Top quark mass and LHC activities

MITP workshop on
High precision fundamental constants at TeV scale
March 10-21, 2014

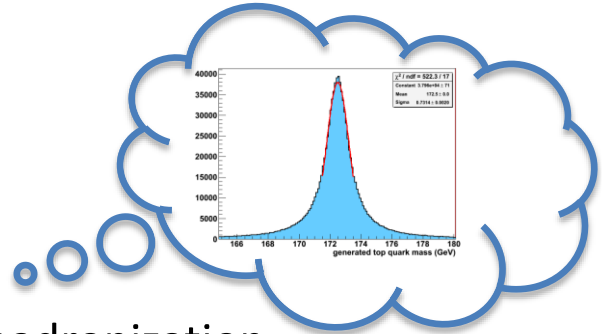
Martijn Mulders (CERN) *on behalf of the ATLAS and CMS collaborations*

Mainz Institute for Theoretical Physics

Outline

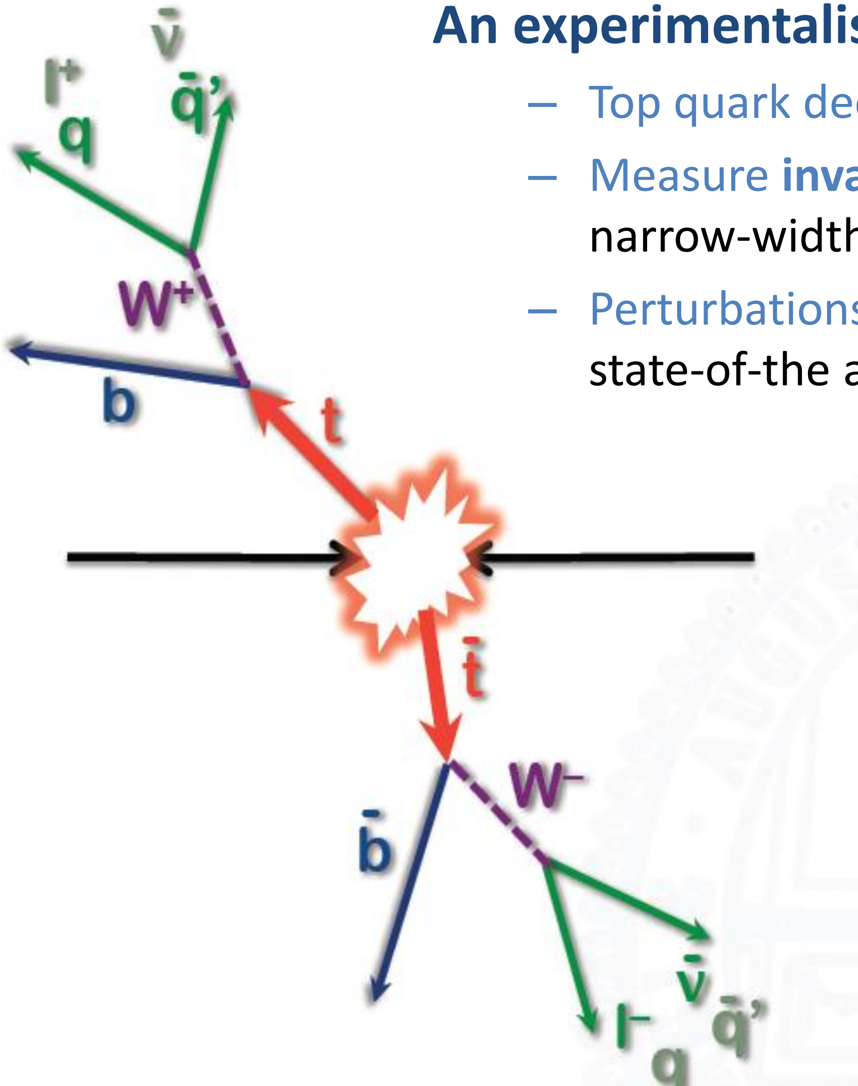
- Top mass – experimentalist’s definition
- Standard Methods and recent results at the LHC
- Alternative approaches, aiming for improved understanding
- Prospects at the LHC
- TOPLHC Working Group activities
- Points for discussion

Measuring the Top Mass:



An experimentalist's view

- Top quark decays before hadronization
- Measure **invariant mass** of decay products, reflecting narrow-width resonance of top quark propagator
- Perturbations from QCD are corrected for, using state-of-the art MC tools

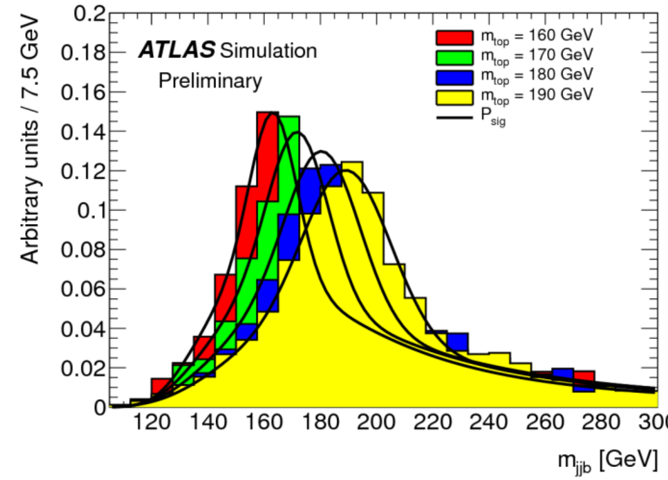


Basic Methods

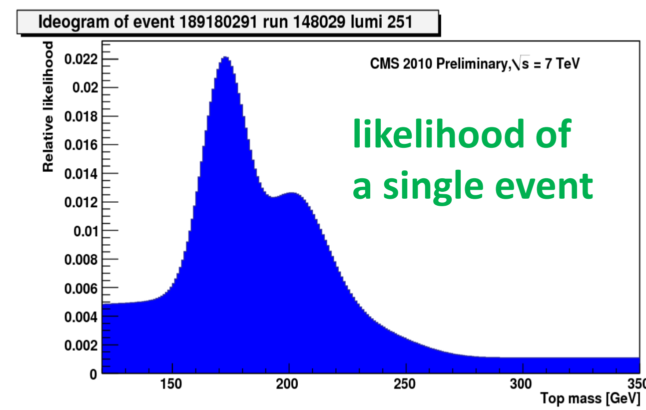
- Full reconstruction of invariant mass → most powerful method
- Partial reconstruction, fitting variable correlated to mass (eg lepton p_T end-point) → less powerful; different systematics
- Indirect, not using mass → eg through cross-section

Full Reconstruction: basic methods

- Template Method ("simple" and fast)
  - compare an observable in data with MC generated with different masses
- Matrix Element (very precise, but slow)
  - build an event likelihood based on ((N)LO) tt matrix element using the full kinematics of the event, multi-dimensional integration
- Ideogram Method (precise and fast)
  - build analytical event likelihood taking into account all jet combinations and background, based on kinematic fit
- >> a special case: Di-lepton channel
  - Various methods to solve under-constrained system: KIN(b), (a)MWT, neutrino weighting, Dalitz-Goldstein…



Allows to capture full event ambiguity:



