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

UNIVERSITY OF VIENNA, NOV 17

BASED ON 1708.02586

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

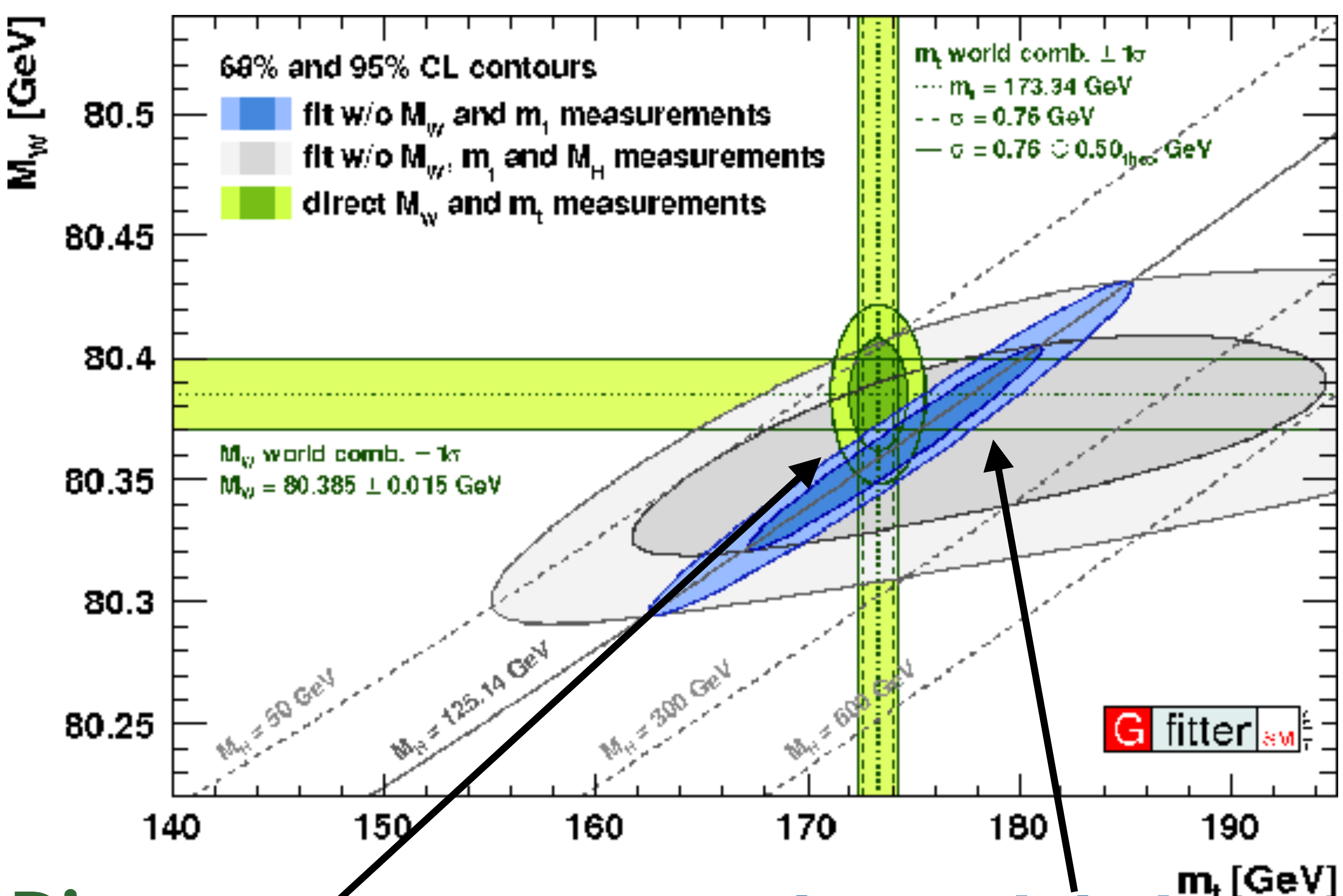
1. MOTIVATION, GOAL, CHALLENGES
2. MODERN TECHNIQUES IN PERTURBATIVE QCD
3. USING THE THEORY TOOLS, TESTING ROBUSTNESS

# TOP MASS MEASUREMENT

Why should we care about a precision $m_t$?

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

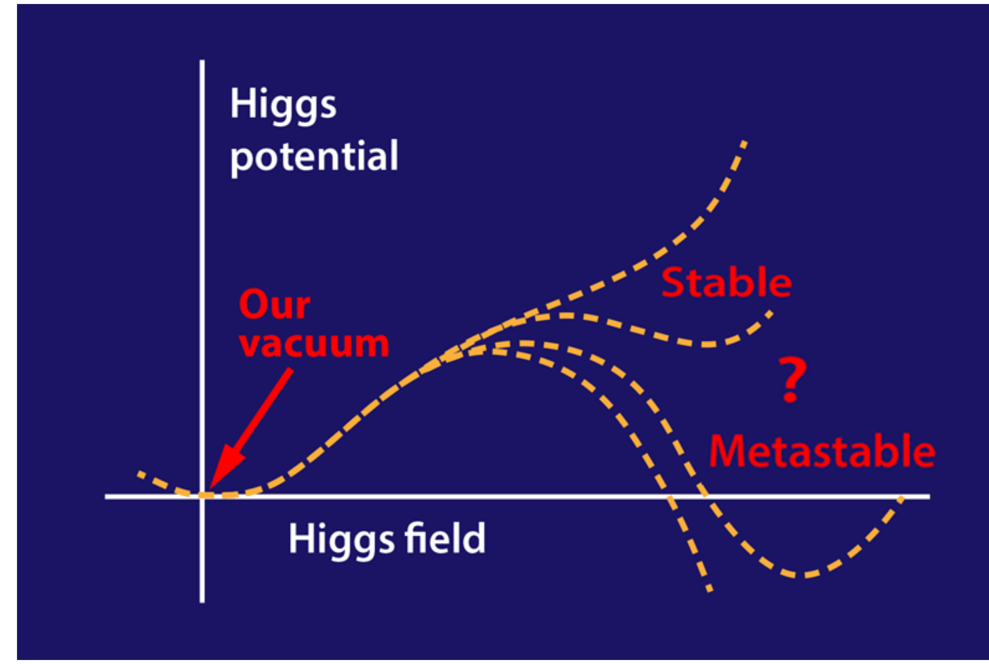
**Gfitter Group, 2014**



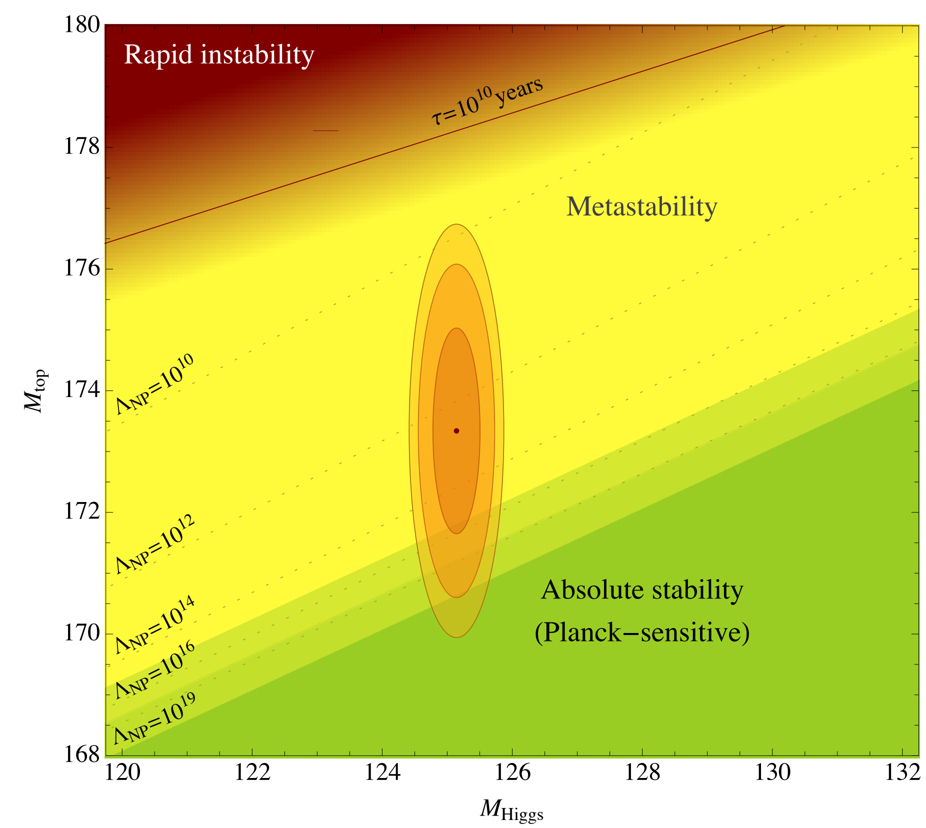

**Direct Measurements**

**Indirect global fit**

**Butazzo, Degrassi, Giardino, Giudice, Sala**




**Andreassen, Frost, Schwartz**




**Significant contribution to uncertainty due to $m_t$**

# STATUS OF TOP MASS PRECISION

## Two categories for top mass extraction:

### Top Mass from total cross section (Inclusive):

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

### Kinematic Top Mass Extractions (Exclusive):

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

# STATUS OF TOP MASS PRECISION

## Two categories for top mass extraction:

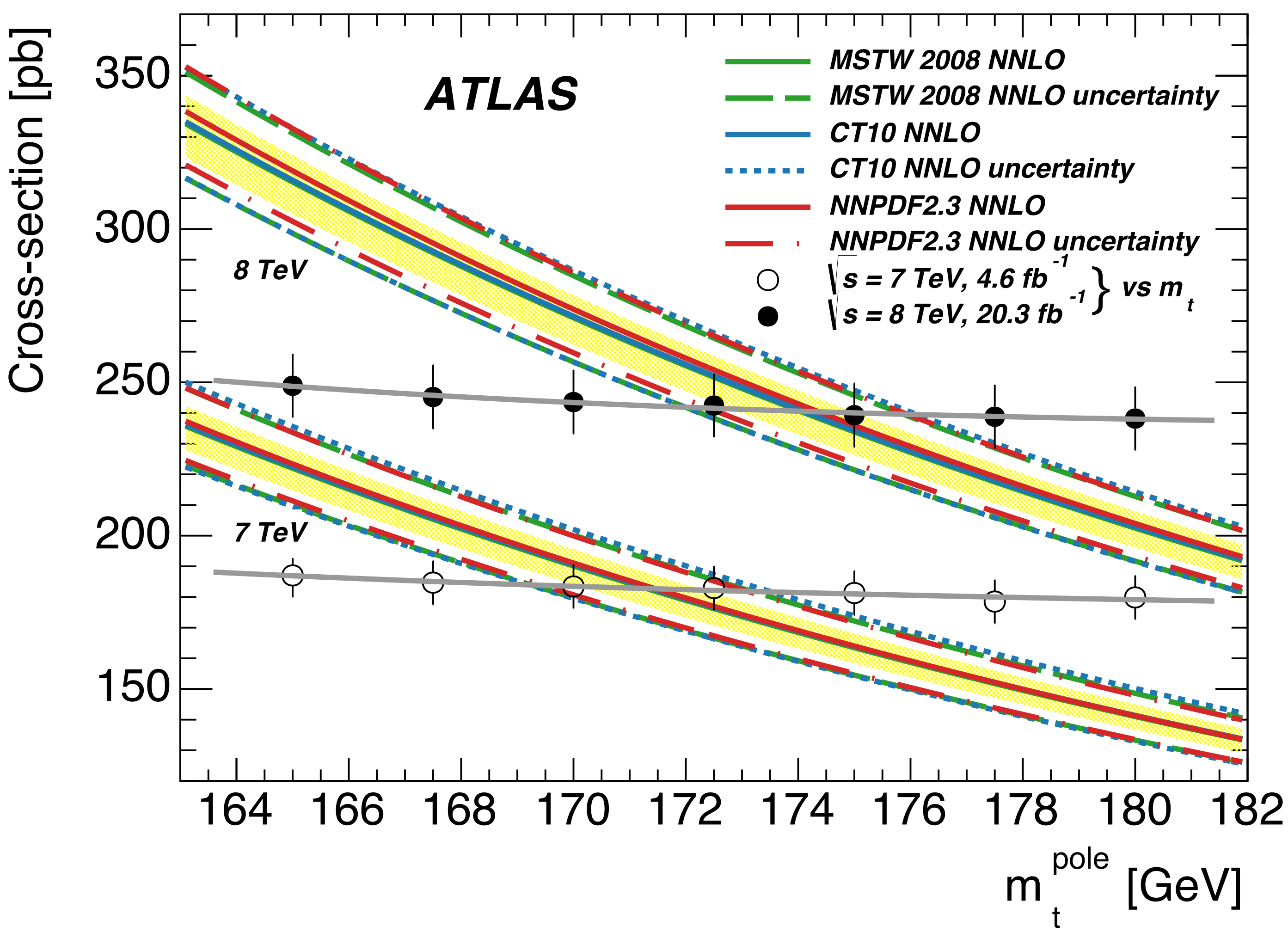
### Top Mass from total cross section (Inclusive):

**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




- You essentially count the number of events with top quarks in a given channel
- Compare with theory cross section that depends on the top mass.
- Uncertainties from PDF, Luminosity, QCD scales, modeling and other experimental systematics

# STATUS OF TOP MASS PRECISION

## Two categories for top mass extraction:

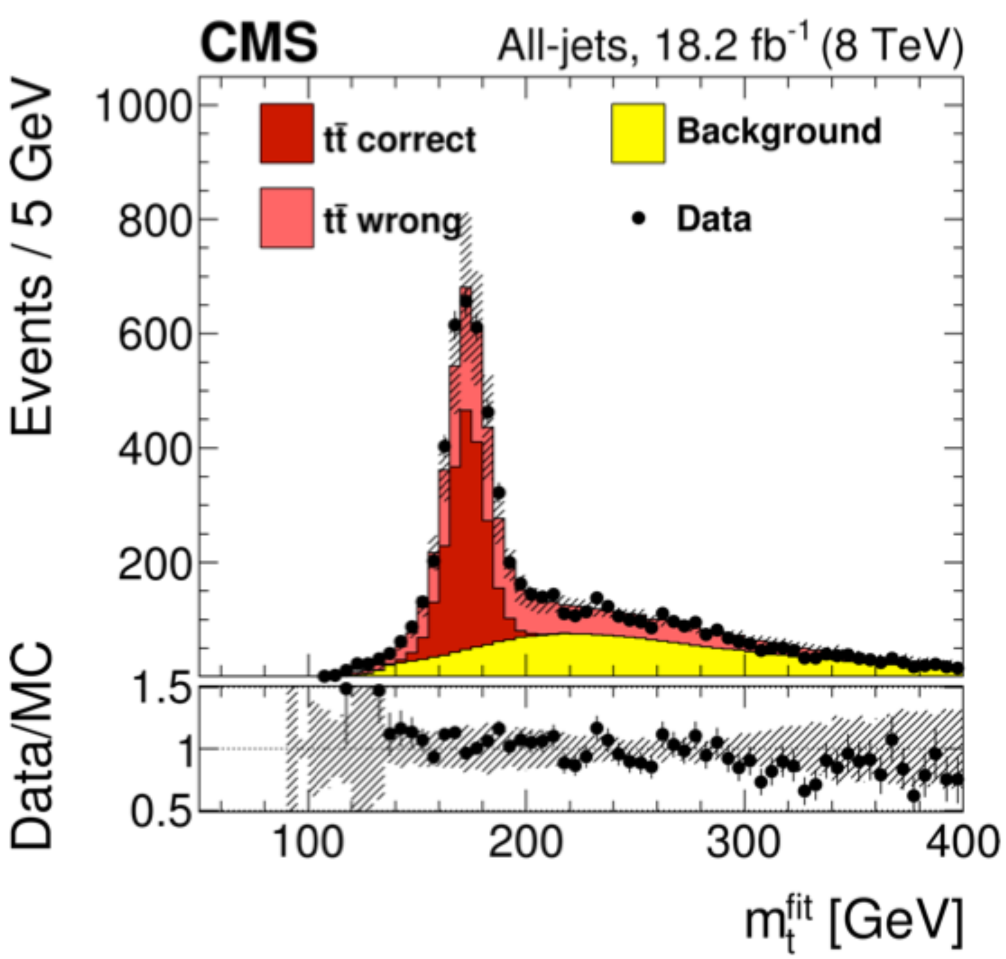
### Kinematic Top Mass Extractions:

**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




*all-jets channel at 8 TeV*

- Make use of kinematic information of final state particles.
- Compare data against Monte Carlo simulations.
- No direct comparison of theory and data.

# STATUS OF TOP MASS PRECISION

## Two categories for top mass extraction:

**Very precise!**

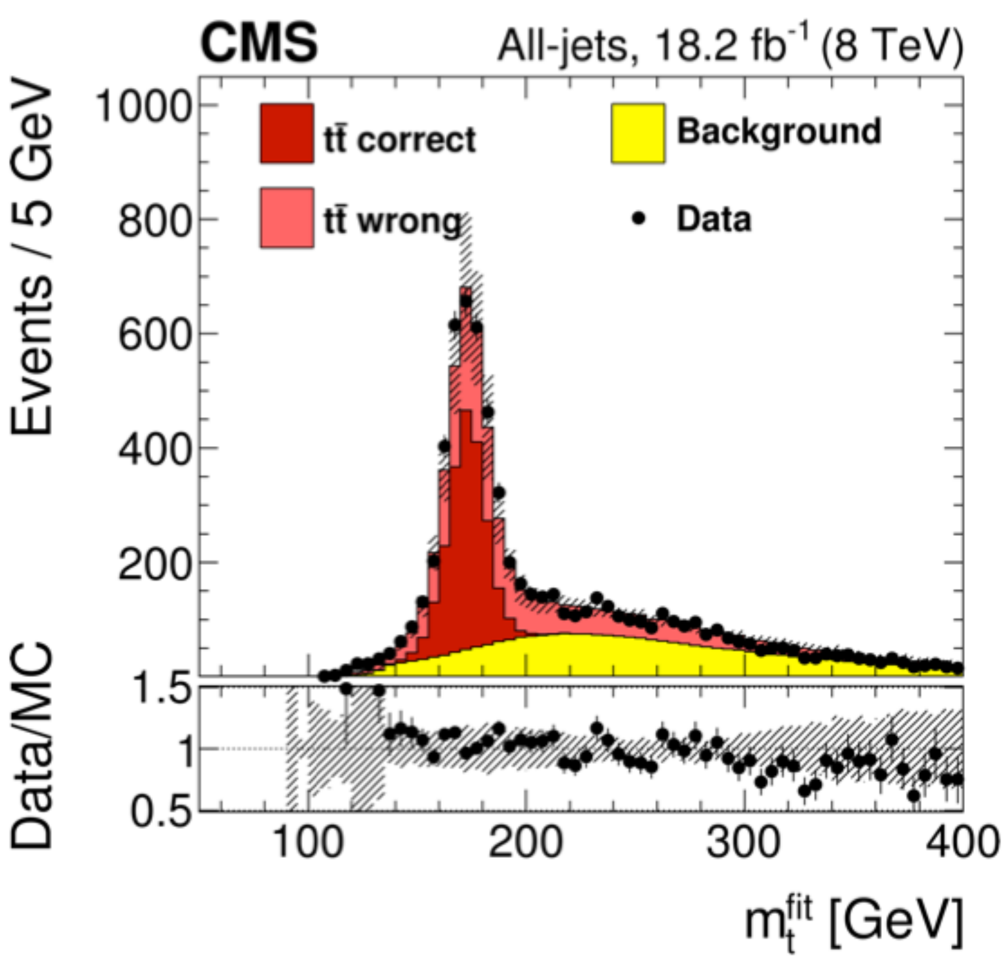
### Kinematic Top Mass Extractions:

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

Phys. Rev. D 93 (2016)

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

ATLAS-CONF-2017-071




*all-jets channel at 8 TeV*

- Make use of kinematic information of final state particles.
- Compare data against Monte Carlo simulations.
- No direct comparison of theory and data.

# STATUS OF TOP MASS PRECISION

## Two categories for top mass extraction:

**Very precise!**

### Kinematic Top Mass Extractions:

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

Phys. Rev. D 93 (2016)

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

ATLAS-CONF-2017-071

### Top Mass from total cross section (Inclusive):

CMS (2016) : $m_t$ = 173.8 ± 1.8 GeV

JHEP08 (2016) 029

ATLAS (2017) : $m_t$ = 173.2 ± 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?**

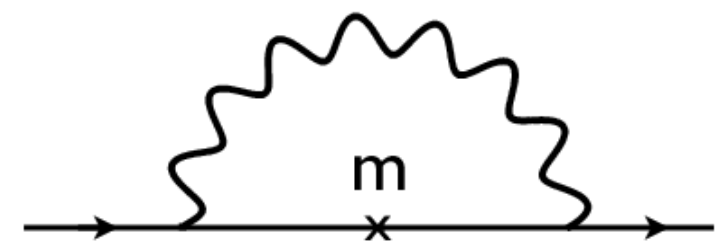
$$\boxed{\delta m_t \sim 1\,\mathrm{GeV}}$$

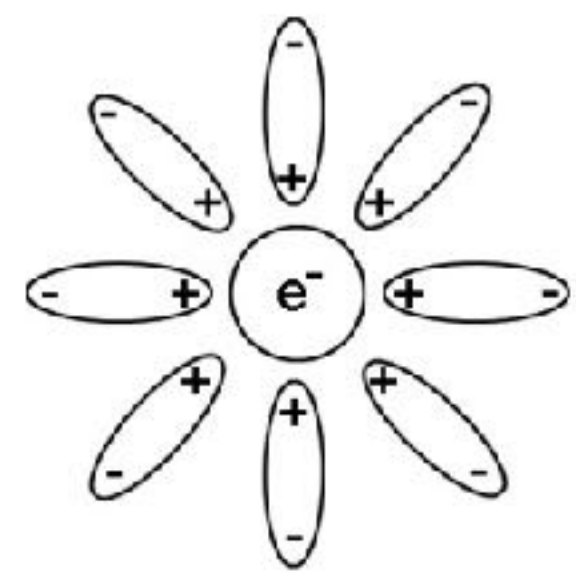
# STATUS OF TOP MASS PRECISION

**Masses in Quantum Field Theory get renormalized.**

$$m^{\mathrm{bare}} \to m^{\mathrm{bare}} + \Sigma(m^{\mathrm{bare}})$$

$$\Sigma(m) = \tfrac{3}{4} C_F \tfrac{\alpha_s}{\pi} m \left( \tfrac{1}{\epsilon} + \mathrm{finite} \right) + \mathcal{O}(\alpha_s^2)$$



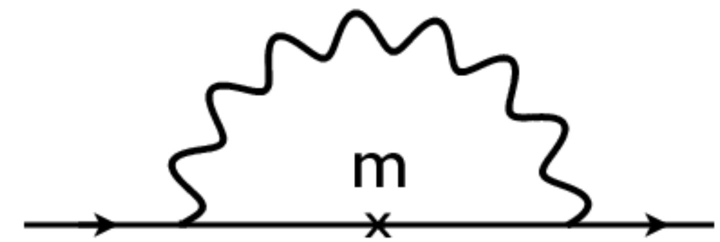

Charge of electron is a scale dependent quantity because of quantum effects.

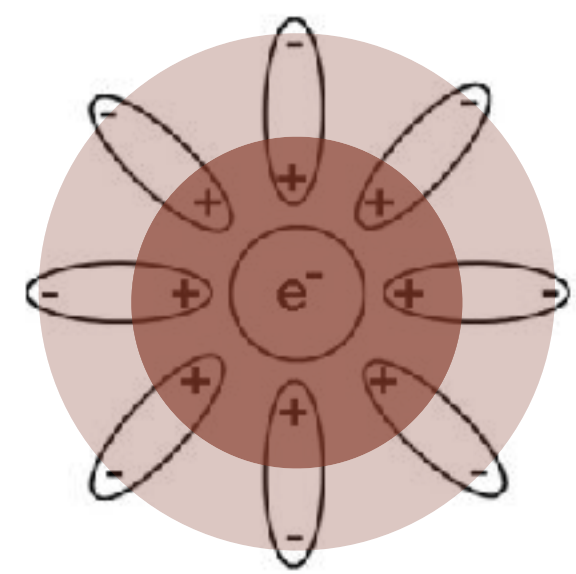
# STATUS OF TOP MASS PRECISION

## Masses in Quantum Field Theory get renormalized.

$$m^{\text{bare}} \to m^{\text{bare}} + \Sigma(m^{\text{bare}})$$

$$\Sigma(m) = \tfrac{3}{4} C_F \tfrac{\alpha_s}{\pi} m \left(\tfrac{1}{\epsilon} + \text{finite}\right) + \mathcal{O}(\alpha_s^2)$$



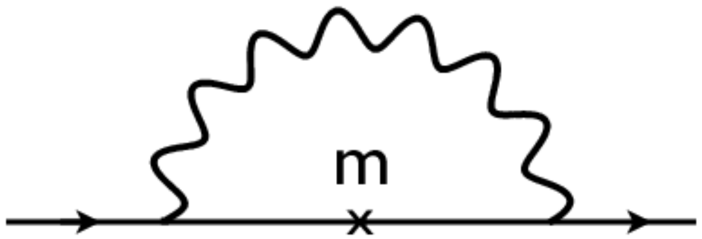

Charge of electron is a scale dependent quantity because of quantum effects.

# STATUS OF TOP MASS PRECISION

**Masses in Quantum Field Theory get renormalized.**

$$m^{\text{bare}} \to m^{\text{bare}} + \Sigma(m^{\text{bare}})$$

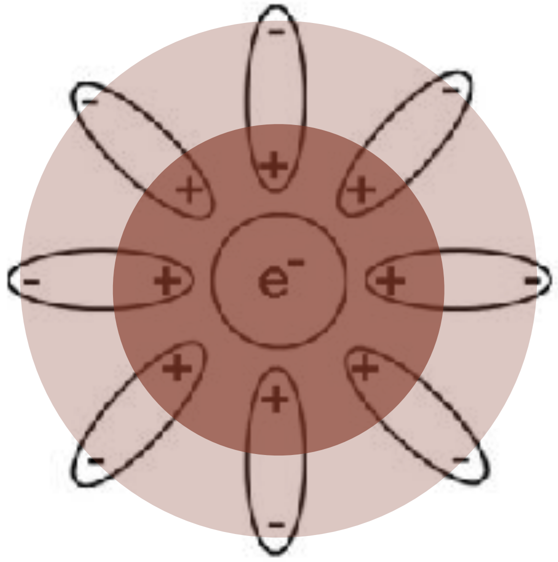
$$\Sigma(m) = \tfrac{3}{4} C_F \tfrac{\alpha_s}{\pi} m \left( \tfrac{1}{\epsilon} + \text{finite} \right) + \mathcal{O}(\alpha_s^2)$$




**Quantum effects changes the meaning of the top mass: A scale dependent quantity.**

**We pick a renormalization scheme:**

- Pole Mass - Remove the full one loop correction $\Sigma$
- $\overline{\text{MS}}$ mass - Remove the $1/\epsilon$ term from $\Sigma$




Charge of electron is a scale dependent quantity because of quantum effects.

# 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) $\pm 0.48$ (sys) GeV

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

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

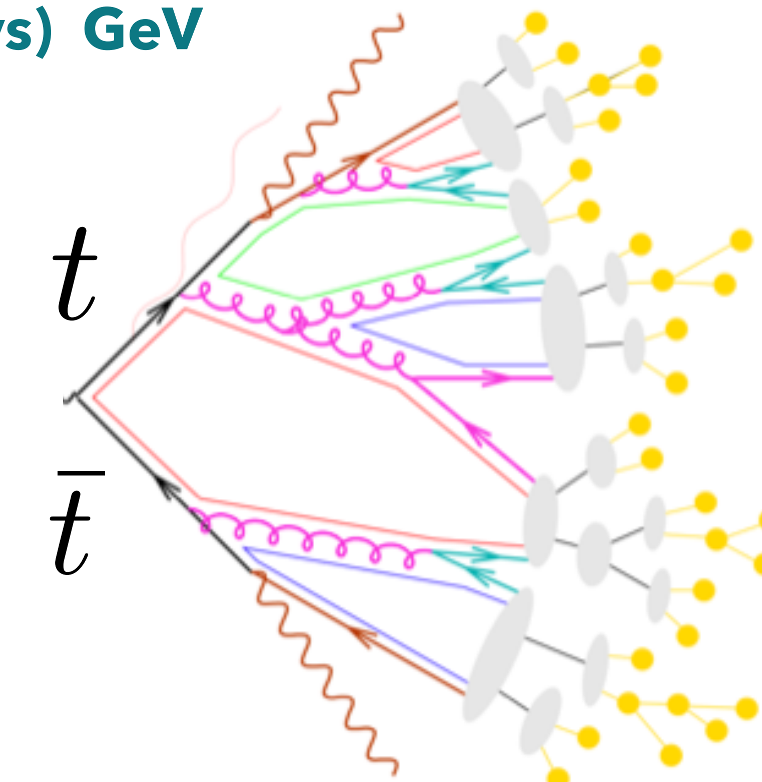
Theory (QFT)

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

Monte Carlo

Experiment

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




**Field Theoretic Definition?**

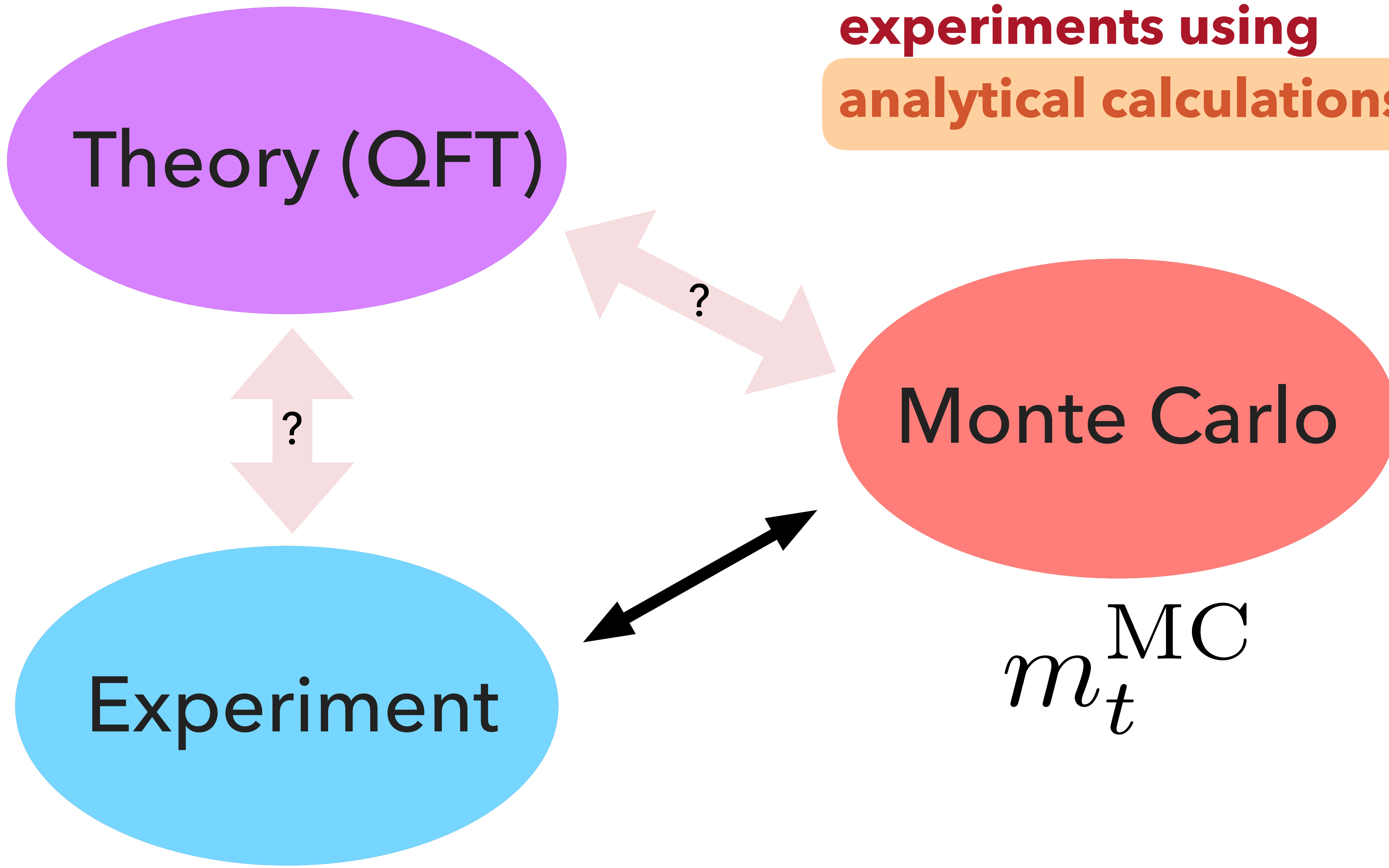
Butenschoen, Dehnadi, Hoang, Mateu, Preisser, Stewart 2016

Hoang, Stewart 2008

# GOAL OF THIS WORK

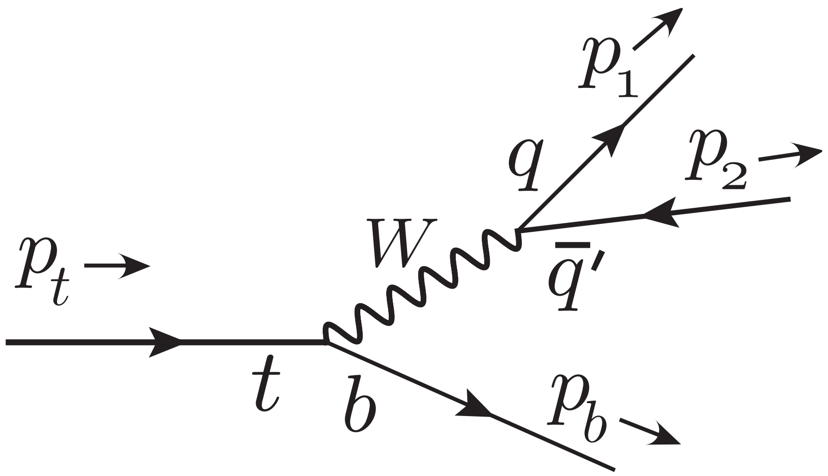
$m_t^{\mathrm{pole}}, \overline{m}_t, m_t^{\mathrm{MSR}}, \ldots$

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



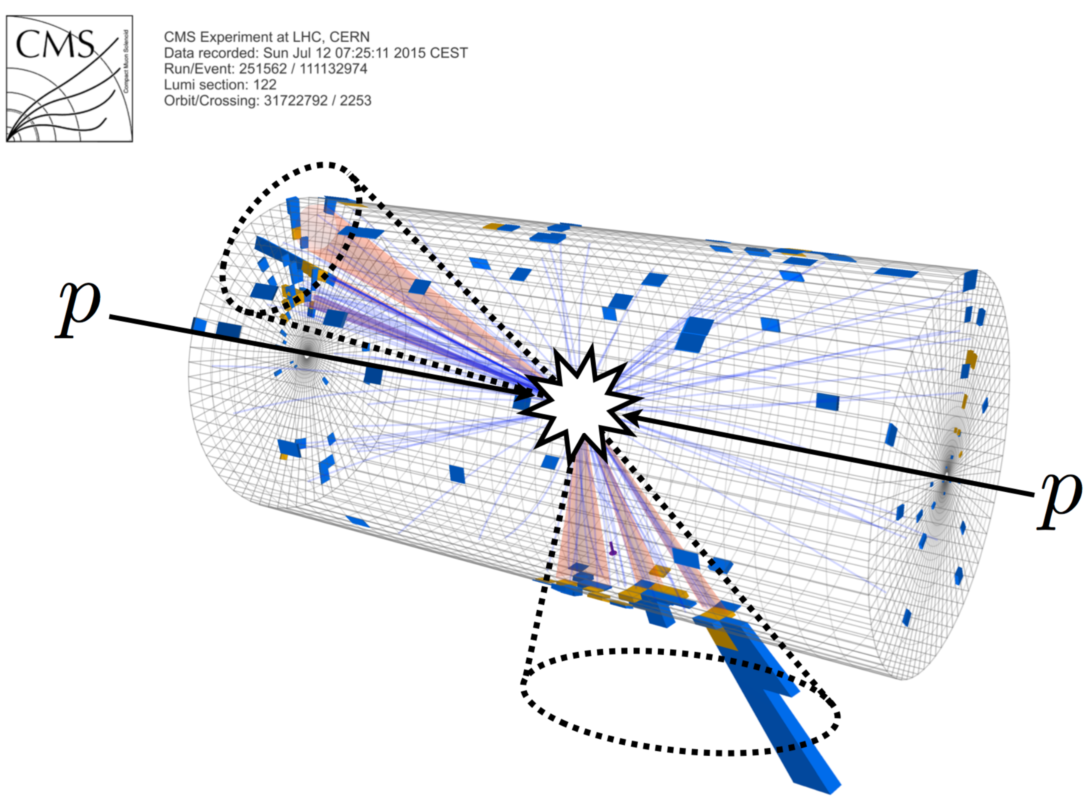

$m_t^{\mathrm{MC}}$

# KINEMATIC EXTRACTIONS

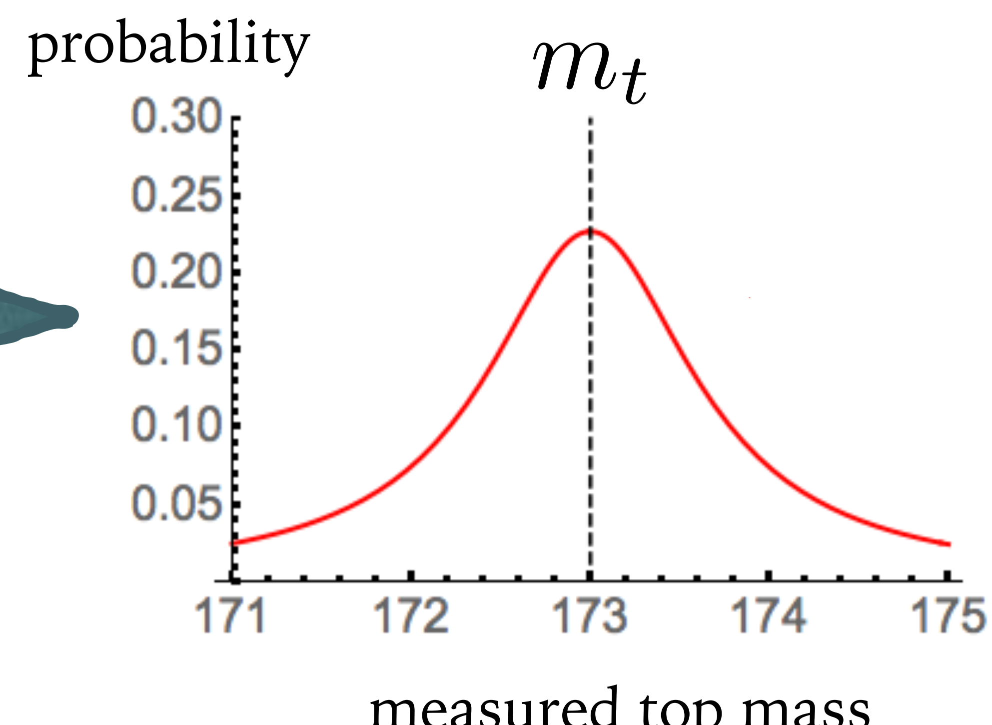



$$m_t^2 = p_t^2 = (p_1 + p_2 + p_b)^2$$

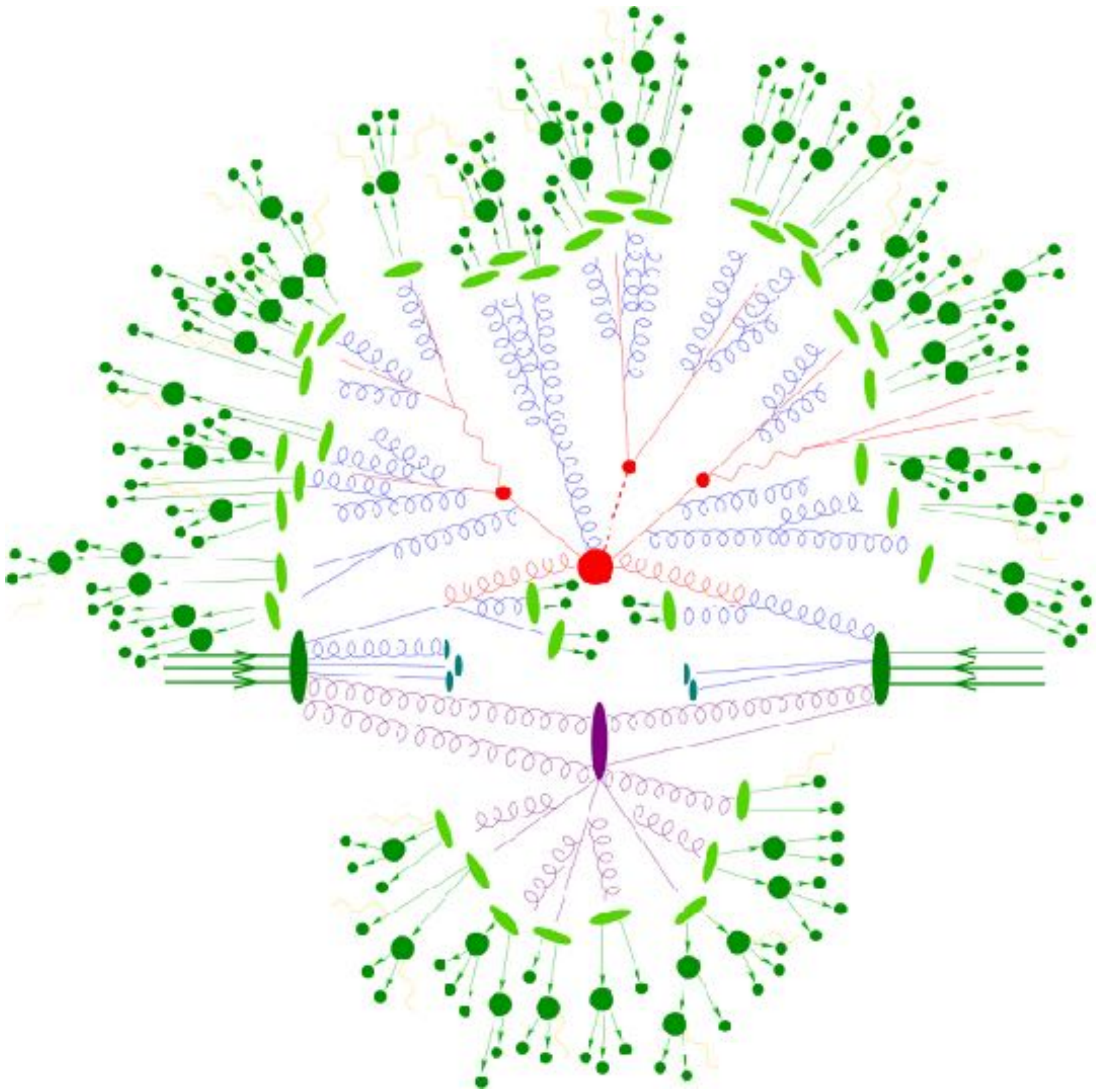
**Find events with top quarks**




**Measure top mass spectrum using decay product momenta**

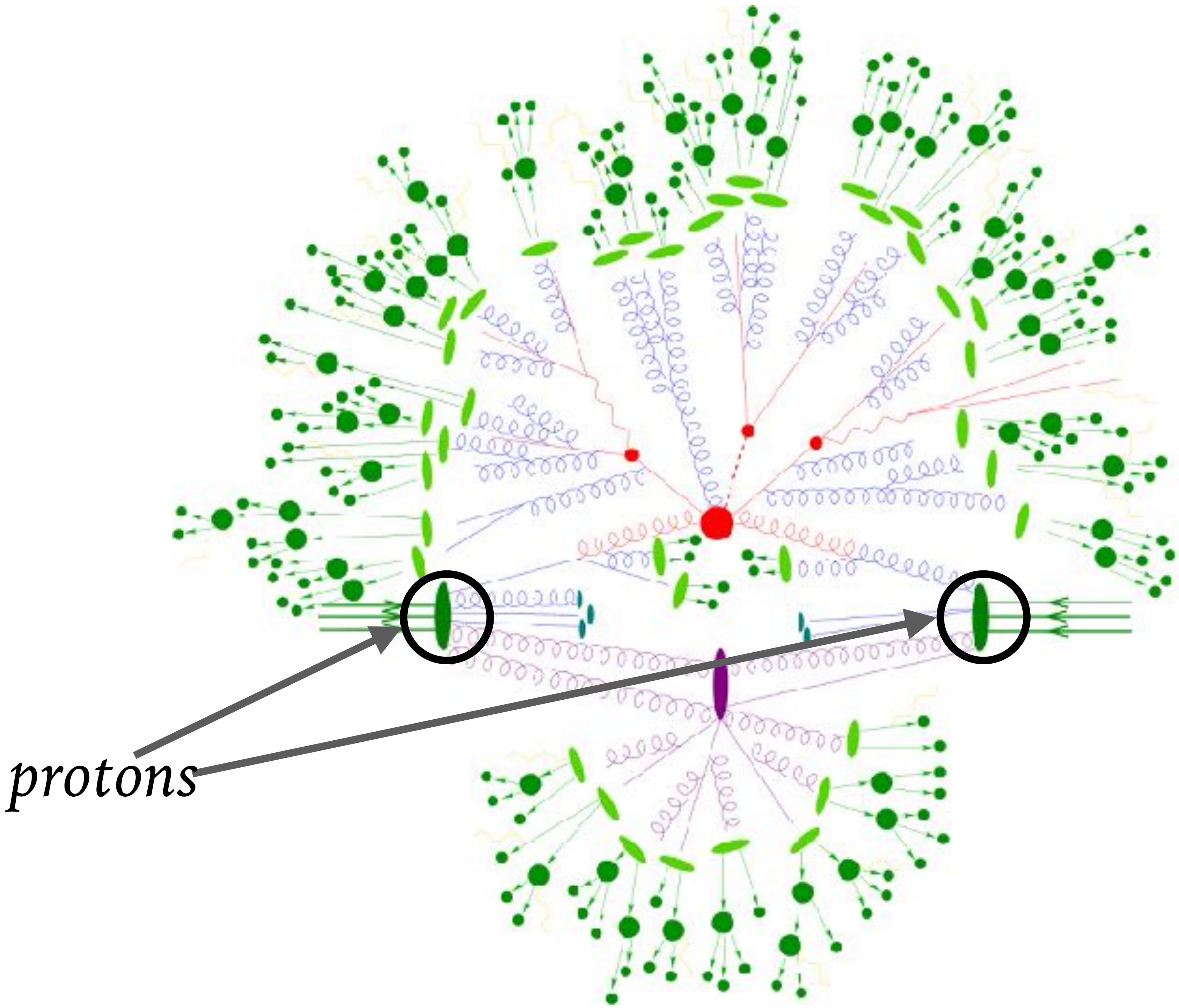


# REAL LIFE IS HARD



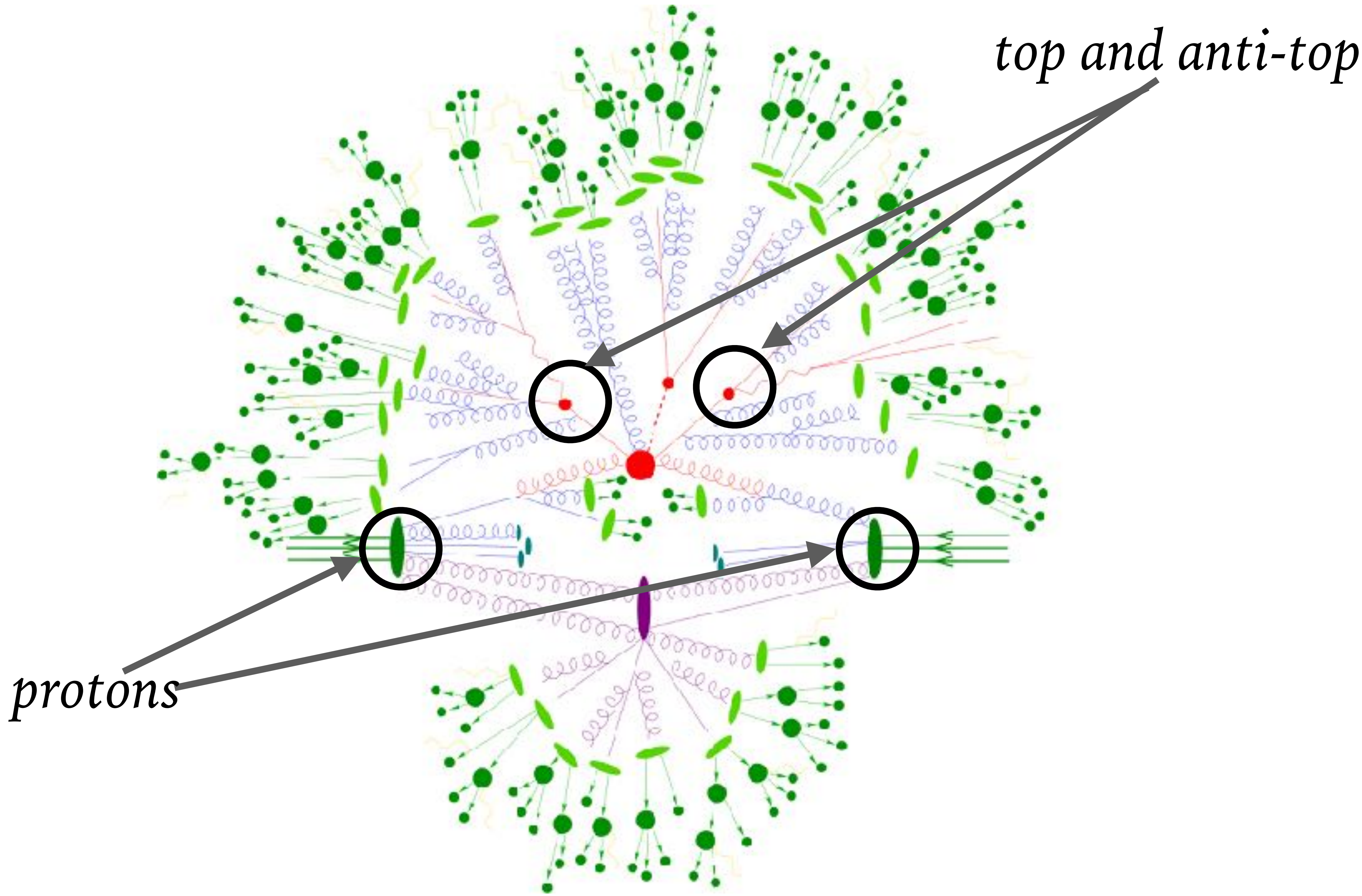
F. Krauss. (Sherpa Collaboration), “Sketch of a $t\bar{t}h$ event”. Available at https: // www.opensciencegrid.org/wp-content/uploads/2014/05/event.jpg

