Top Quark Mass Calibration for Monte-Carlo Event Generators

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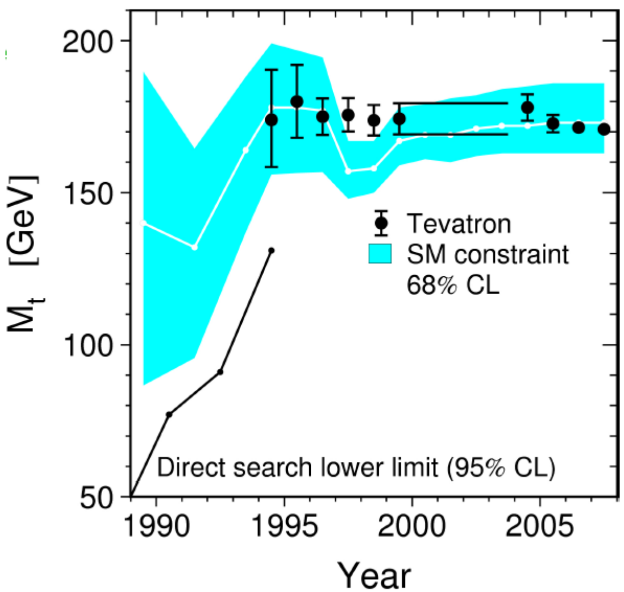
XXIV International Conference on Deep Inelastic Scattering, DESY, April 11-14, 2016

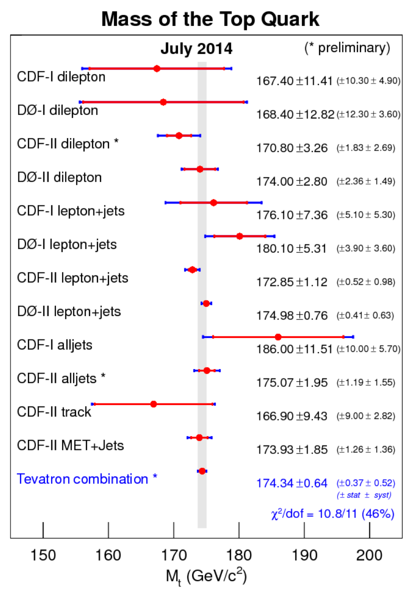
Outline

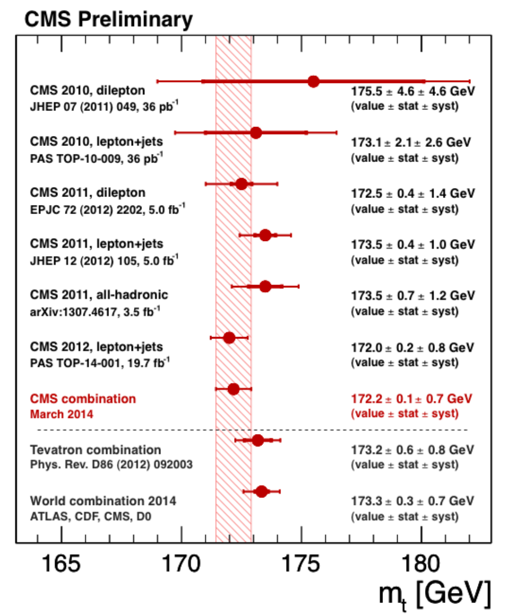
- Basic methods for top mass measurements
- Monte Carlo generators and the top quark mass
- Calibration of the Monte Carlo top mass parameter
- Preliminary results of first serious analysis

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

A small history on top mass reconstruction

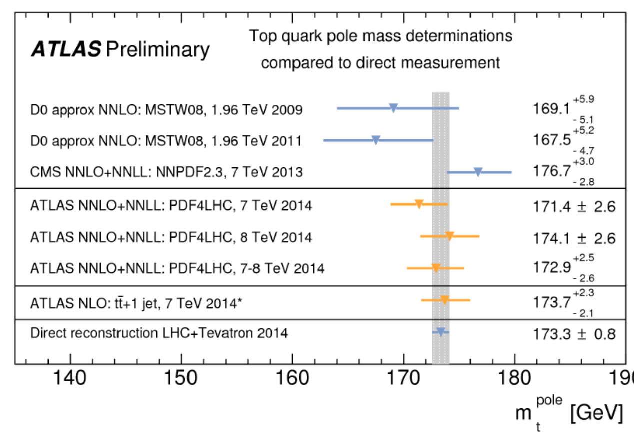






- Many individual measurements with uncertainty below 1 GeV.
- Smallest errors from direct reconstruction/ template fits
- World combination 2014:

$$m_t^{\mathrm{MC}} = 173.34 \pm 0.76\,\mathrm{GeV}$$

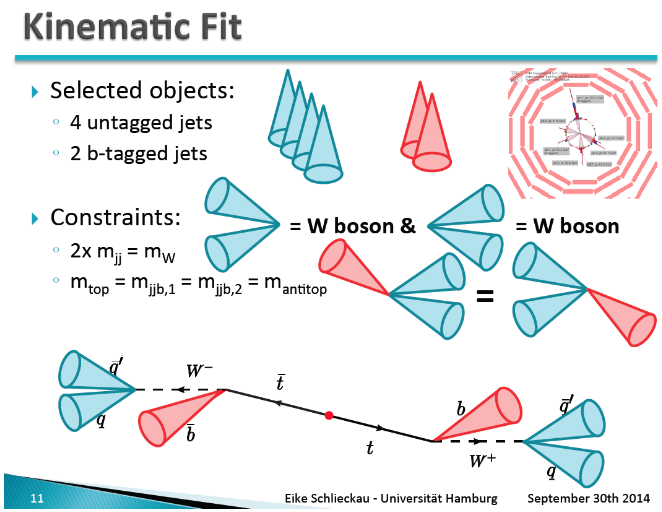


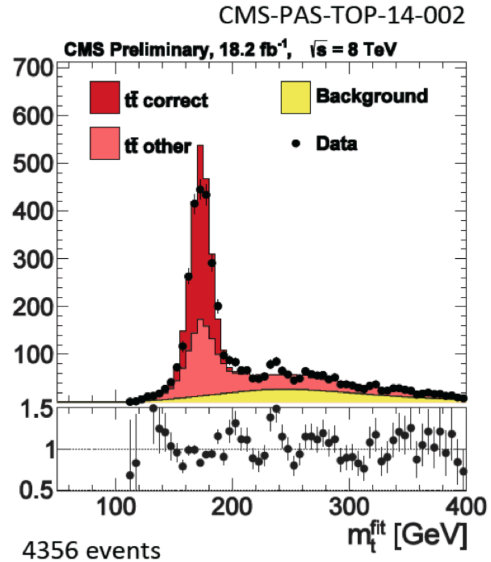
→ Talks by Shabalina, Bevilacqua, Thier

Main Top Mass Measurements Methods

LHC+Tevatron

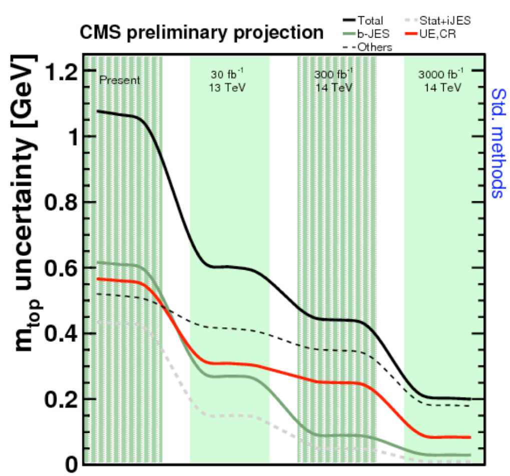
Direct Reconstruction:





