Jet angularities

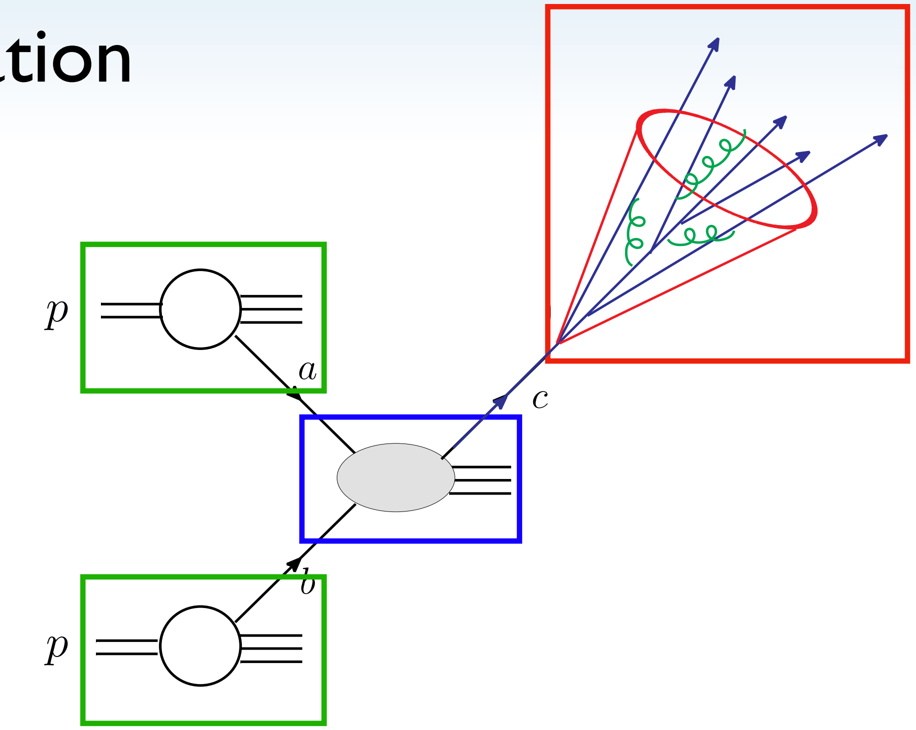
SCET calculations

Kyle Lee
LBNL

CERN,
Jets and EW Bosons WG
10/25/2021

Semi-inclusive jet production

Hard-collinear factorization



Often small

$$\frac{d\sigma^{pp\to \text{jet}(\rho)X}}{dp_T\, d\eta\, d\rho} = \sum_{a,b,c} \underset{\Lambda_{\text{QCD}}}{f_a \otimes f_b} \otimes \underset{p_T}{H_{ab}^c} \otimes \underset{p_T R}{\mathcal{G}_c^{\text{jet}}(\rho)} [1 + \mathcal{O}(R^2)]$$

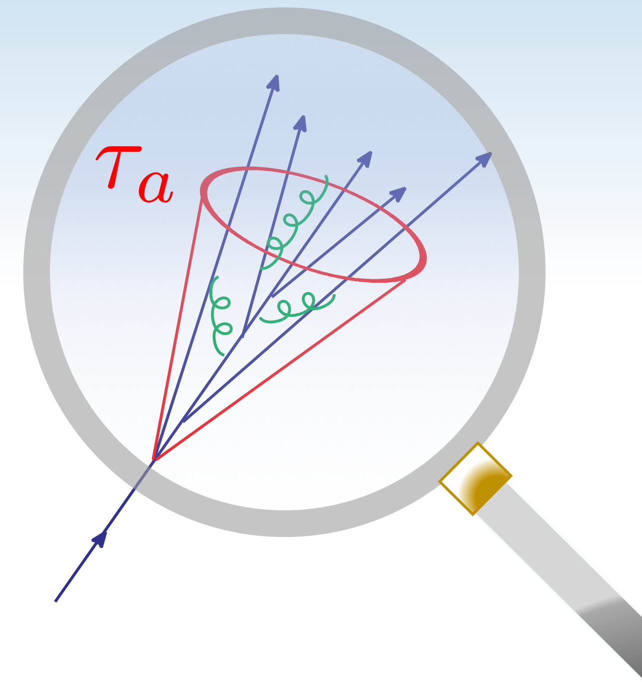
- **Resums large logs of** $\alpha_s^n \ln^n R$

- Sensitive to the jet substructure
  i.e. jet angularities

Kang, Ringer, Vitev `16
Cal, Ringer, Waalewijn `19

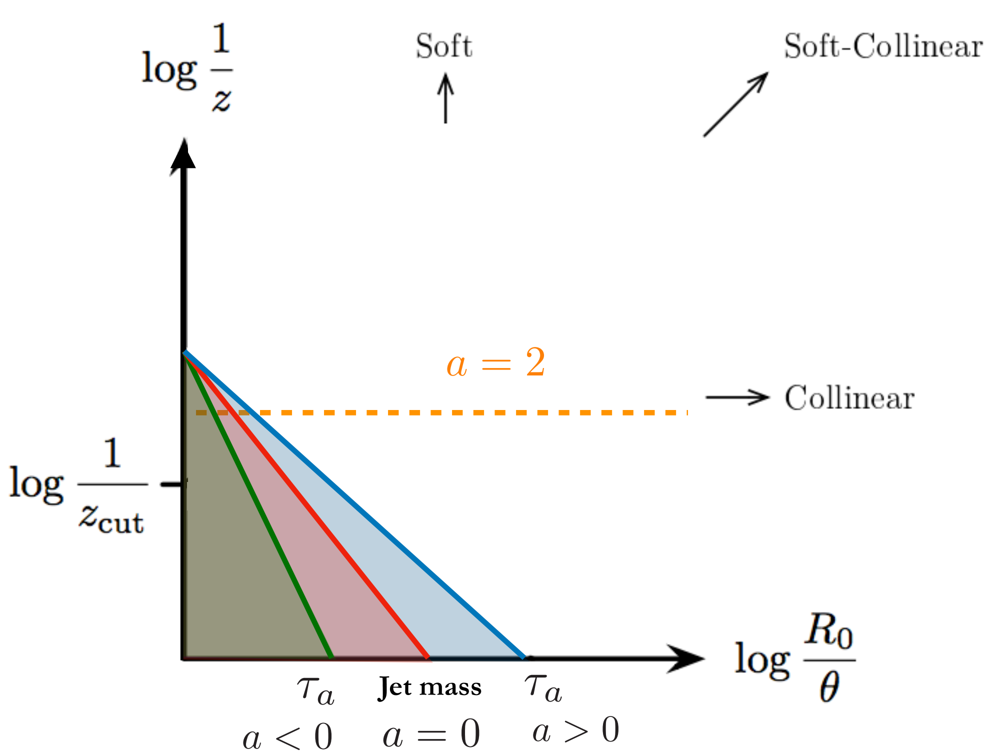
Jet angularity τ_a

$$\frac{d\sigma^{pp\to \text{jet}(\tau_a)X}}{dp_T\, d\eta\, d\tau_a} = \sum_{a,b,c} \underset{\Lambda_{\rm QCD}}{f_a \otimes f_b} \otimes \underset{p_T}{H_{ab}^c} \otimes \underset{p_T R}{\boxed{\mathcal{G}_c(\tau_a)}}$$

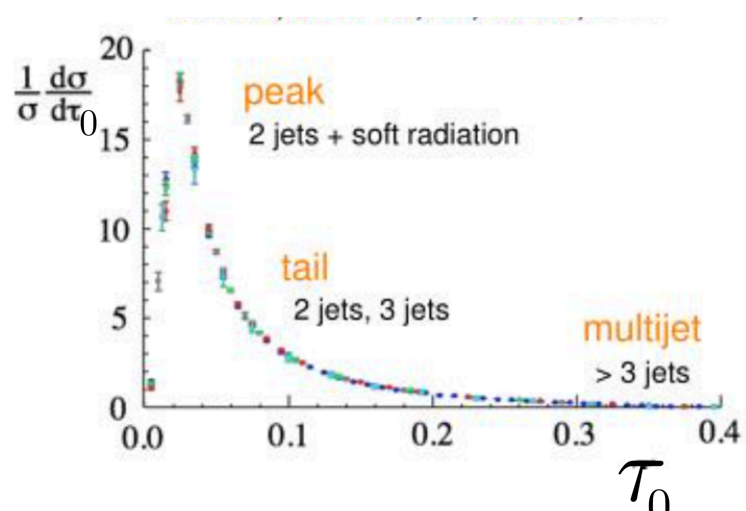


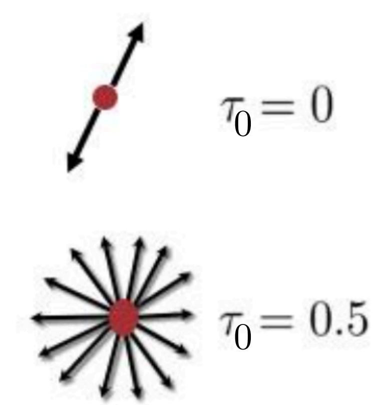
$$\tau_a = \frac{1}{p_T}\sum_{i\in J} p_{T,i}(\Delta R_{iJ})^{2-a}$$ **pp jets**

- **A generalized class of IR safe observables for** $-\infty < a < 2$
- **Parameter** a **gives varying sensitivity to collinear radiations.**



$$\tau_a = \frac{1}{Q}\sum_{i\in N} |\boldsymbol{p}_i^\perp| e^{-\eta_i(1-a)}$$ **event shapes**





Jet angularity τ_a

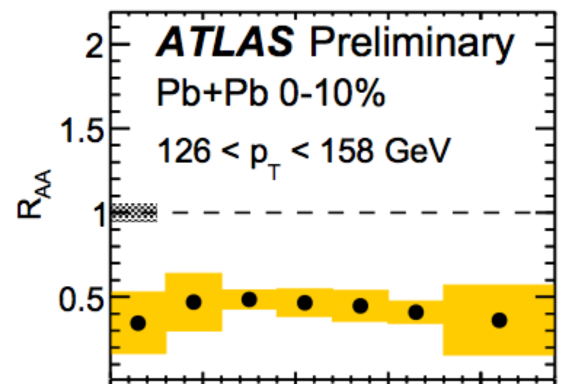
$$\frac{d\sigma^{pp\to \mathrm{jet}(\tau_a)X}}{dp_T\, d\eta\, d\tau_a} = \sum_{a,b,c} \underset{\Lambda_{\mathrm{QCD}}}{f_a \otimes f_b} \otimes \underset{p_T}{H_{ab}^c} \otimes \underset{p_T R}{\boxed{\mathcal{G}_c(\tau_a)}}$$

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

- A generalized class of IR safe observables for $-\infty < a < 2$
- Parameter a gives varying sensitivity to collinear radiations.

