# Groomed and ungroomed jet substructure from SCET

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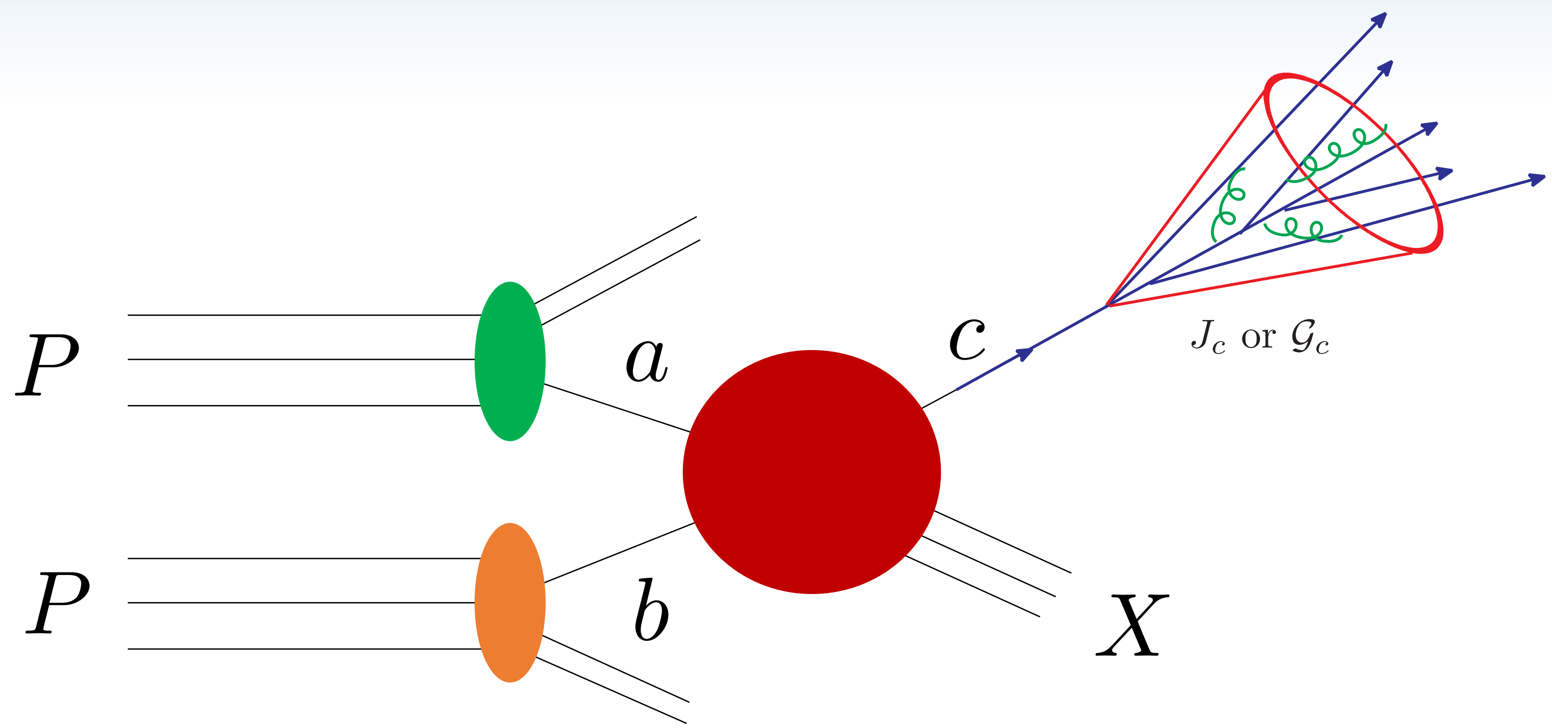
**Works in collaboration with Zhong-Bo Kang, Xiaohui Liu, and Felix Ringer**

Santa Fe Jets and Heavy Flavor Workshop
01/28/19 - 01/30/19

# Processes of Interest



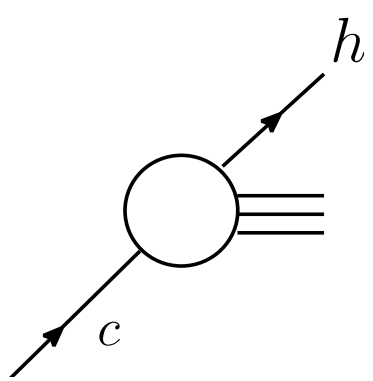

- **We want to study semi-inclusive jet production p + p $\longrightarrow$Jet((with/without) substructure) + X**
- More statistics. No veto on additional jets.

# Plans of this talk

- Inclusive jet production at the LHC
- Ungroomed jet angularity measurements at the LHC
- Role of non-perturbative effects
- Groomed observables
- Conclusions

# Factorization of Inclusive Jet Production

$R \ll 1$

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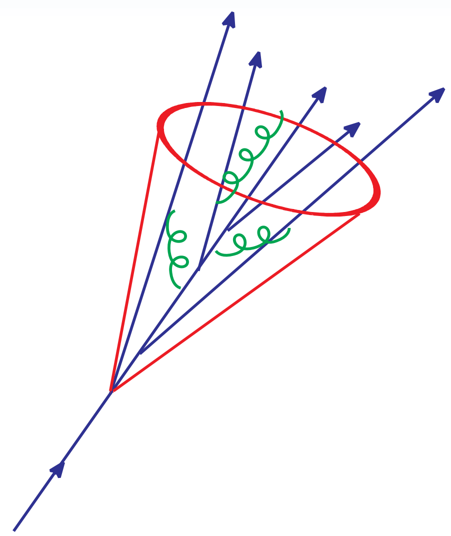

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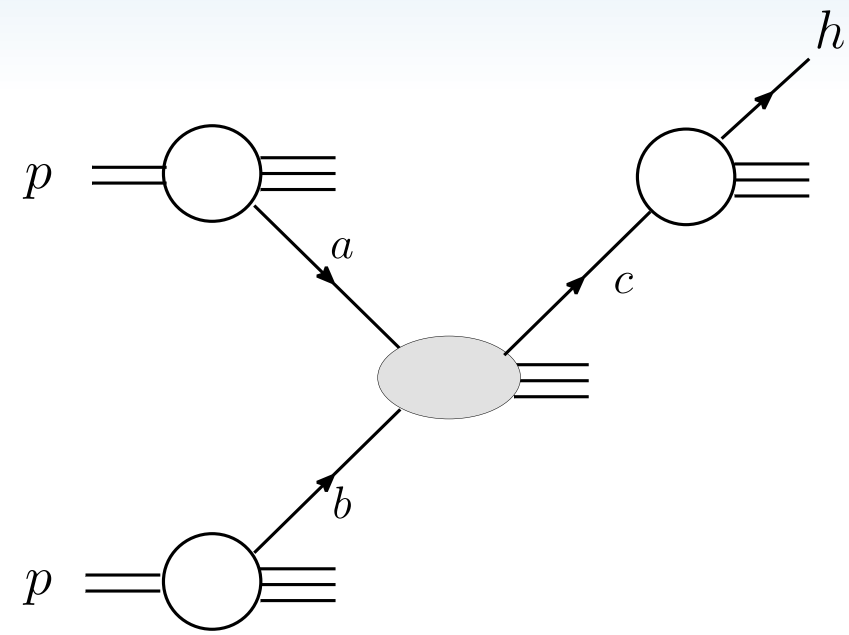


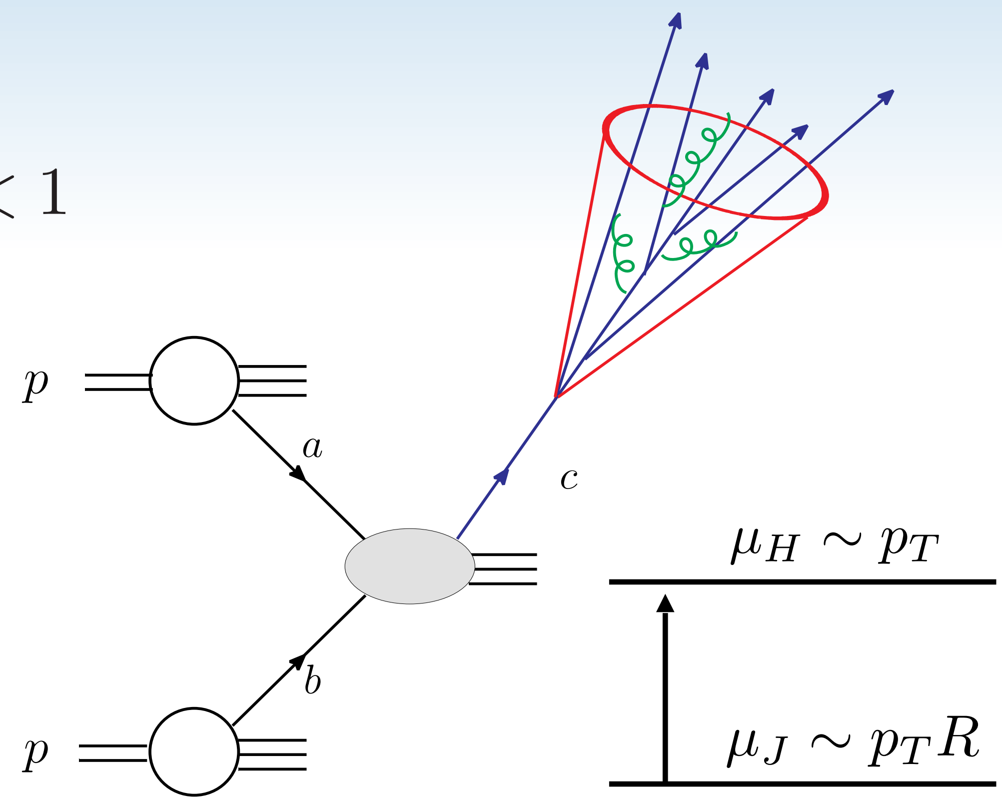

$$D_c^h \quad \rightarrow \quad J_c \qquad\qquad pp \rightarrow hX$$

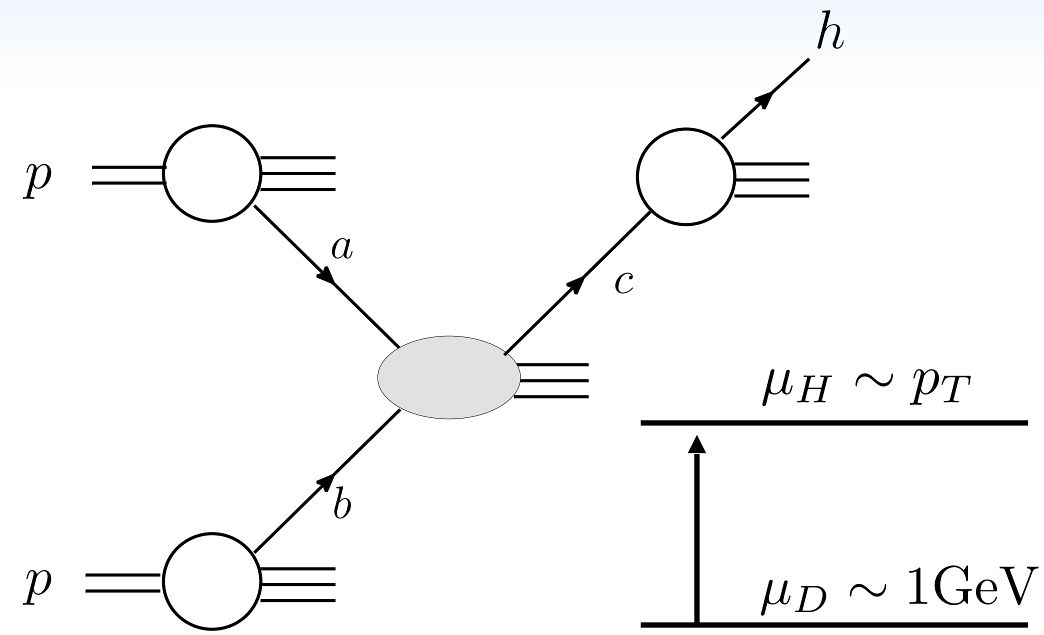
- **Simple replacement of the fragmentation function by "semi-inclusive jet function".**

*Kang, Ringer, Vitev `16*

# Comparison with the inclusive hadron production case

$R \ll 1$

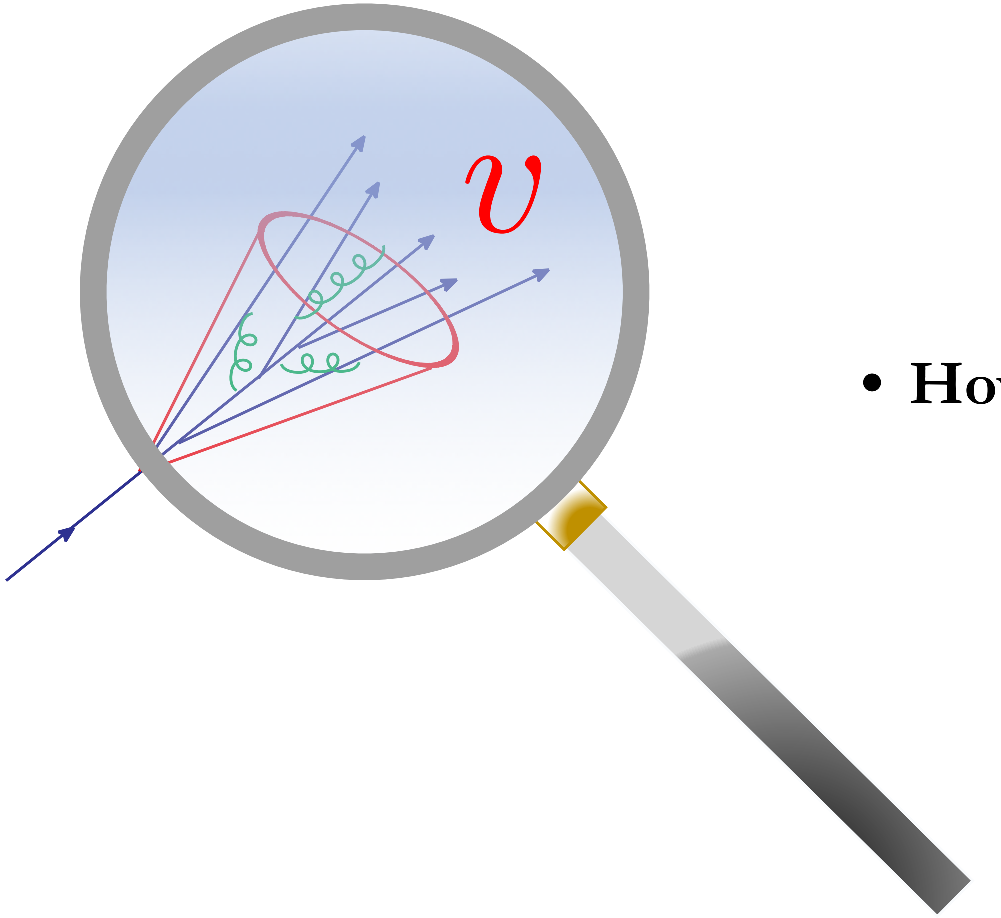



| | Factorization | Evolution |
|---|---|---|
| Inclusive Jet | $\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c + \mathcal{O}(R^2)$ | $\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$ |
| Hadron | $\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes D_c^h$ | $\mu \frac{d}{d\mu} D_i^h = \sum_j P_{ji} \otimes D_j^h$ |

