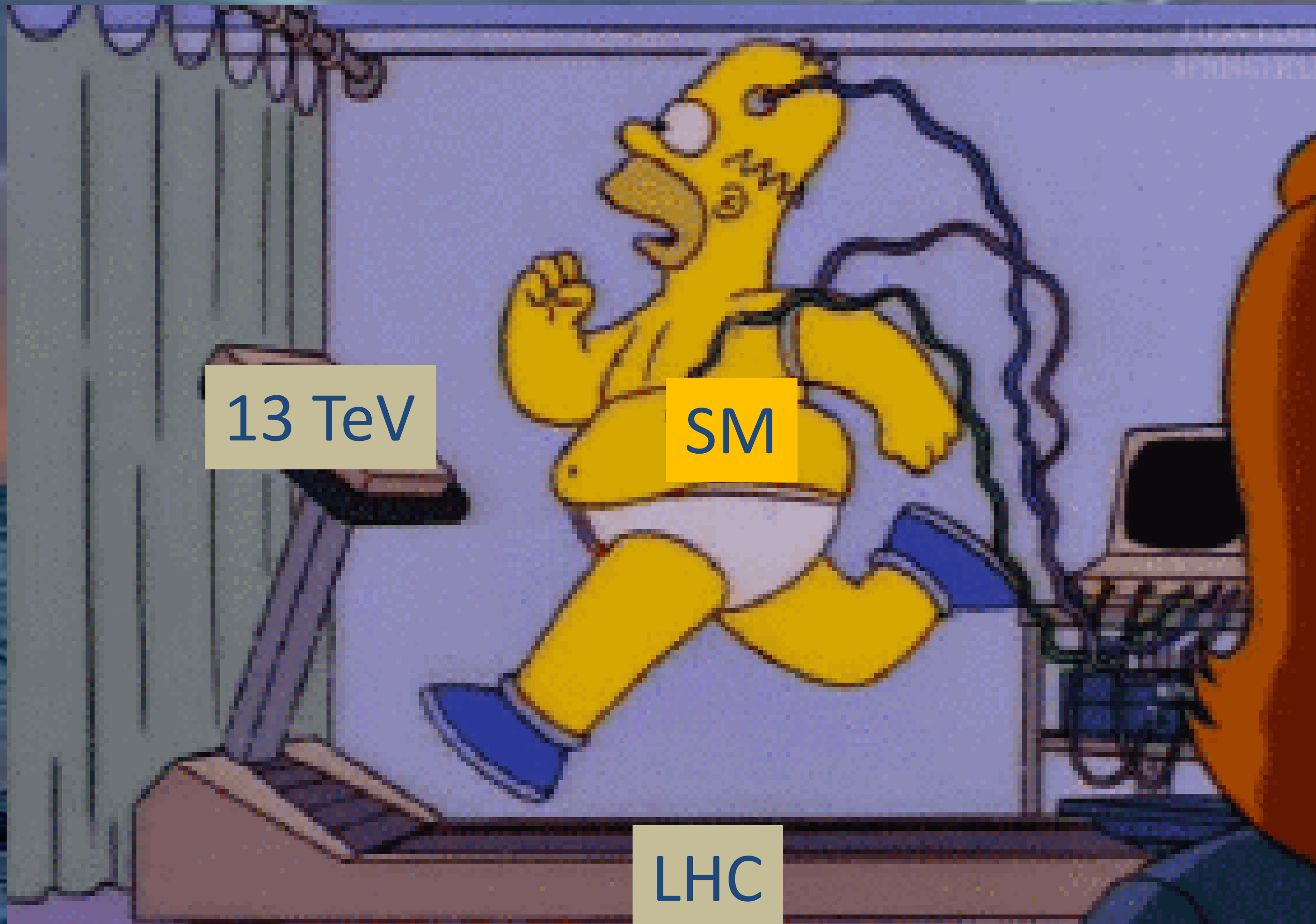
Stress Testing the Standard Model



Jeffrey Berryhill, FNAL

KITP

May 23, 2016

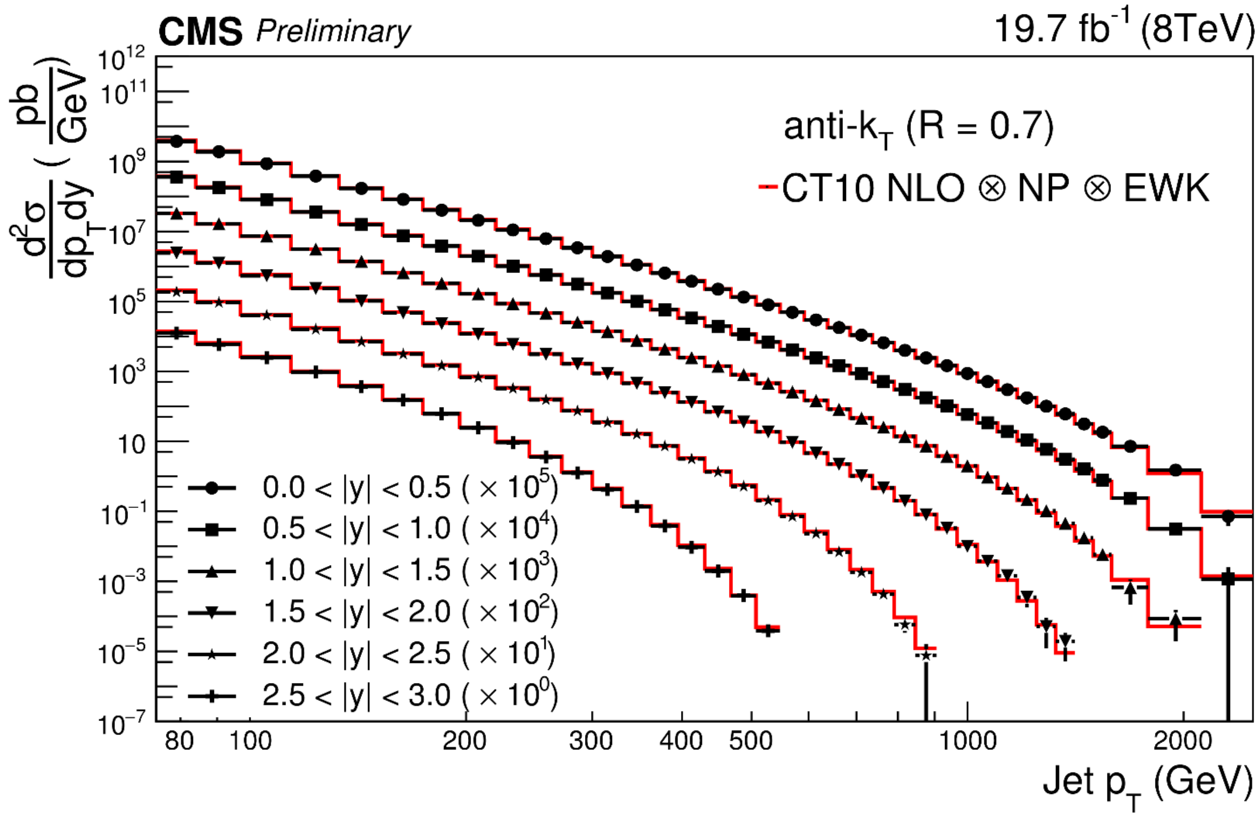
Outline

1. **Jet cross sections**
2. Associated jet production
3. Top quarks
4. Vector boson production
5. Diboson production and TGCs
6. Vector boson scattering and QGCs

Inclusive jet production at LHC

CMS-PAS-SMP-14-001

- Fixed-order NLO prediction folded with non-perturbative corrections
- Agreement observed with data over 2 decades in energy and 13 orders of magnitude in cross section!
- Jets observed with ET> 2 TeV
- ~1% jet energy scale uncertainty dominates cross section error.
- Will improve q, g PDF uncertainty at high x

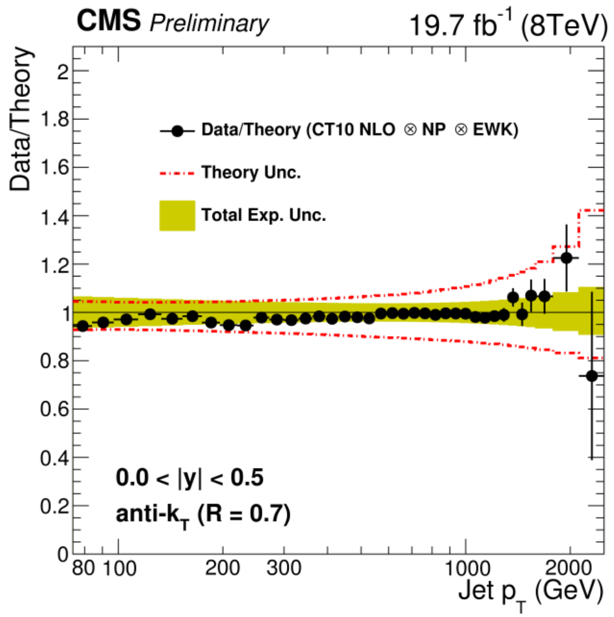


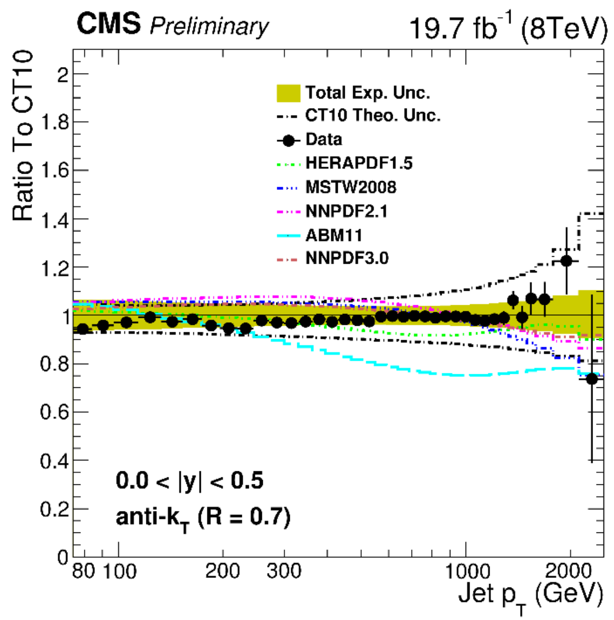
Inclusive jet production at LHC

CMS-PAS-SMP-14-001

- Experimental uncertainty is comparable to theory uncertainty above ~500 GeV jet ET
- Agreement across large x range with contemporary PDFs

- Across PDF families, comparable agreement to data is observed (except for ABM11)

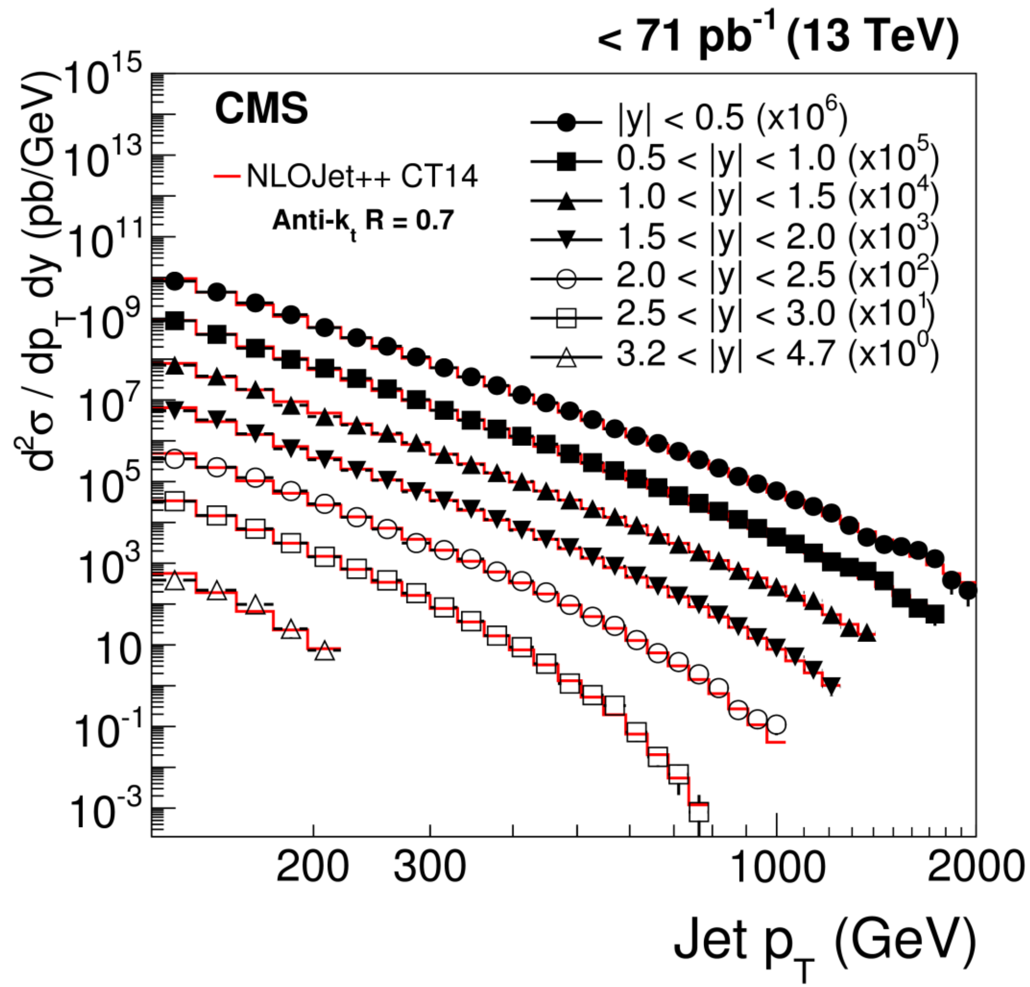




Jet Cross Sections at 13 TeV

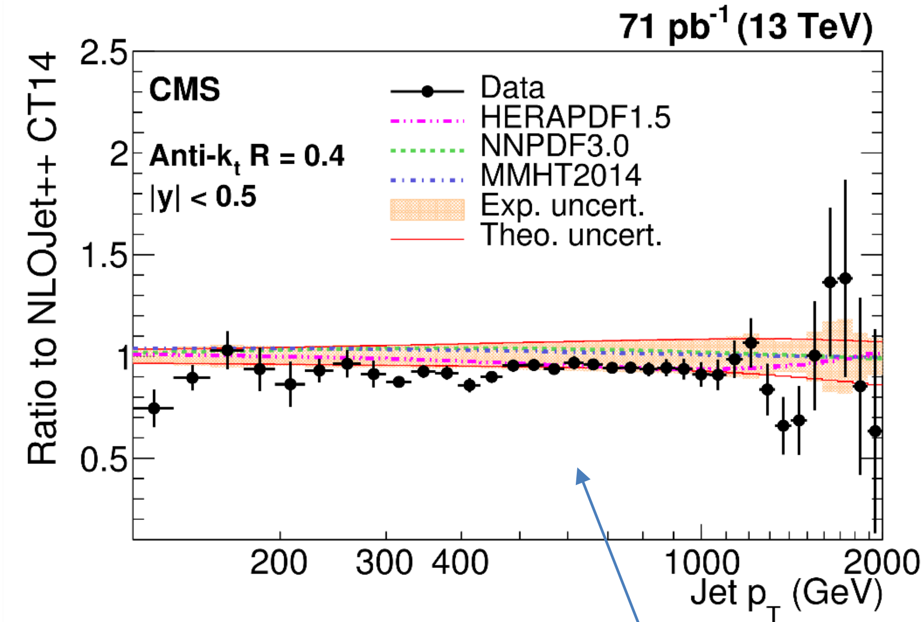
arxiv:1605.04436

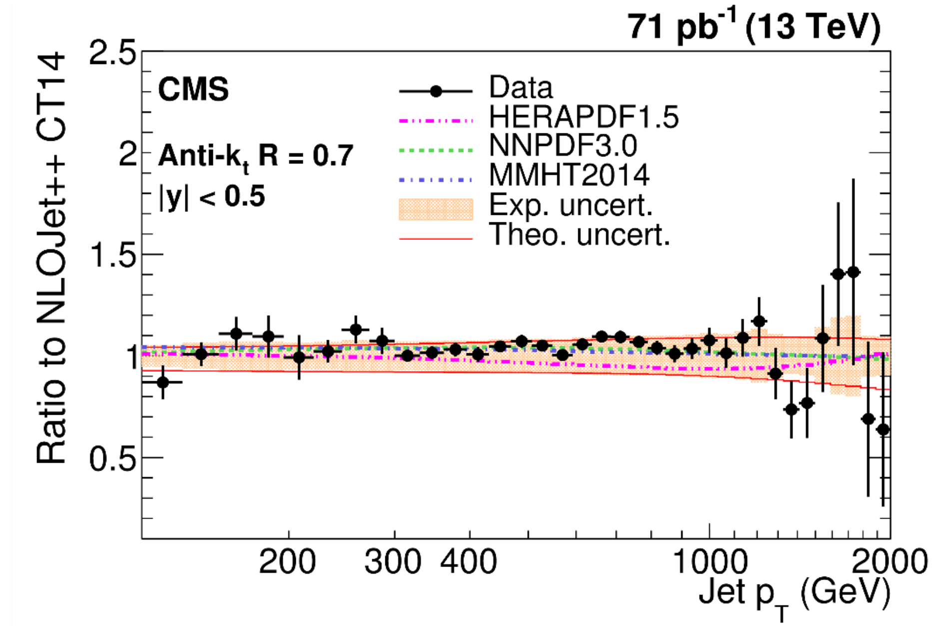
Similar agreement over a similar range at 13 TeV with AK7 jets up to 2 TeV