Calibrate with Monte Carlo **Fit data and extract m_{top}^{MC}**

Standard Analysis Methods

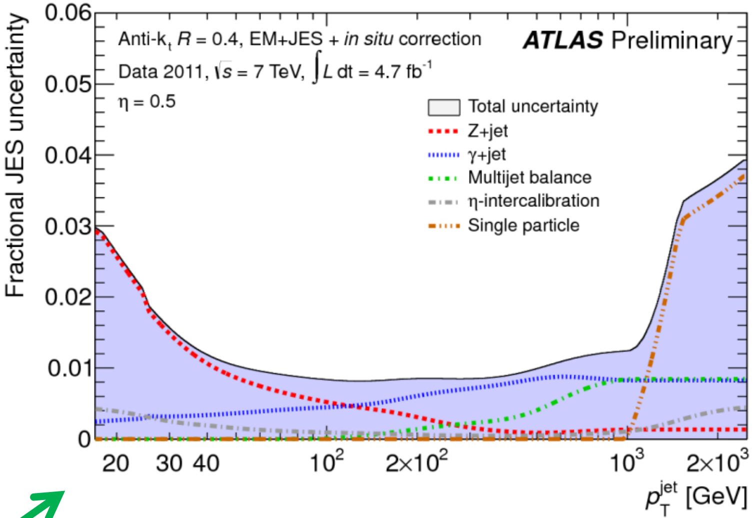
When Tevatron techniques meet LHC data sets…

Main challenge: jet reconstruction

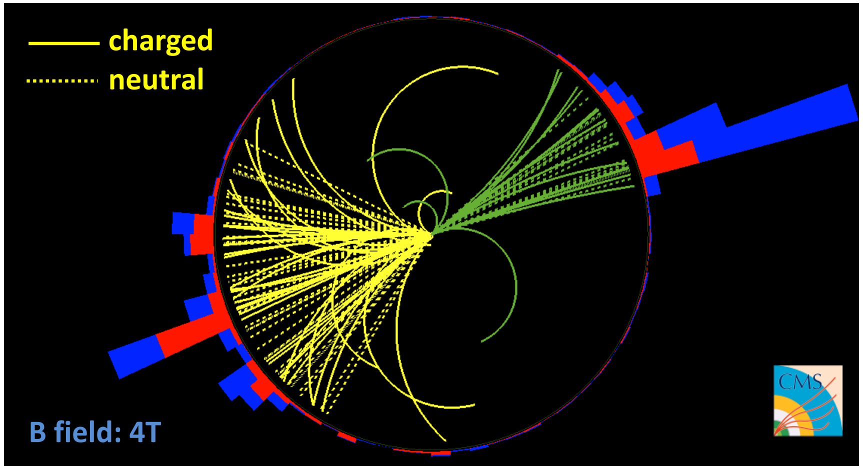
detailed work LHC experiments on jet calibration

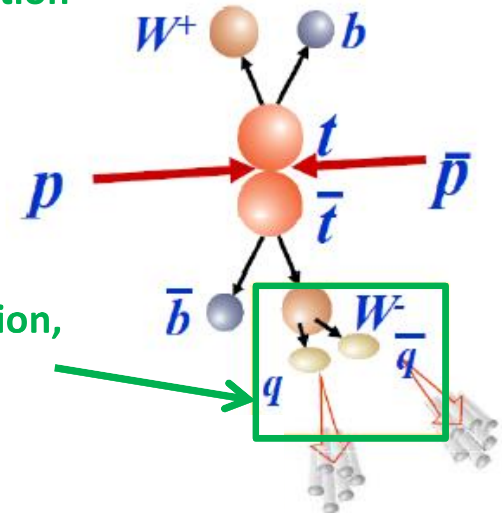
- CDF: iterative cone, ΔR=0.4
- D0: iterative cone, ΔR=0.5
- ATLAS: anti-kT clustering, dR=0.4
  EPJC 73 3 (2013) 2404, 2405 and 2406
- CMS: anti-kT clustering, dR=0.5
  JINST 6 P11002 and JINST 6 P09001

  Note: CMS uses "Particle Flow" combining tracking & calorimetry at particle level, *before* jet clustering



A-priori **JES calibration typically *~1-3 %***

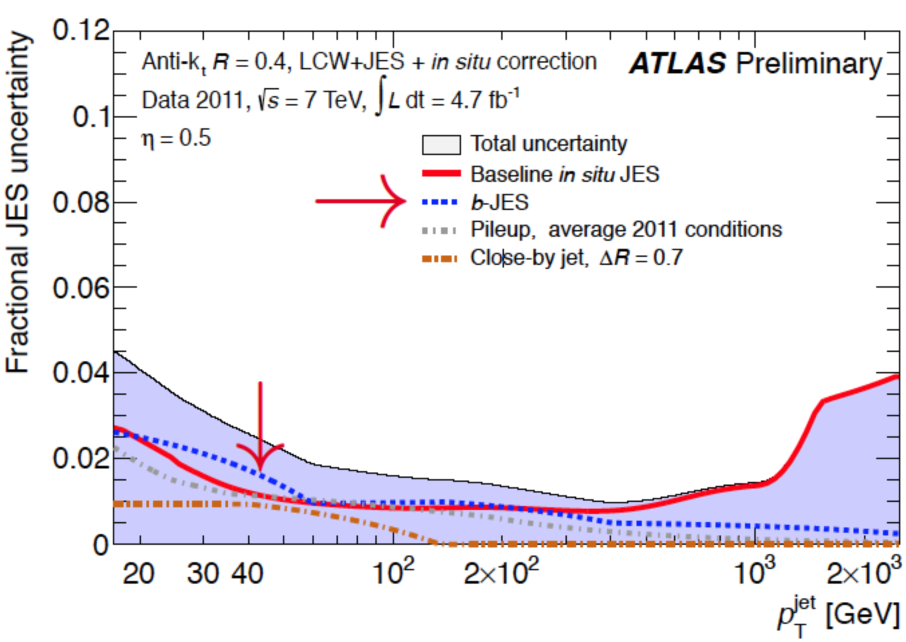


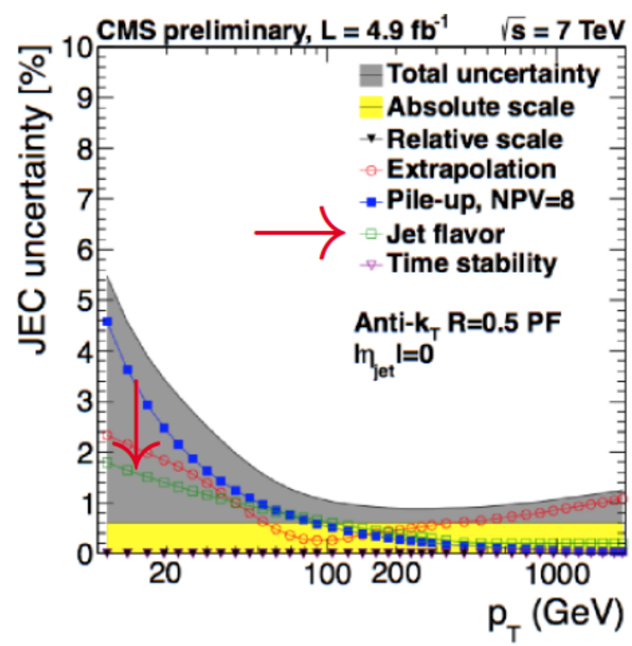


Complement with *In-situ* JES calibration, <1 % possible

Jet Energy Scale Uncertainties

- JES calibrated using γ/Z+jet and dijet events, yielding good understanding after analyzing full datasets (1-3 % overall)
- (Tevatron) 2D method: use m_W to fit a JES scale factor (**JSF**) in-situ using W→jj
  note: sizeable uncertainty remains for difference between jet flavours
- ATLAS 3D method: in l+jets channel → also fit relative b-to-light-jet scale (**bJSF**) inside tt events, using transverse momentum balance

