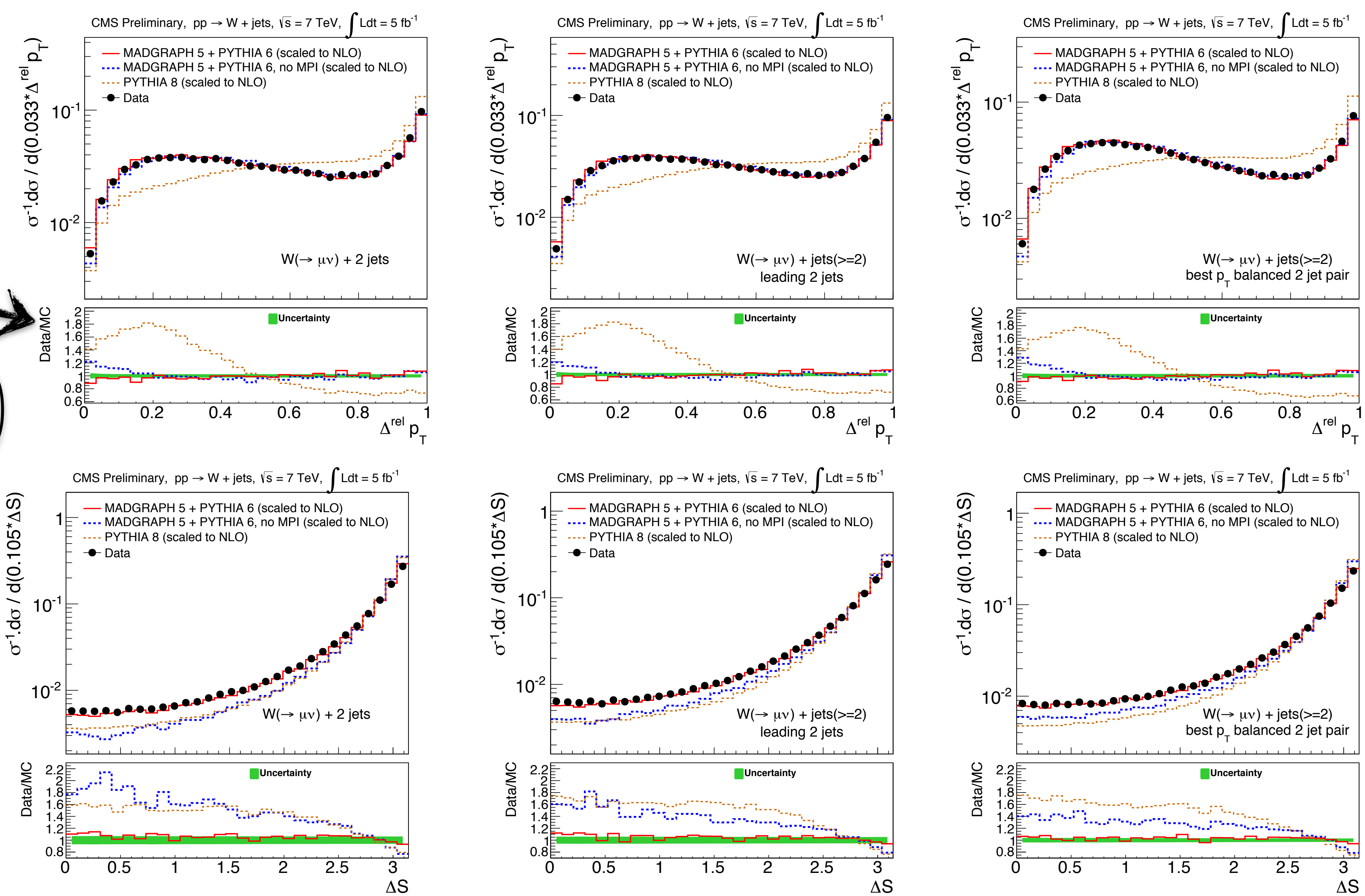
CMS CMS-PAS-FSQ-12-028

- Studied DPI sensitive kinematical distributions at particle level
- Multileg generators needed to describe well W+2jets in single parton interactions

LO 2→2 MC don't describe the data

$$\Delta S = \arccos\left(\frac{\vec{P}_T(\mu,\not{E}_T).\vec{P}_T(j1,j2)}{|\vec{P}_T(\mu,\not{E}_T)|.|\vec{P}_T(j1,j2)|}\right)$$





Double parton interactions

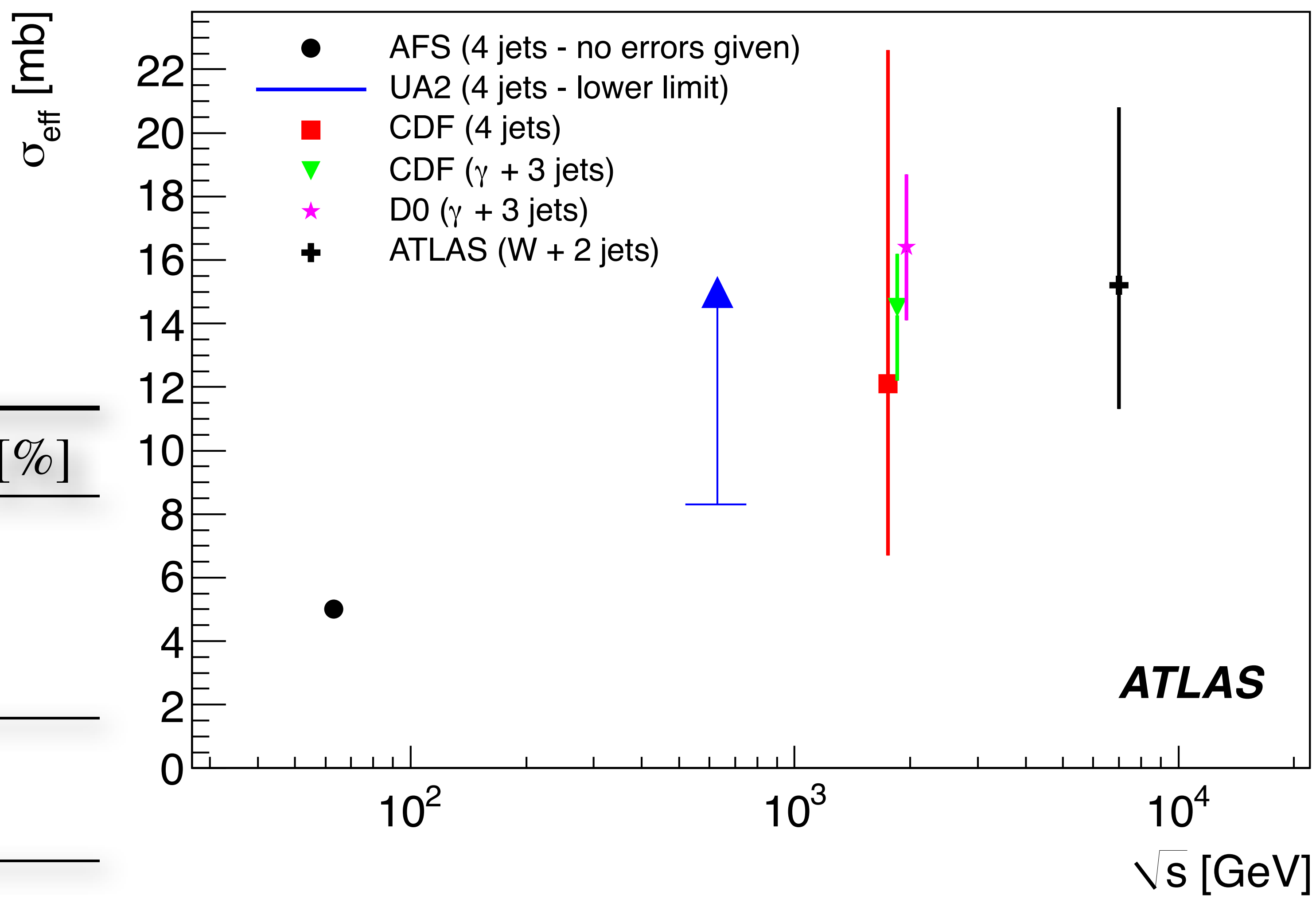
ATLAS New J. Phys. 15 (2013) 033038

- ~35% of uncertainty on the measured total cross section
  - ☑ Need more precision and differential measurements (e.g. as function of p_T)
  - ☑ Exploit other signatures

$$d\hat{\sigma}^{(DPI)}_{Y+Z}(s) = \frac{m}{2\sigma_{\text{eff}}(s)} \int dx_{i_1}\, dx_{j_1}\, dx_{i_2}\, dx_{j_2}\, [f_{i_1 j_1}(x_{i1}, x_{j_1}, \mu_F)$$
$$f_{i_2 j_2}(x_{i_2}, x_{j_2}, \mu_F)\, d\hat{\sigma}_{i_1 i_2 \to Y}(x_{i_1}, x_{i_2}, s)\, d\hat{\sigma}_{j_1 j_2 \to Z}(x_{j_1}, x_{j_2}, s)]$$

Dominant uncertainties

Systematic source	Uncertainty [%]
$f^{(D)}_{DP}$	24
Background & lepton response	5
Luminosity	3
Total systematic	$^{+33}_{-20}$
Total statistical	17

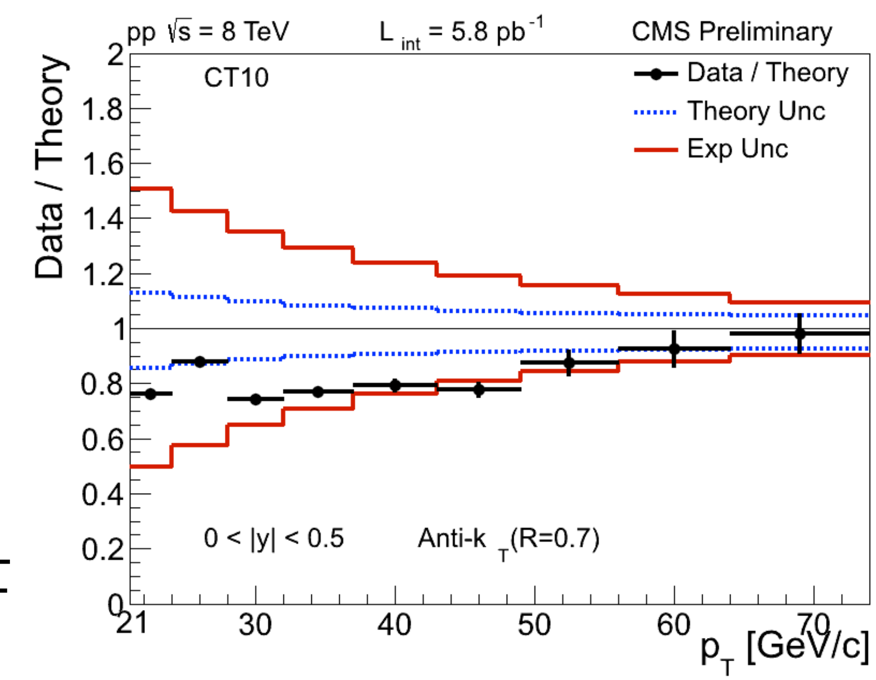


Inclusive jets cross sections at 7 and 8 TeV

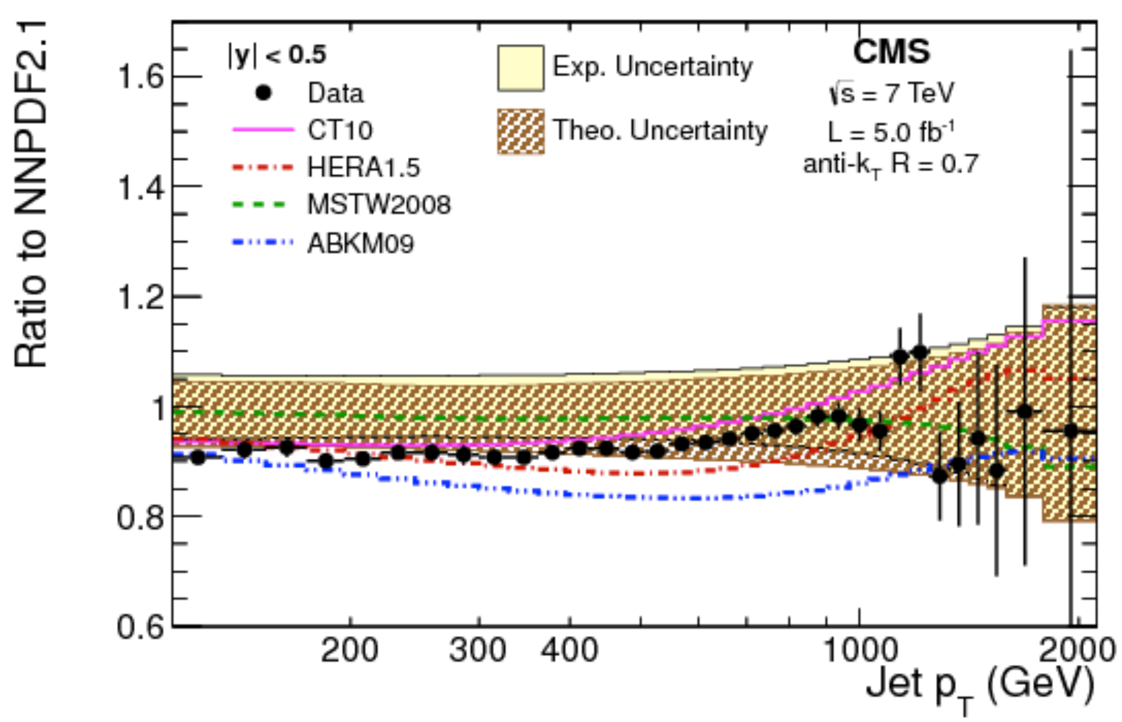
CMS Phys. Rev. D 87 (2013) 112002

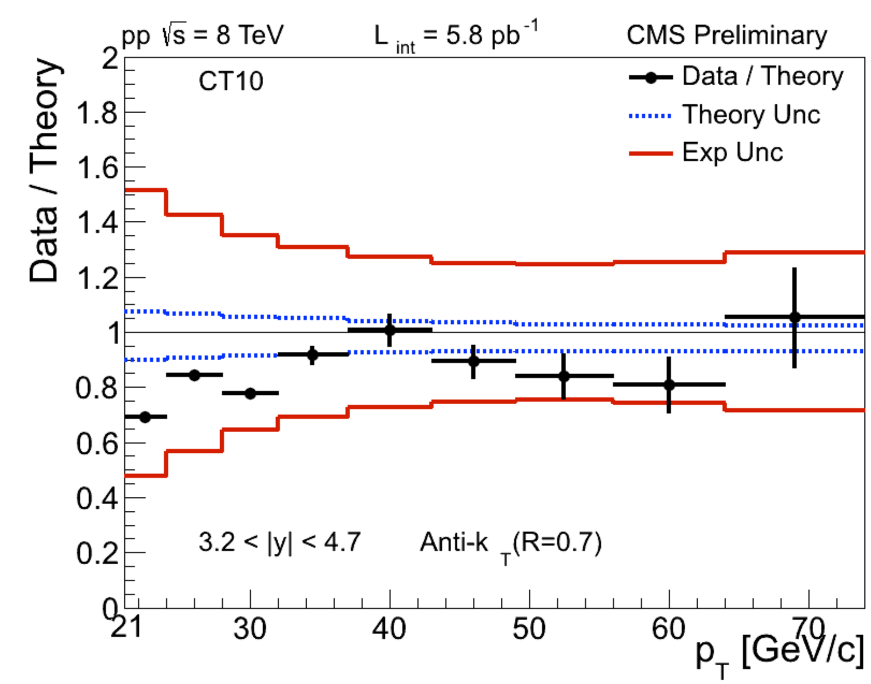
CMS CMS-PAS-SMP-12-012

- Small spread among the NLO QCD calculation obtained using different PDF sets,
  - ☑ but ABKM09
    - Sensitivity to the gluon PDF



Central



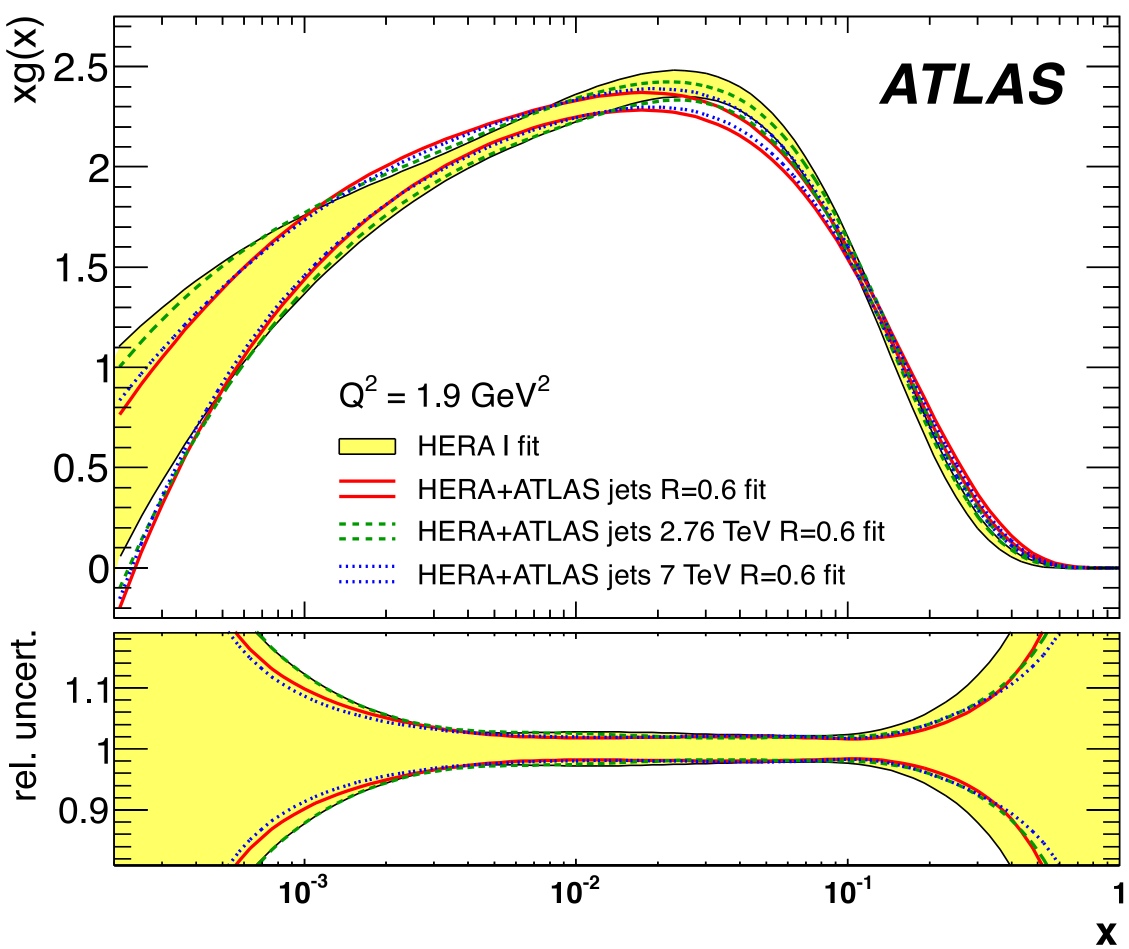


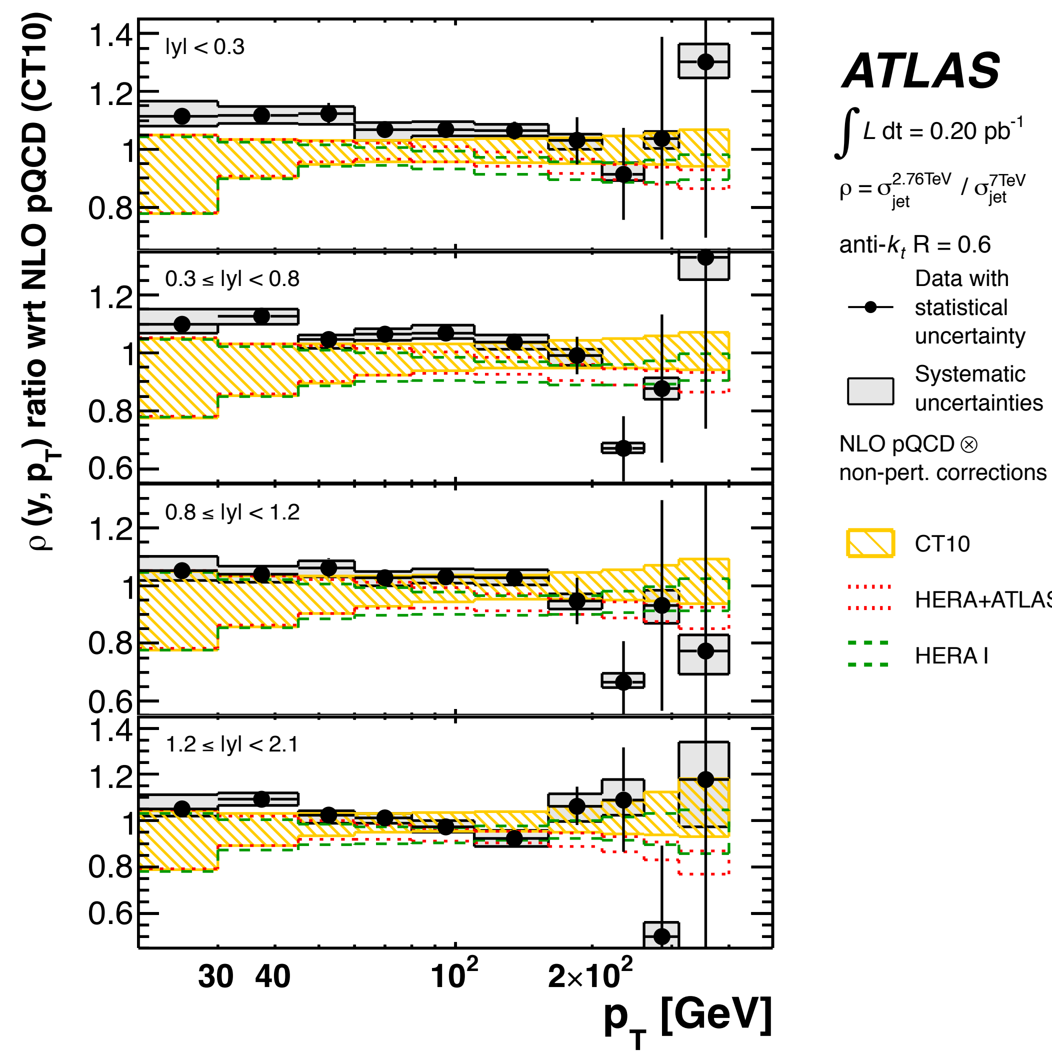
Forward

Gluon PDF from jet data

ATLAS EPJC (2013) 73 2509

- Using ratios of cross sections at 2.76 and 7 TeV to constrain the gluon content of the proton
- ATLAS data sensitive to the high-x region
  - Improved uncertainties are obtained when it is used in combination to the HERA data





