Top-quark pole mass determination using ttbar+1Jet events at LHC

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Third Higgs Tools Annual meeting, 15th-20th May, Torino, Italy

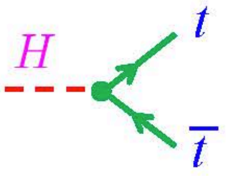
Motivation to measure the top-quark mass

- The Standard Model (SM) has a set of free parameters that need to be determined experimentally

$$\mathcal{L}_{QCD} = -\frac{1}{4}(\partial^\mu G^\nu_a - \partial^\nu G^\mu_a)(\partial_\mu G^a_\nu - \partial_\nu G^a_\mu) + \sum_f \bar{q}^\alpha_f \,(i\gamma^\mu\partial_\mu - m_f)\, q^\alpha_f - g_s G^\mu_a \sum_f \bar{q}^\alpha_f \gamma_\mu \left(\frac{\lambda^a}{2}\right)_{\alpha\beta} q^\beta_f - \frac{g_s}{2} f^{abc}(\partial^\mu G^\nu_a - \partial^\nu G^\mu_a) G^b_\mu G^c_\nu - \frac{g_s{}^2}{4} f^{abc} f_{ade} G^\mu_b G^\nu_c G^d_\mu G^e_\nu$$

$\alpha_s = g_s^2/4\pi$ and quark masses are not predicted by the SM

m_{top}
- Fundamental parameter of the SM interesting per se
- Important for precise tests of the Standard Model, Yukawa coupling ~ 1
- Test of New Physics scenarios i.e. GUT scenarios, vacuum stability



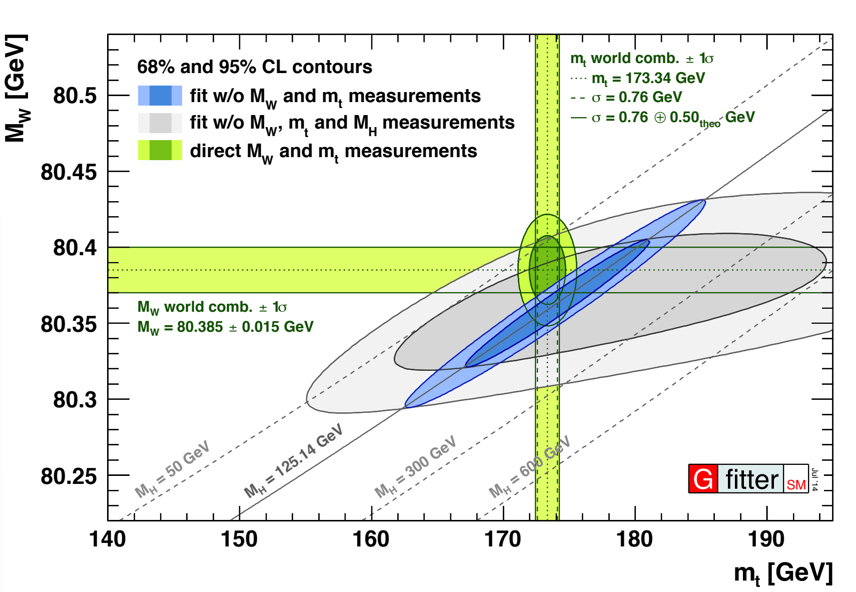
$$y_t = \frac{\sqrt{2}}{v} m_t = 2^{3/4} G_F^{1/2} m_t = 1 \qquad (0.995)$$

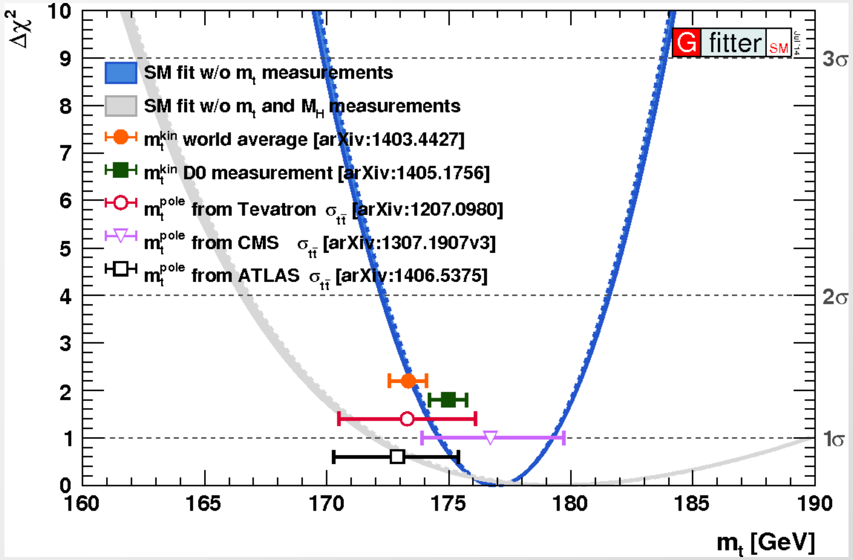
Motivation to measure the top-quark mass