# REAL LIFE IS HARD



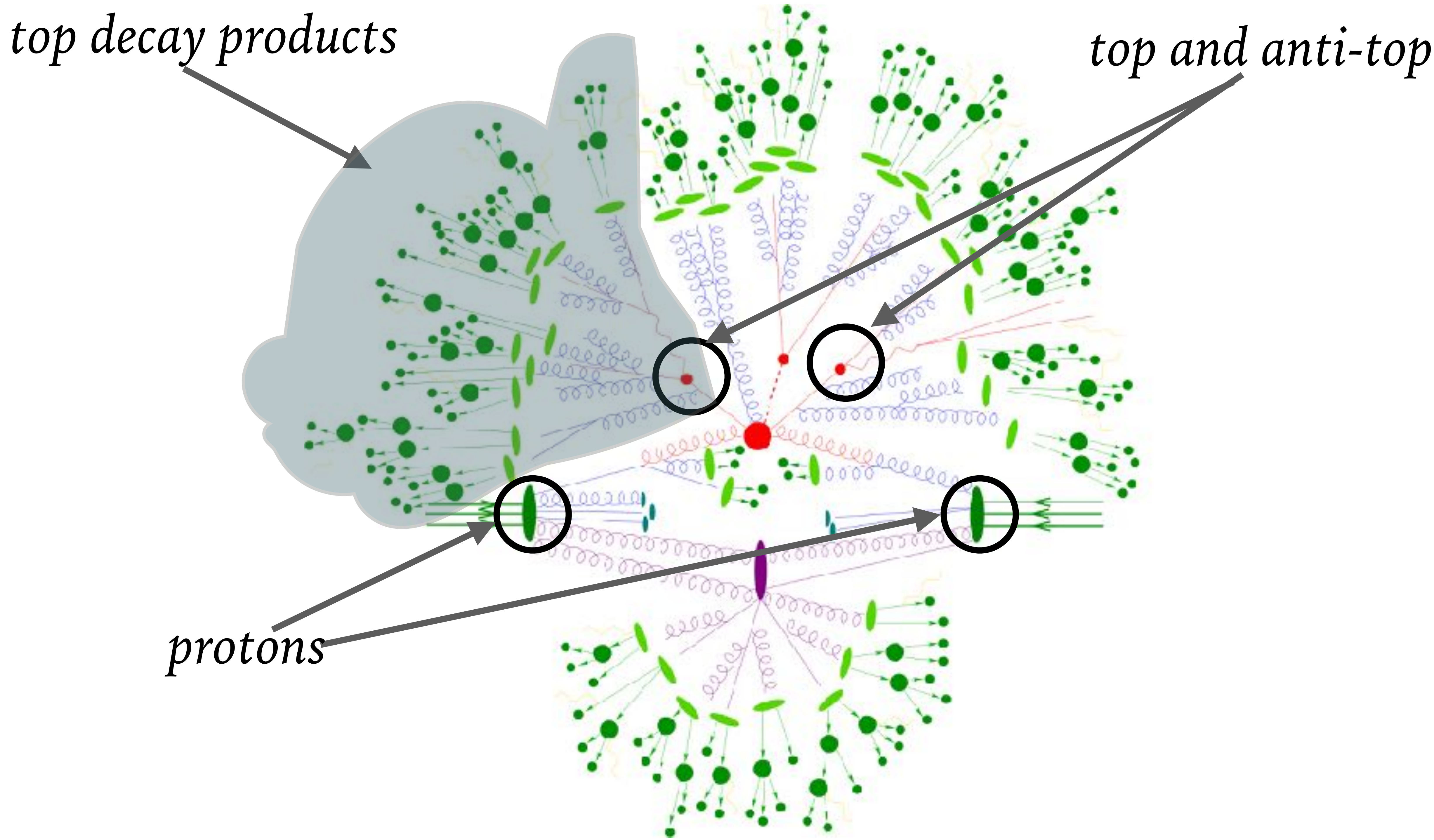

F. Krauss. (Sherpa Collaboration), "Sketch of a $t\bar{t}h$ event". Available at https: // www.opensciencegrid.org/wp-content/uploads/2014/05/event.jpg

# REAL LIFE IS HARD



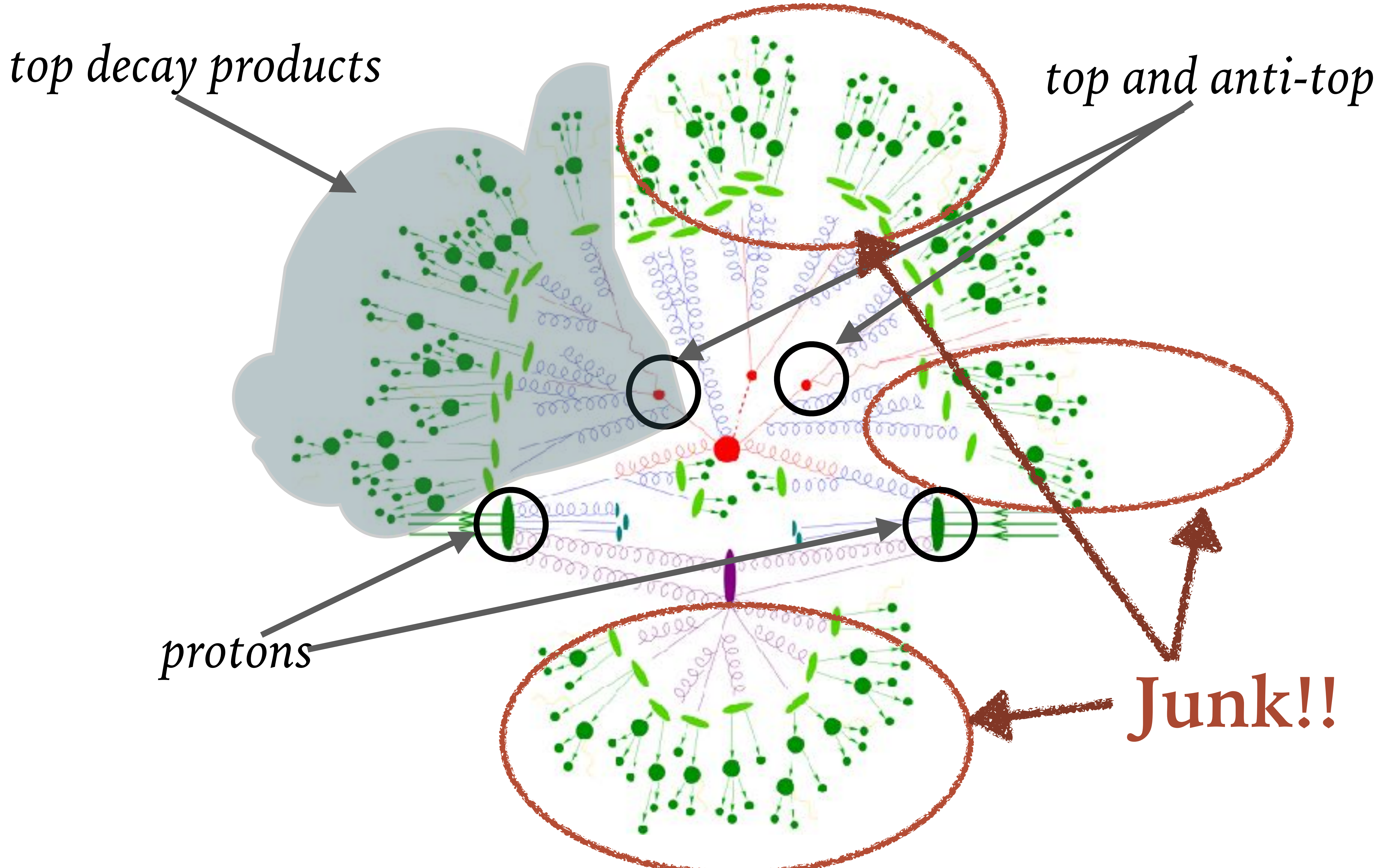

F. Krauss. (Sherpa Collaboration), “Sketch of a $t\bar{t}h$ event”. Available at https: //www.opensciencegrid.org/wp-content/uploads/2014/05/event.jpg

# REAL LIFE IS HARD



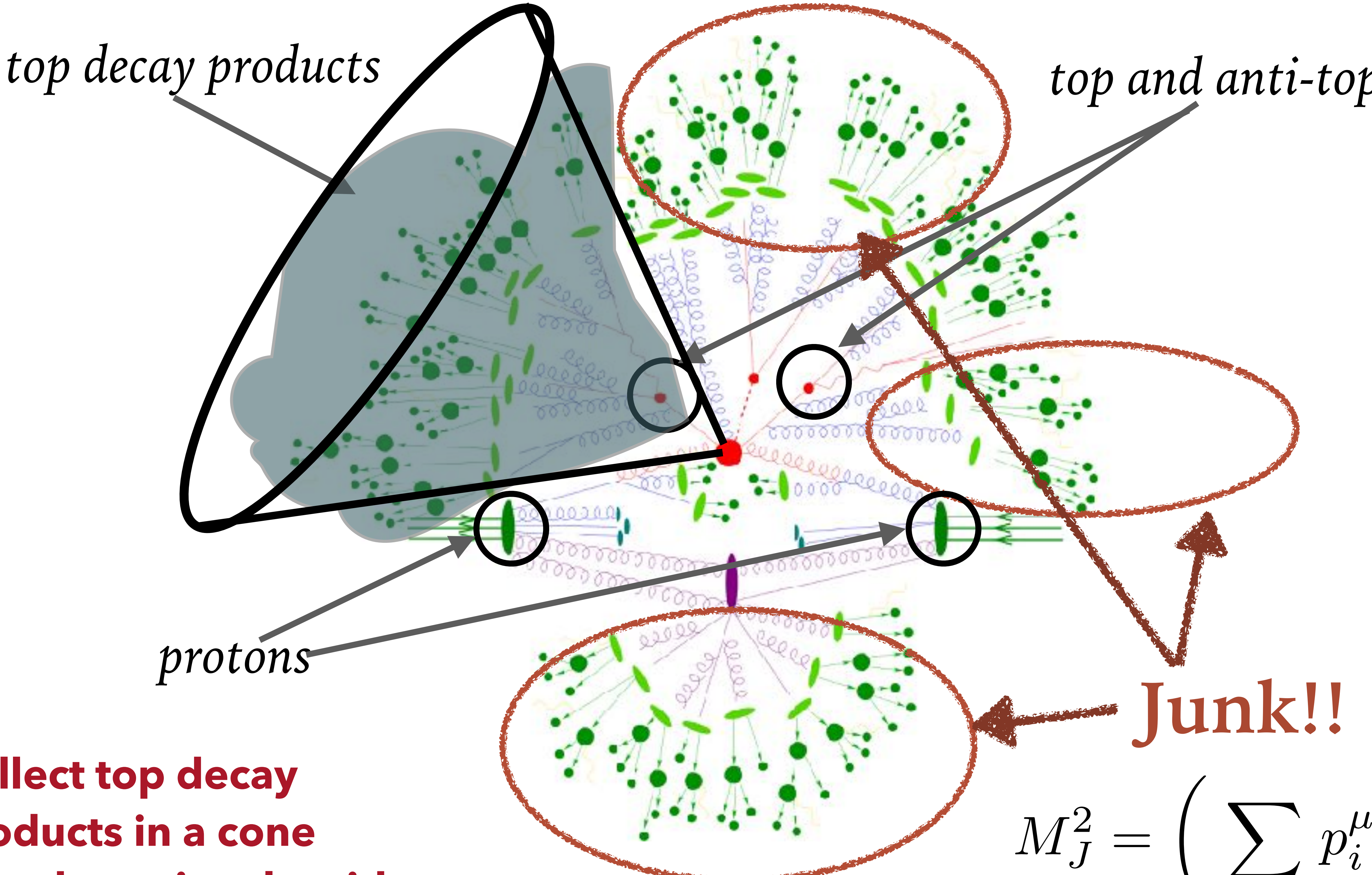

F. Krauss. (Sherpa Collaboration), “Sketch of a $tt$h event”. Available at https: // www.opensciencegrid.org/wp-content/uploads/2014/05/event.jpg

# REAL LIFE IS HARD




F. Krauss. (Sherpa Collaboration), “Sketch of a $t\bar{t}h$ event”. Available at https: //www.opensciencegrid.org/wp-content/uploads/2014/05/event.jpg

# REAL LIFE IS HARD



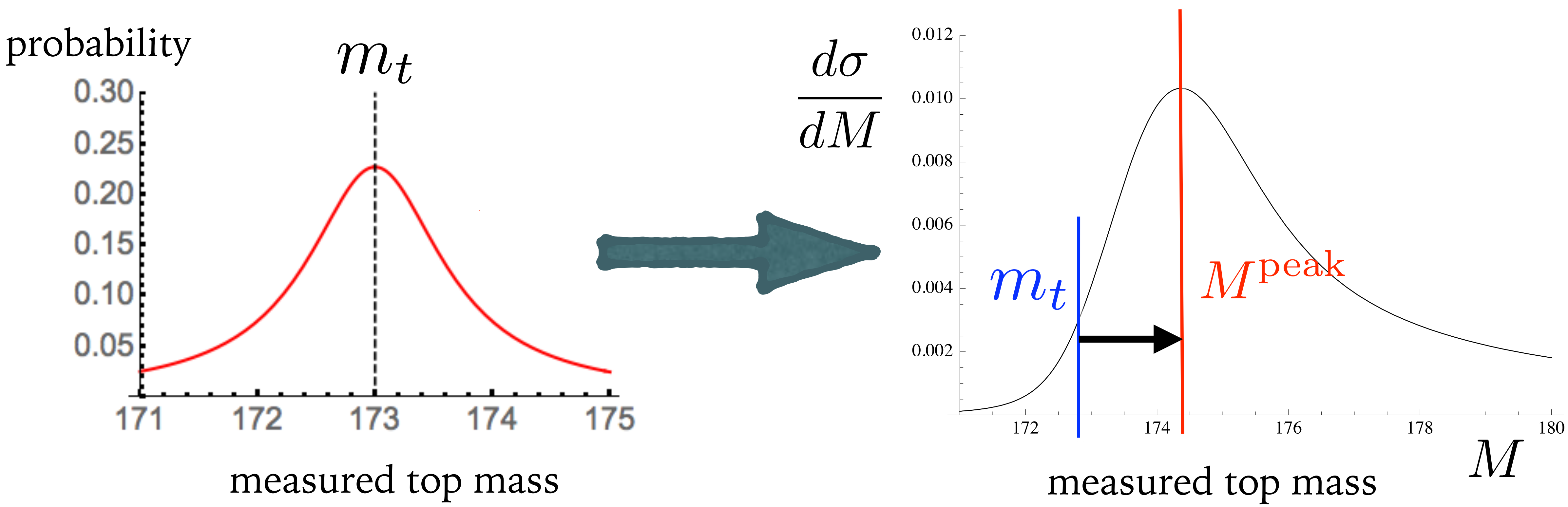

**Collect top decay products in a cone based on a jet algorithm**

F. Krauss. (Sherpa Collaboration), "Sketch of a $t\bar{t}h$ event". Available at https: //www.opensciencegrid.org/wp-content/uploads/2014/05/event.jpg

$$M_J^2 = \left( \sum_{i \in \text{jet}} p_i^\mu \right)^2$$

# EFFECT ON THE MASS SPECTRUM

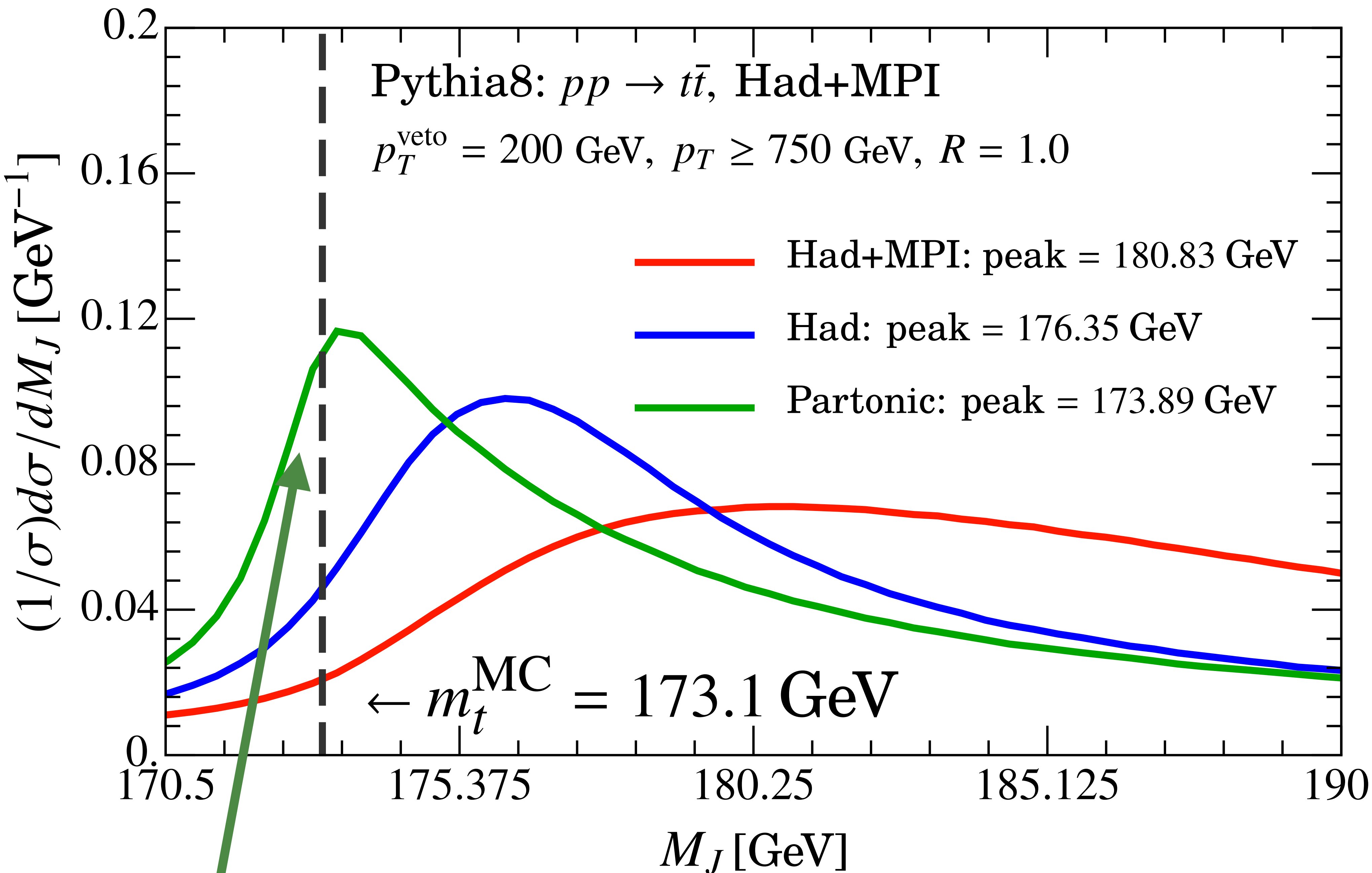
*Collecting additional junk (Underlying Event) +*
*Hadronization effects* ***shift the peak*** *of the top mass spectrum*




*In order to measure top mass accurately we must*
*know how the peak shifts. -> Theoretical challenge!*

# KINEMATIC EXTRACTIONS

## Boosted top jets with R = 1

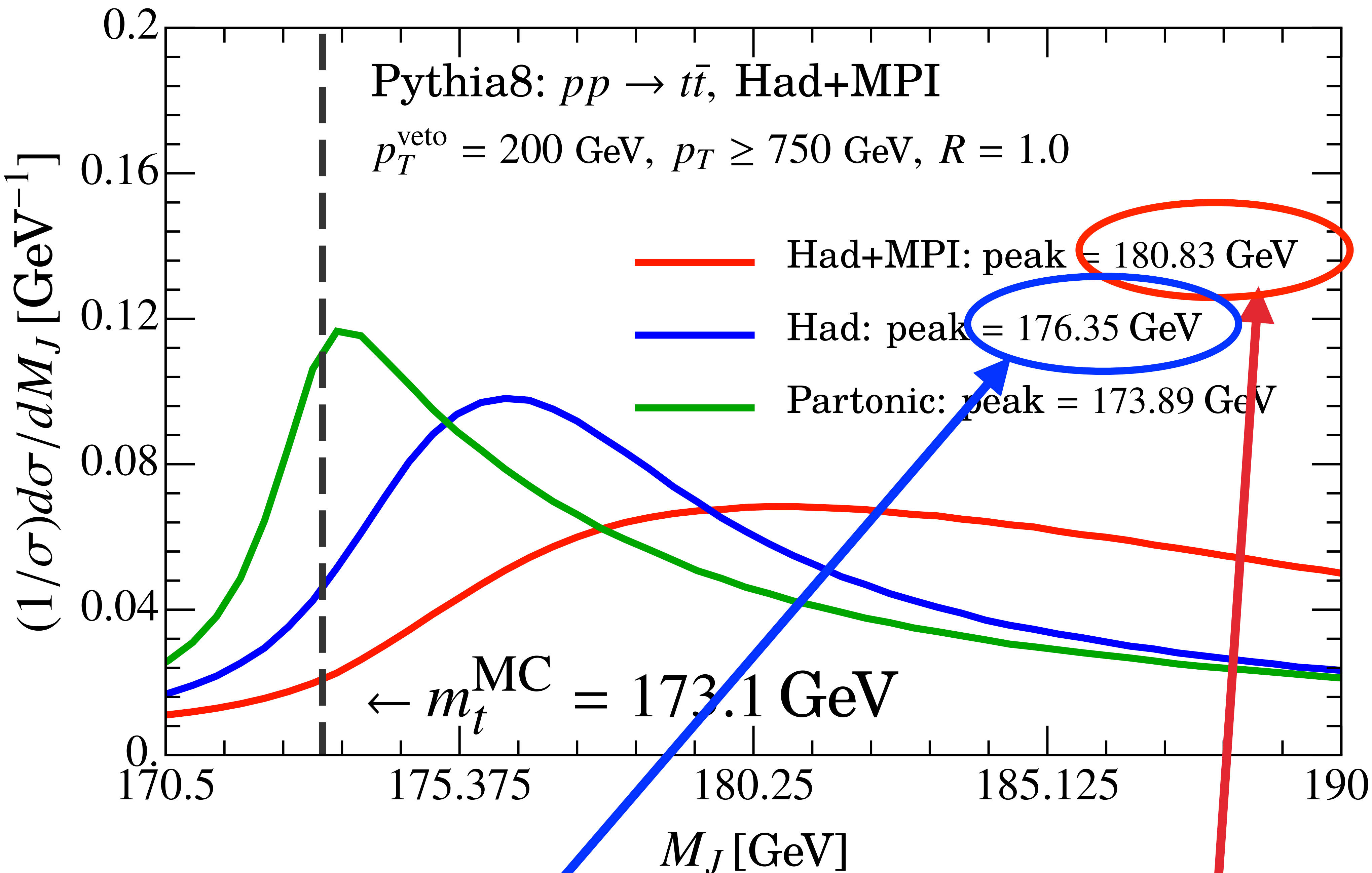



**Partonic Pythia without hadronization and UE (MPI modeled)**

Fastjet: Cacciari, Salam, Soyez, 2011

# KINEMATIC EXTRACTIONS

## Boosted top jets with R = 1




**Effect of hadronization ~ 2 GeV**

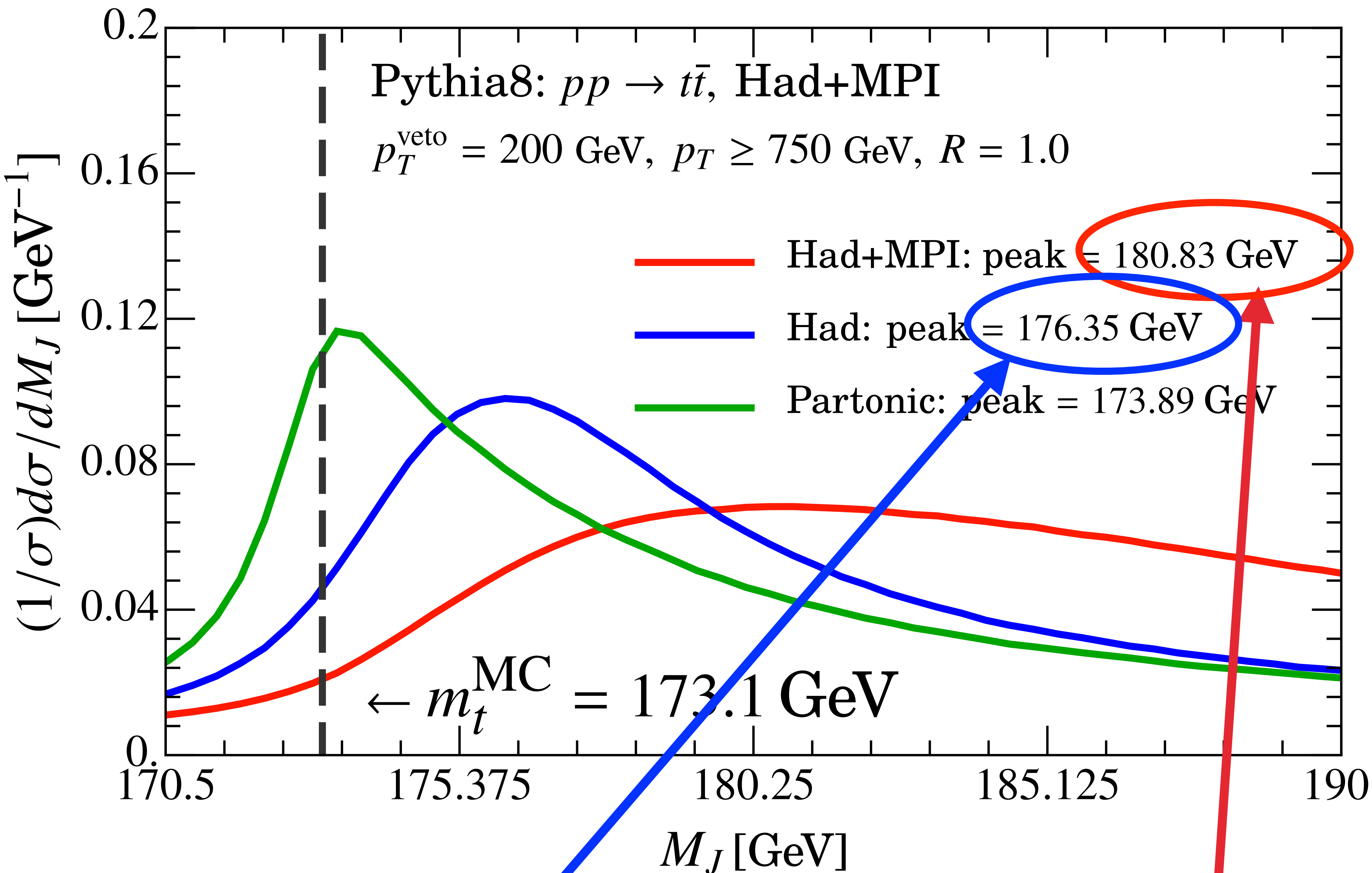
**Contamination from UE ~ 5 GeV!**

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

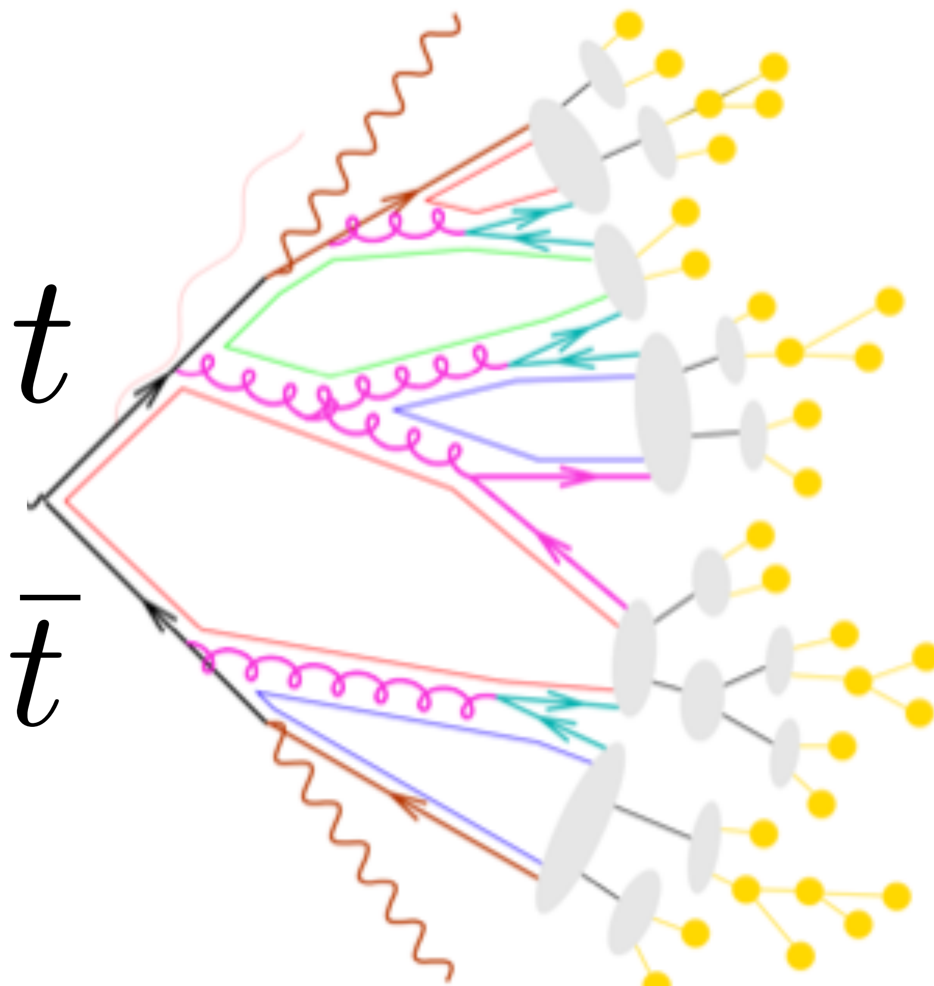
**Allows arbitrary measurements on the final state particles, but limited in accuracy ~ NLO + NLL**

**Devise analytically calculable exclusive observables that**

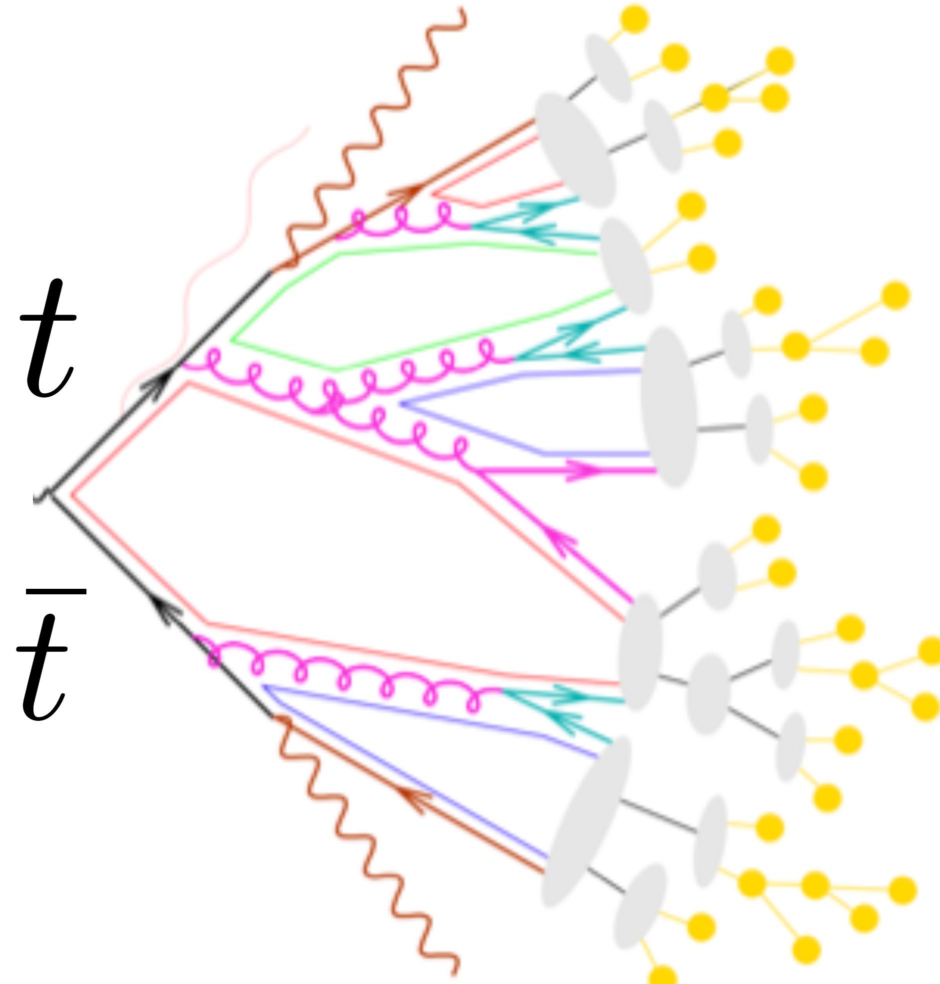
- **are sensitive to the top mass,**
- **describe these components with systematically improvable accuracy,**
- **robust against contamination and account for NP corrections.**

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

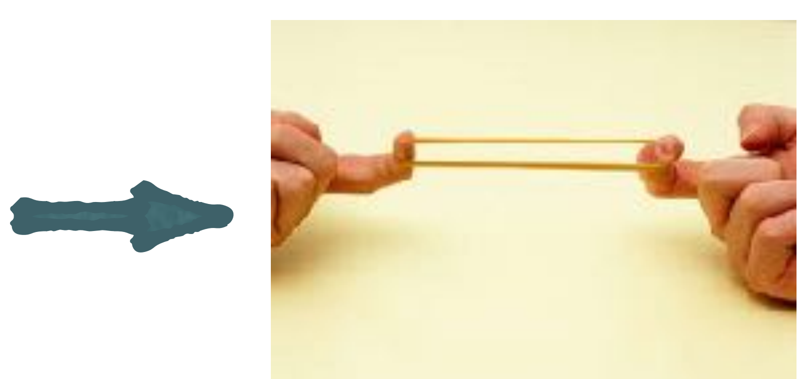
# HARD TO CALCULATE THE TOP MASS SPECTRUM IN THEORY



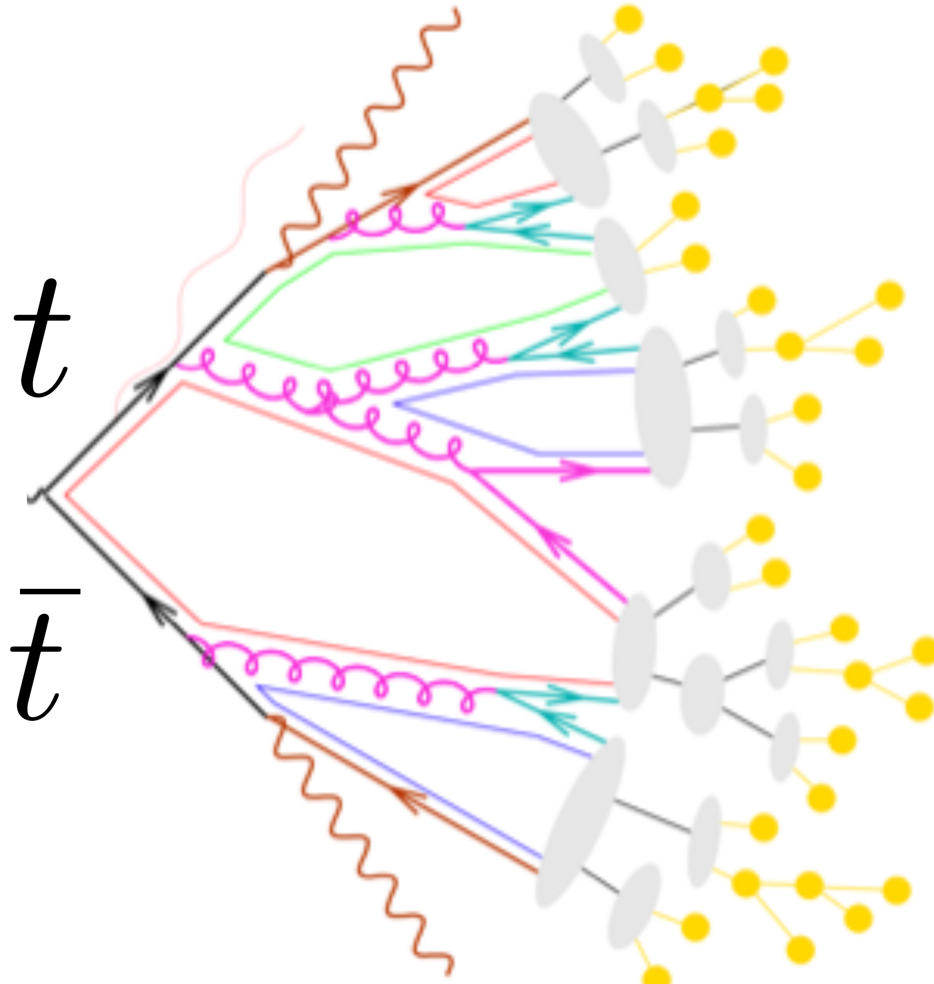

# HARD TO CALCULATE THE TOP MASS SPECTRUM IN THEORY




*Top quark production involves several "energy scales" which make the direct calculation in theory hard.*



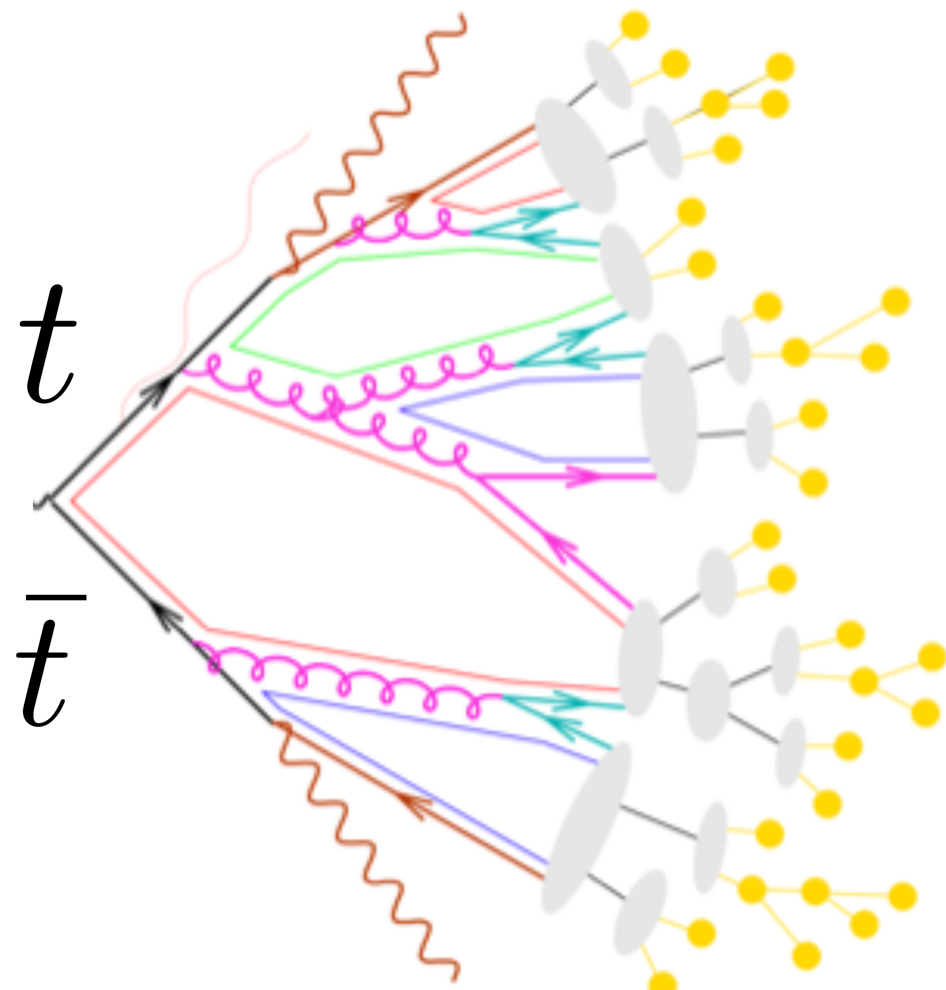
# HARD TO CALCULATE THE TOP MASS SPECTRUM IN THEORY




*Top quark production involves several "energy scales" which make the direct calculation in theory hard.*

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

# HARD TO CALCULATE THE TOP MASS SPECTRUM IN THEORY



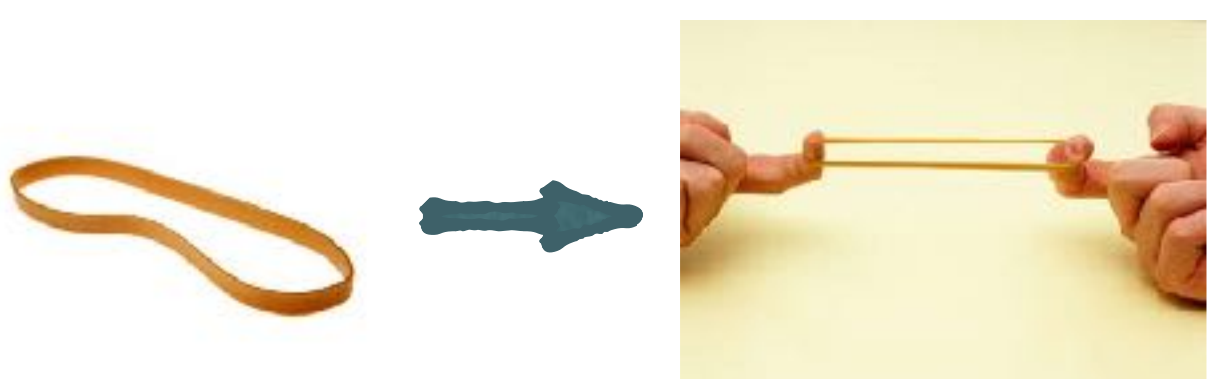

*Top quark production involves several "energy scales" which make the direct calculation in theory hard.*

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

| $Q$ | $m_t$ | $\Gamma_t$ | $\Lambda_{\mathrm{QCD}}$ |
|---|---|---|---|
| >500 GeV | 173.1 GeV | 1.4 GeV | 0.5 GeV |

