# Top physics and the top mass

Lecture 2/3

**2013 CERN-Fermilab HCP Summer School**

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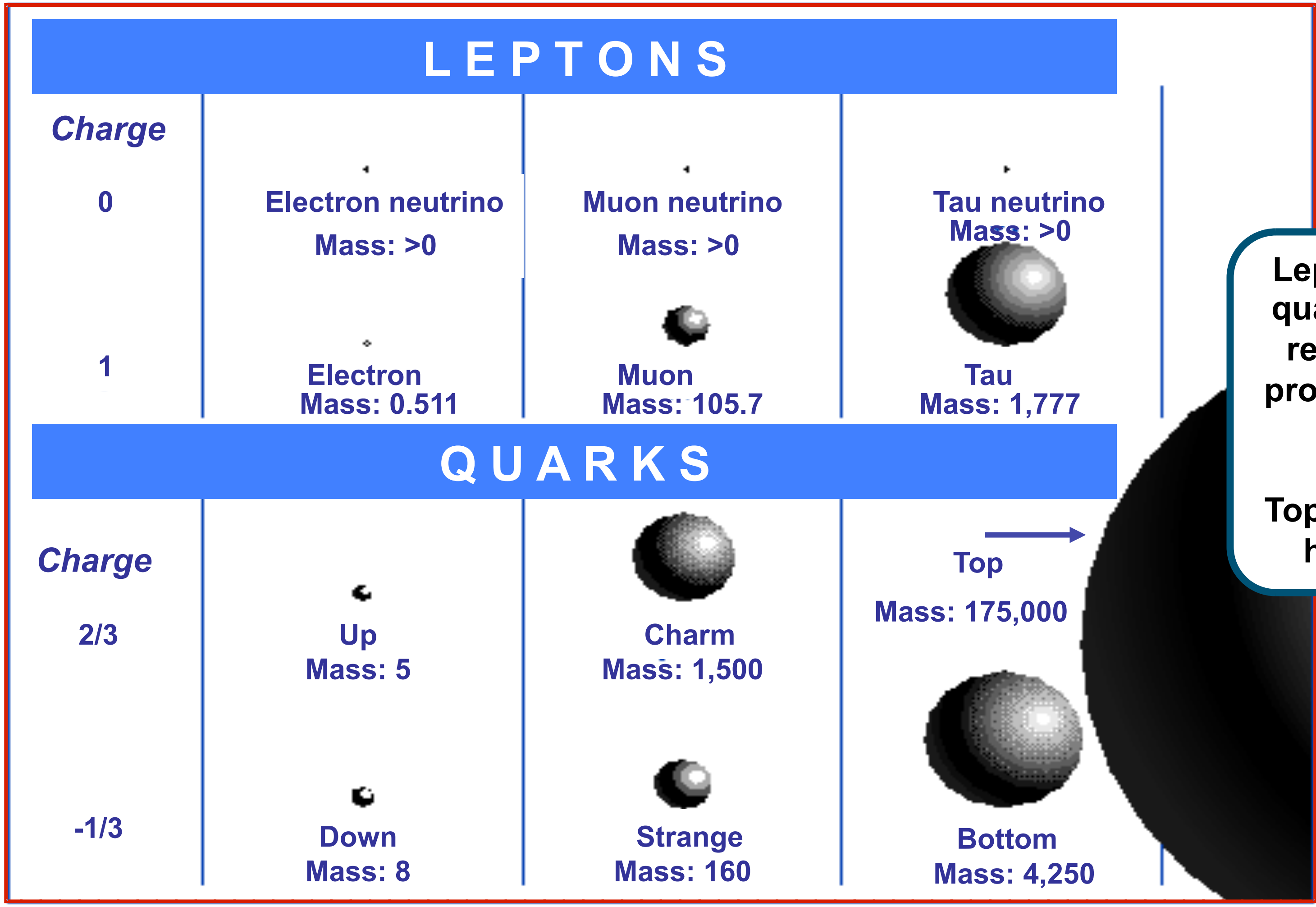
(and this year also: LHC Physics Centre, Fermilab)

Vrije Universiteit Brussel

# Outline

- Wednesday:
  - Lecture 1: Intro to top physics and its jargon.
- Thursday:
  - Lecture 2: SM top physics and the top mass
    - Top mass physics motivation
    - Measuring top properties
    - QCD motivations for precision top physics
- Friday:
  - Lecture 3: SM and top physics, the portal to physics searches

# The building blocks of matter



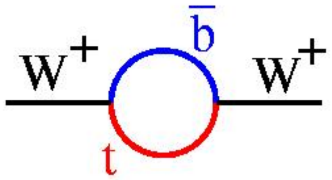

Lepton and quark sizes represent proportional mass

Top quark is heavy!!!

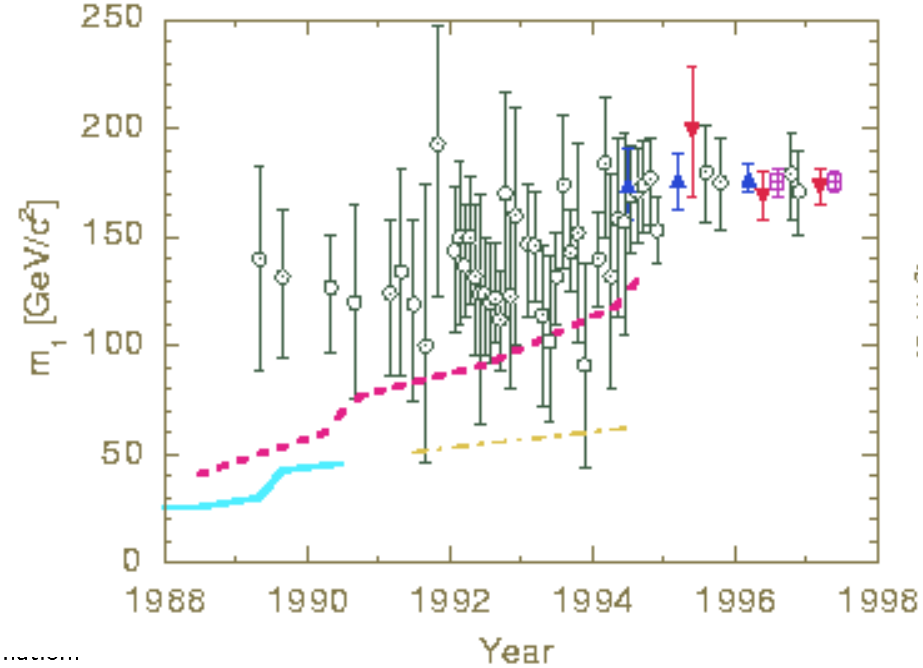
Masses are in millions of Electron Volts [MeV/$c^2$]

# History of the top quark

- 1989: Indirect constraints on top from precision measurements at LEP

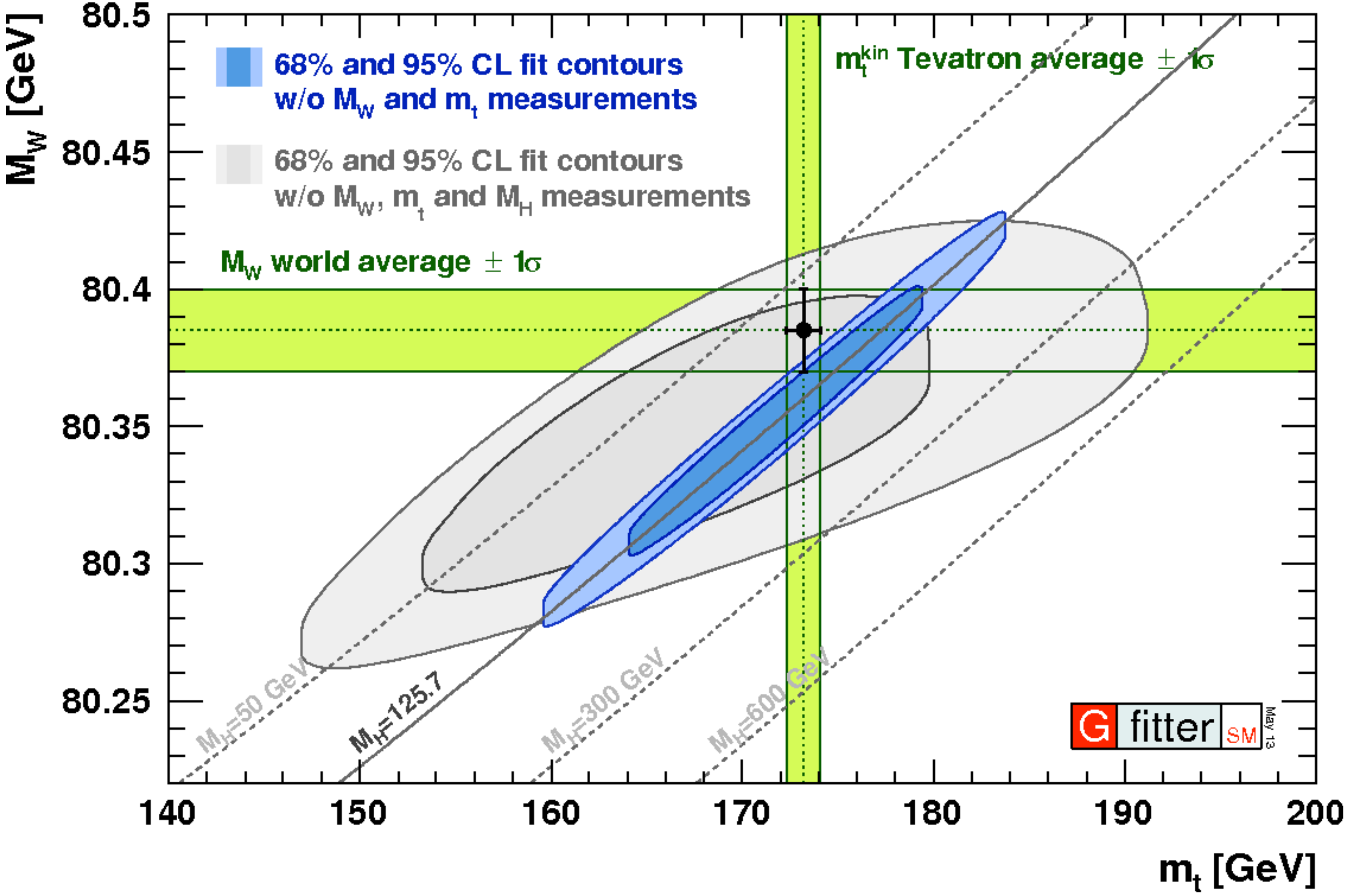



- 1995: Observation of Top-quark at the TeVatron collider at Fermilab
- Historic perspective indirect -> direct measurements -> precision



