Progress on Boosted Top Production in SCET

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$\int dk\,\Pi$ Doktoratskolleg Particles and Interactions

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FWF Der Wissenschaftsfonds.

COST Meeting 2020, Cracow, February 11-13, 2020

Content

- Boosted top quarks
  → disentangle production, (single) top evolution and decay
  → basic features of factorization

- Running mass for scales below m_Q: MSR mass $m_t^{MSR}(R)$
  → C++/Mathematica code: REvolver

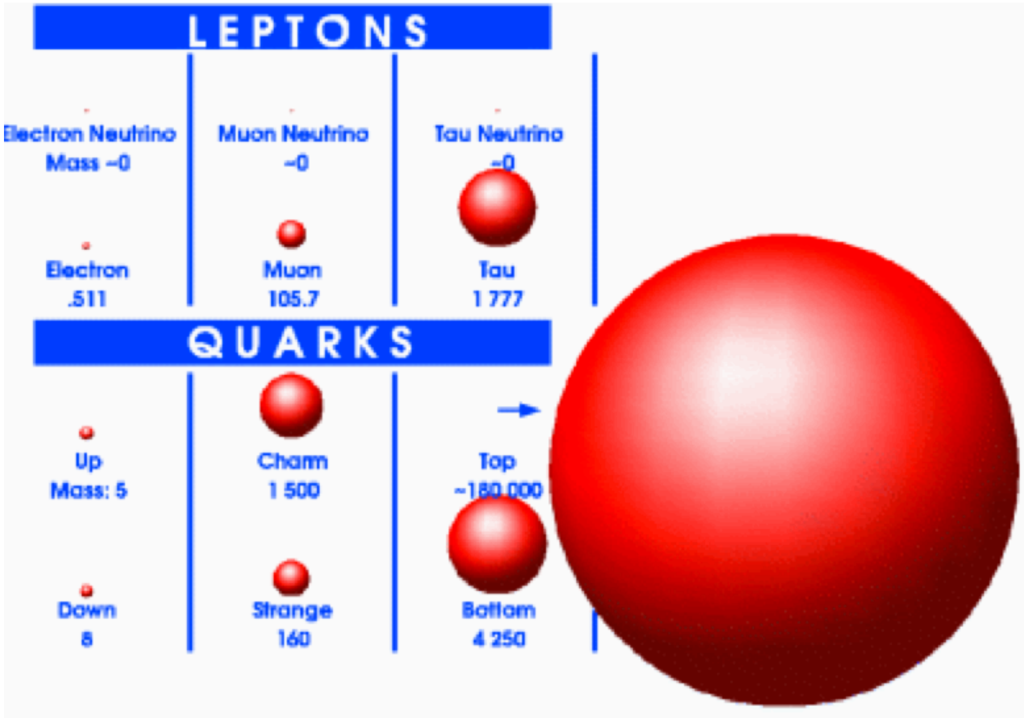
- MC top mass calibration:
  NNNLL + NLO corrections to 2-jettiness for top production in e^+e^- collisions

- First principles studies of Herwig top mass parameter:
  Hadronization model studies

- Conclusions

- Demonstration of REvolver

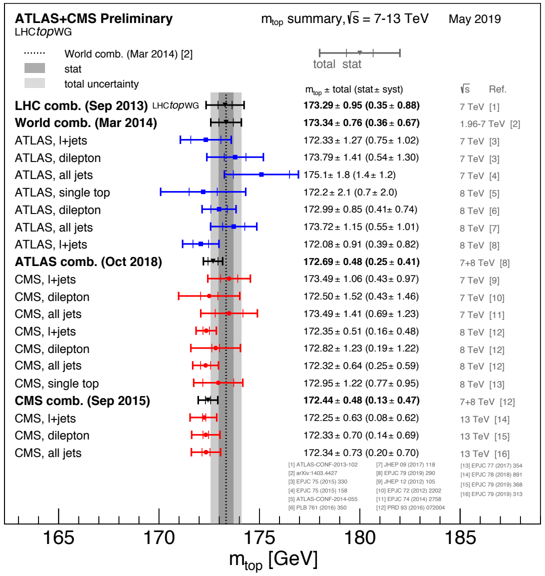
.. not just the heaviest SM particle

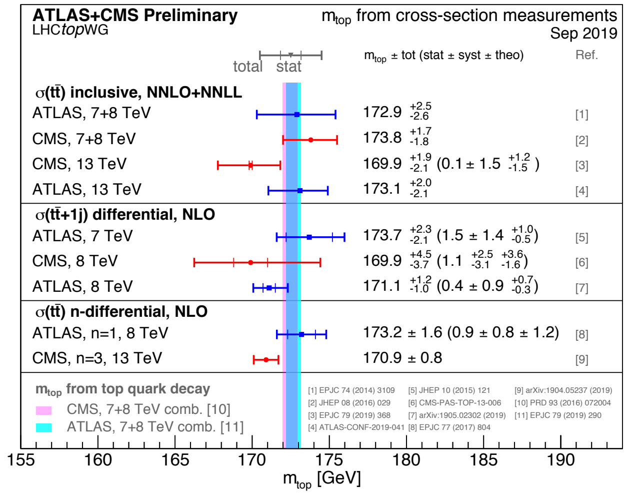


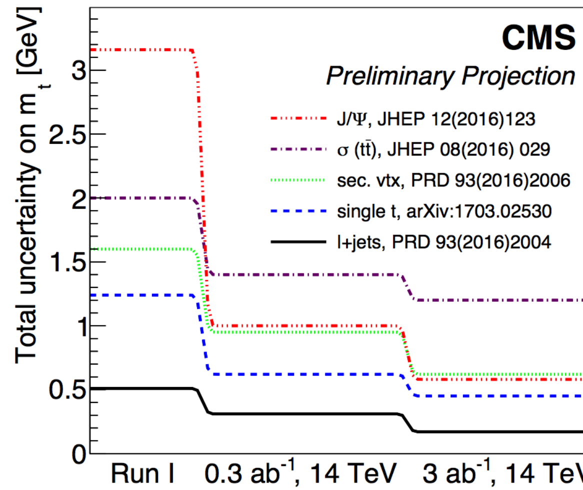
- Top quark: heaviest known particle
- Most sensitive to the mechanism of mass generation
- Peculiar role in the generation of flavor.
- Top might not be the SM-Top, but have a non-SM component.
- Top as calibration tool for new physics particles (SUSY and other exotics)
- Top production major background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

- Very special physics laboratory: $\Gamma_t \gg \Lambda_{QCD}$
  - Top treated a particle: p_T, spin, $\boldsymbol{\sigma}_{tot}$, $\boldsymbol{\sigma}$(single top), $\boldsymbol{\sigma}$(tt+X),.. $\rightarrow q \gg \Gamma_t$
  - Quantum state sensitive low-E QCD and unstable particle effects: m_t, endpoint regions $\rightarrow q \sim \Gamma_t$
  - Multiscale problem: p_T, m_t, Γ_t, Λ_{QCD}, . . . (depends on resolution of observable)

Top Mass Measurements







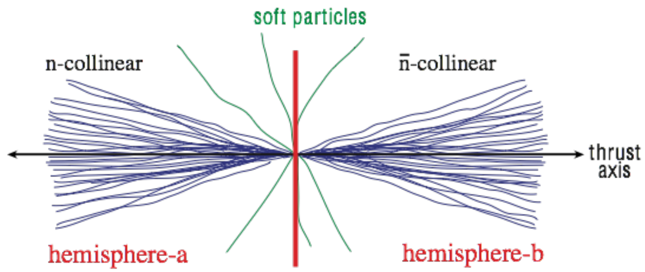
- Most precise measurements from direct reconstruction (uncertainties ~0.5 GeV), but measures MC top mass parameter m_t^{MC}
- Other methods are still less precise, but can measure a field theory top mass.
- Methods based on reconstructed distributions involving top decay products represent delicate multiscale problems: p_T, m_t, Γ_t, Λ_{QCD}
  → perturbation theory insufficient, resummations needed, hadronization at leading order

