The Top Quark Mass
- Theoretical Aspects -

André H. Hoang

University of Vienna

∫dk Π Doktoratskolleg Particles and Interactions

universität wien

FWF Der Wissenschaftsfonds.

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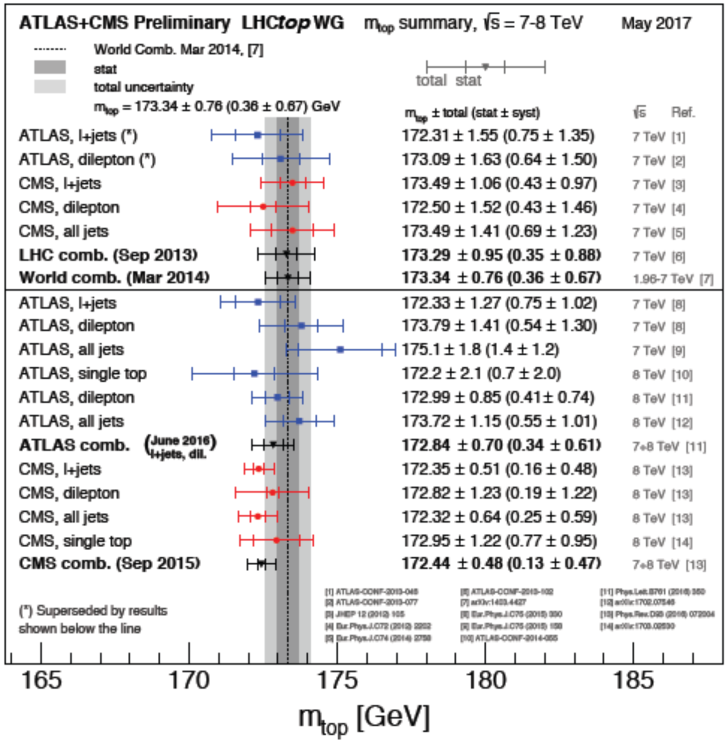
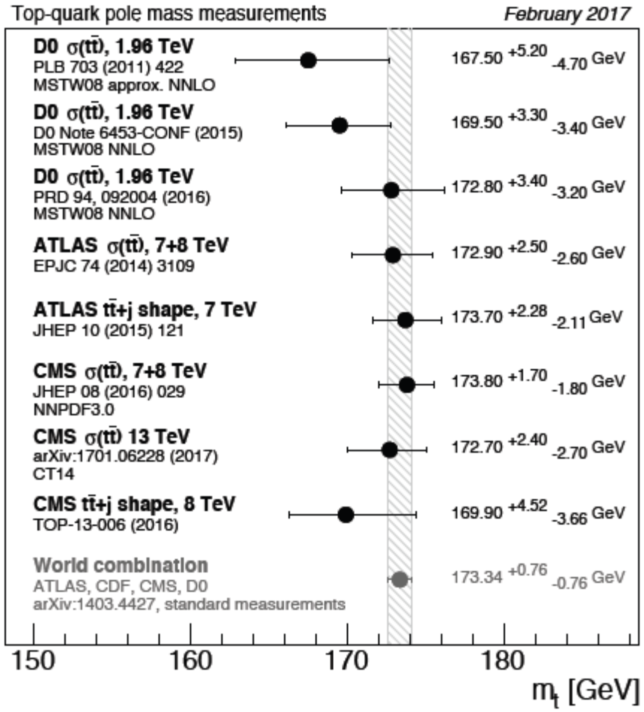
Content

- Introduction / status of experimental top mass determinations
- Recent theoretical work
- Reminder why the issue is non-trivial / controversial
- Recent quantitative studies of the generator top quark mass
- Shower cut in angular ordered parton showers
- Conclusions

Status of Top Mass Measurements





- Most precise measurements from direct reconstruction (uncertainties < 1 GeV):

  → m_t^{MC} measurements

- Less precise measurements based on NLO and NNLO pQCD calculations of **σ**(tt, ttj):

  → “pole mass measurements”, but uncertainties larger than for direct method

- Alternative methods (M_{Bl}, M_{bl}, E_B, $E_{l,}$, T_2, ..):

