Top Mass Measurements with/without Grooming

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Advances in QCD and Applications to Hadron Colliders
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Outline

- Top Mass Measurements at the LHC

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

- Factorization for $e^+e^- \to t\bar{t}$

- Top Mass Calibration for Monte Carlo Generators

  [Butenschoen, Dehnadi, Hoang, Mateu, Preisser, IS arXiv:1608.01318]

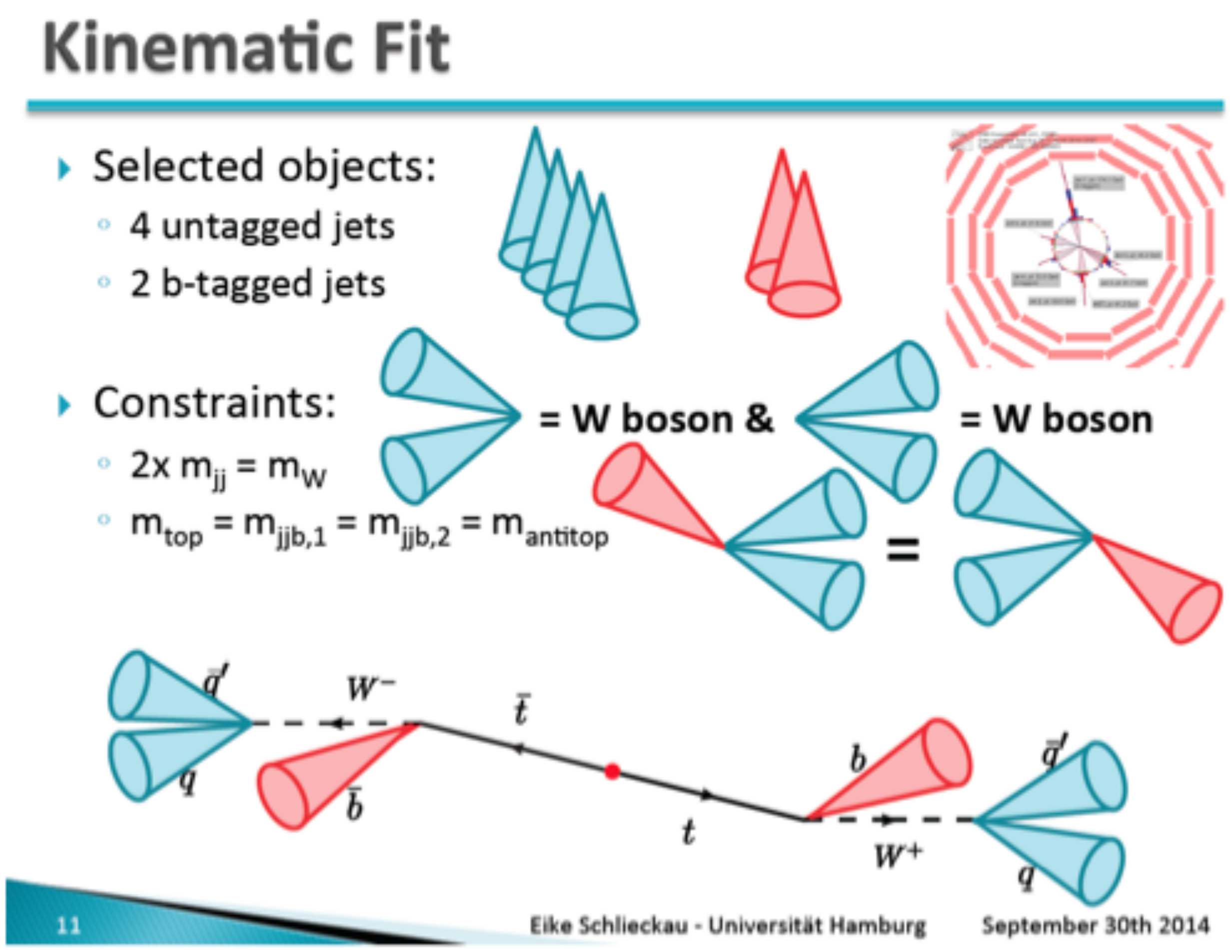
- Factorization for $pp \to t\bar{t}$ with & without Jet grooming

- Predictions for LHC top mass measurements with SoftDrop
  [A.Hoang, S.Mantry, A.Pathak, IS (soon)]

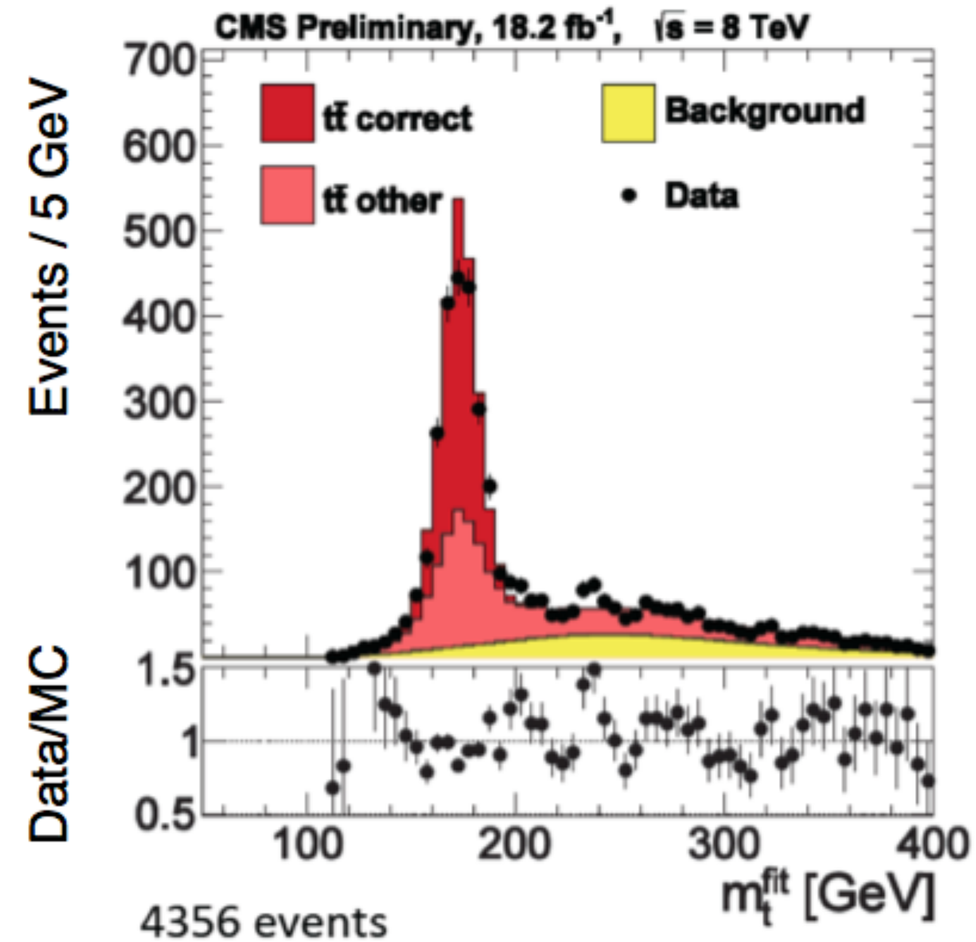
- Conclude

LHC & Tevatron Top Mass Measurements

<u>Use Direct Reconstruction to obtain sensitivity:</u>



CMS-PAS-TOP-14-002



4356 events

Use Monte Carlo Templates

Determine best fit value of Monte Carlo top-mass parameter:

$$\text{CMS:} \quad m_t^{\text{MC}} = 172.44 \pm 0.49 \qquad \text{ATLAS:} \quad m_t^{\text{MC}} = 172.84 \pm 0.70$$

What is m_t^{MC} ?

A.Hoang, IS arXiv:0808.0222

- Natural to think it is the pole mass, but its not.
  - Pole Mass has an infrared renormalon:

    Factorial growth in pert. series: $(2\beta_0)^n \, n! \, \alpha_s^{n+1}$

    Ambiguity: $\delta m_t^{\mathrm{pole}} \sim \Lambda_{\mathrm{QCD}}$

    Due to the shower cutoff, m_t^{MC} does not.
  - Pole Mass involves virtual integration over all momenta.

    MC has shower cutoff which restricts real radiation. Due to unitarity, this cutoff also affects virtual radiation & m_t^{MC} defn.

What is m_t^{MC} ?

A.Hoang, IS arXiv:0808.0222

- It is not the $\overline{\mathrm{MS}}$ mass.

$$\overline{m}_t \alpha_s \gg \Gamma_t \simeq 1.4\,\mathrm{GeV}$$

Not compatible with Breit-Wigner in Monte Carlo.

$$\frac{1}{\left(\frac{q^2 - m_t^2}{m_t}\right)^2 + \Gamma_t^2}$$

What is m_t^{MC} ?

A.Hoang, IS arXiv:0808.0222

- It is most like a short distance mass with cutoff $R \simeq 1\,\mathrm{GeV}$

MSR mass: $m_t^{\mathrm{MSR}}(R \simeq 1\mathrm{GeV}) \simeq m_t^{\mathrm{MC}}$

vary R: $\mathrm{definition\ uncertainty} \sim 0.5\,\mathrm{GeV}$

MS Scheme: $(\mu > \overline{m}(\overline{m}))$

$$\overline{m}(\overline{m}) - m^{\mathrm{pole}} = -\overline{m}(\overline{m})\,[0.42441\,\alpha_s(\overline{m}) + 0.8345\,\alpha_s^2(\overline{m}) + 2.368\,\alpha_s^3(\overline{m}) + \ldots]$$

Hoang, Jain, Scimemi, IS arXiv:0803.4214

MSR Scheme: $(R < \overline{m}(\overline{m}))$

$$m_{\mathrm{MSR}}(R) - m^{\mathrm{pole}} = -R\,[0.42441\,\alpha_s(R) + 0.8345\,\alpha_s^2(R) + 2.368\,\alpha_s^3(R) + \ldots]$$

$$m_{\mathrm{MSR}}(m_{\mathrm{MSR}}) = \overline{m}(\overline{m})$$

Extracting a Short Distance Top Mass at the LHC

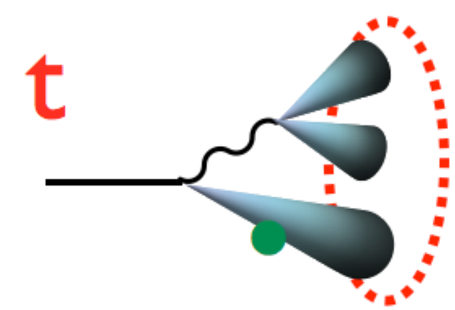
To improve on the current experimental measurements:

- must use a kinematically sensitive LHC observable
- theoretically tractable (= factorization at Hadron level), to obtain a measurement in a precise mass scheme defined at Lagrangian level.
- control contamination (ISR, Underlying Event, ...)

First simplification:

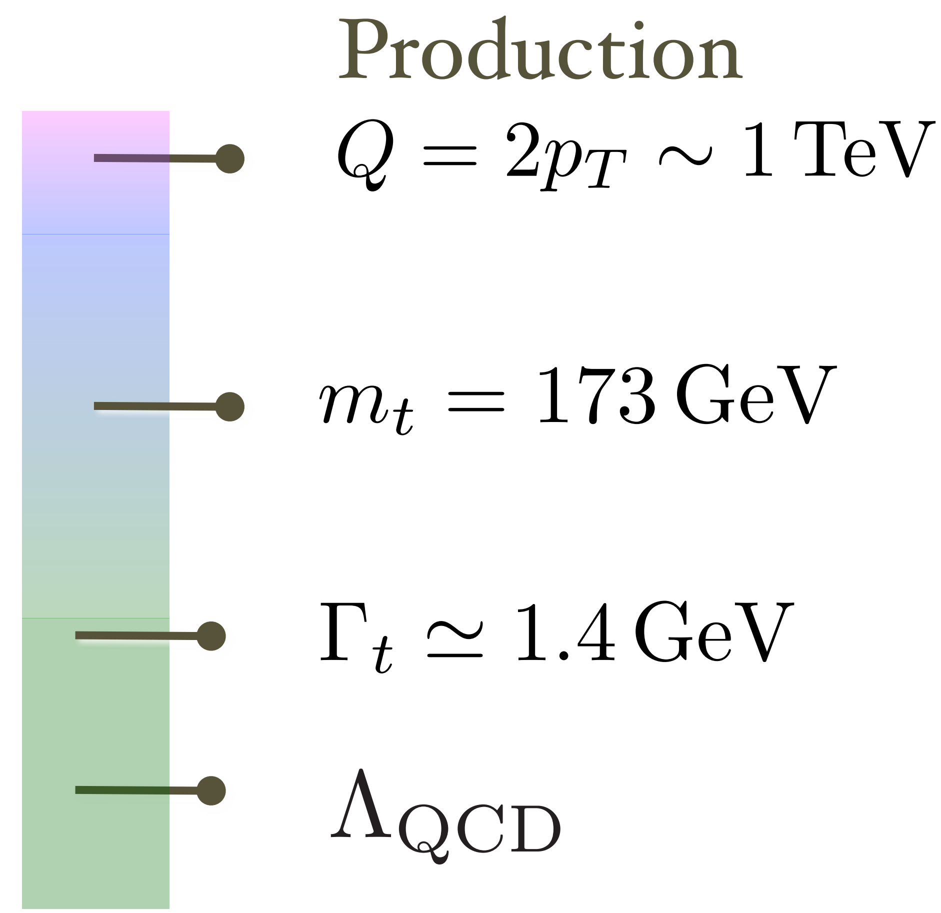
- boosted top quarks, $Q = 2p_T \gg m_t$

  enables us to be inclusive over decay products



Theory Issues for $pp \to t\bar{t}X$

- jet observable
- suitable top mass for jets
- initial state radiation
- final state radiation
- underlying event/MPI
- color reconnection
- beam remnant
- parton distributions
- sum large logs $Q \gg m_t \gg \Gamma_t$



Theory Issues for $pp \to t\bar{t}X$

- jet observable ★★
- suitable top mass for jets ★
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- final state radiation ★
- underlying event/MPI
- color reconnection ★
- beam remnant
- parton distributions
- sum large logs $Q \gg m_t \gg \Gamma_t$ ★

First
$e^+e^- \to t\bar{t}X$
and the issues ★

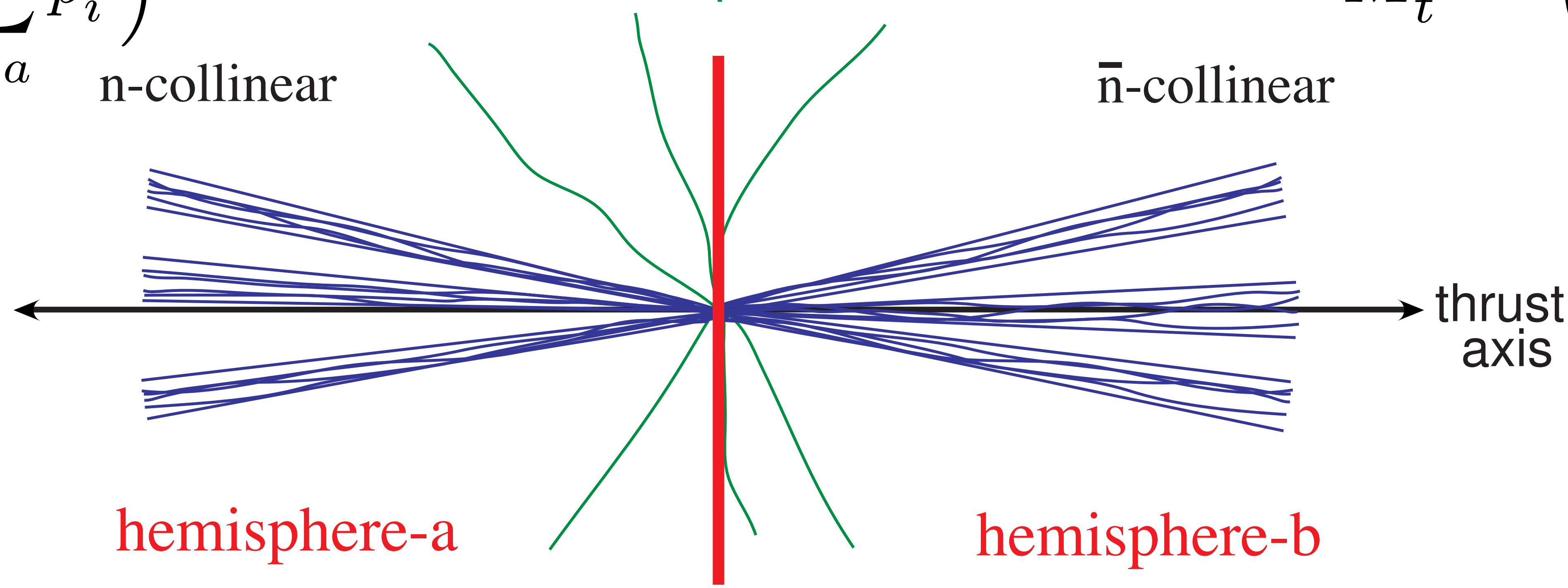
$e^+e^- \to t\bar{t}$

Measure what observable?

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

Hemisphere Invariant Masses

$$M_t^2 = \Big(\sum_{i\in a} p_i^\mu\Big)^2 \qquad M_{\bar{t}}^2 = \Big(\sum_{i\in b} p_i^\mu\Big)^2$$

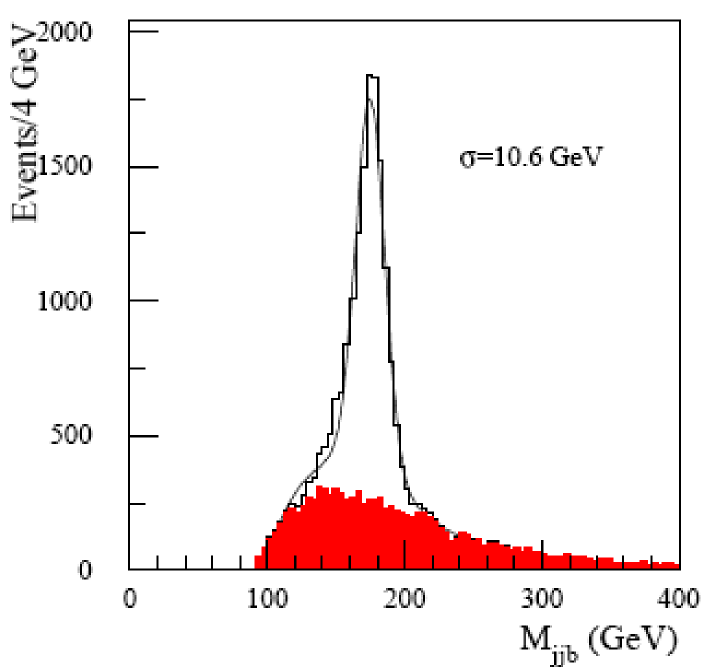


Peak region:

$$s_t \equiv M_t^2 - m^2 \sim m\Gamma \ll m^2$$

$$\hat{s}_t \equiv \frac{M_t^2 - m^2}{m} \sim \Gamma \ll m$$

Breit Wigner: $\frac{m\Gamma}{s_t^2 + (m\Gamma)^2} = \left(\frac{\Gamma}{m}\right)\frac{1}{\hat{s}_t^2 + \Gamma^2}$



Factorization:

Fleming, Hoang, Mantry, IS hep-ph/0703207 hep-ph/0711.2079

Hard Functions

$$\left(\frac{d^2\sigma}{dM_t^2\, dM_{\bar t}^2}\right)_{\text{hemi}} = \sigma_0 H_Q(Q,\mu_m)\, H_m\!\left(m, \frac{Q}{m}, \mu_m, \mu\right)$$

$$\times J_B\!\left(\hat s_t - \frac{Q\ell}{m}, \Gamma, \delta m, \mu\right) J_B\!\left(\hat s_{\bar t} - \frac{Q\ell'}{m}, \Gamma, \delta m, \mu\right) S_{\text{hemi}}(\ell - k, \ell' - k', \mu)\, F(k, k')$$

Answer

Hadronization

QCD

SCET

HQET

(boosted HQET)
Jet Functions

Evolution and decay of top quark close to mass shell

Soft Function

Perturbative Cross talk

control over mass scheme

Factorization:

Fleming, Hoang, Mantry, IS hep-ph/0703207
hep-ph/0711.2079

$$\left(\frac{d^2\sigma}{dM_t^2\, dM_{\bar t}^2}\right)_{\rm hemi} = \sigma_0 H_Q(Q,\mu_m) H_m\Big(m,\frac{Q}{m},\mu_m,\mu\Big)$$
$$\times J_B\Big(\hat s_t - \frac{Q\ell}{m},\Gamma,\delta m,\mu\Big) J_B\Big(\hat s_{\bar t} - \frac{Q\ell'}{m},\Gamma,\delta m,\mu\Big) S_{\rm hemi}(\ell-k,\ell'-k',\mu) F(k,k')$$