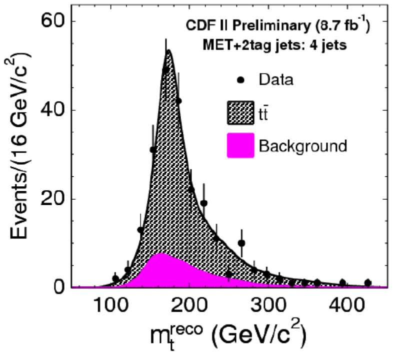
- m_t^{reco}
- $M_{b\text{-jet + lepton}}$
- M_{tt} (close to $2m_t$)
- $M_{J/\psi\text{ + lepton}}$
- M_{T2} and variants
- b-jet energy
- B-meson energy
- $M_{\gamma\gamma}$ (close to $2m_t$)
- Lepton energy endpoints

Factorization for Boosted Top Quarks

Basic event structure:

- Boosted back-to-back (fat) top jets
- Top jets in the resonance region: $M_{J,top} \sim m_t$
- LHC: central top jets: $|\eta_J| \lesssim 1$ (beam separation)
- [Veto on additional hard (gluon) jet]





- Top and ant-top decays separated (interference can be accounted for)
- Soft interactions between jets <u>not sensitive to top decay</u> (top-bottom collinear color line)
- Single-top treatment of top and anti-top decays
- Clean separation of scales: p_T (or E_{cm}) $\gg m_t \gg \Gamma_t \gg \Lambda_{QCD}$
- Factorized cross section:

→ Systematic way to make resumed predictions for top decay sensitive observables.

$$\sigma \sim H_Q \times H_m \times B \otimes D \otimes S$$

"hard" "mass mode" "jet" "decay" "soft"

Factorization for Boosted Top Quarks

- Comes at the cost of smaller statistics at the LHC → not that problematic: see below!
- But clearer theoretically to do systematic predictions with resummation of logarithms and including nonperturbative effects
- Highly useful to answer address subtle high-precision issues such as the direct top mass measurement interpretation problem

CMS, arXiv:1911.03800

CMS-TOP-19-005

CERN-EP-2019-226
2019/11/12

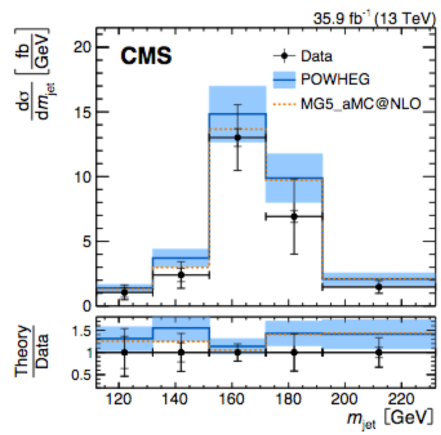
Measurement of the jet mass distribution and top quark mass in hadronic decays of boosted top quarks in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A measurement is reported of the jet mass distribution in hadronic decays of boosted top quarks produced in pp collisions at $\sqrt{s} = 13$ TeV. The data were collected with the CMS detector at the LHC and correspond to an integrated luminosity of 35.9 fb^{-1}. The measurement is performed in the lepton+jets channel of $t\bar{t}$ events, where the lepton is an electron or muon. The products of the hadronic top quark decay $t \to bW \to bq\bar{q}'$ are reconstructed as a single jet with transverse momentum larger than 400 GeV. The $t\bar{t}$ cross section as a function of the jet mass is unfolded at the particle level and used to extract a value of the top quark mass of 172.6 ± 2.5 GeV. A novel jet reconstruction technique is used for the first time at the LHC, which improves the precision by a factor of three relative to an earlier measurement.

Submitted to Physical Review Letters



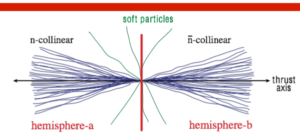
- Groomed X-cone top jets
- 35.9 fb^{-1}, $p_T > 400$ GeV
- $m_t^{MC} = 172.6 \pm 0.4^{stat} \pm 1.6^{exp} \pm 1.5^{model} \pm 1.0^{theo}$ GeV

- Statistics actually not the limiting issue!
- Great potential for higher precision!

Boosted Top Factorization at Resonance

Fleming, AHH, Mantry, Stewart., xxx.xxxx

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



Jet function:

$$B_+(\hat s, \Gamma_t, \mu) = {\rm Im}\left[\frac{-i}{12\pi m_J}\int d^4x\, e^{ir.x}\, \langle 0|\, T\,\{\bar h_{v_+}(0) W_n(0)\, W_n^\dagger(x) h_{v_+}(x)\,\}\,|0\rangle\right]$$

- Soft in the top rest-frame: ULTRA-COLLINEAR
- Perturbative, universal (e^+e^-, LHC)
- dependent on <u>mass, width, color charge</u>
- Contains “Fermi motion” of decaying top quark (analogous to B decays)
- Main top mass sensitivity of production stage dynamics

$$B_\pm^{\rm Born}(\hat s, \Gamma_t) = \frac{1}{\pi m_t}\frac{\Gamma_t}{\hat s^2 + \Gamma_t^2}$$

$$\hat s = \frac{M^2 - m_t^2}{m_t}$$

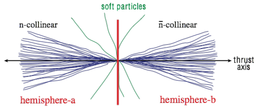
Soft function:

$$S_{\rm hemi}(\ell^+, \ell^-, \mu) = \frac{1}{N_c}\sum_{X_s} \delta(\ell^+ - k_s^{+a})\delta(\ell^- - k_s^{-b})\langle 0|\overline{Y}_{\bar n}\, Y_n(0)|X_s\rangle\langle X_s|Y_n^\dagger\, \overline{Y}_{\bar n}^\dagger(0)|0\rangle$$

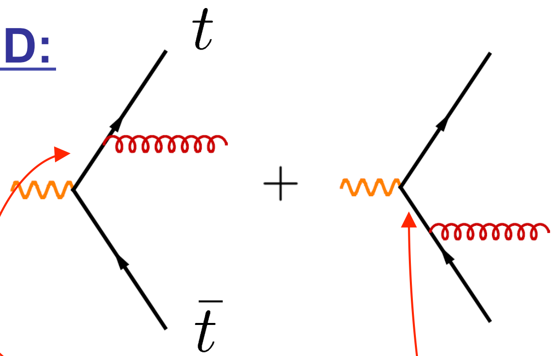
- non-perturbative
- Renormalization scale dependence perturbative
- dependent on <u>color charge, kinematics</u>

Independent of the mass and E_{cm} !

Boosted Top Factorization at Resonance



full QCD:

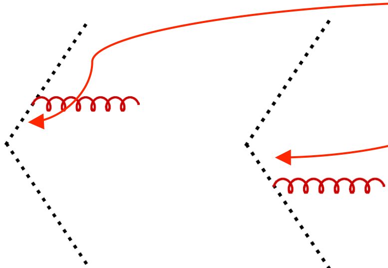


3 phase space regions: $\Lambda \sim \Lambda_{\rm QCD}$

- n-collinear: $(k_+, k_-, k_\perp) \sim (\Lambda, \frac{Q^2}{m^2}\Lambda, \frac{Q}{m}\Lambda)$
- n̄-collinear: $(k_+, k_-, k_\perp) \sim (\frac{Q^2}{m^2}\Lambda, \Lambda, \frac{Q}{m}\Lambda)$
- soft: $(k_+, k_-, k_\perp) \sim (\Lambda, \Lambda, \Lambda)$

$$\frac{1}{(p_{t,\bar{t}}+k)^2 - m_t^2} \qquad (p_{t,\bar{t}}^2 \approx m_t^2\,,\ \ n^2 = 0\,,\ \ \bar{n}^2 = 0)$$

Gluon soft:



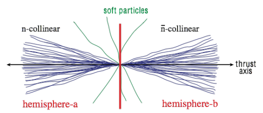
$$\frac{1}{Q\ \ n.k} \qquad \frac{1}{Q\ \ \bar{n}.k}$$

$$Y_n(x) = \overline{\rm P}\ \exp\Big(-ig\int_0^\infty ds\, n\cdot A_s(ns+x)\Big)$$

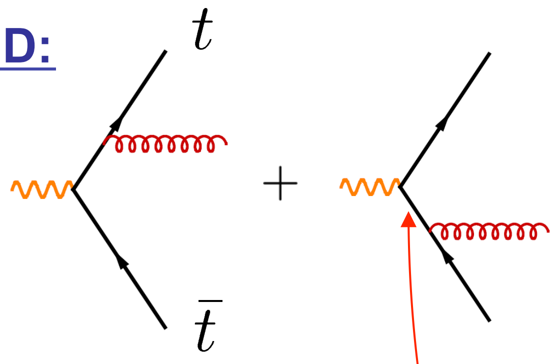
$$\overline{Y_{\bar{n}}}(x) = \overline{\rm P}\ \exp\Big(-ig\int_0^\infty ds\, \bar{n}\cdot \overline{A}_s(\bar{n}s+x)\Big)$$

$$S_{\rm hemi}(\ell^+, \ell^-, \mu) = \frac{1}{N_c}\langle 0|\,(\overline{Y}_n)^{cd}\,(Y_n)^{ce}(0)\,\delta(\ell^- - (\hat{P}_a^+)^\dagger)\delta(\ell^- - \hat{P}_b^-)\,(Y_n^\dagger)^{ef}(\overline{Y}_n^\dagger)^{df}(0)\,|0\rangle$$

Boosted Top Factorization at Resonance



full QCD:



$$\frac{1}{(p_{\bar{t}}+k)^2-m_t^2}$$

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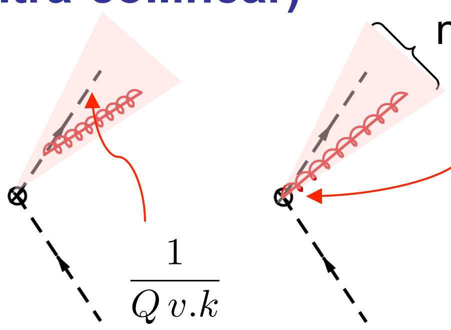
- soft: $(k_+, k_-, k_\perp) \sim (\Lambda, \Lambda, \Lambda)$

$$(p_{\bar{t}}^2 \approx m_t^2\ ,\ \ \bar{n}^2 = 0)$$

Gluon collinear to the top:
(ultra-collinear)



$$\frac{1}{Q\ v.k}$$

$$\frac{1}{Q\ \ \bar{n}.k}$$

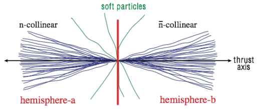
$$W_n^\dagger(\infty, x) = \mathrm{P}\ \exp\left(ig\int_0^\infty ds\bar{n}\cdot A_+(ns+x)\right)$$

$h_{v_+}(x)$ → **gauge dependent**

$W_n^\dagger(\infty, x)\, h_{v_+}(x)$ → **gauge independent**

$$B_+(\hat{s}, \Gamma_t, \mu) \ = \ \mathrm{Im}\left[\frac{-i}{12\pi m_J}\int d^4x\, e^{ir.x}\, \langle 0|\, T\, \{\bar{h}_{v_+}(0) W_n(0)\, W_n^\dagger(x) h_{v_+}(x)\,\}\, |0\rangle\right]$$

Boosted Top Factorization at Resonance



Top mass in the bHQET jet function B:

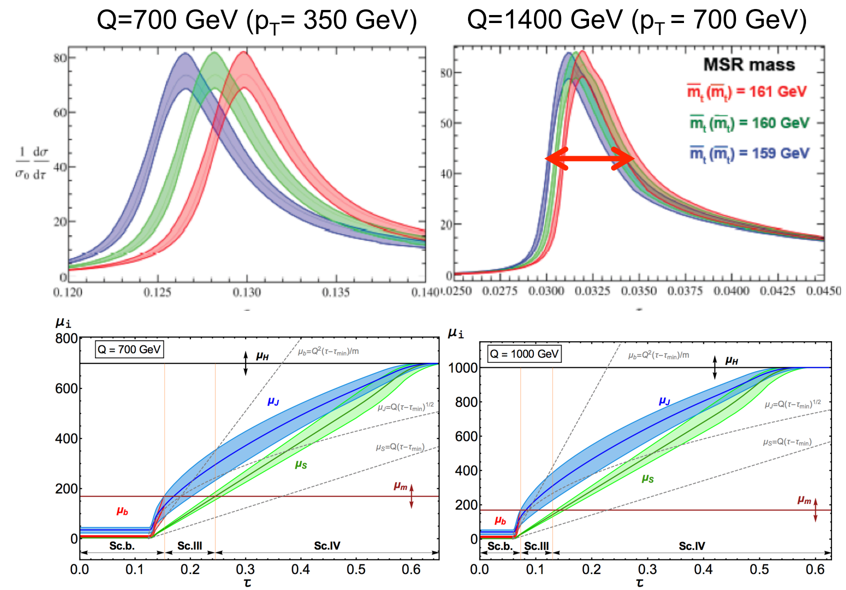
e.g. 2-jettiness distribution in e^+e^-

$$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{n}\cdot\vec{p}_i|}{Q} \qquad \hat{s}_\tau \equiv \frac{Q^2\tau_2 - 2m_t^2}{m_t}$$

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau_2} = m_t\, Q^2 H^{(5,6)}_{\rm evol}(Q, m_t, \upsilon, \mu; \mu_H, \mu_m)$$

$$\times \int d\ell\, d\hat{s}'_\tau\, U_B^{(5)}(\hat{s}_\tau - \upsilon\ell - \hat{s}'_\tau, \mu, \mu_B)\, J^{(5)}_{B,\tau_2}(\hat{s}'_\tau, \Gamma_t, \delta m, \mu_B)$$

$$\times \int d\ell' dk\, U_S^{(5)}(\ell - \ell', \mu, \mu_S)\, \hat{S}^{(5)}_{\tau_2}(\ell' - k, \bar{\delta}, \mu_S)\, F(k, 2\bar{\Delta})$$

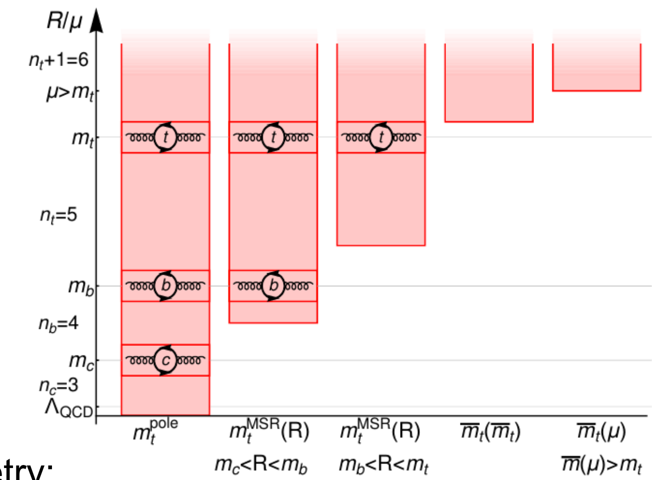


Width of distribution: $\mu_B \sim \frac{Q^2}{m_t}(\tau - \tau_{\rm min}) \ll m_t$

If we want to avoid the pole mass renormalon problem we need a short-distance mass scheme. Short-distance mass schemes always depend on a IR subtraction scale.