Jet Cross Sections at 13 TeV

arxiv:1605.04436

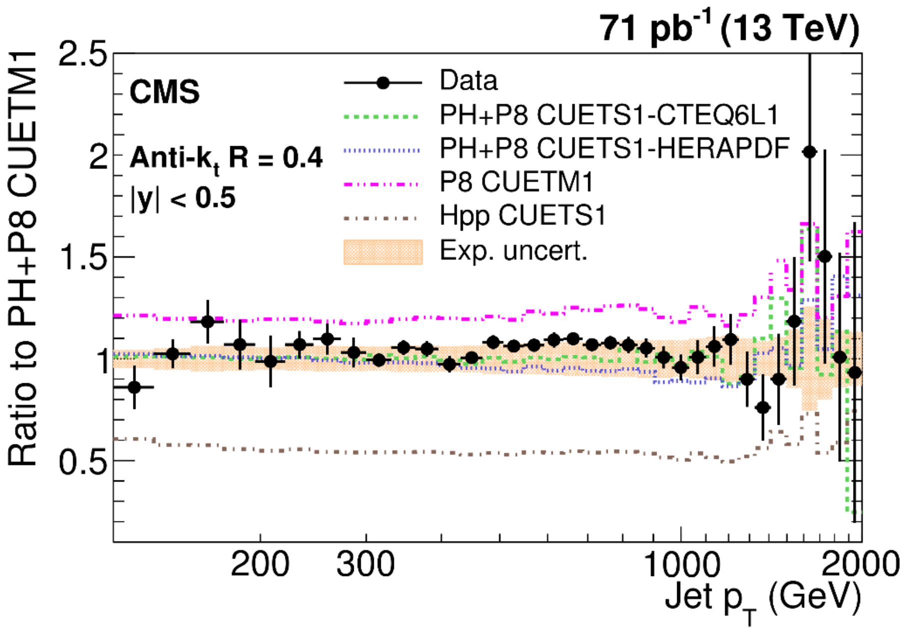


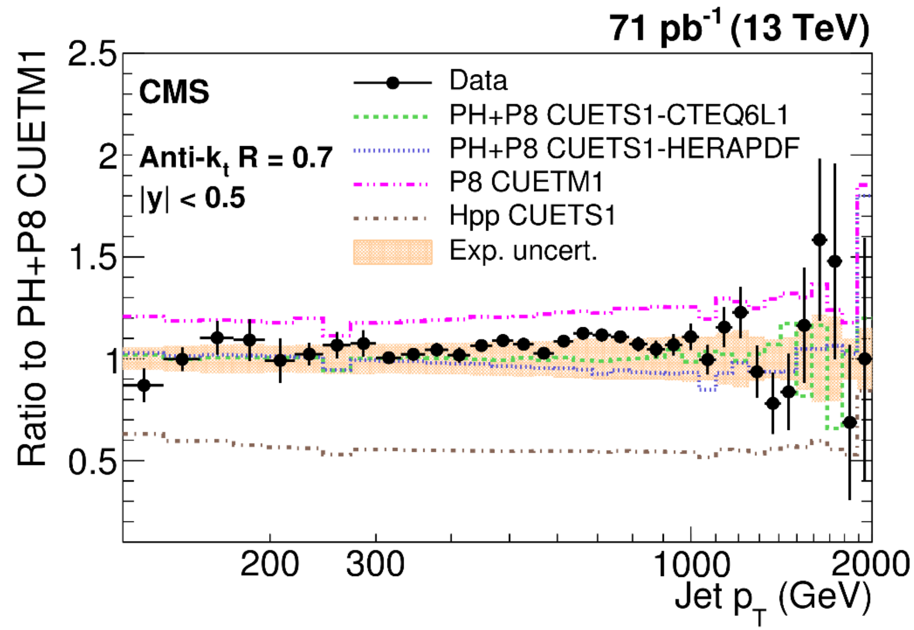


NLOJet++ consistently over-predicts for AK4 jets

Jet Cross Sections at 13 TeV

arxiv:1605.04436



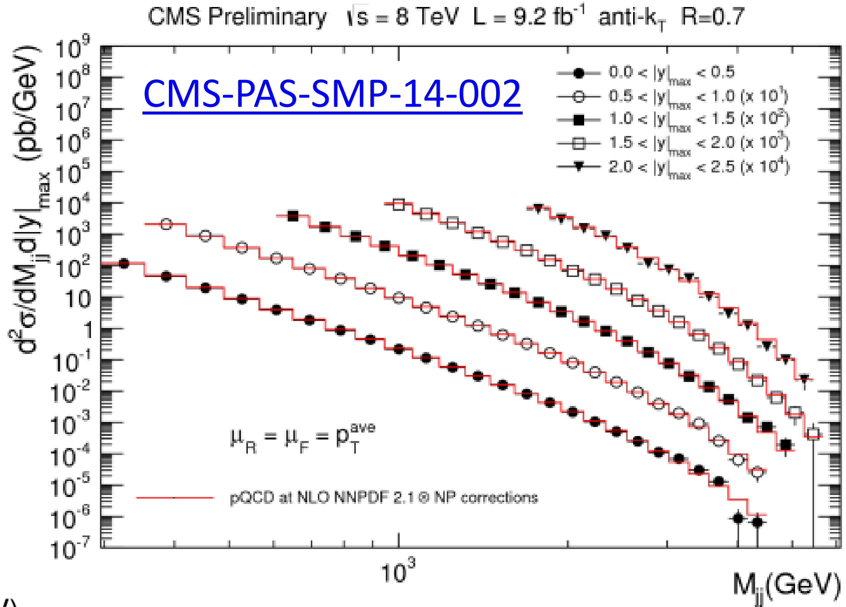


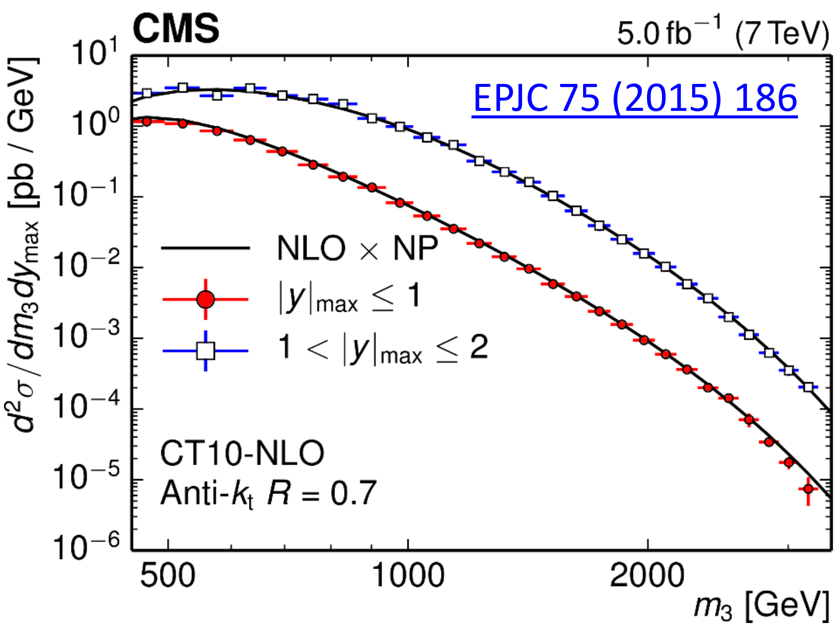
POWHEG+PYTHIA8 does well for both jet sizes → **parton showering matters for AK4 !**

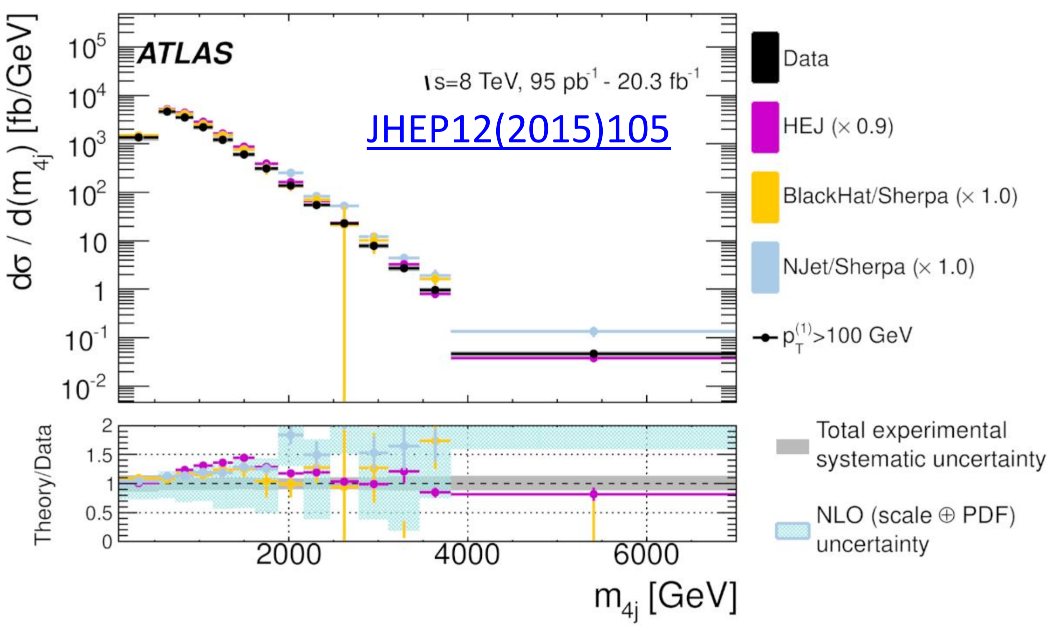
Multi-Jet Cross Sections

Two- and three-jet masses modeled well by NLOJet++.

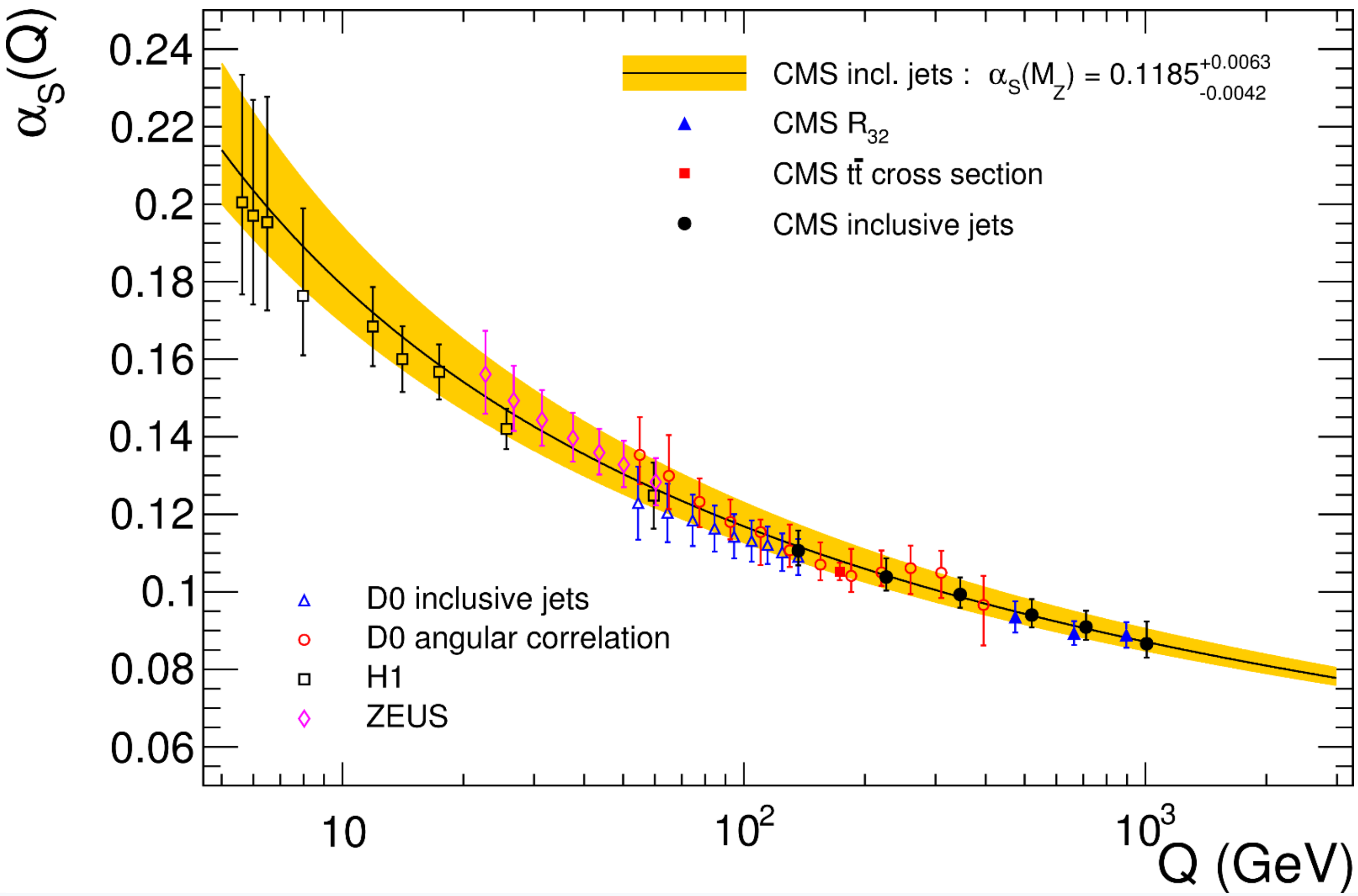
New four-jet result from ATLAS has **varied agreement with different predictions and distributions**







Strong Coupling Constant



Consistent strong coupling behavior for a wide array of jet phenomena

Chief limitation is NLO scale dependence → NNLO jet cross sections will up the stakes considerably!

