Top Mass and its interpretation

-- experimental --

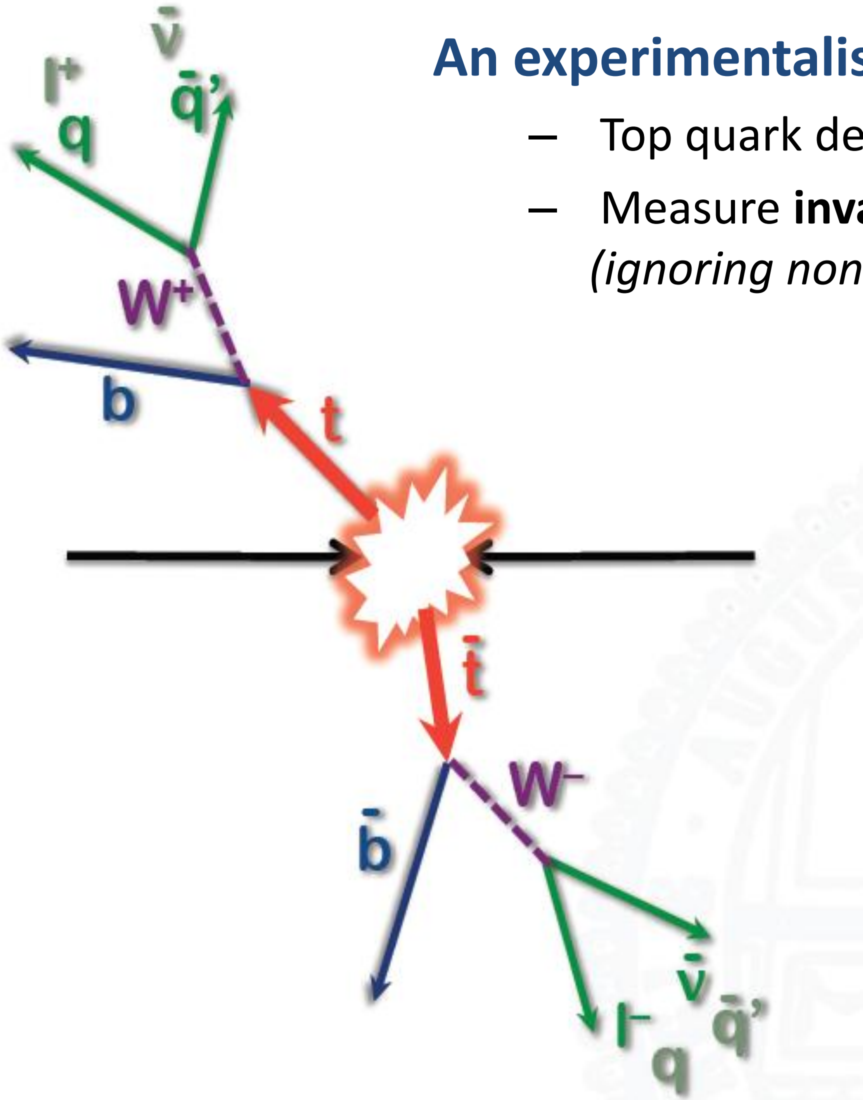
Martijn Mulders (CERN) *on behalf of the ATLAS, CMS, CDF and DØ collaborations*

Outline

- Top mass – an experimentalist’s definition
- Methods and results at Tevatron and LHC
- Interpretation and outstanding issues
- Points for discussion

Disclaimer: this overview is far from complete! Focus more on LHC than Tevatron

Measuring the Top Mass:



An experimentalist's definition

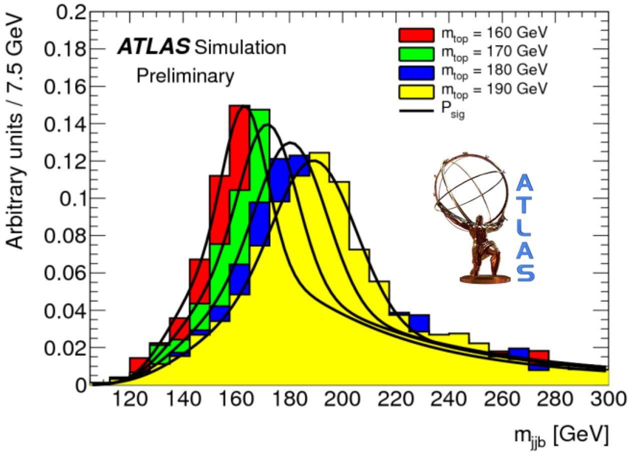
- Top quark decays before hadronization
- Measure **invariant mass** of decay products *(ignoring non-perturbative QCD effects … for now)*

Basic Methods

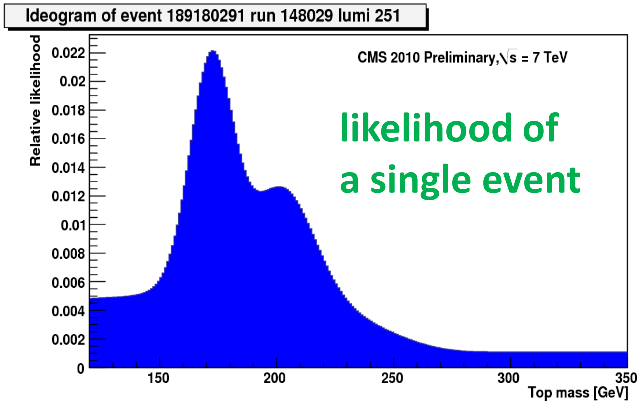
- Full reconstruction of invariant mass → most powerful method
- Partial reconstruction, fitting variable correlated to mass (eg lepton p_T end-point) → less powerful; different systematics
- Indirect, not using mass → through cross-section

Full Reconstruction: basic methods

- Template Method ("simple" and fast)
  - compare observable(s) in data with MC generated with different masses
- Matrix Element (very precise, but slow)
  - build an event likelihood based on (LO) $t\bar{t}$ 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:



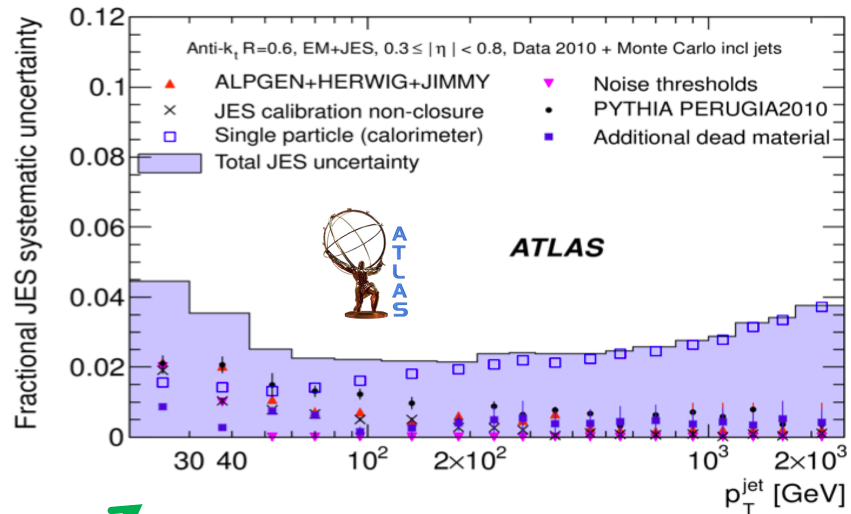
Calibrate with Monte Carlo → **Fit data and extract m_{top}^{MC}**

