# Primary massive quark production in Thrust : Theory vs MC


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# Motivations and Aims

- Top mass is highly correlated to the Higgs mass and electroweak observables

**Problem not addressed:** **What is $M_t^{MC}$ ?**

→ Additional conceptual uncertainty in $M_t^{MC}$: O(1 GeV)

But with respect to what? $M_t^{MC} = m_t^{\text{short-distance}} + O(1\ \text{GeV})$

$$M_t^{\rm MC} = 173.21 \pm 0.51(stat) \pm 0.71(syst)\ \text{GeV}$$

**K.A. Olive et al. (PDG), (2014)**

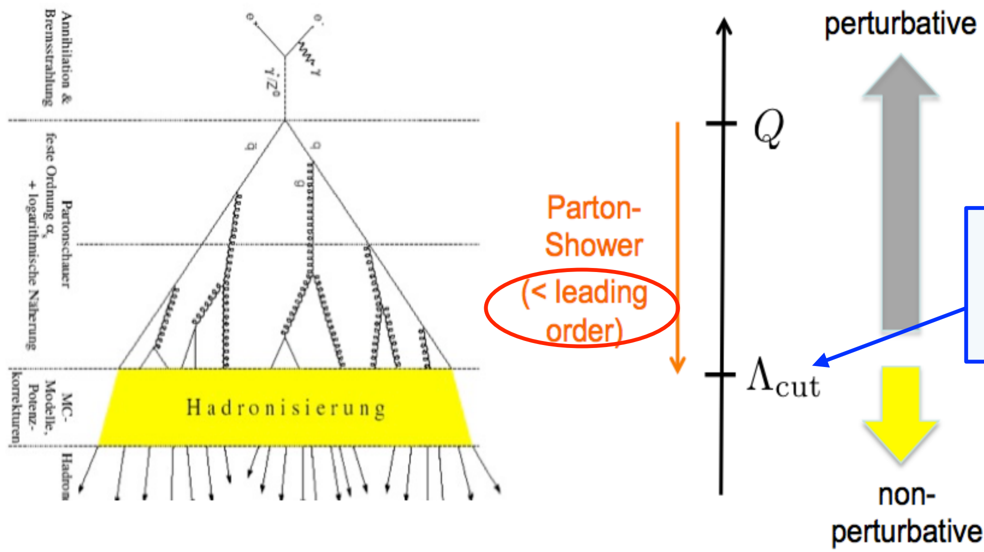
**Aim:** Systematics of heavy quark mass parameter in Monte Carlo generators. (Pythia)

# Motivations and Aims

- ✔ The concept of mass in the MC depends on the structure of the perturbative part and the interplay between the perturbative and the non-perturbative parts in the MC.

Top mass definition contained here!

Affects all top-mass-dependent observables



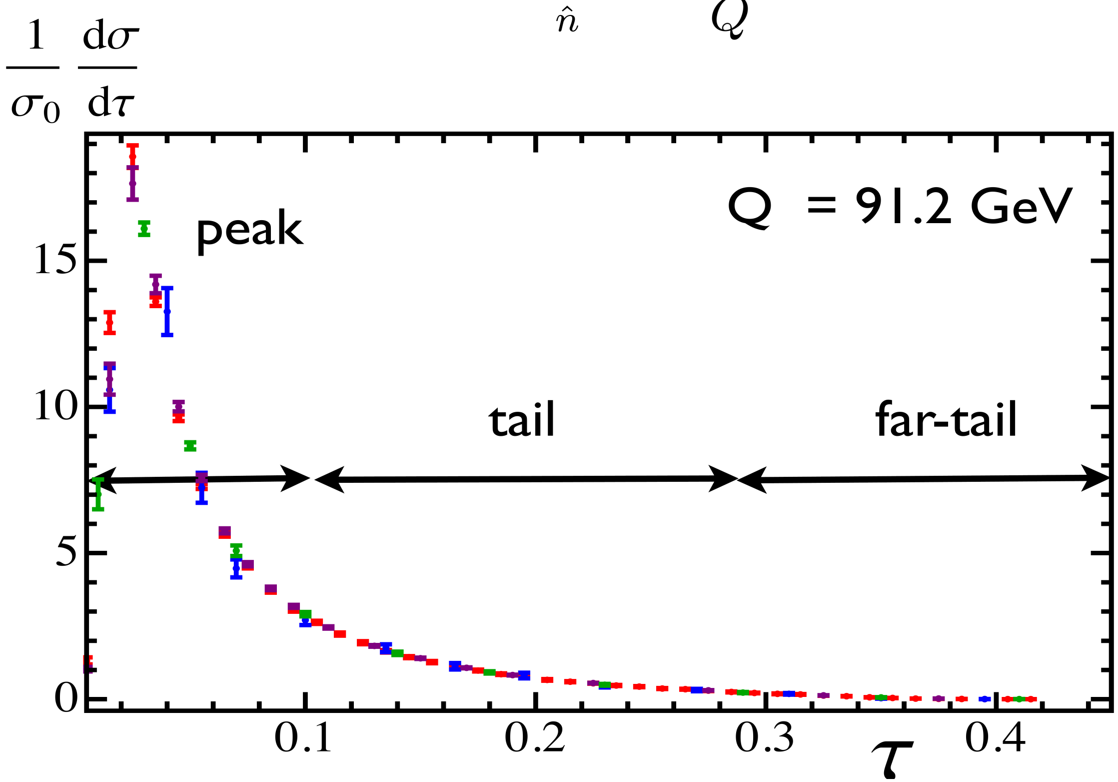

Scheme-dependent separation
Shower cut ~ 1 GeV

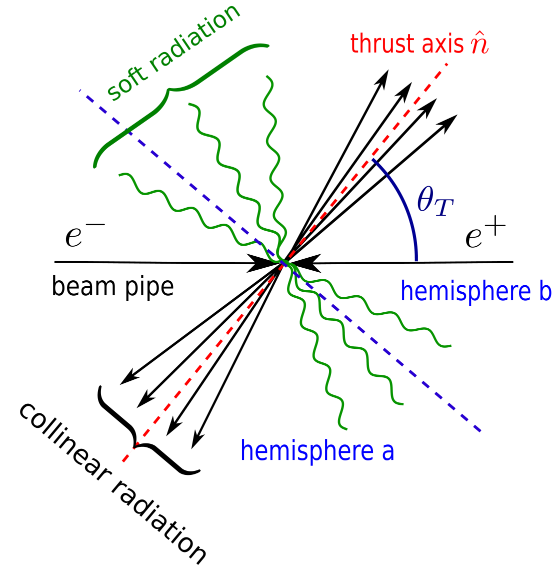
**The MC mass is in principle a short distance mass !?**

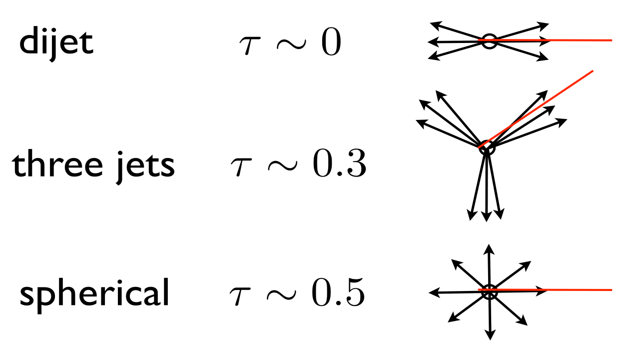
# Thrust Distribution

- Systematic treatment of mass dependence $e^+e^-$ thrust distribution → theoretically clean.
- **Thrust**: Measure for "**Jettiness**" of the final state.

