Top Mass Determinations at Hadron Colliders

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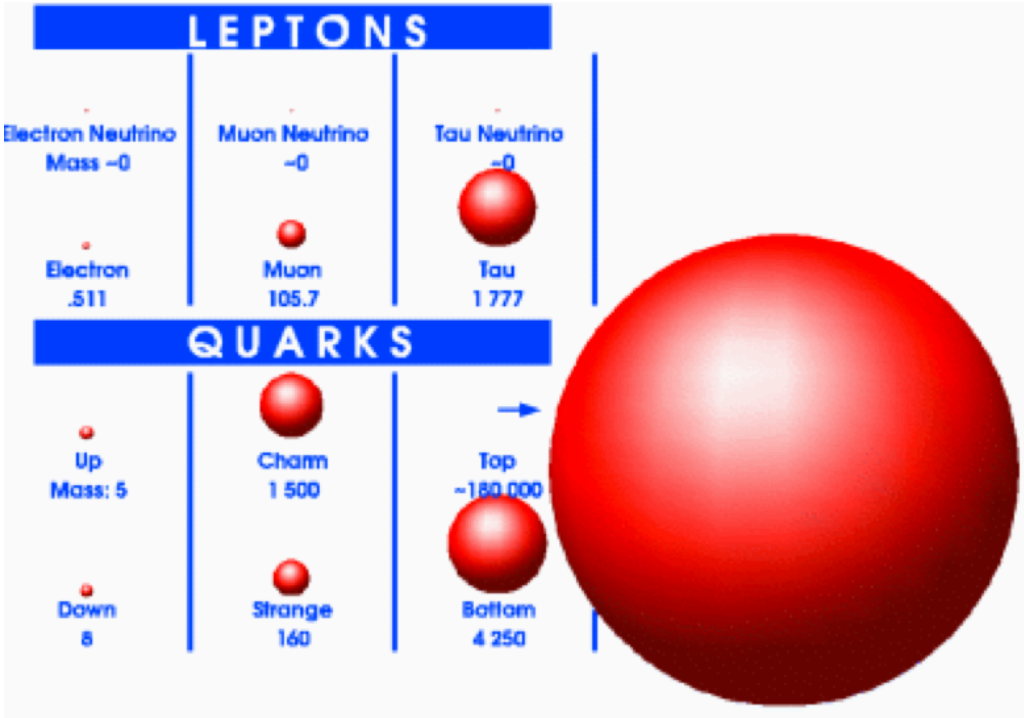
Please refer to EF03 Meeting September 10 2020 and arXiv:2004.12915 for more details.

$\int dk\,\Pi$ Doktoratskolleg Particles and Interactions

universität wien

FWF Der Wissenschaftsfonds.

