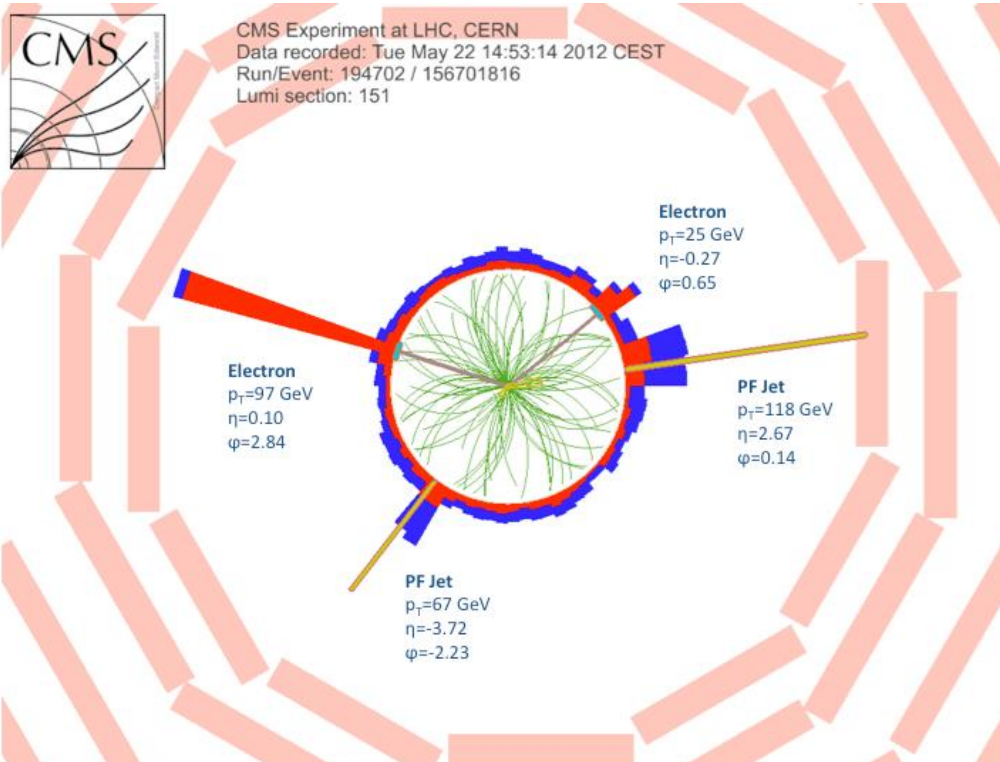
Tests of Vector Boson plus Jets Production at the LHC



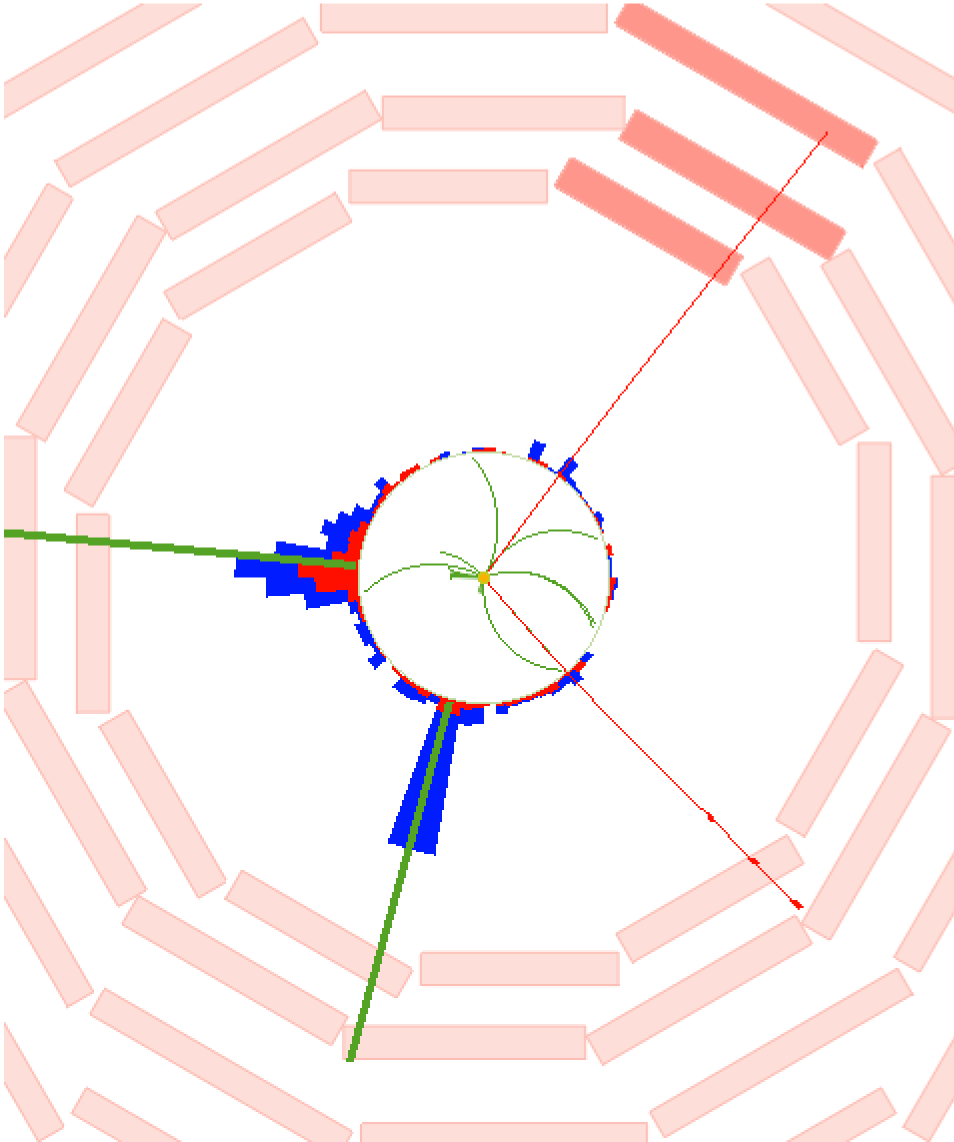
CMS VBF Z+2 jet candidate

CTEQ workshop

November 14, 2013

Jeffrey Berryhill (Fermilab)

On behalf of the CMS and ATLAS collaborations



Photon plus Jets production

Inclusive photon cross section arxiv:1311.1440

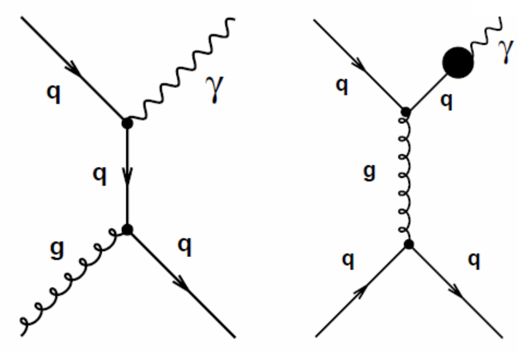
80 GeV photon trigger, with **2 M photons in the 100-1000 GeV range for |η| < 2.37**, with 4.6/fb at 7 TeV

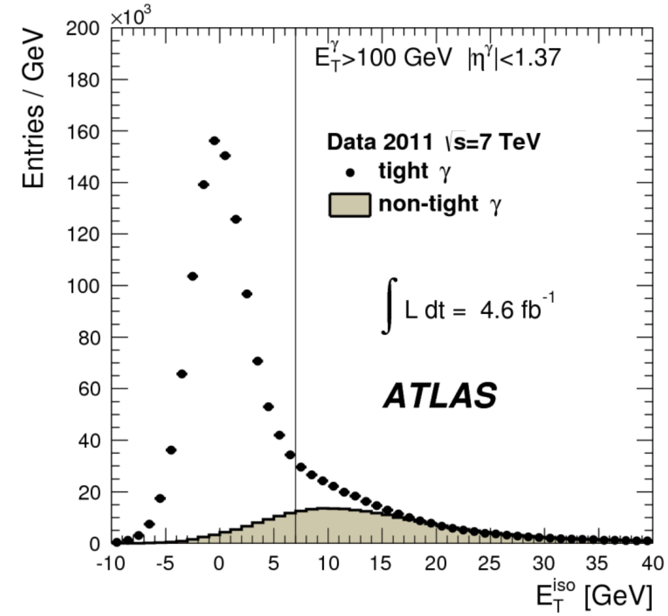
Tight shower shape selection plus isolation ET < 7 GeV in a 0.4 cone

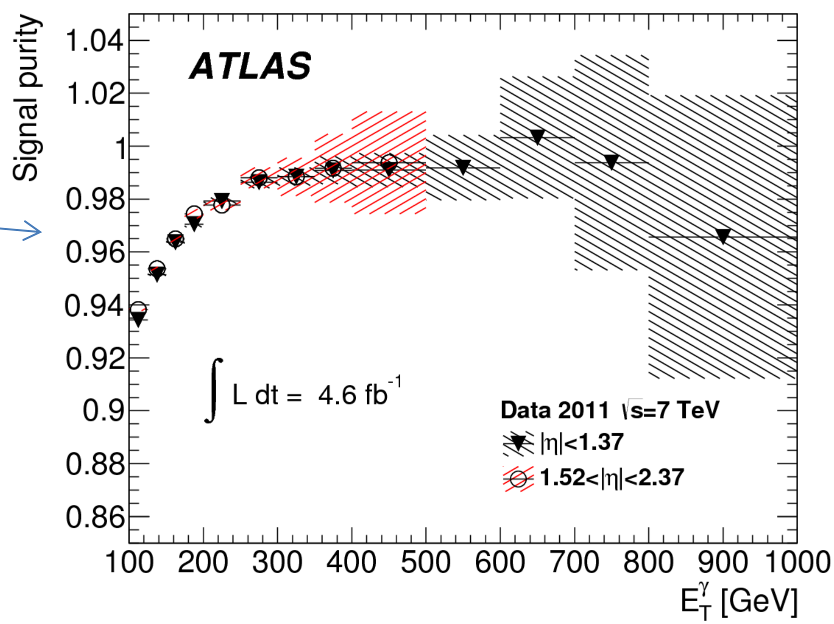
Background isolation rejection estimated from non-tight photons (vs. ET)

>93% purity for ~80% efficiency

6-7% systematic uncertainty is dominant for total cross section estimate > 100 GeV (~25% > 800 GeV)







Inclusive photon cross section arxiv:1311.1440

Comparison with JETPHOX 1.3:

MC/Data ratio dominated by MC scale uncertainty, **12-20%** (except at highest ET where PDFs matter too)

Below 500 GeV **data are 2X more precise than NLO theory**

Shape described well, normalization agrees within scale uncertainty

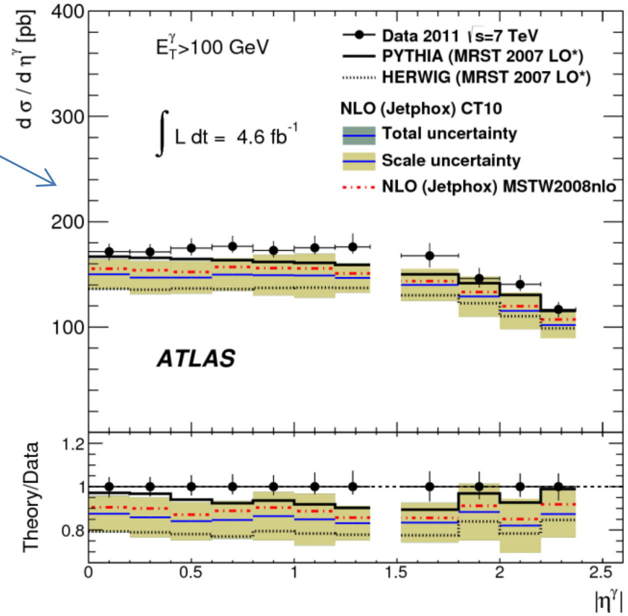
Comparison with LO+PS:

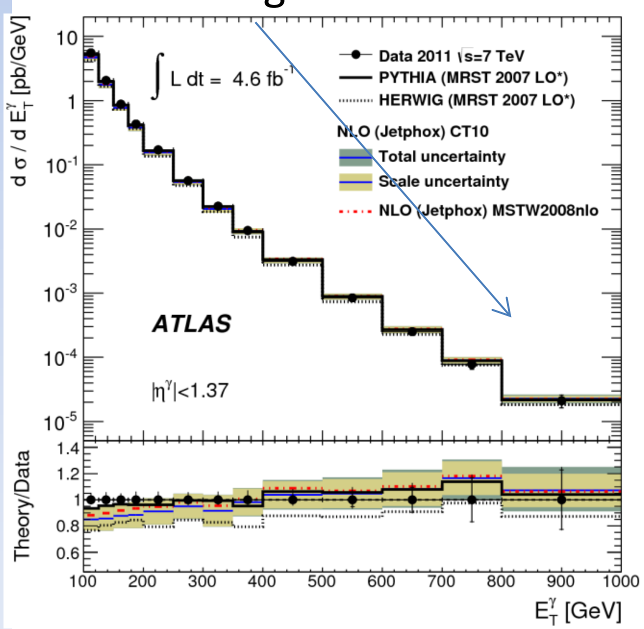
Pythia and Herwig shapes agree well.

