

Top quark mass interpretation from simulation of top-flavoured mesons

Alexander Lind

with Gennaro Corcella

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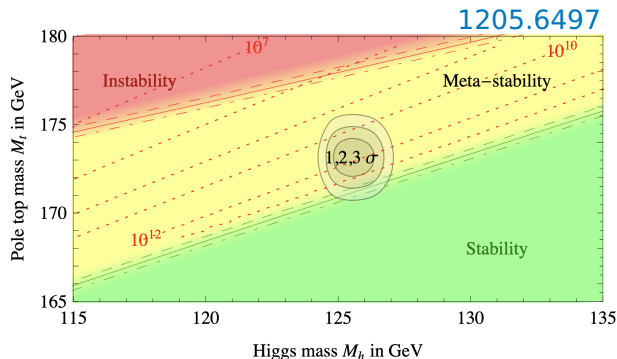


Istituto Nazionale di Fisica Nucleare
Sezione di Roma

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Top quark mass

The top quark mass m_t is a fundamental parameter of the SM



Precision determination important for e.g.:

- ▶ Electroweak precision tests
- ▶ Stability of the electroweak vacuum
- ▶ Higgs inflation models

Experimental measurements of the top mass

m_t is a free parameter — Must be extracted from experiments

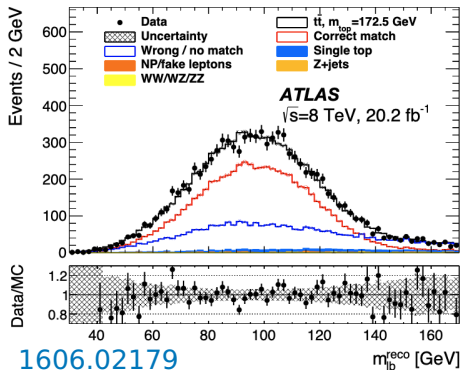
Average (PDG 2024):

$$m_t = 172.57 \pm 0.29 \text{ GeV}$$

This value comes from *direct measurements*
i.e. extraction of the mass from the kinematics of $t\bar{t}$ events

The mass extraction comes from
a comparison to **parton shower**
Monte Carlo event generators

This is often referred to as a
Monte Carlo mass m_t^{MC}



Theoretical top quark mass definitions

Well-defined theoretical definitions of the top mass:

- ▶ Pole mass, m_t^{pole}
- ▶ Minimal-subtraction ($\overline{\text{MS}}$) scheme mass, $\overline{m}_t(\overline{m}_t)$
- ▶ MSR mass, $m_t^{\text{MSR}}(R, \mu)$, [0711.2079](#)

Relation between pole and $\overline{\text{MS}}$ masses calculated up to four loops ([1502.01030](#)):

$$m_t^{\text{pole}} = \overline{m}_t(\overline{m}_t) \left[1 + 0.4244 \alpha_s + 0.8345 \alpha_s^2 + 2.375 \alpha_s^3 + (8.615 \pm 0.017) \alpha_s^4 + \mathcal{O}(\alpha_s^5) \right]$$

Problem:

Active work on how to relate measured m_t^{MC} to a well-defined theoretical definition such as m_t^{pole}

Relation between m_t^{MC} and m_t^{pole}

General relation between Monte Carlo mass and pole mass:

$$m_t^{\text{MC}} = m_t^{\text{pole}} + \underbrace{\delta m}_{\text{Possible shift}} \pm \underbrace{\Delta m}_{\text{Uncertainty}}$$

Two different views:

- ▶ $\delta m \simeq 0$ and m_t^{MC} can be identified as the pole mass

Δm is a theoretical uncertainty $\sim \mathcal{O}(\Lambda_{\text{QCD}})$

(P. Nason) [1602.00443](#) and [1712.02796](#)

- ▶ $\delta m \neq 0$, i.e. m_t^{MC} fundamentally different from m_t^{pole}

δm ranges from 200 MeV to almost 1 GeV, Δm still an uncertainty

(A. Hoang, I. Stewart, et al.) [hep-ph/0703207](#), [0808.0222](#),
[1608.01318](#), [1708.02586](#), [1807.06617](#)

This study:

