**Rencontres du Vietnam 2014: Physics at LHC and beyond**
**Quy Nhon, 12th August 2014**

# Status of and prospects for top quark mass measurements

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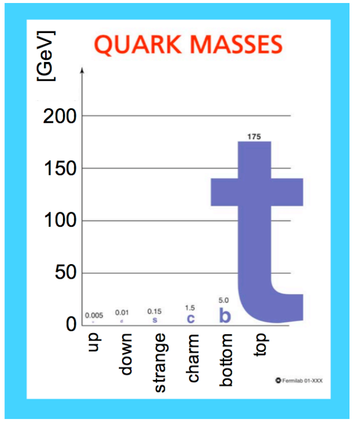
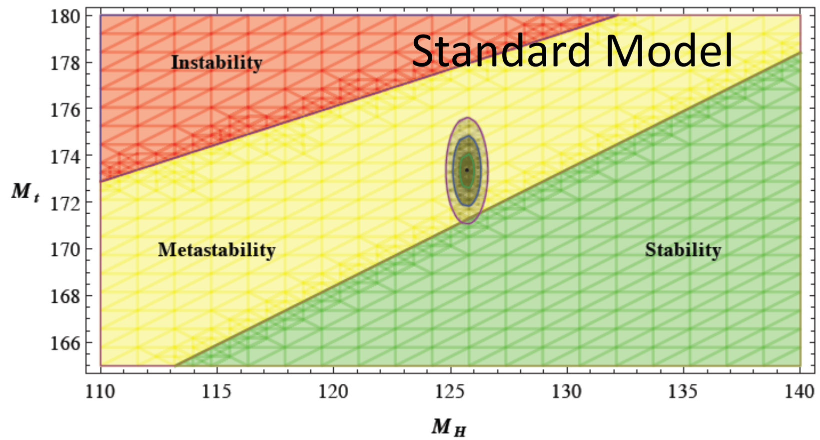
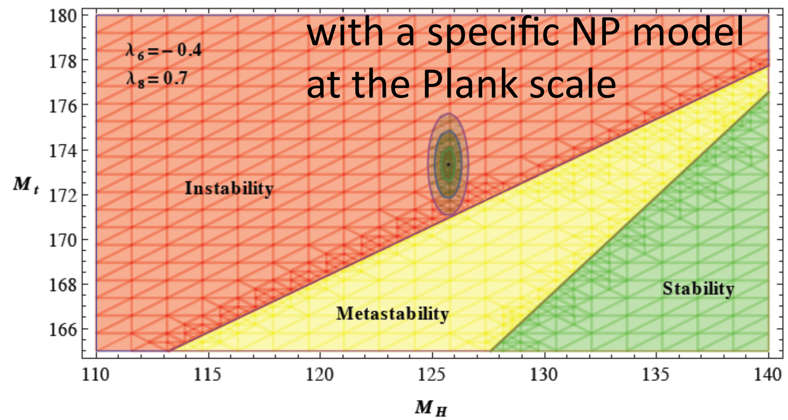
Disclaimer: this is NOT a review talk, the aim is to discuss experimental methods and perspectives. A complete accounting of most recent top mass results is given at http://indico.ific.uv.es/indico/sessionDisplay.py?sessionId=30&confId=2025#20140703

# Its highness, the top quark



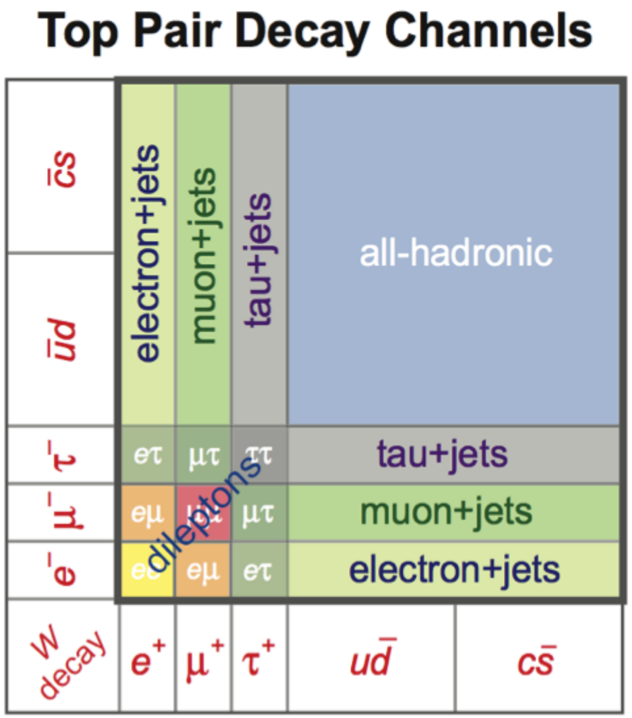

- Because of the non-decoupling properties of electroweak interactions (Veltman, 1977) **the top quark** gives large contributions to pure EWK radiative corrections (**≈$G_F m_t^2$**) hence it **is "the quark" for EWK precision physics**
- The fate of our universe, i.e. the stability of the EWK vacuum (Degrassi et al., arXiv:1205.6497), might not depend (only) on its mass, nevertheless the top mass value opens a window to new physics up to the Planck scale (Branchina et al., arXiv:1407.4112)



# Quick reminder of top properties

- Very high mass → very short lifetime: bound states are not formed, almost a free quark $\tau_{top} \simeq 0.4 \times 10^{-24} s$
- Hierarchy of CKM elements → only decays to a b quark and a W boson are relevant for this discussion, the decay mode is $t \rightarrow Wb$
- Dominant production mode at colliders in top pairs, events usually classified and selected according to their W-pair decays
- **Top pair decay channels** have different rates, different backgrounds, different amount of missing energy (ν) providing useful consistency tests



