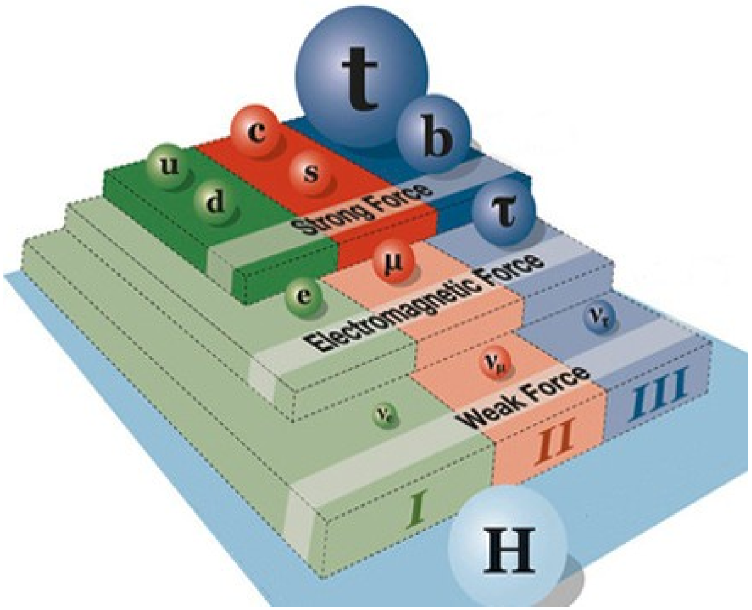
Top quark pole mass determinations from differential $t\bar{t}$+1 jet cross sections.



Adrian Irles

9th Annual Meeting of the Helmholtz Alliance “Physics at the Terascale”

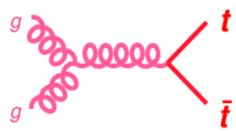
18th November 2015

HELMHOLTZ ASSOCIATION

DESY

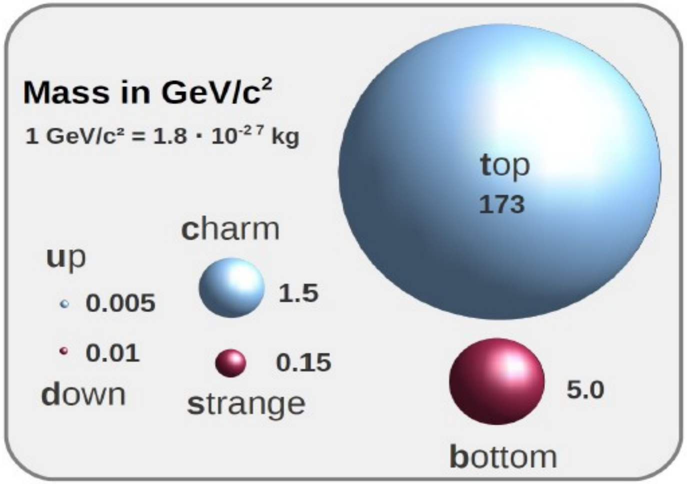
The top quark

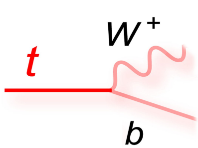
- The **heaviest elementary particle** discovered so far
- Discovered in 1995 → only observed in Tevatron ($p\bar{p}$) and LHC (pp)
- Mainly produced in pairs

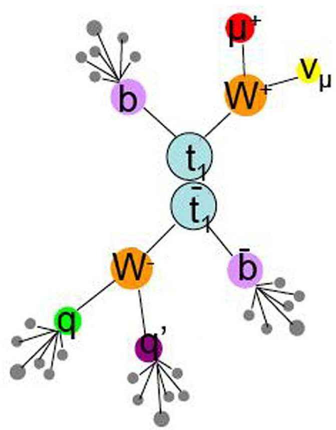


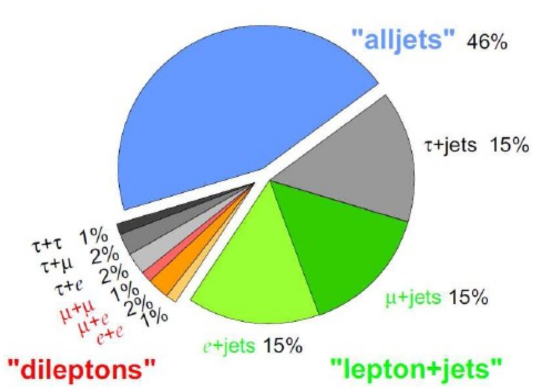
- A peculiar quark with an enormous mass
  - **large coupling to the Higgs**
  - It decays before hadronize

> measure its spin polarization
> **Experimental signature: quasi-free quark**









DESY

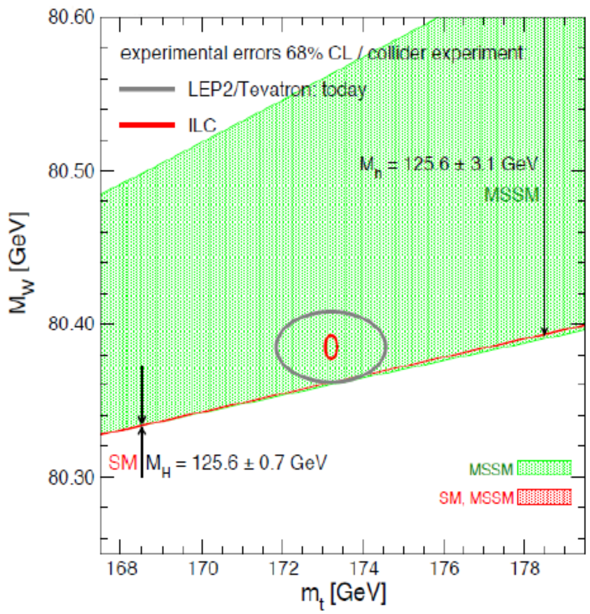
Motivation for precise top quark mass measurements

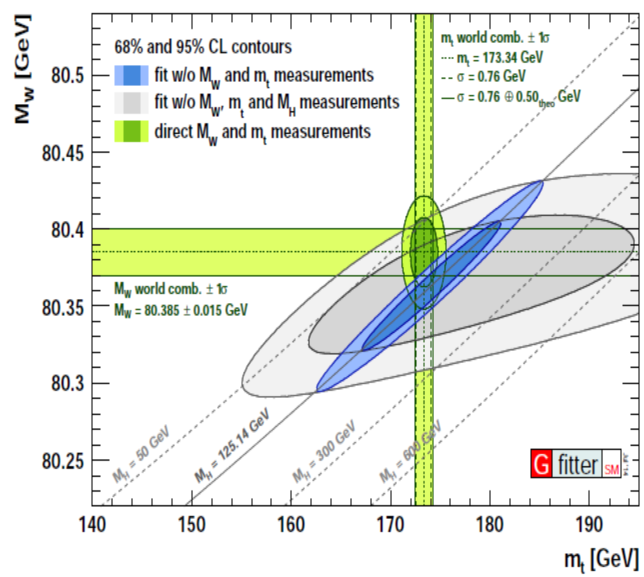
- Is a fundamental parameter of the Standard Model.
- Largest coupling to the Higgs coupling → **special role in the ElectroWeak Sector in the SM and BSM**
- Consistency of the Standard Model and Beyond Standard Models