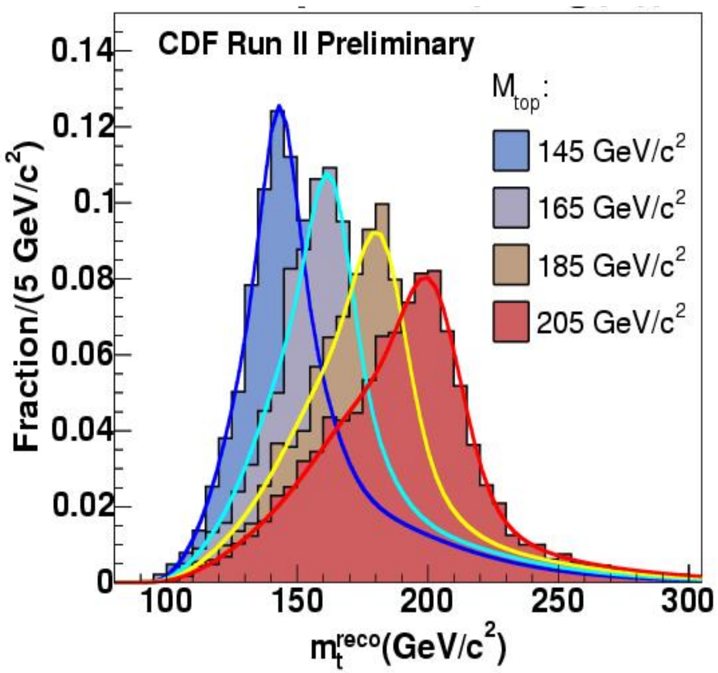

| *VALUE* (GeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **173.07± 0.52± 0.72 OUR EVALUATION** | | | | See comments in the header above. |
| 174.5 ± 0.6 ± 2.3 | [1] AAD | 12I | ATLS | $\ell + \not{E}_T + \geq 4$ jets ( $\geq 1$ $b$), MT |
| 172.85± 0.71± 0.85 | [2] AALTONEN | 12AI | CDF | $\ell + \not{E}_T + \geq 4$j (0,1,2$b$) template |
| 172.7 ± 9.3 ± 3.7 | [3] AALTONEN | 12AL | CDF | $\tau_h + \not{E}_T$ +4j ( $\geq 1b$) |
| 172.5 ± 1.4 ± 1.5 | [4] AALTONEN | 12G | CDF | 6–8 jets with $\geq 1$ $b$ |
| 173.9 ± 1.9 ± 1.6 | [5] ABAZOV | 12AB | D0 | $\ell\ell + \not{E}_T + \geq 2$j ($\nu$WT+MWT) |
| 172.5 ± 0.4 ± 1.5 | [6] CHATRCHYAN | 12BA | CMS | $\ell\ell + \not{E}_T + \geq 2$j ( $\geq 1b$), AMWT |
| 173.49± 0.43± 0.98 | [7] CHATRCHYAN | 12BP | CMS | $\ell + \not{E}_T + \geq 4$j ( $\geq 2b$) |
| 172.3 ± 2.4 ± 1.0 | [8] AALTONEN | 11AK | CDF | $\not{E}_T + \geq 4$ jets ( $\geq 1$ $b$-tag) |
| 172.1 ± 1.1 ± 0.9 | [9] AALTONEN | 11E | CDF | $\ell$ + jets and dilepton |
| 174.94± 0.83± 1.24 | [10] ABAZOV | 11P | D0 | $\ell + \not{E}_T$ + 4 jets ( $\geq 1$ $b$-tag) |
| 173.0 ± 1.2 | [11] AALTONEN | 10AE | CDF | $\ell + \not{E}_T$ + 4 jets ( $\geq 1$ $b$-tag), ME method |
| 170.7 ± 6.3 ± 2.6 | [12] AALTONEN | 10D | CDF | $\ell + \not{E}_T$ + 4 jets ($b$-tag) |

# Top quark mass in Standard Model



# Template method

- Isolate a sample rich in top events
  - Use some form of b-quark identification
- Select the most likely combination of jets, leptons and missing transverse energy
- Have templates of top signal at different masses and of background
- For each event, determine probability signal or background
  - Fit which mass is most probable
  - Modern analyses also use different templates for the di-jet W candidates




DISADVANTAGE:
Only use one possible permutation of jets,leptons, missing energy

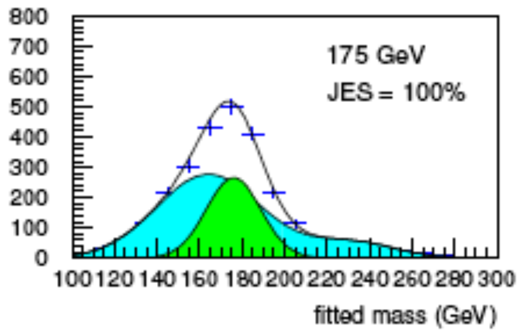
# Matrix element method

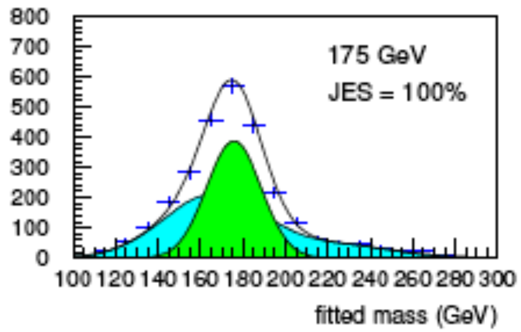
$$P_{t\bar{t}} = \frac{1}{12\sigma_{t\bar{t}}} \int d\rho_1 dm_1^2 dM_1^2 dm_2^2 dM_2^2 \times \sum_{\text{perm.},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \Phi_6 W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}})$$

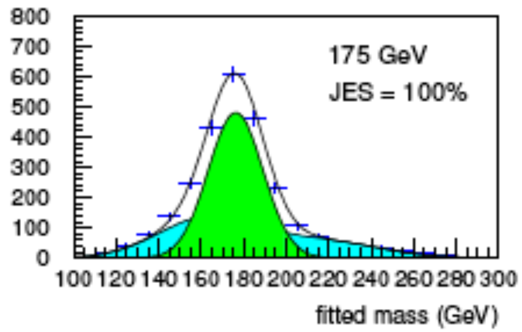
- Method first used for top physics by DØ in Tevatron Run I
- Use LO matrix element
  'Standard' integral (20D)
- put in all known information
  - Eight jet angles
  - Lepton 3-momentum
  - Conservation of energy and momentum (4x)
- Do Monte Carlo integration
  - |M(top)| for range of top masses
  - $|M(BG)|^2$ not dependent of top mass
- Get signal probability per event
  - used in likelihood fit

DISADVANTAGE:
Very computing intensive

# Ideogram method



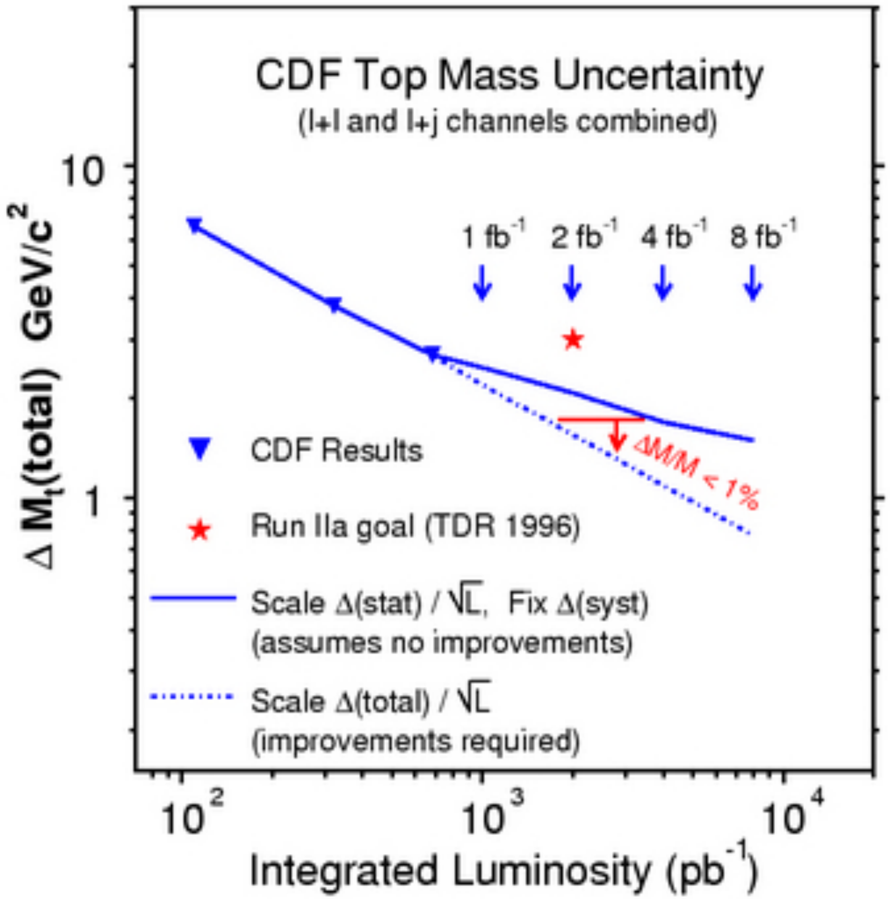




- Already used in LEP era
- Compromise:
  - Use all different permutations in weighted probability
  - Also makes use of topological information

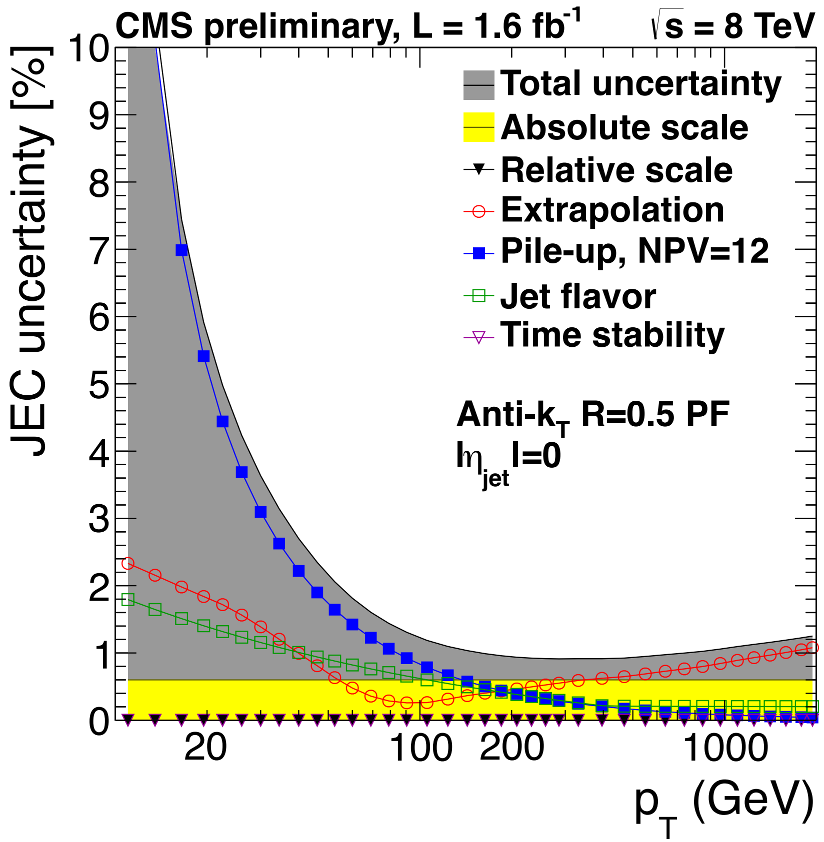
- Takes into account resolutions as observed in simulation
- Include b quark identification
- Include mis-tags