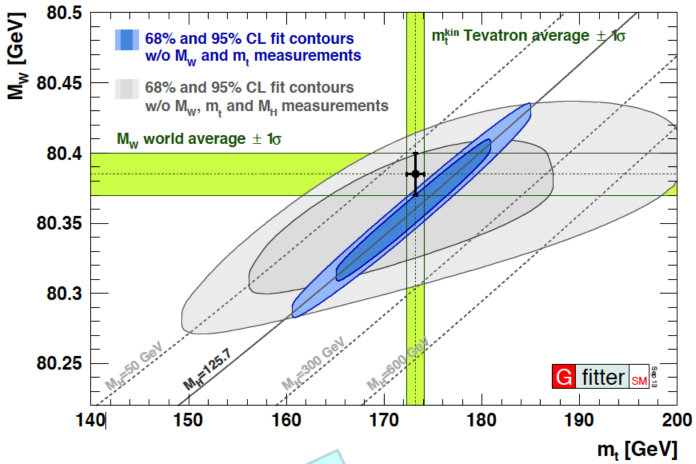
.. not just the heaviest SM particle

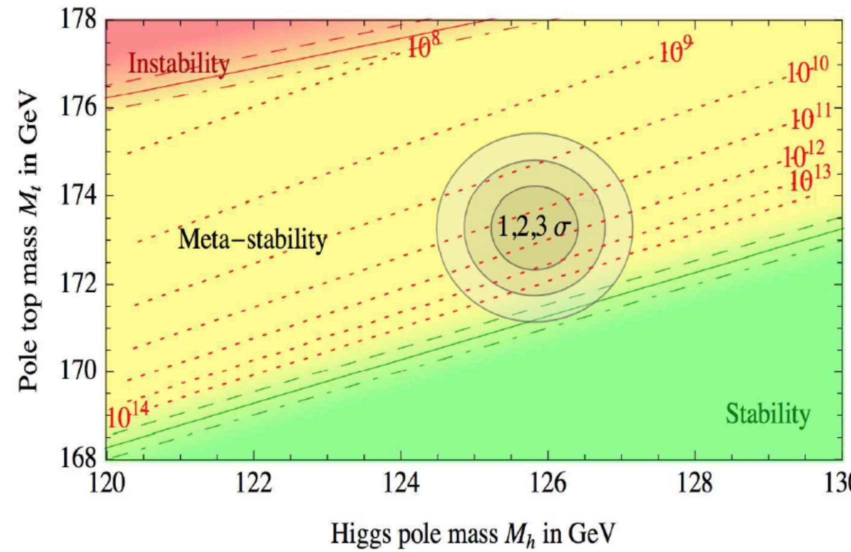


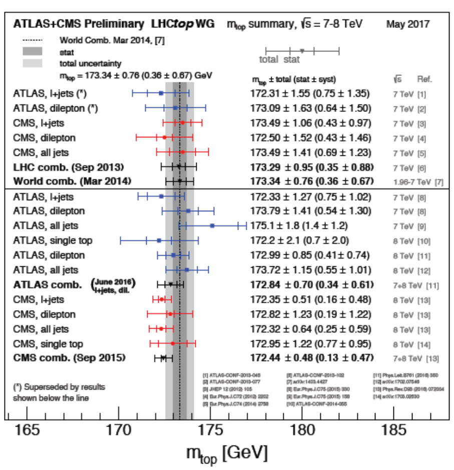
- Top quark: heaviest known particle
- Most sensitive to the mechanism of mass generation
- Peculiar role in the generation of flavor.
- Top might not be the SM-Top, but have a non-SM component.
- Top as calibration tool for new physics particles (SUSY and other exotics)
- Top production major background it new physics searches
- One of crucial motivations for New Physics

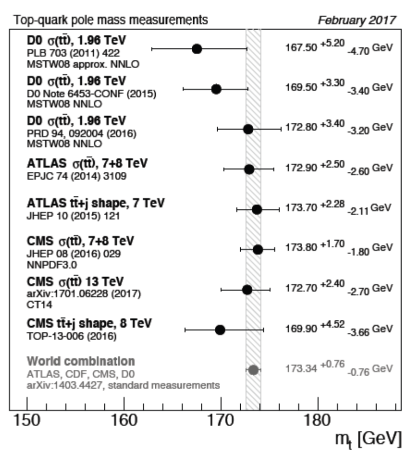
- Very special physics laboratory: $\Gamma_t \gg \Lambda_{QCD}$
  - Top treated a particle: p_T, spin, $\boldsymbol{\sigma}_{tot}$, $\boldsymbol{\sigma}$(single top), $\boldsymbol{\sigma}$(tt+X),.. $\rightarrow q \gg \Gamma_t$
  - Quantum state sensitive low-E QCD and unstable particle effects: m_t, endpoint regions $\rightarrow q \sim \Gamma_t$
  - Multiscale problem: $p_T, m_t \gg \Gamma_t \gg \Lambda_{QCD}, \ldots$ (depends on resolution scale of observable)

Why a Precision Top Mass is Important









Aims: m_{top} wanted !

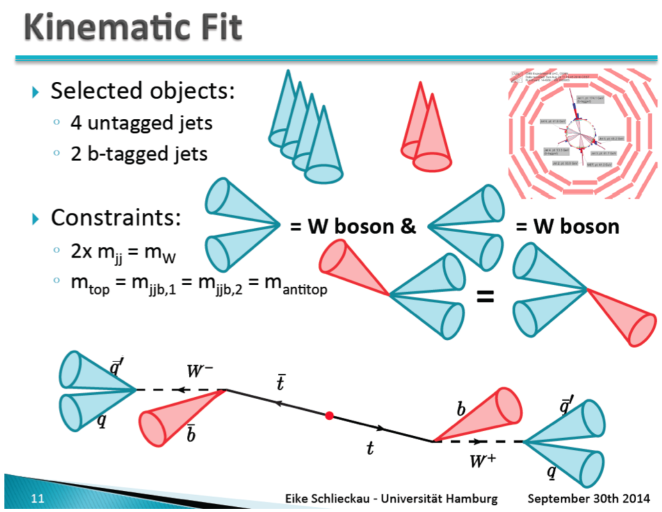
M_{top} is a renormalized QCD parameter !