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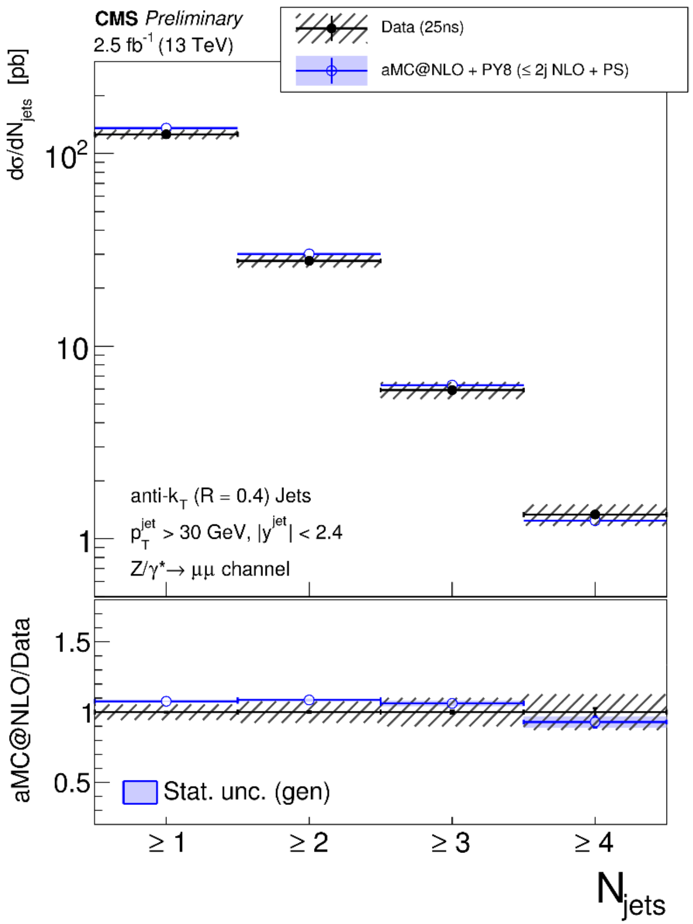
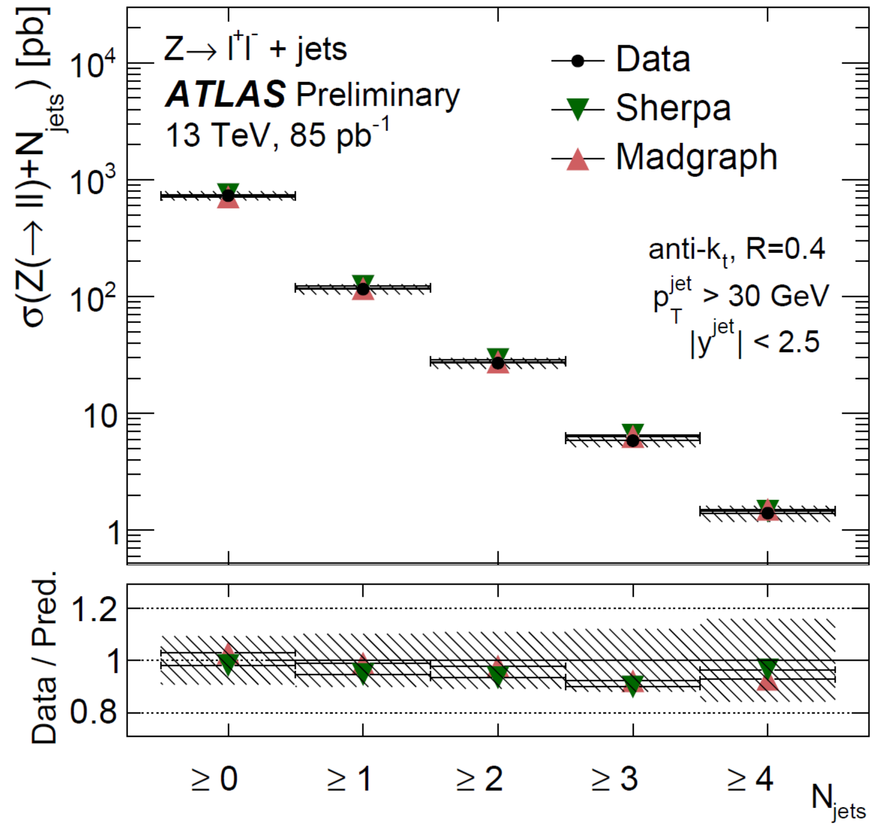
Z + Jets at 13 TeV



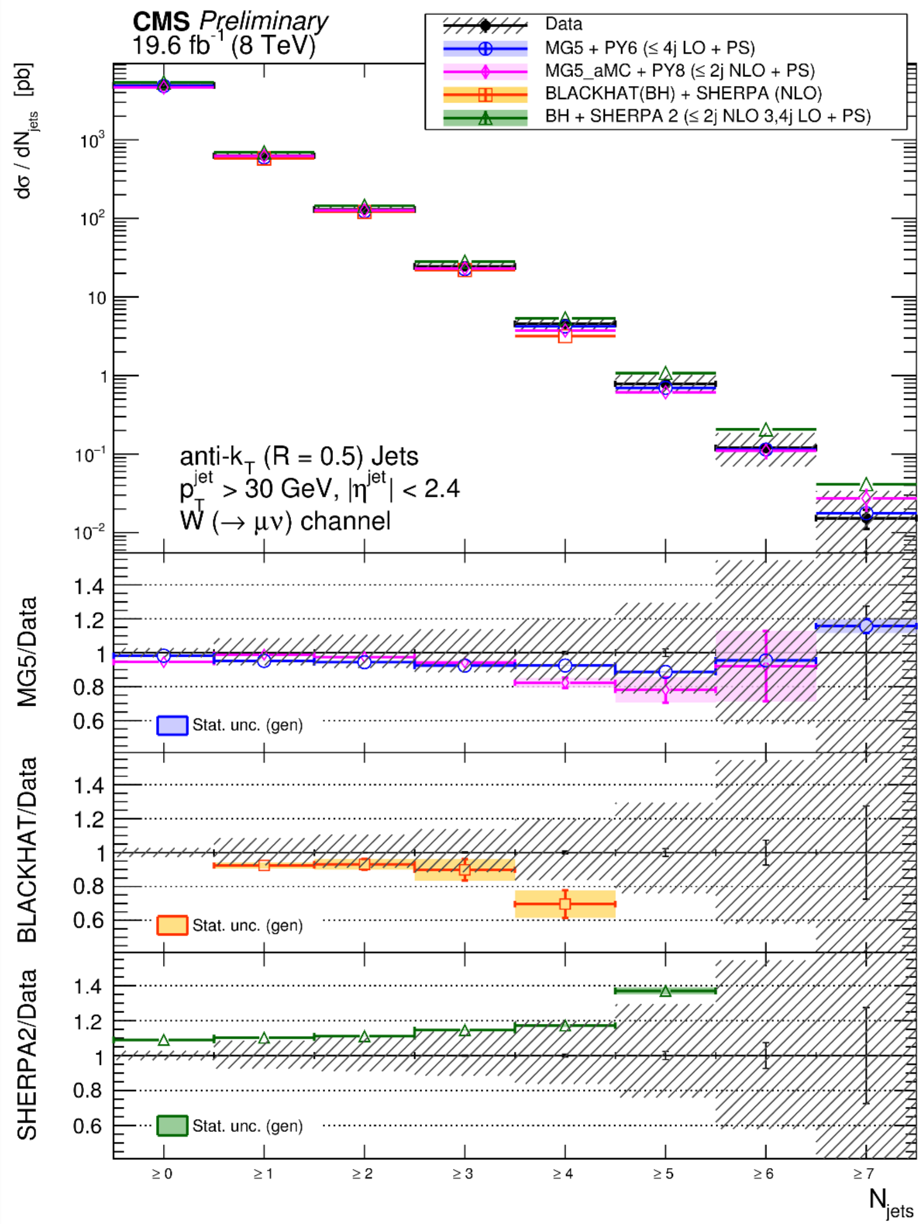


Njet shape at 13 TeV modeled at 10% level by standard PS MCs

W+jets Production at 8 TeV

Z+b Madgraph predictions better with 5FS, esp. at higher PT
POWHEG + Pythia6 predicts well in general

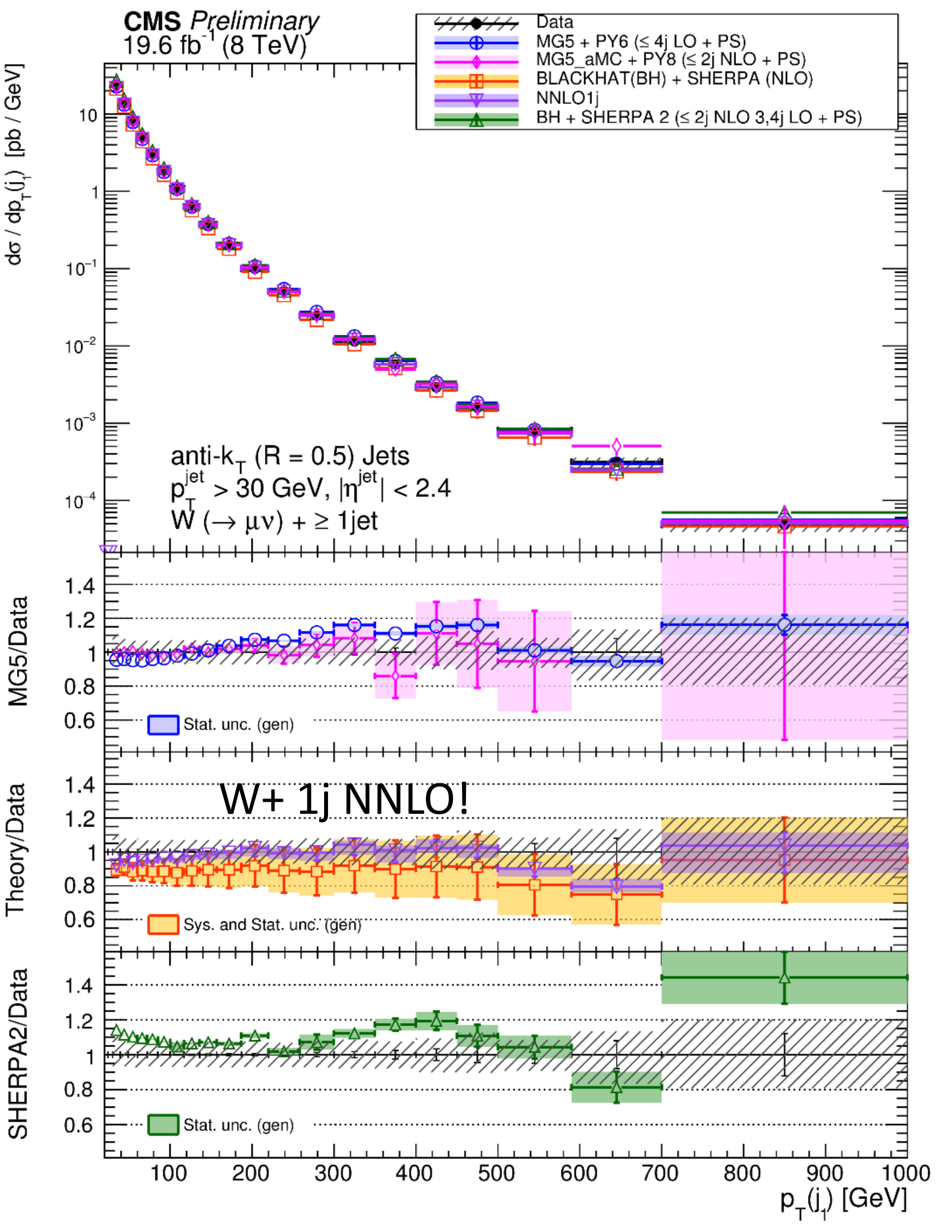
Z+bb PT, Mbb, angular shapes all agree well for Madgraph and POWHEG



W+jets Production at 8 TeV

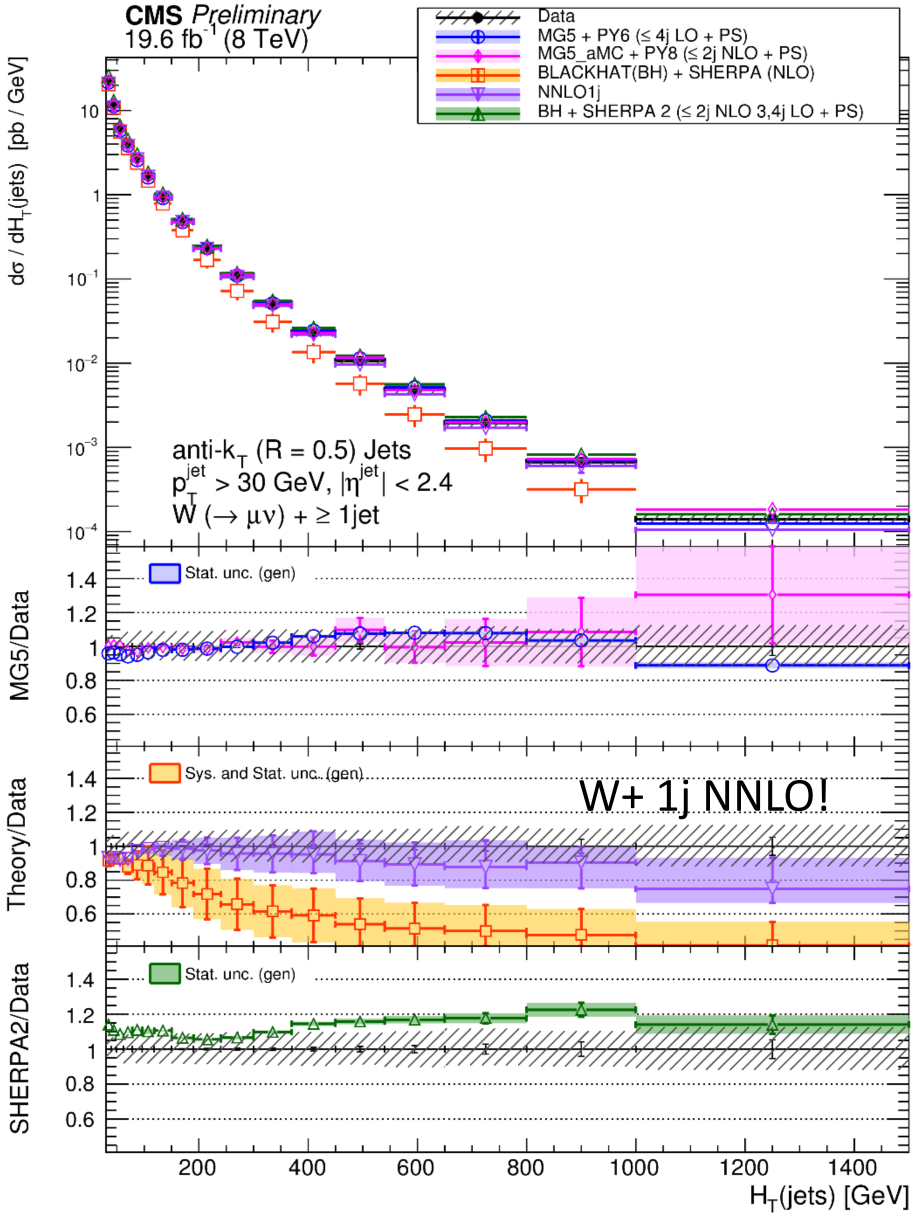
Madgraph and Sherpa2 have difficulties at medium PT

Leading jet PT described well throughout by NNLO W+1j!