# "In situ" jet energy calibration

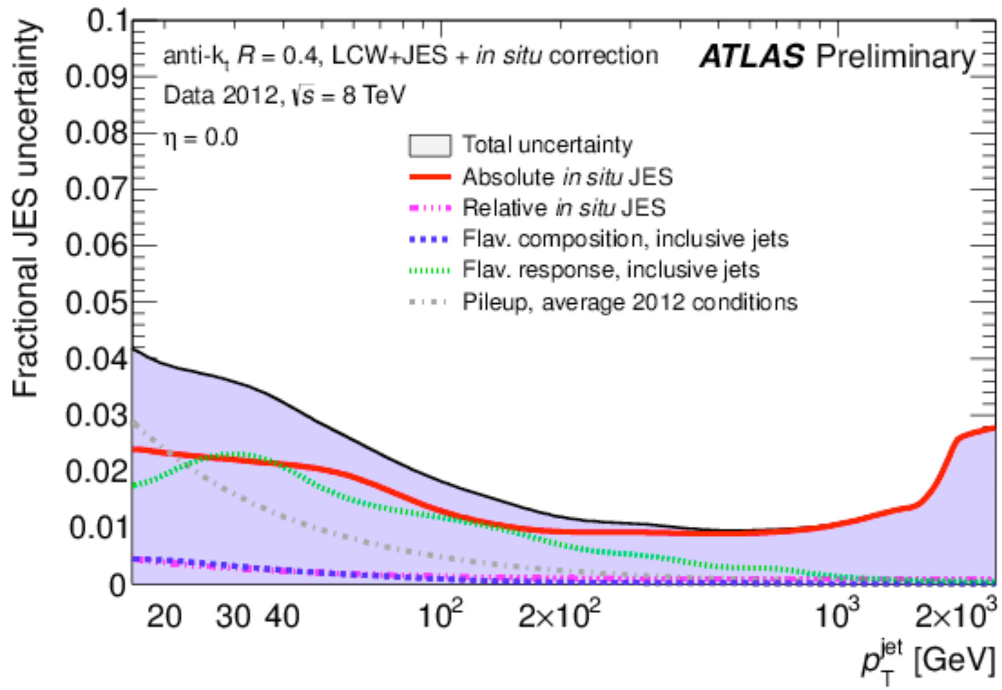
- Tevatron top mass measurements use *in situ* jet energy calibration
  - = Fit energy scale of jets to W mass simultaneously with top mass
- Impressive decrease uncertainties wrt expected!
- Not always necessary at LHC as leading systematic uncertainties can be different



# JES no longer only leading syst. Uncertainty?

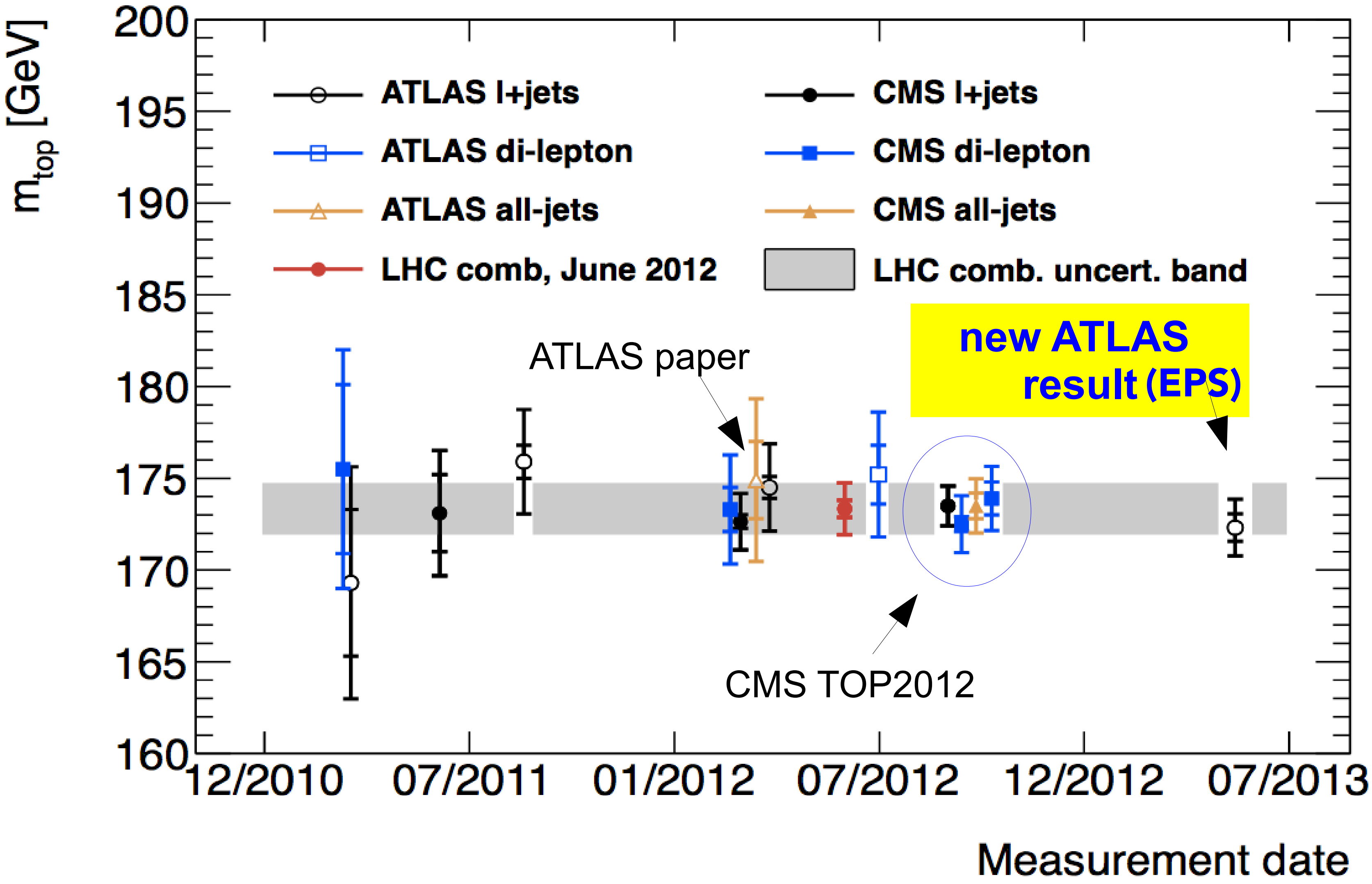



- But of course still crucial for accurate measurement

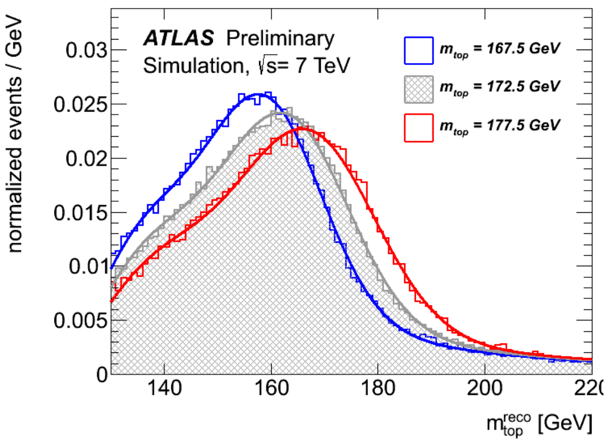


# So let's look at some measurements

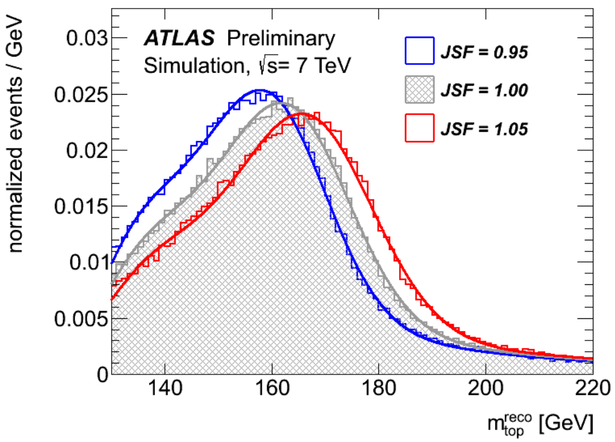
# State of the art measurements



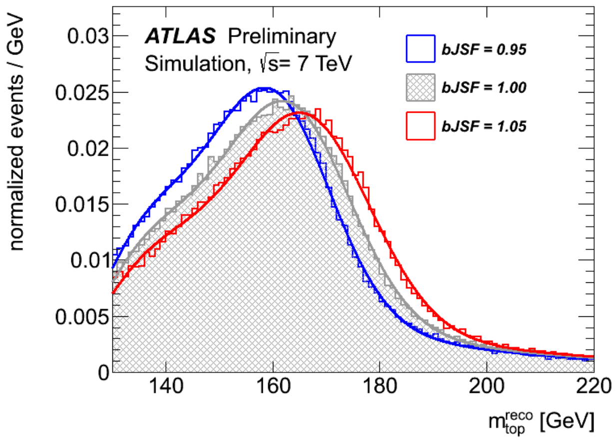
# ATLAS 3D mass




Good sensitivity to the underlying top quark mass.




Large dependence on the jet energy scale → large systematics!

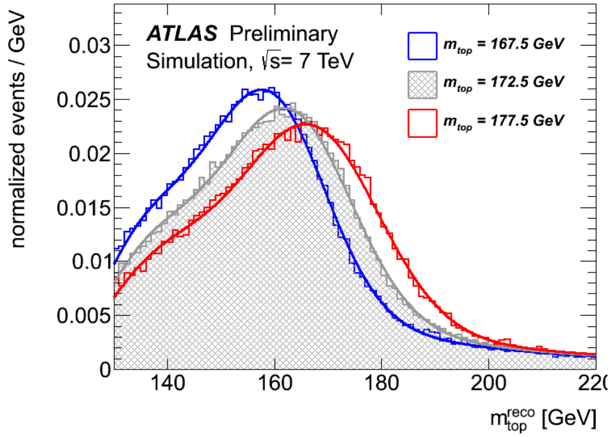



Large dependence on the b-jet energy scale → large systematics!

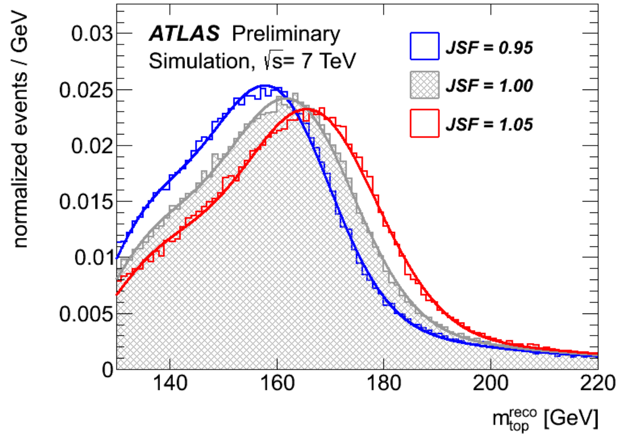
- ATLAS CONF-2013-046
- Determine top mass while simultaneously constraining jet energy scale for light and b jets

# ATLAS 3D mass

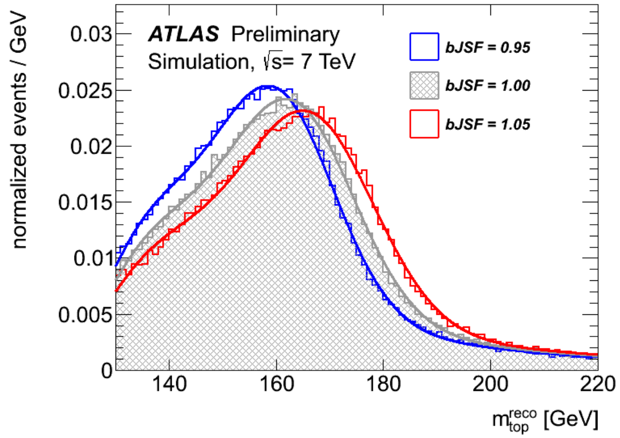
| input $m_{top}$ | JES | bJES |
|---|---|---|




Good sensitivity to the underlying top quark mass.

