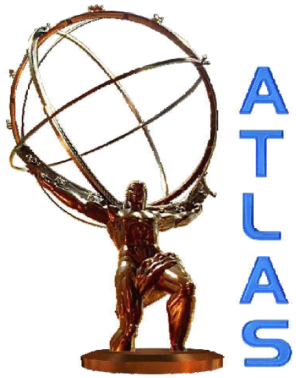
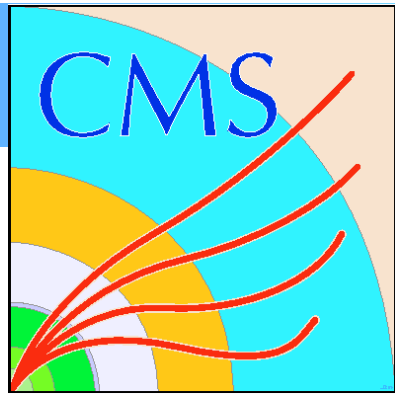




Interpretation of top-quark observables

Stephen Wimpenny
Dept. of Physics & Astronomy, UC Riverside

on behalf of the
ATLAS & CMS Collaborations

Topics covered in this talk

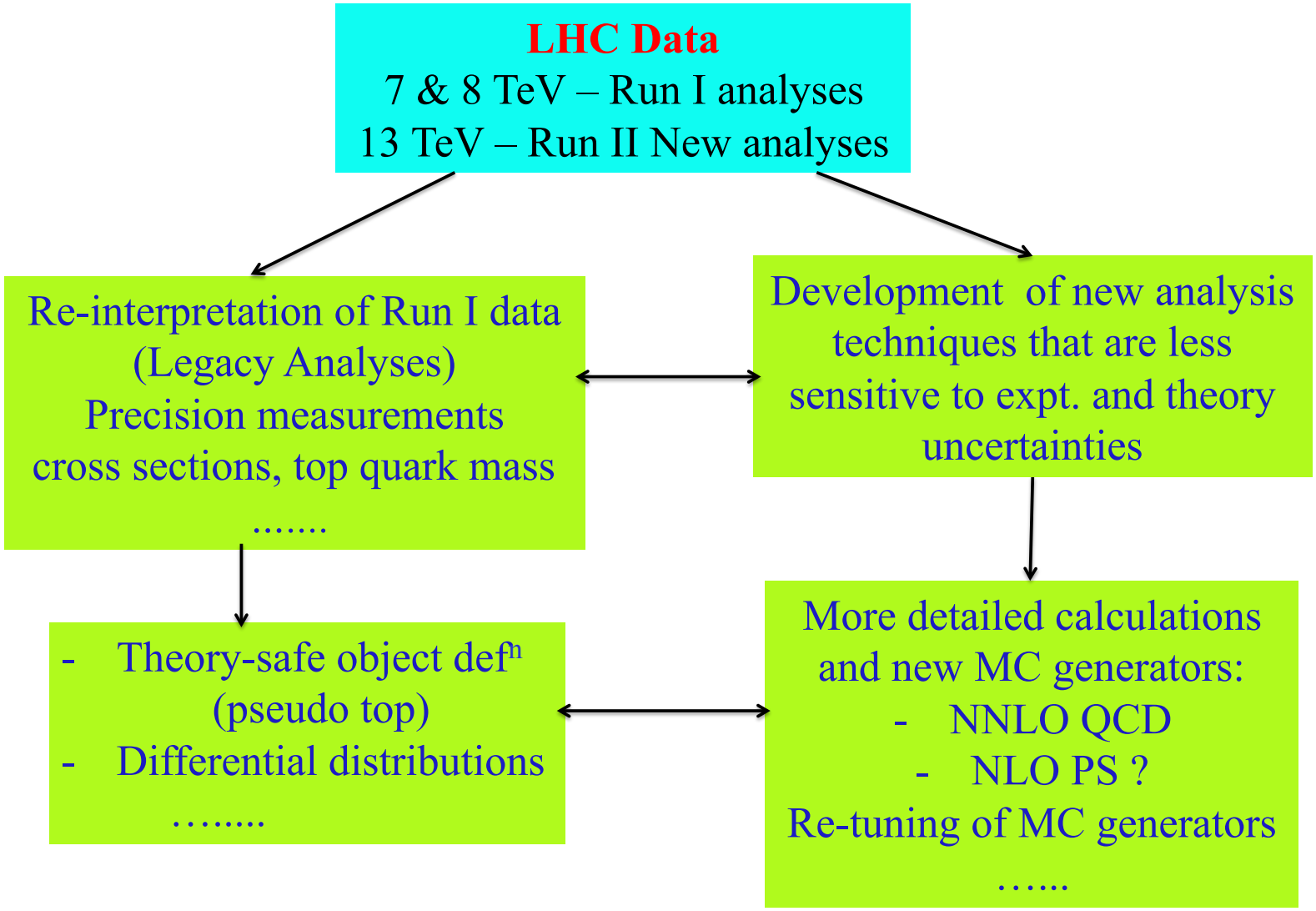
Perspective on the current status for selected top quark observables

ttbar production cross section
modeling of top quark kinematics
top quark mass

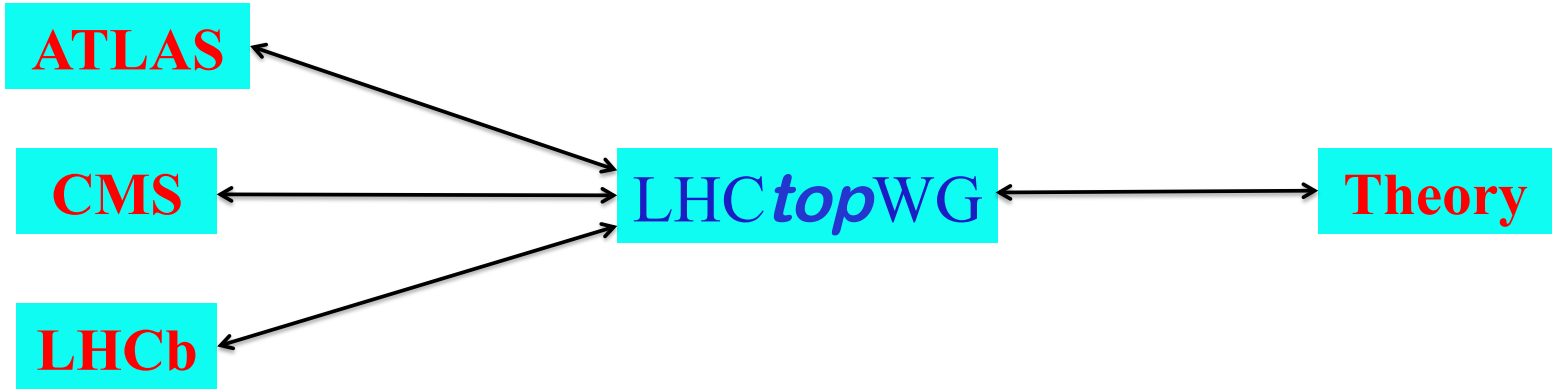
Disclaimer:

In the interests of time, I will not cover measurements of single top and top quark properties (charge, asymmetry, polarization, W-helicity & spin correlations)