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



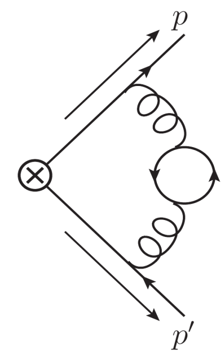



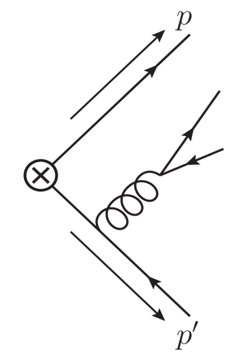
# Jets with Massless Quarks

- **Massless quarks**

  ✔ SCET: Full N$^3$LL + 3-loop non-singular

  Becher, Schwartz
  Bauer, Fleming, Lee, Sterman
  Fleming, Hoang, Mantry, Stewart

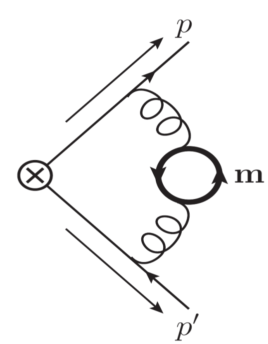


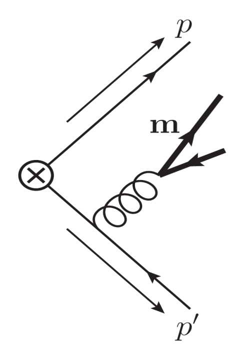




- **Secondary massive quarks**

  ✔ SCET: Full NNLL' / N$^3$LL
  ✔ New degrees of freedom: **mass modes**
  ✔ Continuous description using **VFNS**

  Gritschacher, Hoang, Jemos,
  Pietrulewicz, Mateu (2013 + 2014)
  Presented by Piotr Pietrulewicz (SCET 2013/2014)



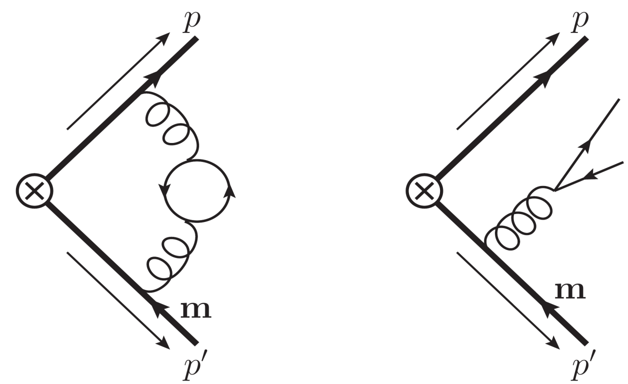



# Jets with Massive Quarks

- **Primary massive quarks**

  ✔ SCET with massive quarks NNLL
  ✔ bHQET: full NNLL' / N$^3$LL

  **Fleming, Hoang, Mantry, Stewart**
  **Jain, Scimemi, Stewart**

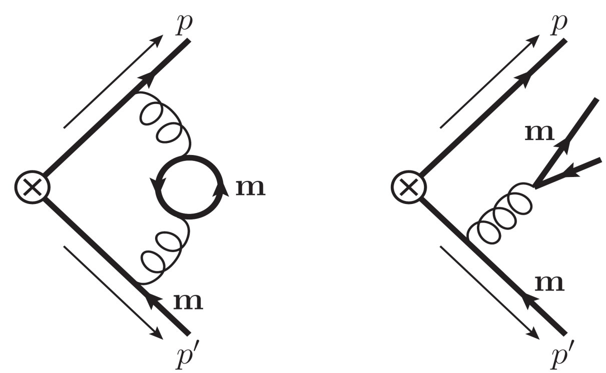



- **Fully massive (primary and secondary) quarks**

  ✔ **Complete and systematic description**

  **Presented by Andre Hoang (SCET 2014)**
  **Presented by Aditya Pathak (SCET 2014)**

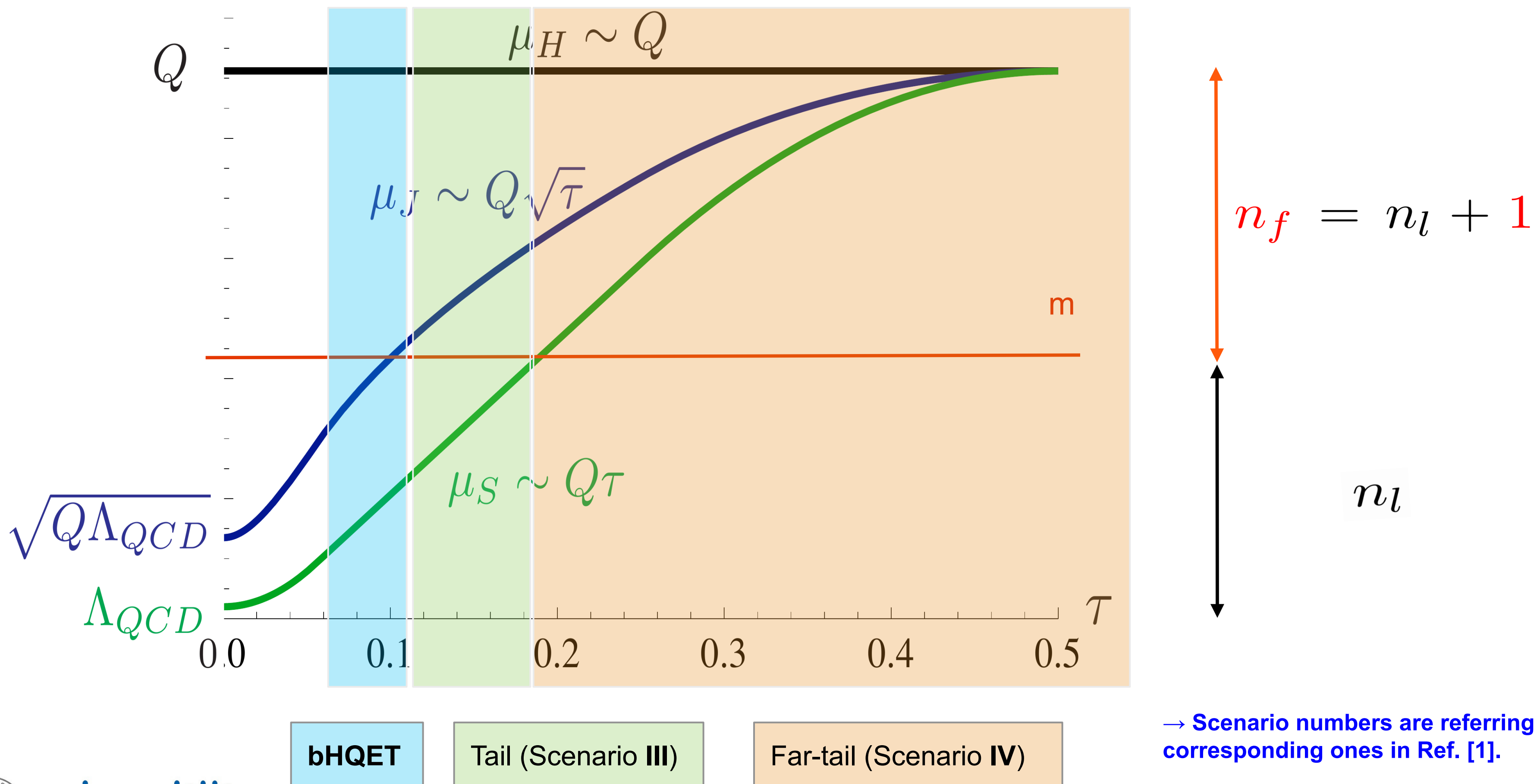
  → Aim of this talk (status report)



# Jets with Massive Quarks

- Complete description of the entire thrust distribution using various scenarios and a sequence of effective field theory setups.

[1]:Pietrulewicz, Gritschacher, Hoang, Jemos, Mateu (2014)



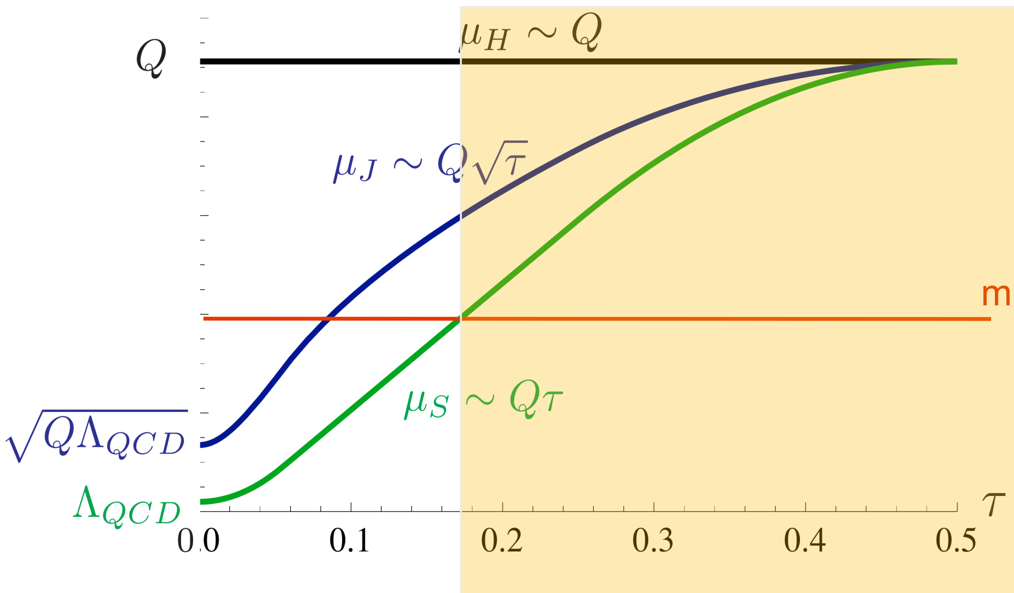

→ Scenario numbers are referring to corresponding ones in Ref. [1].