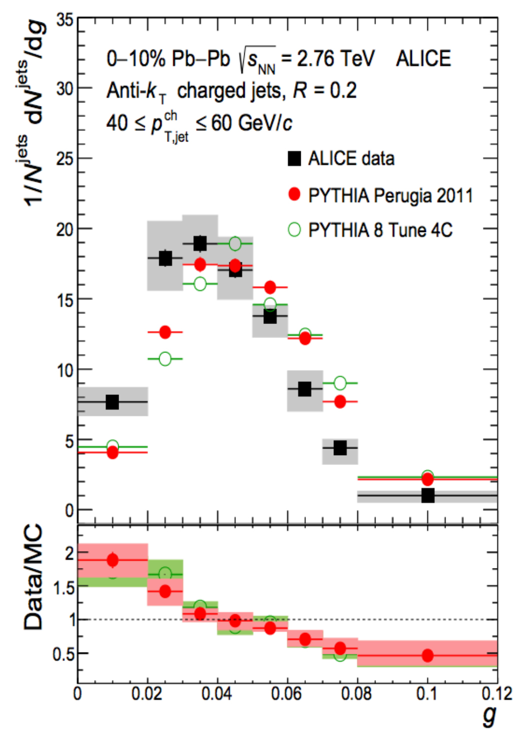
$a=0$

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



$a=1$

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



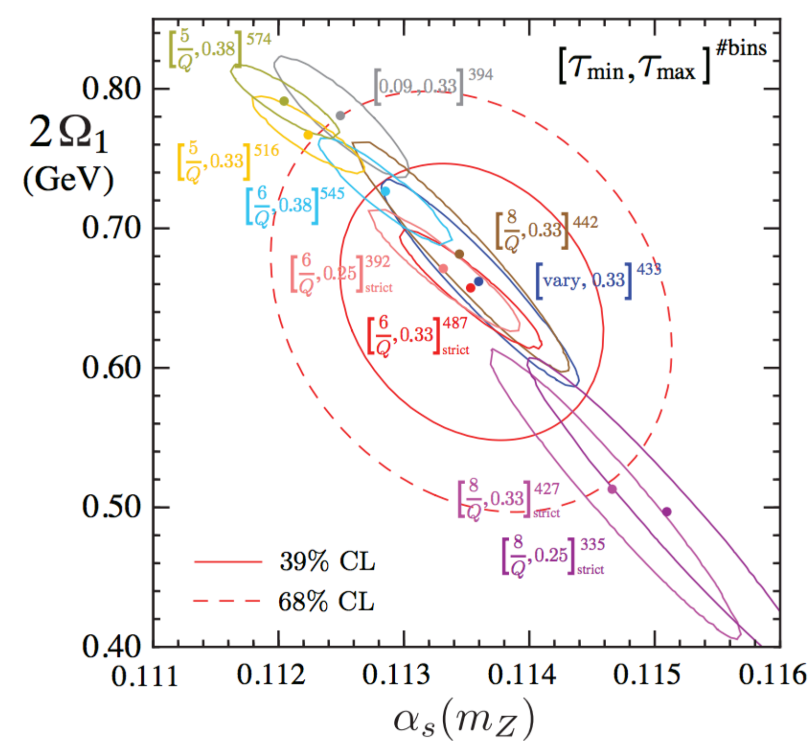
Medium modification

universal NP hadronization

$$\Omega_a^{\mathrm{had}} = \frac{\Omega_{a=0}^{\mathrm{had}}}{1-a}$$

$$\Omega_{a=0}^{\mathrm{had}} = \langle 0|\mathcal{O}|0\rangle \sim 1\,\mathrm{GeV}$$

α_s **extraction**



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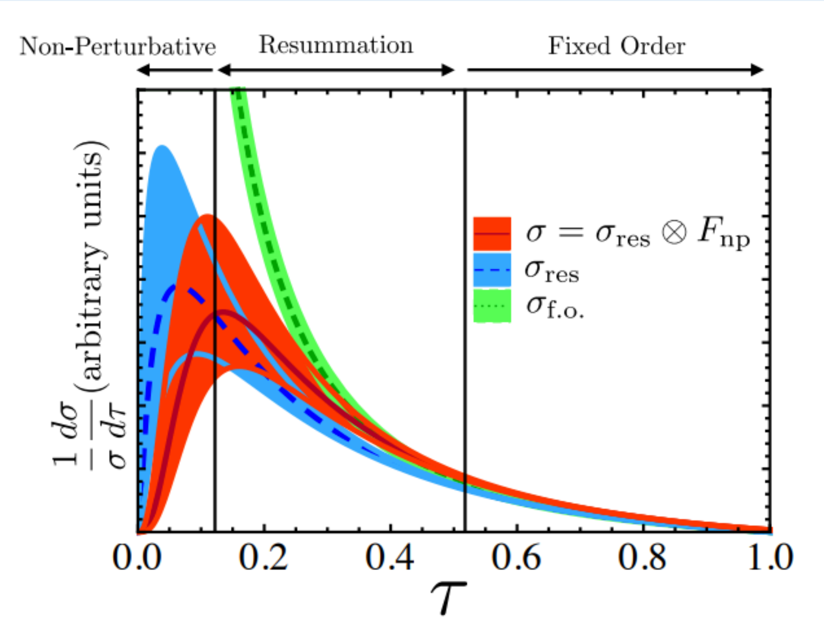
Factorization for the jet angularity



Perturbative Resummation + Fixed order + NP

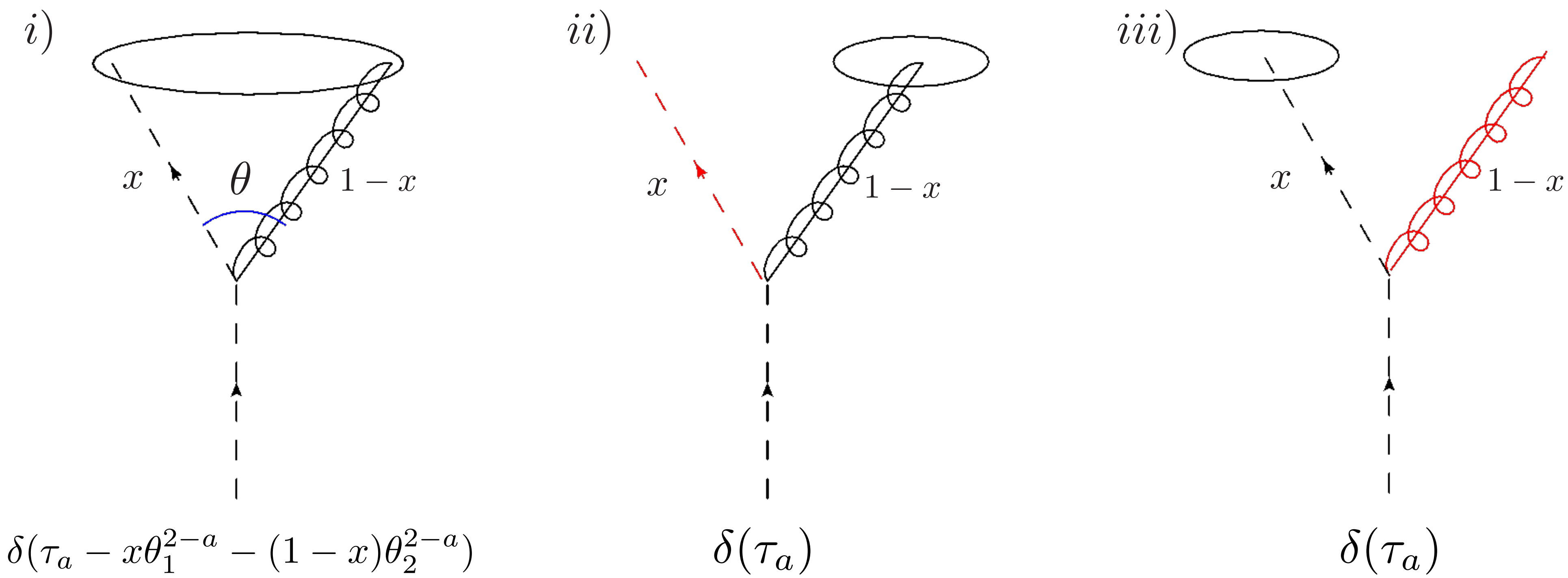
$$\mathcal{G}_i(z, p_T R, \tau_a, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) C_j(\tau_a, p_T, \mu) \otimes S_j(\tau_a, p_T, R, \mu)$$

$$p_T R \qquad p_T\, \tau_a^{\frac{1}{2-a}} \qquad \frac{p_T\, \tau_a}{R^{1-a}}$$

$$+\mathcal{O}(\tau_a/R^{2-a}) + \mathcal{O}(\Lambda_{\rm QCD})$$

Fixed order

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



- **Large logarithms of** $\alpha_s^n \ln^{2n} \tau_a/R^{2-a}$

Kang, KL, Liu, Ringer, `18
Kang, KL, Ringer, `18

Factorization for the jet angularity

Perturbative Resummation $+$ Fixed order $+$ NP

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

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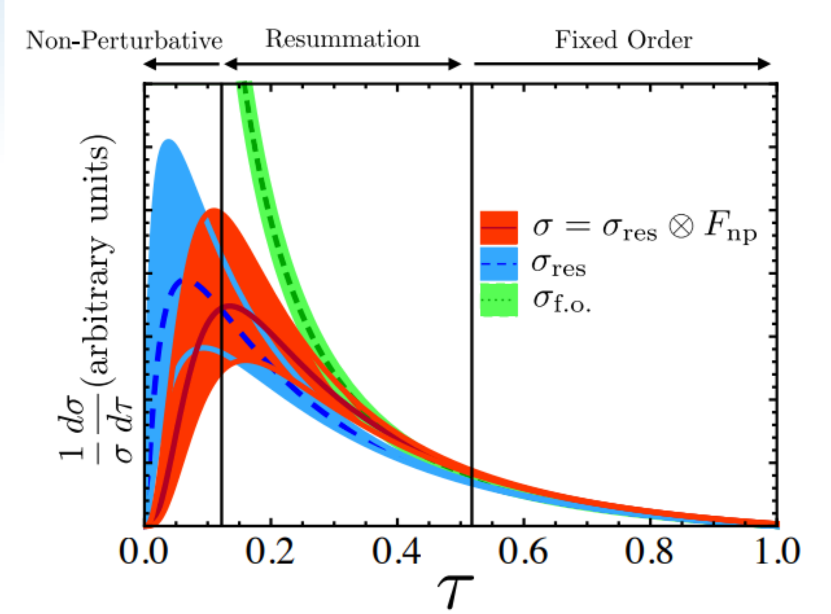


