Defining the Monte Carlo Top Mass Parameter

This talk reports on new work Oliver Jin,
Simon Plätzer and Daniel Samitz
which is being published soon and
arXiv:1807.06617

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∫dkΠ Doktoratskolleg Particles and Interactions

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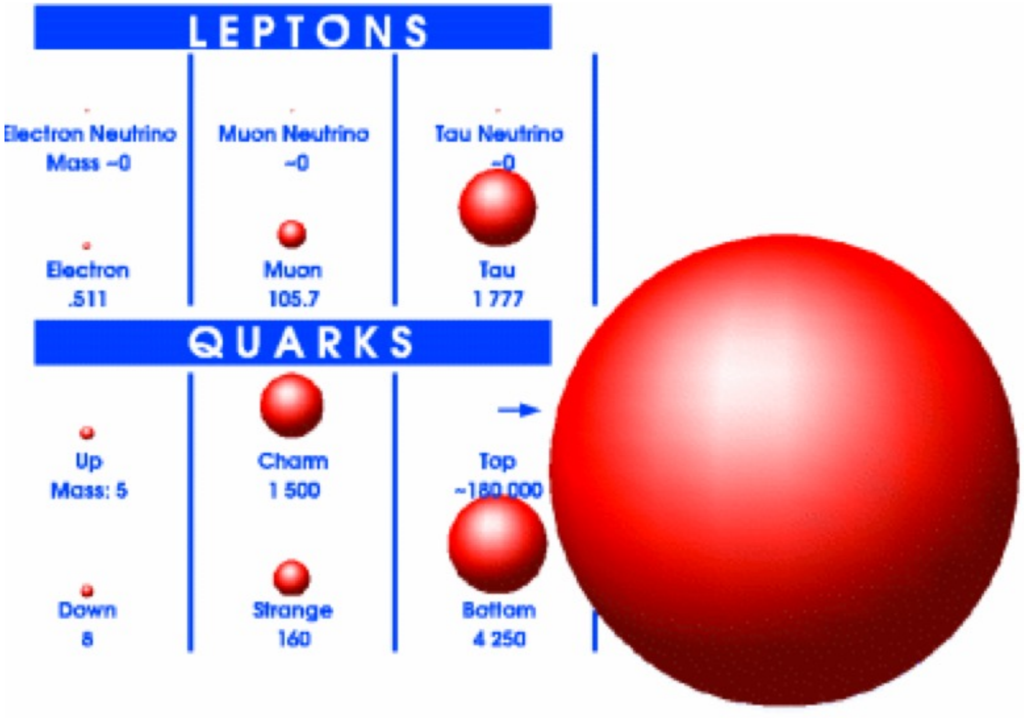
.. not just the heaviest SM particle

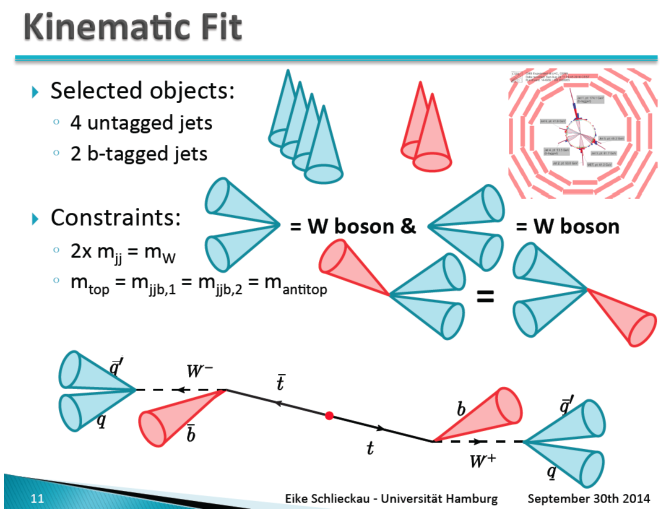


- Top quark: heaviest known particle
- Most sensitive to the mechanism of mass generation
- Peculiar role in the generation of flavor.
- Top might not be the SM-Top, but have a non-SM component.
- Top as calibration tool for new physics particles (SUSY and other exotics)
- Top production major background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

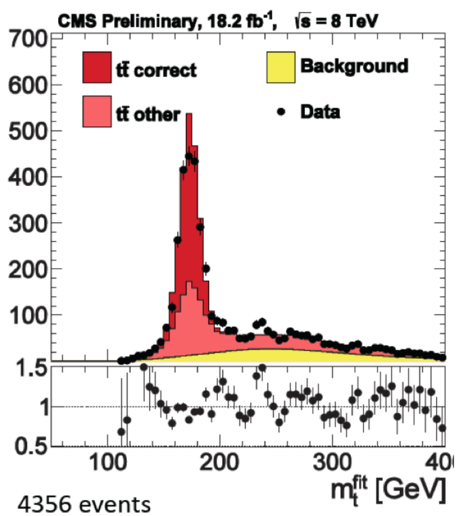
- Very special physics laboratory: $\Gamma_t \gg \Lambda_{QCD}$
  - Top treated a particle: p_T, spin, $\boldsymbol{\sigma}_{tot}$, $\boldsymbol{\sigma}$(single top), $\boldsymbol{\sigma}$(tt+X),.. $\rightarrow q \gg \Gamma_t$
  - Quantum state sensitive low-E QCD and unstable particle effects: m_t,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

