Physics of the Top Quark and its Mass

André H. Hoang

University of Vienna

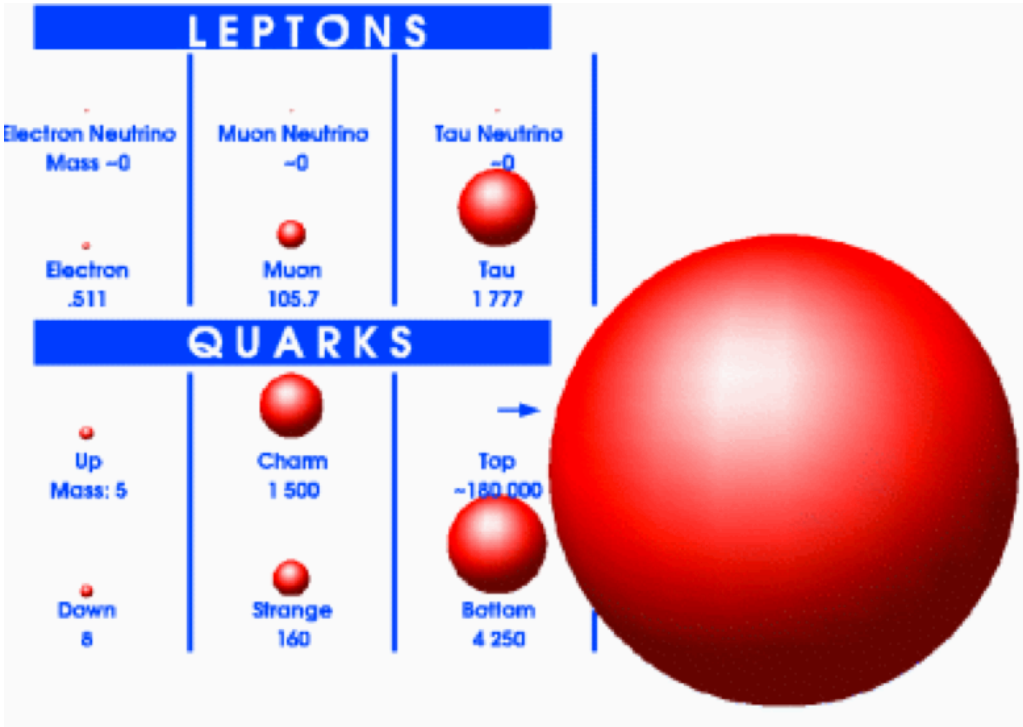
Doktoratskolleg Particles and Interactions

universität wien

FWF Der Wissenschaftsfonds.

QCD@LHC Workshop, Dresden, August 27-31, 2018

.. 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 as a Lab: Rich Collection of Achievements

Just some selection pf recent results. . .

Outline

This talk is a based on a personal selection of new SM calculations that appeared from the last edition of SM@LHC.

- ✖ **Stable Tops**: NNLO+NNLL` in QCD, NNLO QCD + complete-NLO, ✖
- $t\bar{t}$ ✖ merged $t\bar{t}$ and $t\bar{t}+$jet at complete-NLO.
- ✖ **Decays and off-shell effects**: NLO QCD to lepton+jets channel.

✖ t-channel single top — production and decay at NNLO QCD in NWA.

✖ $t\bar{t}+b$-jet — NLO+PS in 4FS.

✖ $t\bar{t}W^{\pm}$ — complete-NLO.

✖ $t\bar{t}t\bar{t}$ — complete-NLO.

From Davide Pagani (SM@LHC2018)

Czakon, Ferroglia, Heymes, Pejcak, Scott, Wang, Yang 2018

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro, 2018

Gütschow, Lindert, Schönherr, 2018

Jezo, Lindert, Oleari, Naron, Pozzorini, 2016

Denner, Pellen, 2016

Berger, Gao, Zhu, 2016, 2018

Bruchseifer, Caola, Melnikov, 2014

Jezo, Lindert, Moretti, Pozzorini, 2018

Frederix, Pagani, Zaro, 2017

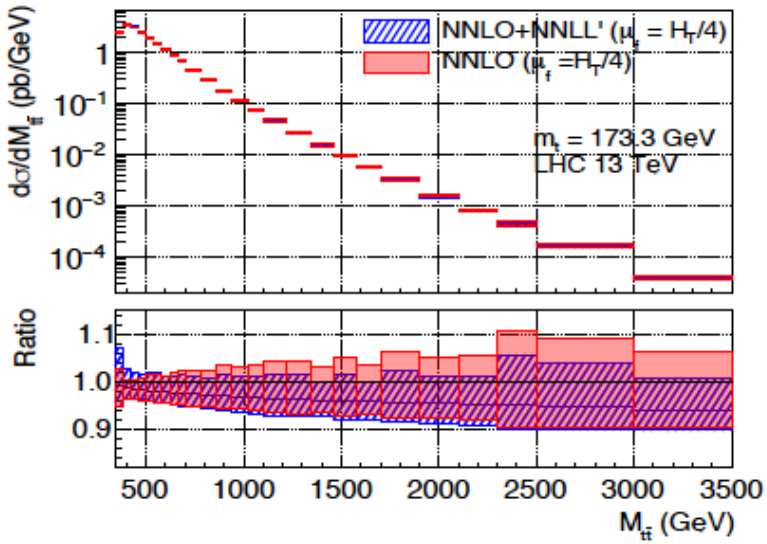
At QCD@LHC:

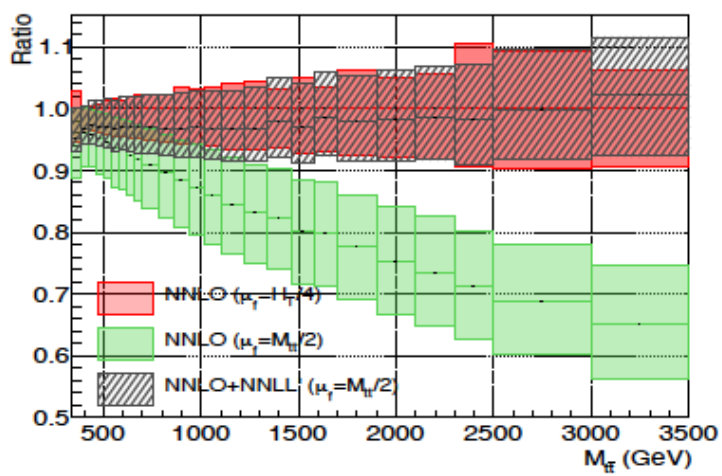
- Review $t\bar{t}H$ — Talk by A. Kulesza
- ✖ $t\bar{t}b\bar{b}$ jet @ NLO — Talk by F. Buccioni
- ✖ $\sigma_{\rm tot}(t\bar{t})$ @ $>$ NNLO — Talk by J. Piclum
- ✖ off-shell $t\bar{t}\gamma$ @ NLO — Talk by T. Weber

✖ on-shell tops

✖ off-shell tops

Top as a Lab: Rich Collection of Achievements



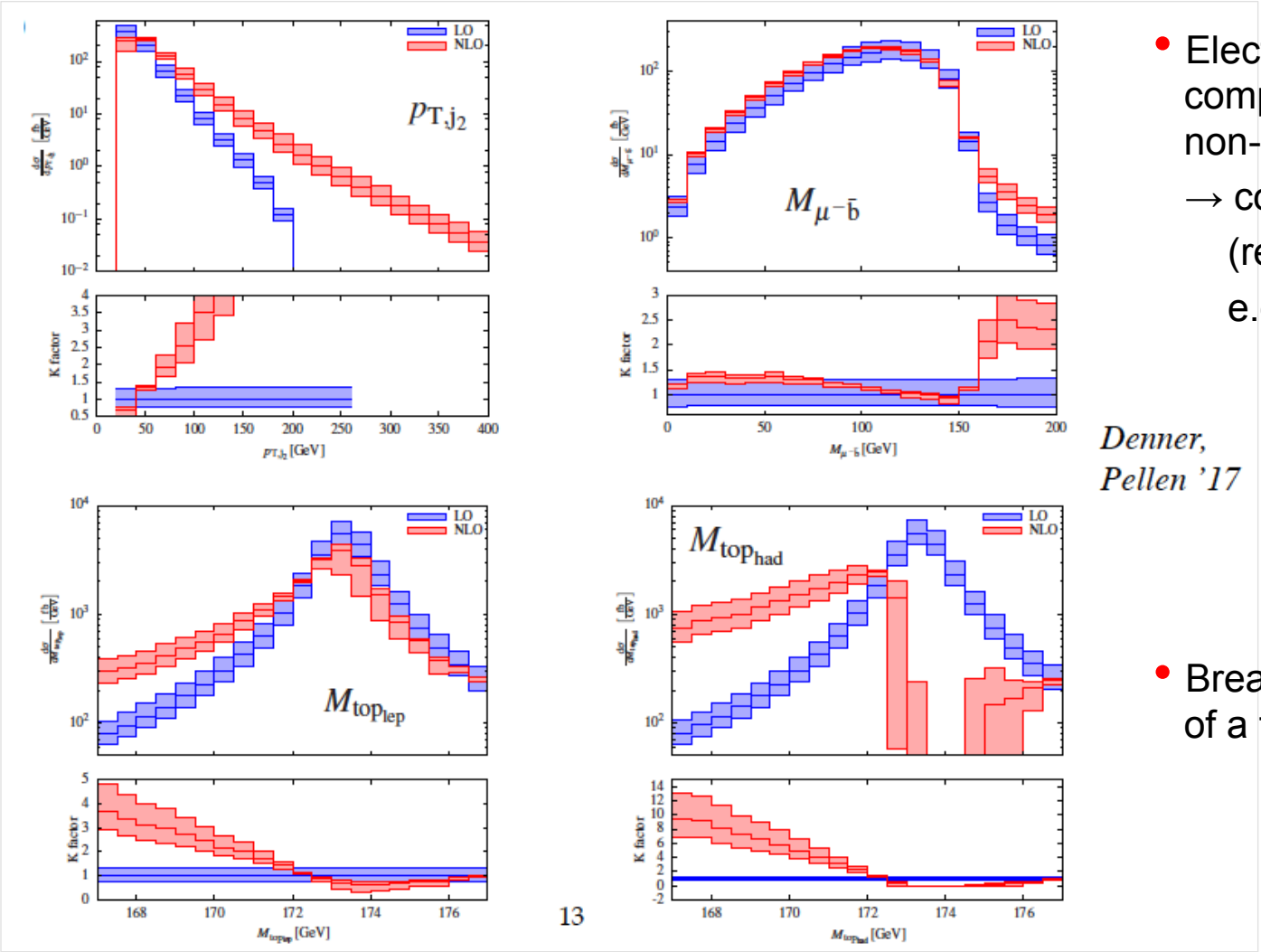


Czakon, Ferroglia, Heymes, Pejcak, Scott, Wang, Yang 2018

- NNLO + NNLL'
  Urge to identify "best" renormalization scale to reduce size of higher order corrections lifted.
  → collider differential cross sections are multi-scale problems