Top Physics – Pathways to Progress



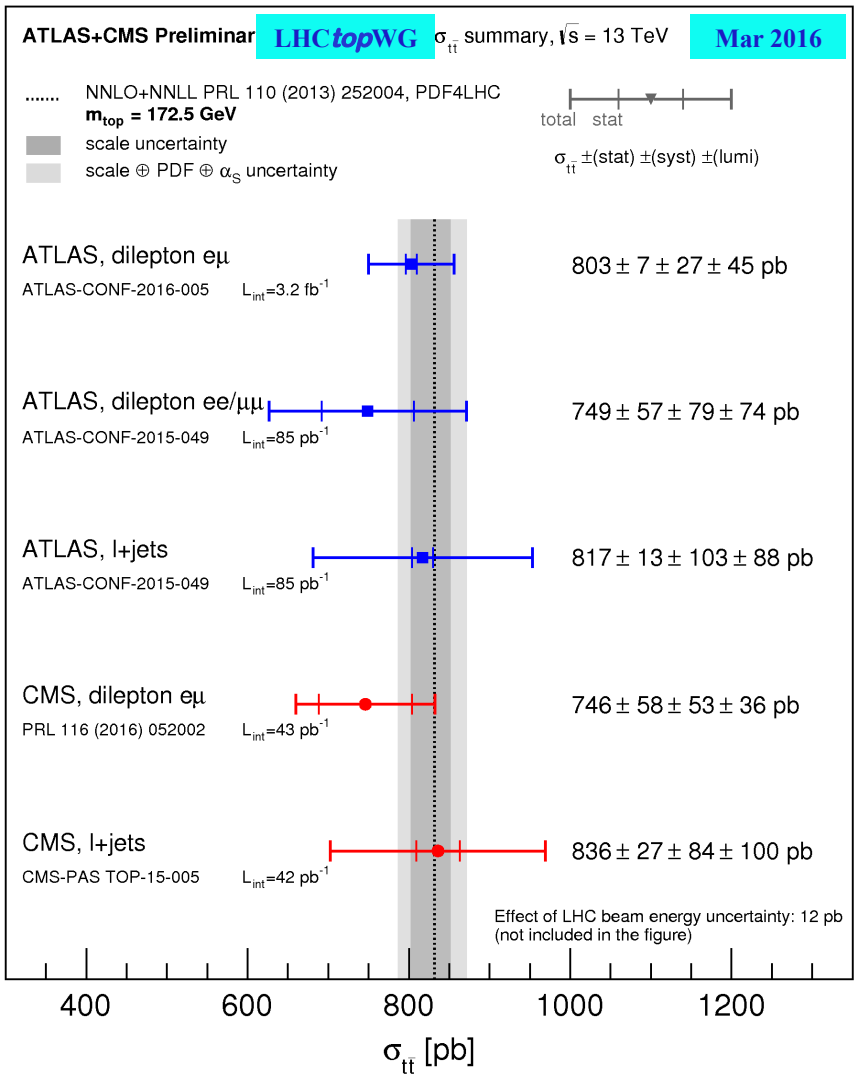
Top Physics – Pathways to Progress



Experiments: more homogeneous treatment of uncertainties between experiments → better understanding of the systematic uncertainties

Theory: improved calculations, new generators & tunes, definition of variables
most sensitive to testing and tunes

ttbar Production Cross Section at 13 TeV



LHC Run II
√s = 13 TeV Results

Results computed for both full and visible (fiducial) phase space

Dominant uncertainties:

luminosity, signal model (knowledge of pdf's, ISR/FSR and Q^2 scale)

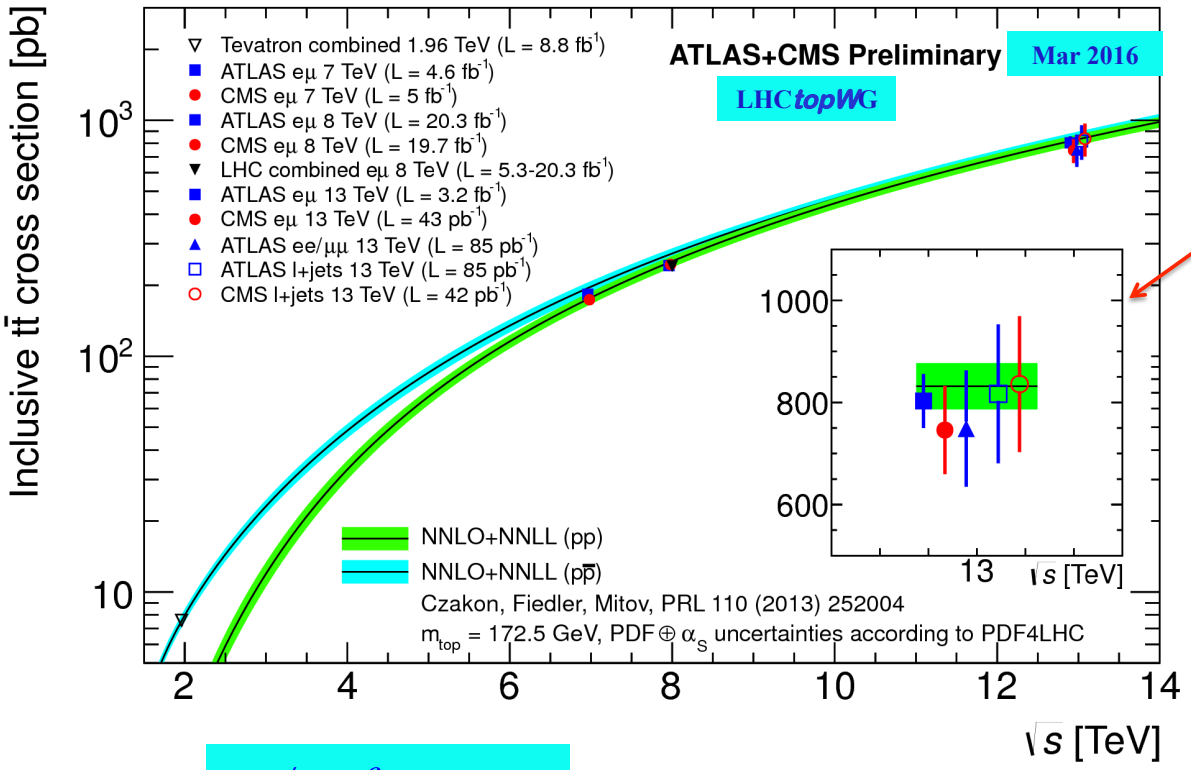
ATLAS CONF-2016-005

σ_{tt} = 803 ± 7 (stat) ± 27 (syst) ± 45 (lumi) ± 12 (beam) pb

CMS-PAS-TOP-16-005

σ_{tt} = 793 ± 8 (stat) ± 38 (syst) ± 21 (lumi) pb

ttbar Production Cross Section as a Function of √s



13 TeV Measurements

√s – evolution well described by NNLO QCD predictions

→ Issue with the 8/7 TeV ratio noted last year appears not to be a real effect.

