What Top Mass is Measured at the LHC?

André H. Hoang

University of Vienna

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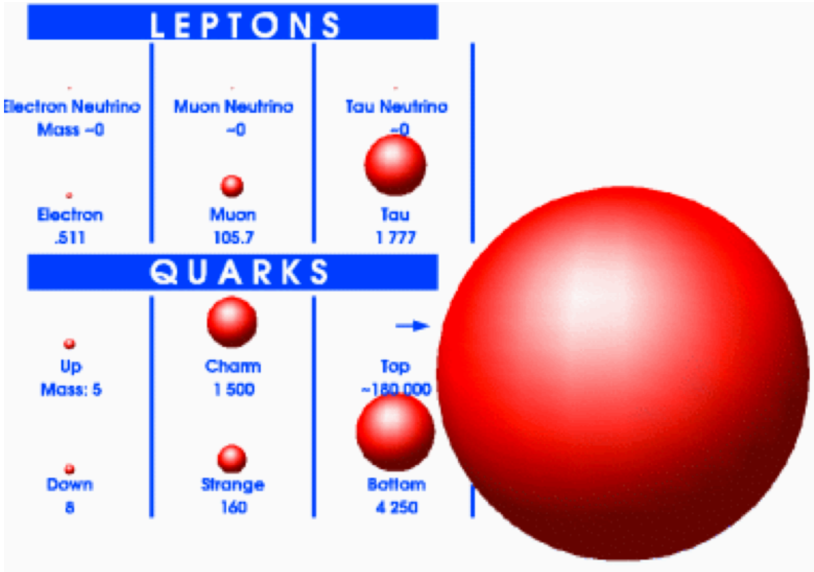
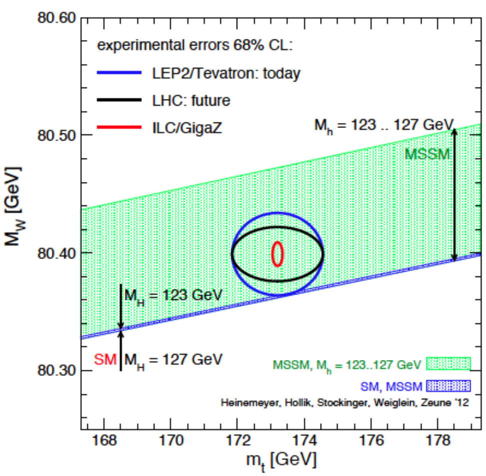
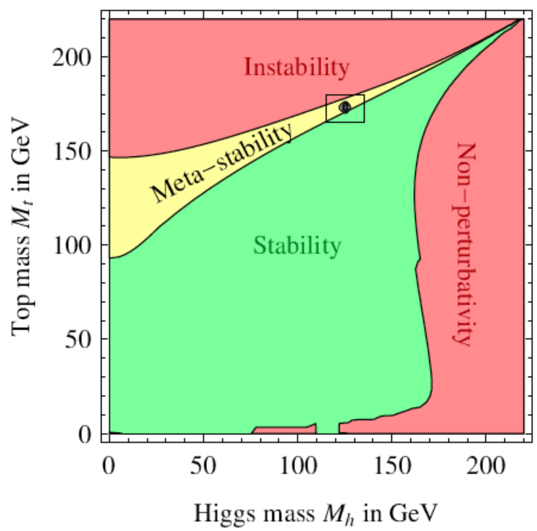
Why the top quark is not just heavy



- 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 SUSY
- Excellent ground for high-precision studies of QCD and electroweak physics



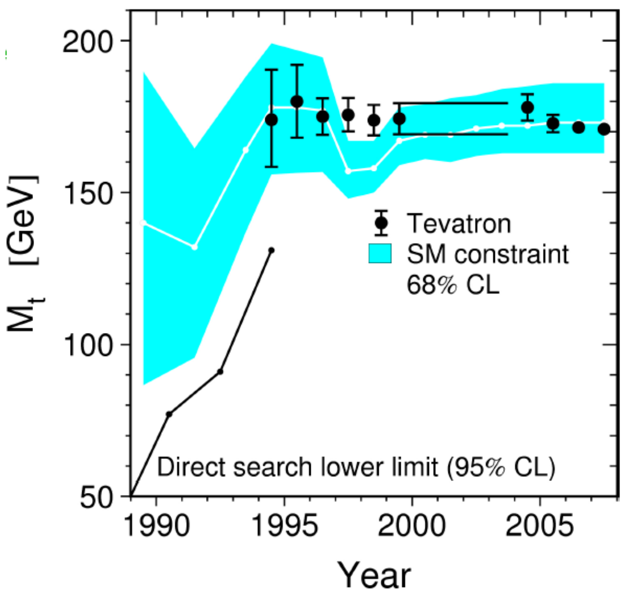


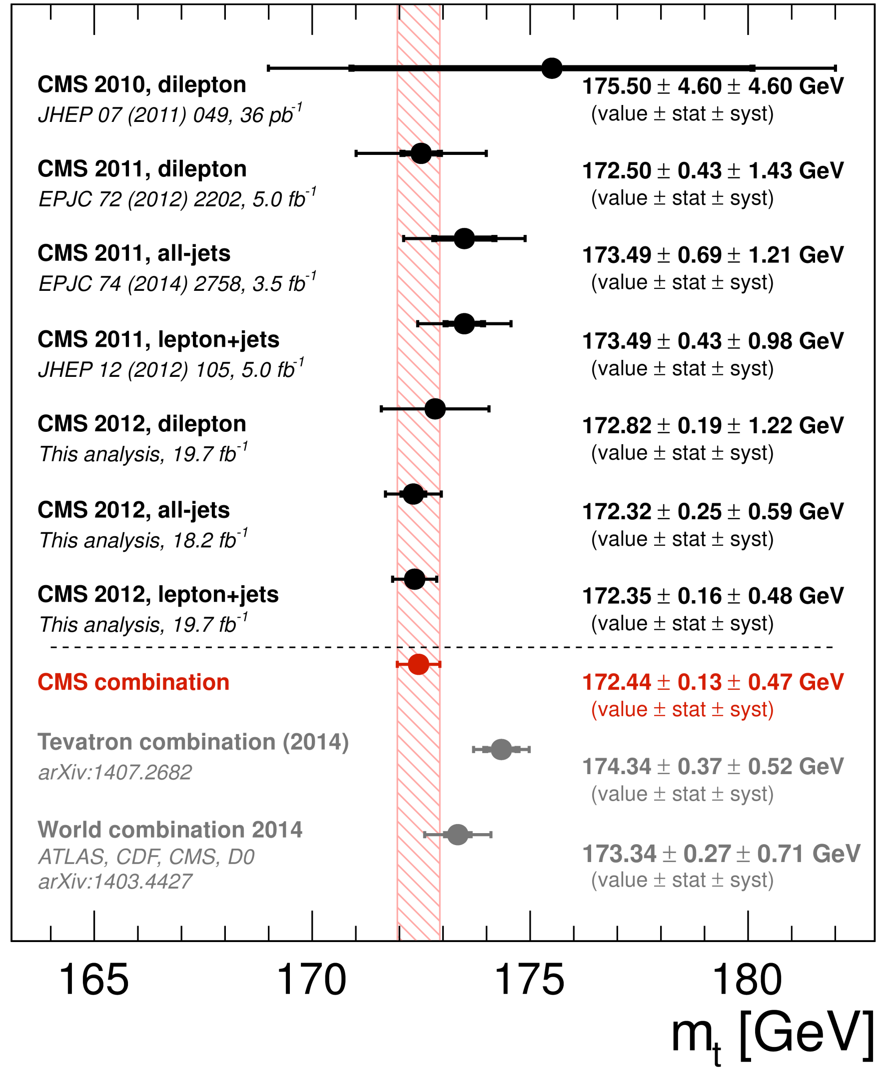
Outline

- Introduction
- Monte Carlo generators and the top quark mass
- Calibration of the Monte Carlo top mass parameter
- Theory for boosted top quarks factorization
- Preliminary detailed results of first serious systematic analysis
- Summary, future plans

In collaboration with:
M. Butenschön
B. Dehnadi,
V. Mateu,
M. Preisser
I. Stewart

A small history on top mass reconstruction



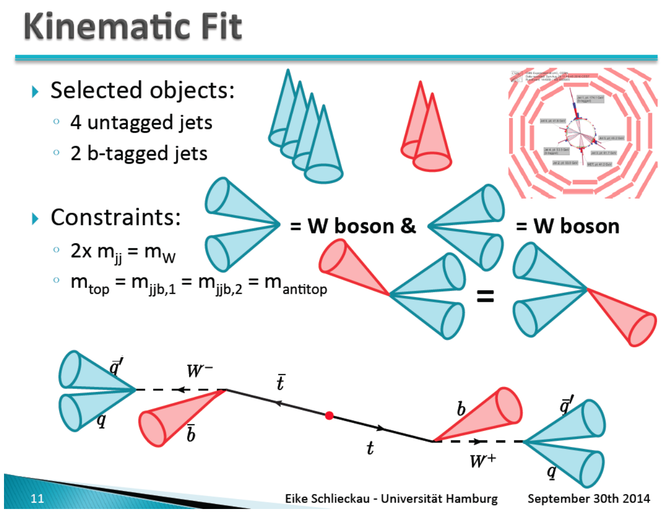


- Many individual measurements with uncertainty below 1 GeV.
- Some discrepancies between LHC and Tevatron
- Reached uncertainties < 0.5 MeV.
- Alternative method with uncertainties > 1.5 GeV.