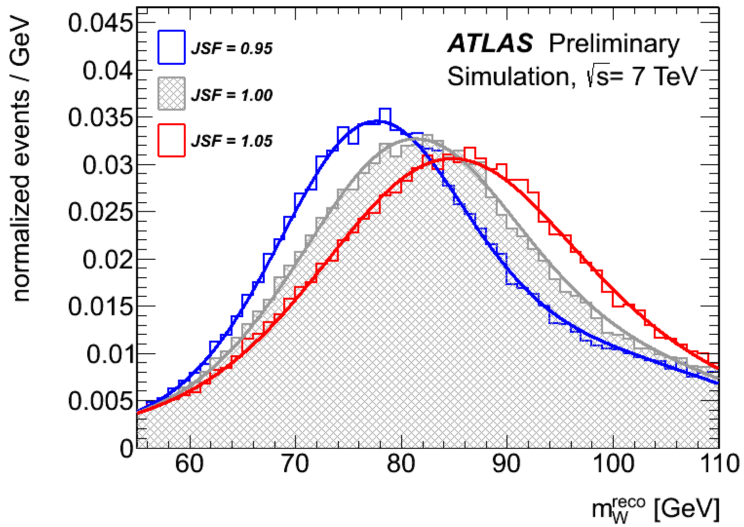



Large dependence on the jet energy scale → large systematics!



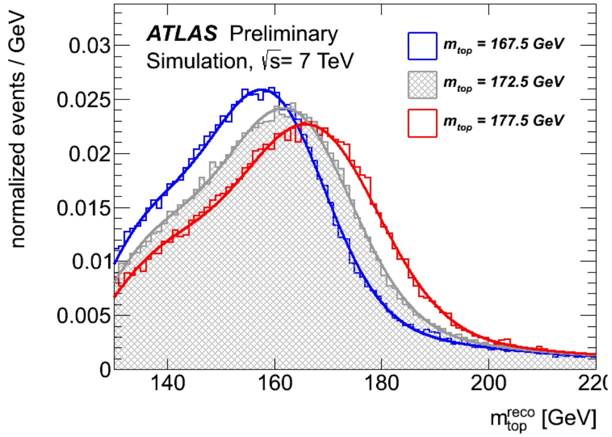

Large dependence on the b-jet energy scale → large systematics!

- Constrain JES using W mass instead of top mass



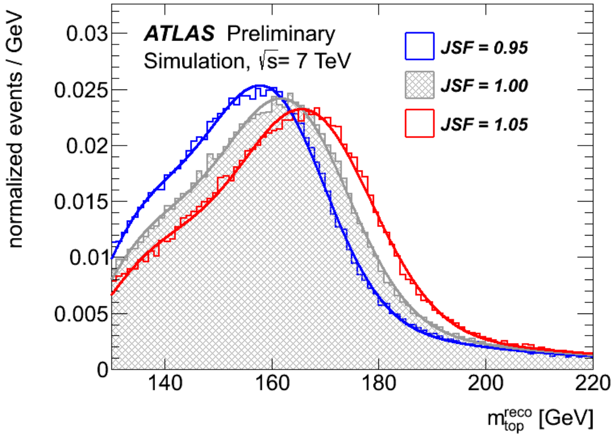
# ATLAS 3D mass

**input $m_{top}$**



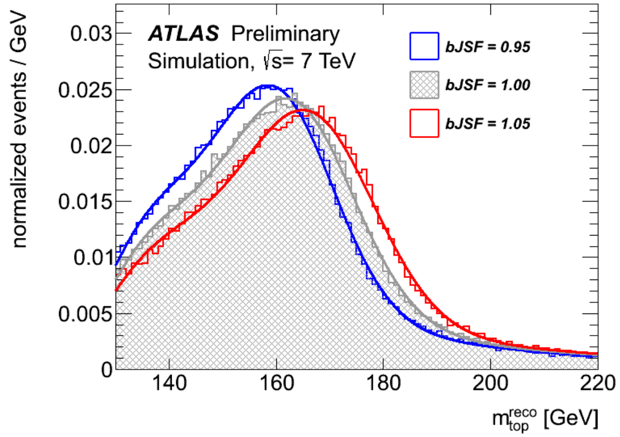

Good sensitivity to the underlying top quark mass.

**JES**



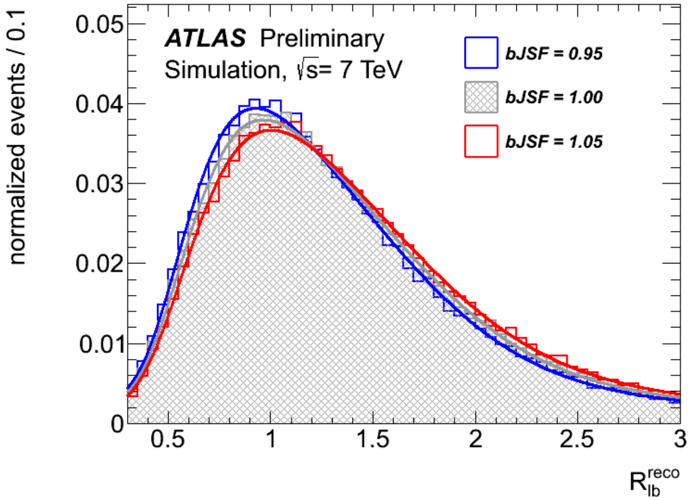

Large dependence on the jet energy scale → large systematics!

**bJES**

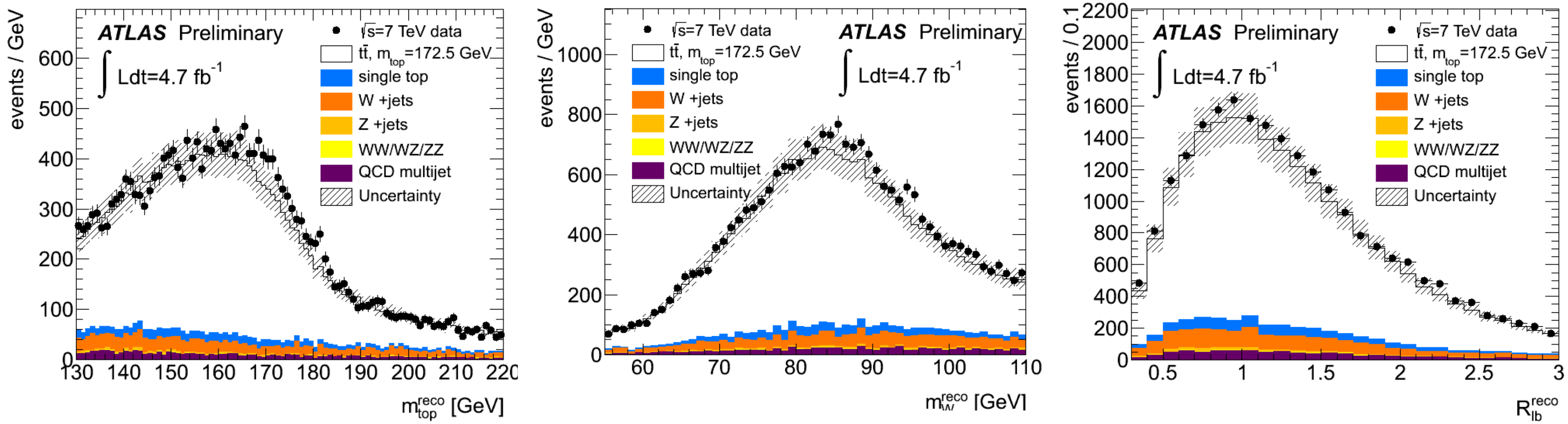



Large dependence on the b-jet energy scale → large systematics!

