Matching Parton Shower Evolution and Hadronization: A Blueprint to resolve the MC top mass interpretation problem

This talk reports on new work Oliver Jin,
Simon Plätzer and Daniel Samitz

arXiv:1807.06617 arXiv:2404.09856 arXiv:2405.xxxxx

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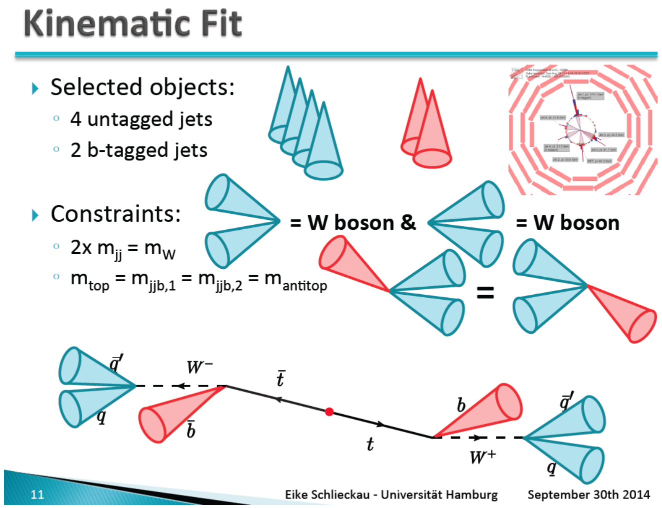
FWF Der Wissenschaftsfonds.

Particle Physics Seminar, IFIC Valencia May 22 2024

Most Precise Top Mass Measurements Method

LHC+Tevatron: Direct top mass measurements

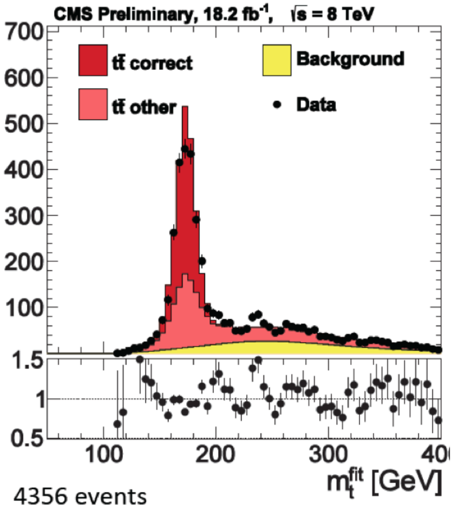


Kinematic Fit

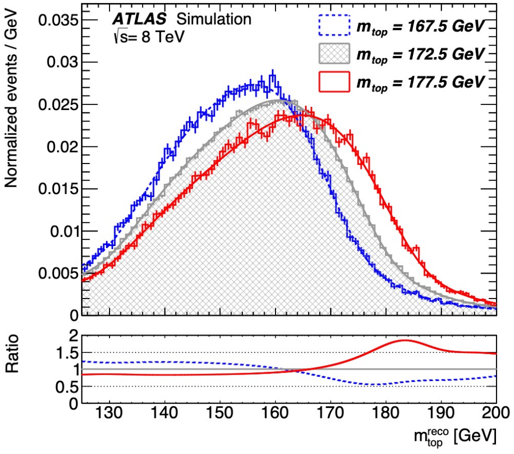
- Selected objects:
  - 4 untagged jets
  - 2 b-tagged jets
- Constraints:
  - 2x $m_{jj} = m_W$
  - $m_{top} = m_{jjb,1} = m_{jjb,2} = m_{antitop}$

11 Eike Schlieckau - Universität Hamburg September 30th 2014

CMS-PAS-TOP-14-002



4356 events



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

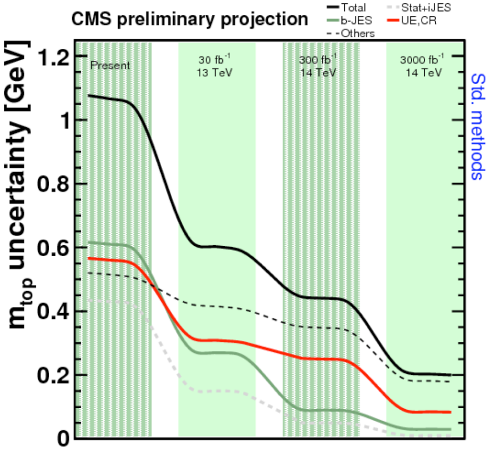
CMS collaboration. arXiv: 2302.01967

→ talk by Mark Owen

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



⊕ High top mass sensitivity

⊖ Precision of MC ?

⊖ Meaning of m_t^{MC} ?

← Δ m_t ~ 200 MeV (projection)

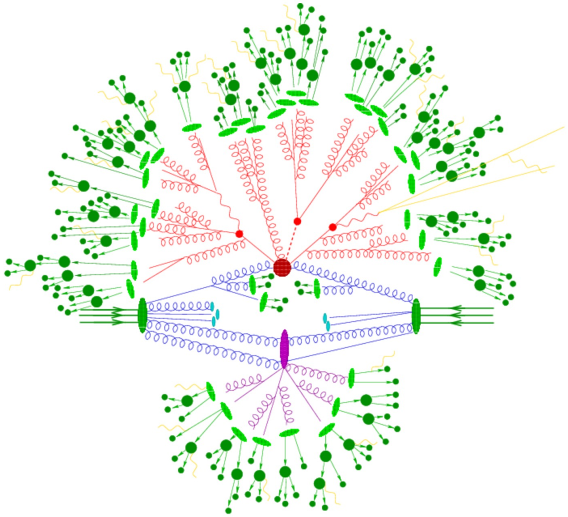
What is m_t^{MC} ?

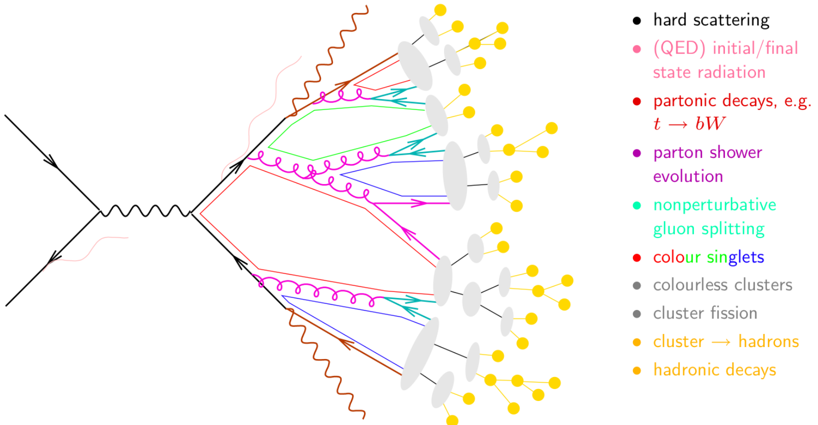
What does the question mean in the first place?

→ It means that we can provide the relation where $\delta m^{\mathrm{scheme}}$ can be **computed in pQCD**

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

The issue is messy as we must understand and control the interplay of the components of MC event generators.





→ The "**MC top mass scheme**"

- Defined in pQCD
- Controlled at the observable hadron level.

Approaches to remedy the m_t^{MC} problem

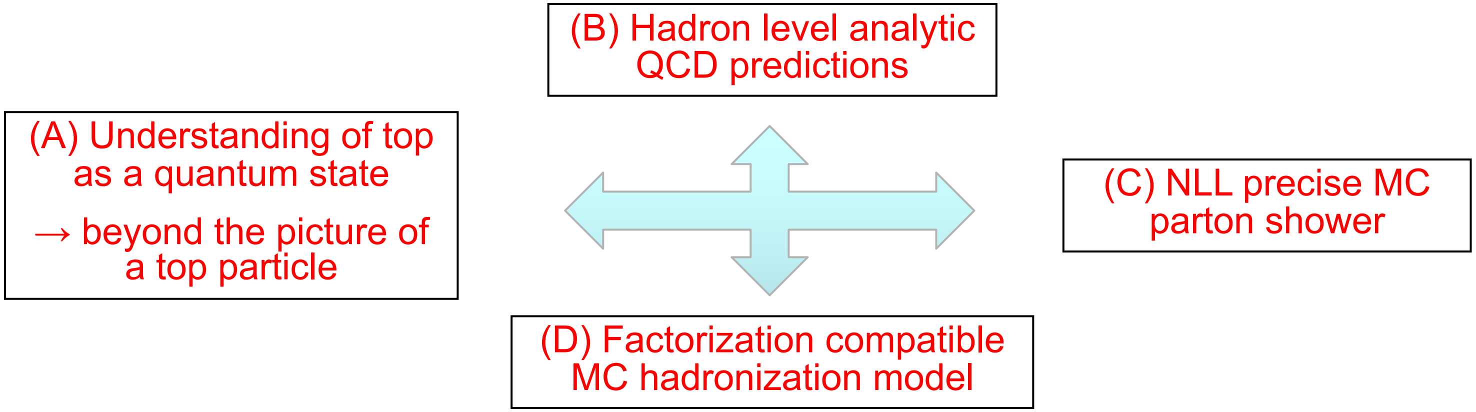
- Indirect top quark mass measurements → ATLAS/CMS e.g. arXiv:2403.01313
  - Unfold data to parton level top-anti top on-shell particle distributions (e.g. m_{tt}) to be compared to N(N)LO fixed order calculations for on-shell top quarks
  - MC modelling aspects now contained in the hadron-to-parton unfolding carried out with the MC generator (no "theory of unfolding")
  - Uncertainties not yet as small as for direct determinations as observables are of more inclusive character
- 'Hadron' level analytic predictions for top mass determinations (ongoing work)
  - Fat top jets with soft drop grooming
    → MPI currently provides a practical limitation for LHC

    Mantry, Pathak, Stewart (2017)
    Mantry, Pathak, Stewart (2019)
  - Energy correlators
    → new type of top mass sensitivity related to decay opening angle

    Holguin, Moult, Pathak, Procura (2022)
    Holguin, Moult, Pathak, Procura, Schöfbeck (2023)
- This talk is about work to truly understand and control the MC top quark mass parameter m_t^{MC} → Improve MCs so that direct measurements can (eventually) be interpreted reliably.

What is m_t^{MC} ?

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



(B) Hadron level analytic QCD predictions

(A) Understanding of top as a quantum state

→ beyond the picture of a top particle

(C) NLL precise MC parton shower

(D) Factorization compatible MC hadronization model

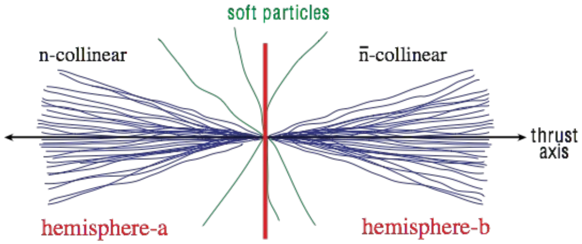
Currently there is only 1 observable where all 4 ingredients are available.

Event-shape observables in e^+e^- collisions

for boosted top pair production:

2-jettiness, thrust, …

(builds on sequence of work since 2007)



Aim of this talk:

- Discuss interplay of (A) – (D) provide conceptual and practical basis to determine and control m_t^{MC} for MC event generators
- (A) – (C) from previous work. New development for (D)
- Explicit realization for e^+e^- event-shape top resonance distribution (e.g. 2-jettiness) for Herwig 7.2

(A) Beyond the picture of a top particle

The top quark does not hadronize due to its large width $\Gamma_t \gg \Lambda_{QCD}$. It therefore has some characteristics of a physical particle (hadron).

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

Due to the top quarks color charge, however, this picture is too restricted when we want to understand the MC top quark mass.

