Top quark mass at the LHC

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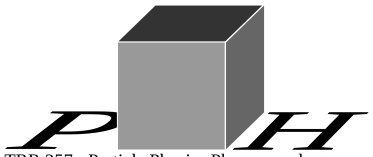


12th International Workshop on Top Quark Physics (TOP2019), Beijing, China, 23rd September 2019

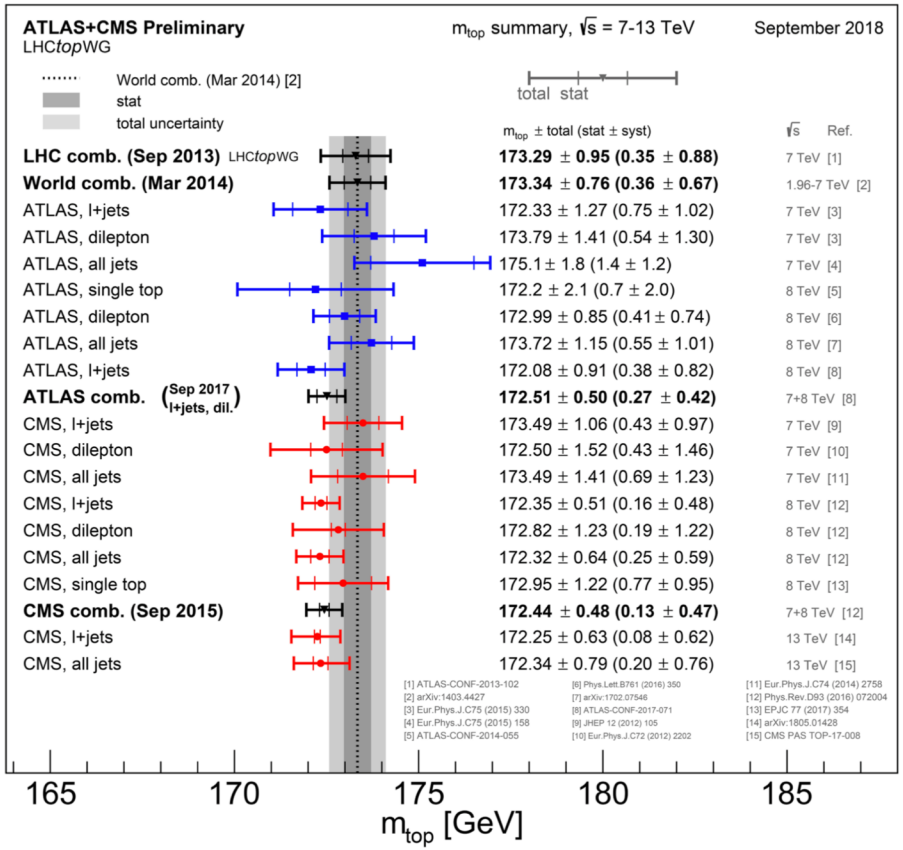
This talk is about issues surrounding the top-quark mass definition

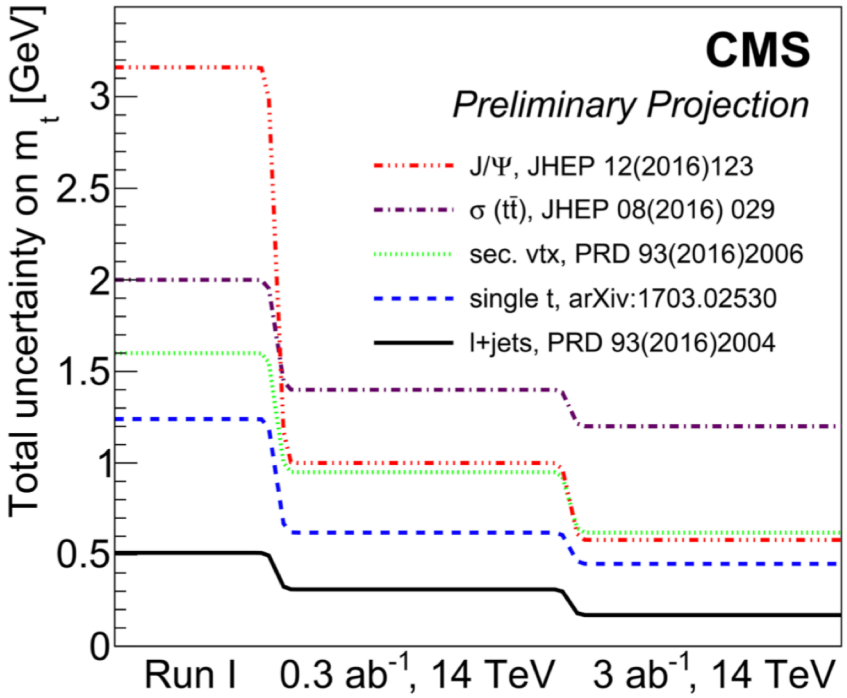
The particular emphasis on some of the issues is due to performing the measurement at the LHC

This talk is for non-experts

The topic is controversial

Status and prospects





Why am I talking about this ?

