Precision Top Mass Determination at the LHC with Jet Grooming

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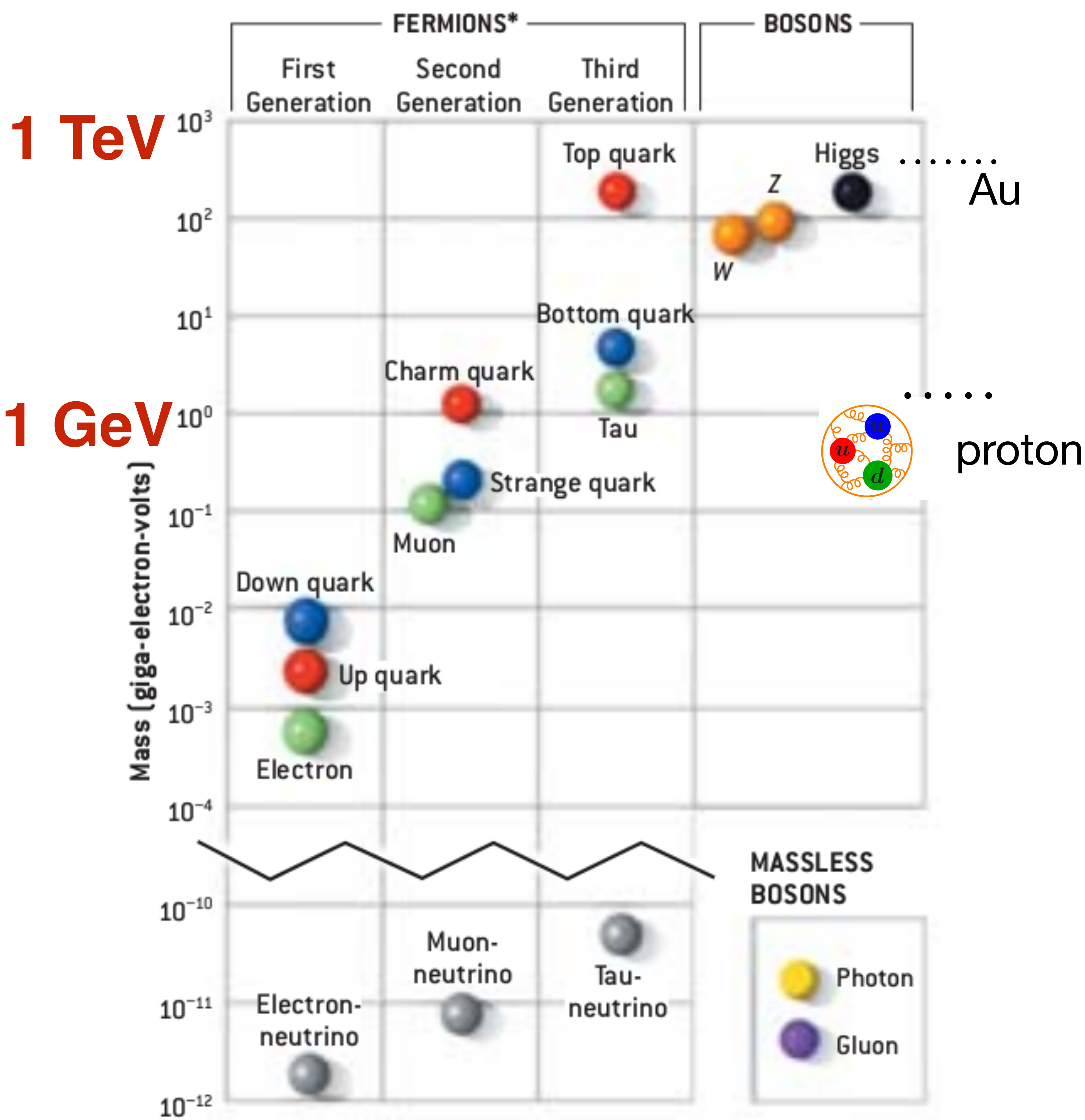
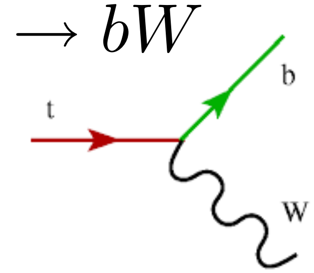
Top Quark is special

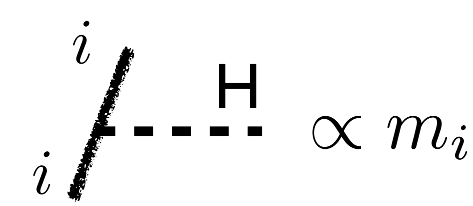


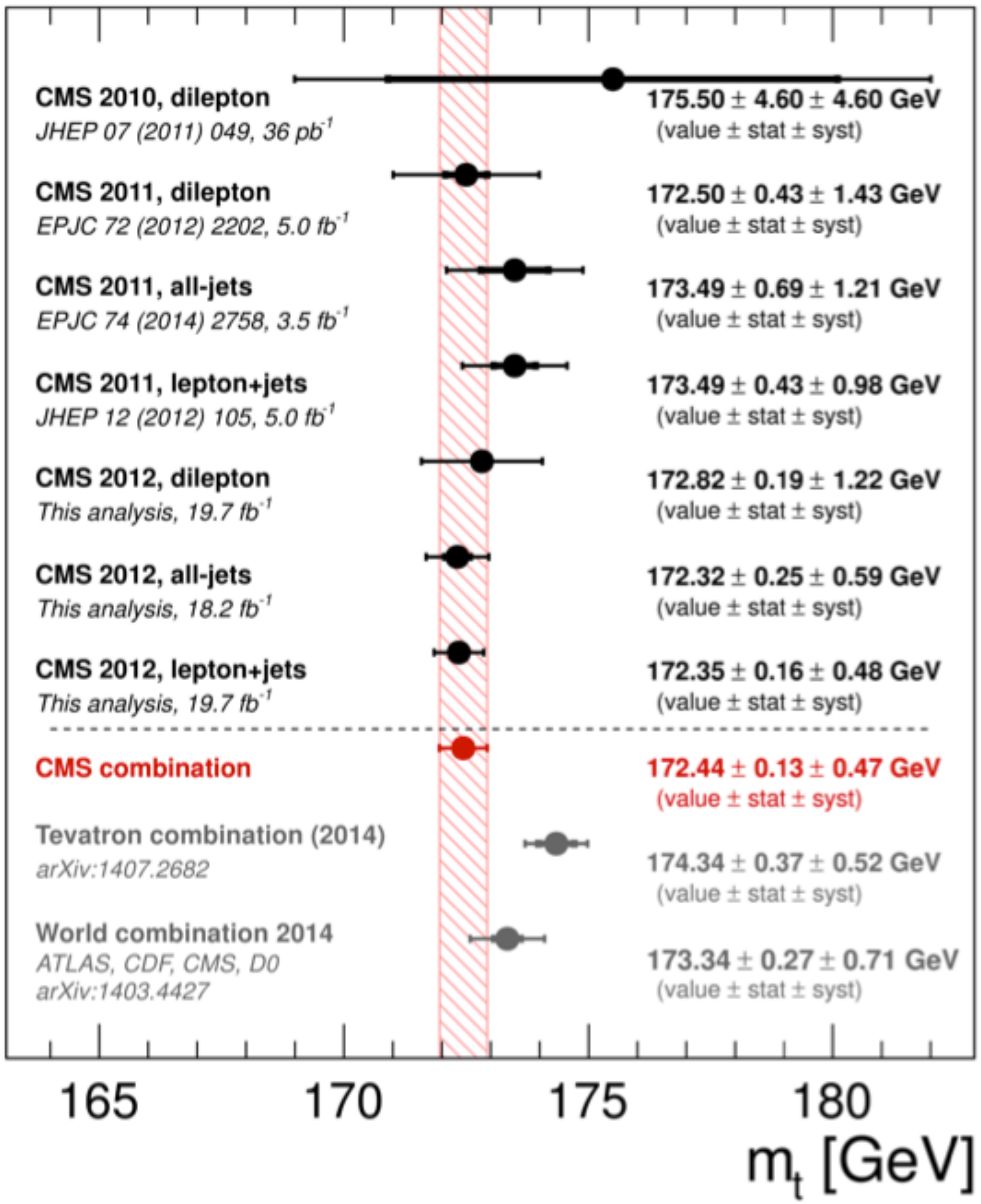
- Heaviest known elementary particle
- Decays before hadronization

$t \rightarrow bW$



- Large coupling to the Higgs





Precision Measurements

Tevatron (2014): $m_t = 174.34 \pm 0.64$ GeV

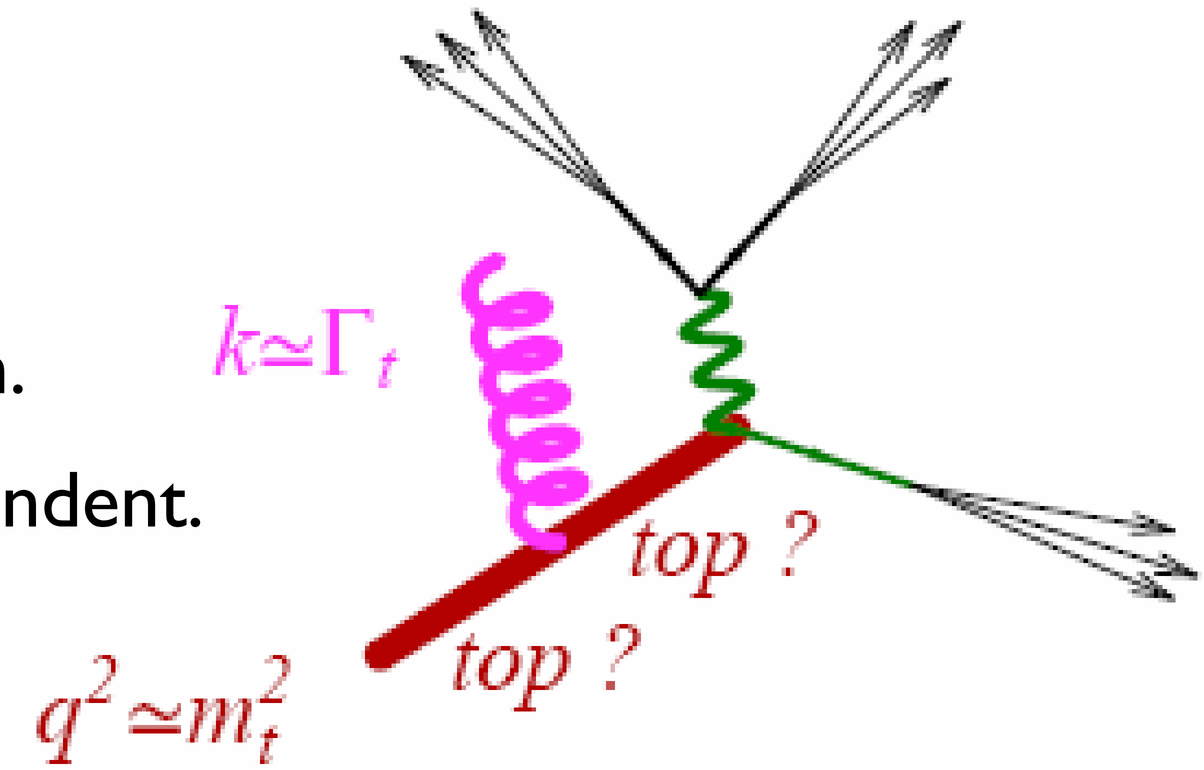
CMS Run 1 (2015): $m_t = 172.44 \pm 0.49$ GeV

ATLAS Run 1 (2016): $m_t = 172.84 \pm 0.70$ GeV

The Top Quark Mass

What is the top mass?

- Top is colored parton.
- Top mass is a parameter of the Lagrangian.
- Top mass is renormalization scheme dependent.



Which top mass?

- Which mass scheme is being measured in kinematic reconstruction methods?

- Mass extracted corresponds to the Monte Carlo (MC) mass.

- How can one relate the MC mass to a well-defined renormalization scheme?

Top Mass Schemes

$$m_t^{\mathrm{pole}} = m_t(R,\mu) + \delta m_t(R,\mu)$$

$$\delta m_t(R,\mu) = R \sum_{n=1}^{\infty} \sum_{k=0}^{n} a_{nk} \left[\frac{\alpha_s(\mu)}{4\pi}\right]^n \ln^k \frac{\mu}{R}$$

- Different schemes correspond to different coefficients and values for "R"

$\overline{\mathrm{MS}}$:	$\overline{m}(\mu)$,	$R = \overline{m}(\mu)$;
RGI [2] :	m_{RGI},	$R = m_{\mathrm{RGI}}$;
kinetic [3] :	m_{kin},	$R = \mu_f^{\mathrm{kin}}$;
1S [4] :	$m_{1\mathrm{S}}$,	$R = m_{1\mathrm{S}} C_F \alpha_s(\mu)$
PS [5] :	m_{PS},	$R = \mu_f^{\mathrm{PS}}$.

"Top Resonance Mass Schemes" $R \sim \Gamma_t$

(Fleming, Hoang, SM, Stewart)

$$m_t^{\rm pole} = m_t(R,\mu) + \delta m_t(R,\mu)$$

$$\delta m_t(R,\mu) = R \sum_{n=1}^{\infty} \sum_{k=0}^{n} a_{nk} \left[\frac{\alpha_s(\mu)}{4\pi}\right]^n \ln^k \frac{\mu}{R}$$

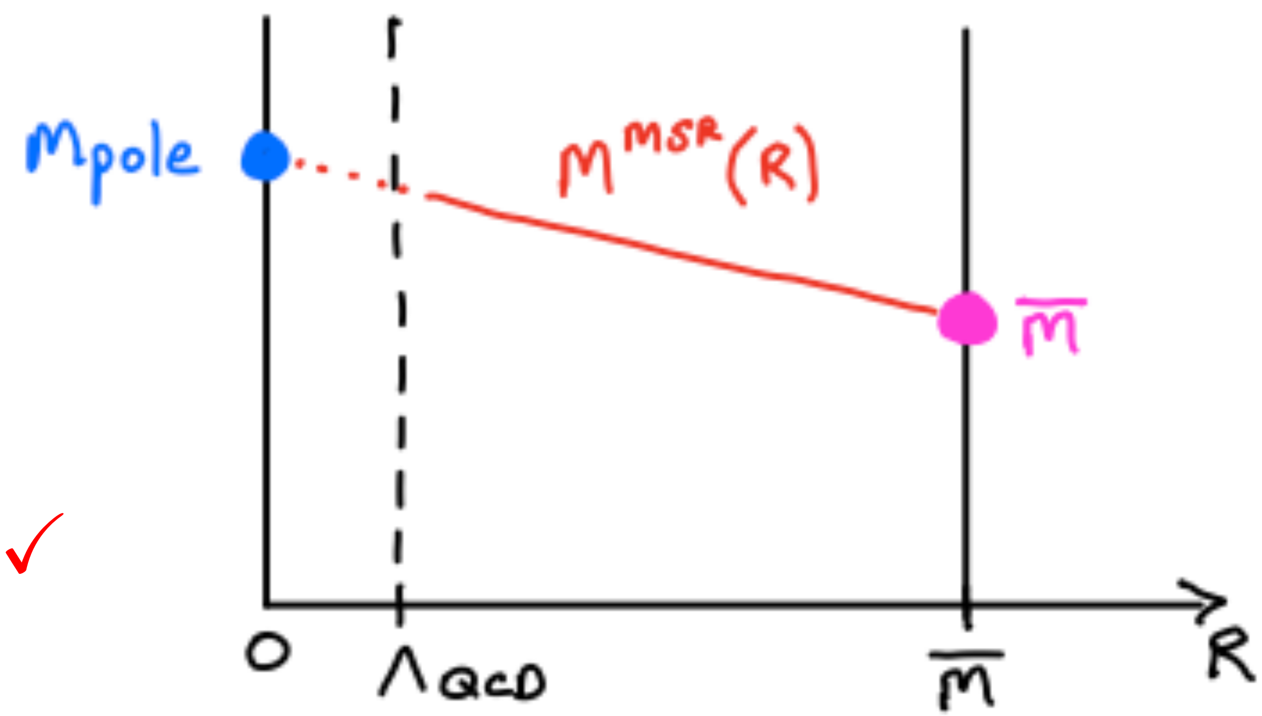
- MSR mass scheme:

(Hoang, Jain, Scimemi, Stewart)

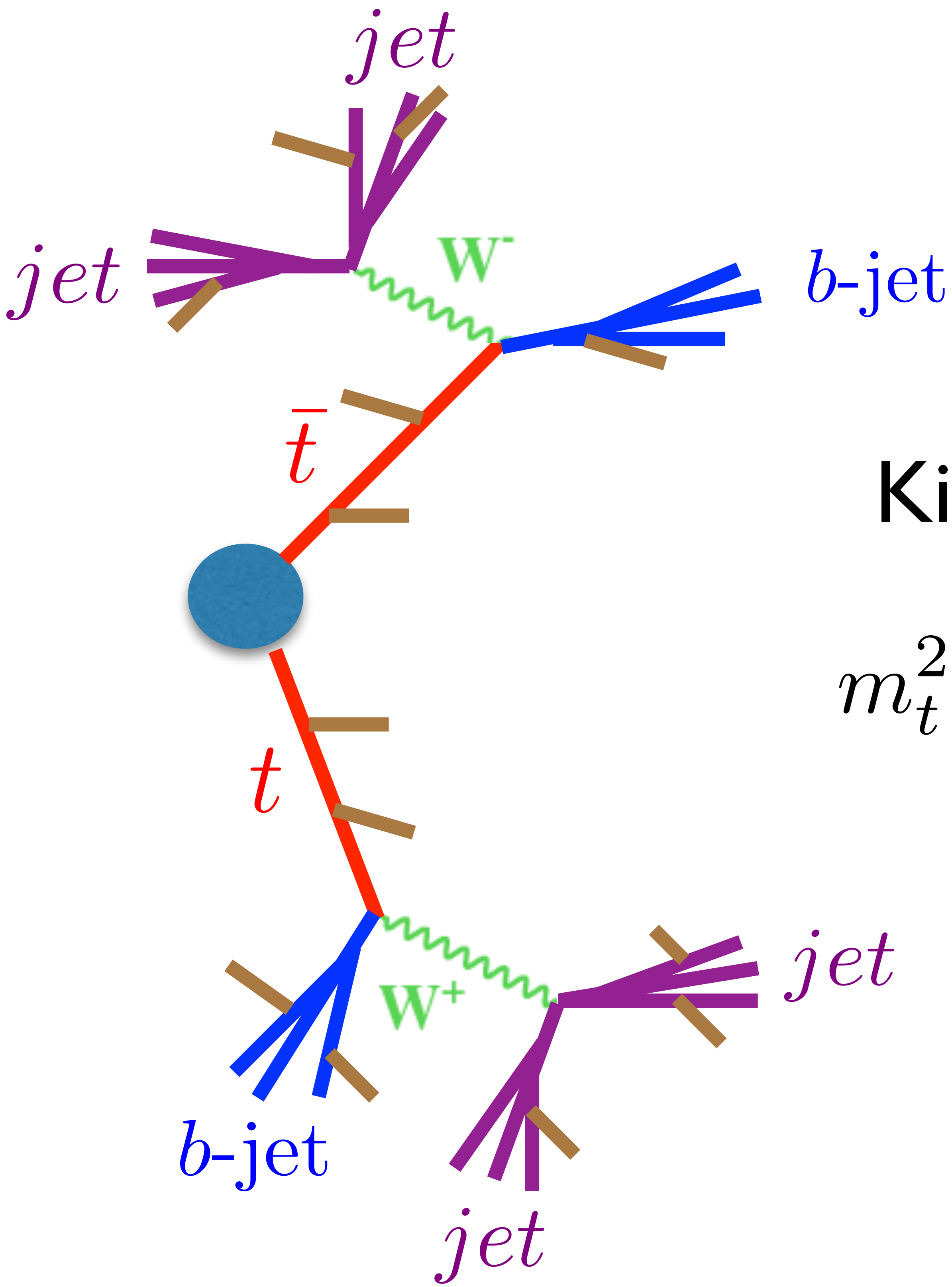
Define using $\overline{\rm MS}$ coefficients a_{nk}