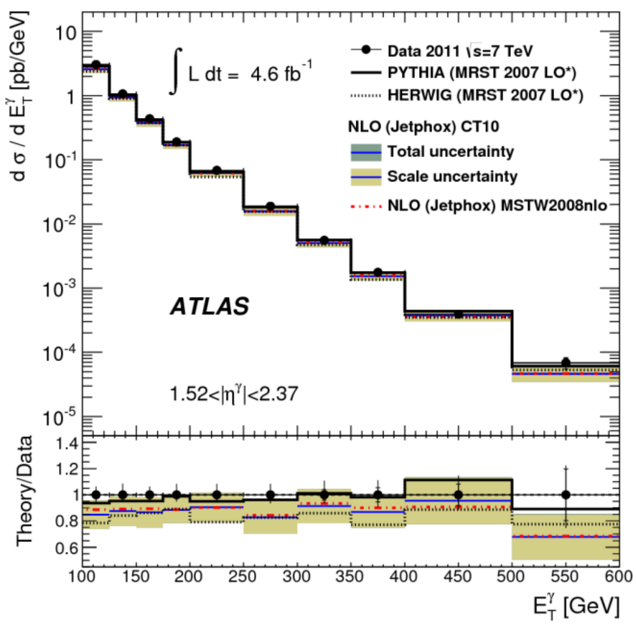
Herwig norm undershoots data by 10-20%

Barrel and endcap performance are very similar

19 candidates in 800-1000 GeV range







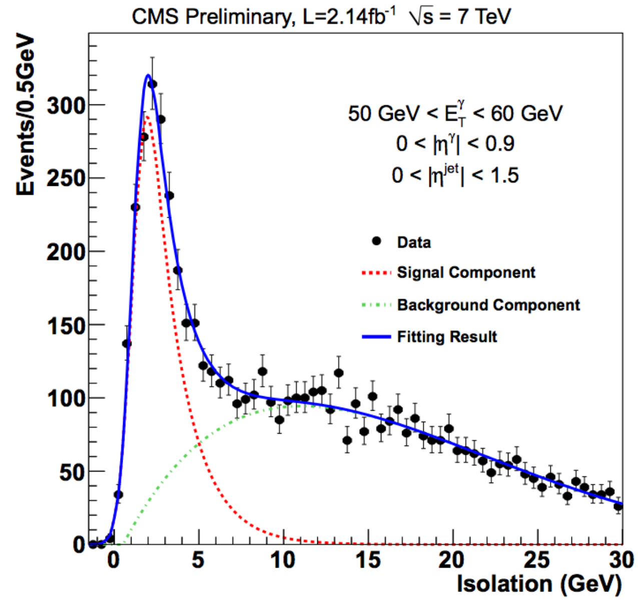
Photon + jet triple diff. cross section

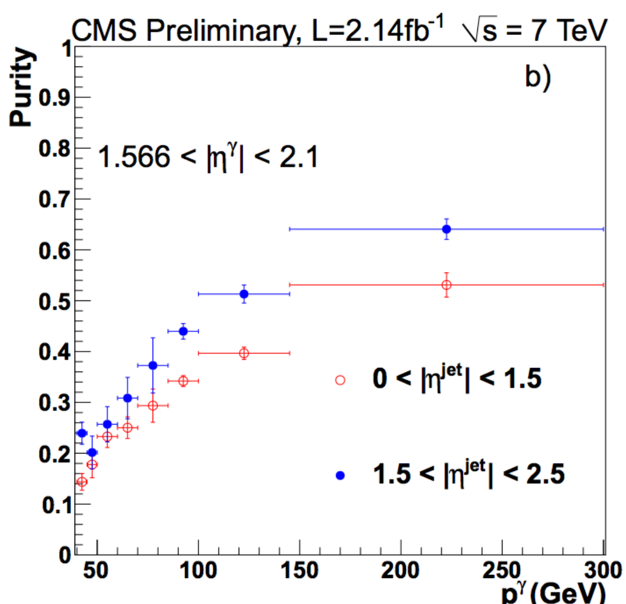
CMS-PAS-QCD-11-005

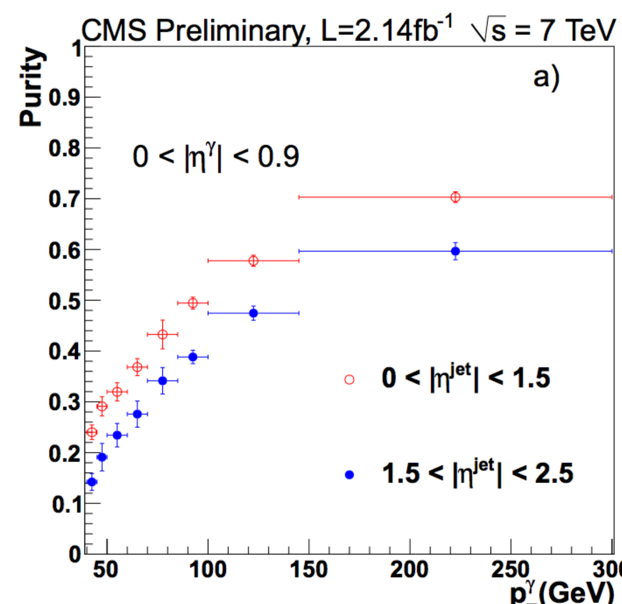
Photons selected in the **40-300 GeV range for |η| < 2.5, jet ET > 30 GeV with |η| < 2.5**, with 2.1/fb at 7 TeV

>20-70% purity for (not strictly isolated) photons at ~70-90% efficiency

~5-8% systematic uncertainty is dominant for cross section estimates near 100 GeV







Photon + jet triple diff. cross section

CMS-PAS-QCD-11-005

Comparison with JETPHOX 1.2.2:

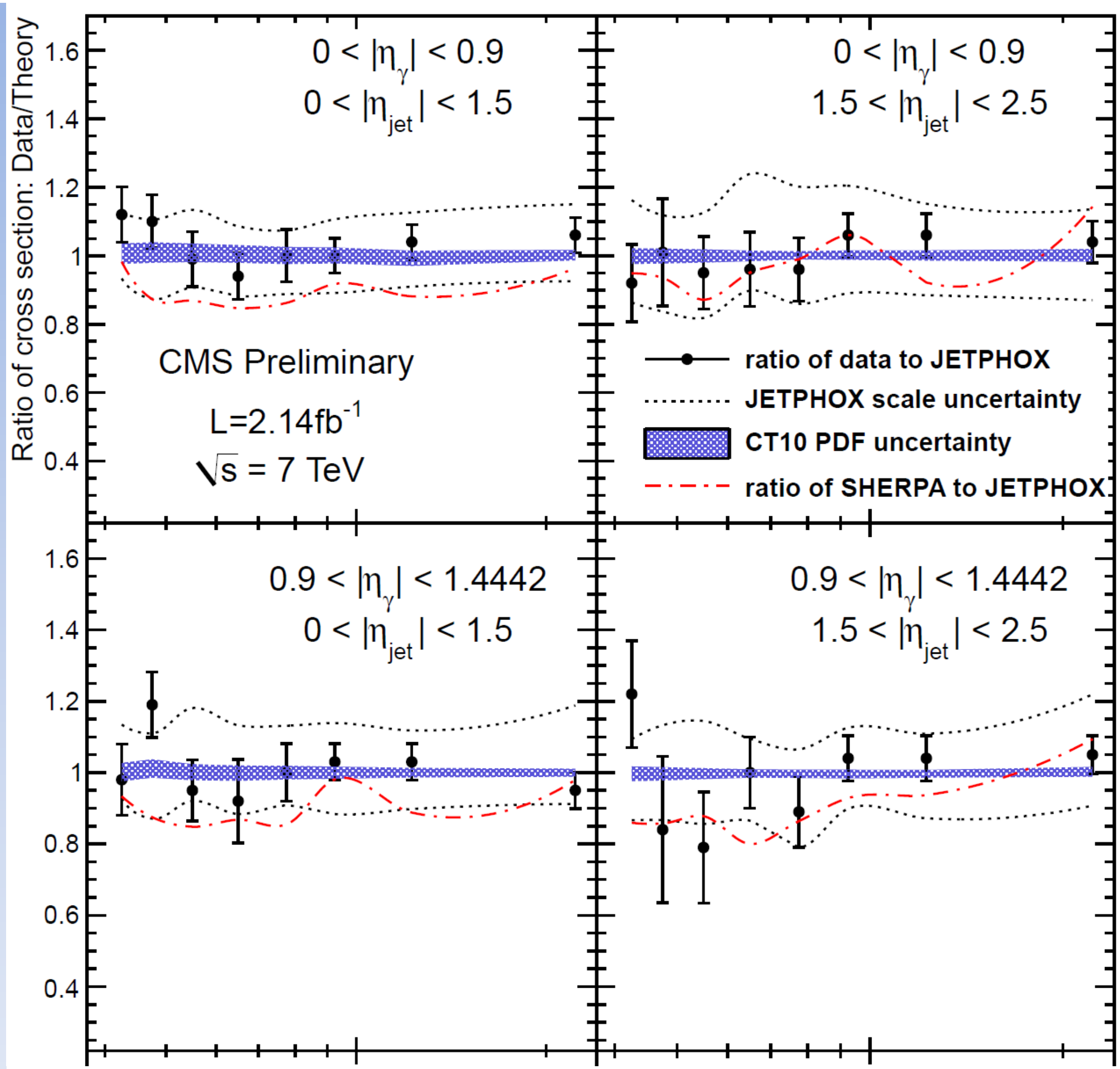
Shape and norm within 10-20% scale uncertainty band

Data ~2x more precise than NLO MC

Comparison with SHERPA 1.3.1 (up to 3 jets):

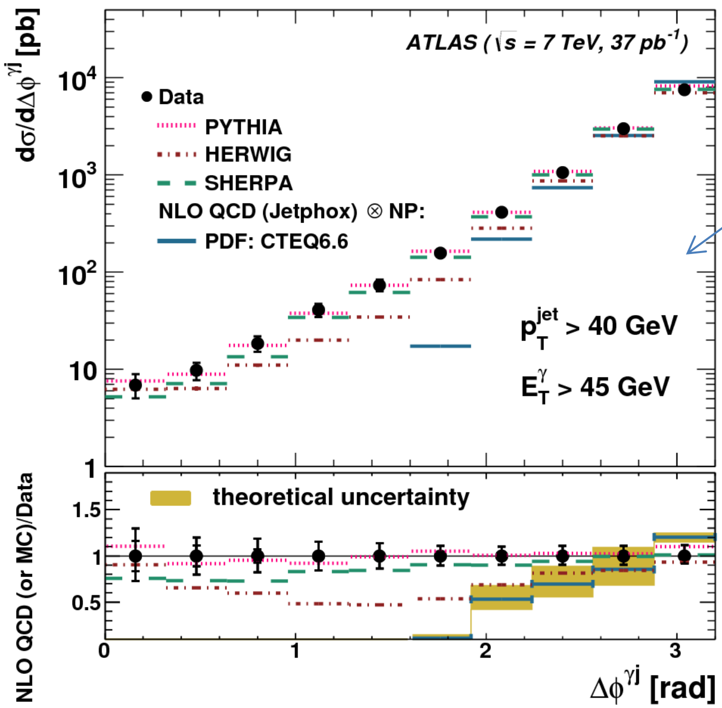
Similar level of agreement to JETPHOX

Prediction defined w.r.t. 5 GeV hadronic isolation in a cone of 0.4



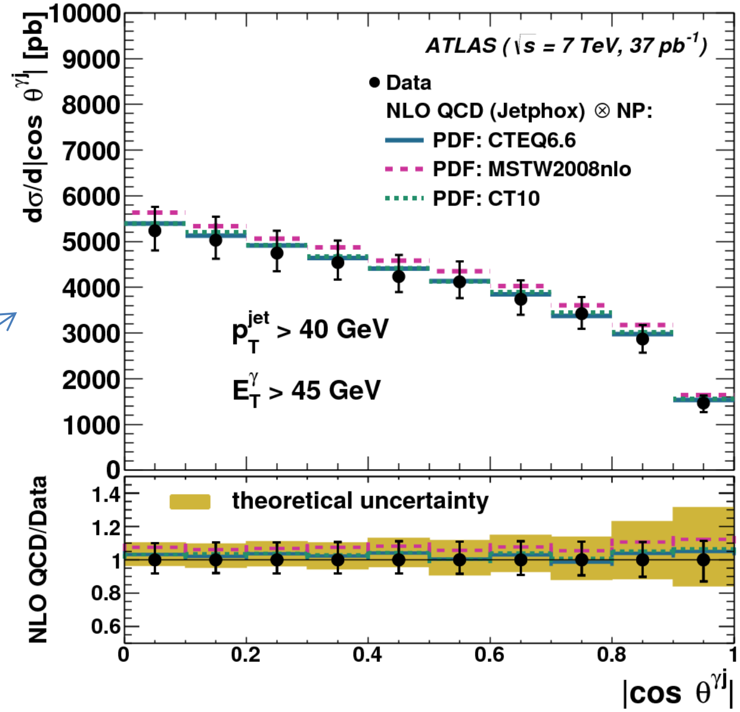
Photon+jet dynamics

arxiv:1307.6795



JETPHOX, HERWIG fail to describe shape of the $\Delta\phi < 2$ region at the 20% level

PYTHIA, SHERPA succeed



Cos θ, mass distributions are in good agreement

Photon+jets: Mini-prospectus

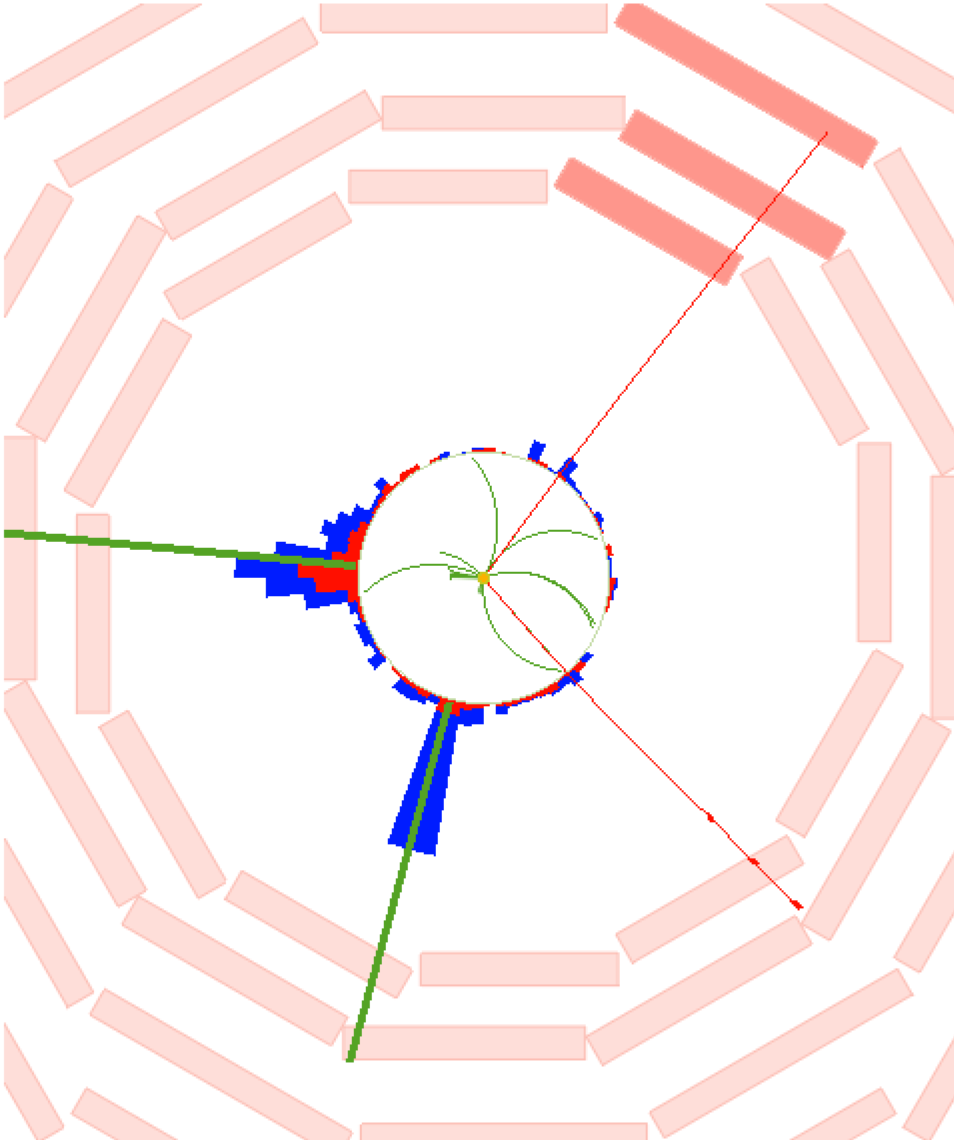
7 TeV conclusions: LO+PS and NLO are doing mostly OK at the 20% scale uncertainty level compared to the 7 TeV photon data. There are some exceptional phase space regions.