**Partonic distribution at NNLL**

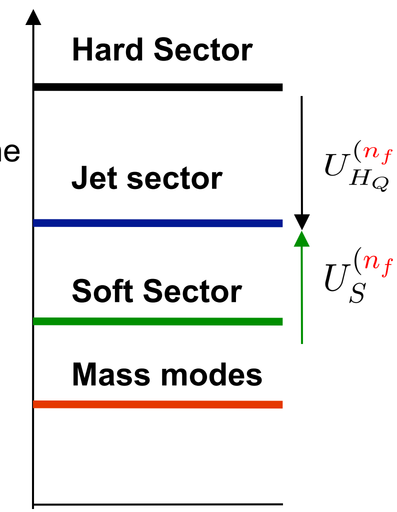
# Scenario (IV)

$$\left|\frac{1}{\sigma_0}\frac{\mathrm{d}\hat\sigma(\tau)}{\mathrm{d}\tau}\right|^{\mathrm{SCET-IV}} = Q\,H_Q^{(n_f)}(Q,\mu_Q)\,U_{H_Q}^{(n_f)}(Q,\mu_Q,\mu_J)\int \mathrm{d}s\int \mathrm{d}k\,J^{(n_f)}(s,\mu_J,\overline{m}^{(n_f)}(\mu_J))\; U_S^{(n_f)}(k,\mu_J,\mu_S)\,S_{\mathrm{part}}^{(n_f)}\!\left(Q\tau - Q\tau_{\min} - \frac{s}{Q} - k,\mu_S\right)$$ **+ (QCD) Non-Singular**

$$n_f = n_l + 1$$




mass modes enter in all the soft, jet and hard sectors.




- (QCD) No-singular → Non-singular + Sub-leading singular contributions

**Partonic distribution at NNLL**

# Scenario (III)

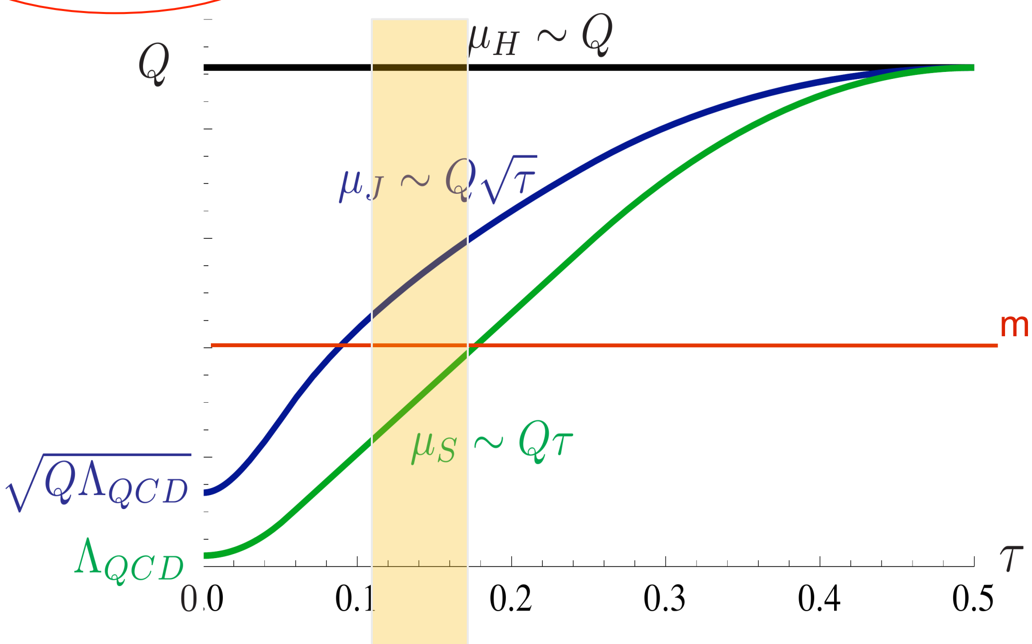
$$\left|\frac{1}{\sigma_0}\frac{d\hat{\sigma}(\tau)}{d\tau}\right|^{\rm SCET-III} = Q\, H_Q^{(n_f)}(Q,\mu_Q)\, U_{H_Q}^{(n_f)}(Q,\mu_Q,\mu_J)\int ds \int dk\, dk'\, dk''\, J^{(n_f)}(s,\mu_J,\overline{m}^{(n_f)}(\mu_J))\, U_S^{(n_f)}(k,\mu_J,\mu_m)$$

$$\mathcal{M}_S^{(n_f)}(k'-k,\overline{m}^{(n_f)}(\mu_m),\mu_m,\mu_s)\, U_S^{(n_l)}(k''-k',\mu_m,\mu_S)\, S_{\rm part}^{(n_l)}\left(Q\tau - Q\tau_{\rm min} - \frac{s}{Q} - k'',\mu_S\right)$$

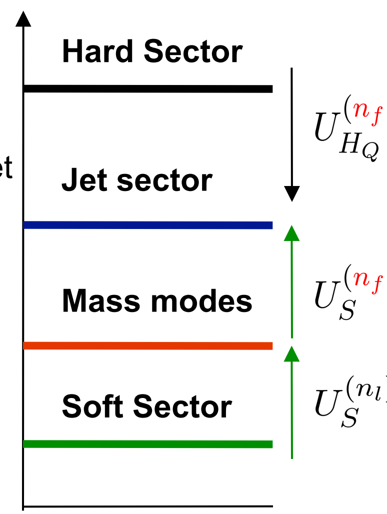
$n_f = n_l + 1$

large rapidity logs
$\alpha_s^2 \log \sim \alpha_s$

**+ (QCD) Non-Singular**




mass modes enter in the jet and hard sectors.




- Soft mass-mode matching: **integrating in** the **mass-mode (secondary)** effects in the **evolution of the soft function** (top-down resummation). $\mathcal{O}(\alpha_s^2)$