Main Top Mass Measurements Methods

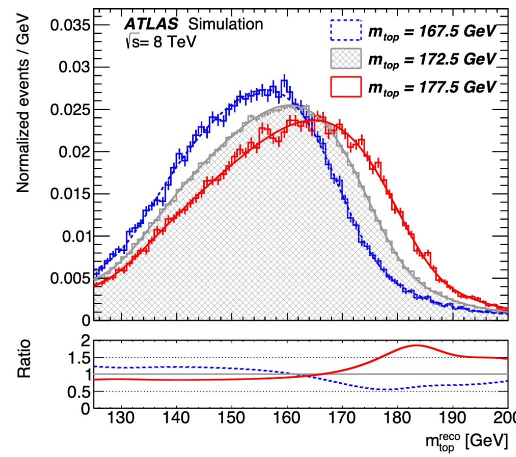
LHC+Tevatron: Direct top mass measurements



CMS-PAS-TOP-14-002



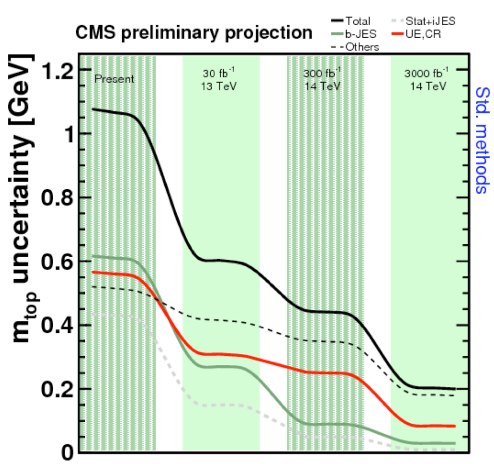
4356 events



kinematic mass determination

based on the picture of a top quark particle

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



$$m_t^{\rm MC} = 171.77 \pm 0.37 \text{ GeV}$$

CMS collaboration. arXiv: 2302.01967

⊕ High top mass sensitivity

⊖ Precision of MC ?

⊖ Meaning of m_t^{MC} ?

← Δ m_t ~ 200 MeV (projection)

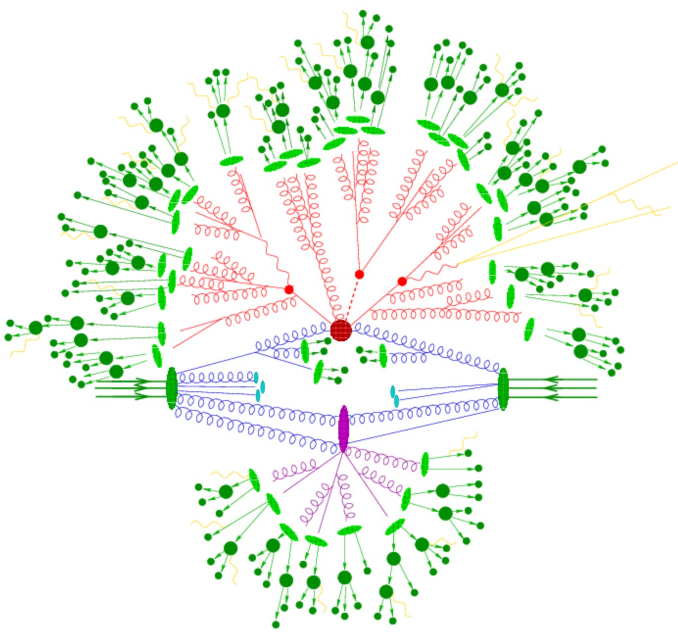
What is m_t^{MC} ?

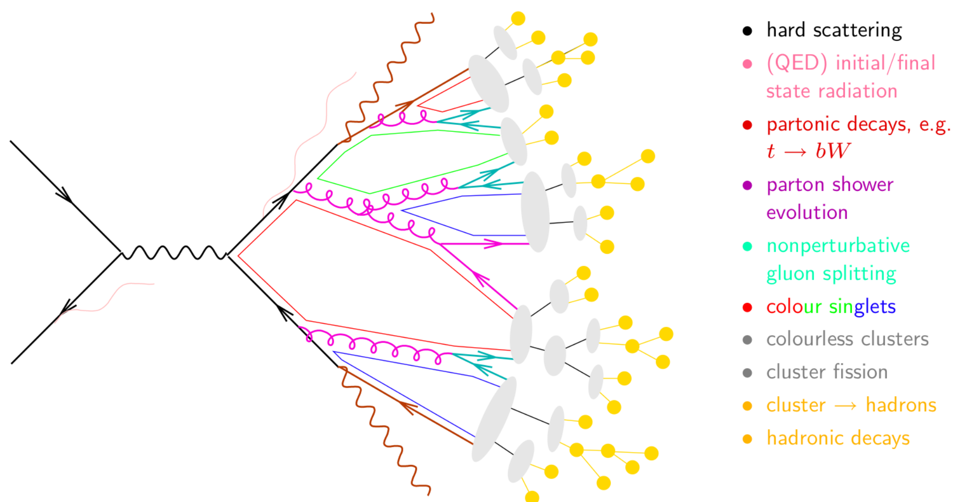
What does the question mean in the first place?

