W, Z, and photon production at the LHC

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PIC 2014 Indiana
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130th Anniversary in 2011

The Large Hadron Collider

- Completed in 2008, CERN, Geneva
- Physics runs in 2010 - 2012 (Run 1)

$\int Ldt$ ~ 5 fb^{-1} 2011

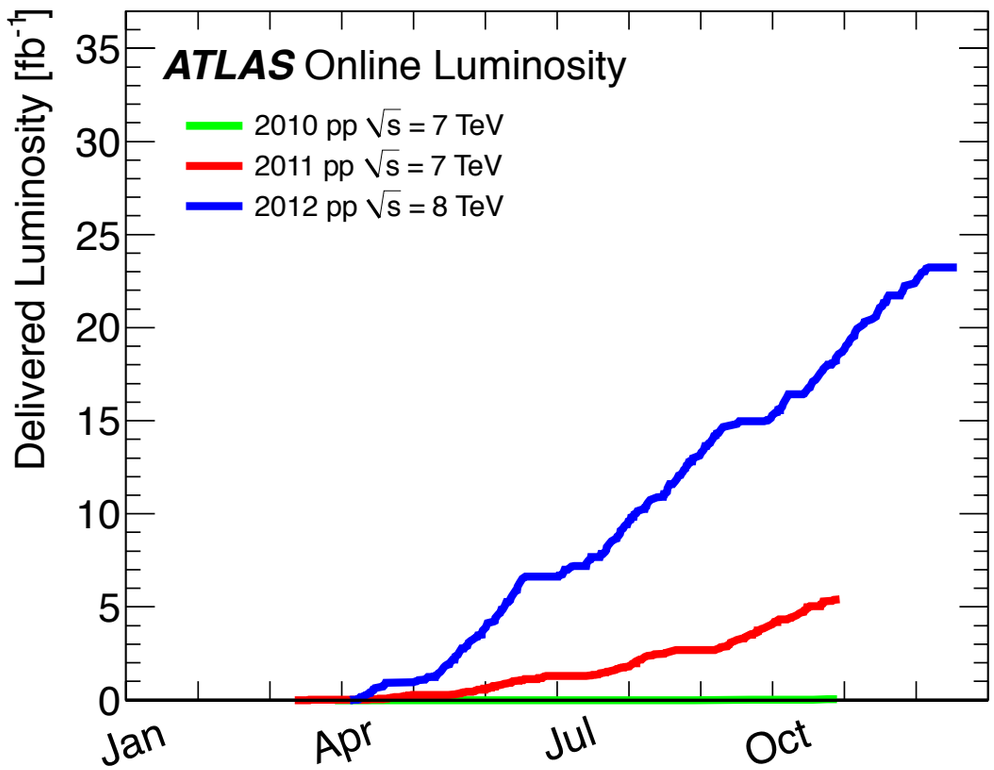
20 fb^{-1} 2012

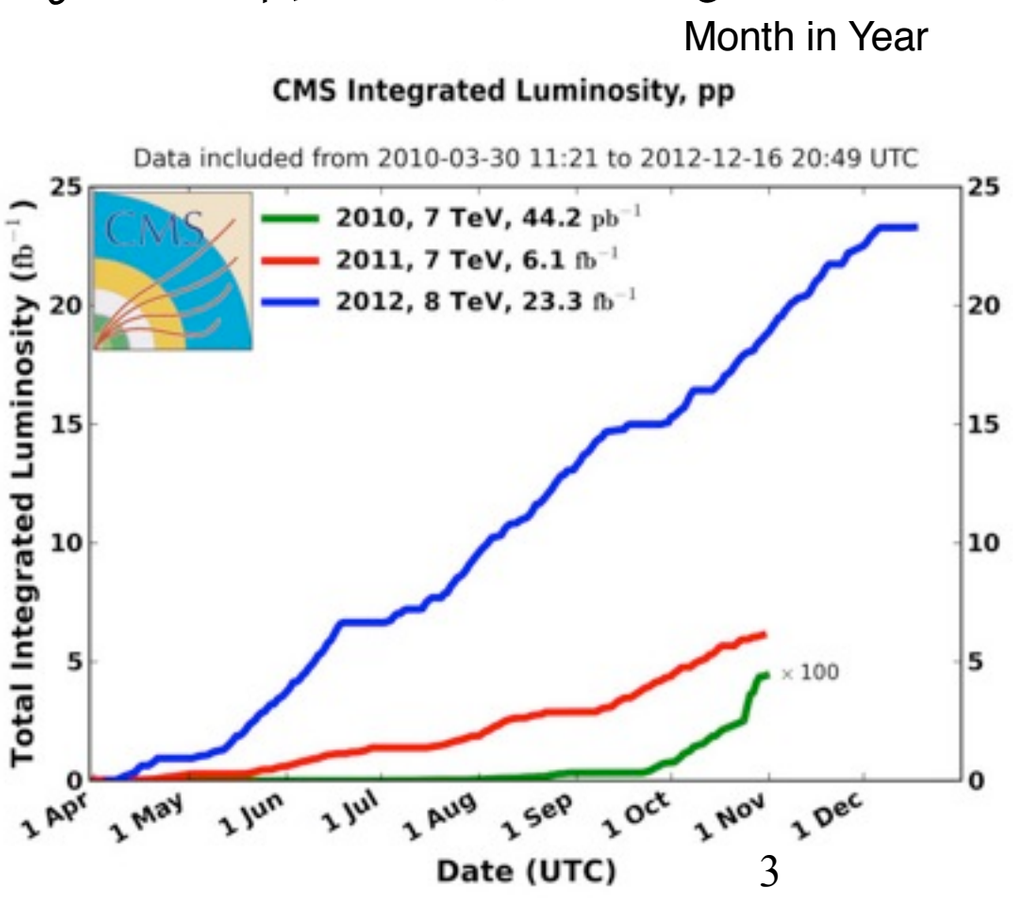
- pp collisions at
  √s = 7 TeV (3.5 + 3.5) for 2010-11
  √s = 8 TeV (4 + 4) for 2012
- also Pb+Pb, p+Pb (not covered here)
- Long Shutdown (LS1) 2013-2014

- Run 2 from 2015
  starting @ √s = 13 TeV
  towards 14 TeV (design)
- LS2 planned 2018-2019
- Run 3 till 2022

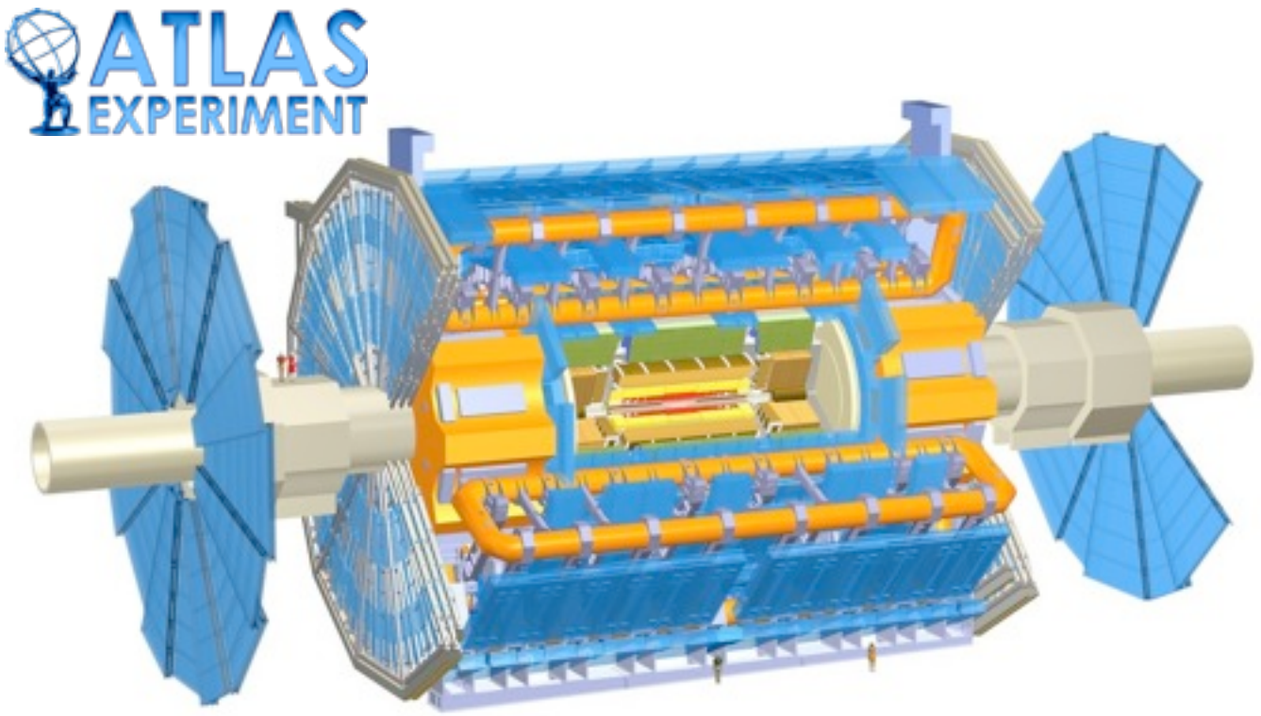
LHC luminosity

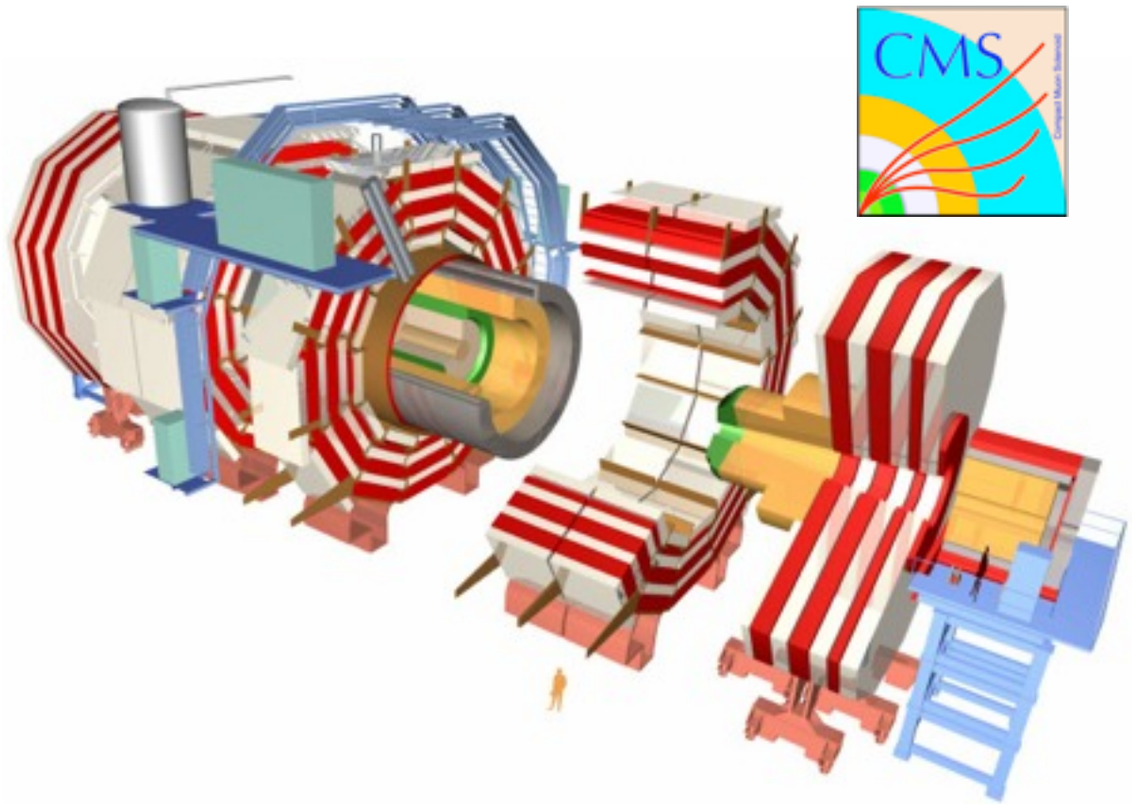
- Main results presented here from:
  - 2011, ~5 fb^{-1} @ 7TeV
  - 2012, ~20 fb^{-1} @ 8TeV
- Peak lumi in Run 1 0.75×10^{34} $cm^{-2}\ s^{-1}$ (design: 1×10^{34})
- Run2/3: 1.5→2×10^{34} 300 fb^{-1} till 2022
- HL-LHC from 2025: 5×10^{34}, 3000 fb^{-1} in 10y

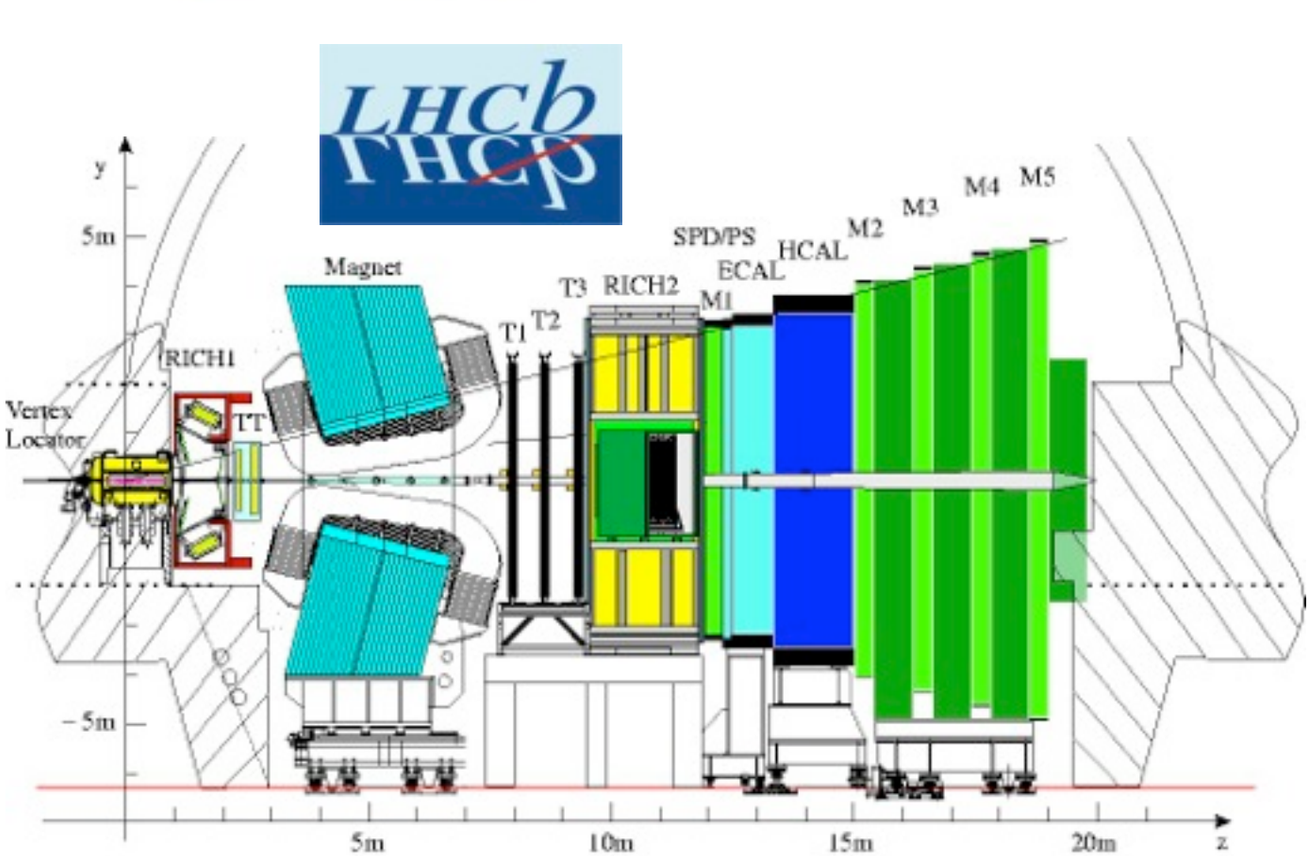


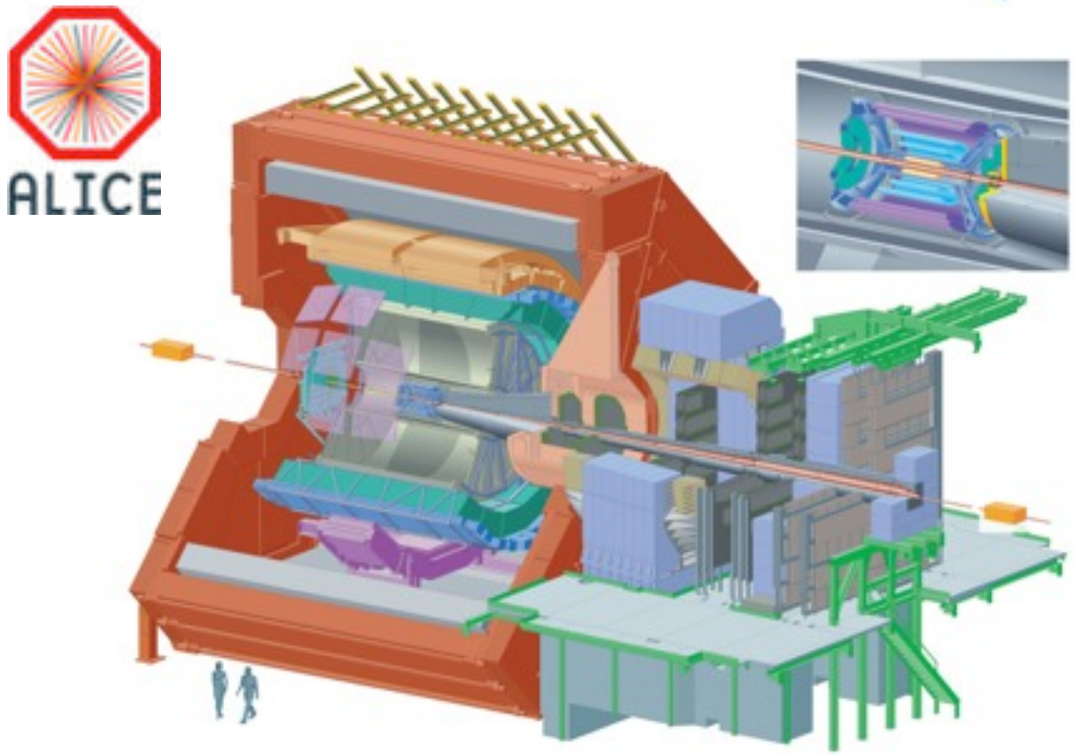


The experiments









W, Z and γ production @LHC

- Electromagnetic and Weak (EW) probes in hadron-hadron collisions
  - Clean signature with lepton/photon/ν ($E_T$miss)
- Benchmark of SM validation at highest energy
  - Large mass of W/Z assures hard scale involved
- Measurements at extreme kinematics/topologies allow tuning of tools for SM predictions
  - (N)NLO calculations, MC event generators
- Crucial in searches for Beyond-SM physics
  - Signal typically involves W/Z/γ (+many jets/$E_T$miss)

Topics covered (new since PIC13!)

