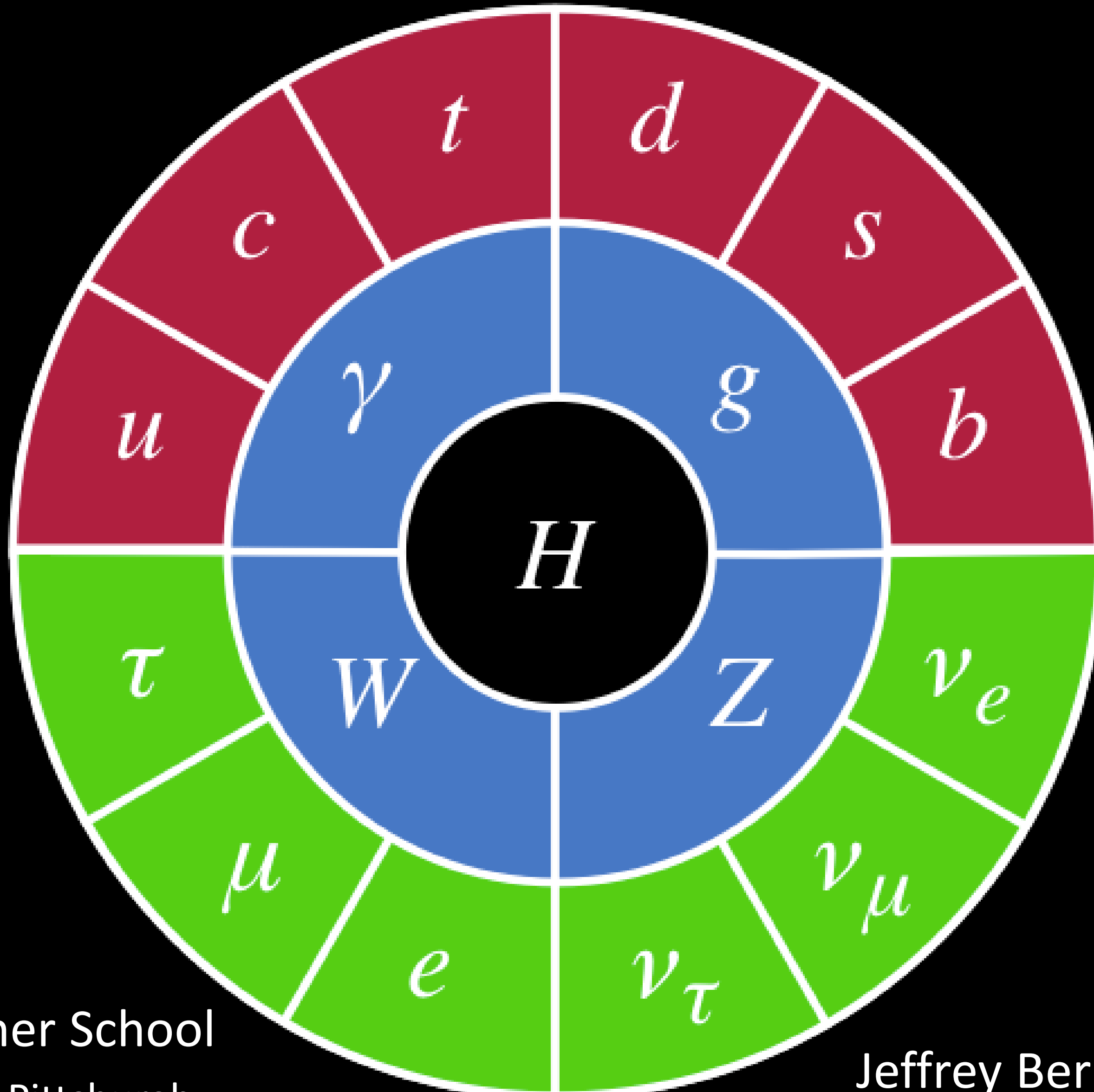
Standard Model Physics at the LHC: QCD, Top, Electroweak



CTEQ Summer School

July 15, 2015 Pittsburgh

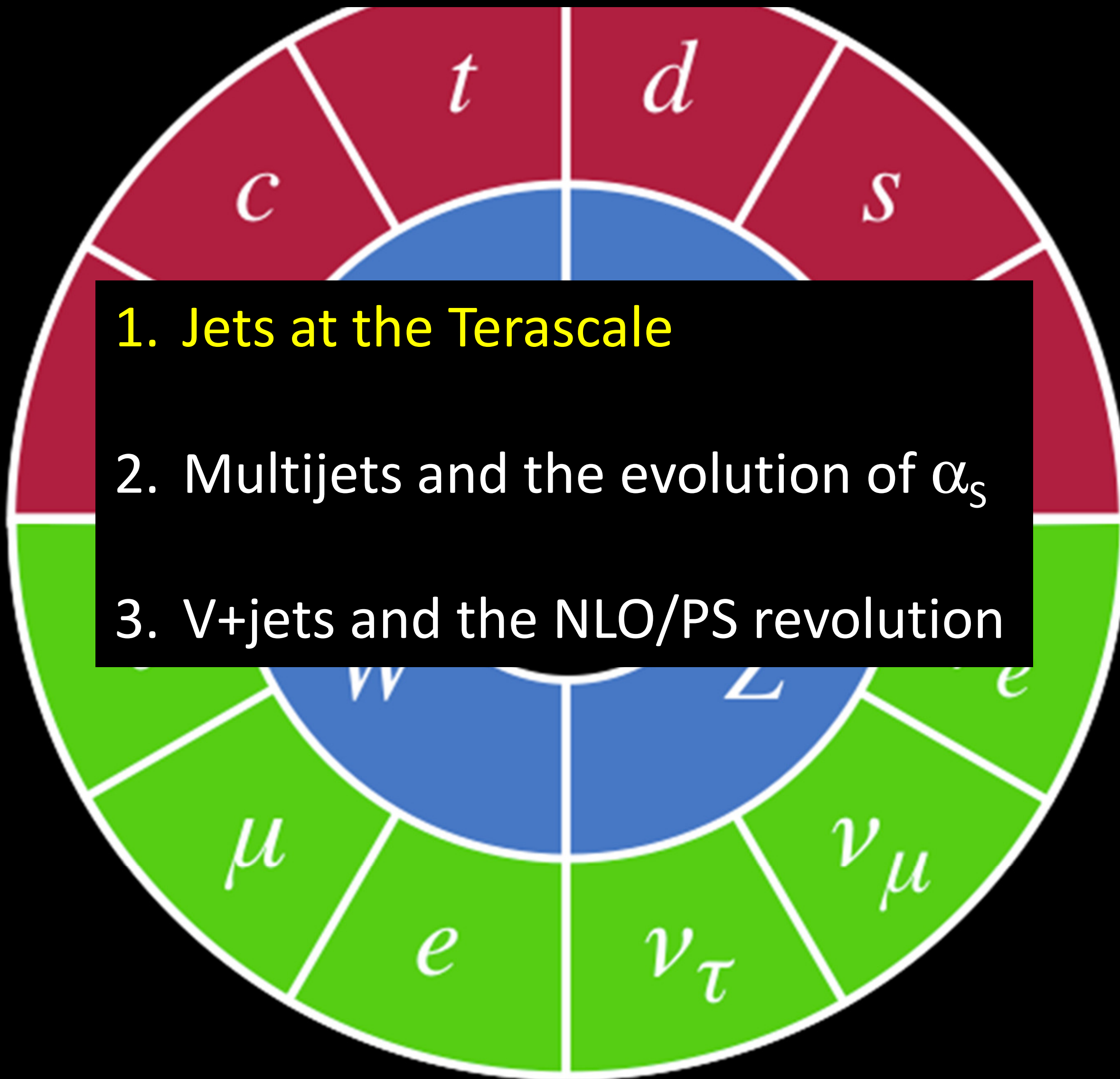
Jeffrey Berryhill (Fermilab)

CMS collaboration

Outline

1. Tests of QCD and jet production
   1. Jet cross sections
   2. The strong coupling
   3. Associated jet production
2. Measurements of the top quark
   1. Top pair production
   2. Top quark mass
   3. Top properties
   4. Single top production
3. Tests of the electroweak theory
   1. Vector boson production
   2. Diboson production and TGCs
   3. Vector boson scattering and QGCs

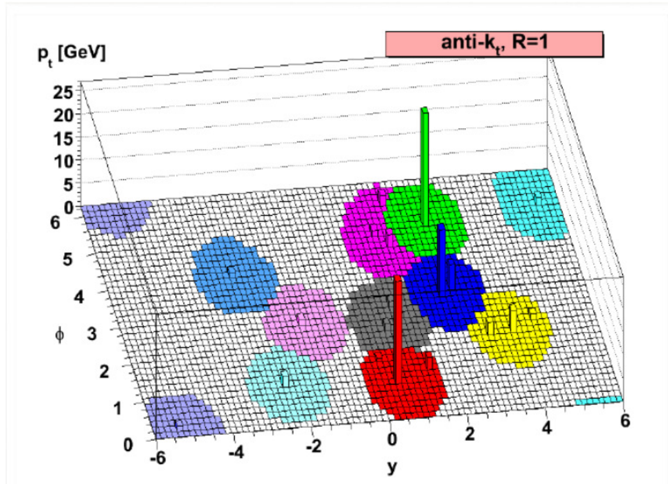
1. QQCD

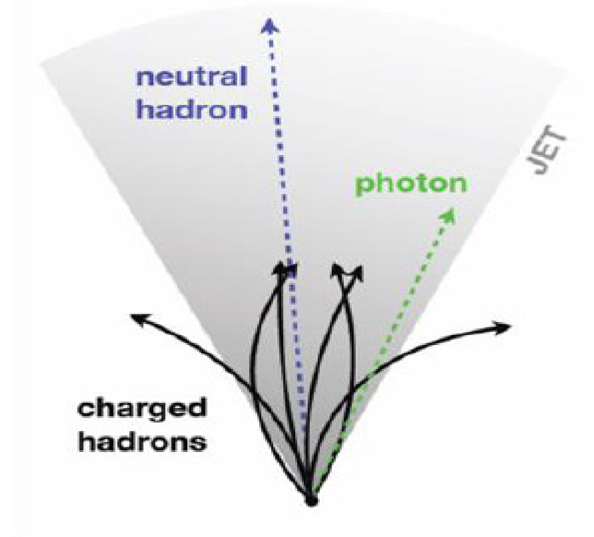


1. Jets at the Terascale
2. Multijets and the evolution of α_s
3. V+jets and the NLO/PS revolution

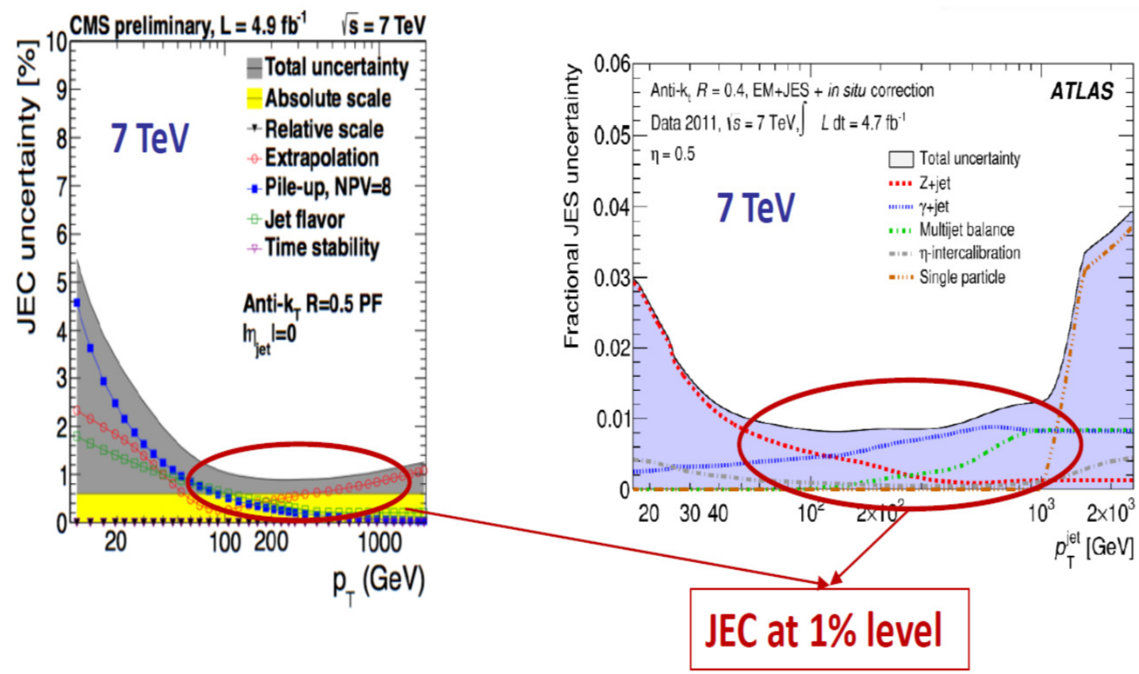
Jets at the LHC

- Anti-kt clustering algorithm common to most all results (R = 0.5 and 0.7 at CMS, R= 0.4 and 0.6 for ATLAS)
- CMS Particle Flow Jets (PF Jets): Clustering of particle flow candidates constructed by combining information from all sub-detector systems
- ATLAS: Clustering of Calorimeter Towers composed of ECAL and HCAL energy deposits
- Jet energy resolution 15% down to 5% going from 20 to 1000 GeV
- Jet energy scale known to 1% over 50-1000 GeV range





CMS : DP-2012-006

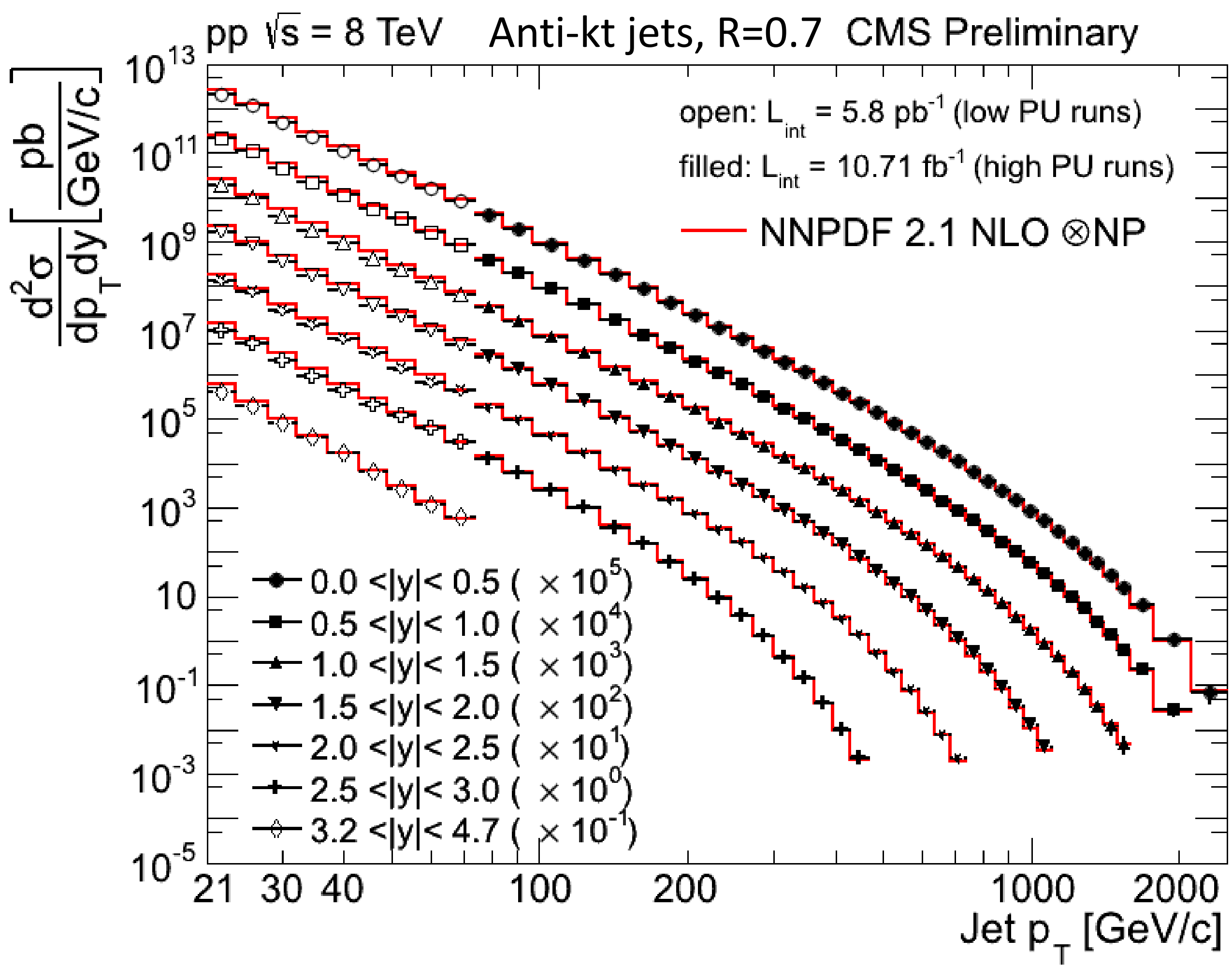


ATLAS : EPJC (2015) 75:17

Inclusive jet production at LHC

CMS-PAS-FSQ-12-031
CMS-PAS-SMP-12-012

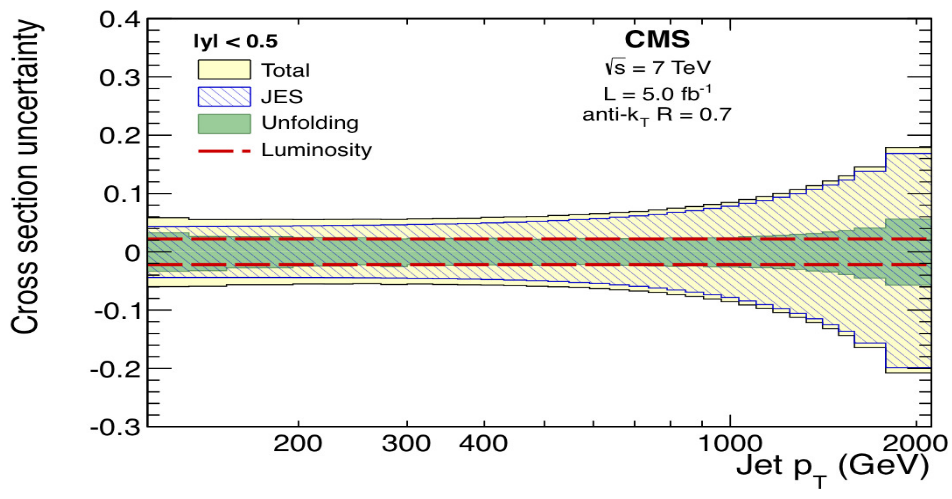
- Fixed-order NLO prediction folded with non-perturbative corrections
- Agreement observed with data over 2 decades in energy and 13 orders of magnitude in cross section!
- Jets observed with ET> 2 TeV
- ~1% jet energy scale uncertainty dominates cross section error.
- Will improve q, g PDF uncertainty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



Inclusive jet production at LHC

- Jet energy scale uncertainty dominates over the entire energy range

PRD 87 (2013) 112002



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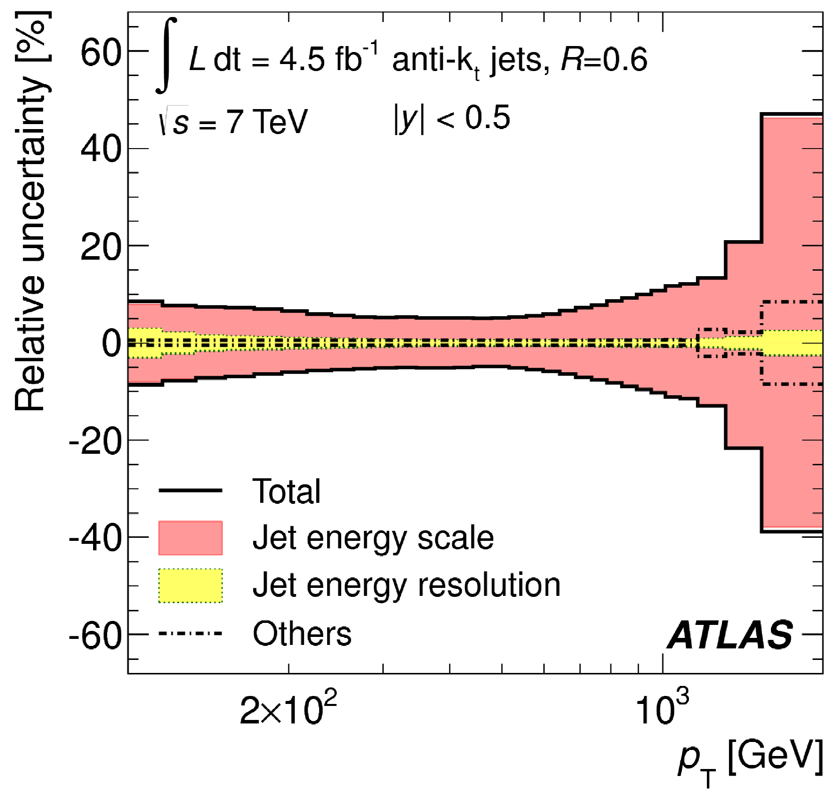
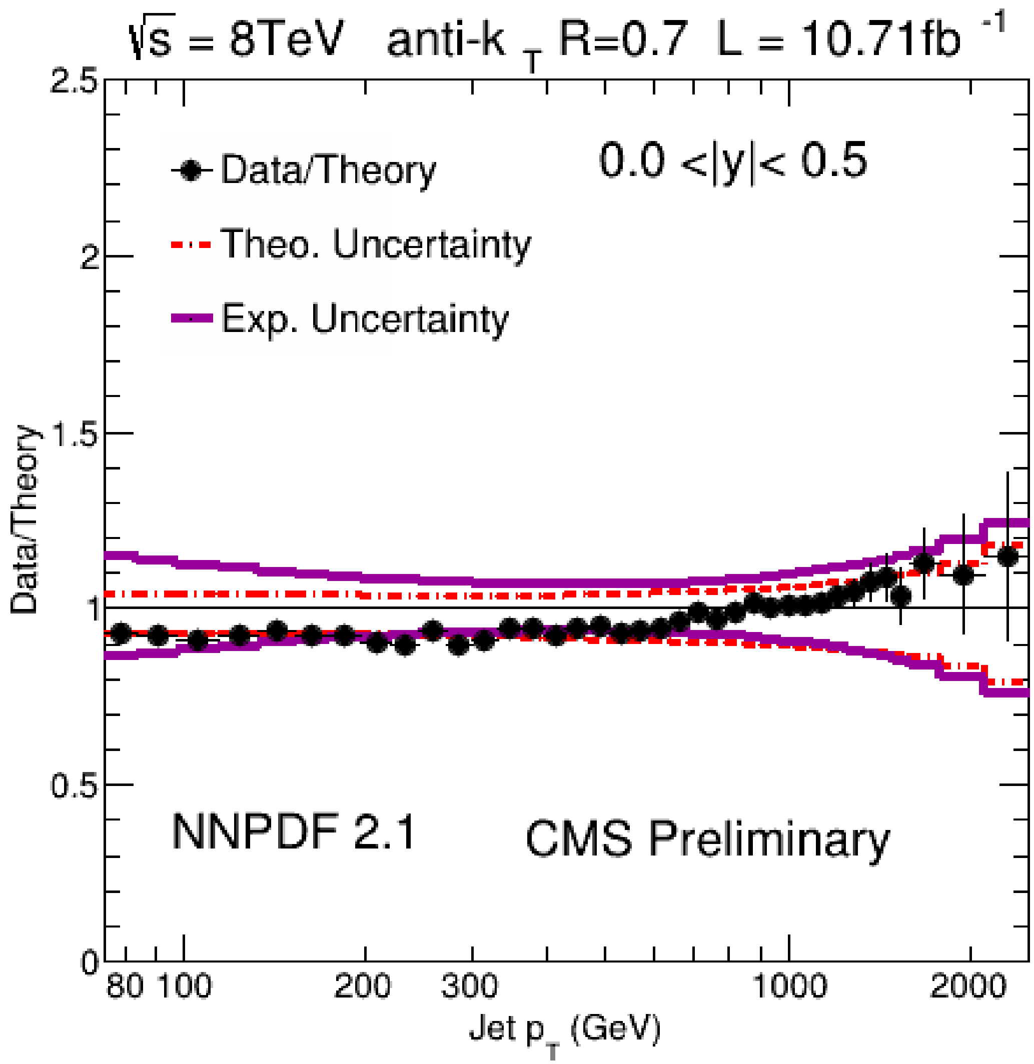