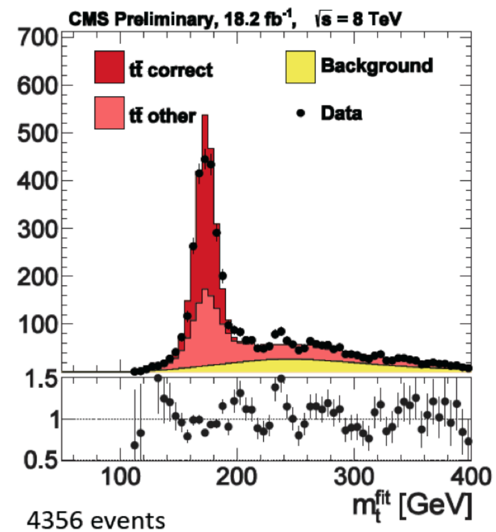
Main Top Mass Measurements Methods

LHC+Tevatron

Direct Reconstruction:



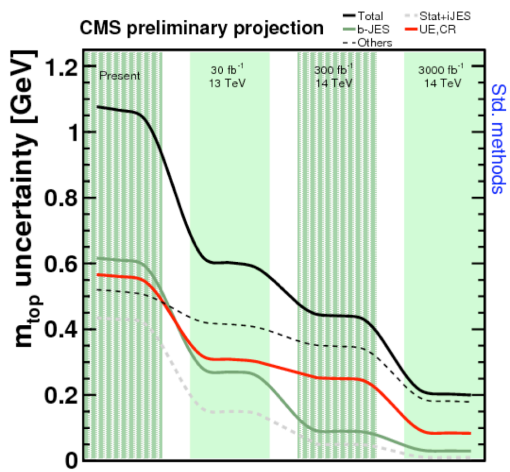
CMS-PAS-TOP-14-002



4356 events

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

kinematic mass determination



Δm_t ~ 200 MeV (projection)

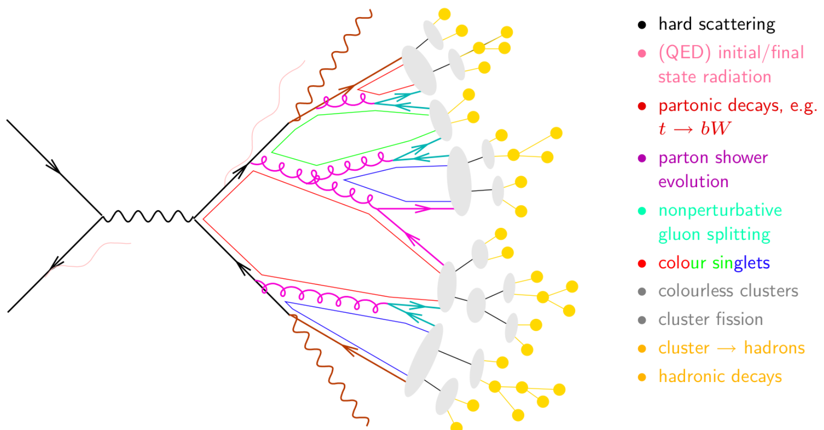
⊕ High top mass sensitivity

⊖ Precision of MC ?

⊖ Meaning of m_t^{MC} ?

Δm_t ~ 0.5 GeV

Monte-Carlo Event Generators



- Full simulation of all processes (all experimental aspects accessible)
- QCD-inspired: partly first principles QCD ⇔ partly model (observable-dependent)
- Description power of data better than intrinsic theory accuracy.
- Top quark: treated like a real particle ($m_t^{MC} \approx m_t^{pole}$ +?).

  But pole mass ambiguous by O(1 GeV) due to confinement.

  Better mass definition needed.

Uncertainty (a): But how precise is modelling? ⟶ Part of exp. Analyses

Unvertainty (b): What is the meaning of MC QCD parameters? ⟶

Depends strictly speaking on the observable, because of model character of MCs !

Must be adressed for each type of observable (until we have better MCs).

MC Top Quark Mass

AHH, Stewart 2008
AHH, 2014

$$m_t^{\rm MC} = m_t^{\rm MSR}(R=1\ {\rm GeV}) + \Delta_{t,\rm MC}(R=1\ {\rm GeV})$$

$$\Delta_{t,\rm MC}(1\ {\rm GeV}) \sim \mathcal{O}(1\ {\rm GeV})$$

- small size of $\Delta_{t,MC}$
- Renormalon-free
- little parametric dependence on other parameters

MSR Mass Definition

MS Scheme: $(\mu > \overline{m}(\overline{m}))$

$$\overline{m}(\overline{m}) - m^{\rm pole} = -\overline{m}(\overline{m})\,[0.42441\,\alpha_s(\overline{m}) + 0.8345\,\alpha_s^2(\overline{m}) + 2.368\,\alpha_s^3(\overline{m}) + \ldots]$$

⇓

MSR Scheme: $(R < \overline{m}(\overline{m}))$

$$m_{\rm MSR}(R) - m^{\rm pole} = -R\,[0.42441\,\alpha_s(R) + 0.8345\,\alpha_s^2(R) + 2.368\,\alpha_s^3(R) + \ldots]$$

$$m_{\rm MSR}(m_{\rm MSR}) = \overline{m}(\overline{m})$$

⇒ $m_{\rm MSR}(R)$ Short-distance mass that smoothly interpolates all R scales

Calibration of the MC Top Mass

Method:

✓ 1) Strongly mass-sensitive hadron level observable (as closely as possible related to reconstructed invariant mass distribution !)

✓ 2) Accurate analytic hadron level QCD predictions at ≧ NLL/NLO with full control over the quark mass scheme dependence.

✓ 3) QCD masses as function of m_t^{MC} from fits of observable.

4) Cross check observable independence

$$m_t^{\rm MC} = m_t^{\rm MSR}(R = 1\ {\rm GeV}) + \Delta_{t,\rm MC}(R = 1\ {\rm GeV})$$

$$\Delta_{t,\rm MC}(1\ {\rm GeV}) = \bar{\Delta} + \delta\Delta_{\rm MC} + \delta\Delta_{\rm pQCD} + \delta\Delta_{\rm param}$$

Experimental systematics

Monte Carlo errors:

- different tunings
- parton showers
- color reconnection
- Intrinsic error, …

QCD errors:

- perturbative error
- scale uncertainties
- electroweak effects

Parametric errors:

- strong coupling α_s
- Non-perturbative parameters

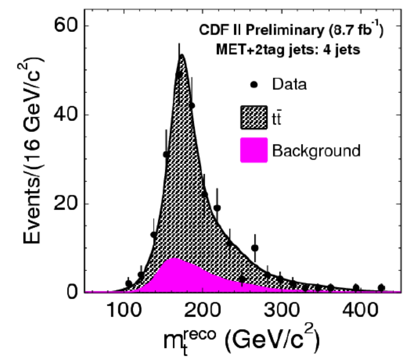
Treated in our analysis

Thrust Distribution

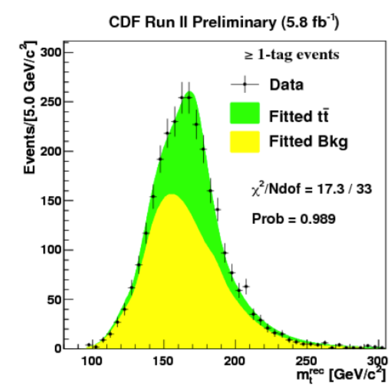
Observable: 2-jettiness in e+e- for $Q \sim p_T \gg m_t$ (boosted tops)

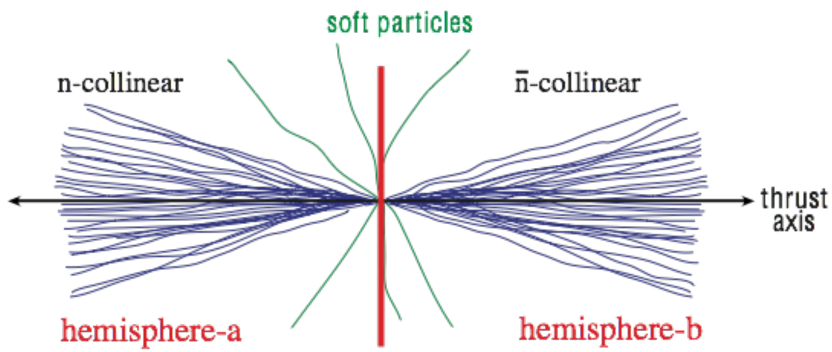
$$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{n} \cdot \vec{p}_i|}{Q}$$

$$\stackrel{\tau \to 0}{\approx} \frac{M_1^2 + M_2^2}{Q^2}$$

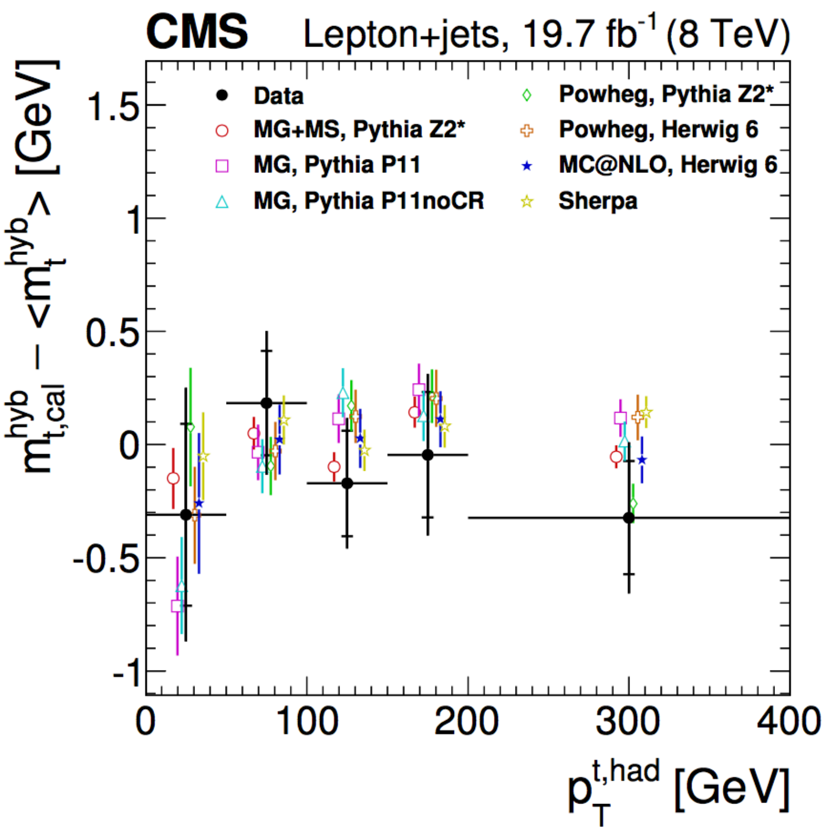


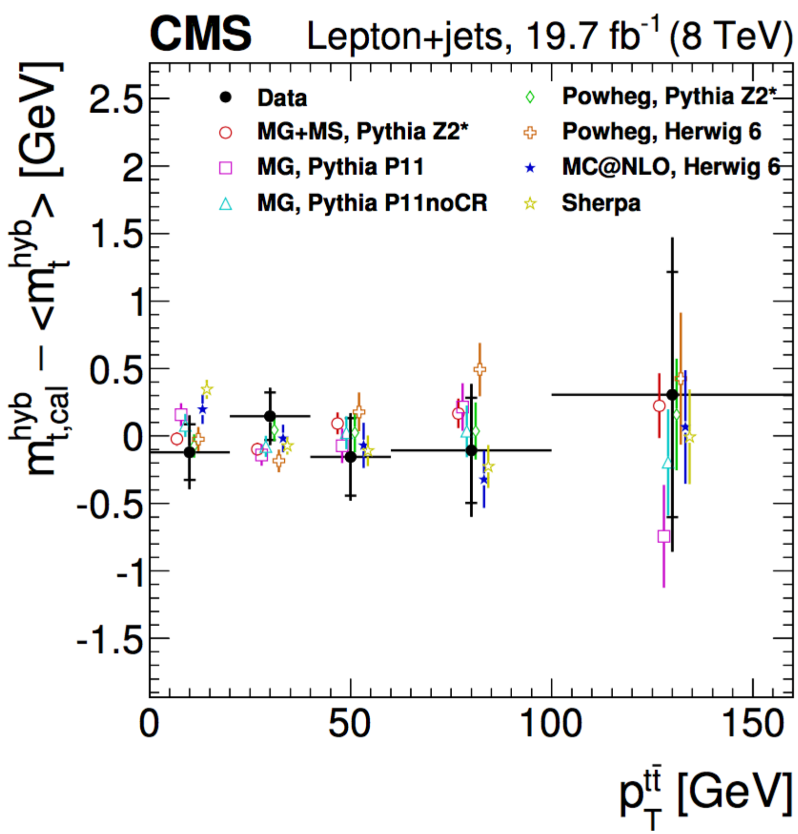
Invariant mass distribution in the resonance region of wide hemisphere jets !