Resummation

Relevant modes for $\tau_a \ll R^{2-a}$

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

- **Resums large logs of** $\alpha_s^n \ln^{2n}\tau_a/R^{2-a}$

Collinear

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

(Collinear-)soft

$$\theta_s\sim R \qquad z_{cs}\sim\frac{\tau_a}{R^{2-a}} \qquad \mu_S\sim\frac{p_T\tau_a}{R^{1-a}}$$

Hard-collinear

$$\theta_{\mathcal{H}}\sim R \qquad z_{\mathcal{H}}\sim 1 \qquad \mu_{\mathcal{H}}\sim p_T R$$

Kang, KL, Liu, Ringer, `18
Kang, KL, Ringer, `18

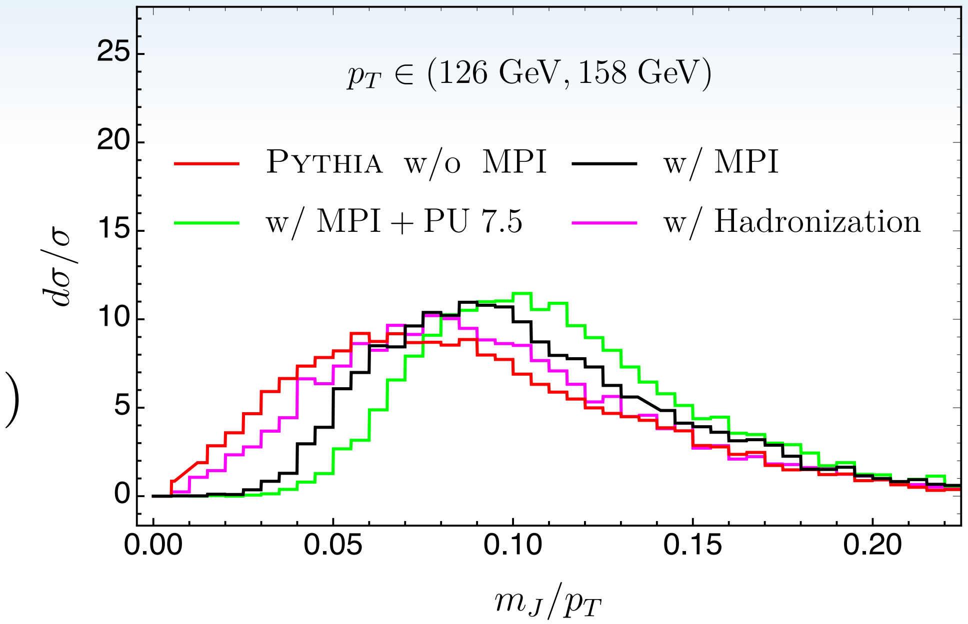
Factorization for the jet angularity

Perturbative Resummation $+$ Fixed order $+$ NP

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

$$p_T R \qquad p_T\,\tau_a^{\frac{1}{2-a}} \qquad \frac{p_T\,\tau_a}{R^{1-a}}$$

$$+\mathcal{O}(\tau_a/R^{2-a}) + \mathcal{O}(\Lambda_{\mathrm{QCD}})$$



Non-perturbative effects

$\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$ **softest scale gives the dominant NP corrections**

$$\frac{d\sigma}{dp_T d\eta d\tau_a} = \int dk F_a(k) \frac{d\sigma^{\mathrm{pert}}}{dp_T d\eta d\tau_a}\left(\tau_a - \frac{R^{1-a}}{p_T}k\right); \qquad \Omega_a = \int dk\, k\, F_a(k)$$

This shifts the first moment of the distribution to

$$M_1 \equiv \frac{1}{\sigma_0}\int d\tau_a \tau_a \frac{d\sigma}{d\tau} = M_1^{\mathrm{pert}} + \frac{R^{1-a}}{p_T}\Omega_a \qquad \textbf{where} \qquad \Omega_a = \Omega_a^{\mathrm{had}} + \boxed{\Omega^{\mathrm{MPI}}}$$

non-universal

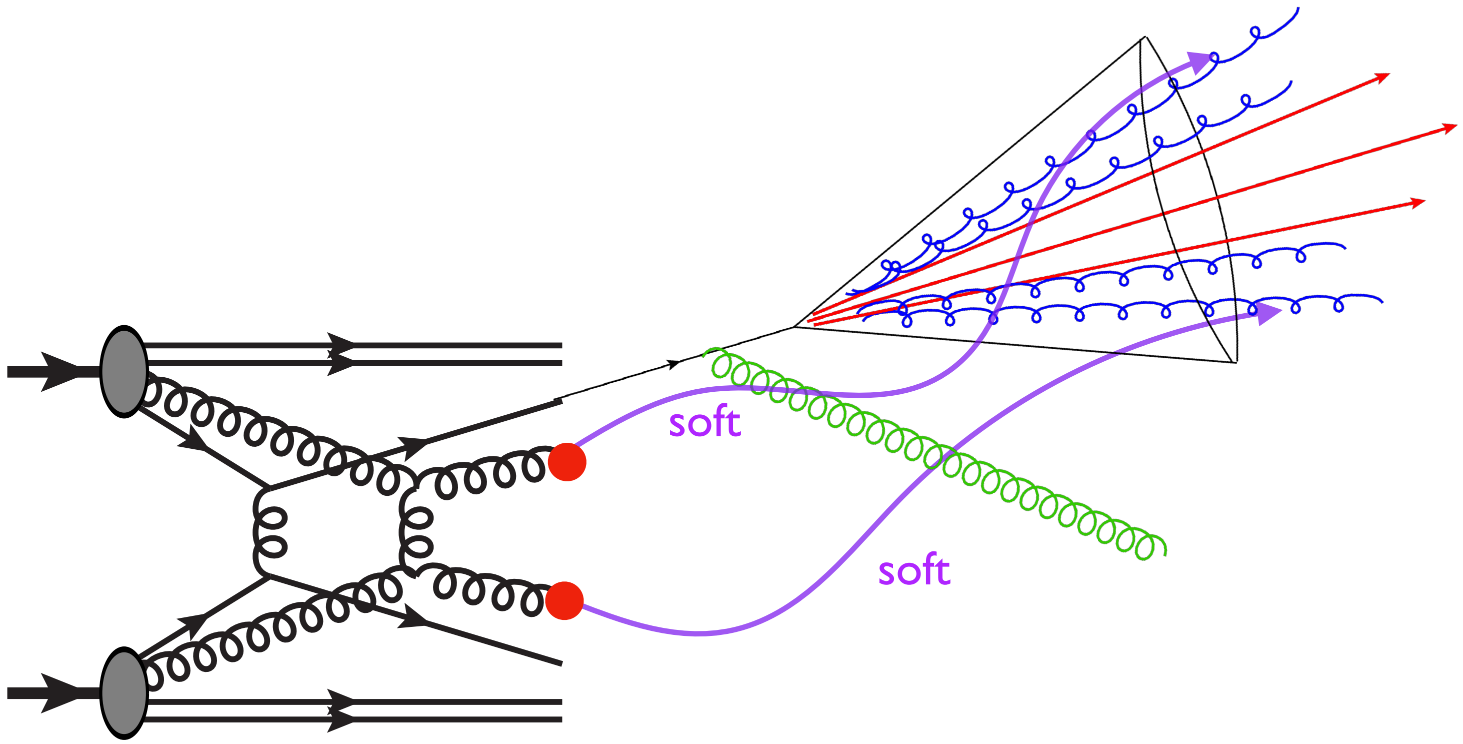
$$\Omega_a^{\mathrm{had}} = \frac{\Omega_{a=0}^{\mathrm{had}}}{1-a} \qquad \Omega_{a=0}^{\mathrm{had}} = \langle 0|\mathcal{O}|0\rangle \sim 1\,\mathrm{GeV}$$ **is universal**