In the resonance region we need a short-distance mass $m_t(\mu_B \ll m_t)$

Boosted Top Factorization at Resonance



- Short-distance mass $m_t(\mu)$ only absorbes self energy corrections from scales > μ
- MSbar mass only appropriate for $\mu \gtrsim m_t$
- MSR mass: AHH,Jain, Scimemi, Stewart, 0803.4214
  - Defined from self-energy diagrams
  - Consistent RG-flow for $\mu < m_t$
  - Accounts systematically for lower flavor thresholds
  - Implements universality consistent to heavy quark symmetry:

    t ↔ b ↔ c
  - RG-evolution is linear in μ

MSbar:
$$m_Q^{\rm pole} - \overline{m}_Q = \overline{m}_Q \sum_{n=1}^{\infty} a_n^{\overline{\rm MS}}(n_\ell, n_h) \left(\frac{\alpha_s^{(n_\ell+1)}(\overline{m}_Q)}{4\pi} \right)^n$$

MSR:
$$m_Q^{\rm pole} - m_Q^{\rm MSRn}(R) = R \sum_{n=1}^{\infty} a_n^{\overline{\rm MS}}(n_\ell, 0) \left(\frac{\alpha_s^{(n_\ell)}(R)}{4\pi} \right)^n$$

1 massive quark: 1704.01580

Several massive quarks: 1706.08526

Boosted Top Factorization at Resonance

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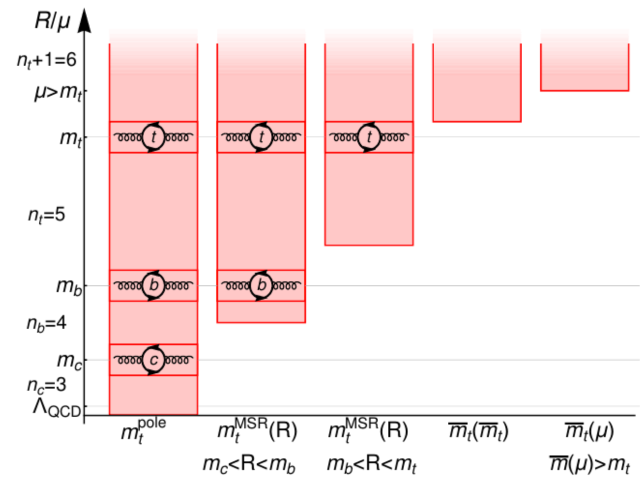
  only absorbes self energy corrections from scales > μ
- MSbar mass only appropriate for $\mu \gtrsim m_t$
- MSR mass:



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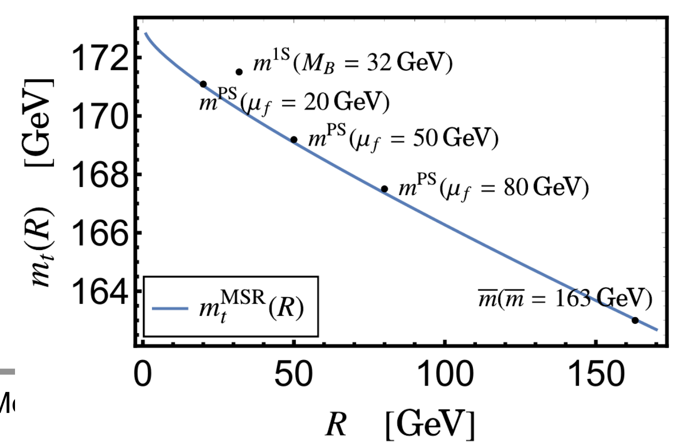
  - Implements universality due to heavy quark symmetry:

    t ↔ b ↔ c
  - RG-evolution is <u>linear in μ</u>

MSbar $$\overline{m}_Q^{(n_\ell+1)}(m_Q) = \overline{m}_Q^{(n_\ell+1)}(\mu)\,\exp\left[-\sum_{k=0}^{\infty}\gamma_{m,k}^{(n_\ell+1)}\int_{\log\mu^2}^{\log m_Q^2} \mathrm{d}\log\bar{\mu}^2 \left(\frac{\alpha_s^{(n_\ell+1)}(\bar{\mu})}{4\pi}\right)^{k+1}\right]$$

MSR: $$m_Q^{\mathrm{MSR}}(m_Q) - m_Q^{\mathrm{MSR}}(R) = -\sum_{n=0}^{\infty}\gamma_n^R \int_R^{m_Q} \mathrm{d}R \left(\frac{\alpha_s^{(n_\ell)}(R)}{4\pi}\right)^{n+1}$$

"R-evolution"



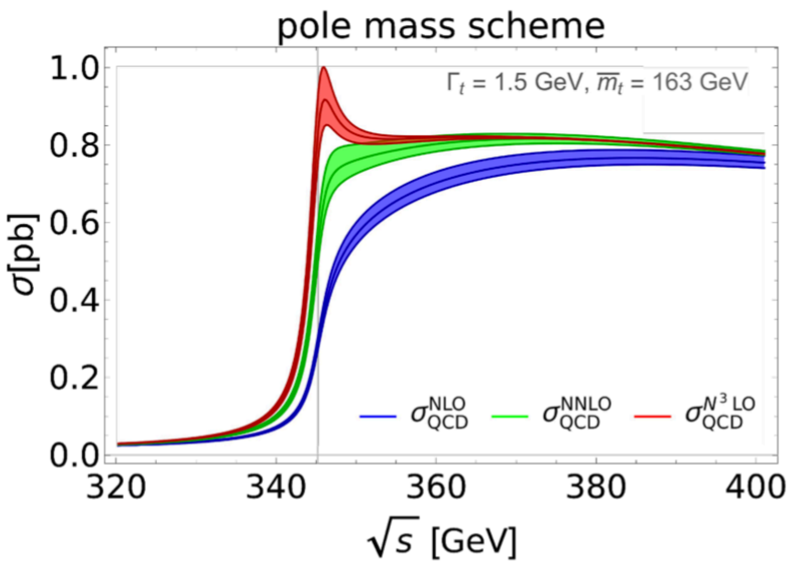
- MSR mass closely related to previously defined
  low scale short-distance masses: 1S, PS, RS,..

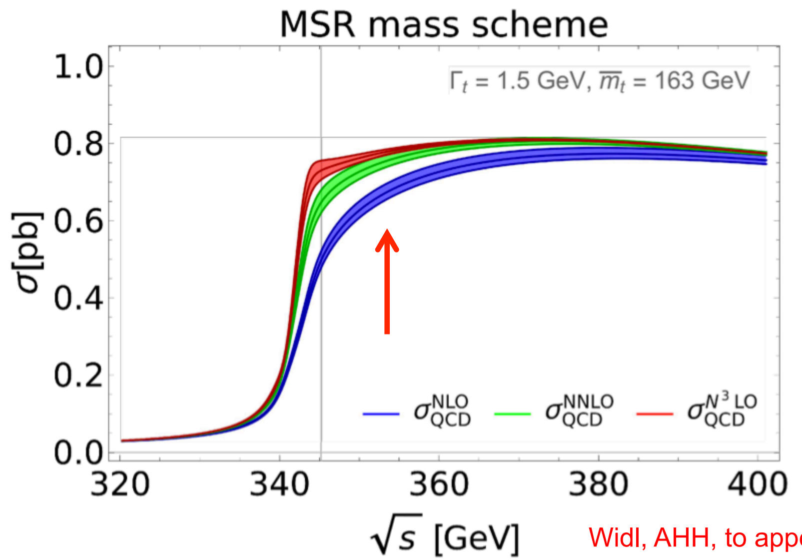
Boosted Top Factorization at Resonance

- MSR mass can reduce the size of corrections in threshold related problems for an appropriate physical choice of scale.

e.g. Total inclusive cross section $\sigma(e^+e^- \to tt + X)$

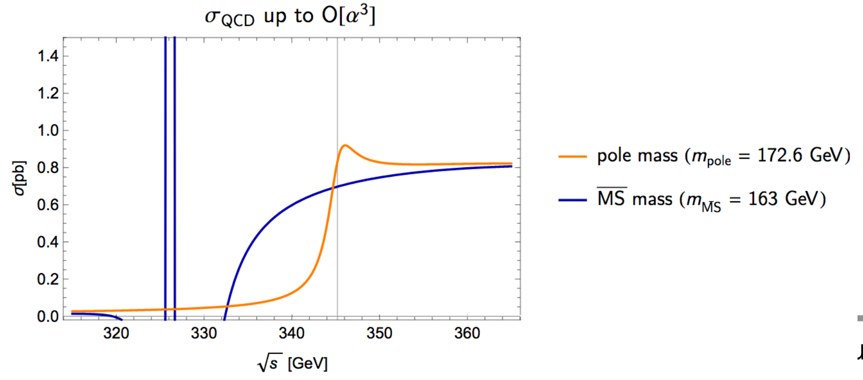
$m_t^{MSR}(R = m_t v)$





Widl, AHH, to appear

Catastrophic results for MSbar scheme:



REvolver

Mateu, Lepenik, AHH, to appear NEW !!