- Reduce error in m_{top}^{MC}
- Improve / understand better MC
- Clarify mass scheme m_{top}^{MC} !

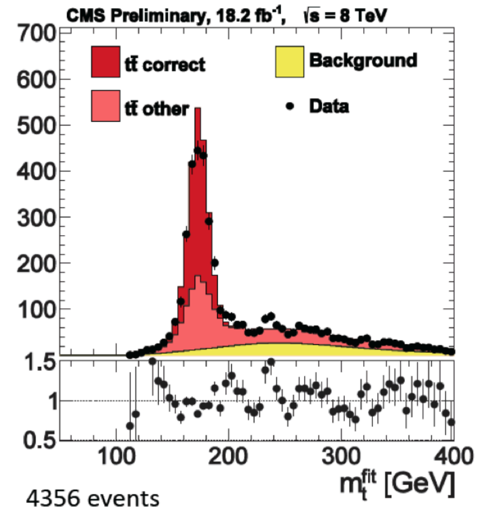
Top Mass Measurements

Most precise method: Direct Reconstruction

kinematic mass determination



CMS-PAS-TOP-14-002



4356 events

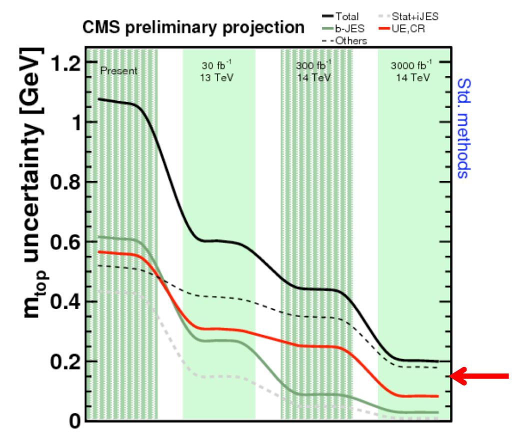
Determination of the best-fit value of the Monte-Carlo top quark mass parameter

⊕ High top mass sensitivity

⊖ Precision of MC ?

⊖ Meaning of m_t^{MC} ?

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
172.76± 0.30 OUR AVERAGE	Error includes scale factor of 1.2.		
172.69± 0.25± 0.41	[1] AABOUD 19AC	ATLS	7, 8 TeV ATLAS combination
172.26± 0.07± 0.61	[2] SIRUNYAN 19AP	CMS	lepton+jets, all-jets channels
172.33± 0.14 $^{+0.66}_{-0.72}$	[3] SIRUNYAN 19AR	CMS	dilepton channel ($e\mu$, $2e$, 2μ)
172.95± 0.77 $^{+0.97}_{-0.93}$	[4] SIRUNYAN 17L	CMS	t-channel single top production
172.44± 0.13± 0.47	[5] KHACHATRY... 16AK	CMS	7, 8 TeV CMS combination
174.30± 0.35± 0.54	[6] TEVEWWG 16	TEVA	Tevatron combination



Mass Extraction and Renormalization Schemes

The Principle of Top Mass Determinations

- Top quark is not a physical particle ("colored parton")
- Top mass defined from theoretical prescriptions (renormalization schemes)

- Different schemes are related by a perturbative series.

$$m_t^A - m_t^B = \sum_{n=1} c_n \alpha_s^n(\mu)$$

Parton level cross section formally scheme-invariant,
but can be practically scheme-dependent due to truncation

$$\hat{\sigma}(Q, m_t^A, \alpha_s(\mu), \mu; \delta m^A) = \hat{\sigma}(Q, m_t^B, \alpha_s(\mu), \mu; \delta m^B)$$