EW consistency between: M_W ⌘ M_H ⌘ M_t

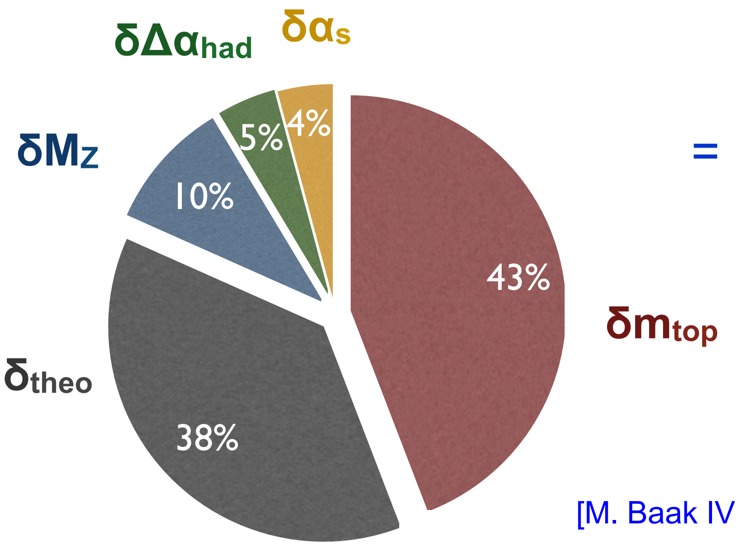
Gfitter group

http://project-gfitter.web.cern.ch/project-gfitter/Standard_Model/





$$M_W = M_W^{LO} + \Delta r_{top} + \Delta r_H$$



- δM_W (indirect) = = 11 MeV
  - Large contributions to δM_W (and $\delta \sin^2\theta^l_{eff}$) from top and unknown higher-order EW corrections.
- δM_W (direct) = 15 MeV

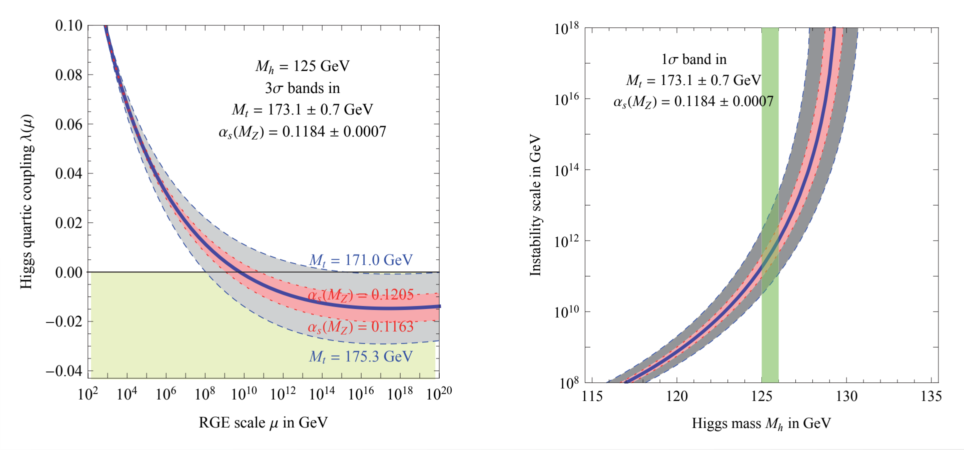
[M. Baak IVICFA2013]