Inclusive jet production at LHC

CMS-PAS-FSQ-12-031
CMS-PAS-SMP-12-012

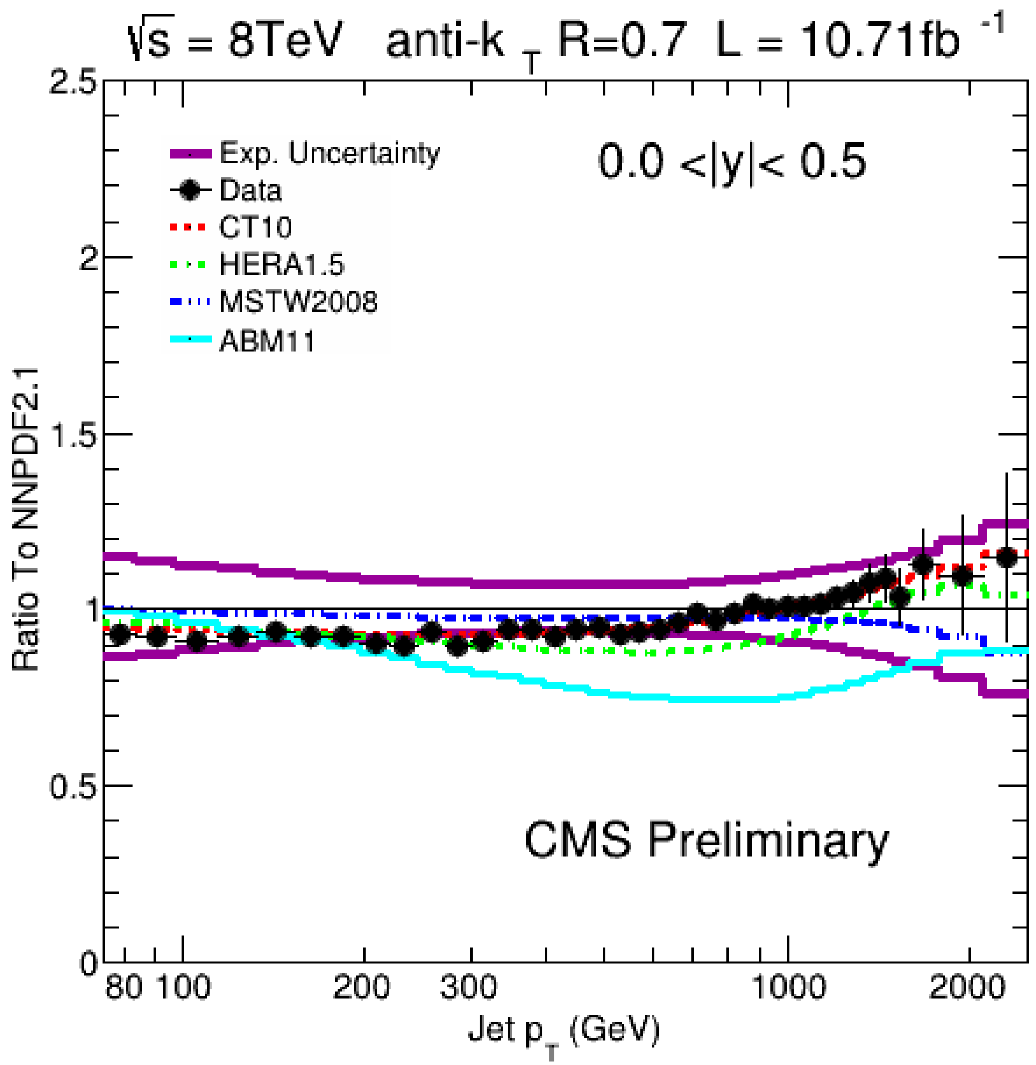
- Experimental uncertainty is comparable to theory uncertainty above ~500 GeV jet ET
- Agreement across large x range with contemporary PDFs



Inclusive jet production at LHC

CMS-PAS-FSQ-12-031
CMS-PAS-SMP-12-012

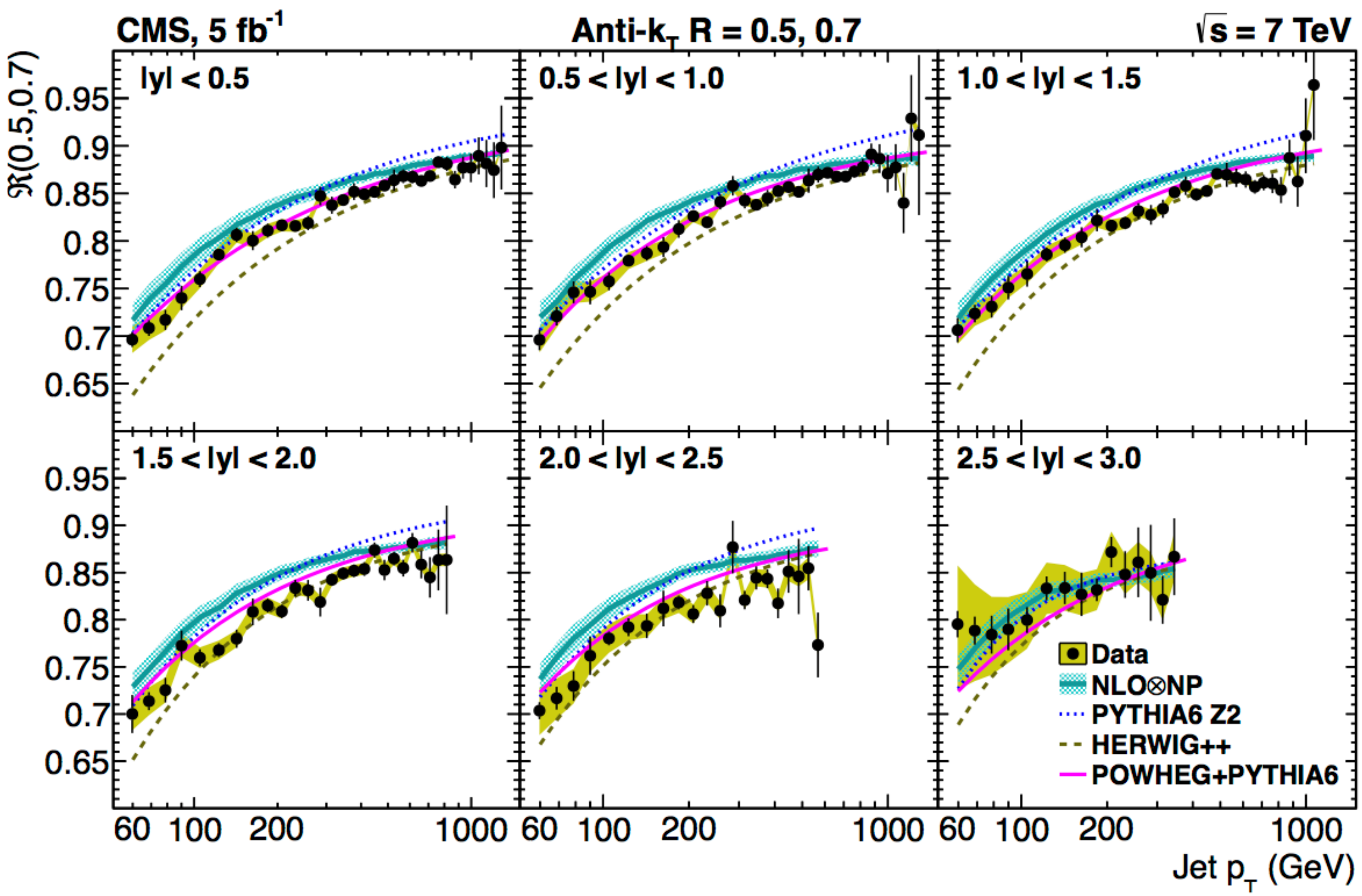
- Across PDF families, comparable agreement to data is observed (except for ABM11)



Inclusive jet production at LHC

- Are we doing just as well at lower jet radius?
- Ratio of jet cross sections at different jet anti-kt radii R(0.5,0.7) indicates that the NLOXNP scheme is not accounting for the out-of-cone radiation well, however.

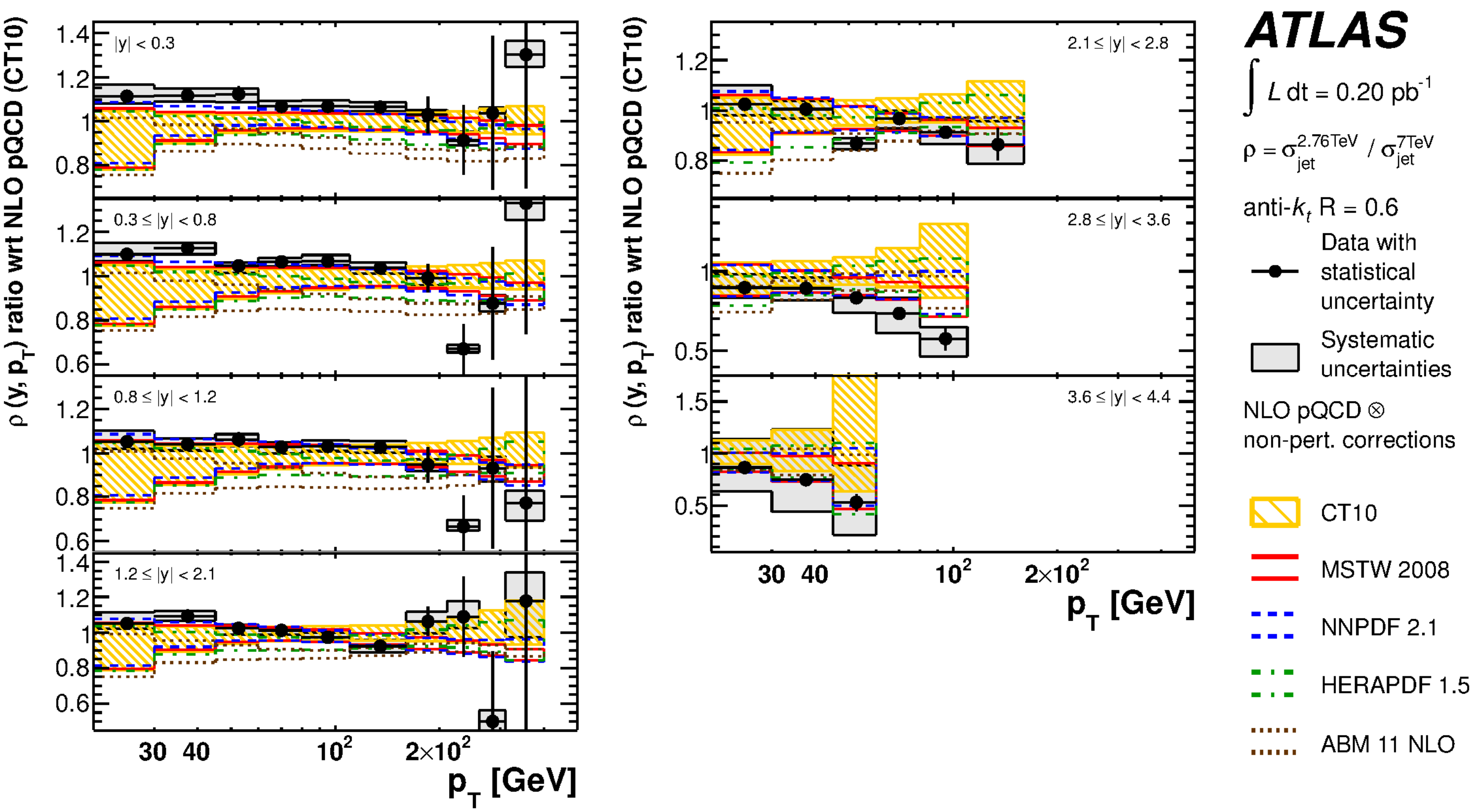
[PRD 90 (2014) 072006](PRD 90 (2014) 072006)



Inclusive jet production at LHC

- Double ratio of (Data/MC, 2.76 TeV)/(Data/MC, 7 TeV) also explored as a high-precision test of QCD, and potentially reveal onset of new phenomena at higher sqrt(s).

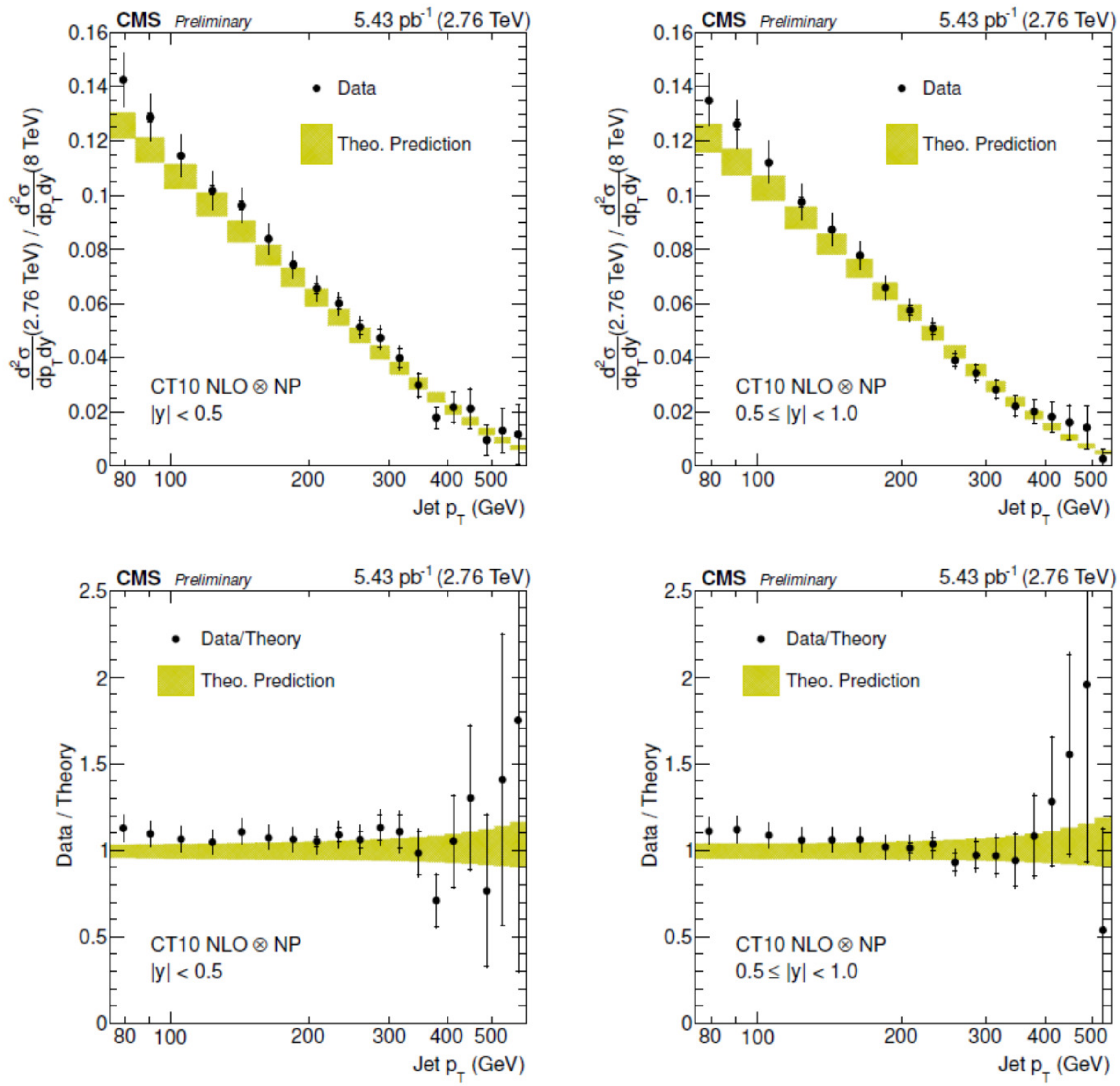
EPJC 73 (2013) 2509



Inclusive jet production at LHC

- Ratio of 8 TeV (10/fb) and 2.76 TeV data (5/pb) recently observed by CMS to be in agreement with NLOXNP scheme up to 500 GeV

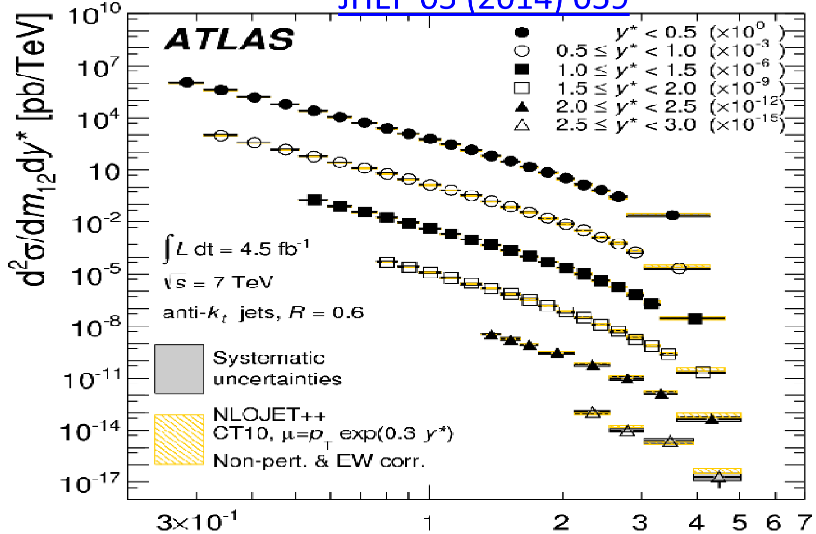
CMS-PAS-SMP-14-017

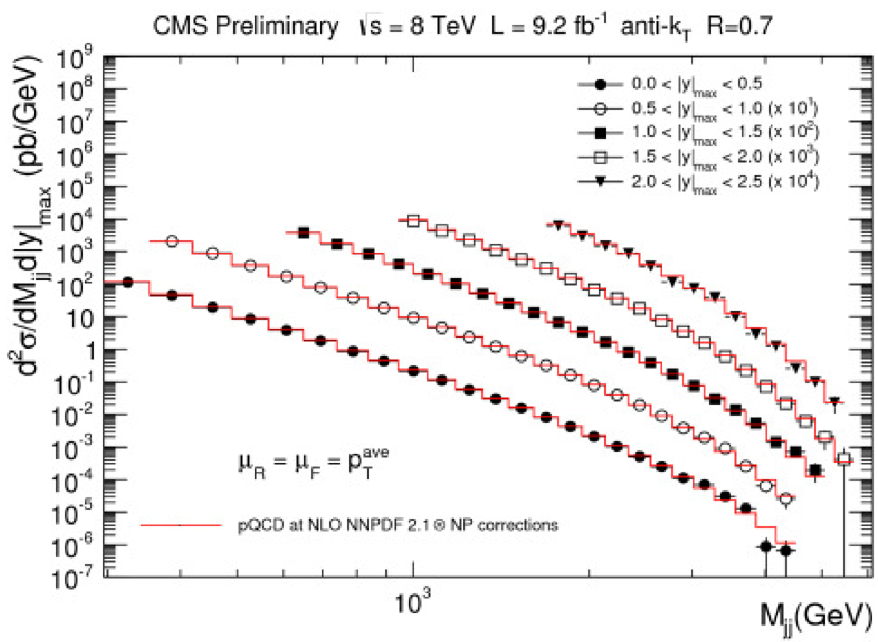


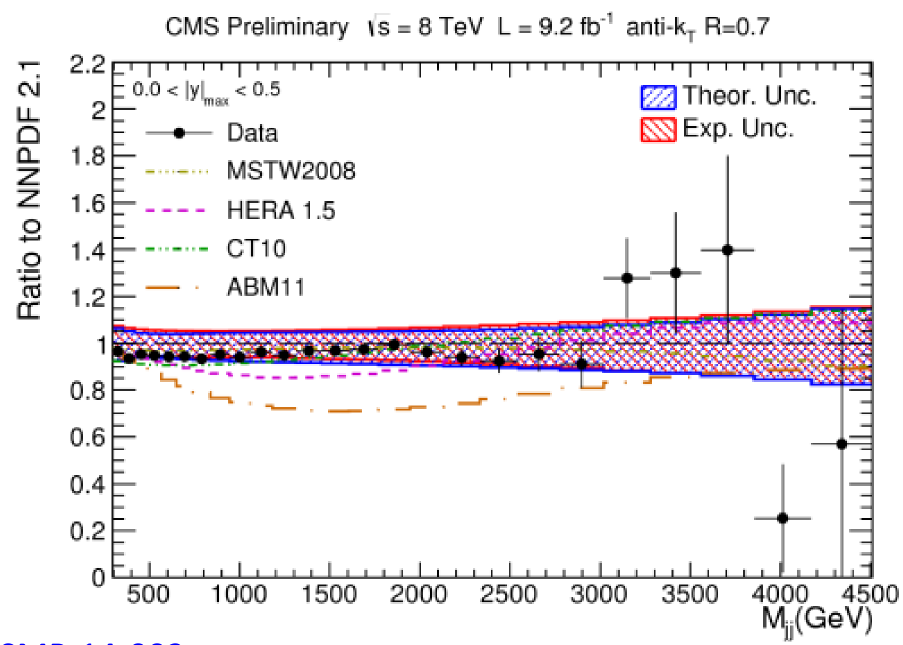
Dijet production at LHC

- Dijet predictions at 7 TeV and 8 TeV also observed in agreement with data.
- Dijet masses > 5 TeV observed

JHEP 05 (2014) 059

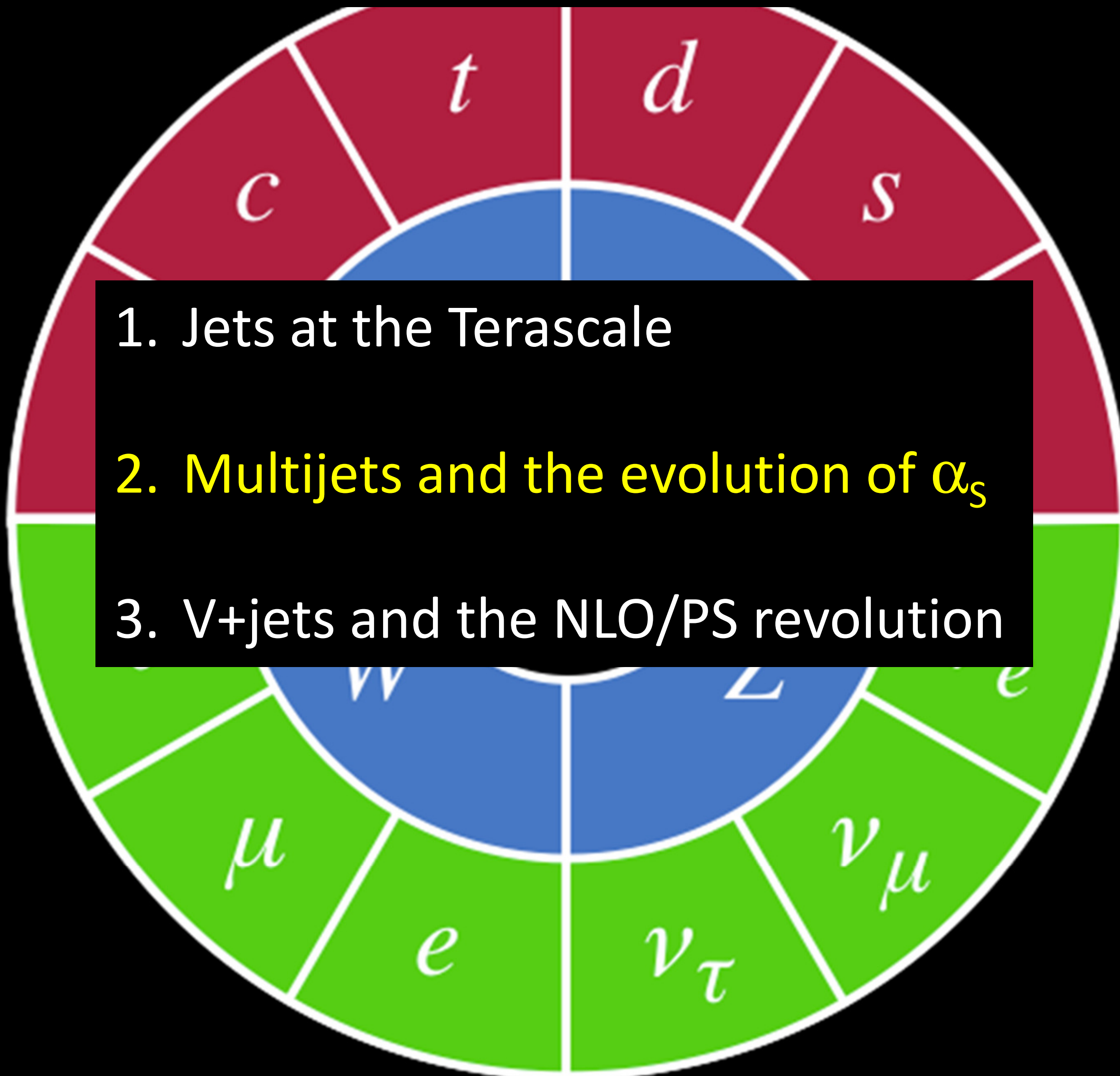






CMS-PAS-SMP-14-002

1. QCD



1. Jets at the Terascale
2. Multijets and the evolution of α_s
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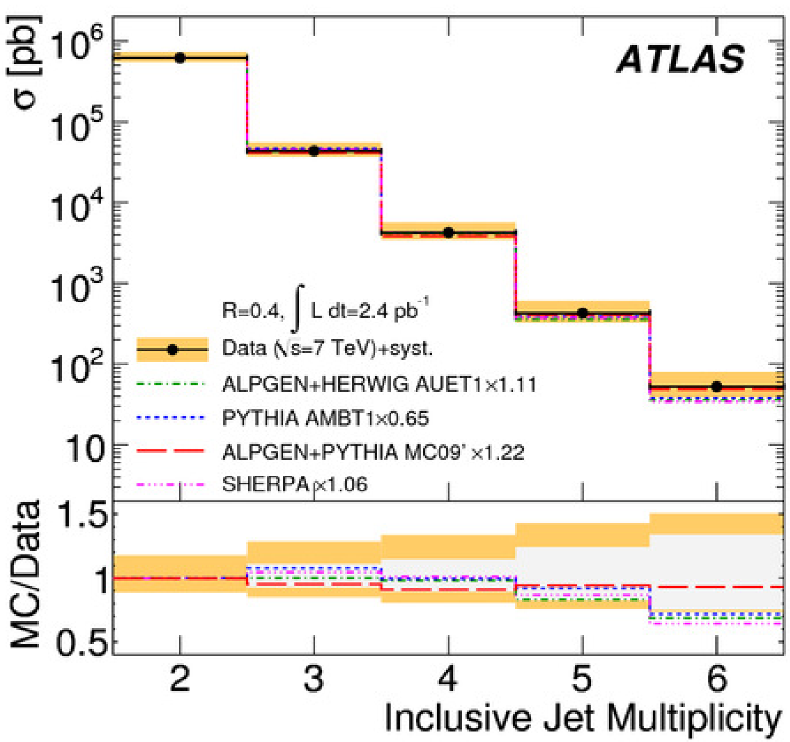
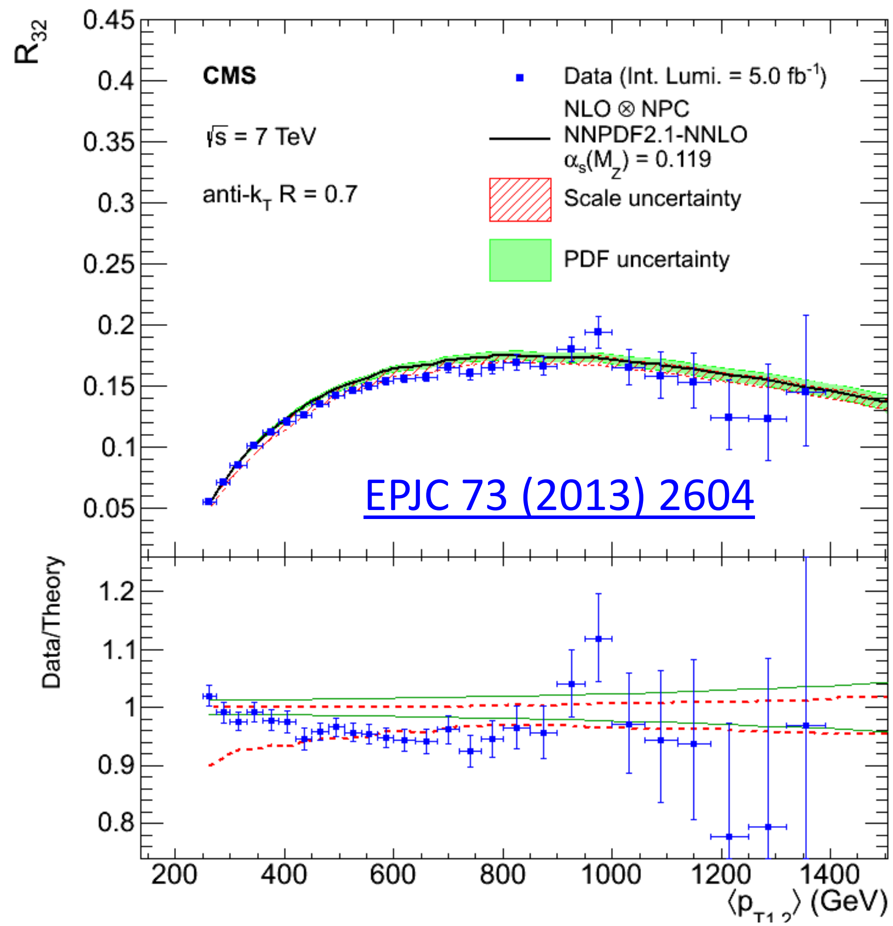
Multijet production at LHC