→ It means that we can provide the relation

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{scheme}}(\mu) + \frac{\alpha_s(\mu)}{\pi}\delta m^{\mathrm{scheme}} + \ldots$$

How can we address this messy question in the first place?





What is m_t^{MC} ?

What does the question mean in the first place?

→ It means that we can provide the relation $$m_t^{\rm MC} = m_t^{\rm scheme}(\mu) + \frac{\alpha_s(\mu)}{\pi}\delta m^{\rm scheme} + \ldots$$

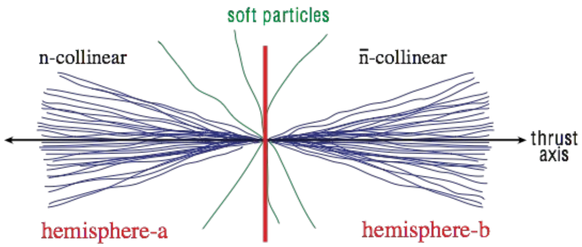
There are 4 essential ingredients to address the problem from first principles:

Understanding of top as a quantum state	NLL precise MC parton shower	Factorization compatible MC hadronization model	Hadron level analytic QCD predictions

Is there an observable where all 4 ingredients are known ?

Yes: Event-shape observables in e^+e^- collisions for boosted top pair production: 2-jettiness, thrust, …

Fleming, AHH, Mantry, Stewart 2007

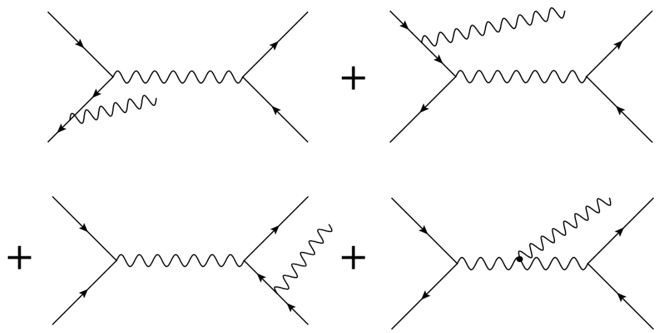


(A) Beyond the picture of a top particle

If we stick to the picture of a top particle the only mass that is ever relevant is the pole mass = pole of the top propagator.

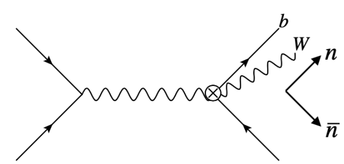
For boosted top quarks the effects of QCD and electroweak radiation (incl. top decay) in the top direction can be described by a QCD+electroweak Wilson line, which generalizes the top particle picture.

$$\psi_t(x) \to J_t(x) = W^\dagger(x)\psi_t(x)$$



$$\xrightarrow{\frac{m_t^2}{p_T^2} \ll 1}$$

n-collinear Wilson line



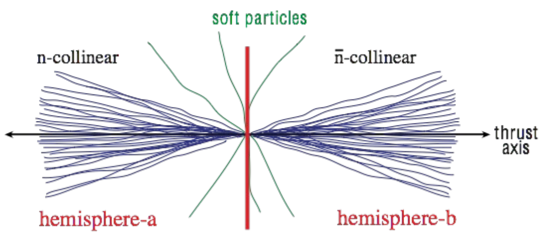
$$W_n(x) = \mathrm{P}\ \exp\left[-ig\int_{-\infty}^{0} \mathrm{d}s\,\bar{n}\cdot W^a(x+\bar{n}s)\tau^a + \ldots\right]$$

isospin generators($+\frac{1}{2}$ for top quark)

- Wilson line also contains gluons collinear with the top quark
- Describes coherent (collinear) gauge-invariant coherent off-shell (top decay products)+gluon states $\longrightarrow$ "top state" defined by measurement
- Process universality (in analogy to PDFs) $\longrightarrow$ factorization
- Only soft gluon radiation radiation is process dependent

This is not a new concept in QCD, but rather new for top decays. AHH, Plätzer, Regner, Ruffa w.i.p

(B) Boosted top eventshapes



$$\tau \;=\; 1 - \max_{\vec{n}} \frac{\sum_i |\vec{n}\cdot\vec{p}_i|}{Q} \;\overset{\tau\to 0}{\approx}\; \frac{M_1^2 + M_2^2}{Q^2}$$