*Kang, Ringer, Vitev `16*

# Jet Substructure Measurements



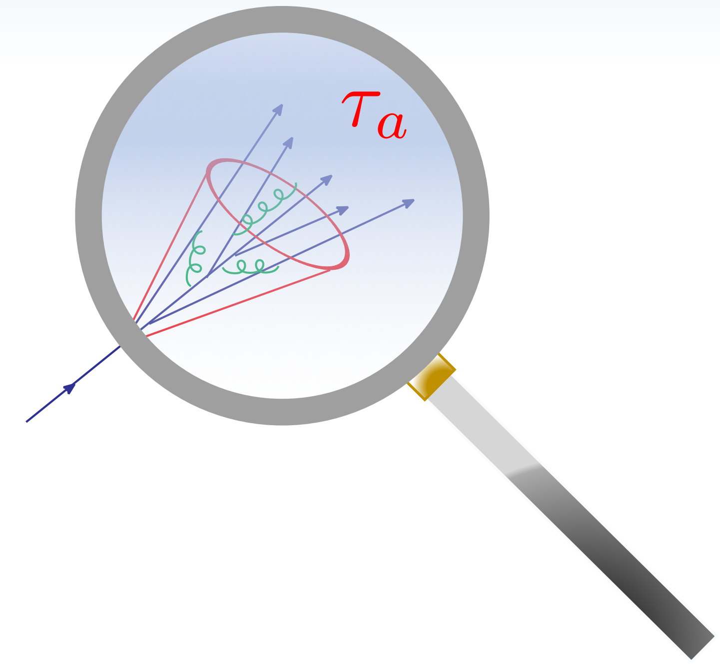

- How do we measure a substructure $v$ inside the jet?

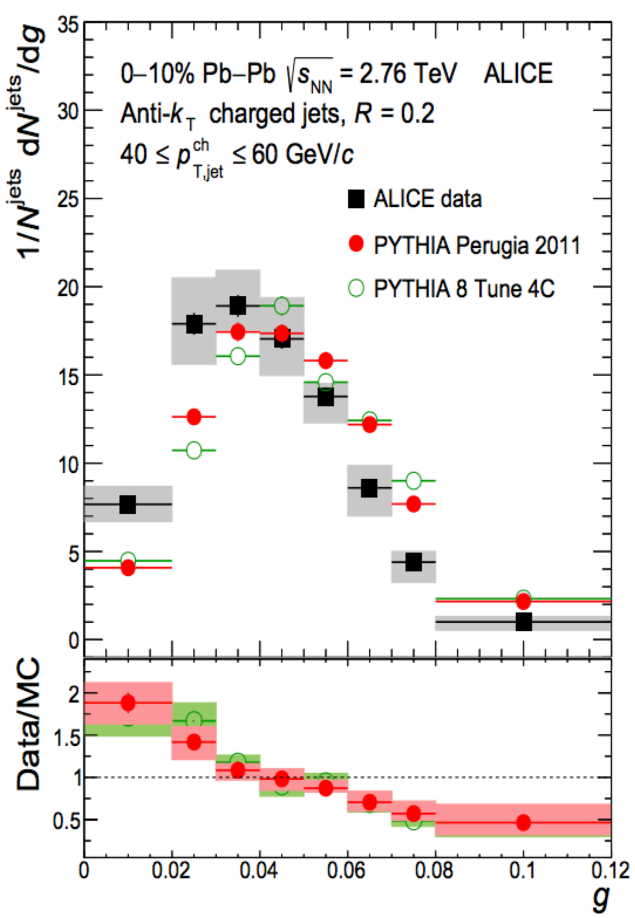
# Jet angularity

- A generalized class of IR safe observables ($-\infty < a < 2$), angularity (applied to jet):

$$\tau_a^{pp} = \frac{1}{p_T}\sum_{i\in J} p_{T,i}(\Delta R_{iJ})^{2-a}$$

$$\tau_0^{pp} = \frac{m_J^2}{p_T^2} + \mathcal{O}((\tau_0^{pp})^2)$$



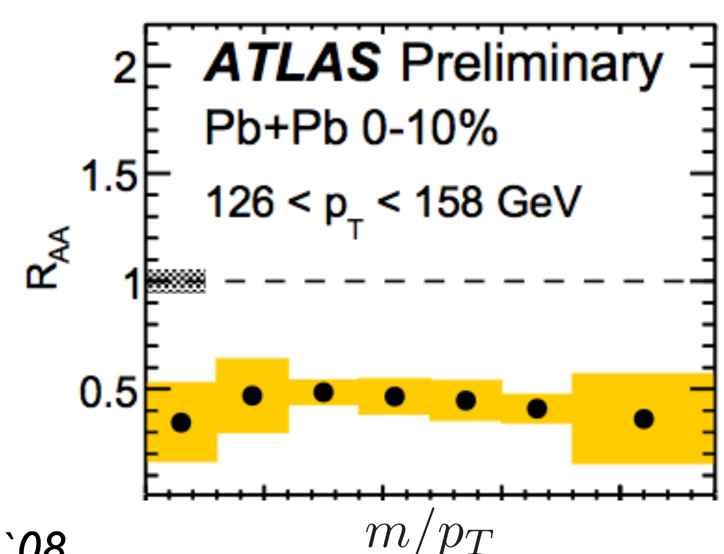




**Medium modifications**

$a = 1$

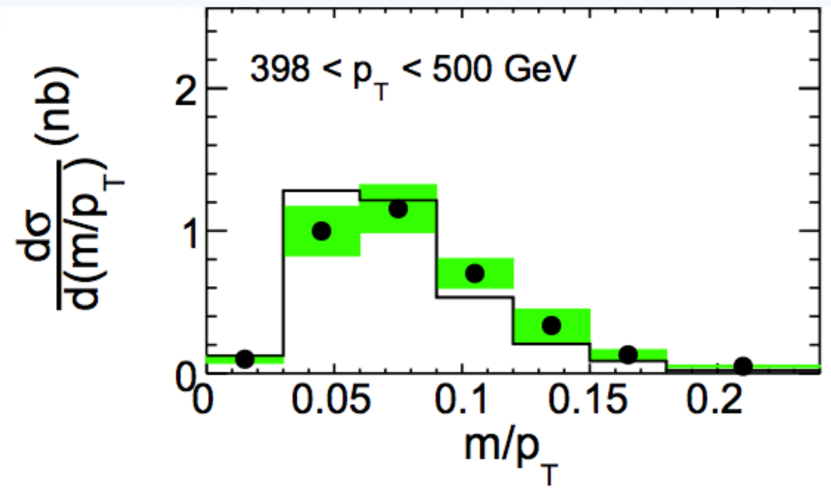
$$g(\text{girth}) = \frac{1}{p_T}\sum_{i\in J} p_{T,i}\,(\Delta R_{iJ})$$

$a = 0$

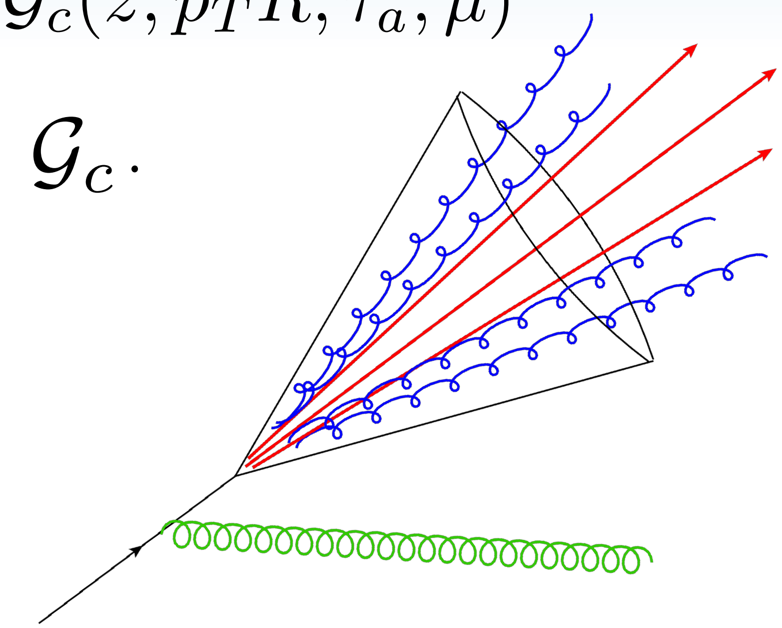



*Sterman et al. `03, `08,*
*Hornig, C. Lee, Ovanesyan `09, Ellis, Vermilion, Walsh, Hornig, C.Lee `10,*
*Chien, Hornig, C. Lee `15, Hornig, Makris, Mehen `16, Kang, KL, Ringer `18*

# Factorization for jet angularity




- Replace $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau_a, \mu)$
- When $\tau_a \ll R^2$, refactorize $\mathcal{G}_c$ .



## Relevant modes for $\tau_a \ll R^2$

$$\tau_a \sim z\,\theta^{2-a}$$

**Collinear**

$$z_c \sim 1 \qquad \theta_c \sim \tau_a^{\frac{1}{2-a}}$$

**Collinear-soft**

$$\theta_s \sim R \qquad z_{cs} \sim \frac{\tau_a}{R^{2-a}}$$

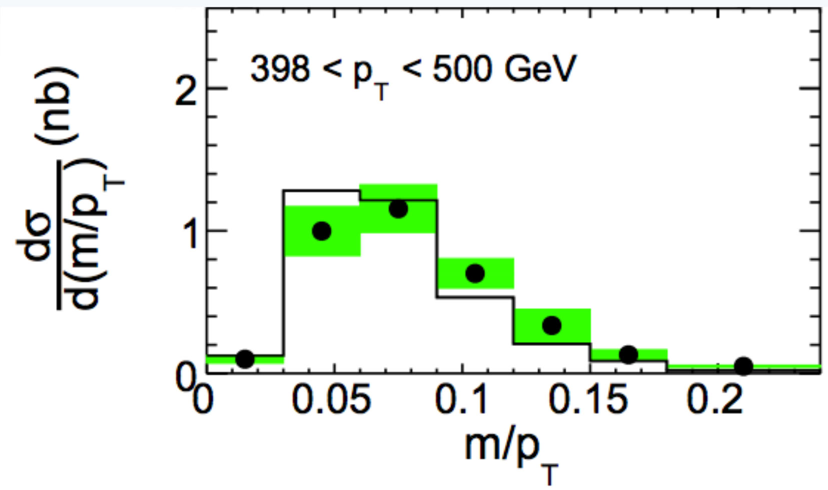
**Hard-collinear**

$$\theta_H \sim R \qquad z_H \sim 1$$



*Kang, KL, Ringer, arXiv:1801.00790*

# Factorization for jet angularity




- Replace $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau_a, \mu)$
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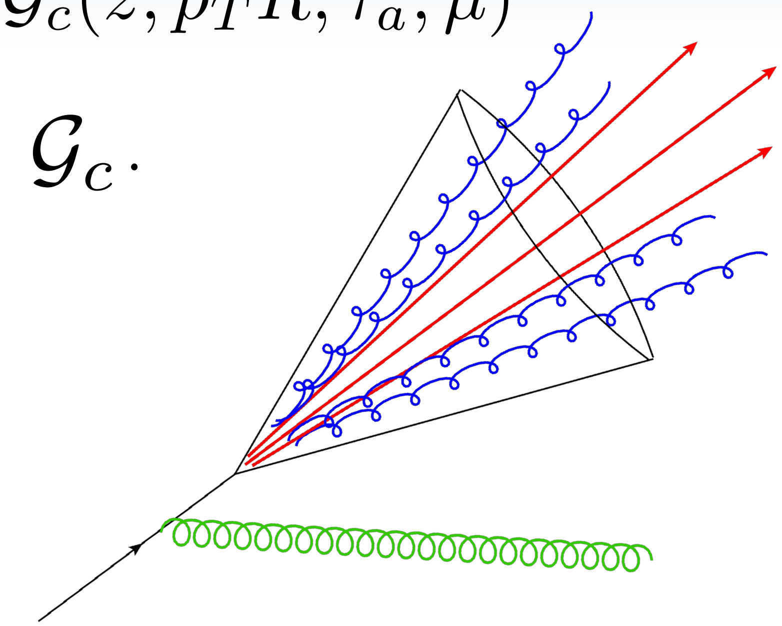
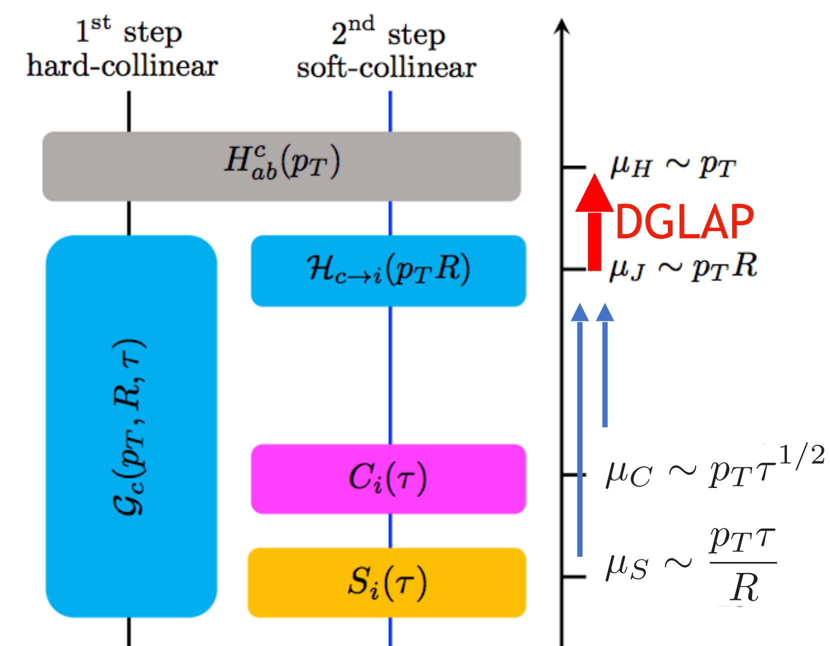