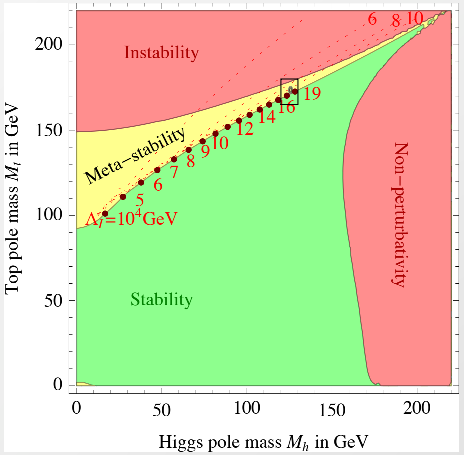
Motivation to measure the top-quark mass

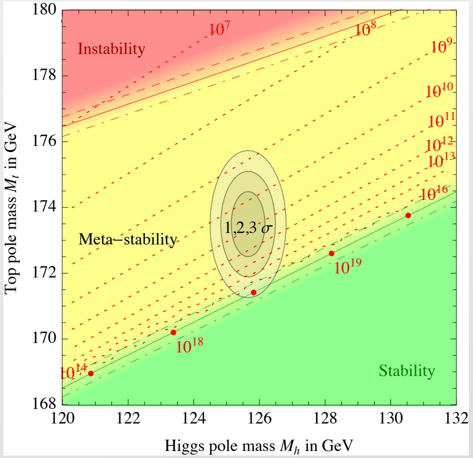
Vacuum Stability ($\lambda(\Lambda) \geq 0$)

$\lambda(\Lambda)$ the $\overline{\text{MS}}$ quartic Higgs Coupling

Degrassi et al, **JHEP 1208 (2012) 098**
Butazzo et al, **1307.3536 (2013)**







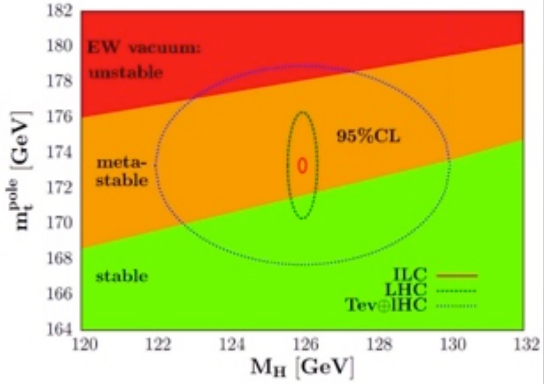
Assume SM valid up to $\Lambda \leq M_{planck}$

$M_t = (173.35 \pm 0.72)$ GeV $\longrightarrow$ $M_h > (129.6 \pm 1.5)$ GeV

$M_h = (125.66 \pm 0.34)$ GeV $\longrightarrow$ $M_t < (171.36 \pm 0.46)$ GeV

Take M_t from ttbar X-section (pole mass)

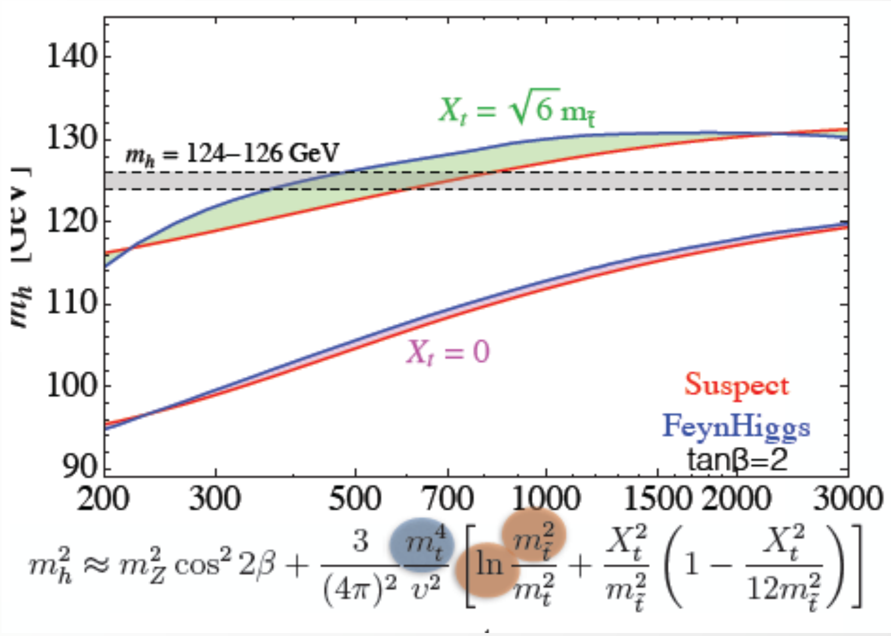
$M_t = (173.3 \pm 2.8)$ GeV $\longrightarrow$ $M_h > (129.4 \pm 5.6)$ GeV



