Phenomenology of top quarks at the LHC and future colliders

Alexander Lind

work with Gennaro Corcella, Vishakha Lingadahally, Andrea Banfi, and Jonas Lindert

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

Seminar, Dipartimento di Fisica, Università degli Studi di Milano

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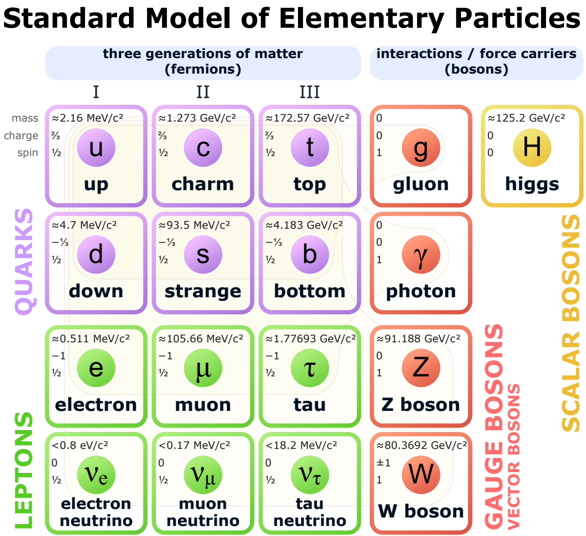
Top quark



Heaviest particle in the SM

Interesting probe for new physics

Non-trivial issues in the modelling and implementation in Monte Carlo event generators

Outline

General theory challenge: *Precision*

I will present two projects on top quark physics

Covering (among other topics):

- Top quark mass determination
- Monte Carlo modelling uncertainties
  - Hadronisation
  - Parton showers, recoil
- The top quark as a probe for new physics

Top quark mass interpretation from simulation of top-flavoured mesons

with Gennaro Corcella

Top quark mass

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

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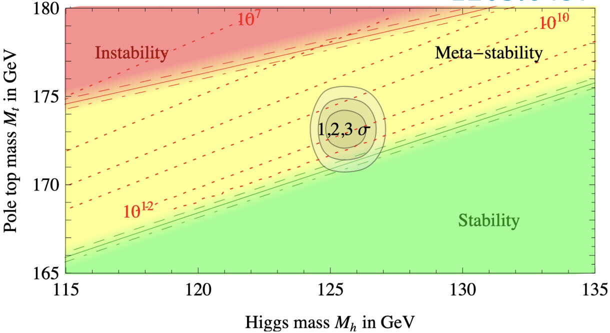


Precision determination important for e.g.:

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

Experimental measurements of the top mass

m_t is a free parameter — Must be extracted from experiments

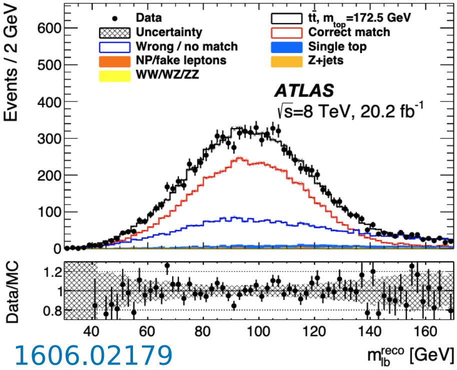
Average (PDG 2024):

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

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}



1606.02179

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:

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

Two different views:

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

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

  (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 and Herwig on Δm

Contribution to Δm from hadronisation systematics

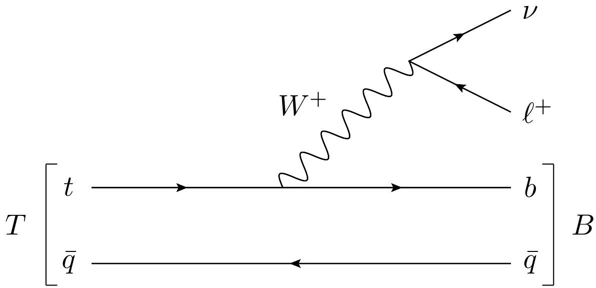
Idea:

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:

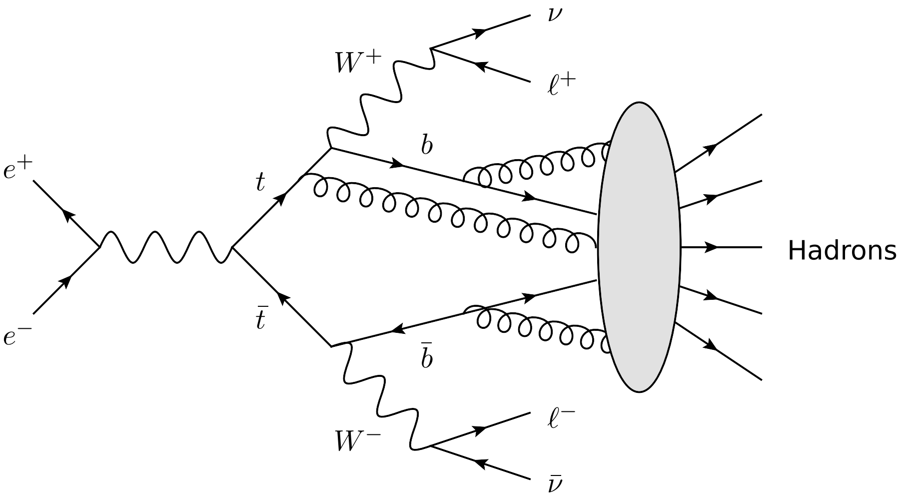
$$T^+(t\bar{d}) \to (b\bar{d})\ell^+\nu + X$$

where X is mainly gluon radiation from the b quark

$$x_q = m_q/m_T$$

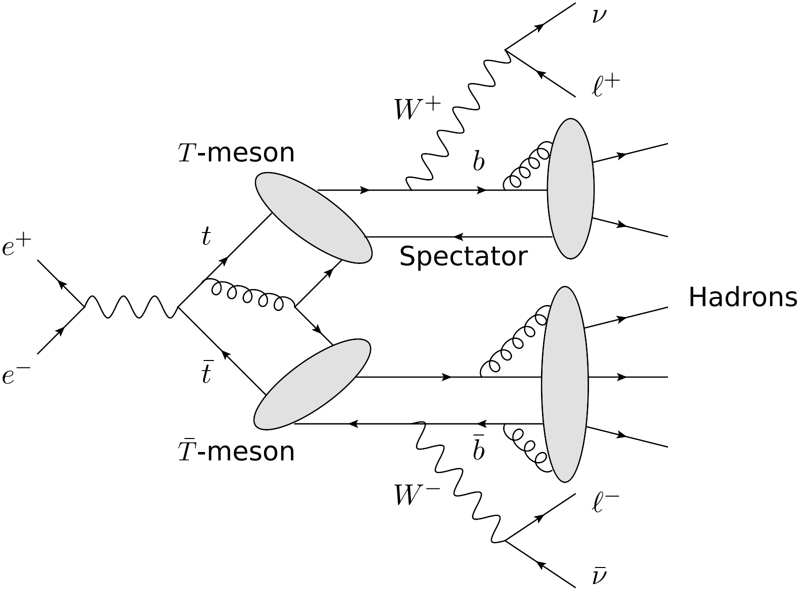
Top pair production

$e^+e^- \to t\bar{t}$ with leptonic decays of the Ws 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 $m_t^{\rm pole}$ 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)

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

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

where

- $\overline{\Lambda}$ 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

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

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

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

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 $\bar{\Lambda} = 0.49 \pm 0.08\ \text{GeV}$