C++/Mathematica code for automated running and matching of masses and couplings in QCD

- Implements all knowledge available for most popular mass schemes:
  MSbar, MSR, 1S, PS, RS, RGI + pole
- Fully automatized RG-evolution (linear and linear)
- Implementation of all flavor threshold effects (top, bottom, charm)
- Full control over all input (order, scale-dependence, parametric input, etc.)
- Core concept to deal with parametric and order-dependent issues (uncertainties)
- Pole mass series implemented to all orders.

Factorization for Boosted Top Quarks

Applications to far:

- e^+e^- 2-jettiness distribution
  - Top MC mass calibration (ungroomed hemisphere jet masses) — Butenschoen etal., 1604.08122
  - Systematic relation between m_t^{MC} and field theory mass schemes (parton level) — AHH, Plätzer, Samitz 1807.06617
  - Consistency of width and hadronization in Pythia and Herwig — AHH, Plätzer, Samitz w.i.p.
  - NNNLL + NNLO corrections in resonance region — AHH, Mateu, Pathak, Stewart, w.i.p.
- Soft-dropped groomed top jet masses at the LHC — AHH, Pathak. Stewart, 1708.02586; AHH, Pathak. Stewart, 1906.11843
  - Top MC mass calibration
  - Structure of nonperturbative effects — AHH, Plätzer, Samitz w.i.p.
- More to come: e.g. lepton energy distribution (semi-leptonic and all-lepton decays)

Main motivation: Improved understanding of top quark mass measurements with high precision, but interesting by itself.

MC Top Quark Mass

- Direct top mass measurements determine the Mont-Carlo top mass parameter.
  → Aim: learn about the relation of m_t^{MC} to field theory renormalization schemes.

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

pQCD contribution:

- Perturbative correction
- Depends on MC parton shower setup
- (Affected by finite width effects?)

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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→ MC top mass calibration for Pythia 8.2

- Boosted (quasi-collinear) top quarks
- 2-jettiness (production stage QCD dynamics only)
- No distinction between the three Δ contributions

Butenschoen etal., 1604.08122

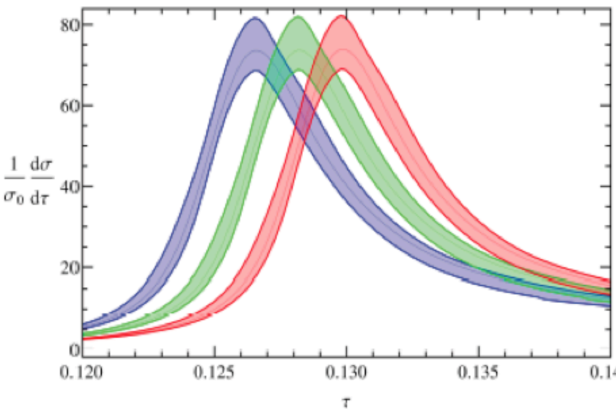
2-Jettiness Distribution at NNLL/NLO

Hadron-level prediction:

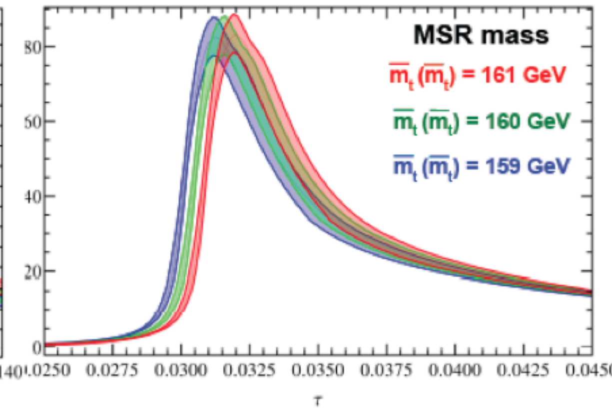
$$\frac{d\sigma}{d\tau_2} = f(m_t^{\mathrm{MSR}}(R), \delta m^{\mathrm{MSR}}, \alpha_s(M_Z), \Omega_1, \Omega_2, \mu_h, \mu_j, \mu_s, \mu_m, R, \Gamma_t)$$

any scheme possible — Non-perturbative — renorm. scales — finite lifetime

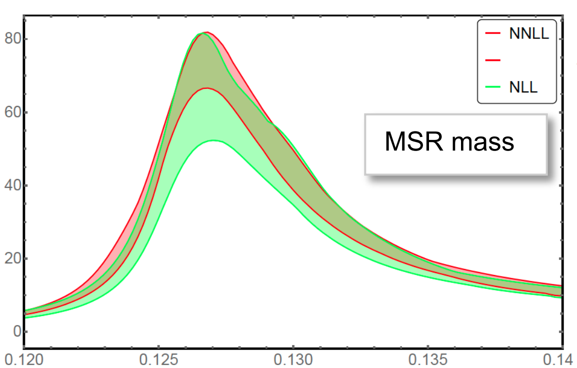
Q=700 GeV (p_T= 350 GeV)



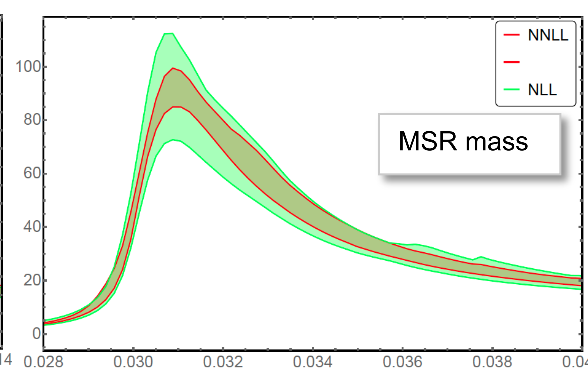
Q=1400 GeV (p_T = 700 GeV)



Q=700 GeV



Q=1400 GeV



- Higher mass sensitivity for lower Q (p_T)
- Finite lifetime effects included
- Dependence on non-perturbative parameters
- Convergence: $\Omega_{1,2,\ldots}$

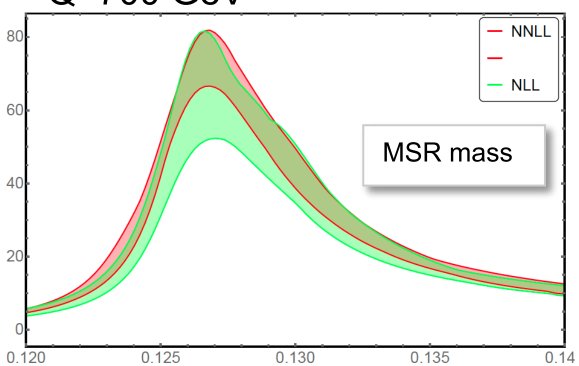
- Good convergence
- Reduction of scale uncertainty (NLL to NNLL)
- Control over whole distribution
- Any mass scheme possible