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

kinematic mass determination



⊕ High top mass sensitivity

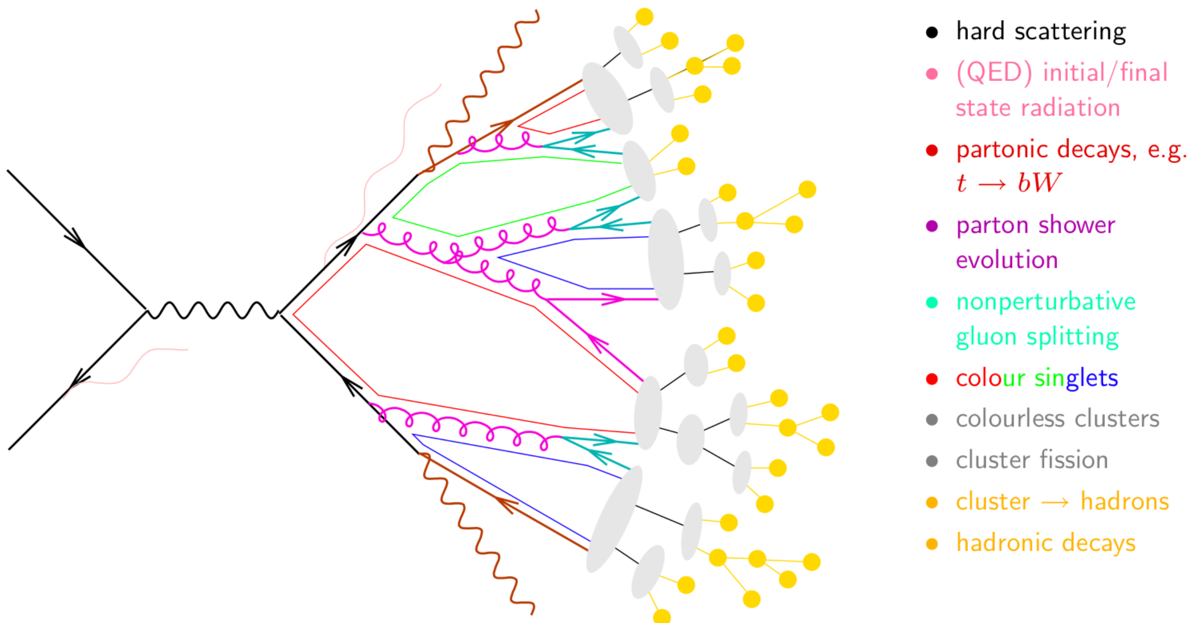
⊖ Precision of MC ?

⊖ Meaning of m_t^{MC} ?

$\Delta m_t \gtrsim 0.5$ GeV

$\Delta m_t \sim 200$ MeV (projection)

Monte-Carlo Event Generators



- Full simulation of all processes (all experimental aspects accessible)
- QCD-inspired: partly first principles QCD ⇔ partly model
- Description power of data better than intrinsic accuracy. (But how precise?)
- 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.

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 observable (closely 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

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

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

Monte Carlo errors:

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

QCD errors:

- perturbative error
- scale uncertainties
- electroweak effects

Parametric errors:

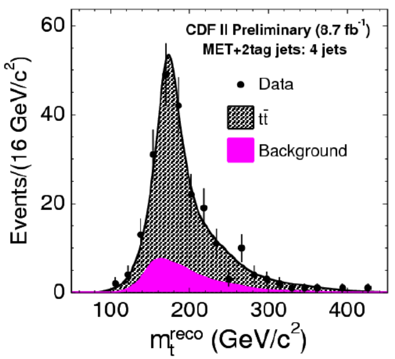
- strong coupling α_s
- Non-perturbative parameters

Thrust Distribution

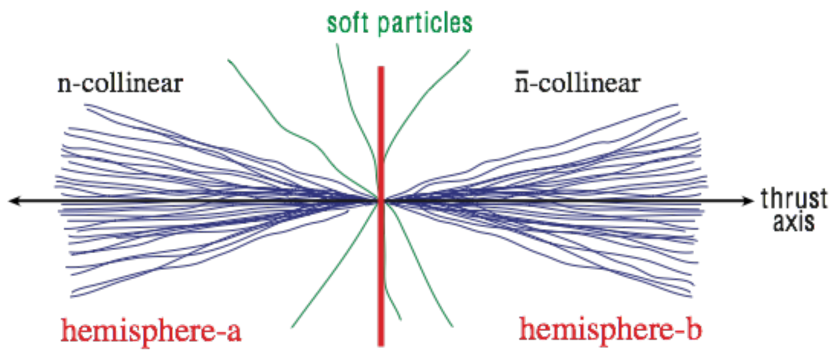
Observable: 2-jettiness in e+e- for $Q \sim p_T \gg m_t$ (boosted tops)

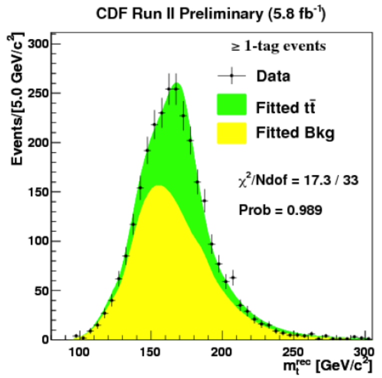
$$\tau \;=\; 1-\max_{\vec{n}}\frac{\sum_i|\vec{n}\cdot\vec{p}_i|}{Q}$$

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

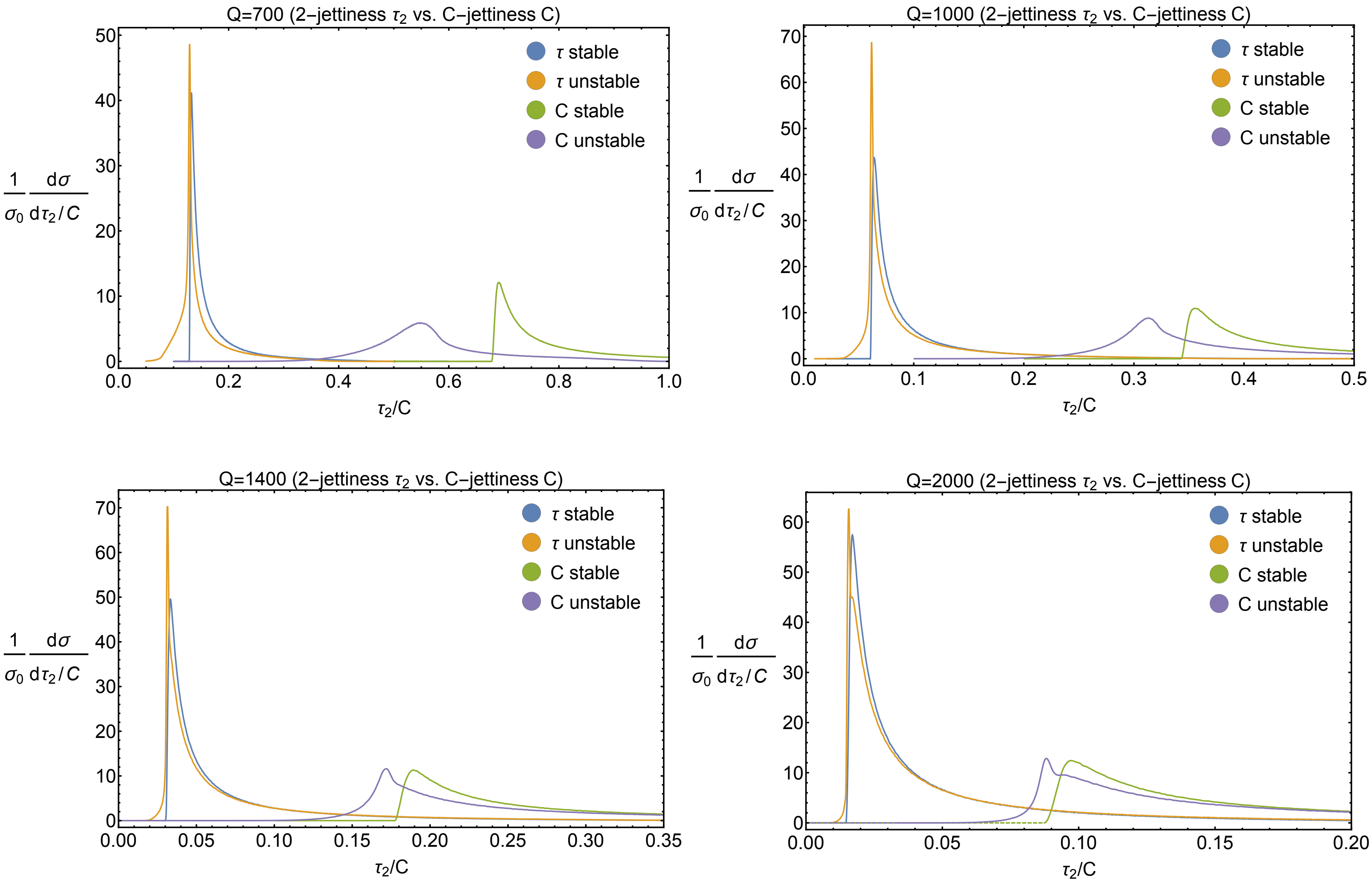


Invariant mass distribution in the resonance region of wide hemisphere jets !