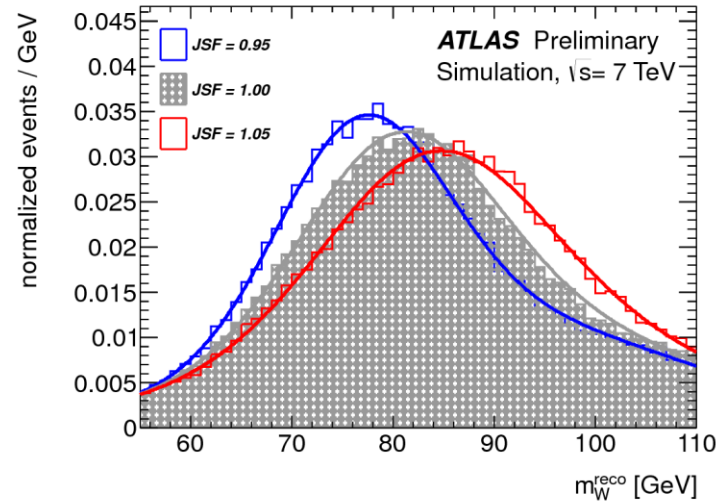


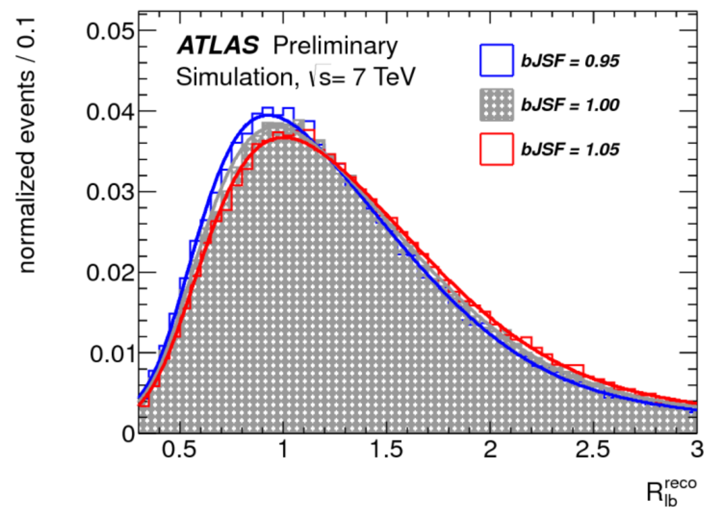


ATLAS 3D method (l+jets channel)

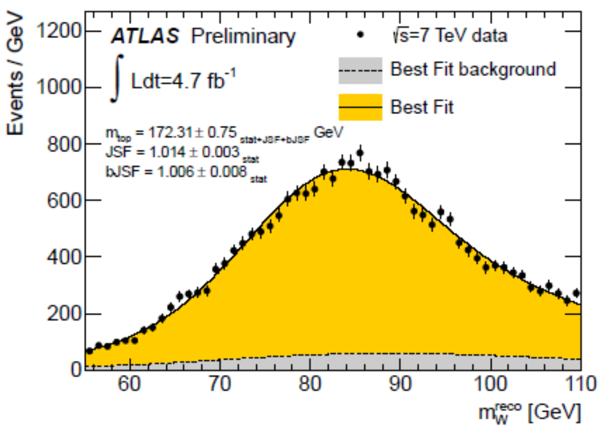
ATLAS-CONF-2013-046

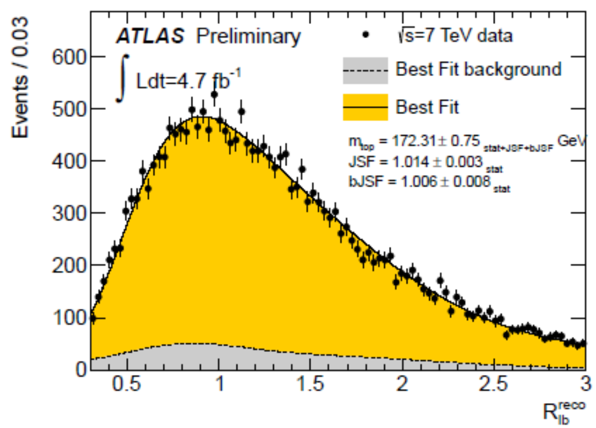
- 1 high-p_T lepton, ≥ 4 jets, ≥1 b-tag
- Kinematic fit for reconstruction and choice of jet combination
- Fit simultaneously templates of
  - m^{reco}_W
  - R^{reco}_{lb} $= \dfrac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{W_{jet1}} + p_T^{W_{jet2}}}$
  - m_{top}
- m^{reco}_W used to fit overall jets scale factor (JSF)
- R^{reco}_{lb} used to constrain overall ratio of b- to light-flavour jet energy scale (bJSF)
- First measurement with *in-situ* calibration of b-quark JES

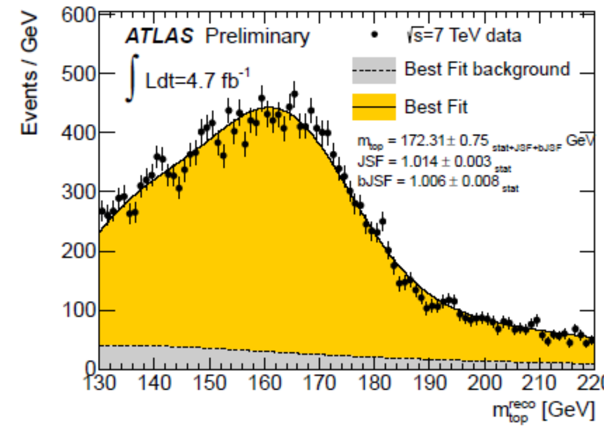




ATLAS 3D method







$$m_t = 172.31 \pm 0.75 \underbrace{(\mathrm{stat} + \mathrm{JSF} + \mathrm{bJSF})}_{\textit{purely statistical in nature}} \pm 1.35\ (\mathrm{syst})\ \mathrm{GeV}$$

Main systematic uncertainties	Δm_{top} [GeV]
Jet energy scale	0.79
b-jet energy scale	0.08
ISR/FSR	0.45
b-tagging	0.81
Colour reconnection	0.32
Total (incl. all uncertainties)	**1.35**

residual p_T- and η-dependence of jet energy scale

reliance on b-tagging increased, (also p_T- and η-dependent)

ATLAS m_{lb} (di-lepton channel)

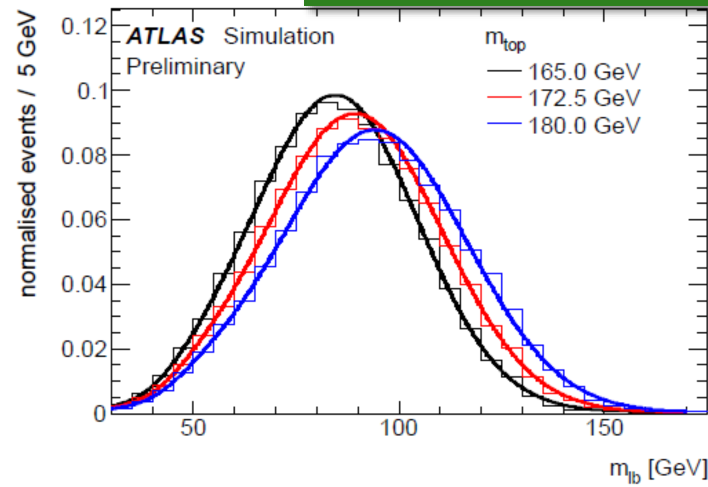
ATLAS-CONF-2013-077

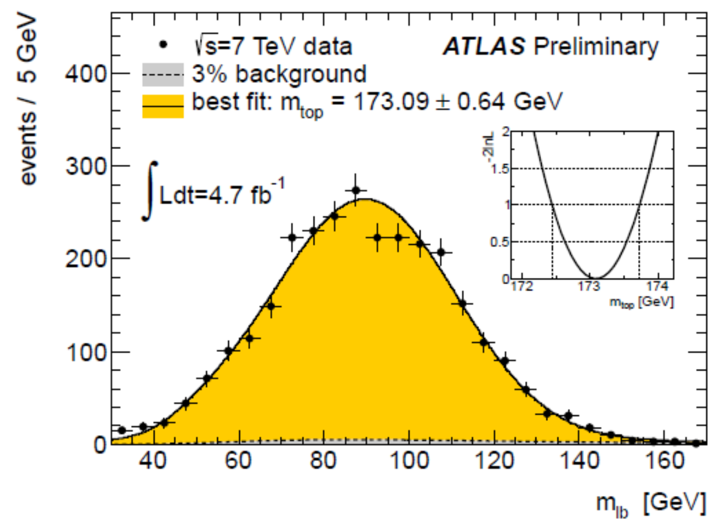
- 2 opposite-sign high-pT leptons, MET, ≥ 2 jets, =2 b-tags
- 97% pure selection