**Partonic distribution at NNLL**

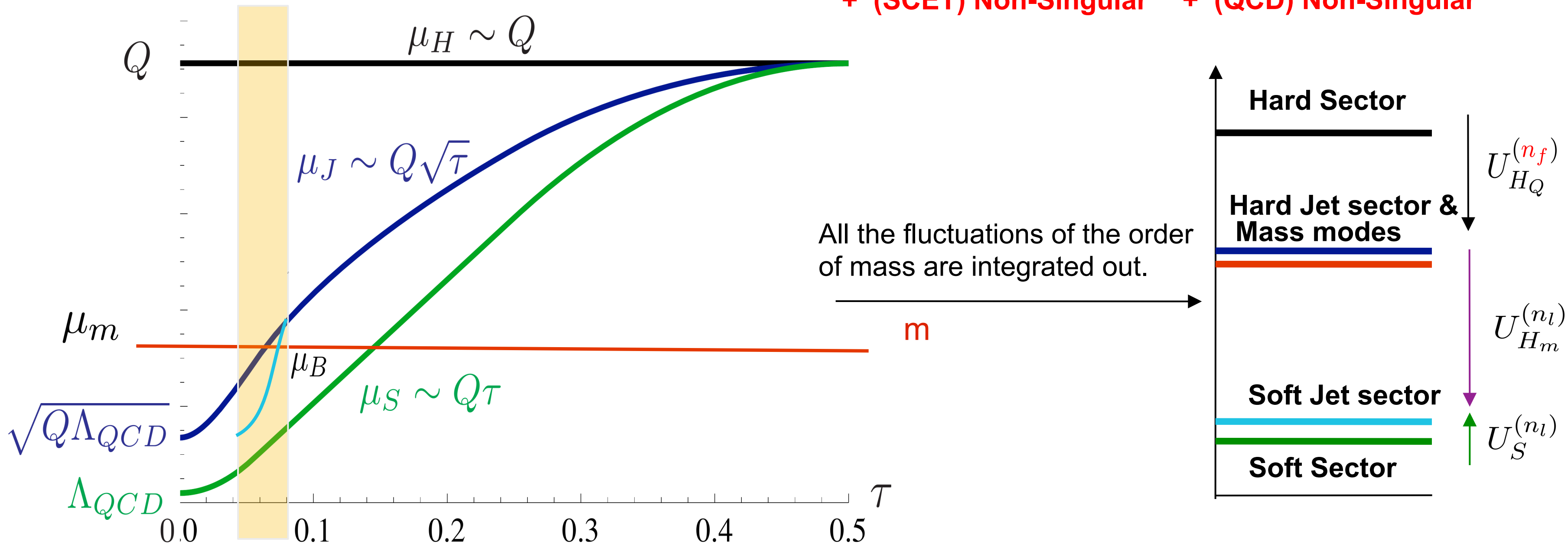
# bHQET

$$\left|\frac{1}{\sigma_0}\frac{\mathrm{d}\hat{\sigma}(\tau)}{\mathrm{d}\tau}\right|^{\rm bHQET} = Q\, H_Q^{(n_f)}(Q,\mu_Q)\, U_{H_Q}^{(n_f)}(Q,\mu_Q,\mu_m)\, H_m^{(n_f)}(\overline{m}^{(n_f)},\mu_m)\, U_{H_m}^{(n_l)}\Big(\frac{Q}{\overline{m}^{(n_l)}},\mu_m,\mu_B\Big)$$

$$\int \mathrm{d}s \int \mathrm{d}k\; B^{(n_l)}\Big(\frac{s}{m_J^{(n_l)}},\mu_B, m_J^{(n_l)}\Big)\, U_S^{(n_l)}(k,\mu_B,\mu_S)\, S_{\rm part}^{(n_l)}\Big(Q\tau - Q\tau_{\rm MIN} - \frac{s}{Q} - k,\mu_S\Big)$$

$n_f = n_l + 1$

**+ (SCET) Non-Singular  + (QCD) Non-Singular**




- Matching coefficient of SCET and bHQET have a large log from secondary corrections.

# Further Theoretical Remarks

- **Non-singular** terms for vector and axial-vector channels computed analytically at NLO

$$\frac{d\sigma^{\text{nonsing.}}_{\text{part.}}(\tau)}{d\tau} = \frac{d\sigma^{\text{FO}}(\tau)}{d\tau} - \frac{d\sigma^{\text{SCET}}_{\text{part.}}(\tau)}{d\tau}$$

- Convolution with a **shape** function to incorporate non-perturbative effects

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \int \mathrm{d}k \left(\frac{\mathrm{d}\sigma^{\text{SCET}}_{\text{part}}}{\mathrm{d}\tau} + \frac{\mathrm{d}\sigma^{\text{nonsing}}_{\text{part}}}{\mathrm{d}\tau}\right)\left(\tau - \frac{k}{Q}\right) \times S^{\text{model}}_{\tau}(k - 2\Delta(R,\mu))$$

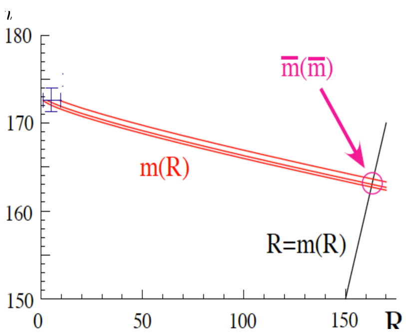
- **Short distance masses**
  - Mass dependence in all matrix elements and threshold corrections.
  - Most relevant quark mass dependence is encoded in jet functions.
  - The short-distance mass definition should not upset the power counting of the theory.

$\mu \geq m$ : **$\overline{\text{MS}}$ mass ($n_l$+1)** $\bar{m}(\mu) = m_{\text{pole}} - \bar{m}(\mu) \sum_{n=1}^{\infty} \sum_{k=0}^{n} a_{nk} \left(\frac{\alpha_s(\mu)}{4\pi}\right)^n \ln^k \frac{\mu}{\bar{m}}$

$\mu < m$ : **R-scale short distance mass ($n_l$)** **Hoang, Jain, Scimemi, Stewart**

- Jet mass from bHQET jet function
- MSR mass: derived form $\overline{\text{MS}}$ mass relation

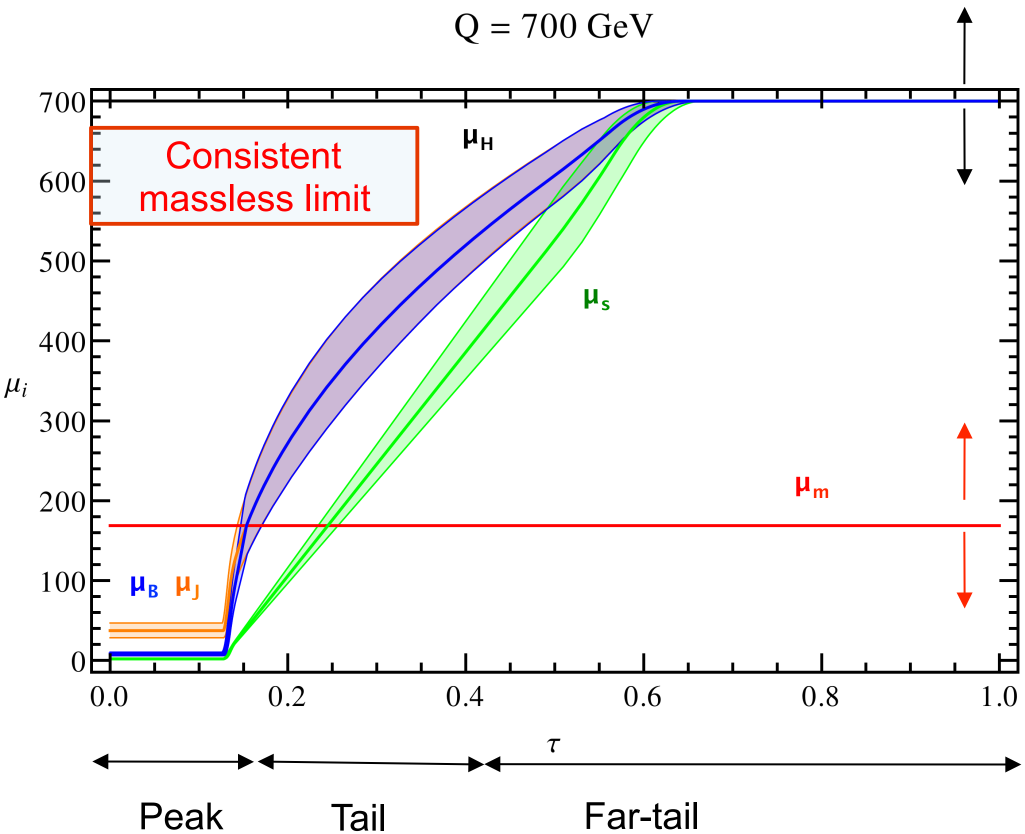
$$m_{\text{MSR}}(R) = m_{\text{pole}} - R \sum_{n=1}^{\infty} a_n \left(\frac{\alpha_s(R)}{4\pi}\right)^n$$



# Profile Function

Profile functions should sum up large logarithms and achieve smooth transition between the peak, tail and far-tail.

$$\log\left(\frac{Q}{\mu_H}\right) \quad \log\left(\frac{m_J}{\mu_m}\right) \quad \log\left(\frac{\mu_J^2}{Q\mu_s}\right) \quad \log\left(\frac{m_J\mu_B}{Q\mu_s}\right) \quad \log\left(\frac{Q(\tau-\tau_{\min})+2\Lambda_{\rm QCD}}{\mu_s}\right)$$