7 TeV data are at <10% precision so 2X theory improvements can be readily confronted (NLO+PS, NNLO?)

With 8 TeV data: TeV scale cross sections will ~double in precision to the 10% level, and extend differentially beyond 1 TeV

At lower scales multiply differential distributions can be more completely explored.

Unexplored so far at LHC:
Photon + multijet production
Photon + heavy flavor
Diphoton or V+photon + multijet
VBF photon, diphoton, or V+photon + 2 jet



W, Z plus Jets production

Z+jets diff. cross section

JHEP07(2013)032

~500k Z candidates selected in 4.6/fb at 7 TeV with >=1 AK4 jet with PT>30 GeV, |y| < 4.4; **up to 7 jets observed**

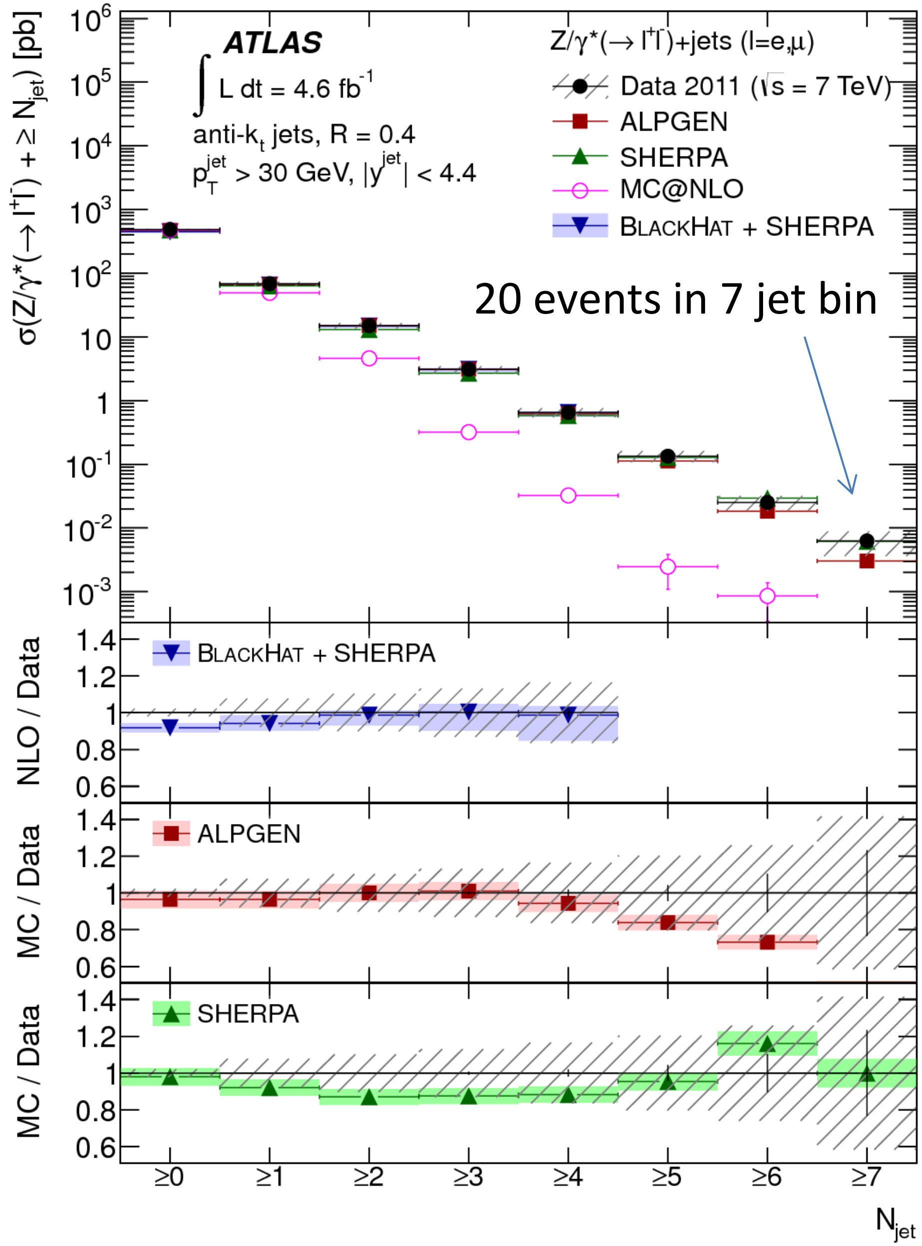
tt background at 20% level for 6 jets (est. from emu)

JES systematic uncertainty dominates (8% for N>=1, 20% for N>=4)

Scale uncertainty dominates NLO error (4-13% for N=1-4)

Data error is 2X NLO theory

NLO and LO+PS describe data well where applicable (N=4 and 5, resp.)



Z+jets diff. cross section

JHEP07(2013)032

Leading Jet PT probed in bins out to 700 GeV

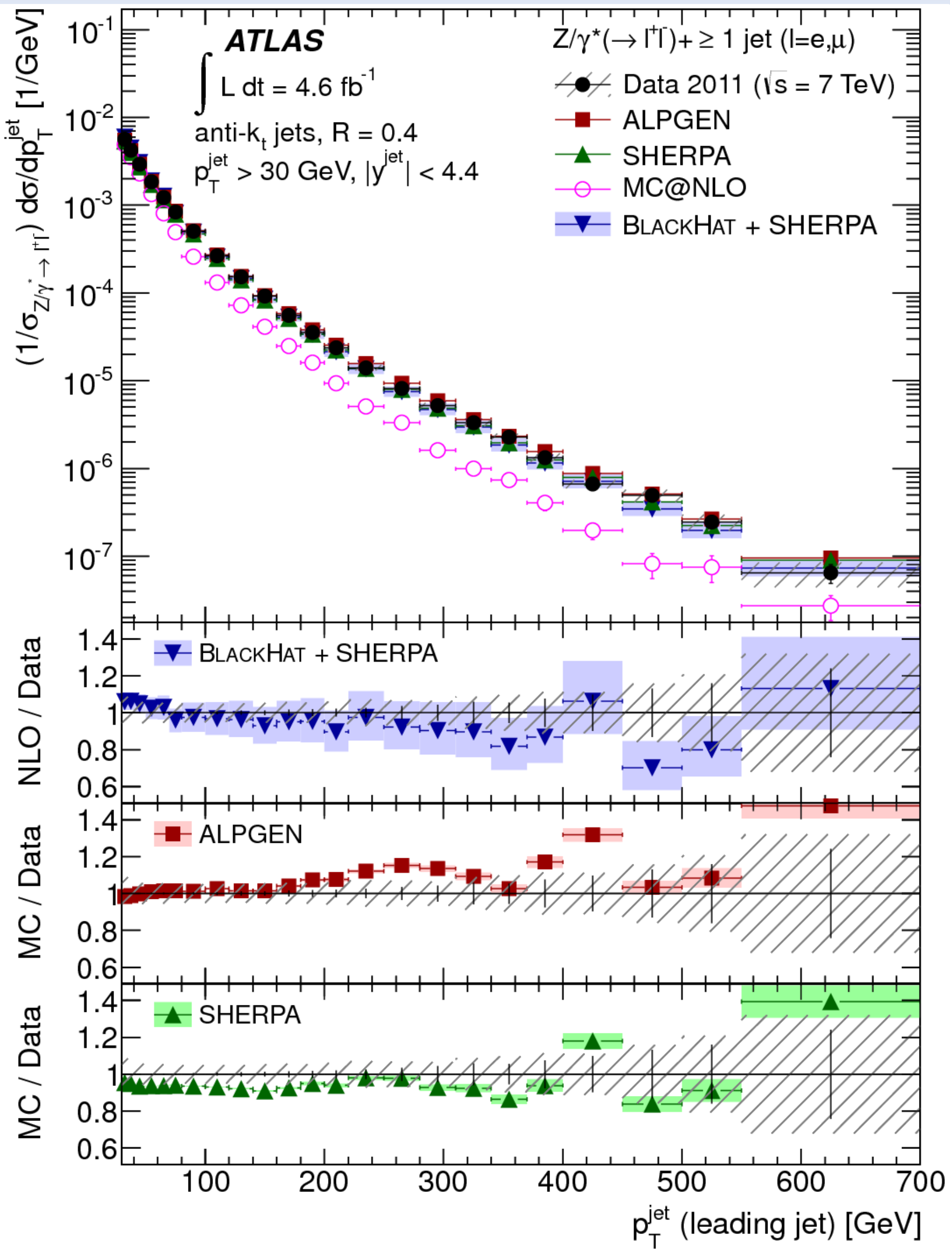
Data unc. < NLO MC unc. for PT>= 100 GeV

BlackHAT+Sherpa describe data well.

ALPGEN, SHERPA show 20% discrepancies

Insufficient generated partons leads to worse disagreement at higher PT (MC@NLO Z+1jet)

NLO EWK is also a factor at highest PT



Z+jets diff. cross section

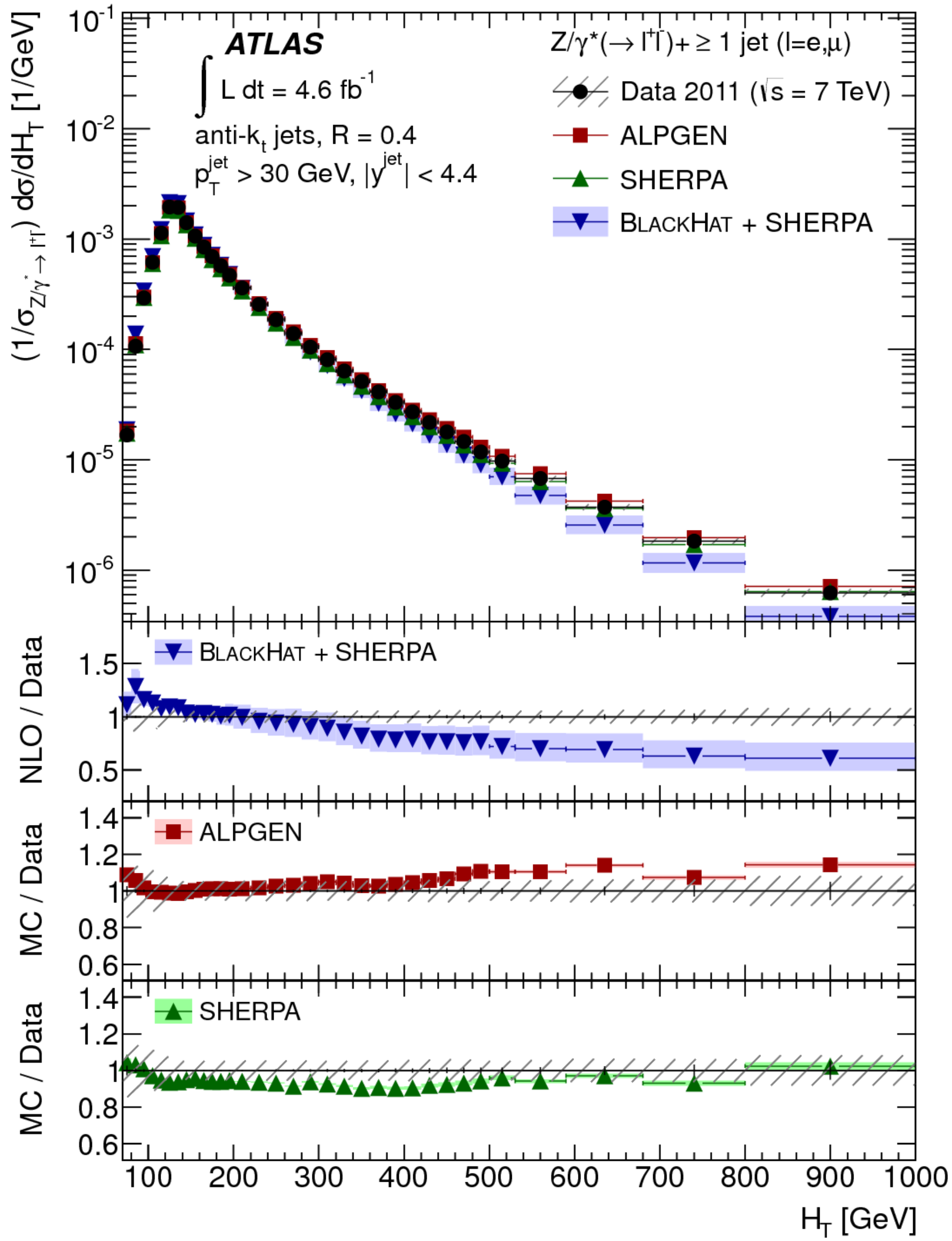
JHEP07(2013)032

BlackHat+Sherpa fails to describe HT shape.

LO+PS does a somewhat better job.

Which of the following would improve the prediction the most?:

More partons
NLO+PS
NLO EWK
NNLO QCD



Z+jets diff. cross section

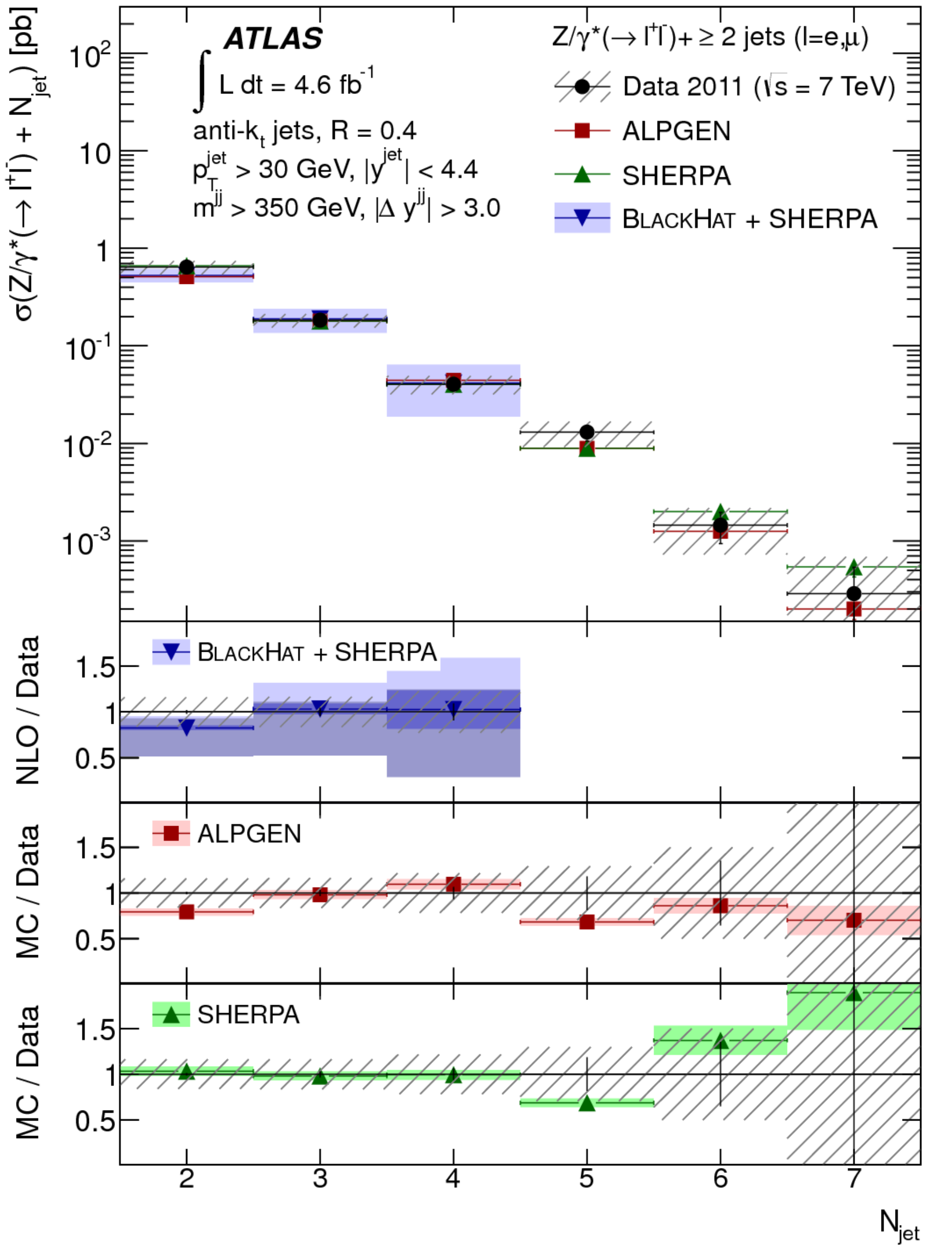
JHEP07(2013)032

Jet properties explored with **Two leading jets in a "VBF" configuration:**

Mjj > 350 GeV
|Δyjj| > 3

This is still predominantly QCD Z+2 jets, so a background study for future VBF Higgs and VBS analysis

NLO and LO+PS describe data well in this regime, at the 25-50% level.