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

$$\Delta r_{top} \simeq -\frac{3 G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{\tan\theta_W}$$

$$\Delta r_H \simeq \frac{11 G_F M_Z^2 \cos\theta_W}{24\sqrt{2}\pi^2}\ln\frac{M_H^2}{M_Z}$$



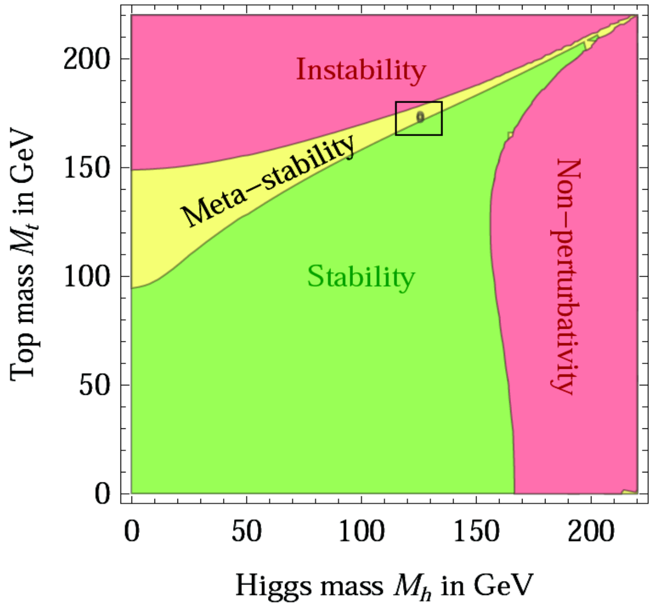


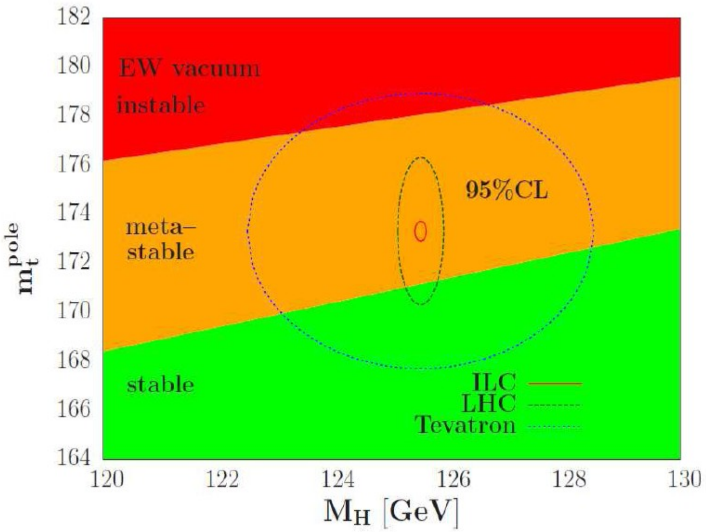
[Heinemeyer et al updated to summer 2014]

Motivation for precise top quark mass measurements

- Standard Model Vacuum stability
- “Only asummption”: there is no no new physics up to the Planck scale

$$M_H > 129.6\ \text{GeV} + 2.0\left(m_t^{pole} - 173.34\ \text{GeV}\right) - 0.5\ \text{GeV}\ \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \pm 0.3\ \text{GeV}$$





[Degrassi, Di Vita, Elias-Miro,Spinosa,Giudici ’ 12,
Alekhin, Djouadi, Moch ’ 12]

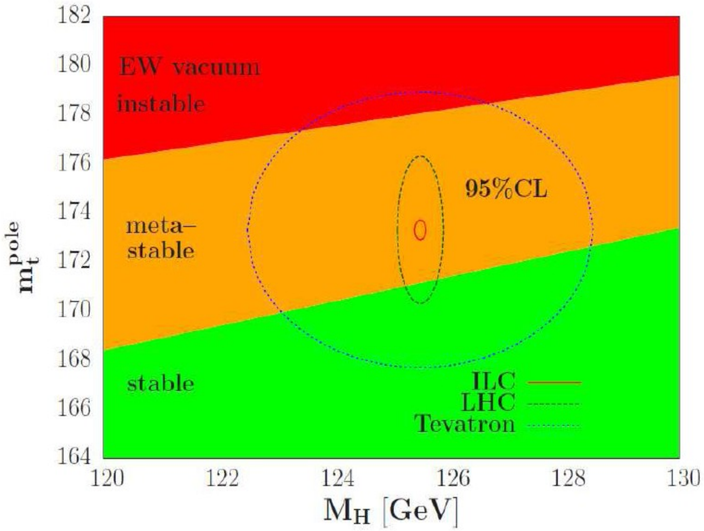
Motivation for precise top quark mass measurements

- Standard Model Vacuum stability
- “Only asummption”: there is no new physics up to the Planck scale
- What if new physics?

Motivation for precise top quark mass measurements

- Standard Model Vacuum stability
- “Only asummption”: there is no new physics up to the Planck scale
- What if new physics?

$$V(\phi) = \lambda\phi^4/4 + \lambda_6\phi^6/(6M_P^2) + \lambda_8\phi^8/(8M_P^4)$$



[Degrassi, Di Vita, Elias-Miro,Spinosa,Giudici ’ 12,
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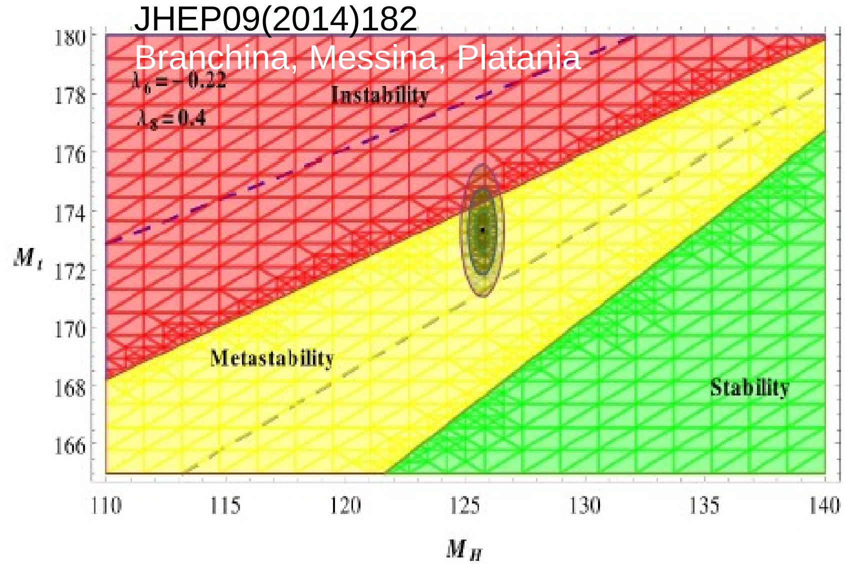
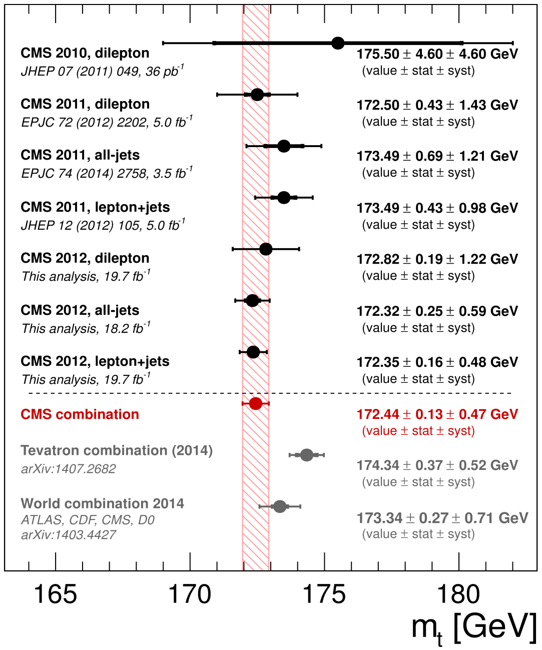