No ambiguity, R > Λ_{QCD} ✓

Compatible with Breit Wigner, R ~ Γ_t ✓



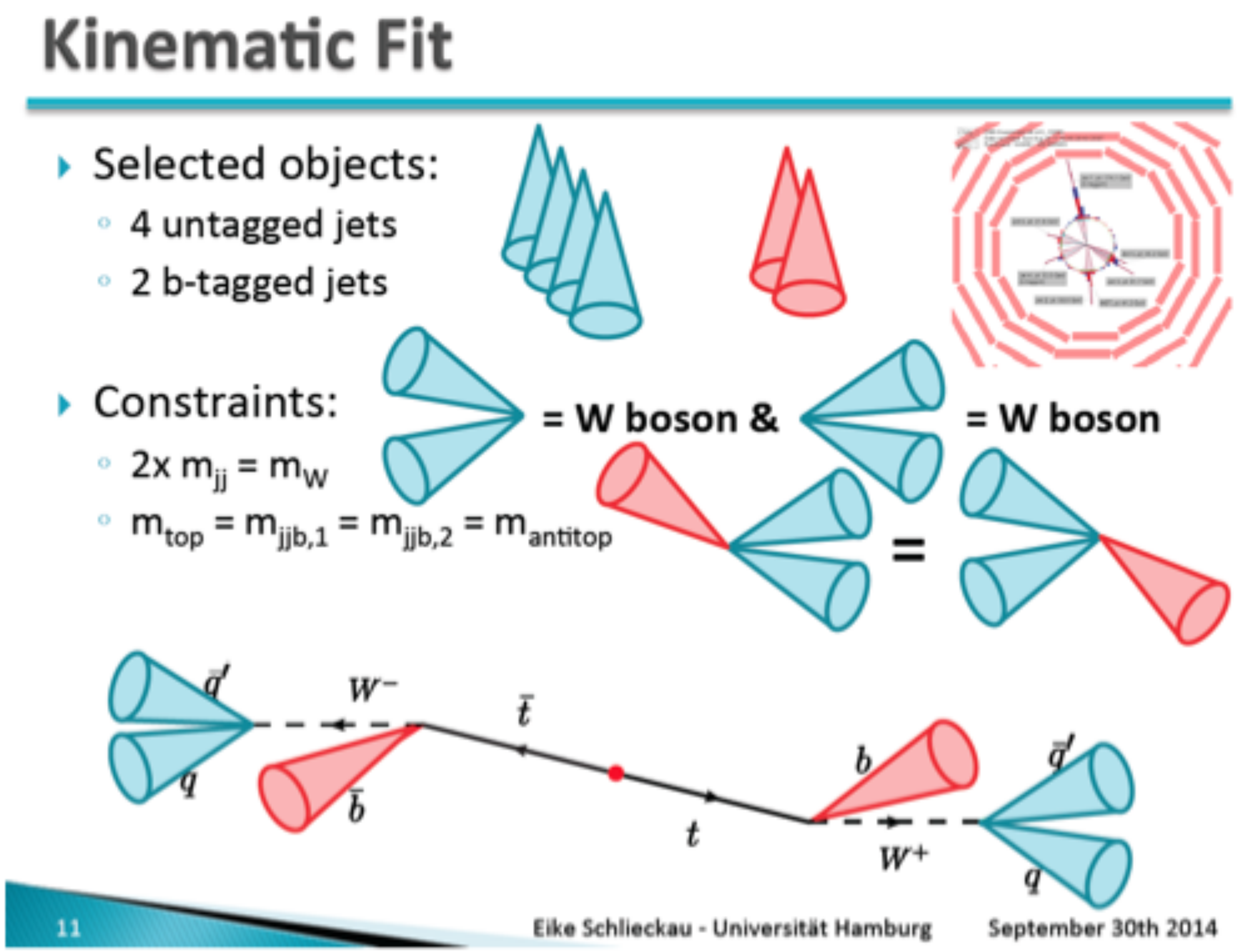
Top Mass from Direct Reconstruction



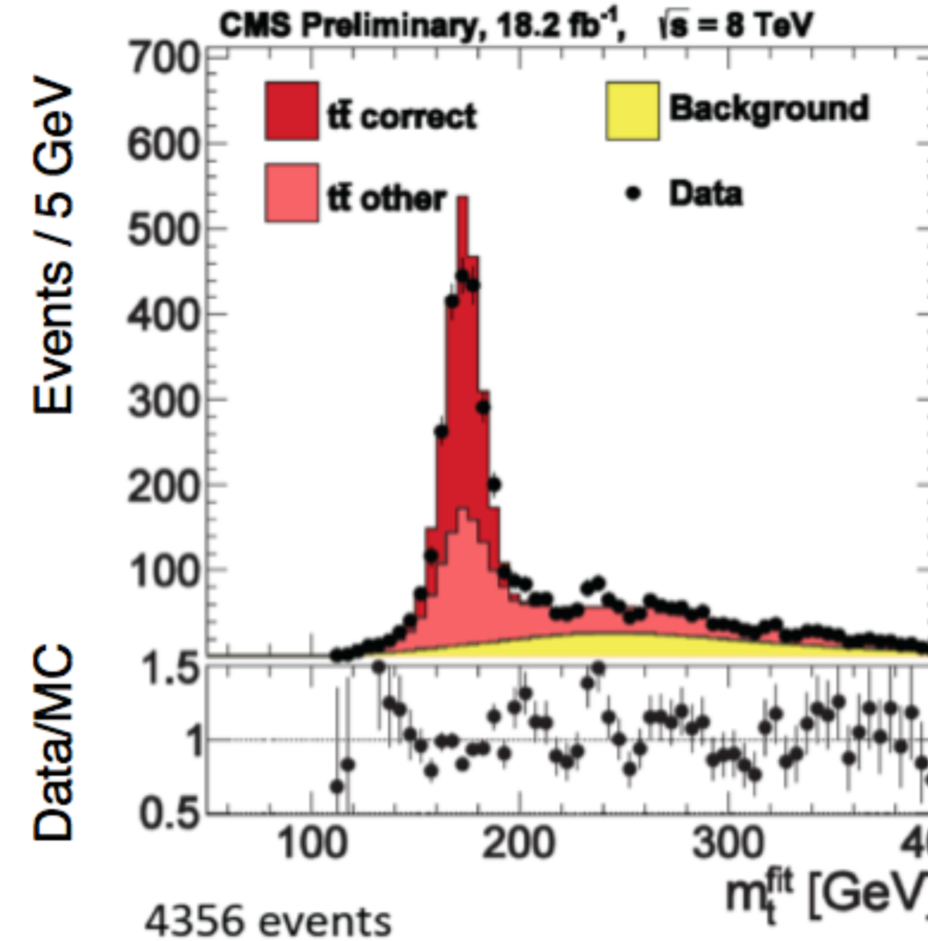
Kinematic Fit:

$$m_t^2 = p_t^2 = (p_{Jb} + p_{J1} + p_{J2})^2$$

Top Mass from Direct Reconstruction



CMS-PAS-TOP-14-002



4356 events

all-jets channel at 8 TeV

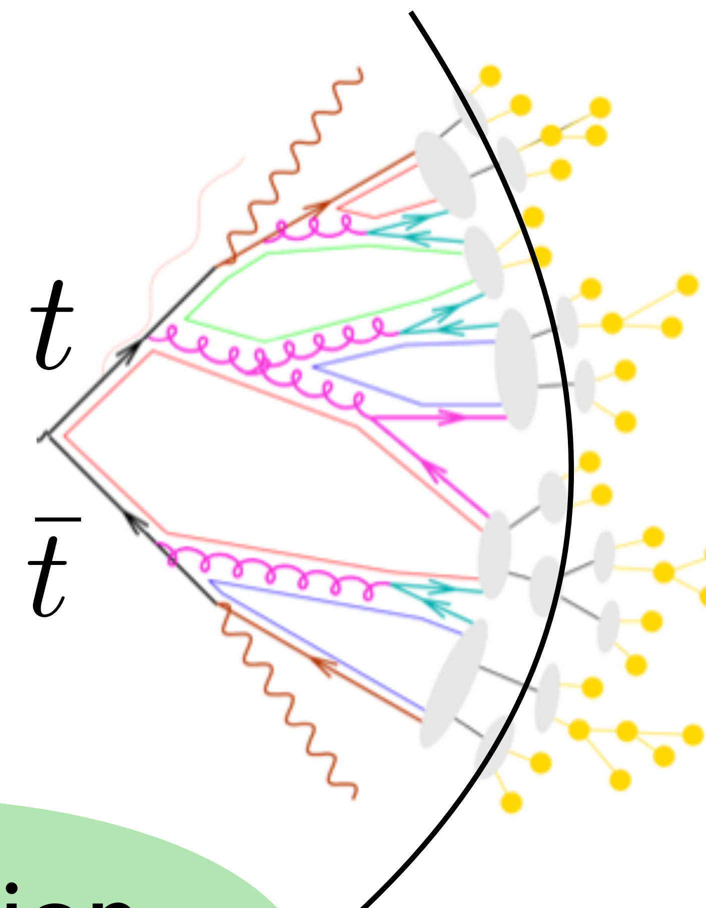
Use Monte Carlo Simulations for templates

Determine best fit value for Monte Carlo top-mass parameter

CMS: $m_t^{\mathrm{MC}} = 172.44 \pm 0.49$

ATLAS: $m_t^{\mathrm{MC}} = 172.84 \pm 0.70$

$m_t^{\mathrm{pole}}, \overline{m}_t, m_t^{\mathrm{MSR}}, \ldots$



hadrons

$\Lambda^{\mathrm{shower}} = 1\,\mathrm{GeV}$

Theory (QFT)

Simulation
(Monte Carlo)

Experiment

m_t^{MC}

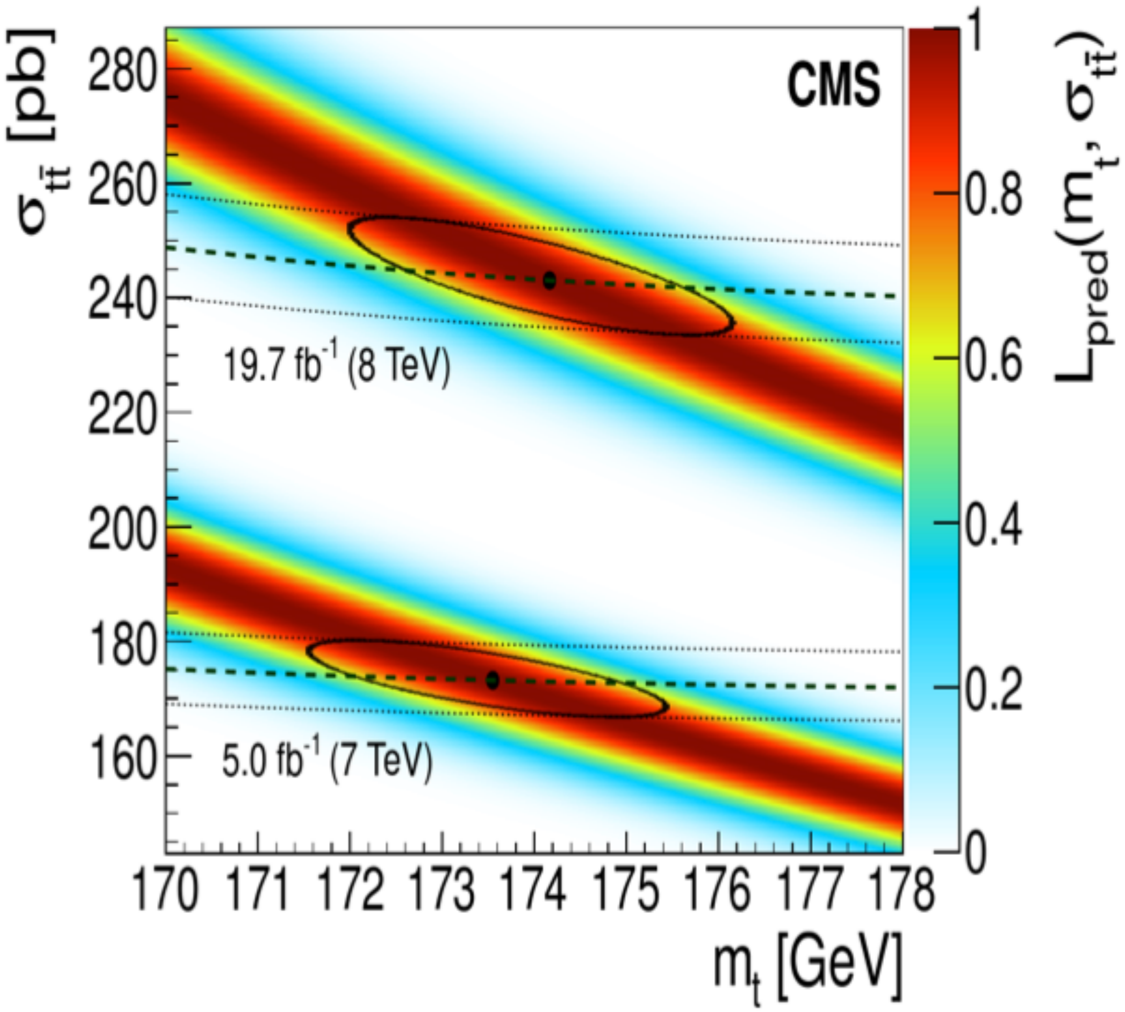
No Ambiguity ✓

Breit Wigner ✓

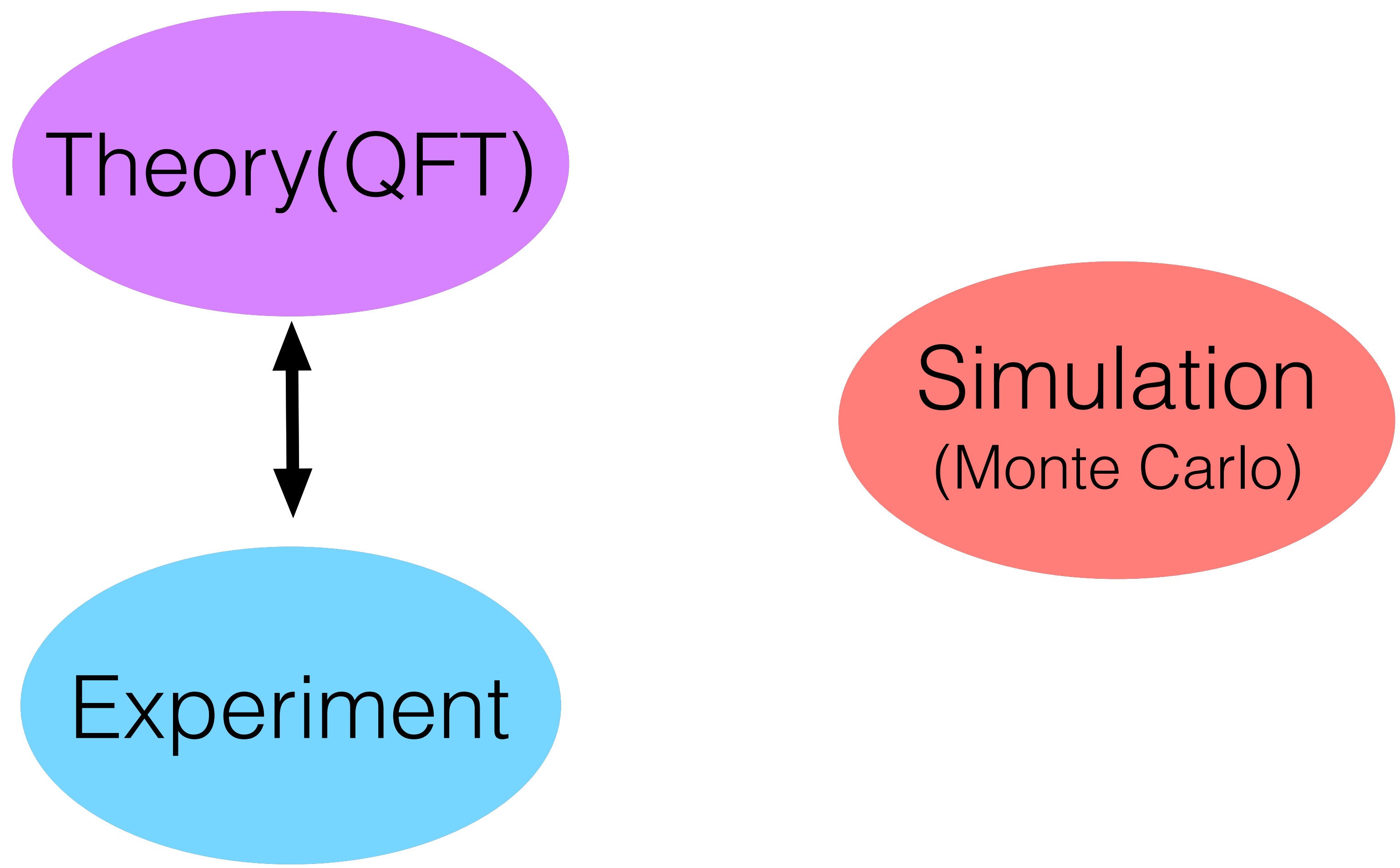
Definition ?

Top Pole Mass from Total Cross-Section

- Clean interpretation of top mass scheme is possible from cross-section measurements



$$\sigma^{\rm exp}(pp \to t\bar{t}) = \sigma^{\rm th}_{t\bar{t}}(m_t)$$



	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$

NNLO+NNLL
(Czakon,Fielder,Mitov)

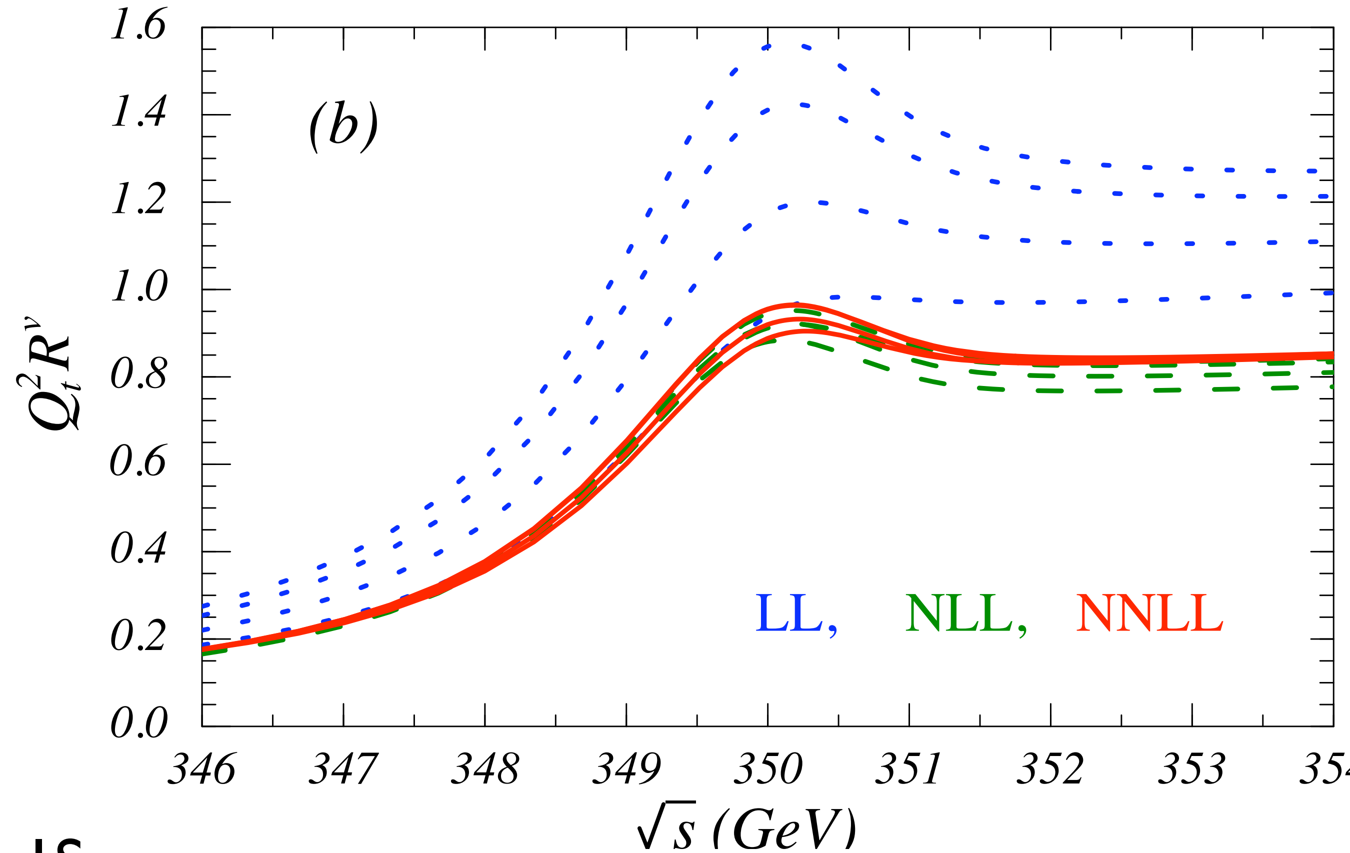
Threshold Scan

(Fadin, Khoze; Peskin, Strassler;Hoang, Manohar, Stewart, Teubner; Kuhn, Martinez, Miquel; Beneke, Kiyo, Schuller; Kniehl,Penin,...)

- Clean interpretation of top mass scheme is possible from Threshold Scan

Top pair-production at threshold

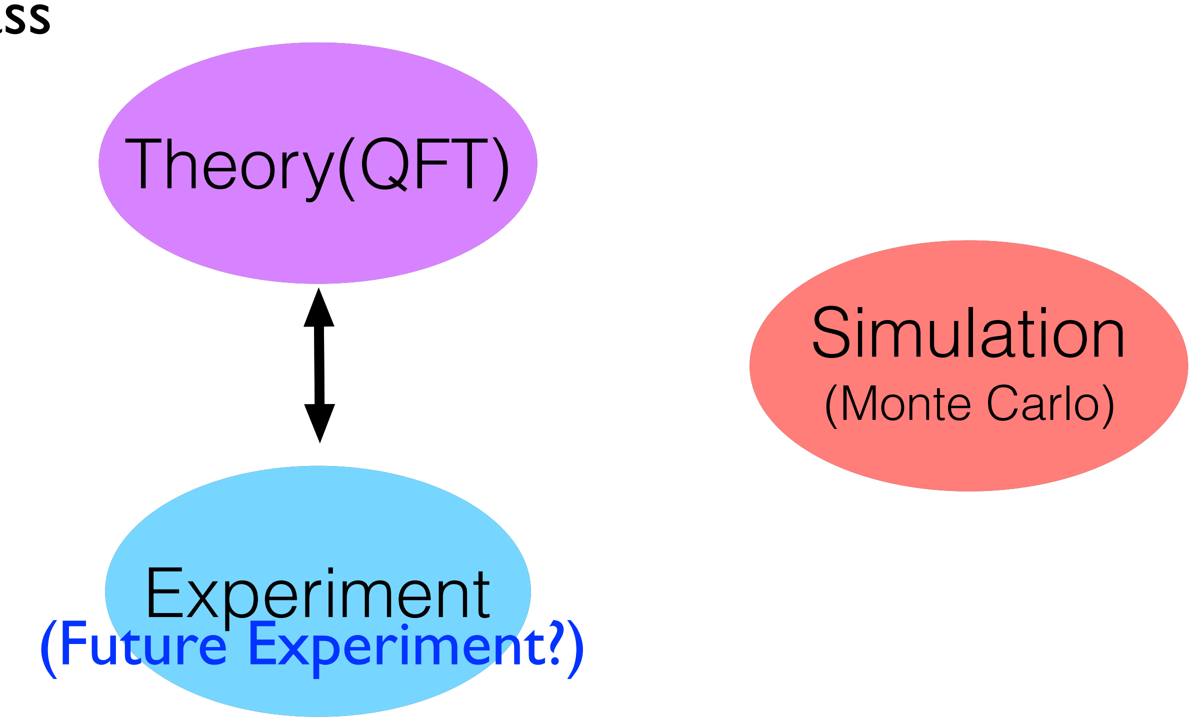
- Shape of cross-section sensitive to top mass.
- Top width provides IR cutoff.
- Non-perturbative effects are small.



