Precise Measurement of the Top Mass at Proton and Electron Colliders

Top Quark Mass Calibration for Monte-Carlo Event Generators

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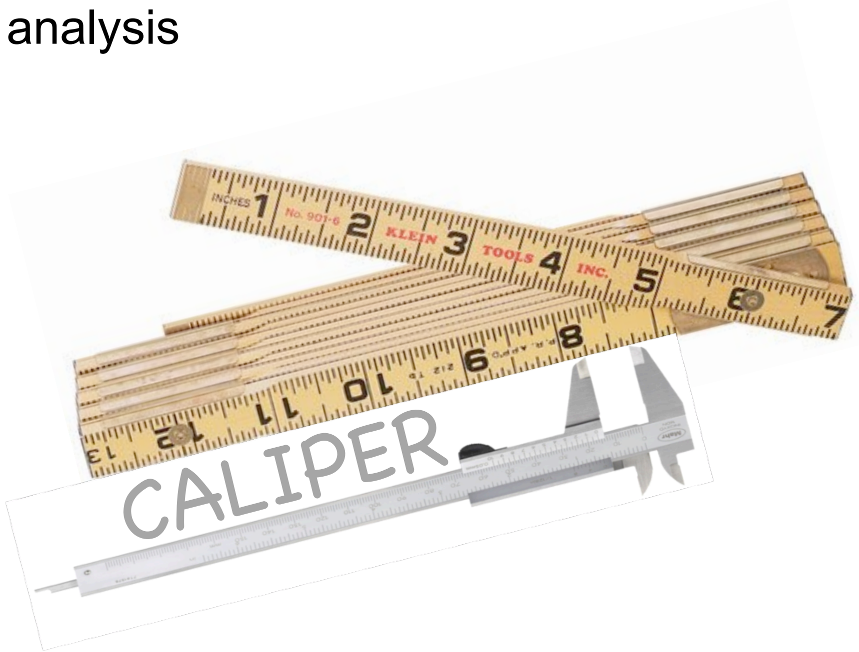
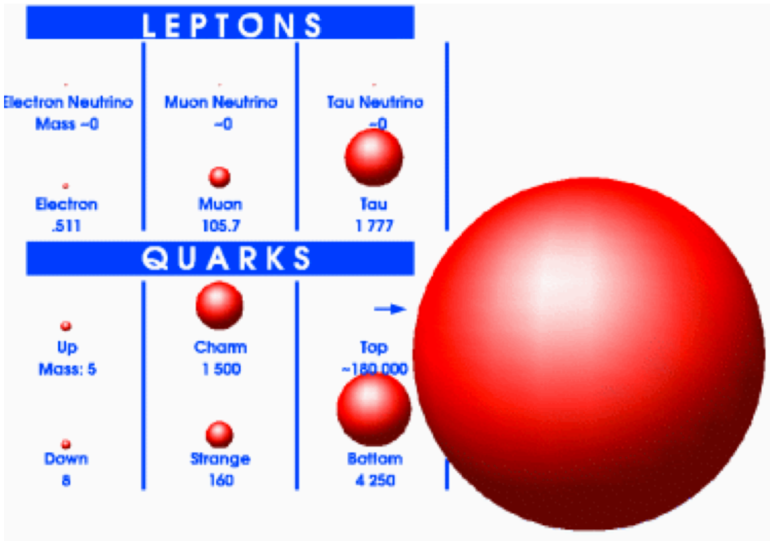
Outline

- Why precise top quark mass?
- Methods for top mass measurements
- Monte Carlo 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

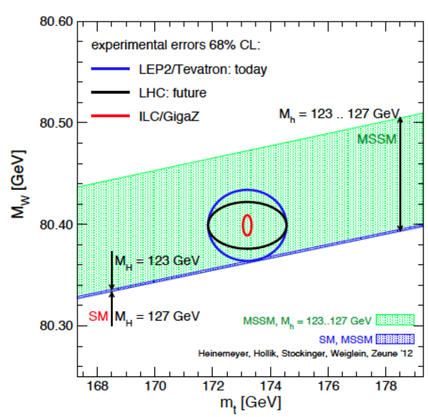


Why the top quark is not just heavy

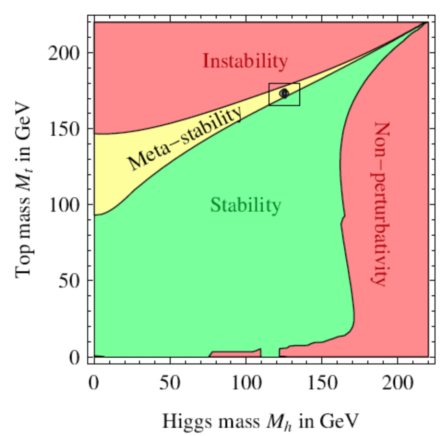


- Top quark: heaviest known particle
- Most sensitive to the mechanism of mass generation
- Peculiar role in the generation of flavor.
- Top might not be the SM-Top, but have a non-SM component.
- Top as calibration tool for new physics particles (SUSY and other exotics)
- Top production major background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