Boosted Top Mass Measurements at CMS

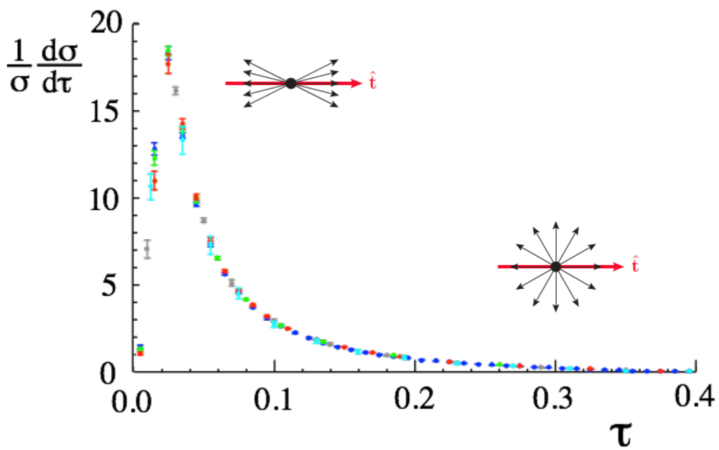




- Top mass from reconstruction of boosted tops consistent with low p_T results.
- More precise studies possible with more statistics from Run2.

Factorization for Event Shapes

$$\frac{d\sigma}{d\tau} = Q^2 \sigma_0 H_0(Q,\mu) \int d\ell \, J_0(Q\ell,\mu) \, S_0\left(Q\tau - \ell, \mu\right)$$



Massless quarks:

Korshemski, Sterman 1995-2000

Bauer, Fleming, Lee, Sterman (2008)

Becher, Schwartz (2008)

Abbate, AHH, Fickinger, Mateu, Stewart 2010

Extension to massive quarks:

- VFNS for final state jets (with massive quarks): log summation incl. mass
- Boostet fat top jets

Fleming, AHH, Mantry, Stewart 2007

Gritschacher, AHH, Jemos, Mateu Pietrulewicz 2013-2014

Butenschön, Dehnadi, AHH, Mateu 2016 (to appear soon)

➡ NNLL + NLO + non-singular + hadronization + renormalon-subtraction

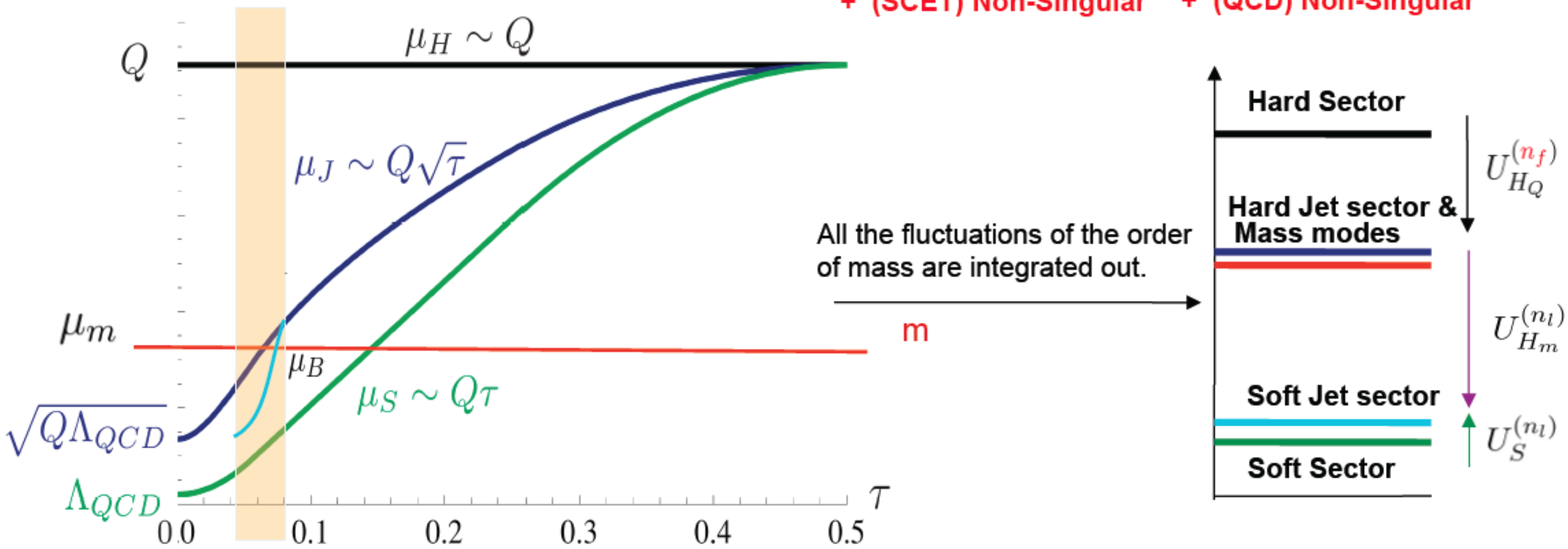
b(oosted)HQET Factorization

$$\left|\frac{1}{\sigma_0}\frac{\mathrm{d}\hat\sigma(\tau)}{\mathrm{d}\tau}\right|^{\mathrm{bHQET}} = Q\, H_Q^{(n_f)}(Q,\mu_Q)\, U_{H_Q}^{(n_f)}(Q,\mu_Q,\mu_m)\, H_m^{(n_f)}(\overline{m}^{(n_f)},\mu_m)\, U_{H_m}^{(n_l)}\Big(\frac{Q}{\overline{m}^{(n_l)}},\mu_m,\mu_B\Big) \int \mathrm{d}s \int \mathrm{d}k\, B^{(n_l)}\Big(\frac{s}{m_J^{(n_l)}},\mu_B, m_J^{(n_l)}\Big)\, U_S^{(n_l)}(k,\mu_B,\mu_S)\, S_{\mathrm{part}}^{(n_l)}\Big(Q\tau - Q\tau_{\mathrm{MIN}} - \frac{s}{Q} - k,\mu_S\Big)$$

$n_f = n_l + 1$

Yukawa corrections here!

+ (SCET) Non-Singular + (QCD) Non-Singular

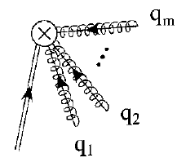


- Matching coefficient of SCET and bHQET have a large log from secondary corrections.

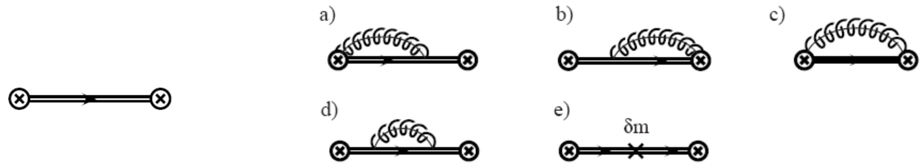
b(oosted)HQET Factorization

Jet function: $$B_+(2v_+\cdot k) = \frac{-1}{8\pi N_c m}\,\mathrm{Disc}\int d^4x\, e^{ik\cdot x}\langle 0|\mathrm{T}\{\bar{h}_{v_+}(0)W_n(0)W_n^\dagger(x)h_{v_+}(x)\}|0\rangle$$

- perturbative, any mass scheme
- depends on m_t, Γ_t
- Breit-Wigner at tree level
- Gauge-invariant off-shell top quark dynamics



$$W = \sum_{m=0}^{\infty}\sum_{\mathrm{perms}}\frac{(-g)^m}{m!}\frac{\bar{n}\cdot A^{a_1}_{n,q_1}\cdots\bar{n}\cdot A^{a_m}_{n,q_m}}{\bar{n}\cdot q_1\,\bar{n}\cdot(q_1+q_2)\cdots\bar{n}\cdot(\sum_{i=1}^m q_i)}T^{a_m}\cdots T^{a_1}$$



$$\hat{s} = \frac{M^2 - m_t^2}{m_t}$$

$$\mathcal{B}_\pm(\hat{s},0,\mu,\delta m) = -\frac{1}{\pi m}\frac{1}{\hat{s}+i0}\left\{1+\frac{\alpha_s C_F}{4\pi}\left[4\ln^2\left(\frac{\mu}{-\hat{s}-i0}\right)+4\ln\left(\frac{\mu}{-\hat{s}-i0}\right)+4+\frac{5\pi^2}{6}\right]\right\} - \frac{1}{\pi m}\frac{2\delta m}{(\hat{s}+i0)^2}$$

Fleming, AHH, Mantry, Stewart 2007

b(oosted)HQET Factorization

Is the pole mass determining the top single particle pole?