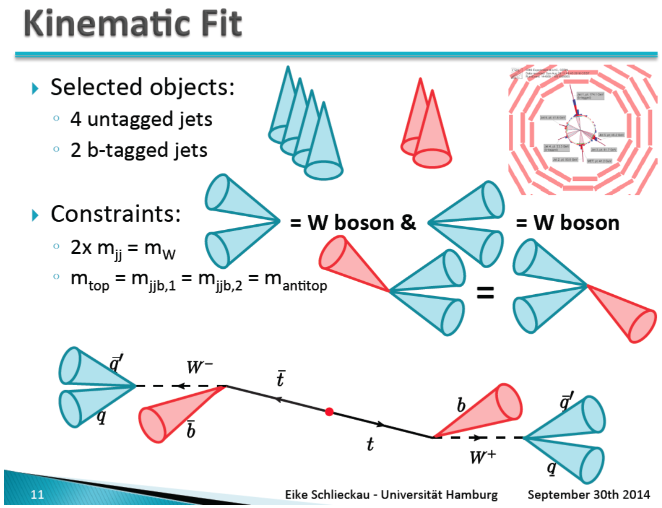
  → Simulations studies indicate: All result in uncertainties larger than for direct method

Direct Measurement

Most precise method: Direct Reconstruction

kinematic mass determination

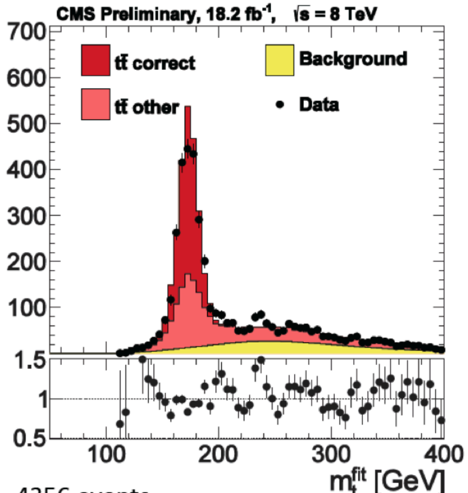
Determination of the best-fit value of the Monte-Carlo top quark mass parameter m_t^{MC}



Kinematic Fit

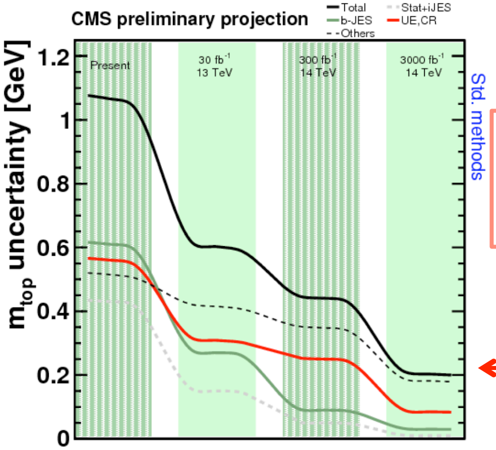
- Selected objects:
  - 4 untagged jets
  - 2 b-tagged jets
- Constraints:
  - 2x $m_{jj} = m_W$
  - $m_{top} = m_{jjb,1} = m_{jjb,2} = m_{antitop}$

CMS-PAS-TOP-14-002



4356 events

- ⊕ High top mass sensitivity
- ⊕ Mass closely related to pole of top propagator



- ⊖ Precision of MC ?
- ⊖ Meaning of m_t^{MC} ?

$$m_t^{MC} = 174.34 \pm 0.64 \quad \text{(Tevatron final, 2014)}$$
$$m_t^{MC} = 172.44 \pm 0.49 \quad \text{(CMS Run-1 final, 2015)}$$
$$m_t^{MC} = 172.84 \pm 0.70 \quad \text{(ATLAS Run-1 final, 2016)}$$

← $\Delta m_t \sim 200$ MeV (HL-LHC projection)