Lee, Sterman `07

Kang, KL, Liu, Ringer, `18
Kang, KL, Ringer, `18

Non-perturbative Effects

- **Non-perturbative effects:**



- **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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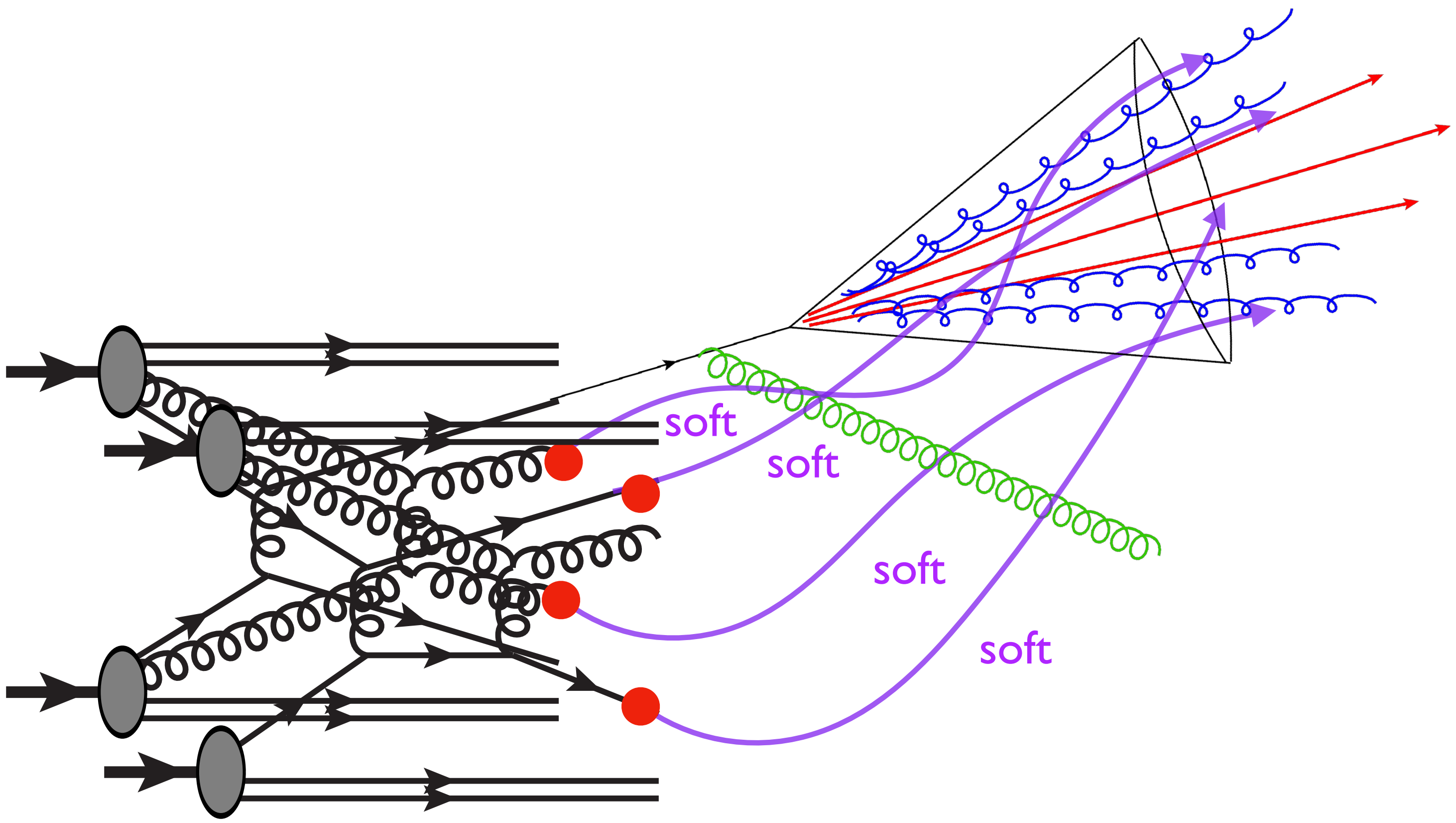

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- **Pileups**
  Secondary proton collisions in a bunch may enter and contaminate jet.

Non-perturbative Effects

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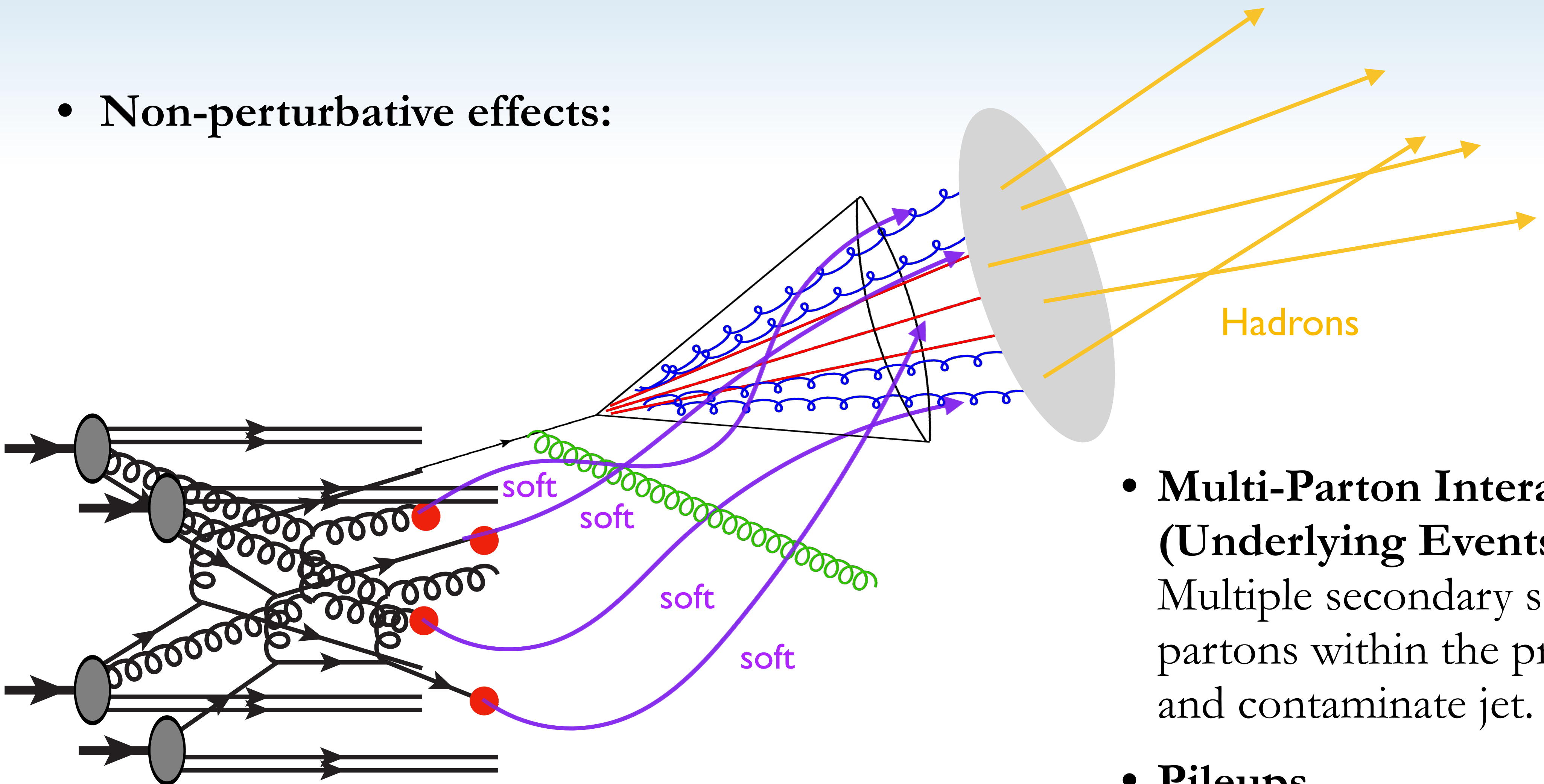
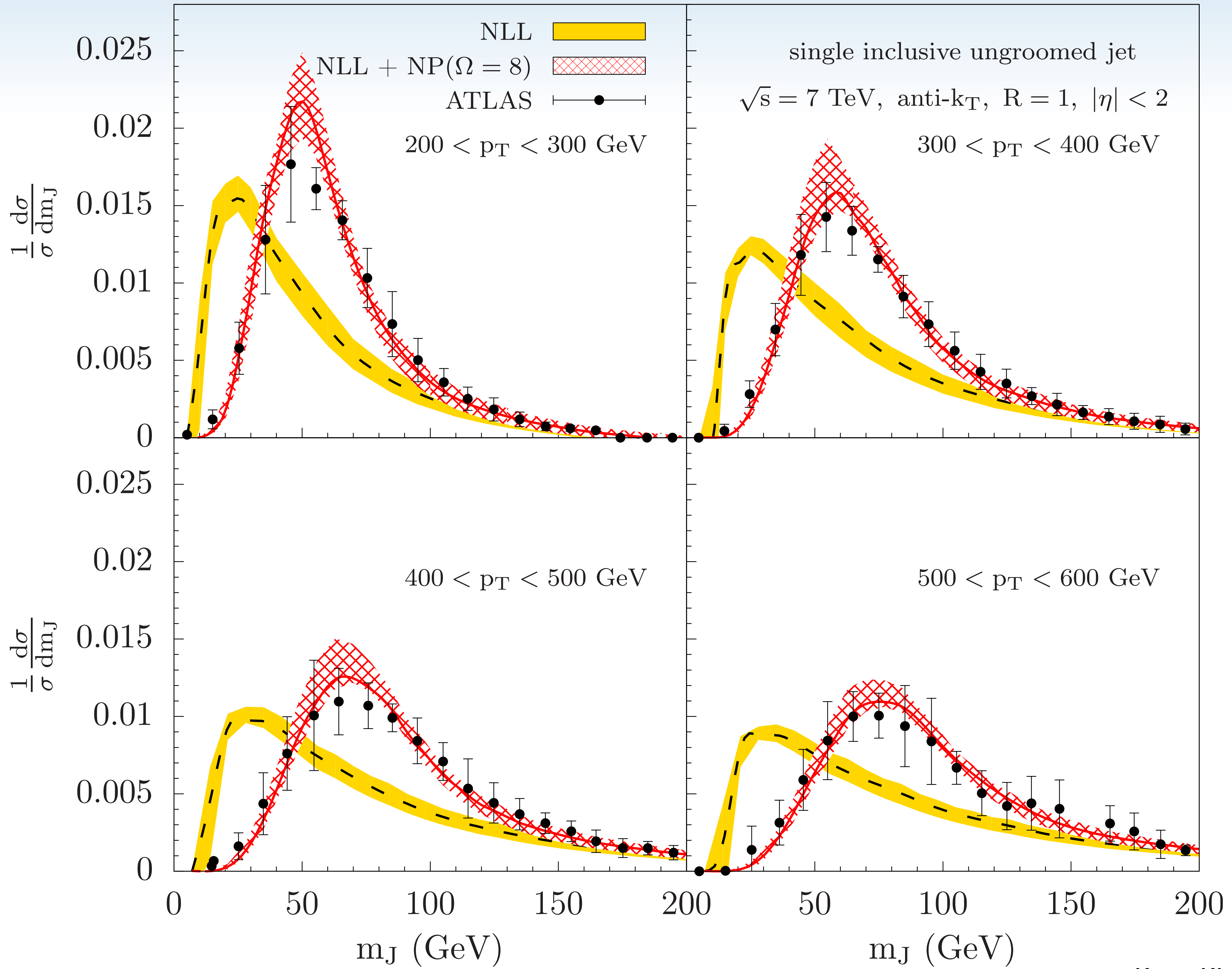