Effect of hadronisation systematics in Pythia on Δm

Contribution to Δm from hadronisation systematics

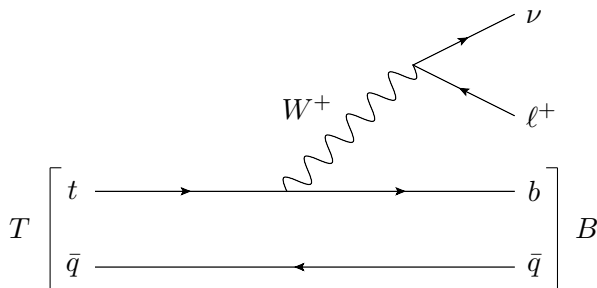
Idea:

Consider hadronisation of top quarks into top-flavoured mesons
(e.g. $T^+ = (t\bar{d})$, $T^0 = (t\bar{u})$, $T^- = (\bar{t}d)$, etc.)
and then let them decay according to the spectator model

1. B -lepton invariant mass $m_{B\ell}$
2. Find relation between m_t^{MC} and m_T by fitting $m_{B\ell}$
3. Find relation between m_T and m_t^{pole} with HQET
4. Obtain estimate of Δm from hadronisation systematics

Decay of T -mesons due to the spectator model

Semi-leptonic decays of the T -mesons



Spectator model decay:

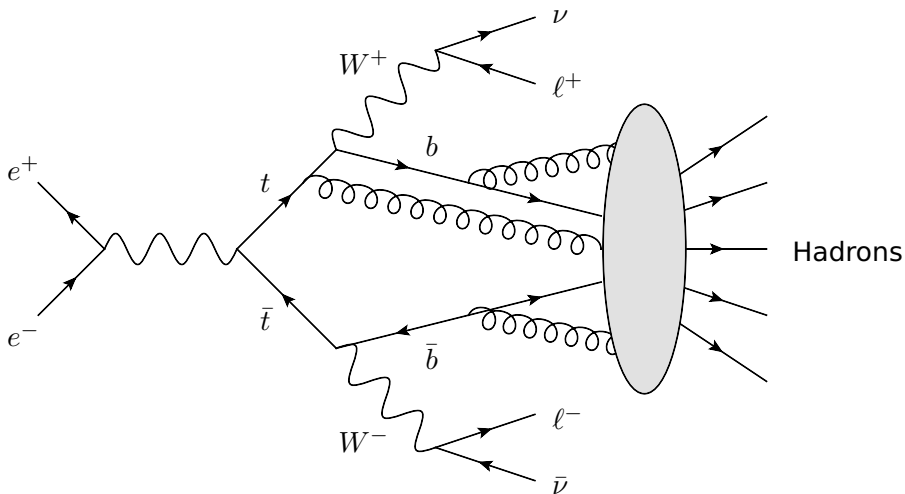
$$T^+(t\bar{d}) \rightarrow (b\bar{d})\ell^+\nu + X$$

where X is mainly gluon radiation from the b quark

$$x_q = m_q/m_T$$

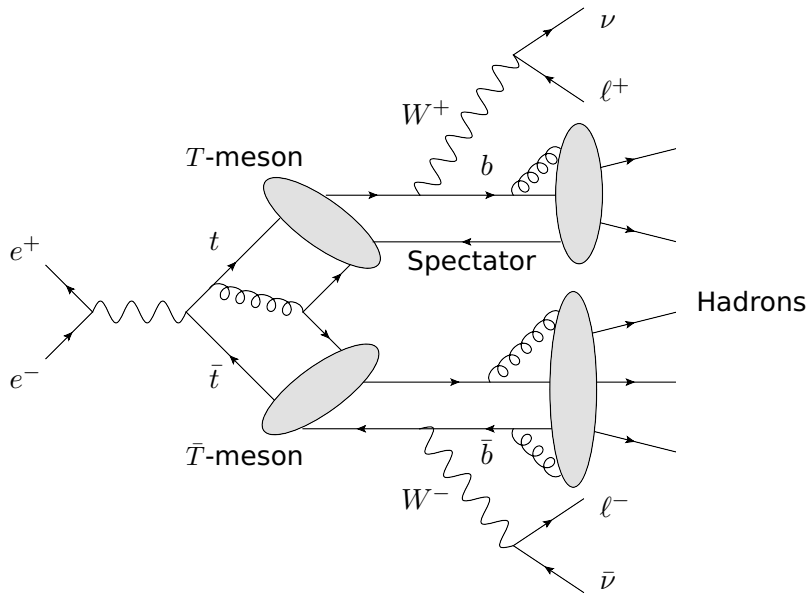
Top pair production

$e^+e^- \rightarrow t\bar{t}$ with leptonic decays of the W s and parton showers



Top-flavoured mesons

Hadronisation of the top quarks to fictitious top mesons (e.g. $T^+ = (t\bar{d})$)