$$\mathcal{G}_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu)$$

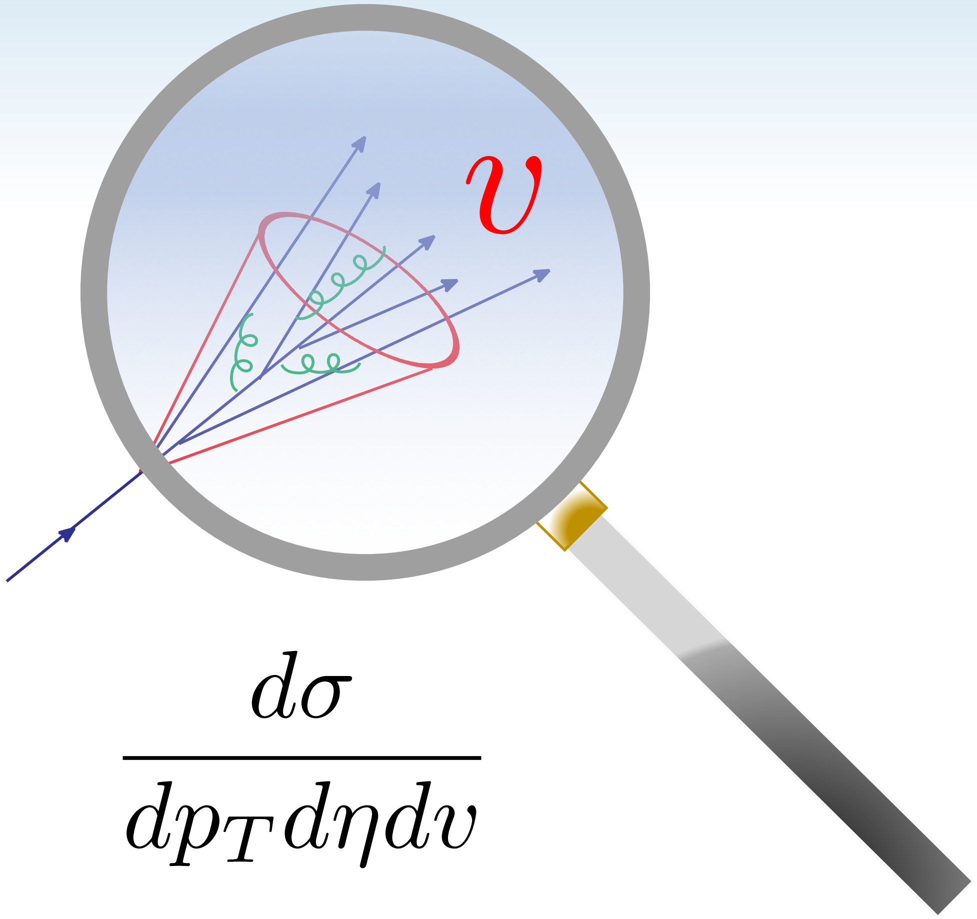
$$\times \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{\frac{1}{2-a}}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu) + \mathcal{O}\left(\tau_a / R^2\right)$$

- Each piece describes physics at different scales.
- $\mu_J \to \mu_H$ evolution follows DGLAP evolution equation again
- Resums $(\alpha_s \ln R)^n$ and $\left(\alpha_s \ln^2 \frac{R}{\tau^{1/2}}\right)^n$

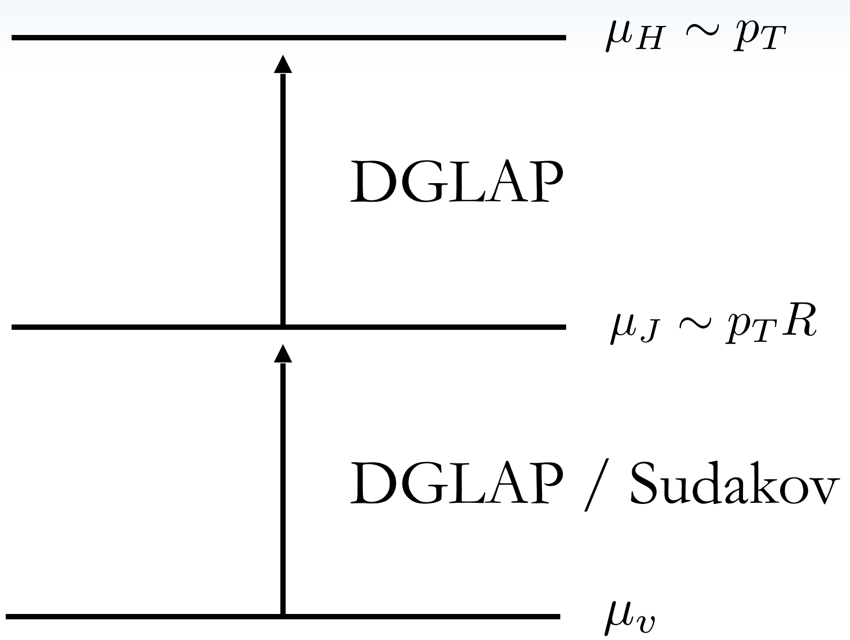



Kang, KL, Ringer, arXiv:1801.00790

# Patterns emerging



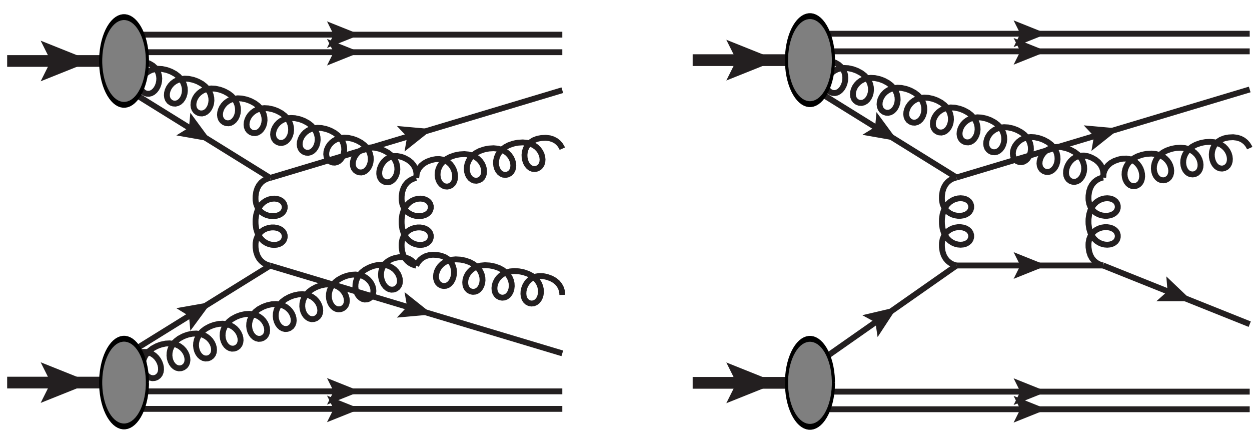

$$\frac{d\sigma}{dp_T d\eta dv}$$



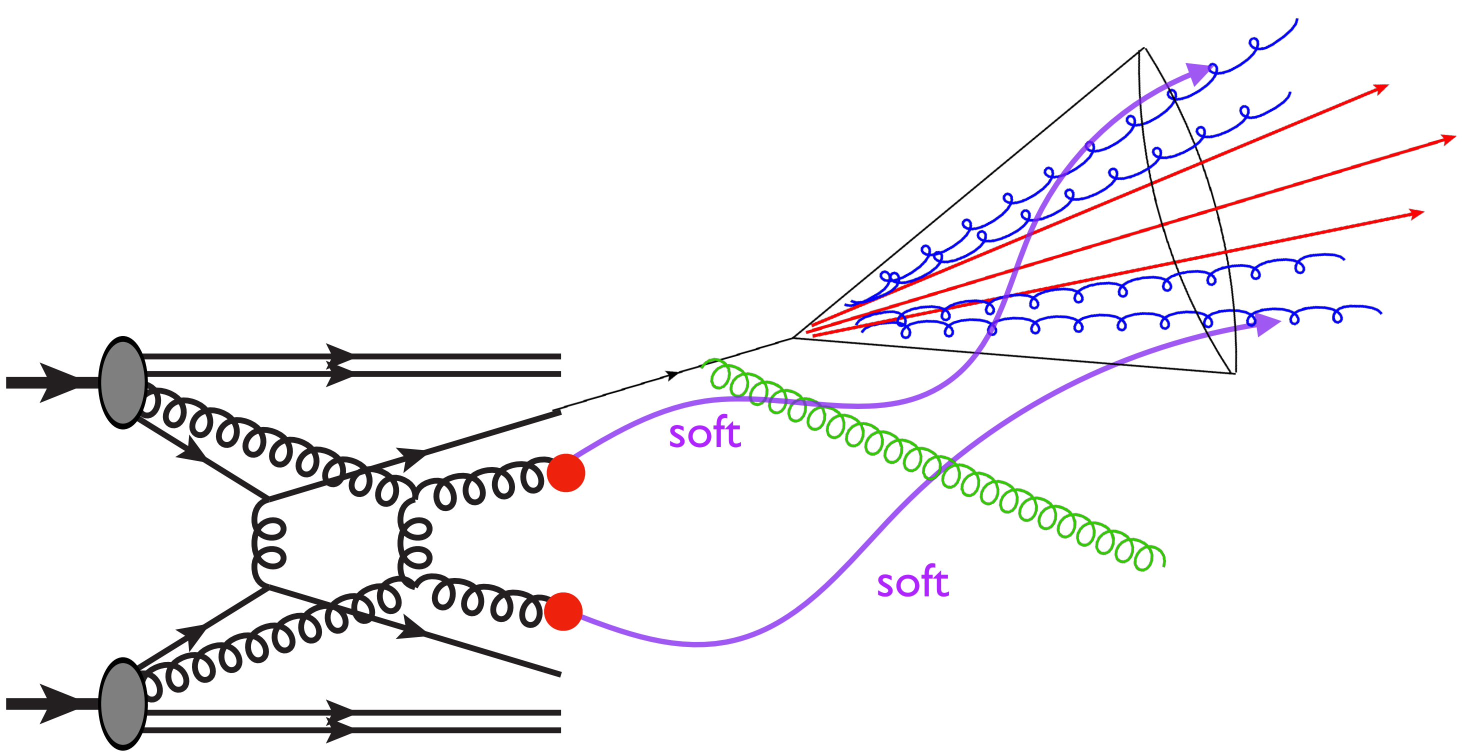

- When we measure a substructure $v$ from the jet, once we evolve to $\mu_J$ the remaining evolution to $\mu_H$ is given by DGLAP evolution!
- Two step factorization:
  a) production of a jet
  b) probing the internal structure of the jet produced.

# Non-perturbative Effects

- **Non-perturbative effects:**



Figs from P. Bartalini et al. `11




- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.

# Non-perturbative Effects

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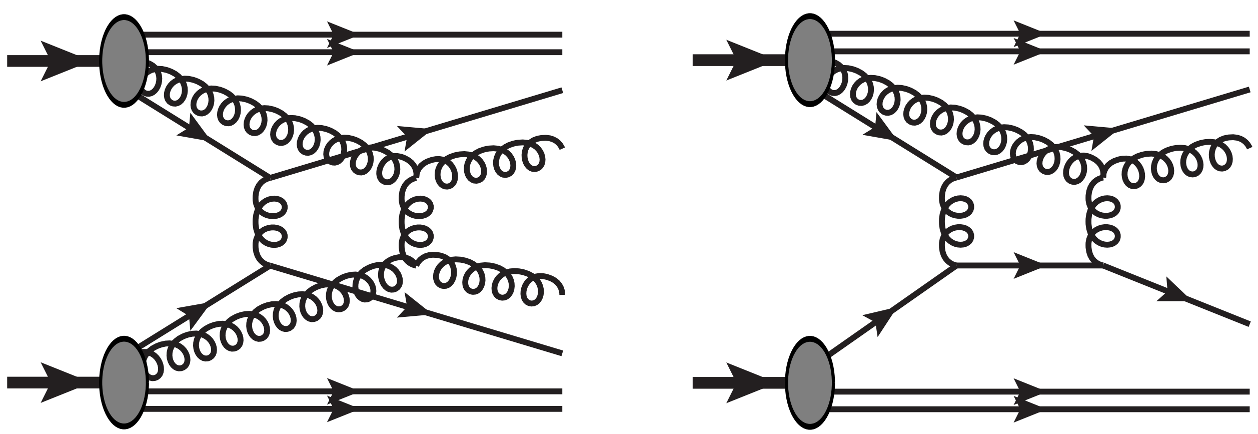