**Scales Variation**

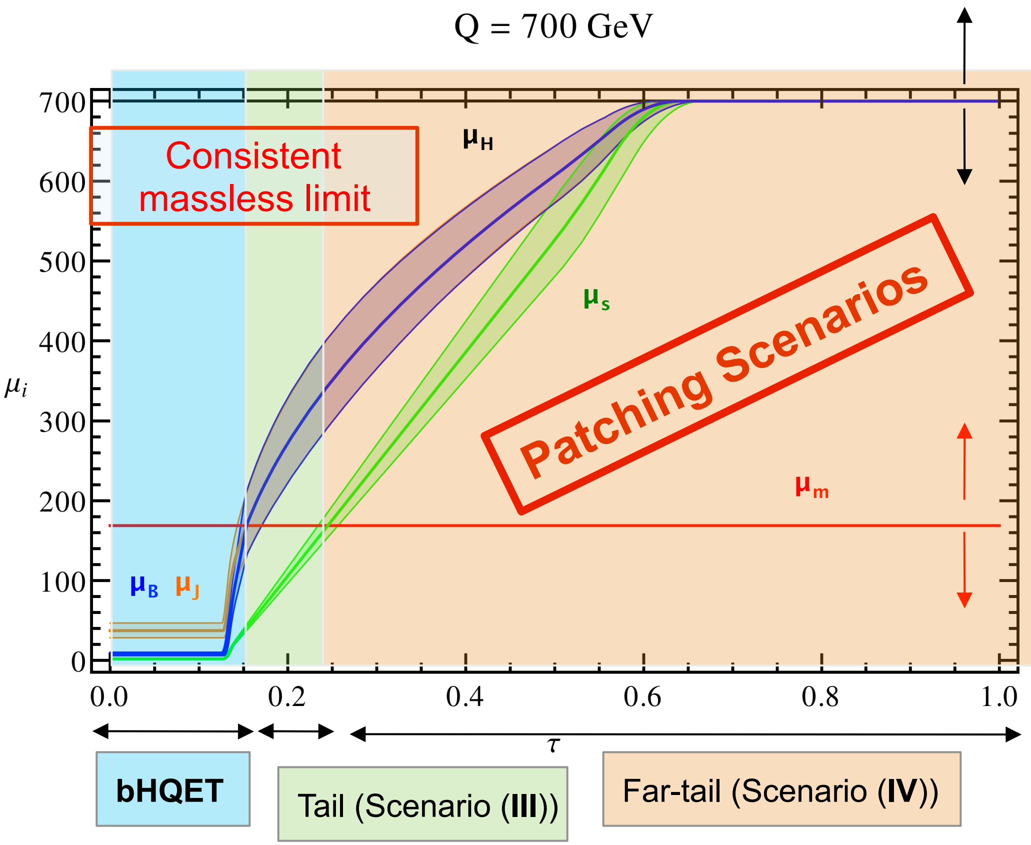
- ✔ **Generalized to arbitrary mass values**
- ✔ **Compatible with massless profiles**

Proper scale variations are essential in reliable estimation of missing higher order terms.

# Profile Function

Profile functions should sum up large logarithms and achieve smooth transition between the peak, tail and far-tail.

$$\log\left(\frac{Q}{\mu_H}\right) \quad \log\left(\frac{m_J}{\mu_m}\right) \quad \log\left(\frac{\mu_J^2}{Q\mu_s}\right) \quad \log\left(\frac{m_J\mu_B}{Q\mu_s}\right) \quad \log\left(\frac{Q(\tau-\tau_{\min})+2\Lambda_{\rm QCD}}{\mu_s}\right)$$




**Scales Variation**

- ✔ **Generalized to arbitrary mass values**
- ✔ **Compatible with massless profiles**

Proper scale variations are essential in reliable estimation of missing higher order terms.

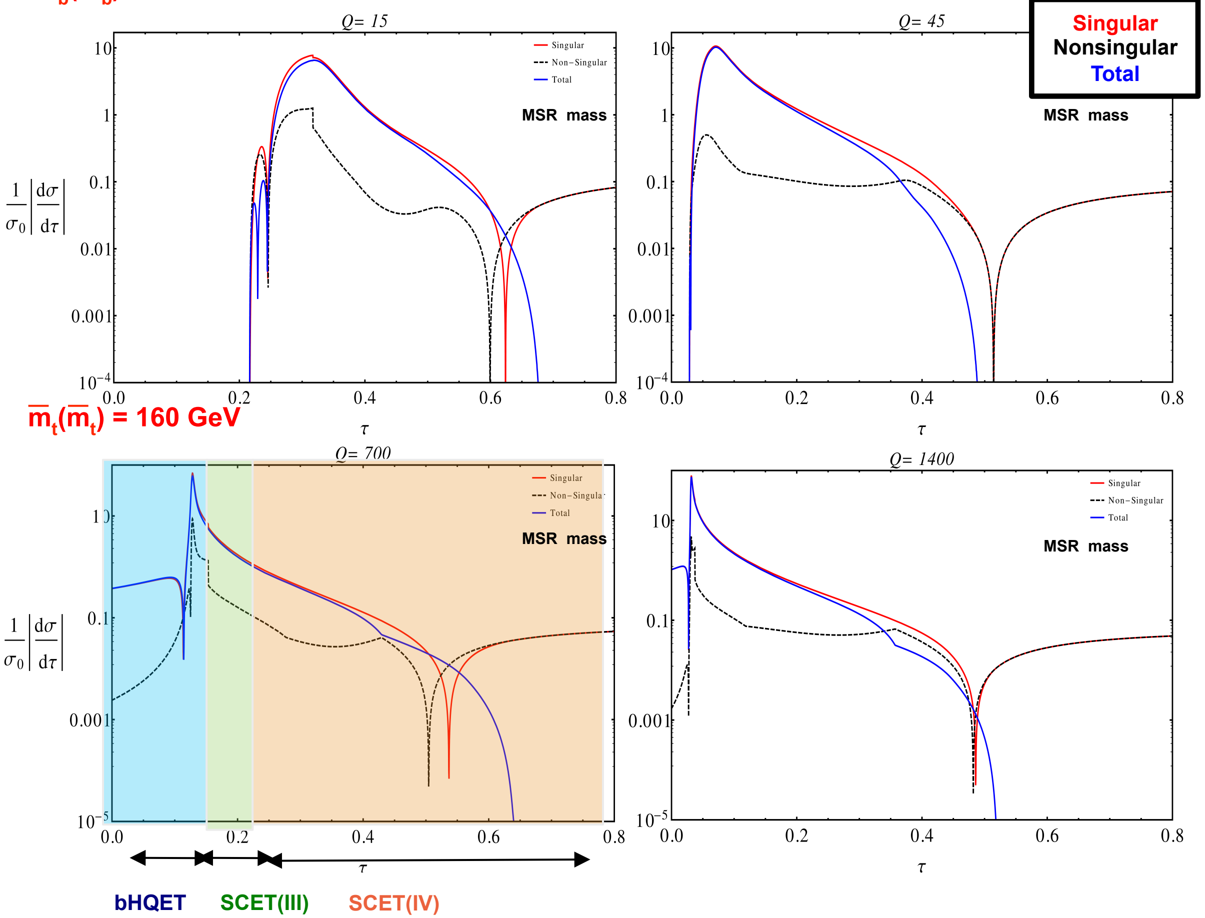
# bottom and top production in thrust

**NNLL (singular) + NLO (non-singular) + power correction and renormalon subtraction**

**Singular vs Nonsingular**

A. H. Hoang, V. Mateu, BD,
M. Butenschoen & Iain W. Stewart

$\overline{m}_b(\overline{m}_b)$ = 4.2 GeV




- Cancellation of singular and nonsingular contributions at far-tail.
- Finite width effects turned off at tail.