*energy at which top quark is produced*

*energy at which quarks combine to form hadrons.*



## HOW DO WE CALCULATE THIS IN THEORY TO ACCOUNT FOR QUANTUM CORRECTIONS?

# USING EFFECTIVE THEORIES

https://www.flickr.com/photos/1uk3/3913309568

https://www.musely.com/tips/how-To-Grow-13-Inches-Of-Hair-In-A-Week/10645683

# USING EFFECTIVE THEORIES

*Same fluid equations describe flow of both water and olive oil!*

https://www.flickr.com/photos/1uk3/3913309568

$$\rho[\frac{\partial V}{\partial t} + (V.\nabla)V] = -\nabla P + \rho g + \mu \nabla^2 V$$

change of velocity with time

Convective term

Pressure term: Fluid flows in the direction of largest change in pressure

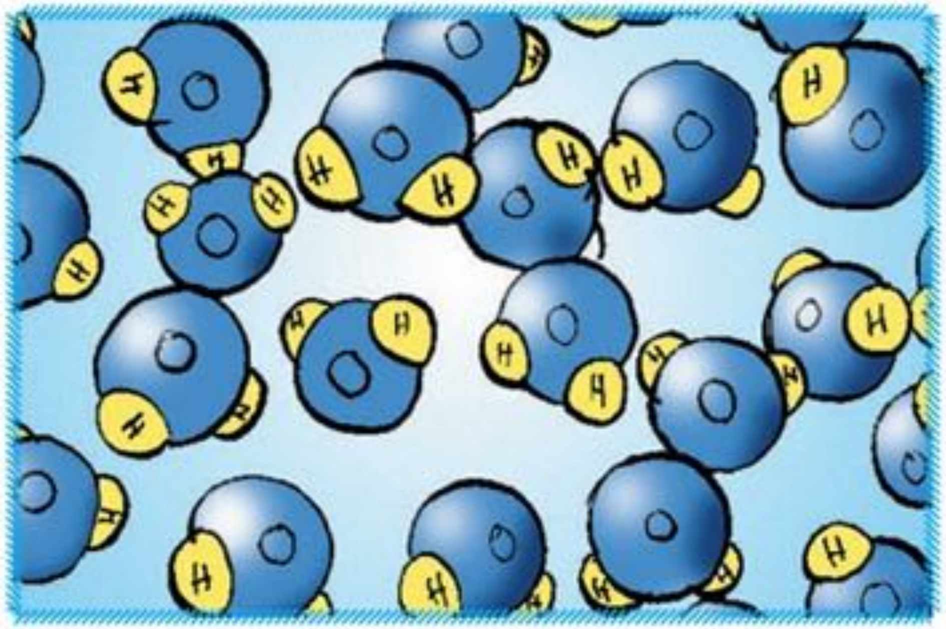
Body force term: external forces that act on the fluid (such as gravity, electromagnetic, etc.)

viscosity controlled velocity diffusion term

https://www.musely.com/tips/how-To-Grow-13-Inches-Of-Hair-In-A-Week/10645683

# USING EFFECTIVE THEORIES

$$\text{Water} = H_2O \longrightarrow$$

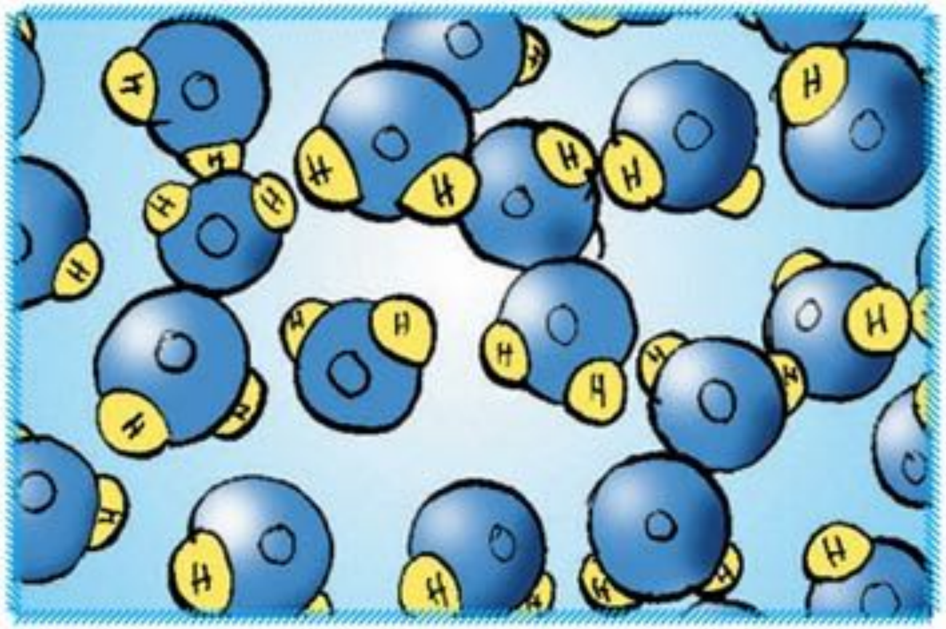



http://www.waterwise.co.za/export/sites/water-wise/images/water/water-molecules.jpg

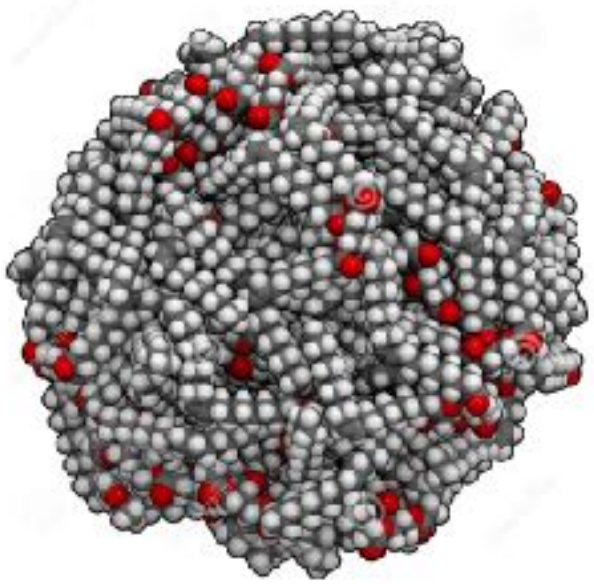
# USING EFFECTIVE THEORIES

*Very different in their molecular composition!*

Water = $H_2O$ ⟶



http://www.waterwise.co.za/export/sites/water-wise/images/water/water-molecules.jpg



⟵ Olive Oil!

https://www.dreamstime.com/royalty-free-stock-photography-olive-oil-chemical-composition-image25717637

# USING EFFECTIVE THEORIES

$$\boxed{\rho\left[\frac{\partial V}{\partial t}+(V.\nabla)V\right]=-\nabla P+\rho g+\mu\nabla^2 V}$$

*Hydrodynamics is an* ***'Effective Theory'*** *that does not care, and know, about physics at short distances.*

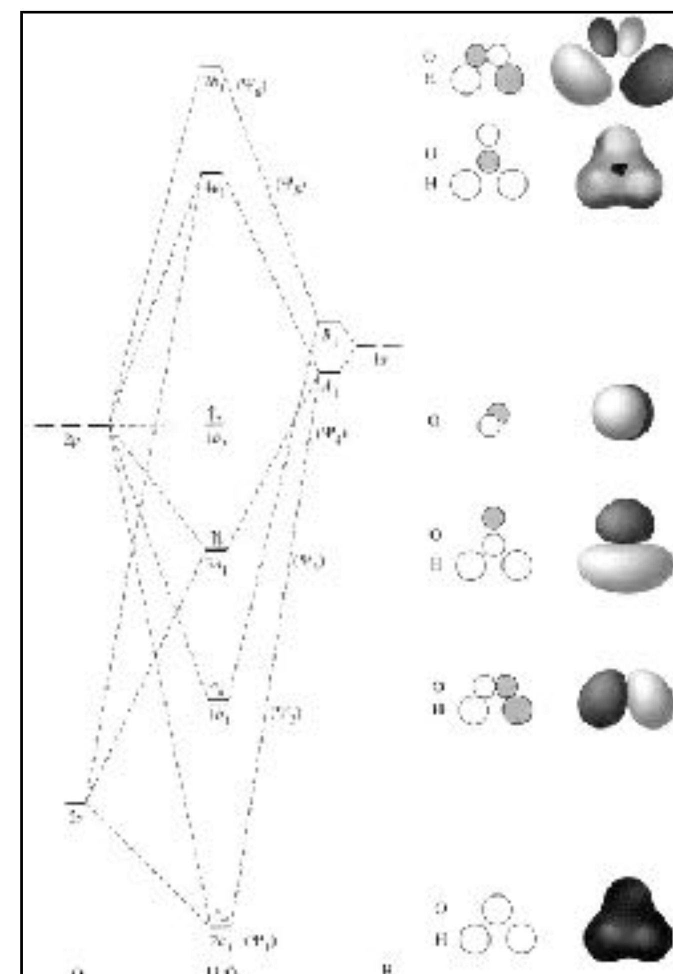
# USING EFFECTIVE THEORIES

$$\boxed{\rho[\frac{\partial V}{\partial t}+(V.\nabla)V]=-\nabla P+\rho g+\mu\nabla^2 V}$$

*Hydrodynamics is an* ***'Effective Theory'*** *that does not care, and know, about physics at short distances.*

***'Full theory'*** *knows about physics at all distances:*

Molecular Orbital Theory for $H_2O$: Very Complex! Not suitable for macroscopic physics.



https://www.thestudentroom.co.uk/showthread.php?t=1903024

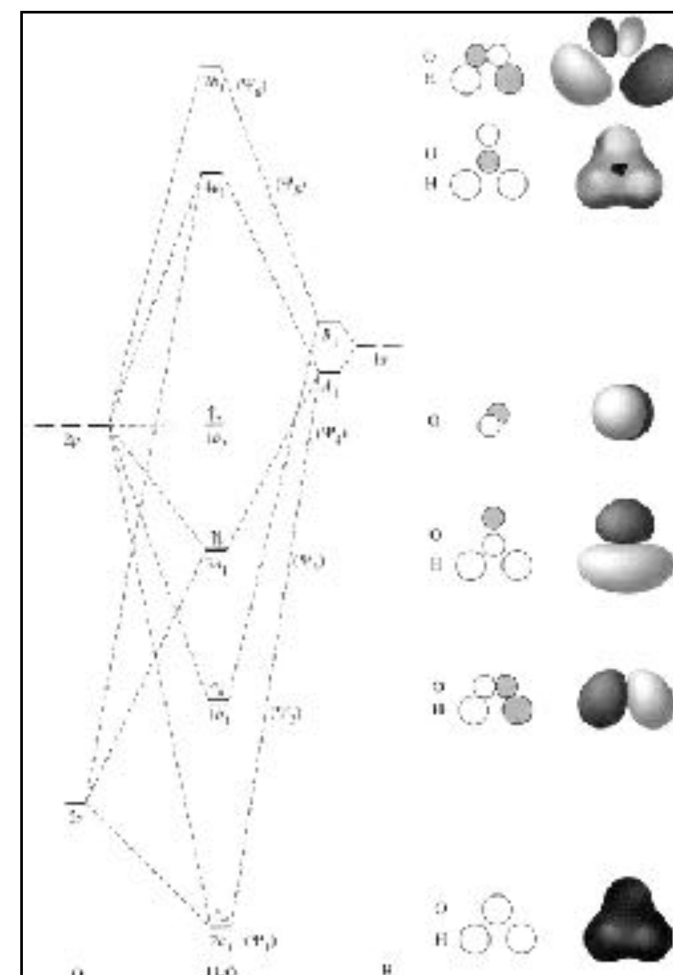
# USING EFFECTIVE THEORIES

$$\rho[\frac{\partial V}{\partial t}+(V.\nabla)V]=-\nabla P+\rho g+\mu\nabla^2 V$$

*Hydrodynamics is an* ***'Effective Theory'*** *that does not care, and know, about physics at short distances.*

***'Full theory'*** *knows about physics at all distances:*

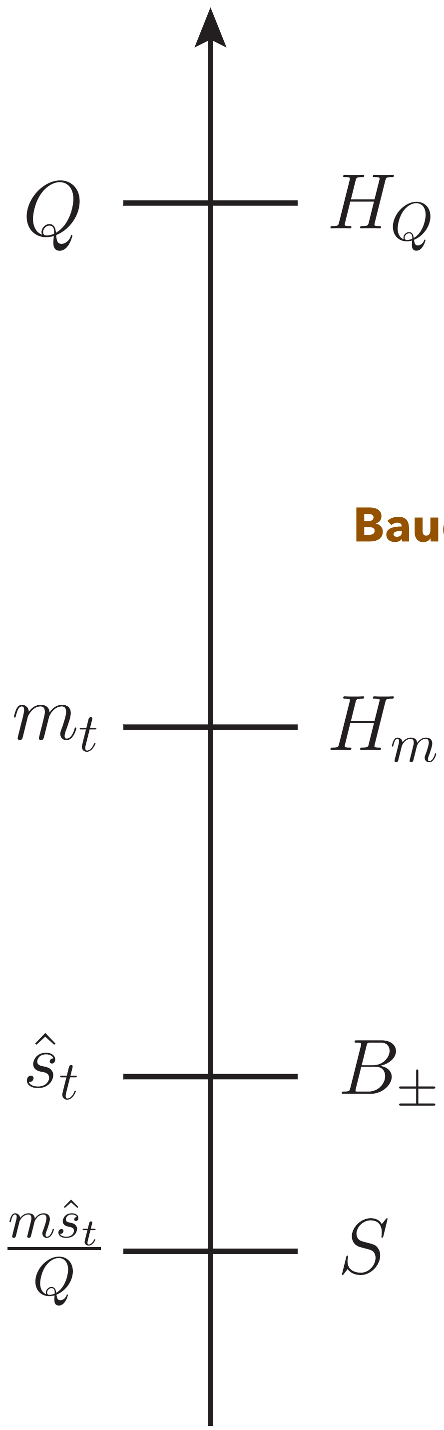
Molecular Orbital Theory for $H_2O$: Very Complex! Not suitable for macroscopic physics.



https://www.thestudentroom.co.uk/showthread.php?t=1903024

**This exact philosophy can be applied to QFT calculations for strong force.**

# EFFECTIVE FIELD THEORIES




QCD

$\mathrm{SCET}^{(6)}$

**Bauer, Pirjol, Stewart 2002**

- ***Soft Collinear Effective Theory:*** *collider physics applications*

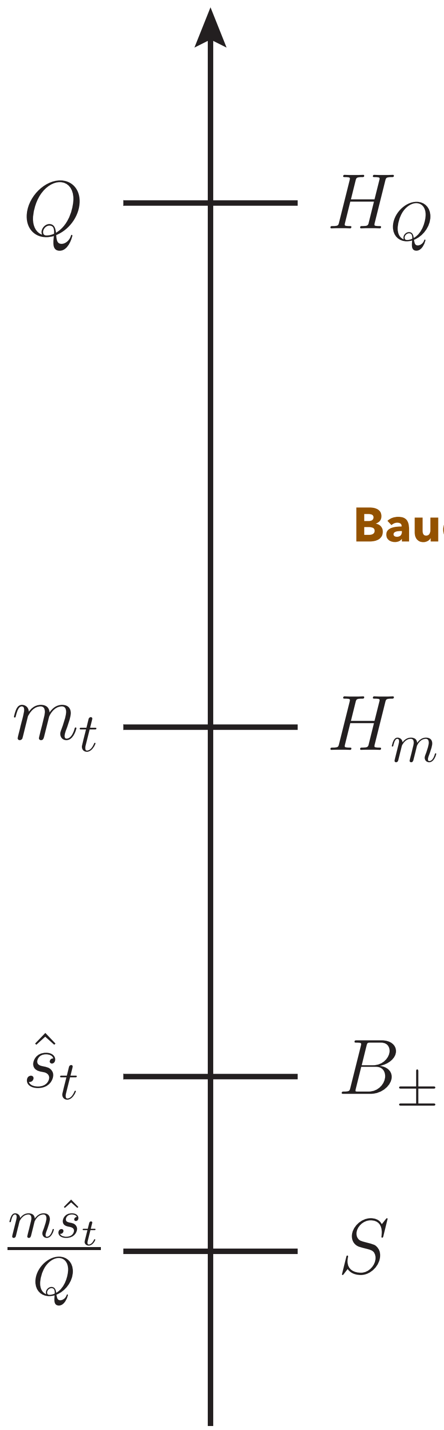
$\mathrm{bHQET}^{(5)}$

**Isgur, Wise 1989**

- ***Heavy Quark Effective Theory:*** *decay of top quark close to mass shell*

**Fleming, Hoang, Mantry, Stewart 2007**

# EFFECTIVE FIELD THEORIES




$\mathrm{QCD}$

$\mathrm{SCET}^{(6)}$

**Bauer, Pirjol, Stewart 2002**

- ***Soft Collinear Effective Theory:***
  *collider physics applications*

$\mathrm{bHQET}^{(5)}$

**Isgur, Wise 1989**

- ***Heavy Quark Effective Theory:***
  *decay of top quark close to mass shell*

**Fleming, Hoang, Mantry, Stewart 2007**

# SOFT COLLINEAR EFFECTIVE THEORY

## Sterman-Weinberg criteria for infrared-collinear safety (1977)

Cross section for $e^+e^-$ to hadrons contained in back to back cones with energy $E(1\text{-}\varepsilon)$ and angle $\delta$:

$$\sigma(E,\theta,\Omega,\epsilon,\delta)=(d\sigma/d\Omega)_0\,\Omega[1-(g_E{}^2/3\pi^2)(3\ln\delta+4\ln\delta\ln 2\epsilon+\pi^2/3-\tfrac{5}{2})]$$

Sensitive to collinear and soft emissions

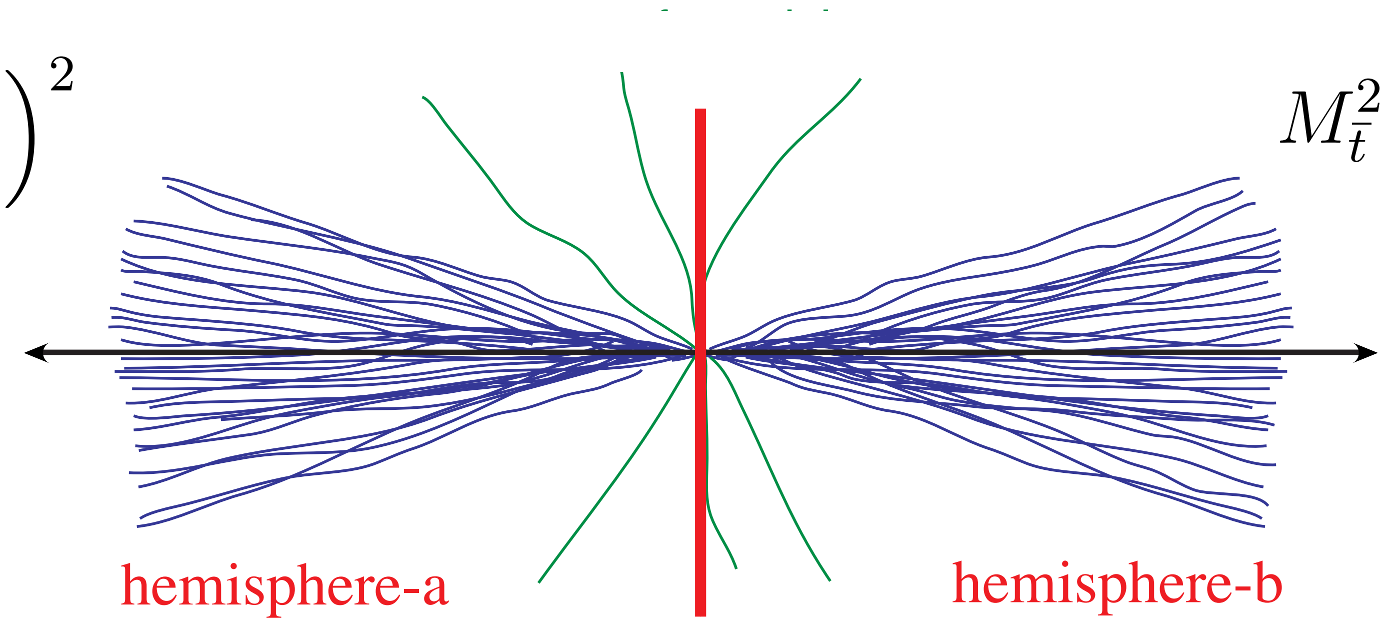
- Excludes observables sensitive to arbitrary collinear/soft emissions, e.g. particle multiplicity in a jet.
- Sufficient to ensure calculability, (but not necessary: e.g. Sudakov Safe observables)

**Larkoski, Thaler 2013**

# SOFT COLLINEAR EFFECTIVE THEORY

## Consider back to back jets in $e^+e^-$ collisions:

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



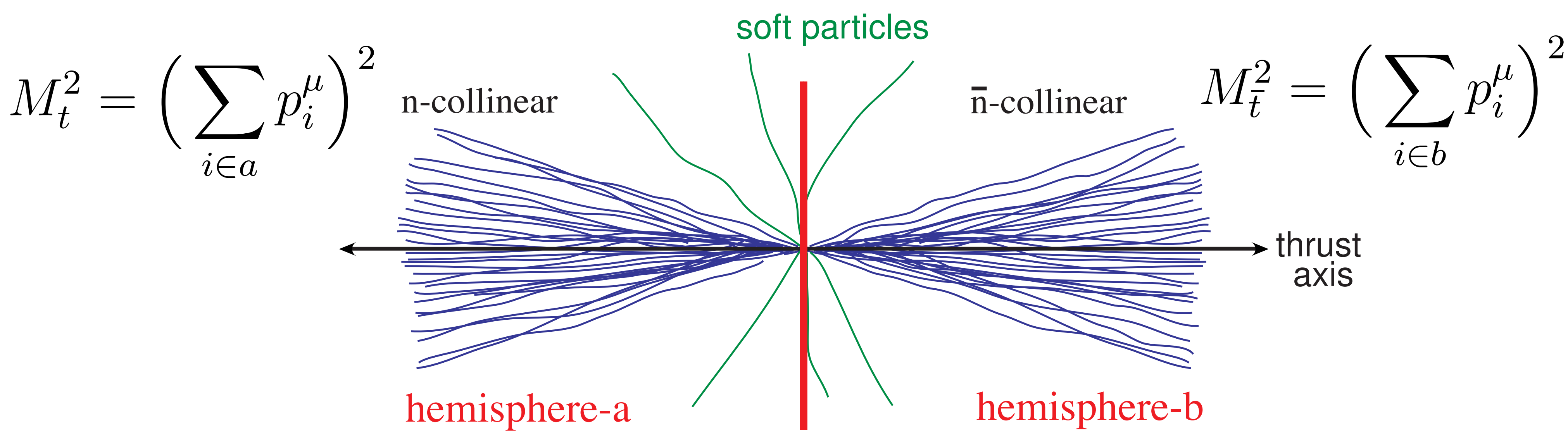

## Jet Directions:

$$n^\mu = \big(1, \hat{n}\big)\,, \qquad \bar{n}^\mu = \big(1, -\hat{n}\big)$$

## Light cone coordinates:

$$p^\mu = p^- \frac{n^\mu}{2} + p^+ \frac{\bar{n}^\mu}{2} + p_\perp\,, \qquad p^\mu \equiv (p^+,\, p^-,\, p_\perp) \qquad p^2 = p^+ p^- - p_\perp^2$$

# SOFT COLLINEAR EFFECTIVE THEORY




**Distinguish particles based on their momentum:**

$$p^2 = p^+ p^- - p_\perp^2$$

$$n\text{-collinear} \sim Q\,(\lambda^2, 1, \lambda)\,,$$

$$\bar{n}\text{-collinear} \sim Q\,(1, \lambda^2, \lambda)\,,$$

$$\text{ultrasoft} \sim Q(\lambda^2,\, \lambda^2,\, \lambda^2)\,.$$

$$\lambda = \frac{M_{\text{jet}}}{Q} \ll 1$$

$$M_{\text{jet}}^2 = p^+ p^- + \mathcal{O}(p_\perp^2) = p^+ Q + \mathcal{O}(p_\perp^2)$$

**With carefully aligned axis jet mass is simply given by the + component**

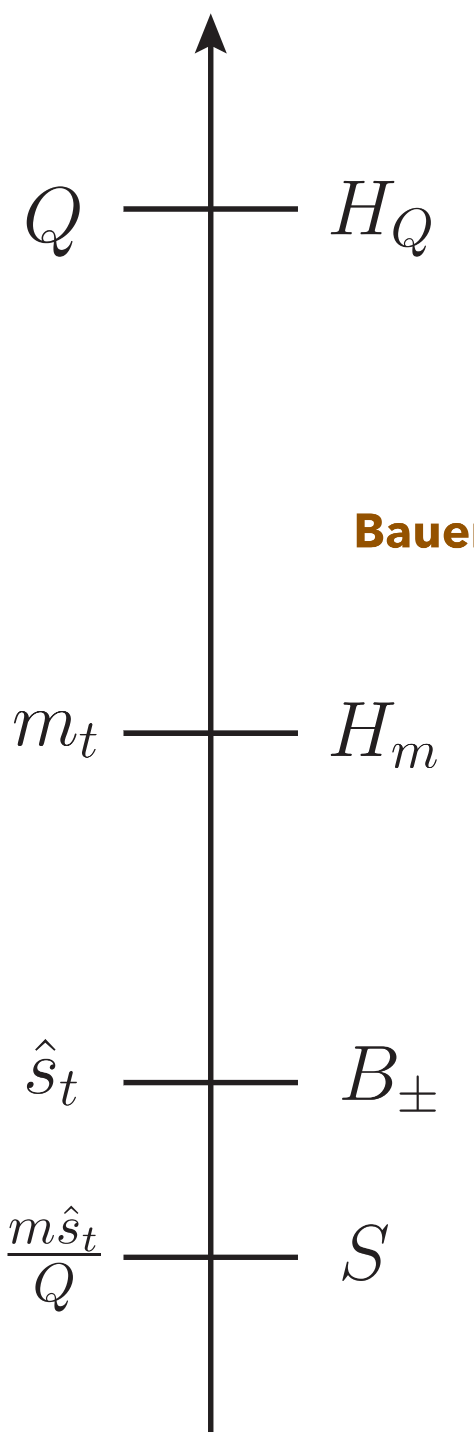
# SOFT COLLINEAR EFFECTIVE THEORY

$$\lambda = \frac{M_{\text{jet}}}{Q} \ll 1$$

| SCET Modes | Scaling | Fields |
|---|---|---|
| $n$-collinear | $Q(\lambda^2, 1, \lambda)$ | $(\xi_n,\ A_n^\mu)$ |
| $\bar{n}$-collinear | $Q(1, \lambda^2, \lambda)$ | $(\xi_{\bar{n}},\ A_{\bar{n}}^\mu)$ |
| ultrasoft | $Q(\lambda^2,\ \lambda^2,\ \lambda^2)$ | $(\psi_{us},\ A_{us}^\mu)$ |

- **Quarks and gluons now distinguished based on their momenta.**
- **Three characteristic scales:** $Q \gg Q\lambda \gg Q\lambda^2$
- **Ultrasoft modes couple to both collinear modes through + component**

# EFFECTIVE FIELD THEORIES




QCD

$\mathrm{SCET}^{(6)}$

**Bauer, Pirjol, Stewart 2002**

$\mathrm{bHQET}^{(5)}$

**Isgur, Wise 1989**

- ***Soft Collinear Effective Theory:*** *collider physics applications*
- ***Heavy Quark Effective Theory:*** *decay of top quark close to mass shell*

**Fleming, Hoang, Mantry, Stewart 2007**

# HEAVY QUARK EFFECTIVE THEORY

$$\mathcal{L}_{\mathrm{HQET}} = \bar{h}_{v_+}\left(iv_+ \cdot D_+ - \delta m + \frac{i}{2}\Gamma_t\right)h_{v_+}$$

$$\hat{s}_{t,\bar{t}} \equiv \frac{M_{t,\bar{t}}^2 - m^2}{m} \ll m$$

$$v_+^\mu = \left(\frac{m}{Q}, \frac{Q}{m}, \mathbf{0}_\perp\right)$$

| bHQET Modes | Scaling | Fields |
|---|---|---|
| $n$-ucollinear | $\left(\frac{m\hat{s}_t}{Q}, \frac{Q\hat{s}_t}{m}, \hat{s}_t\right)$ | $(h_{v_+}, A_+^\mu)$ |
| $\bar{n}$-ucollinear | $\left(\frac{Q\hat{s}_t}{m}, \frac{m\hat{s}_t}{Q}, \hat{s}_t\right)$ | $(h_{v_-}, A_-^\mu)$ |
| ultrasoft | $\left(\frac{m\hat{s}_t}{Q}, \frac{m\hat{s}_t}{Q}, \frac{m\hat{s}_t}{Q}\right)$ | $(\psi_{us}, A_{us}^\mu)$ |

- **Top quark now labeled with velocity**
- **Expansion in** $\Gamma_t/m$
- **Same ultrasoft modes as before but at lower virtuality**
- **Residual term for mass scheme** $\delta m$

# HEAVY QUARK EFFECTIVE THEORY

$$\mathcal{L}_{\mathrm{HQET}} = \bar{h}_{v_+}\big(iv_+ \cdot D_+ - \delta m + \frac{i}{2}\Gamma_t\big)h_{v_+}$$

$$\hat{s}_{t,\bar{t}} \equiv \frac{M_{t,\bar{t}}^2 - m^2}{m} \ll m$$

$$v_+^\mu = \left(\frac{m}{Q}, \frac{Q}{m}, \mathbf{0}_\perp\right)$$

| bHQET Modes | Scaling | Fields |
|---|---|---|
| $n$-ucollinear | $\left(\frac{m\hat{s}_t}{Q}, \frac{Q\hat{s}_t}{m}, \hat{s}_t\right)$ | $(h_{v_+}, A_+^\mu)$ |
| $\bar{n}$-ucollinear | $\left(\frac{Q\hat{s}_t}{m}, \frac{m\hat{s}_t}{Q}, \hat{s}_t\right)$ | $(h_{v_-}, A_-^\mu)$ |
| ultrasoft | $\left(\frac{m\hat{s}_t}{Q}, \frac{m\hat{s}_t}{Q}, \frac{m\hat{s}_t}{Q}\right)$ | $(\psi_{us}, A_{us}^\mu)$ |

- **Top quark now labeled with velocity**
- **Expansion in** $\Gamma_t/m$
- **Same ultrasoft modes as before but at lower virtuality**
- **Residual term for mass scheme** $\delta m$

# 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):

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

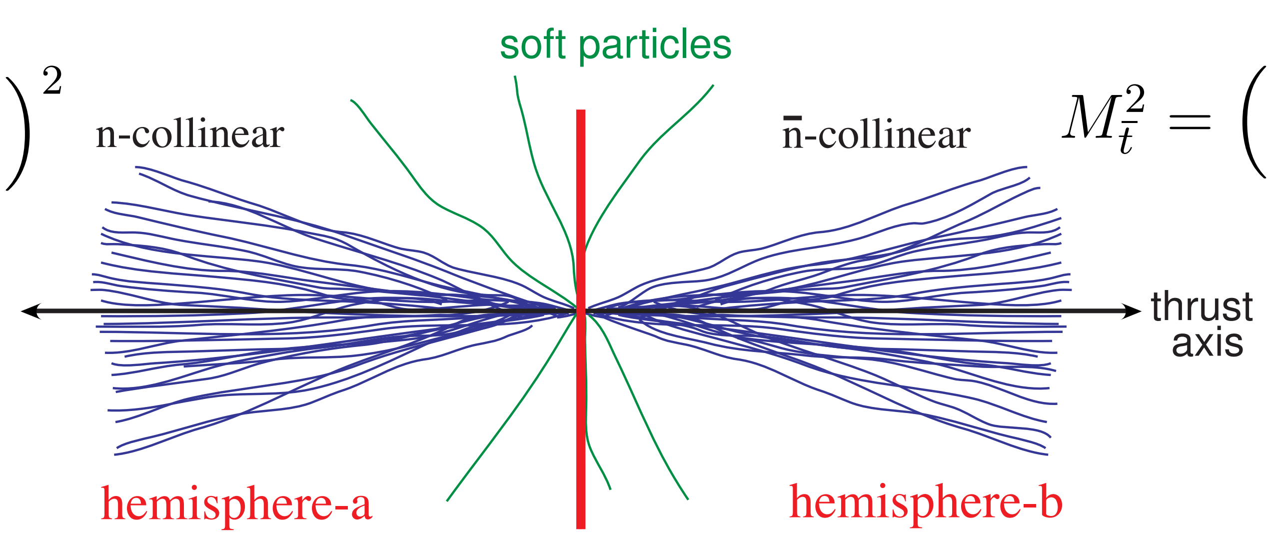
$$\times \int dl^+ dl^-\, J_B\left(\hat{s}_t - \frac{Ql^+}{m_J}, \Gamma_t, \delta m, \mu\right) J_B\left(\hat{s}_{\bar{t}} - \frac{Ql^-}{m_J}, \Gamma_t, \delta m, \mu\right)$$

$$\times S_{\text{hemi}}(l^+ - k, l^- - k', \mu)\, F(k,k')$$

(boosted HQET) Jet Functions — Control Over Mass Scheme — Soft Function — Hadronization

**Fleming, Hoang, Mantry, Stewart 2007, 2008**

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



# 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

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

$$\boxed{M^{\text{peak}} = m_t + \Gamma_t(\alpha_s + \alpha_s^2 + \dots) + \frac{Q\Lambda_{\text{QCD}}}{m_t}}$$

**model this**

**measure this**

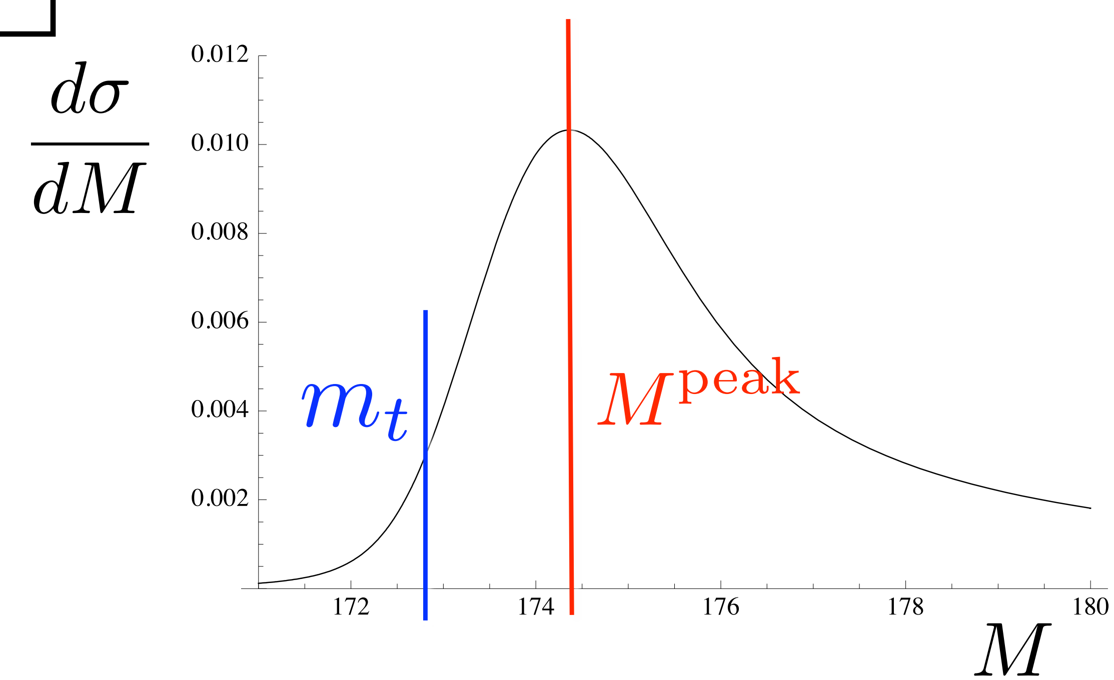
**extract this**

**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*

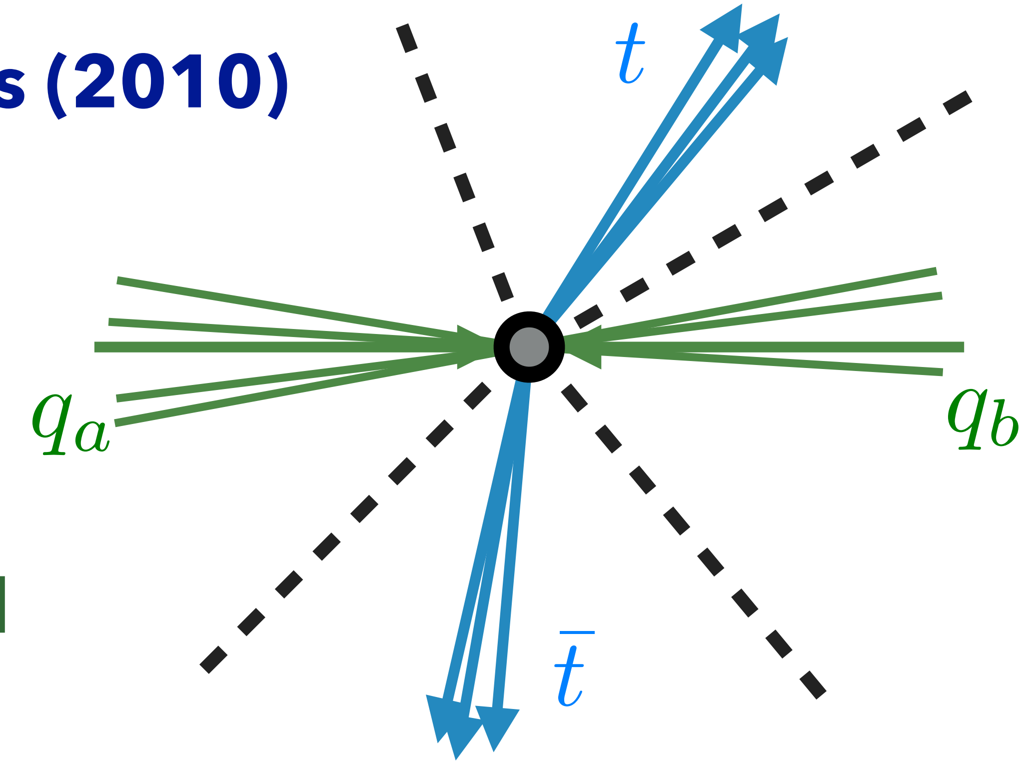
# WHAT CAN WE CALCULATE ANALYTICALLY?

Stewart, Tackmann, Waalewijn 2010

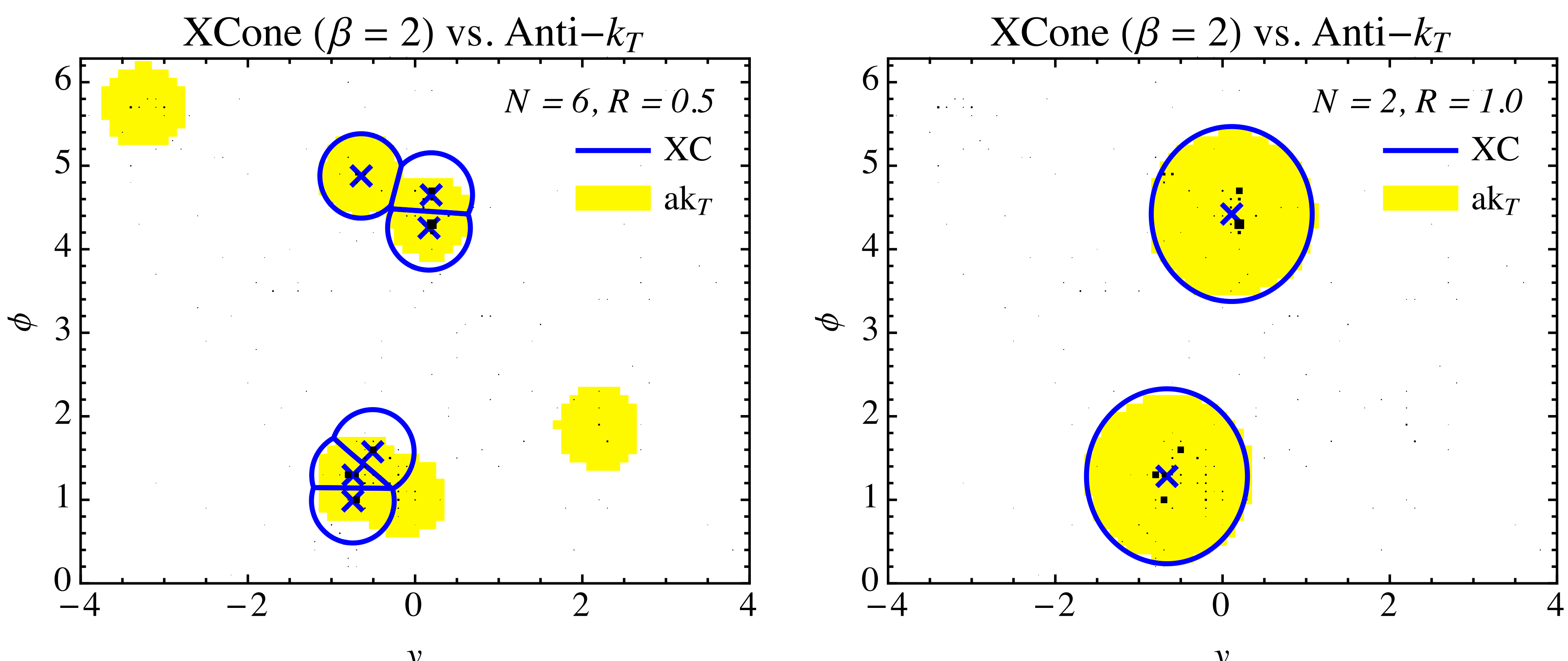
## Event shapes for hadron colliders: N-jettiness (2010)

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

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




**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

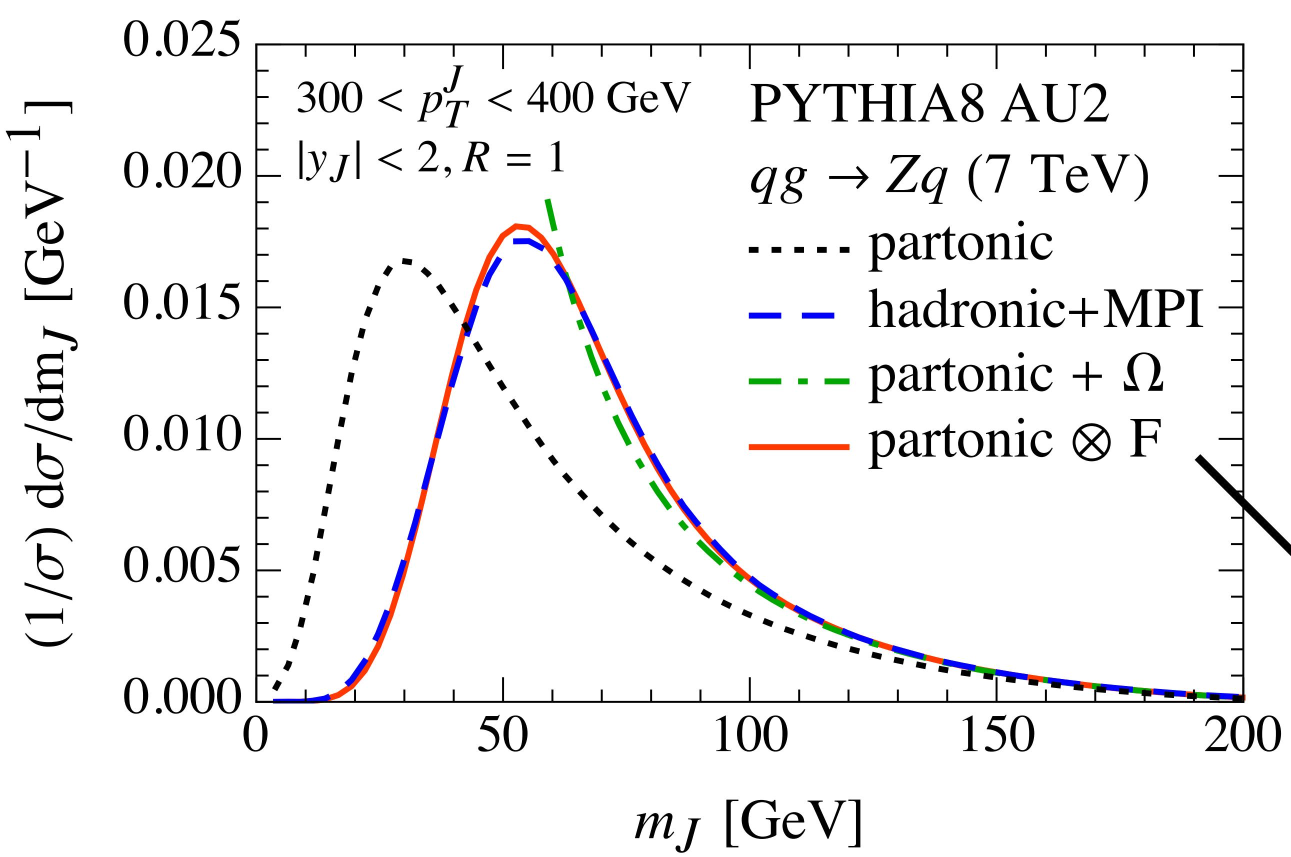
$$\frac{d^2\sigma}{dM_{J1}^2 dM_{J2}^2 d\mathcal{T}^{\text{cut}}} = \text{tr}\left[\hat{H}_{Qm}\hat{S}(\mathcal{T}^{\text{cut}}, R, \ldots)\otimes F\right]\otimes J_B \otimes J_B \otimes \mathcal{I}\mathcal{I} \otimes f\, f$$