(ellipses: best top quark kinematic mass)

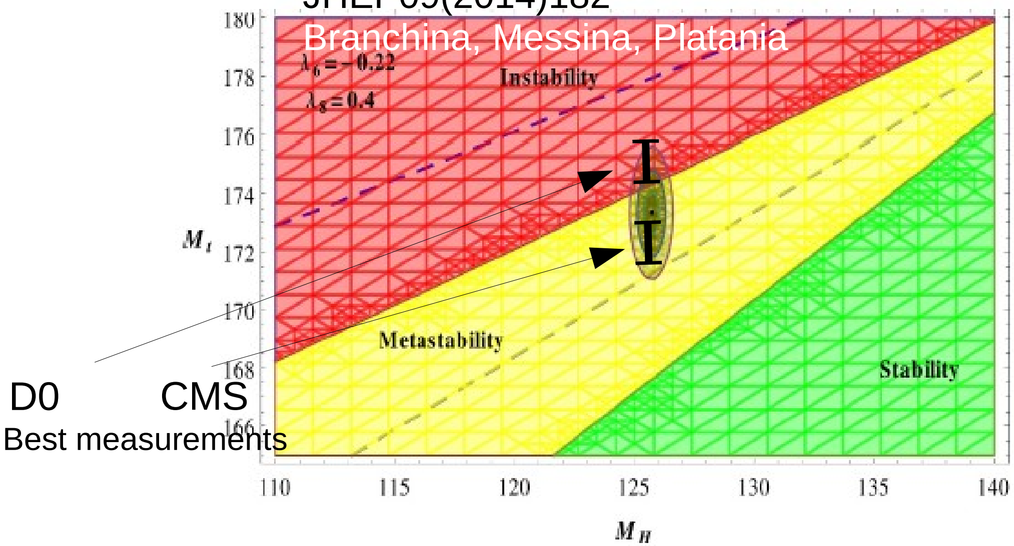
DESY

Top quark kinematic mass measurement

- > Top quark mass measurement from the reconstruction of the invariant mass of its decay products.
- > **Very small experimental uncertainties**
  - ~ 0.3-0.4% of its mass (~0.7% for b, ~2% for c and ~2-5% for light quarks)
  - Huge improvement in last years (over expectations) in our understanding of the detectors and tt signal modelling.
  - Experimental precision of ~0.6 GeV (best measurements)
- > stress between different experiments results?



JHEP09(2014)182



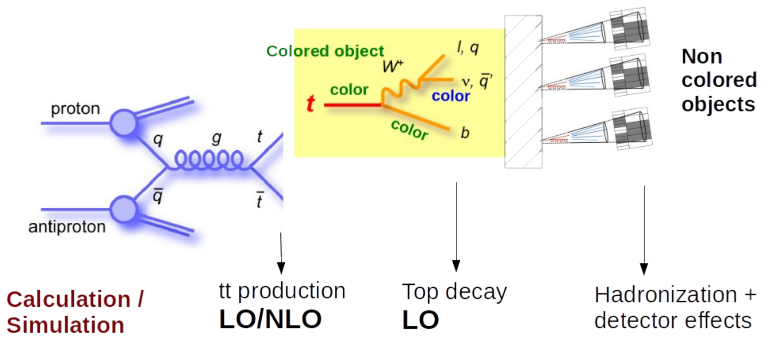
$$V(\phi) = \lambda\phi^4/4 + \lambda_6\phi^6/(6M_P^2) + \lambda_8\phi^8/(8M_P^4)$$

http://arxiv.org/abs/1509.04044

DESY

Top quark kinematic mass measurement

- Top quark mass extracted from the invariant mass of its decay products
  - Top quark is treated as a “free stable particle” even since quarks do not exist as asymptotic free states (due to color charge)
  - Mass calibrated to the mass definition used in the Monte Carlo simulations, dominated by soft-collinear approximation.



- Mass interpretation? Read “First Tevatron+LHC combination” paper arXiv1403.442 conclusions

. Given the current experimental uncertainty on m_{top}, clarifying the relation between the top quark mass implemented in the MC and the formal top quark pole mass demands further theoretical investigations.

- $m_t^{kin} = m_t^{pole} (1 + \Delta)$, $\Delta \rightarrow$ **unknown**
  - **¿~ 1 GeV ?** *(see for example Hoang, Stewart arXiv:0808.0222)*

Measuring the top quark mass

- Quark masses are not observables, are parameters of the theory (i.e. strong coupling constant)
- They need to be determined through their influence on hadronic observables
  - Theoretical predictions are compared with measurements and the parameters (mass, strong coupling constant etc) are extracted through a fit

- Such observables should fulfill the following requirements:
  - show **good sensitivity** $\frac{\Delta O}{O} \leftrightarrow \frac{\Delta m_t}{m_t}$
  - be theoretically calculable and have **small theoretical uncertainties.**
  - **be defined using well defined mass scheme**
  - **be experimentally accessible** (small experimental uncertainties)

P. Uwer,
La Thuile, Feb. 2013

The R- observable

Alioli, Fernandez, Fuster, Irles, Moch, Uwer, Vos   Eur.Phys.J. C73 (2013) 2438

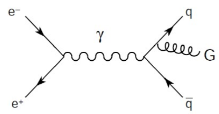
> The observable :

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s), \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$

m_0=170 GeV

> tt+1 jet cross section

- The production of extra gluons (quarks) depend on the top quark mass



$$\sigma_{q\bar{q}g} \propto A(\alpha_s, \sqrt{s}) + B(\alpha_s, \sqrt{s}, m_q)\frac{m_q^2}{s} + \dots$$