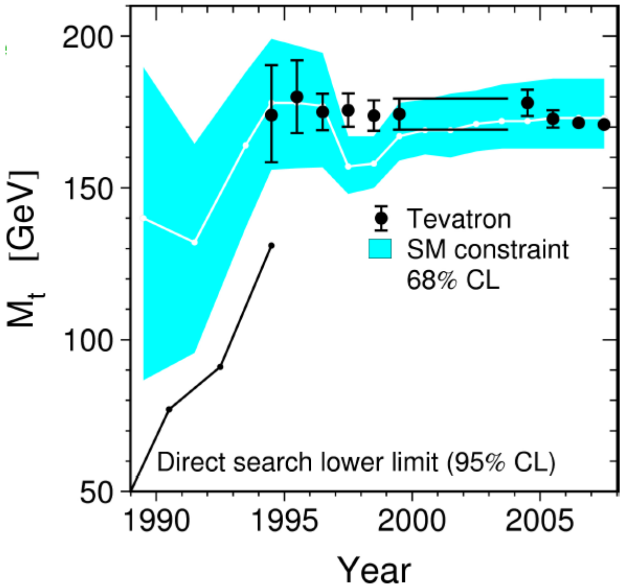
Electroweak precision observables

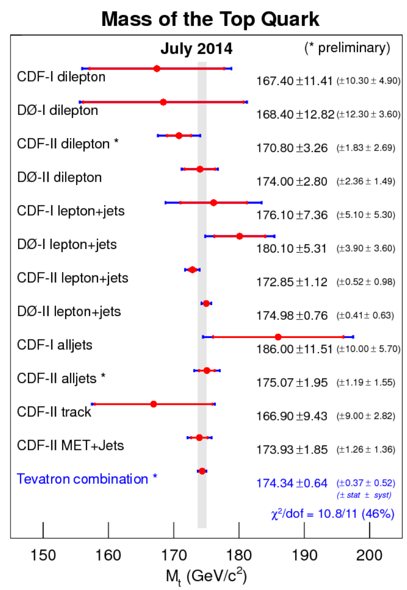


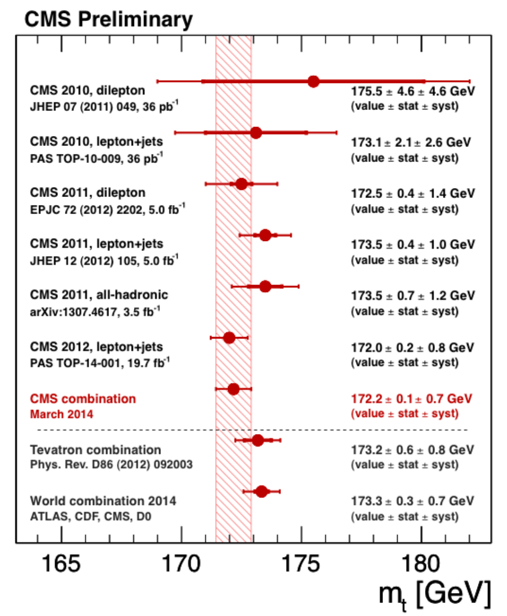
SM vacuum stability



A small history on top mass reconstruction

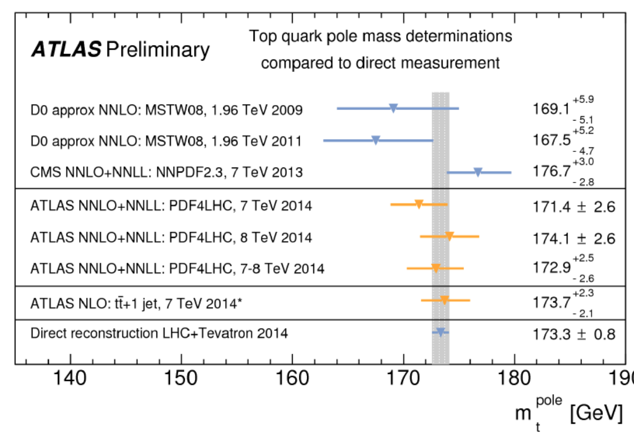






- Many individual measurements with uncertainty below 1 GeV.
- World combination 2014:

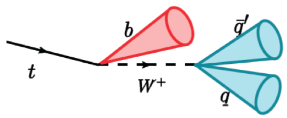
$$m_t^{\mathrm{MC}} = 173.34 \pm 0.76\,\mathrm{GeV}$$



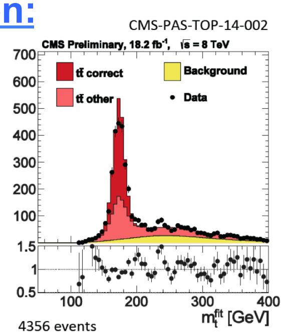
Top Mass Measurements Methods

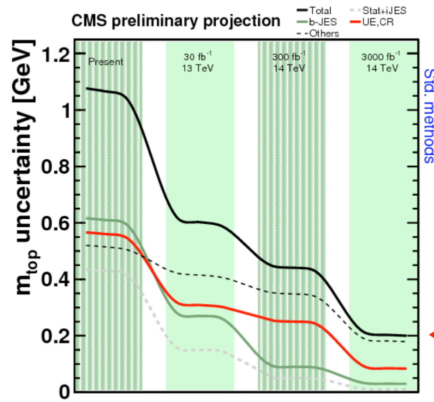
LHC+Tevatron

Direct Reconstruction:



kinematic mass determination





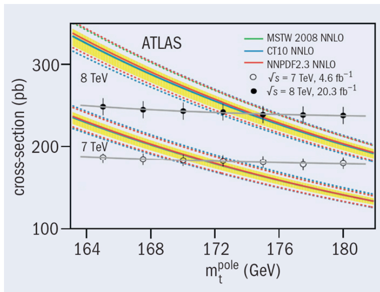
- ⊕ High top mass sensitivity
- ⊖ Precision of MC ?
- ⊖ Meaning of m_t^{MC} ?

$\Delta m_t \sim 0.5$ GeV

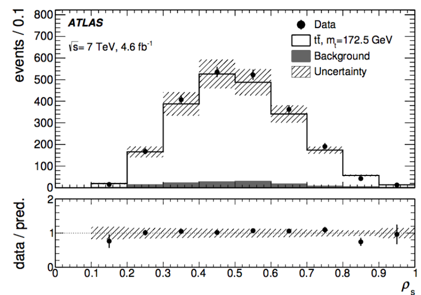
$\Delta m_t \sim 200$ MeV (projection)

Indirect Mass Fit:

global mass dependence



Total cross section



tt+jet invariant mass

- ⊕ pQCD calculations dominate
- ⊕ Control of mass scheme
- ⊖ Lower top mass sensitivity
- ⊖ High sensitivity to norm errors

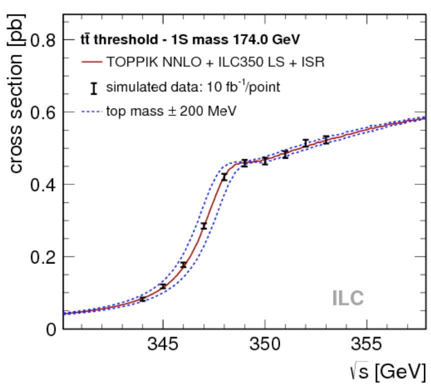
$\Delta m_t \sim 1\text{-}2$ GeV

Future Linear Collider:

Top Pair Threshold:

kinematic mass determination

perturbative toponium



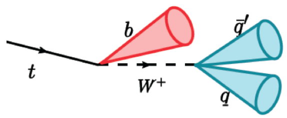
- ⊕ High top mass sensitivity
- ⊕ pQCD calculations dominate
- ⊕ Control of mass scheme

$\Delta m_t \sim 100$ MeV

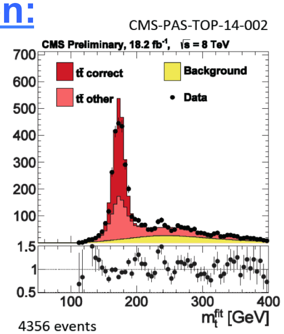
Top Mass Measurements Methods

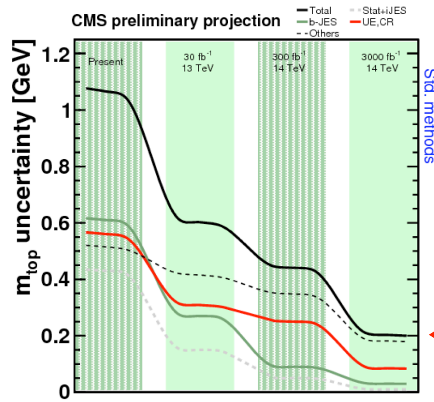
LHC+Tevatron

Direct Reconstruction:



kinematic mass determination





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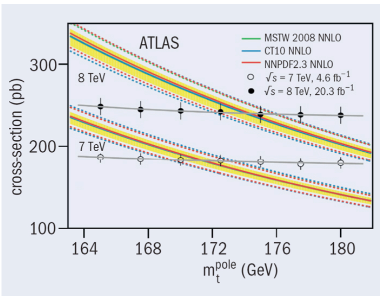
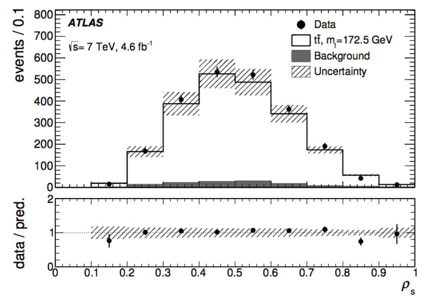