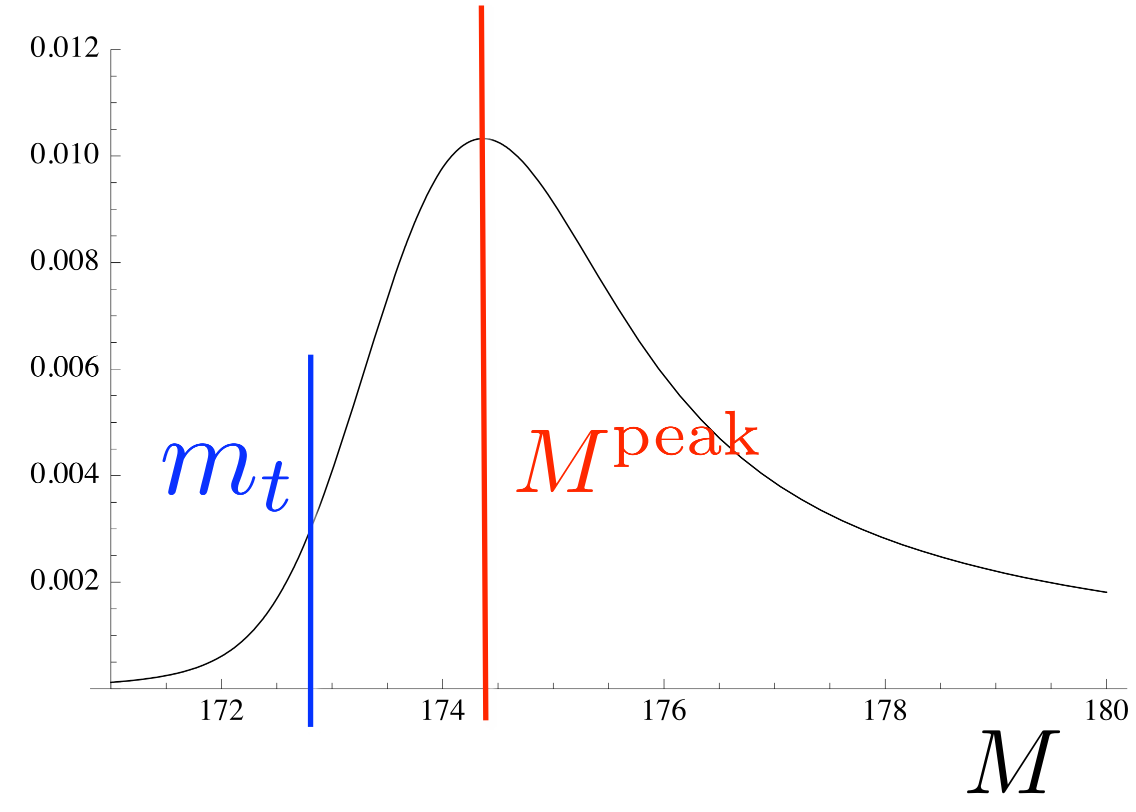
Answer

$$M^{\rm peak} = m_t + \Gamma_t(\alpha_s + \alpha_s^2 + \ldots) + \frac{Q\Lambda_{\rm QCD}}{m_t}$$

measure this

extract this

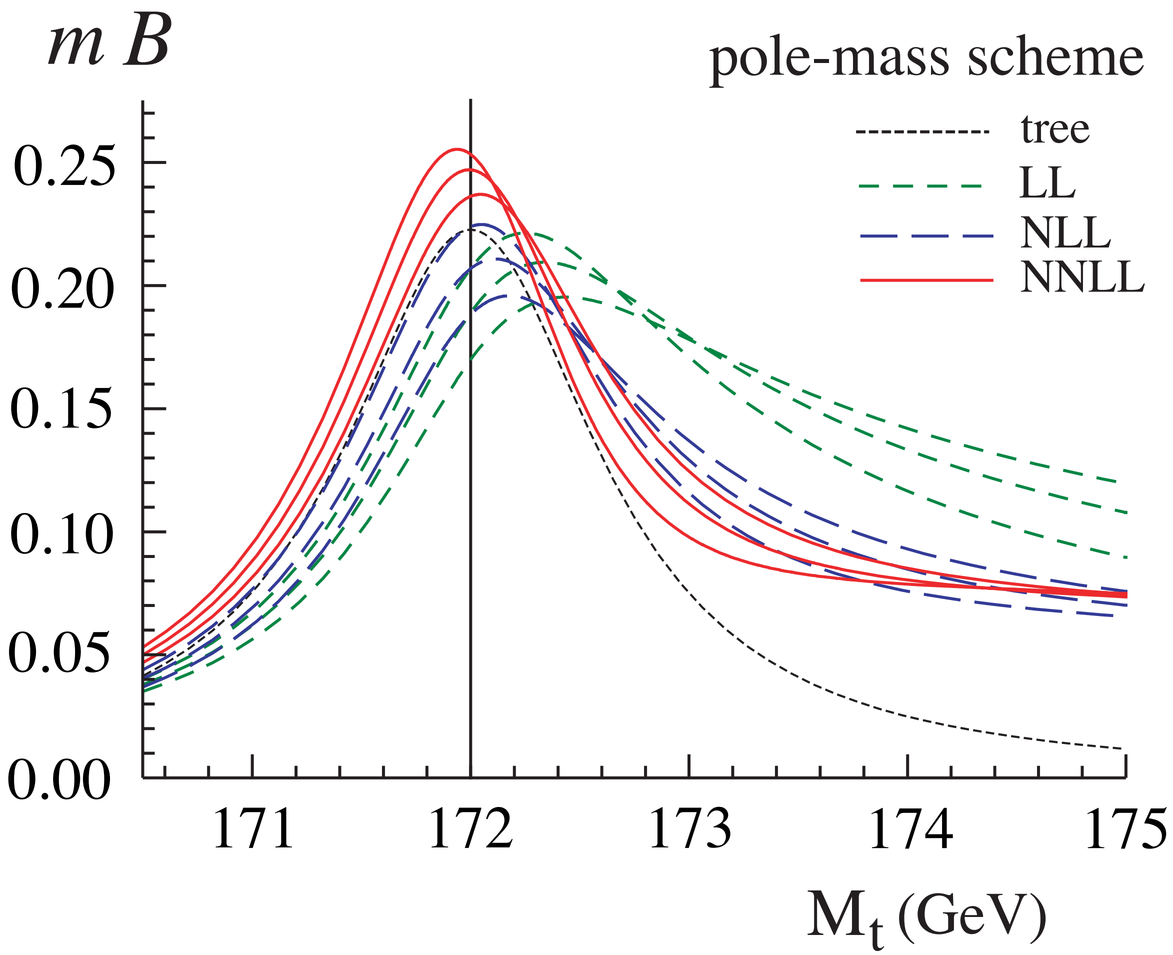
$$\frac{d\sigma}{dM}$$

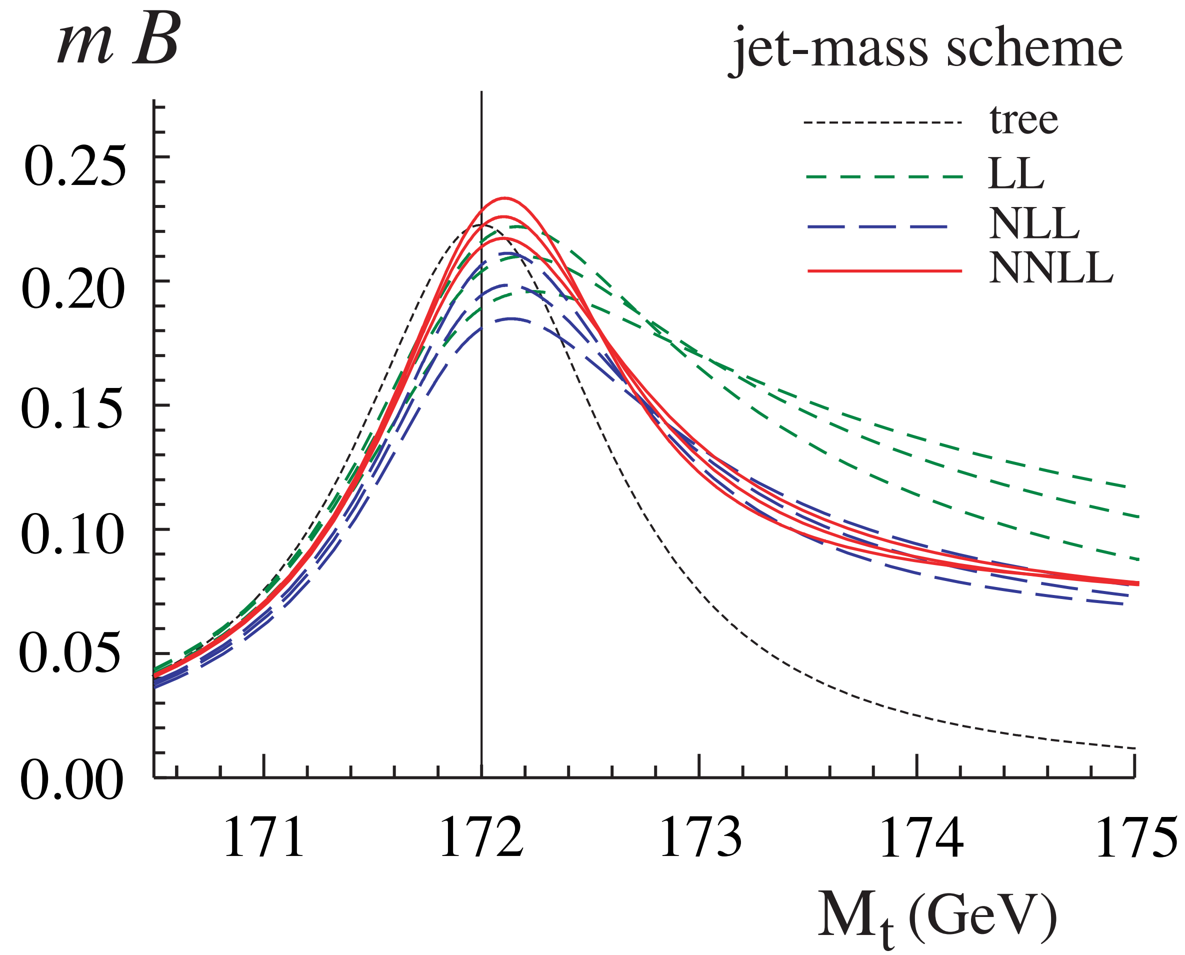


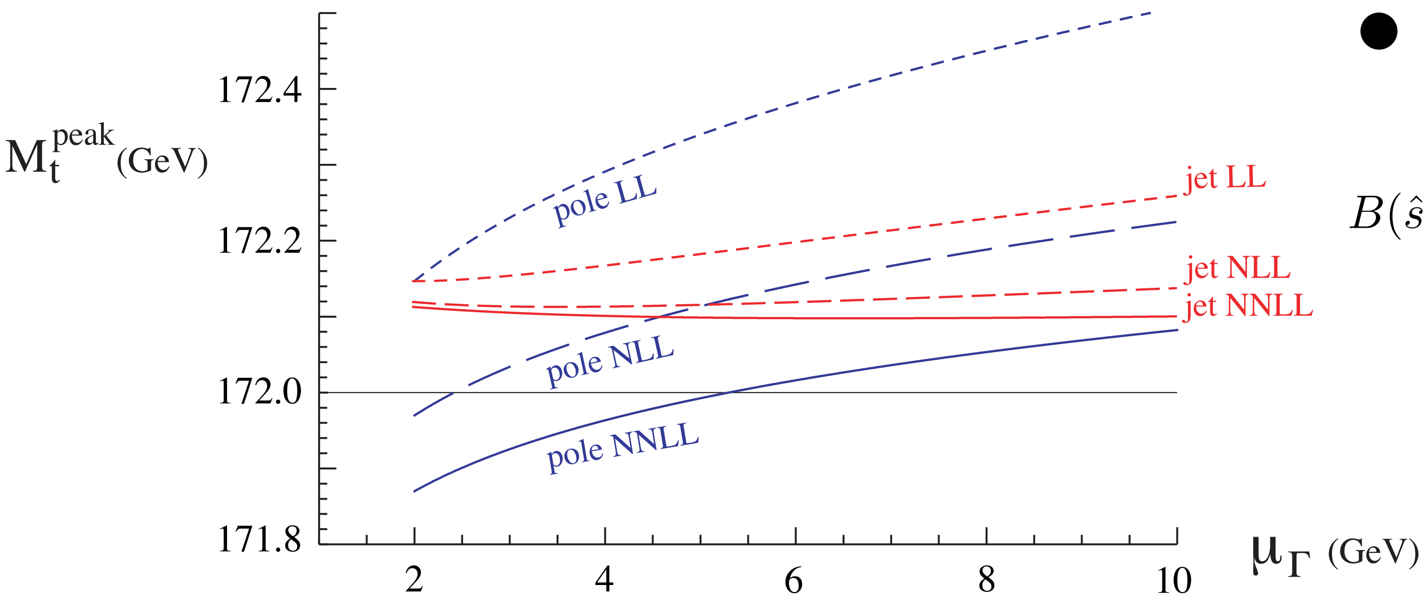
Short distance m_t can (in principle) be determined to better than $\Lambda_{\rm QCD}$

Jet Function Results up to $\mathcal{O}(\alpha_s^2)$ & NNLL:

Jain, Scimemi, I.S. arXiv:0801.0743







- 3 curves vary μ_Γ

$$B(\hat{s},\delta m_J,\Gamma_t,\mu_\Lambda,\mu_\Gamma) \equiv \int d\hat{s}'\ U_B(\hat{s}-\hat{s}',\mu_\Lambda,\mu_\Gamma)\ B(\hat{s}',\delta m_J,\Gamma_t,\mu_\Gamma)$$

$$= \int d\hat{s}'\, d\hat{s}''\ U_B(\hat{s}-\hat{s}',\mu_\Lambda,\mu_\Gamma)\ B(\hat{s}'-\hat{s}'',\delta m_J,\mu_\Gamma)\ \frac{\Gamma_t}{\pi(\hat{s}''^{\,2}+\Gamma_t^2)}$$

Top Mass Calibration of Monte Carlo

[Butenschoen, Dehnadi, Hoang, Mateu, Preisser, IS arXiv:1608.01318]

Calibrate the m_t^{MC} parameter in Monte Carlo against Hadron level theory predictions with definite m_t parameter

$e^+e^- \to t\bar{t}$ theory:

- NNLL + NLO + nonsingular + hadronization + renormalon subt.
- VFNS for final state jets with massive quarks

  [Gritschacher, Hoang, Jemos, Mateu, Pietrulewicz 2013, 2014]

  [Butenschon, Dehnadi, Hoang, Mateu (to appear)]
- MSR mass, Soft Gap Scheme, and R-evolution [Hoang, Jain, Scimemi, Stewart 2010] [Hoang, Kluth 2008]
- 2-jettiness variable: $\tau_2 = 1 - \max_{\vec{n}_t} \frac{\sum_i |\vec{n}_t \cdot \vec{p}_i|}{Q}$

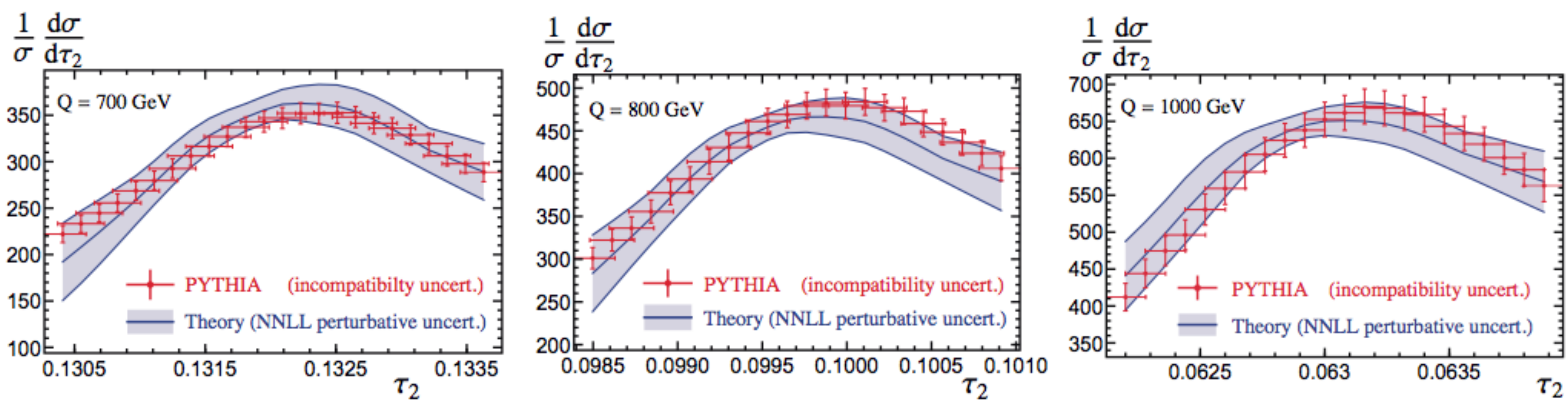
$$\frac{d\sigma}{d\tau} = f(m_t^{\mathrm{MSR}}, \alpha_s(m_Z), \Omega_1, \Omega_2, \ldots, \mu_H, \mu_J, \mu_S, \mu_M, R, \Gamma_t)$$

any scheme — non-perturbative — renorm. scales — finite lifetime

Fit Procedure:

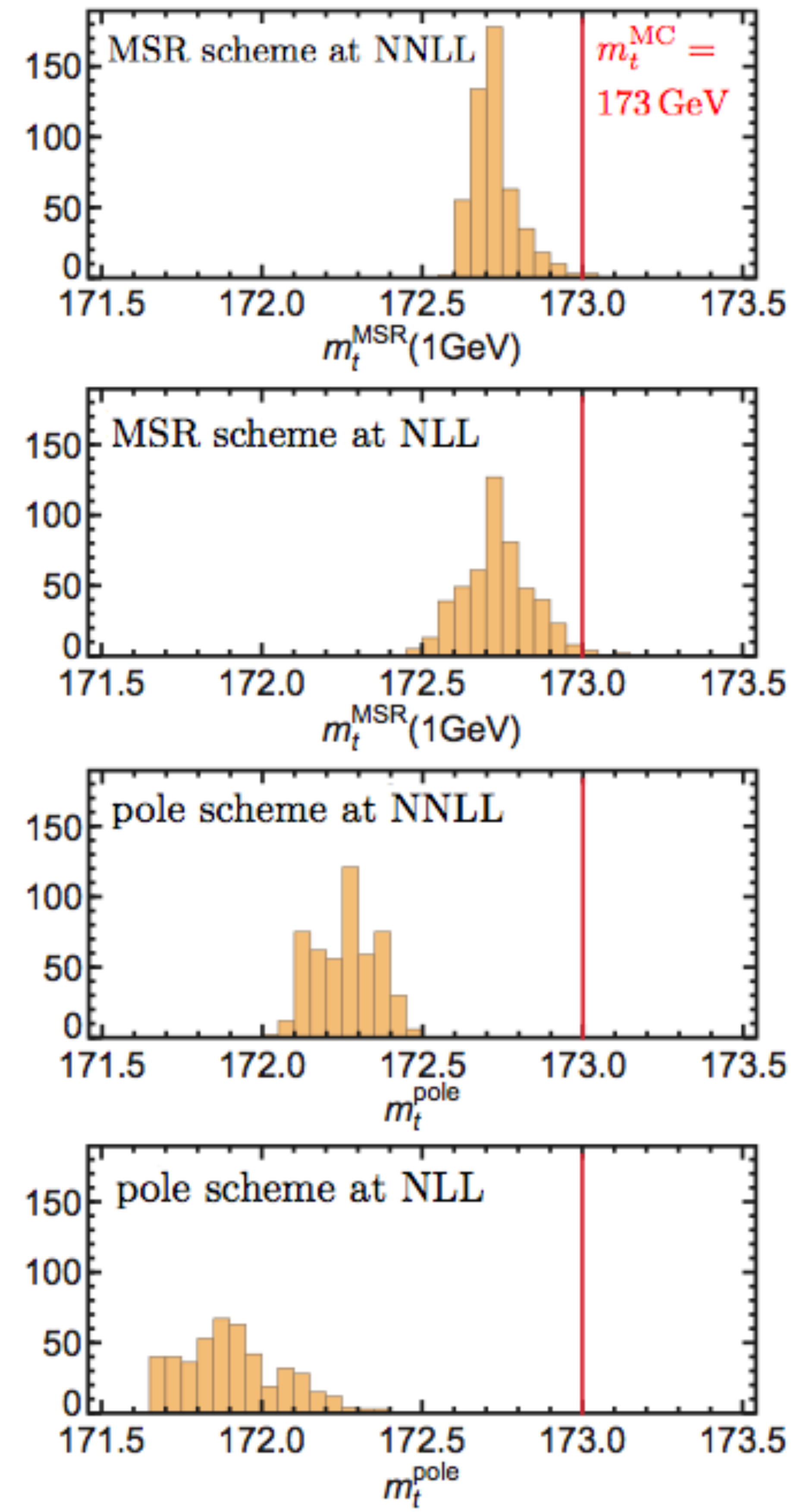
PYTHIA 8.205

- Fix m_t^{MC}. Generate MC data with $Q = 700, 800, \ldots, 1300, 1400$ GeV.
- For given μ_i , Fit theory in peak region to determine Ω_i and m_t
- Repeat 500 times for different μ_i to obtain perturbative uncertainty



Results:

- $m_t^{\rm MC}$ differs from $m_t^{\rm pole}$ by 0.9 GeV (NNLL) or 0.6 GeV (NLL)
- $m_t^{\rm MC}$ compatible with $m_t^{\rm MSR}(R = 1\,{\rm GeV})$



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

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

Theory Issues for $pp \to t\bar{t}X$

- jet observable ★★
- suitable top mass for jets ★
- initial state radiation
- final state radiation ★
- underlying event/MPI
- color reconnection ★
- beam remnant
- parton distributions
- sum large logs $Q \gg m_t \gg \Gamma_t$ ★

Can apply this to current measurements if we trust Pythia extrapolation for remaining items

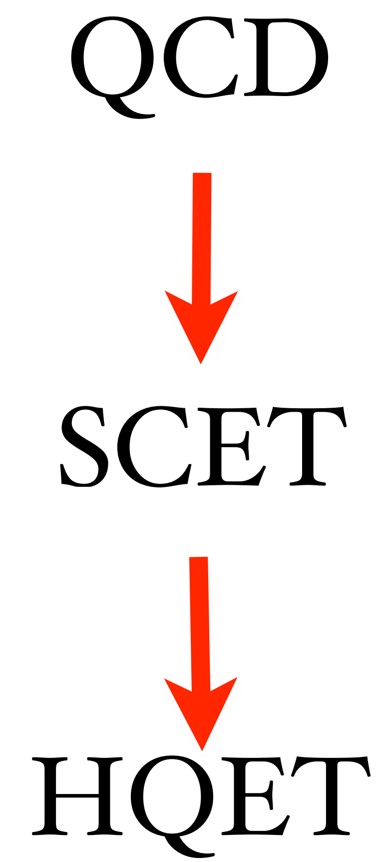
Theory Issues for $pp \to t\bar{t}X$

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

Better: factorization for pp

$pp \to t\bar{t}$

A. Hoang, S. Mantry, A. Pathak, IS



- Can be extended to pp (using N-jettiness) (Stewart, Tackmann, Waalewijn)

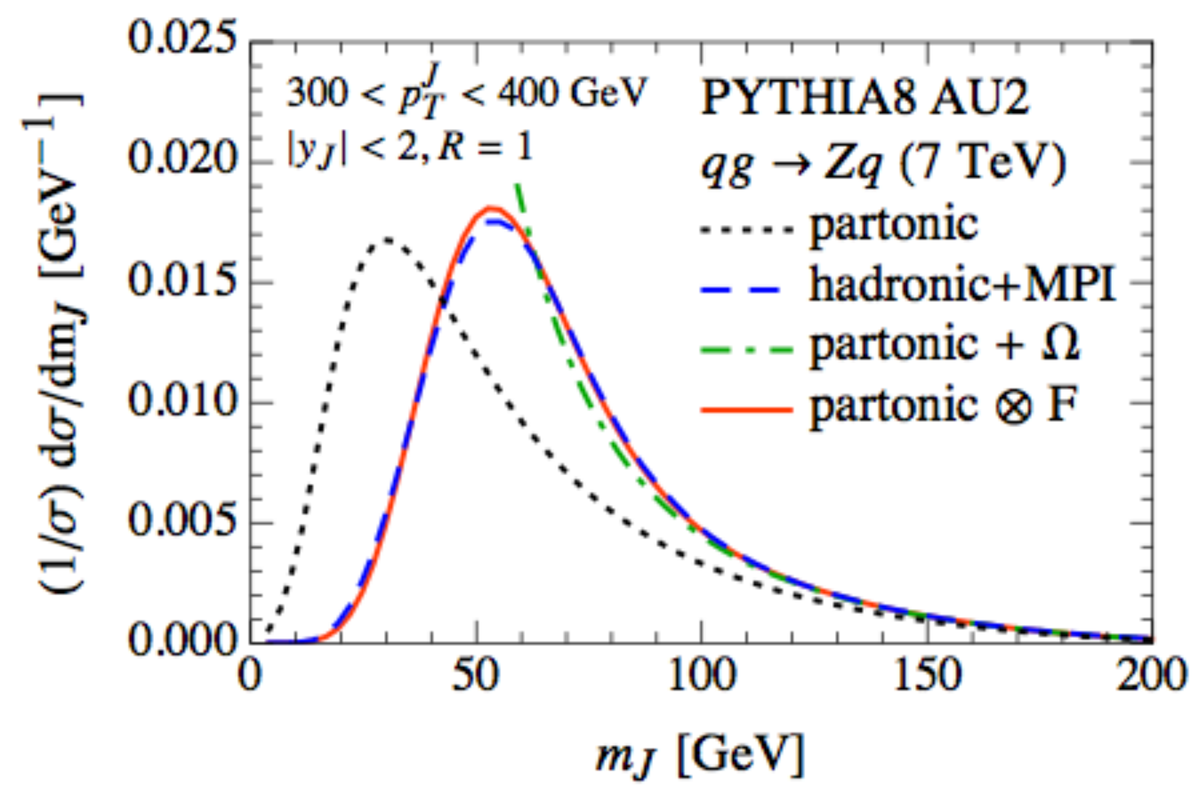
$$\frac{d^2\sigma}{dM_{J1}^2 dM_{J2}^2 d\mathcal{T}^{\rm cut}} = {\rm tr}\big[\hat{H}_{Qm}\hat{S}(\mathcal{T}^{\rm cut}, R, \ldots)\otimes F\big]\otimes J_B \otimes J_B \otimes \mathcal{I}\mathcal{I} \otimes f\,f$$

same jet functions!

