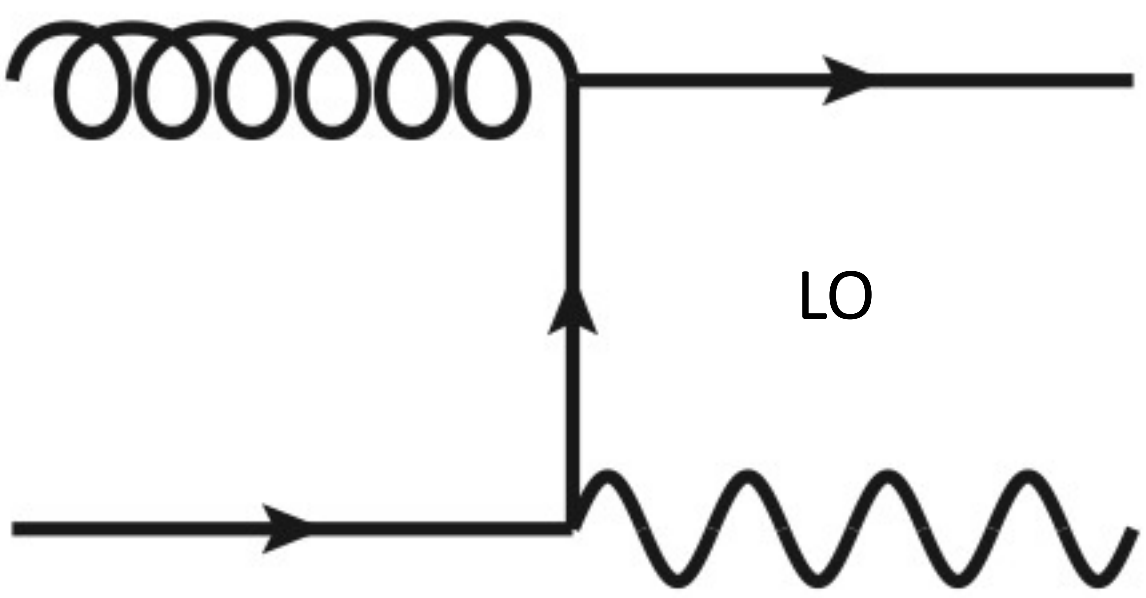
W/Z + Jets and W/Z + HF Production at the LHC

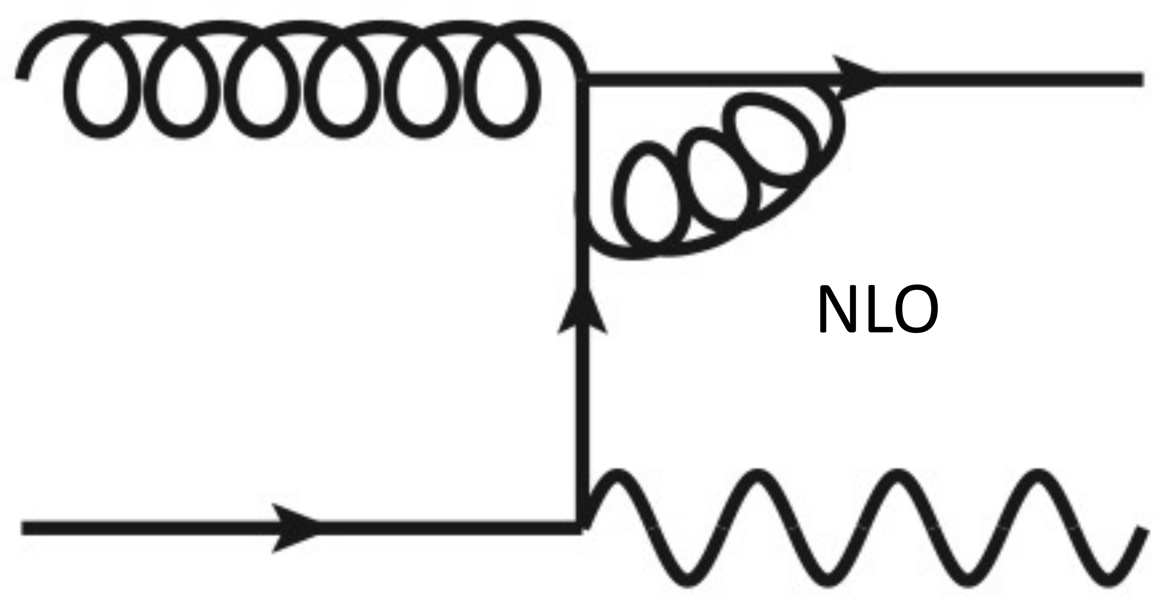
K. Theofilatos (Moriond QCD 2013)
on behalf of ATLAS & CMS collaborations

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

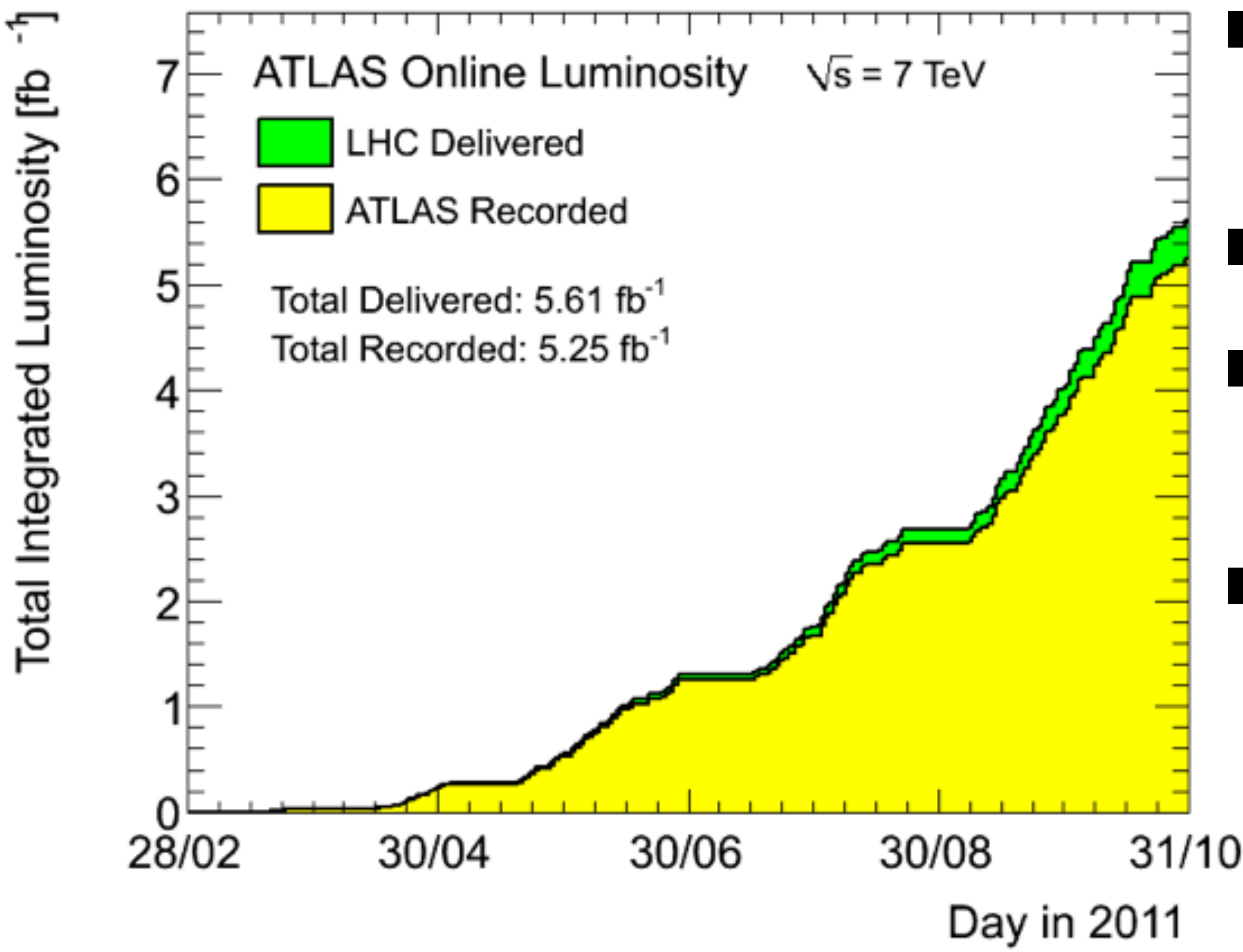
Why W/Z + jets ?

- Confront pQCD (very precise for EW vertices)
- Small experimental uncertainty
- Nearly background free
- But itself: background to BSM
- Study structure of the proton $\{f_i(x_1), f_j(x_2)\}$
- We can't do it without precise partonic cross-sections





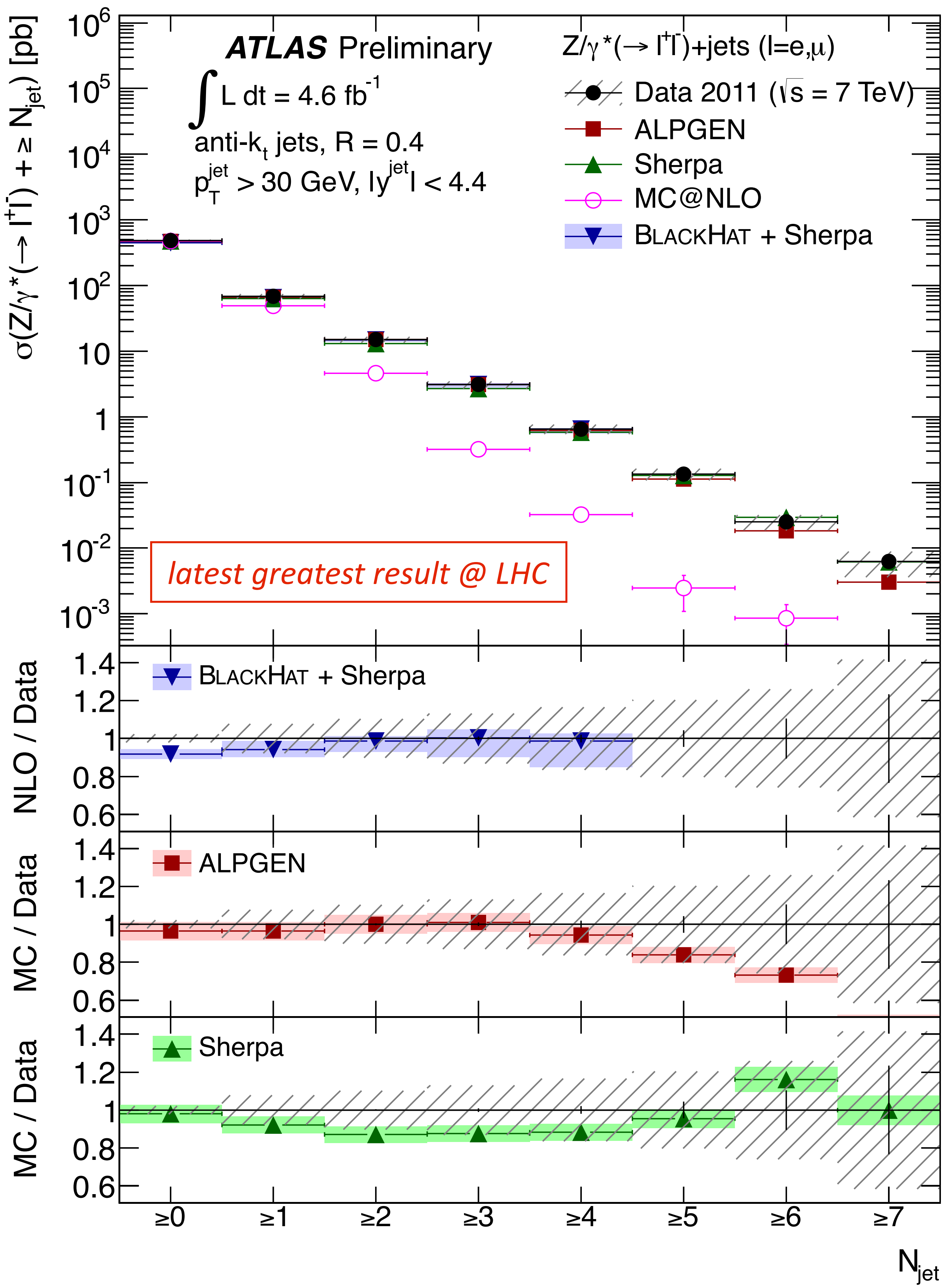
LHC data & MC samples



- Smooth operation during 2011 & 2012
- 5fb^{-1}@7 TeV, 22fb^{-1}@ 8TeV
- MC: need typically x10 more simulated luminosity
- Great challenge
  - CPU/Disk Storage
  - Complexity of MC tools

NLO fixed order calculations and (N)LO ME+PS are required to describe extremely rare events & kinematic configurations reachable with this data luminosity

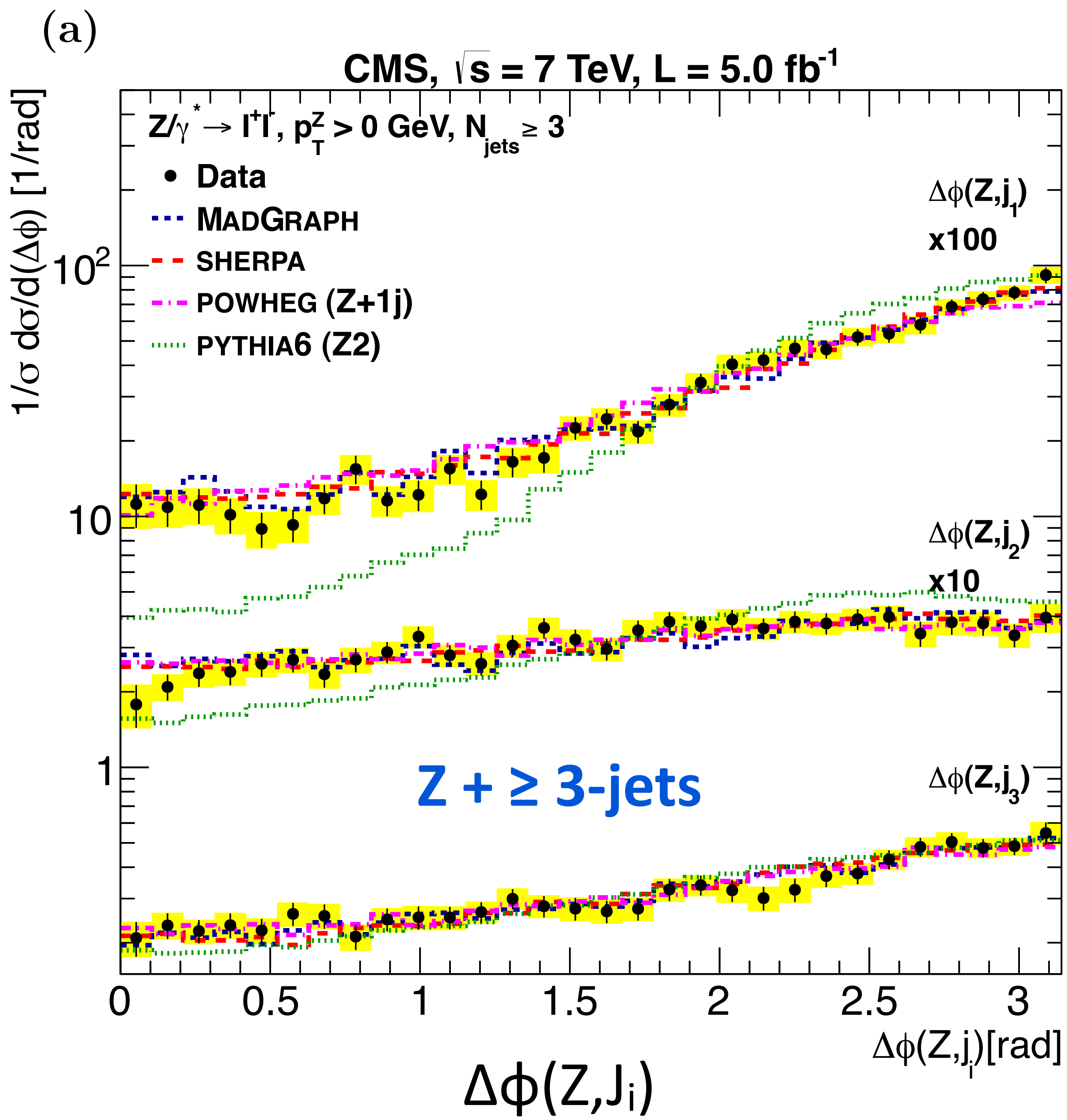
Z + jets @ 7 TeV

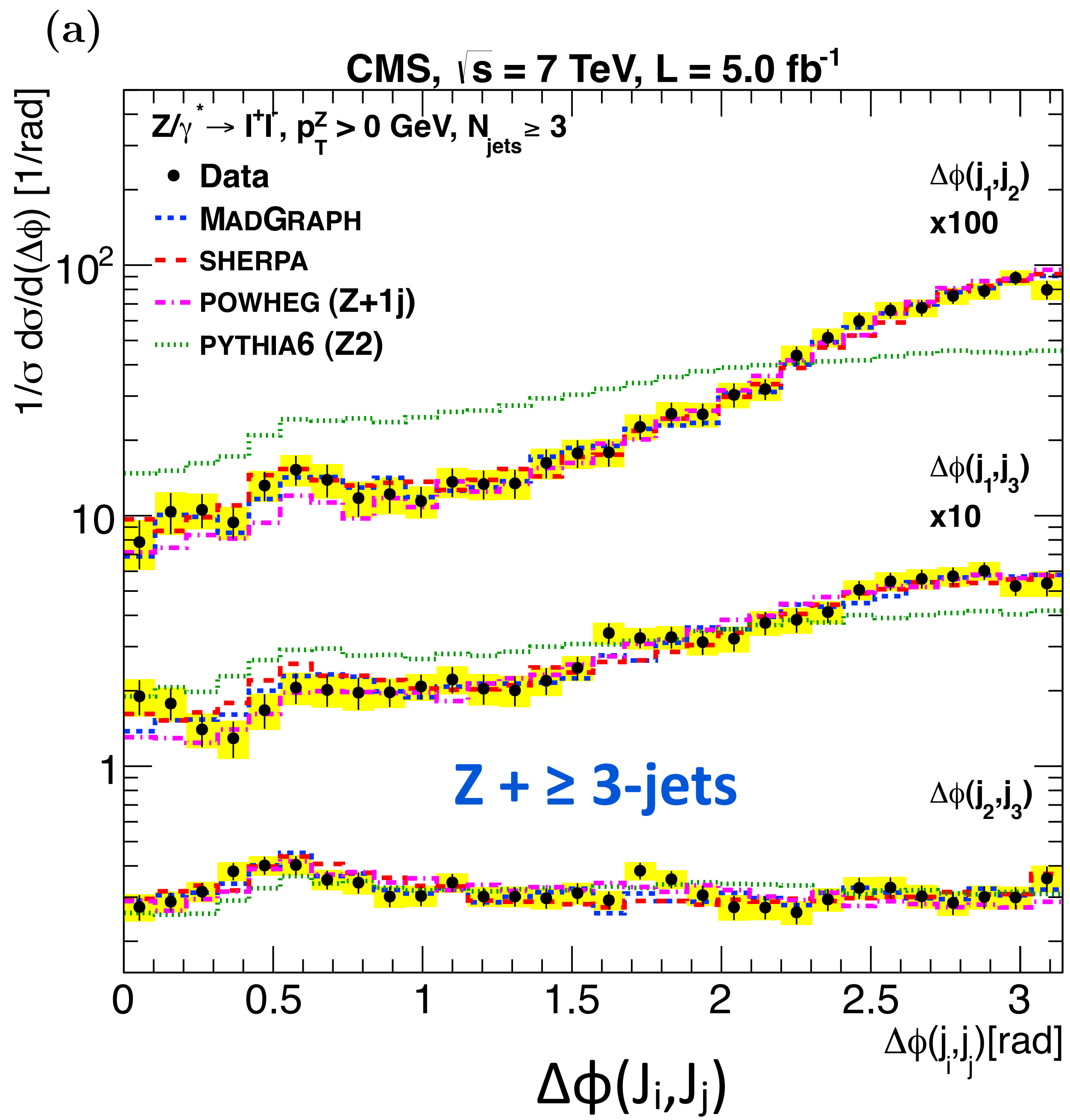


- Data with Z + ≥ 7 jets
- Good agreement with BlackHat + Sherpa NLO (up to ≥ 4 partons)
- MC@NLO (DY@NLO + 1 real emission + PS)
- ALPGEN/Sherpa: LO ME up to 5 partons, PS copes with the additional radiation
- Multiplicity is ~OK (within uncert.)
- Are the angular correlations and Jet p_T OK for high N_{jets}?