Total cross section



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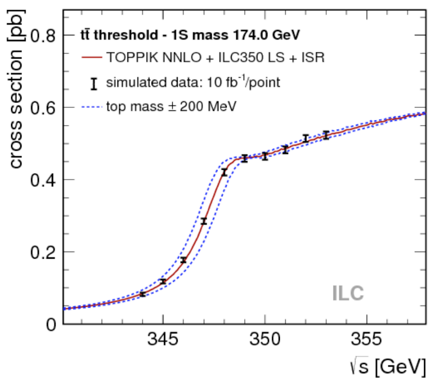

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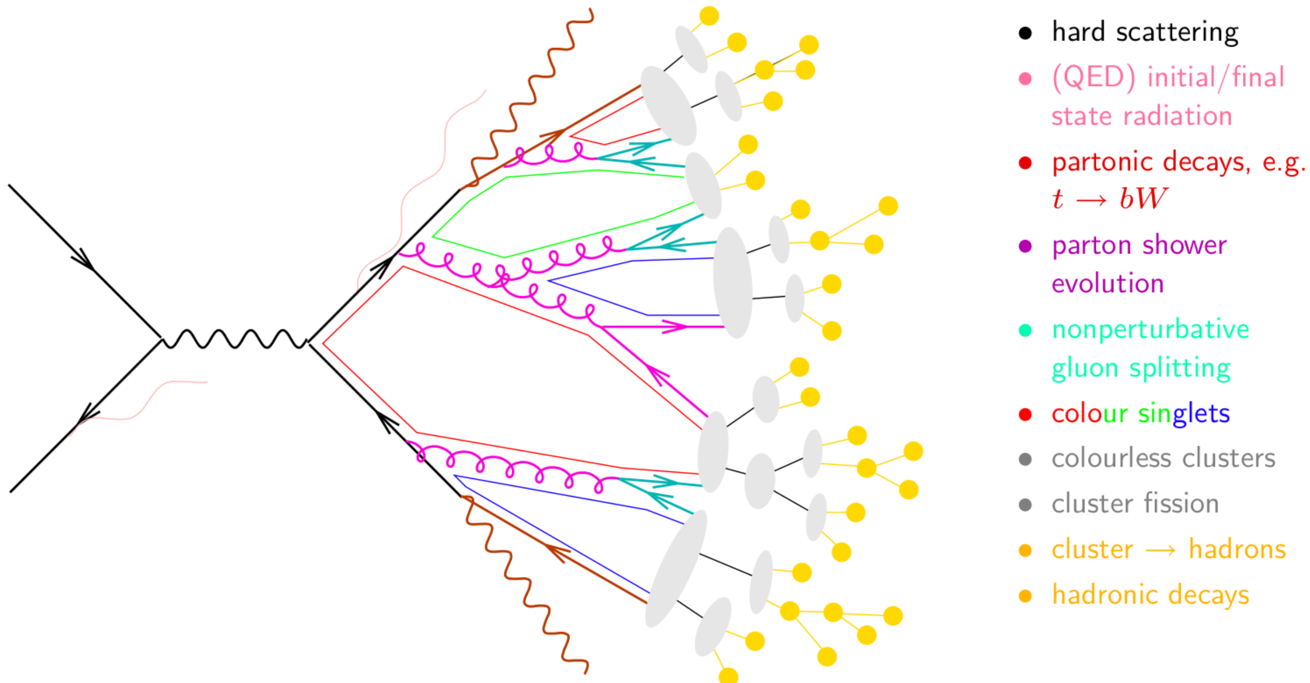
$\Delta m_t \sim 100$ MeV

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.

MC Top Quark Mass

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

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

AHH, Stewart 2008
AHH, 2014

- small size
- 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

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

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

- different tunings
- parton showers
- color reconnection
- …

- perturbative error
- scale uncertainties
- electroweak effects

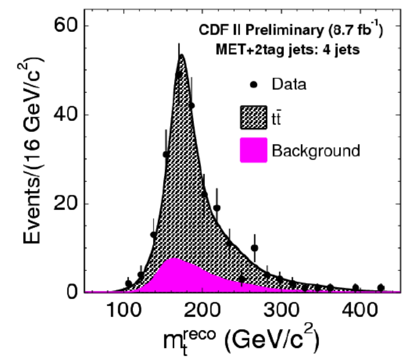
- strong coupling α_s
- Non-perturbative parameters

Thrust Distribution

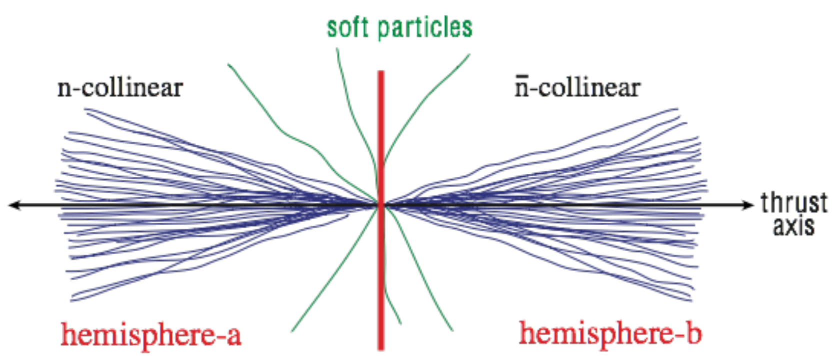
Observable: 2-jettiness in e+e- (event shape distributions)

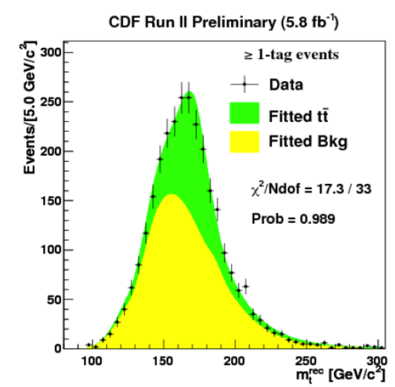
$$\tau \;=\; 1 - \max_{\vec{n}} \frac{\sum_i |\vec{n}\cdot\vec{p}_i|}{Q}$$