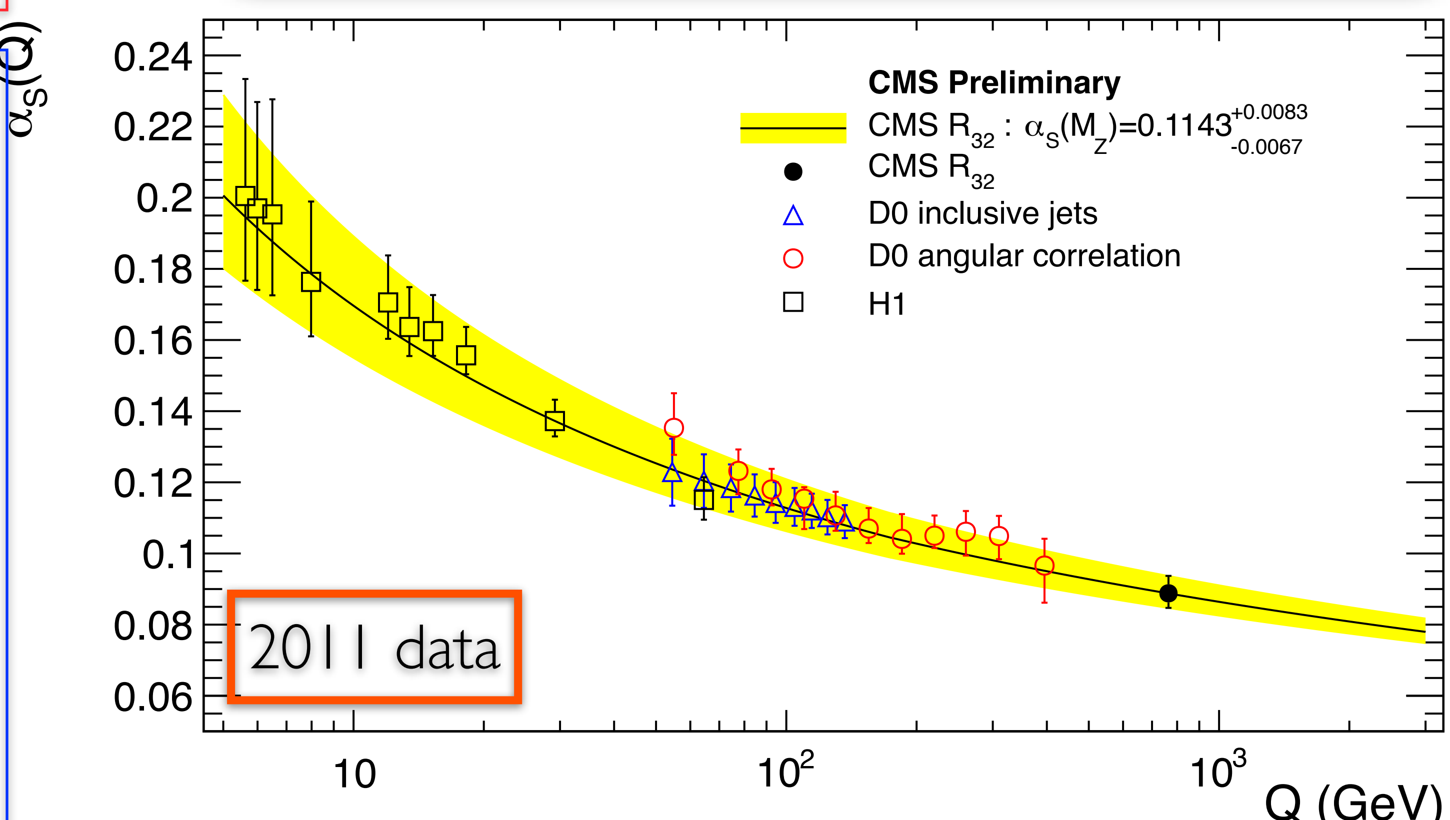
ATLAS and CMS measurements of αs

CMS CMS-PAS-SMP-12-026

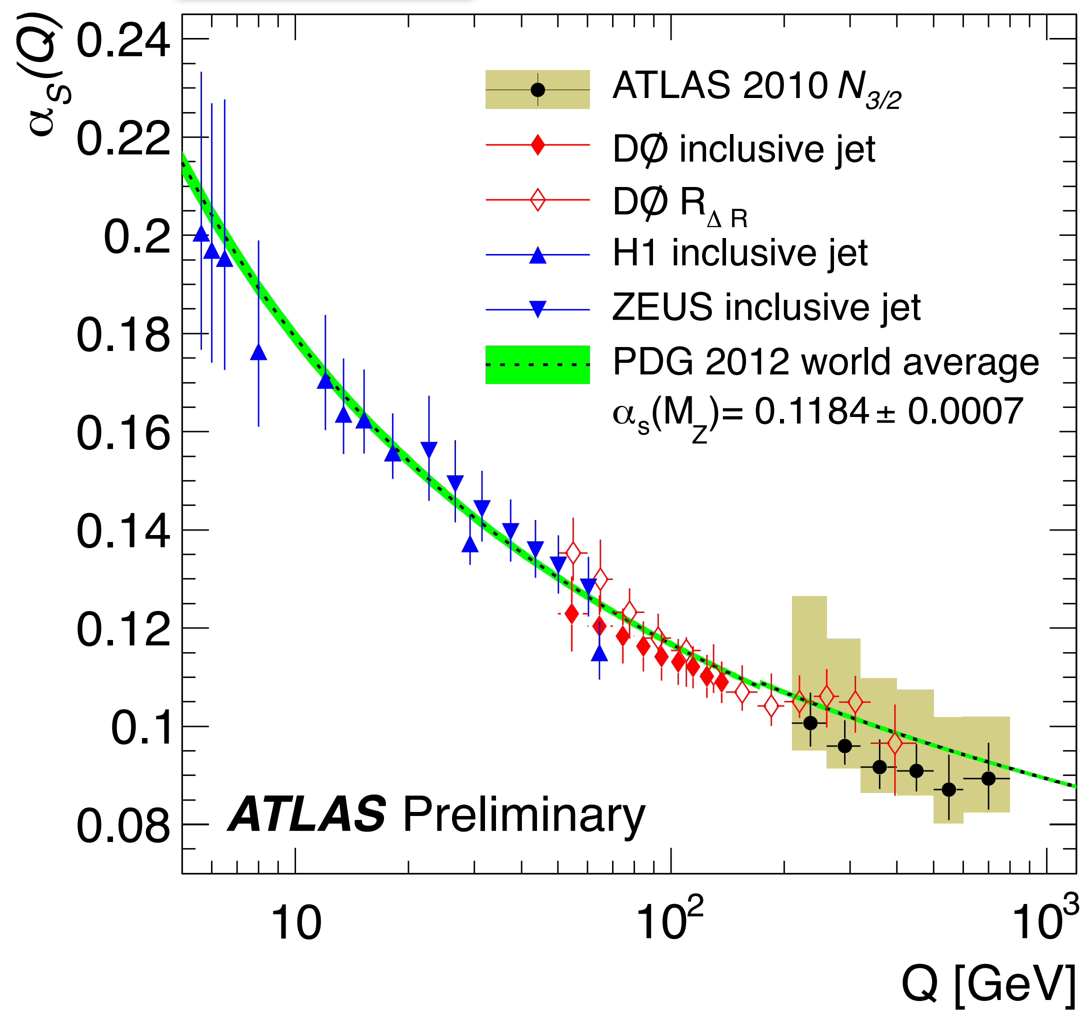
ATLAS ATLAS-CONF-2013-041

- Ratio of 3-jet to 2-jet cross sections used to measure the strong coupling
  - Precision comparable to previous measurements

ATLAS	0.111 ±0.006(exp.) +0.016 -0.003(theory)
CMS	0.1143 +0.0083 -0.0067(total)
World average	0.1184 ±0.0007



2010 data

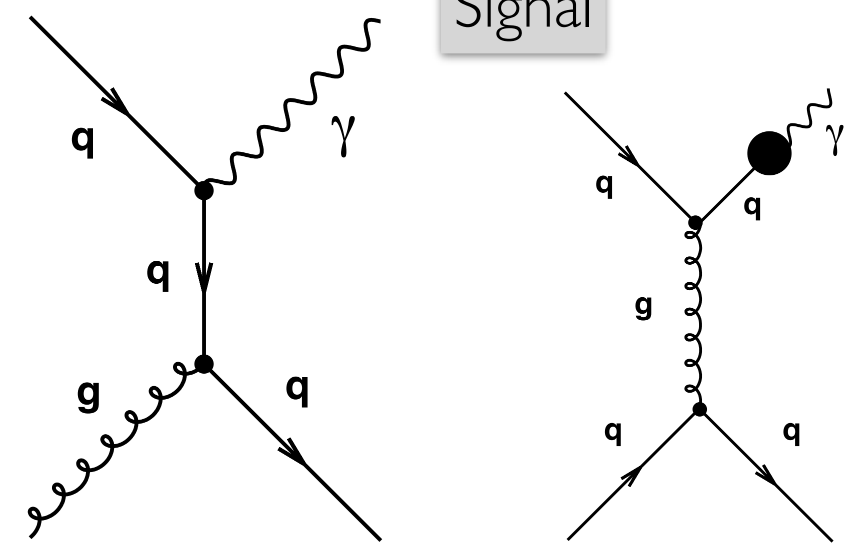


Photon cross sections

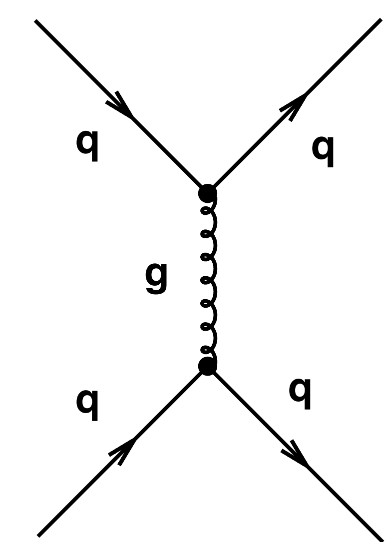
CMS CMS-PAS-QCD-11-005

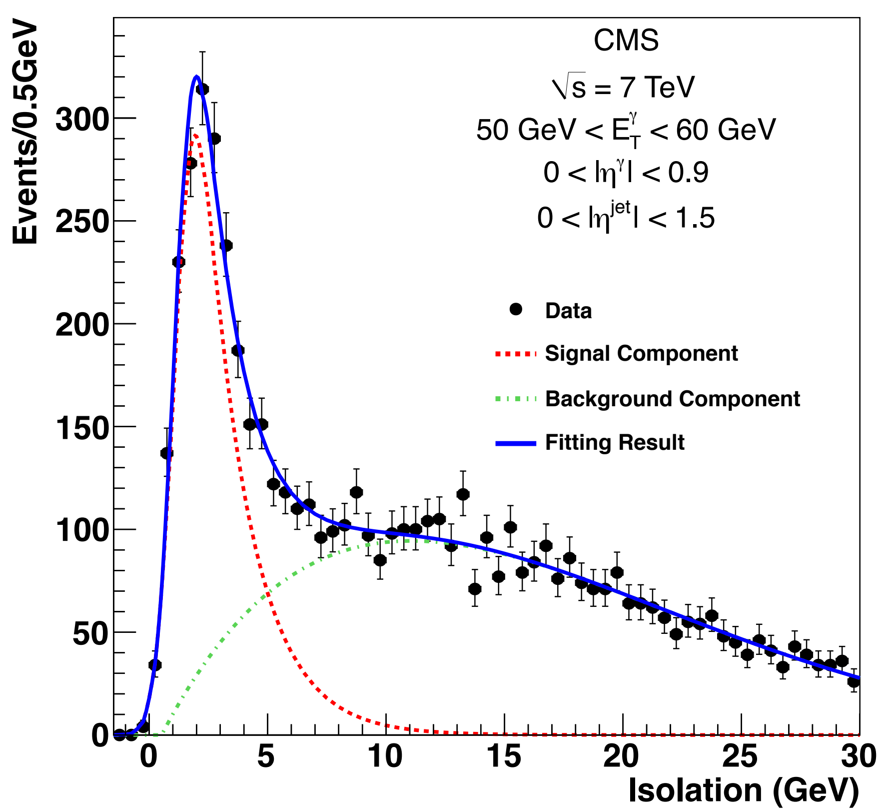
- Why study the QCD with photons
  - ☑ Testing event generators used in searches
  - ☑ Tool to constrain the gluon PDF
- Background dominated by π and η decays

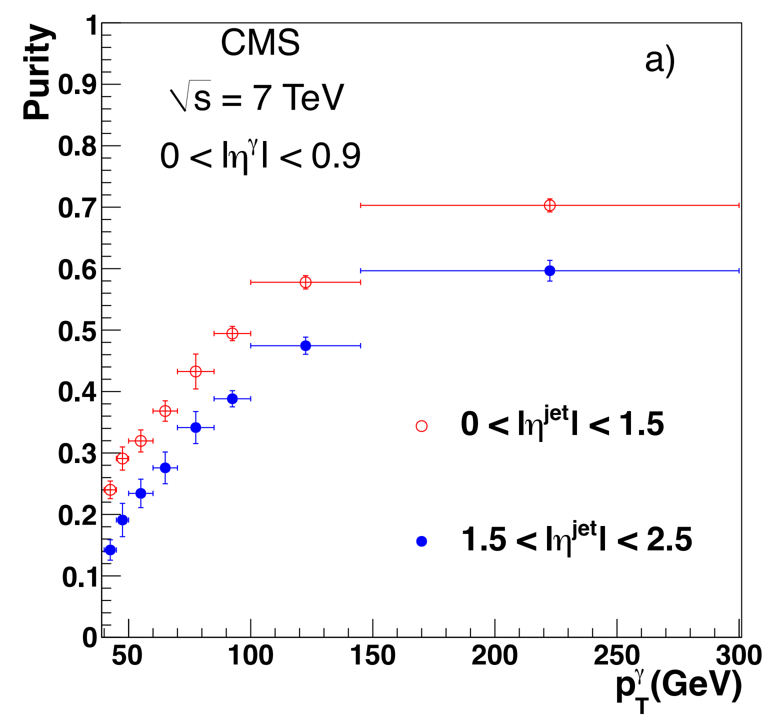
Signal



Background



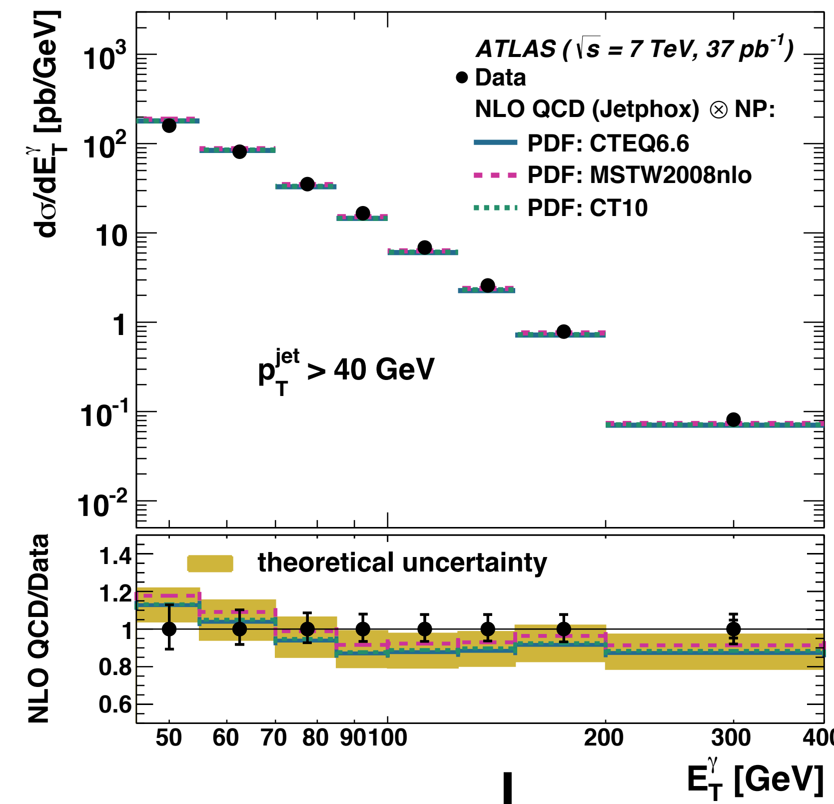




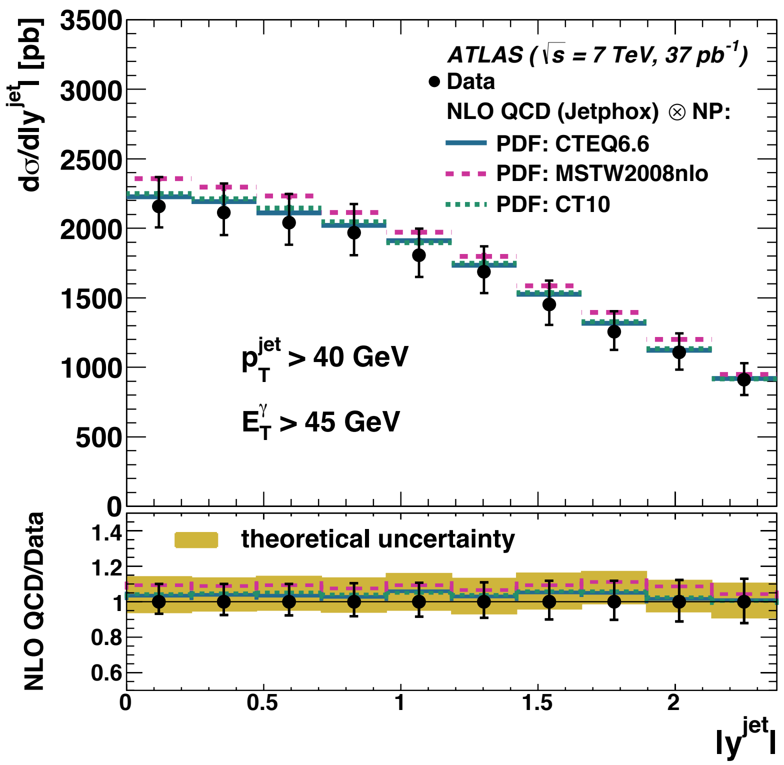
γ+jets cross section

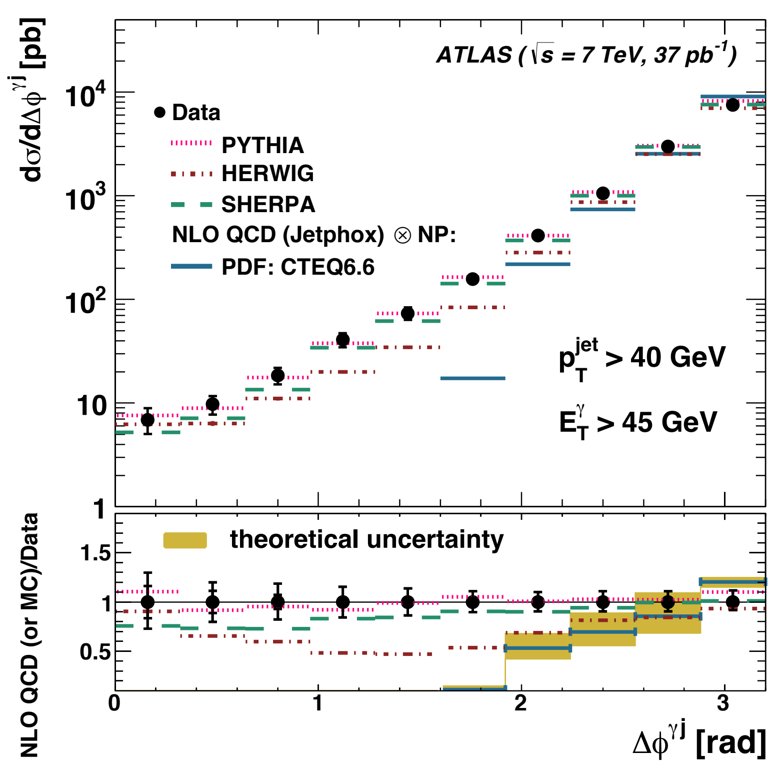
ATLAS Nucl. Phys. B 875 (2013) 483-535

- Overall good description of the data is obtained by event generators and NLO QCD predictions
- Data uncertainties starts to challenge the theory predictions