more details about the MC setup in the backup

Δϕ correlations, Z + jets

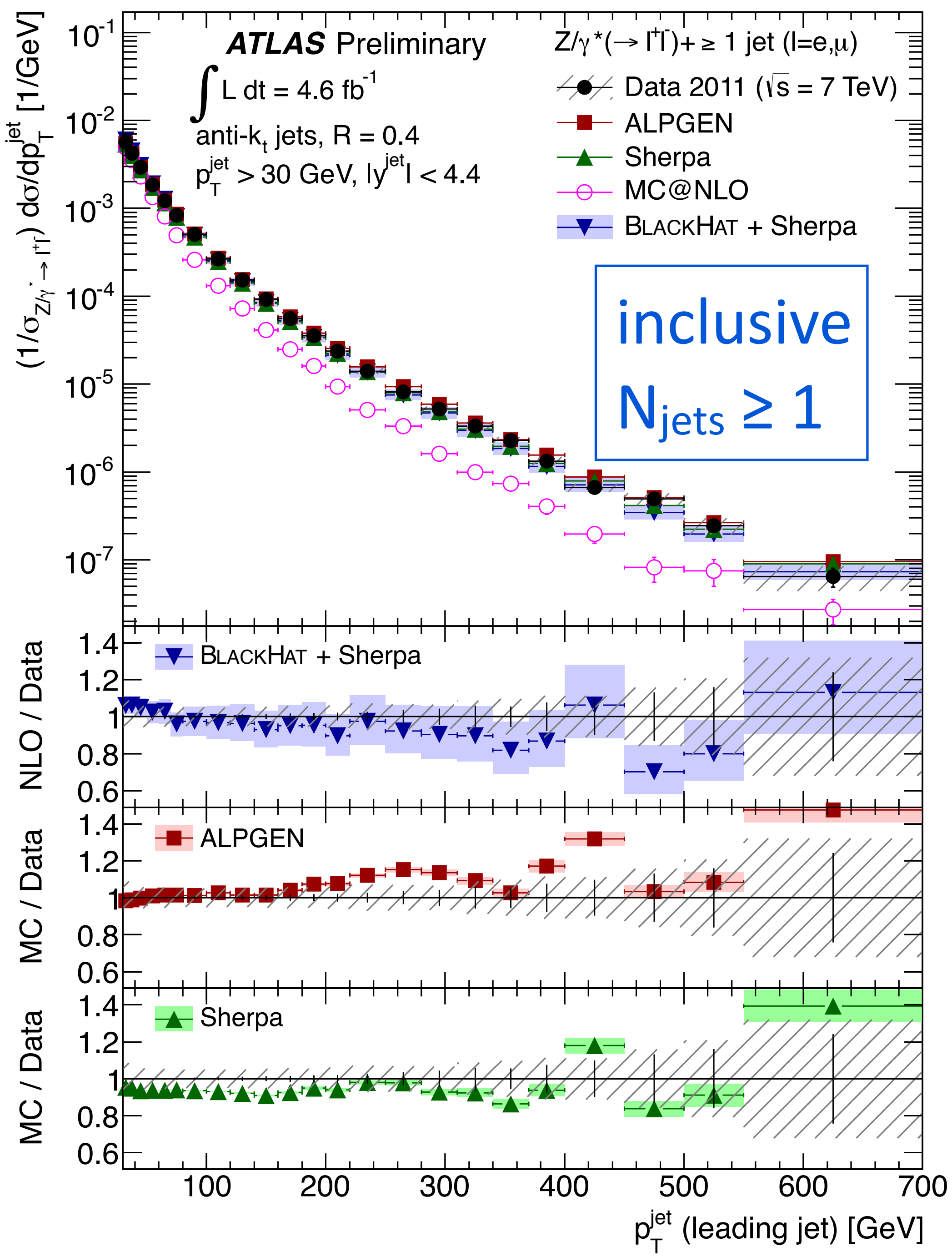


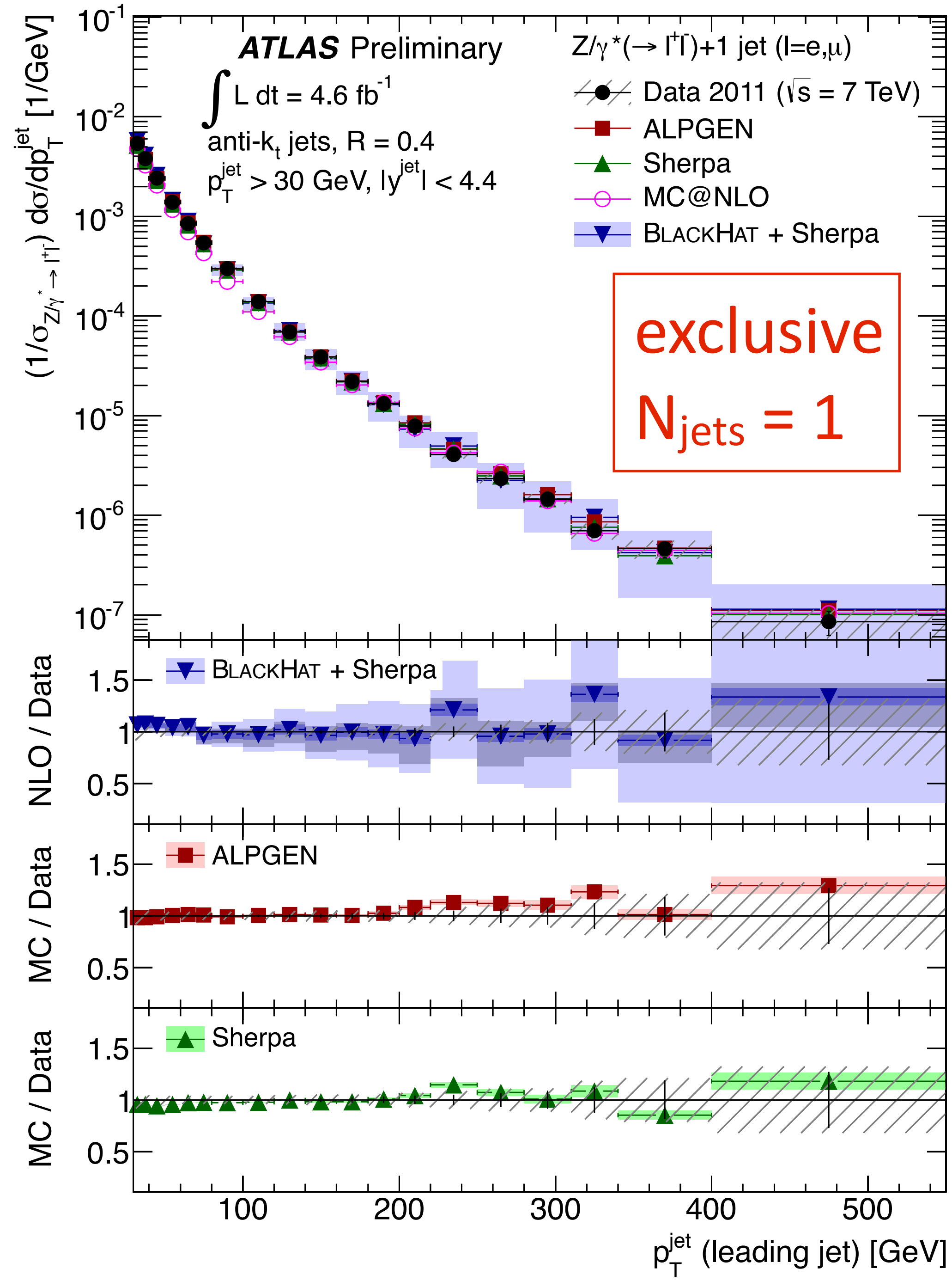


- Standalone Pythia meant to show here what PS can do
- Powheg has NLO (Z + 1-jet) + PS: gets the ≥ 3-jet picture

Leading jet P_T, Z + jets

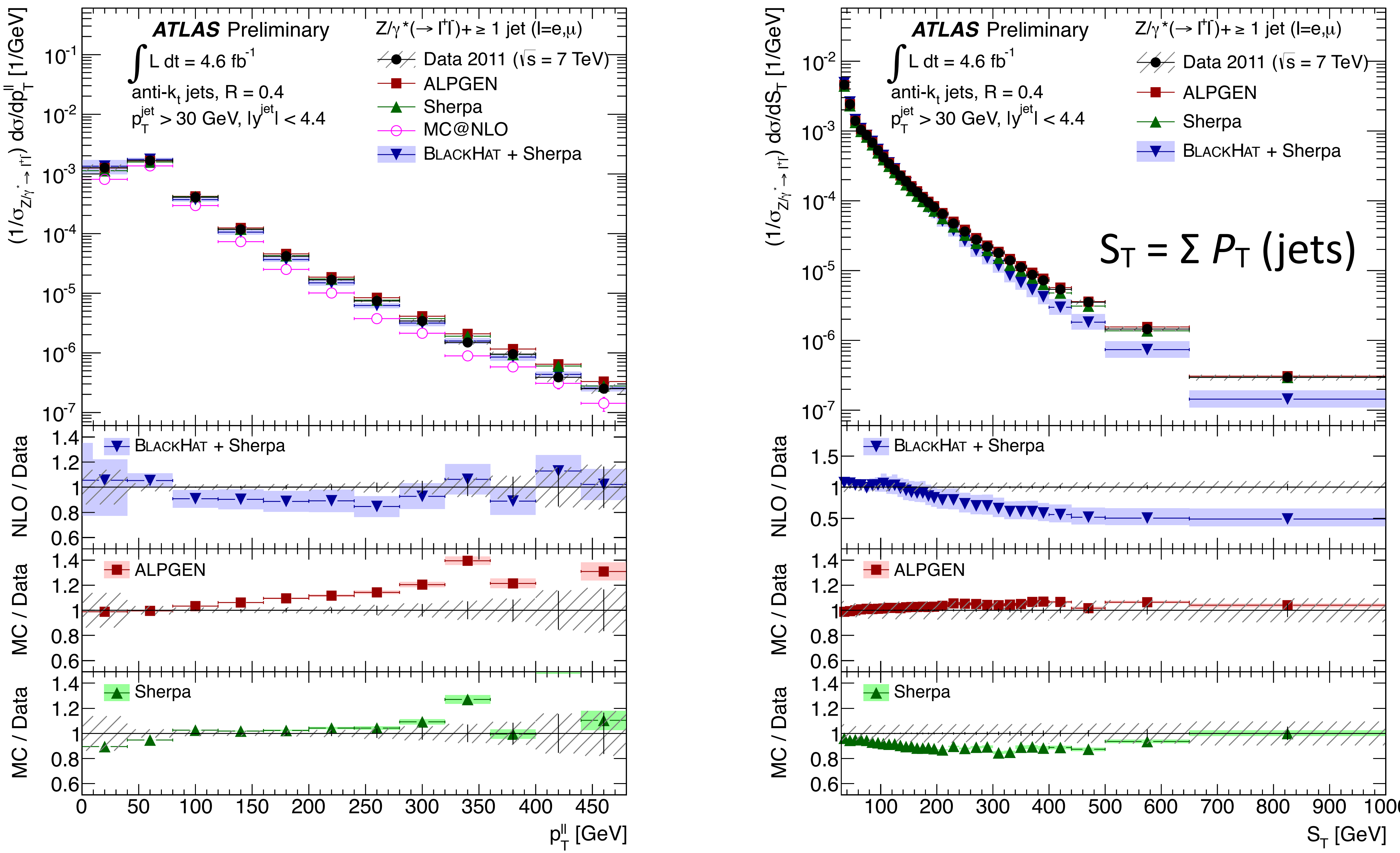
ETH Zürich





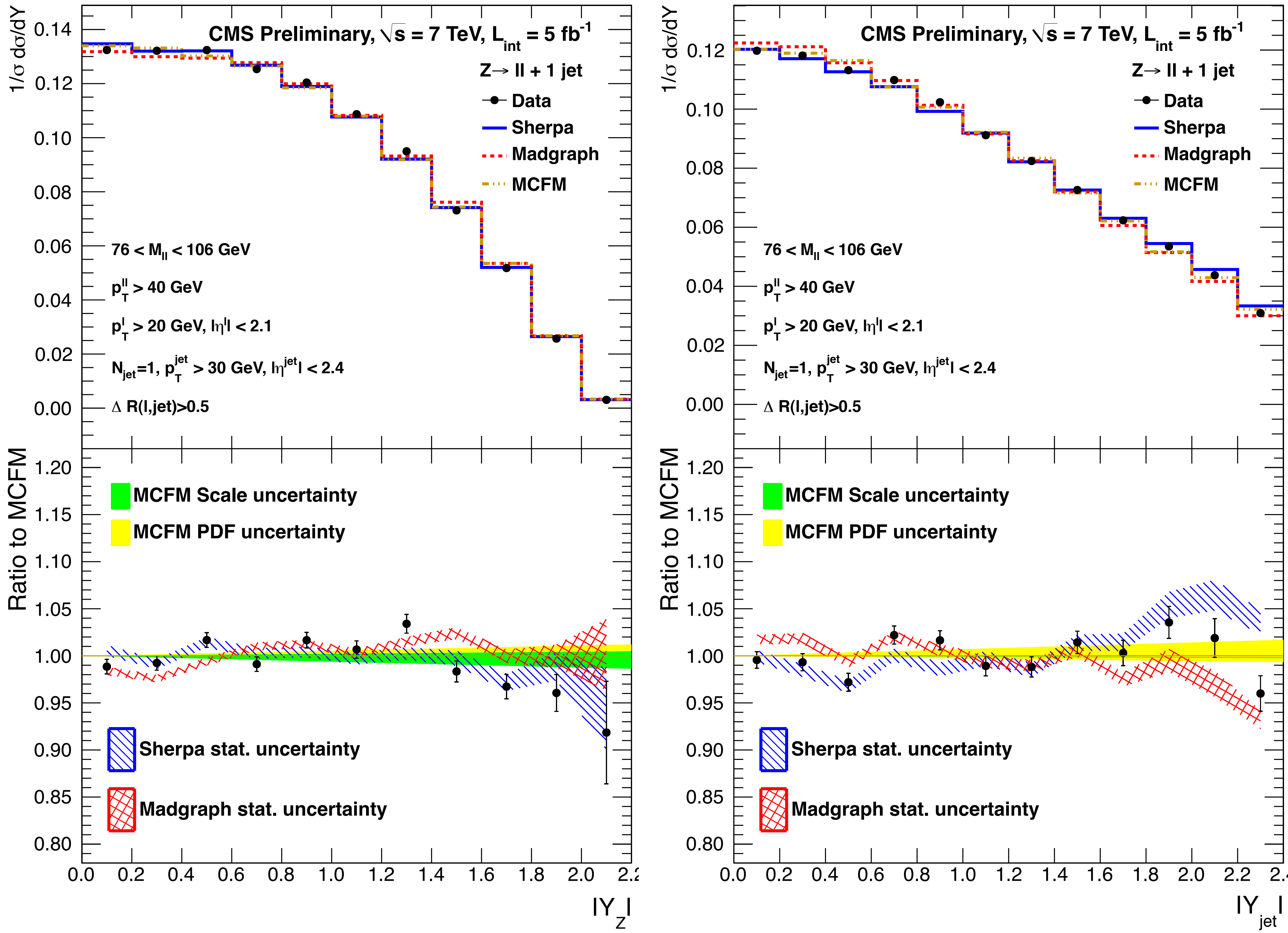
For inclusive, higher order multi-parton emission is important; For exclusive MC@NLO (DY@NLO + 1 real emission) is OK; good agreement with NLO (BlackHat + Sherpa) in both inclusive & exclusive cases

p_T(Z) and Σ p_T(jets), Z + jets



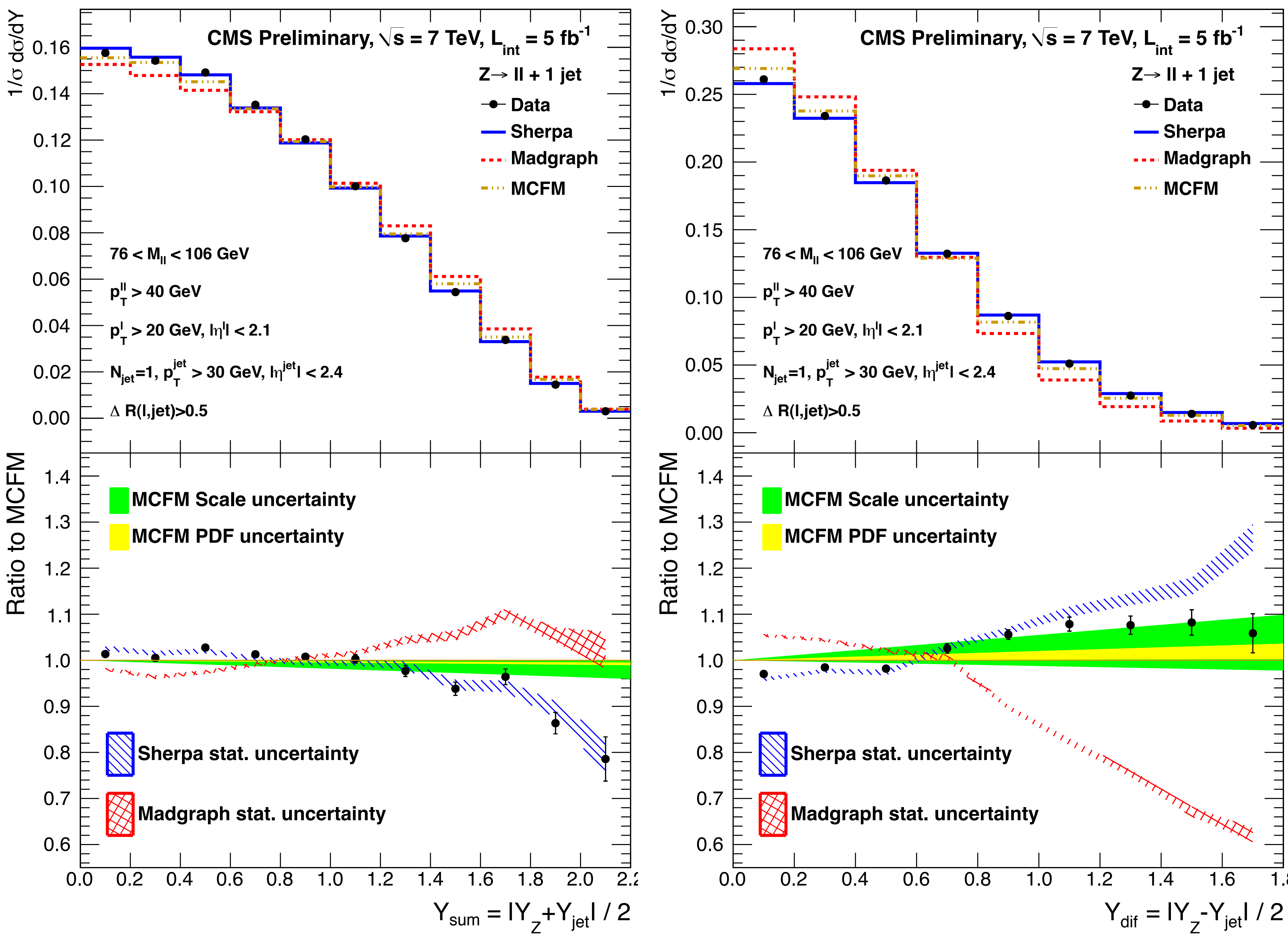
MC fails for boosted events, *indicating missing higher orders* (EWK/QCD?); important for searches: think of p_T(Z) as MET when Z→νν