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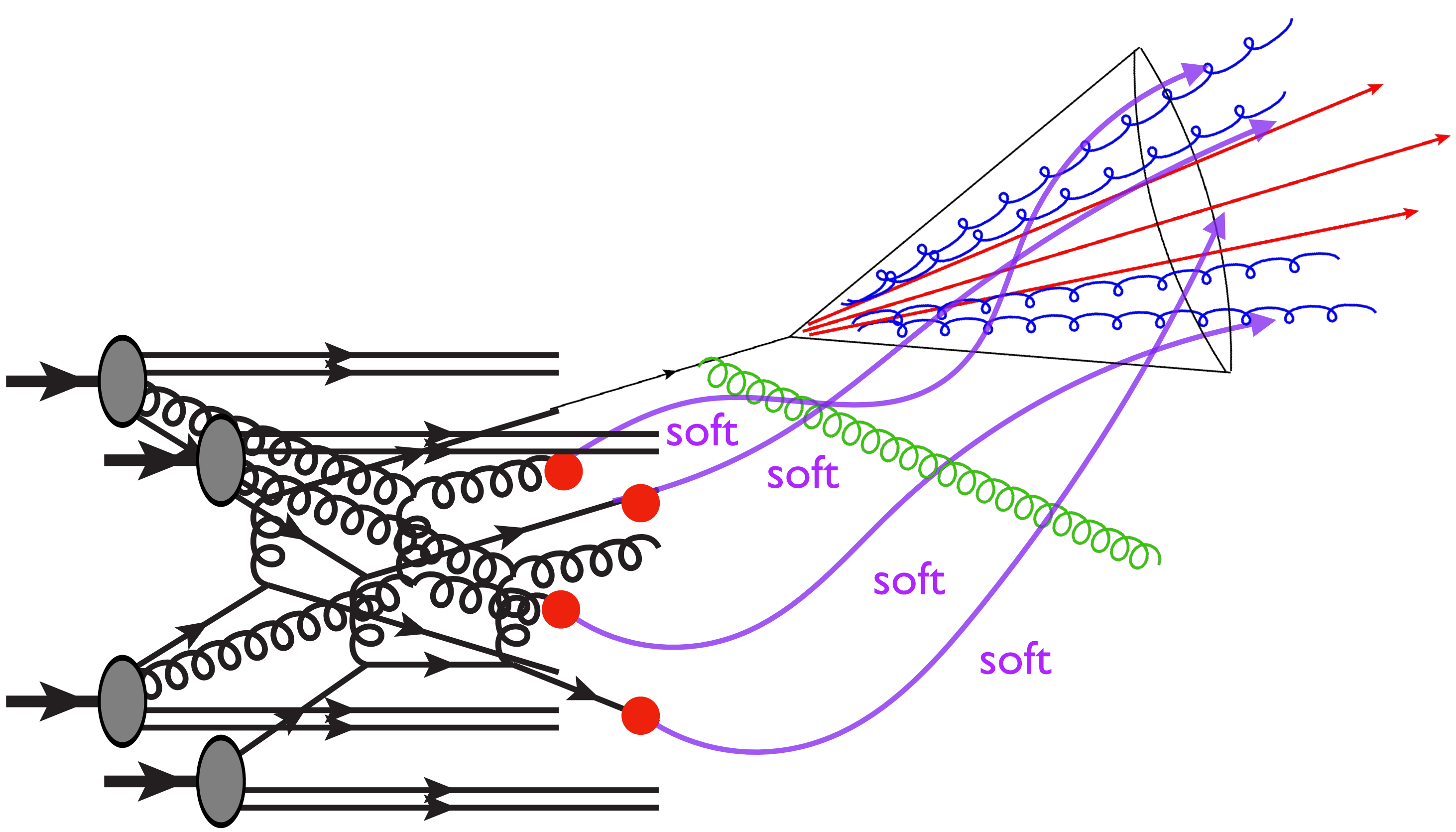
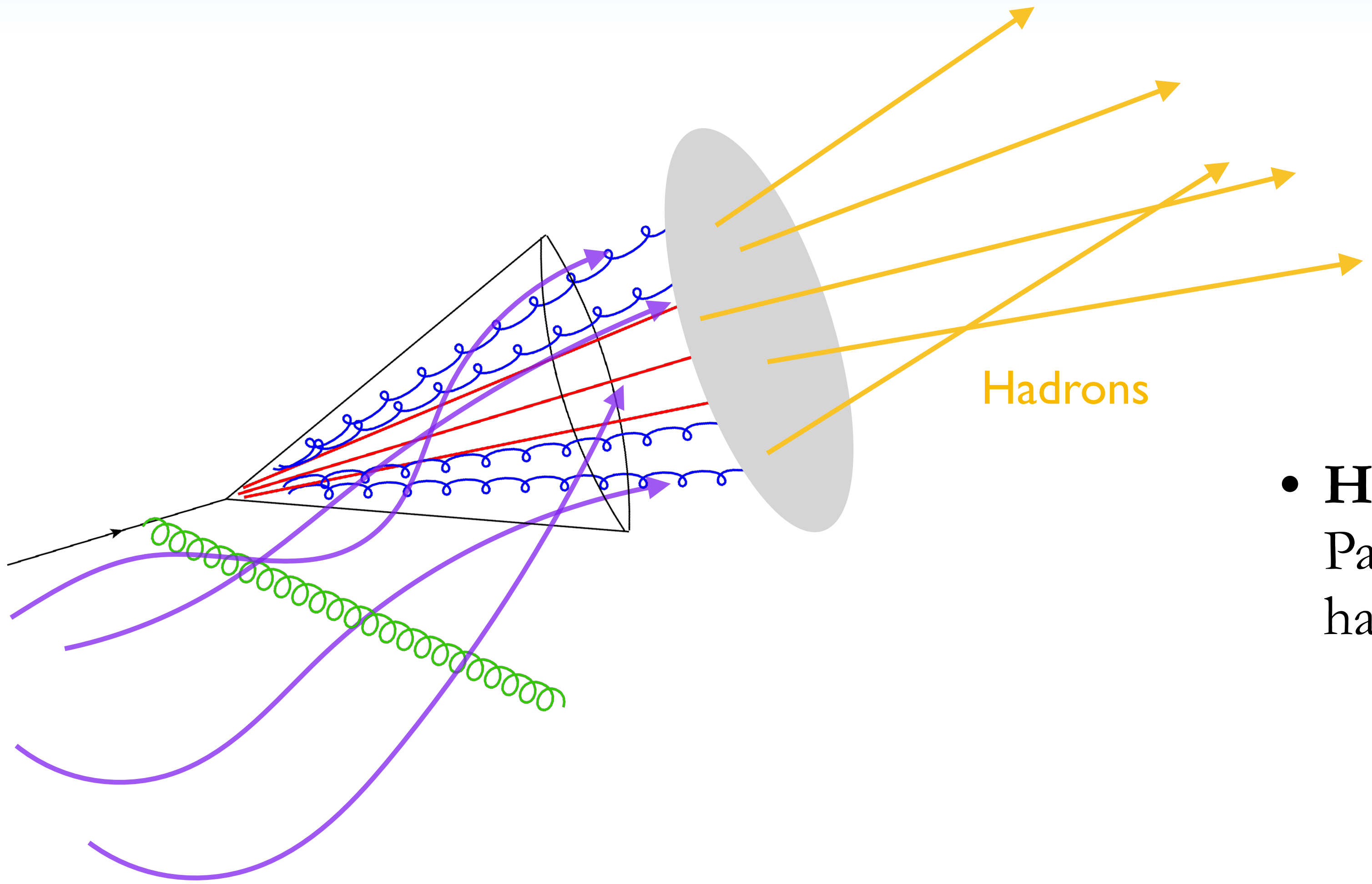



- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.
- **Pileups**
  Secondary proton collisions in a bunch may enter and contaminate jet.

# Non-perturbative Effects

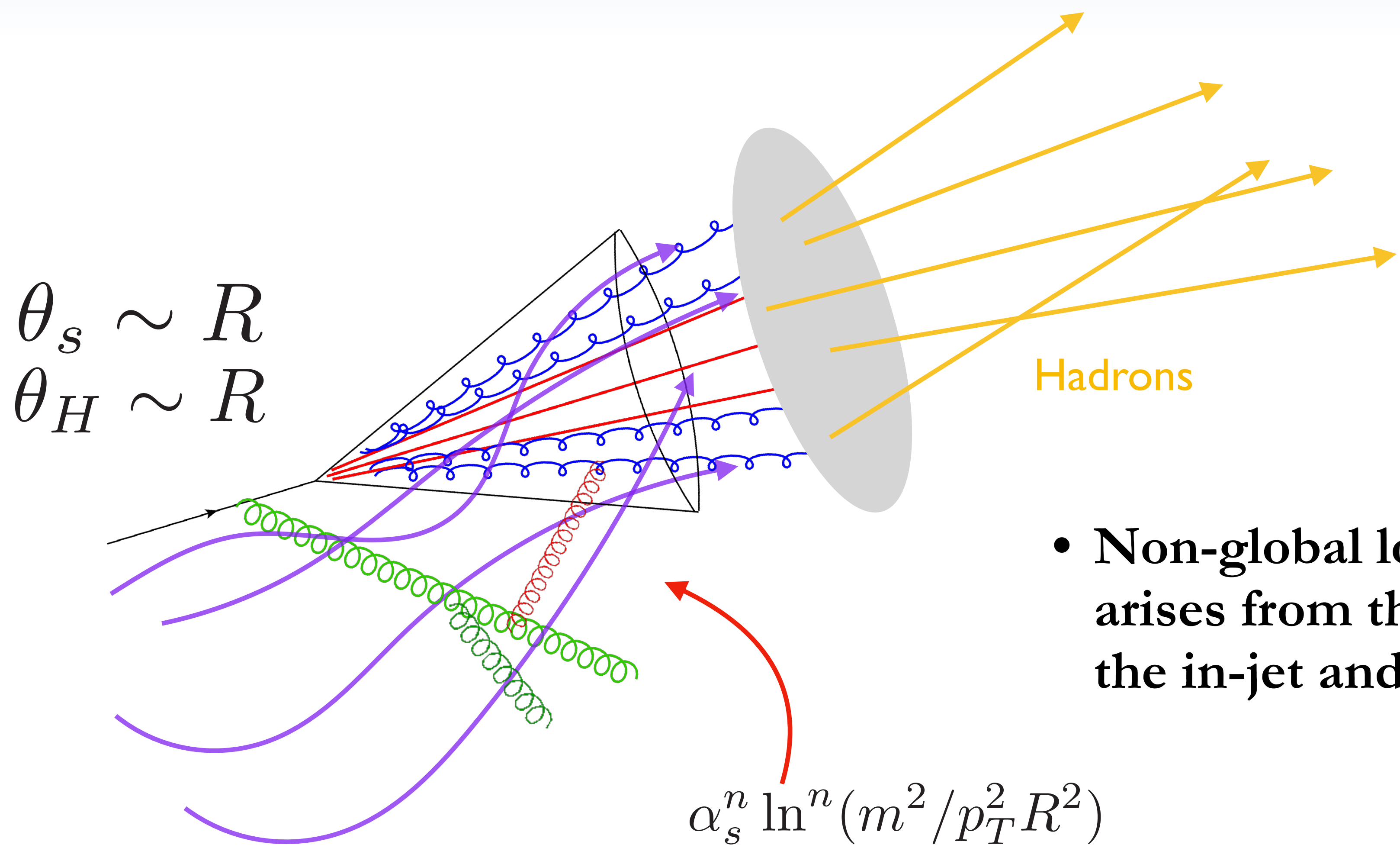
- **Non-perturbative effects:**




- **Hadronization**
  Partons forming the jet eventually hadronizes.

# Non-global logarithms

*Dasgupta, Salam `01*
*Banfi, Marchesini, Smye `02*
*Larkoski, Moult, Neill `15*
*Becher, Neubert, Rothen, Shao `15, `16 …*




- **Non-global logarithms (NGLs): arises from the correlation between the in-jet and out-of-jet radiation.**

**rather small effect for jet mass**

# Non-perturbative Model

- As $\tau$ gets smaller, $\mu_S \sim \frac{p_T \tau}{R}$ (smallest scale) can approach a non-perturbative scale.

  We shift our perturbative results by convolving with non-perturbative shape function to smear

$$\frac{d\sigma}{d\eta dp_T d\tau} = \int dk F_\kappa(k) \frac{d\sigma^{\text{pert}}}{d\eta dp_T d\tau} \left( \tau - \frac{R}{p_T} k \right)$$

- Single parameter NP soft function :

$$F_\kappa(k) = \left( \frac{4k}{\Omega_\kappa^2} \right) \exp\left( -\frac{2k}{\Omega_\kappa} \right)$$

*Stewart, Tackmann, Waalewijn `15*

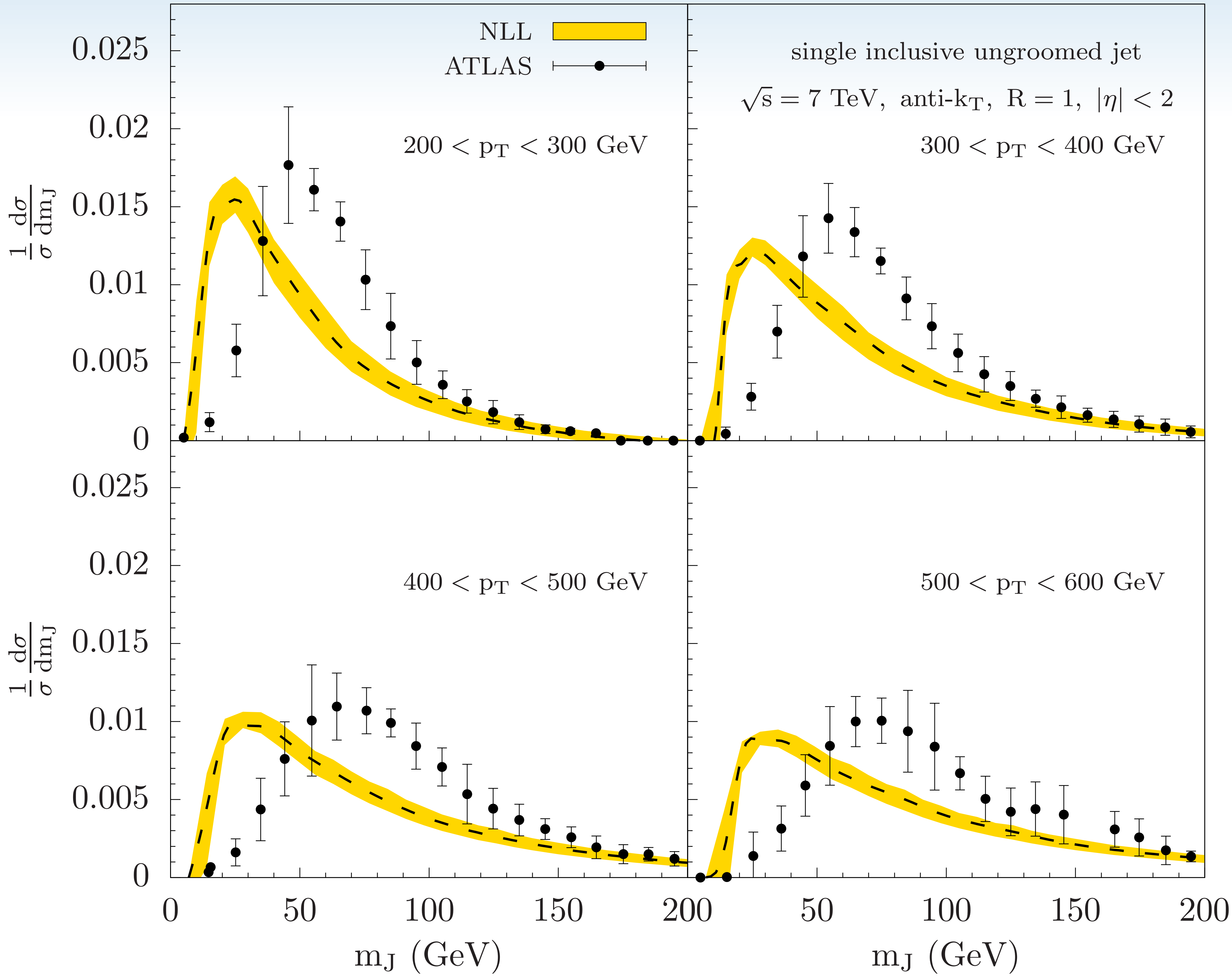
- Both hadronization and MPI effects in jet mass is well-represented by just shifting first-moments.

- The parameter $\Omega_\kappa$ is related to shift in the distribution:

$$\tau = \tau_{\text{pert}} + \tau_{\text{NP}} = \tau_{\text{pert}} + \frac{R\Omega_\kappa}{p_T} = \tau_{\text{pert}} + \frac{R\left(\Lambda_{\text{hadro.}} + \Lambda_{\text{MPI}}\right)}{p_T}$$

$\Omega_\kappa \sim \Lambda_{had} \sim 1\,\text{GeV}$ corresponds to non-perturbative effects coming primarily from the hadronization alone.