- Two possible assignments per event, each: take average of two values of m_{lb}
- Template fit of lowest average m_{lb}

$$m_t = 173.09 \pm 0.64\ (\mathrm{stat}) \pm 1.50\ (\mathrm{syst})\ \mathrm{GeV}$$

- Dominant systematic uncertainties: **(b)JES**, ISR/FRS, hadronisation, UE
- *Clean, competitive result even with* <u>*partial*</u> *reconstruction*
- *Calibrated to give MC top mass*

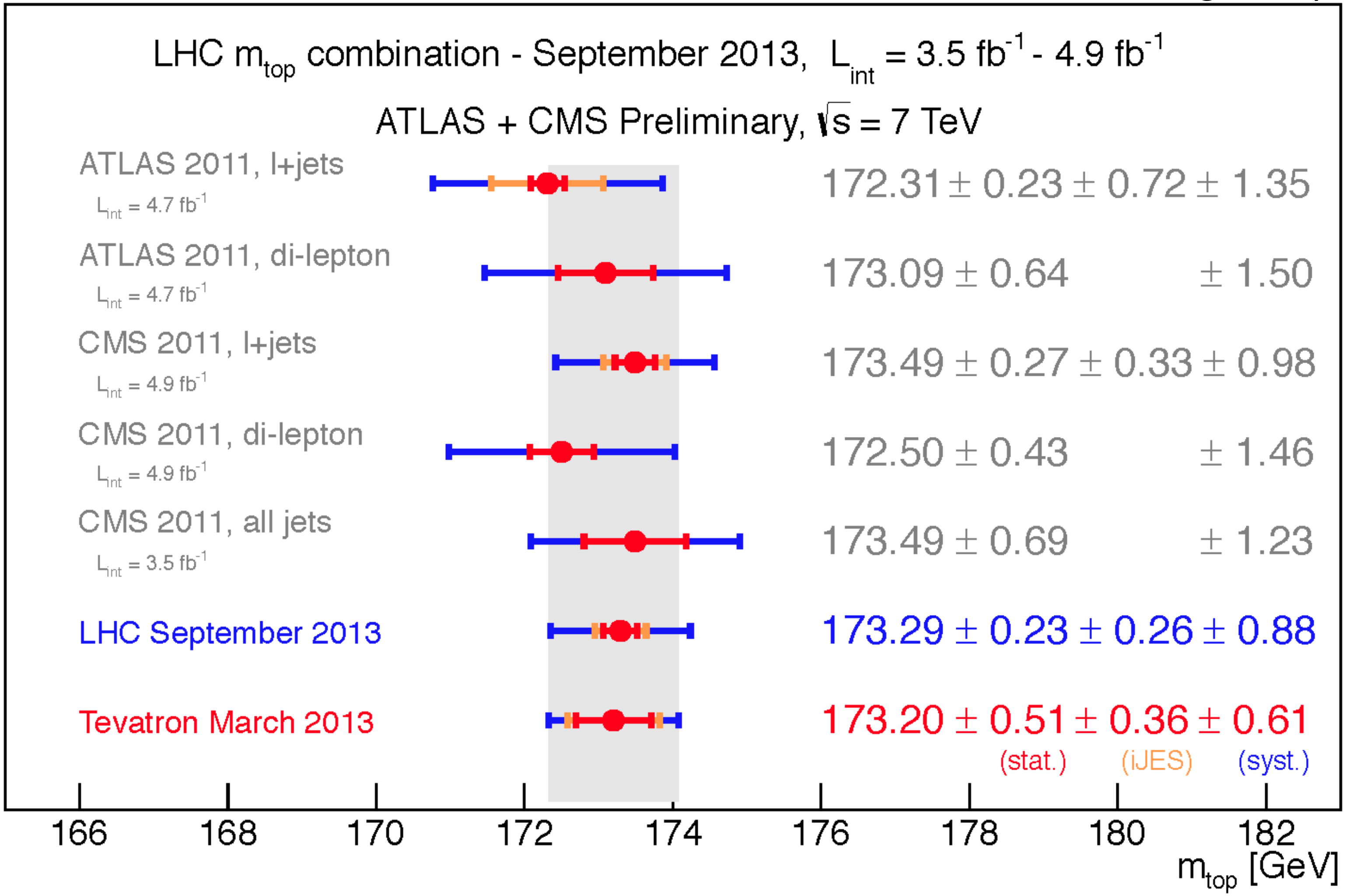




LHC combination

ATLAS-CONF-2013-102
CMS-PAS-TOP-13-005

TOP LHC Working Group



LHC top mass combination

TOP LHC Working Group

	ATLAS comb.	CMS comb.	LHC comb.
Measured M_T	172.65	173.59	173.29
iJES	0.41	0.27	0.26
uncorrelated JES comp.	0.66	0.32	0.29
in-situ JES comp.	0.30	0.08	0.10
intercalib. JES comp.	0.28	0.02	0.07
flavour JES comp.	0.21	0.19	0.16
b-jet energy scale	0.35	0.56	0.43
Monte Carlo simulation	0.40	0.06	0.14
Radiation modelling	0.42	0.28	0.32
Colour reconnection	0.31	0.48	0.43
Underlying event	0.25	0.17	0.17
Proton PDF	0.15	0.07	0.09
Detector modelling	0.22	0.25	0.20
b-tagging	0.66	0.11	0.25
Lepton reconstruction	0.07	0.00	0.01
Background from MC	0.06	0.10	0.08
Background from Data	0.06	0.03	0.04
Method	0.08	0.07	0.06
Multiple Hadronic Interactions	0.02	0.06	0.05
Statistics	0.31	0.29	0.23
Systematics	1.40	0.99	0.92
Total Uncertainty	1.43	1.03	0.95