> Differential cross section

- The mass dependence is enhanced in certain regions of the phase space

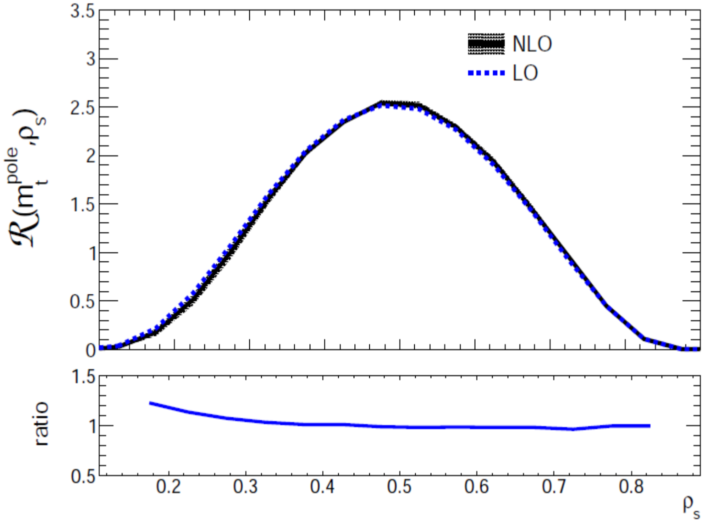
> Normalized cross section

- Cancelation and reduction of systematic uncertainties (theoretical and experimental)

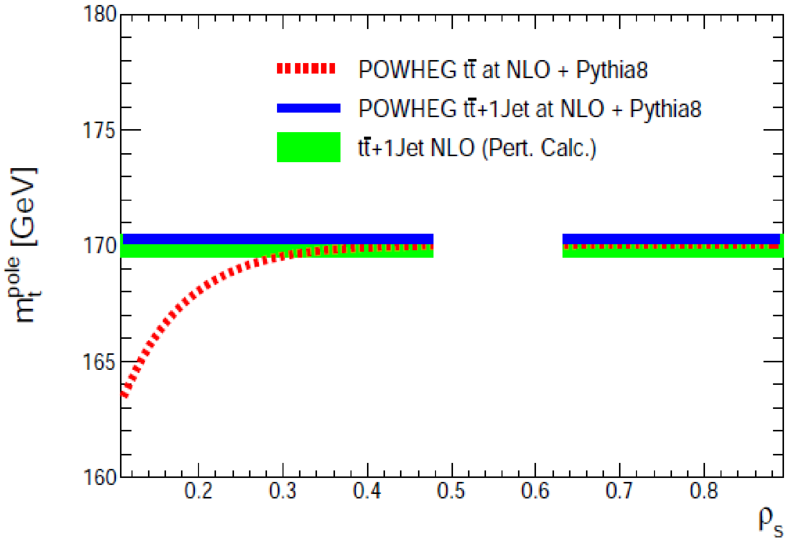
The R- observable: calculation

> Robust observable with small NLO and PS corrections

- NLO vs LO, both at fixed order [Dittmaier et al Eur.Phys.J. C59 (2009)]
- *NLO vs NLO+PS, calculation implemented in PowHeg and matched with PS algorithms (NLO+PS)* [Alioli et al, JHEP 1201 (2012) 137]