# Phenomenology




*Kang, KL, Liu, Ringer, arXiv:1803.03645*

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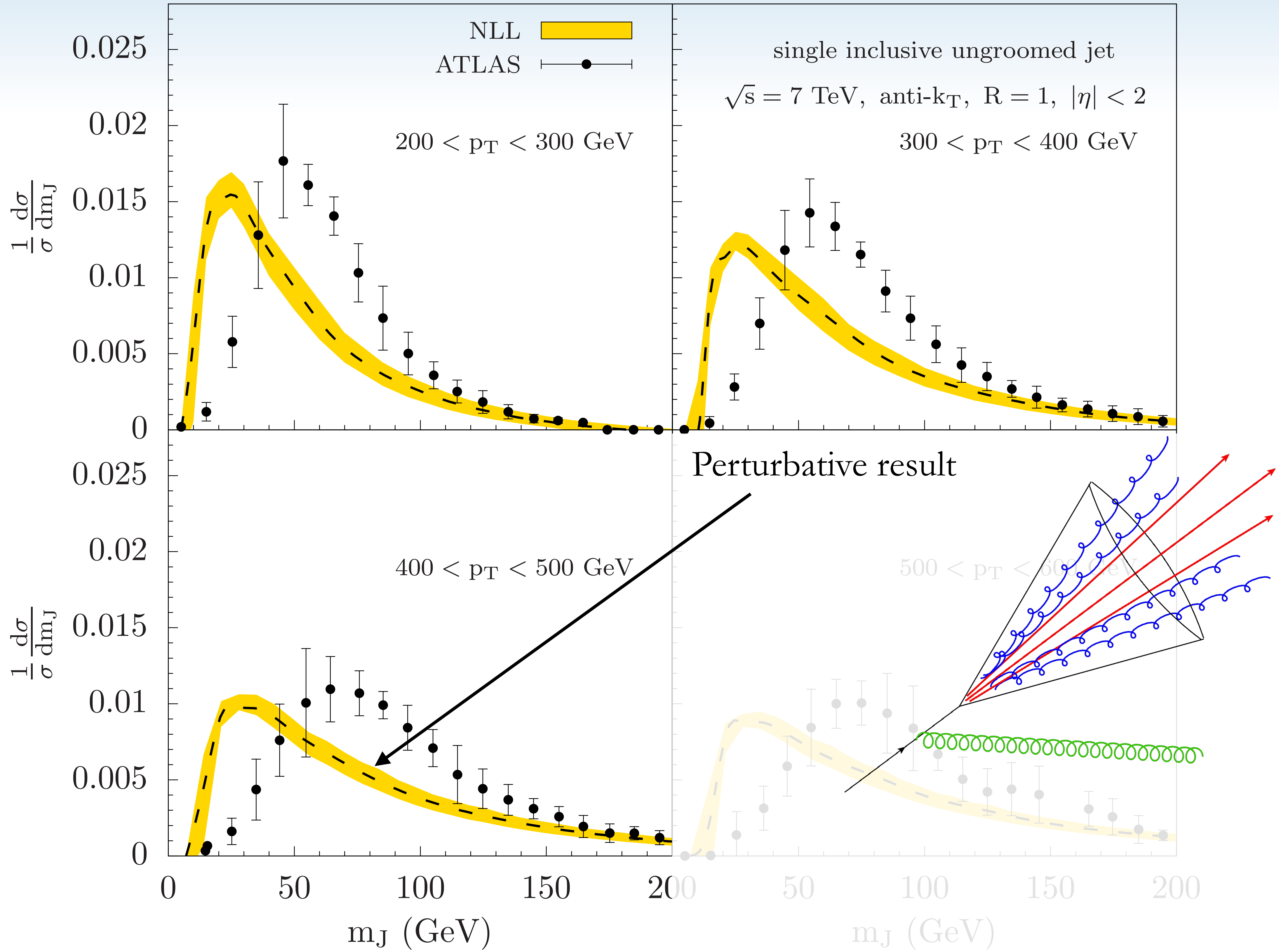




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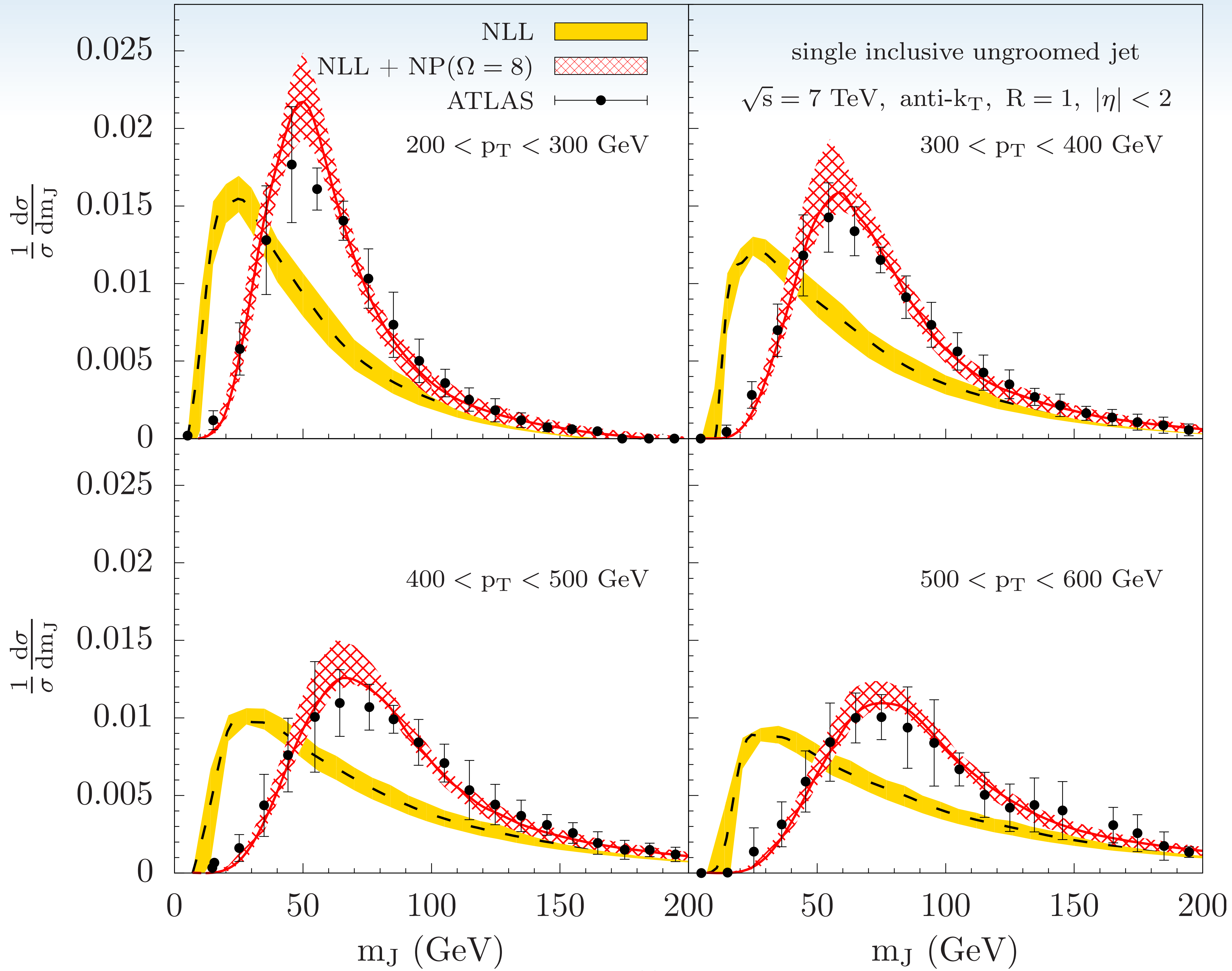
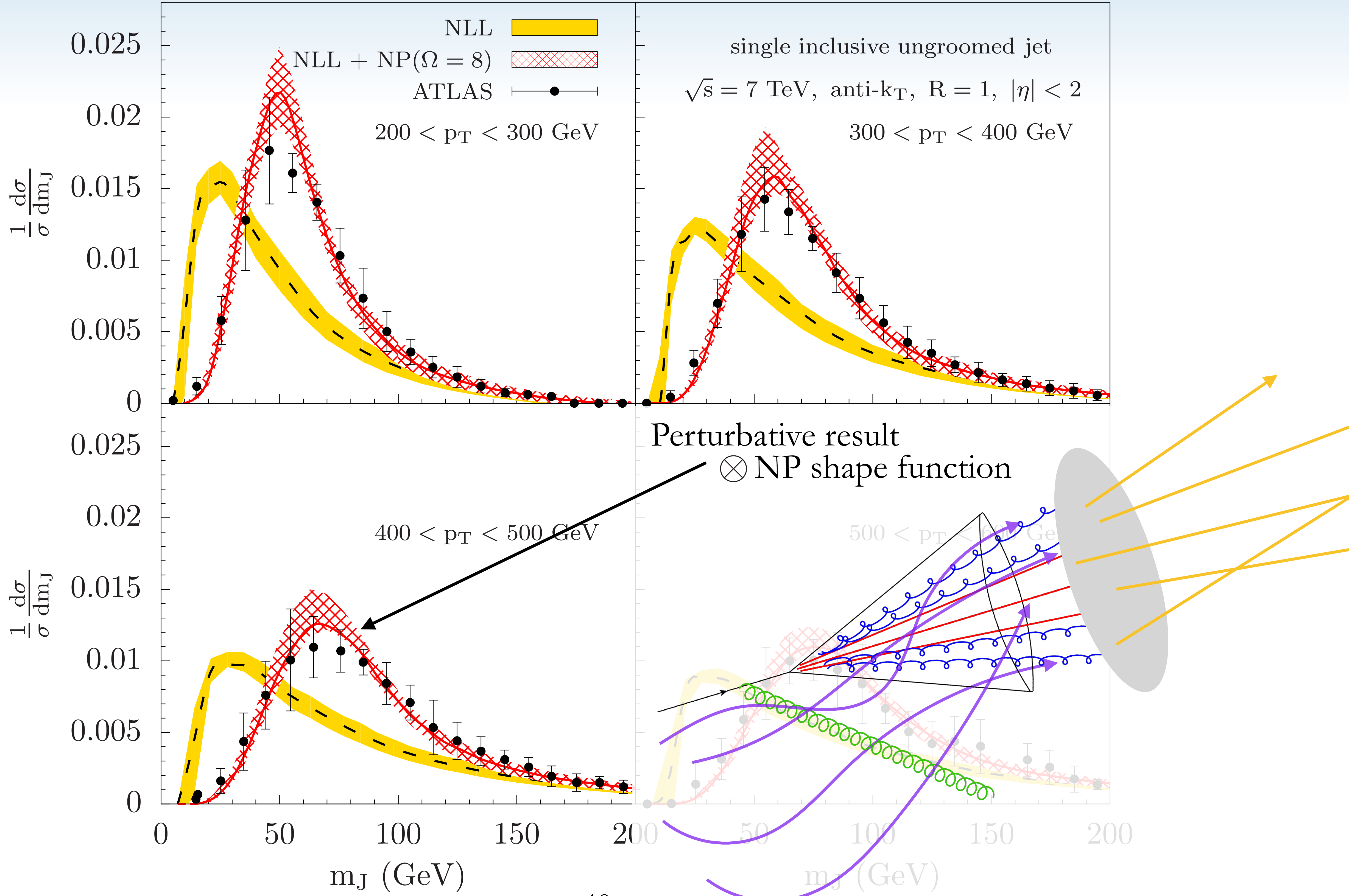





*Kang, KL, Liu, Ringer, arXiv:1803.03645*

# Phenomenology




*Kang, KL, Liu, Ringer, arXiv:1803.03645*

# Getting a better hold of MPI

- **Underlying Events (UE) are difficult to understand.**

  **How do we get a better hold of these contaminations in the jet?**

- **Hint : contamination generally from soft radiations.**

1. **Subtracted jet mass moments (See Yiannis's talk)**
   *Chien, Kang, KL, Makris, arXiv:1812.06977*
2. **Grooming**

# Soft Drop Grooming

- Underlying Events (UE) are difficult to understand.

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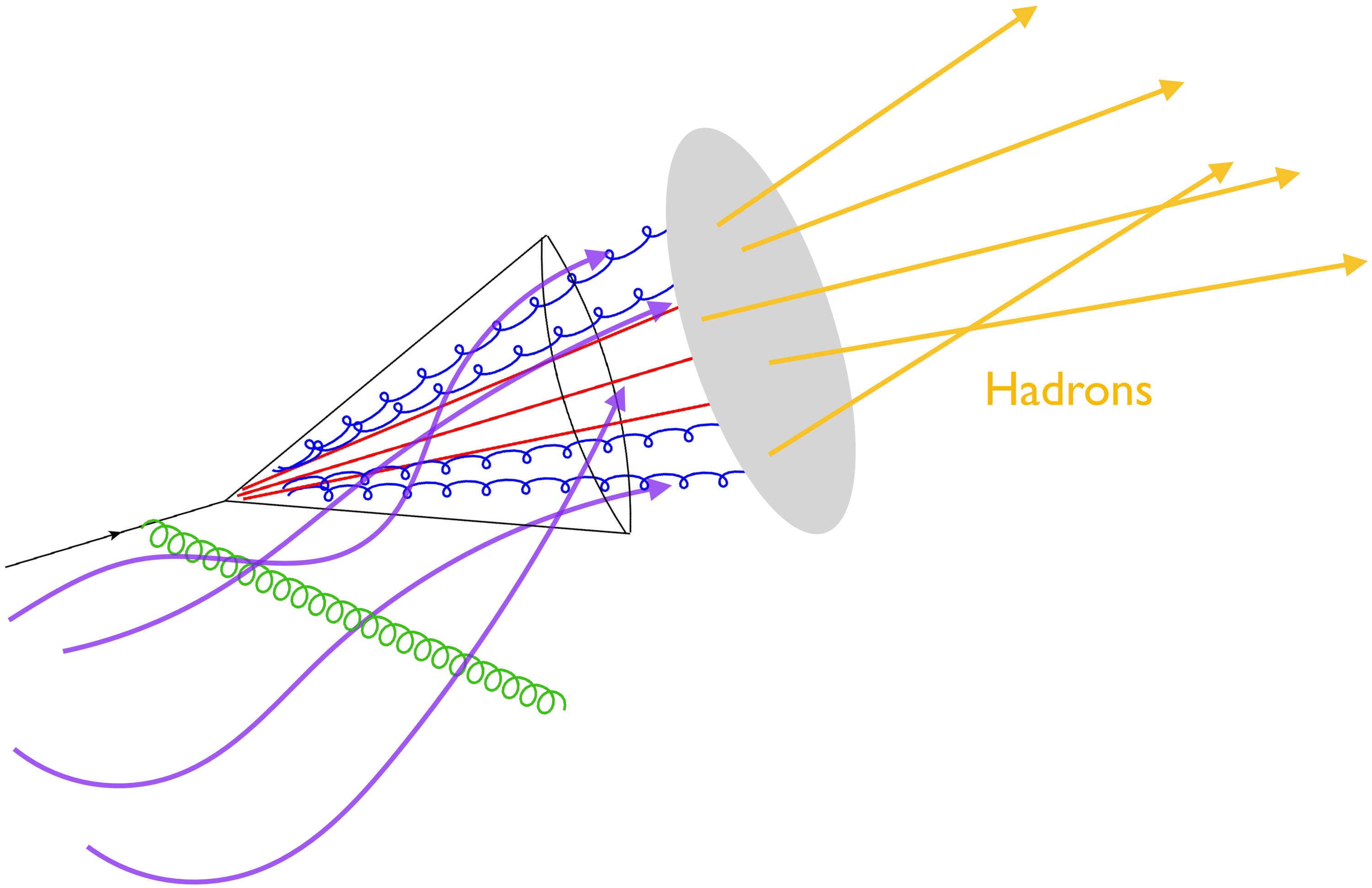