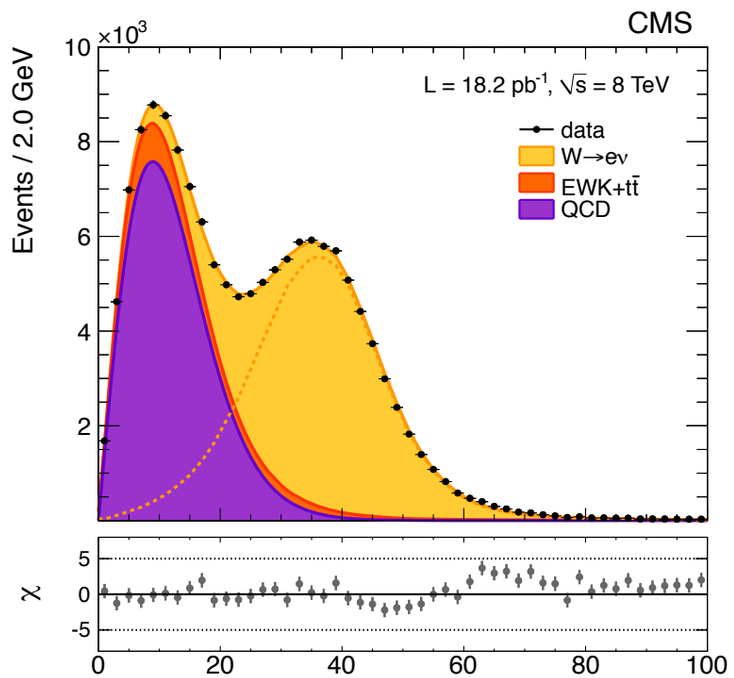
- Inclusive W, Z/γ^* production
  - cross sections, p_T, η distributions, Drell-Yan
  - hadronic decays, Z→4 leptons
- W+jets, Z+jets production
  - # of jets, jet kinematics, W+jets/Z+jets ratio
- Z/W+heavy flavor production
  - Z+b, Z+bb, W+bb, ...
- Prompt γ production, $\gamma\gamma$ pair
  - also γ+jets and γ+jets/Z+jets ratio
- PDF related → covered in PDF talk (V. Radescu)
  - W charge asymmetry, W+charm

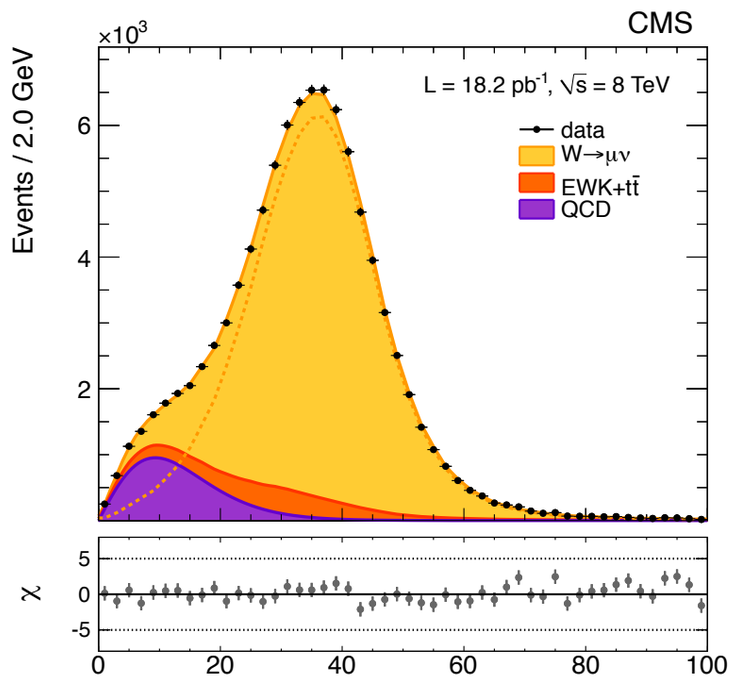
Inclusive W/Z at 8 TeV

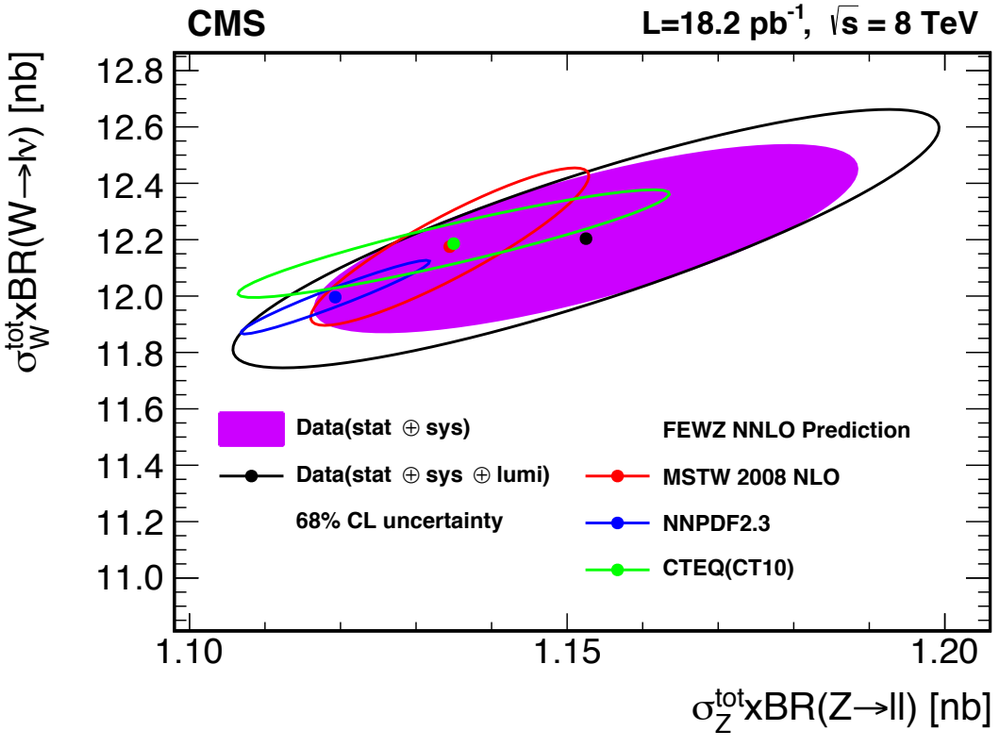
arXiv:1402.0923 PRL112 (2014) 191802

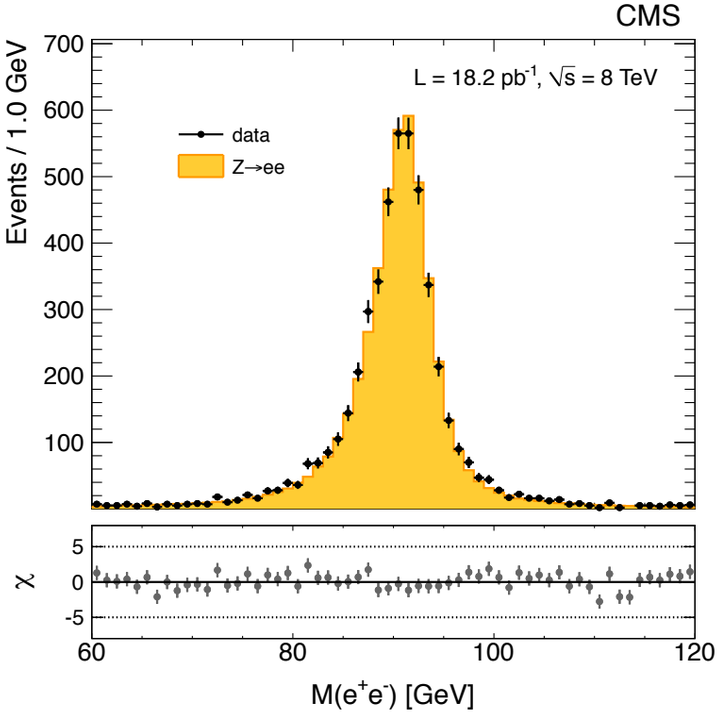
- Special data set with low pile-up

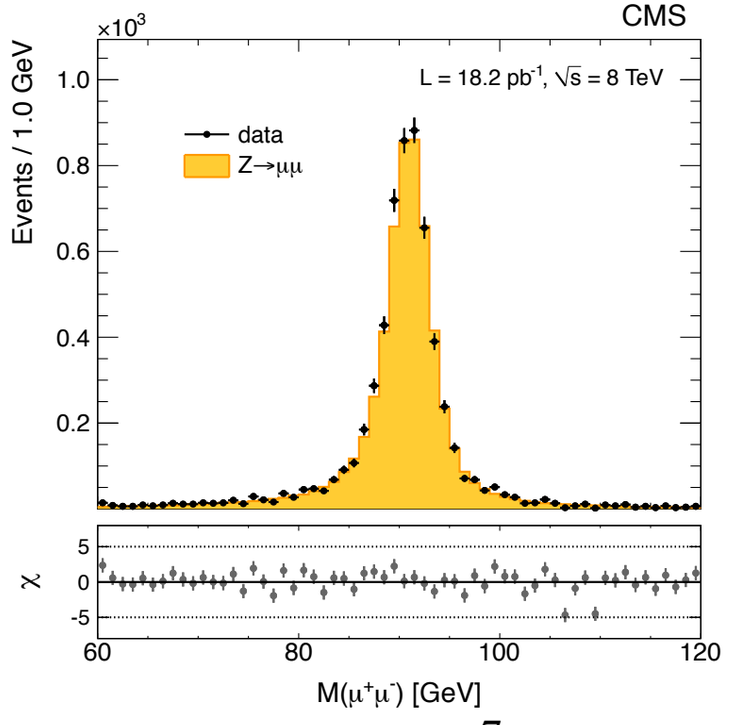
- $R_{W/Z}$ = 10.63±0.11(stat.)±0.25(syst.) (FEWZ NNLO: 10.74±0.04)
- R_{W^+/W^-} = 1.39±0.01(stat.)±0.02(syst.) (FEWZ NNLO: 1.41±0.01)





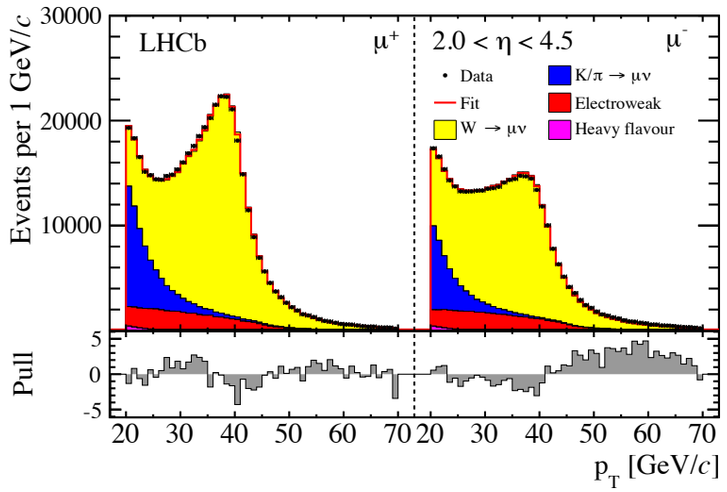


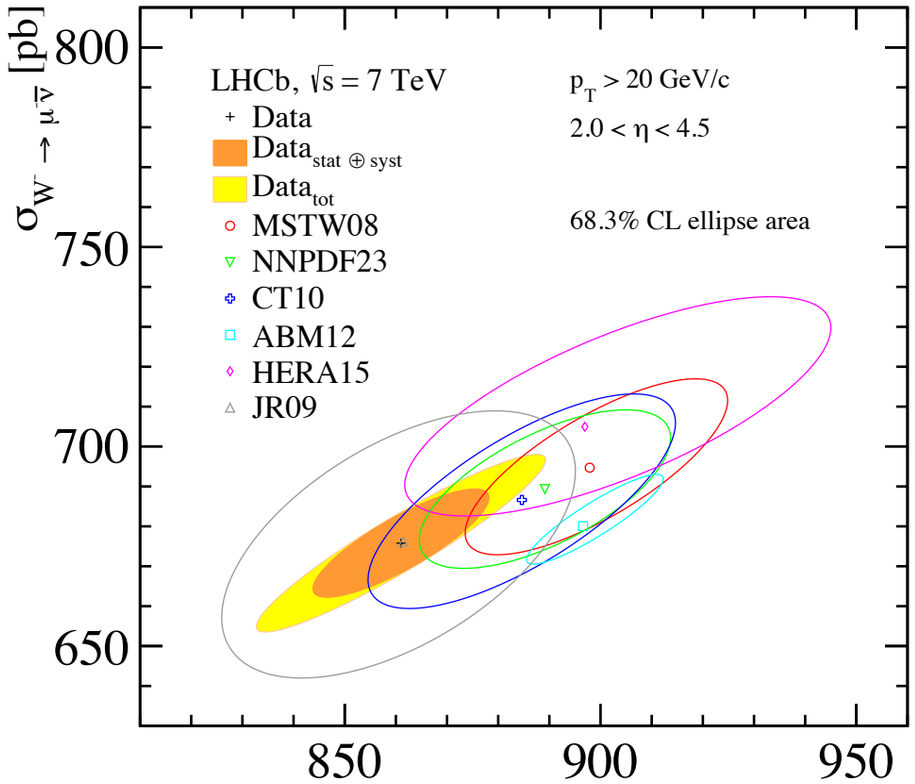




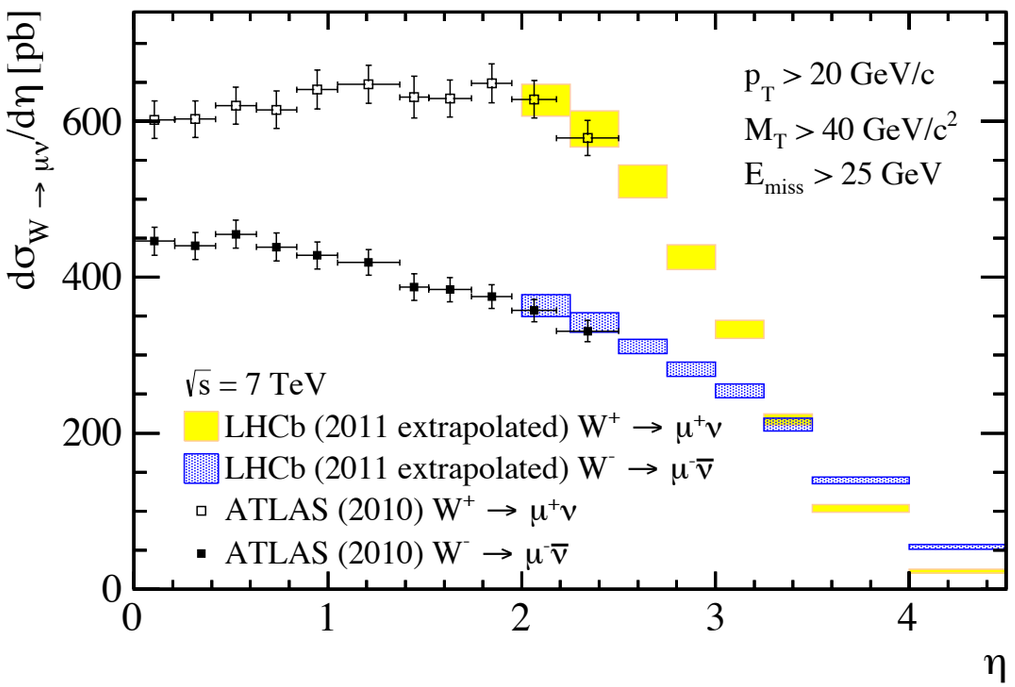
Forward W in LHCb

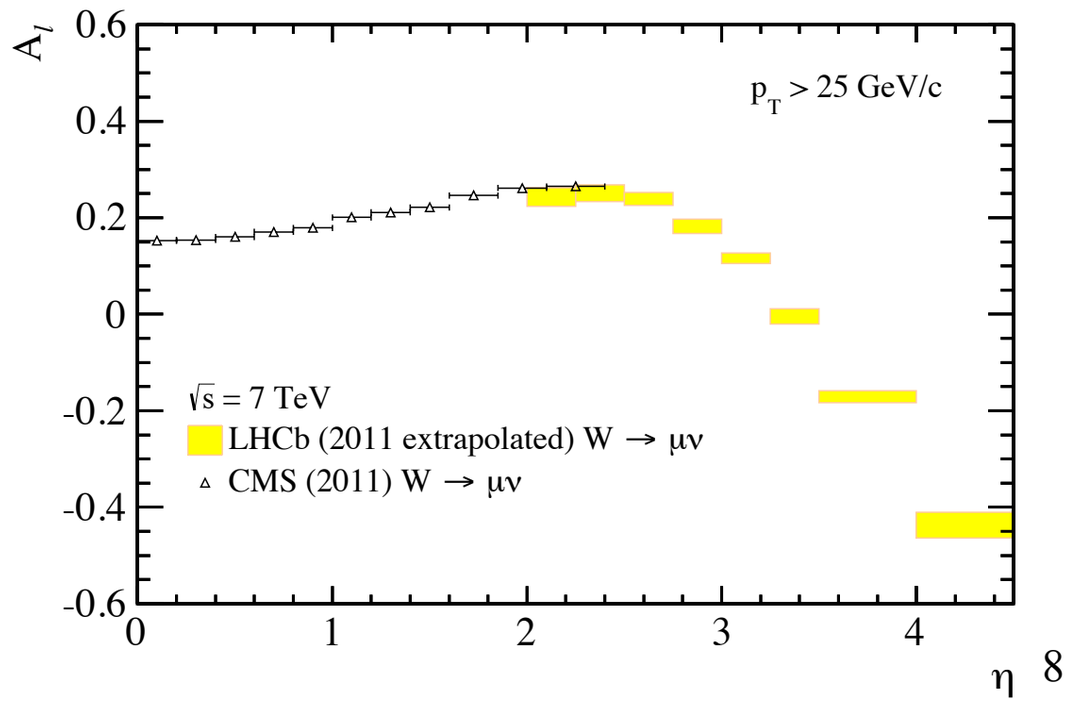
- Acceptance in $2<\eta(\mu)<5$ (η=-ln tan θ/2)
- Sensitive to PDF
- Nicely extends ATLAS/CMS measurements to larger η





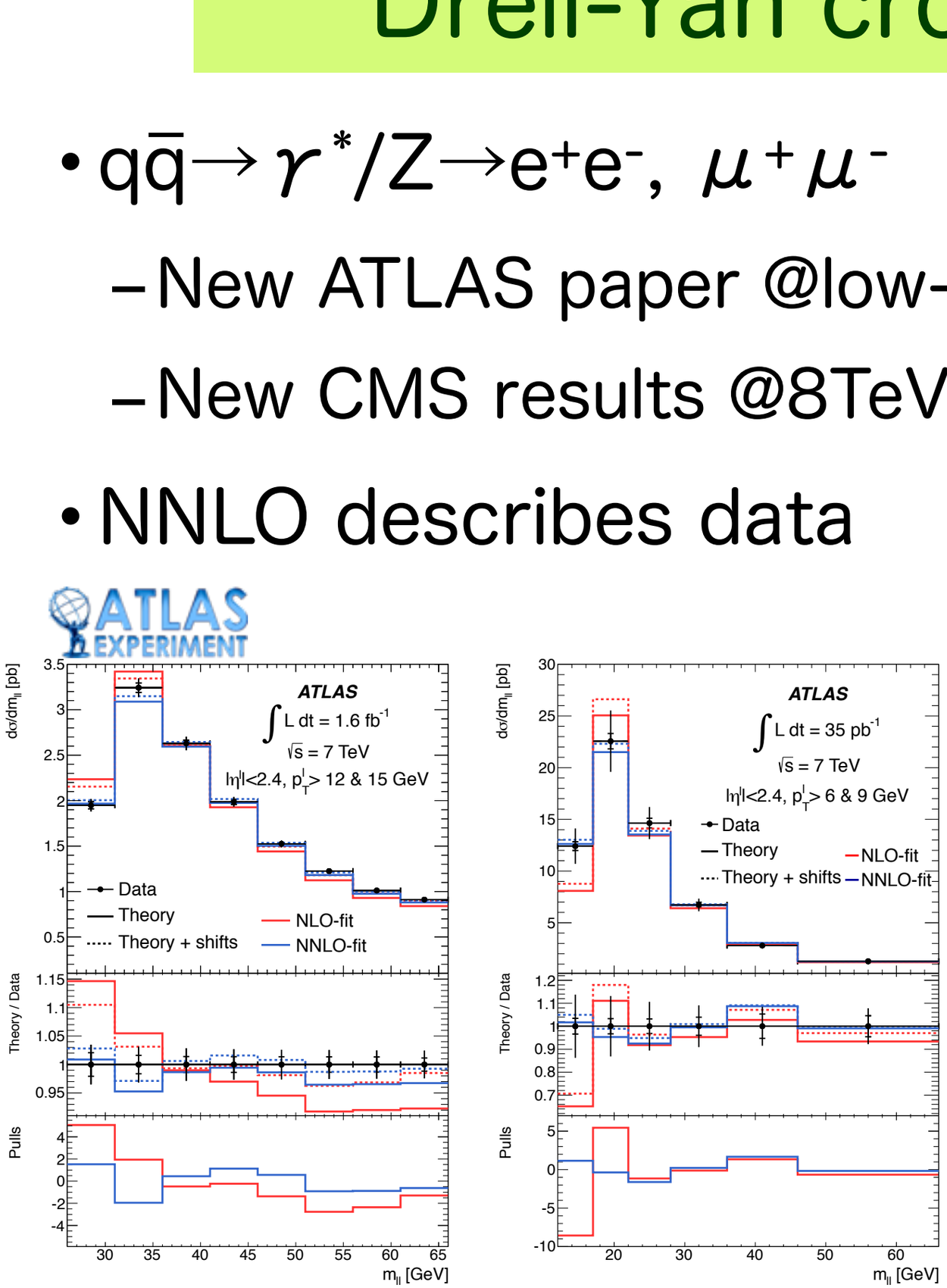
LHCb-CONF-2014-002→arXiv:1408.4354 (new!)