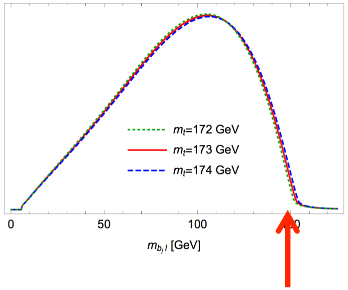
Recent Work

Ravasio, Jezo, Nason, Oleari, arXiv: 1801.03944 (m_t^{MC} from direct reconstruction)

- POWHEG study: NLO corrections in various approximations (production, decay, full off-shell) leads to small numerical differences ($hva,\ t\bar{t}dec,\ b\bar{b}4\ell$)
- Numerical effects on the observed end point (e.g. peak position of reconstr. inv. Mass) MC dependent (Pythia (smaller) compared to Herwig (larger))

Corcella, Franceschini, Kim, arXiv: 1712.05801 (m_t^{MC} from alternative methods)

- Dependence of m_t^{MC} determination from kinematic decay distributions on fragmentation parameters in Pythia 8 and Herwig 6
- Hadronization model parameters cannot be determined precise enough such that alternative fragmentation based methods (exclusive observables, m_{Bl}, E_B) can compete with direct mass measurements.
- **Endpoints not sensitive to hadronization model** variations (fragmentation)



Heinrich, Maier, Nisius, Schlenk, Schulze, Winter: 1709.08615 (alternative methods)

- Effects of off-shell top production compared to narrow width approximation ($M_{j_b\ell}$)
- Effects related to off-shell effects as large as 0.5 − 1 GeV for m_t^{MC} determination

Monte-Carlo Top Quark Mass Parameter

Why is there an non-trivial issue in the the interpretation of m_t^{MC} ?

- Picture of **"top quark particle"** does not apply (non-zero color charge!)
  - m_t is a scheme-dependent parameter of a perturbative computation

    → In which scheme do MC event generators calculate ?
  - **Hadronization effects** (affect all methods in a similar way, particularly important for direct method)
  - **Relation of m_t^{MC} to any field theory mass** definition can be affected by different contributions: (let's consider pole mass just for convention)

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

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

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

  - There is general agreement that Δ_m^{pert} and , $\Delta_m^{\text{non-pert}}$ can exist, but has been a controversy how important and relevant they are.

    Discussions have been qualitative over many years:

    View B: Δ_m's can be at the level of 0.5 GeV, $\Delta_m^{\text{pert}} \sim Q_0\, \alpha_S(Q_0)$ [Q_0 = shower cut]

    AHH, Stewart, arXiv;:0808.0222; AHH. arXiv:1412.3649

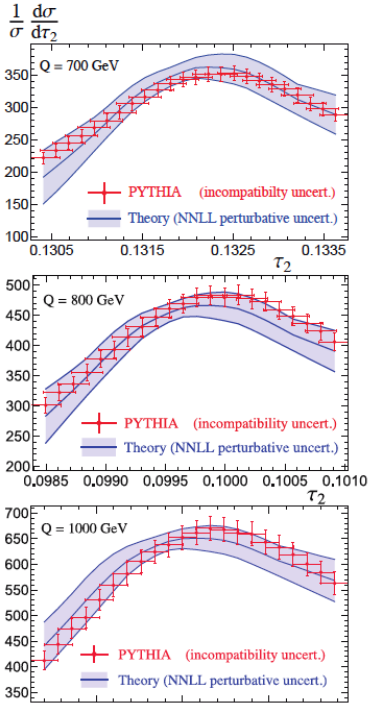
    View C: Δ_m^{pert} likely negligible, $\Delta_m^{\text{non-pert}} \sim \Delta_{\text{QCD}}$ Nason, arXiv:1712.02796