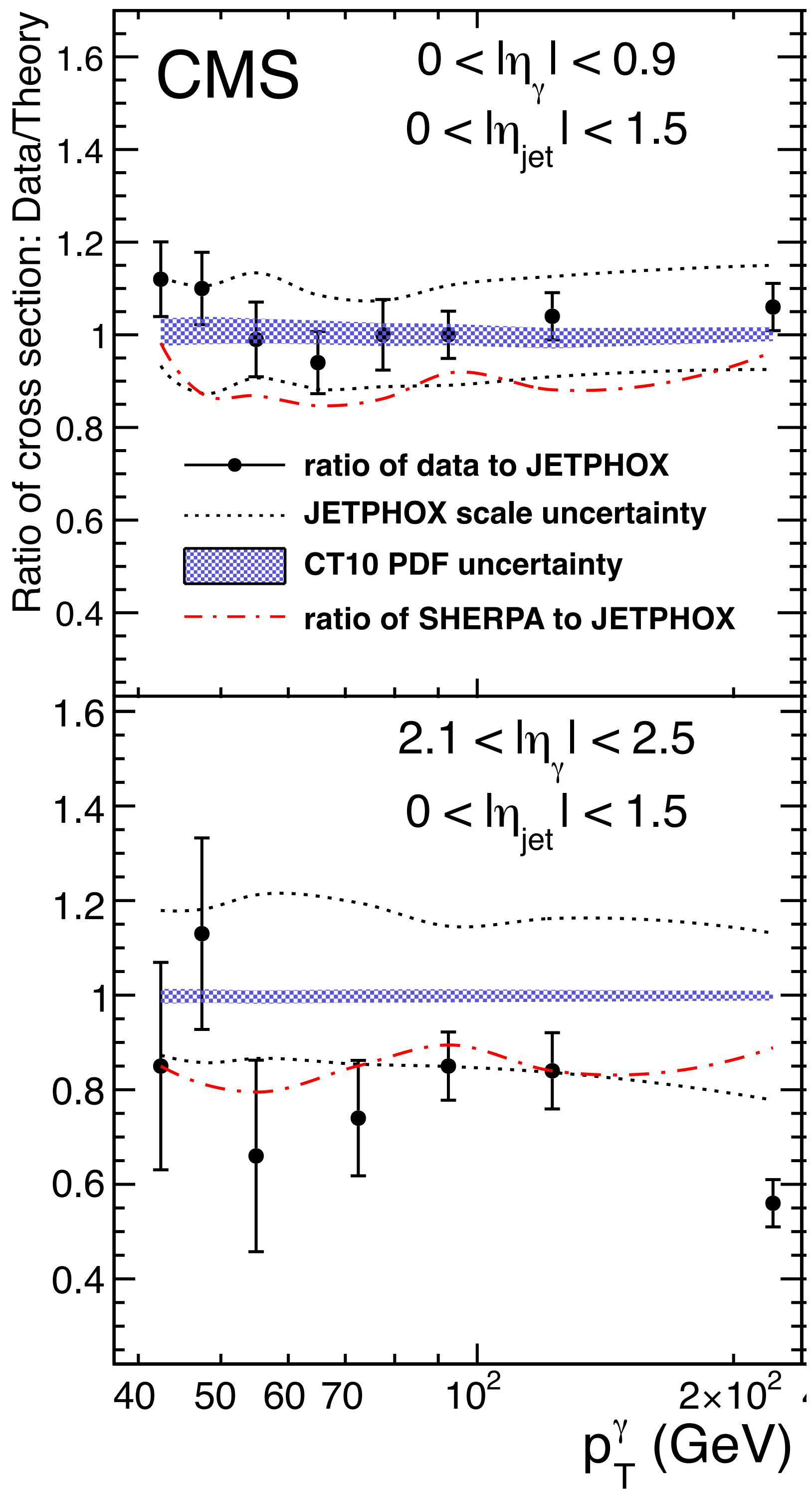
NLO QCD predict softer photon p_T spectrum?



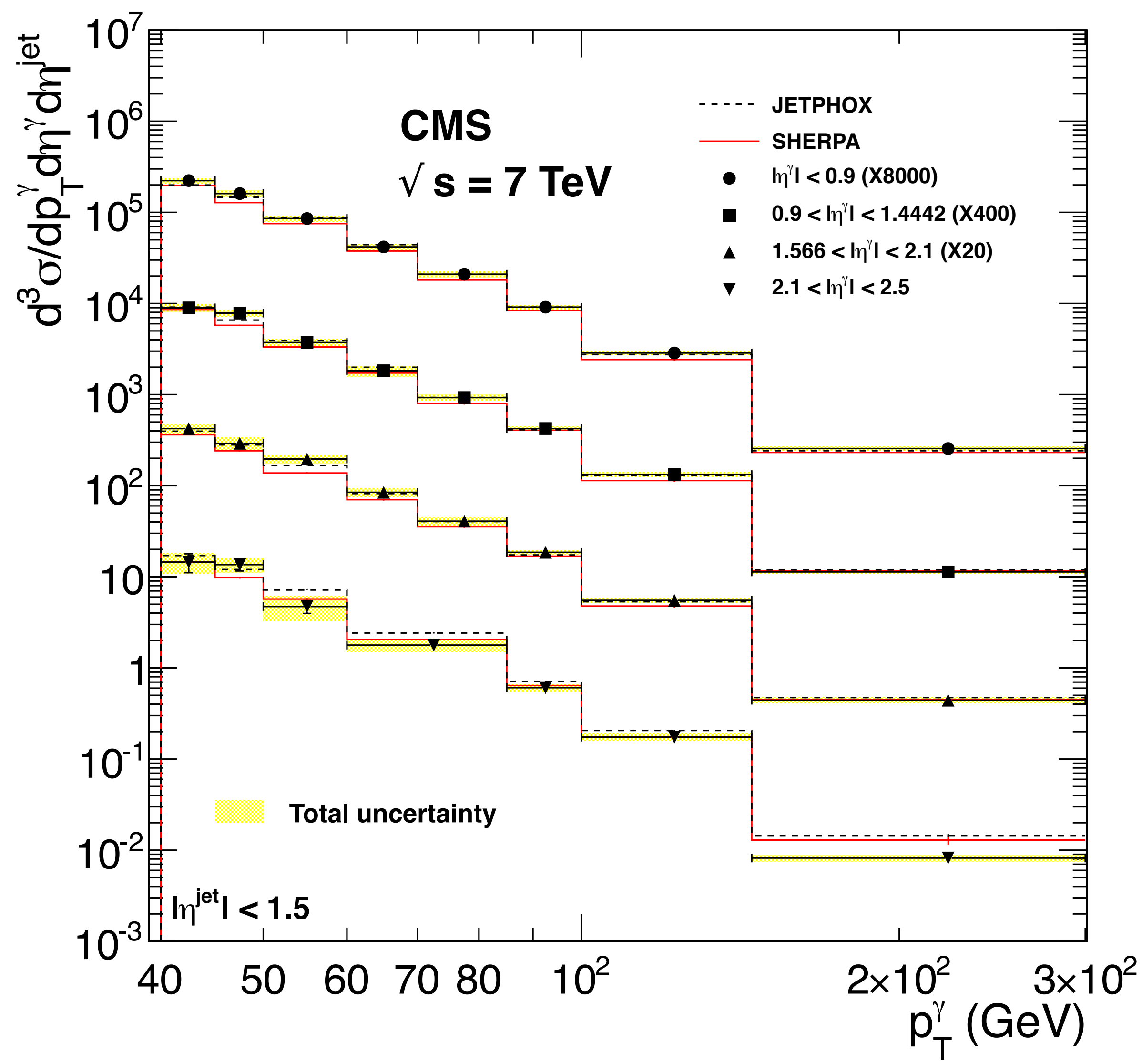


γ+jets cross section

CMS CMS-PAS-QCD-11-005



- ☐ NLO QCD predict softer photon pT spectrum?
  - ☑ More data is needed!



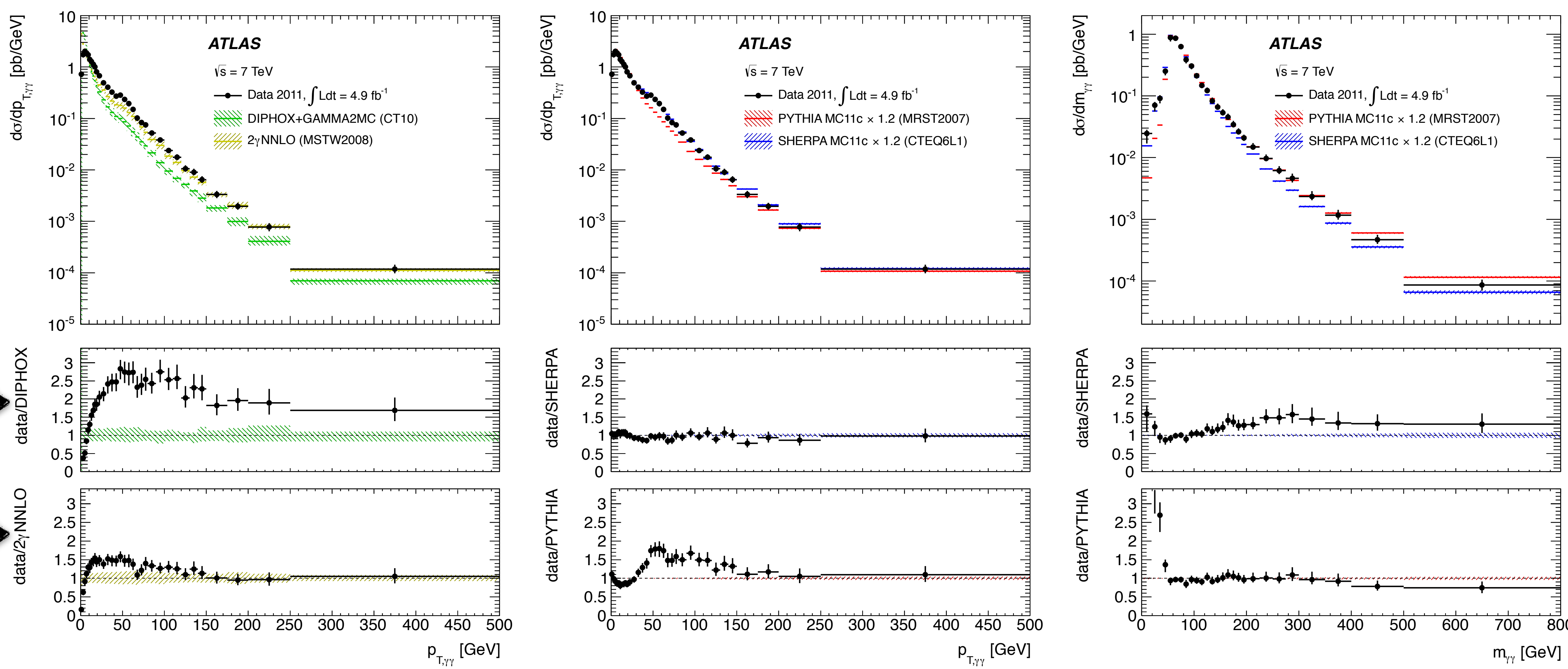
γγ cross section

ATLAS JHEP01(2013)086

- γγ cross sections shows great sensitivity to beyond LO effects and even beyond NLO
- NNLO QCD or multileg generators are mandatory to understand the data

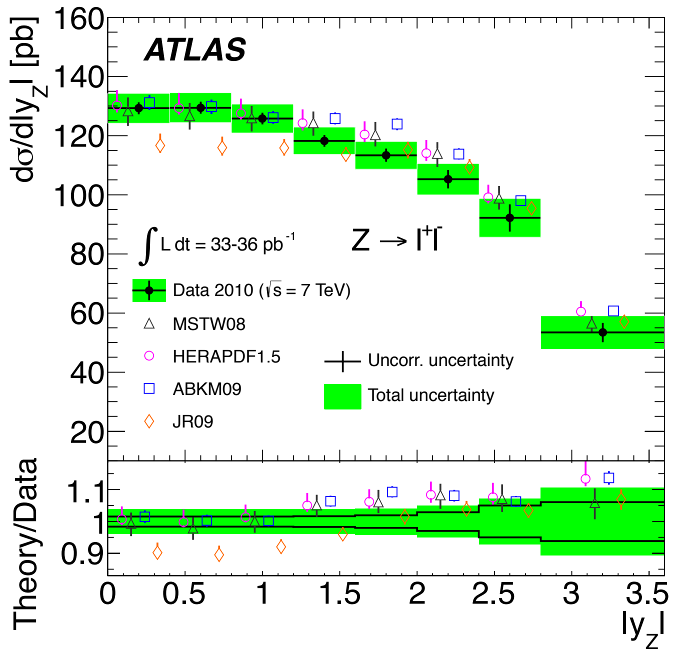
Ratio to **NLO**

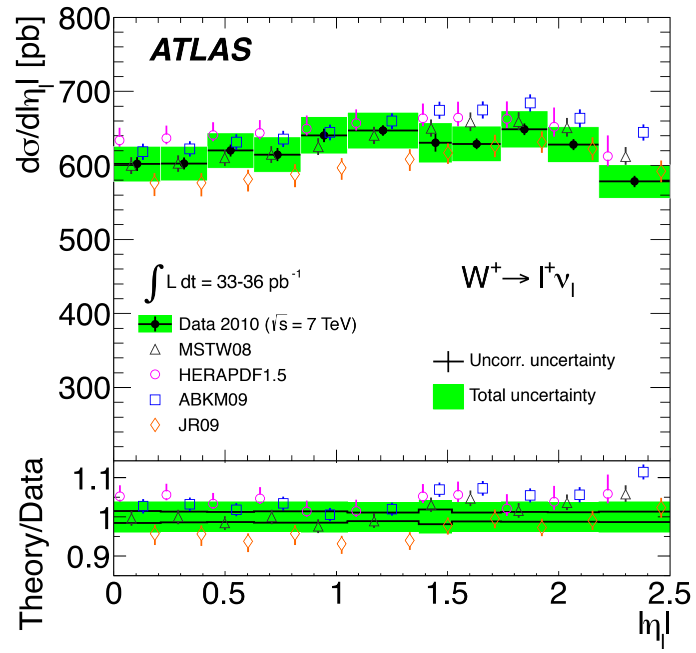
Ratio to **NNLO**

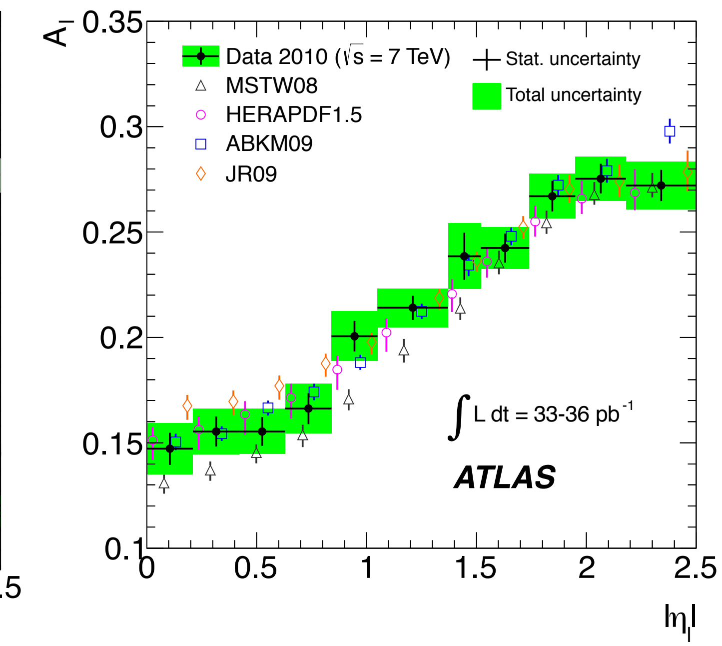


Intrinsic strange PDF

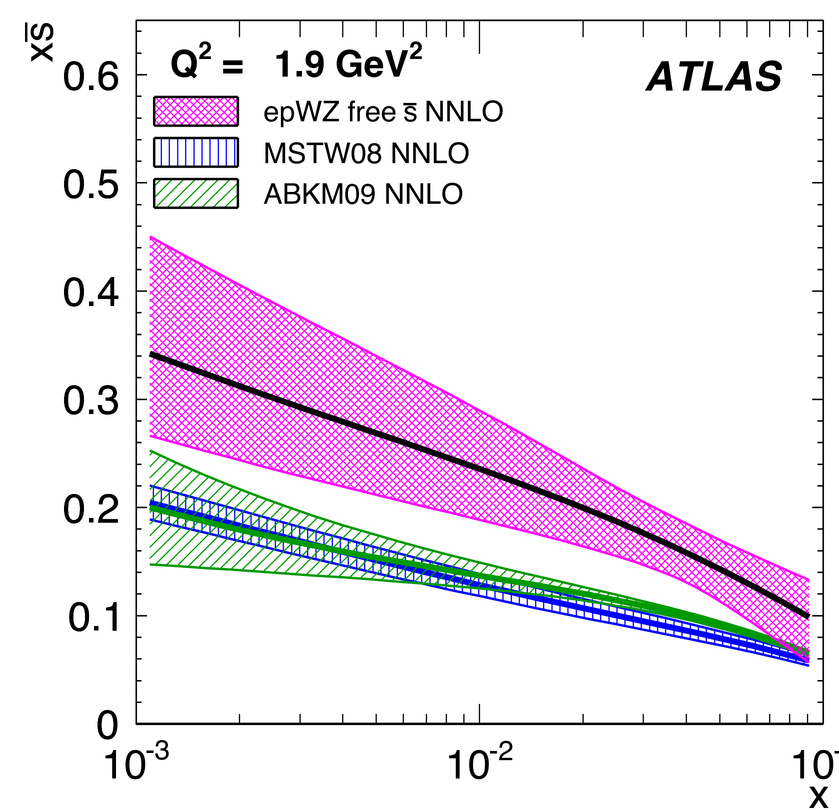
ATLAS Phys. Rev. D85 (2012) 072004







- Early measurement of W/Z cross sections already provide an handle on the sea-quark content of the proton
  - Measurements used to fit the strange quark PDF
  - The data push the strange PDF to higher density values



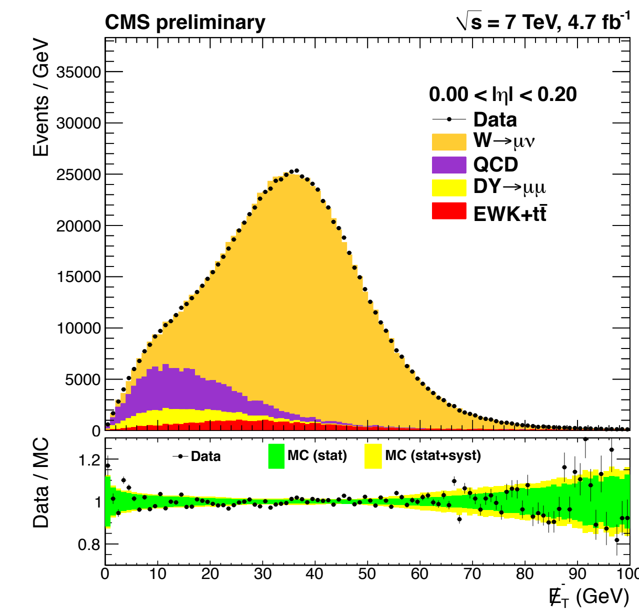
ATLAS Phys.Rev.Lett. 109 (2012) 012001

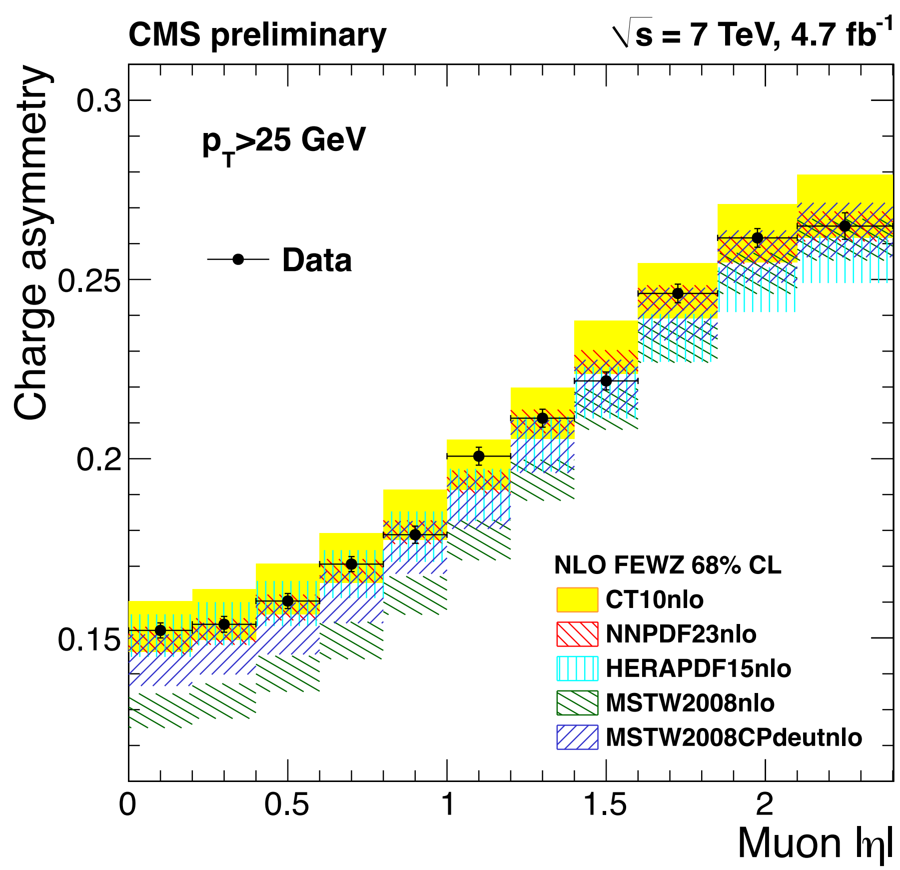
Muon charge asymmetry in W production

CMS CMS-PAS-SMP-12-021

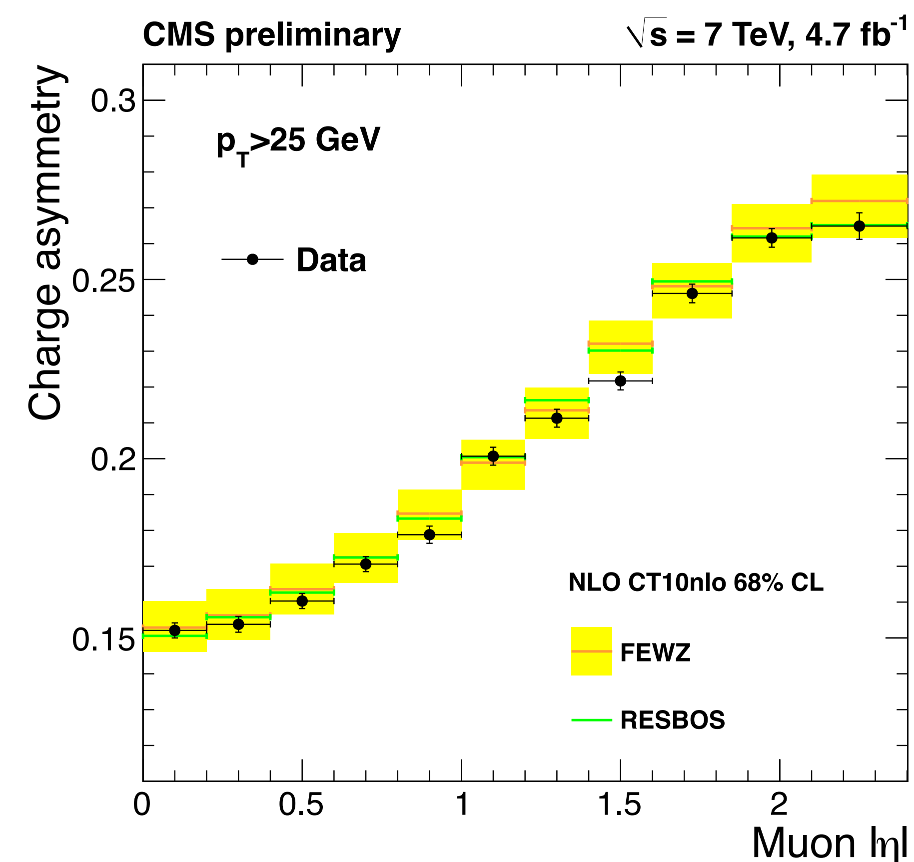
$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}$$