Insensitive to details of top decay

$$Q = E_{\mathrm{c.m.}}$$

Hadron level:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau}(\tau, Q, m, \delta m) = \int_0^{Q\tau} \mathrm{d}\ell\, \frac{\mathrm{d}\hat{\sigma}_s}{\mathrm{d}\tau}\Big(\tau - \frac{\ell}{Q}, Q, m, \delta m\Big)\; S_{\mathrm{mod}}(\ell)$$

Partonic cross section

Shape function

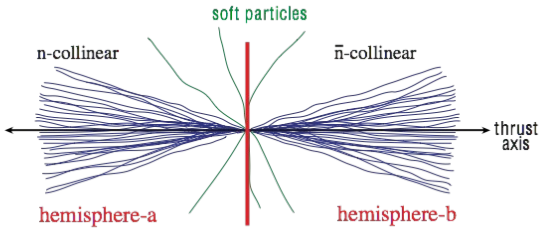
Partonic cross section (uses effective theories SCET, bHQET):

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

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

(B) Boosted top eventshapes

AHH, Plätzer, Samitz (2018)



$$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{n}\cdot\vec{p}_i|}{Q} \overset{\tau\to 0}{\approx} \frac{M_1^2 + M_2^2}{Q^2}$$

$$Q = E_{\rm c.m.}$$

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Hadron level:
$$\frac{d\sigma}{d\tau}(\tau, Q, m, \delta m) = \int_0^{Q\tau} d\ell\, \frac{d\hat{\sigma}_s}{d\tau}\left(\tau - \frac{\ell}{Q}, Q, m, \delta m\right)\, S_{\rm mod}(\ell)$$

Parton cross section

Shape function

- S_{mod} leading nonperturbative corrections <u>only from large-angle soft radiation</u>: linear sensitive to Λ_{QCD}
- Any top mass renormalization scheme can be implemented $m_t^{\rm pole} = m + \delta m$
- Can be calculated with a finite IR cut λ for the parton cross section:
  - Redefinition of S_{mod} (large-angle soft radiation)
  - Change of mass scheme: (ultra-collinear radiation)
    $m_t^{pole} \rightarrow m_t(\lambda) = m_t^{pole} - \delta m(\lambda)$, $\delta m(\lambda) \sim \alpha_s(\lambda)\,\lambda$

$m_t(\lambda)$ is the pole of the top propagator in the presence of the IR cutoff λ

(C) Angular ordered parton shower (Herwig)

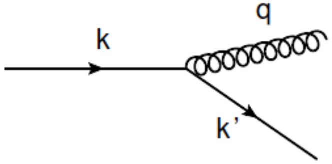
Partonic level cross section

Catani, Trentadue, Turnock Webber (1993)

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\tau} = \int \mathrm{d}k^2\, \mathrm{d}k'^2\, \delta\big(\tau - \frac{k^2 + k'^2}{Q^2}\big)\, J(Q^2, k^2) J(Q^2, k'^2)$$

AHH, Plätzer, Samitz (2018)

- Agrees exactly with partonic cross section obtained from analytic factorized calculations at NLL!
- CB is NLL precise for inclusive event shapes.
- For vanishing IR cutoff: CB mass parameter $m_t^{CB} = m_t^{pole}$



BUT: Parton showers in MC generators have an IR cutoff to prevent infinite multiplicities

$$q_\perp > Q_0$$

- Linear dependence on Q_0 from large-angle soft and ultracollinear radiation
- Matches analogous calculations for analytic calculations
- Realized accurately by Herwig's shower

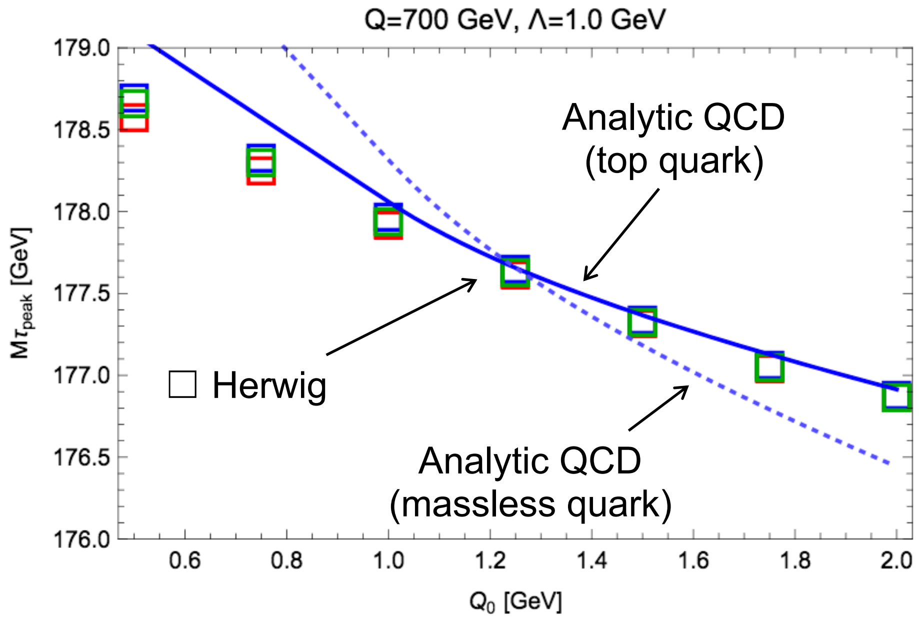
$$m_t^{\mathrm{CB}}(Q_0) = m_t^{\mathrm{pole}} - \frac{2}{3} Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s(Q_0)^2)$$