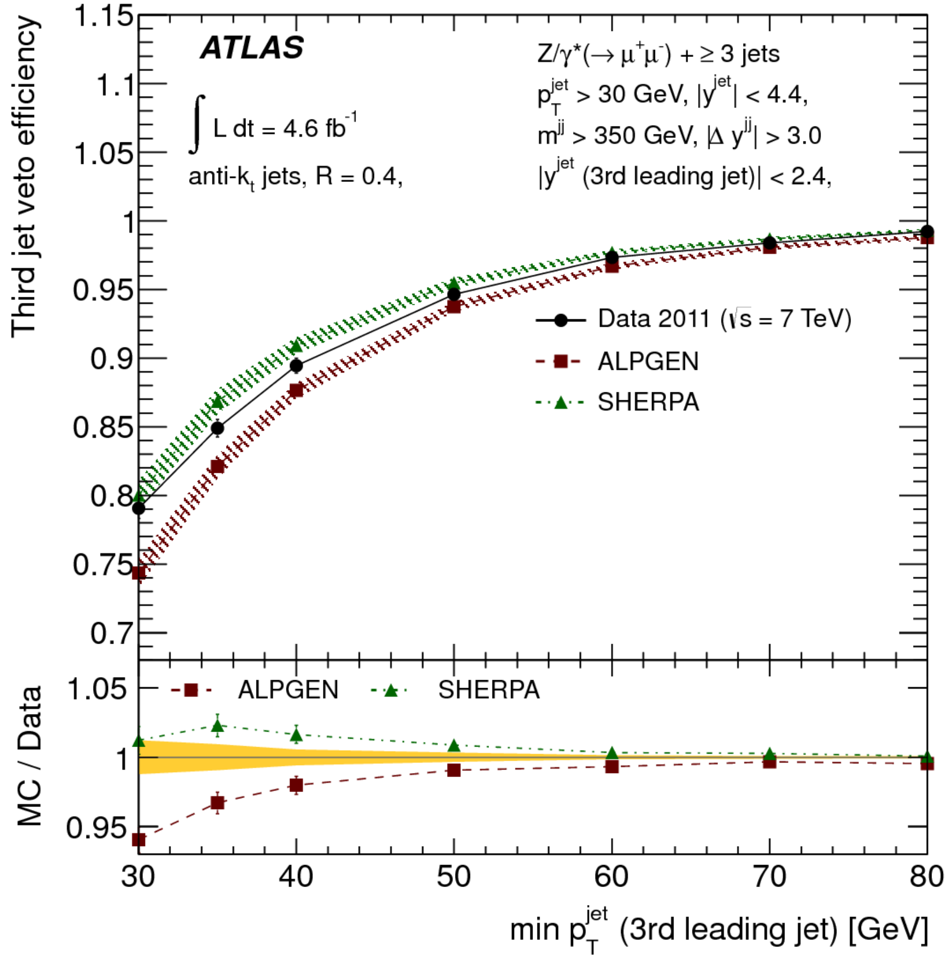
Z+jets diff. cross section

JHEP07(2013)032

Efficiency of 3rd central jet veto as a function of 3rd jet PT threshold for VBF Z+>=2 jet

20 (7)% inefficiency observed at 30 (50) GeV central jet threshold

Agrees with LO+PS at <5% level



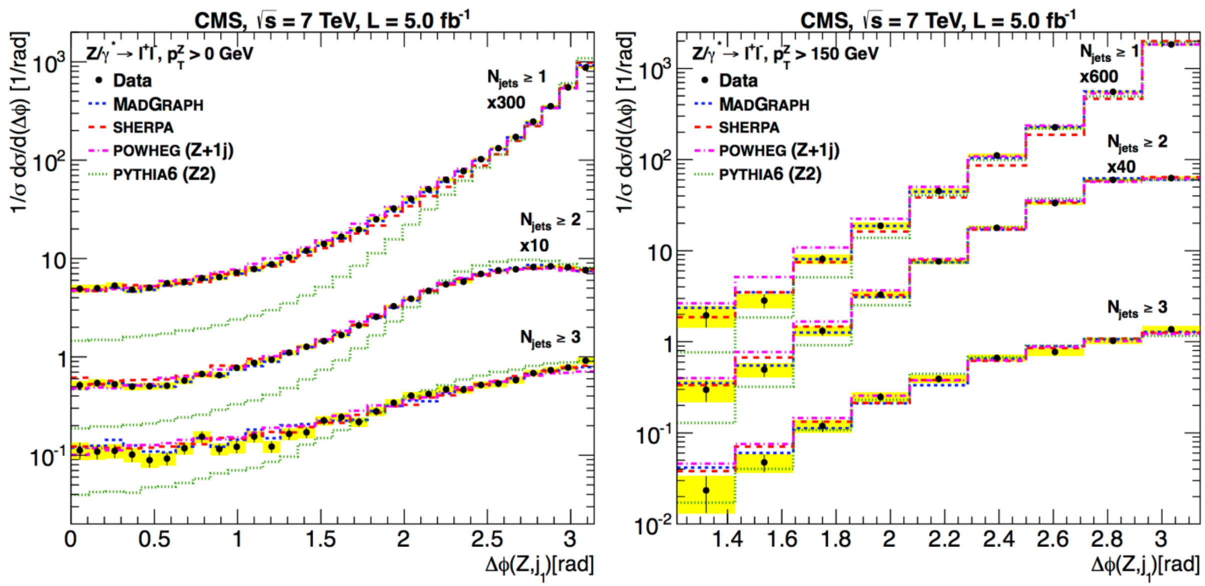
Z+jets event shape

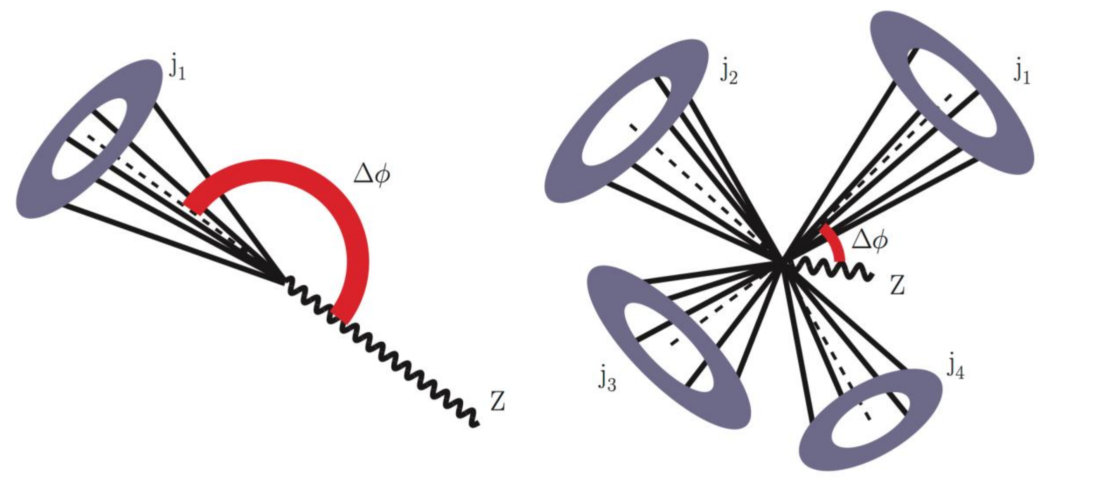
PLB 722(2013)238

With 5/fb at 7 TeV, azimuthal Z-jet and jet-jet angular shapes and transverse thrust explored, inclusively and for Z PT > 150 GeV

Madgraph, Sherpa describe data well at low and high ZPT for Njet >= 1-3

POWHEG, PYTHIA have too few partons and so have limited applicability



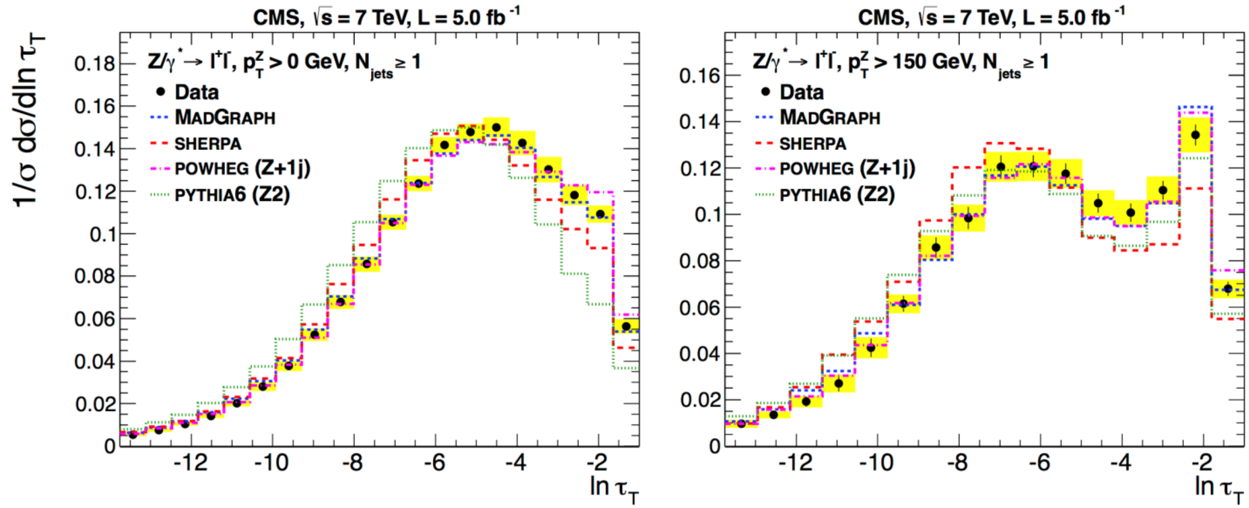


$\Delta\Phi \sim \pi$, ln $\tau T \sim -\infty$

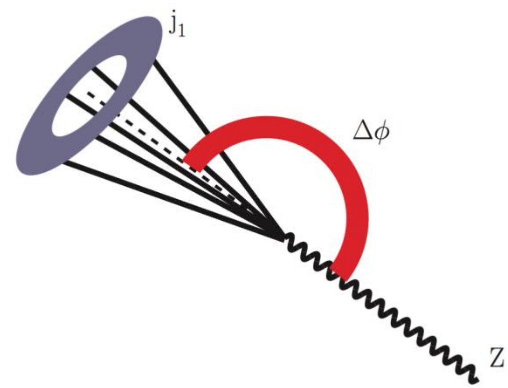
$\Delta\Phi << \pi$, ln $\tau T \sim -1$

Z+jets event shape

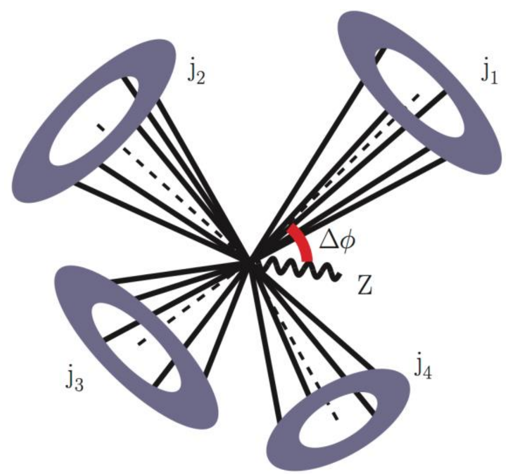
PLB 722(2013)238



Madgraph describes log transverse thrust well, Sherpa shows 10-20% discrepancies



$\Delta\Phi \sim \pi$, ln τT ~-∞



$\Delta\Phi \ll \pi$, ln τT ~-1

Z+=1 jet rapidity shape

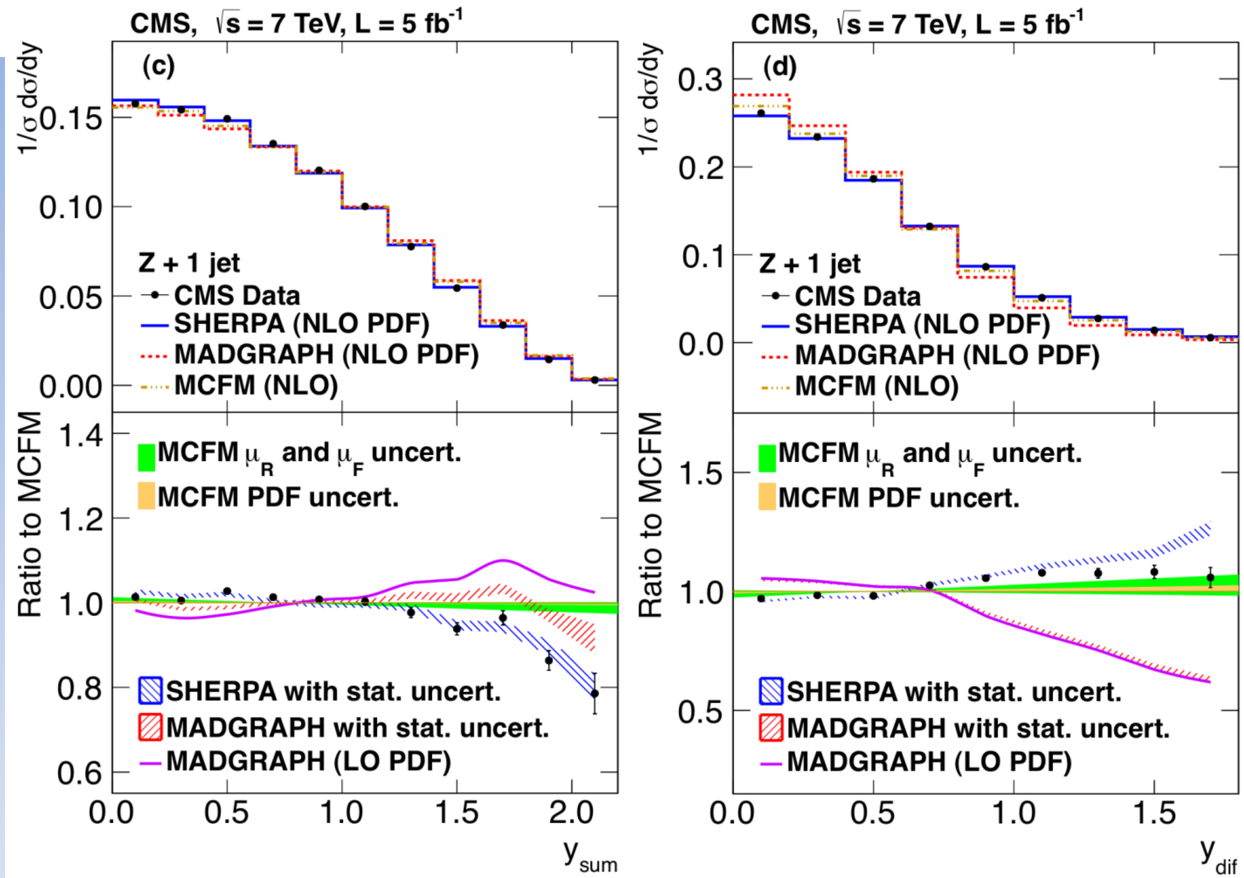
arxiv:1310.3082

yZ and yjet well described by LO+PS

BUT |yZ+yjet|/2 and |yZ-yjet|/2 exhibit large discrepancies at large values

SHERPA and Madgraph diverge from data in different directions. Attributed to parton-shower matching differences.