- Jet multiplicity slope for jet ET > 60 GeV agrees with LO+PS. Absolute scale agreement varies +/-35%
- Ratio of 3-jet to 2-jet production vs. leading dijet average PT agrees well with NLOXNP predictions. Scale uncertainty from theory dominates over large range!
- 3rd jet spectra sensitive to FSR → probes strong coupling running

EPJC 71 (2011) 1763

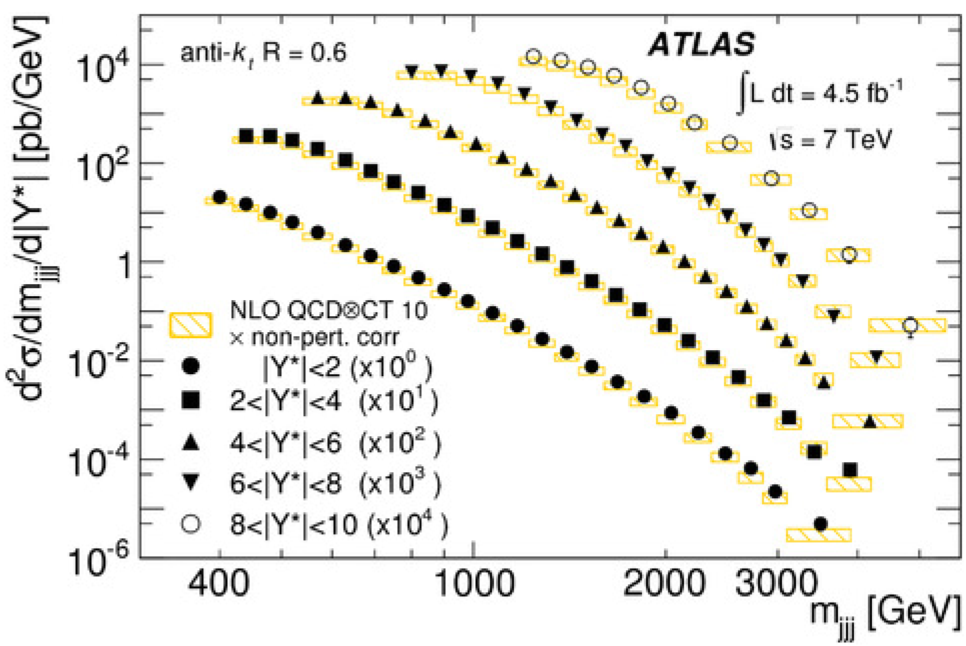




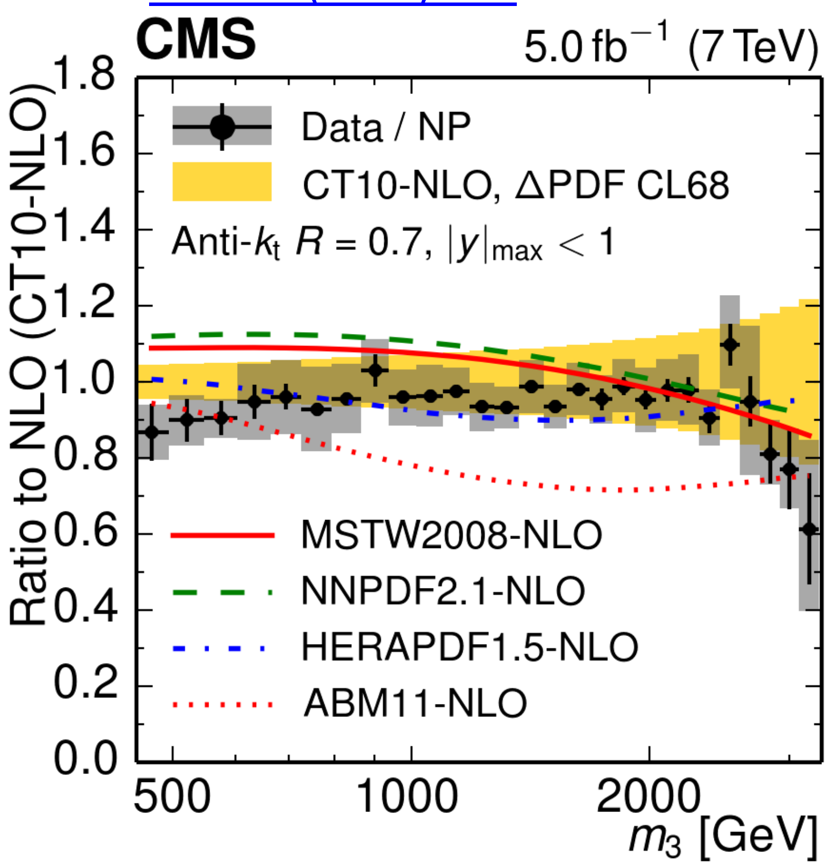
Multijet production at LHC

- Differential cross section vs. 3-jet mass also in agreement over a large range of masses.
- Some PDFs do better than others.

EPJC 75 (2015) 228

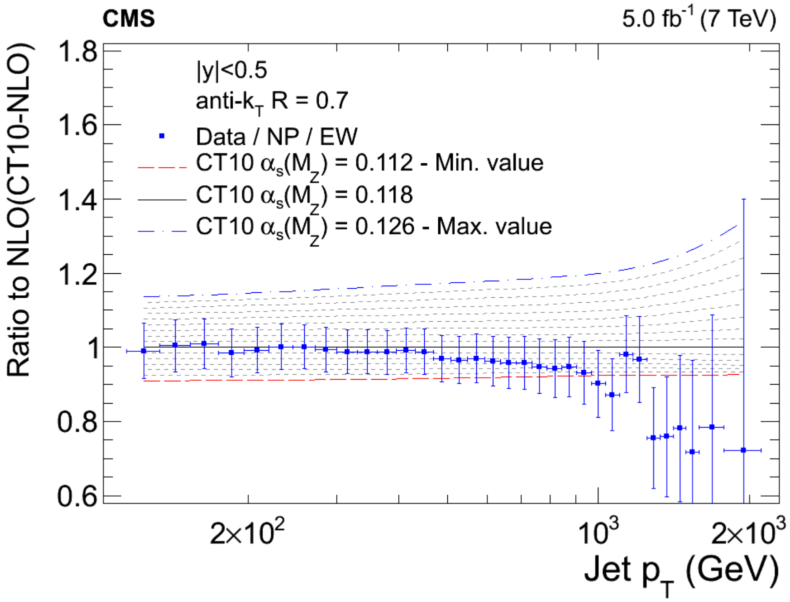


EPJC 75 (2015) 186



Measuring α_S: Inclusive jet production

- Within a given PDF framework (CTEQ, MSTW, NNPDF) , can consistently vary αs and PDFs simultaneously
- Each variation gives a different double-differential inclusive jet cross section
- Global correlated chi2 analysis gives best fit of αs to the data



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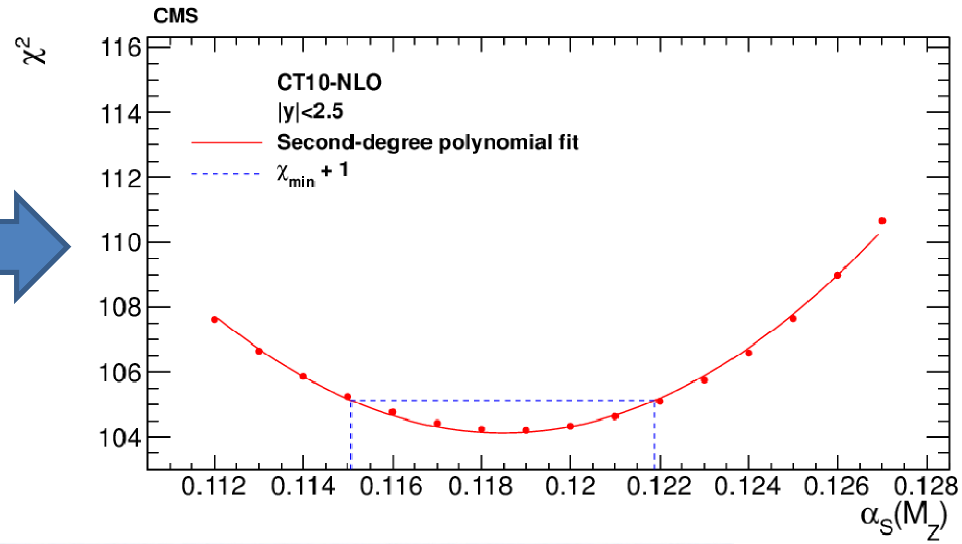
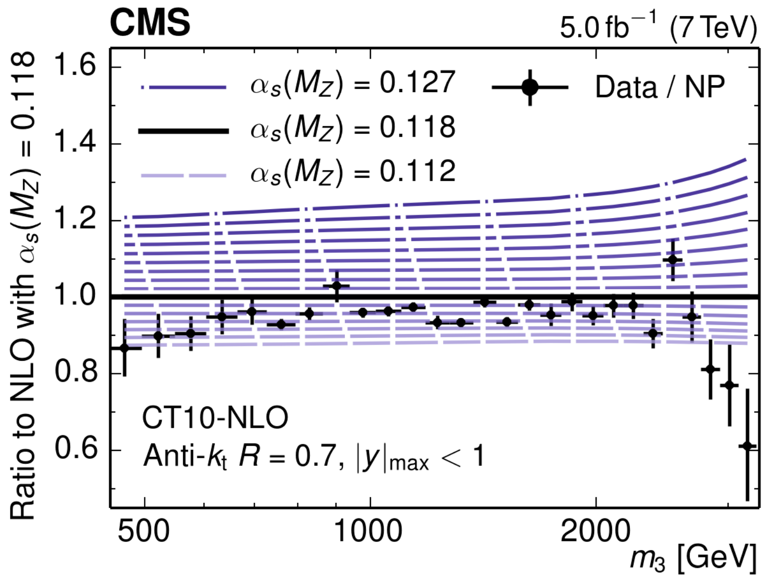


$$\alpha_s(M_z) = 0.1185 \pm 0.0019(\text{exp}) \pm 0.0028(PDF) \pm 0.0004(NP) \pm {}^{0.0055}_{0.0022}\,(scale)$$

- Consistent across six jet energy bins
- Scale uncertainty dominated! NNLO jet cross section would improve this immediately
- MSTW and NNPDF have similar agreement

Measuring α_s: Three-jet mass

- cross section ~ αs^3 , comparable sensitivity to inclusive jets

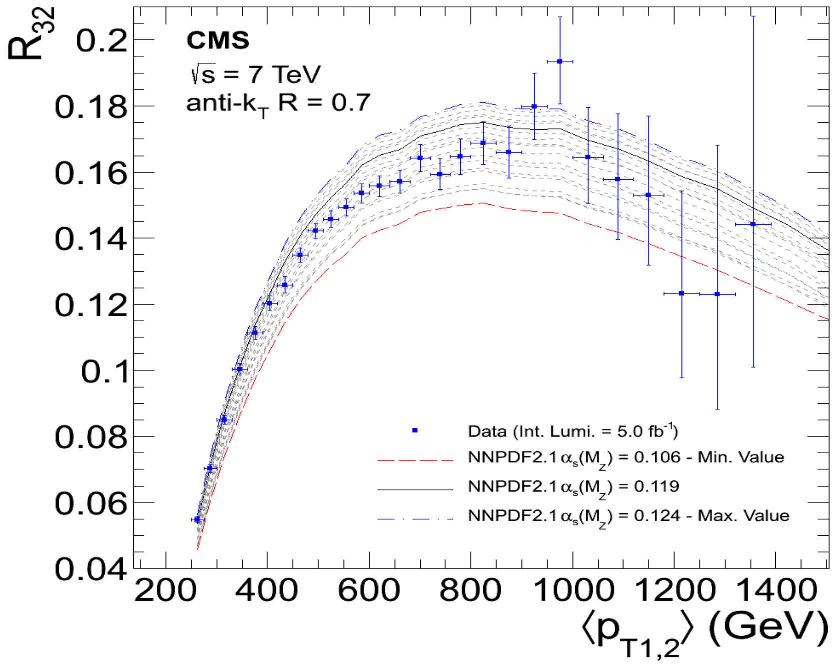


$$\alpha_s(M_z) = 0.1171 \pm 0.0013(\exp) \pm 0.0024(PDF) \pm 0.0008(NP) \pm {}^{0.0069}_{0.0040}\,(scale)$$

- Consistent across multiple jet mass bins and two ymax bins
- Scale uncertainty dominated!

Measuring α_S: Three-jet/Two-jet ratio

- Ratio is ~ αs, has comparable sensitivity to inclusive jets



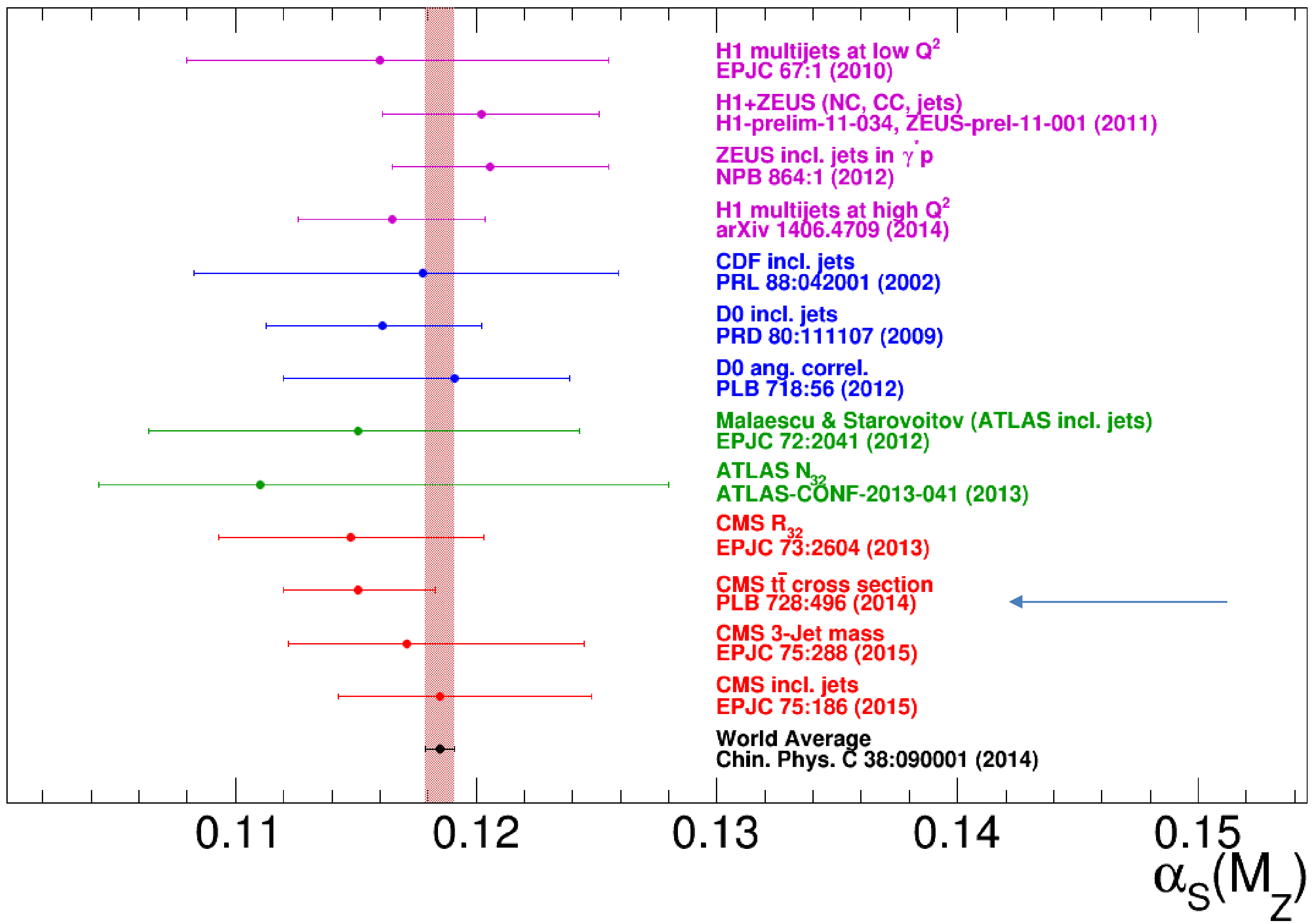
$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\exp) \pm 0.0018\,(PDF) \pm 0.0050\,(Theory)$$

α_S Running

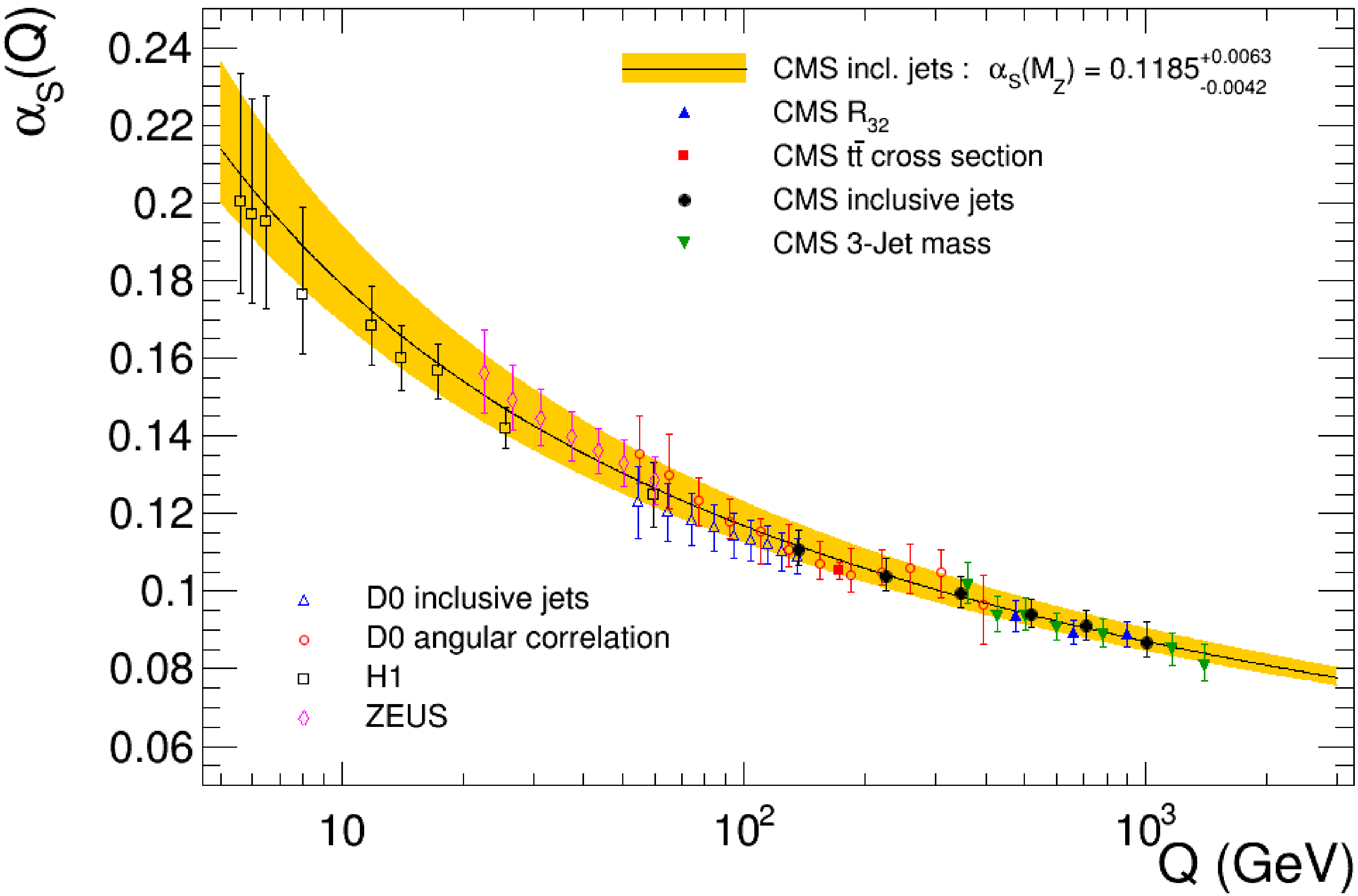
$\langle p_{T1,2}\rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/N_{dof}
420–600	474	0.1147 ± 0.0061	0.0936 ± 0.0041	6	4.4/5
600–800	664	0.1132 ± 0.0050	0.0894 ± 0.0031	5	5.9/4
800–1390	896	0.1170 ± 0.0058	0.0889 ± 0.0034	10	5.7/9

Strong-coupling evolution

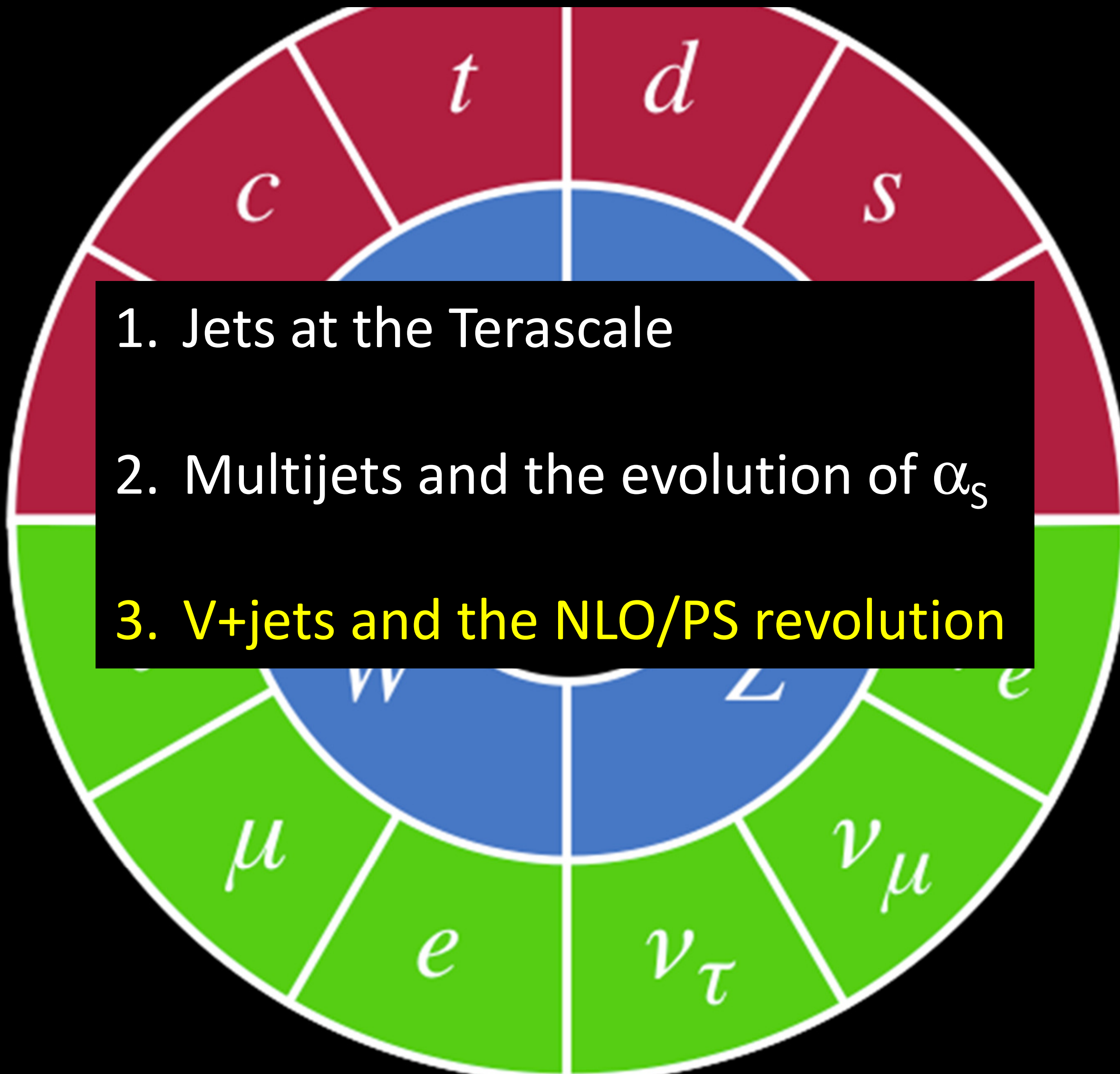
- Run to fixed Q^2 (MZ^2), agreement observed in hadron collider data with e+e- determination, for a broad range of phenomena and production energy