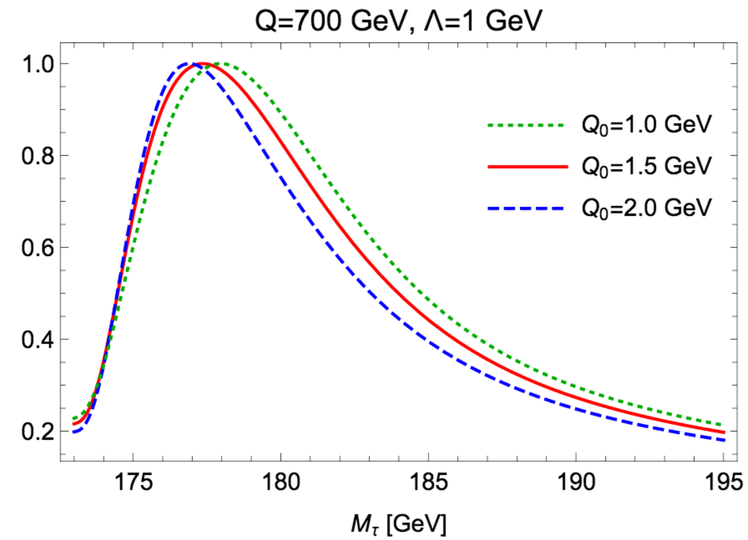
$$m_t^{\mathrm{CB}}(Q_0) = m_t^{\mathrm{MSR}}(Q_0) - \frac{2}{3}\left(1 - \frac{2}{\pi}\right) Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2(Q_0))$$

(C) Angular ordered parton shower (Herwig)

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

Parton level analysis (no hadronization corrections)





- Herwig parton level simulations in full agreement with analytic calculations
- Change of Q_0:

  Physical predictions should remain unchanged when

How well does a hadronization model satisfy this criterium?

- hadronization model is retuned (Q_0 dependent tune)
- generator mass is interpreted as $m_t^{CB}(Q_0)$

(D) Factorization compatible hadronization model

AHH, Jin. Plätzer, Samitz to appear

Standard shower cut treatment for all MC generators:

- Shower-cutoff scale Q_0 = one of many hadronization model parameters

BUT: To gain control over the shower's top mass parameter:

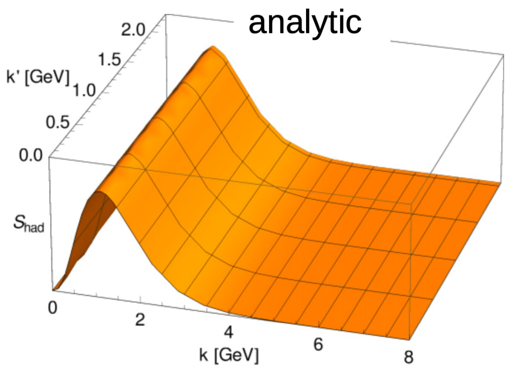
- The shower-cutoff scale Q_0 must be promoted to a factorization scale, such that hadron level descriptions are shower-cut independent. Plätzer arXiv:2204.06956
- The parton-level to hadron-level transfer matrix must behave like a shape function!

$$\frac{d\sigma}{d\tau}(\tau,Q) = \int d\hat{\tau}\,\frac{d\hat{\sigma}}{d\hat{\tau}}(\hat{\tau},Q)\,T(\tau,\hat{\tau},\{Q,Q_0\}))$$

Transfer matrix should have the property $T(\tau,\hat{\tau},\{Q,Q_0\}) = T(\tau-\hat{\tau})$

$$T\left(\frac{k}{Q}=\tau-\hat{\tau},\frac{k'}{Q}=\hat{\tau},\{Q,Q_0\}\right)$$

Transfer matrix should have this form:



(D) Factorization compatible hadronization model

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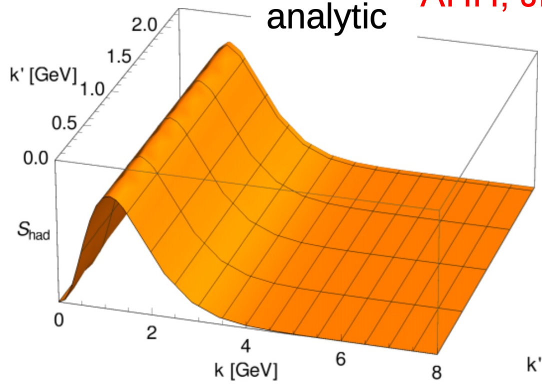
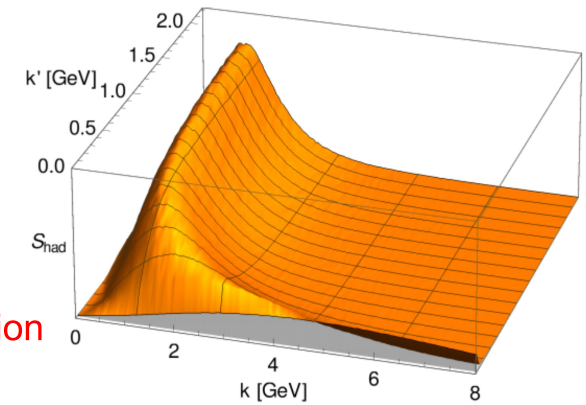
$$T\left(\frac{k}{Q}=\tau-\hat{\tau},\frac{k'}{Q}=\hat{\tau},\{Q,Q_0\}\right)$$