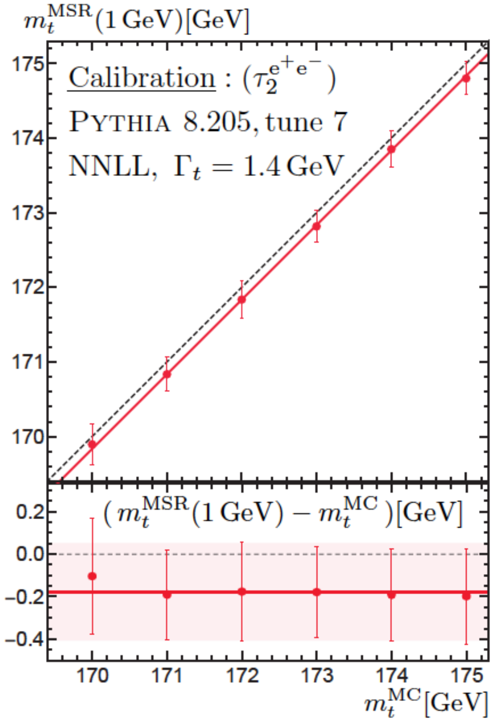
Monte-Carlo Top Quark Mass Parameter

Quantitative examinations of m_t^{MC}

- Butenschoen, Dehnadi, Hoang, Mateu, Preisser, Stewart (2017), arxiv:1608.01318
  - ► numerical relation between Pythia MC top mass and MSR mass using 2-jettiness in e^+e^- in the resonance region from calibration fits
  - ► $m_t^{\mathrm{MC}} = m_t^{\mathrm{MSR}}(1\,\mathrm{GeV}) + (0.18 \pm 0.22)\,\mathrm{GeV}$ $\qquad m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + (0.57 \pm 0.28)\,\mathrm{GeV}$
  - ► universality conjectured but not proven

- Fits of NNLL+NLO+had.corr. theory predictions with Pythia 8.205
- Good agreement between Pythia and analytic calculation
- **“MC top mass calibration”**

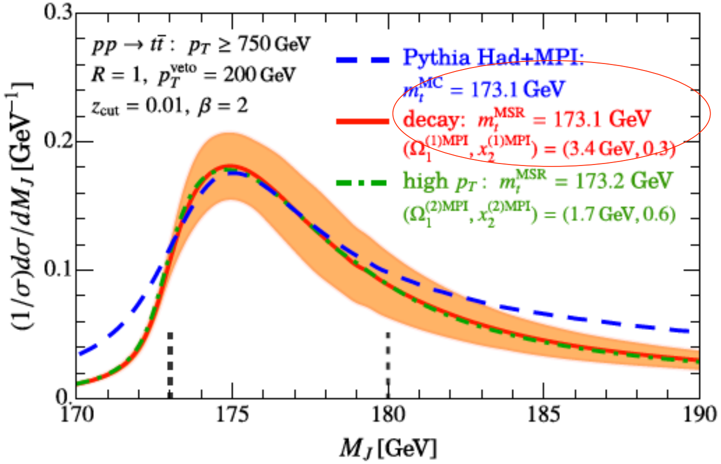




Monte-Carlo Top Quark Mass Parameter

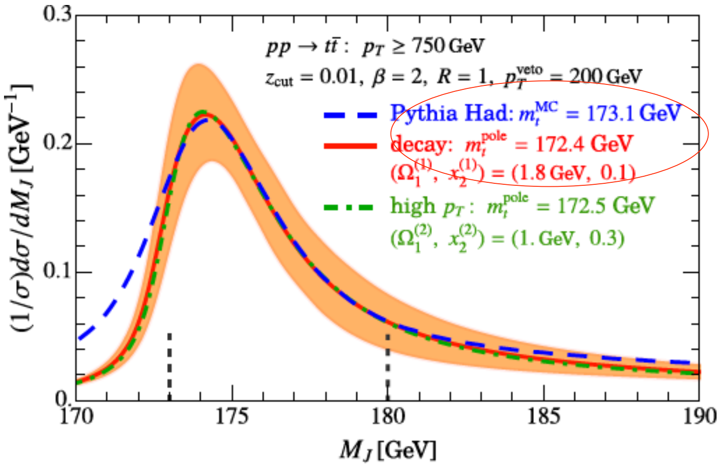
Quantitative examinations of m_t^{MC}

- Hoang, Mantry, Pathak, Stewart (2017), arxiv:1708.02586
  - ▶ extension of the framework to groomed jet masses at the LHC for boosted top quarks
  - ▶ results consistent with e^+e^- calibration
  - ▶ full calibration analysis still to be done



- Comparison of NLL+had.corr. theory predictions with Pythia 8.205

- Good description of Pythia output.