Physics well understood

- NRQCD is the appropriate EFT.
- Well-defined relation to short distance mass; eg.1S mass
- Precision:

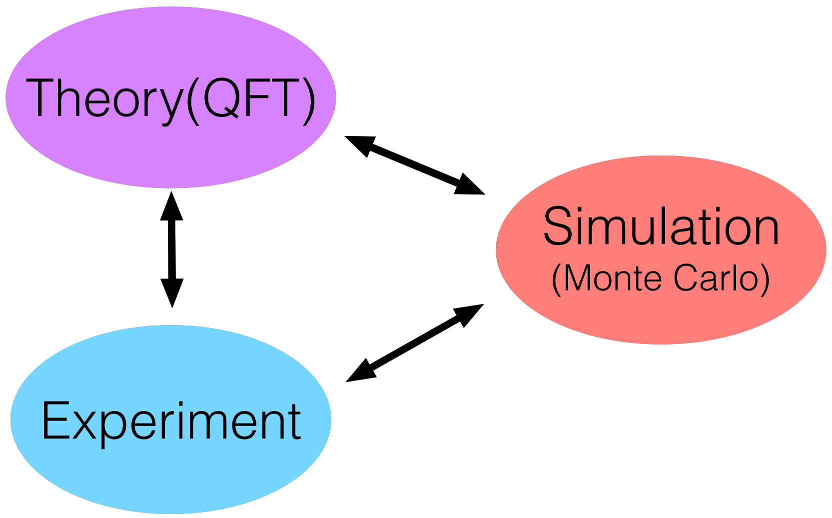
$$\delta m_t \sim 100 \text{ MeV}$$



Improving Top Mass Measurement at the LHC

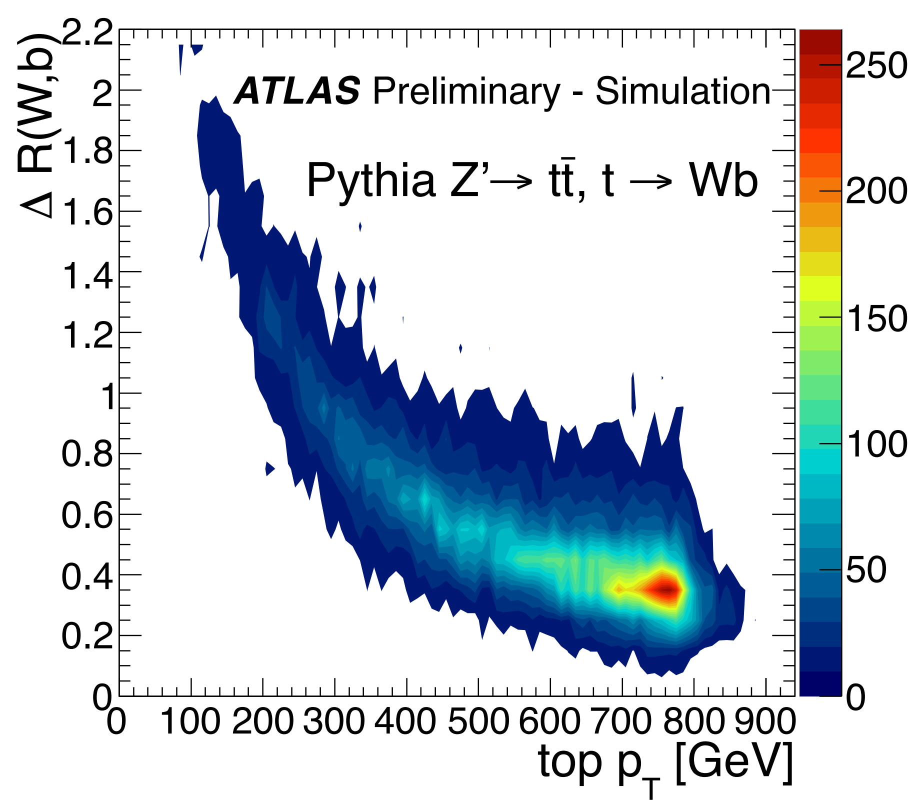
$$M_t^{\rm peak} = m_t + (\text{nonperturbative effects}) + (\text{perturbative effects})$$

- Observable must be kinematically sensitive to the Top Mass
- Observable must be theoretically tractable
- Observable must have well-defined relation to top mass scheme
- Control contamination from hadron collider environment

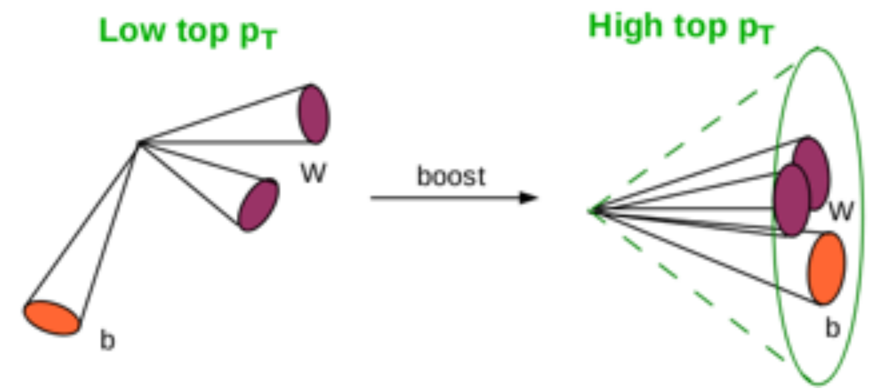


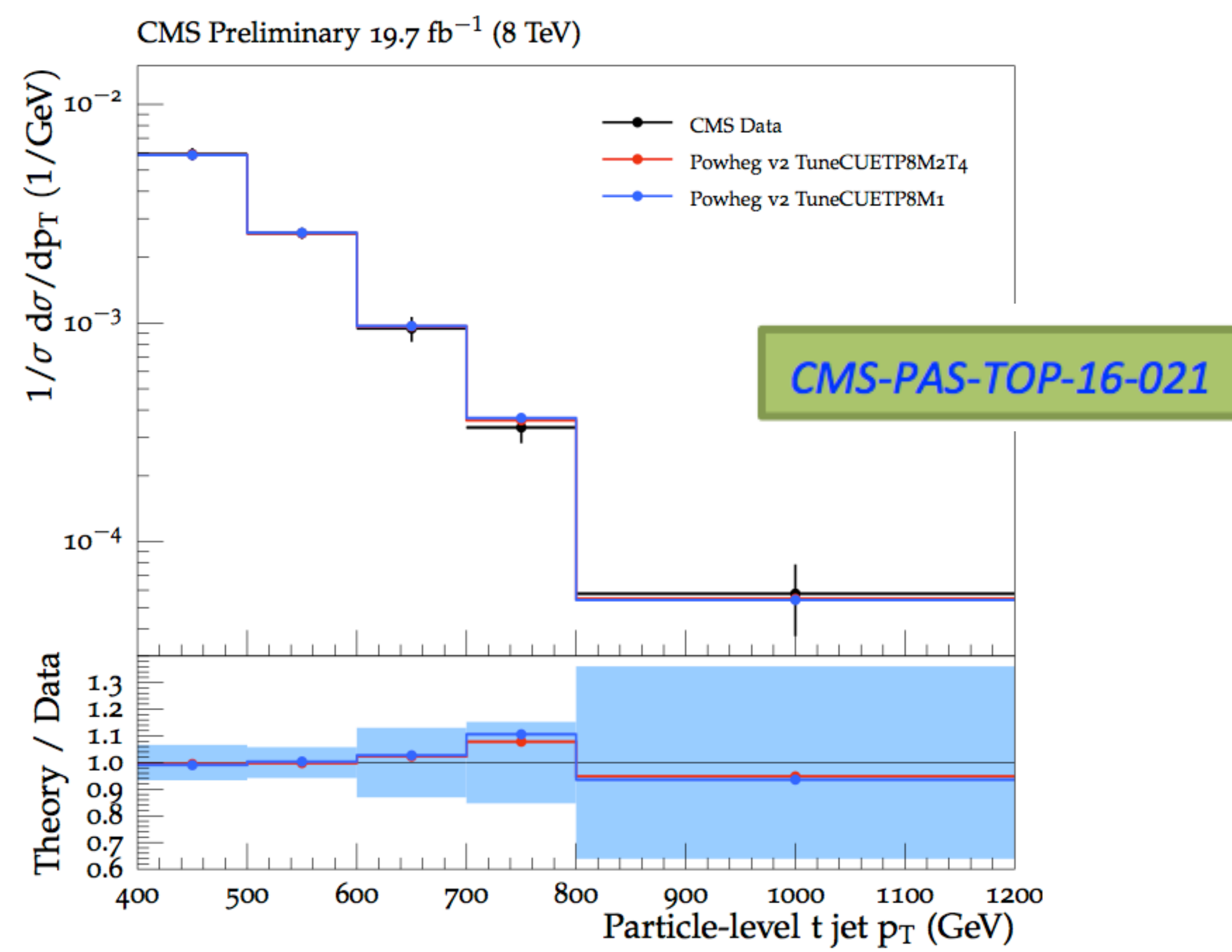
Boosted Top Quarks

- Boosted top quarks provide first simplification
- Decay products contained in a “fat” jet



(a) $t \to Wb$



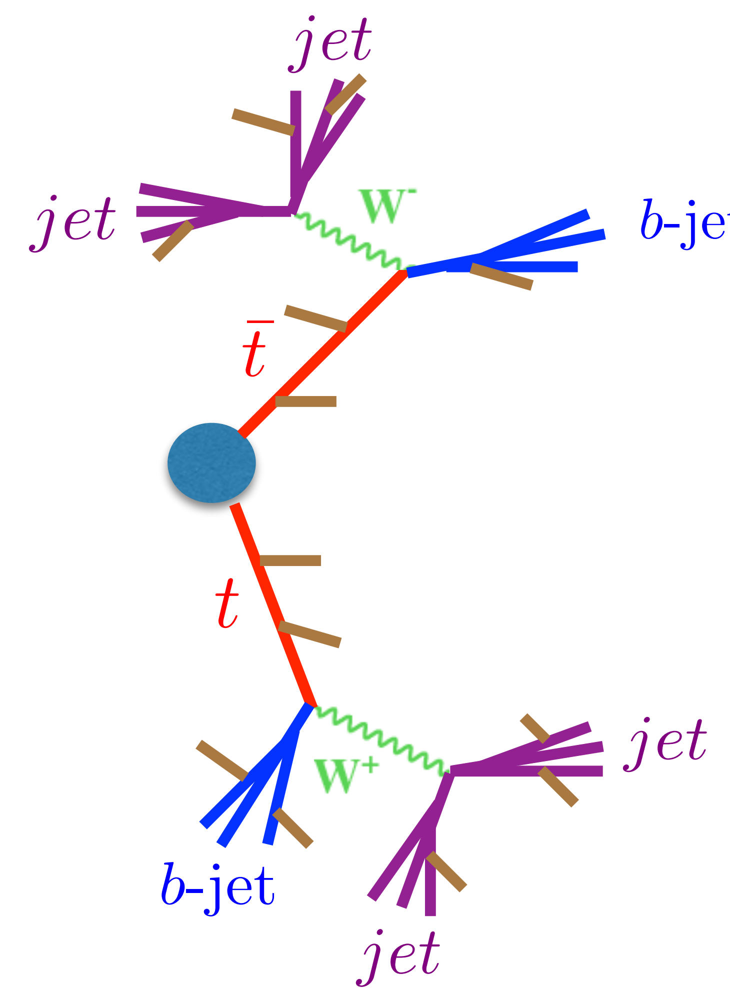


Rule of thumb for decay products:

$$\Delta R(W,b) \sim \frac{2m_t}{p_T}$$

Theory Issues at Hadron Collider

- Jet observable
- Clear relation to top mass scheme
- Initial state radiation
- Final state radiation
- Beam remnant
- Parton distribution functions
- Color reconnection
- Underlying events, pile up
- Summing large logs



Theory Issues at Hadron Collider

- Jet observable ★
- Clear relation to top mass scheme ★
- Initial state radiation
- Final state radiation ★
- Beam remnant
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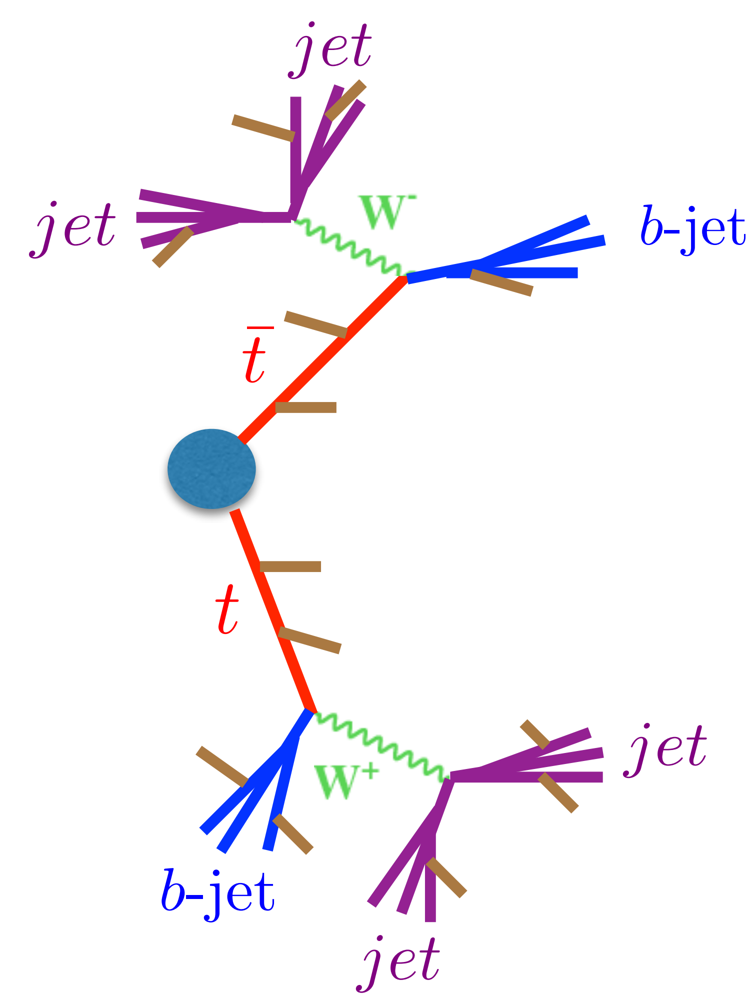
- Color reconnection ★
- Underlying events, pile up
- Summing large logs ★

First

$e^+e^- \to t\bar{t}X$

and the issues ★



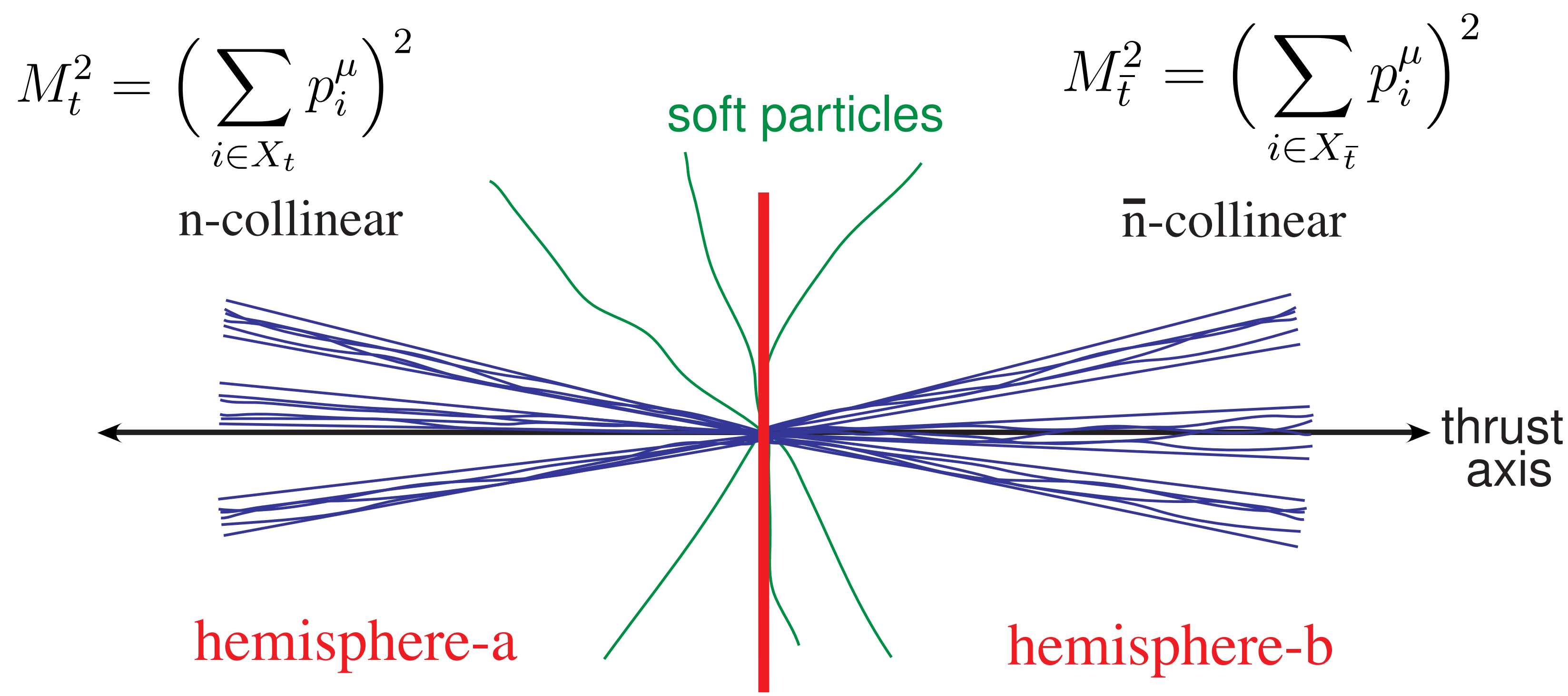
Top Mass From Jet Distributions

(Fleming, Hoang, SM, Stewart)

$$e^+e^- \to t\bar{t}X$$

- Top jet hemisphere mass distribution sensitive to top mass:

$$\frac{d^2\sigma}{dM_t^2\, dM_{\bar{t}}^2}$$



- Peak region:

$$\frac{M_{t,\bar{t}}^2 - m^2}{m} \sim \Gamma \ll m$$

Top Mass From Jet Distributions

$$e^+e^- \to t\bar{t}X$$

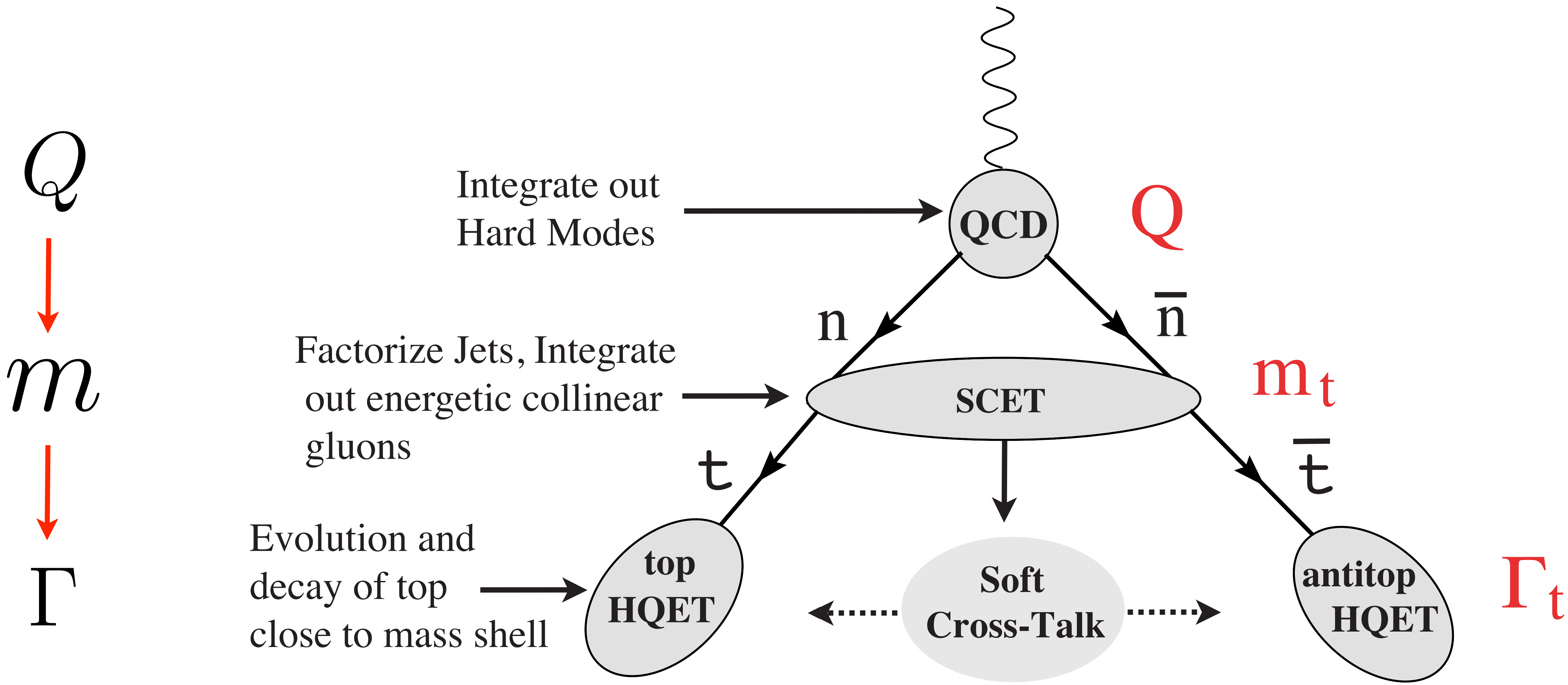
Boosted top quark pair-production:

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

Q	m_t	Γ_t	$\Lambda_{\rm QCD}$
↑	↑	↑	↑
CM Energy	Top Mass	Top Width	Non-perturbative scale

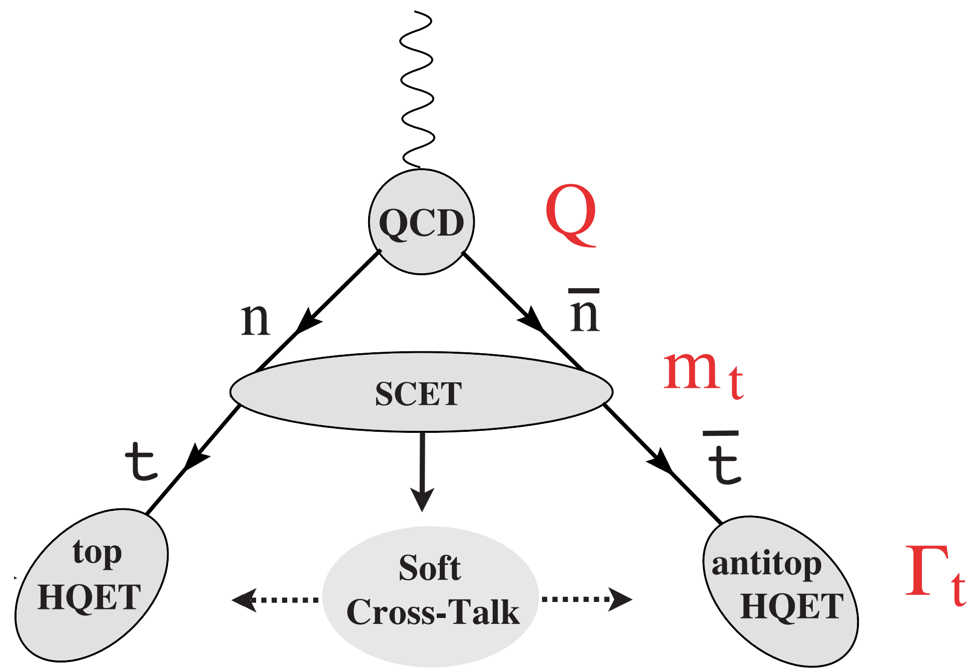
Four scales in the problem!