- Great sensitivity to quarks PDFs at low-x
- Using a template fit to the missing E_T for the signal extraction
- NNLO QCD calculation interfaced with various PDFs sets



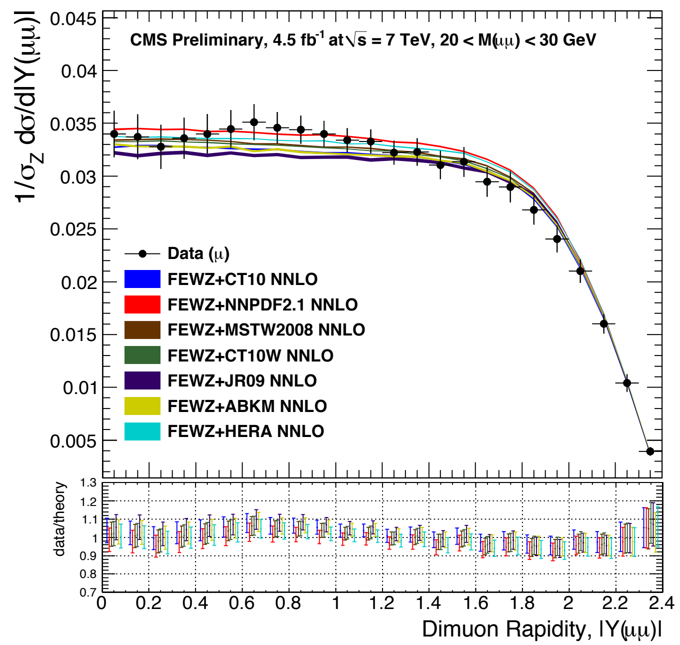


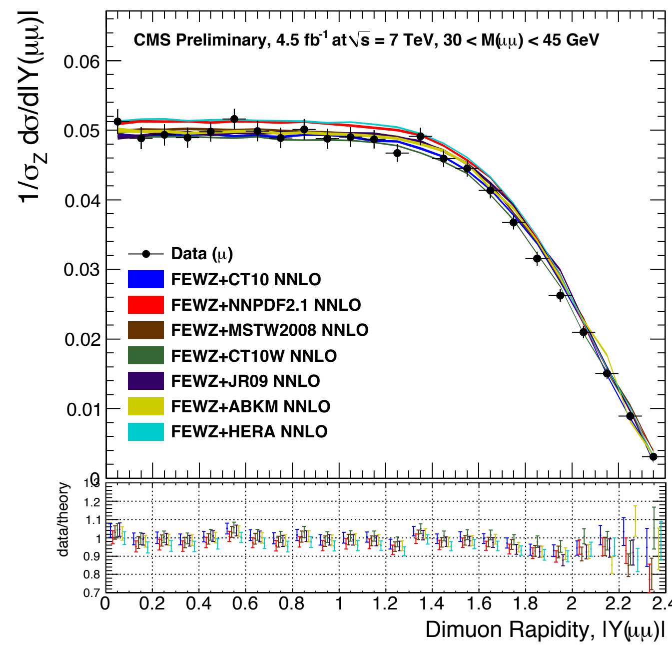
Physical interpretation don't change if an NNLL accuracy calculation is used

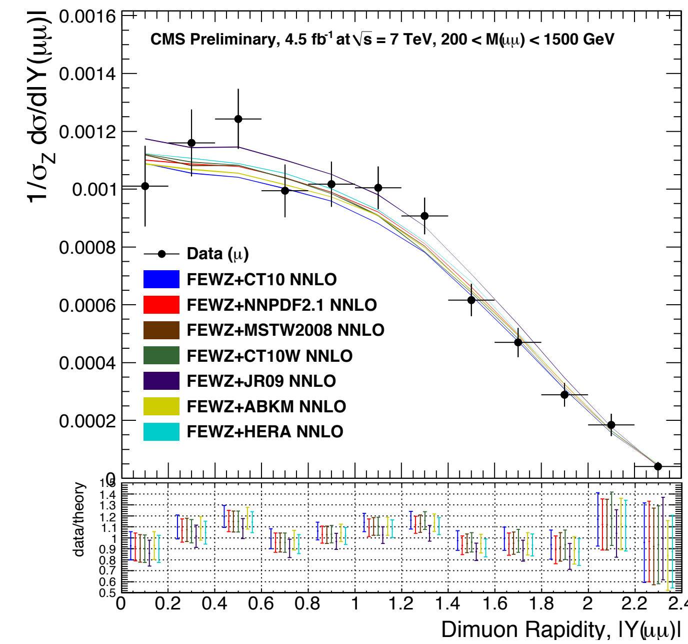


Double differential Drell-Yan cross section

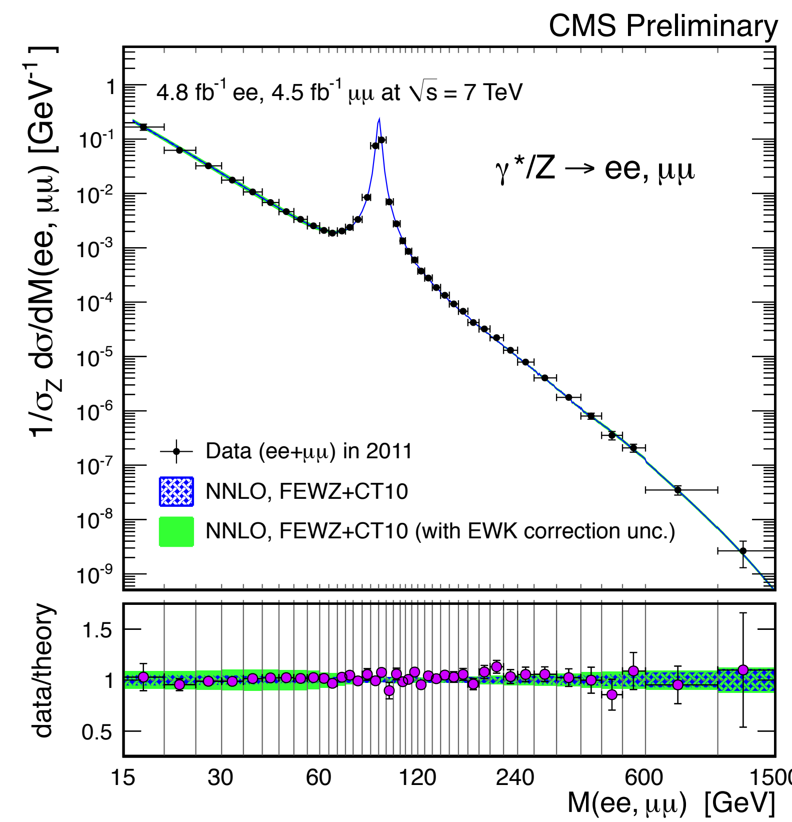
CMS CMS-PAS-SMP-12-026







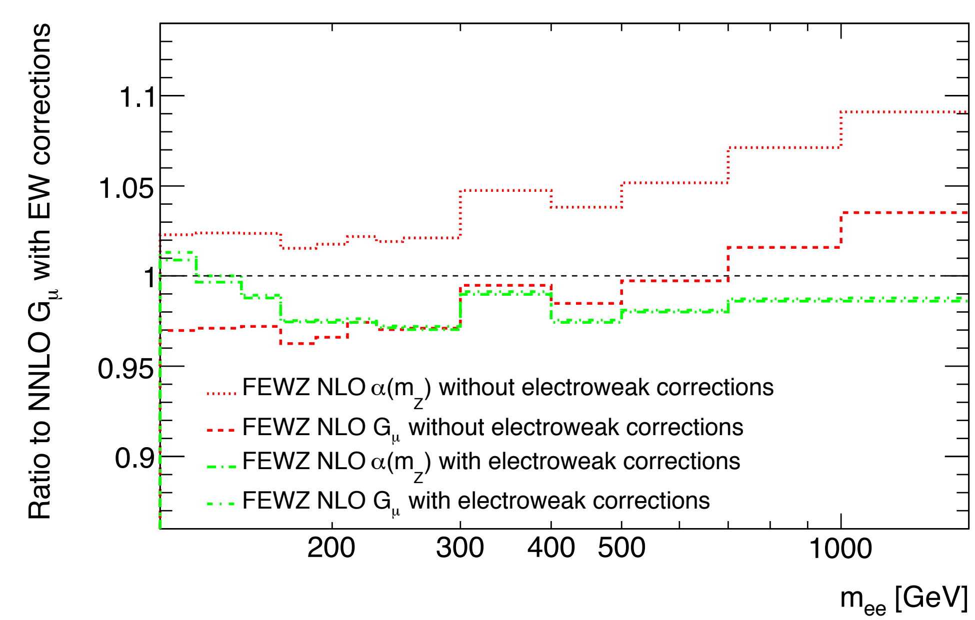
- Drell-Yan measured in the mass range between 15 to 1500 GeV
- NNLO QCD describe well the data in the full mass range
  - ☑ But electroweak corrections are no more negligible with the current data precision



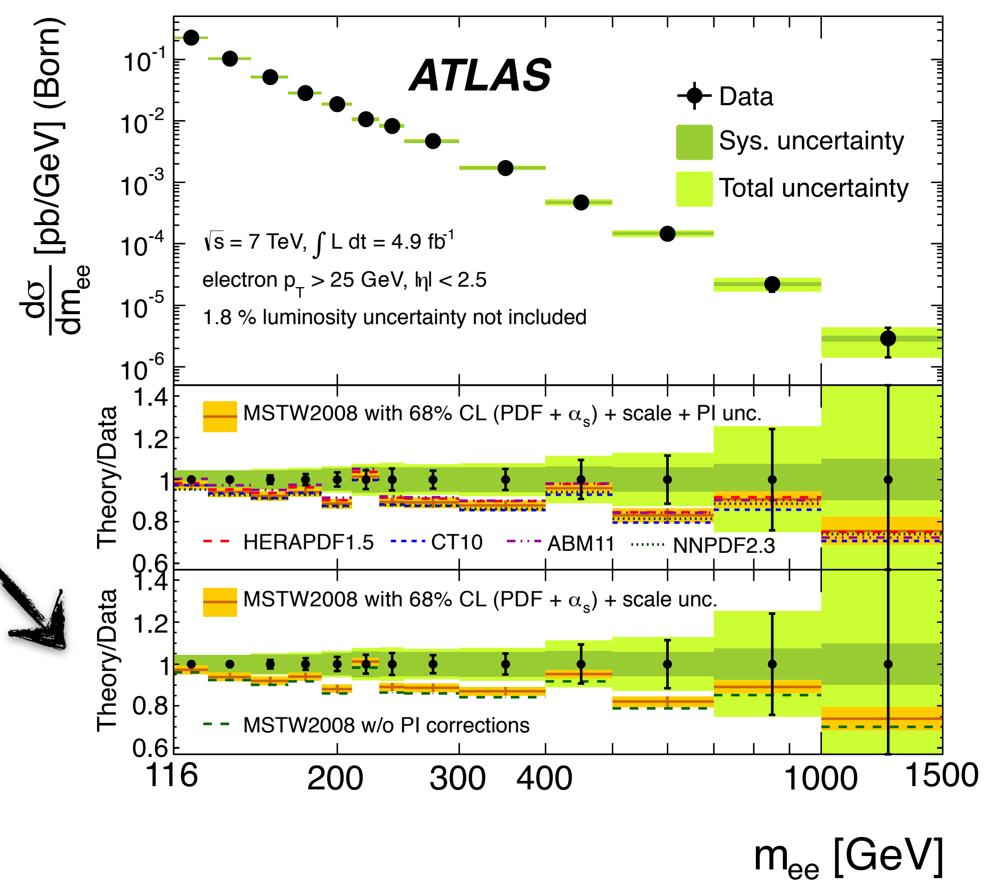
Drell-Yan production at high mass

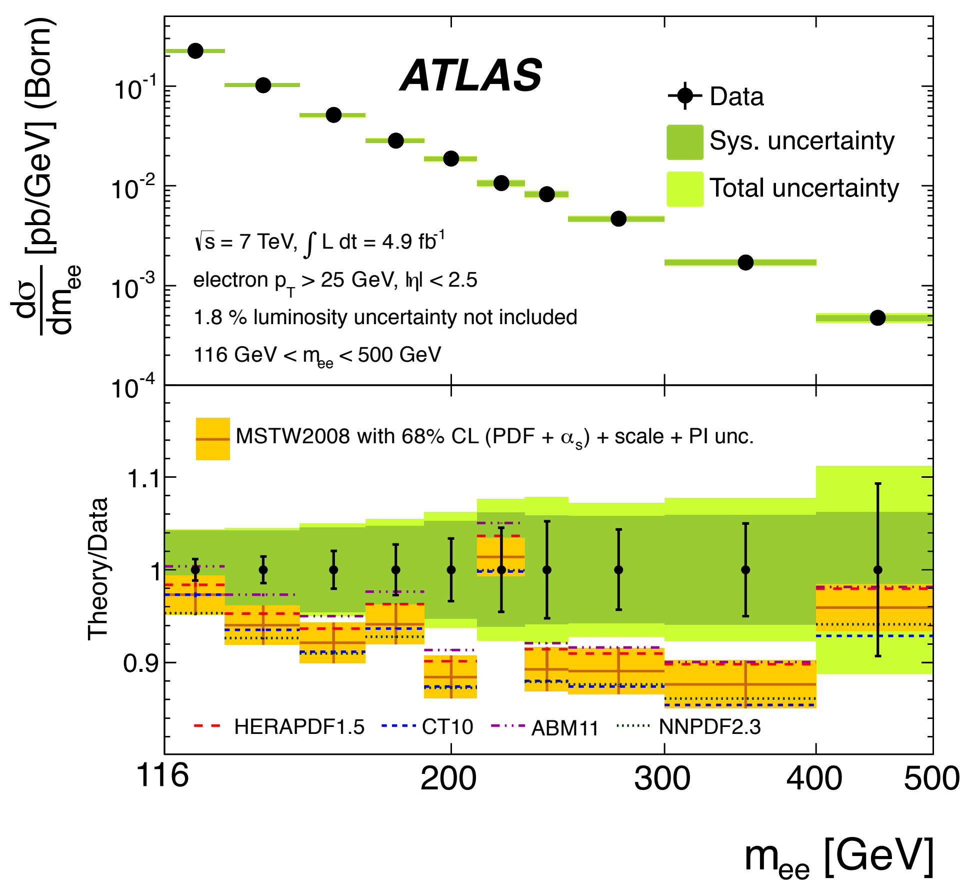
ATLAS [arXiv:1305.4192](https://arxiv.org/abs/1305.4192)

- Electroweak corrections needed to understand the data
  - Sensitivity to photon induced lepton pairs production (γγ→ll)
    - Need to understand the photon PDF as best as we can



Photon induced contribution as large as the PDF uncertainty





Gauge bosons p_T

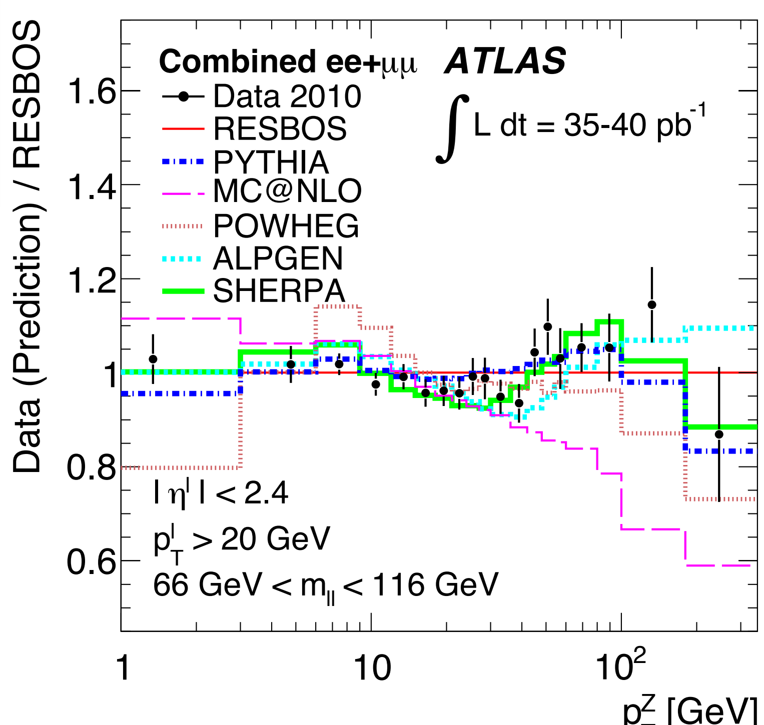
- Early measurements at 7 TeV and 8 TeV of the Z and W p_T spectrum
  - Only a limited part of the collected data has been used
  - Expected significant improvement with larger datasets