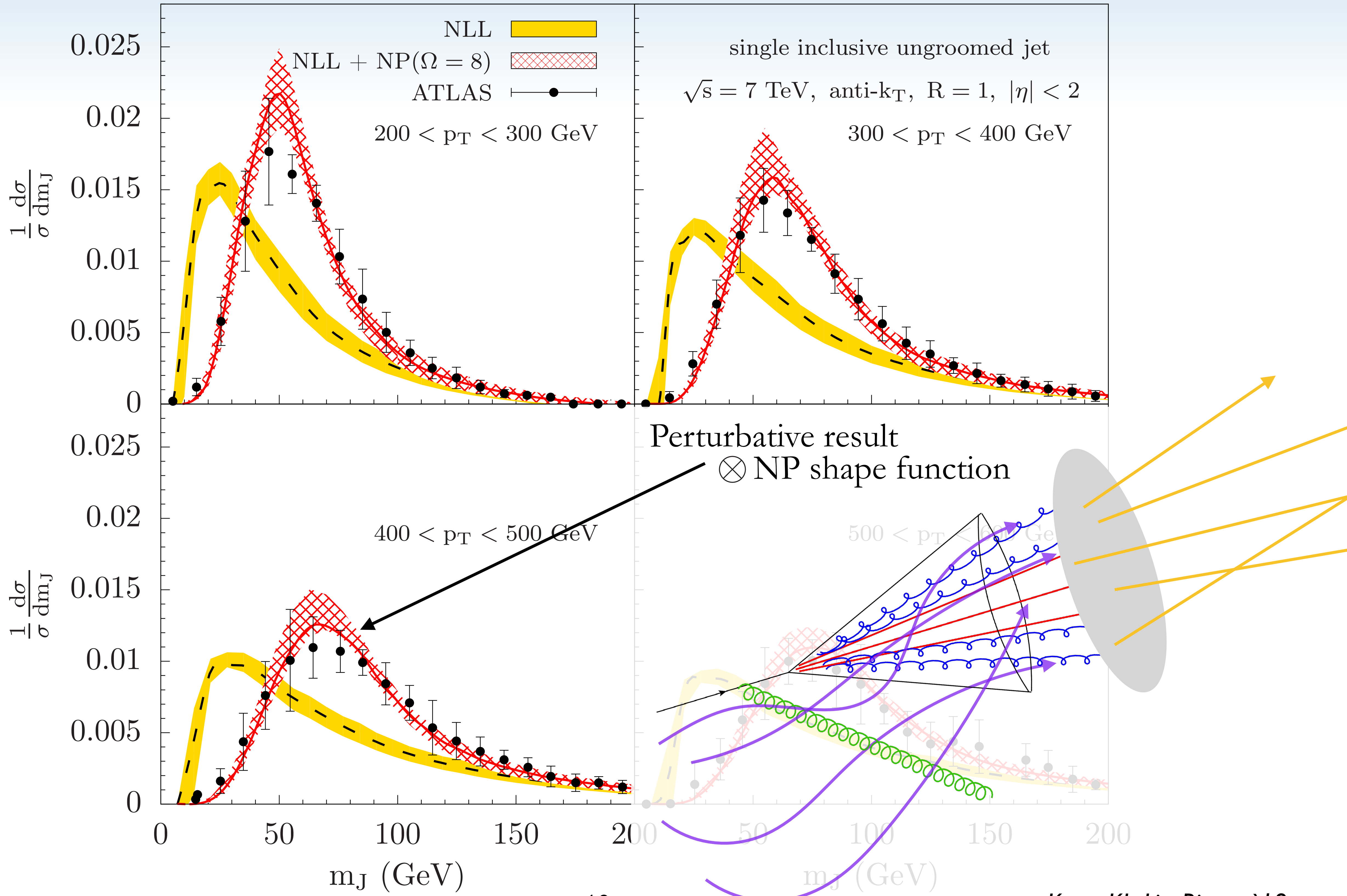
- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.
- **Pileups**
  Secondary proton collisions in a bunch may enter and contaminate jet.
- **Hadronization**
  Partons forming the jet eventually hadronizes.