A Symphony of Effective Field Theories



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

Factorization Formula



Hard modes integrated out

"Hard" collinear modes integrated out

Evolution and decay of top quarks close to mass shell

Soft cross-talk

$$\frac{d\sigma}{dM_t^2\, dM_{\bar t}^2} = \sigma_0\, H_Q(Q,\mu_m) H_m\Big(m_J, \frac{Q}{m_J}, \mu_m, \mu\Big)$$

$$\times \int d\ell^+ d\ell^- B_+\Big(\hat s_t - \frac{Q\ell^+}{m_J}, \Gamma_t, \mu\Big)\, B_-\Big(\hat s_{\bar t} - \frac{Q\ell^-}{m_J}, \Gamma_t, \mu\Big) S(\ell^+, \ell^-, \mu)$$

Top Mass From Jet Distributions

$$\frac{d\sigma}{dM_t^2\, dM_{\bar t}^2} = \sigma_0\, H_Q(Q,\mu_m) H_m\Big(m_J, \frac{Q}{m_J}, \mu_m, \mu\Big)$$
$$\times \int d\ell^+ d\ell^- B_+\Big(\hat s_t - \frac{Q\ell^+}{m_J}, \Gamma_t, \mu\Big)\, B_-\Big(\hat s_{\bar t} - \frac{Q\ell^-}{m_J}, \Gamma_t, \mu\Big) S(\ell^+, \ell^-, \mu)$$

- HQET Lagrangian determines dynamics of top-jet functions B:

$$\mathcal{L}_\pm = \bar h_{v_\pm}\big(iv_\pm \cdot D_\pm - \delta m + \frac{i}{2}\Gamma_t\big) h_{v_\pm} \qquad \delta m = m_{\rm pole} - m$$

- EFT power counting defines the "top resonance" mass schemes:

$$\delta m \sim \hat s_t \sim \hat s_{\bar t} \sim \Gamma$$

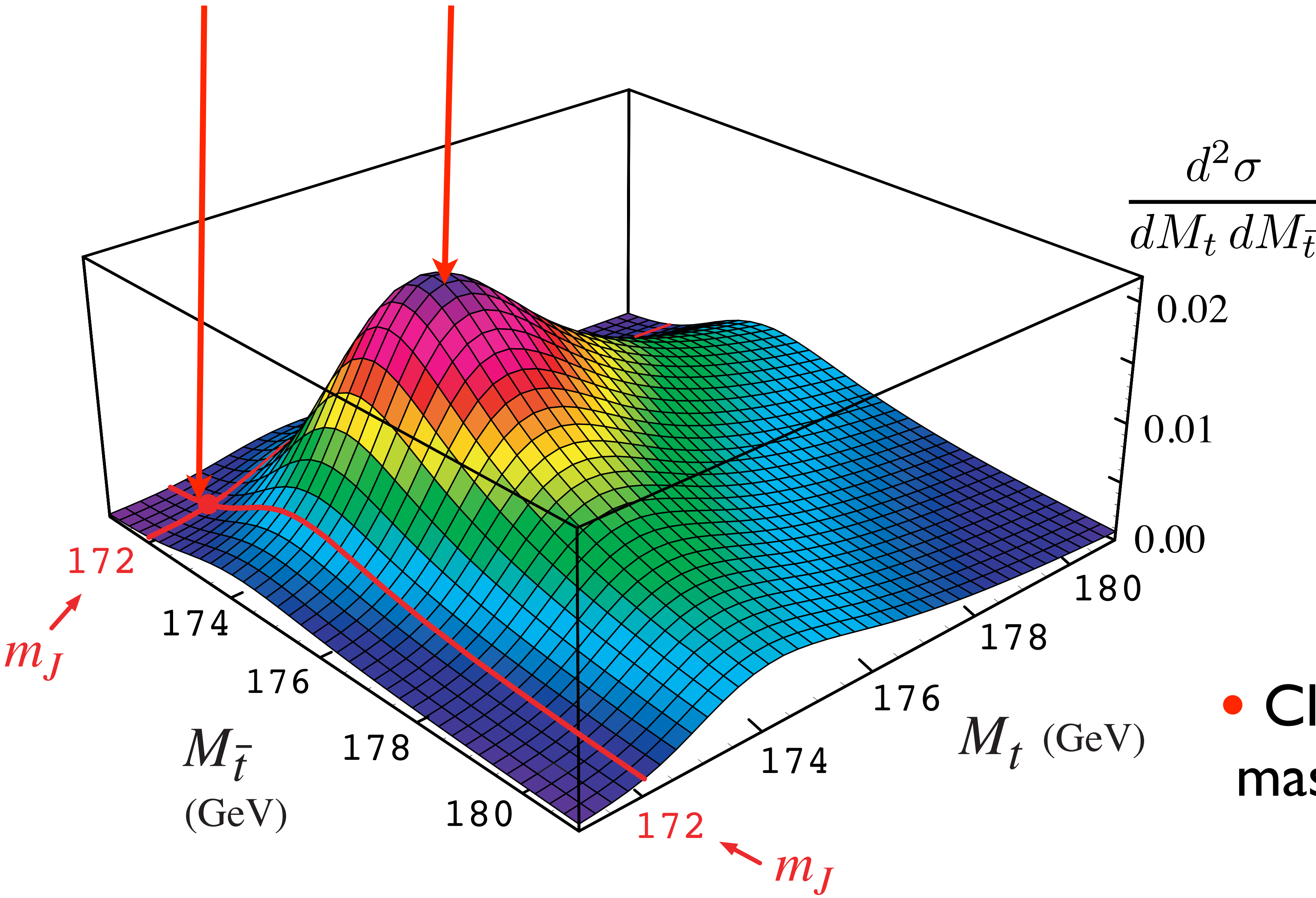
- Note power counting of EFT breaks down for MSbar mass:

$$\delta \bar m \sim \alpha_s \bar m \gg \Gamma$$

Top Mass From Jet Distributions

$$\frac{d\sigma}{dM_t^2\, dM_{\bar t}^2} = \sigma_0\, H_Q(Q,\mu_m) H_m\Big(m_J, \frac{Q}{m_J}, \mu_m, \mu\Big)$$
$$\times \int d\ell^+ d\ell^- B_+\Big(\hat s_t - \frac{Q\ell^+}{m_J}, \Gamma_t, \mu\Big)\, B_-\Big(\hat s_{\bar t} - \frac{Q\ell^-}{m_J}, \Gamma_t, \mu\Big) S(\ell^+, \ell^-, \mu)$$

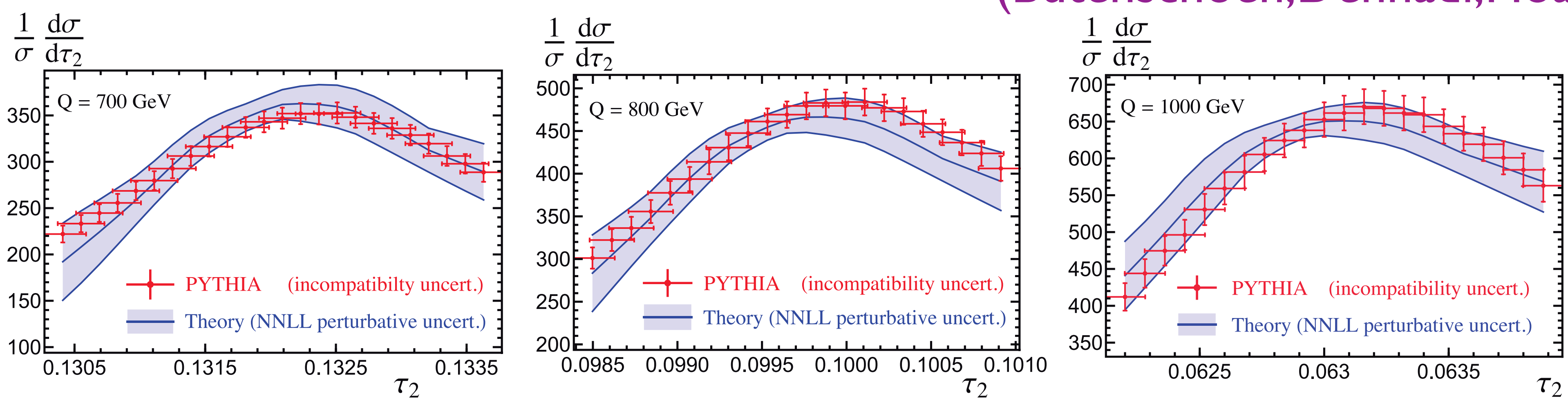
$$m_J = M_{\rm peak} - \Gamma(\alpha_s + \cdots) - \frac{Q\Lambda_{QCD}}{m}$$

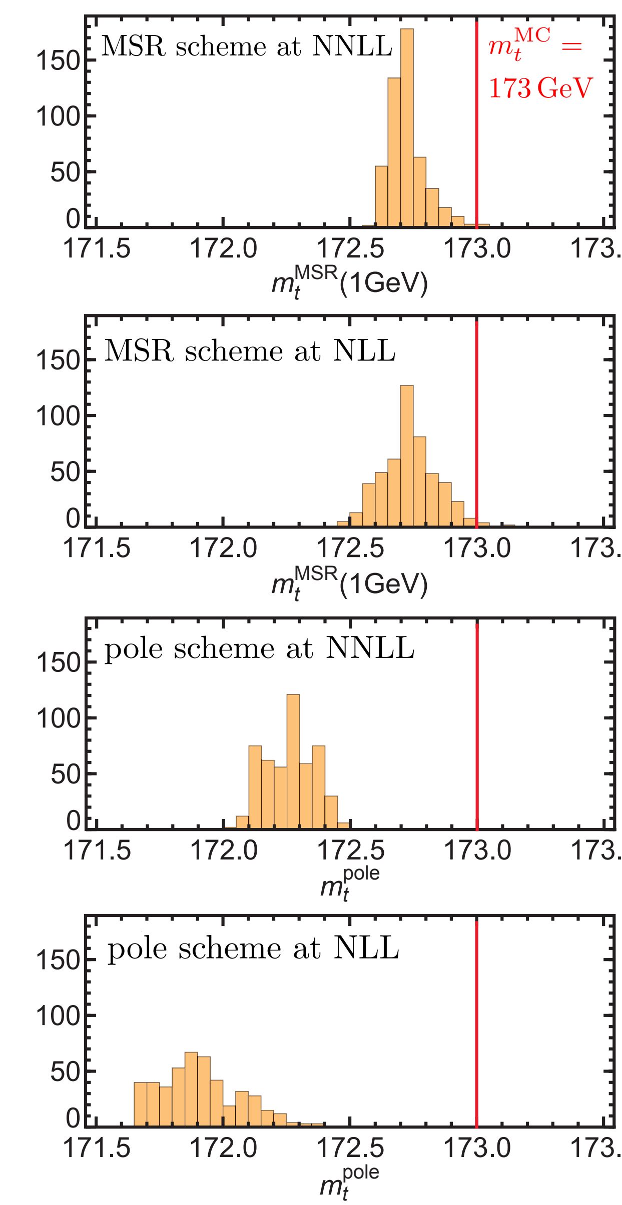


- Clear relation between top mass and peak position

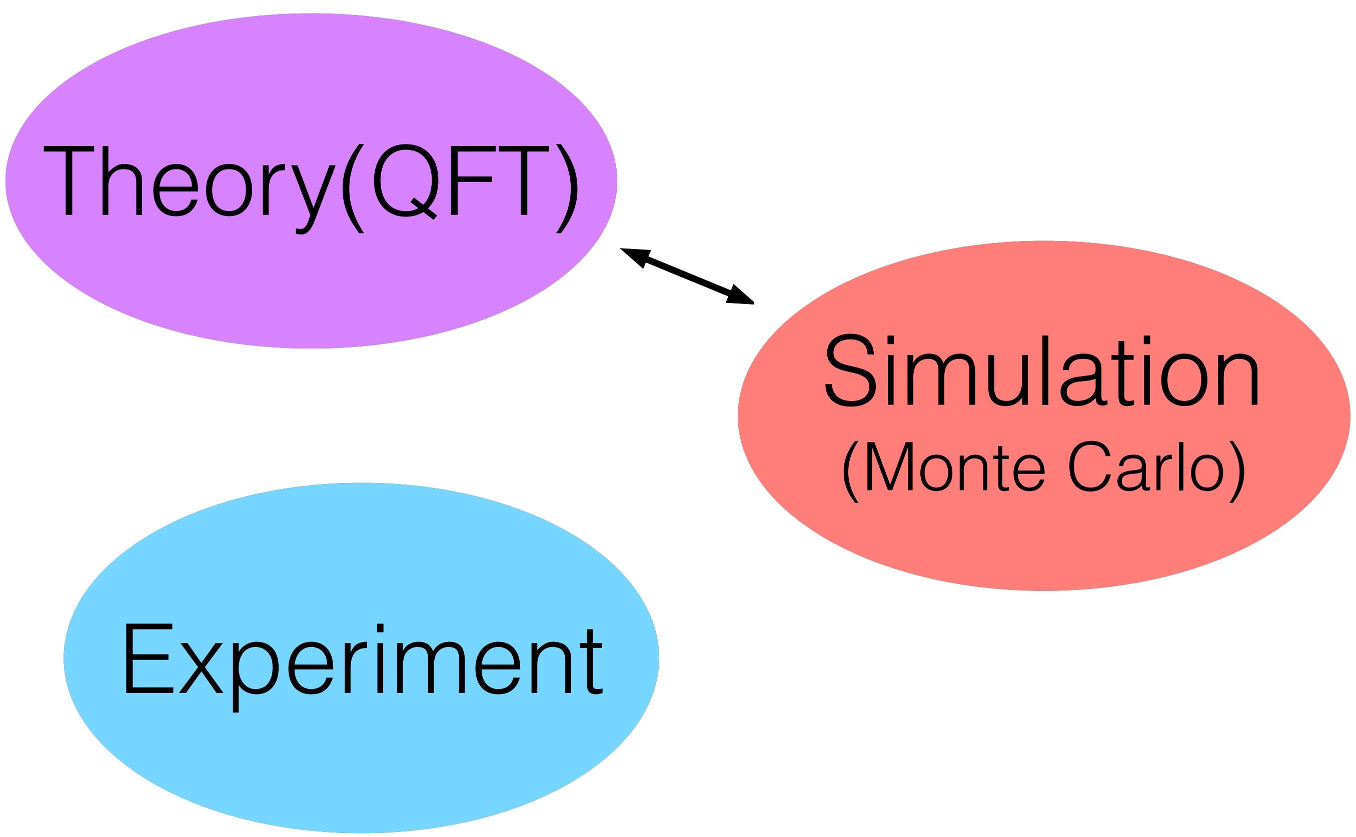
Top Mass Calibration of Monte Carlo

(Butenschoen,Dehnadi,Hoang, Mateu,Preisser, Stewart)





- Monte Carlo top mass is found to be closer to the MSR mass than the pole mass.



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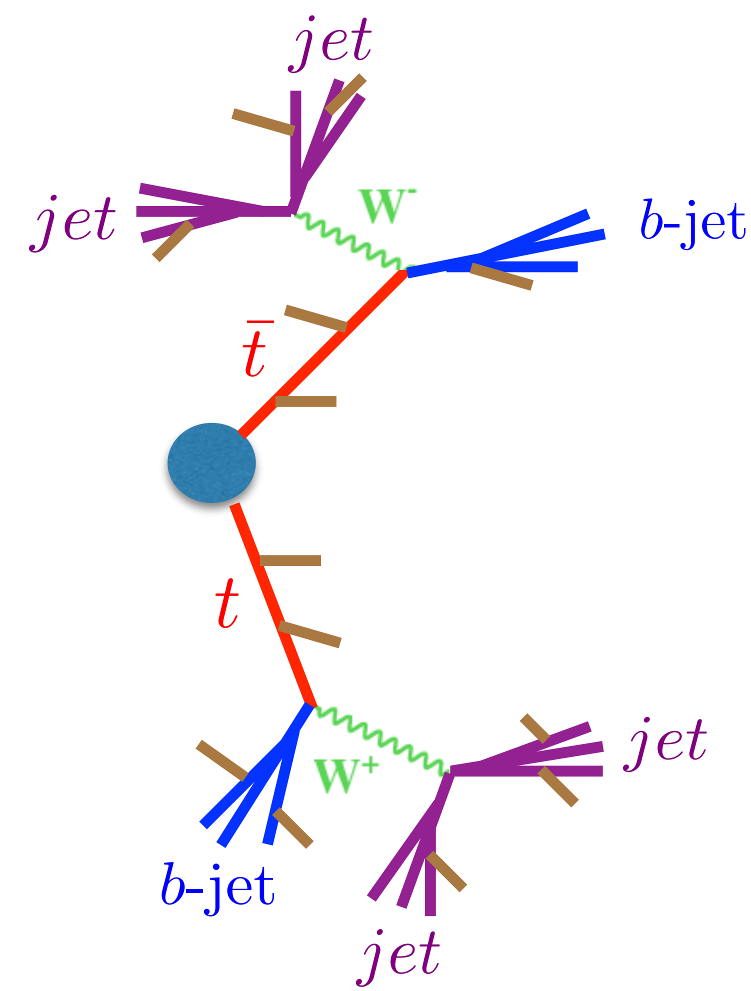
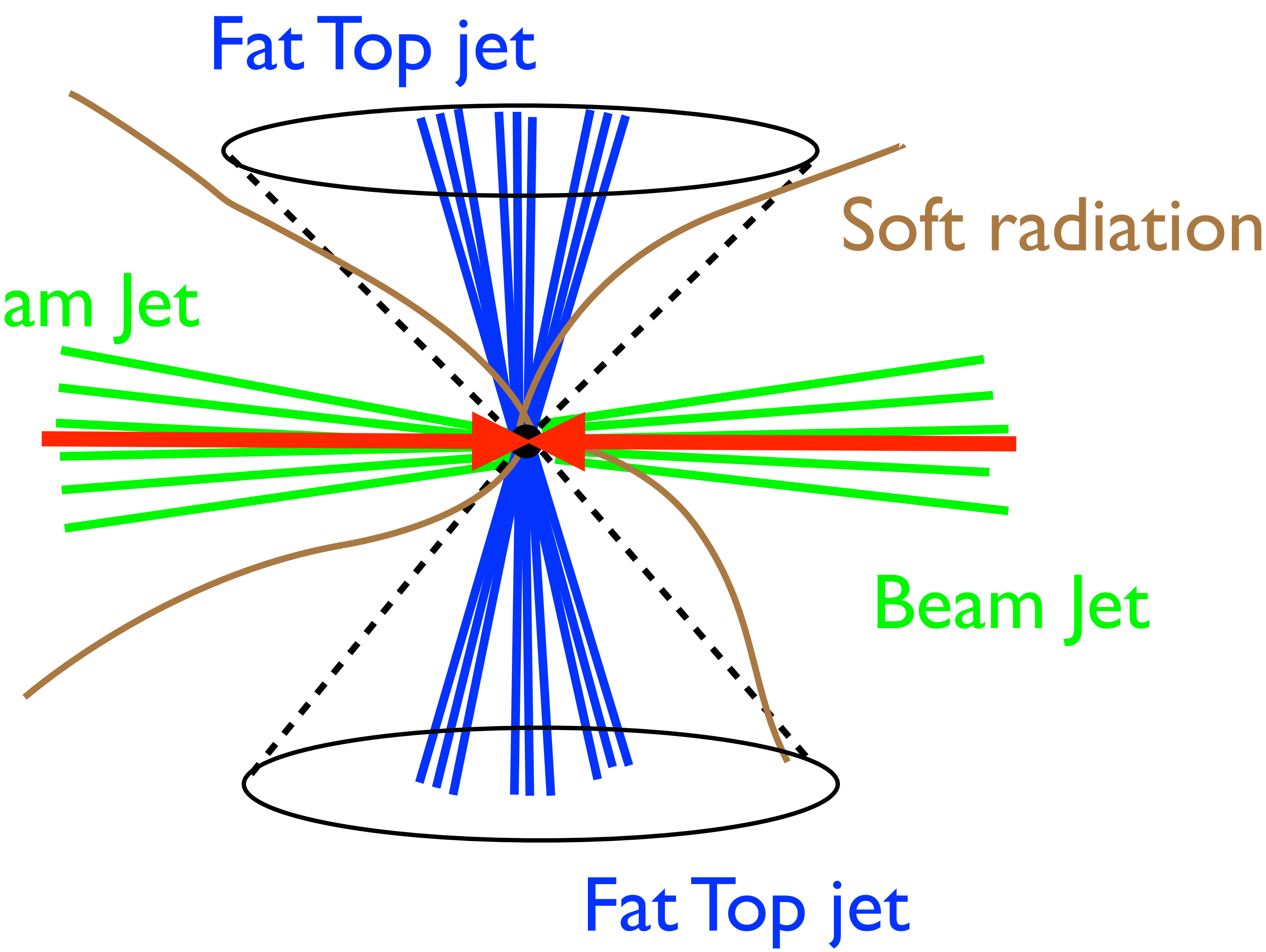


Factorization for Boosted Tops at Hadron Colliders

(Hoang, SM, Pathak, Stewart)

- Lepton collider methods can be extended to hadron colliders.
- Make use of the 2-Jettiness event shape. (Stewart, Tackmann, Waalewijin)



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

Factorization for Boosted Tops at Hadron Colliders

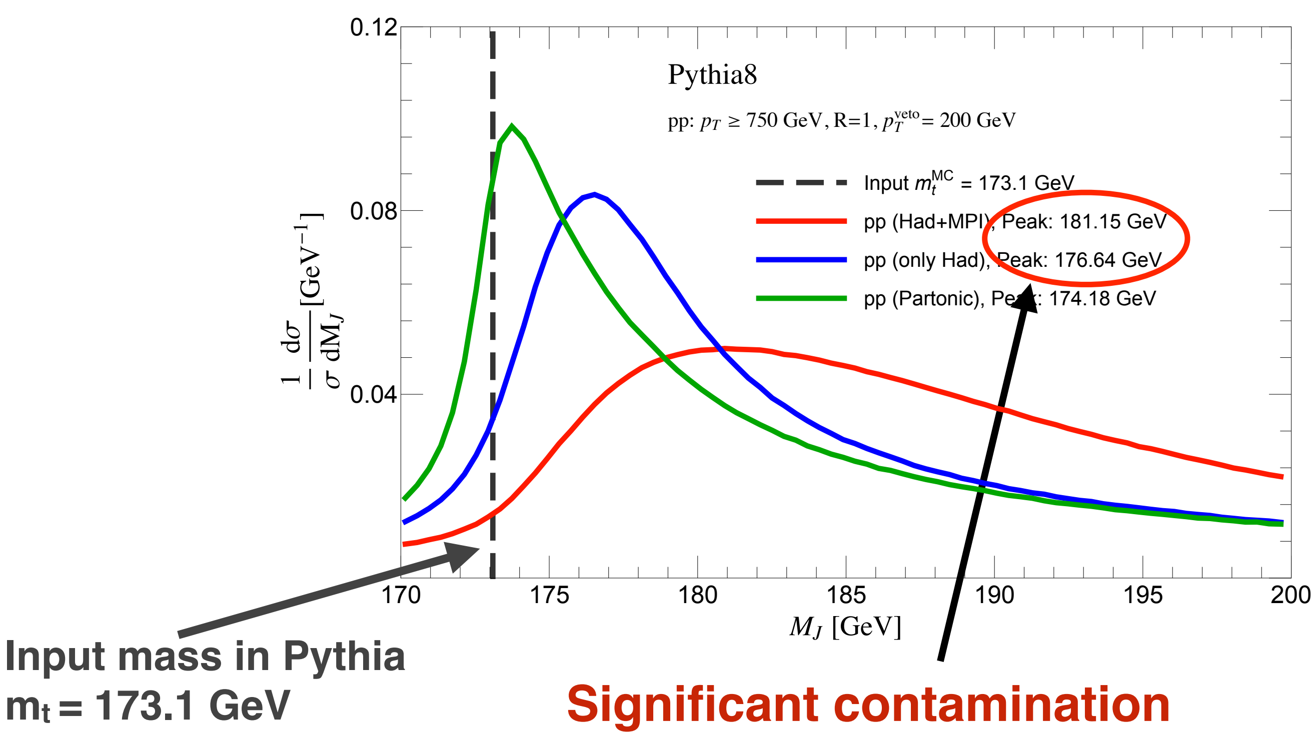
(Hoang, SM, Pathak, Stewart)