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
```

Results

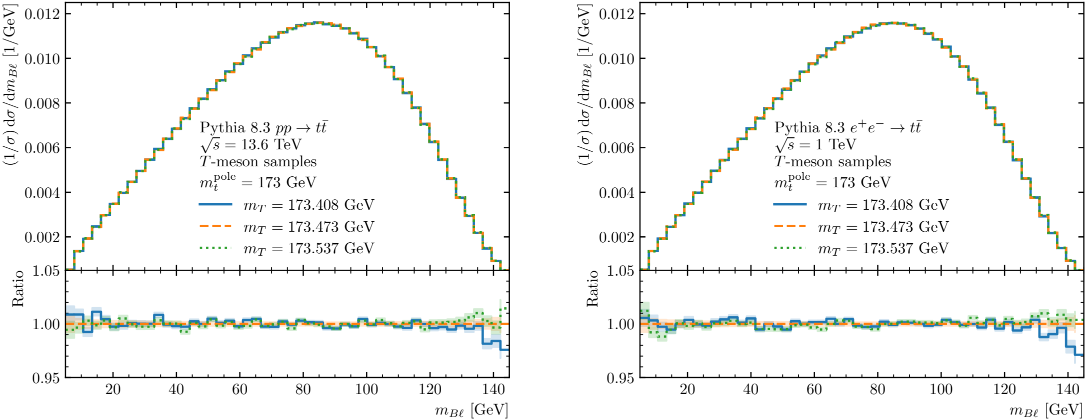
With Pythia 8.3 we simulate:

- standard $t\bar{t}$ samples,
- T-meson samples,

for two different collider setups:

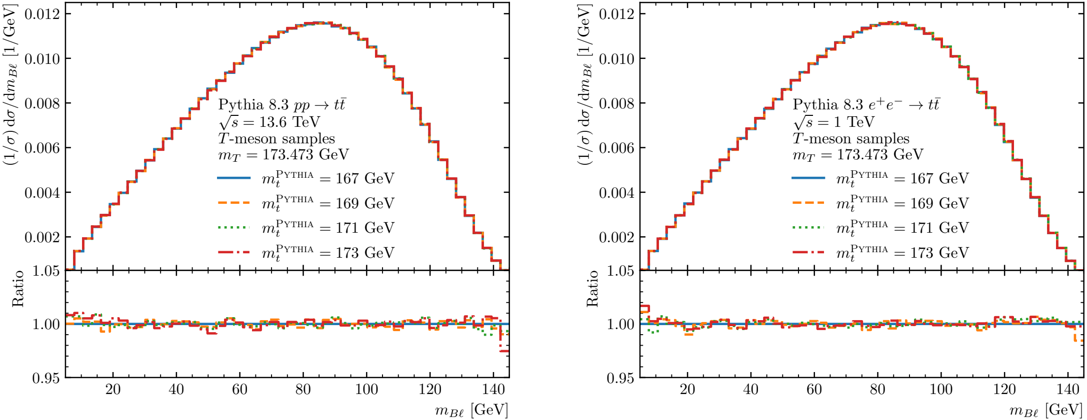
- current LHC setup, $pp \to t\bar{t}$, at $\sqrt{s} = 13.6$ TeV;
- a future lepton collider, $e^+e^- \to t\bar{t}$, at $\sqrt{s} = 1$ TeV.

Results: $m_{B\ell}$ distributions



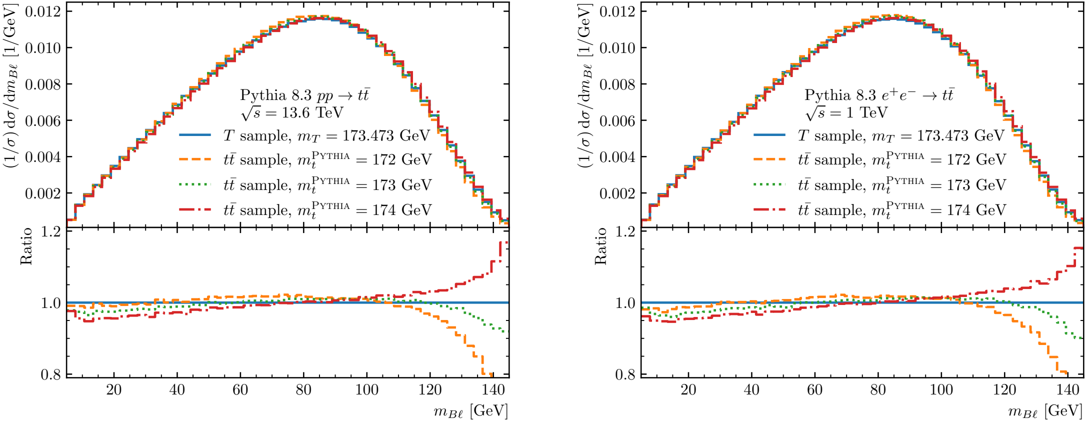
Uncertainty on $\bar{\Lambda}$ is negligible

Results: $m_{B\ell}$ distributions



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

Results: $m_{B\ell}$ distributions



Comparison of distributions for different m_t^{Pythia}

Results: Mellin moments

pp collisions at $\sqrt{s} = 13.6$ TeV

Standard $t\bar{t}$ samples

m_t^{Pythia} [GeV]	$\langle m_{B\ell} \rangle$ [GeV]	$\langle m_{B\ell}^2 \rangle$ [GeV^2]
170.5	75.884(7)	$6.633(1) \times 10^3$
171.0	76.164(7)	$6.681(1) \times 10^3$
171.5	76.474(7)	$6.735(1) \times 10^3$
172.0	76.745(7)	$6.782(1) \times 10^3$
172.5	77.044(7)	$6.833(1) \times 10^3$
173.0	77.324(7)	$6.883(1) \times 10^3$
173.5	77.608(7)	$6.932(1) \times 10^3$
174.0	77.907(7)	$6.985(1) \times 10^3$
174.5	78.191(7)	$7.034(1) \times 10^3$
175.0	78.466(7)	$7.083(1) \times 10^3$
175.5	78.739(7)	$7.132(1) \times 10^3$
176.0	79.017(7)	$7.181(1) \times 10^3$

T-meson samples

m_T [GeV]	$\langle m_{B\ell} \rangle$ [GeV]	$\langle m_{B\ell}^2 \rangle$ [GeV^2]
170.5	75.496(9)	$6.579(1) \times 10^3$
171.0	75.789(9)	$6.630(1) \times 10^3$
171.5	76.084(9)	$6.681(1) \times 10^3$
172.0	76.365(9)	$6.730(1) \times 10^3$
172.5	76.644(9)	$6.779(1) \times 10^3$
173.0	76.933(9)	$6.828(1) \times 10^3$
173.5	77.199(9)	$6.876(1) \times 10^3$
174.0	77.488(9)	$6.926(1) \times 10^3$
174.5	77.770(9)	$6.975(1) \times 10^3$
175.0	78.058(9)	$7.026(1) \times 10^3$
175.5	78.318(9)	$7.073(1) \times 10^3$
176.0	78.601(9)	$7.122(1) \times 10^3$

Results: Mellin moments

e^+e^- collisions at $\sqrt{s} = 1$ TeV

Standard $t\bar{t}$ samples