(almost)
every statement in physics
is only approximate

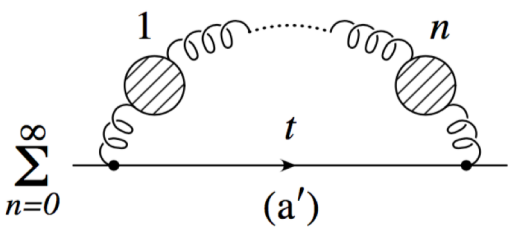
- The Operator Product Expansion (used to decompose observables into non-perturbative and perturbative factors) does not converge

- The perturbative expansion of a partonic cross section does not converge

- The relation between the on-shell and short-distance masses of a quark does not converge

We are only optimizing asymptotic series

Renormalons in the relation between on-shell and $\overline{\rm MS}$ mass



$$m_{\rm pole} = m_{\overline{\rm MS}} + \mu C_F \frac{\alpha_S}{\pi} e^{-C/2} \sum_{n=0}^{\infty} 2^n n! \left(a_S b_0\right)^n$$

Bigi, Shifman, Uraltsev, Vainstein `94
Beneke, Braun `94

Ambiguity estimate: $1/\pi$ of imaginary part of Borel transform

$$\delta m = \mu 2 C_F \frac{e^{-C/2}}{b_0} e^{-1/2 a_S b_0} \qquad a_S(\mu^2) = \frac{1}{b_0 \ln \mu^2/\Lambda^2_{\rm QCD}}$$

$$\delta m = 2 C_F \frac{e^{-C/2}}{b_0} \Lambda_{\rm QCD}$$

Deeper understanding using renormalization group methods

Beneke `94

Renormalons in the relation between on-shell and $\overline{\text{MS}}$ mass

Relation to $\overline{\text{MS}}$ mass up to 4-loops

$$m_P = 163.643 + 7.557 + 1.617 + 0.501 + (0.195 \pm 0.005)\,\text{GeV}$$

Beneke, Marquard, Nason, Steinhauser '16

Recent estimate of the ambiguity

$$\delta^{(5+)} m_P = 0.304^{+0.012}_{-0.063}\,(N) \pm 0.030\,(m_{b,c}) \pm 0.009\,(\alpha_s) \pm 0.108\ (\text{ambiguity})\ \text{GeV}$$

…Countered with an estimate of ambiguity at 250 MeV
Hoang, Lepenik, Preisser '17

This ambiguity is not the crux of the problem

A finite top-quark width does not solve the renormalon problem

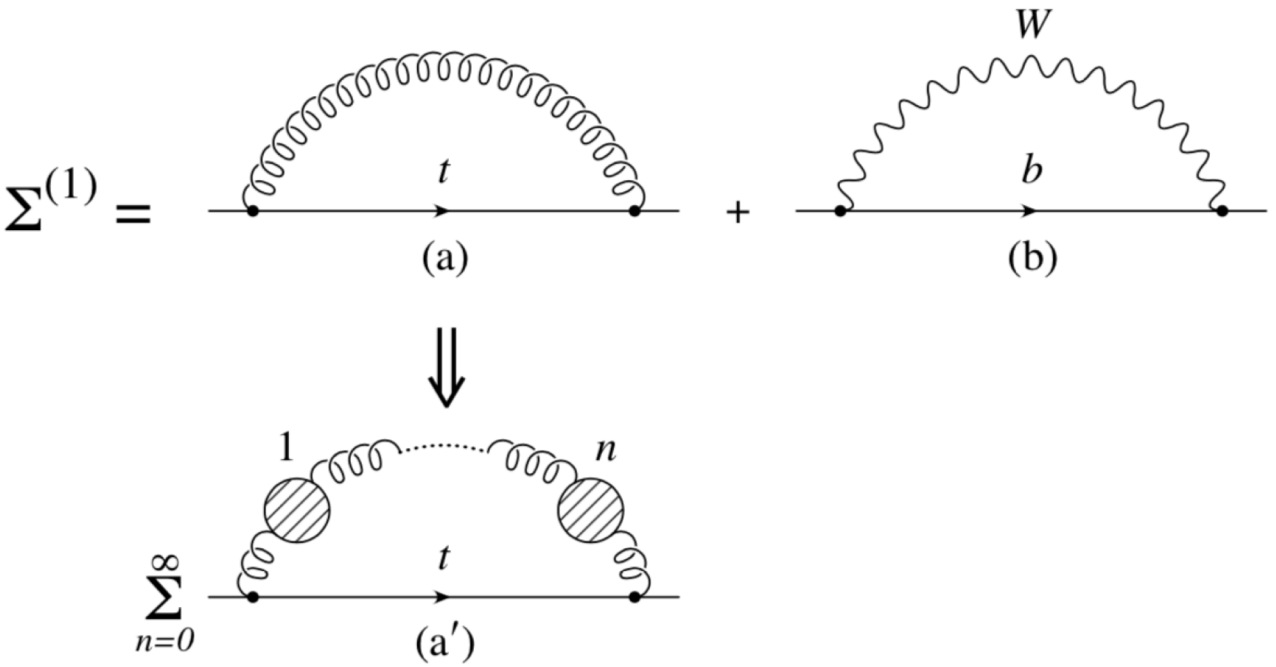


Figure 3: Diagrams contributing to the top-quark self-energy at leading order in α_s and α_W. Fig. (a′) replaces Fig. (a) when summing to all orders in $\beta_0\alpha_s$.