# Soft Drop Grooming

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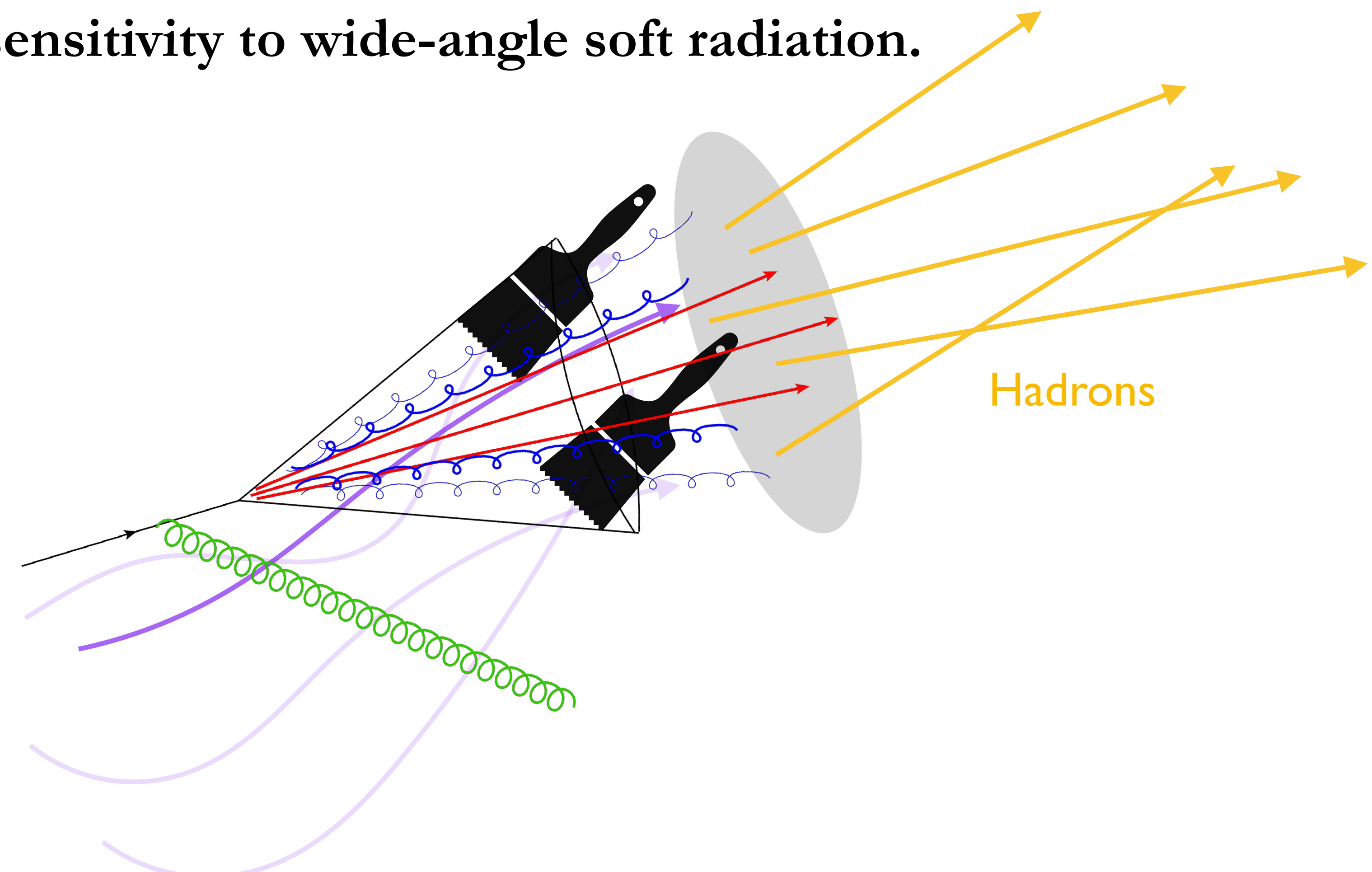
  **Groom** jets to reduce sensitivity to wide-angle soft radiation.



# Soft Drop Grooming

- **Underlying Events (UE) are difficult to understand.**

  **How do we get a better hold of these contaminations in the jet?**

- **Hint : contamination generally from soft radiations.**

  **Groom jets to reduce sensitivity to wide-angle soft radiation.**


- **Soft drop grooming algorithms:**

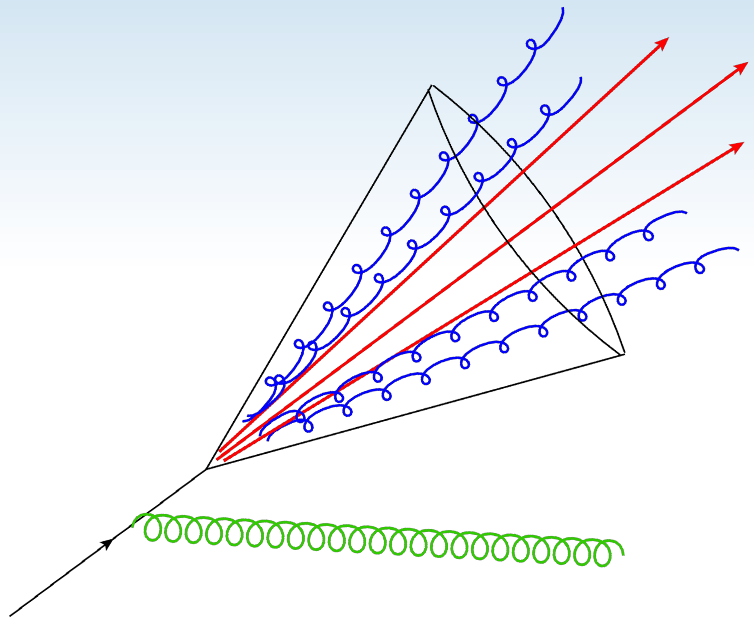
1. Reorder emissions in the identified jet according to their relative angle using C/A jet algorithm.

2. Recursively remove soft branches until soft drop condition is met:

$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{\rm cut} \left(\frac{R_{ij}}{R}\right)^{\beta}$$

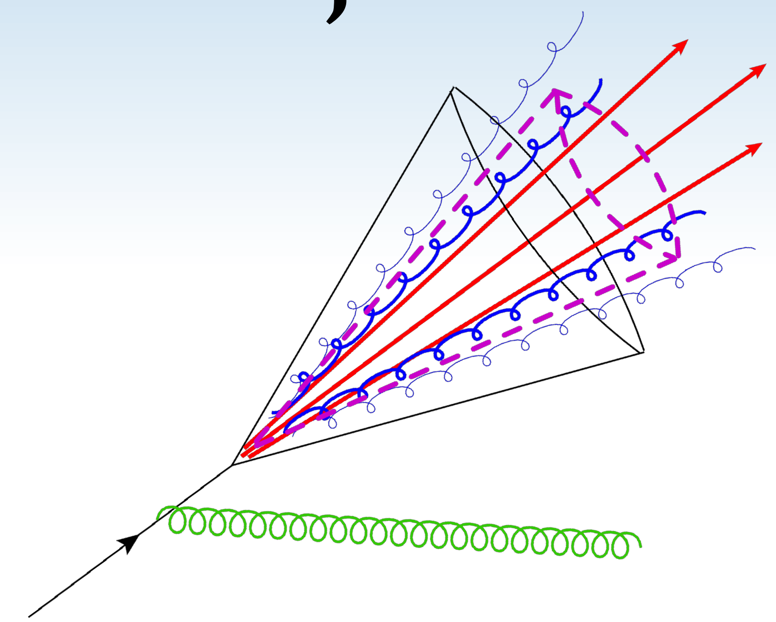
*Larkoski, Marzani, Soyez, Thaler `14*
*Frye, Larkoski, Schwartz, Yan `16*

# Relevant modes in the groomed jet



$$\tau_a \sim z\,\theta^{2-a}$$

$$z > z_{\text{cut}}(\theta/R)^{\beta}$$



- **The ungroomed case ( $\tau \ll R^2$ )**

**Hard-collinear**

$$\theta_H \sim R \qquad z_H \sim 1$$

**Collinear**

$$z_c \sim 1 \qquad \theta_c \sim \tau_a^{\frac{1}{2-a}}$$

**Collinear-soft**

$$\theta_s \sim R \qquad z_{cs} \sim \frac{\tau_a}{R^{2-a}}$$

- **The groomed case ( $\tau_{\text{gr}}/R^2 \ll z_{\text{cut}} \ll 1$ )**

**Hard-collinear**

$$\theta_H \sim R \qquad z_H \sim 1$$

**Collinear**

$$z_c \sim 1 \qquad \theta_c \sim \tau_a^{\frac{1}{2-a}}$$

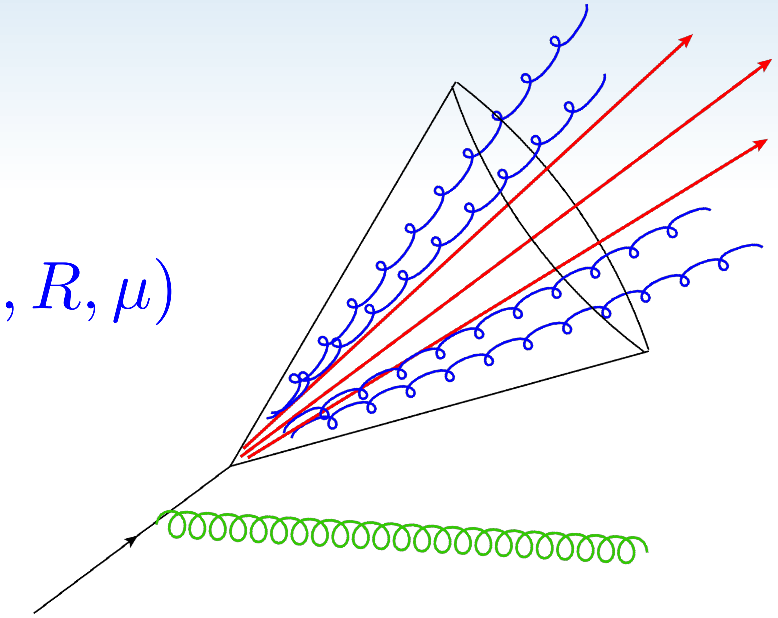
**$\notin$ *gr* soft**

$$\theta_{\notin \text{gr}} \sim R \qquad z_{\notin \text{gr}} \sim z_{\text{cut}}\left(\frac{\theta}{R}\right)^{\beta} = z_{\text{cut}}$$

**$\in$ *gr* soft**

$$z_{\in \text{gr}} \sim z_{\text{cut}}\left(\frac{\theta}{R}\right)^{\beta} = z_{\text{cut}}^{\frac{2-a}{2-a+\beta}}\left(\frac{\tau_a}{R^{2-a}}\right)^{\frac{\beta}{2-a+\beta}} \qquad \theta_{\in \text{gr}} \sim \left(\frac{\tau_a R^{\beta}}{z_{\text{cut}}}\right)^{\frac{1}{2-a+\beta}}$$

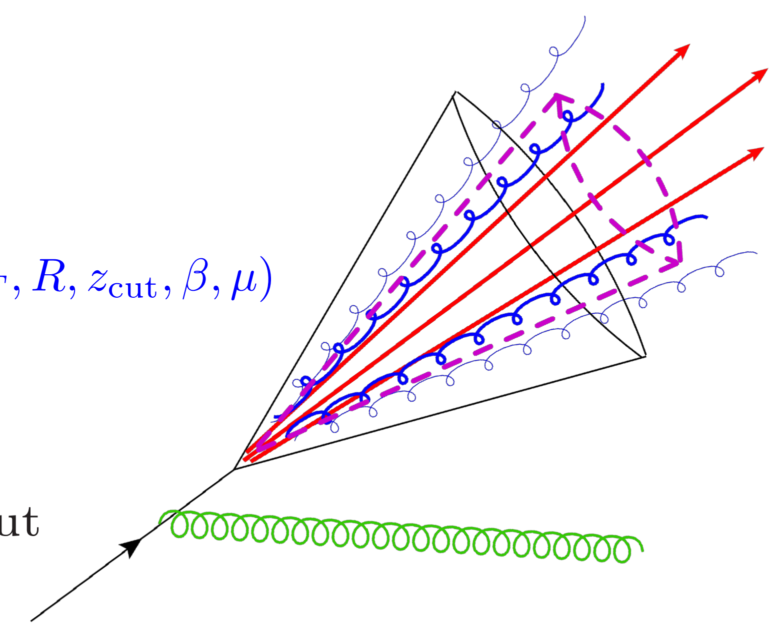
# Groomed jet mass factorization



- **The ungroomed case (** $\tau \ll R^2$ **)**

$$\mathcal{G}_i(z, p_T R, \tau, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) C_j(\tau, p_T, \mu) \otimes S_j(\tau, p_T, R, \mu)$$

- **Resums global logs** $\alpha_s^n \ln^n R$ **and** $\alpha_s^n \ln^{2n} \tau/R^2$



- **The groomed case (** $\tau_{\mathrm{gr}}/R^2 \ll z_{\mathrm{cut}} \ll 1$ **)**

$$\mathcal{G}_i(z, p_T R, \tau_{\mathrm{gr}}, z_{\mathrm{cut}}, \beta, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) S_j^{\notin \mathrm{gr}}(p_T, R, z_{\mathrm{cut}}, \beta, \mu) C_j(\tau, p_T, \mu) \otimes S_j^{\in \mathrm{gr}}(\tau, p_T, R, z_{\mathrm{cut}}, \beta, \mu)$$