m_t^{Pythia} [GeV]	$\langle m_{B\ell} \rangle$ [GeV]	$\langle m_{B\ell}^2 \rangle$ [GeV^2]
170.5	75.935(7)	$6.640(1) \times 10^3$
171.0	76.237(7)	$6.692(1) \times 10^3$
171.5	76.515(7)	$6.741(1) \times 10^3$
172.0	76.816(7)	$6.792(1) \times 10^3$
172.5	77.098(7)	$6.842(1) \times 10^3$
173.0	77.392(7)	$6.893(1) \times 10^3$
173.5	77.682(7)	$6.944(1) \times 10^3$
174.0	77.950(7)	$6.991(1) \times 10^3$
174.5	78.240(7)	$7.042(1) \times 10^3$
175.0	78.506(7)	$7.089(1) \times 10^3$
175.5	78.786(7)	$7.139(1) \times 10^3$
176.0	79.065(7)	$7.189(1) \times 10^3$

T-meson samples

m_T [GeV]	$\langle m_{B\ell} \rangle$ [GeV]	$\langle m_{B\ell}^2 \rangle$ [GeV^2]
170.5	75.498(9)	$6.580(1) \times 10^3$
171.0	75.775(9)	$6.628(1) \times 10^3$
171.5	76.075(9)	$6.680(1) \times 10^3$
172.0	76.371(9)	$6.731(1) \times 10^3$
172.5	76.649(9)	$6.779(1) \times 10^3$
173.0	76.936(9)	$6.829(1) \times 10^3$
173.5	77.205(9)	$6.877(1) \times 10^3$
174.0	77.506(9)	$6.929(1) \times 10^3$
174.5	77.784(9)	$6.978(1) \times 10^3$
175.0	78.043(9)	$7.024(1) \times 10^3$
175.5	78.331(9)	$7.075(1) \times 10^3$
176.0	78.606(9)	$7.123(1) \times 10^3$

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

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

Linear dependence on m_t^{Pythia}:

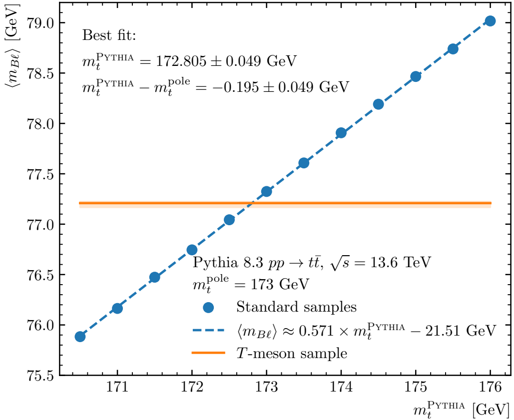
$$\langle m_{B\ell} \rangle_{\text{standard}} \simeq a \times m_t^{\text{Pythia}} + b$$

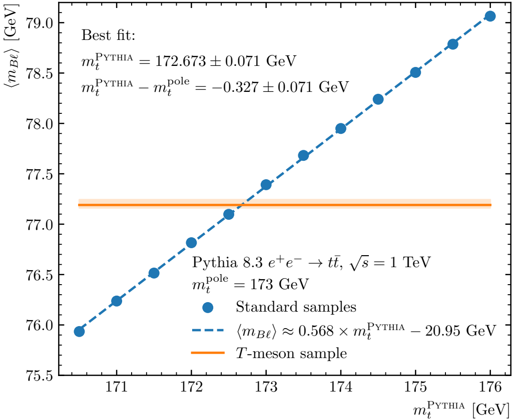
Compare to the T-meson sample for a fixed

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

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

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





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

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

	pp at $\sqrt{s} = 13.6$ TeV	e^+e^- at $\sqrt{s} = 1$ TeV
a	0.571 ± 0.002	0.568 ± 0.002
b	-21.51 ± 0.33 GeV	-20.95 ± 0.40 GeV
δ_{fit}	0.011 GeV	0.014 GeV

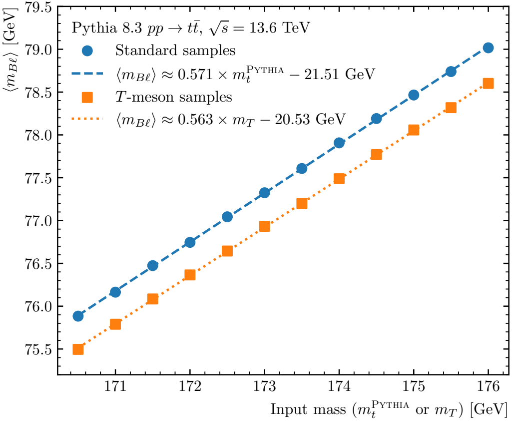
Fit $\langle m_{B\ell} \rangle = a' \times m_T + b'$ to the T-meson samples