transfer matrix should have this form:

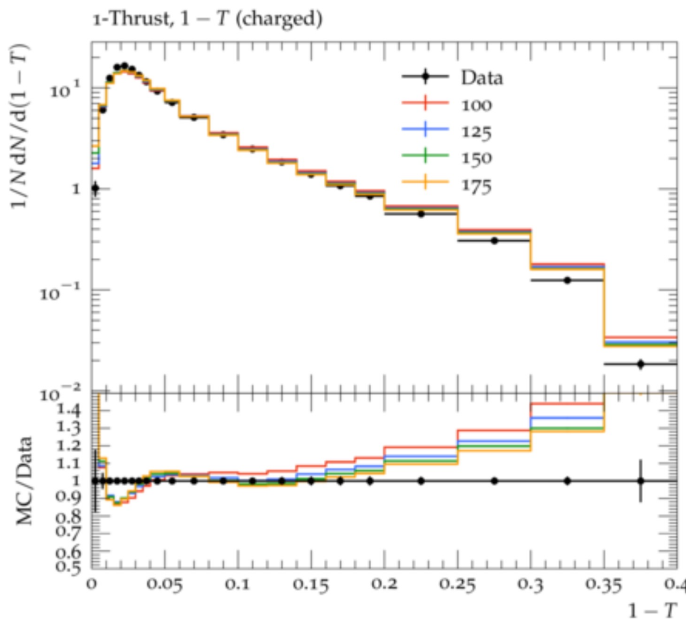


But it actually looks like this:

(Q_0= 1.00 GeV)



Peak region hadronization inconsistent with QCD factorization!



Description of observables not quite shower-cutoff independent (after tuning)

(Thrust at $Q=M_Z$)

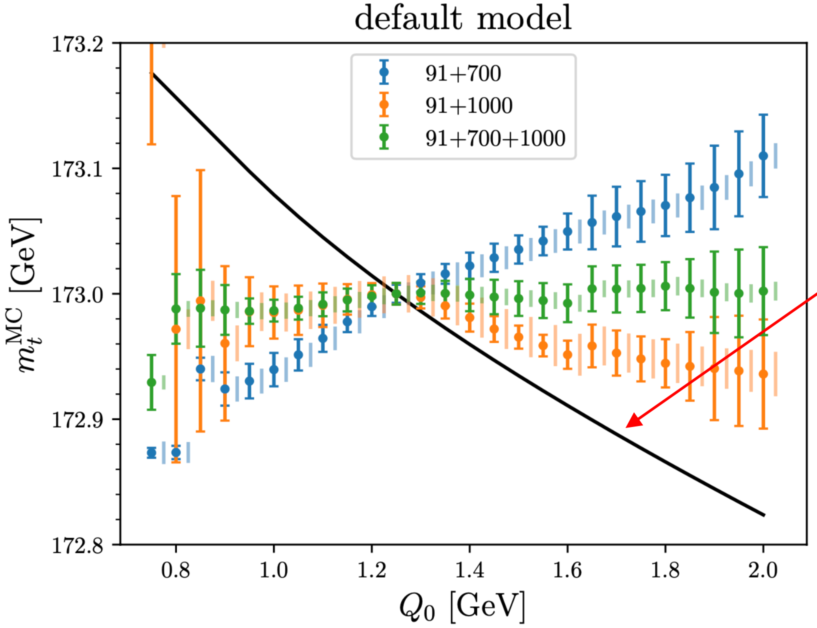
Q_0 = (1.00, 1.25, 1.50, 1.75) GeV

(D) Factorization compatible hadronization model

AHH, Jin. Plätzer, Samitz to appear

Include top "pseudo" 2-jettiness data into the standard tuning data set:

- Also tune the top mass parameter m_t^{MC} for different Q_0 values (to top pseudo data generated for Q_0=1.25 GeV



Q_0 dependence expected from $m_t^{CB}(Q_0)$

preliminary

Default Herwig hadronization model modifies m_t^{MC} in an unphysical way in compatible with QCD factorization.