Jets and Jet Energy Scale (JES)

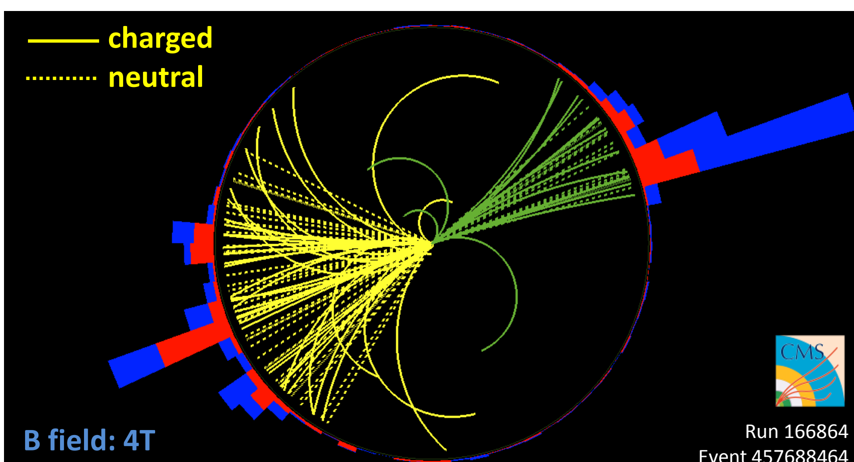
- CDF: iterative cone, ΔR=0.4
- D0: iterative cone, ΔR=0.5
- ATLAS: anti-kT clustering, dR=0.4
  arXiv:1112.6426 submitted to EJPC
- CMS: anti-kT clustering, dR=0.5
  JINST **6** P11002 and *JINST* **6** P09001

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

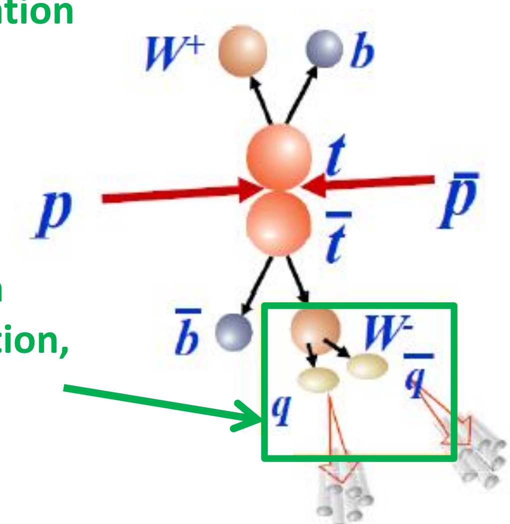
detailed work LHC experiments on jet calibration