- Multi-scale problem:
  In general there IS no "best" renormalization scale because no choice can eliminate all large logs

Top as a Lab: Rich Collection of Achievements



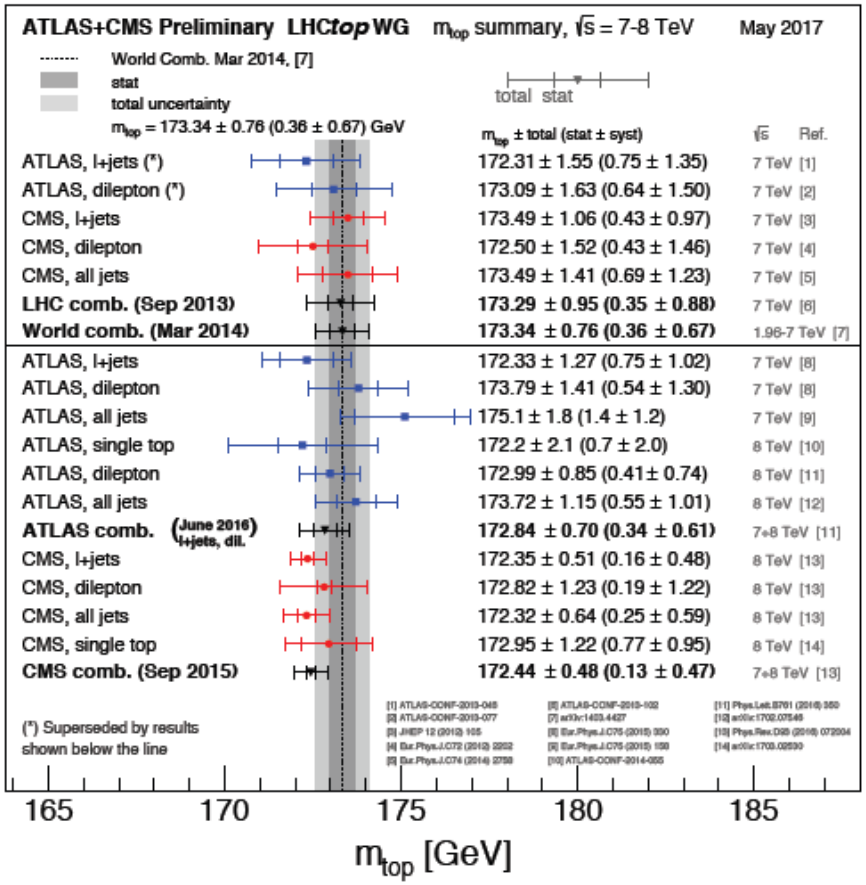
- Electroweak and QCD compete and interfere non-trivially
  → coherent treatment
  (resummation needed)
  e.g. parton showers

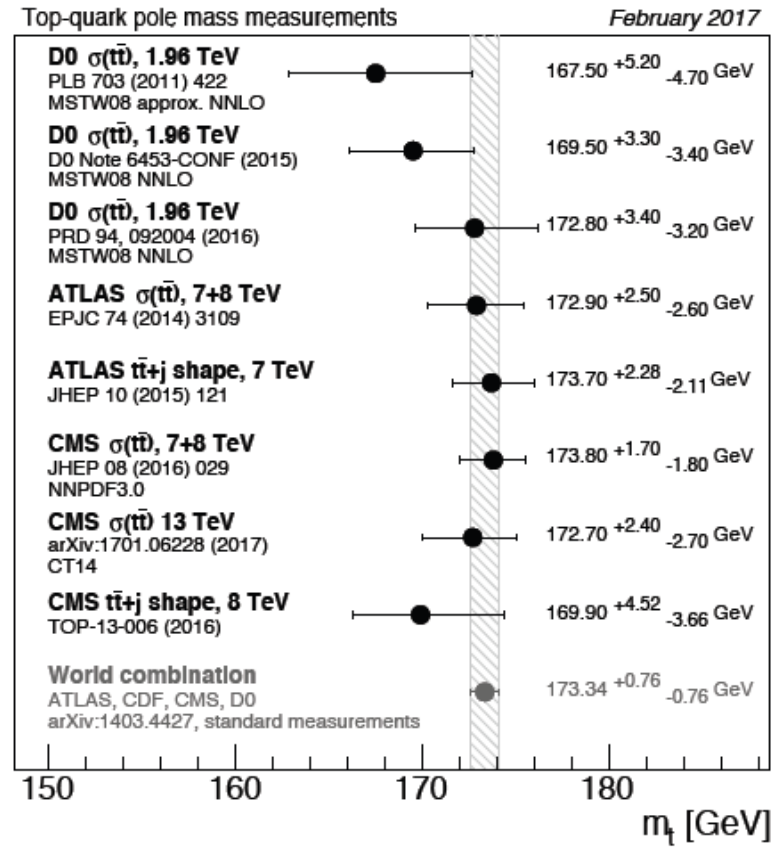
Denner, Pellen '17

- Breakdown of the picture of a top quark "particle"

From Davide Pagani (SM@LHC2018)

Top Mass Measurements



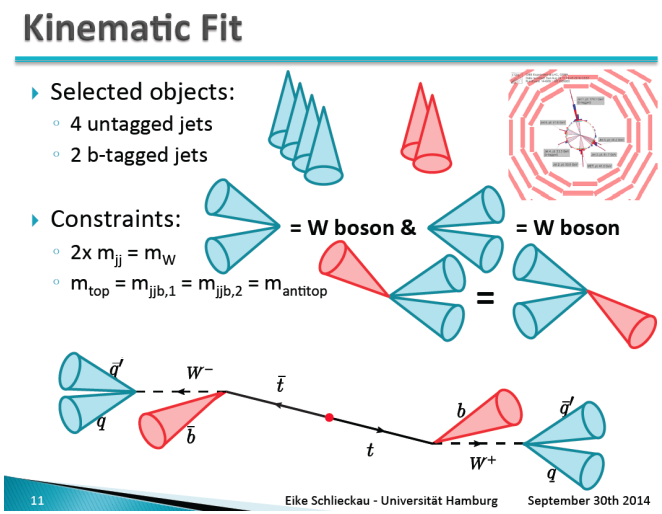


- Most precise measurements from direct reconstruction (uncertainties < 1 GeV)
- Other methods are less precise since top mass sensitivity smaller.
- Some of these are based on NLO (or NNLO) pQCD calculations in the pole mass scheme → "pole mass measurements"

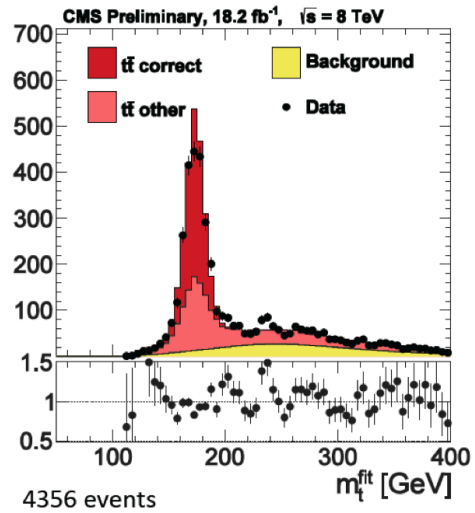
Top Mass Measurements

Most precise method: **Direct Reconstruction**

kinematic mass determination

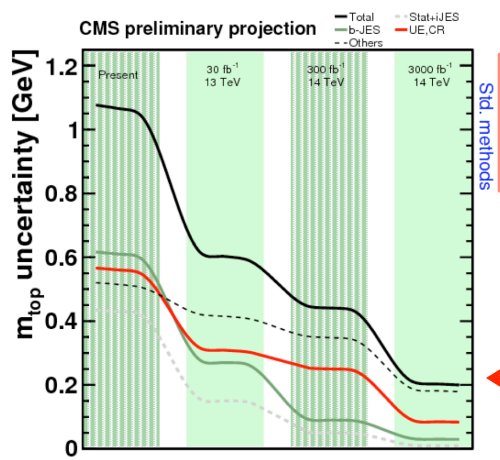


CMS-PAS-TOP-14-002



Determination of the best-fit value of the Monte-Carlo top quark mass parameter

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



⊕ High top mass sensitivity

⊖ Precision of MC ?

⊖ Meaning of m_t^{MC} ?

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

Top Mass Measurements

Why is there a controversy on the interpretation of m_t^{MC} ?

- Picture of **"top quark particle"** does not apply
  - 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, most relevant for most precise method)
  - Different / incoherent views about the numerical / conceptual importance of this issue
- Different views about the "precision" of MC event generators

- List of other sources of uncertainty that are independent of the m_t^{MC} problem:
  - Jet, b-jet modelling
  - Fragmentation, hadronization model description
  - NLO matching
  - Color reconnection
  - Finite lifetime effects

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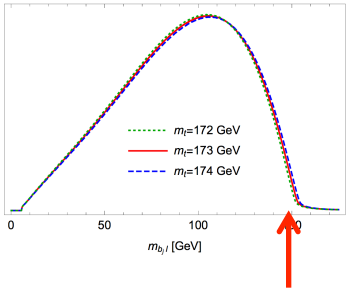
Emphasis of this talk

Recent Work

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 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 ($M_{jb\ell}$)
- Effects related to off-shell effects as large as 0.5 − 1 GeV for m_t^{MC} determination

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 compared to Herwig)

Content

- An approach to pin down m_t^{MC} in a systematic way:
  → boosted top factorization
  → e^+e^- 2-jettiness distribution

- Calibration of $m_t^{\text{Pythia 8.2}}$ using e^+e^- 2-jettiness

  Butenschön, Dehnadi, Mateu, Preisser, Stewart,AHH; 2016

- Role of the shower cut in the coherent branching formalism and angular ordered parton showers

  Plätzer, Samitz ,AHH; 2018
  → Talk on Thursday

- Extension to pp collisions

  Mantry Pathak, Stewart,AHH; 2017

- Coherent branching mass

- Conclusions

An Approach to Pin Down m_t^{MC}

At the present stage it appears that a general answer to how to interpret m_t^{MC} is not yet possible, so we can at least attempt to address the issue from the perspective of a particular observable.