NLO vs LO
→ small corrections

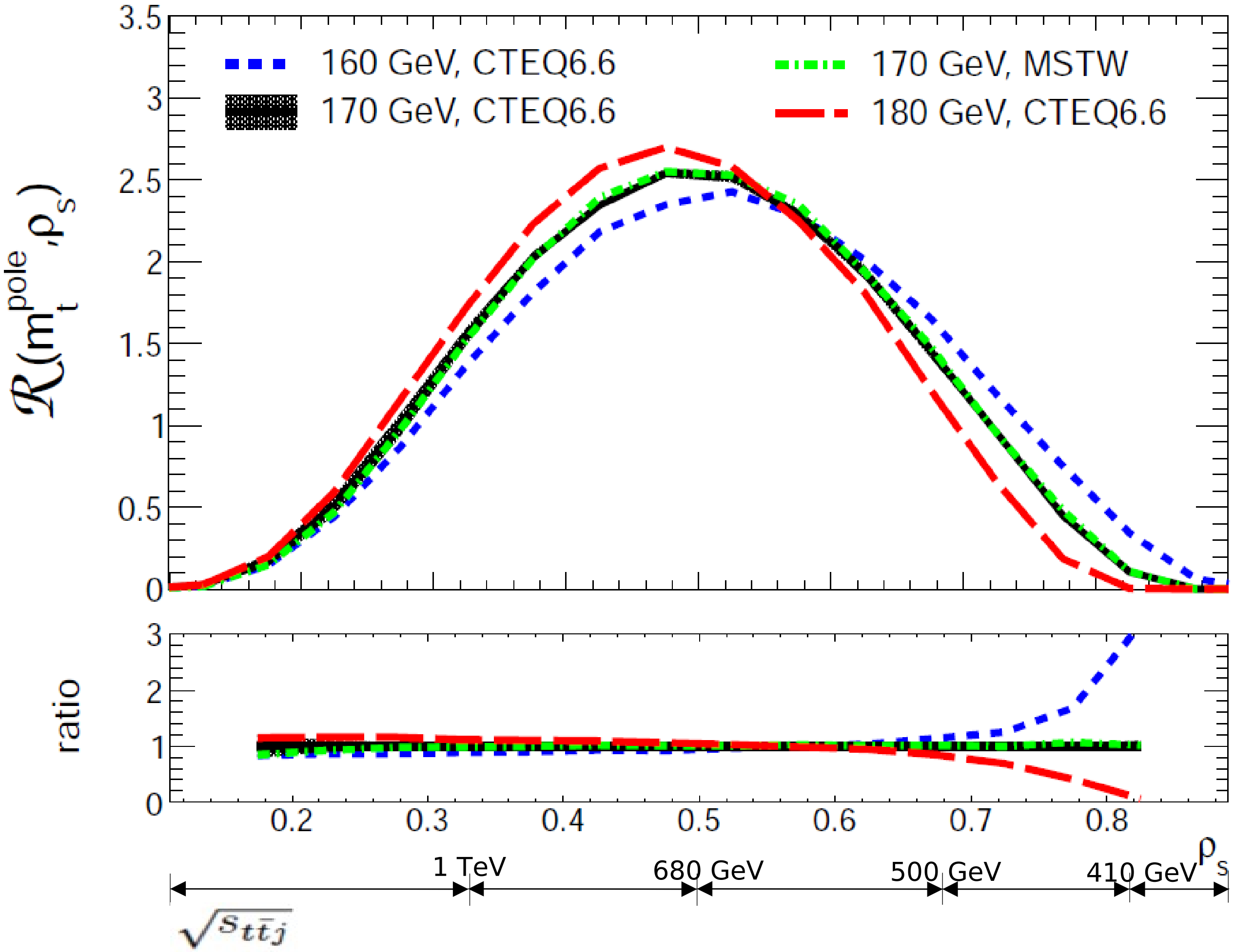


Fixed NLO vs NLO+PS
→ small corrections

Eur.Phys.J. C73 (2013) 2438

The R-observable: mass dependence

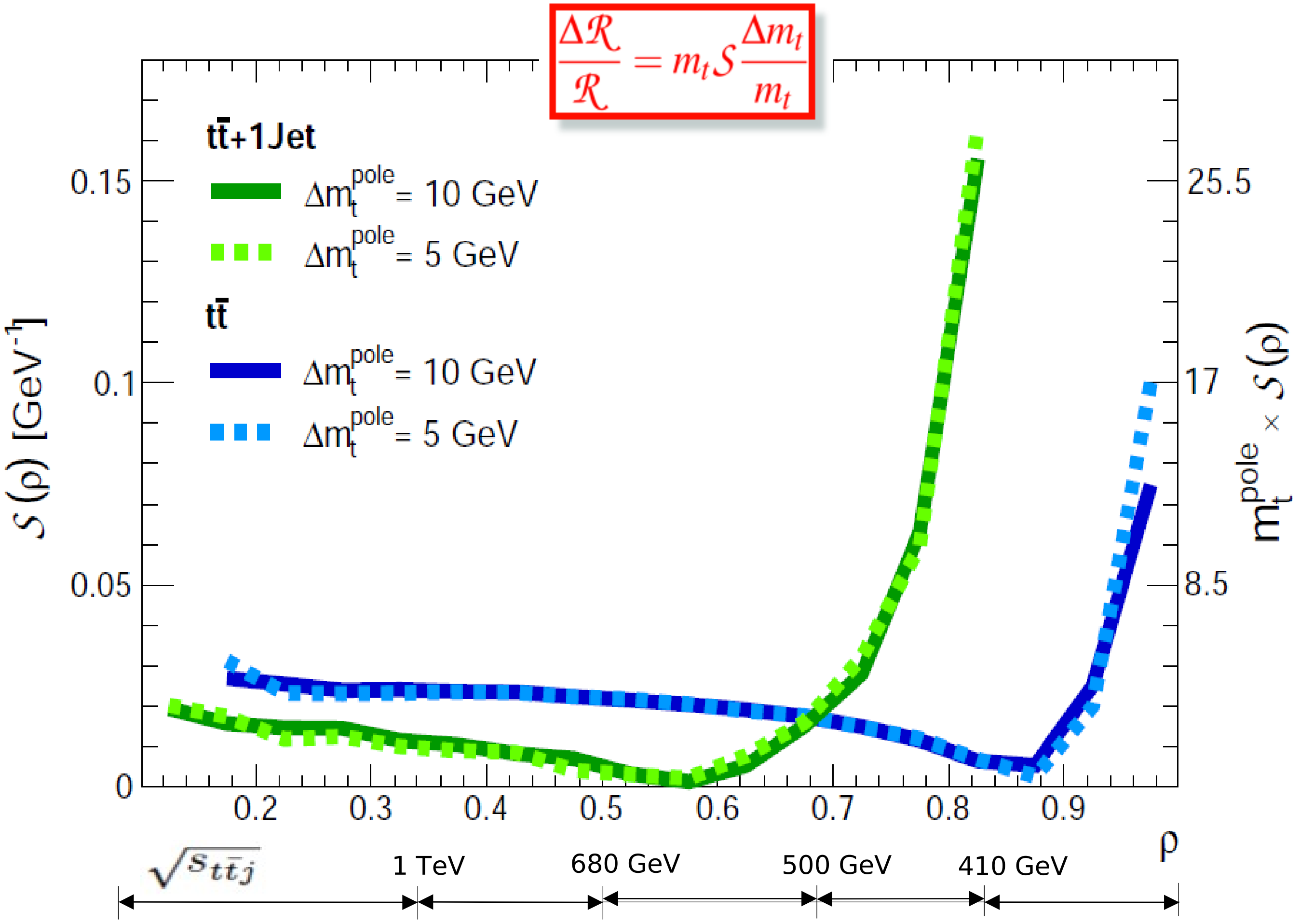
- Mass dependence



Eur.Phys.J. C73 (2013) 2438

The R-observable: mass sensitivity

> High sensitivity



Eur.Phys.J. C73 (2013) 2438

Experimental determination

- This method is being used by the LHC experiments
- I will focus in the ATLAS result (the only which is already public)
  - **JHEP 1510 (2015) 121**

Determination of the top-quark pole mass using $t\bar{t}$ + 1-jet events collected with the ATLAS experiment in 7 TeV pp collisions

The ATLAS Collaboration

Abstract

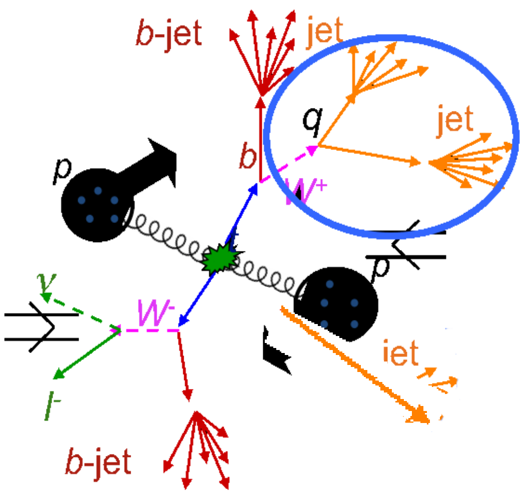
The normalized differential cross section for top-quark pair production in association with at least one jet is studied as a function of the inverse of the invariant mass of the $t\bar{t}$+1-jet system. This distribution can be used for a precise determination of the top-quark mass since gluon radiation depends on the mass of the quarks. The experimental analysis is based on proton–proton collision data collected by the ATLAS detector at the LHC with a centre-of-mass energy of 7 TeV corresponding to an integrated luminosity of 4.6 fb^{-1}. The selected events were identified using the lepton+jets top-quark-pair decay channel, where lepton refers to either an electron or a muon. The observed distribution is compared to a theoretical prediction at next-to-leading-order accuracy in quantum chromodynamics using the pole-mass scheme. With this method, the measured value of the top-quark pole mass, m_t^{pole}, is:

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

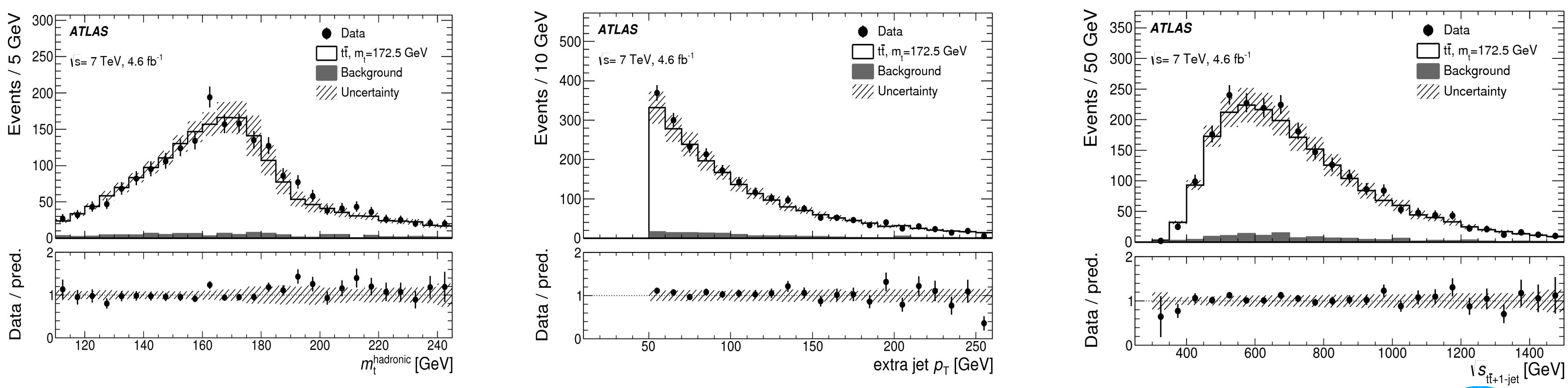
This result represents the most precise measurement of the top-quark pole mass to date.