$$\alpha_s(m_Z) = 0.1184$$
$$\Omega_1 = 0.5\,\mathrm{GeV}$$

Preliminary Results

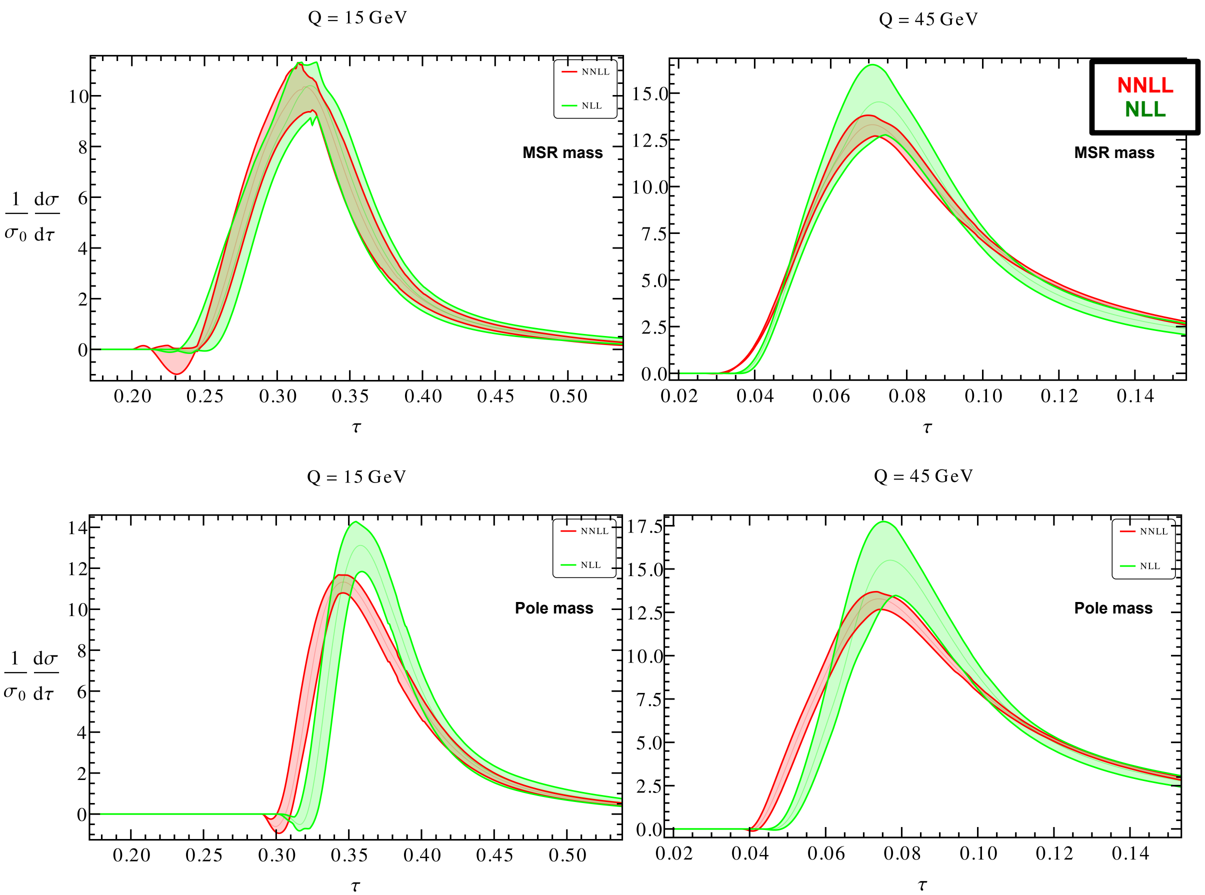
# bottom and top production in thrust

**NNLL/NLL (singular) + NLO (non-singular) + power correction and renormalon subtraction**

$\overline{m}_b(\overline{m}_b)$ = 4.2 GeV

**Theory uncertainty (bottom)**

A. H. Hoang, V. Mateu, BD,
M. Butenschoen & Iain W. Stewart




- **Theory uncertainty is under control for bottom thrust distribution.**
- **Convergence of perturbation theory.**
- **The peak position in thrust is very sensitive to the mass.**
- **Stability of peak position with short distance mass scheme w.r.t. the pole mass scheme.**

$$\alpha_s(m_Z) = 0.1184$$
$$\Omega_1 = 0.5\,\mathrm{GeV}$$

**Preliminary Results**

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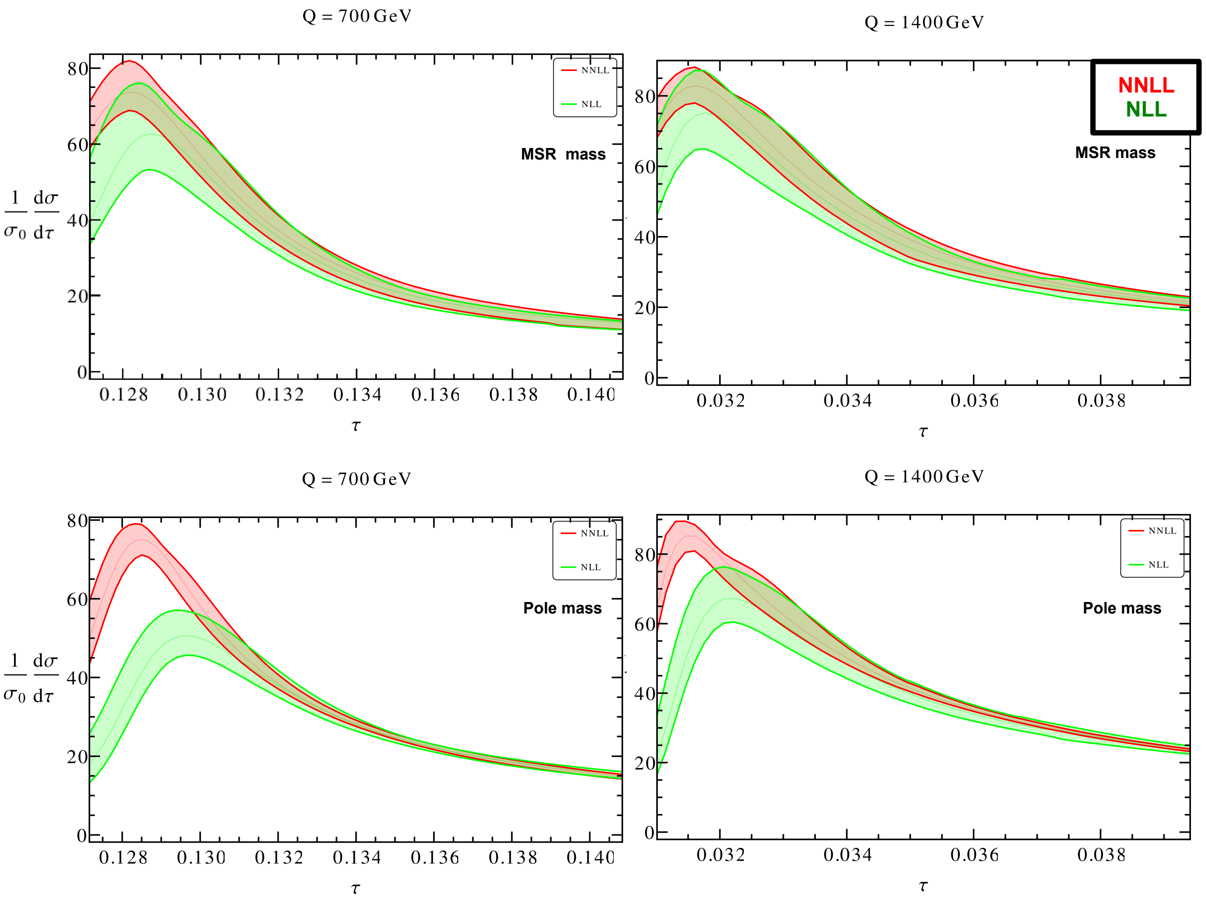
# bottom and top production in thrust

**NNLL/NLL (singular) + NLO (non-singular) + power correction and renormalon subtraction**

$\overline{m}_t(\overline{m}_t)$ = 160 GeV

**Theory uncertainty (top)**

A. H. Hoang, V. Mateu, BD,
M. Butenschoen & Iain W. Stewart




- ➢ **Theory uncertainty in peak + tail is under control for top thrust distribution**
- ➢ **Convergence of perturbation theory**
- ➢ **Stability of peak position with short distance mass scheme w.r t. the pole mass scheme**