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

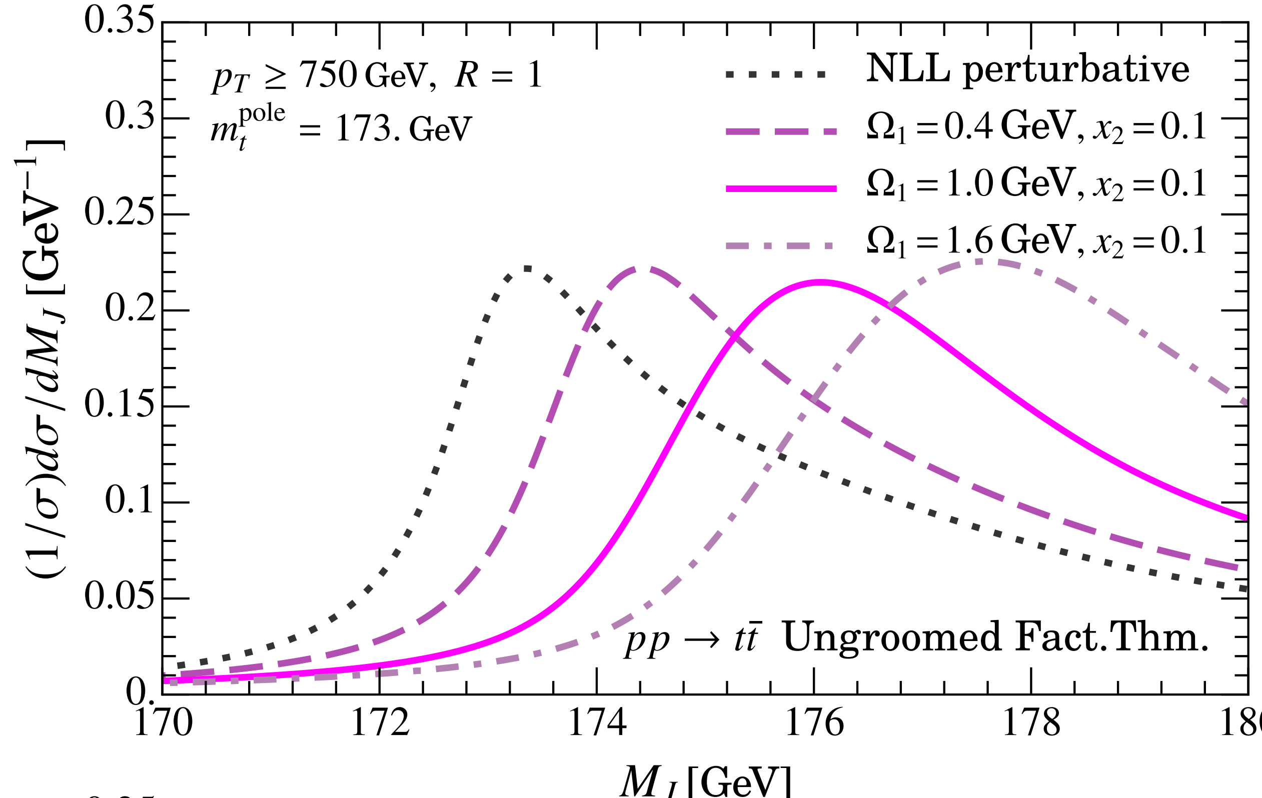
**Dominant dependence on the first moment:**

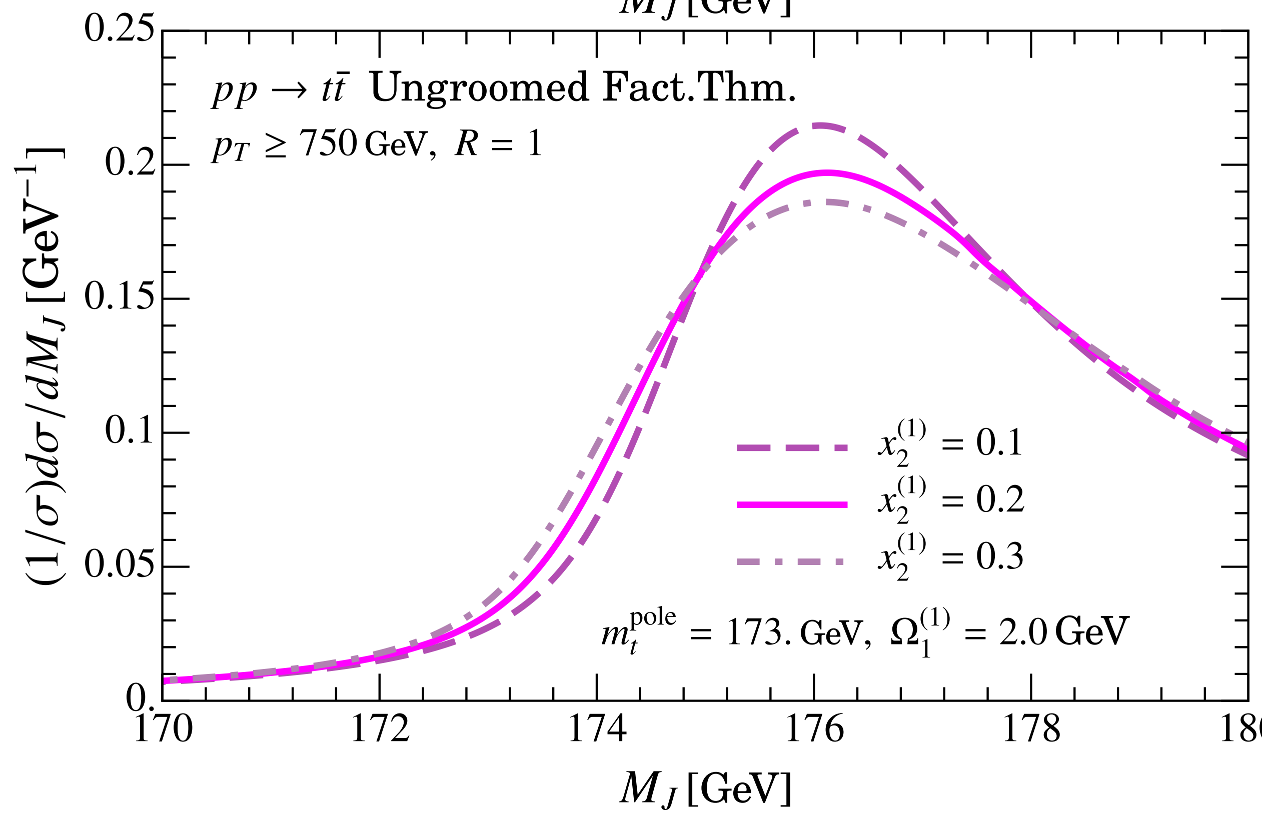
$$\Omega_1 = \int dk\, k F(k)$$

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

**Less sensitive to $x_2$ (higher moments)**

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



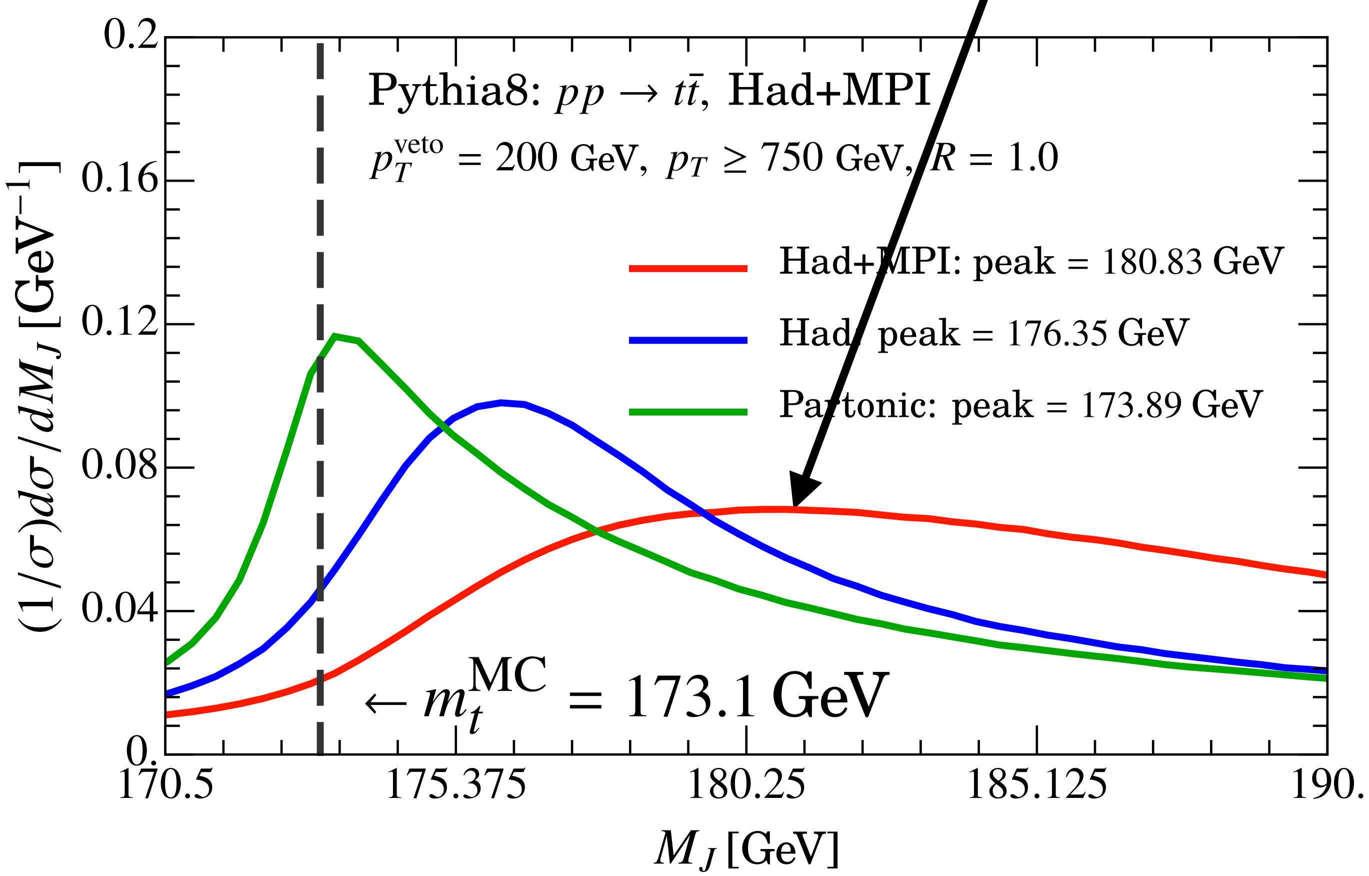
# WHAT CAN WE CALCULATE ANALYTICALLY?

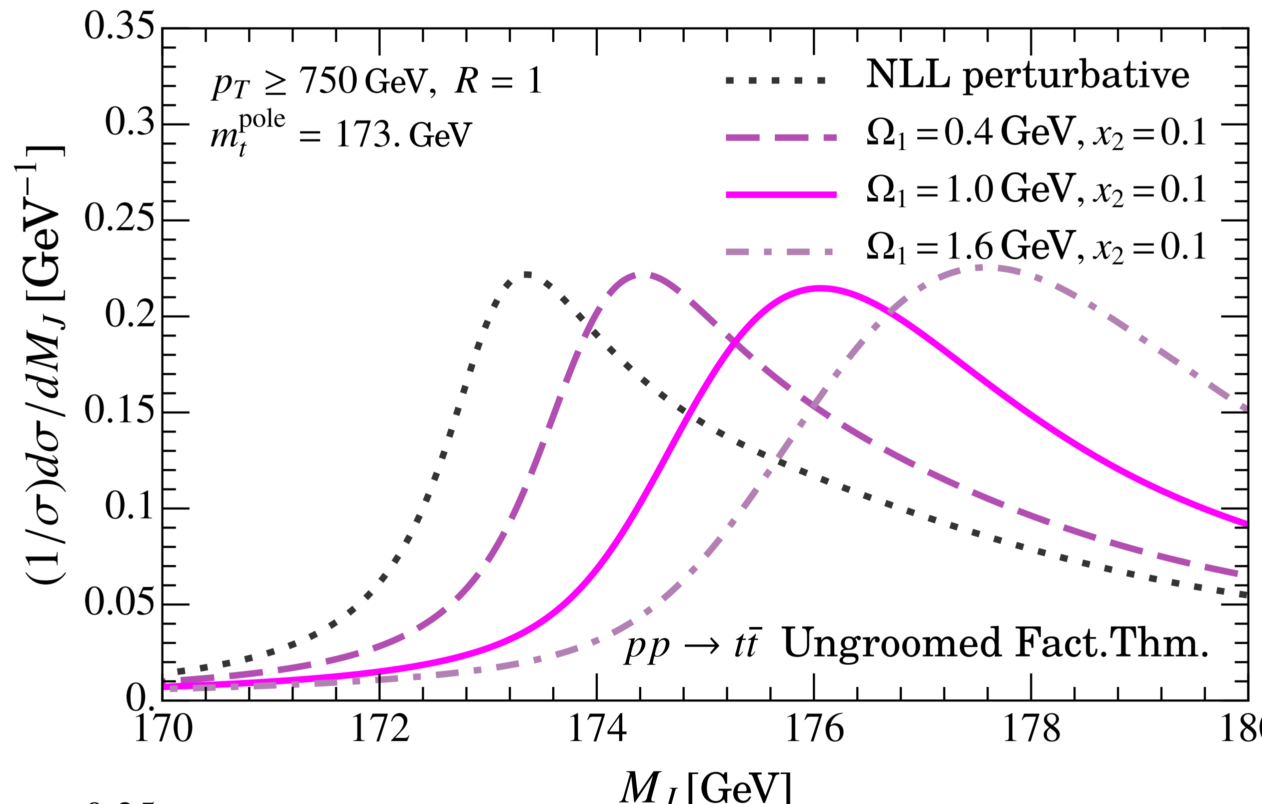
**Hoang, Mantry, AP, Stewart (soon)**

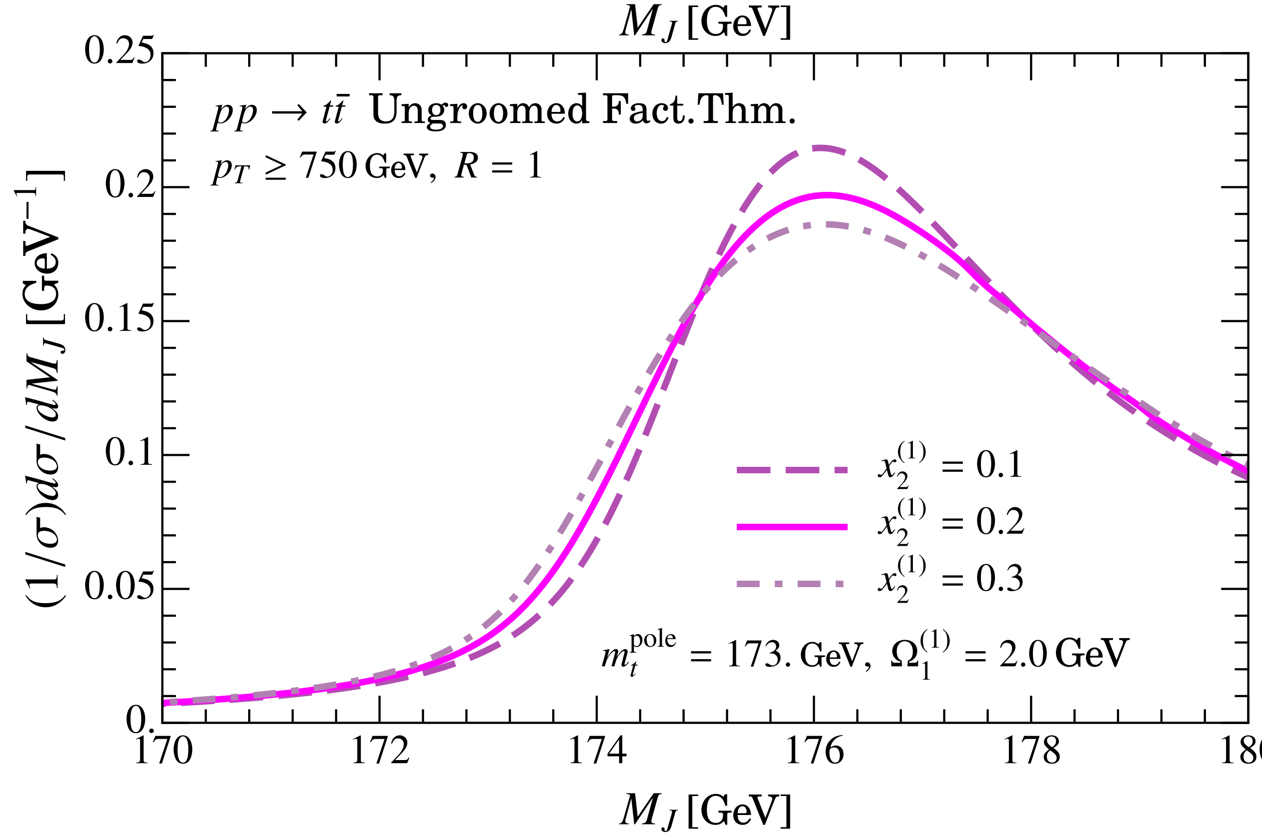
$$F(\ell) \;=\; \theta(\ell)\frac{\mathcal{N}(a,\Lambda)}{\Lambda}\left(\frac{\ell}{\Lambda}\right)^{a-1}\exp\left(\frac{-2\ell}{\Lambda}\right)$$

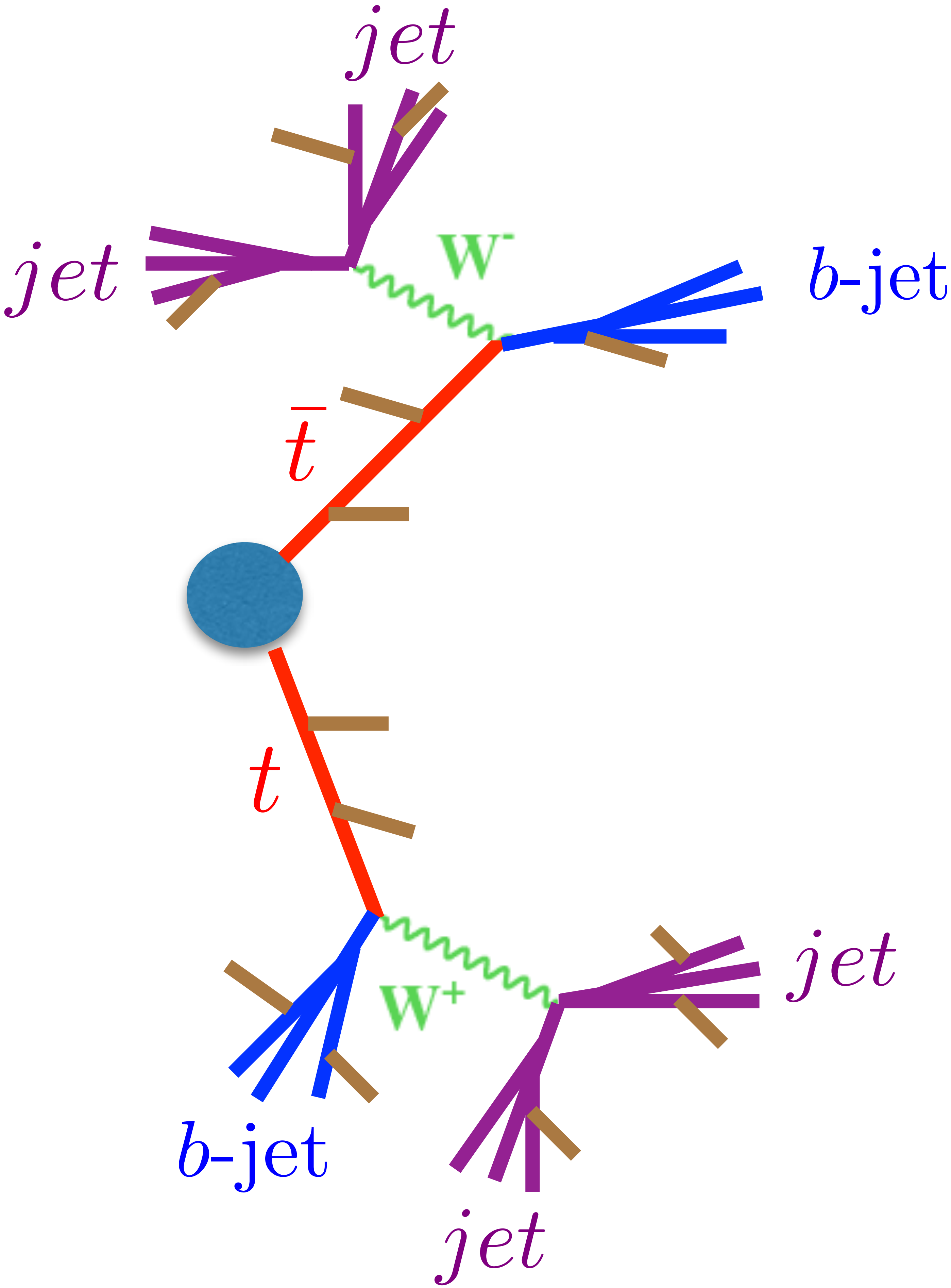
## Top jets at the LHC using 2-jettiness

**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**

# WHAT CAN WE CALCULATE ANALYTICALLY?

## Novel jet substructure techniques: Jet Grooming

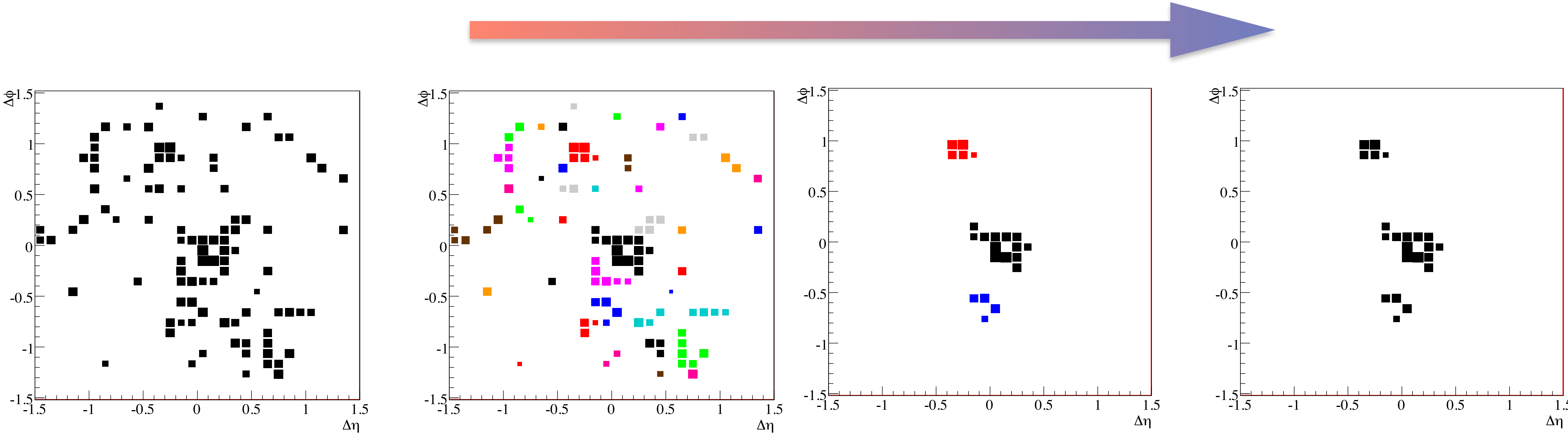
Butterworth, Davison, Rubin, Salam, 2008

Ellis, Vermillion, Walsh, 2009, 2010

Krohn, Thaler, Wang, 2010

**Jet grooming selectively removes radiation that includes contamination from the UE and pile up.**

**Trimming (2010):**




Krohn, Thaler, Wang, 2010

# WHAT CAN WE CALCULATE ANALYTICALLY?

## Novel jet substructure techniques: Jet Grooming

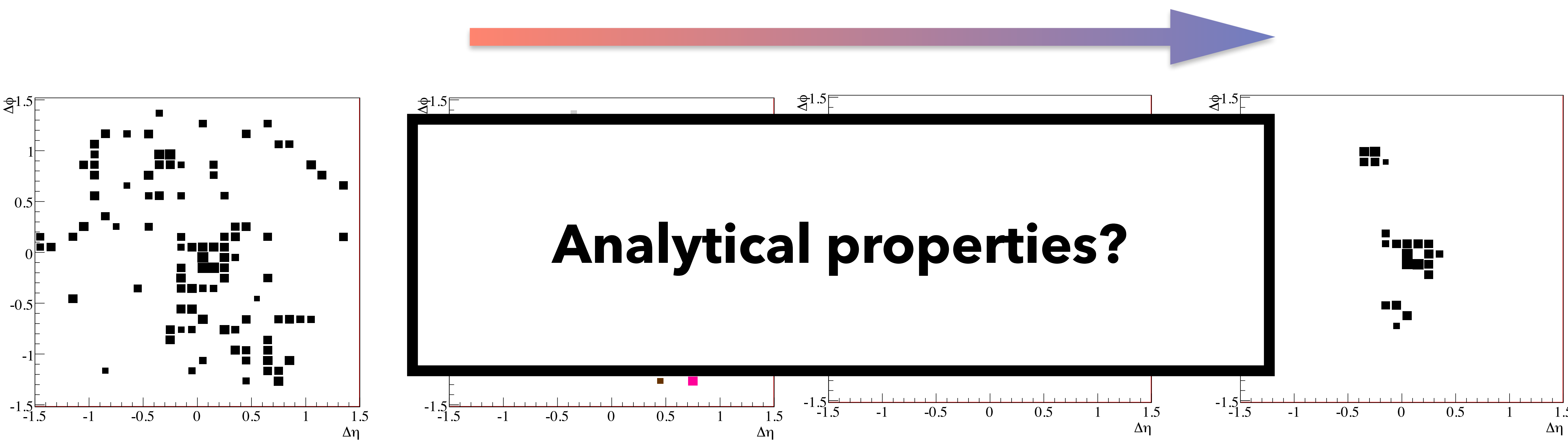
Butterworth, Davison, Rubin, Salam, 2008

Ellis, Vermillion, Walsh, 2009, 2010

Krohn, Thaler, Wang, 2010

**Jet grooming selectively removes radiation that includes contamination from the UE and pile up.**

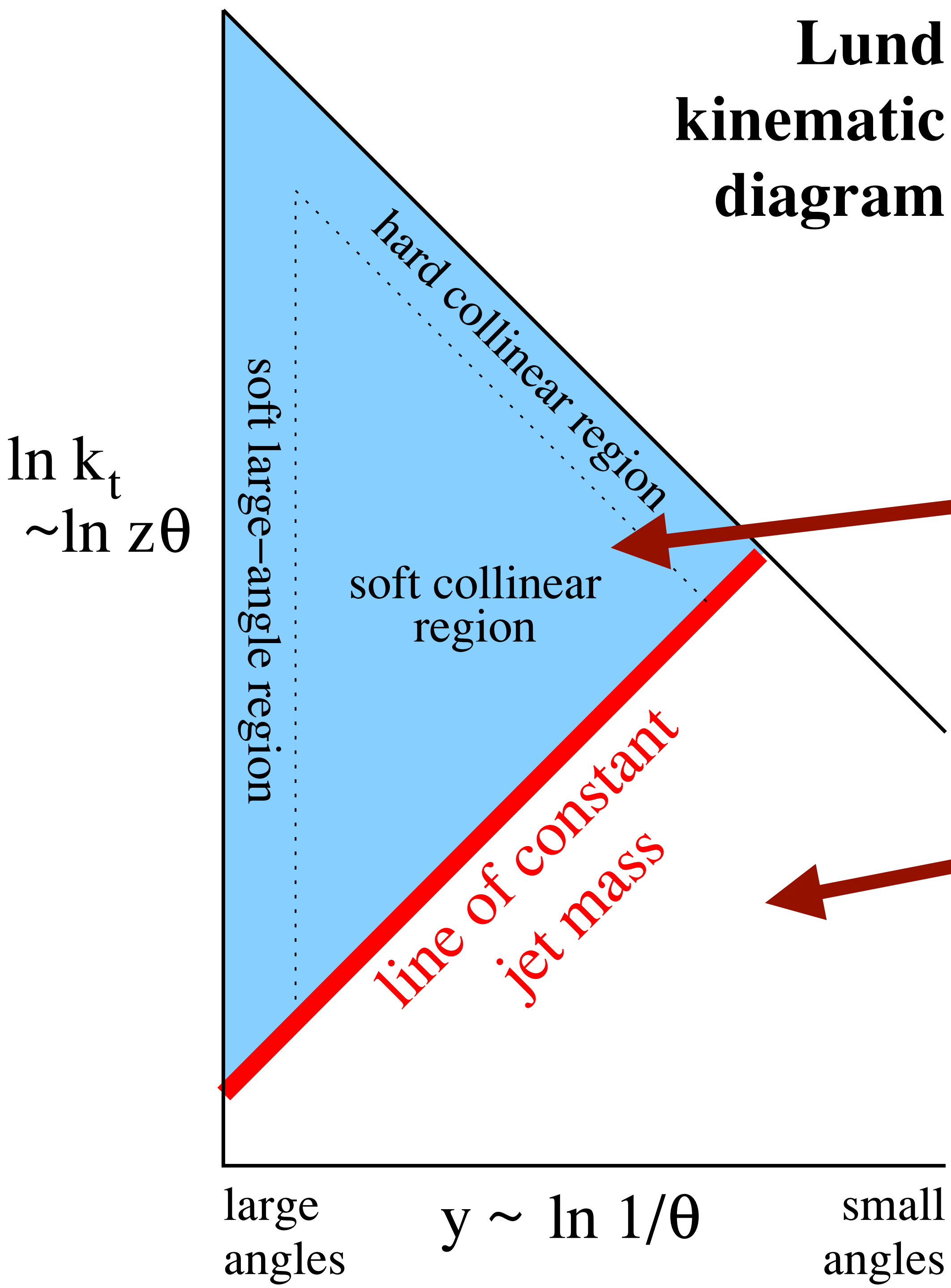
**Trimming (2010):**




Krohn, Thaler, Wang, 2010

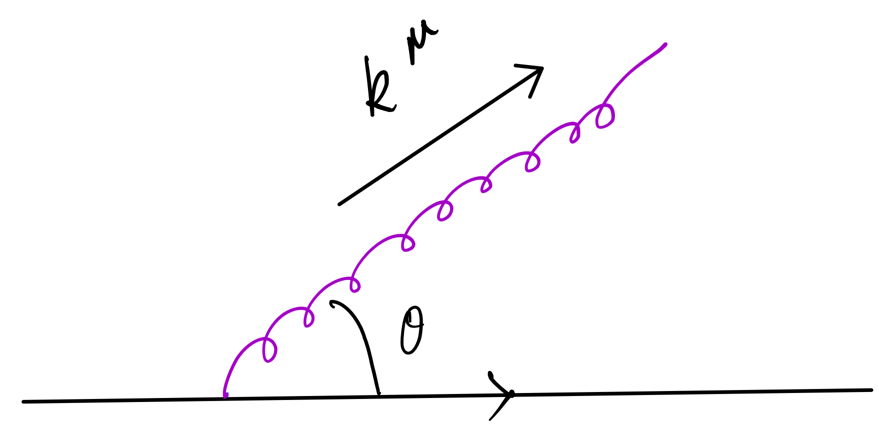
# WHAT CAN WE CALCULATE ANALYTICALLY?

**Probe the analytical properties by considering radiation off an energetic parton**




Want no emissions here.

These emissions don't affect the groomed jet mass

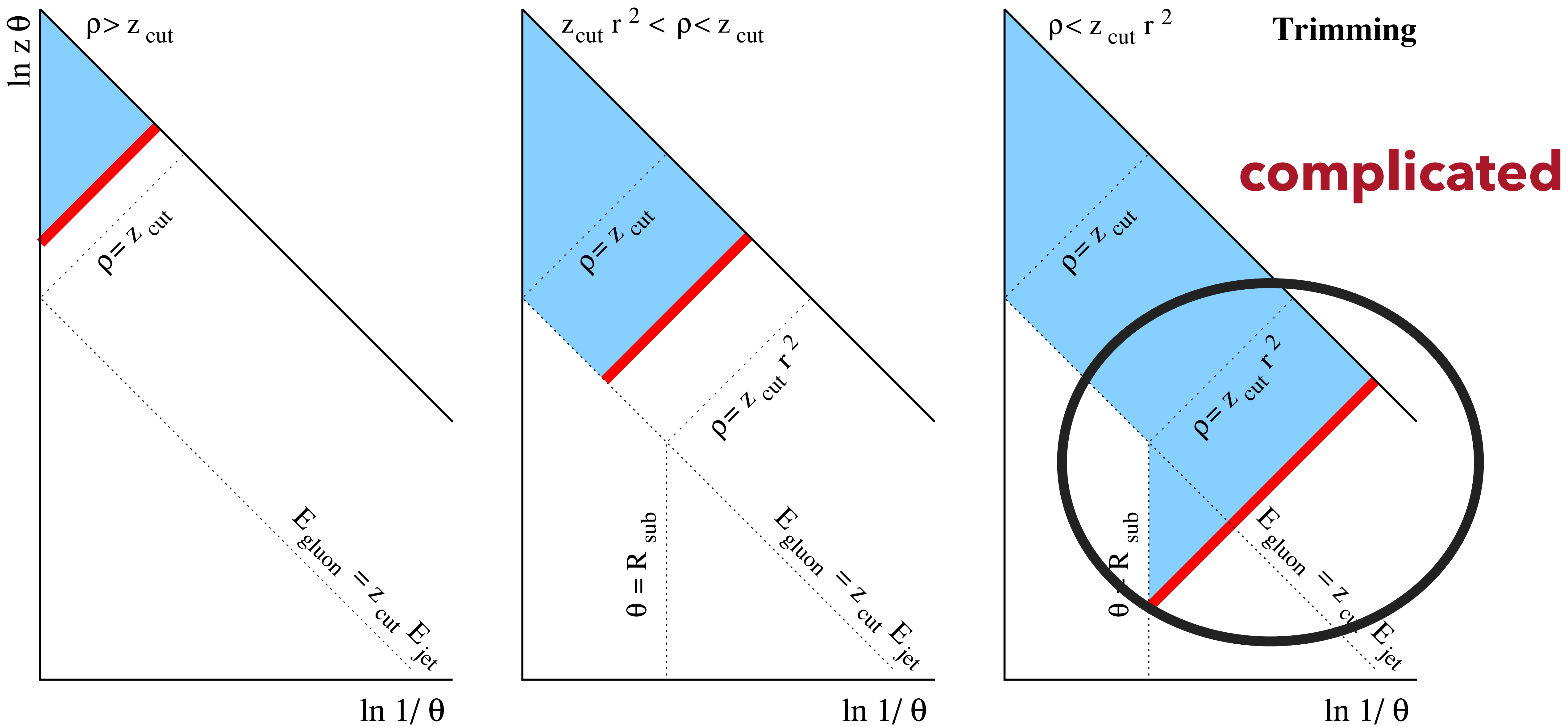



**Dasgupta, Fregoso, Marzani, Salam 2013**

# WHAT CAN WE CALCULATE ANALYTICALLY?

$$\rho \equiv \frac{m^2}{p_t^2 R^2}$$

**Probe the analytical properties by considering radiation off an energetic parton**



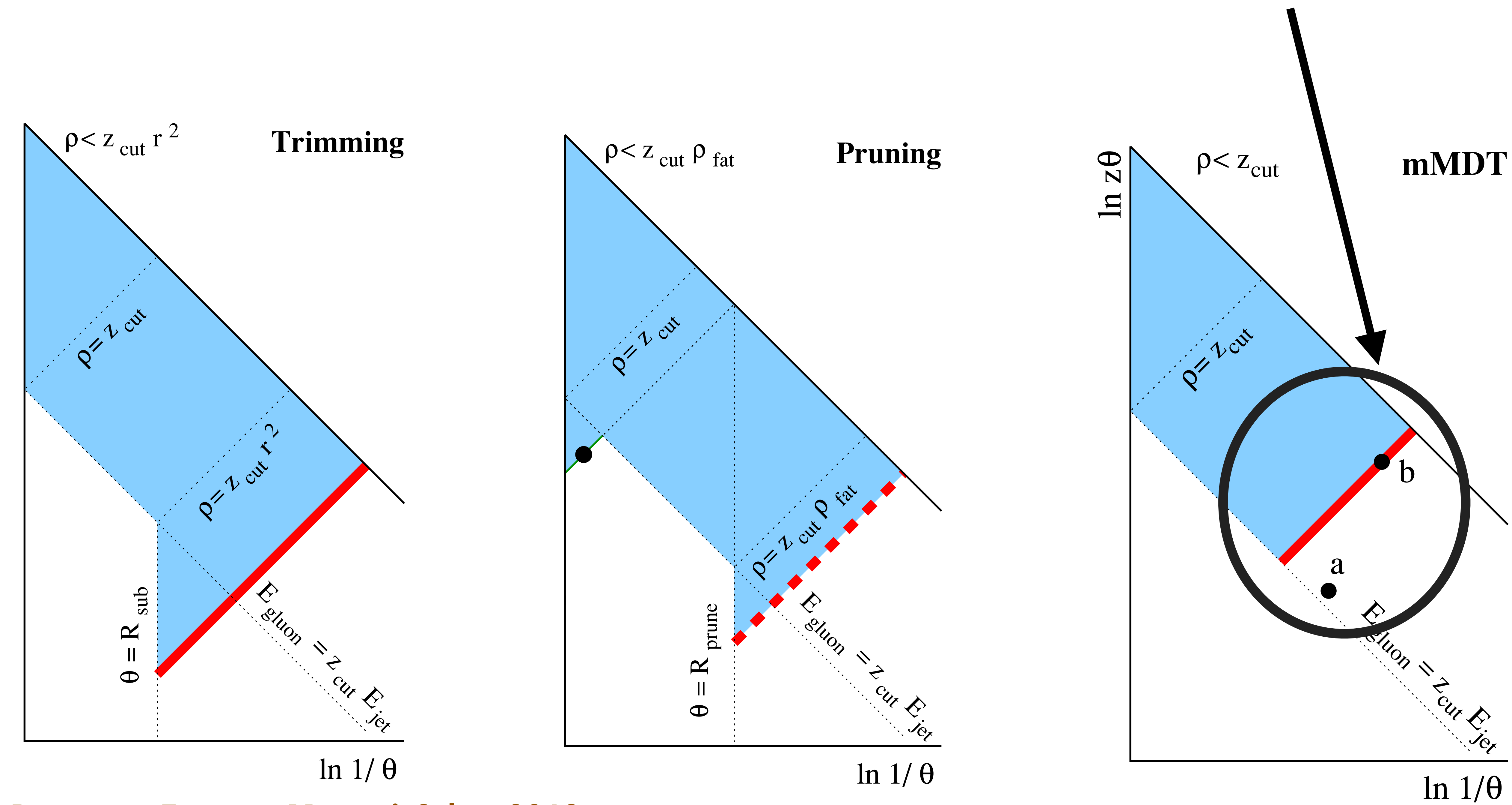

Dasgupta, Fregoso, Marzani, Salam 2013

# WHAT CAN WE CALCULATE ANALYTICALLY?

$$\rho \equiv \frac{m^2}{p_t^2 R^2}$$

**Compare different groomers:**

**Starting to understand**




Dasgupta, Fregoso, Marzani, Salam 2013

# SOFT DROP GROOMING

Larkoski, Marzani, Soyez, Thaler 2014

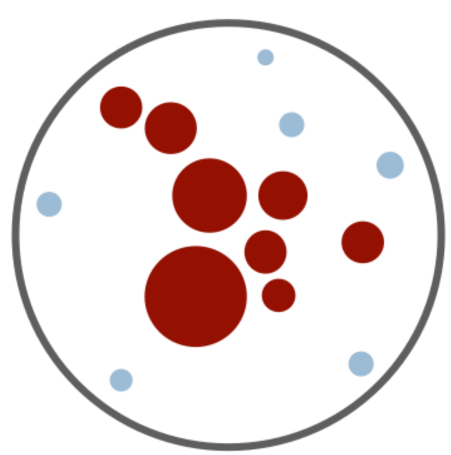
**Two grooming parameters:**

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

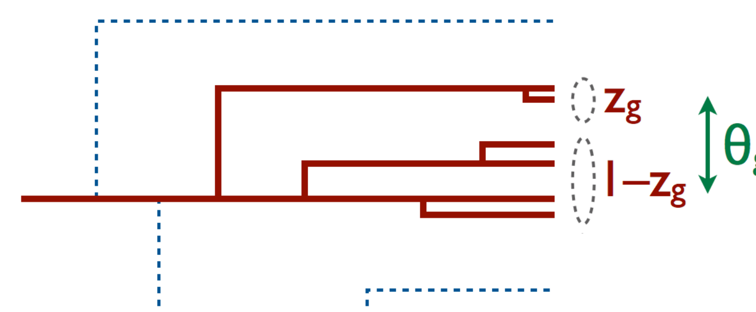
**Grooms soft radiation from the jet**

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

**Groomed jet**



**Groomed Clustering tree**



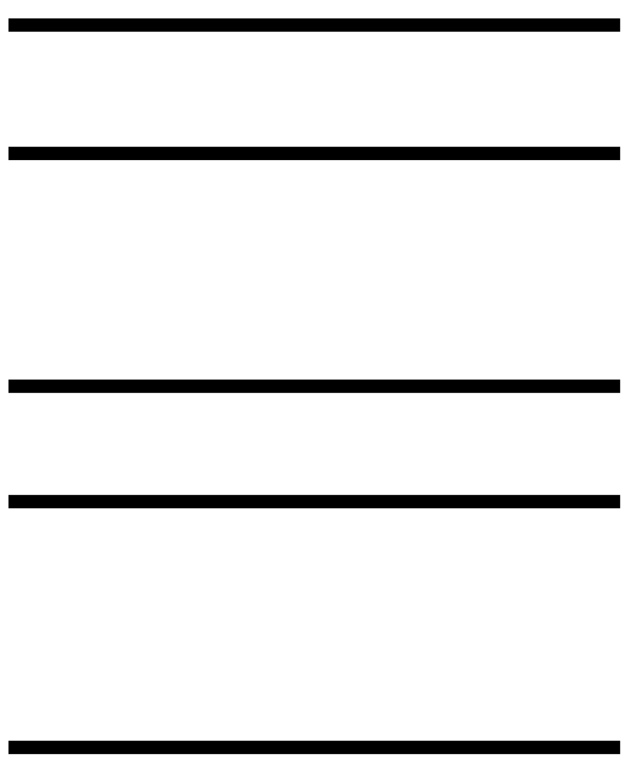

More Grooming — Less Grooming

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

# CLUSTERING AND GROOMING

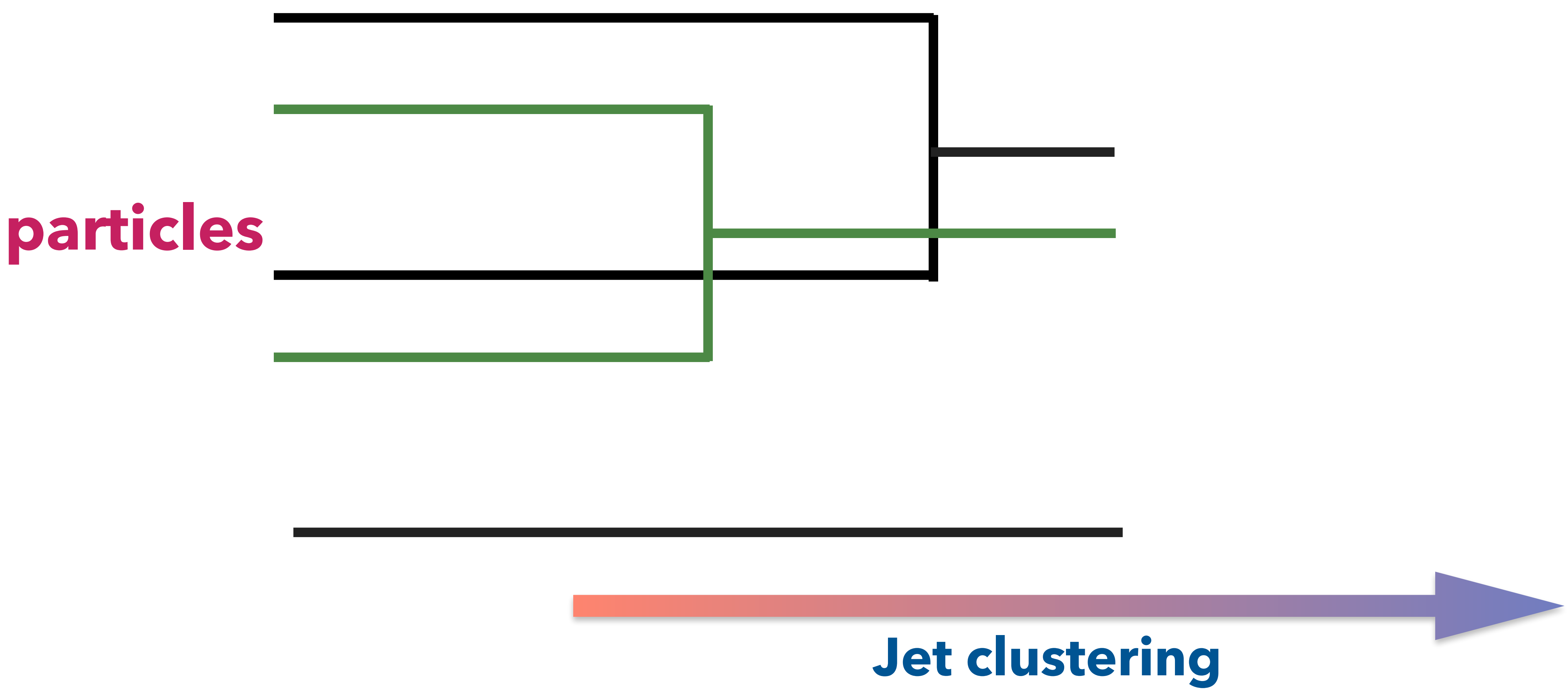
**Cluster particles in a jet defined by some algorithm**