ATLAS Phys.Lett. B705 (2011) 415-434

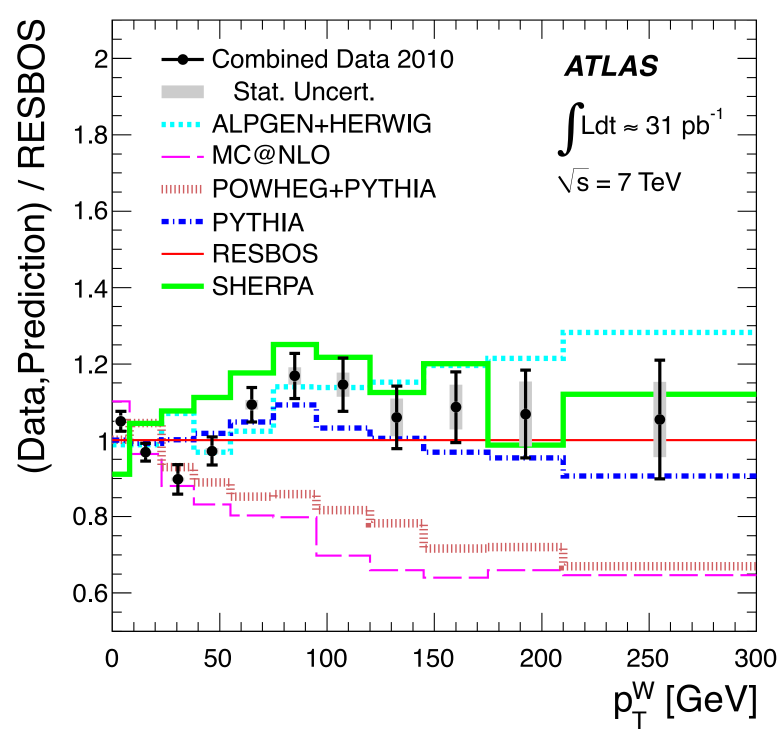
ATLAS Phys.Rev. D85 (2012) 012005

CMS CMS-PAS-SMP-12-025

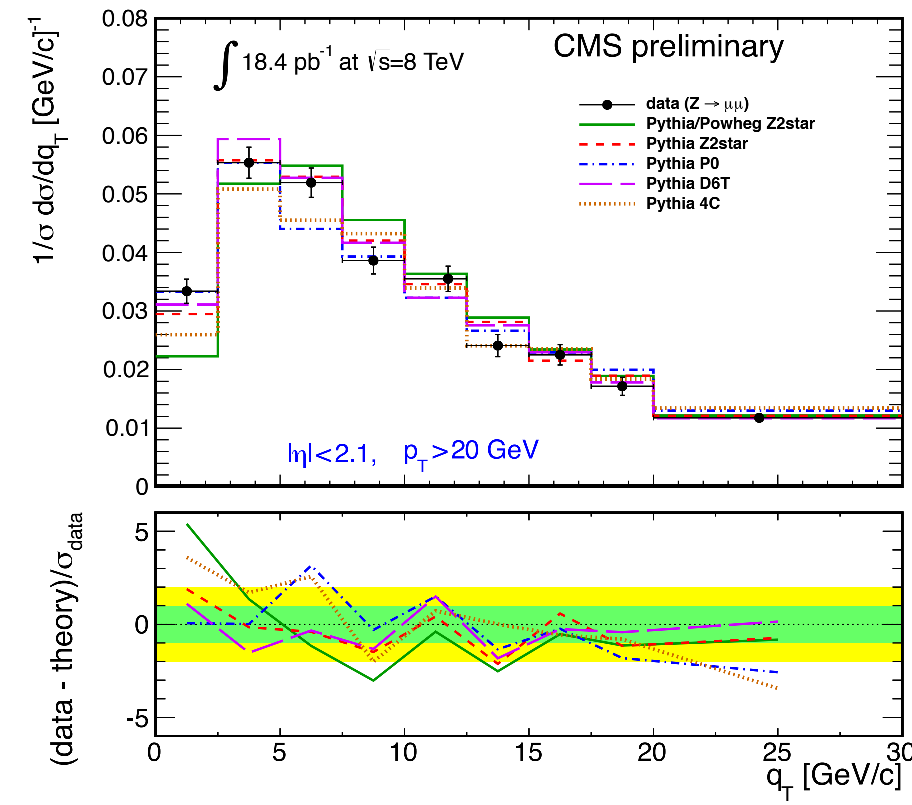
7 TeV, 35-40 pb^{-1}



7 TeV, 31 pb^{-1}



8 TeV, 18 pb^{-1}



Gauge bosons p_T: lepton angular correlations

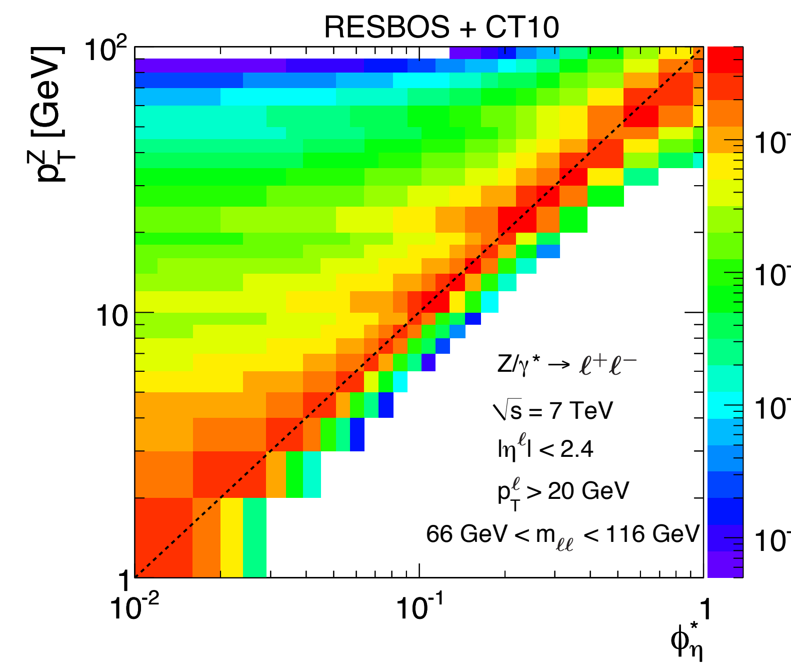
ATLAS Phys. Lett. B 720 (2013) 32-51

- Exploit new observable to study the p_T spectrum of the electroweak bosons

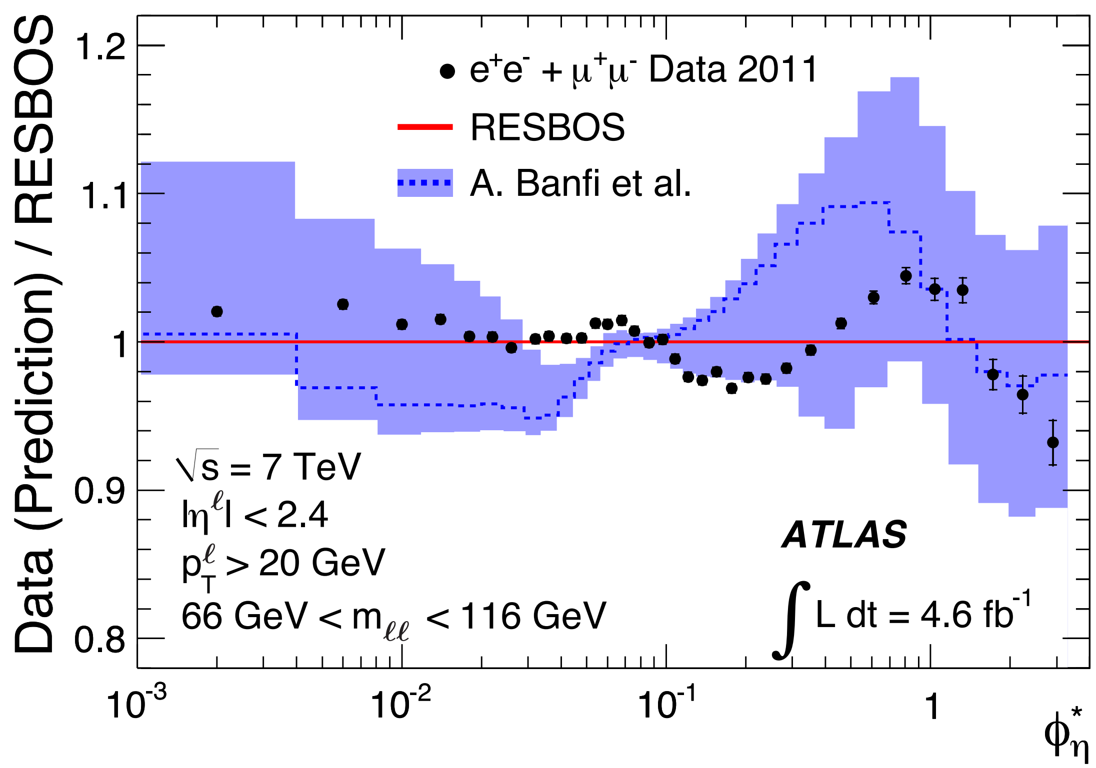
$$\phi^*_\eta = \tan(\phi_{acop}/2)\sin(\theta^*_\eta)$$

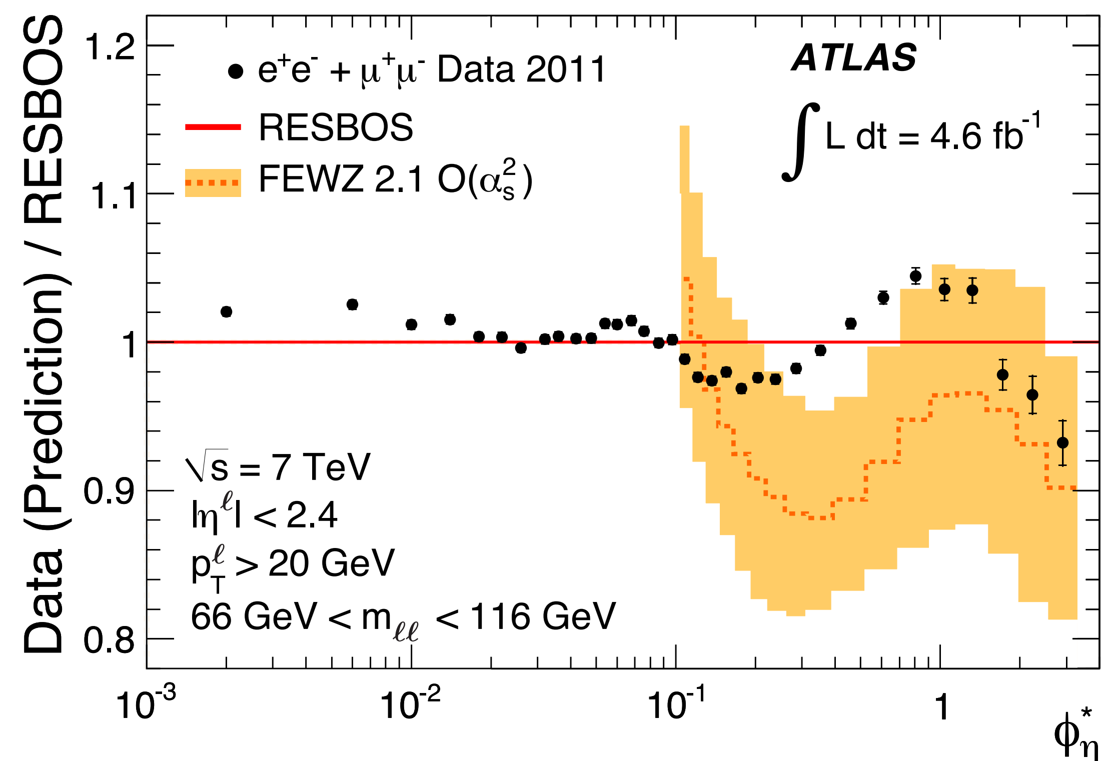
$$\phi_{acop} = \pi - \Delta\phi(\ell^+,\ell^-)$$

$$\cos(\theta^*_\eta) = \tanh\left[\frac{(\eta(\ell^-)-\eta(\ell^+))}{2}\right]$$



- Uncertainties in the data significantly smaller than the uncertainty on the theory predictions

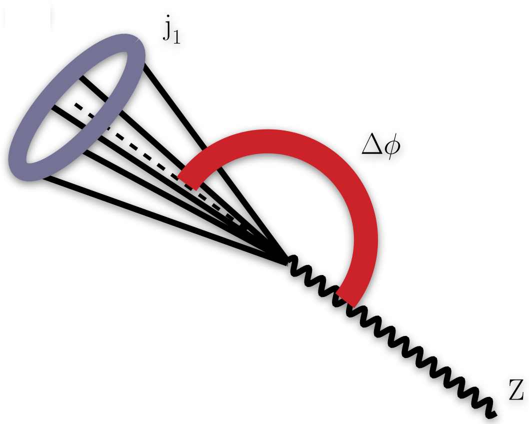


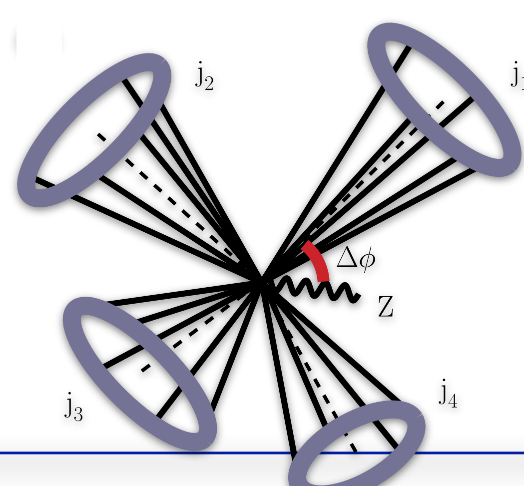


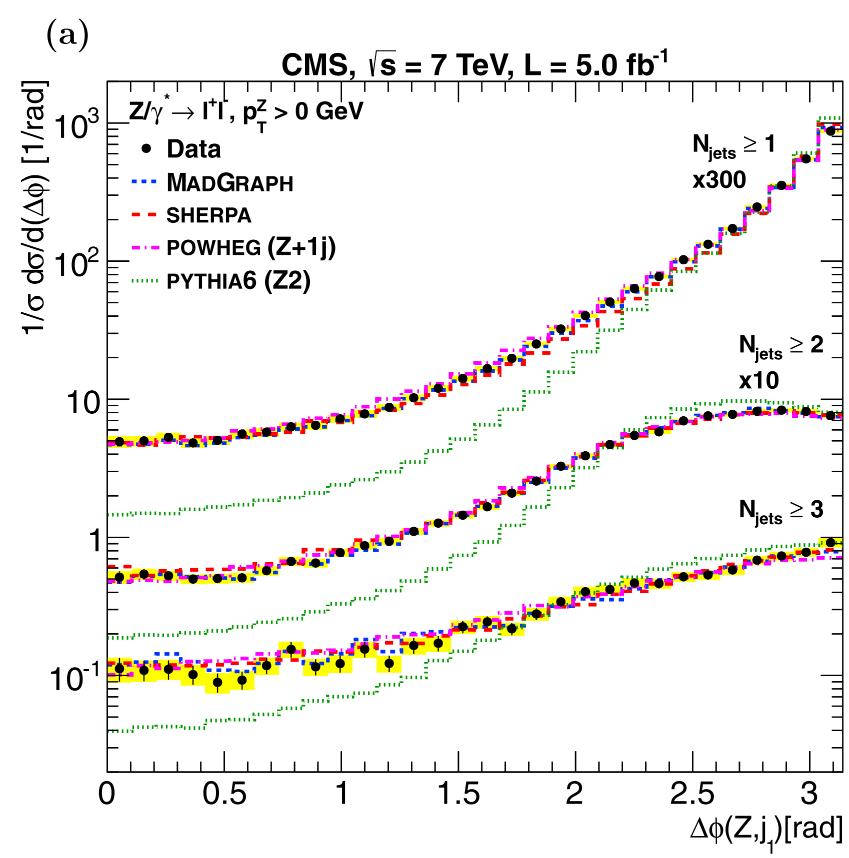
Azimuthal correlation in Z+jets events

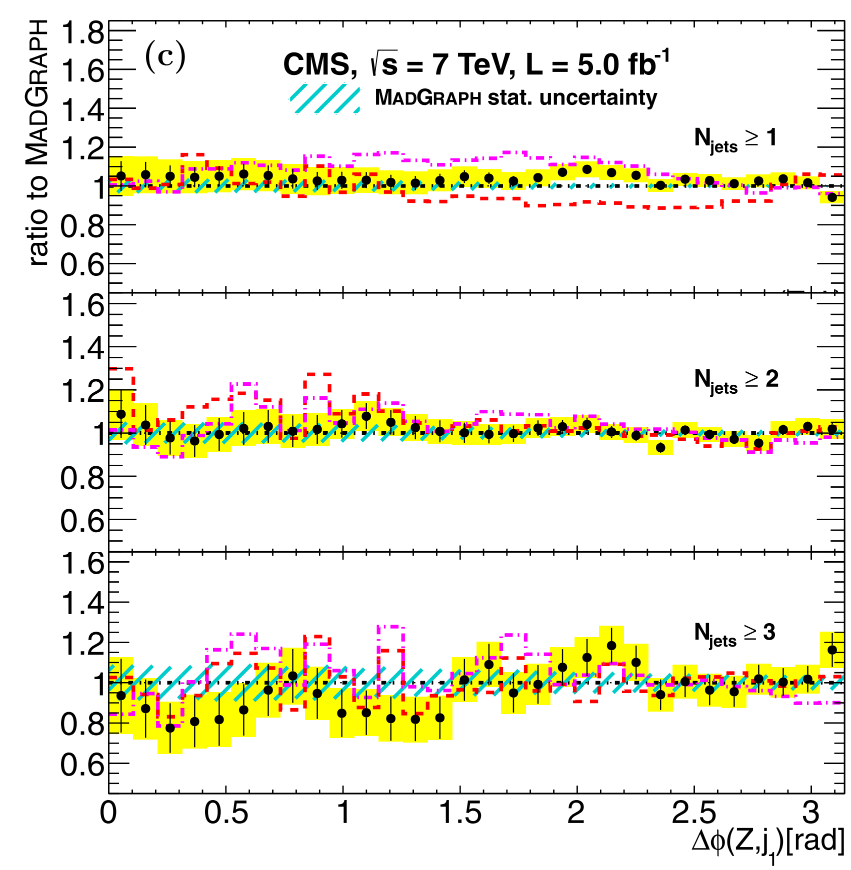
CMS Phys. Lett. B 722 (2013) 238-261

- Azimuthal correlations between pairs of jets and Z-jets measured for multiplicities up to three jets
- Good agreement between data and multileg generators
  - ☑ "Simple" leading order paradigm not enough to describe the data





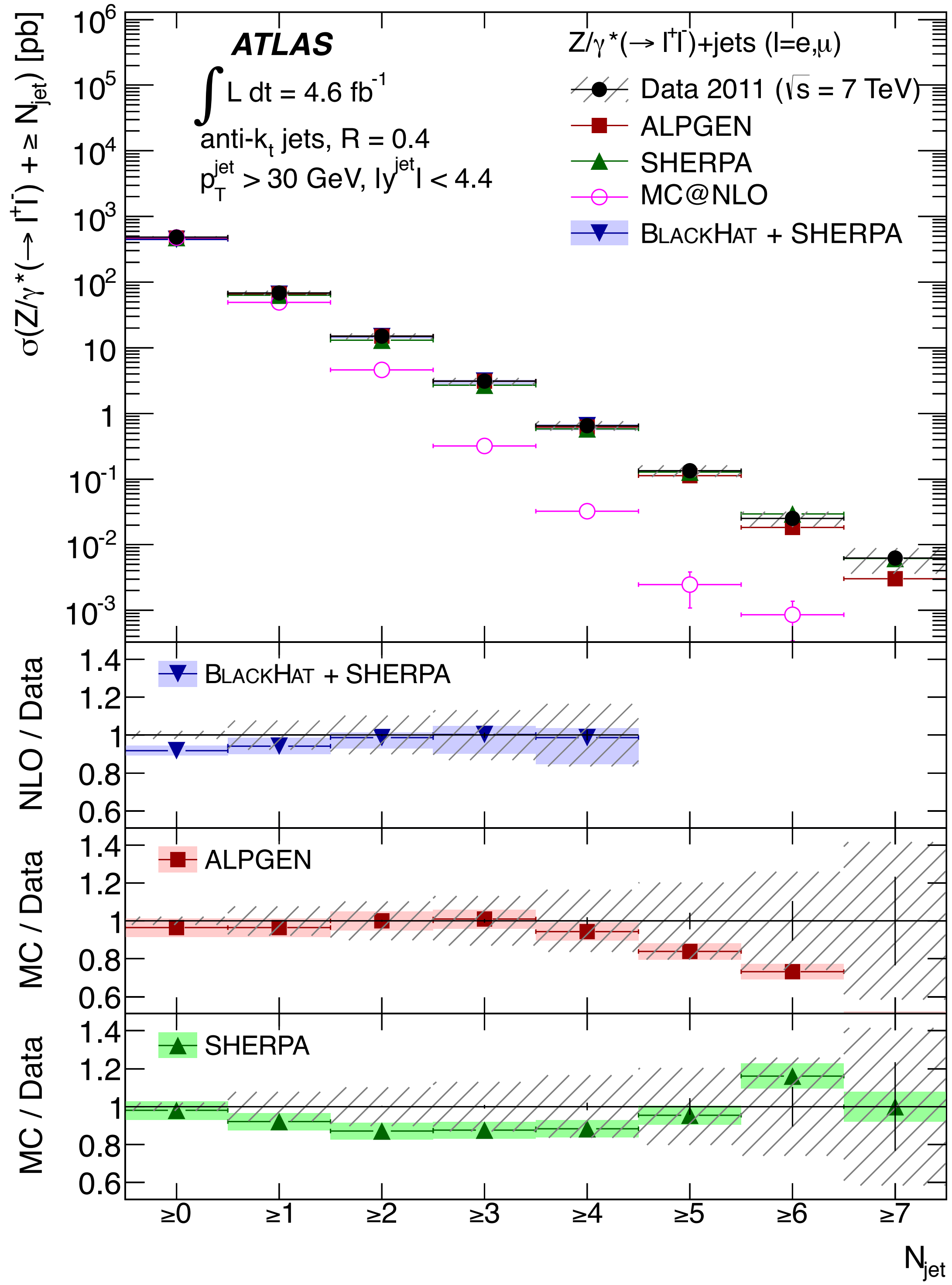




Z+jets studies: inclusive jet multiplicities

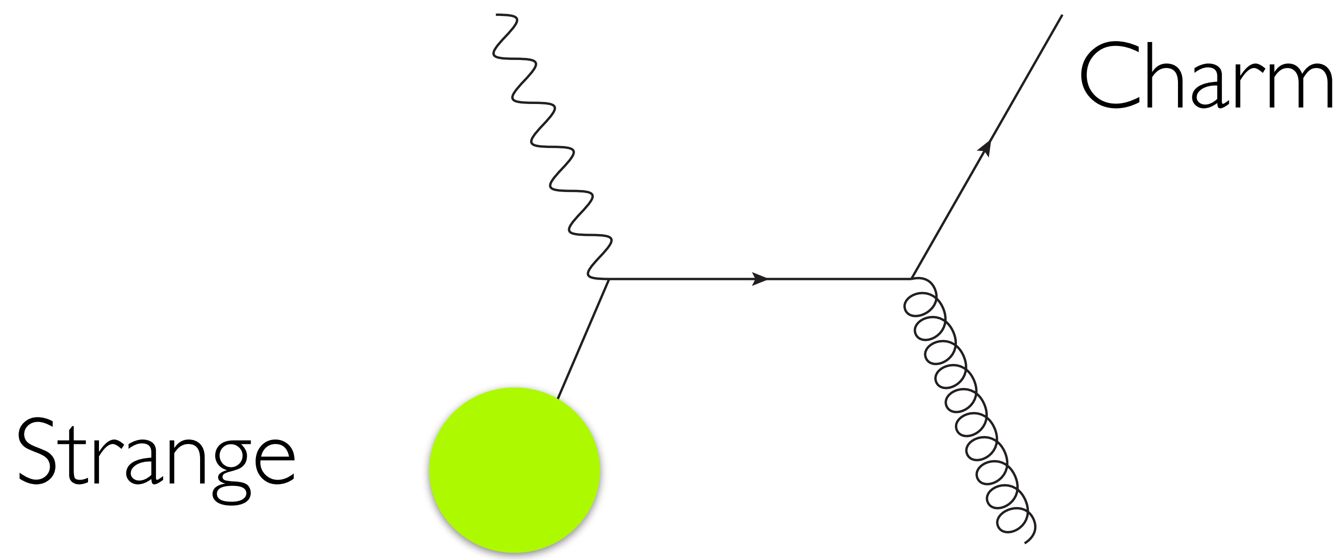
ATLAS JHEP07(2013)032

- Study topologies with large jet multiplicities
- NLO Monte Carlo not enough
- Data very well described by multileg predictions