***JES**: good progress, 5 common correlation groups defined*

***MC/Radiation**: different MCs and treatment*

***CR/UE**: somewhat ad-hoc, testing available simplified models/tunes; to be improved*

***b-tagging**: working on similar understanding of correlations as for JES*

Radiation uncertainties

ATLAS

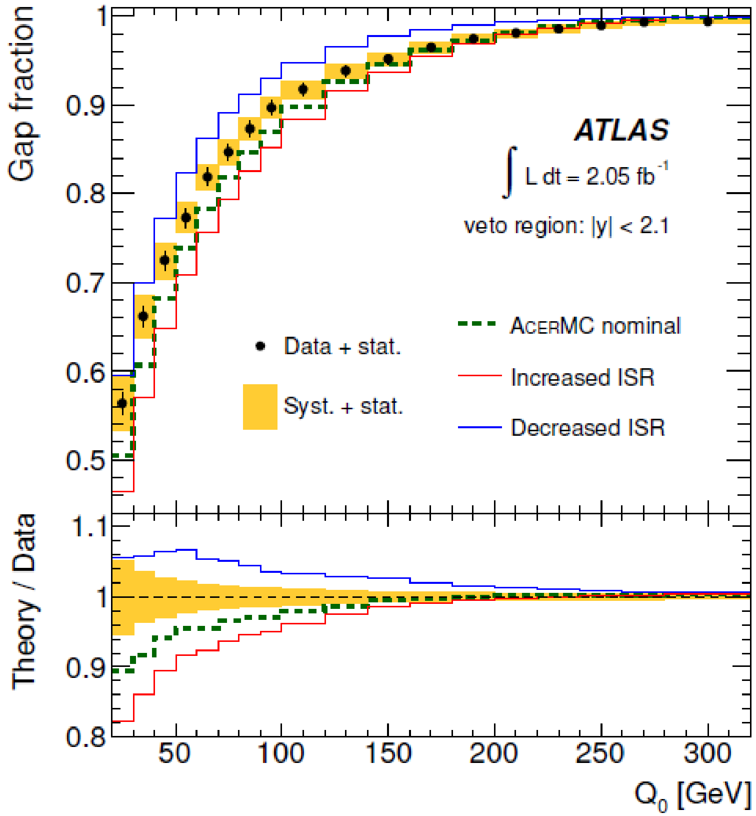
- MC generator: MC@NLO vs Powheg
- ISR/FSR: Half of Pythia Hard vs Soft

CMS *default: MadGraph + Pythia*

- Factorization and renorm. scales
- ME-PS matching threshold
- MC generator: MadGraph vs Powheg

NEXT :

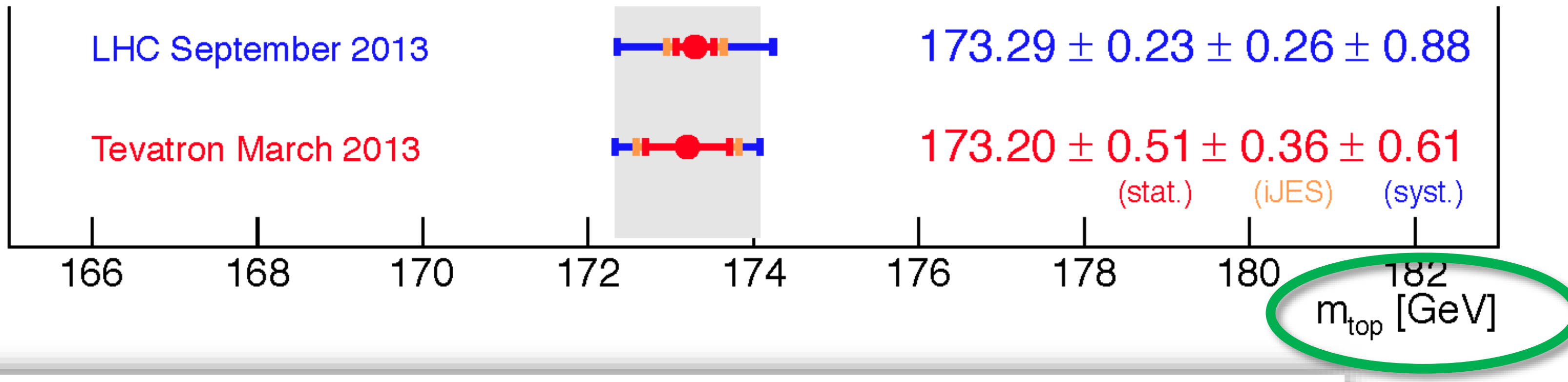
- Harmonise / compare on equal footing
- Move to full NLO ME+PS matching
- Constrain with data



Current impact :

- ISR/FSR impact up to 1 GeV, depending on analysis strategy
- Can be reduced by selecting ‘clean’ events (exact number of jets vs inclusive, b-tagging, compatibility with ttbar fit hypothesis …)

LHC combination



3.3 Measurements calibration

In all measurements considered in the present combination, the fitting procedures are calibrated to the Monte Carlo (MC) top-quark mass definition. The baseline MC program for the simulation and calibration of the top-quark mass analyses in ATLAS is PowHeg interfaced with Pythia for the parton shower and underlying event modelling [13–15]; MadGraph interfaced with Pythia is used within CMS [14, 16]. The parton configurations generated by MadGraph are matched with the parton showers using the MLM prescriptions [17]. It is expected that the difference between the MC mass definition and the top-quark pole mass is of order 1 GeV [18]. A systematic uncertainty, ranging from 0.02 GeV to 0.20 GeV, depending on the analysis, is assigned to the input measurements, covering differences between MC models.

?

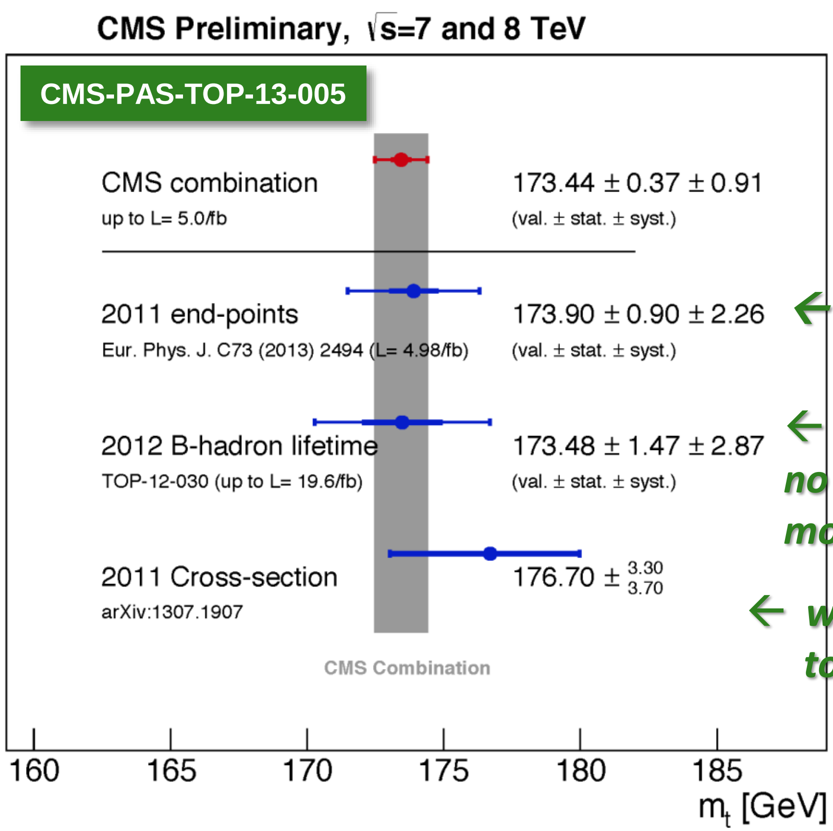
[18] A. Buckley et al., "General-purpose event generators for LHC physics", *Phys. Rept.* **504** (2011) 145, doi:10.1016/j.physrep.2011.03.005, arXiv:1101.2599.