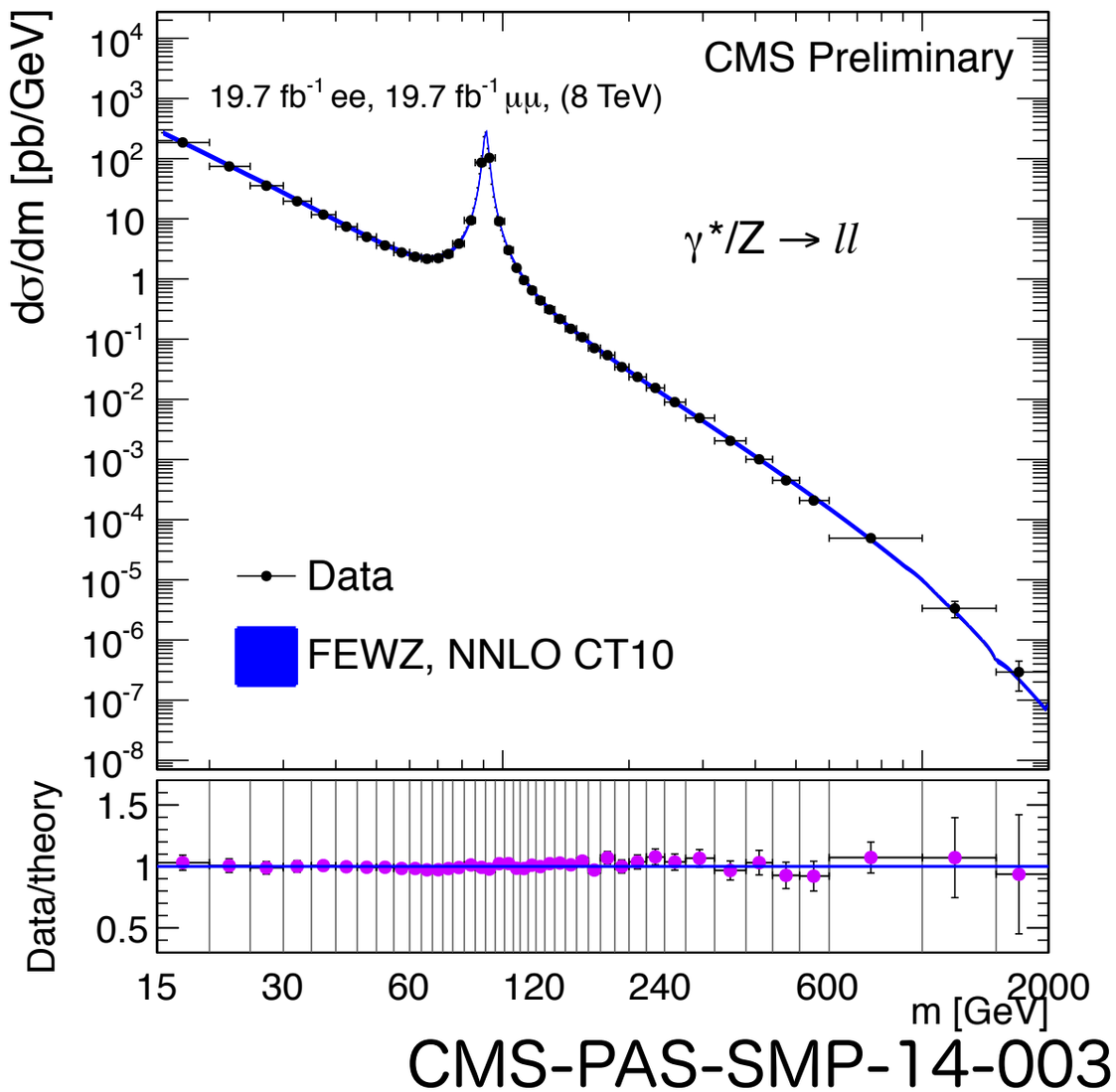




Drell-Yan cross sections

- $q\bar{q} \rightarrow \gamma^*/Z \rightarrow e^+e^-,\ \mu^+\mu^-$
  - New ATLAS paper @low-mass (incl. low-p_T events in 2010)
  - New CMS results @8TeV (double diff. $d^2\sigma/dm d|y|$)
- NNLO describes data





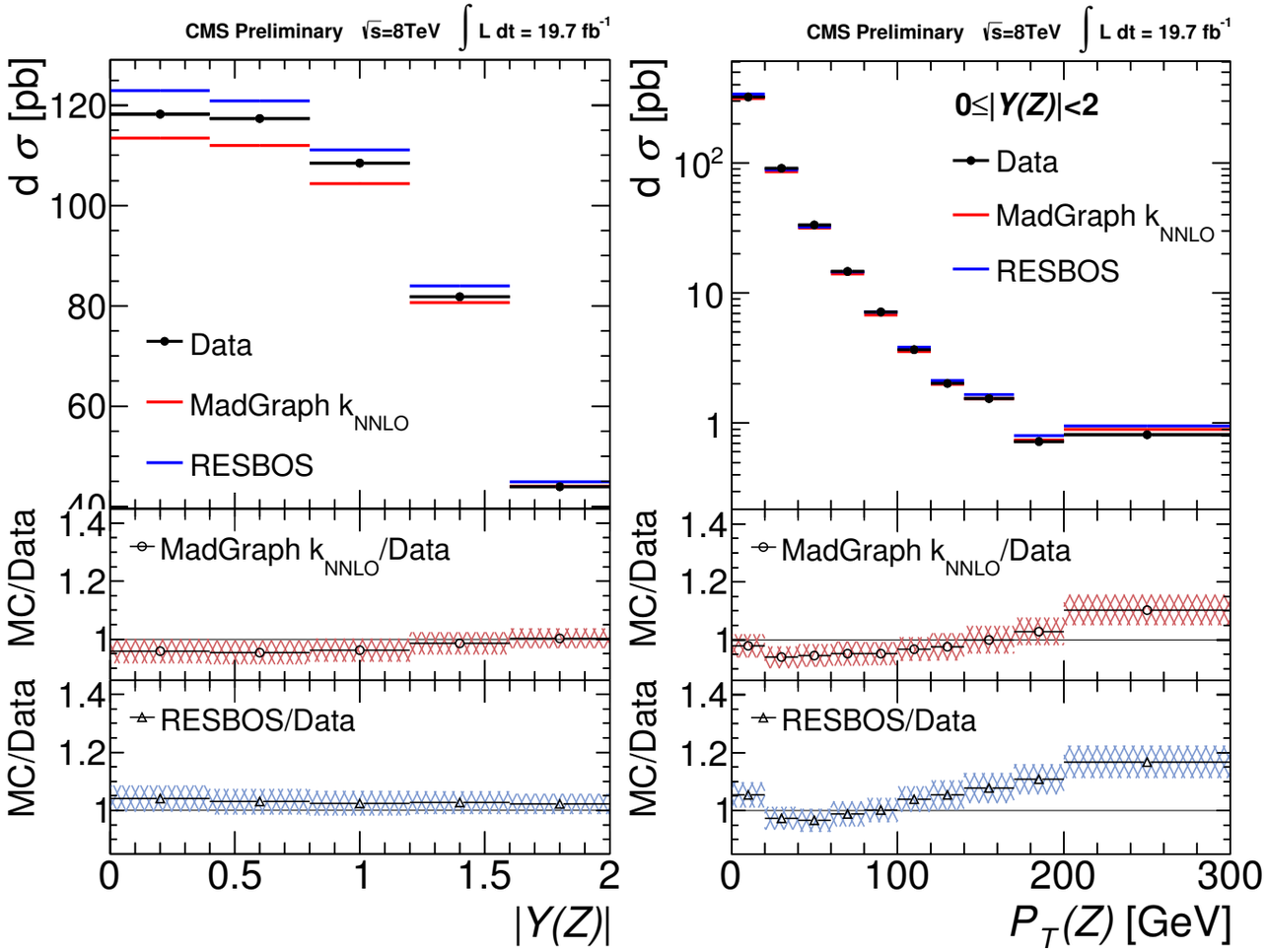
arXiv:1404.1212 JHEP06 (2014) 112

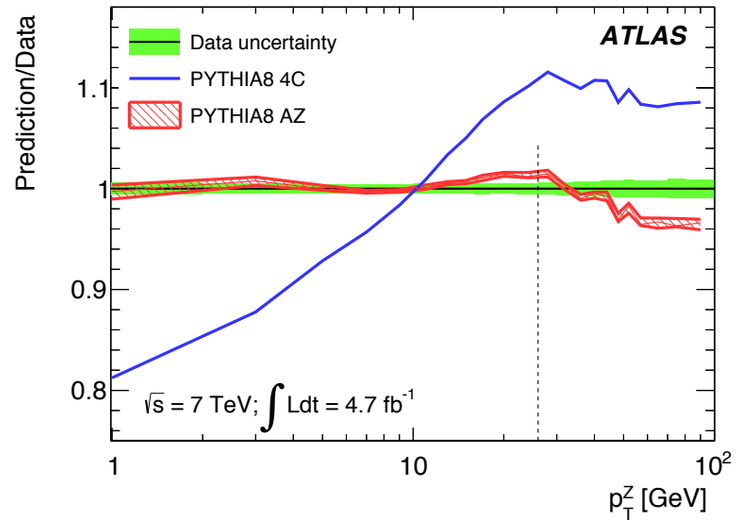
CMS-PAS-SMP-14-003

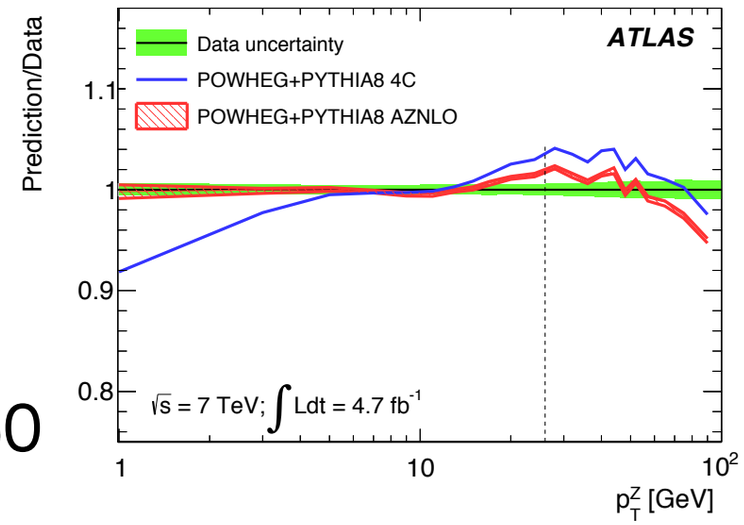
p_T and rapidity of Z

- $Y=(1/2)\ln\{(E+p_z)/(E-p_z)\}$
- At large $p_T(Z)$, data softer than prediction

CMS-PAS-SMP-13-013







arXiv: 1406.3660

- Low-pT data (< 26GeV) used for parton-shower tuning of generators
- better than 2% agreement up to 50 GeV

Z/W in hadronic decay

- Large QCD multijet BG
- Use b-tag

  (dijet p_T>200GeV)

  or

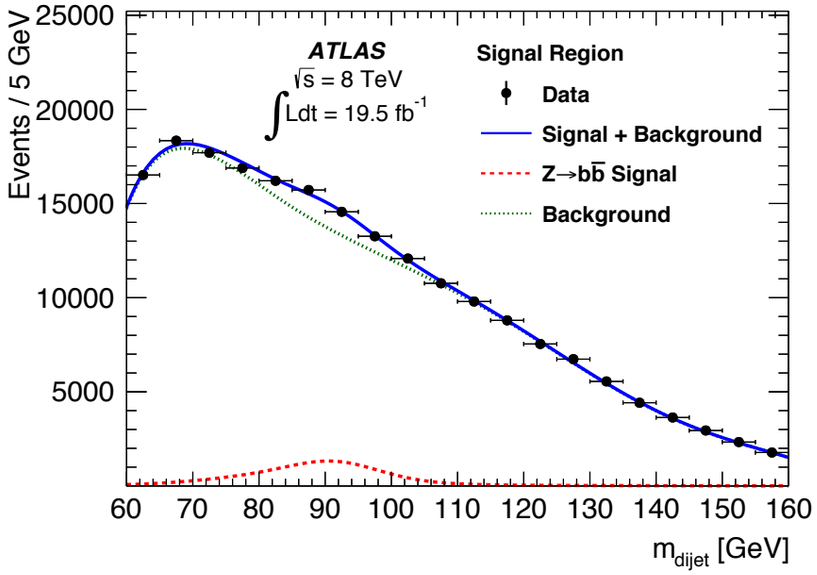
- Jet substructure

  (jet p_T>320GeV)

  to suppress BG
- Boosted W/Z important for heavy particles

  (see K. Behr's talk)

Z→bb 1404.7042



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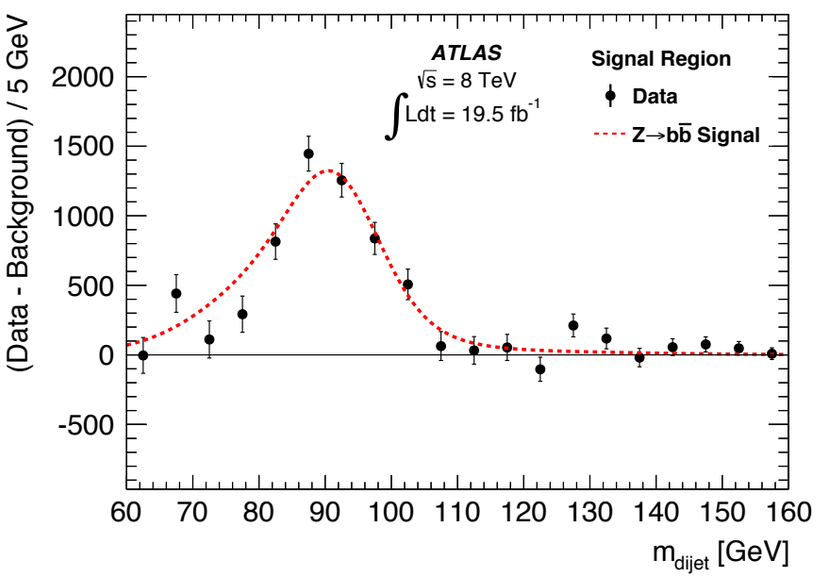
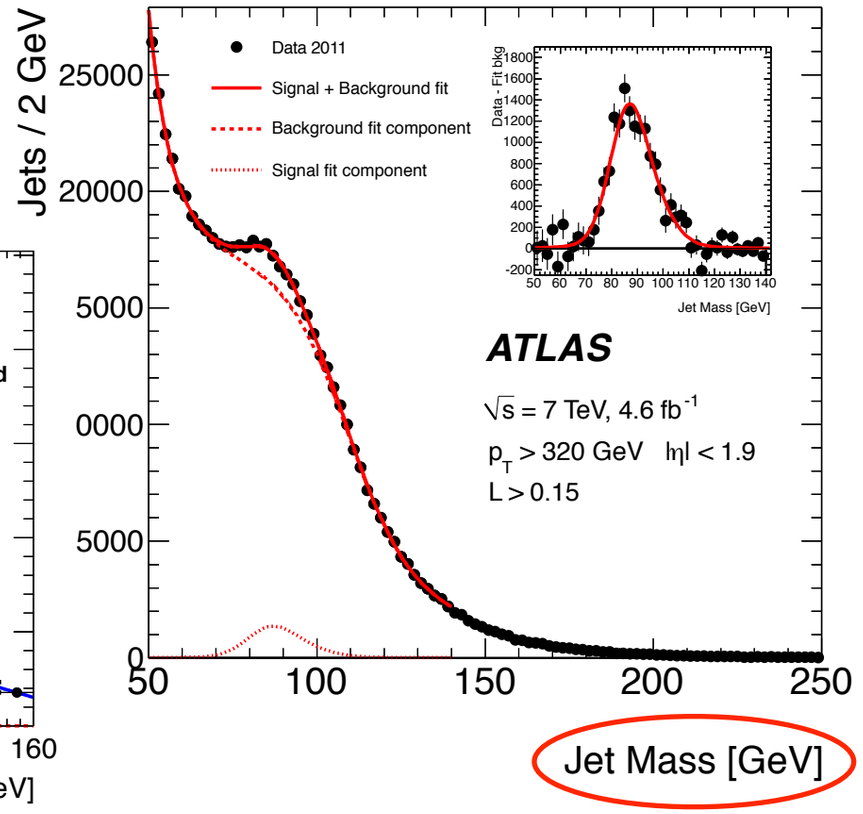
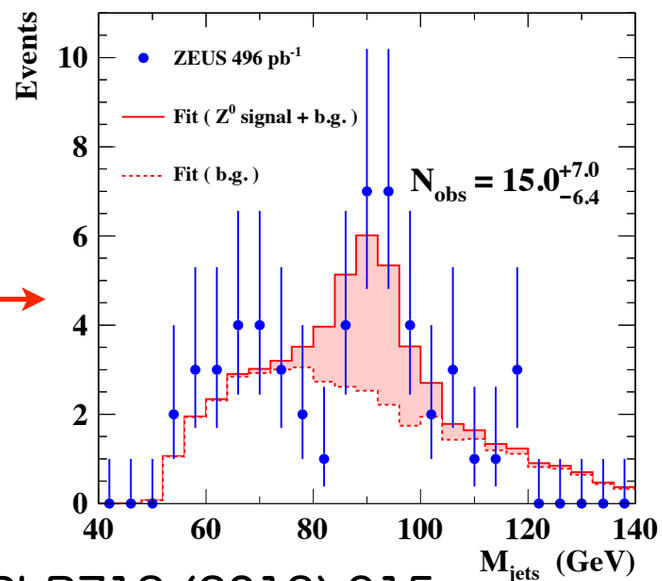


(c)