Alekhin et al, **Phys.Lett. B716 (2012) 214**

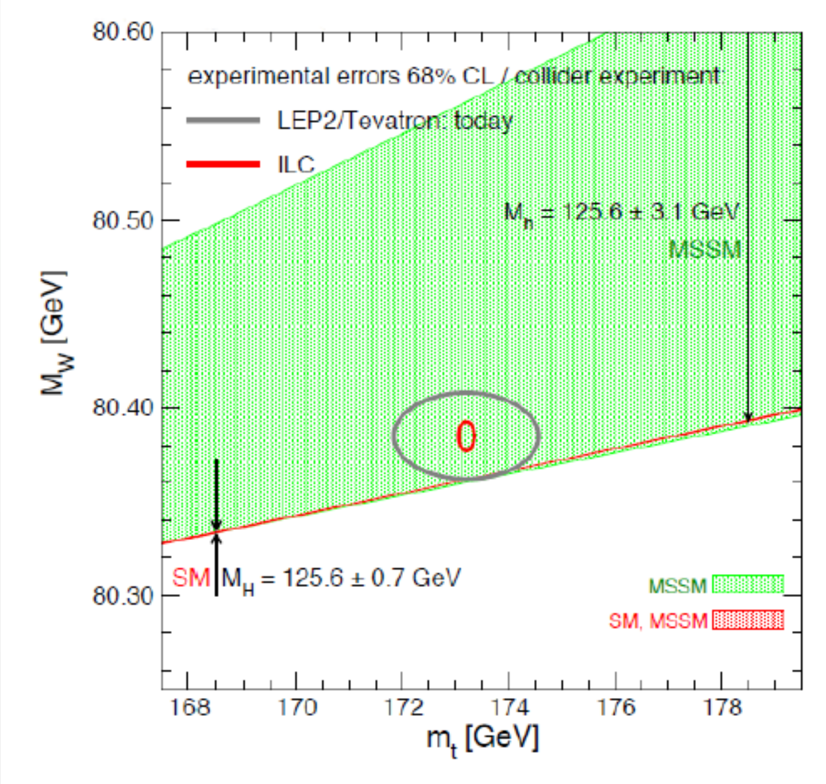
Motivation to measure the top-quark mass

Consistency checks with the SM and possible New Physics



$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde t}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde t}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde t}^2}\right)\right]$$

Roberto Franceschini (IFIC seminar, Valencia 2015)



Large mass ⟷ Sizeable effects

[www.ifca.unican.es/users/heinemey/uni/plots]

The top-quark mass defintion

- Free quarks are not observed in nature as they are confined into colorless hadrons, so there is no pole in the S-matrix

  - ✓ quark-masses, in particular the top-quark mass, are not “observables” and they are parameters of the underlying theory

    ➔ fit $O^{exp}(x)$ with $O^{th}(M_t,\alpha_s;x)$ and extract M_t ➔

  - ✓ precise value depends on the definition of the renormalization scheme selected (pole mass, $\overline{\text{MS}}$, etc..)

  - ✓ to fix the renormalization scheme at least a NLO calculation is required

Pole mass
vs
running mass

$$m_t = \overline{m}(\mu)\left(1+\frac{\alpha_s(\mu)}{\pi}\left[\frac{4}{3}+\ln\left(\frac{\mu^2}{\overline{m}(\mu)^2}\right)\right]+O(\alpha_s^2)\right)$$

The top-quark mass definition

- Different mass definitions used in present determinations:
  - ✓ The MC mass (m_t^{MC}) as the parameter used in the MC generator program
  - ✓ The pole mass (m_t^{pole})

- There is no well defined prescription how to relate m_t^{MC} with m_t^{pole}

- Current “estimation” of the uncertainty/difference ~ O(1) GeV

  - S. Moch et al., arXiv:1405.4781,
  - ATLAS, CDF, CMS and D0 Collaborations, arXiv:1403.4427,
  - A. H. Hoang and I. W. Stewart, 500 Nouvo Cimento B123 (2008) 1092–1100,
  - A. Buckley et al., arXiv:1101.2599
  - A. H. Hoang, arXiv:1412.3649.
  - M. Butenschoen et al., PoS(ICHEP2016)698.