Smith, Willenbrock `96

A finite top-quark width does not solve the renormalon problem

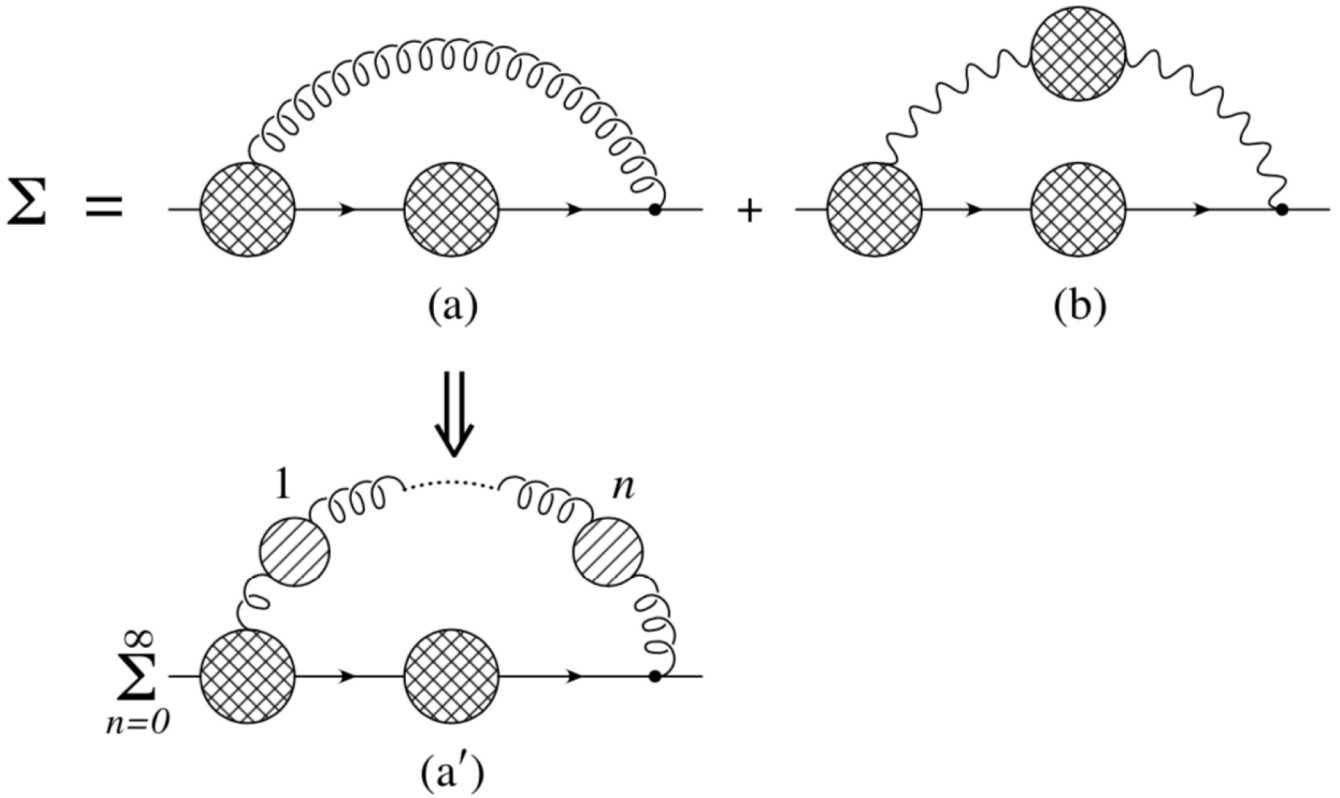


Figure 4: Diagrams contributing to the top-quark self energy at leading order in α_s, but to all orders in α_W. Fig. (a′) replaces Fig. (a) when summing to all orders in $\beta_0\alpha_s$.

Smith, Willenbrock `96

A quark does not have a pole mass

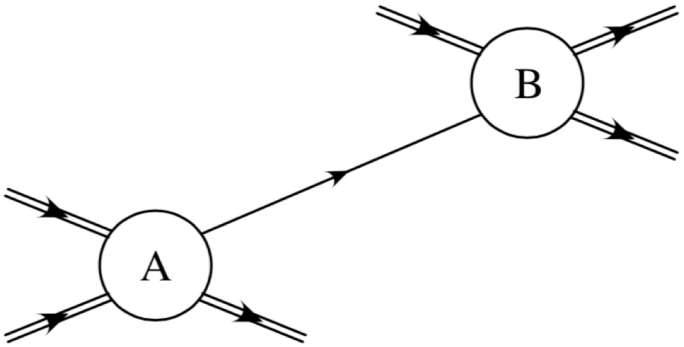


Figure 1: A scattering amplitude factorizes when an internal propagator is near its pole. The external lines represent color-singlet asymptotic states.

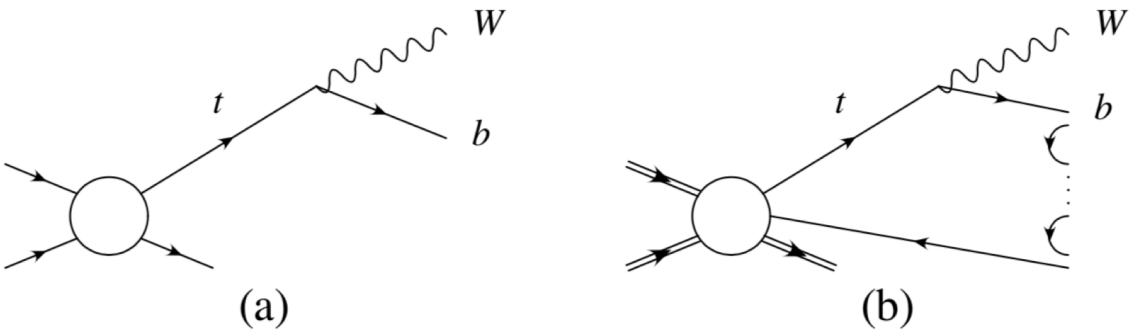


Figure 2: The production and decay of a top quark in (a) perturbation theory, and (b) nonperturbatively.