Relating m_T to m_t^{pole} with HQET

Relating heavy-light meson masses to pole masses with
Heavy-Quark Effective Theory (HQET)

See e.g. introduction by M. Neubert ([hep-ph/9610385](https://arxiv.org/abs/hep-ph/9610385))

The mass of a meson Q containing a heavy quark q can in general be expanded as:

$$m_Q = m_q + \bar{\Lambda} - \frac{\Delta m^2}{2m_q} + \mathcal{O}\left(\frac{1}{m_q^2}\right)$$

where

- ▶ $\bar{\Lambda}$ comes from terms in the Lagrangian independent of m_q
- ▶ Δm^2 comes from $\mathcal{O}(1/m_q)$ terms in the effective HQET Lagrangian

$$\Delta m^2 = \lambda_1 - 2 \left[J(J+1) - \frac{3}{2} \right] \lambda_2(m_q) = \lambda_1 + n\lambda_2(m_q)$$

- ▶ J is the total meson spin

Relating m_T to m_t^{pole} with HQET

$\bar{\Lambda}$, λ_1 , and λ_2 are scheme-dependent universal QCD parameters

Exploiting flavour-independence and subtracting m_B and m_T we get

$$m_T = m_t + m_B - m_b - \lambda_1 \left(\frac{1}{2m_t} - \frac{1}{2m_b} \right) - \frac{n}{2} \left[\frac{\lambda_2(m_t)}{m_t} - \frac{\lambda_2(m_b)}{m_b} \right]$$

which can be well approximated by

$$m_T \approx m_t + \bar{\Lambda}$$

where $\bar{\Lambda}$ is the shift between T -meson and top-quark masses and reads

$$\bar{\Lambda} = m_t + m_B - m_b + \frac{1}{2m_b} [\lambda_1 + n \lambda_2(m_b)]$$

We will use that $n = +3$ and the latest PDG values for m_t , m_b , and m_B in the pole mass scheme

Relating m_T to m_t^{pole} with HQET

Generally we have

$$|\lambda_1| \sim \lambda_2 \sim \Lambda_{\text{QCD}}^2 \sim 0.1 \text{ GeV}^2$$

But we want a precise determination

Jeong and Kim ([hep-ph/9811475](#)) gives

$$\lambda_1 = -0.58 \pm 0.23 \text{ GeV}^2,$$

while A. Nefediev ([2404.11158](#)) gives the relation

$$\lambda_2(m_b) \approx \frac{m_b}{2} (m_{B^*} - m_B) \approx 0.1080 \pm 0.0014 \text{ GeV}$$

Hence, we find for $\bar{\Lambda}$ an approximate value of

$$\bar{\Lambda} = 0.473 \pm 0.064 \text{ GeV}$$

which agrees with the value found in [2404.11158](#) of $\bar{\Lambda} = 0.49 \pm 0.08 \text{ GeV}$

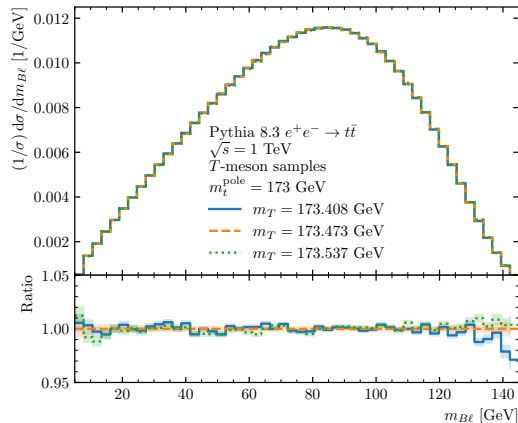
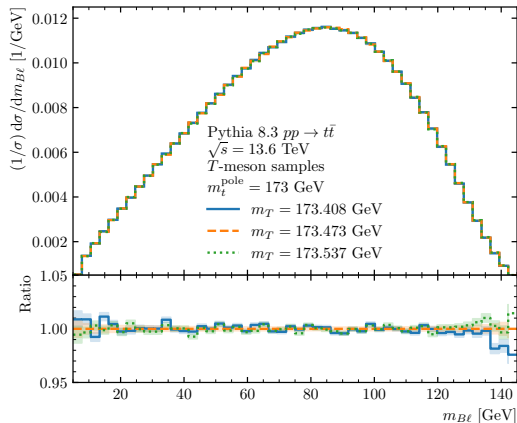
With Pythia 8.317 we simulate:

- ▶ Standard $t\bar{t}$ samples,
- ▶ T -meson samples,

For two different collider setups:

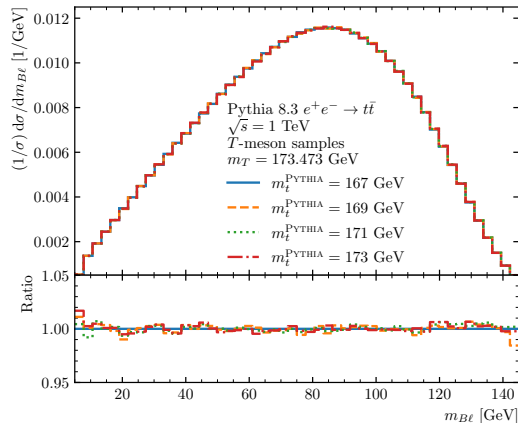
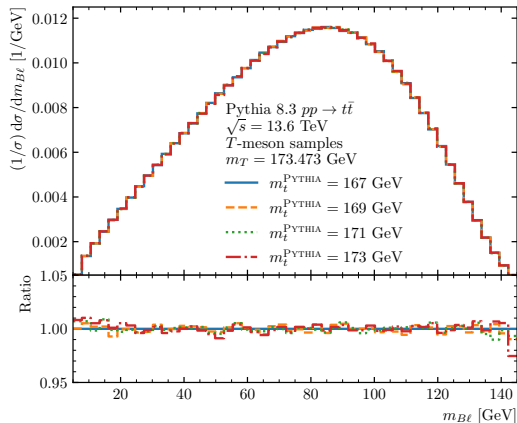
- ▶ Current LHC setup, $pp \rightarrow t\bar{t}$, at $\sqrt{s} = 13.6$ TeV;
- ▶ A future lepton collider, $e^+e^- \rightarrow t\bar{t}$, at $\sqrt{s} = 1$ TeV.

Results: $m_{B\ell}$ distributions



Uncertainty on $\bar{\Lambda}$ is negligible

Results: $m_{B\ell}$ distributions



The T -meson sample is independent of the input top mass m_t^{Pythia}

Results: Fit to $\langle m_{B\ell} \rangle$

Fit $\langle m_{B\ell} \rangle = a \times m_t^{\text{Pythia}} + b$ to the standard $t\bar{t}$ samples

$$\langle m_{B\ell} \rangle_{pp} \simeq 0.571 m_t^{\text{Pythia}} - 21.51 \text{ GeV}, \quad \delta = 0.011 \text{ GeV};$$

$$\langle m_{B\ell} \rangle_{ee} \simeq 0.568 m_t^{\text{Pythia}} - 20.95 \text{ GeV}, \quad \delta = 0.014 \text{ GeV}.$$