Strong-coupling evolution



1. QCD



1. Jets at the Terascale
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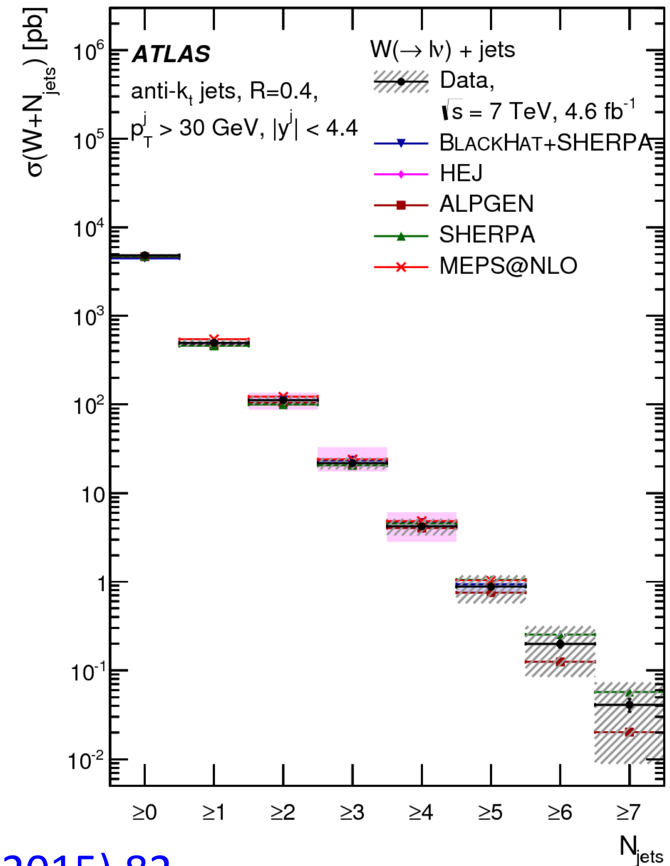
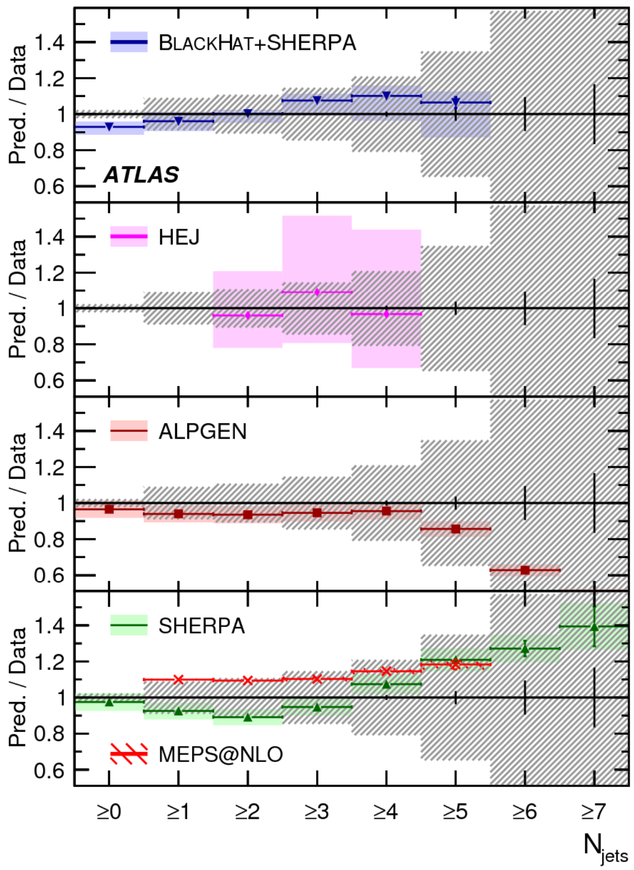
W + jet production

- Key proving ground for **NLO+PS revolution**: Sherpa2, aMC@NLO, MINLO, et al. and the ME engines driving them (BlackHat, OpenLoops, Madgraph et al.)
  - **NLO up to 5 jets!!**
  - **With fully merged/matched PS**
  - **Mostly automated and for large array of final states**
- W+jets cross section at 7 TeV: Validates BlackHat+Sherpa, Sherpa+MEPS@NLO out to 5 jets





[EPJC 75 (2015) 82](#)

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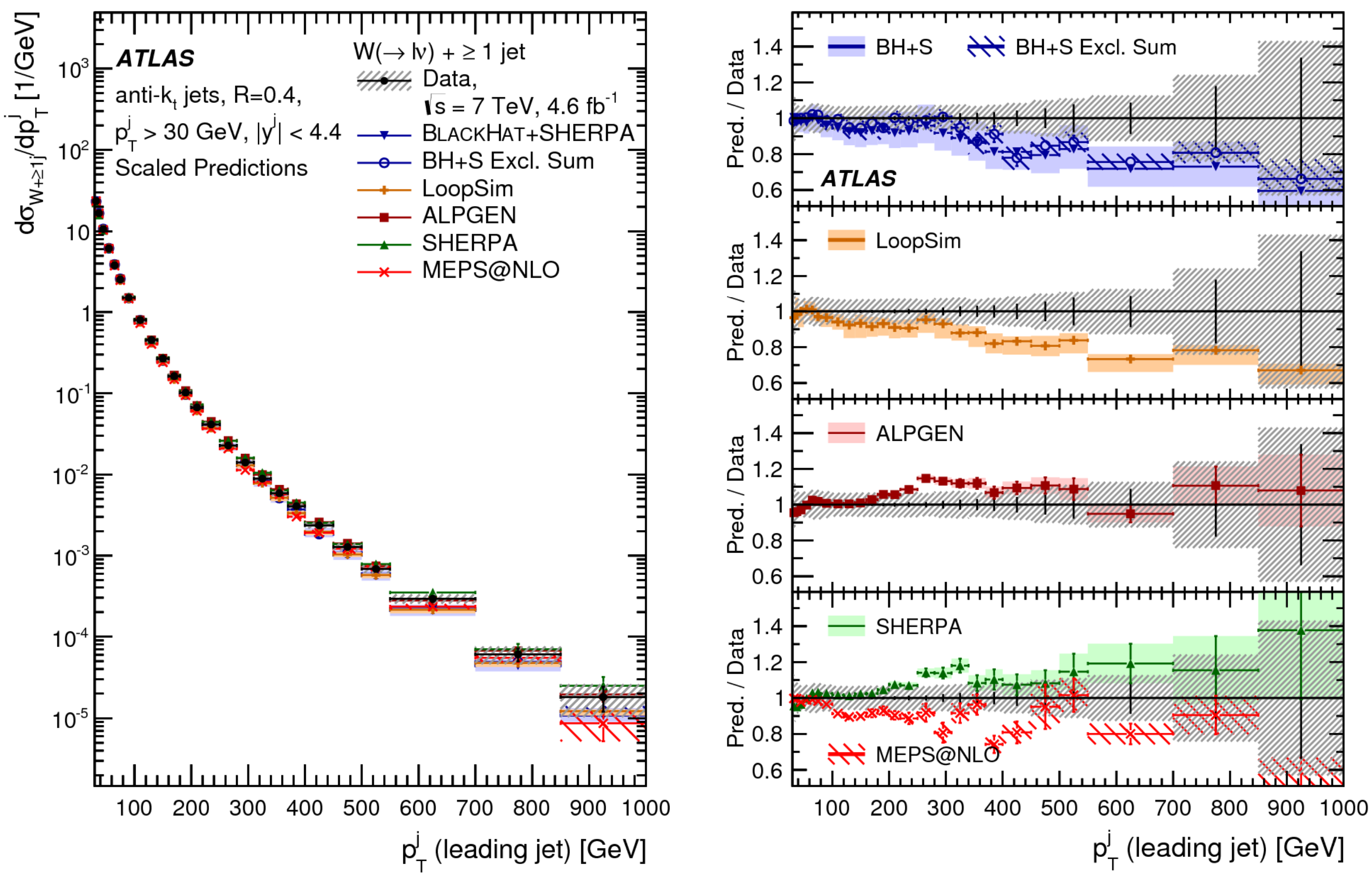
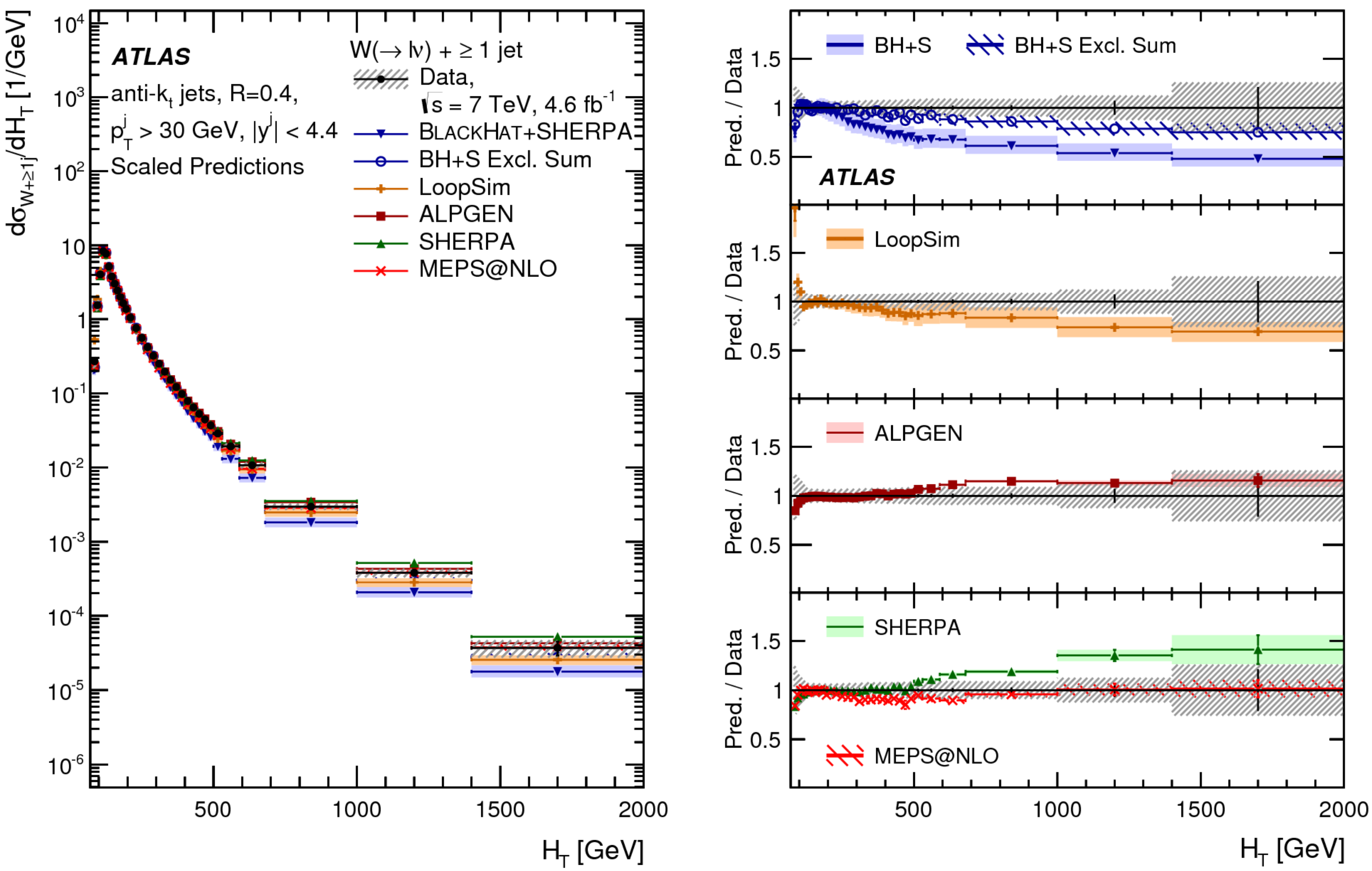


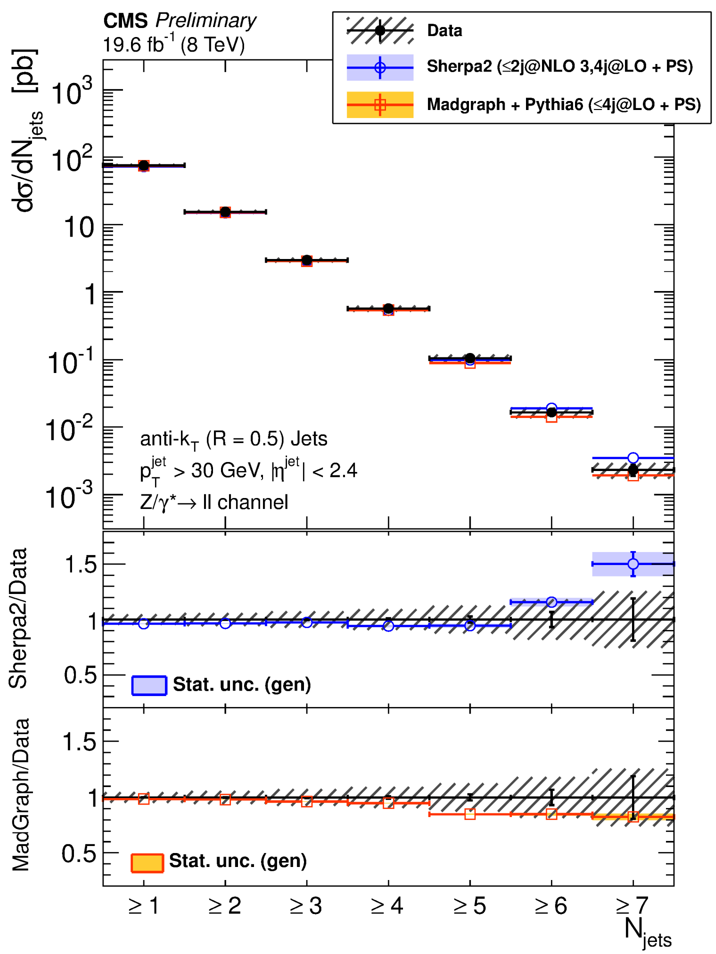
W + jet production

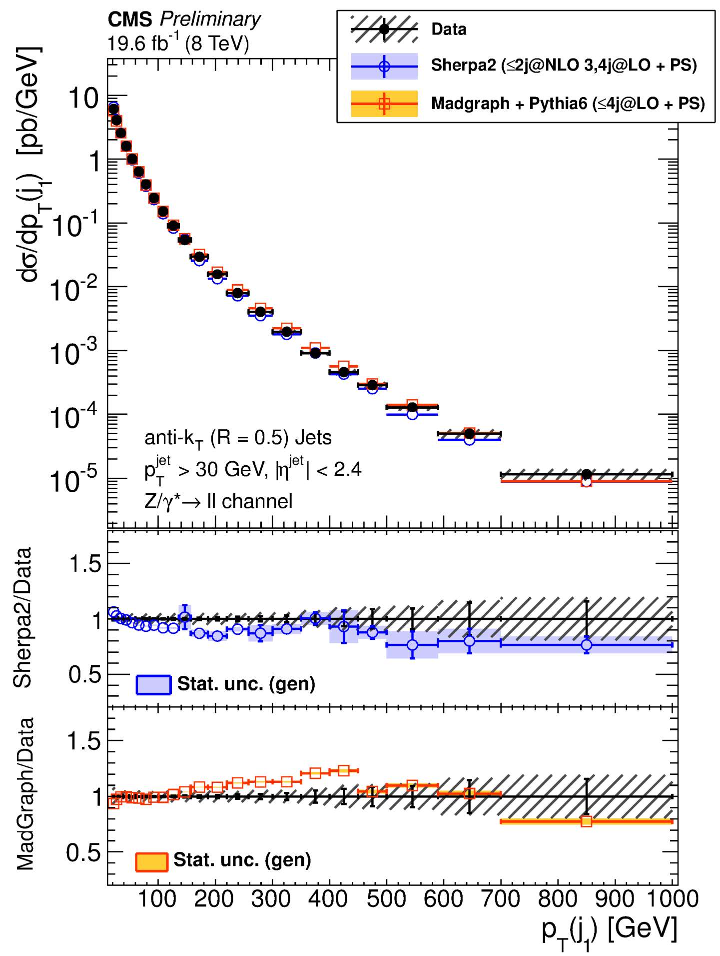
- W+jets cross section at 7 TeV: Less successful for observables like HT which sum over (possibly higher order) jet activity



Z + jet production

- Z+jets cross section at 8 TeV: out to Njet = 7 and jet PT of 1 TeV
- Sherpa2 does well with inclusive rate, under-predicts leading jet spectrum at highest ET

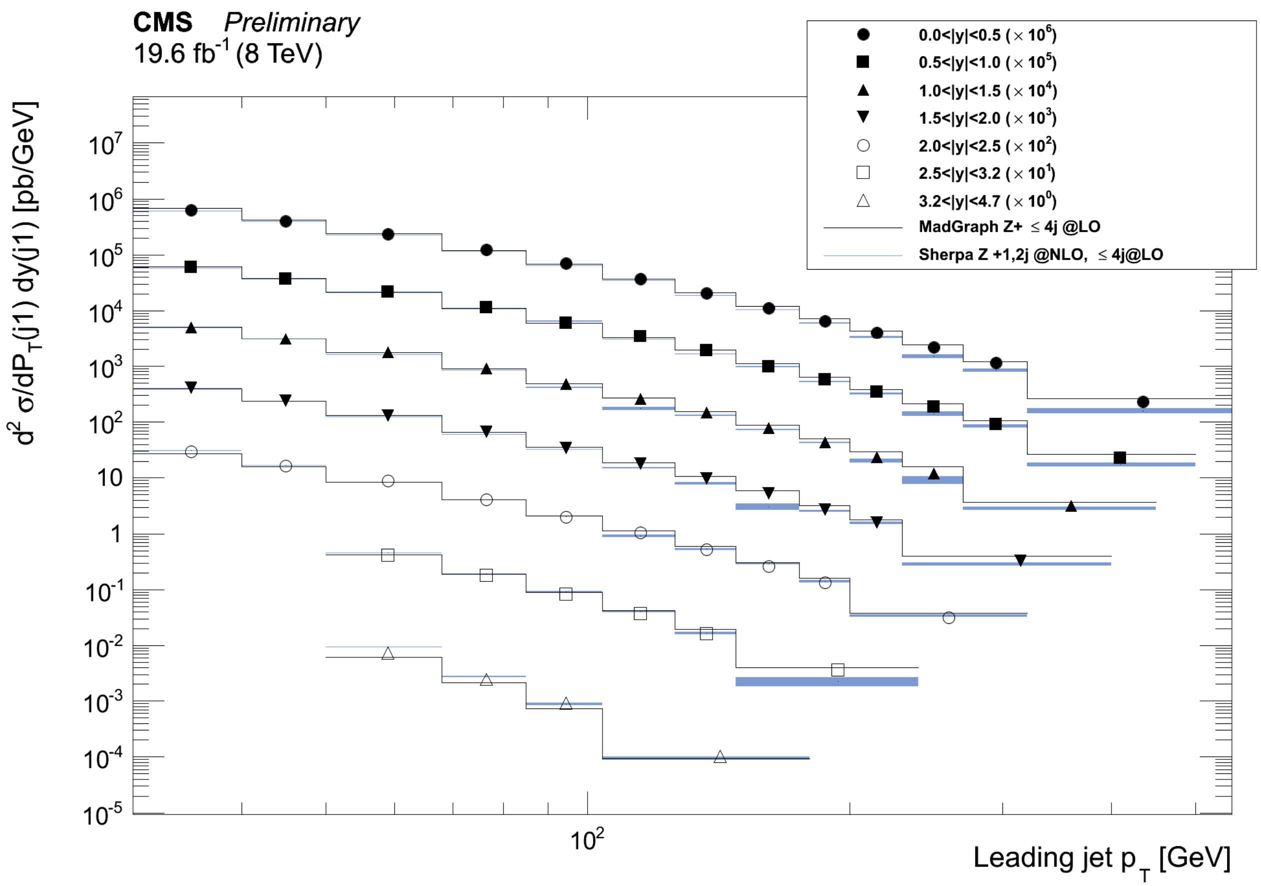




CMS-PAS-SMP-13-007

Z + jet production

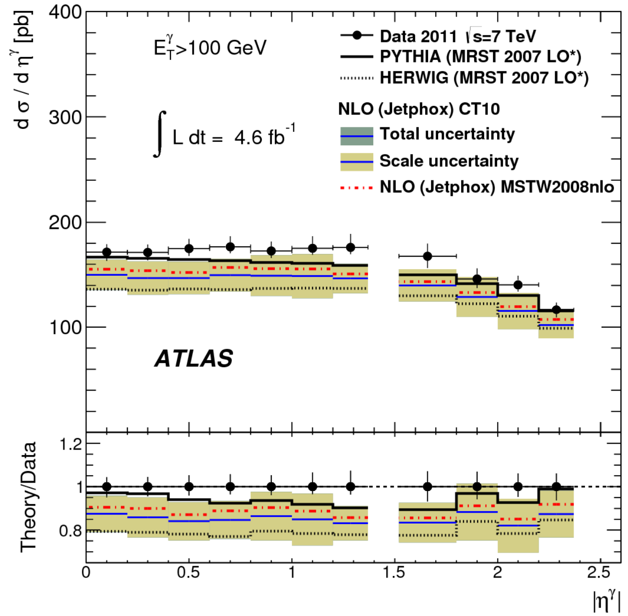
- Z+jets cross section at 8 TeV
- Now available doubly-differentially in jet PT and Y (suitable for future PDF fitting, à la inclusive jet)
- Sherpa2 does better than Madgraph, but under-predicts at highest jet ET

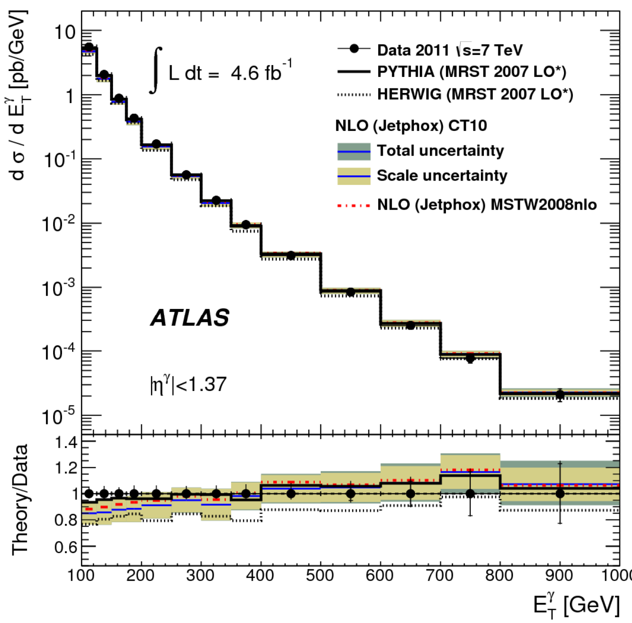


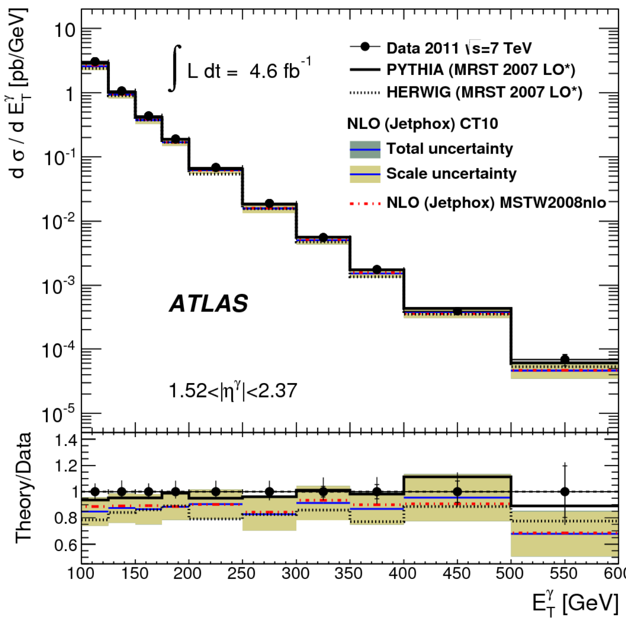
[CMS-PAS-SMP-14-009](CMS-PAS-SMP-14-009)

Inclusive photon production

- In 7 TeV data, ~2M photons ranging from 100-1000 in ET
- 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