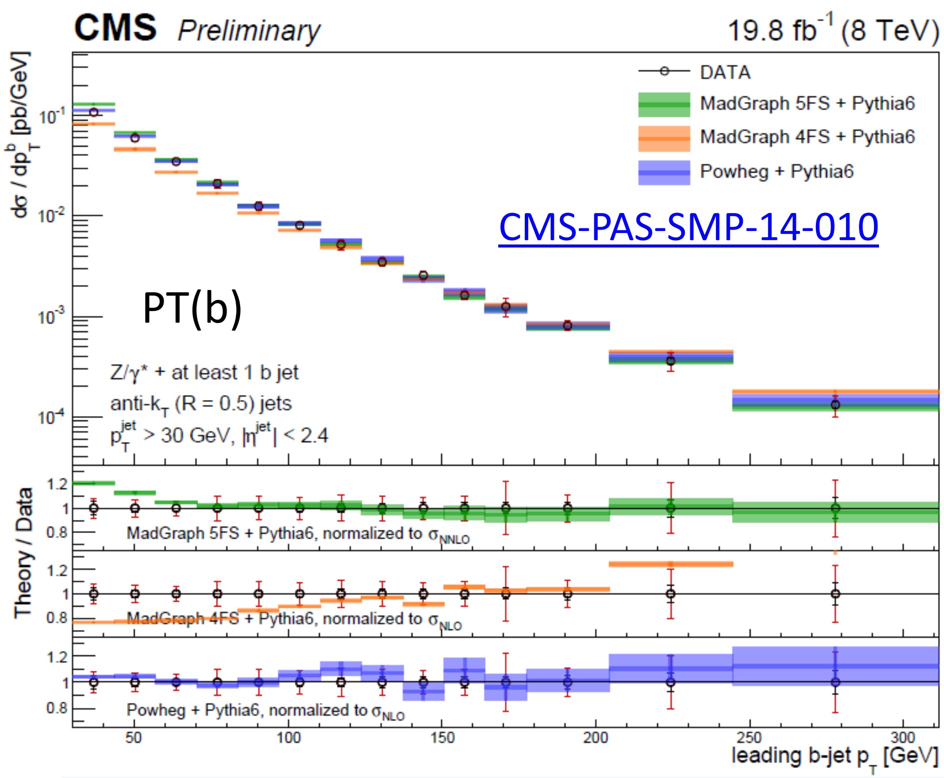


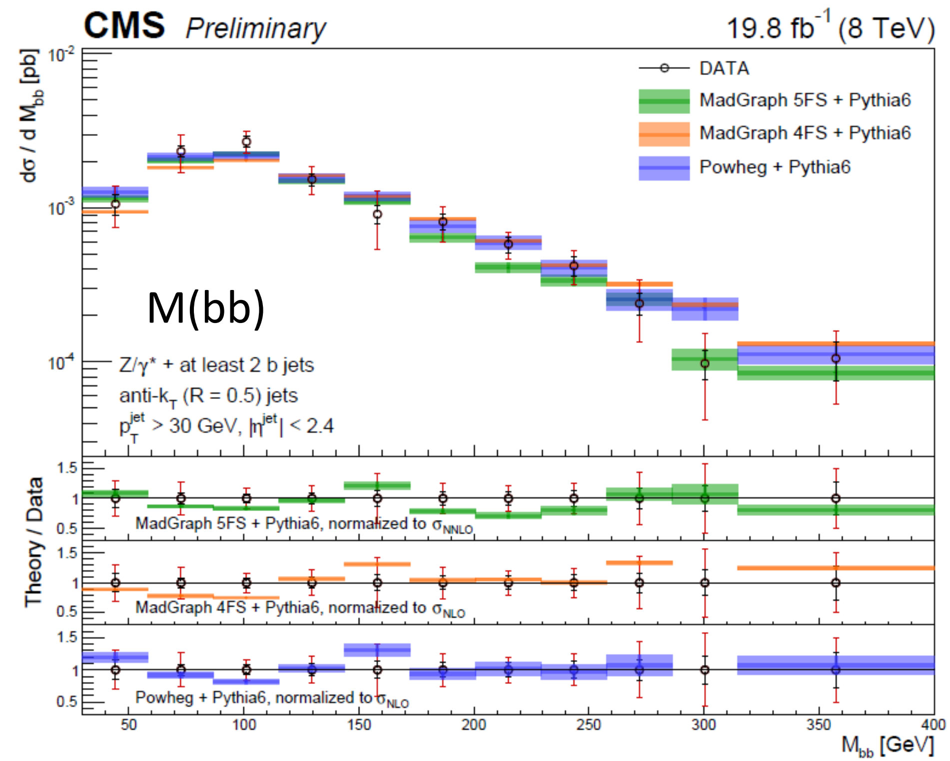
W+jets Production at 8 TeV

NNLO W+1j also restores agreement in HT…



Z+b, bb Production at 8 TeV

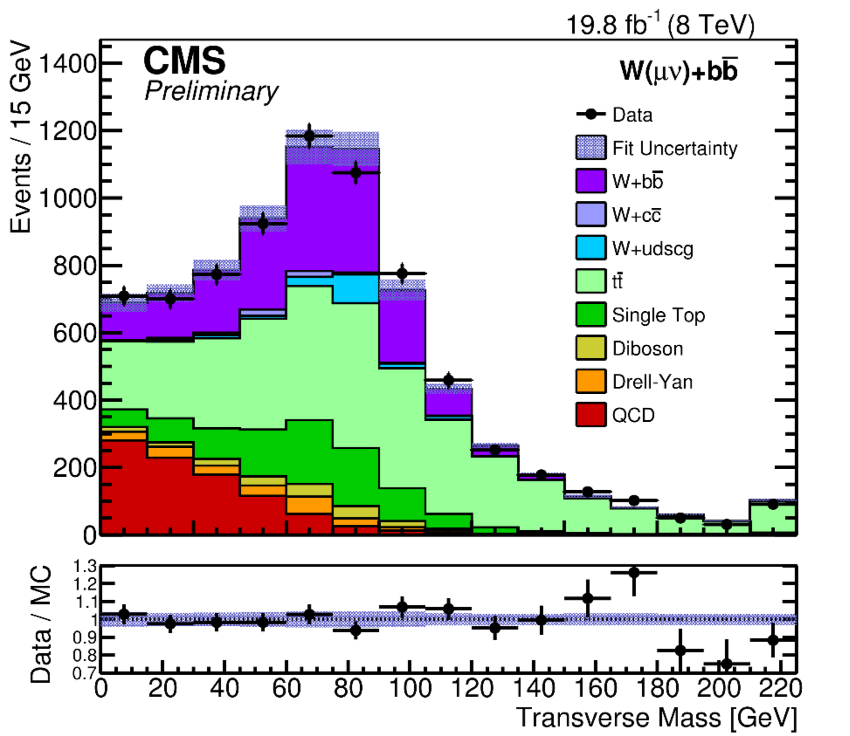


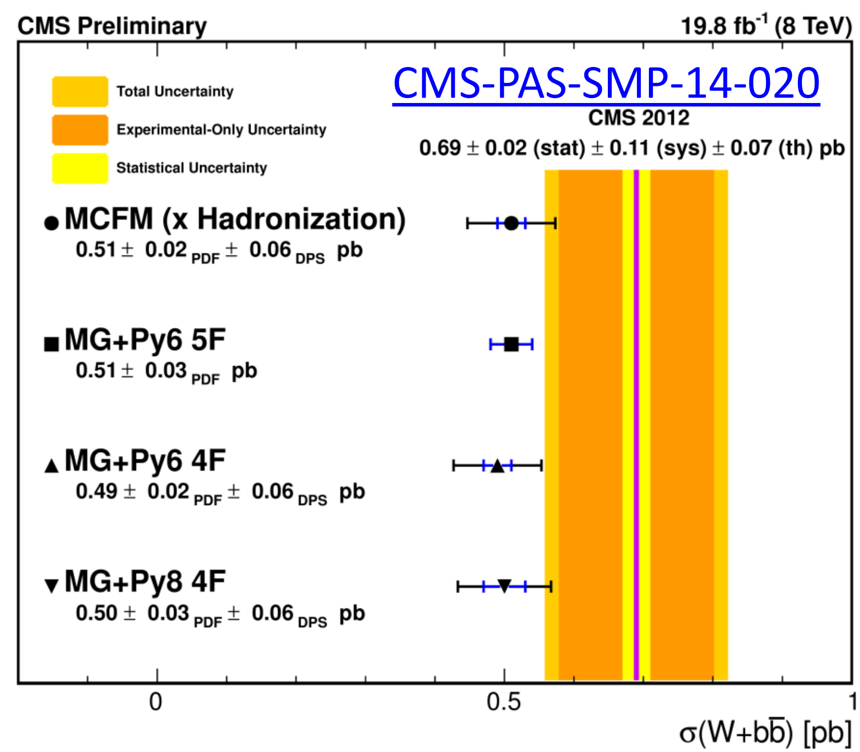


Z+b Madgraph predictions better with 5FS, esp. at higher PT
POWHEG + Pythia6 predicts well in general

Z+bb PT, Mbb, angular shapes all agree well for Madgraph and POWHEG

W+bb Production at 8 TeV





A transverse mass fit separates W+bb from top, V+light jets

Signal strength is consistent with Madgraph, MCFM at 20% level

Good agreement seen also at 7 TeV

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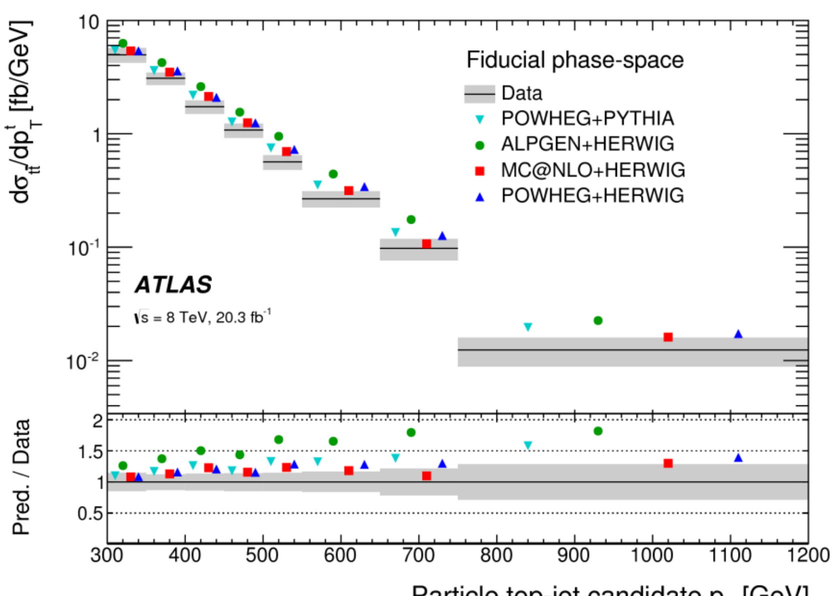
Top quark production

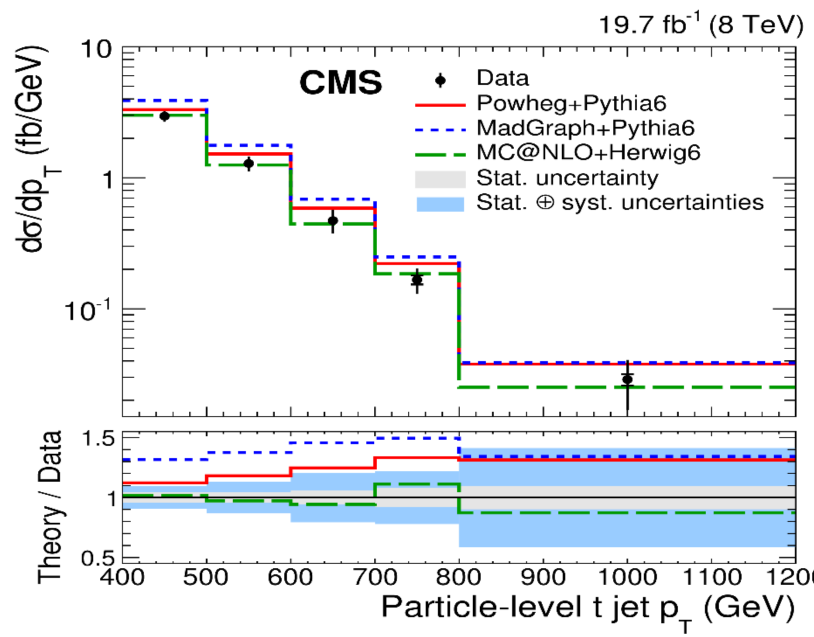
Inclusive cross sections check out at all energies.
Interest is in differential cross sections compared with various generators

Ex: Boosted top production reconstructed as fat jets

Agreement varies a lot with the NLO+PS generator, mostly overpredicting
MC@NLO is doing the best job.



[PRD93 (2016) 032009]



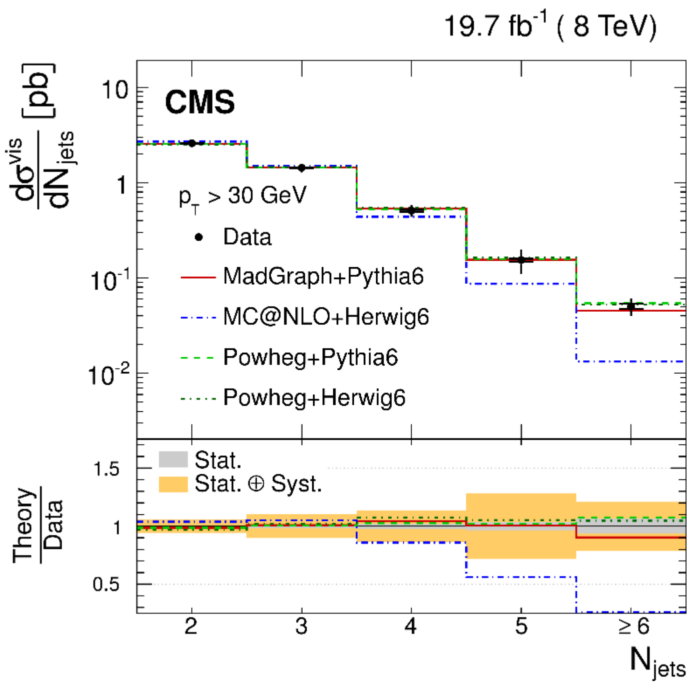
[arxiv:1605.00116]

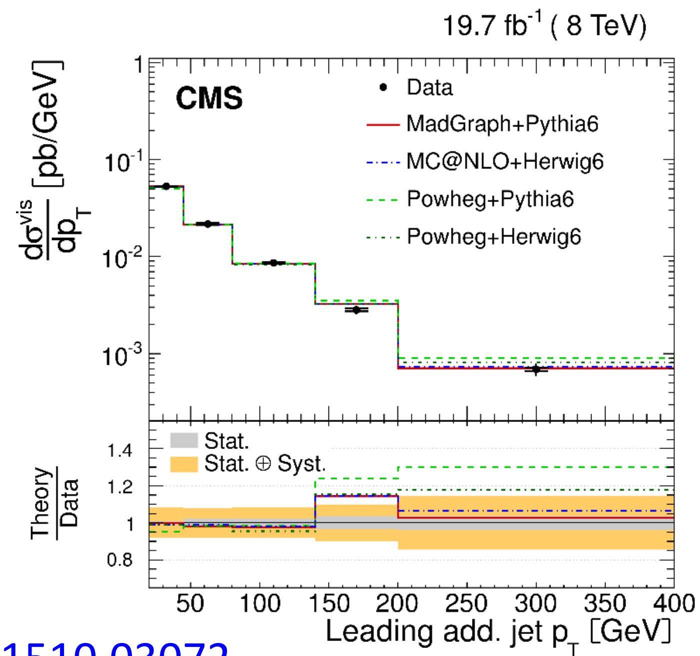
Top quark production

Inclusive cross sections check out at all energies.
Interest is in differential cross sections compared with various generators

Ex: Additional jet production

Performance varies for multiplicity and jet PT



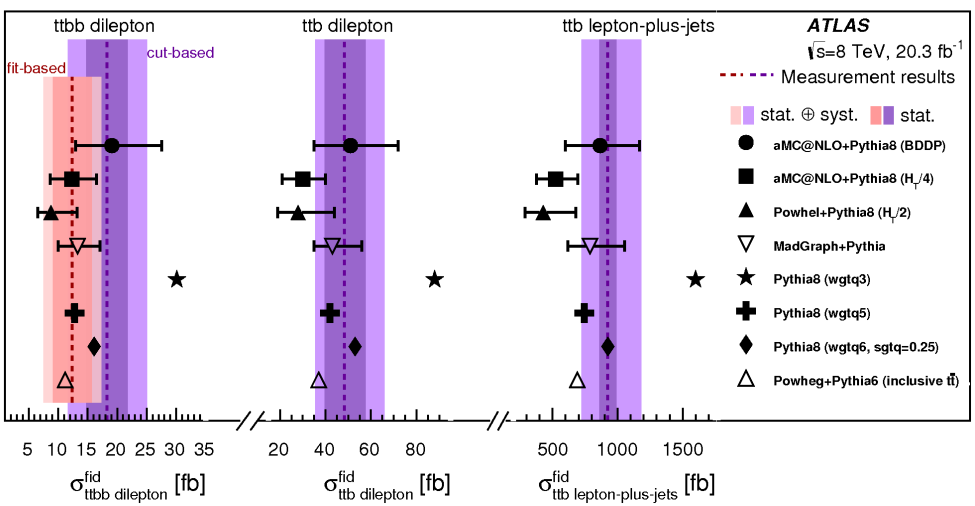


arxiv:1510.03072

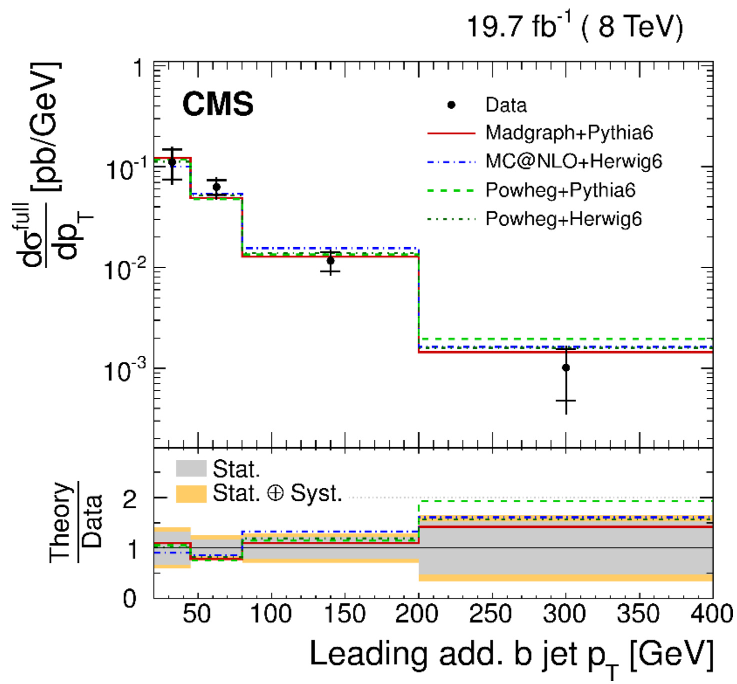
Top quark production

Additional b-jet production total rate agreeing at the 20% level

Additional b-jet kinematic models agree with data



[EPJC (2016) 76:11]