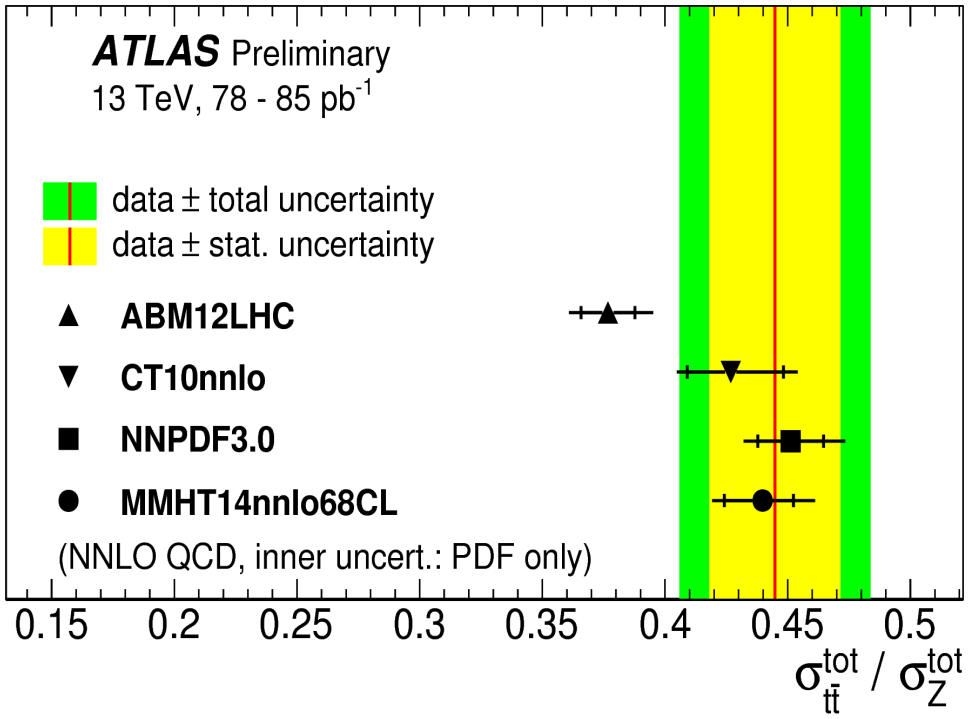
gg/qq fractions

7 TeV: ~ 80%

14 TeV: ~ 90%

Expt. & Theory uncertainties ~ few % level → can use the data to further constrain the gluon pdf

Re-interpreting the Measurements



ATLAS-CONF-2015-049

Ratio of Z/ttbar production cross sections at 13 TeV as a test of pdf compatibility

R(ttbar/Z) = 0.445 ± 0.027 (stat) ± 0.028 (syst)

luminosity 9% → ~1%, systematics dominated by ttbar

Reducing the Uncertainties

Run I Legacy Analysis:
eμ channel at 7 and 8 TeV

CMS arXiv:1603.02303
(sub to JHEP)
ATLAS EPJC 74 (2014) 3109

Differential event categorization
→ *determine signal and modeling sensitivity*

Fiducial measurements
→ *constrain backgrounds and main systematics*

7 TeV

$\sigma_{tt} = 173.6 \pm 2.1\ (stat)\ ^{+4.5}_{-4.0}\ (syst) \pm 3.8\ (lumi)\ pb$

CMS

$\sigma_{tt} = 244.9 \pm 1.4\ (stat)\ ^{+6.3}_{-5.5}\ (syst) \pm 6.4\ (lumi)\ pb$

8 TeV

$\sigma_{tt} = 242.5 \pm 1.7\ (stat) \pm 5.5\ (syst) \pm 7.5\ (lumi)\ pb$

ATLAS

non-lumi systematics ~2.5%, full uncertainty ~3.7%

→ *significant improvement in precision & consistency with NNLO QCD and agreement between the experiments*

Top Quark Kinematics

Comparison of theory and unfolded quantities based on final state observables

Use theory-safe definitions (pseudo top) where possible and for comparison to fixed order calculations, unfold data to parton level

Status (7, 8 and 13 TeV):

- reasonable agreement observed for global variables such as H_T and E_T^{miss} between data and predictions with NLO + PS

Exceptions:

- top quark p_T → need NNLO to get a consistent model

- jets 'associable' to the PS simulation ('extra' jets) for 13 TeV → need further tuning of PS modeling and/or HO PS ?

for pseudo-top definition see LHCtopWG twiki
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG

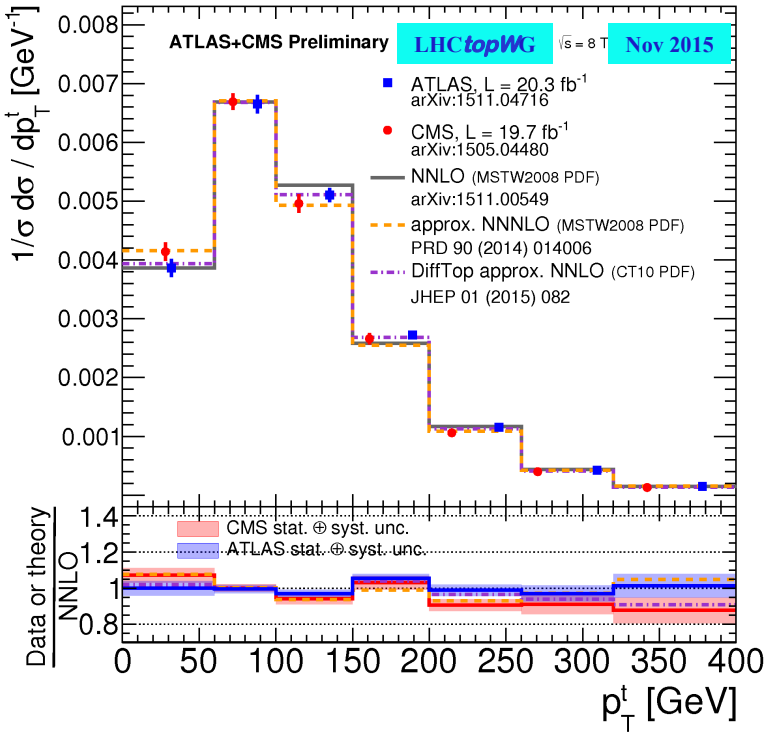
Top Quark Kinematics at Parton Level - p_T^t

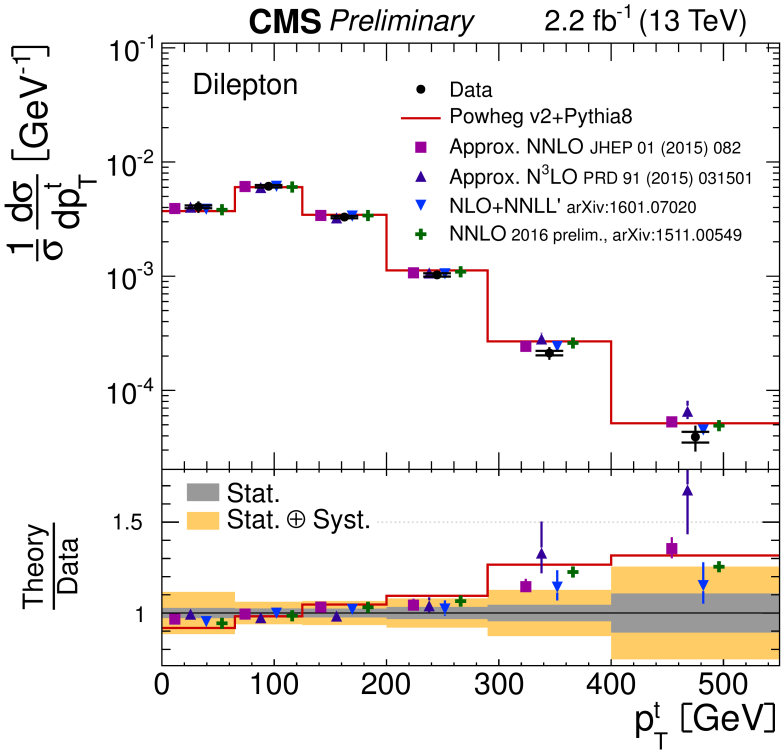
8 TeV

ATLAS & CMS

13 TeV

CMS-PAS-TOP-16-011





NNLO QCD → reasonable description of the data (data is softer than NLO+PS predictions)

p_T^t for p_T > 300 GeV (Boosted Regime)