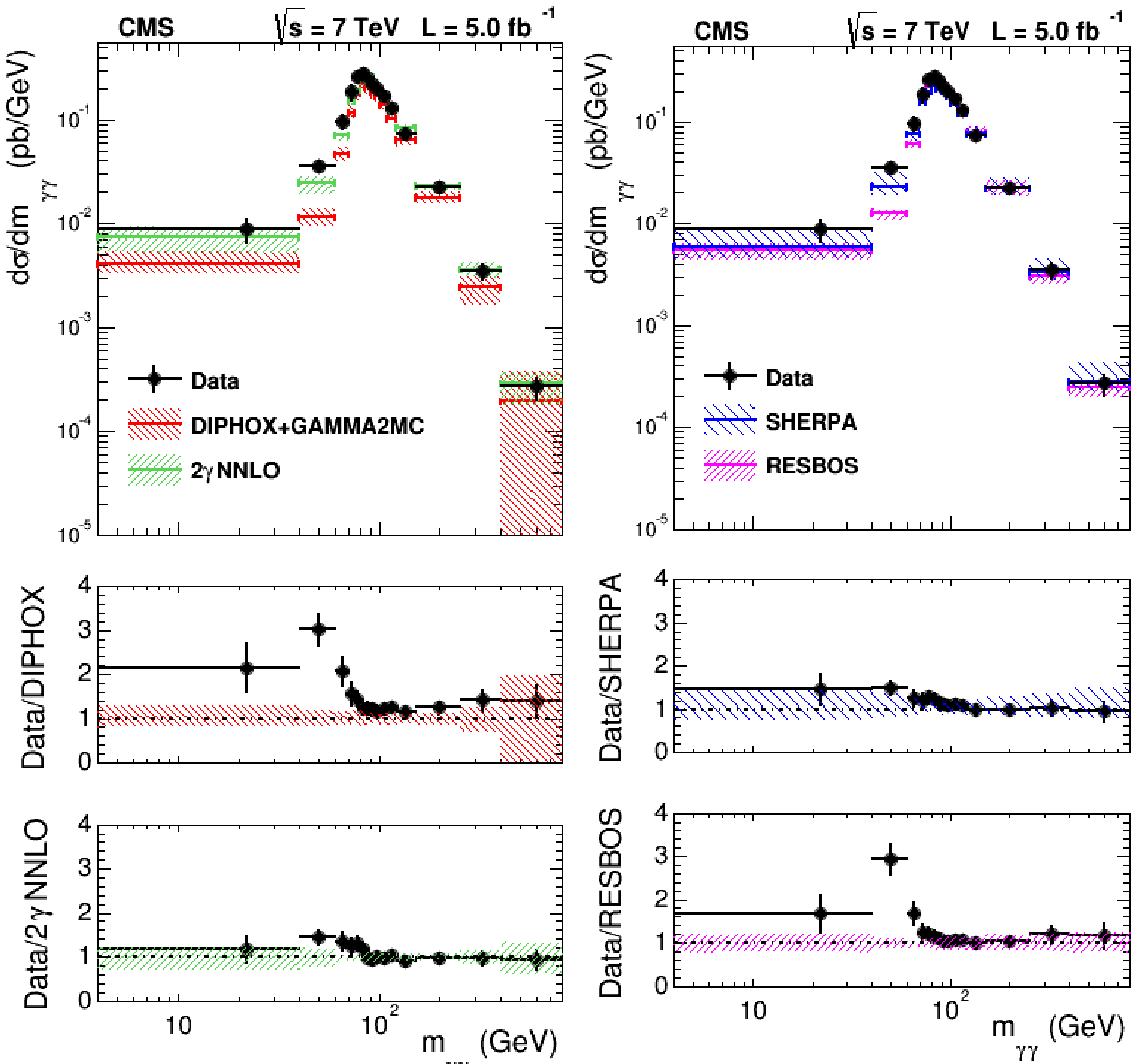






Diphoton production

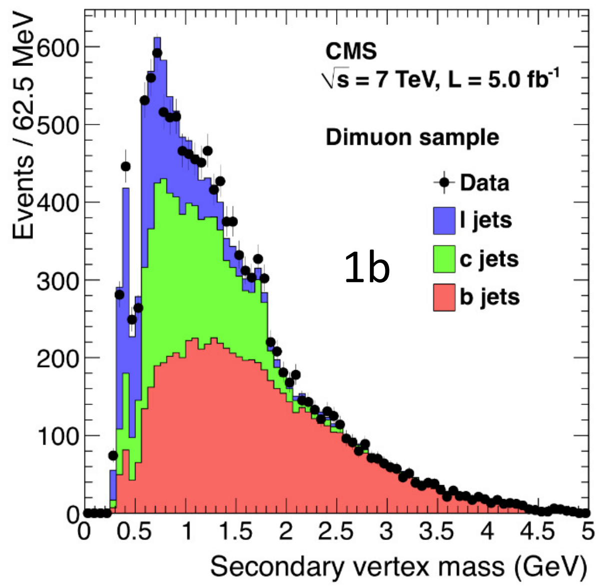
- Away from photon ET selection threshold, fixed-order NNLO, as well as Sherpa or RESBOS describe data well.
- Regions of phase space where higher-order/fragmentation/resummation, etc. are needed: high diphoton PT, low delta phi, low mass

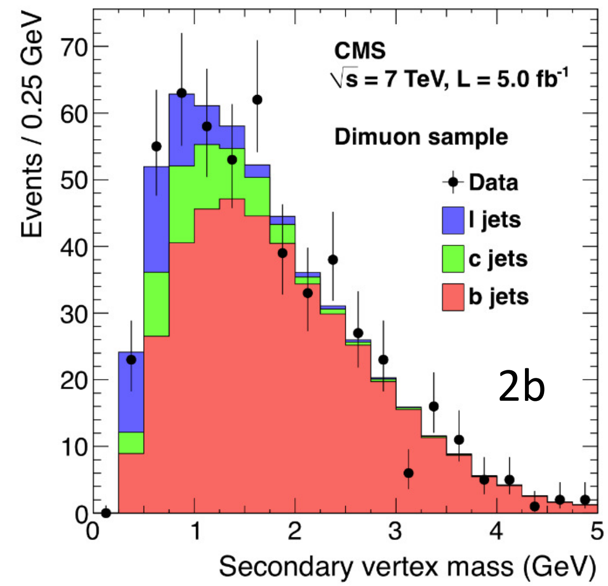


Z + b,bb production

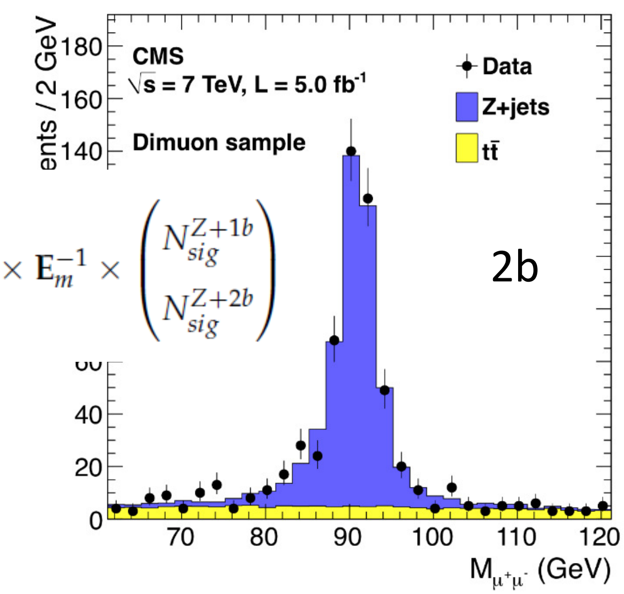
[JHEP 1406 (2014) 120](#)

- 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





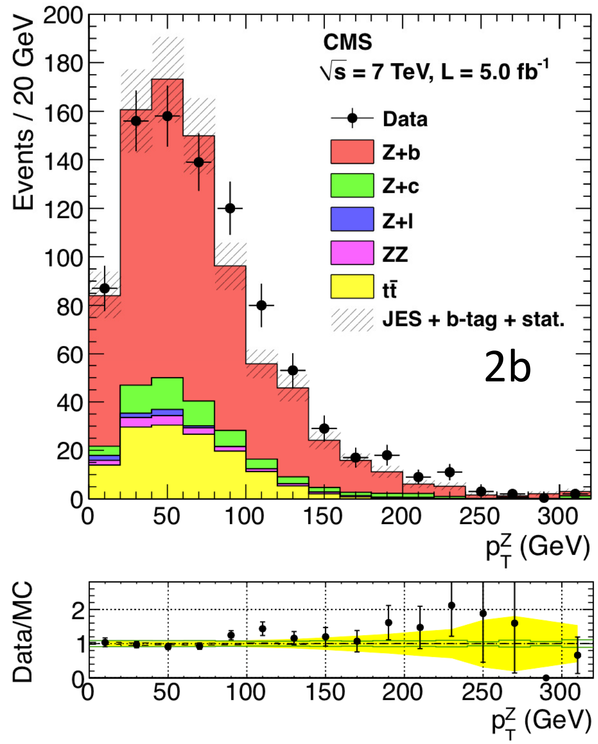
$$\begin{pmatrix} \sigma(Z+1b) \\ \sigma(Z+2b) \end{pmatrix} = \frac{1}{\mathcal{L}} \times \mathbf{E}_r^{-1} \times \mathbf{E}_l^{-1} \times \mathbf{E}_b^{-1} \times \mathbf{E}_m^{-1} \times \begin{pmatrix} N_{sig}^{Z+1b} \\ N_{sig}^{Z+2b} \end{pmatrix}$$

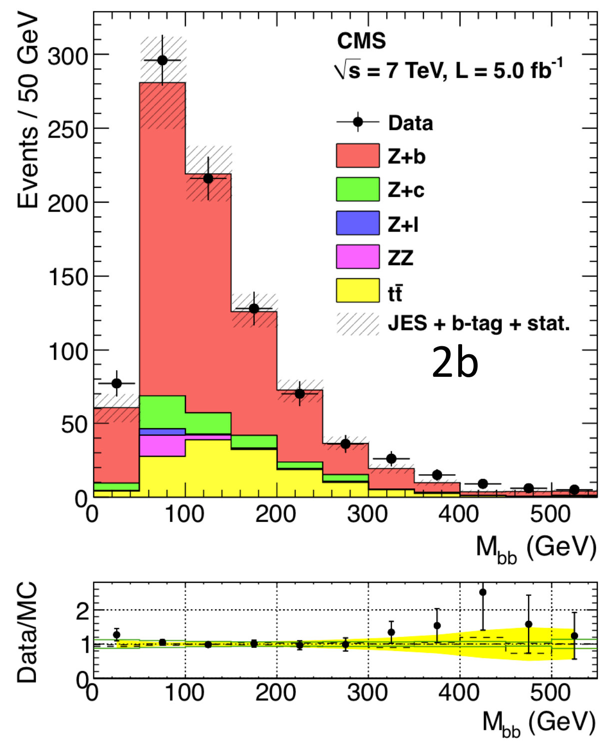


Z + b,bb production

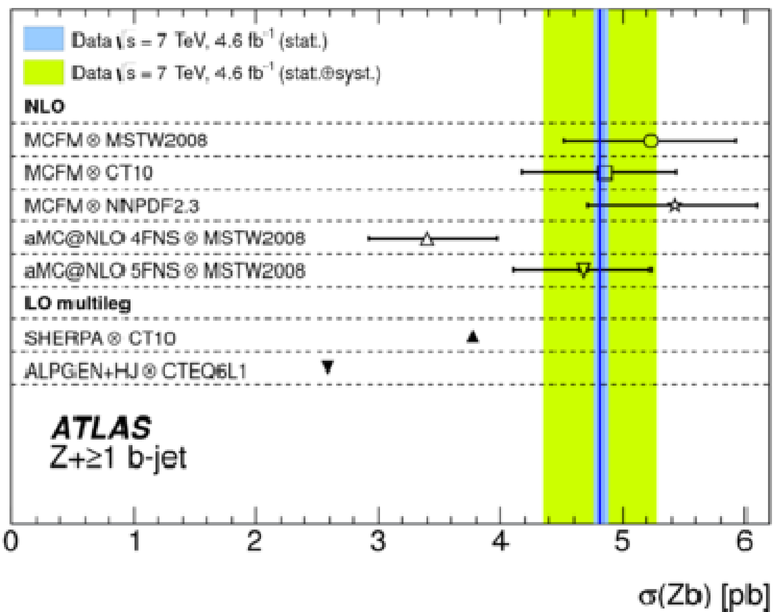
- Exclusive cross sections agree with MadGraph 4F and 5F predictions.
- B-tag efficiency and mistag uncertainty dominate total cross sections
- Z PT in 2b case is somewhat harder than MadGraph.
- Mbb and other variables in good agreement

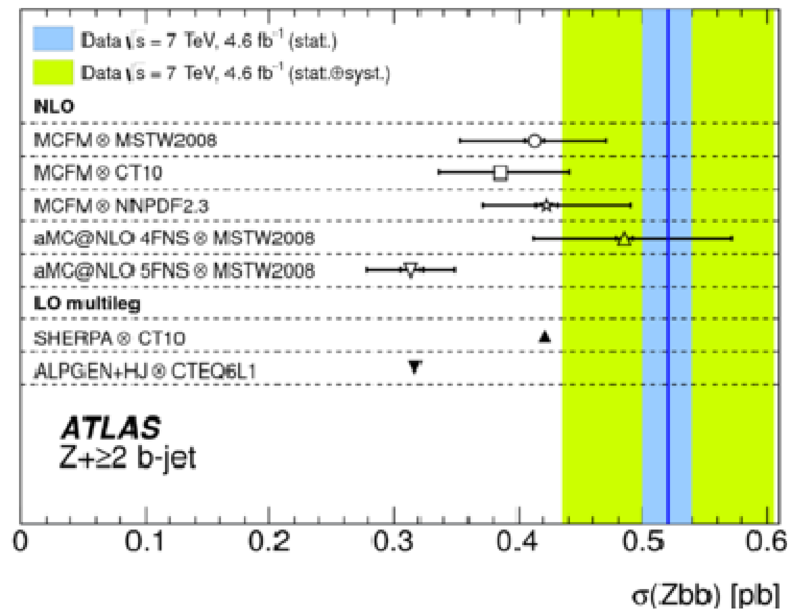
Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
$\sigma(Z(\ell\ell)+1b)$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
$\sigma(Z(\ell\ell)+2b)$ (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01
$\sigma(Z(\ell\ell)+b)$ (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.02	3.49 ± 0.03
$\sigma(Z(\ell\ell)+b)/\sigma(Z(\ell\ell)+j)$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

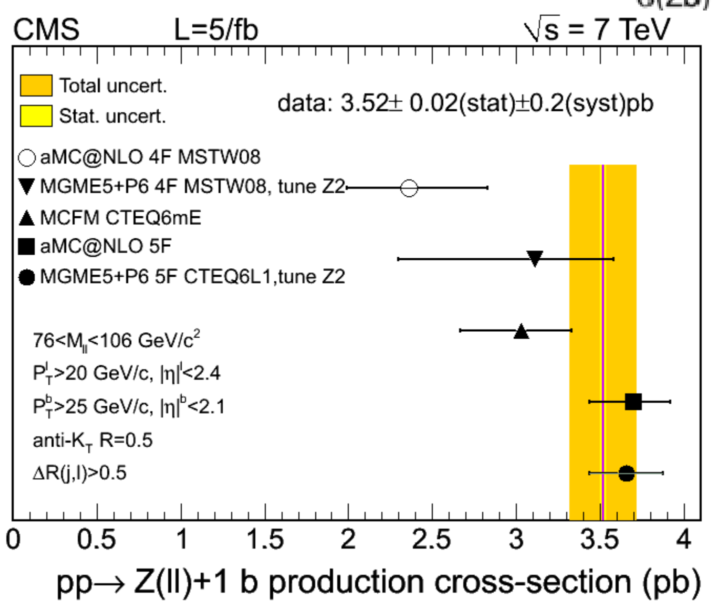


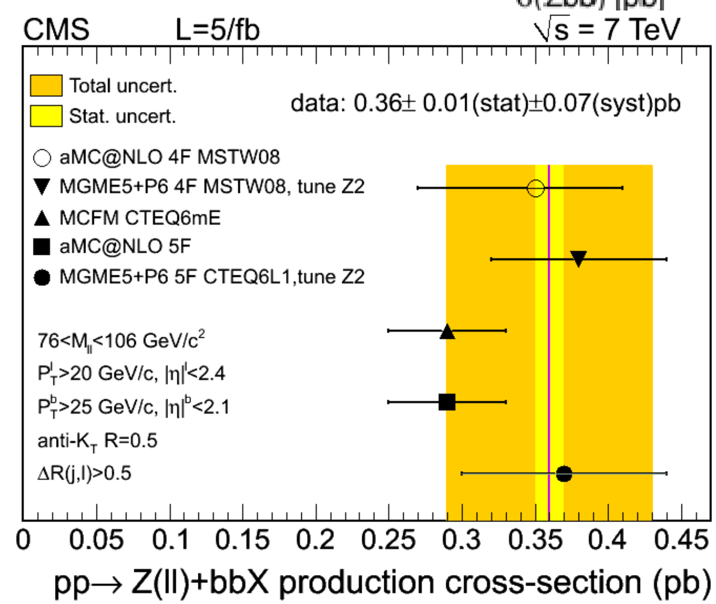


Z + b,bb production



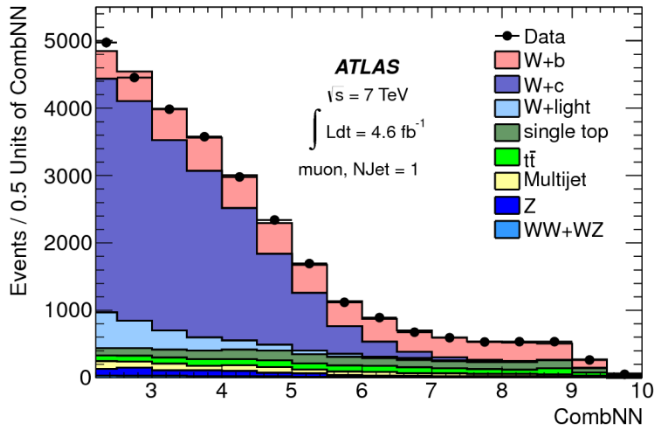


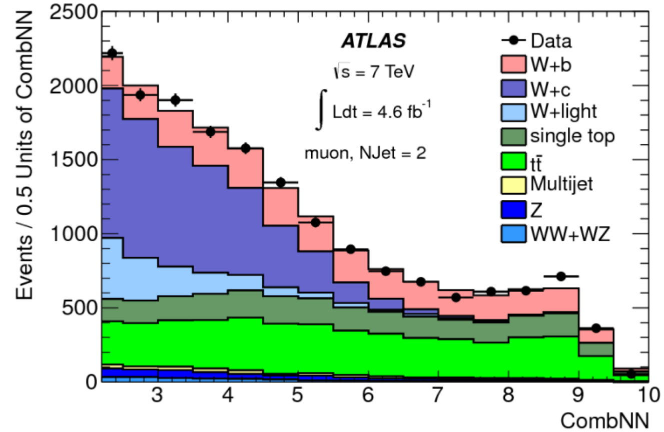


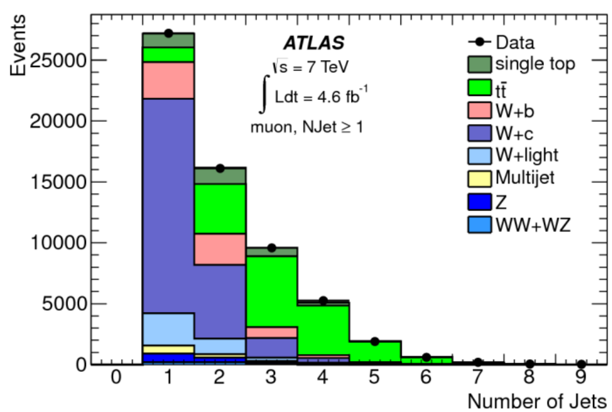


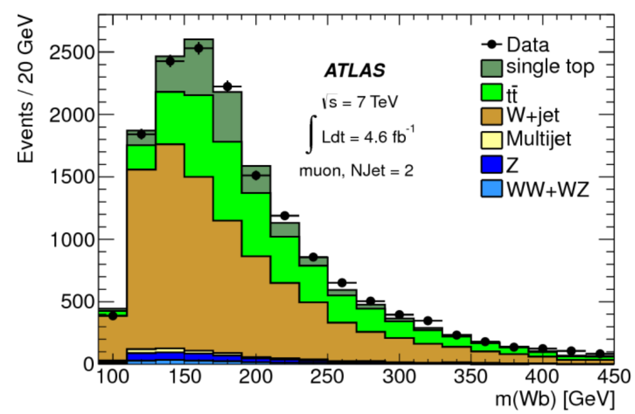
W+b production

- 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





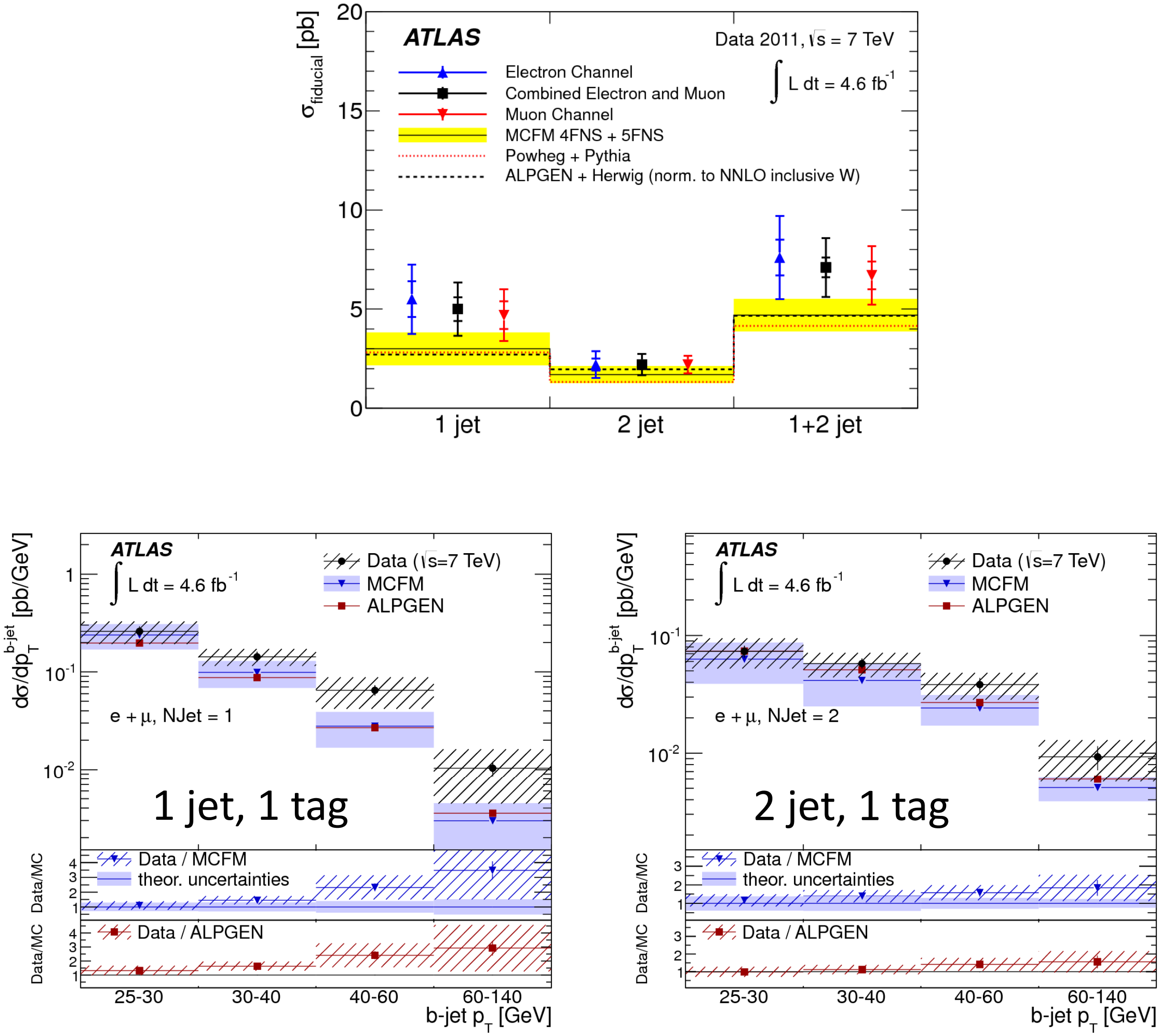




JHEP06(2013)084

W+b production

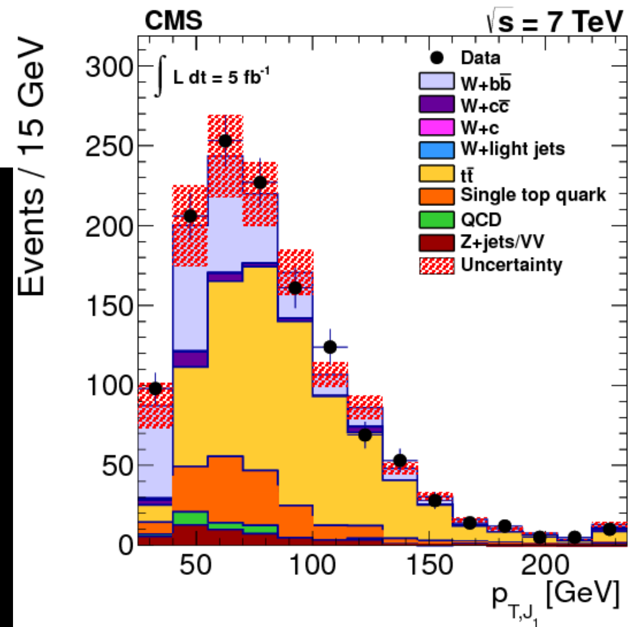
- **Exclusive cross sections measured to 20% precision (dominated by JES syst.)**
- **W+b + single top results also presented**
- **MCFM NLO and LO+PS predictions consistent with data at 1.5σ**
- **Data and MC precision comparable**
- **Diff. b PT cross sections a bit harder than MCFM/ALPGEN**

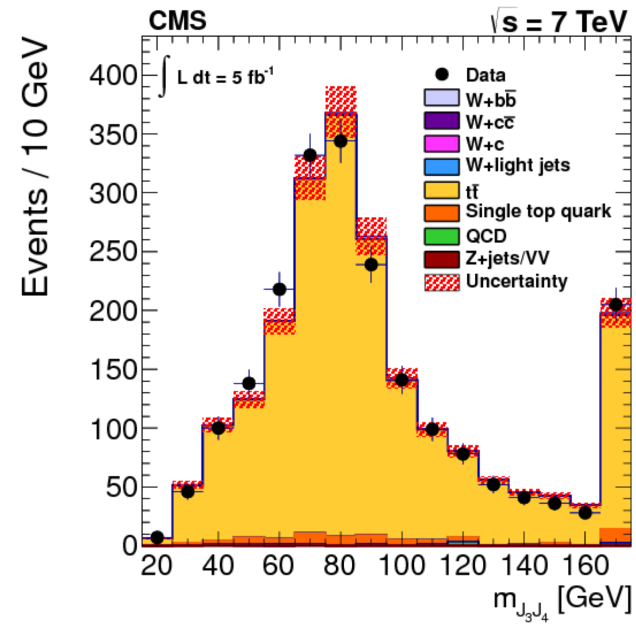


JHEP06(2013)084

W+bb production

- W candidates with =2 jets and =2 btags
- W+c,cc reduced by combined cut on the MSV of the two b-tags
- tt background 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