MCFM somewhat better in yDIF but still with poor Sherpa-like ySUM



W+jets diff. cross section

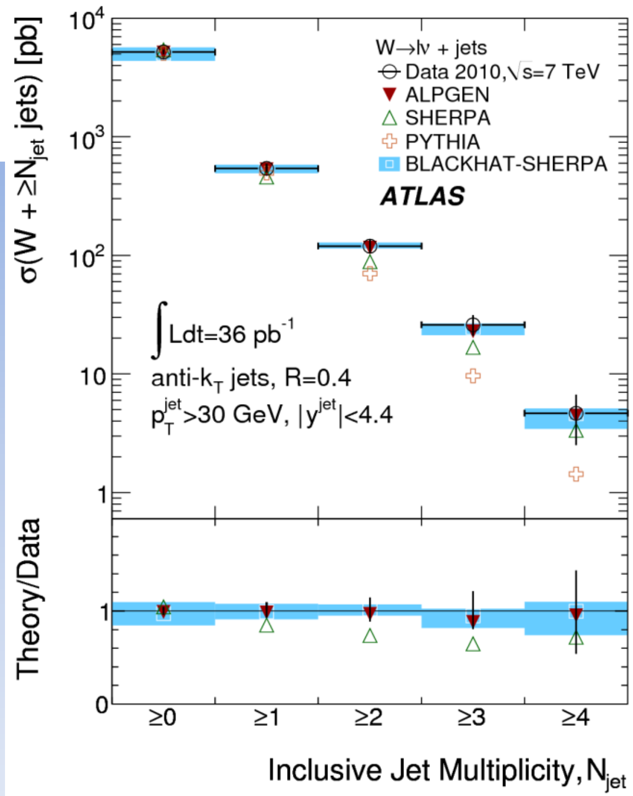
[PRD85(2012)092002](PRD85(2012)092002)

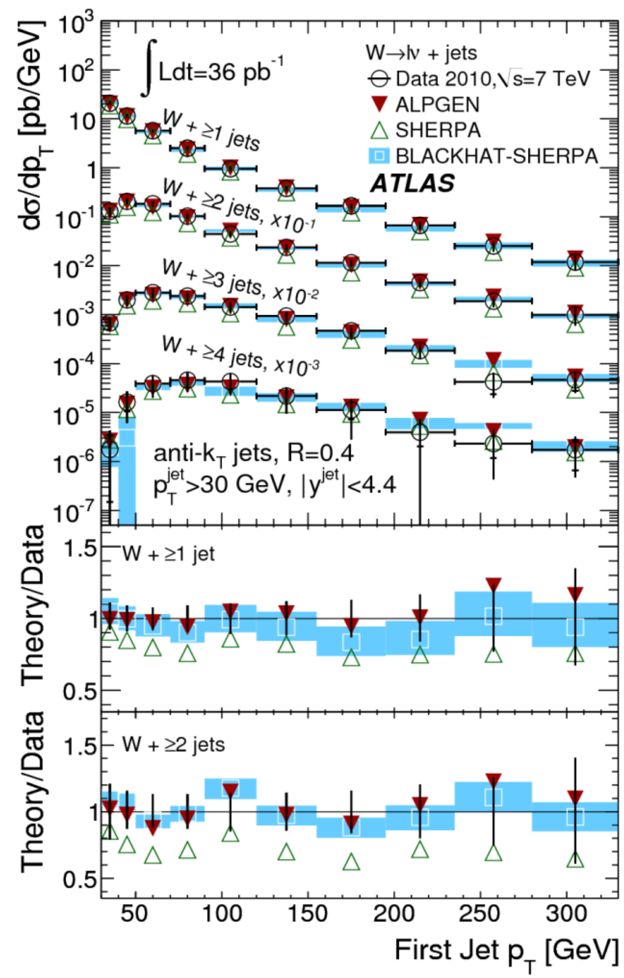
W+light jets only examined in 2010 data thus far.

Similar level of agreement to Z+jets

Larger (tt) backgrounds at high Njet

Larger comparable reach in leading jet PT and HT





Towards VBF/VBS: VBF Z production

Purely electroweak Z + 2 jets (interfering)

Comprehensive study of Z+forward dijet production at 7 and 8 TeV.

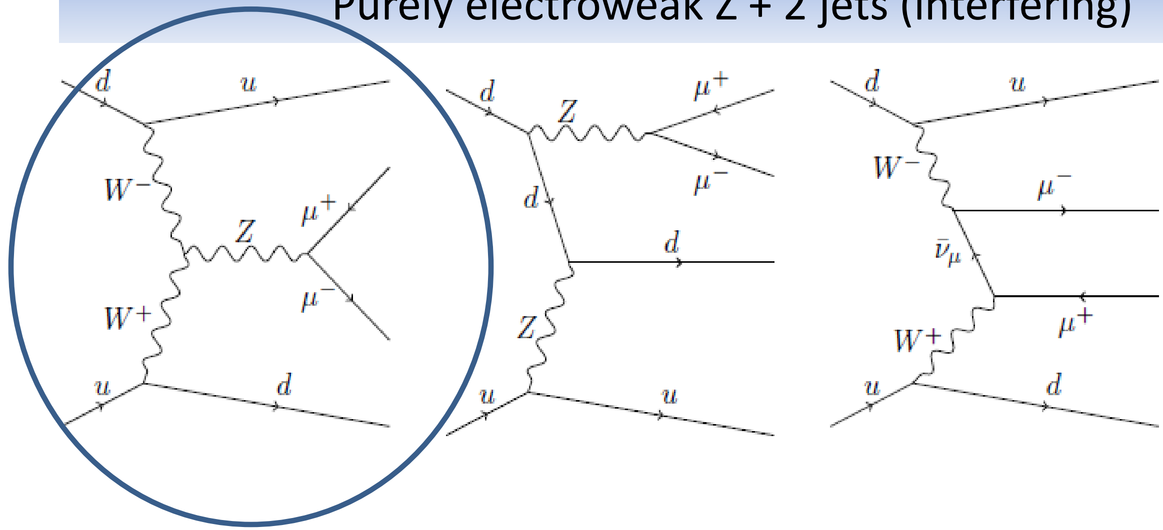
VBF Z one of the interfering amplitudes

Z+2jet events selected with "VBF topology": large dijet mass, large dijet Δy

Small S/B enhanced with BDT selection exploiting all Z+2jet kinematics

5 sigma signal for electroweak Z+jet production observed, fully consistent with SM

TGC potential under study

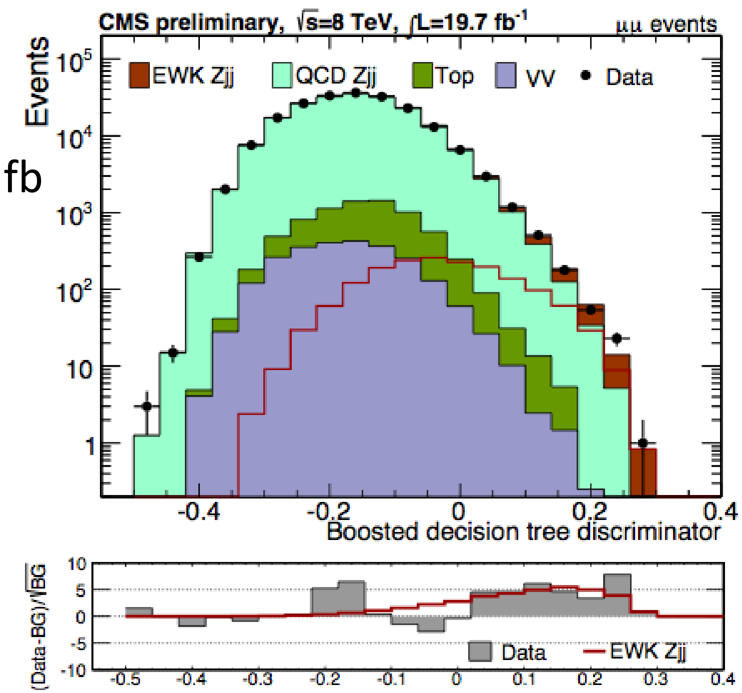


σEWK = 226 ± 26 stat ± 35 syst fb

σVBFNLO = 239 fb

CMS-PAS-FSQ-12-035

JHEP10(2013)101



Towards VBF/VBS: VBF Z production

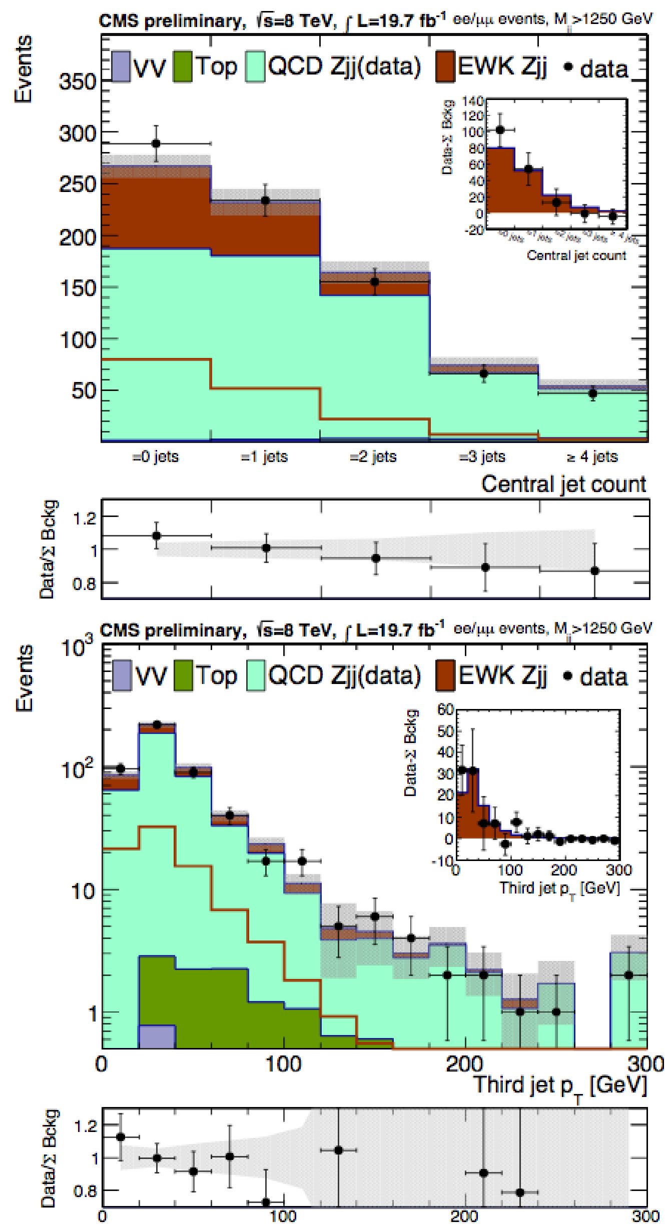
CMS-PAS-FSQ-12-035

JHEP10(2013)101

Multijet properties explored in EWK-enriched subsample (Mjj > 1250 GeV)

Madgraph w/K factor describes central jet multiplicity well

Third jet PT also well described.



W,Z+jets: Mini-prospectus

7 TeV conclusions: LO+PS and NLO are doing mostly OK at the 10-20% scale uncertainty level compared to the 7 TeV data. There are some exceptional phase space regions, especially in angular patterns of radiation and high HT. Data precision leads theory precision at highest PT.

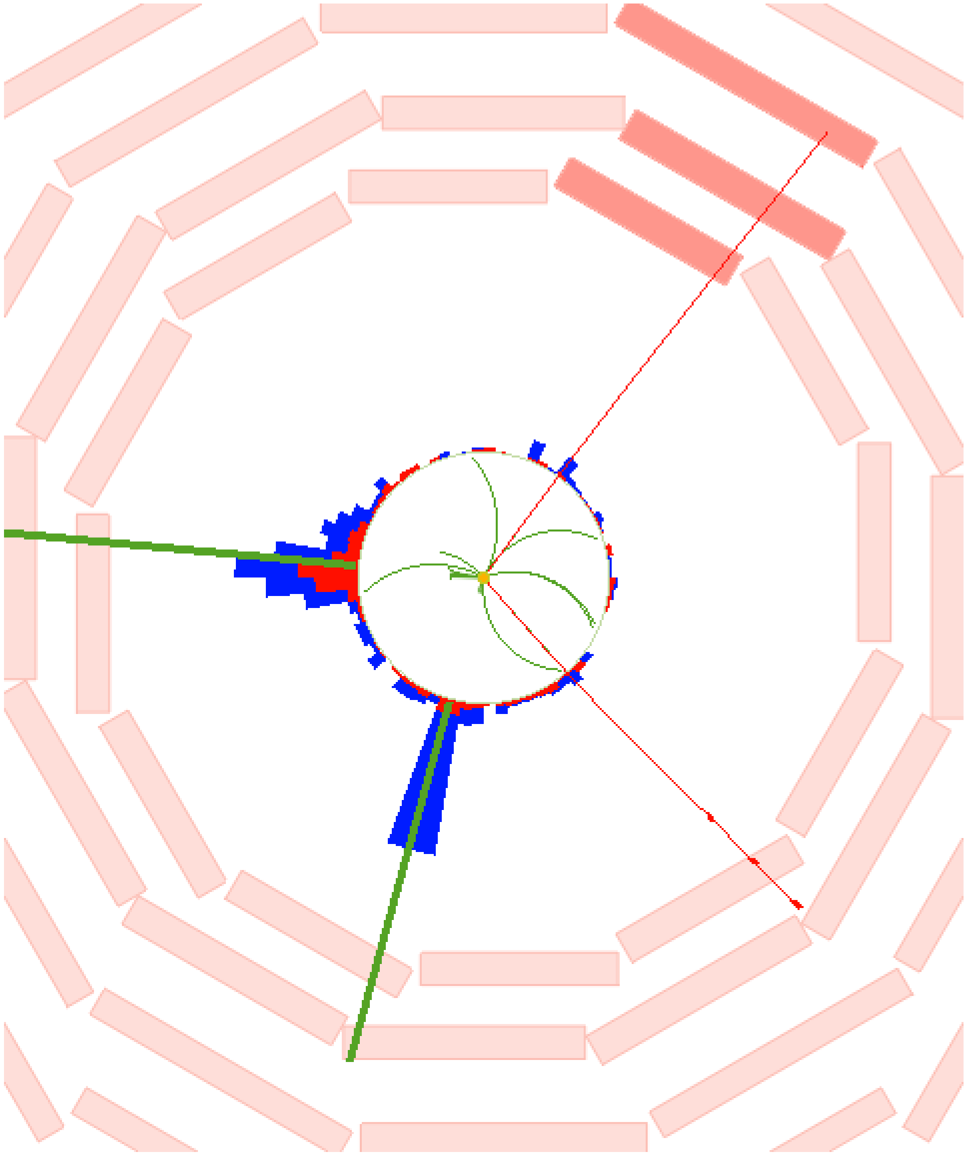
VBF-like V+2 jet production is now a detailed topic of study in its own right

With 8 TeV data: Close to probing TeV PT scale and very large jet multiplicities (8 or more)

At lower scales multiply differential distributions can be more completely explored.