Large p_T (also large m_{tt}) → significant fraction of the top decay products are not resolved and the leptons in the events are less isolated

Use p_T-dependent isolation definitions and wide jets with sub-jet analyses to identify the top decays

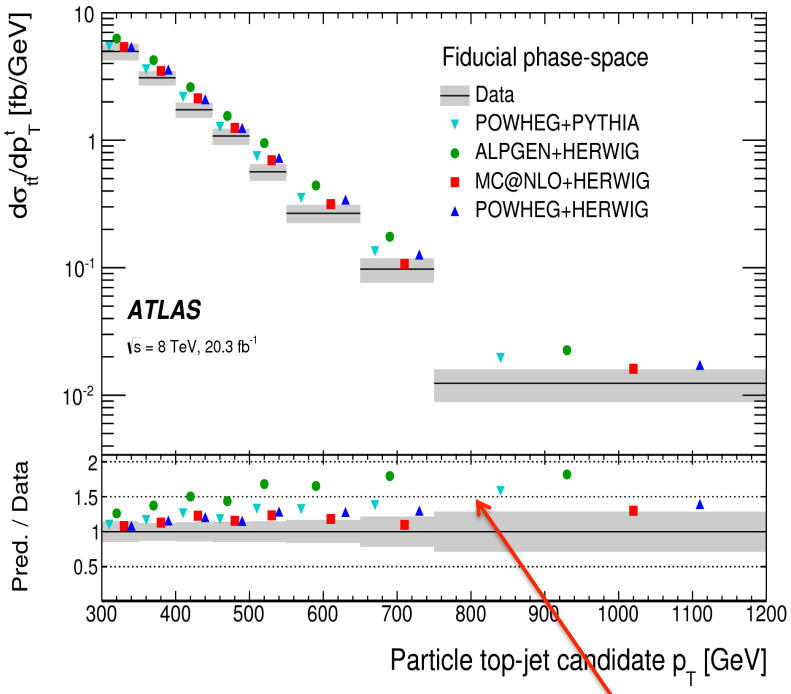
Unfolding becomes more difficult and may introduce MC model-dependent bias into the unfolded observable

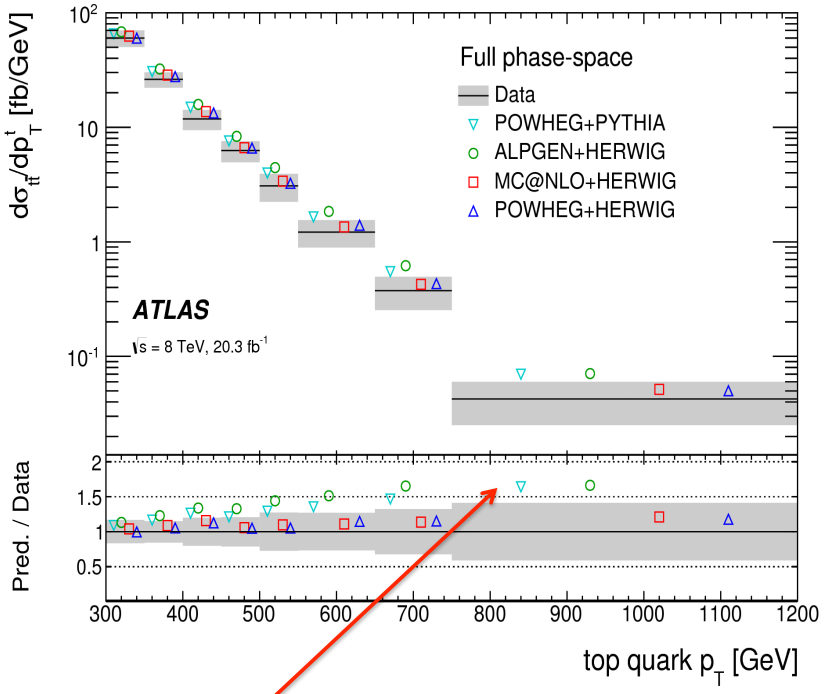
Important to study observables using at both particle and parton level when performing tests in this regime

p_T^t for p_T > 300 GeV (Boosted Regime)