# Methods for top mass measurement (1)

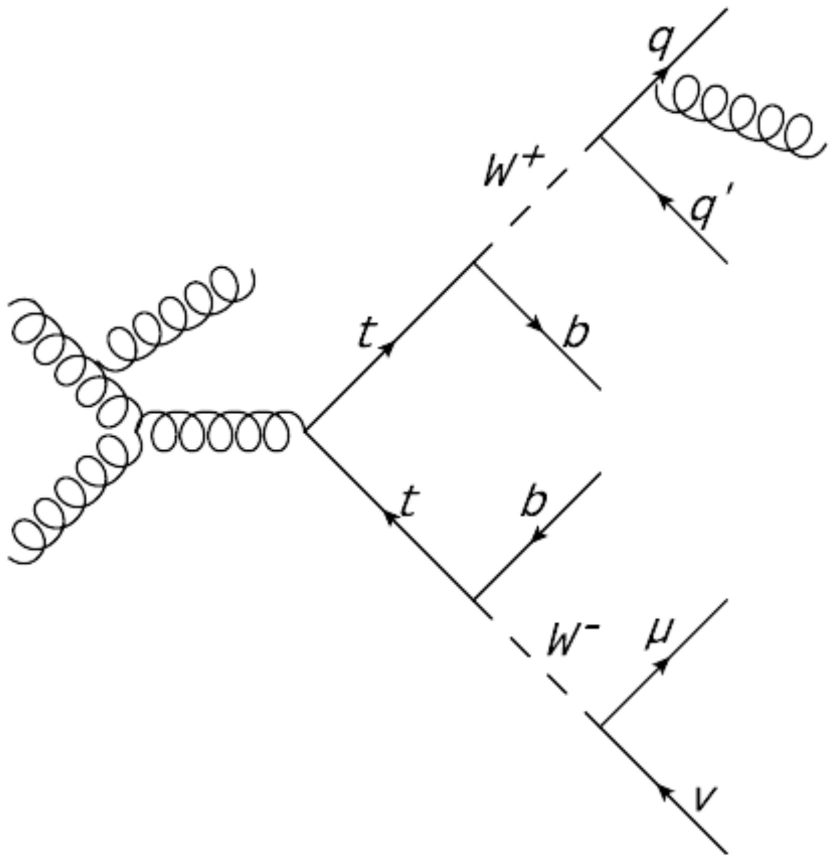
- *Standard methods* at hadron colliders: measure the top mass from the decay products in a specific **top pair decay channel**
  - from the simplest versions: measure invariant mass of, e.g. three jets in lepton+jets events
  - to the more sophisticated versions: use of the full event information to gain sensitivity, e.g. Matrix Element method
- The *standard methods* are the most precise with the current statistics
  - they are used in current LHC, Tevatron, World combinations
  - the top mass in EWK fits comes from these methods
- Crucial points for the *standard methods*
  - accurate calibration of physics objects, in particular Jet Energy Scale: use of kinematic fits for JES calibration in situ, e.g. use the W mass to constraint light quarks **jet energy scale (JES)** from two-jet invariant mass
  - associate measured objects (jets, leptons, missing $E_T$) to top candidate: e.g. use b-tagging to choose the right b-jet for the 3-jet combination

A couple of examples from the lepton+jets channel

# Event selection: lepton+jets final state

[example from CMS, TOP-14-001 / JHEP 12 (2012) 105 ]

- Trigger for isolated muon or electron + jets (pT > 33 GeV)
- Exactly 1 isolated lepton with $p_T$ >30 GeV, $|\eta|<2.1$ (veto additional isolated e, μ)
- ≥ 4 "particle flow" jets (anti-kt , R = 0.5) with $p_T$ >30GeV, $|\eta|<2.4$
- 2 jets b-tagged among the 4 leading jets
- Composition:
  - 94% $\bar{t}t$, 2% W+jets, 3% single-top, 1% other
- 108000 events in 19.5 $fb^{-1}$ at 8 TeV selected

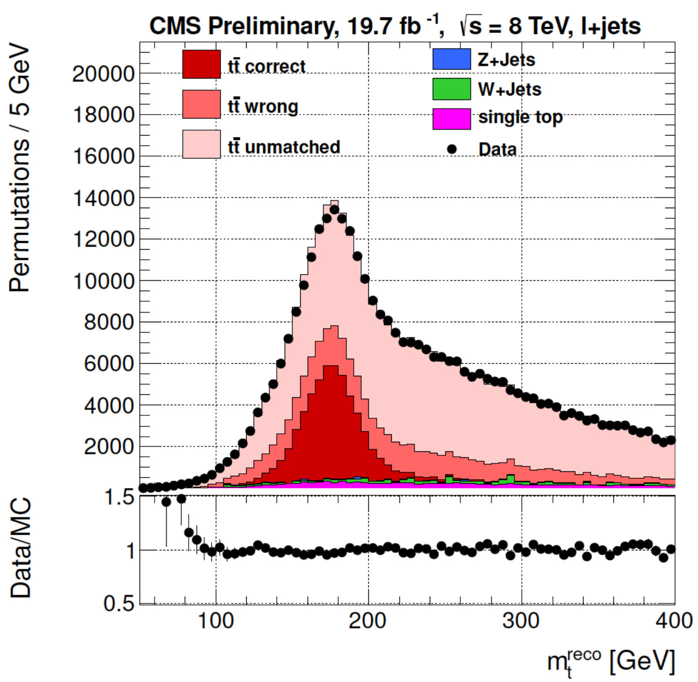



Compare with selections at Tevatron with full statistics: about 2500 events

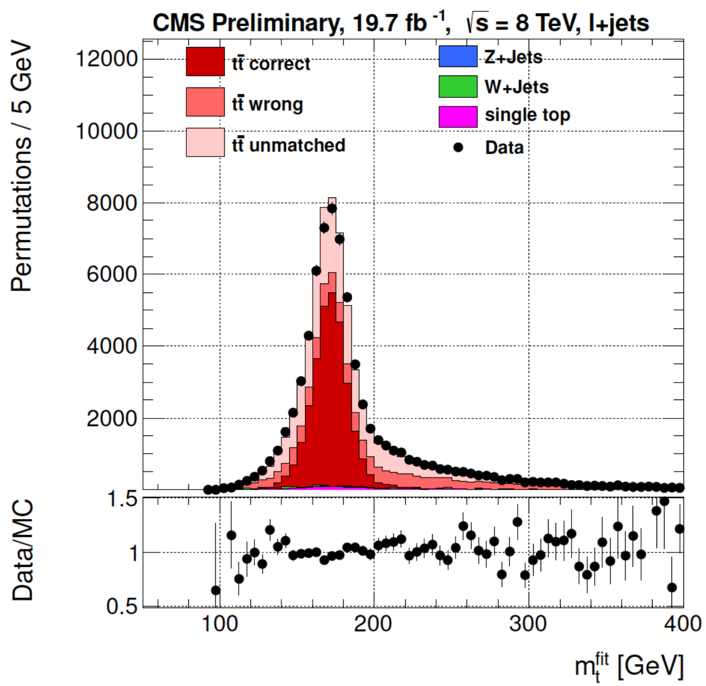
# Event reconstruction

[example from CMS, TOP-14-001 / JHEP 12 (2012) 105 ]

- Assign 4 leading jets to partons from $t\bar{t}$ decay (obey b-tag)
  - Kinematic fit with constraints: $m_W$ = 80.4 GeV, $m_t = m_{tbar}$
  - Weight each permutation by $P_{gof} = \exp-(1/2\chi^2)$, select $P_{gof} > 0.2$
- 28750 events in 19.7 $fb^{-1}$ 2012 data (94% $t\bar{t}$, 44% correct perm.)