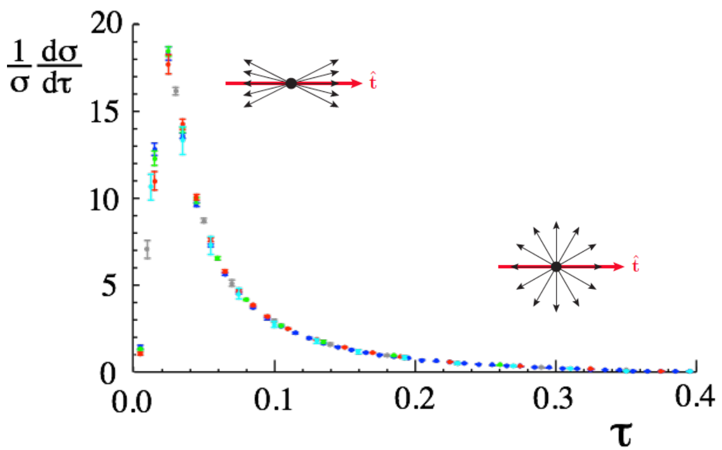


Event Shape Distributions (Pythia 8.2)



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

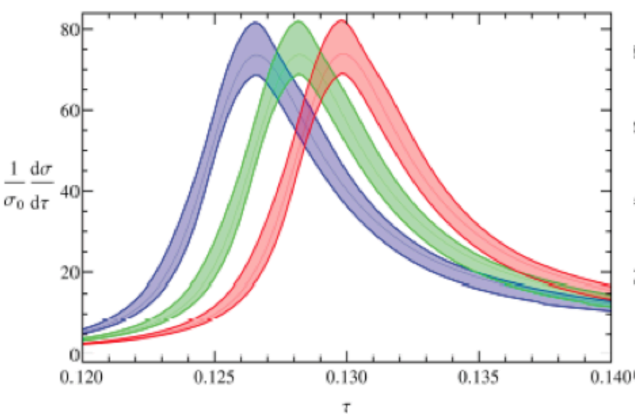
Butenschön, Dehnadi, AHH, Mateu 2016 (to appear soon)

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

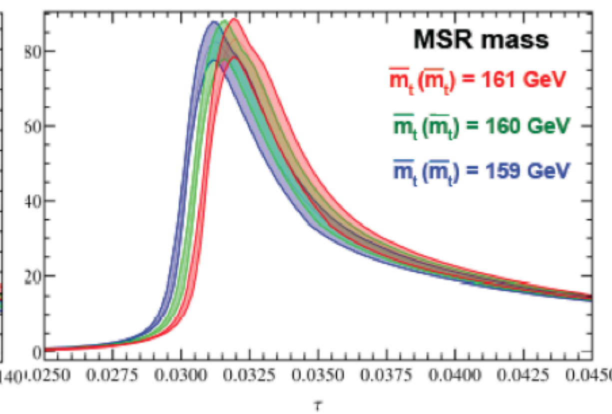
2-Jettiness for Top Production (QCD)

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

Q=700 GeV



Q=1400 GeV



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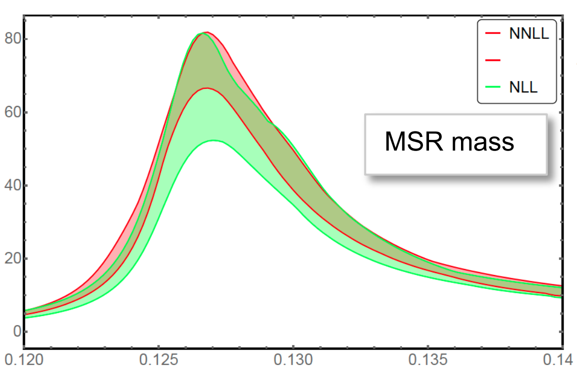
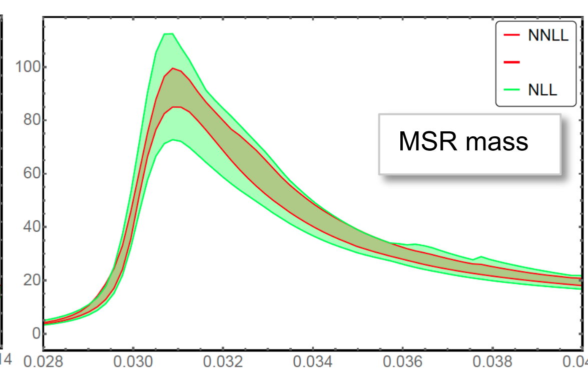


Q=1400 GeV



- 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

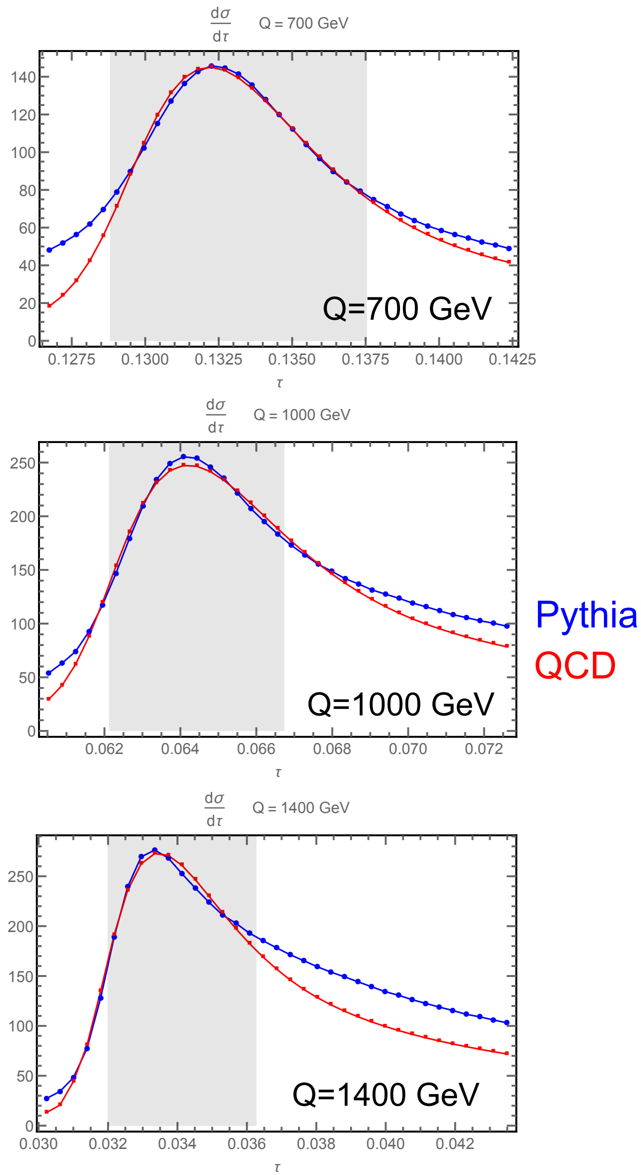
Fit Procedure Details

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

QCD parameters measured from Pythia

- Fit parameters: $m_t^{\rm MSR}(R),\ \alpha_s(M_Z),\ \Omega_1,\ \Omega_2,\ \ldots,$
- Perturbative error: fits for 500 randomly picked sets of renor. scales
- Tunings: 1, 3, 7 (default)
- Top quark width: $\Gamma_t\ =\ \text{dynamical (default)},\ 0.7,\ 1.4,\ 2.0\,\text{GeV}$
- External smearing (Detector effects): $\Omega_{1,\text{smear}}\ =\ 0,\ 0.5,\ \ldots,\ 3.0,\ 3.5,\ \text{GeV}$
- Pythia masses: $m_t^{\tt Pythia}\ =\ 170,\ \ldots\ ,\ 175\,\text{GeV}$
- Fit possible for any mass scheme