- For comparison with exp. data one has to account for non-perturbative corrections

$$\sigma^{\exp} = \hat{\sigma}(Q, m_t^X, \alpha_s(\mu), \mu; \delta m^X) + \sigma^{\rm NP}(Q, \Lambda_{\rm QCD})$$

Typically at LHC: $\sigma^{\rm NP} \sim \left(\frac{\Lambda_{\rm QCD}}{Q}\right)^n, \quad n = 1$

Linear effects always arise from color neutralization processes.
→ High precision control over soft partonic and NP effects needed when mass sensitivity generated by small dynamical scales

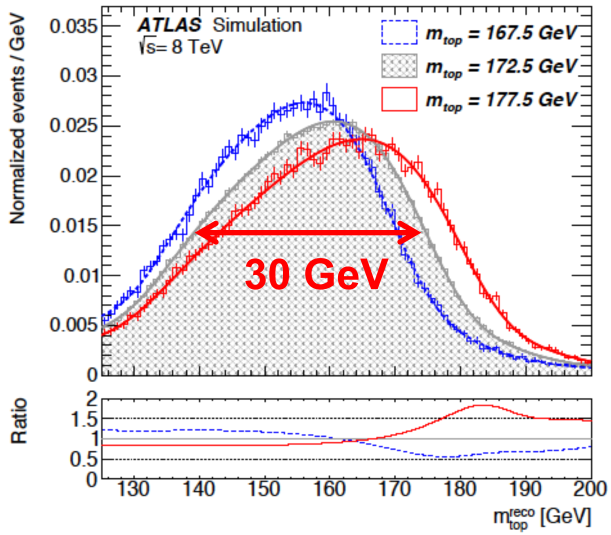
Mass Extraction and Renormalization Schemes

- Parton level cross section and NP corrections MUST be separately consistent with QCD so that the top quark mass (as well as $\alpha_S(Q)$) can be determined reliably!
  → otherwise systematic bias: model instead of field theory parameters

- Which mass scheme is best? → Consider analogy to strong coupling α_S
  - Relevant dynamical scale Q ⇒ $\alpha_S(Q)$ frequently best choice (MSbar)
  - All quantum corrections to quark-gluon interactions from <u>scales above Q</u> are absorbed into $\alpha_S(Q)$ → IR-save definition of strong coupling
  - Multiple scale problems: factorization allows to make adequate scale choices

We seek for a scale-dependent mass scheme $m_t(Q)$ with properties similar to the strong coupling $\alpha_S(Q)$.

- Multi-scale issue:
  In general high mass sensitivity is associated with QCD dynamics at a low scale
  → typically: scale ~ width of distribution



Mass Extraction and Renormalization Schemes

Top Pole mass

- Theoretical precision limit: ~ 120 - 250 MeV   (pole mass renormalon)
- Most codes naturally in this scheme
- Scale independent

Top Mass Renormalization Schemes (renormalon-free running masses)

- Theoretical precision limit: ~ 10 - 20 MeV
- Theoretical work needed to implement scheme change
- Scale-dependent

$\overline{\text{MS}}$ mass: • Adequate for total cross sections, production rates (scales above m_t)

MSR mass: • Adequate for thresholds, resonances, kinks (scales below m_t)

REvolver

- C++ / Mathematica / Python package
- All common mass schemes supported
- All known corrections implemented

Release shortly   arXiv: 2101:xxx

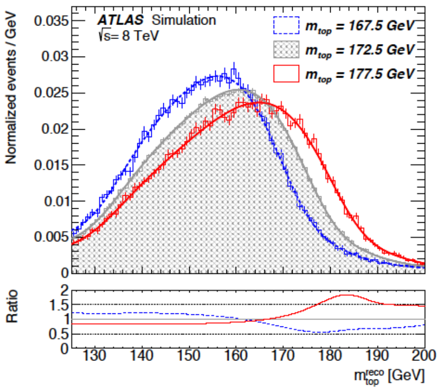
Status of Top Mass Determinations at the LHC

Direct Measurements: → 1st path to make progress

- Template method (ATLAS), matrix element/ideogram method (CMS)

- Based on highly top mass sensitive distributions ($M_{lb\text{-}jet}$, m_t^{reco}, etc) that are dominated by parton shower and hadronization model and cannot be systematically improved by NLO or NNLO matching.