NLO+PS and NLO EWK effects can be tested.

W+jets has been neglected but has stronger sensitivity to high PT/VBF phenomena.



W, Z plus Heavy Flavor production

Z+b, bb production

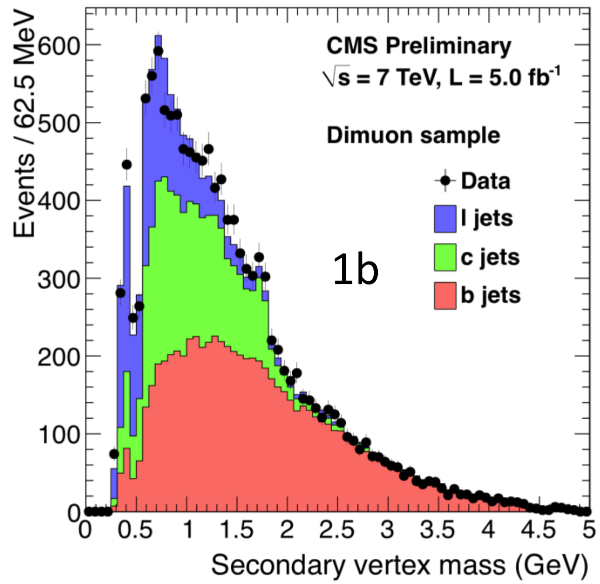
CMS-PAS-SMP-13-004

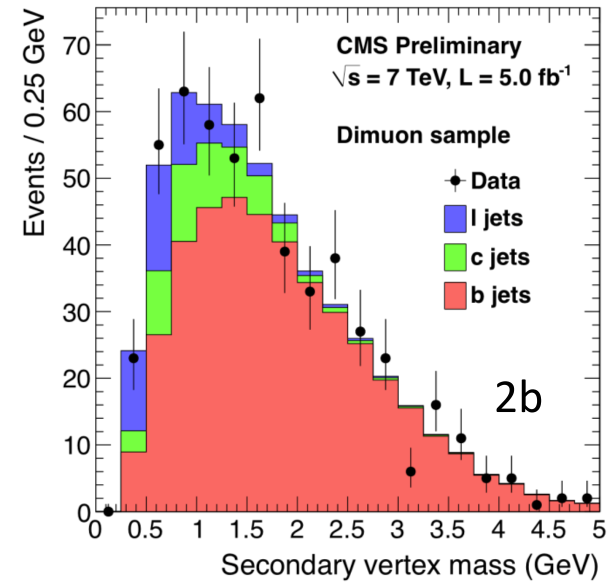
12k Z+1 b-tag and
500 Z+2 b-tag events
expected in 5/fb at 7 TeV.

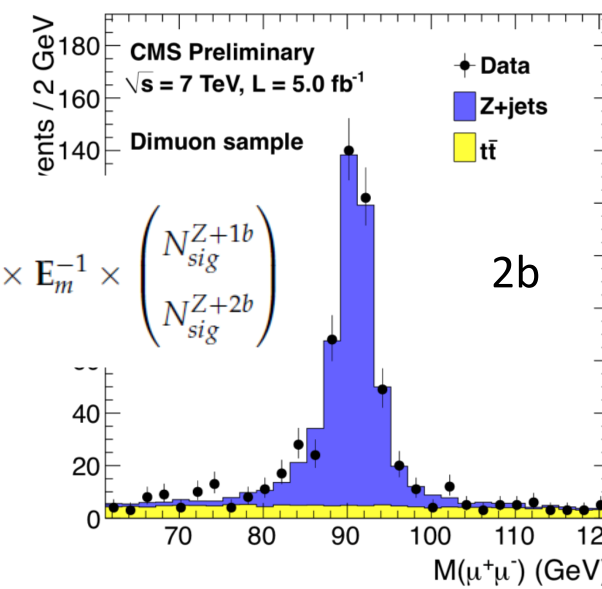
tt suppressed by Z mass and MET significance cut, Z+light/charm jets rejected by large secondary vertex mass (MSV).

Z+b (bb) extracted from 1D (2D) template fit to MSV (MSV1, MSV2)

Exclusive 1,2-tag cross section estimated after N-tag-wise unfolding of MET, lepton, JES, and b-tag response







$$\begin{pmatrix}\sigma(Z+1b)\\ \sigma(Z+2b)\end{pmatrix} = \frac{1}{\mathcal{L}} \times \mathrm{E}_r^{-1} \times \mathrm{E}_l^{-1} \times \mathrm{E}_b^{-1} \times \mathrm{E}_m^{-1} \times \begin{pmatrix}N_{sig}^{Z+1b}\\ N_{sig}^{Z+2b}\end{pmatrix}$$

Z+b, bb production

CMS-PAS-SMP-13-004

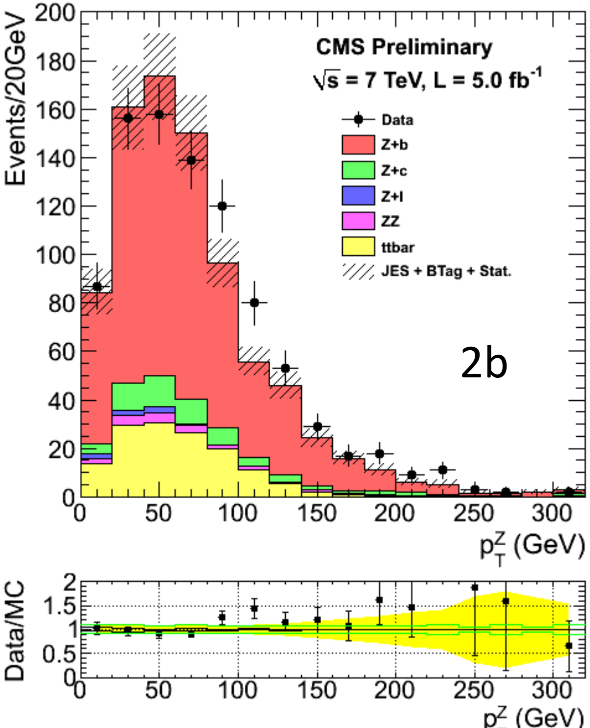
Exclusive cross sections agree with MadGraph 4F and 5F predictions.

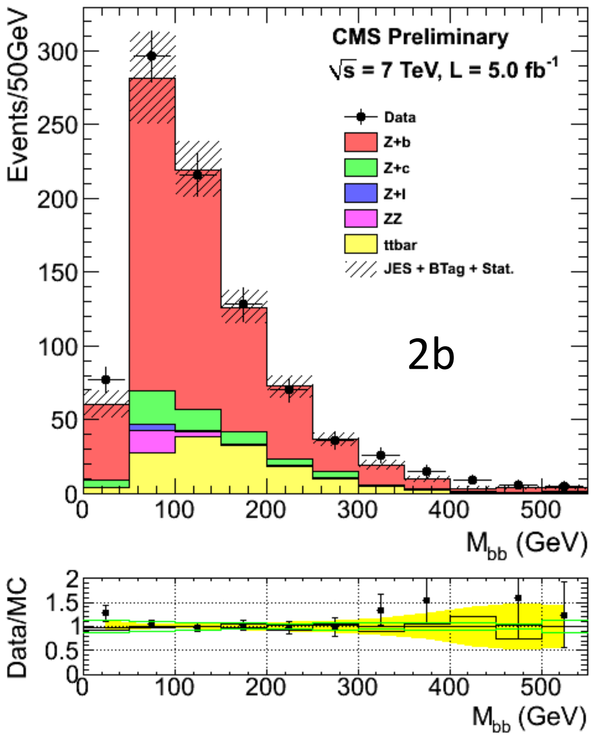
B-tag efficiency and mistag uncertainty dominate total cross sections

Z PT in 2b case is somewhat harder than MadGraph.

Mbb and other variables in good agreement

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





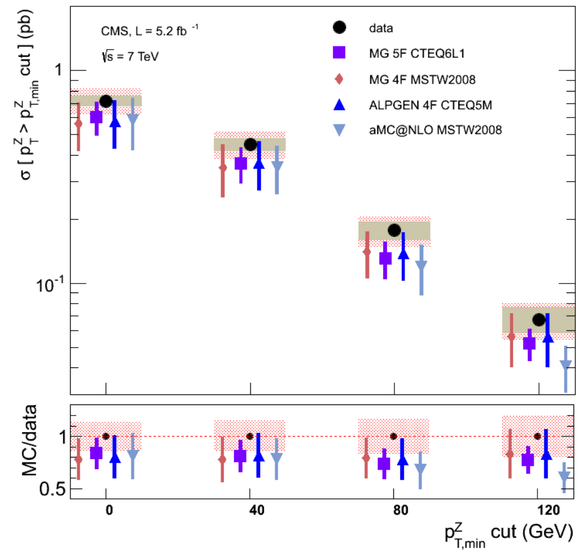
Z+BB hadrons cross section

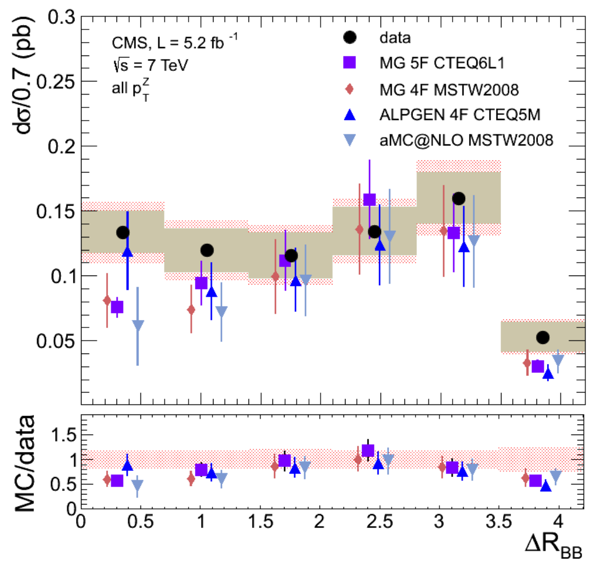
arxiv:1310.1349

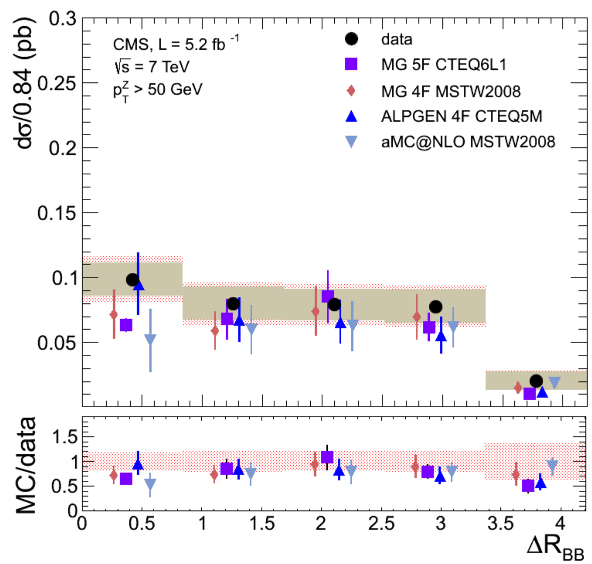
Using a tracker-driven inclusive vertex reconstruction technique, B-hadron pairs can be identified with excellent angular resolution→can explore **very collinear production from e.g. gluon splitting**.

Total cross sections predicted by MadGraph 4F/5F, ALPGEN, aMC@NLO about 15% low, worse at high ZPT.

Madgraph, aMC@NLO underpredicting lowest ΔR







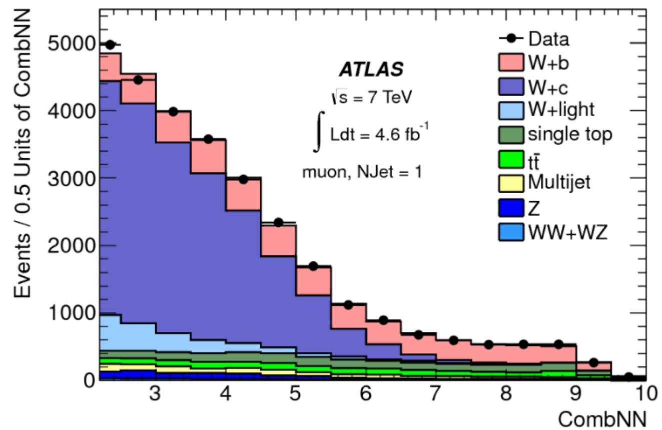
W+b cross section

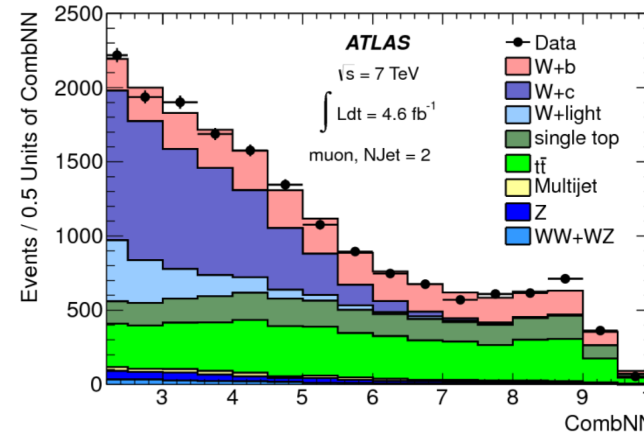
JHEP06(2013)084

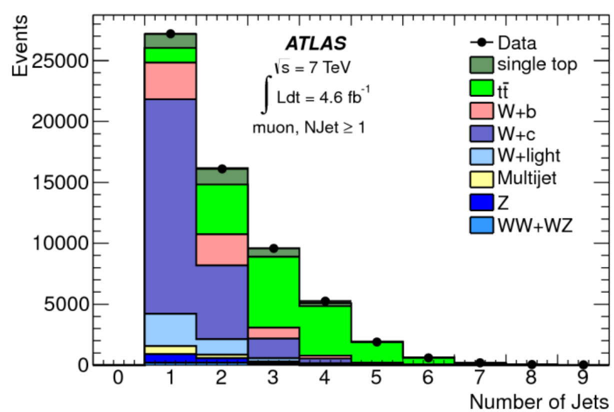
W candidates with =1 or 2 jets and = 1 b-tag selected from 4.6/fb at 7 TeV