Preliminary Peak Fits

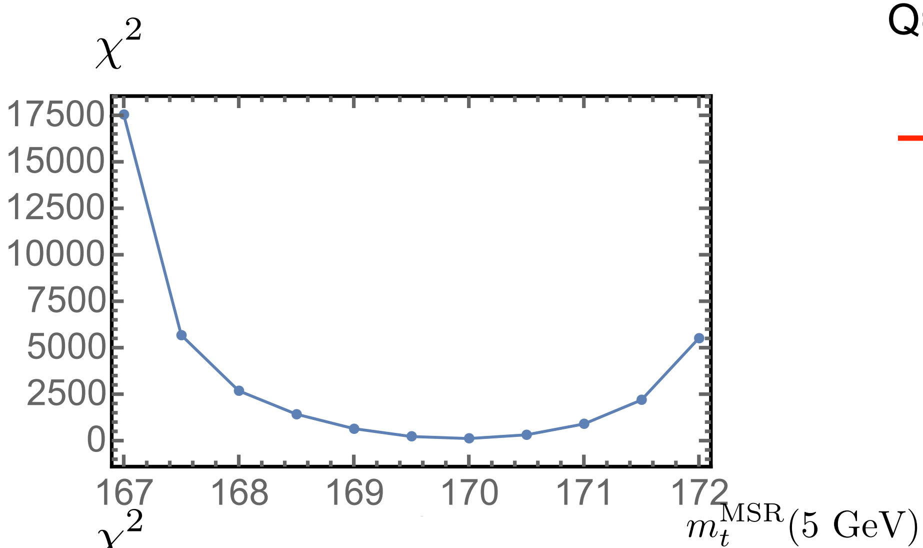


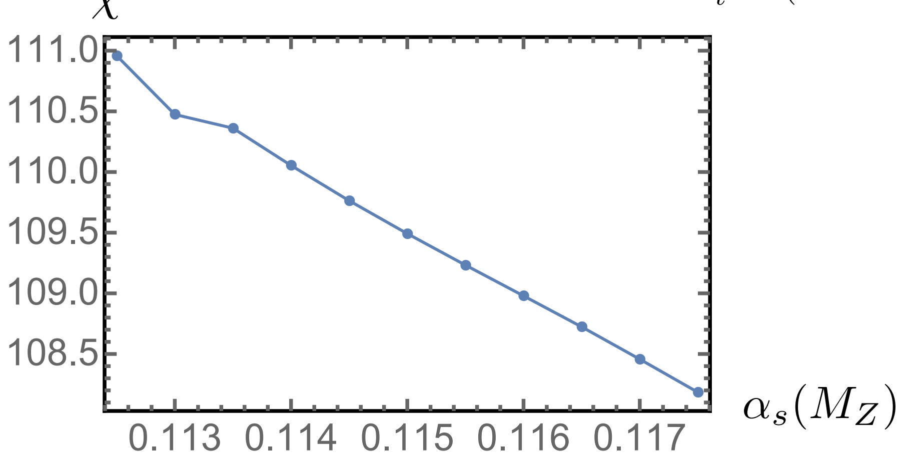
Default renormalization scales; Γ_t=1.4 GeV, tune 7, $\Omega_{1,smear}$=2.5 GeV, m_t^{Pythia}=171 GeV, Q={700, 1000, 1400} GeV, peak fit (60/80)%

- 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)
- Excellent sensitivity to the top quark mass.

Preliminary

Peak Fits





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→ 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

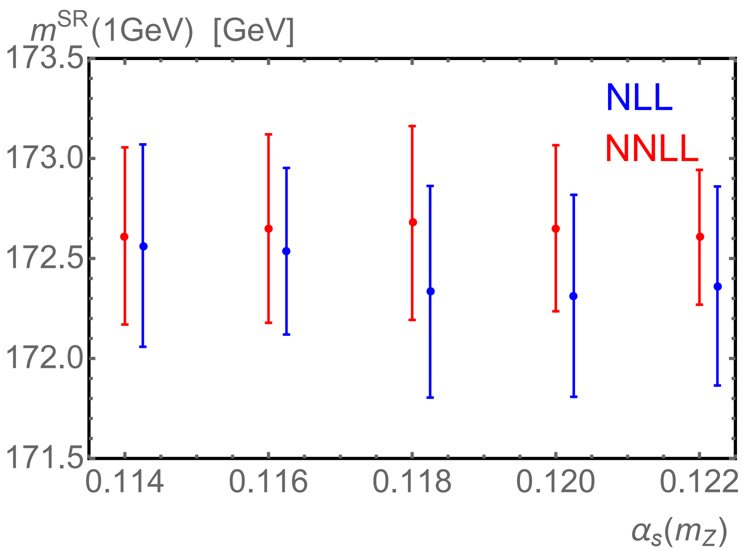
- We use rescaled χ^2/dof (PDG prescreption) to defind “intrinsic MC compatibility uncertainty”

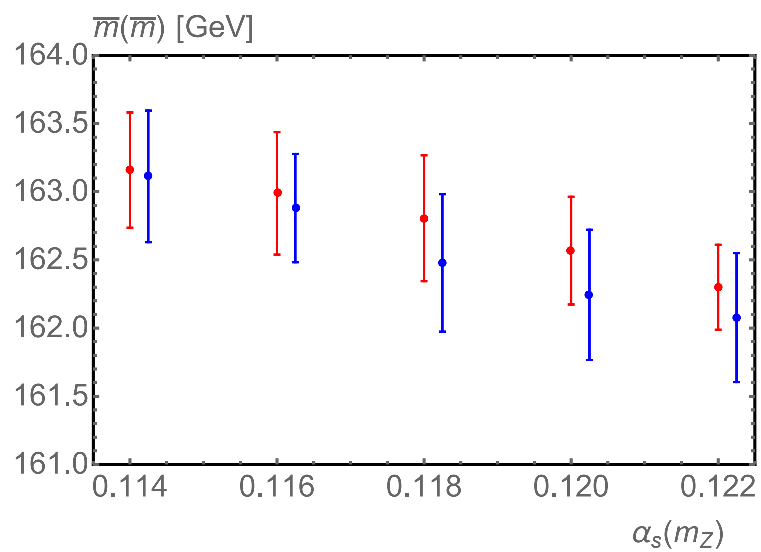
Preliminary

Peak Fits

First serious run: Γ_t=1.4 GeV, tunes 1, 3, 7,
$\Omega_{1,smear}$=1.5, 2.0, 2.5, 3.0, 3.5 GeV,
Q={700, 1000, 1400} GeV, peak fit (60/80)%
m_t^{Pythia}=173 GeV,
NLL: 177 scan survivors, NNLL: 254 scan survivors

Preliminary





- Very low sensitivity of m_t^{MSR}(5GeV) on $\alpha_s(M_z)$. ✔
- Large sensitivity of MSbar mass on $\alpha_s(M_z)$. ✔

MC top mass indeed closely related to m_t^{MSR}(R~1 GeV) !!

Peak Fits

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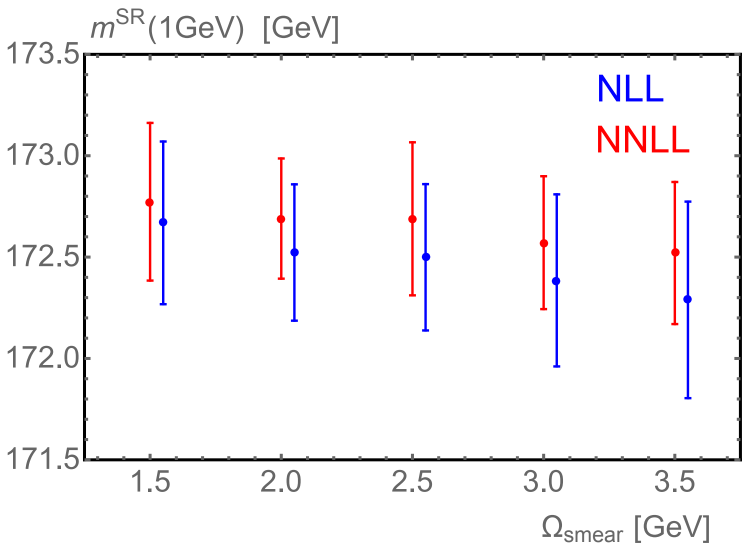

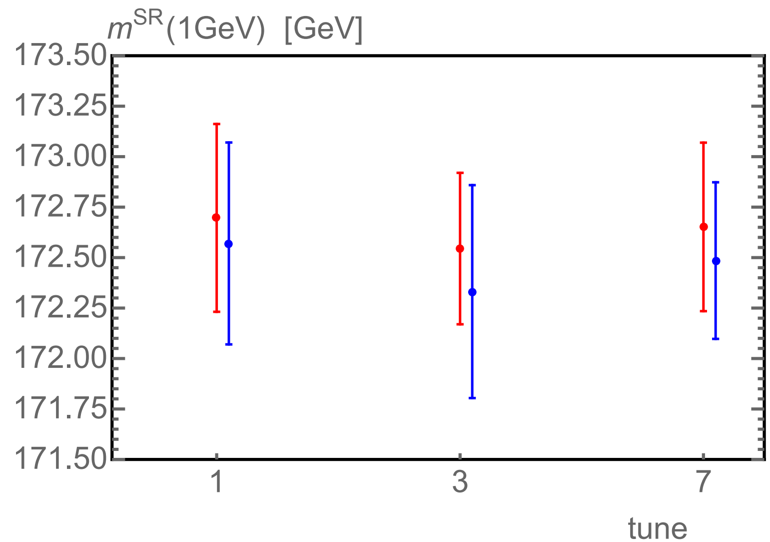

- "Detector effects" (~100 MeV) << perturbative uncertainty ($\lesssim$ 500 MeV). ✔
- MC tune dependence ($\lesssim$ 100 MeV) << perturbative uncertainty ($\lesssim$ 500 MeV). ✔

MC top mass indeed closely related to m_t^{MSR}(R~1 GeV) !!