- Constrain JES for b jets using ration bJES/light JES

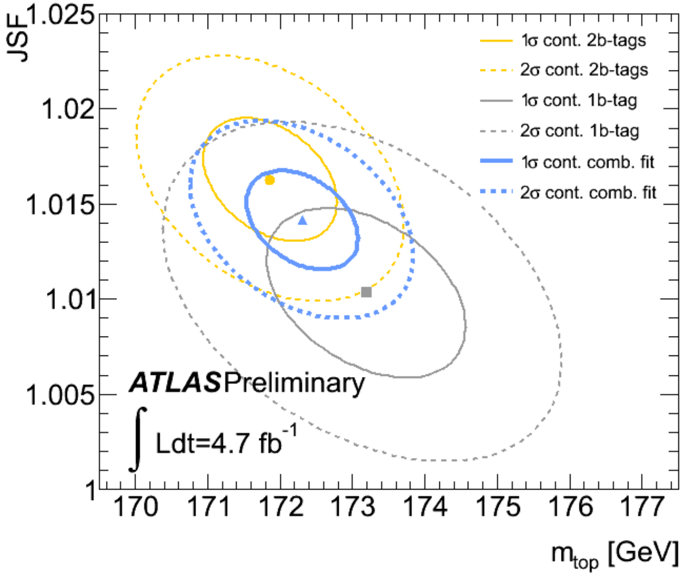


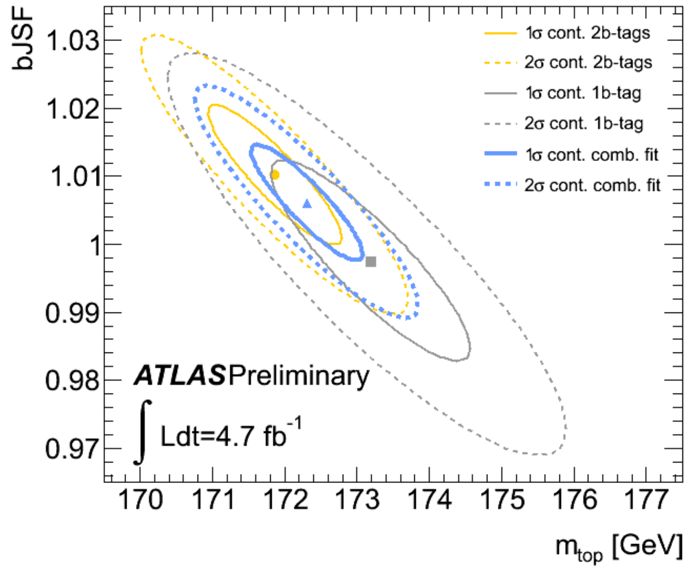
# With Data, before fit




- All this information combined in 3D template fit

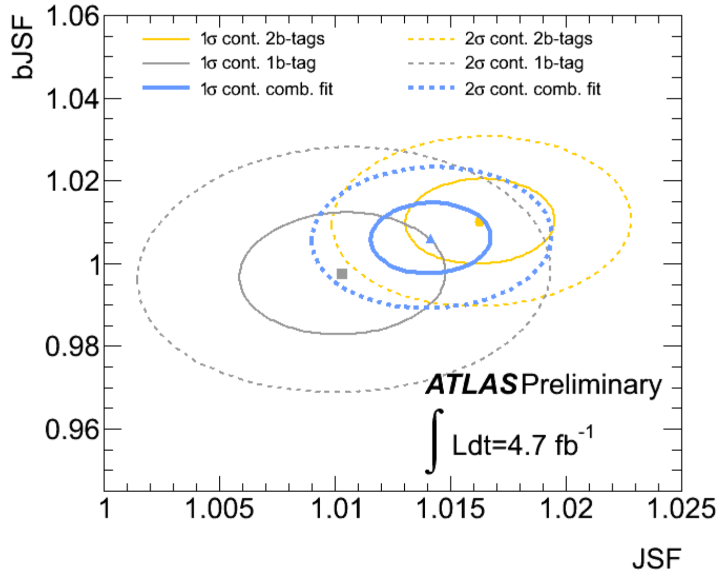
# Repeat in 1 b-tag/2 b-tag/combined



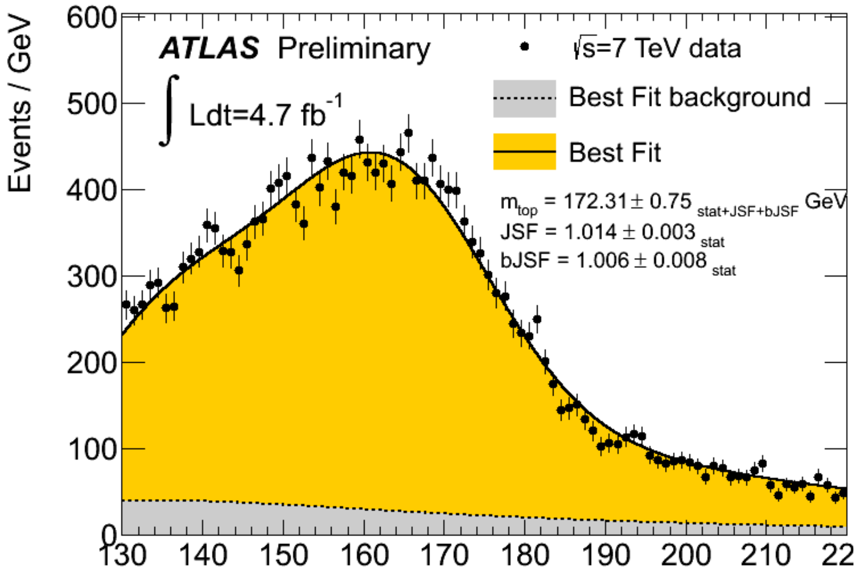



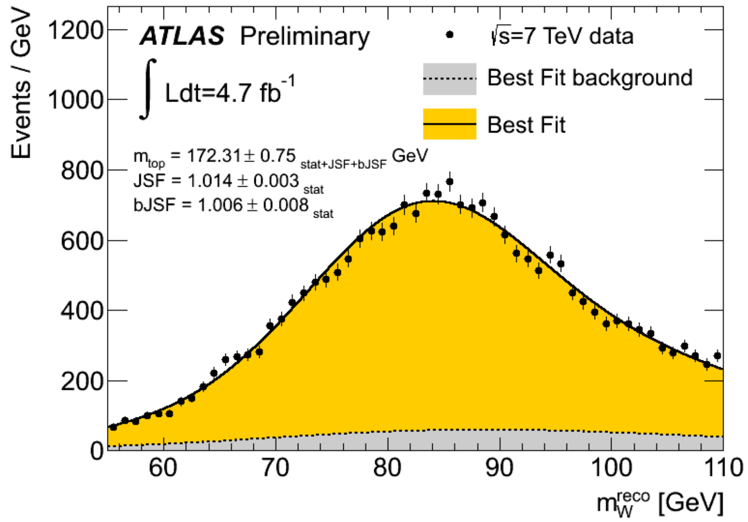

- Fits are consistent
- JES and bJES almost uncorrelated

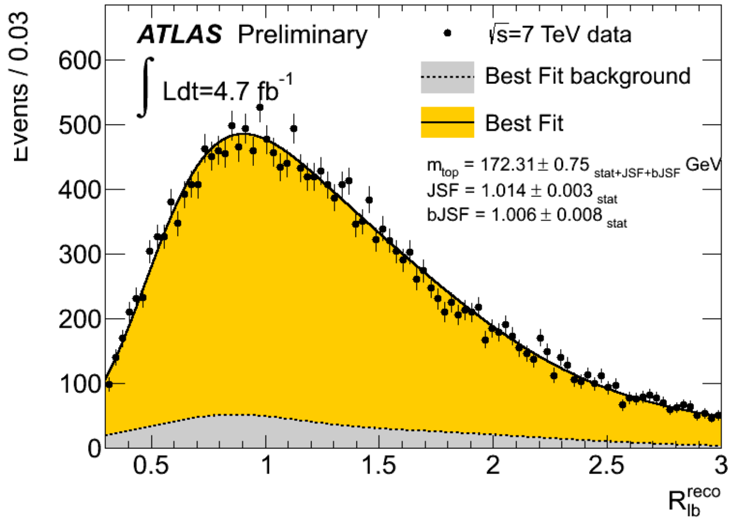
- (stat uncertainties only)



# Post-fit




- After applying fit consistent picture in all three variables
- And $m_{top}$= 172.31 ±0.75 ±1.35 GeV