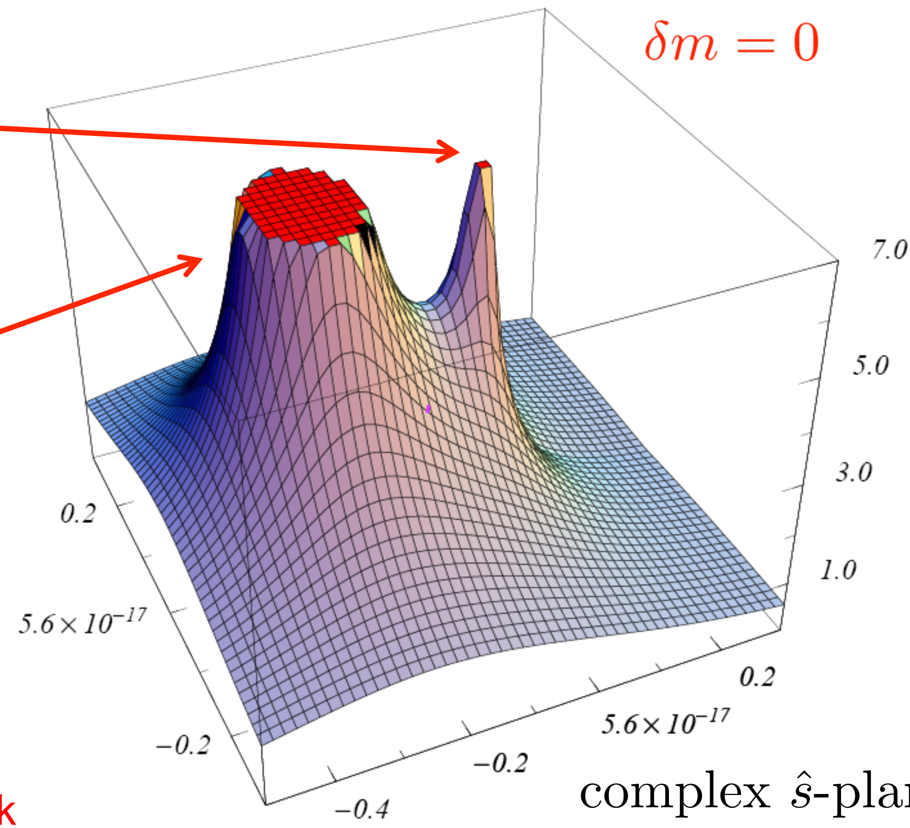
NO !

$$\hat{s} = \frac{M_t^2 - m_t^2}{m_t}$$

$$|\mathcal{B}_\pm(\hat{s}, \Gamma_t, \mu)|^2$$
$$\delta m = 0$$

pole mass peak

observable peak



complex $\hat{s}$-plane

→ pole mass and observable peak separated by renormalon

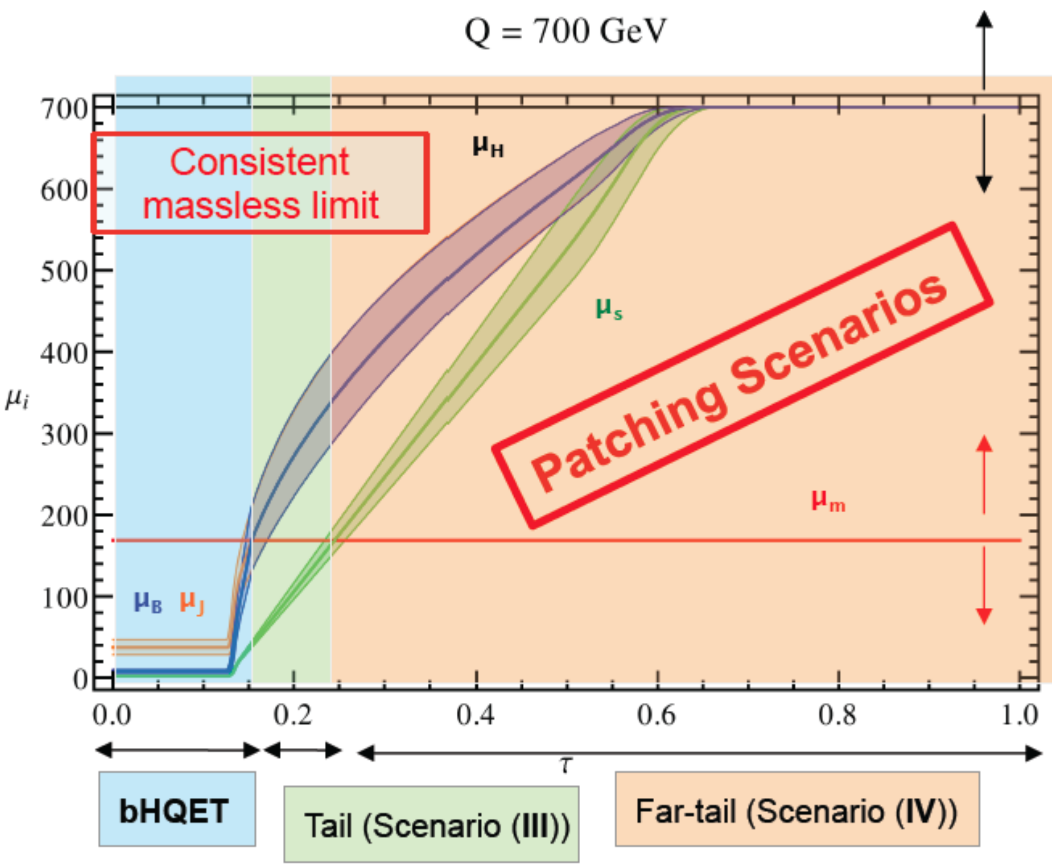
→ pole mass peak residue decreases with order

→ MSR mass close to observable peak

Profile Functions

Profile functions should sum up large logarithms and achieve smooth transition between the peak, tail and far-tail.

$$\log\left(\frac{Q}{\mu_H}\right) \quad \log\left(\frac{m_J}{\mu_m}\right) \quad \log\left(\frac{\mu_J^2}{Q\mu_s}\right) \quad \log\left(\frac{m_J\mu_B}{Q\mu_s}\right) \quad \log\left(\frac{Q(\tau-\tau_{\min})+2\Lambda_{\rm QCD}}{\mu_s}\right)$$



Scales Variation

- ✔ **Generalized to arbitrary mass values**
- ✔ **Compatible with massless profiles**

Proper scale variations are essential in reliable estimation of missing higher order terms.

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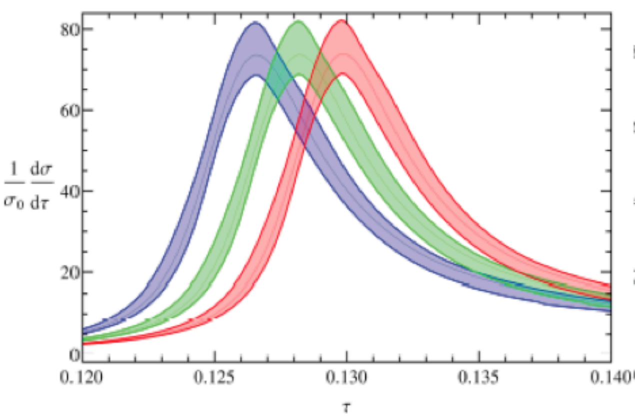
2-Jettiness for Top Production (QCD)

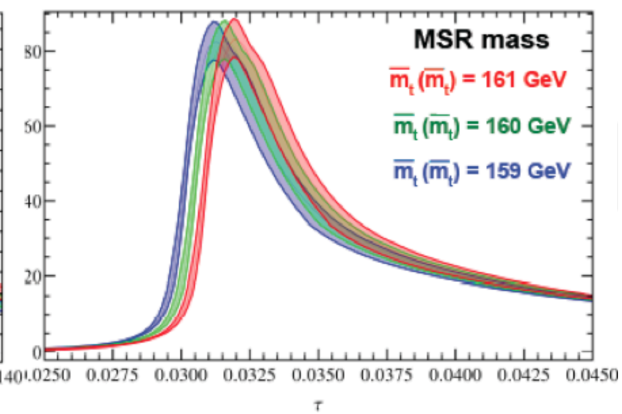
$$\frac{d\sigma}{d\tau_2} = f(m_t^{\rm MSR}(R), \alpha_s(M_Z), \Omega_1, \Omega_2, \ldots, \mu_h, \mu_j, \mu_s, \mu_m, R, \Gamma_t)$$

any scheme possible — Non-perturbative — renorm. scales — finite lifetime

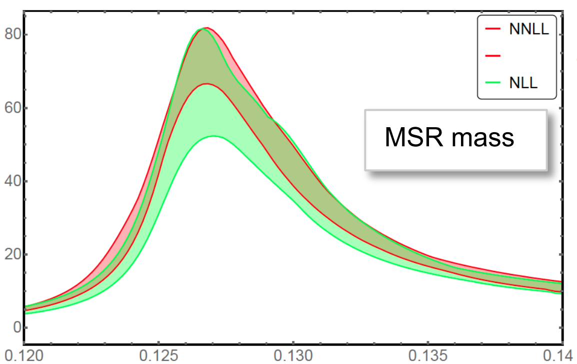
Q=700 GeV



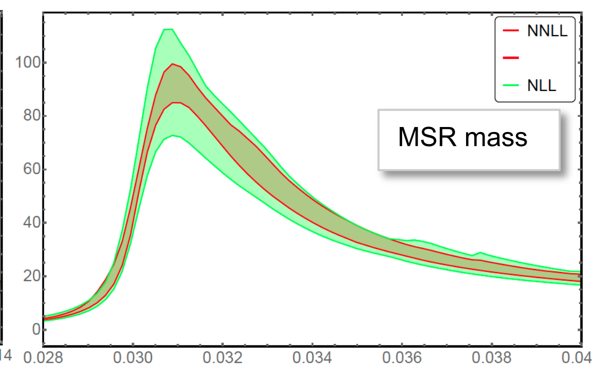
Q=1400 GeV



Q=700 GeV



Q=1400 GeV



- Higher mass sensitivity for lower Q (p_T)
- Finite lifetime effects included
- Dependence on non-perturbative parameters
- Convergence: $\Omega_{1,2,\ldots}$

- Good convergence
- Reduction of scale uncertainty (NLL to NNLL)
- Control over whole distribution

Fit Procedure Details

$$\frac{d\sigma}{d\tau_2} = f(\underbrace{m_t^{\mathrm{MSR}}(R)}_{\text{any scheme possible}}, \alpha_s(M_Z), \underbrace{\Omega_1, \Omega_2, \ldots}_{\text{Non-perturbative}}, \underbrace{\mu_h, \mu_j, \mu_s, \mu_m}_{\text{renorm. scales}}, R, \Gamma_t)$$