What we mean by a top quark is however related to

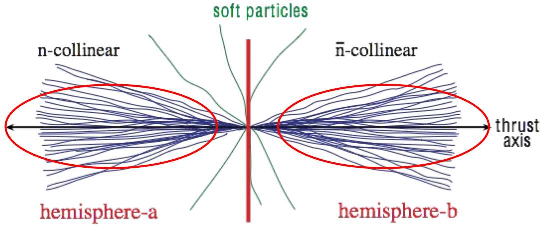
well known aspect

- a particular experimental measurement prescription (of a color singlet state)
  → calculations/simulations must properly account color neutralization effects
  → implies that we need accurate hadron level QCD predictions/simulations

novel aspect

- the way how we treat soft gluons in the top rest frame
  → MC simulations impose an IR cut Q_0 of the parton shower gluon radiation
  → the shower cutoff Q_0 act as a resolution scale
  → changes the physical meaning of the top quark (and its mass) in the simulation
  → impact of the shower cutoff needs to be quantified and controlled accurately

(B) Boosted top eventshapes



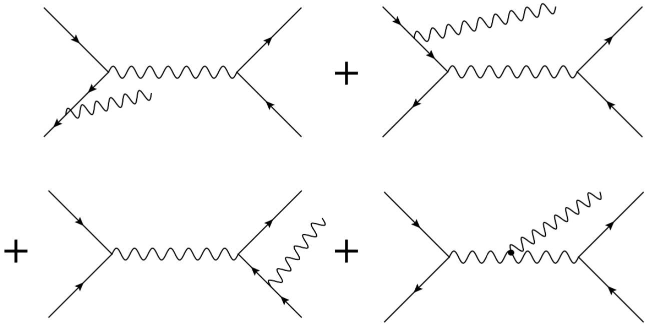
$$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{n}\cdot\vec{p}_i|}{Q} \overset{\tau\to 0}{\approx} \frac{M_1^2 + M_2^2}{Q^2}$$

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

Insensitive to details of top decay

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

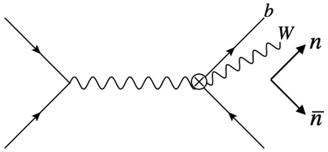
$$\psi_t(x) \to J_t(x) = W^\dagger(x)\psi_t(x)$$



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

SCET →

n-collinear Wilson line

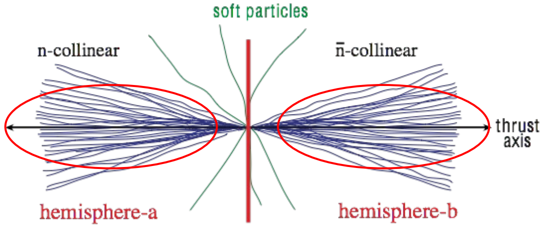


$$W_n(x) = \mathrm{P}\,\exp\left[-ig\int_{-\infty}^{0} \mathrm{d}s\,\bar{n}\cdot W^a(x+\bar{n}s)\tau^a + \ldots\right]$$

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

- Wilson line contains ultra-collinear gluons, soft in top rest frame (+ top decay)
- Describes coherent (collinear) gauge-invariant coherent off-shell (top decay products)+gluon states → "top state" defined by measurement
- Allows for gauge-invariant treatment of IR cutoff dependence for off-shell top → IR parton shower cutoff-dependence can be calculated

(B) Boosted top eventshapes



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

Insensitive to details of top decay

Hadron level:

$$\frac{d\sigma}{d\tau}(\tau, Q, m, \delta m) = \int_0^{Q\tau} d\ell \, \underbrace{\frac{d\hat{\sigma}_s}{d\tau}\Big(\tau - \frac{\ell}{Q}, Q, m, \delta m\Big)}_{\text{Parton cross section}} S_{\rm mod}(\ell)$$

Shape function

First principles prediction of QCD and NOT A MODEL !!

nonpert. large angle soft

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

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

pert. ultra-collinear soft

pert. large-angle soft

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

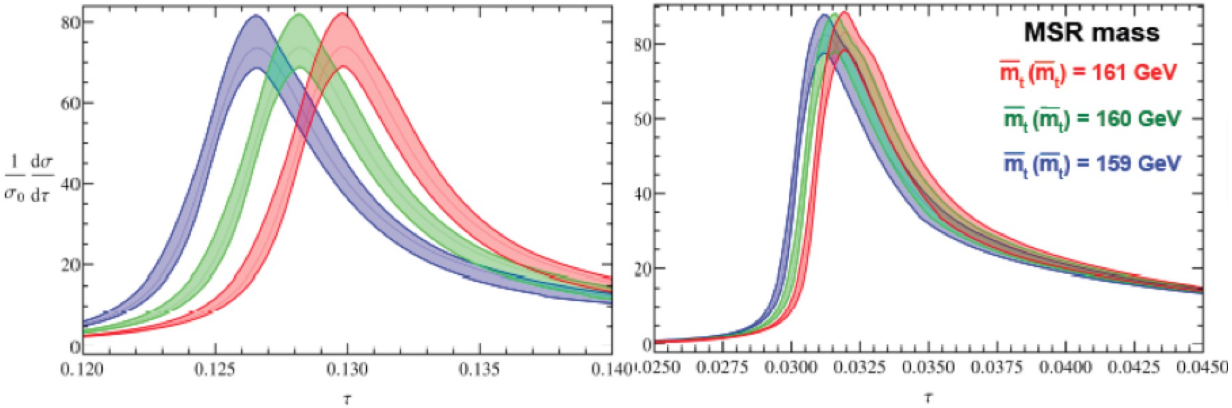
(B) Boosted top eventshapes

Accurate hadron level predictions

→ highly top mass sensitive

→ but still depend on the shape function that needs to be determined from experiment

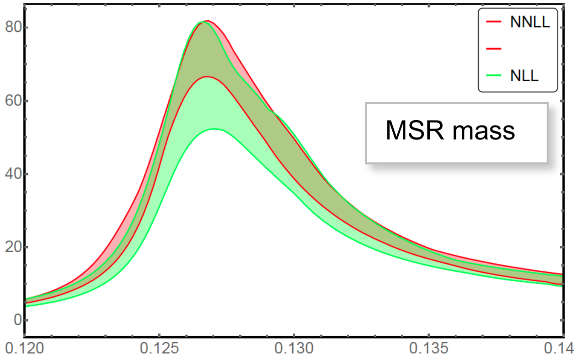
Q=700 GeV (p_T= 350 GeV)



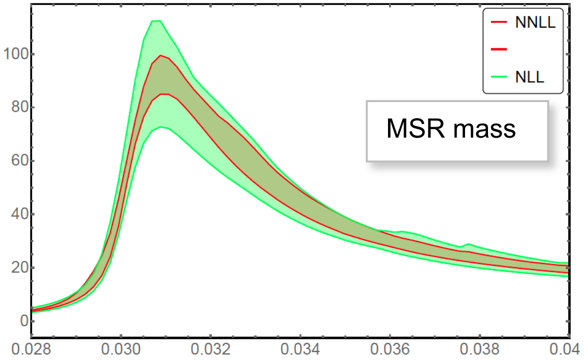
Available:

- NNLL+NLO (full)
- NNNLL+NLO (singular)

Q=700 GeV



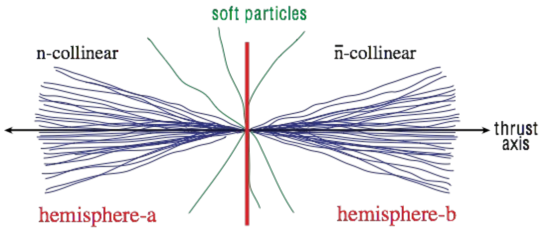
Q=1400 GeV



Dehnadi, AHH, Mateu, Stewart, arXiv:1608.01418

AHH, Pathak, Stewart arXiv:2012.12304

(B) Boosted top eventshapes



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

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

Insensitive to details of top decay

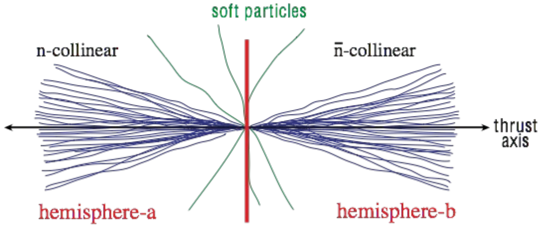
Hadron level:

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

- 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 $m_t^{\mathrm{pole}} = m + \delta m$

- Can be calculated with a finite IR cutoff Q_0 for the parton cross section
- IR cutoff Q_0 = factorization scale for parton-level vs. hadronization corrections
  - Defines scheme for S_{mod} (large-angle soft radiation): $S_{\mathrm{mod}}(l) \to S_{\mathrm{mod}}(l,Q_0)$
  - Defines scheme for parton distribution: $\frac{d\hat\sigma}{d\tau}(\tau,Q,m) \to \frac{d\hat\sigma}{d\tau}(\tau,Q,m,Q_0)$

(B) Boosted top eventshapes



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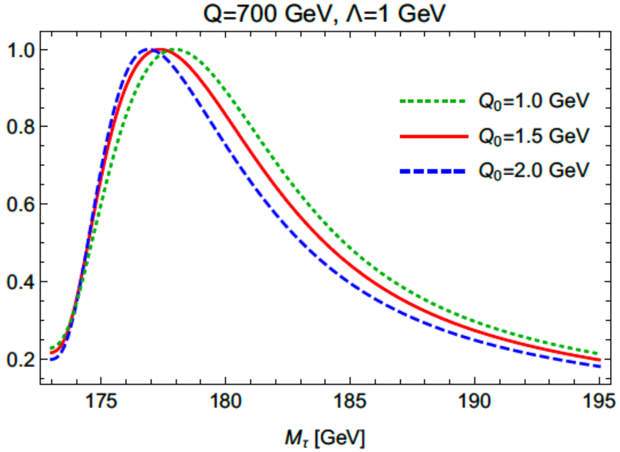
Insensitive to details of top decay

Hadron level:

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

- IR cutoff Q_0-dependent partonic cross section can be computed



For $q_\perp^{\mathrm{gluon}} > Q_0$:

$$\frac{d}{d\ln Q_0}\tau_{\mathrm{peak}}^{\mathrm{parton}}(Q_0) = \frac{C_F\alpha_s(Q_0)}{4\pi}\frac{Q_0}{Q}\left[16 - 8\pi\frac{m_t}{Q}\right]$$

large-angle soft

Must be compensated by hadronization corrections in S_{mod}

ultra-collinear (represents a mass correction)

Modifies pole of top propagator away from m_t^{pole} :

$m_t^{\mathrm{pole}} \longrightarrow m_t(Q_0) = m_t^{\mathrm{pole}} - \delta m(Q_0)$, $\delta m(Q_0) = 2/3\, \alpha_s(Q_0)\, Q_0 + \ldots$

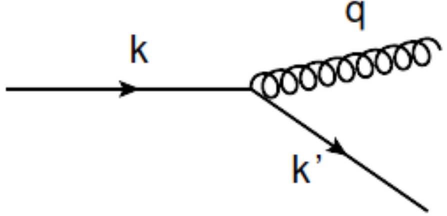
(C) Angular ordered parton shower (Herwig)

→ Coherent Branching algorithm (default Herwig shower):

Dokshitzer, Fadin, Khoze (1982)
Bassetto, Ciafaloni, Marchesini (1983)
Catani, Marchesini, Webber (1991)
Gieseke, Stephens, Webber (2003)

$$k'^\mu = z k^- \frac{n^\mu}{2} + \frac{k'^2 - q_\perp^2}{z k^-}\frac{\bar{n}^\mu}{2} - q_\perp^\mu$$

$$q^\mu = (1-z)k^- \frac{n^\mu}{2} + \frac{q^2 - q_\perp^2}{(1-z)k^-}\frac{\bar{n}^\mu}{2} + q_\perp^\mu$$



momentum conservation:

$$k^2 = \frac{k'^2}{z} + \frac{q^2}{1-z} + \frac{q_\perp^2}{z(1-z)}$$

evolution variables: $z\,,\ \tilde{q} = \dfrac{q_\perp^2}{z^2(1-z)^2}$

probabilities from splitting functions and Sudakov form factors

color coherence of soft gluon emissions → angular ordering: $z_i^2 \tilde{q}_i^2 > \tilde{q}_{i+1}^2$

→ analytic jet mass distribution (inv. mass generated from CB from one boosted quark)

$k^2 \approx$ hemisphere mass (does not account for out of cone radiation)

$$\begin{aligned} J(Q^2, k^2 - m^2, m^2) &= \delta(k^2 - m^2) \\ &+ \int_0^{Q^2} \frac{d\tilde{q}^2}{\tilde{q}^2} \int_0^1 dz\, P_{QQ}\big[\alpha_s(z(1-z)\tilde{q}), z, m\big]\, \theta\Big(\tilde{q}^2 - \frac{Q_0^2 + m^2(1-z)^2}{z^2(1-z)^2}\Big) \\ &\times \Big[zJ\big(z^2\tilde{q}^2, z(k^2-m^2) - z^2(1-z)\tilde{q}^2\big) - J\big(\tilde{q}^2, k^2 - m^2\big)\Big] \end{aligned}$$