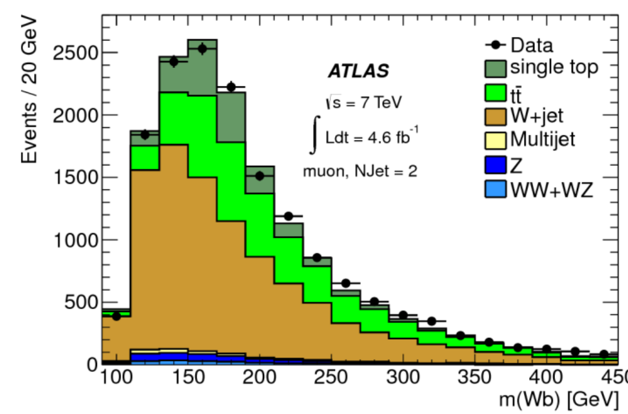
Two different taggers with complementary info combined into an ANN discriminant against light/charm jets. 40-60% of tags retained for signal extraction via MLH template fit of ANN.

tt contribution constrained by 4-jet 1-tag sample; single top constrained by m(Wb) distribution









W+b cross section

JHEP06(2013)084

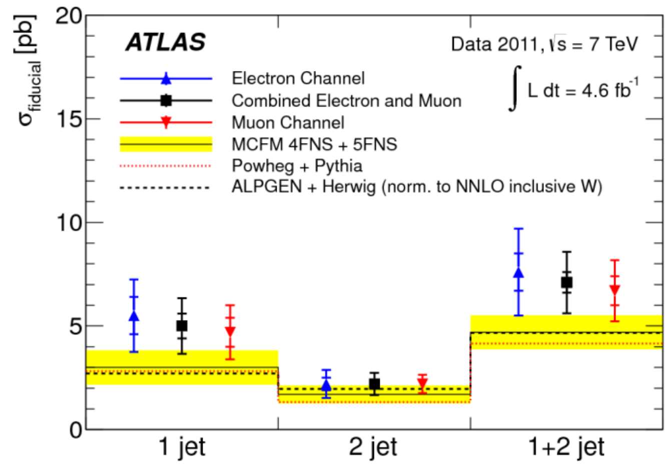
Exclusive cross sections measured to 20% precision (dominated by JES syst.)

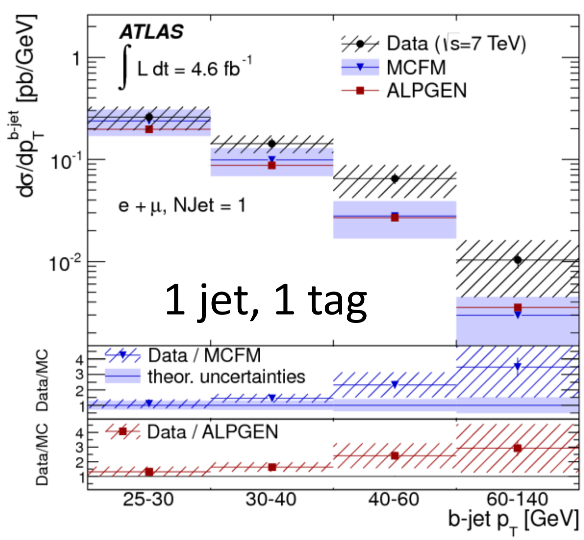
W+b + single top results also presented

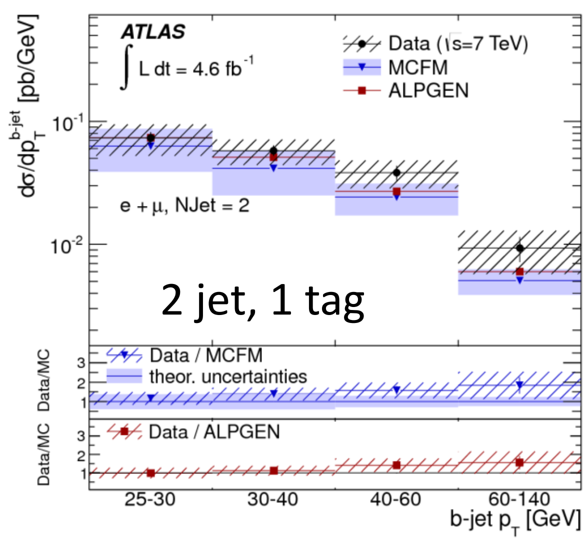
MCFM NLO and LO+PS predictions consistent with data at 1.5σ

Data and MC precision comparable

Diff. b PT cross sections a bit harder than MCFM/ALPGEN







W+bb cross section

CMS-PAS-SMP-12-026

W candidates with =2 jets and =2 btags selected from 5/fb at 7 TeV

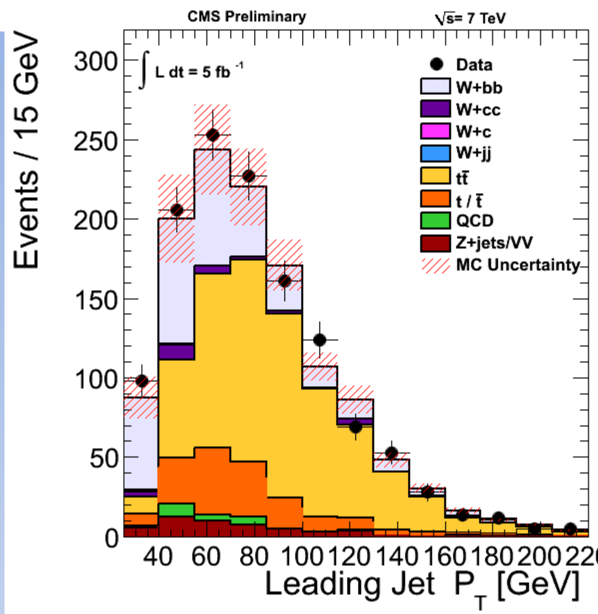
W+c,cc reduced by combined cut on the MSV of the two b-tags

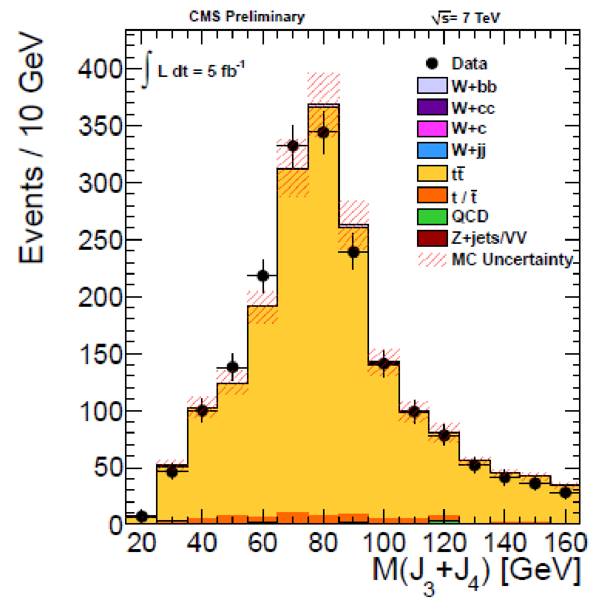
tt normalized by =4jet,2-tag sample

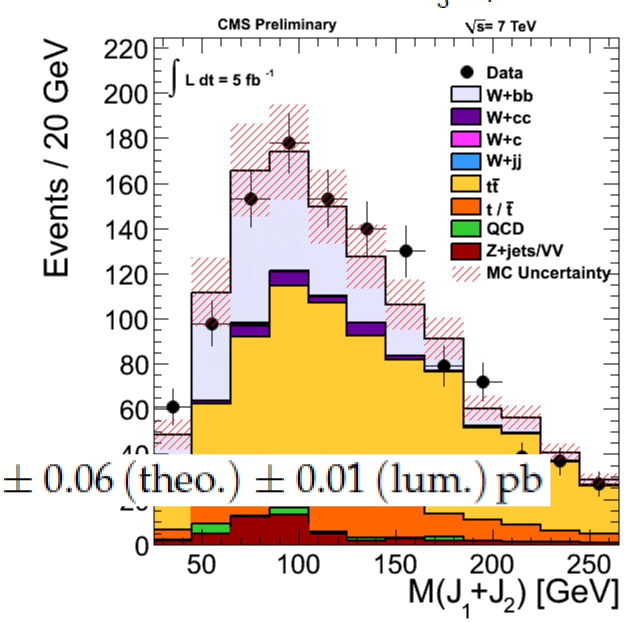
Remaining top discrimination from leading jet PT templates.

MCFM in good agreement with measured cross section.

MadGraph agrees with Mbb distribution







MCFM

$0.52 \pm 0.03\,\mathrm{pb}$

CMS data

$0.53 \pm 0.05\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.06\,(\mathrm{theo.}) \pm 0.01\,(\mathrm{lum.})\,\mathrm{pb}$

W+charm cross section

arXiv:1310.1138

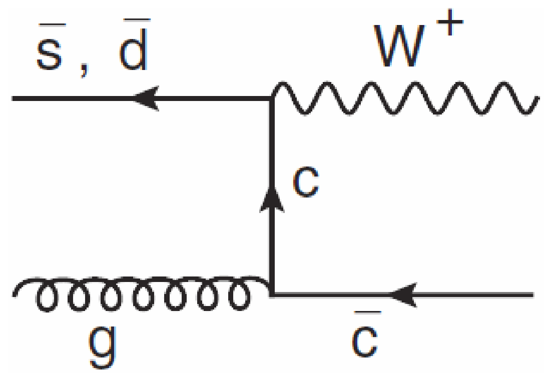
Leading order W+c directly probes **strange quark PDF**

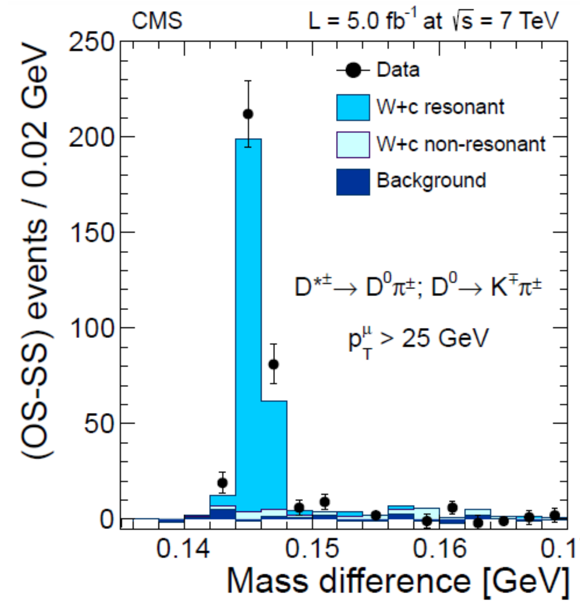
Strange and anti-strange probed independently by W+, W-

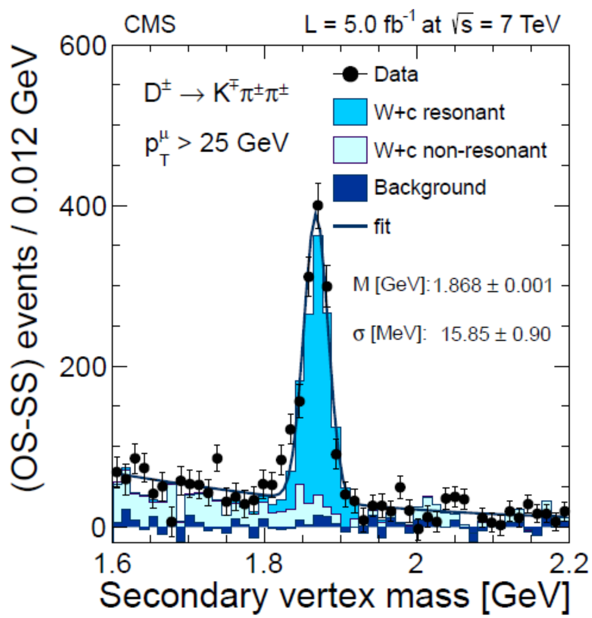
W and c are opposite sign

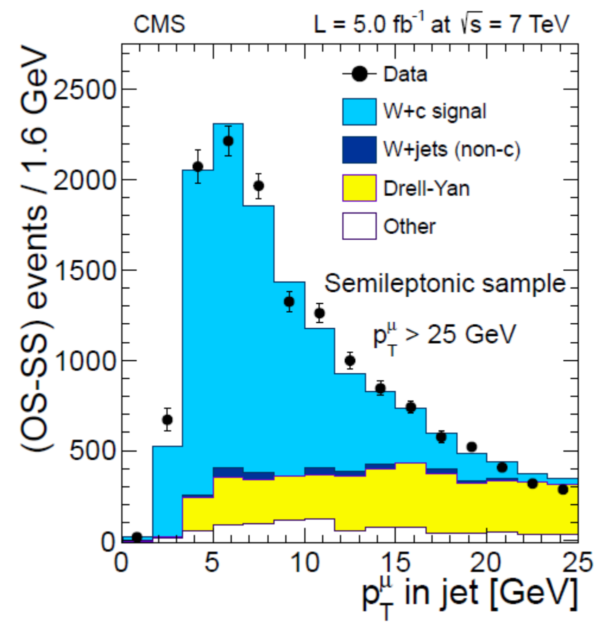
Higher-order W+cc, W+bb, top are **same-sign/opposite-sign symmetric**→subtract with same-sign data

(semi-)exclusive **charm hadron reconstruction** gives high-purity, self-charge-tagged W+c samples