***a-priori* JES calibration typically ~2-3 %**



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



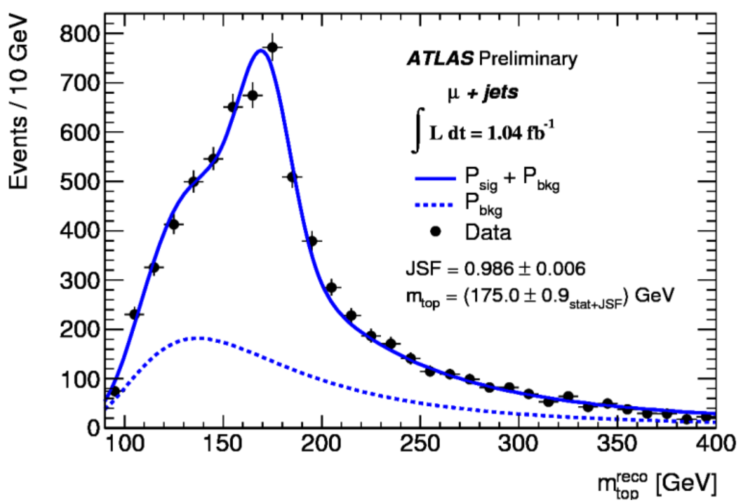
Top Mass results from Tevatron and LHC

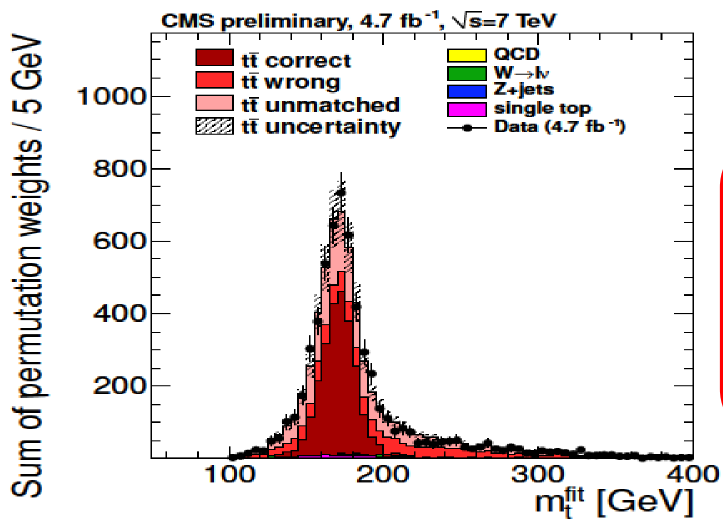
Selection of the most recent results…

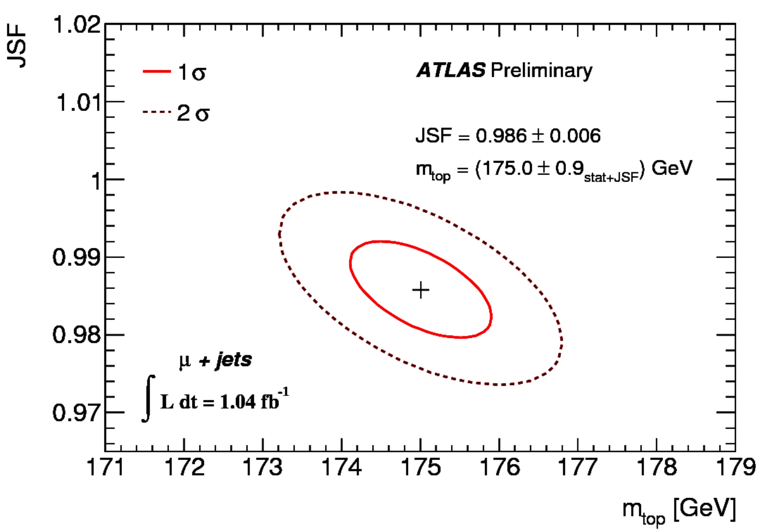
Lepton+jets

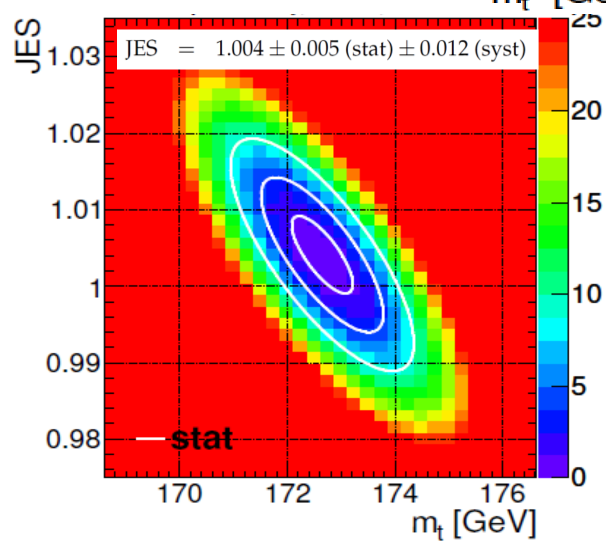
ATLAS: 2D Template fit as function of JES factor and top mass

CMS: kinematic fit + Ideogram-like method → Combine event-per-event likelihood









Results

ATLAS

174.4 ± 0.6 (stat+JES) ± 2.3 (syst) GeV

CMS

172.64 ± 0.57 (stat+JES) ± 1.18 (syst) GeV

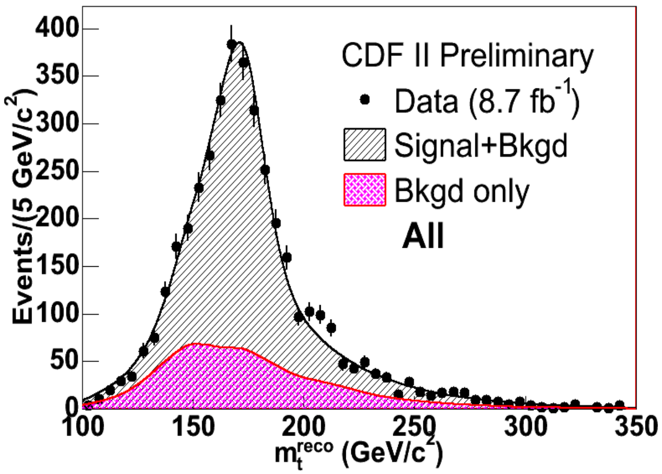
Note: Some systematics are still being evaluated by CMS (expected to be in $\%m_{top}$: underlying event ~0.1%, color reconnection~0.4%)

Both use mW for in-situ calibration of light-quark JES

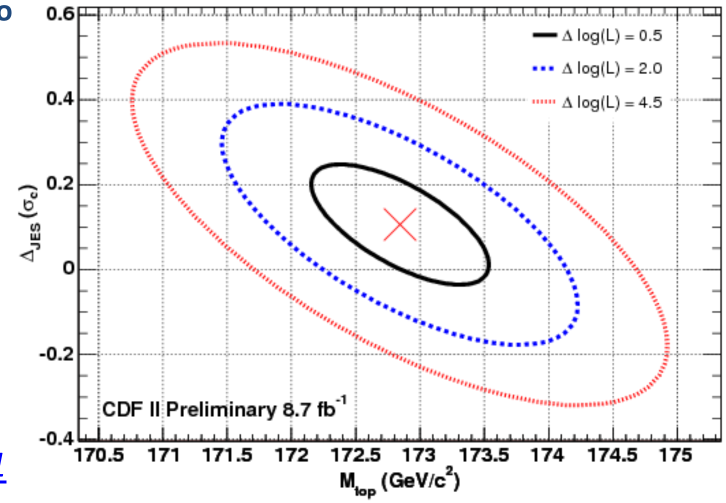
Lepton+jets

CDF: 3D Kernel Density Estimator of m_{jj} and 2 m_{reco} per event as function of JES factor and top mass

Full CDF Run II data set



ΔJES = 0.11 ± 0.15 *σ JES*



CDF Conf Note 10761

The most precise single-channel, single-experiment measurement

Most precise l+jets measurements per experiment

	lumi (fb^{-1})	comment	method	JES fit?	Mt ±(stat) ±(syst) GeV	%
CDF	8.7	Conf note 10761	Template	Yes	172.85 ± 0.71 ± **0.84**	**0.6**
D0	3.6	PRD 84, 032004 (2011)	Matrix El.	Yes	174.94 ± 1.14 ± 1.04	0.9
ATLAS	1.0	submitted to EPJC	Template	Yes	174.50 ± **0.6** ± 2.3	1.4
CMS	4.7	only μ+jets	Ideogram	Yes	172.64 ± **0.57** ± 1.18	**0.8**

Lepton+jets systematics

CDF II Preliminary 8.7 fb^{-1}

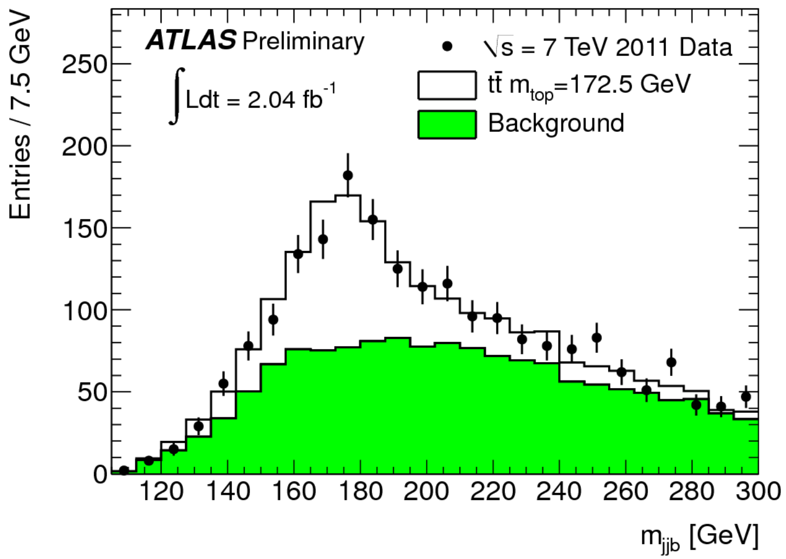
Systematic	GeV/c^2
Residual JES	0.52
Generator	0.56
Next Leading Order	0.09
PDFs	0.08
b jet energy	0.10
b tagging efficiency	0.03
Background shape	0.20
gg fraction	0.03
Radiation	0.06
MC statistics	0.05
Lepton energy	0.03
MHI	0.07
Color Reconnection	0.21
Total systematic	0.84

CMS Preliminary (μ+jets) 4.7 fb^{-1}

Systematic	GeV/c2
Residual JES	0.23
Factorization Scales	0.76
ME-PS matching threshold	0.25
PDFs	0.05
b jet energy	0.66
b tagging efficiency	0.17
Background	0.09
Missing transverse energy	0.08
Jet energy resolution	0.21
MC statistics	0.15
Pile-up	0.38
MC generator tune	to be added
Color Reconnection	to be added
Total systematic	1.18

Fully Hadronic channel

NEW



A Challenge…!