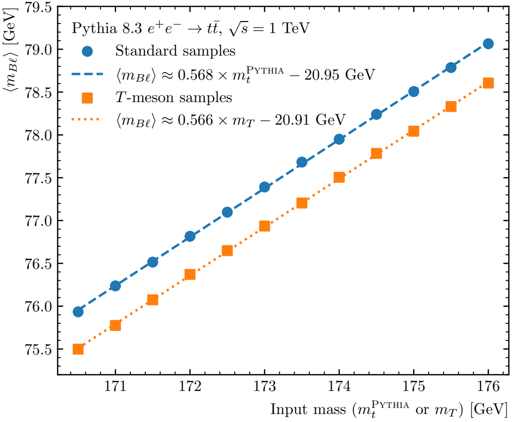
	pp at $\sqrt{s} = 13.6$ TeV	e^+e^- at $\sqrt{s} = 1$ TeV
a'	0.563 ± 0.002	0.566 ± 0.002
b'	-20.53 ± 0.29 GeV	-20.91 ± 0.37 GeV
δ_{fit}	0.010 GeV	0.013 GeV

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 $\langle m_{B\ell} \rangle$

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

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

Re-performing the linear fits with fixed slopes, we get

$$m_t^{\text{Pythia}} \approx m_T - (0.708 \pm 0.009)\ \text{GeV} \qquad \text{(for } pp \text{ collisions)},$$

$$m_t^{\text{Pythia}} \approx m_T - (0.80 \pm 0.01)\ \text{GeV} \qquad \text{(for } e^+e^- \text{ collisions)}.$$

From the HQET result, $m_T \approx m_t^{\text{pole}} + \bar{\Lambda}$, with $\bar{\Lambda} \approx 0.473$, we find that

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

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

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:

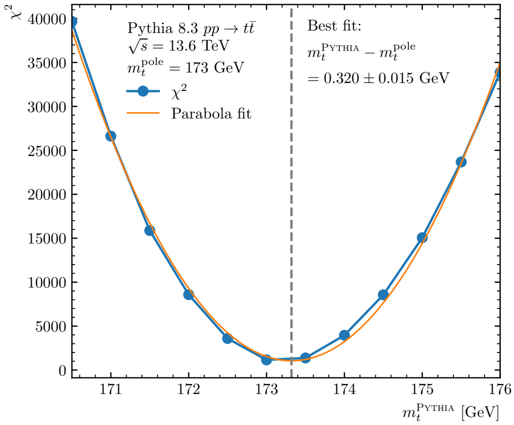
$$p_i = \frac{x_i + y_i}{X + Y}$$

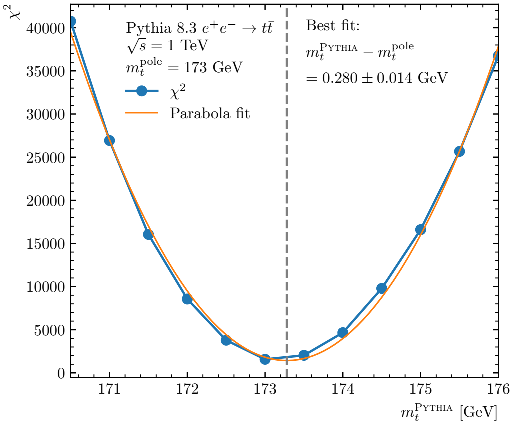
Test statistics:

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

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:

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

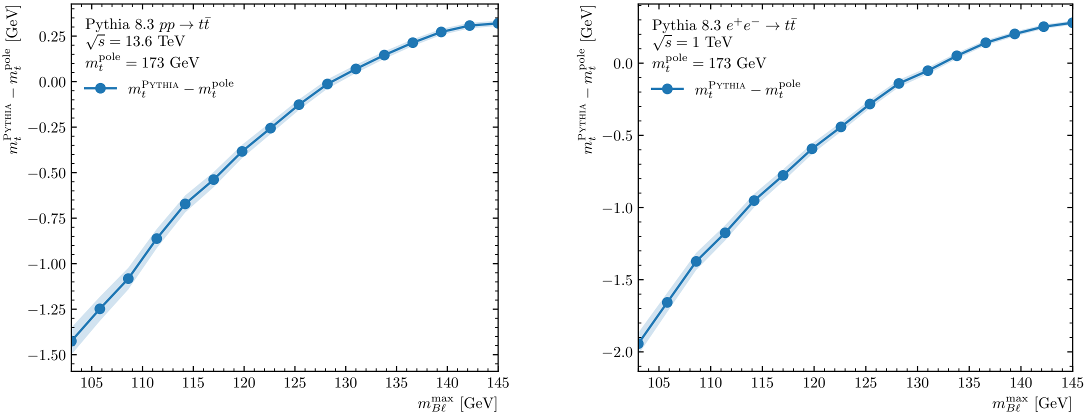
For e^+e^- collisions at a future lepton collider:

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

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

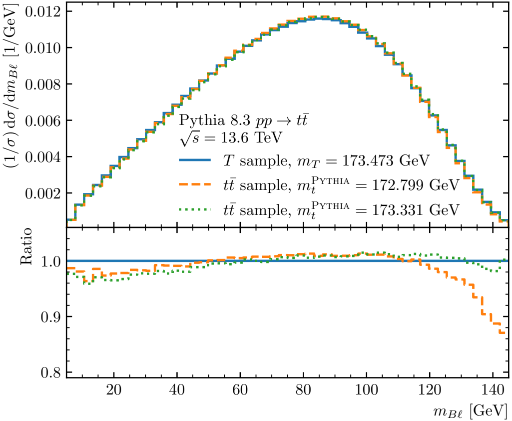
But opposite sign compared to the $\langle m_{B\ell} \rangle$ fit

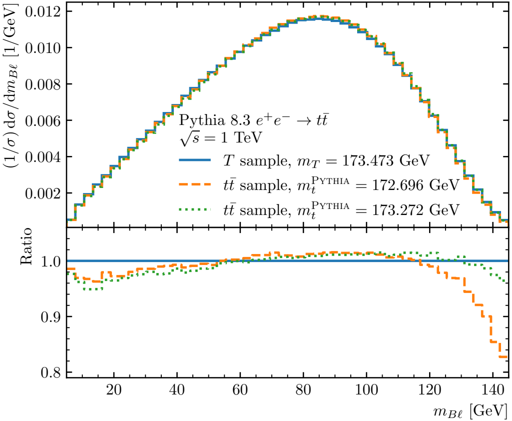
Results: χ^2 fit of $m_{B\ell}$ shape



Large dependence on upper bound of distribution $m_{B\ell}^{\max}$ used in fit

Results: $m_{B\ell}$ distributions





Comparison to best fits

Results: x_B distributions

Scaled B-hadron energy fraction:

$$x_B \equiv \left(\frac{1}{1 - m_W^2/m_{t,T}^2 + m_b^2/m_{t,T}^2} \right) \frac{2\, p_B \cdot p_{t,T}}{m_{t,T}^2}$$

for either the top quark t or top-flavoured meson T

In the top rest frame:

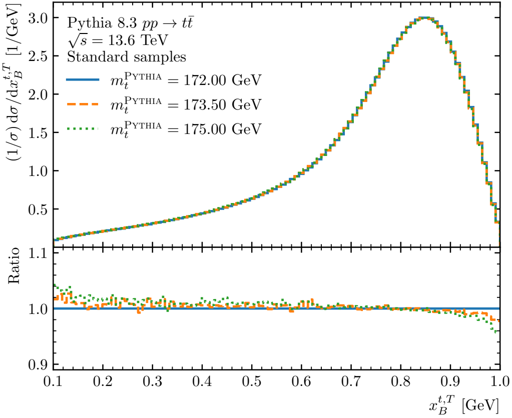
$$x_B \simeq \frac{2\, E_B}{m_{t,T}}$$

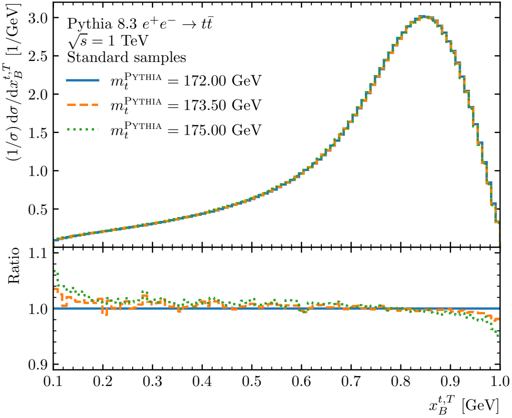
where we neglect terms of $\mathcal{O}(1/m_{t,T}^2)$

x_B probes primarily the B fragmentation

Experimentally difficult

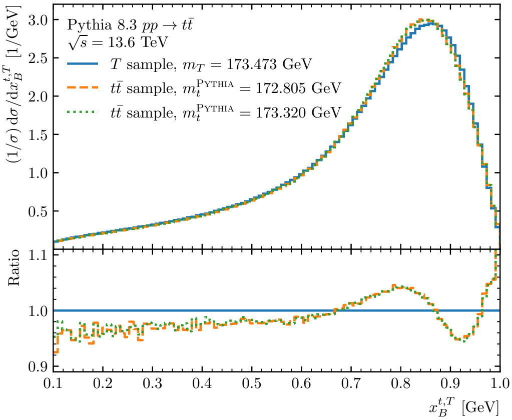
Results: x_B distributions

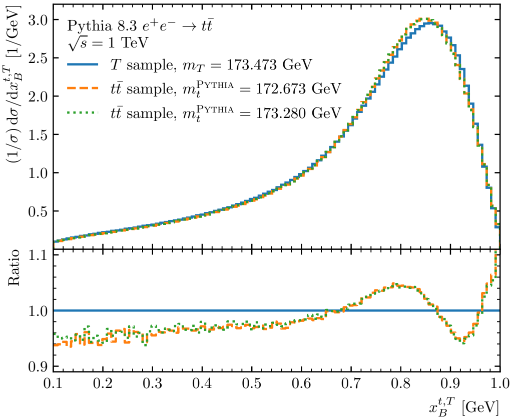




Small dependence on input top mass

Results: x_B distributions





Comparison to best fits

Sensitivity to non-perturbative modelling

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

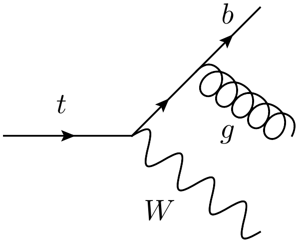
- Colour reconnection
- Recoil treatment in top decay
- Radiation from b quarks

Recoil options in the showering of top decays

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

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

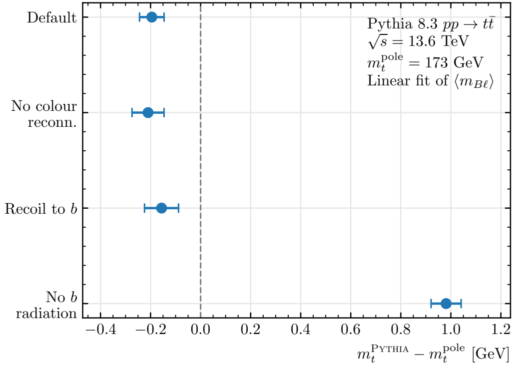
Ambiguity on the 2nd gluon emission:
Different possible recoil strategies

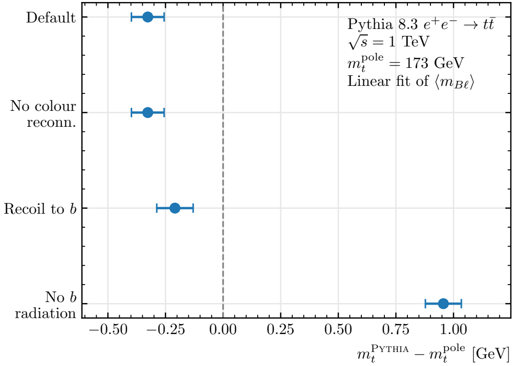


Important for precise determination of m_t

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 and outlook

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 $\mathcal{O}(\Lambda_{\mathrm{QCD}})$

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

Top Quark Pair Production and Decay:

Interference effects between loop-induced Higgs-mediated amplitudes and QCD background

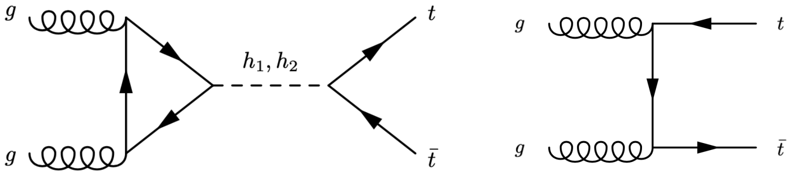
with Vishakha Lingadahally, Andrea Banfi, and Jonas Lindert

Process of interest

Top pair production in QCD and Higgs-mediated

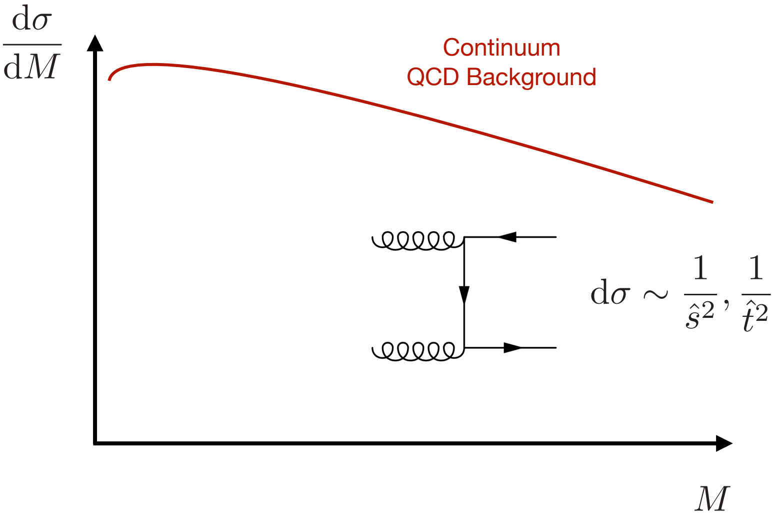
$$pp\,(\rightarrow H) \rightarrow t\bar{t}$$

Probe for new physics, e.g. extensions of the Higgs sector (heavy Higgs, pseudoscalar Higgs)



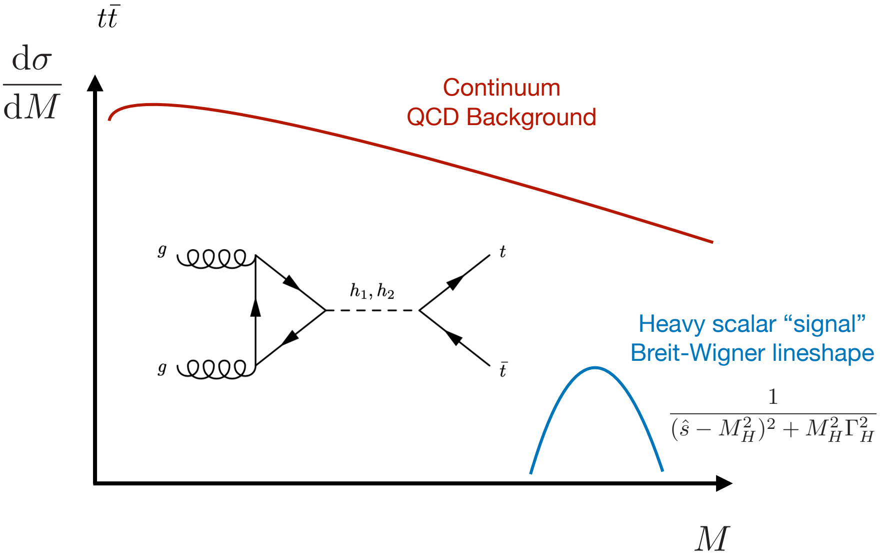
"Bump hunting"

Invariant mass spectrum:



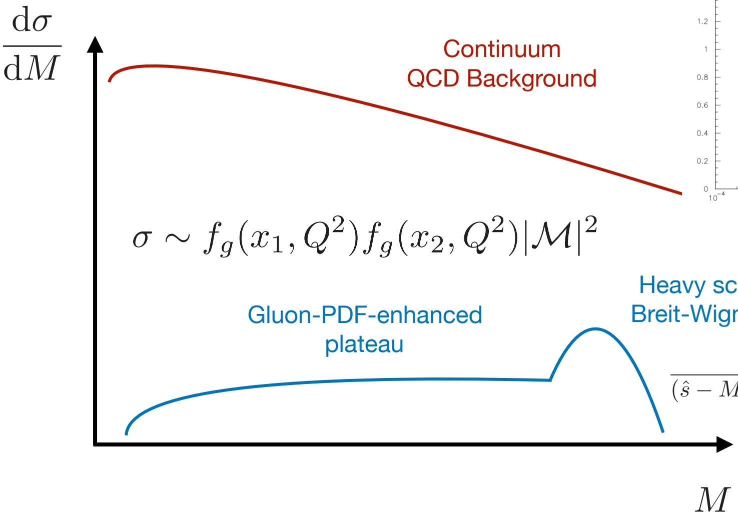
"Bump hunting"

Invariant mass spectrum:



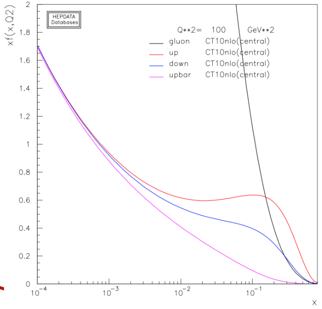
Alternative to “bump hunting”

Invariant mass spectrum:



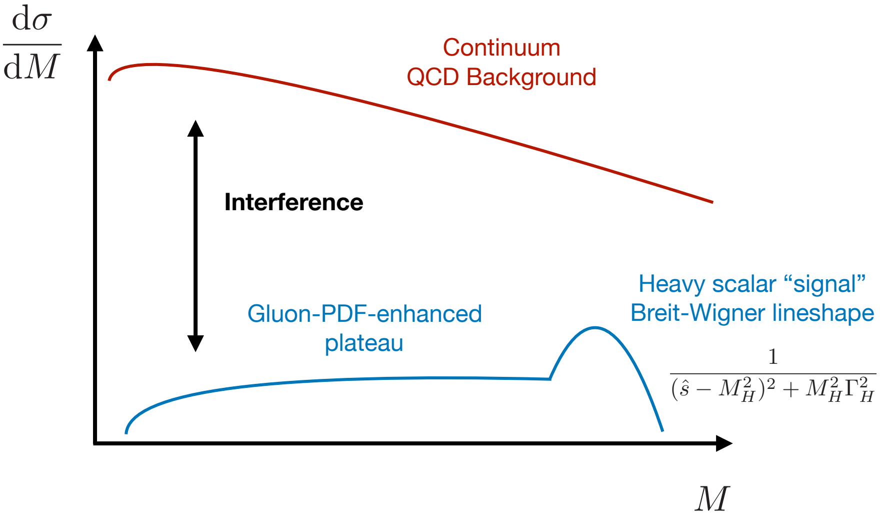