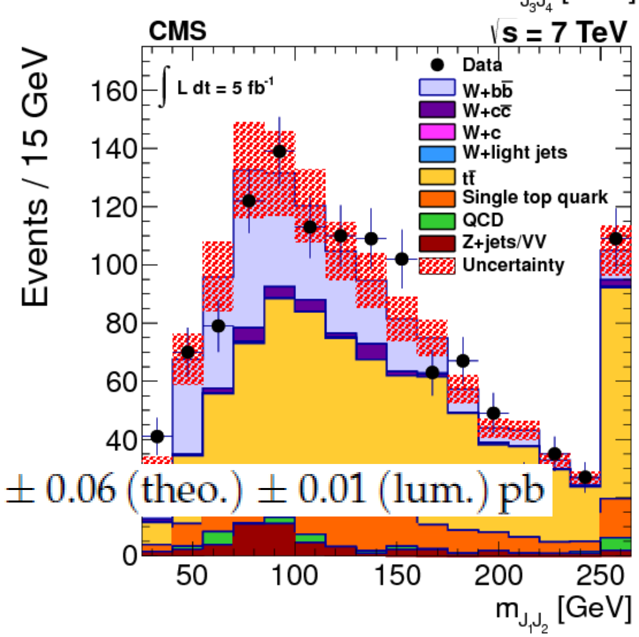
[PLB 735 (2014) 204]

MCFM

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

CMS data

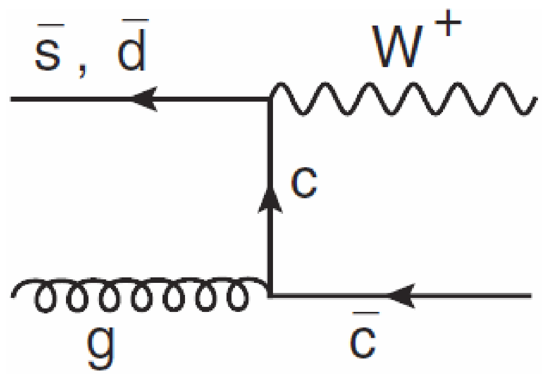
$0.53 \pm 0.05\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.06\,(\mathrm{theo.}) \pm 0.01\,(\mathrm{lum.})\,\mathrm{pb}$

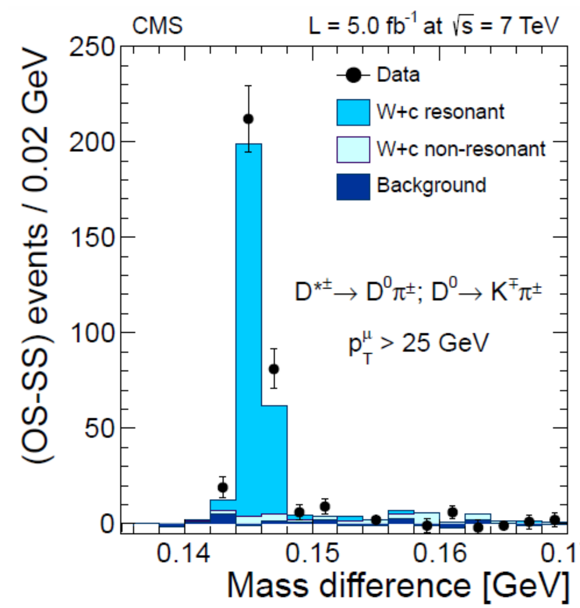


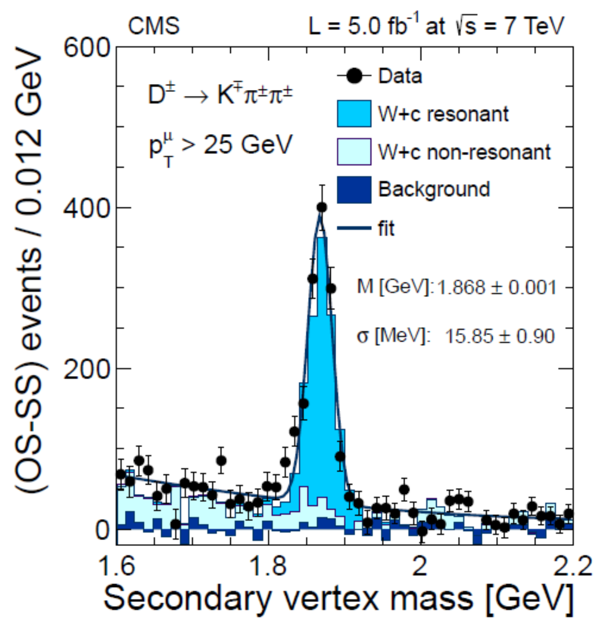
W+charm production

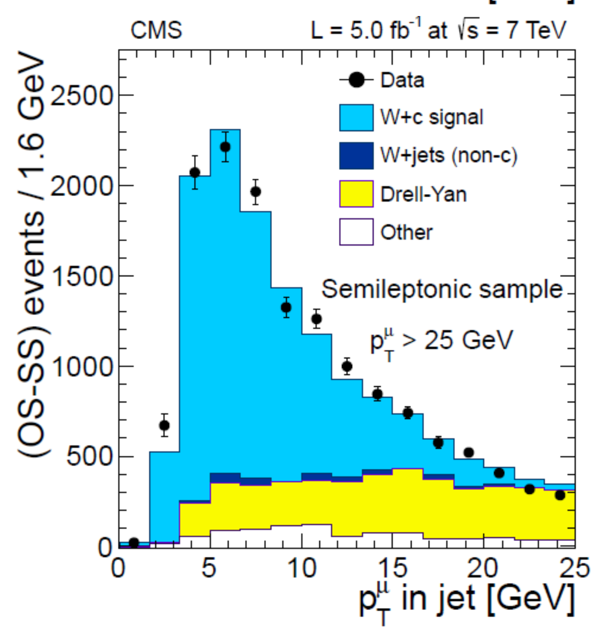
JHEP 02 (2014) 023

- Leading order W+c directly probes strange quark PDF
- Strange and anti-strange probed independently by W+, W-
- W and c are opposite sign
- W+cc,bb, top pair backgrounds same-sign/opposite-sign symmetric→subtract with same-sign data
- (semi-)exclusive charm hadron reconstruction gives high-purity, self-charge tagged W+c samples



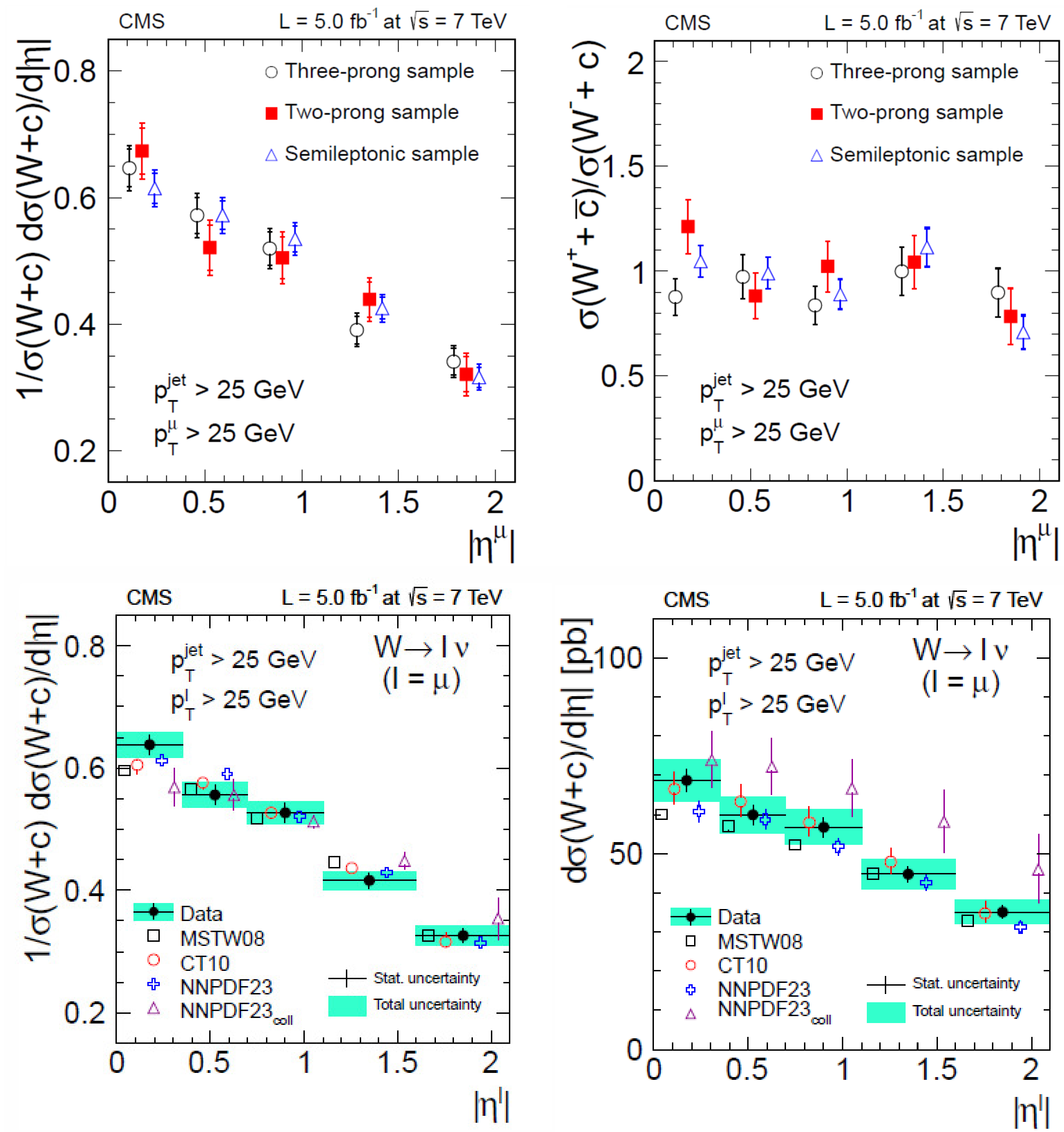






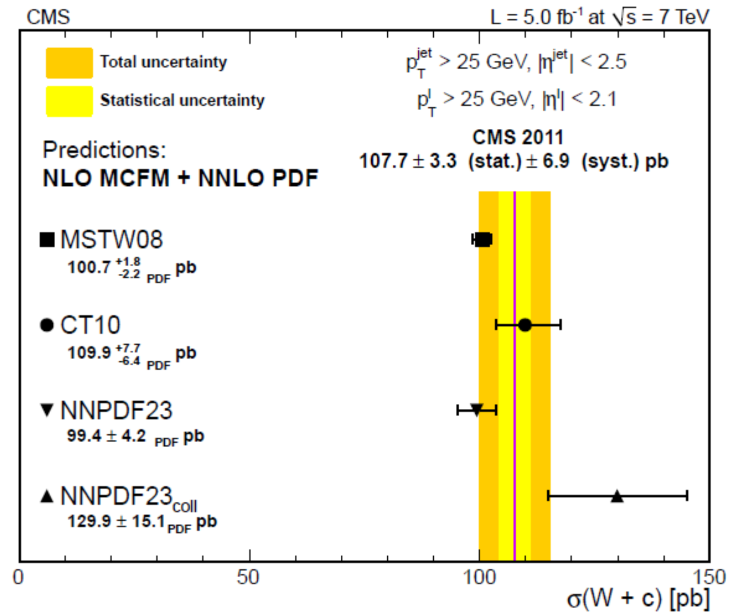
W+charm production

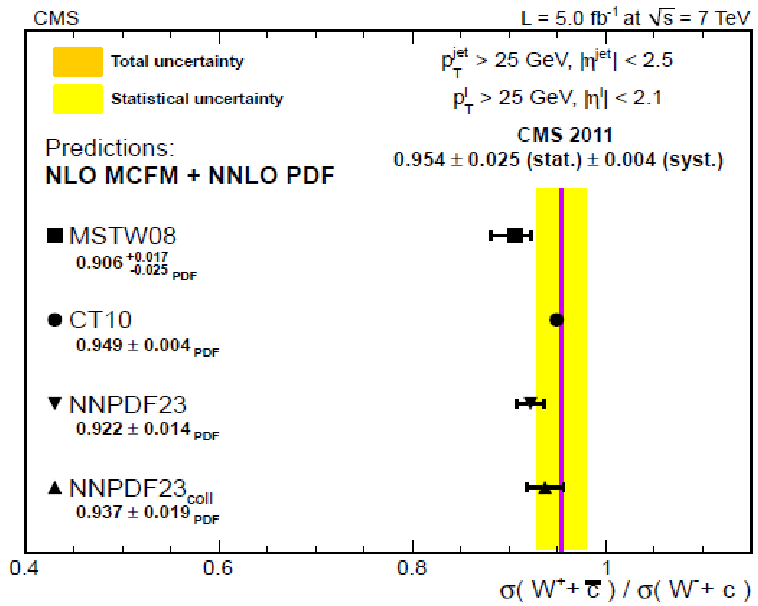
- **Measure cross section and charged ratio vs. lepton rapidity**
- **Consistent across three different hadron reco methods**
- **Leading syst. are JES, charm BF**
- **Consistent with NLO MC predictions**



W+charm production

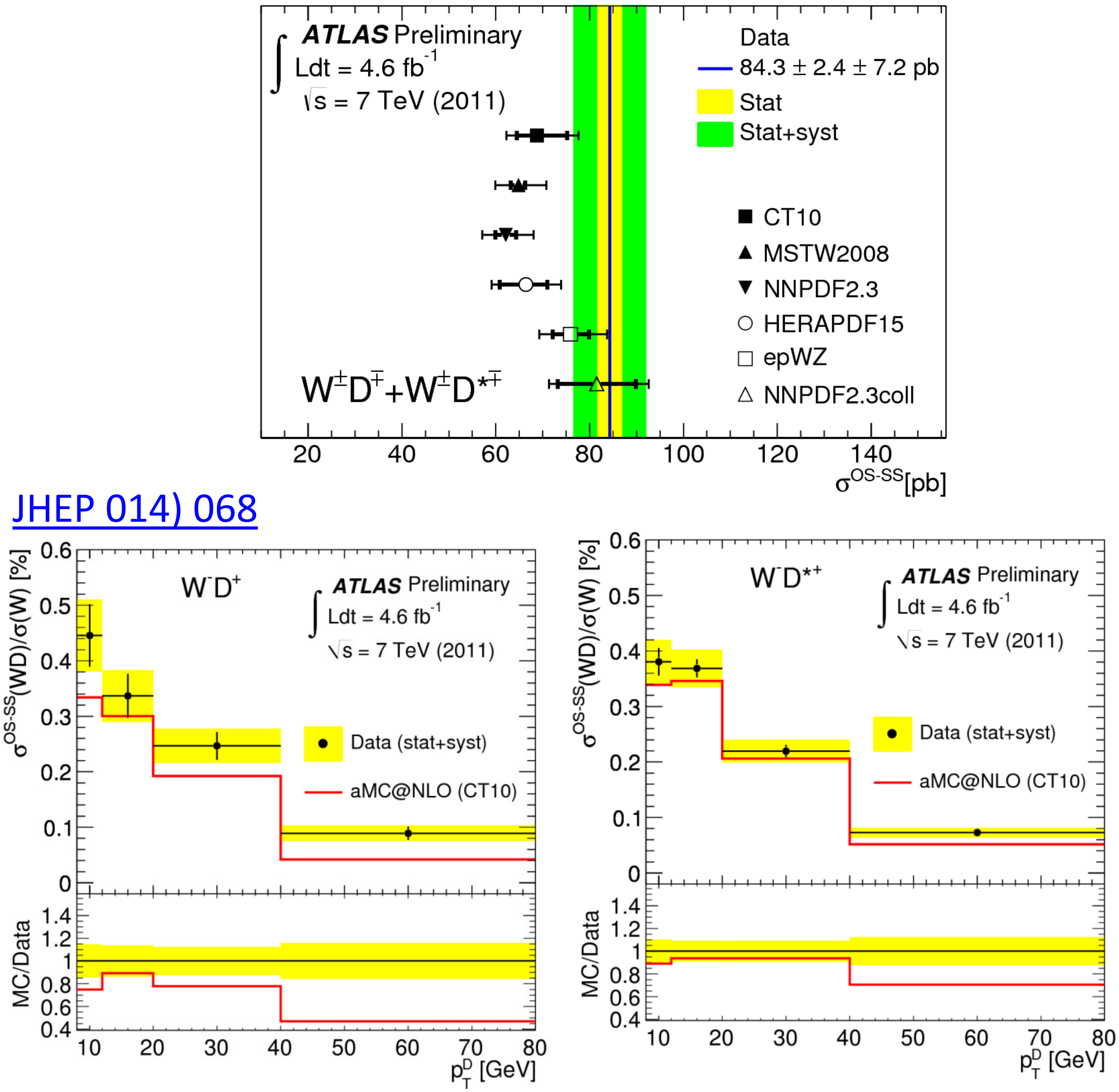
- **Data consistent with strange content of pre-LHC PDFs (neutrino fixed target), approaching good precision**
- **Data consistent with charge symmetric strange PDF**





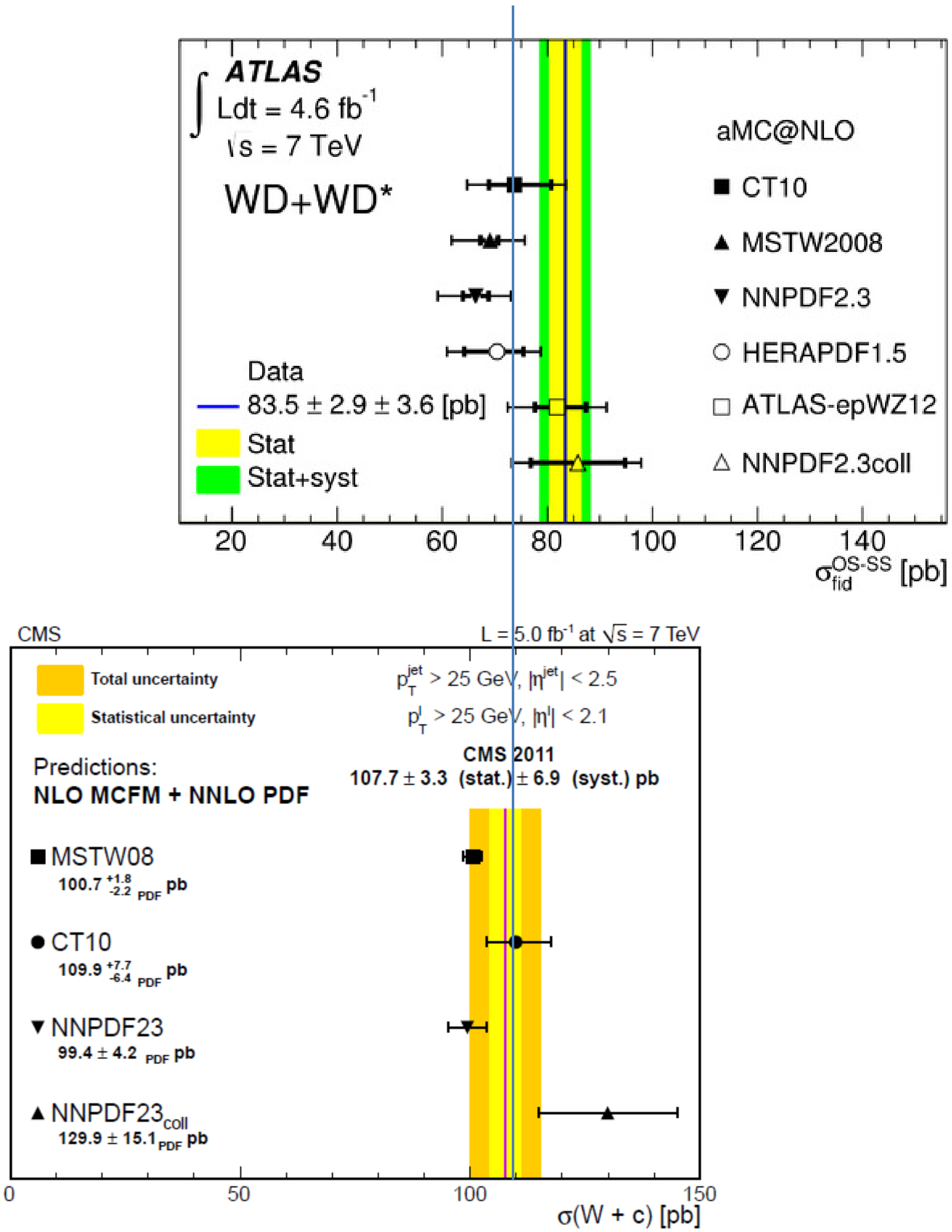
W+charm hadron production

- **ATLAS analysis very similar with somewhat different phase space and cross section definitions**
- **Cross sections measured for charm hadrons, not partons**
- **Favors somewhat higher strange sea**
- **Measures also PTD cross section as well as lepton rapidity**

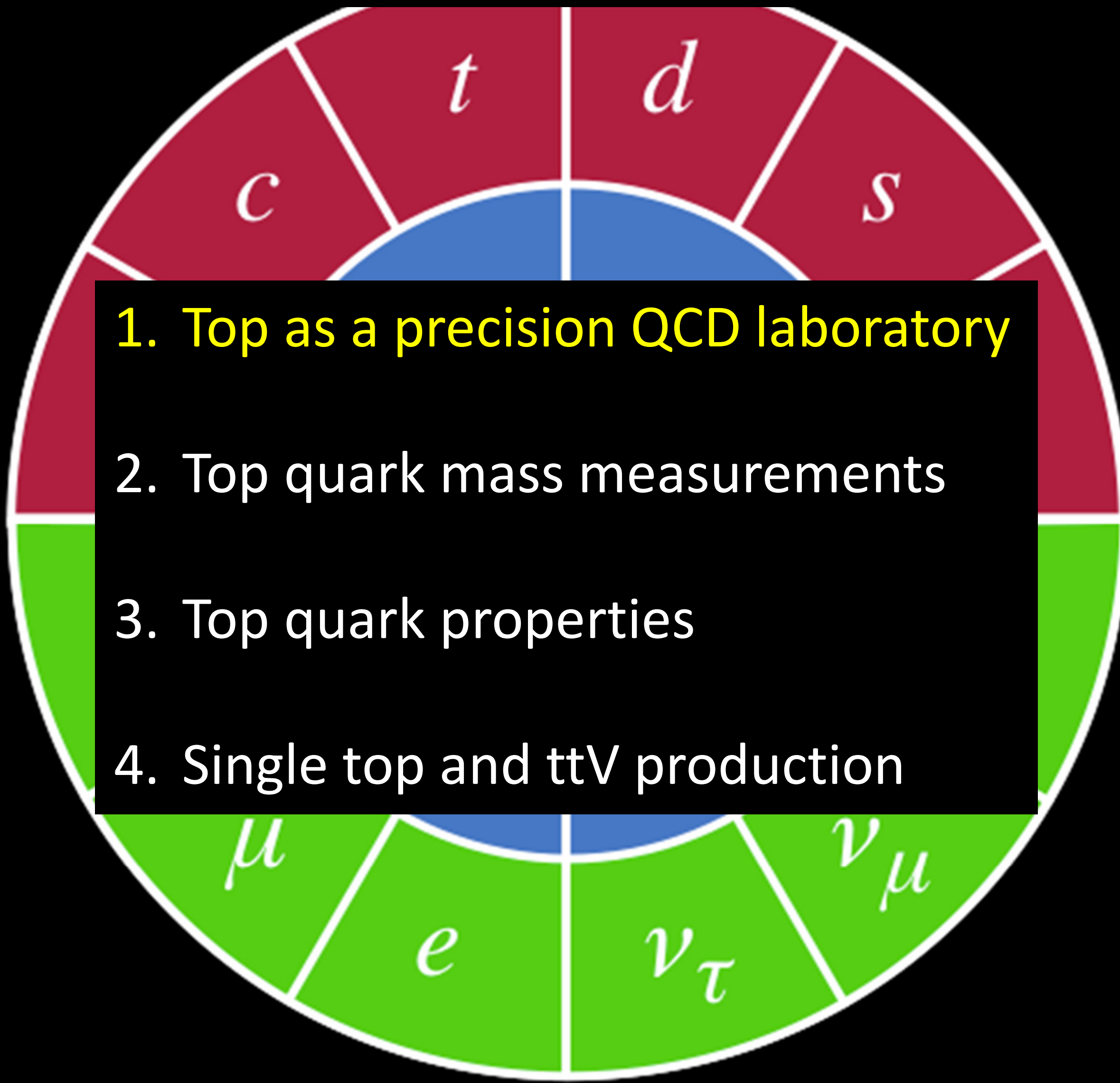


W+charm production

CMS and ATLAS differ between 1-2 sigma, roughly, since CMS~CT10 with similar error



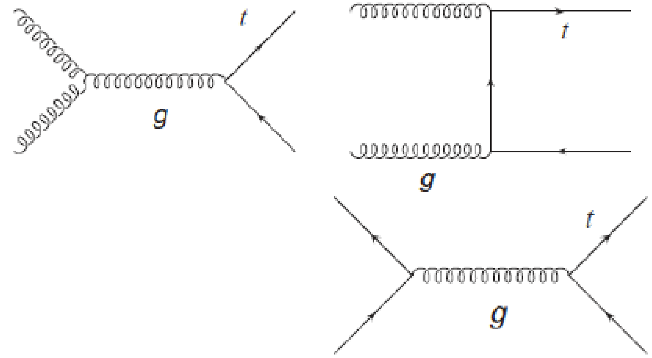
3. The top quark

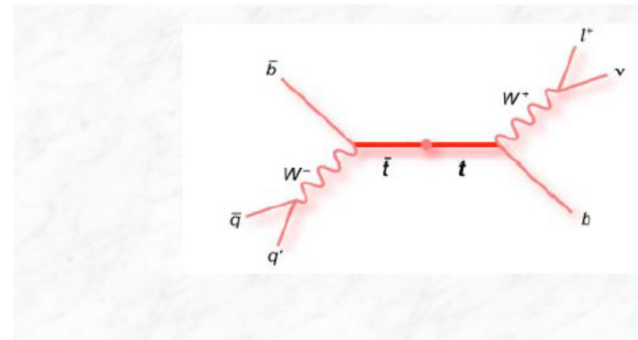


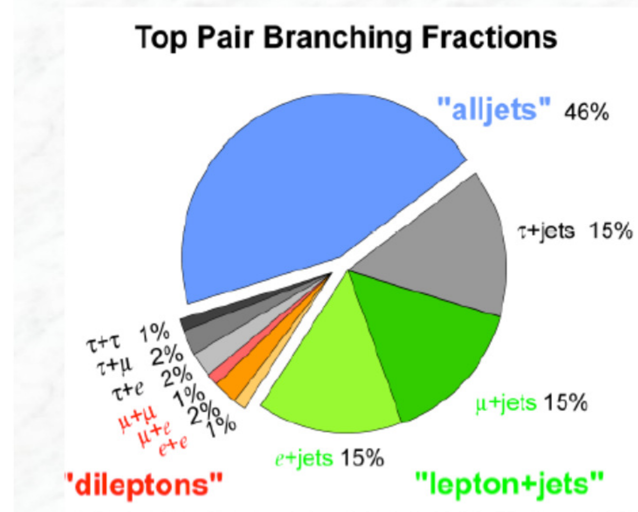
1. Top as a precision QCD laboratory
2. Top quark mass measurements
3. Top quark properties
4. Single top and ttV production

tt production at the LHC

- Very high-purity tt and high-statistics samples allow for precision tests of pQCD
- Predominantly through gg s- and t-channel scattering
- Now providing a serious test of NNLO+NNLL calculations
- Quark direct mass precision at ~700 MeV level and below
- Indirect mass precision from cross section is at 2.5 GeV level