(C) Angular ordered parton shower (Herwig)

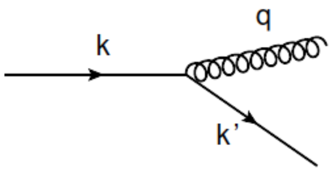
Partonic level cross section

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 $m_t^{\mathrm{CB}} = m_t^{\mathrm{pole}}$



BUT: Parton showers in MC generators have an finite shower cutoff Q_0 to prevent infinite multiplicities

$$\boxed{q_\perp > Q_0}$$

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

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

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

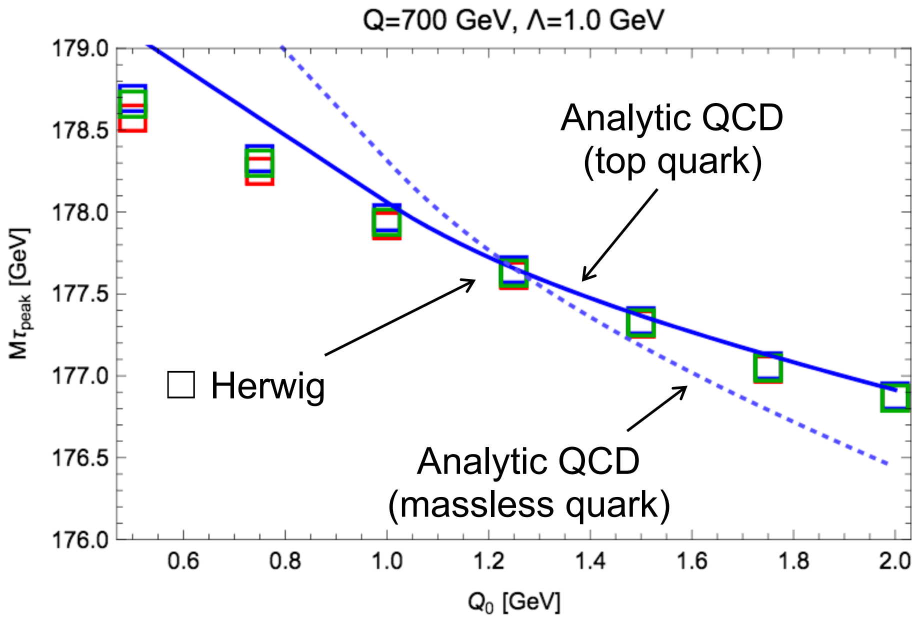
(C) Angular ordered parton shower (Herwig)

AHH, Plätzer, Samitz (2018)

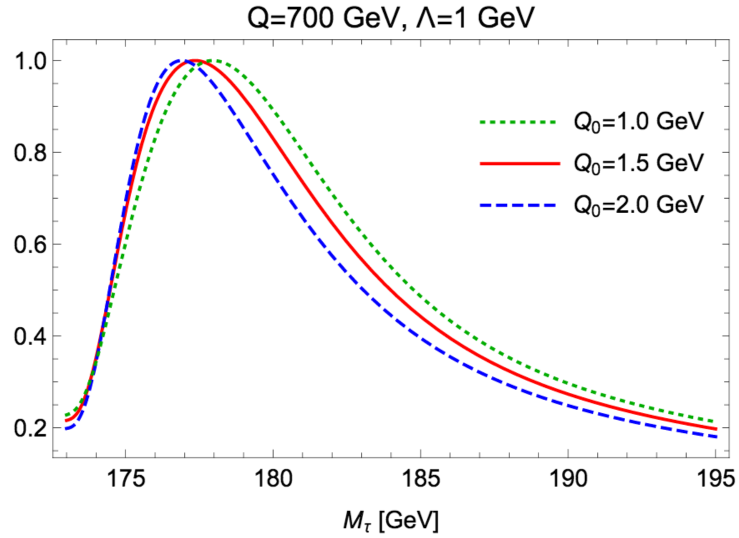
Peak position of $M_\tau = \dfrac{Q^2\tau_2}{2m_t} \quad (Q = E_{\rm cm})$

Parton level analysis (no hadronization corrections
fixed value for m_t)

$$\frac{d}{dQ_0}\tau_{\rm peak}(Q_0) = \frac{C_F\alpha_s(Q_0)}{4\pi}\frac{Q_0}{Q}\left[16 - 8\pi\frac{m_t}{Q}\right]$$



Q=700 GeV, Λ=1.0 GeV



Q=700 GeV, Λ=1 GeV

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

  Physical predictions should remain unchanged: Q_0-invariance

How well does a hadronization model satisfy this criterium?

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

(D) Factorization compatible hadronization model

AHH, Jin, Plätzer, Samitz
arXiv:2404.09856

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:

Plätzer arXiv:2204.06956

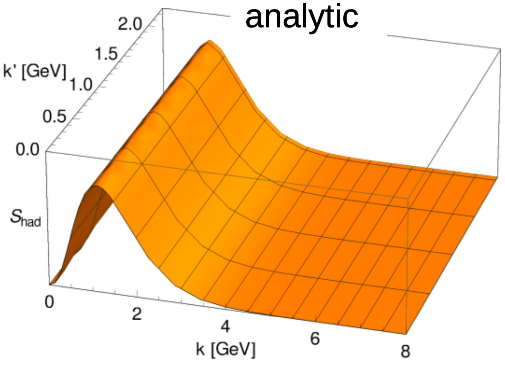
- The shower-cutoff scale Q_0 must be promoted to a factorization scale, such that hadron level descriptions are shower-cut independent.
- The parton-level to hadron-level migration matrix must behave like a shape function!

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

Migration 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:

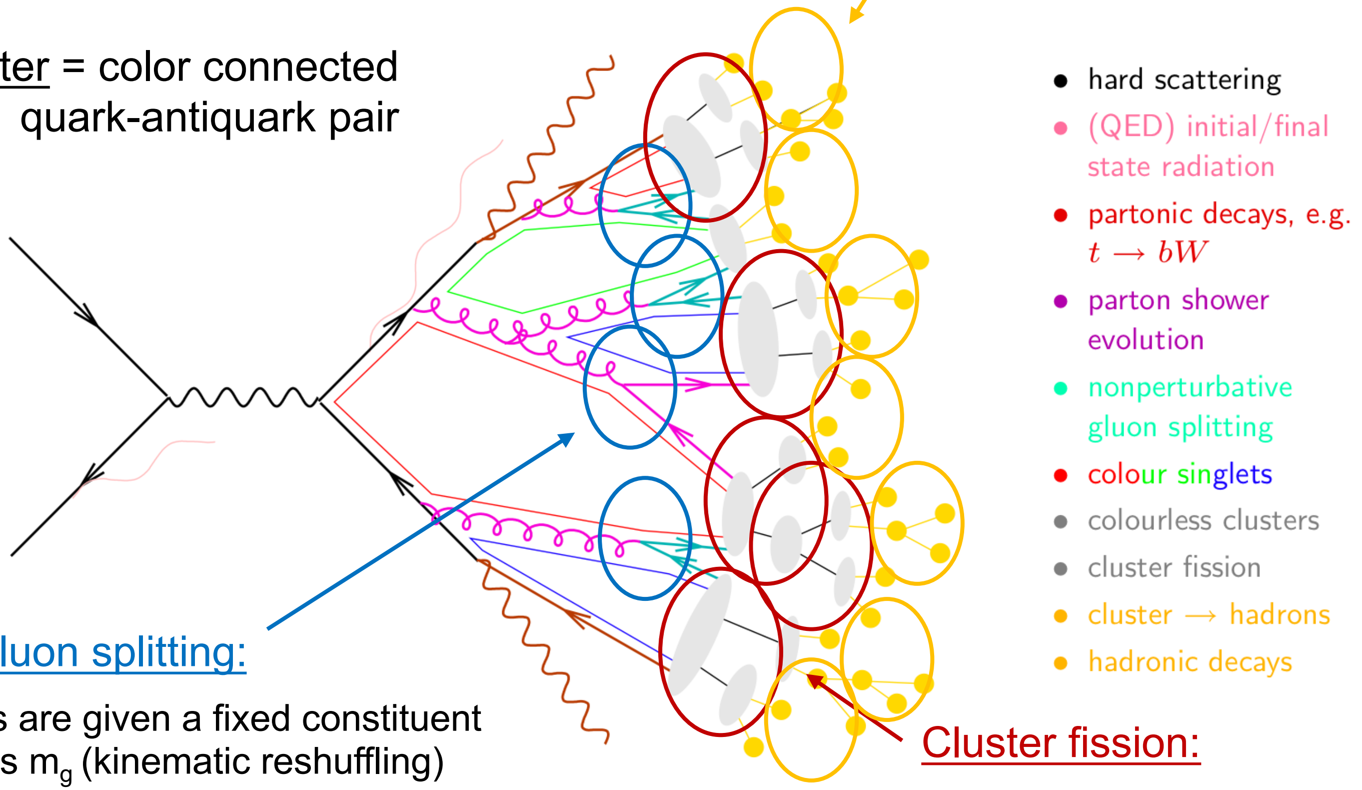


(D) Factorization compatible hadronization model

Cluster hadronization model (basics, no details):

Hadron formation and decays

Cluster = color connected quark-antiquark pair



Forced gluon splitting:

- Gluons are given a fixed constituent masses m_g (kinematic reshuffling)
- Isotropic decay into light qqbar pair in gluon rest frame

➡ Ad hoc modelling: unclear Q_0

Cluster fission:

- Cluster fission as a 1-dim process along the qqbar axis
- Adhoc functional ansatz for cluster mass distribution

Q_0-dependent tuning analyses

AHH, Jin, Plätzer, Samitz
arXiv:2404.09856

Tuning software: APPRENTICE

Reference tune = standard e^+e^- tune (Z-pole LEP data [3180 observable bins]

Reference data = simulated data for Q_0= 1.25 GeV for

- Z-pole LEP data [3180]
- Z-pole 2-jettiness [peak region]
- ttbar 2-jettiness at E_{cm} = 700 and 1000 GeV [peak region]

Q_0-dependent tunes: tunes to reference data for different shower cut Q_0 values

Tuned parameters: 6 tuning parameters + m_t^{MC}

Default model

- m_g (force gluon splitting)
- PSplit (cluster fission, mass distr.)
- Cl_{max} (cluster fission, condition)
- Cl_{pow} (cluster fission, condition)
- PwtSquark (cluster hadronization)
- PwtDIquark (cluster hadronization)

Interpolation grids: cubic and quartic polynomials

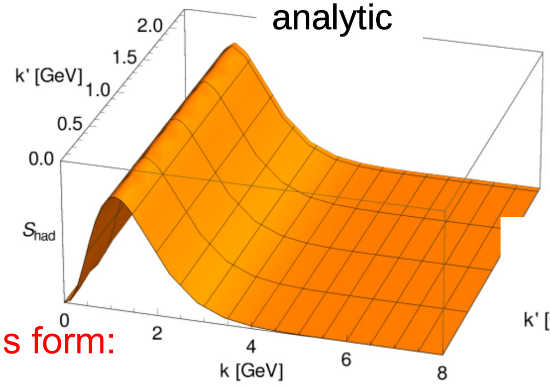
(D) Factorization compatible hadronization model

Predictions from Q_0-tuned MC simulations: LEP observables

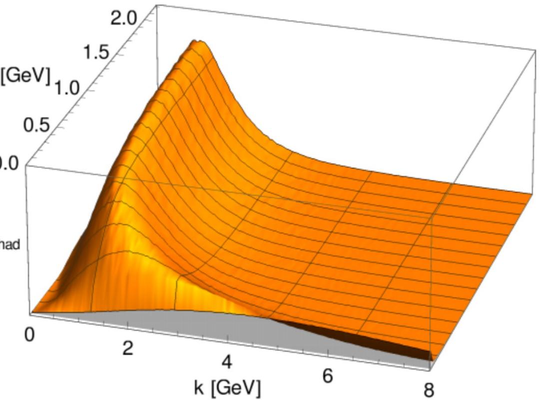
AHH, Jin, Plätzer, Samitz
arXiv:2404.09856

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

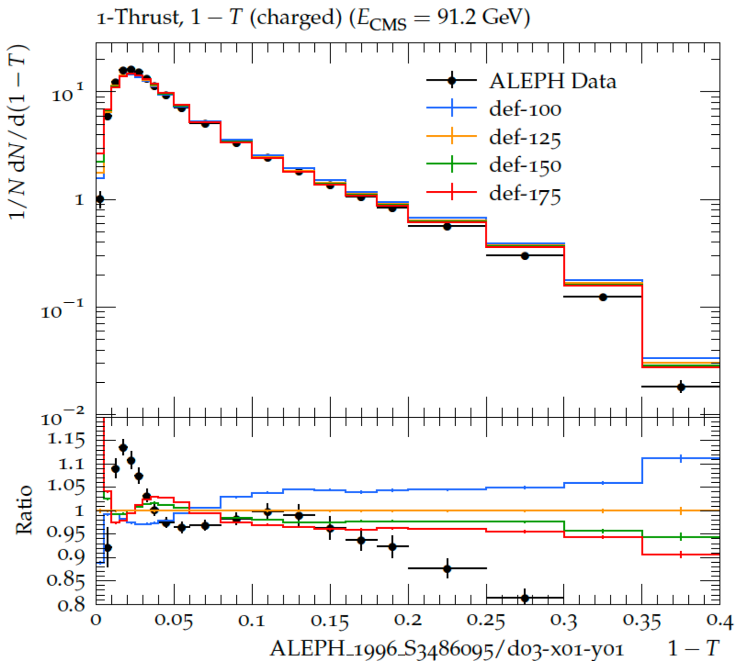
migration matrix should have this form:



But it actually looks like this:



Peak region hadronization inconsistent with QCD factorization!