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

Hard function — Soft function — Top HQET jet functions (identical to lepton collider!) — ISR — PDFs

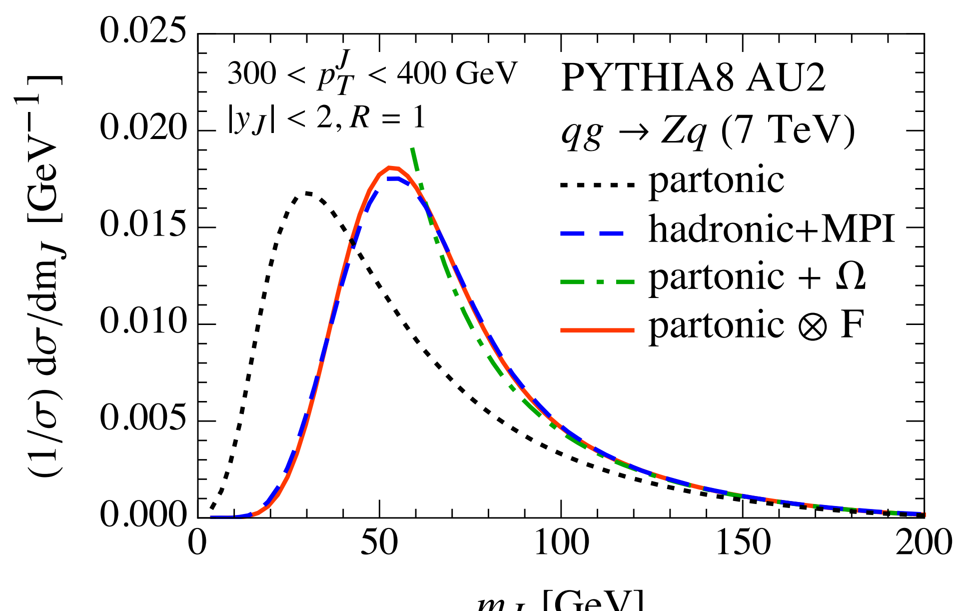
- Jet mass spectrum is quite sensitive to contamination:

Effect of UE/MPI



- Same soft model for hadronization can describe UE

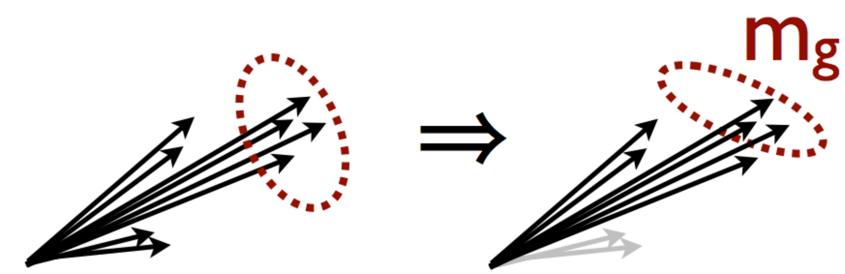
(Stewart, Tackmann, Waalewijin)



Soft Drop

(Larkoski, Marzani, Soyez, Thaler)

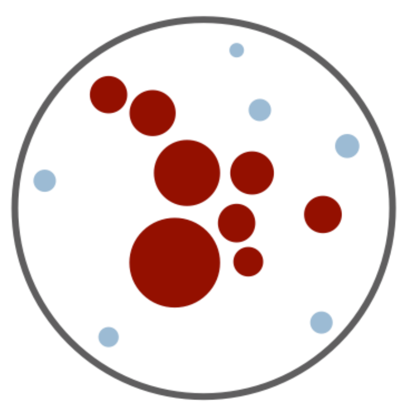
- Soft drop grooming reduces sensitivity for jet mass spectrum to soft contamination.



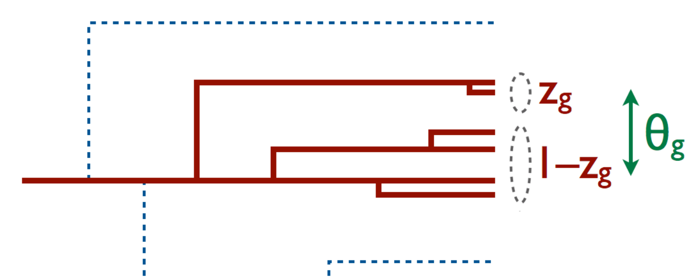
$$\frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} > z_{\rm cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

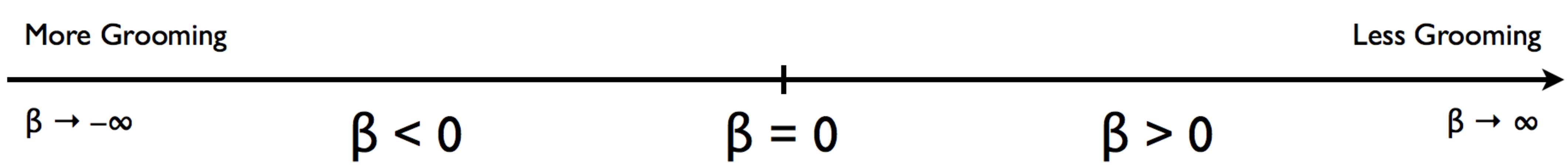
$$z > z_{\rm cut}\, \theta^{\beta}$$

Groomed jet



Groomed Clustering tree

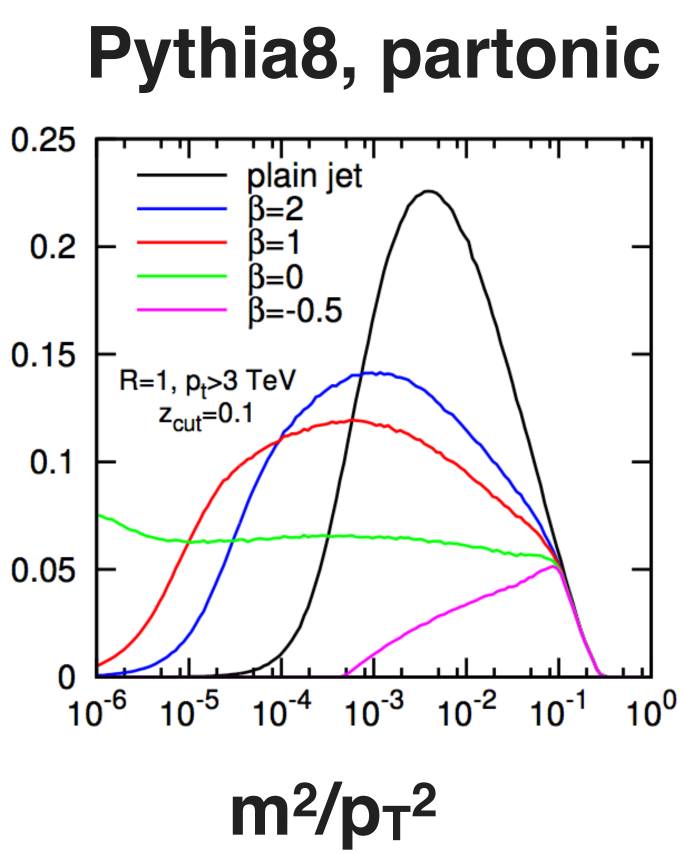


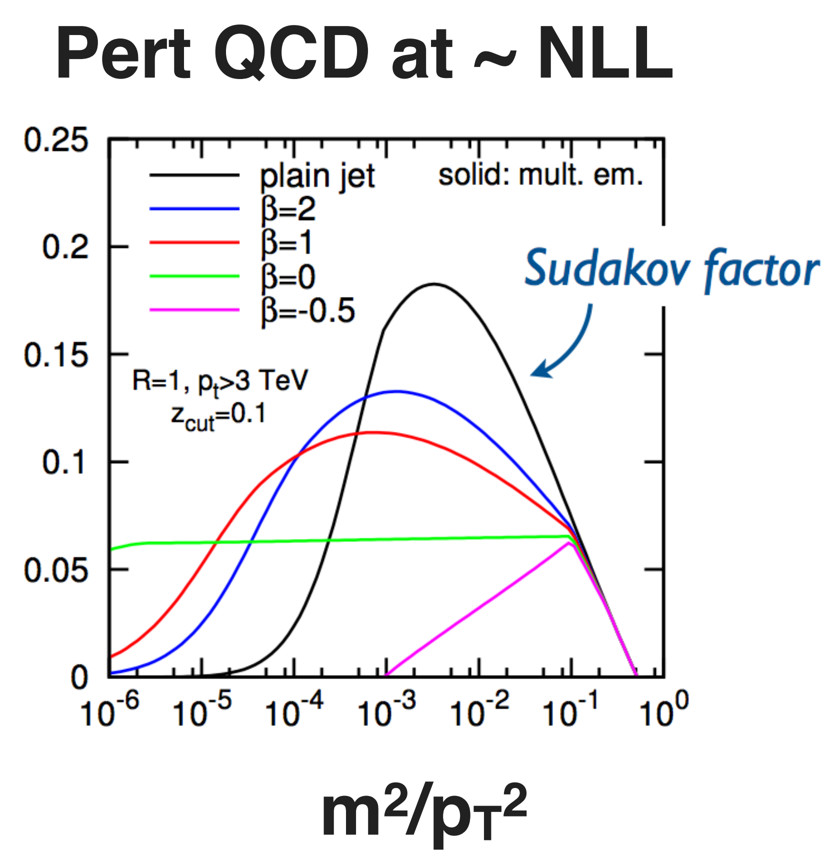


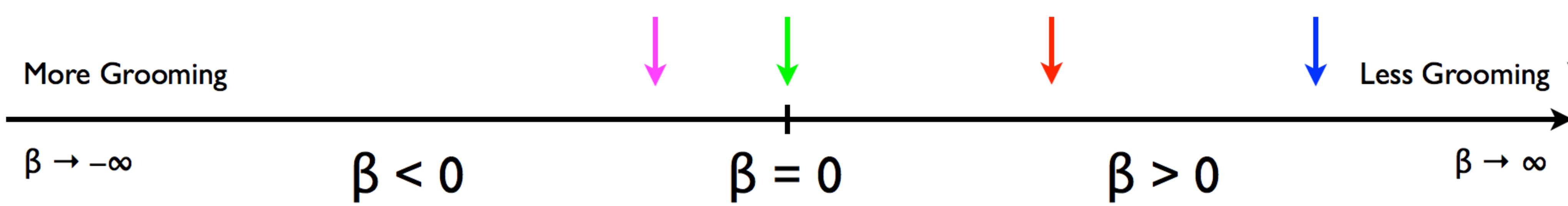
Soft Drop

(Larkoski, Marzani, Soyez, Thaler)

- Jet mass spectrum for massless partons:

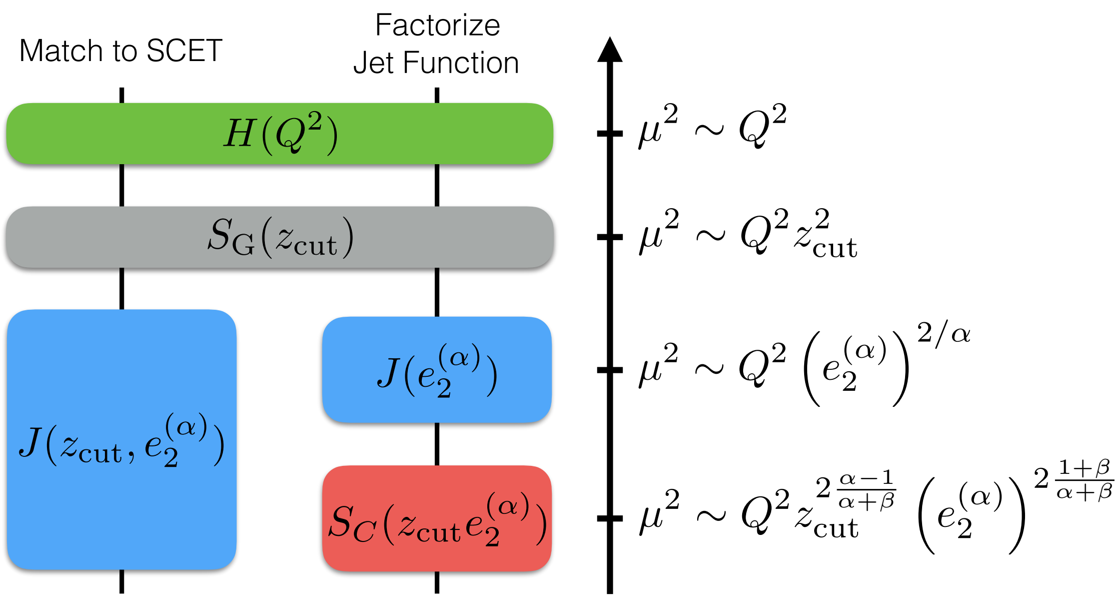


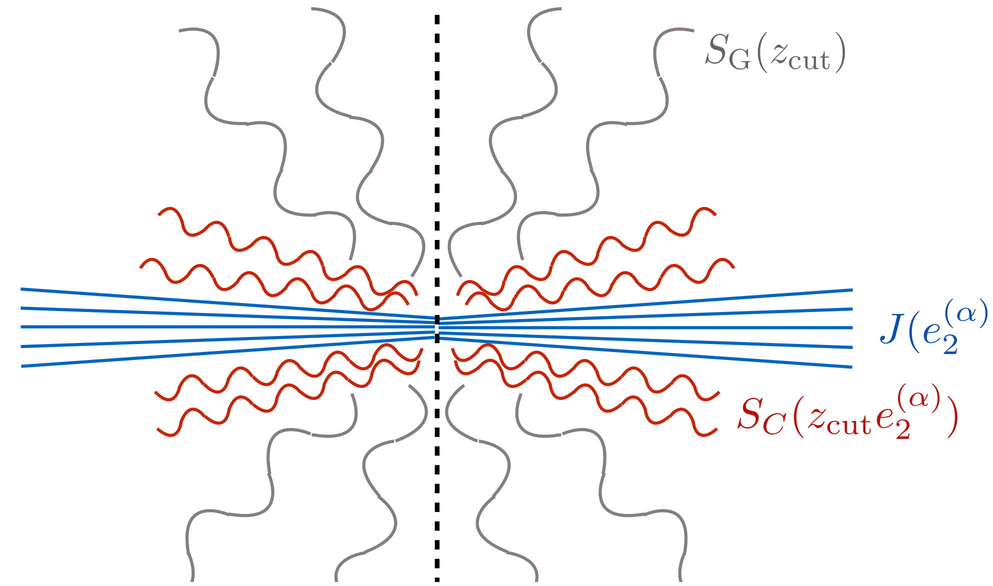


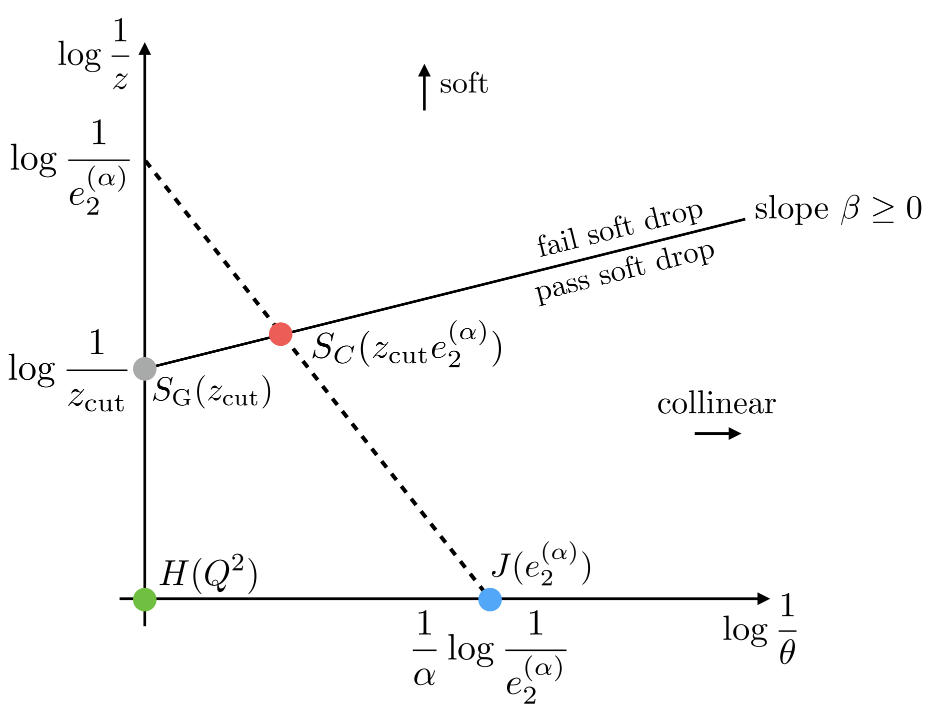


Soft Drop Factorization

(Fyre, Larkoski, Marzani, Schwartz, Yan)







- Factorization

$$\frac{d^2\sigma}{de_{2,L}^{(\alpha)}\, de_{2,R}^{(\alpha)}} = H(Q^2) S_G(z_{cut}) \left[S_C(z_{cut} e_{2,L}^{(\alpha)}) \otimes J(e_{2,L}^{(\alpha)}) \right] \left[S_C(z_{cut} e_{2,R}^{(\alpha)}) \otimes J(e_{2,R}^{(\alpha)}) \right]$$

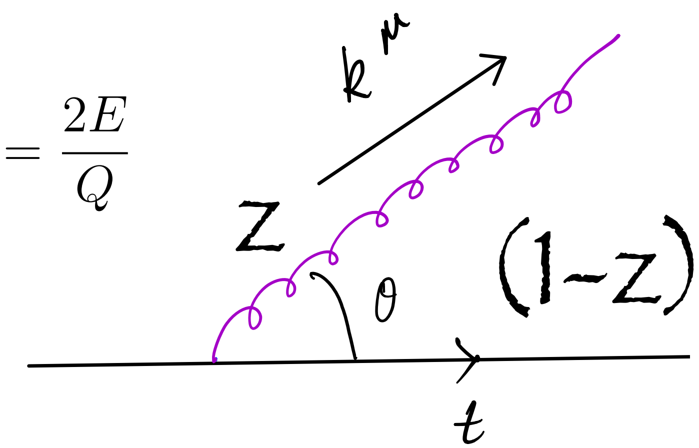
- Wide angle soft radiation groomed away

- No non-global logs

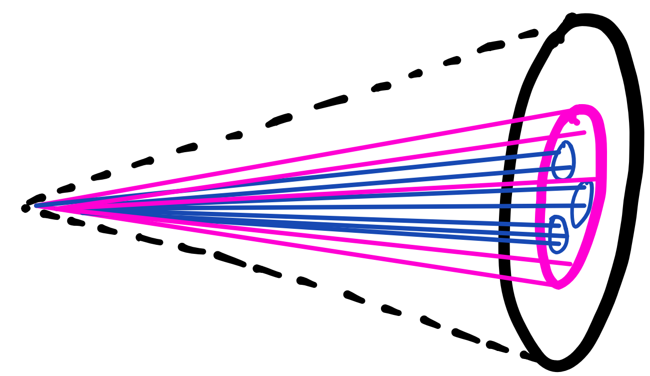
Top Jet Mass with Soft Drop

Top Jet Mass Constraints with Soft Drop

$z = \frac{2E}{Q}$



$$k_j^\mu = (k^+, k^-, k_\perp) = (E(1-\cos\theta), E(1+\cos\theta), k_\perp)$$



- Top jet mass constraint in the peak region:

$$\frac{M_{t,\bar{t}}^2 - m^2}{m} \sim \Gamma \ll m \quad \longrightarrow \quad z\left[(1-\cos\theta) + \frac{m^2}{Q^2}(1+\cos\theta)\right] \sim \frac{2m\Gamma_t}{Q^2}$$

- Soft Drop constraint:

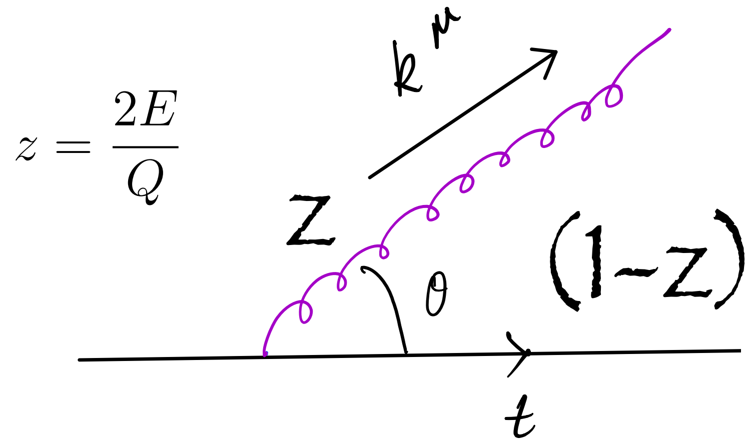
$$z > z_{\rm cut}\, \theta^\beta \quad \longrightarrow \quad \left(\frac{Q}{2m}\right)^\beta \gg \frac{\Gamma_t}{m_t}\left(\frac{Q}{2m}\right)^\beta \gg z_{\rm cut} \gg \frac{2m_t\Gamma_t}{Q^2}$$

keep decay products

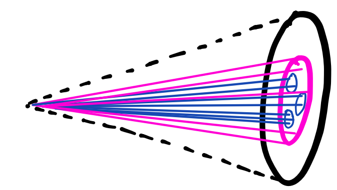
keep ucollinear radiation that satisfies jet mass constraint

removes usoft radiation that satisfies jet mass constraint (usoft contamination)

Soft Drop Constraints: Light Grooming



$$k_j^\mu = (k^+, k^-, k_\perp) = (E(1-\cos\theta), E(1+\cos\theta), k_\perp)$$



- Soft Drop constraint (soft radiation at wide angles are groomed away):