Need:

Observable with **strong kinematic top mass dependence** that allows for a systematic theoretical description via

- Analytic QCD (e.g. QCD factorization, mass scheme under control)
- MC simulations

with the following properties:

- Hadron-level predictions
- NLO/NLL precision

→ The relation between analytic QCD and MC simulations can be studied in detail.

The relation between m_t^{MC} and other field theory mass schemes can be understood and quantified by direct comparison.

→ Currently there are only very, very, … few such observables!

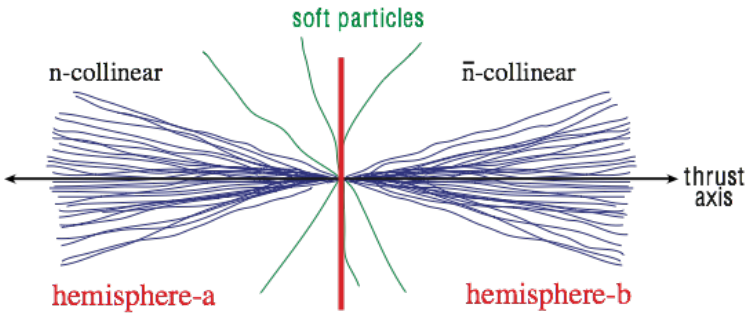
Factorization for Boosted Top Quarks

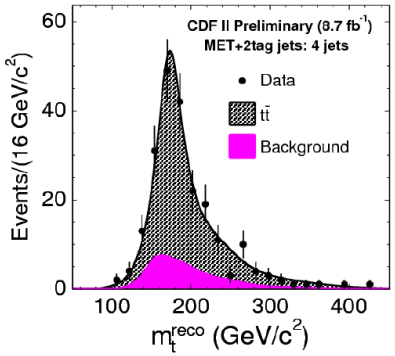
Observable: Thrust in e+e- (2-Jettiness τ_2)

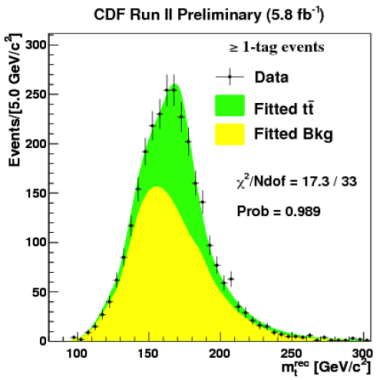
$$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{n} \cdot \vec{p}_i|}{Q}$$

$$\overset{\tau \to 0}{\approx} \frac{M_1^2 + M_2^2}{Q^2}$$

Fat jet invariant mass distribution in the resonance region !



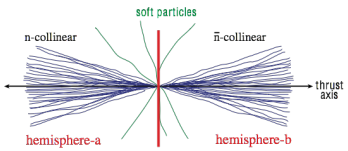




- Insensitive to top quark decay
- Can be extended to LHC (event shapes, fat jet masses)
- Can be extended to account for grooming effects (soft drop)

Boosted Top Factorization at Resonance

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



Jet functions:

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

- perturbative
- dependent on <u>mass, width, color charge</u>

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

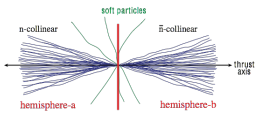
Soft function:

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

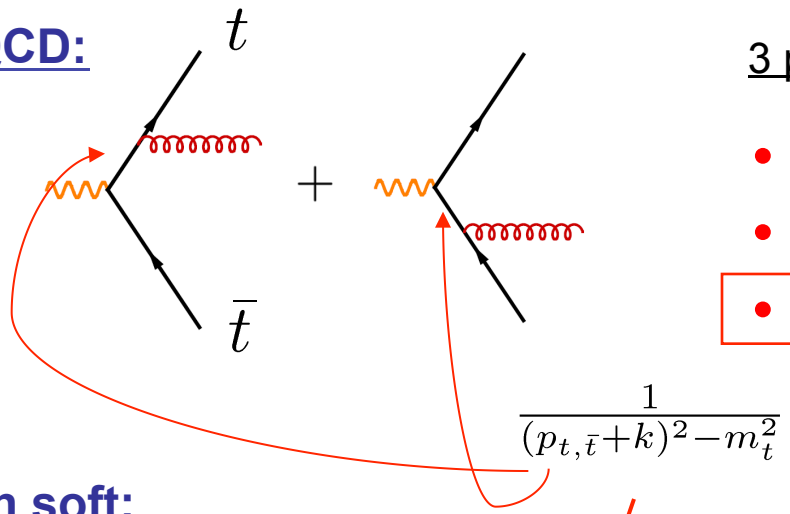
- non-perturbative
- Renormalization scale dependence perturbative
- dependent on <u>color charge, kinematics</u>

Independent of the mass and E_{cm} !

Boosted Top Factorization at Resonance



full QCD:

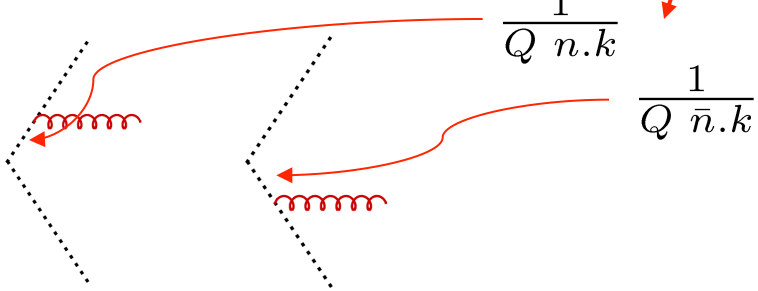


3 phase space regions: $\Lambda \sim \Lambda_{\rm QCD}$

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

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

Gluon soft:

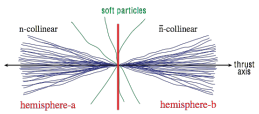


$$Y_n(x) = \overline{\rm P}\ \exp\Big(-ig\int_0^\infty ds\, n\cdot A_s(ns+x)\Big)$$

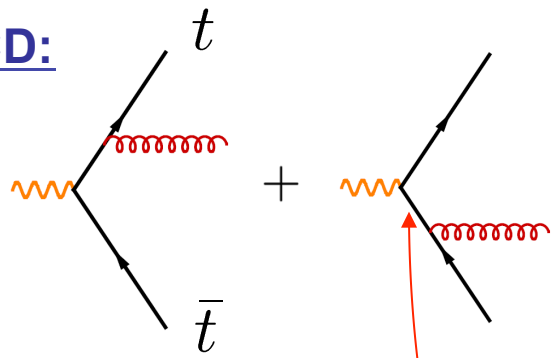
$$\overline{Y_{\bar{n}}}(x) = \overline{\rm P}\ \exp\Big(-ig\int_0^\infty ds\, \bar{n}\cdot \overline{A}_s(\bar{n}s+x)\Big)$$

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

Boosted Top Factorization at Resonance



full QCD:



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

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

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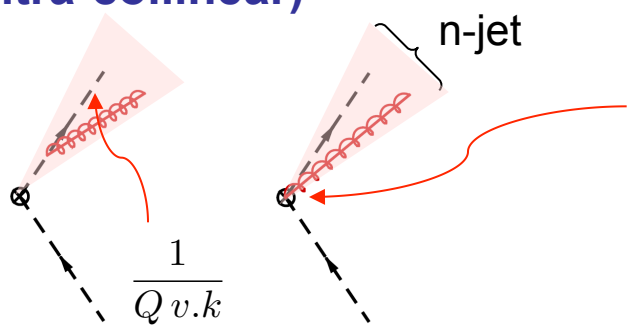
- soft: $(k_+, k_-, k_\perp) \sim (\Lambda, \Lambda, \Lambda)$

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

Gluon collinear to the top:
(ultra-collinear)



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

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

$h_{v_+}(x)$ → **gauge dependent**

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

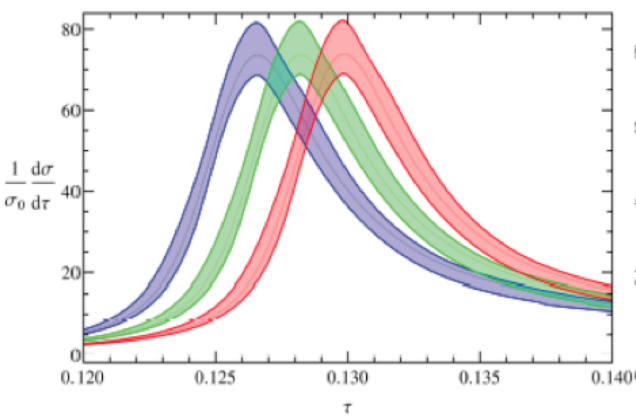
$$B_+(\hat{s}, \Gamma_t, \mu) = \mathrm{Im}\left[\frac{-i}{12\pi m_J}\int d^4x\, e^{ir.x}\,\langle 0|\,T\,\{\bar{h}_{v_+}(0)W_n(0)\,W_n^\dagger(x)h_{v_+}(x)\}\,|0\rangle\right]$$

2-Jettiness Distribution at NNLL/NLO

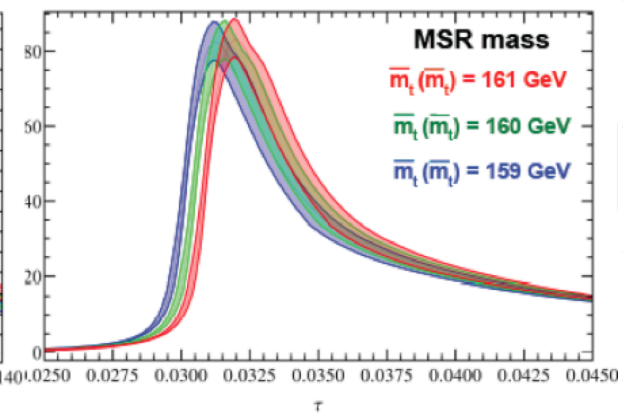
Hadron-level prediction:

$$\frac{d\sigma}{d\tau_2} = f(\underbrace{m_t^{\mathrm{MSR}}(R), \delta m^{\mathrm{MSR}}}_{\text{any scheme possible}}, \alpha_s(M_Z), \underbrace{\Omega_1, \Omega_2}_{\text{Non-perturbative}}, \underbrace{\mu_h, \mu_j, \mu_s, \mu_m}_{\text{renorm. scales}}, R, \underbrace{\Gamma_t}_{\text{finite lifetime}})$$