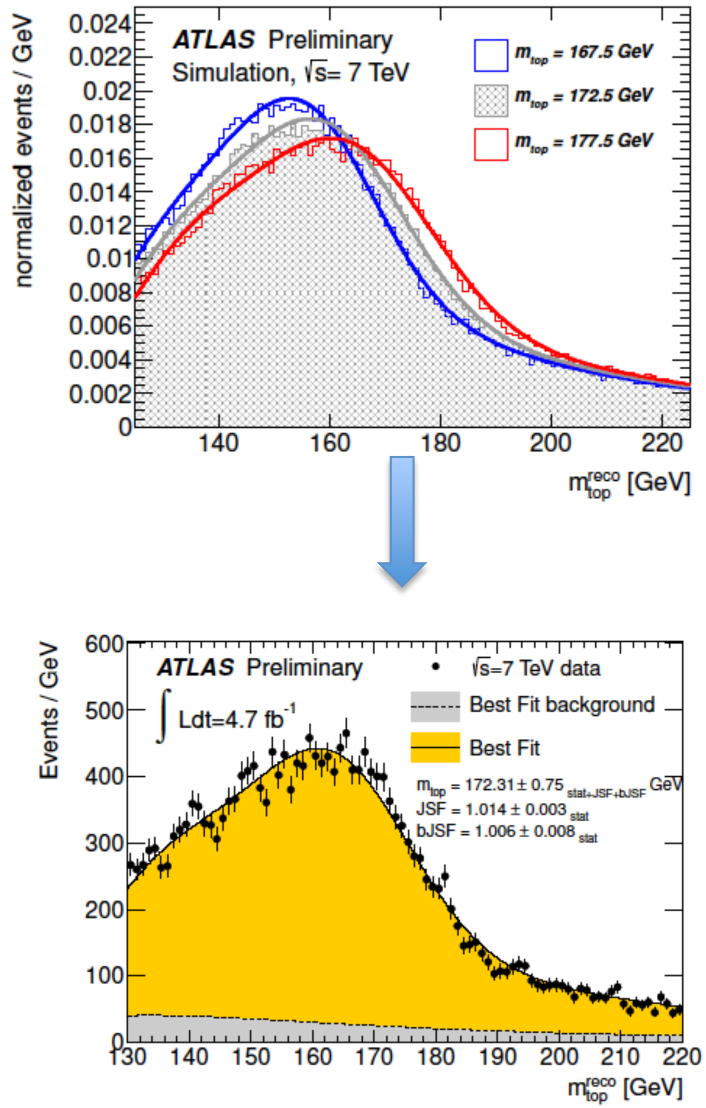



$P_{gof} > 0.2$



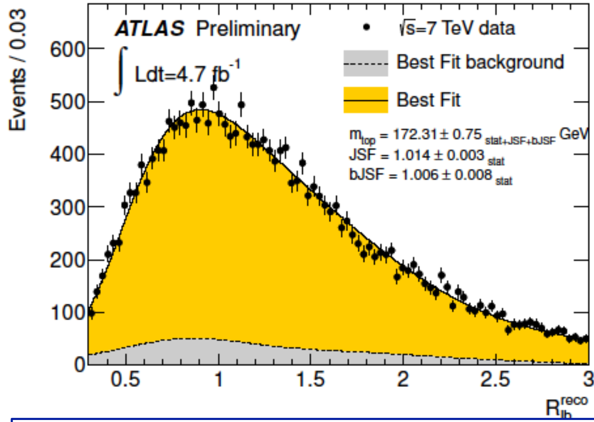
# Top mass fitting techniques
## [example from ATLAS, CONF-2013-046]

- Invariant mass distributions are distorted by
  - phase space constraints
  - detector resolution
  - wrong particle assignments to jets
  - backgrounds, pileup
  - selection cuts
- Need a MC simulation, tuned to data, to construct templates or probability densities
  - **important: at this stage the top mass definition in MC is not too relevant.**



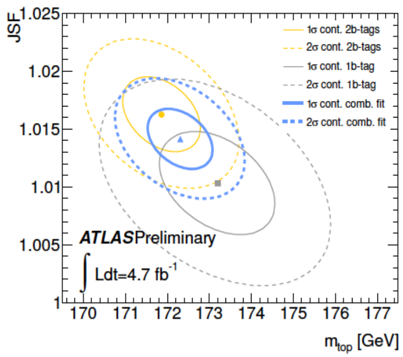
# Top mass fitting techniques and JES

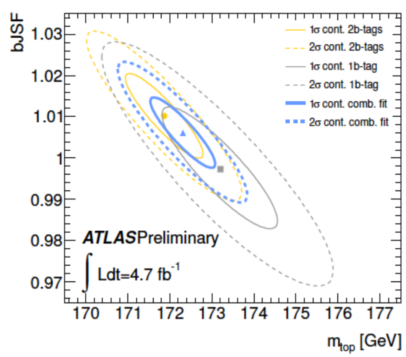
- The Jet Energy Scale is the most important source of experimental uncertainties, the W mass constraint is a powerful tool for light quark JES
- Can also find a variable sensitive to b-jet JES and constraint it in situ [ATLAS, CONF-2013-046] in this case b-tagging is used not only for jet classification, but also for JES determination
- Otherwise the simulation is used for b-jet JES, the impact of modeling assumption depends on the jet reconstruction technique




$$R_{\rm lb}^{\rm reco,2b} = \frac{p_{\rm T}^{b_{\rm had}} + p_{\rm T}^{b_{\rm lep}}}{p_{\rm T}^{W_{\rm jet_1}} + p_{\rm T}^{W_{\rm jet_2}}},$$

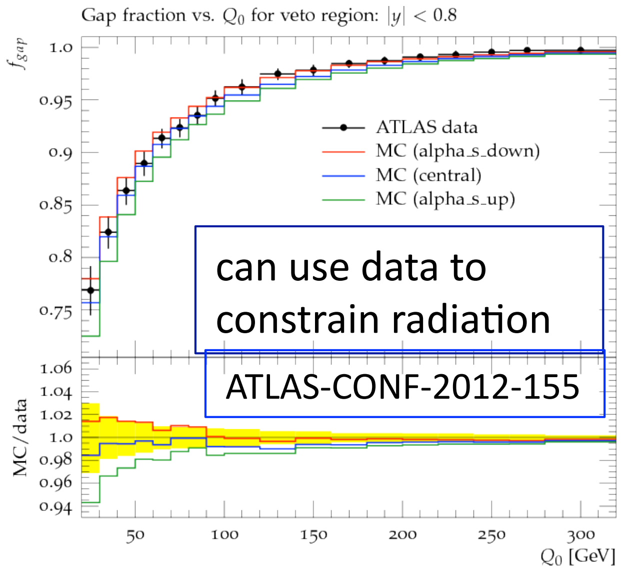
$$R_{\rm lb}^{\rm reco,1b} = \frac{p_{\rm T}^{b_{\rm tag}}}{(p_{\rm T}^{W_{\rm jet_1}} + p_{\rm T}^{W_{\rm jet_2}})/2}$$