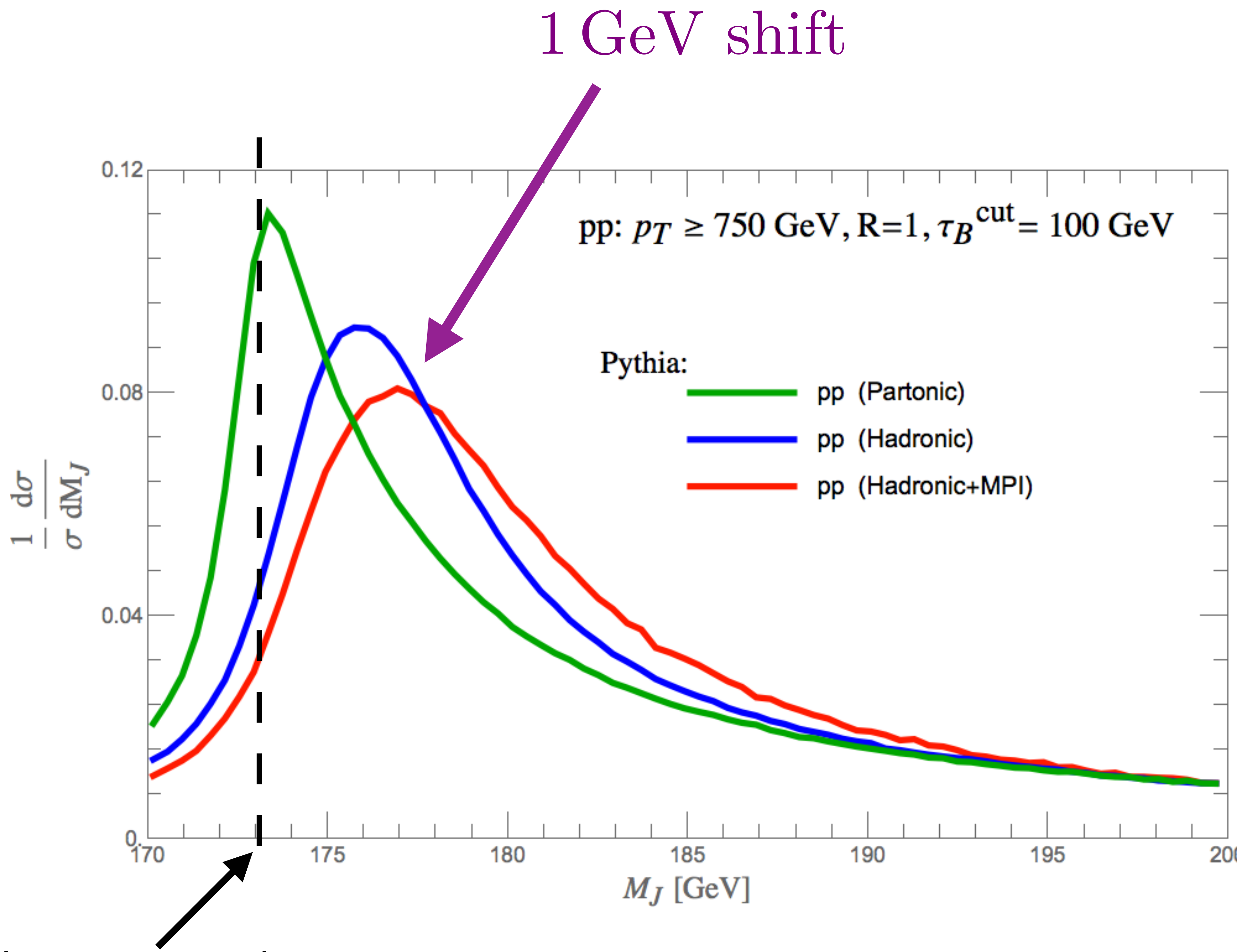
- BUT control of underlying event is model dependent.

Simple one parameter function F does give a reasonable model which reproduces Pythia

(IS, Tackmann, Waalewijn 2015)



Issue is that UE / MPI is significant:



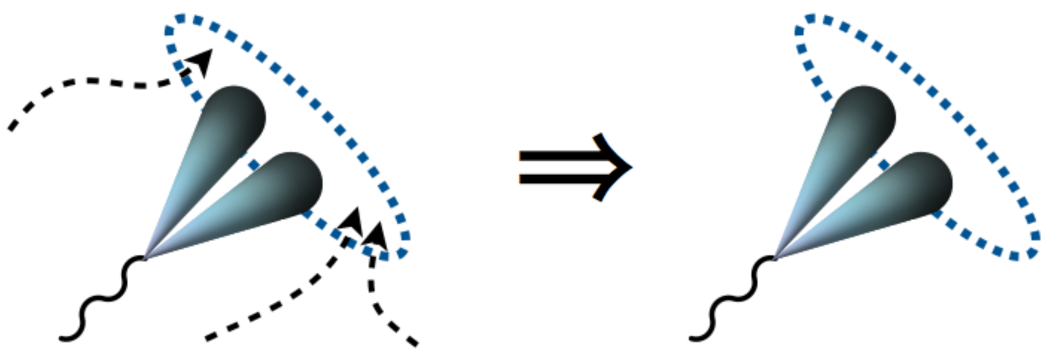
input mass in
Pythia m_t=173.1 GeV

Jet Substructure Interlude:

key tools for:
- grooming jets
- tagging subjets

eg. W/Z tagging in 2016

CMS | ATLAS EXPERIMENT

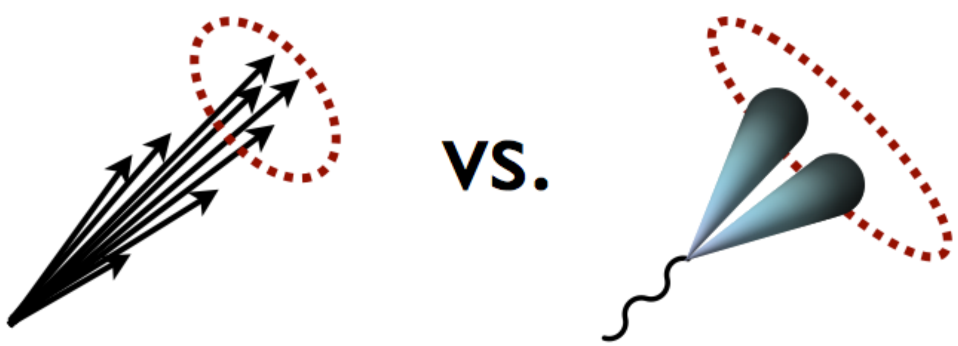


Soft Drop

Larkoski, Marzani, Soyez, Thaler

Trimming

Krohn, Thaler, Wang



N-subjettiness

Thaler, van Tilburg
(see also Stewart, Tackmann, Waalewijn)

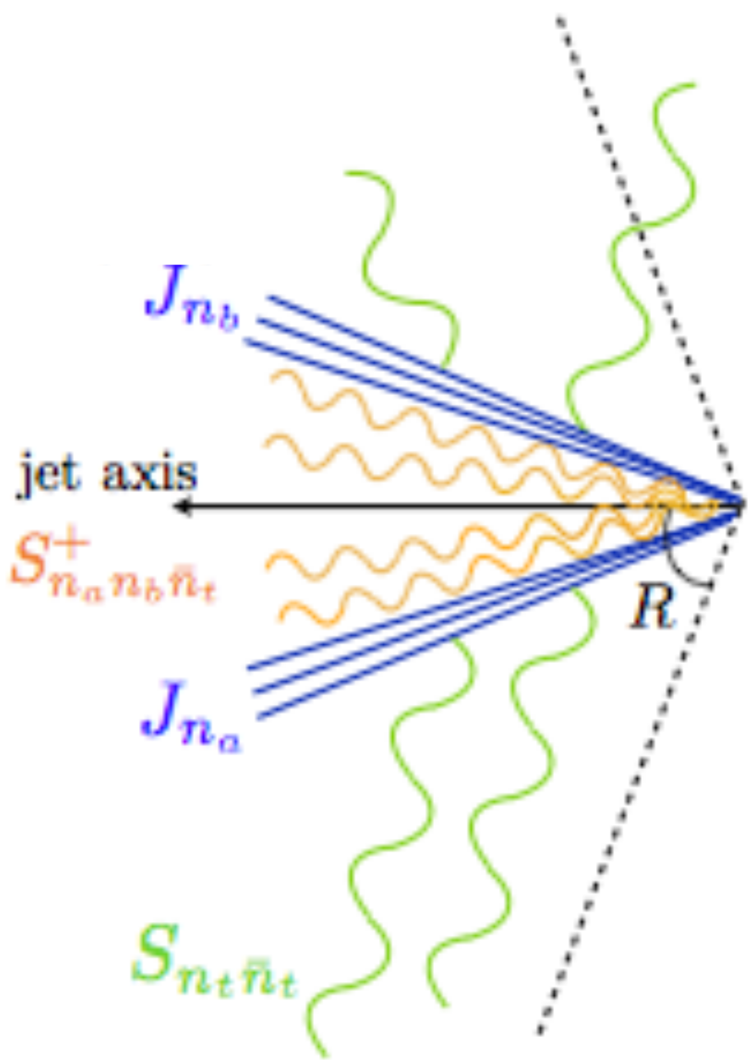
D_2

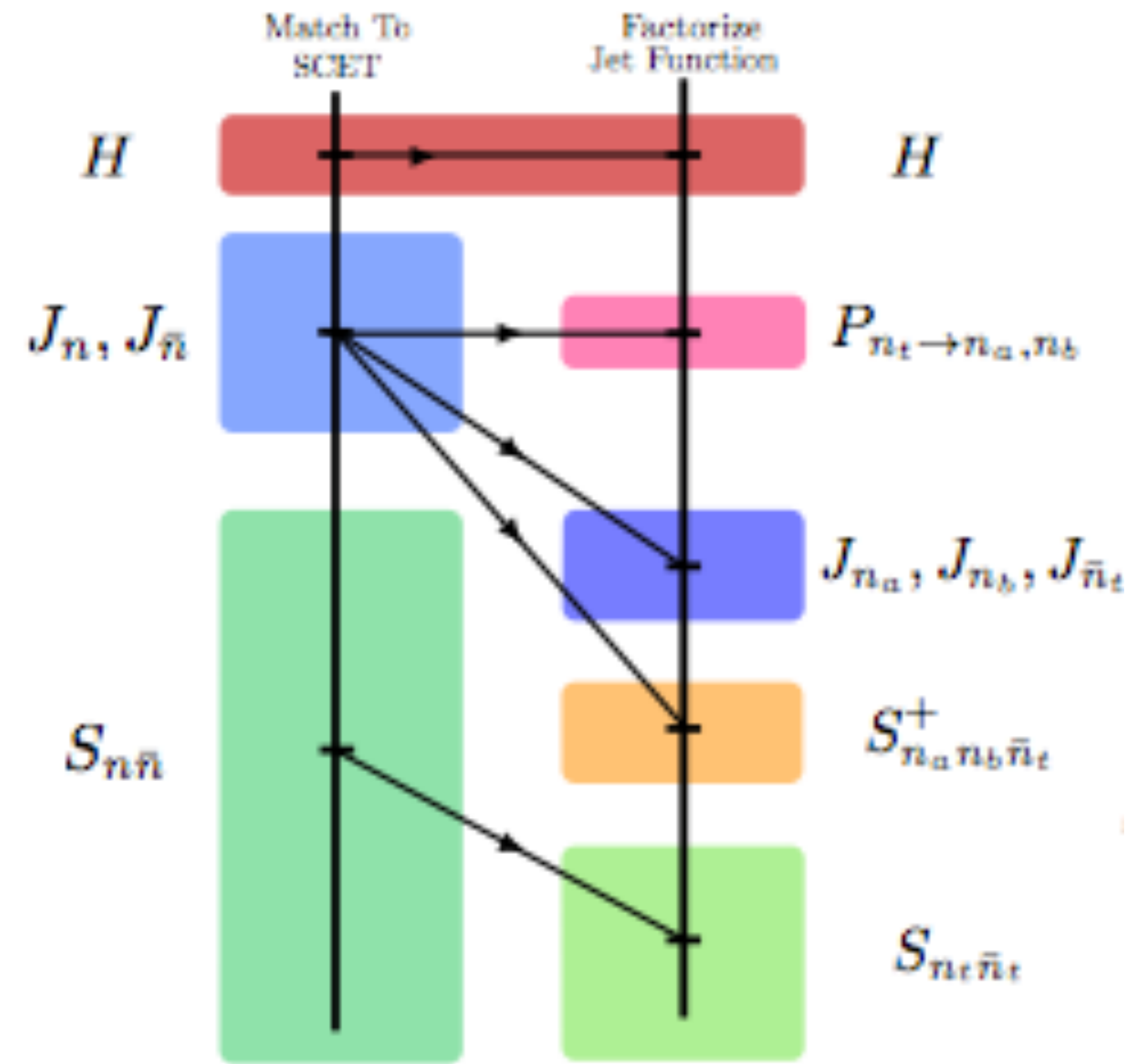
Larkoski, Moult, Neill

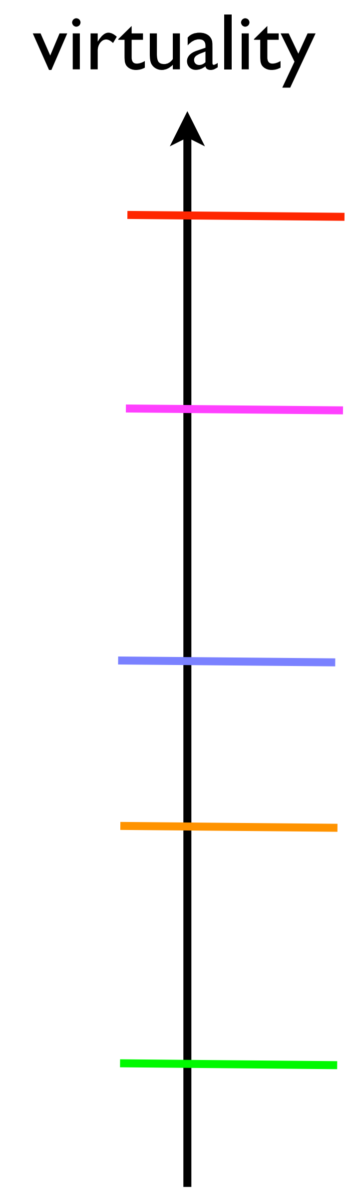
More scales:

Collinear Subjets

Bauer, Tackmann, Walsh, Zuberi 2012







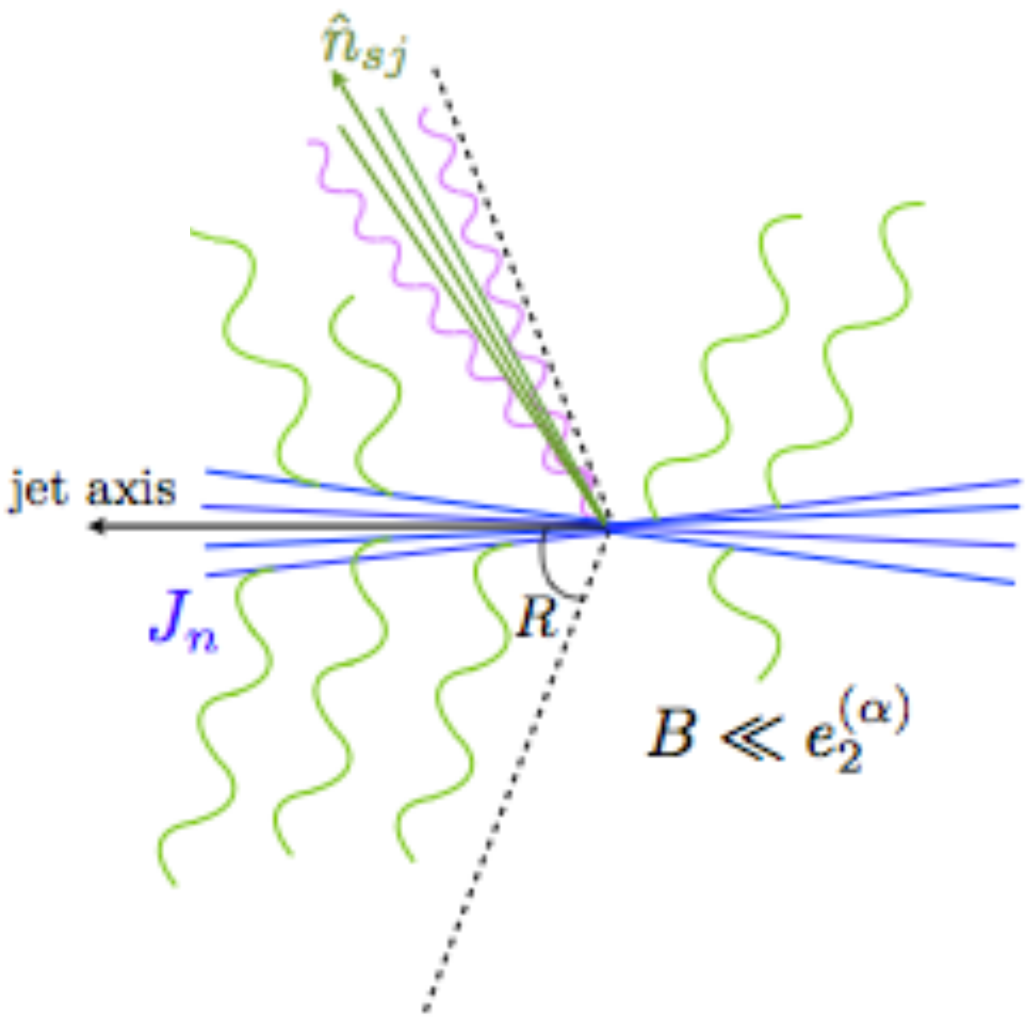
<u>also used for:</u>

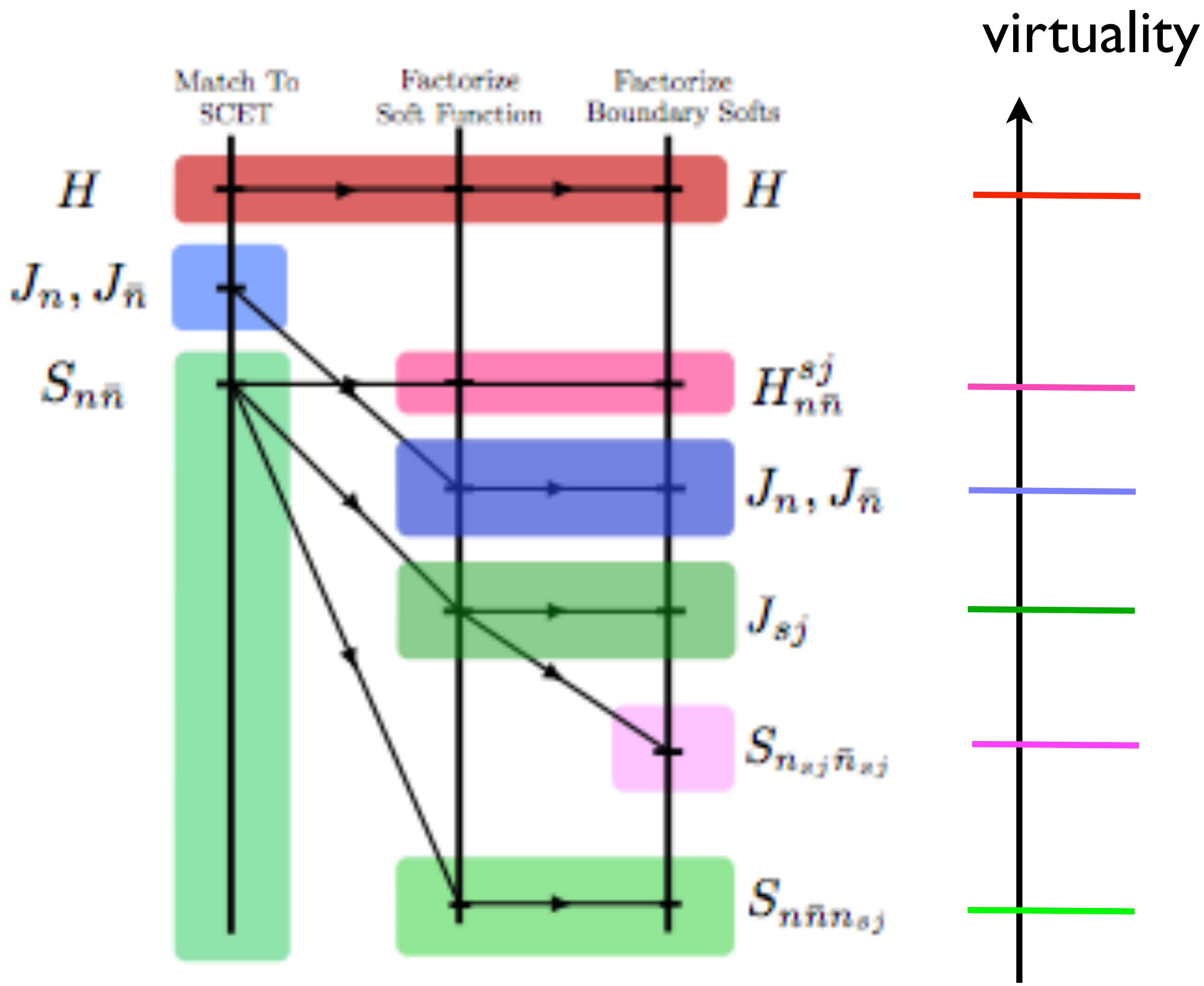
Multiple Measurements: Procura, Waalewijn, Zeune 2014