→ $m_t^{Herwig}(Q_0) \neq m_t^{CB}(Q_0)$

Factorization compatible hadronization model

AHH, Jin. Plätzer, Samitz to appear

Dynamic model: forced gluon splitting

- If the splitting had taken place in the parton shower it would have been generated from the splitting function

$$\mathrm{d}P(g \to q\bar{q}) \sim \frac{\mathrm{d}q^2}{q^2}\alpha_s(q^2)\left(1 - 2z(1-z) + \frac{2m_q^2}{q^2}\right)\Theta\left(q^2 z(1-z) - m_q^2\right)$$

giving the gluon a virtuality q^2

- Use the probability distribution for this dynamically generated virtuality as „gluon constituent mass" m_g

- Set a highest possible scale for the non-pert. gluon splitting $\tilde{Q}_g$

(new tuning parameter instead of fixed m_g)

- Need to IR regularize the splitting function (because evolve below cutoff): $\mathrm{d}P(g \to q\bar{q}) \to \mathrm{d}\tilde{P}(g \to q\bar{q})$

    freeze out strong coupling at some low scale to avoid Landau pole

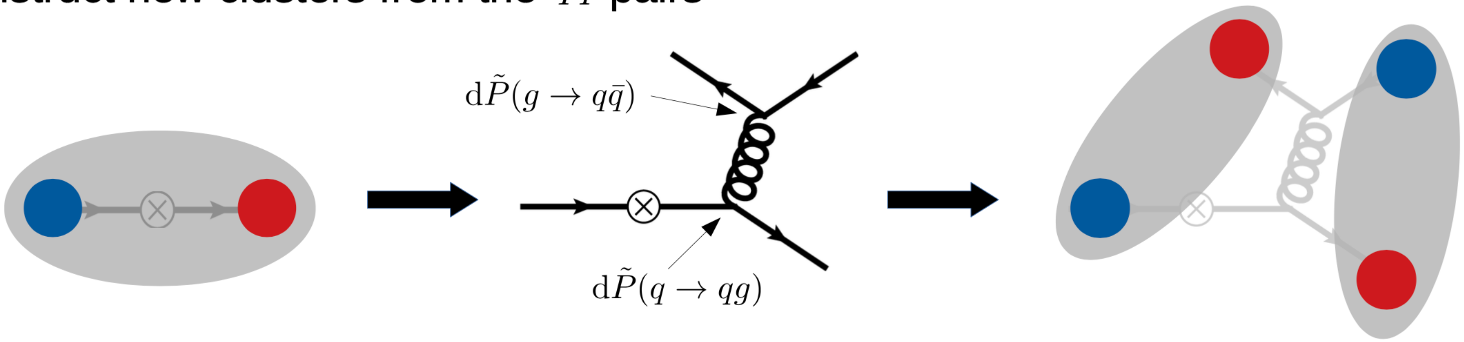
    use constituent masses for quarks

Factorization compatible hadronization model

AHH, Jin. Plätzer, Samitz to appear

Dynamic model: cluster fission

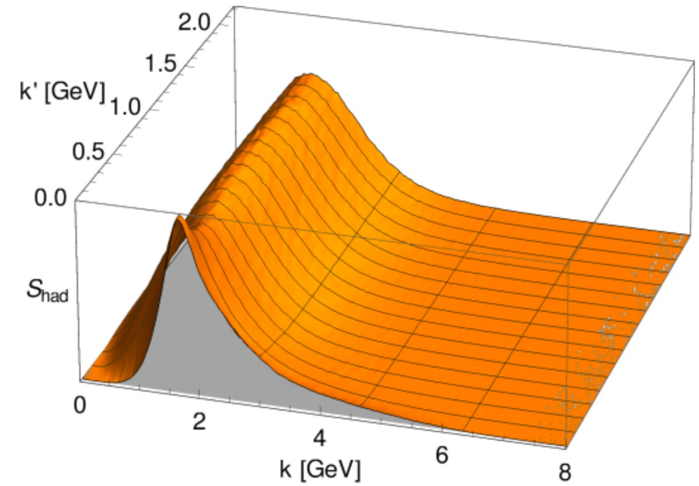
- Want a mass distribution of the daughter clusters that resembles as much as possible the mass distribution dynamically generated by low scale emissions of the parton shower
- Radiate a gluon from one of the cluster's constituents according to $\mathrm{d}\tilde{P}(q \to qg)$ set a maximum scale $\tilde{Q}_q$ of the splitting (new tuning parameter for fission instead of P_{Split})
- Split the gluon according to $\mathrm{d}\tilde{P}(g \to q\bar{q})$
- Construct new clusters from the $q\bar{q}$ pairs

