ADITYA PATHAK (UNIVERSITY OF VIENNA)
IN COLLABORATION WITH
ANDRÉ HOANG (UNIV. OF VIENNA),
SONNY MANTRY (UNIV. OF NORTH GEORGIA),
IAIN STEWART (MIT)

EXTRACTING SHORT DISTANCE TOP MASS WITH LIGHT GROOMING

LHC TOP WORKING GROUP, NOV. 2017

BASED ON 1708.02586

1. MOTIVATION, GOAL, CHALLENGES
2. MODERN TECHNIQUES IN PERTURBATIVE QCD
3. USING THE THEORY TOOLS, TESTING ROBUSTNESS

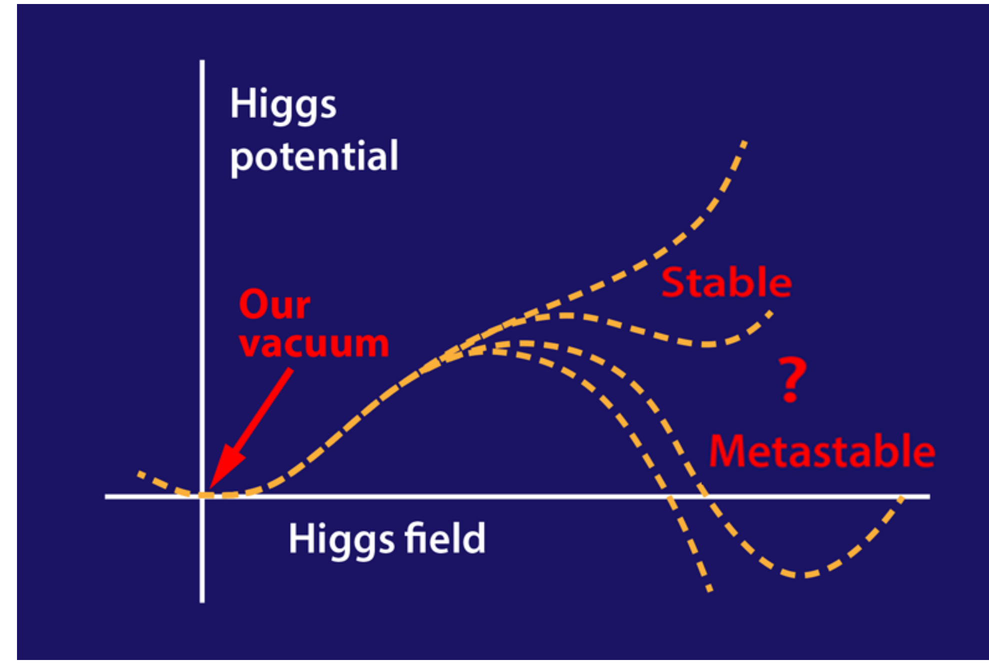
1. MOTIVATION, GOAL, CHALLENGES
2. MODERN TECHNIQUES IN PERTURBATIVE QCD
3. USING THE THEORY TOOLS, TESTING ROBUSTNESS

TOP MASS MEASUREMENT

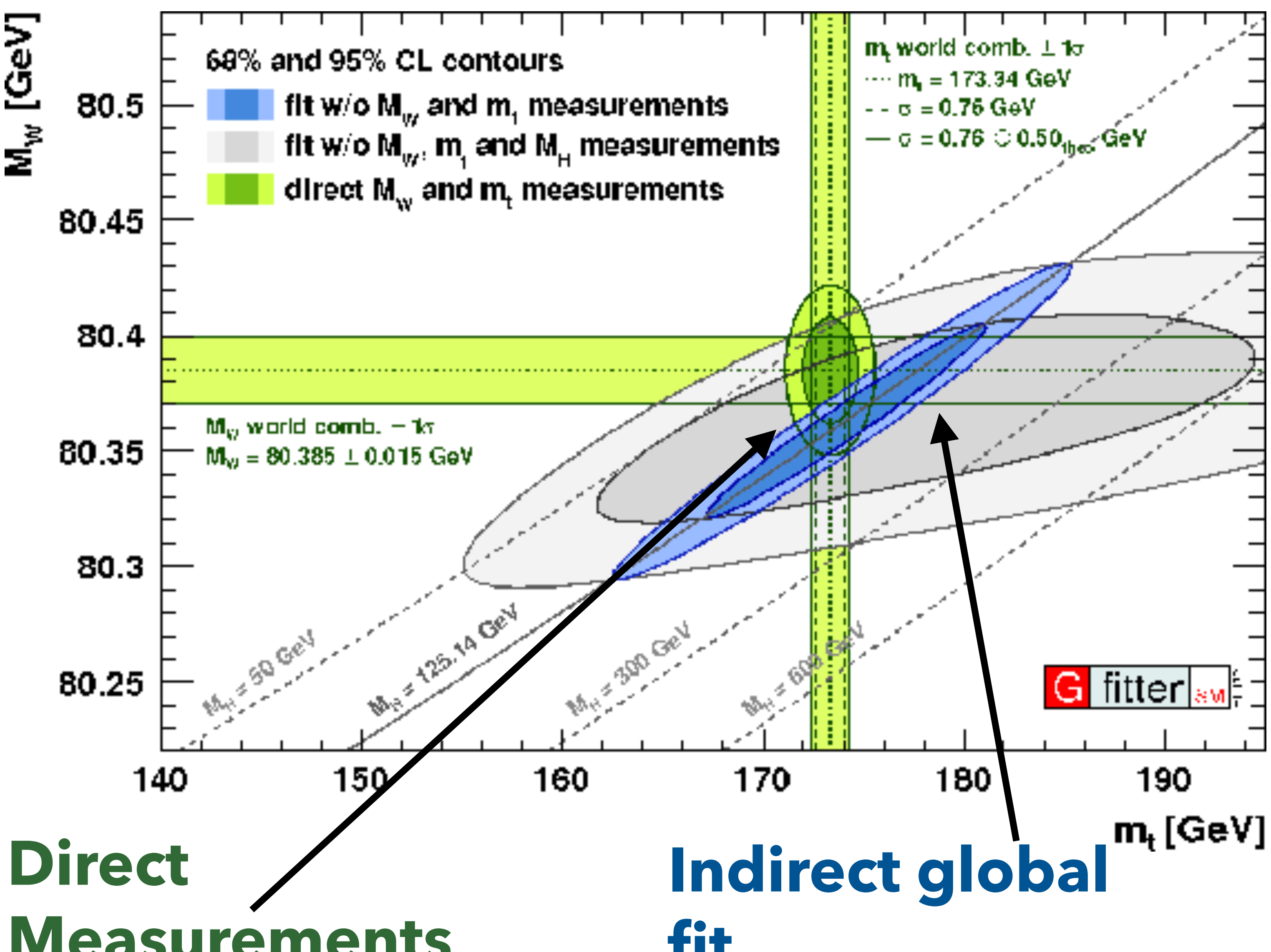
Why should we care about a precision m_t?

- **Stability of SM Vacuum**
- **Precision Electroweak Measurements**
- **BSM Searches**

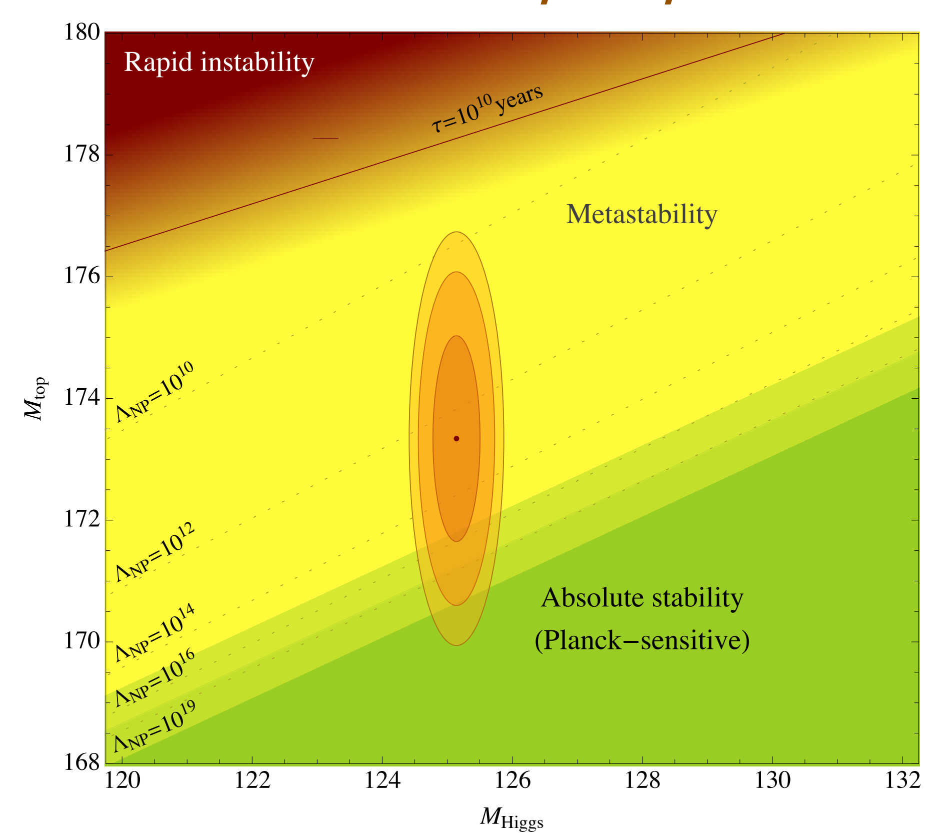
Butazzo, Degrassi, Giardino, Giudice, Sala



Gfitter Group, 2014



Andreassen, Frost, Schwartz



Significant contribution to uncertainty due to m_t

STATUS OF TOP MASS PRECISION

Most precise top mass measurements are based on kinematic extractions.

Kinematic Top Mass Extractions:

CMS @ 8 TeV (2016) : $m_t = 172.35 \pm 0.16$ (stat + JES) $\pm\ 0.48$ (sys) GeV

Phys. Rev. D 93 (2016)

ATLAS @ 8 TeV (2017) : $m_t = 172.08 \pm 0.41$ (stat) $\pm\ 0.81$ (sys) GeV

ATLAS-CONF-2017-071

Top Mass from total cross section:

CMS (2016) : $m_t = 173.8 \pm 1.8$ GeV

JHEP08 (2016) 029

ATLAS (2017) : $m_t = 173.2 \pm 1.6$ GeV

ATLAS-CONF-2017-044

STATUS OF TOP MASS PRECISION

Most precise top mass measurements are based on kinematic extractions.

Kinematic Top Mass Extractions:

CMS @ 8 TeV (2016) : $m_t = 172.35 \pm 0.16$ (stat + JES) $\pm$ 0.48 (sys) GeV

Phys. Rev. D 93 (2016)

ATLAS @ 8 TeV (2017) : $m_t = 172.08 \pm 0.41$ (stat) $\pm$ 0.81 (sys) GeV

ATLAS-CONF-2017-071

Top Mass from total cross section:

CMS (2016) : $m_t = 173.8 \pm 1.8$ GeV

JHEP08 (2016) 029

ATLAS (2017) : $m_t = 173.2 \pm 1.6$ GeV

ATLAS-CONF-2017-044

In this talk we discuss another source of uncertainty.

How precisely do we know the mass definition?

What mass is it?

$$\delta m_t \sim 1\,\mathrm{GeV}$$

STATUS OF TOP MASS PRECISION

What scheme is the top mass measured in?

Kinematic extractions make use of Monte Carlo and hence are measuring a MC top mass parameter.

CMS @ 8 TeV (2016) : $m_t = 172.35 \pm 0.16$ (stat + JES) ± 0.48 (sys) GeV

ATLAS @ 8 TeV (di lepton) : $m_t = 172.08 \pm 0.41$ (stat) ± 0.81 (sys) GeV

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

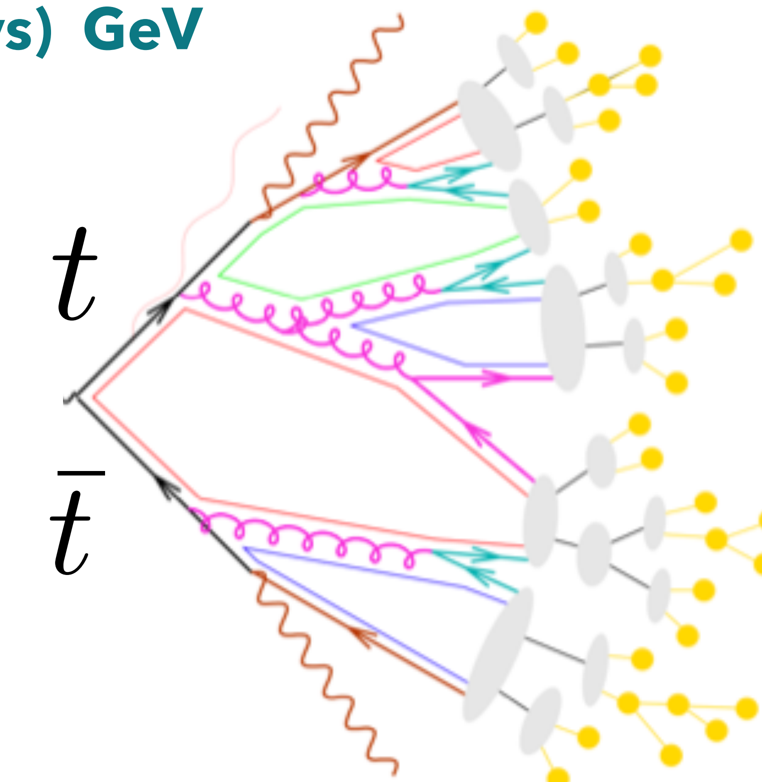
Theory (QFT)

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

Monte Carlo

Experiment

$$m_t^{\text{MC}}$$



Field Theoretic Definition?

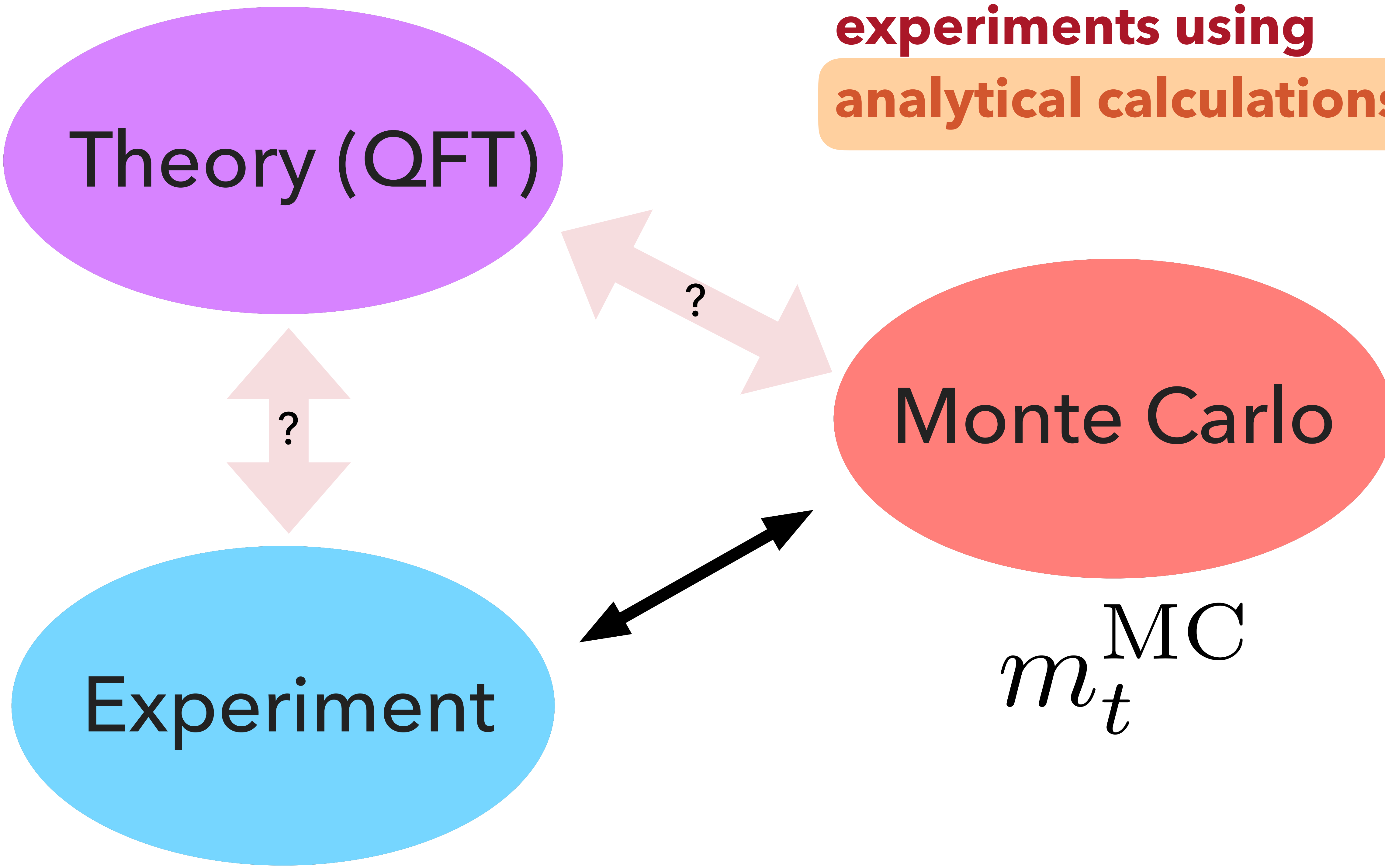
Butenschoen, Dehnadi, Hoang, Mateu, Preisser, Stewart 2016

Hoang, Stewart 2008

GOAL OF THIS WORK

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

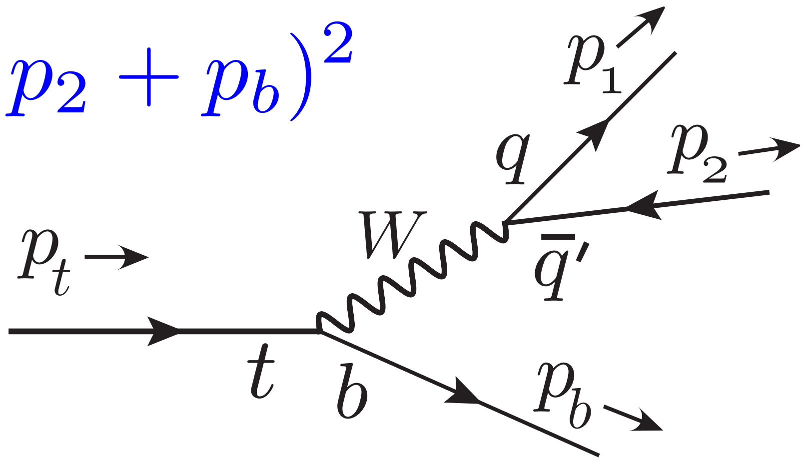
Bridge the gap between theory, MC and experiments using analytical calculations

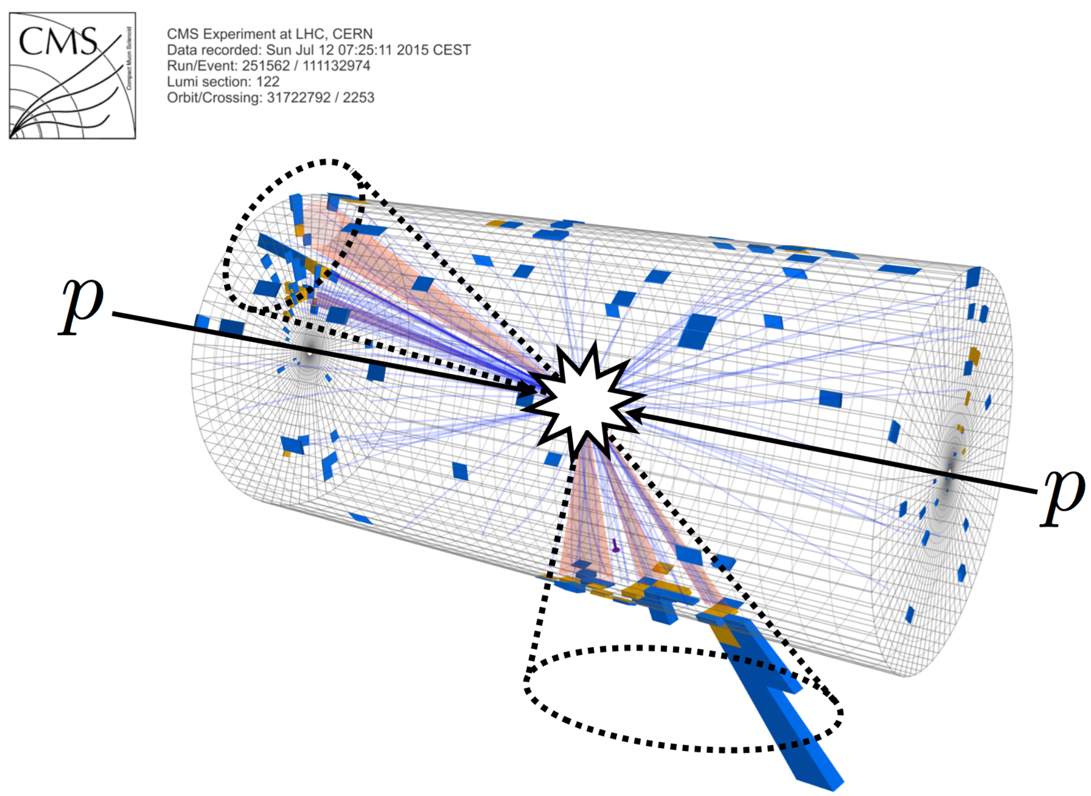


KINEMATIC EXTRACTIONS

Measure top mass using decay product momenta:

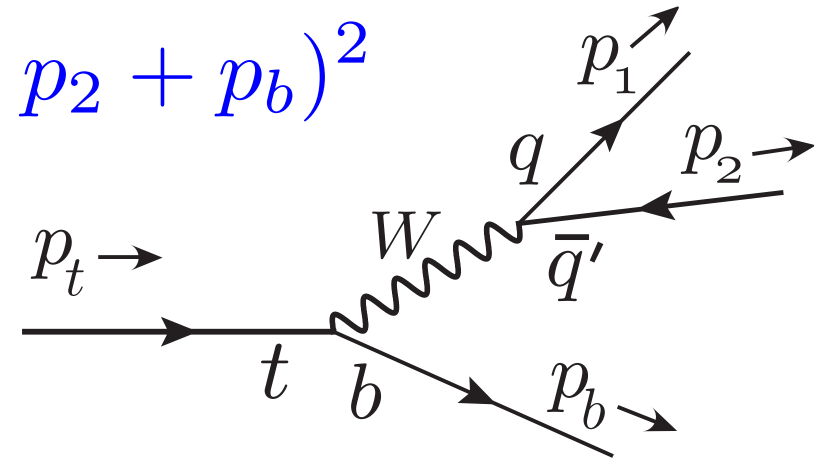
$$m_t^2 = p_t^2 = (p_1 + p_2 + p_b)^2$$



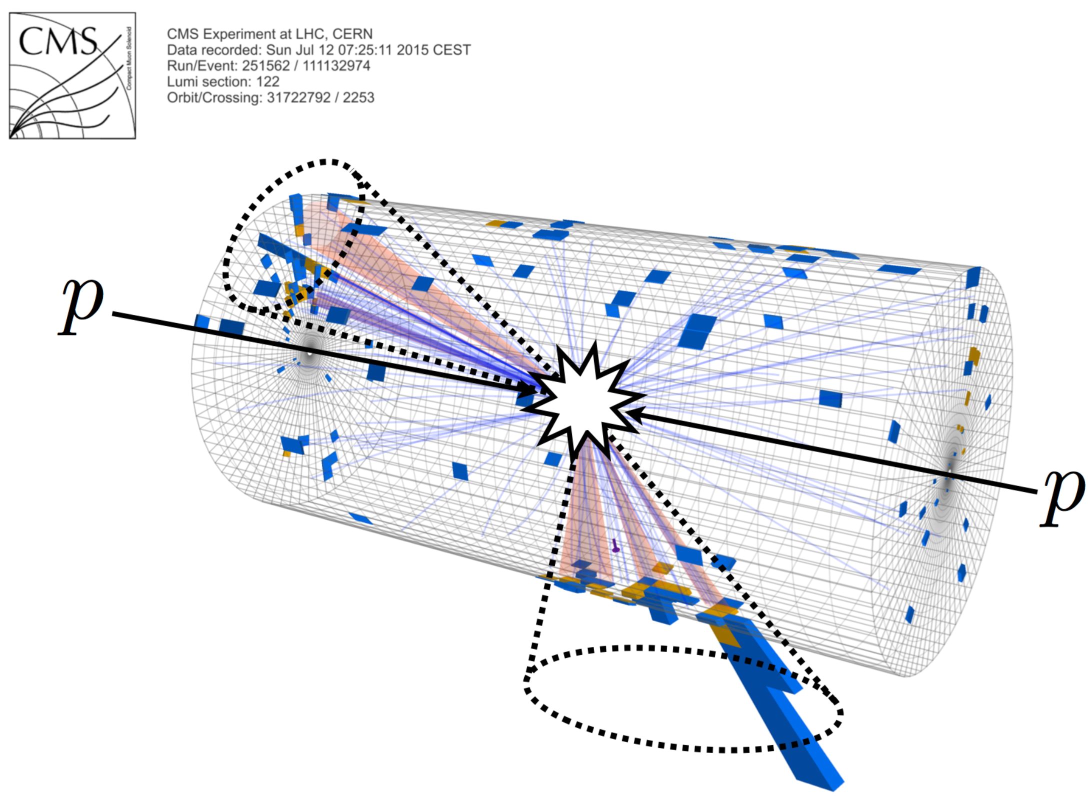


KINEMATIC EXTRACTIONS

$$m_t^2 = p_t^2 = (p_1 + p_2 + p_b)^2$$



Measure top mass using decay product momenta:

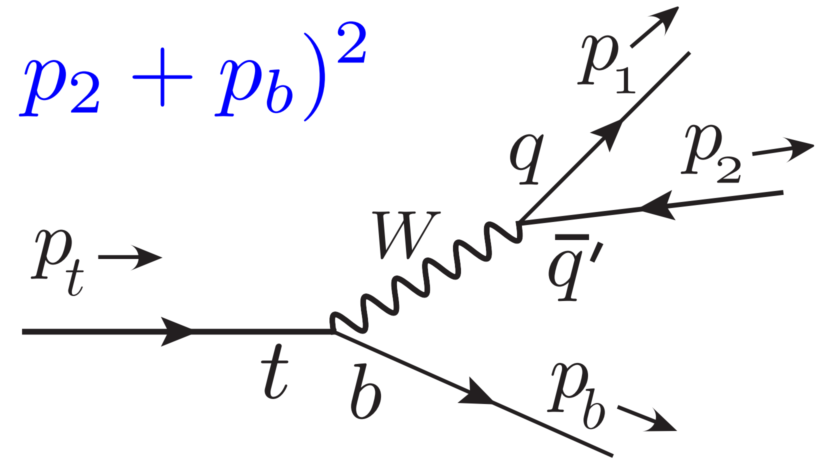


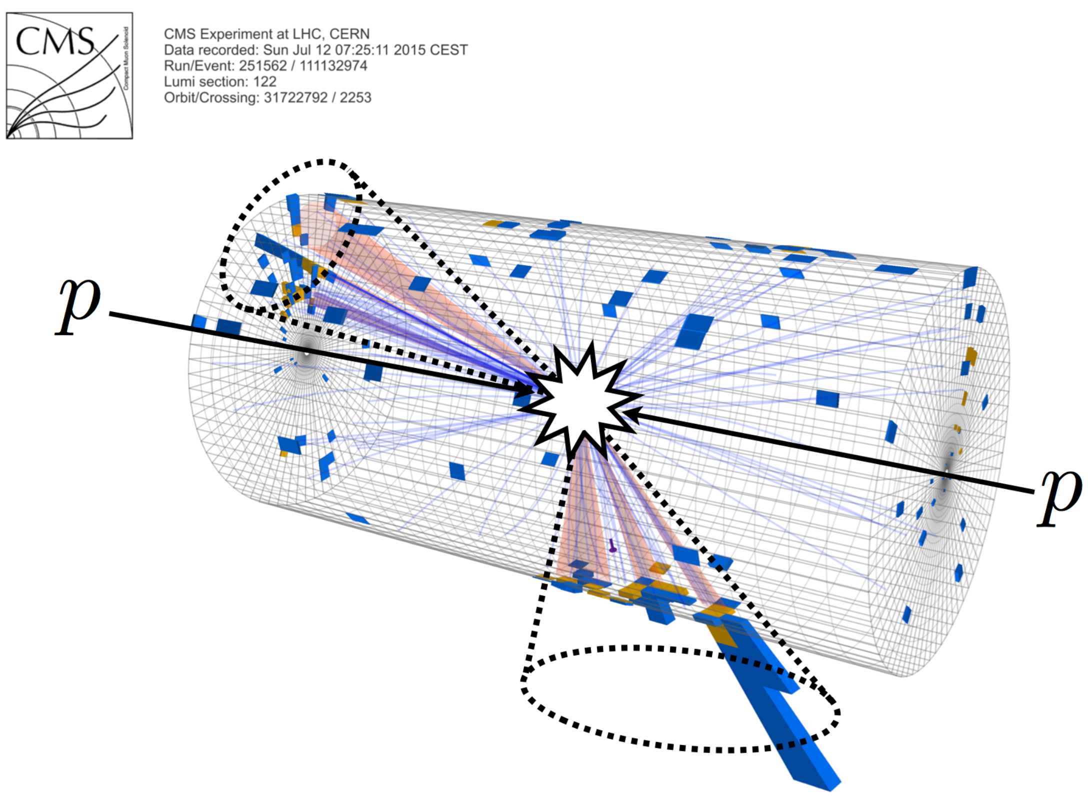
In reality kinematic based methods at hadron colliders are a lot more complicated than inclusive measurements:

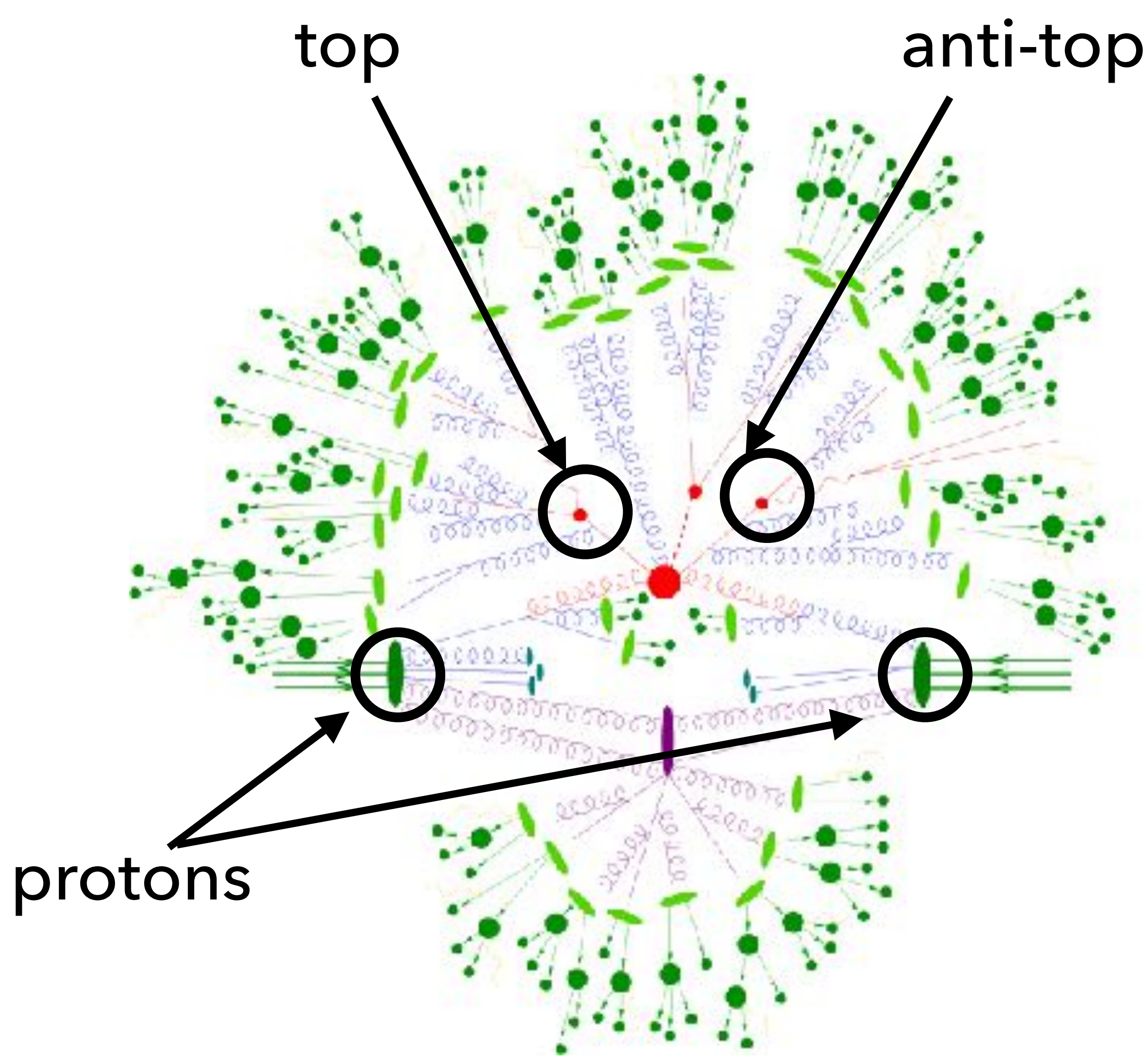
KINEMATIC EXTRACTIONS

Measure top mass using decay product momenta:

$$m_t^2 = p_t^2 = (p_1 + p_2 + p_b)^2$$







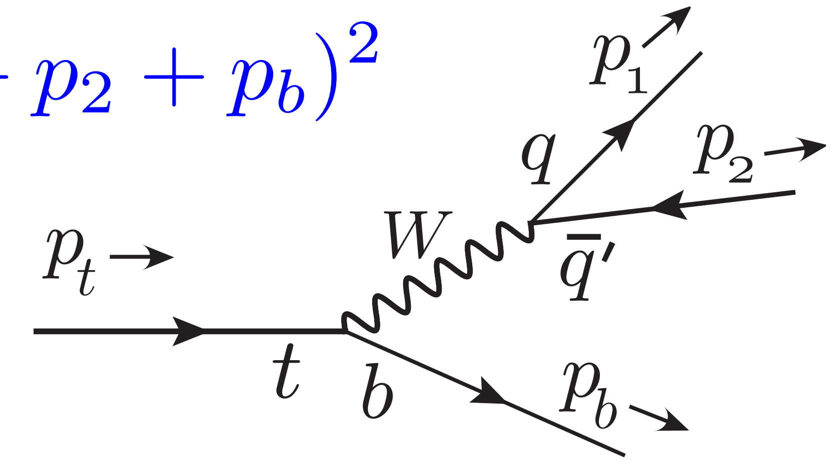
In reality kinematic based methods at hadron colliders are a lot more complicated than inclusive measurements:

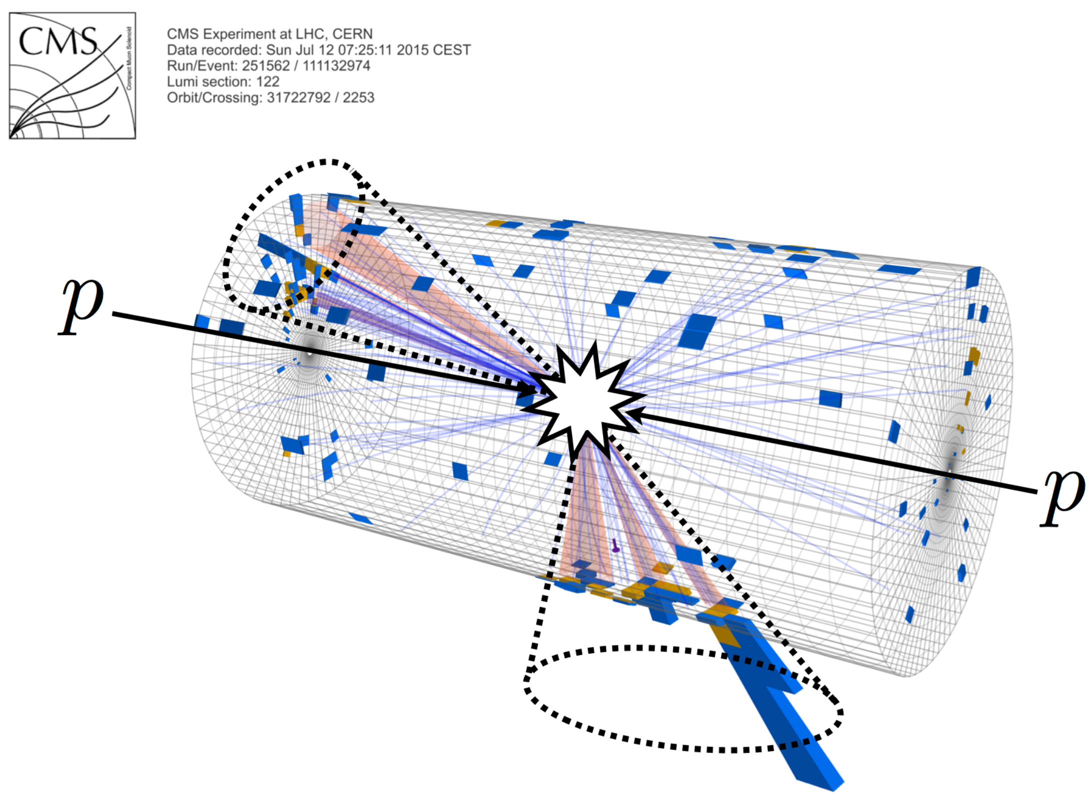
F. Krauss. (Sherpa Collaboration), "Sketch of a tth event"

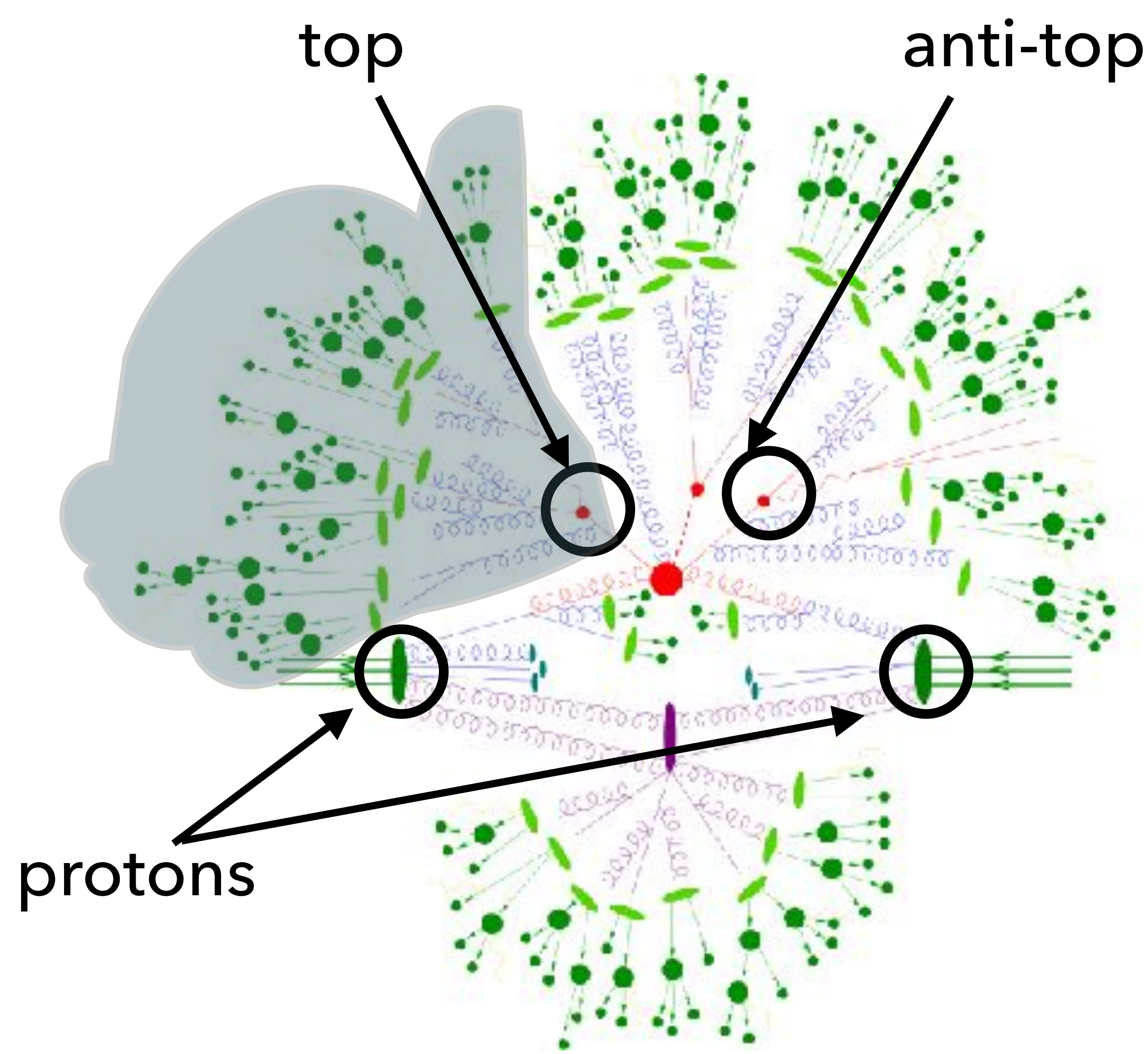
KINEMATIC EXTRACTIONS

Measure top mass using decay product momenta:

$$m_t^2 = p_t^2 = (p_1 + p_2 + p_b)^2$$







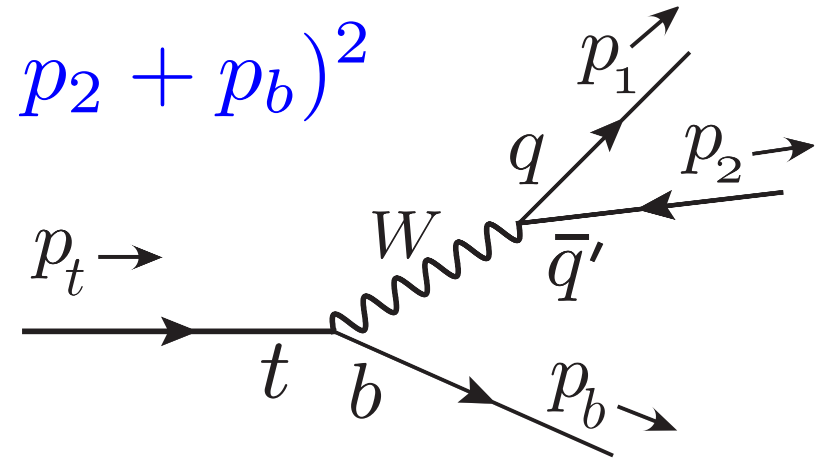
In reality kinematic based methods at hadron colliders are a lot more complicated than inclusive measurements:

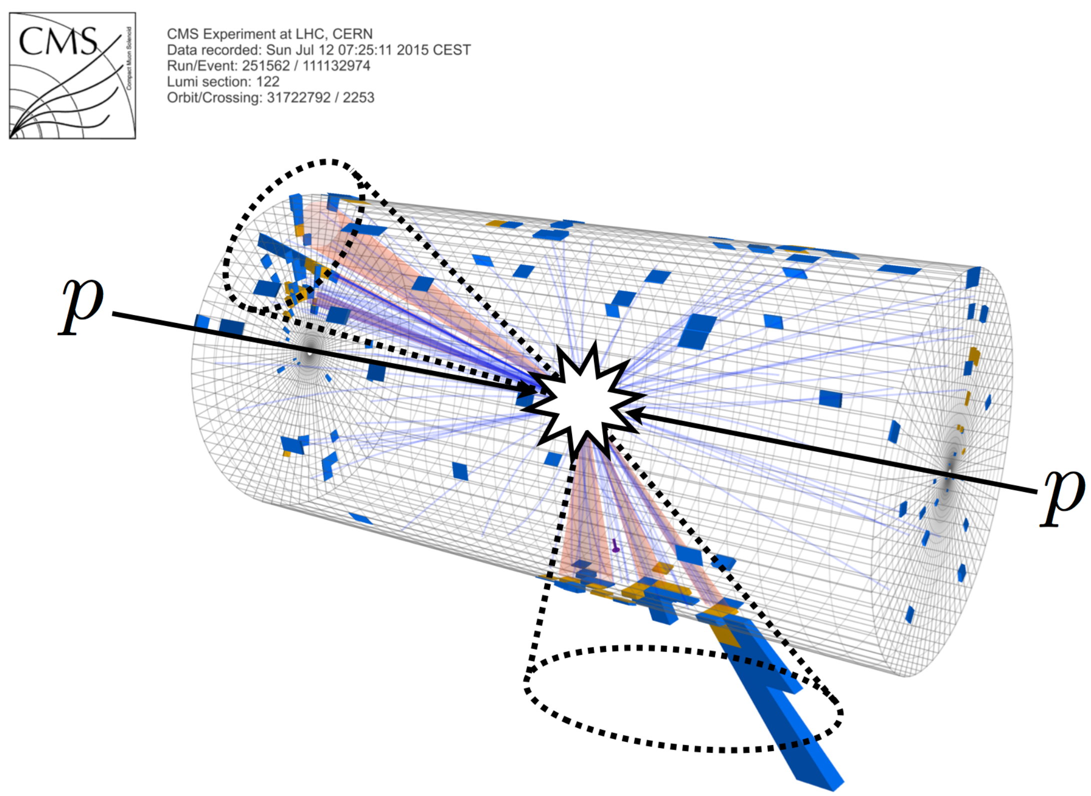
F. Krauss. (Sherpa Collaboration), "Sketch of a tth event"

KINEMATIC EXTRACTIONS

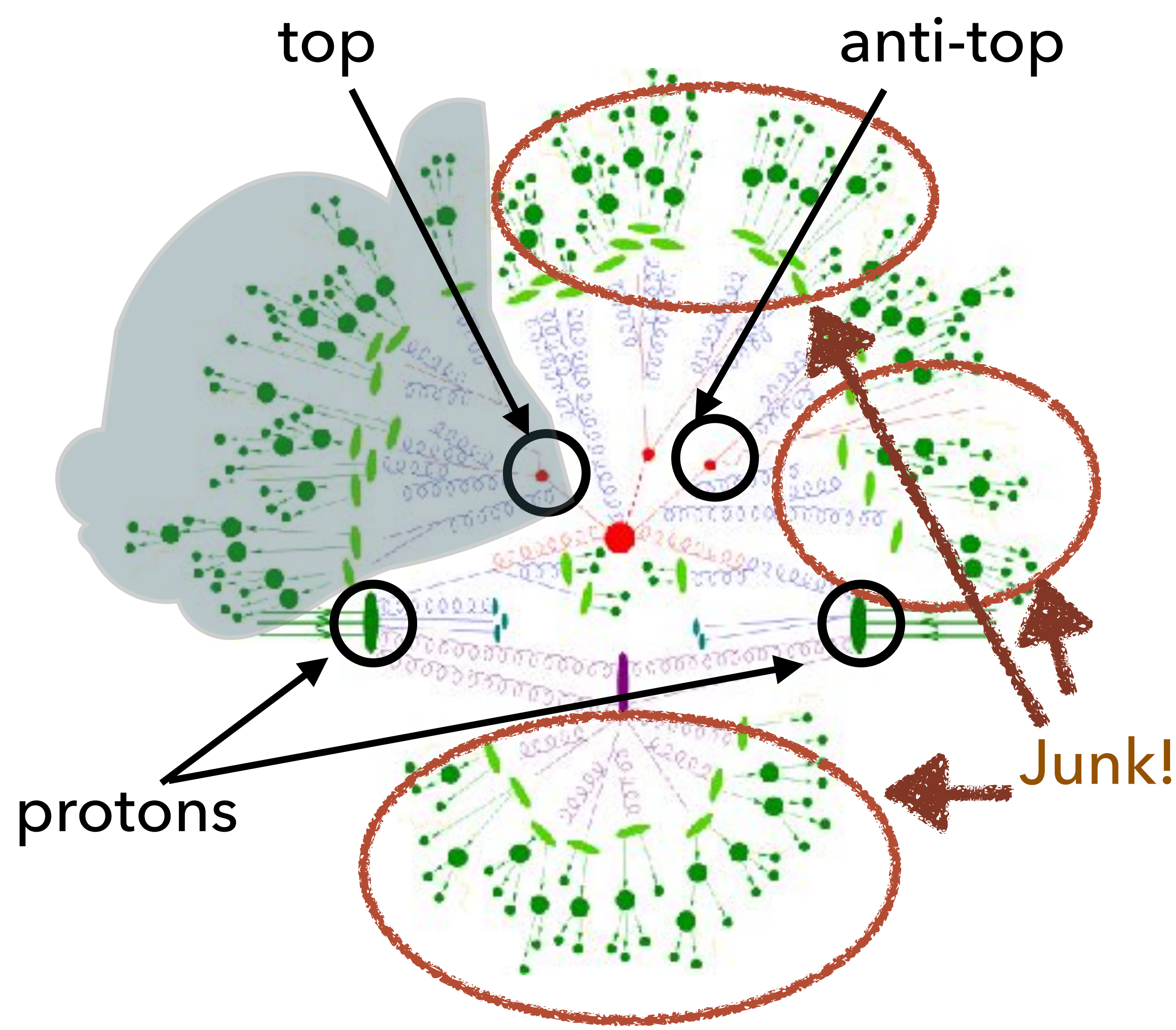
Measure top mass using decay product momenta:

$$m_t^2 = p_t^2 = (p_1 + p_2 + p_b)^2$$





In reality kinematic based methods at hadron colliders are a lot more complicated than inclusive measurements:

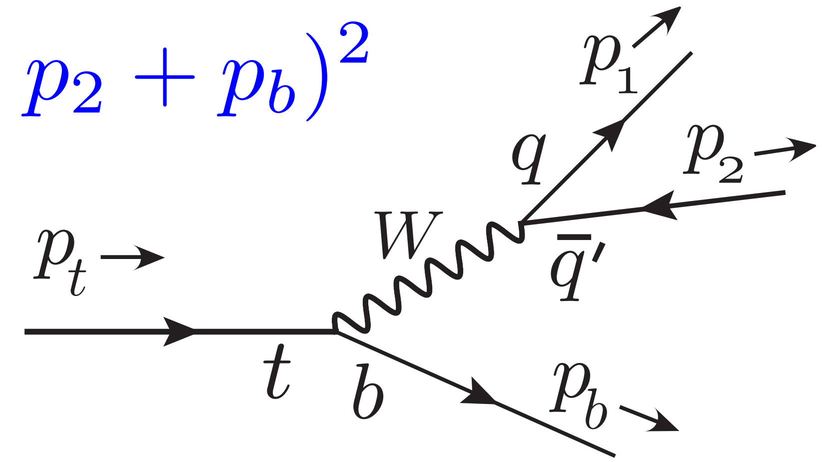


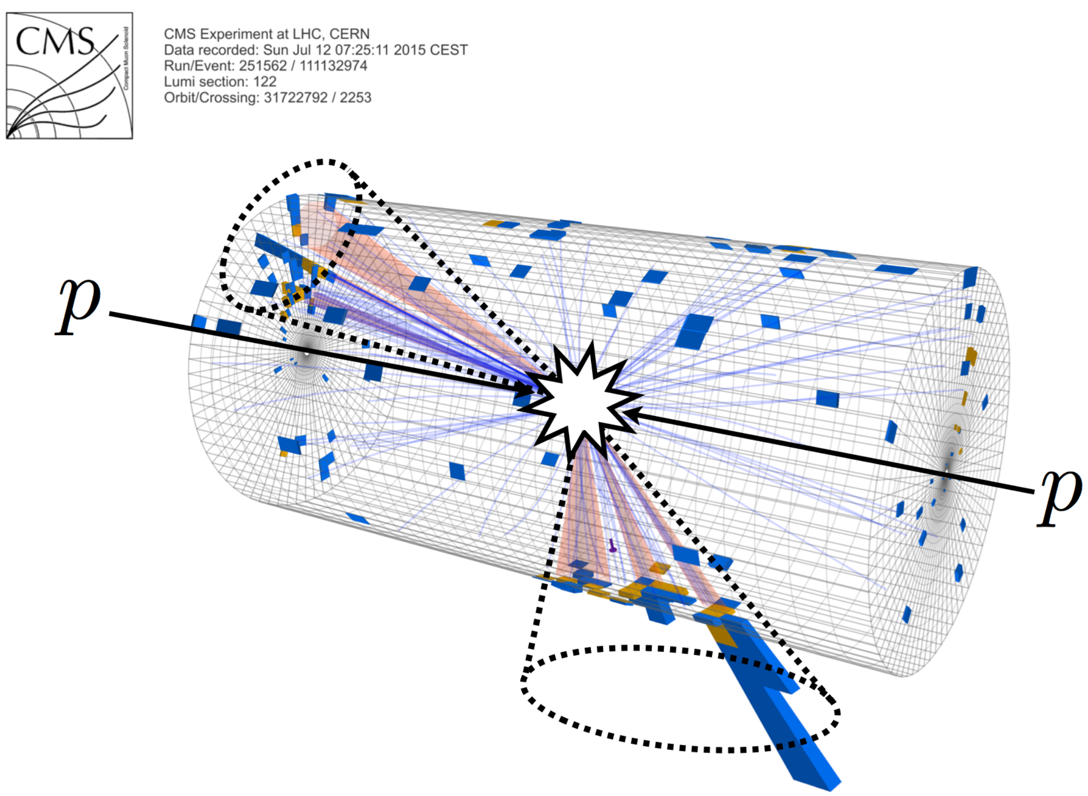
F. Krauss. (Sherpa Collaboration), "Sketch of a tth event"

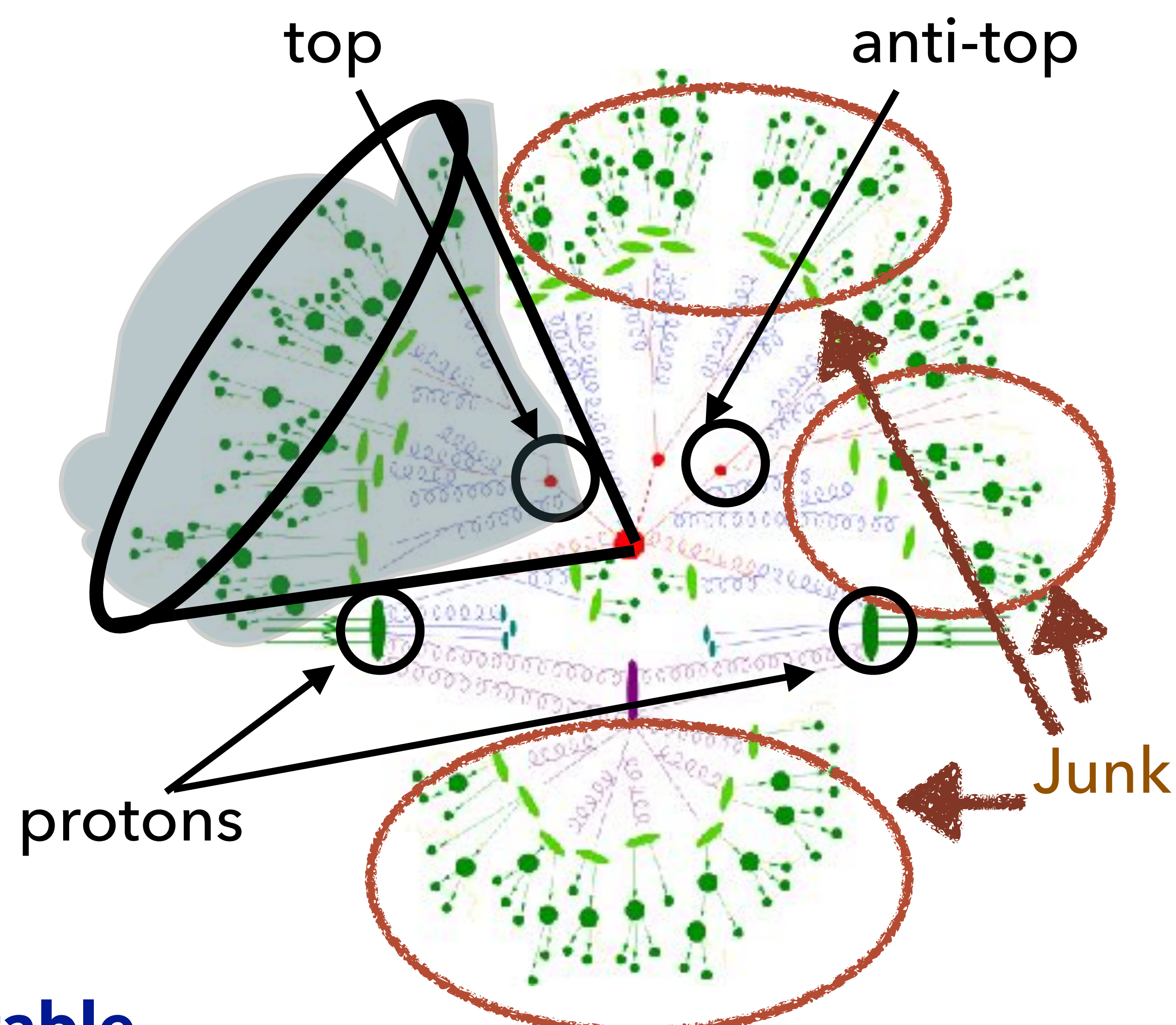
KINEMATIC EXTRACTIONS

Measure top mass using decay product momenta:

$$m_t^2 = p_t^2 = (p_1 + p_2 + p_b)^2$$







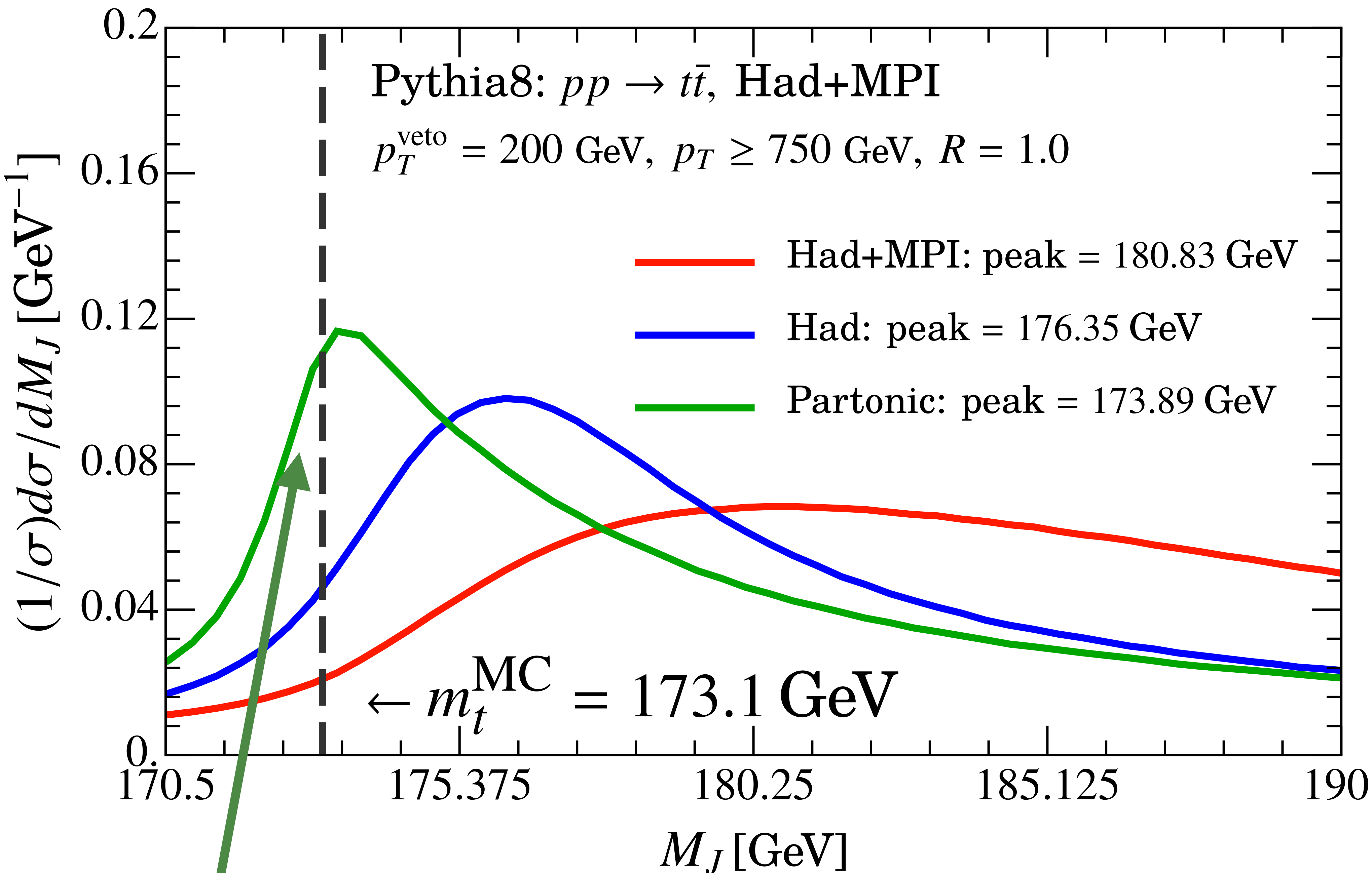
In reality kinematic based methods at hadron colliders are a lot more complicated than inclusive measurements:

Contamination in the jet is inevitable

F. Krauss. (Sherpa Collaboration), "Sketch of a tth event"

KINEMATIC EXTRACTIONS

Boosted top jets with R = 1

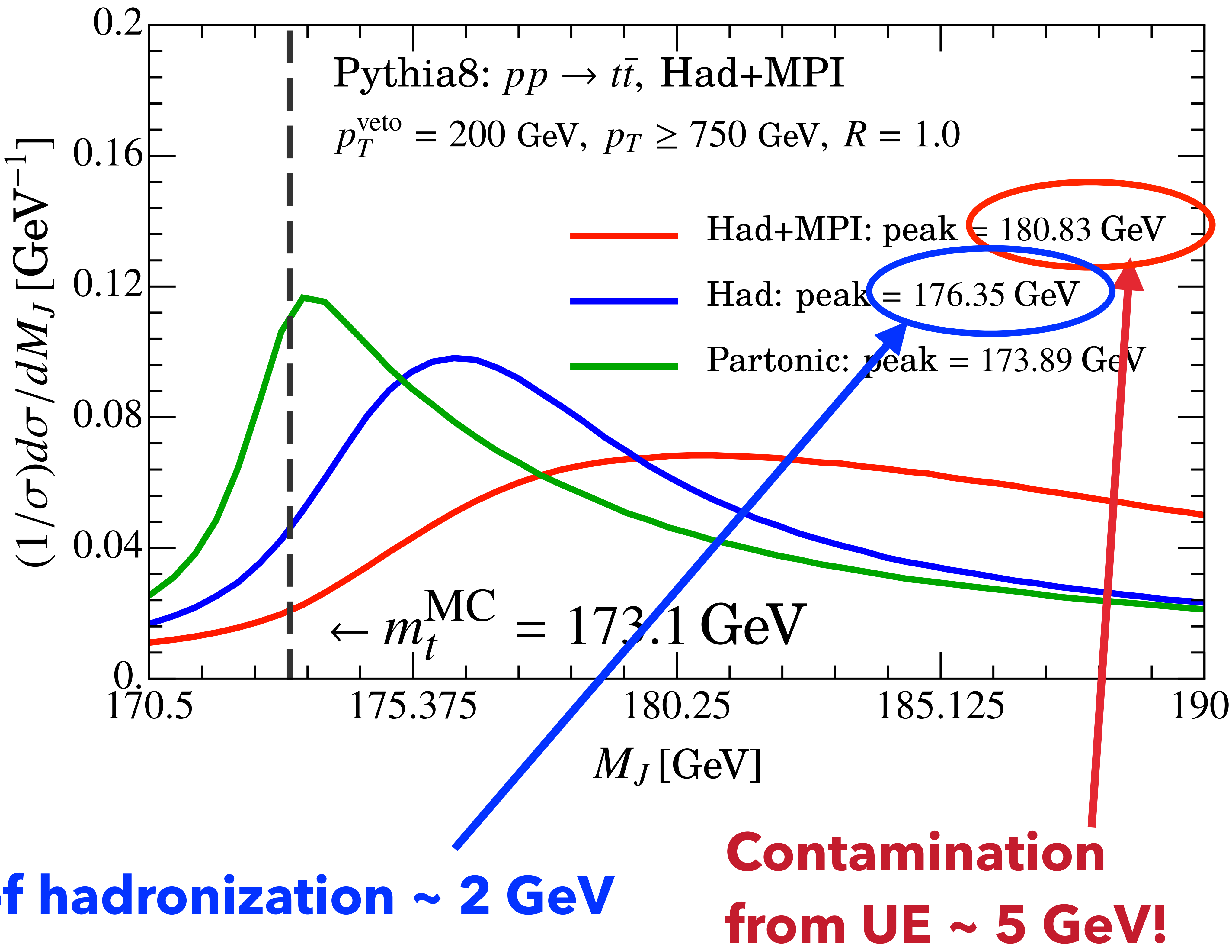


Partonic Pythia without hadronization and UE (MPI modeled)

Fastjet: Cacciari, Salam, Soyez, 2011

KINEMATIC EXTRACTIONS

Boosted top jets with R = 1

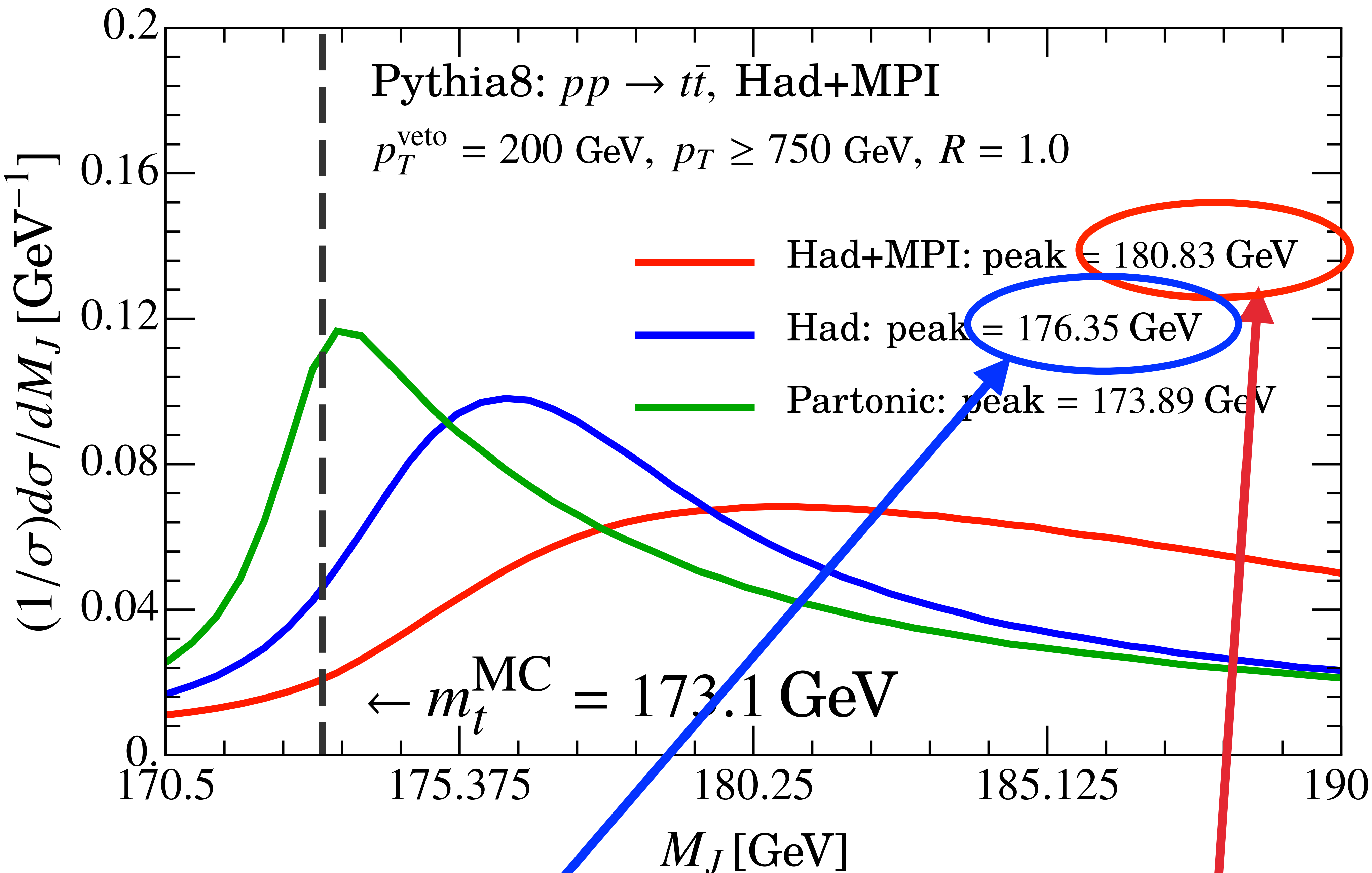


Fastjet: Cacciari, Salam, Soyez, 2011

KINEMATIC EXTRACTIONS

Boosted top jets with R = 1

In order to aim for m_t precision <1 GeV we must account for these effects in our analytical calculations



Effect of hadronization ~ 2 GeV

Contamination from UE ~ 5 GeV!

Fastjet: Cacciari, Salam, Soyez, 2011

1. MOTIVATION, GOAL, CHALLENGES
2. MODERN TECHNIQUES IN PERTURBATIVE QCD
3. USING THE THEORY TOOLS, TESTING ROBUSTNESS

1. MOTIVATION, GOAL, CHALLENGES
2. MODERN TECHNIQUES IN PERTURBATIVE QCD
3. USING THE THEORY TOOLS, TESTING ROBUSTNESS

WHAT CAN WE CALCULATE ANALYTICALLY?

Components of MCs based on factorization:

- hard scattering
- perturbative shower
- non-perturbative hadronization
- underlying event model

Allows arbitrary measurements on the final state particles, but limited in accuracy ~ NLO + NLL

See the recent Jet Substructure review by Moult, Larkoski and Nachman 2017

WHAT CAN WE CALCULATE ANALYTICALLY?

Components of MCs based on factorization:

- hard scattering
- perturbative shower
- non-perturbative hadronization
- underlying event model

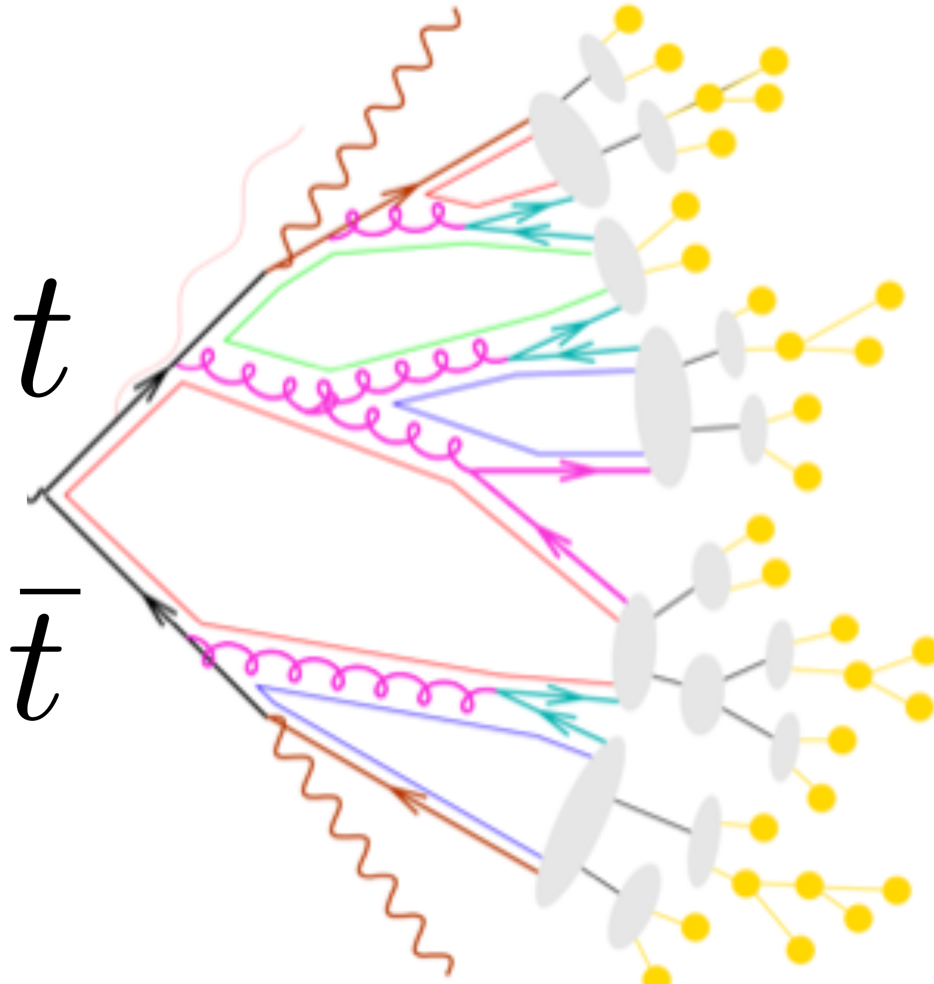
Allows arbitrary measurements on the final state particles, but limited in accuracy ~ NLO + NLL

Devise analytically calculable exclusive observables that

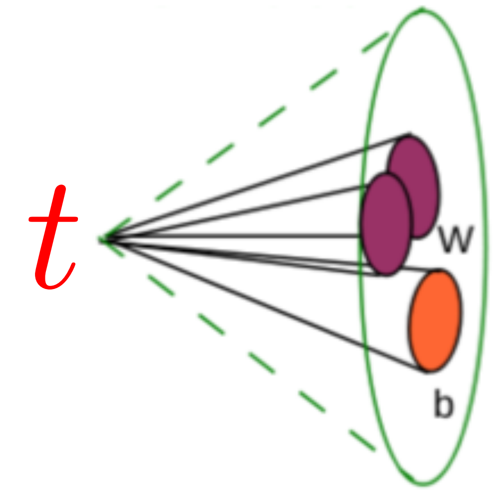
- **are sensitive to the top mass,**
- **describe these components with systematically improvable accuracy,**
- **robust against contamination and account for NP corrections.**

See the recent Jet Substructure review by Moult, Larkoski and Nachman 2017

EFFECTIVE FIELD THEORIES



Need boosted tops to capture decay products

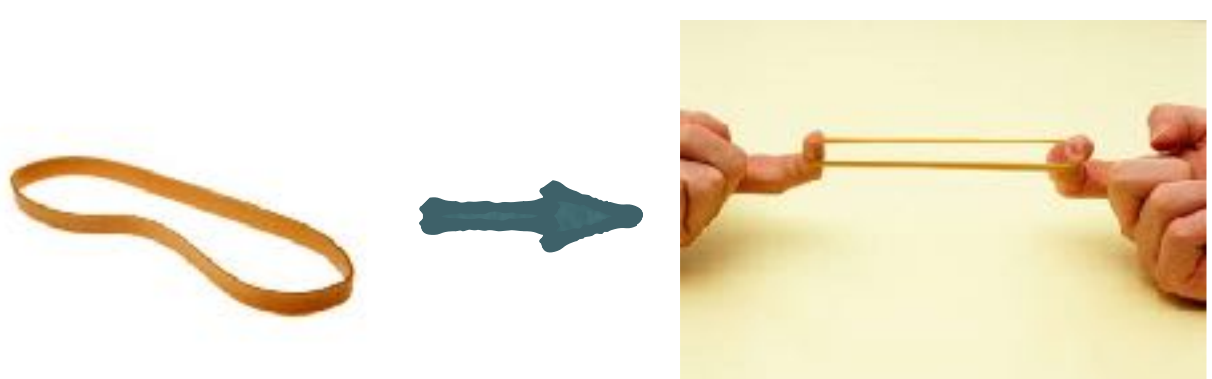


$$Q \gg m_t \gg \Gamma_t > \Lambda_{\mathrm{QCD}}$$

Q	m_t	Γ_t	Λ_{QCD}
>500 GeV	173.1 GeV	1.4 GeV	0.5 GeV

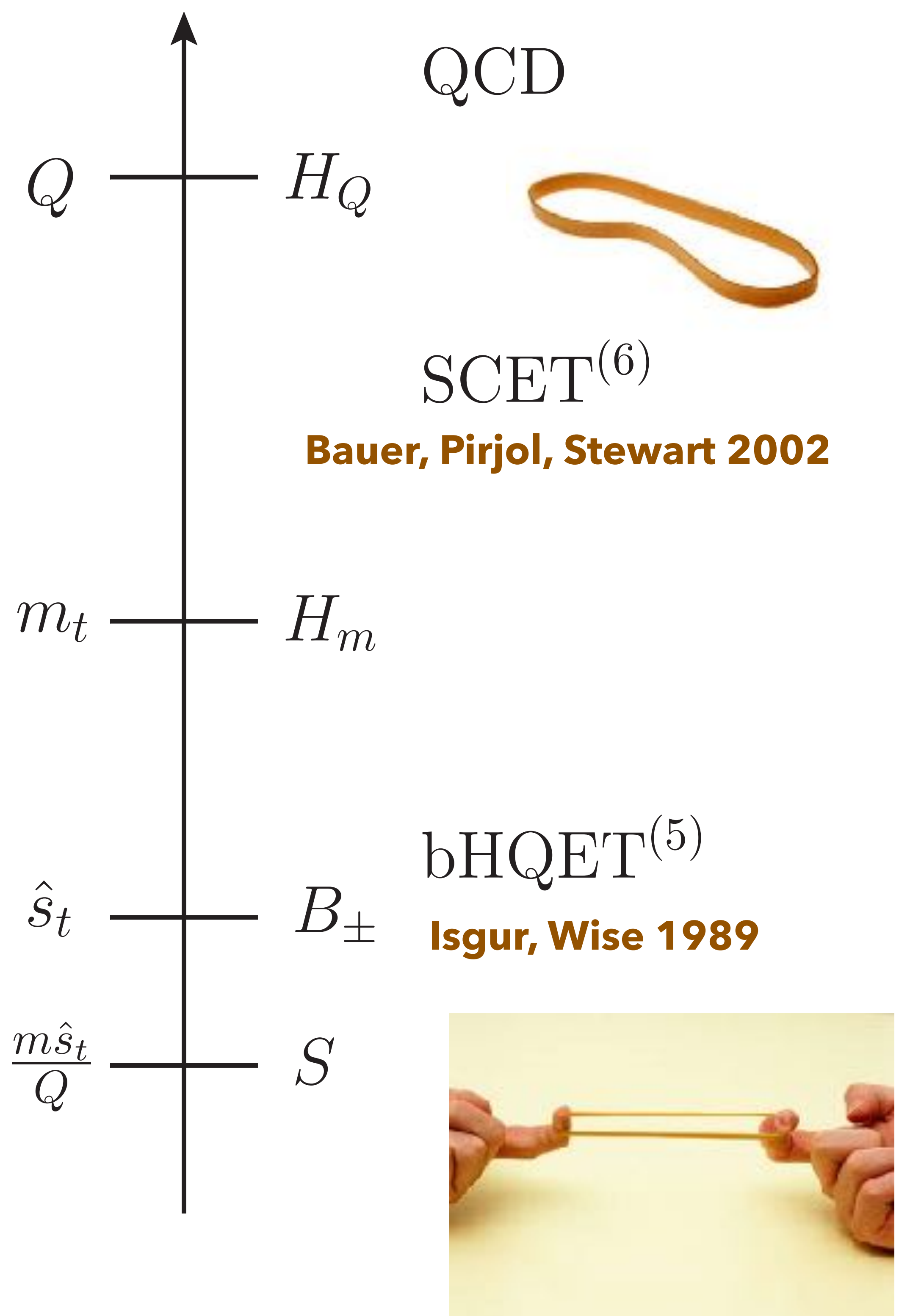
hard scale

hadronization scale



CHALLENGING PROBLEM DUE TO MULTIPLE SCALES

EFFECTIVE FIELD THEORIES



- *SCET is the appropriate Effective theory for collider physics applications*
- *HQET is the appropriate theory that describes decay of top quark close to mass shell*

Fleming, Hoang, Mantry, Stewart 2007

WHAT CAN WE CALCULATE ANALYTICALLY?

Peak Region:

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

Boosted top jets at ee collider (2008)

Factorization Theorem derived using Soft Collinear Effective Theory (SCET) and Heavy Quark Effective Theory (HQET):

$$\left(\frac{d\sigma}{dM_t^2 dM_{\bar{t}}^2}\right)_{\text{hemi}} = \sigma_0\, H_Q(Q,\mu_m)\, H_m\!\left(m_J, \frac{Q}{m_J}, \mu_m, \mu\right) \times \int dl^+ dl^-\, J_B\!\left(\hat{s}_t - \frac{Ql^+}{m_J}, \Gamma_t, \delta m, \mu\right) J_B\!\left(\hat{s}_{\bar{t}} - \frac{Ql^-}{m_J}, \Gamma_t, \delta m, \mu\right) \times S_{\text{hemi}}(l^+ - k, l^- - k', \mu)\, F(k,k')$$

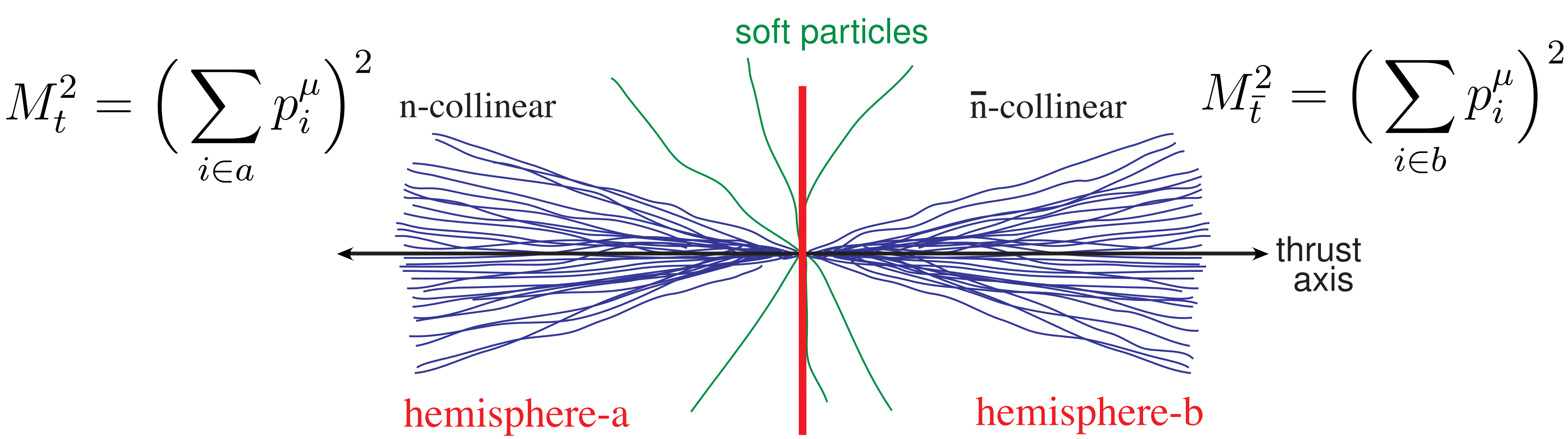
(boosted HQET) Jet Functions

Control Over Mass Scheme

Soft Function

Hadronization

Fleming, Hoang, Mantry, Stewart 2007, 2008



WHAT CAN WE CALCULATE ANALYTICALLY?