$$\alpha_s(m_Z) = 0.1184$$
$$\Omega_1 = 0.5\,\text{GeV}$$

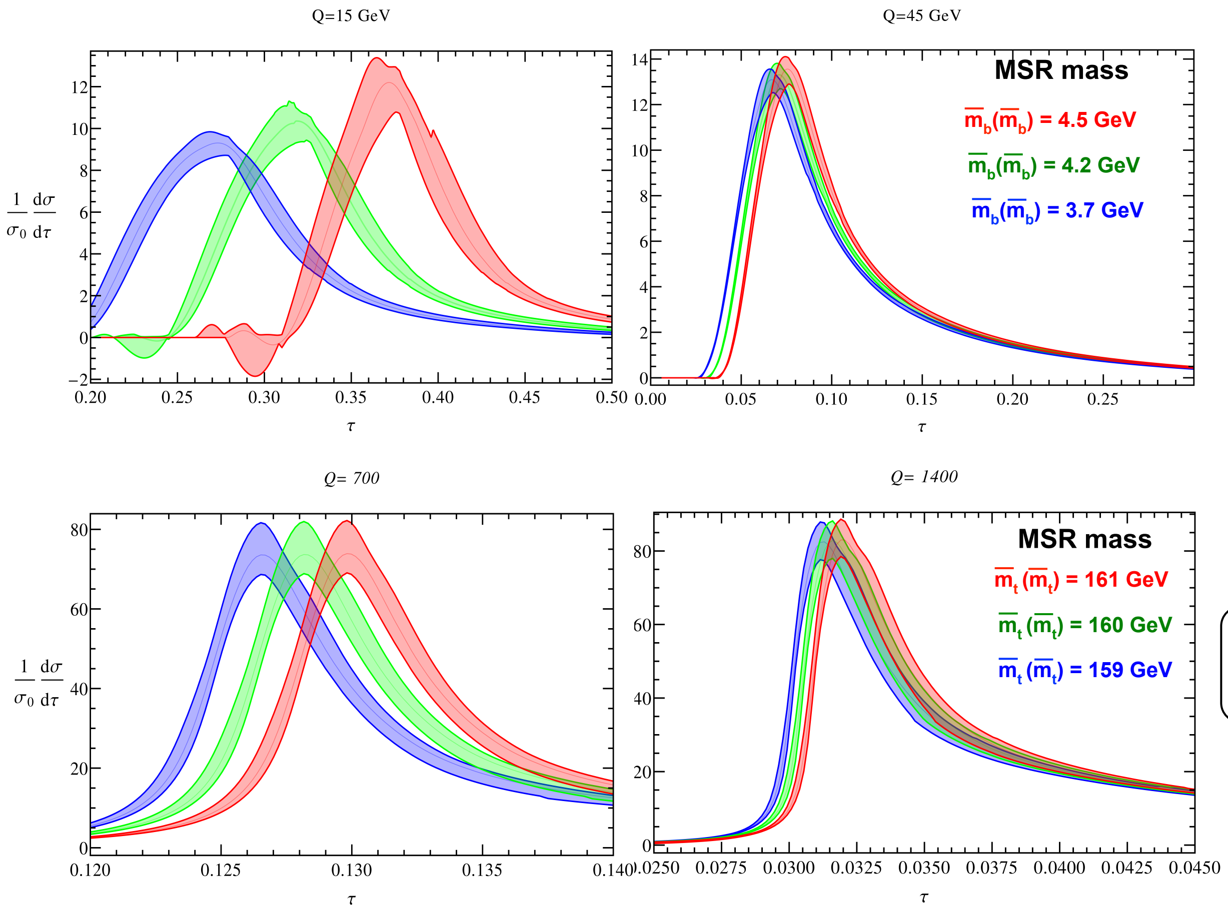
**Preliminary Results**

# bottom and top production in thrust

**NNLL (singular) + NLO (non-singular) + power correction and renormalon subtraction**

Peak sensitivity to mass

A. H. Hoang, V. Mateu, BD,
M. Butenschoen & Iain W. Stewart




- **Peak position is more sensitive to the mass at low energies**
  - **bottom with better than 0.5 GeV**
  - **top with better than 1 GeV**

$\alpha_s(m_Z) = 0.1184$

$\Omega_1 = 0.5\,\mathrm{GeV}$

**Preliminary Results**

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# bottom and top production in thrust

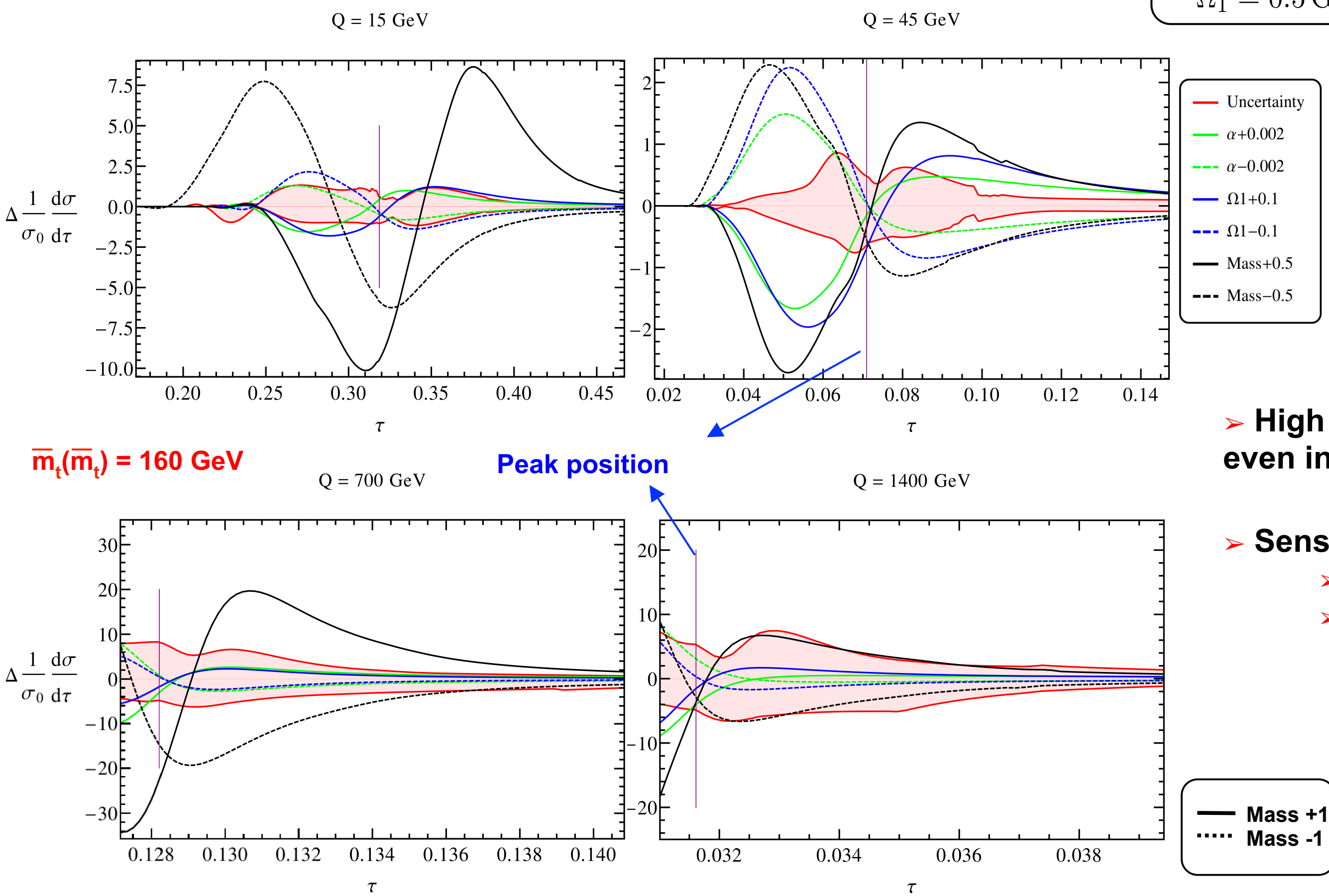
**NNLL (singular) + NLO (non-singular) + power correction and renormalon subtraction**

$\overline{m}_b(\overline{m}_b)$ = 4.2 GeV

**Sensitivity of theory parameters**

$$\alpha_s(m_Z) = 0.1184$$
$$\Omega_1 = 0.5\,\text{GeV}$$

**A. H. Hoang, V. Mateu, BD, M. Butenschoen & Iain W. Stewart**




Comparison of the difference between the default cross section and the cross section varying only one parameter of theory w.r.t. the theory uncertainties.

- **High sensitivity to (top & bottom) mass even in tail regions at low energies.**
- **Sensitivity to $\alpha_s$ and $\Omega_1$**
  - **bottom → low sensitivity**
  - **top → negligible sensitivity (should be fixed externally)**