Selection and event reconstruction

JHEP 1510 (2015) 121



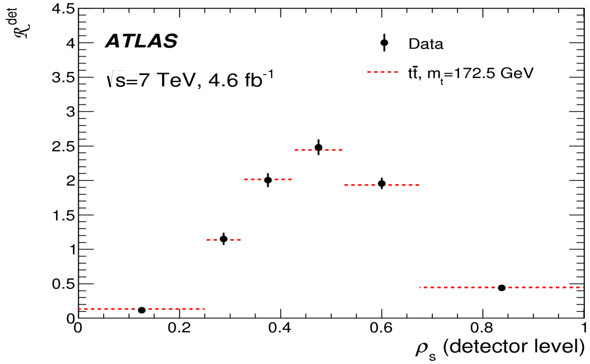
- Semileptonic decay channel. Selection
  - Exactly 1 lepton (no taus) with pT>25 GeV
  - Large amount of missing energy (E_T^{miss} > 30 GeV)
  - Two btagged jets with pT> 25 GeV (exploiting the long lifetime of the b-hadrons)
  - At least non b-tagged jets with pT>25 GeV
  - M_T^W > 30 GeV, to reduce bkgs $m_T^W = \sqrt{2 p_{T,l}\, p_{T,\nu} [1 - \cos(\phi_l - \phi_\nu)]}$
- Kinematical event reconstruction to identify the tt candidates + the adittional jet candidate with pT> 50 GeV



Correction to parton level

JHEP 1510 (2015) 121

> Compare measured distribution with theoretical calculations

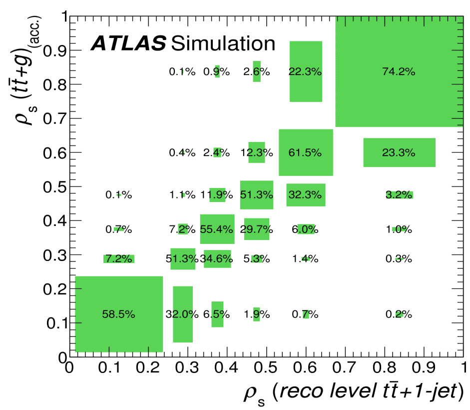


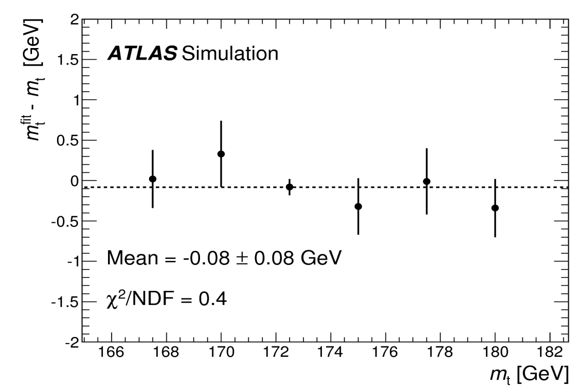
The cross section needs to be compared to theoretical calculations

in this case, to tt+1jet NLO+PS calculations at parton level

> Unfolding procedure based on the inversion and regularization of the matrix that describes the migrations between parton and detector level events.*

- Correct for acceptance and reconstruction efficiency and detector and hadronization effects.
- **The method is no MC mass dependent**





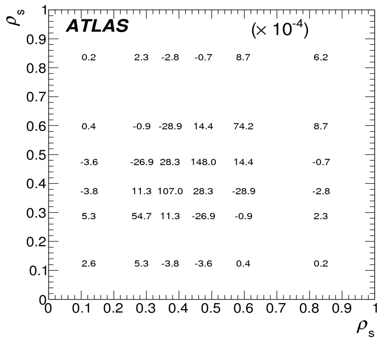
Choice of the bin size to optimize the sensitivity→ efficiency in the diagonal >50%

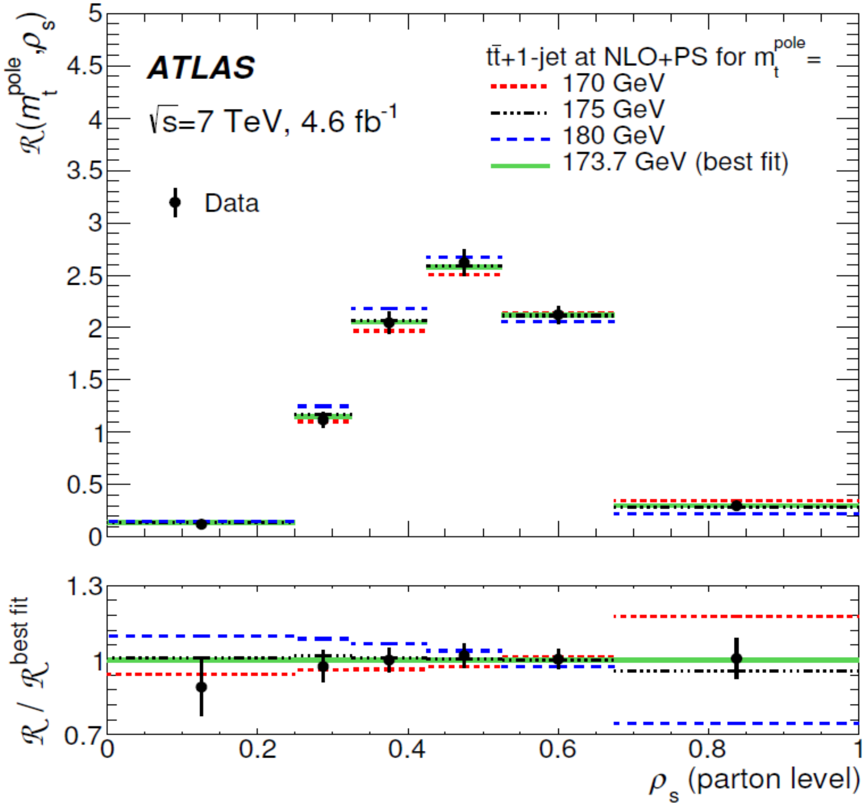
* see backup for more details

> Comparison with NLO+PS calculations

$$\chi^2 = \sum_{ij} (\mathcal{R}_i^{\text{cor-data}} - \mathcal{R}_i^{\text{theory}}(m_t^{\text{pole}})) V_{ij}^{-1} (\mathcal{R}_j^{\text{cor-data}} - \mathcal{R}_j^{\text{theory}}(m_t^{\text{pole}})),$$

- Where V is the covariance matrix derived during the unfolding





Uncertainties

- The uncertainties are separated in three categories.
  - Statistical uncertainties: is the dominant due to limited number of events in the data sample
    - **1.50 GeV**
  - Experimental systematic uncertainties, associated to detector, background and signal mismodellings
    - **0.94 GeV** due to Jet Energy scale calibration
    - **0.72 GeV** associated to ISR/FSR modelling
  - Theoretical systematic uncertainties: basically scale variations to estimate the uncertainties due to uncalculated higher orders in the perturbative calculation
    - **0.95 GeV**