Boosted top jets at ee collider (2008)

Fleming, Hoang, Mantry, Stewart 2007, 2008

Hm: A. Hoang, AP, P. Pietrulewicz, I. Stewart 2015

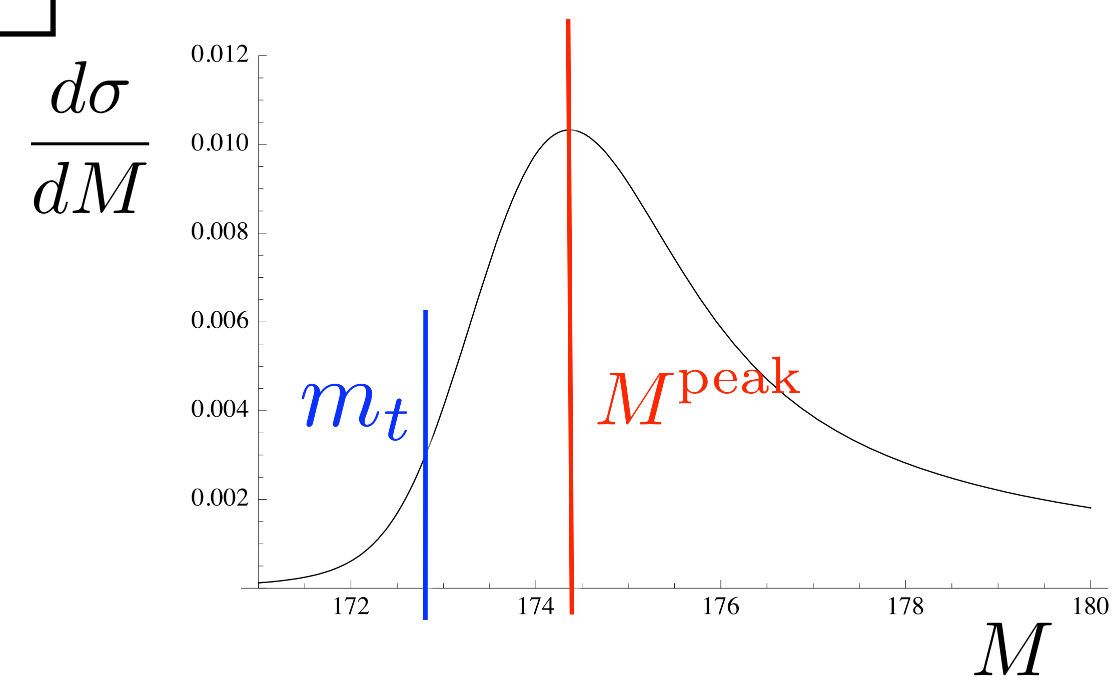
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}M_t^2\mathrm{d}M_{\bar t}^2}\right)_{\mathrm{hemi}} = \sigma_0\, H_Q(Q,\mu_m)\, H_m\left(m_J, \frac{Q}{m_J}, \mu_m, \mu\right) \times \int \mathrm{d}l^+\mathrm{d}l^-\, J_B\left(\hat{s}_t - \frac{Ql^+}{m_J}, \Gamma_t, \delta m, \mu\right) J_B\left(\hat{s}_{\bar t} - \frac{Ql^-}{m_J}, \Gamma_t, \delta m, \mu\right) \times S_{\mathrm{hemi}}(l^+ - k, l^- - k', \mu)\, F(k,k')$$

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

model this

measure this

extract this



Includes a non-perturbative function:

$$f(\varepsilon) = \sum_N |\langle 0|W(0)|N\rangle|^2\, \delta\left(\varepsilon - k_R^- - k_L^+\right)$$

Korchemsky, Sterman 1999

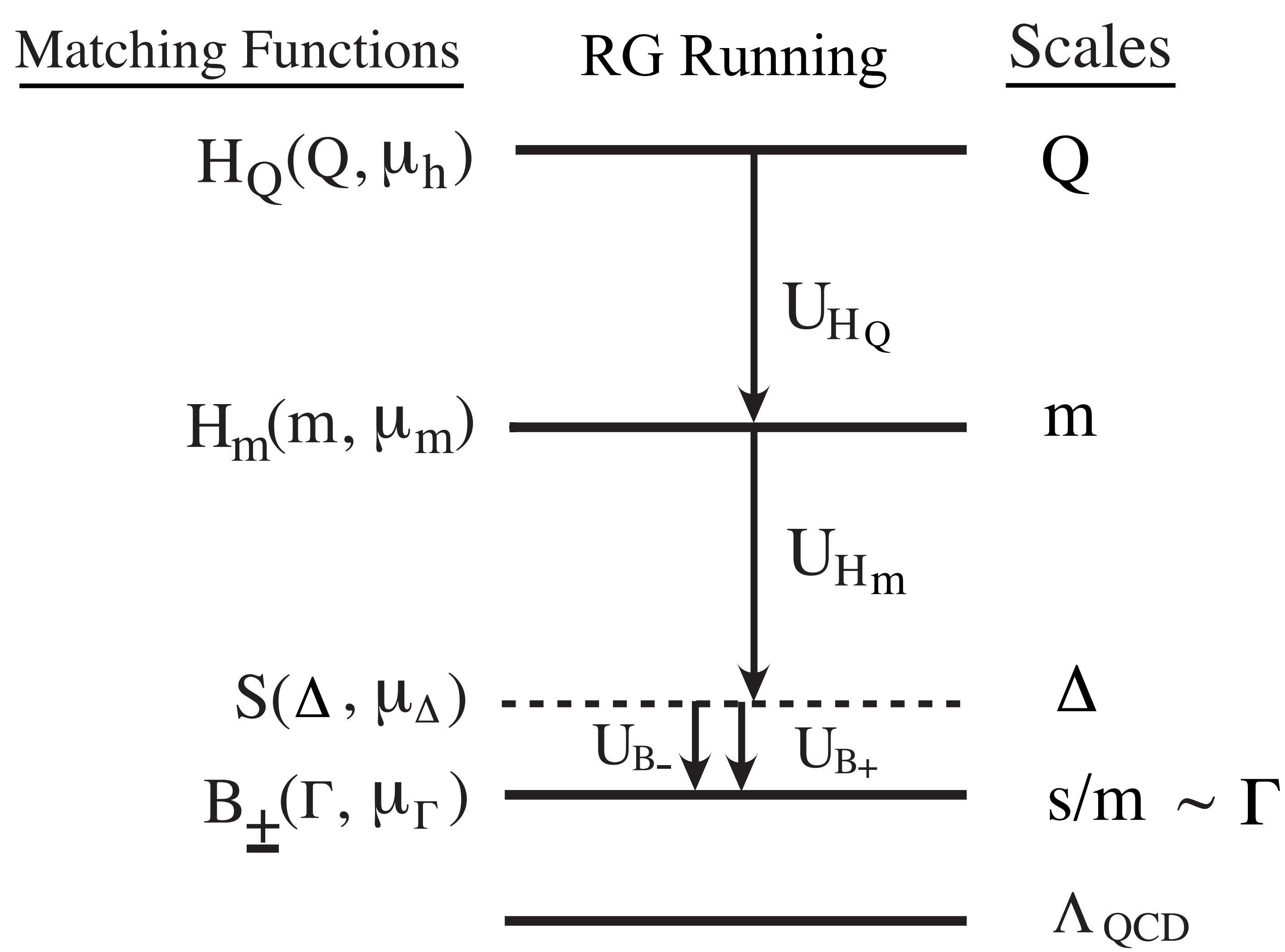
Hoang, Stewart 2007

Improved understanding of hadronization corrections

WHAT CAN WE CALCULATE ANALYTICALLY?

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}M_t^2\mathrm{d}M_{\bar t}^2}\right)_{\text{hemi}} = \sigma_0\, H_Q(Q,\mu_m)\, H_m\!\left(m_J, \frac{Q}{m_J}, \mu_m, \mu\right) \times \int \mathrm{d}l^+\mathrm{d}l^-\, J_B\!\left(\hat s_t - \frac{Ql^+}{m_J}, \Gamma_t, \delta m, \mu\right) J_B\!\left(\hat s_{\bar t} - \frac{Ql^-}{m_J}, \Gamma_t, \delta m, \mu\right) \times S_{\text{hemi}}(l^+ - k, l^- - k', \mu)\, F(k,k')$$

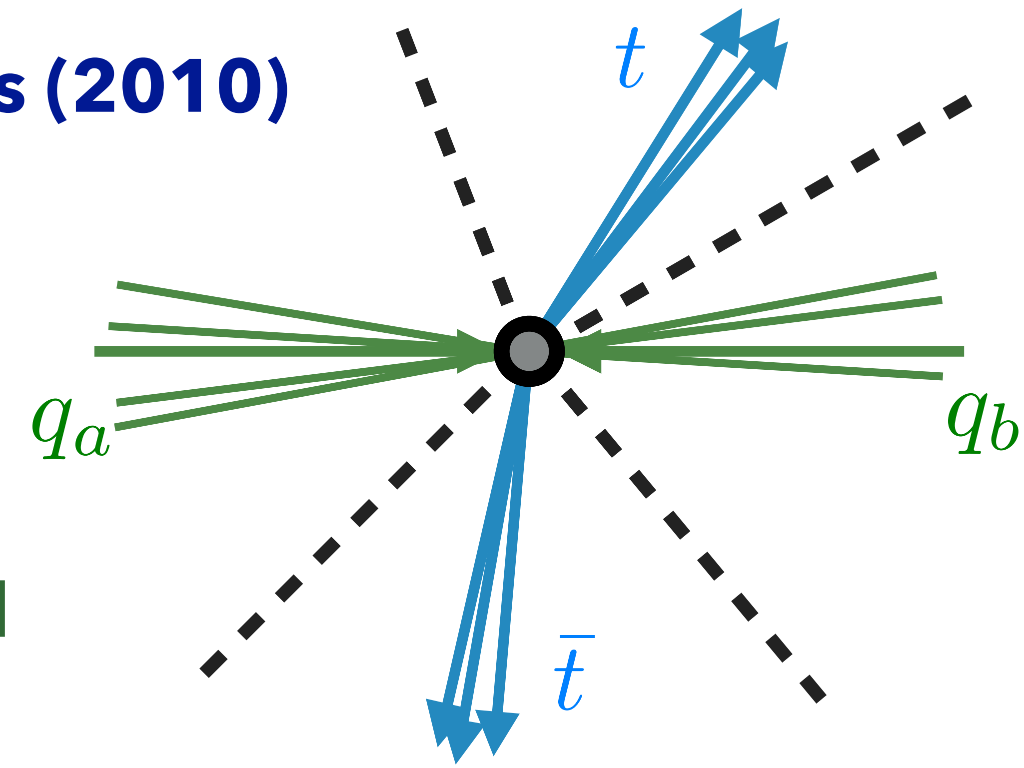
- Inclusive over decay products
- Accounts for soft and collinear gluon radiation from top and decay products
- Allows use of short distance top mass
- Can be extended to NNNLL accuracy



WHAT CAN WE CALCULATE ANALYTICALLY?

Stewart, Tackmann, Waalewijn 2010

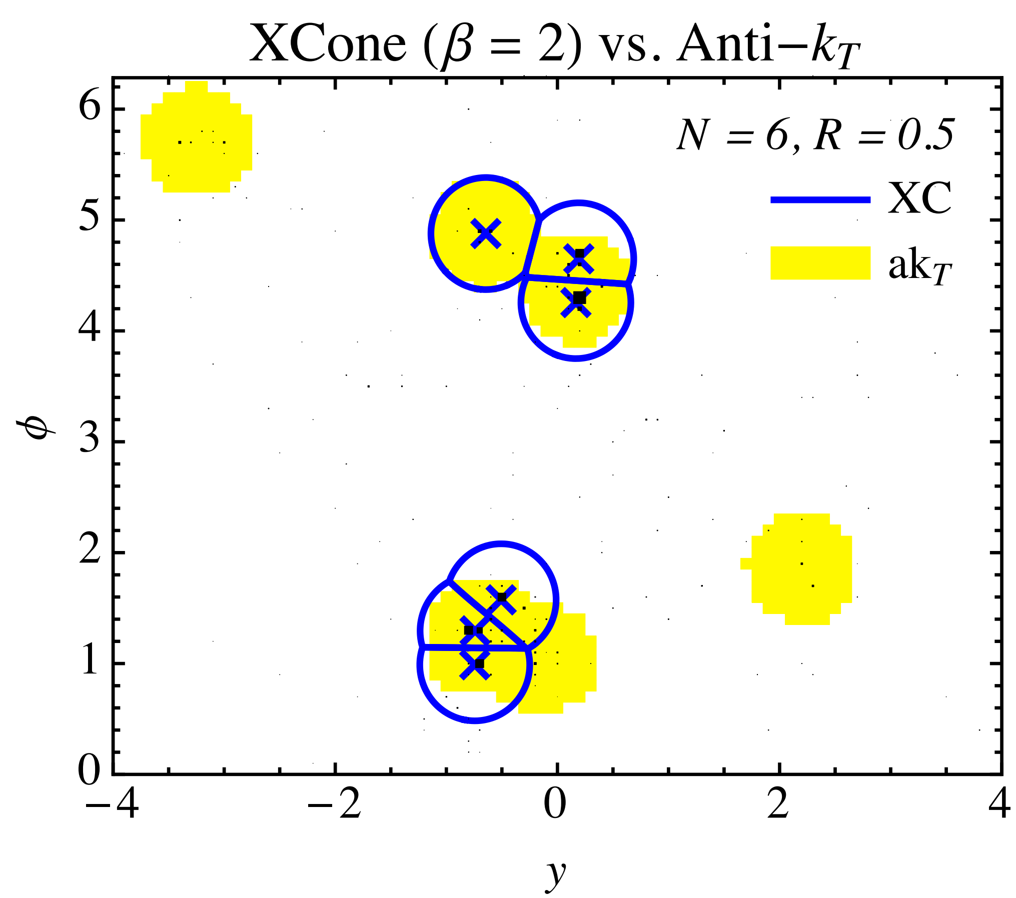
Event shapes for hadron colliders: N-jettiness (2010)

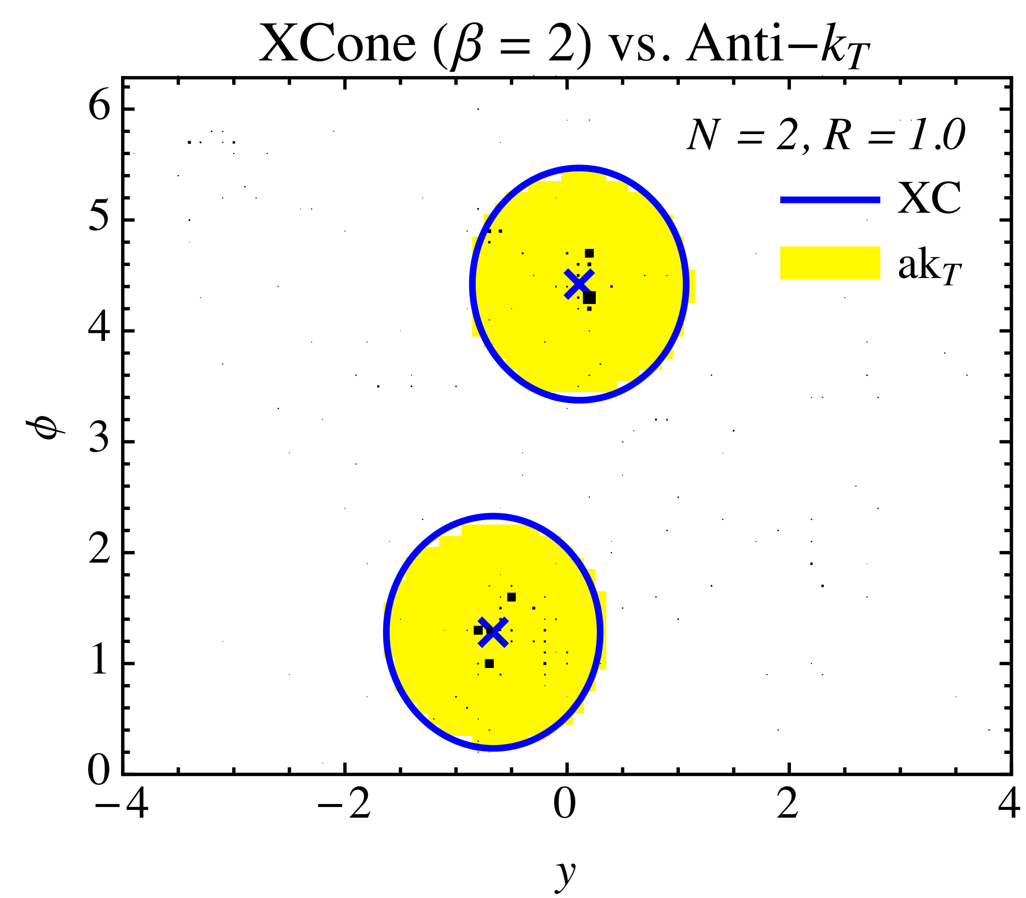


$$\mathcal{T}_2 = \min_{n_t, n_{\bar{t}}} \sum_i \min\{\rho_{\rm jet}(p_i, n_t), \rho_{\rm jet}(p_i, n_{\bar{t}}), \rho_{\rm beam}(p_i)\}$$

$$= \mathcal{T}_2^{t} + \mathcal{T}_2^{\bar{t}} + \mathcal{T}_2^{\rm beam} ,$$

XCone is a particularly nice choice for jet and beam measures





Stewart, Tackmann, Thaler, Vermilion, Wilkason, 2015

WHAT CAN WE CALCULATE ANALYTICALLY?

Hoang, Mantry, AP, Stewart (soon)

Top jets at the LHC using 2-jettiness

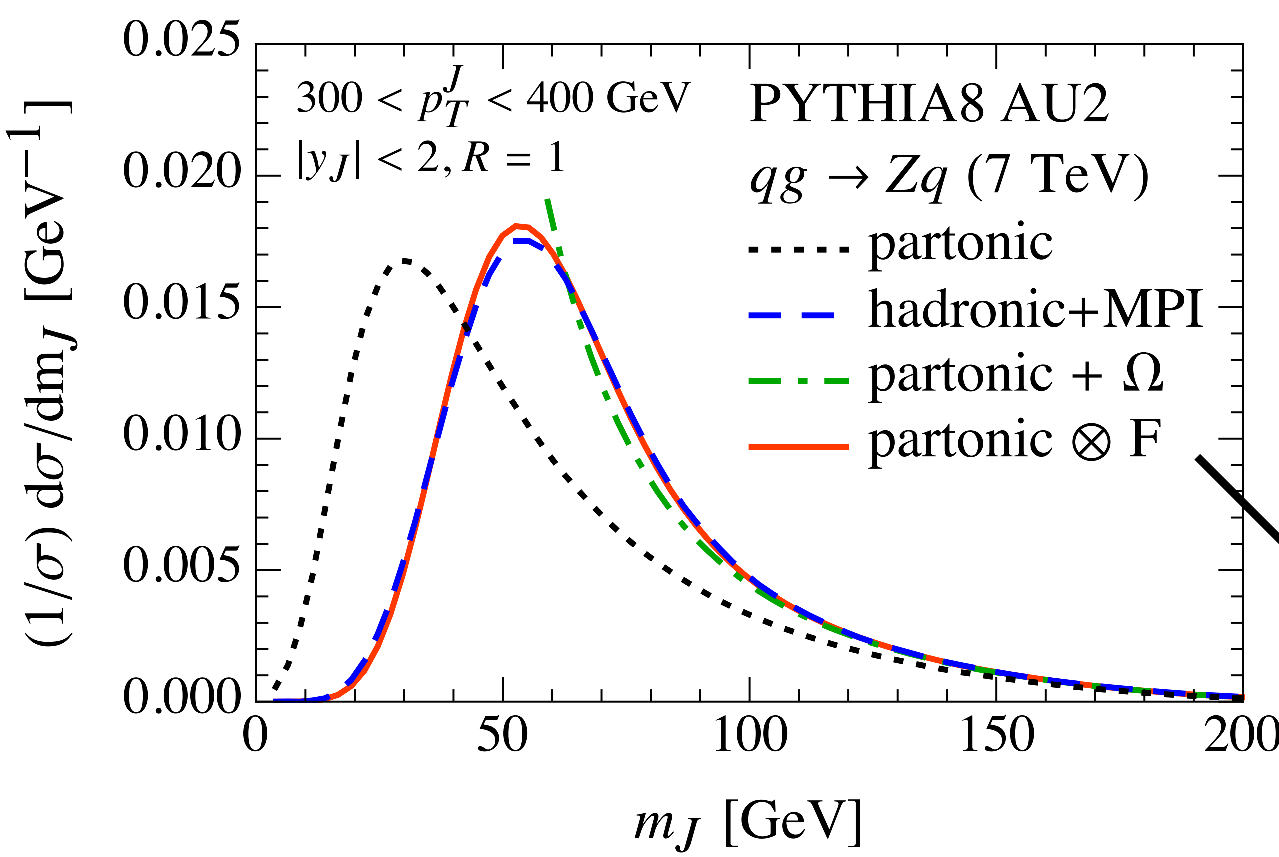
$$\frac{d^2\sigma}{dM_{J1}^2 dM_{J2}^2 d\mathcal{T}^{\rm cut}} = {\rm tr}\left[\hat{H}_{Qm}\hat{S}(\mathcal{T}^{\rm cut}, R, \ldots)\otimes F\right]\otimes J_B \otimes J_B \otimes \mathcal{I}\mathcal{I} \otimes f\, f$$

Jet Veto in Beam Region

Same Jet Functions!

Initial State Radiation

PDFs



Stewart, Tackmann, Waalewijn 2015

- Generalization of the ee result for the LHC
- Non-perturbative corrections are modeled and can account for the UE

$$F(\ell) = \theta(\ell)\frac{\mathcal{N}(a,\Lambda)}{\Lambda}\left(\frac{\ell}{\Lambda}\right)^{a-1}\exp\left(\frac{-2\ell}{\Lambda}\right)$$

WHAT CAN WE CALCULATE ANALYTICALLY?

Hoang, Mantry, AP, Stewart (soon)

Top jets at the LHC using 2-jettiness

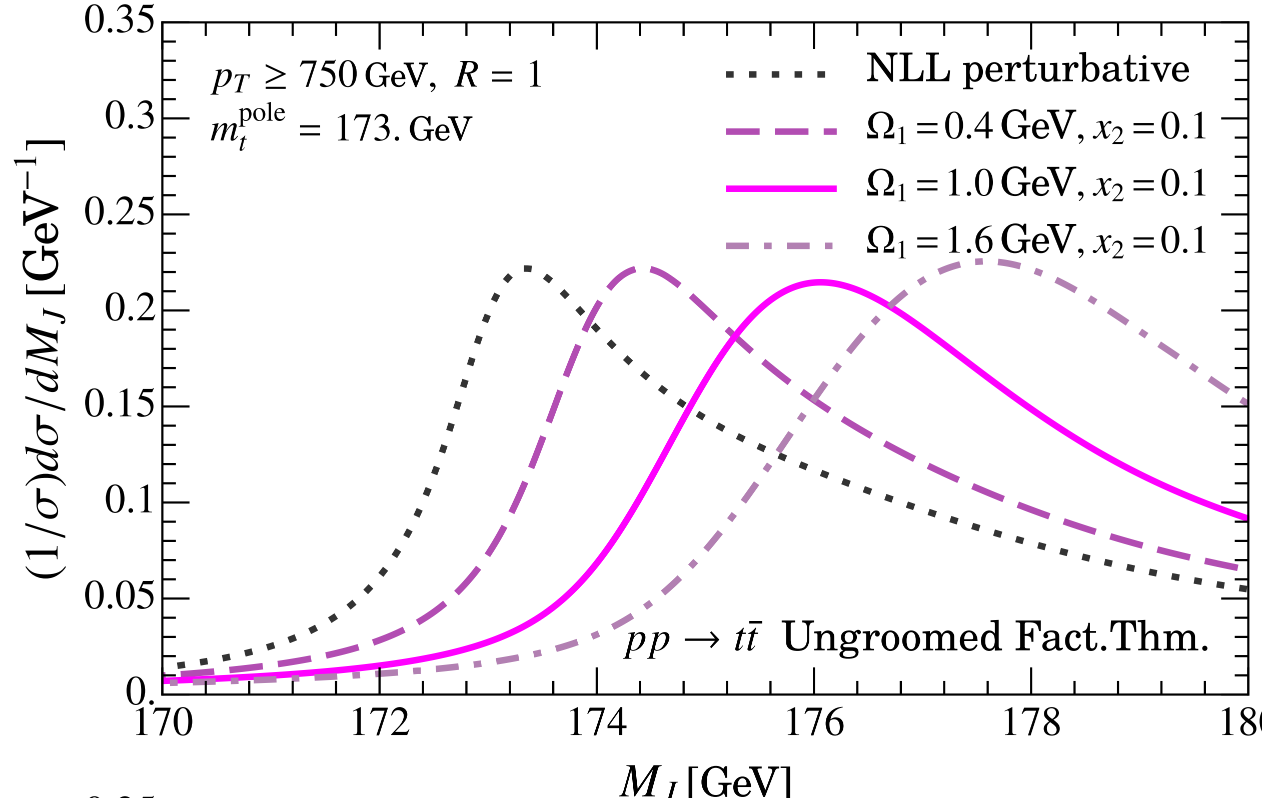
Dominant dependence on the first moment:

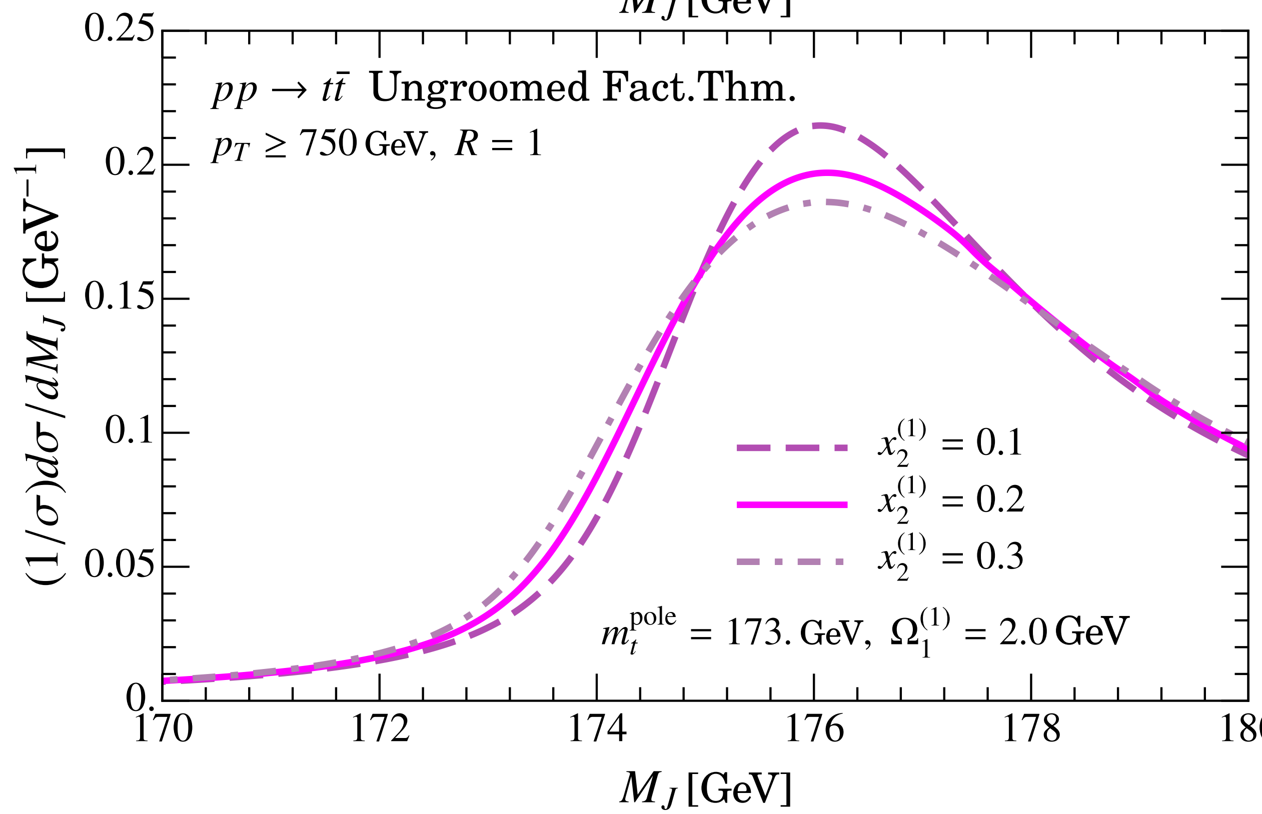
$$\Omega_1 = \int dk\, k F(k)$$

$$F(\ell) = \theta(\ell)\frac{\mathcal{N}(a,\Lambda)}{\Lambda}\left(\frac{\ell}{\Lambda}\right)^{a-1}\exp\left(\frac{-2\ell}{\Lambda}\right)$$

Less sensitive to x_2 (higher moments)

$$x_2 = \frac{\Omega_2^c}{\Omega_1^2} = \frac{\Omega_2 - \Omega_1^2}{\Omega_1^2}$$





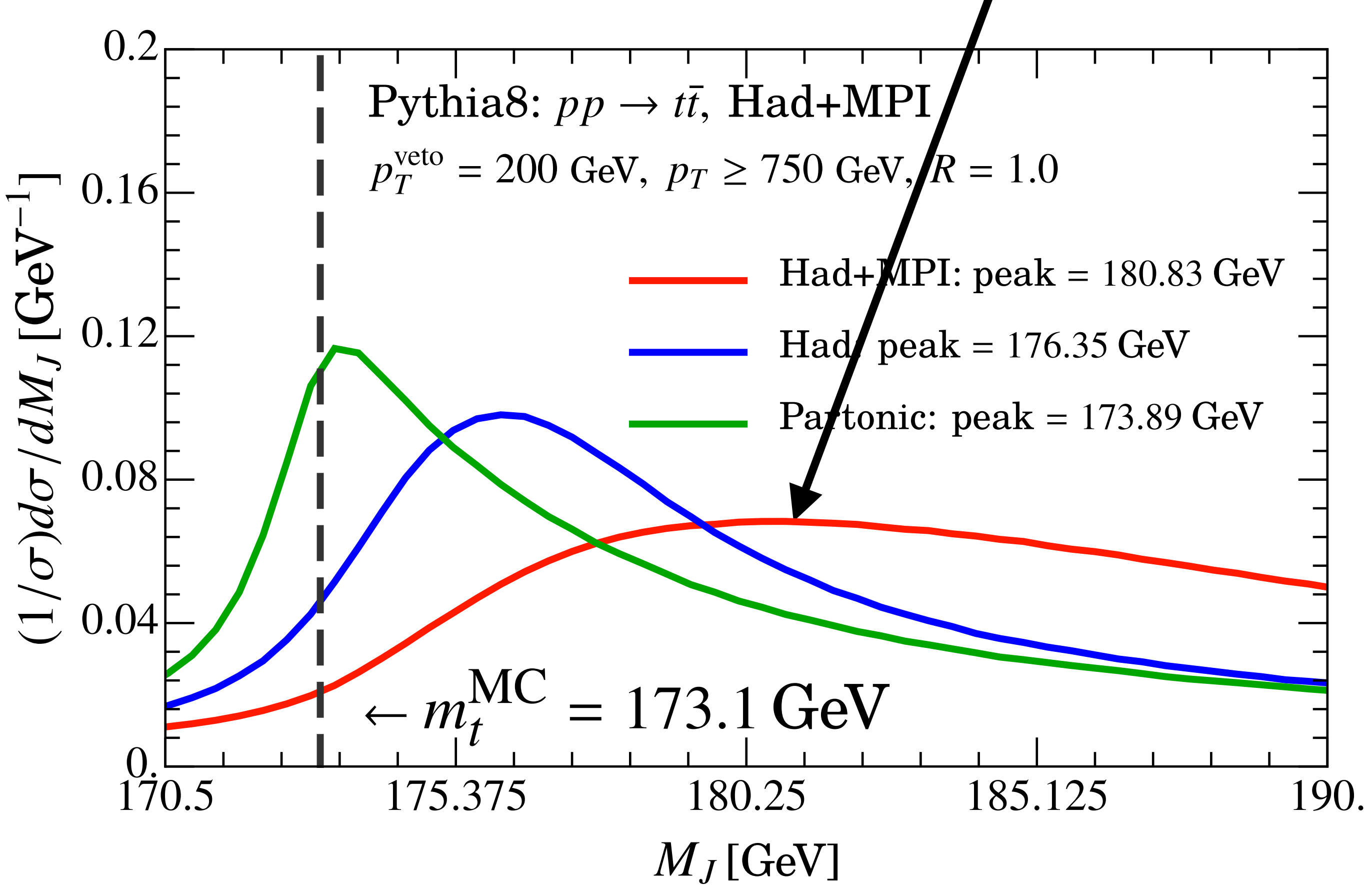
WHAT CAN WE CALCULATE ANALYTICALLY?

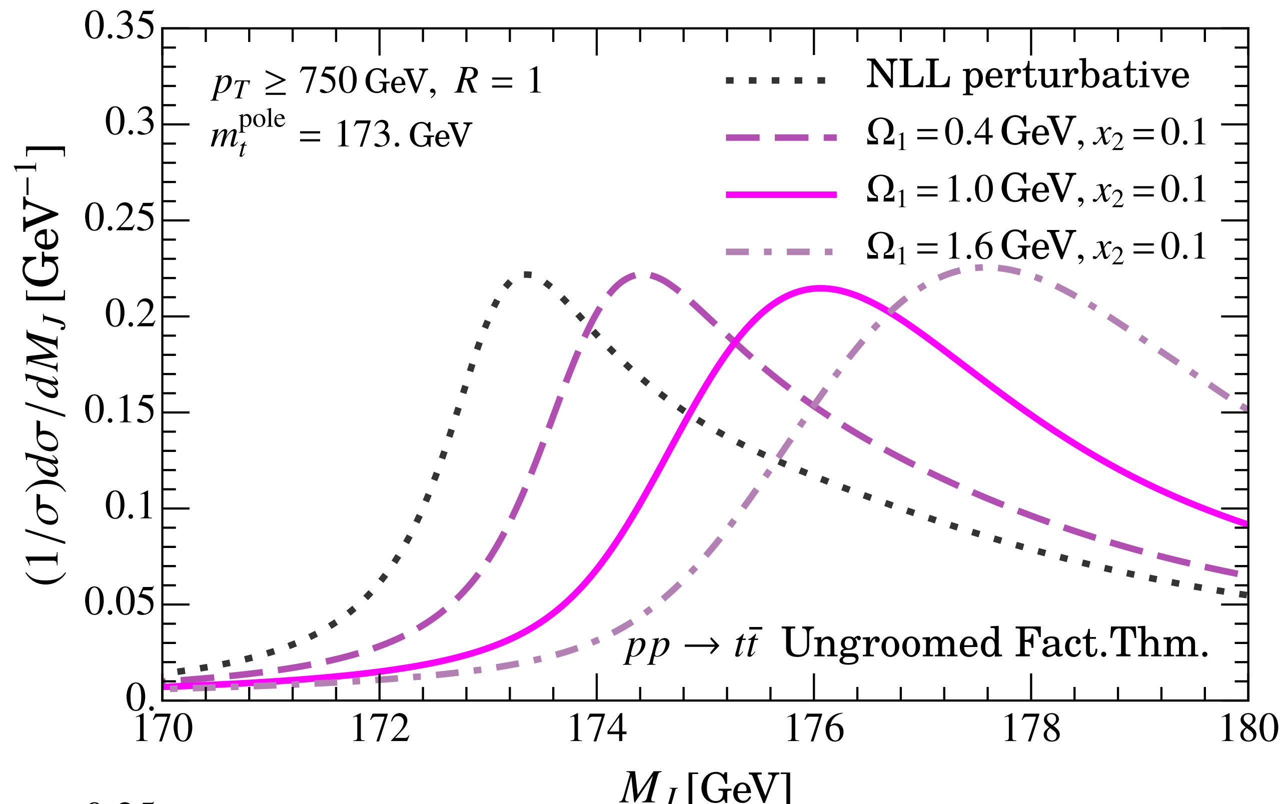
Hoang, Mantry, AP, Stewart (soon)

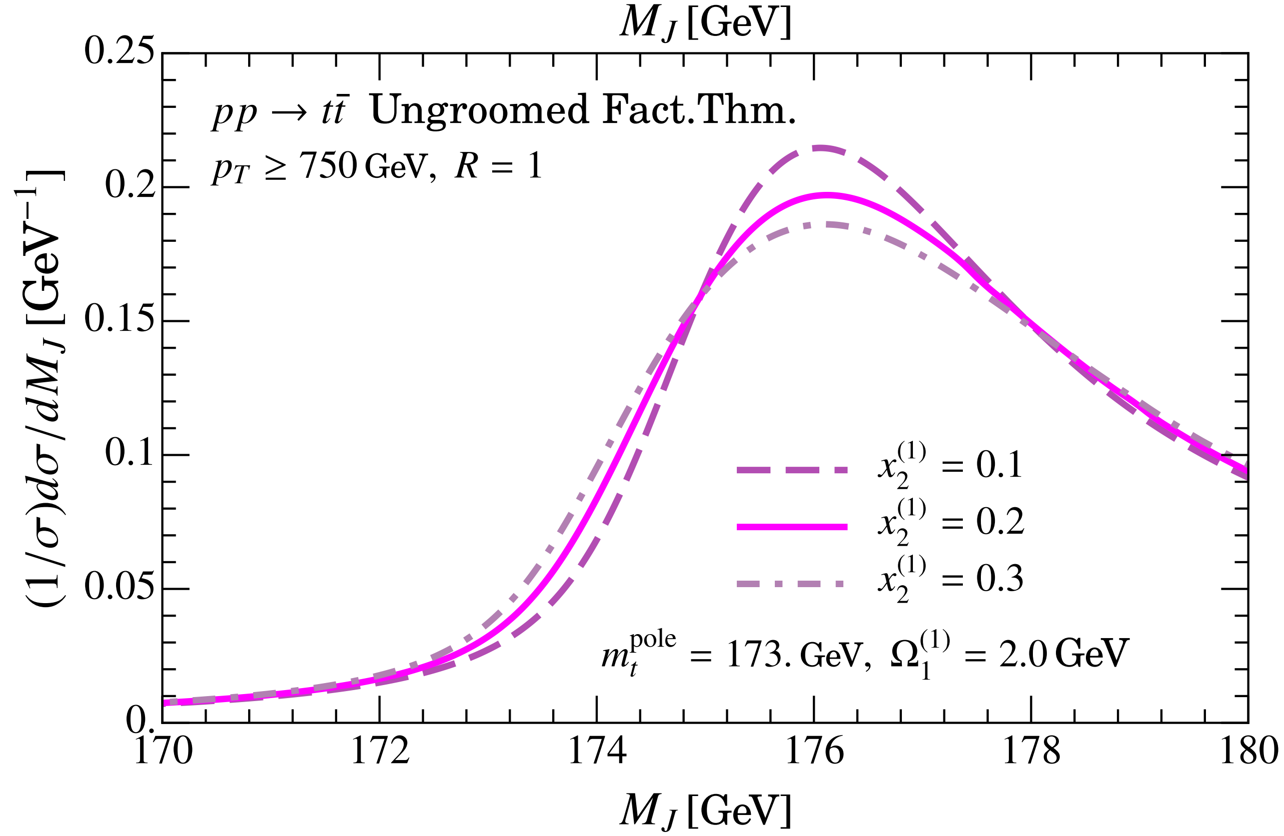
$$F(\ell) = \theta(\ell)\frac{\mathcal{N}(a,\Lambda)}{\Lambda}\left(\frac{\ell}{\Lambda}\right)^{a-1}\exp\left(\frac{-2\ell}{\Lambda}\right)$$

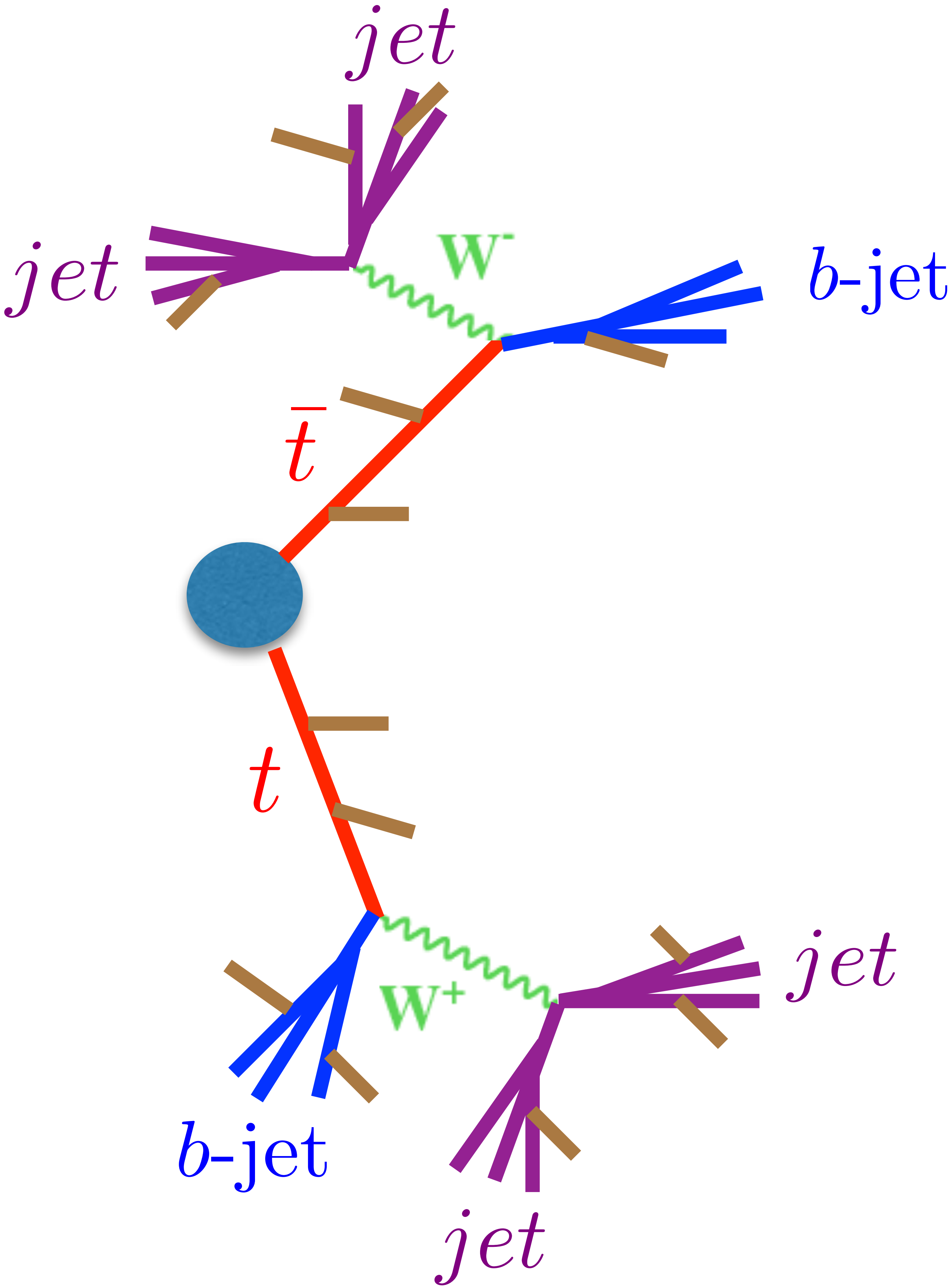
Top jets at the LHC using 2-jettiness

While the underlying event can be modeled in this framework, we would like to explore methods to directly reduce the contamination while retaining calculability in pQCD.