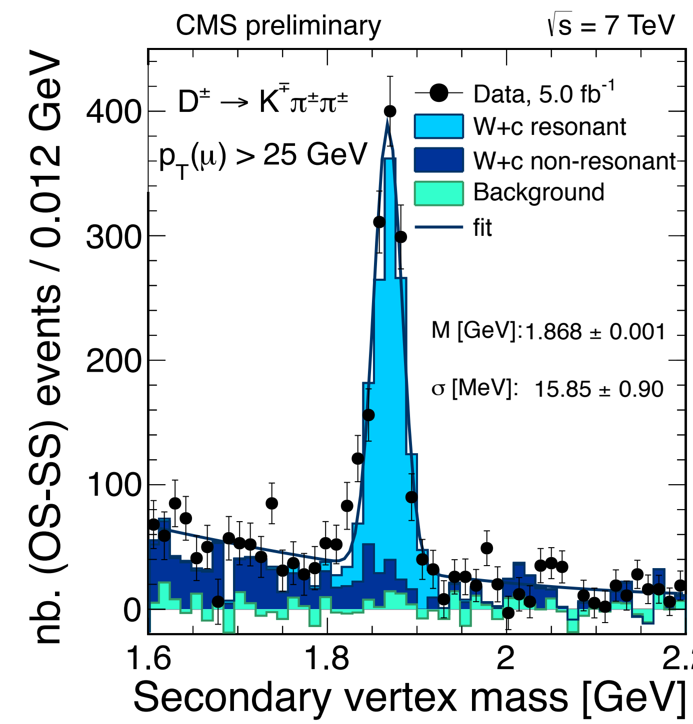


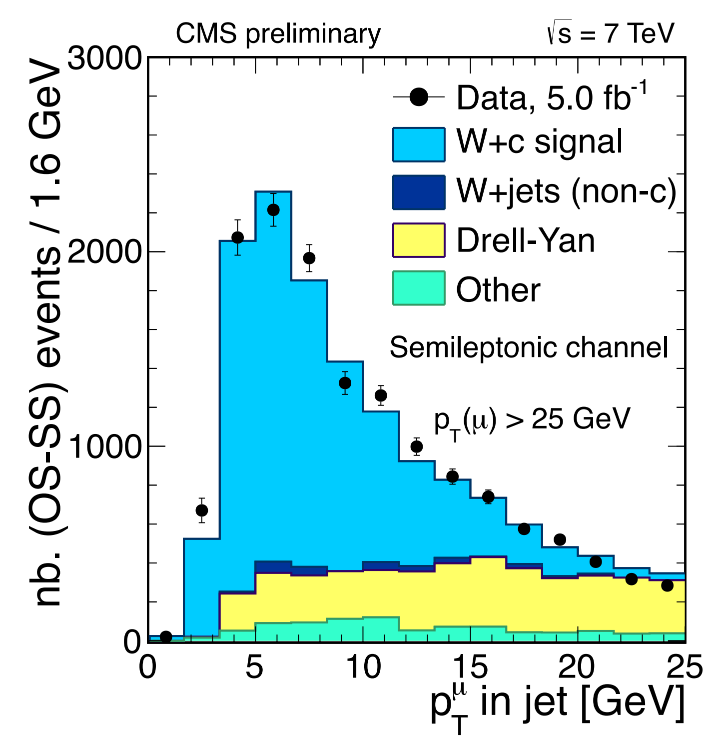
W+charm

CMS CMS-PAS-SMP-12-002



- Sensitive to the strange parton distribution function
- Charm hadrons identification is a challenge
  - ☑ Combination of exclusive charm decays identification and soft muon tagging is exploited



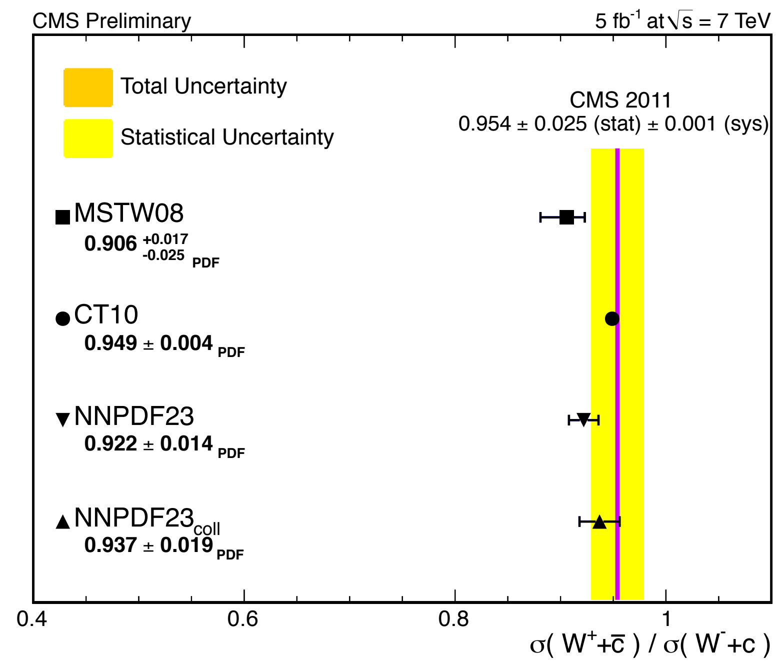


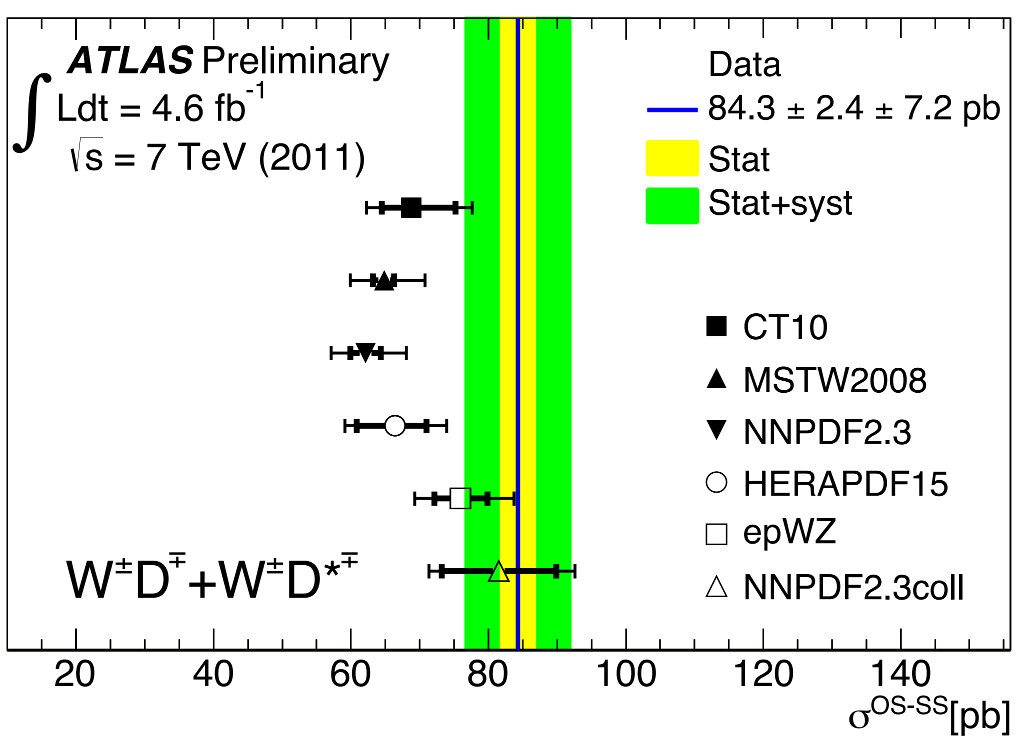
W+charm

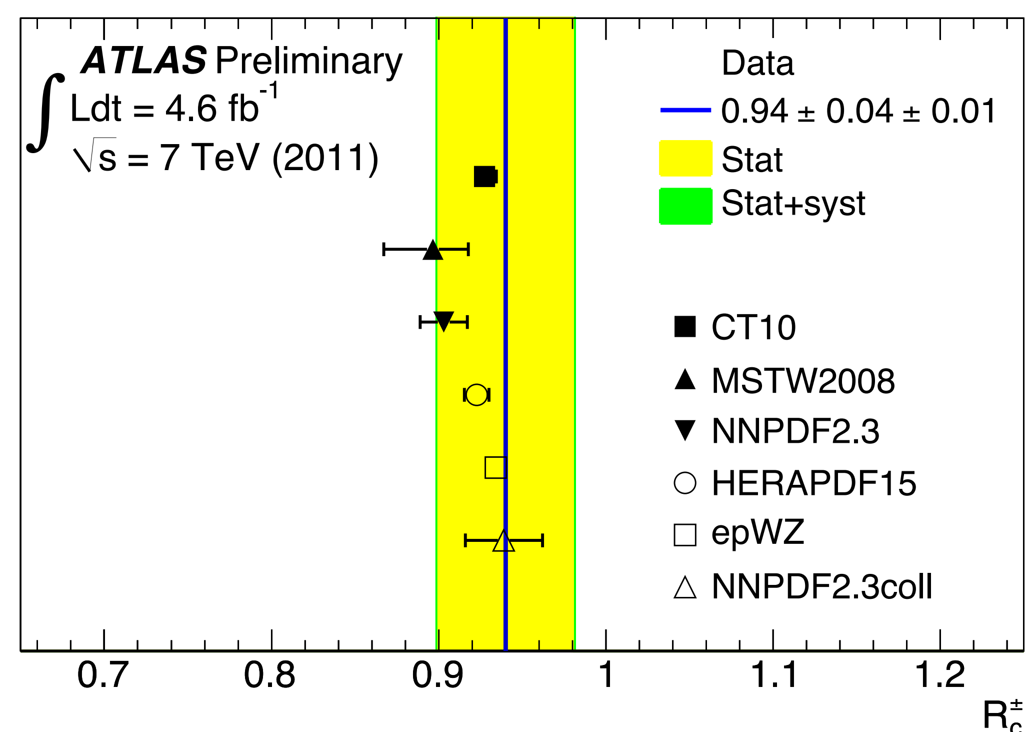
ATLAS ATLAS-CONF-2013-045

CMS CMS-PAS-SMP-12-002

- Room for improving the understanding of the strange quark content of the proton
  - ☑ Only preliminary results are available at LHC





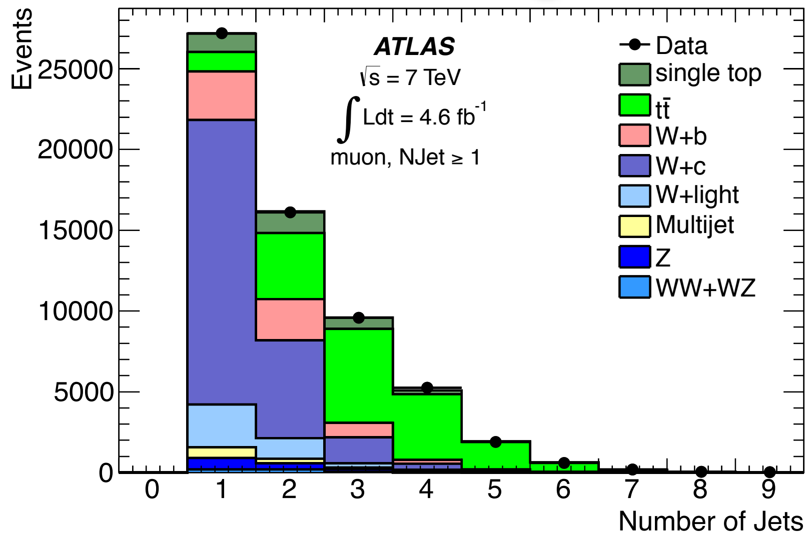


W+b

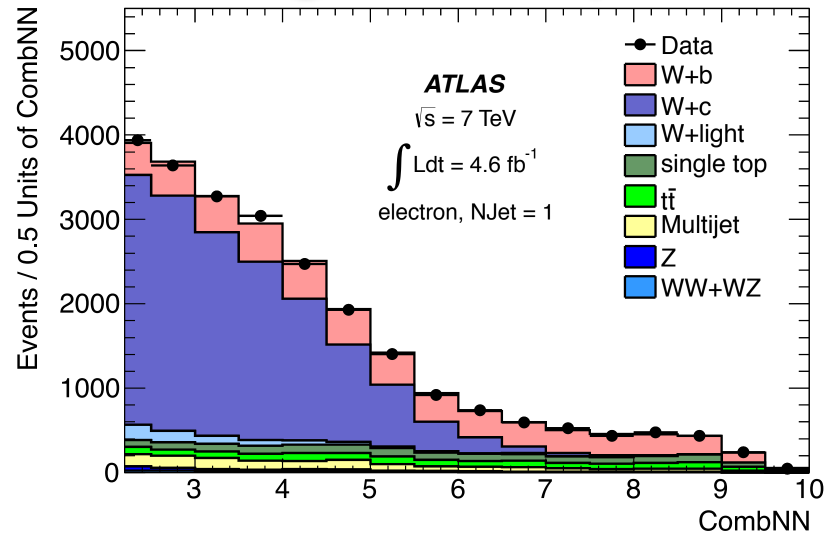
ATLAS JHEP 06 (2013) 084

CMS CMS-PAS-SMP-12-026

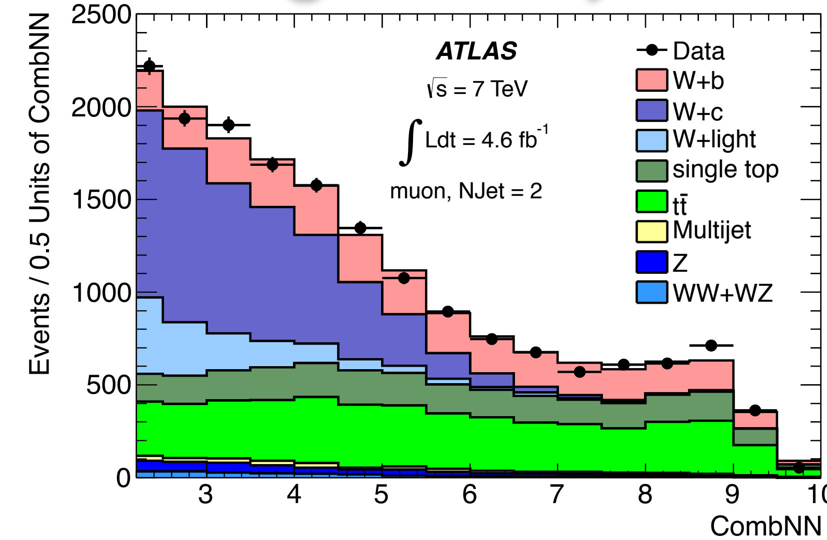
1 tag



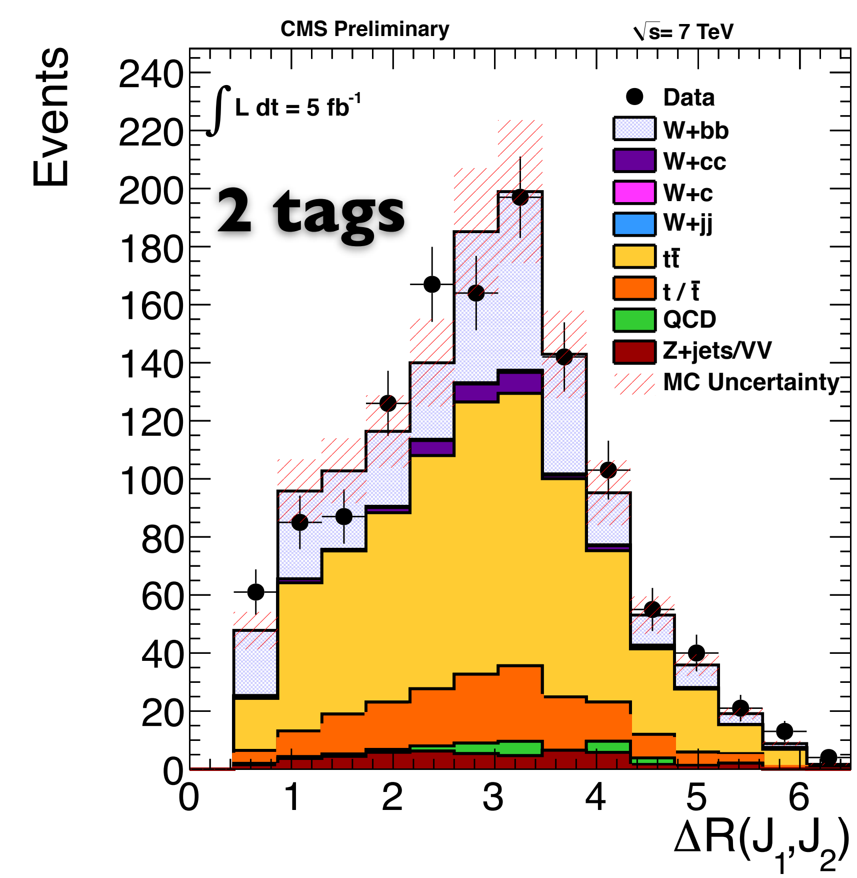
1 tag and ≥1 jet



1 tag and ≥2 jets



- Important channel to understand QCD predictions for massive quarks production
- Background for searches as well as single top properties measurements
- .. but
  - Backgrounds is hard to control at high jet multiplicity

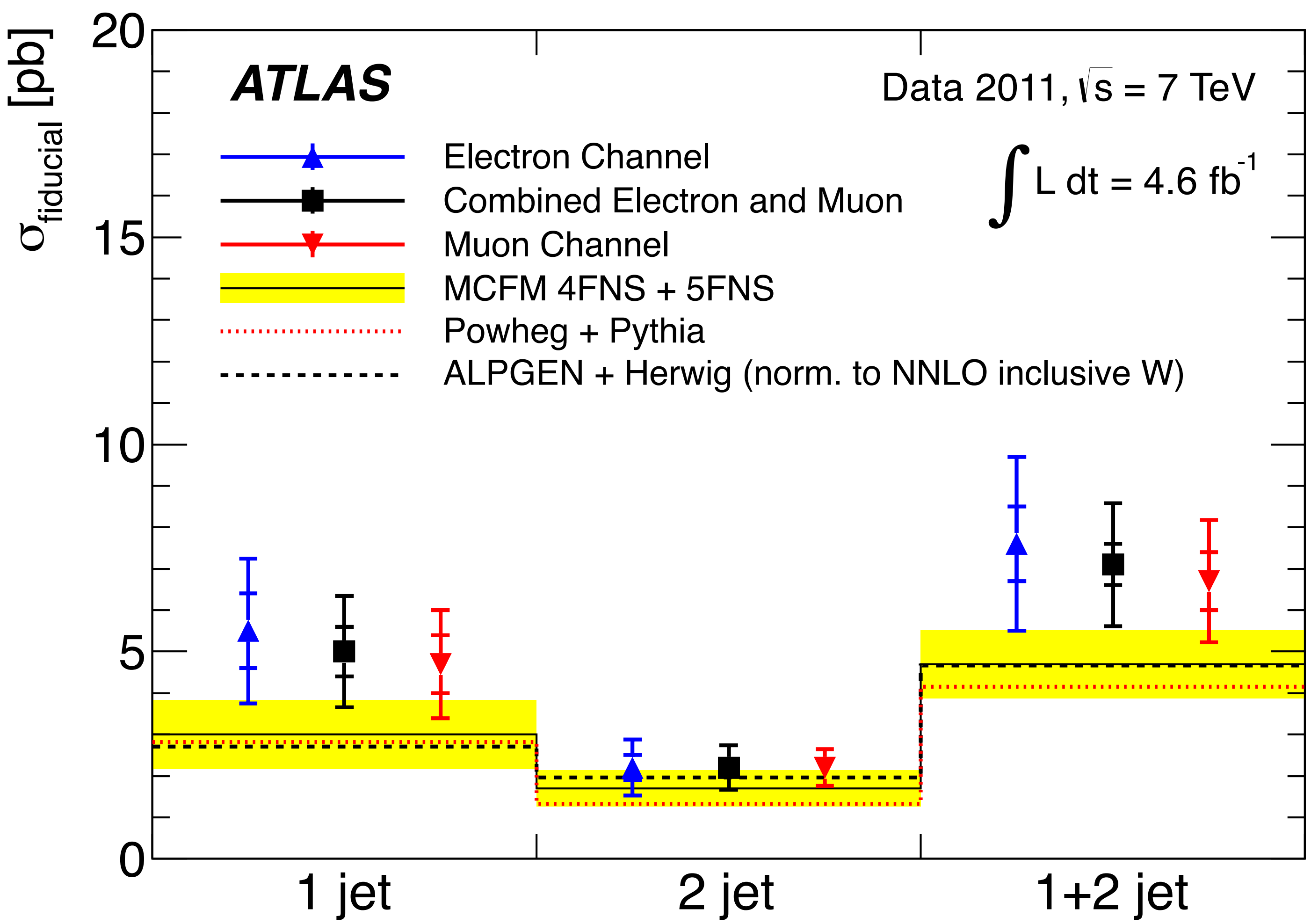


W+b

ATLAS JHEP 06 (2013) 084

CMS CMS-PAS-SMP-12-026

- W+bb well described by NLO QCD and LO multileg calculations
- Some tensions in the W+b cross section
  - ☑ W+bb well predicted by NLO QCD as well as LO multileg calculations