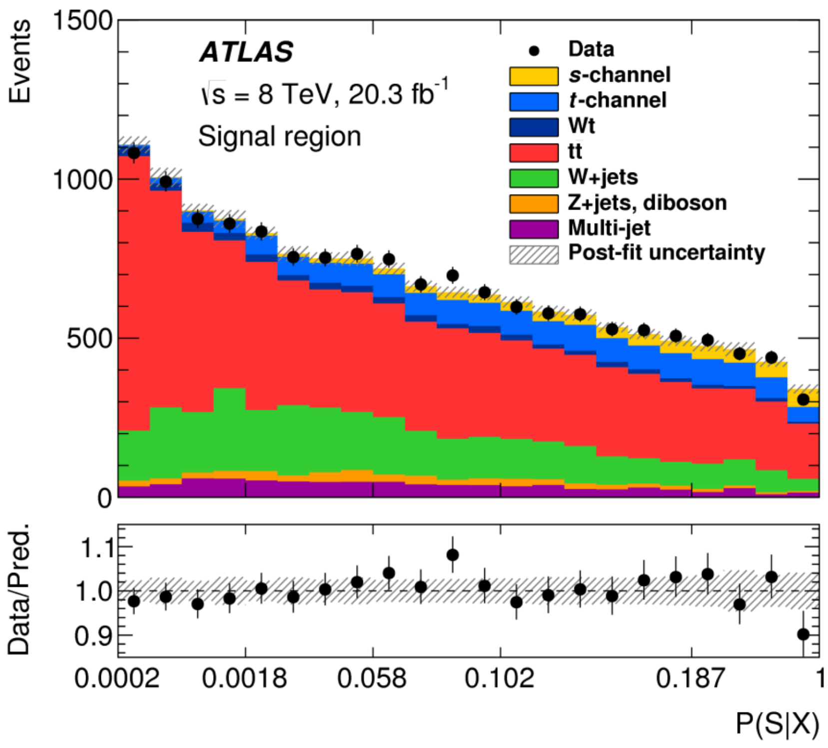


[arxiv:1510.03072]

Single top quark production

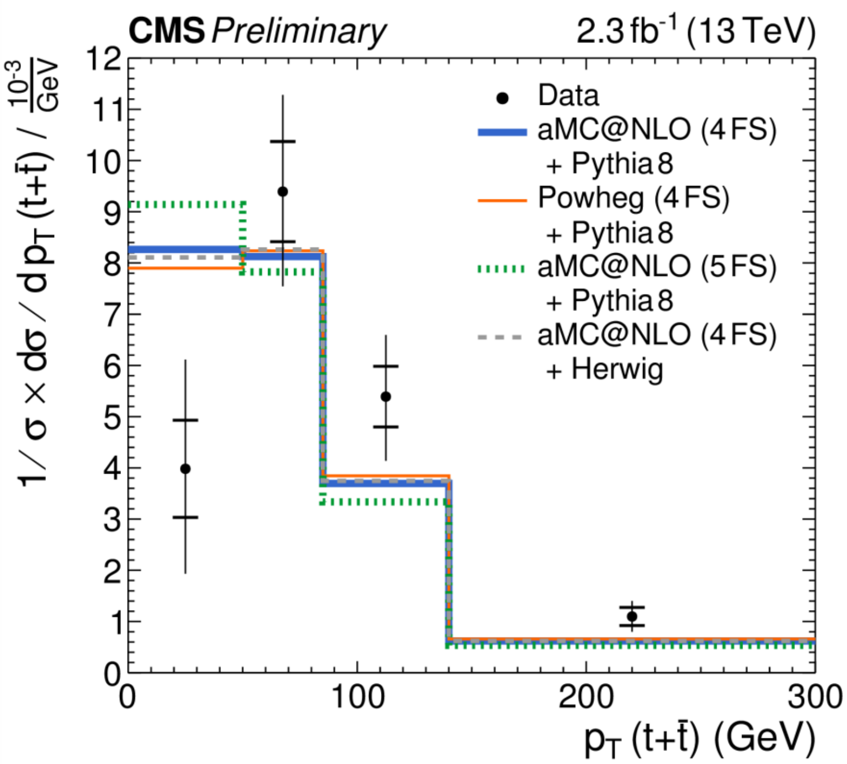
3.2σ evidence for s-channel single top at 8 TeV, in agreement with predictions, 34% precision.

arxiv:1511.05980



Differential t-channel single top already available at 13 TeV

CMS-PAS-TOP-16-004

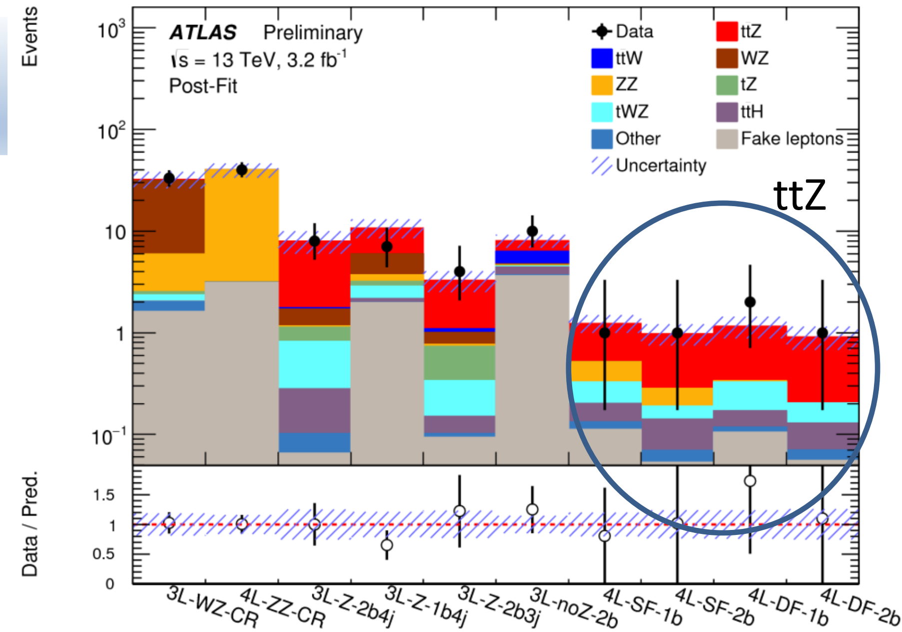


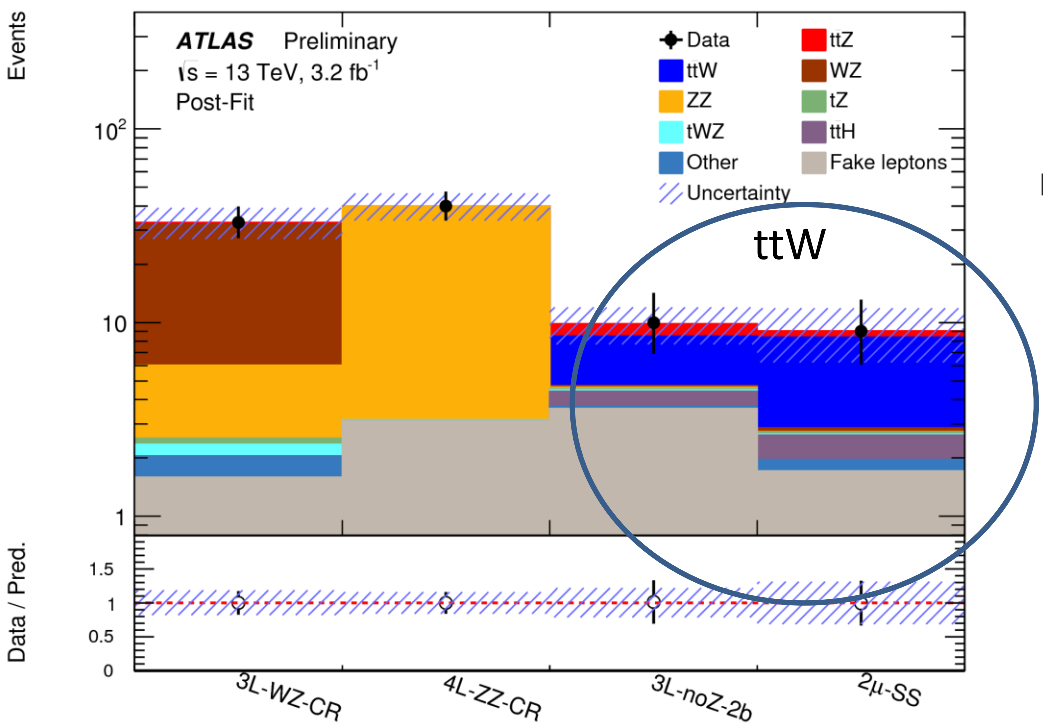
tt+V production

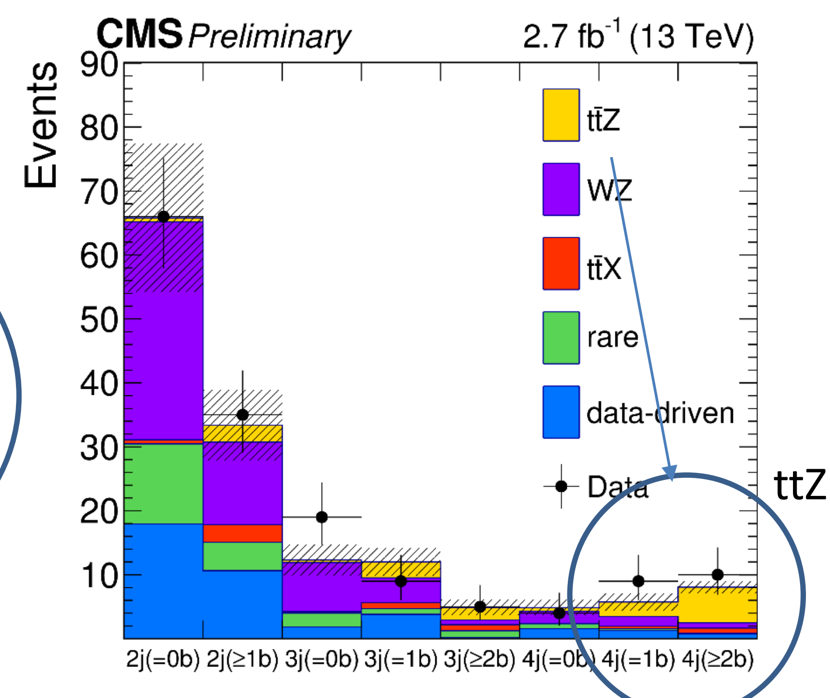
ttW and ttZ now clearly visible in 13 TeV data

Cross sections as expected.

ATLAS-CONF-2016-003







CMS-PAS-TOP-16-009

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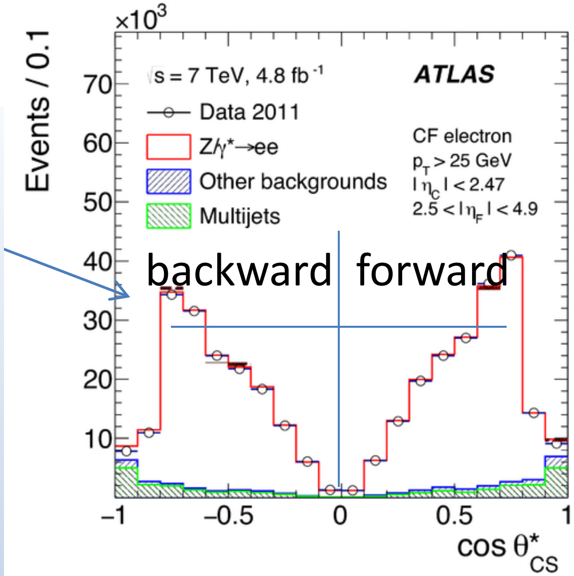
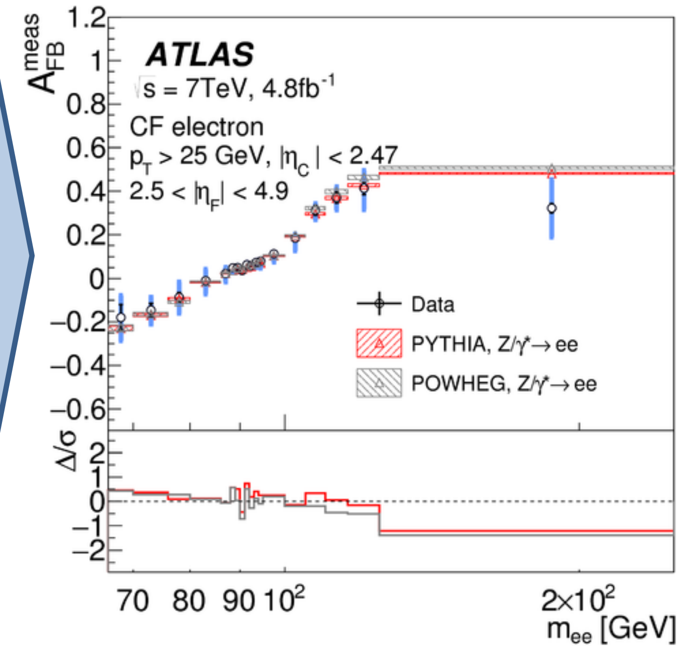
Weak mixing angle at hadron colliders

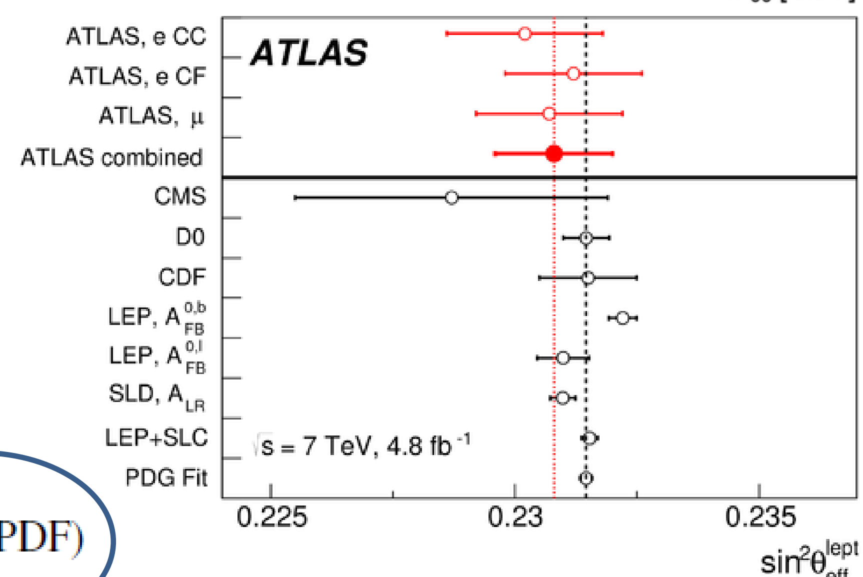
JHEP09(2015)049

- Select central dilepton pairs, and also central-forward electrons with full 7 TeV dataset
- Raw AFB = Count forward/backward abundance in CS frame
- AFB in good agreement with PYTHIA * PHOZPR NNLO K-factor (MSTWNNLO2008)
- 1.8σ lower angle than LEP+SLD average