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

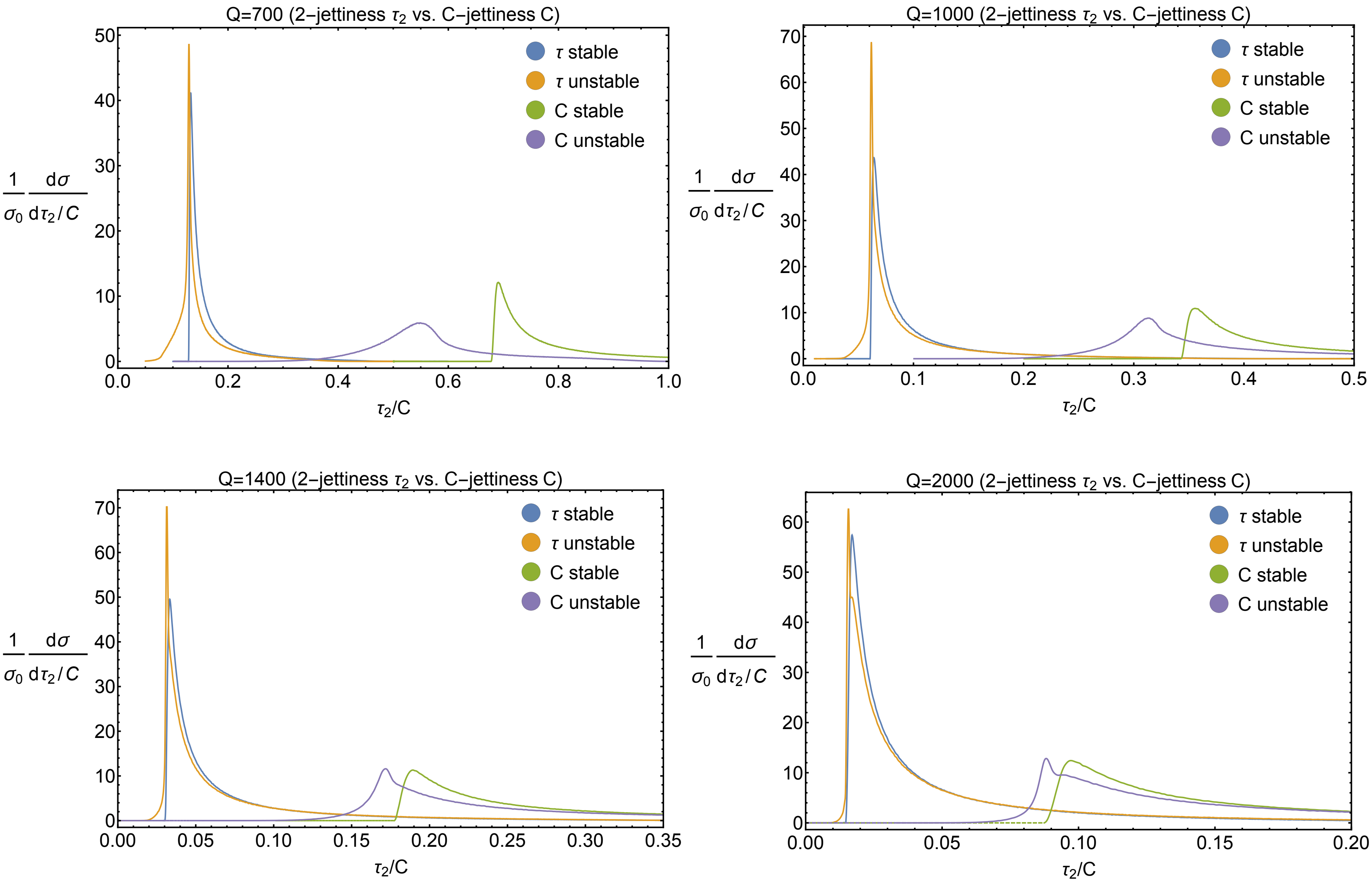


Invariant mass distribution in the resonance region !



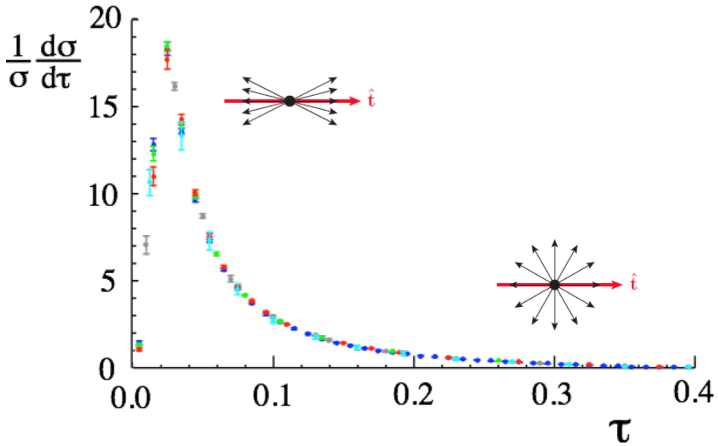


Event Shape Distributions (Pythia 8.2)



Factorization for Event Shapes

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



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

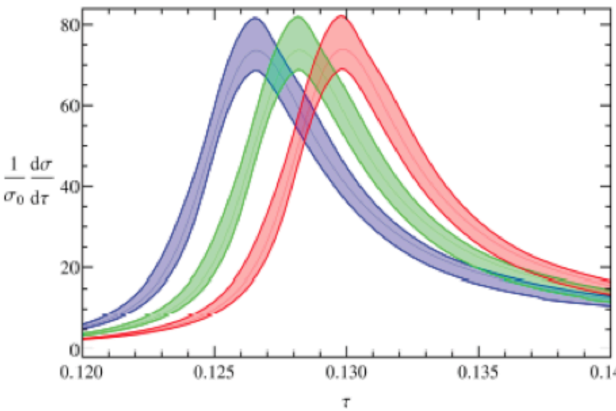
Butenschön, Dehnadi, AHH, Mateu 2016 (to appear)

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

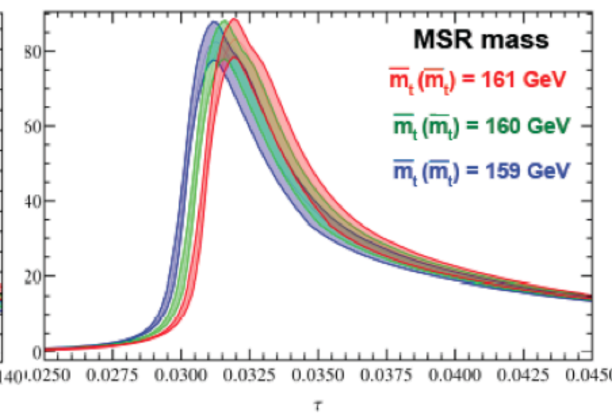
2-Jettiness for Top Production (QCD)