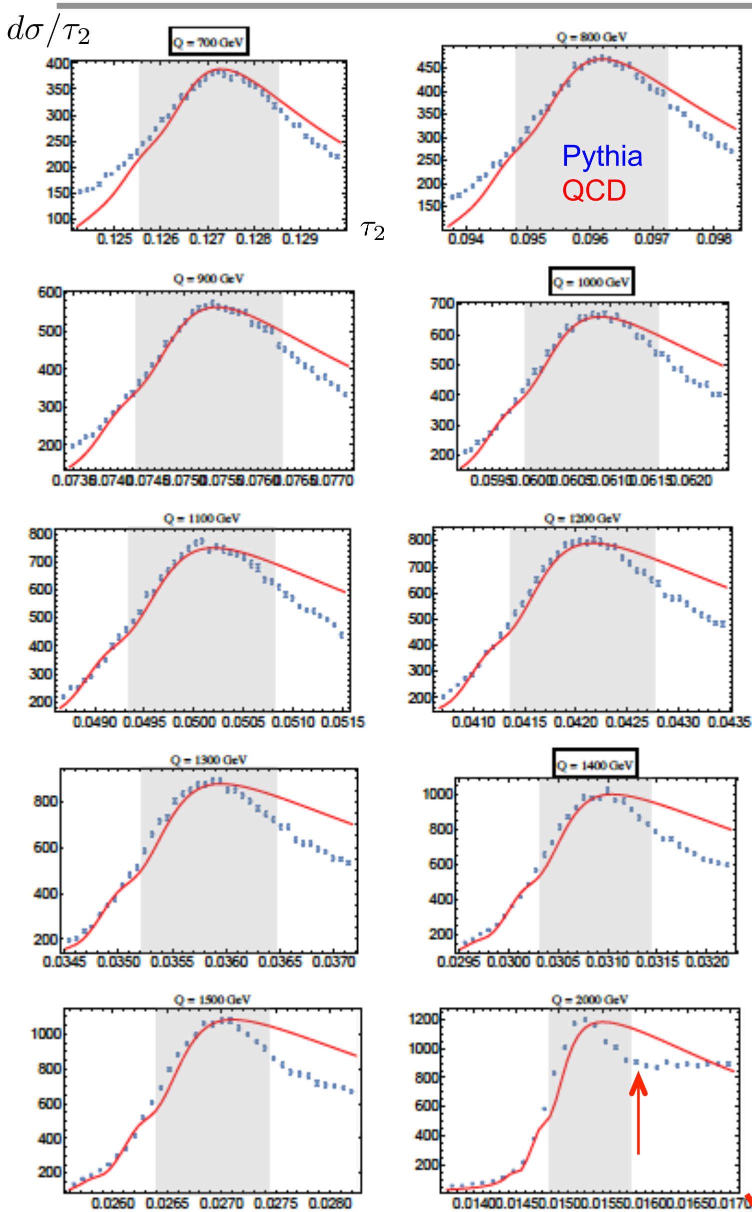
any scheme possible — Non-perturbative — renorm. scales — finite lifetime

QCD parameters measured from Pythia

- Fit parameters: $m_t^{\mathrm{MSR}}(R),\ \alpha_s(M_Z),\ \Omega_1,\ \Omega_2,\ \ldots,$
- Perturbative error: fits for 500 randomly picked sets of renor. scales
- Tunings: 1 (“very old”), 3 (“LEP”), 7 (“Monash”)
- Top quark width: $\Gamma_t\ =\ \mathrm{dynamical\ (default)},\ 0.7,\ 1.4,\ 2.0\,\mathrm{GeV}$
- External smearing (Detector effects): $\Omega_{1,\mathrm{smear}}\ =\ 0,\ 0.5,\ \ldots,\ 3.0,\ 3.5,\ \mathrm{GeV}$ (just for cross checks)
- Pythia masses: $m_t^{\mathtt{Pythia}}\ =\ 170,\ \ldots\ ,\ 175\,\mathrm{GeV}$
- Strong coupling: $\alpha_s(M_Z)\ =\ 0.114,\ 0.116,\ 0.118,\ 0.120,\ 0.122$
- Fit possible for any order / mass scheme (so far NLL+NNLL / MSR)

Number of fits entering the first analysis: 2.8 10^6

Peak Fits



Default renormalization scales; Γ_t=1.4 GeV, tune 3, $\Omega_{1,\text{smear}}$=0 GeV, m_t^{Pythia}=170 GeV, Q={700, 1000, 1400} GeV, peak fit (60/80)%, normalized to fit range

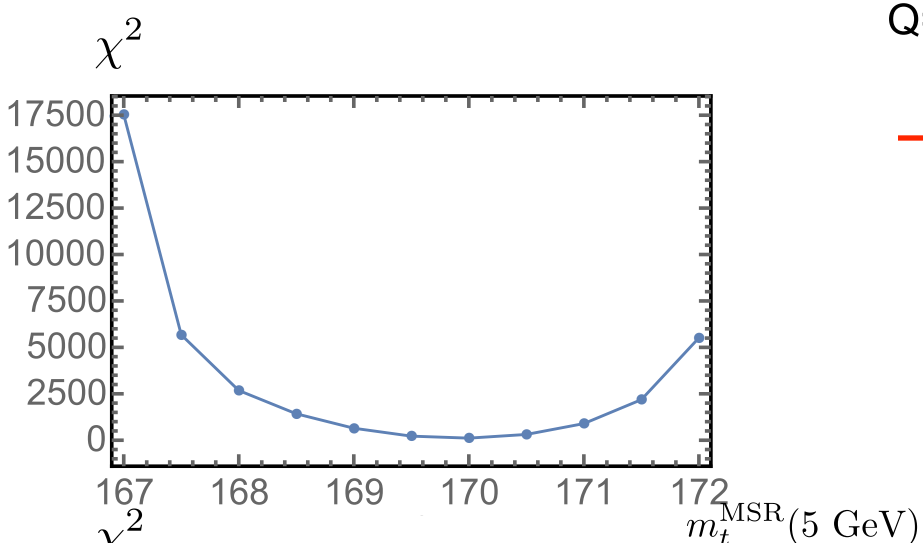
- Good agreement of Pythia 8.2 with NNLL+NLO QCD description
- Pythia statistics: 10^6 events
- Discrepancies in distribution tail and for higher energies (Pythia is less reliable where fixed-order results valid, well reliable in soft-collinear limit)
- Pythia kink issue ?
- Excellent sensitivity to the top quark mass.
- Tree-Level: $\tau_2^{\text{peak}} = 1 - \sqrt{1 - \frac{4m_t^2}{Q^2}}$

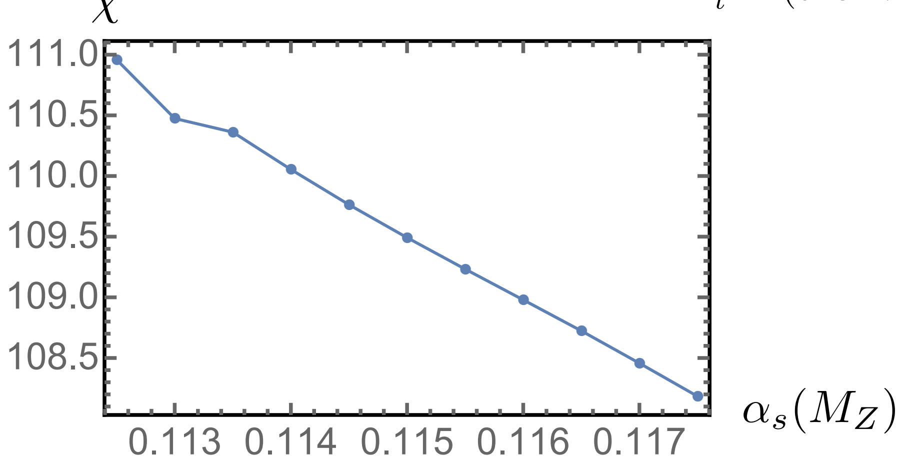
tune = 3
m_{MC} = 170.
Γ_t = –1. GeV
α = 0.118
m^{SR}(5 GeV) = 169.138 ± 0.099
$\frac{\chi^2}{\text{dof}}$ = 35.36

Ω_1 = 0.434 ± 0.060 GeV
Ω_2 = 0.473 ± 0.060 GeV
Ω_3 = –0.158 ± 0.300 GeV
Ω_4 = –2.226 ± 1.000 GeV

Preliminary

Peak Fits





Default renormalization scales; Γ_t=1.4 GeV, tune 7, $\Omega_{1,smear}$=2.5 GeV, m_t^{Pythia}=171 GeV, Q={700, 1000, 1400} GeV, peak fit (60/80)%

→ χ^2_{min} ~ O(100)

- Very strong sensitivity to m_t
- Low sensitivity to strong coupling

- Take strong coupling as input
- χ^2_{min} and δm_t^{stat} do not have any physical meaning

- We use rescaled χ^2/dof (PDG prescription) to define "intrinsic MC compatibility uncertainty"