Q=700 GeV (p_T= 350 GeV)

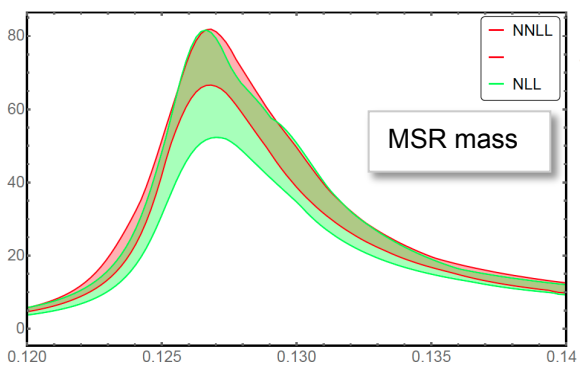


Q=1400 GeV (p_T = 700 GeV)

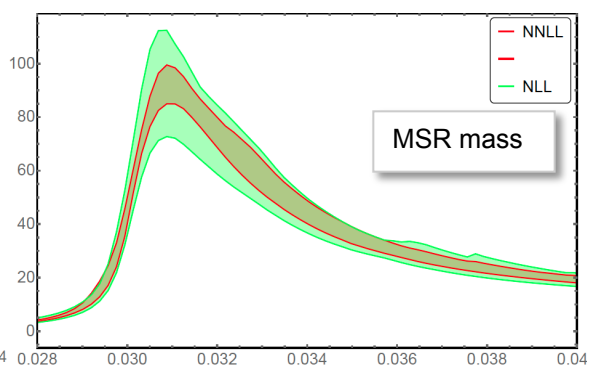


- Higher mass sensitivity for lower Q (p_T)
- Finite lifetime effects included
- Dependence on non-perturbative parameters
- Convergence: $\Omega_{1,2,...}$

Q=700 GeV



Q=1400 GeV



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

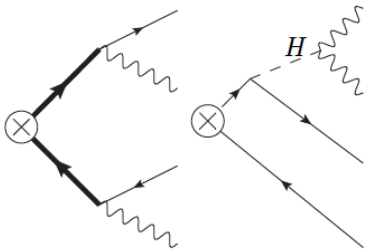
Signal ttbar vs full ee→WWbb

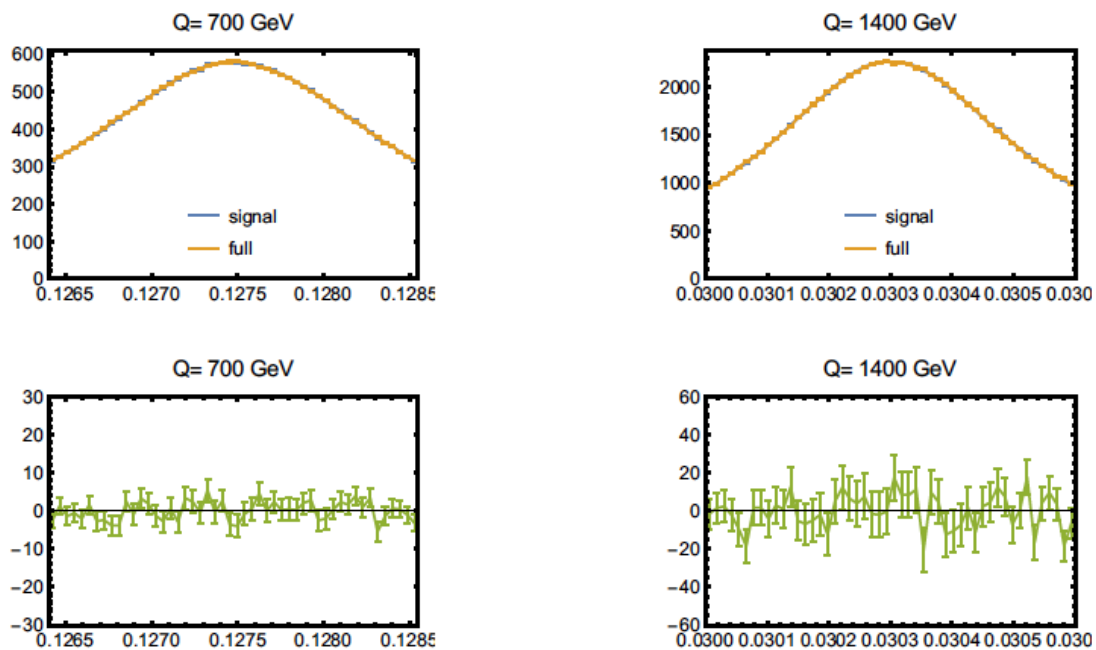
MadGraph 5 study:

- Non-resonant contributions are irrelevant for τ_2 distribution
  - PYTHIA (or similar MCs) will give a good description of the production process at LO
  - hemisphere invariant mass ∼ top invariant mass (no pollution from background)

→ **Top width important effect**

→ **Non-trivial finite lifetime (interference, non-resonant) effects strongly suppressed.**





Calibration of $m_t^{\text{Pythia 8.205}}$

Butenschön, Dehnadi, Mateu, Preisser, Stewart,AH; PRL 117 (2016) 153

- $\frac{d\sigma}{d\tau} = f(m_t^{\text{MSR}}, \alpha_s(m_Z), \Omega_1, \Omega_2, \ldots, \mu_H, \mu_J, \mu_S, \mu_M, R, \Gamma_t)$

  any scheme non-perturbative renorm. scales finite lifetime

- Generating PYTHIA Samples: (PYTHIA 8.205)

  at different energies: $Q = 600, 700, 800, \ldots, 1400$ GeV

  - masses: $m_t^{\text{MC}} = 170, 171, 172, 173, 174, 175$ GeV
  - width: $\Gamma_t = 1.4$ GeV
  - Statistics: 10^7 events for each set of parameters

  - Tune 7 (Monash)

- Feed MC data into **Fitting Procedure:** all ingredients are there

  Fit parameters: m_t^{MSR}, $\alpha_s(m_Z)$, $\Omega_1, \Omega_2, \ldots$

  - Take $\alpha_S(M_Z)$ as input from world average. (Sensitivity to strong coupling very weak.)

  - standard fit based on χ^2 minimization
  - analysis with 500 sets of profiles (τ_2 dependent renorm. scales) for the each MC sample
  - different Q-sets: 7 sets with energies between 600 - 1400 GeV
    different n-sets: 3 choices for fitranges - (xx/yy)% of maximum peak height

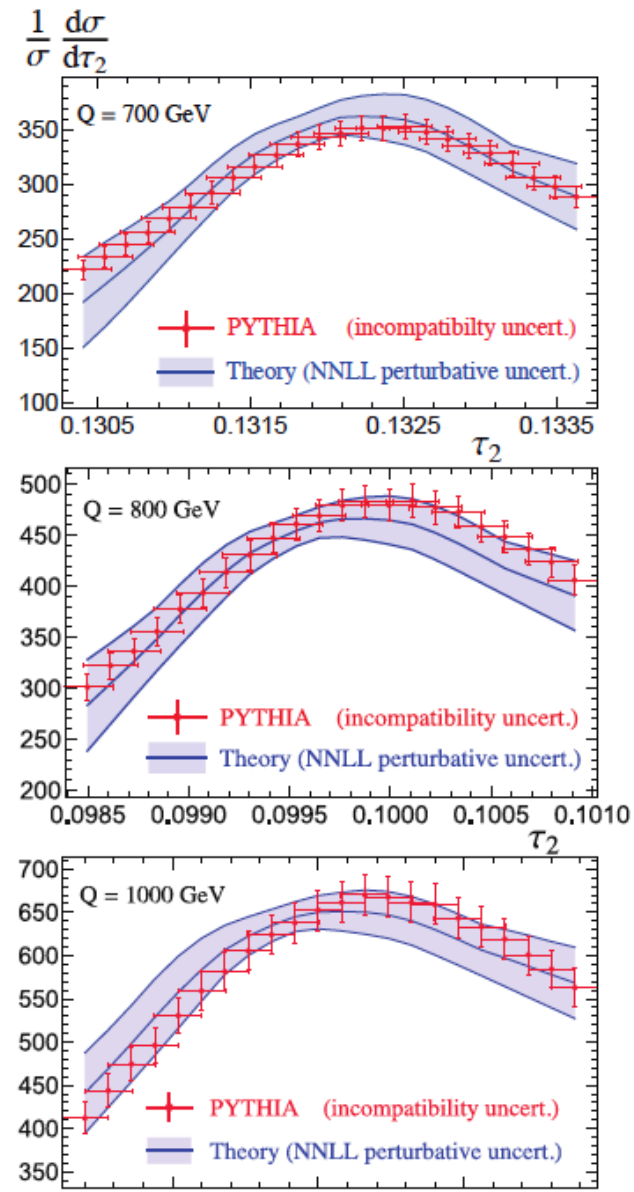
    } 21 fit setups

Fit Result: Pythia 8.205 vs. Theory

Γ_t=1.4 GeV, tune 7,
m_t^{MC} = 173 GeV

Ω_1 = 0.44 GeV,
m_t^{MSR}(1GeV) = 172.81 GeV

- Good agreement of PYTHIA with NNLL/NLO theory predictions
- Perturbative uncertainties of theory predictions based on scale uncertainties (profiles)
- MC uncertainties:
  - Vertical: rescaled statistical error (PDF rescaling method) → independent on statistics
  - Horizontal: fit coverage from 21 fit setups (incompatiblity uncertainty)



Fit Result: MSR vs. Pole Mass

500 profiles; $\alpha_s = .118$; $\Gamma_t = 1.4$ GeV; tune 7;
$Q = 700, 1000, 1400$ GeV; peak$(60/80)\%$