particles



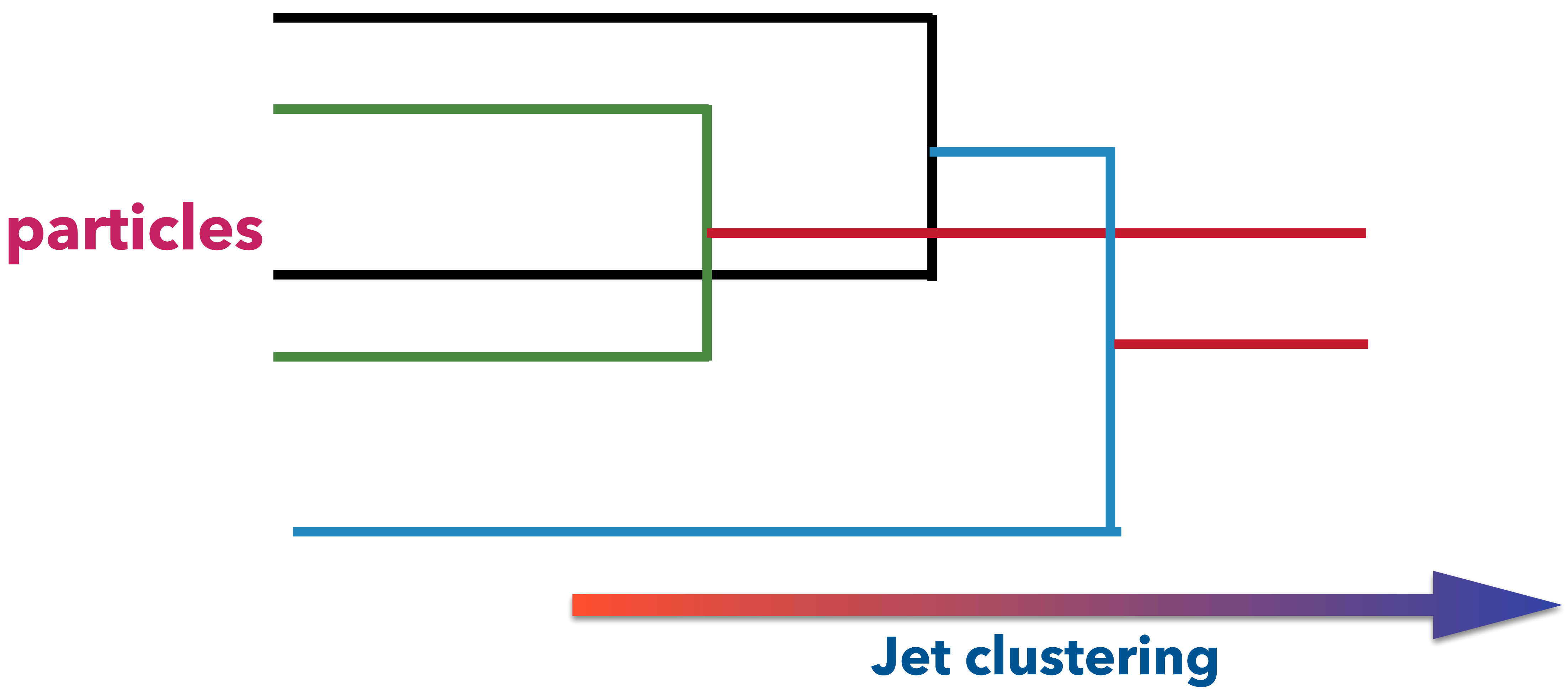
# CLUSTERING AND GROOMING

**Cluster particles in a jet defined by some algorithm**



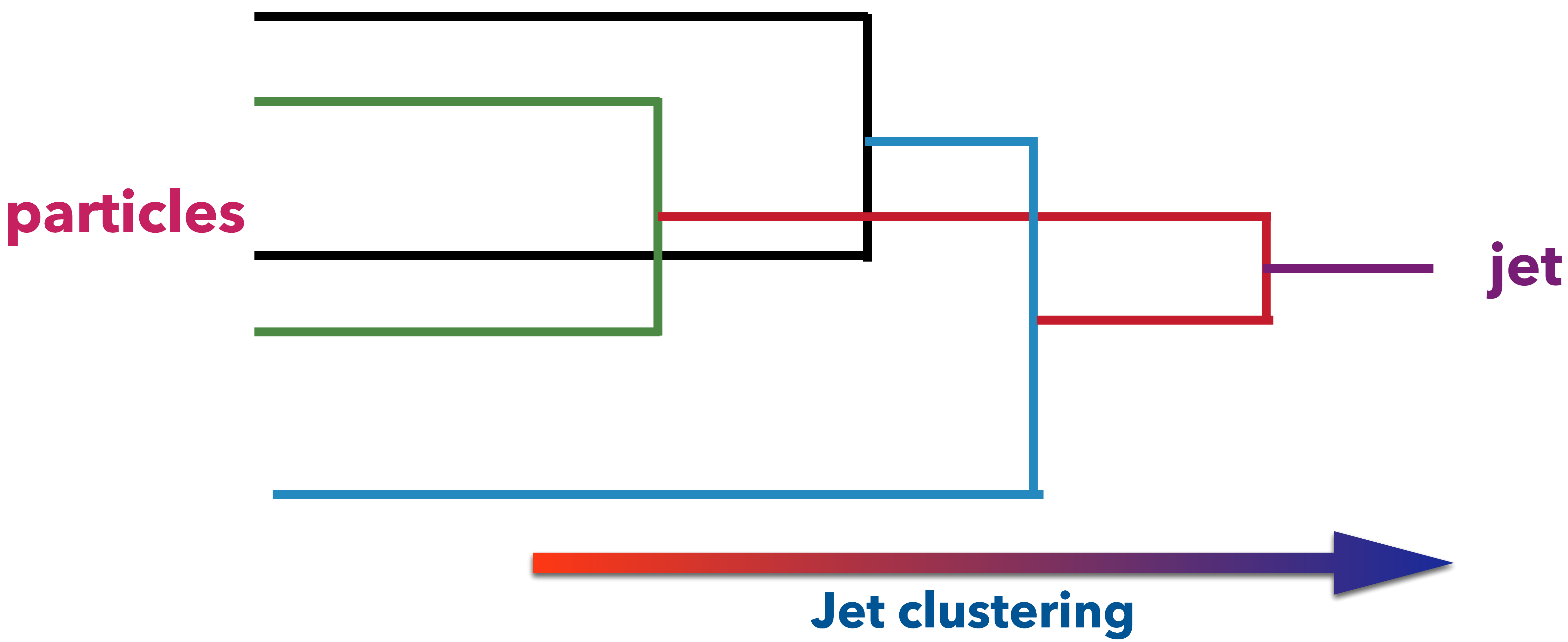
# CLUSTERING AND GROOMING

**Cluster particles in a jet defined by some algorithm**



# CLUSTERING AND GROOMING

**Cluster particles in a jet defined by some algorithm**

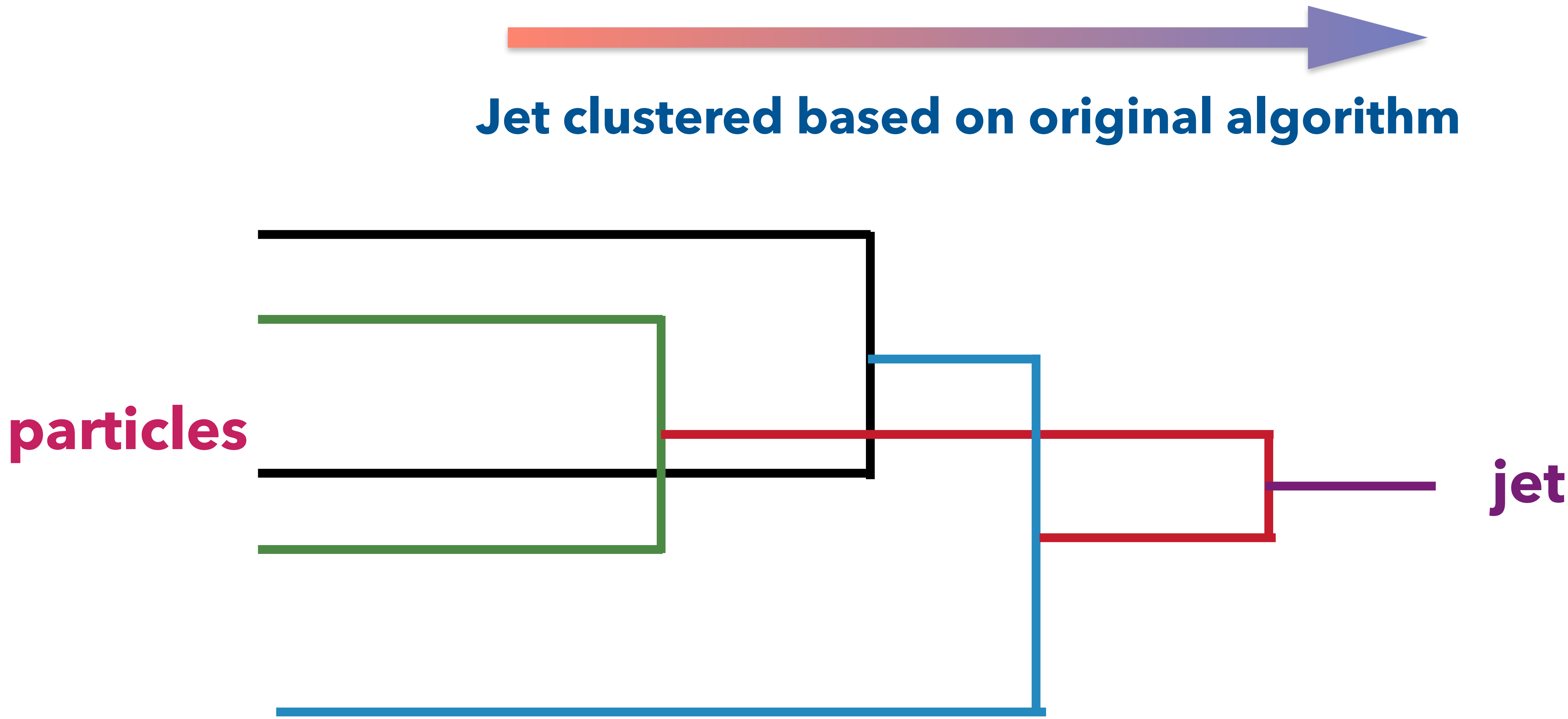


# CLUSTERING AND GROOMING

## Soft Drop grooming

Apply soft drop grooming on this jet

Jet clustered based on original algorithm

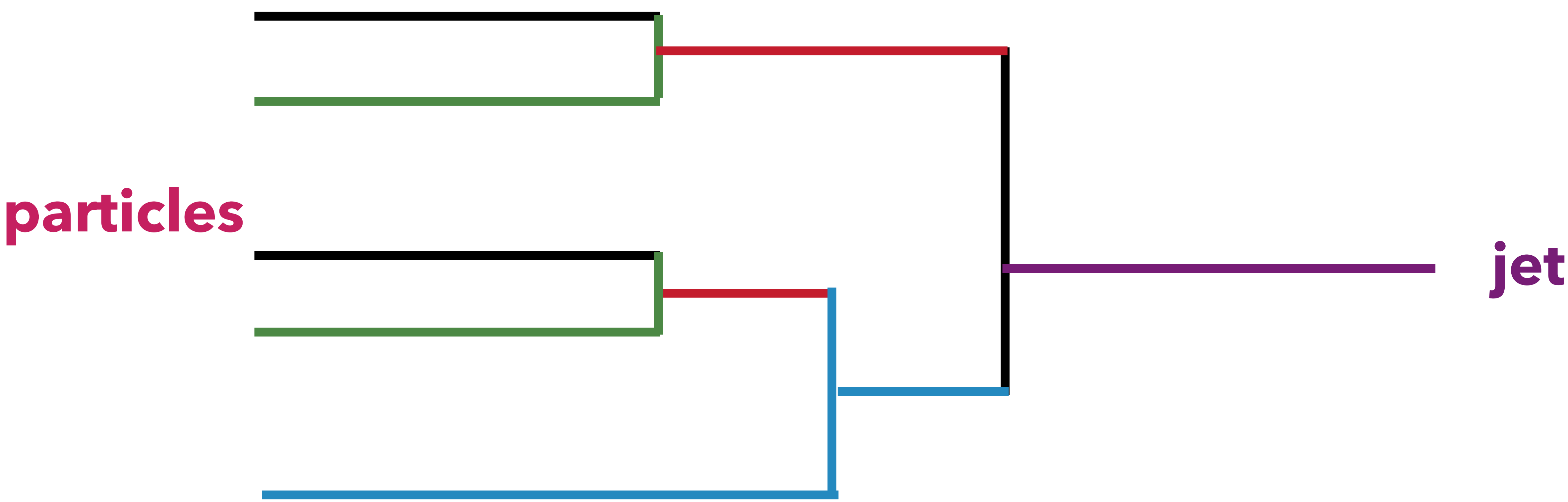


# CLUSTERING AND GROOMING

## Soft Drop grooming

**Recluster the jet:**

**Re-cluster particles pairwise based on angluar distance**



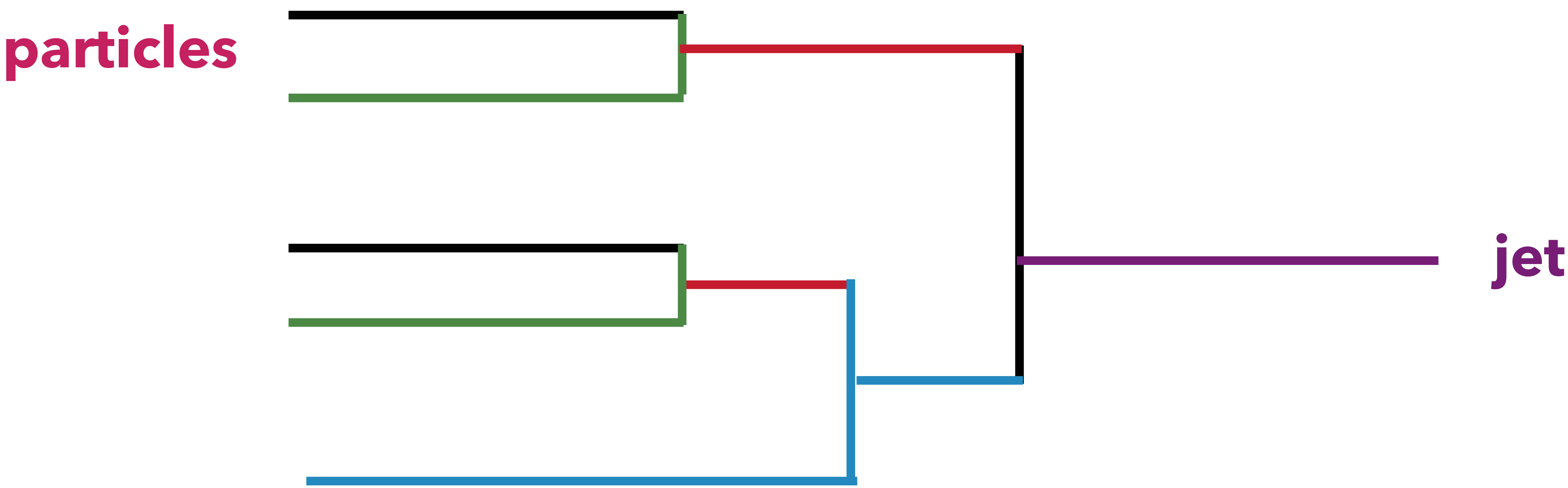
# CLUSTERING AND GROOMING

## 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!**

**Apply soft drop condition at every branch**

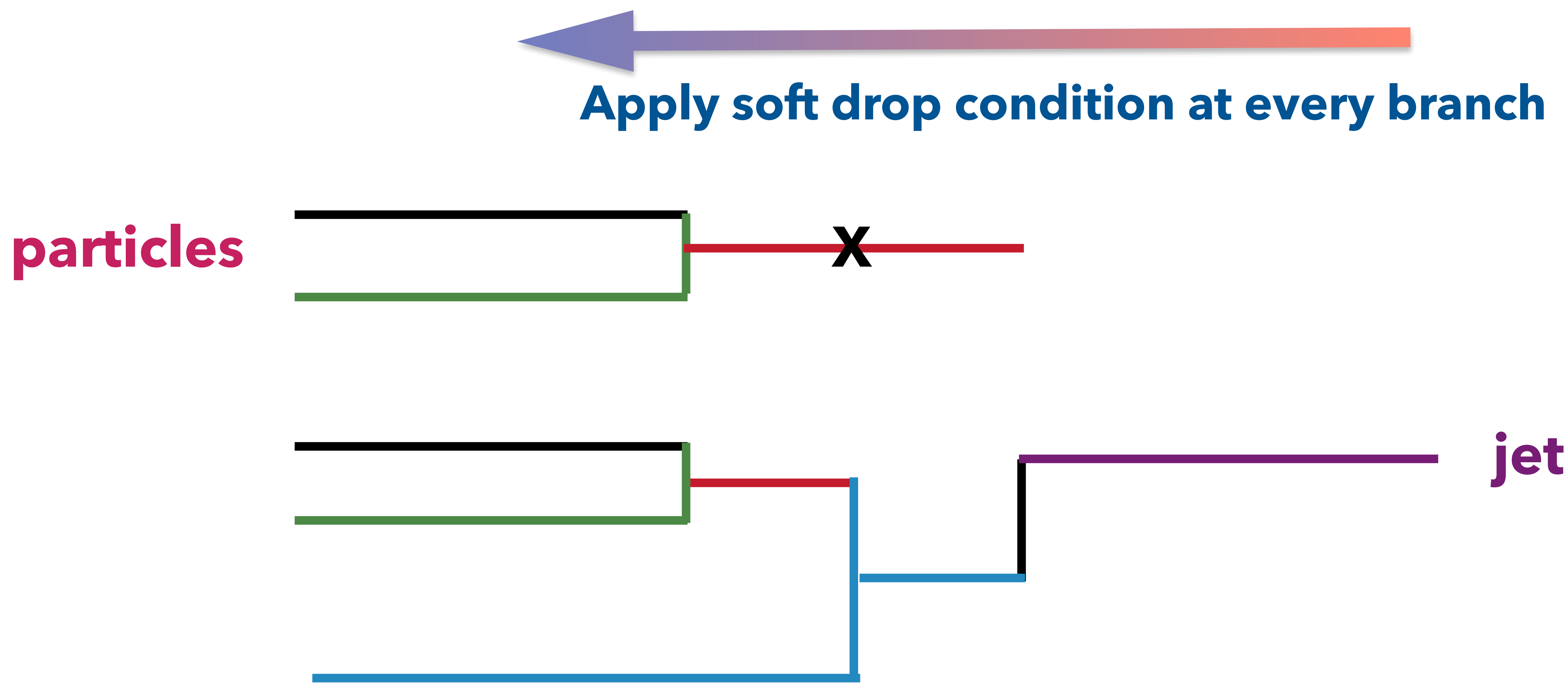


# CLUSTERING AND GROOMING

## 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!**



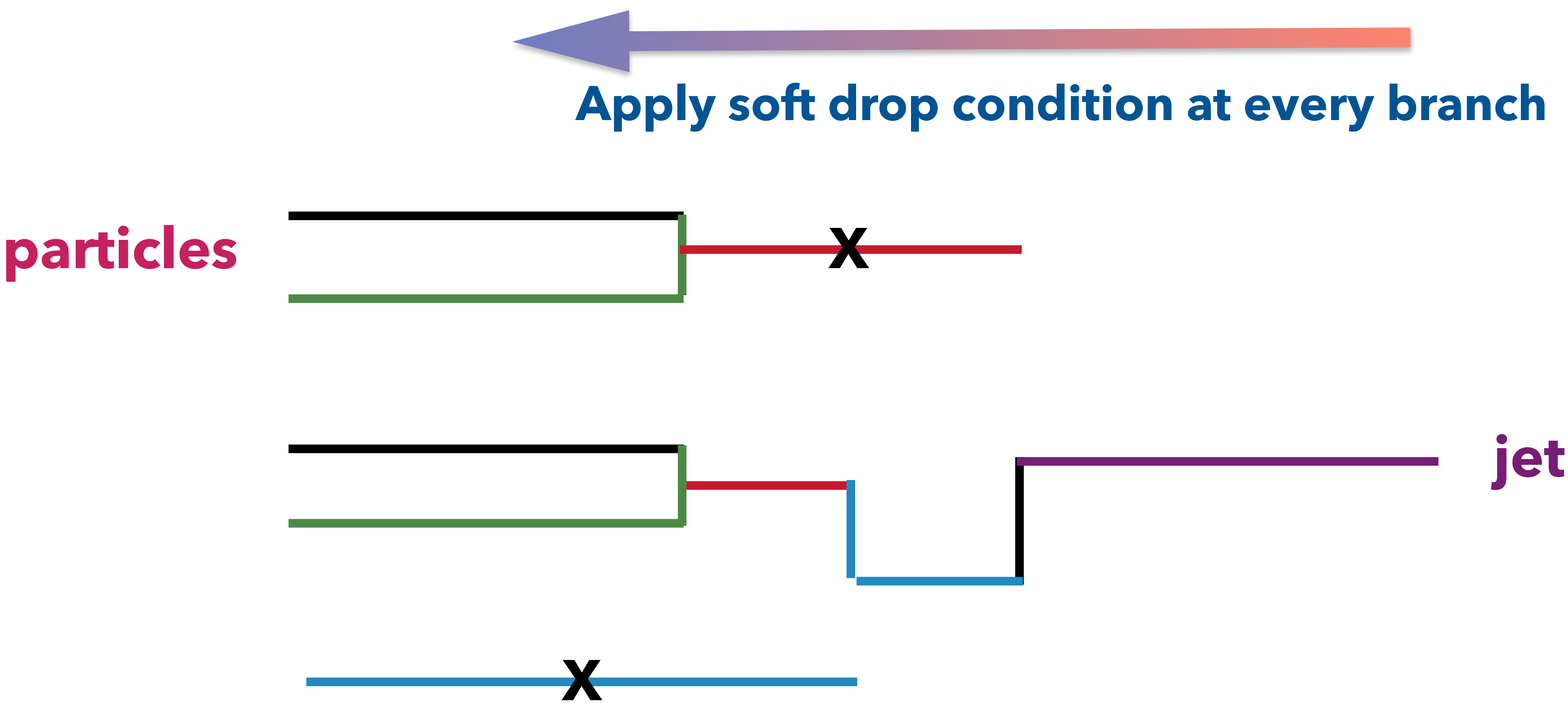
# CLUSTERING AND GROOMING

## 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**



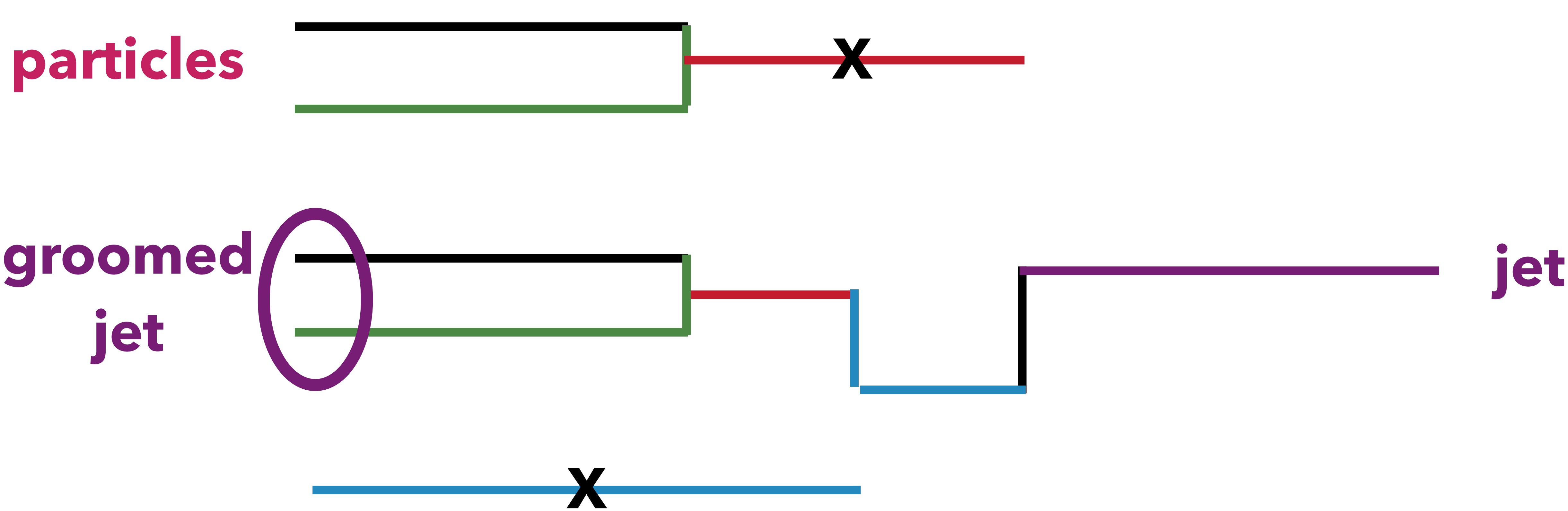
# CLUSTERING AND GROOMING

## Soft Drop grooming

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

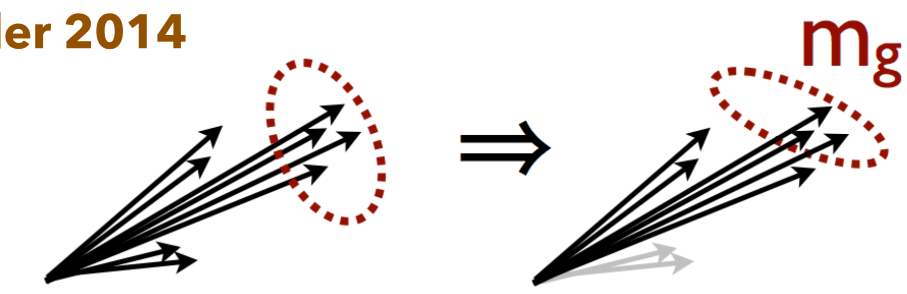
**Go back and groom!**

**Apply soft drop condition at every branch**



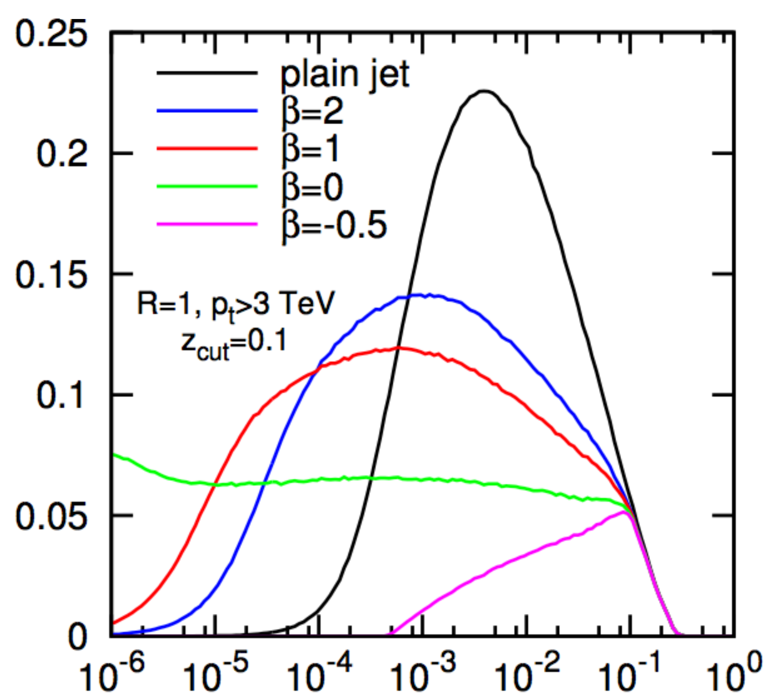
# GROOMED JET MASS

Larkoski, Marzani, Soyez, Thaler 2014



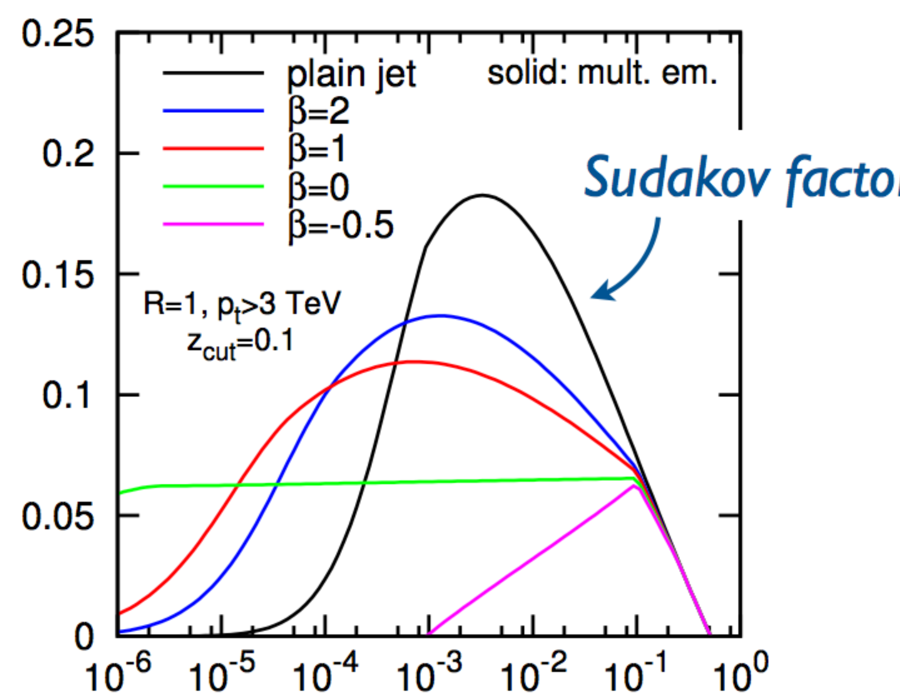

**Soft drop has an advantage of being amenable to theoretical calculations**

**Pythia8, partonic**

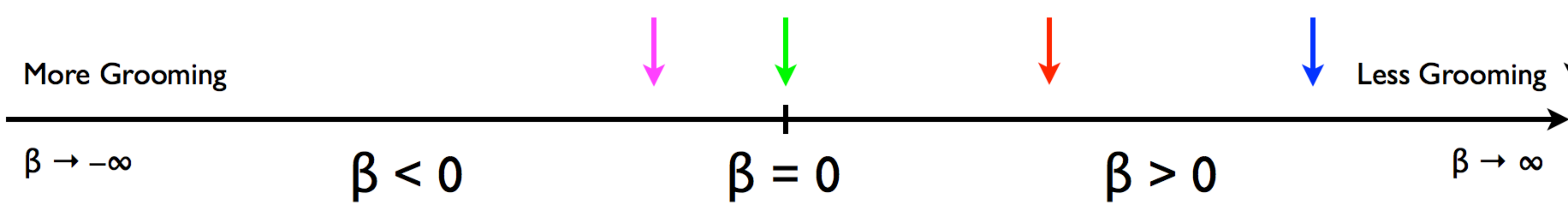



**$m^2/p_T^2$**

**Pert QCD at ~ NLL**




**$m^2/p_T^2$**



# 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:

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

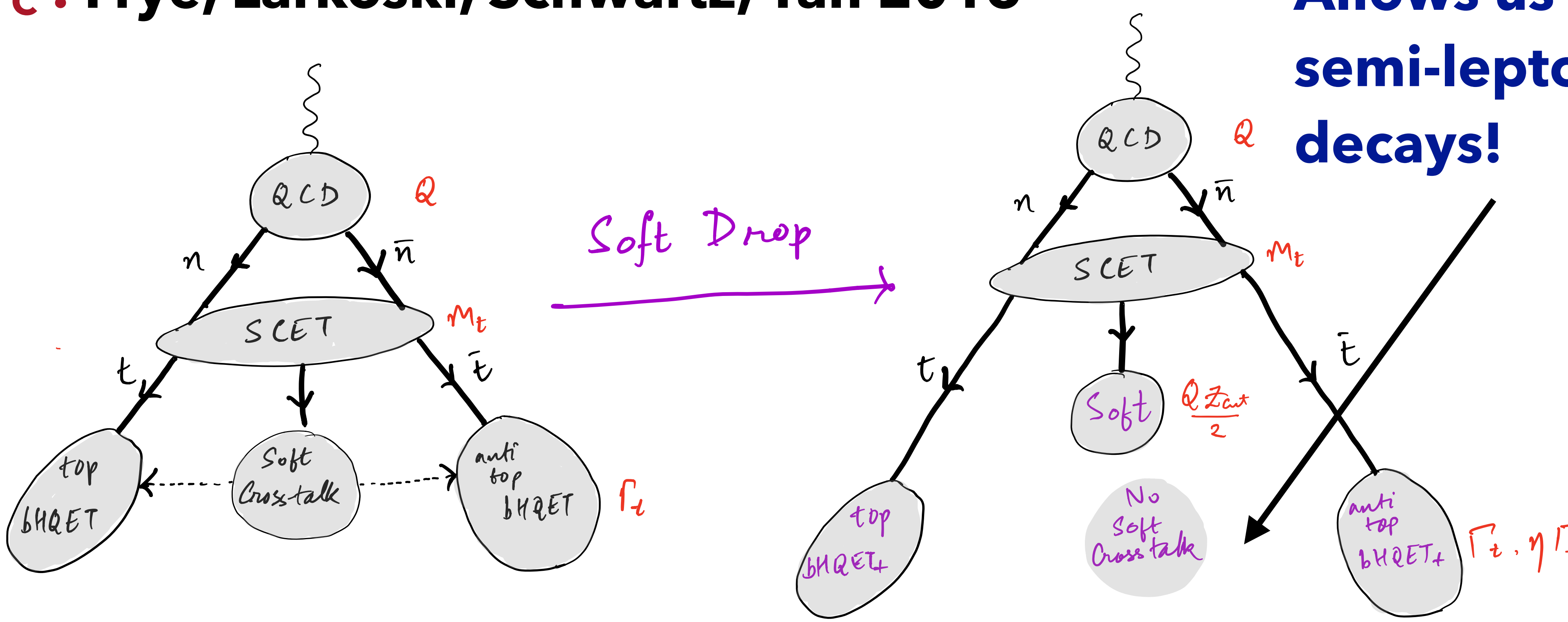
(more precise version up next)

**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

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

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

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

**Parameters in the factorization formula:**

- **Kinematic scales $p_T$, $\eta_J$ :** **determines statistics of boosted top events**
- **$m_t$ and $\Omega_1$ :** **parameters to be fitted ($\Gamma_t$ is fixed to SM value)**
- **$\delta m$ :** **choice of renormalization scheme**
- **Soft drop parameters $z_{cut}$ and $\beta$:** **adjust the strength of the groomer**
- **Renormalization scale $\mu$:** **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 $p_T$, $\eta_J$ : determines statistics of boosted top events**
- **$m_t$ and $\Omega_1$ : parameters to be fitted ($\Gamma_t$ is fixed to SM value)**
- **$\delta m$ : choice of renormalization scheme**
- **Soft drop parameters $z_{cut}$ and $\beta$: adjust the strength of the groomer**
- **Renormalization scale $\mu$: use for estimating perturbative uncertainties**

# HOW DO WE USE THESE THEORETICAL TOOLS?

## Groomed top jet mass cross section:

Hoang, Mantry, AP, Stewart 2017

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

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

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

**Parameters in the factorization formula:**

- **Kinematic scales $p_T$, $\eta_J$ :** determines statistics of boosted top events
- **$\boxed{m_t}$ and $\boxed{\Omega_1}$ :** parameters to be fitted ($\Gamma_t$ is fixed to SM value)
- **$\delta m$ :** choice of renormalization scheme
- **Soft drop parameters $z_{cut}$ and $\beta$:** adjust the strength of the groomer
- **Renormalization scale $\mu$:** 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 $p_T$, $\eta_J$ :** **determines statistics of boosted top events**
- **$m_t$ and $\Omega_1$ :** **parameters to be fitted ($\Gamma_t$ is fixed to SM value)**
- **$\delta m$ :** **choice of renormalization scheme**
- **Soft drop parameters $z_{cut}$ and $\beta$:** **adjust the strength of the groomer**
- **Renormalization scale $\mu$:** **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 $p_T$, $\eta_J$ : determines statistics of boosted top events**
- **$m_t$ and $\Omega_1$ : parameters to be fitted ($\Gamma_t$ is fixed to SM value)**
- **$\delta m$ : choice of renormalization scheme**
- **Soft drop parameters $z_{\rm cut}$ and $\beta$: adjust the strength of the groomer**
- **Renormalization scale $\mu$: 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 $p_T$, $\eta_J$ :** **determines statistics of boosted top events**
- **$m_t$ and $\Omega_1$ :** **parameters to be fitted ($\Gamma_t$ is fixed to SM value)**
- **$\delta m$ :** **choice of renormalization scheme**
- **Soft drop parameters $z_{\rm cut}$ and $\beta$:** **adjust the strength of the groomer**
- **Renormalization scale $\mu$:** **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:**

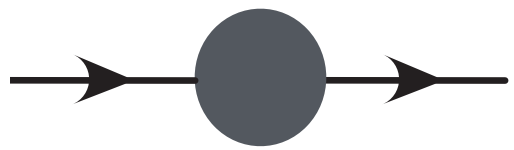
- **Kine**... **ents**
- **$m_t$ an**...
- **δm :** ...
- **Soft c**... **ner**
- **Renormalization scale μ:** use for estimating perturbative uncertainties

**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:**  $\propto \dfrac{1}{\not{p} - m_t^{\text{pole}}}$ $\quad \Delta m_t^{\text{pole}} \sim \Lambda_{\text{QCD}}$

- **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 ~ $\Gamma_t$ : No Ambiguity and Compatible with Breit Wigner**

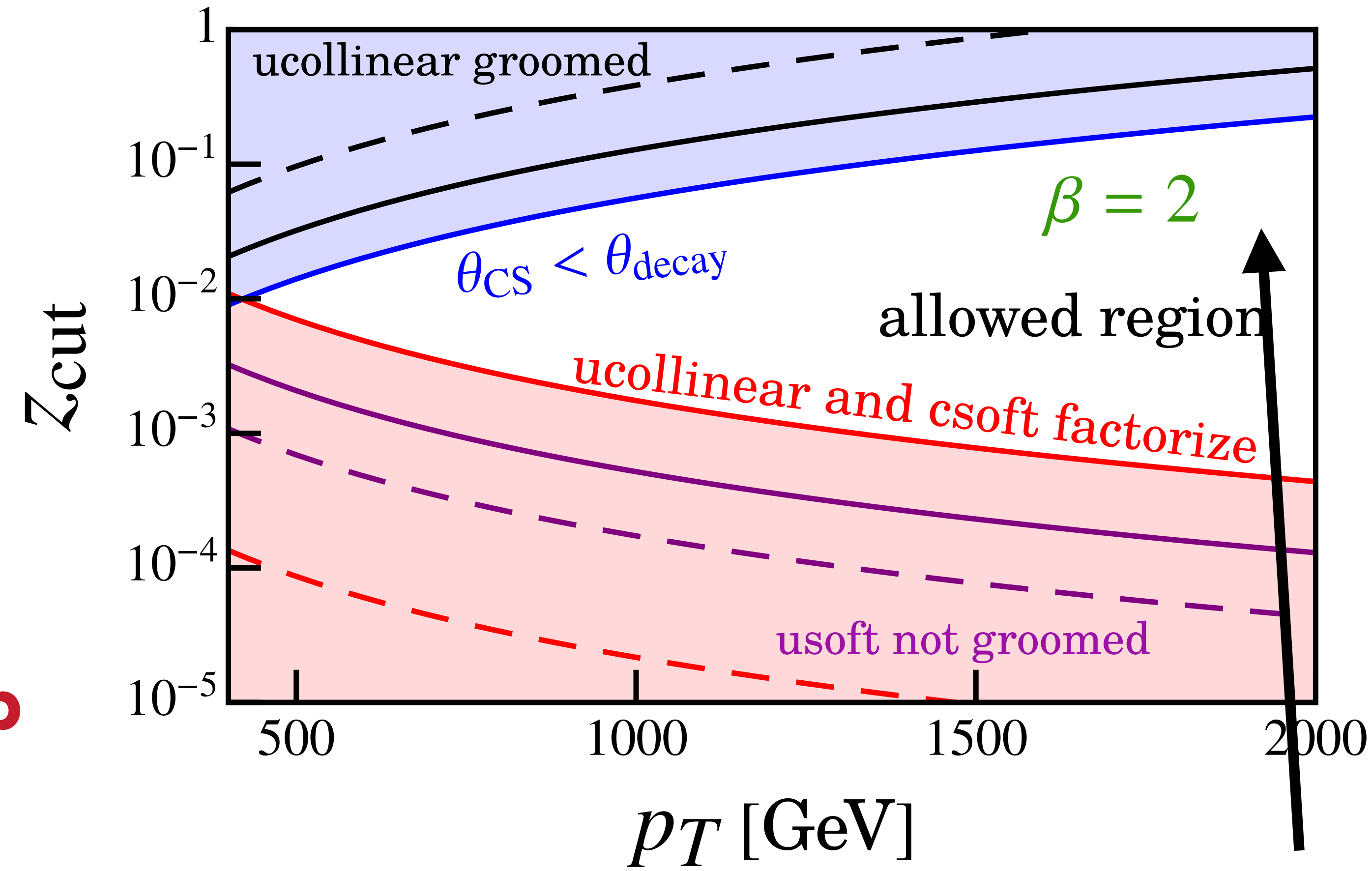
# CONSTRAINTS FROM POWER COUNTING

**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

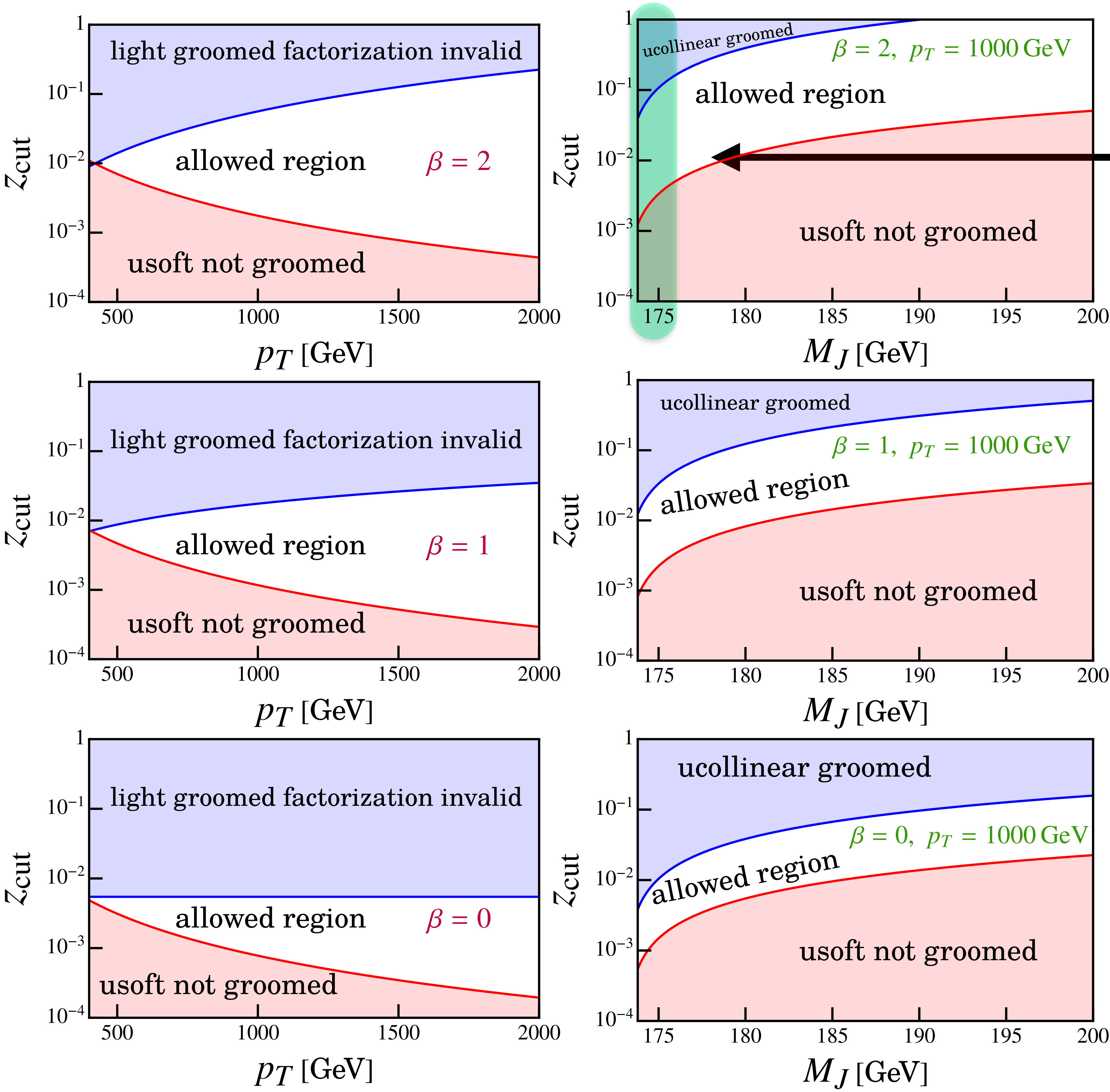
Ensure soft drop removes most contamination