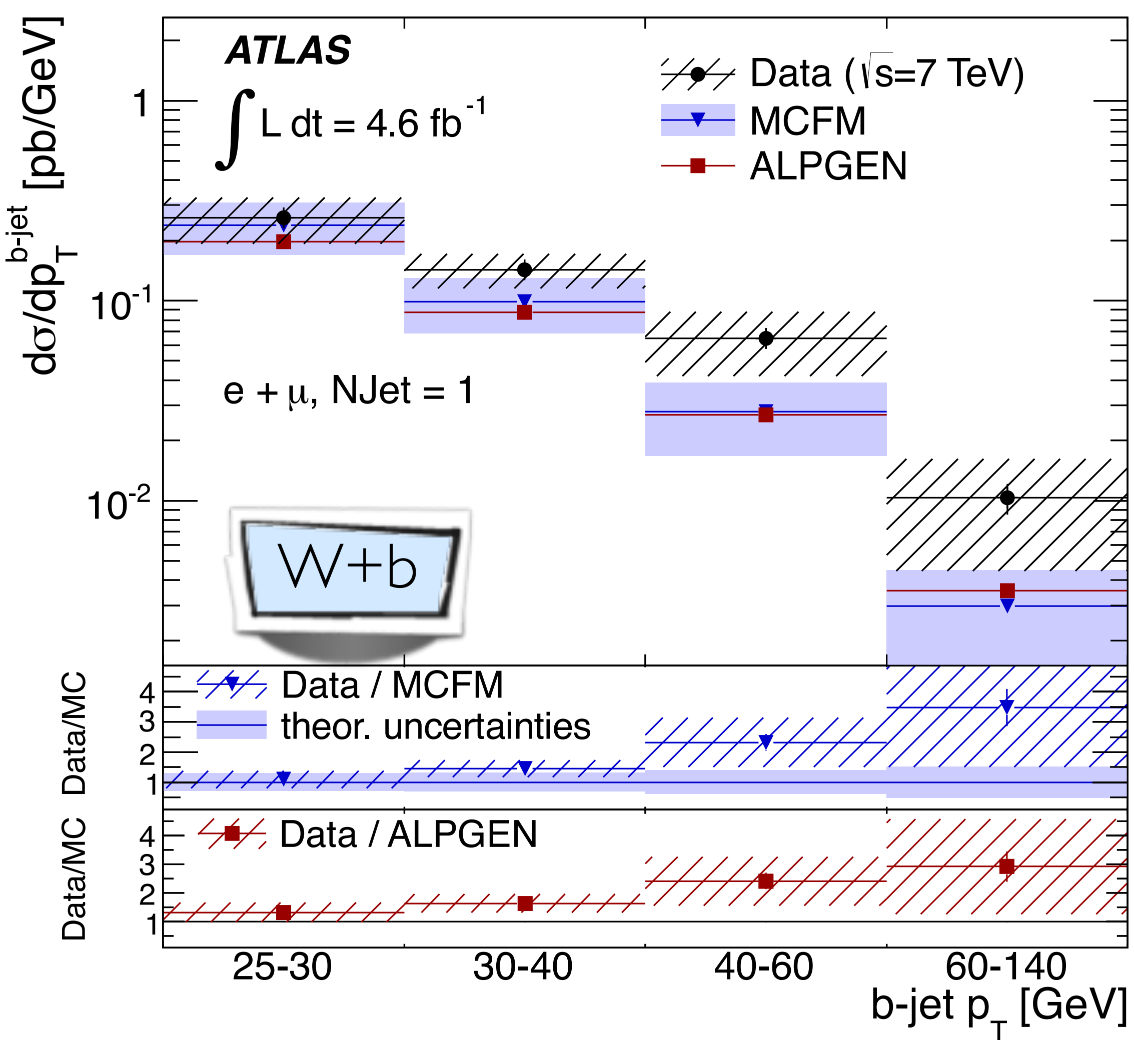
σ(pp→Wbb)×BR(W→μν)

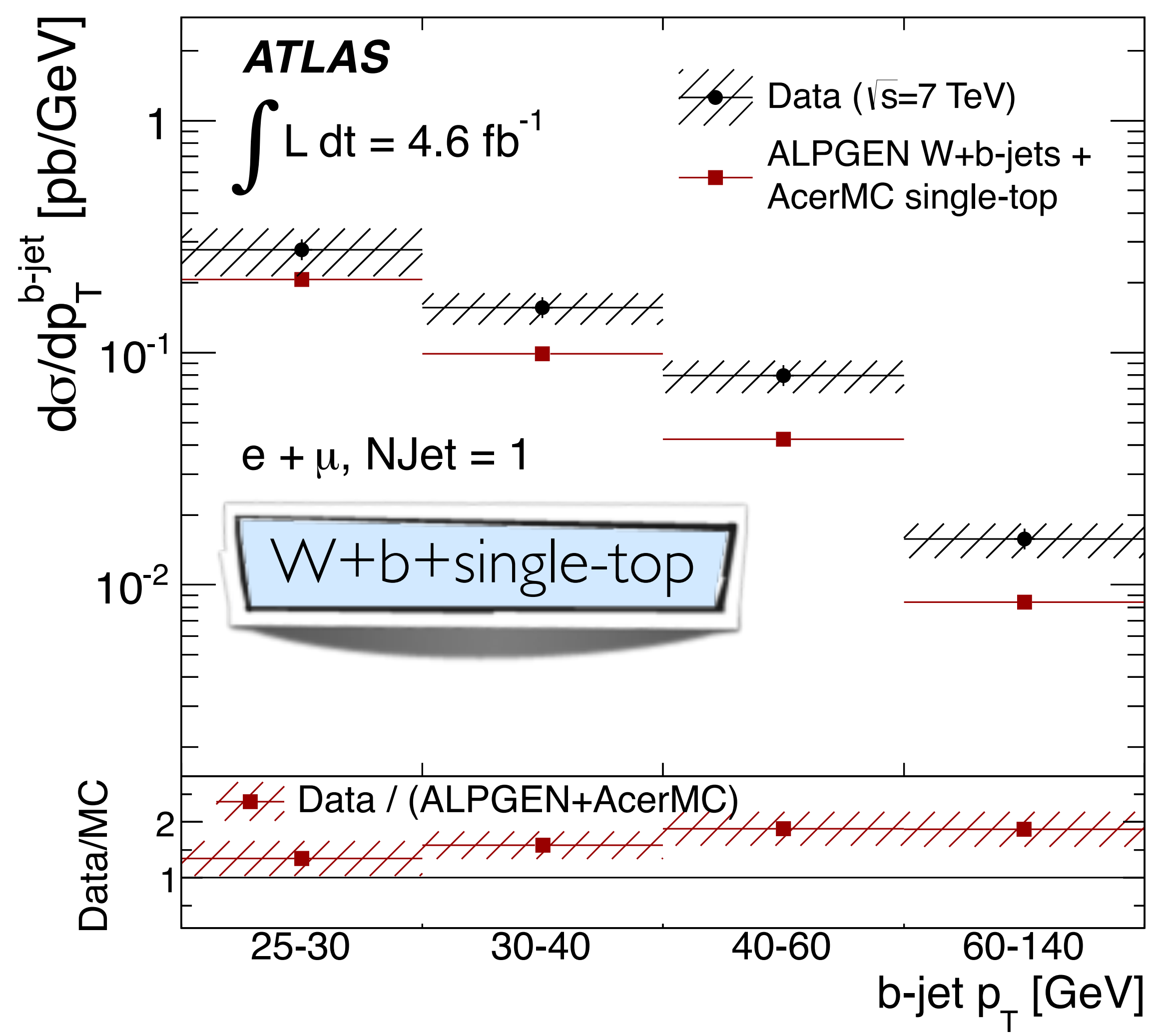
Data (CMS)	0.53 ± 0.05 (stat.) ± 0.09 (sist.) ± 0.06 (teo.) ± 0.01 (lumi.) pb
NLO QCD (MCFM)	0.52 ± 0.03 pb

W+b

ATLAS JHEP 06 (2013) 084

- Data underestimated especially at high p_T
  - More evident when including the single top in the signal definition

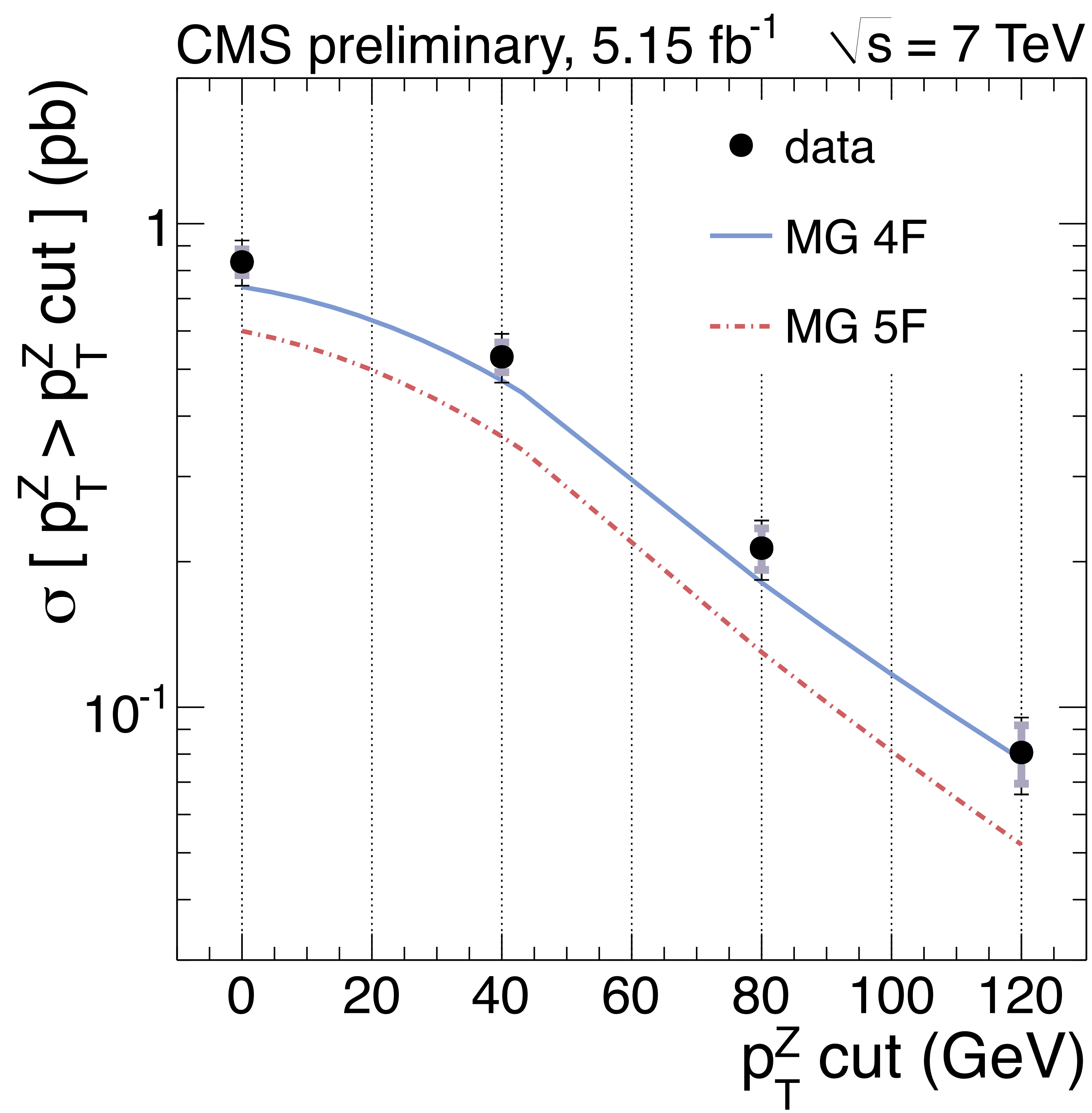




B-hadron angular correlations in Z+bb

CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11015

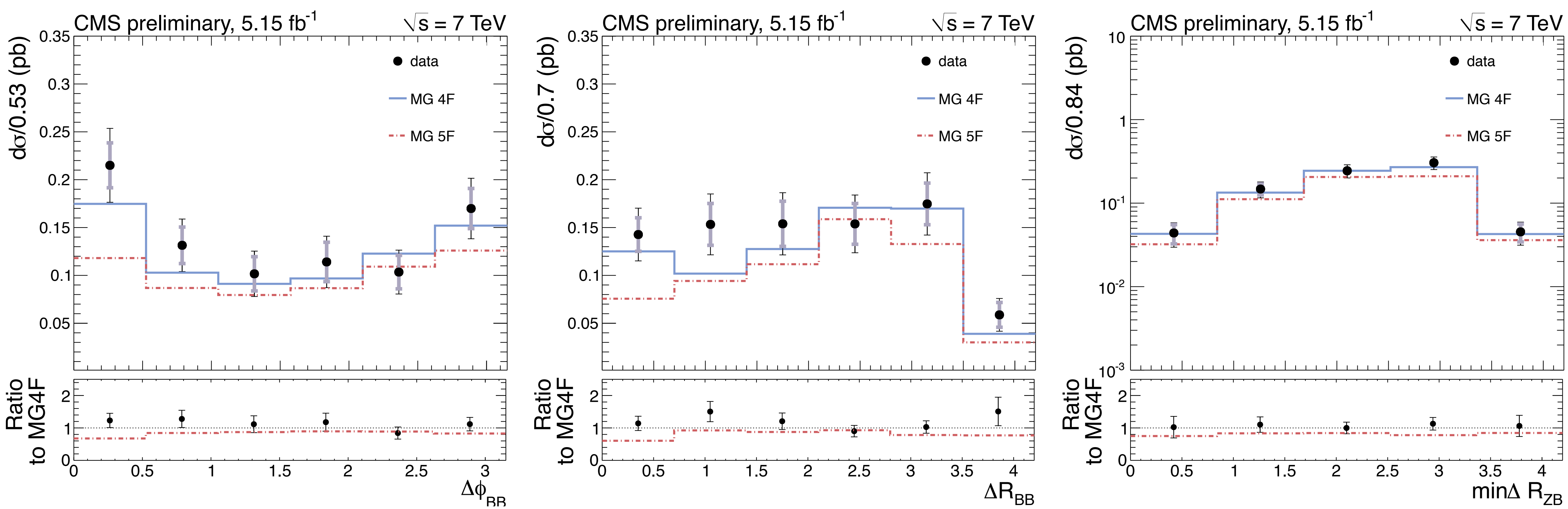
- Z+bb allows more precise measurements compared to W+bb
  - ☑ Background very small
- Emerging picture is controversial
  - ☑ 4F and 5F predictions significantly different



B-hadron angular correlations in Z+bb

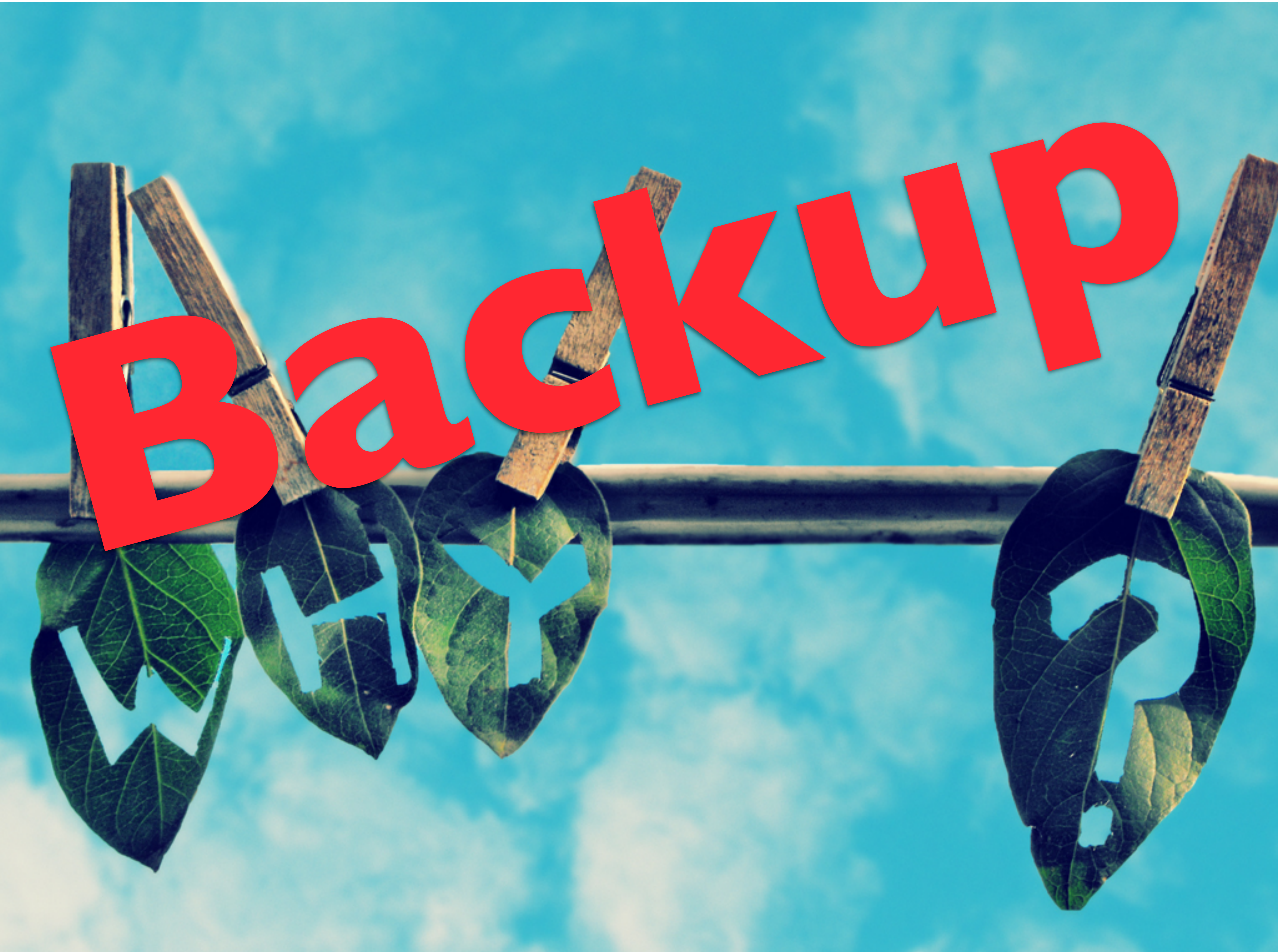
CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11015

- Angular correlation of b-hadrons in events with Z bosons gives further insight into the interplay between the production mechanisms
- Data distributions profiles well reproduced by theory predictions



Conclusions

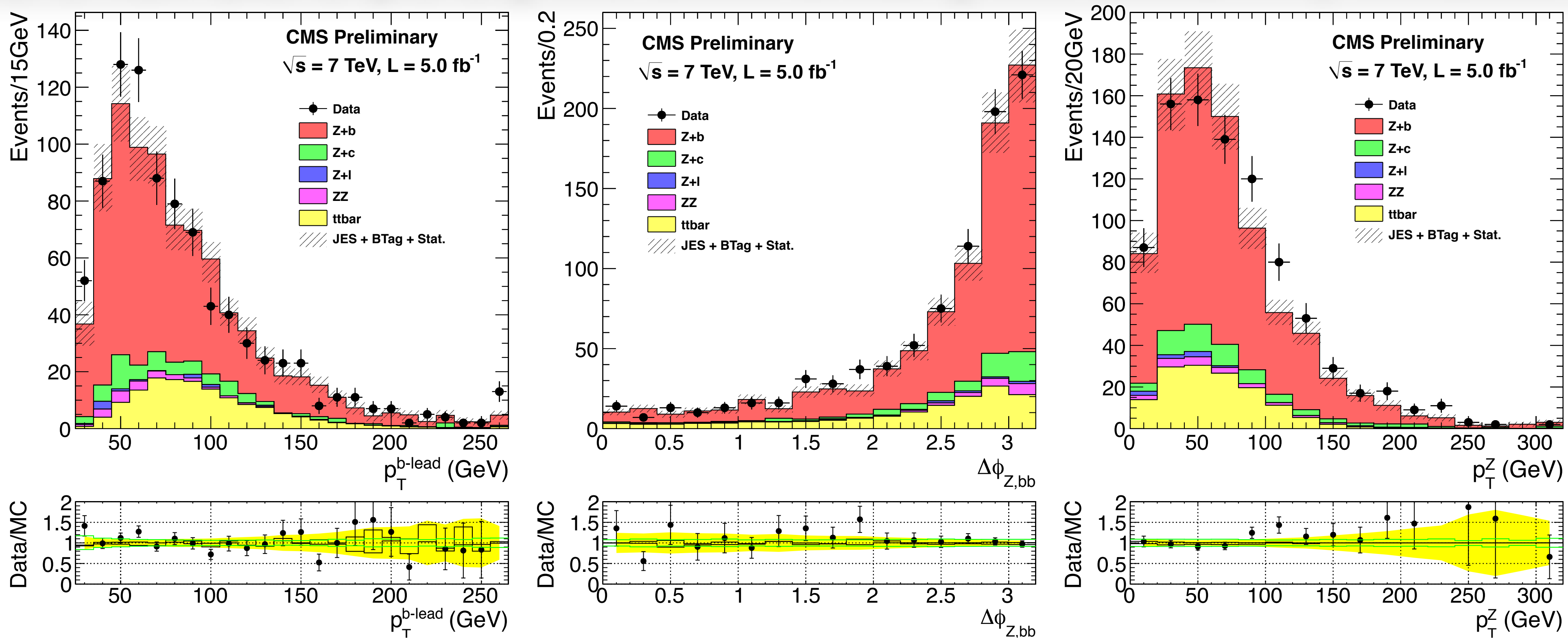
- A wide spectrum of QCD measurements have been performed by ATLAS and CMS
- Most of the analysis make use of small amount of available Run I data
- Work toward the completion of all the 2011 data analysis is ongoing
- Use the 2012 dataset to perform more precise and/or more differential measurements
  - ☑ Extend the phase space
  - ☑ Multi-differential measurements
- Validation of complex event generators used in searches
- PDFs fits
- Monte Carlo tunes


Backup
Why?