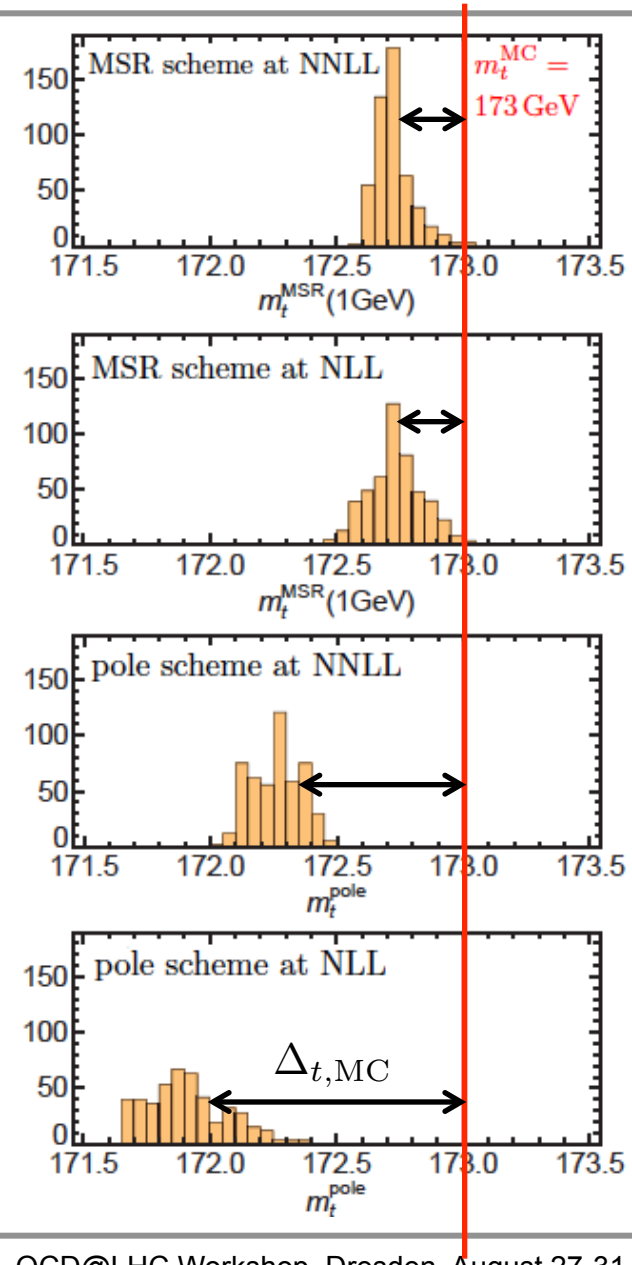
Input: $m_t^{\mathrm{MC}} = 173$ GeV

fit to find $m_t^{\mathrm{MSR}}(1\mathrm{GeV})$ or m_t^{pole}

- Good convergence & stability for MSR mass
- Mass m_t^{MSR}(1GeV) mass definition closest to the MC top mass m_t^{MC}.

- Pole mass shows worse convergence.
- Pole mass not compatible with MC mass within errors
- 1100/700 MeV difference at NLL/NNLL
- $m_t^{pole} \neq M_t^{Pythia\ 8.2}$

Similar analyses from the 20 other Q-set and n-range setups.



Fit Result: m_t^{MC} and $m_t^{MSR}(1\ GeV)$

- All investigated MC top mass values show consistent picture
- MC top quark mass is indeed closely related to MSR mass

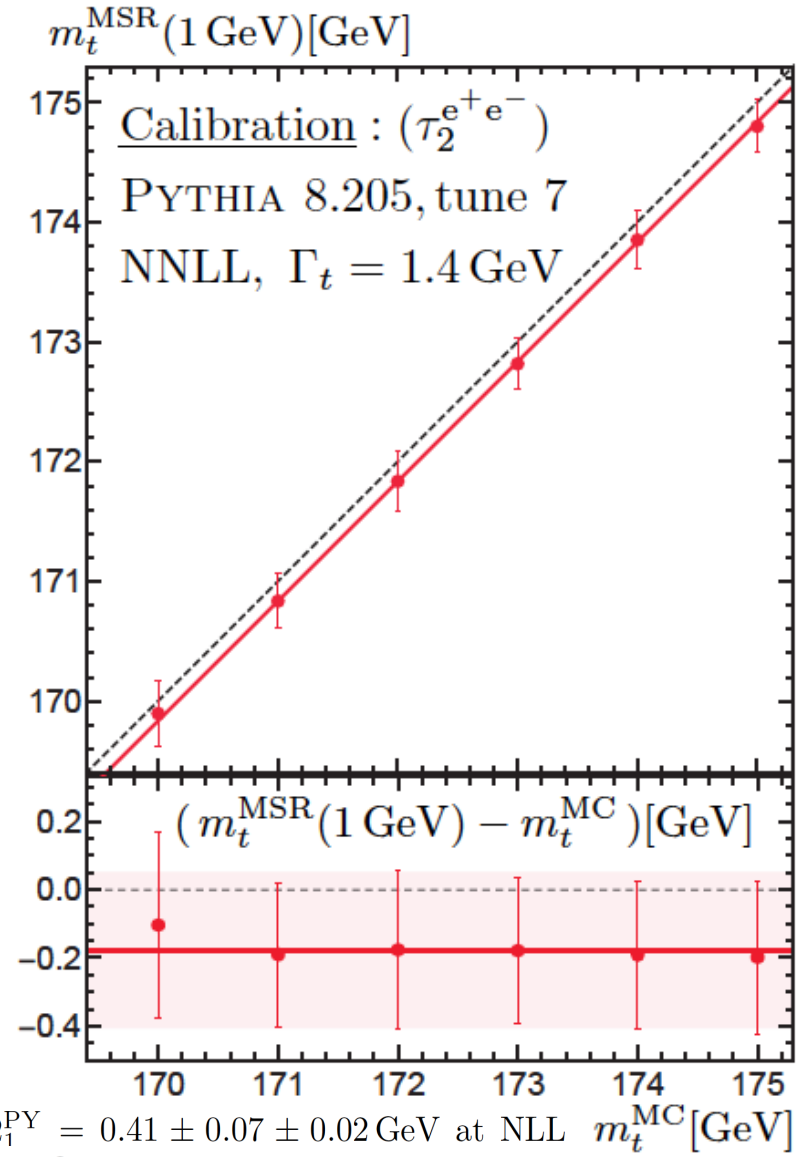
  within uncertainties:
  $m_t^{\rm MC} \simeq m_t^{\rm MSR}(1{\rm GeV})$

$m_t^{\rm MC} = 173\,{\rm GeV}\ \ (\tau_2^{e^+e^-})$

mass	order	central	perturb.	incompatibility	total
$m_{t,1\,\rm GeV}^{\rm MSR}$	NLL	172.80	0.26	0.14	0.29
$m_{t,1\,\rm GeV}^{\rm MSR}$	N^2LL	172.82	0.19	0.11	0.22
$m_t^{\rm pole}$	NLL	172.10	0.34	0.16	0.38
$m_t^{\rm pole}$	N^2LL	172.43	0.18	0.22	0.28

Spread of results from 21 fit setups

$m_t^{MSR}(1GeV) = 172.82 \pm 0.22$ GeV



$\Omega_1^{\rm PY} = 0.41 \pm 0.07 \pm 0.02\,{\rm GeV}$ at NLL

$\Omega_1^{\rm PY} = 0.42 \pm 0.07 \pm 0.03\,{\rm GeV}$ at N^2LL

Fit Result: Tune Dependence

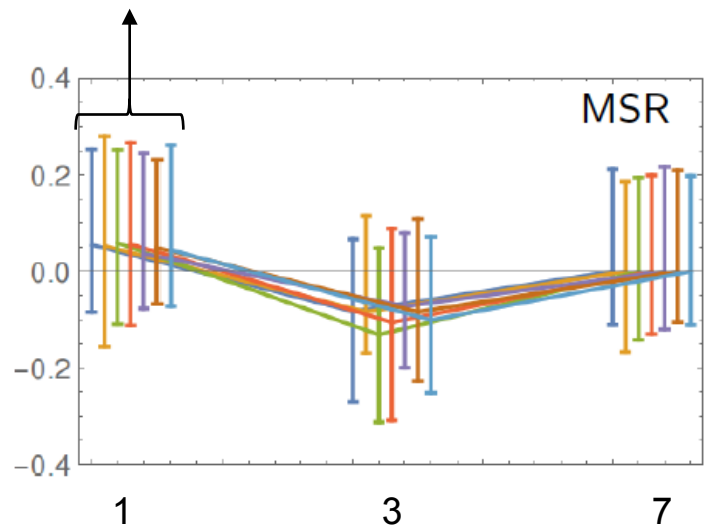
500 profiles; $\Gamma_t = 1.4$,-1 GeV;tune $1, 3, 7$;
diff. Q-sets; peak$(60/80)\%$

$$m_t^{\texttt{PYTHIA}} = 173 \text{ GeV}$$

- tune dependence:
  $m^{\mathrm{MSR}}[\mathrm{tune}] - \mathrm{m}^{\mathrm{MSR}}[7]$

- clear sensitivity to tune
- m^{MC} will depend on tune
- tune dependence is not a calibration uncertainty:

  (different tune $\Rightarrow$ different MC $\Rightarrow m_t^{\mathrm{MC}}$)



Fit Result: Top Width Dependence

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

Top width dependence

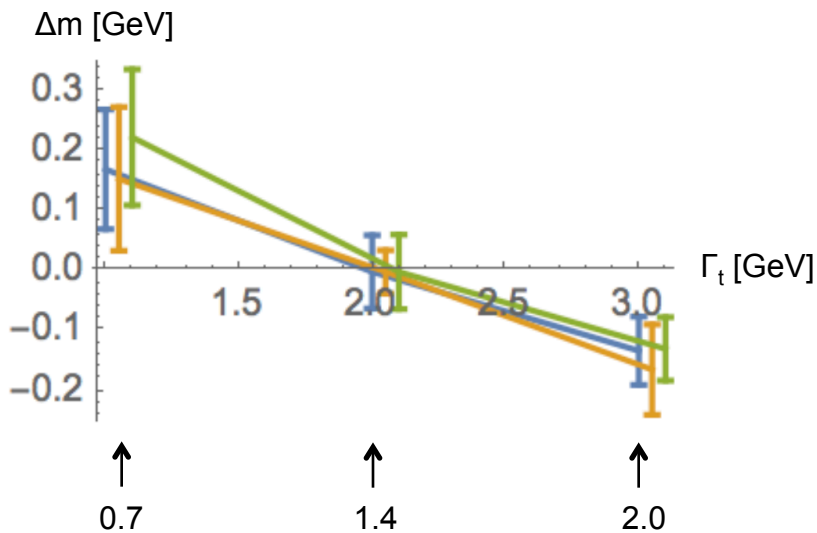
$$\Delta m = m_t^{MSR}[\Gamma_t] - m_t^{MSR}[\Gamma_t=1.4]$$

$\alpha_S(M_Z)=0.118$

$m_t^{MC}=173$

- 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.