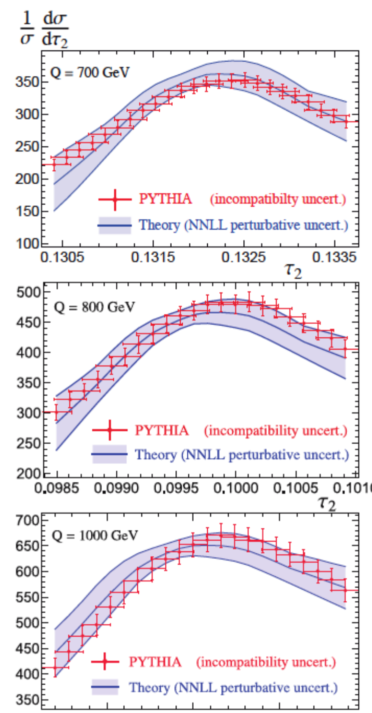
m_t^{MC} Calibration using e^+e^- 2-jettiness

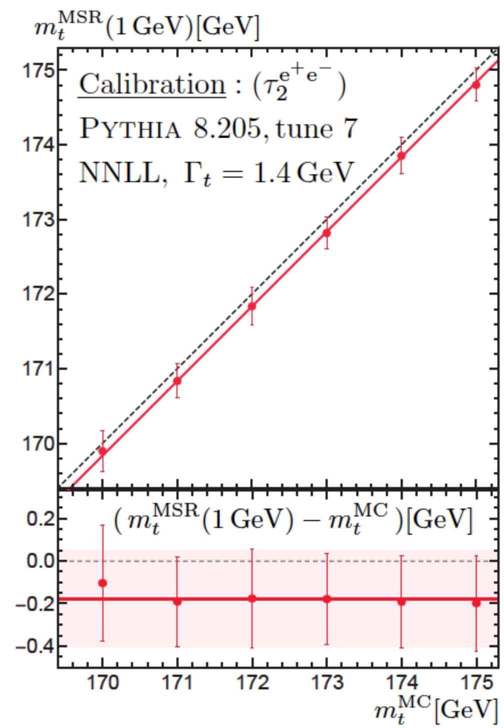
- Butenschoen, Dehnadi, Hoang, Mateu, Preisser, Stewart (2017), arxiv:1608.01318
  - numerical relation between Pythia MC top mass and MSR mass using 2-jettiness in e^+e^- in the resonance region from calibration fits
  - $m_t^{\mathrm{MC}} = m_t^{\mathrm{MSR}}(1\,\mathrm{GeV}) + (0.18 \pm 0.22)\,\mathrm{GeV}$ $\qquad m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + (0.57 \pm 0.28)\,\mathrm{GeV}$

- Fits of NNLL+NLO+had.corr. theory predictions with Pythia 8.205
- Good agreement between Pythia and analytic calculation

Q=700 GeV



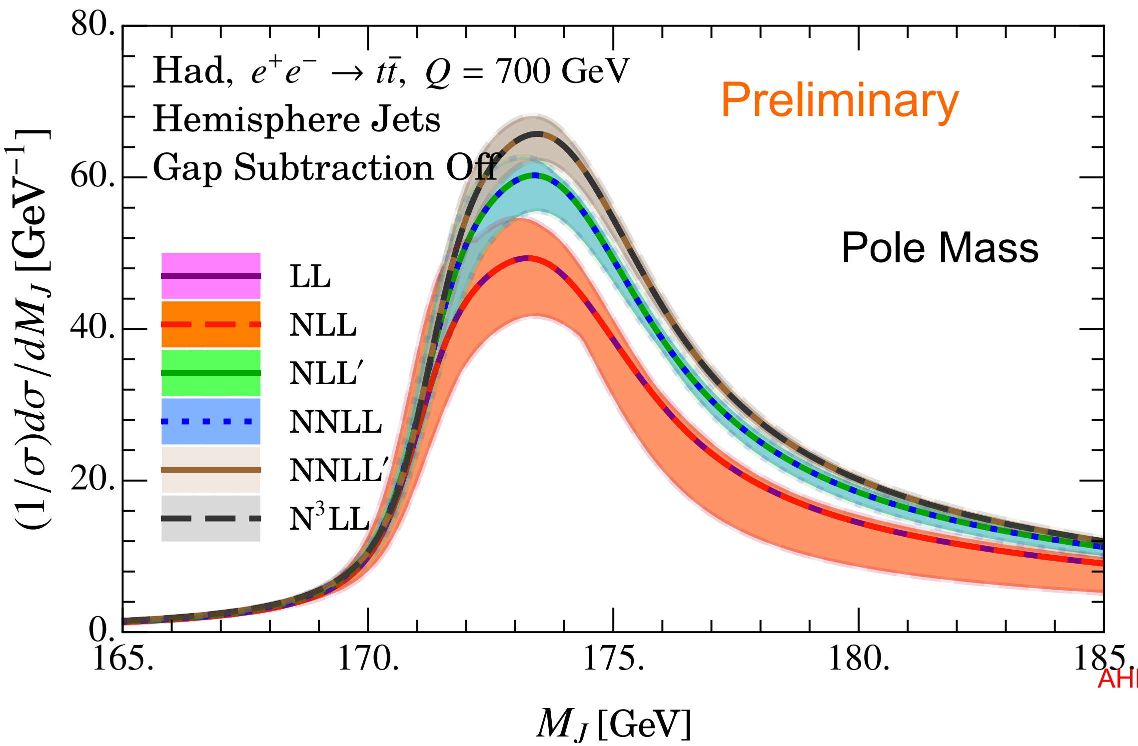




2-Jettiness Distribution at NNNLL/NNLO

- NNLO-FO corrections to hard, mass-mode, soft and jet functions
- NNNLL corrections to all RG – evolution (4-loop cusp and 3-loop non-cusp)
- NNLO SCET jet function to extend away from resonance also known

AHH, Lepenik, Stahlhofen, 1904.12839



AHH, Mateu, Pathak, Stewart., w.i.p.

- Resonant (bHQET) cross section, subleading (~10%) SCET and non-singular corrections still missing.
- Imposing no soft-function gap-subtraction and using the pole mass scheme leads to a reasonable convergence due to a cancellation of renormalon contributions in the soft and the jet function.

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau_2} = m_t\, Q^2 H^{(5,6)}_{\rm evol}(Q, m_t, v, \mu; \mu_H, \mu_m) \times \int d\ell\, d\hat{s}'_\tau\, U^{(5)}_B(\hat{s}_\tau - v\ell - \hat{s}'_\tau, \mu, \mu_B)\, J^{(5)}_{B,\tau_2}(\hat{s}'_\tau, \Gamma_t, \delta m, \mu_B)$$
$$\times \int d\ell' dk\, U^{(5)}_S(\ell - \ell', \mu, \mu_S)\, \hat{S}^{(5)}_{\tau_2}(\ell' - k, \bar{\delta}, \mu_S)\, F(k, 2\bar{\Delta})$$

Fit Result: Top Width Dependence

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

Top width dependence

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

- Clear sensitivity to top width value.

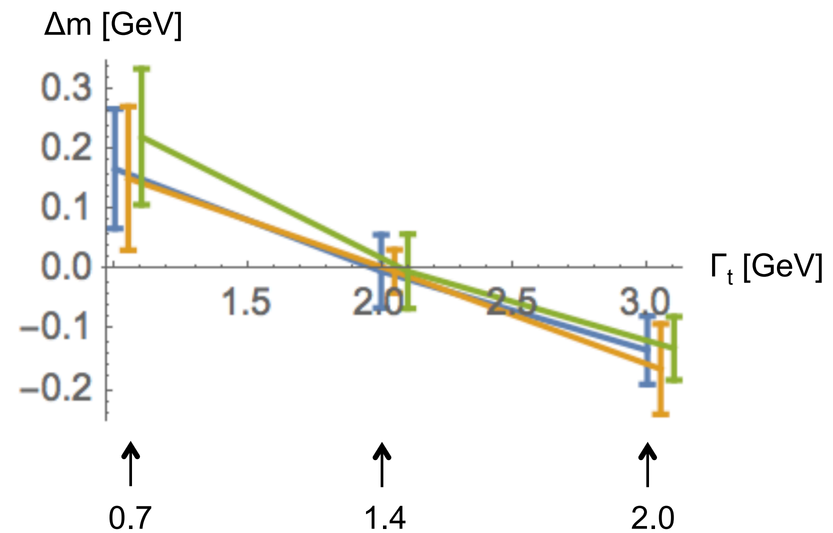
- Pythia resonance peak position does not depend on value of Γ_t
- Theory resonance peak position increases with Γ_t

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

The m_t^{MC} calibration results obtained with Pythia$^{8.205}$ contain a systematic shift related to Pythia's incorrect description of finite-lifetime effects.