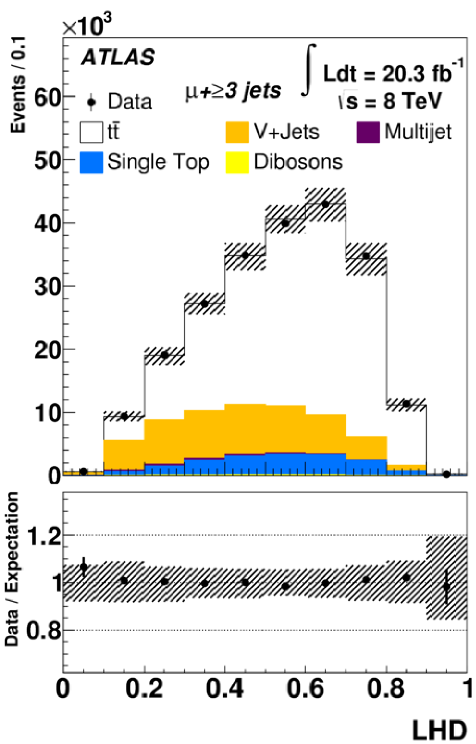




tt production cross section: lepton + jets

PRD 91 (2015) 112013

- **Optimal selection purity from tuning b-tagging and using a kinematic MVA**



- **Largest uncertainties from signal modelling, esp. PDFs!**

Uncertainty on inclusive $\sigma_{t\bar{t}}$	e+jets	μ+jets	ℓ+jets
Lepton reconstruction	$+2.7\ -2.6$	$+2.1\ -1.9$	$+1.7\ -1.6$
Jet reconstruction and E_T^{miss}	$+3.3\ -3.9$	$+2.6\ -3.2$	$+2.8\ -3.4$
b-tagging	$+2.1\ -1.9$	$+2.2\ -1.9$	$+2.1\ -1.9$
Backgrounds	$+2.8\ -3.0$	$+1.8\ -2.1$	$+1.7\ -2.1$
Monte Carlo generator	$-2.2\ +2.2$	$-3.3\ +3.3$	$-2.7\ +2.7$
Parton shower and fragmentation	$+2.0\ -2.0$	$+2.6\ -2.6$	$+2.3\ -2.3$
Initial- and final-state radiation	$-4.1\ +4.1$	$-1.8\ +1.8$	$-3.0\ +3.0$
Parton distribution functions	$+6.2\ -6.0$	$+5.6\ -5.9$	$+5.9\ -5.9$
Total	$+9.7\ -9.8$	$+8.4\ -8.7$	$+8.6\ -8.9$

Uncertainty on fiducial $\sigma_{t\bar{t}}$	e+jets	μ+jets	ℓ+jets
Monte Carlo generator	$-2.1\ +2.1$	$-3.5\ +3.5$	$-2.8\ -2.8$
Parton shower and fragmentation	$-2.6\ +2.6$	$-3.1\ +3.1$	$-2.9\ +2.9$
Initial- and final-state radiation	$+0.4\ -0.4$	$+0.2\ -0.2$	$+0.3\ -0.3$
Total	$+8.9\ -9.0$	$+8.5\ -8.8$	$+8.3\ -8.6$

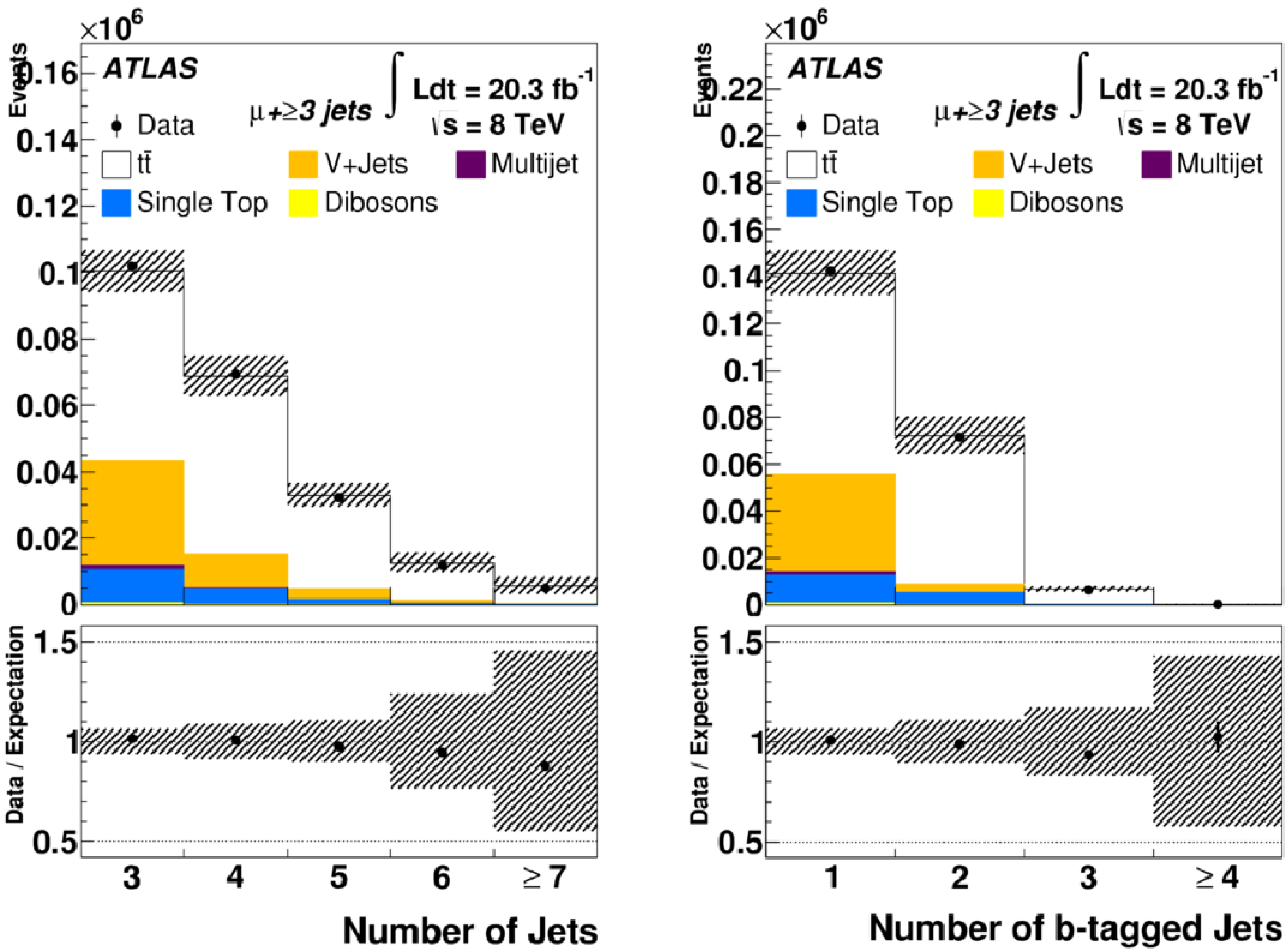
$$e\text{+jets}: \sigma_{t\bar{t}} = 256 \pm 2(\text{stat.}) \pm 25(\text{syst.}) \pm 7(\text{lumi.}) \pm 4(\text{beam})\ \text{pb},$$

$$\mu\text{+jets}: \sigma_{t\bar{t}} = 260 \pm 1(\text{stat.})\ ^{+22}_{-23}(\text{syst.}) \pm 8(\text{lumi.}) \pm 4(\text{beam})\ \text{pb},$$

$$\ell\text{+jets}: \sigma_{t\bar{t}} = 258 \pm 1(\text{stat.})\ ^{+22}_{-23}(\text{syst.}) \pm 8(\text{lumi.}) \pm 4(\text{beam})\ \text{pb},$$

tt production cross section: lepton + jets

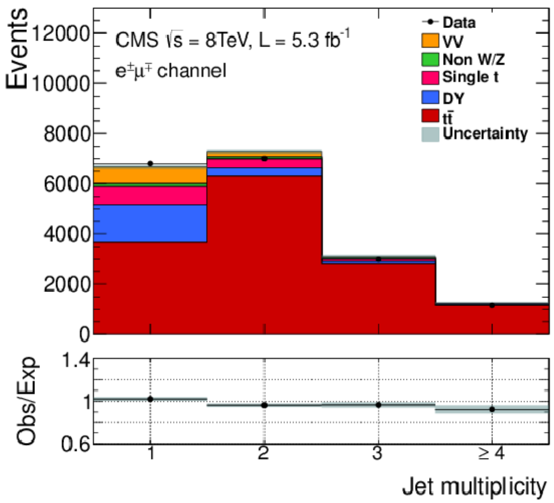
Jet and b-Jet multiplicity well modeled up to 7 jets and 4 tags!

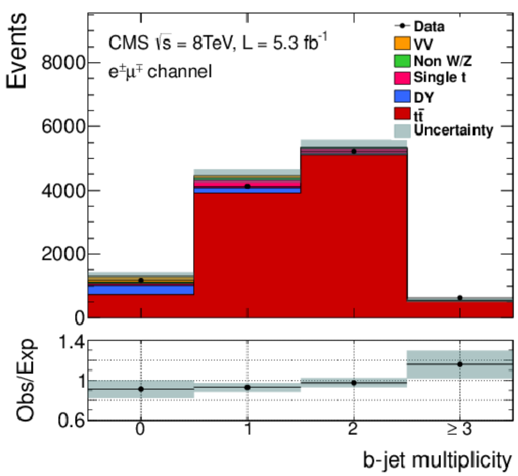


tt production cross section: dileptons

JES and signal model scale dependence are biggest uncertainties

[JHEP 02 (2014) 014]





Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiencies	4.1	3.0	3.6
Lepton efficiencies	5.8	5.6	4.0
Lepton energy scale	0.6	0.3	0.2
Jet energy scale	10.3	10.8	5.2
Jet energy resolution	3.2	4.0	3.0
b-jet tagging	1.9	1.9	1.7
Pileup	1.7	1.5	2.0
Scale (μ_F and μ_R)	5.7	5.5	5.6
Matching partons to showers	3.9	3.8	3.8
Single top quark	2.6	2.4	2.3
VV	0.7	0.7	0.5
Drell–Yan	10.8	10.3	1.5
Non-W/Z leptons	0.9	3.2	1.9
Total systematic	18.6	18.6	11.4
Integrated luminosity	6.4	6.1	6.2
Statistical	5.2	4.5	2.6

	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
ϵ_{total} (%)	0.203 ± 0.012	0.270 ± 0.017	0.717 ± 0.033
$\sigma_{t\bar{t}}$ (pb)	$244.3 \pm 5.2 \pm 18.6 \pm 6.4$	$235.3 \pm 4.5 \pm 18.6 \pm 6.1$	$239.0 \pm 2.6 \pm 11.4 \pm 6.2$

tt production cross section: all hadrons

JHEP 1305 (2013) 065

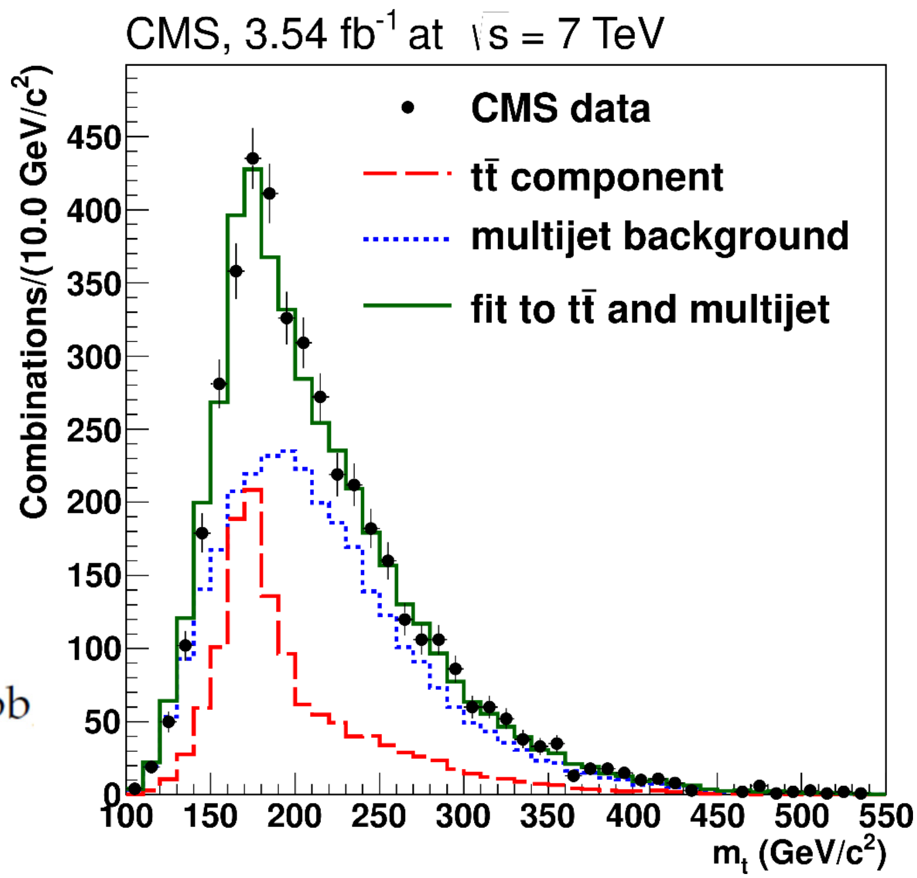
6-jet, 2-tag events subjected to a kinematic fit assuming MW and equal masses for the top candidates.

Accepting the highest chi-squared candidates increases signal purity to 40%

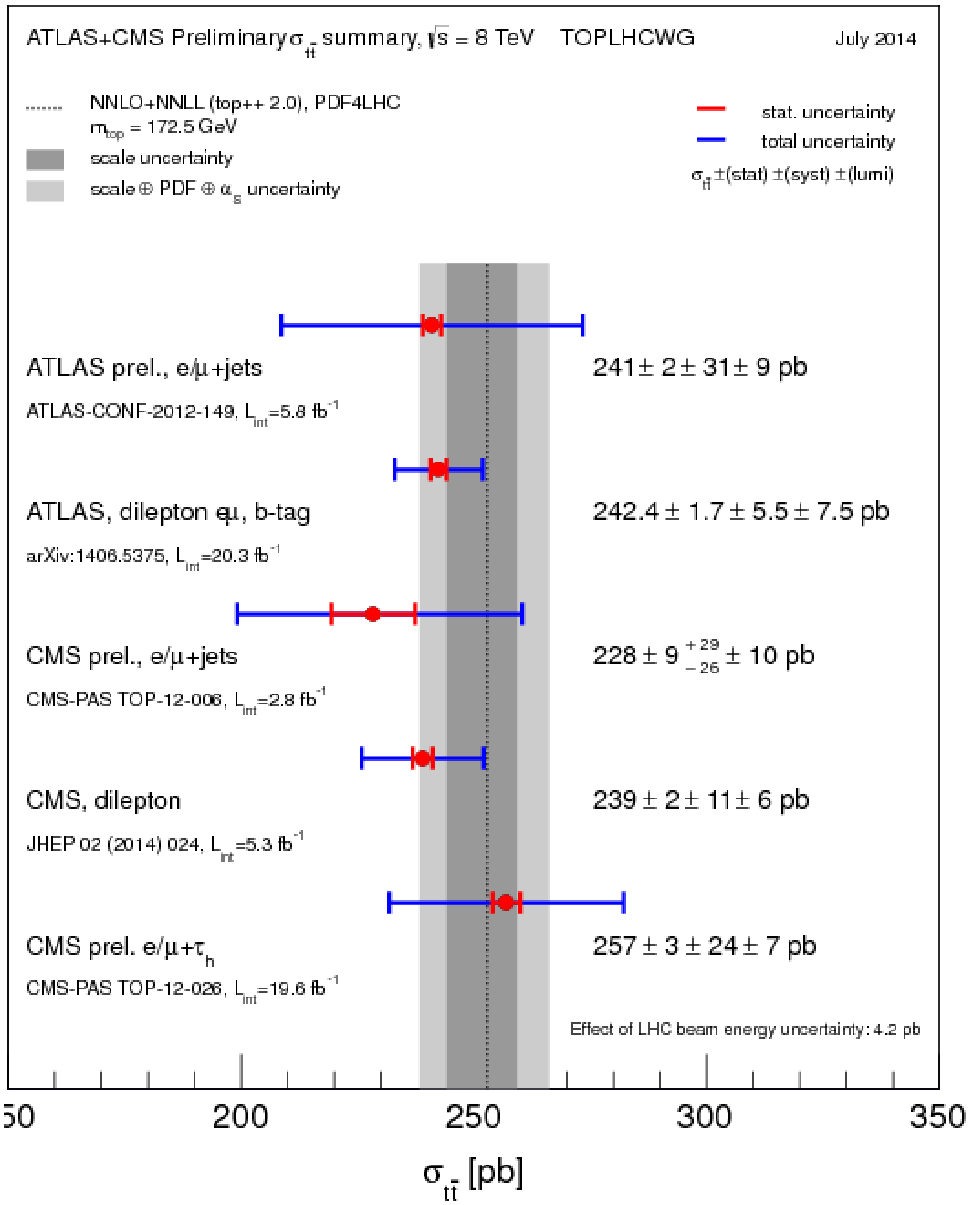
Signal cross section extracted from MLH fit

JES and background modelling dominate the total uncertainty

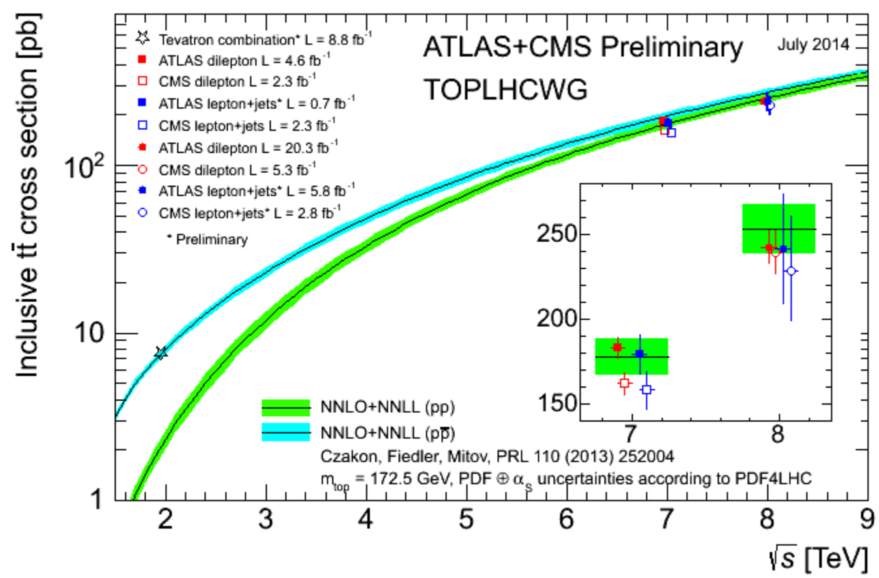
$$\sigma_{t\bar{t}} = 139 \pm 10\,(\text{stat.}) \pm 26\,(\text{syst.}) \pm 3\,(\text{lum.})\,\text{pb}$$



tt production cross section



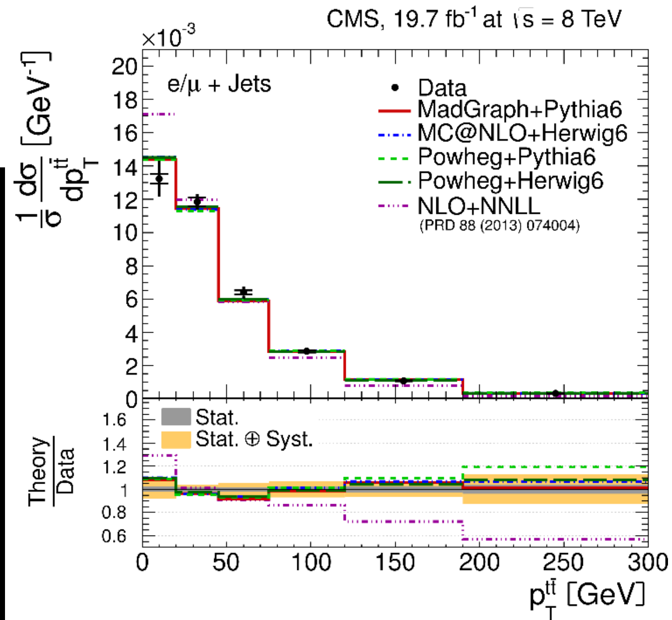
- **Cross sections consistent with each other and with the SM prediction for mtop = 172.5 GeV**
- **Lumi and beam energy are the limiting factors for most precise measurement!**
- **8/7 ratio looks low, TBC**

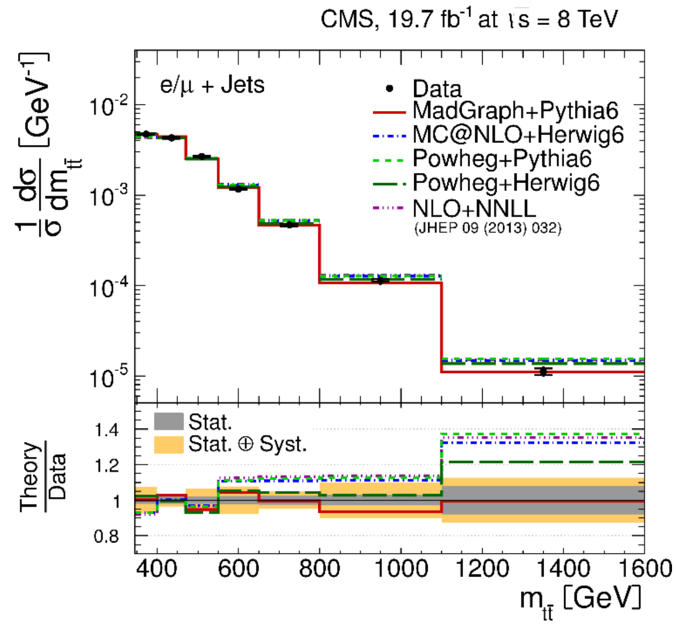


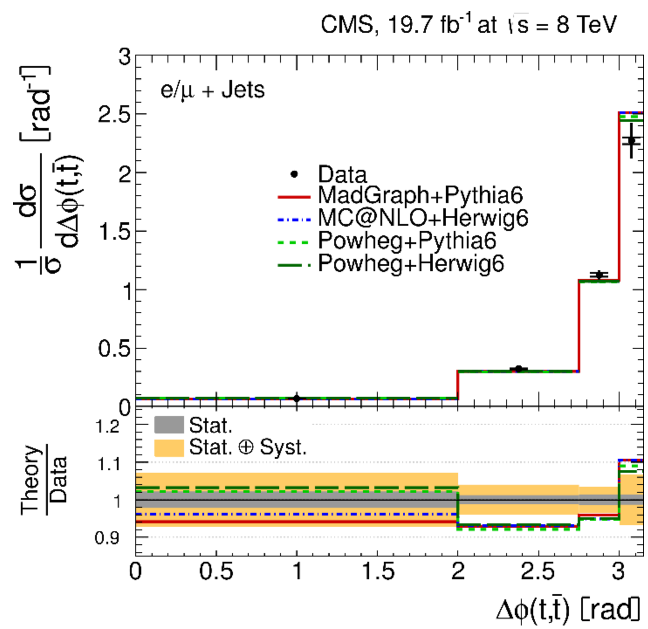
tt production differential cross sections

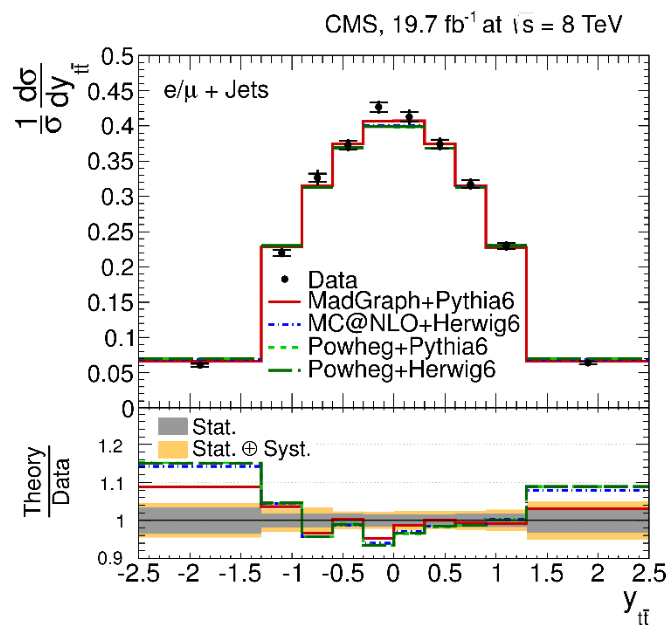
[1505.04480](1505.04480)

- **Normalized differential cross sections for numerous kinematic variables**
- **Varying degrees of agreement with fixed order and PS predictions**
- **Theory is overpredicting high mass and high y tt**