Description of observables at hadron level not quite shower-cutoff independent (Thrust at $Q=M_Z$)

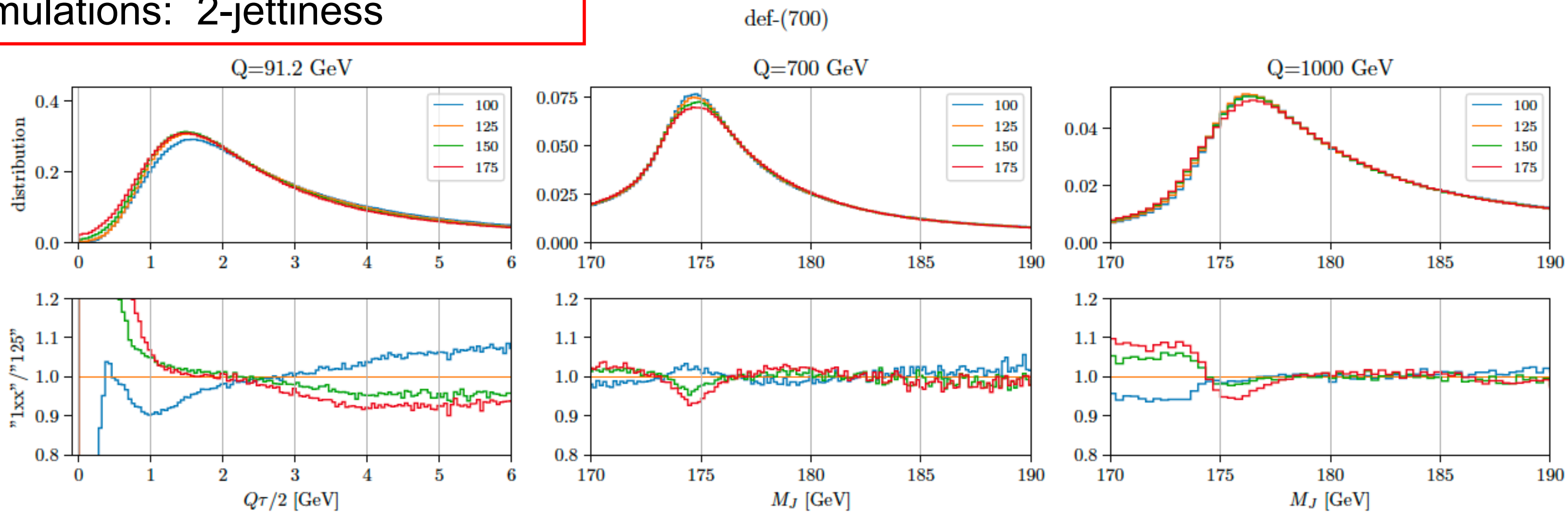
Q_0 = (1.00, 1.25, 1.50, 1.75) GeV

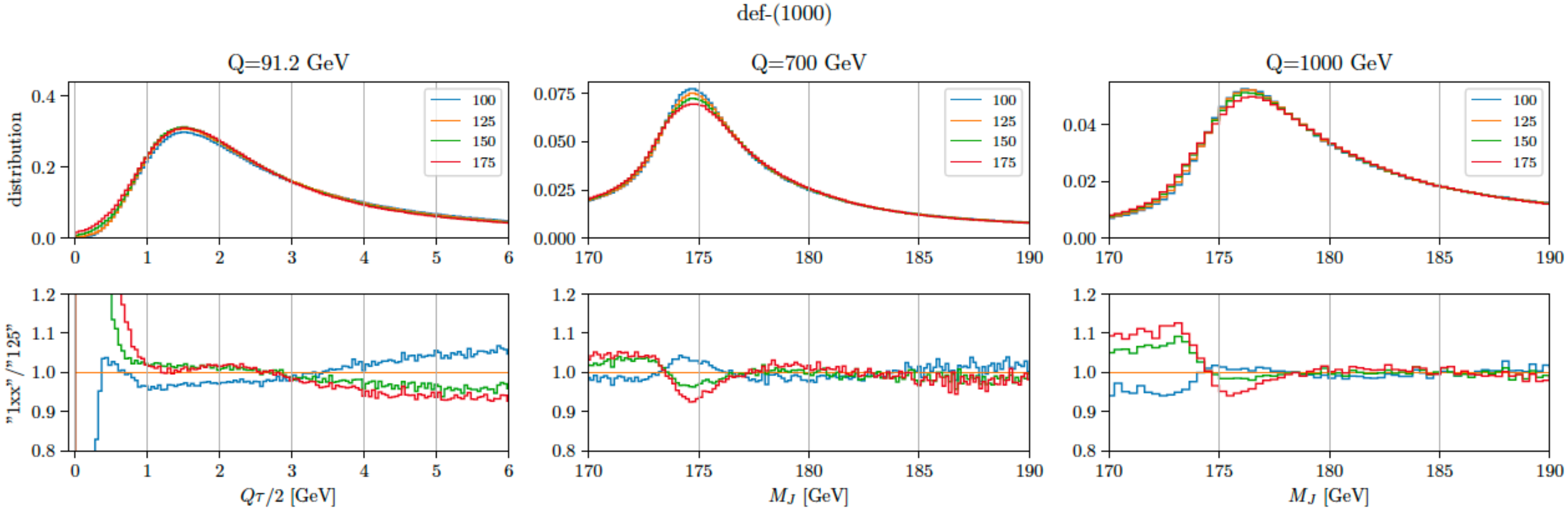
(Reference data for tune: Simulation for Q_0=1.25 GeV)

(D) Factorization compatible hadronization model

Predictions from Q_0-tuned MC simulations: 2-jettiness

AHH, Jin, Plätzer, Samitz
to appear



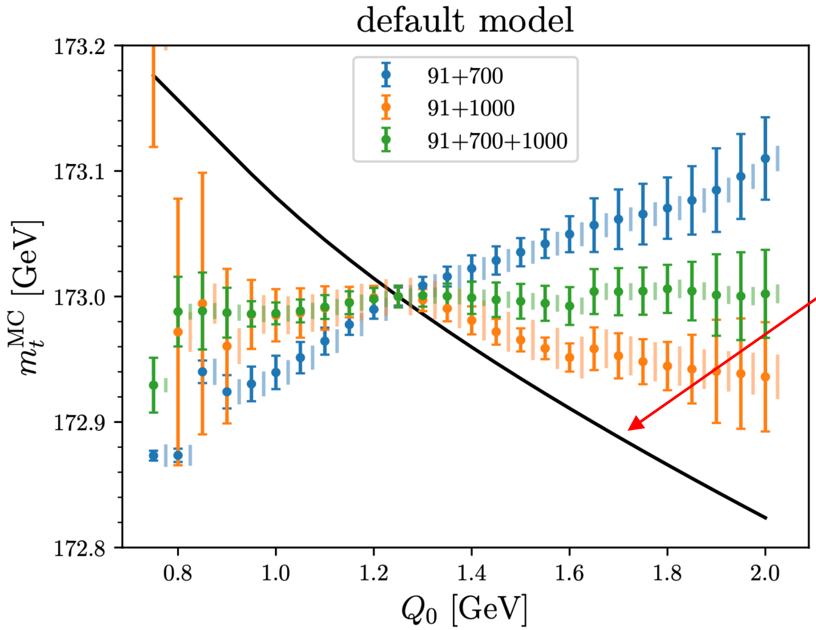


(D) Factorization compatible hadronization model

AHH, Jin. Plätzer, Samitz to appear

Q_0-dependent tunes m_t^{MC} :

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



Q_0 dependence expected if hadronization model would be consistent with QCD factorization

preliminary

Default Herwig hadronization model modifies m_t^{MC} in an unphysical way incompatible with QCD factorization: uncertainty ~ 0.5 GeV

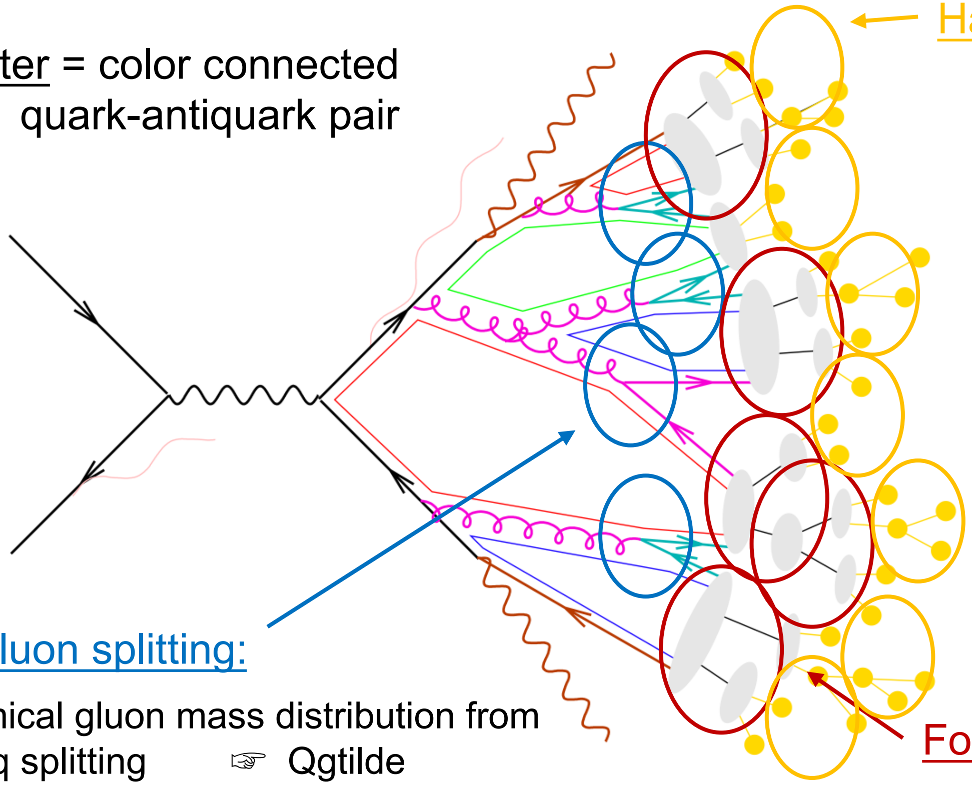
→ $m_t^{Herwig}(Q_0) \neq m_t^{CB}(Q_0)$ for the default hadronization model

(D) Factorization compatible hadronization model

AHH, Jin. Plätzer, Samitz 2024.09856

Modified cluster hadronization that mimics aspects of parton shower dynamics:

Cluster = color connected quark-antiquark pair



Hadron formation and decays

- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

Forced gluon splitting:

- Dynamical gluon mass distribution from g → qq splitting ☞ Qgtilde
- Kinematics in analogy to parton shower

Forced gluon splitting:

- Cluster splitting from branching q → q g and splitting g → qq ☞ Qqtilde
- Kinematics in analogy to the parton shower

➡ Model parameters can consistently adapt to changes of Q_0

Q_0-dependent tuning analyses

AHH, Jin, Plätzer, Samitz
arXiv:2404.09856

Tuning software: APPRENTICE

Reference tune = standard e^+e^- tune (Z-pole LEP data [3180 observable bins]

Reference data = simulated data for Q_0= 1.25 GeV for

- Z-pole LEP data [3180]
- Z-pole 2-jettiness [peak region]
- ttbar 2-jettiness at E_{cm} = 700 and 1000 GeV [peak region]

Q_0-dependent tunes: tunes to reference data for different shower cut Q_0 values

Tuned parameters: 6 tuning parameters + m_t^{MC}

Default model

- m_g (force gluon splitting)
- PSplit (cluster fission, mass distr.)
- Cl_{max} (cluster fission, condition)
- Cl_{pow} (cluster fission, condition)
- PwtSquark (cluster hadronization)
- PwtDIquark (cluster hadronization)

Dynamic model

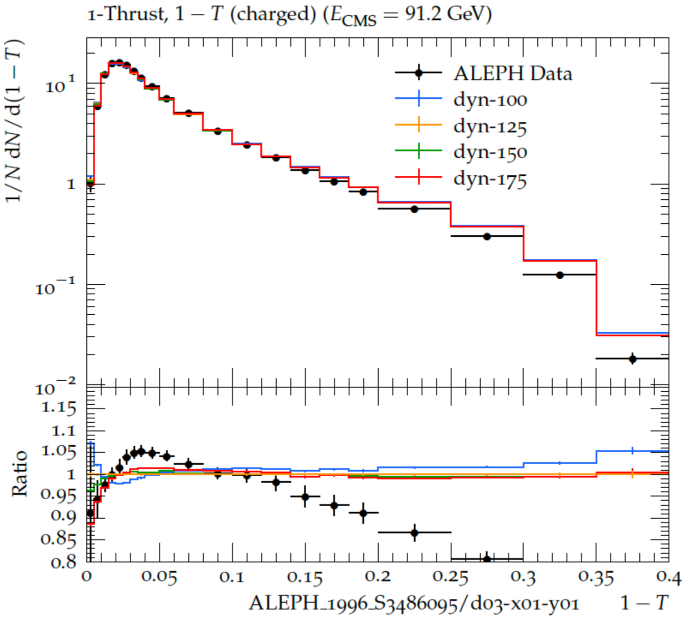
- Qgtilde (forced gluon splitting)
- Qqtilde (cluster fission splitting)
- Cl_{max} (cluster fission, condition)
- Cl_{pow} (cluster fission, condition)
- PwtSquark (cluster hadronization)
- PwtDIquark (cluster hadronization)

Interpolation grids: cubic and quartic polynomials

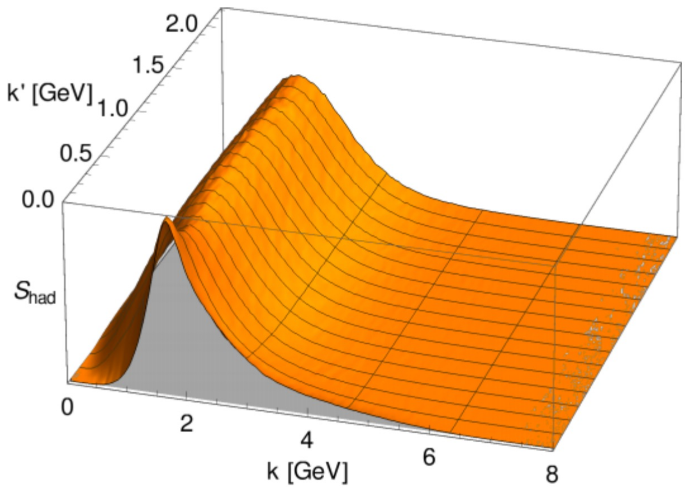
(D) Factorization compatible hadronization model

AHH, Jin. Plätzer, Samitz to appear

Migration function much better consistent with QCD factorization



Observables much less dependent on Q_o



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

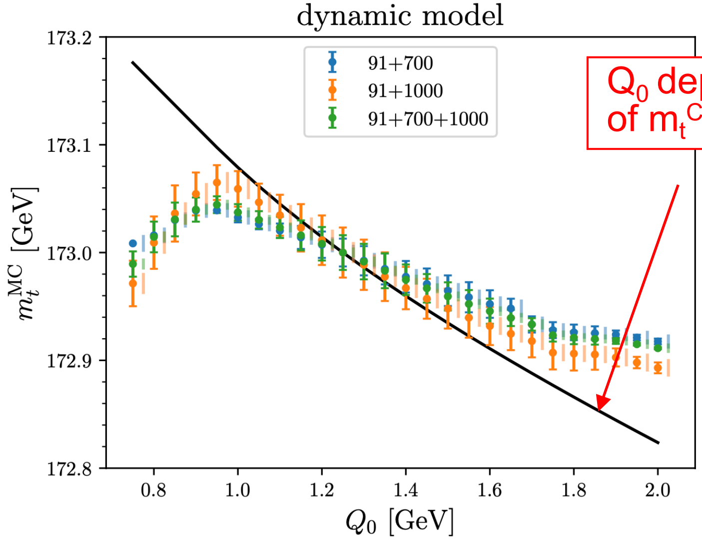
(“pseudo data” generated for Q_0=1.25 GeV)

⇒ $m_t^{\mathrm{Herwig}}(Q_0) = m_t^{\mathrm{CB}}(Q_0)$

within a precision of better than 50 MeV

preliminary

Thrust



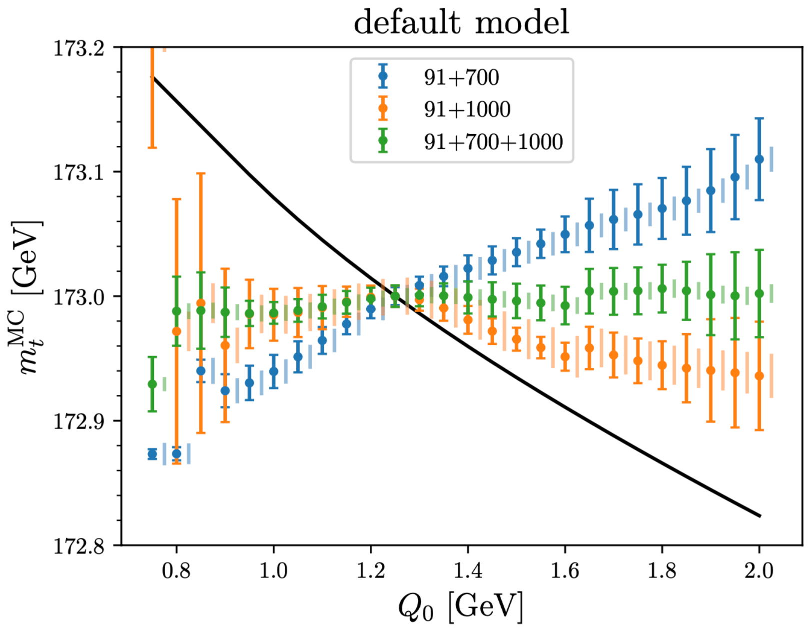
Q_0 dependence of $m_t^{CB}(Q_0)$

Old Default Model vs. New Dynamical Model

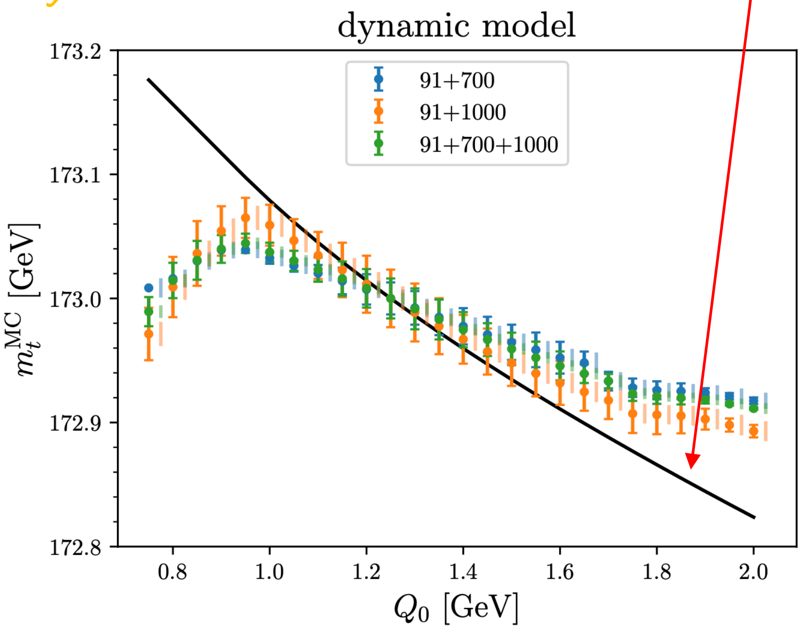
AHH, Jin. Plätzer, Samitz to appear

Shower cutoff dependence of tuned MC top quark mass to reference data including top quark 2-jettiness distributions at 700 and/or 1000 GeV

preliminary



Q$_0$ dependence expected from m$_t^{CB}$(Q$_0$)

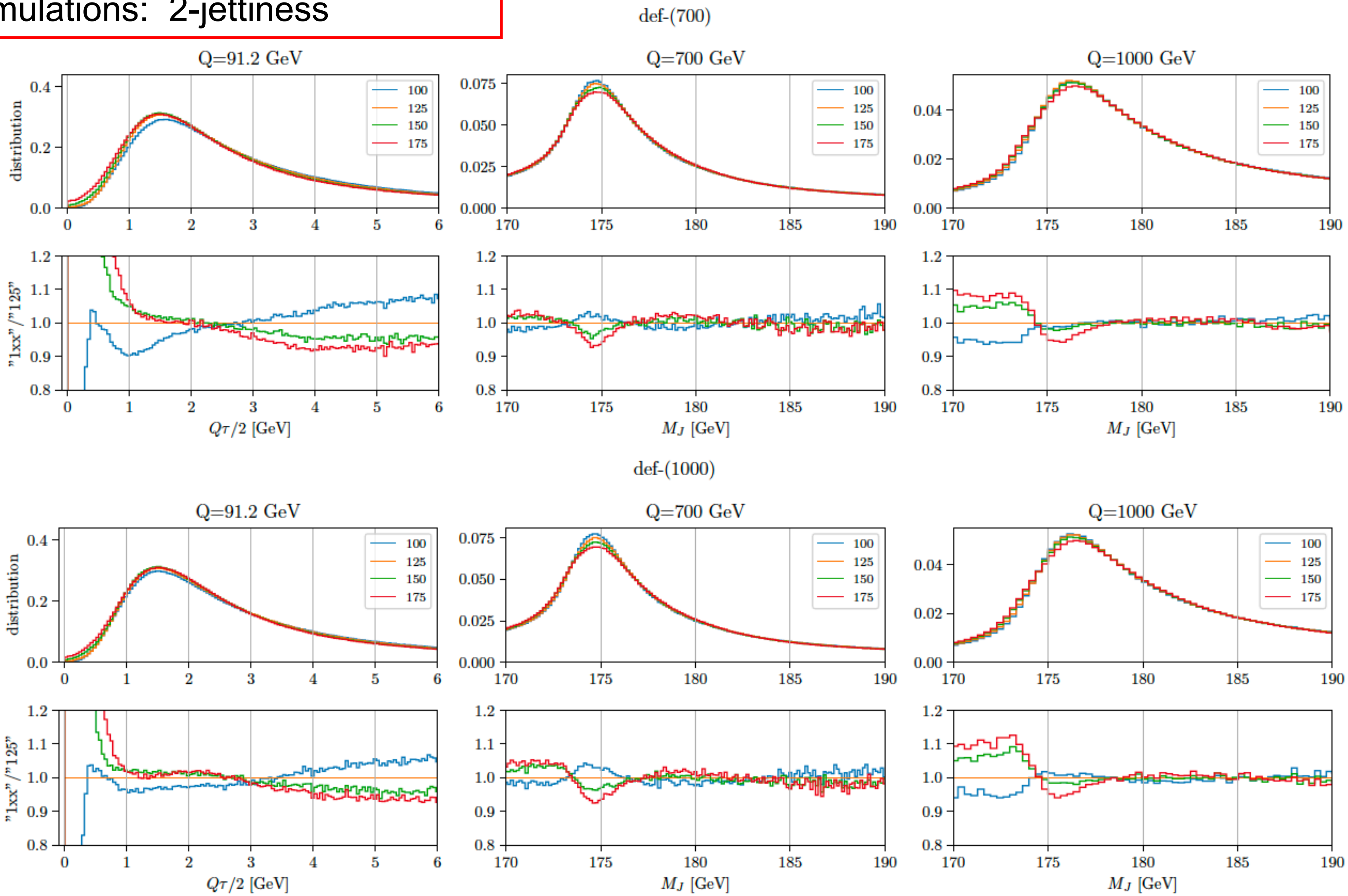


Agreement of m$_t^{MC}$ with m$_t^{CB}$(Q$_0$) within 50 MeV !