Smith, Willenbrock `96

No infrared region in definition of quark mass improves convergence

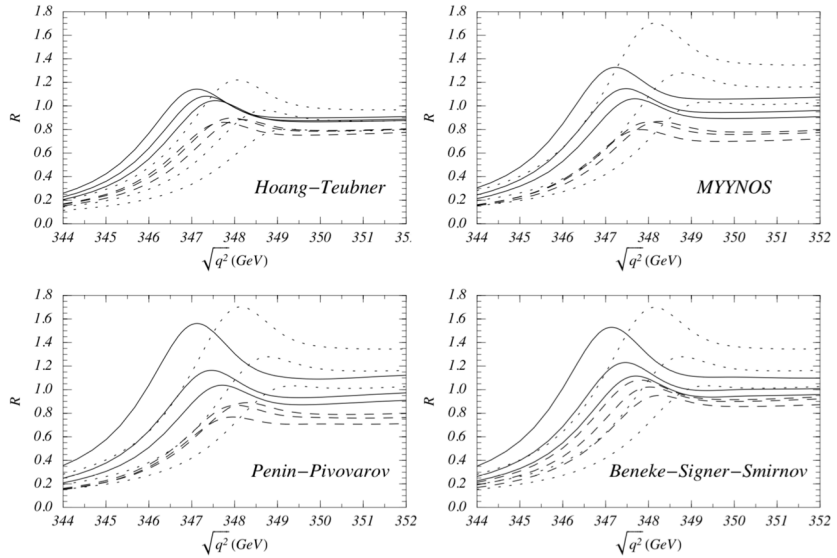


Figure 1: The total normalised photon-induced $t\bar{t}$ cross section R at the LC versus the c.m. energy in the threshold regime at LO (dotted curves), NLO (dashed) and NNLO (solid) in the pole mass scheme for $M_t^{\rm pole} = 175.05$ GeV, $\alpha_s(M_Z) = 0.119$, $\Gamma_t = 1.43$ GeV and $\mu_{\rm soft} = 15$, 30, 60 GeV. The plots have been generated from results provided by the groups Hoang-Teubner (HT), Melnikov-Yelkhovsky-Yakovlev-Nagano-Ota-Sumino (MYYNOS), Penin-Pivovarov (PP) and Beneke-Signer-Smirnov (BSS).

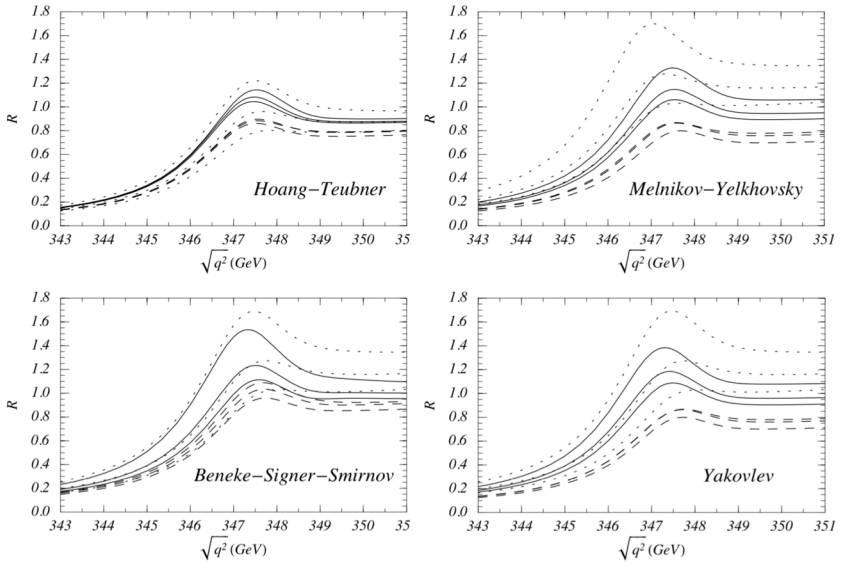
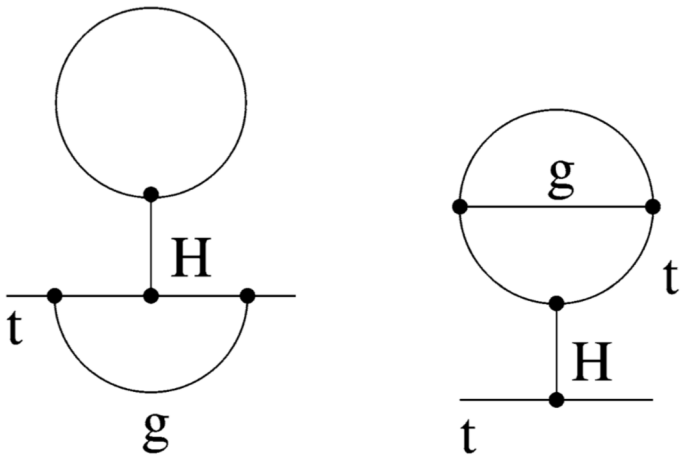


Figure 2: The total normalised photon-induced $t\bar{t}$ cross section R at the LC versus the c.m. energy in the threshold regime at LO (dotted curves), NLO (dashed) and NNLO (solid). Hoang–Teubner used the 1S mass scheme with $m_t^{1S} = 173.68$ GeV, Melnikov–Yelkhovsky the kinetic mass at 15 GeV with $m_{t,15\,\rm GeV}^{\rm kin} = 173.10$ GeV, and Beneke–Signer–Smirnov and Yakovlev the PS mass at 20 GeV with $m_{t,20\,\rm GeV}^{\rm PS} = 173.30$ GeV. The plots have been generated from results provided by the groups Hoang–Teubner (HT), Melnikov–Yelkhovsky (MY) and Beneke–Signer–Smirnov (BSS) and Yakovlev.