W/Z→1 jet 1407.0800



cf. HERA *ep* ZEUS Uranium CAL



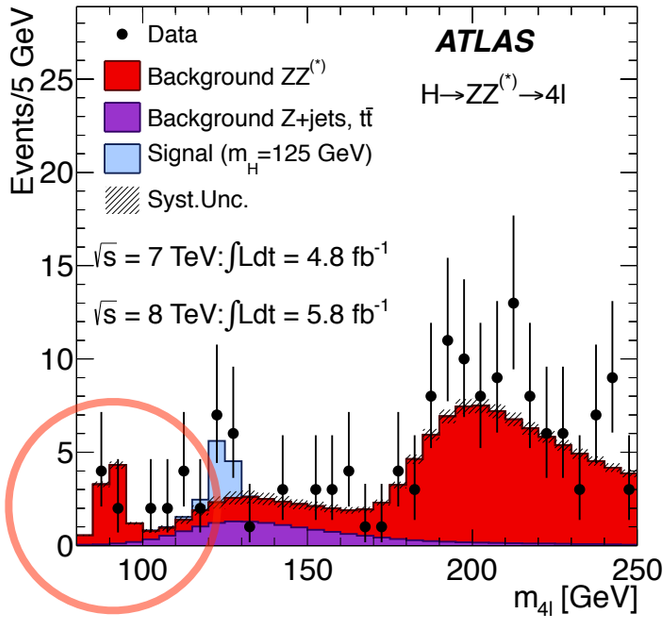
PLB718 (2013) 915

Z → 4 leptons

1403.5657

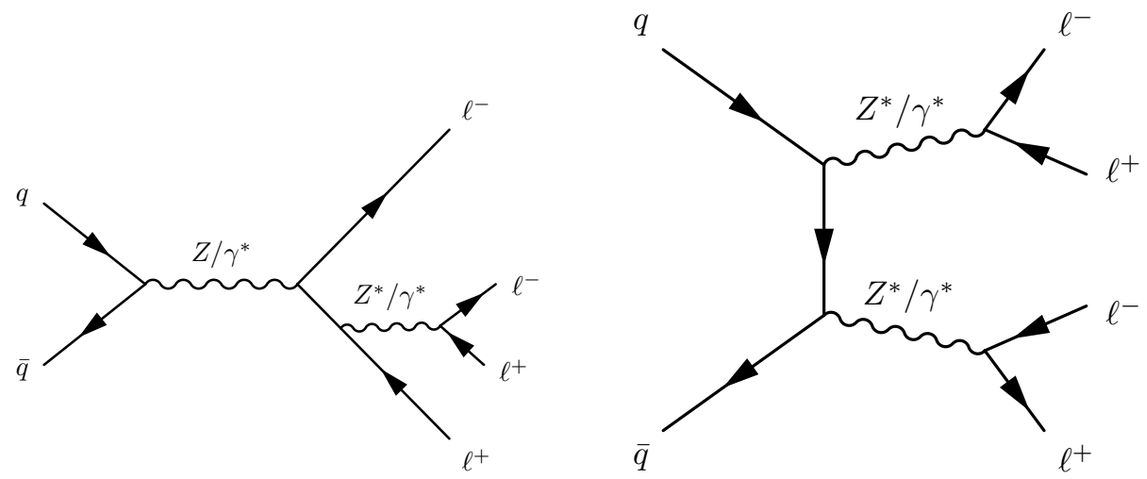
PRL112 (2014) 231806

- Already seen in Higgs discovery paper

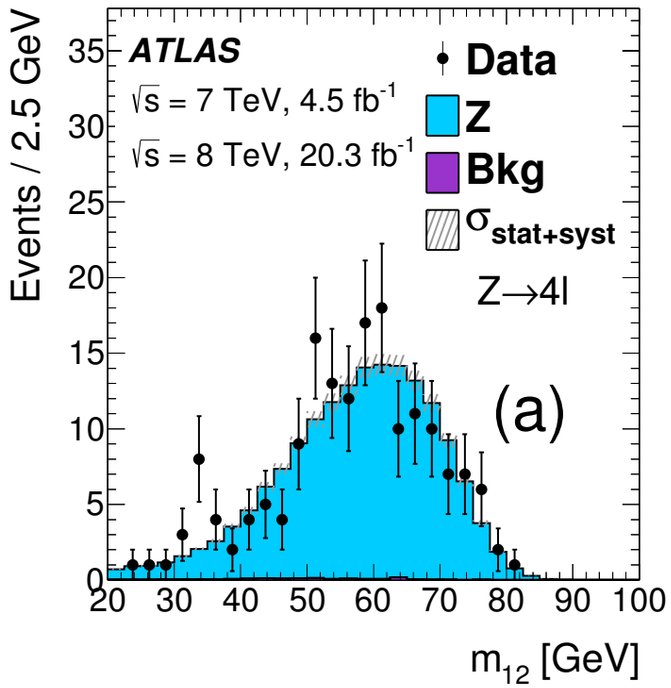


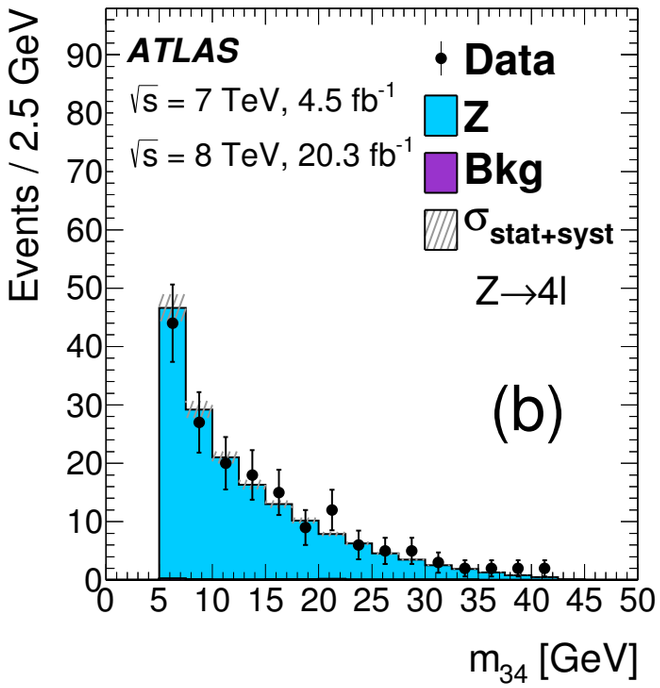
PLB716 (2012) 1

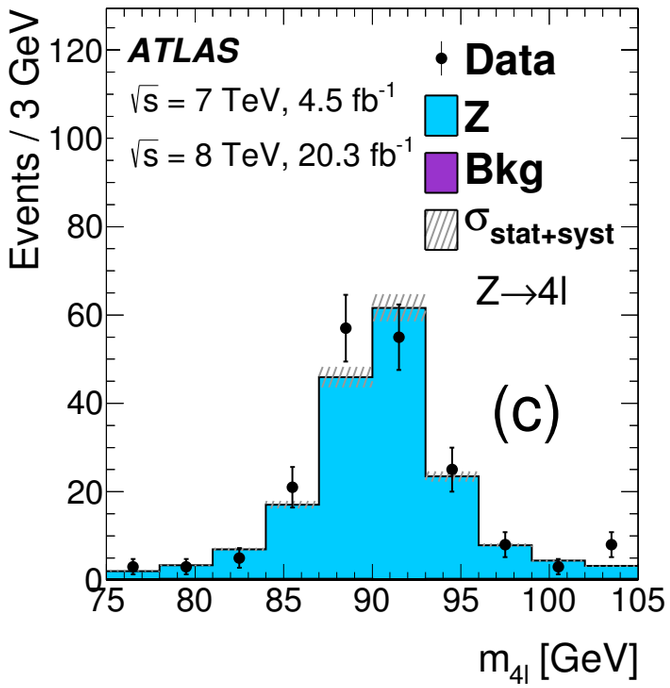
- Br(Z→4l) = (3.20±0.25(stat)±0.13(syst))×10^{-6}
  SM: 3.33×10^{-6}



non-resonant BG







Z+jets @8TeV

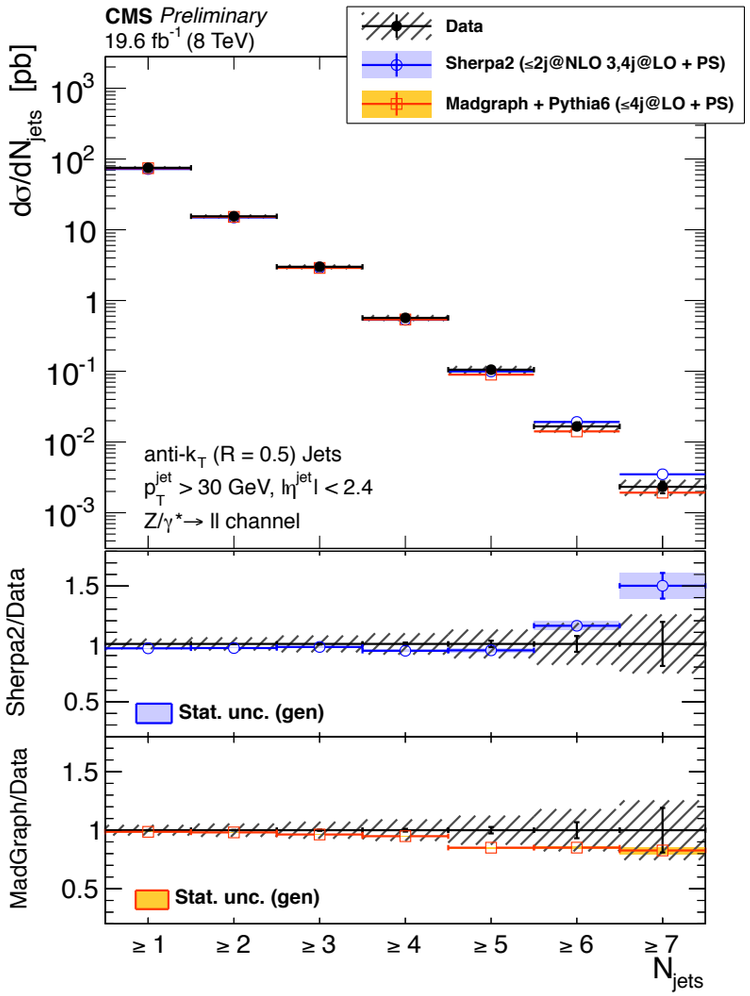
CMS-PAS-SMP-13-007

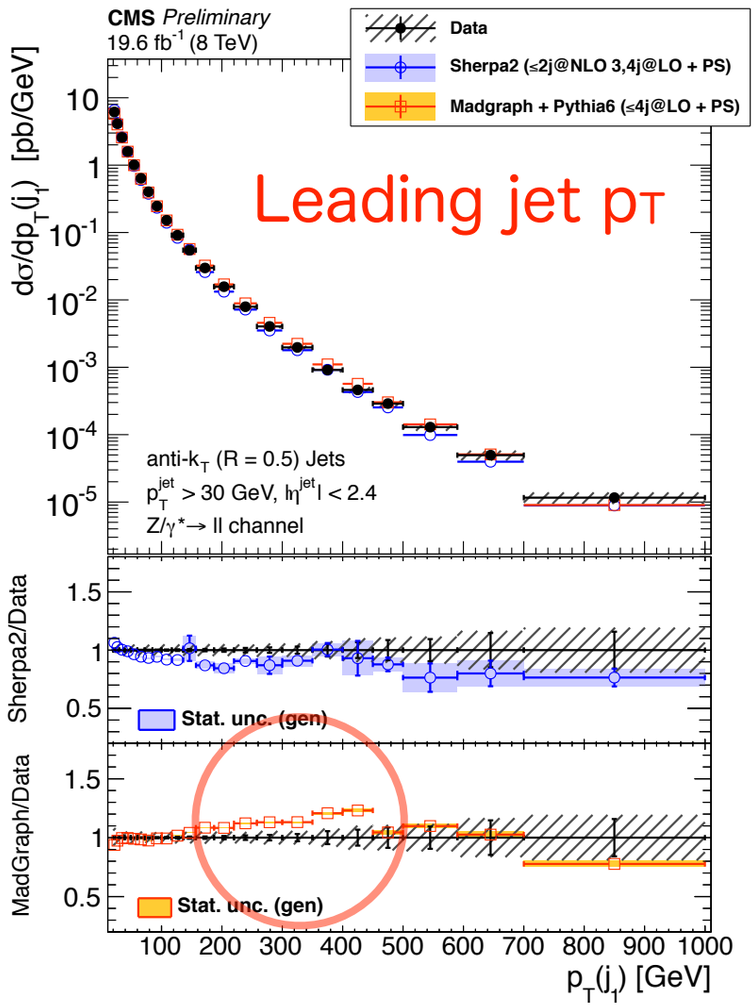
cf. ATLAS 7TeV: JHEP07 (2013) 032

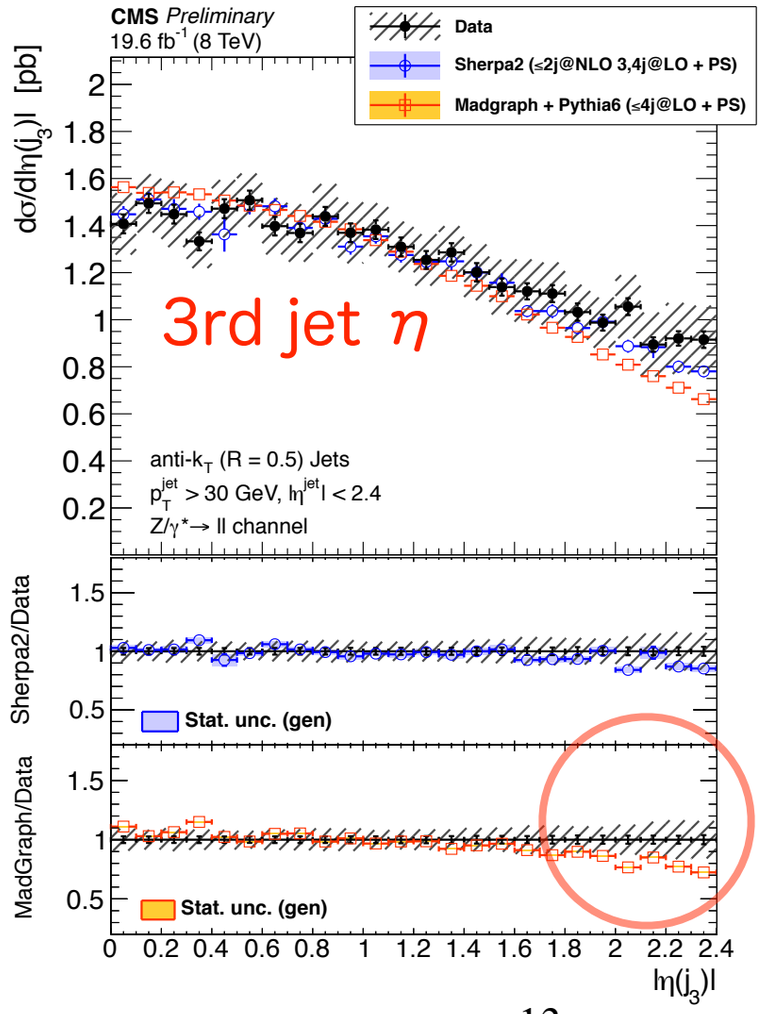
LHCb 7TeV ($2 < \eta_{\mu,\text{jet}} < 4.5$)

arXiv:1310.8197 JHEP01 (2014) 033

- Up to N_{jets}=7
- Jet pT, η, H_T distributions up N_{jets}>=5
- Also double diff. in pT and y of jets (CMS-PAS-SMP-14-009)
- NLO Sherpa2 describes data well

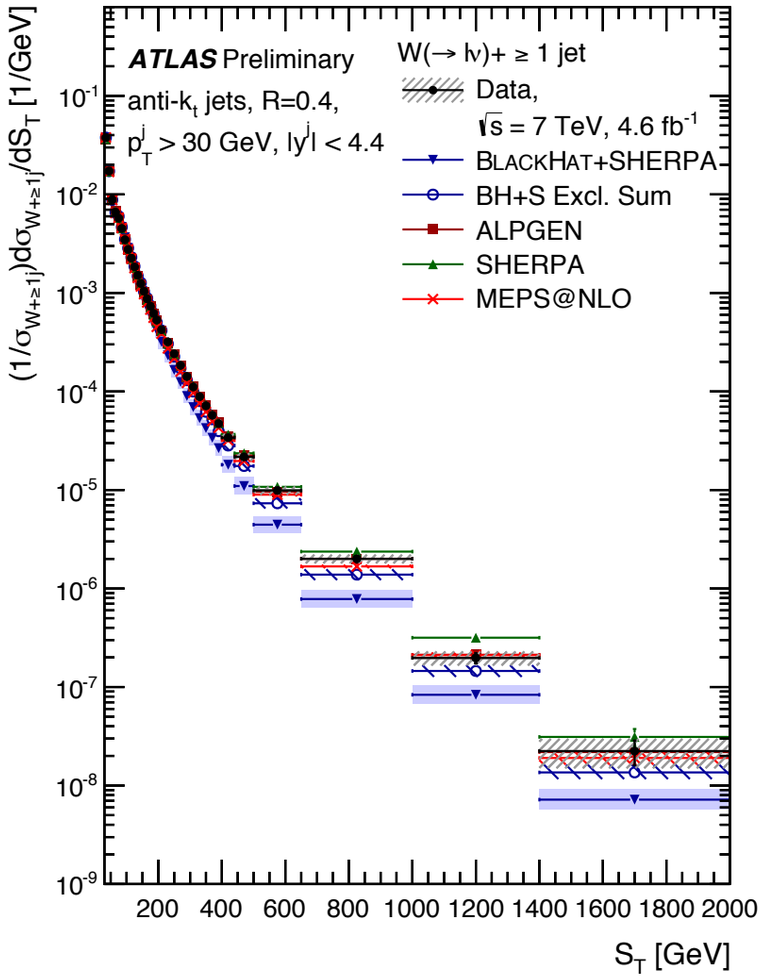


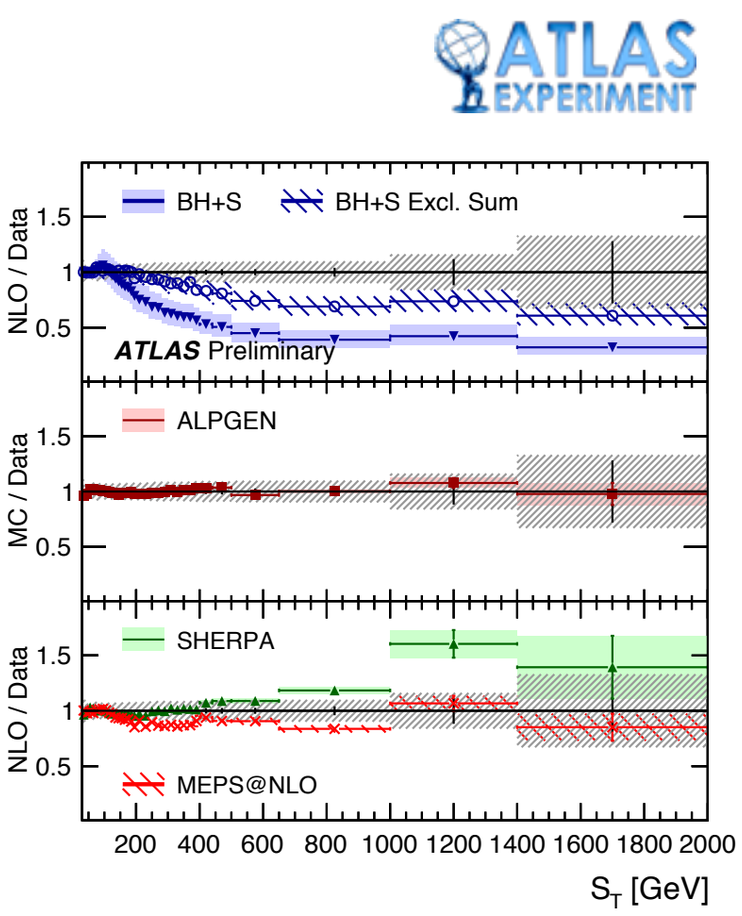


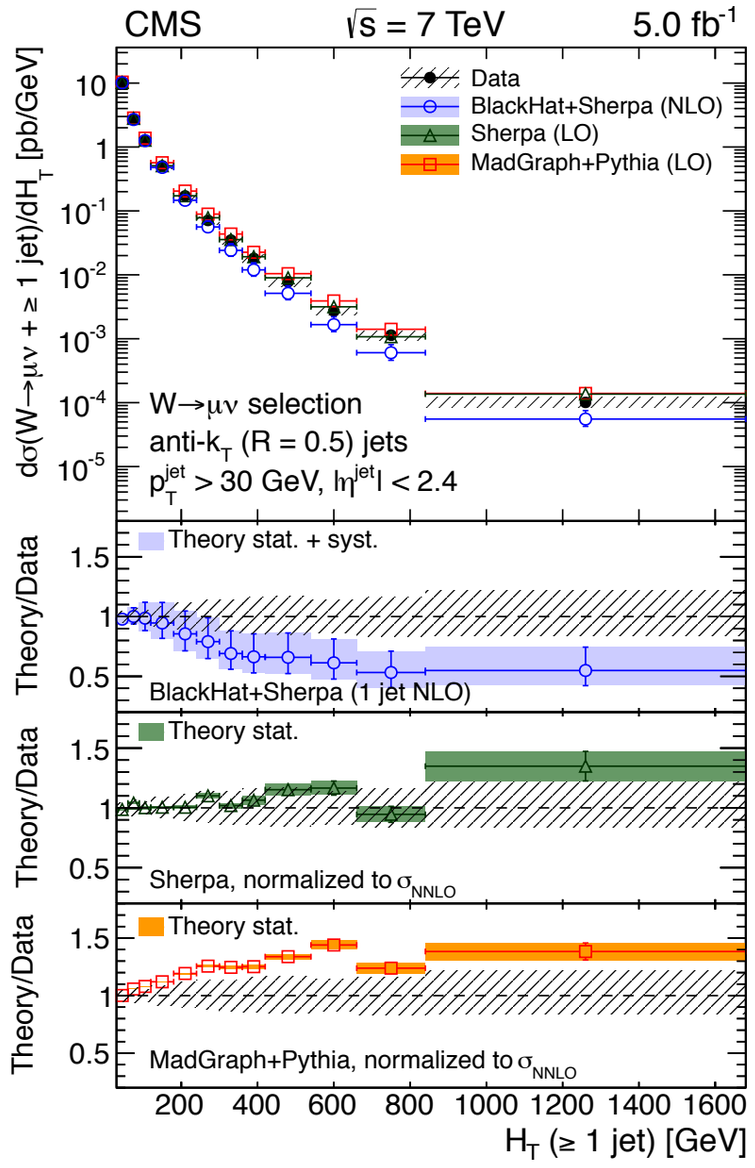


W+jets

- NLO BlackHat+Sherpa (1) does good job for most distributions, but it's fixed-order calculation (higher jet multiplicity missing)
- Discrepancy seen in E_T sum of all jets (S_T in ATLAS, H_T in CMS)
- Improved in Sherpa 2 (Z+jets)





