Groomed observables and jet mass at colliders

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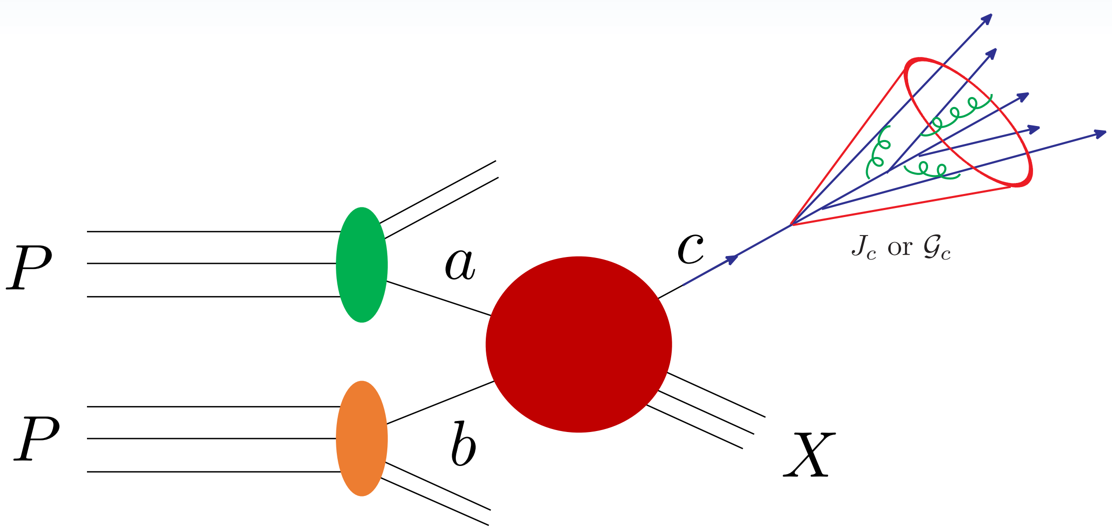
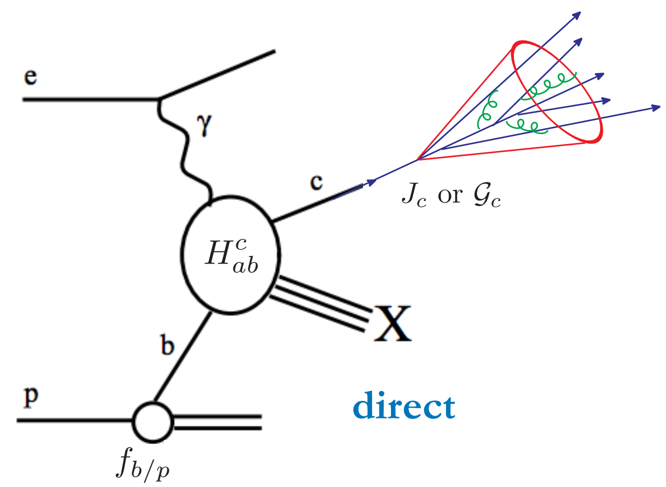
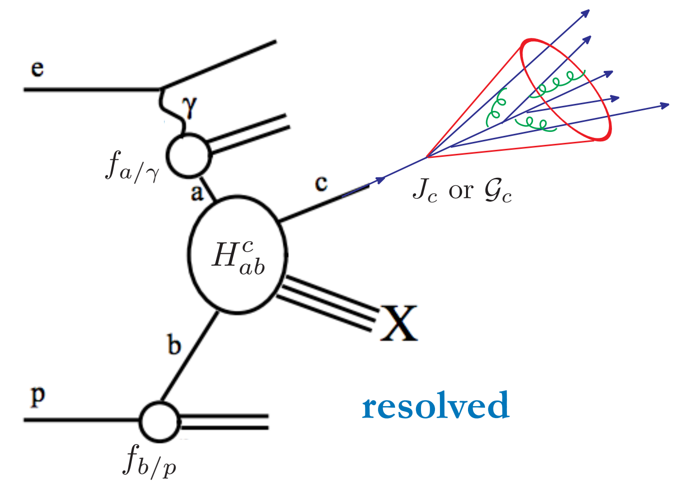
Stony Brook University

Probing quark-gluon matter with jets
07/23/18 - 07/25/18

Processes of Interest







- **We want to study semi-inclusive jet production**
  p + p $\longrightarrow$ Jet((with/without) substructure) + X

  photoproduction at the EIC
  e + p $\longrightarrow$ e + Jet((with/without) substructure) + X

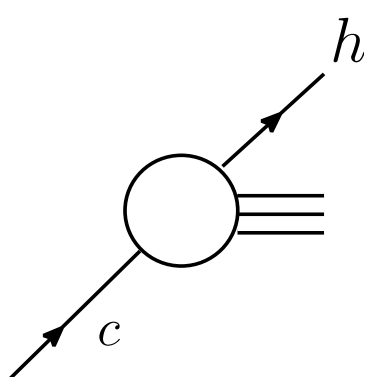
- More statistics. No veto on additional jets.

Plans of this talk

- Inclusive jet production at the LHC
- Jet mass measurements at the LHC
- Role of non-perturbative effects
- Subtracted Moments and Groomed observables
- Extension to the EIC case
- Conclusions

Factorization of Inclusive Jet Production

$R \ll 1$



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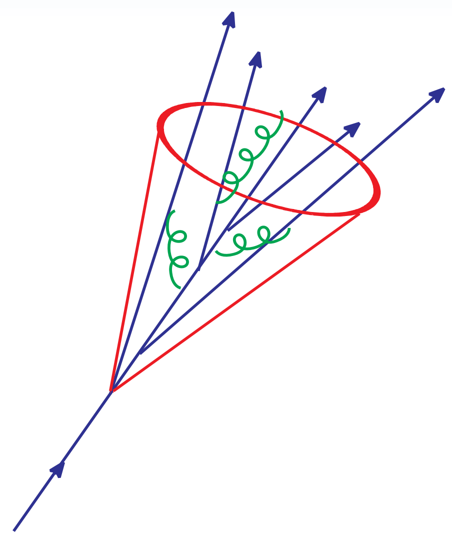