Peak Fits

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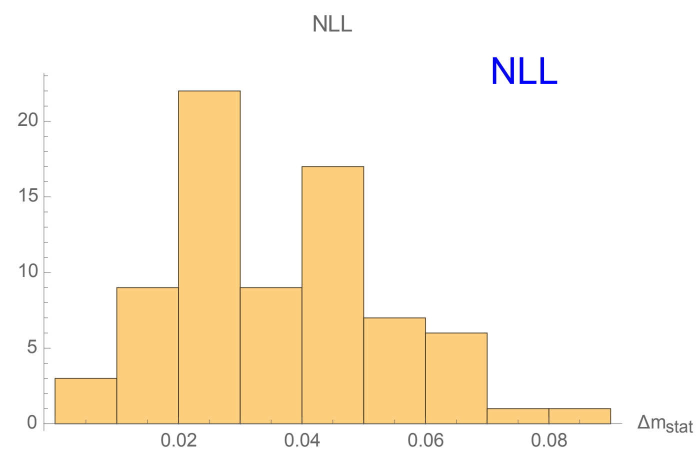

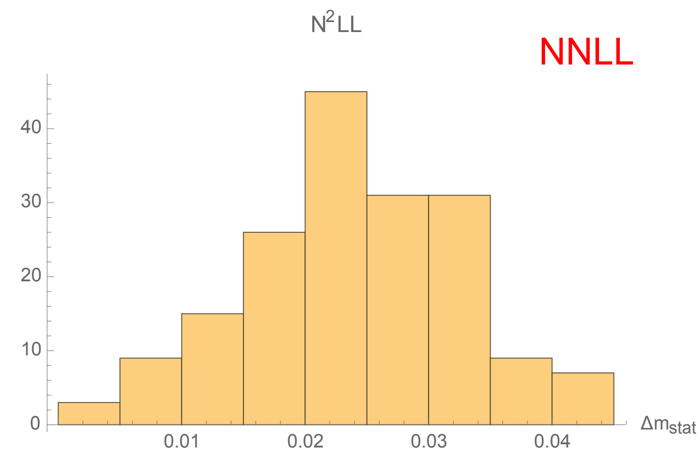

- "MC compatibility error" ~ tuning error ~ detector effect error ✔
- Effects are O(100) MeV. (Maybe represents for ultimate precision)

Peak Fits

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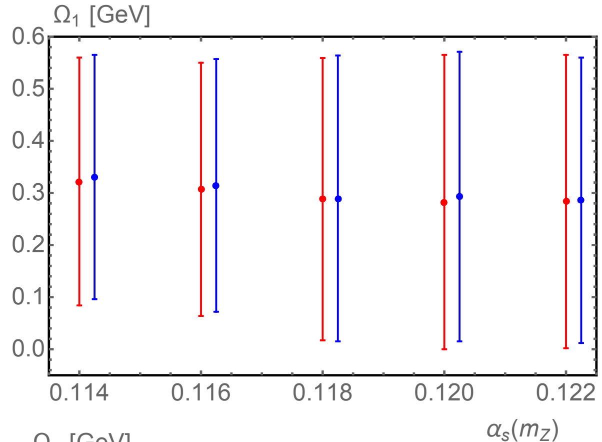
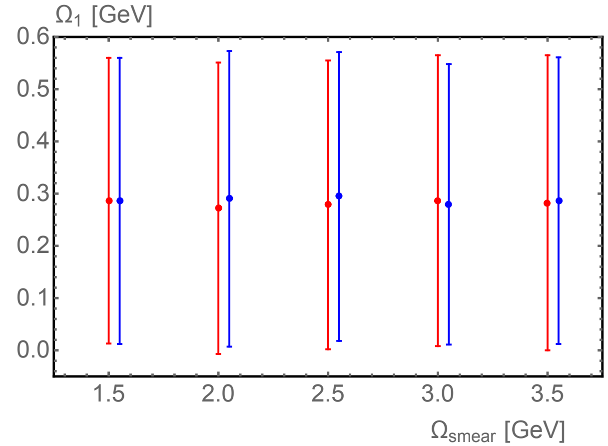
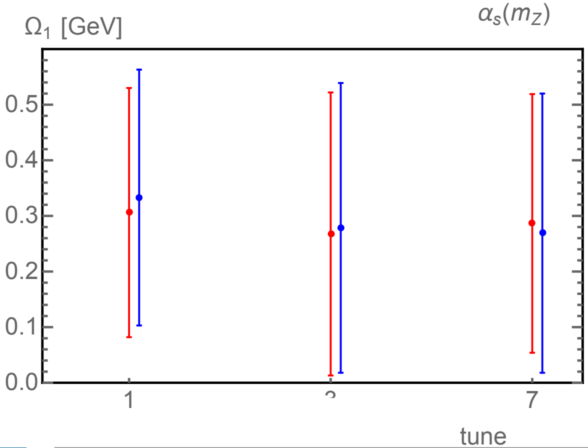
NLL
NNLL

Preliminary







- Reliable determination of non-perturbative matrix element Ω_1 (hadronization effects)
- Expected: $\delta m_t \sim \delta\Omega_1$ ✔
- Compatible with α_s-fits to e^+e^- data tail fits (Abbate etal, AHH etal.), larger err.

Peak Fits

First serious run: Γ_t=1.4 GeV, tunes 1, 3, 7,
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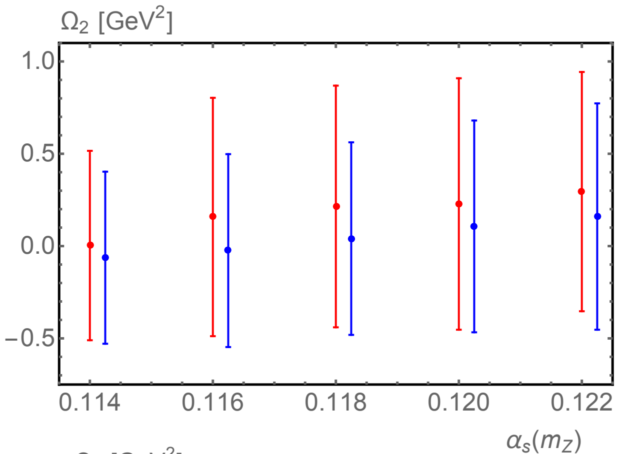
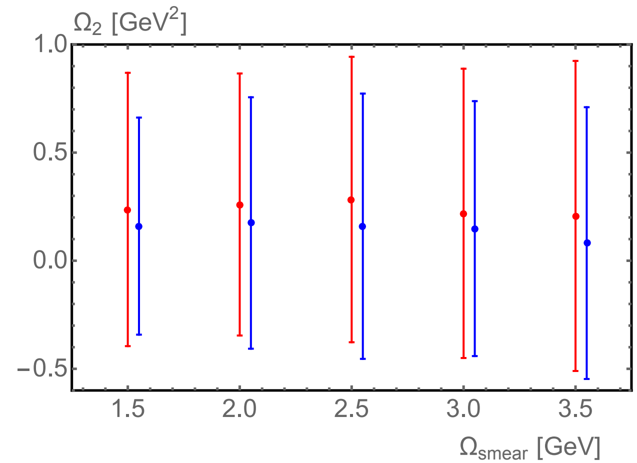
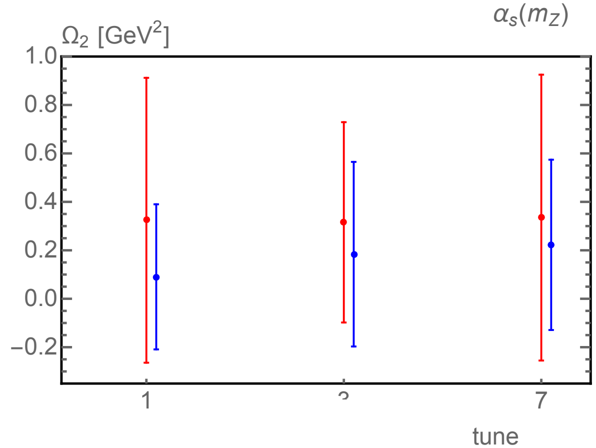
NLL
NNLL