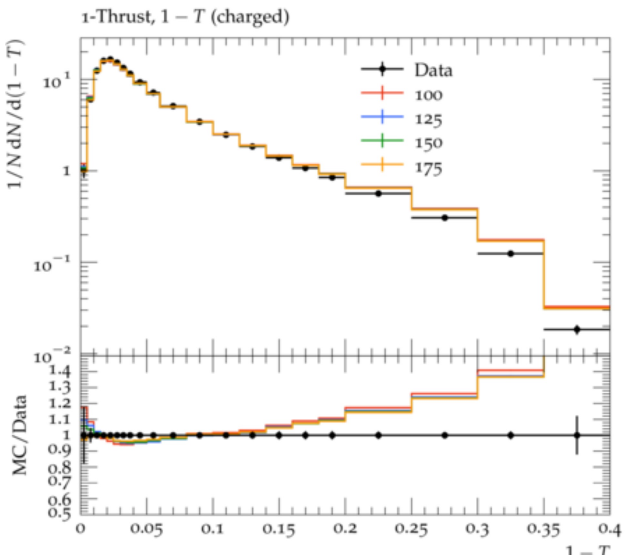


Factorization compatible hadronization model

AHH, Jin. Plätzer, Samitz to appear

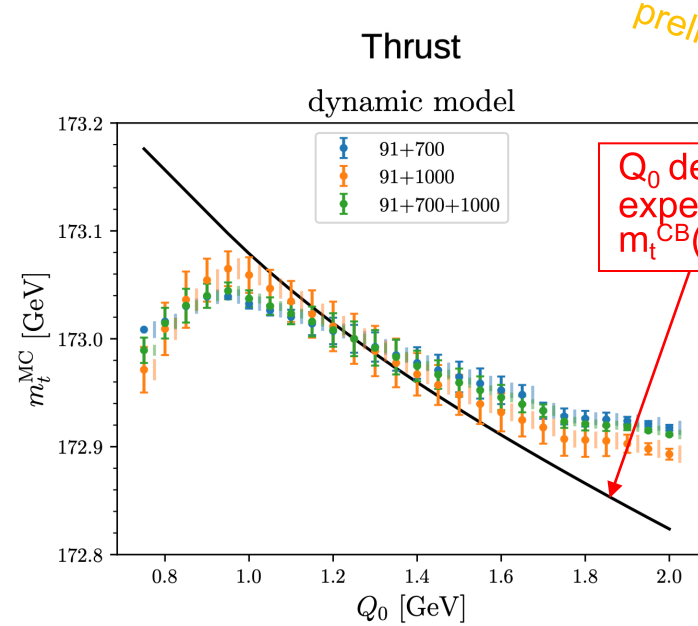
Transfer function much better consistent with QCD factorization





Observables much less dependent on Q_o

preliminary



Q_0 dependence expected from $m_t^{CB}(Q_0)$

Tunes m_t^{MC} fully consistent with expectations from analytic QCD calculation

(“pseudo data” generated for Q_0=1.25 GeV)

→ $m_t^{Herwig}(Q_0) = m_t^{CB}(Q_0)$

AHH, Jin. Plätzer, Samitz to appear

What is m_t^{MC} ?

What does the question mean in the first place?

→ It means that we can provide the relation $$m_t^{\rm MC} = m_t^{\rm scheme}(\mu) + \frac{\alpha_s(\mu)}{\pi}\delta m^{\rm scheme} + \ldots$$

There are 4 essential ingredients to address the problem from first principles:

Understanding of top as a quantum state

- Abandon top as on-shell asymptotic state ("top particle")
- Beyond narrow-width limit (top = top decay final states)
- Top has color and needs additional gluons to become observable
- Observable top state = coherent top+gluon (color singlet) state

Hadron level analytic QCD predictions

- NLL precise analytic QCD perturbative prediction
- First principles treatment of hadronization corrections
- NLO control over IR factorization scale for perturb. and non-pert. Effects
- Analytic description of shower cut Q_0 dependence

NLL precise MC parton shower

- NLL precision needed to achieve NLO accurate definition of m_t^{MC}
- Analytic NLO precision concerning the IR cutoff Q_0 or the parton shower evolution
- Shower cutoff Q_0 = an IR factorization scale
- Parton shower determines the meaning of $m_t^{MC}(Q_0)$

Factorization compatible MC hadronization model

- Shower cutoff Q_0 is not treated as a tuning variable, but as factorization scale
- Hadronization model has to respond to different choices of Q_0 to compensate for changes of Q_0 in the parton shower.
- Should not provide nonperturbative corrections to m_t^{MC}

→ The MC top mass parameter can be promoted to a renormalization scheme and its NLO relation to any other top mass renormalization scheme can be calculated.

Final remarks and Outlook

- Universality of the current insights
  - So far we have all theoretical ingredients to interpret m_t^{MC} only for e^+e^- eventshape distributions and the Herwig MC generator (coherent branching + cluster hadronization)
  - MC generators do not have the same precision for all observables
  - It could be that the parton shower cutoff Q_0 may lead to observable-dependent interpretations of m_t^{MC}
- Progress to generalize the current results will take many years of work because many new theory tools need to be developed (→ coherent top state)
- Upcoming: factorization of differential coherent (off-shell) top decay → observables such as E_{lepton}, $M_{b\text{-jet lepton}}$ for fiducial top states
- Future plans: dipole shower, string hadronization (Pythia)
- LHC: MPI and UE hadronization models still need to be better understood from the QCD perspective (→ theoretical brickwall for LHC hadronization models)

Old Default Model — New Dynamical Model

Shower cutoff dependence of predictions with tuned hadronization model