$$\sigma \sim f_g(x_1, Q^2) f_g(x_2, Q^2) |\mathcal{M}|^2$$

$$\frac{1}{(\hat{s} - M_H^2)^2 + M_H^2 \Gamma_H^2}$$



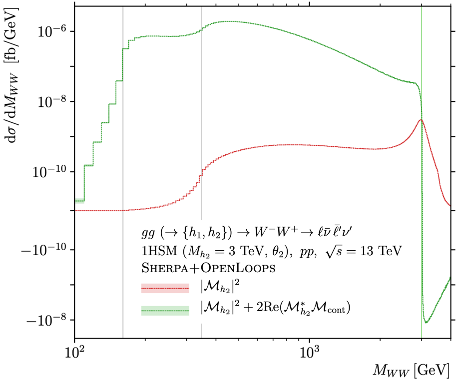
Alternative to "bump hunting"

Invariant mass spectrum:

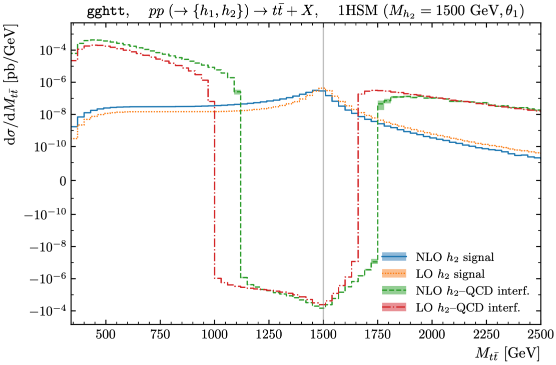


Alternative to “bump hunting”

Invariant mass spectrum:

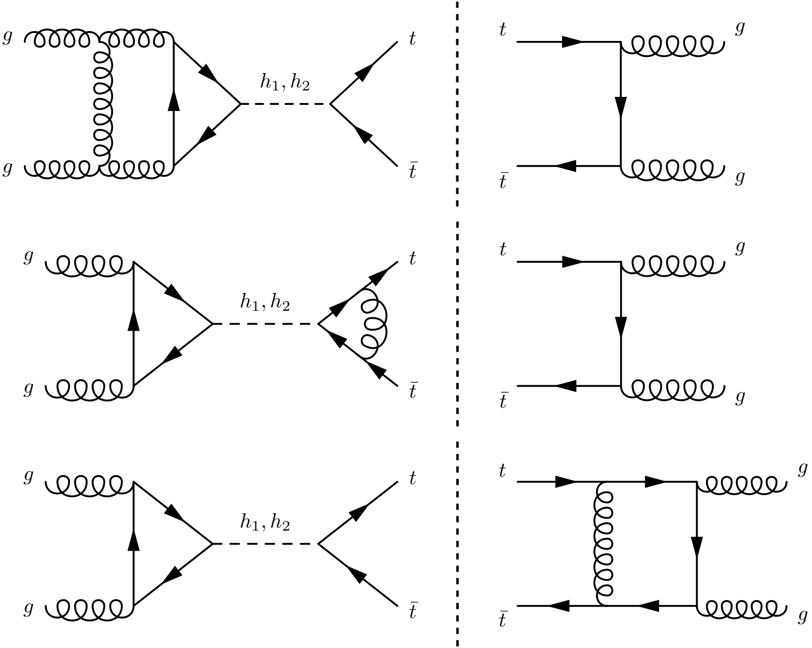


$$\mathrm{d}\sigma \sim \frac{1}{\hat{s}^2}$$



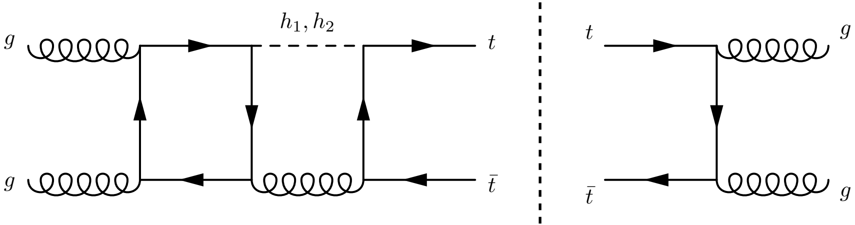
$$\mathrm{d}\sigma \sim \frac{1}{(\hat{s} - M_H^2)^2} \sim \frac{1}{M_H^4}$$

NLO QCD corrections to the interference



Non-factorisable corrections

Non-factorisable two-loop virtual corrections



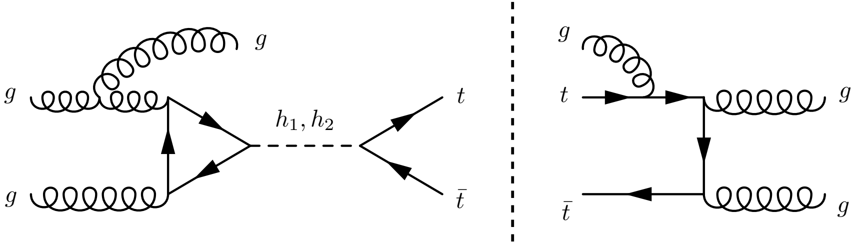
Non-zero for a (heavy) Higgs of finite width

Three different masses in internal propagators
$\Rightarrow$ Beyond today's loop technology

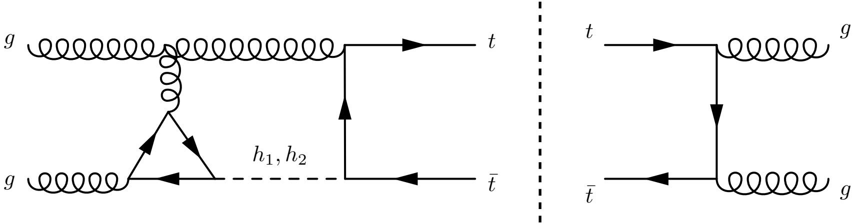
Could be calculated by expansions in $\frac{\Gamma_{h_i}}{M_{h_i}}$

Non-factorisable corrections

IR divergent non-factorisable **real** contribution

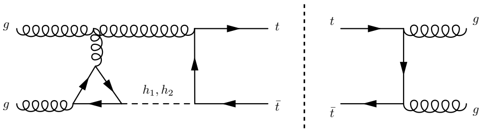


IR divergent non-factorisable **virtual** contribution

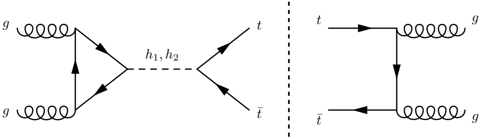


Non-factorisable corrections

However, in the soft limit:

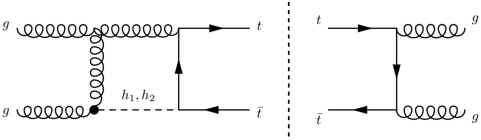


$= C \times$



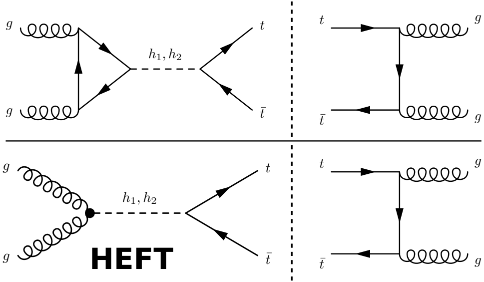
Singular term

Reweighting:



HEFT

$\times$



Form factors for $gg \to H$

Coupling of a Higgs doublet to two on-shell gluons

$$\mathcal{V}^{\mu\nu,ab}(q_1, q_2) = \frac{\alpha_s}{4\pi v} F \, \delta^{ab} \left((q_1 \cdot q_2) \, g^{\mu\nu} - q_1^{\nu} \, q_2^{\mu} \right)$$

Form factor F can be represented as a series expansion in powers of α_s

$$F = F_1 + \frac{\alpha_s}{2\pi} F_2 + \mathcal{O}(\alpha_s^2)$$

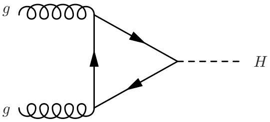
Davies, Herren, Steinhauser [1911.10214]

The one-loop form factor is

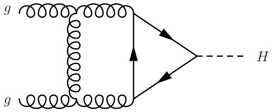
$$F_1 = -\sum_q \frac{2}{\tau_q^2} \left[\tau_q + \frac{1}{4}(1 - \tau_q) \ln^2 x_q \right]$$

Harlander, Kant [hep-ph/0509189]

F_1:



F_2:

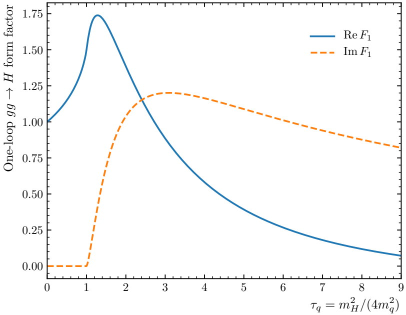


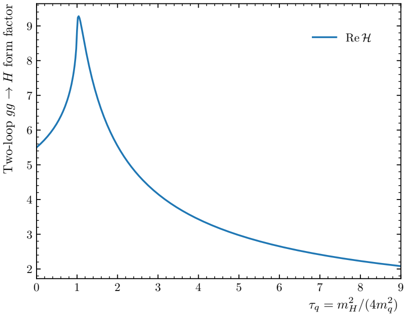
Form factors for $gg \to H$

The two-loop form factor is

$$F_2 = \left(\frac{4\pi\mu_R^2}{-2(q_1\cdot q_2)-i0}\right)^\epsilon \frac{1}{\Gamma(1-\epsilon)} \left\{-\left(\frac{C_A}{\epsilon^2}+\frac{\beta_0}{\epsilon}+\beta_0 \ln\left(\frac{2(q_1\cdot q_2)}{\mu_R^2}\right)\right)F_1 \right.$$
$$\left. +2\sum_q \left[C_F\left(\mathcal{F}^{2l,a}_{1/2}(x_q)+\frac{4}{3}\mathcal{F}^{2l,b}_{1/2}(x_q)\right)+C_A\mathcal{G}^{2l}_{1/2}(x_q)\right]\right\}$$

Aglietti, Bonciani, Degrassi, Vicini [hep-ph/0611266]





Results: Integrated cross sections

NLO predictions with stable tops

QCD background: $|\mathcal{M}_{\text{QCD}}|^2$

Higgs signal: $|\mathcal{M}_{h_1}|^2 + |\mathcal{M}_{h_2}|^2 + 2\,\text{Re}\left(\mathcal{M}^*_{h_1}\mathcal{M}_{h_2}\right)$

Higgs–QCD interference: $2\,\text{Re}\left(\left(\mathcal{M}^*_{h_1} + \mathcal{M}^*_{h_2}\right)\mathcal{M}_{\text{QCD}}\right)$

$pp\ (\to \{h_1\}) \to t\bar{t} + X$ in the SM					
QCD background		Higgs signal		Higgs-QCD Interference	
$\sigma^{\text{QCD}}_{\text{NLO}}$ [pb]	K^{QCD}	$\sigma^{\text{Higgs}}_{\text{NLO}}$ [pb]	K^{Higgs}	$\sigma^{\text{interf}}_{\text{NLO}}$ [pb]	K^{interf}
$675.23(4)$	$1.5965(1)$	$0.030971(3)$	$1.6512(2)$	$-1.4625(1)$	$2.0101(2)$

Ansatz from Hespel, Maltoni, Vryonidou, [1606.04149]:

$$\sigma^{\text{interf}}_{\text{NLO}} = \sqrt{K^{\text{Higgs}} \cdot K^{\text{QCD}}}\,\sigma^{\text{interf}}_{\text{LO}}$$

This ansatz yields $K^{\text{interf}}_{\text{estimate}} = \sqrt{K^{\text{Higgs}} \cdot K^{\text{QCD}}} = 1.62$ vs. ours $K^{\text{interf}} = 2.01$

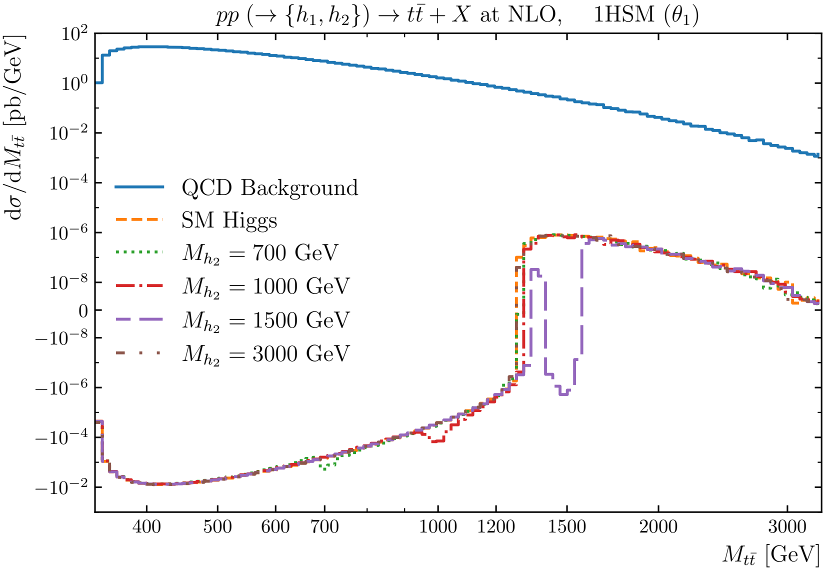
Results: Integrated cross sections

Same story for our considered BSM model

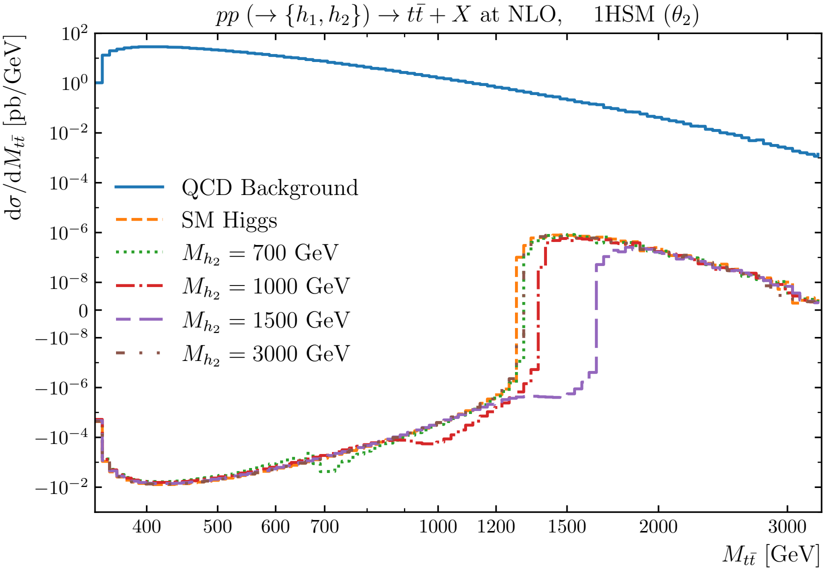
$pp\ (\to \{h_1, h_2\}) \to t\bar{t} + X$ in the 1HSM					
		Higgs signal		Higgs–QCD interference	
	M_{h_2} [GeV]	$\sigma_{\text{NLO}}^{\text{Higgs}}$ [pb]	K^{Higgs}	$\sigma_{\text{NLO}}^{\text{interf}}$ [pb]	K^{interf}