Description	Value [GeV]	%
m_t^{pole}	**173.71**	
Statistical uncertainty	**1.50**	**0.9**
Scale variations	(+0.93, −0.44)	(+0.5, −0.3)
Proton PDF (theory) and α_s	0.21	0.1
Total theory systematic uncertainty	**(+0.95, −0.49)**	**(+0.5, −0.3)**
Jet energy scale (including b-jet energy scale)	0.94	0.5
Jet energy resolution	0.02	< 0.1
Jet reconstruction efficiency	0.05	< 0.1
b-tagging efficiency and mistag rate	0.17	0.1
Lepton uncertainties	0.07	< 0.1
Missing transverse momentum	0.02	0.1
MC statistics	0.13	< 0.1
Signal MC generator	0.28	0.2
Hadronization	0.33	0.2
ISR/FSR	0.72	0.4
Colour reconnection	0.14	< 0.1
Underlying event	0.25	0.1
Proton PDF (experimental)	0.54	0.3
Background	0.20	0.1
Total experimental systematic uncertainty	**1.44**	**0.8**
Total uncertainty	**(+2.29, −2.14)**	**(+1.3, −1.2)**

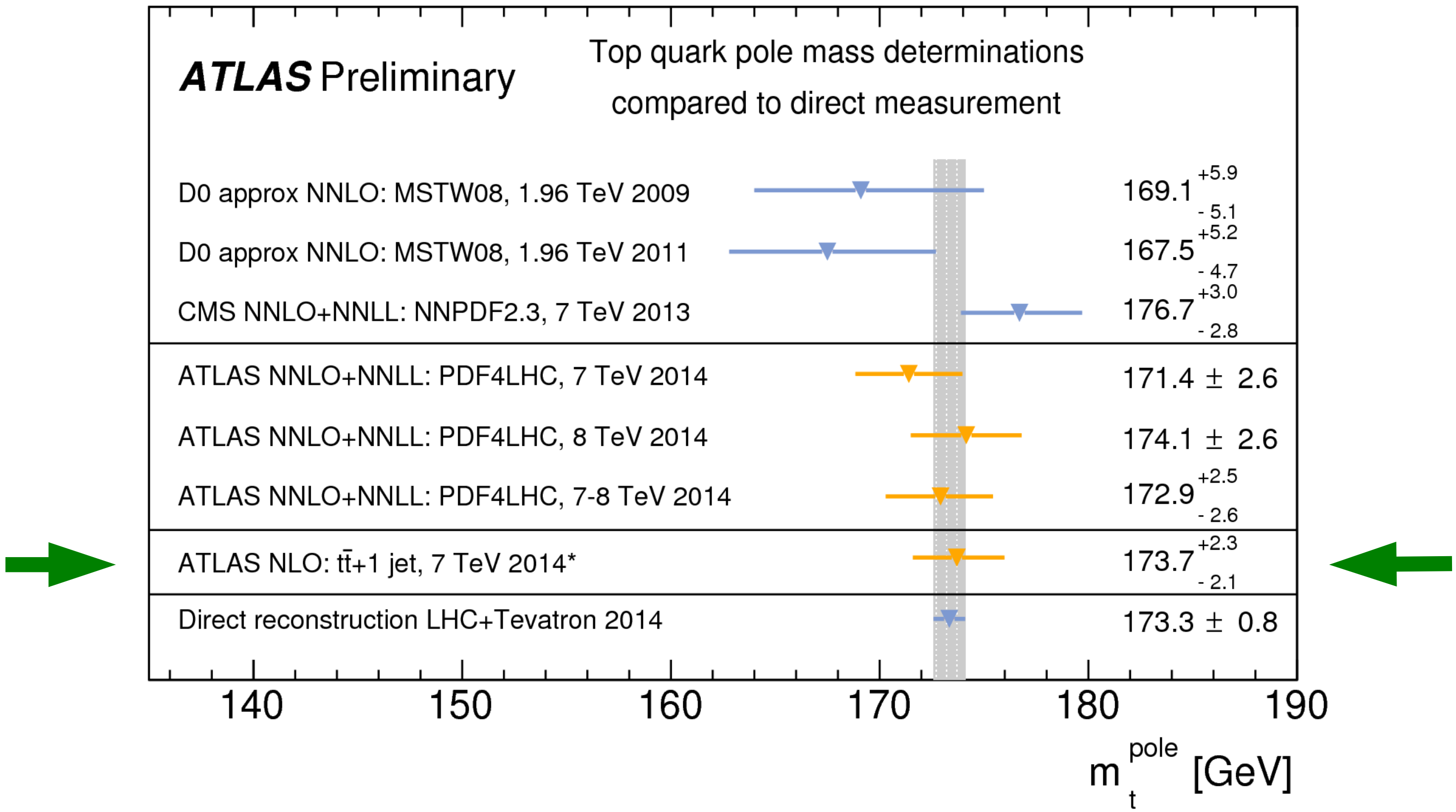
Table 3: Value of the inferred top-quark pole mass and breakdown of their associated uncertainties.

ρ_s interval	$\mathcal{R}$	Stat. Unc. (%)	Syst. Unc. (%)
0 to 0.25	0.126	12.8	7.1
0.25 to 0.325	1.122	6.6	4.5
0.325 to 0.425	2.049	5.0	3.5
0.425 to 0.525	2.622	4.6	2.1
0.525 to 0.675	2.125	4.1	3.1
0.675 to 1.0	0.302	8.2	8.1

Table 4: Measured values of the $\mathcal{R}$-distribution and their experimental uncertainties in percent. The statistical uncertainties are derived from the covariance matrix of eq. 9.

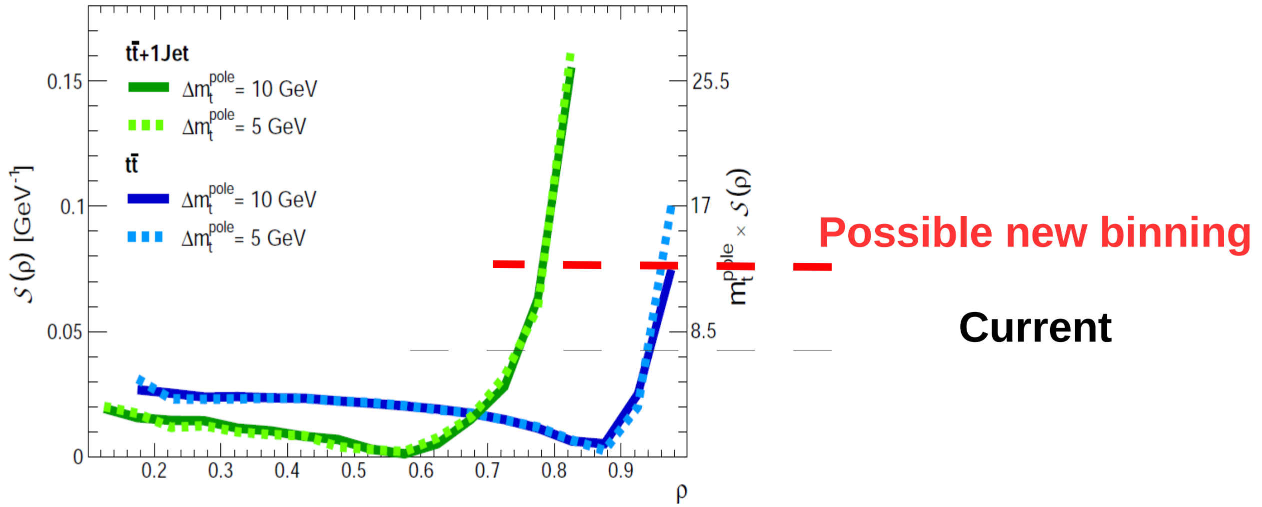
Best top quark pole mass determintation to date

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



Prospects of the method

- This is the first time that this method is applied to real data !!
  - Room for better understanding of (lower?) experimental systematic uncertainties
- The precision is limited (in the presented measurement) by the statistical uncertainty
  - Going to 8 TeV (without any other improvement in selection and reconstruction) the number of events is multiplied by ~ 5
- But more statistics might also means more sensitivity
  - More statistics may allow bin size reduction → increase of sens.