8 TeV

Phys Rev D93 (2016) 032009





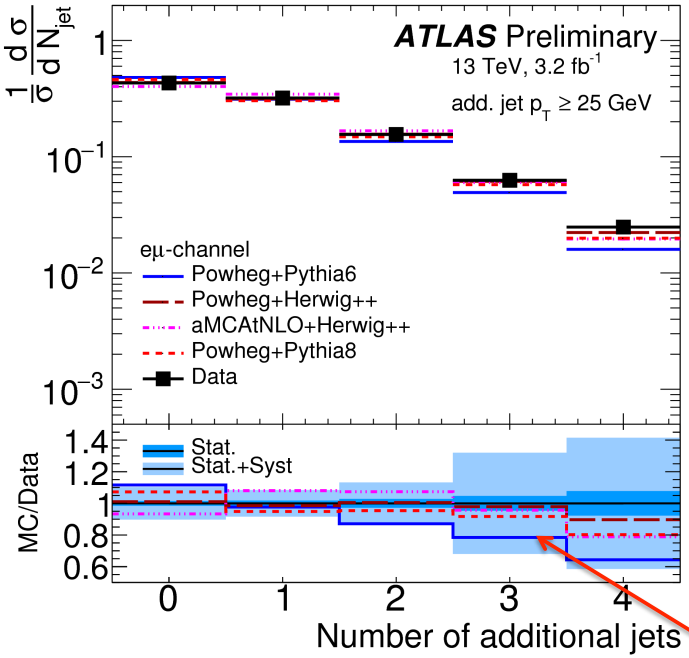
Particle Level

Parton Level

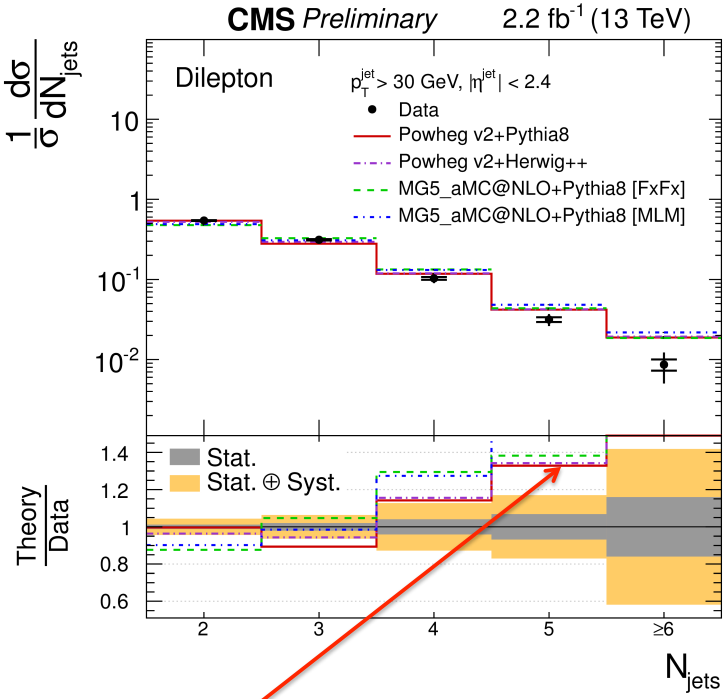
data is softer than NLO+PS predictions

Additional (ISR/FSR) Jets – e/μ Channel at 13 TeV

ATLAS-CONF-2015-065



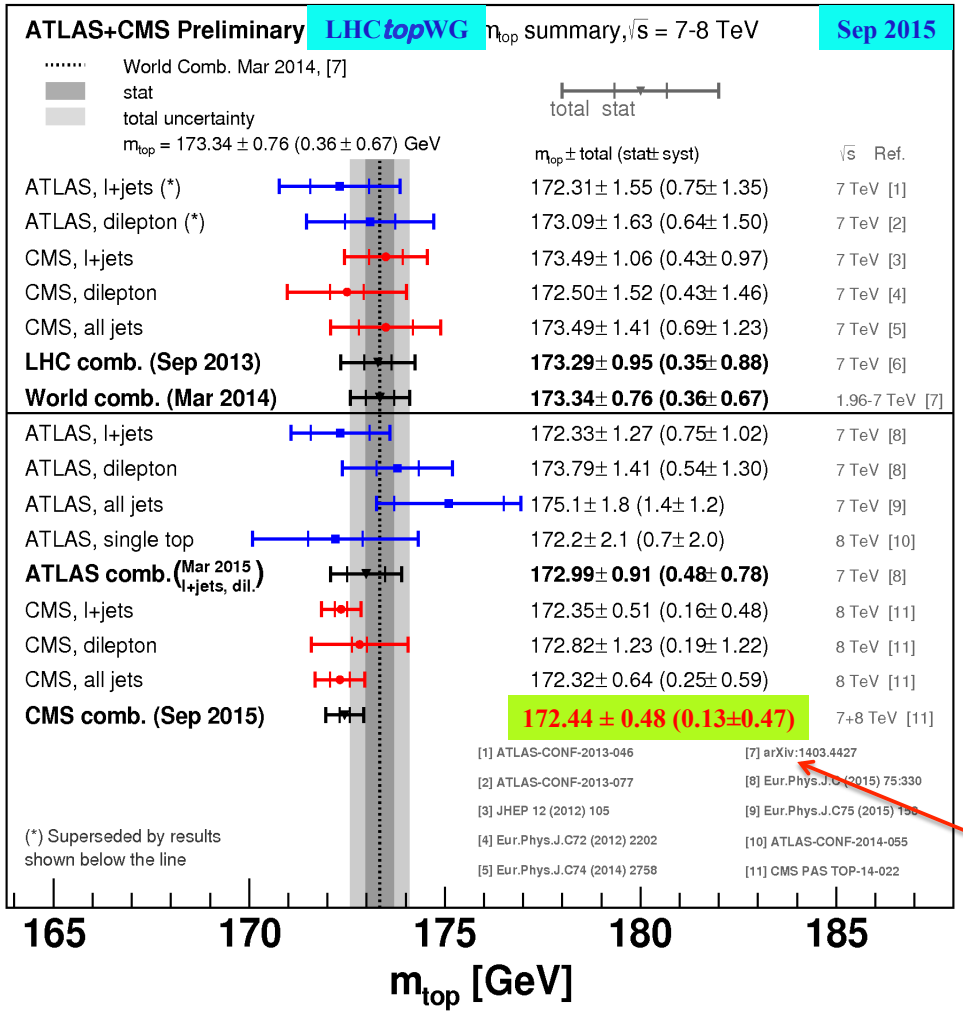
CMS-PAS-TOP-16-011



Some discrepancies in the large N_{jets} region dominated by the PS modeling

Some disagreement between the data and current MC calculations (tunes?)

Top Quark Mass



CMS Run I
Legacy Analysis
$\sqrt{s}$ = 8 (7) TeV

Significant progress over the last 2 years

Direct measurements based on kinematic reconstruction limited by systematic uncertainties

Precision ~ 480 MeV (0.3%)

CMS: Phys. Rev. D93 (2016) 072004

Top Quark Mass

Dominant uncertainties (≥ 100 MeV):

Experimental:

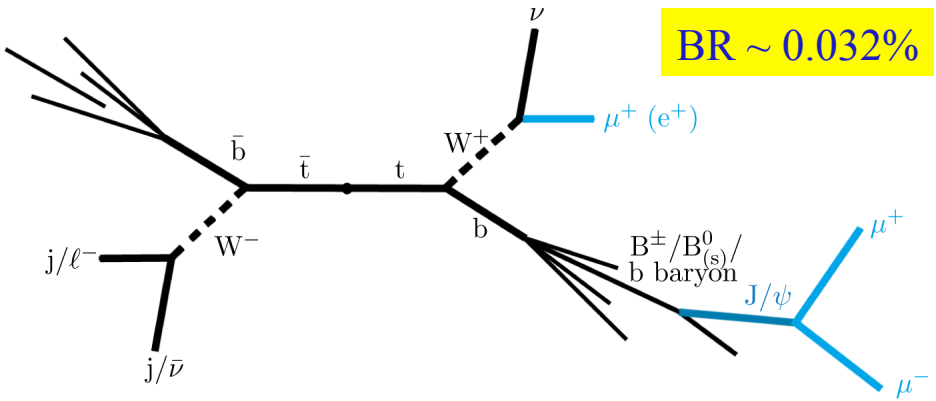
- *Flavor – dependent jet energy corrections*
- *Jet energy corrections*
- *Pileup*

Progress → need improved theory input and new experimental methods that marginalize some of uncertainties

Modeling:

- *Hadronization: flavor – dependent jet energy corrections**
  (string vs cluster fragmentation)
- *b-jet modeling (fragmentation and BR)*
- *Renormalization & factorization scales*
- *Matrix element generator*
- *Underlying event*