Phenomenology



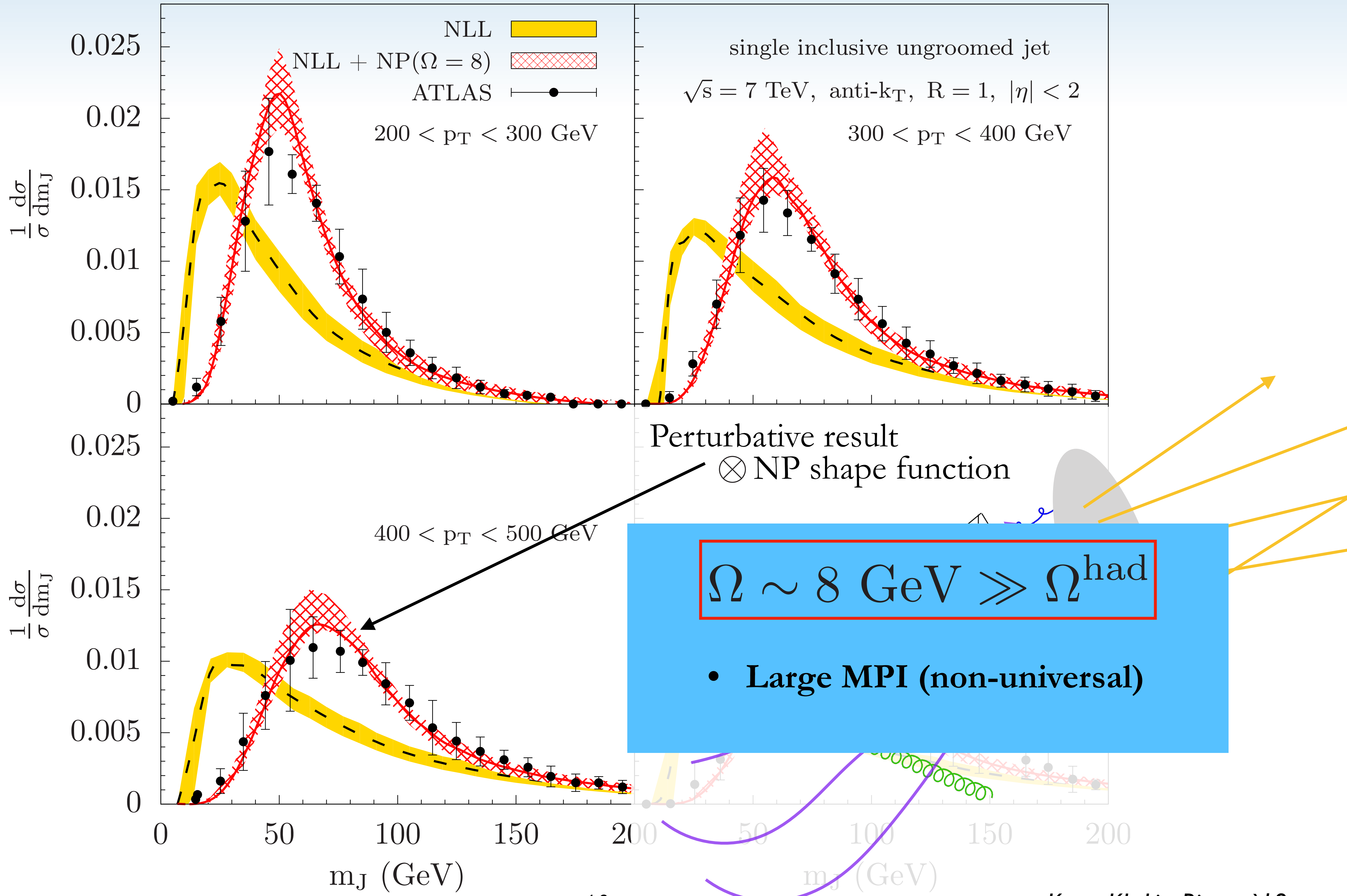
Kang, KL, Liu, Ringer `18

Phenomenology



Kang, KL, Liu, Ringer `18

Phenomenology



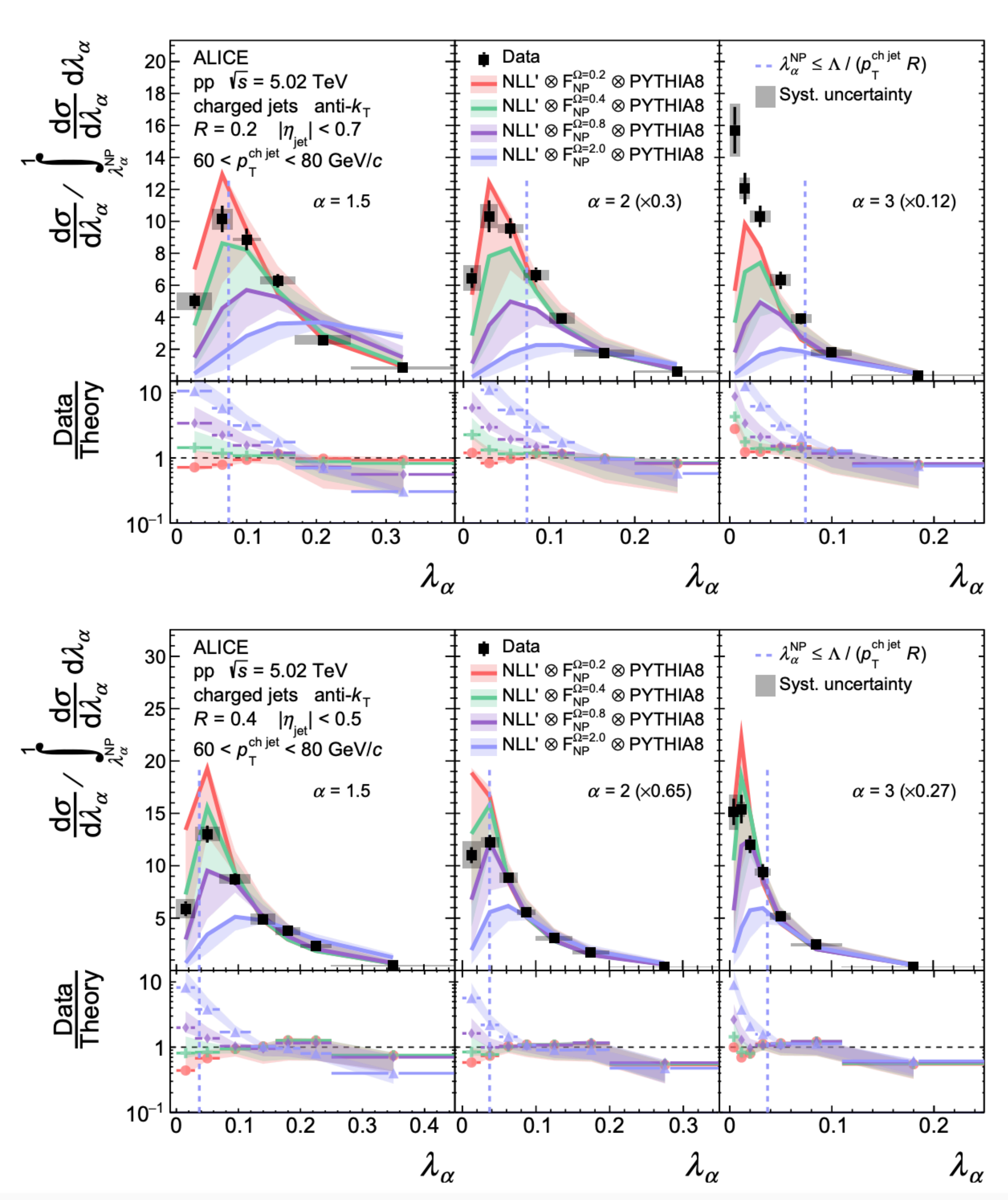
Perturbative result
⊗ NP shape function

$\boxed{\Omega \sim 8\ \mathrm{GeV} \gg \Omega^{\mathrm{had}}}$

- **Large MPI (non-universal)**

Kang, KL, Liu, Ringer `18

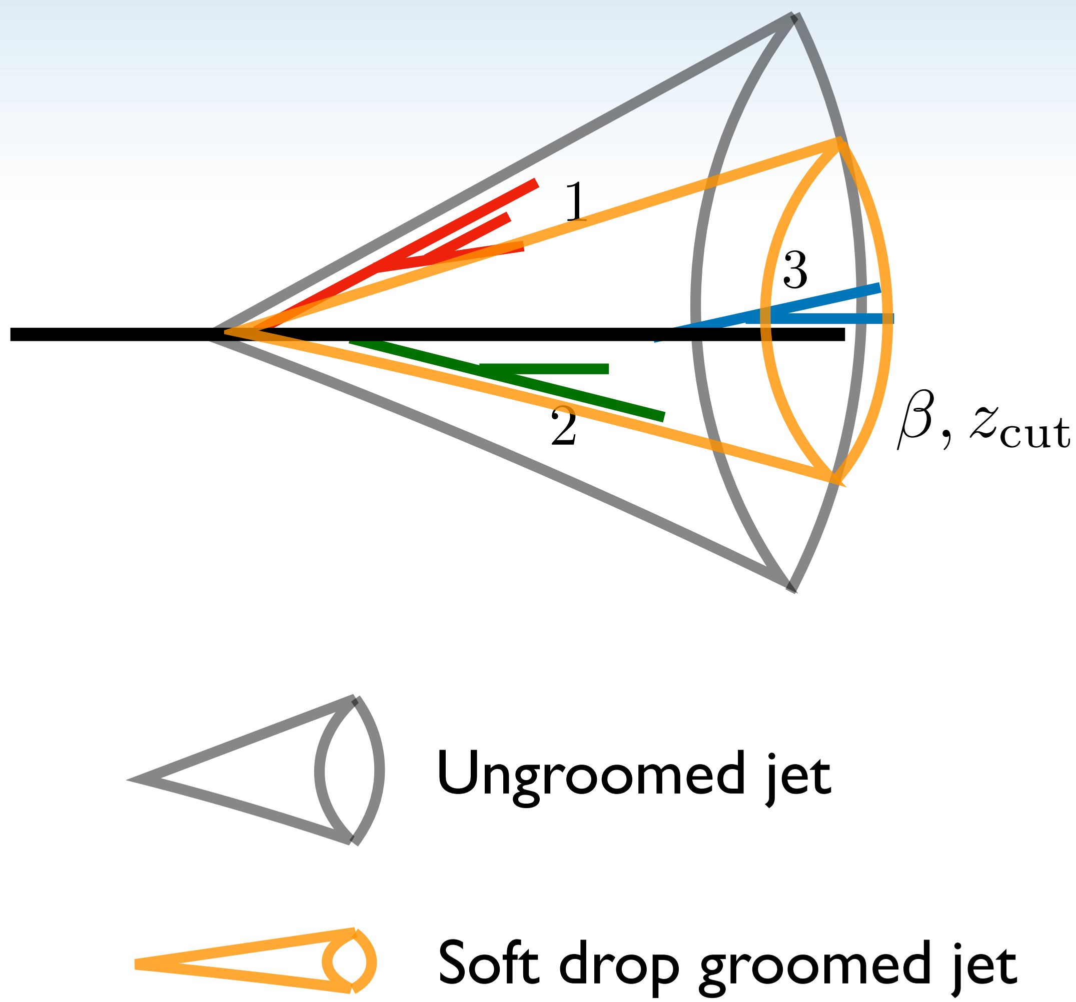
Phenomenology

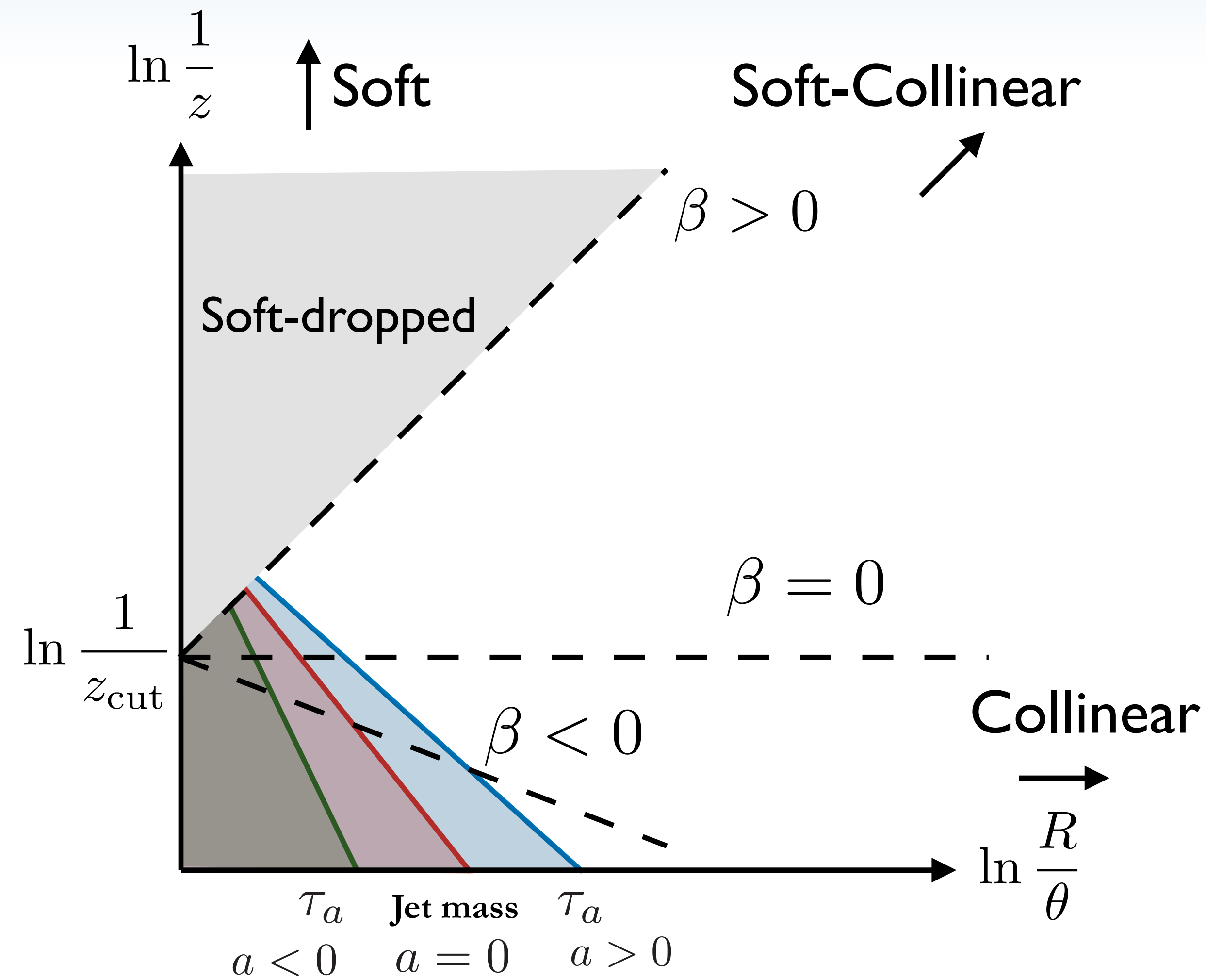


- **ALICE collaboration comparison in the next talk by Ezra!**

$$\lambda_\alpha = \tau_{2-\alpha}$$

Soft drop grooming





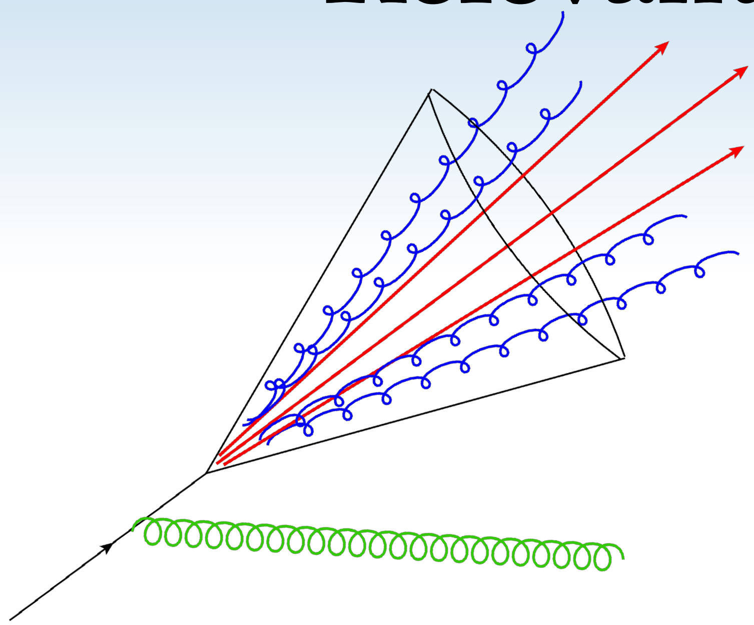
- Soft drop reduces sensitivity to the soft emissions

Soft Drop Condition

$$z > z_{\rm cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

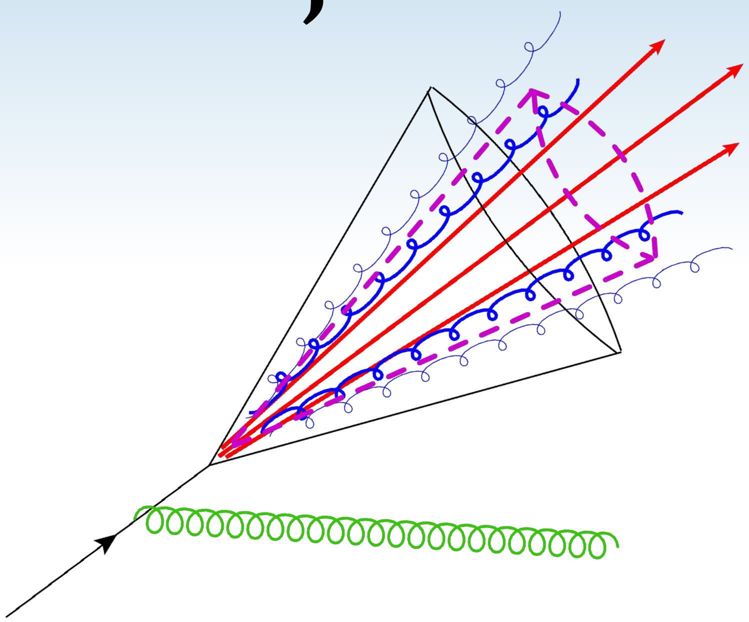
Larkoski, Marzani, Soyez, Thaler `14

Relevant modes in the groomed jet



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

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



- **The ungroomed case ($\tau_a \ll R^{2-a}$)**

Hard-collinear