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

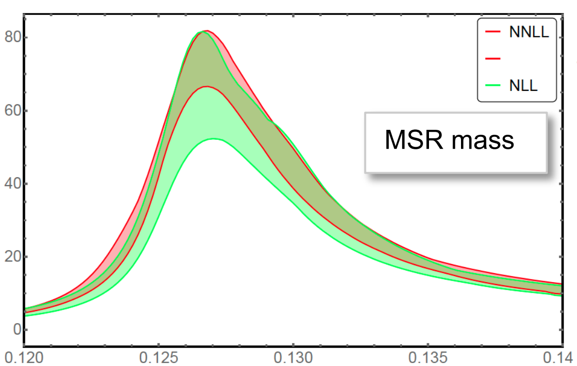
Q=700 GeV



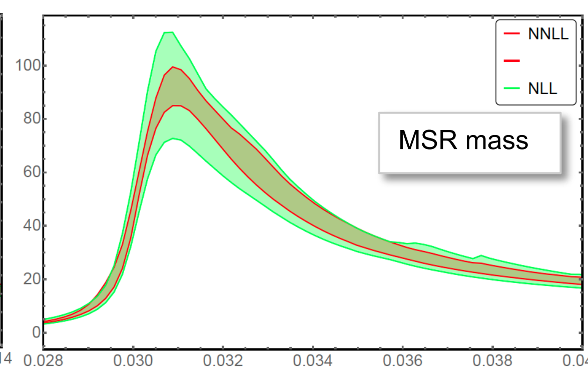
Q=1400 GeV



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

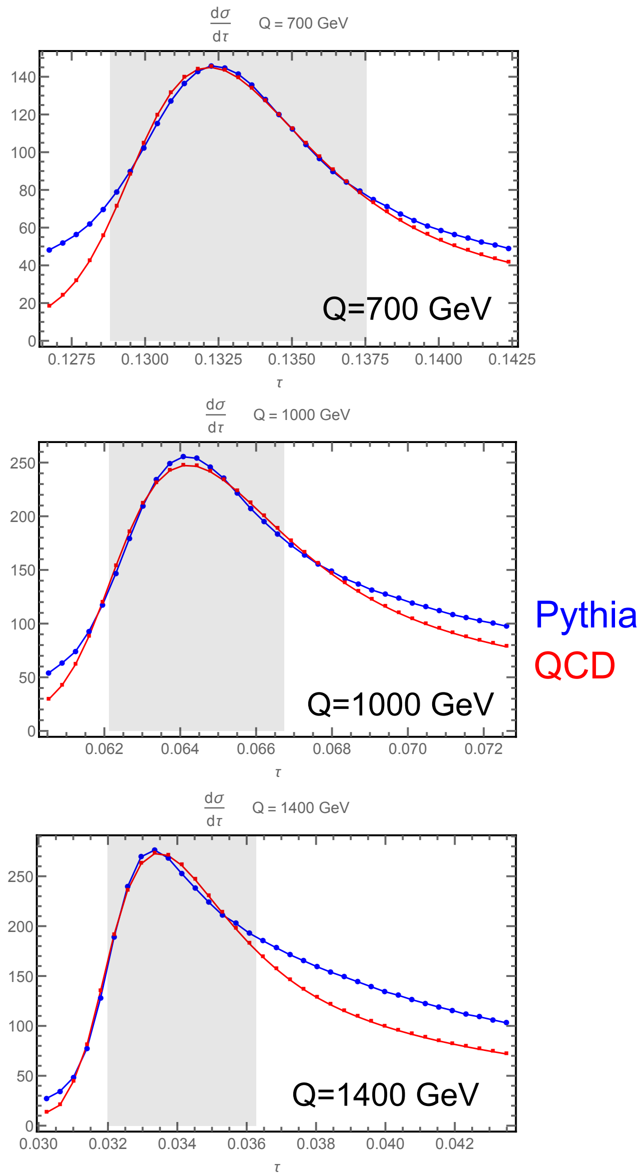
$$\frac{d\sigma}{d\tau_2} = f(\underbrace{m_t^{\rm MSR}(R)}_{\text{any scheme possible}}, \alpha_s(M_Z), \underbrace{\Omega_1, \Omega_2, \ldots}_{\text{Non-perturbative}}, \underbrace{\mu_h, \mu_j, \mu_s, \mu_m}_{\text{renorm. scales}}, R, \Gamma_t)$$

any scheme possible — Non-perturbative — renorm. scales — 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): $\Omega_{1,\rm smear} = 0,\ 0.5,\ \ldots,\ 3.0,\ 3.5,\ \text{GeV}$
- Pythia masses: $m_t^{\tt Pythia} = 170,\ \ldots\ ,\ 175\,\text{GeV}$
- Fit possible for any mass scheme

Preliminary Peak Fits



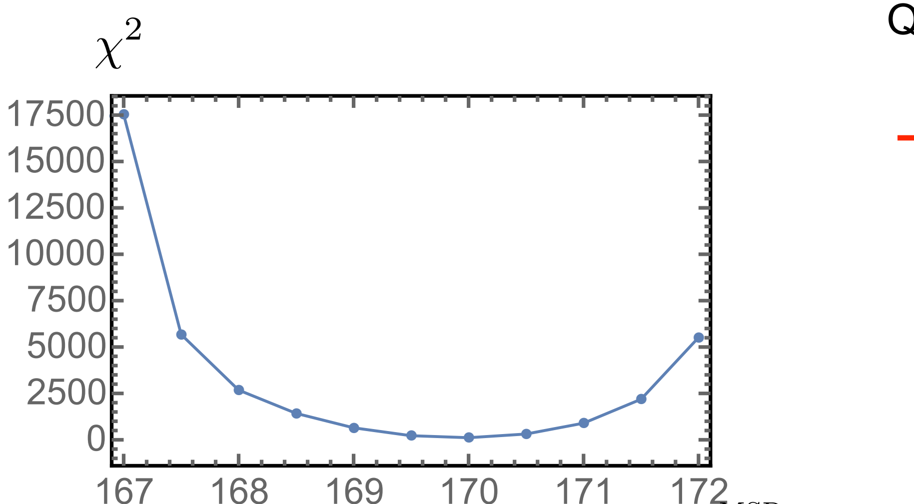
Default renormalization scales; Γ_t=1.4 GeV, tune 7, $\Omega_{1,smear}$=2.5 GeV, m_t^{Pythia}=171 GeV, Q={700, 1000, 1400} GeV, peak fit (60/80)%

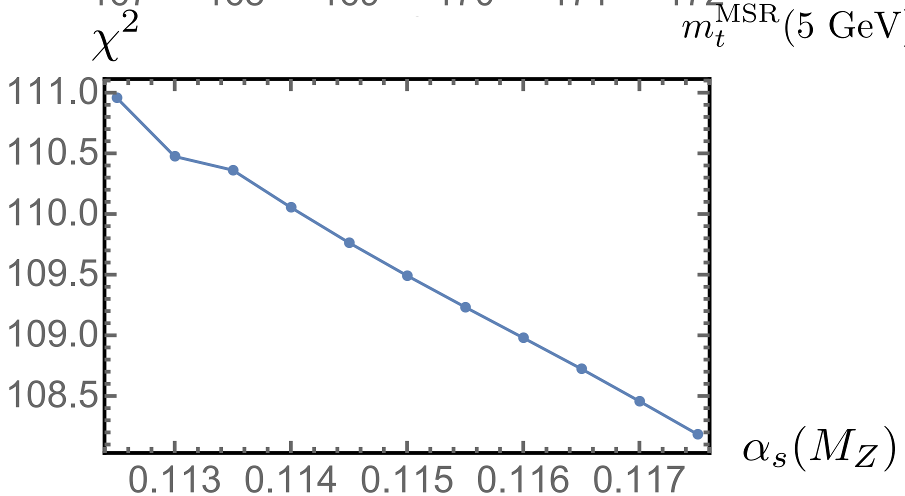
- Good agreement of Pythia 8.2 with NNLL+NLO QCD description
- Pythia statistics: 10^6 events
- Discrepancies in distribution tail and for higher energies (Pythia is less reliable where fixed-order results valid, well reliable in soft-collinear limit)
- Excellent sensitivity to the top quark mass.