Extracting the top-quark mass using ttbar+1-jet events

tt+1-jet event topologies
Jet requirement → P_T > 50 GeV
(IR-safe observable)

- Large event rates at the LHC (~30% at 7-8 TeV)
- NLO and NLO+shower corrections available
- Gluon emission & threshold effects depend on top-quark mass

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

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$

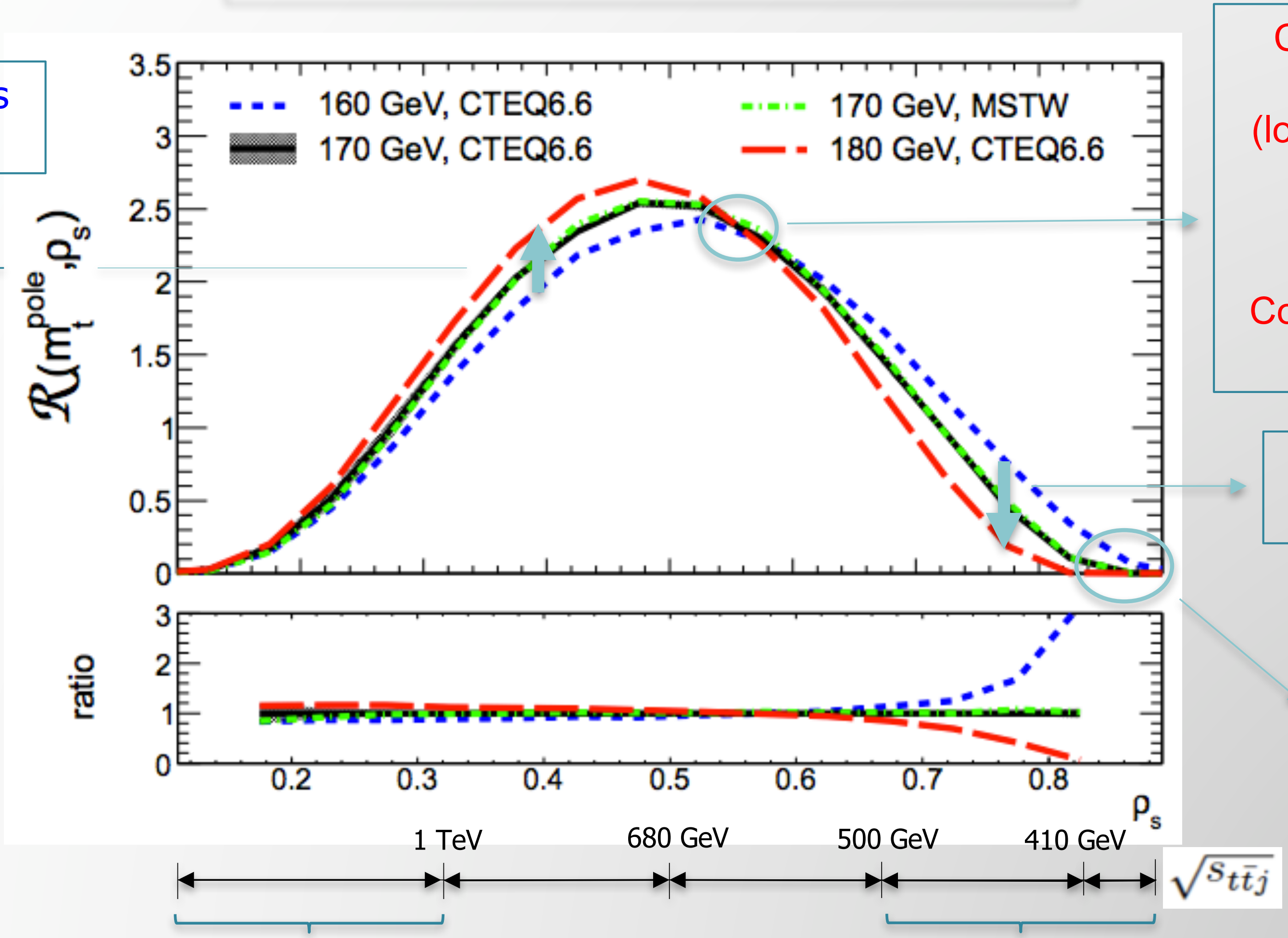
and m_0 = 170 GeV

Normalized 3-jet differential cross section as a function of the inverse of the system invariant mass