Rapidity distributions, Z + 1-jet



- Data/Theory for $|Y_Z|$ and $|Y_{jet}|$ within 5%

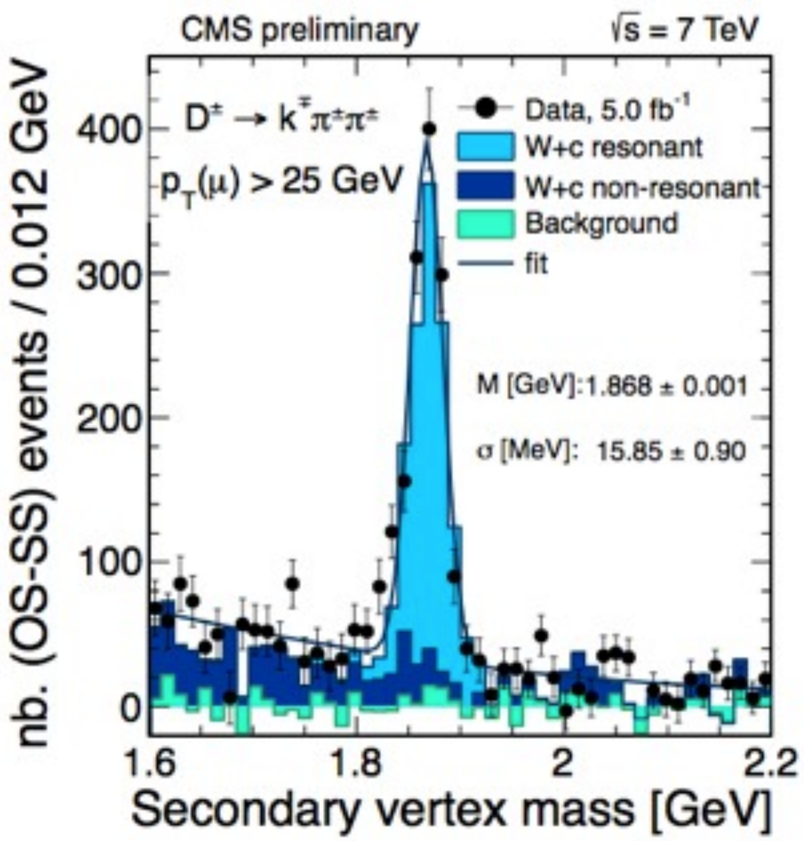
Rapidity differences, Z + 1-jet

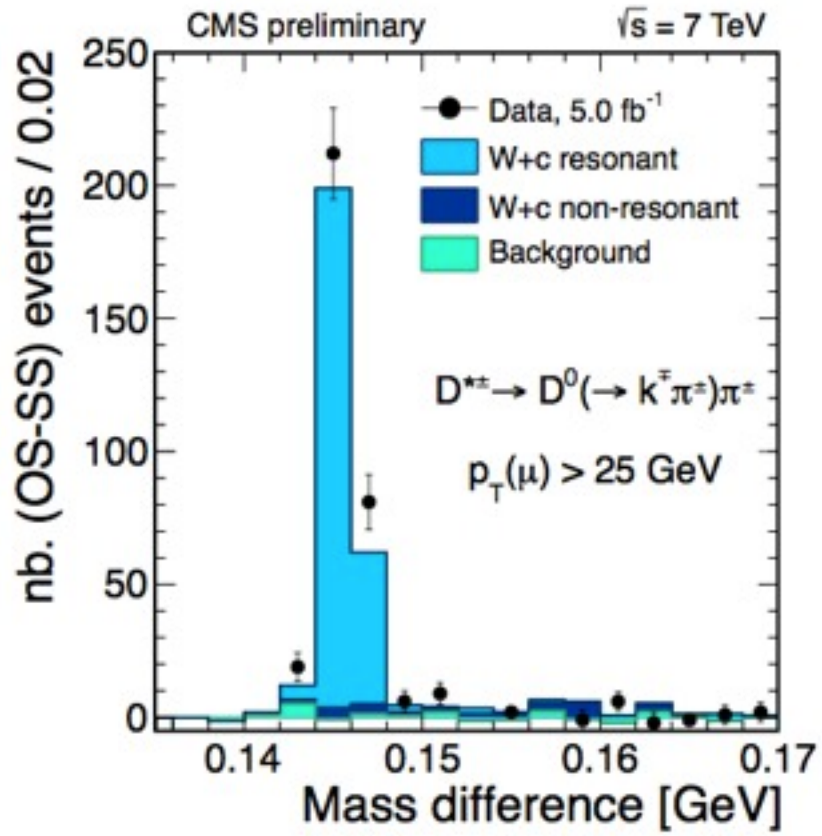


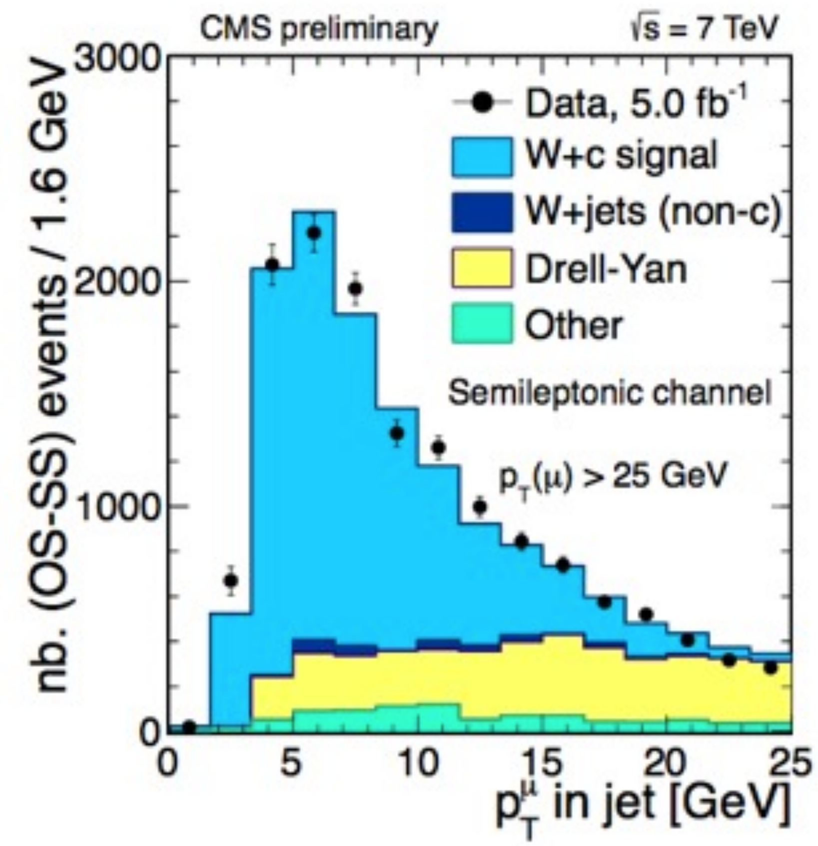
Correlations (Y_Z,Y_{jet}) do not agree (Data/MC); Madgraph and Sherpa have different predictions; Data are more consistent with Sherpa; Differences attributed to jet matching in ME+PS

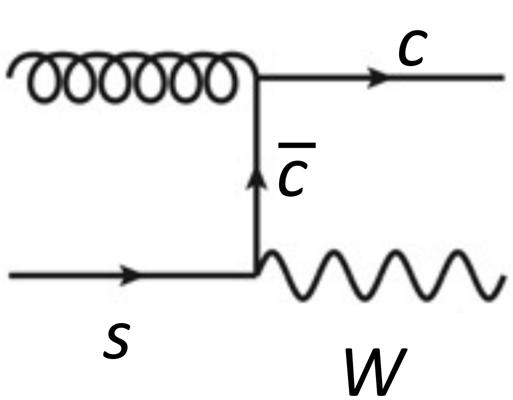
V + HF production

W + c-jet





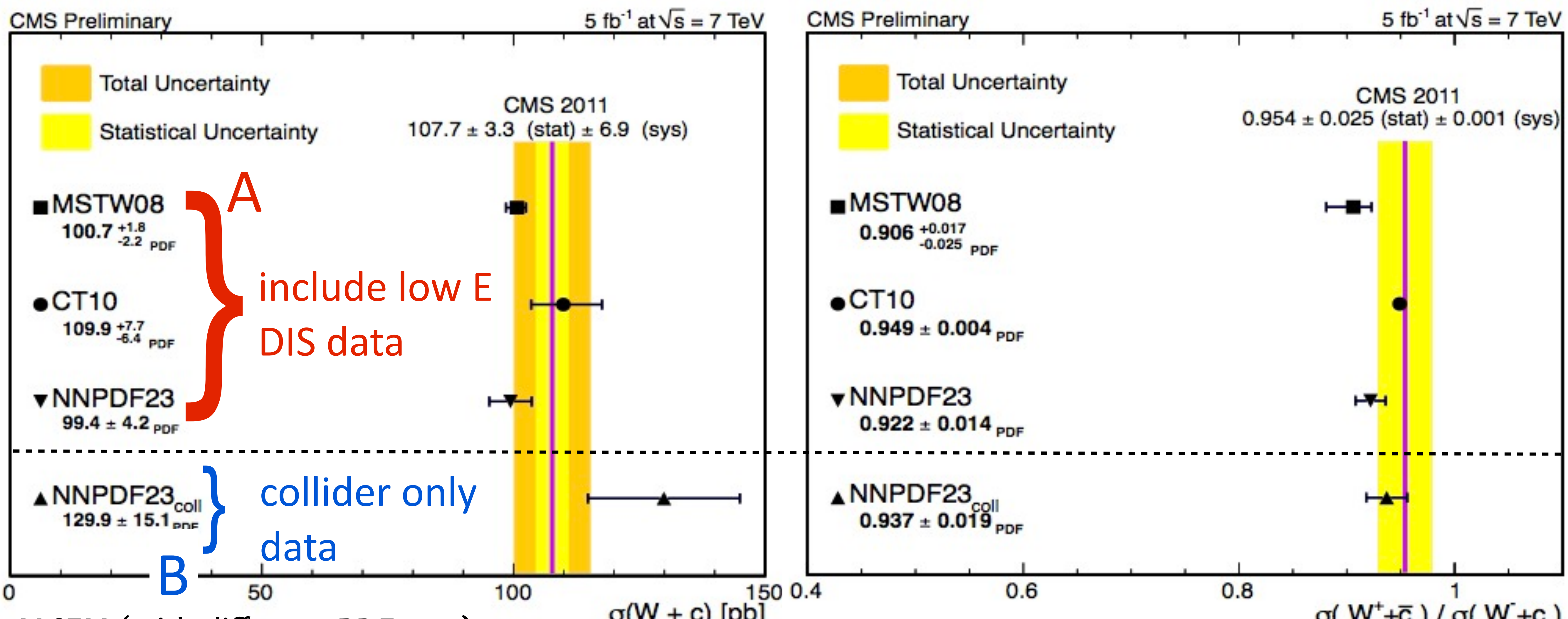




3 channels with W + c purity 80-90%

- σ(W + c-jet) sensitive to strange content of the proton
- c-jet viable through charm mesons reconstruction

W + c-jet

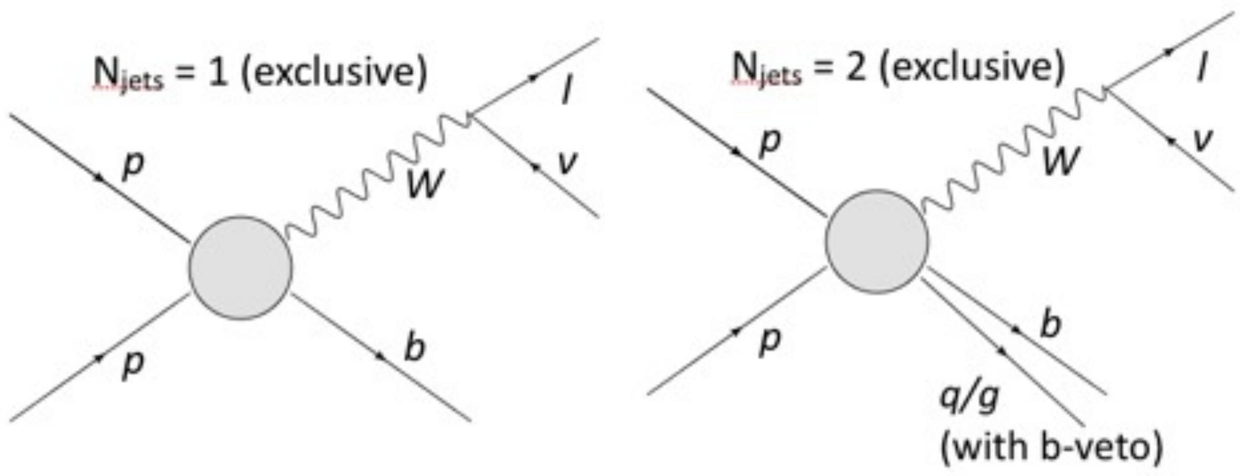


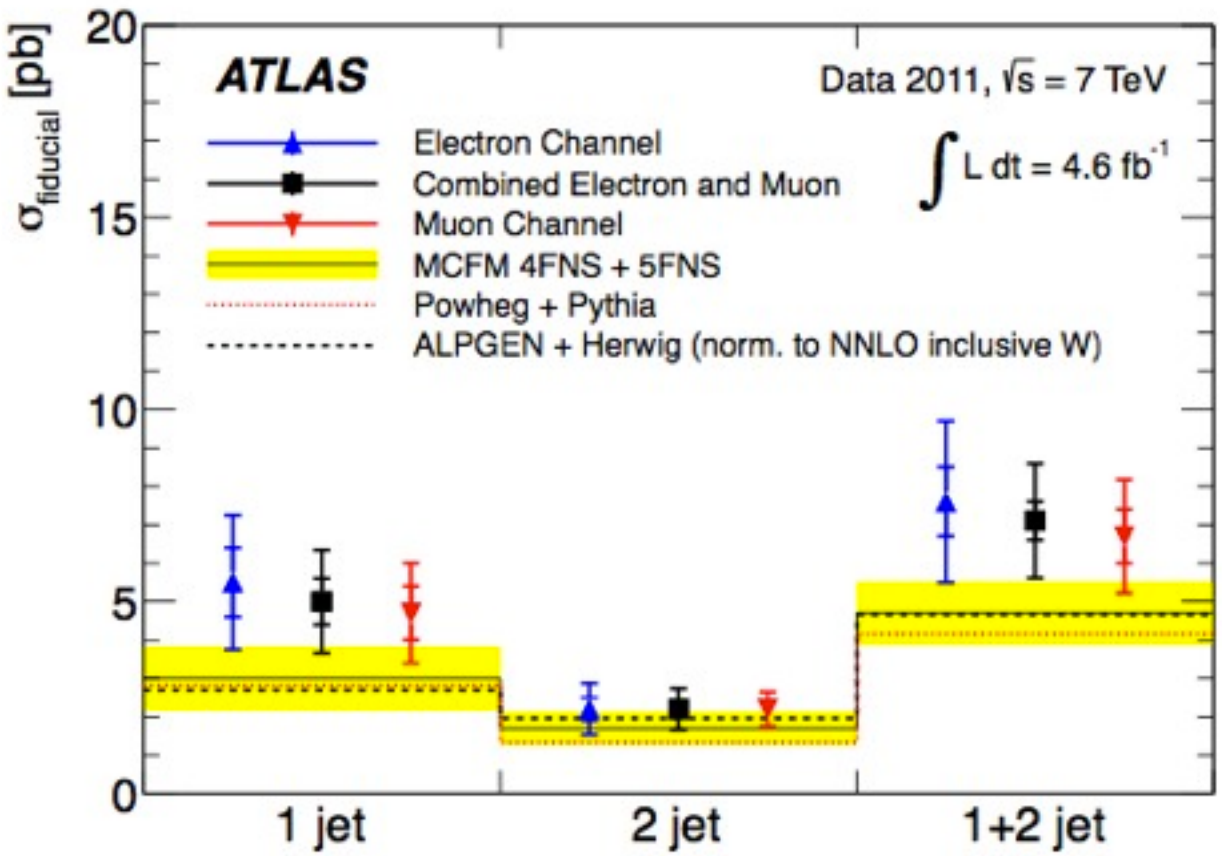
MCFM (with different PDF sets)