Preliminary

universität wien

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

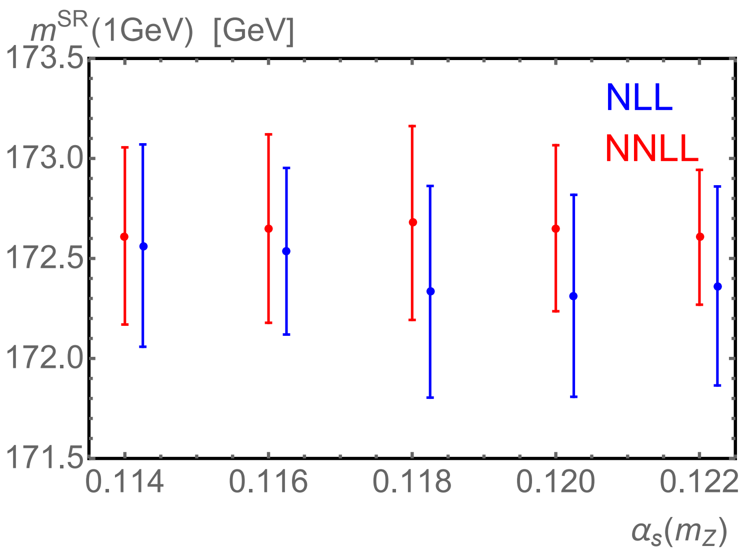
- We use rescaled χ^2/dof (PDG prescreption) to defind "intrinsic MC compatibility uncertainty"

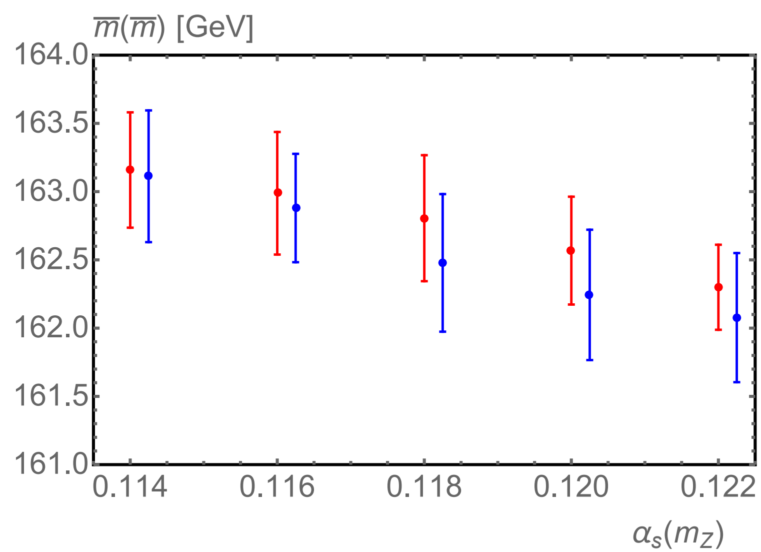
Preliminary

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) !!

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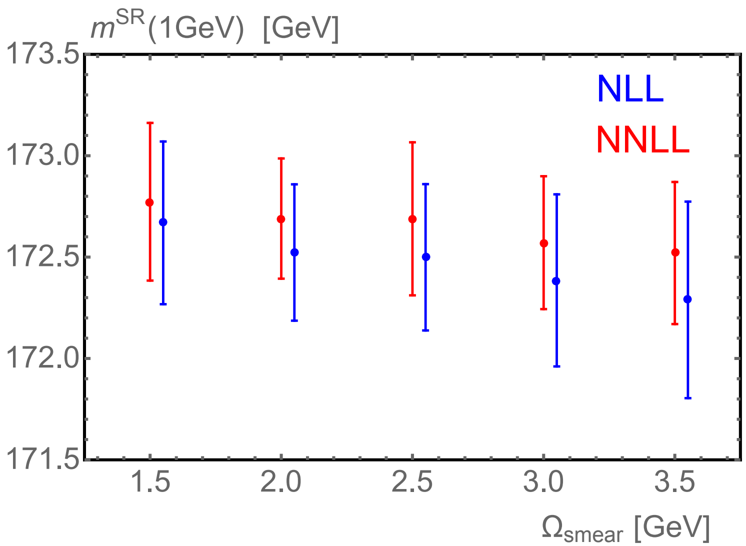

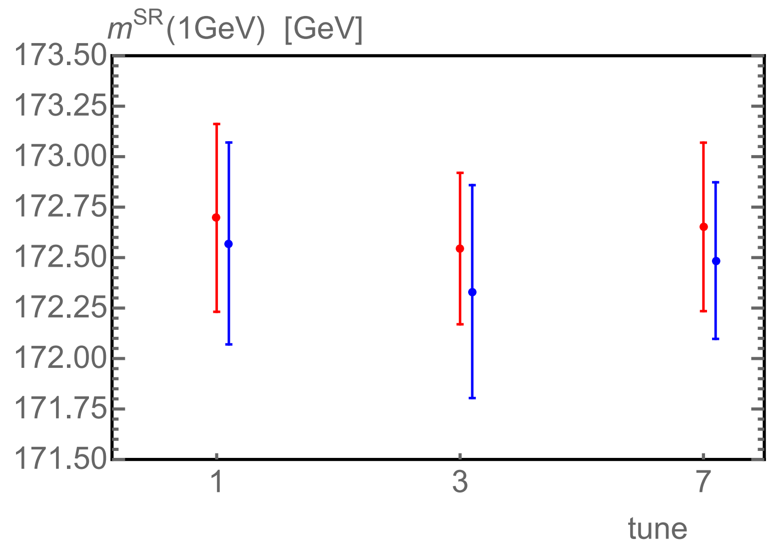

- "Detector effects" << perturbative uncertainty. ✔
- MC tune dependence << perturbative uncertainty. ✔