e^+e^- Calibration Result: Top Width Dependence

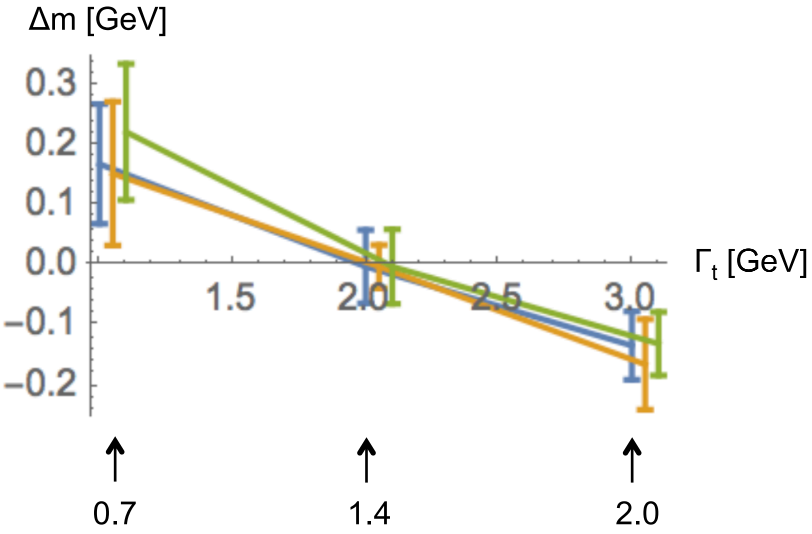
Plätzer, Preisser, Samitz, AHH, w.i.p.

Top width dependence

$$\Delta m = m_t^{MSR}[\Gamma_t] - m_t^{MSR}[\Gamma_t=1.4]$$

$\alpha_S(M_Z)=0.118$

$m_t^{MC}=173$



- Sensitivity to top width value.

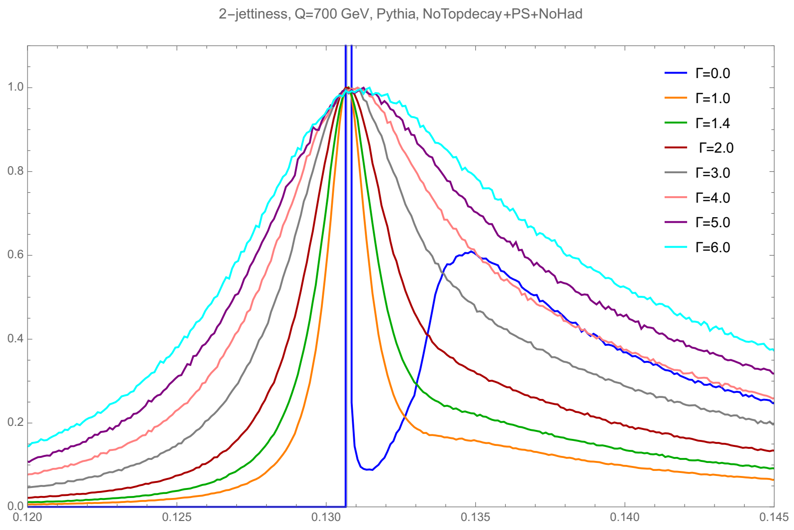
- Pythia resonance peak position does not depend on value of Γ_t
- Theory resonance peak position increases with Γ_t

- Three colors: tunes 1, 3, 7
- Error bars: standard deviation of best mass value distribution in 500 profile function fits