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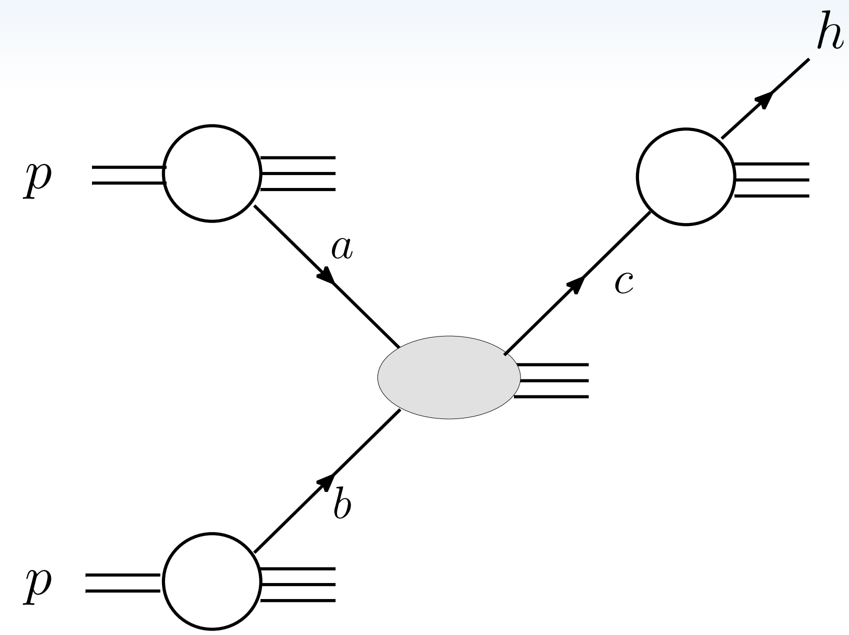


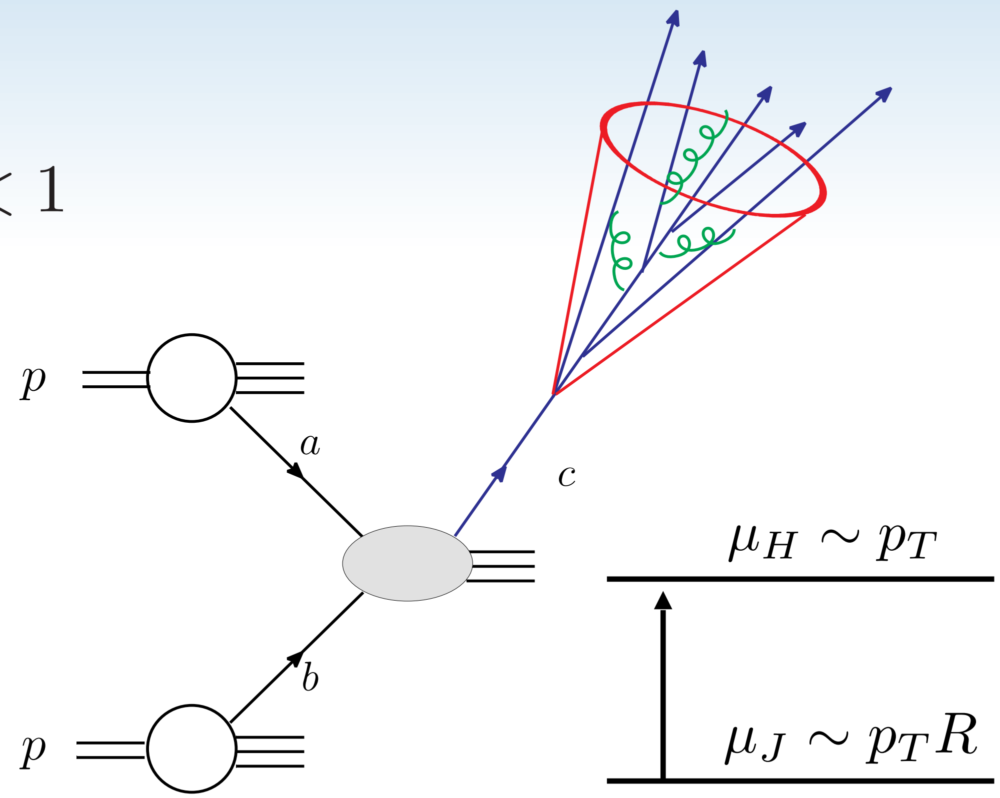
$$D_c^h \quad \rightarrow \quad J_c \qquad\qquad pp \rightarrow hX$$

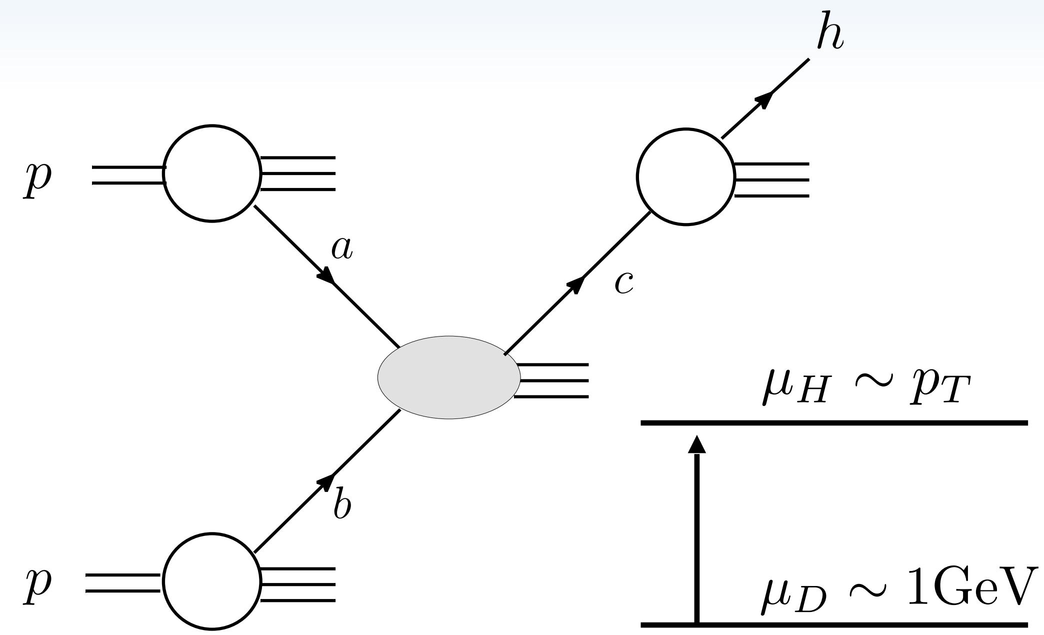
- **Simple replacement of the fragmentation function by "semi-inclusive jet function".**