Hoang, Beneke, Melnikov, Nagano, Ota, Penin, Pivovarov, Signer, Smirnov, Sumino, Teubner, Yakovlev, Yelkhovsky `00

The $\overline{\text{MS}}$ mass is not as universal as The $\overline{\text{MS}}$ strong coupling



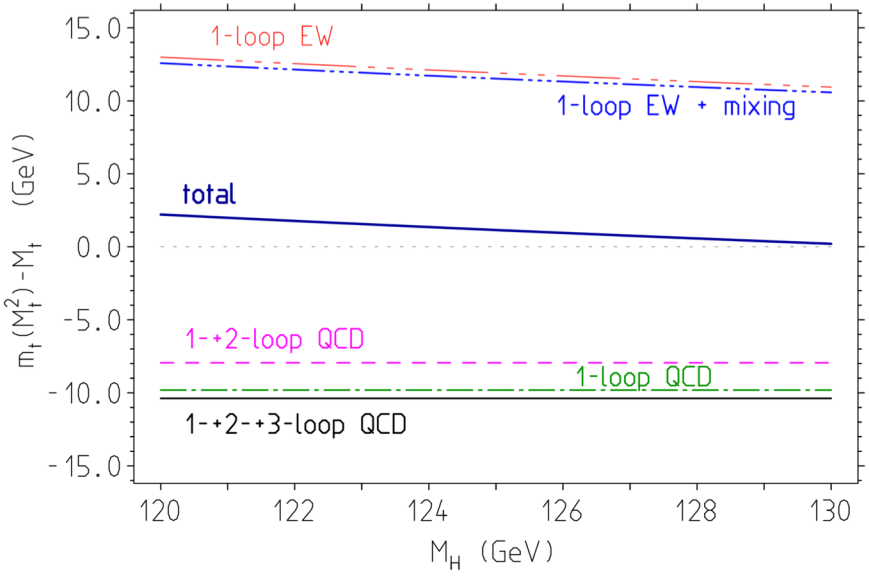


Table 1: The various contributions to $m_t(M_t^2) - M_t$ in GeV.

M_H [GeV]	$O(\alpha)$	$O(\alpha\alpha_s)$	$O(\alpha)+O(\alpha\alpha_s)$	$O(\alpha_s)+O(\alpha_s^2)+O(\alpha_s^3)$	total
124	12.11	−0.39	11.72	−10.38	1.34
125	11.91	−0.39	11.52	−10.38	1.14
126	11.71	−0.38	11.32	−10.38	0.94

Jegerlehner, Kalmykov, Kniehl `12

Renormalons are a proxy for non-perturbative effects

First discussed in the context of soft and collinear radiation for the thrust distribution in electron—positron collisions