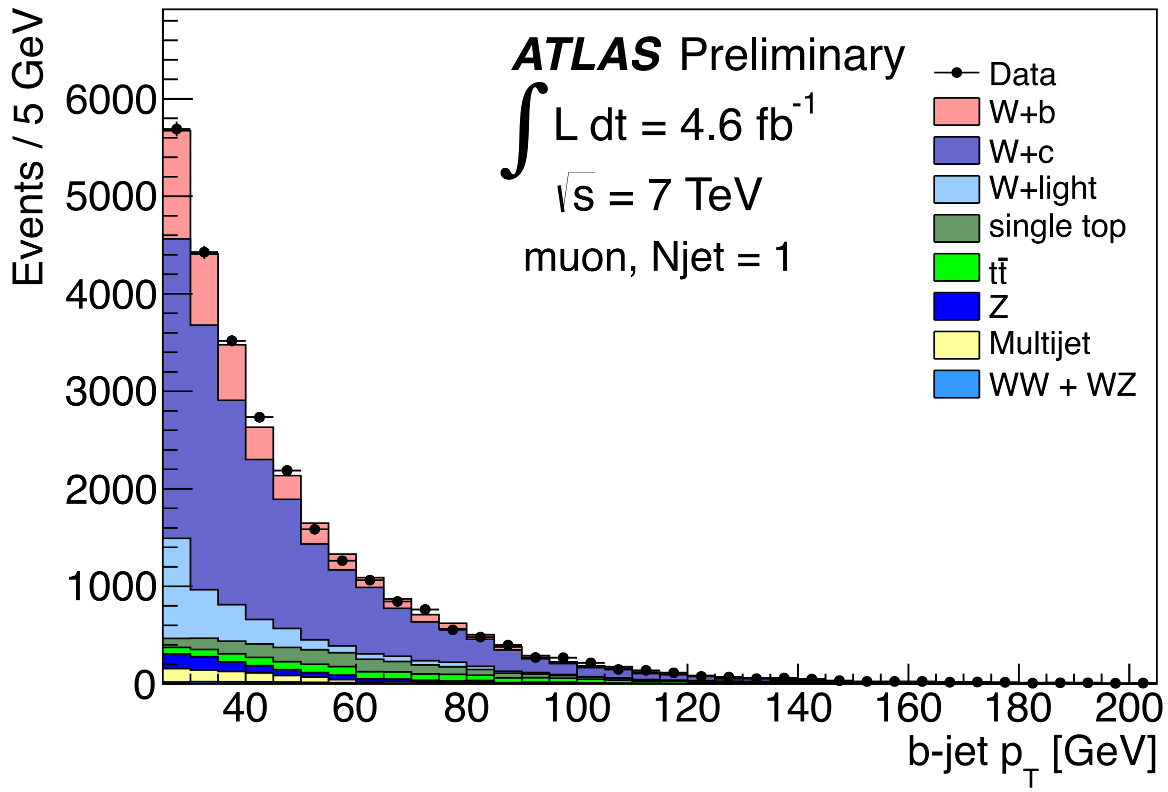
- Symmetric quark sea $\bar{s}/\bar{d} \sim 1$ is predicted from B
- Strange suppression $\bar{s}/\bar{d} \leq 0.5$ is predicted from A
- CMS data consistent with A

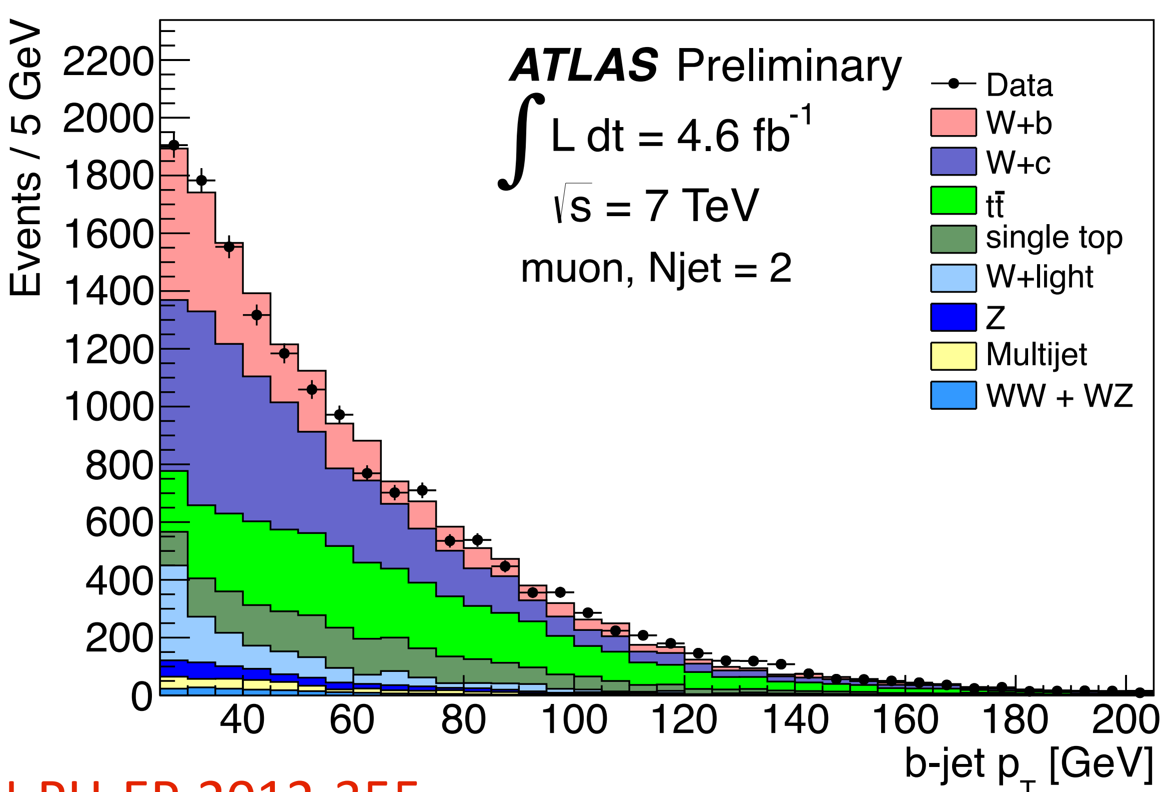
W + 1 b-jet

measurement targets to phase space with previously known Data/Theory tension 2.8σ (CDF) 1.5σ (ATLAS)





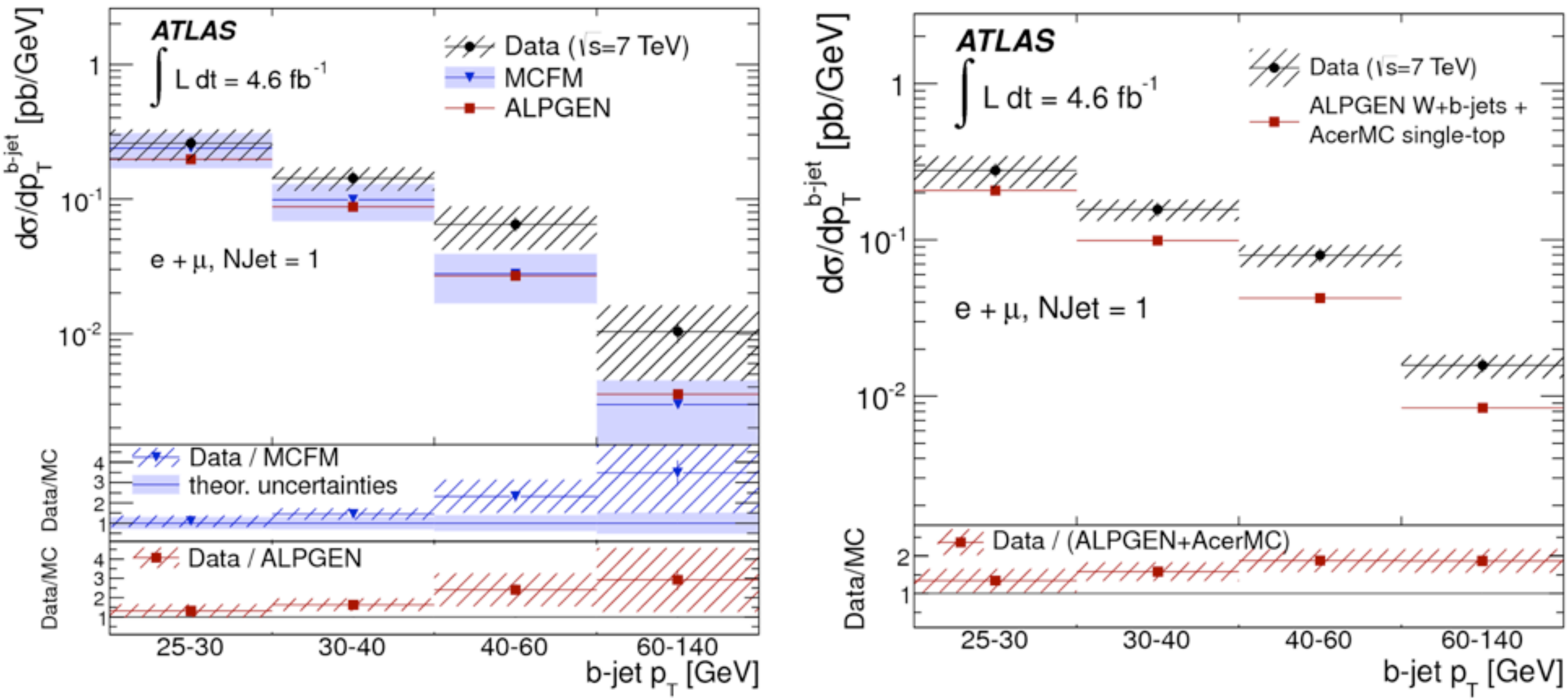




MCFM corrected ~30% for DPS

Dedicated DPS study with W + 2jets in backup & CERN-PH-EP-2012-355

W + 1 b-jet

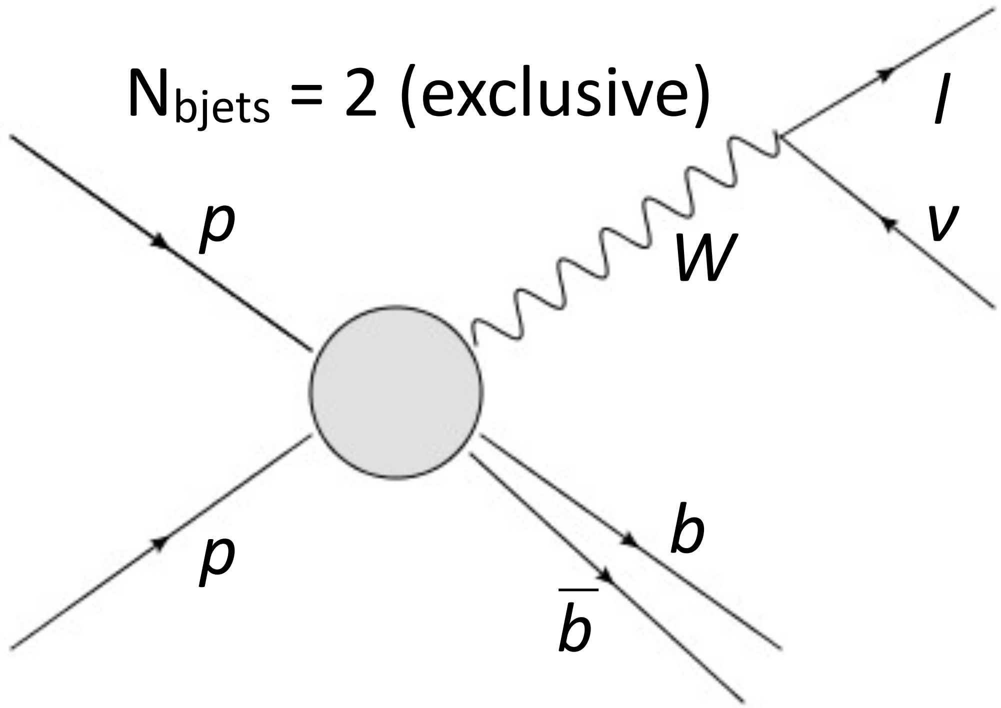


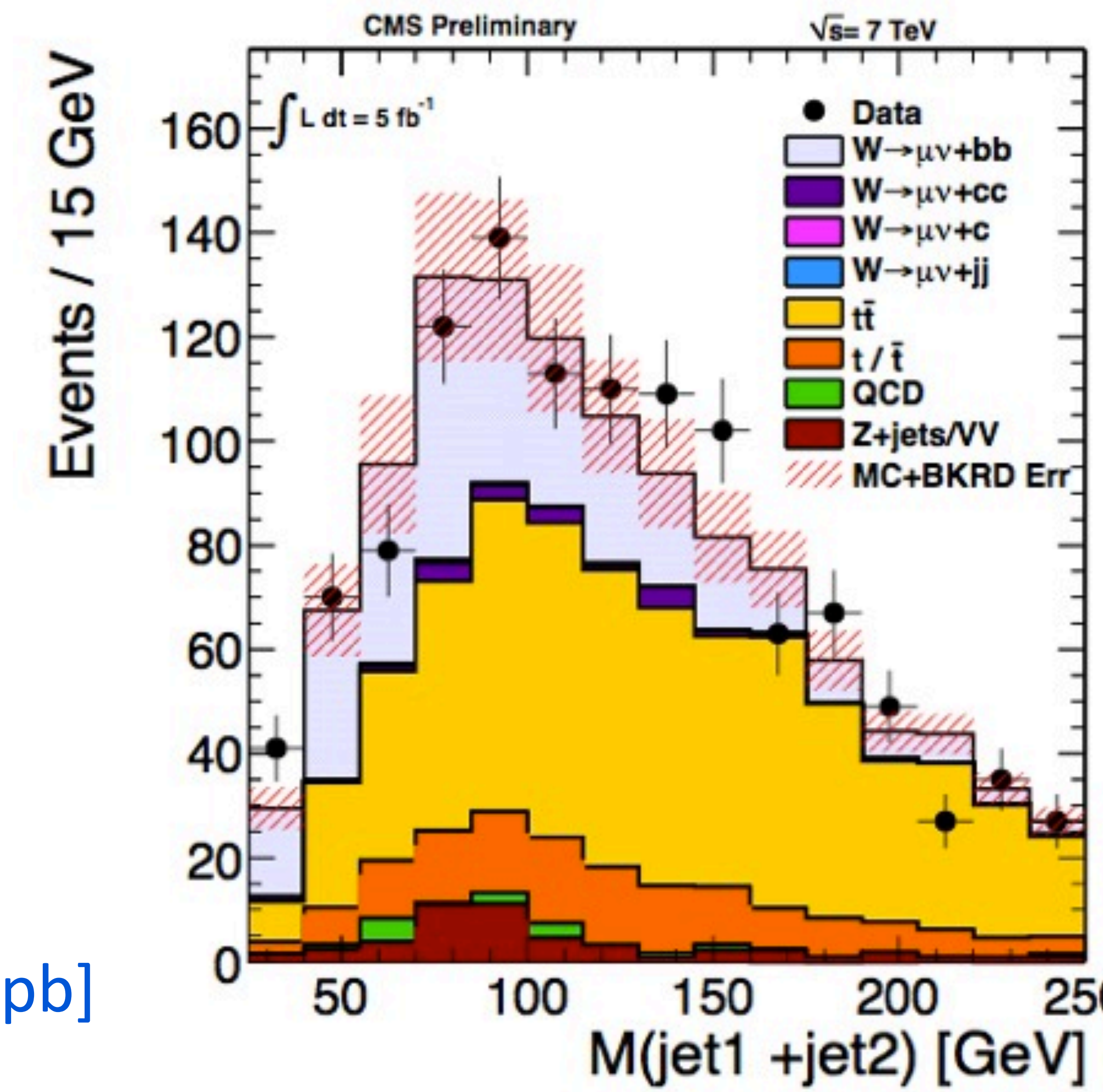
First measurement of W + 1 b-jet differentially vs $d\sigma/dp_T$

- Njet = 1 Data/MC increases as function of b-jet p_T
- Results are also provided without single top subtraction

W + 2 b-jet

$N_{bjets} = 2$ (exclusive)



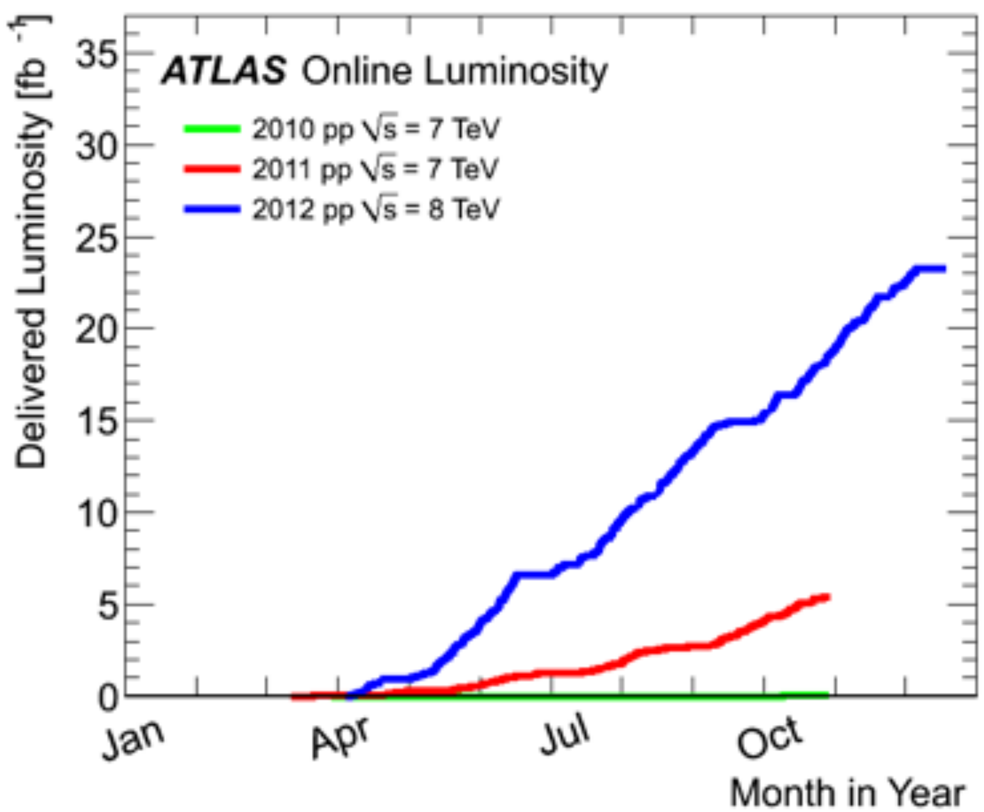


	$\sigma(W \rightarrow bb)$
Data (CMS)	0.53 ± 0.05 stat ± 0.1 sys [pb]
MCFM (MSTW08NNLO)	0.52 ± 0.03 [pb]

Complementary phase space w.r.t. the W + 1 b-jet measurement, very good Data/Theory agreement; Important for WH with $H \rightarrow bb$

Summary

- LHC delivered substantial data in 2011: MC is required to describe extreme kinematics of rare events with small cross-section
- Data/MC tension was observed in key distributions important for LHC physics searches
- Need to improve MC in order to be able to extract the smallest signals of interest at LHC



More luminosity (x 4) at 8 TeV yet to be analyzed

References

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12002
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12004
  - CDS record: CMS-PAS-SMP-12-004
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12026
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11015
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11021
  - CDS record: CERN-PH-EP-2013-001
- http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-11/
  - CDS record: CERN-PH-EP-2012-357
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-04/
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11012
  - http://dx.doi.org/10.1007/JHEP06(2012)126
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/SMP12003TWiki
  - https://cdsweb.cern.ch/record/1428117
- http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-12/
  - CDS record: CERN-PH-EP-2013-003

MC setup (ATLAS)

- ALPGEN v2.13 + HERWIG v6.520 + JIMMY v4.31 + AUET2-CTEQ61L
- ALPGEN v2.14 + PYTHIA v6.425 + PERUGIA2011C + CTEQ61L (for sys studies)
- Sherpa v1.4.1 using MENLOPS for 0-jet bin + CT10
- MC@NLO v4.01 + HERWIG + CT10 (DY@NLO + 1 real emission)
- PHOTOS used for QED FSR both in ALPGEN + PYTHIA
- YSF for QED-FSR in Sherpa
- ALPGEN + Sherpa both ME with up to 5 partons
- FEWZ + MSTW08NNLO for NNLO DY inclusive cross sections
- BlackHat+Sherpa NLO Z + (1-4) partons + CT10 PDFs