Sum Logs of Jet Radius, ln(R): See Chris Lee's talk

More scales:

Soft Subjet Larkoski, Moult, Neill





Factorization theorems for both collinear and soft subjects were use for for their calculation of D_2

Soft Drop

Larkoski, Marzani, Soyez, Thaler 2014

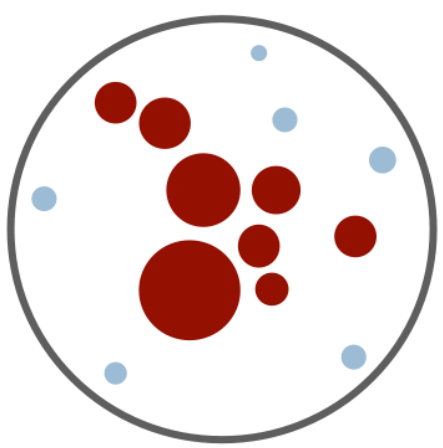
Grooms soft radiation from the jet

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

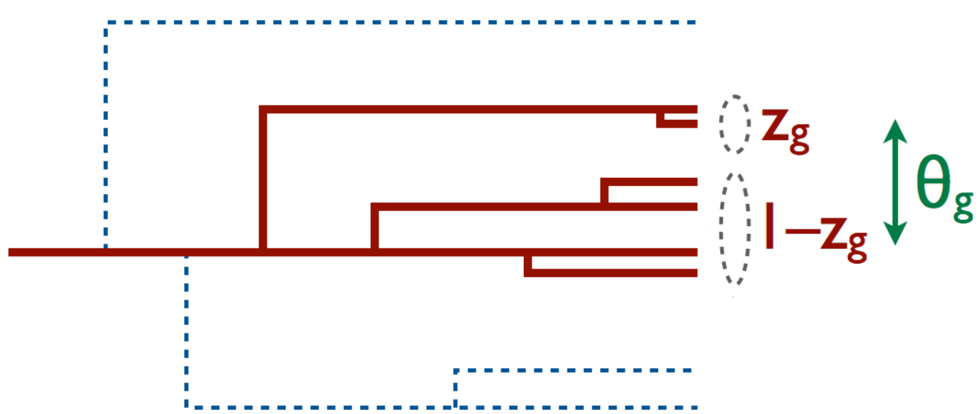
$$z > z_{\text{cut}}\ \theta^{\beta}$$

two grooming parameters

Groomed Jet



Groomed Clustering Tree

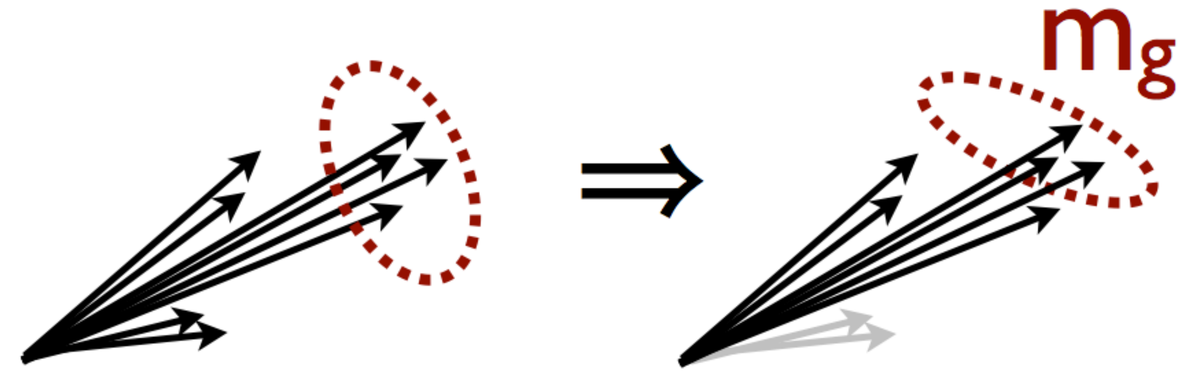


More Grooming — Less Grooming

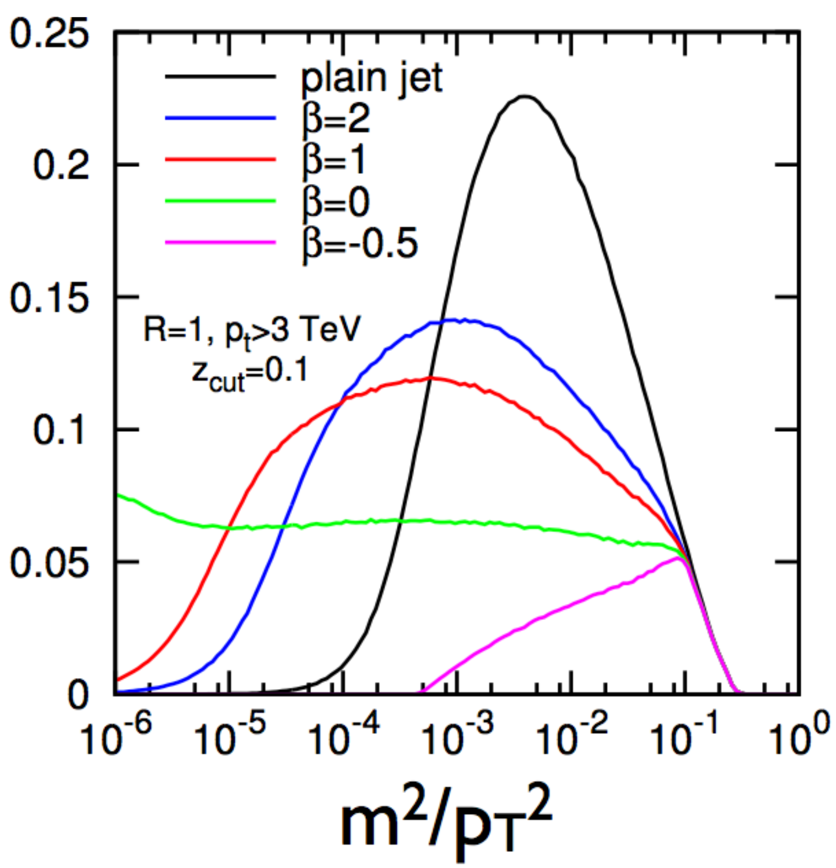
$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

Calculating Mass?

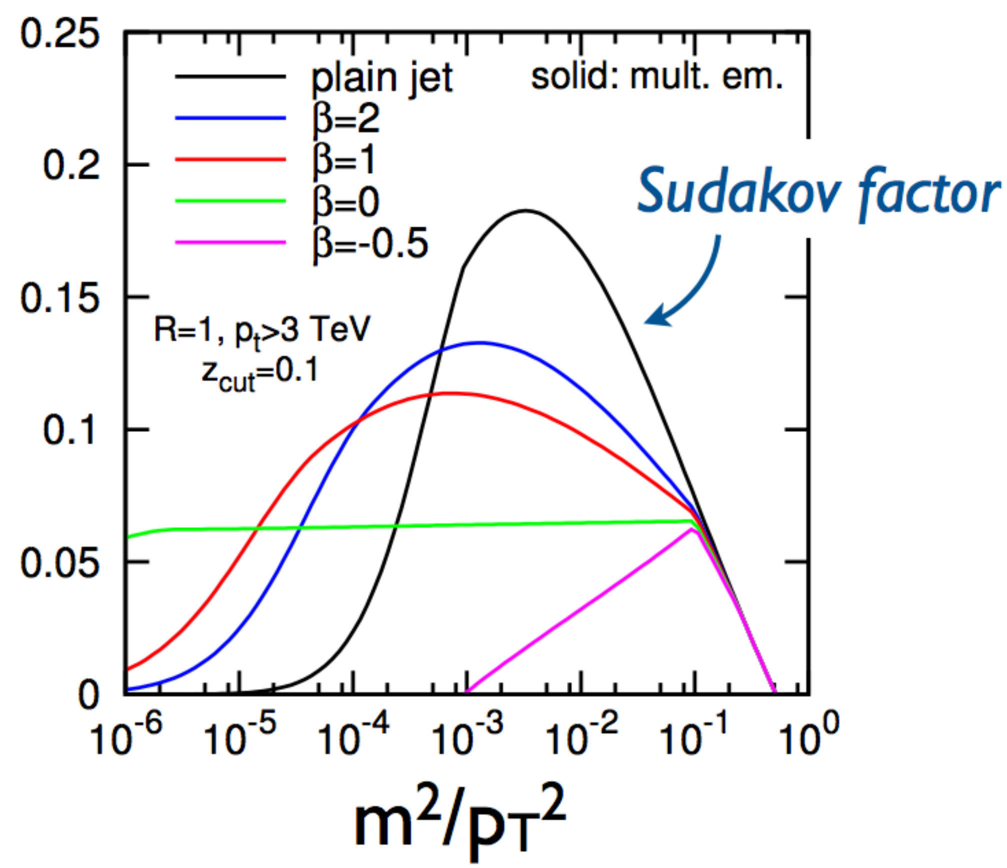
Larkoski, Marzani, Soyez, Thaler 2014

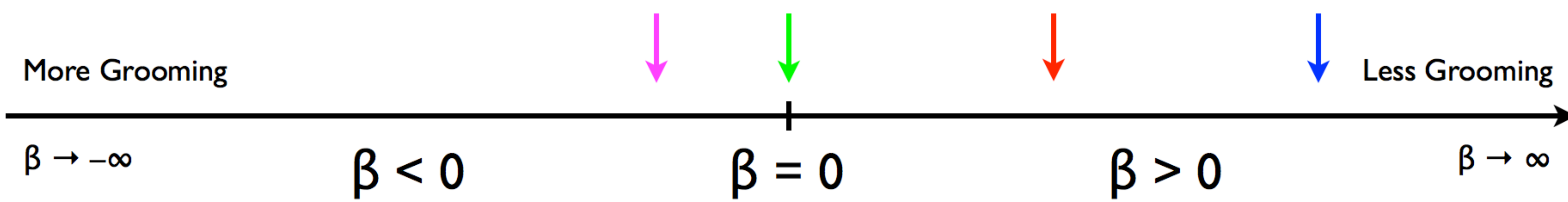


Pythia 8, partonic



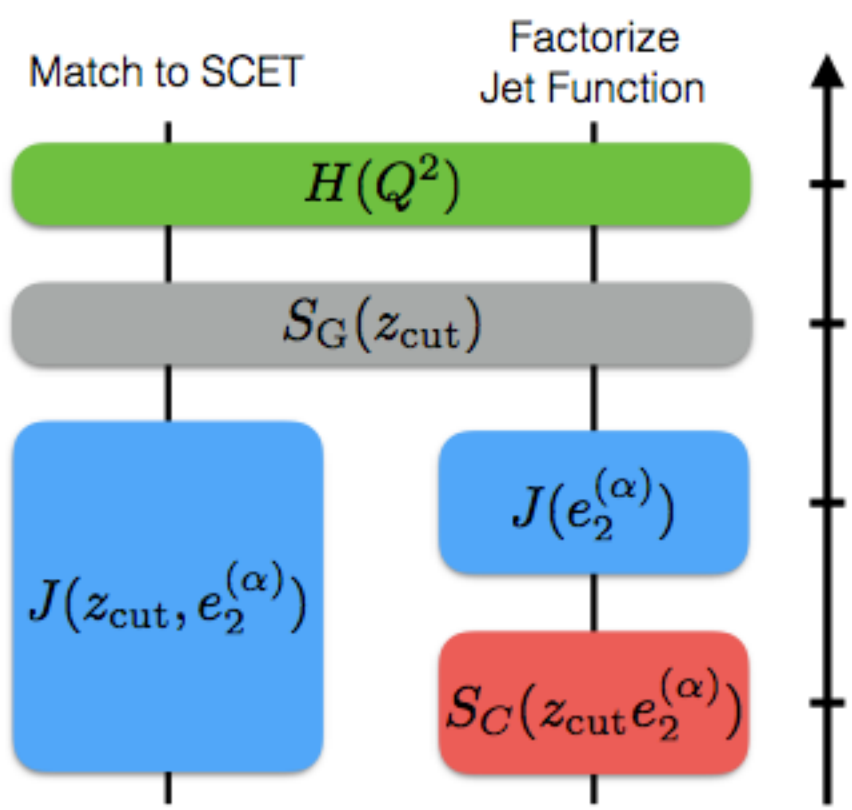
Pert. QCD at $\simeq$NLL

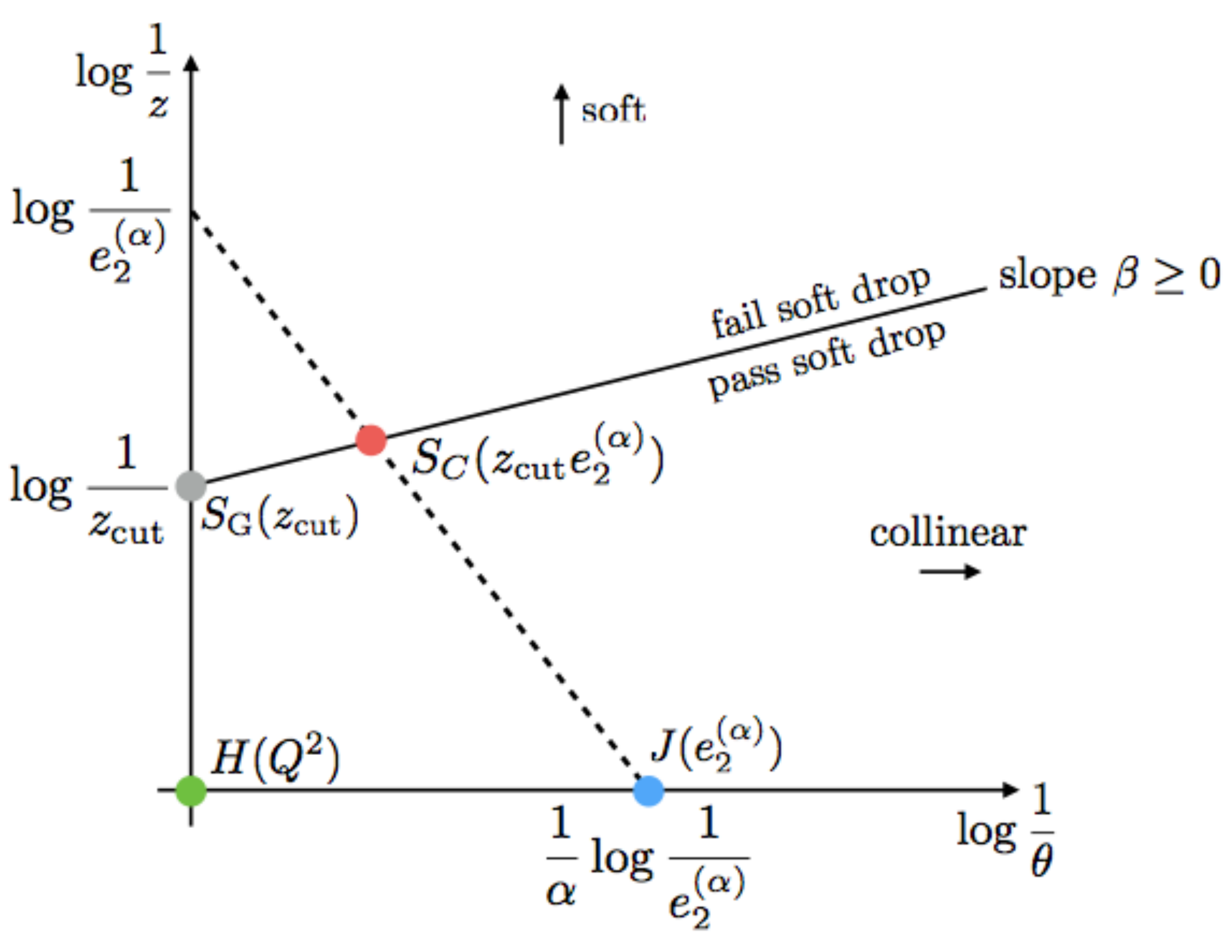


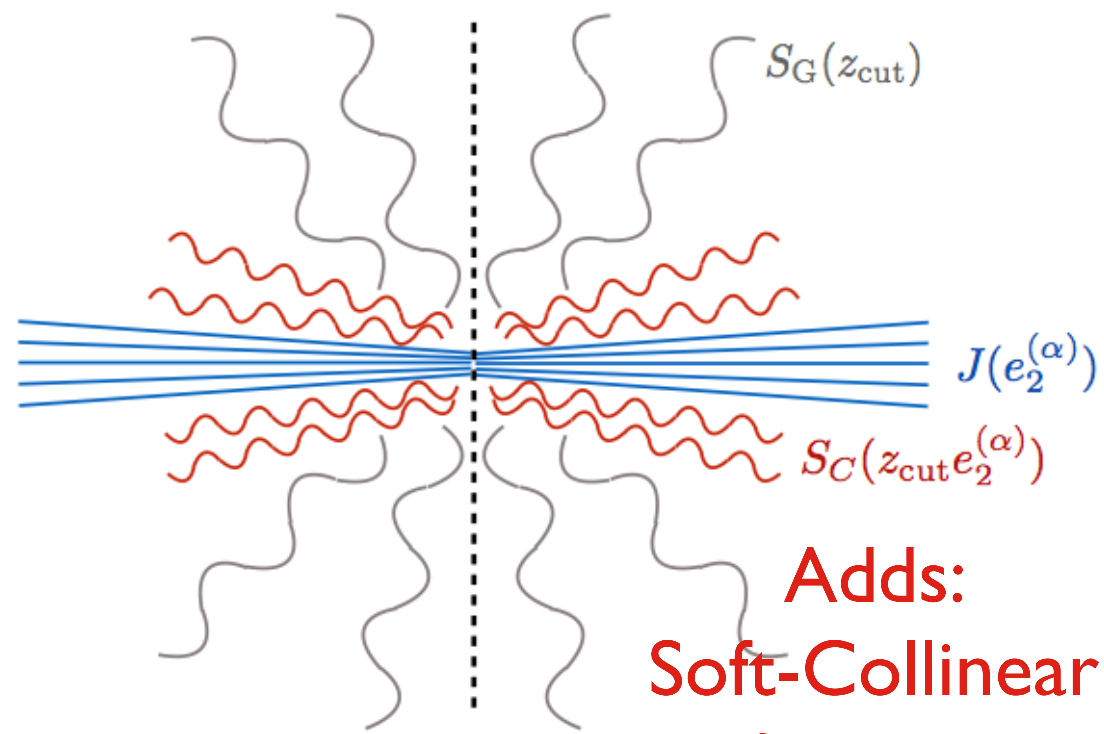


Soft Drop Factorization

Frye, Larkoski, Schwartz, Yan 2016







Adds:
Soft-Collinear function S_C

$$\frac{d\sigma}{de_2 \ldots} = H(Q^2) S_G(z_{cut}, \beta) \times \left[S_C(e_2, z_{cut}, \beta) \otimes J(e_2) \right]$$

isolates measurement
achieve NNLL precision

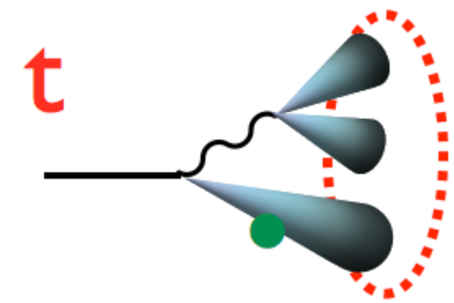
Top Jet Mass with Soft Drop

$$pp \to t\bar{t}$$

A. Hoang, S. Mantry, **A. Pathak**, IS (to appear)

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

- Boosted Tops $\quad p_T \gg m_t \quad$ retain top decay products



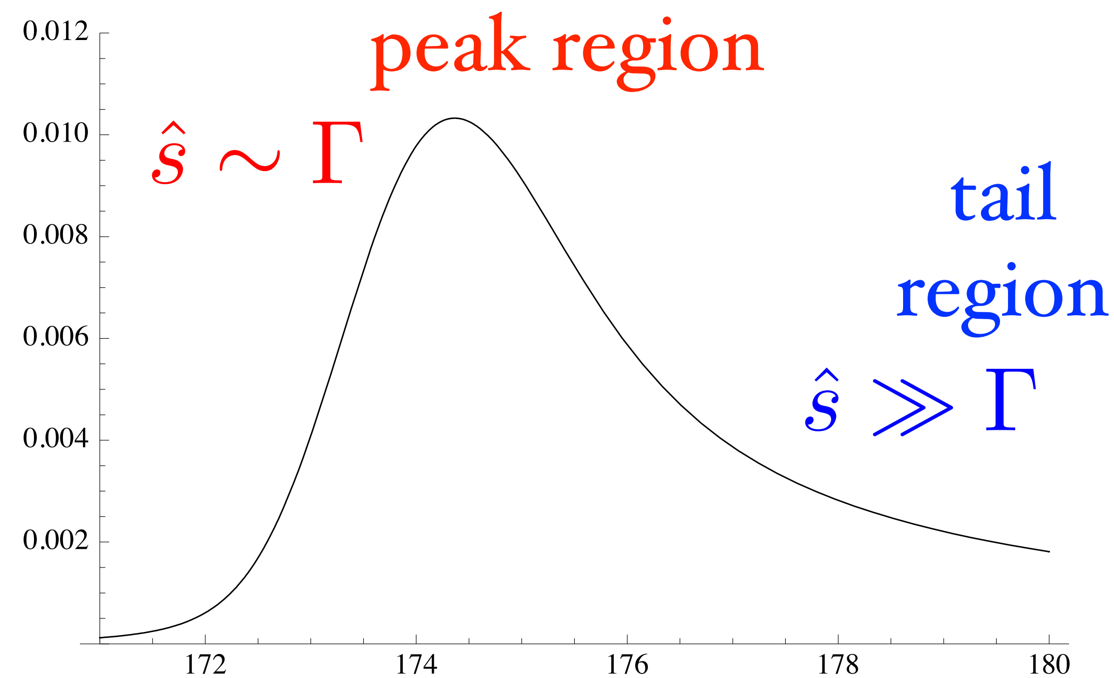
- Fat Jets $\quad R \gg \dfrac{m_t}{p_T}$