Summary

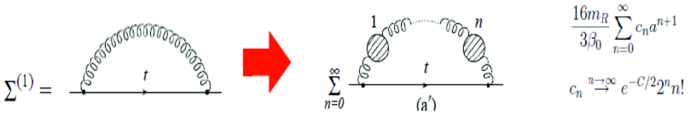
- **Top quark mass measurements** with high **precision** and a clear theoretical **interpretation** are crucial for top quark & EW physics understanding.
- Differential cross sections show great potential for this prospects: specifically **the differential tt+1 jet cross section**
  - **Sensitive** method, with small theoretical uncertainties and a **well defined mass scheme.**
- First public result presented with this method (by ATLAS) is the best top-quark pole mass measurement to date.
- **Future prospects: room for improvement** and reduction of statistical and systematic uncertainties

Backup slides

Quark masses (introduction)

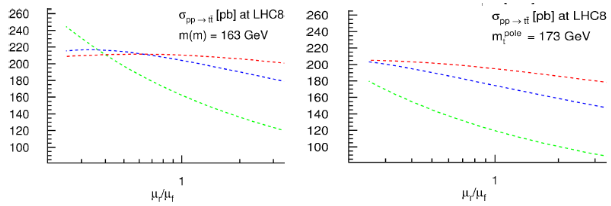
- Masses are parameters in the Lagrangian → normalized quantities (i.e. α_s)
  - Running mass scheme vs pole mass scheme (“stable particles” in event by event MC)

$$S(q) = \frac{1}{q - m_R - \Sigma_R}$$



[Bigi, Shifman, Uraltsev, Vainshtein 94 Beneke, Braun,94 Smith, Willenbrock 97]

Renormalon, pole mass has an intrinsic ambiguity of the order of Λ_{QCD}



Running mass definition provides better perturbative stability (tt)

Langenfeld, Moch, Uwer PRD 80, 054009 (2009)
Czakon, Fiedler, Mitov hep-ph/1303.6254

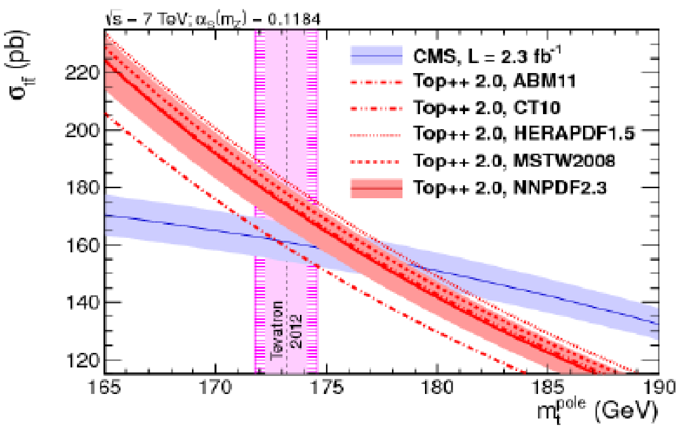
- Physics is independent of the renormalization choice

$$m_{pole} = \overline{m}(\overline{m}) \left(1 + \frac{4}{3}\frac{\overline{\alpha}_s(\overline{m})}{\pi} + 8.28 \left(\frac{\overline{\alpha}_s(\overline{m})}{\pi}\right)^2 + \cdots\right) + O(\Lambda_{QCD})$$

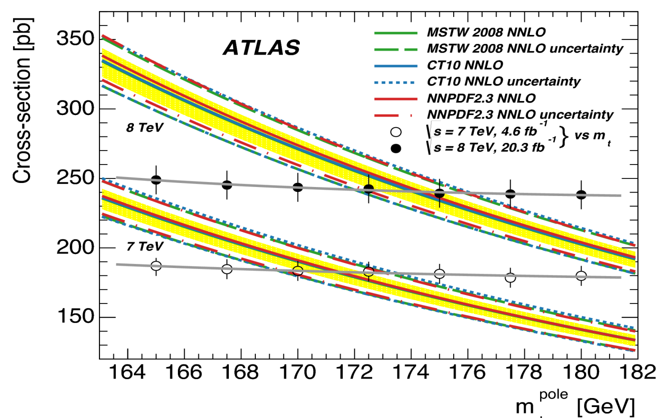
Measuring the top quark mass from inclusive cross sections

> Observable to measure and calculate: the $t\bar{t}$ inclusive cross section.

- MC simulations are used to correct for detector acceptance and reconstruction efficiency estimation.
- "Limited" theoretical sensitivity: **$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \approx -5\ \Delta m_t/m_t$**
- Limited precision?



$m_t^{pole} = 176.7^{+3.0}_{-2.8}$ GeV CMS, Phys. Lett B 728 (2014) 496



$m_t^{pole} = 172.9^{+2.5}_{-2.6}$ GeV ATLAS, Eur. Phys. J. C74 (2014) 3109

Larger unc:

PDF	→ ***~1.5 GeV***
Scale	→ ***~1.0. GeV***
Lum.	→ ***~0.7 GeV***

Unfolding procedure in two steps

The first step: Regularization matrix inversion *to unfold to the $t\bar{t}$+1jet system where the $t\bar{t}$ is defined at parton level and the jet is associated to the first powheg emission.*

Second step → Small correction factor *that introduces ~1% correction in the mass.*

$$t\bar{t} + 1\text{-jet (detector level)} \rightarrow t\bar{t}\text{+g (parton level)} \rightarrow t\bar{t} + 1\text{-jet (parton level)},$$

$$\mathcal{R}^{\text{cor-data}}(\rho_s) \equiv \left[\left(\mathcal{M}^{-1} \otimes \mathcal{R}^{\text{det-data}}(\rho_s)\right) \cdot \left(\frac{\mathcal{R}^{t\bar{t}+\text{g}}_{\text{acc.}}(\rho_s)}{\mathcal{R}^{t\bar{t}+\text{g}}(\rho_s)}\right)^{-1}\right] \cdot \left(\frac{\mathcal{R}^{t\bar{t}+1\text{-jet}}(\rho_s)}{\mathcal{R}^{t\bar{t}+\text{g}}(\rho_s)}\right),$$