Old Default Model vs. New Dynamical Model

Predictions from Q_0-tuned MC simulations: 2-jettiness

AHH, Jin, Plätzer, Samitz
to appear

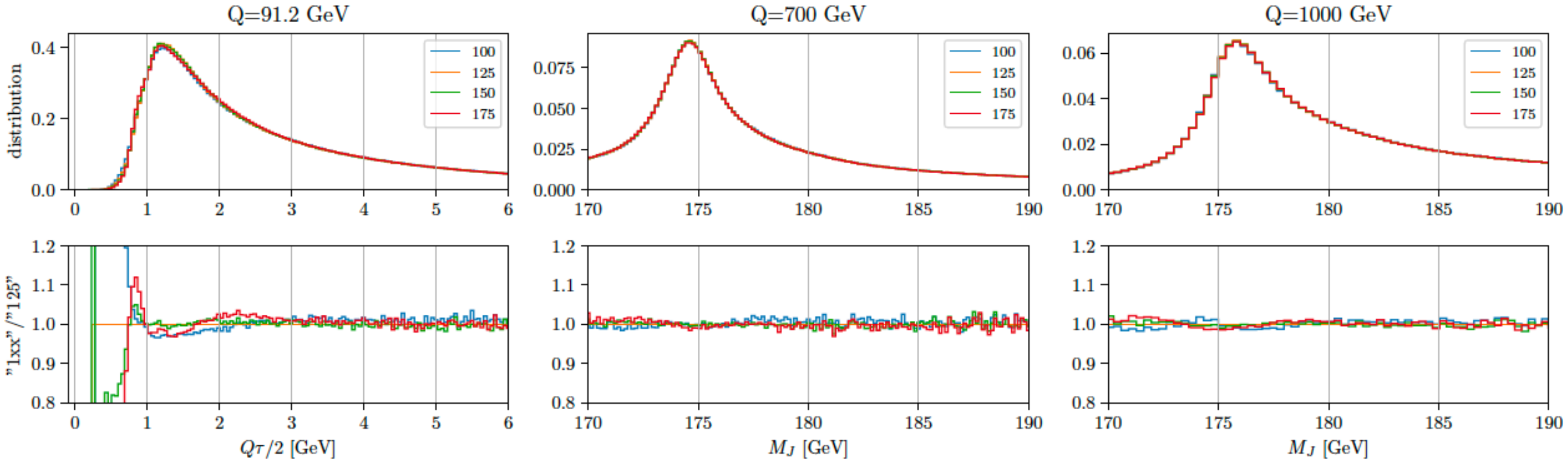


Old Default Model vs. New Dynamical Model

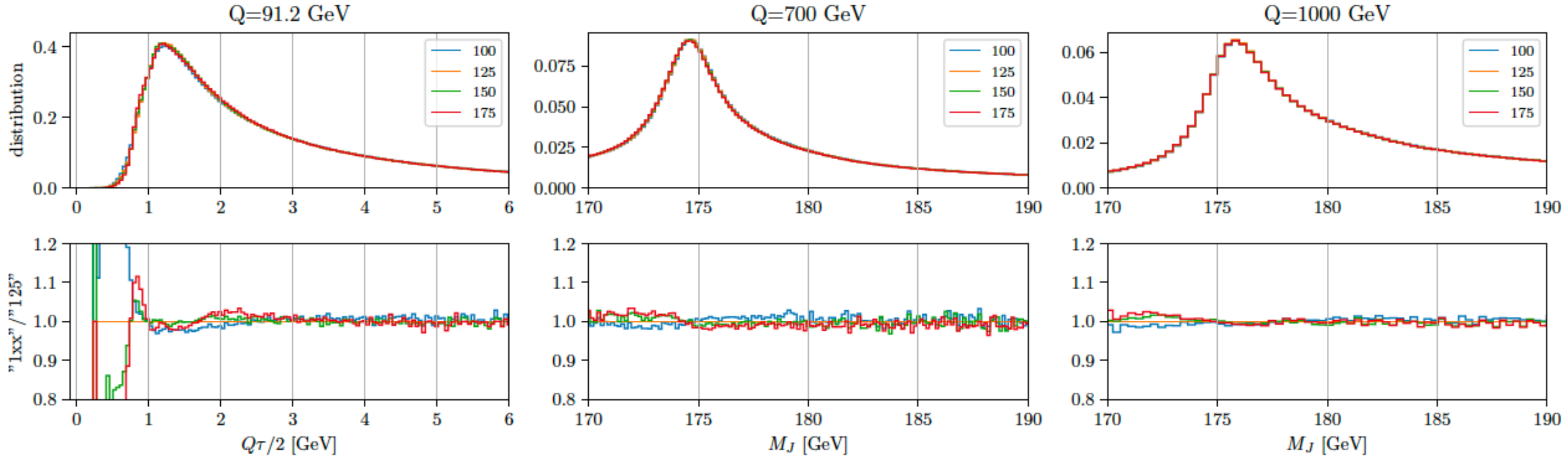
Predictions from Q_0-tuned MC simulations: 2-jettiness

AHH, Jin, Plätzer, Samitz
to appear

dyn-(700)



dyn-(1000)

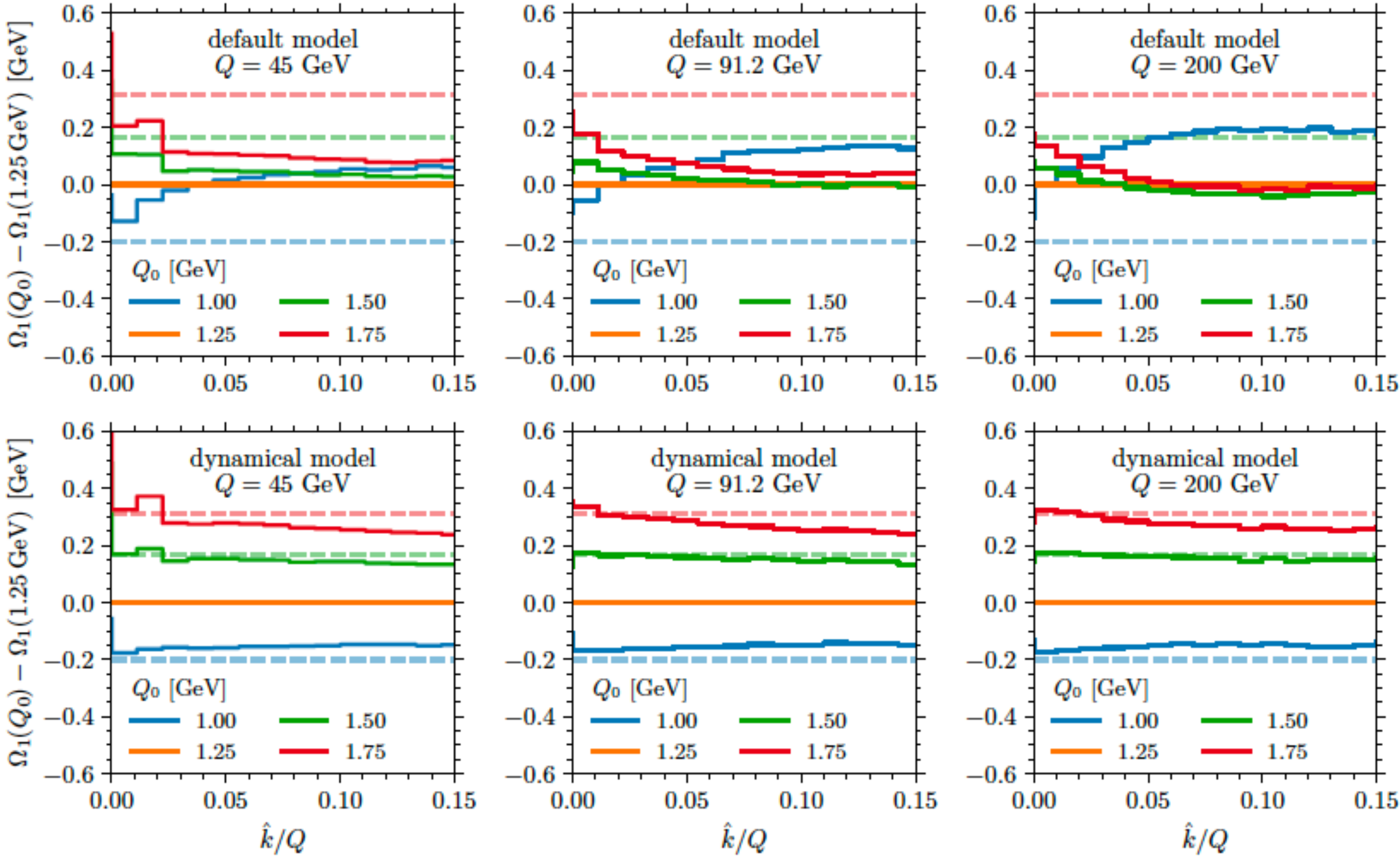


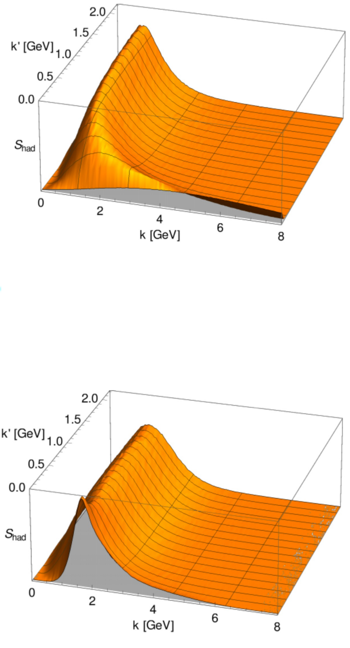
Old Default Model vs. New Dynamical Model

AHH, Jin. Plätzer, Samitz 2404.09856

Shower cutoff dependence of first moment Ω_1 of migration matrix from simulations for 2-jettiness → "MC scheme for hadronization correction"

$$\Omega_1^{\rm MC}(\hat{k}, Q, Q_0) - \Omega_1^{\rm MC}(\hat{k}, Q, Q_{0,\rm ref} = 1.25\,\text{GeV})$$