Fit $\langle m_{B\ell} \rangle = a' \times m_T + b'$ to the T -meson samples

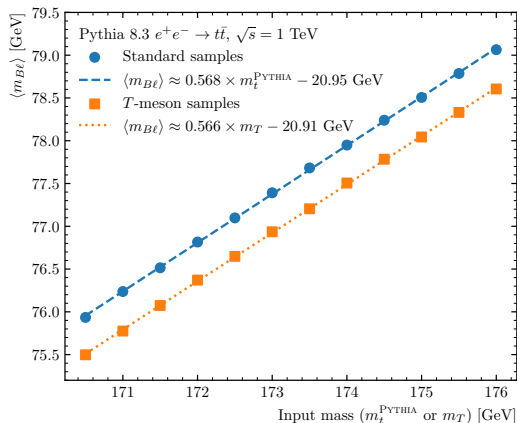
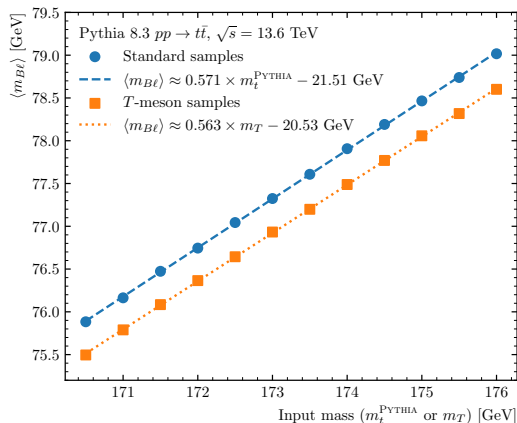
$$\langle m_{B\ell} \rangle_{pp} \simeq 0.563 m_T - 20.53 \text{ GeV}, \quad \delta = 0.010 \text{ GeV};$$

$$\langle m_{B\ell} \rangle_{ee} \simeq 0.566 m_T - 20.91 \text{ GeV}, \quad \delta = 0.013 \text{ GeV},$$

The residual standard deviation of the fit

$$\delta_{\text{fit}} = \sqrt{\frac{1}{N-2} \sum_{i=1}^N \left[\langle m_{B\ell} \rangle_i - \left(a \times m_{t,i}^{\text{Pythia}} + b \right) \right]^2},$$

Results: Fit to $\langle m_{B\ell} \rangle$



We observe a constant shift in $\langle m_{B\ell} \rangle$

The slopes agree well within the errors, i.e. $a \approx a'$

Re-performing the linear fits with fixed slopes, and using the HQET result, $m_T \approx m_t^{\text{pole}} + \bar{\Lambda}$, with $\bar{\Lambda} \approx 0.473$ GeV, we find that

$$m_t^{\text{Pythia}} - m_t^{\text{pole}} = -0.24 \pm 0.07 \text{ GeV} \quad (\text{for } pp \text{ collisions}),$$

$$m_t^{\text{Pythia}} - m_t^{\text{pole}} = -0.33 \pm 0.07 \text{ GeV} \quad (\text{for } e^+e^- \text{ collisions}).$$

Consistent with $\mathcal{O}(\Lambda_{\text{QCD}})$

Monte Carlo event generators includes phenomenological models of non-perturbative QCD effects which are not necessarily derived from first principles

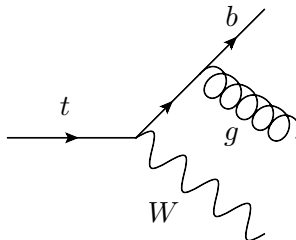
- ▶ Colour reconnection
- ▶ Recoil treatment in top decay
- ▶ Radiation from b quarks

Recoil options in the showering of top decays

Dipole parton shower of top decay $t \rightarrow Wb + X$

First emission, $t \rightarrow Wbg$, controlled by matrix element corrections

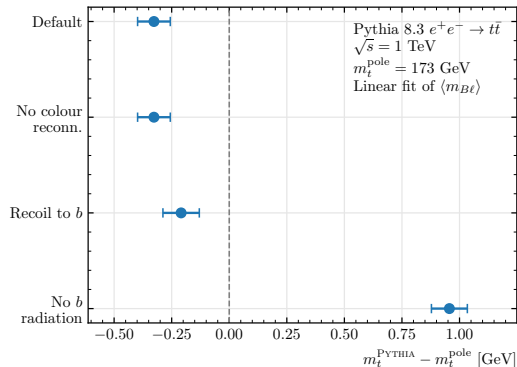
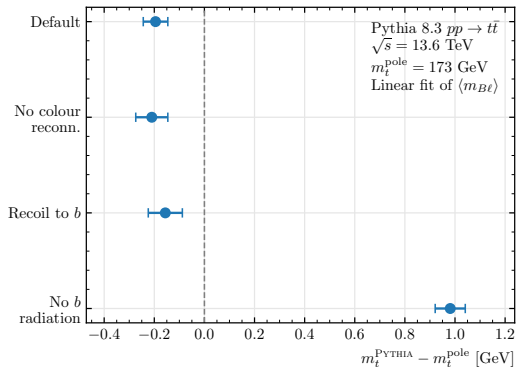
Ambiguity on the 2nd gluon emission:
Different possible recoil strategies