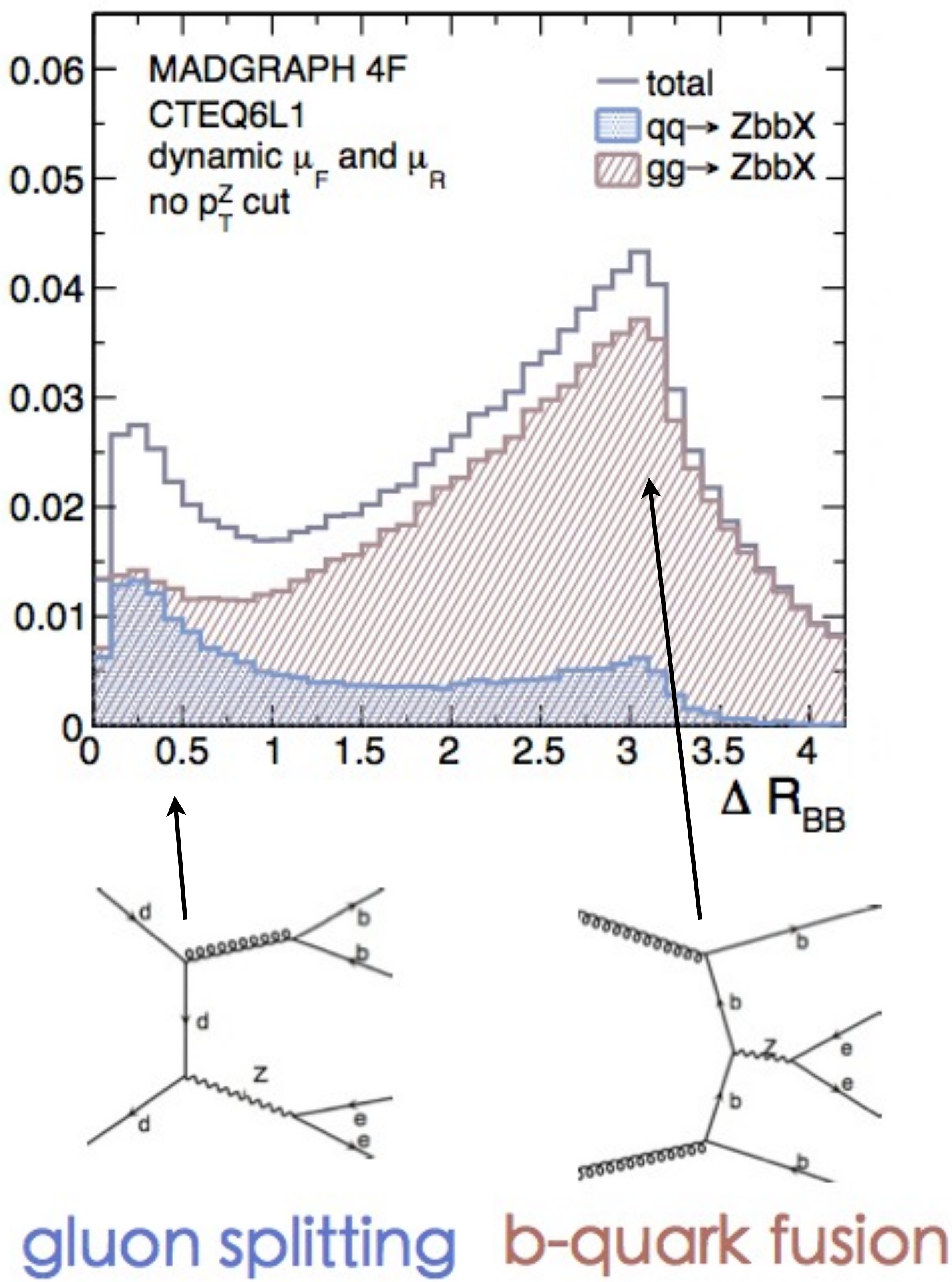
MC setup (CMS)

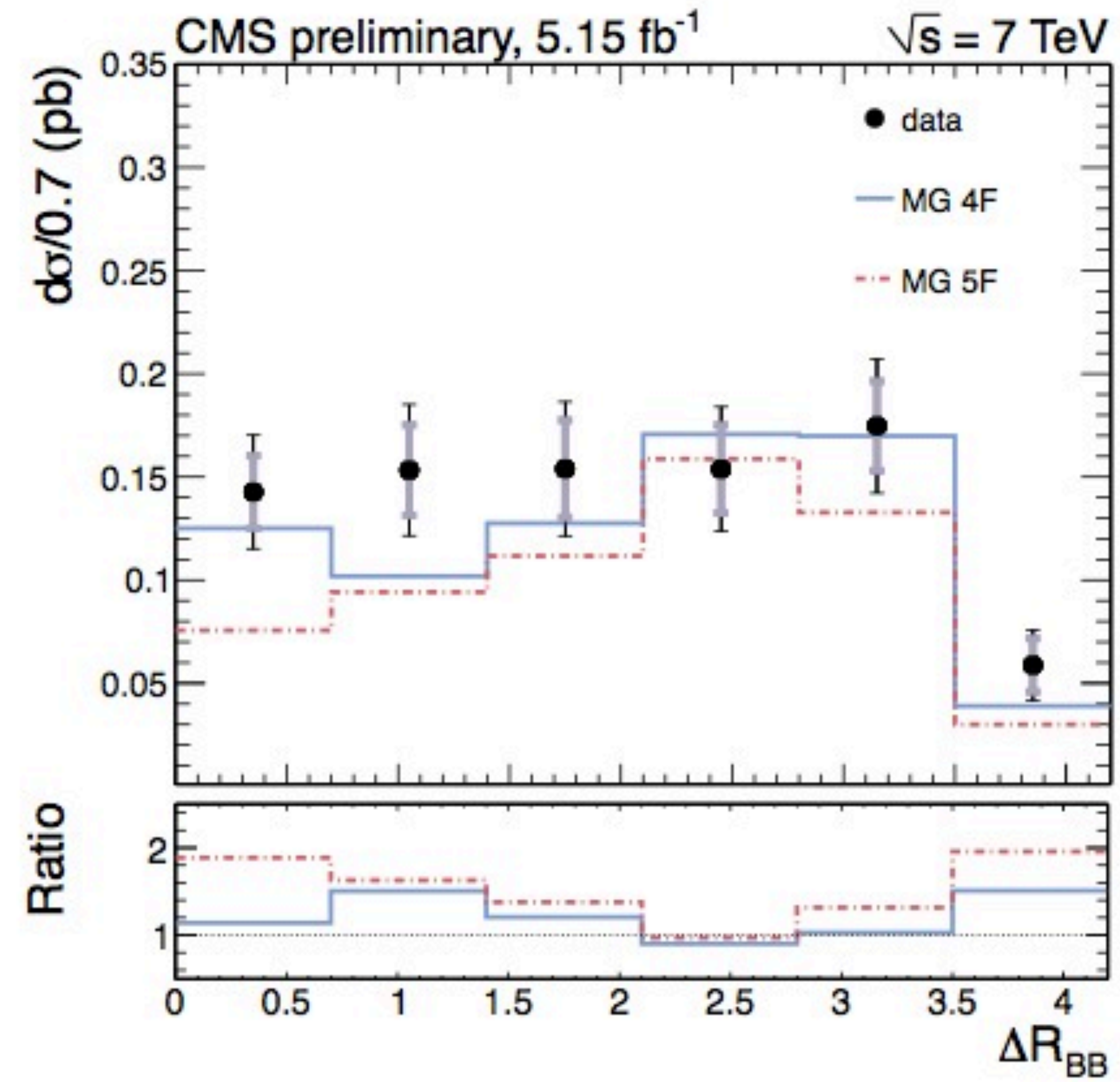
- Madgraph v5.1.1.0 (ME up to 4 partons) + Pythia v6.4.24 + Z2 tune + CTEQ6L1
- Sherpa v1.3.1 (ME up to 4 partons) + CTEQ6m
- Powheg DY + 1-jet @ NLO + Pythia v6.4.24 + Z2 tune + CT10
- Pythia v6.4.24 + Z2 tune
- FEWZ for NNLO DY inclusive cross sections
- MCFM for NLO Z/W + 1-jet + CTEQ6.6M, MSTW2008, NNPDF21

Backup Slides

Z bb angular correlations

ETH Zürich

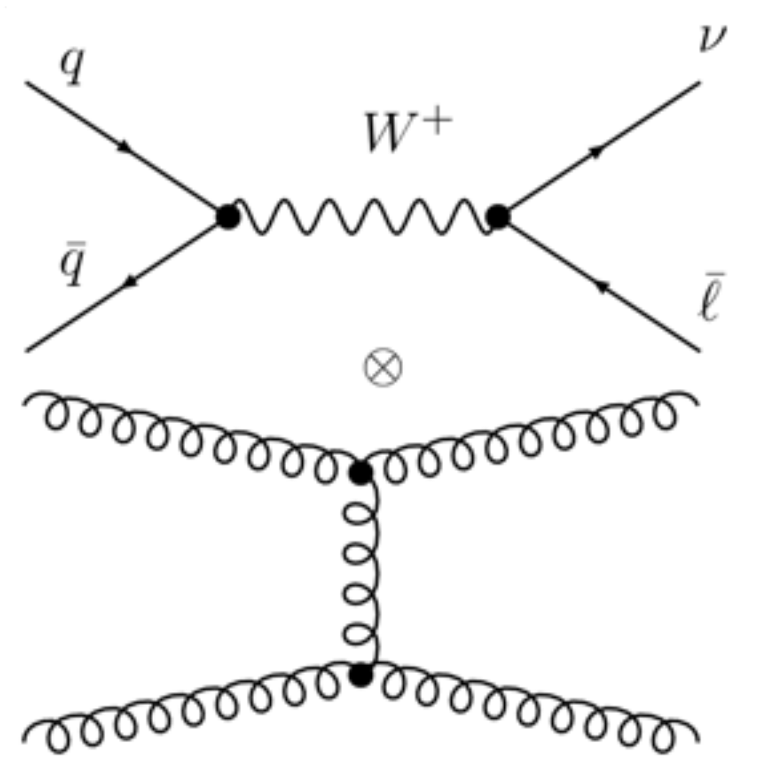




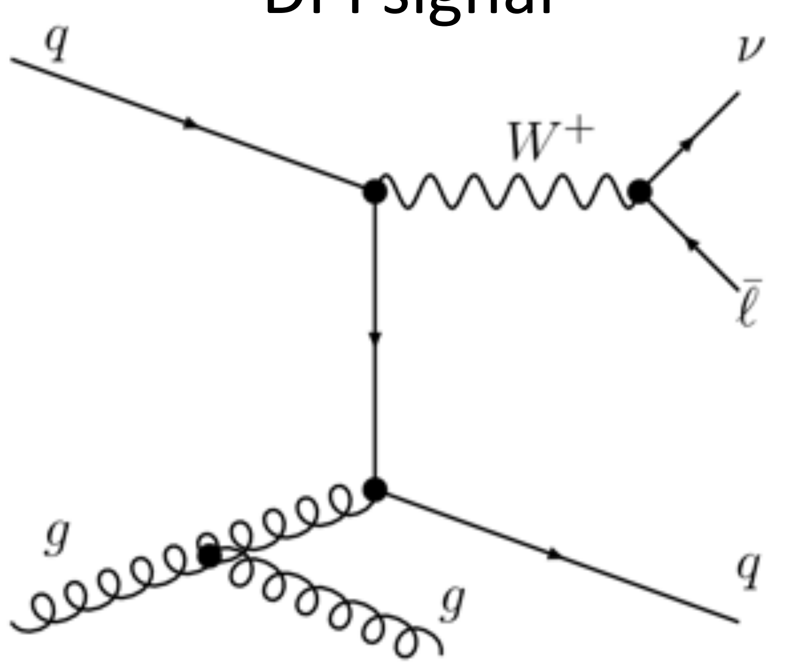
Madgraph with 4F PDFs approach gives best description of data (normalization and shape)
Madgraph with 5F PDFs underestimates collinear BB hadron production (gluon splitting)

Z+b-jets cross section also published with 2.2 fb^{-1} @ 7 TeV J. HEP 06 (2012) 126