- Reliable determination of non-perturbative matrix element Ω_2 (hadronization effects)
- Found to be have huge error as expected due to little sensitivity ✔

Peak Fits

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$\Omega_{1,smear}$=1.5, 2.0, 2.5, 3.0, 3.5 GeV,
Q={700, 1000, 1400} GeV, peak fit (60/80)%
m_t^{Pythia}=170,171, 172, 173, 174, 175 GeV
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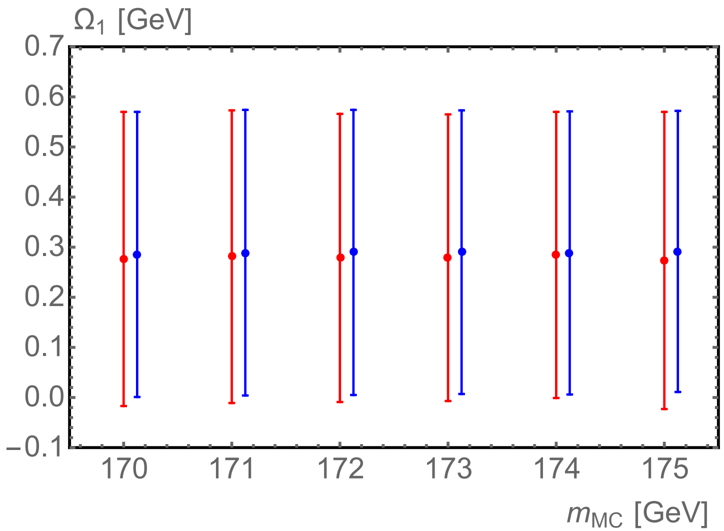
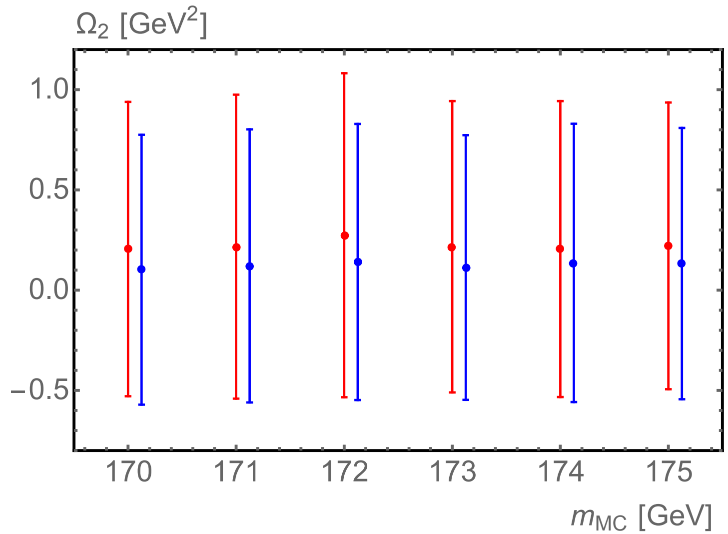
Preliminary

NLL
NNLL





- Non-pert. matrix elements $\Omega_{1,2}$ independent of top mass. ✔

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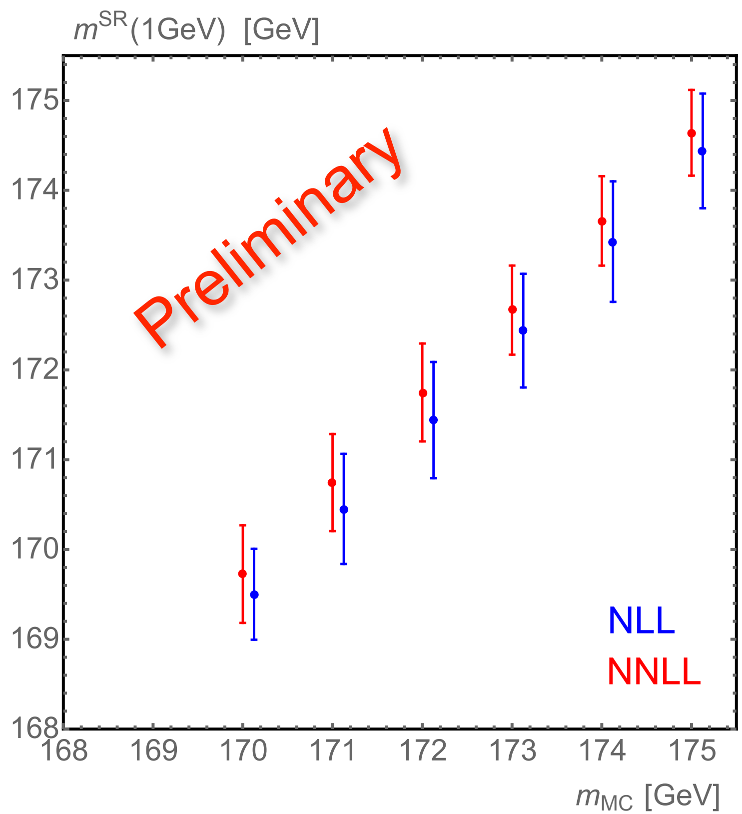

- Many more cross checks to be done.
- Calibration error: 0.5 GeV seems feasible at NNLL !

Conclusions & Outlook

- First serious precise MC top quark mass calibration based on e^+e^- 2-jettiness (large p_T): preliminary results.
- 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 MSR mass with perturbative error O(500 MeV) appears feasible at NNLL+NLO
- Intrinsic MC error seems O(100 MeV).

Outlook:

- Full verified error analysis @ NNLL+NLO on the way
- Calibration for other MC generators
- Heavy jet mass, C-parameter (NNLL), pp-2 jettiness analysis (NLL) w.i.p.
- NNNLL+NNLO (2jettiness for e^+e^-) w.i.p
- Mass (+ Yukawa coupling) conversions w. QCD + electroweak

Backup Slides

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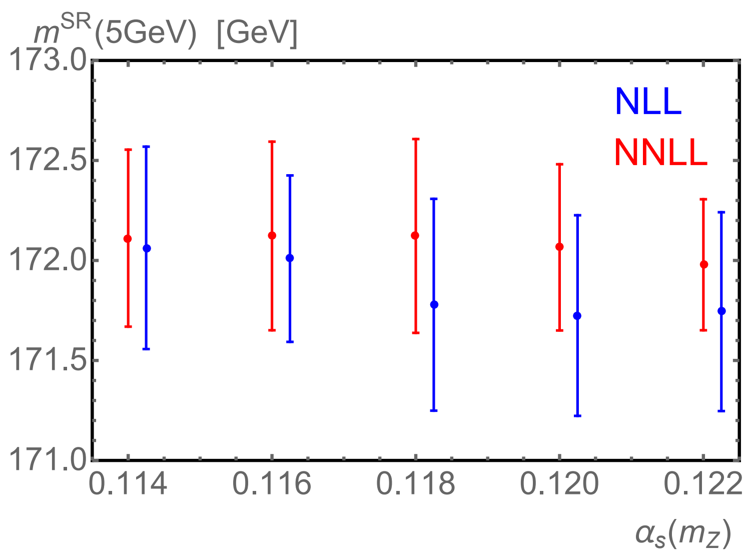