TOP JET MASS WITH SOFT DROP

Factorization for Groomed Top Jets

SOFT DROP GROOMING

Larkoski, Marzani, Soyez, Thaler 2014

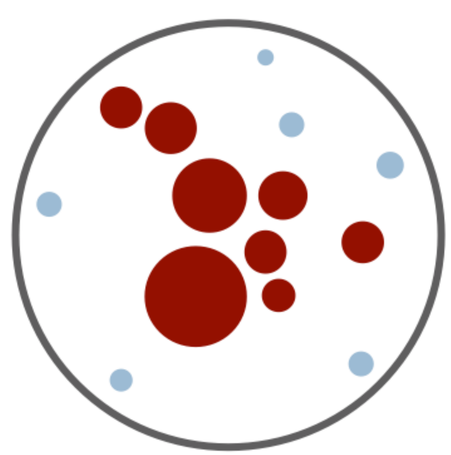
Two grooming parameters:

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

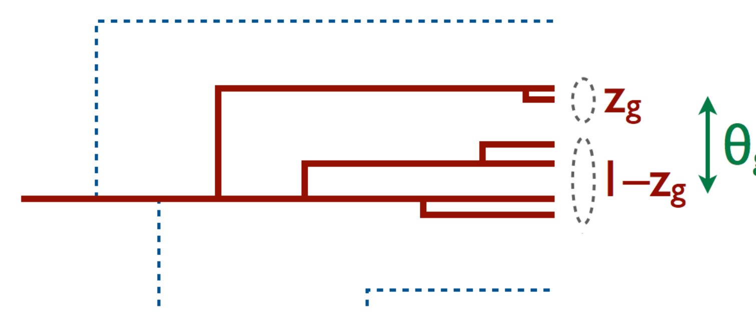
Grooms soft radiation from the jet

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

Groomed jet



Groomed Clustering tree



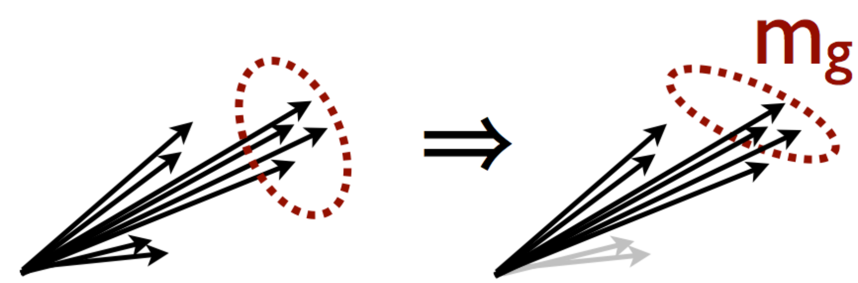
More Grooming — Less Grooming

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

GROOMED JET MASS

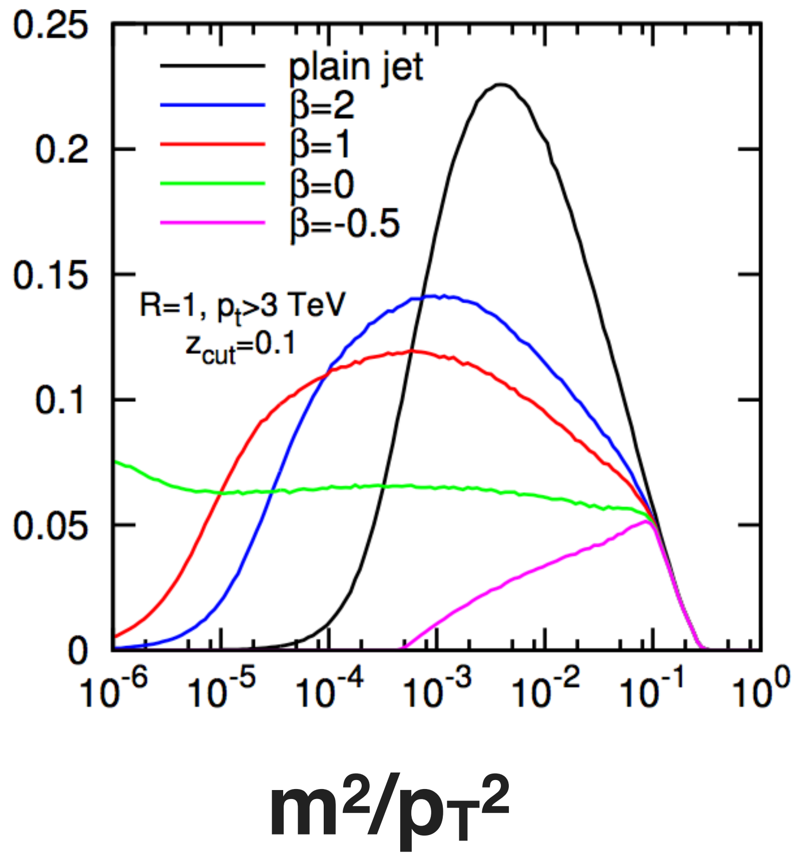
Larkoski, Marzani, Soyez, Thaler 2014

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

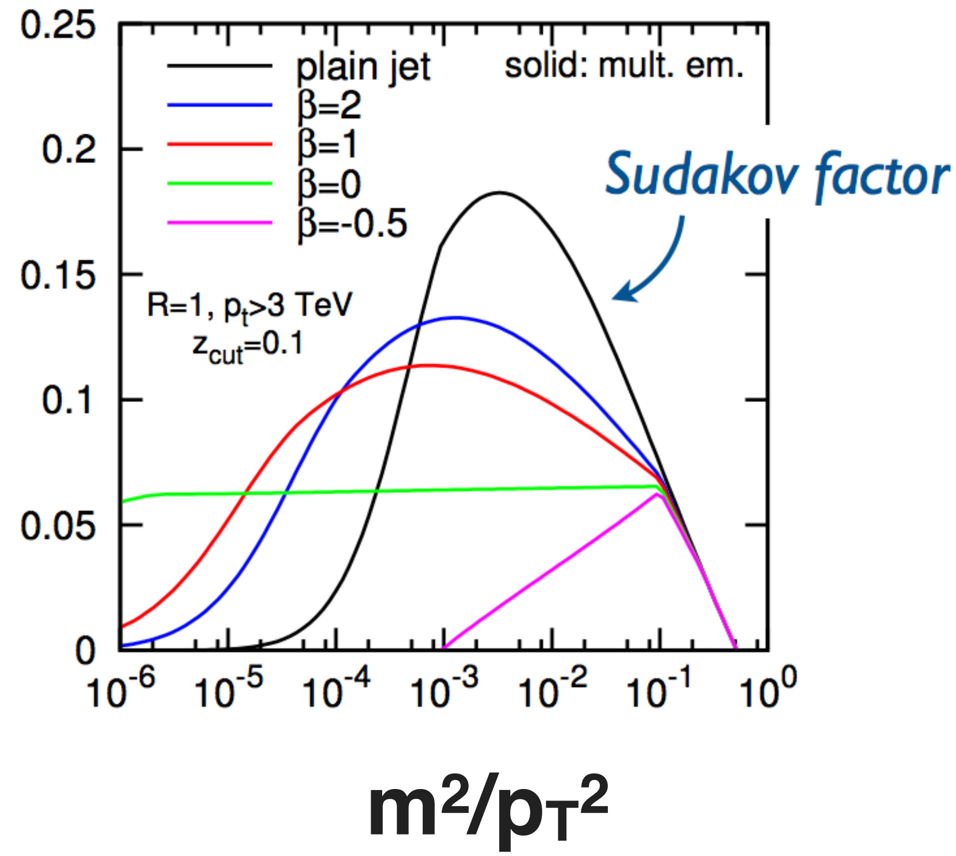


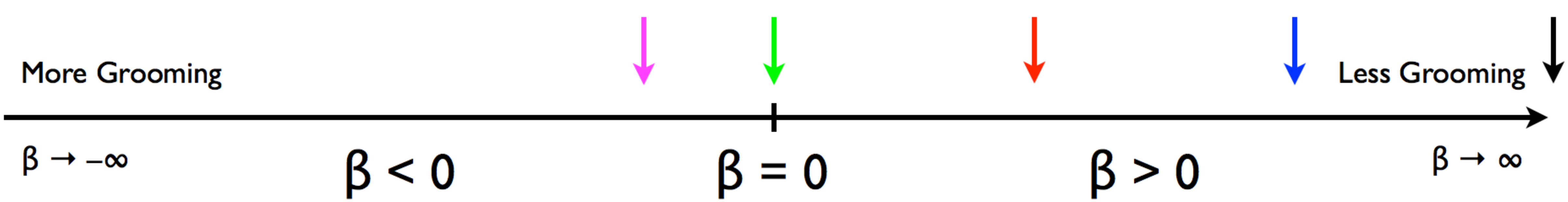
Soft drop has an advantage of being amenable to theoretical calculations

Pythia8, partonic



Pert QCD at ~ NLL





GROOMED TOP JET MASS

Hoang, Mantry, AP, Stewart 2017

Top quarks at the LHC with jet grooming (2017)

Factorization Theorem for Soft Drop Groomed Top Jets:

$$\frac{d\sigma}{dM_J} = N \int J_B \otimes S_C \otimes F_C$$

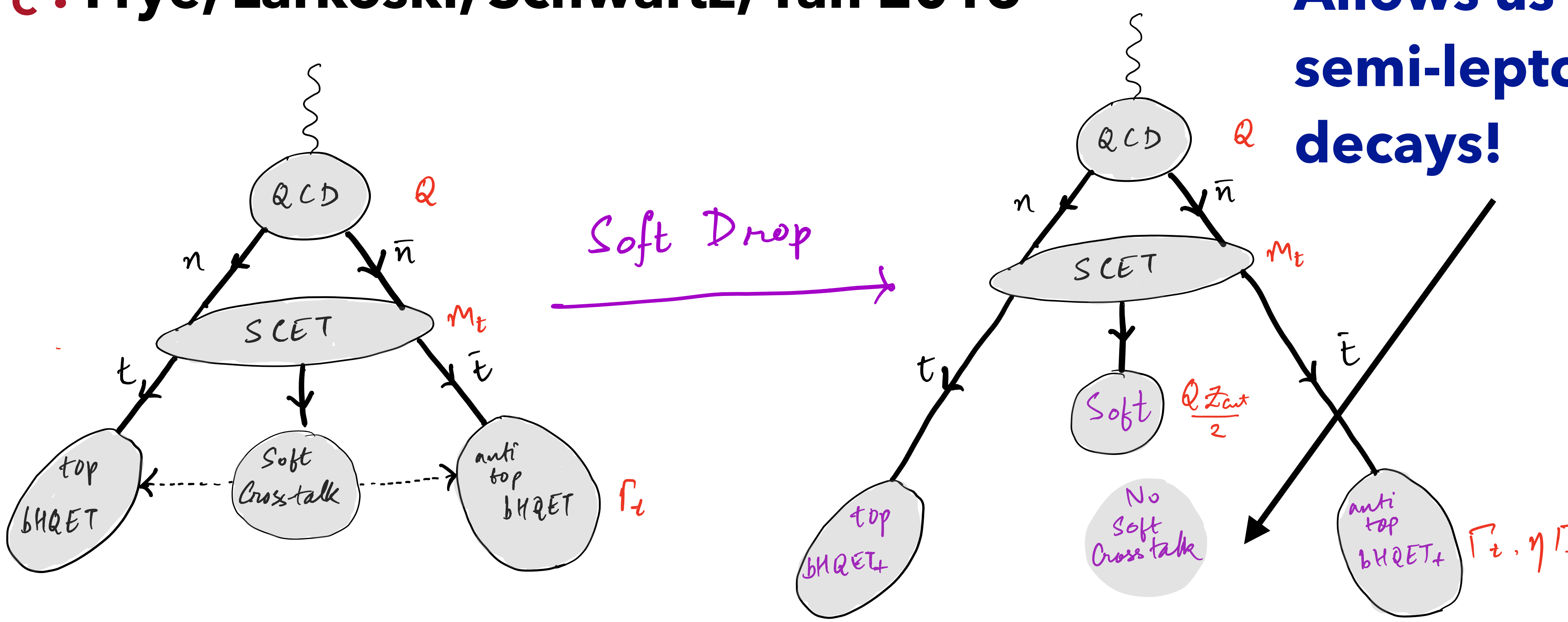
(more precise version up next)

The factorized cross section uses universal ingredients:

- **J_B : Fleming, Hoang, Mantry, Stewart 2007**
- **S_C, F_C : Frye, Larkoski, Schwartz, Yan 2016**

Allows us to use semi-leptonic decays!

EFTs:



1. MOTIVATION, GOAL, CHALLENGES
2. MODERN TECHNIQUES IN PERTURBATIVE QCD
3. USING THE THEORY TOOLS, TESTING ROBUSTNESS

1. MOTIVATION, GOAL, CHALLENGES
2. MODERN TECHNIQUES IN PERTURBATIVE QCD
3. USING THE THEORY TOOLS, TESTING ROBUSTNESS

HOW DO WE USE THESE THEORETICAL TOOLS?

Groomed top jet mass cross section: Hoang, Mantry, AP, Stewart 2017

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d,\, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)\big(2^\beta Q z_{\rm cut}\big)^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k,1) \qquad Q = 2\, p_T \cosh(\eta_J)$$

("decay" factorization)

$$D_t(\hat{s}', \Phi_d,\, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)}\, d_t(\Phi_d,\, m/Q)$$

HOW DO WE USE THESE THEORETICAL TOOLS?

Groomed top jet mass cross section:

Hoang, Mantry, AP, Stewart 2017

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu)\int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d,\, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)\big(2^\beta Q z_{\rm cut}\big)^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k,1) \qquad Q = 2\, p_T \cosh(\eta_J)$$

$$D_t(\hat{s}', \Phi_d,\, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)}\, d_t(\Phi_d,\, m/Q)$$

Merits of EFT calculation:

- **Fully correct computation:** **gluon radiation off the top and decays properly accounted for. Width dependence of radiation taken care of.**
- **Scale settings:** **Bulk of higher order corrections already taken care of through scale settings. Experience from ee studies.**
- **Resummation of logarithms:** **EFT approach designed for specific kinematics of this process.**

HOW DO WE USE THESE THEORETICAL TOOLS?

Groomed top jet mass cross section:

Hoang, Mantry, AP, Stewart 2017

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d,\, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)(2^\beta Q z_{\rm cut})^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k, 1) \qquad Q = 2\, p_T \cosh(\eta_J)$$

$$D_t(\hat{s}', \Phi_d,\, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)}\, d_t(\Phi_d,\, m/Q)$$

Parameters in the factorization formula:

- **Kinematic scales p_T, η_J : determines statistics of boosted top events**
- **m_t and Ω_1 : parameters to be fitted (Γ_t is fixed to SM value)**
- **δm : choice of renormalization scheme**
- **Soft drop parameters z_{cut} and β: adjust the strength of the groomer**
- **Renormalization scale μ: use for estimating perturbative uncertainties**

HOW DO WE USE THESE THEORETICAL TOOLS?

Groomed top jet mass cross section:

Hoang, Mantry, AP, Stewart 2017

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu)\int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d,\, m/Q)\int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\Big(\Phi_d, \frac{m}{Q}\Big)\Big)\big(2^\beta Q z_{\rm cut}\big)^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k, 1) \qquad Q = 2\, p_T \cosh(\eta_J)$$

$$D_t(\hat{s}', \Phi_d,\, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)}\, d_t(\Phi_d,\, m/Q)$$

Parameters in the factorization formula:

- **Kinematic scales p_T, η_J : determines statistics of boosted top events**
- **m_t and Ω_1 : parameters to be fitted (Γ_t is fixed to SM value)**
- **δm : choice of renormalization scheme**
- **Soft drop parameters $z_{\rm cut}$ and β: adjust the strength of the groomer**
- **Renormalization scale μ: use for estimating perturbative uncertainties**

HOW DO WE USE THESE THEORETICAL TOOLS?

Groomed top jet mass cross section:

Hoang, Mantry, AP, Stewart 2017

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\text{cut}}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)\big(2^\beta Q z_{\text{cut}}\big)^{\frac{1}{1+\beta}}, \beta, \mu\Big] F_C(k, 1) \qquad Q = 2\, p_T \cosh(\eta_J)$$

$$D_t(\hat{s}', \Phi_d, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^2 + \Gamma_t^2)}\, d_t(\Phi_d, m/Q)$$

Parameters in the factorization formula:

- **Kinematic scales p_T, η_J :** determines statistics of boosted top events
- **m_t and Ω_1 :** parameters to be fitted (Γ_t is fixed to SM value)
- **δm :** choice of renormalization scheme
- **Soft drop parameters z_{cut} and β:** adjust the strength of the groomer
- **Renormalization scale μ:** use for estimating perturbative uncertainties

HOW DO WE USE THESE THEORETICAL TOOLS?

Groomed top jet mass cross section:

Hoang, Mantry, AP, Stewart 2017

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu)\int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d,\, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)\big(2^\beta Q z_{\rm cut}\big)^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k,1) \qquad Q = 2\, p_T \cosh(\eta_J)$$

$$D_t(\hat{s}', \Phi_d,\, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)}\, d_t(\Phi_d,\, m/Q)$$

Parameters in the factorization formula:

- **Kinematic scales p_T, η_J : determines statistics of boosted top events**
- **m_t and Ω_1 : parameters to be fitted (Γ_t is fixed to SM value)**
- **δm : choice of renormalization scheme**
- **Soft drop parameters z_{cut} and β: adjust the strength of the groomer**
- **Renormalization scale μ: use for estimating perturbative uncertainties**

HOW DO WE USE THESE THEORETICAL TOOLS?

Groomed top jet mass cross section:

Hoang, Mantry, AP, Stewart 2017

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\Big(\Phi_d, \frac{m}{Q}\Big)\Big)\big(2^\beta Q z_{\rm cut}\big)^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k, 1) \qquad Q = 2\, p_T \cosh(\eta_J)$$

$$D_t(\hat{s}', \Phi_d, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)}\, d_t(\Phi_d, m/Q)$$

Parameters in the factorization formula:

- **Kinematic scales p_T, η_J :** **determines statistics of boosted top events**
- **m_t and Ω_1 :** **parameters to be fitted (Γ_t is fixed to SM value)**
- **δm :** **choice of renormalization scheme**
- **Soft drop parameters $z_{\rm cut}$ and β:** **adjust the strength of the groomer**
- **Renormalization scale μ:** **use for estimating perturbative uncertainties**

HOW DO WE USE THESE THEORETICAL TOOLS?

Groomed top jet mass cross section:

Hoang, Mantry, AP, Stewart 2017

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)\big(2^\beta Q z_{\rm cut}\big)^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k,1) \qquad Q = 2\, p_T \cosh(\eta_J)$$

$$D_t(\hat{s}', \Phi_d, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)}\, d_t(\Phi_d, m/Q)$$

Parameters in the factorization formula:

- **Kinematic scales p_T, η_J :** determines statistics of boosted top events
- **m_t and Ω_1 :** parameters to be fitted (Γ_t is fixed to SM value)
- **δm :** choice of renormalization scheme
- **Soft drop parameters z_{cut} and β:** adjust the strength of the groomer
- **Renormalization scale μ:** use for estimating perturbative uncertainties

HOW DO WE USE THESE THEORETICAL TOOLS?

Groomed top jet mass cross section:

Hoang, Mantry, AP, Stewart 2017

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)(2^\beta Q z_{\rm cut})^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k, 1) \qquad Q = 2\, p_T \cosh(\eta_J)$$

$$D_t(\hat{s}', \Phi_d, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^2 + \Gamma_t^2)}\, d_t(\Phi_d, m/Q)$$

Parameters in the factorization formula:

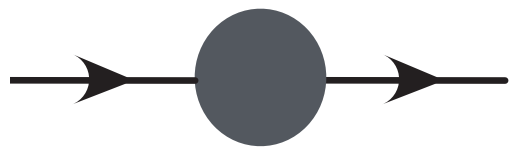
- **Kinematic scales p_T, η_J : determines statistics of boosted top events**
- **m_t an**
- **δm : (**
- **Soft (** ... **ner**
- **Renormalization scale μ: use for estimating perturbative uncertainties**

Power counting in the EFTs involved imposes strong constraints on the ranges of these parameters.

CONSTRAINTS FROM POWER COUNTING

Constraints on the top mass scheme choice:

(pole mass does not violate power counting)

Pole Mass:  $\propto \frac{1}{\not{p} - m_t^{\text{pole}}}$ $\qquad \Delta m_t^{\text{pole}} \sim \Lambda_{\text{QCD}}$

- **Good for electron in QED, but NOT for quarks: renormalon ambiguity**

$\overline{\text{MS}}$ Mass: $\overline{m}_t$

- **No ambiguity and suitable for inclusive cross sections, but NOT for kinematic extraction: incompatible with Breit-Wigner**

$$m_t^{\text{pole}} = \overline{m}_t + \underbrace{0.4\,\alpha_s \overline{m}_t}_{7\,\text{GeV}\ \gg\ \Gamma_t = 1.4\,\text{GeV}} + \ldots$$

MSR Mass:

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

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

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

- **Take R ~ Γ_t : No Ambiguity and Compatible with Breit Wigner**

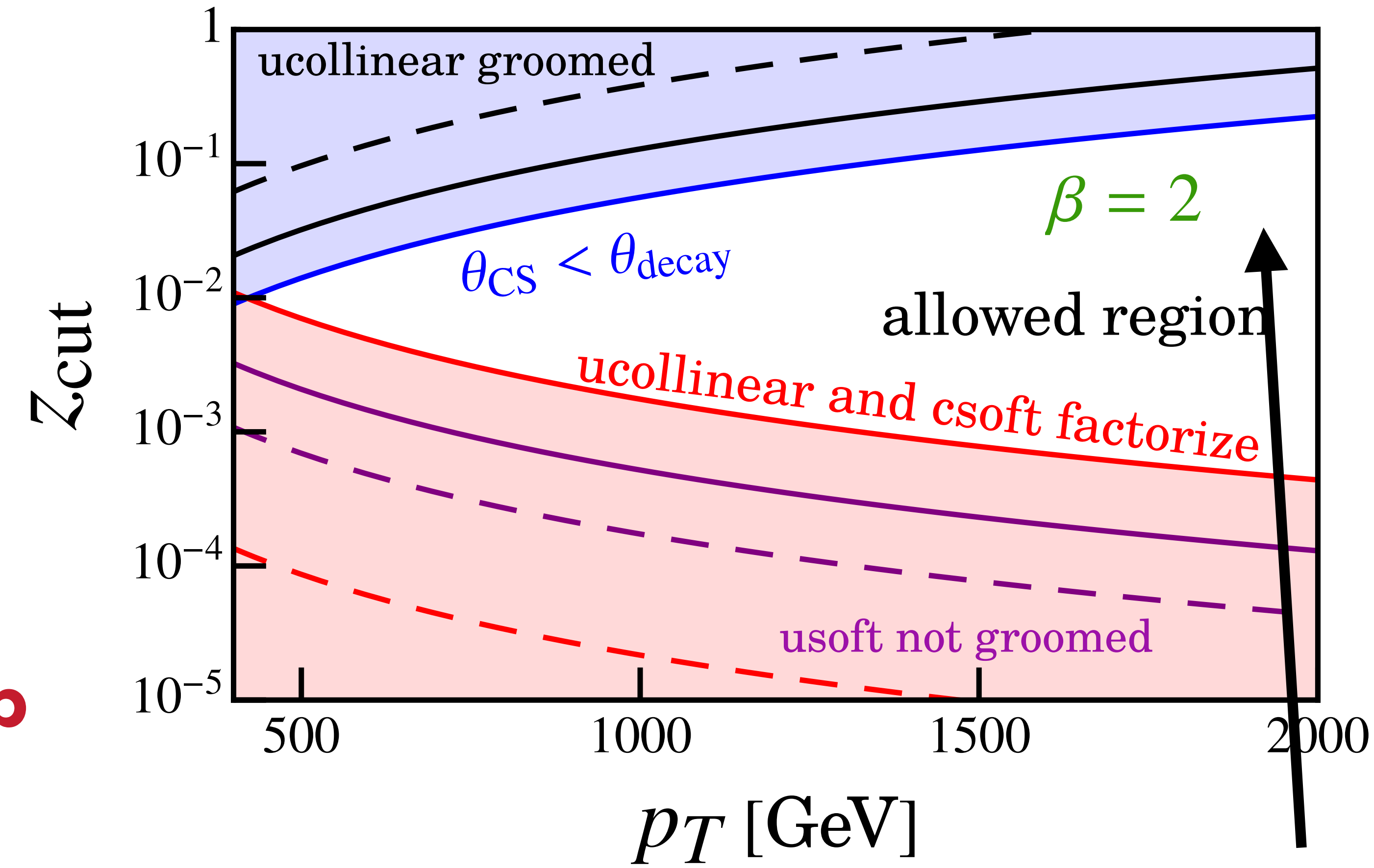
CONSTRAINTS FROM POWER COUNTING

Constraints on the kinematic region and soft drop parameters:

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

Ensure soft drop does not touch mass

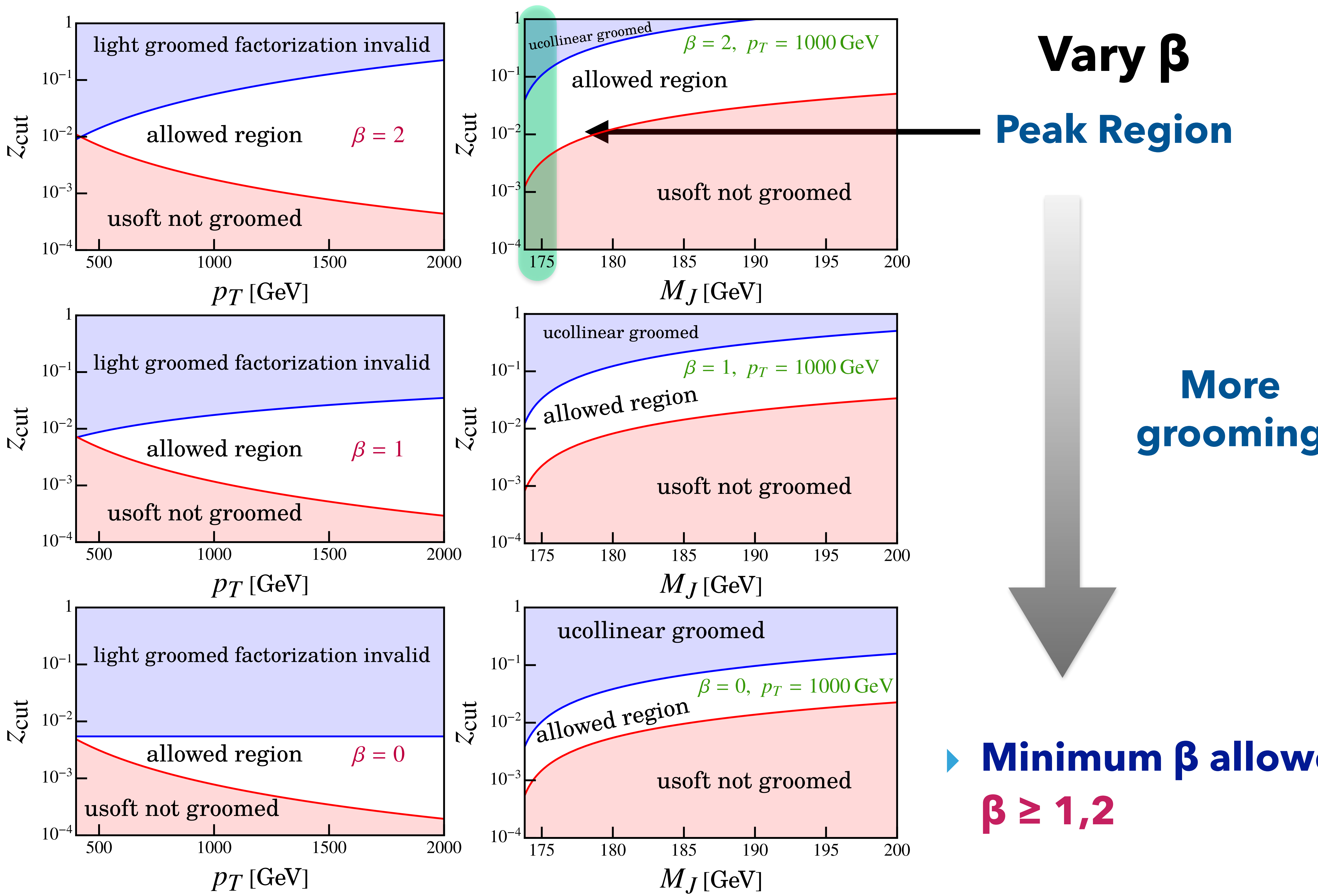
Ensure soft drop removes most contamination



"light grooming" here

- **Light grooming region: $z_{\rm cut}$ ~ 1%**
- **Minimum p_T allowed by constraints: p_T ~ 500 GeV**

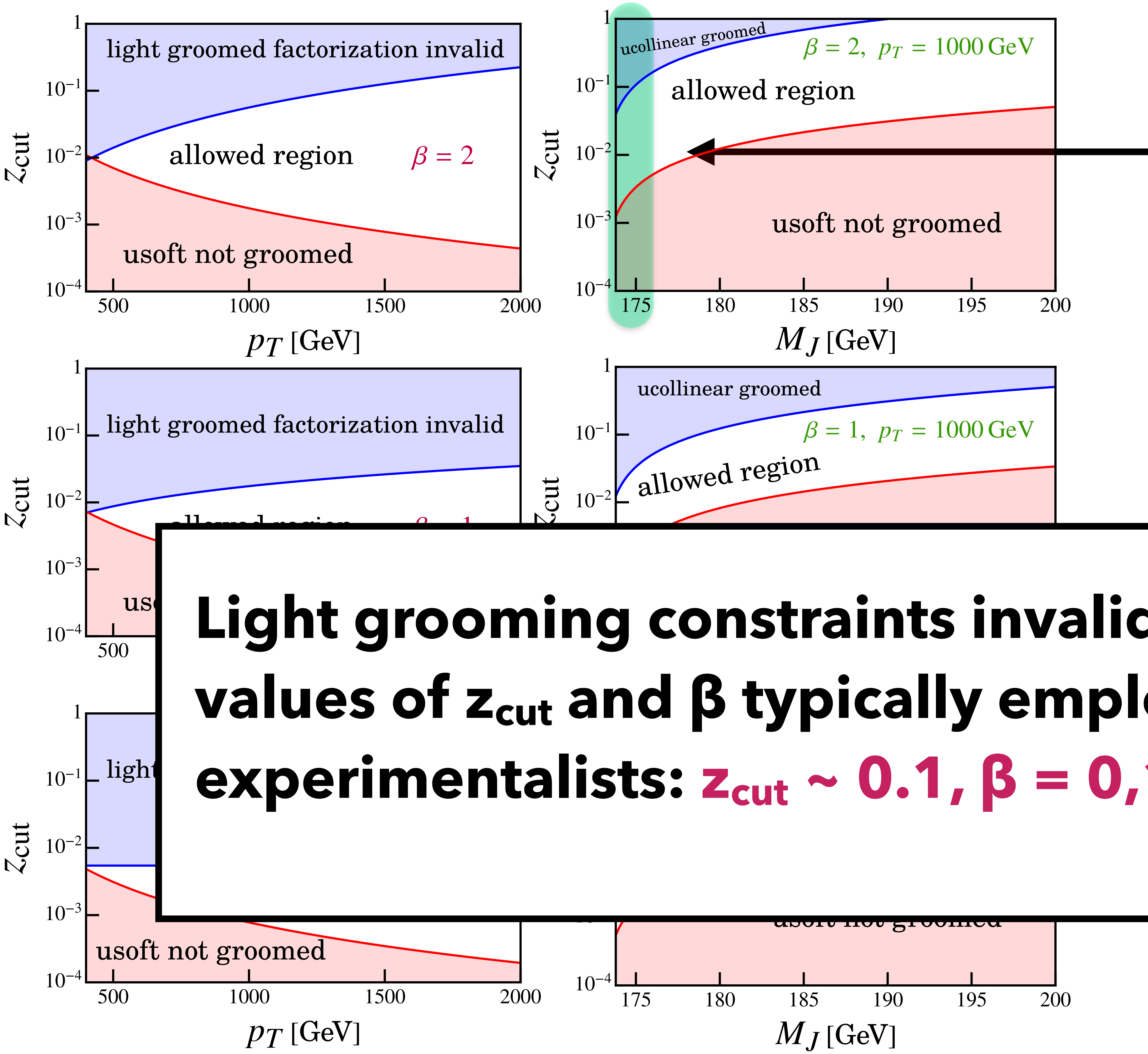
CONSTRAINTS FROM POWER COUNTING



Vary β

- **Minimum β allowed:** **β ≥ 1,2**

CONSTRAINTS FROM POWER COUNTING



Vary β

Peak Region

More grooming

owed:

β ≥ 1,2

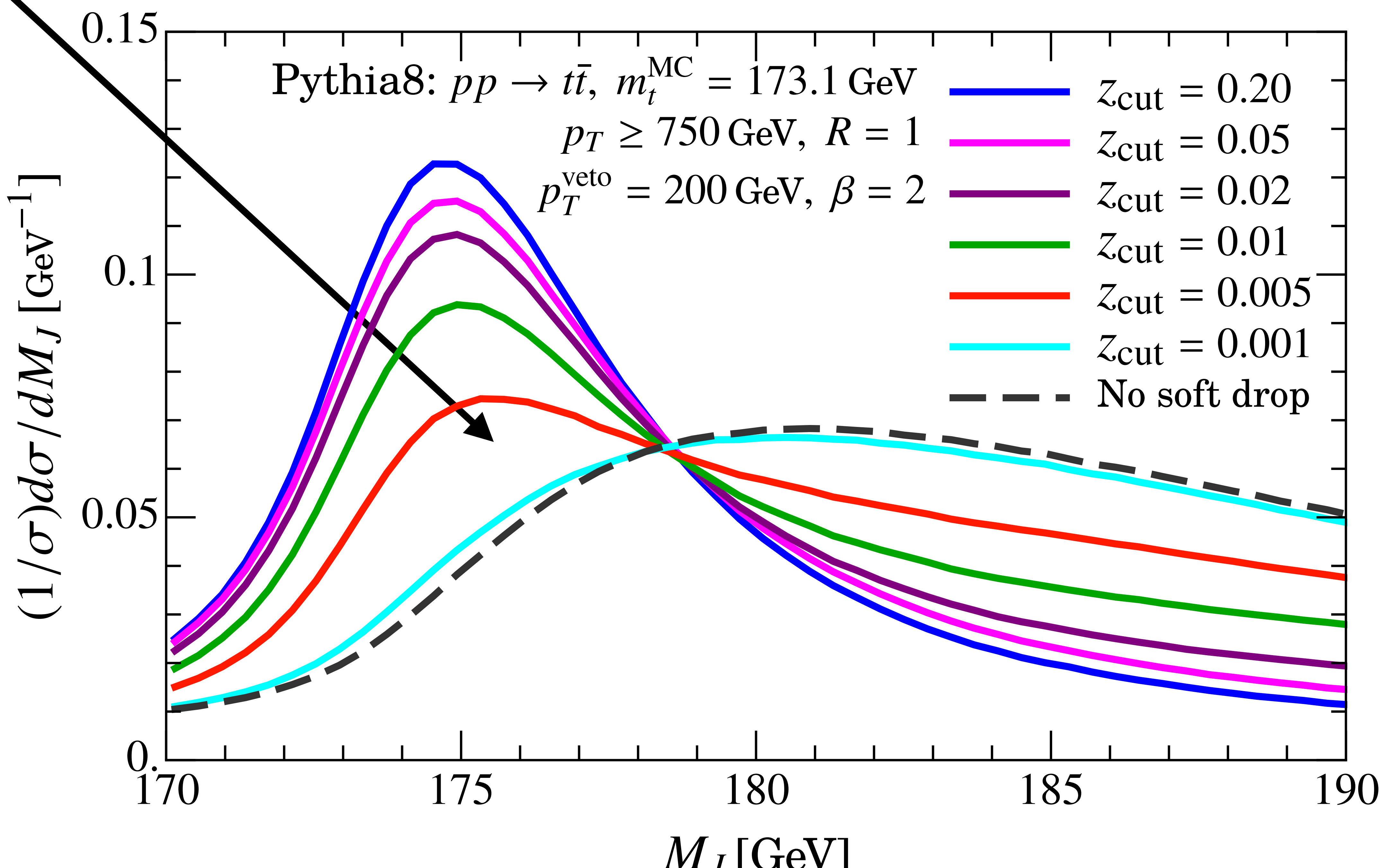
Light grooming constraints invalidate values of z_{cut} and β typically employed by experimentalists: $z_{cut} \sim 0.1$, β = 0,1

TESTING EFFECTIVENESS OF LIGHT GROOMING

TESTING EFFECTIVENESS OF LIGHT GROOMING

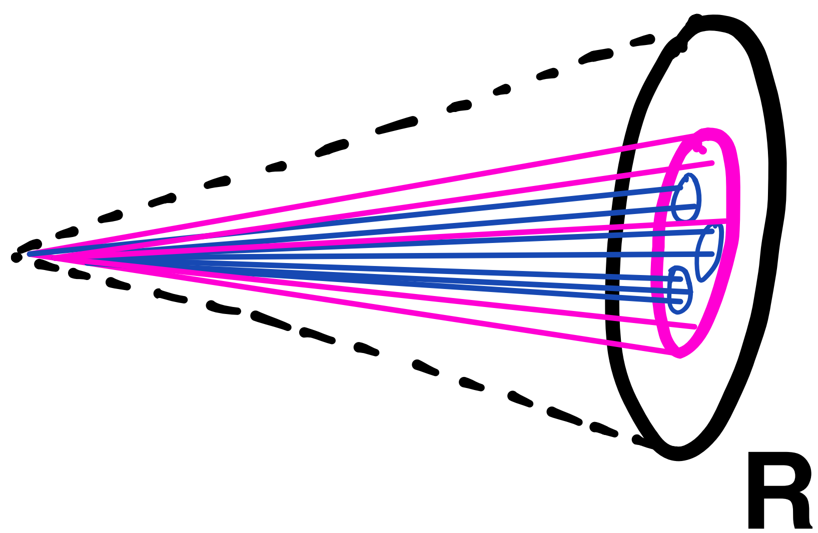
- **Most Contamination is removed with light grooming.**

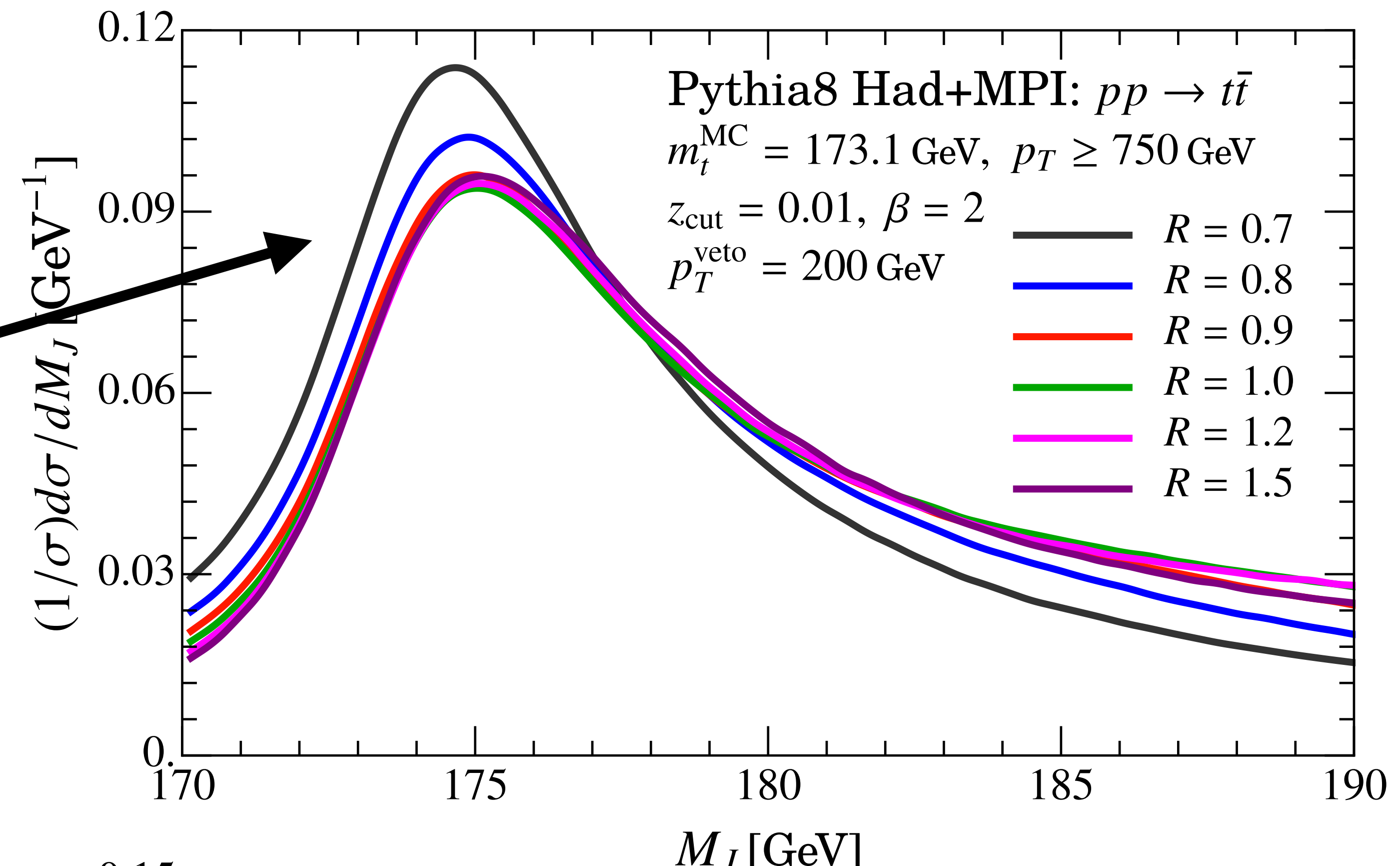
Predict: transition at z_{cut} ~ 1% ✓



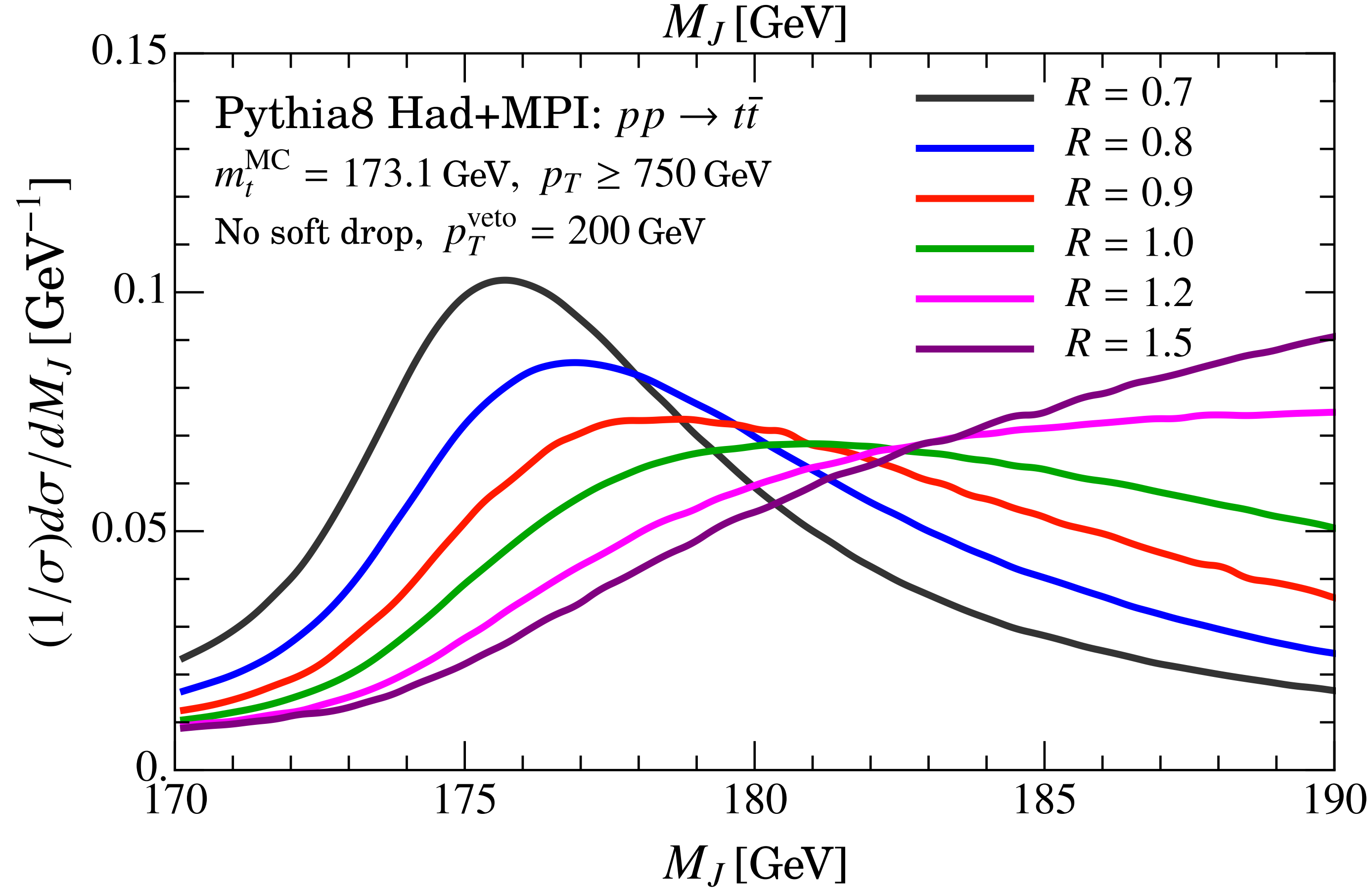
TESTING EFFECTIVENESS OF LIGHT GROOMING

Predict: Independent of Jet Radius ✓



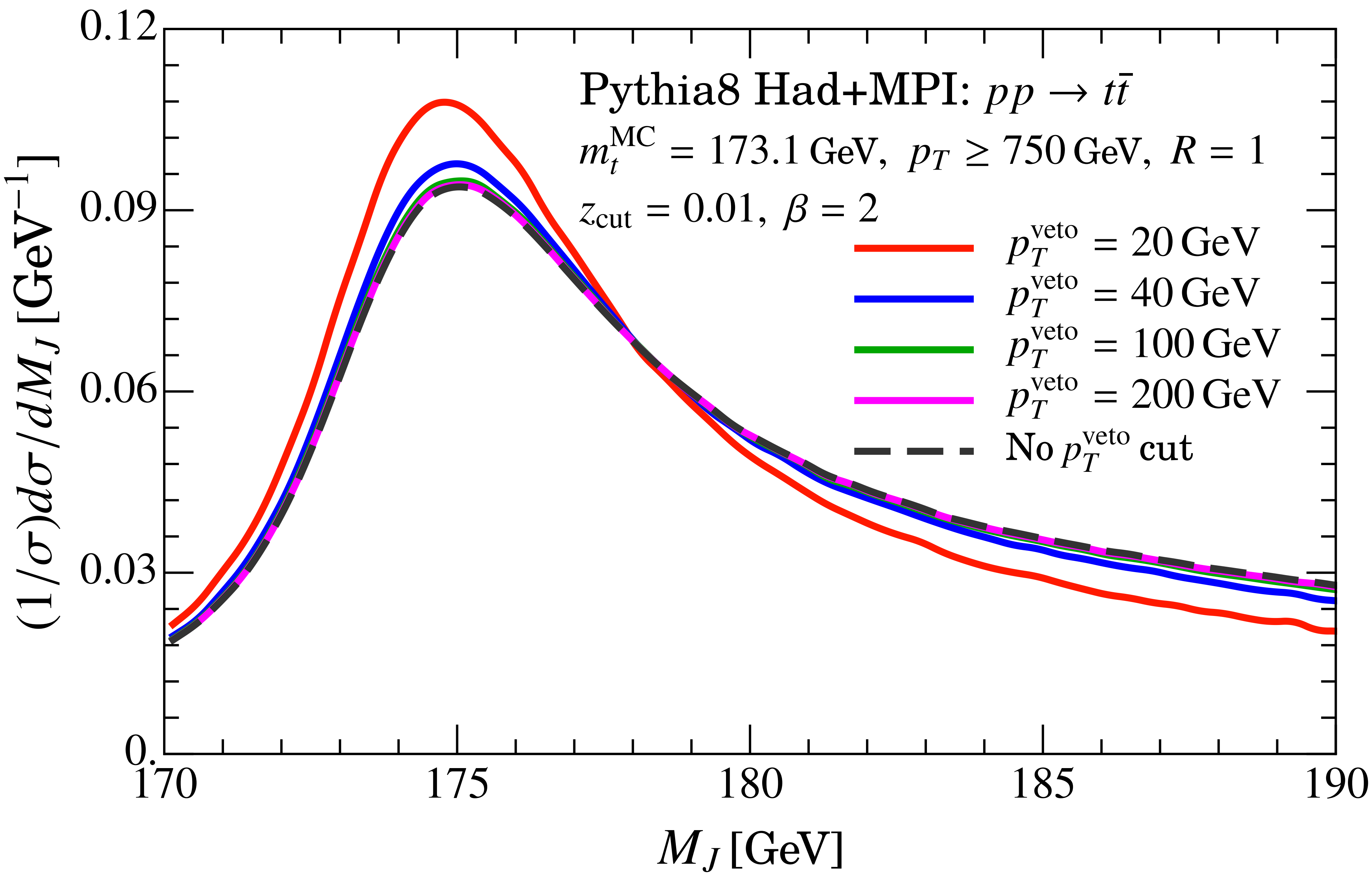


- **Without Soft Drop (huge):**



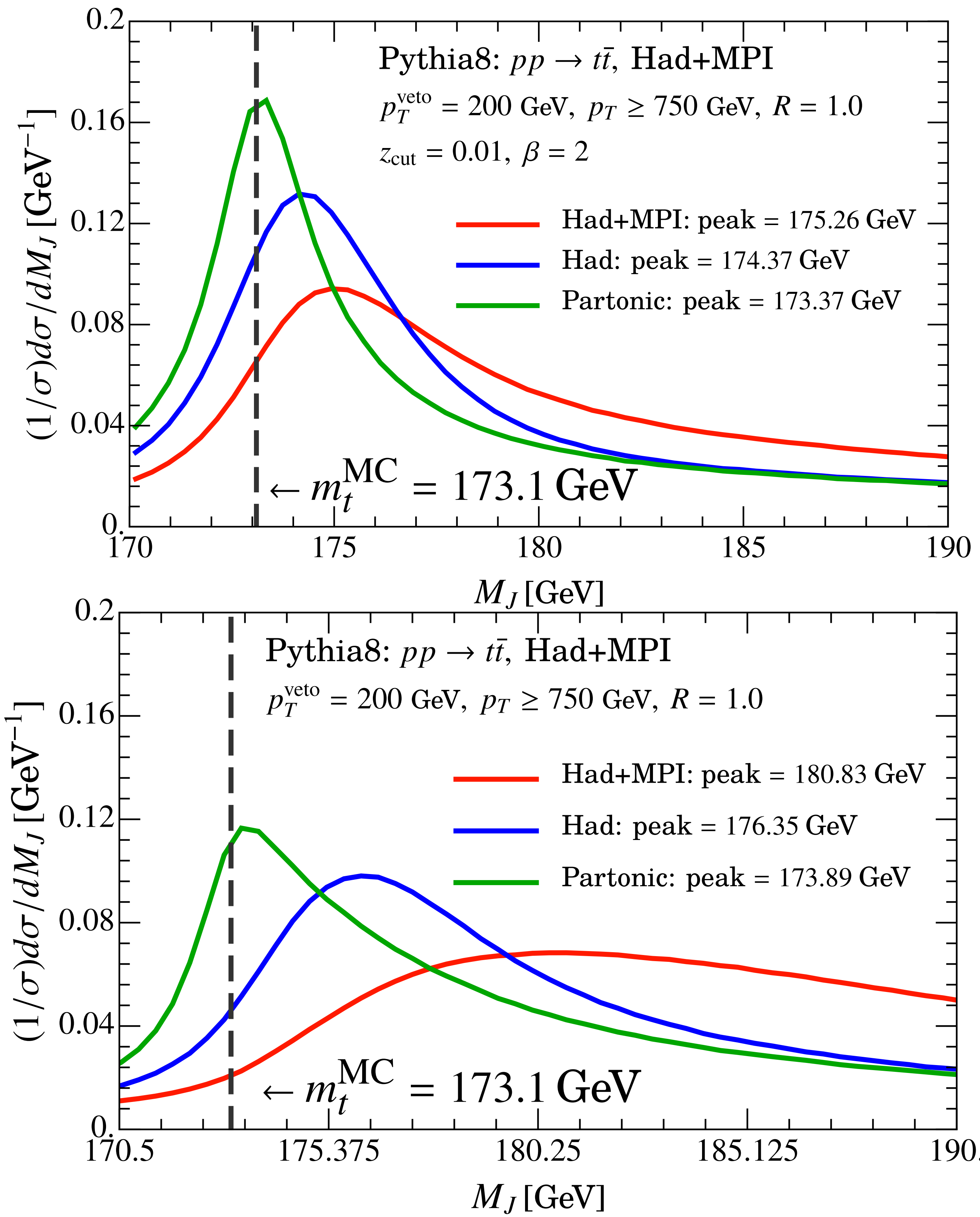
TESTING EFFECTIVENESS OF LIGHT GROOMING

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



TESTING EFFECTIVENESS OF LIGHT GROOMING

Significant improvement with soft drop:

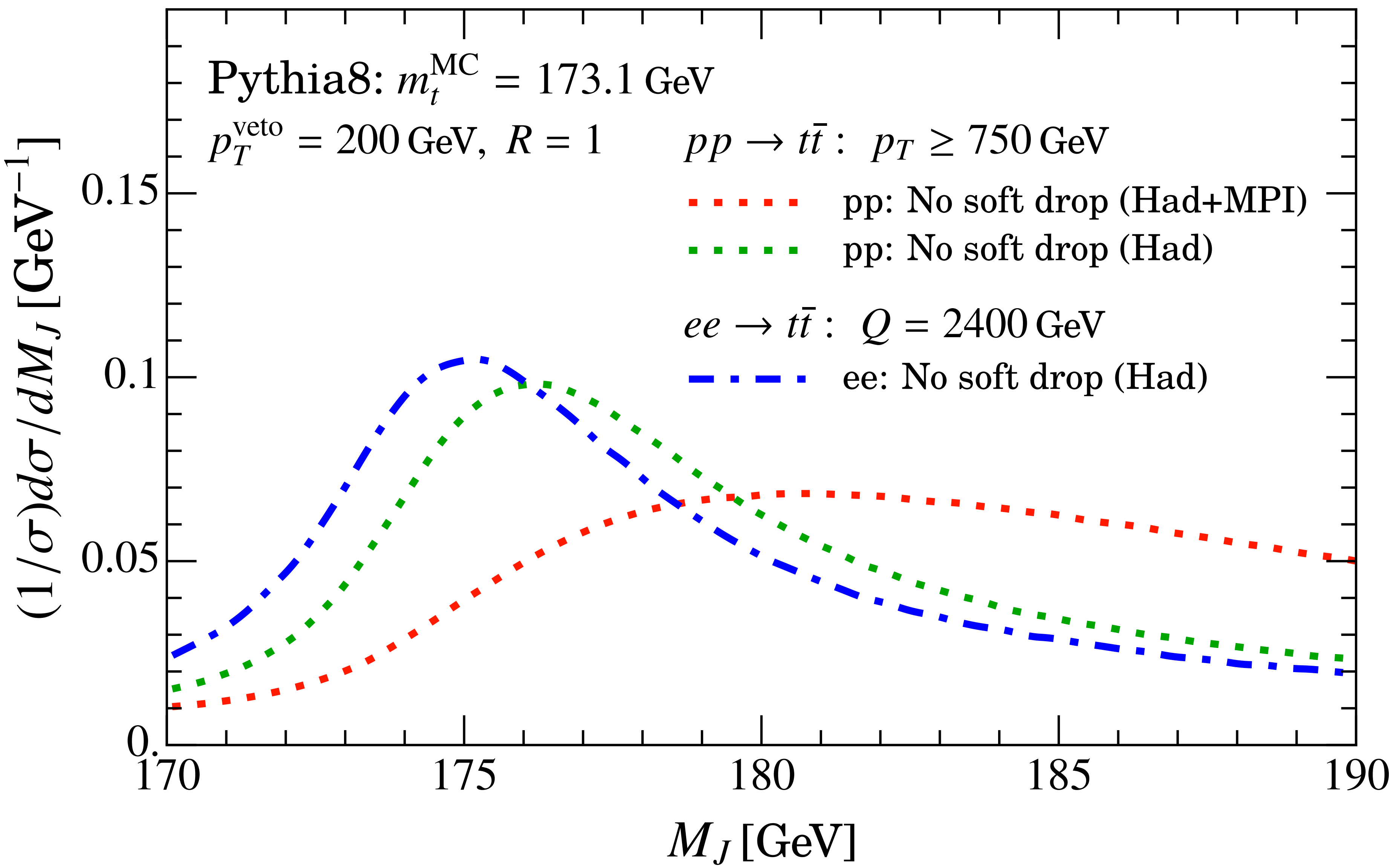


TESTING EFFECTIVENESS OF LIGHT GROOMING

$$Q = 2\, p_T \cosh(\eta_J)$$

Soft Drop Prediction:
e^+e^- and pp collisions should be close for similar kinematics

Without Soft Drop (differ):



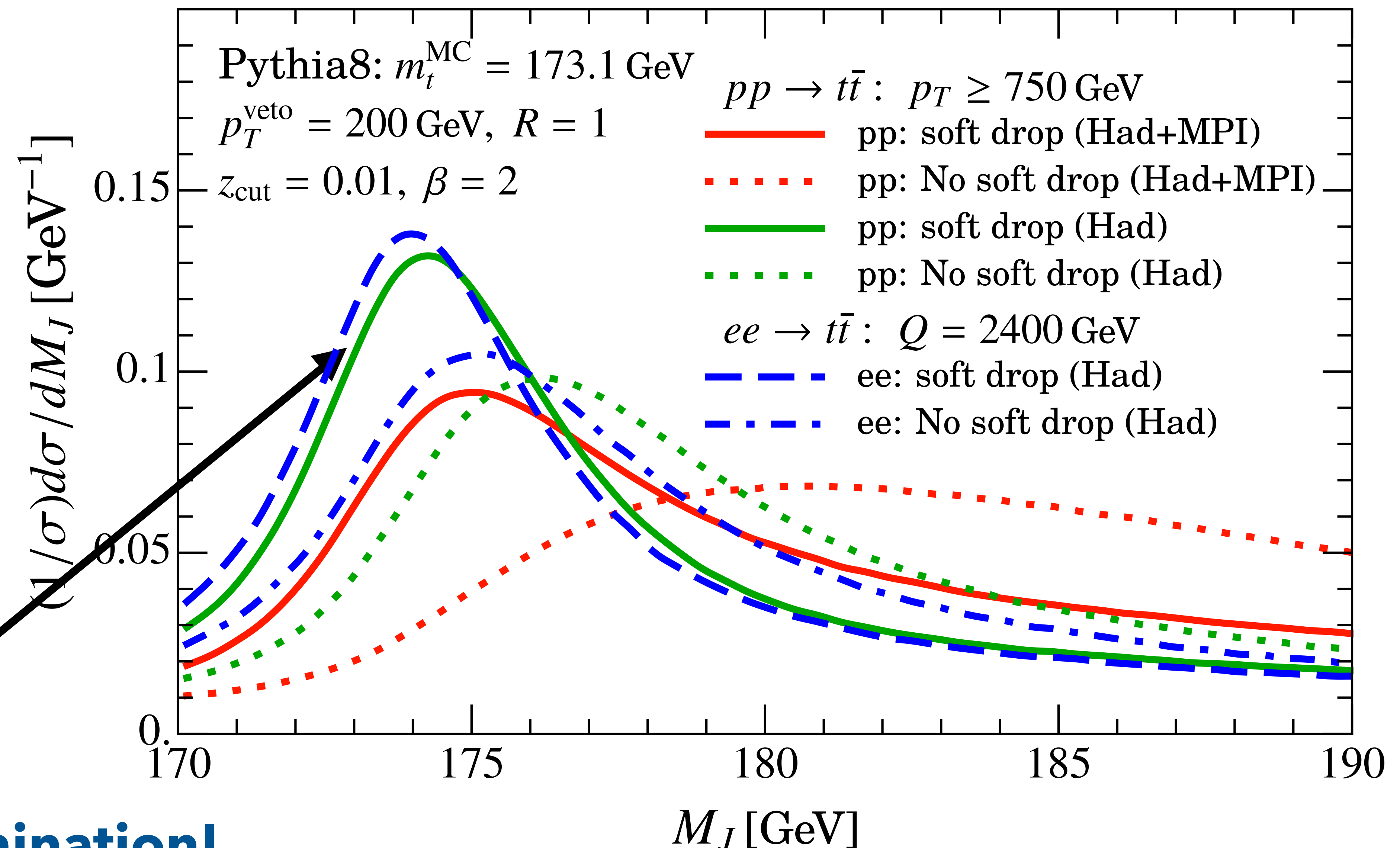
TESTING EFFECTIVENESS OF LIGHT GROOMING

Soft Drop Prediction: ✓

$$Q = 2\, p_T \cosh(\eta_J)$$

e^+e^- and pp collisions should be close for similar kinematics

With Soft Drop (peaks within 0.2 GeV):



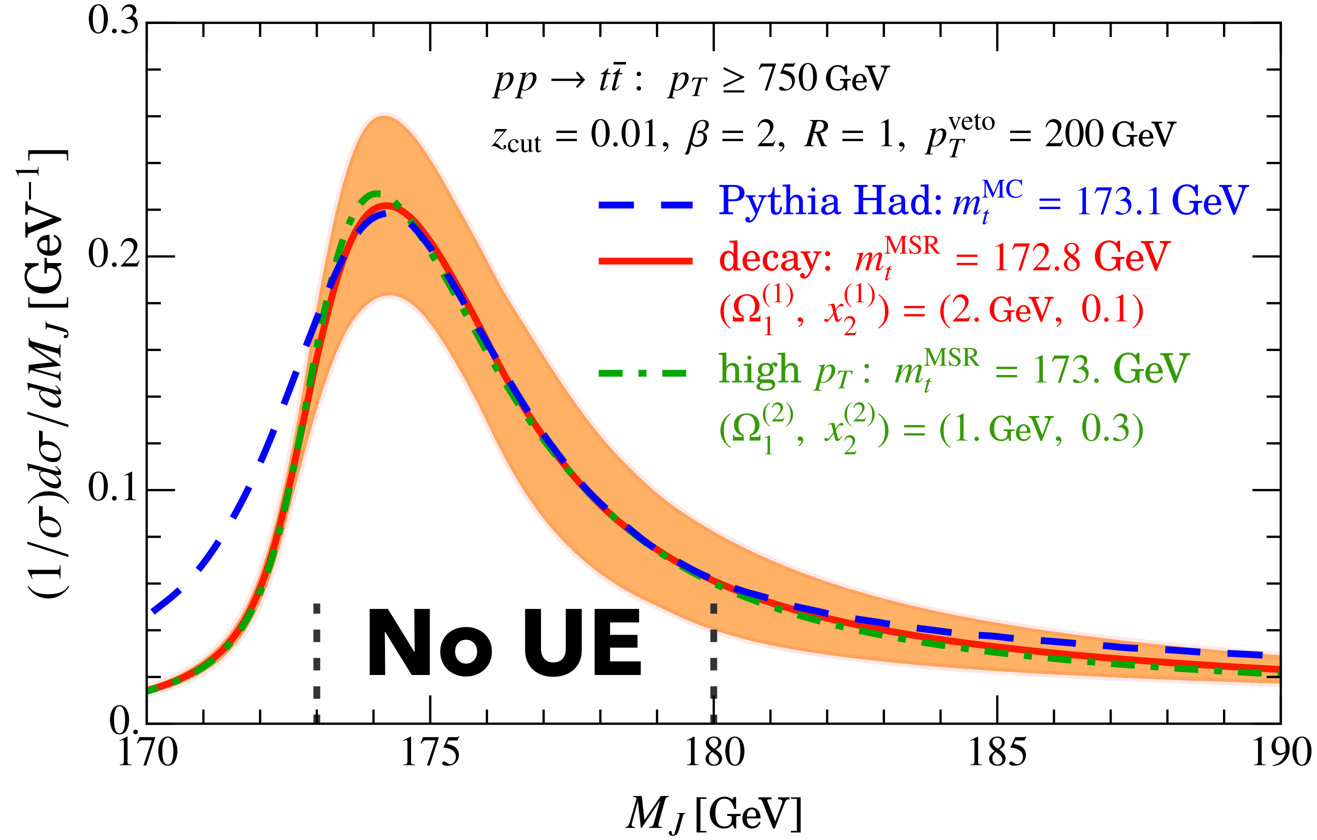
Much Smaller Contamination!

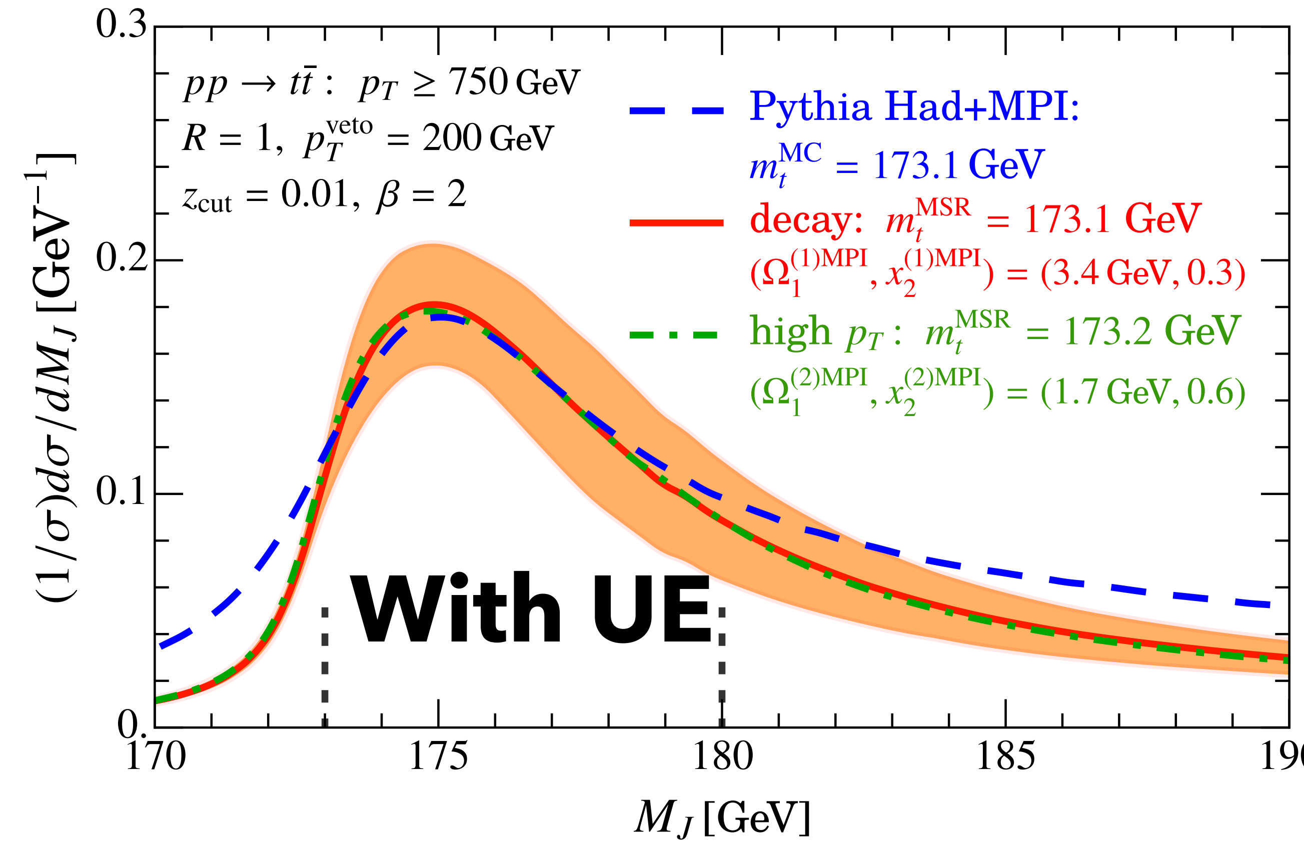
TESTING ROBUSTNESS OF THE THEORY

TESTING ROBUSTNESS OF THE THEORY

Independent NLL theory fits to Had-only and Had+MPI Pythia

- **Expect a dominant change in Ω_1:** **Nonperturbative corrections can model UE.**
- **Expect m_t to remain the same:** **Nonperturbative corrections well understood and do NOT mix with the perturbative components.**

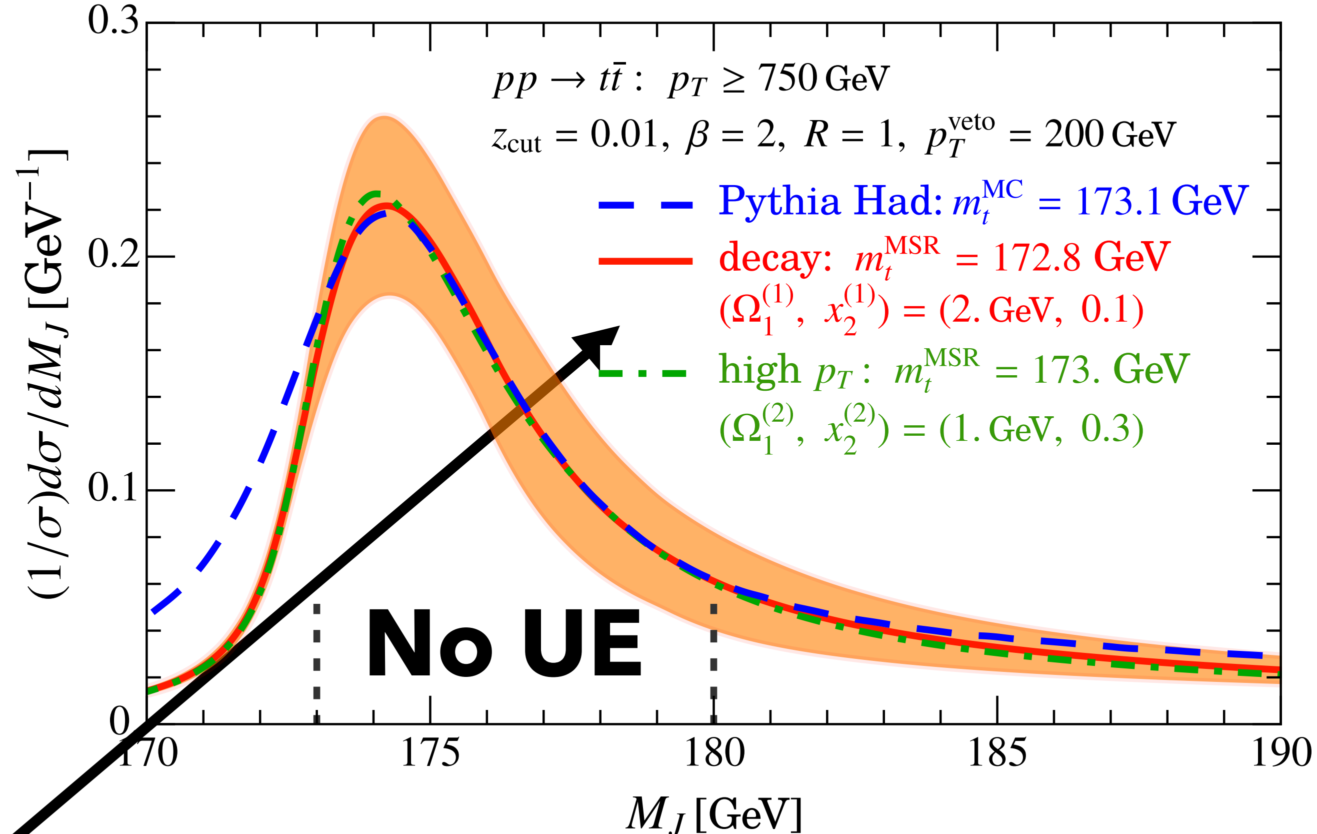


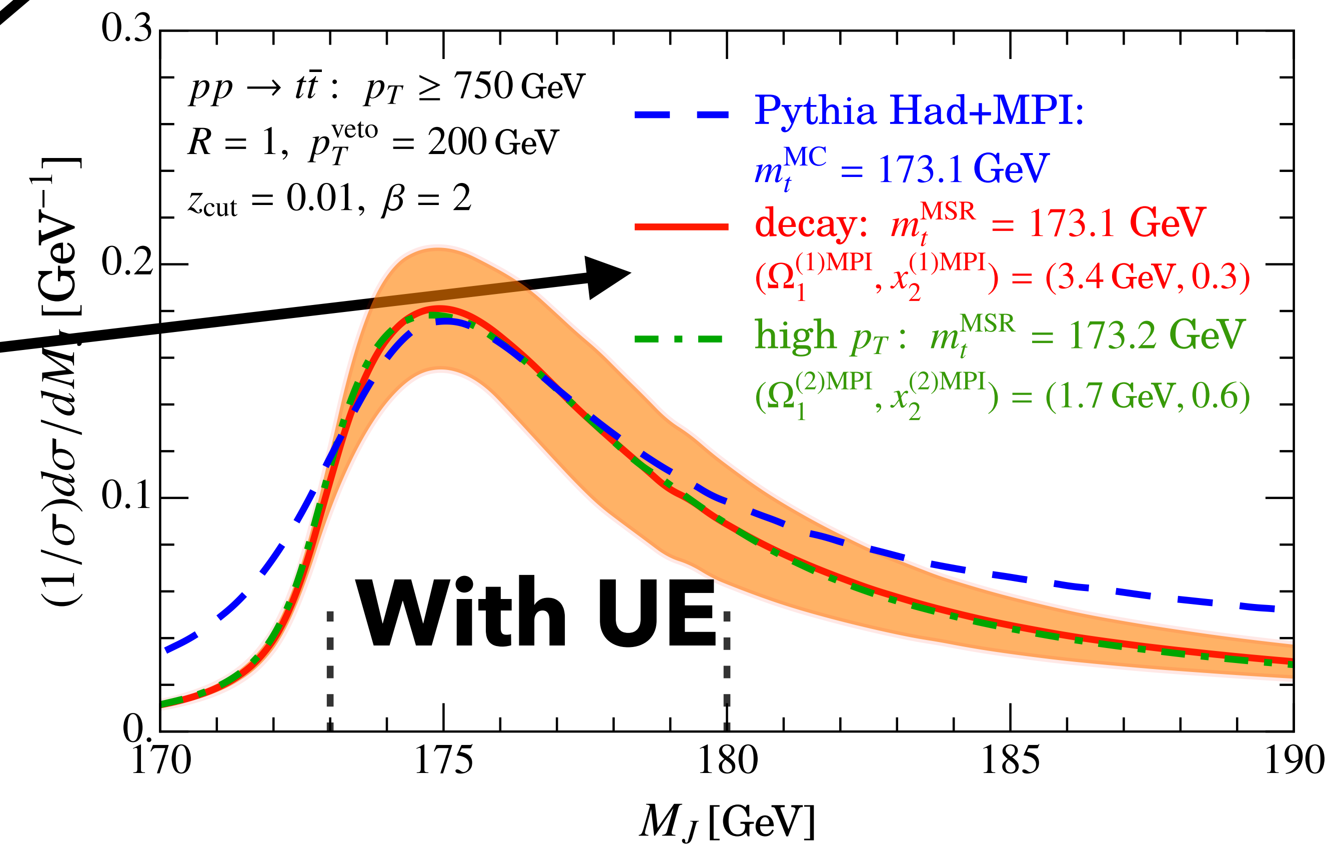


TESTING ROBUSTNESS OF THE THEORY

Independent NLL theory fits to Had-only and Had+MPI Pythia

- **Expect a dominant change in Ω_1:** Nonperturbative corrections can model UE.
- **Expect m_t to remain the same:** Nonperturbative corrections well understood and do NOT mix with the perturbative components.
- **Get m_t within 0.3 GeV**
- **Bands correspond to perturbative uncertainty**



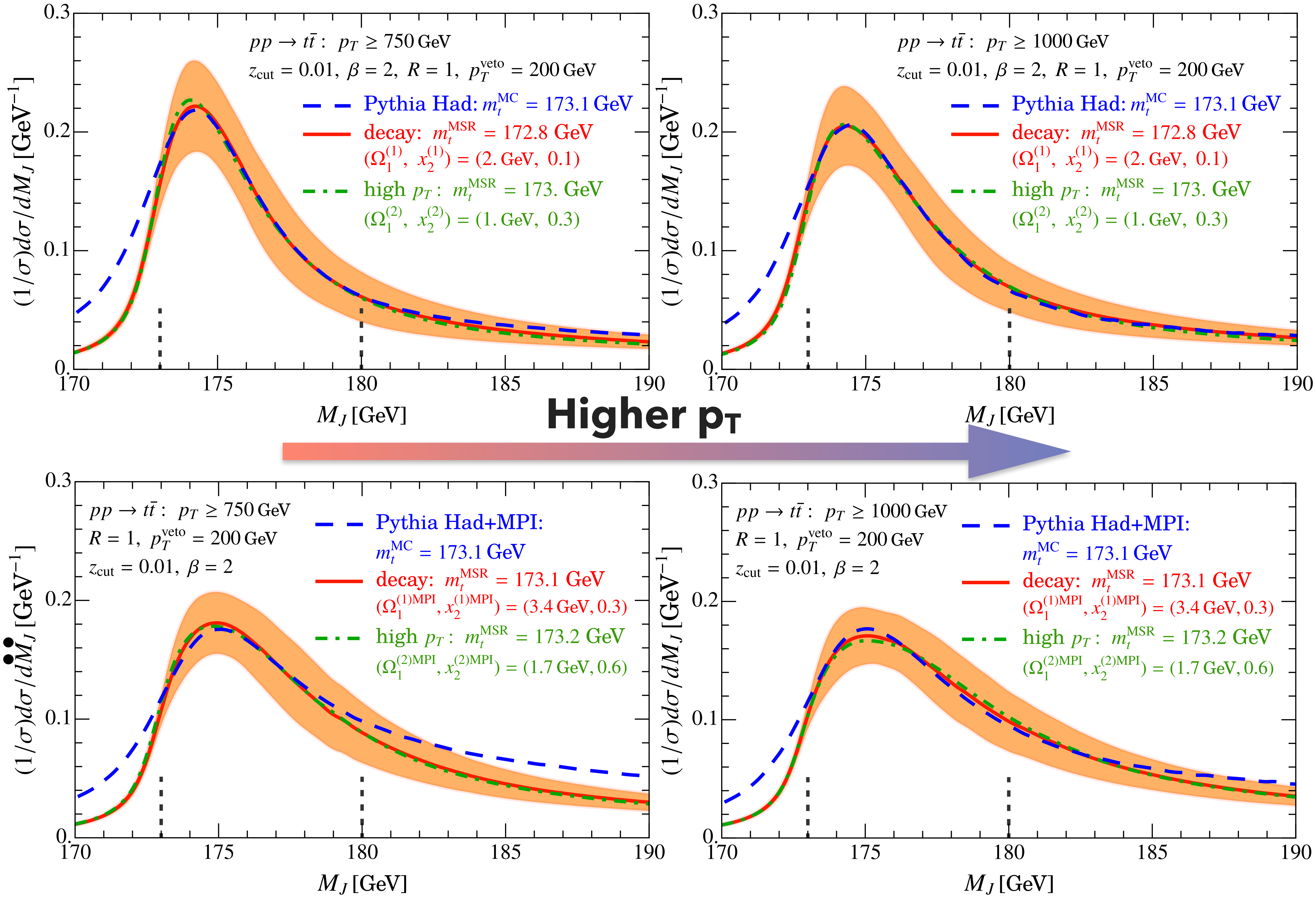


TESTING ROBUSTNESS OF THE THEORY

Independent NLL theory fits to Had-only and Had+MPI Pythia

No UE:

With UE:



TESTING ROBUSTNESS OF THE THEORY

Summarizing the fit results:

Not shown: results for "high p_T" fact. theorem.

No UE:

Had, decay, MSR : $m_t^{\rm MSR} = 172.8\,{\rm GeV}, \quad \Omega_1^{(1)} = 2.0\,{\rm GeV}, \quad x_2^{(1)} = 0.1$

Had, decay, pole: $m_t^{\rm pole} = 172.4\,{\rm GeV}, \quad \Omega_1^{(1)} = 1.8\,{\rm GeV}, \quad x_2^{(1)} = 0.1$

With UE:

Had+MPI, decay, MSR: $m_t^{\rm MSR} = 173.1\,{\rm GeV}, \quad \Omega_1^{(2){\rm MPI}} = 3.4\,{\rm GeV}, \quad x_2^{(2){\rm MPI}} = 0.3$

Had+MPI, decay, pole: $m_t^{\rm pole} = 172.7\,{\rm GeV}, \quad \Omega_1^{(2){\rm MPI}} = 3.2\,{\rm GeV}, \quad x_2^{(2){\rm MPI}} = 0.3$

TESTING ROBUSTNESS OF THE THEORY

Summarizing the fit results:

Not shown: results for "high p_T" fact. theorem.

No UE:

$$\text{Had, decay, MSR}: \quad m_t^{\rm MSR} = 172.8\,\text{GeV}, \quad \Omega_1^{(1)} = 2.0\,\text{GeV}, \quad x_2^{(1)} = 0.1$$

$$\text{Had, decay, pole}: \quad m_t^{\rm pole} = 172.4\,\text{GeV}, \quad \Omega_1^{(1)} = 1.8\,\text{GeV}, \quad x_2^{(1)} = 0.1$$

With UE:

$$\text{Had+MPI, decay, MSR}: \quad m_t^{\rm MSR} = 173.1\,\text{GeV}, \quad \Omega_1^{(2)\rm MPI} = 3.4\,\text{GeV}, \quad x_2^{(2)\rm MPI} = 0.3$$

$$\text{Had+MPI, decay, pole}: \quad m_t^{\rm pole} = 172.7\,\text{GeV}, \quad \Omega_1^{(2)\rm MPI} = 3.2\,\text{GeV}, \quad x_2^{(2)\rm MPI} = 0.3$$

- **(Preliminary) Fits to Pythia with m_t^{MC} = 173.1 GeV yield m_t^{MSR}~ 173 GeV for R = 1 GeV: Compatible with ee calibration by Butenschön et. al, 2016.**

Butenschoen, Dehnadi, Hoang, Mateu, Preisser, Stewart 2016

TESTING ROBUSTNESS OF THE THEORY

Summarizing the fit results:

Not shown: results for "high p_T" fact. theorem.

No UE:

Had, decay, MSR : $m_t^{\rm MSR} = 172.8\,{\rm GeV}$, $\Omega_1^{(1)} = 2.0\,{\rm GeV}$, $x_2^{(1)} = 0.1$

Had, decay, pole: $m_t^{\rm pole} = 172.4\,{\rm GeV}$, $\Omega_1^{(1)} = 1.8\,{\rm GeV}$, $x_2^{(1)} = 0.1$

With UE:

Had+MPI, decay, MSR: $m_t^{\rm MSR} = 173.1\,{\rm GeV}$, $\Omega_1^{(2){\rm MPI}} = 3.4\,{\rm GeV}$, $x_2^{(2){\rm MPI}} = 0.3$

Had+MPI, decay, pole: $m_t^{\rm pole} = 172.7\,{\rm GeV}$, $\Omega_1^{(2){\rm MPI}} = 3.2\,{\rm GeV}$, $x_2^{(2){\rm MPI}} = 0.3$

- **(Preliminary) Fits to Pythia with m_t^{MC} = 173.1 GeV yield m_t^{MSR}~ 173 GeV for R = 1 GeV: Compatible with ee calibration by Butenschön et. al, 2016.**

Butenschoen, Dehnadi, Hoang, Mateu, Preisser, Stewart 2016

- **Pole mass fits yield values 0.4-0.6 GeV smaller than m_t^{MC}: Can be explained by evolution of MSR mass at NLL**

$$m_t^{\rm pole} \simeq m_t^{\rm MSR}(R = 5\,{\rm GeV})$$

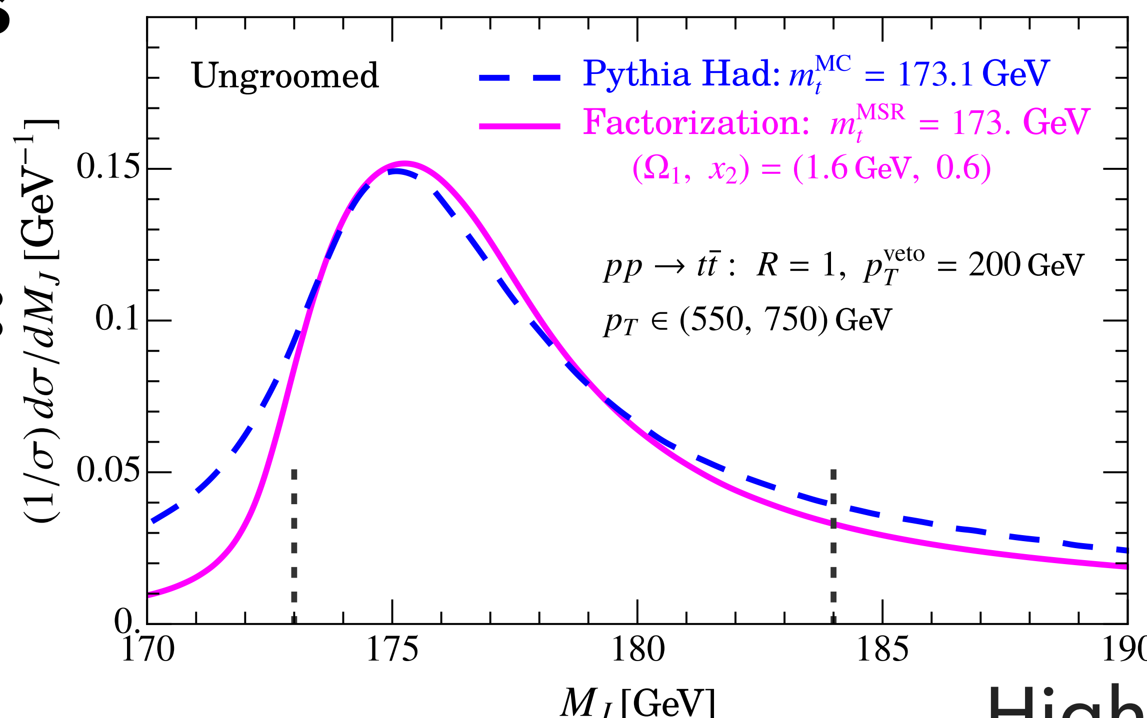
$$m_t^{\rm MSR}(1\,{\rm GeV}) - m_t^{\rm MSR}(5\,{\rm GeV}) = 0.53\,{\rm GeV}$$

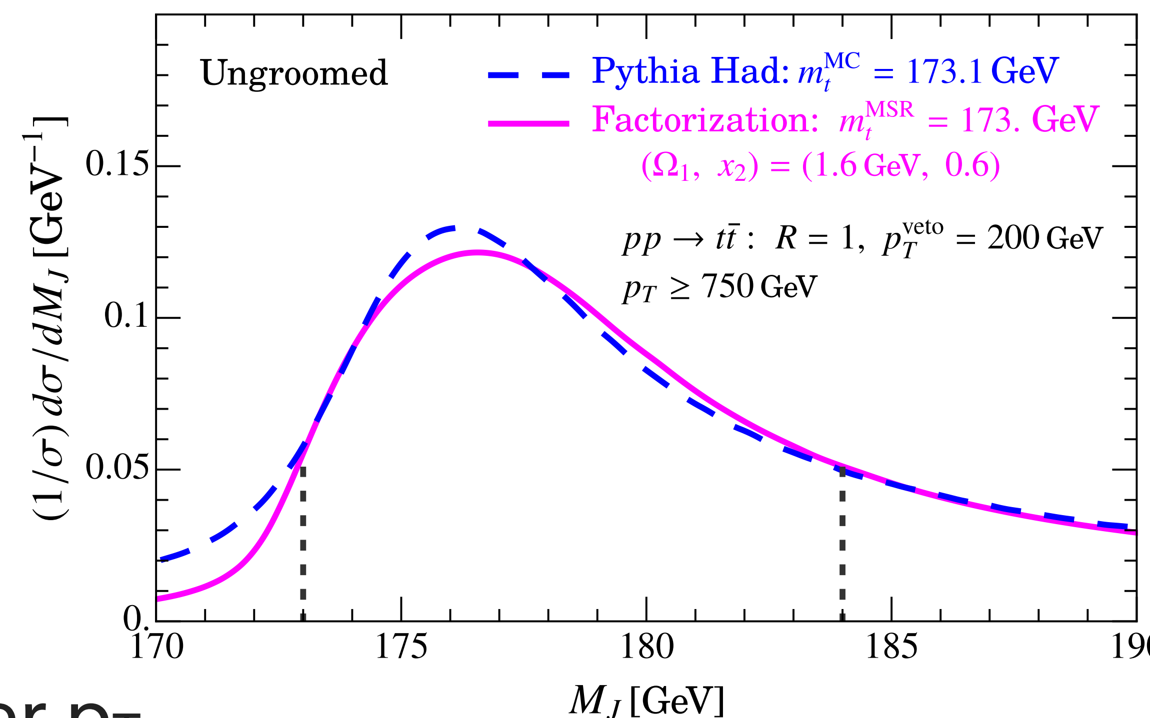
TESTING ROBUSTNESS OF THE THEORY

Fits for ungroomed top jets

Fits to Pythia with m_t^{MC} = 173.1 GeV yield m_t^{MSR}~ 172.8 GeV

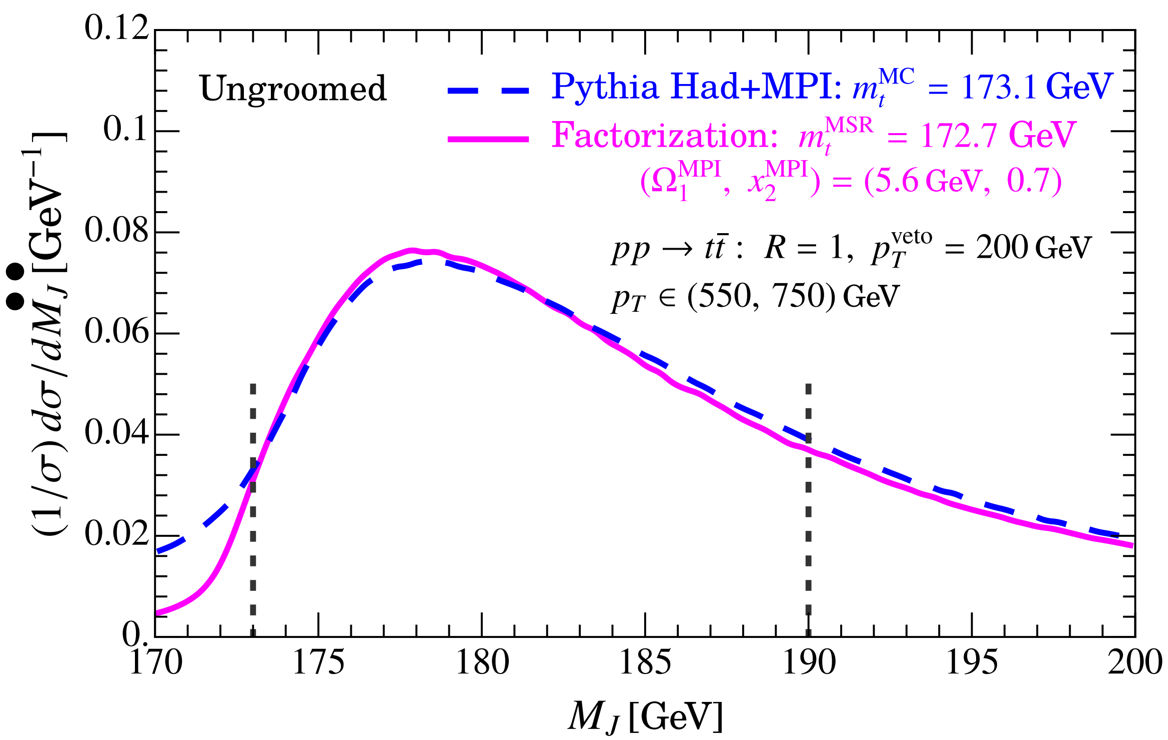
No UE:

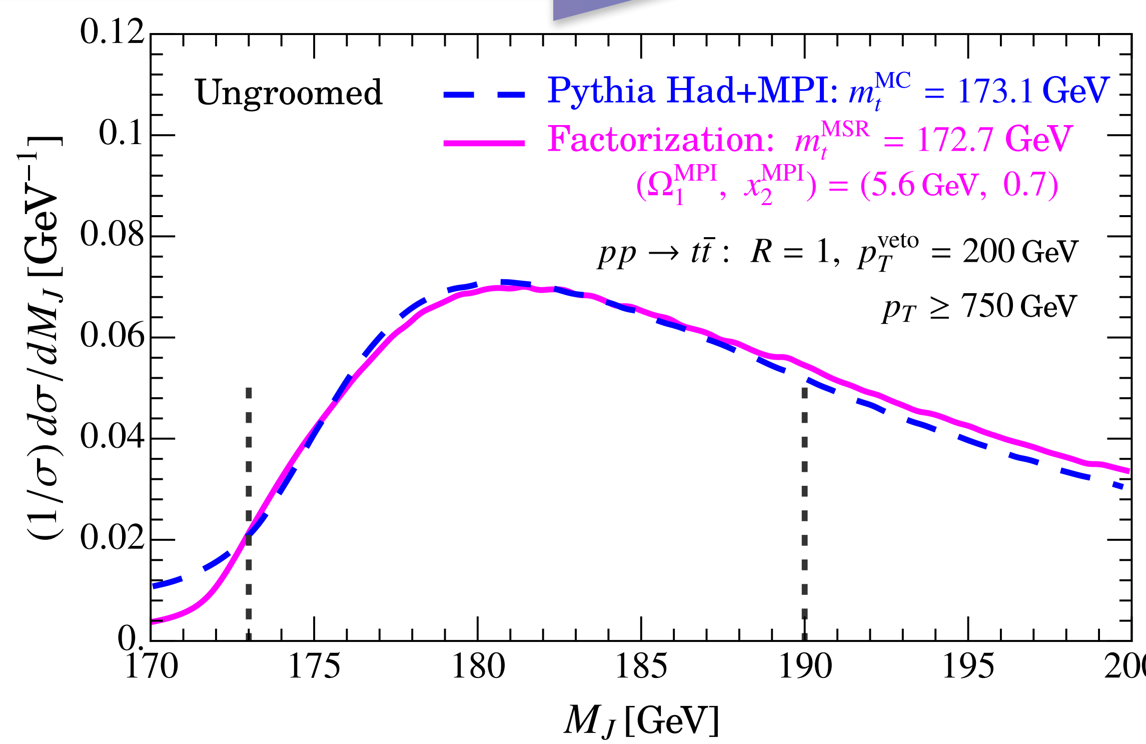




Higher p_T

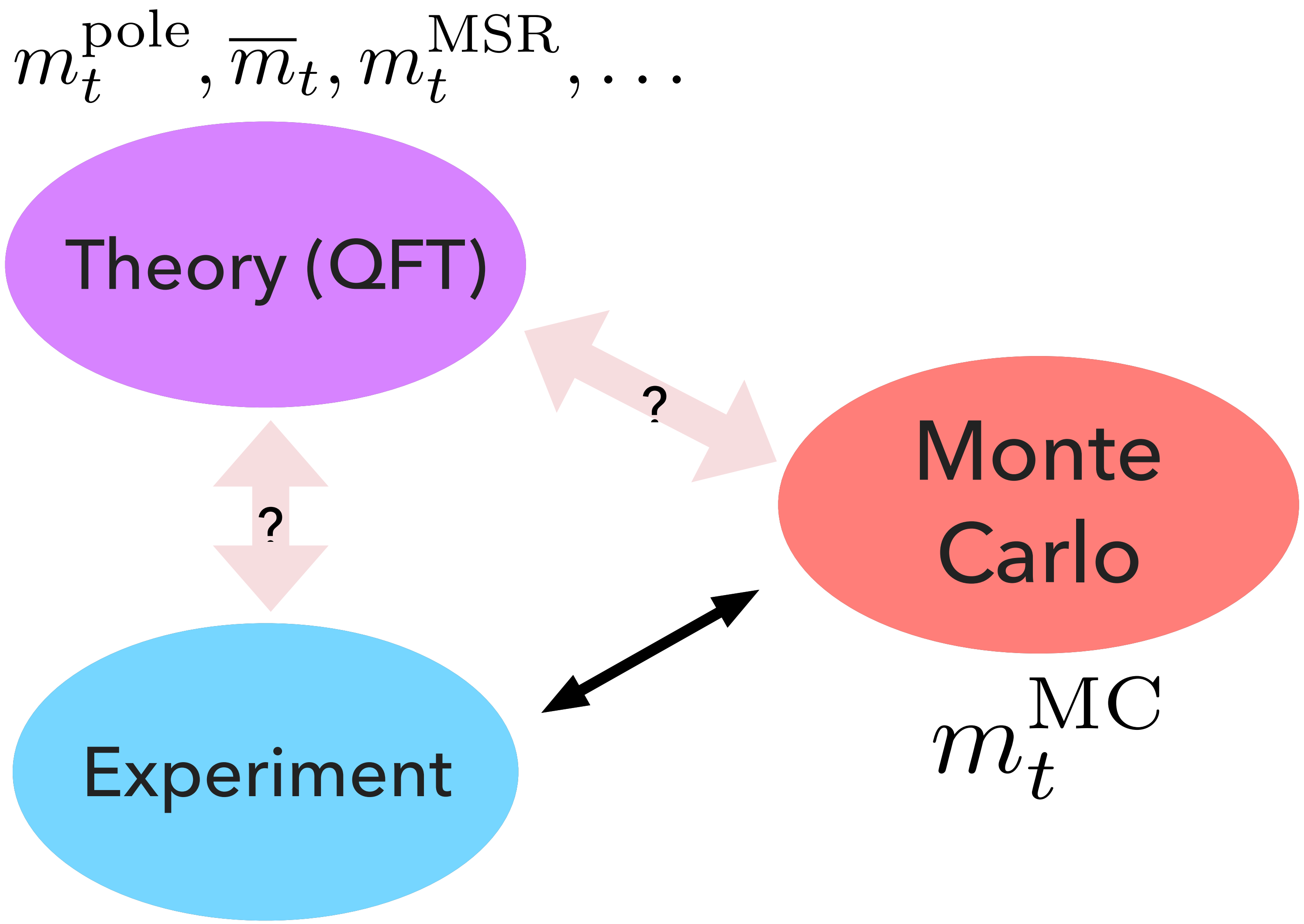
With UE:





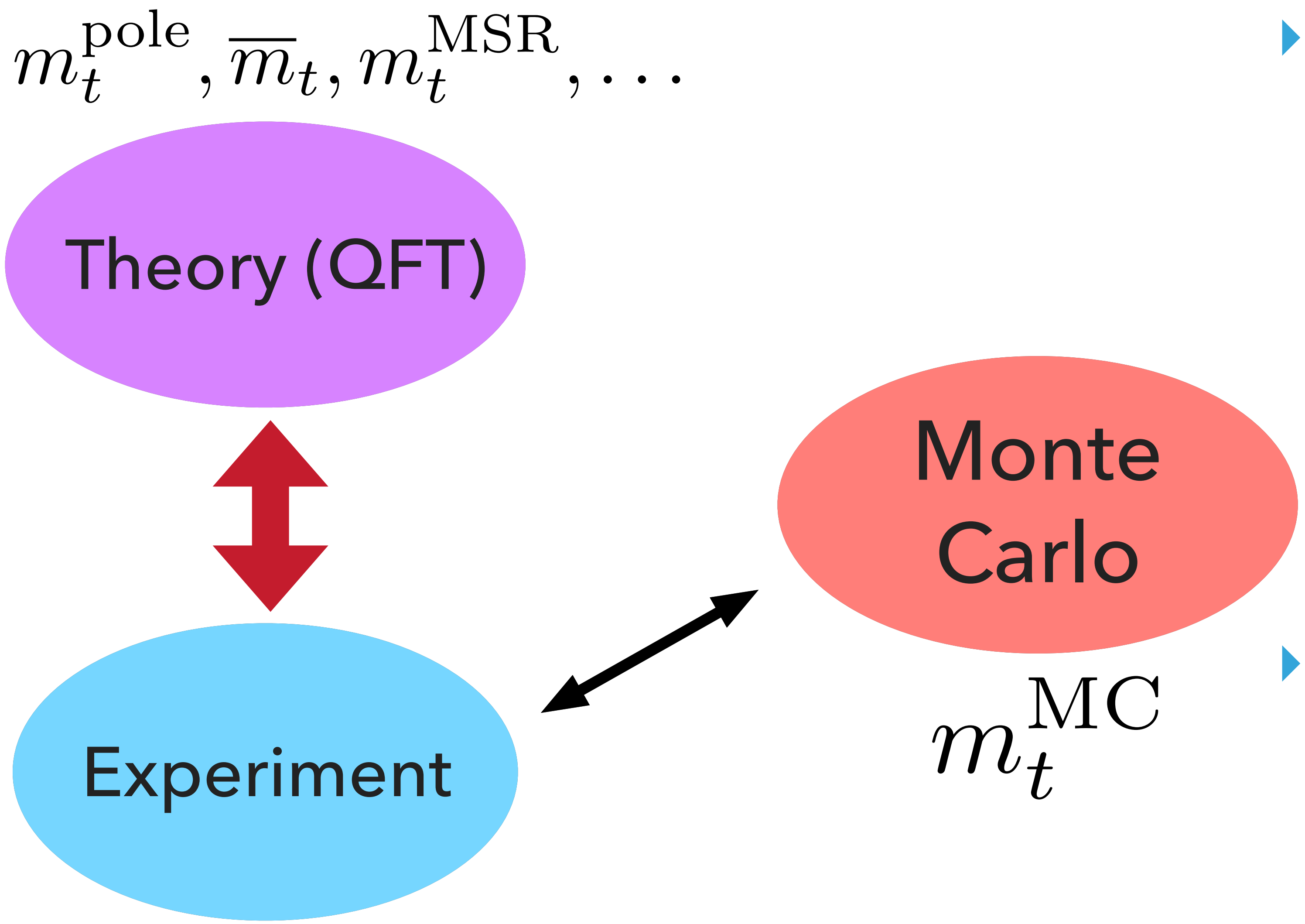
OUTLOOK

Bridging the gaps between Theory, Data and MC



OUTLOOK

Bridging the gaps between Theory, Data and MC



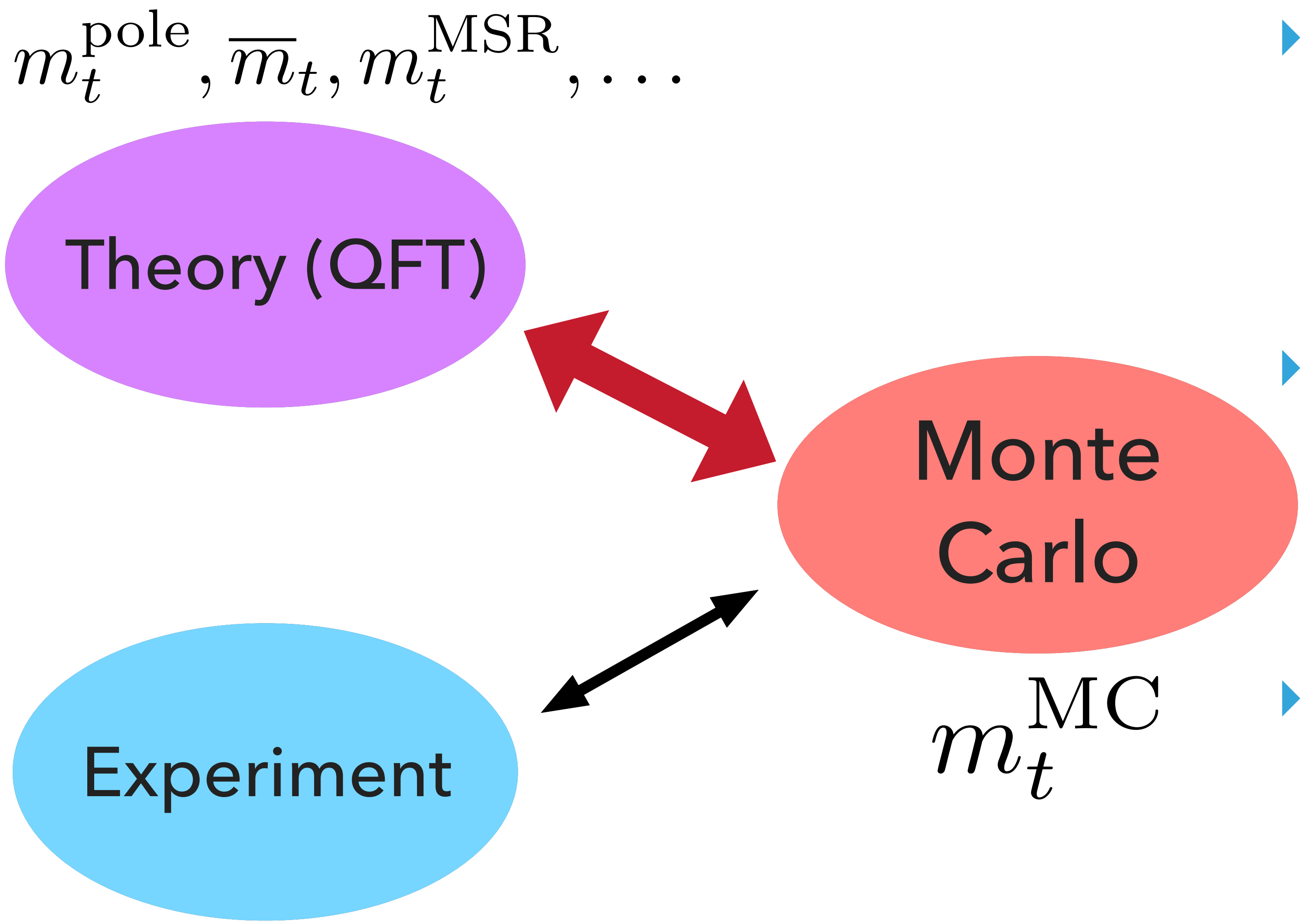
- Major challenge - limited statistics at high p_T required by light grooming.
  - Ungroomed factorization can be used to analyze lower p_T top jets.
- Light grooming effective in reducing the UE - pile up? If pile up behaves like soft radiation:

$$\Omega_1 \to \Omega_1^{\mathrm{MPI+Pile\,up}}$$

- Track based pile up subtraction methods likely to be compatible.

OUTLOOK

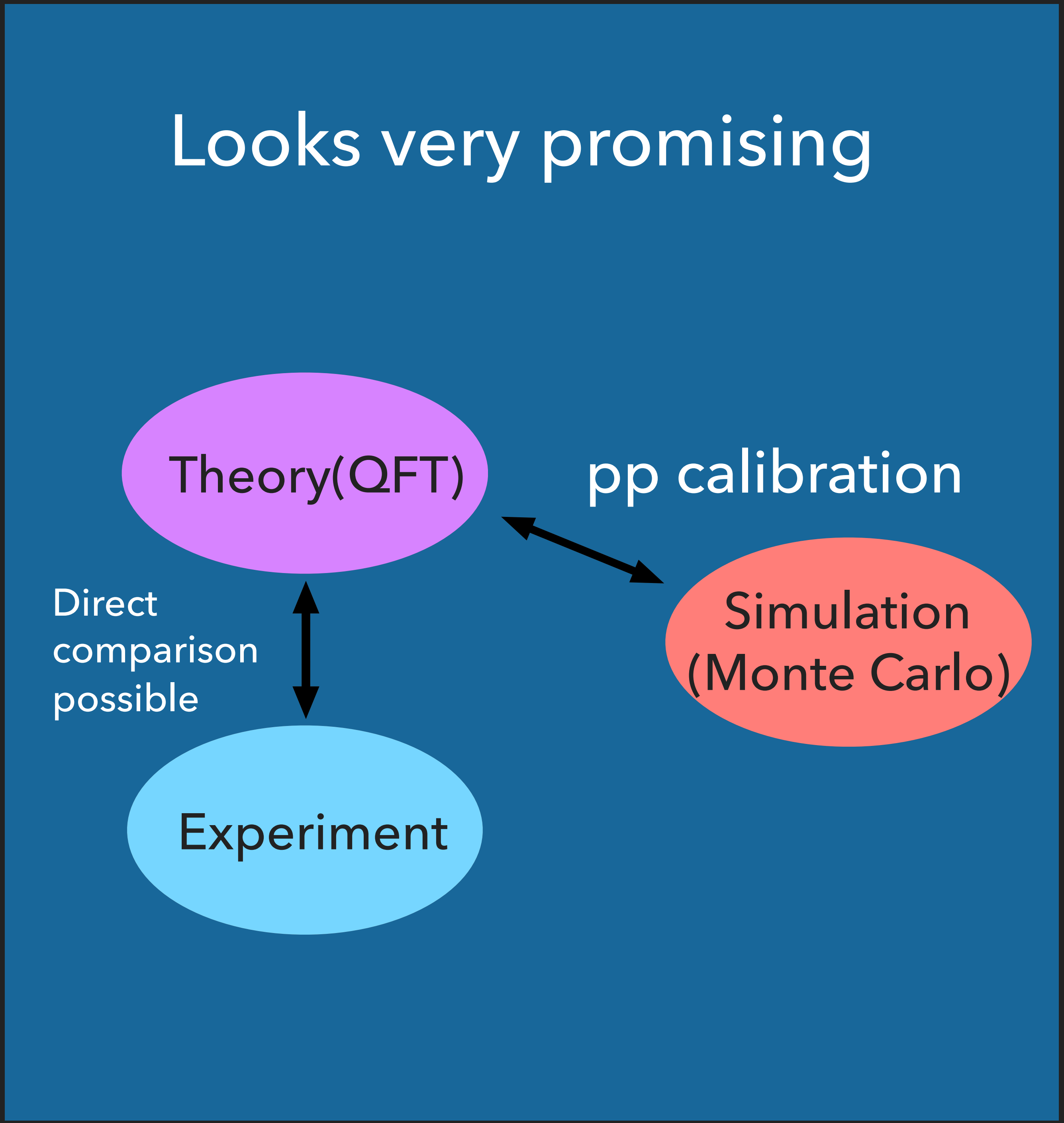
Bridging the gaps between Theory, Data and MC



- Monte Carlo Top Mass Calibration - not limited by statistics.
- A more thorough calibration studies with multiple p_T bins, other values of z_{cut} and β.
- Observed agreement between e^+e^- calibration and our preliminary studies suggest that one may be able to use MCs to extrapolate outside the range of factorization theorem.

CONCLUSION

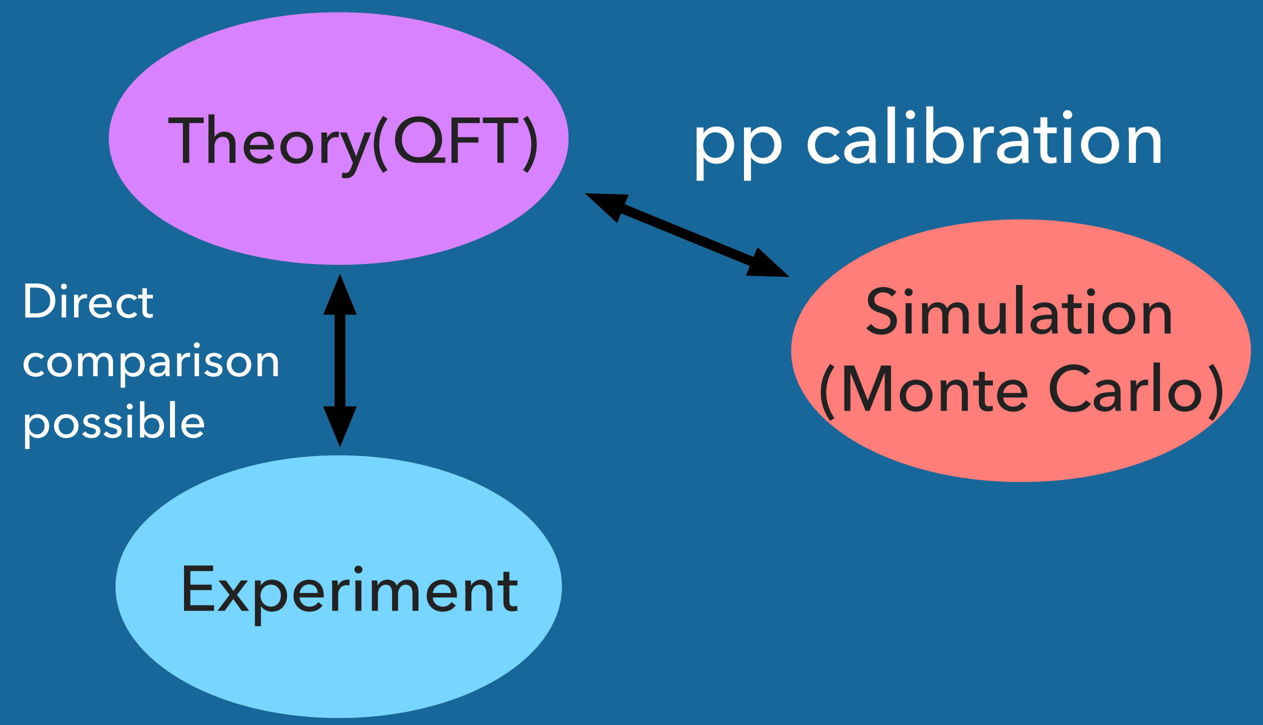
- Factorization Theorems for Soft Drop jet mass enable direct QCD calculation of hadronic cross section
- Light Grooming with Soft Drop
  - Dramatically reduces Underlying Event (factor ~5)
  - Retains events without need for strong selection cuts
  - Enables both semi-leptonic and hadronic channels to be used
  - Gives result that is insensitive to jet radius and jet veto
- Theory depends on m_t and Ω_1, and agrees well with Pythia.
  - Pythia UE shifts Ω_1 with small effect on m_t



CONCLUSION

- Factorization Theorems for Soft Drop jet mass enable direct QCD calculation of hadronic cross section
- Light Grooming with Soft Drop
  - Dramatically reduces Underlying Event (factor ~5)
  - Retains events without need for strong selection cuts
  - Enables both semi-leptonic and hadronic channels to be used
  - Gives result that is insensitive to jet radius and jet veto
- Theory depends on m_t and Ω_1, and agrees well with Pythia.
  - Pythia UE shifts Ω_1 with small effect on m_t

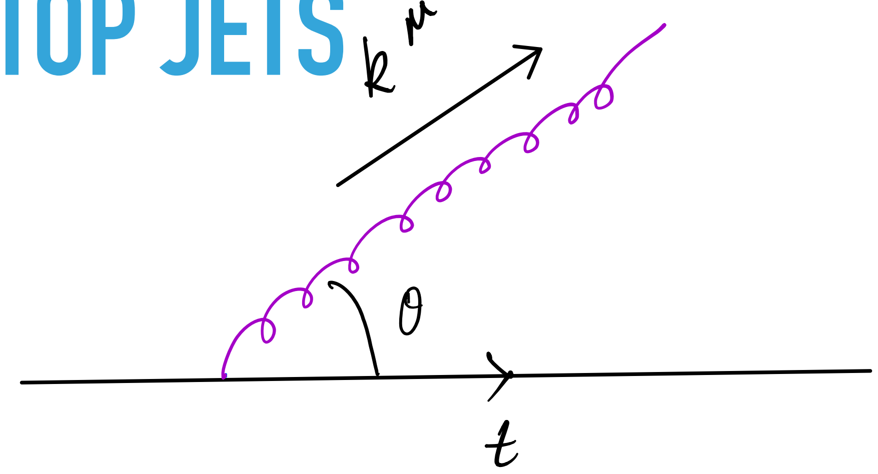
Looks very promising



THANKS!

BACKUP SLIDES

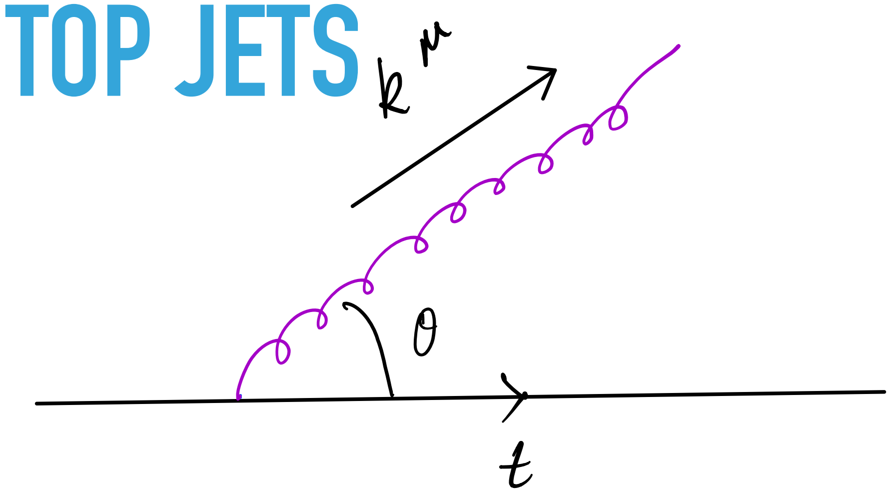
CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS



Radiation off the top quark (either collinear or soft):

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

CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS



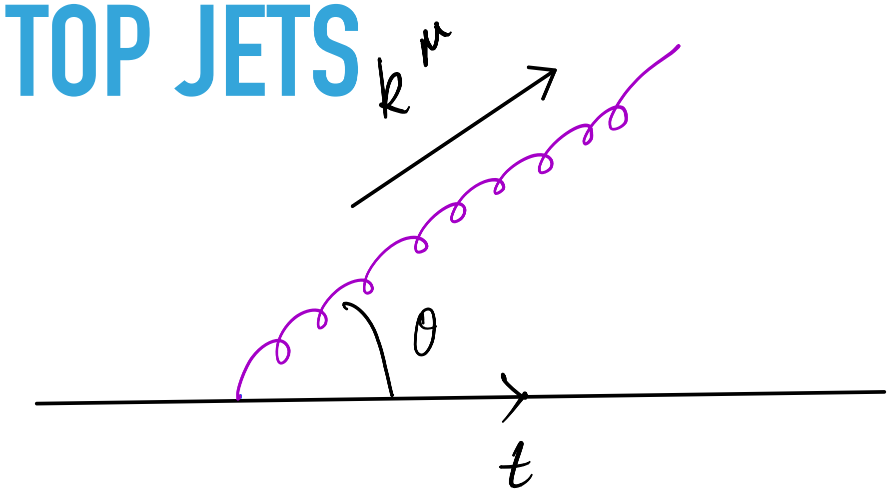
Radiation off the top quark (either collinear or soft):

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

Peak Region: $M_{t,\bar{t}}^2 - m^2 \sim m\Gamma \ll m^2$

$$z\left[(1-\cos\theta) + \frac{m^2}{Q^2}(1+\cos\theta)\right] \sim \frac{2m\Gamma_t}{Q^2}$$

CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS



Radiation off the top quark (either collinear or soft):

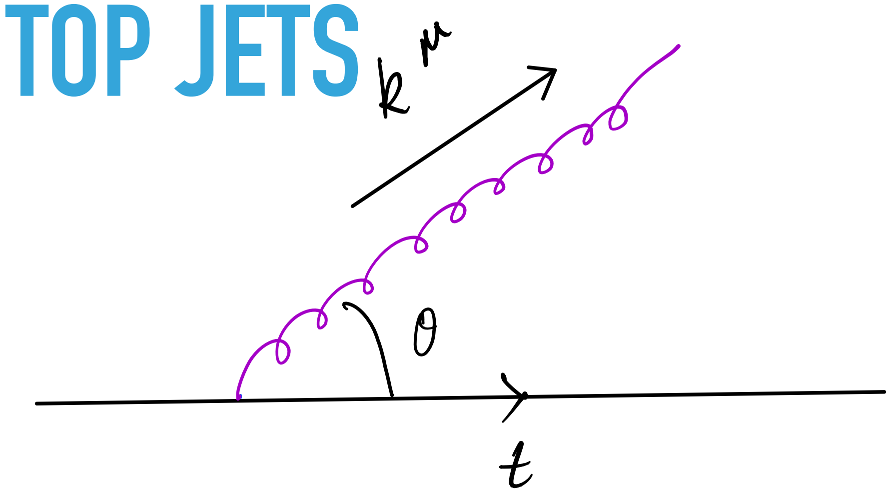
$$k_j^\mu = \big(k^+, k^-, k_\perp\big) = \big(E(1-\cos\theta), E(1+\cos\theta), k_\perp\big)$$

Peak Region: $M_{t,\bar{t}}^2 - m^2 \sim m\Gamma \ll m^2$

$$z\left[(1-\cos\theta) + \frac{m^2}{Q^2}(1+\cos\theta)\right] \sim \frac{2m\Gamma_t}{Q^2}$$

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

CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS



Radiation off the top quark (either collinear or soft):

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

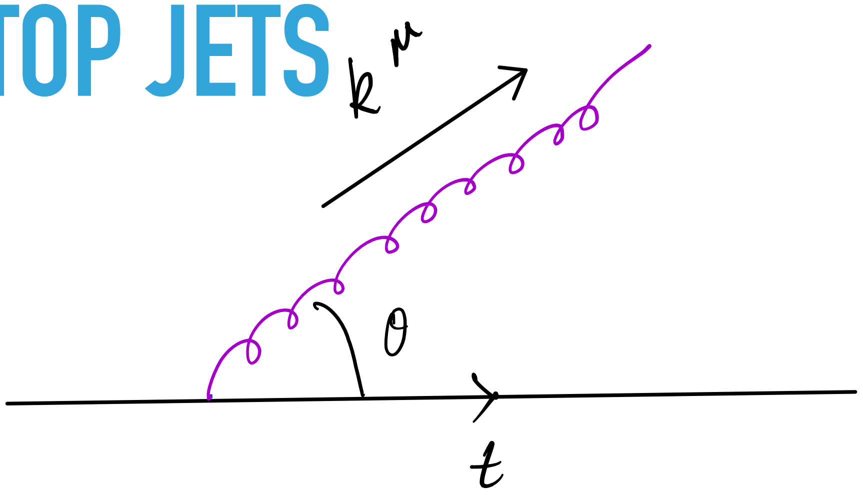
Peak Region: $M_{t,\bar{t}}^2 - m^2 \sim m\Gamma \ll m^2$

$$z\left[(1-\cos\theta) + \frac{m^2}{Q^2}(1+\cos\theta)\right] \sim \frac{2m\Gamma_t}{Q^2}$$

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

How to decide whether to keep the gluon or groom it away?

CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS



Radiation off the top quark (either collinear or soft):

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

Peak Region: $M_{t,\bar{t}}^2 - m^2 \sim m\Gamma \ll m^2$

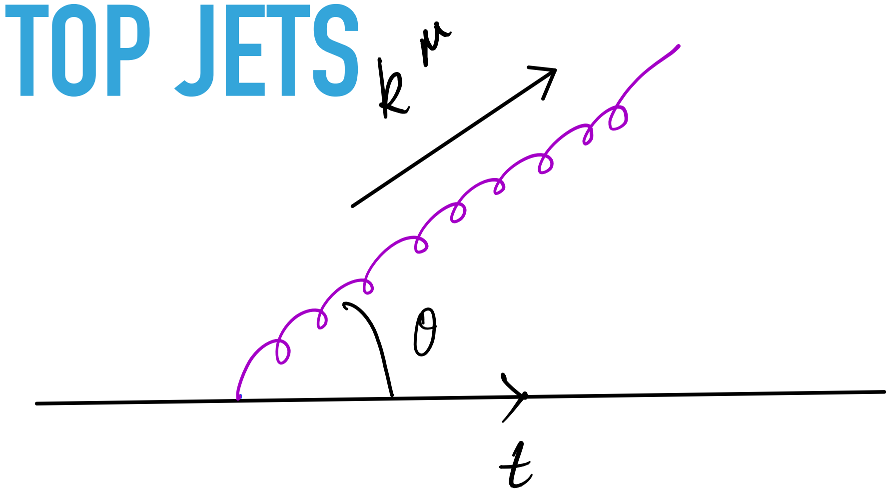
$$z\left[(1-\cos\theta) + \frac{m^2}{Q^2}(1+\cos\theta)\right] \sim \frac{2m\Gamma_t}{Q^2}$$

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

How to decide whether to keep the gluon or groom it away?

Answer: Decide based on what EFT modes are important.

CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS



Radiation off the top quark (either collinear or soft):

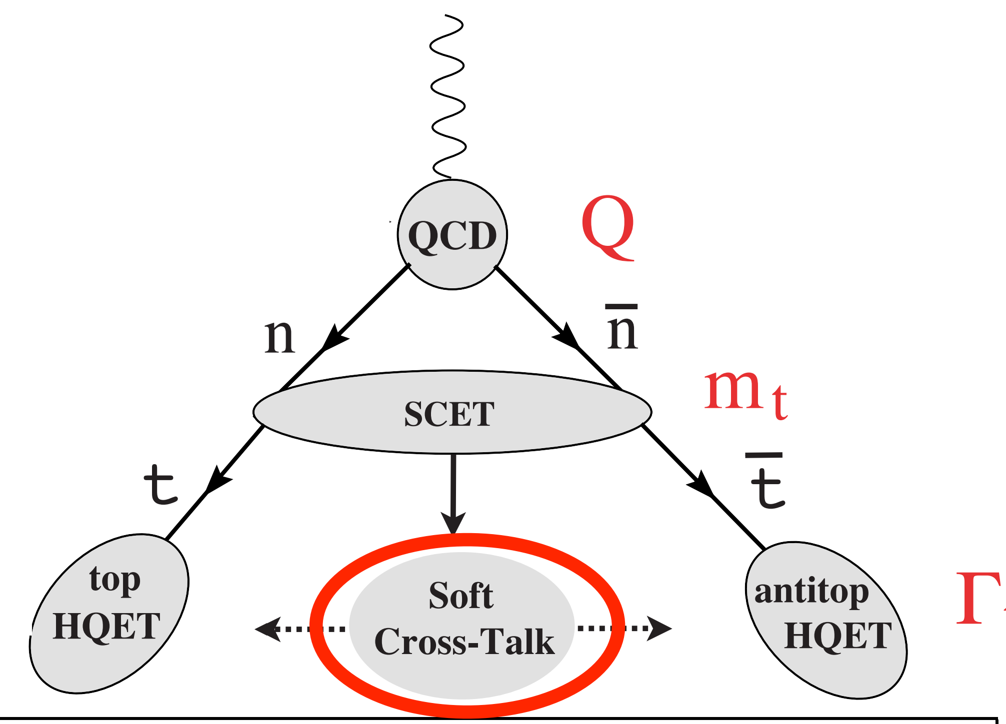
$$k_j^\mu = (k^+, k^-, k_\perp) = \big(E(1-\cos\theta), E(1+\cos\theta), k_\perp\big)$$

Peak Region: $M_{t,\bar t}^2 - m^2 \sim m\Gamma \ll m^2$

$$z\left[(1-\cos\theta) + \frac{m^2}{Q^2}(1+\cos\theta)\right] \sim \frac{2m\Gamma_t}{Q^2}$$

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

Mass scheme is specified in HQET



Keep Ultra-collinear modes

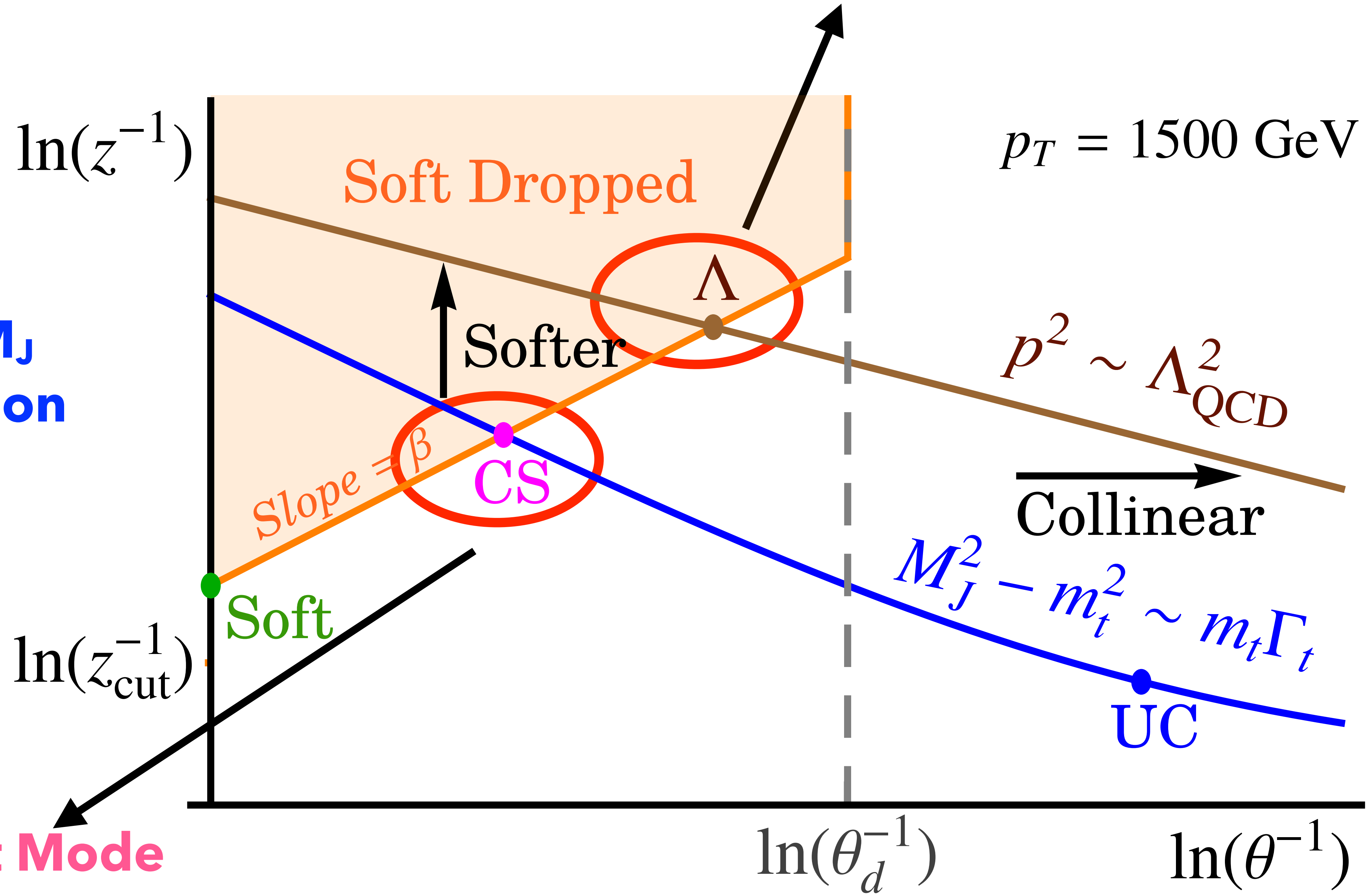
Groom away Soft modes

SCET $[\lambda \sim m/Q \ll 1]$		bHQET $[\Gamma/m \ll 1]$	
n-collinear $(\xi_n,\ A_n^\mu)$	$p_n^\mu \sim Q(\lambda^2, 1, \lambda)$	n-ucollinear $(h_{v_+},\ A_+^\mu)$	$k^\mu \sim \Gamma(\lambda, \lambda^{-1}, 1)$
$\bar n$-collinear $(\xi_{\bar n},\ A_{\bar n}^\mu)$	$p_{\bar n}^\mu \sim Q(1, \lambda^2, \lambda)$	$\bar n$-ucollinear $(h_{v_-},\ A_-^\mu)$	$k^\mu \sim \Gamma(\lambda^{-1}, \lambda, 1)$
mass-modes $(q_m,\ A_m^\mu)$	$p_m^\mu \sim Q(\lambda, \lambda, \lambda)$		
Crosstalk: soft $(q_s,\ A_s^\mu)$	$p_s^\mu \sim Q(\lambda^2, \lambda^2, \lambda^2)$	same soft $(q_s,\ A_s^\mu)$	$p_s^\mu \sim (\Delta, \Delta, \Delta)$

WHAT MODES ARE LEFT AFTER SOFT DROP?