Marginalizing Uncertainties: *l + J/ψ Mass*

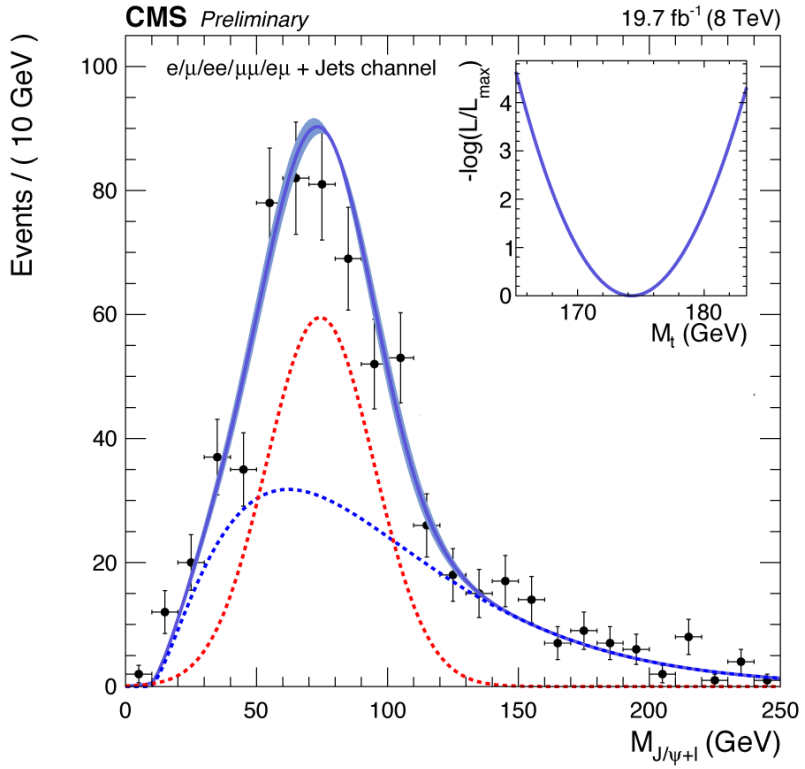


BR ~ 0.032%

CMS-PAS-TOP-15-014

8 TeV: lepton+jets & dilepton channels

Fit m_t dependence of the l + J/ψ mass distribution



marginal sensitivity to JES and light quark/gluon fragmentation uncertainties

m_t = 173.5 ± 3.0 (stat) ± 0.9 (syst) GeV

dominant systematics:

top p_T distribution, b-fragmentation, pdfs, Q^2 and matching scales

Marginalizing Uncertainties: *Secondary Vertex Mass*

CMS-PAS-TOP-12-030

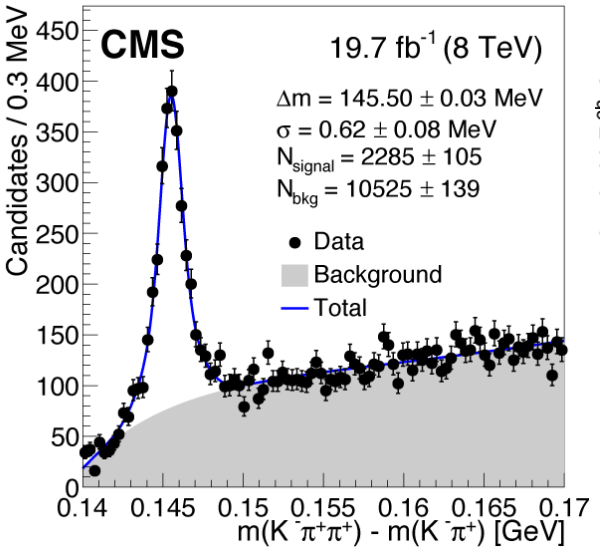
8 TeV: lepton+jets & dilepton channels

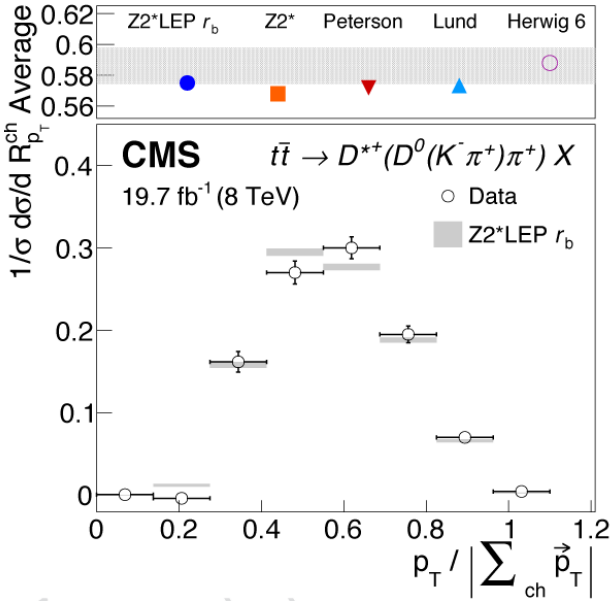
Fit m_t dependence of the mass formed from the charged tracks associated with the displaced vertex from the b-decay

$m_t = 173.7 \pm 0.2\ (\text{stat})\ ^{+1.6}_{-1.0}\ (\text{syst})$ GeV

dominant systematics:

b-fragmentation, top p_T distribution
Q^2 and matching scales





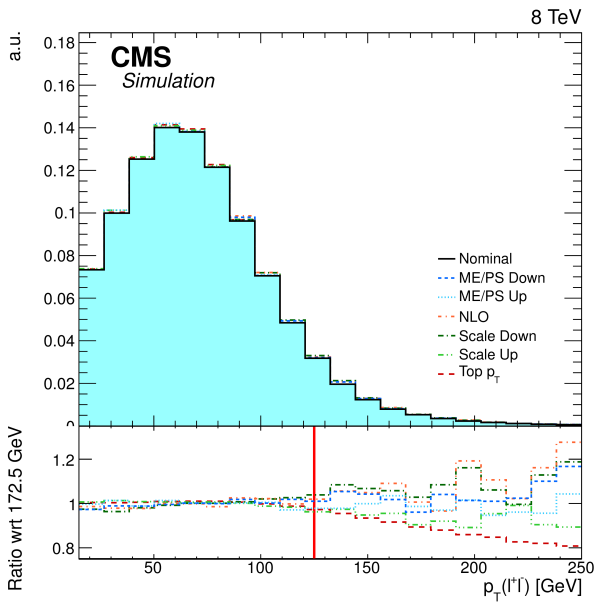
Reconstruction of J/ψ, D0 and D± in these events → first look at b-quark fragmentation in ttbar events*

Marginalizing Uncertainties: *Dilepton Kinematics*

CMS-PAS-TOP-16-002

motivation → Frixione & Mitov JHEP 09 (2014) 012

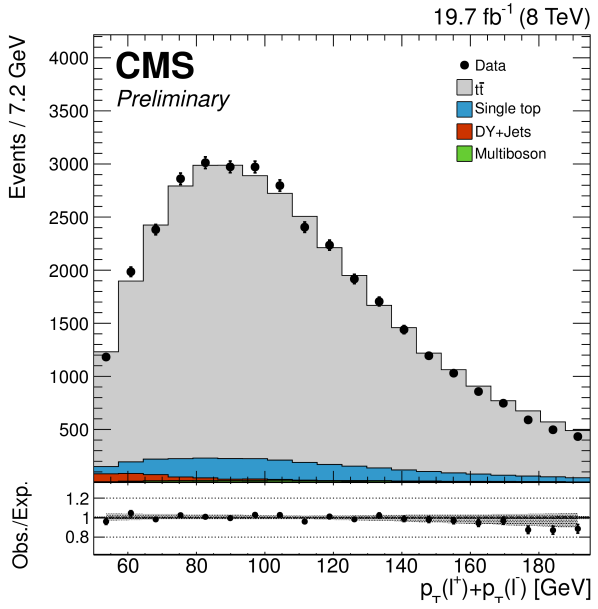
8 TeV: dilepton eμ channel



Look for experimentally clean variable that is theoretically calculable

most sensitive:
$p_T(l^+l^-)$

Expt. limitation: lepton momentum scale (well controlled)