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

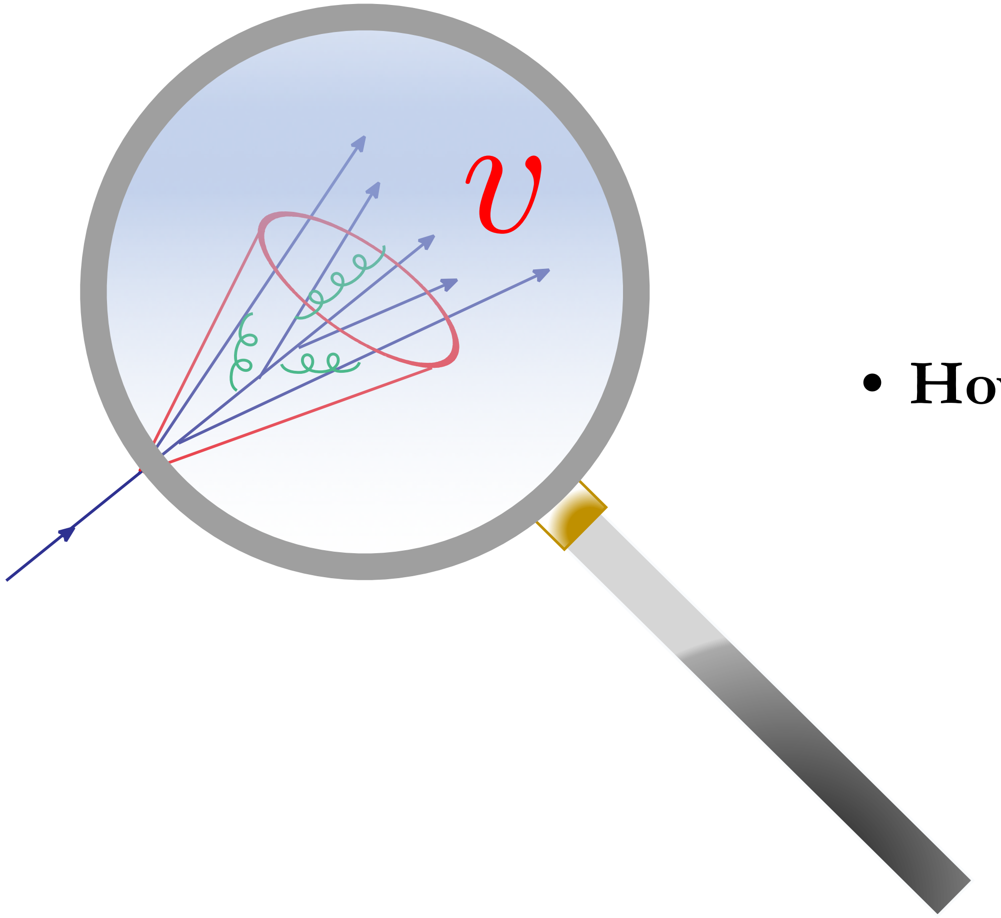
$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes D_c^h$$

$$\mu \frac{d}{d\mu} D_i^h = \sum_j P_{ji} \otimes D_j^h$$

- **See Xiaohui's talk for phenomenology study**

Kang, Ringer, Vitev `16

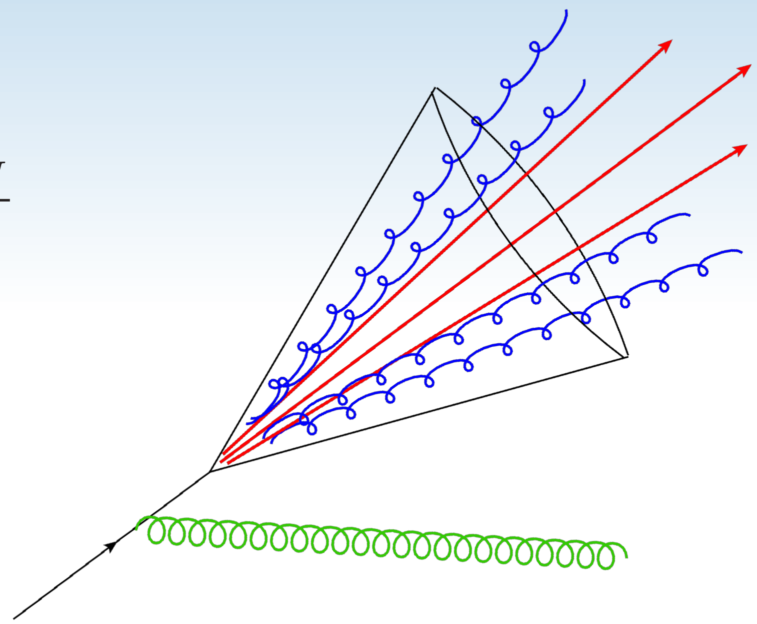
Jet Substructure Measurements



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

Jet mass

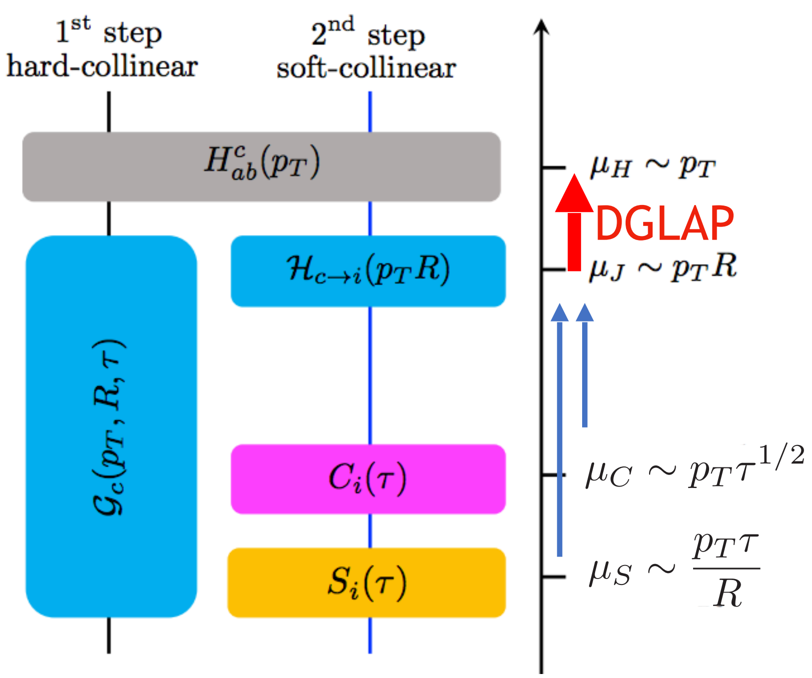
- $m_J^2 = \left(\sum_{i\in J} p_i\right)^2$
- $\tau = \frac{m_J^2}{p_T^2}$