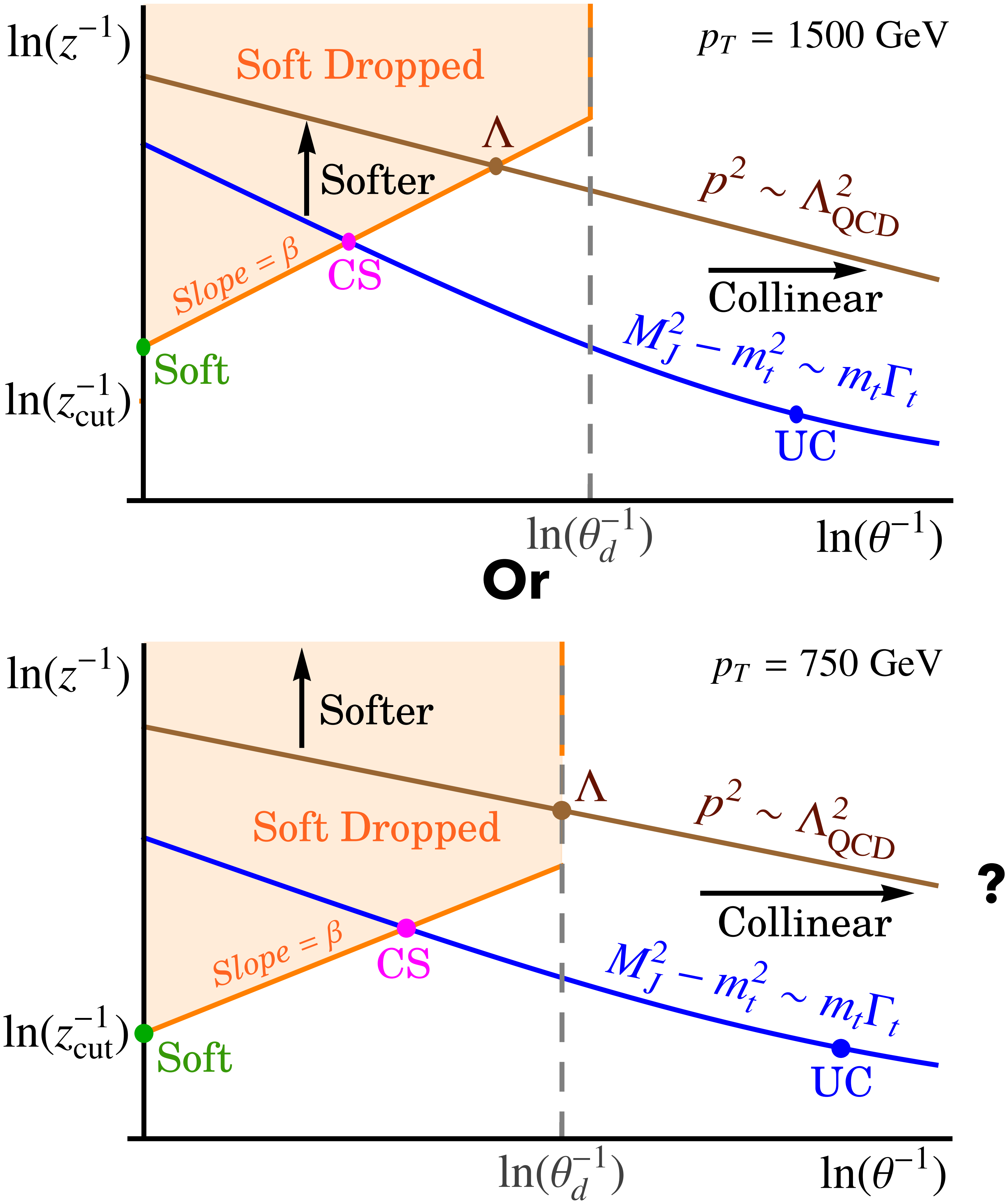
Non Perturbative Mode

blue curve: measurement M_J in the peak region



Collinear Soft Mode

- **Collinear Soft Mode: widest angle soft mode allowed**
- **Non Perturbative Mode: determines scale of NP corrections**



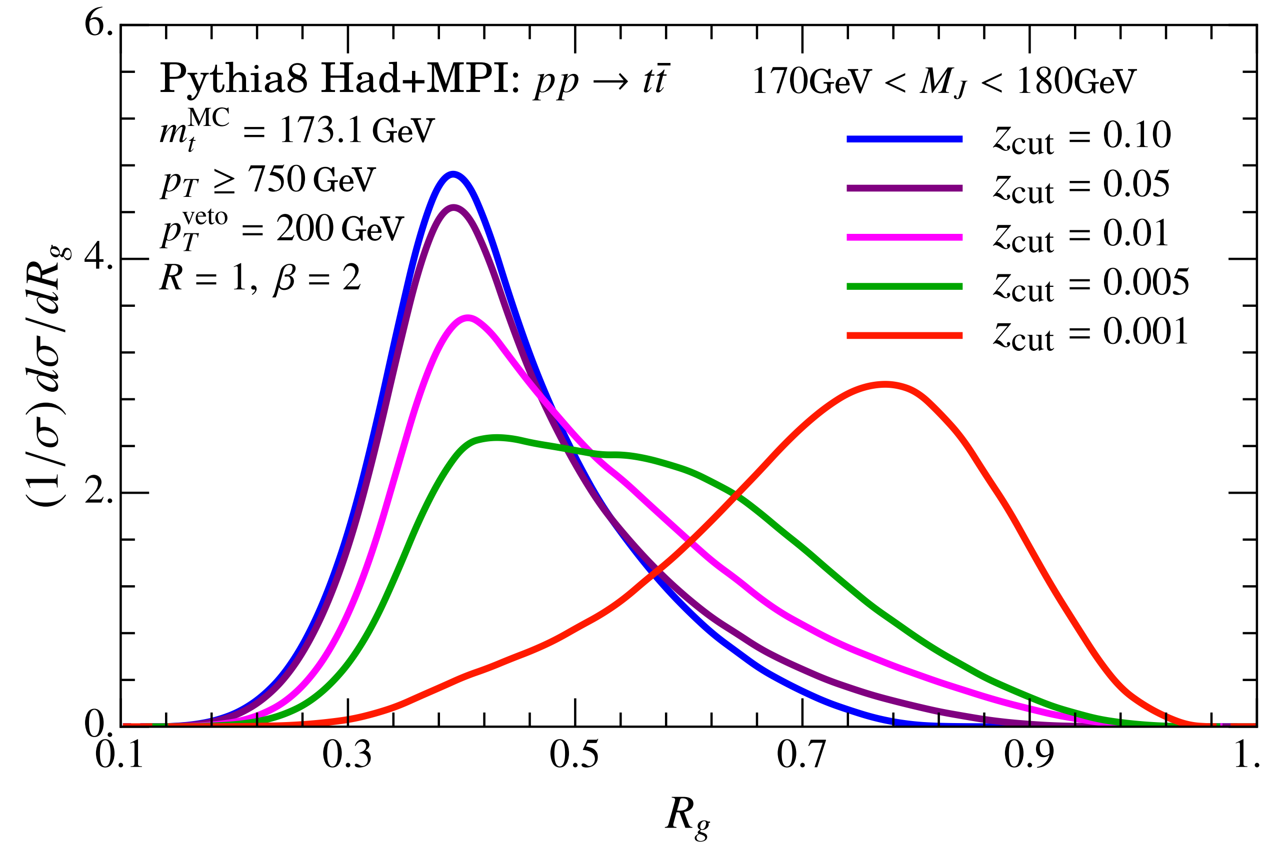
WHEN DOES SOFT DROP STOP?

WHAT IS THE SIZE OF NONPERTURBATIVE CORRECTIONS?

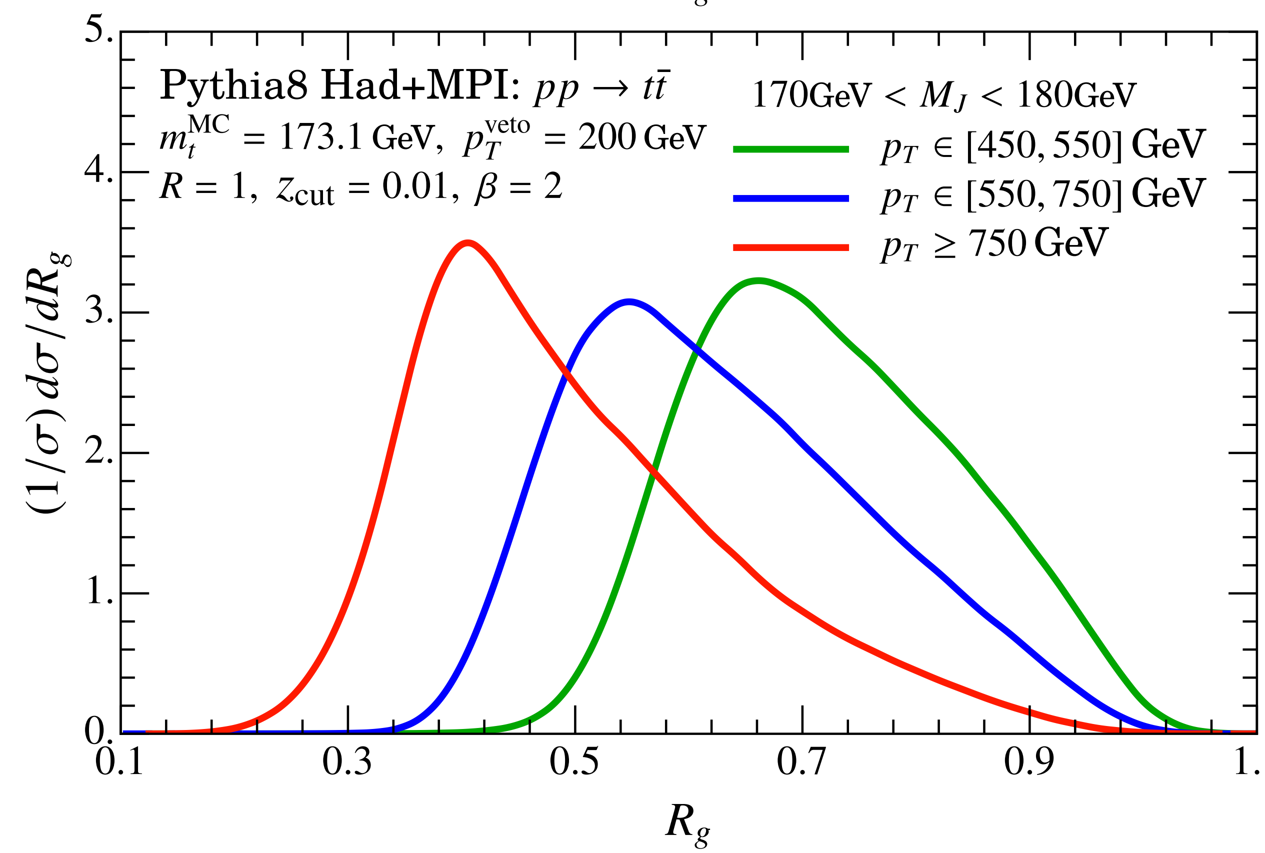
Affects location of the Λ mode.

GROOMED JET RADIUS DISTRIBUTION

Groomed Jet Radius shows similar transition at z_{cut} ~ 1%

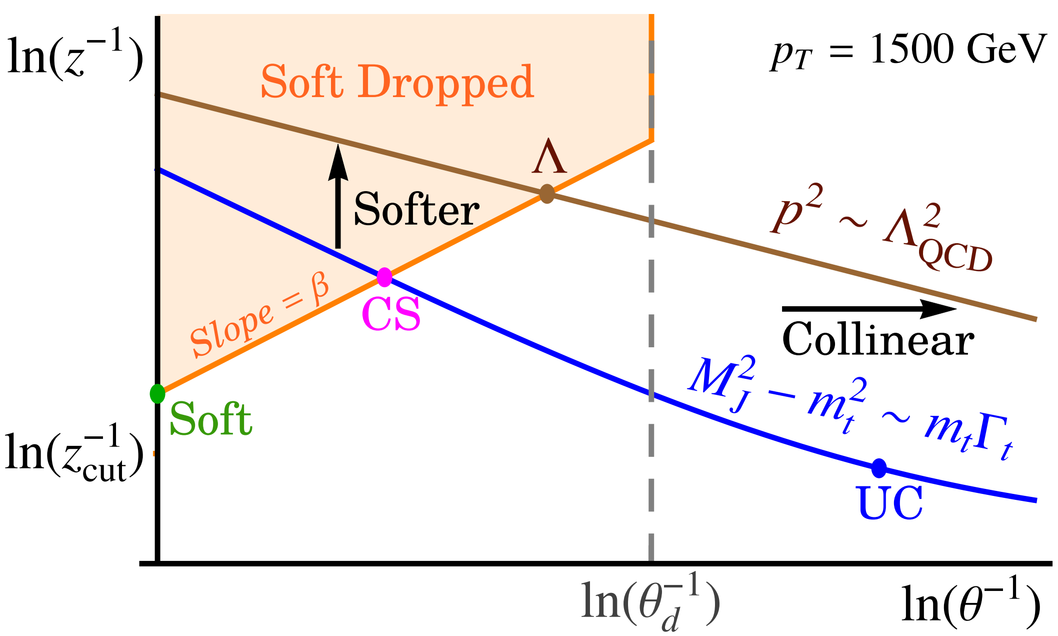


The peak of R_g distribution decreases as a function of p_T:



Soft Drop can be satisfied by top decay products, and give rise to this behavior.

TWO CASES FOR NONPERTURBATIVE CONVOLUTION

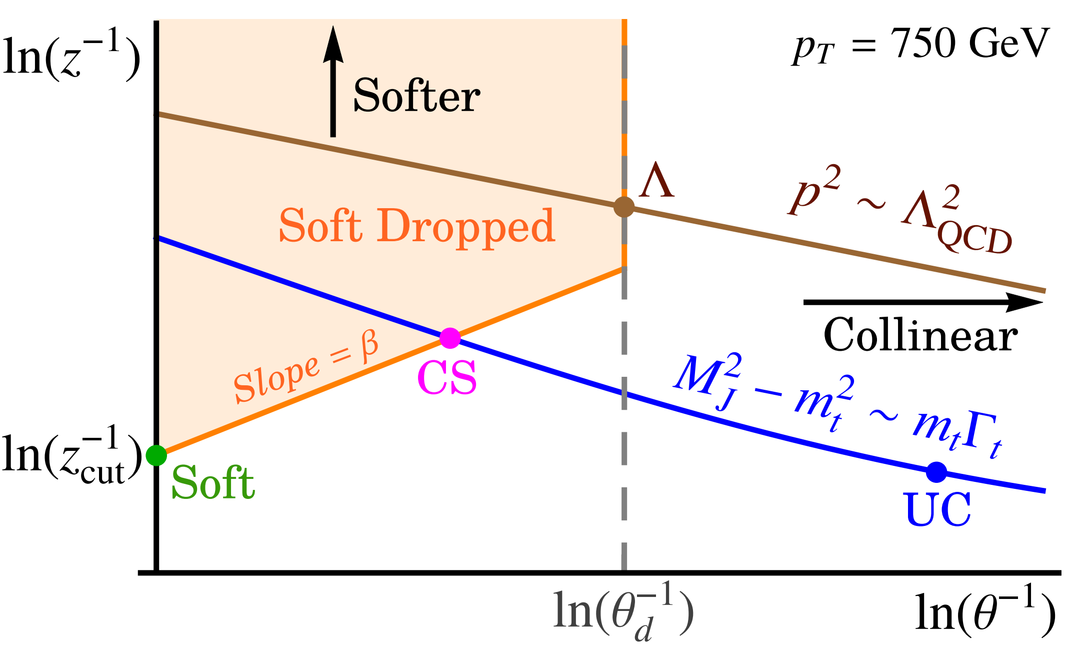


Factorization at High p_T: $Q > 2m\left(\frac{m z_{cut} h^{\beta+1}}{\Lambda_{QCD}}\right)^{\frac{1}{\beta}}$

$$\frac{d\sigma}{dM_J} = N(2^\beta Q z_{cut}, \mu) \int d\ell \, J_B\left(\frac{M_J^2 - m_t^2 - Q\ell}{m_t}, \Gamma_t, \delta m, \mu\right)$$

$$\times \int dk \, S_C\left[\left(\ell - k\left(\frac{k}{2^\beta Q z_{cut}}\right)^{\frac{1}{1+\beta}}\right)(2^\beta Q z_{cut})^{\frac{1}{1+\beta}}, \beta, \mu\right] F_C(k, \beta)$$

$m/Q \, h \sim R_g/4$ $\qquad$ $Q = 2 \, p_T \cosh(\eta)$



Factorization with Decay Products Effects:

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{cut}, \beta, \mu) \int d\hat{s}' \, d\Phi_d \, D_t(\hat{s}', \Phi_d, m/Q) \int d\ell \, J_B\left(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\right)$$

$$\times \int dk \, S_C\left[\left(\ell - \frac{mk}{Q} h\left(\Phi_d, \frac{m}{Q}\right)\right)(2^\beta Q z_{cut})^{\frac{1}{1+\beta}}, \beta, \mu\right] F_C(k, 1)$$

$$D_t(\hat{s}', \Phi_d, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^2 + \Gamma_t^2)} \, d_t(\Phi_d, m/Q)$$

FACTORIZATION WITH DECAY PRODUCTS EFFECTS

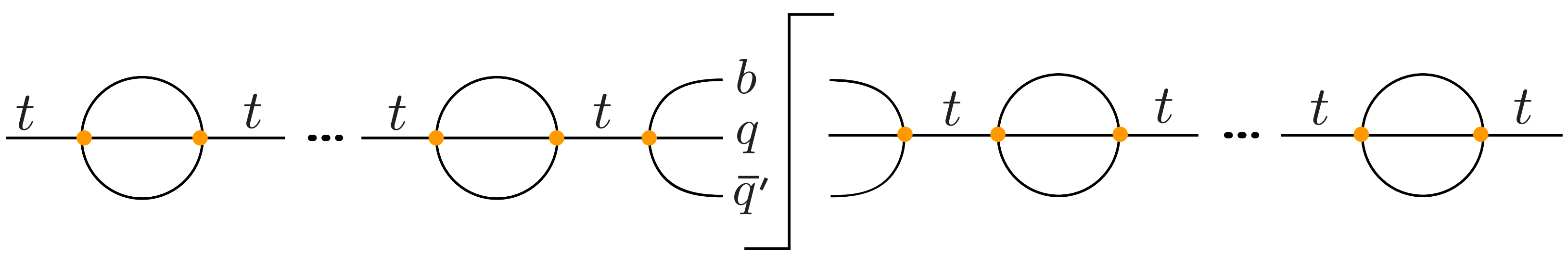
$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\mathrm{cut}}, \beta, \mu)\int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d,\, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)\big(2^\beta Q z_{\mathrm{cut}}\big)^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k, 1)$$

$$h \simeq \frac{\theta_d}{2}\,\frac{Q}{m}$$

$$D_t(\hat{s}', \Phi_d,\, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)}\; d_t(\Phi_d,\, m/Q)$$

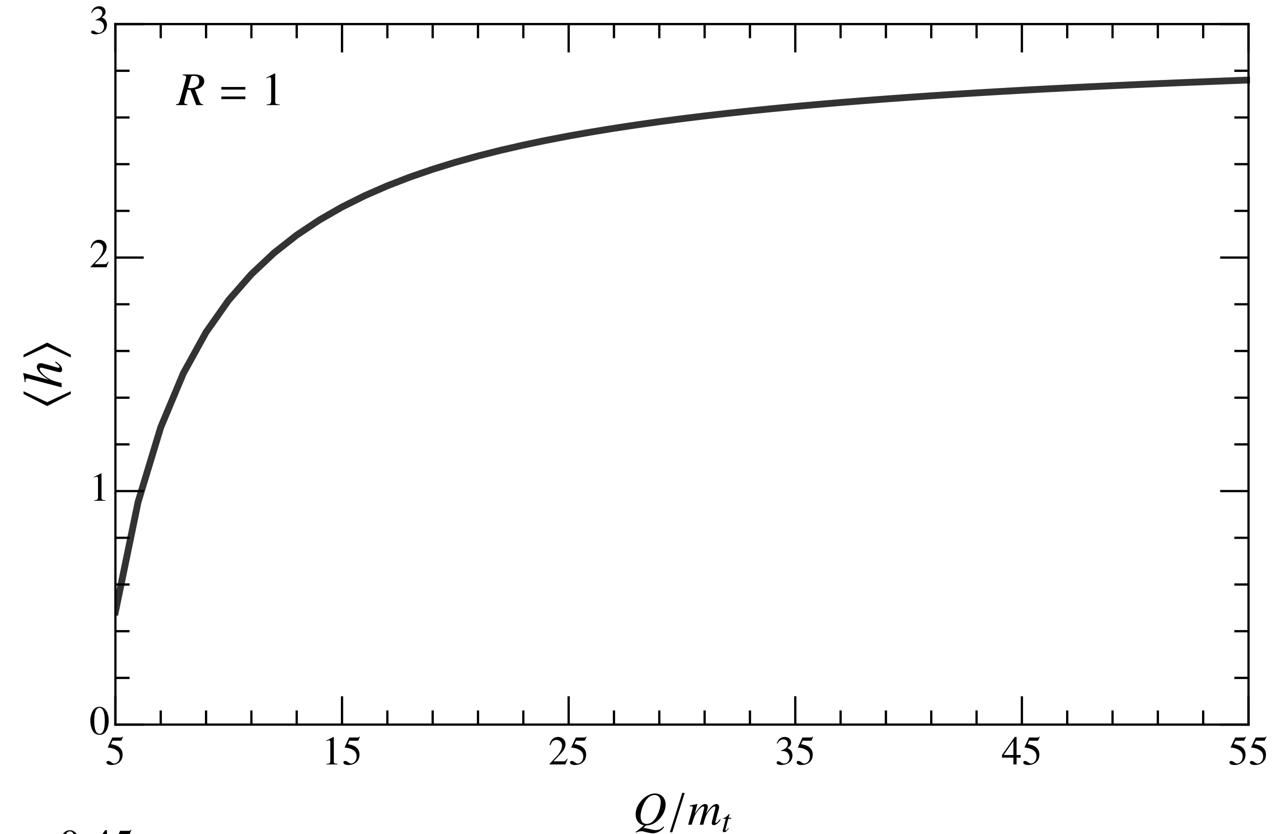
$$Q = 2\, p_T \cosh(\eta_J)$$



- **Factorization now depends on angluar distribution of decay products**
- **Model function now beta dependent**

$$F_C(k)^{\mathrm{decay}} = F_C^{\mathrm{high}\, p_T}(k,\, \beta = 1)$$

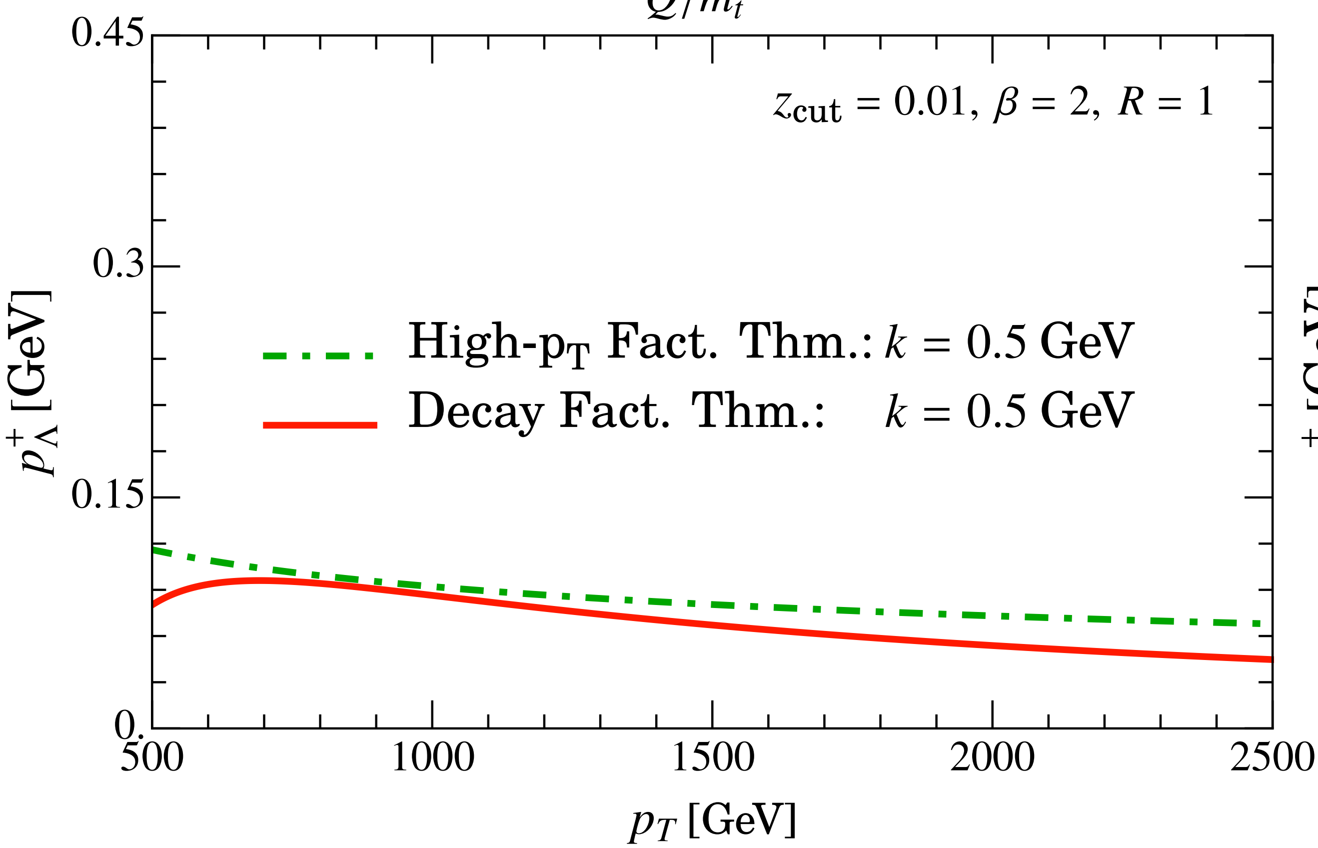
FACTORIZATION WITH DECAY PRODUCTS EFFECTS

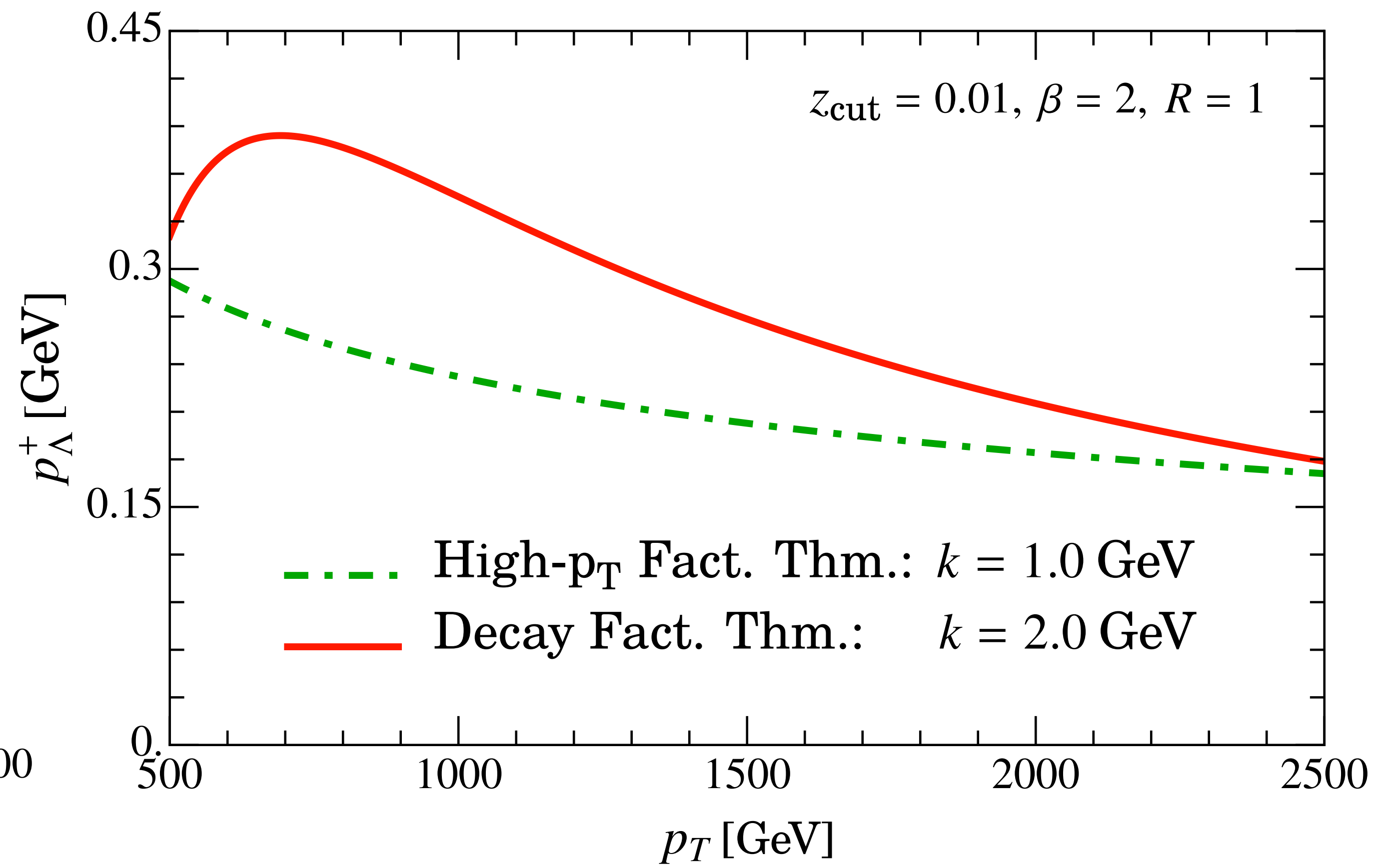


Which factorization to use?

$$\Omega_n^{(1)\mathrm{eff}} = \langle h^n \rangle \, \Omega_n^{(1)} \qquad h \simeq \frac{\theta_d}{2} \frac{Q}{m}$$

Compare the + component of non perturbative mode

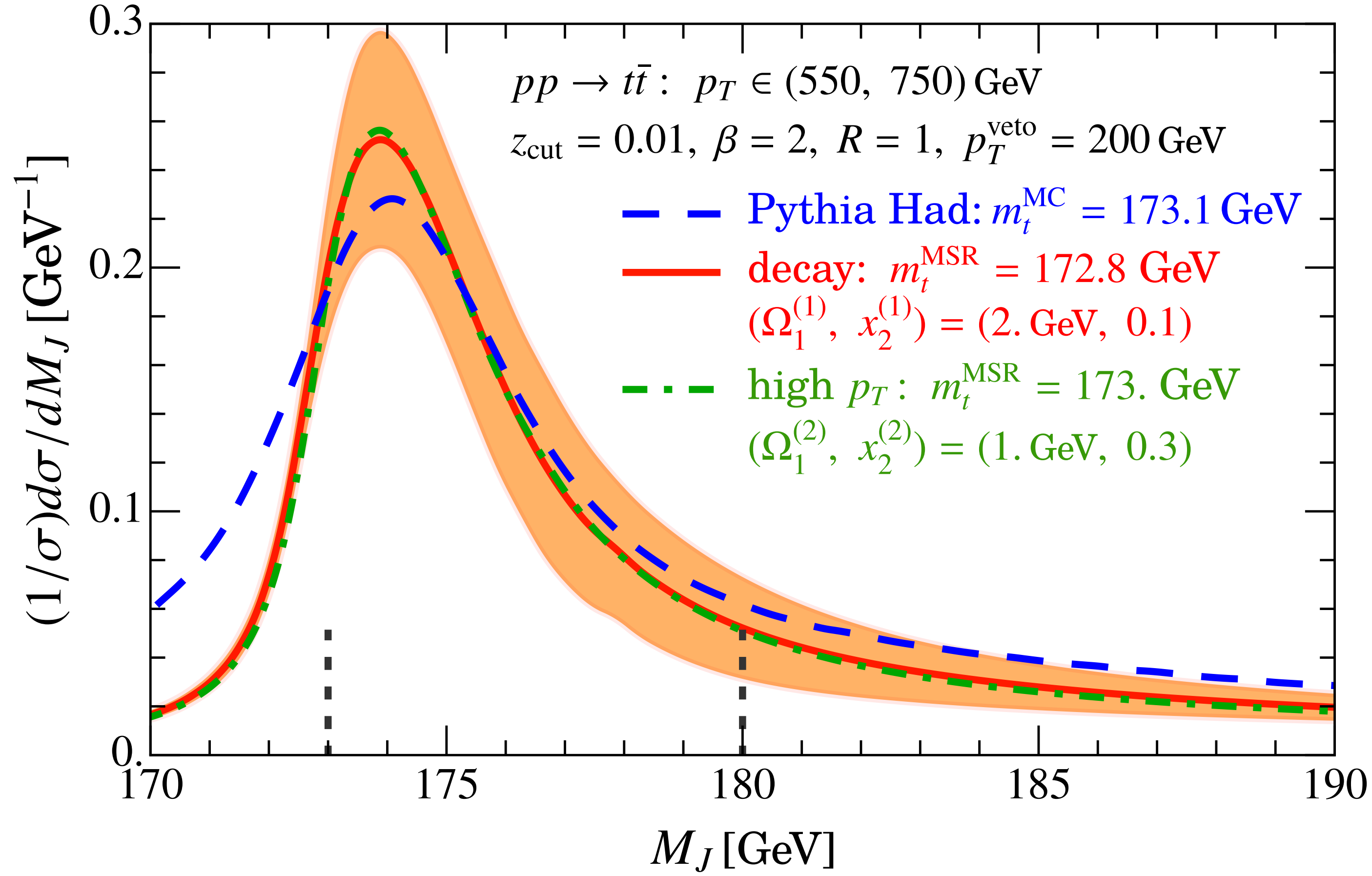




RESULTS FOR SMALLER PT

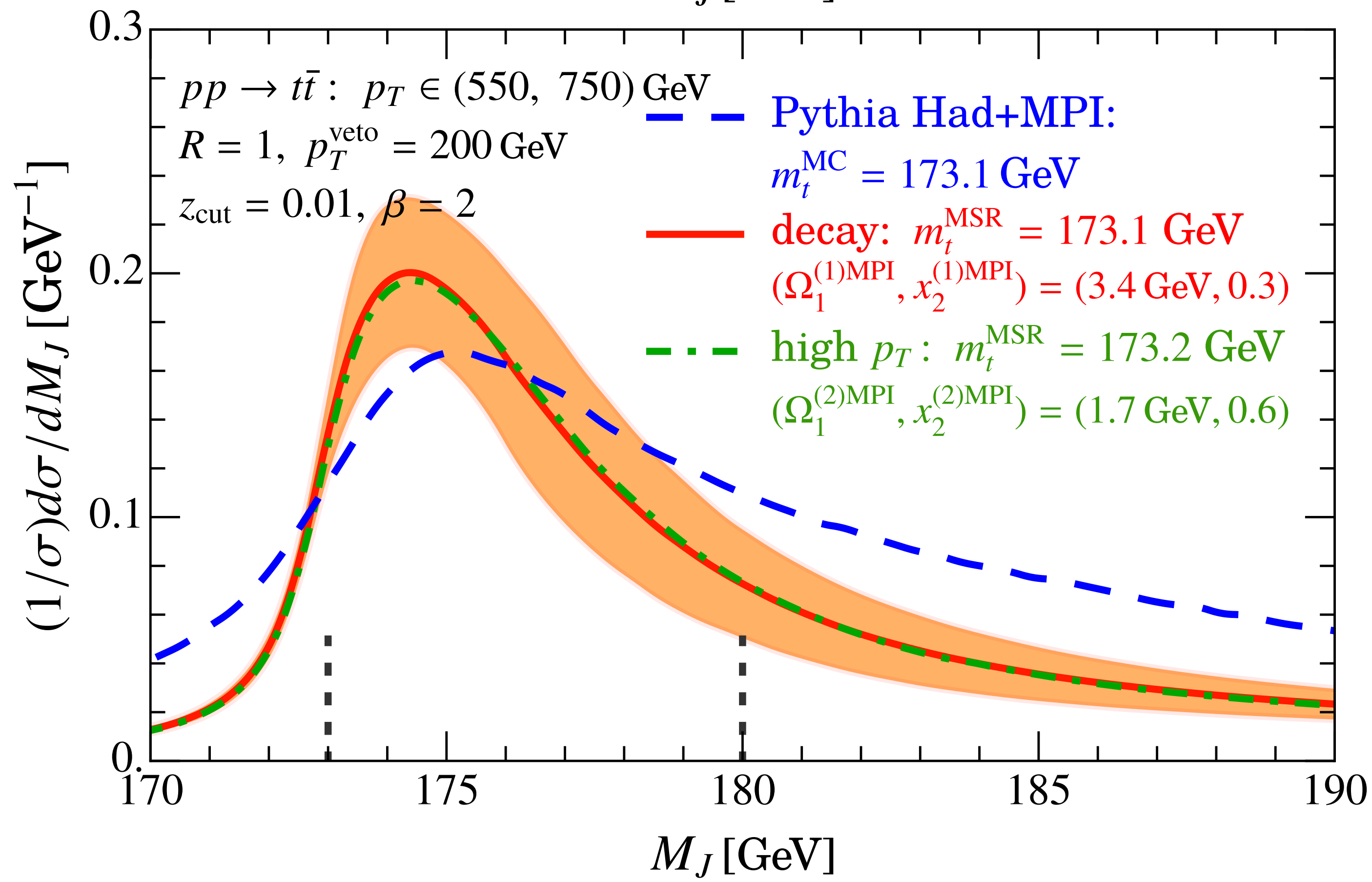
Use values obtained from fits to higher p_T bins

MPI-off:

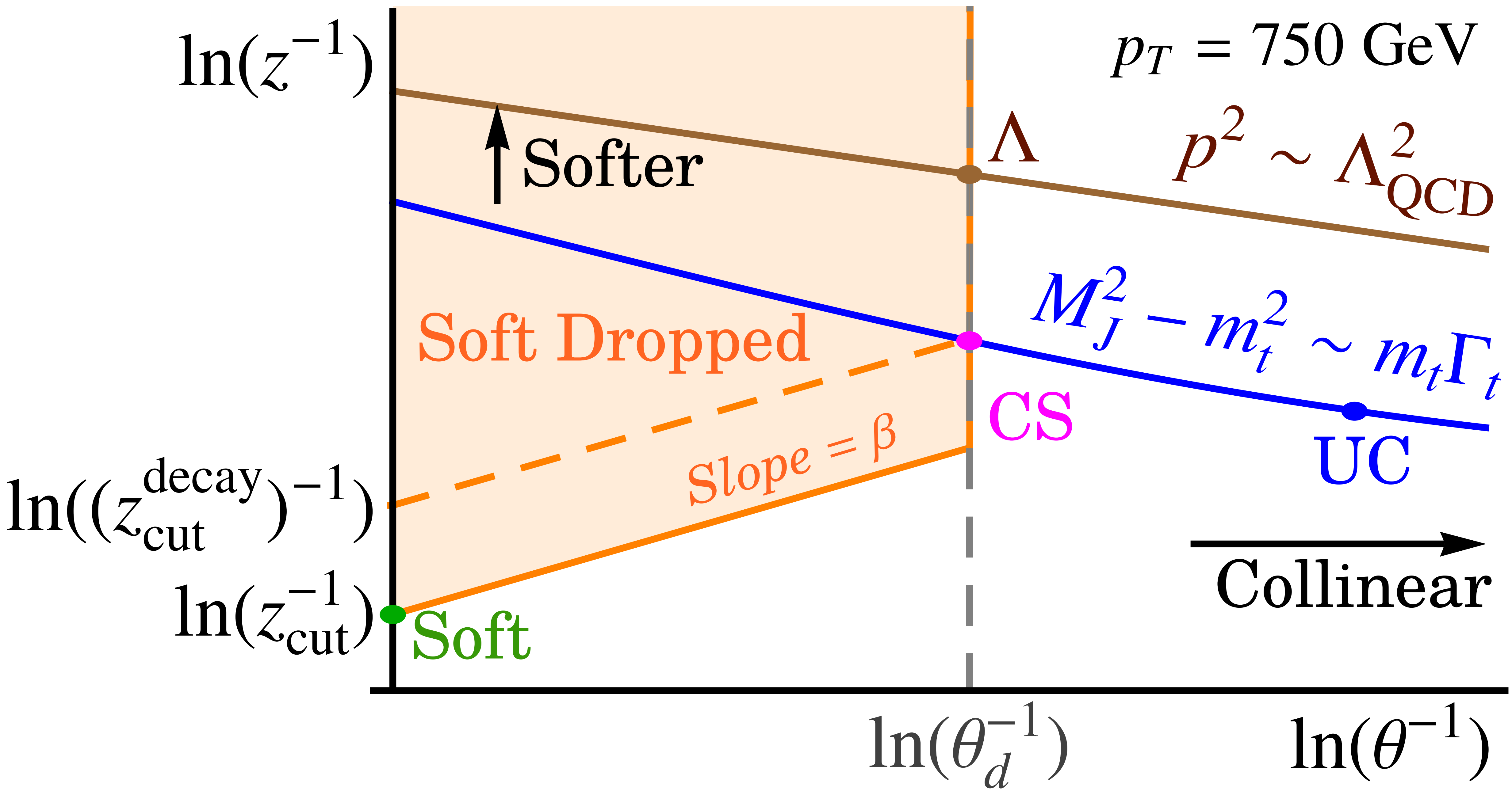


Factorization and Pythia are no longer in agreement.
Larger expansion parameters

MPI-on:

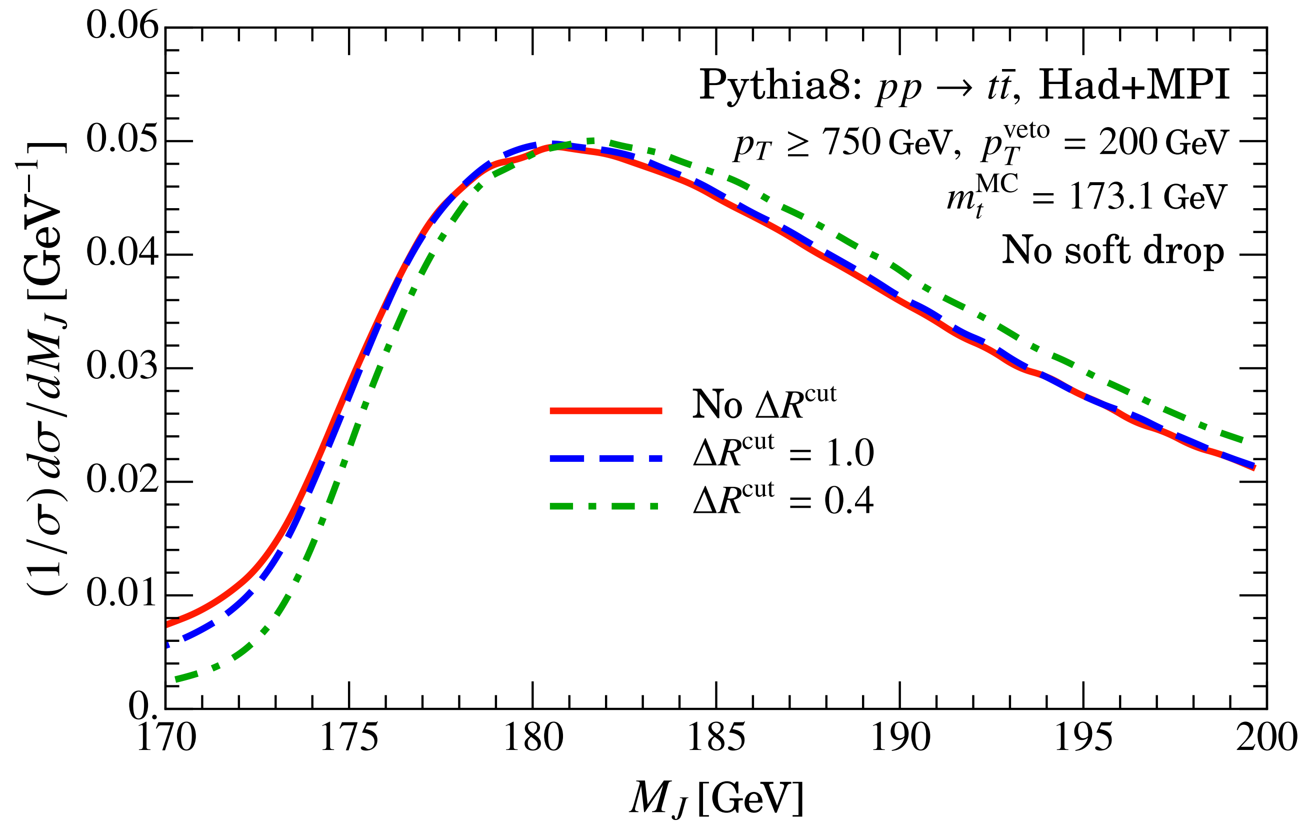


LARGE ZCUT VALUES: BREAK DOWN OF LIGHT GROOMING FACT.