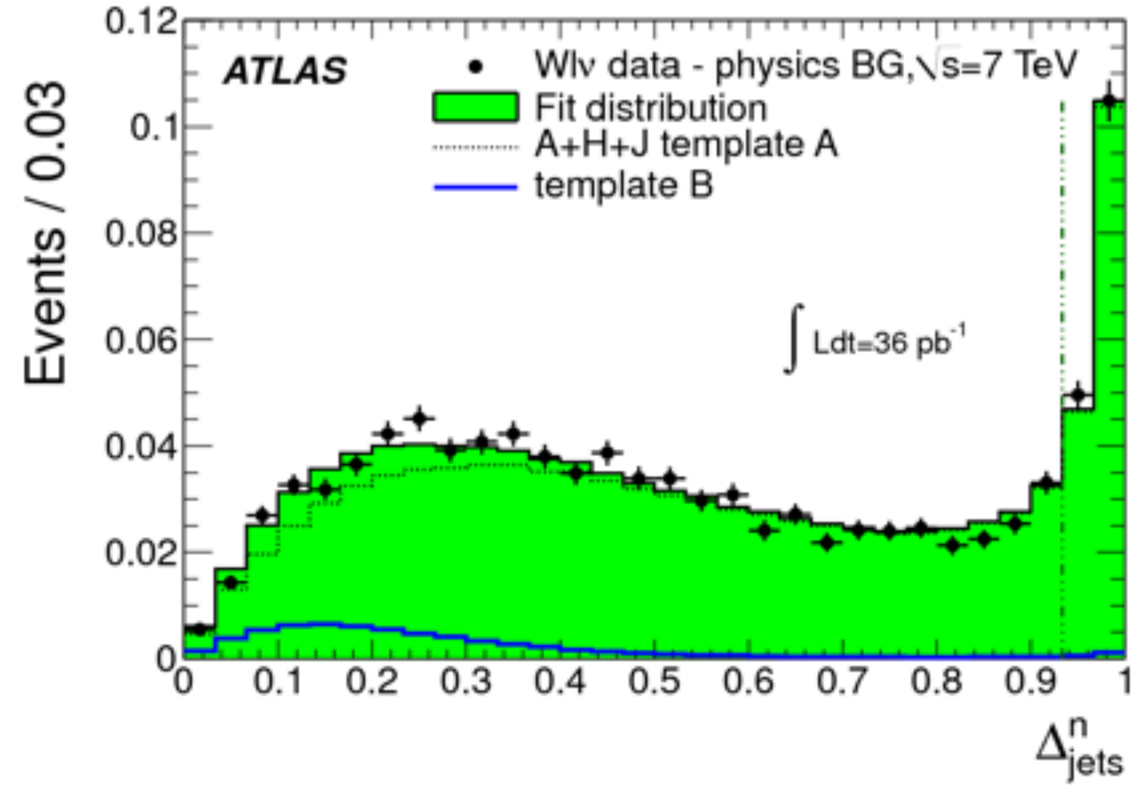
W + 2j

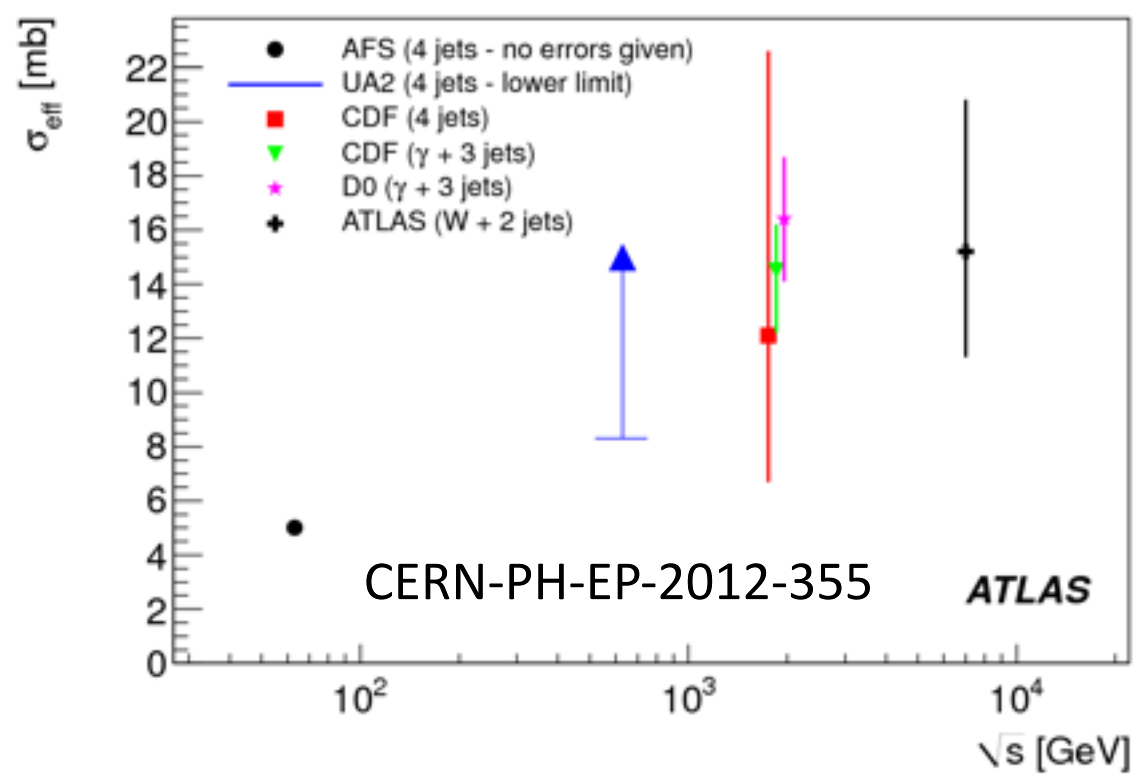


DPI signal



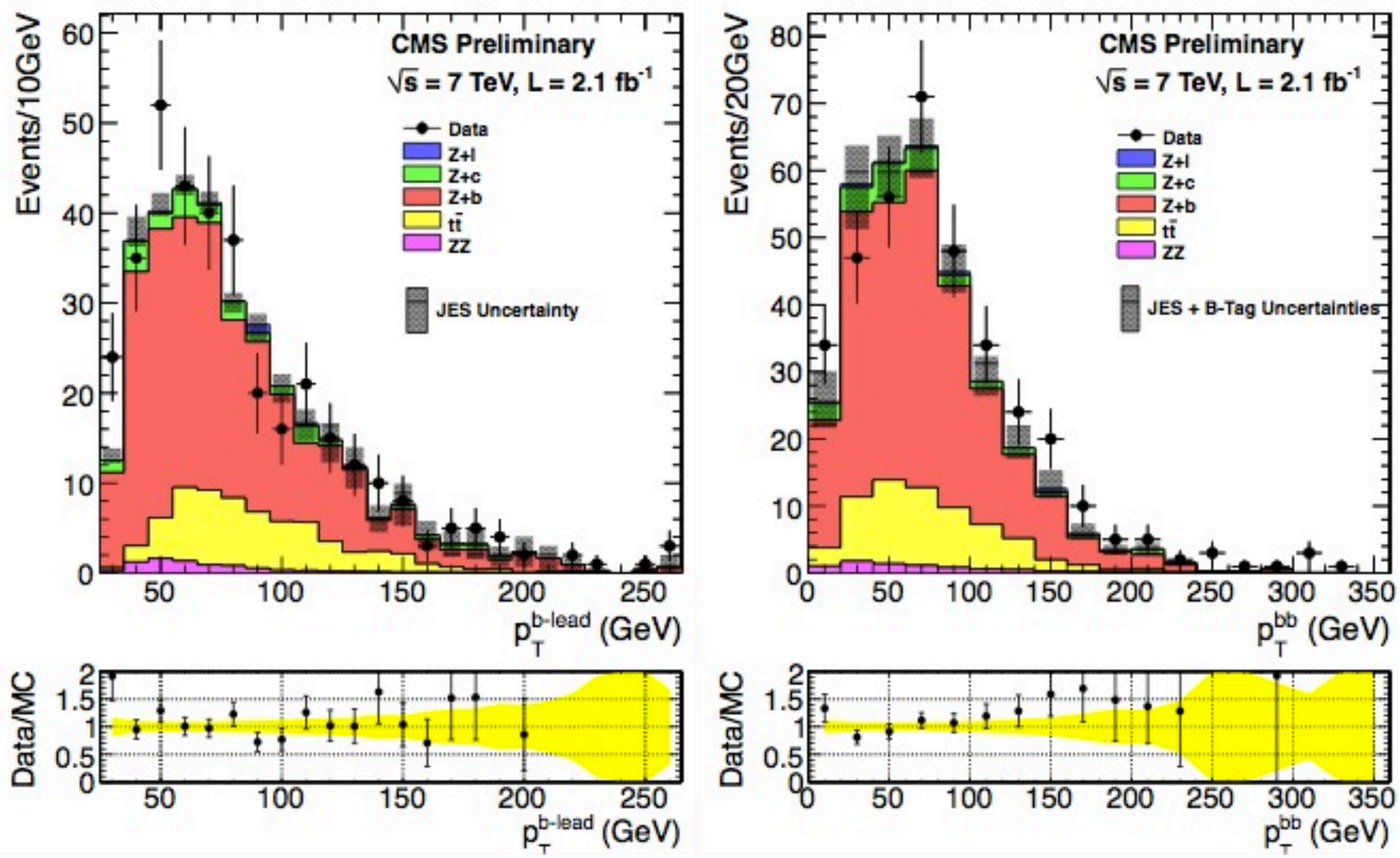
W + 2j background





CERN-PH-EP-2012-355

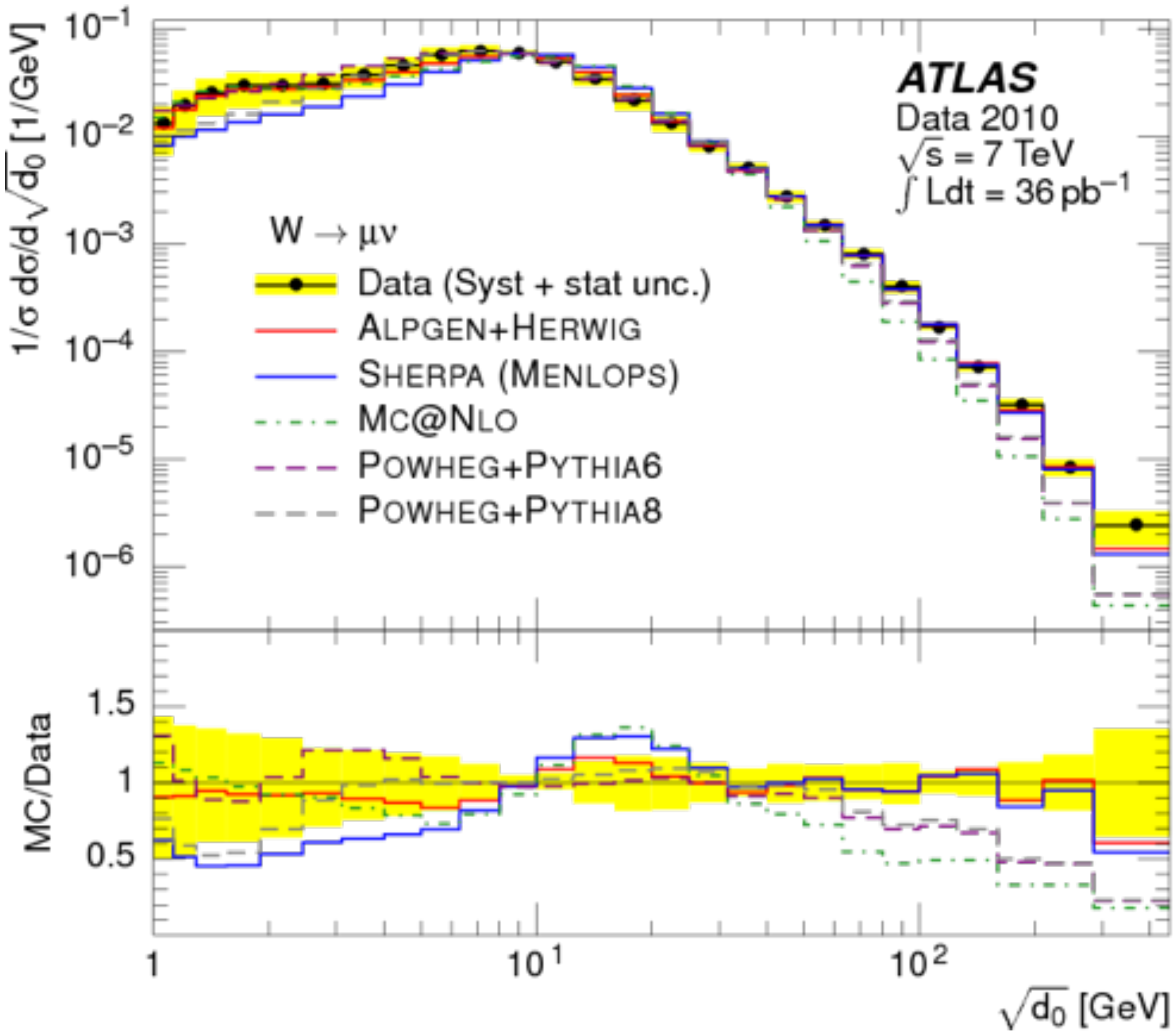
Z + b jets

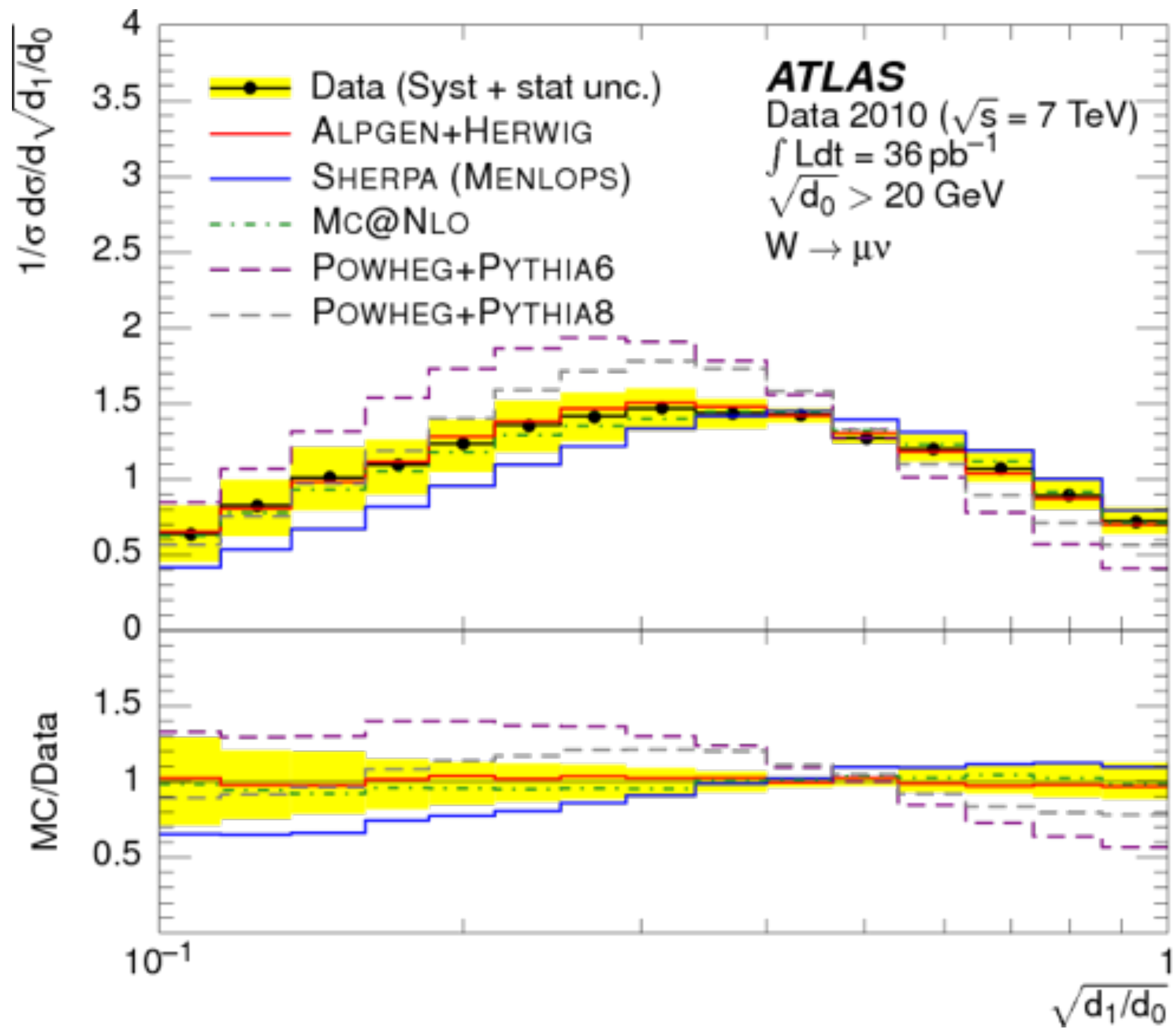


Multiplicity bin	ee	$\mu\mu$
σ_{hadron}(Z+1b,Z$\rightarrow \ell\ell$)(pb)	$3.25 \pm 0.08 \pm 0.29 \pm 0.06$	$3.47 \pm 0.06 \pm 0.27 \pm 0.11$
σ_{hadron}(Z+2b,Z$\rightarrow \ell\ell$)(pb)	$0.39 \pm 0.04 \pm 0.07 \pm 0.02$	$0.36 \pm 0.03 \pm 0.07 \pm 0.03$
σ_{hadron}(Z+b,Z$\rightarrow \ell\ell$)(pb)	$3.64 \pm 0.09 \pm 0.35 \pm 0.08$	$3.83 \pm 0.07 \pm 0.31 \pm 0.14$

Z+bb cross section 10% higher than tree-level prediction by Madgraph 5F rescaled by k = 1.23; Some tensions in the description of the event dynamics

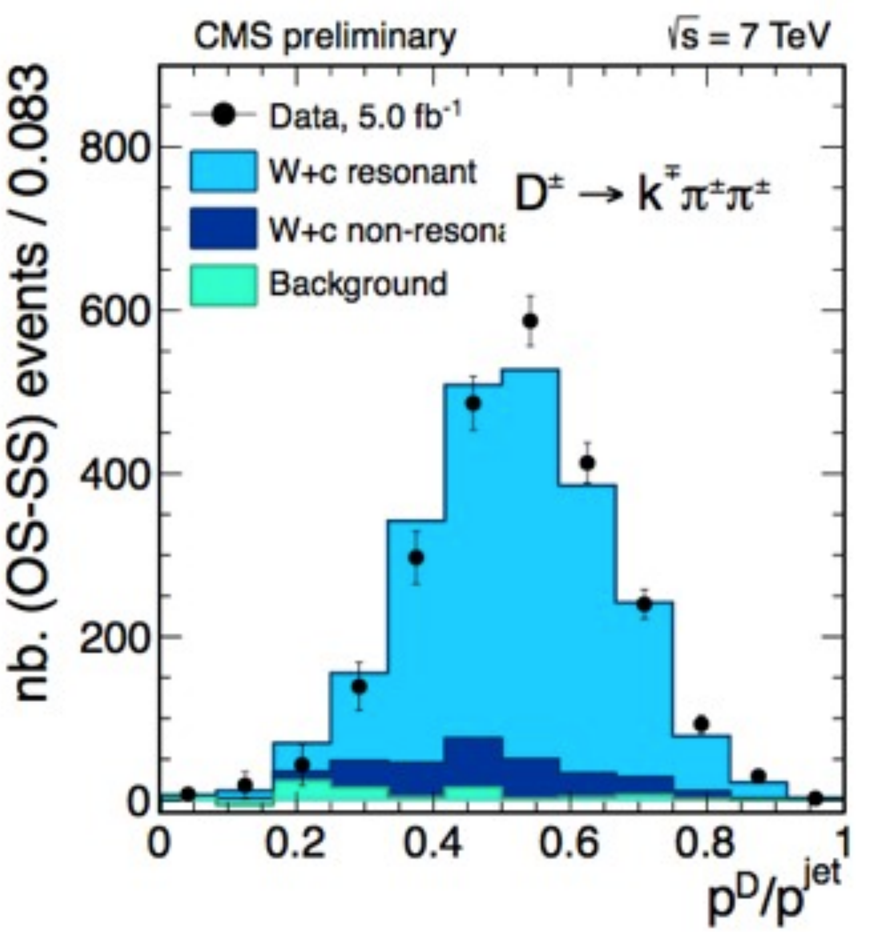
k_T splitting



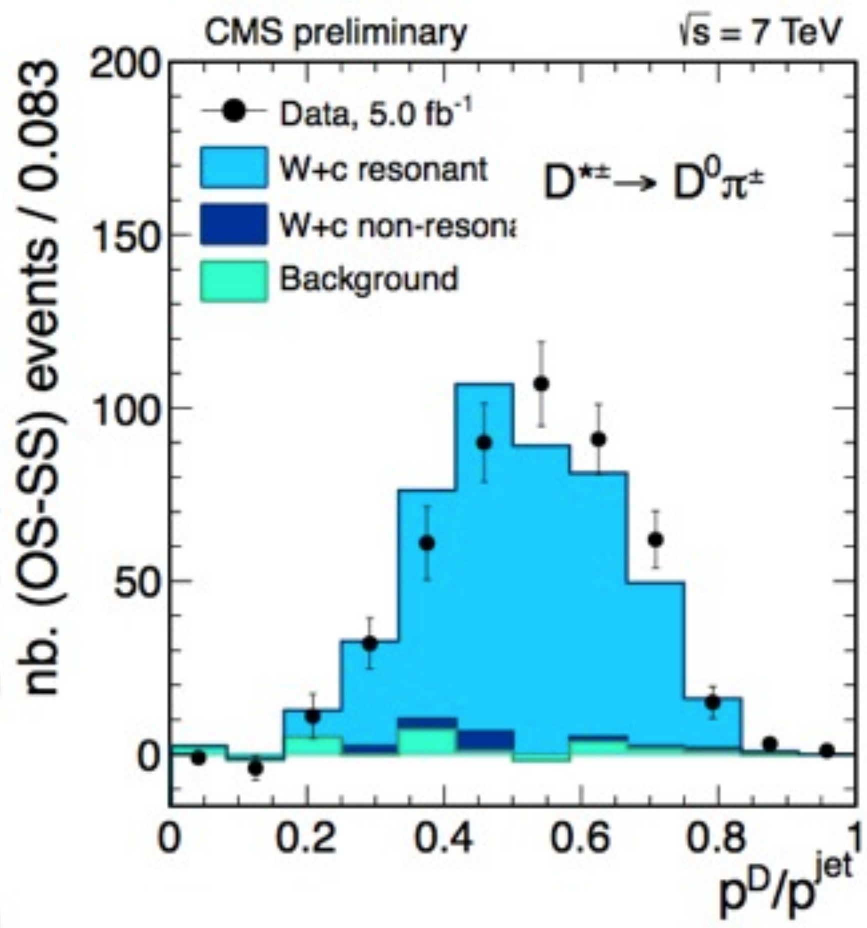


arXiv:1302.1415

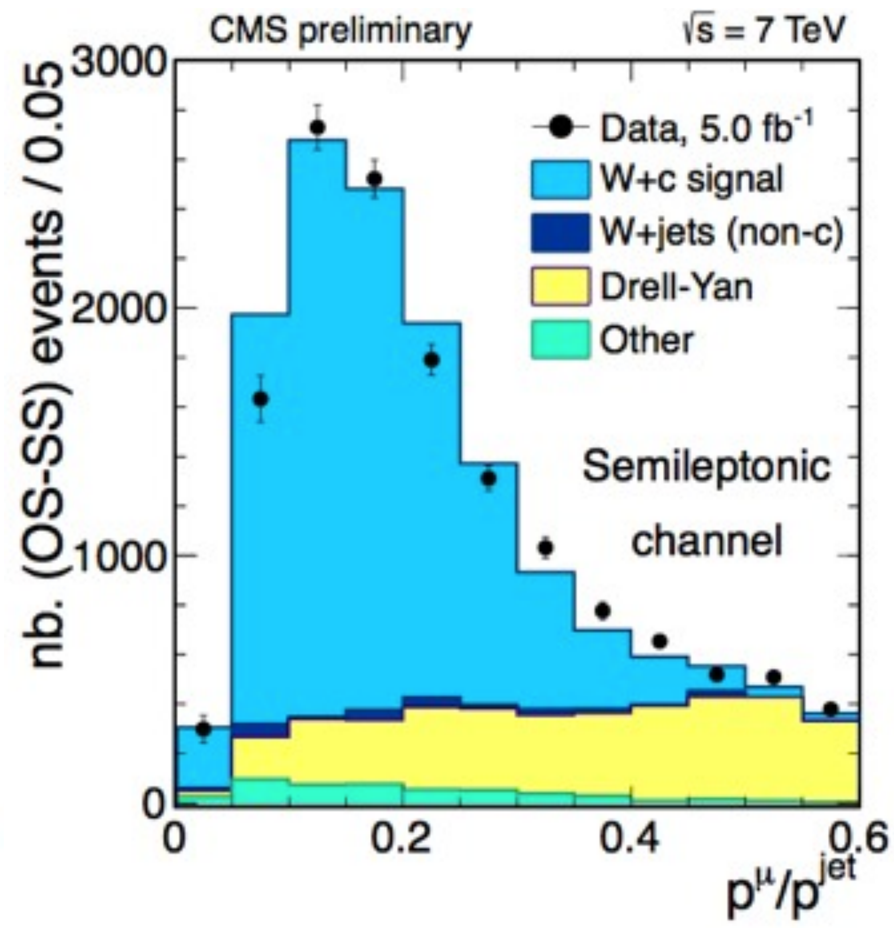
W + c (backup)



CMS preliminary
√s = 7 TeV
Data, 5.0 fb-1
W+c resonant
W+c non-resona
Background
D± → k∓π±π±
nb. (OS-SS) events / 0.083
pD/pjet