Thrust

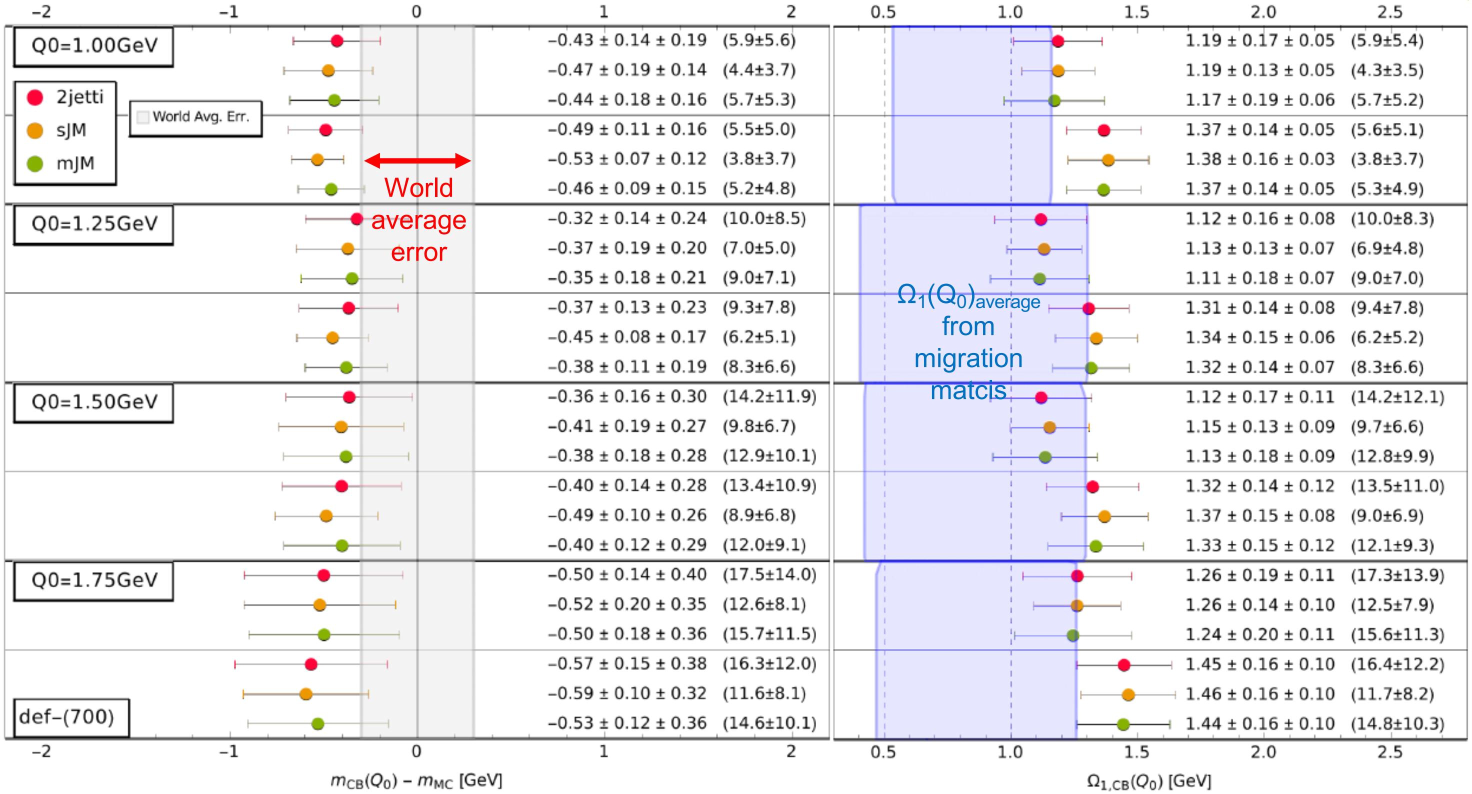
Old Default Model vs. New Dynamical Model

AHH, Jin. Plätzer, Samitz to appear

Cross check: apply top mass calibration to determine $m_t^{CB}(Q_0)$

preliminary

default model



Default: m_t^{MC} incompatible with $m_t^{CB}(Q_0)$

First moment of migration matrix with large variations, Q_0-evolution not visible

Dynamical: m_t^{MC} compatible with $m_t^{CB}(Q_0)$

First moment of migration matrix with smaller variations, Q_0-evolution clearly visible

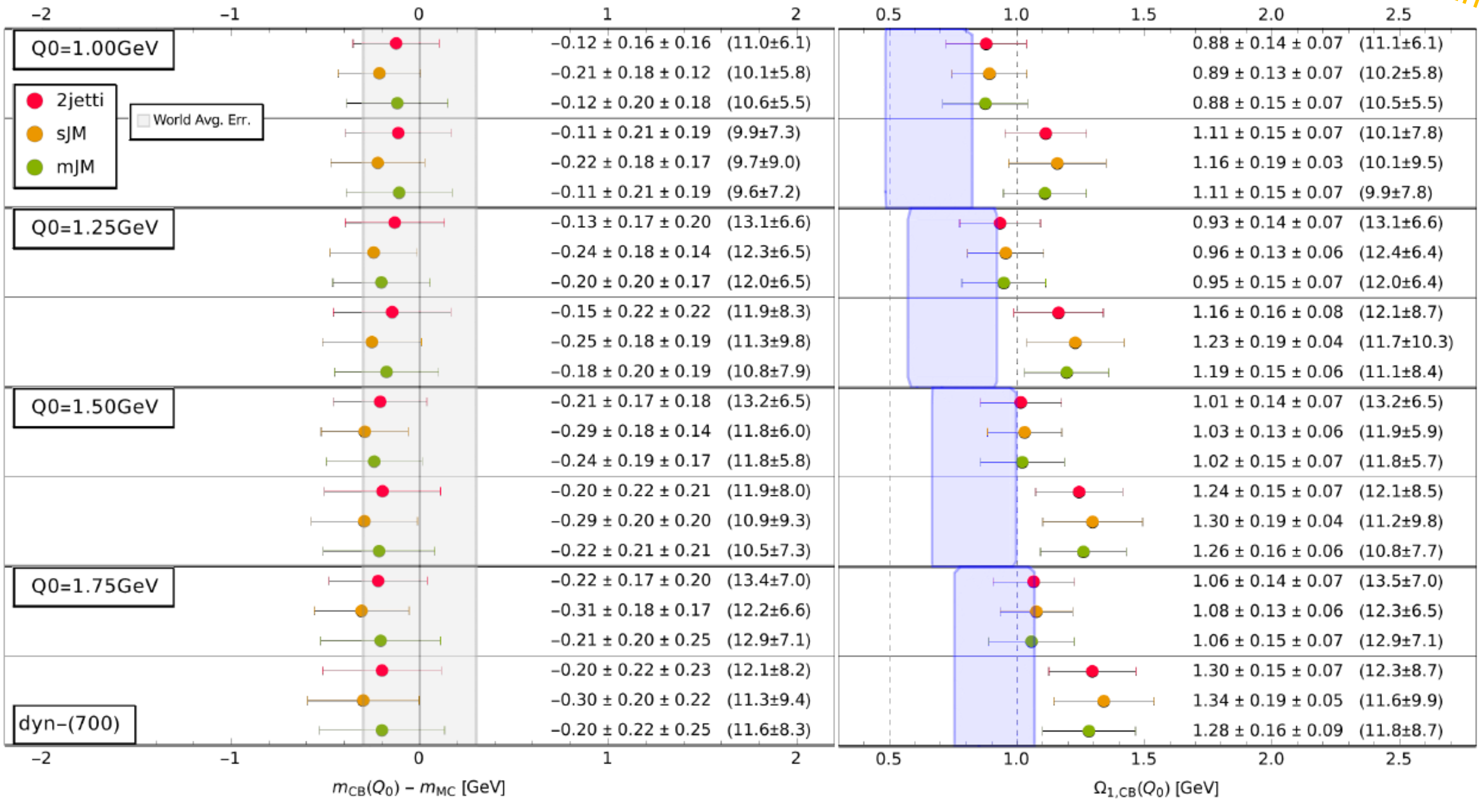
Old Default Model vs. New Dynamical Model

AHH, Jin. Plätzer, Samitz to appear

Cross check: apply top mass calibration to determine $m_t^{CB}(Q_0)$

preliminary

dynamical model



Default: m_t^{MC} incompatible with $m_t^{CB}(Q_0)$

First moment of migration matrix with large variations, Q_0-evolution not visible

Dynamical: m_t^{MC} compatible with $m_t^{CB}(Q_0)$

First moment of migration matrix with smaller variations, Q_0-evolution clearly visible

Final remarks and Outlook

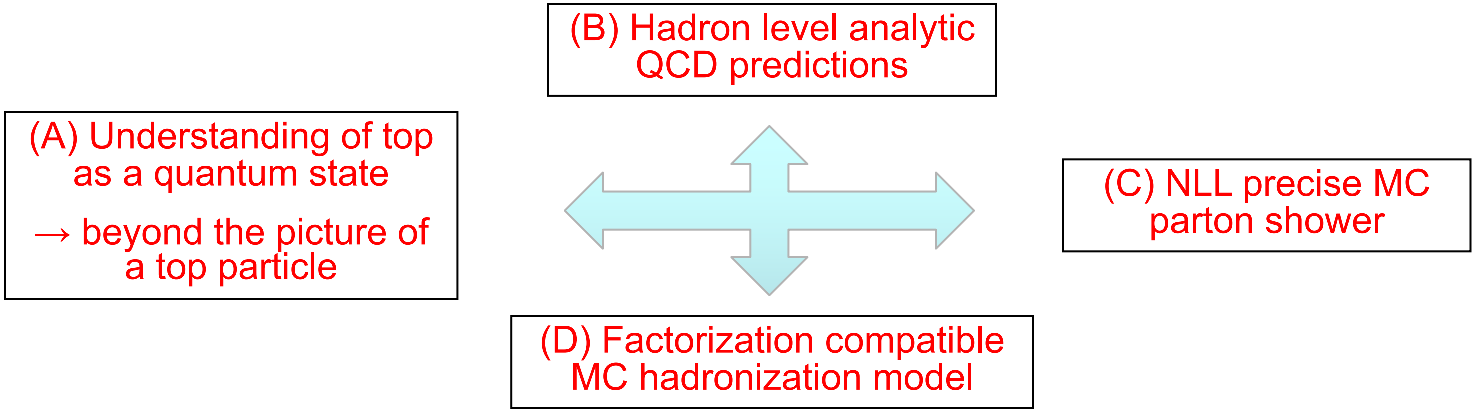
→ We have demonstrated: The MC top mass parameter m_t^{MC} can be promoted to a renormalization scheme so that its NLO relation to any other top mass renormalization scheme can be calculated.

→ $m_t^{MC} = m_t^{CB}(Q_0)$

→ Key aspect: Parton shower cutoff Q_0 = Factorization scale separating pQCD and npQCD

→ Currently: Worked out approach available only for e^+e^- event-shapes

→ The realization of (A)-(D) provides a concrete blueprint that can be in principle applied also to other classes of observables more closely related to direct measurements.