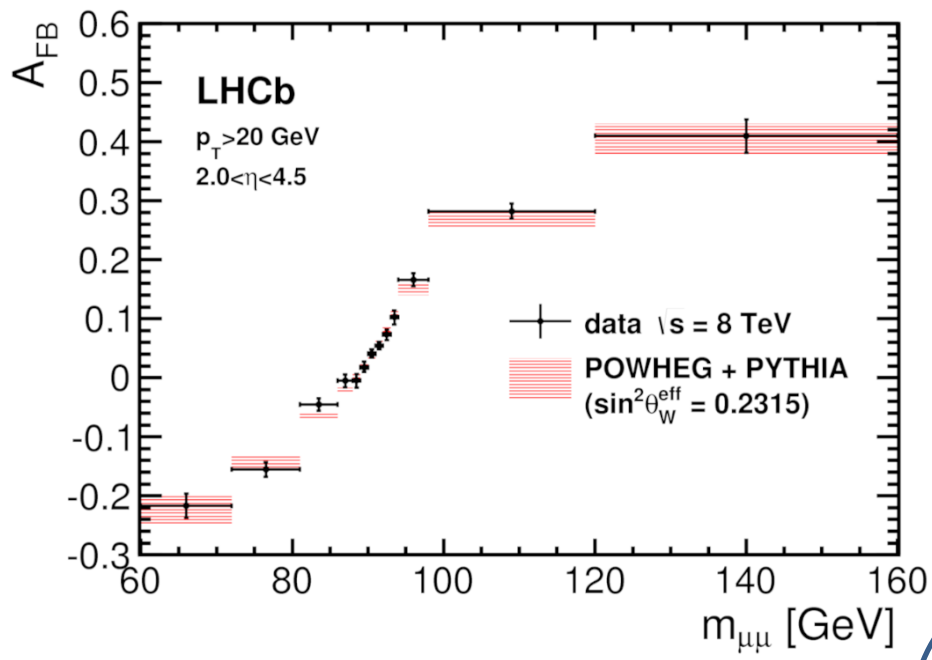
ATLAS 5/fb



$$\sin^2\theta_{eff}^{\text{lept}} = 0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF})$$

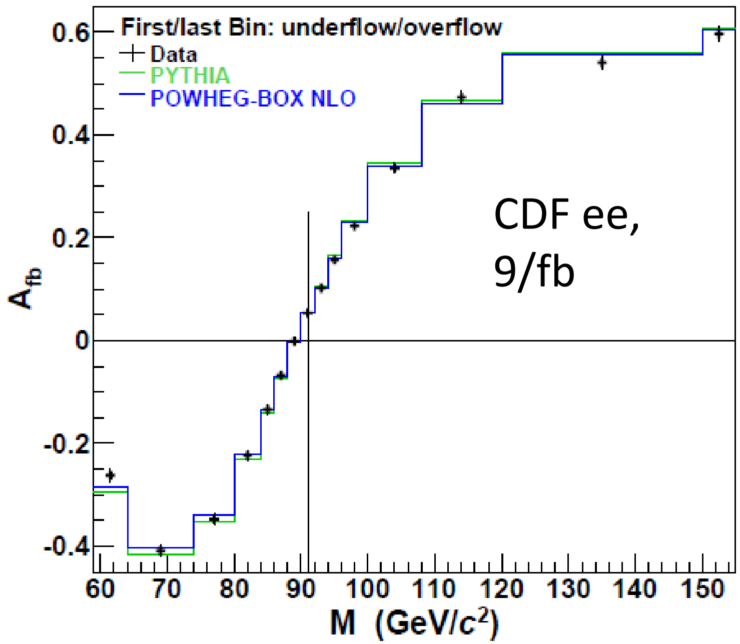
Weak mixing angle at hadron colliders

- LHCb acceptance has even less dilution, better PDF error leads to somewhat better sensitivity
- Main limitation relative to ATLAS/CMS is luminosity/statistics



$$\sin^2\theta_W^{\text{eff}} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056$$

Weak mixing angle at hadron colliders



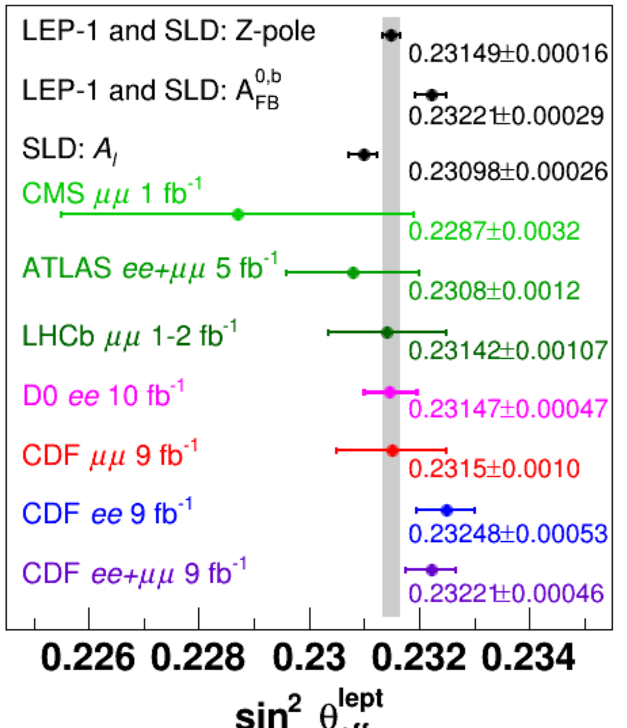
CDF ee,
9/fb

Tevatron has no dilution, low PDF errors, adequate luminosity to give the world's best hadron collider measurement

Surmounting PDF error through large in situ statistics, can LHC eventually reach LEP-like precision?

$$\sin^2 \theta_{\rm eff}^{\rm lept} = 0.23221 \pm 0.00043 \pm 0.00018$$

arxiv:1605.02719



Approaching the W mass at LHC

- The LHC has excellent detectors and semi-infinite statistics and thus has a good a priori prospect for a <10-MeV measurement
- Biggest three obstacles to surmount:
  - PDFs: sea quarks play a much stronger role than the Tevatron. Need at least 2X better PDFs.
  - Production modelling: boson PT, polarization
  - Momentum scale, MET response calibration

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}$[fb^{-1}]	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

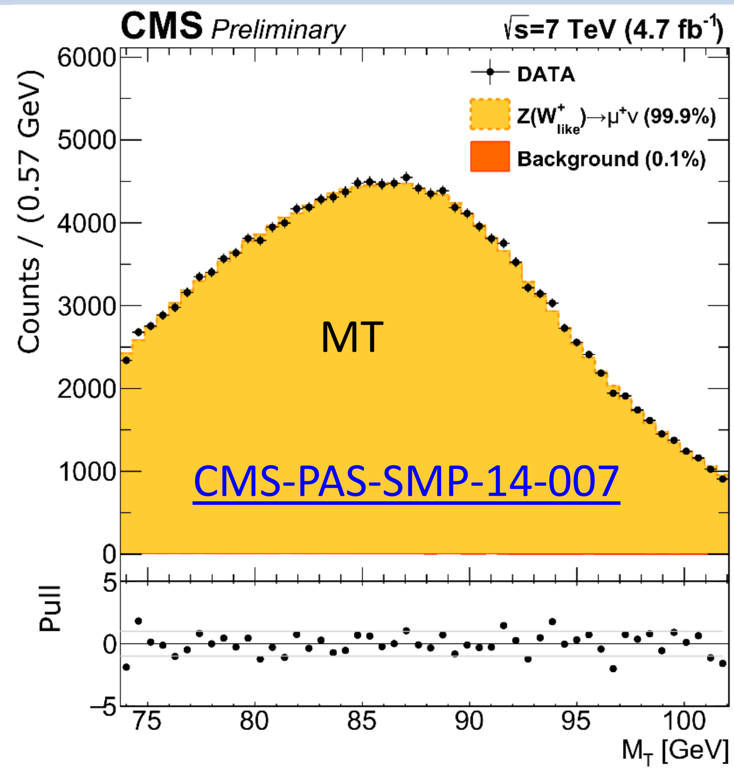
arxiv:1310.6708

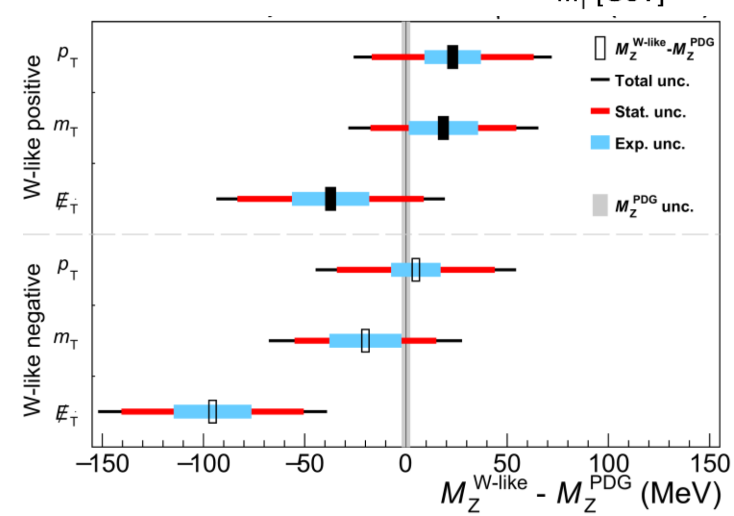
ATLAS-PHYS-PUB-2014-015

	MW-NLO	CT10nlo	MSTW2008CPdeutnlo	NNPDF30_nlo_as_118
W^+	+13 -12	+18 -22	+11 -10	+8 -10
W^-	+22 -22	+18 -23	+11 -10	+8 -9
$W^\pm$	+11 -11	+14 -18	+7 -7	+6 -5

Progress on experimental scales: W-like MZ

- Measure the Z mass in 7 TeV dimuon events using a "W-like" final state (ignore one muon)
- Momentum scale calibration with J/psi and Upsilon: **+/- 12-15 MeV on MZ**
- MET reconstructed from tracks alone (TKMET): **+/- 9 MeV on MZ from MT**
- PT, MET, and MT separately used to extract MZ
- Consistent results with MZ(PDG), with pos/neg muons, with all three variables (best single exp syst error +/- 17 MeV)
- Need to do ~3x better on scale errors to do better than 10 MeV on MW





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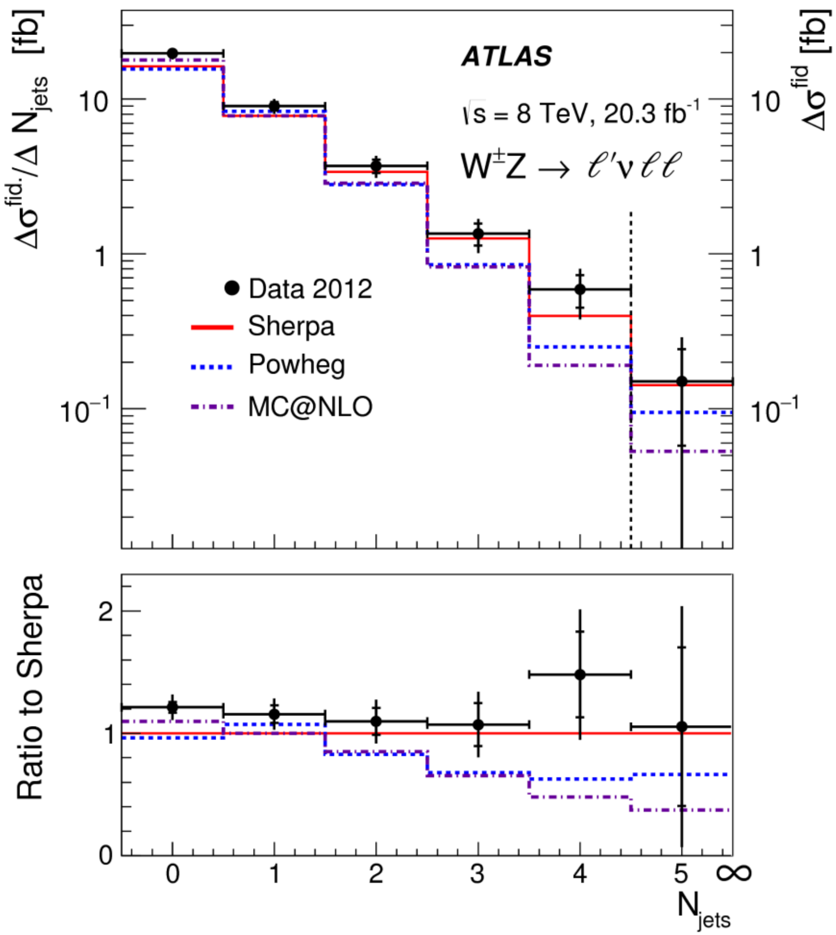
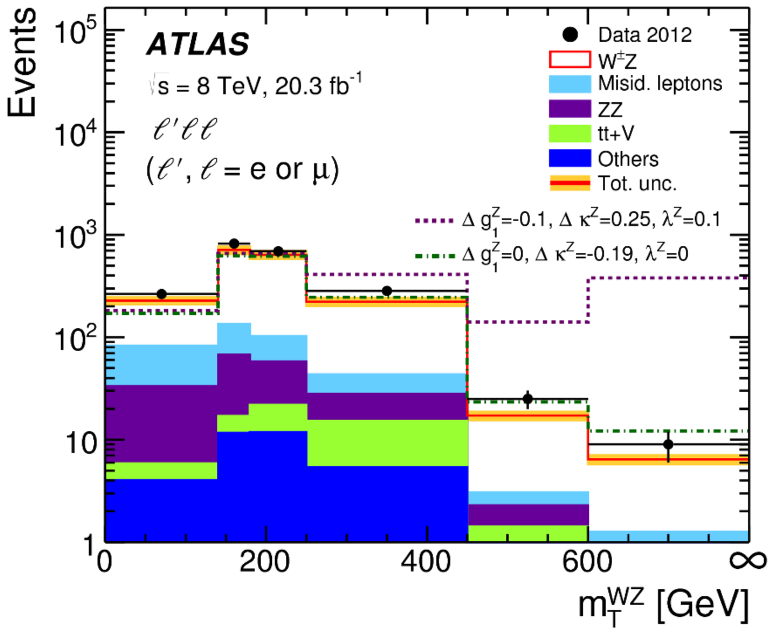
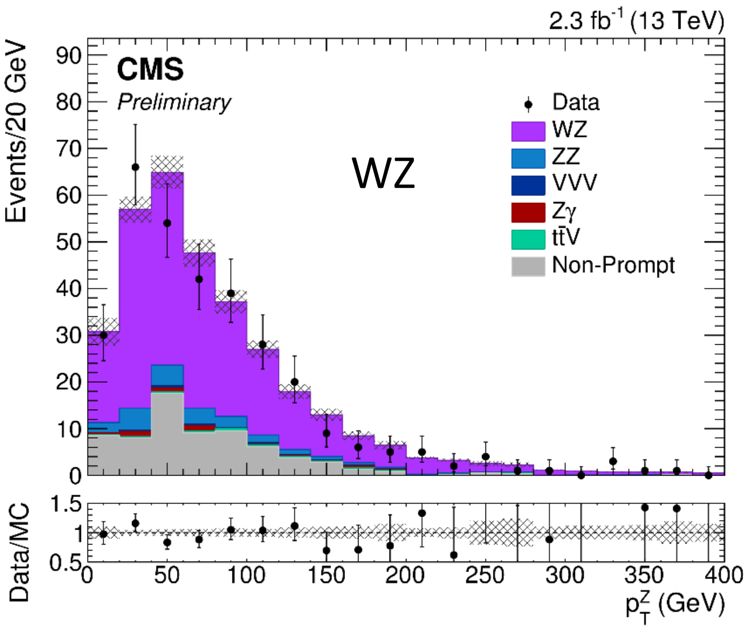
Diboson production and TGCs

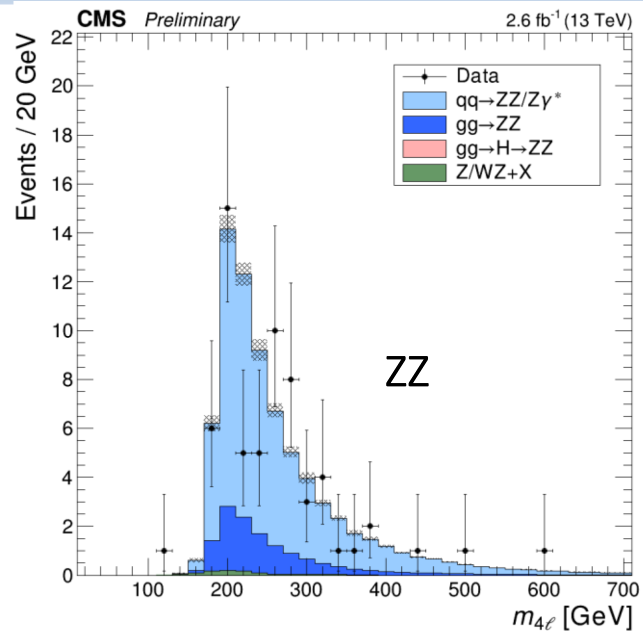
Differential cross sections available for comparison with theory.
Dim-6 TGCs probing $\Lambda \approx$ 200-500 GeV for c ≈ 1