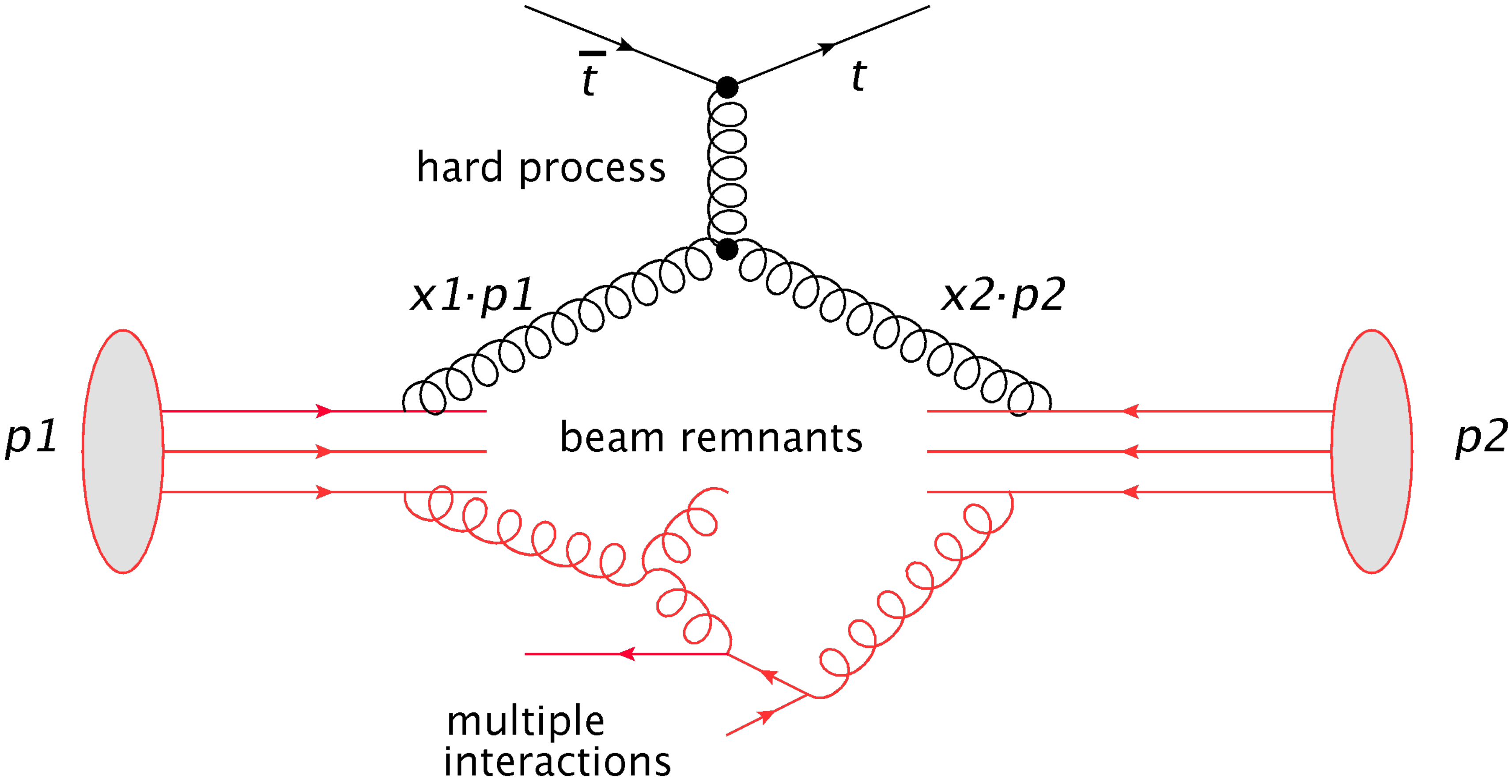
JES, stat

Other systematic uncertainties

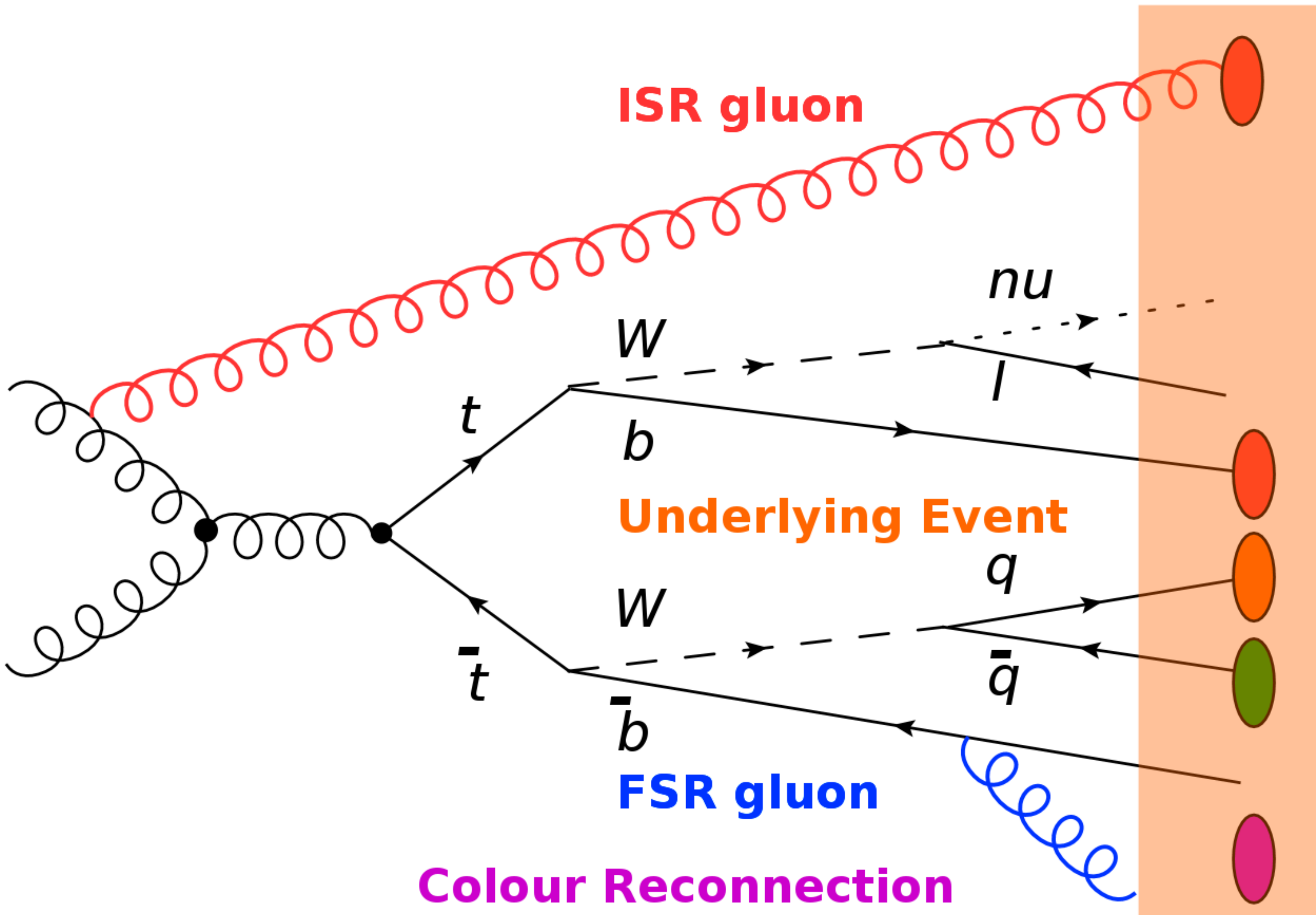
# Systematic uncertainties

| | 2d-analysis | | 3d-analysis | | |
|---|---|---|---|---|---|
| | $m_{top}$ [GeV] | JSF | $m_{top}$ [GeV] | JSF | bJSF |
| Measured value | 172.80 | 1.014 | 172.31 | 1.014 | 1.006 |
| Data statistics | 0.23 | 0.003 | 0.23 | 0.003 | 0.008 |
| Jet energy scale factor (stat. comp.) | 0.27 | n/a | 0.27 | n/a | n/a |
| bJet energy scale factor (stat. comp.) | n/a | n/a | 0.67 | n/a | n/a |
| Method calibration | 0.13 | 0.002 | 0.13 | 0.002 | 0.003 |
| Signal MC generator | 0.36 | 0.005 | 0.19 | 0.005 | 0.002 |
| Hadronisation | 1.30 | 0.008 | 0.27 | 0.008 | 0.013 |
| Underlying event | 0.02 | 0.001 | 0.12 | 0.001 | 0.002 |
| Colour reconnection | 0.03 | 0.001 | 0.32 | 0.001 | 0.004 |
| ISR and FSR (signal only) | 0.96 | 0.017 | 0.45 | 0.017 | 0.006 |
| Proton PDF | 0.09 | 0.000 | 0.17 | 0.000 | 0.001 |
| single top normalisation | 0.00 | 0.000 | 0.00 | 0.000 | 0.000 |
| $W$+jets background | 0.02 | 0.000 | 0.03 | 0.000 | 0.000 |
| QCD multijet background | 0.04 | 0.000 | 0.10 | 0.000 | 0.001 |
| Jet energy scale | 0.60 | 0.005 | 0.79 | 0.004 | 0.007 |
| $b$-jet energy scale | 0.92 | 0.000 | 0.08 | 0.000 | 0.002 |
| Jet energy resolution | 0.22 | 0.006 | 0.22 | 0.006 | 0.000 |
| Jet reconstruction efficiency | 0.03 | 0.000 | 0.05 | 0.000 | 0.000 |
| $b$-tagging efficiency and mistag rate | 0.17 | 0.001 | 0.81 | 0.001 | 0.011 |
| Lepton energy scale | 0.03 | 0.000 | 0.04 | 0.000 | 0.000 |
| Missing transverse momentum | 0.01 | 0.000 | 0.03 | 0.000 | 0.000 |
| Pile-up | 0.03 | 0.000 | 0.03 | 0.000 | 0.001 |
| Total systematic uncertainty | 2.02 | 0.021 | 1.35 | 0.021 | 0.020 |
| Total uncertainty | 2.05 | 0.021 | 1.55 | 0.021 | 0.022 |

# Underlying event



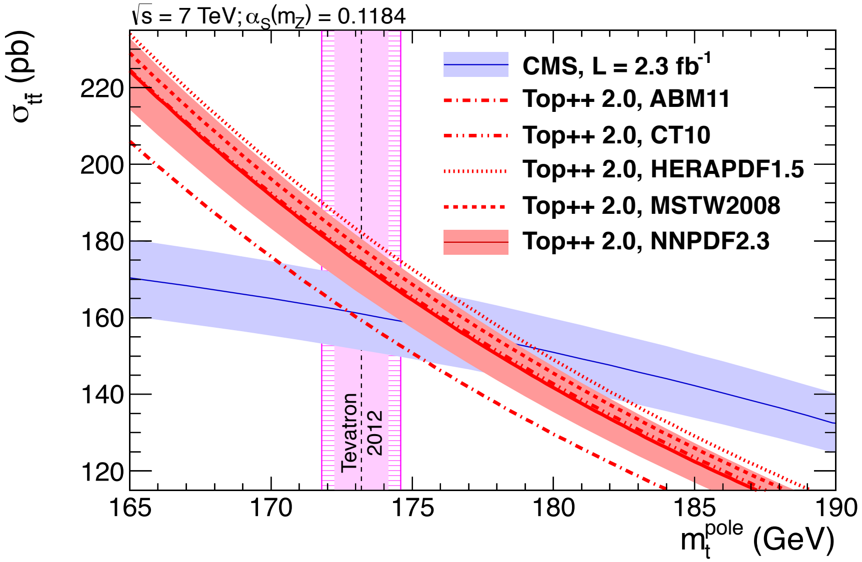
# Other generator uncertainties

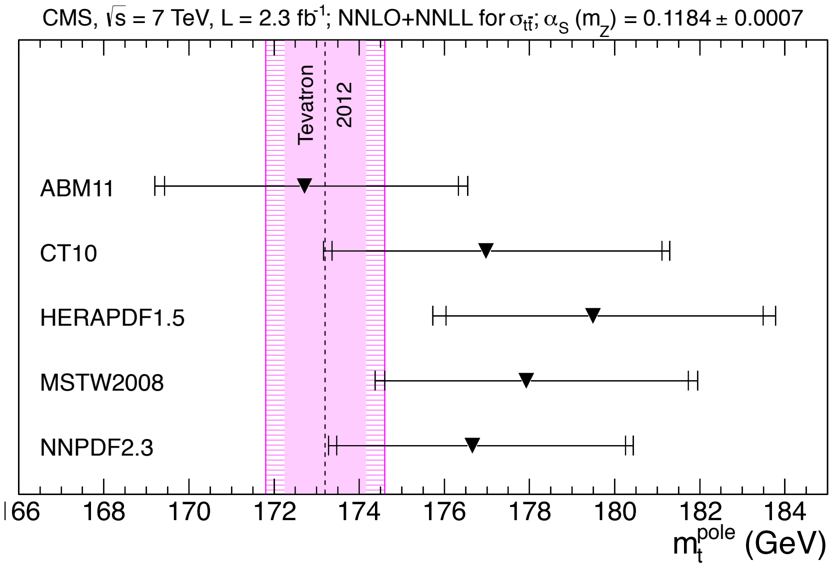


# What top mass, really?

- When measurements are so accurate question is what one really measures
  - The top quark mass is a parameter of the SM
    - Mass is usually defined as a pole mass or $\overline{\mathrm{MS}}$ mass
    - Definition is confusing, we typically use pole mass when dealing with mass/yukawa couplings, while $\overline{\mathrm{MS}}$ is used for prediction cross sections.
    - There is a transformation from one scheme to the other, but this relies on order of calculation and strong coupling constant.
- The measured mass effectively is a number we use as input to a MC generator

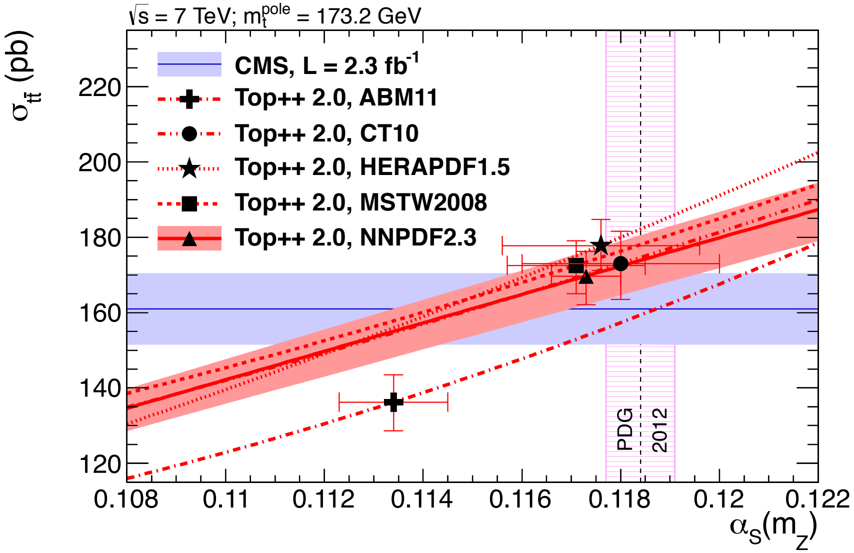
# Derive top mass from cross section




- Comparison of most accurate ttbar cross section measurement and do transformation mass
  - Measure xsec for different mTop
  - And $\alpha_S$, best NNLO calculation
  - $M_t^{pole} = 176.7^{+3.8}_{-3.4}$ GeV

# Or use cross section to find $\alpha_s$

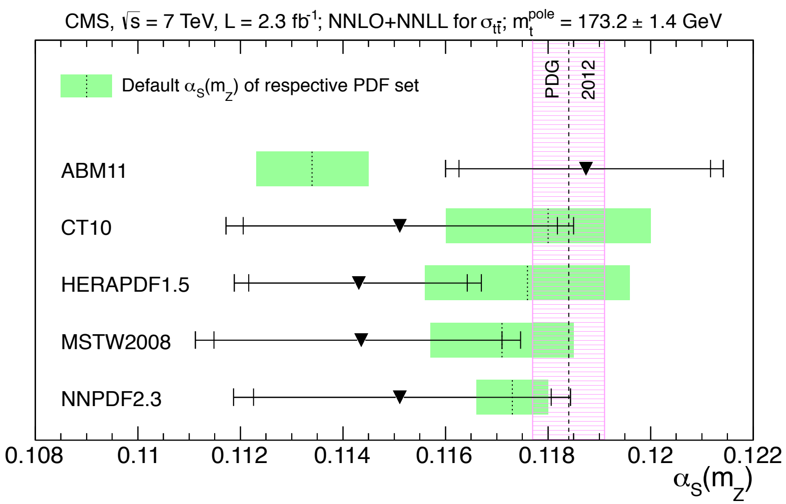



- Use precise pole mass measurement and compare to cross section

- Derive $\alpha_s$ using NNLO theoretical cross section predictions

$$\alpha_s(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$

- Strong pdf dependence!