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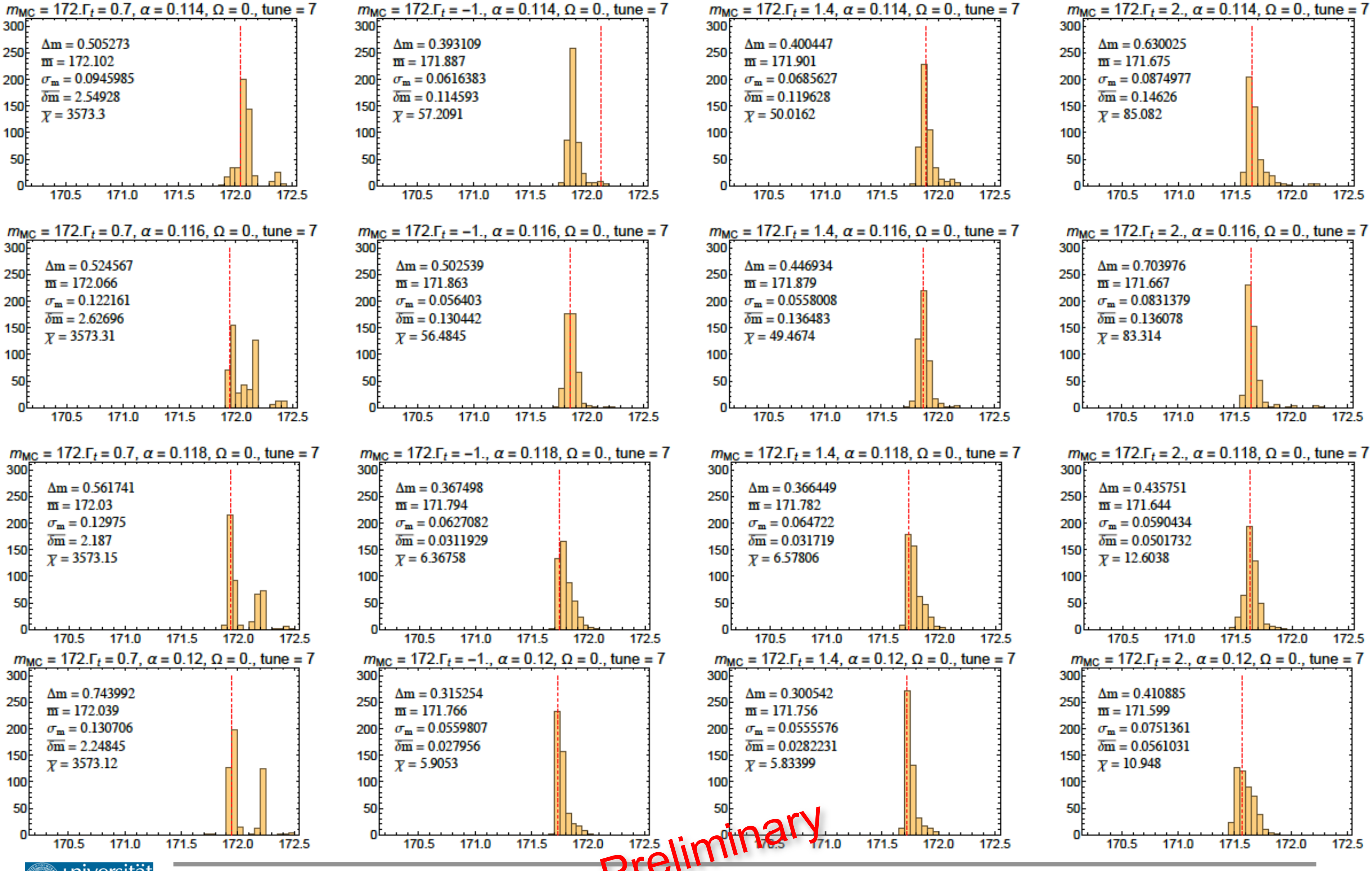
Peak Fits: m_t^{MSR}(1 GeV)



Order Behavior: MSR vs. Pole Mass

m_{MC}=173 GeV

Γ_t=1.4 GeV

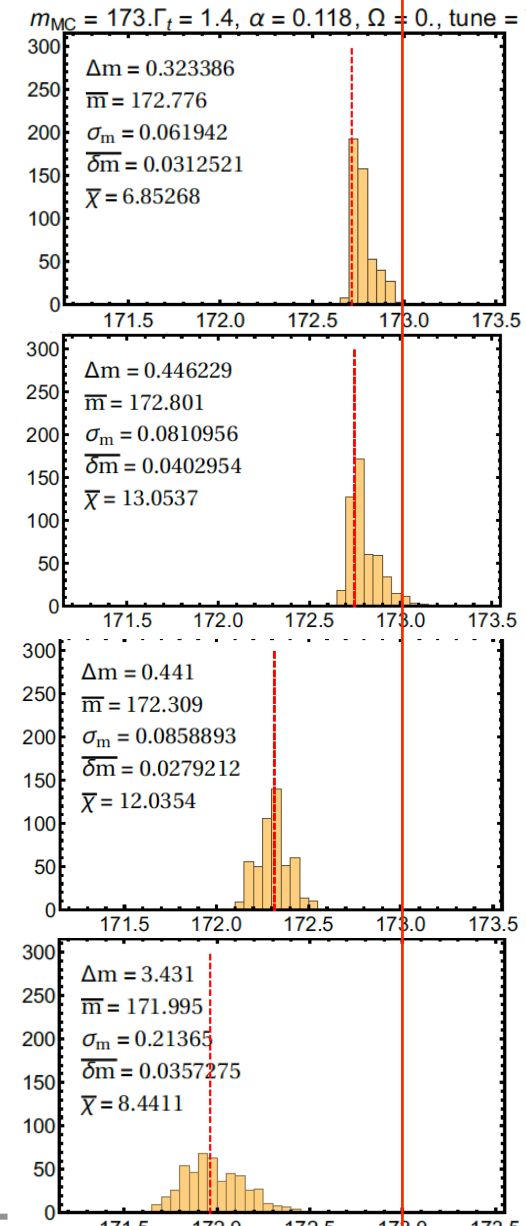
Preliminary

- Very good stability for MSR mass
- Mass m_t^{MSR}(1GeV) mass definition closest to the MC mass.

- Pole mass shows much worse convergence.
- Poles mass not close numerically to the MC mass: numbers are observable dependent and great care has to be taken to use the results as input in other calculations.

- Current world average:

  m_{MC} = 172.44 ± 0.49 GeV



m_t^{MSR}(1GeV) [NNLL]

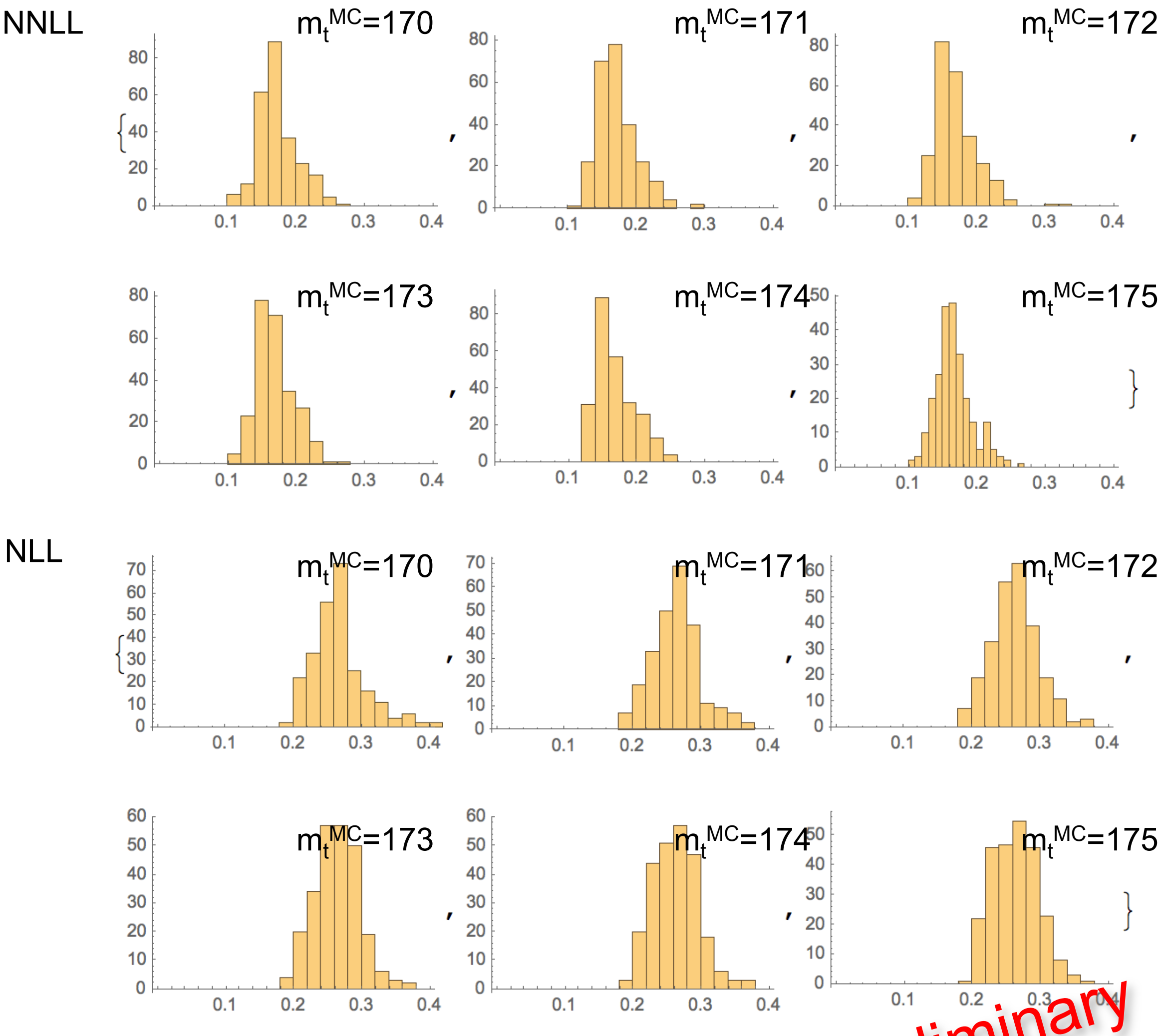
m_t^{MSR}(1GeV) [NLL]

m_t^{pole} [NNLL]

m_t^{pole} [NLL]

Peak Fits: $m_t^{MSR}(1\ \mathrm{GeV})$

Distribution of covervage range /2: each from scan over 500 profile functions



- Renormalization scale error
- NNLL: 150-170 MeV
- NLL: 250-300 MeV
- Good convergence!