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

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

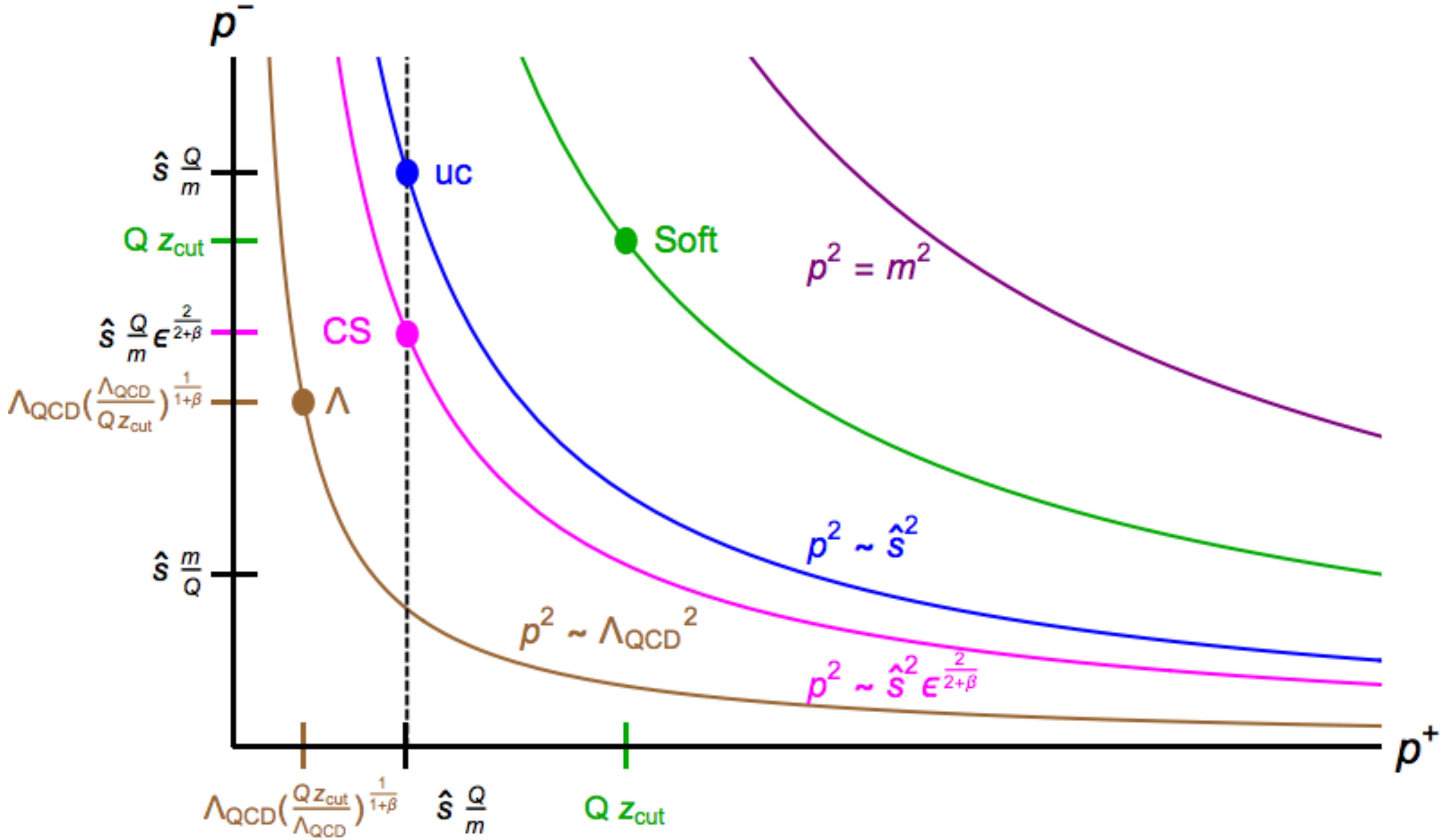
- Grooming $\quad z_{\rm cut}, \beta$

- Jet Veto $\quad \mathcal{T}^{\rm cut}$ or $p_T^{\rm cut}$

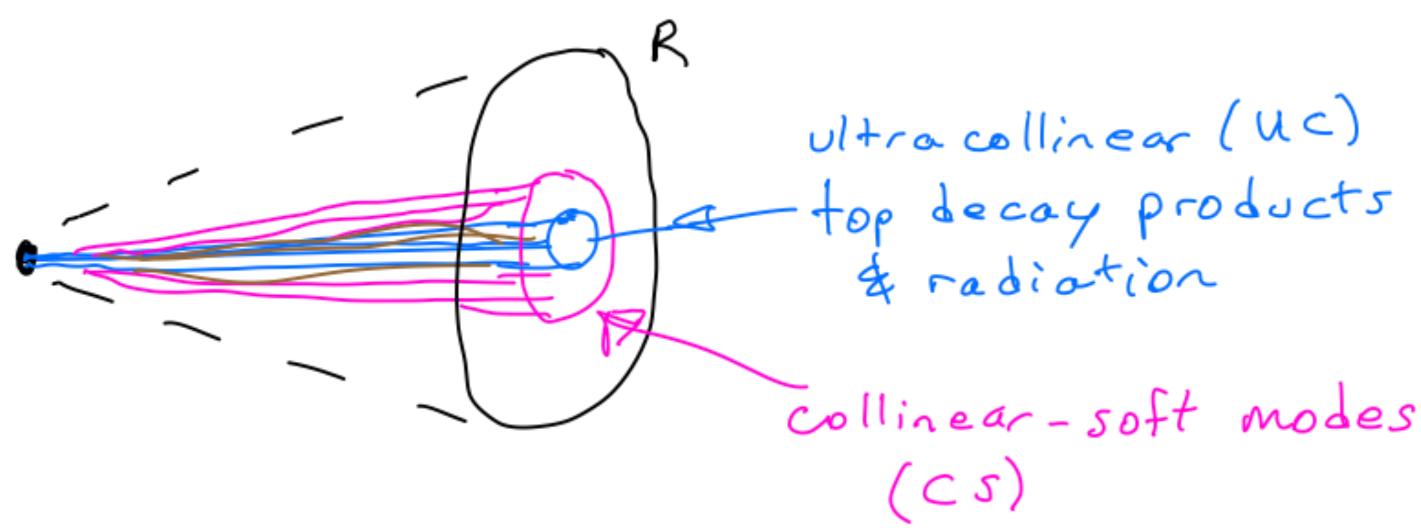


(Perturbative and Nonperturbative effects give $\Gamma > \Gamma_t$)

Modes:

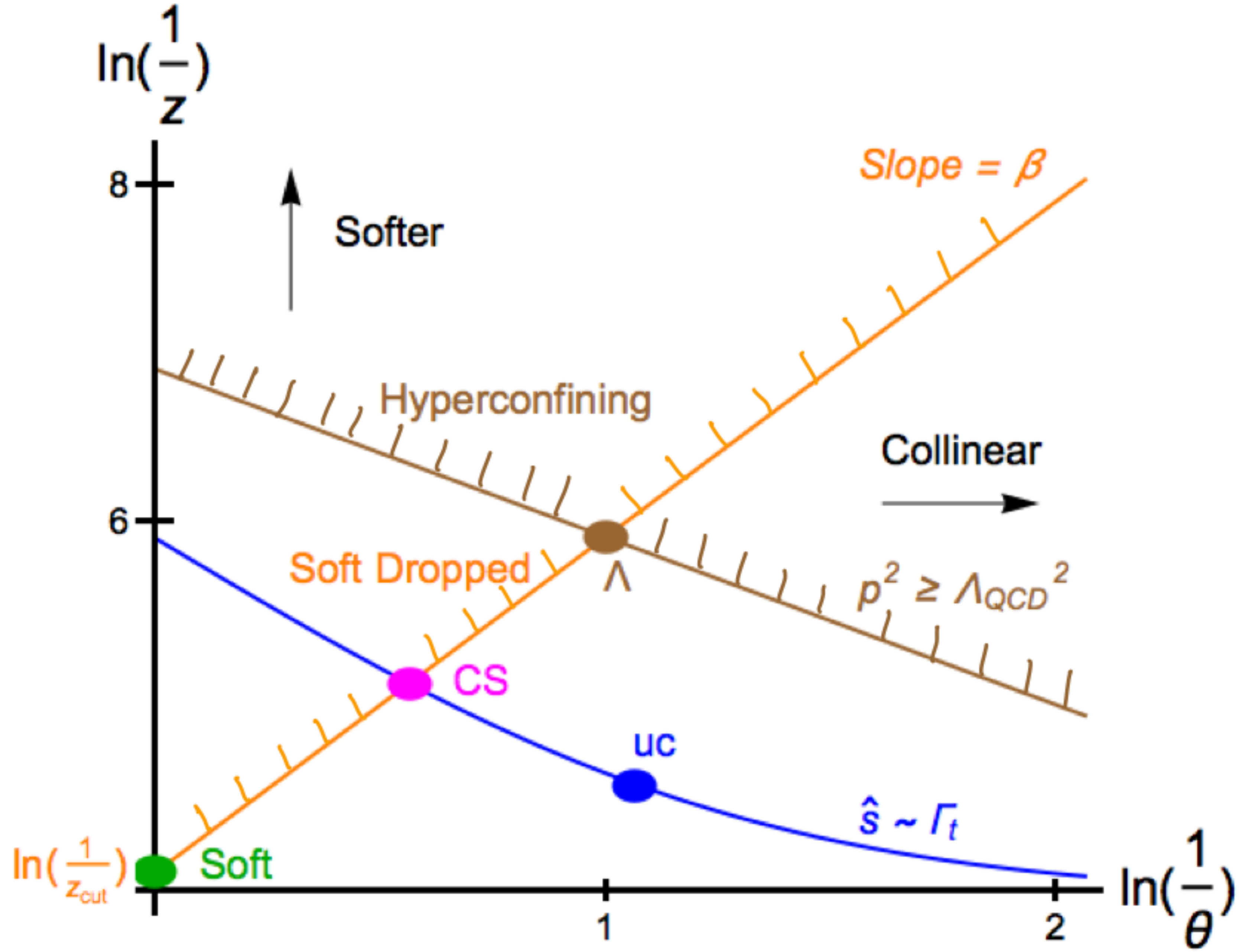


p⁻
p⁺
uc
Soft
CS
Λ
p² = m²
p² ~ ŝ²
p² ~ Λ_QCD²
p² ~ ŝ² ε^(2/(2+β))
ŝ Q/m
Q z_cut
ŝ (Q/m) ε^(2/(2+β))
Λ_QCD (Λ_QCD / (Q z_cut))^(1/(1+β))
ŝ m/Q
Λ_QCD ((Q z_cut) / Λ_QCD)^(1/(1+β))
ŝ Q/m
Q z_cut

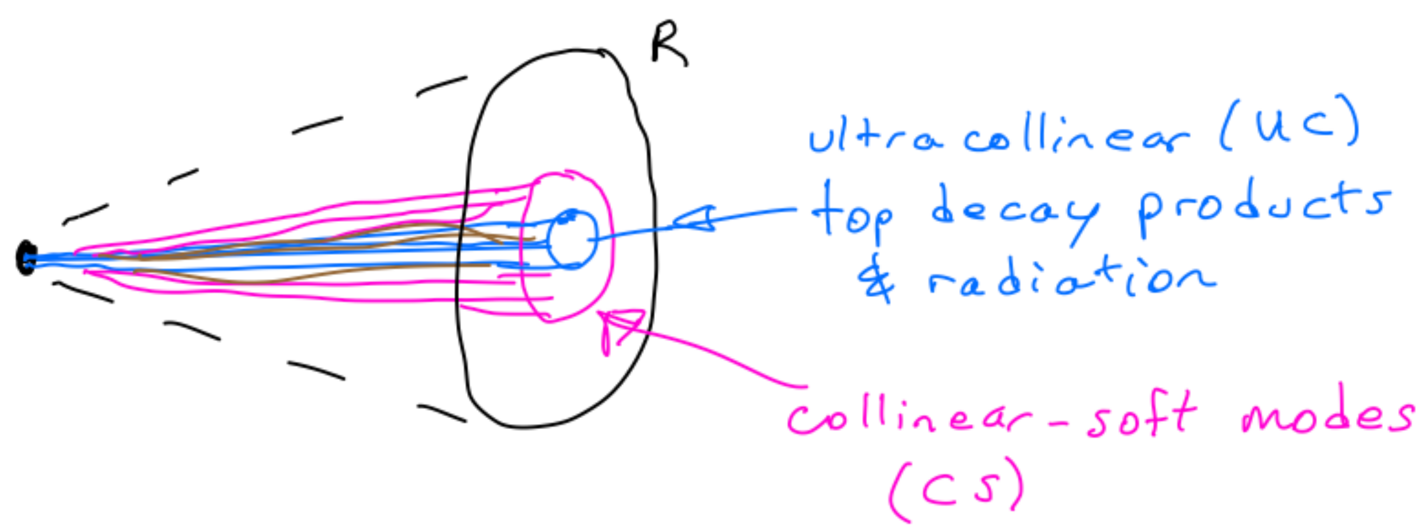


R
ultra collinear (uc)
top decay products
& radiation
collinear-soft modes
(cs)

Modes:



ln(1/z)
8
6
Softer
Slope = β
Hyperconfining
Collinear
Soft Dropped
Λ
p² ≥ Λ_QCD²
CS
uc
ŝ ~ Γ_t
ln(1/z_cut)
Soft
1
2
ln(1/θ)



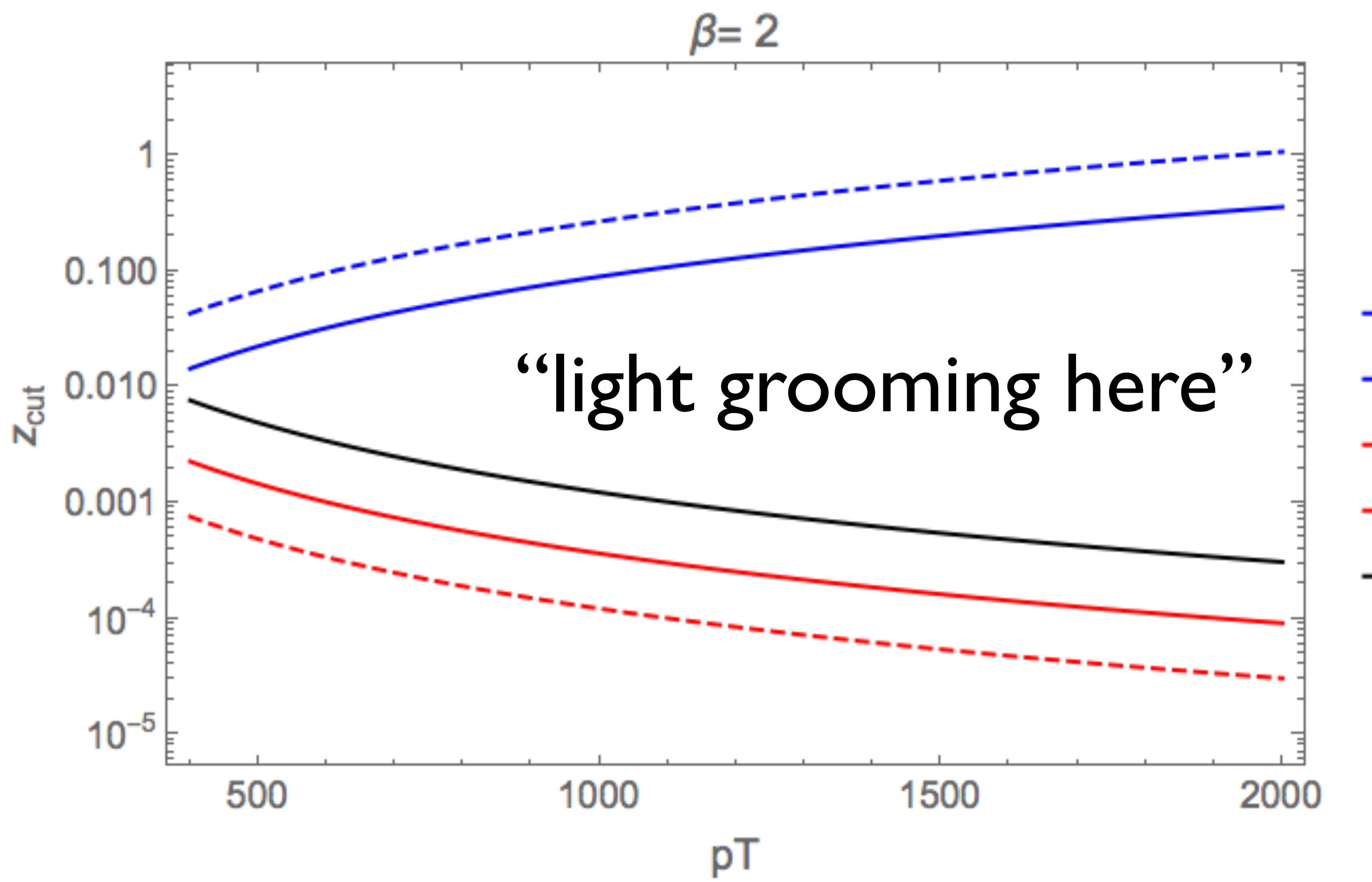
R
ultra collinear (uc)
top decay products
& radiation
collinear-soft modes
(cs)

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

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

Ensure soft drop does not touch J_B

Ensure soft drop removes global soft radiation from measurement



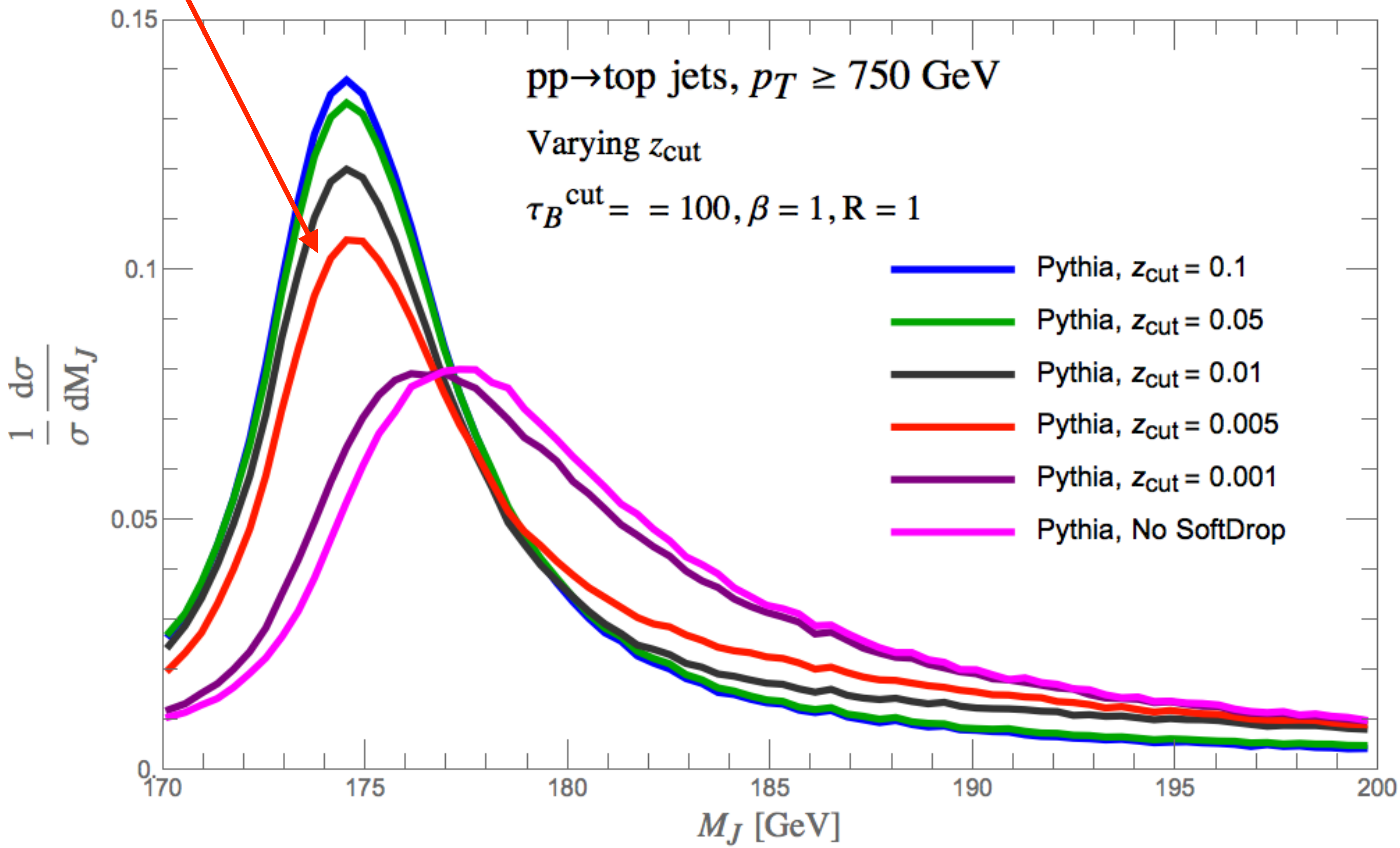
Factorization with Soft Drop on one jet:

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

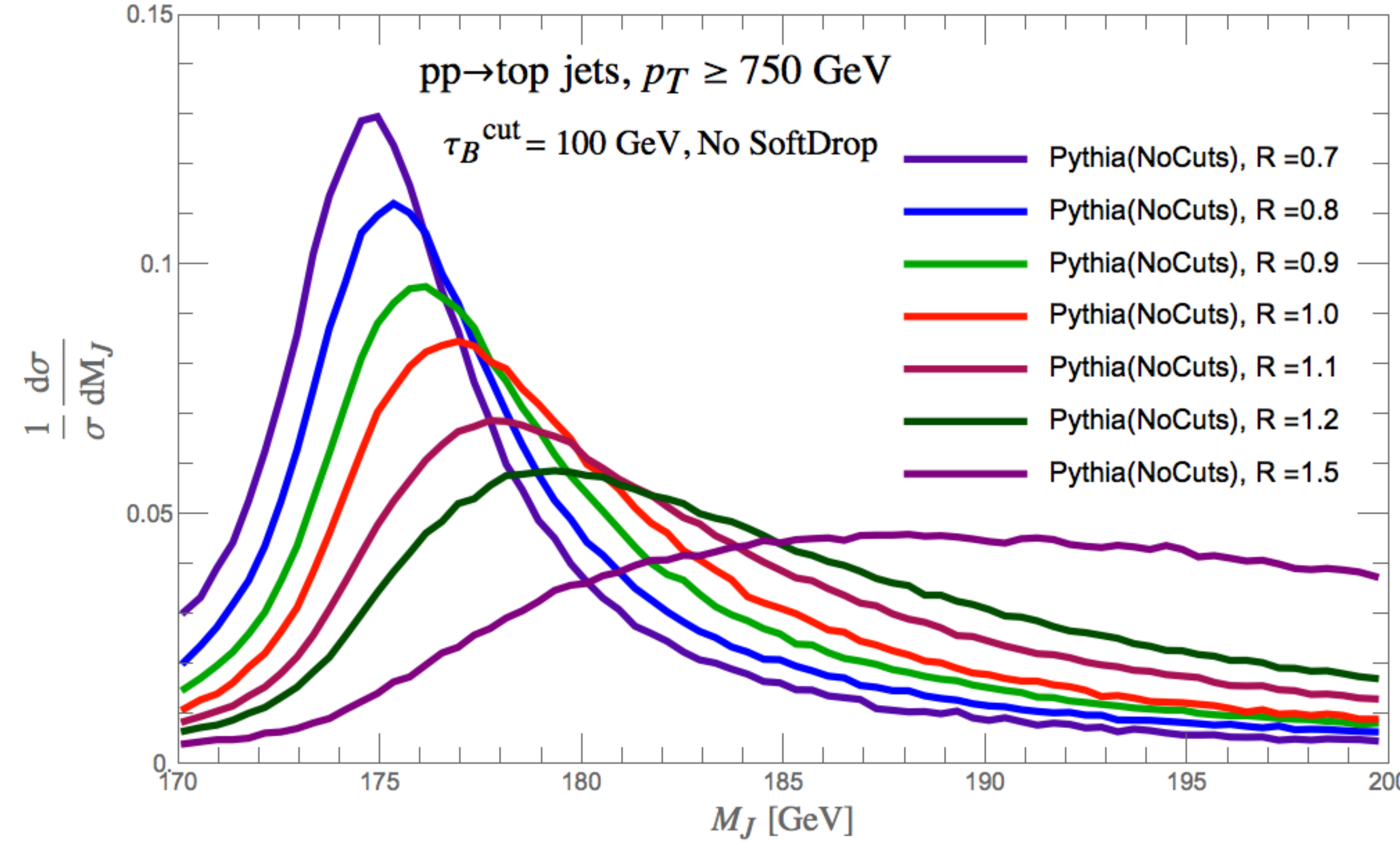
Pythia Tests

z_{cut} dependence

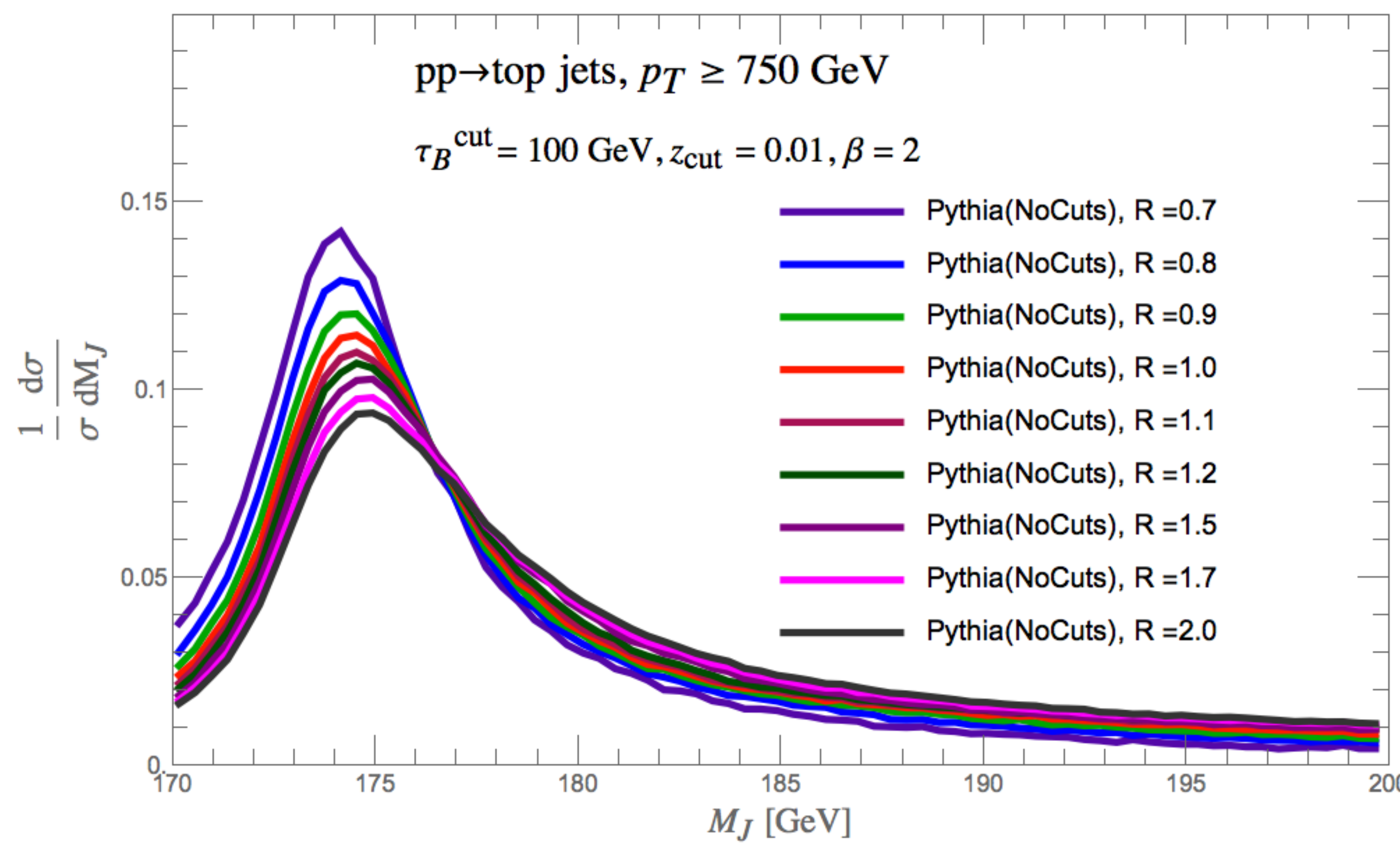
Transition for "light grooming" as predicted by factorization!



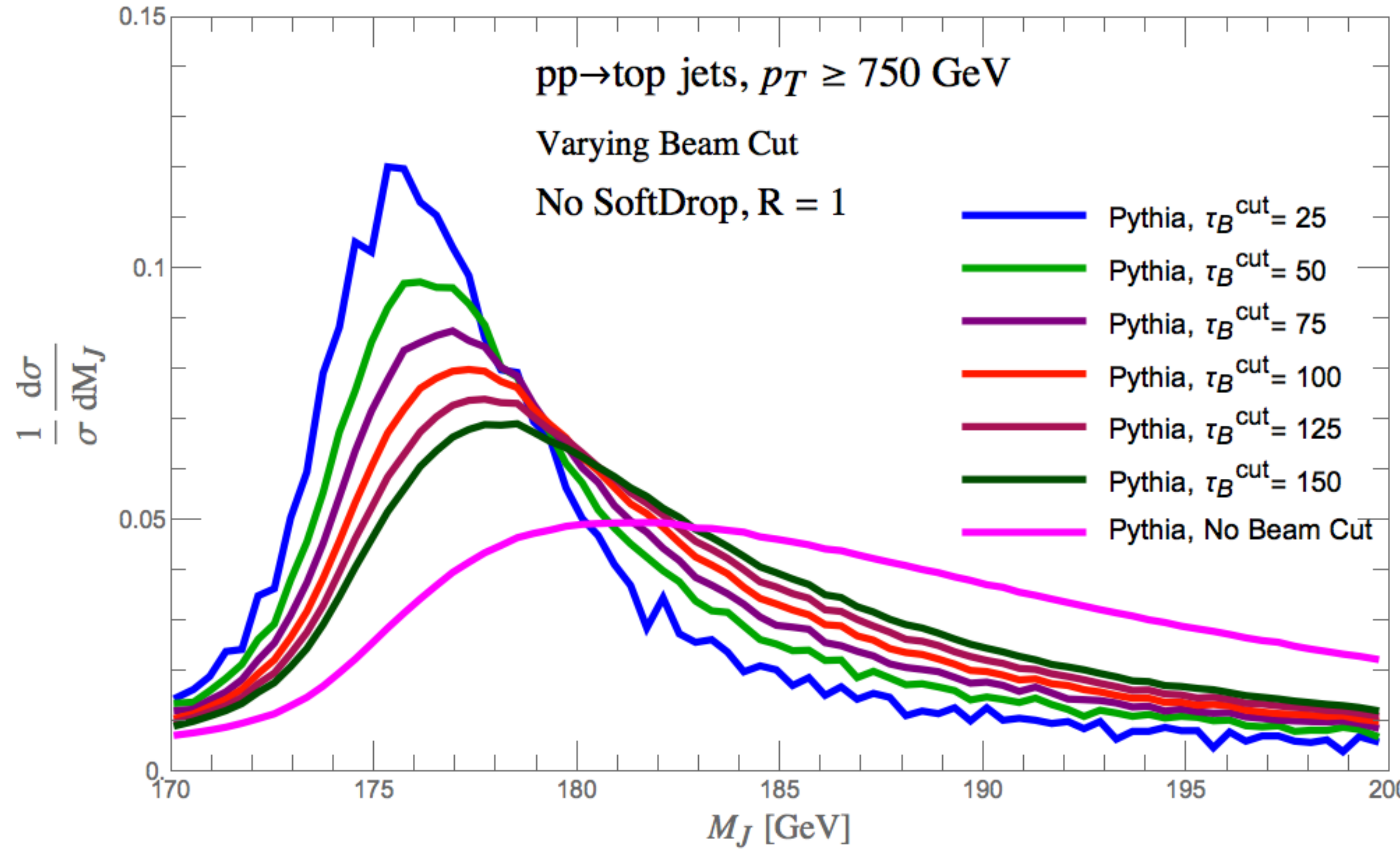
Jet Radius Dependence

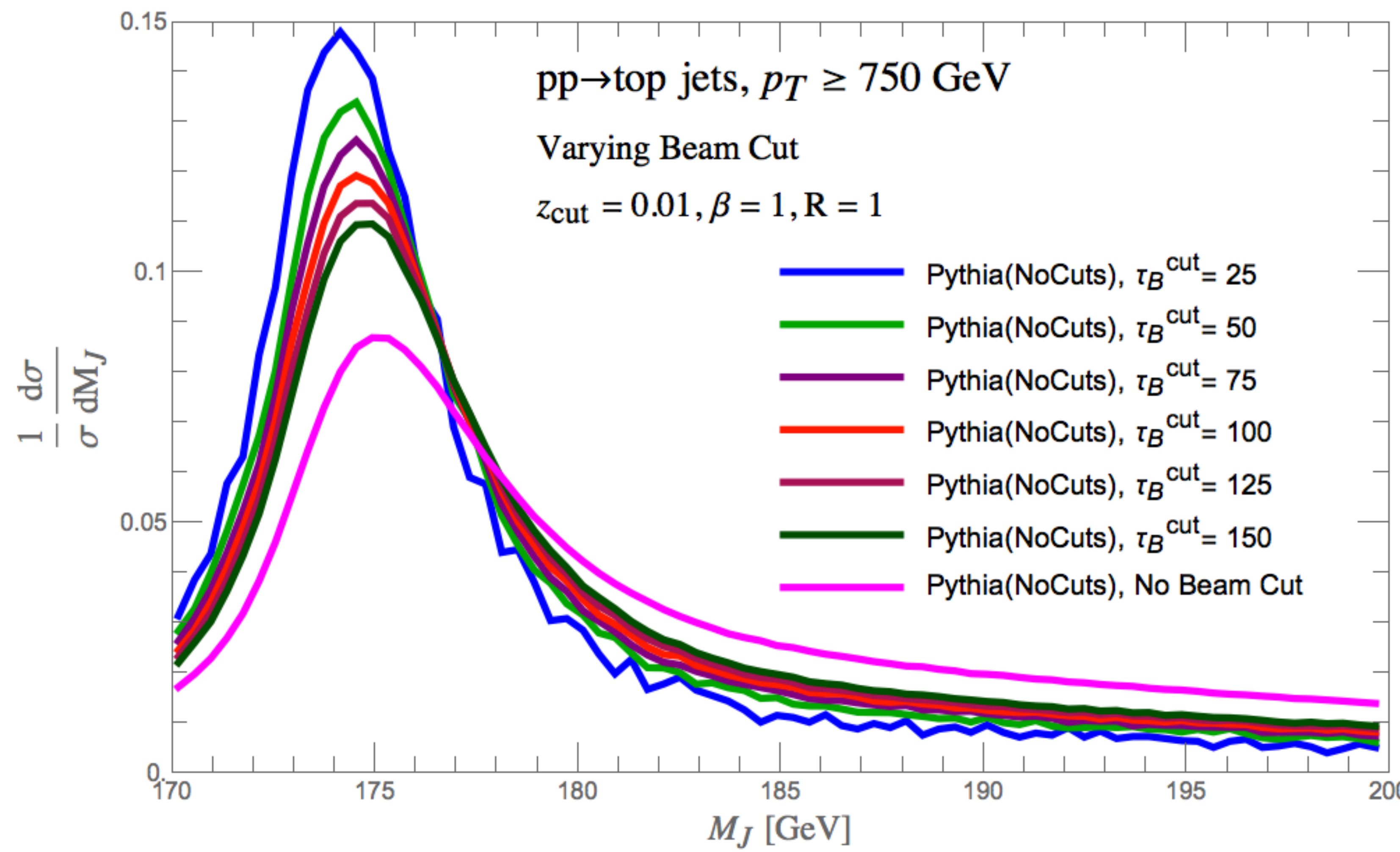


residual dependence
~ 200 MeV (this pT)

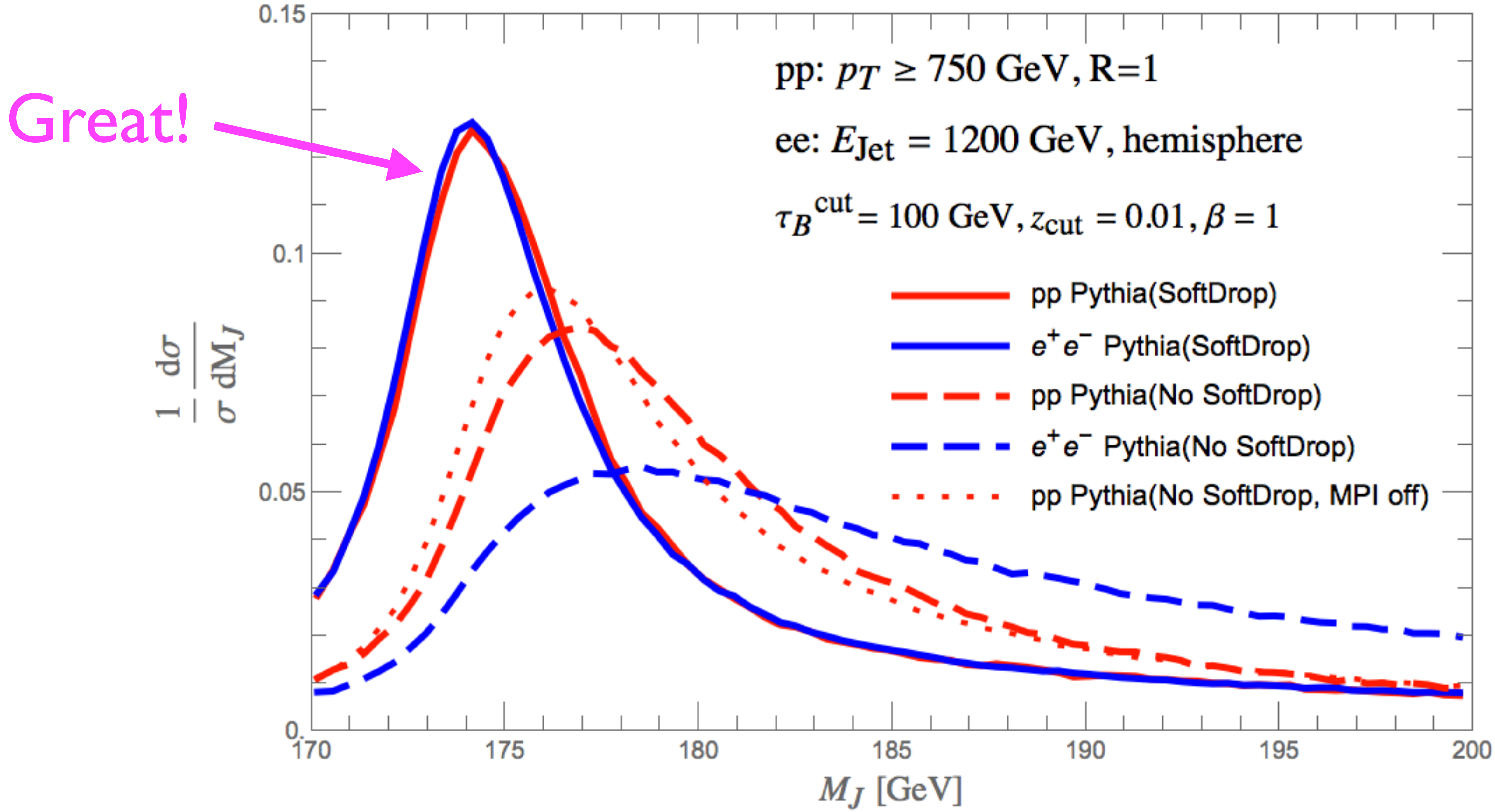


Beam Cut Dependence



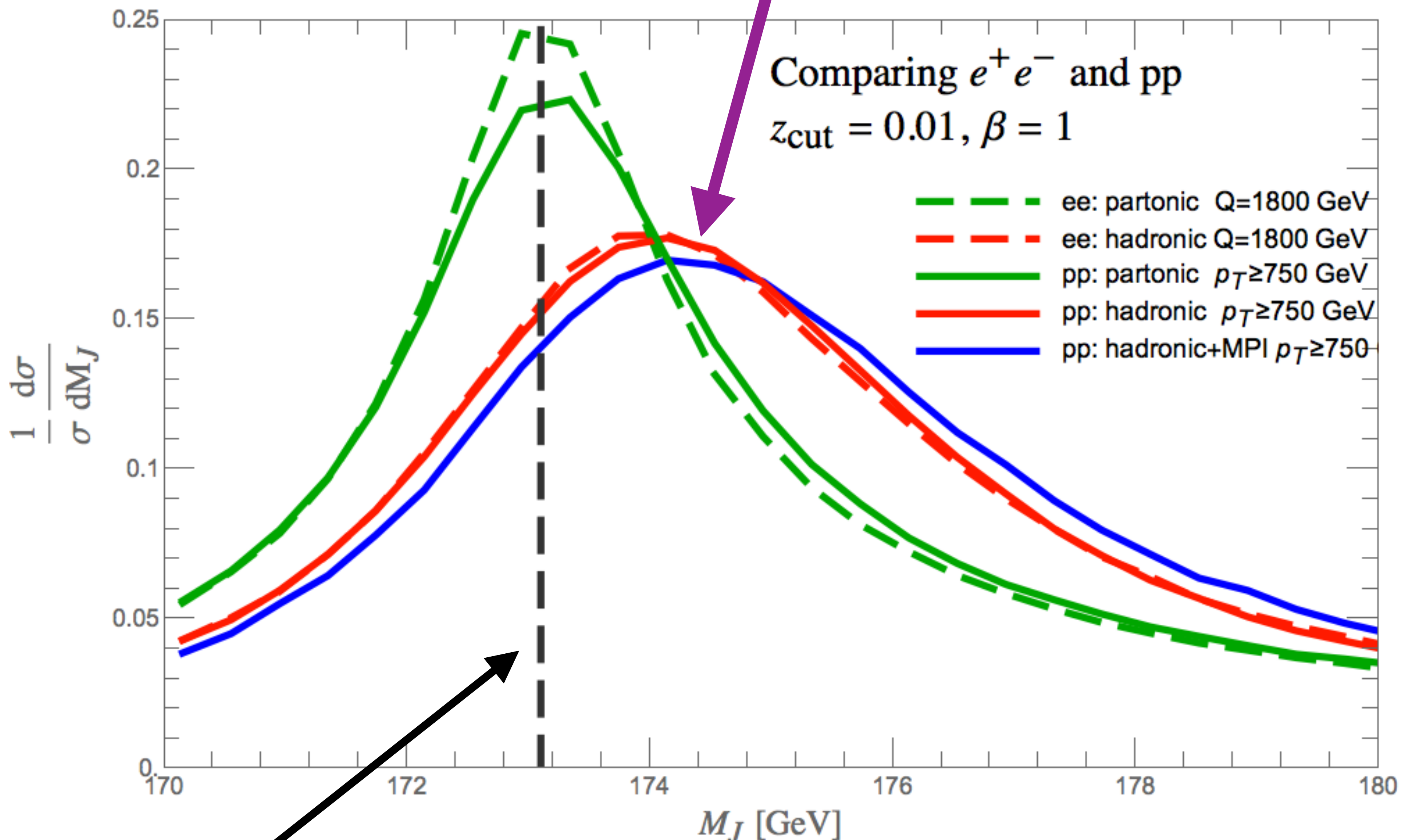


Pythia (Hadronic e+e-) versus (Hadronic+MPI pp)



e+e- comparison with pp: MPI and Hadronization effects (All curves with SoftDrop)