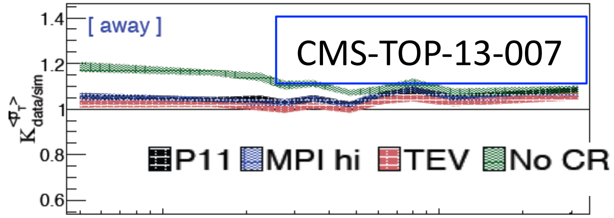


# Main sources of systematic uncertainties

- Jet Energy Scale (depends on technique and jet reco, in situ statistical not included)
  - light jets, detector response [0.2-0.7 GeV]
  - b jets [0.1-0.6 GeV]
- Modeling of gluon radiation [0.3 – 0.45 GeV]
- Modeling of underlying event [0.1 – 0.2 GeV]
- Modeling of Colour Reconnection [0.2 – 0.5 GeV]
- Proton PDF [0.1 – 0.2 GeV]
- Hadronization, b-fragmentation (included also in JES) [0.3 -0.6 GeV]
- b-tagging [0.1 – 0.8 GeV]
- pileup modeling (included also in JES) (0.1-0.3 GeV)

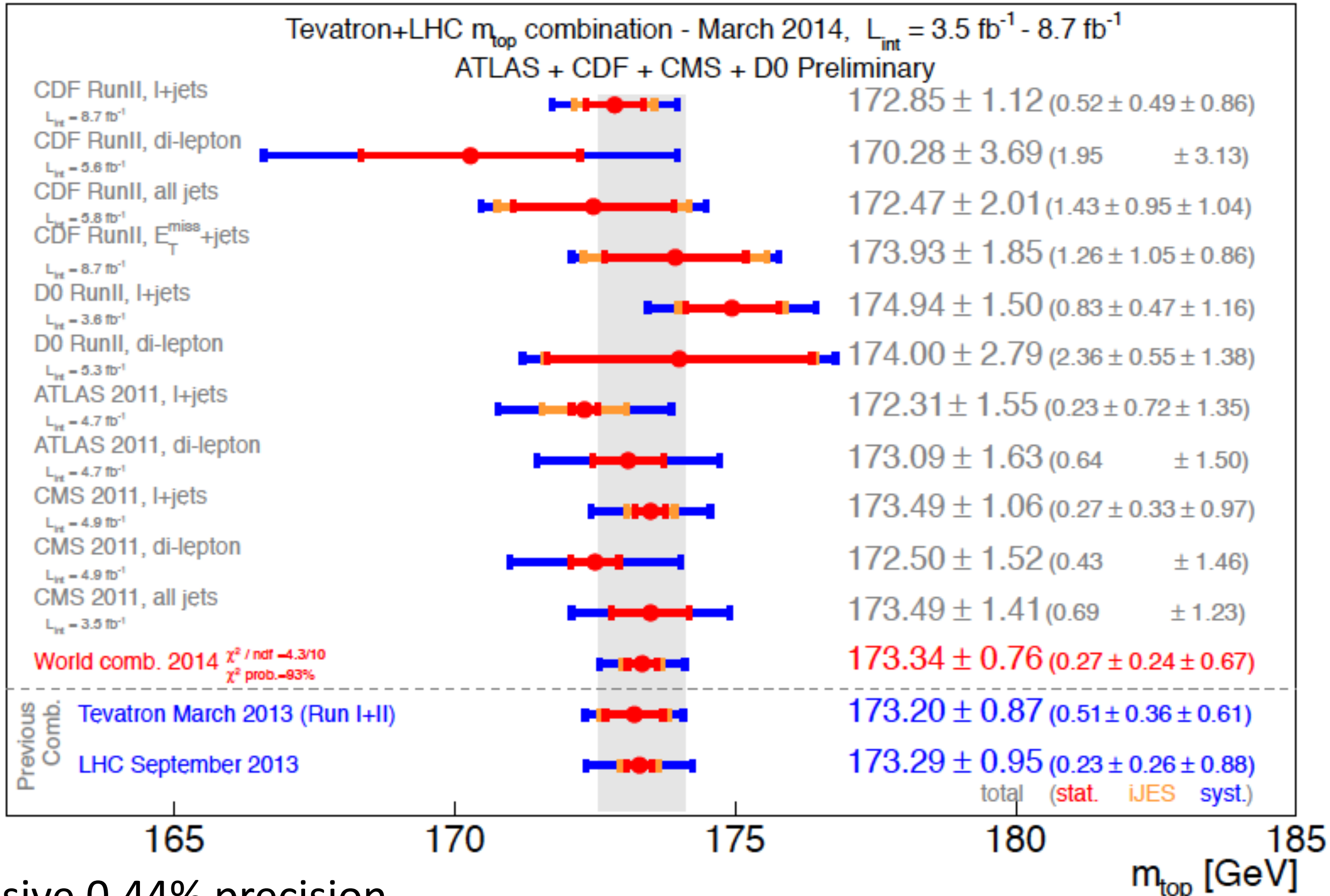



can use data to constrain generator modeling

[The numbers are ranges for illustration only, more details in specific analysis and LHC combination notes]

# World combination of $m_{top}$

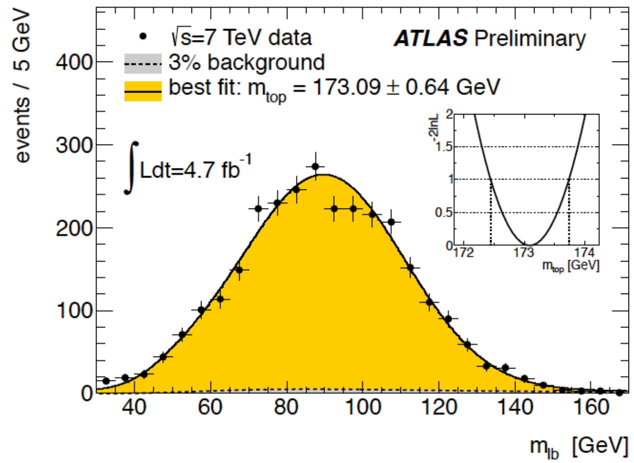



- An impressive 0.44% precision
- Some of the most precise measurements non included yet, e.g.
  - D0 full statistics, matrix element method, arXiv:1405.1756, $m_t$=174.98±0.76
  - CMS l+jets at 8 TeV, L=19.6 $fb^{-1}$ CMS-TOP-2014-001, $m_t$=172.04±0.77

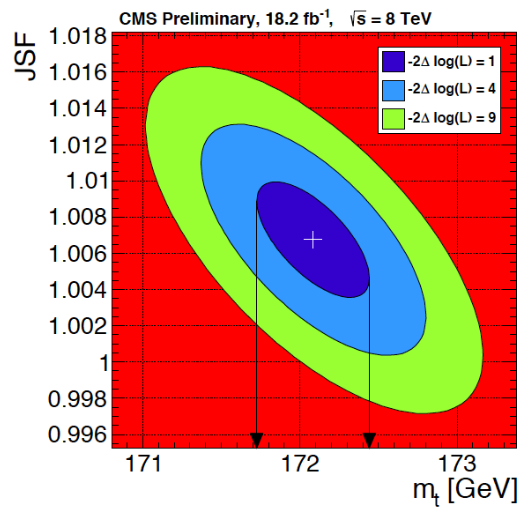
# A note on the other channels at LHC

ATLAS-CONF-2013-077

- The dilepton and all-hadronic decay channels provide and important cross check, given the difference in colour structure of the final state (next slide).
- The dilepton channel is kinematically underconstrained (2 $\nu$'s), but with low background
- The all-hadronic channel can profit of an accurate in-situ fit of the JES, already providing a result factor 2 better than Tevatron