- Histograms include $\alpha_S(M_Z)$=0.114 – 0.122 and Γ_t=-1,1.4, and tunes 1,3,7; 7 Q sets, 2 bin fit ranges (252 combinations)

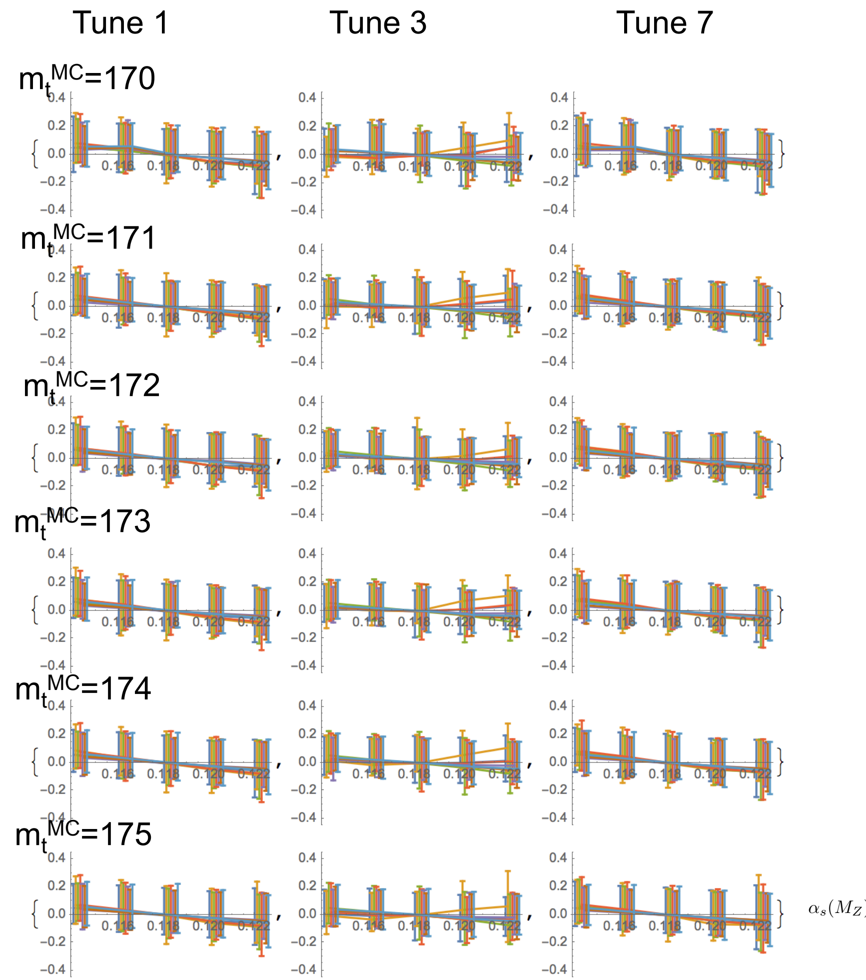
Preliminary

Peak Fits: $m_t^{MSR}(1\ \text{GeV})$

Parametric dependence on strong coupling

$$m_t^{MSR}[\alpha_s(M_Z)] - m_t^{MSR}[0.118]$$

- Small sensitivity of $m_t^{MSR}(1\text{GeV})$ on $\alpha_s(M_z)$. [~50 MeV error] ✔
  - Error bars: envelope of best mass value distribution in 500 profile function fits

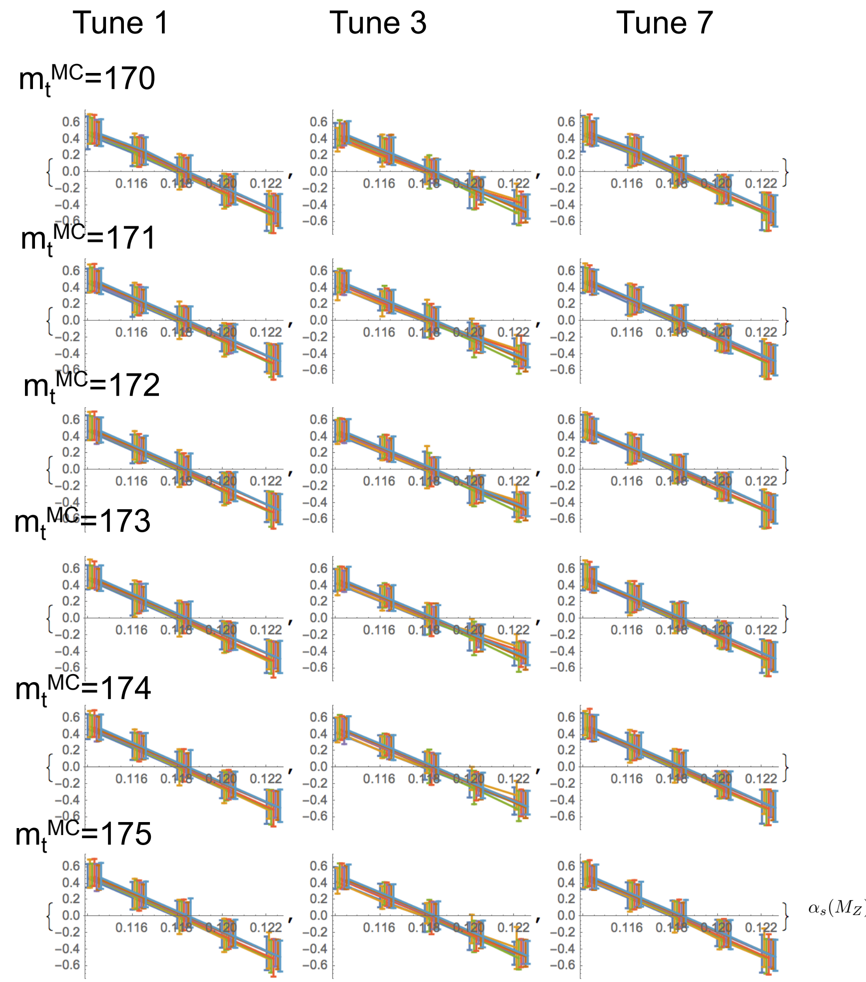


Preliminary

Peak Fits: $m_t^{MSR}(1\ \mathrm{GeV})$

Parametric dependence on strong coupling

$m_t(m_t)[\alpha_s(M_Z)] - m_t(m_t)[0.118]$



- Large sensitivity of MSbar mass on $\alpha_s(M_z)$. [not an error, but calculated from MSR mass] ✔
- The MC top mass IS FAR AWAY from the MSbar mass.
  - Error bars: envelope of best mass value distribution in 500 profile function fits

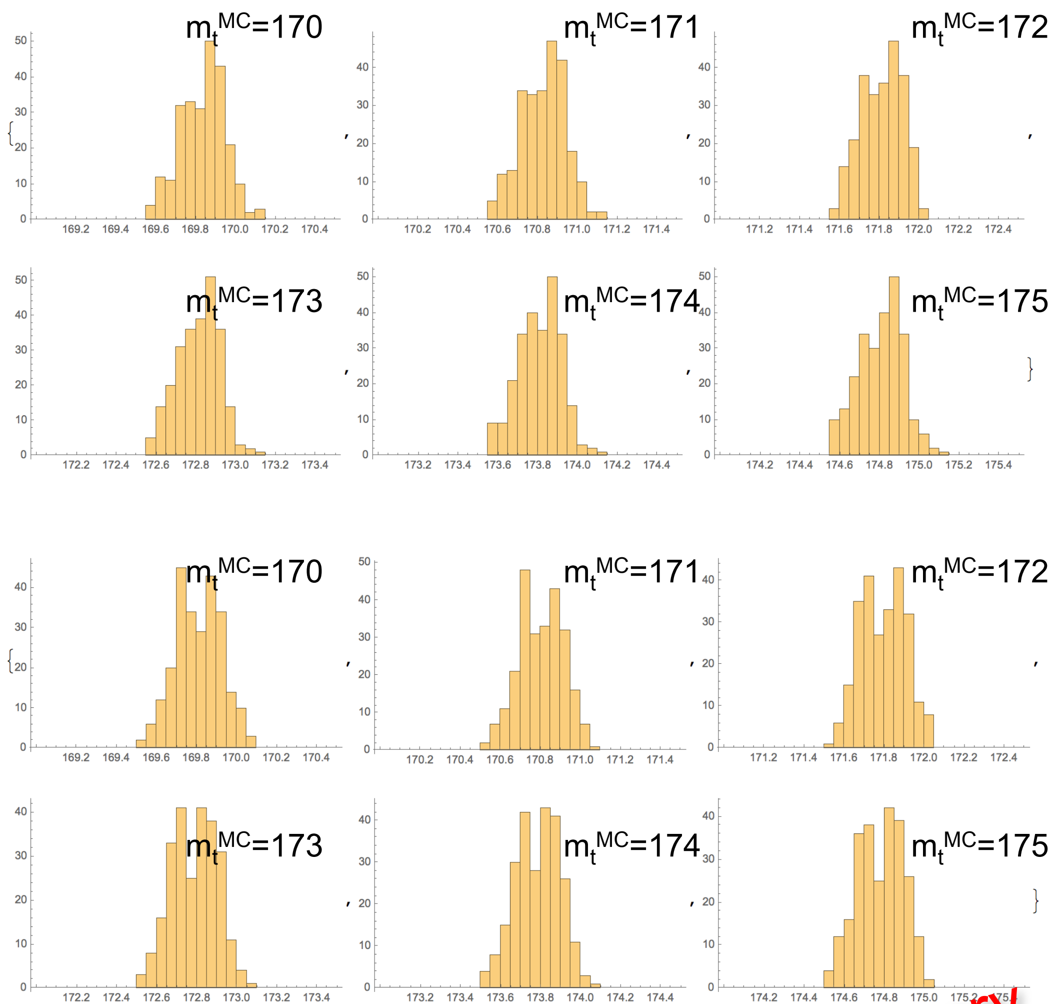
Preliminary

Peak Fits: $m_t^{MSR}(1\ \text{GeV})$

Intrinsic MC Compatibility Error (distribution of mean values)

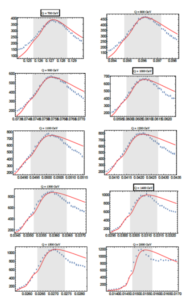
NNLL

NLL



- Coverage is measure for intrinsic MC uncertainty
- NNLL: ~200 MeV
- NLL: ~ 200 MeV

- Probably never before accounted in reconstruction analyses
- Measure for ultimate precision (MC dependent !)