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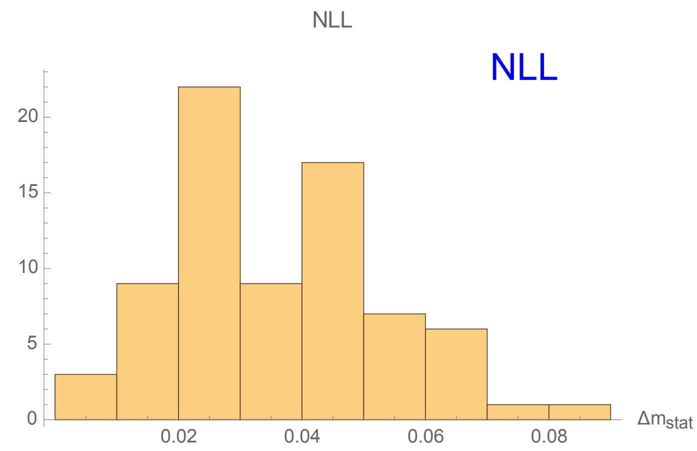

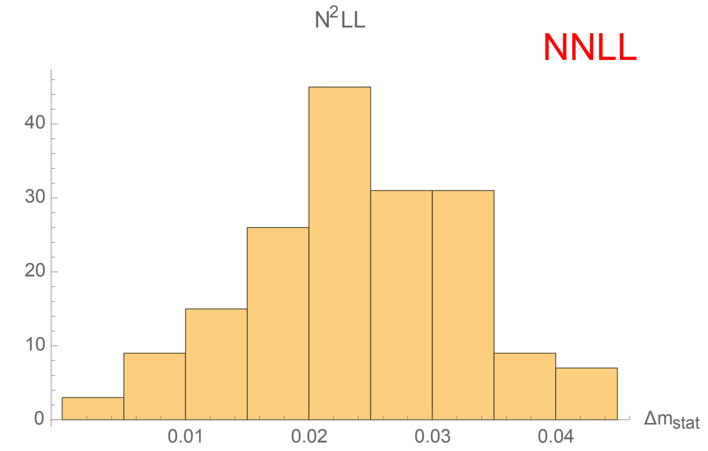

- "MC compatibility error" ~ tuning error ~ detector effect error ✔
- Effects < 100 MeV. (Maybe estimate for ultimate precision)

Peak Fits

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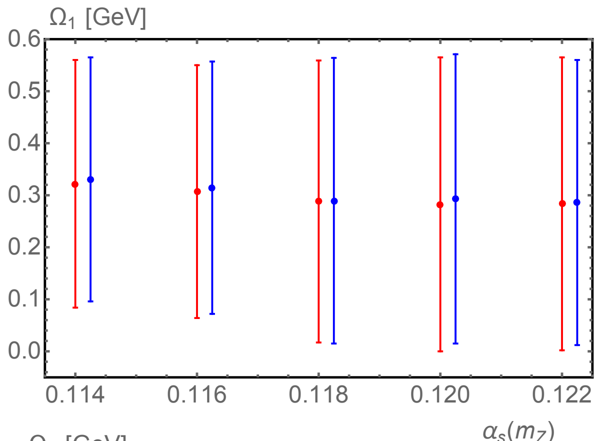
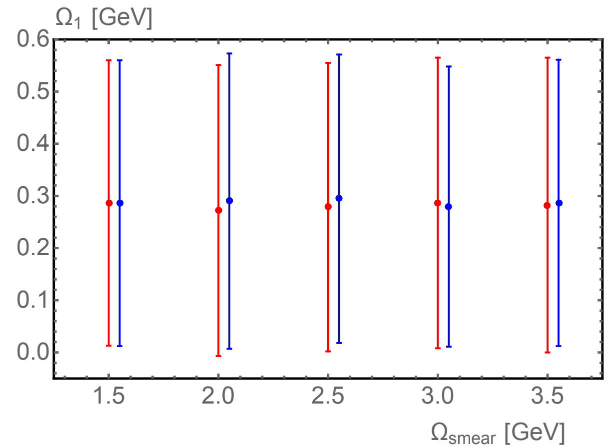
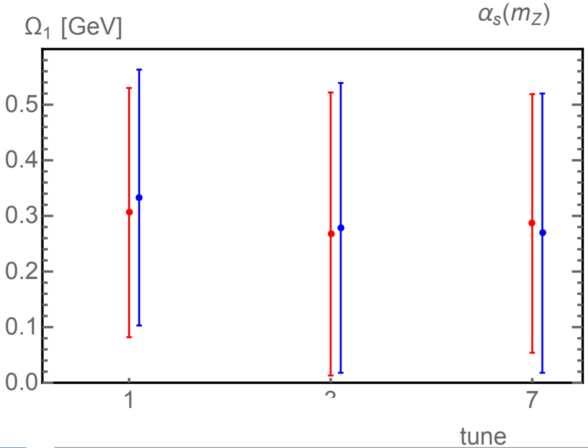
Preliminary

NLL

NNLL







- 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

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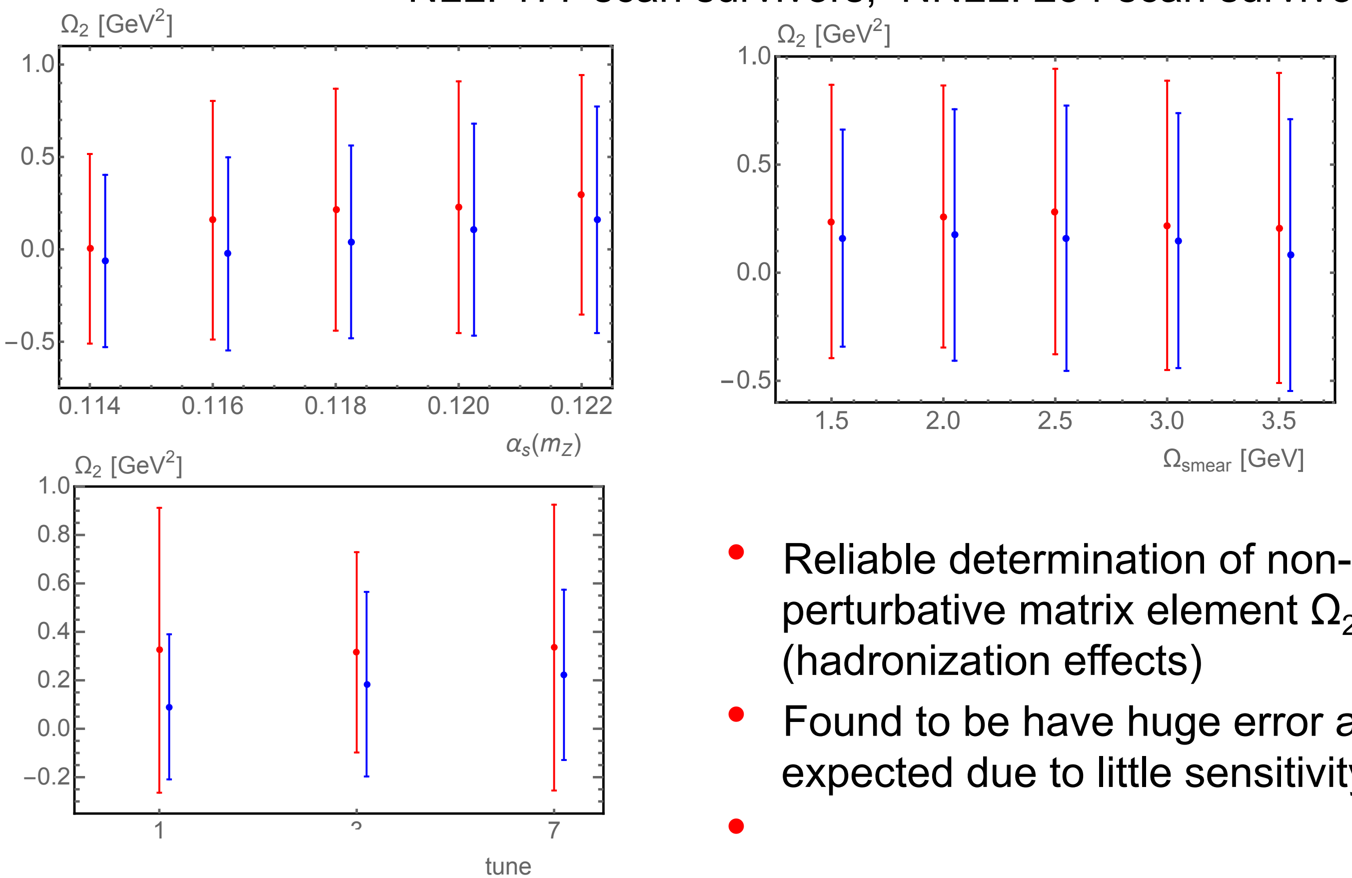