- Large QCD multi-jets background
- Require 6 jets, 2 b-tags, small MET, two jet pairs compatible with W-mass hypothesis
- Background modeled from data with event mixing technique
- Template method
- Dominant uncertainty: Jet Energy Scale (not fitted in-situ)

ATLAS-CONF-2012-030

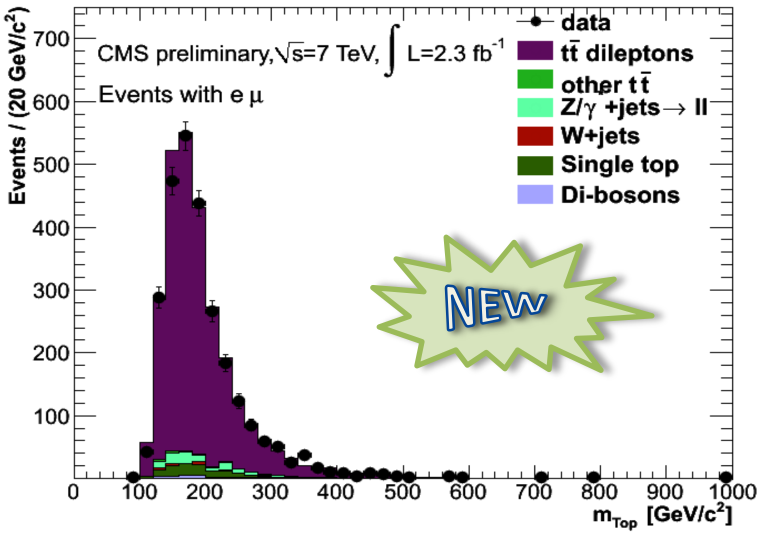
Most precise all-hadronic measurements per experiment

	lumi (fb^{-1})	comment	method	JES fit?	Mt ±(stat) ±(syst) GeV	%
CDF	5.8	CONF note 10456	Template	**YES**	172.5 ± **1.7 ± 1.1**	**1.2**
ATLAS	2.0	ATLAS-CONF-2012-030	Template	**No**	174.9 ± 2.1 ± 3.8	2.5

Dilepton

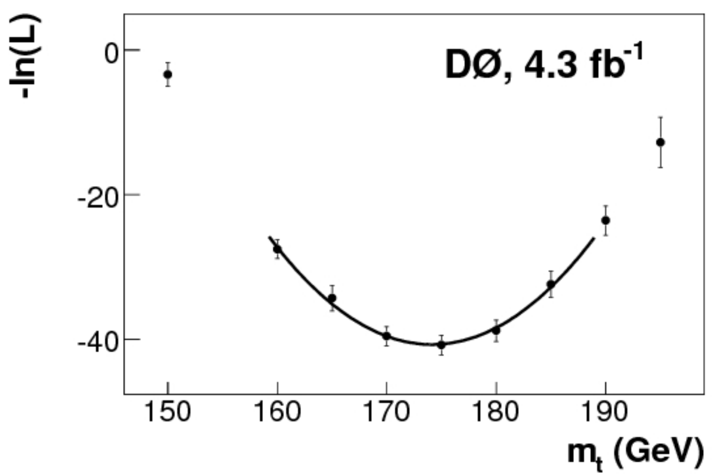
CMS: KINb Method

- Up to 8 solutions per event, pick most likely one, do Template Fit



D0: Neutrino weighting technique

- Use JES calibration obtained from l+jets events



Submitted to PRL, arXiv 1201.5172

Most precise di-lepton measurement per experiment

	lumi (fb^{-1})	comment	method	JES fit?	Mt ±(stat) ±(syst) GeV	%
CDF	2.0	Conf note 10635	Dalitz-Goldstein	From l+jets	172.3 ± 3.4 ± 2.1	2.3
D0	5.4	Submitted to PRL	νWeight.	**From l+jets**	174.0 ± 2.4 ± **1.4**	**1.6**
CMS	2.3	TOP-11-016	KINb	**No**	173.3 ± **1.2** ± 2.6	**1.7**

Alternative Methods

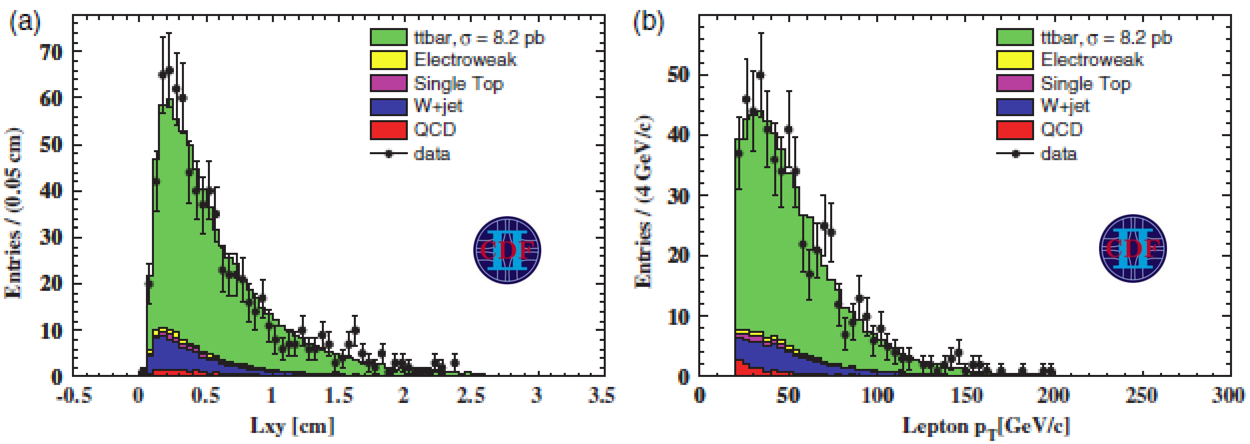
Partial Mass Reconstruction (no jets – tracking only)

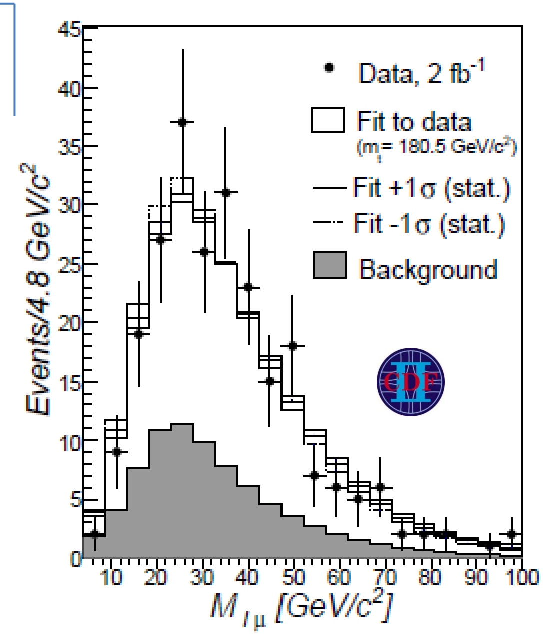
(-) a considerable loss in (statistical) sensitivity

(+) different systematics (?) → can become interesting with large LHC data sets…

$$170.7 \pm 6.3(\mathrm{stat}) \pm 2.6(\mathrm{syst})\ \mathrm{GeV}$$

$$m_t = 180.5 \pm 12.0(\mathrm{stat.}) \pm 3.6(\mathrm{syst.})\ \mathrm{GeV}$$





transverse decay length of b-hadrons from top decay

lepton p_T (endpoint)

not Lorentz-invariant ; sensitive to PDFs and b-jet fragmentation

invariant mass of lepton and soft muon in b-jet

NEW!!!