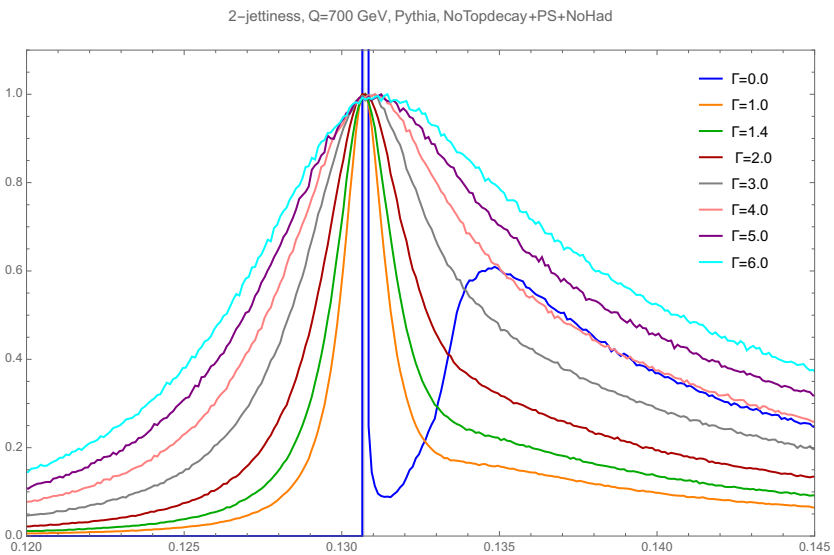


- Three colors: tunes 1, 3, 7
- Error bars: standard deviation of best mass value distribution in 500 profile function fits

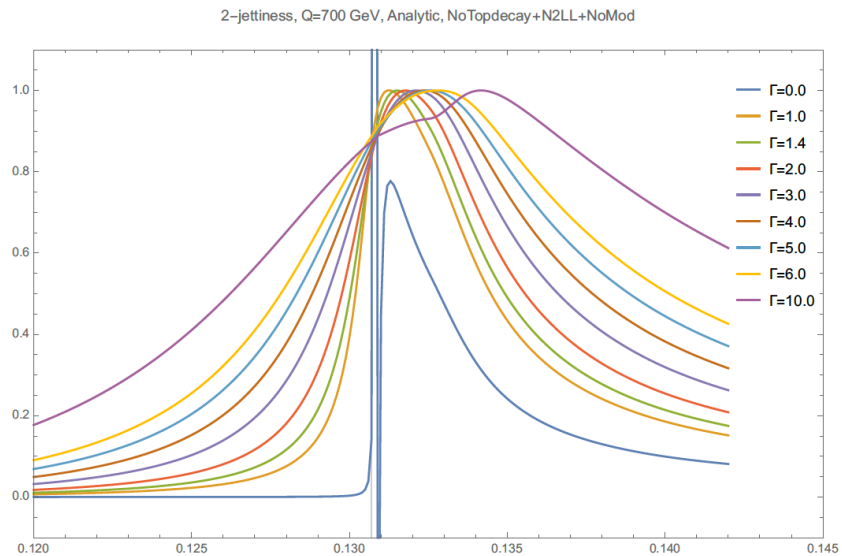
Top Resonance: factorization vs. Pythia

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)

Central Questions

- Does the MC contain sufficient higher-order information to specify a quark mass scheme?

- Do we have information on how higher-order corrections may look like?

  → “MC scheme”

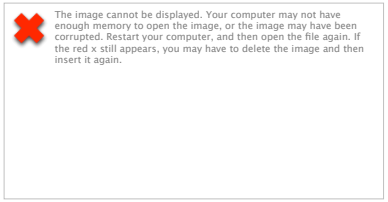
- Does the MC provide a description that is in full accordance to the SM (QCD+electroweak) ?
  - Log summation
  - Properties of hadronization model
  - Finite Lifetime effects
  - …

- Which role do MC specific implementations play?
  - Shower cutoff Q_0
  - Kinematic reconstruction
  - …

Cutoff in Angular Ordered Parton Showers

Plätzer, Samitz, AHH; arXiv:1807.06617

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



scale in α_S: cutoff:

not present in analytic QCD !

2-Jettiness τ_2 distribution (for e^+e^- and boosted tops) can be analytically computed in QCD factorization (SCET) and coherent branching (CB).

Catani, Webber, Marchesini, 1991

Issues that have been addressed for τ_2: → More details in my talk on Thursday

(Boosted top quarks, Narrow width approximation !!)

$Q_0=0$:

- 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}

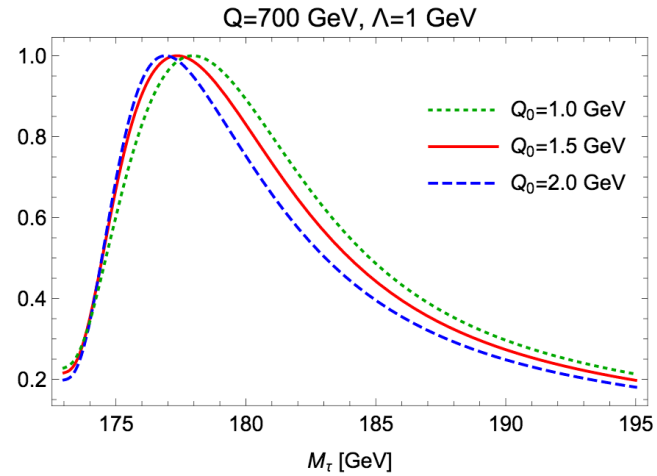
$Q_0>0$:

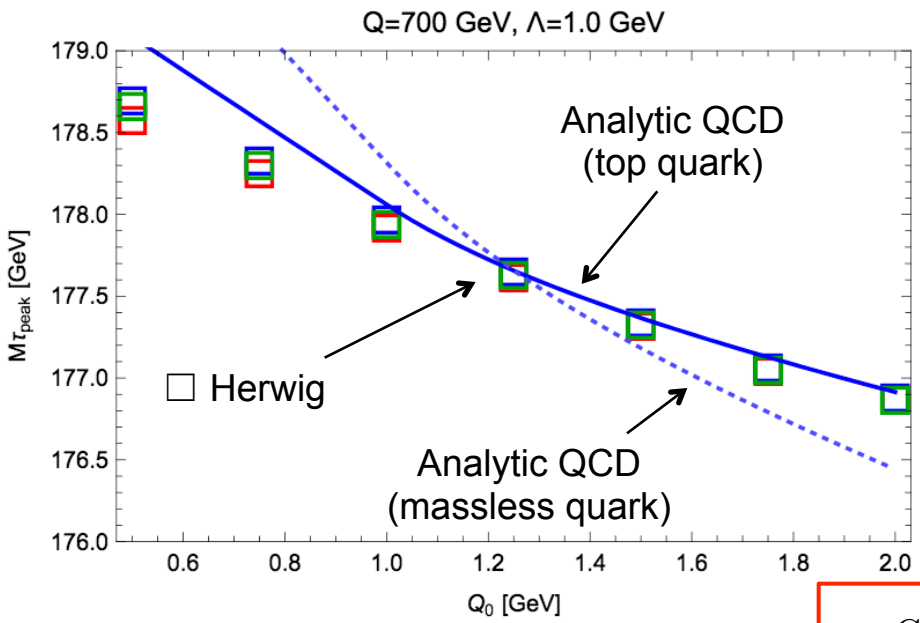
- Pole of the top quark propagator = $m_t^{CB}(Q_0) \neq m_t^{pole}$
- Equivalence of CB and SCET at NLL **enforces** that shower cut Q_0 acts like change in the mass scheme $m_t^{pole} \rightarrow m_t^{CB}(Q_0)$ and a modification of hadronization effects

Q_0 Dependence: Herwig vs analytic QCD

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

- Depends on value of Q_0
- Different Q behavior of Q_0 effects concerning hadronization and the top mass





- Herwig simulations in full agreement with analytic calculations
- M_{bl} and M_{bW} distributions compatible
- Change of Q_0:

  Physical predictions unchanged when hadronization model tune is retuned (tune is Q_0 dependent) and generator model is interpreted as the CB mass:

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

Plätzer, Samitz, AHH; arXiv:1807.06617

CB Mass $m_t^{CB}(Q_0)$: Universality

Plätzer, Samitz, AHH; arXiv:1807.06617

Result obtained for

- 2-Jettiness τ_2 distribution → Valid for all hemisphere mass based event shape type observables free of non-global logs (jet masses).
  No factorization predictions for direct reconstruction.
- Boosted top quarks → Coherent branching formalism only valid in quasi-collinear limit.
  No parton shower formalism exists for low p_T tops !
- NWA → Coherent branching formalism only valid in for stable top quarks (NWA).
  No formalism exists for unstable tops!

Observable-indpendence of $m_t^{MC} = m_t^{CB}(Q_0)$ for any observable not proven at this time.

But – if universality applies – the answer is

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

Extension to pp Collisions

- jet observable ★ ★ Jet Mass in Jet of radius R
- suitable top mass for jets ★
- initial state radiation ★
- final state radiation ★
- underlying event ← Note: no star here
- color reconnection ★
- beam remnant ★ Jet veto
- parton distributions ★ multiple channels
- sum large logs $Q \gg m_t \gg \Gamma_t$ ★
- Pile-up ← No star here

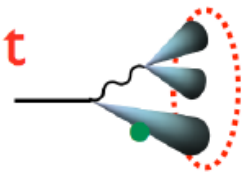
Better: factorization for pp

Extension to pp Collisions

AH, Mantry, Pathak, Stewart; arXive:1708.02586

$$p_T \gg m_t \gg \Gamma_t > \Lambda_{\rm QCD}$$

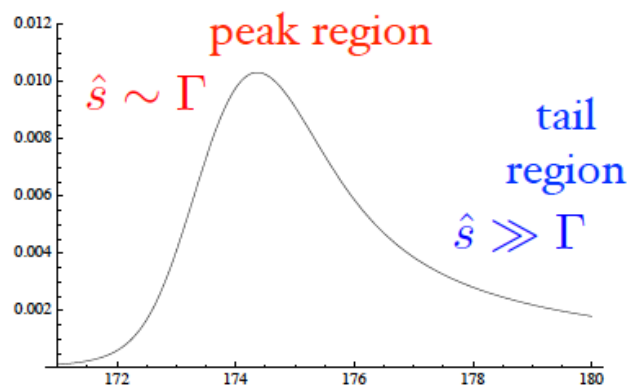
- Boosted Tops $p_T \gg m_t$ retain top decay products
- Fat Jets $R \gg \dfrac{m_t}{p_T}$