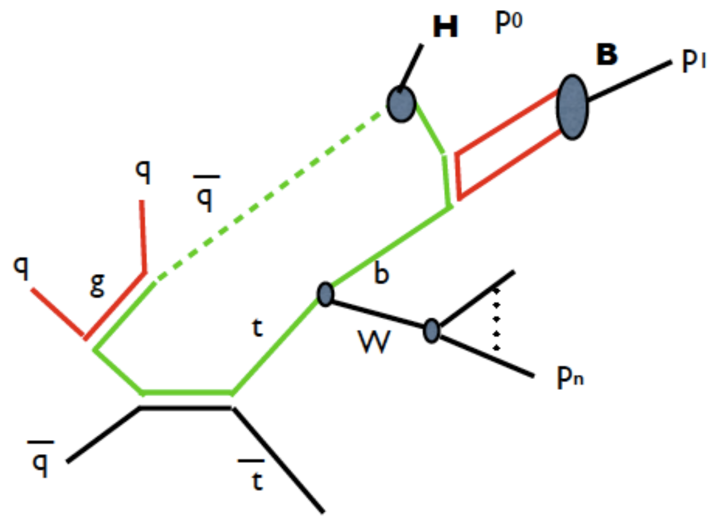

CMS-TOP-2014-002



# About measuring the top mass from its decay products

- **Top is a coloured fermion**, it decays before hadronizing, but the b quark from its decay must hadronize
  - **there is no way to assign final state particles only to the original top**, the concept is ill-defined as it is the use of a pole mass for a coloured particle
  - the effect is expected to be of the order of $\Lambda_{QCD} \approx 0.2$ GeV but the actual impact depends on the experimental method

1. **important to test variables sensitive to the final state definition**
2. **important to measure the mass with alternative techniques**

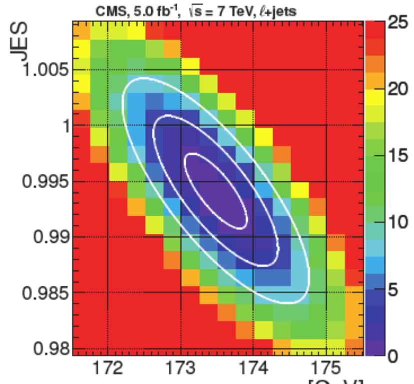



plot courtesy of Michelangelo Mangano

In prospect **1** and **2** will take advantage of the large LHC statistics

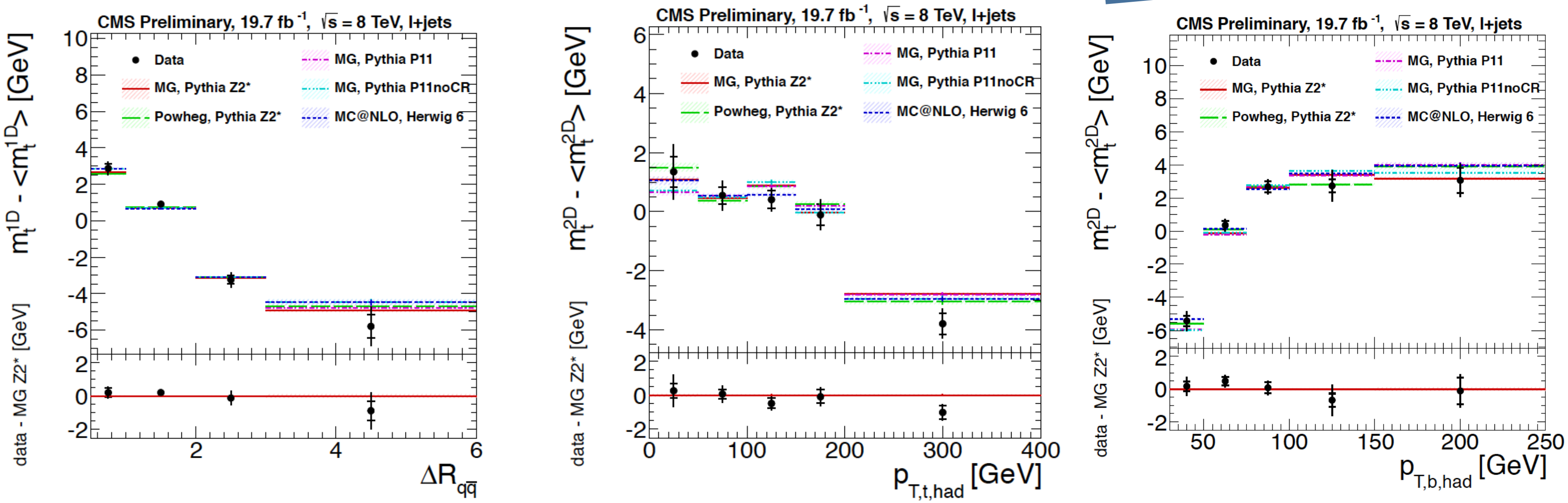
# Dependence of Top Mass observable on event kinematics

- test variables sensitive to the final state definition
  - kinematic dependence on final state properly modeled by MC? → 12 kinematic variables checked, related to Color Reconnection, ISR/FRS, b-jet kinematics
  - Good data/MC agreement rules out dramatic effects → need to pursue the study with Run 2 high statistics !!




JHEP 12 (2012) 105

CMS-TOP-12-029
CMS-TOP-14-001



# Methods for top mass measurement (2)

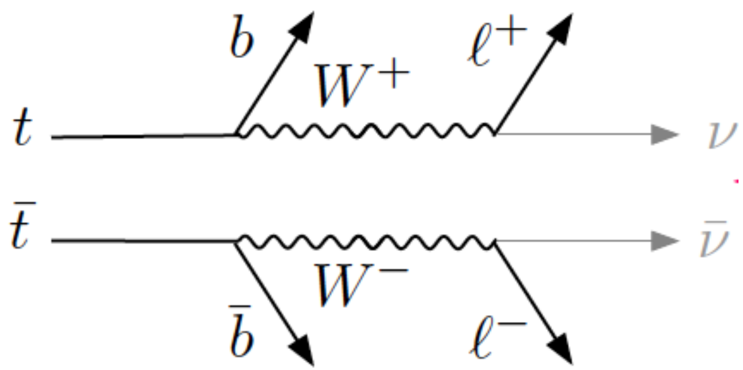
- Given the potential bias in measuring the top mass from its decay products, important to explore **alternative techniques**, e.g.
  - Measure the **decay length** (the boost) of B hadrons produced in top decays, the boost is related to the original top mass
  - Select **specific channels**, for example top with $W \rightarrow l\ \nu$ and $B \rightarrow J/\psi + X$ decays and measure the three-lepton invariant mass
  - Measure the **endpoint** of the lepton **spectrum** or other quantities in top decays
  - Measure the mass from single top events (great potential !)
- Alternative methods have typically larger statistical uncertainties, however at LHC we have large ttbar samples
  - Systematic uncertainties can be controlled with data, again large samples help.
- Another alternative: move away from properties of the decay products
  - **extract the top mass from the top cross section**