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

$$\mathcal{G}_c(z, p_T R, \tau, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu) \times \int d\tau^{C_i} d\tau^{S_i} \delta(\tau - \tau^{C_i} - \tau^{S_i}) \mathcal{C}_i(\tau^{C_i}, p_T \tau^{1/2}, \mu) \mathcal{S}_i\left(\tau^{S_i}, \frac{p_T \tau}{R}, \mu\right)$$

- 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, Liu, Ringer `18

Jet mass

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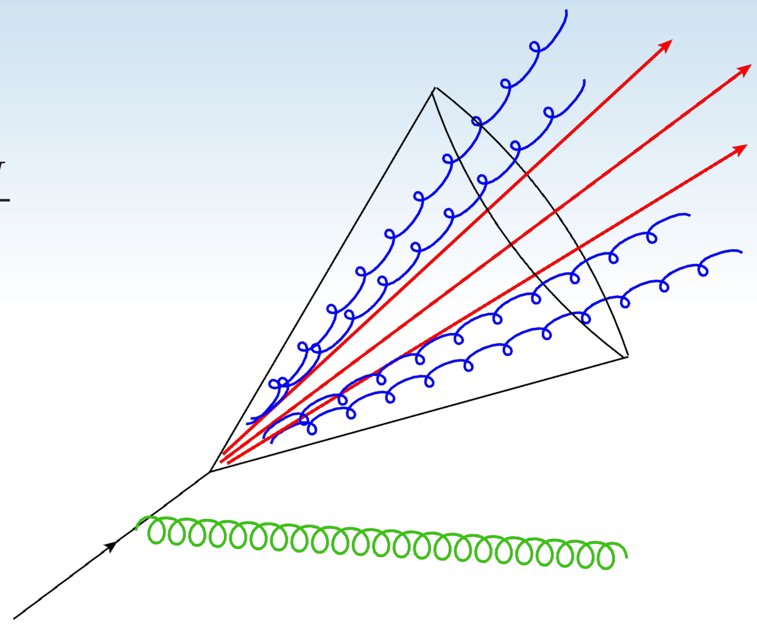
- $\tau = \frac{m_J^2}{p_T^2}$



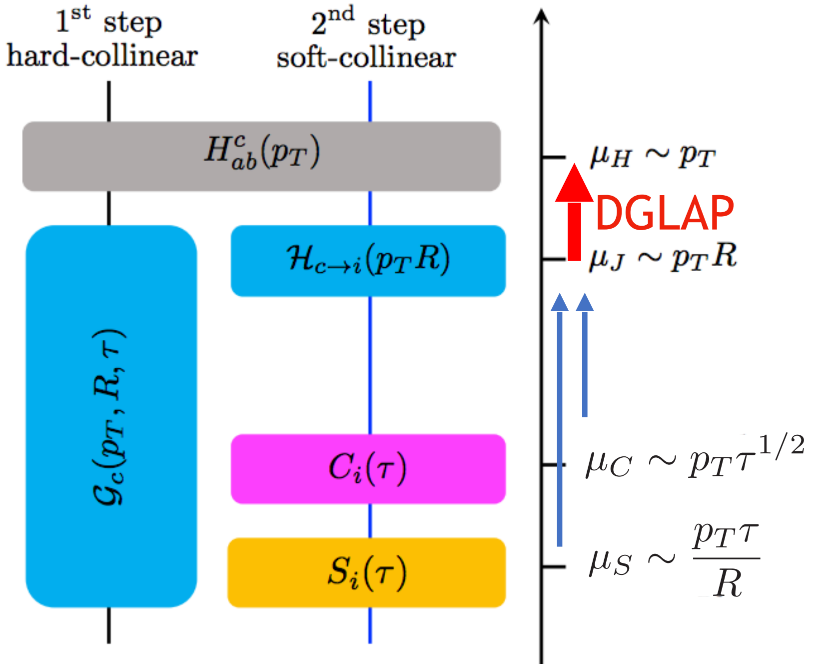
- Replace $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau, \mu)$
- Refactorize $\mathcal{G}_c$ as

$$\mathcal{G}_c(z, p_T R, \tau, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu)$$
$$\times \int d\tau^{C_i} d\tau^{S_i} \delta(\tau - \tau^{C_i} - \tau^{S_i}) \mathcal{C}_i(\tau^{C_i}, p_T \tau^{1/2}, \mu) \mathcal{S}_i(\tau^{S_i}, \frac{p_T \tau}{R}, \mu)$$

- $H_{c\to i}$, C_i and S_i have double poles, which cancel once evolved to μ_J.

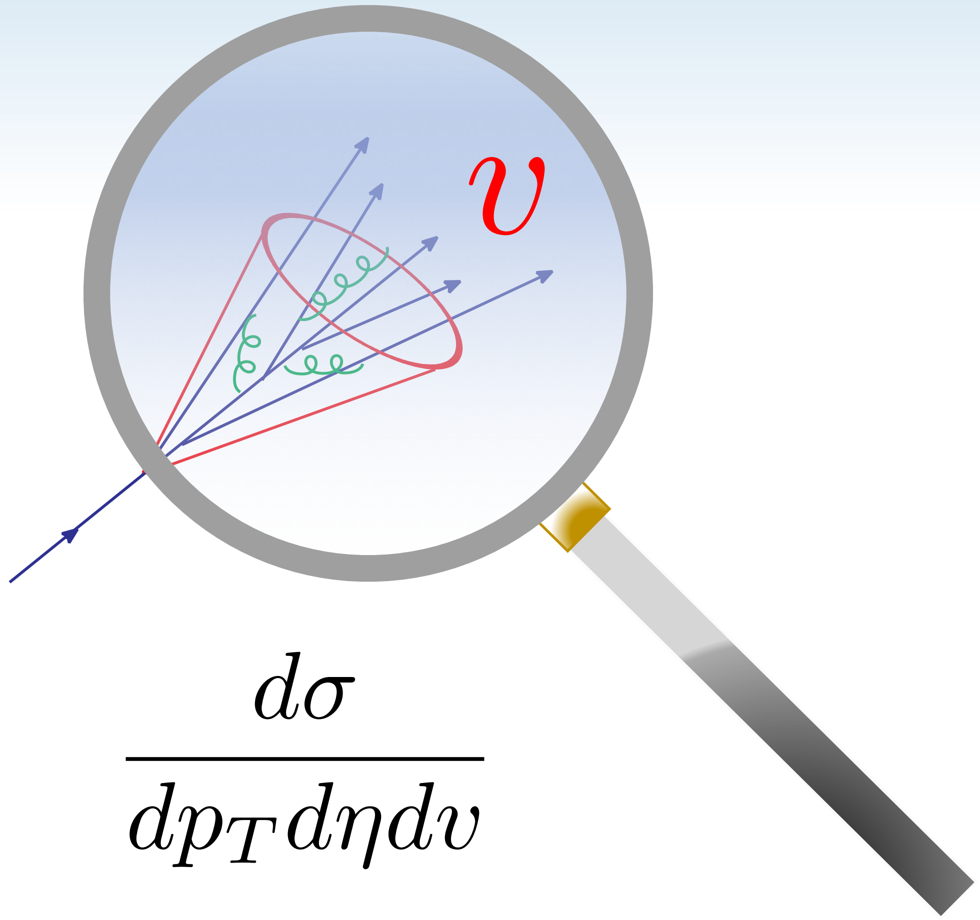
- $\mathcal{G}_c(z, p_T R, \tau, \mu)$ follows DGLAP from μ_J to μ_H:

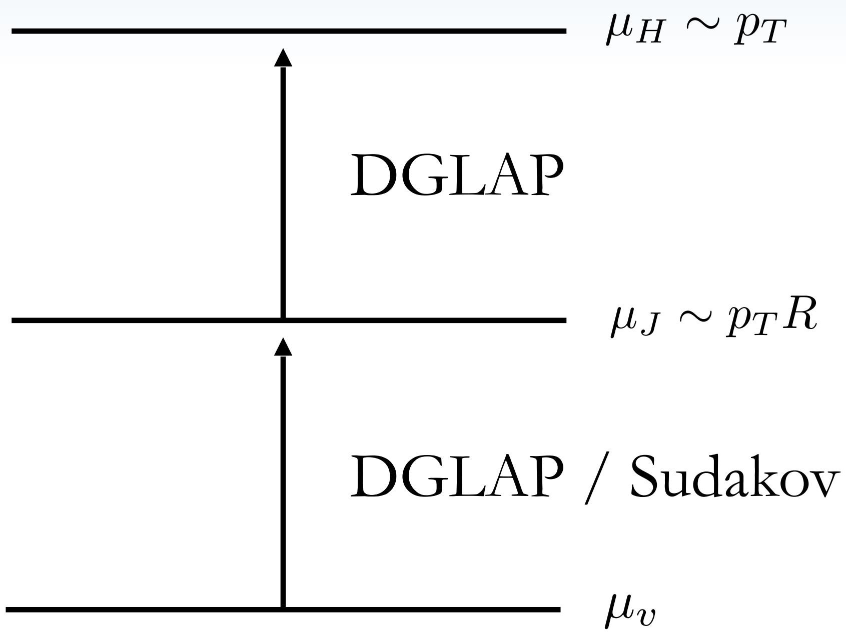
$$\mu \frac{d}{d\mu} \mathcal{G}_i(z, p_T R, \tau, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}(\frac{z}{z'}, \mu) \mathcal{G}_j(z', p_T R, \tau, \mu)$$



Kang, KL, Liu, Ringer `18

Patterns emerging

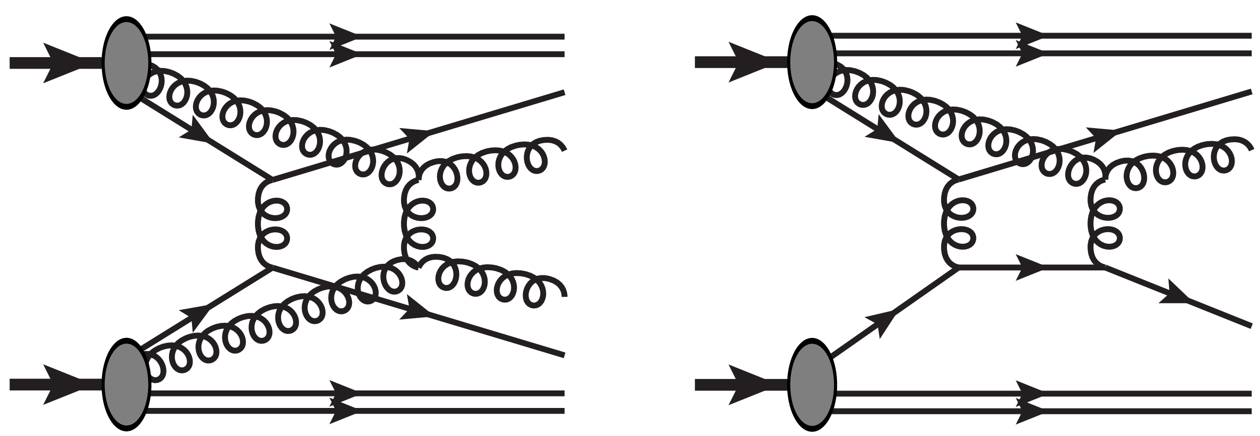




- When we measure a substructure v from the jet, once we evolve to μ_J the remaining evolution to μ_H is given by DGLAP evolution!
- Two step factorization:
  a) production of a jet
  b) probing the internal structure of the jet produced.