"light grooming" here

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

# CONSTRAINTS FROM POWER COUNTING



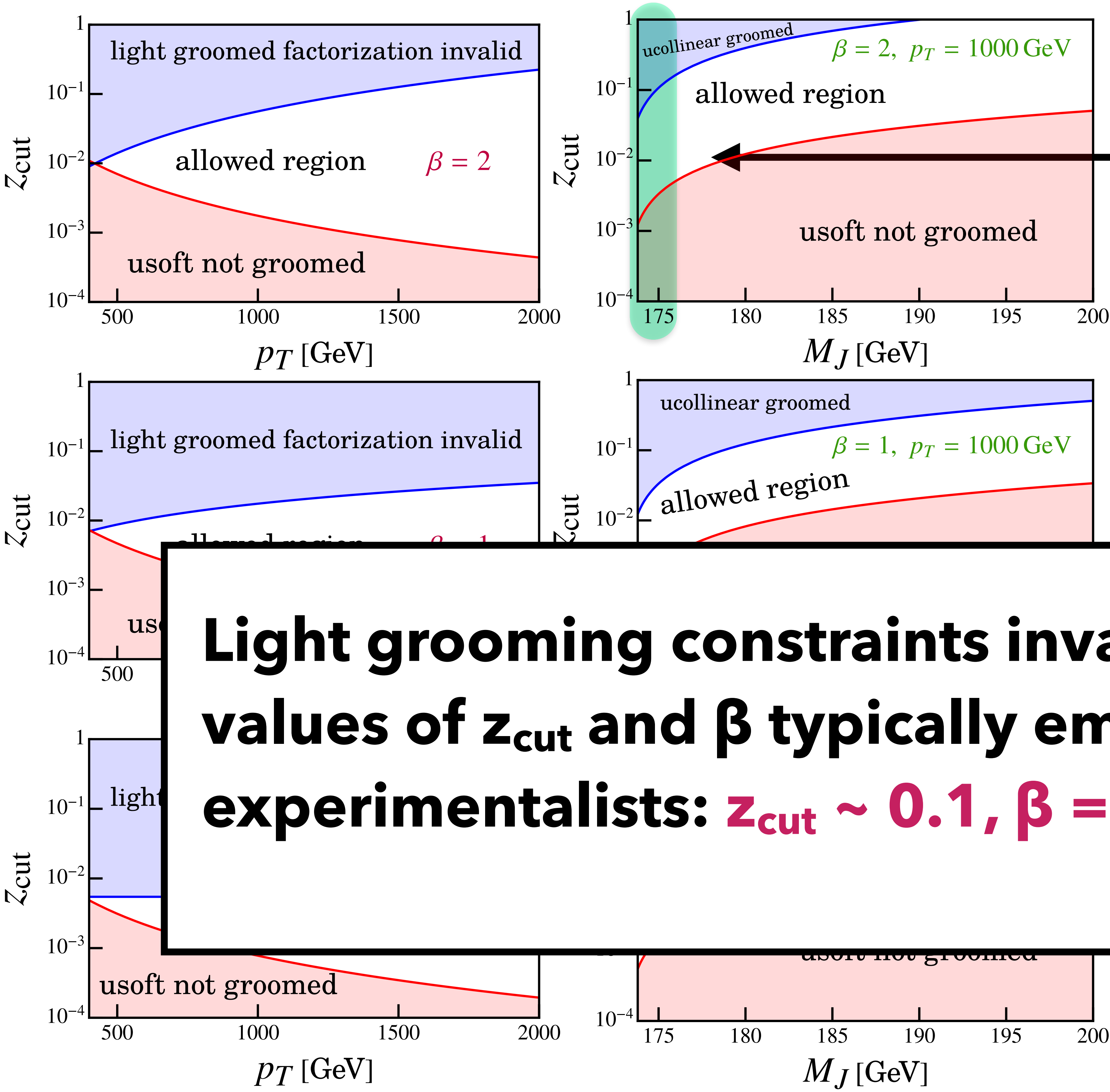

## Vary β

**Peak Region**

**More grooming**

- **Minimum β allowed: β ≥ 1,2**

# CONSTRAINTS FROM POWER COUNTING




**Vary β**

**Peak Region**

**More grooming**

**...owed:**

**$\beta \geq 1,2$**

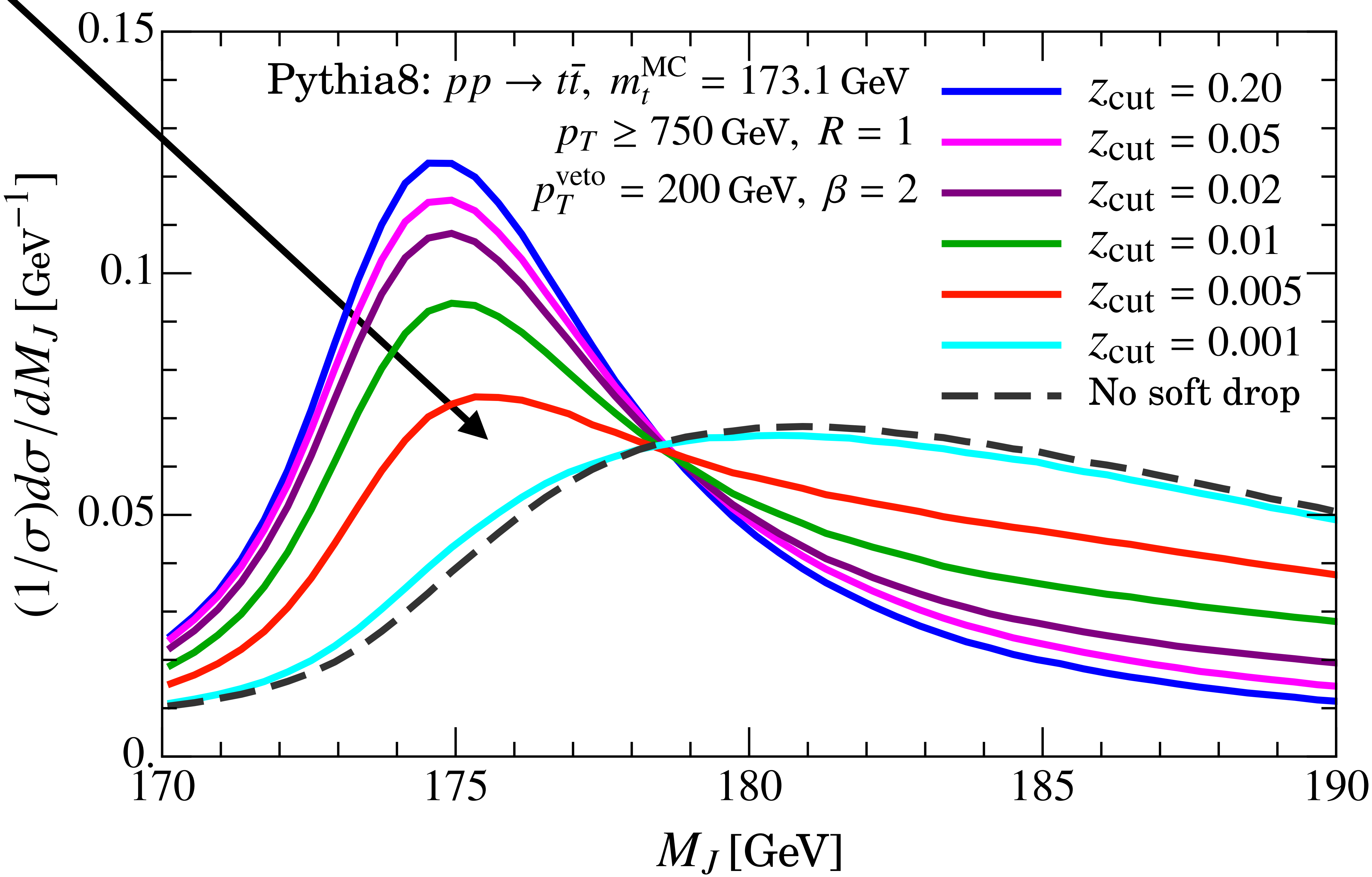
**Light grooming constraints invalidate values of $z_{cut}$ and β typically employed by experimentalists: $z_{cut} \sim 0.1,\ \beta = 0,1$**

# TESTING EFFECTIVENESS OF LIGHT GROOMING

# TESTING EFFECTIVENESS OF LIGHT GROOMING

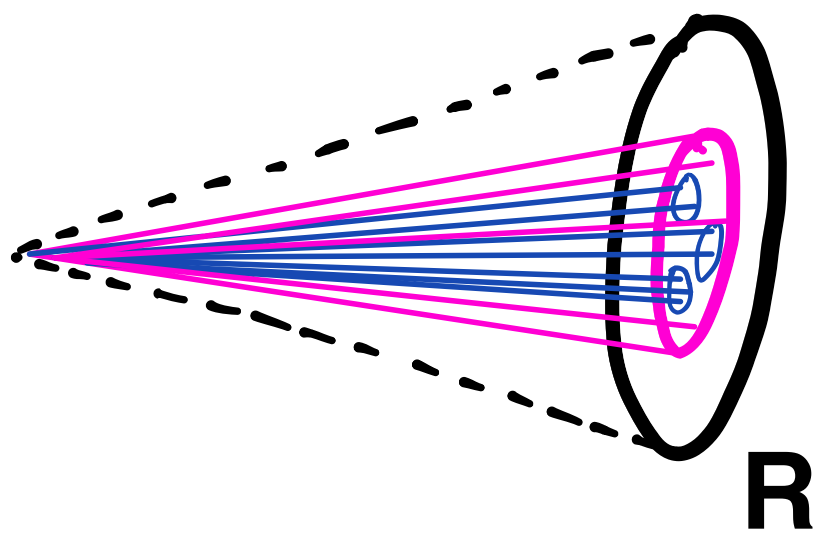
- **Most Contamination is removed with light grooming.**

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

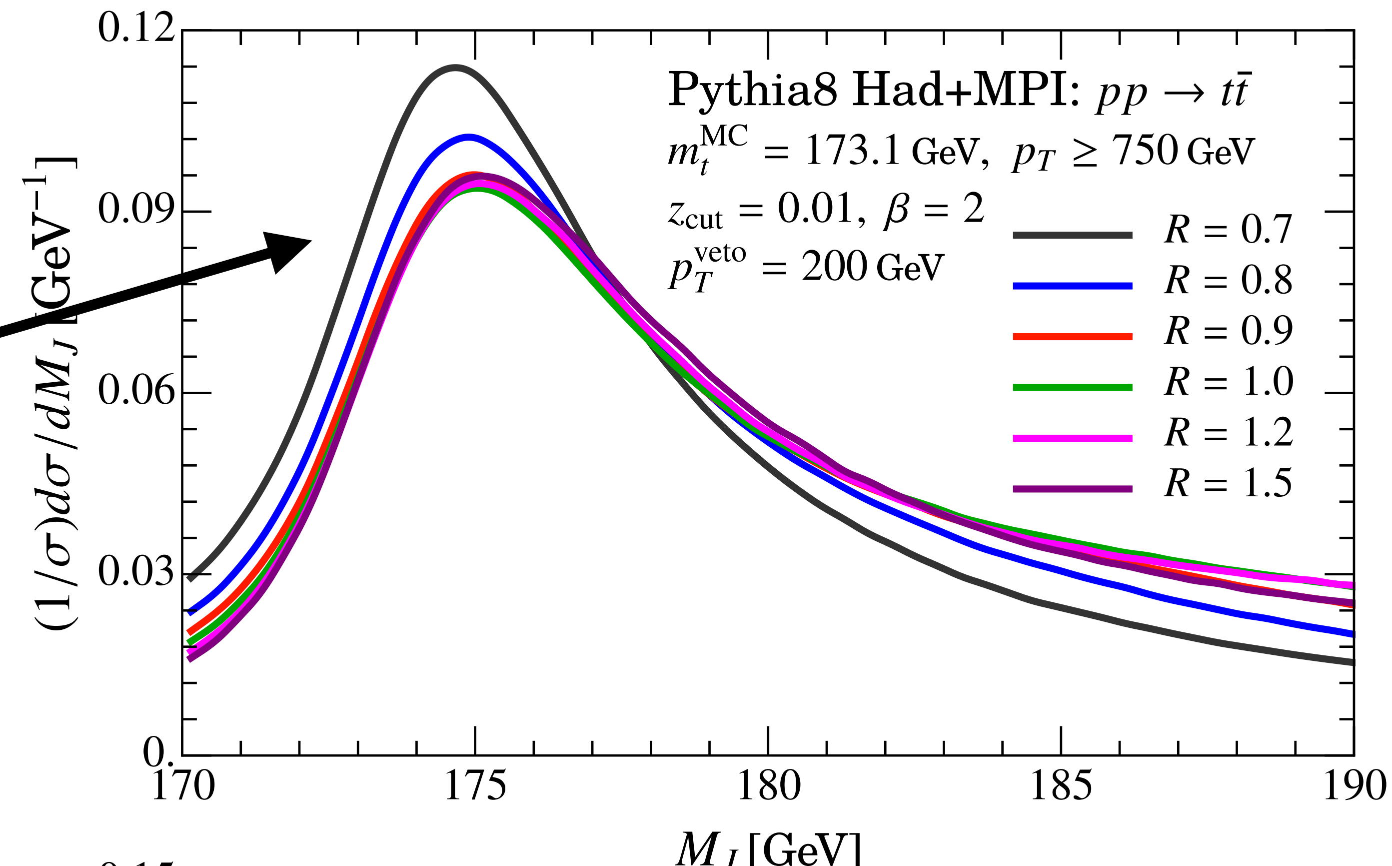


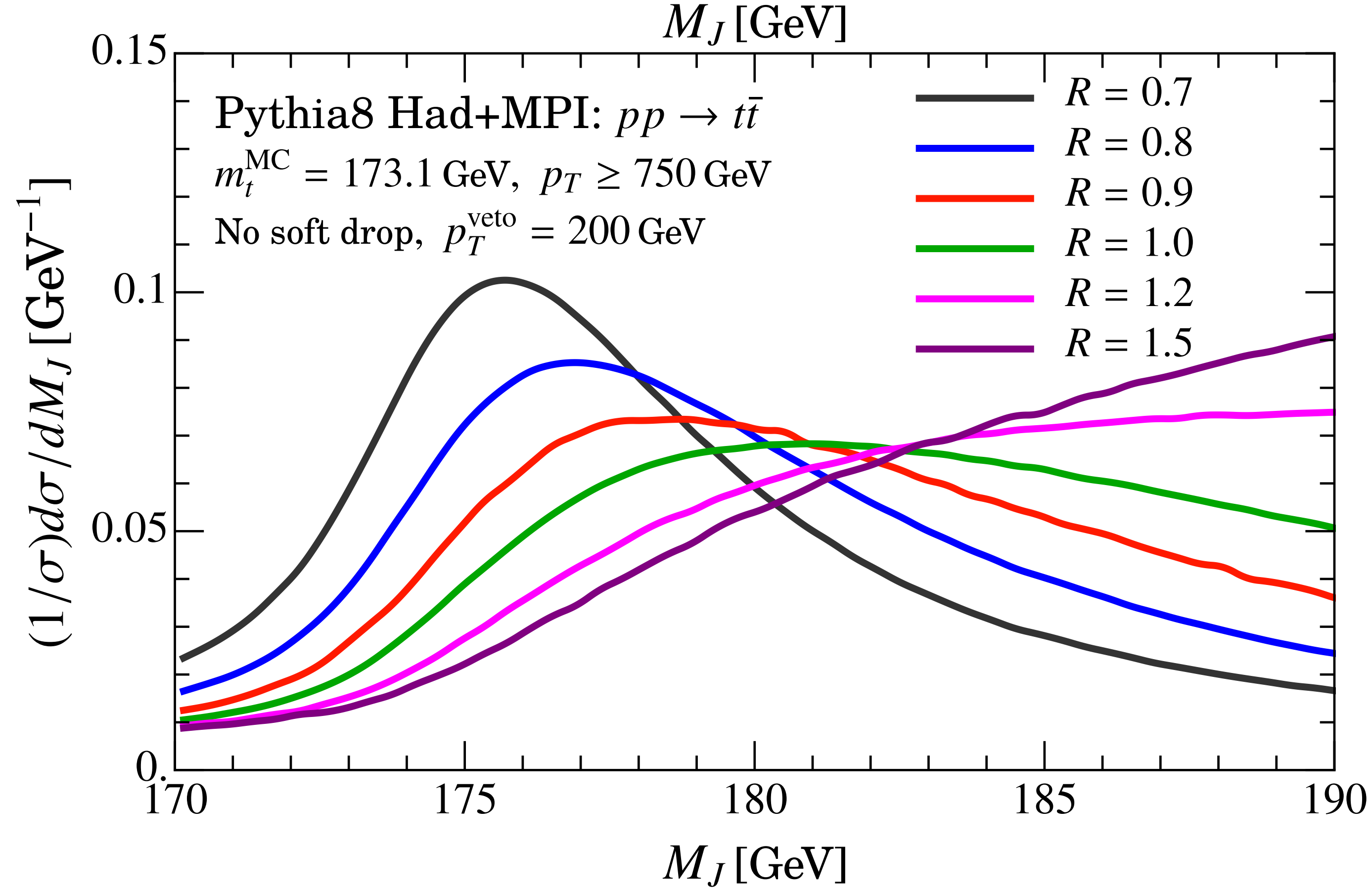
# TESTING EFFECTIVENESS OF LIGHT GROOMING

**Predict: Independent of Jet Radius** ✓



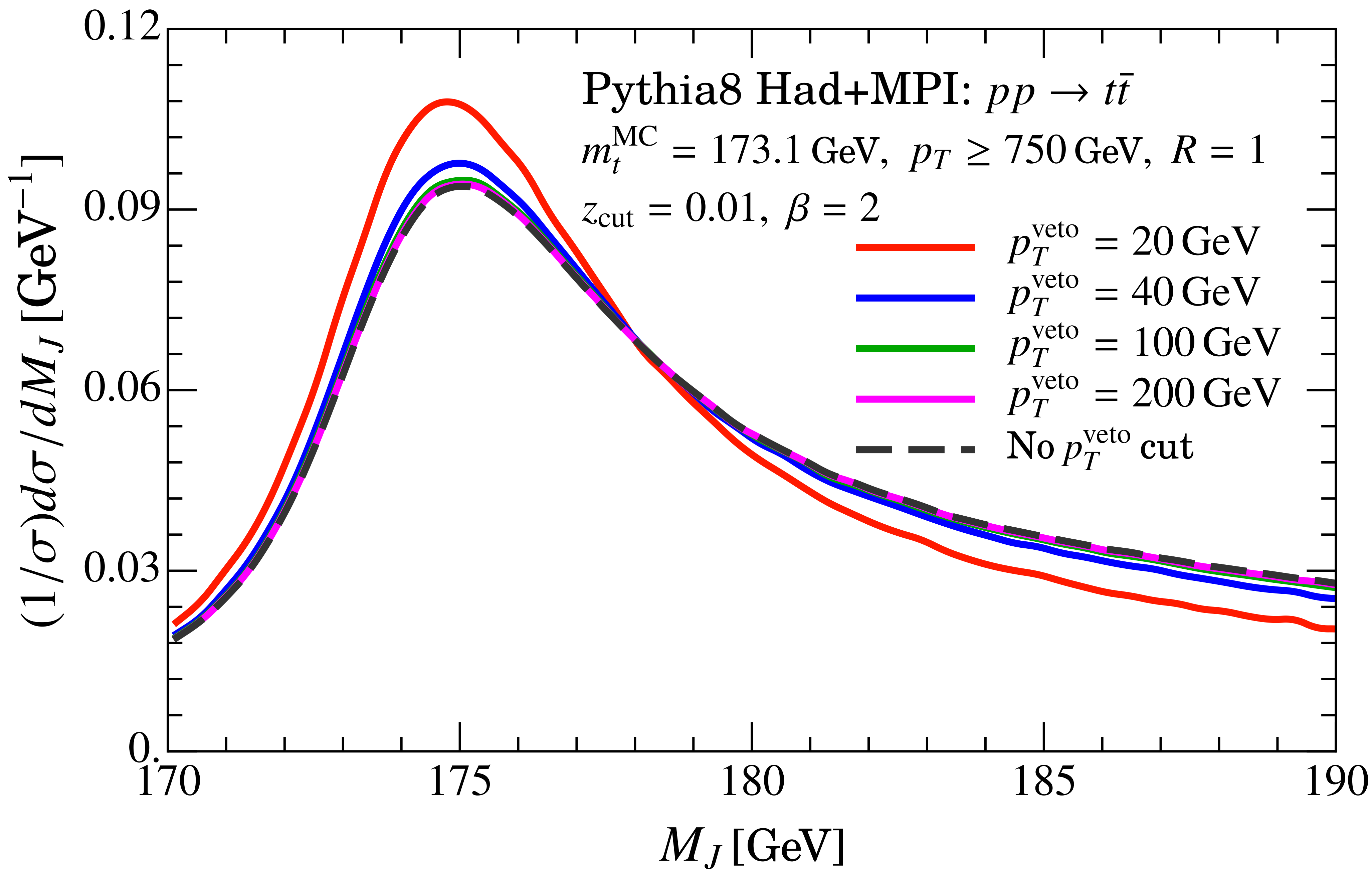

- **Without Soft Drop (huge):**



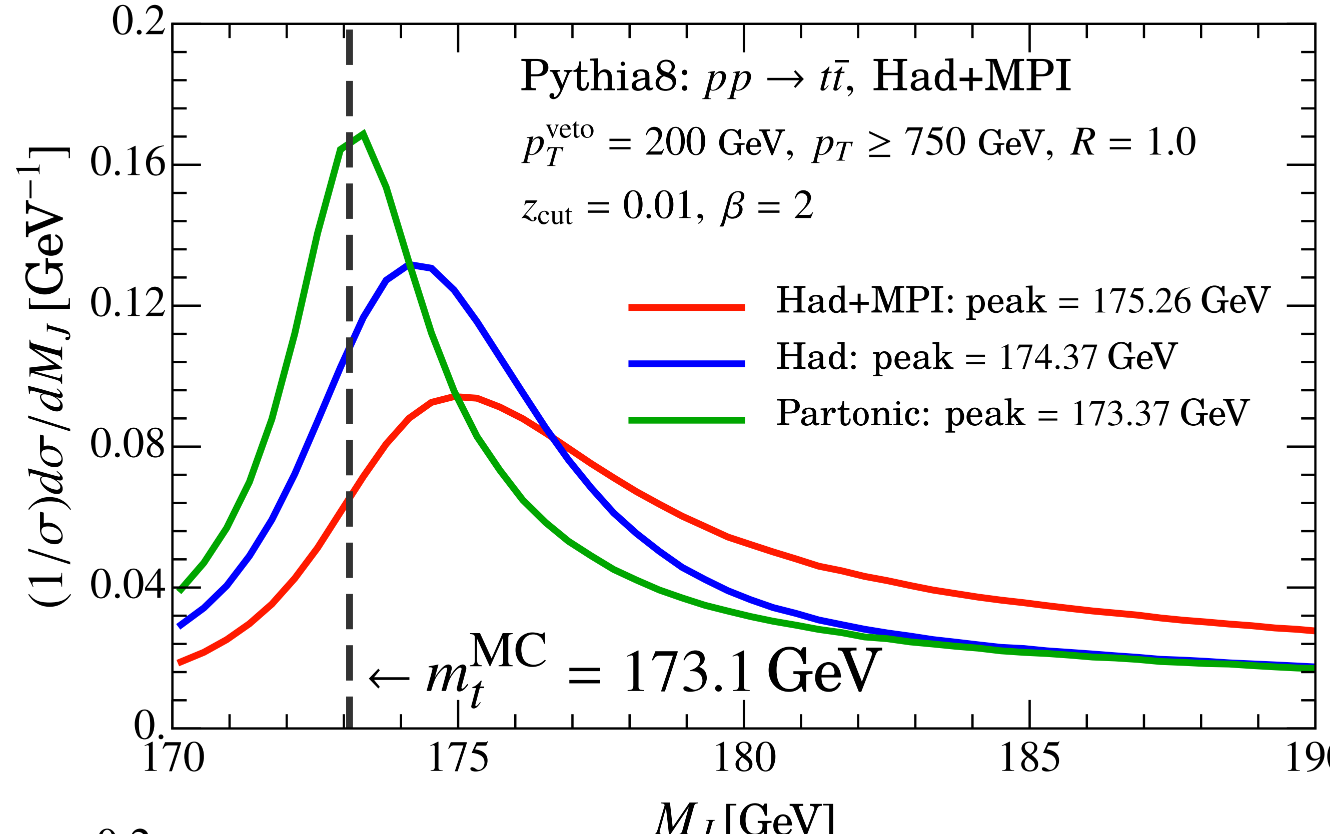
# TESTING EFFECTIVENESS OF LIGHT GROOMING

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

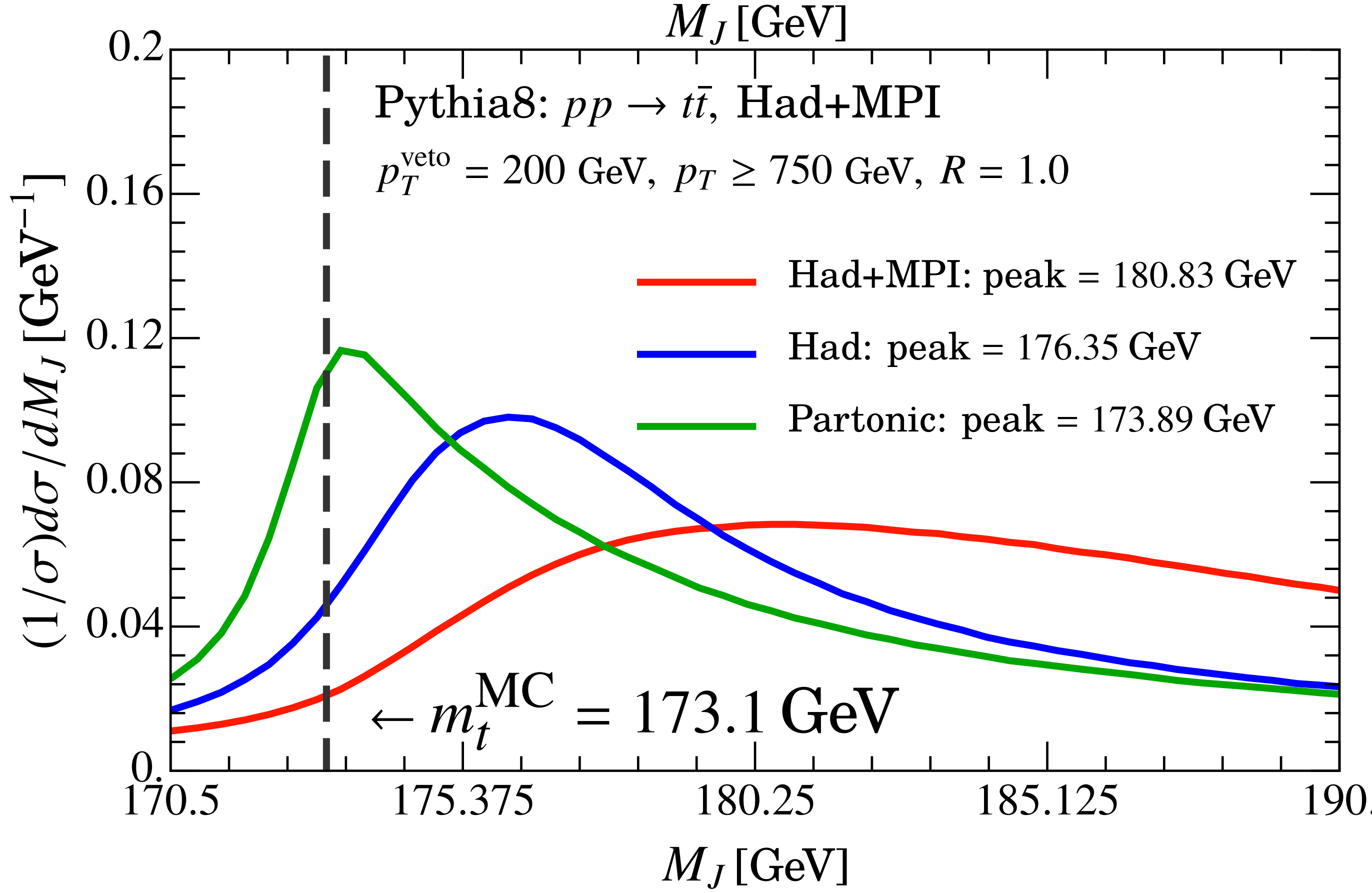


# TESTING EFFECTIVENESS OF LIGHT GROOMING

**Significant improvement with soft drop:**




**Without soft drop:**

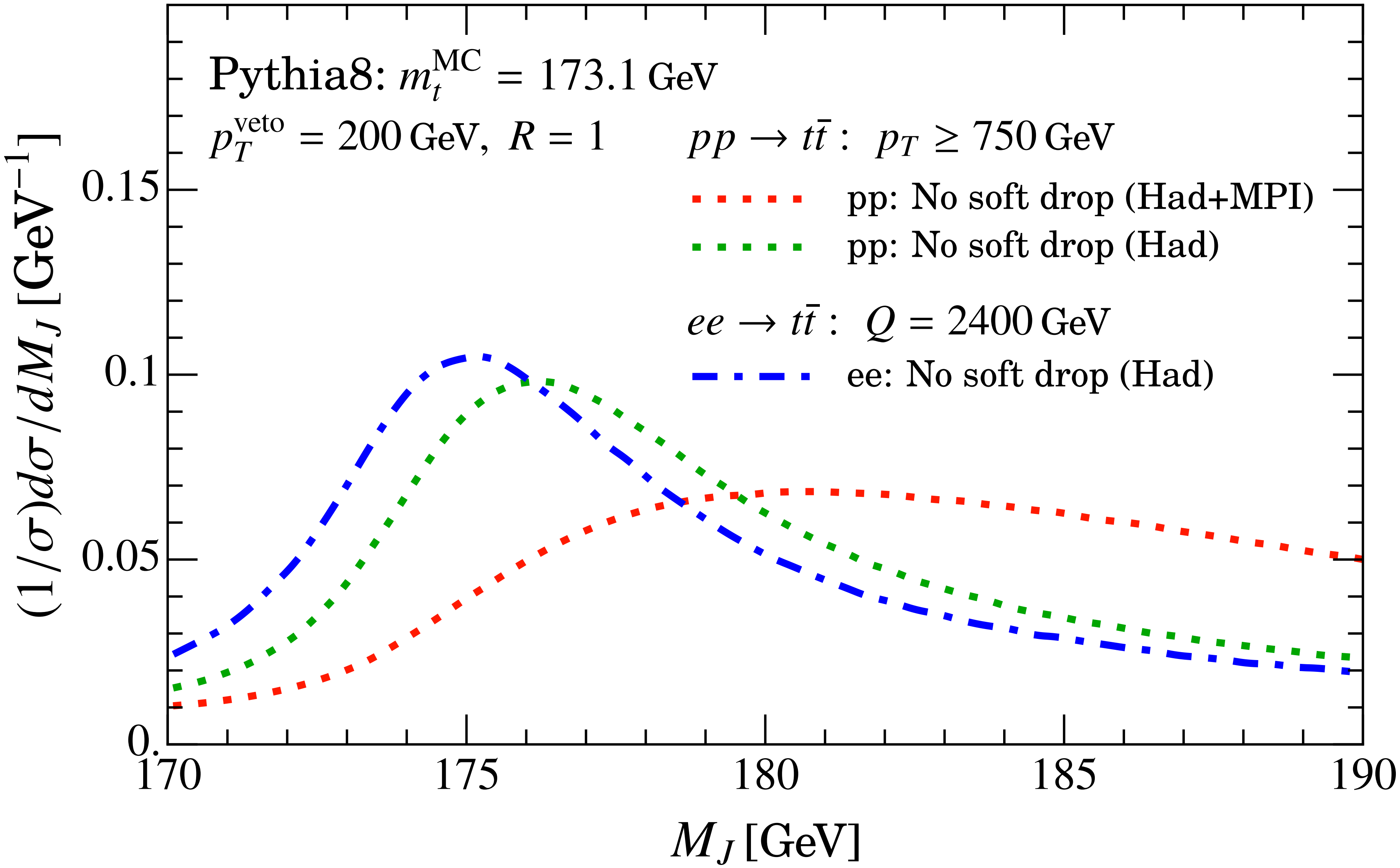


# TESTING EFFECTIVENESS OF LIGHT GROOMING

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

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

**Without Soft Drop (differ):**



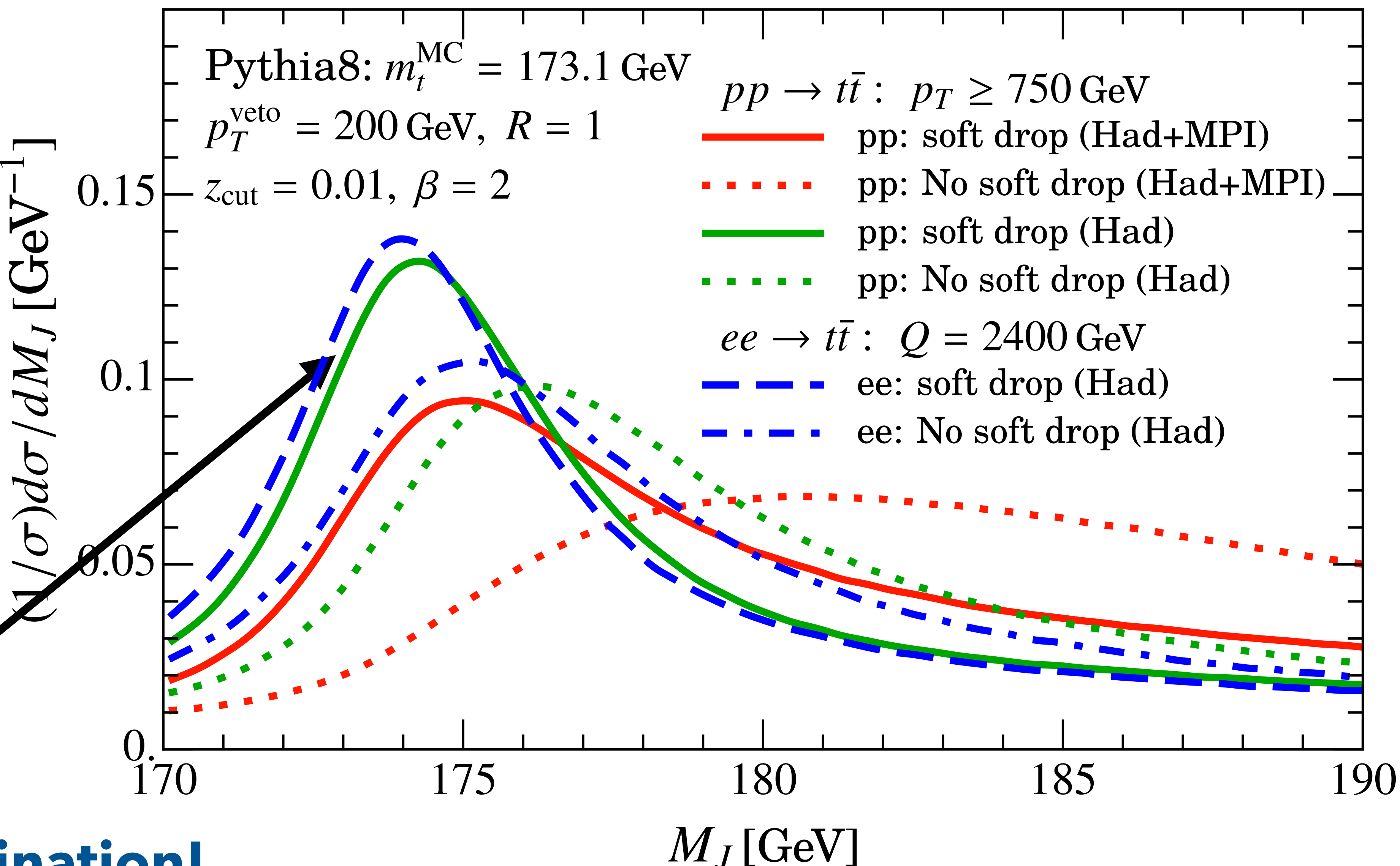
# TESTING EFFECTIVENESS OF LIGHT GROOMING

**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 ):**



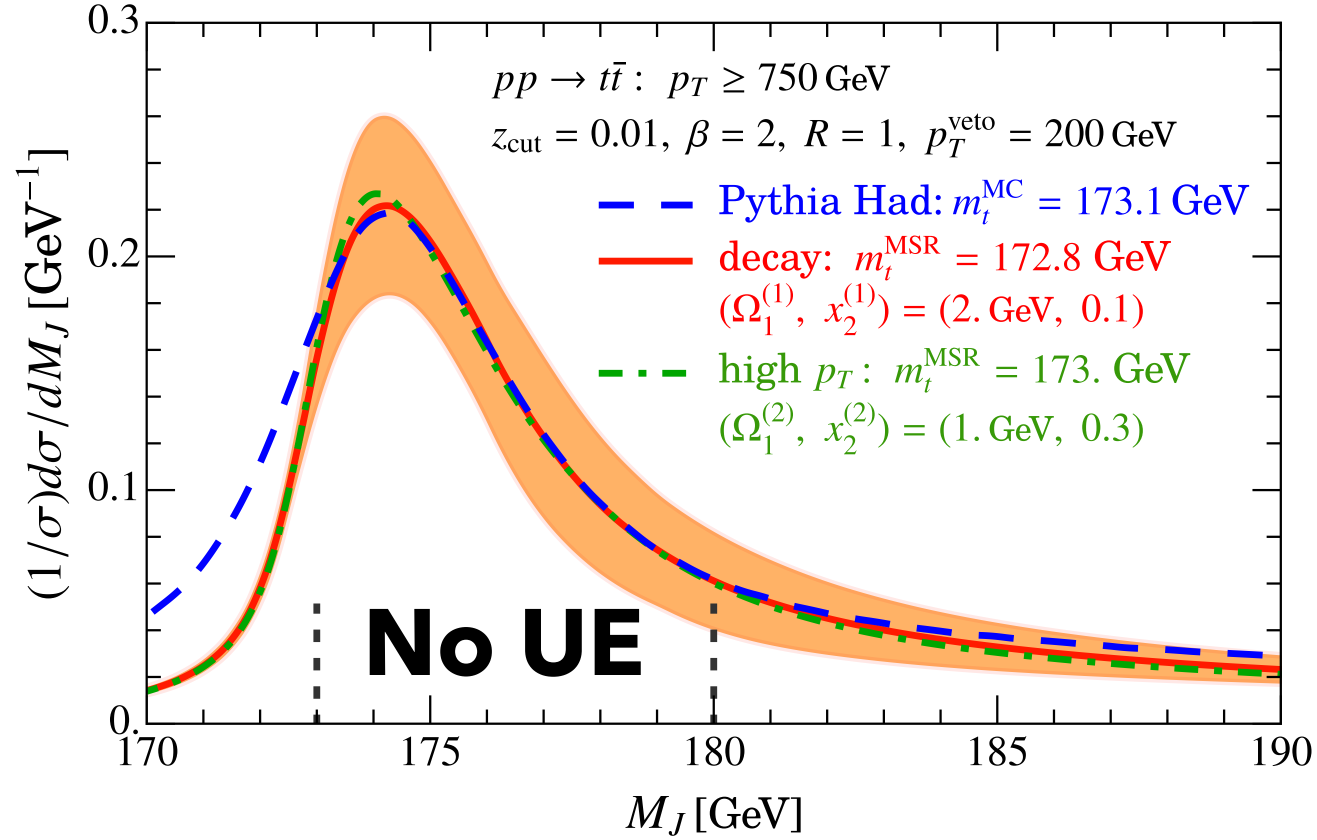

**Much Smaller Contamination!**

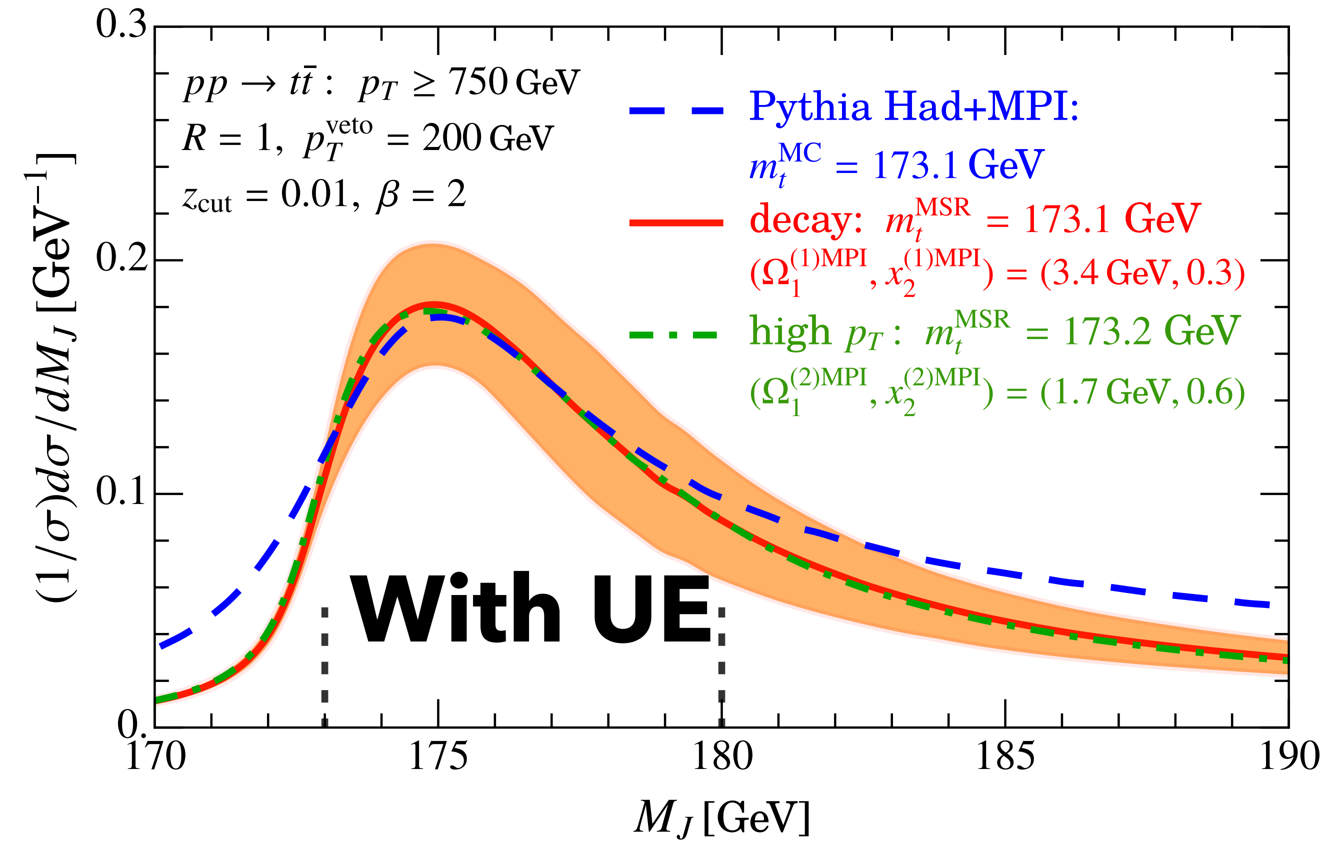
# TESTING ROBUSTNESS OF THE THEORY

# TESTING ROBUSTNESS OF THE THEORY

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

- **Expect a dominant change in $\Omega_1$: Nonperturbative corrections can model UE.**
- **Expect $m_t$ to remain the same: Nonperturbative corrections well understood and do NOT mix with the perturbative components.**

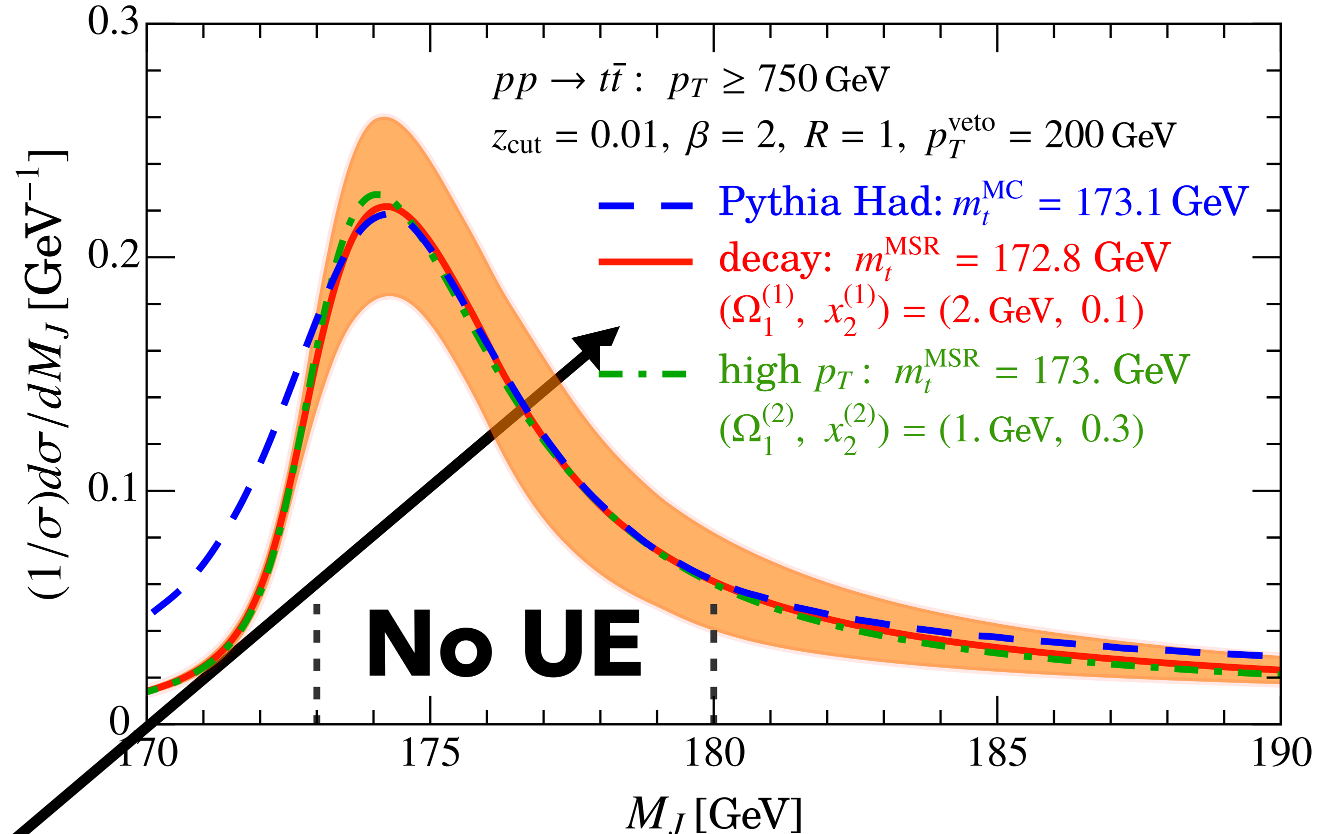


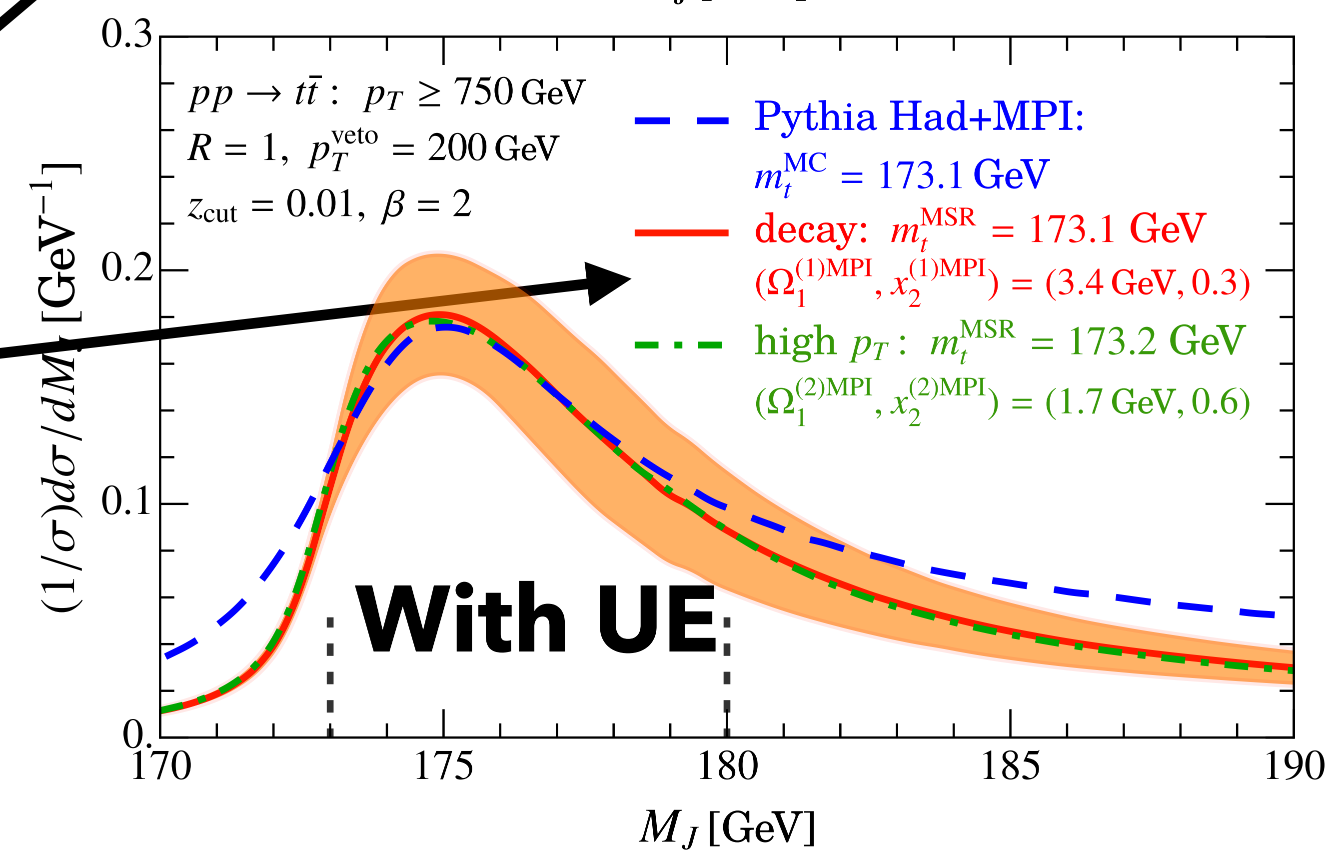



# TESTING ROBUSTNESS OF THE THEORY

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

- **Expect a dominant change in $\Omega_1$: 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**