Top-Antitop Mass Difference

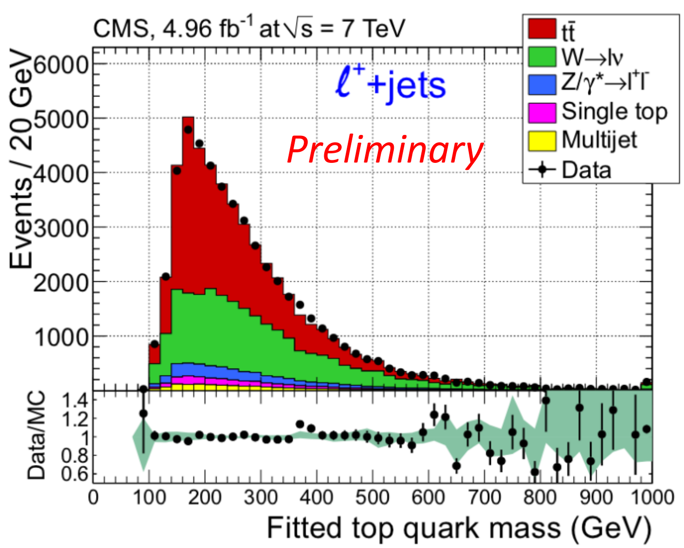
CMS-TOP-11-019, to be submitted for publication soon

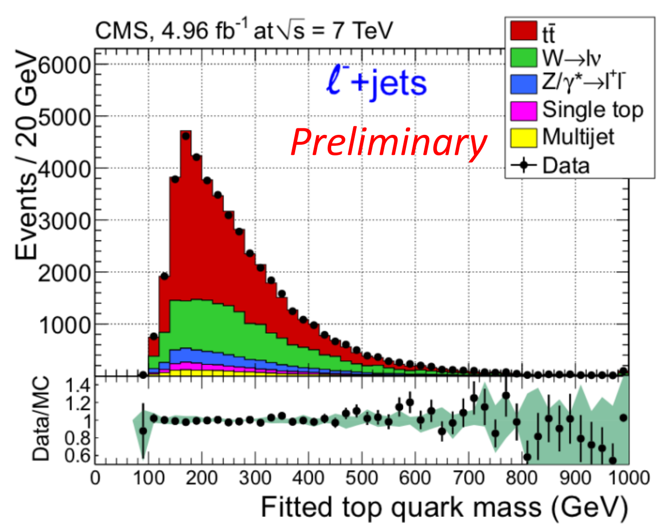
Test of CPT invariance

- Kinematic Fit w/o equal-mass constraint + Ideogram likelihood
- Calibrate with MC simulation
- Split samples using lepton charge
- Measure top and antitop masses independently and take difference:

$$\Delta m_{\mathrm{t}} = -0.44 \pm 0.46\ (\mathrm{stat.}) \pm 0.27\ (\mathrm{syst.})\ \mathrm{GeV}$$

Source	Estimated effect (GeV)
Jet energy scale	$0.04 \pm \mathbf{0.08}$
Jet energy resolution	$0.04 \pm \mathbf{0.06}$
b vs. $\bar{\mathrm{b}}$ jet response	$\mathbf{0.10} \pm 0.10$
Signal fraction	$\mathbf{0.02} \pm 0.01$
Difference in W^+/W^- production	$\mathbf{0.014} \pm 0.002$
Background composition	$\mathbf{0.09} \pm 0.07$
Pileup	$\mathbf{0.10} \pm 0.05$
b-tagging efficiency	$\mathbf{0.03} \pm 0.02$
b vs. $\bar{\mathrm{b}}$ tagging efficiency	$\mathbf{0.08} \pm 0.03$
Method calibration	$0.11 \pm \mathbf{0.14}$
Parton distribution functions	**0.088**
Total	0.27



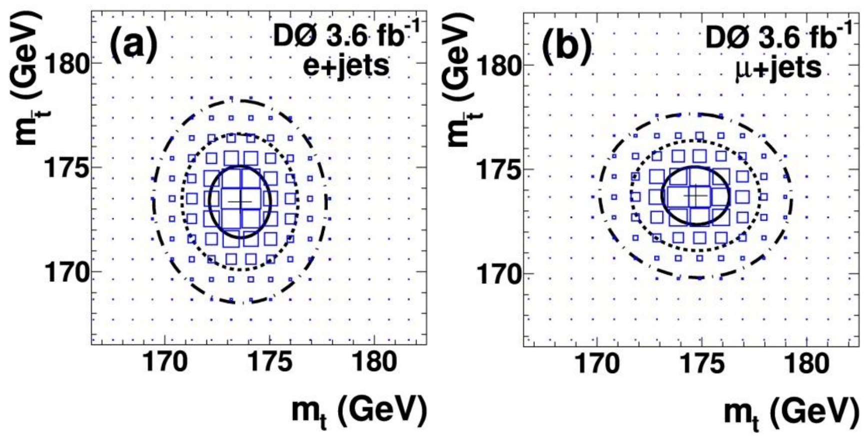


~50k $t\bar{t}$ events!