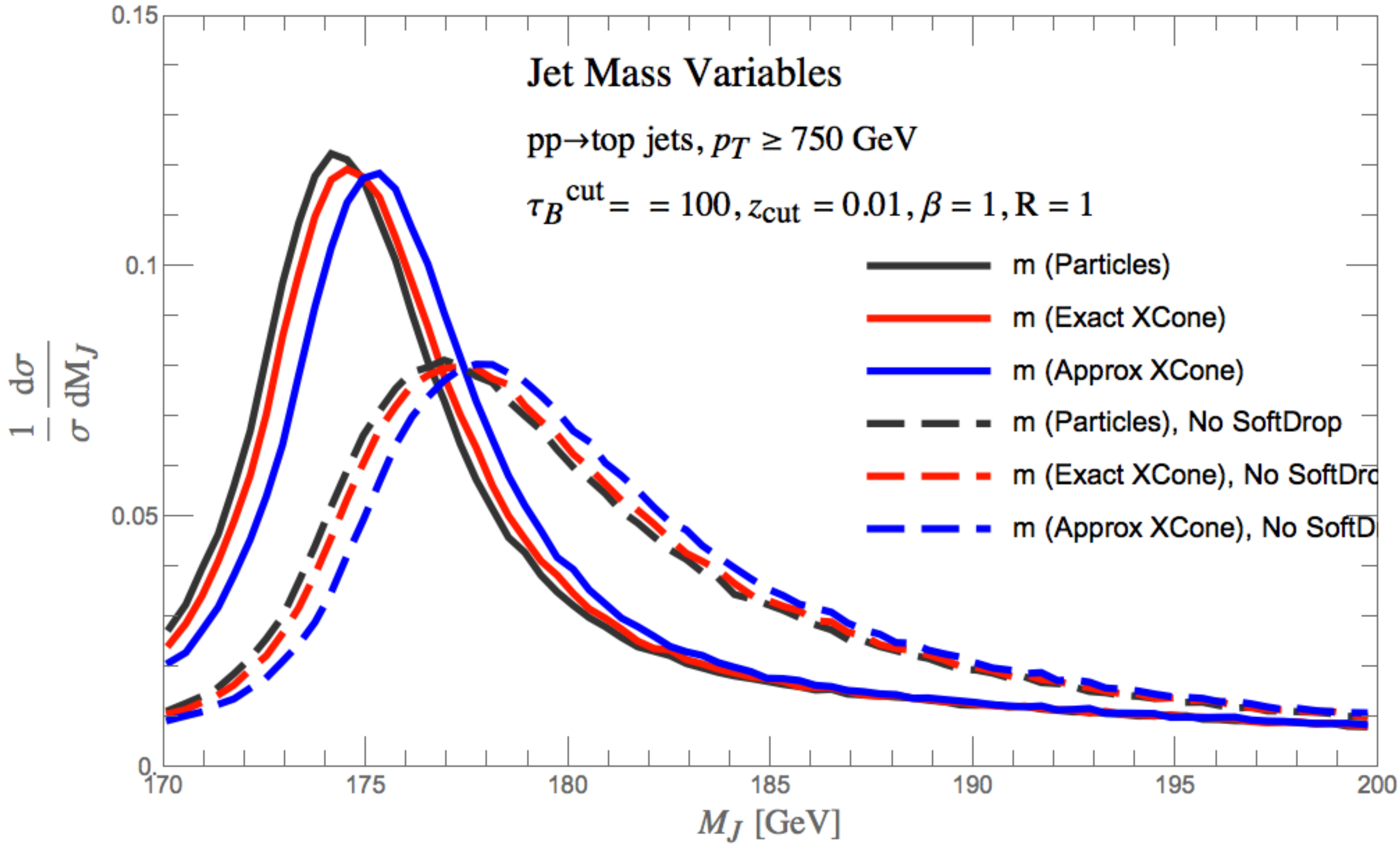
Only 0.19 GeV shift from MPI



input mass in Pythia =173.1 GeV

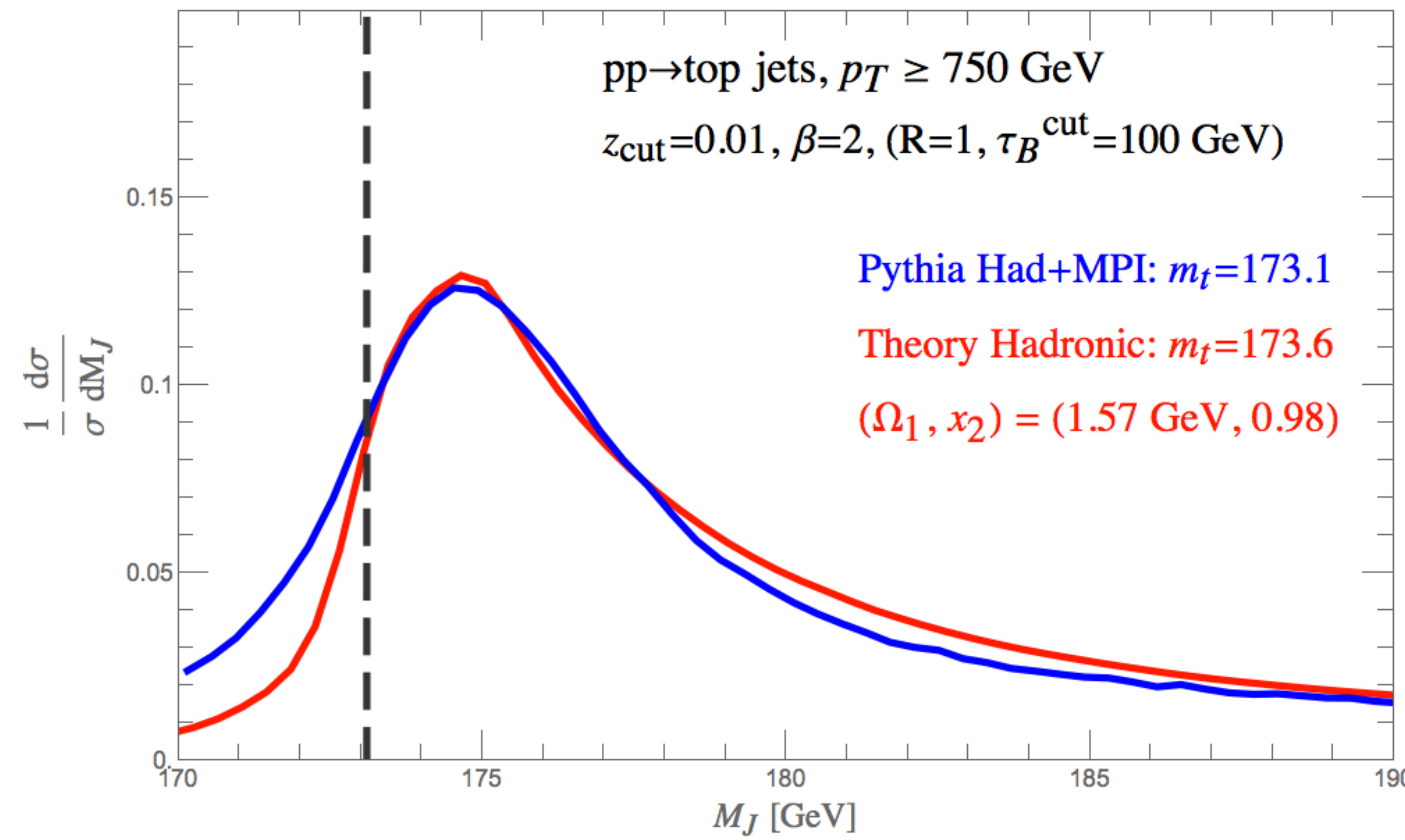
Pythia vs. Factorization

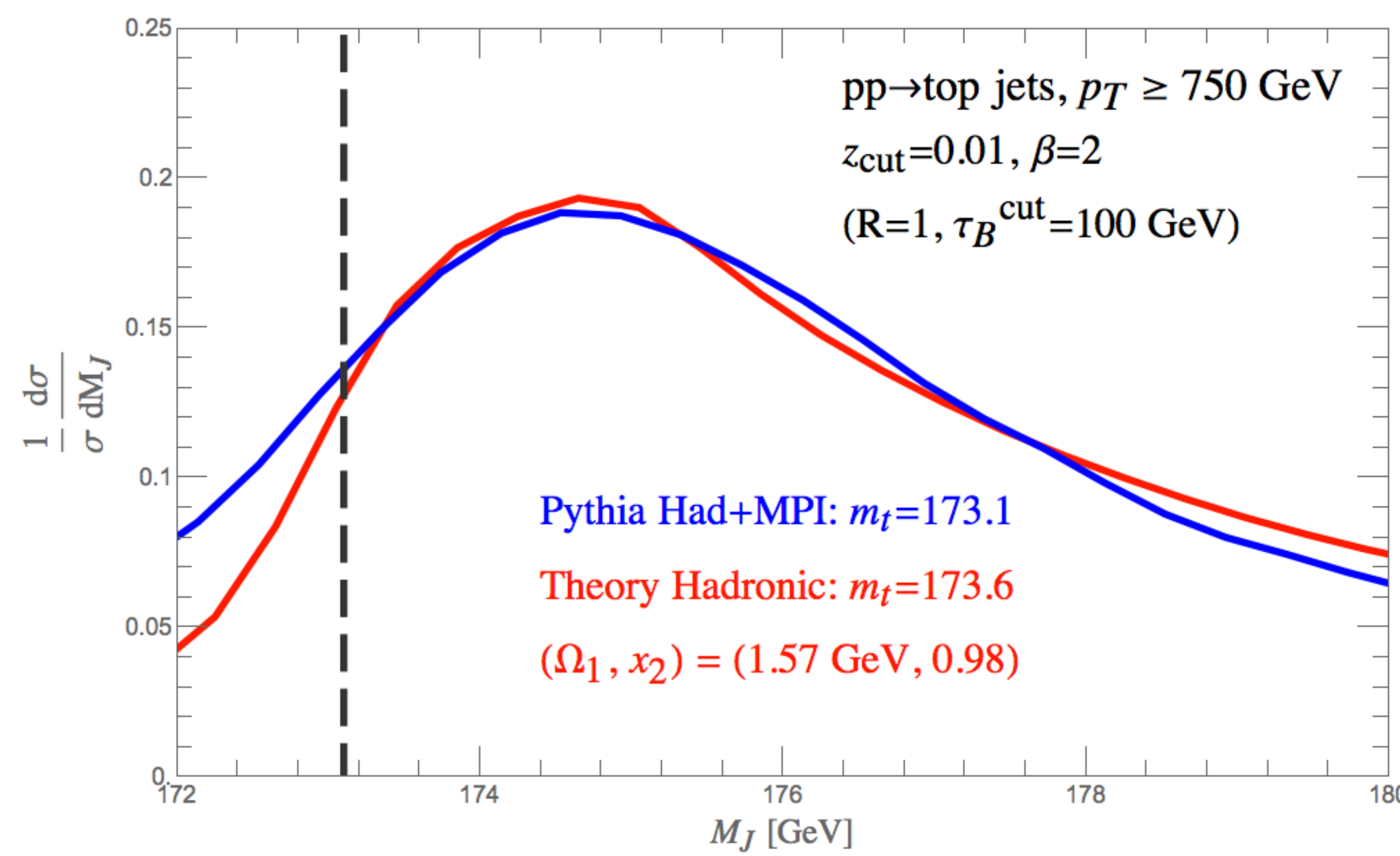
Which M_J Variable?