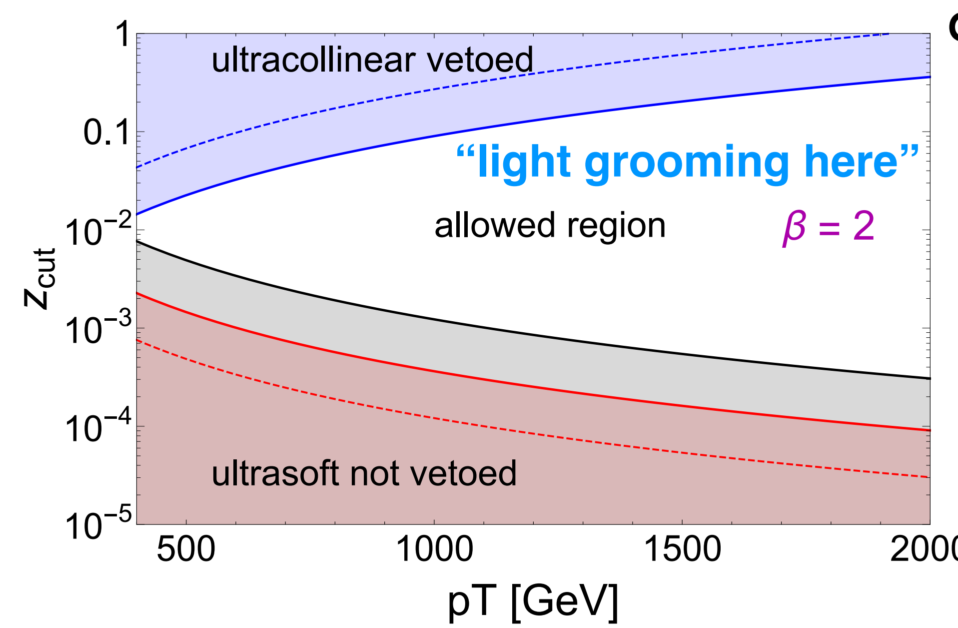
$$z > z_{\rm cut}\, \theta^\beta \;\longrightarrow\; \left(\frac{Q}{2m}\right)^\beta \gg \frac{\Gamma_t}{m_t}\left(\frac{Q}{2m}\right)^\beta \gg z_{\rm cut} \gg \frac{2m_t\Gamma_t}{Q^2}$$

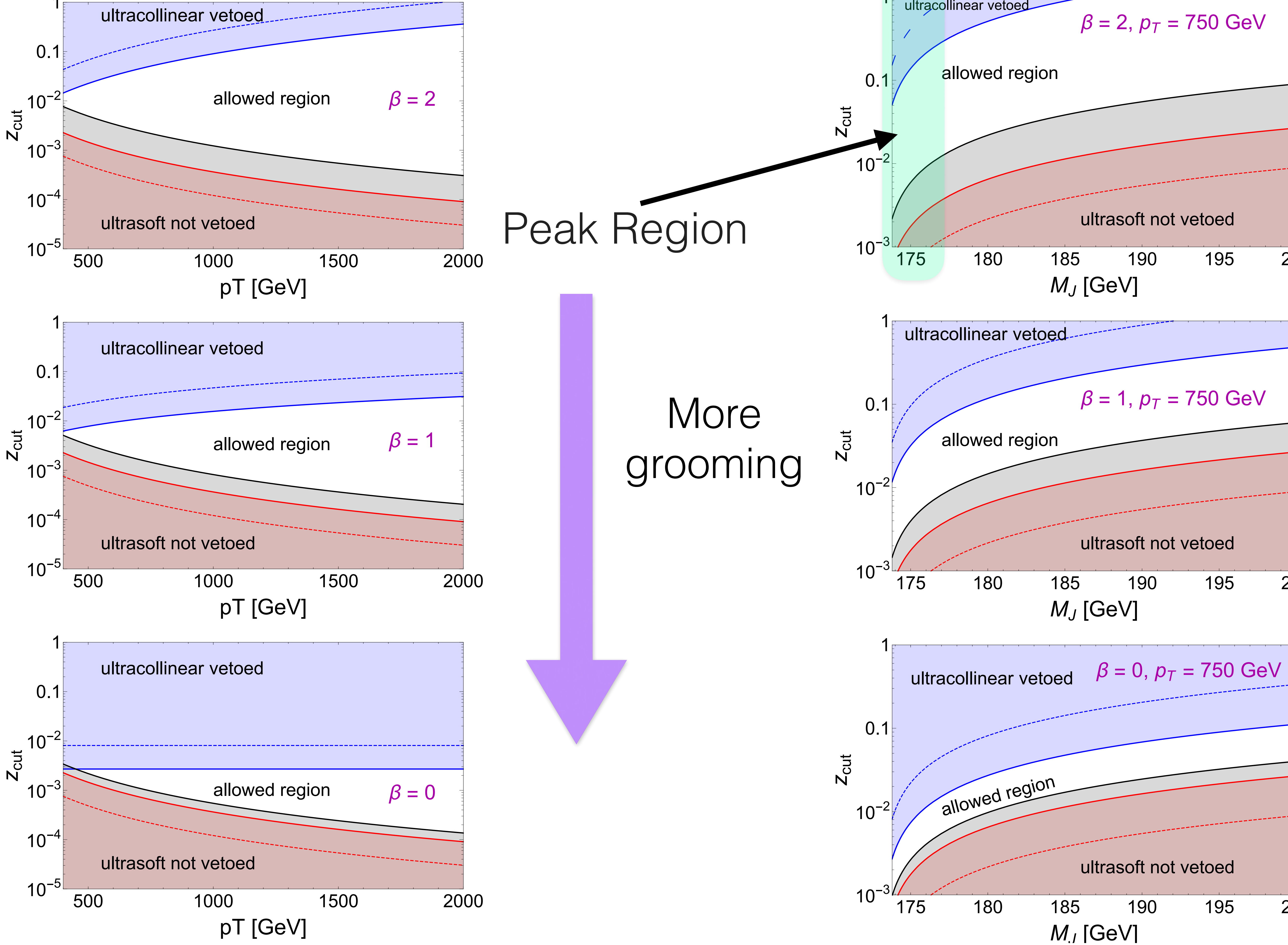
keep decay products

keep ucollinear radiation, not touch top mass

removes usoft radiation that satisfies jet mass constraint (usoft contamination)

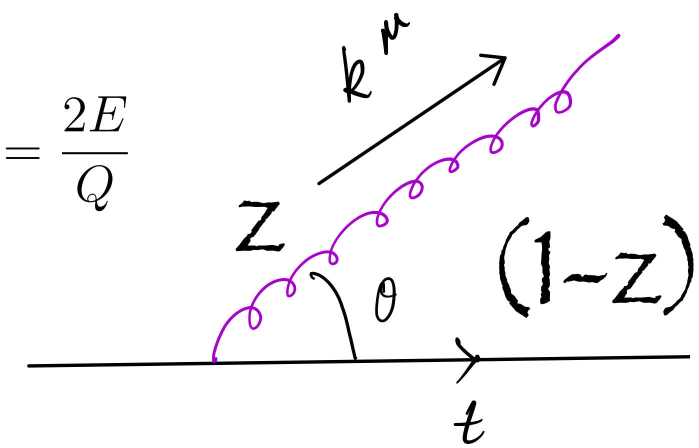
- Soft Drop parameter ranges are restricted to "light grooming":
- Greater allowed Soft Drop parameter range at higher pT:



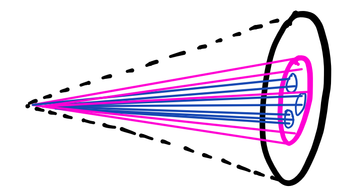

ultracollinear vetoed
allowed region
β = 2
ultrasoft not vetoed
z_cut
pT [GeV]
ultracollinear vetoed
allowed region
β = 1
ultrasoft not vetoed
z_cut
pT [GeV]
ultracollinear vetoed
allowed region
β = 0
ultrasoft not vetoed
z_cut
pT [GeV]
Peak Region
More grooming
ultracollinear vetoed
β = 2, p_T = 750 GeV
allowed region
ultrasoft not vetoed
z_cut
M_J [GeV]
ultracollinear vetoed
β = 1, p_T = 750 GeV
allowed region
ultrasoft not vetoed
z_cut
M_J [GeV]
ultracollinear vetoed
β = 0, p_T = 750 GeV
allowed region
ultrasoft not vetoed
z_cut
M_J [GeV]

Soft Drop Constraints: Collinear Soft and Global Soft Modes

$z = \frac{2E}{Q}$



$$k_j^\mu = \left(k^+, k^-, k_\perp\right) = \left(E(1-\cos\theta), E(1+\cos\theta), k_\perp\right)$$



- Ultra-Collinear modes trivially pass soft drop (only constrained by invariant mass of jet):

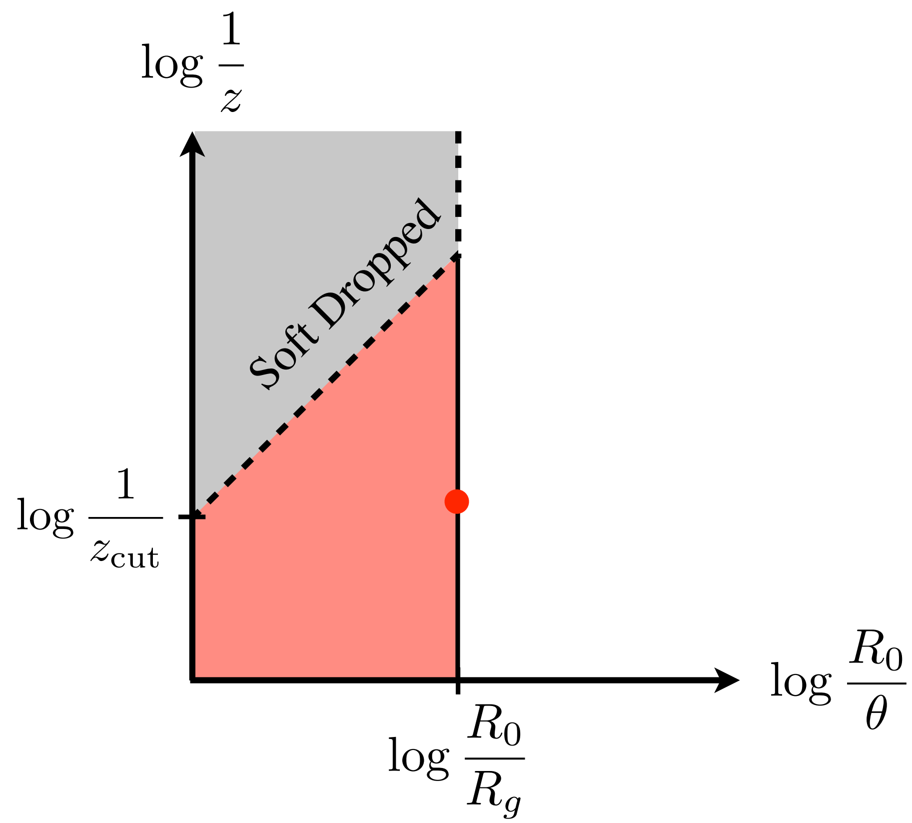
- Ultra-Soft modes trivially fail soft drop and don't contribute to jet mass.

- A "collinear-soft" mode arises at the boundary that "saturates" soft drop and jet mass constraints.

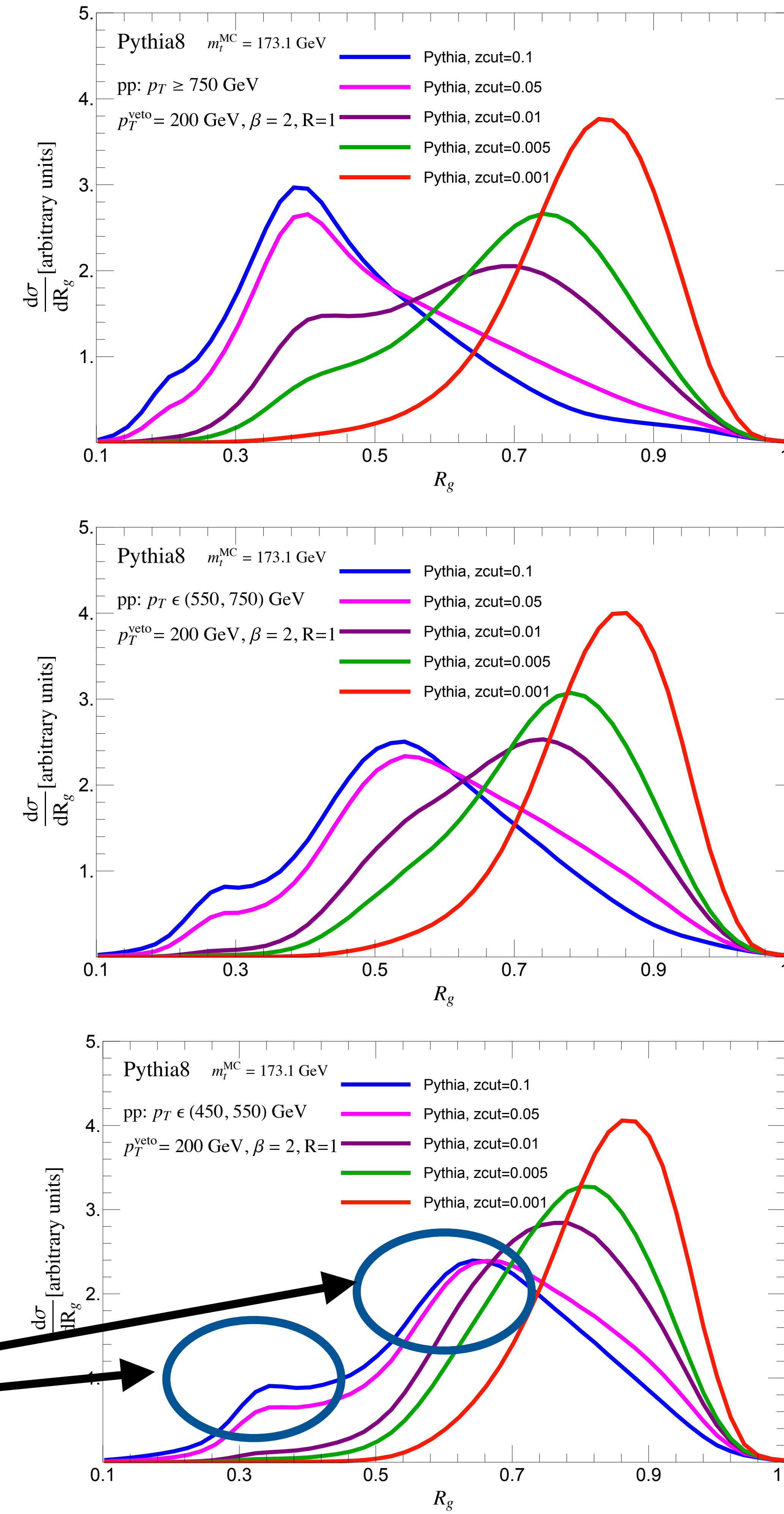
- "Global-soft" modes at large angles with energy comparable to $\sim Qz_{\rm cut}$ are also sensitive to the soft drop constraint.

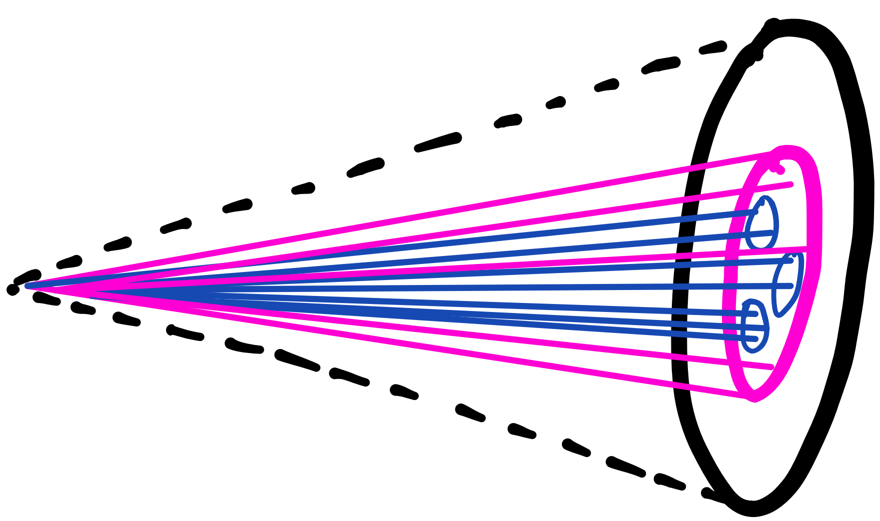
Groomed Jet Radius: R_g

(Larkoski, Marzani, Soyez, Thaler)