Top-Antitop Mass Difference

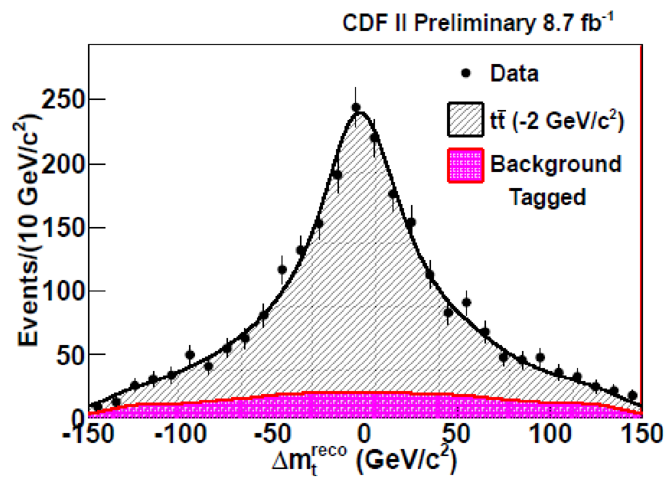
D0: Matrix Element Method

- Independent measurement of top and antitop mass:



CDF: 2D Kernel density estimator

- Measurement of difference with condition that <m> = 172.5 GeV



Most precise measurement per experiment

	lumi (fb^{-1})	comment	method	JES fit?	Mt ±(stat) ±(syst) GeV	%
CDF	8.7	Conf note 10777	Template	From l+jets	-1.95 ± 1.11 ± 0.59	0.7
D0	3.6	PRD 84, 052005	Matrix El.	**From l+jets**	0.8 ± 1.8 ± 0.5	1.1
CMS	4.9	TOP-11-019	Ideogram	**No**	-0.44 ± **0.46 ± 0.27**	**0.3**

UNOFFICIAL

Approximate combination of preliminary results

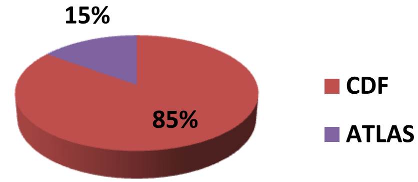
Disclaimer: private combination of results in previous slides,

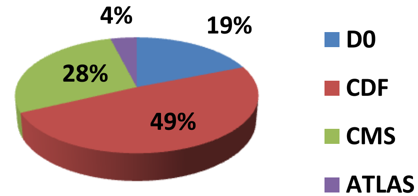
using Tevatron systematics categories and BLUE to take into account correlations (checked that results are stable under variations 0.5 – 1.0 for main correlated uncertainties b-JES and Signal

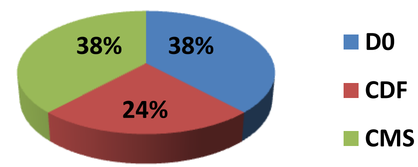
Top Mass

- All hadronic ….. 172.8 ± 1.9 GeV 60% fit prob
- Lepton+jets ….. 173.2 ± 0.9 GeV 40% fit prob
- Di-lepton* …….. 173.3 ± 2.0 GeV 93% fit prob

without first 1 fb^{-1} of DØ data



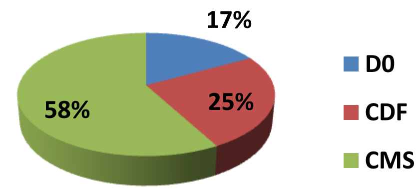




Top - antitop mass difference

- Lepton+jets**….. -0.61 ± 0.31 GeV

***assuming uncorrelated uncertainties*



TOPLHC WG has started preparations for proper LHC combination

… an LHC-Tevatron combination would be a logical next step!

… and its interpretation

Mass definition, mass from cross-section

Definition of Top Mass

Top quark is a colored object; mass definition depends on renormalization scheme

m_{top}^{MC} ≈ $m_{top}^{POLE} \pm \Lambda_{QCD}$ ≈ $m_{top}^{\overline{MS}}$ + 10 GeV

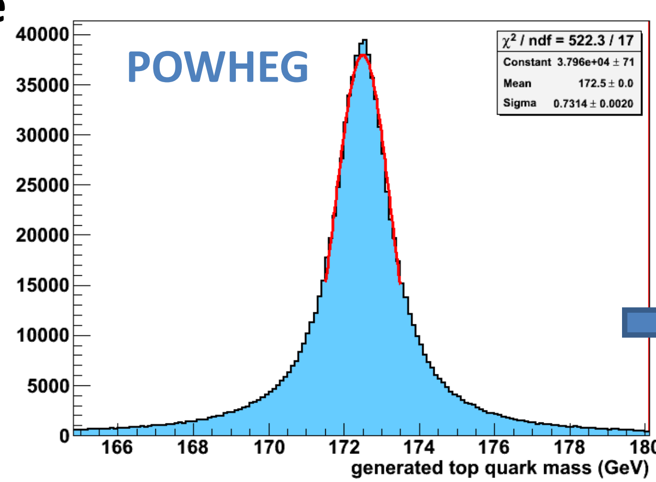
= What we measure

Needed for EWK fit

Theoretical interpretation…

m_{top}^{MC}

172.5 GeV



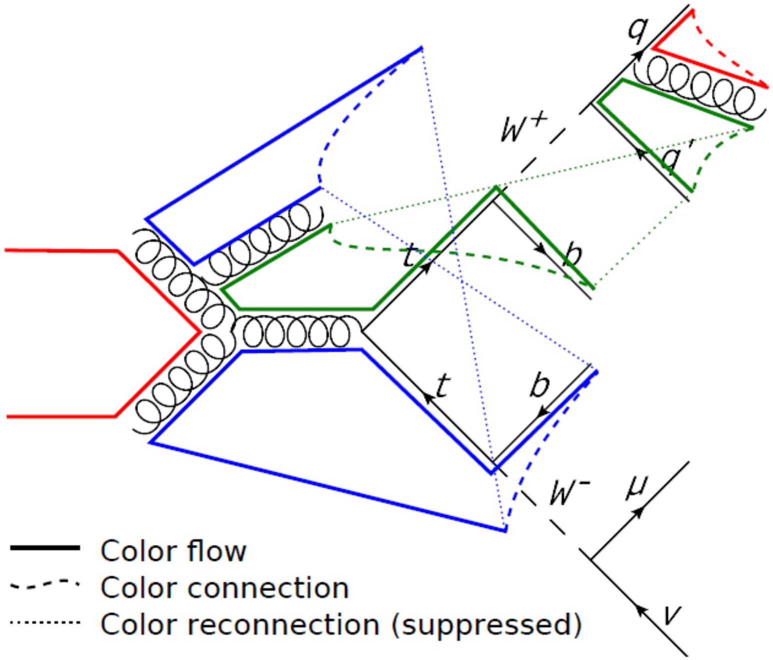
= invariant mass of decay Products in event ?

= mean of generated masses

<m> = 172.5 +- 0.1 GeV

Non-perturbative QCD effects

- Top and anti-top are color-connected to the rest of the event -- how does this alter the “invariant mass” of the decay?
- At LHC we use PYTHIA 6.4 which includes new color reconnection models – compare tuned “CR on” to tuned “CR off” to estimate systematic uncertainty. Latest D0 and CDF estimates: 0.2 – 0.3 GeV. ATLAS: 0.55 GeV CMS: comparison of Perugia2011 and 2011noCR(*) in progress