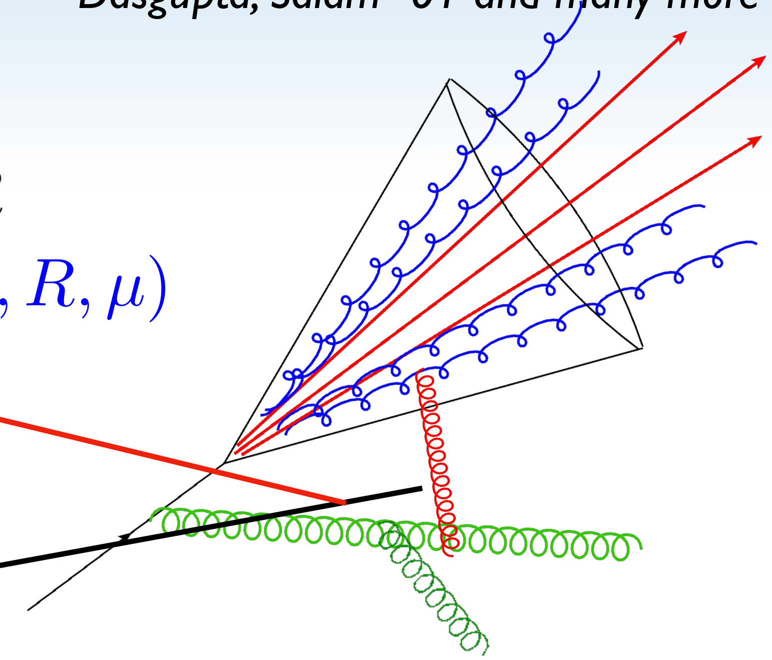
- **Resums global logs** $\alpha_s^n \ln^n R$**,** $\alpha_s^n \ln^{2n} \tau/R^2$**, and** $\alpha_s^n \ln^{2n} z_{\mathrm{cut}}$

# Non-global Logarithms

*Dasgupta, Salam `01 and many more*

- **The ungroomed case ( $\tau \ll R^2$ )**

$$\theta_H \sim R$$
$$\theta_s \sim R$$



$$\mathcal{G}_i(z, p_T R, \tau, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) C_j(\tau, p_T, \mu) \otimes S_j(\tau, p_T, R, \mu)$$

- **Non-global logs directly affect the jet mass spectrum.**

$$\alpha_s^n \ln^n(\tau/R^2) \qquad n \geq 2$$

# Non-global Logarithms

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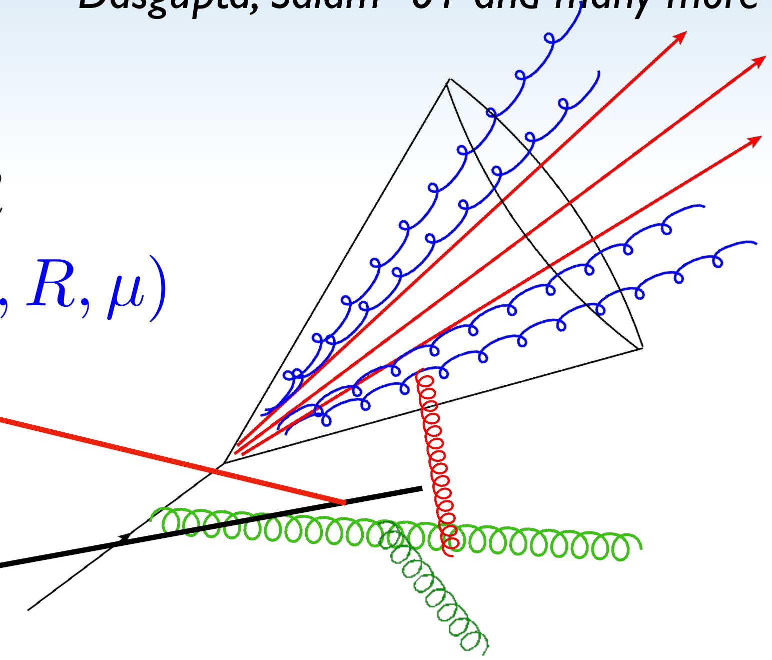


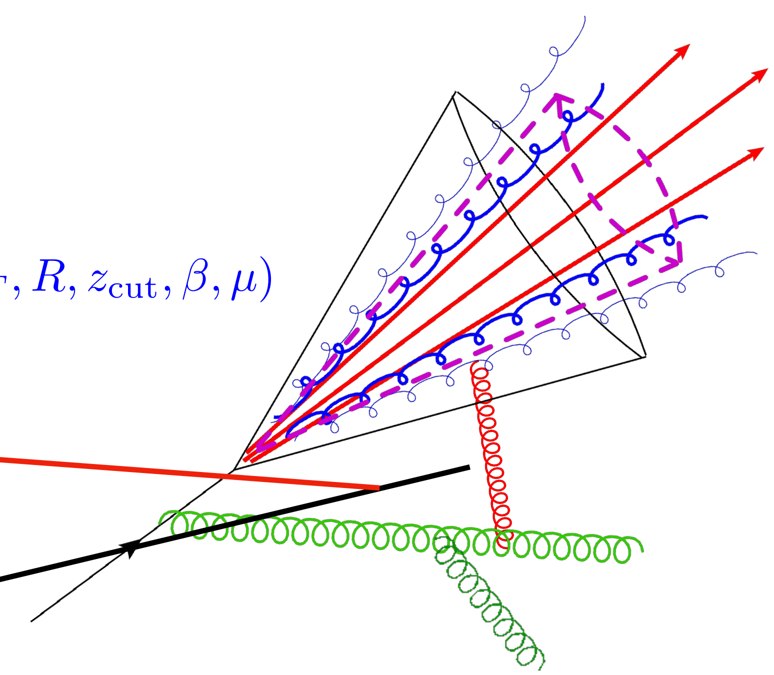
- **Non-global logs directly affect the jet mass spectrum.**

$$\alpha_s^n \ln^n(\tau/R^2) \qquad n \geq 2$$

- **The groomed case ( $\tau_{\rm gr}/R^2 \ll z_{\rm cut} \ll 1$ )**

$\theta_H \sim R$
$\theta_{\notin \rm gr} \sim R$

$$\mathcal{G}_i(z, p_T R, \tau_{\rm gr}, z_{\rm cut}, \beta, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) S_j^{\notin \rm gr}(p_T, R, z_{\rm cut}, \beta, \mu) C_j(\tau, p_T, \mu) \otimes S_j^{\in \rm gr}(\tau, p_T, R, z_{\rm cut}, \beta, \mu)$$



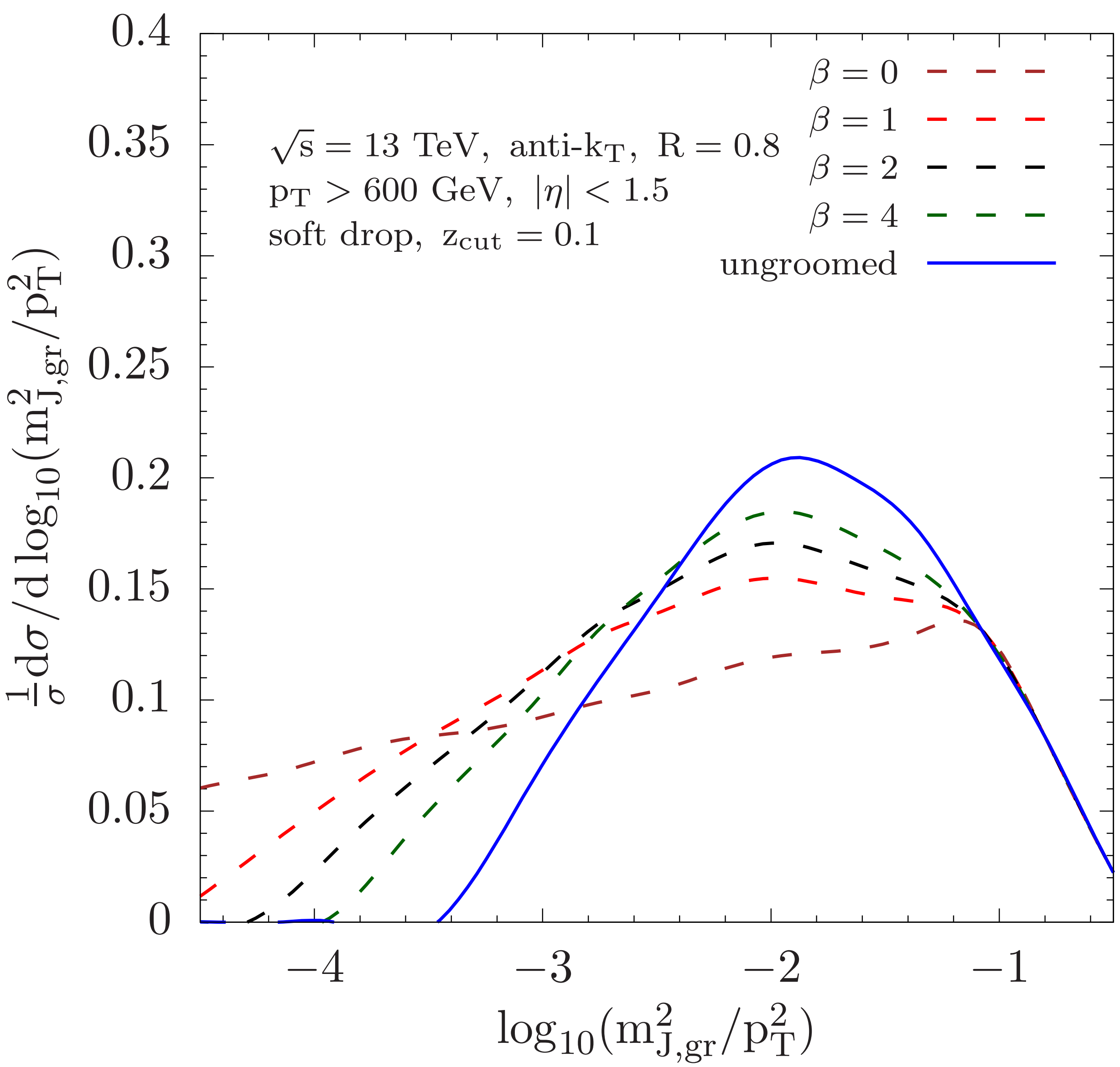
- **Non-global logs only indirectly affects the jet mass spectrum through normalization.**

$$\alpha_s^n \ln^n(z_{\rm cut}) \qquad n \geq 2$$

# Limit to the ungroomed case

- **Soft drop condition is passed trivially when $\beta \to \infty \Leftrightarrow$ returns ungroomed case.**

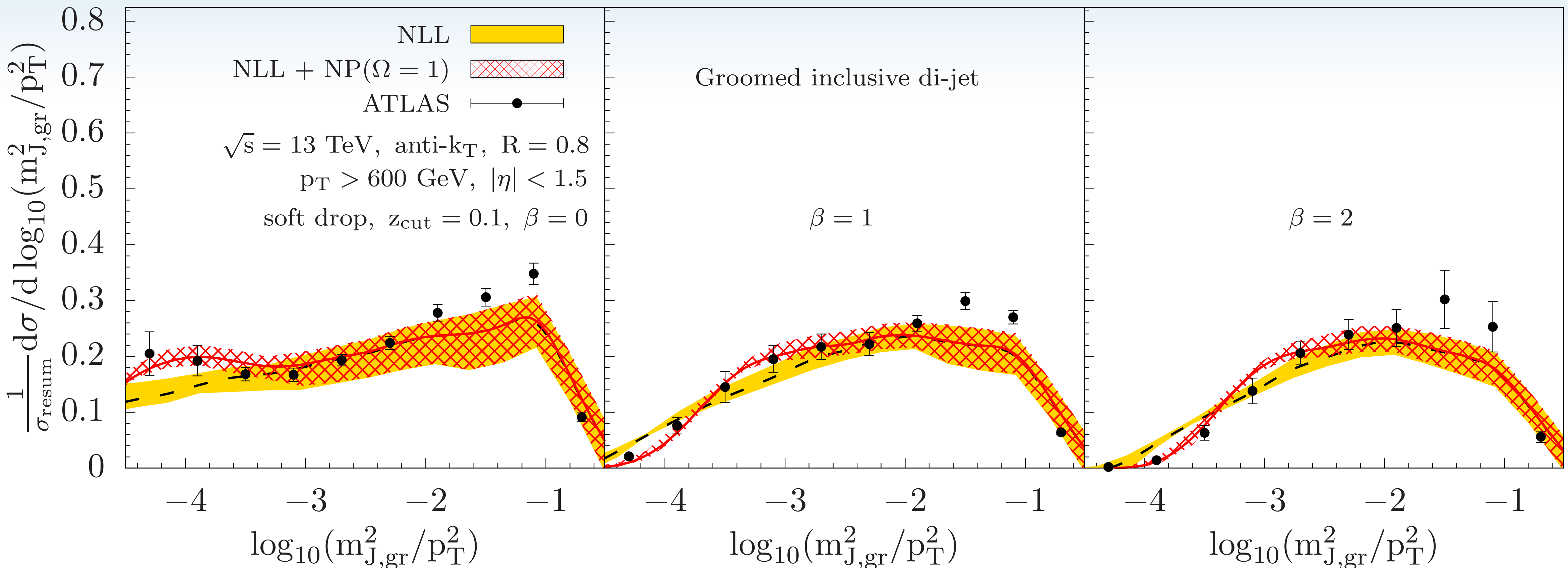
$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{R_{ij}}{R}\right)^{\beta} \to 0 \quad \textbf{when} \quad \beta \to \infty$$




**Checked both numerically and analytically.**

- **At $\tau_{\text{gr}} = z_{\text{cut}} R^2$, the groomed result transitions to the ungroomed case.**

# Phenomenology (groomed jet mass)



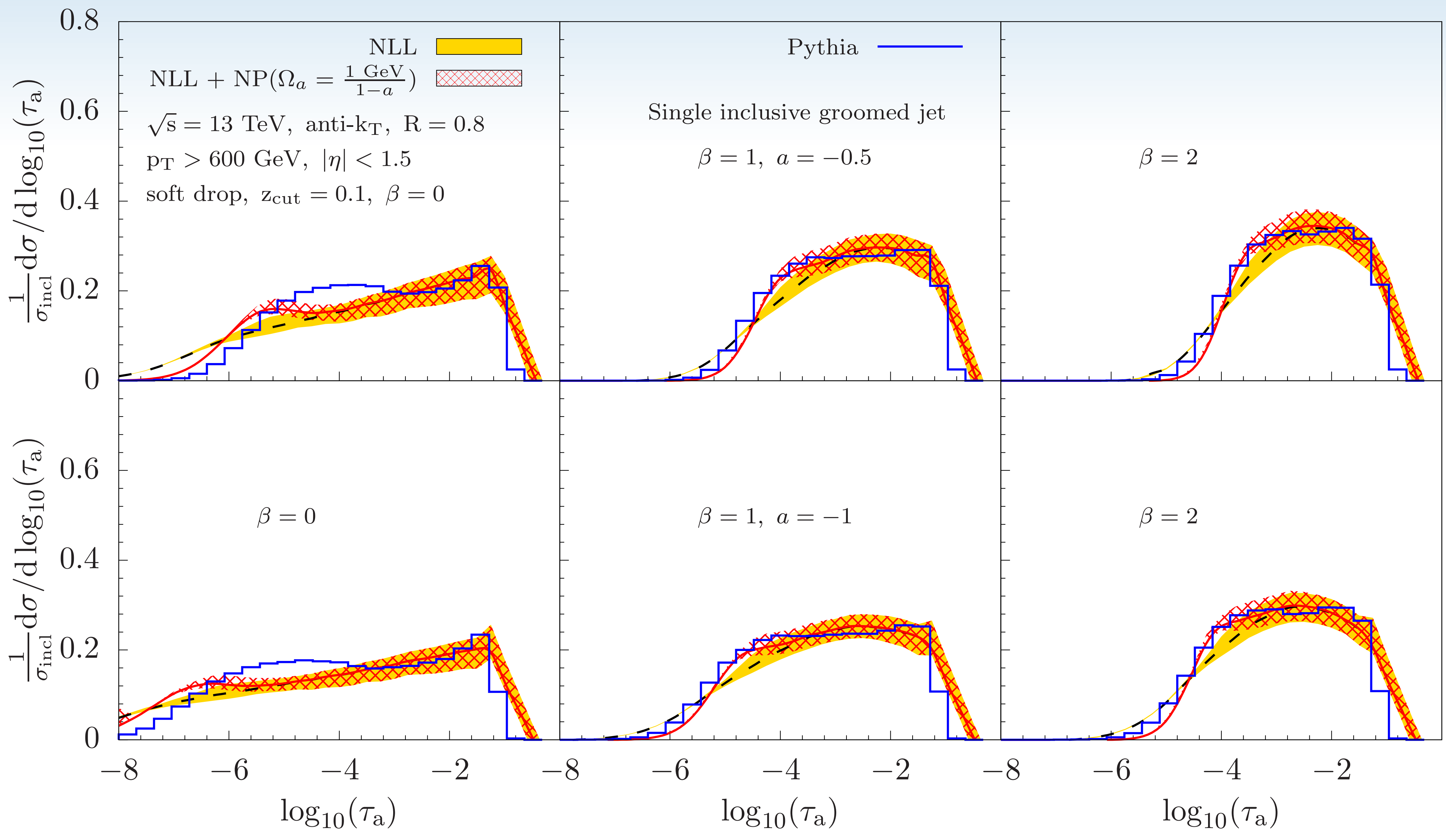

- Developed the formalism for single inclusive groomed jet mass cross-section.
- Shows very good agreement with the data.
- $\Omega_k = 1$ GeV $\Longrightarrow$ Reduced contamination as expected. NP effects mostly from hadronization.