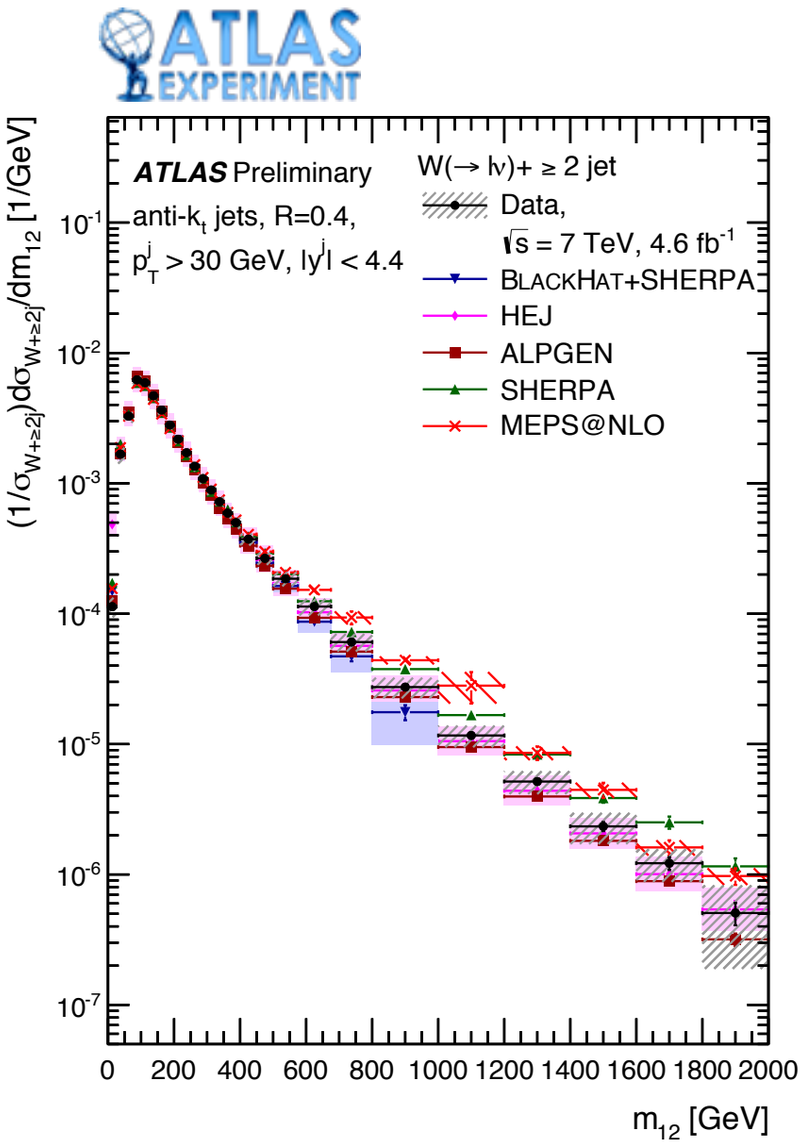


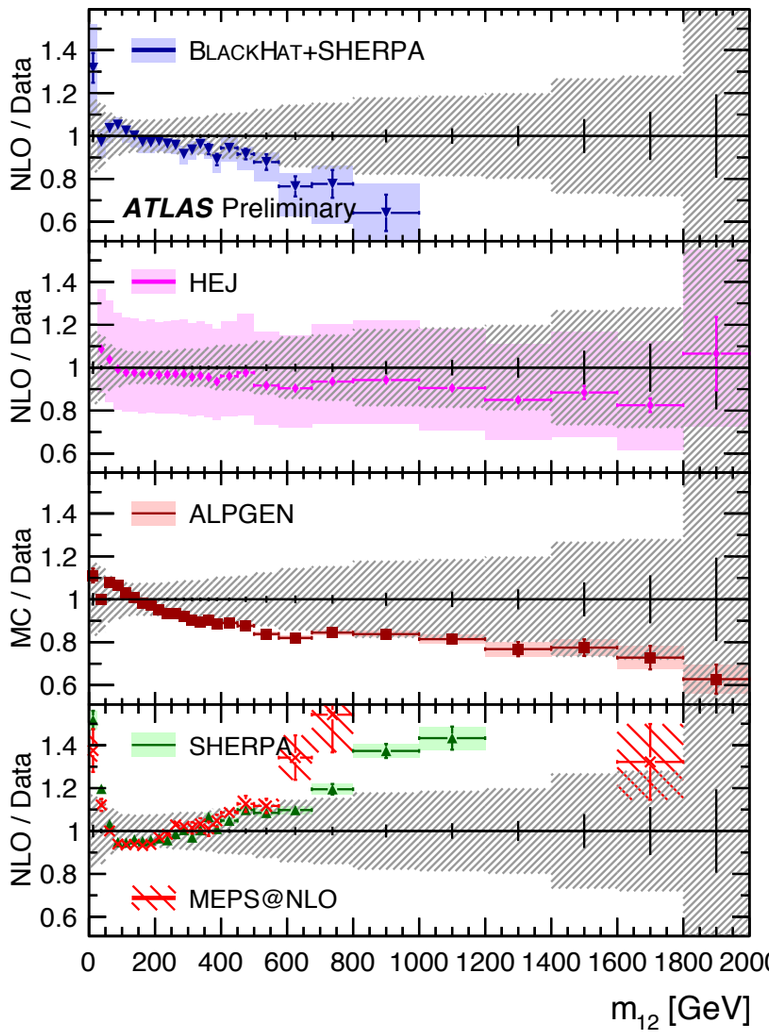
ATLAS-CONF-2014-035 (Appendix)

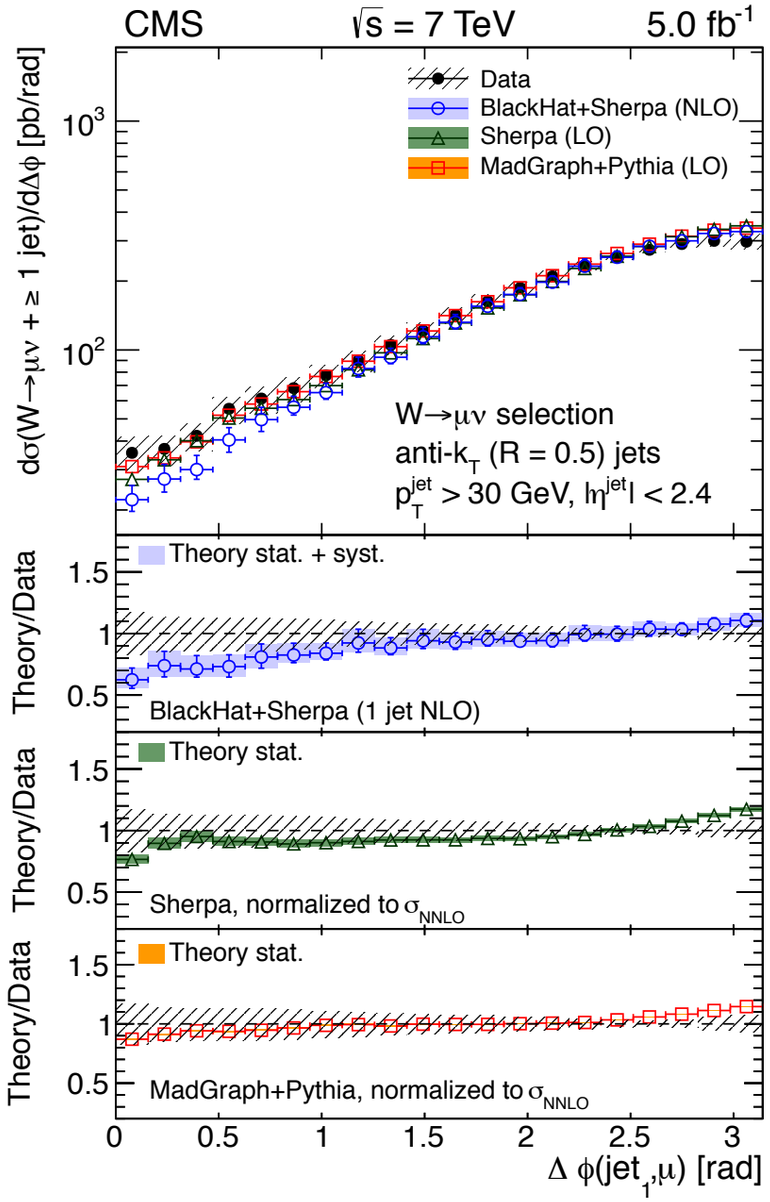
arXiv:1406.7533

W+jets - cont.

- Discrepancy also seen in: dijet mass, $\Delta\phi(\text{jet}_1, \mu)$
- Data are crucial inputs for tuning state-of-art MC generators & QCD calculations



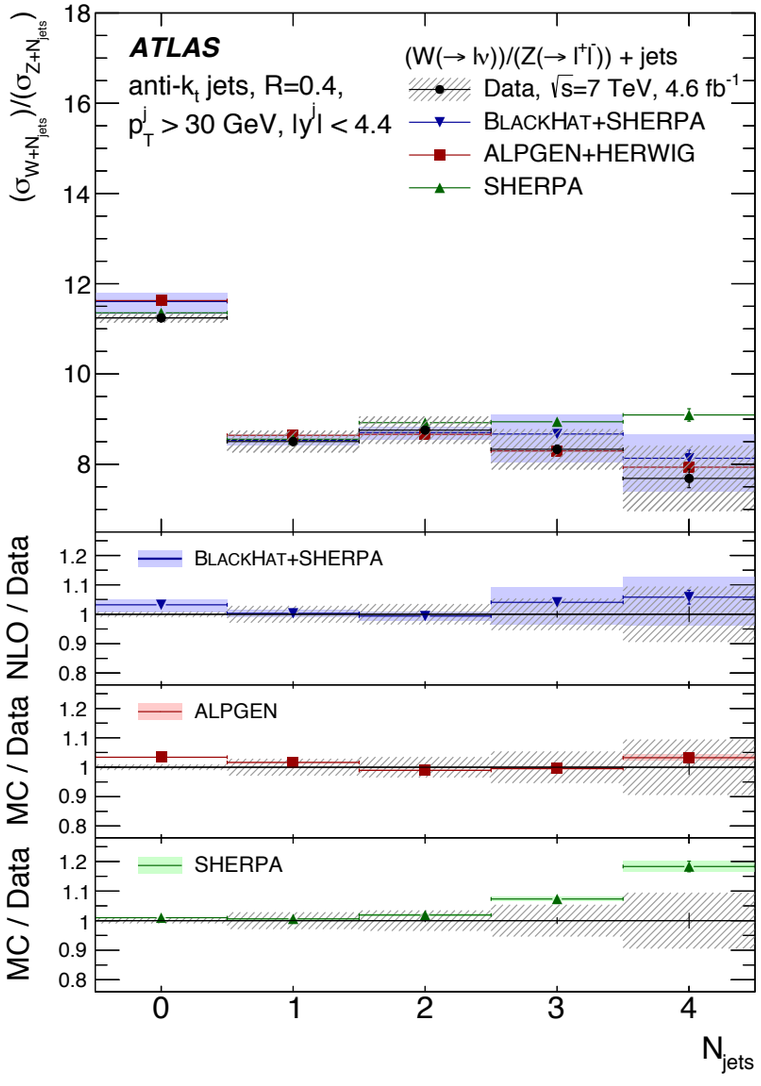


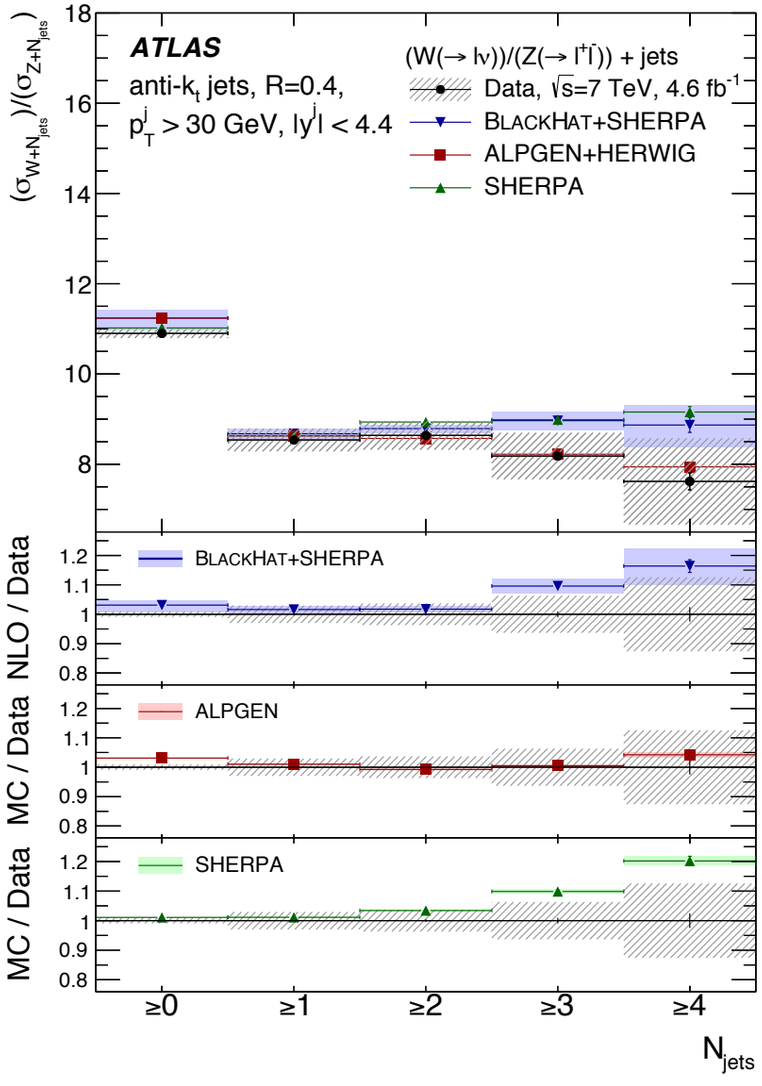


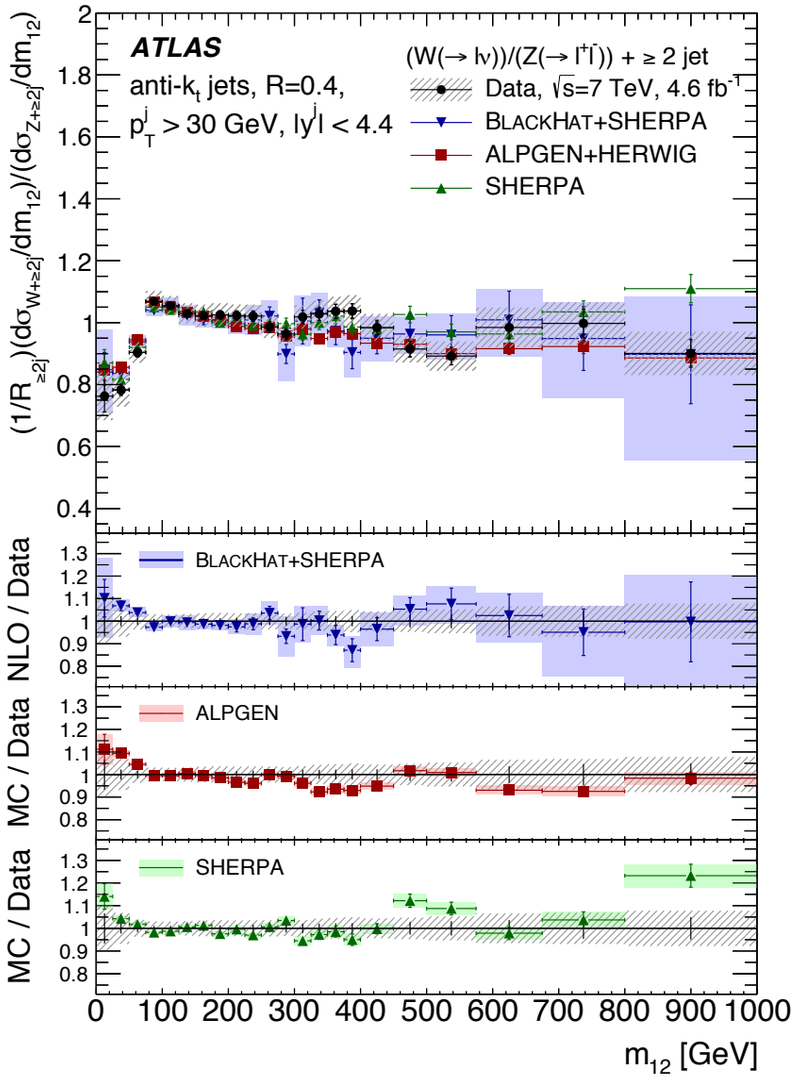
ATLAS-CONF-2014-035 arXiv:1406.7533

$R_{jets} = \sigma_{W+jets} / \sigma_{Z+jets}$

- Take a ratio of W+jets/Z+jets for the same jet kinematics
- Some systematics cancel, improved precision
- BH+Sherpa agrees with data for dijet mass







ATLAS-CONF-2014-034 → arXiv:1408.6510 (new!)

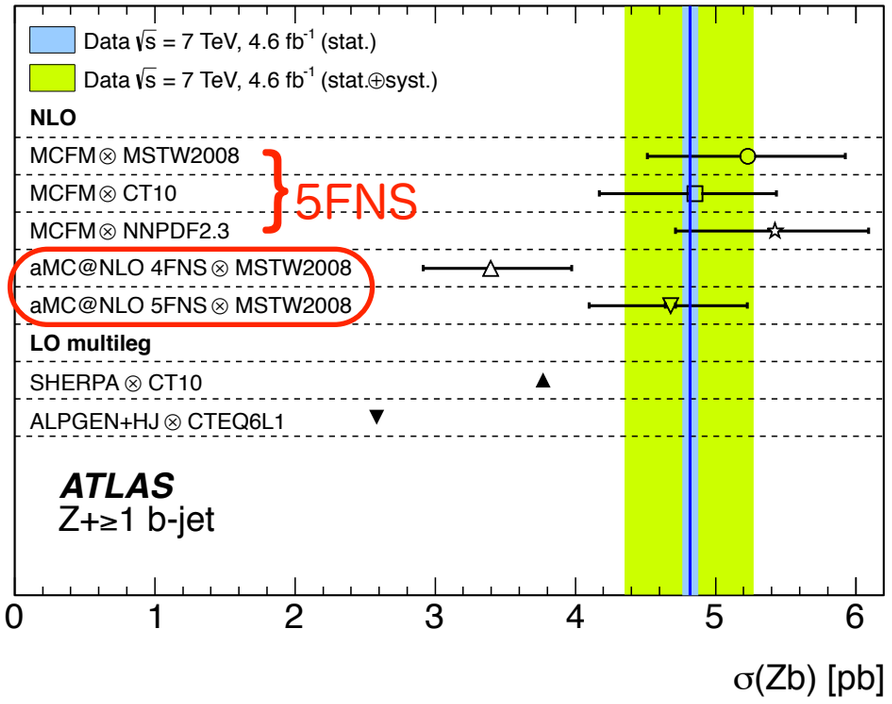
Z+b, Z+bb

arXiv:1407.3643

- BG to ZH(WH), H→bb
- Z(W)+heavy flavor: larger theo. uncertainty than light quarks
- 4FNS, 5FNS schemes (udsc+g or udscb+g in proton)

$Z \to e^+e^-,\ \mu^+\mu^-$

p_T(b-jet) > 20GeV



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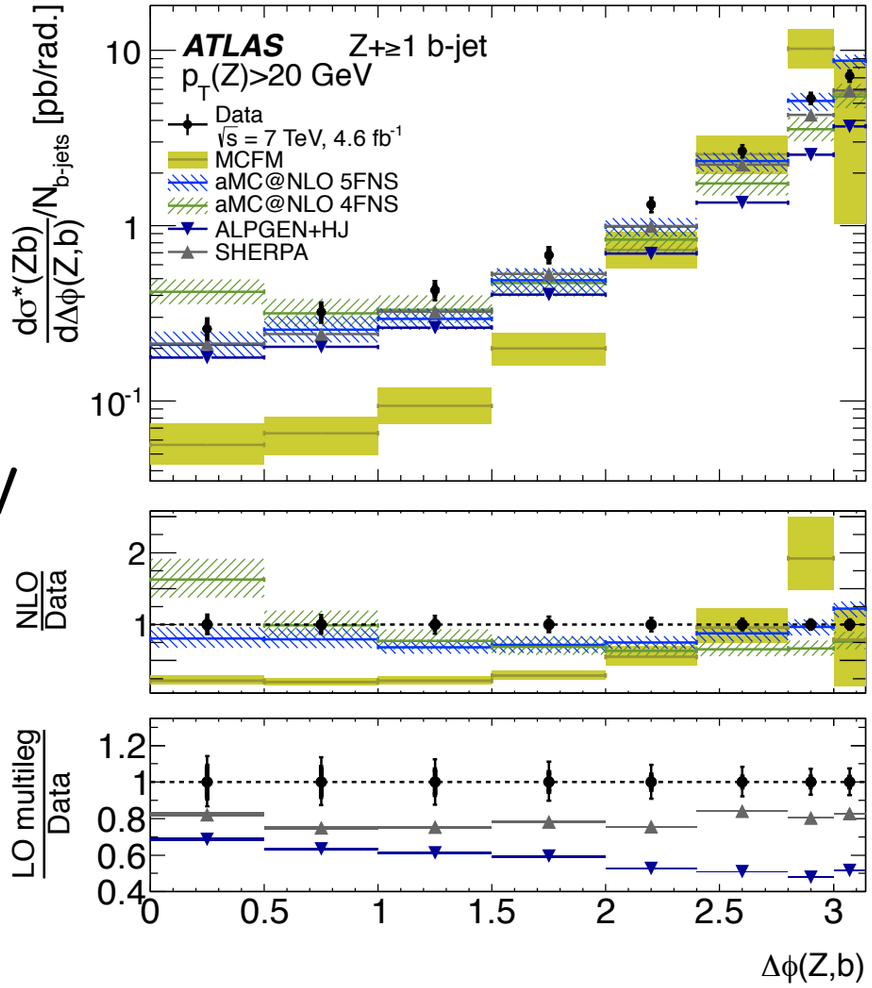
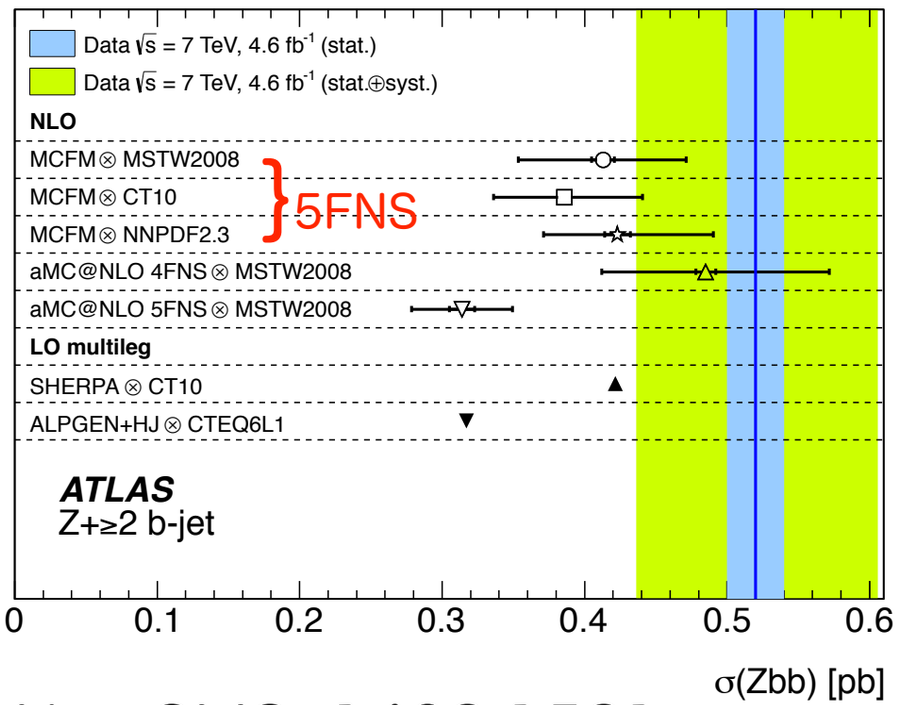