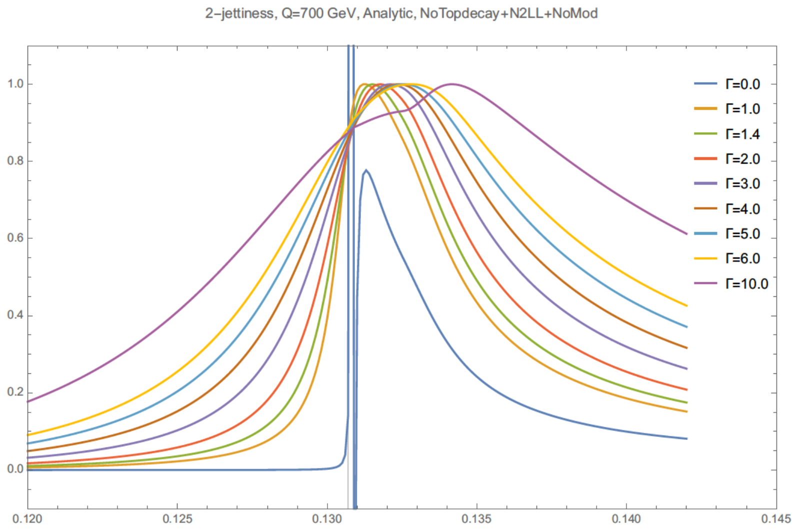
Top Resonance: factorization vs. Pythia

Plätzer, Preisser, Samitz, AHH, w.i.p.

Pythia



QCD Factorization



→ **Pythia does not describe the top width dependence in a way compatible with theory.**

→ MC generators themselves need to be scrutinized and understood thoroughly in order to fix the relation of the MC top quark mass to field theory masses.

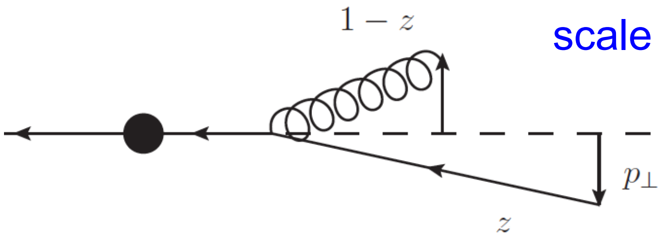
$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} \boxed{+ \Delta_m^{\mathrm{pert}} + \Delta_m^{\mathrm{non-pert}} + \Delta_m^{\mathrm{MC}}}$$

Numerical calibration
cannot distinguish the
three contributions

Cutoff in Angular Ordered Parton Showers

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

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



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

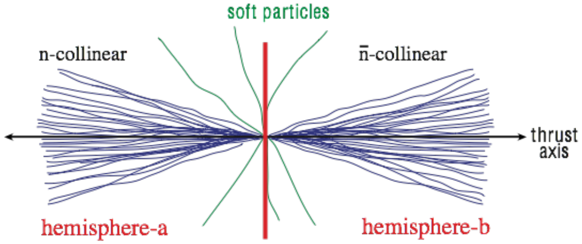
↑

Usually not present in analytic QCD !

2-Jettiness τ_2 distribution In the peak region (for e^+e^- and boosted tops) can be analytically computed in QCD factorization (SCET) at NLL+NLO and coherent branching (CB).

Fleming, Mantri, Stewart, AHH, 2007

$$\left(\frac{d^2\sigma}{dM_t^2\,dM_{\bar t}^2}\right)_{\text{hemi}} = \sigma_0\, H_Q(Q,\mu_m)\, H_m\!\left(m,\frac{Q}{m},\mu_m,\mu\right) \times \int_{-\infty}^{\infty} d\ell^+ d\ell^-\, B_+\!\left(\hat{s}_t-\frac{Q\ell^+}{m},\Gamma,\mu\right) B_-\!\left(\hat{s}_{\bar t}-\frac{Q\ell^-}{m},\Gamma,\mu\right) S_{\text{hemi}}(\ell^+,\ell^-,\mu)$$



↑ Ultra-collinear radiation

↑ Large-angle soft radiation

Plätzer, Samitz, AHH; arXiv:1807.06617

Cutoff in Angular Ordered Parton Showers

Δ_m^{pert} can be systematically examined at $\mathcal{O}(\alpha_S)$ for $\boldsymbol{\tau}_2$ in the resonance region:

- Parton level (with common shape function)
- Boosted top quarks (factorization and shower algorithm reliable)
- Narrow width approximation (no systematic shower algorithm for non-res. effects)

$\underline{Q_0=0 :}$ (strict perturbation theory in $\alpha_S(Q)$)

- Equivalence of CB and SCET at NLL order for $Q_0=0$ (massive quark case new!)
- Generator mass m_t is the pole mass m_t^{pole}

But MC parton showers require $Q_0 \gtrsim 1$ GeV, so it is mandatory to include the finite shower cut !