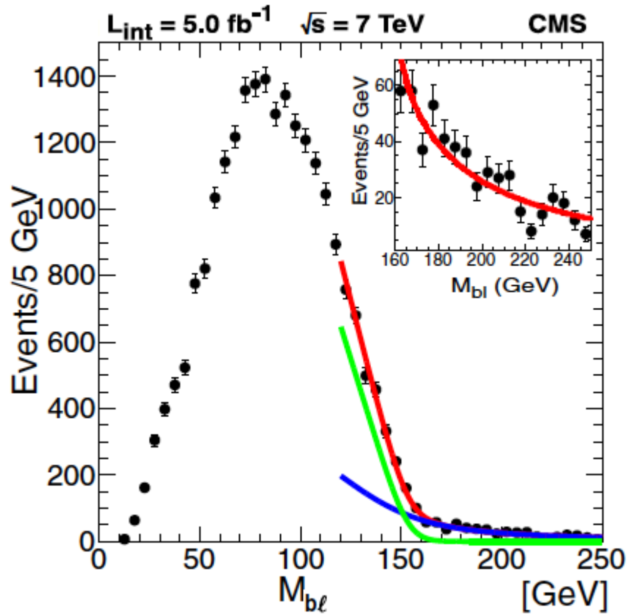
# TOP mass from alternative techniques

- Example of a technique already yielding interesting precision: Endpoint method
- The shape of the signal can be computed analytically, background data-driven
- Use of MC limited to study underlying assumption: independent decay of two tops (color connections and reconnections violate this assumption)

arXiv:1304.7498

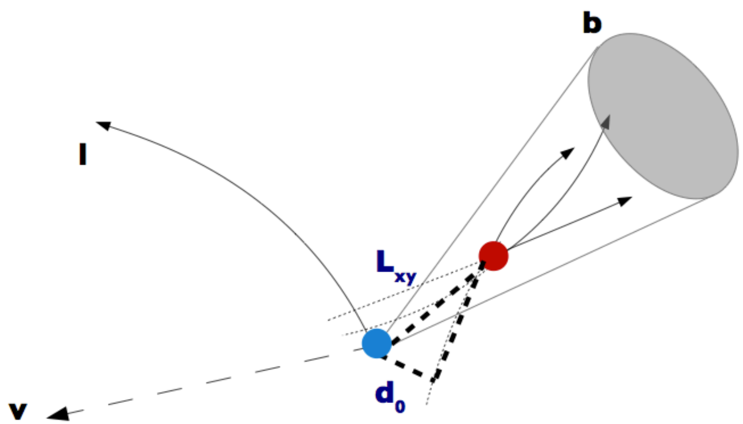
$$M_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.6}_{-2.0}\,(\text{syst.})\,\text{GeV}$$



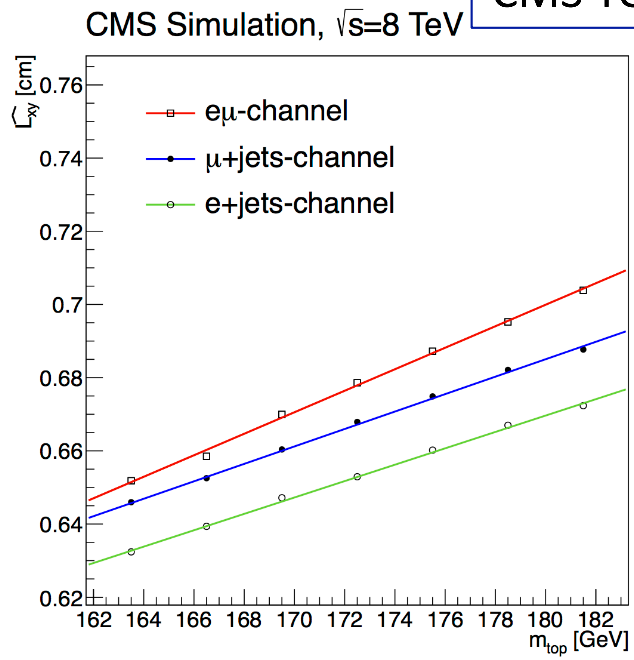



# Another example: top mass from the b decay length

- The decay length of b hadrons from top decays is correlated to their boost, i.e. to the top mass




CMS TOP-12-030

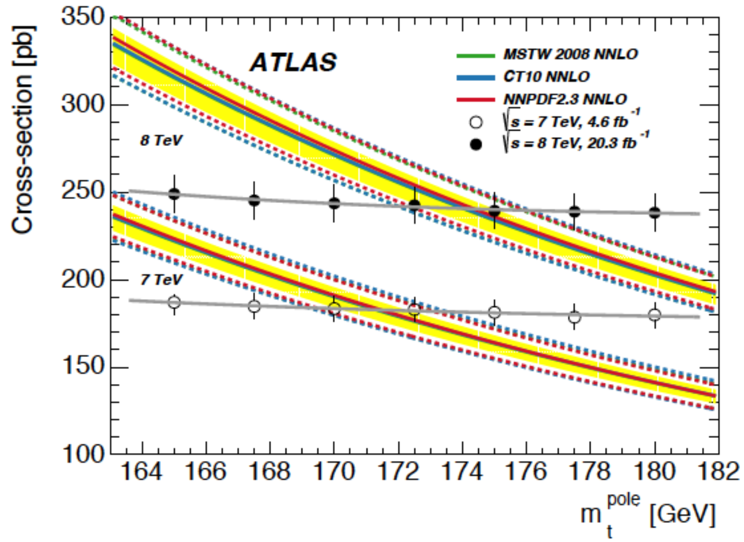



$m_t = 173.5 \pm 1.5\text{stat} \pm 1.3\text{syst} \pm 2.6p_t(\text{top})$ GeV

# ttbar cross section: mass interpretation

[example from ATLAS, arXiv:1406.5375]