- Sensitivity $\hat{s} \sim \Gamma_t$ for measurement of jet-mass m_J

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

- Grooming $z_{\rm cut}, \beta$
- Jet Veto $\mathcal{T}^{\rm cut}$ or $p_T^{\rm cut}$



(Perturbative and Nonperturbative effects give $\Gamma > \Gamma_t$)

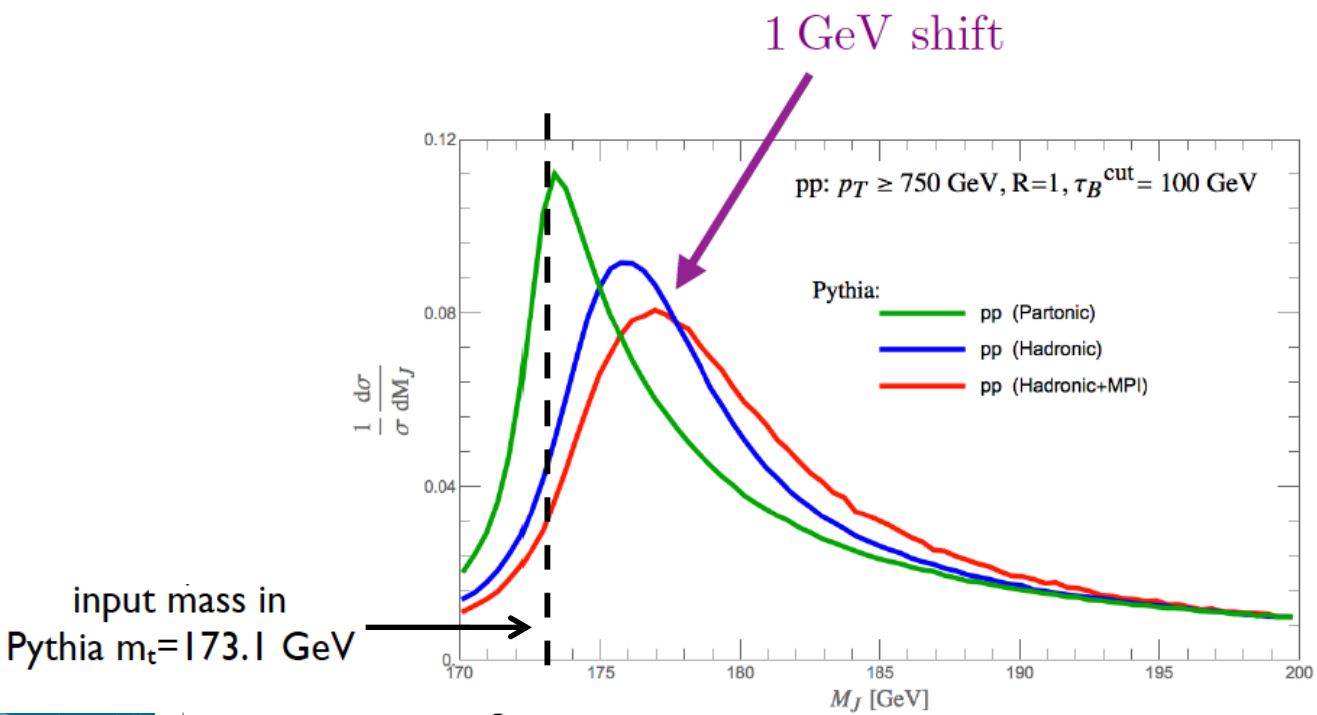
Extension to pp Collisions

Extension to pp (in principle) straightforward: (e.g. N-jettiness & X-Cone jets)

$$\frac{d^2\sigma}{dM_{J1}^2 dM_{J2}^2 d\mathcal{T}^{\rm cut}} = {\rm tr}\left[\hat{H}_{Qm}\hat{S}(\mathcal{T}^{\rm cut}, R, \ldots)\otimes F\right]\otimes J_B \otimes J_B \otimes \mathcal{I}\mathcal{I} \otimes f\, f$$

Issue is that UE / MPI is significant:

Same jet functions as e^+e^-



Extension to pp Collisions

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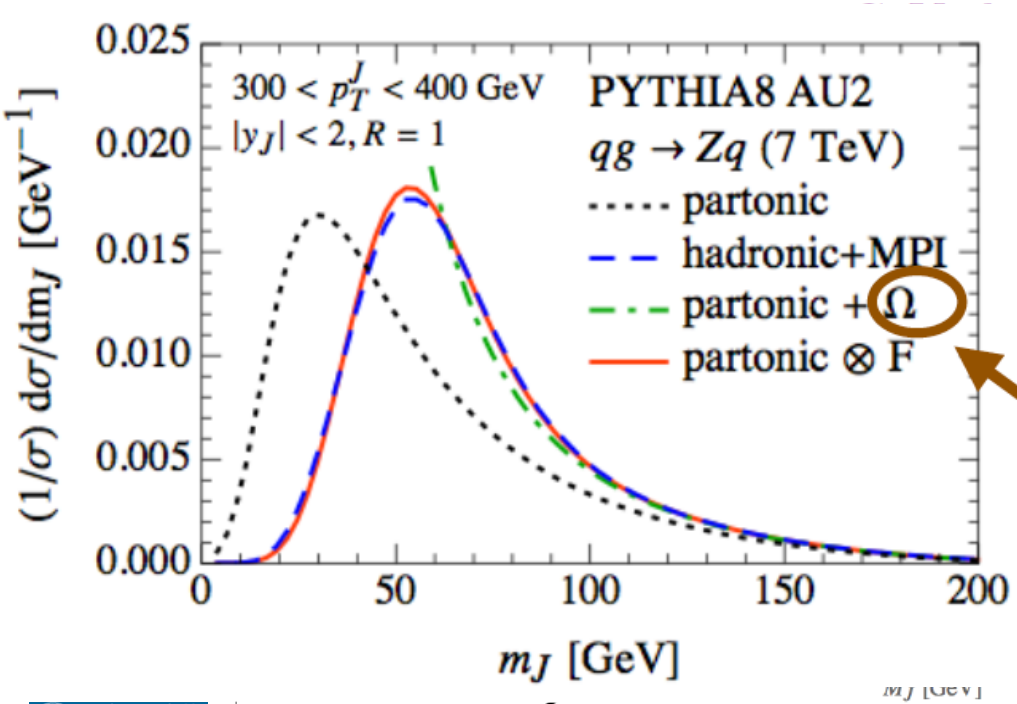
Same jet functions as e^+e^-

Issue is that UE / MPI is significant:



BUT control of Underlying Event is model dependent.

Same model used for Hadronization can describe UE by (primarily) tuning one parameter Ω.

$$\Omega = \int {\rm d}k\, k\, F(k)$$

Stewart, Tackmann, Waalewijn, 2015

Extension to pp Collisions

- Grooms soft radiation from the jet

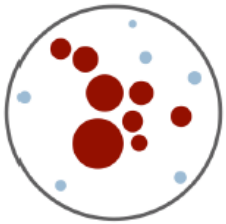
Larkowski, Marzani, Soyez, Thaler, 2014

$$\frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} > z_{\rm cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

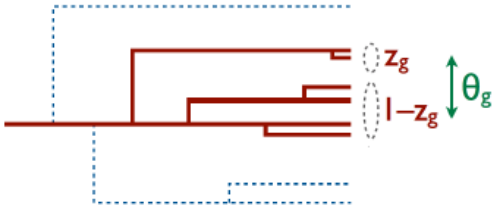
$$z > z_{\rm cut}\, \theta^{\beta}$$

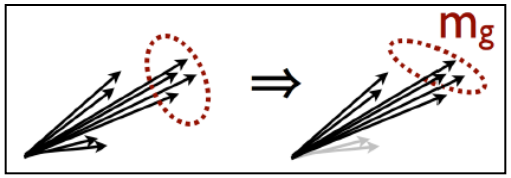
two grooming parameters

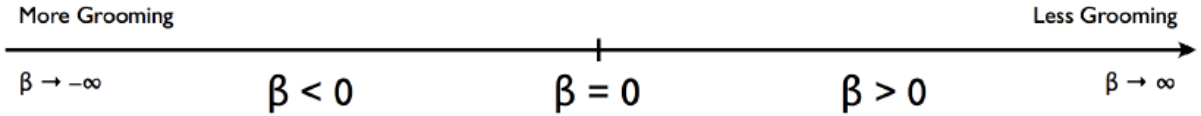
Groomed Jet



Groomed Clustering Tree



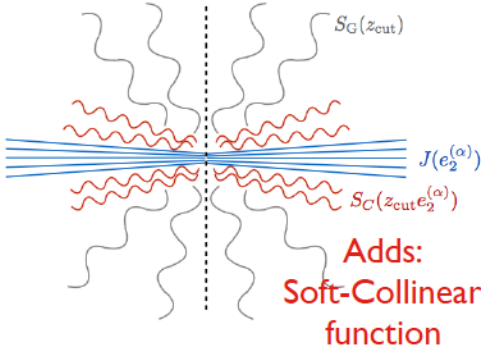




- Allows for factorization calculations

Frye, Larkowski, Schwartz, Yan, 2016

Mode separation: additional soft-collinear modes



Extension to pp Collisions

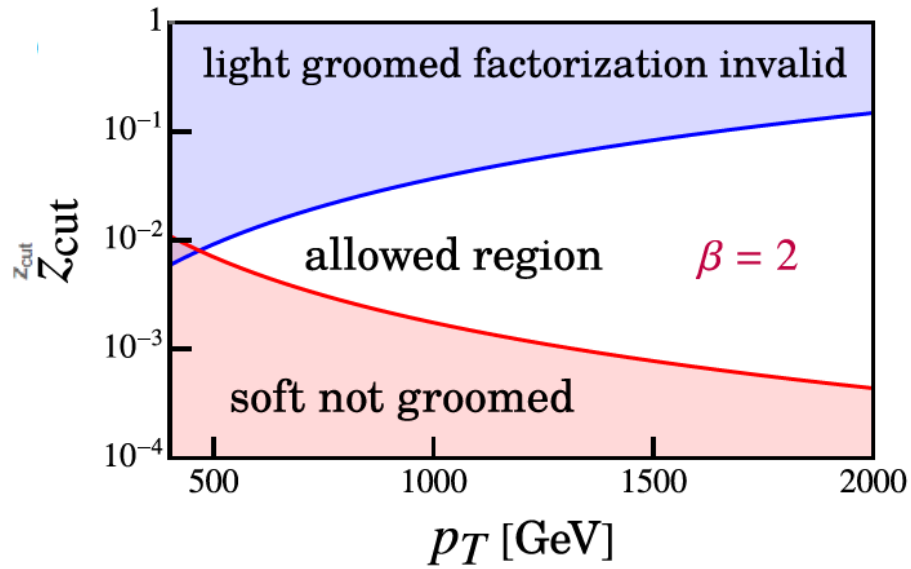
AH, Mantry, Pathak, Stewart; arXive:1708.02586