*See also*
*ATLAS, arXiv:1711.08341*
*Larkoski, Marzani, Soyez, Thaler `14*
*Frye, Larkoski, Schwartz, Yan `16*



*Kang, KL, Liu, Ringer, arXiv:1803.03645*

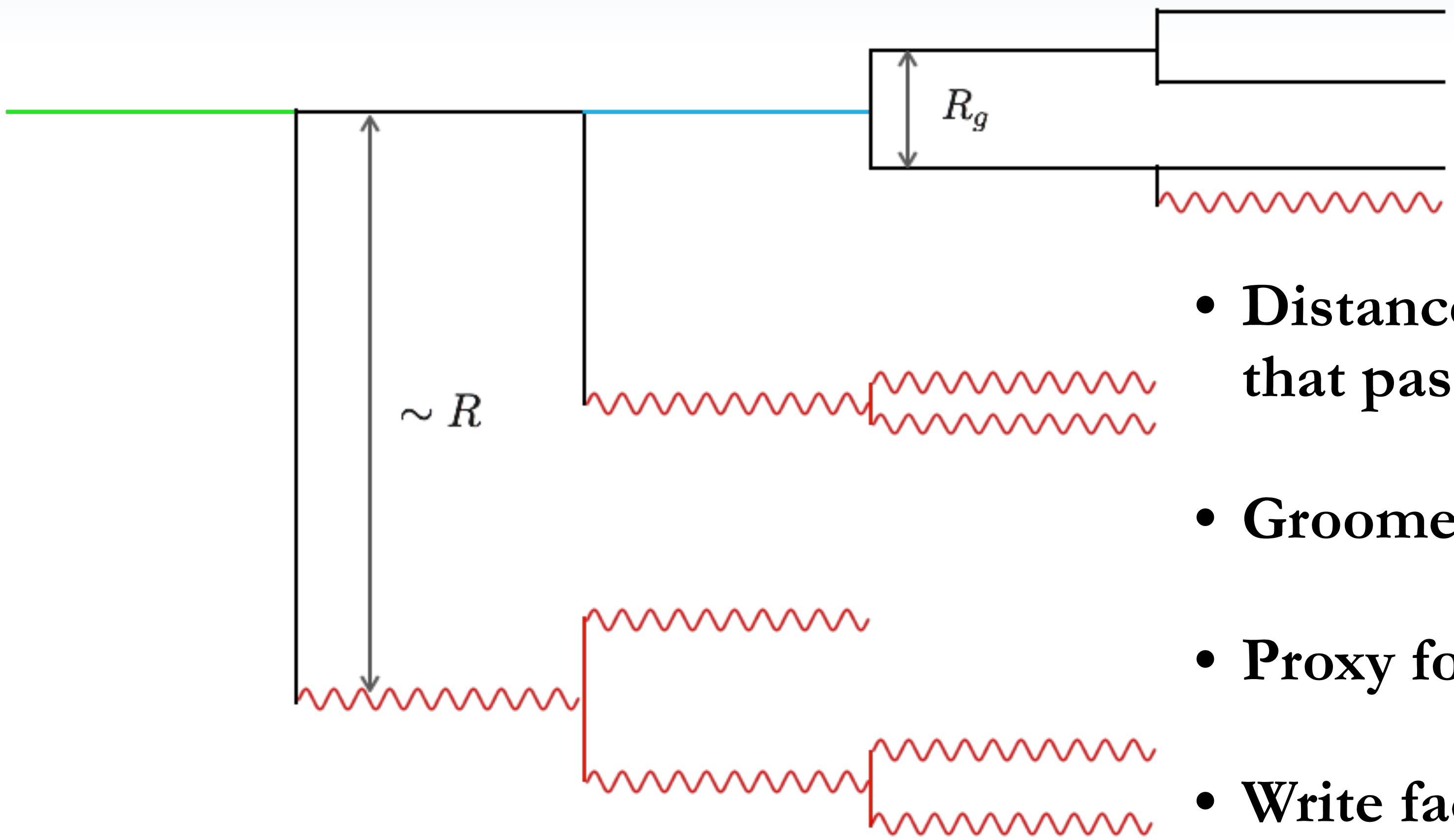
# Phenomenology




- General angularities show decent agreement with Pythia with reduced contamination from UE/PU.

*Kang, KL, Liu, Ringer, arXiv:1811.06983*

# Groomed Jet Radius, $R_g$




*Larkoski, Marzani, Soyez, Thaler `14*
*Tripathee, Xue, Larkoski, Marzani, Thaler`17*

- Distance between the two branches that passes the soft drop condition.
- Groomed jet area is approximately $\approx \pi R_g^2$
- Proxy for the sensitivity to contamination from pileup.
- Write factorization for cumulative distribution.

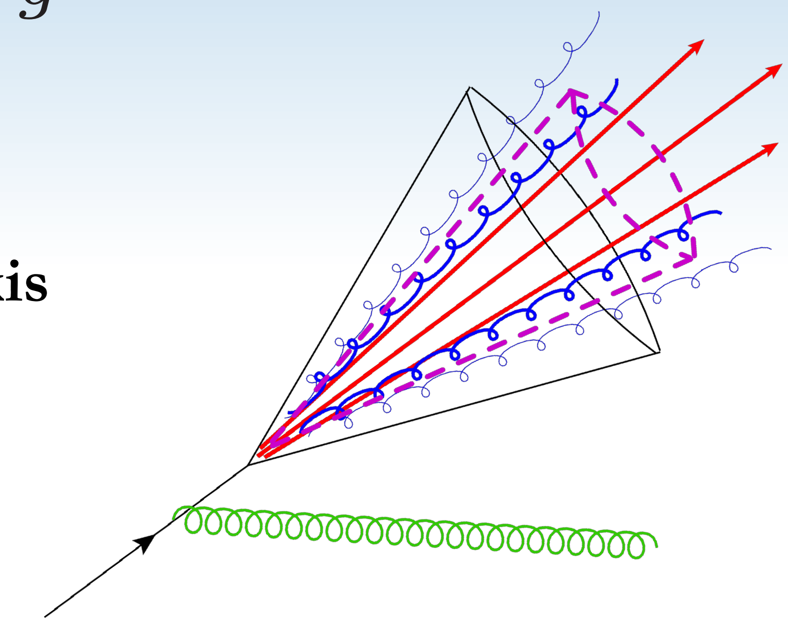
$$\frac{d\Sigma(\theta_g)}{d\eta dp_T} = \sum_{abc} f_a(x_a,\mu) \otimes f_b(x_b,\mu) \otimes H_{ab}^c(x_a, x_b, \eta, p_T/z, \mu) \otimes \mathcal{G}_c(z, p_T, \theta_g, \mu; z_{\rm cut}, \beta)$$



*Kang, KL, Liu, Ringer, In Preparation*

# Factorization for $R_g$

- $z_{\rm cut} \ll 1$ and $R_g \ll R$
- **For $z_{\rm cut} \ll 1$, groomed jet axis and ungroomed jet axis**



**Hard-collinear**

$$z_H \sim 1 \qquad \theta_H \sim R$$

**correlation**

**$\notin gr$ soft**

$$z_{\notin \rm gr} \sim z_{\rm cut}\left(\frac{\theta}{R}\right)^{\beta} = z_{\rm cut} \qquad \theta_{\notin \rm gr} \sim R$$

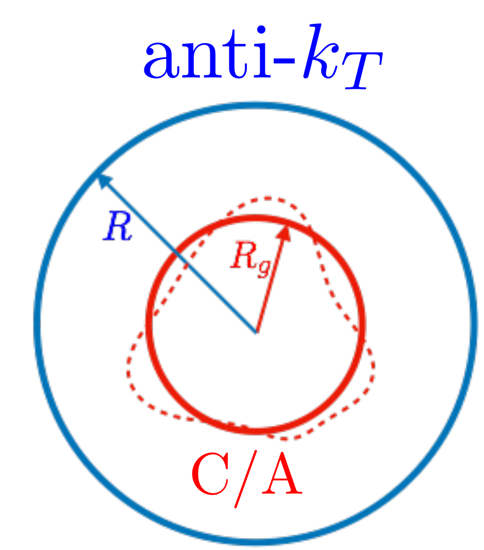
**Collinear**

$$z_c \sim 1 \qquad \theta_c \sim R_g$$

**correlation**

**$\in gr$ soft**

$$z_{\in \rm gr} \sim z_{\rm cut}\left(\frac{\theta}{R}\right)^{\beta} = z_{\rm cut}\left(\frac{R_g}{R}\right)^{\beta} \qquad \theta_{\in \rm gr} \sim R_g$$



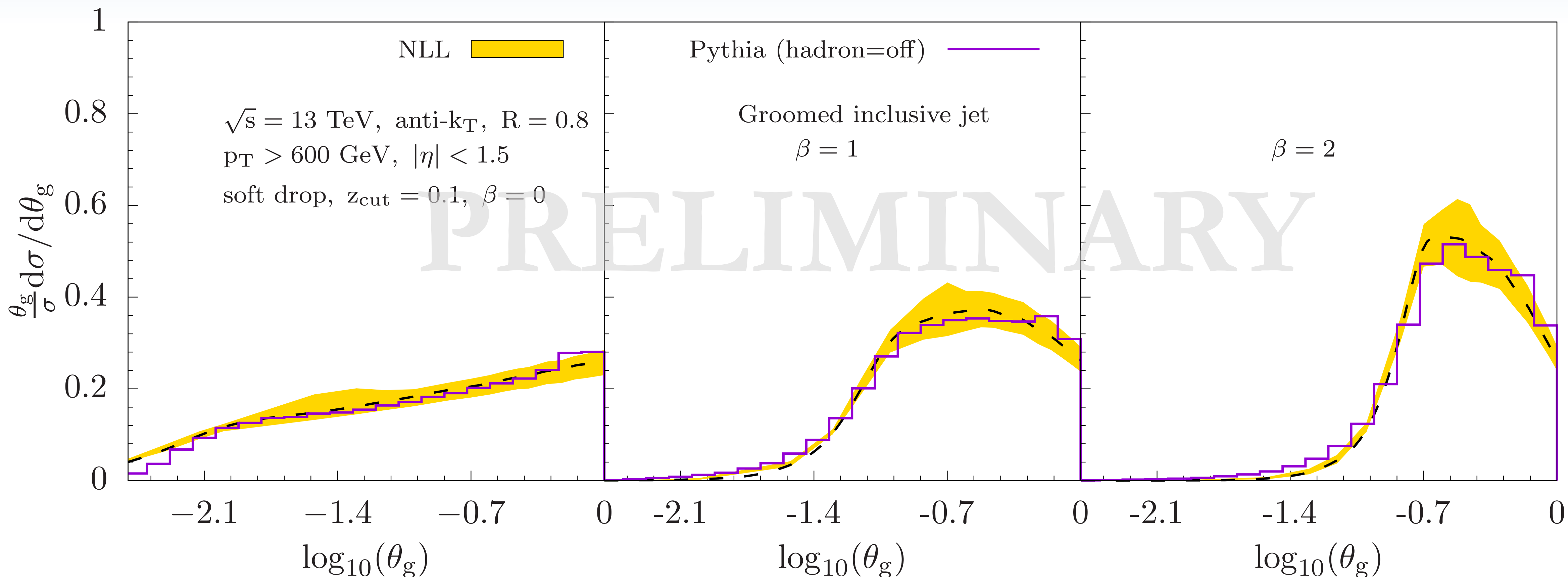

*Kelley, Walsh, Zuberi `12*
*Becher, Neubert, Rothen, Shao `15, `16*

$$\mathcal{G}_c(z, p_T, R, R_g, \mu; z_{\rm cut}, \beta) = \sum_i \sum_n \mathcal{H}^n_{c\to i}(z, p_T R, \mu) \otimes_\Omega S^{\notin \rm gr}_{i,n}(z_{\rm cut} p_T R, \mu) \sum_m C^m_i(p_T R_g, \mu) \otimes_\Omega S^{\in \rm gr}_{i,m}(\theta_g z_{\rm cut} p_T R, \mu; \beta)$$



*Kang, KL, Liu, Ringer, In Preparation*

# Phenomenology (groomed jet radius)




$$\theta_g = \frac{R_g}{R}$$

- Shows very good agreement without having to account for NGLs and clustering logs.



*Kang, KL, Liu, Ringer, In Preparation*

# Conclusions

- Formalisms for studying semi-inclusive jet production with and without a substructure measurement were introduced.
- Discussed phenomenology of ungroomed jet mass in the LHC.
- Discussed various non-perturbative effects.
- Discussed soft drop grooming which reduce contaminations from the uncorrelated radiations.
- Discussed factorization of groomed angularities and groomed jet radius, and demonstrated reduced contamination and good agreements with Pythia.