$\alpha_S(M_Z)$=0.118

m_t^{MC}=173

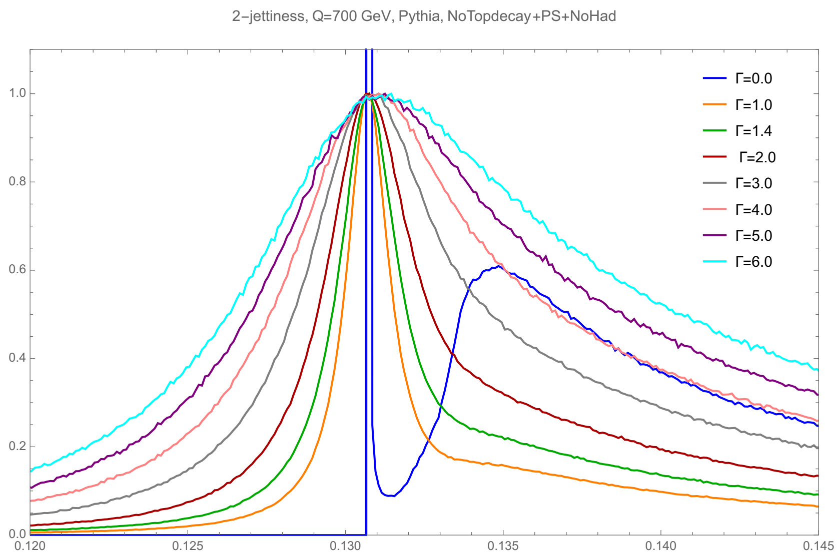


- Three colors: tunes 1, 3, 7
- Error bars: standard deviation of best mass value distribution in 500 profile function fits

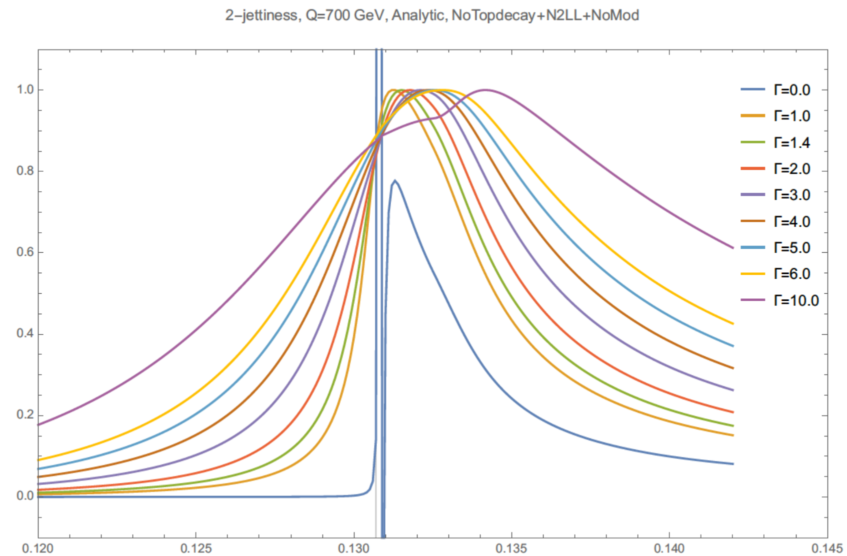
Top Resonance: factorization vs. Pythia

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

Pythia



QCD Factorization



MC generators themselves need to be scrutinized and understood thoroughly when/before addressing the interpretation of the MC top quark mass.

→ Motivation for "On the Shower Cut Dependence of the Quark Mass Parameter in Angular Ordered Parton Showers" (arXiv:1807.06617)

MC Top Quark Mass

- Direct top mass measurements determine the Mont-Carlo top mass parameter.
  → Aim: learn about the relation of m_t^{MC} to field theory renormalization schemes.

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

pQCD contribution:

- Perturbative correction
- Depends on MC parton shower setup
- (Affected by finite width effects?)

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, ...
- Should be covered by ‘MC uncertainty’ or better negligible

Analysed for Herwig angular-ordered parton

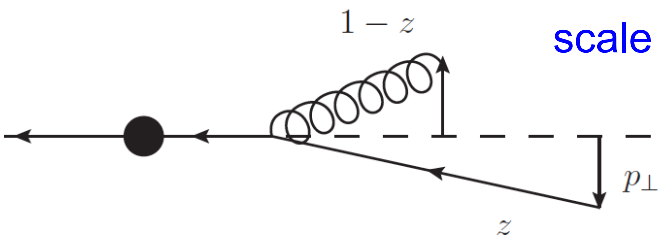
- Boosted (quasi-collinear) top quarks
- Stable top quarks
- 2-jettiness (production stage QCD dynamics only)

AHH, Plätzer, Samitz 1807.06617

Cutoff in Angular Ordered Parton Showers

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

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



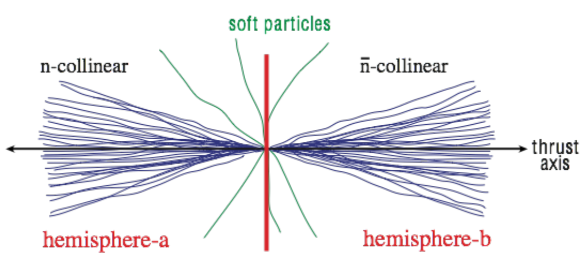
scale in α_S: $\mu^2 = p_\perp^2 + (1-z)^2 m^2$ cutoff: $p_\perp^2 > Q_0^2$

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) at NLL.

Fleming, Mantri, Stewart, AHH, 2007

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



Ultra-collinear radiation

Large-angle soft radiation

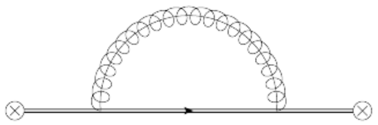
Plätzer, Samitz, AHH; arXiv:1807.06617

Cutoff in Angular Ordered Parton Showers

Dependence on the parton shower cut Q_0 :

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

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



- 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 $m_t^{CB}(Q_0)$.

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

$$\delta m = m_2 - m_1$$

Scheme change correction

- The shower cut also affects **large-angle soft radiation. T**he 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.

Plätzer, Samitz, AHH; arXiv:1807.06617

Hadronization: Herwig vs analytic QCD

Plätzer, Samitz, AHH; w.i.p

How well does Herwig's hadronization model match the analytic prediction?

We start with an analysis for massless quarks first.