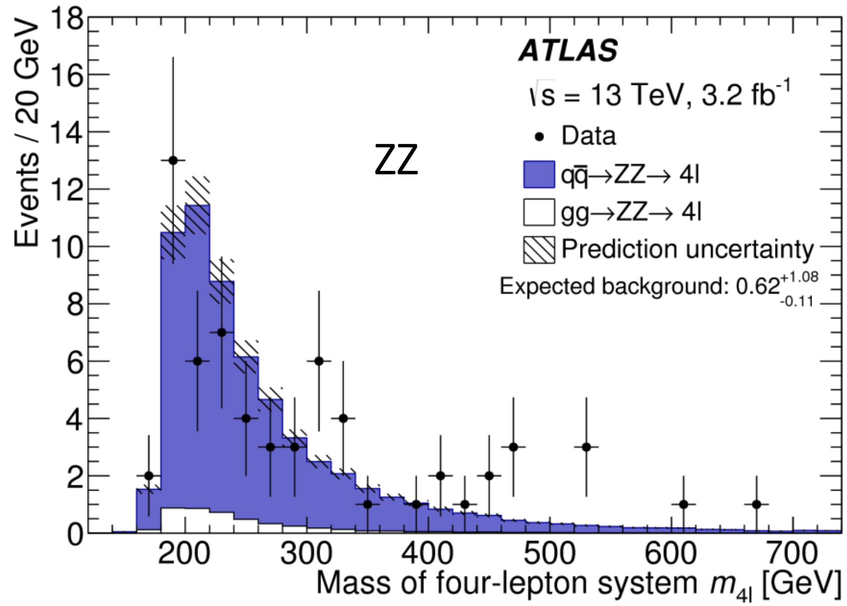


Diboson production and TGCs





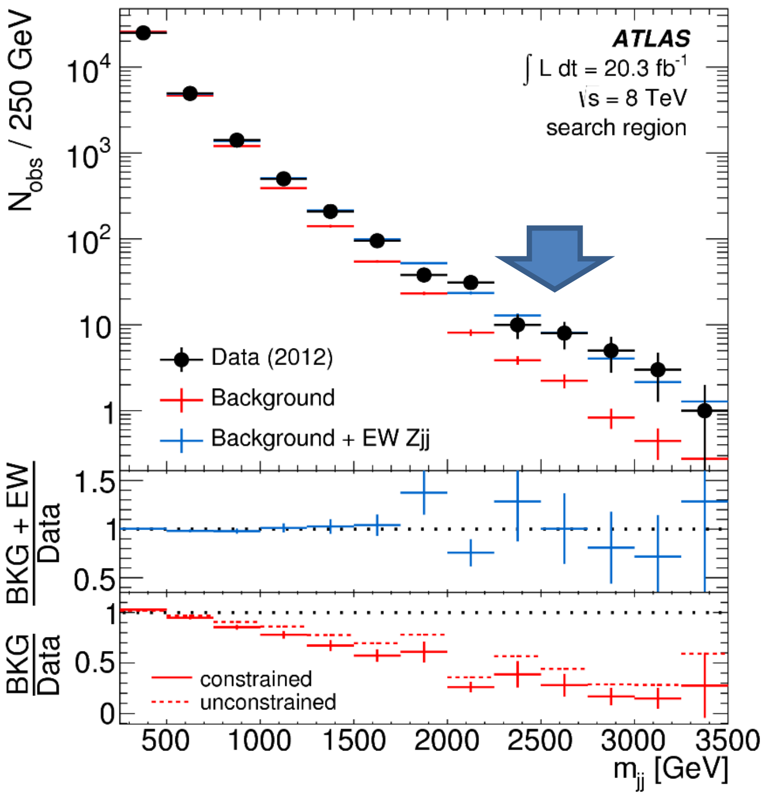
No obvious signs of trouble at 13 TeV…yet

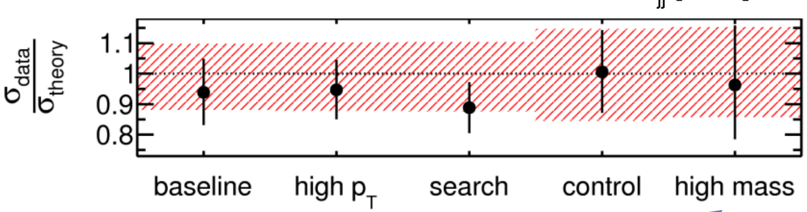


Electroweak Z + 2 jet production

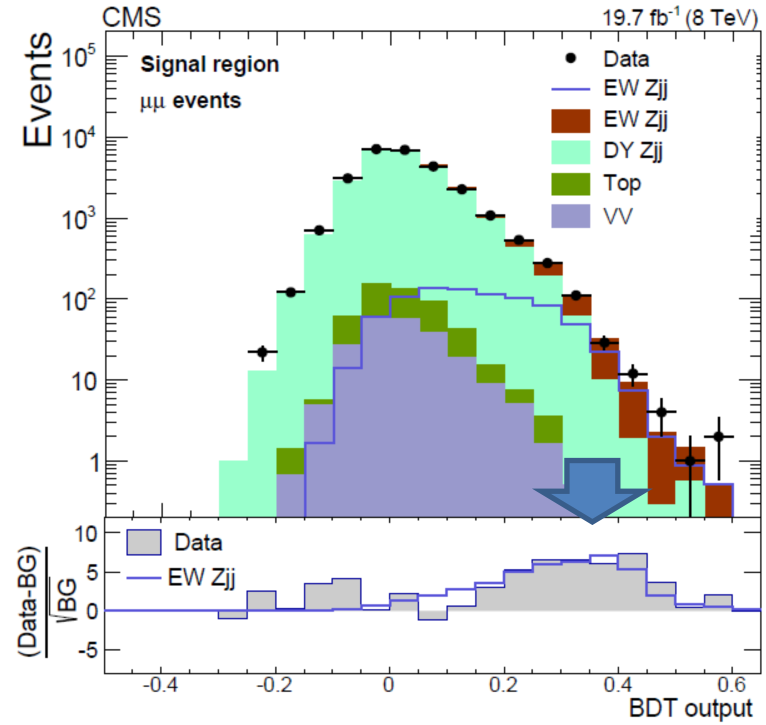
- **>5 σ evidence** has been reported by both experiments at 8 TeV, first published by ATLAS. Cross sections are consistent with SM predictions.

σ_{EWK} = 226 ± 44 fb
σ_{VBFNLO} = 239 fb





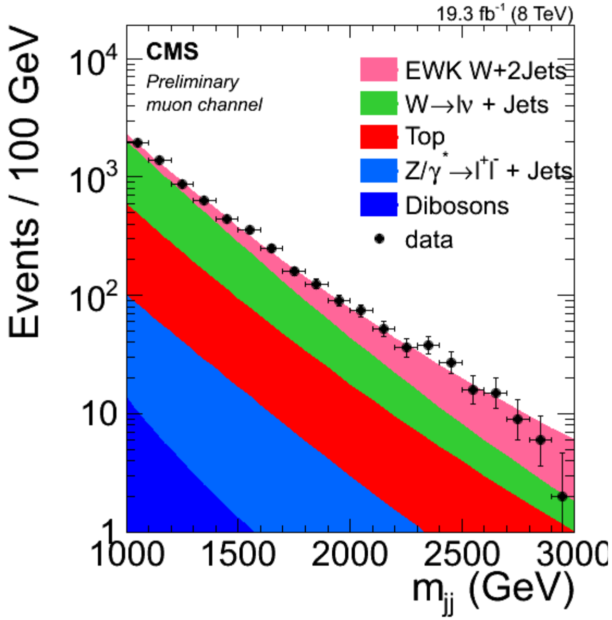
σ_{EWK} = 10.7 ± 2.1 fb
σ_{POWHEG} = 9.4 fb

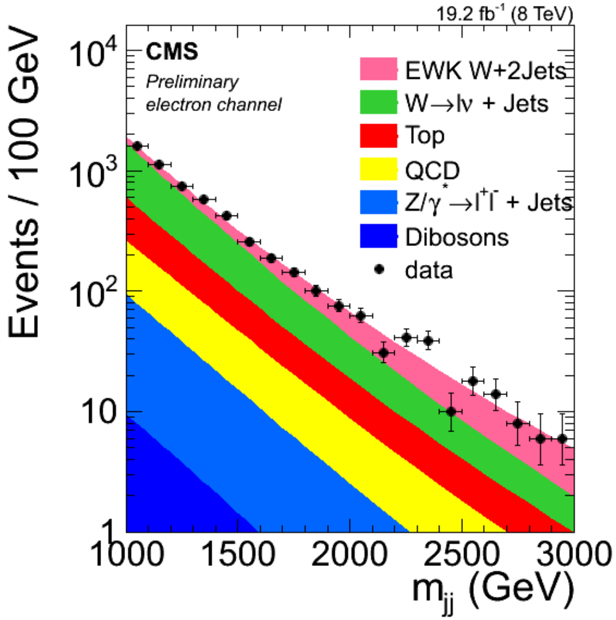


- After reweighting QCD Z+2 jets in sidebands, jet dynamics well-modeled in and around search regions

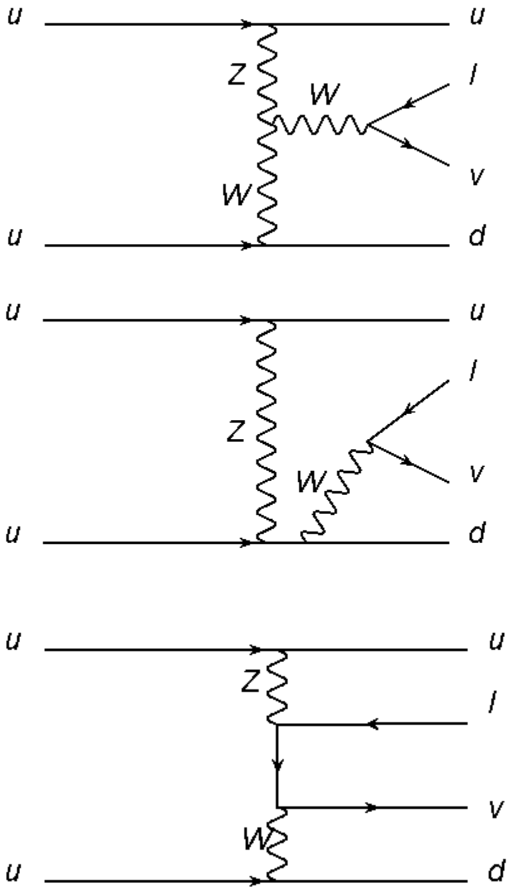
Electroweak W + 2 jet production

- **Recent observation of electroweak W+2 jet production as well. Consistent with SM. TGC limits a bit weaker than from dibosons.**





CMS-PAS-SMP-13-012



Madgraph SM = 0.5 pb

Event category	Measured cross section
μjj	0.43 ± 0.04 (stat.) ± 0.10 (syst.) ± 0.01 (lumi.) pb
ejj	0.41 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb
combined μjj and ejj	0.42 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb

QCD/EWK interference modelling, W+jets background modelling dominate systematics

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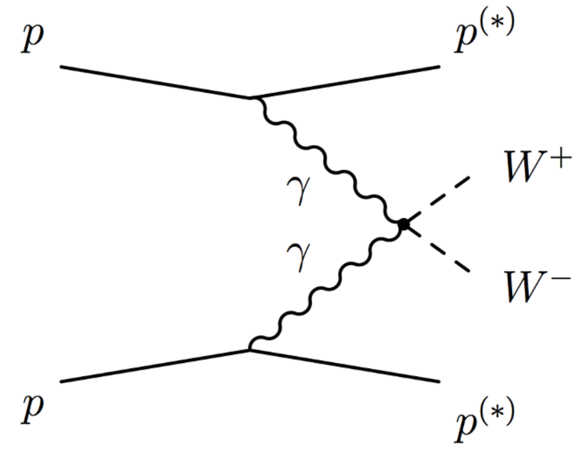
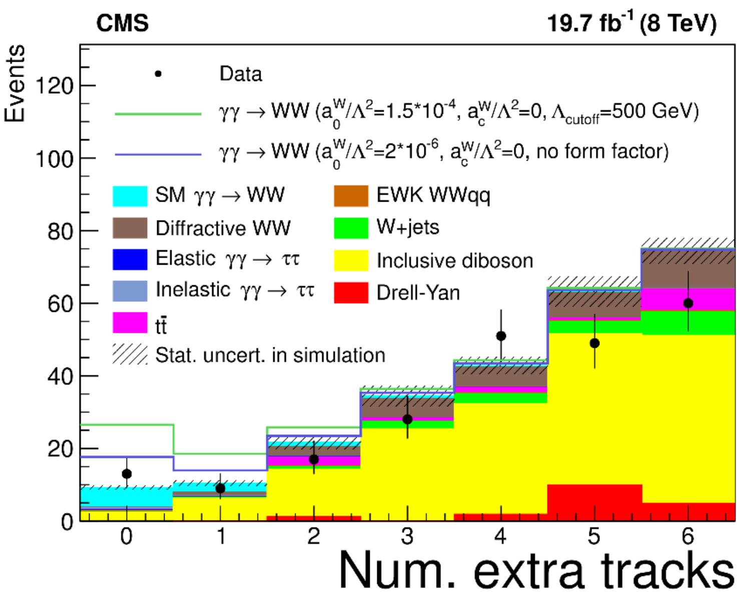
Multiboson production and QGCs

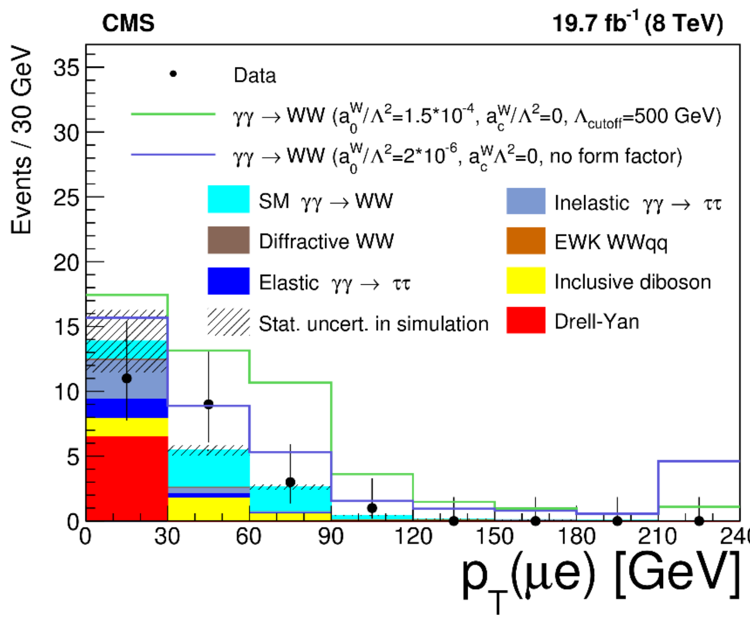
Exclusive WW production has 3.4σ evidence and is easily the most sensitive to WWγγ QGC!