  (Mazitelli etal. arXiv:2012.14267)



- Problem: How is m_t^{MC} related to field theory mass schemes? (Top mass interpretation problem)

  Better theoretical understanding of MC event generators needed! → work in progress (will not be resolved quickly, comparable in complexity to the task to develop NLL precise MC generators)

  See talk at EF03, Sept 10, 2020 and arXiv:2004.12915

Status of Top Mass Determinations at the LHC

"Pole Mass Measurements":

- Based on total and differential cross section for which the parton level calculation can be done reliably at NLO or NNLO/NNLL → mass scheme under control

- Called "pole mass measurements" only because theorists used pole mass scheme for their calculations. → misleading!

  Better: Measurements of m_t in well-defined scheme

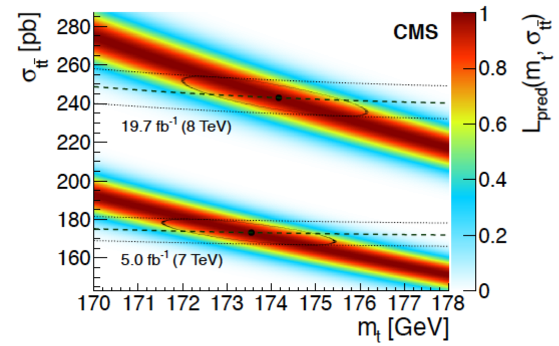
- Total inclusive cross section:

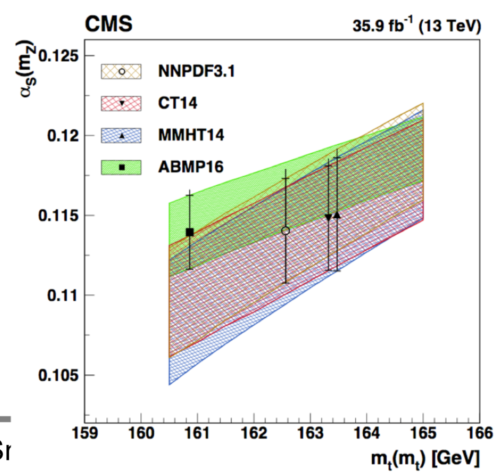
$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\,\text{GeV (ATLAS, 7 and 8 TeV data)}$$
$$m_t^{\text{pole}} = 173.8^{+1.7}_{-1.8}\,\text{GeV (CMS, 7 and 8 TeV data)}$$
$$m_t^{\text{pole}} = 169.9^{+2.0}_{-2.2}\,\text{GeV (CMS, 13 TeV data)}$$

lower precision due to impact of norm uncertainties

(strong additional correlation to pdfs, α_S)

→ reliable mass interpretation, but imprecise





CMS arXiv:1812.10505

Status of Top Mass Determinations at the LHC

Differential Cross Section Measurements: → 2^{nd} path to make progress

- Recently also differential cross sections: M_{tt+jet}, M_{tt} + y(tt), lepton energies
  → based on concrete theory improvable (FO) calculations (with mass scheme control)
  → distributions elevate top mass sensitivity due to structures

$$M_{t\bar{t}} + y(t\bar{t}): \quad m_t^{\rm pole} = 170.5 \pm 0.8\,\mathrm{GeV} \quad (\mathrm{CMS})$$
$$M_{t\bar{t}+jet}: \quad m_t^{\rm pole} = 171.1^{+1.2}_{-1.1}\,\mathrm{GeV} \quad (\mathrm{ATLAS})$$
$$\mathrm{leptons}: \quad m_t^{\rm pole} = 173.2 \pm 1.6\,\mathrm{GeV} \quad (\mathrm{ATLAS})$$

Important questions to address:

- Reliability of FO parton level differential cross sections
- Test pole mass versus running masses → Garzelli, Kemmler, Moch, Zenaiev 2009.07763 → Catani, Devoto, Grazzini, Kallweit, Mazzitelli 2005.00557
- Much more difficult (theory + experiment) than inclusive cross sections
  (Hard work needed: Do not expect easy competition with direct measurement)

- Recent studies:
  Soft-dropped boosted top jet masses AHH, Mantry, Pathak, Stewart 1708.02586
  Lepton energy distribution (t-channel single top) → Yuan, Gao, Gao 2007.15527