(B) Hadron level analytic QCD predictions

(A) Understanding of top as a quantum state

→ beyond the picture of a top particle

(C) NLL precise MC parton shower

(D) Factorization compatible MC hadronization model

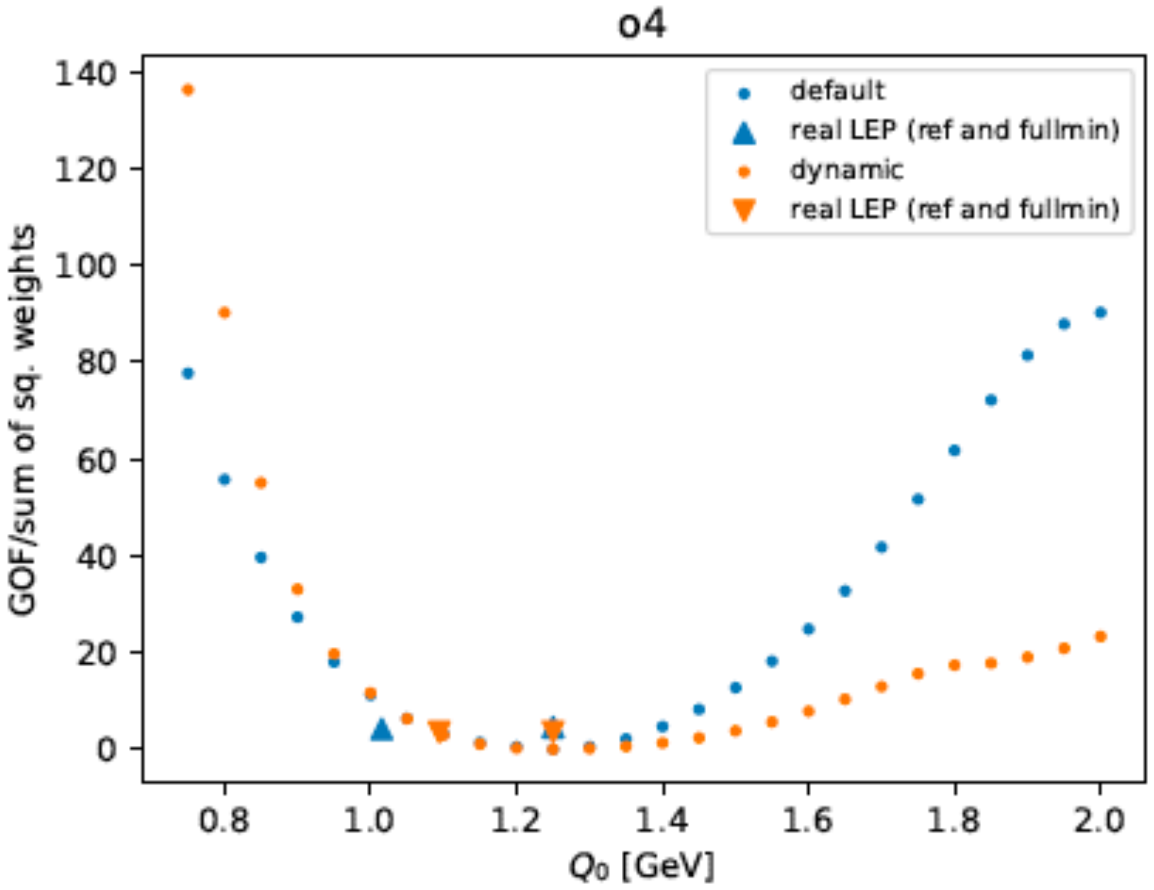
Final remarks and Outlook

- 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)
  - Novel dynamical hadronization model: public with Herwig 7.4 release
  - Recall: MC generators do not have the same precision for all observables
- Progress to generalize the current results will take some more years of work because many new theory tools need to be developed (→ e.g. differential in top decay)
- Future plans:
  - ▸ investigate dipole shower, string hadronization (Pythia)
  - ▸ universality: observables differential in top decay (→ e.g. $M_{\text{b-jet lepton}}$)
  - ▸ final aim: b-jets with small jet radius
  - ▸ establish a m_t^{MC} verification tool box
  - ▸ theory of "unfolding" → relevant for indirect m_t measurements
- Cetero censeo: MPI and UE hadronization models still need to be better understood from the QCD perspective

Old Default Model vs. New Dynamical Model

AHH, Jin, Plätzer, Samitz arXiv:2404.09856

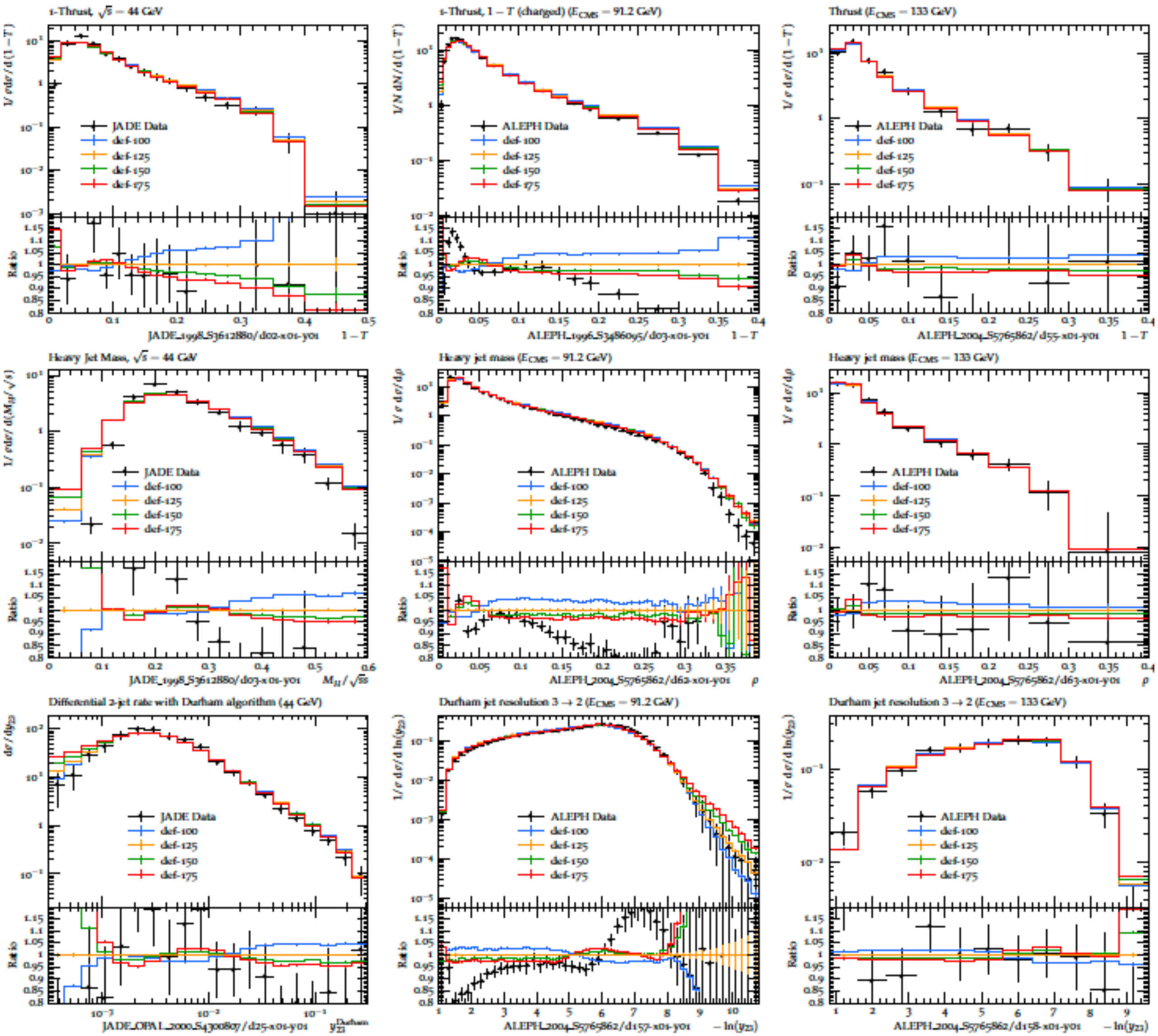
Shower cutoff Q_0 minimal χ^2-values obtained in the tuning fits



Old Default Model vs. New Dynamical Model

AHH, Jin, Plätzer, Samitz arXiv:2404.09856

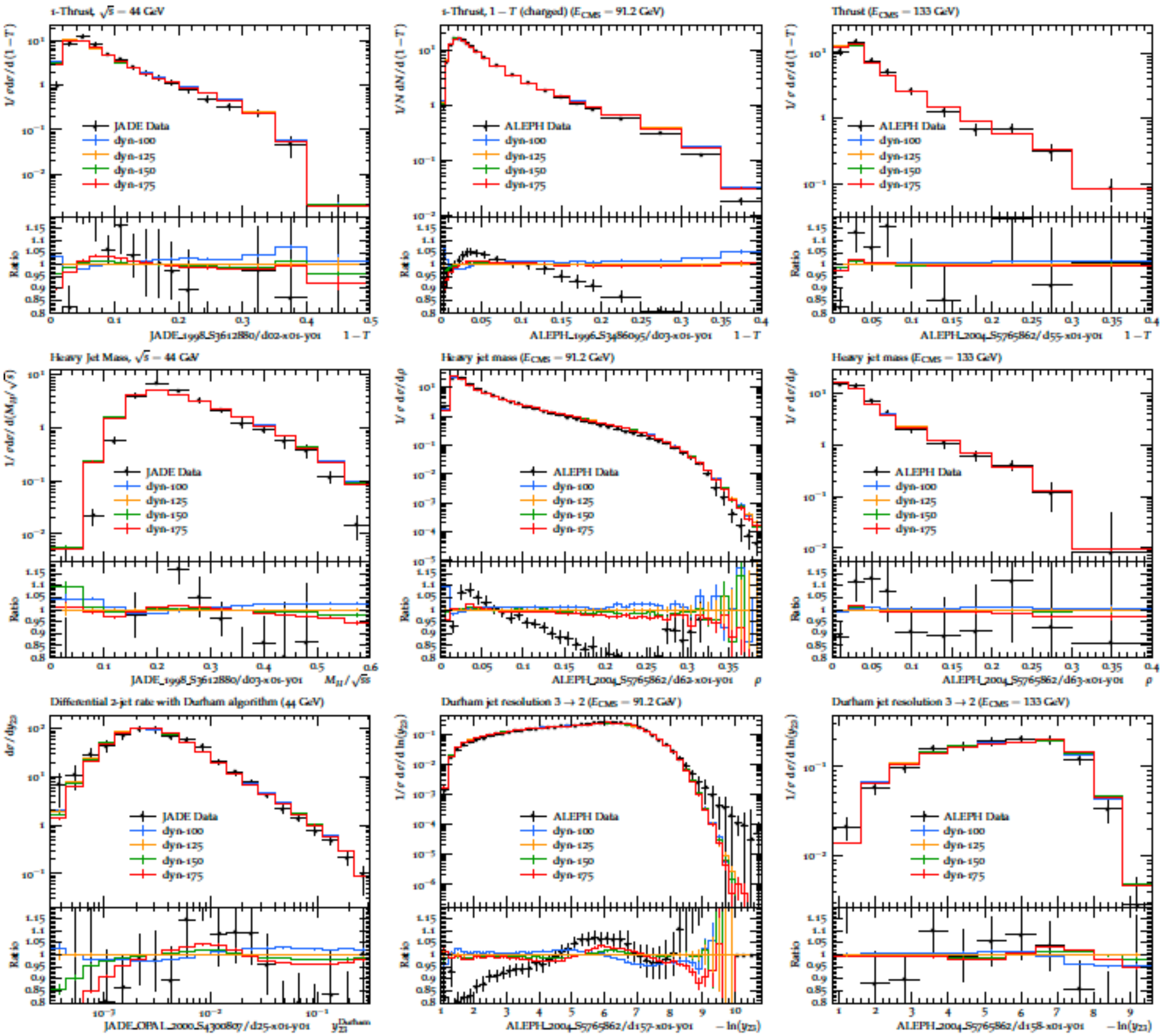
Default



Old Default Model vs. New Dynamical Model

AHH, Jin, Plätzer, Samitz arXiv:2404.09856

Dynamical

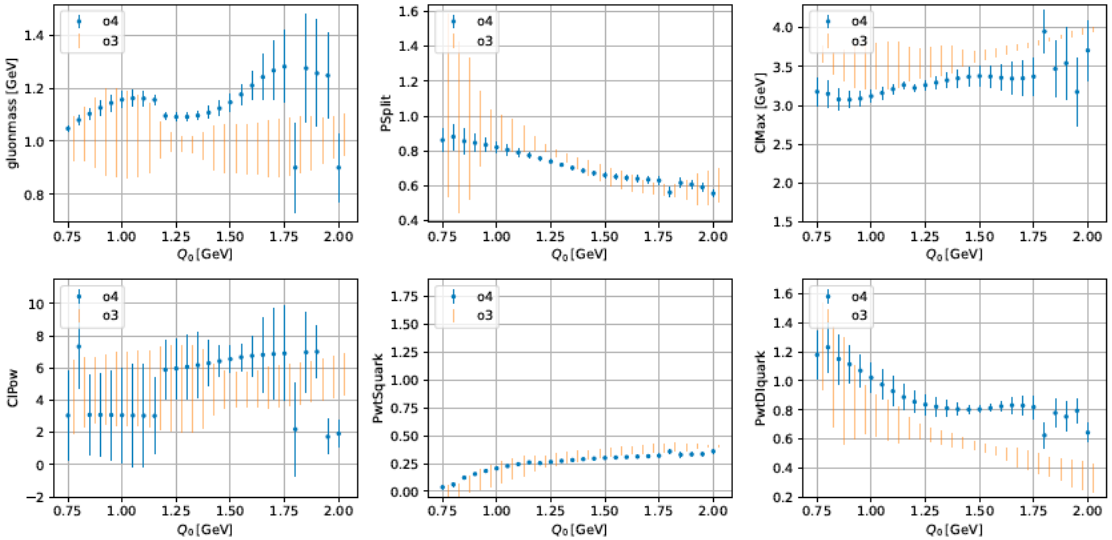


Old Default Model vs. New Dynamical Model

Tuned parameters for Q_0-dependent tuning analyses (apart from m_t^{MC})

AHH, Jin, Plätzer, Samitz
arXiv:2404.09856

Default model



Dynamical model