In agreement with predictions, but only after accounting for strong (80%) dissociated proton component (inferred from exclusive dilepton)



arxiv:1604.04464



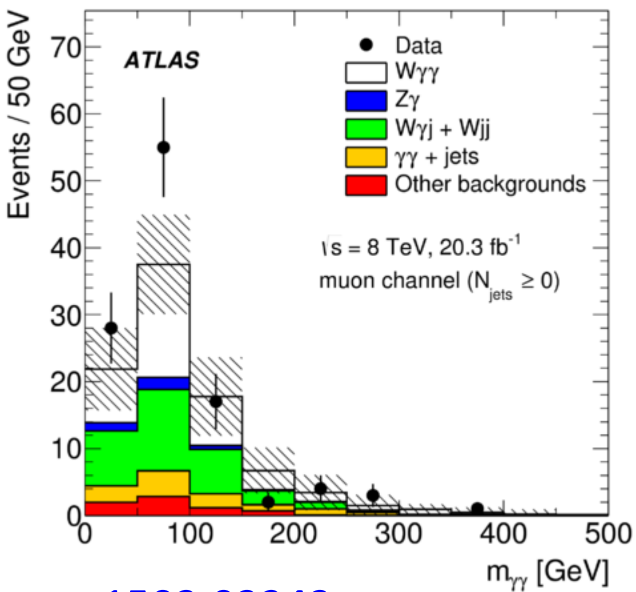


Multiboson production and QGCs

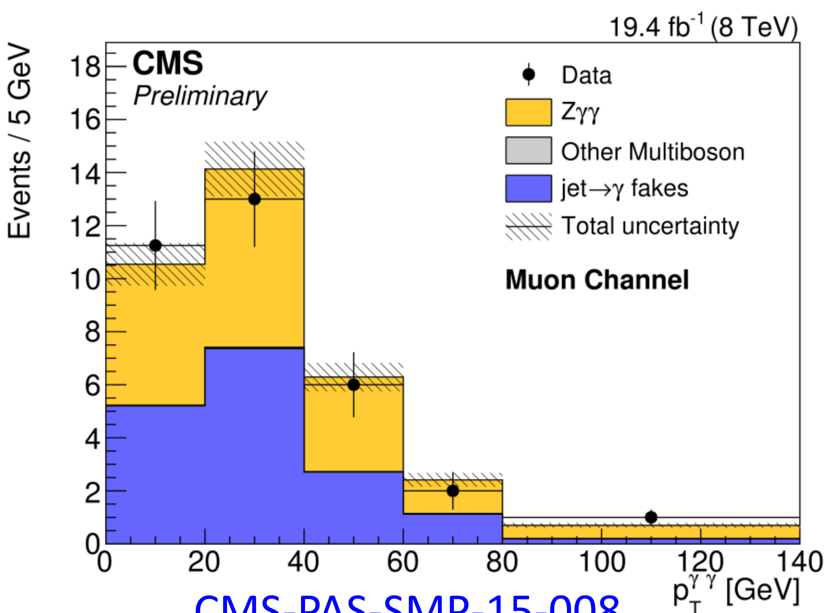
Triboson production seen in the Vγγ sector
On the high side of NLO predictions (expected)

Signal depends strongly on photon fiducial phase space.

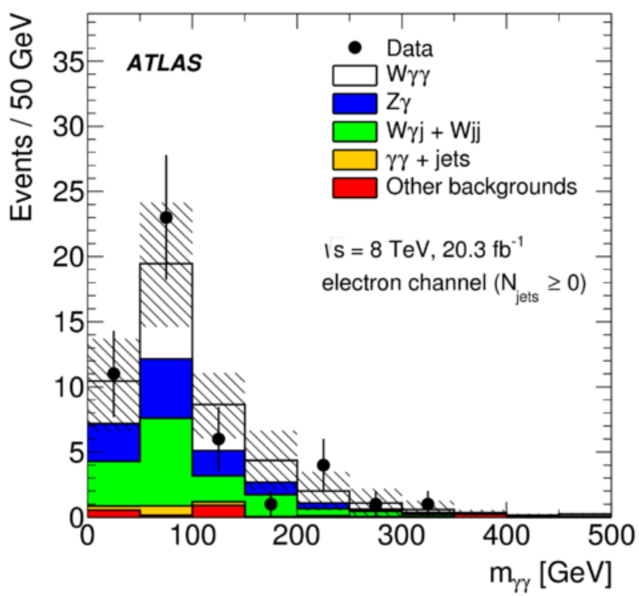
Not as QGC sensitive as VBS final states (next)



1503.03243



CMS-PAS-SMP-15-008

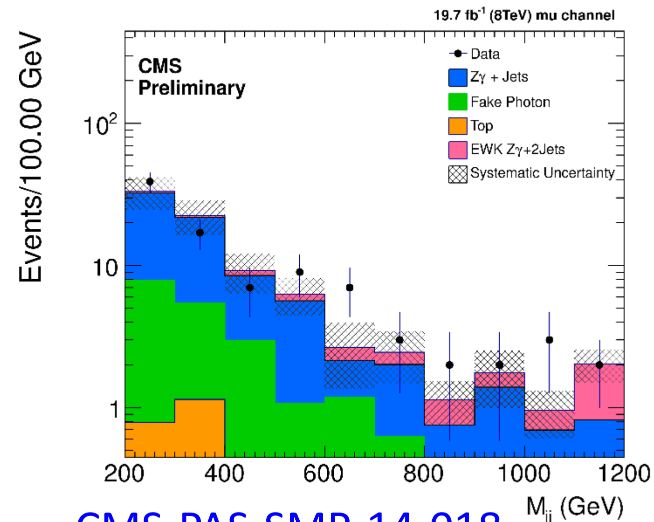


Recent VBS channels: Zγ

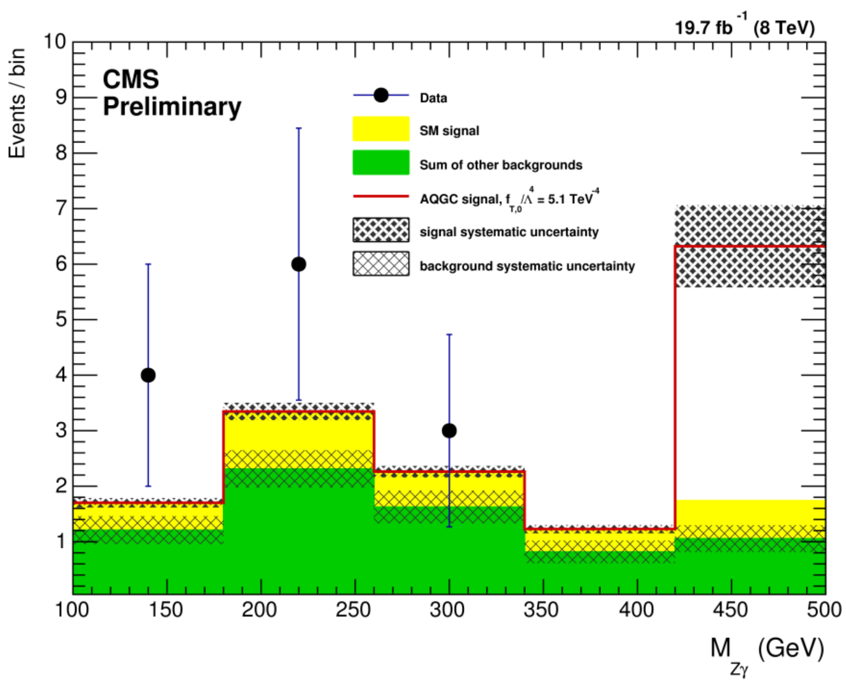
3.0 σ excess in the Zγ+2 jet Mjj tail

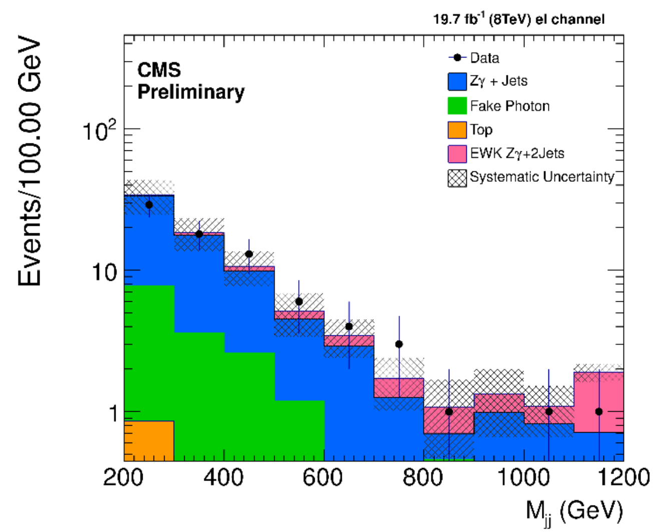
Signal strength
$\mu = 1.47{+0.87}{-0.63}$

Competitive for probing the WWZγ QGC



[CMS-PAS-SMP-14-018]



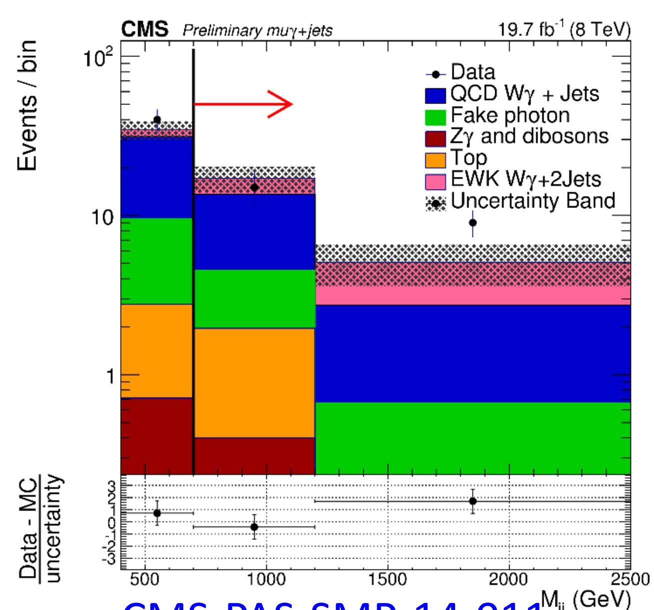


Recent VBS channels: Wγ

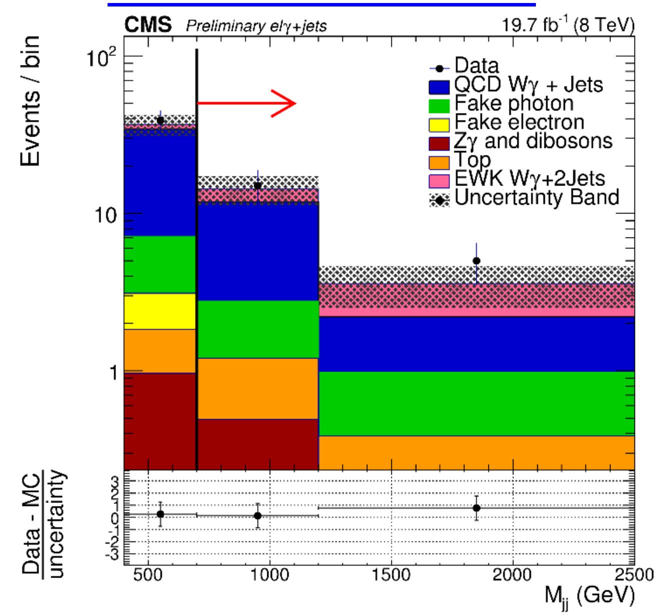
2.7 σ excess in the Wγ+2 jet Mjj tail

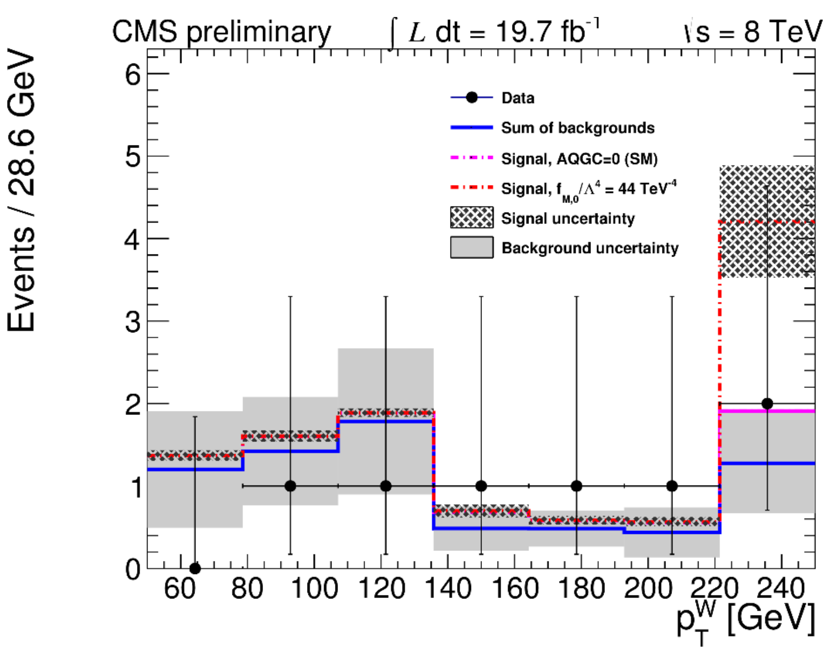
Signal strength
μ = 1.78+0.99-0.76

Competitive for probing the WWZγ QGC



CMS-PAS-SMP-14-011

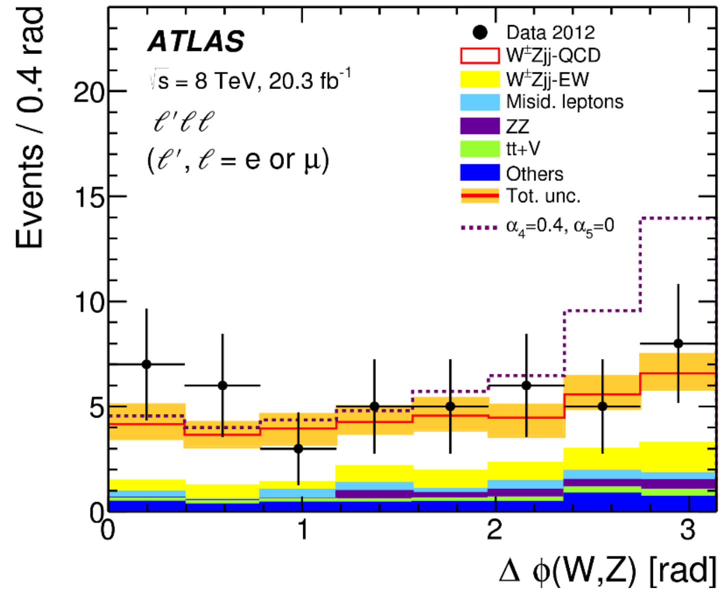


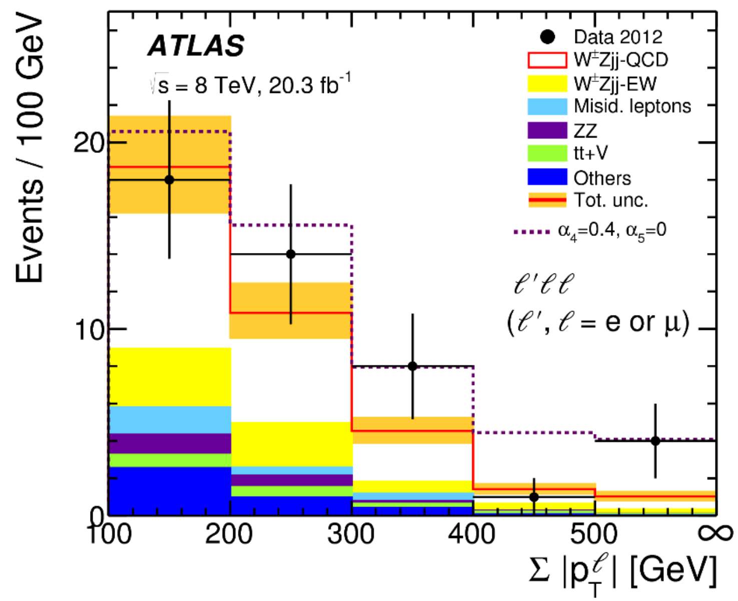


Recent VBS channels: WZ

- <2 σ excess in the WZ+2 jet Mjj tail
- Signal is 0.29+/-0.14 fb, 0.13 fb expected
- Competitive for probing the WWZZ QGC

95% CL upper limit on $\sigma^{\text{fid.}}_{W^\pm Zjj\text{-EW}\to\ell'\nu\ell\ell}$ [fb]		
	VBS only	VBS + tZj
VBS phase space		
Observed	0.63	0.67
Expected	0.45	0.49
$\pm1\sigma$ Expected	[0.28 ; 0.62]	[0.33 ; 0.67]
$\pm2\sigma$ Expected	[0.08 ; 0.80]	[0.19 ; 0.84]
aQGC phase space		
Observed	0.25	0.25
Expected	0.13	0.13
$\pm1\sigma$ Expected	[0.08 ; 0.20]	[0.08 ; 0.20]
$\pm2\sigma$ Expected	[0.04 ; 0.28]	[0.06 ; 0.28]





Conclusions

1. Smaller radius jet simulation benefits from parton showering.

2. NNLO starting to fill some gaps in V+jets predictions.

3. Top quark differential cross sections challenging NLO+PS, needs diffe

4. Precision electroweak measurements at LHC are coming but we will improve production modelling and PDFs as we go.

5. No sign of TGCs but without NNLO+NLO EWK these will become harc interpret.

6. Vector boson scattering is here in multiple channels and will soon rec same technology!

Conclusions

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