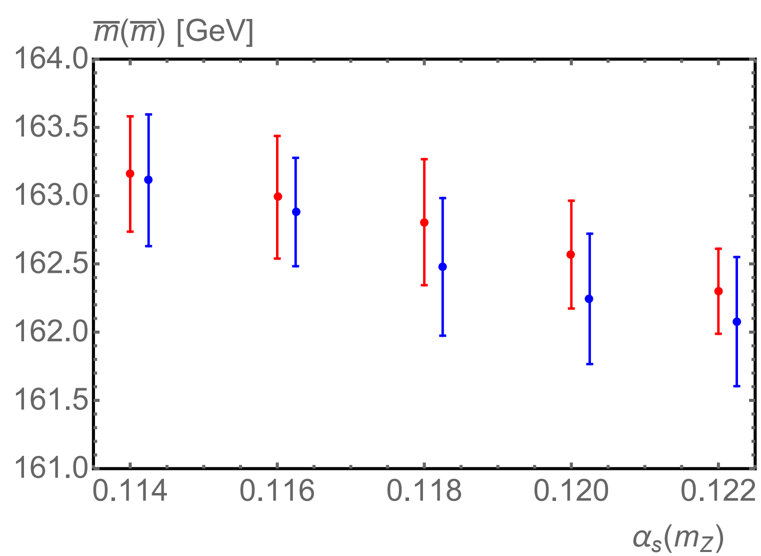

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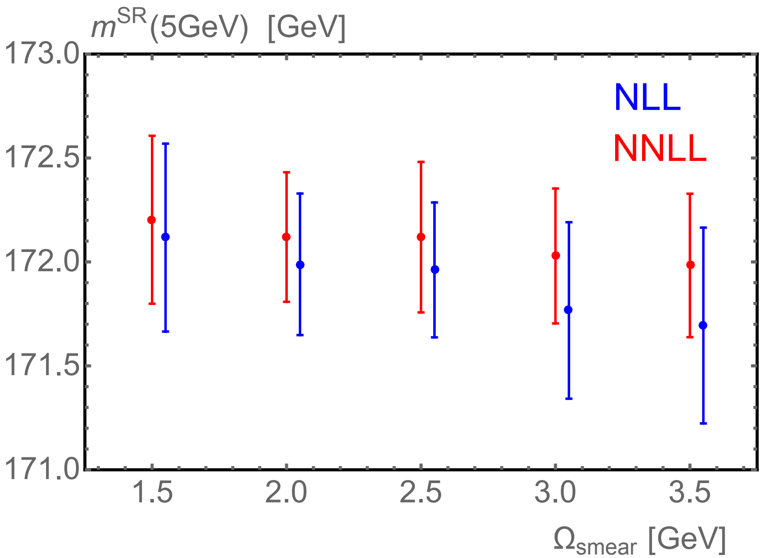

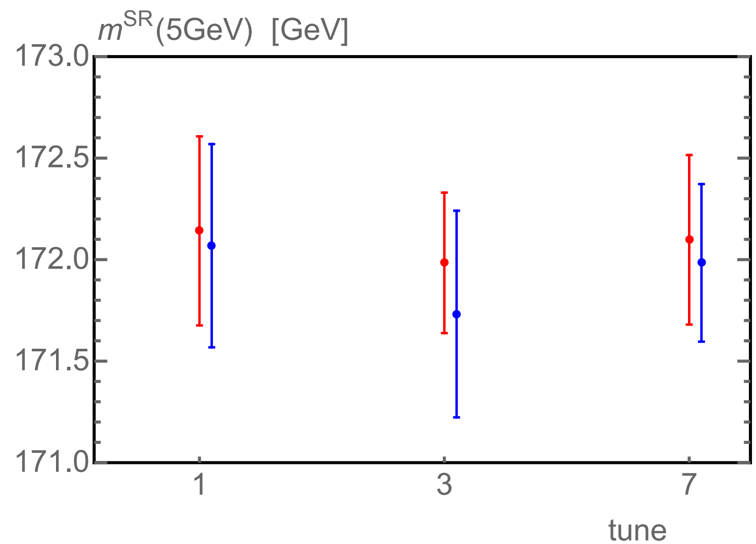

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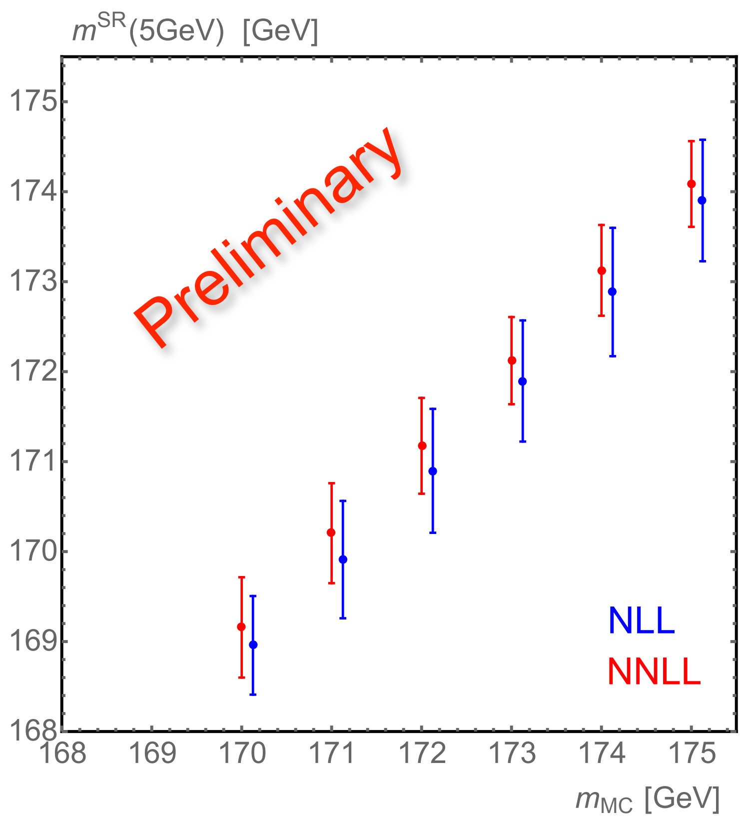
$\Omega_{1,smear}$=1.5, 2.0, 2.5, 3.0, 3.5 GeV,
Q={700, 1000, 1400} GeV, peak fit (60/80)%
m_t^{Pythia}=170,171, 172, 173, 174, 175 GeV
NLL: 177 scan survivors, NNLL: 254 scan survivors

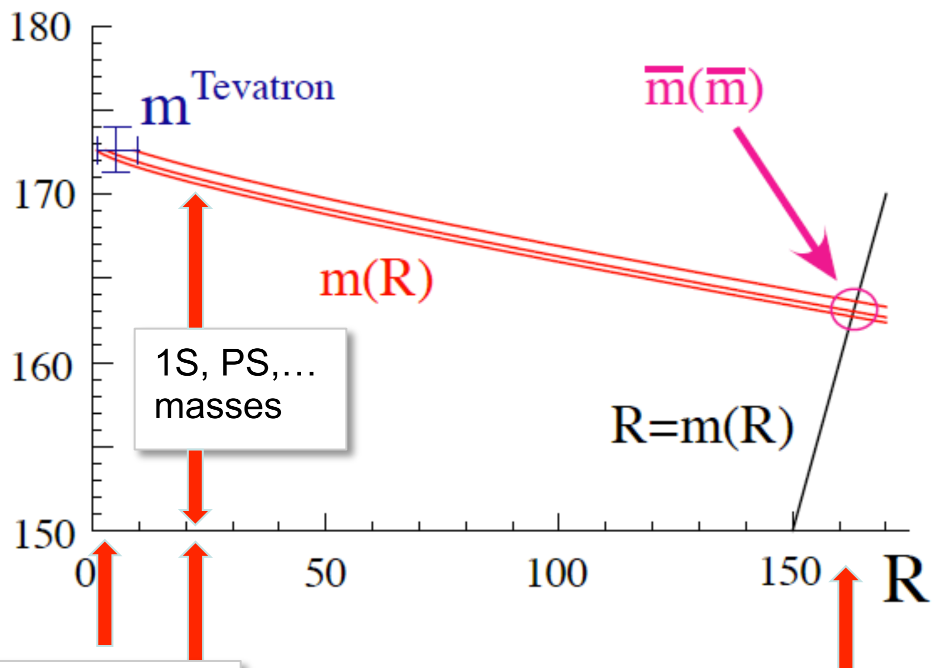


- Many more cross checks to be done.
- Calibration error: 0.5 GeV seems feasible at NNLL !