# Final word definitely not said

*Summary*

*Top quark mass*

- On-shell scheme (pole mass) at NNLO in QCD

$$m_t = 173.18 \pm 0.94 \pm \mathcal{O}(\text{few})\,\text{GeV}$$

- Running mass ($\overline{\text{MS}}$ scheme) at NNLO in QCD

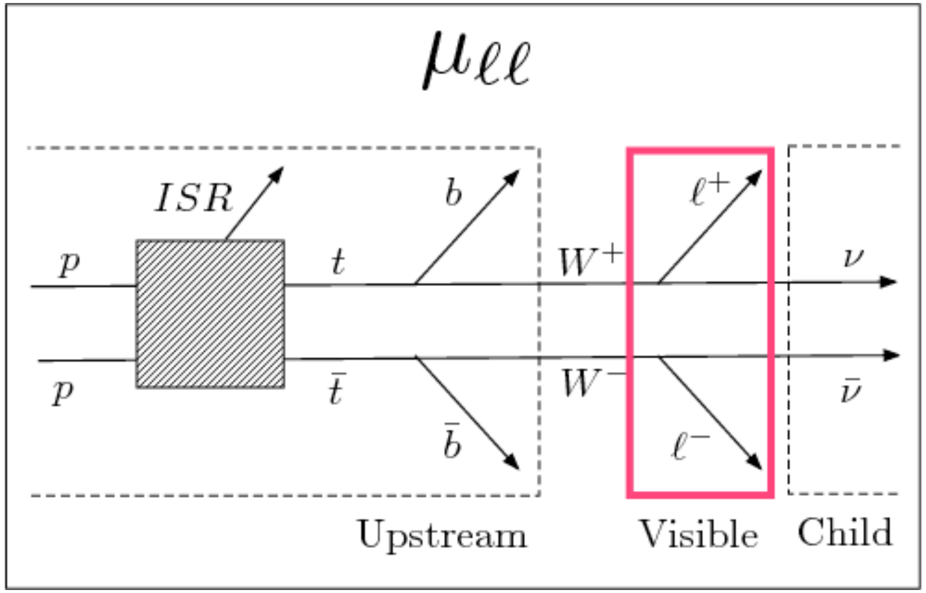
$$m_t(m_t) = 163.3 \pm 2.7\text{GeV}$$

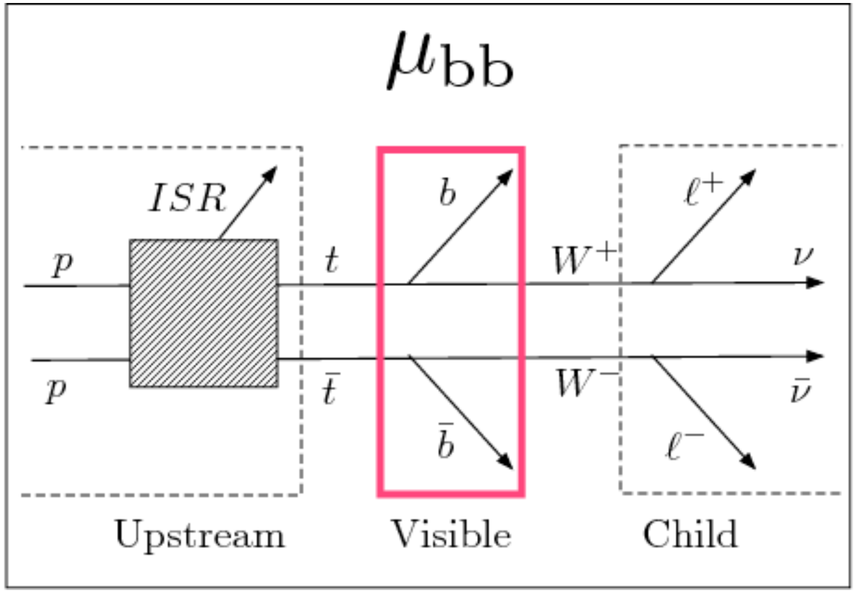
Sven-Olaf Moch

Interpreting top quark mass measurements – p.24

source: top2012 talk by S-O Moch

# Or measure in other ways?

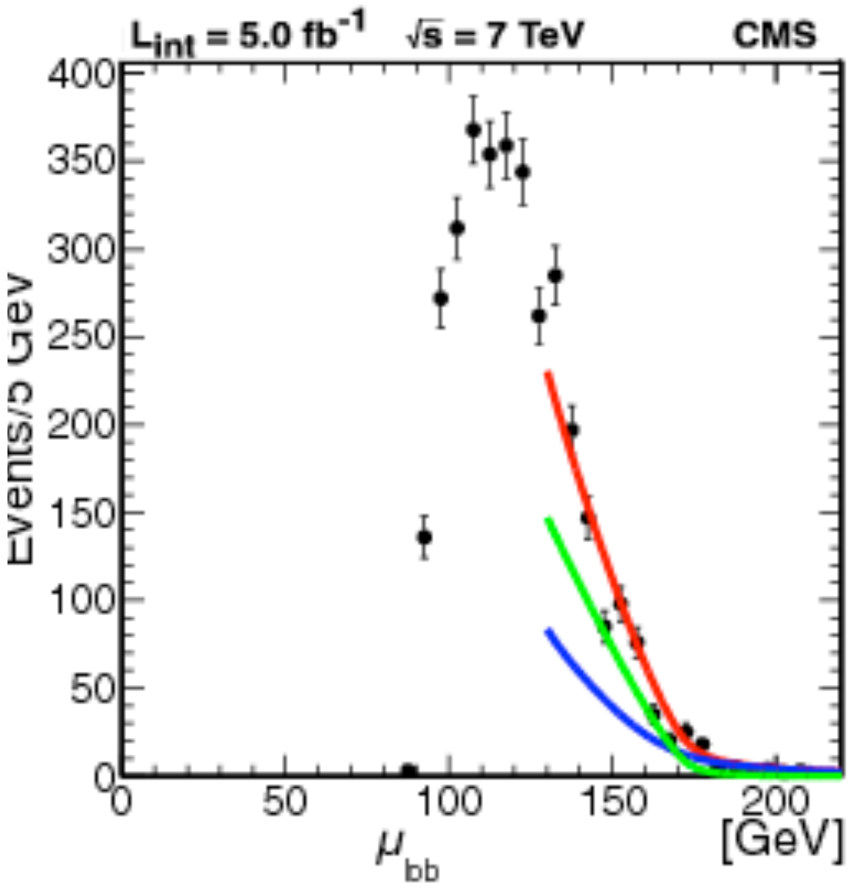


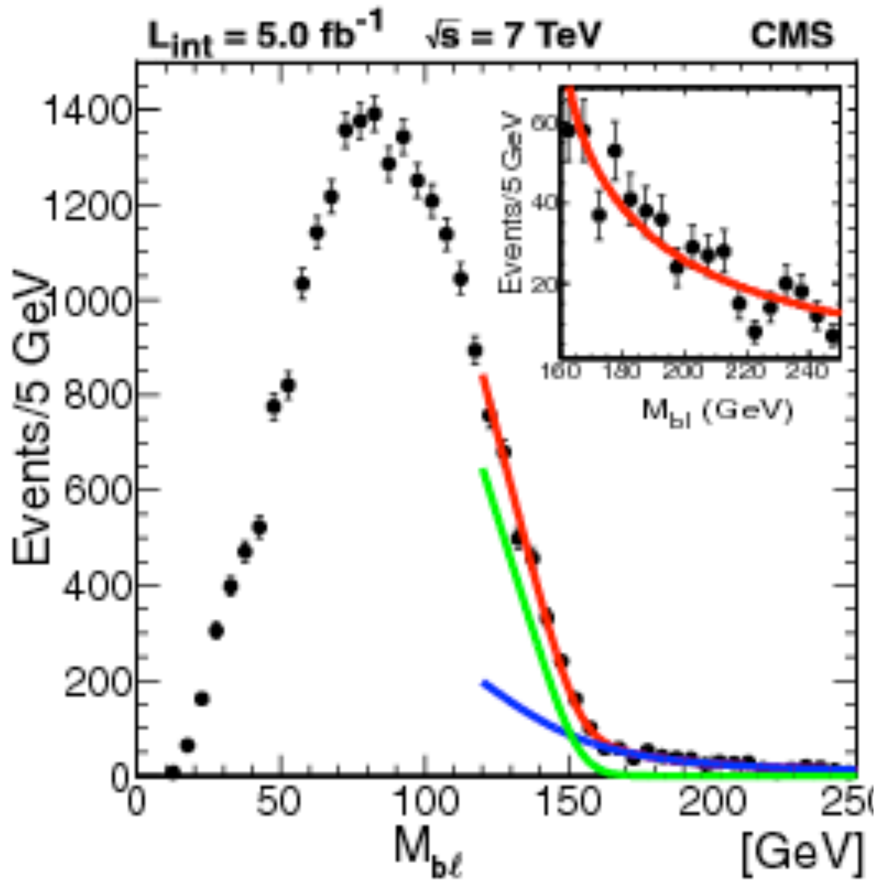




- In di-lepton events the di-lepton mass has a direct kinematic correlation to the top mass
  - Or with possible new physics particles if applied to cascade decays
- Measuring 'endpoint' of m(ll) distribution accurately means measuring the top quark mass accurately
- Basis of CMS endpoint measurement (arXiv:1304.5783)

# Detailed fit with backgrounds included

- Small Background contribution derived from data



# Advantage: very different syst. uncertainties

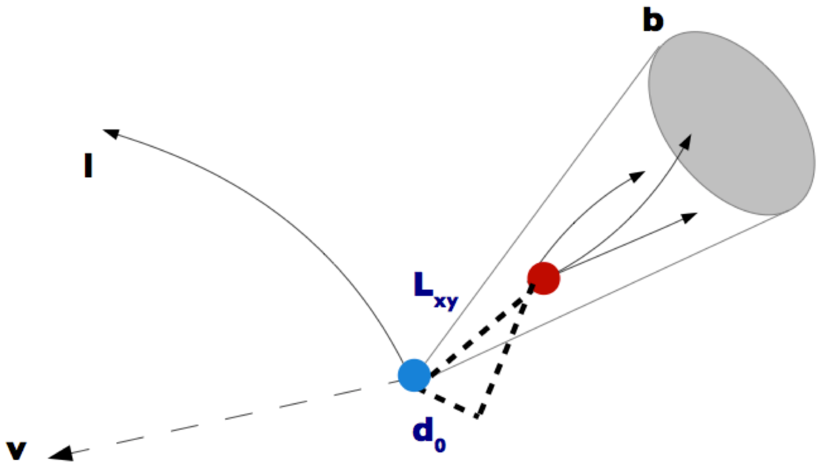
| Source | $\delta M_t$ (GeV) |
|---|---|
| Jet energy scale | $^{+1.3}_{-1.8}$ |
| Jet energy resolution | $\pm 0.5$ |
| Lepton energy scale | $^{+0.3}_{-0.4}$ |
| Fit range | $\pm 0.6$ |
| Background shape | $\pm 0.5$ |
| Jet and lepton efficiencies | $^{+0.1}_{-0.2}$ |
| Pileup | $<0.1$ |
| QCD effects | $\pm 0.6$ |
| Total | $^{+1.7}_{-2.1}$ |

- Jet energy scale still there, but few theory/ modeling uncertainties

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

- Not the best measurement in the world, but still competitive!

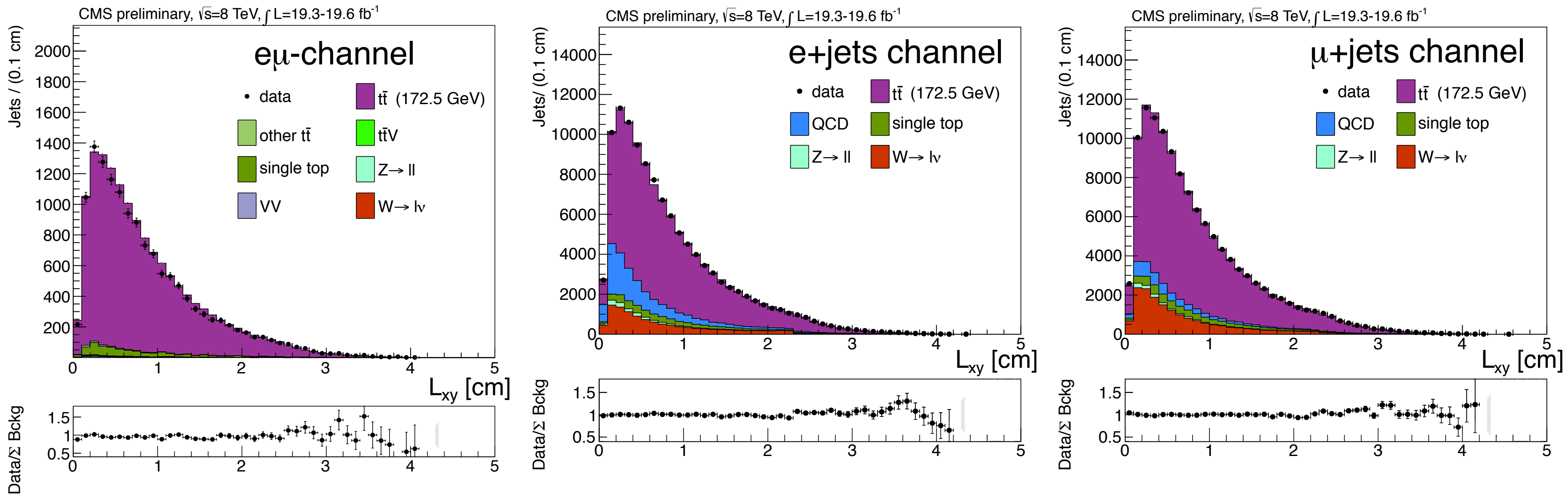
# Lifetime method




- Boost of b quark correlated with top mass
- Decay length of secondary vertex can be used to measure top mass
  - Also possible: momentum of soft leptons from b-quarks
  - Technique pioneered by CDF

(CMS PAS TOP-12-030)