  - Histograms include $\alpha_S(M_Z)$=0.114 – 0.122 and Γ_t=-1,1.4, and tunes 1,3,7; 7 Q sets, 2 bin fit ranges (252 combinations)

Preliminary

Peak Fits: m_t^{MSR}(1 GeV)

Tune dependence

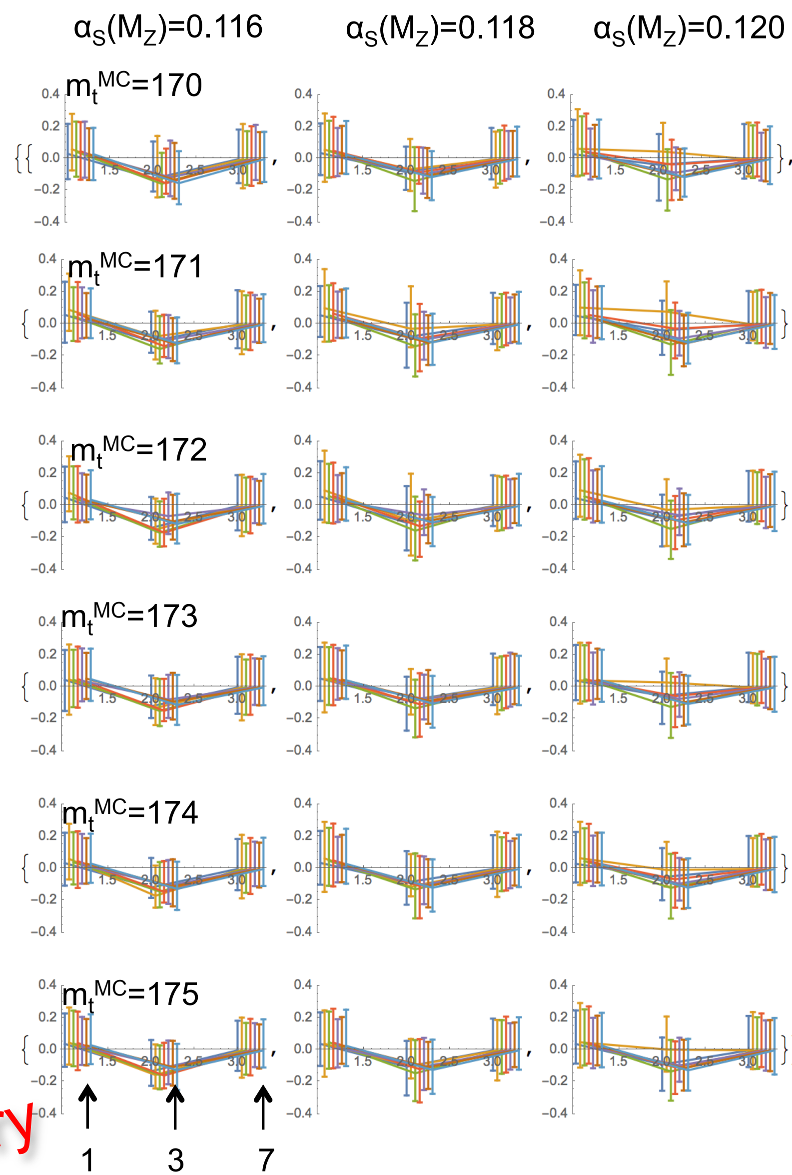
$$m_t^{MSR}[\text{tune}] - m_t^{MSR}[\text{tune } 7]$$

- Clear sensitivity to tune.

- MC top mass is tune-dependent !
- Tune-dependence is not an error !

- Opposite dependence should be visible in MC top mass determinations from experimental data.
  (highly nontrivial validation)

  - Top widths: Γ_t=-1,1.4
  - Error bars: standard deviation of best mass value distribution in 500 profile function fits



Preliminary

Summary

- First serious precise MC top quark mass calibration based on e^+e^- 2-jettiness (large p_T): closely related to observables dominating the reconstruction method

- NNLL+NLO QCD calculations based on an extension of the SCET approach concerning massive quark effects (all large logs incl. Ln(m)'s summed systematically).

- The Monte Carlo top mass calibration in terms of $m_t^{MSR}(1\text{GeV})$:

  - Scale dependence (NNLL): ~ 170 MeV
  - α_S dependence ($\delta\alpha_S$ =0.002): ~ 50 MeV
  - Intrinsic MC error: ~ 200 MeV

Preliminary !!!

- MC top mass is tune-dependent and MC dependent !
  Using MC top mass calibration might eliminate these error sources from the experimental analyses.
  Confirmation of the dependence predicted by calibration provides highly non-trivial cross check concerning the universality of the calibration.

Outlook & Plans

- Full verified error analysis @ NNLL/NLO → publication
  - Different sets of Q (p_T) values
  - Different fit ranges
  - Bug fixes
- Calibration Package for public use
  - Calibration m_t^{MC} → $m_t^{MSR}(1GeV)$
  - Code $m_t^{MSR}(1GeV)$ → any other scheme
- Heavy jet mass, C-parameter (NNLL),
- pp-2-jettiness analysis (NLL) w.i.p.
- NNNLL+NNLO (2-jettiness for e^+e^-) w.i.p
- Mass (+ Yukawa coupling) conversions w. QCD + electroweak (Yukawa effects)

Backup Slides

Pole Mass from MSR Mass

$$\alpha_s(M_Z) = 0.118$$
$$n_f = 5$$

$$\begin{aligned} m_t^{\rm pole} - m_t^{\rm MSR}(1\,\mathrm{GeV}) = & \overset{\mathcal{O}(\alpha_s)}{0.173} + \overset{\mathcal{O}(\alpha_s^2)}{0.138} + \overset{\mathcal{O}(\alpha_s^3)}{0.159} + \overset{\mathcal{O}(\alpha_s^4)}{0.23}\ \mathrm{GeV} \\ & + 0.53 + 1.43 + 4.54 + 16.6\ \mathrm{GeV} \\ & + 68.6 + 317.7 + 1629 + 9158\ \mathrm{GeV} \end{aligned}$$

← calculated

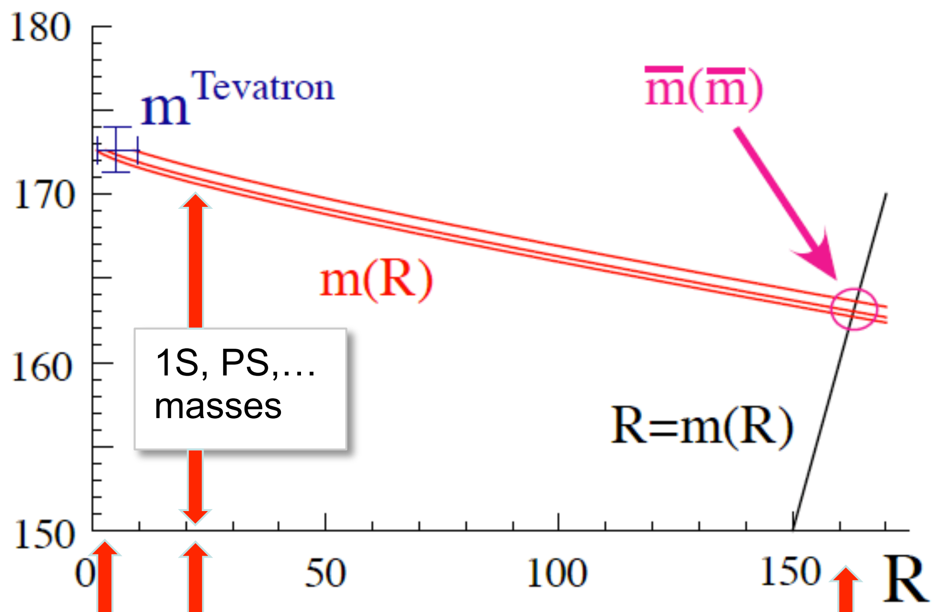
← extrapolated

- Size of terms consistent with scale error estimate of calibration.
- No stable determination of pole mass.

MSR Mass Definition

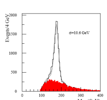
$$m_t^{\mathrm{MC}} = m_t^{\mathrm{MSR}}(3^{+6}_{-2}\ \mathrm{GeV}) = m_t^{\mathrm{MSR}}(3\ \mathrm{GeV})^{+0.6}_{-0.3}$$

AH, Stewart: arXive:0808.0222



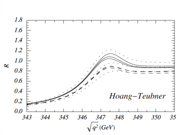
Good choice for R:

Of order of the typical scale of the observable used to measure the top mass.



Peak of invariant mass distribution, endpoints

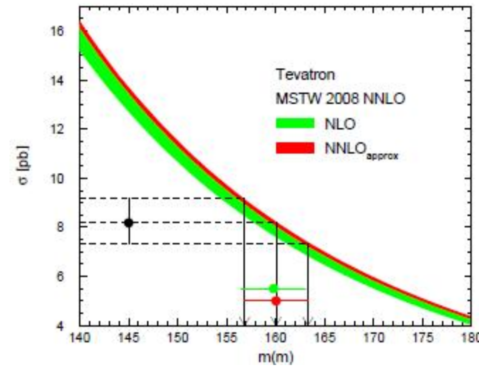
Top-antitop threshold at the ILC



Total cross section, e.w.precsion obs., Unification, MSbar mass

Masses Loop-Theorists Like to use

Langenfeld, Moch, Uwer



Total cross section (LHC/Tev):

$$m_t^{\rm MSR}(R=m_t)=\overline{m}_t(\overline{m}_t)$$

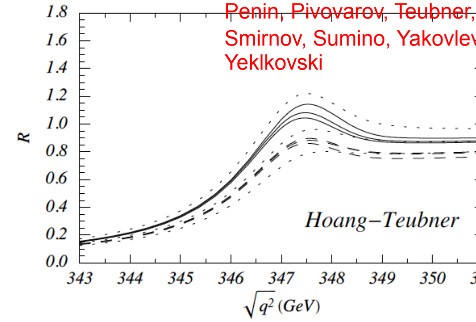
- more inclusive
- sensitive to top production mechanism (pdf, hard scale)
- indirect top mass sensitivity
- large scale radiative corrections

$$M_t \;=\; M_t^{(O)} \,+\, M_t(0)\alpha_s \,+\, \ldots$$

Mass schemes related to different computational methods

Relations computable in perturbation theory

Beneke, AH, Melnikov, Nagano, Penin, Pivovarov, Teubner, Signer, Smirnov, Sumino, Yakovlev, Yeklkovski



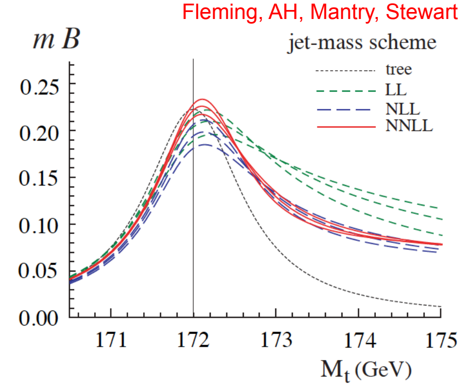
Threshold cross section (ILC):

$$m_t^{\rm MSR}(R\sim 20\text{ GeV})\,,\;m_t^{\rm 1S}\,,\;m_t^{\rm PS}(R)$$

$$M_t \;=\; M_t^{(O)} \,+\, \langle p_{\rm Bohr}\rangle\alpha_s \,+\, \ldots$$

$$\langle p_{\rm Bohr}\rangle \;=\; 20\,\text{GeV}$$

Fleming, AH, Mantry, Stewart



Inv. mass reconstruction (ILC/LHC):

$$m_t^{\rm MSR}(R\sim \Gamma_t)\,,\;m_t^{\rm jet}(R)$$

$$M_t \;=\; M_t^{(O)} \,+\, \Gamma_t\alpha_s \,+\, \ldots$$

$$\Gamma_t \;=\; 1.3\,\text{GeV}$$

- more exclusive
- sensitive to top final state interactions (low scale)
- direct top mass sensitivity
- small scale radiative corrections