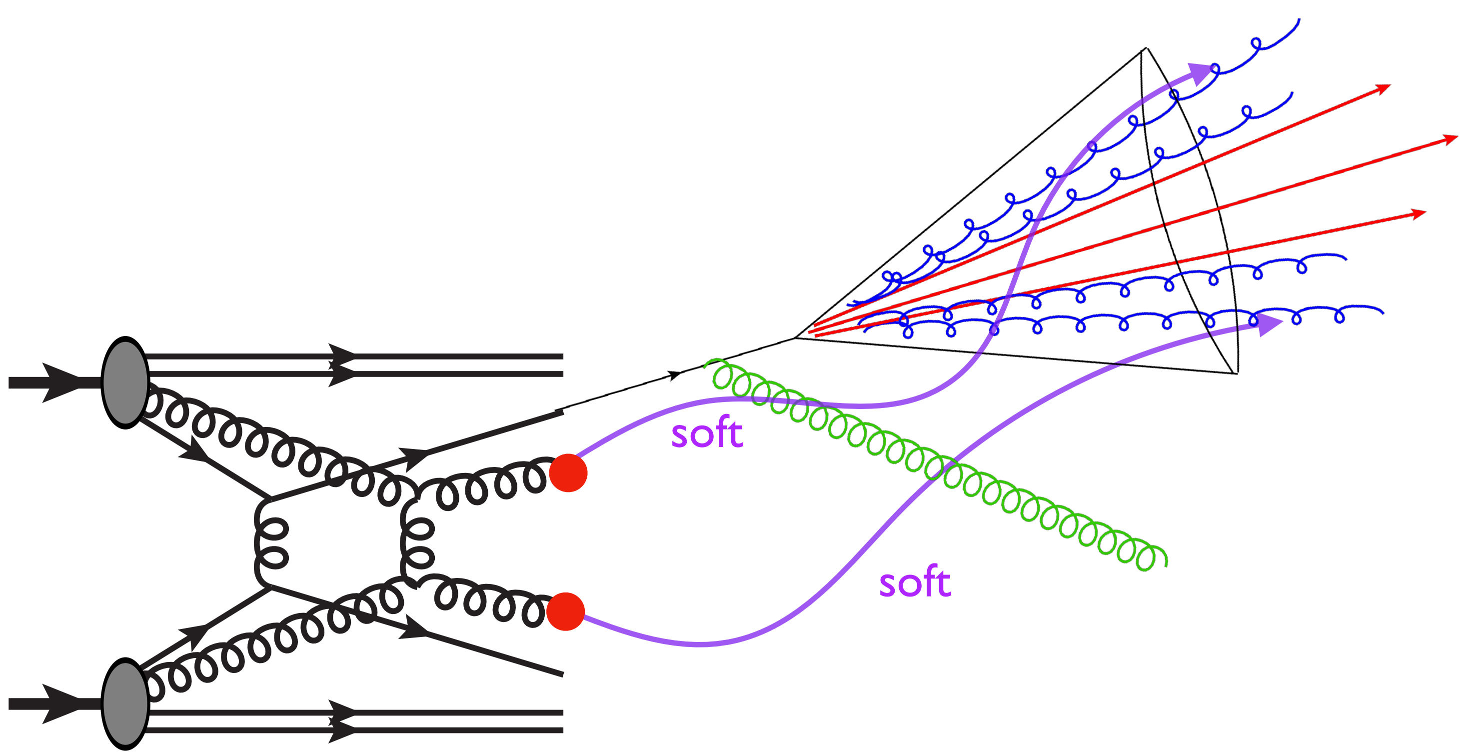
Non-perturbative Effects

- **Non-perturbative effects:**



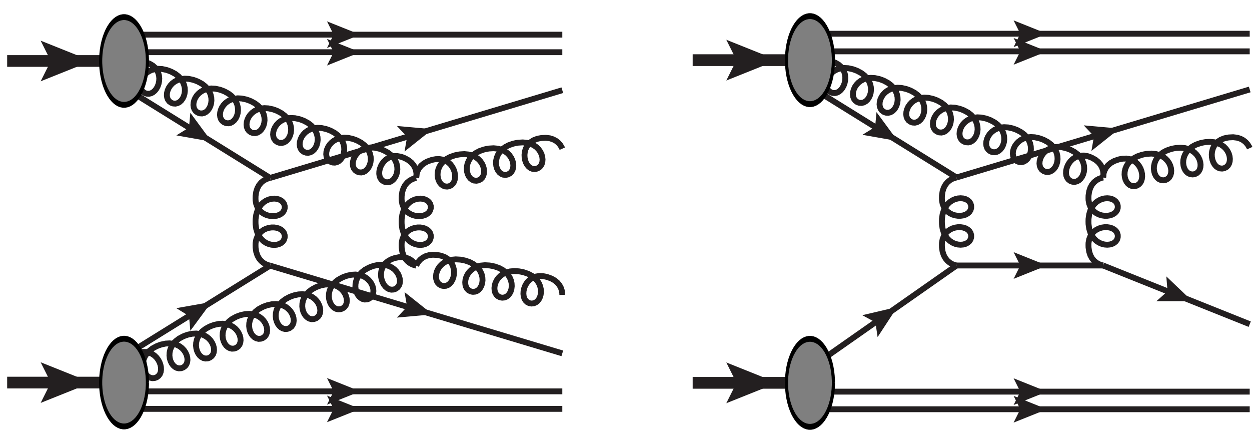
Figs from P. Bartalini et al. `11

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

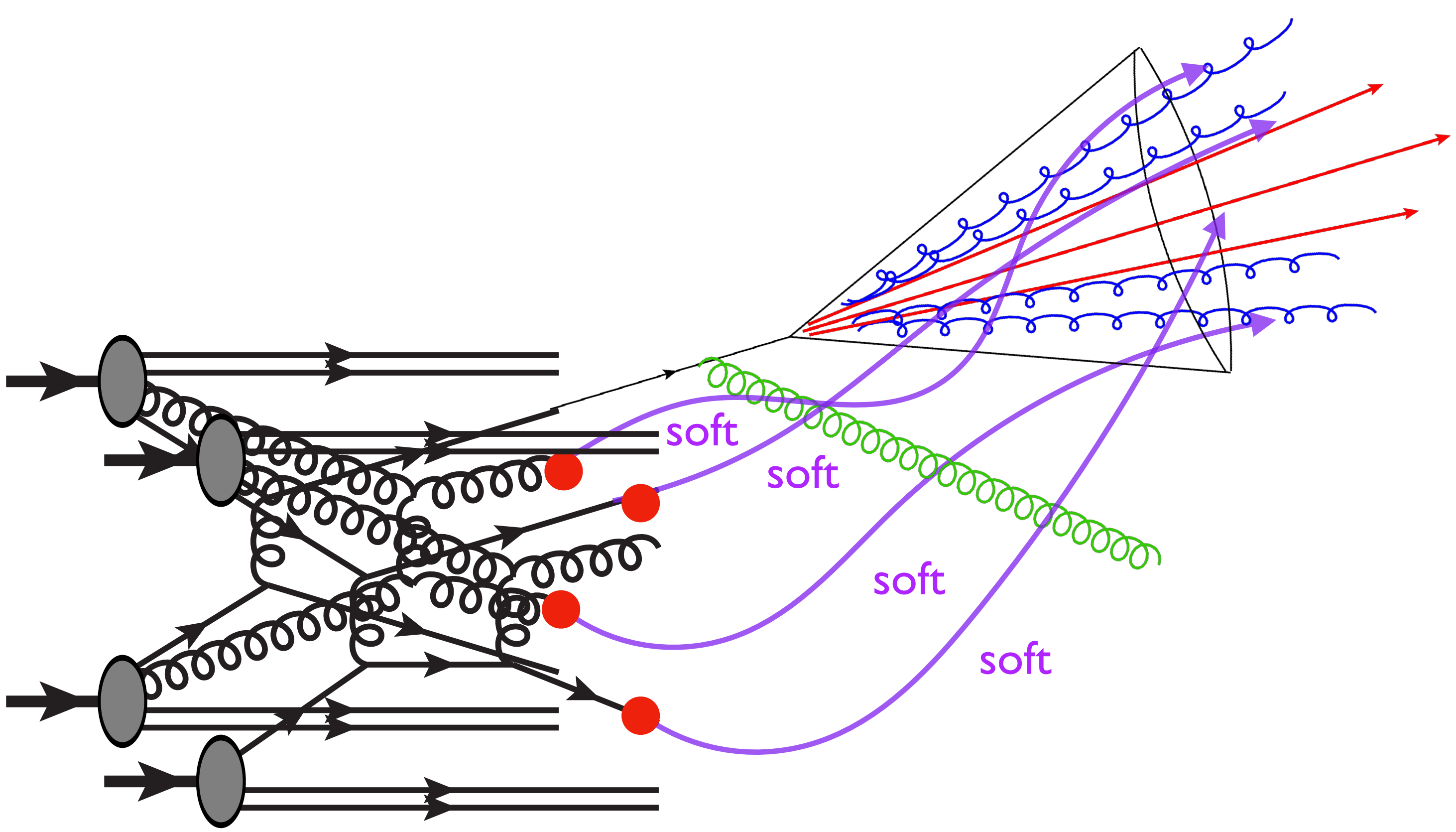


Non-perturbative Effects

- Non-perturbative effects:



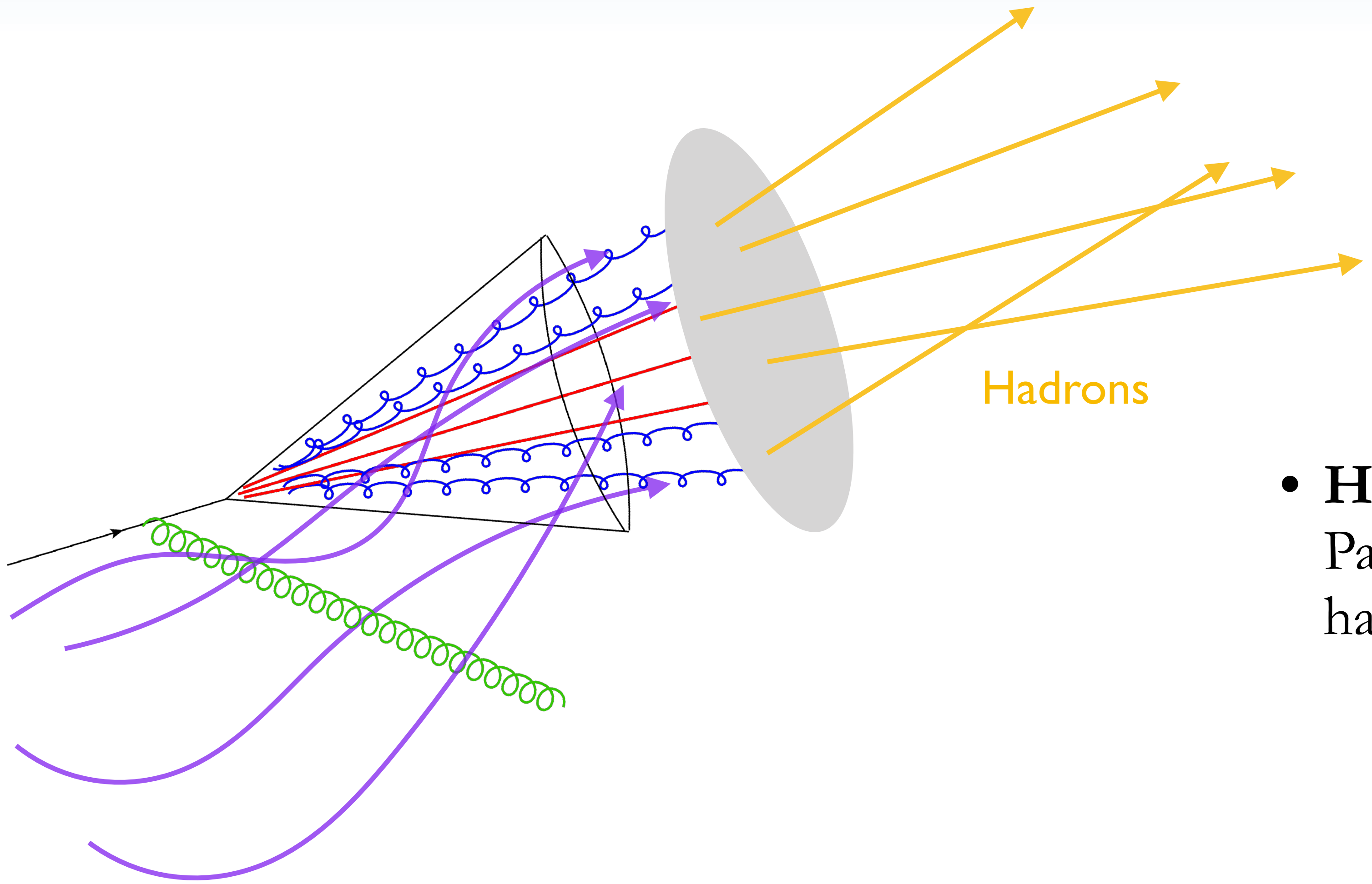
Figs from P. Bartalini et al. `11



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

Non-perturbative Effects

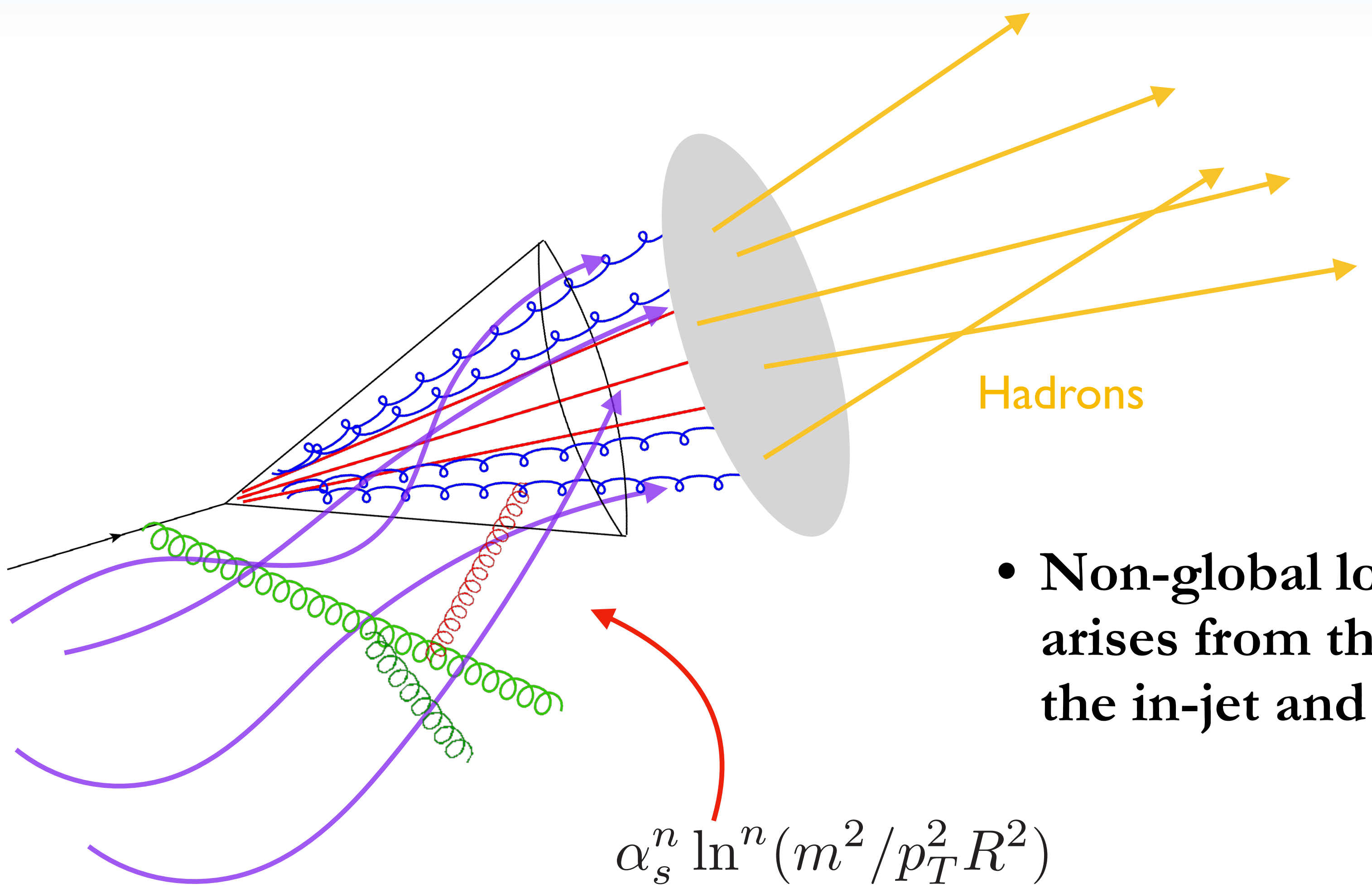
- **Non-perturbative effects:**



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

Non-global logarithms

Dasgupta, Salam `01
Banfi, Marchesini, Smye `02
Larkoski, Moult, Neill `15
Becher, Rahn, Shao `17 …