- Reliable determination of non-perturbative matrix element Ω_2 (hadronization effects)
- Found to be have huge error as expected due to little sensitivity ✔
-

Peak Fits

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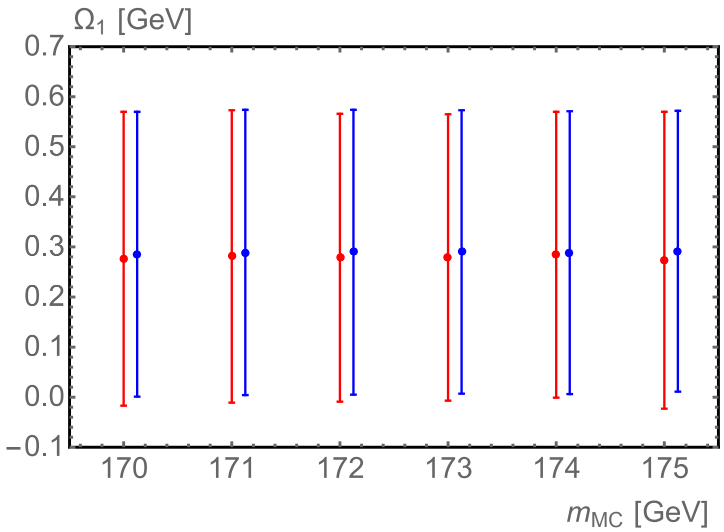
Q={700, 1000, 1400} GeV, peak fit (60/80)%

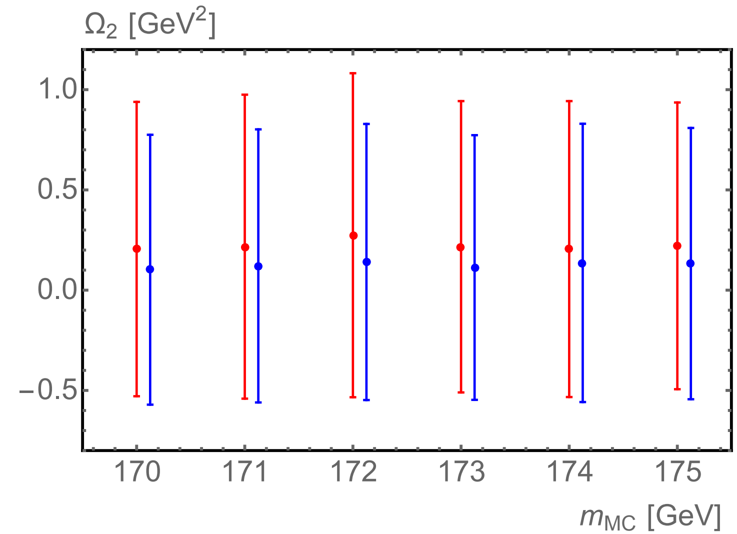
m_t^{Pythia}=170,171, 172, 173, 174, 175 GeV

NLL: 177 scan survivors, NNLL: 254 scan survivors

Preliminary

NLL
NNLL

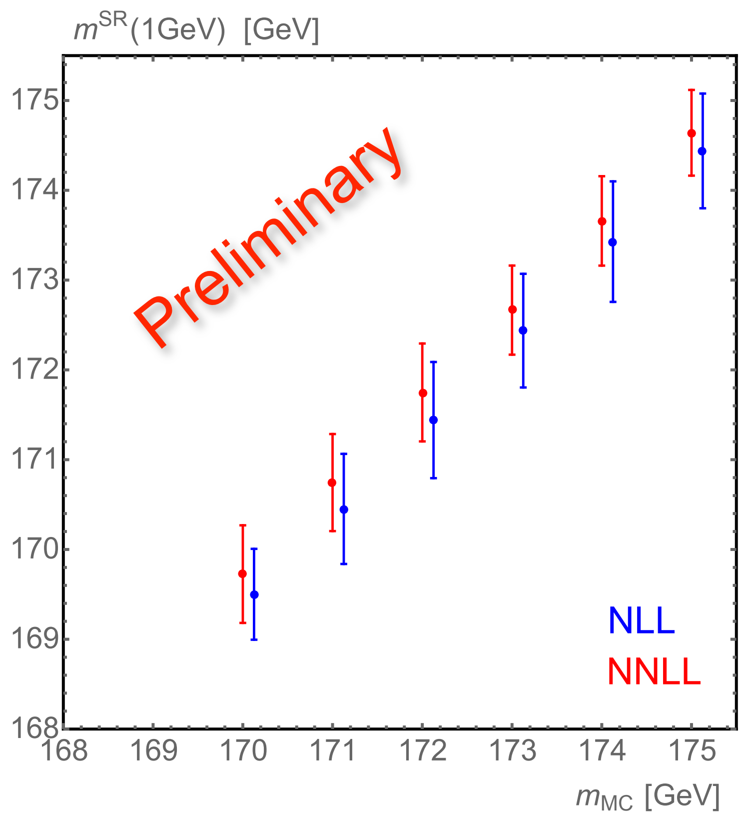




- Non-pert. matrix elements $\Omega_{1,2}$ indpendent of top mass. ✔

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}=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 !

Conclusions & Outlook

- First serious precise MC top quark mass calibration based on e^+e^- 2-jettiness: 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) w.i.p
- Mass (+ Yukawa coupling) conversions w. QCD + electroweak