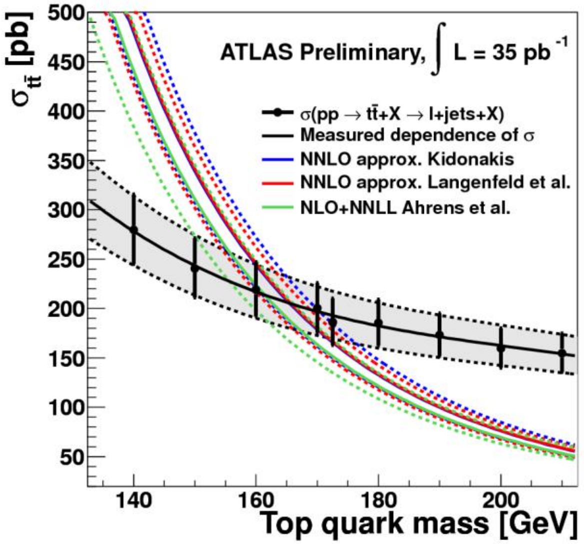


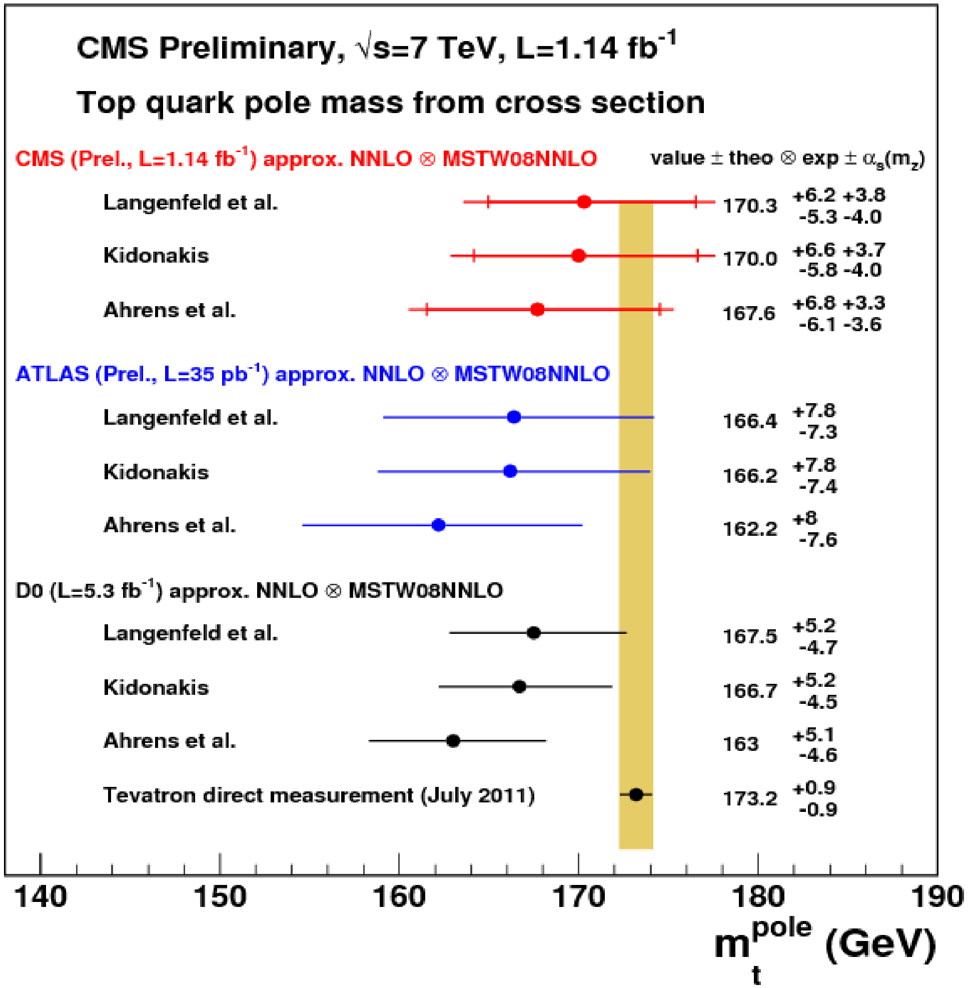
Is this sufficient to cover systematic effects of “color flow” on the invariant mass of the top decays ??

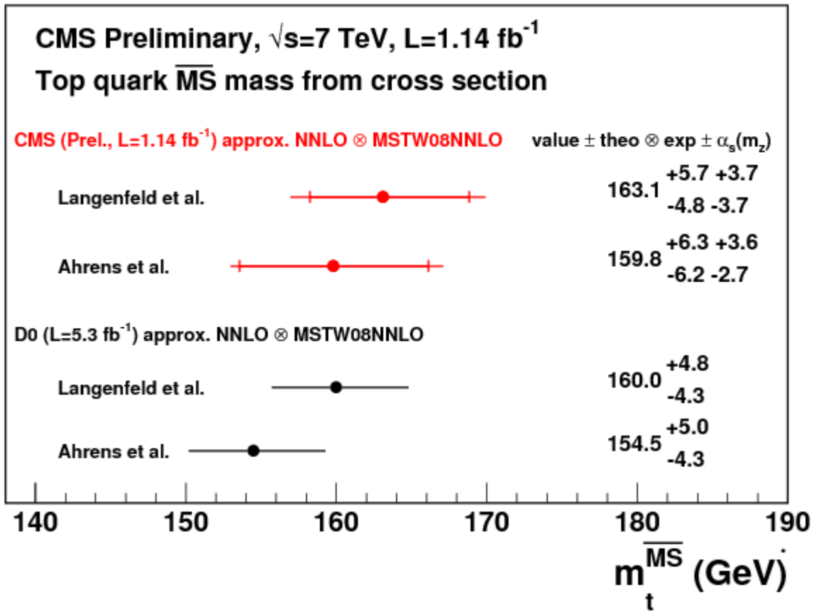
* “Tuning MC Generators: The Perugia Tunes” - PRD82 (2010) 074018

Mass from cross-section

- Measure $\sigma_{t\bar{t}}$ for different assumptions of m_t
- Compare to theoretical prediction of $\sigma_{t\bar{t}}(m_t^{pole})$