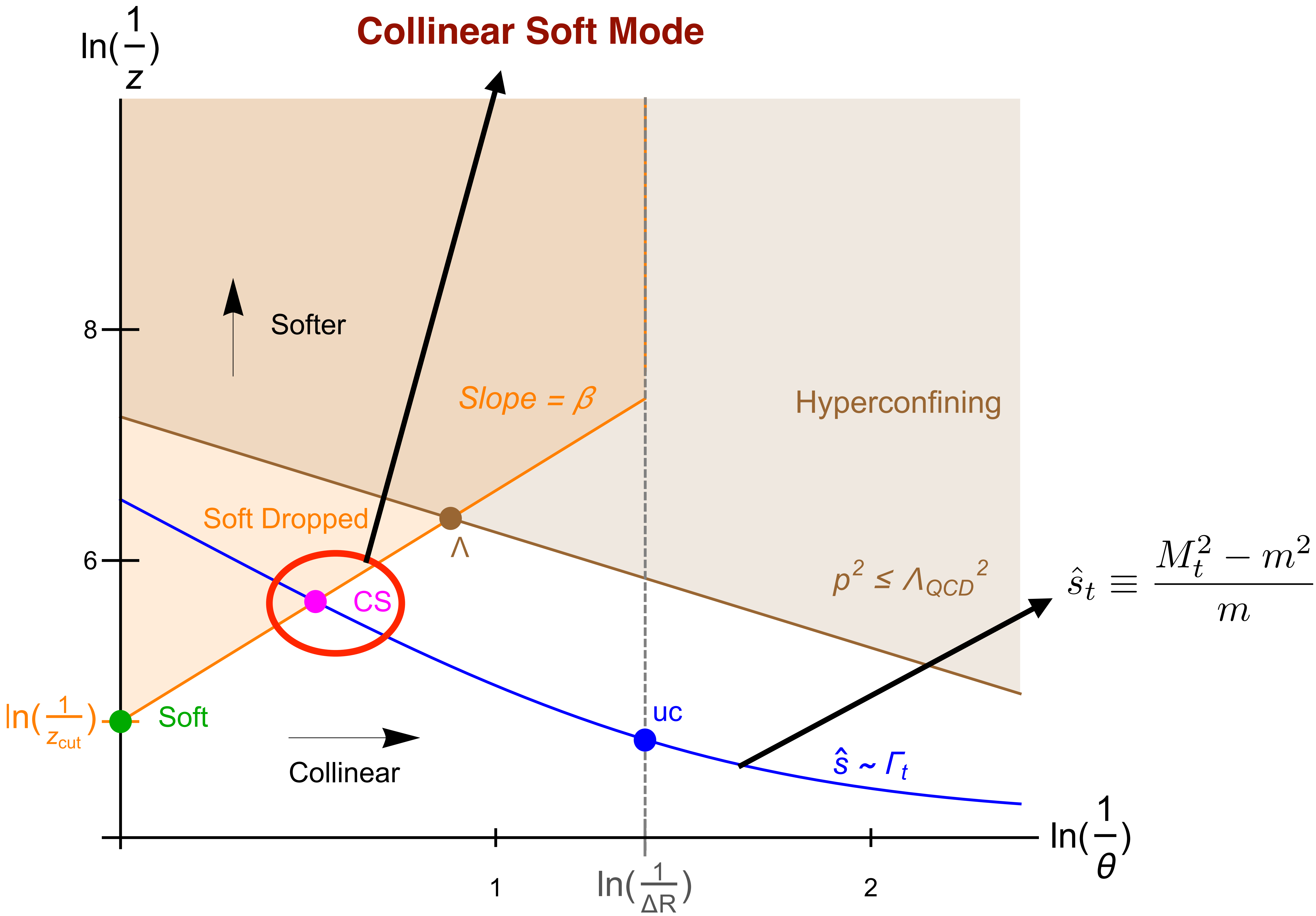
Lower p_T





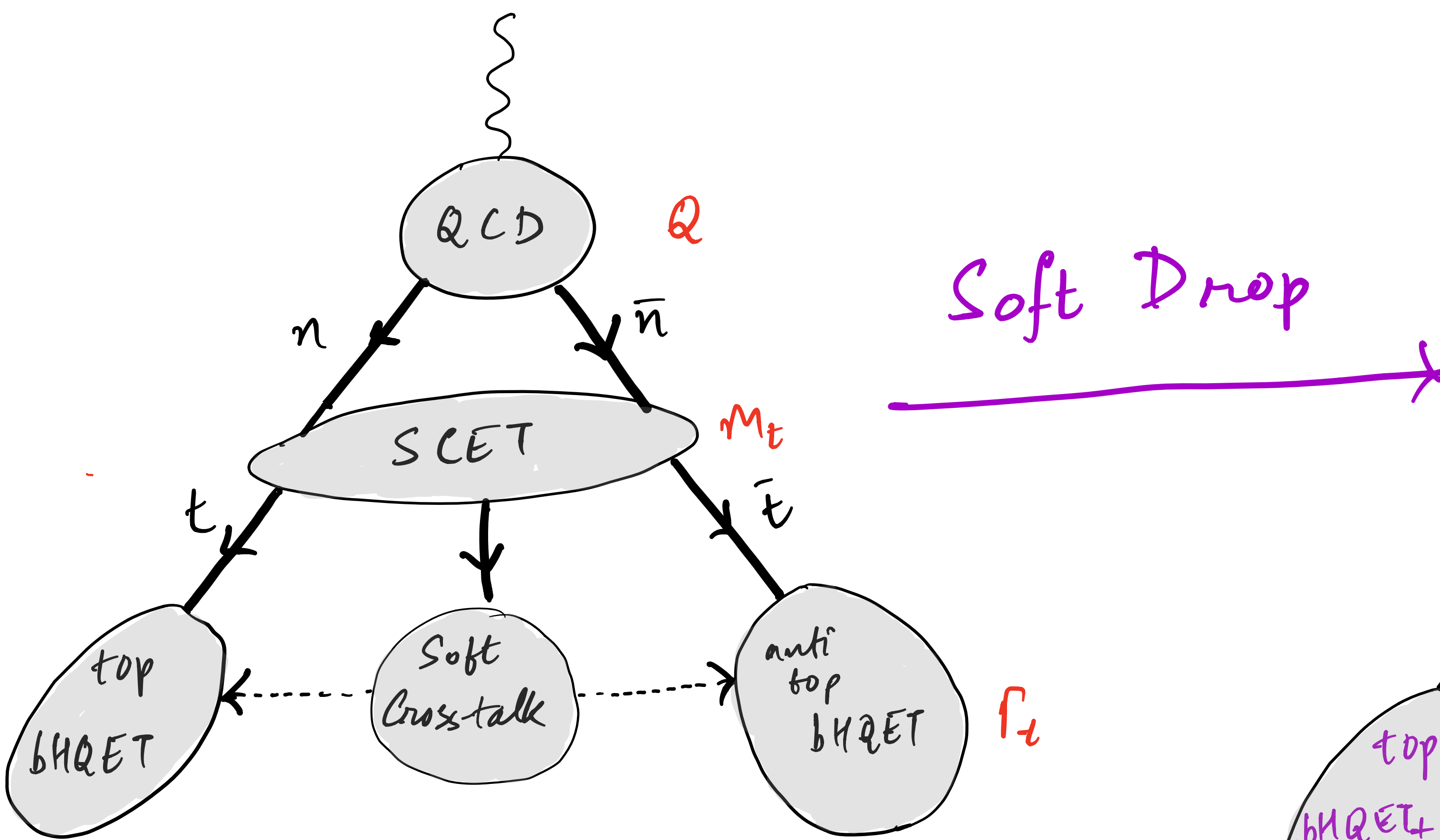
from decay products

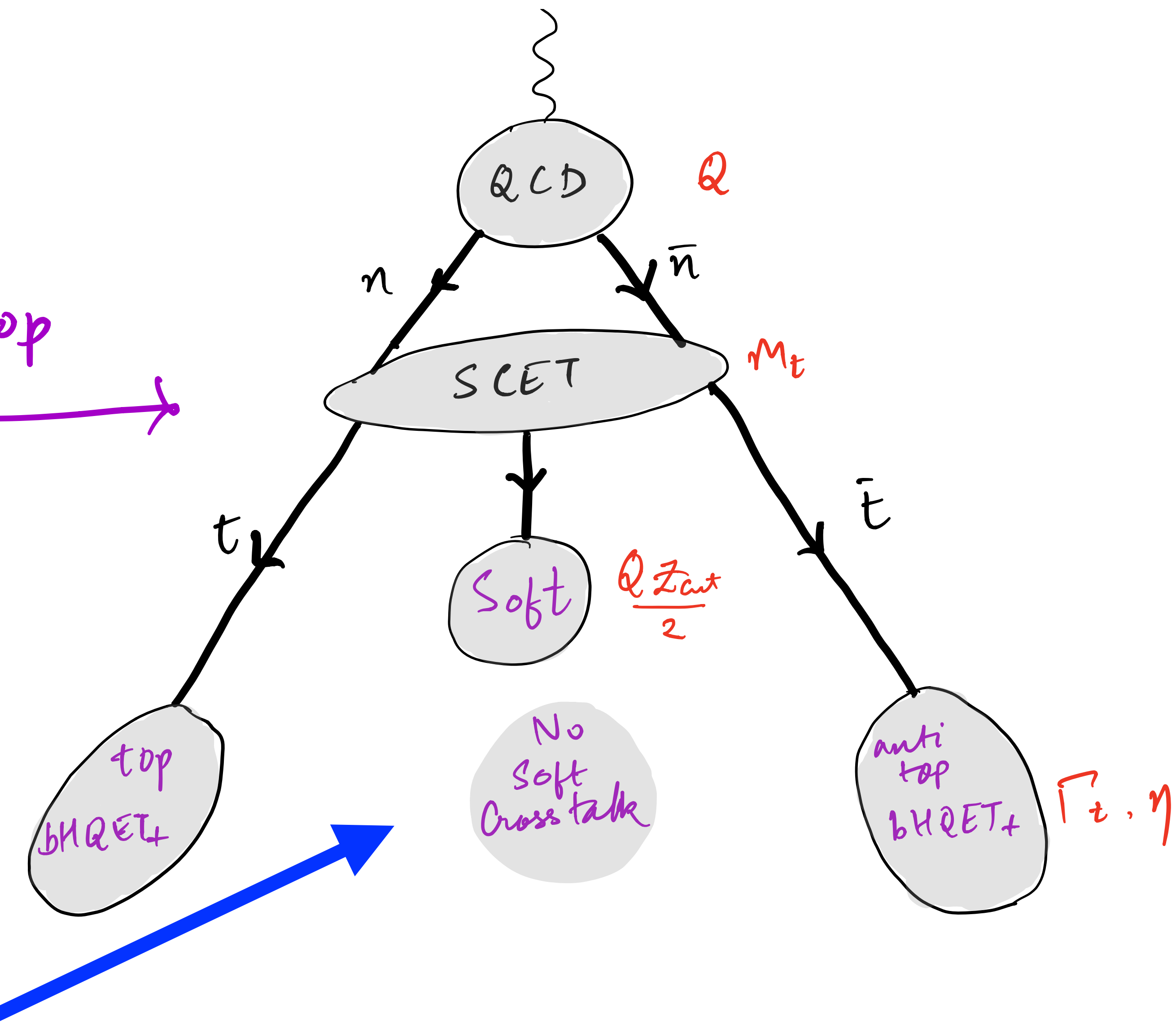
Top Jet Mass with Soft Drop



Factorization with Soft Drop

$$\frac{d\sigma}{dM_J} = N \int d\ell dk \, J_B\Big(\hat{s}_t - \frac{Q\ell}{m}, \Gamma_t, \delta m\Big) S_C\Big[\Big(\ell - \frac{m}{Q}k\Big)^{\frac{1+\beta}{2+\beta}} \big(2^\beta Q z_{\rm cut}\big)^{\frac{1}{1+\beta}}, \beta\Big] F_C(k)$$



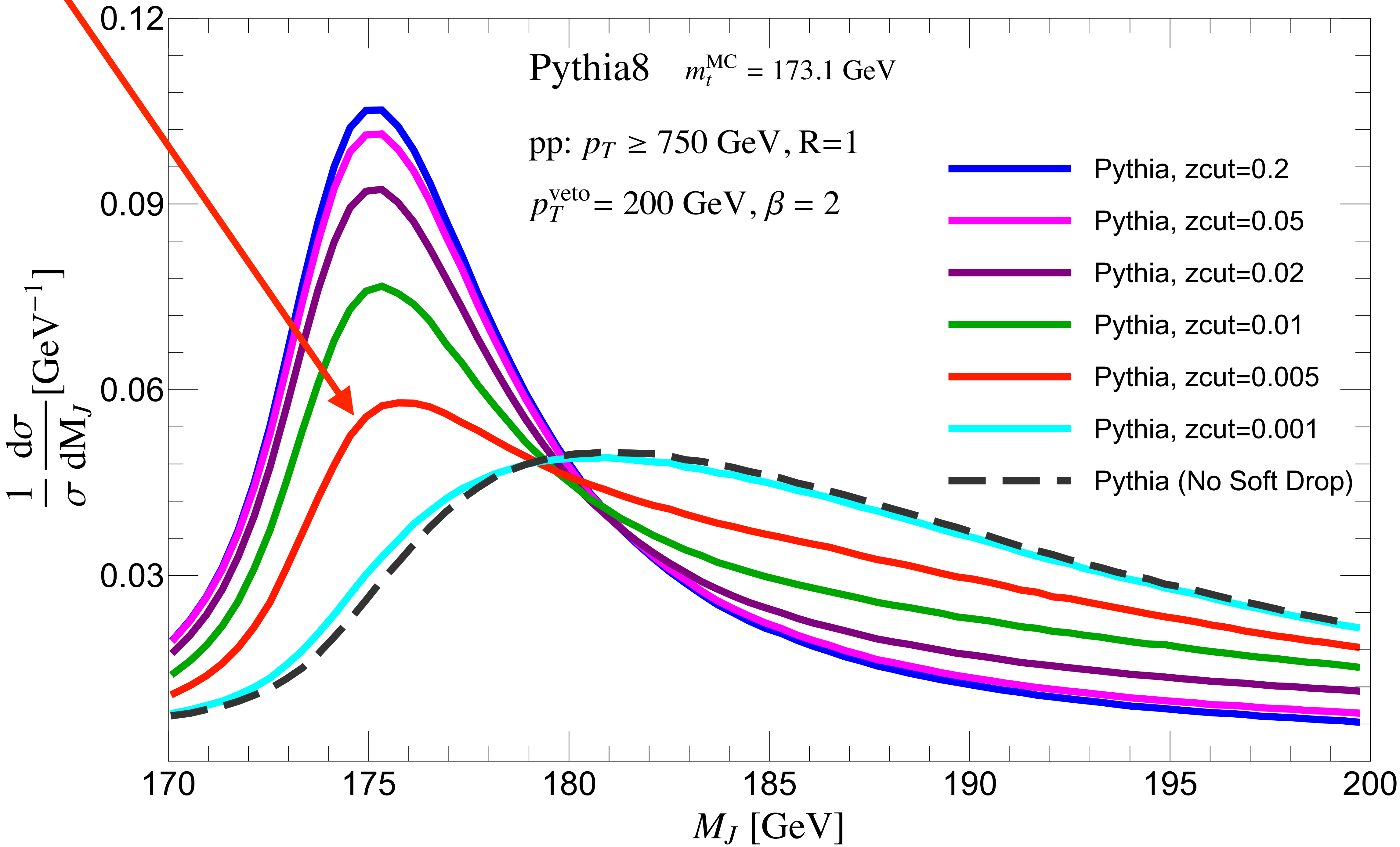


Now includes semi leptonic decays!

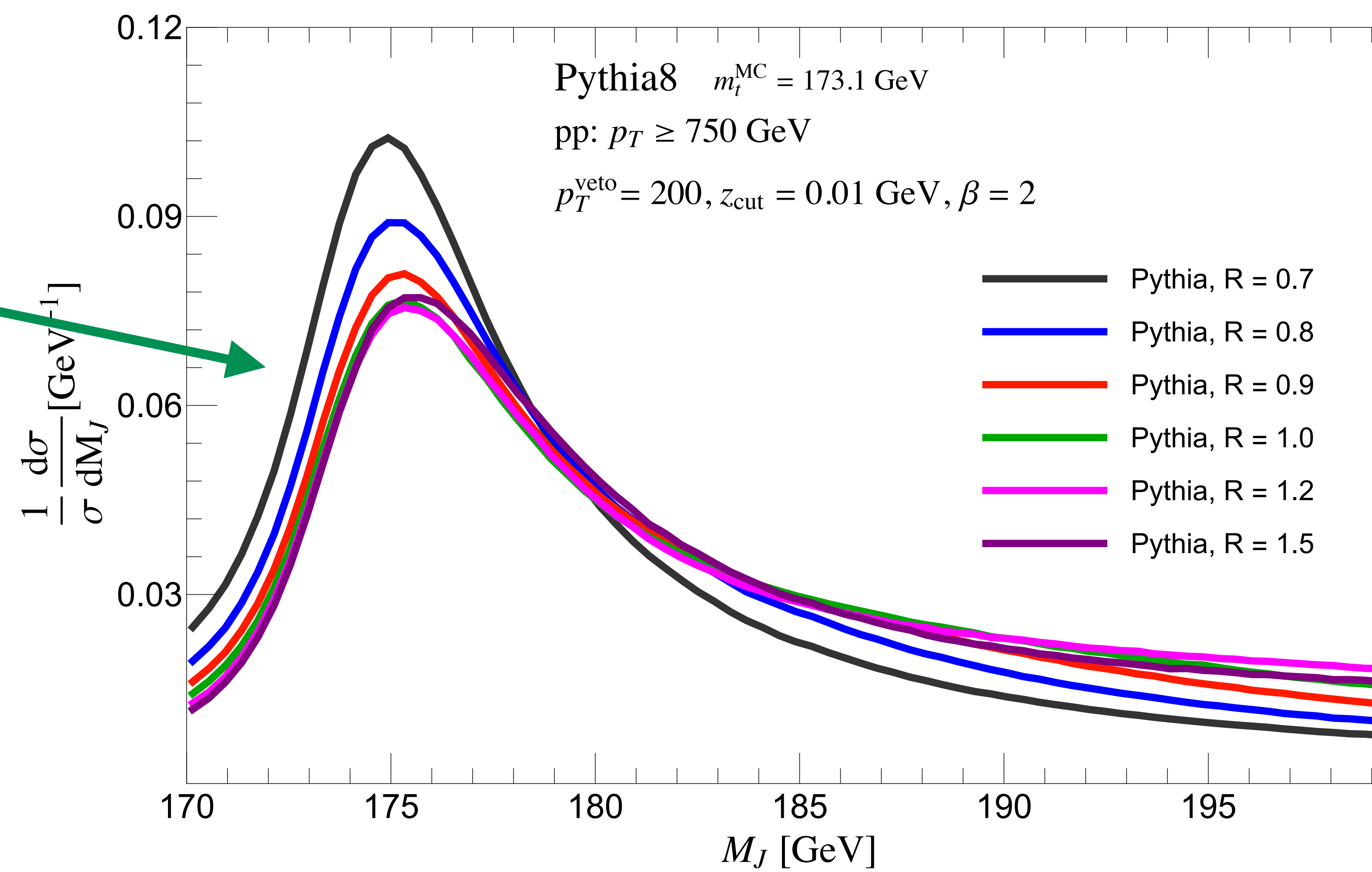
z_{cut} dependence

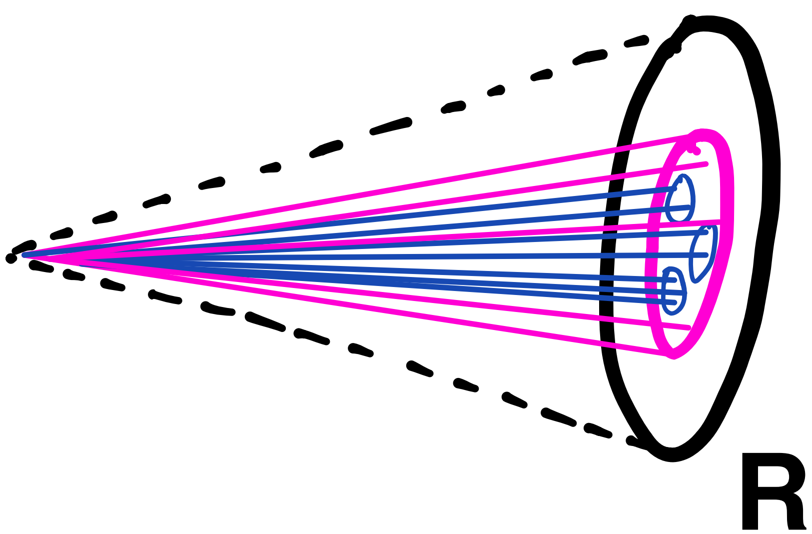
predict transition for "light Soft Drop" ✓

most contamina is removed

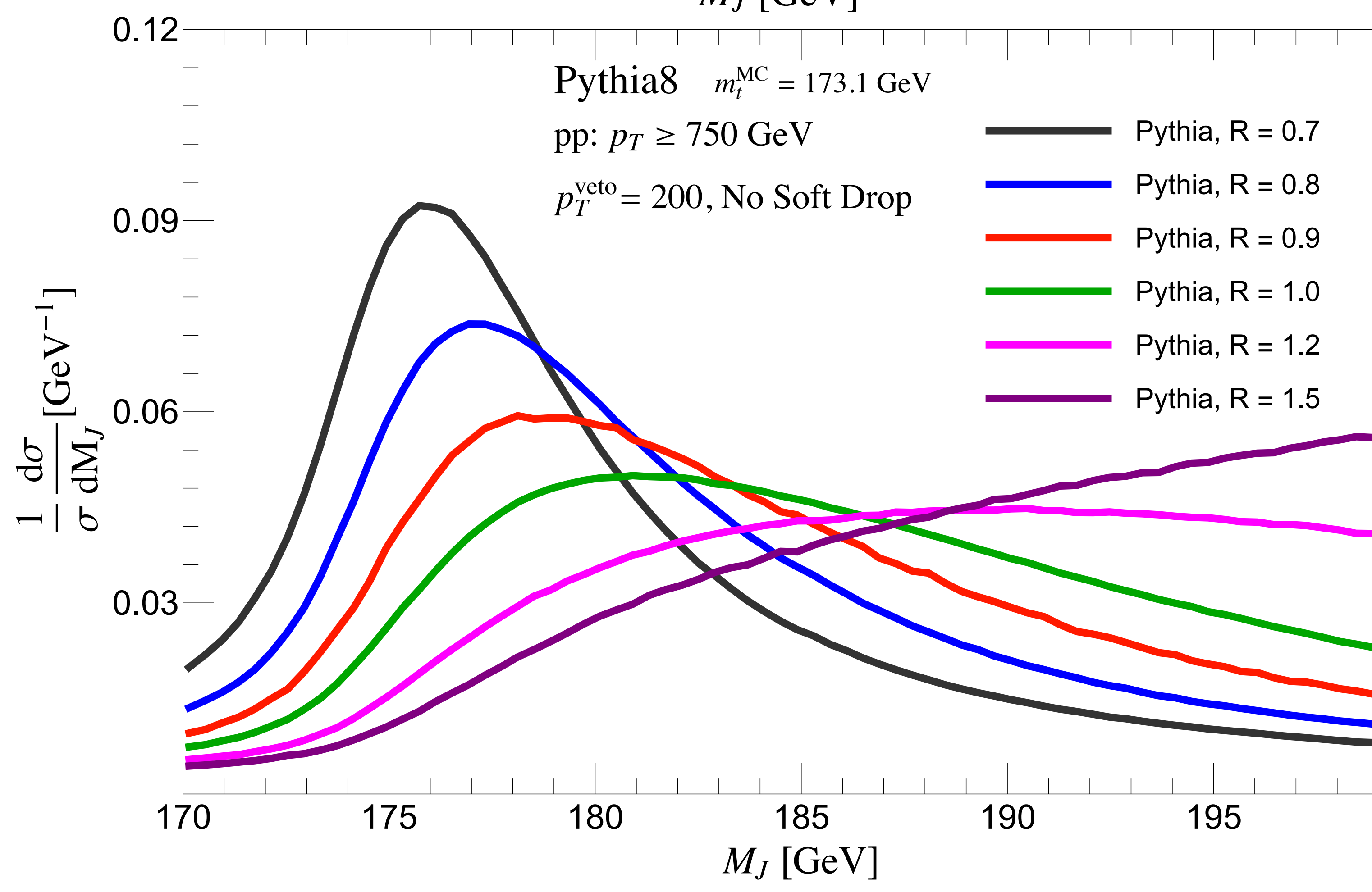


predict: independent of Jet Radius ✓

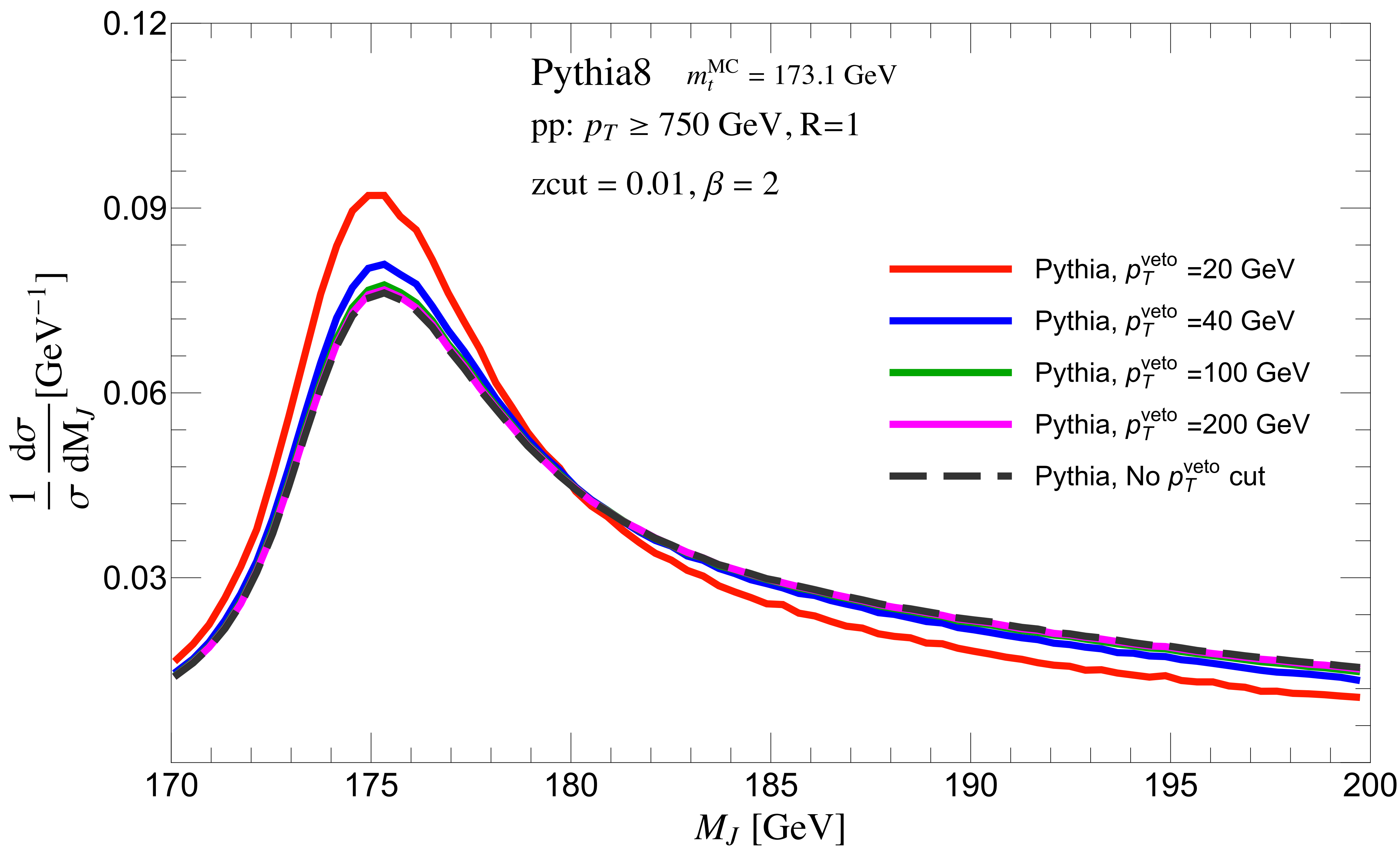




Without Soft Drop (huge):