MSR Mass Definition

AH, Stewart: arXive:0808.0222

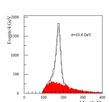
$$m_t^{\rm MC} = m_t^{\rm MSR}(3^{+6}_{-2}\ {\rm GeV}) = m_t^{\rm MSR}(3\ {\rm GeV})^{+0.6}_{-0.3}$$



1S, PS,… masses

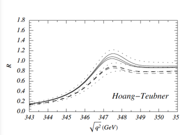
Good choice for R:

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

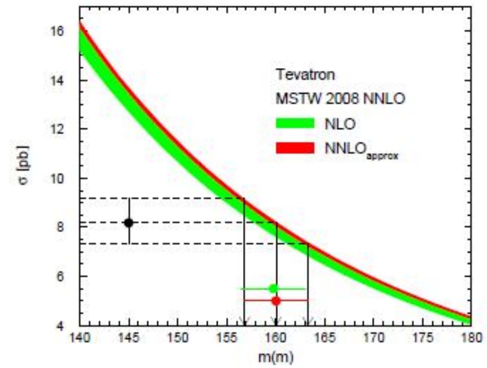
Total cross section (LHC/Tev):

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

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

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

Langenfeld, Moch, Uwer



Mass schemes related to different computational methods

Relations computable in perturbation theory

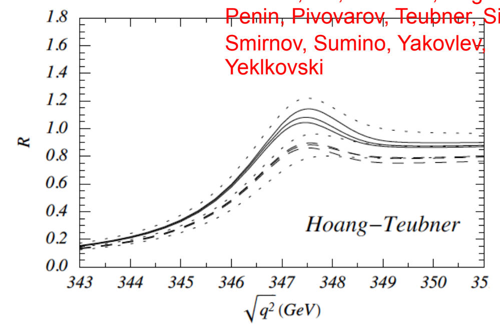
Threshold cross section (ILC):

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

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

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

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



Inv. mass reconstruction (ILC/LHC):

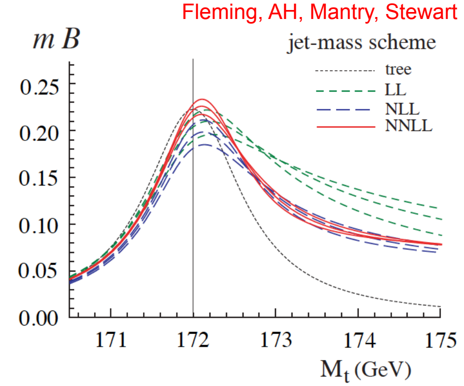
$$m_t^{\rm MSR}(R\sim\Gamma_t)\,,\ m_t^{\rm jet}(R)$$

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

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

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

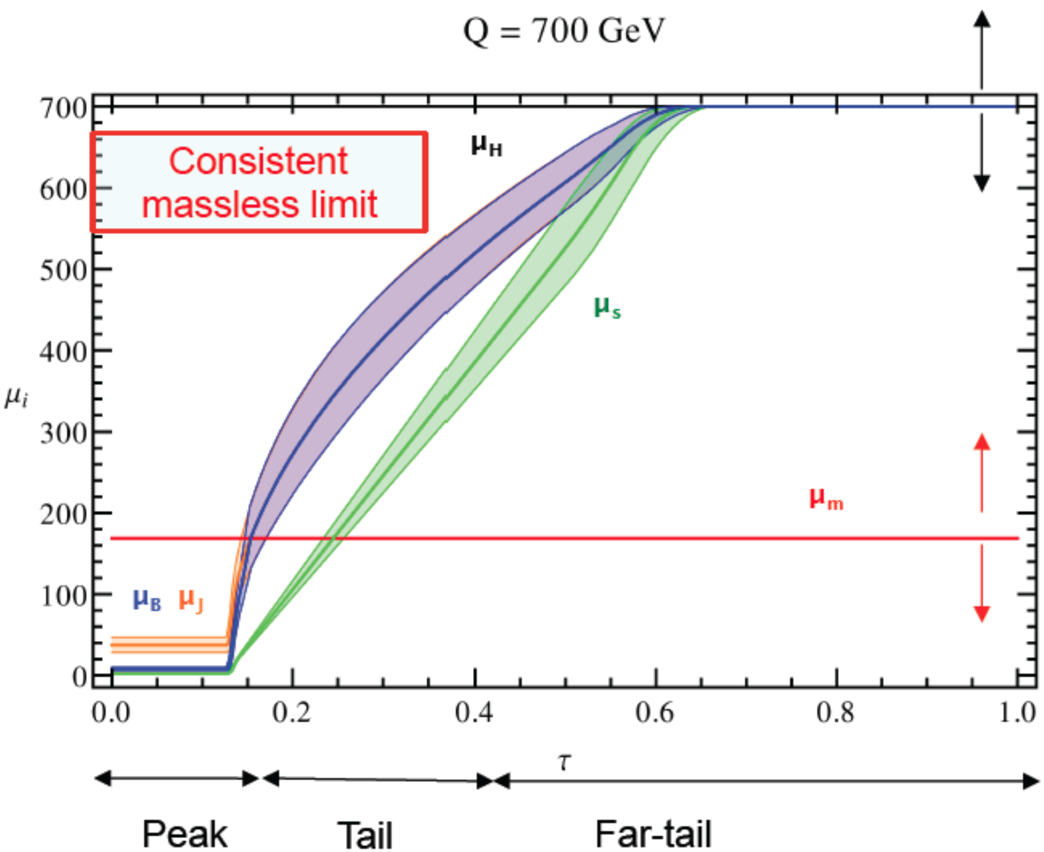
Fleming, AH, Mantry, Stewart



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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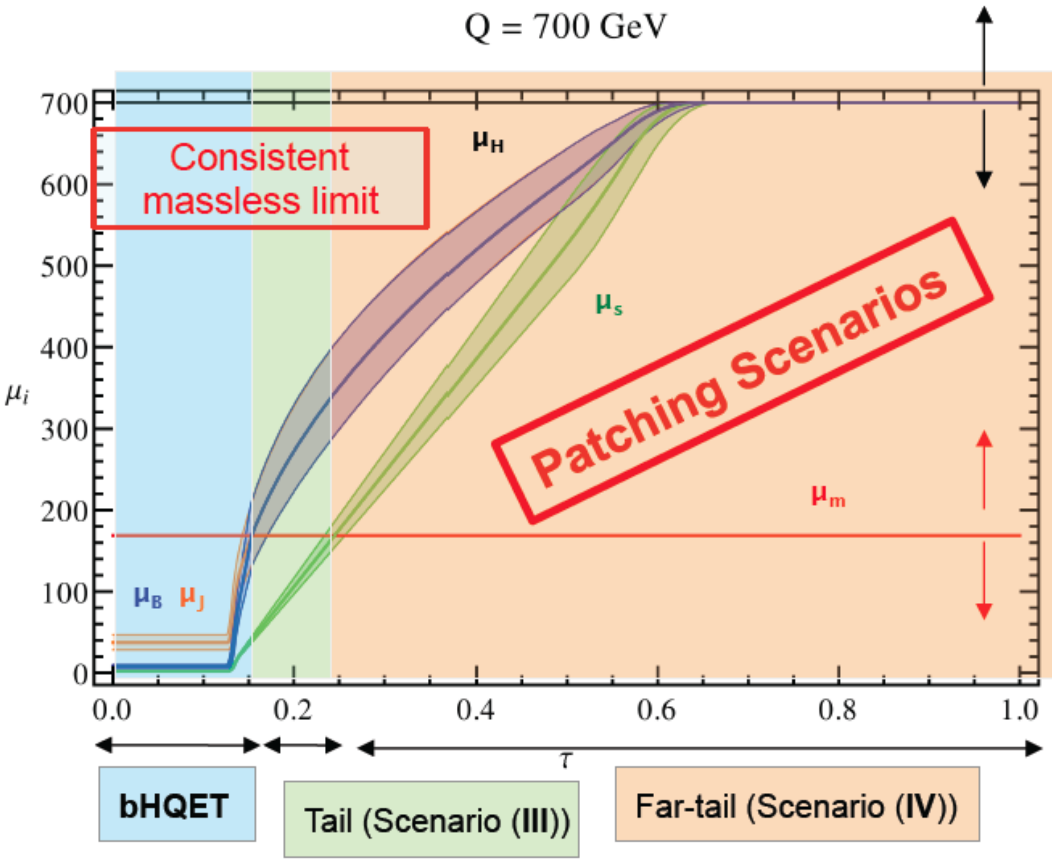

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