Pythia vs. Factorization with SoftDrop

includes:
Hadronization+MPI

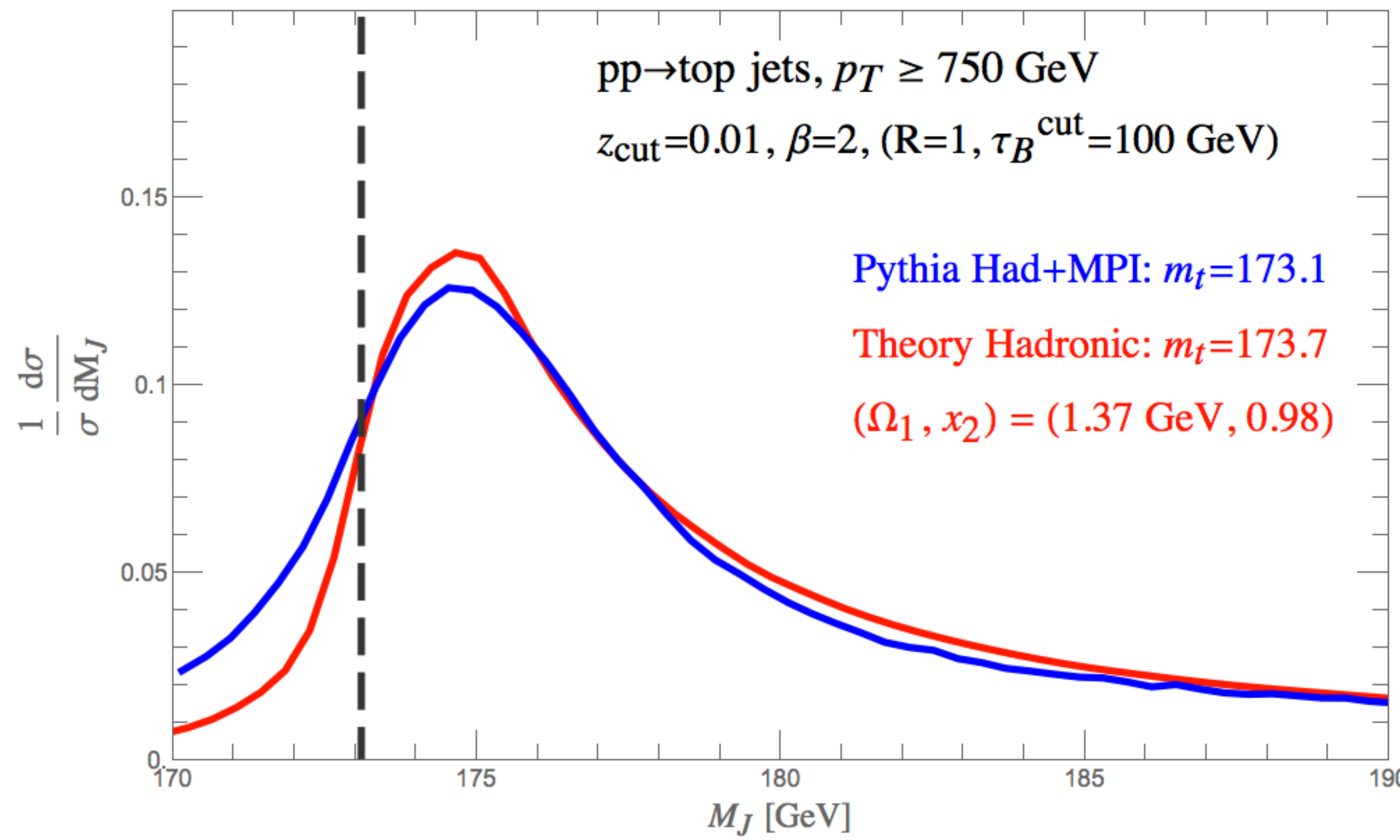


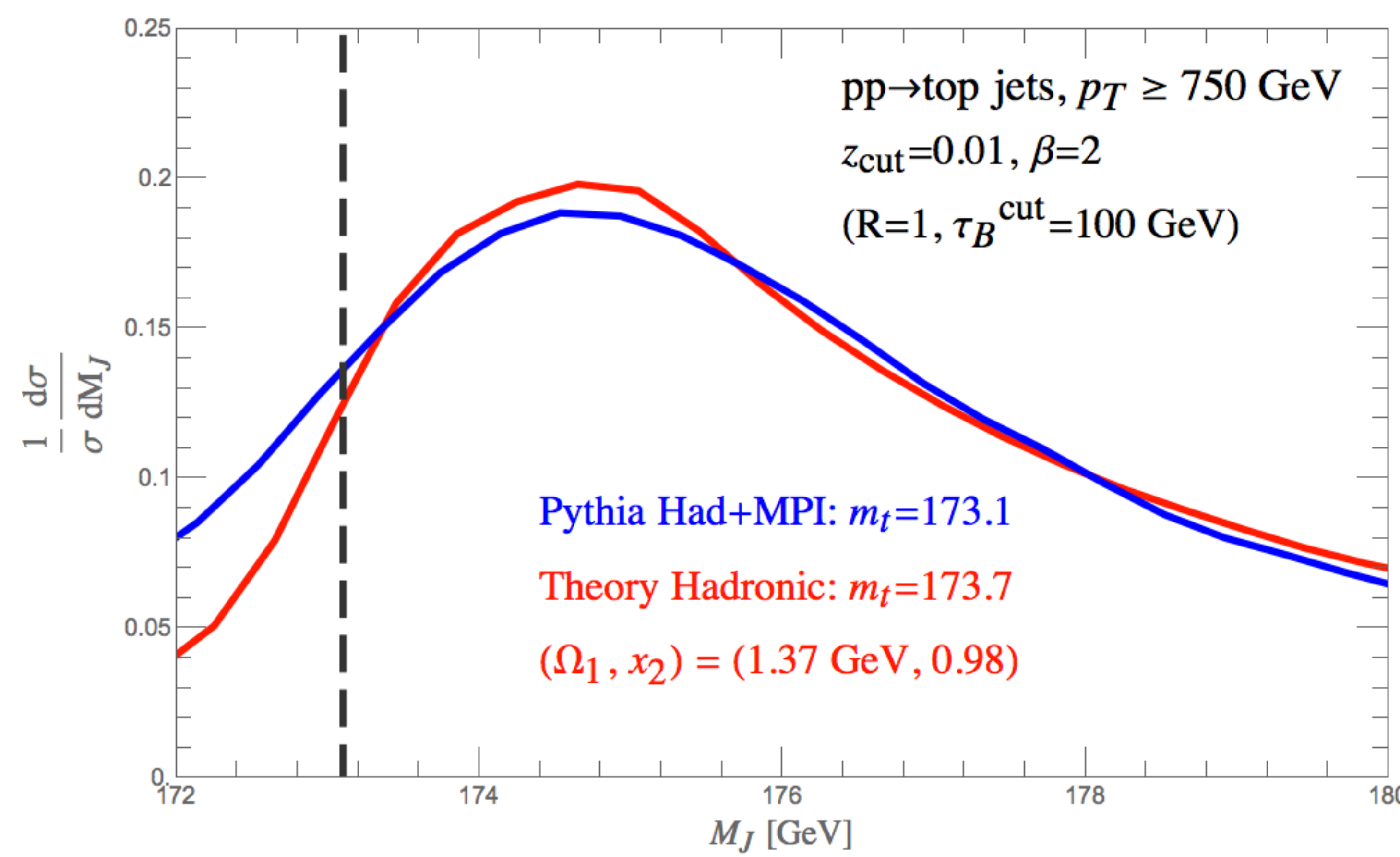


input mass in
Pythia =173.1 GeV

Pythia vs. Factorization with SoftDrop

includes:
Hadronization+MPI

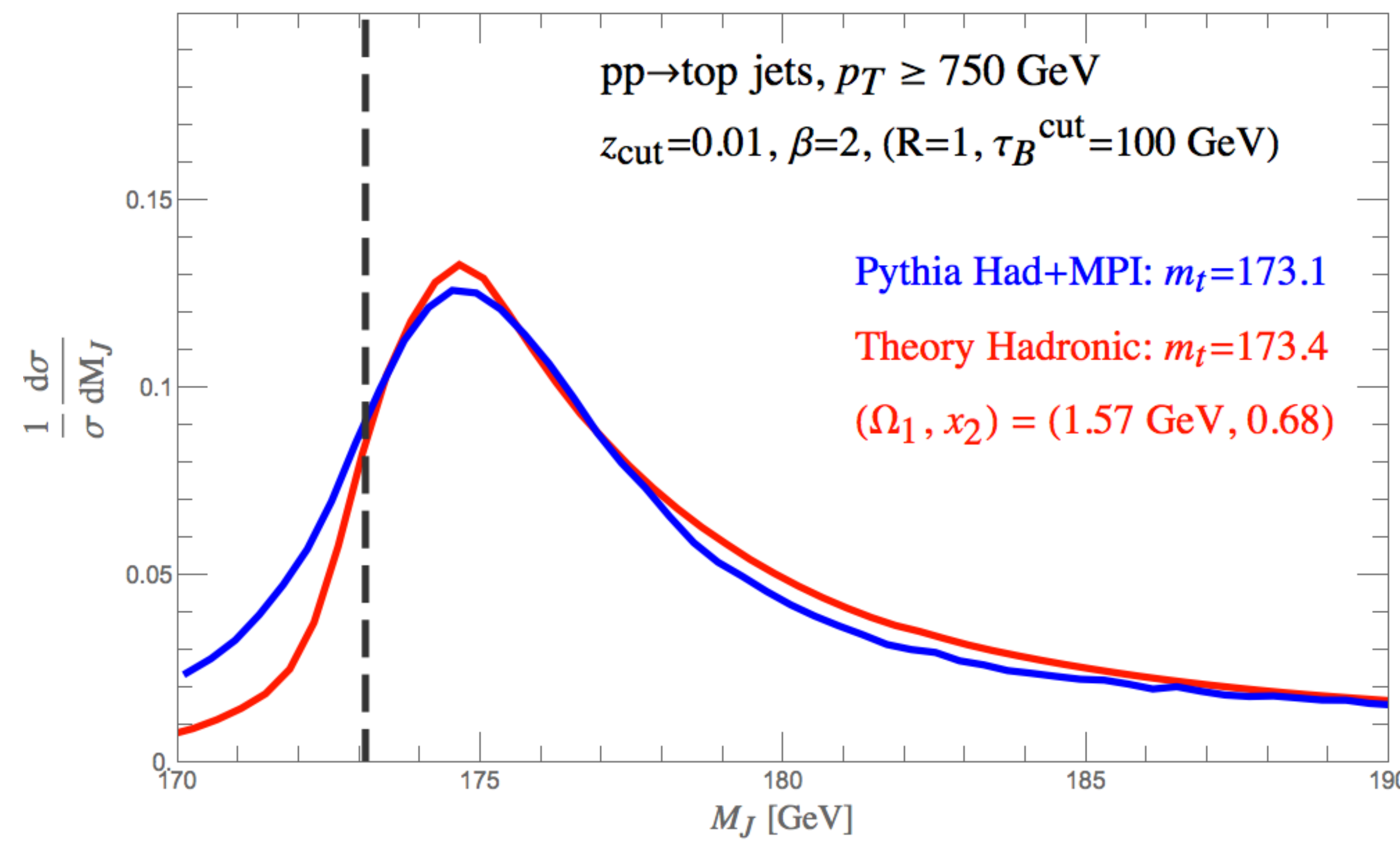


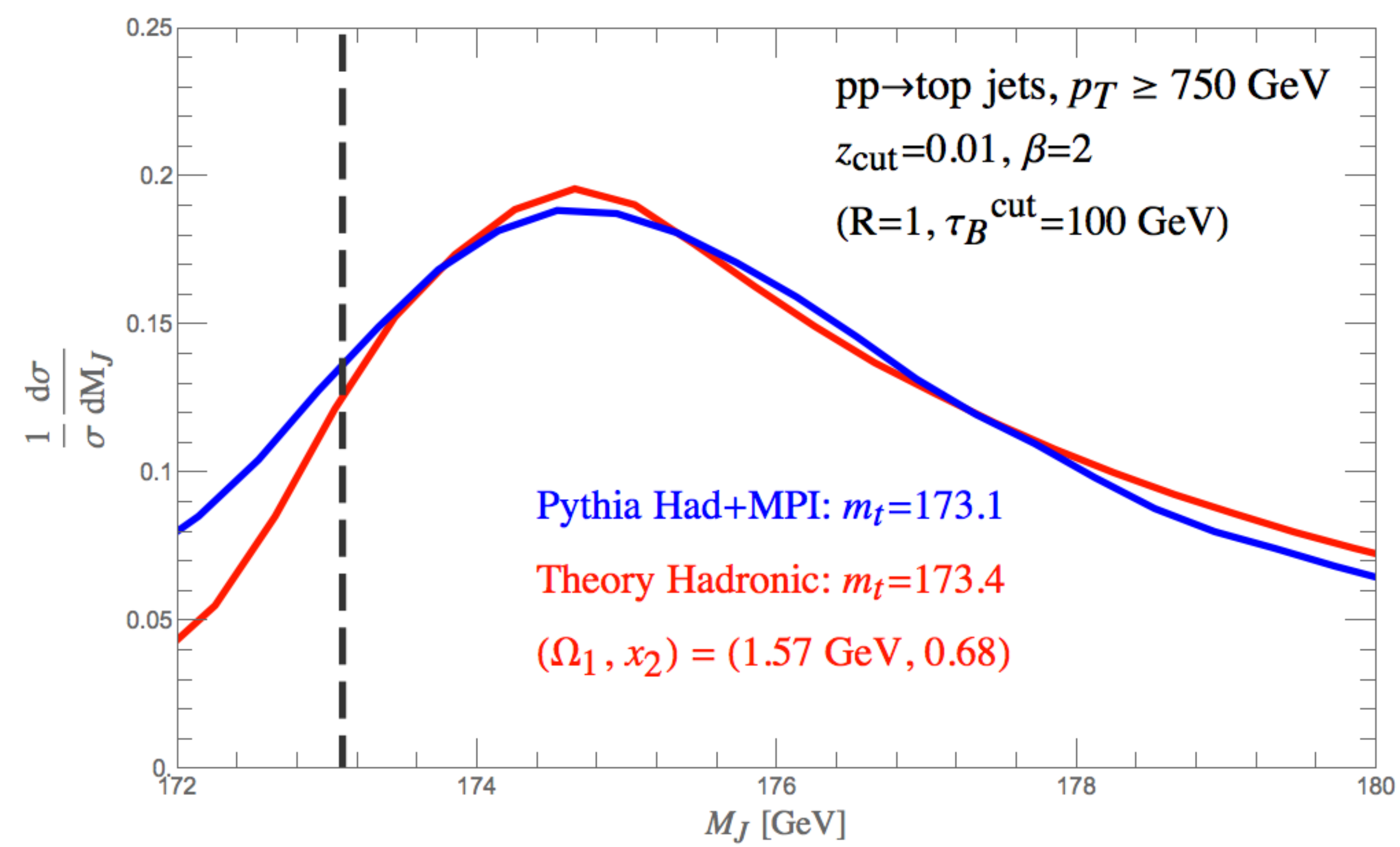


input mass in
Pythia =173.1 GeV

Pythia vs. Factorization with SoftDrop

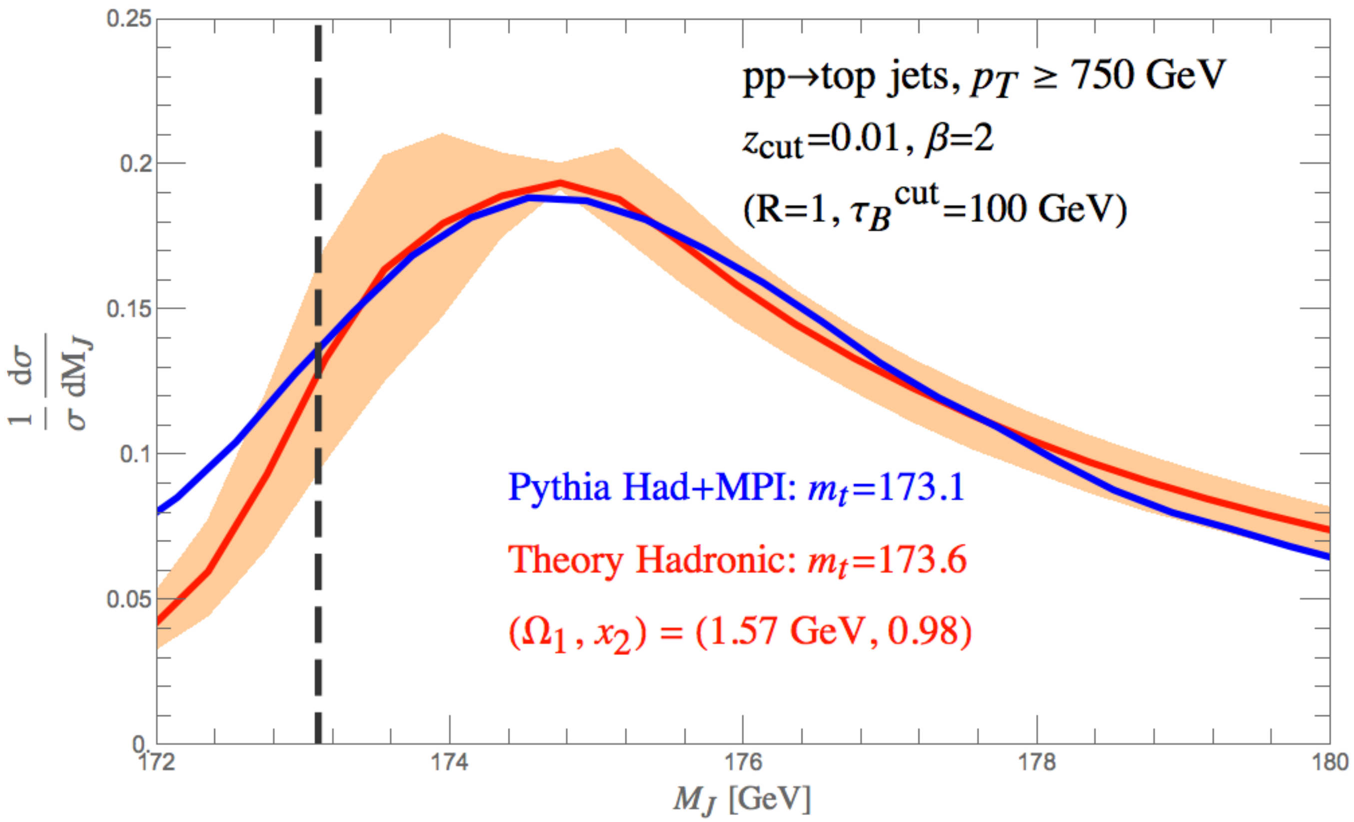
includes:
Hadronization+MPI

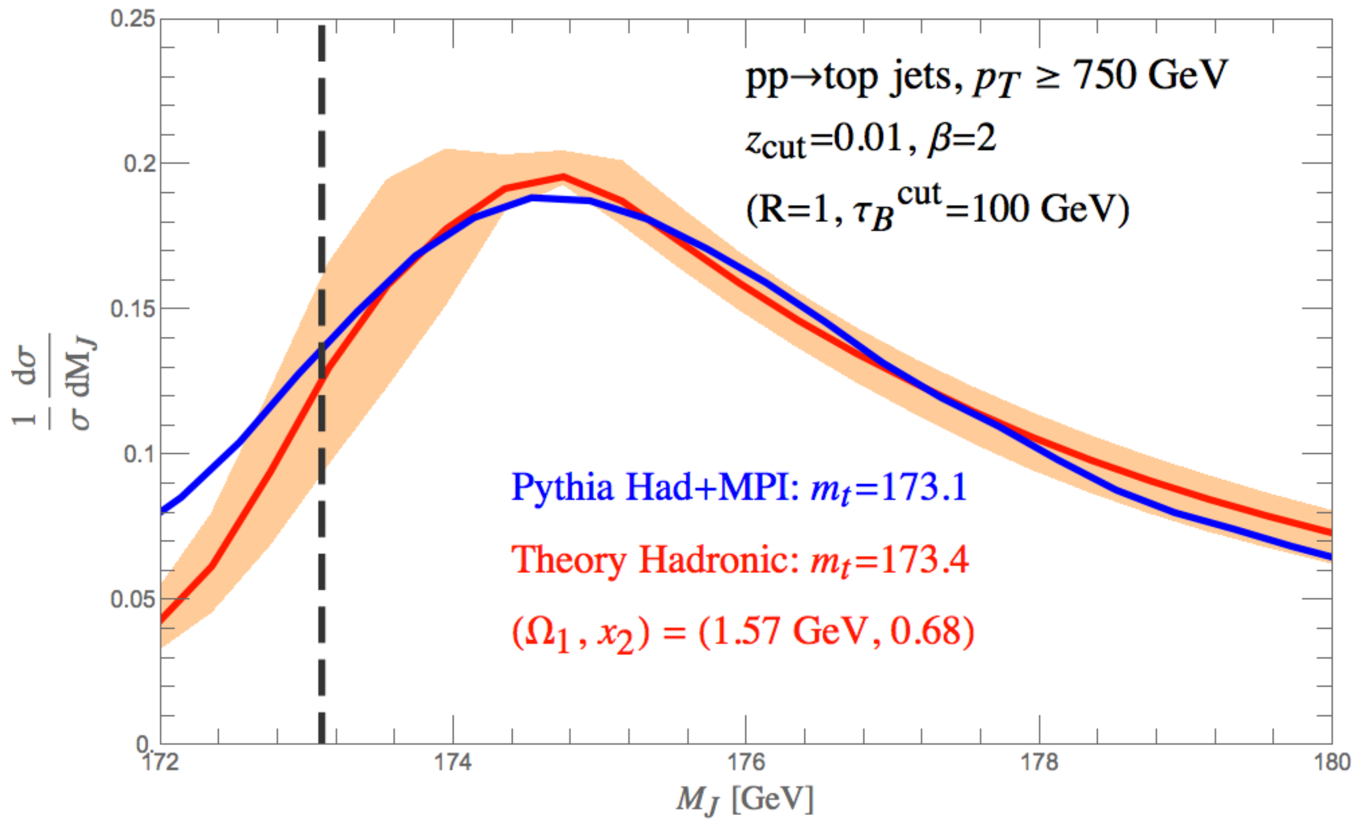


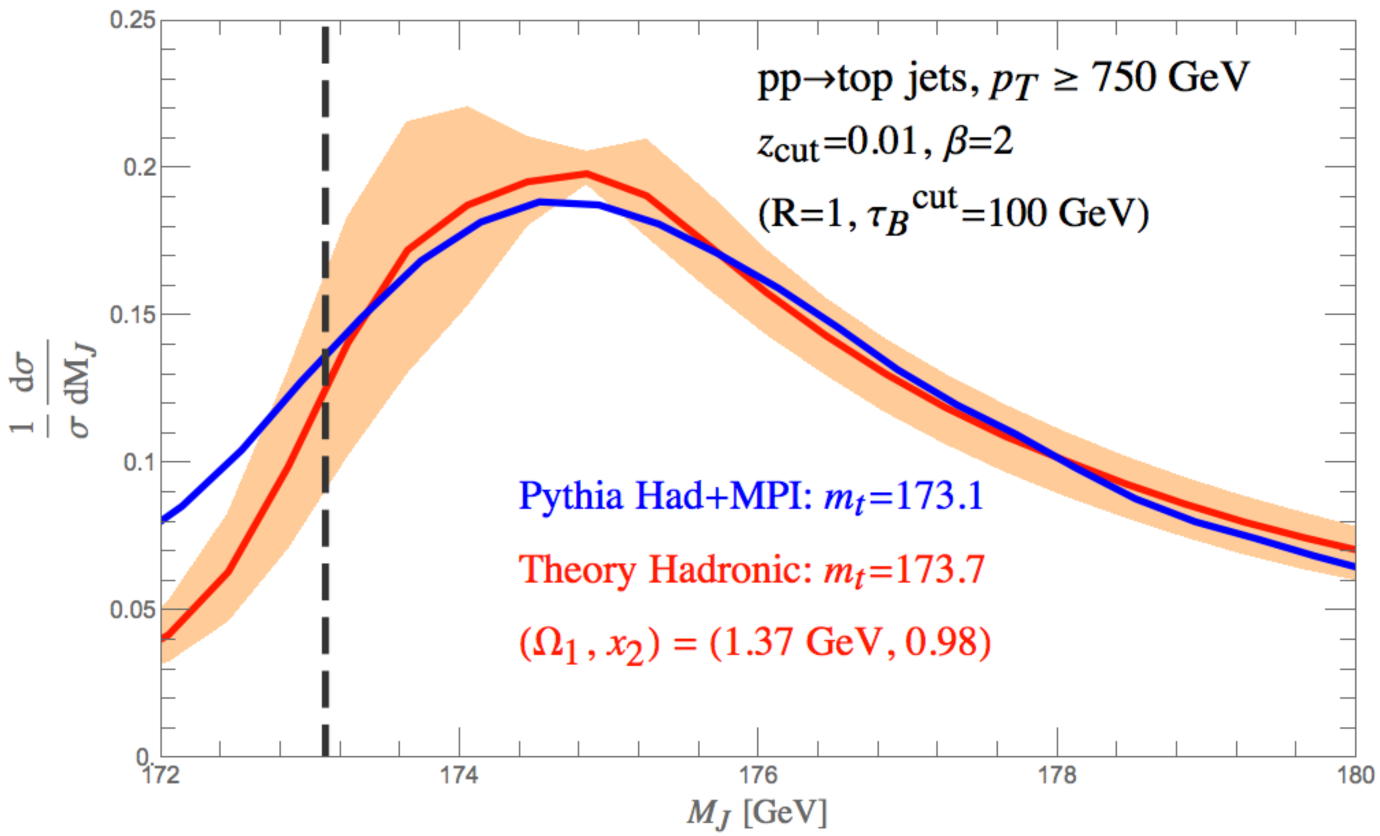


input mass in
Pythia =173.1 GeV

Adding NLL uncertainty bands







Looks very promising.

But do note that this was high pT.

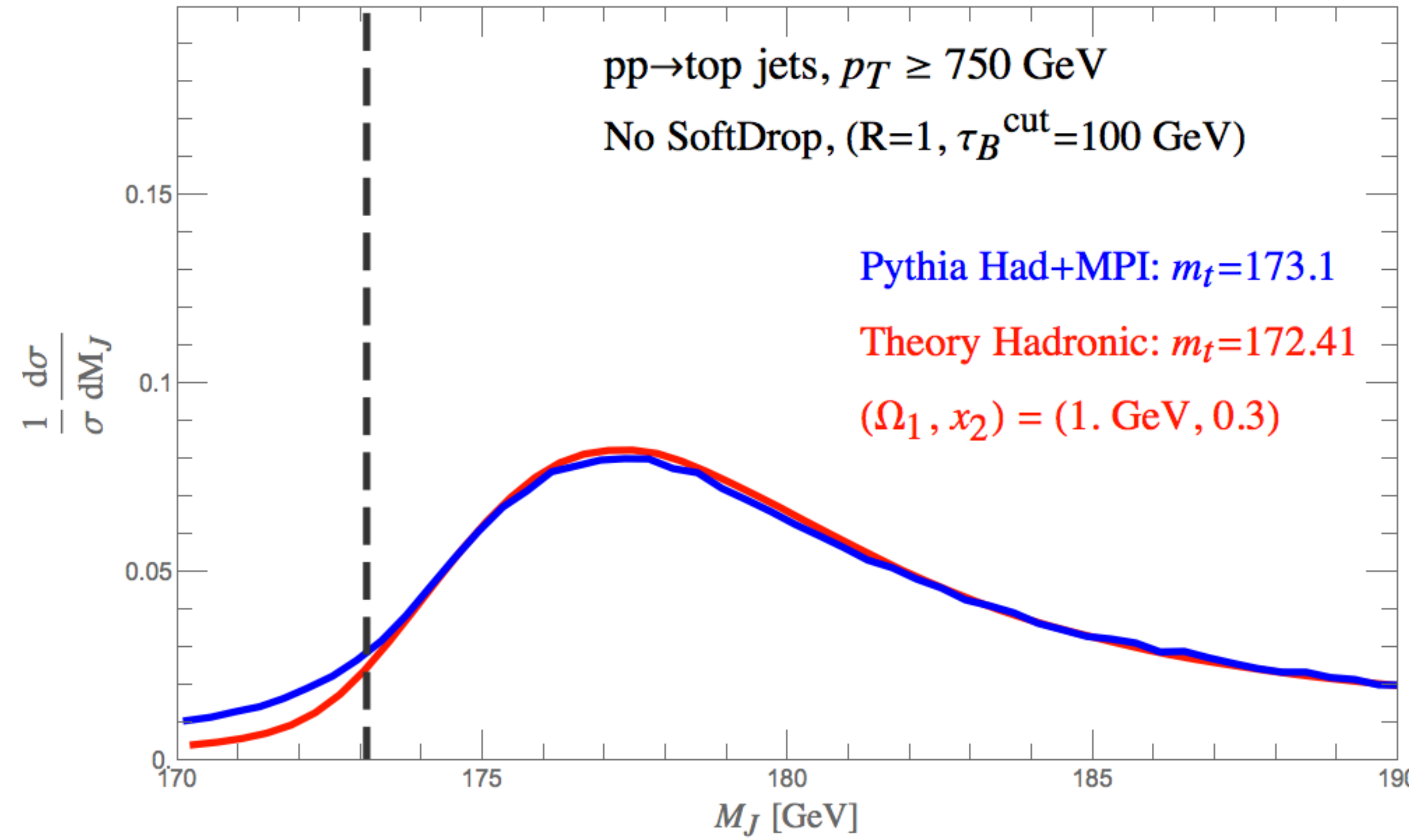
Pythia: curves do not change for lower pT with R=1

Not yet clear whether lower pT values can be predicted with SoftDrop.

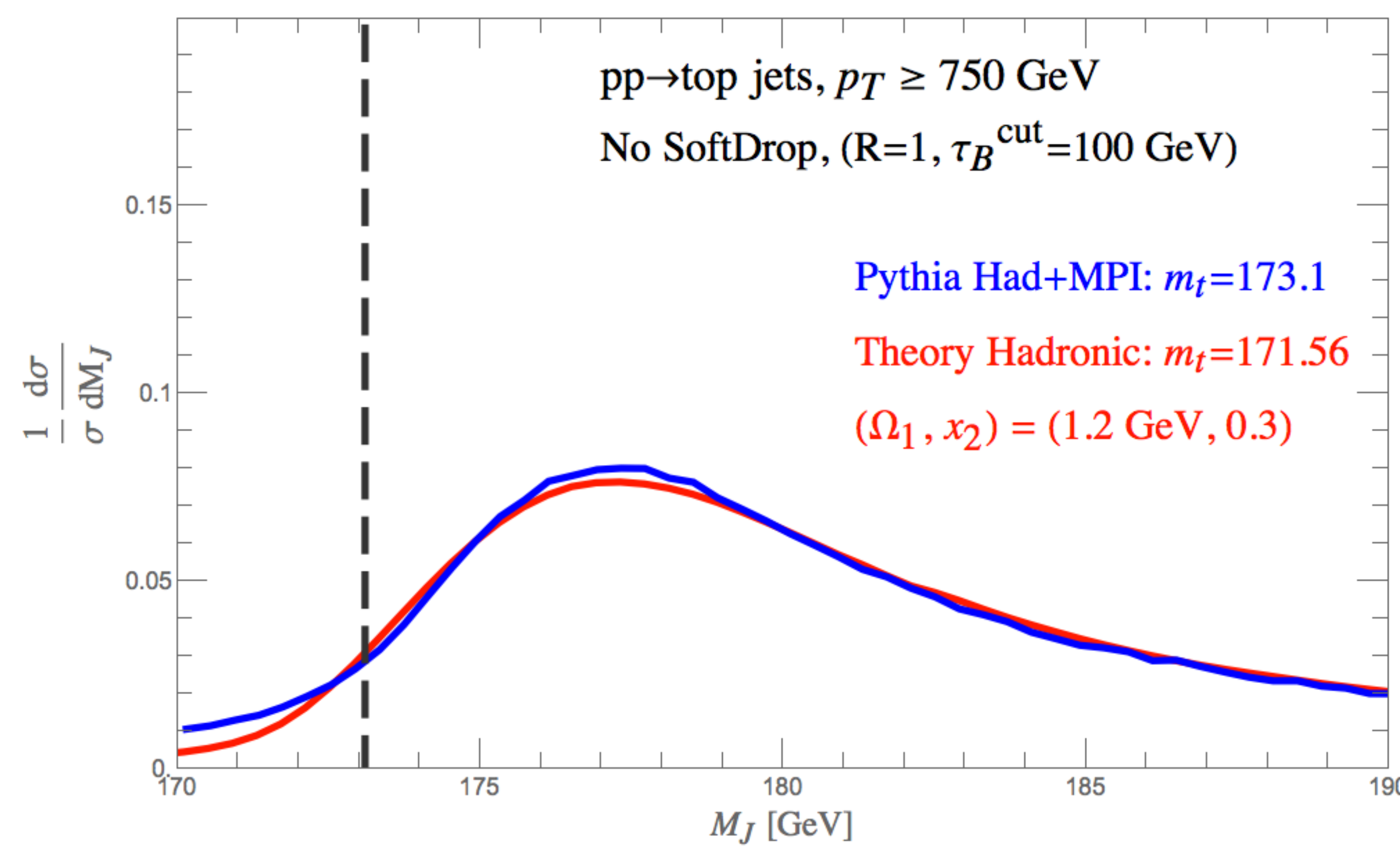
For Comparison:

no SoftDrop

Pythia vs. Factorization



two reasonable fits with quite different masses



Summary

- Largest uncertainty in the top mass is "what mass is it?"
- Factorization provides answers with short distance m_t parameters
- Can Calibrate MC to determine relation: $m_t^{\rm MC} = m_t + \ldots$
- Discussed promising new method in pp to measure Top Quark Mass

Future Directions

- More pT bins, NNLL, fits , combine SoftDrop & no SoftDrop, …
- pp Monte Carlo calibration