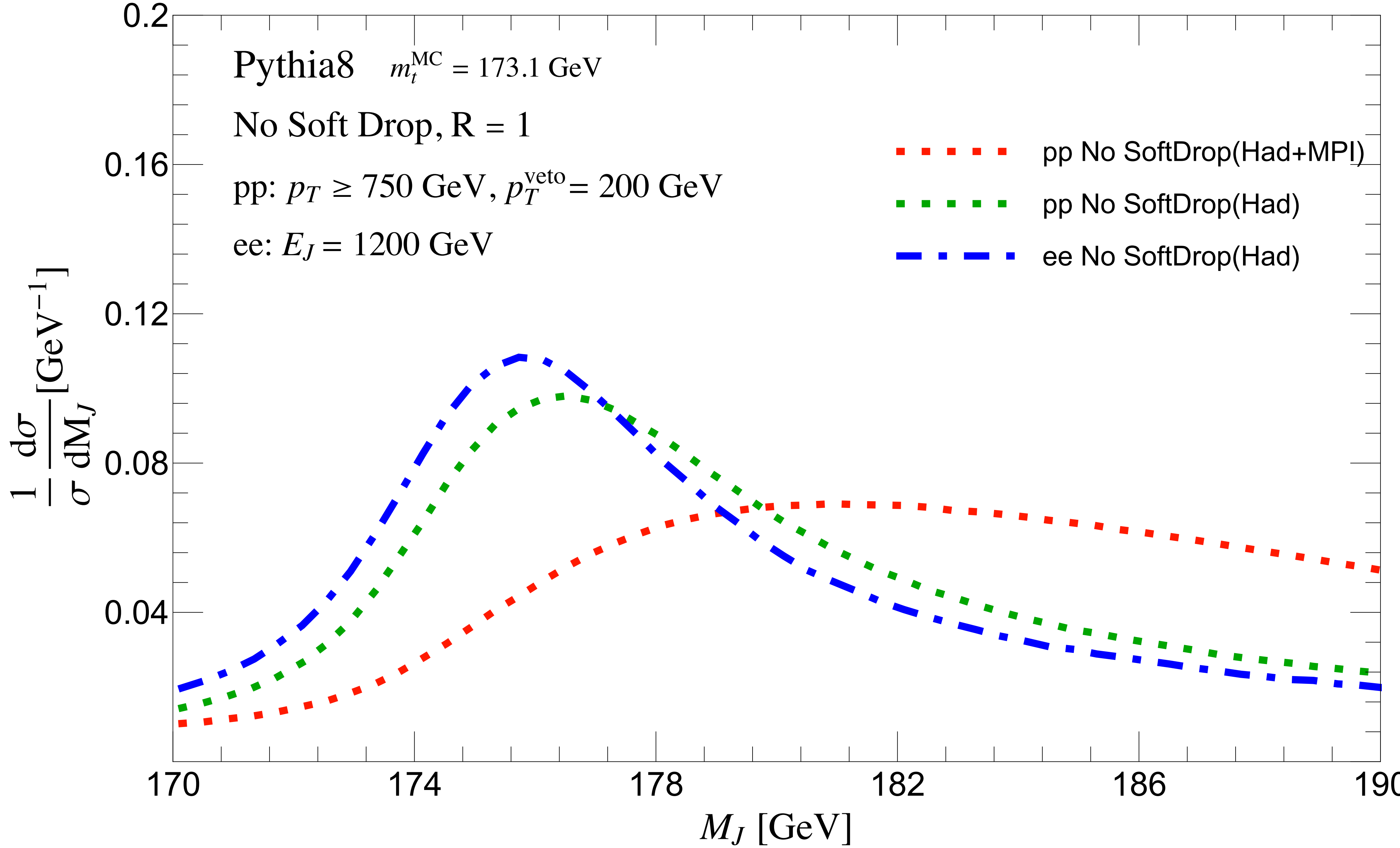


Predict independent of cutoff on radiation outside the jet ("jet veto"): ✓



Soft Drop prediction: Same Result for e^+e^- and pp collisions

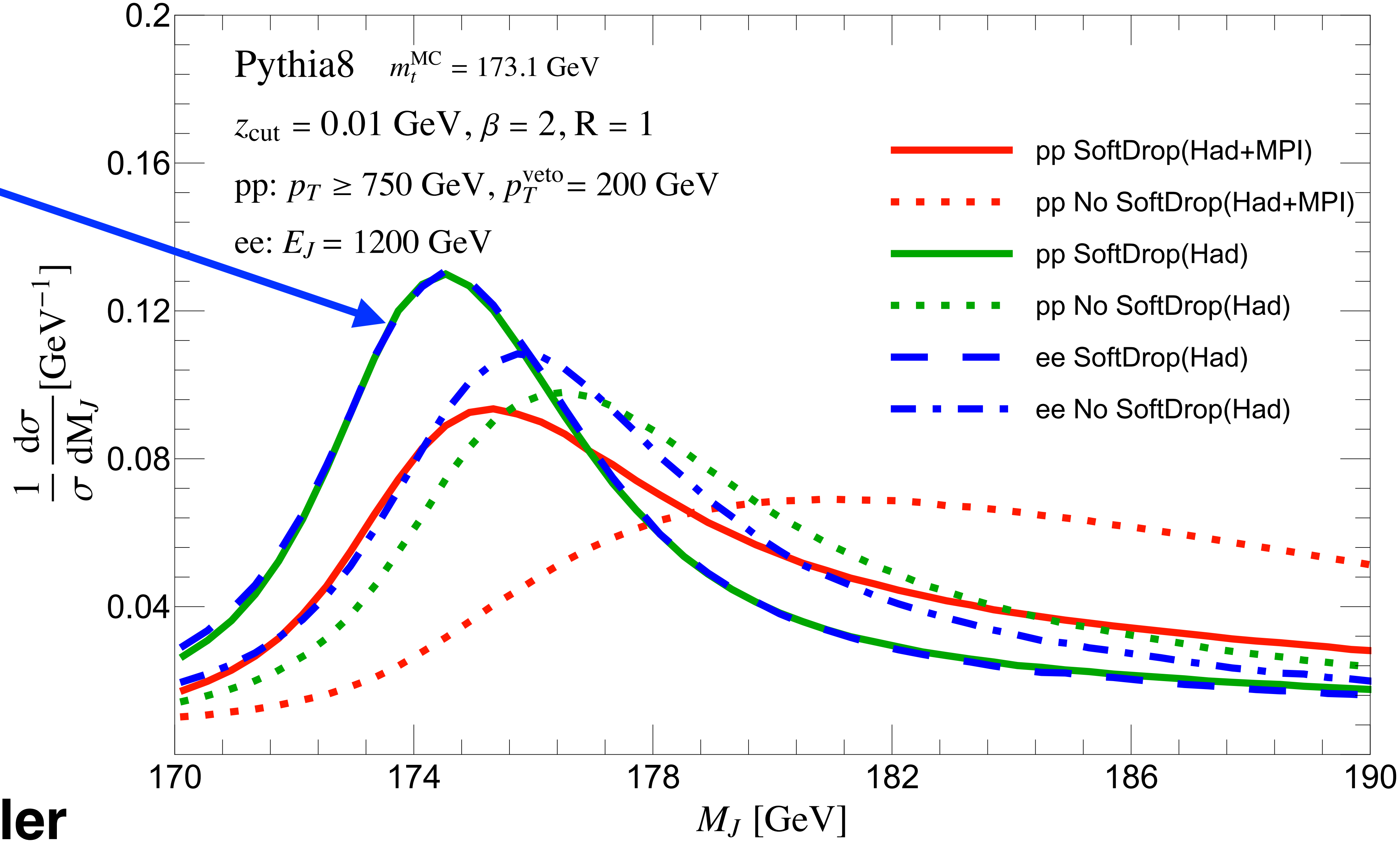
Without Soft Drop (differ):



Soft Drop prediction: Same Result for e^+e^- and pp collisions

With Soft Drop:

Great!



much smaller contamination

Compare Simulations to Our Theory

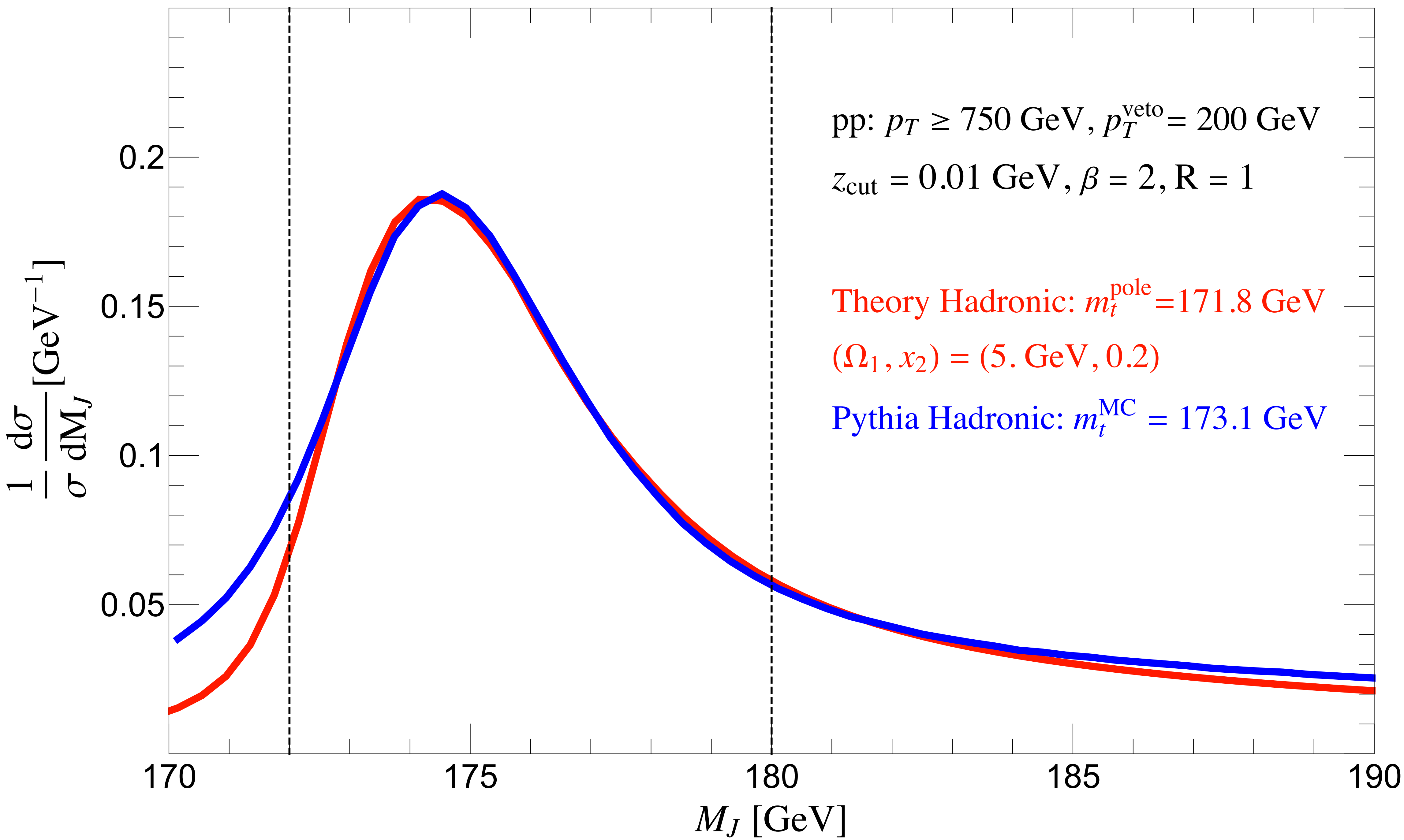
(preliminary)

Pythia Simulation vs. Theory (with Soft Drop)

without contamination:

$m_t^{\text{pole}} = 171.8 \text{ GeV}$

$m_t^{\text{MC}} = 173.1 \text{ GeV}$



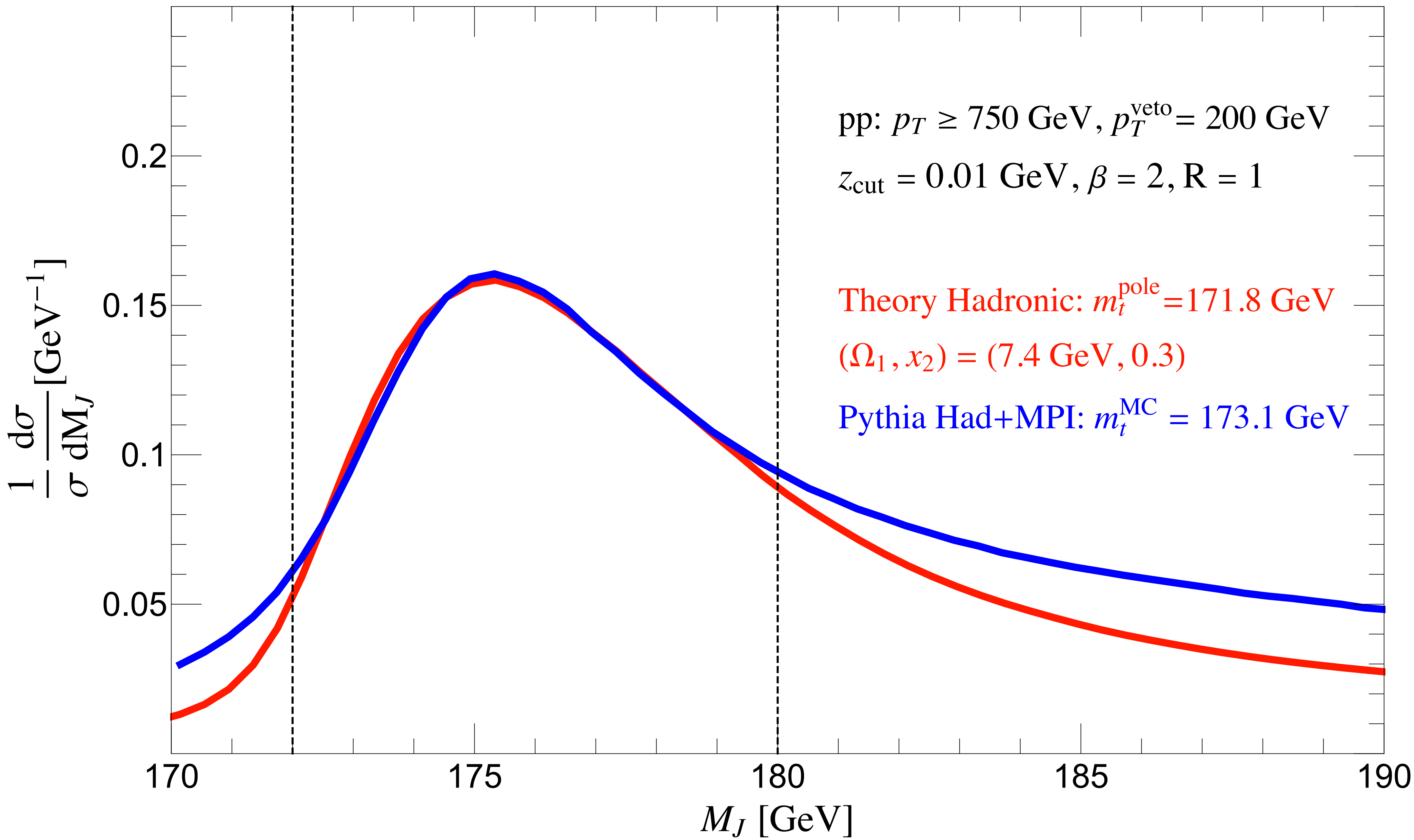
Pythia Simulation vs. Theory (with Soft Drop)

with contamination:

$m_t^{\text{pole}} = 171.8\ \text{GeV}$

Same!

$m_t^{\text{MC}} = 173.1\ \text{GeV}$

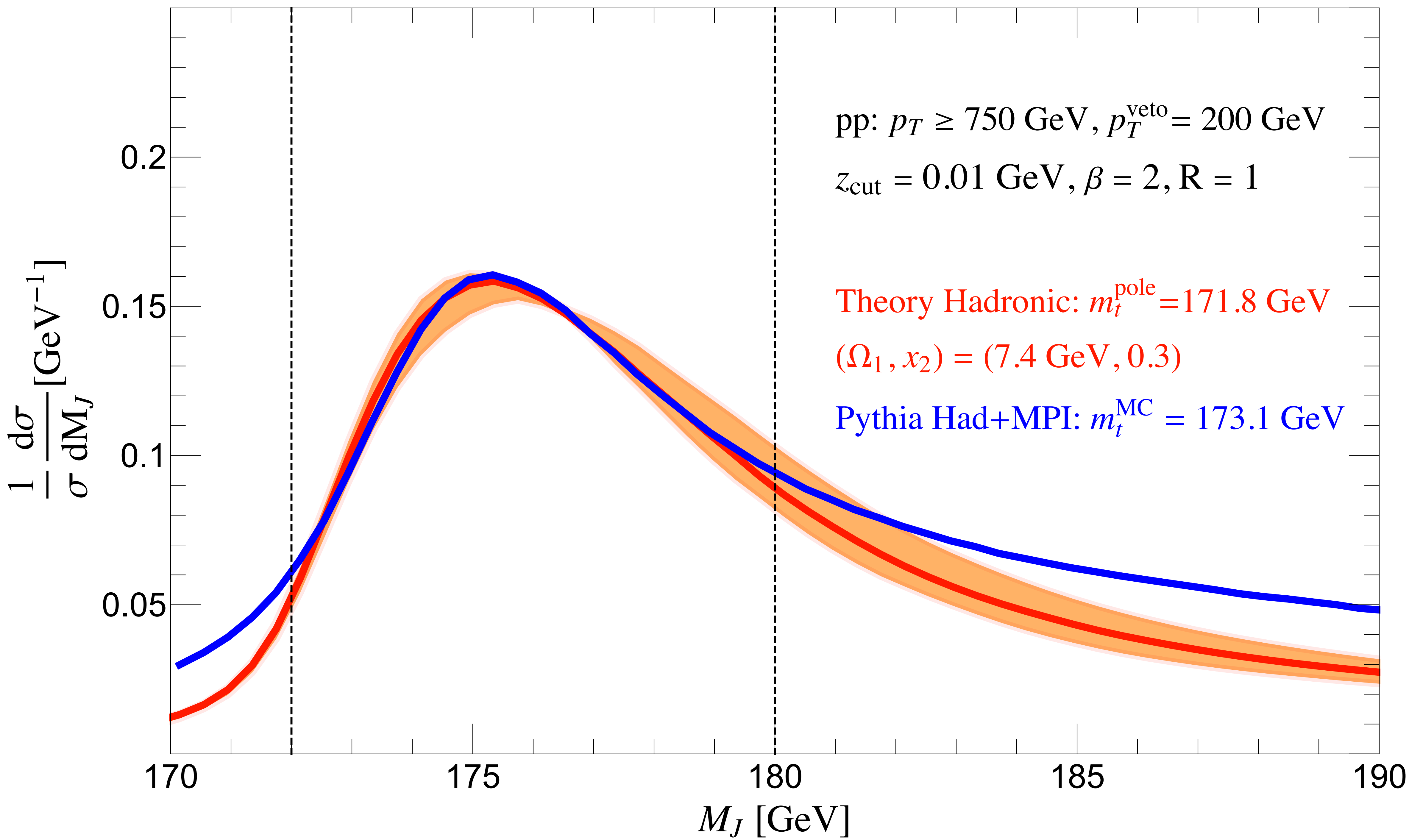


Dominant change is expected: Ω_1 (hadronization)

Pythia Simulation vs. Theory (with Soft Drop)

Add uncertainties from scale variation:

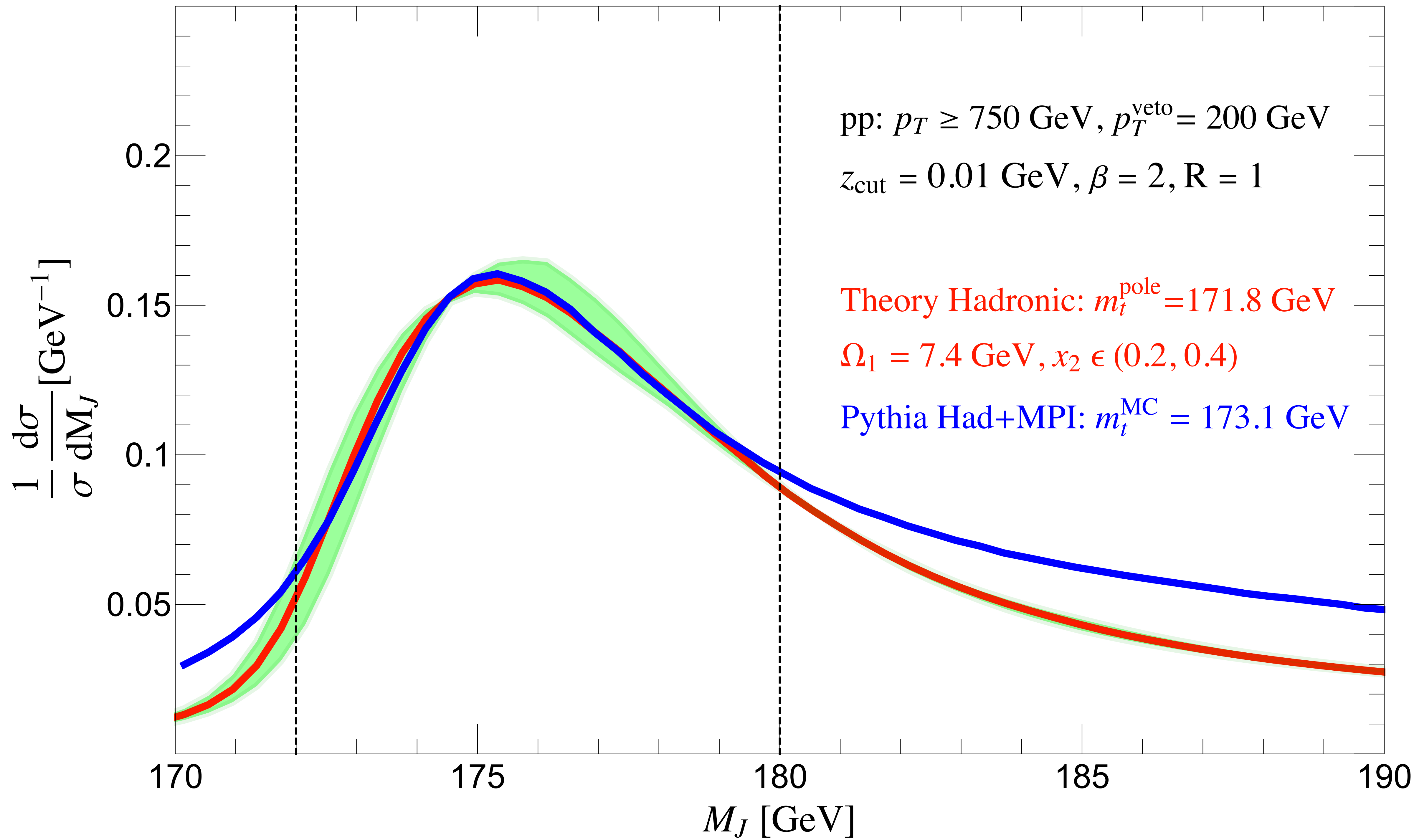
Translation of theory uncertainties to the fit parameters is in progress.



Pythia Simulation vs. Theory (with Soft Drop)

Testing sensitivity to higher moments:

$$\Omega_1 = \int \mathrm{d}k\, k\, F^{\mathrm{model}}(k) \qquad x_n = \frac{\Omega_n^c}{(\Omega_1)^n}$$



Summary

- Dominant uncertainty in top mass is identifying the renormalization scheme.

- Requires a QFT factorization framework, with clear top mass scheme information, to be compared to simulation or data.

- Discussed a new factorization framework for boosted top quarks.

- Exploited soft drop grooming techniques to reduce sensitivity to contamination.