- Renormalization scheme is fixed through NLO calculation → M_t^{pole} defined here and $\overline{\text{MS}}$ –the running mass scheme- can also be used
- Differential distribution enhance the top-quark mass sensitivity
- Theoretical and experimental uncertainties are minimized through normalization

Properties of R

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



Top-quark mass sensitivity

Crossing due to normalization (loss of sensitivity)

No mass dependece – Control/Calibration Region

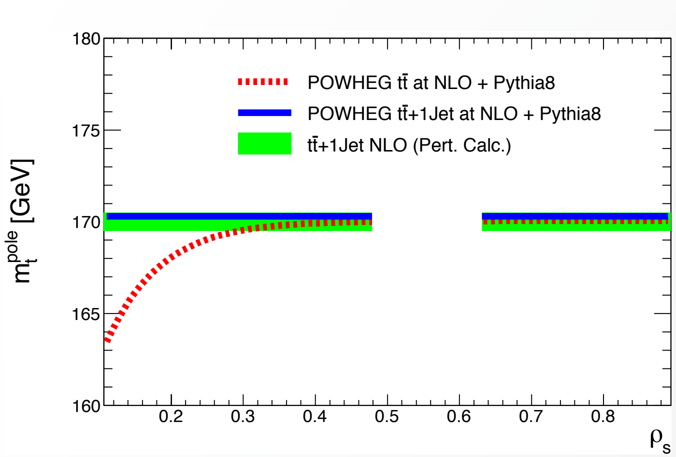
Top-quark mass sensitivity

Threshold

High energies (control region)

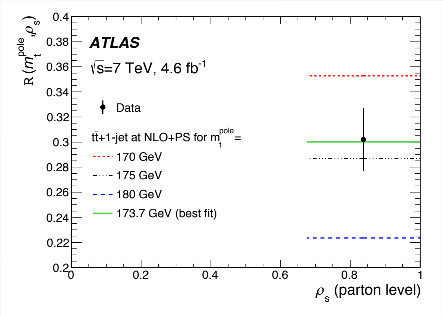
Low energies (high sensitivity)