Important for precise determination of m_t

ATLAS analysis [2209.00583](#) sees an effect of ~ 250 MeV

Sensitivity to non-perturbative modelling



Tiny effects of $\mathcal{O}(10 \text{ MeV})$ – except b radiation of course

Summary:

- ▶ We have implemented T -mesons in Pythia with spectator decays
- ▶ T -meson masses can be related to m_t^{pole} with HQET
- ▶ T -meson masses can be fitted to m_t^{MC}
- ▶ We see an effect size of $\mathcal{O}(\Lambda_{\text{QCD}})$

Outlook:

- ▶ Study T -mesons with Herwig 7.3.0 and compare to Pythia
- ▶ Study other observables, e.g. reconstructing b -jets
- ▶ Use MC implementation for searches of possible T -mesons

**Thank you very much
for your attention! :)**



Backup Slides

Implementation of T -mesons in Pythia

Implementation of the production and decay of the fictitious T -mesons in Pythia 8.3

Uses the existing R -hadron interface but with modifications to allow for spectator decay with a fixed m_T

Similar results can be achieved with the parameter options:

```
RHadrons:allow = on  
RHadrons:idStop = 6  
RHadrons:mOffsetCloud = 0  
RHadrons:mCollapse = 0
```

Event-wise average value $\langle m_{B\ell} \rangle$ for the standard $t\bar{t}$ samples

Linear dependence on m_t^{Pythia} :

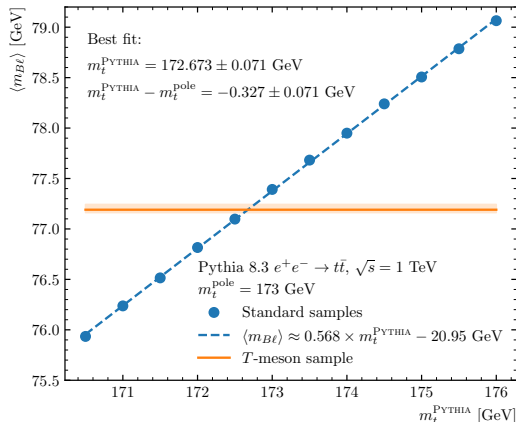
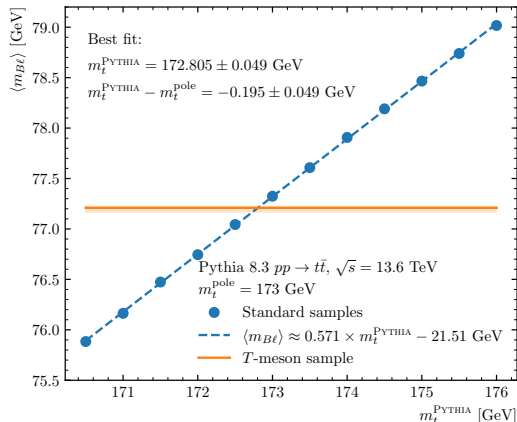
$$\langle m_{B\ell} \rangle_{\text{standard}} \simeq a \times m_t^{\text{Pythia}} + b$$

Compare to the T -meson sample for a fixed

$$m_T = m_t^{\text{pole}} + \bar{\Lambda}$$

with $m_t^{\text{pole}} = 173 \text{ GeV}$ and $\bar{\Lambda} \approx 0.473 \text{ GeV}$

Results: Fit to $\langle m_{B\ell} \rangle$



From the linear fit to $\langle m_{B\ell} \rangle$ we see that $m_t^{\text{Pythia}} - m_t^{\text{pole}} \approx -(200\text{--}300) \text{ MeV}$
 consistent with Λ_{QCD}

Results: χ^2 fit of $m_{B\ell}$ shape

Compare shape of $m_{B\ell}$ distribution

$$\chi^2 = \sum_{\text{bins}} \frac{(O - E)^2}{E}$$

where we can consider the T -meson sample as *observation* and the standard $t\bar{t}$ samples as *expectation*

Pooled bin probability:

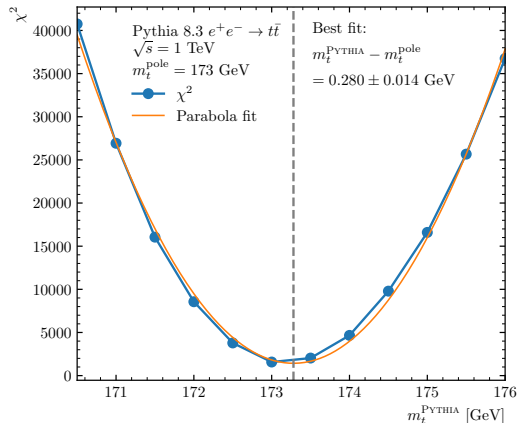
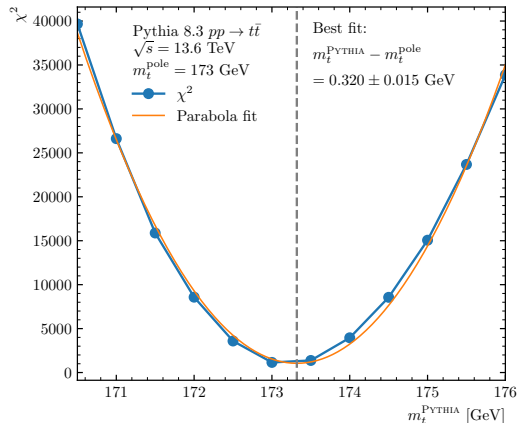
$$p_i = \frac{x_i + y_i}{X + Y}$$

Test statistics:

$$\chi^2 = \sum_{i=1}^n \left[\frac{(x_i - p_i X)^2}{p_i X} + \frac{(y_i - p_i Y)^2}{p_i Y} \right]$$

Range: $m_{B\ell} \in \{5, 145\}$ GeV

Results: χ^2 fit of $m_{B\ell}$ shape



From the χ^2 fit to $m_{B\ell}$ shape we see that $m_t^{\text{Pythia}} - m_t^{\text{pole}} \approx 300$ MeV

Results: χ^2 fit of $m_{B\ell}$ shape

Results from the χ^2 fit

For pp collisions at LHC energy:

$$m_t^{\text{Pythia}} - m_t^{\text{pole}} = 0.320 \pm 0.015 \text{ GeV}$$

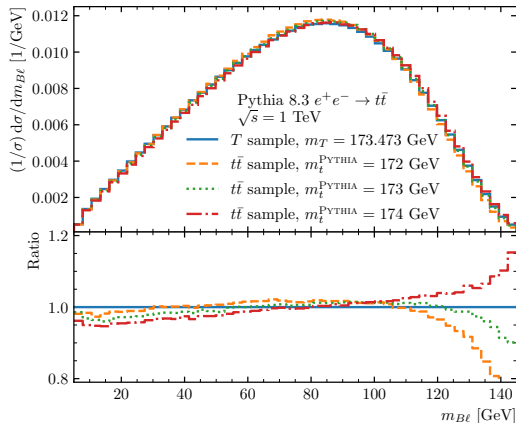
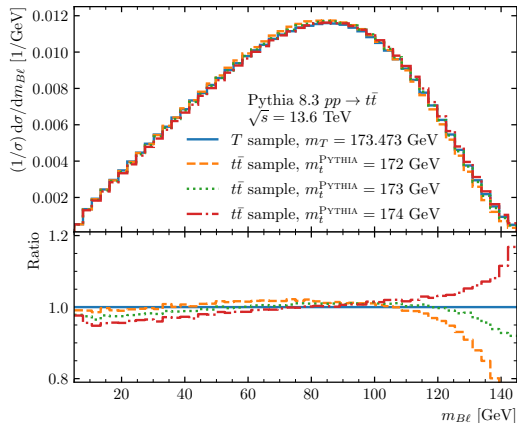
For e^+e^- collisions at a future lepton collider:

$$m_t^{\text{Pythia}} - m_t^{\text{pole}} = 0.280 \pm 0.014 \text{ GeV}$$

Similar size $\sim \Lambda_{\text{QCD}}$

But opposite sign compared to the $\langle m_{B\ell} \rangle$ fit

Results: $m_{B\ell}$ distributions



Comparison of distributions for different m_t^{Pythia}