# Examine decay length in dilepton and l+jets



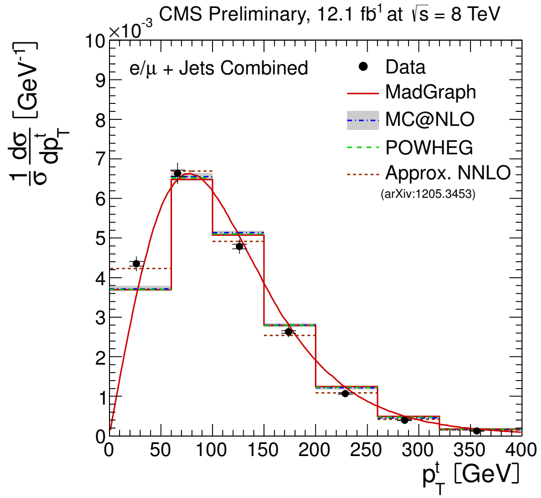

$\widehat{L_{xy}} = 0.682 \pm 0.004\ cm$ $\widehat{L_{xy}} = 0.6536 \pm 0.0013\ cm$ $\widehat{L_{xy}} = 0.6690 \pm 0.0013\ cm$

$m_t^{MC} = 173.7 \pm 2.0$ GeV $m_t^{MC} = 172.8 \pm 1.0$ GeV $m_t^{MC} = 173.2 \pm 1.0$ GeV

# Again – different systematic uncertainties

| | | $\mu$+jets | $e$+jets | $e\mu$ |
|---|---|---|---|---|
| Experimental | Jet energy scale | $0.30 \pm 0.01$ | $0.30 \pm 0.01$ | $0.30 \pm 0.01$ |
| | Multijet normalization ($\ell$+jets) | $0.50 \pm 0.01$ | $0.67 \pm 0.01$ | - |
| | W+jets normalization ($\ell$+jets) | $1.42 \pm 0.01$ | $1.33 \pm 0.01$ | - |
| | DY normalization ($\ell\ell$) | - | - | $0.38 \pm 0.06$ |
| | Other backgrounds normalization | $0.05 \pm 0.01$ | $0.05 \pm 0.01$ | $0.15 \pm 0.07$ |
| | W+jets background shapes ($\ell$+jets) | $0.40 \pm 0.01$ | $0.20 \pm 0.01$ | - |
| | Single top background shapes | $0.20 \pm 0.01$ | $0.20 \pm 0.01$ | $0.30 \pm 0.06$ |
| | DY background shapes ($\ell\ell$) | - | - | $0.04 \pm 0.06$ |
| | Calibration | $0.42 \pm 0.01$ | $0.50 \pm 0.01$ | $0.21 \pm 0.01$ |
| Theory | $Q^2$-scale | $0.47 \pm 0.13$ | $0.20 \pm 0.03$ | $0.11 \pm 0.08$ |
| | ME-PS matching scale | $0.73 \pm 0.01$ | $0.87 \pm 0.03$ | $0.44 \pm 0.08$ |
| | PDF | $0.26 \pm 0.15$ | $0.26 \pm 0.15$ | $0.26 \pm 0.15$ |
| | Hadronization model | $0.95 \pm 0.13$ | $0.95 \pm 0.13$ | $0.67 \pm 0.10$ |
| | B-hadron composition | $0.39 \pm 0.01$ | $0.39 \pm 0.01$ | $0.39 \pm 0.01$ |
| | B-hadron lifetime | $0.29 \pm 0.18$ | $0.29 \pm 0.18$ | $0.29 \pm 0.18$ |
| | Top quark $p_T$ modeling | $3.27 \pm 0.48$ | $3.07 \pm 0.45$ | $2.36 \pm 0.35$ |
| | Underlying event | $0.27 \pm 0.51$ | $0.25 \pm 0.48$ | $0.19 \pm 0.37$ |
| | Colour reconnection | $0.36 \pm 0.51$ | $0.34 \pm 0.48$ | $0.26 \pm 0.37$ |

- Leading systematic: $p_T^{top}$ modeling




## Final results

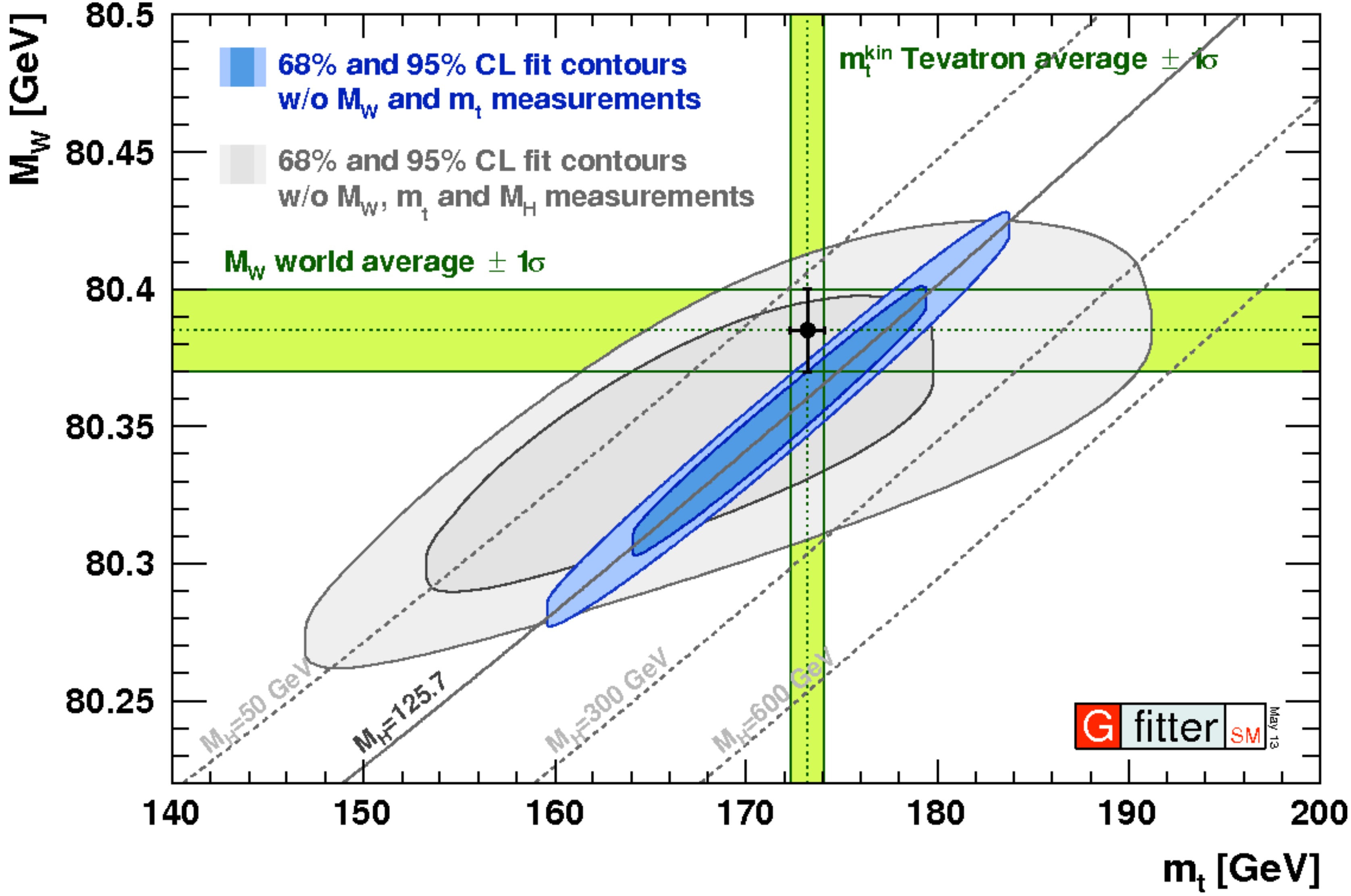
| Channel | $m_t$ [GeV] |
|---|---|
| muon+jets | $173.2 \pm 1.0_{stat} \pm 1.6_{syst} \pm 3.3_{p_T(t)}$ |
| electron+jets | $172.8 \pm 1.0_{stat} \pm 1.7_{syst} \pm 3.1_{p_T(t)}$ |
| electron-muon | $173.7 \pm 2.0_{stat} \pm 1.4_{syst} \pm 2.4_{p_T(t)}$ |

## Combination of all channels

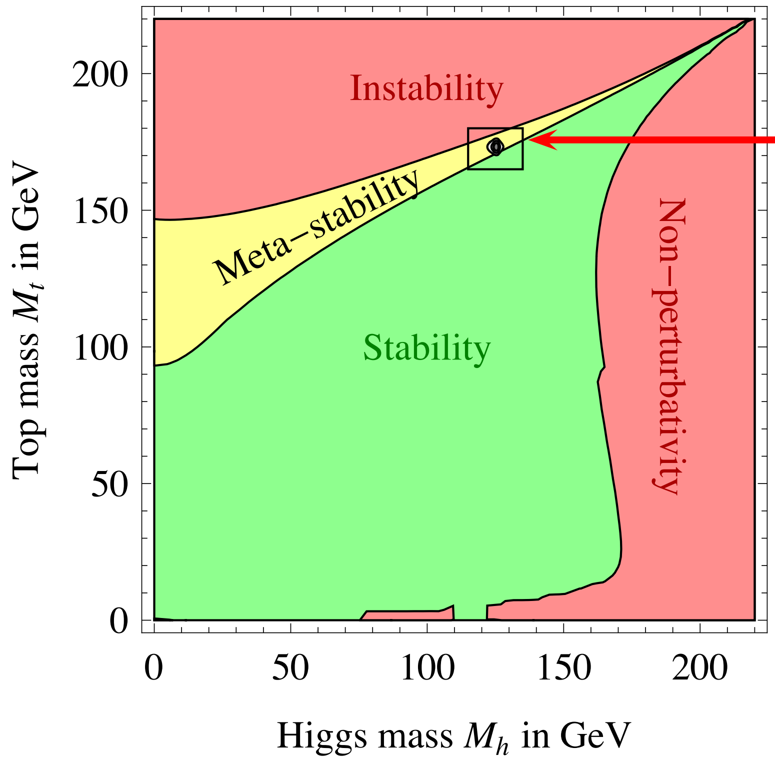
$$m_t^{MC} = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{p_T^{top}}$$

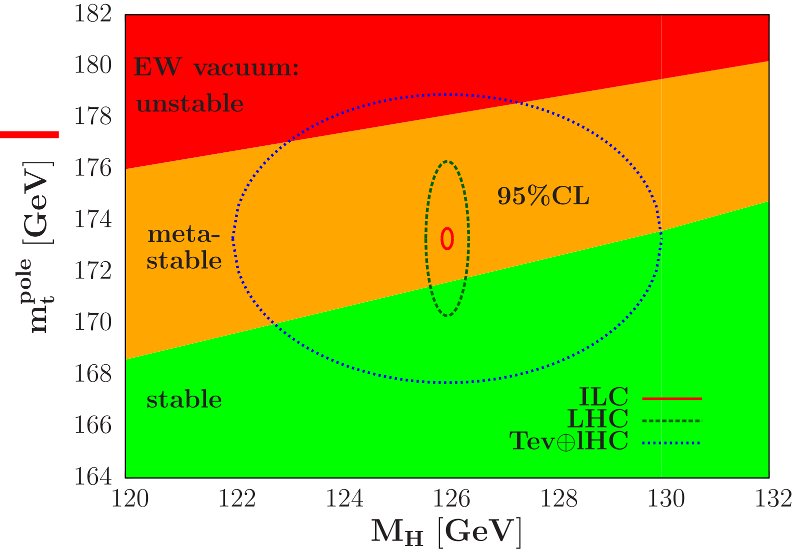
src: Stijn Blyweert @EPS-HEP 2013

# Top quark mass in Standard Model



# The top mass vs stability of the universe




- Constraints from the SM can also be used to assess stability of physics laws
  - Example: arXiv:1205.6497

# End of lecture two – questions?