Also CMS: 1402.1521

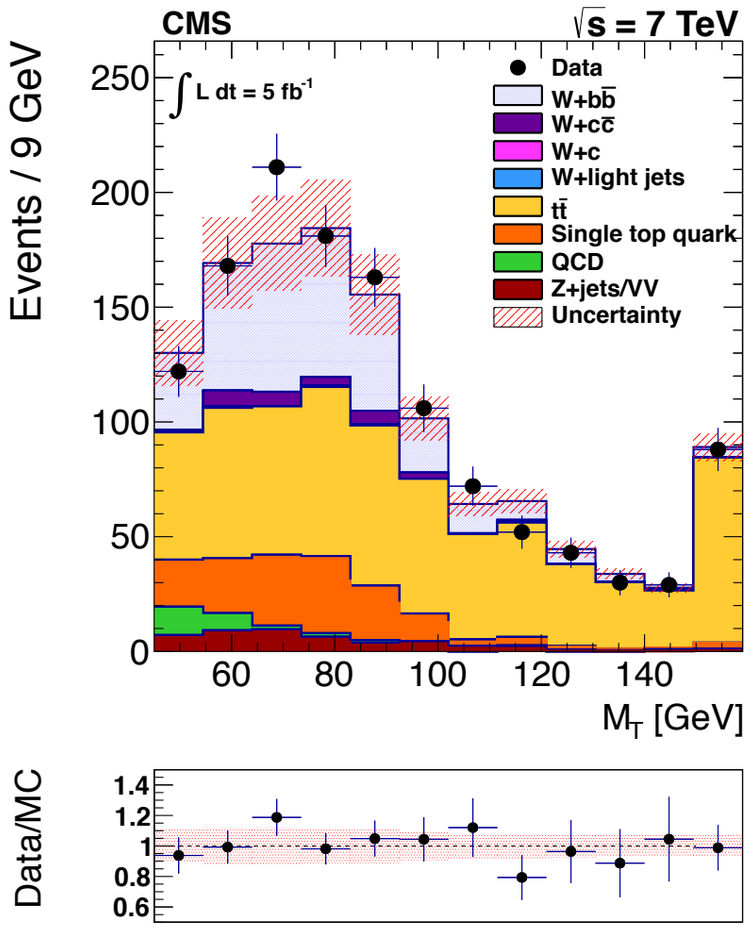
W+bb

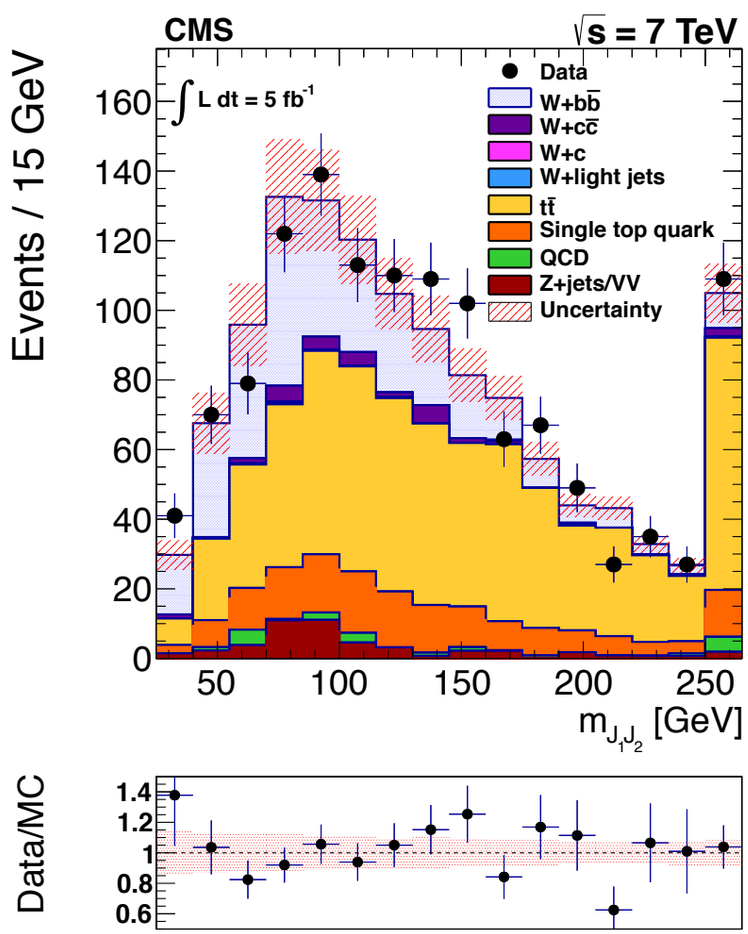
arXiv:1312.6608
PLB735 (2014) 204

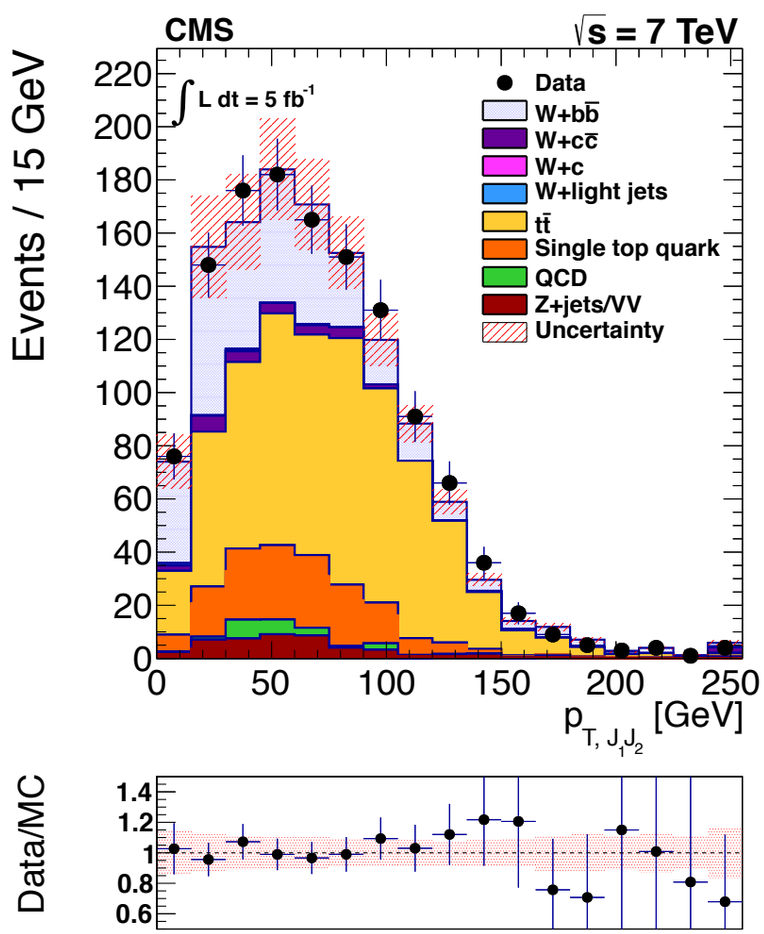
- Largest BG: top-quark pair production
- Well separated 2 b-jets → less theoretical uncertainty

$$\sigma(\mathrm{pp} \to \mathrm{W} + \mathrm{b\bar{b}}) \times \mathcal{B}(\mathrm{W} \to \mu\nu) = 0.53 \pm 0.05\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst}) \pm 0.06\,(\mathrm{theo.}) \pm 0.01\,(\mathrm{lumi})\,\mathrm{pb}.$$

$$\text{Theory:} \quad 0.55 \pm 0.03\,(\mathrm{MCFM}) \pm 0.01\,(\mathrm{had.}) \pm 0.05\,(\mathrm{DPS})\,\mathrm{pb}.$$







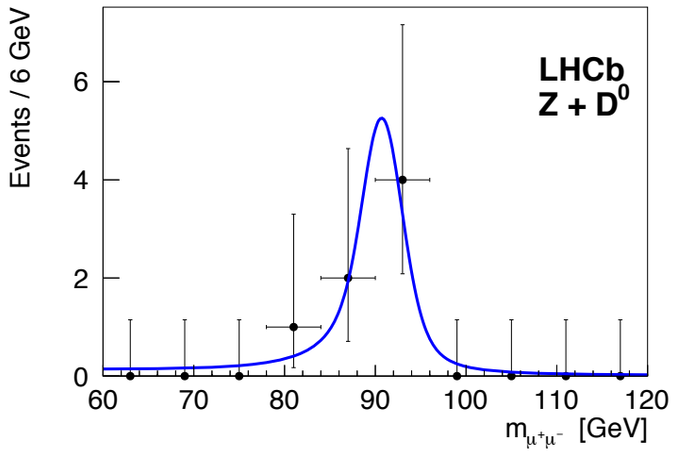
cf. ATLAS W+b: JHEP06 (2013) 084

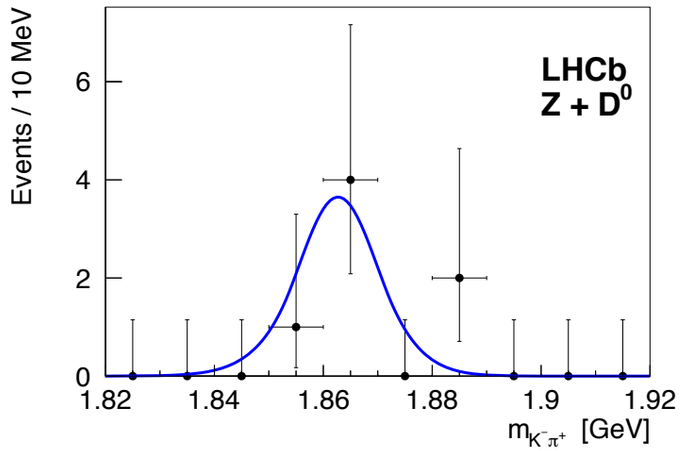
Z+D from LHCb

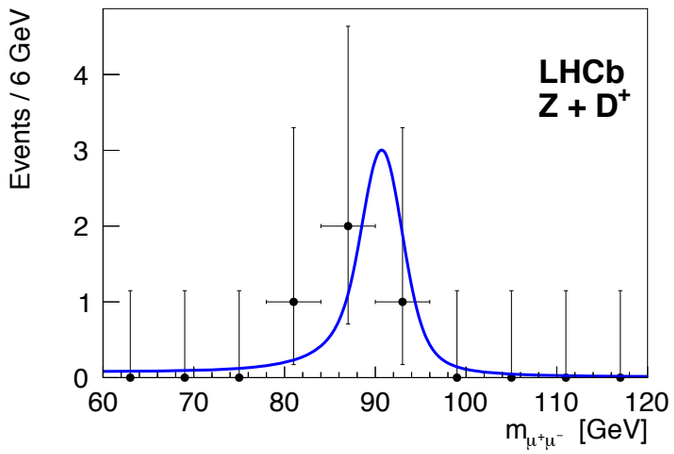
- Exclusive reconstruction of $Z \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^-\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$ (+c.c.)

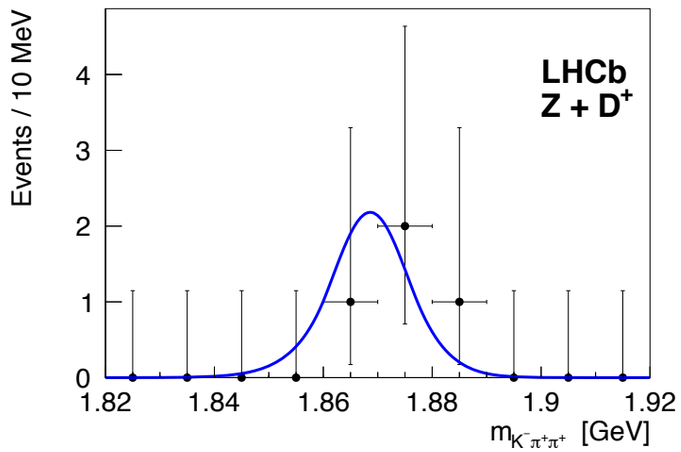
arXiv:1401.3245
JHEP04 (2014) 091

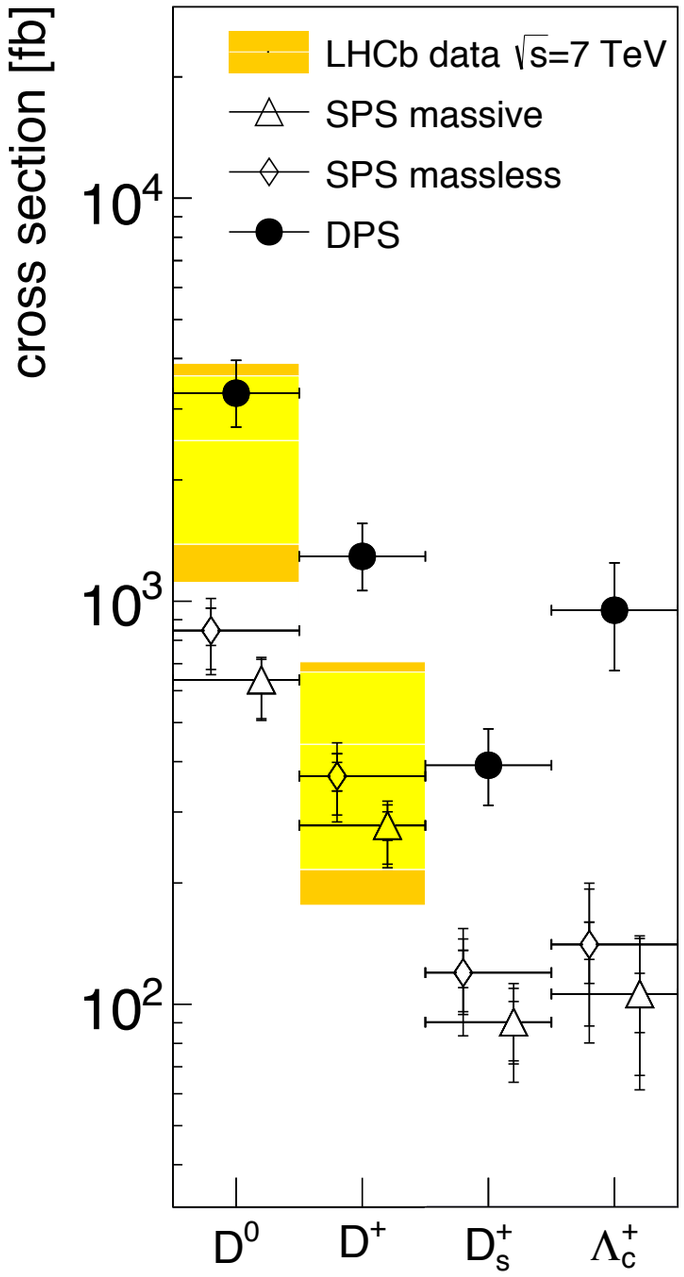
- Compared with Single Parton Scattering (one parton-parton collision creates Z & D) and Double Parton Scattering (one collision creates Z and another for D)









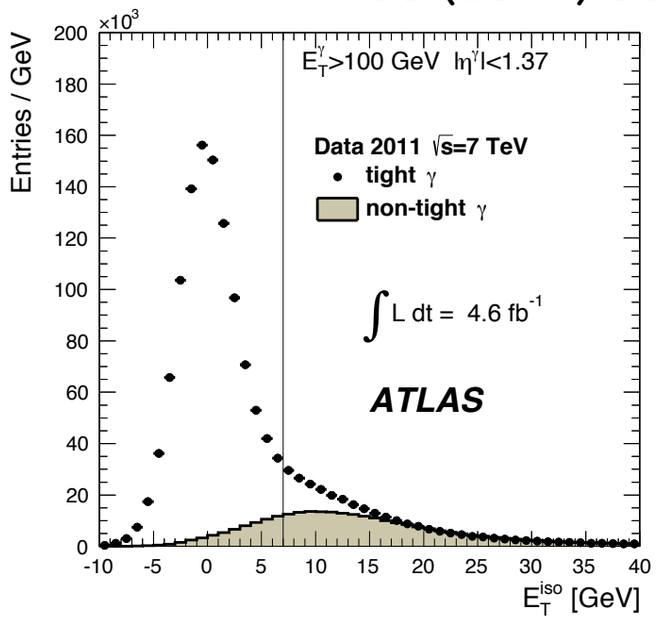


Prompt γ

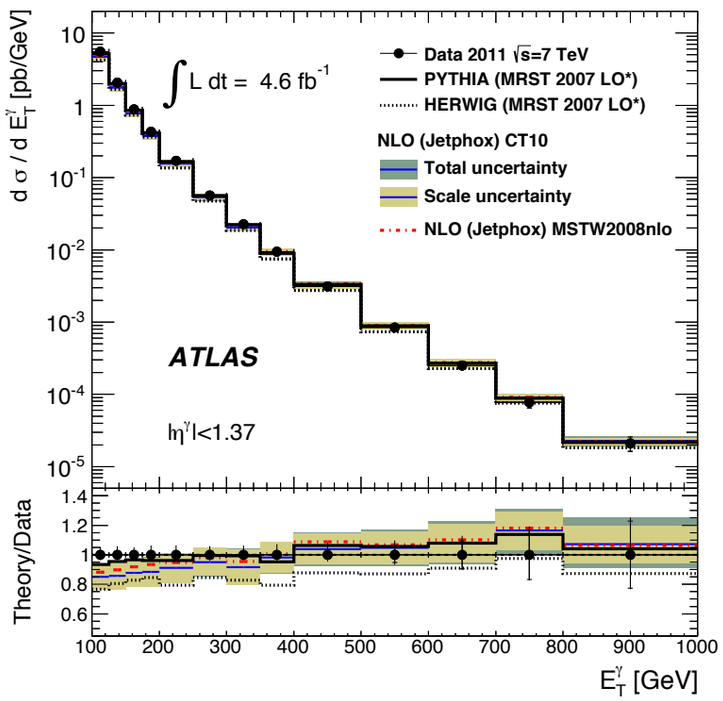
arXiv:1311.1440

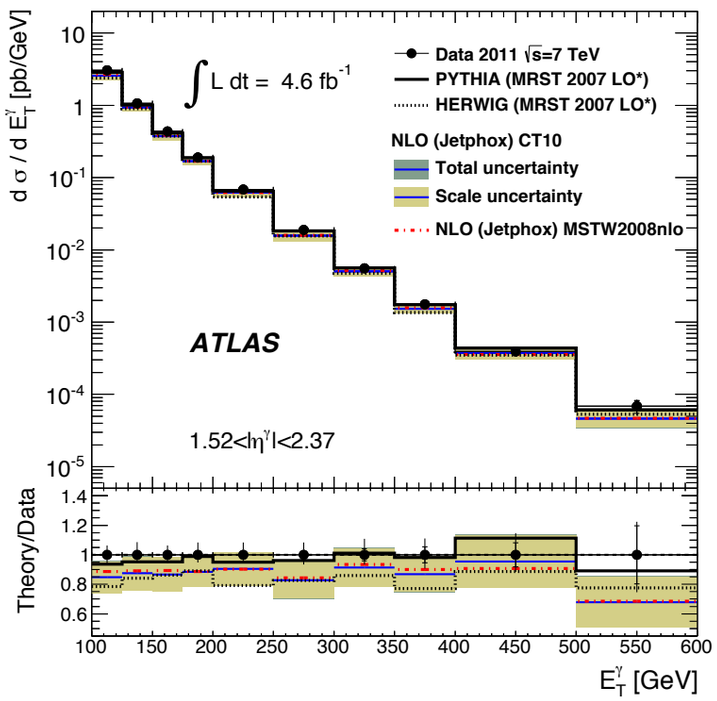
PRD89 (2014) 052004

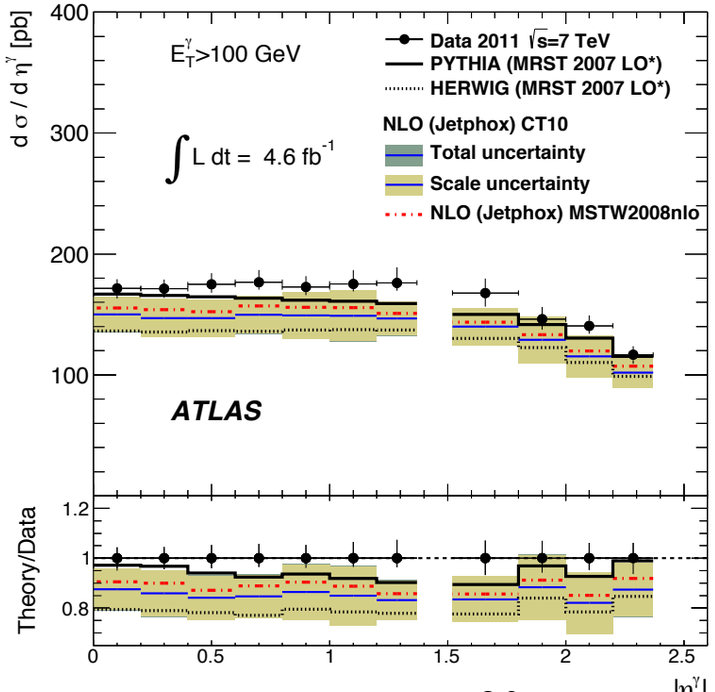
- $qg \rightarrow q\gamma$, $q\bar{q} \rightarrow g\gamma$
- Sensitive to gluon PDF
- Signal extraction using isolation E
- Compared to NLO calculations and LO MC generators