$$\theta_{\mathcal{H}} \sim R \qquad z_{\mathcal{H}} \sim 1$$

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 ($\tau_{a,gr}/R^{2-a} \ll z_{\rm cut} \ll 1$)**

Hard-collinear

$$\theta_{\mathcal{H}} \sim R \qquad z_{\mathcal{H}} \sim 1$$

Collinear

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

$\notin$ *gr* soft

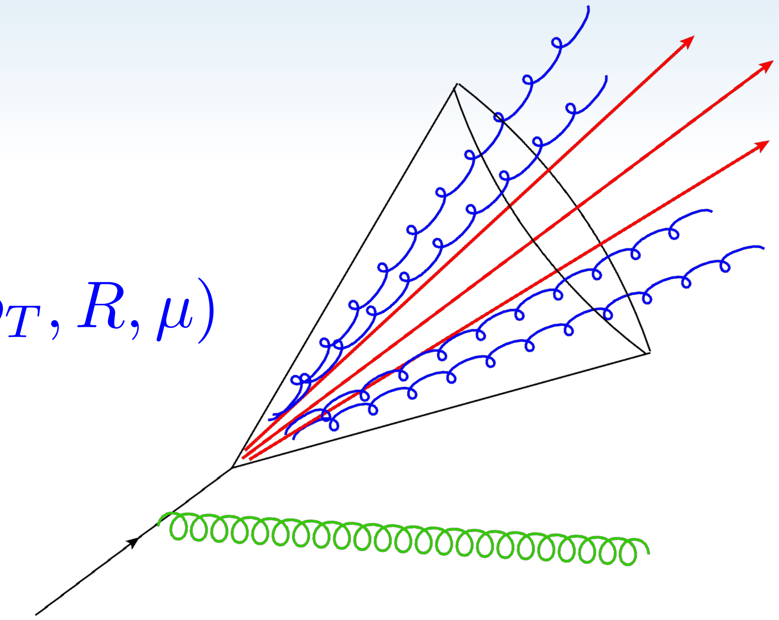
$$\theta_{\notin \rm gr} \sim R \qquad z_{\notin \rm gr} \sim z_{\rm cut}\left(\frac{\theta}{R}\right)^\beta = z_{\rm cut}$$

$\in$ *gr* soft (collinear-soft)

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

Factorization for the groomed jet angularity

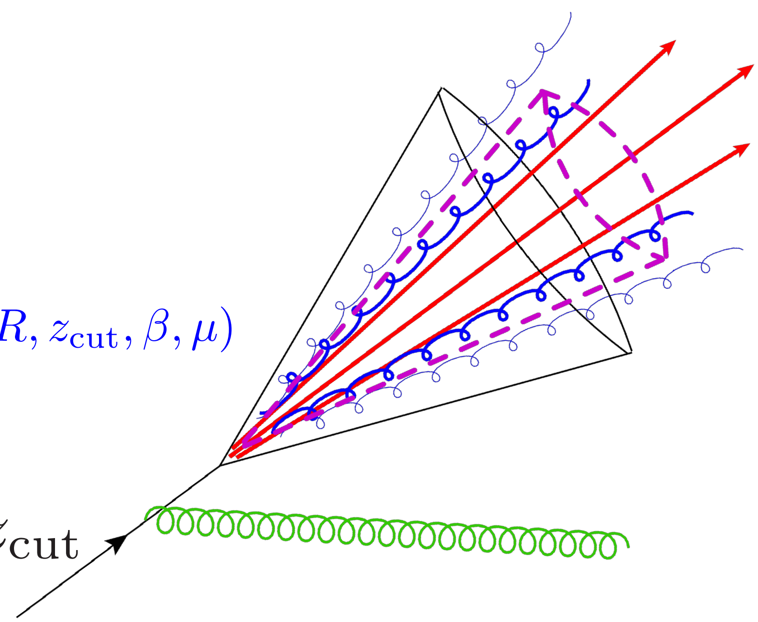
$$J_c \to \mathcal{G}_c$$



- **The ungroomed case (** $\tau_a \ll R^{2-a}$ **)**

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

- **Jointly resums large logs** $\alpha_s^n \ln^n R$ **and** $\alpha_s^n \ln^{2n} \tau_a^{\frac{1}{2-a}}/R$



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

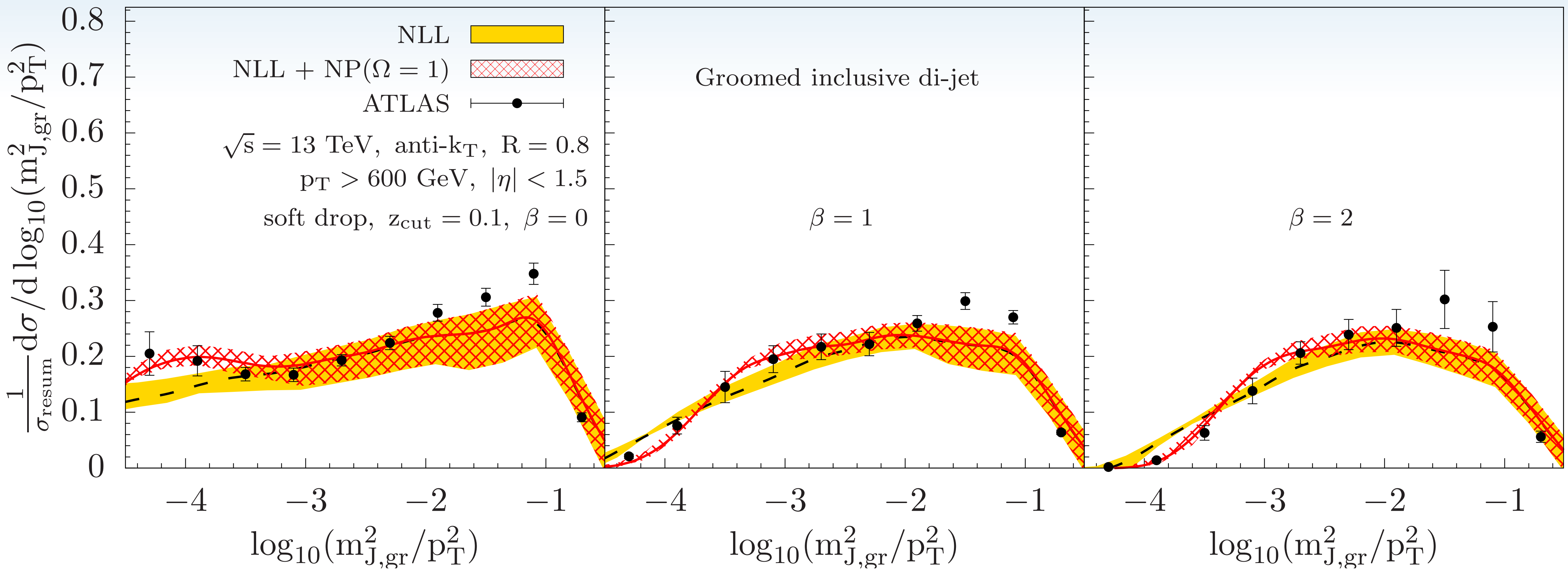
$$\theta_{\mathcal{H}} \sim R$$
$$\theta_{\notin \rm gr} \sim R$$