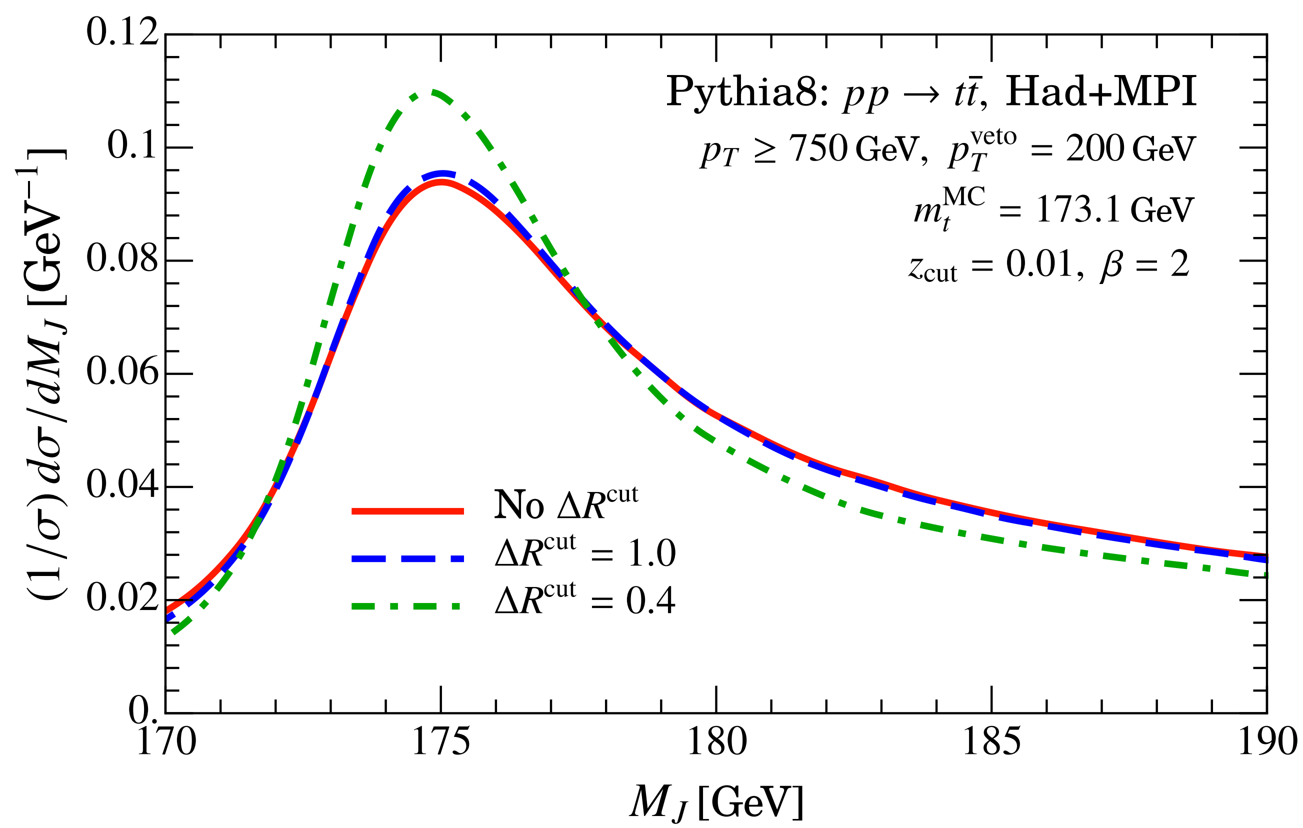
EFFECT OF CUTS ON DECAY PRODUCT SEPARATION

We observed disagreement on the left of the peak



Possibly due to decay products at wider angles

Improvement on the left of the peak with a stronger cut

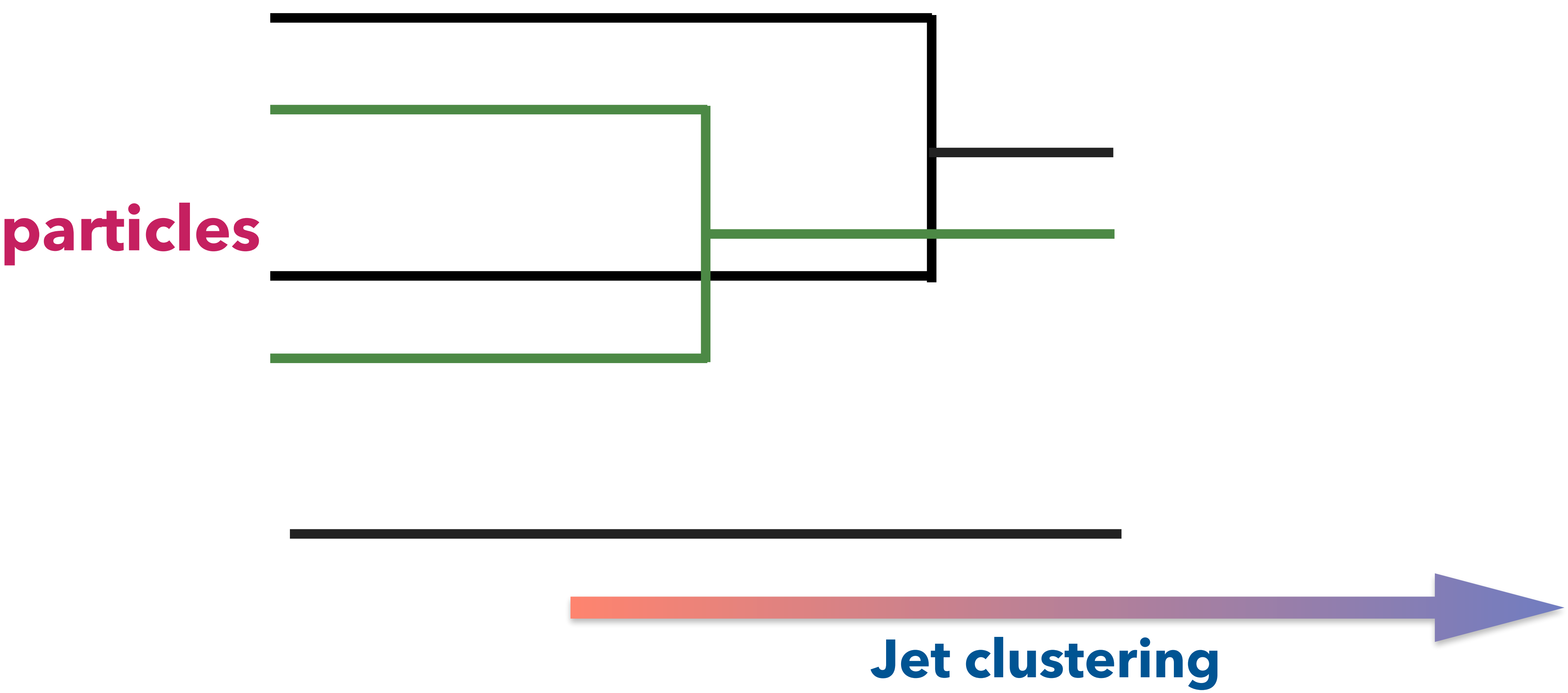


CLUSTERING AND GROOMING

Cluster particles in a jet defined by some algorithm

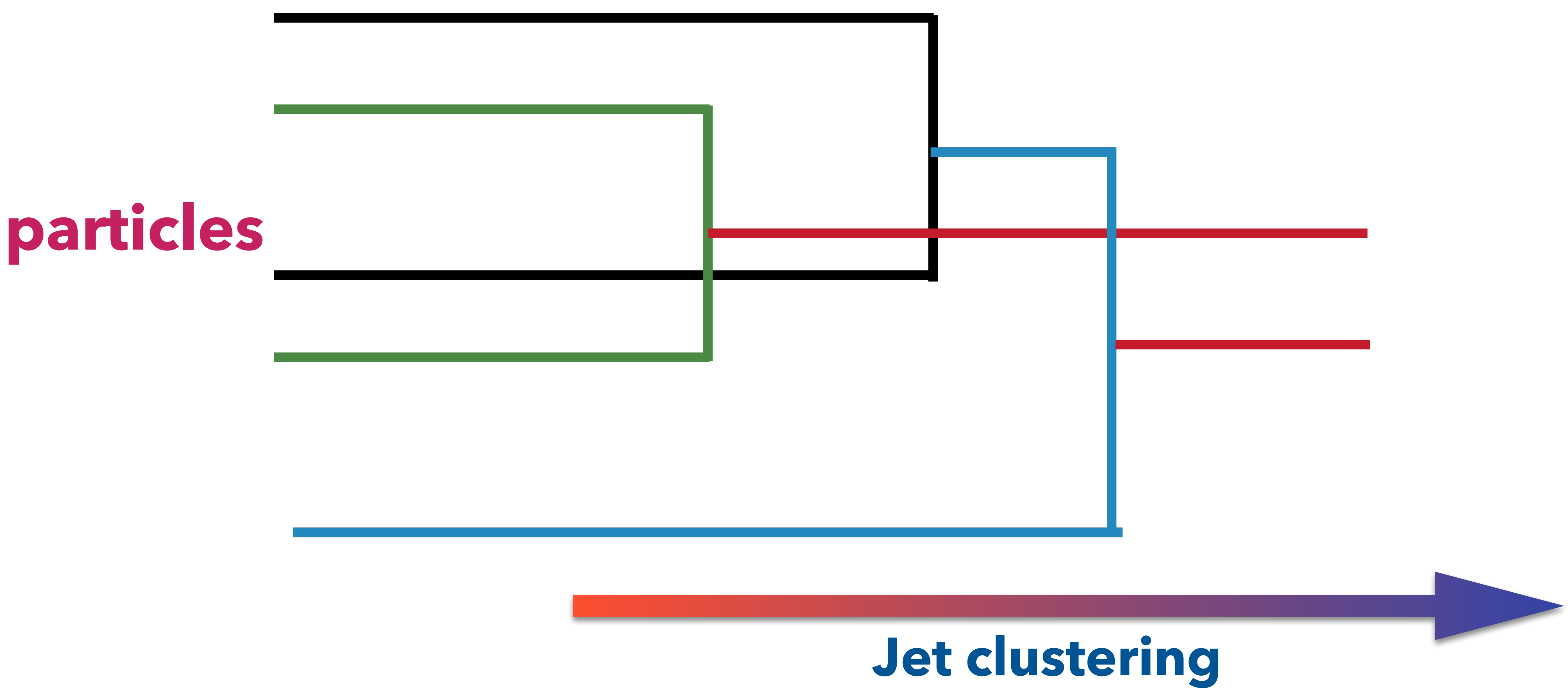
CLUSTERING AND GROOMING

Cluster particles in a jet defined by some algorithm



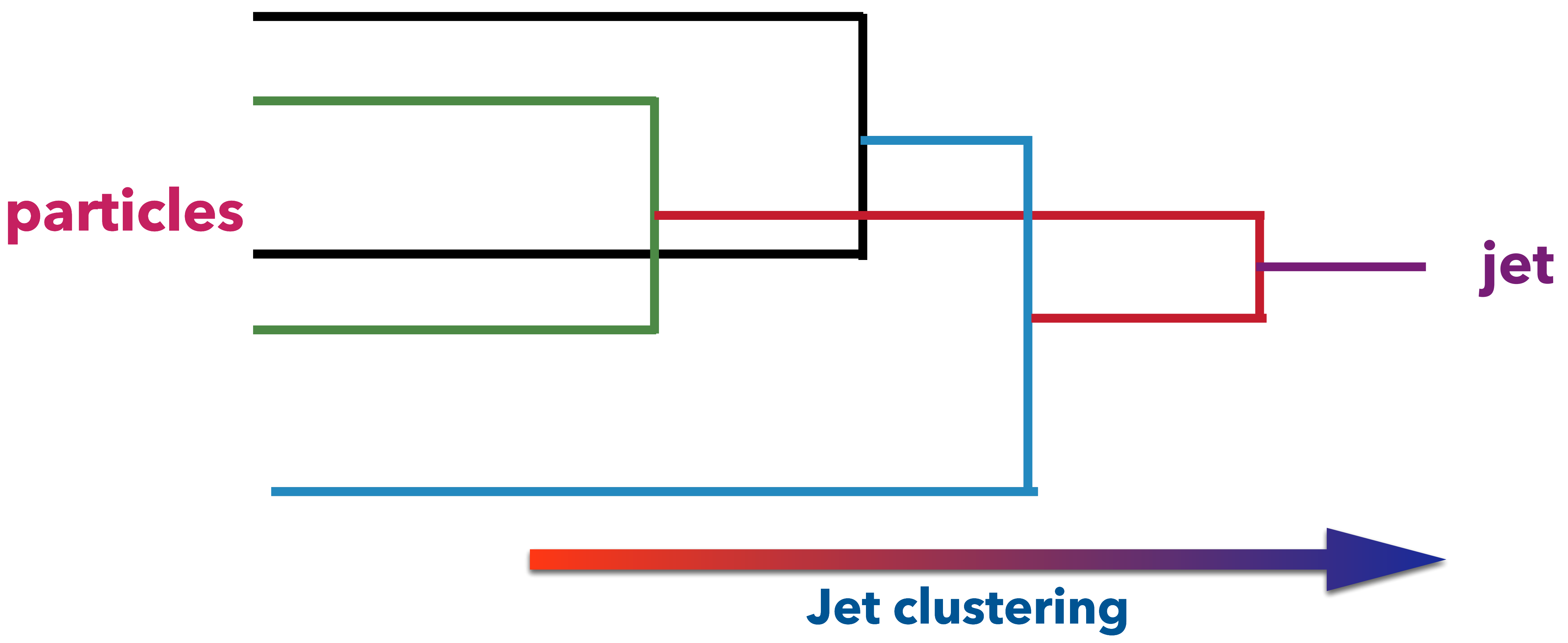
CLUSTERING AND GROOMING

Cluster particles in a jet defined by some algorithm



CLUSTERING AND GROOMING

Cluster particles in a jet defined by some algorithm

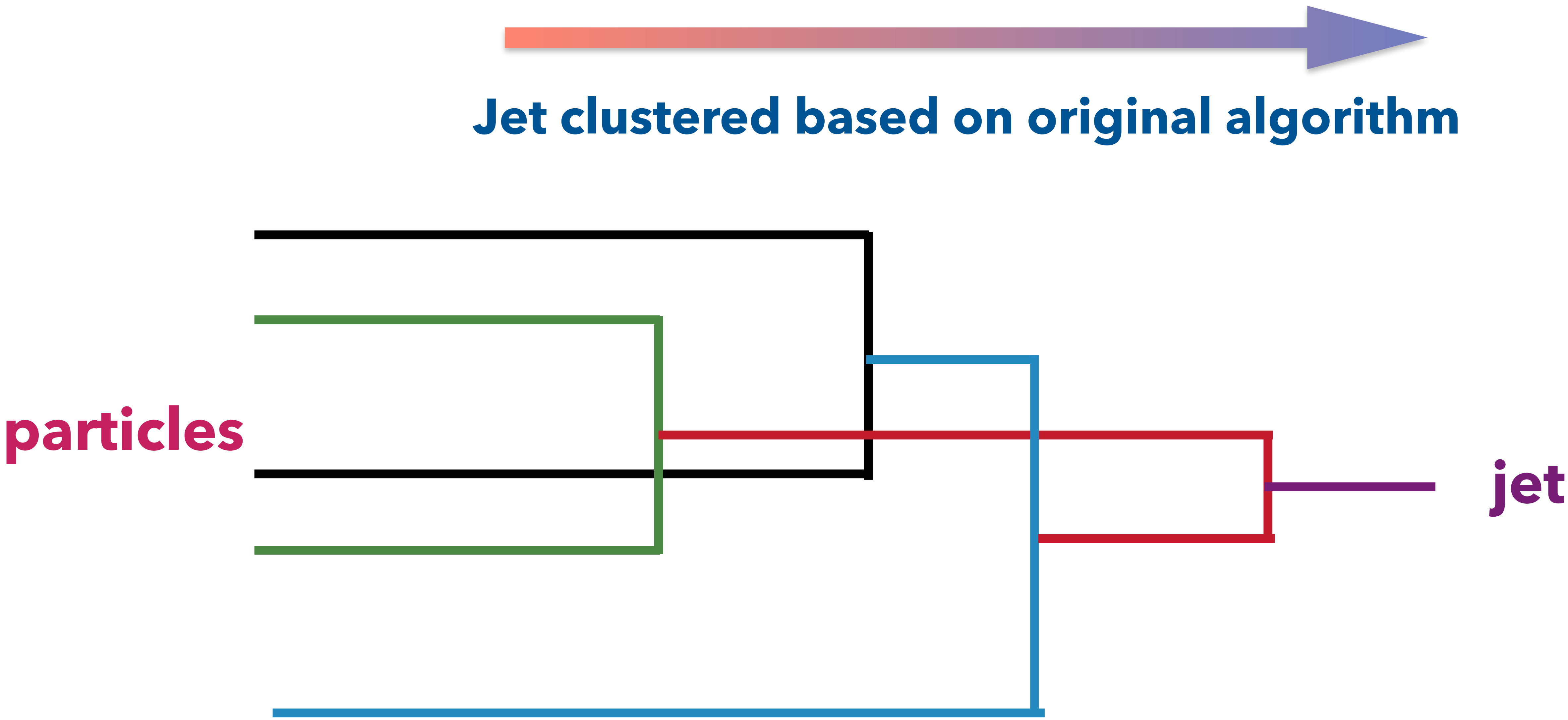


CLUSTERING AND GROOMING

Soft Drop grooming

Apply soft drop grooming on this jet

Jet clustered based on original algorithm

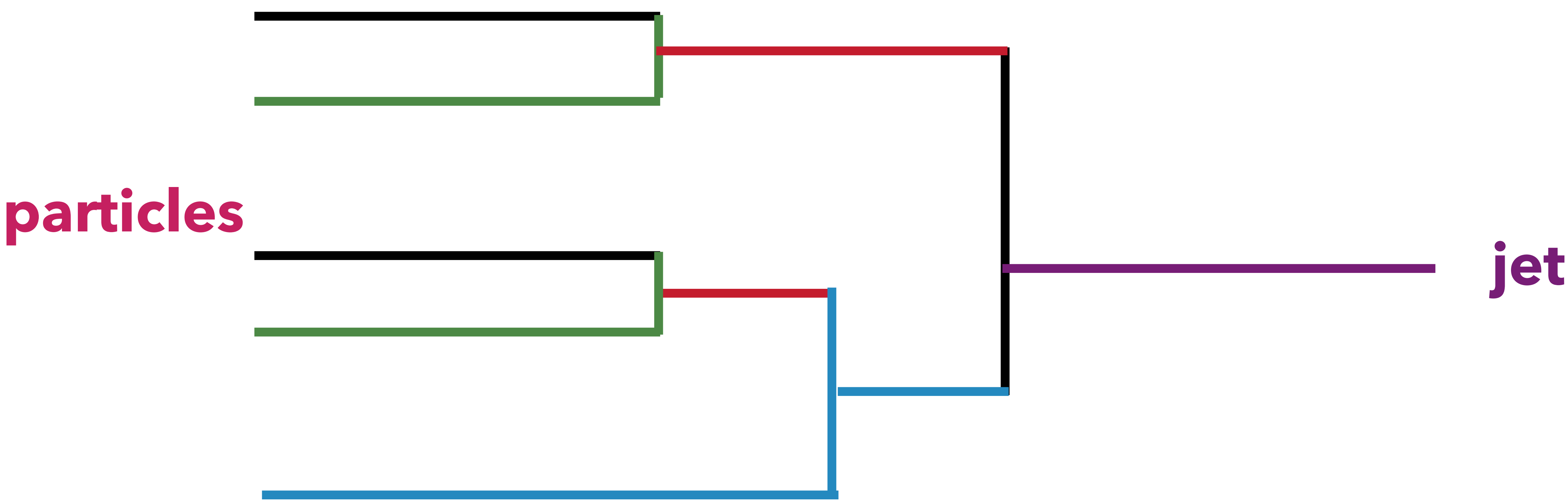


CLUSTERING AND GROOMING

Soft Drop grooming

Recluster the jet:

Re-cluster particles pairwise based on angluar distance

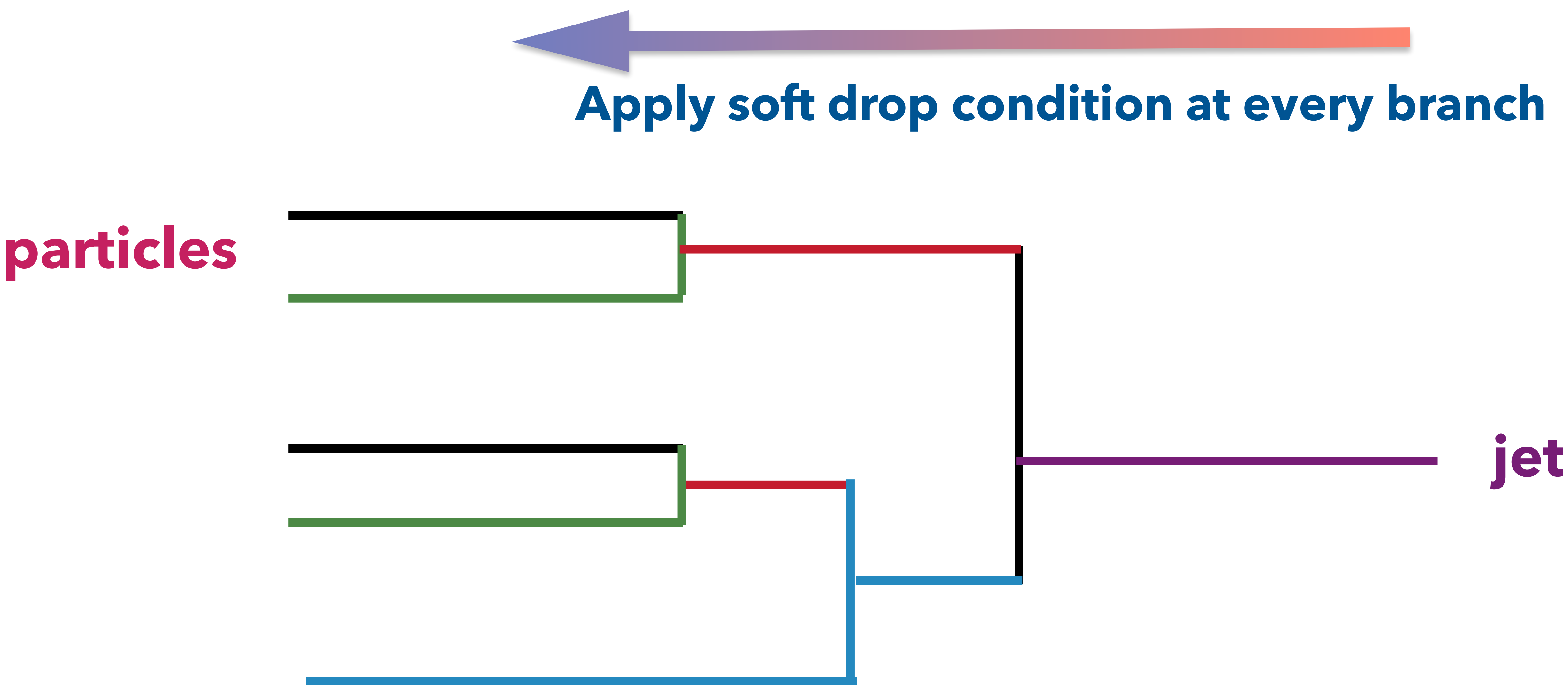


CLUSTERING AND GROOMING

Soft Drop grooming

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

Go back and groom!



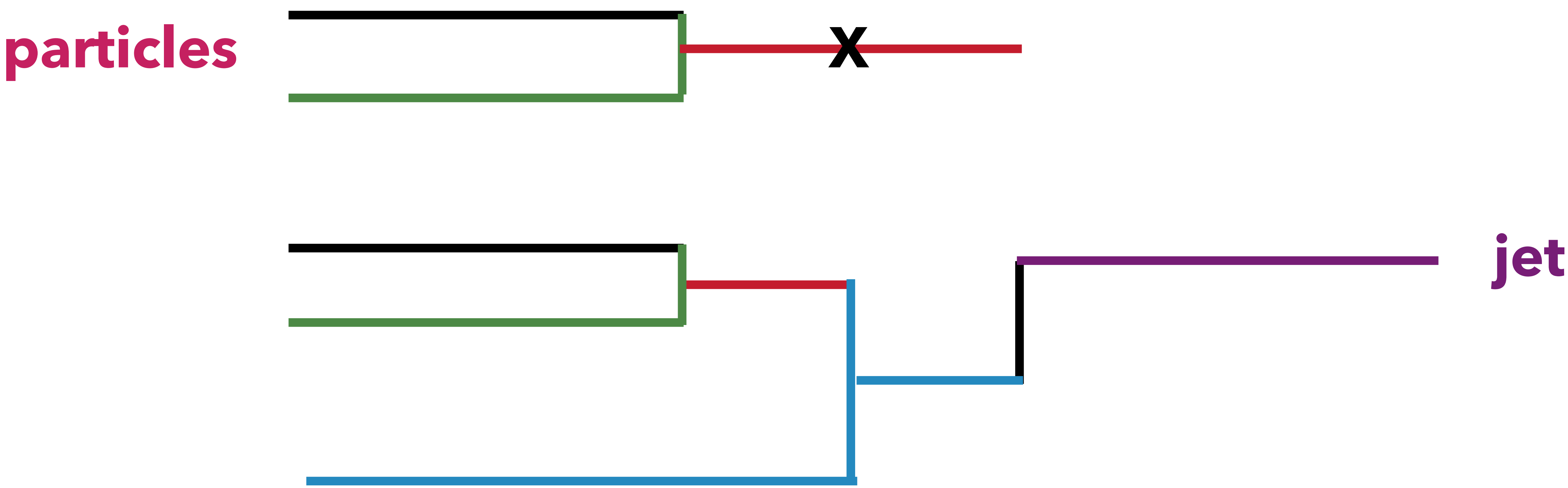
CLUSTERING AND GROOMING

Soft Drop grooming

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

Go back and groom!

Apply soft drop condition at every branch

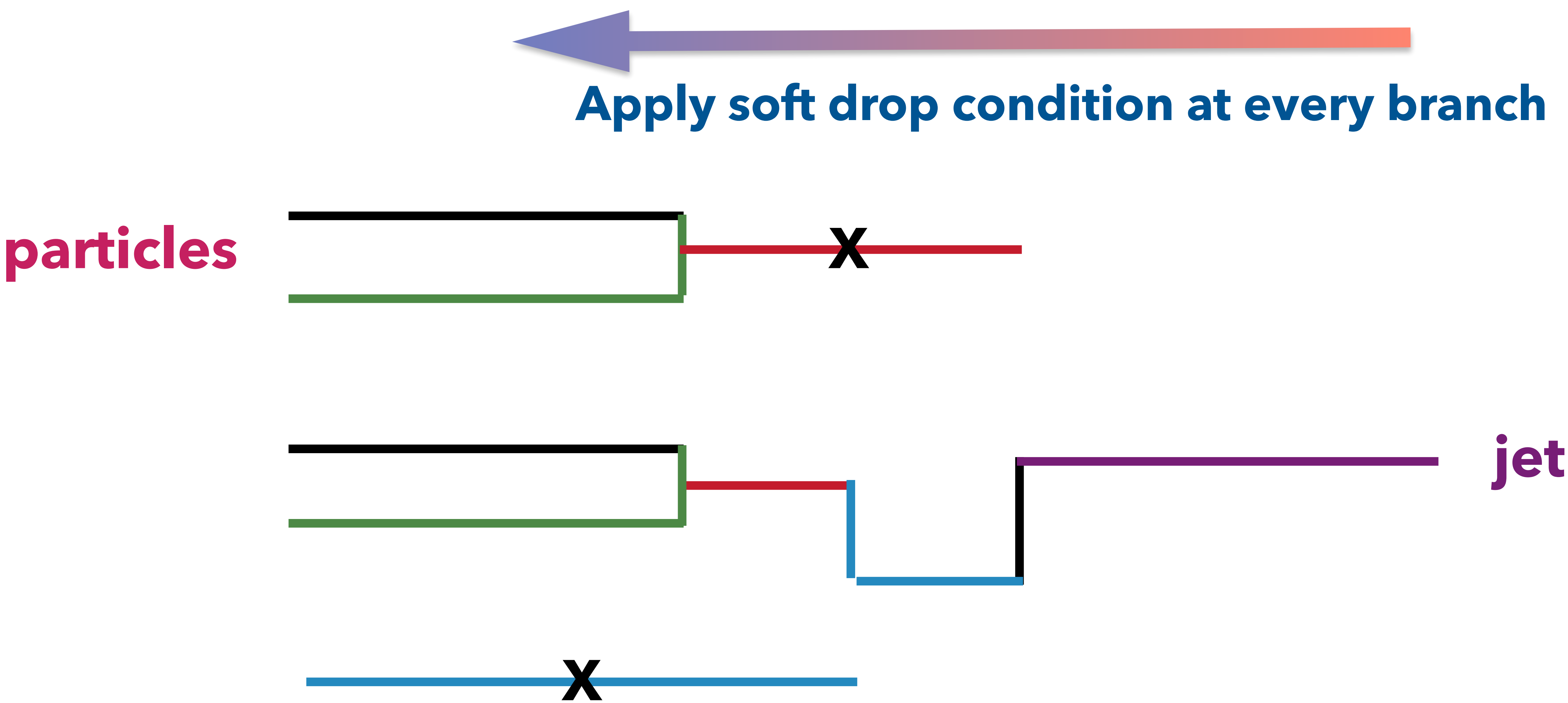


CLUSTERING AND GROOMING

Soft Drop grooming

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

Go back and groom!



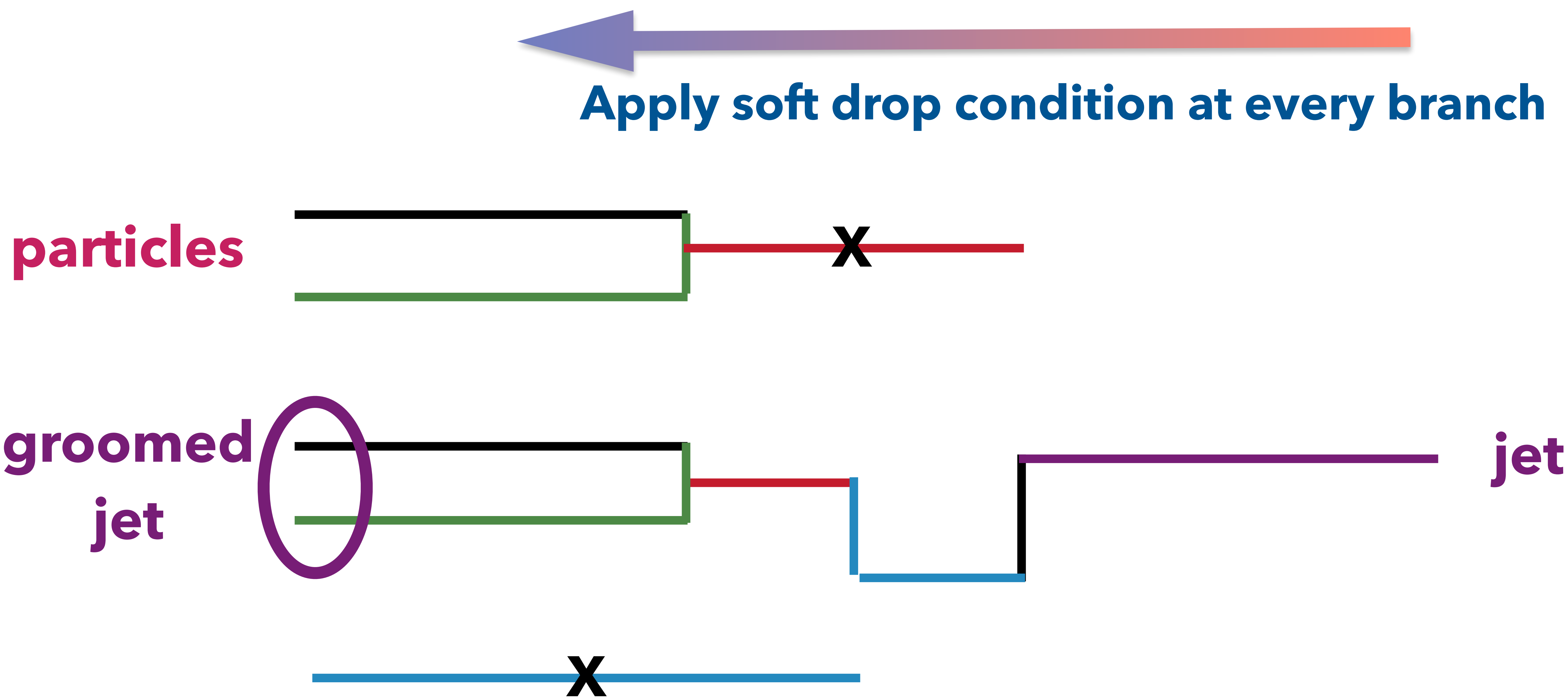
CLUSTERING AND GROOMING

Soft Drop grooming

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

Go back and groom!

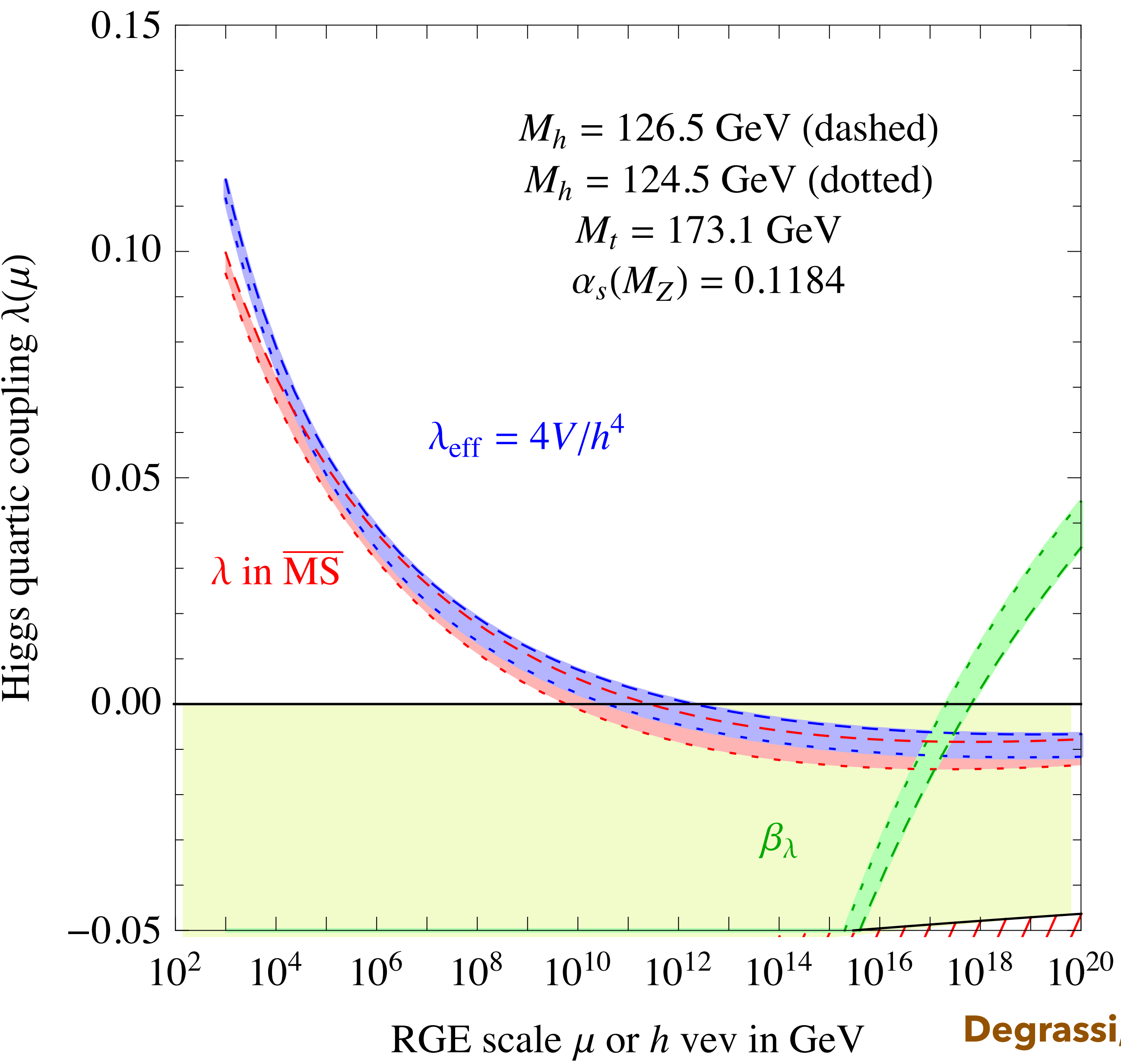
Apply soft drop condition at every branch

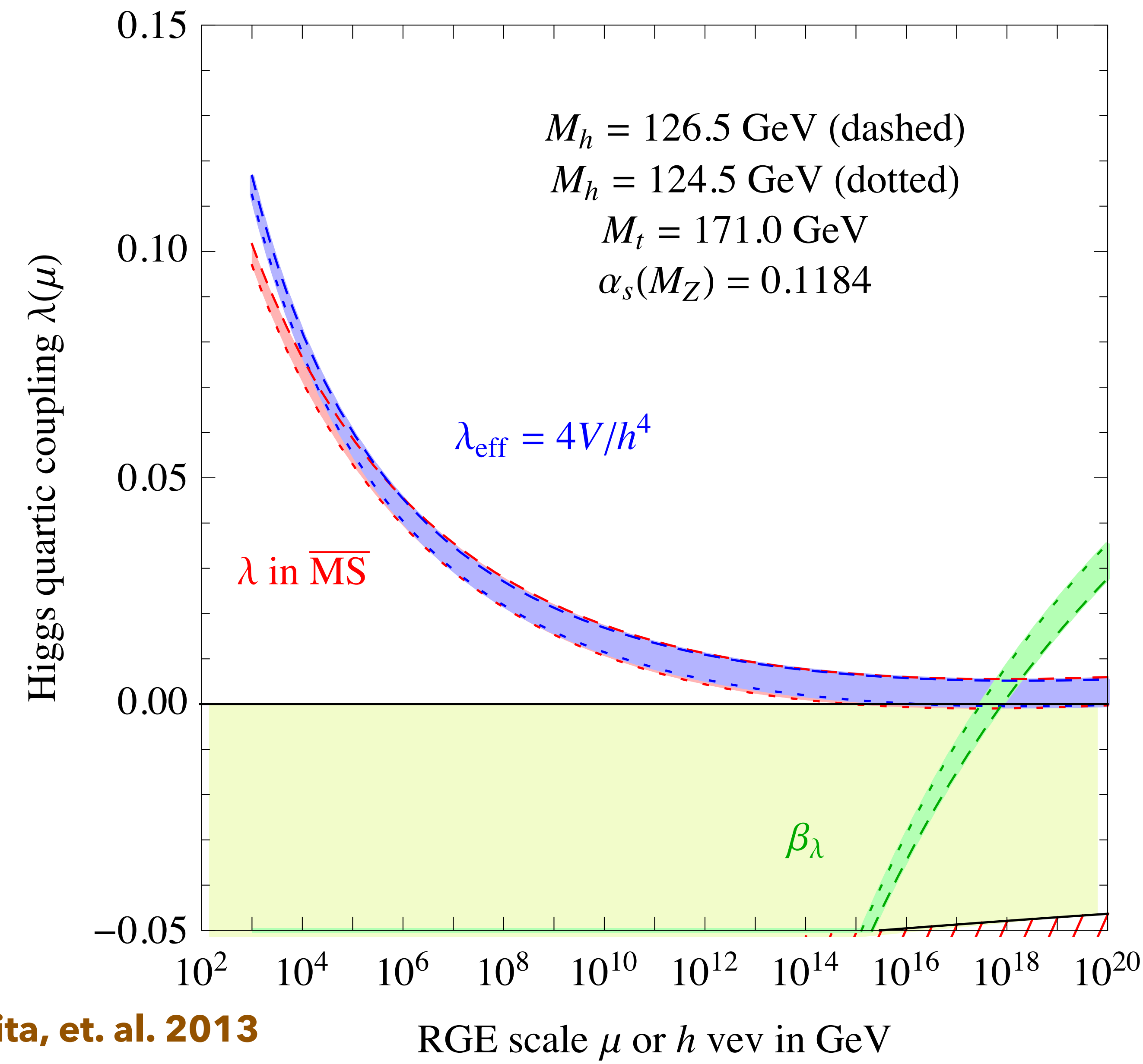


TOP MASS MEASUREMENT

- **Stability of SM Vacuum**

λ should always remain positive for the Higgs potential to be a true minimum.





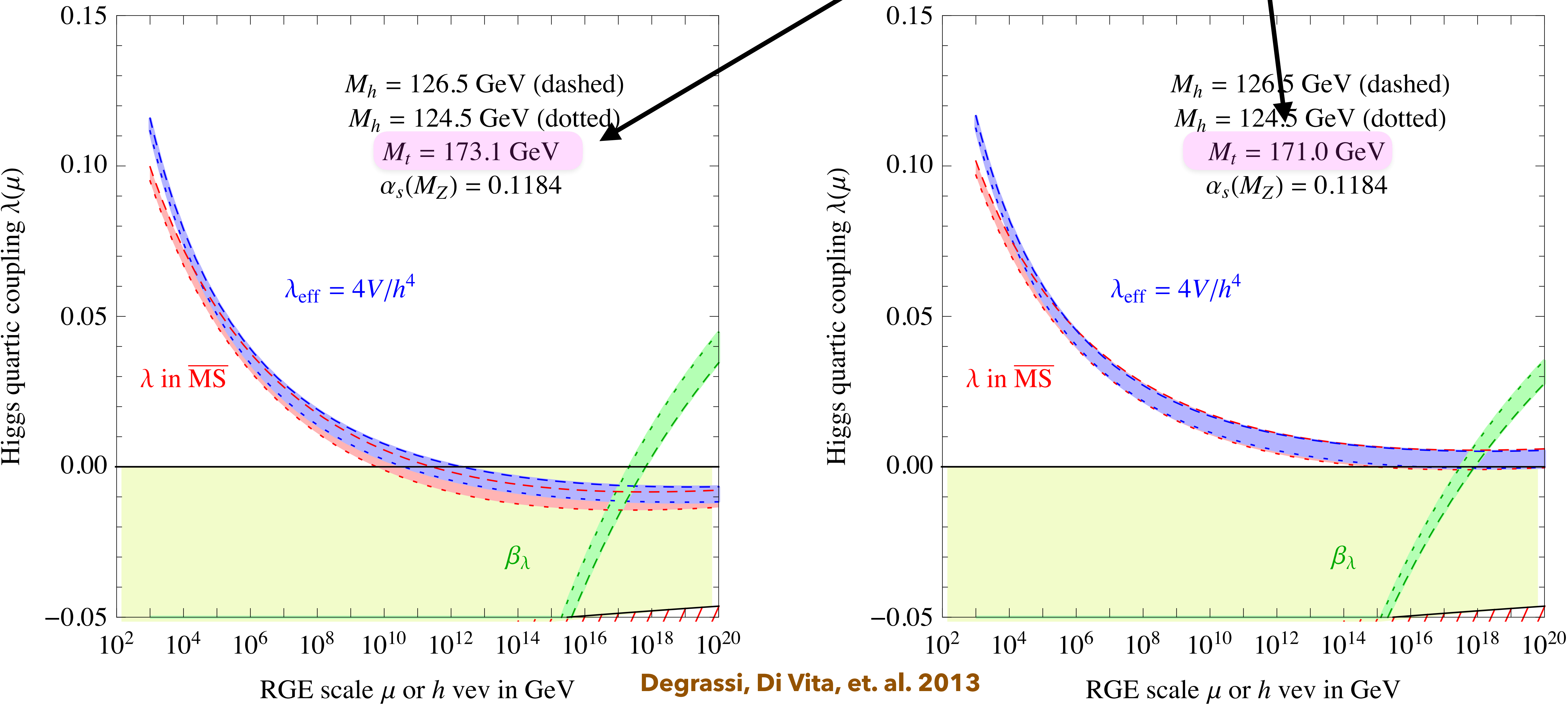
Degrassi, Di Vita, et. al. 2013

TOP MASS MEASUREMENT

- **Stability of SM Vacuum**

Rather sensitive to m_t

λ should always remain positive for the Higgs potential to be a true minimum.



Degrassi, Di Vita, et. al. 2013