- For massless quark production a change of Q_0 only modifies the soft function

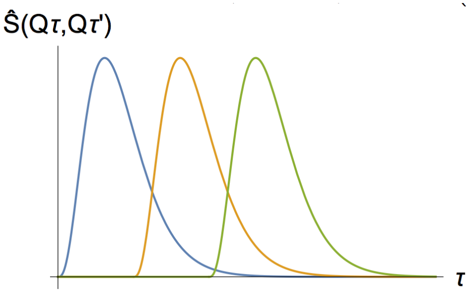
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau}(\tau, Q, Q_0) = \int_0^{Q\tau} \mathrm{d}\ell \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\tau}\left(\tau - \frac{\ell}{Q}, Q, Q_0'\right) S_{\mathrm{mod}}(\ell + \Delta_{\mathrm{soft}}(Q_0) - \Delta_{\mathrm{soft}}(Q_0'))$$

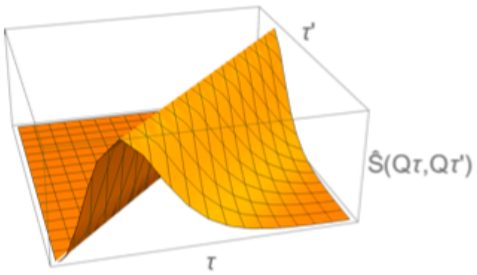
- Any change of the shower cut from Q_0 to Q_0' can be compensated by a modification of the soft function gap (or its first moment) by the amount

$$\Delta_{\mathrm{soft}}(Q_0) - \Delta_{\mathrm{soft}}(Q_0') = 16 \int_{Q_0'}^{Q_0} \mathrm{d}R \left[\frac{\alpha_s(R) C_F}{4\pi} + \mathcal{O}(\alpha_s^2) \right]$$

- Convolution above implies that each parton level bin τ' get smeared with a function that should satisfy

$$\hat{S}(Q\tau, Q\tau') = S_{\mathrm{mod}}(Q(\tau - \tau'))$$





Hadronization: Herwig vs analytic QCD

Herwig Cluster Model

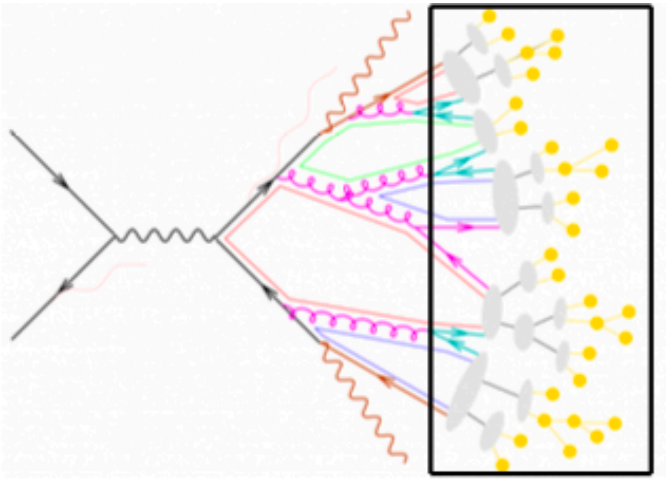


Figure from D. Zeppenfeld

- standard hadronization model of Herwig: cluster hadronization model [Webber (1984)]
- final state gluons split into $q\bar{q}$
- color-connected quarks combined into preconfined clusters
- for heavy clusters: fission along string axis (repeat until light enough)
- final clusters decay isotropically into hadrons
- various tuning parameters, specifying e.g. mass spectrum of daughter clusters, maximum mass of final clusters, constituent masses, ...

Hadronization: Herwig vs analytic QCD

Plätzer, Samitz, AHH; w.i.p

We want to study Herwig's cluster model in more detail.

- Define (observable dependent) hadronization transfer function

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau}(\tau, Q) = \int \mathrm{d}\tau' \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\tau}(\tau', Q)\hat{S}(Q\tau, Q\tau')$$

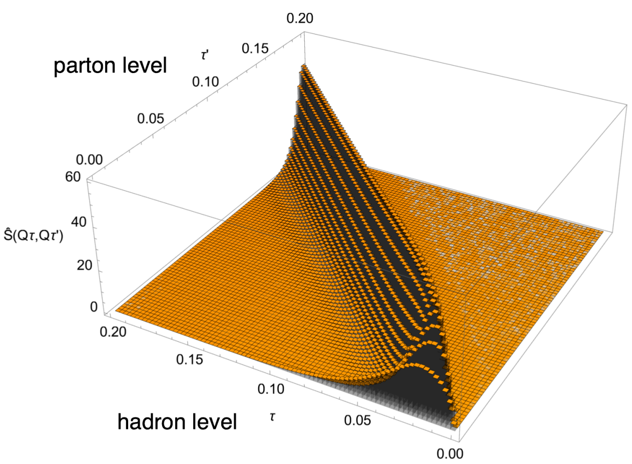
- Interpretation of $\hat{S}(Q\tau, Q\tau')$: probability distribution that an event with partonic value τ' has a hadron level value τ.

- Compatibility with QCD factorization demands: $\hat{S}(Q\tau, Q\tau') = S(Q(\tau - \tau'))$

We modified Herwig to allow the extraction of the event-by-event parton-to-hadron level transfer matrix.

- Results can be filled in a 2D histogram that shows how each parton level bin is migrated into hadron level bins

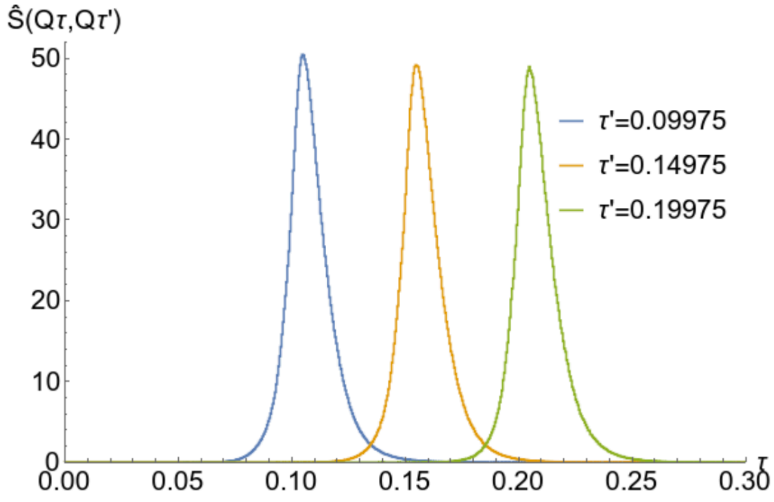
- Can be used to extract Herwig's hadronization function



Hadronization: Herwig vs analytic QCD

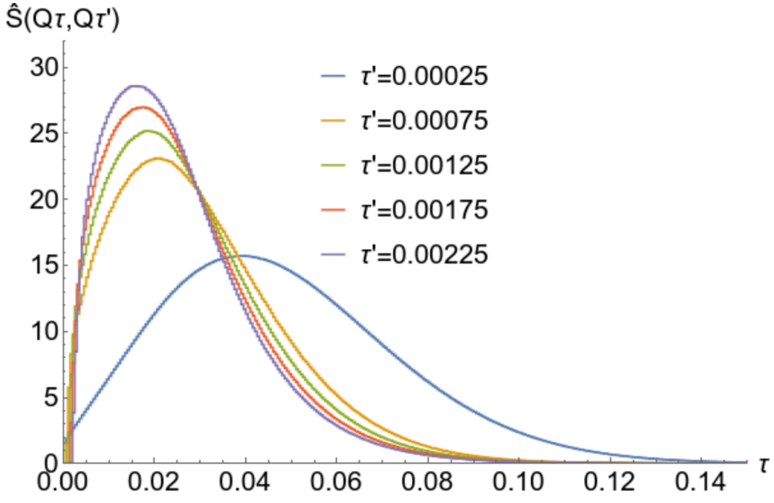
Plätzer, Samitz, AHH; w.i.p

effective hadronization function in the tail:



compatibel with $\hat{S}(Q\tau, Q\tau') = S(Q(\tau - \tau'))$

effective hadronization function in the peak:



not compatibel with $\hat{S}(Q\tau, Q\tau') = S(Q(\tau - \tau'))$

- This means that $\Delta_m^{\text{non-pert}}$ has a significant size for Herwig's cluster hadronization model.
- Modification of Herwig's cluster fission algorithms mandatory to make it compatible with QCD factorization in the resonance region where the highest top mass sensitivity arises.

Conclusions / Outlook

- Boosted top quarks are a very useful system to study because production, single top evolution and top decay can be nicely separated in the context of QCD factorization

- Allows to do many first principles calculations

- Allows to study subtle questions (e.g. MC top mass parameter interpretations for boosted top observables)

- Allows to scrutinize the components of MC generators (parton shower and hadronization model) and check the individual compatibility to QCD