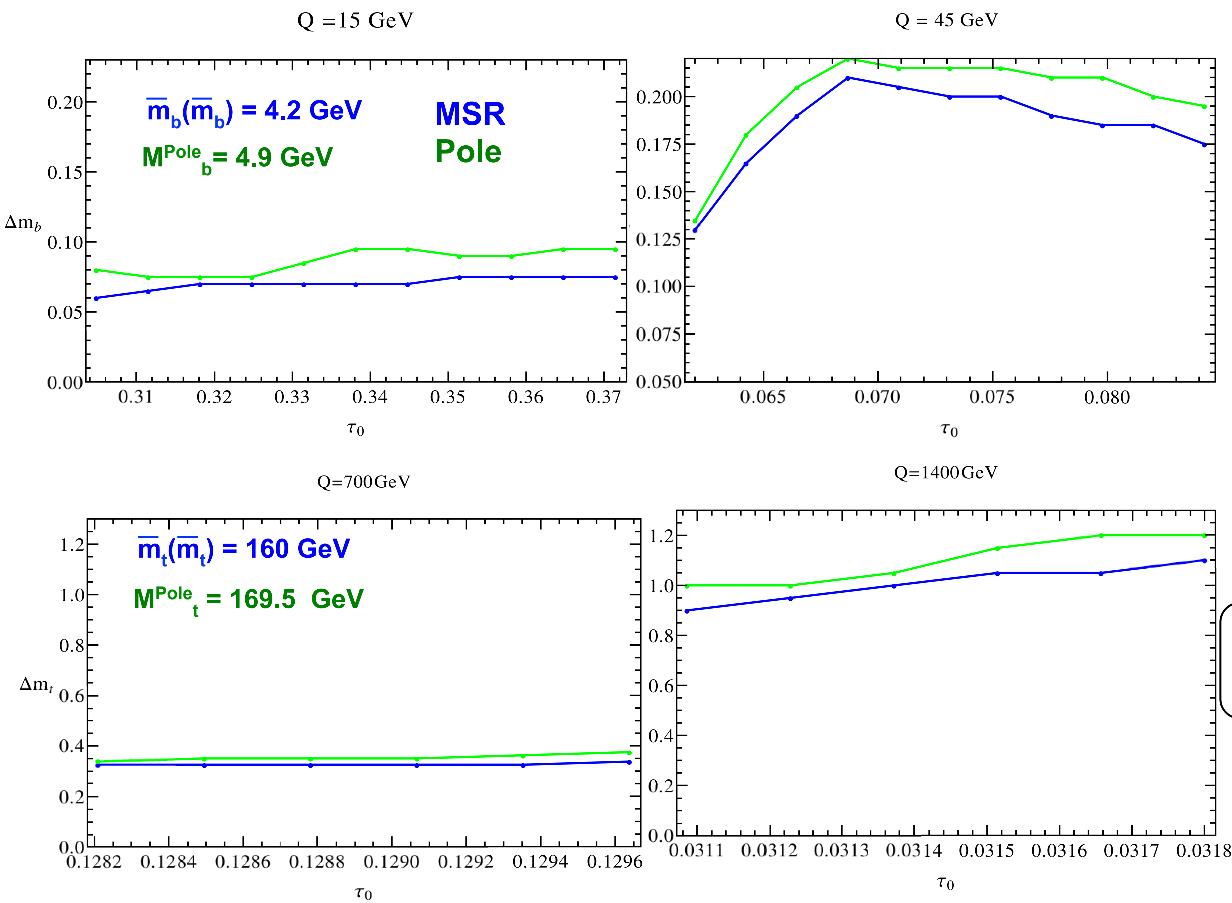
**Preliminary Results**

# bottom and top production in thrust

**NNLL (singular) + NLO (non-singular) + power correction and renormalon subtraction**

**Theory uncertainty in mass**

A. H. Hoang, V. Mateu, BD,
M. Butenschoen & Iain W. Stewart




**Error band method:** Fitting the mass parameter of default cross section to the error band of default cross section.

- **bottom mass uncertainty < 0.5 GeV**
- **top mass uncertainty ~ 0.5 GeV**
- **Pole mass extractions are less precise.**

$$\alpha_s(m_Z) = 0.1184$$
$$\Omega_1 = 0.5\,\mathrm{GeV}$$

Preliminary Results

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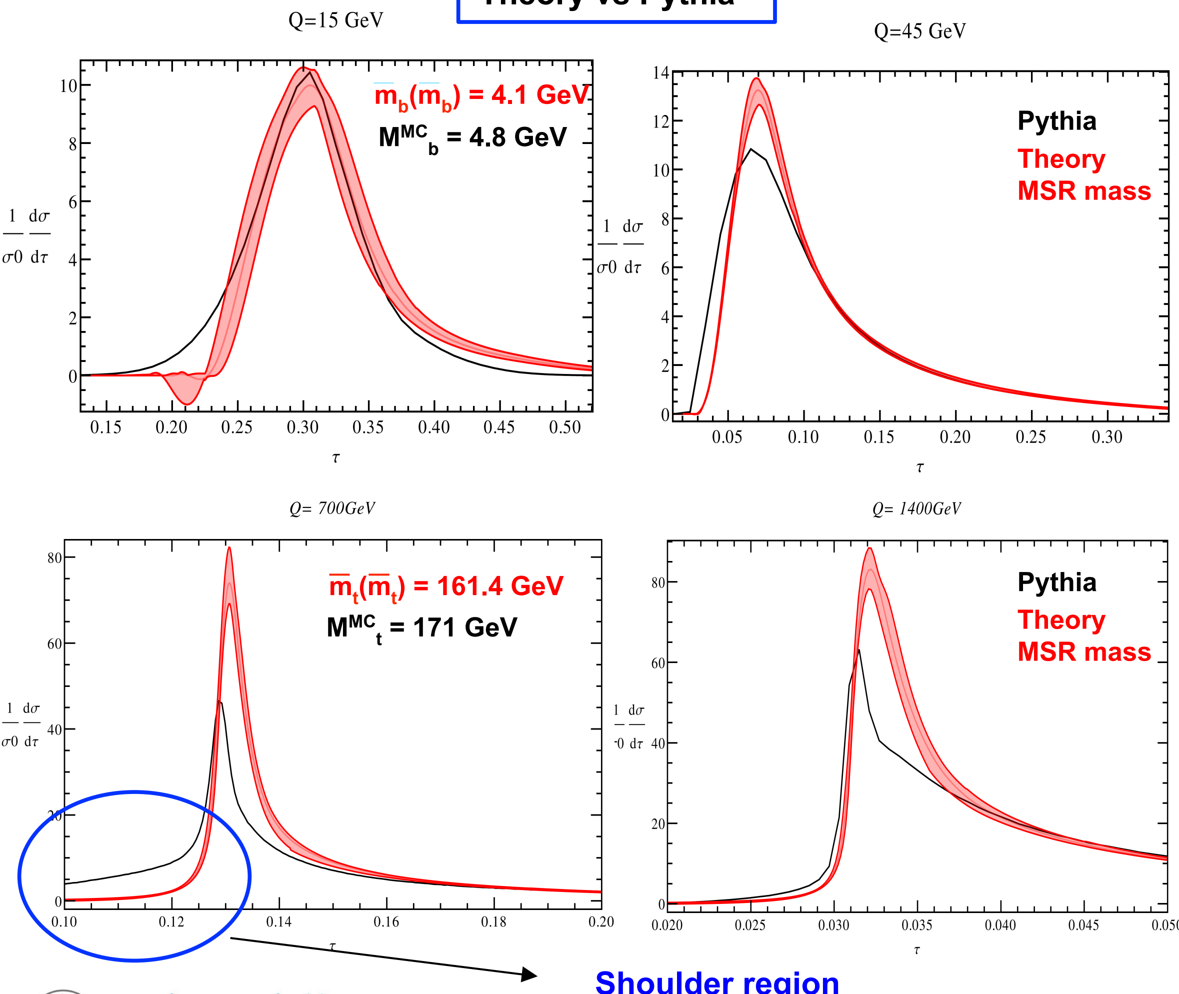
# bottom and top production in thrust

**NNLL (singular) + NLO (non-singular) + power correction and renormalon subtraction**

**Theory vs Pythia**

A. H. Hoang, V. Mateu, BD,
M. Butenschoen & Iain W. Stewart




- ➢ **Agreement of theory - Pythia :**
  - ✔ **Good for bottom**
  - ✔ **Some effect are likely missing (shoulder region) → off shell top + electroweak effects**

$$\alpha_s(m_Z) = 0.1184$$
$$\Omega_1 = 0.5\,\mathrm{GeV}$$

**Preliminary Results**

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# Conclusions and outlook

## Conclusions

- Complete description of the entire thrust distribution for boosted heavy quarks achieved with the formalism of VFNS for final-state jets and a sequence of effective field theory setups.

- The peak position in thrust is very sensitive (particularly at low energies) to the mass.
- Estimating theory errors is challenging
  - ✔ Under control directly at peak and tail.
  - ✔ Below peak still under investigation.

- Our theory uncertainty for the mass extraction is reasonable and encouraging
  - ✔ Bottom → less than 0.5 GeV
  - ✔ Top → almost 0.5 GeV

- Simultaneous fit for $\alpha_s$ and $\Omega_1$ is difficult, particularly for top → could be fixed externally
- Agreement between theory and Pythia:
  - ✔ Good for bottom
  - ✔ Some effects are likely missing for top (shoulder region) → off shell top + electroweak effects

## Outlook

- Improving the precision to $N^3LL$ seems mandatory.
- Off-shell top production + electroweak effects.