Plätzer, Samitz, AHH; arXiv:1807.06617

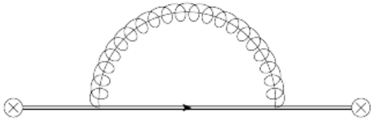
Cutoff in Angular Ordered Parton Showers

Plätzer, Samitz, AHH; arXiv:1807.06617

Q_0>0 :

- Pole of the top quark propagator = $m_t^{CB}(Q_0) \neq m_t^{pole}$ (**coherent branching mass**)

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



- In the presence of the shower cut the **ultra-collinear radiation** generated by CB produces exactly the mass scheme change correction that is required so that the generator mass is exactly the coherent branching mass $m_t^{CB}(Q_0)$.

$$\sigma(m_1, Q, \ldots) = \sigma(m_2, Q, \ldots) + \delta m \times \frac{\mathrm{d}}{\mathrm{d}m} \sigma(m, Q, \ldots)\Big|_{m=m_1} + \ldots$$

$$\delta m = m_2 - m_1$$

Scheme change correction

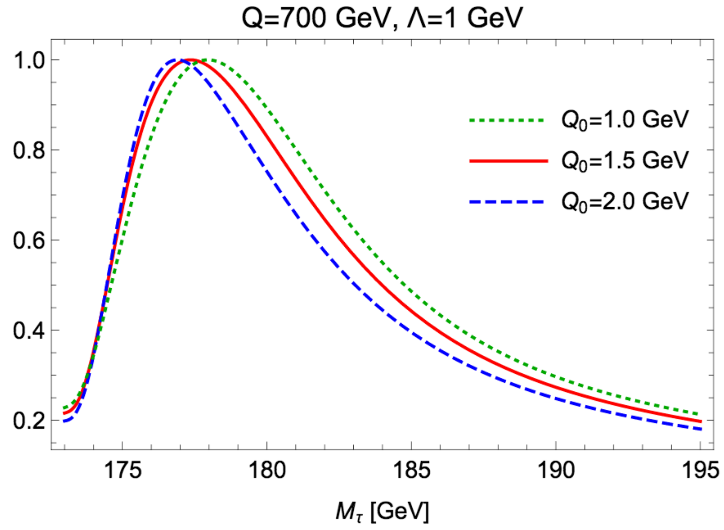
- The shower cut also affects **large-angle soft radiation.** The corresponding effects are directly tied to the amount of hadronization effects that are fixed by tuning

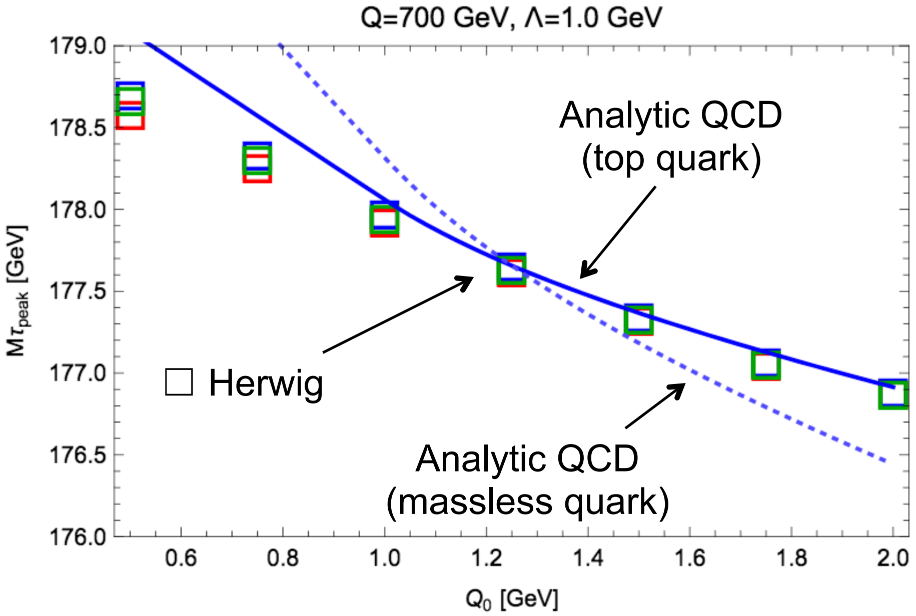
- All conclusions explicitly cross checked by correspondence between analytic QCD factorization calculations and analytic solutions of the CB algorithm.