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

- **Jointly resums large logs** $\alpha_s^n \ln^n R$, $\alpha_s^n \ln^{2n} \tau_a^{\frac{1}{2-a}}/R$, **and** $\alpha_s^n \ln^{2n} z_{\rm cut}$

Kang, KL, Liu, Ringer `18

Phenomenology (groomed jet mass)



Nonperturbative effects is no longer simply *Hoang, Mantry, Pathak, Stewart `19 Pathak, Stewart, Vaidya, Zoppi `21*

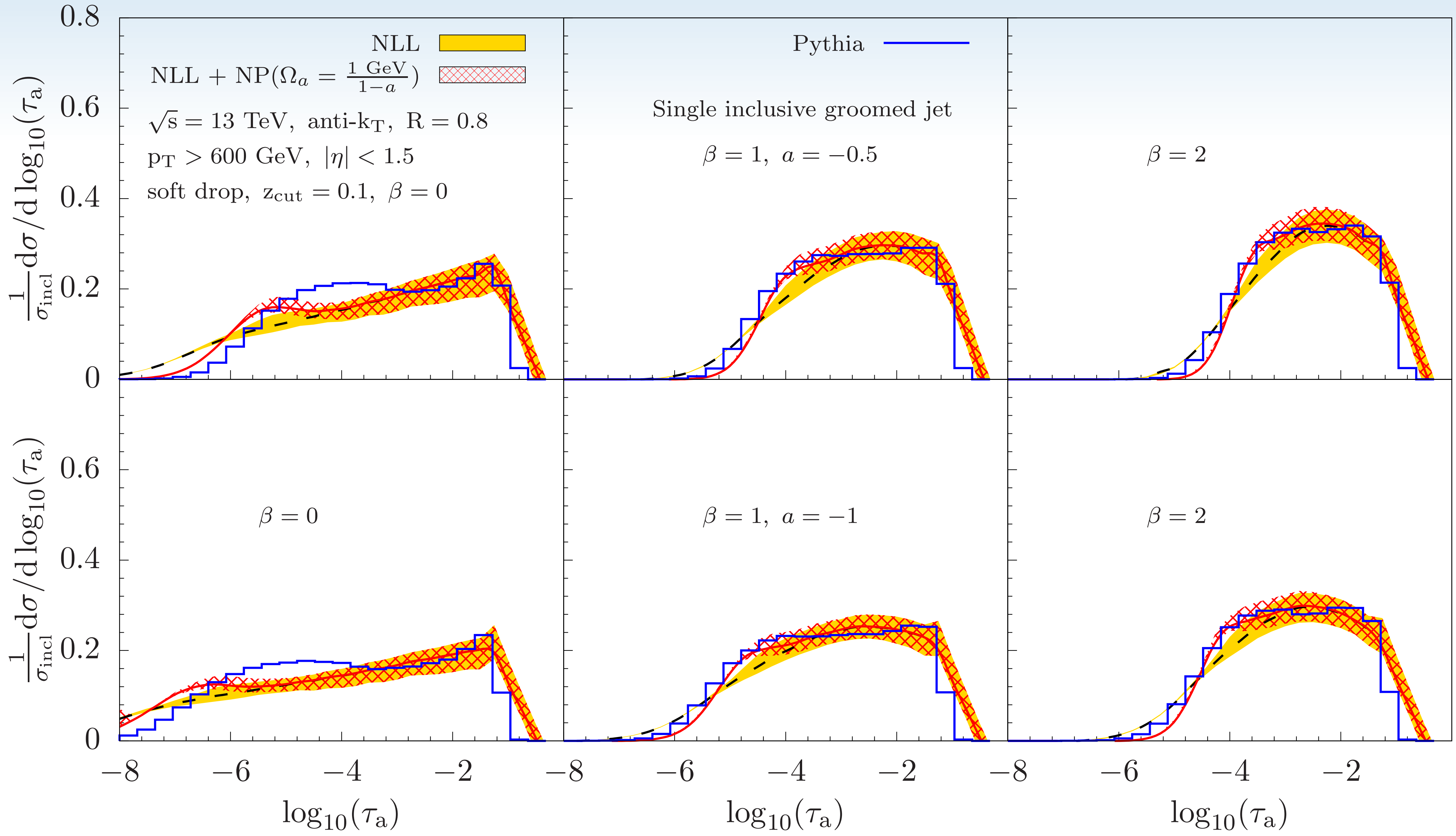
$$\frac{d\sigma}{dp_T d\eta d\tau_a} = \int dk F_a(k) \frac{d\sigma^{\text{pert}}}{dp_T d\eta d\tau_a}\left(\tau_a - \frac{R^{1-a}}{p_T} k\right); \qquad \Omega_a = \int dk\, k\, F_a(k)$$

- **In addition to shift correction, boundary correction exists.** *Ferdinand, KL, Pathak, In Progress*

  However, naive shift correction form shows good agreement and reasonable NP parameter values.

Kang, KL, Liu, Ringer `18

Phenomenology

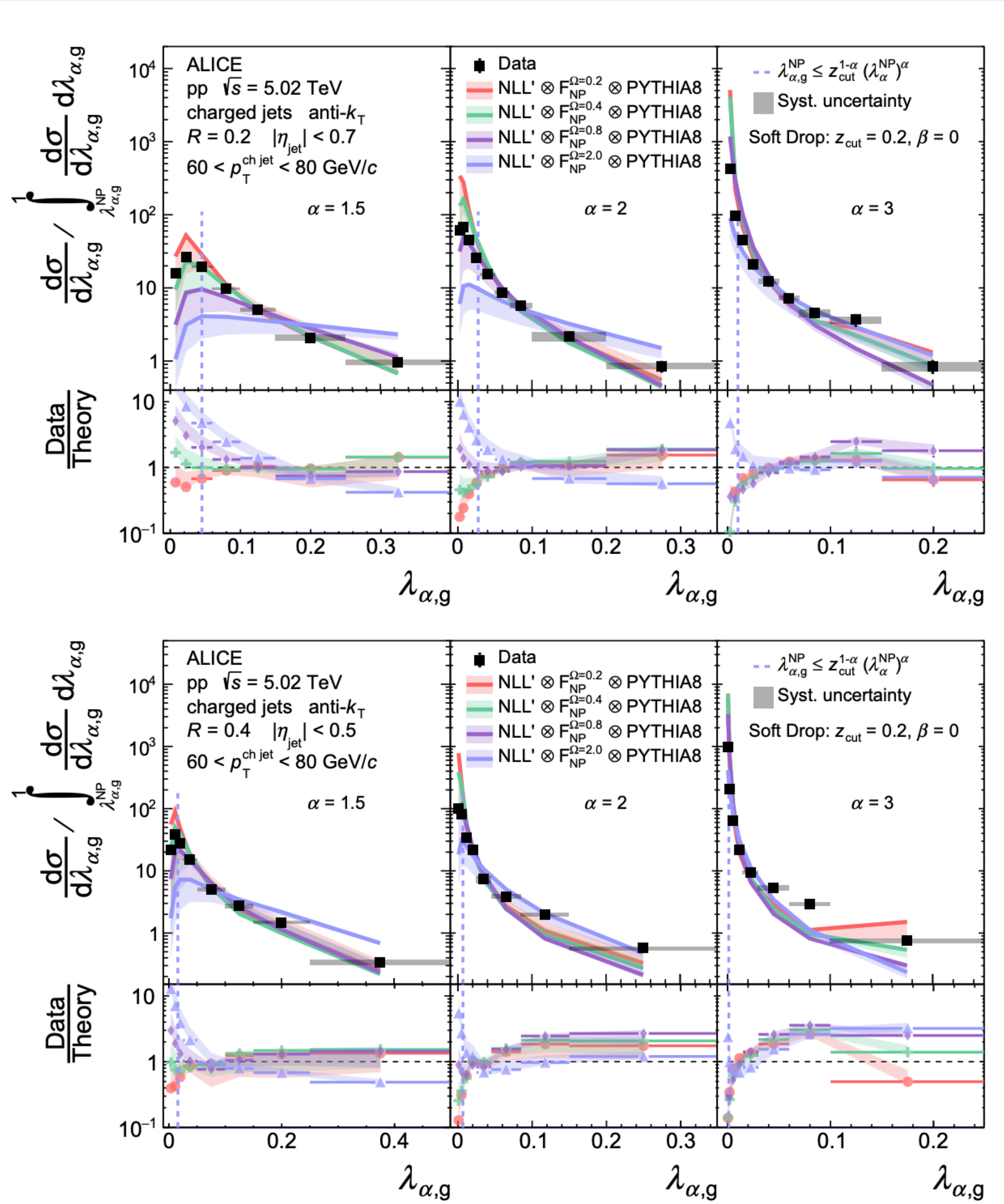


- Assuming $\Omega_a^{had} = \dfrac{\Omega_{a=0}^{had}}{1-a}$, find a reasonable agreement.

Lee, Sterman `07

Kang, KL, Liu, Ringer `19

Phenomenology



- First measurement of the general groomed jet angularities at the LHC.
- ALICE collaboration comparison in the next talk by Ezra!

$$\lambda_\alpha = \tau_{2-\alpha}$$

Thank you!