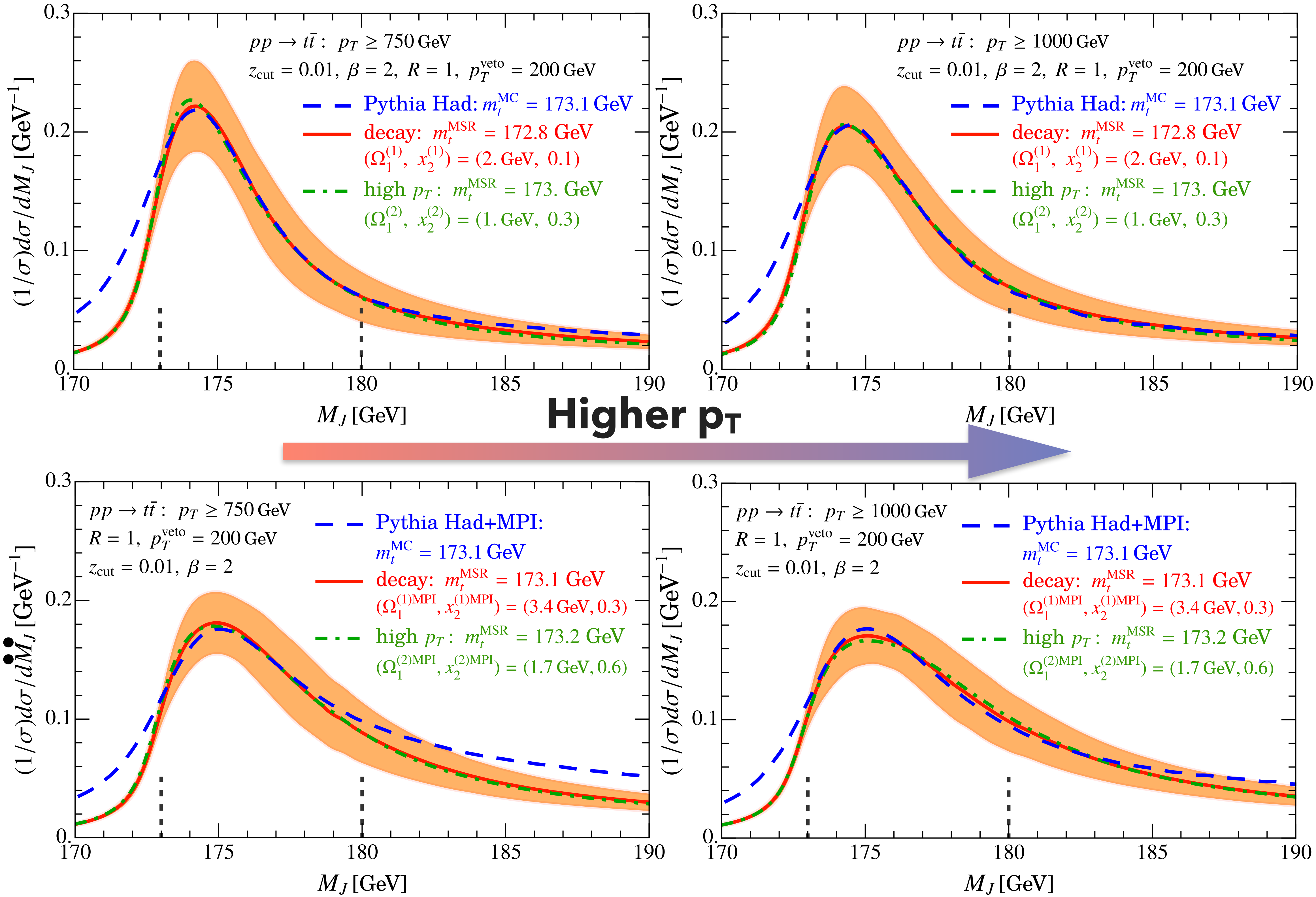



# TESTING ROBUSTNESS OF THE THEORY

## 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 : $m_t^{\mathrm{MSR}} = 172.8\,\mathrm{GeV}$, $\Omega_1^{(1)} = 2.0\,\mathrm{GeV}$, $x_2^{(1)} = 0.1$

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

**With UE:**

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

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

# 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:**

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

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

**With UE:**

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

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

- **(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**

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

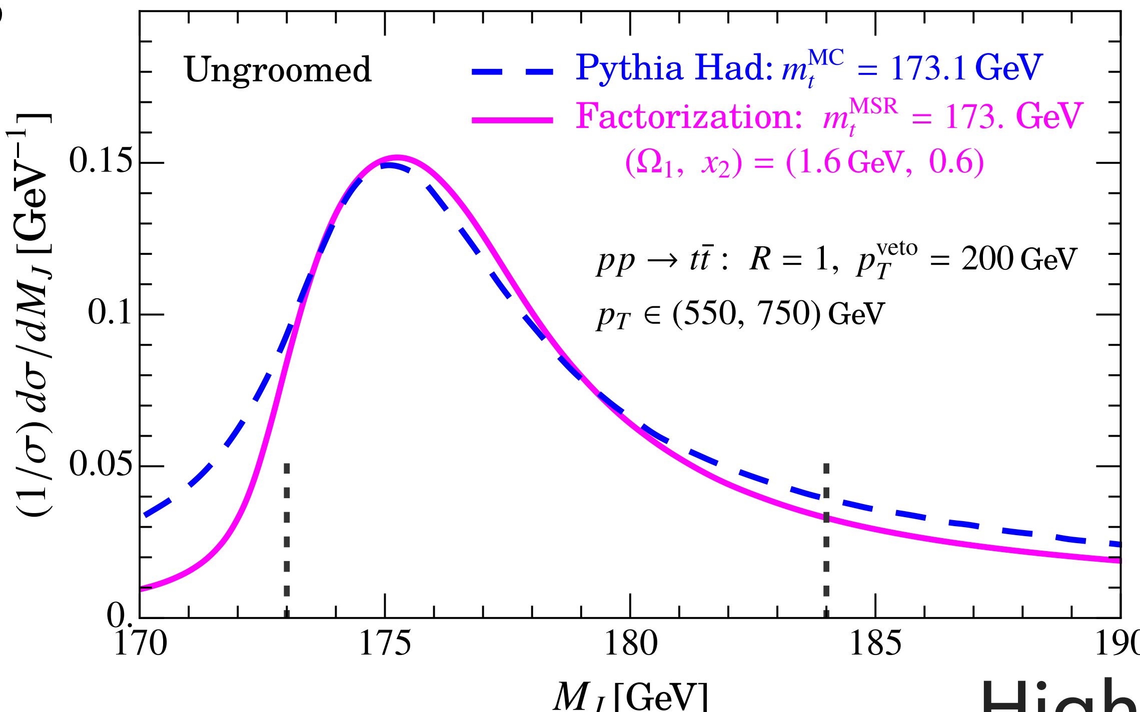
$$m_t^{\text{MSR}}(1\,\text{GeV}) - m_t^{\text{MSR}}(5\,\text{GeV}) = 0.53\,\text{GeV}$$

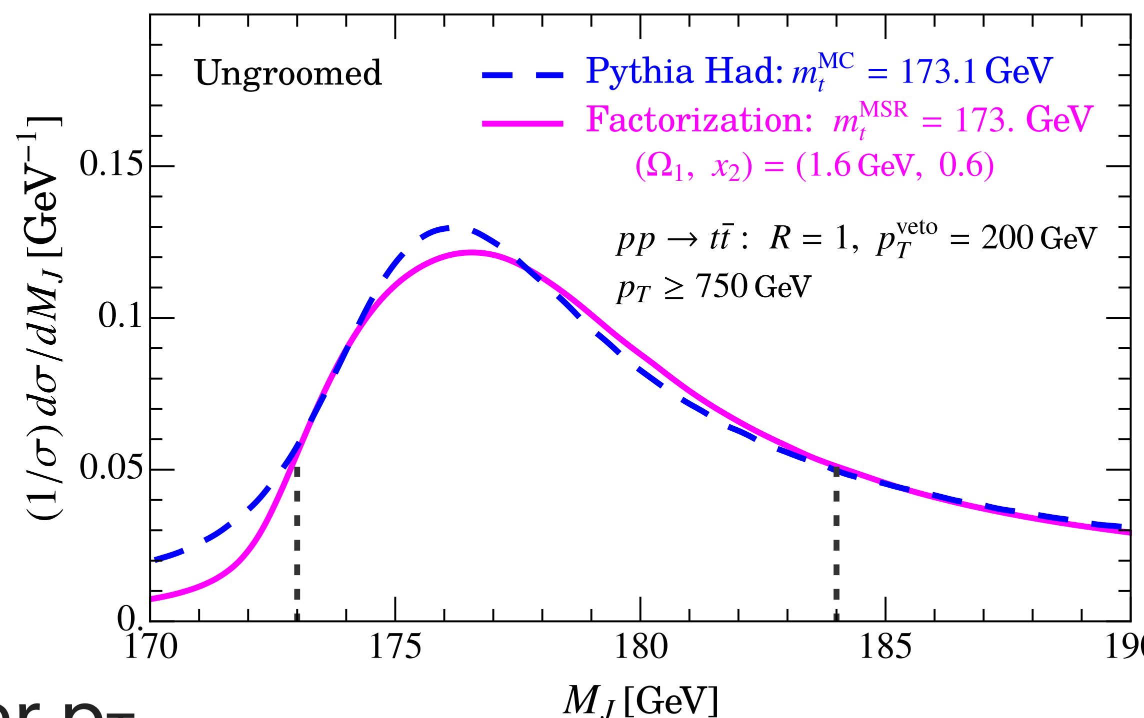
# TESTING ROBUSTNESS OF THE THEORY

**Fits for ungroomed top jets**

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

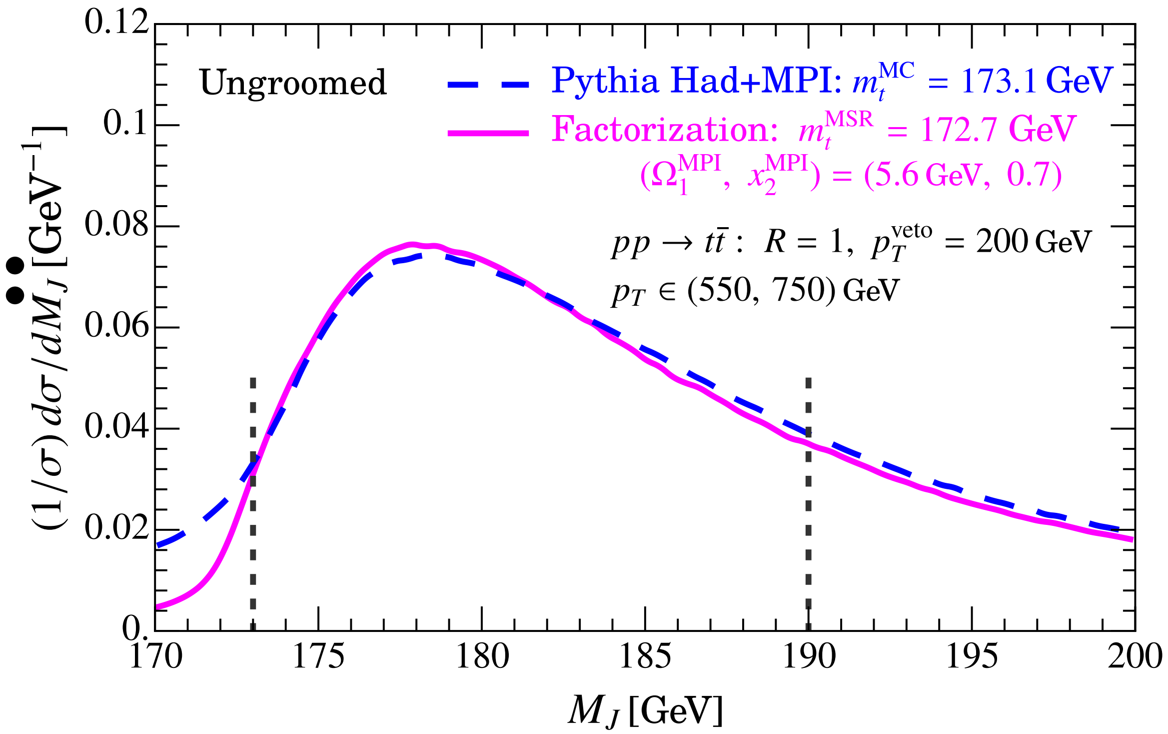
**No UE:**

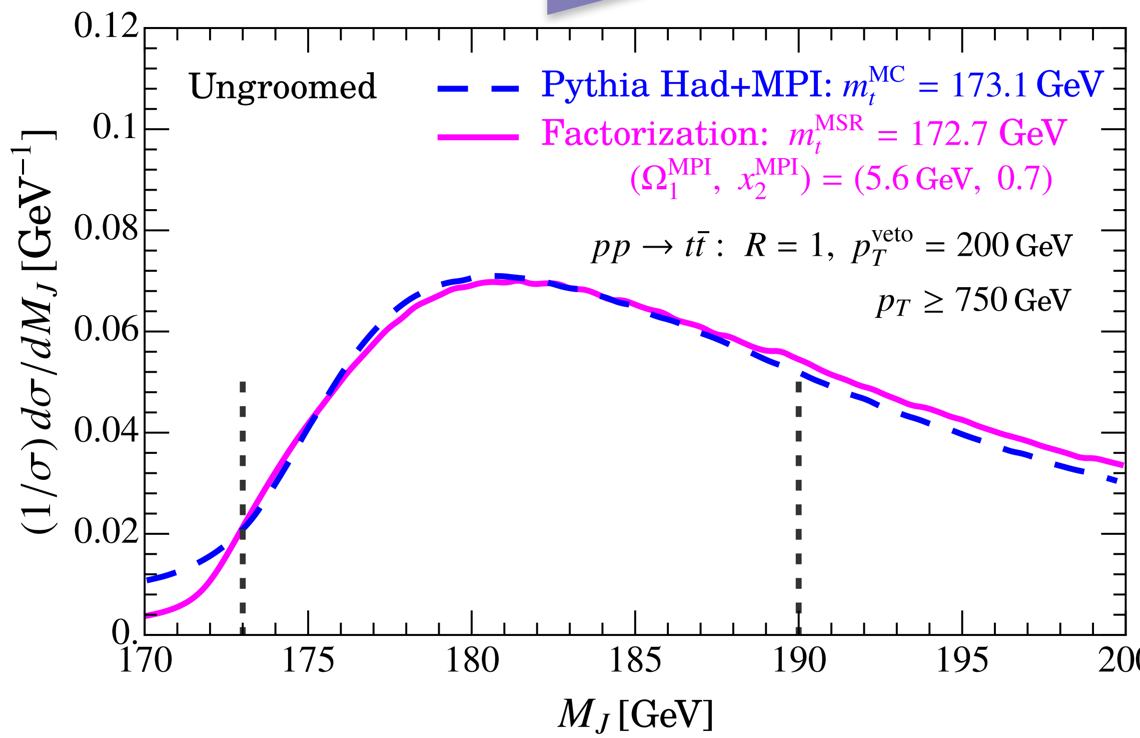



Higher $p_T$

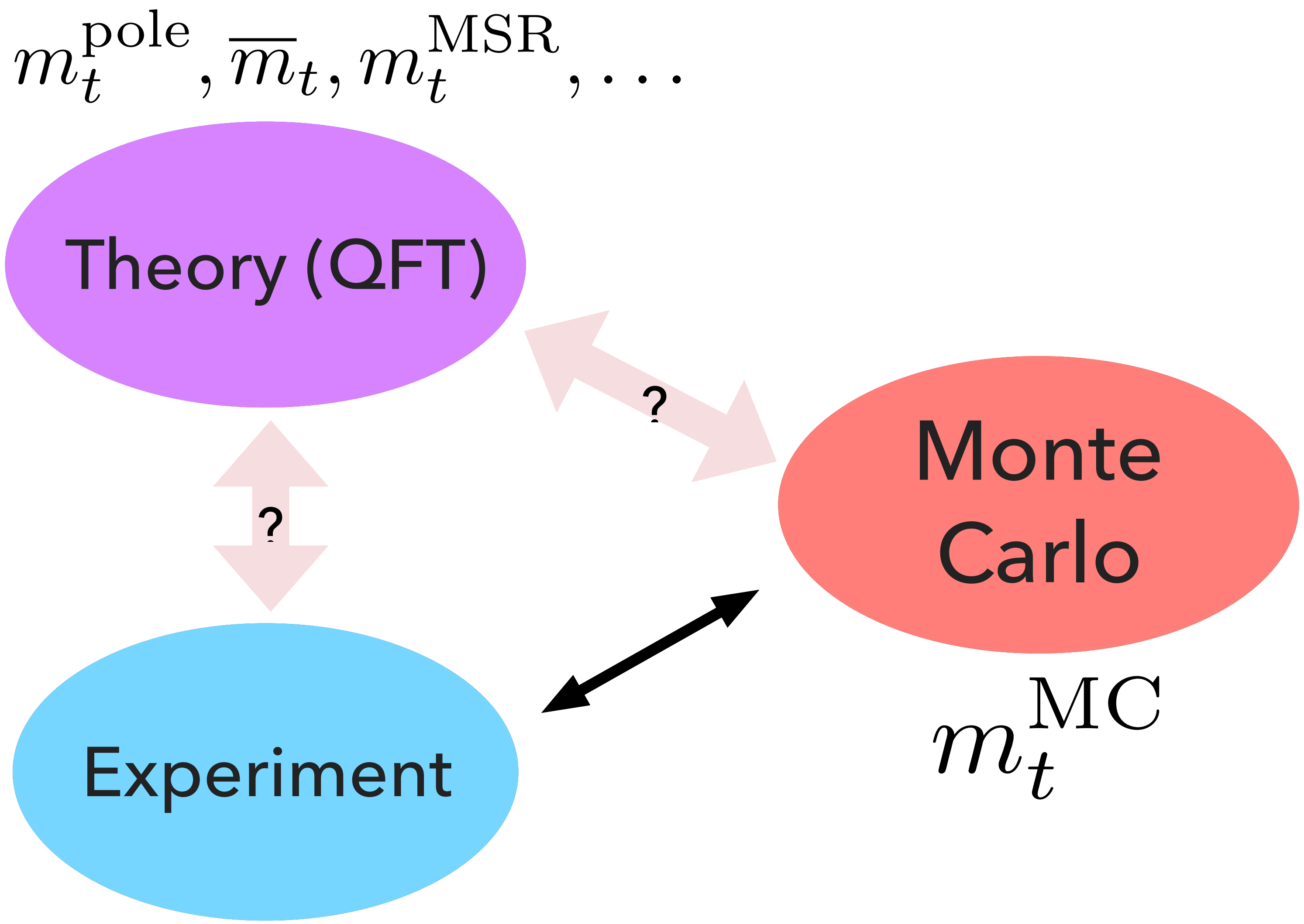
**With UE:**



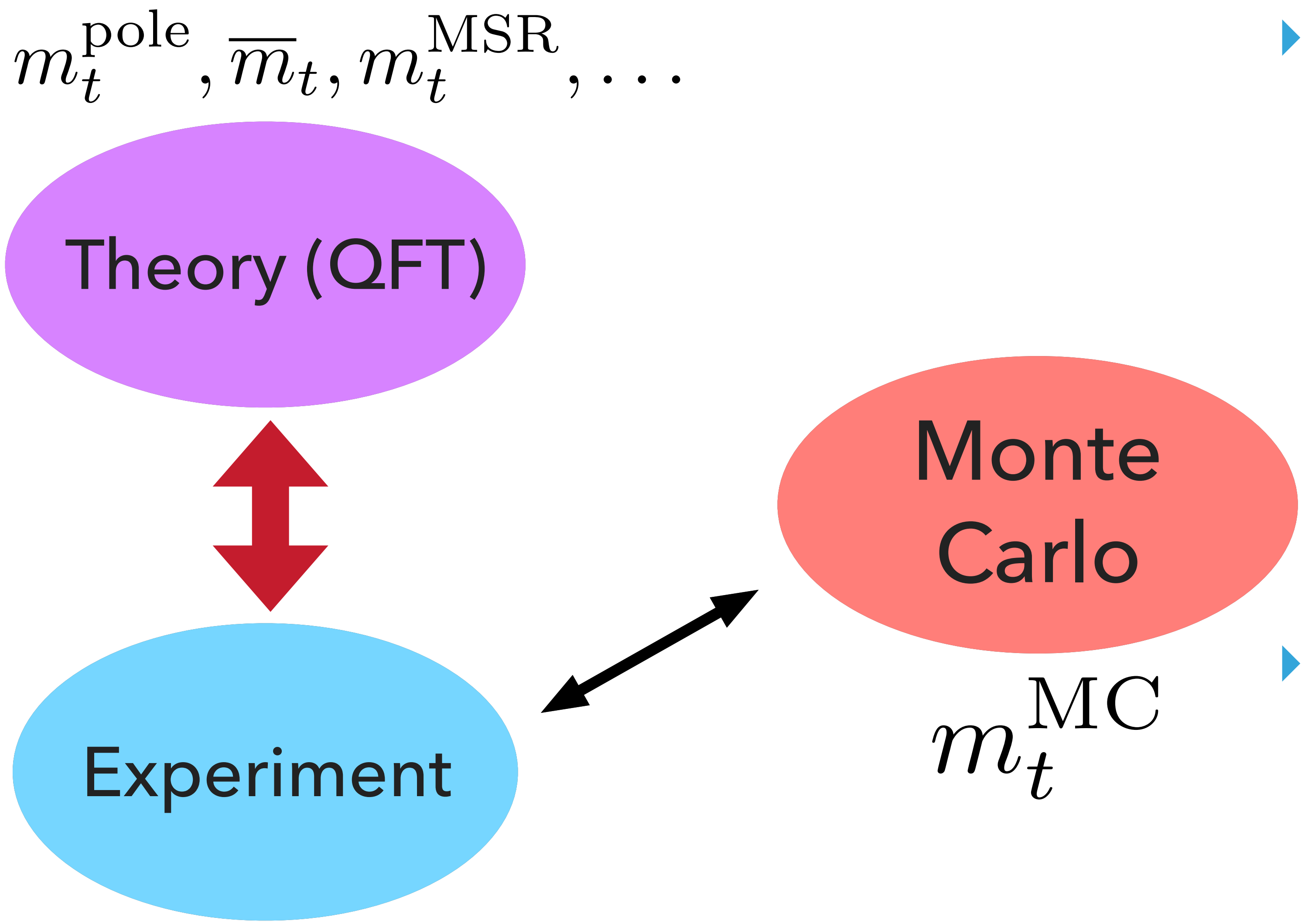
# OUTLOOK

**Bridging the gaps between Theory, Data and MC**



# OUTLOOK

## Bridging the gaps between Theory, Data and MC



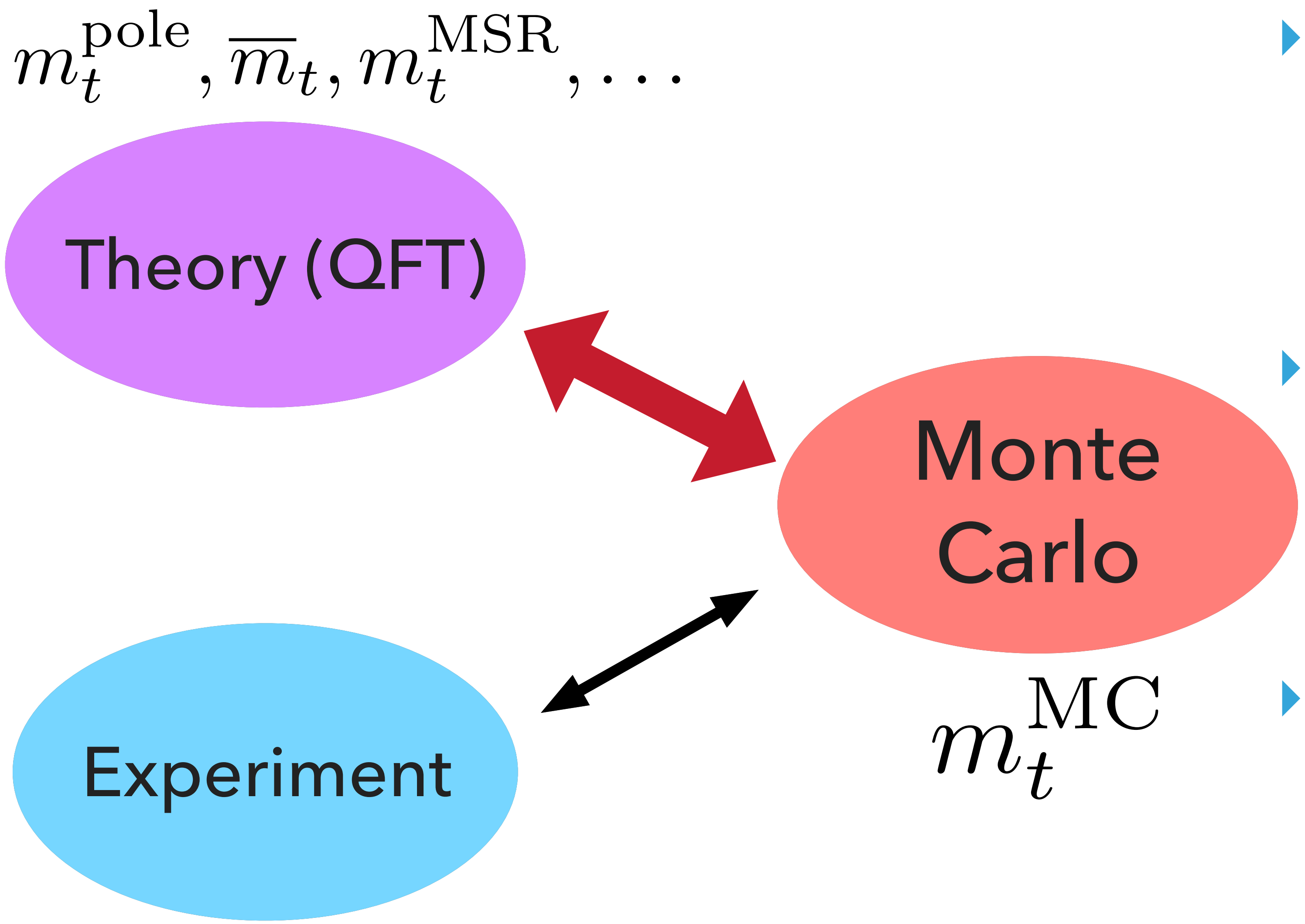

- Major challenge - limited statistics at high $p_T$ required by light grooming.
  - Ungroomed factorization can be used to analyze lower $p_T$ top jets.
- Light grooming effective in reducing the UE - pile up? If pile up behaves like soft radiation:

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

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

# OUTLOOK

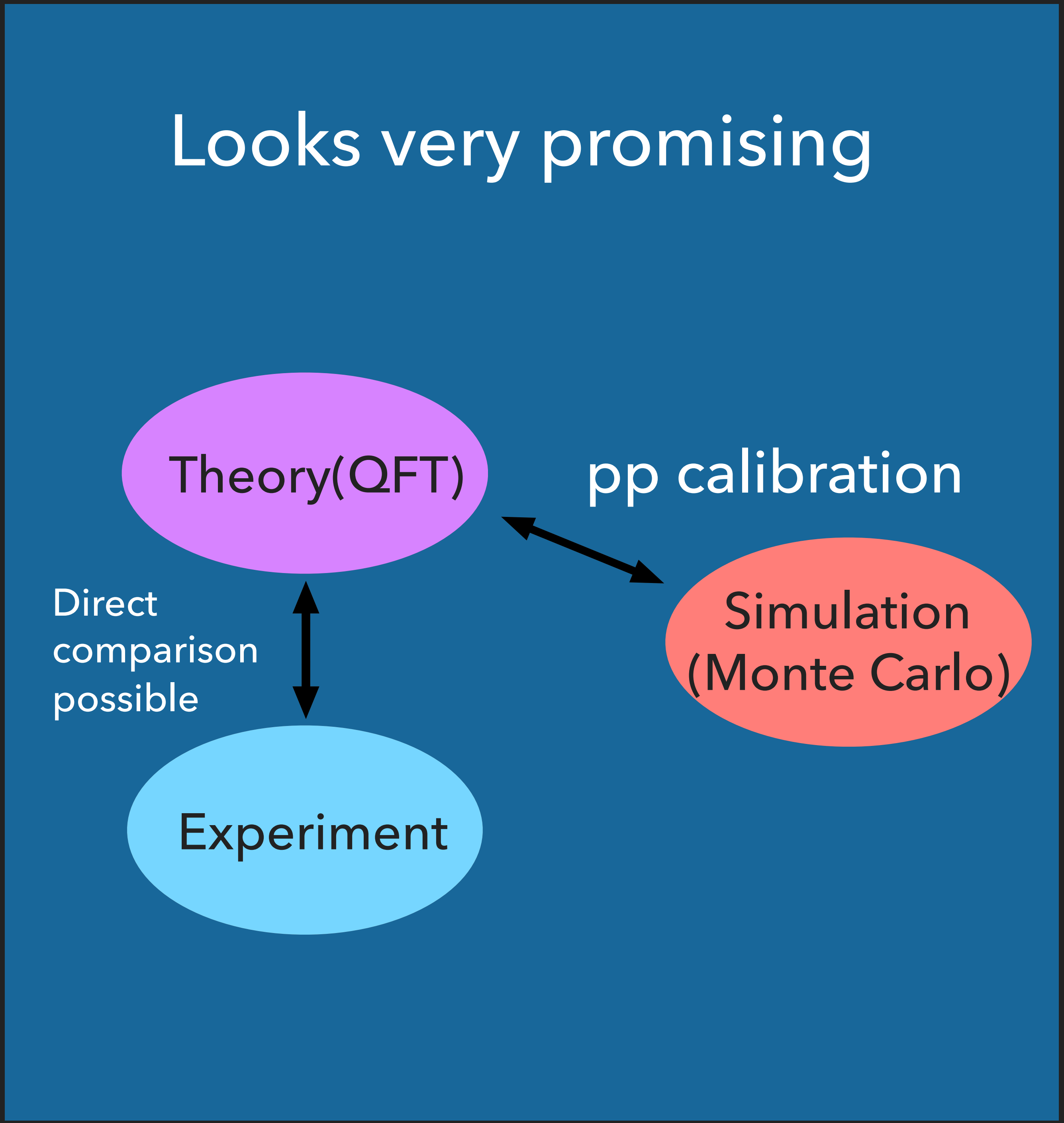
## Bridging the gaps between Theory, Data and MC




- 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 $\beta$.
- 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.

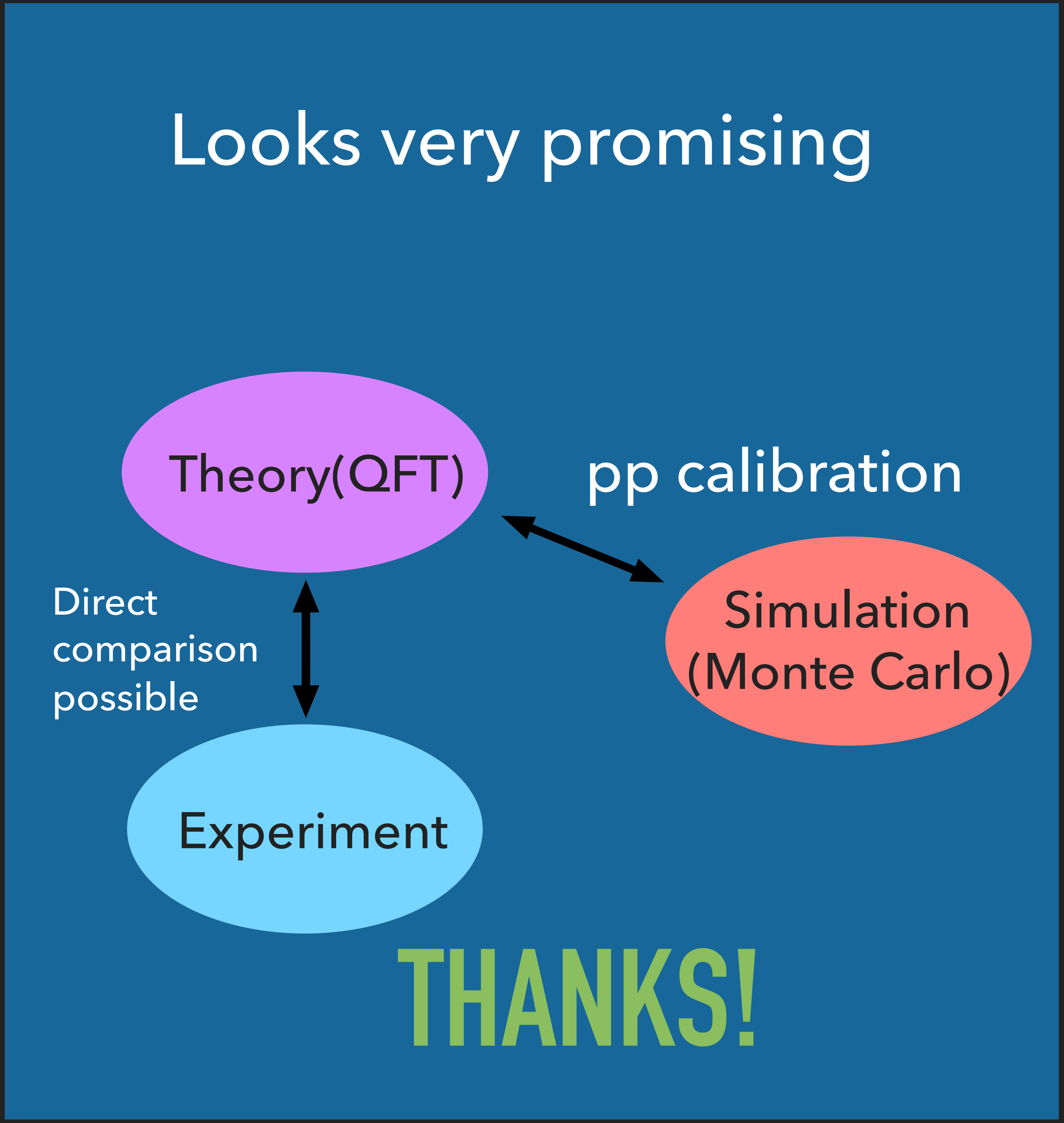
# CONCLUSION

- 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 $\Omega_1$, and agrees well with Pythia.
  - Pythia UE shifts $\Omega_1$ with small effect on $m_t$



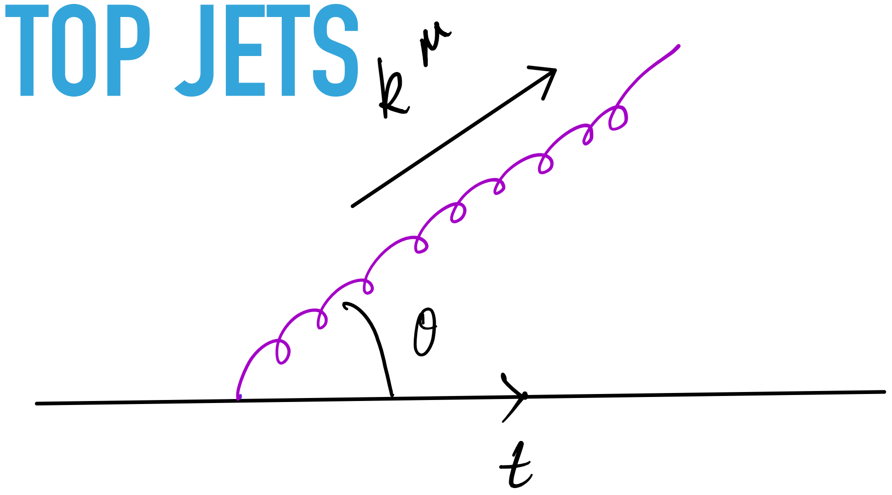
# CONCLUSION

- 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 $\Omega_1$, and agrees well with Pythia.
  - Pythia UE shifts $\Omega_1$ with small effect on $m_t$



# BACKUP SLIDES

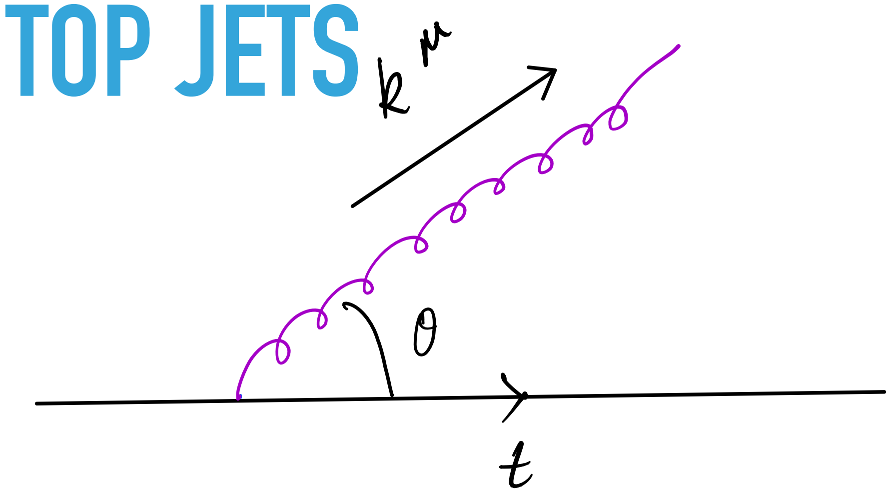
# CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS




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

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

# CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS



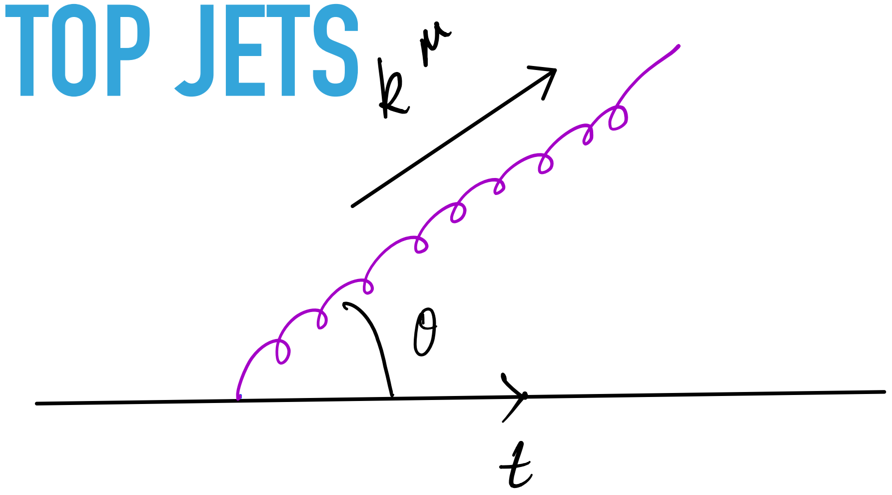

**Radiation off the top quark (either collinear or soft):**

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

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

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

# CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS




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

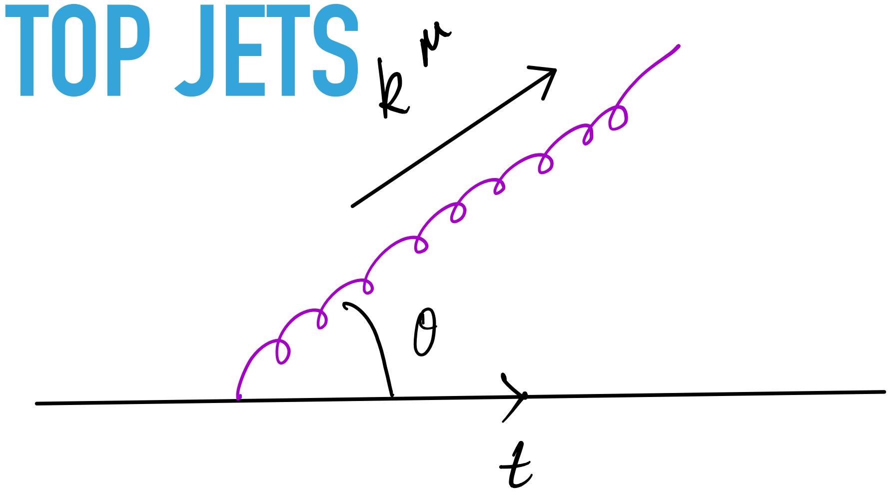
$$k_j^\mu = \left(k^+, k^-, k_\perp\right) = \left(E(1-\cos\theta), E(1+\cos\theta), k_\perp\right)$$

**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:** $z > z_{\mathrm{cut}}\ \theta^\beta$

# CONSTRAINTS FOR SOFT DROP ON BOOSTED TOP JETS




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

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

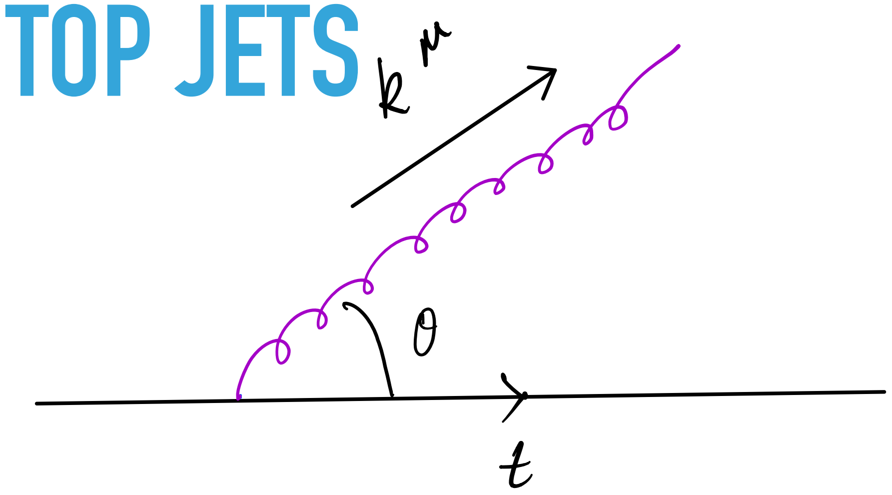
**Peak Region:** $M_{t,\bar{t}}^2 - m^2 \sim m\Gamma \ll m^2$

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

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

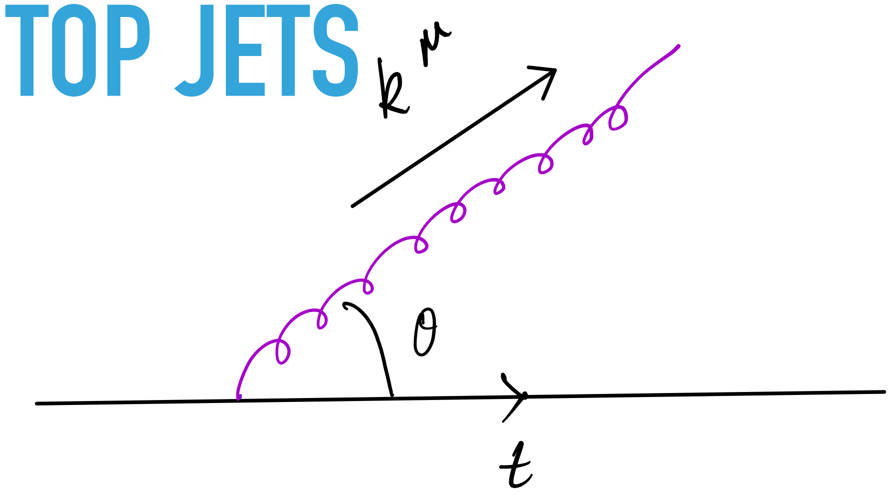
$$z\left[(1-\cos\theta) + \frac{m^2}{Q^2}(1+\cos\theta)\right] \sim \frac{2m\Gamma_t}{Q^2}$$

**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):**

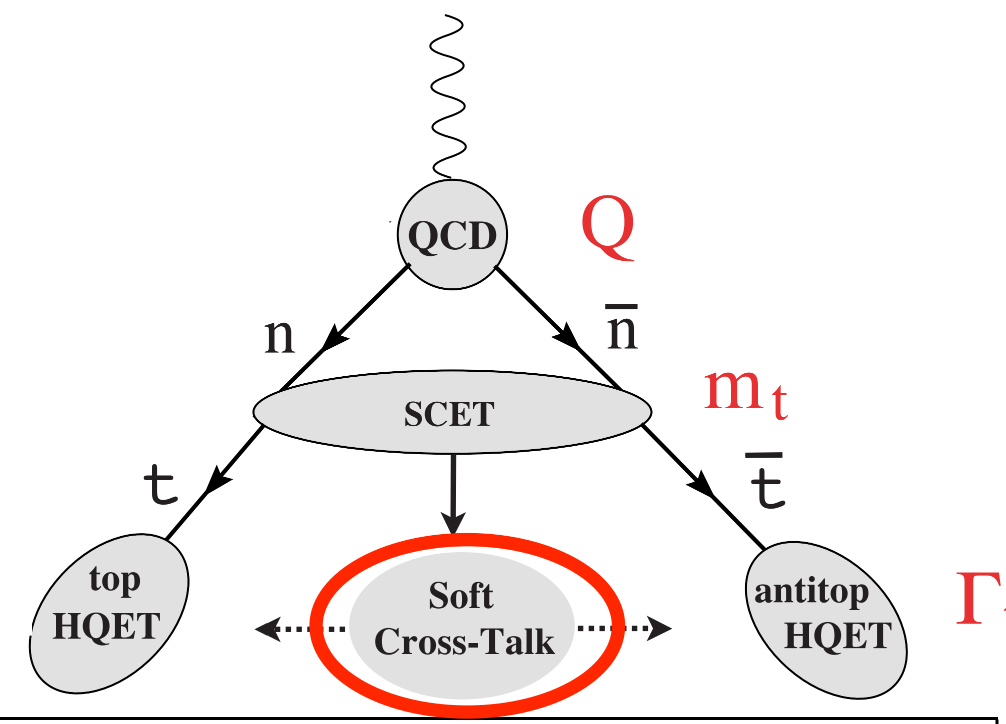
$$k_j^\mu = (k^+, k^-, k_\perp) = \big(E(1-\cos\theta), E(1+\cos\theta), k_\perp\big)$$