Can only apply a "light soft drop" for tops:

$$\frac{\Gamma_t}{m}\left(\frac{Q}{2m}\right)^{\beta} \gg z_{\rm cut} \gg \frac{2m\Gamma_t}{Q^2}$$

Ensure soft drop does not touch J_B

Ensure soft drop removes global soft radiation from measurement



Factorization with Soft Drop on one jet:

$$\frac{d^2\sigma}{dM_J^2 d\mathcal{T}^{\rm cut}} = {\rm tr}\big[\hat{H}_{Qm}\hat{S}(\mathcal{T}^{\rm cut}, Qz_{\rm cut}, \beta, \ldots)\otimes F\big]\otimes J_B \otimes \mathcal{I}\mathcal{I} \otimes ff$$
$$\times\left\{\int d\ell dk\, J_B\Big(\hat{s}_t - \frac{Q\ell}{m}, \Gamma_t, \delta m\Big) S_C\left[\Big(\ell - k\Big(\frac{k}{Q_{\rm cut}}\Big)^{\frac{1}{1+\beta}}\Big) Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\right] F_C(k)\right\}$$

("high-p_T factorization")

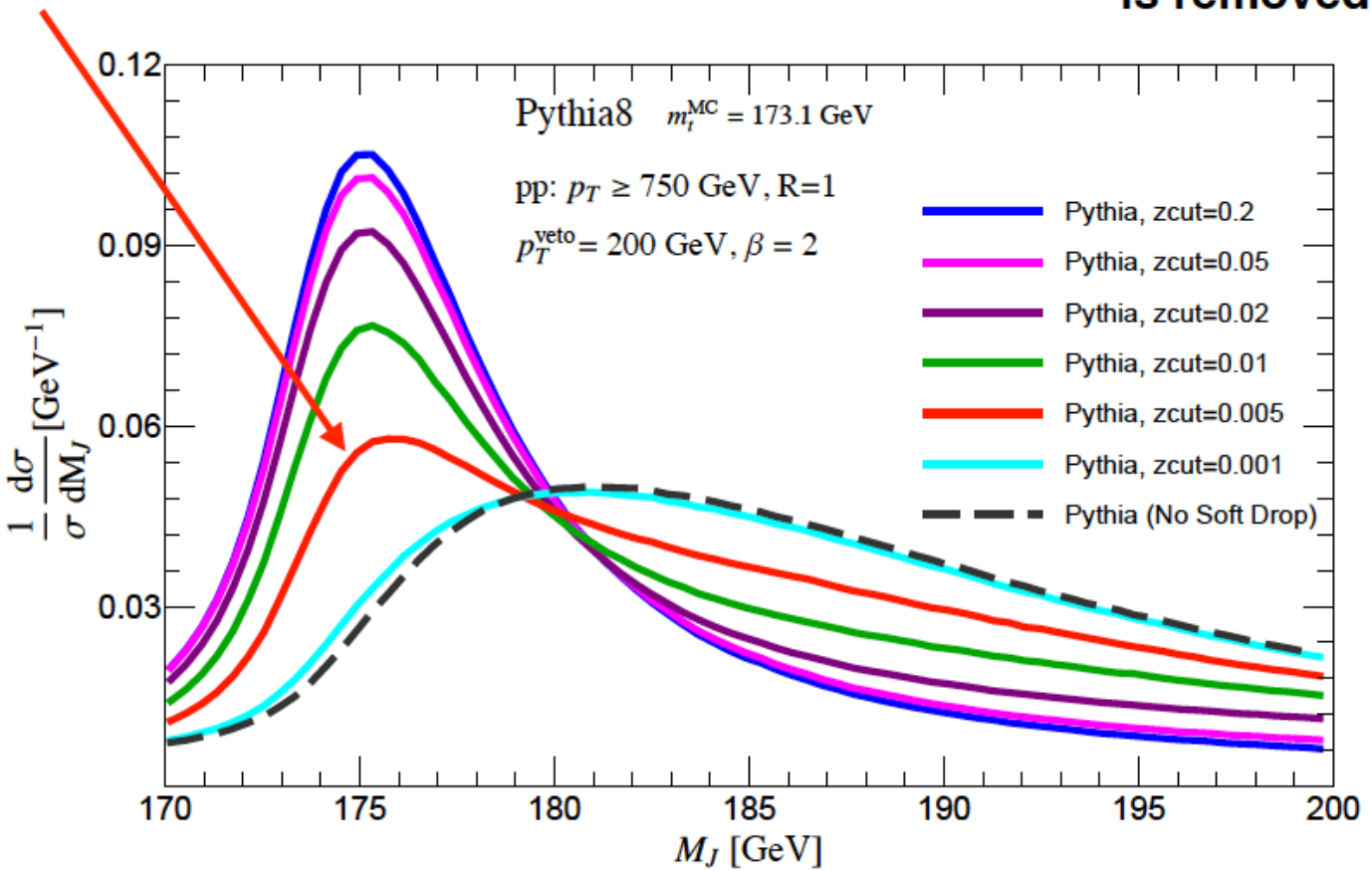
Extension to pp Collisions

AH, Mantry, Pathak, Stewart; arXive:1708.02586

z_{cut} dependence

predict transition for "light Soft Drop" ✓

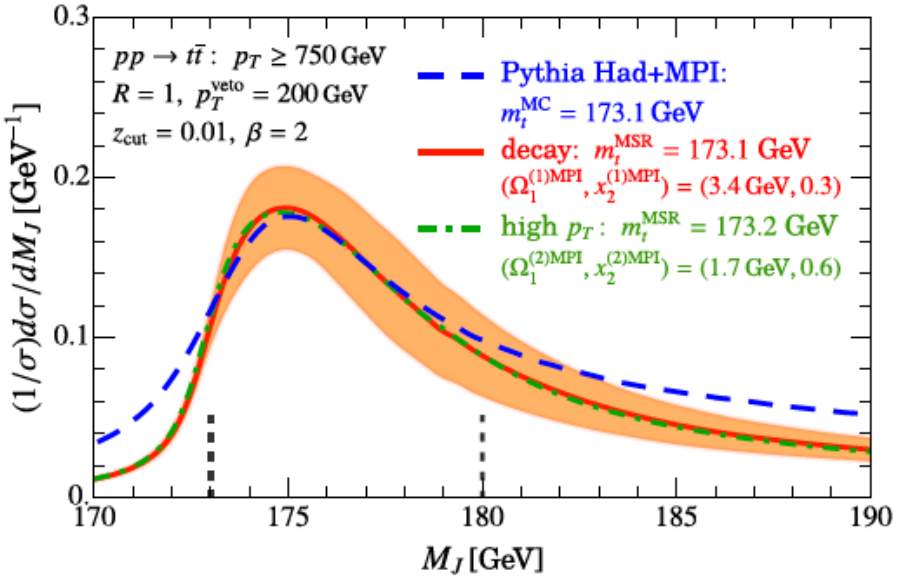
most contamination is removed

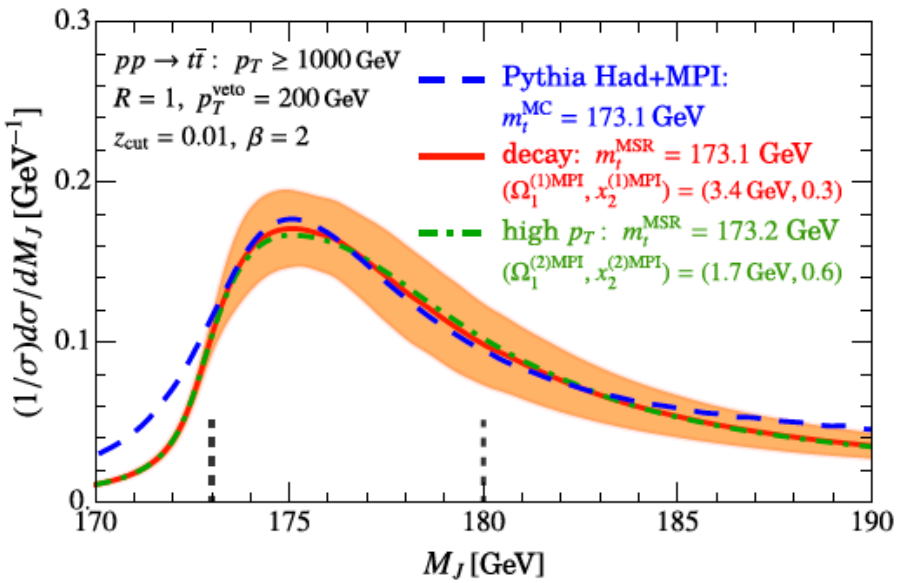


Extension to pp Collisions

AH, Mantry, Pathak, Stewart; arXive:1708.02586

Hadronization + MPI: MC mass and MSR mass compatible





Result very encouraging:

Realistic full hadron level jet mass distributions for boosted top quarks.

“Light grooming” restriction may be lifted. → separation of ultra-collinear modes

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

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

MSR Mass

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

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

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

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

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

- CB and MSR masses do not suffer from the $O(\Lambda_{QCD})$ renormalon $\rightarrow$ good convergence
- Uncertainty estimated from difference between α_s in $\overline{\rm MS}$ 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 needed for ILC top quark physics

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

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

Pole Mass

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

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

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

Lepenik, Preisser, AHH 2017

±110 MeV: Beneke, Marquard, Nason, Steinhause 2017

- Pole mass suffers from the $O(\Lambda_{QCD})$ renormalon $\rightarrow$ 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

- QCD factorization (e^+e^- τ_2 boosted) − MC (angular ordered parton shower) studies
  - We know m_t^{MC} at NLO for angular ordered parton showers (Herwig)
    Current limitation: NWA, boosted tops
  - Numerical calibration tool (NNLL/NLO) available for any MC

- Finite lifetime effects well known in QCD factorization
  → MC improvements in reach

- QCD factorization for top decay differential observables for boosted top quarks:
  → not available, difficult, but appear possible

- Comparable studies for direct reconstruction (low p_T unboosted top quarks):
  QCD factorization / analytic QCD currently out of reach → serious challenge

- Top mass problem requires scrutiny of MC event generators and is a vehicle to better understand the systematics of MCs and improve their theoretical prediction