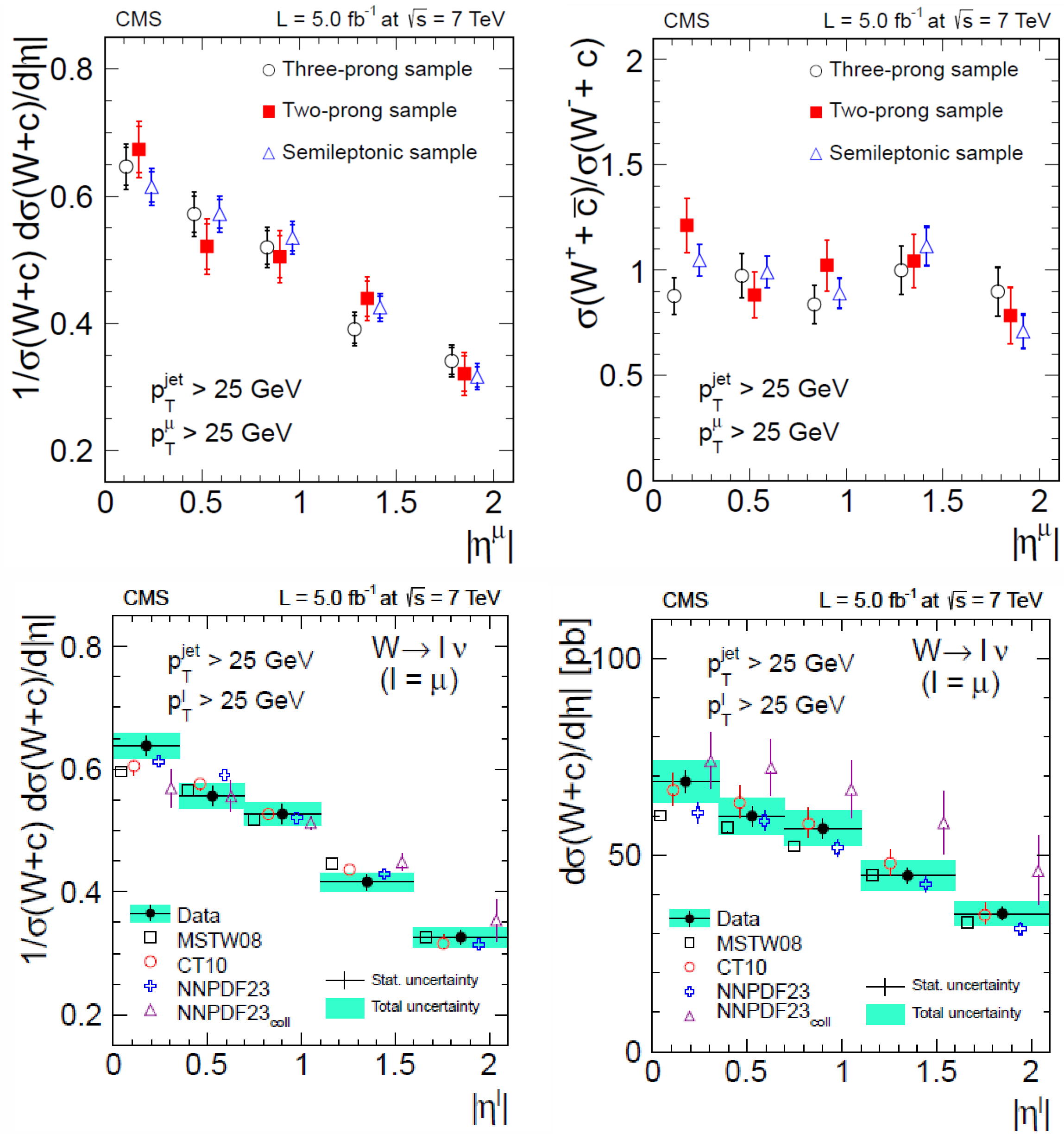




W+charm cross section

arXiv:1310.1138

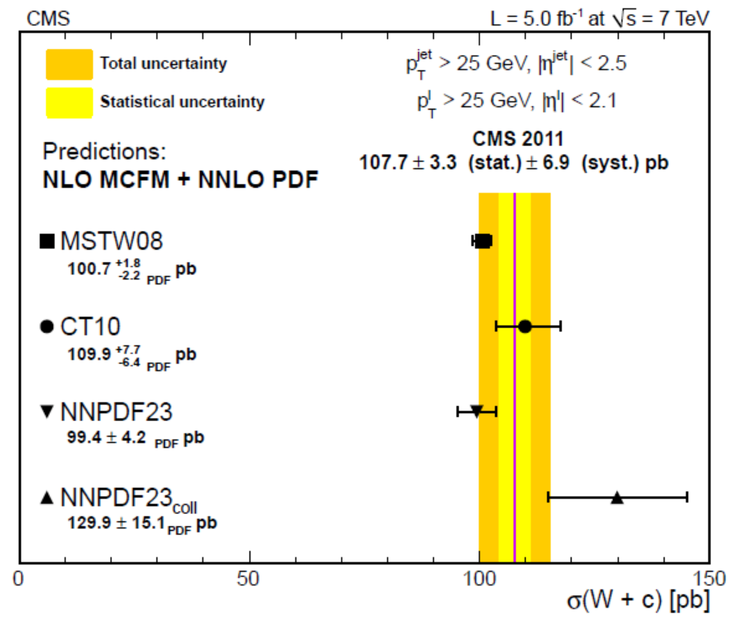
- Measure cross section and charged ratio vs lepton |η|
- Consistent across three different hadron reco methods
- Leading syst. are JES, charm branching fractions
- Consistent with NLO MCFM predictions

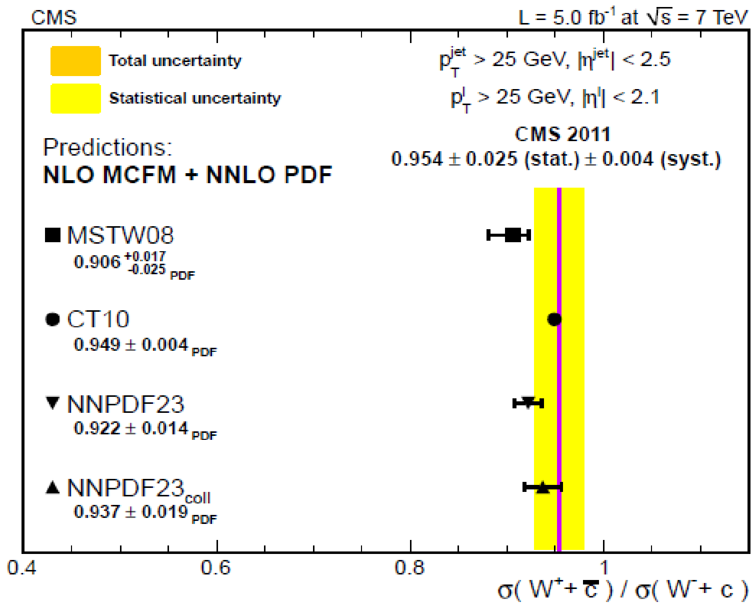


W+charm cross section

arXiv:1310.1138

- Data consistent with strange content of pre-LHC PDFs (neutrino fixed-target), approaching good precision
- Data consistent with charge symmetric strange PDF





W+charm hadron cross section

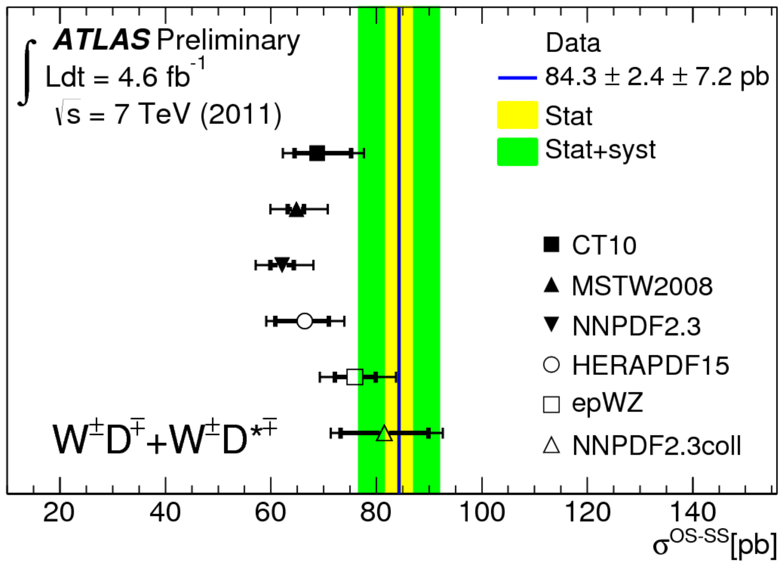
ATLAS has a very similar analysis with somewhat different selected phase space and cross section definitions.

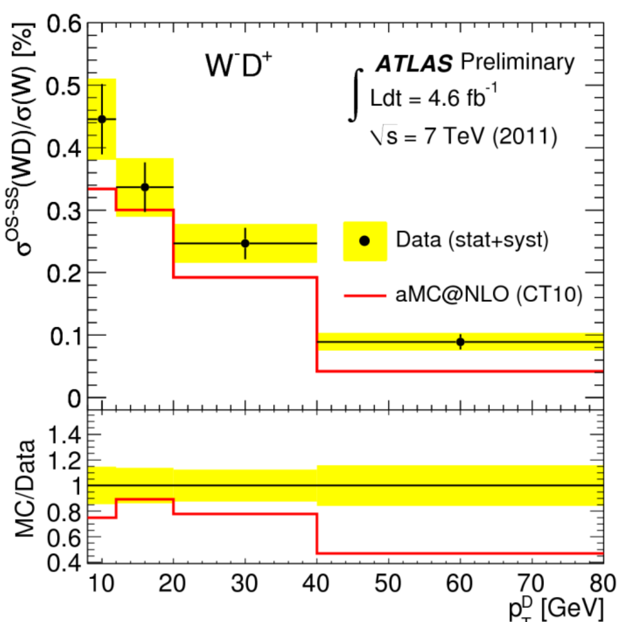
Cross sections measured for charm hadrons, not partons

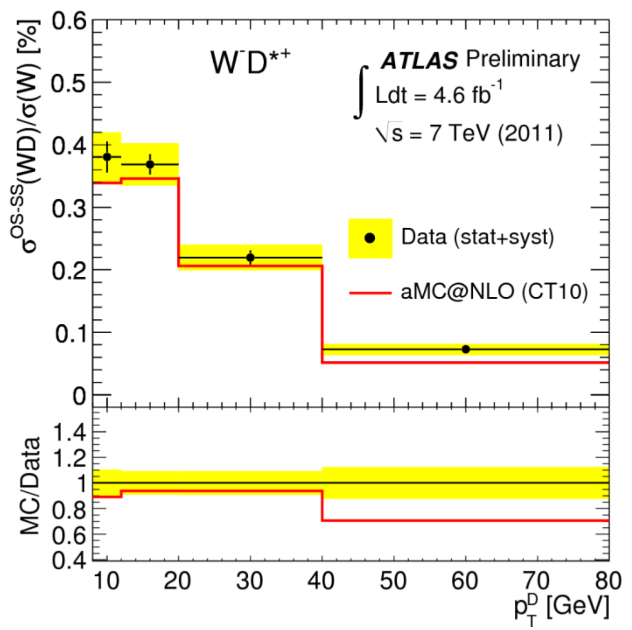
Compared with aMC@NLO:
Minimum PT(D) > 8 GeV, |ηD|<2.2
PTl > 25 GeV, MET>25 GeV, MT> 40 GeV

Favors somewhat higher s-sea

Measures also PTD diff. cross section as well as η(lepton)

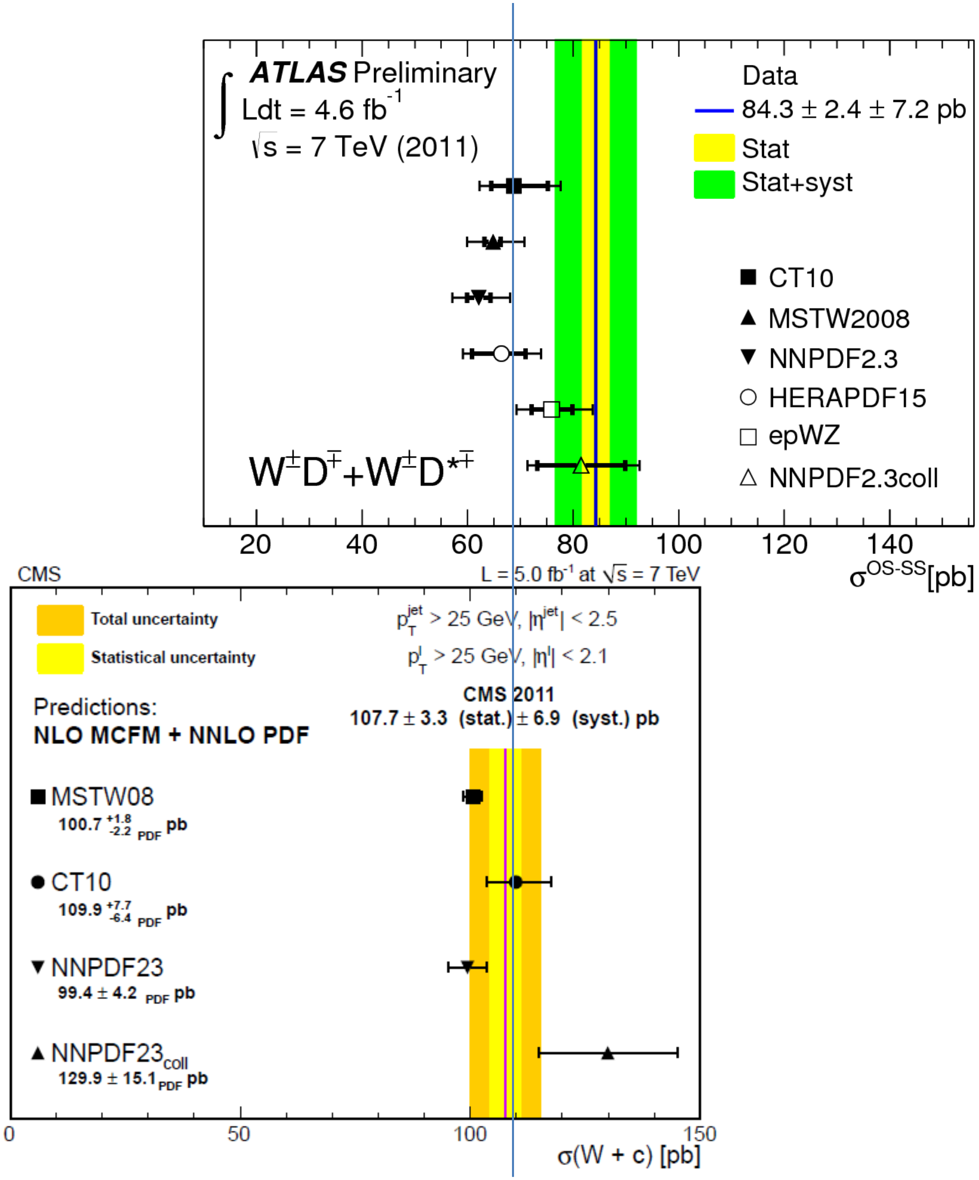






W+charm hadron cross section

CMS-ATLAS difference is between 1-2 sigma, roughly, since CMS ~ CT10 with similar error.



W,Z+heavy flavor: Mini-prospectus

7 TeV conclusions: LO+PS and NLO are doing mostly OK at the 20% scale uncertainty level compared to the 7 TeV data. There are some exceptional phase space regions. Interesting sensitivity to sea quark PDFs.

With 8 TeV data: differential cross sections to be explored in more detail and in regions more relevant for Higgs/searches

Unexplored so far at LHC:
Z+c(cc)
W+cc
Z+b angular distributions
Comprehensive W+Njet+Mtags

Summary

- V+jets production measurement has been explored in most all relevant areas with the 7 TeV data. But almost no 8 TeV results available yet!
- NLO and LO+PS are successfully describing the data at the advertised level of accuracy in a wide variety of situations. But there are exceptional distributions everywhere. Can the next generation of predictions resolve those exceptions?
- V+jets is not the only precision laboratory for multijet QCD going forward. Also look at jet dynamics:
  - In VV and VBF, relevant for precision Higgs physics
  - In phase space relevant for high PT searches