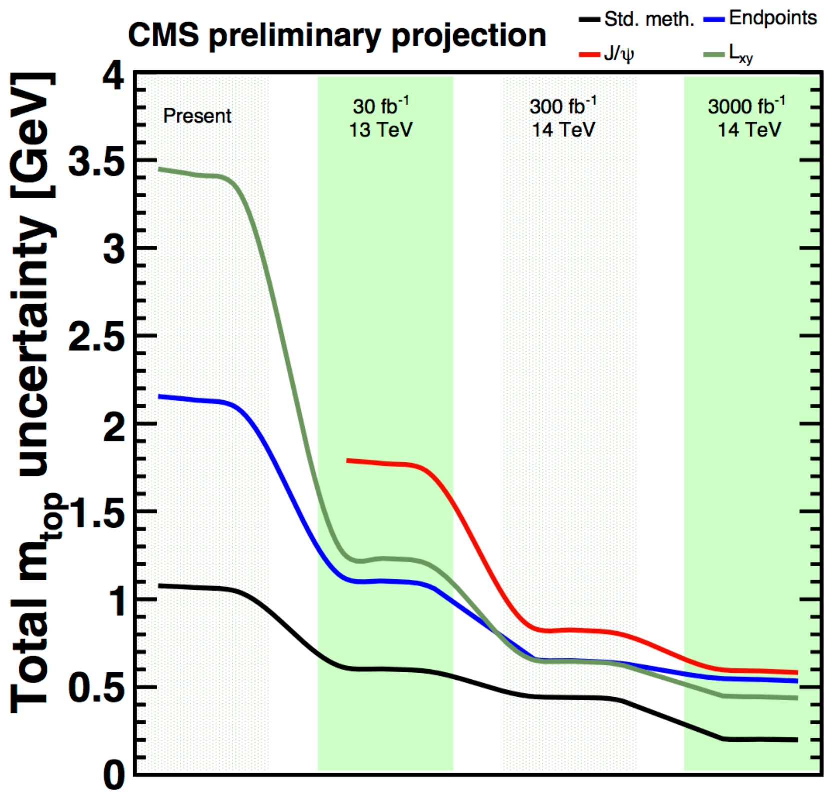
- Measure cross section in the most precise channel: dilepton eμ
- Use b-tagging and double tag method to avoid dependence on b-tag efficiency
  - interesting by-product: acceptance dependence on $m_t$ is flat because of calibration of the jet acceptance in situ and cancelation with Wt background
- Use recent NNLO calculation of top pair cross section to extract $m_t$
- The method takes advantage of the excellent luminosity knowledge at LHC (~2%), which is also the long-term experimental limitation, together with the knowledge of the LHC beam energy




$$m_t = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$

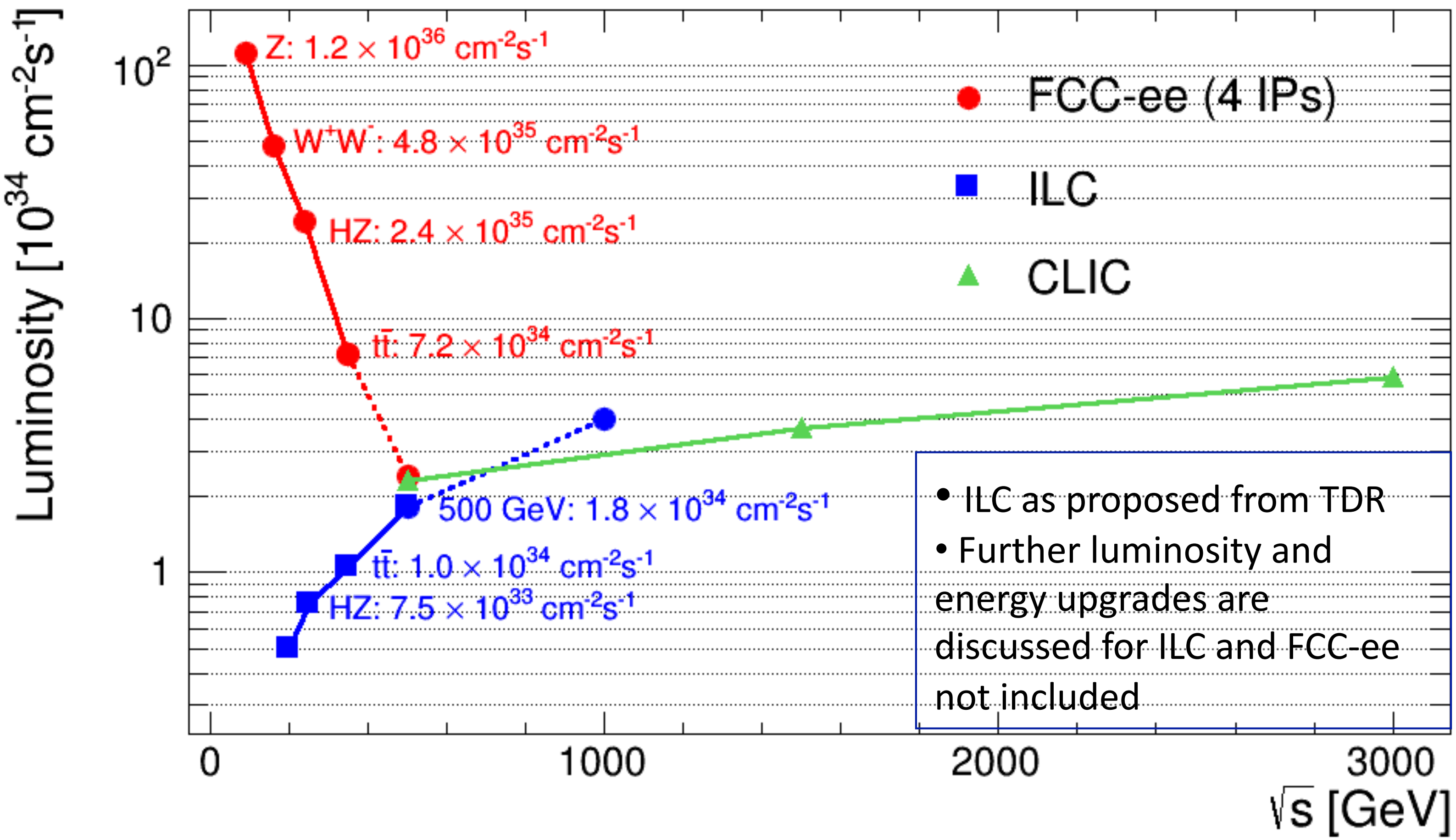
# Prospects for top mass at the LHC

- There is potential to improve standard methods, taking advantage of the high statistics for, e.g., in-situ JES calibration, constraining models from differential studies, etc.
- There is even greater potential for alternative methods, most of the current systematic uncertainties can be reduced with higher statistics, e.g. top pt modeling, in-situ JES again
- Improvements on the cross section method are linked to improvements in the luminosity and beam energy uncertainties at LHC
- A optimistic view (maybe realistic give past experience at colliders !) of the evolution in precision is given in the picture




From CMS PAS FTR-13-017, prepared for the "European Strategy for particle physics" discussions