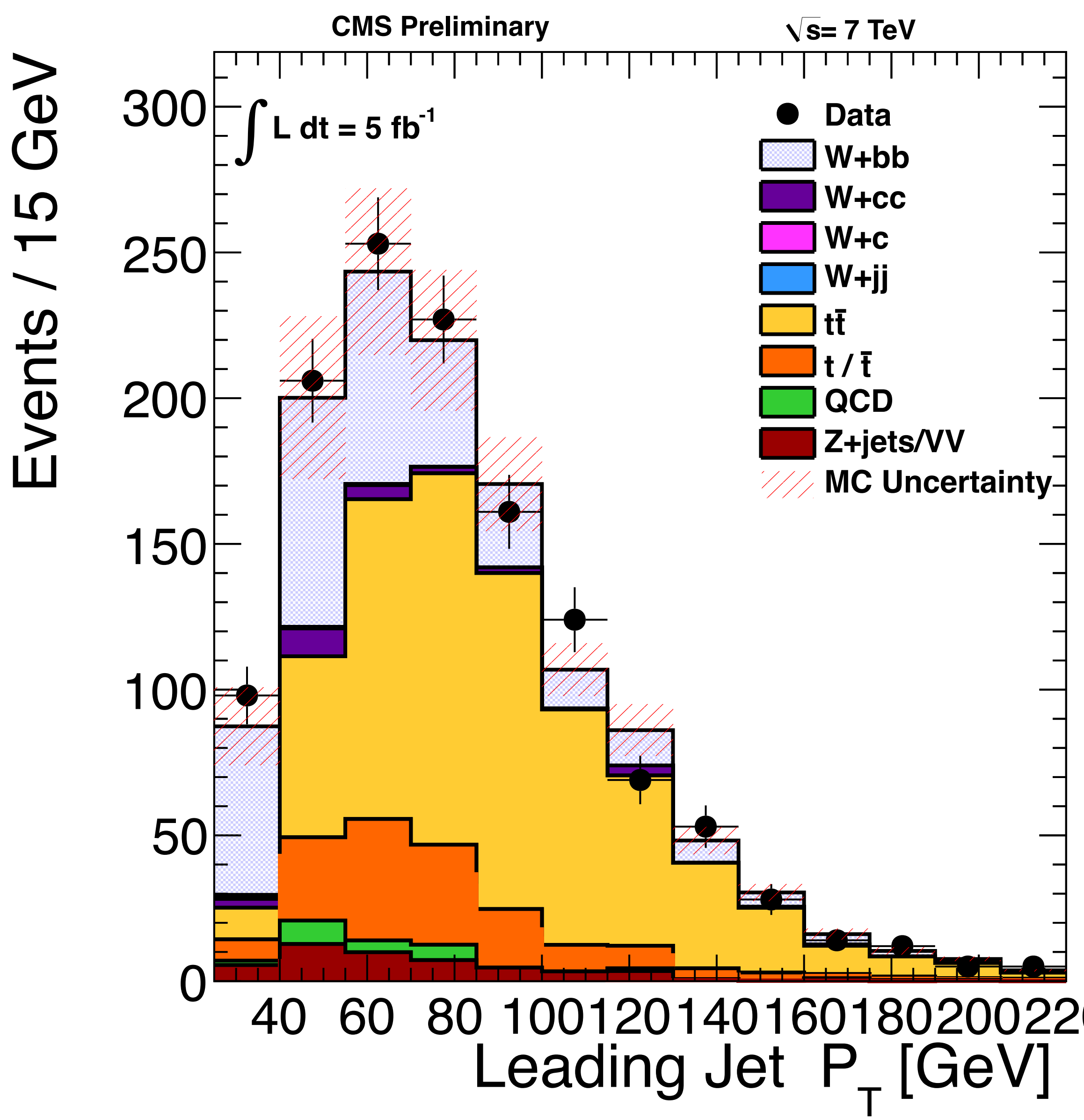


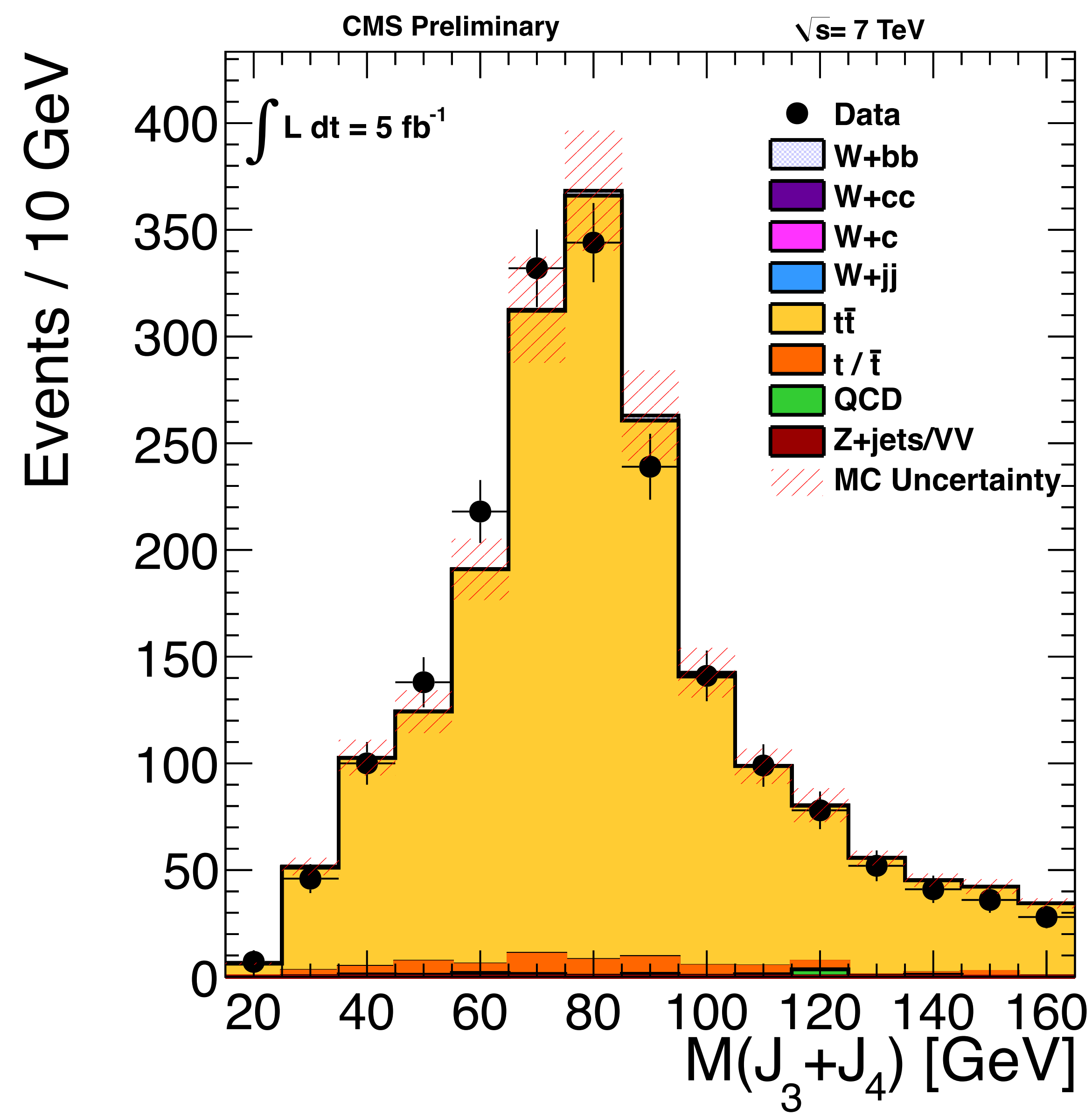
CMS preliminary
√s = 7 TeV
Data, 5.0 fb-1
W+c resonant
W+c non-resona
Background
D*± → D0π±
nb. (OS-SS) events / 0.083
pD/pjet



CMS preliminary
√s = 7 TeV
Data, 5.0 fb-1
W+c signal
W+jets (non-c)
Drell-Yan
Other
Semileptonic
channel
nb. (OS-SS) events / 0.05
pμ/pjet

W + bb (backup)

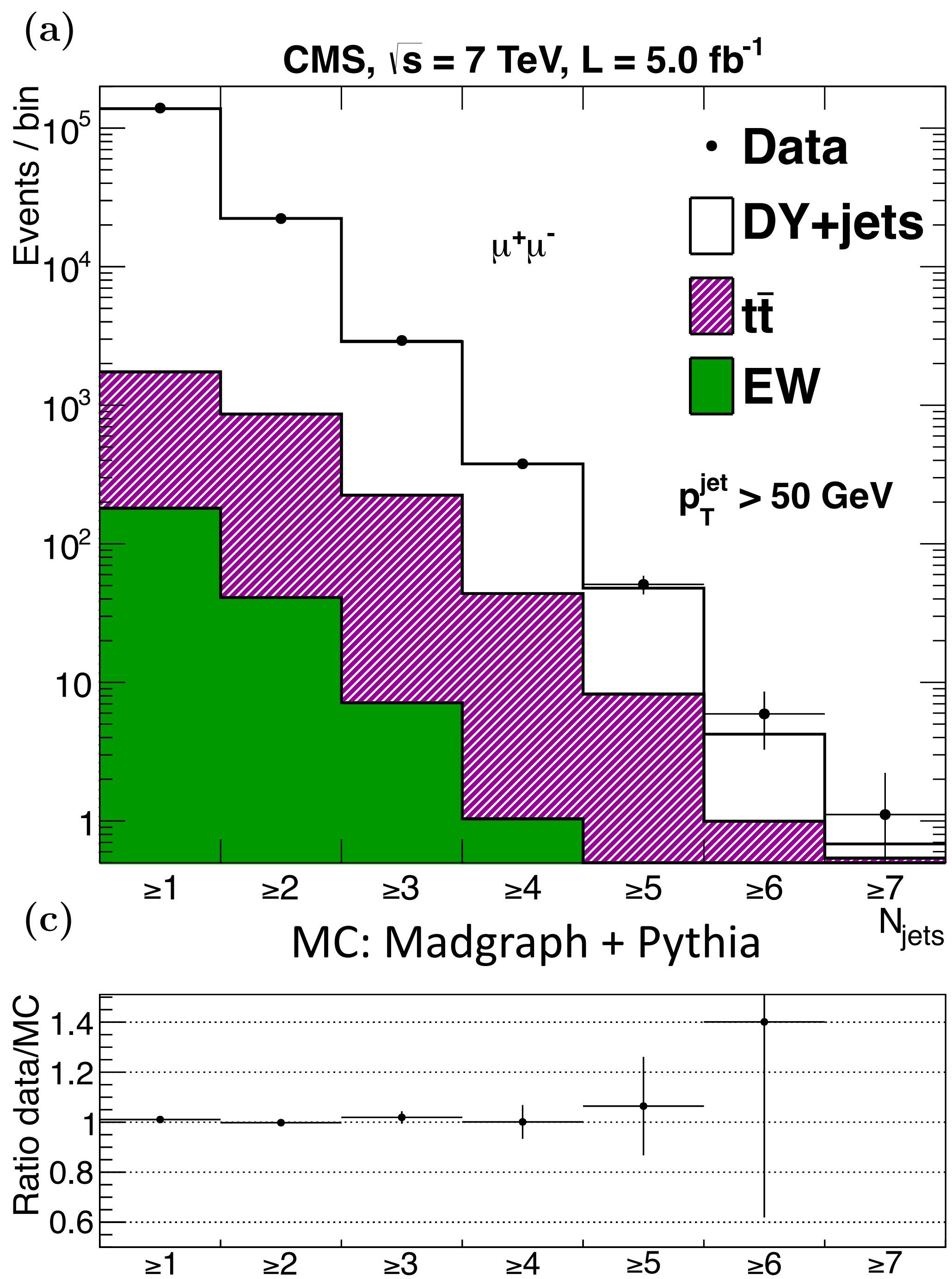

CMS Preliminary
√s= 7 TeV
∫ L dt = 5 fb-1
Data
W+bb
W+cc
W+c
W+jj
tt̄
t / t̄
QCD
Z+jets/VV
MC Uncertainty
Events / 15 GeV
Leading Jet P_T [GeV]

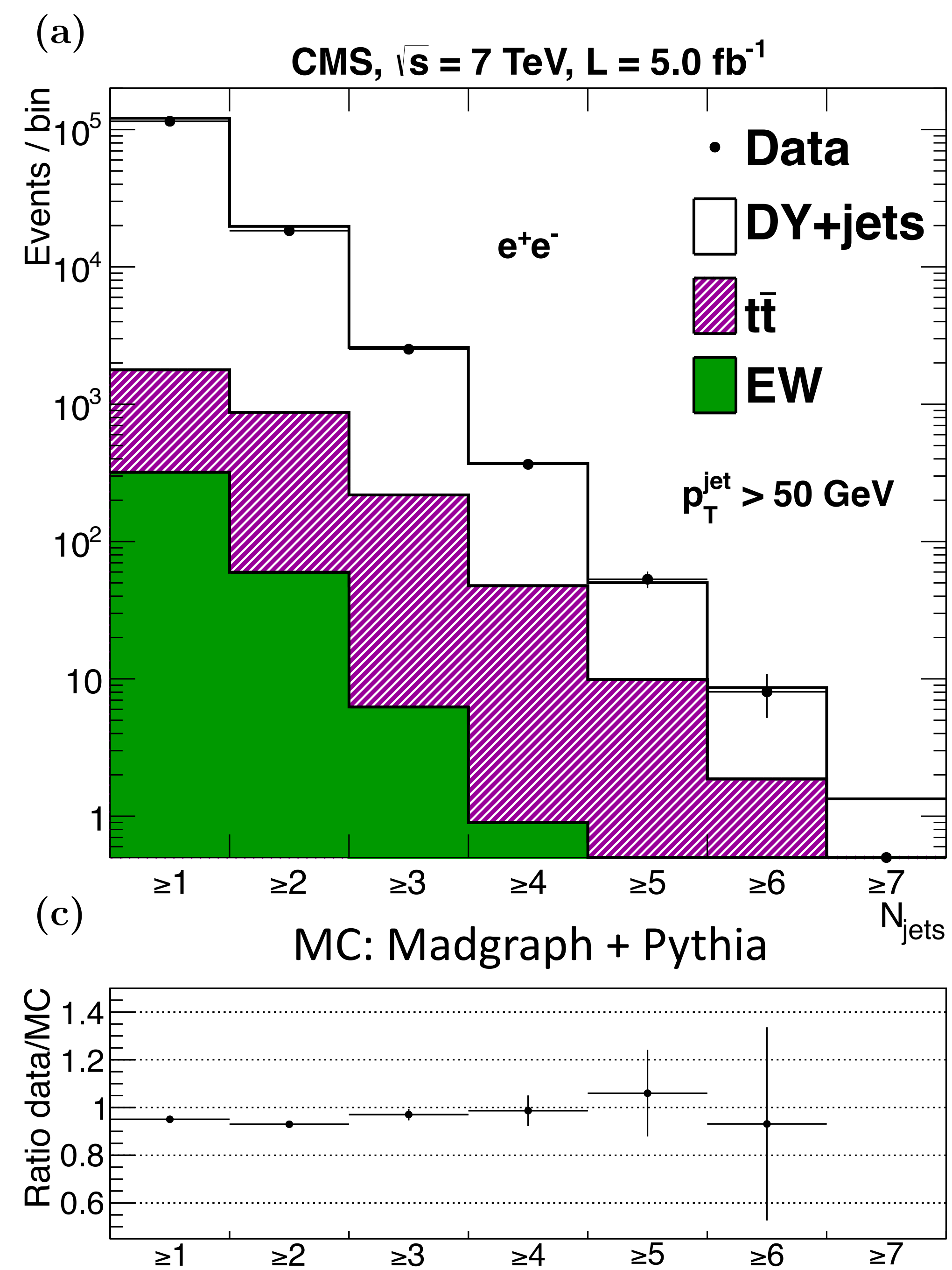

CMS Preliminary
√s= 7 TeV
∫ L dt = 5 fb-1
Data
W+bb
W+cc
W+c
W+jj
tt̄
t / t̄
QCD
Z+jets/VV
MC Uncertainty
Events / 10 GeV
M(J3+J4) [GeV]

Detector Level Spectra (CMS)

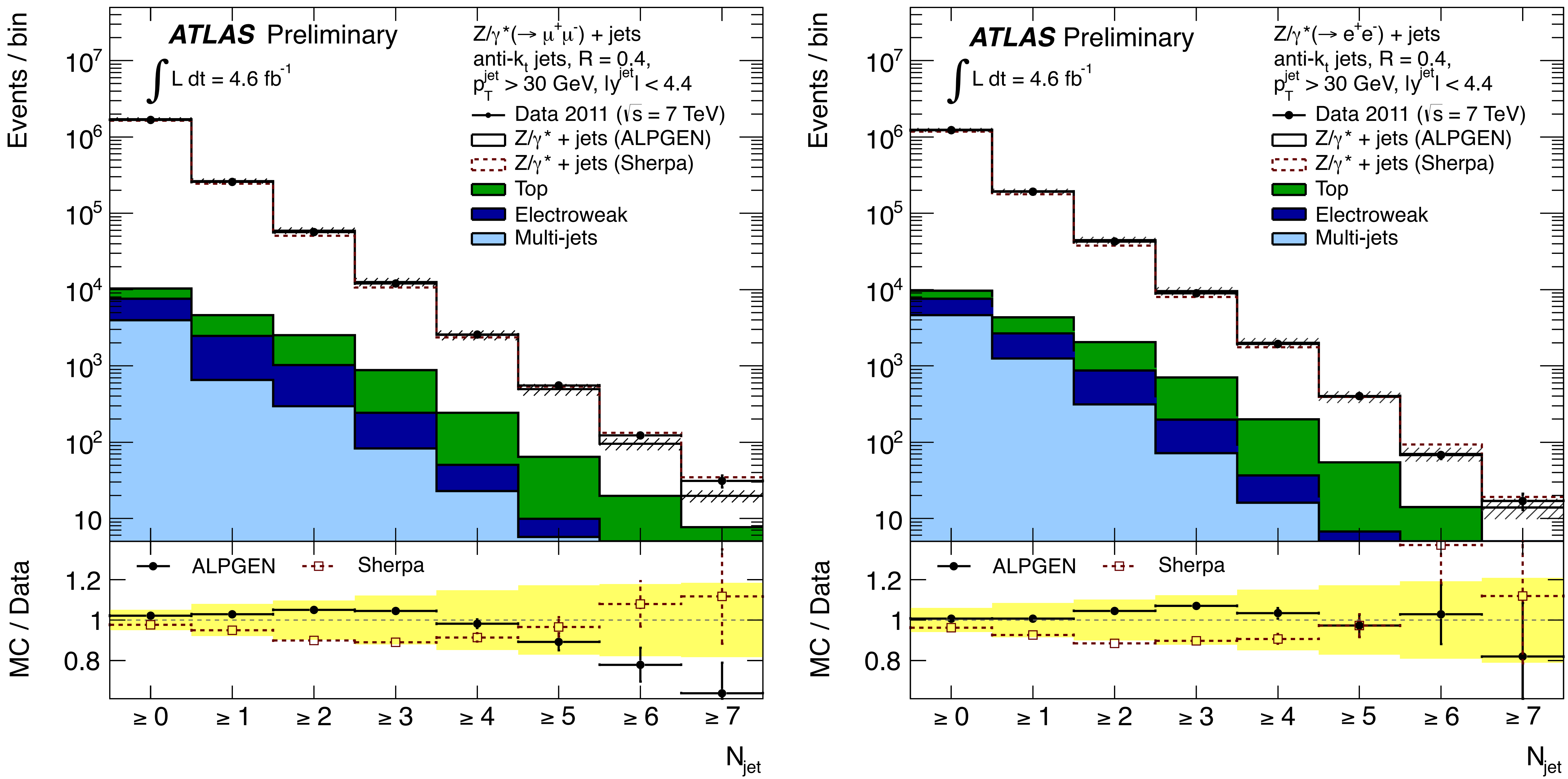
ETH Zürich

Madgraph + Pythia normalized to NNLO (or NLO for tt & EW)