Alternative approaches

Deeper understanding for improved precision…

Alternative approaches

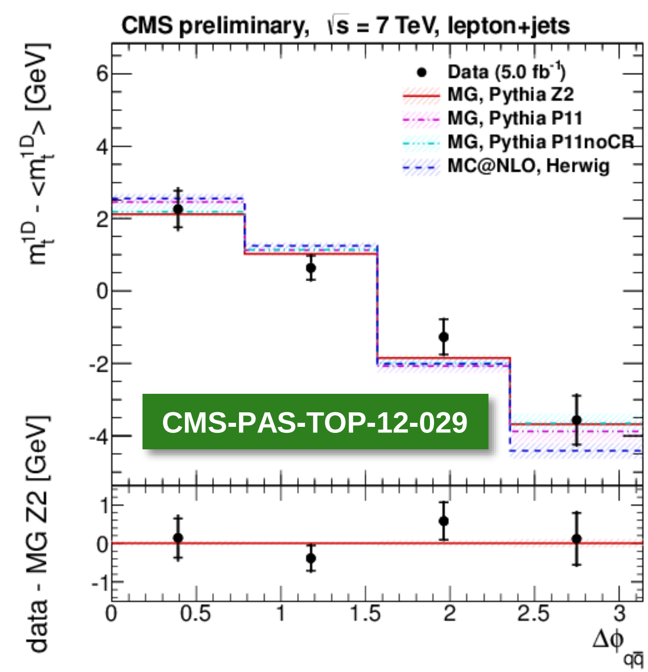
- Extract m^{pole}_{top} from the inclusive cross-section
- Look for alternative methods with different systematic uncertainties
- Probe m_{top} invariant mass observable in different corners of phase space



← No MC used

← Lxy method
no jets, but top pT model is crucial

← well-defined top 'pole mass'



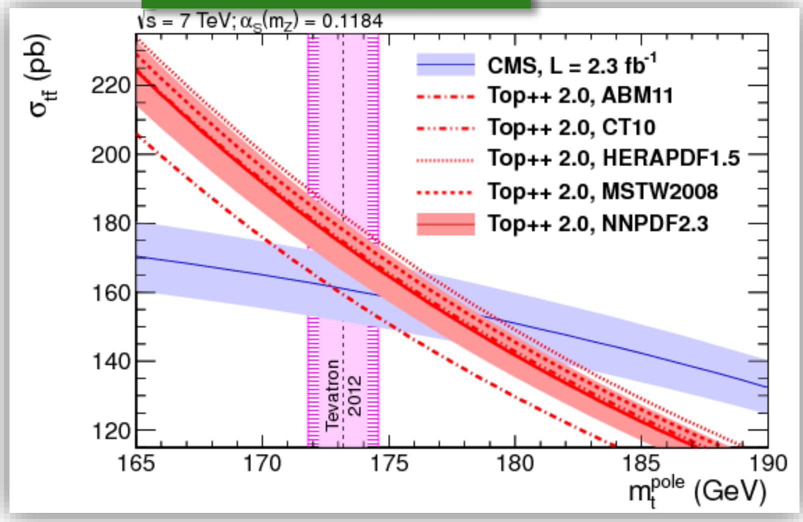
Top mass observable vs event variables

Top mass from cross-section

- Extract well-defined pole mass from cross-section at 7 TeV (CMS di-lepton)
- OR: extract α_s / constrain PDF

- Prospects for improvements in precision are limited:
  - Already using NNLO+NNLL
  - Precision of experimental cross-section is good (~4%)
- Improve slope of experimental result (due to acceptance)?

PLB 728 (2013) 496



$$176.7^{+3.8}_{-3.4}\ \mathrm{GeV}$$

Optimistic projections LHC:

Scenario	precision
A: 3% σ_{exp} + no slope	2 GeV
B: 2% σ_{exp} + no slope + 2x reduction σ_{theory}	1 GeV

CMS-PAS-FTR-13-017

CMS end-point method (di-lepton)

EPJC 73 (2013) 2494

(<u>Partial</u> reconstruction)

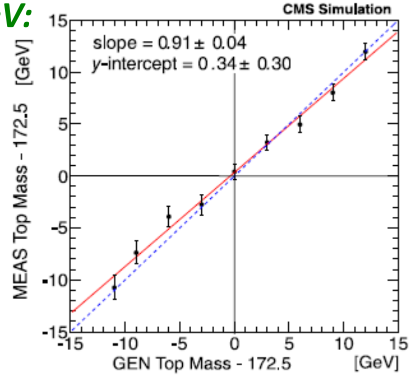
- Fit to end-points of 3 variables
- *Without use of Monte Carlo for mass definition (calibration)*
- Allows extraction of neutrino, W and top mass…
- Based on analytical end-point formulas, eg

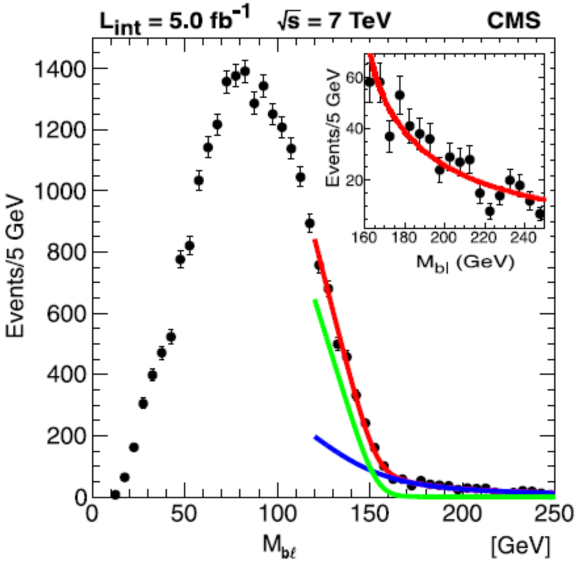
$$M_{b\ell}^{\max} = \sqrt{m_b^2 + \left(1 - \frac{m_\nu^2}{M_W^2}\right)\left(E_W^* + p^*\right)\left(E_b^* + p^*\right)}$$

(extracts something like a pole mass, using a narrow-width picture)

$$\boxed{M_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.7}_{-2.1}\,(\text{syst.})\ \text{GeV}}$$

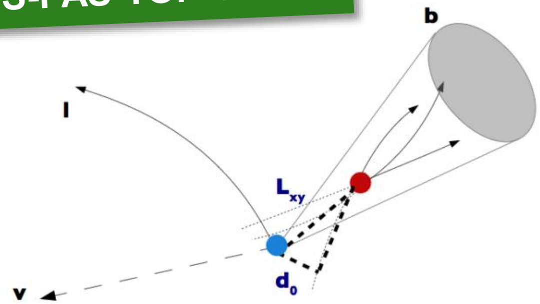
Cross-check shows agreement with MC mass < 0.3 GeV:

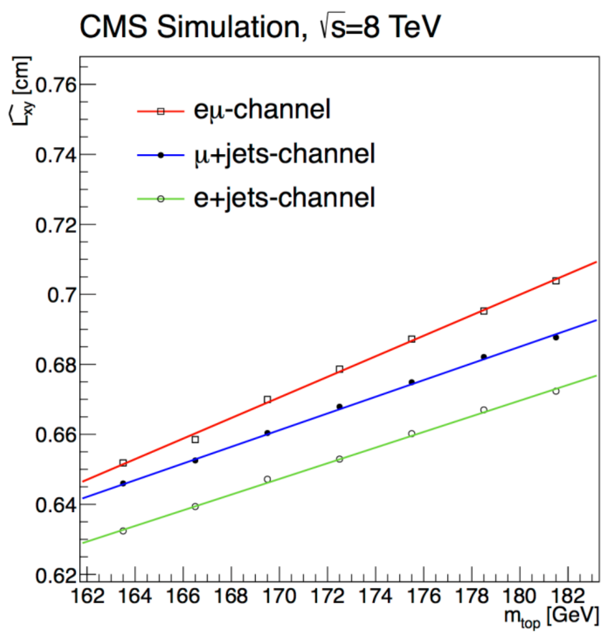




B hadron lifetime (L_{xy}) technique

CMS-PAS-TOP-12-030

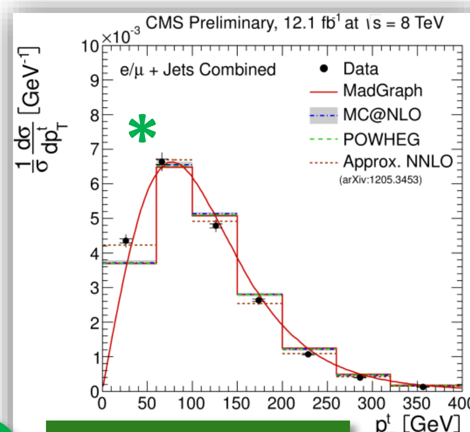




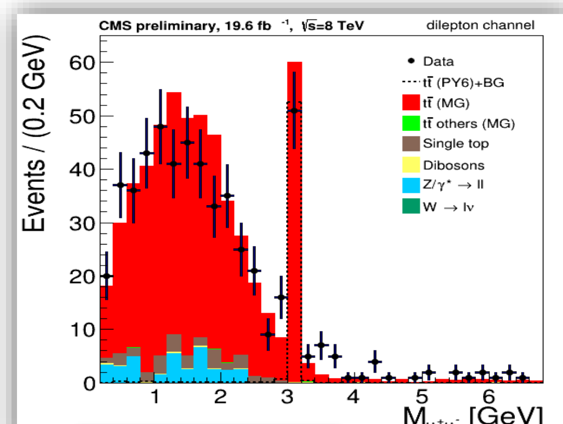
- Transverse decay length of B hadrons in $t\bar{t}$ events has linear dependence on m_t (pioneered by CDF)
- Only uses tracks … no jet reconstruction, no JES
- However:
  - Not a Lorentz-invariant quantity → *sensitive to modeling of top pair production kinematics* *
    (effect ~10x reduced for inv. mass analyses)
  - Requires knowledge b-fragmentation
- Proposed alternatives / improvements:
  - Use invariant mass of B-hadron vertex + ℓ from W
  - Use invariant mass of J/psi (→μμ) + ℓ from W

*

$$m_t = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{p_T(t)}\,\mathrm{GeV}$$



CMS-PAS-TOP-12-027/028

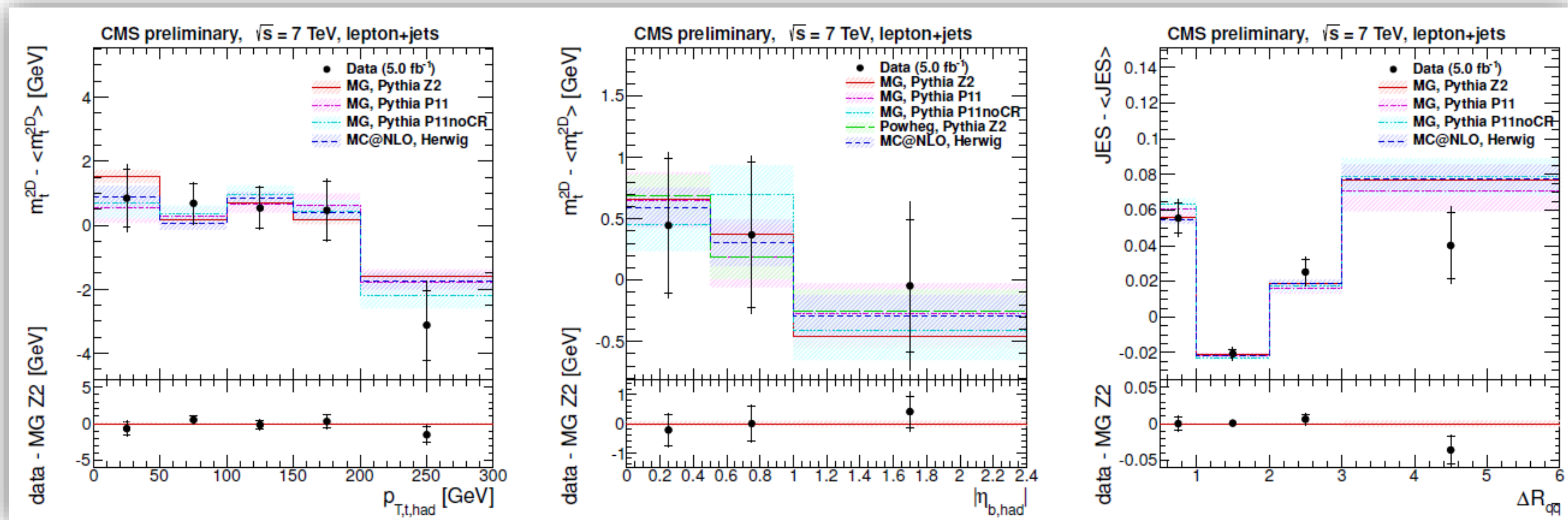


CMS-PAS-TOP-13-007

How invariant is the "invariant mass"?

CMS-PAS-TOP-12-029

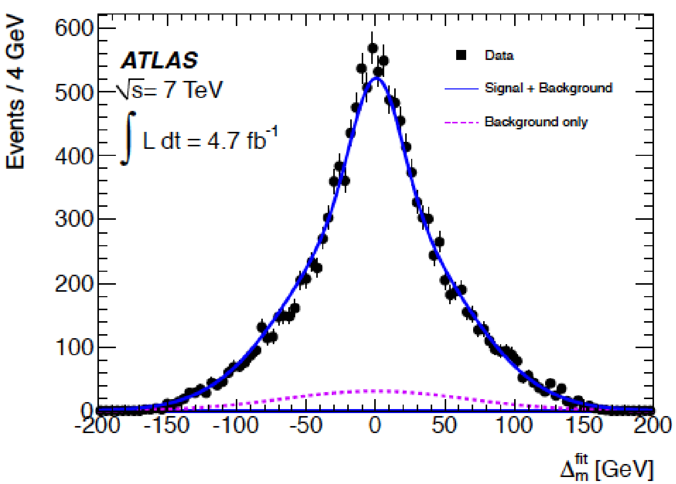
- Huge top event samples at LHC allow to probe top mass observable as a function of event variables (here: using l+jets, standard 2D fit)

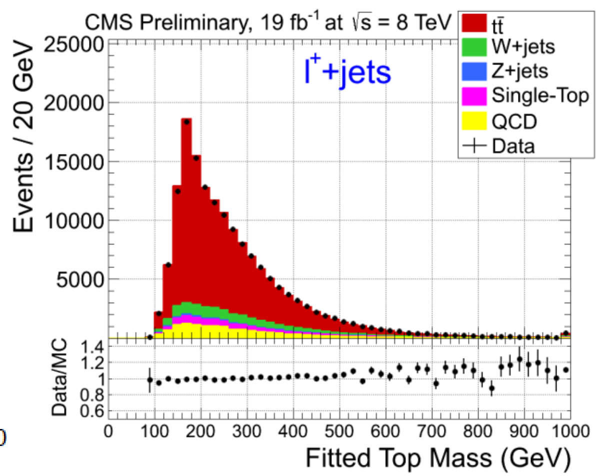


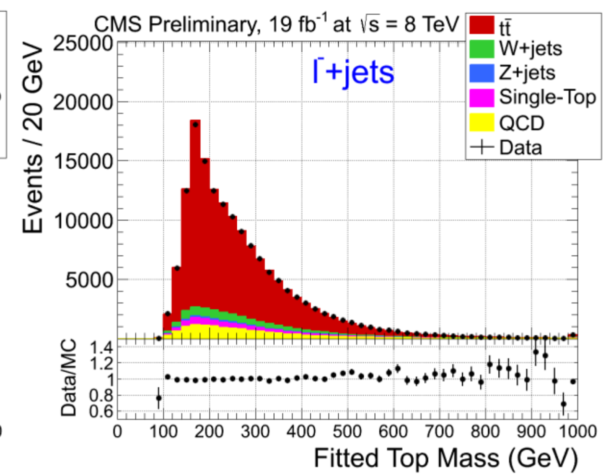
- Any sign of color connections between b jets and beam, spoiling inv. mass?
- Tested 12 observables, global chi2/ndf = 69/78→prob=77% (data vs MG Z2)
- Various dependencies well modeled, by all MC models/tunes tested
- Mass measurement is stable; tests will be *more precise* with *more statistics*