# Prospects at future $e^+e^-$ Colliders: Linear and Circular

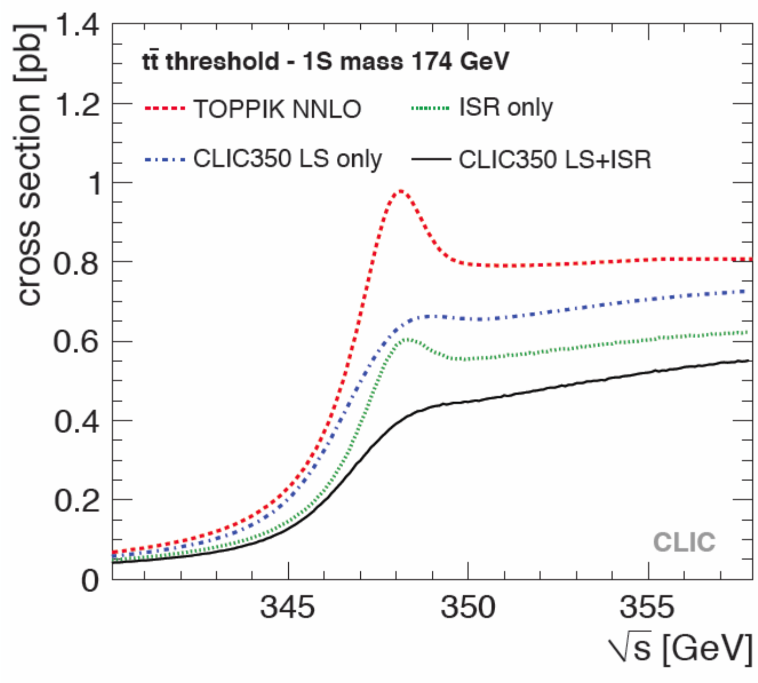


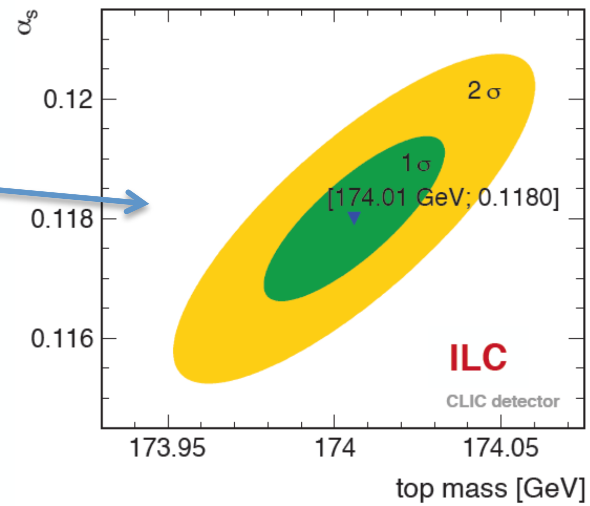

- ILC as proposed from TDR
- Further luminosity and energy upgrades are discussed for ILC and FCC-ee not included

TLEP physics study group: arXiv:1308.6176

# top mass from threshold scan

- Same conceptual advantage as cross section measurement at LHC, but experimentally dependent only on beam energy spectrum
- Other source of uncertainty is the modification of threshold lineshape related to $\alpha_s$ , **top width** and top-Higgs **Yukawa coupling** (with high statistics 2D / 3D fits possible)



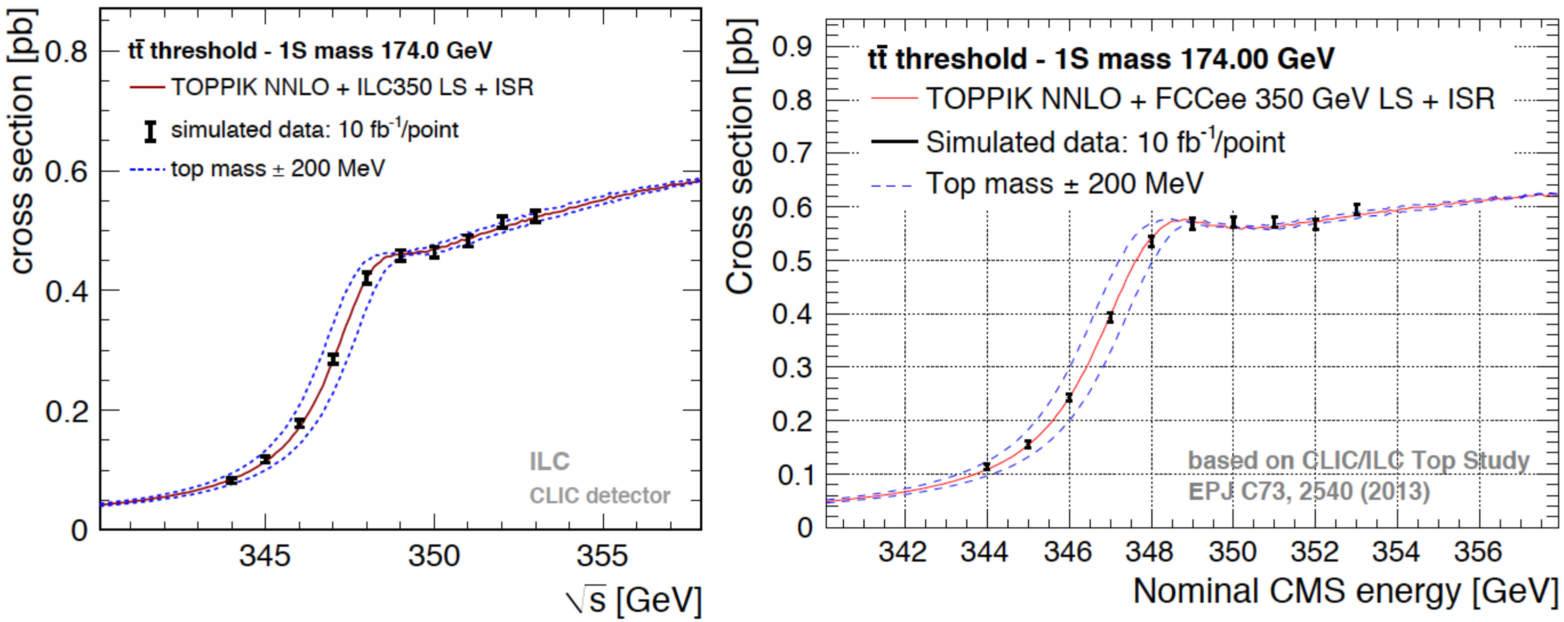




Eur. Phys. J. C73 (2013) 2530

# e+e- at 350 GeV: threshold scan

- At ILC statistical uncertainty of 30 MeV with 10 fb-1 scan
- At FCC statistical uncertainty of 10 MeV expected - Advantage of a very low level of beamstrahlung at FCC
- Theoretical *current* uncertainty from higher order QCD contribution ~ 100 MeV

- Comparing ILC and FCCee - assuming identical detector performance




Simulated data points - same integrated luminosity

NB: Assuming unpolarized beams - LC beams can be polarized, increasing cross-sections / reducing backgrounds

From Frank Simon, presented at 7th TLEP-FCC-ee workshop, CERN, June 2014

# Conclusions

- The 2014 top mass world average is 173.34±0.76 GeV
- High statistics at LHC offers a unique opportunity of studying the robustness of top mass determination based on top decay products
  - data-based constraints on systematics
  - differential measurements
  - alternative techniques
- We need e+e- colliders to reach precisions in the range 100 MeV → 10 MeV