- $100 < E_T^{\gamma} < 1000$ GeV, $|\eta^{\gamma}| < 2.37$







γ pair production

- $q\bar{q} \rightarrow \gamma\gamma$ in LO. BG in $H \rightarrow \gamma\gamma$
- SHERPA and 2γ NNLO describes data well

arXiv:1405.7225

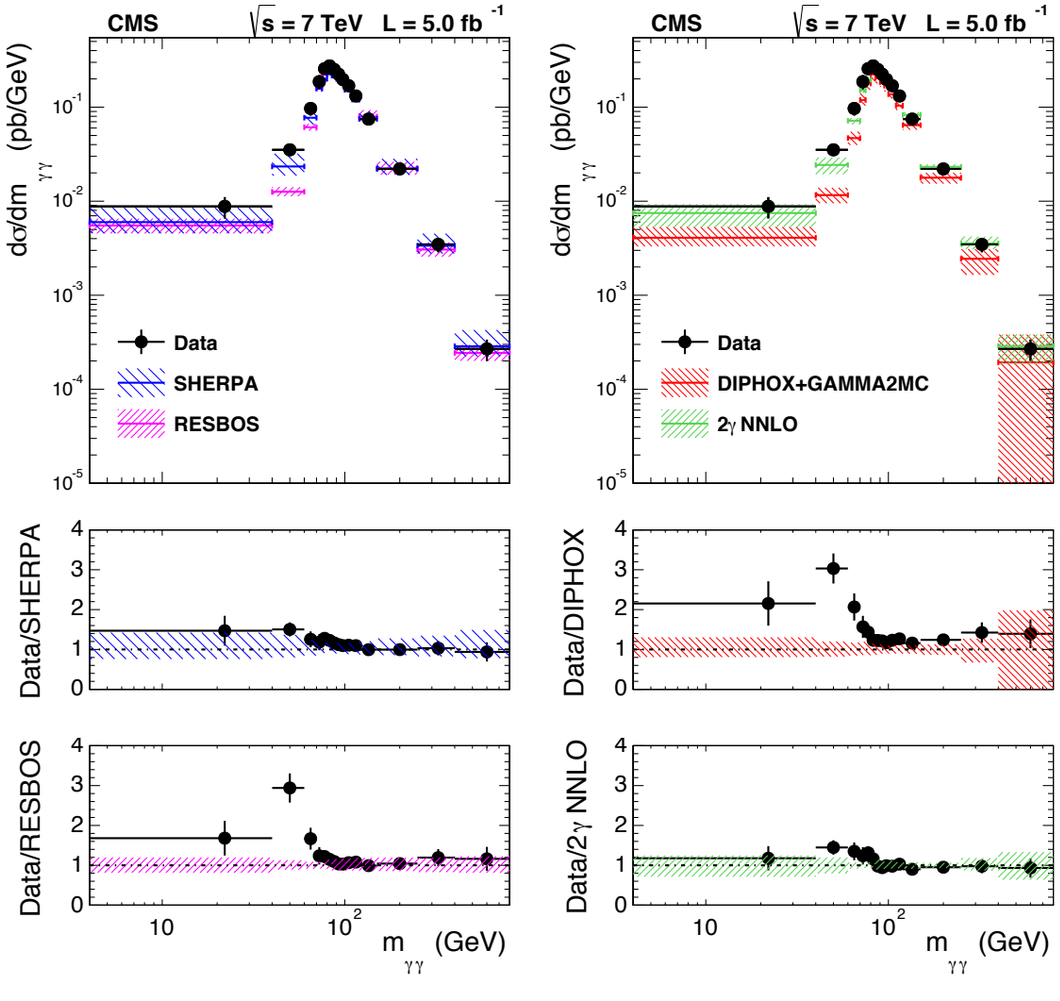
$|\eta(\gamma)| < 2.5$

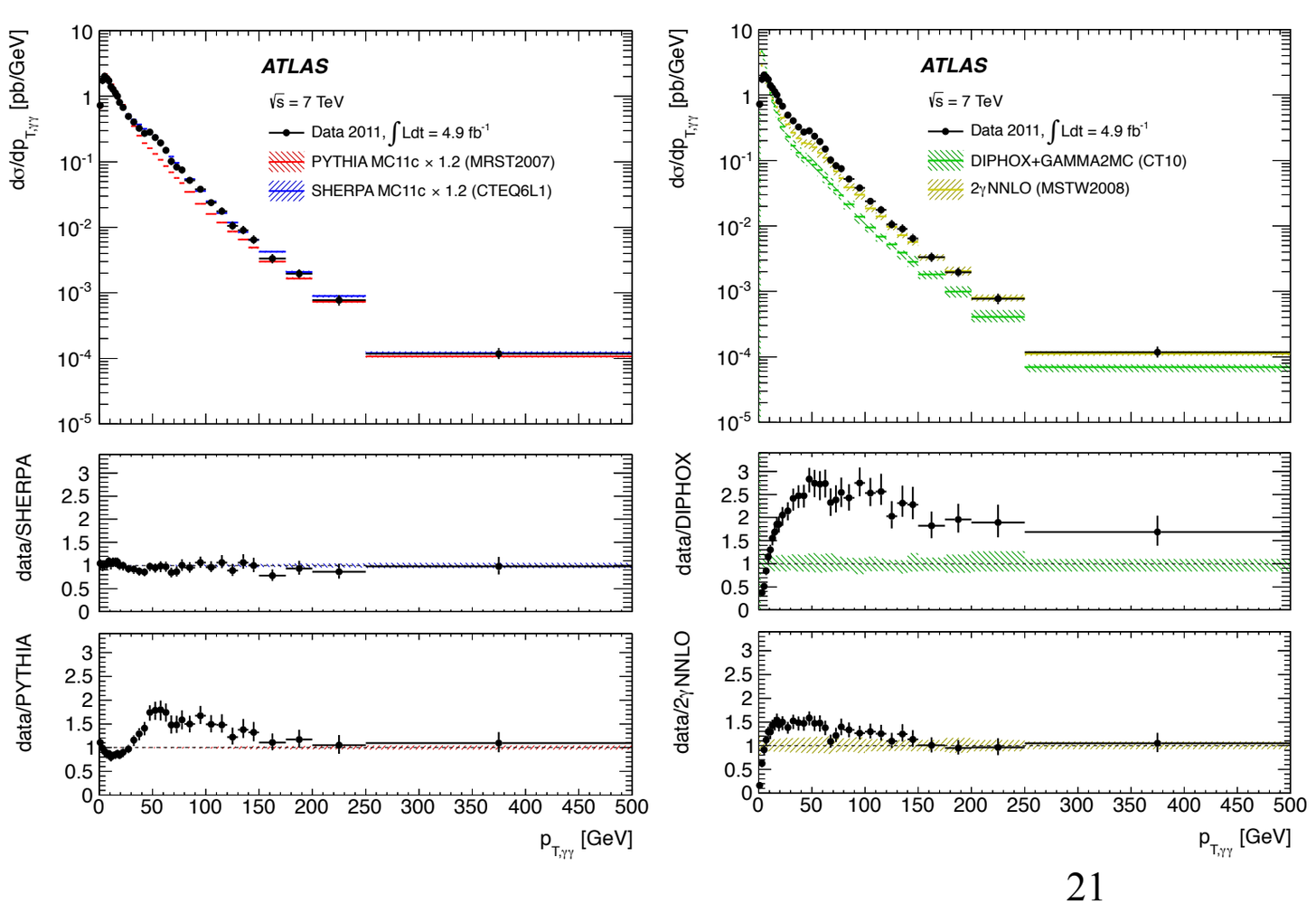
$E_T(\gamma_1) > 40\text{GeV}$, $E_T(\gamma_2) > 25\text{GeV}$

arXiv:1211.1913 JHEP01 (2013) 086

$|\eta(\gamma)| < 2.37$

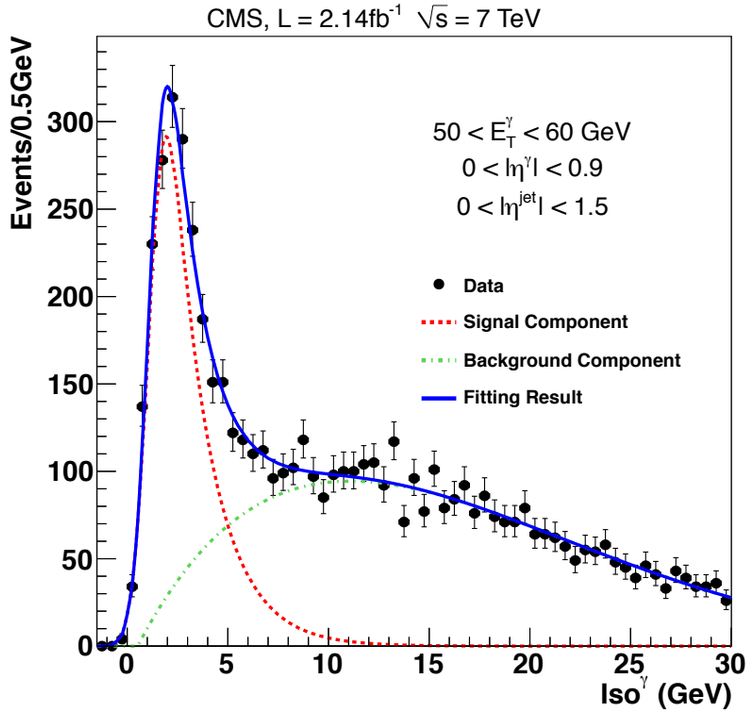
$E_T(\gamma_1) > 25\text{GeV}$, $E_T(\gamma_2) > 22\text{GeV}$



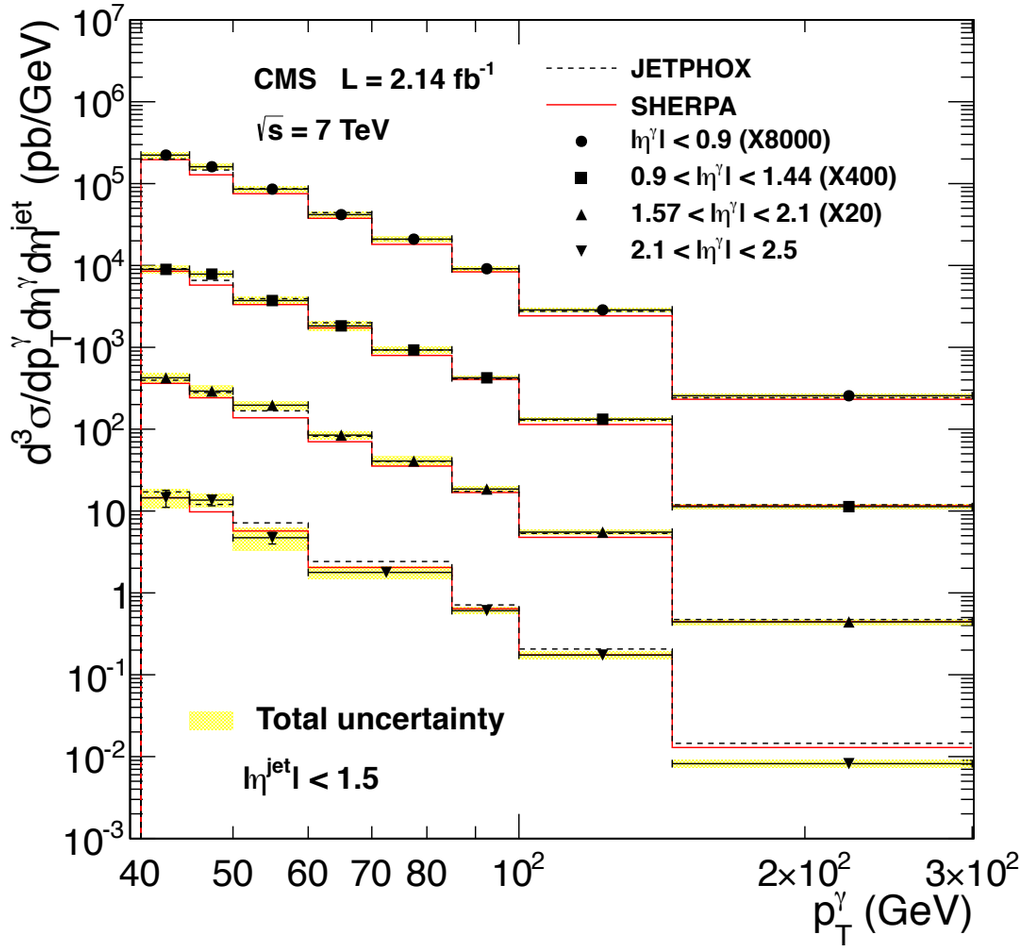


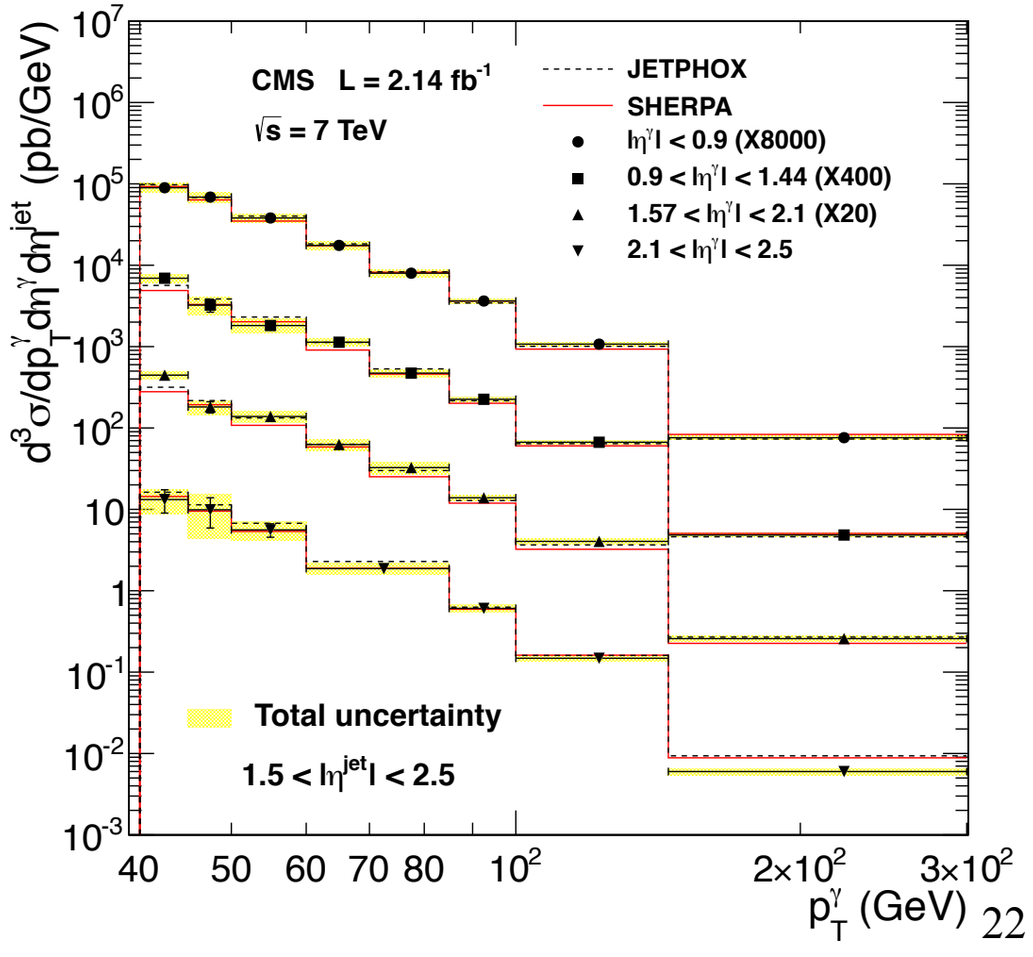
γ+jets

- Triple differential in p_T^{γ}, η^{γ}, η^{jet}
- Signal extraction using isolation E
- Predictions agree with data except for highest p_T^{γ} and η^{γ}



arXiv:1311.6141 JHEP06 (2014) 009

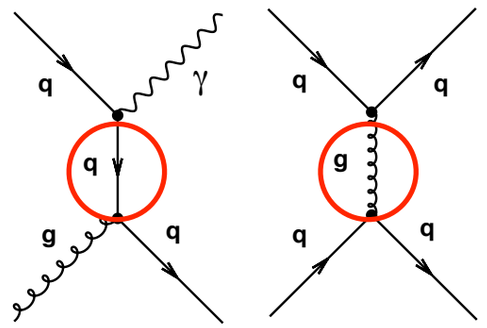




γ+jets - cont.

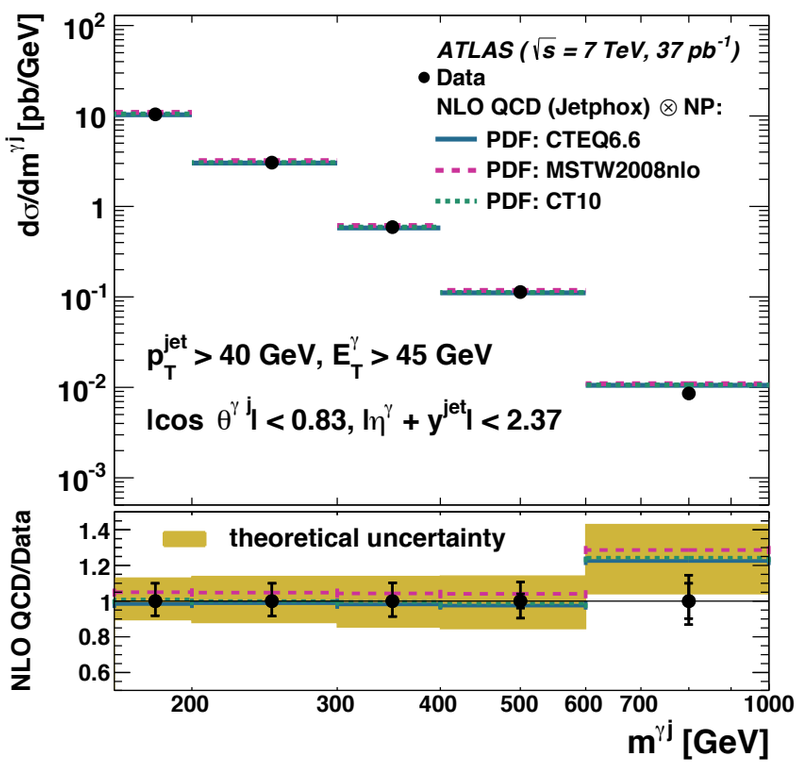
NPB875 (2013) 483

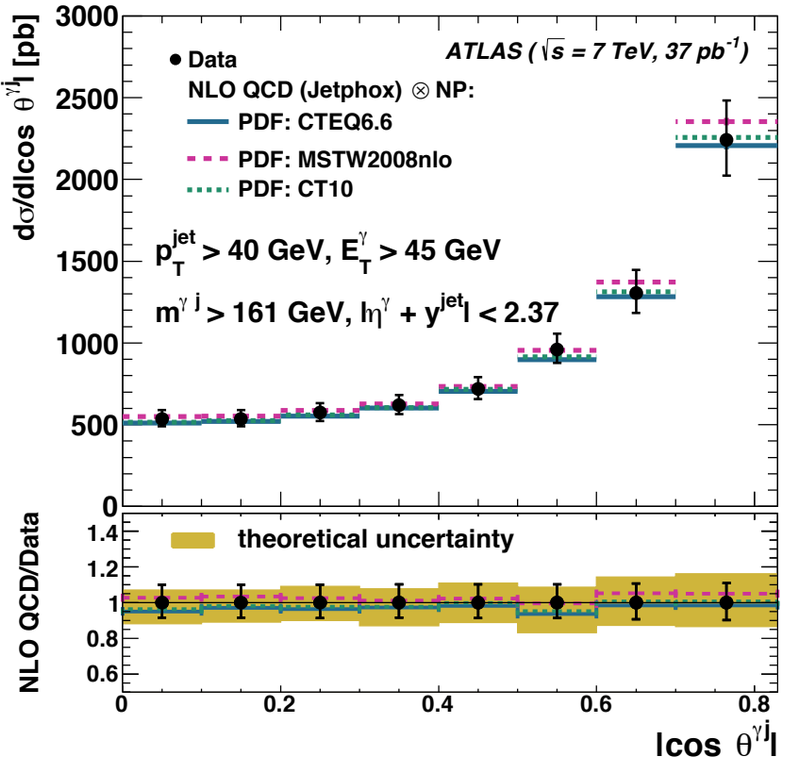
- Dynamics of γ+jet production tested
  - $m^{\gamma j}$, scattering angle in CM system ($|\cos\theta^{\gamma j}|$) well described by NLO
  - spin 1/2 quark propagator (cf. dijet)
  - difficulty in $\Delta\Phi^{\gamma j}$: can't have two in same hemisphere