$m_t = 171.7 \pm 1.1\ (stat) \pm 0.5\ (expt)\ ^{+3.1}_{-2.5}\ (thy)\ ^{+0.8}\ (top\ p_T)$ GeV

dominant systematics: QCD scale uncertainty, top quark p_T modeling

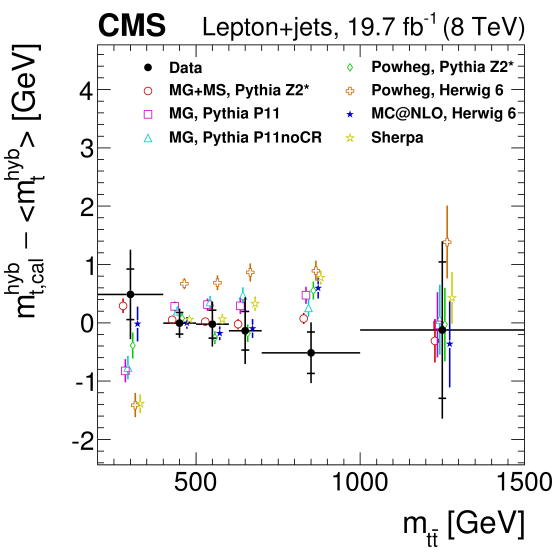
Caveat: analysis done only using LO multileg MC

Thinking Differentially

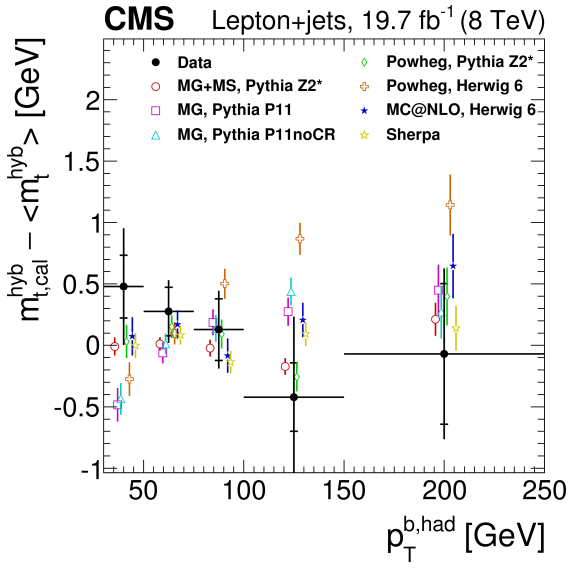
CMS Phys. Rev. D93 (2016) 072004

8 TeV lepton+jets channel

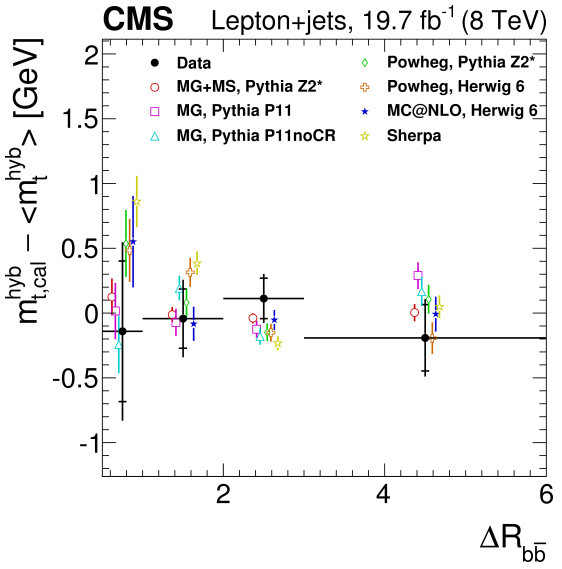
m_{ttbar}



p_t^b



ΔR_{bbbar}

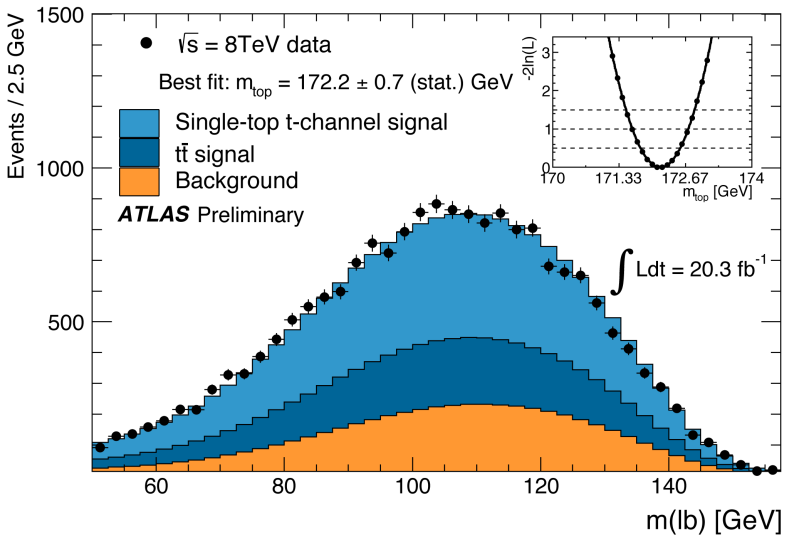


measure m_t differentially as a function of the event kinematics to test the modeling of observables

Results are statistically limited for Run I but may be viable for Run II

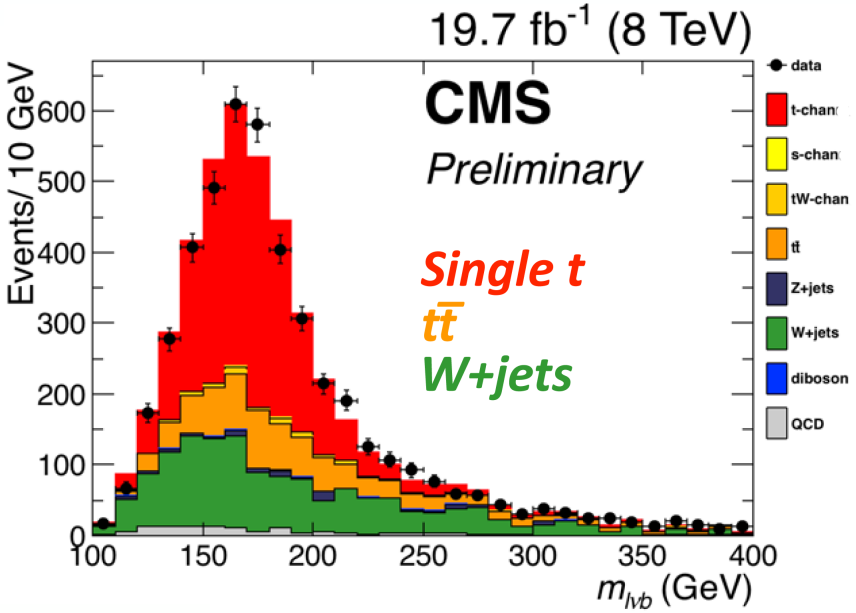
Alternative Event Topologies: *t-channel single top*