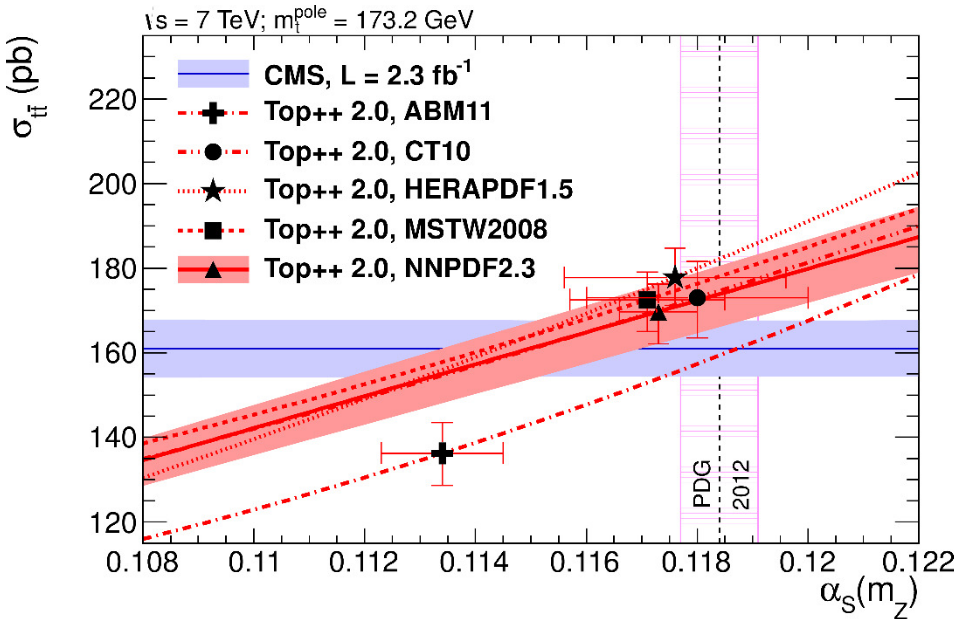


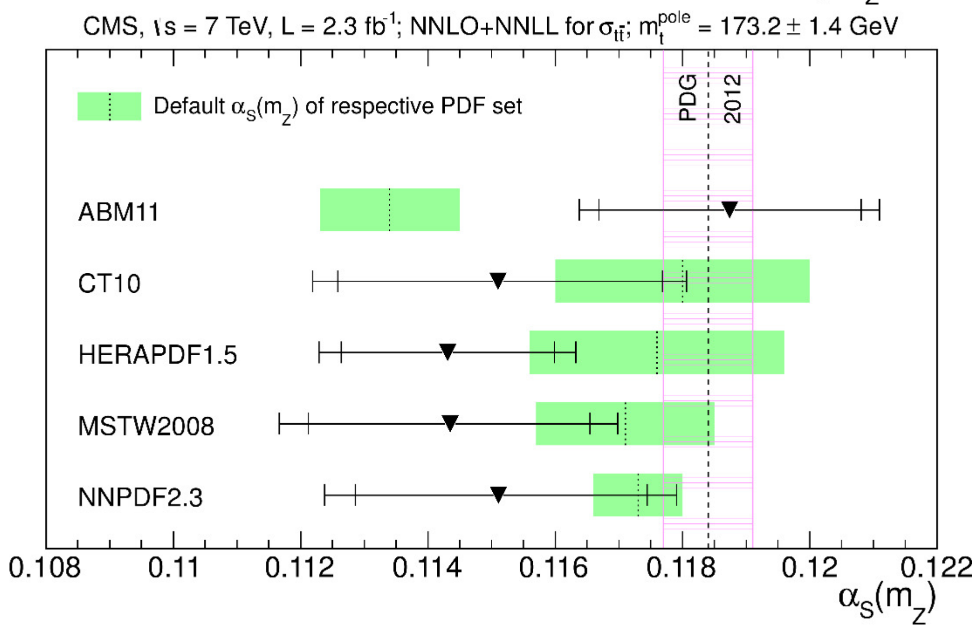


tt production and α_s

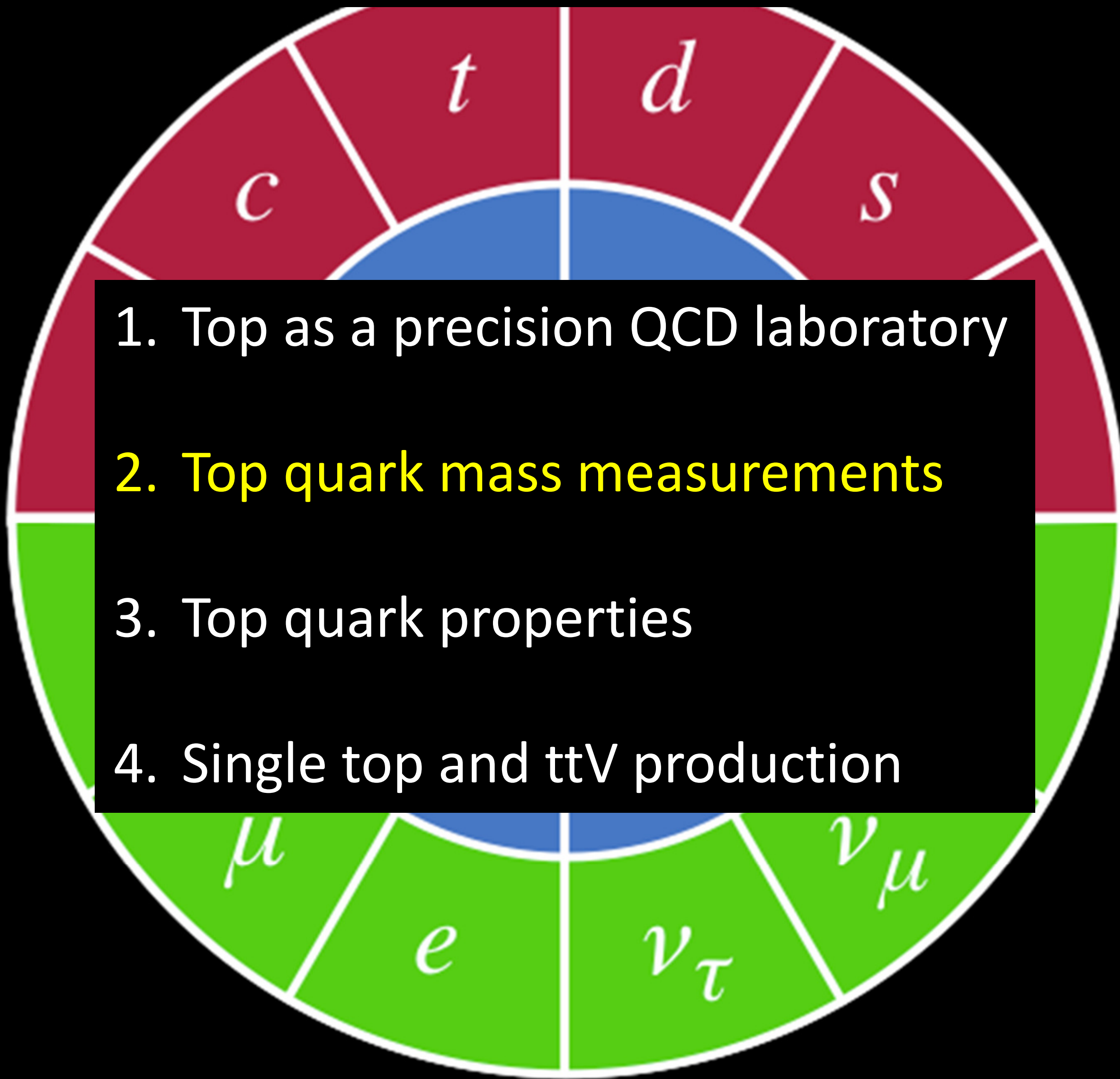
PLB 728 (2013) 496

- With well-measured cross section and mass, strong coupling is significantly constrained by NNLO+NNLL predictions
- α_s agrees with PDG at 3X worse error
- Leading uncertainties are experimental!
- cross section, mt, PDF could improve it by 2x





3. The top quark



1. Top as a precision QCD laboratory
2. Top quark mass measurements
3. Top quark properties
4. Single top and ttV production

Top mass measurement: lepton+jets

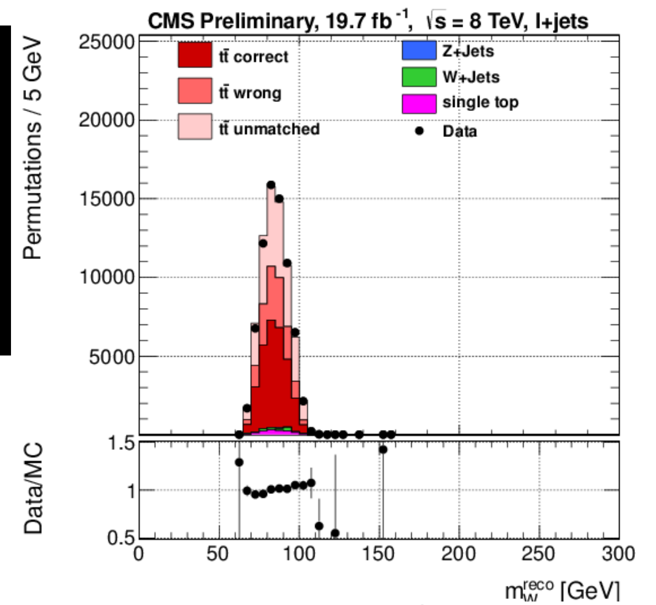
Kinematic fit to tt hypothesis extracts mass and JSF

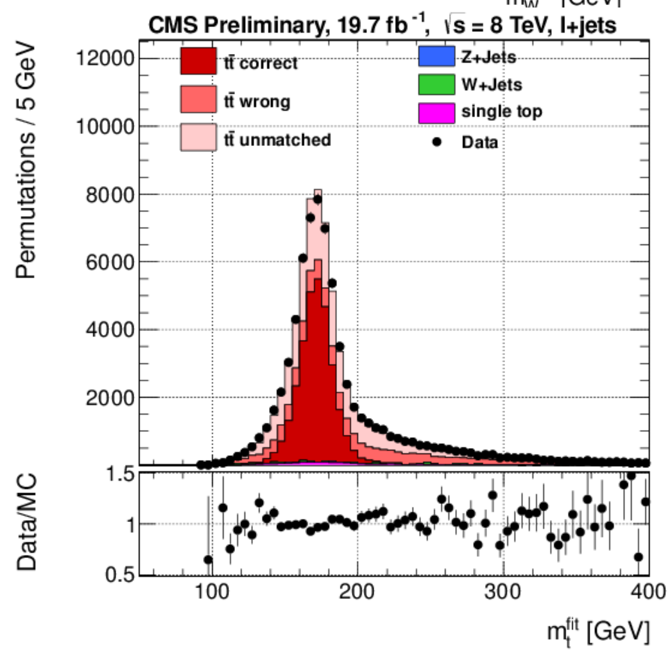
$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV},$$
$$\text{JSF} = 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).$$

CMS 8 TeV l+jets: 770 MeV precision, systematics are 50/50 detector/modeling

CMS-PAS-TOP-14-001

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	1.17
Lepton energy scale	0.03	<0.001	0.03
MET	0.09	0.001	0.01
Jet energy resolution	0.26	0.004	0.07
b tagging	0.02	<0.001	0.01
Pileup	0.27	0.005	0.17
Non-$t\bar{t}$ background	0.11	0.001	0.01
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.32
b fragmentation	0.06	0.001	0.04
Semi-leptonic B hadron decays	0.16	<0.001	0.15
Modeling of the hard scattering process			
PDF	0.09	0.001	0.05
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.25±0.08
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.07±0.08
ME generator	0.23±0.14	0.003±0.001	0.20±0.08
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.06±0.10
Color reconnection modeling	0.08±0.15	0.002±0.001	0.07±0.09
Total	0.75	0.012	1.29





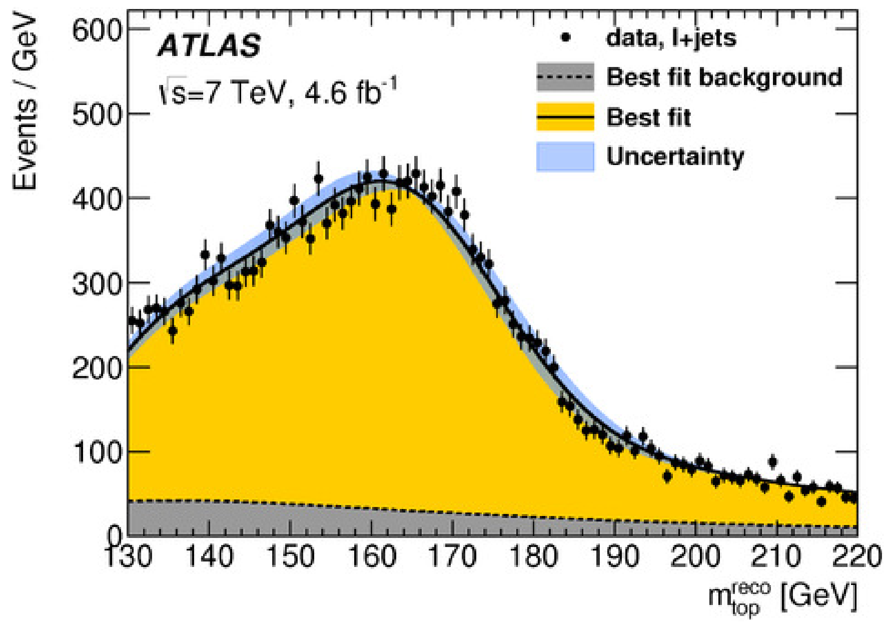
Top mass measurement: dilepton

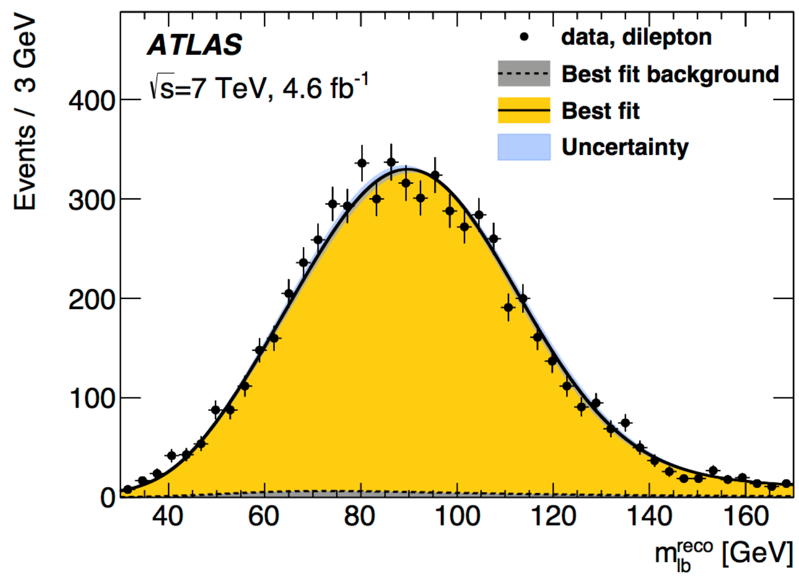
1503.05427

exploits a one-dimensional template method using the mℓb observable (avg of two lb pairs)

ATLAS 7 TeV dilepton+jets:
640 MeV stat
1500 MeV syst

B-JSF and JES errors dominate





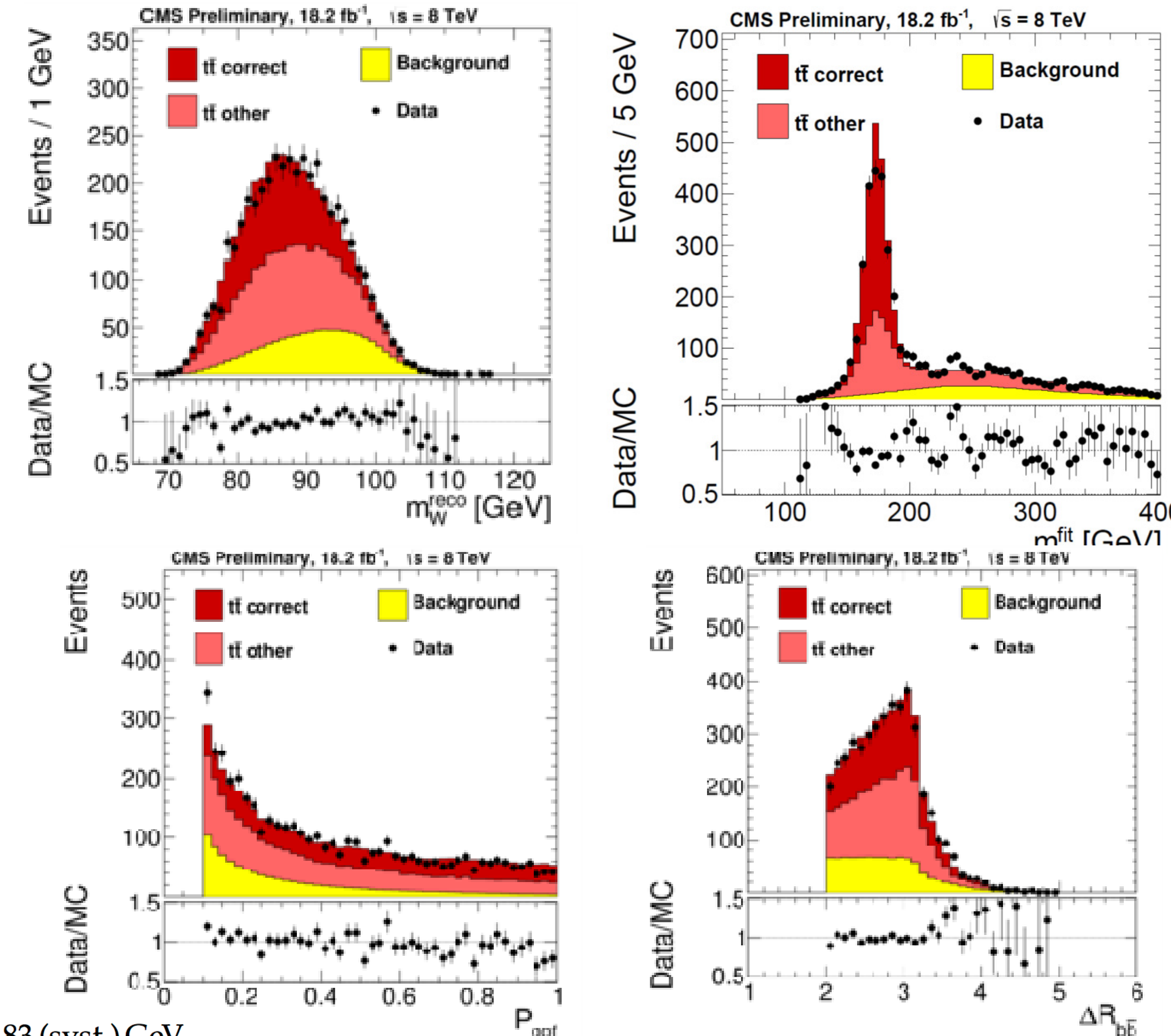
173.79 ± 0.54 (stat) ± 1.30 (syst) GeV

Top mass measurement: all jets

CMS-PAS-TOP-14-002

Kinematic fit method similar to cross section extraction

JES is dominant uncertainty



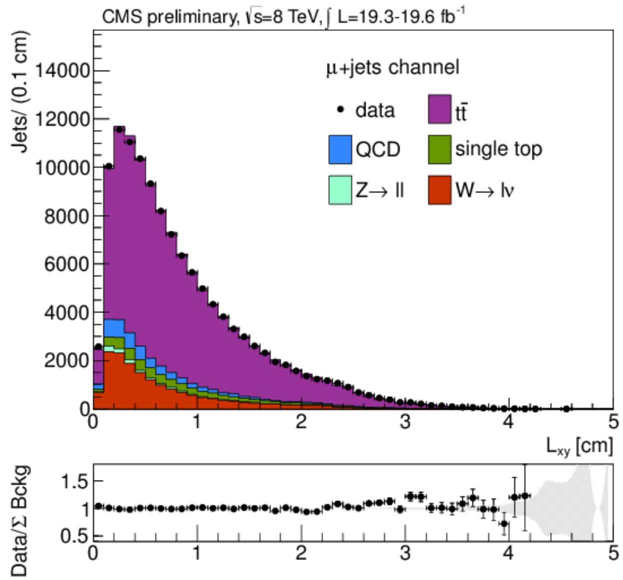
$$m_t = 172.08 \pm 0.36\,(\text{stat.+JSF}) \pm 0.83\,(\text{syst.})\,\text{GeV},$$
$$\text{JSF} = 1.007 \pm 0.003\,(\text{stat.}) \pm 0.011\,(\text{syst.}).$$

Top mass measurement: other methods

CMS-PAS-TOP-12-030

using the transverse decay length (Lxy) of B-hadrons

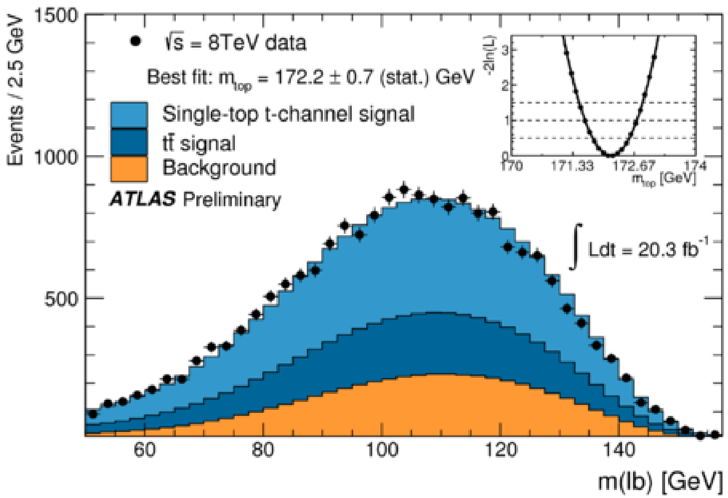
Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{\text{stat}} \pm 1.6_{\text{syst}} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{\text{stat}} \pm 1.7_{\text{syst}} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{\text{stat}} \pm 1.4_{\text{syst}} \pm 2.4_{p_T(t)}$



ATLAS-CONF-2014-055

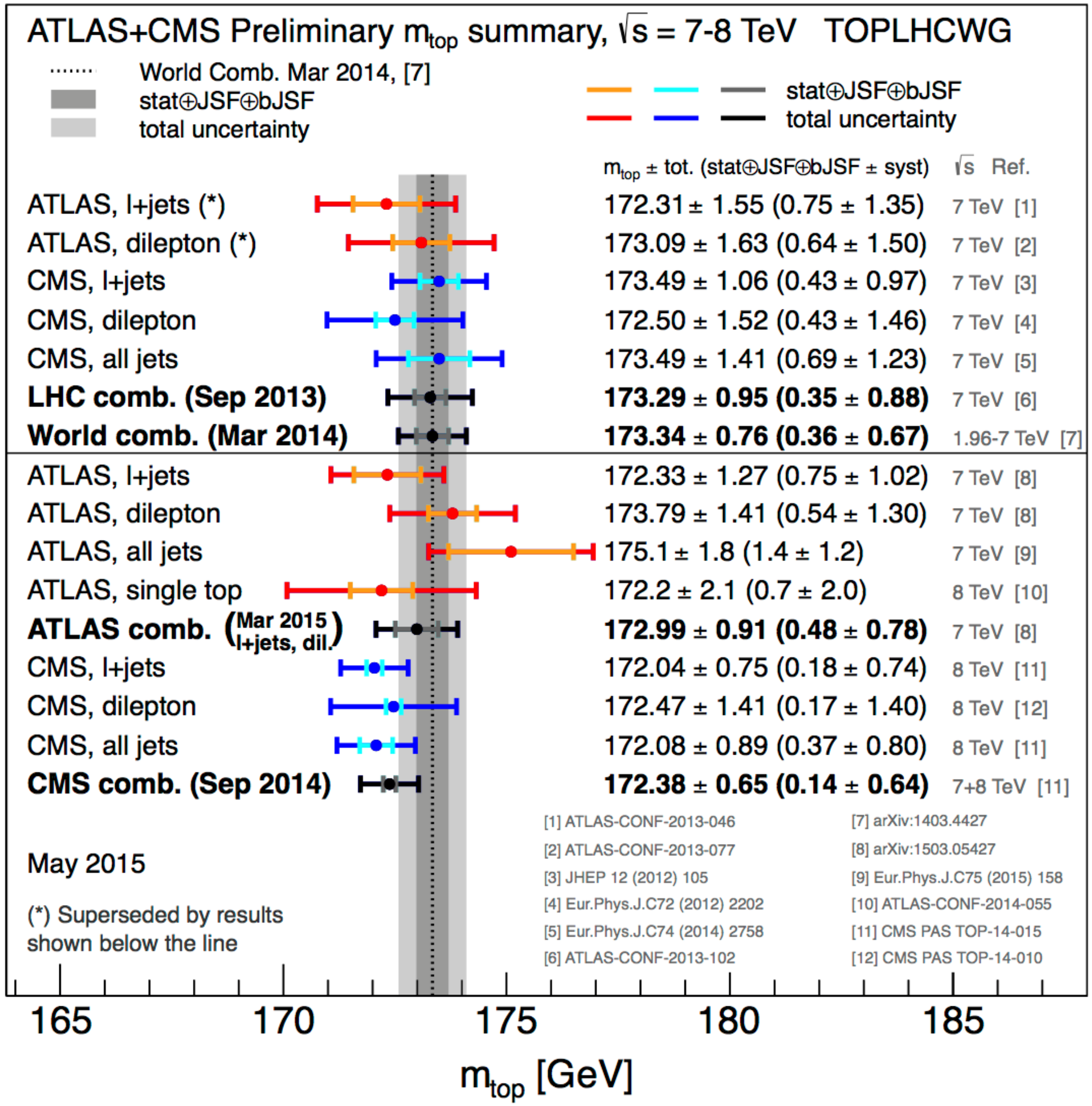
using single top quark production

$$m_{\text{top}} = 172.2 \pm 0.7(\text{stat.}) \pm 2.0(\text{syst.})\ \text{GeV}$$



Top quark mass

- **Overall consistency observed between ATLAS, CMS, and Tevatron.**
- **Consistent between 7 and 8 TeV data**
- **Sub-GeV single results are now a common occurrence**
- **Next factor of two in precision will be hard!**



Conclusion, Part 1

NLOxNP QCD predictions are successfully describing copious LHC jet data. Eagerly await NNLO predictions and 13 TeV data!

Wealth of jet and multijet (and top) observables to sample the strong coupling/improve PDFs

(N)LO+PS V+jets predictions are being confronted by data on every front. NLO+PS show improved agreement with some residual weaknesses. Onto NNLO QCD+NLO EWK!

LHC is a top quark factory providing numerous precision tests of NNLO+NNLL QCD.