Top quark vs anti-quark mass difference

- Test of CPT invariance OR possibly sensitive probe of 'asymmetric' QCD effects
- lepton +jets topology with ≥2 (ATLAS) or ≥1 (CMS) b-tagged jets
- ATLAS: measure Δm_{top} per event --- CMS: split sample by lepton charge







PLB 728 (2014) 363-379

CMS-PAS-TOP-12-031

JHEP 06 (2012) 109

ATLAS: $m_t - m_{\bar{t}}$ = 0.67 ± 0.61 (stat) ± 0.41 (syst) GeV

CMS 8 TeV: $m_t - m_{\bar{t}}$ = -0.27 ± 0.20 (stat) ± 0.12 (syst) GeV (8 TeV)

CMS 7 TeV: $m_t - m_{\bar{t}}$ = -0.44 ± 0.46 (stat) ± 0.27 (syst) GeV (7 TeV)

dominant uncertainties: choice of *b* fragmentation model (ATLAS: 0.34 GeV) and *b*/$\bar{b}$-jet response (CMS: 0.06 GeV; ATLAS: 0.08 GeV)

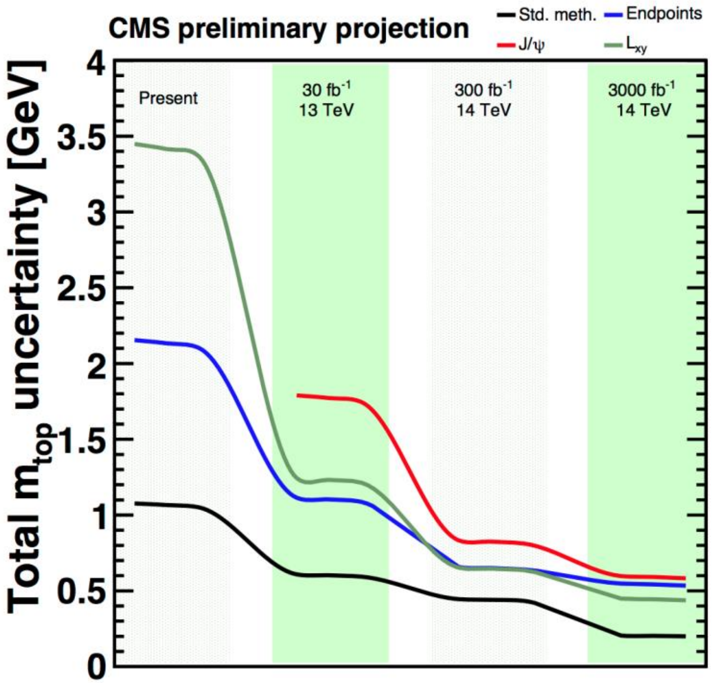
Prospects at the LHC

Projections and Top LHC Working Group

Prospects for m_{top} at the LHC

CMS-PAS-FTR-13-017

- Top mass projections (CMS, ECFA)
  - Cautiously optimistic estimates of possible experimental precision at LHC
  - Assumes reduction in experimental and theoretical modeling, using the ATLAS 3D fit and differential studies with high statistics
- Some alternative methods can reach sub-GeV precision with 300 fb^{-1}
- Standard method may reach 0.2 GeV experimental precision, provided
  - Fundamental improvements in knowledge on key uncertainties:
  - Radiation, (b-)jet fragmentation, non-perturbative QCD effects, tuning of event generators
- Worthwhile to understand precise relation between m_{top}^{MC} and m_{top}^{pole} !



	Ref.[13]	Projections				
CM Energy	7 TeV	14 TeV				
Luminosity	$5 fb^{-1}$	$100 fb^{-1}$		$300 fb^{-1}$		$3000 fb^{-1}$
Pileup	9.3	19	30	19	30	95
Syst. (GeV)	0.95	0.7	0.7	0.6	0.6	0.6
Stat. (GeV)	0.43	0.04	0.04	0.03	0.03	0.01
Total, GeV	**1.04**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**

See also Snowmass Top working group report http://arxiv.org/pdf/1311.2028v1.pdf

Snowmass: less optimistic for standard approach

TOP LHC Working Group

LPCC

LHC Physics Centre at CERN

http://lpcc.web.cern.ch/LPCC/index.php?page=top_wg

- Coordinators: Roberto Chierici, Maria Costa, Michelangelo Mangano
- Forum for discussion between LHC experiments and with theorists
- The goal: to provide combinations of key top quark measurements
  - *so far: LHC top mass (2x) , top pair cross section, W helicity, single top t-channel*
  - *coming soon: first top mass World Average (LHC + Tevatron) and LHC Ac combination*
- This requires close collaboration to understand each other's techniques, systematic uncertainties, and correlations between uncertainties
- One important aspect: to harmonize methods & converge to more optimal treatment of systematic uncertainties

Next Open Meeting: 21-23 May 2014 https://indico.cern.ch/event/301787/

The first day, **Wednesday May 21**, will be dedicated to the **measurement of the top mass**, in the format of a **mini workshop**, with a specific focus on the discussion of the theoretical systematics, the theoretical interpretation, and of ideas/proposals for new m_{top} measurements at the LHC.

Summary

- Rich legacy of 20 years of top mass results and methods from the Tevatron, helped to kick-start top mass analyses at the LHC
- Measurements from ATLAS and CMS show beautiful agreement with Tevatron results, and have now reached equal precision!
- LHC experiments still have huge potential for improvements (in the next 20 years) with large datasets, powerful detectors and excellent simulations.
- *Understanding systematic uncertainties (experimental and theoretical) and correlations will be the key to progress*
- *It is time for fundamentally new (experimental and theoretical) ideas, tools and methods to constrain remaining uncertainties and enter new territory in terms of precision and understanding*

Questions for Discussion

- m_{top}^{MC} vs m_{top}^{pole} : for a given MC generator, would it be possible to pin down the difference between the MC mass and a well-defined mass by comparing the predicted distribution of an observable (like lepton p_T) between a well-defined calculation and the MC generator? Which observables would be most useful?
- Will NLO+PS Monte Carlo solve this issue? What about NNLO?
- What other observables can we use to measure the top mass?
- Non-perturbative QCD: is it sufficient to explore cluster- and string-based fragmentation models with all possible different tunes (UE, CR) that describe LHC data? Or could we be missing some important QCD effects?
- Any data-driven methods, observables, other than m_{top} that can be used to probe / discover / constrain unexpected, badly modeled QCD effects ?
- What can we learn from the "differential" studies, using the m_{top} observable as a probe of anomalous effects? What variables should we look at?

BACKUP


Cluster of Excellence
Precision Physics, Fundamental Interactions
and Structure of Matter

References

- D0 Top quark results:
  - http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
- CDF Top quark results:
  - http://www-cdf.fnal.gov/physics/new/top/top.html
- ATLAS Top quark results:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- CMS Top quark results:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
- TOP LHC WG combinations:
  - http://lpcc.web.cern.ch/LPCC/index.php?page=top_wg_docs