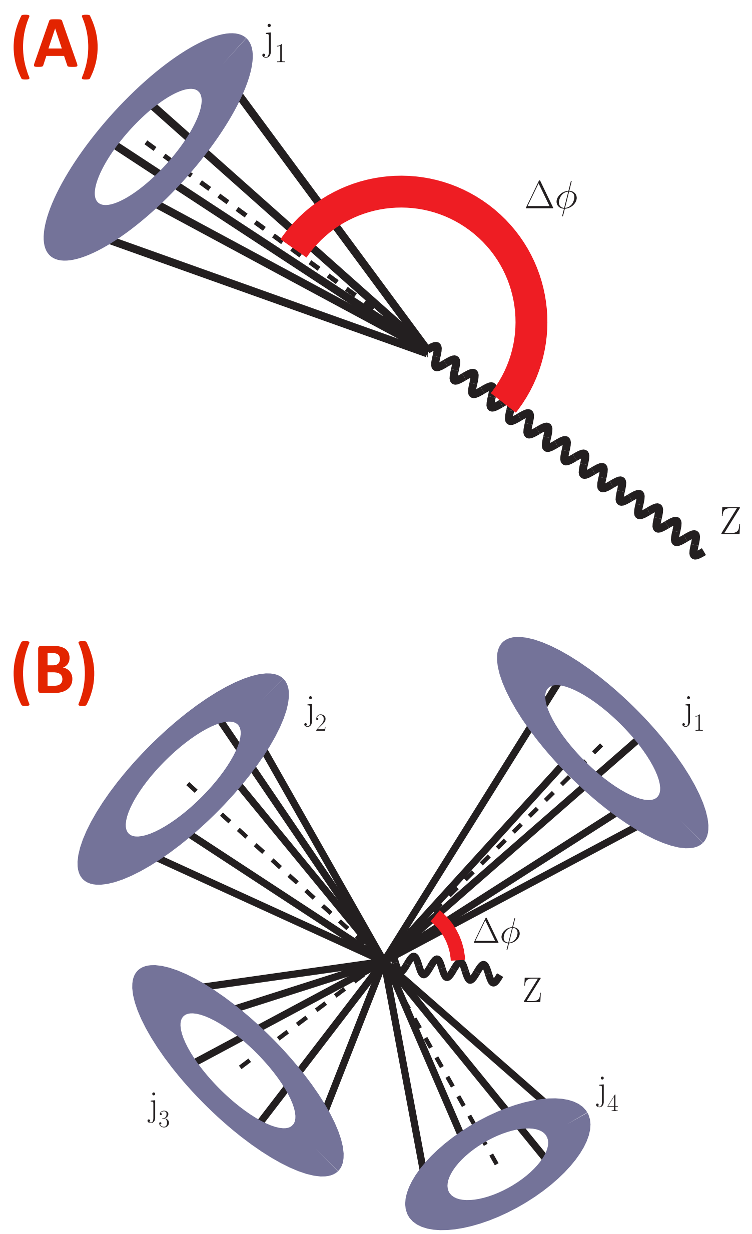


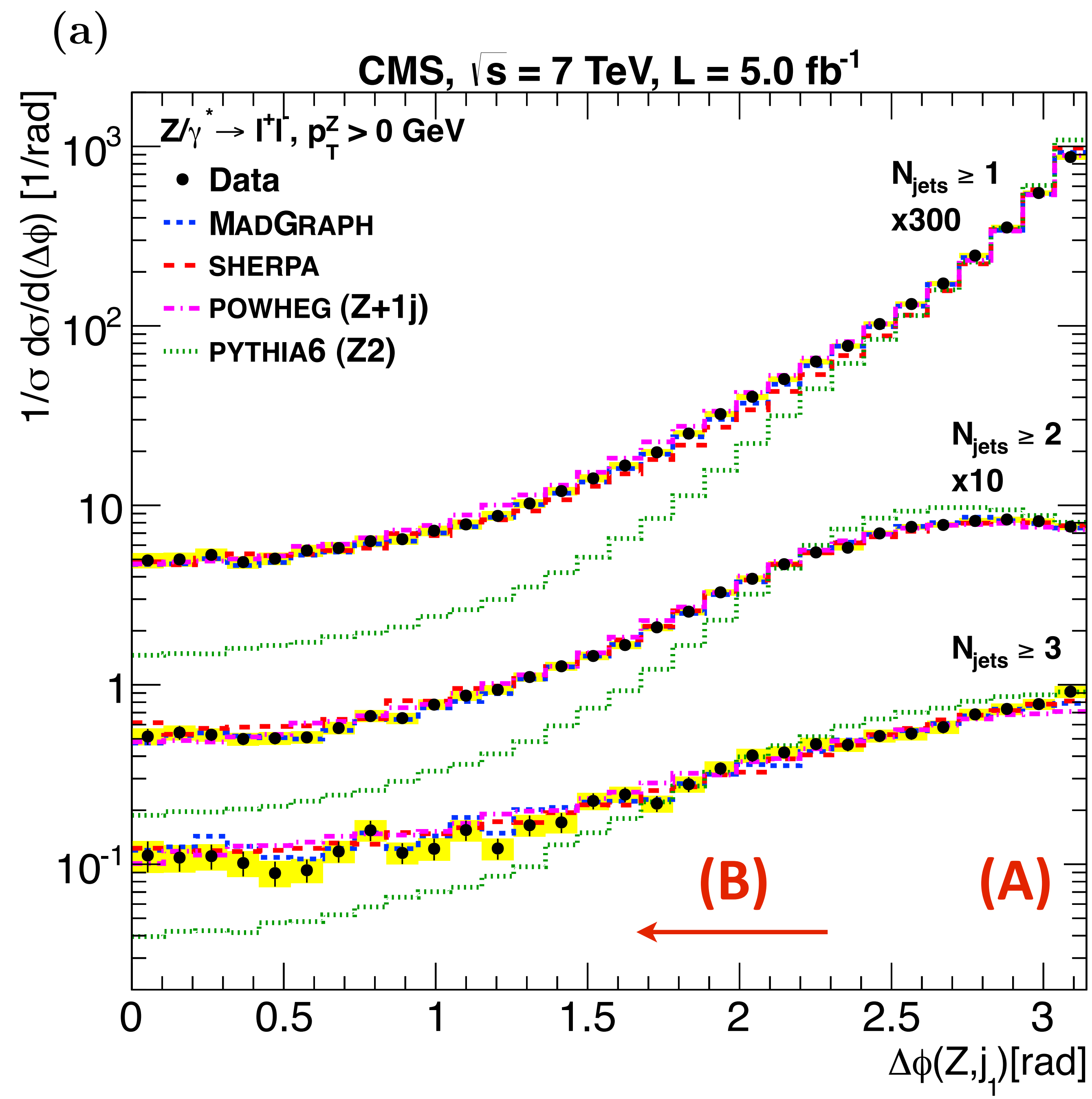


Detector Level Spectra (ATLAS)



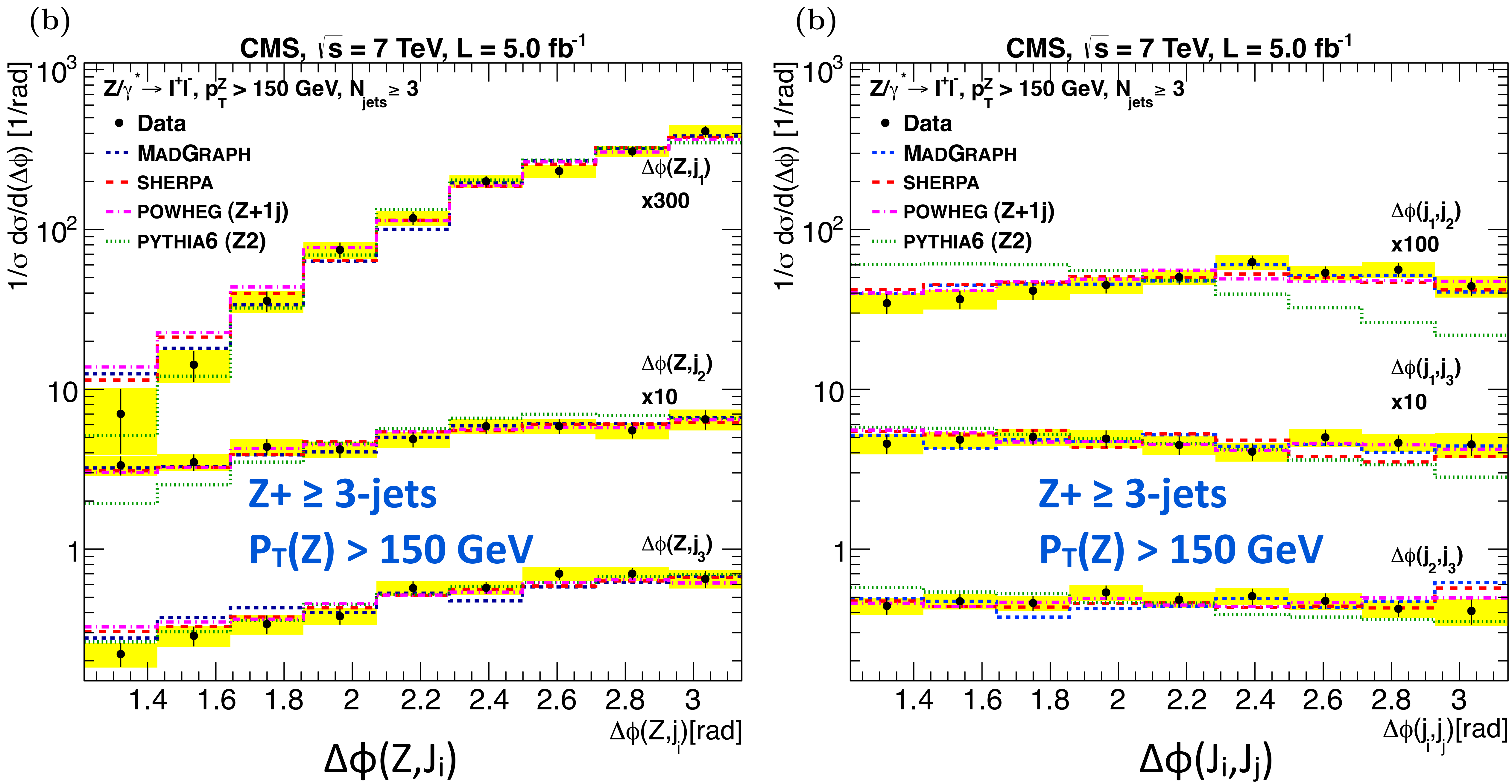
Z + jets Δϕ Correlations





- Multileg ME + PS is needed to describe **(B)**
- Powheg NLO Z + 1j ME + PS is good even for ≥ 3-jets

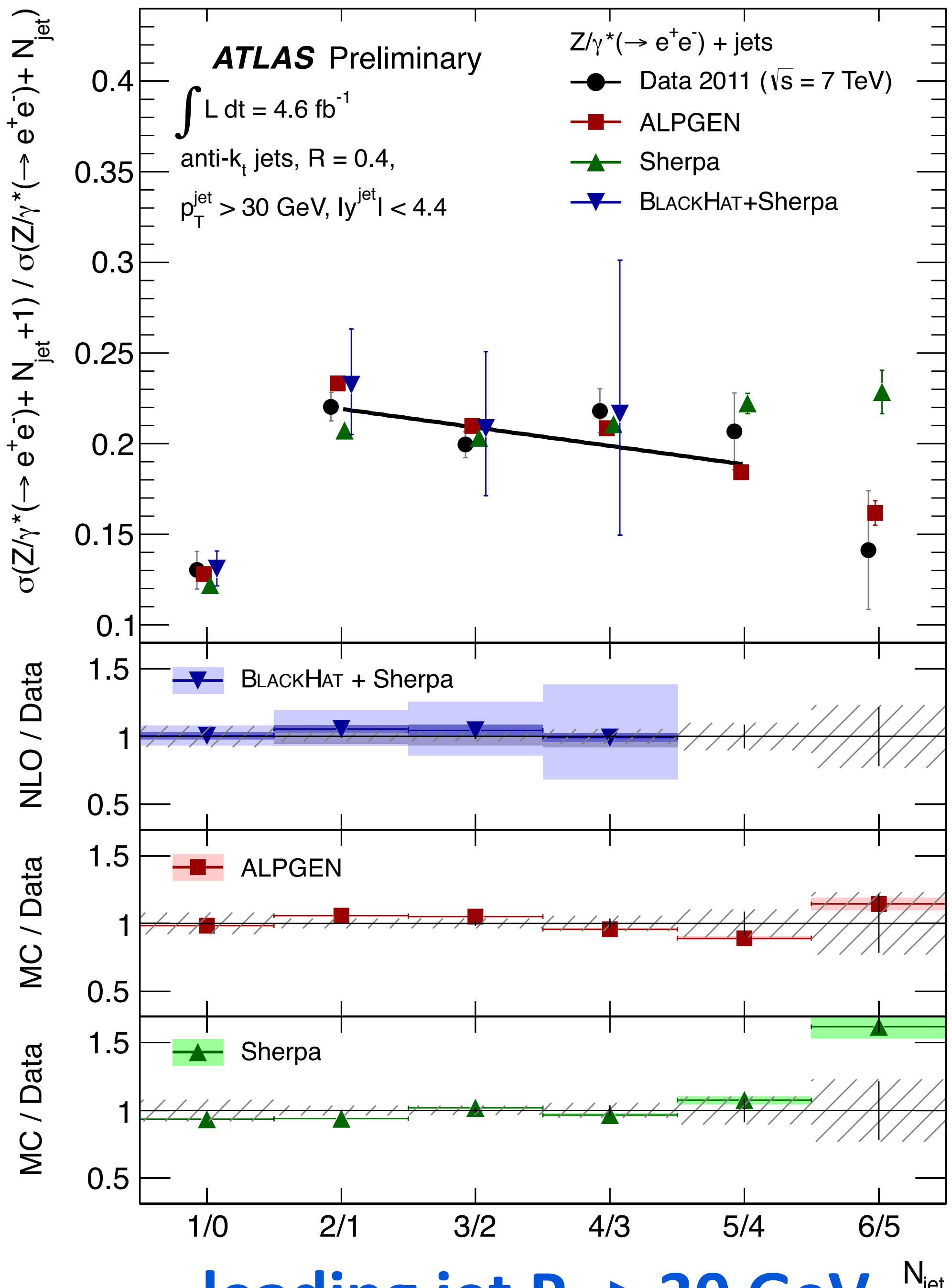
Δϕ correlations, Z+jets (boosted)



- For boosted multijet final states $\Delta\phi(J_i,J_j)$ → uniform
- Pythia gets better at boosted topologies

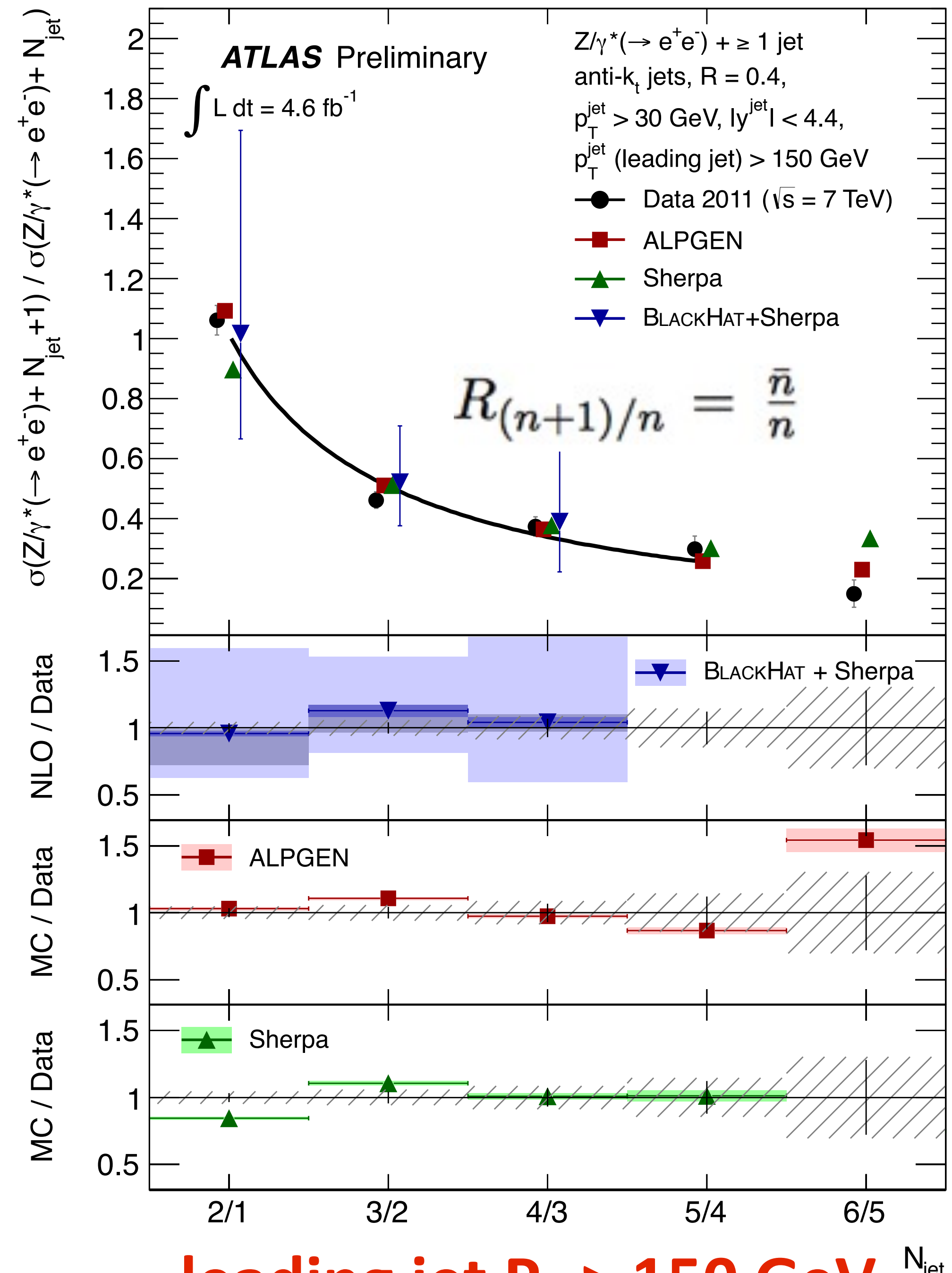
N_{jets} scaling, Z + jets

Staircase scaling



leading jet P_T > 30 GeV

Poisson scaling



leading jet P_T > 150 GeV

Both scaling patterns are anticipated from first principles JHEP 1210 (2012) 162 and are predicted from NLO and ME+PS; rather good Data/Theory; Poisson scaling typically expected in physics searches

Subleading jets p_T, Z + jets