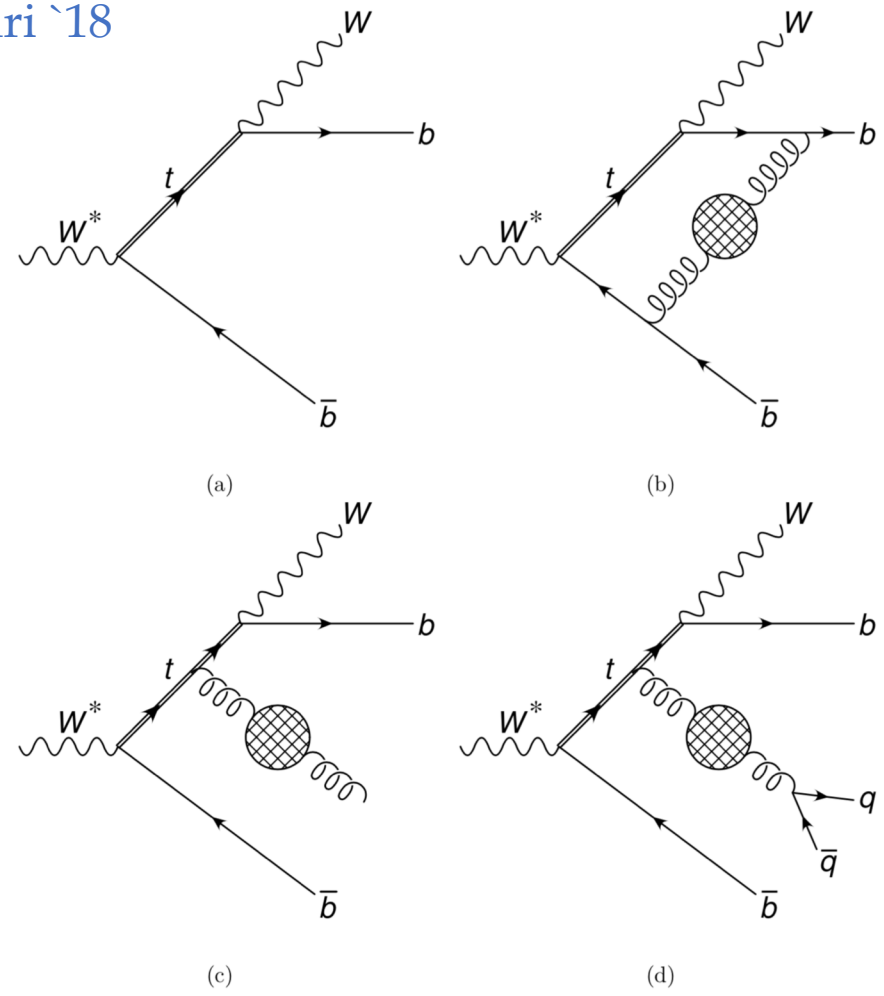
Gardi, Rathsman `01

and higher-twist contributions to deep inelastic scattering

Gardi, Roberts `02

Renormalons are a proxy for non-perturbative effects

Recently revisited in
Ravasio, Nason, Oleari `18



Renormalons are a proxy for non-perturbative effects

Recently revisited in
Ravasio, Nason, Oleari `18

1. total cross section: no infra-red sensitivity if the result is written in terms of short-distance masses; gets reflected in the convergence of perturbative series;

2. jet selection introduces linear infra-red sensitivity (1/R) ; independent of the mass definition used; this is known and anticipated effect; the jet energy/momentum is affected by the hadronization in that way;

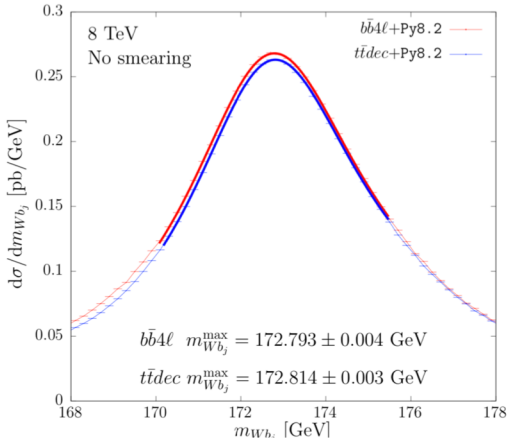
3. W-b invariant mass has linear infra-red sensitivity due to a final state jet, irrespective of the mass definition used;

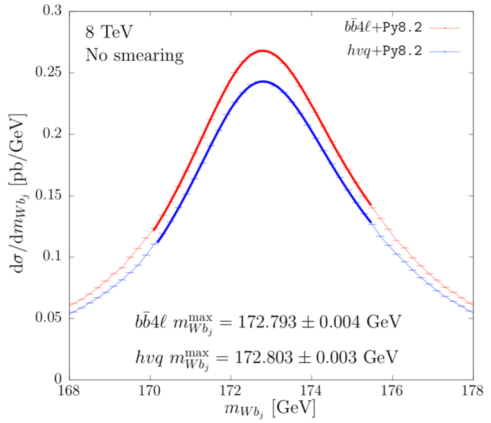
4. Average energy of the W-boson: exhibits linear infra-red sensitivity in the narrow width limit, regardless of the mass used (boost to top rest frame); however, if the calculation is done keeping the width of the top quark, there is no linear infra-red sensitivity in case the short-distance mass is used.

Modelling at hadron colliders

Parton showers matched after decay with NLO precision

Ravasio, Jezo, Nason, Oleari `18





	PS only		full	
	No smearing	smearing	No smearing	smearing
$b\bar{b}4\ell$	172.522 GeV	171.403 GeV	172.793 GeV	172.717 GeV
$t\bar{t}dec - b\bar{b}4\ell$	-18 ± 2 MeV	$+191 \pm 2$ MeV	$+21 \pm 6$ MeV	$+140 \pm 2$ MeV
$hvq - b\bar{b}4\ell$	-24 ± 2 MeV	-89 ± 2 MeV	$+10 \pm 6$ MeV	-147 ± 2 MeV

Table 1: Differences in the $m^{\max}_{Wb_j}$ for m_t=172.5 GeV for $t\bar{t}dec$ and hvq with respect to $b\bar{b}4\ell$, showered with `Pythia8.2`, at the NLO+PS level and at the full hadron level. Results obtained after smearing the m_{Wb_j} distribution with a Gaussian function with a 15 GeV width are also shown in order to mimic effects due to experimental uncertainties.

hvq:
NLO production

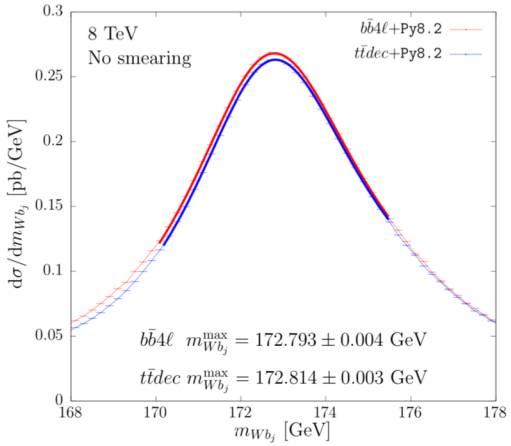
tTdec:
NLO production and decay, narrow width