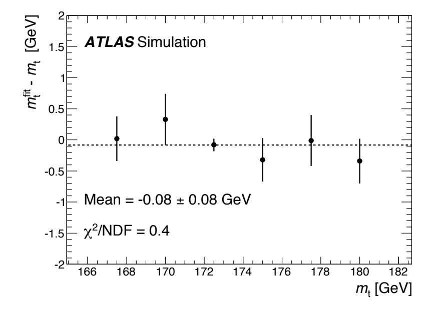
Main results at 7 TeV

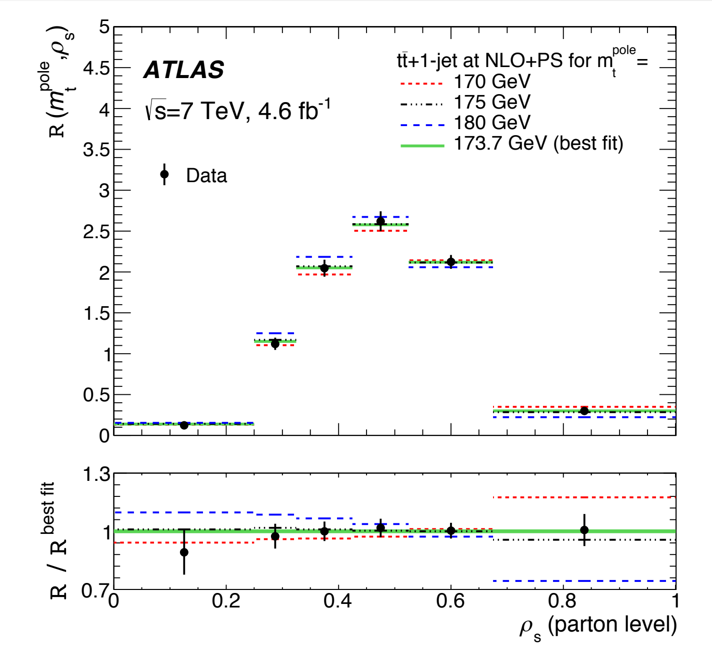


S. Alioli et al., Eur. Phys. J. 513 C73 (2013) 2438

ATLAS, JHEP 1510 (2015) 175







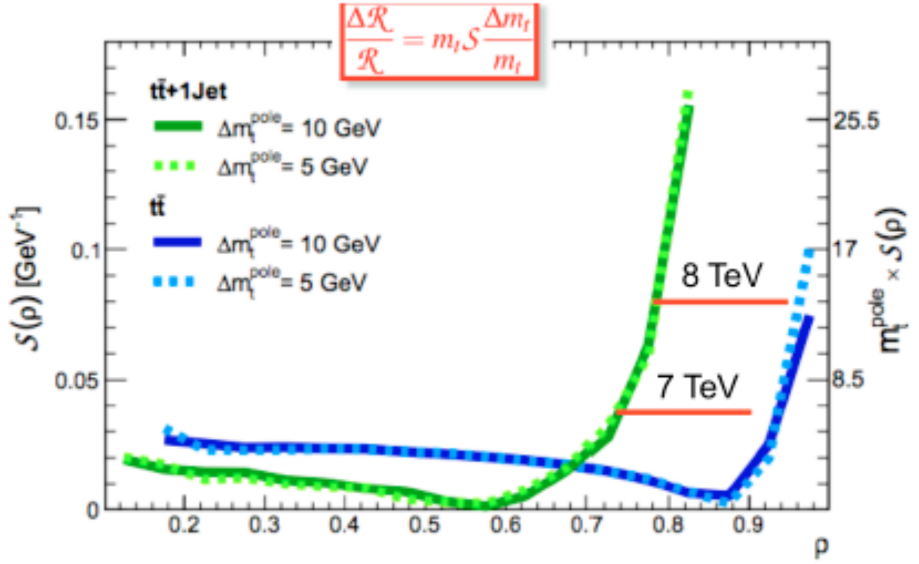
- Top-quark pole mass extracted from a fit to R using NLO+PS theoretical calculation:

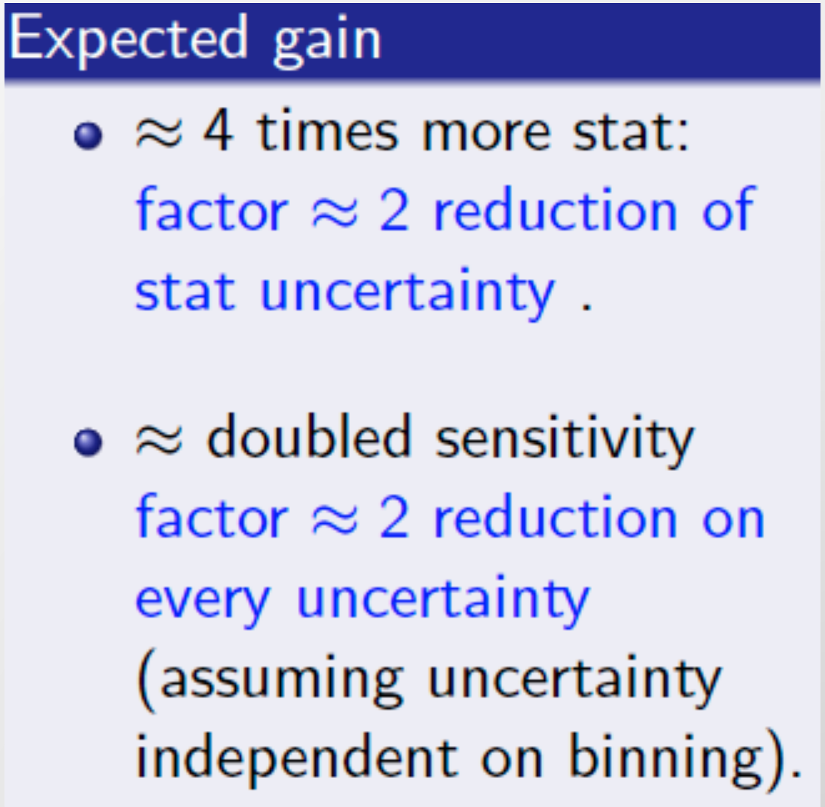
$$m_t^{pole} = 173.7 \pm 1.5(stat.) \pm 1.4(syst.)^{+1.0}_{-0.5}(theo.)\ \text{GeV}$$