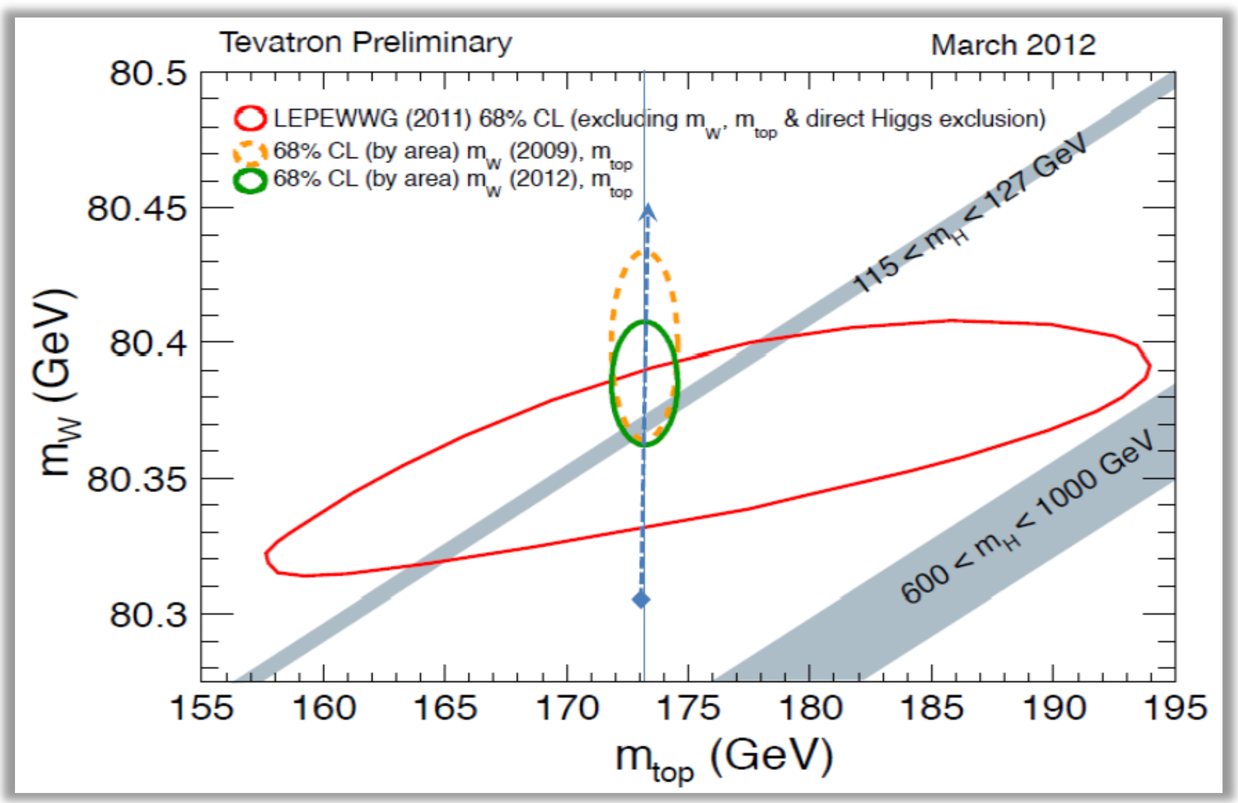
Correlation with W mass

- By using m_W for *in-situ* constraint for JES, m_{top} becomes correlated with m_W (and m_Z ..!). Should this be taken into account in EWK fit?
- No! m_W is known so precisely that it doesn't matter → propagated to m_{top} , the effect is 0.03 GeV, a factor 30 below current precision

Orientation of ellips:

With correlation

Without correlation



Summary

- Rich legacy of > 15 years of top mass results and methods from the Tevatron!

- First *independent* measurements from ATLAS and CMS show beautiful agreement with Tevatron results.

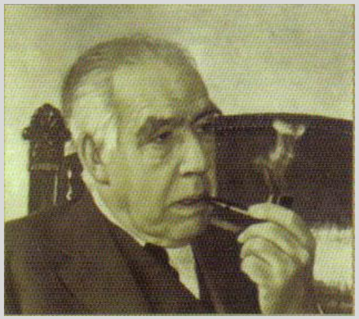
- LHC experiments are quickly improving precision, with large datasets, powerful detectors, excellent simulations.

- *Understanding systematic uncertainties (experimental and theoretical) and correlations will be the key to progress*

- Time for the LHC and Tevatron working groups to combine forces and prepare a single top mass world average!

Questions for Discussion

1. Huge samples of top quarks at the LHC allow measurement of m_{top} vs other variables… what would be interesting variables to use?
   – To get a handle on systematic effects (QCD or other…) ?
   – To be sensitive to effects of new physics ?
2. How well do we know the differences between m_{top}^{pole} , m_{top}^{MC} , and m_{top}^{MS}… and what are the prospects for improvement?
3. How much do the color connections of the top quarks with the rest of the event alter the mass? How well is this modeled? How can we estimate the uncertainty?
4. In the top-antitop mass difference measurement most systematic uncertainties cancel to a large extent. But would it be possible that non-perturbative QCD effects are different for top and antitop, given that the initial state is proton-proton?
5. Open question: what would be an appropriate way for CMS and ATLAS to estimate and harmonize the signal modeling systematics ?



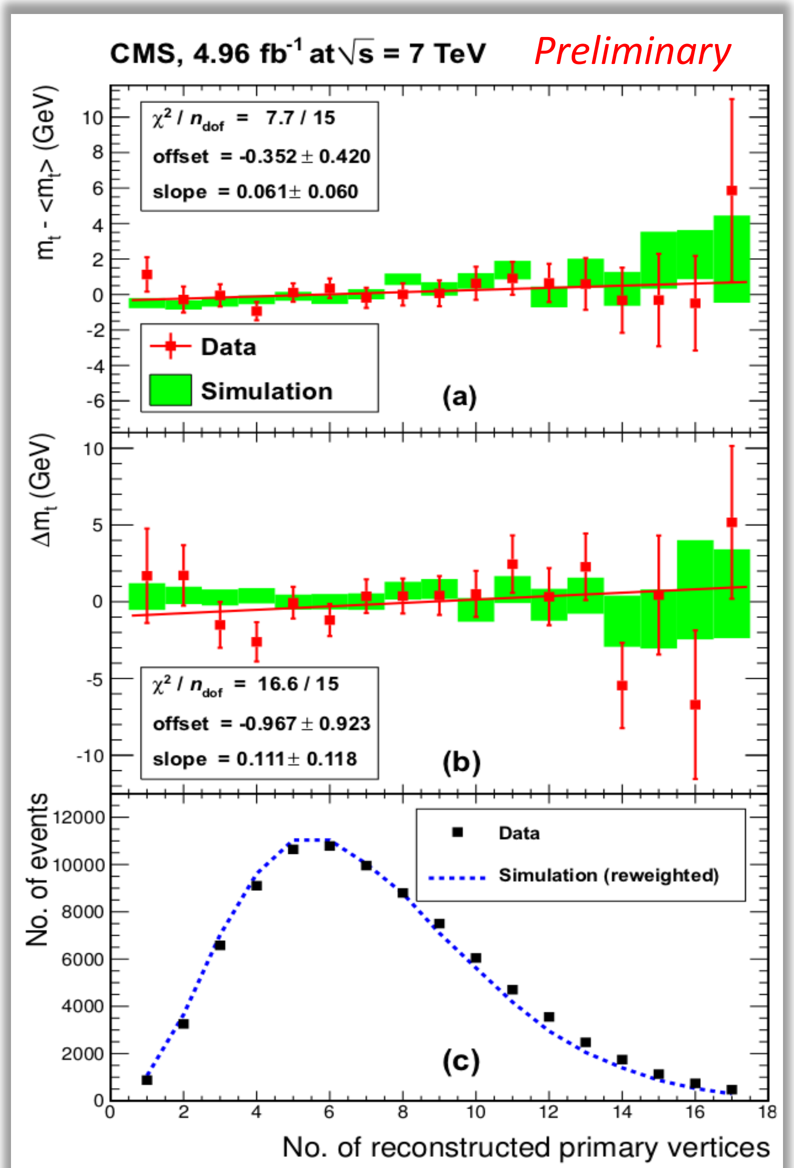
BACKUP slides

References

More details and updates:

- 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

Effect of Pile-up on the top mass



CMS-PAS-TOP-11-019