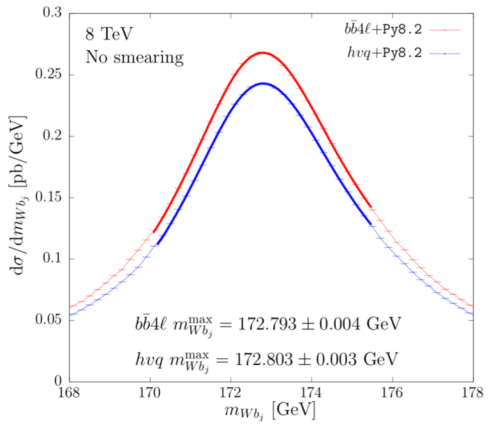
bB4l:
full NLO, off-shell

Modelling at hadron colliders

Parton showers matched after decay with NLO precision

Ravasio, Jezo, Nason, Oleari `18





	No smearing		15 GeV smearing	
	He7.1	Py8.2 − He7.1	He7.1	Py8.2 − He7.1
$b\bar{b}4\ell$	172.727 GeV	$+66 \pm 7$ MeV	171.626 GeV	$+1091 \pm 2$ MeV
$t\bar{t}dec$	172.775 GeV	$+39 \pm 5$ MeV	171.678 GeV	$+1179 \pm 2$ MeV
hvq	173.038 GeV	-235 ± 5 MeV	172.319 GeV	$+251 \pm 2$ MeV

Table 2: m_{Wb_j} peak position for m_t=172.5 GeV obtained with the three different generators, showered with Herwig7.1 (He7.1). The differences with Pythia8.2 (Py8.2) are also shown.

hvq:
NLO production

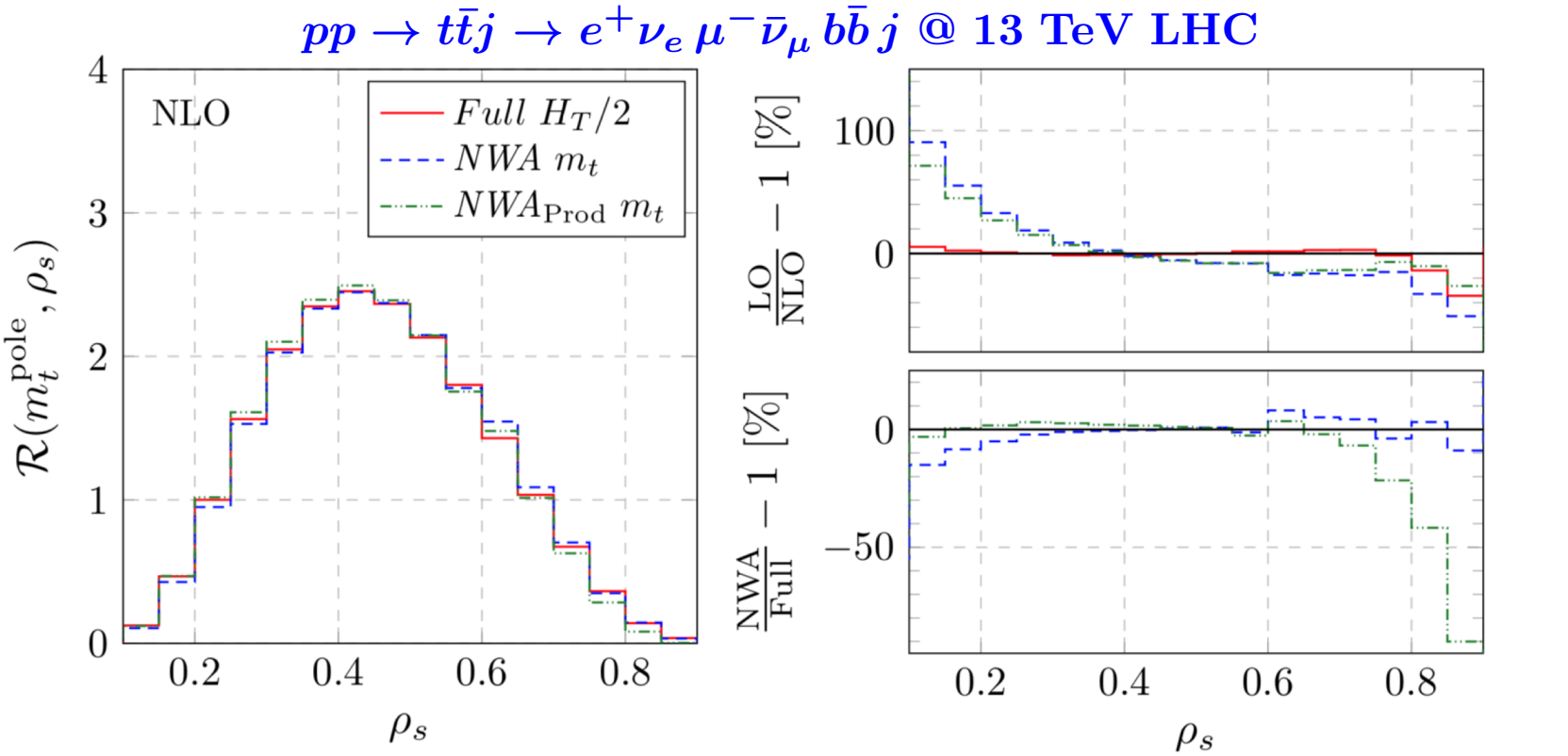
tTdec:
NLO production and decay, narrow width

bB4l:
full NLO, off-shell

Modelling at hadron colliders

Observable used for a recent top quark mass determination

Off-shell, NWA



$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}}{d\rho_s}(m_t^{\text{pole}}, \rho_s) \qquad \rho_s = \frac{2m_0}{M_{t\bar{t}j}}$$