Z+b

CMS-PAS-SMP-13-004

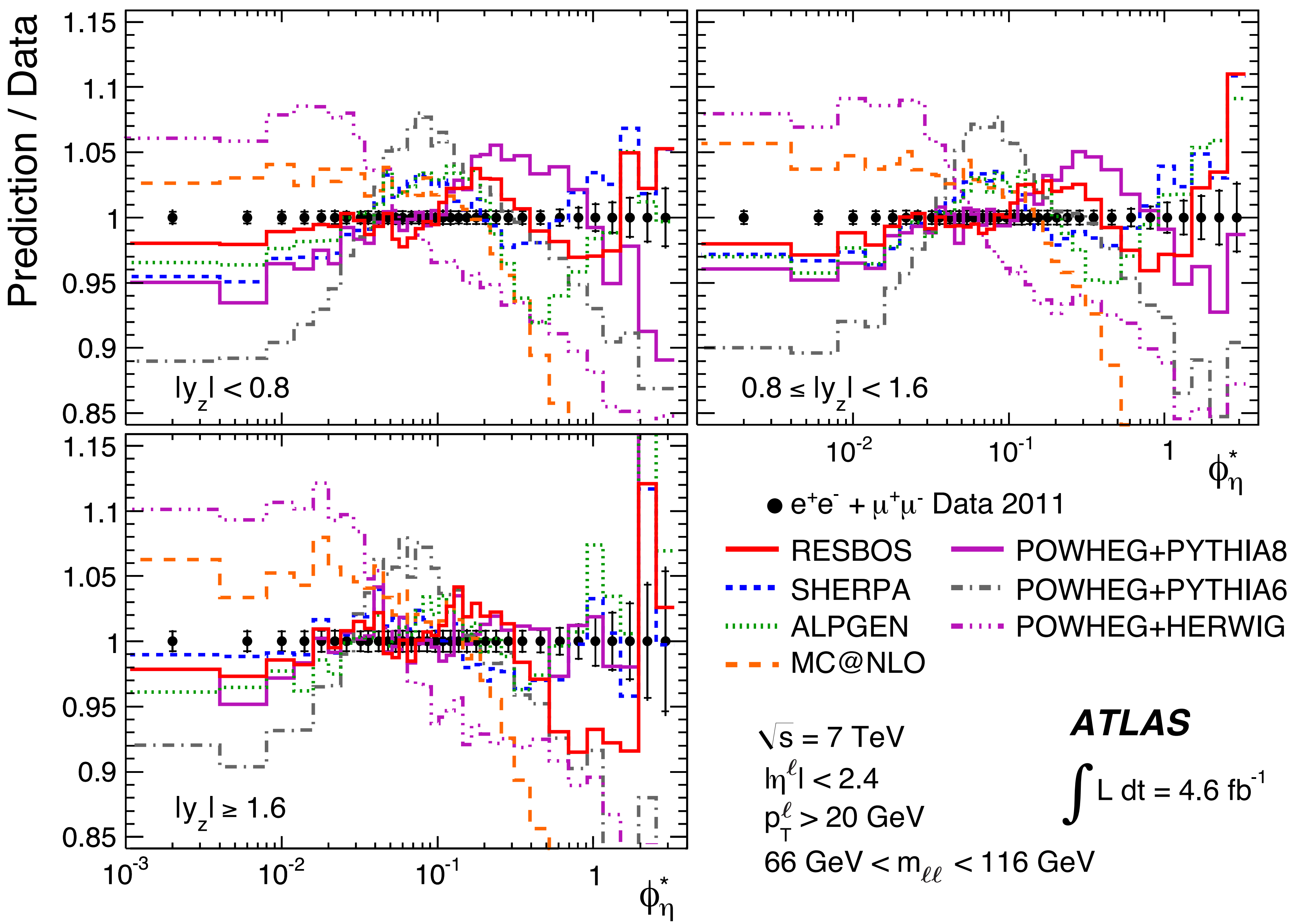
Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
$\sigma(Z(\ell\ell)\text{+1b})$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
$\sigma(Z(\ell\ell)\text{+2b})$ (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01
$\sigma(Z(\ell\ell)\text{+b})$ (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.02	3.49 ± 0.03
$\sigma(Z(\ell\ell)\text{+b})/\sigma(Z(\ell\ell)\text{+j})$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.02	4.60 ± 0.03



Lepton angular correlations

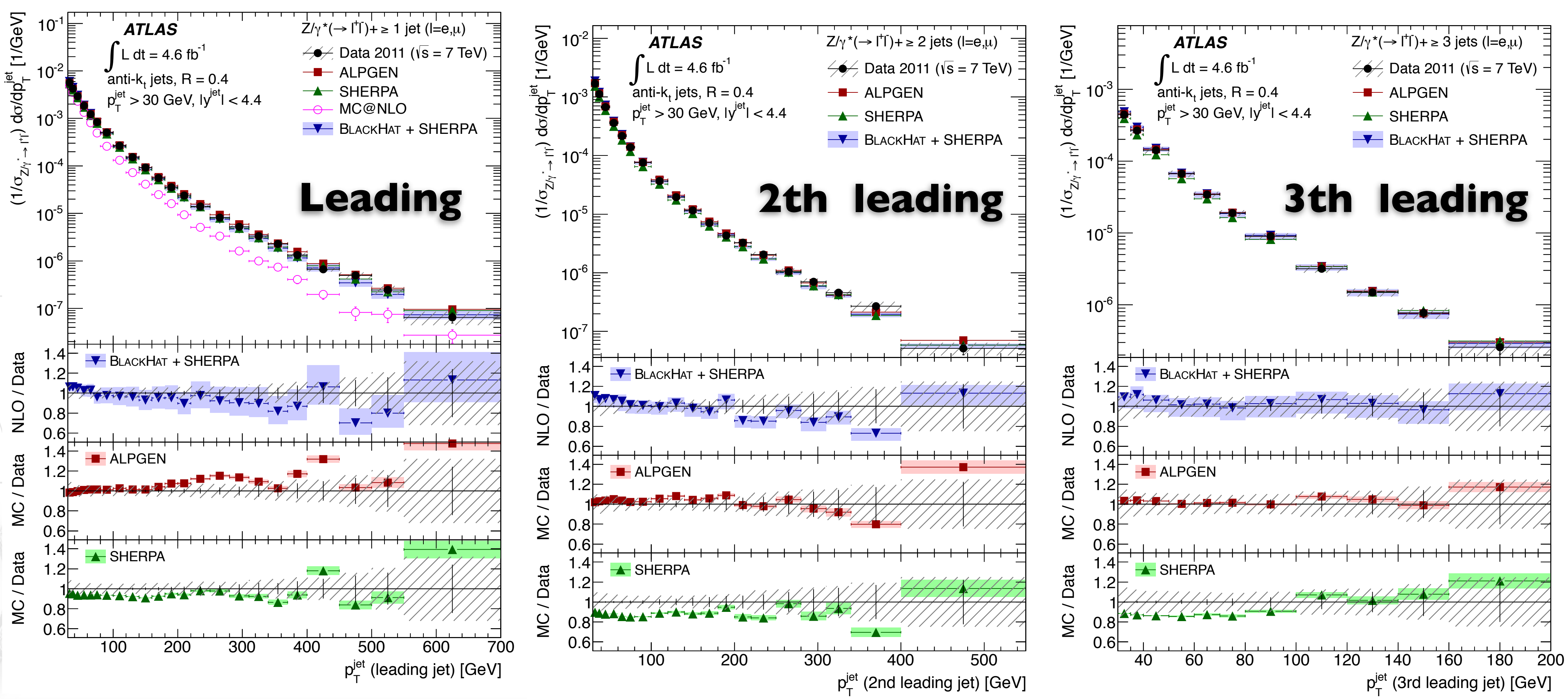
ATLAS Phys. Lett. B 720 (2013) 32-51

- Data sensitive to different generators



Z+jets studies: p_T spectrum

- Transverse momentum spectrum of the leading, 2th leading and 3th leading jet
  - Small bump observed in the Alpgen prediction for the leading jet p_T



Charged tracks multiplicity studies at 8TeV

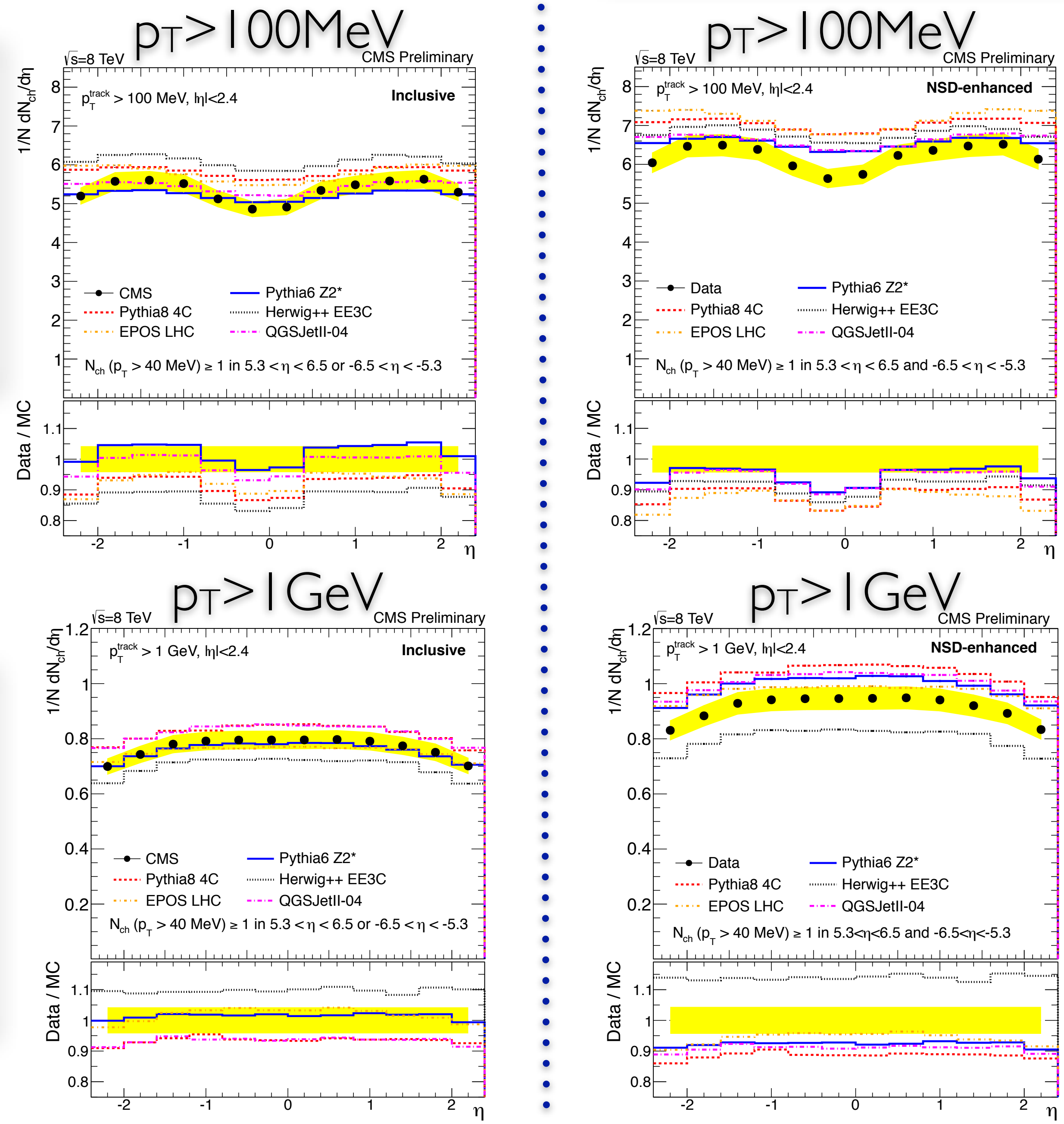
CMS CMS-PAS-FSQ-12-026

- Triggering soft pp collisions with TOTEM
  - ☑ Events dominated by single diffractive and non-single diffractive collisions
- Observed large differences between the MC generators
  - ☑ If the minimum p_T cut on the tracks is raised (p_T>1GeV), the discrepancies becomes larger

Inclusive | Non-single diffractive enanched

Soft diffraction: p_T>100MeV

Hard diffraction: p_T>1GeV

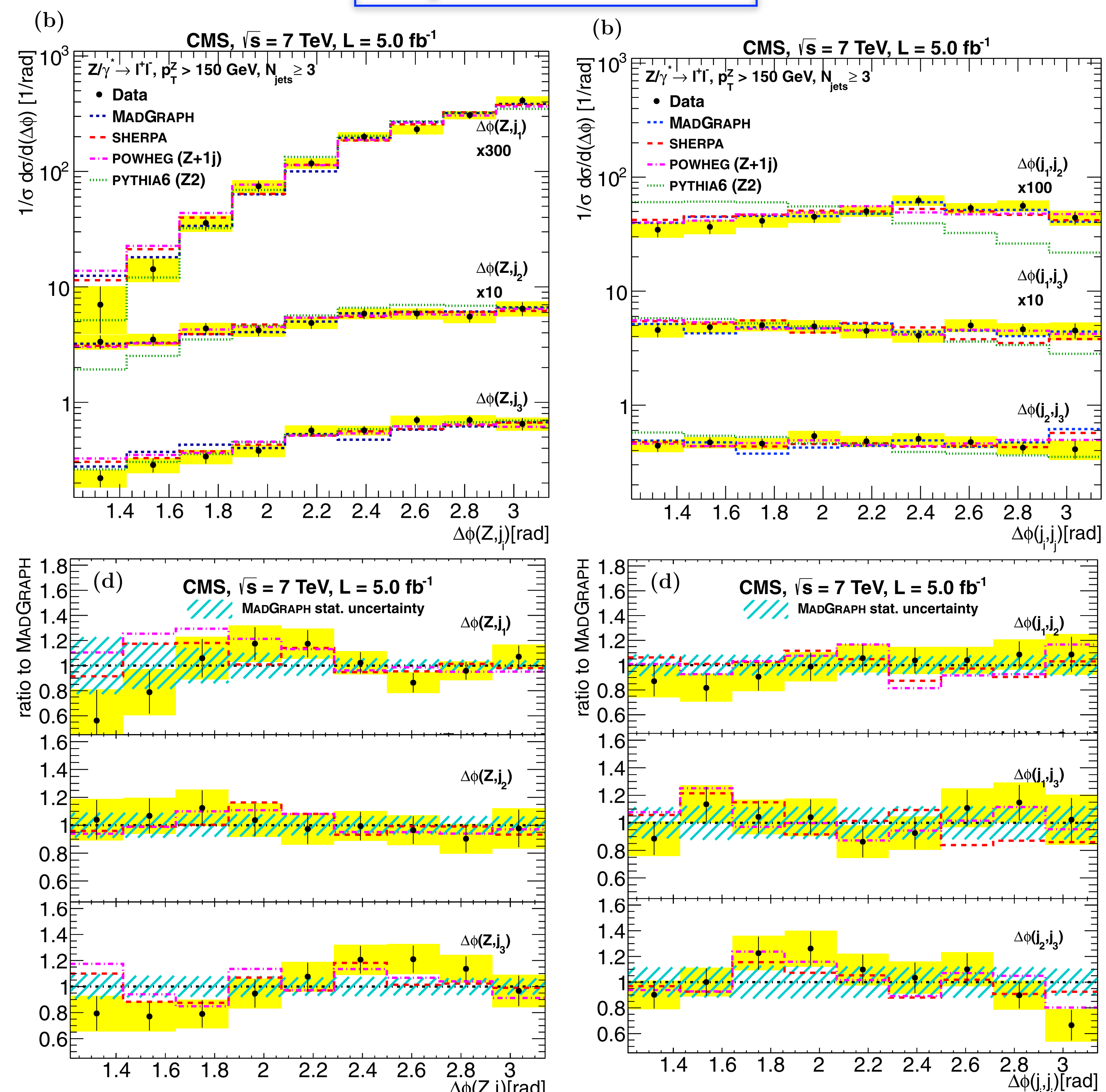


Azimuthal correlation in Z+jets events

CMS Phys. Lett. B 722 (2013) 238-261

Z pT > 150 GeV

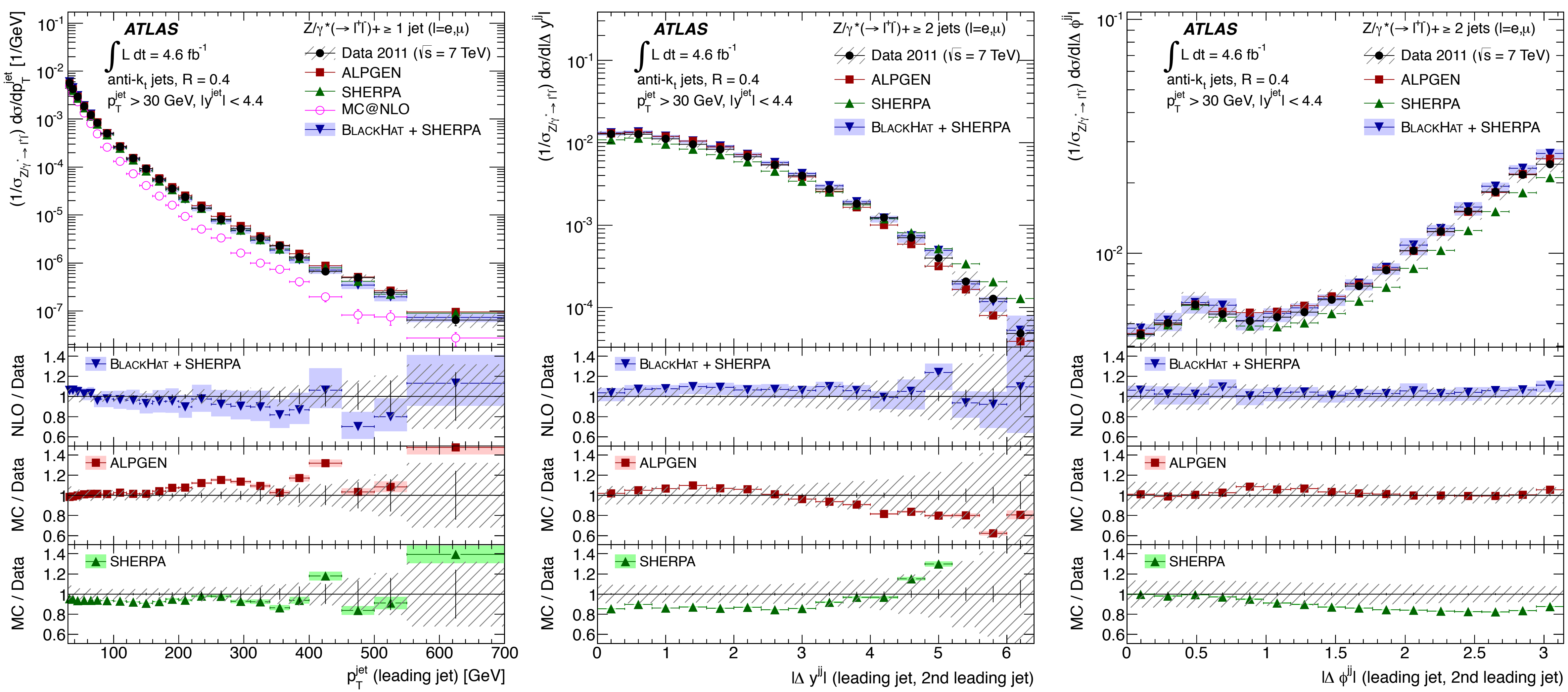
- ☐ Angular correlations also measured in the boosted regime
  - ☑ Multileg and NLO QCD predictions describe well the data



Z+jets studies: p_T spectrum and angular correlations

ATLAS JHEP07(2013)032

- Several other distributions have been measured and are found to be well described by multileg generators
  - ☑ jet p_T spectrum, angular correlations, etc..



W+charm

CMS CMS-PAS-SMP-12-002

$W \to \mu\nu$, $p_T^\mu > 25\,\text{GeV}$				
Final state	$(S+B)_{\text{data}}$	S_{data}	$\mathcal{A}\,\epsilon$ [%]	$\sigma(W+\text{c})$ [pb]
$\text{D}^{\pm}$	1502 ± 62	1203 ± 91	11.1 ± 0.3	103.6 ± 7.8 (stat.) $\pm$ 8.1 (syst.)
$\text{D}^{*\pm}(2010)$	318 ± 21	309 ± 23	8.5 ± 0.4	116.9 ± 8.7 (stat.) $\pm$ 10.0 (syst.)
$\text{c} \to \mu$	14215 ± 196	9867 ± 237	20.4 ± 0.2	106.5 ± 2.6 (stat.) $\pm$ 9.6 (syst.)
Average				107.7 ± 3.3 (stat.) $\pm$ 6.9 (syst.)