ATLAS CONF-2014-055



ATLAS (2014)*: fit to m(lb)*

CMS-PAS-TOP-15-001



CMS (2016)*: fit to m(tb)*

$m_t = 172.2 \pm 0.7\ (stat) \pm 2.0\ (syst)$ GeV

$m_t = 172.6 \pm 0.8\ (stat)\ ^{+1.0}_{-0.9}\ (syst)$ GeV

Dominant uncertainties: Jet energy scales & hadronization

Mass Reconstruction – Summary

Significant improvement in precision over the last 2 years

Moving beyond 500 MeV precision will be challenging

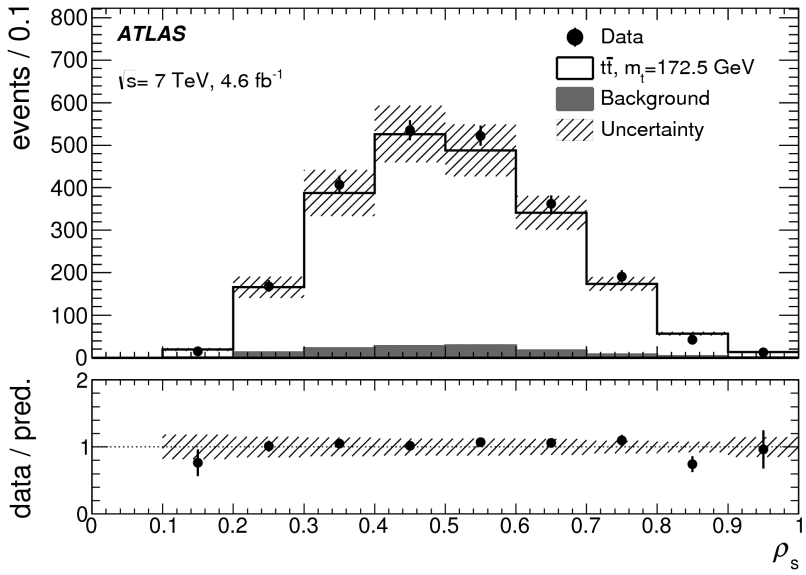
Experimental Issues
- knowledge of jet energy scale
- pileup effects with 13 TeV data may be more significant

Theory Issues
- modeling of flavor-dependent jet energy corrections
- modeling of top quark p_T spectrum
- modeling of b-jet fragmentation
- modeling of color reconnection effects
- uncertainty due to limitations of generator choice
- ISR/FSR and NLO parton showering

……

What is the relationship between the observable and the pole and/or MSBar masses??

Top Quark Pole Mass – *(lepton+jets) + 1 jet*



JHEP 10 (2015) 121

motivation → Alioli & Collaborators
arXiv:1303.6415

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{\mathrm{d}\sigma_{t\bar{t}+1\text{-jet}}}{\mathrm{d}\rho_s}(m_t^{\text{pole}}, \rho_s)$$

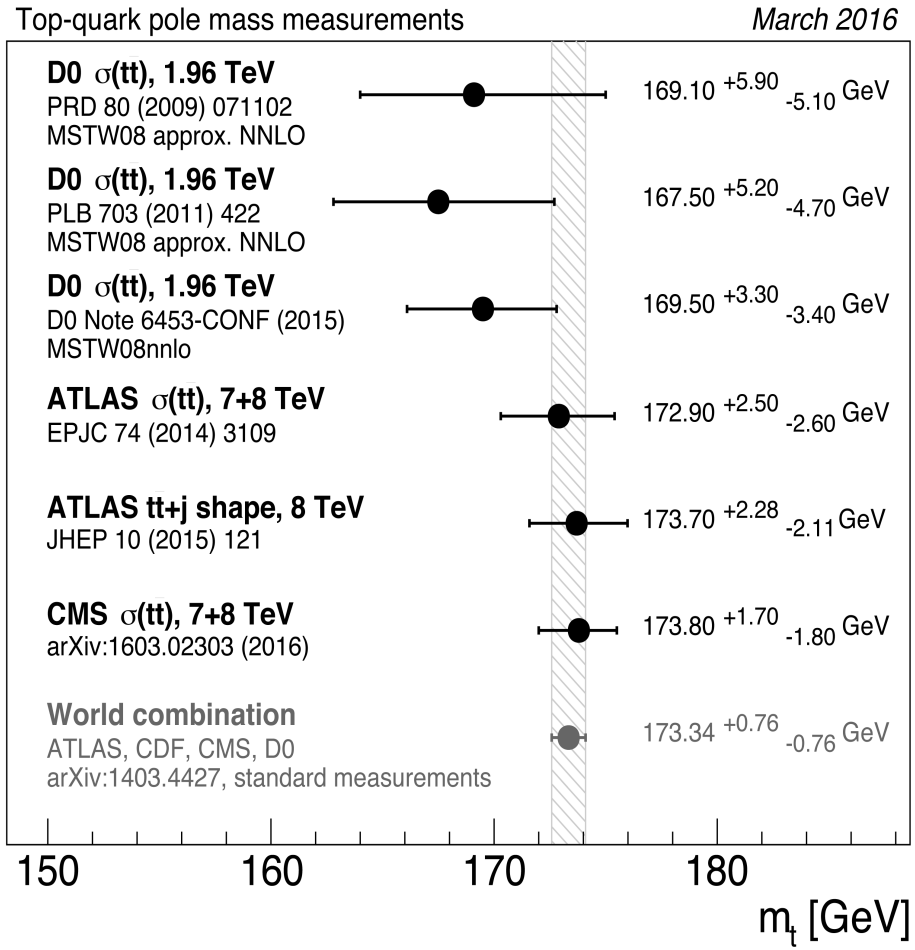
$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}} \qquad m_0 = 170 \text{ GeV}$$

Normalized ttbar + 1 jet differential cross section → top quark pole mass

Dominant uncertainties: statistics (only 7 TeV data),
Jet energy scales & knowledge ISR/FSR and Q^2 scale

$$m_t^{\text{pole}} = 173.7 \pm 1.5\ (\text{stat}) \pm 1.4\ (\text{syst})\ ^{+1.0}_{-0,5}\ (\text{thy})\ \text{GeV}$$

Top Quark Pole Mass – Summary



New results
→ Significant improvement in precision

Precision limited by knowledge of:

a.) Cross Sections:
LHC beam energy & luminosity, pdf's & α_s

b.) ttbar+1 jet:
Jet Energy Scales, ISR/FSR modeling and Q^2 scale

Not competitive in precision with kinematic mass reconstruction but it does produce a theoretically simpler mass observable

Summary & Outlook

– Progress on almost all fronts with significant improvements in precision and understanding of ttbar measurables

– Although many measurements are systematics limited, new techniques using higher statistics 13 TeV data should yield further improvements in precision

– Starting to work in a regime where observables such as differential spectra and m_t can be used to probe higher order QCD effects and constrain some of the modeling uncertainties (b-fragmentation, pdf's, color reconnection….)

– Within the current experimental precision, predictions from NNLO QCD give a good description of the data

– So far, no evidence for any BSM anomalies