**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**



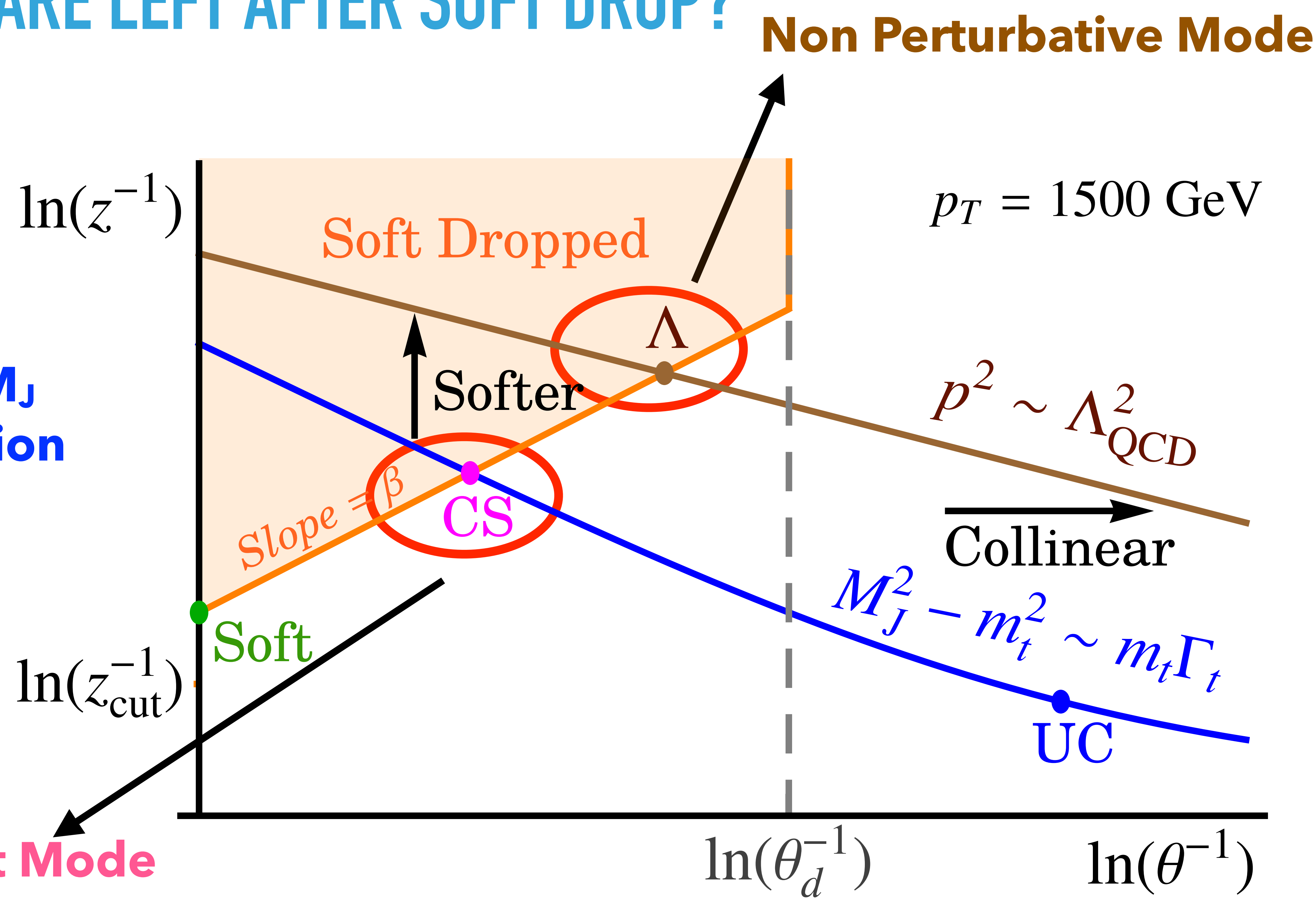

**Keep Ultra-collinear modes**

**Groom away Soft modes**

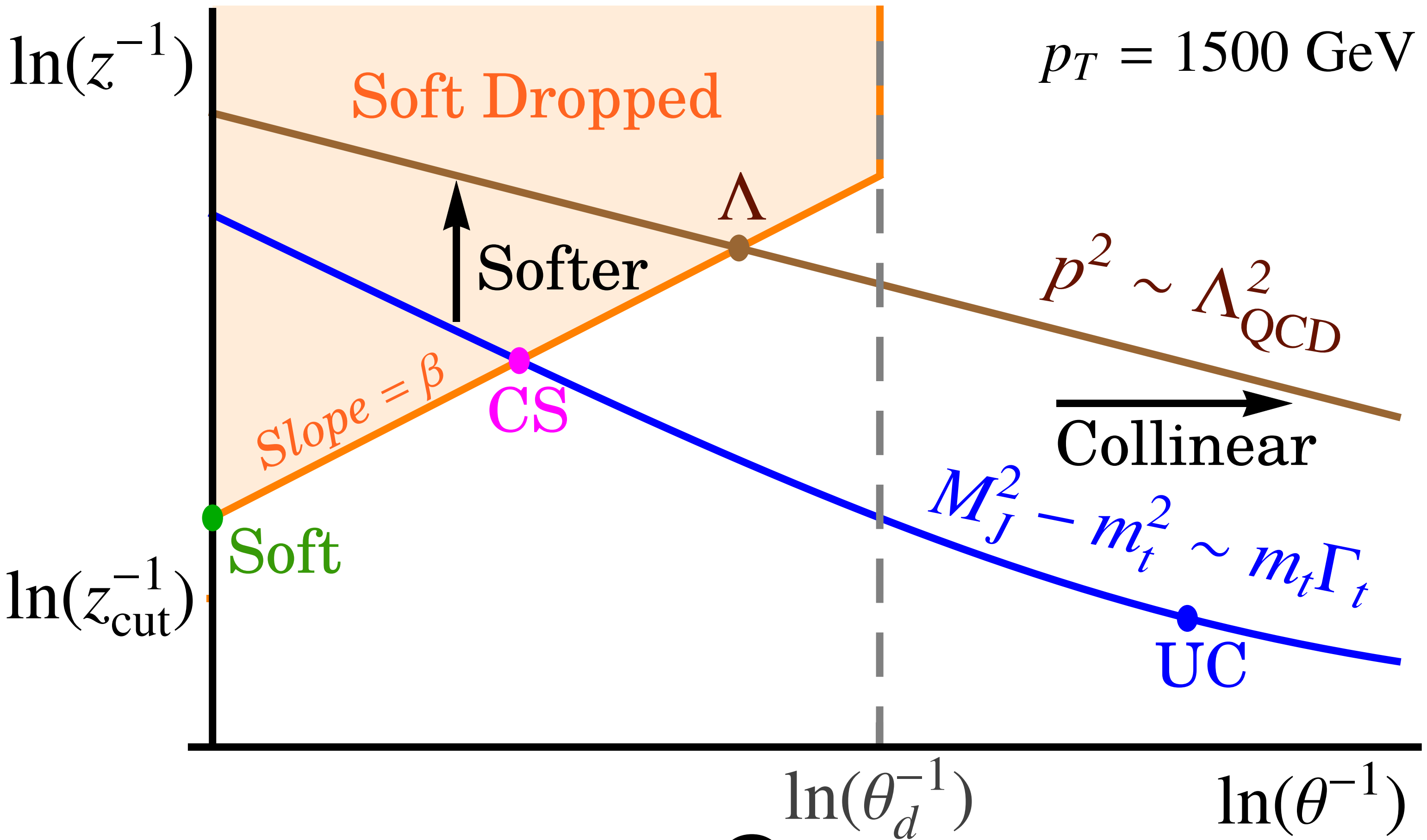
| SCET $[\lambda \sim m/Q \ll 1]$ | | bHQET $[\Gamma/m \ll 1]$ | |
|---|---|---|---|
| $n$-collinear $(\xi_n,\ A_n^\mu)$ | $p_n^\mu \sim Q(\lambda^2, 1, \lambda)$ | $n$-ucollinear $(h_{v_+},\ A_+^\mu)$ | $k^\mu \sim \Gamma(\lambda, \lambda^{-1}, 1)$ |
| $\bar n$-collinear $(\xi_{\bar n},\ A_{\bar n}^\mu)$ | $p_{\bar n}^\mu \sim Q(1, \lambda^2, \lambda)$ | $\bar n$-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?

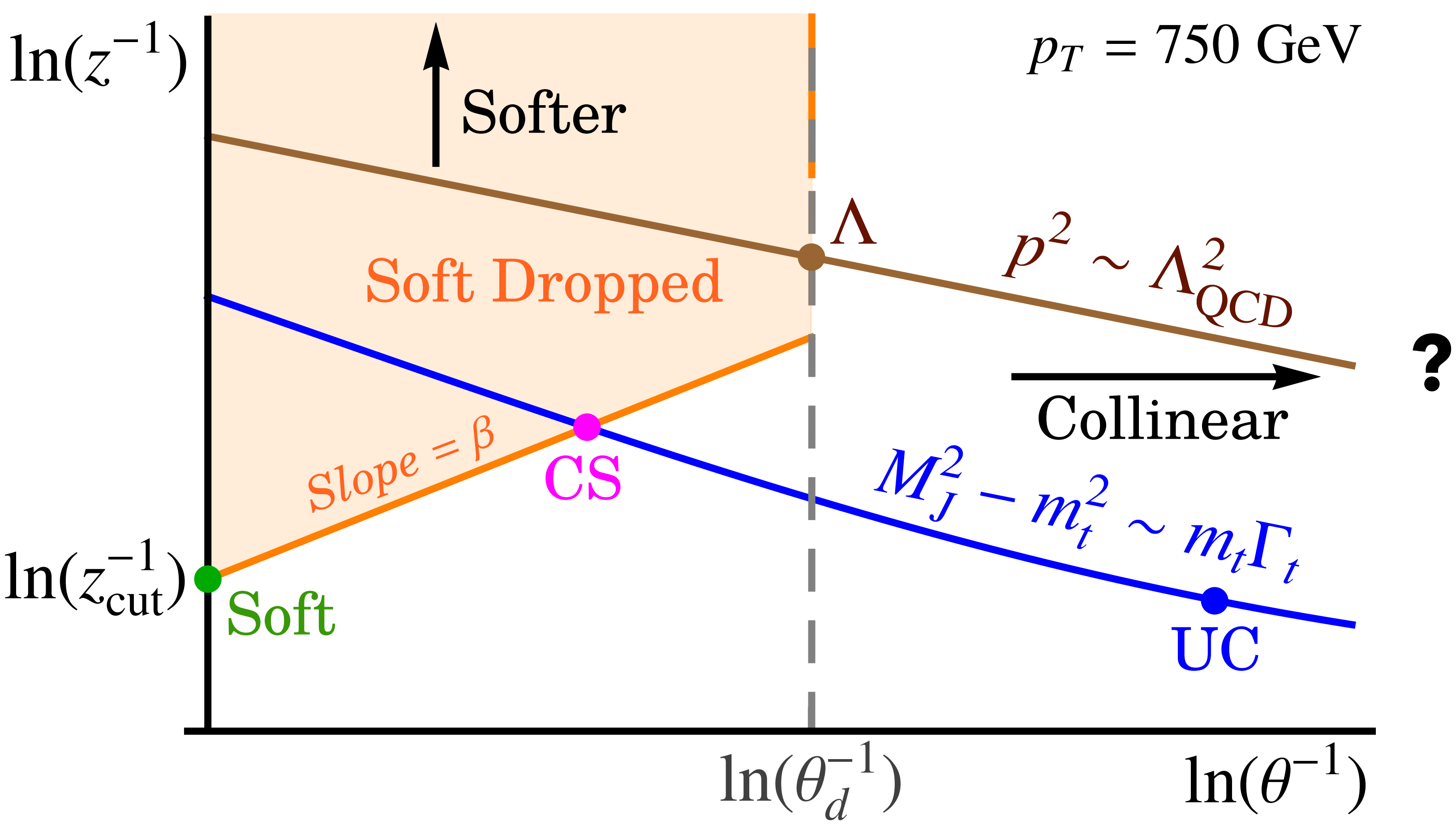
**blue curve: measurement $M_J$ in the peak region**




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




**Or**



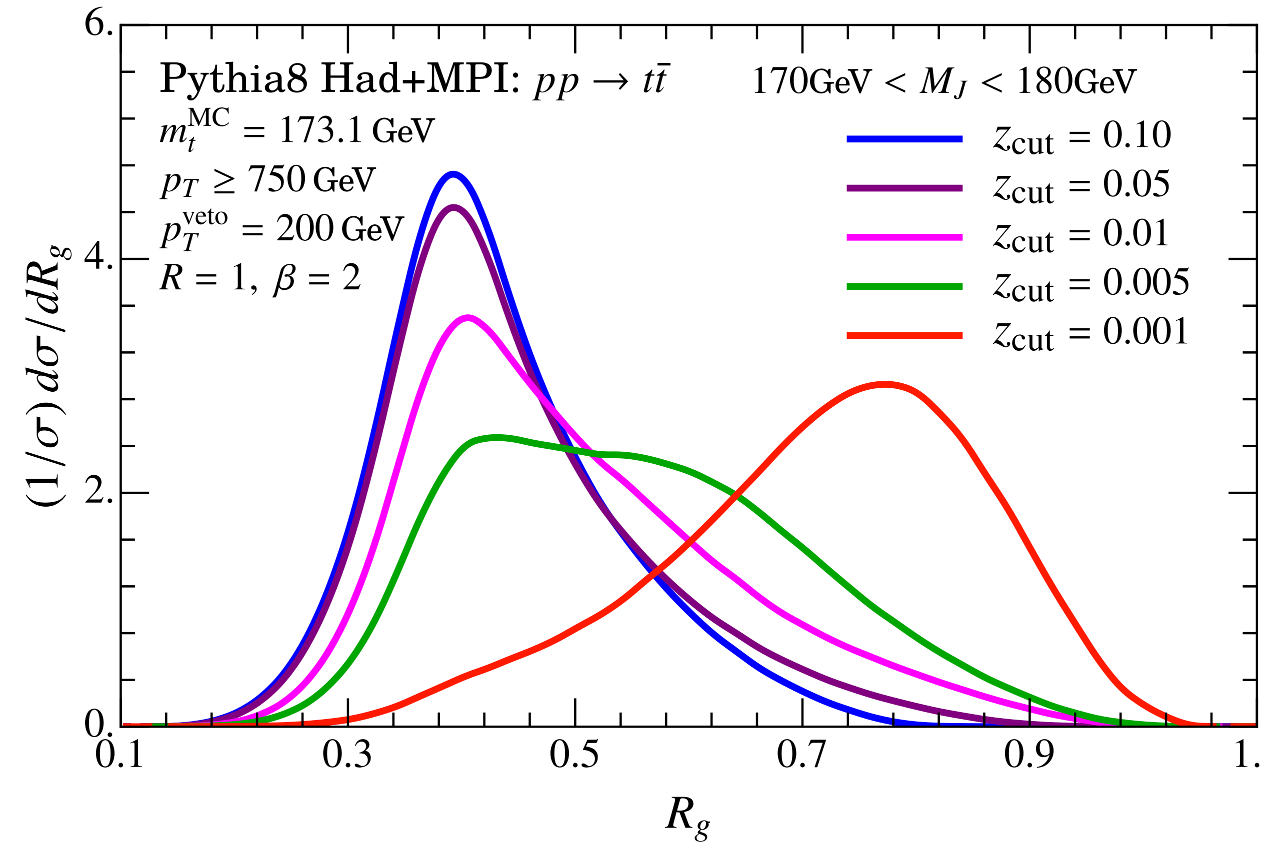

WHEN DOES SOFT DROP STOP?

WHAT IS THE SIZE OF NONPERTURBATIVE CORRECTIONS?

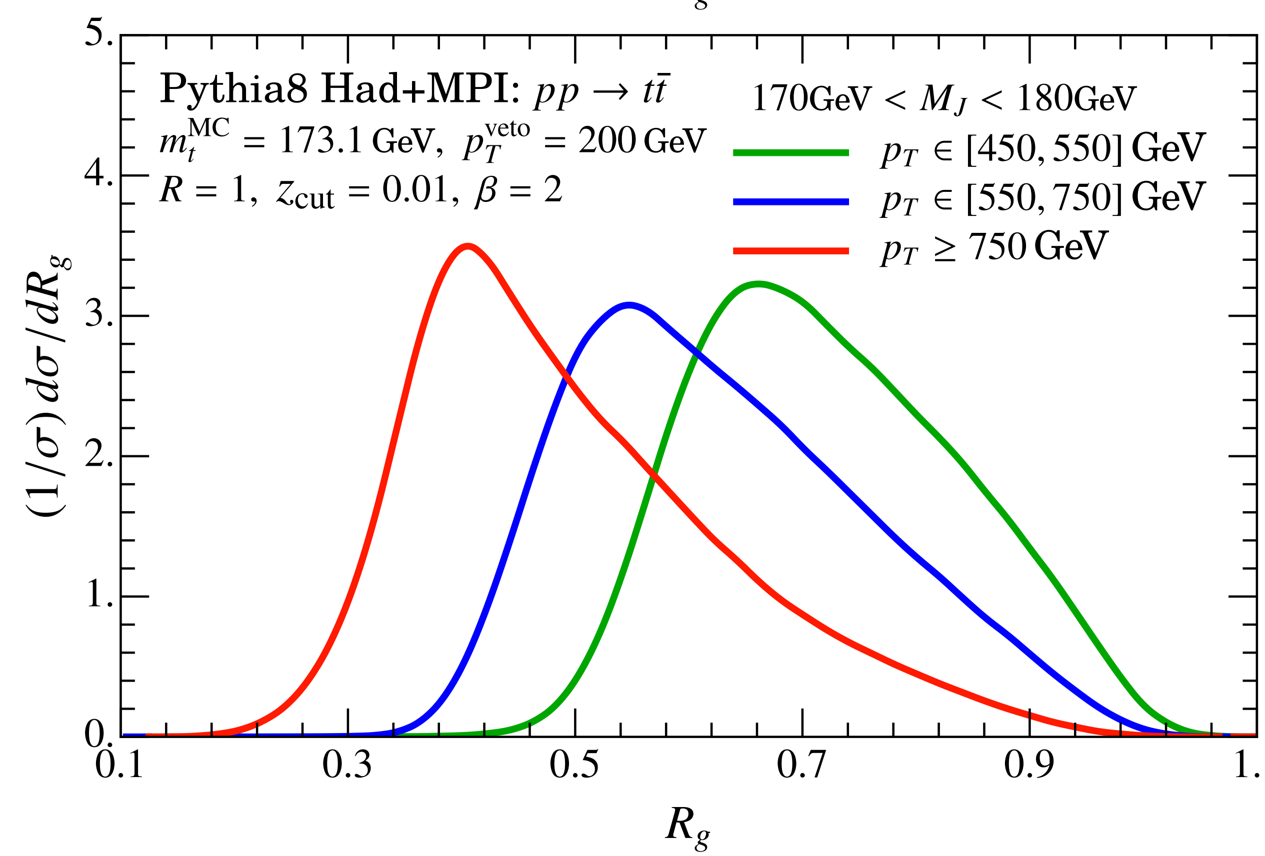
**Affects location of the $\Lambda$ mode.**

# GROOMED JET RADIUS DISTRIBUTION

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

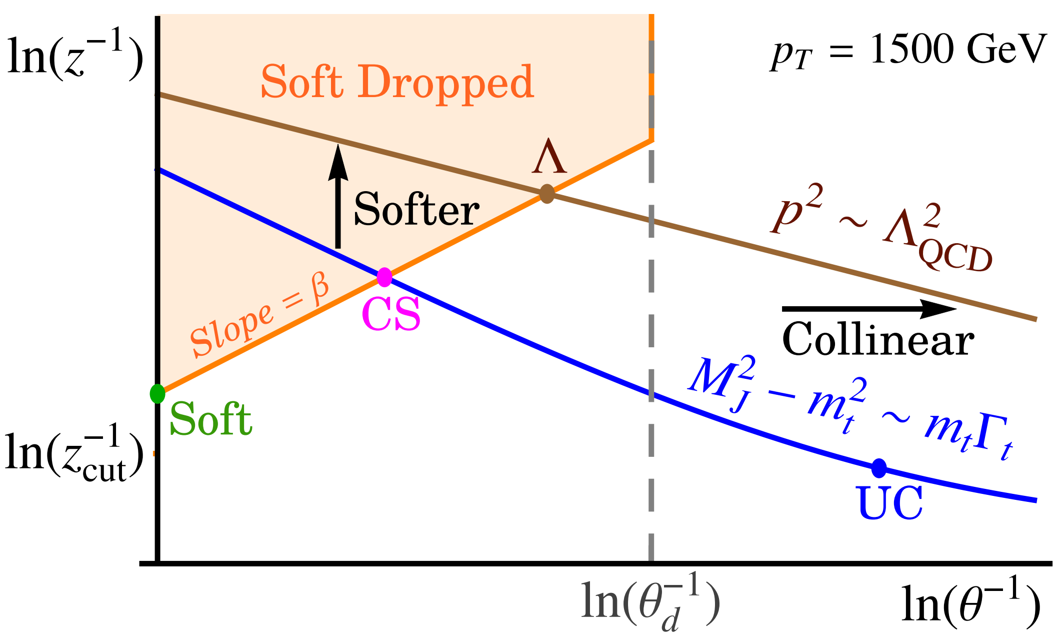



**The peak of $R_g$ distribution decreases as a function of $p_T$:**




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

# TWO CASES FOR NONPERTURBATIVE CONVOLUTION

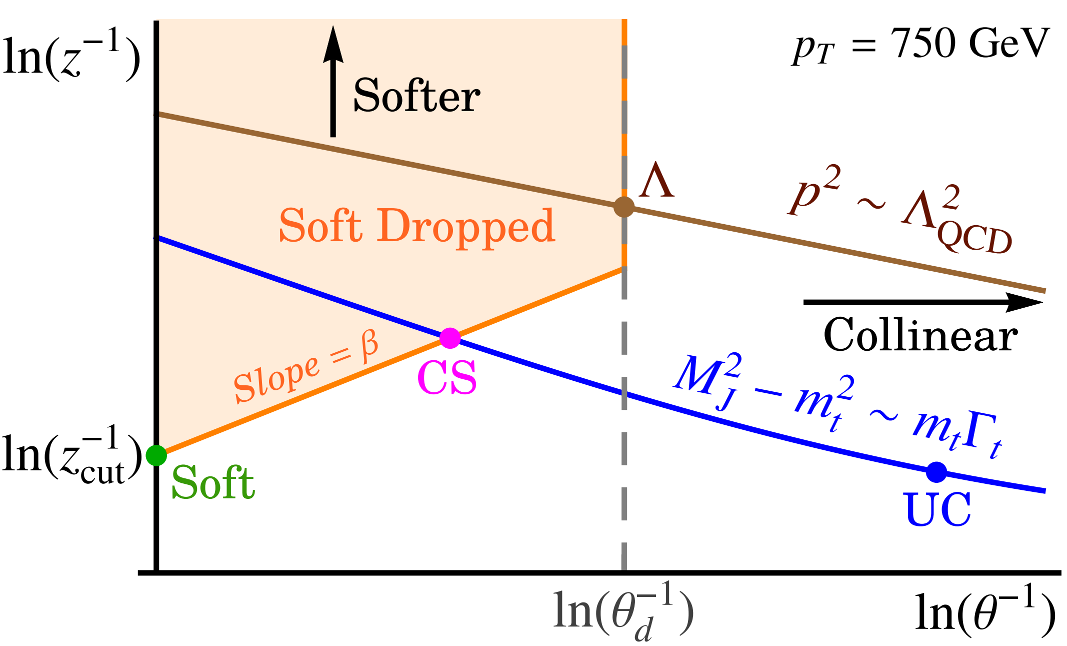



Factorization at High $p_T$: $Q > 2m\left(\frac{m z_{\rm cut} h^{\beta+1}}{\Lambda_{QCD}}\right)^{\frac{1}{\beta}}$

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

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

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




Factorization with Decay Products Effects:

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

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

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

# FACTORIZATION WITH DECAY PRODUCTS EFFECTS

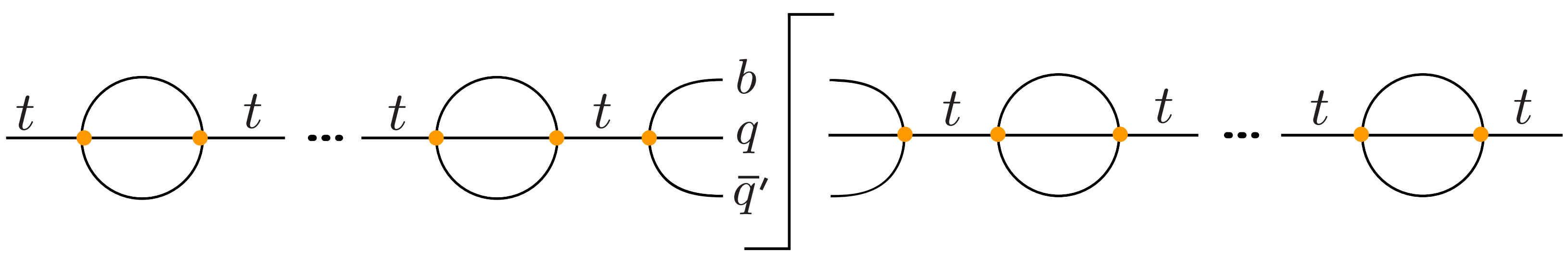
$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu)\int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d,\, m/Q)\int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$

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

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

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

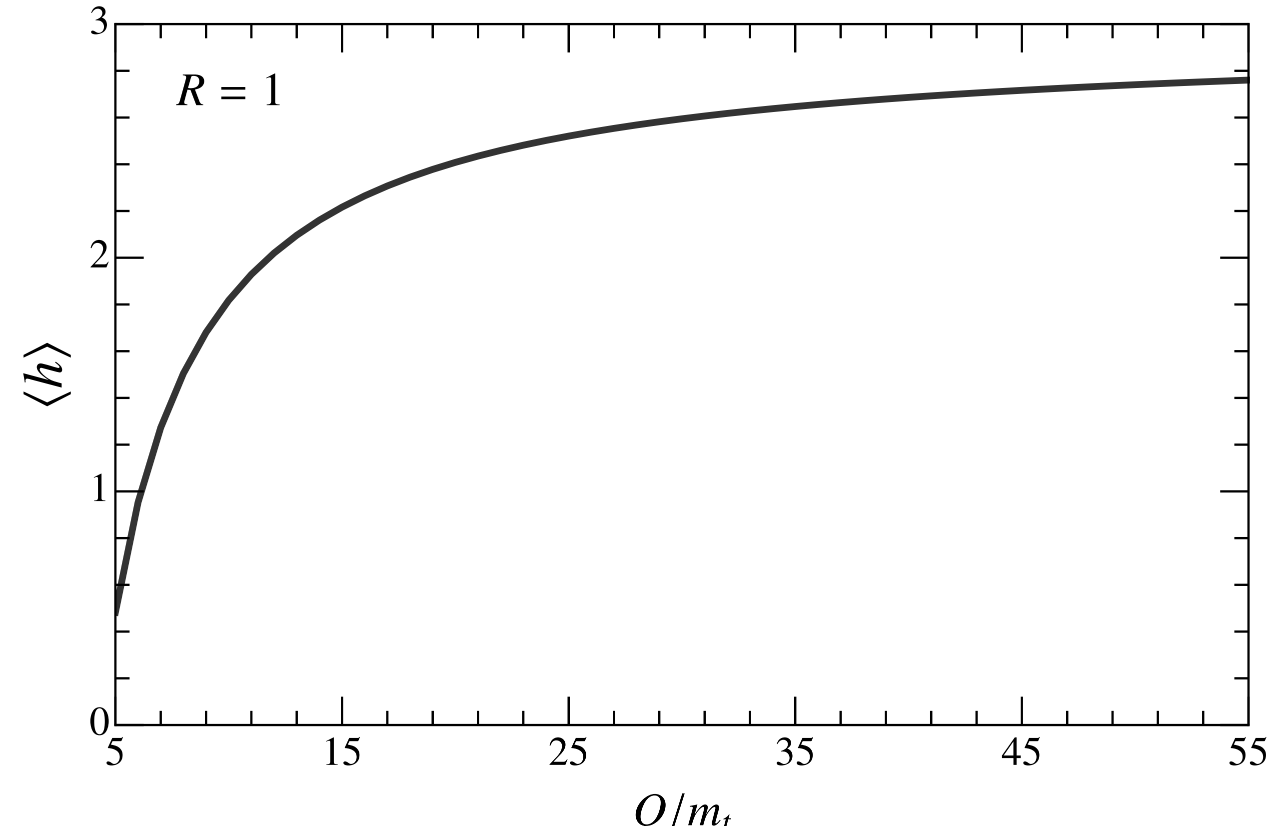
$$Q = 2\, p_T \cosh(\eta_J)$$




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

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

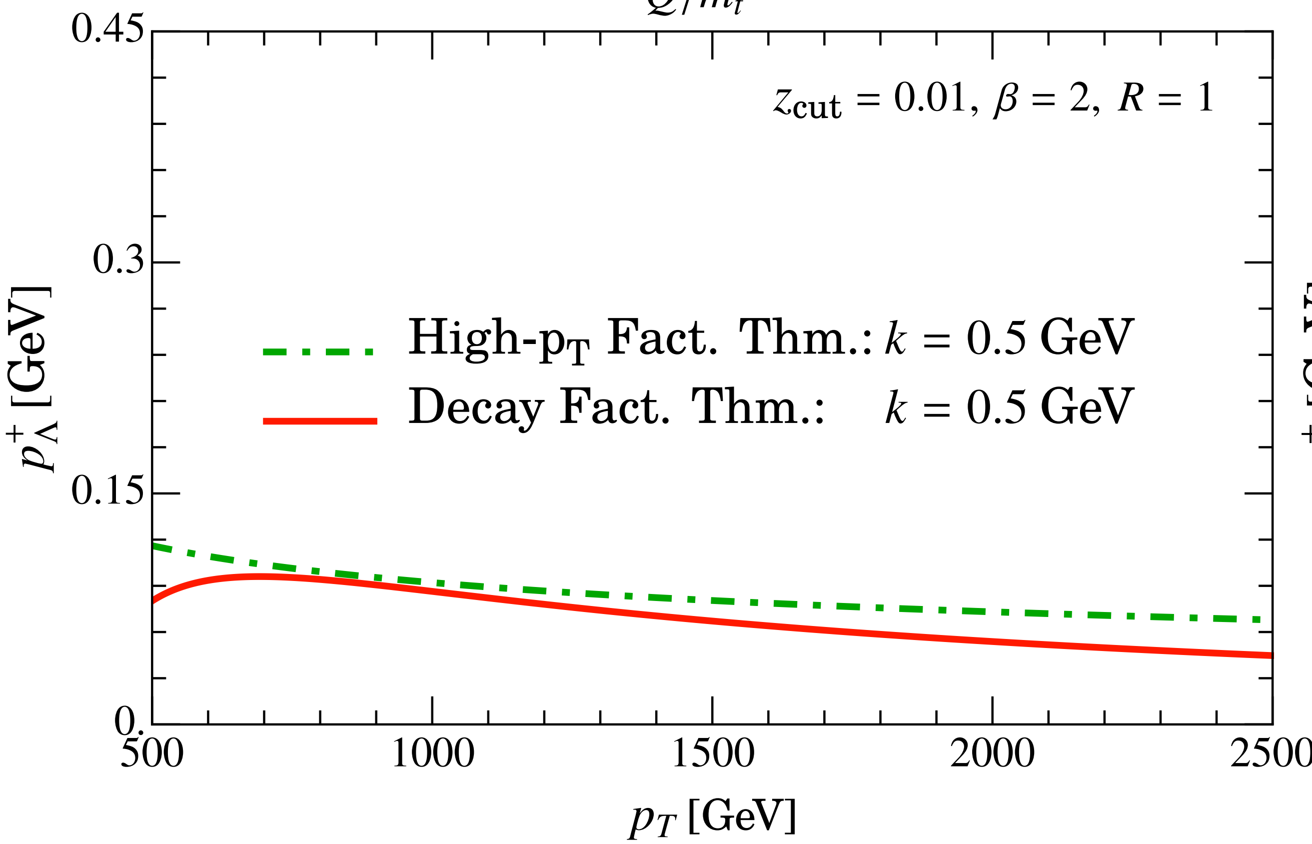
# FACTORIZATION WITH DECAY PRODUCTS EFFECTS

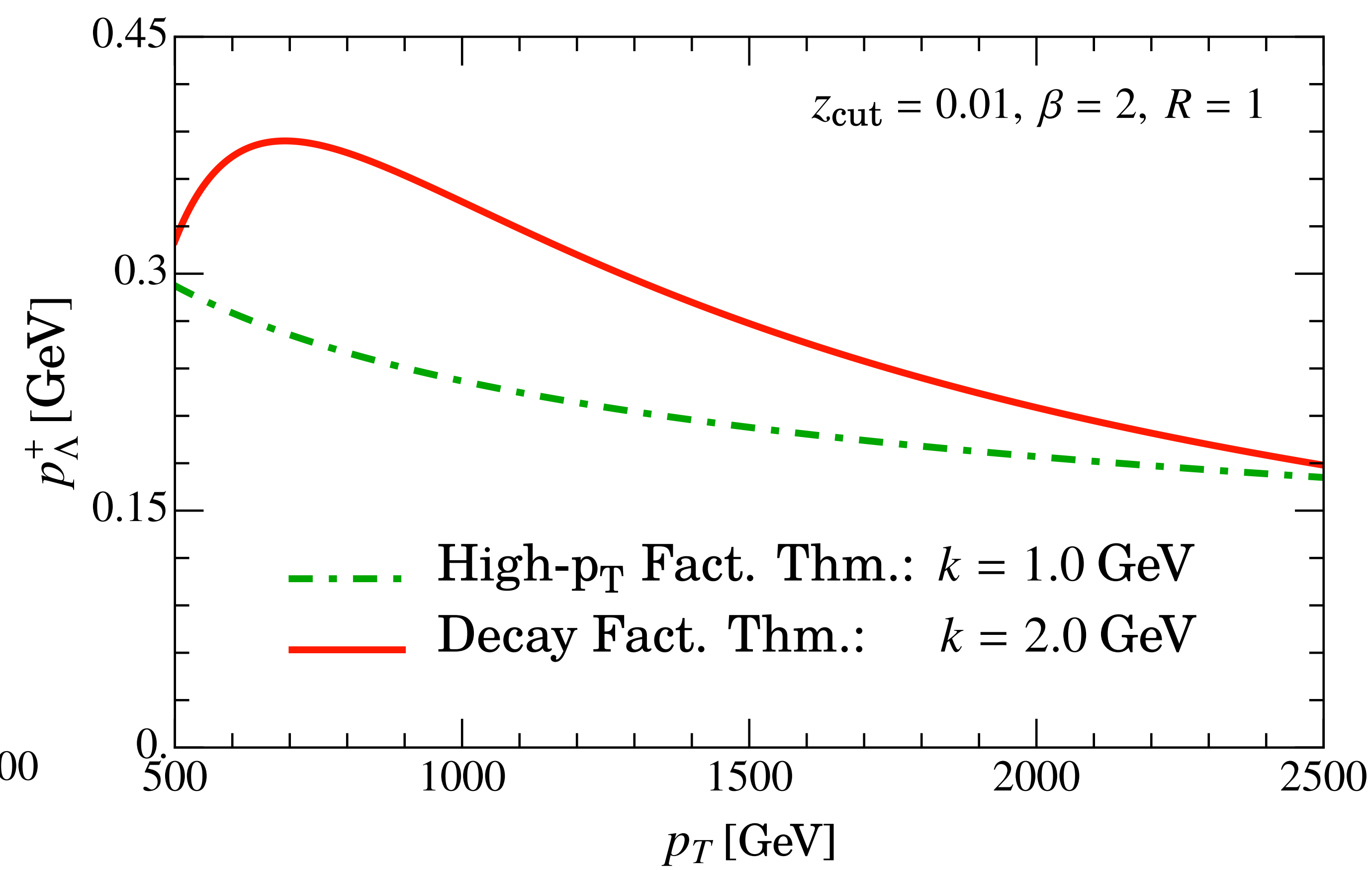



**Which factorization to use?**

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

**Compare the + component of non perturbative mode**

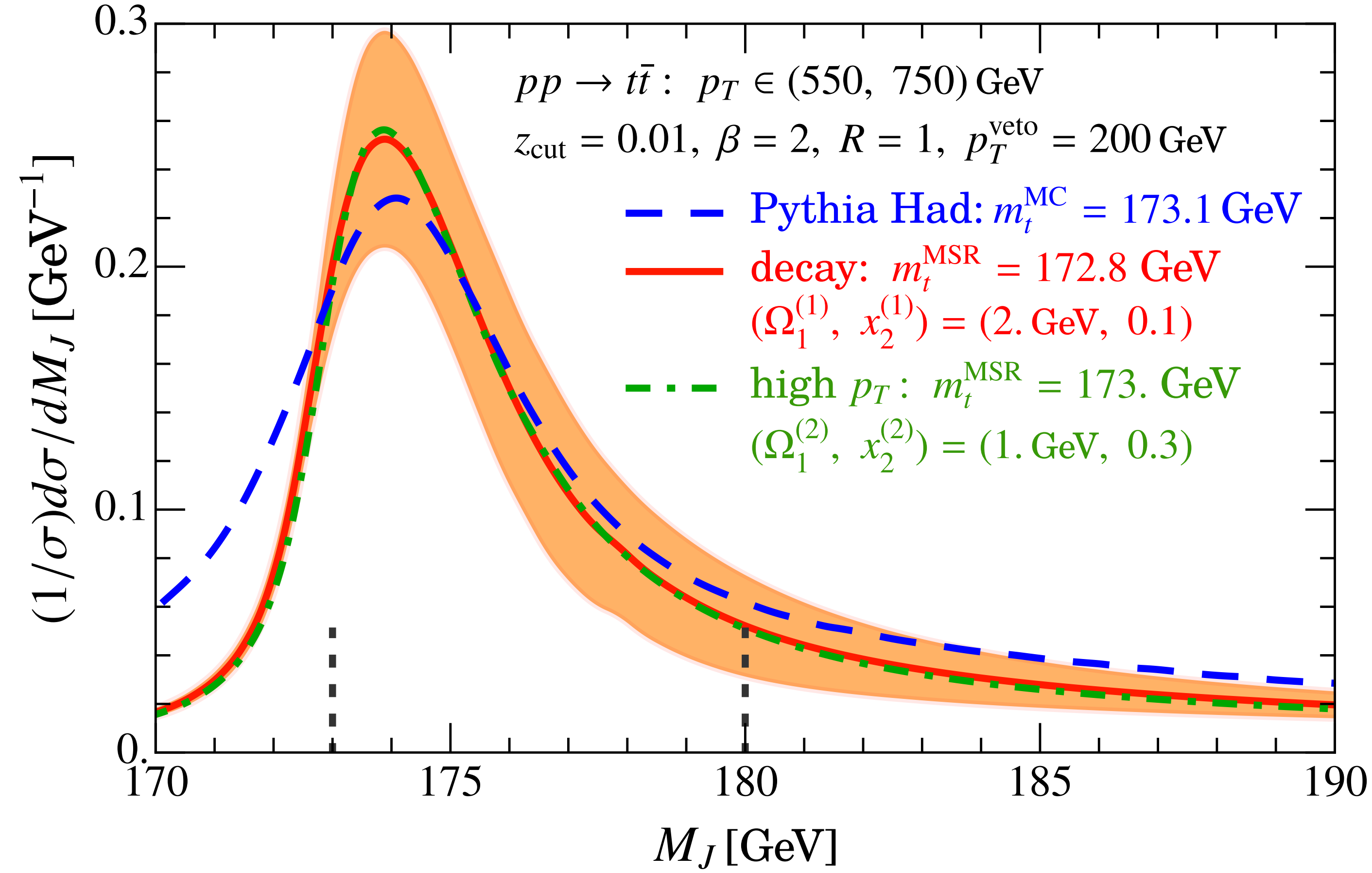


# RESULTS FOR SMALLER PT

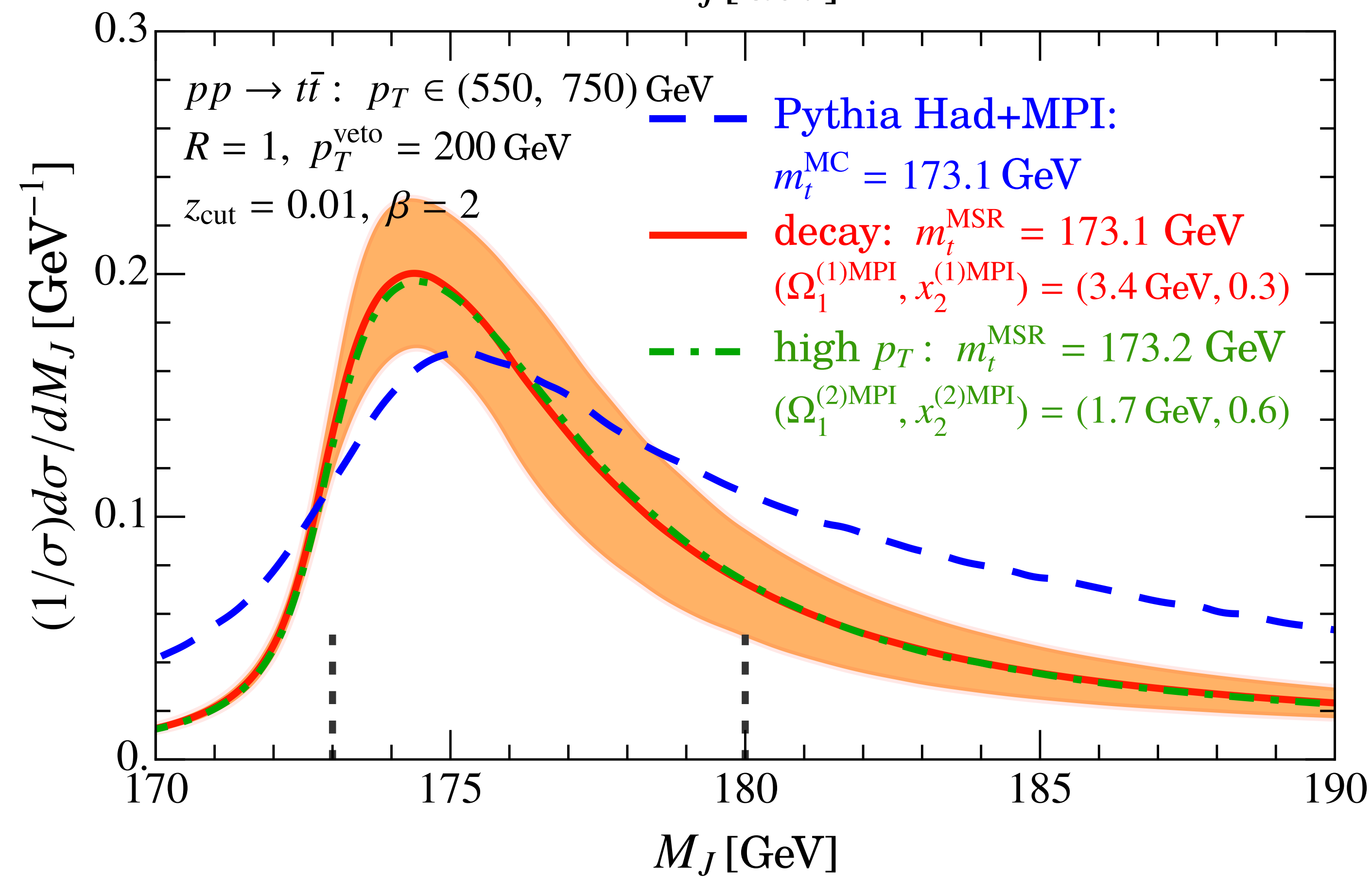
**Use values obtained from fits to higher $p_T$ bins**

**MPI-off:**

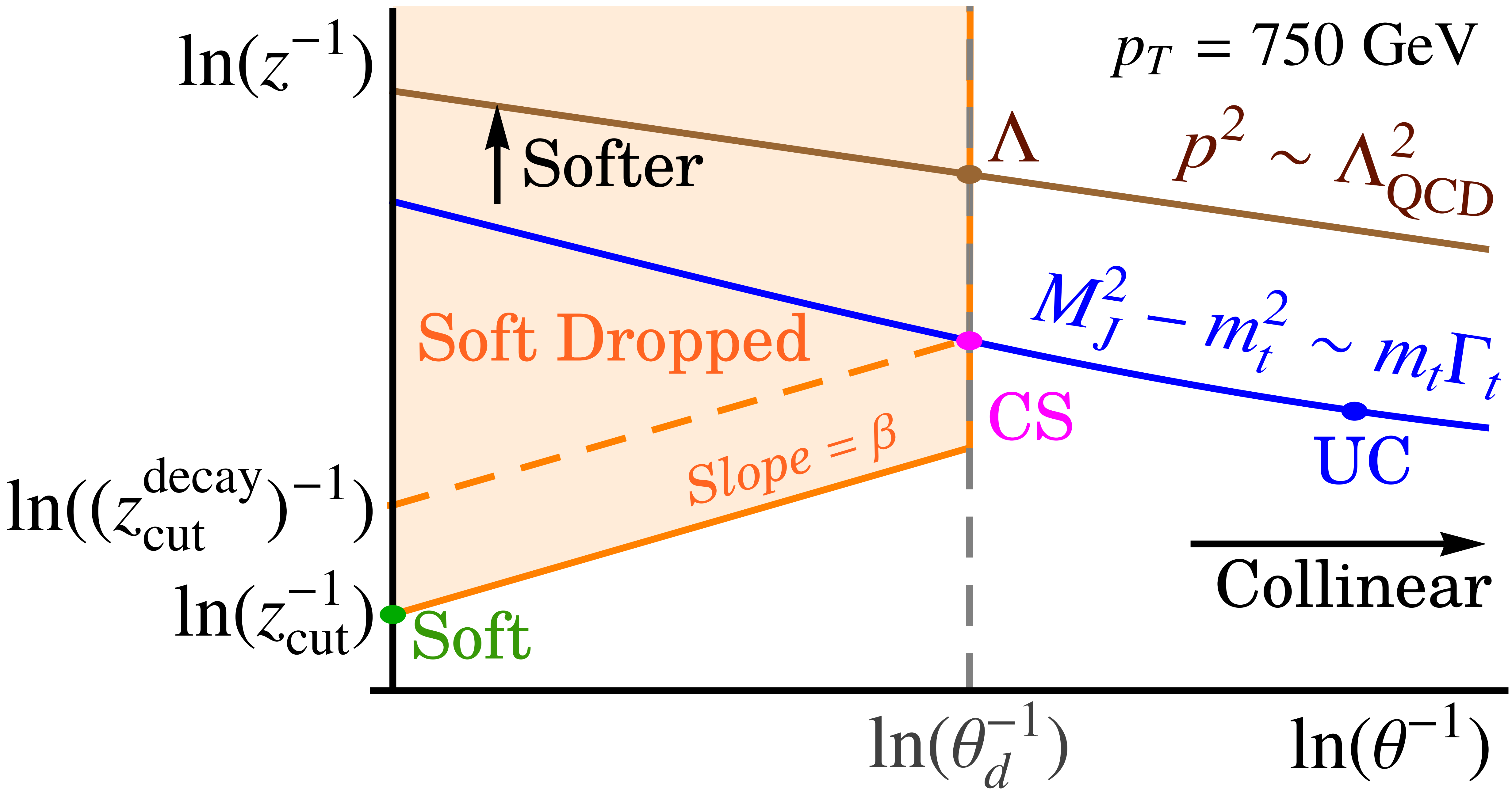



**Factorization and Pythia are no longer in agreement. Larger expansion parameters**

**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**