θ_1	700	$0.029108(2)$	$1.6234(2)$	$-1.388(8)$	$1.99(2)$
	1000	$0.027334(2)$	$1.6459(2)$	$-1.3924(2)$	$2.0151(2)$
	1500	$0.029932(3)$	$1.6745(2)$	$-1.4369(2)$	$2.0194(2)$
	3000	$0.030933(3)$	$1.6661(2)$	$-1.4781(2)$	$2.0414(2)$
θ_2	700	$0.027231(2)$	$1.5689(2)$	$-1.186(8)$	$1.88(2)$
	1000	$0.020114(2)$	$1.6442(2)$	$-1.21053(9)$	$1.9867(2)$
	1500	$0.026519(2)$	$1.6617(2)$	$-1.34853(9)$	$1.9958(2)$
	3000	$0.029772(2)$	$1.6452(2)$	$-1.4365(2)$	$2.0097(2)$

Results: Differential Distributions

$M_{t\bar{t}}$ distribution for benchmark points with $\theta = \theta_1$



$M_{t\bar{t}}$ distribution for benchmark points with $\theta = \theta_2$

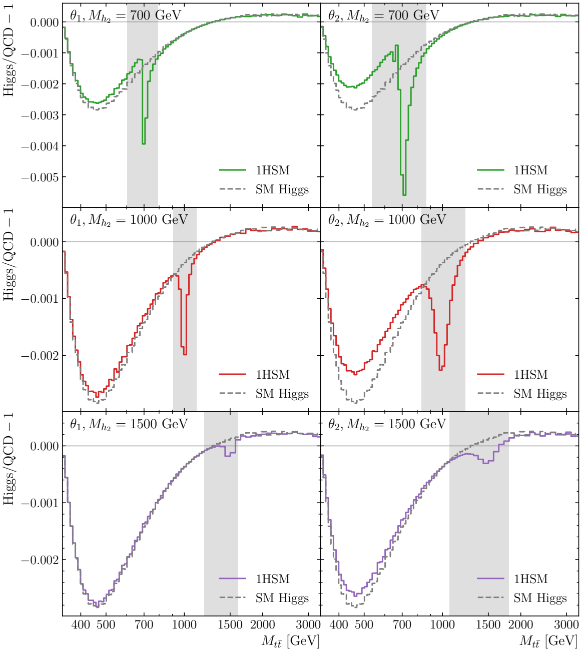


Results: Differential distributions

Peak/dip structure in the BSM scenarios

Higgs/QCD-1 vs. $M_{t\bar{t}}$

Grey bands: Invariant mass windows



M_{h_2}

700 GeV

1000 GeV

1500 GeV

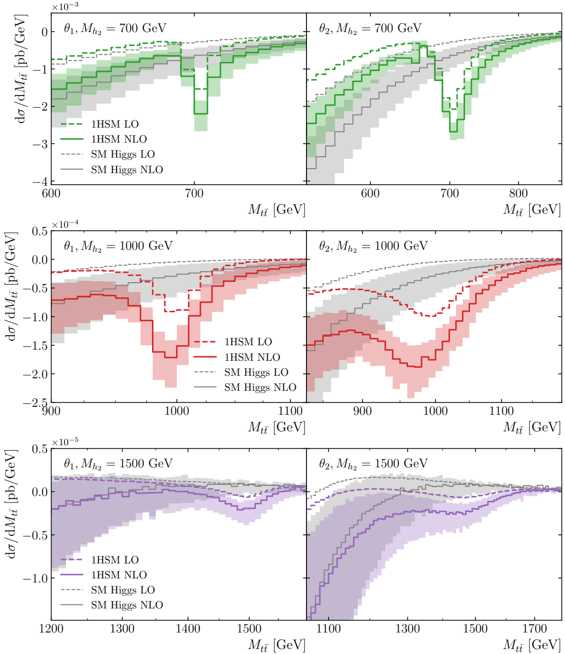
Results: Differential distributions

NLO vs. LO

Zoomed in at the invariant mass windows

Estimation of theoretical uncertainties:

- 7-point scale variation
- 20–30%



M_{h_2}

700 GeV

1000 GeV

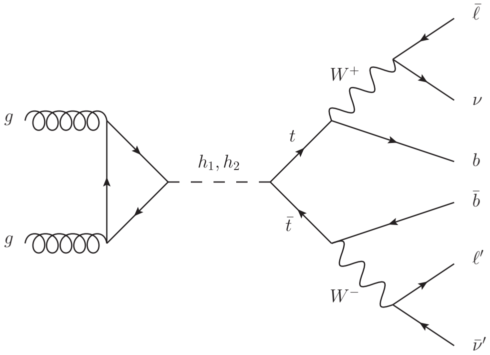
1500 GeV

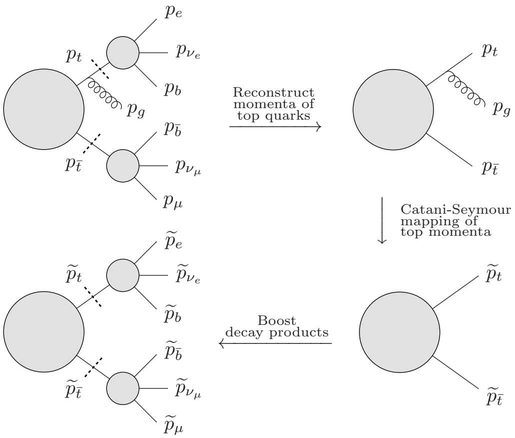
Top decays

Can consider the full $2 \to 6$ top decay amplitudes

$$pp\,(\to \{h_1, h_2\}) \to t\bar{t} \to W^+W^-b\bar{b} \to \bar{\ell}\nu\ell'\bar{\nu}'b\bar{b}$$

with spin correlations in the double pole approximation



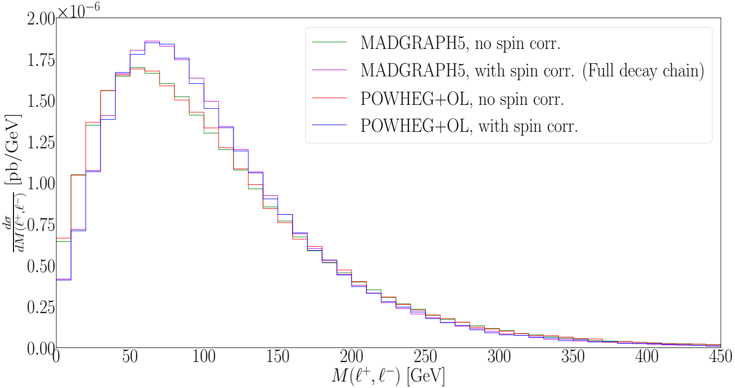


Bevilacqua, Hartanto, Kraus, Weber, Worek [1912.09999]

Top decays

POWHEG+OpenLoops

Alioli, Moch, Uwer (1110.5251)



The SM signal at LO has been validated against MadGraph5 aMC@NLO at the differential level

Summary and outlook

Summary:

- We have studied the interference of a heavy Higgs with the continuum QCD background at NLO QCD
- The interference is loop-induced $\times$ tree-level at LO, and has a complicated structure at NLO
- This has required a specially built Monte Carlo – which can be now be used for other loop-induced processes

Thank you very much for your attention! :)