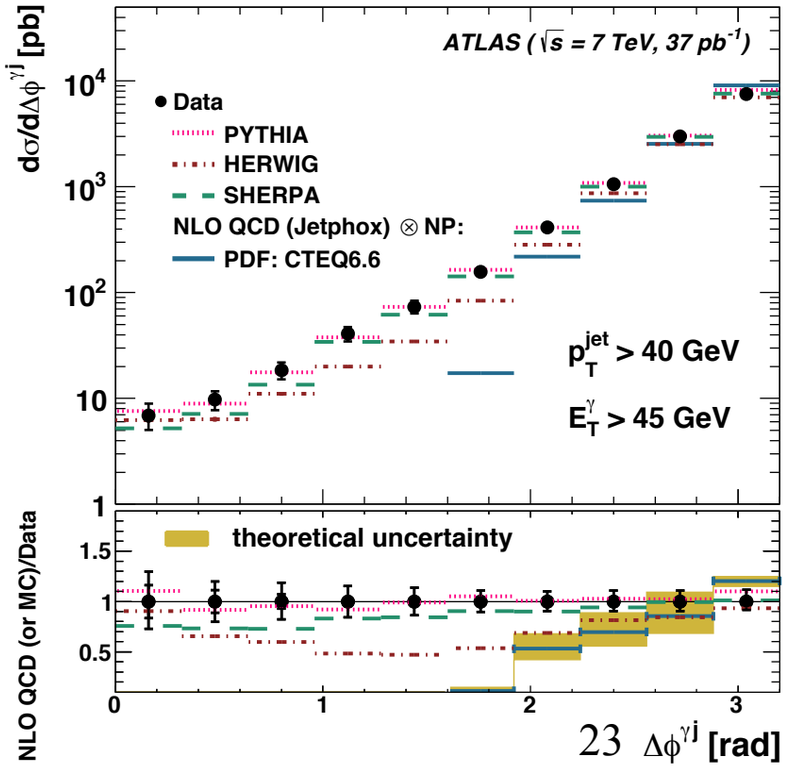


spin-1/2 spin-1

(Pythia LO + parton shower does a good job)

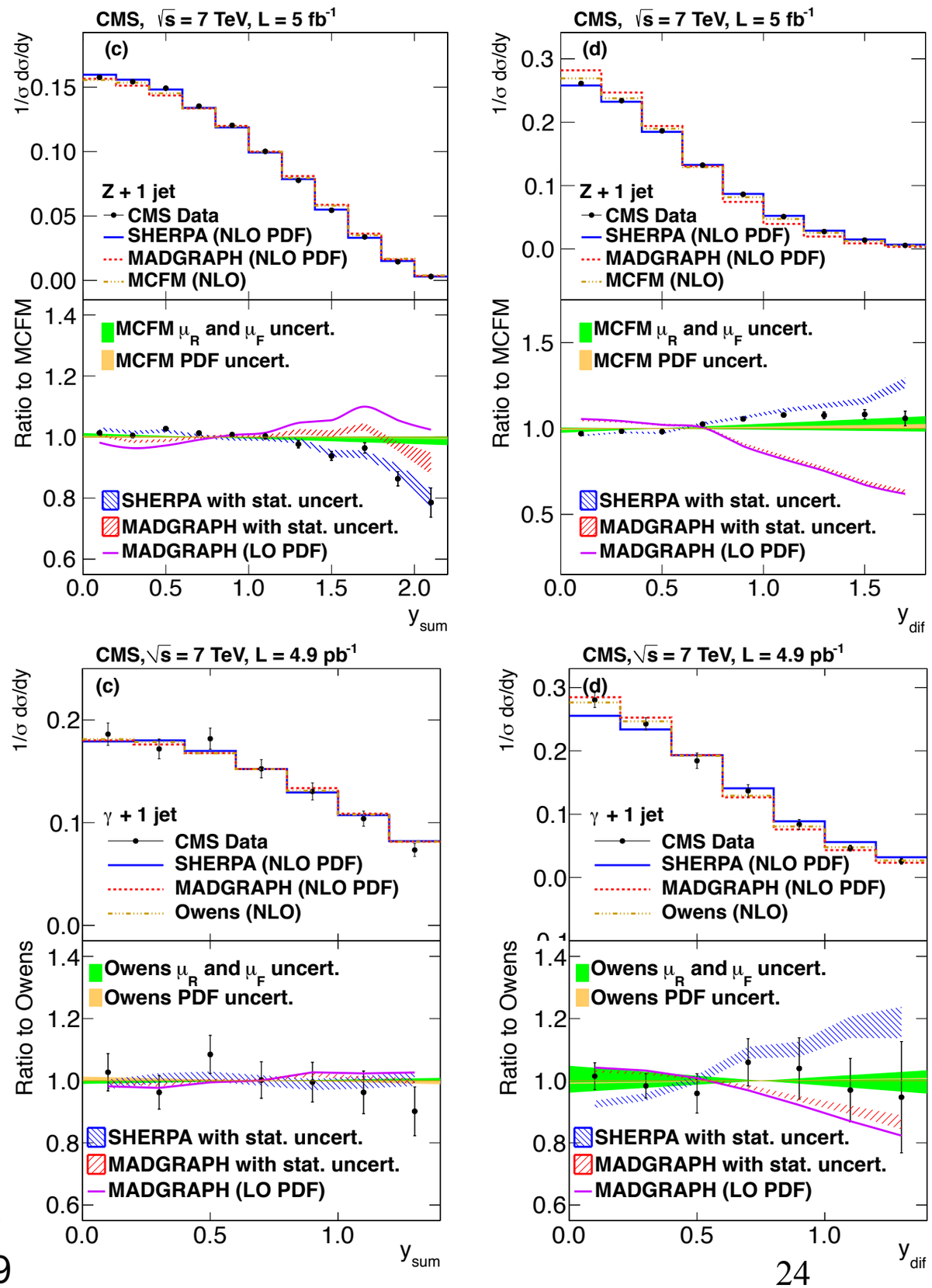






γ+jet, Z+jet rapidity dist.

- $y_{sum}=|y_{\gamma,Z}+y_{jet}|/2$
  $y_{dif}=|y_{\gamma,Z}-y_{jet}|/2$
- y_{sum} is total boost, sensitive to PDF
- y_{dif} reflects scattering dynamics
- Predictions differ at large y_{dif}
- NLO calculations agree both in γ and Z cases

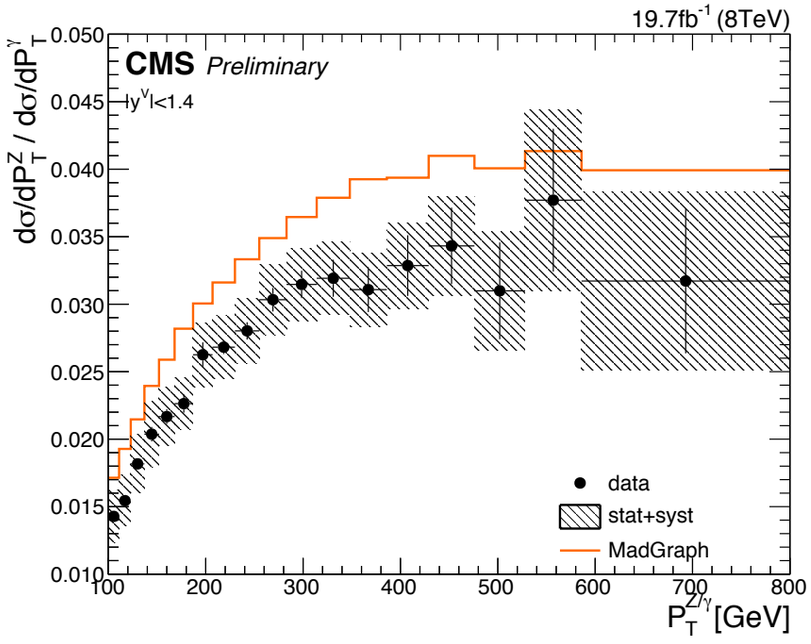


arXiv:1310.3082
PRD88 (2013) 112009

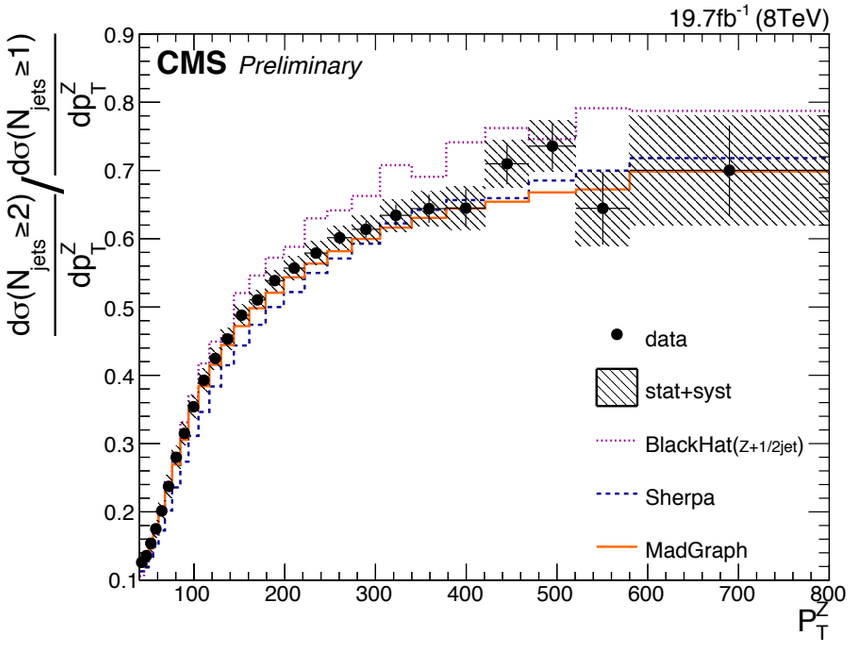
Z+jets/γ+jets ratio @8TeV

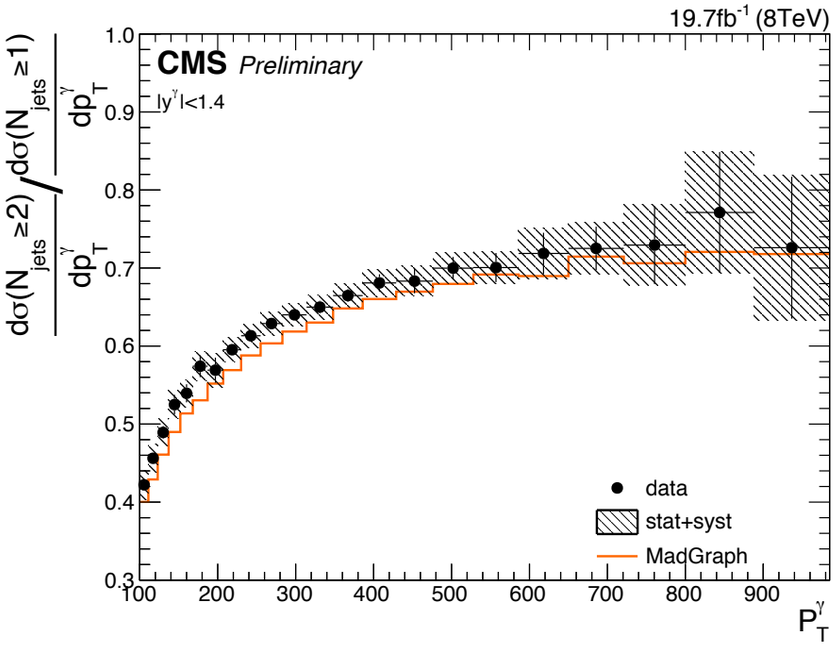
- Compare Z/γ*+jets and γ+jets cross sections at the same vector boson kinematics
- Z/γ ratio reaches plateau (~0.03) for $p_T^{\gamma,Z}$ > ~300 GeV
- Validate the ($Z\to\nu\bar{\nu}$)+jet BG in new physics searches based on γ+jet kinematics

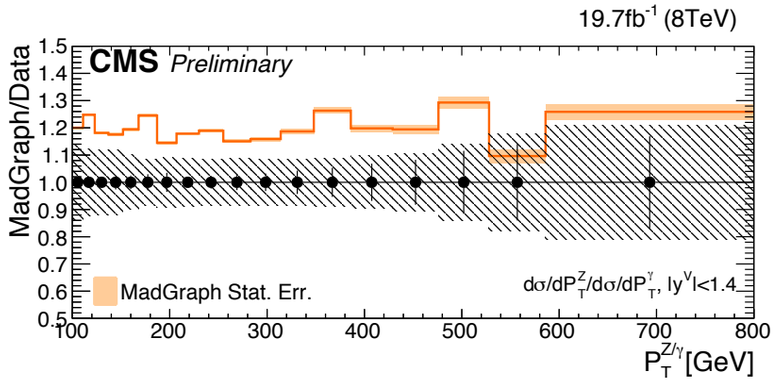
CMS-PAS-SMP-14-005



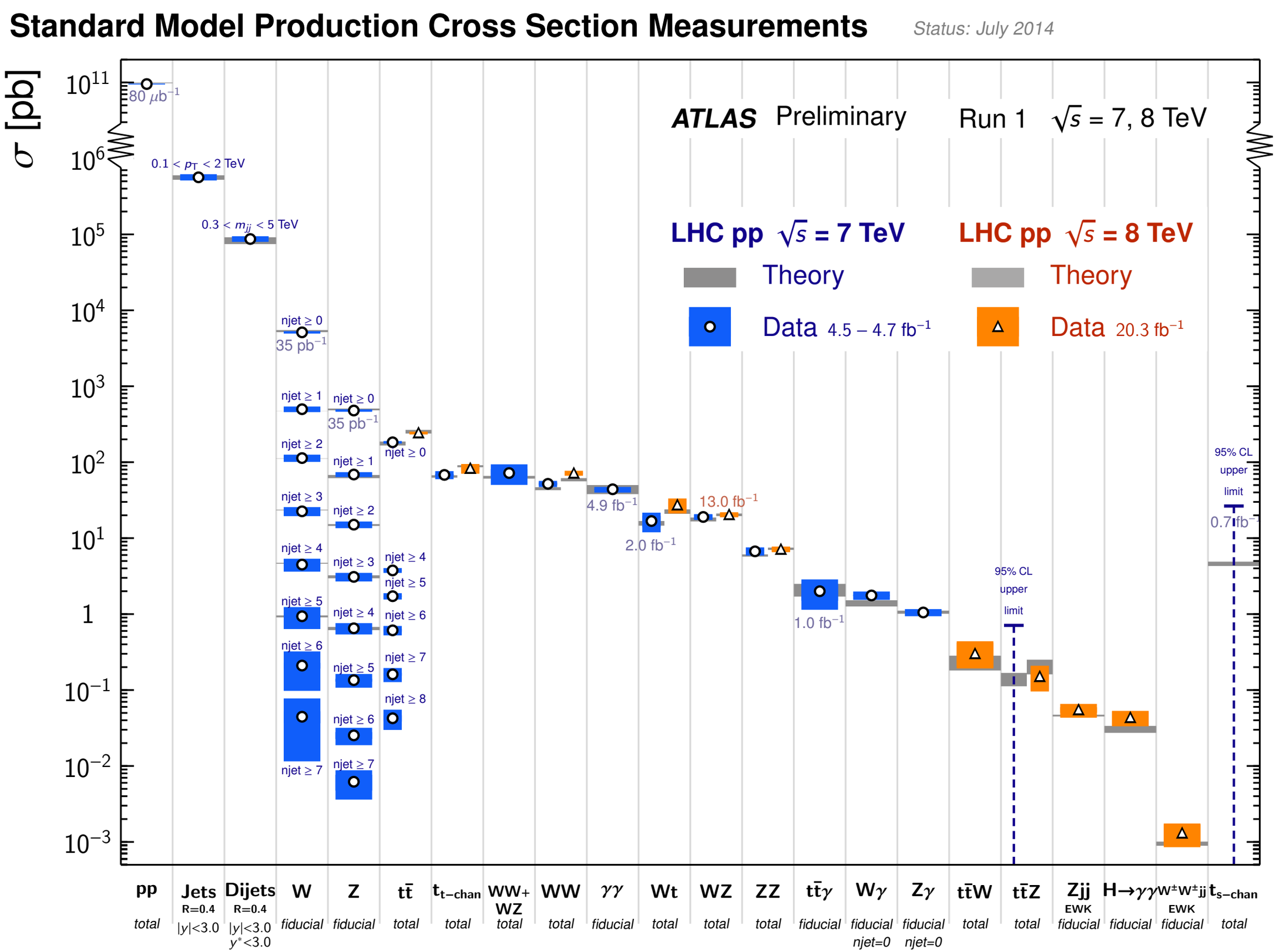
>=2 jets / >=1 jets ratio for Z and γ



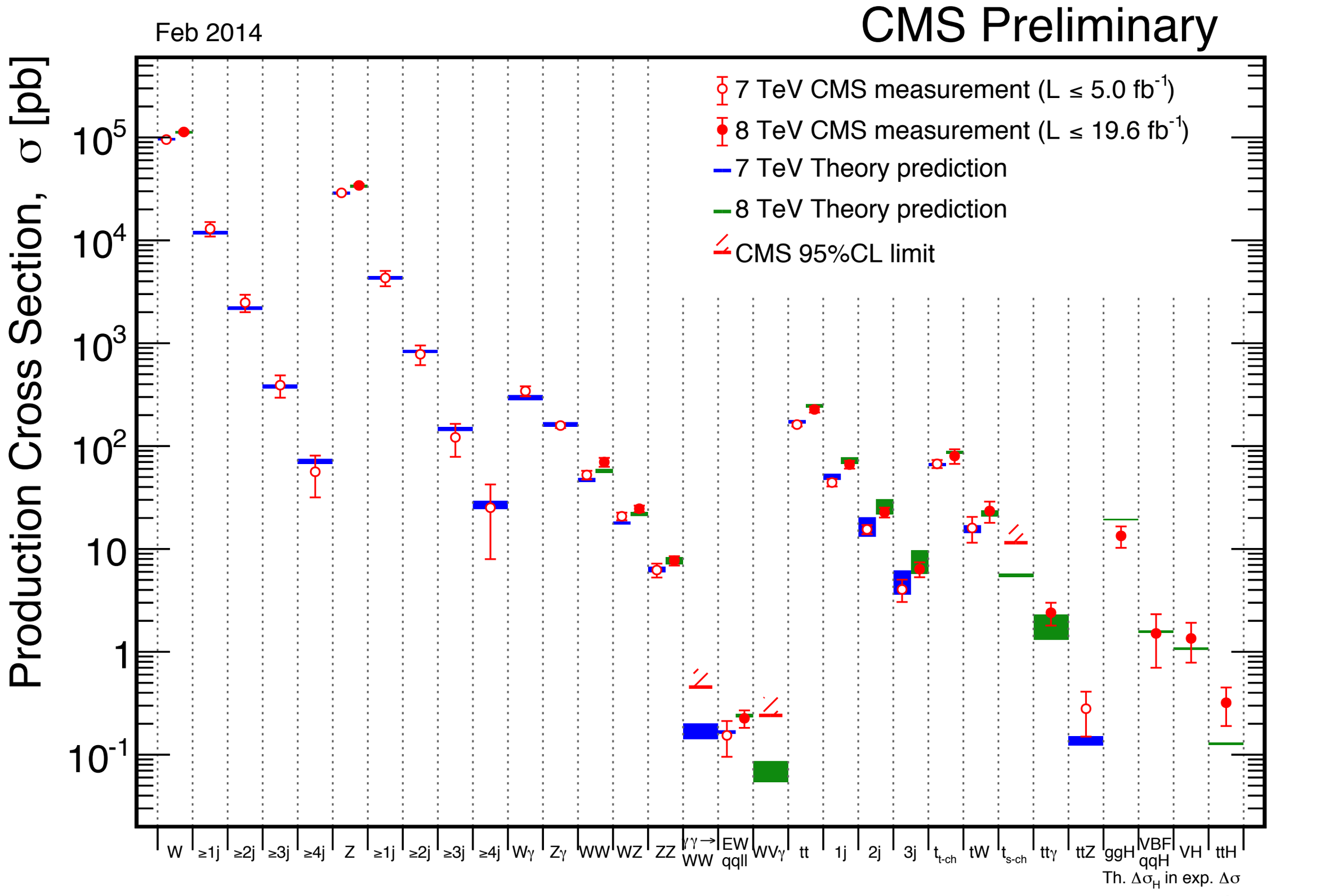




Summary plot - ATLAS



Summary plot - CMS



Conclusions

- Wealth of results in W/Z/γ production at the LHC from Run 1 (most are new since PIC 2013)
- Tests of SM (EW+QCD) at the highest energy for extreme kinematics (< ~1TeV) and topologies (many jets, heavy flavors, ...)
- Crucial inputs for developments of theoretical predictions (NLO, NNLO) and MC generators
- Be ready for new physics signals in Run 2 (2015-)
- More 8 TeV results expected in PIC 2015 !