Alioli, Fernandez, Fuster, Irles, Moch, Uwer, Vos '13

Bevilacqua, Hartanto, Kraus, Schulze, Worek '18

Modelling at hadron colliders

2.5 fb^{-1}

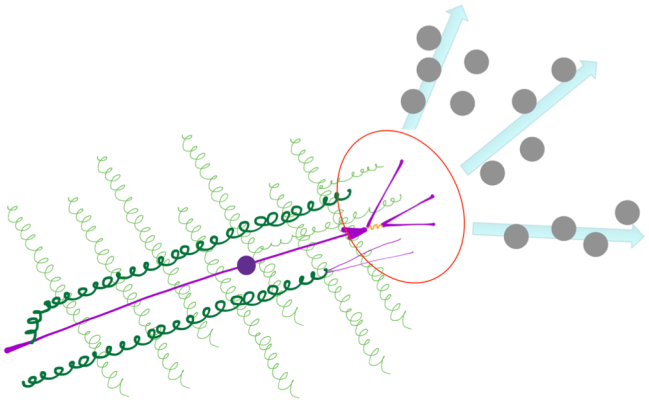
$pp \to t\bar{t}j \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,j$ @ 13 TeV LHC

Theory, NLO QCD CT14 PDF	$m_t^{\rm out} \pm \delta m_t^{\rm out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{\rm in} - m_t^{\rm out}$ [GeV]
31 bins				
Full, $\mu_0 = H_T/2$	173.38 ± 1.34	1.04	0.40 (0.8σ)	-0.18
Full, $\mu_0 = E_T/2$	172.84 ± 1.33	1.05	0.39 (0.9σ)	$+0.36$
Full, $\mu_0 = m_t$	174.11 ± 1.39	1.07	0.37 (0.9σ)	-0.91
NWA, $\mu_0 = m_t$	175.70 ± 0.96	1.17	0.24 (1.2σ)	-2.50
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	169.93 ± 0.98	1.20	0.20 (1.3σ)	$+3.27$
5 bins				
Full, $\mu_0 = H_T/2$	173.15 ± 1.32	0.93	0.44 (0.8σ)	$+0.05$
Full, $\mu_0 = E_T/2$	172.55 ± 1.18	1.07	0.37 (0.9σ)	$+0.65$
Full, $\mu_0 = m_t$	173.92 ± 1.38	1.48	0.20 (1.3σ)	-0.72
NWA, $\mu_0 = m_t$	175.54 ± 0.97	1.38	0.24 (1.2σ)	-2.34
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	169.37 ± 1.43	1.16	0.33 (1.0σ)	$+3.83$

Bevilacqua, Hartanto, Kraus, Schulze, Worek '18

Modelling at hadron colliders

- Output of a measurement using Monte Carlo event generators is function of the pole mass



$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_m^{\mathrm{pert}} + \Delta_m^{\mathrm{non-pert}} + \Delta_m^{\mathrm{MC}}$$

pQCD contribution:

- Perturbative correction
- Depends on MC parton shower setup

Non-perturbative contribution:

- Effects of hadronization model
- May depend on parton shower setup

Monte Carlo shift:

- Contribution arising from systematic MC uncertainties
- E.g. color reconnection, b-jet modeling, finite width, ...
- Should be covered by 'MC uncertainty' or better negligible

- Study the effects by comparison of an event generator and analytic QCD predictions in a controlled environment

- For example lepton collider in boosted topologies

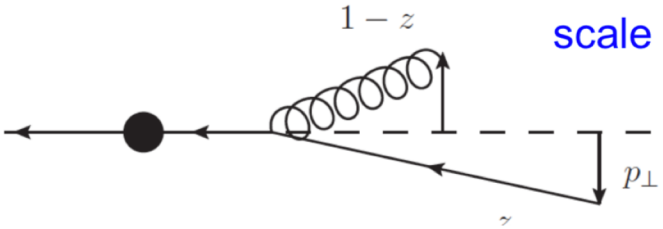
Hoang et al. (ongoing)

Modelling at hadron colliders

- One source of shifts may be due to radiation cutoffs

→ Coherent branching: (basis of the Herwig parton shower)

Catani, Marchesini, Webber 1991
Gieseke, Stephens, Webber, 2003



scale in α_S: $\mu^2 = p_\perp^2 + (1-z)^2 m^2$ cutoff: $p_\perp^2 > Q_0^2$

Usually not present in analytic QCD !

$$m_t^{\rm CB}(Q_0) = m_t^{\rm pole} - \frac{2}{3} Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s(Q_0)^2)$$

"Coherent-branching mass" is here the "Monte Carlo mass"

Herwig 7: Q_0 = 1.25 GeV → $m_t^{\rm Herwig} = m_t^{\rm CB}(1.25\ {\rm GeV})$

Hoang, Plätzer, Samitz `18

Modelling at hadron colliders

- Unanswered question: does this effect persist if matching after decay ?

- Further restrictions of the analysis
  - Boosted top quarks
  - Narrow width approximation
  - Top production (2-jettiness)

- Needed to remove the restrictions
  - Parton shower algorithm for slow tops
  - Parton shower for unstable top quark
  - Factorized predictions including top decay

Conclusions

- Direct measurements of the top-quark mass can be interpreted in terms of the pole mass

- While not necessary at present, it is possible to directly determine a short distance mass
  - This is easy for specific observables by re-expanding theory predictions in the on-shell scheme in terms of a different mass parameter
  - This is difficult using parton showers, since the underlying differential fixed-order prediction is given in function of the on-shell mass

- Ambiguities of parton shower modelling may and should be studied further