Q_0 Dependence: Herwig vs analytic QCD

Peak position of $M_\tau = \dfrac{Q^2\tau_2}{2m_t} \quad (Q = E_{\mathrm{cm}})$

- Depends on value of Q_0 (while keeping hadronization effects unchanged)
- Relative Q_0 dependence of hadronization and the top mass depends on Q





- Herwig simulations in full agreement with analytic calculation for CB algorithm
- M_{bl} endpoint and M_{bW} resonance position show compatible Q_0 behavior.

Plätzer, Samitz, AHH; arXiv:1807.06617

Relation of $m_t^{CB}(Q_0)$ to other Masses

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

MSR Mass

$$m_t^{\text{MC}} = m_t^{\text{CB}}(Q_0) = m_t^{\text{pole}} - \frac{2}{3} Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2) = m_t^{\text{pole}} - 0.67\, Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2)$$

$$m_t^{\text{MSR}}(Q_0) = m_t^{\text{pole}} - \frac{4}{3\pi} Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2) = m_t^{\text{pole}} - 0.42\, Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2)$$

$$\rightarrow\ m_t^{\text{MSR}}(Q_0) - m_t^{\text{CB}}(Q_0) = 0.24\, Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2)$$

$$\boxed{m_t^{\text{MSR}}(Q_0) - m_t^{\text{CB}}(Q_0) = (0.190 \pm 0.070)\ \text{GeV}}$$

$$\alpha_S^{\overline{\text{MS}}}(M_Z) = 0.118$$

- CB and MSR masses do not suffer from the $O(\Lambda_{QCD})$ renormalon → good convergence
- Uncertainty estimated from difference between α_s in $\overline{\text{MS}}$ and MC schemes
- MSR mass can be related to $\overline{m}_t(\overline{m}_t)$ with uncertainty of 15 MeV.

- Precision sufficient for all possible applications at the LHC
- Two-loop corrections to $m_t^{CB}(Q_0)$-m_t^{pole} needed for ILC top quark physics

Relation of $m_t^{CB}(Q_0)$ to other Masses

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

Pole Mass

$$m_t^{\text{MSR}}(Q_0) - m_t^{\text{CB}}(Q_0) = (0.190 \pm 0.070)\ \text{GeV}$$

$$m_t^{\text{pole}} - m_t^{\text{MSR}}(Q_0) = (0.350 \pm 0.250)\ \text{GeV}$$

Lepenik, Preisser, AHH 2017
[±110 MeV: Beneke, Marquard, Nason, Steinhause 2017]

$$\rightarrow \boxed{m_t^{\text{pole}} - m_t^{\text{CB}}(Q_0) = (0.540 \pm 0.260)\ \text{GeV}}$$

All order relation!

- Pole mass suffers from the $O(\Lambda_{QCD})$ renormalon → irreducible ambiguity 250 MeV
- **Pole mass around 0.5 GeV larger than Herwig top generator mass.**
  Shift as large as current experimental uncertainty from direct methods.

Conclusions / Outlook

- For angular order partons showers (Herwig MC) one can derive the **perturbative** contributions to the relation between generator mass and pole mass (Δ_m^{pert})

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

-

Current Restrictions:	Needed to remove restriction
• Boosted top quarks	• Parton shower algorithm for slow tops
• Narrow width approximation	• Parton shower for unstable top quark
• Top production (2-jettiness)	• Factorized predictions including. top decay

- There are good prospects that all three restriction can be addressed in near future (w.i.p.). But for all three new conceptual developments are required.

- Study of **non-perturbative** contributions to the relation between generator and pole mass ($\Delta_m^{\text{non-pert}}$) can be carried out by dedicated MC simulations (w.i.p.)

- Numerical calibration still important tool for consistency checks.