- No mass dependence on the top-quark mass used in the MC simulation (≤80 MeV)
- Main uncertainties: σ(JES)=0.94 GeV, $\sigma(\mu_{R/F})$=0.93 GeV; σ(ISR/FSR)=0.72 GeV

The 8 TeV analysis and beyond

$$\mathcal{S}_\Delta(\rho_s) = \frac{|\mathcal{R}(m_0+\Delta) - \mathcal{R}(m_0-\Delta)|}{2\Delta\mathcal{R}(m_0)}$$





Expected gain

- ≈ 4 times more stat: factor ≈ 2 reduction of stat uncertainty .
- ≈ doubled sensitivity factor ≈ 2 reduction on every uncertainty (assuming uncertainty independent on binning).

- Larger event sample reduces the statistical and systematic uncertainties
- A potential reduction of 40% total uncertainty is in reach when using 8 TeV data (of course needs to be confirmed by making the real analysis).
- 8 TeV analysis will be included in Davide’s PhD.

The 8 TeV analysis and beyond: Running mass

Alternative renormalisation scheme: $m_t^{\overline{\mathrm{MS}}}$

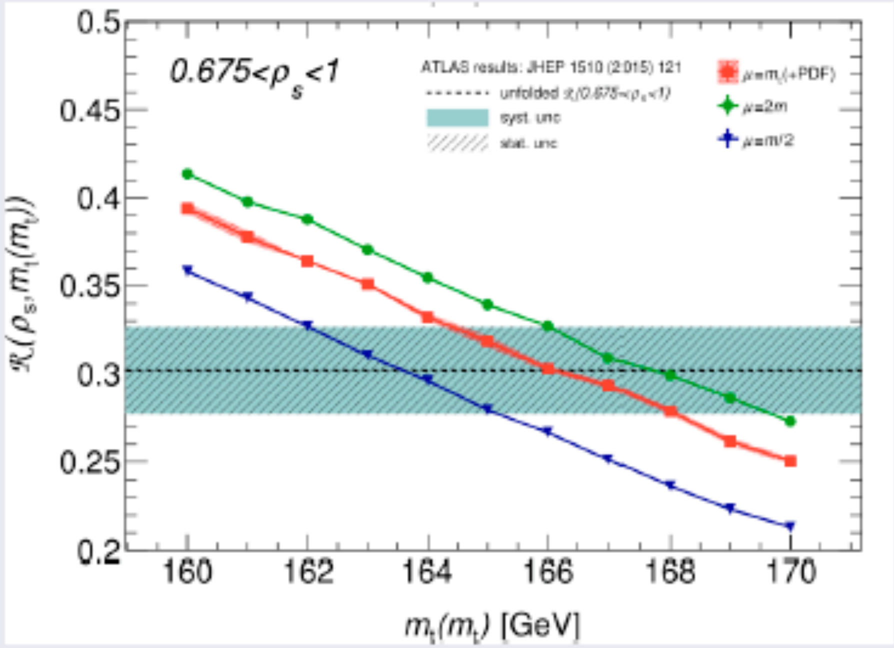
Recent article in collaboration with A.Irles and P.Uwer: arXiv:1704.00540

Use $m_{top}^{pole}(m_t^{\overline{\mathrm{MS}}})$ relation to obtain $\sigma_{t\bar{t}+1\,\mathrm{jet}}(m_t^{\overline{\mathrm{MS}}})$@NLO+PS

Method applied to 7 TeV data:

$$m_t^{\overline{\mathrm{MS}}} = 165.9^{+2.4}_{-2.0}\ \mathrm{GeV}$$
$$m_{top}^{pole} = 173.7^{+2.3}_{-2.1}\ \mathrm{GeV}$$

- No changes in data correction procedure.
- Just need to produce theoretical template and redo fits.
- No big changes expected in systematics
- Could be added in a later stage of approval (time issues)



Davide’s PhD

- ATLAS 8 TeV analysis. Internal note produced. Approval process ongoing.

- Running mass scheme included and results provided. Combined theoretical and experimental paper produced (ArXiv:1704.00540)

- Prospects for 13 TeV and 100 fb^{-1}