$$\alpha_s^n \ln^n(m^2/p_T^2 R^2)$$

- **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 τ 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

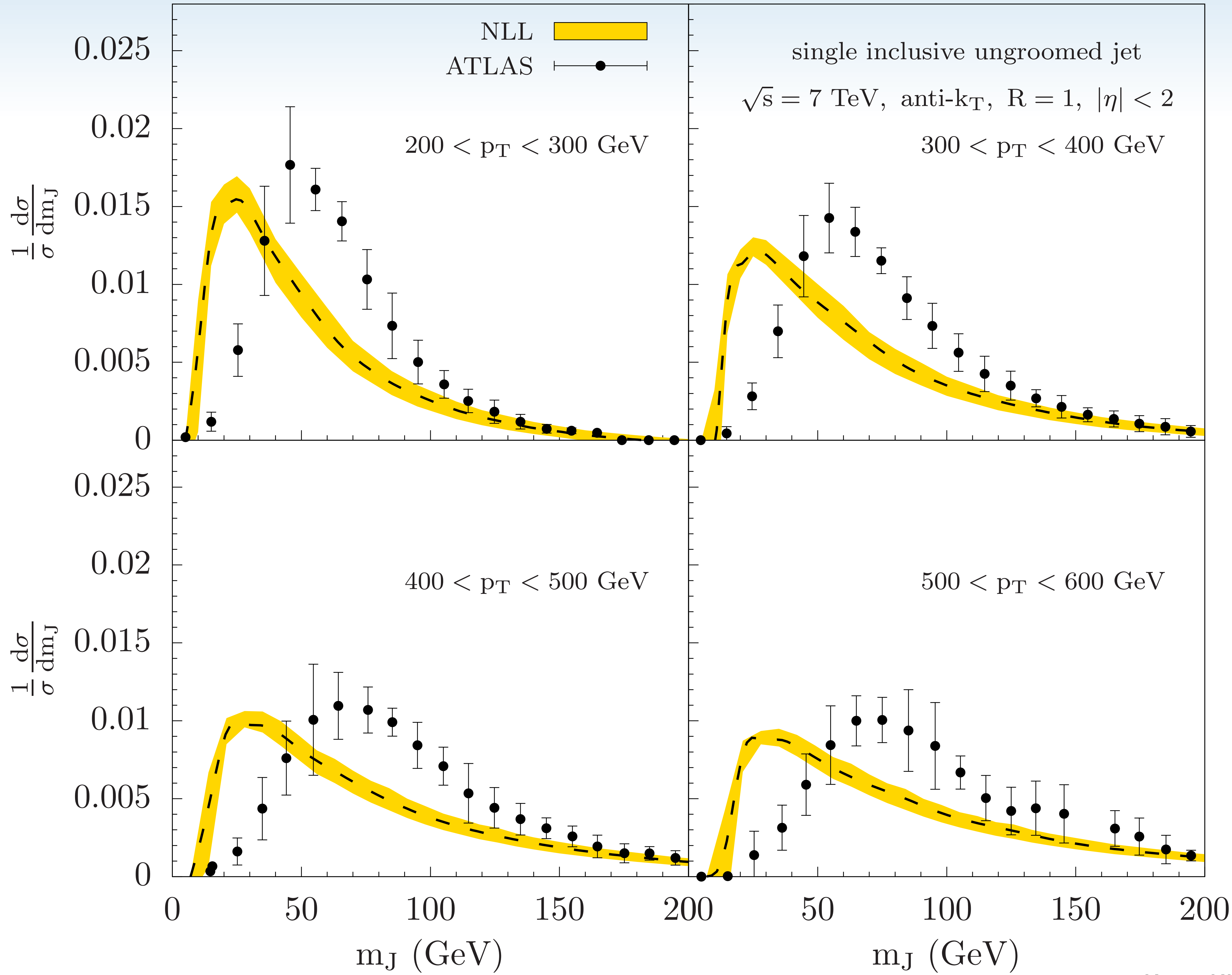
- Both hadronization and MPI effects in jet mass is well-represented by just shifting first-moments.

- The parameter Ω_κ is related to shift in the distribution:

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

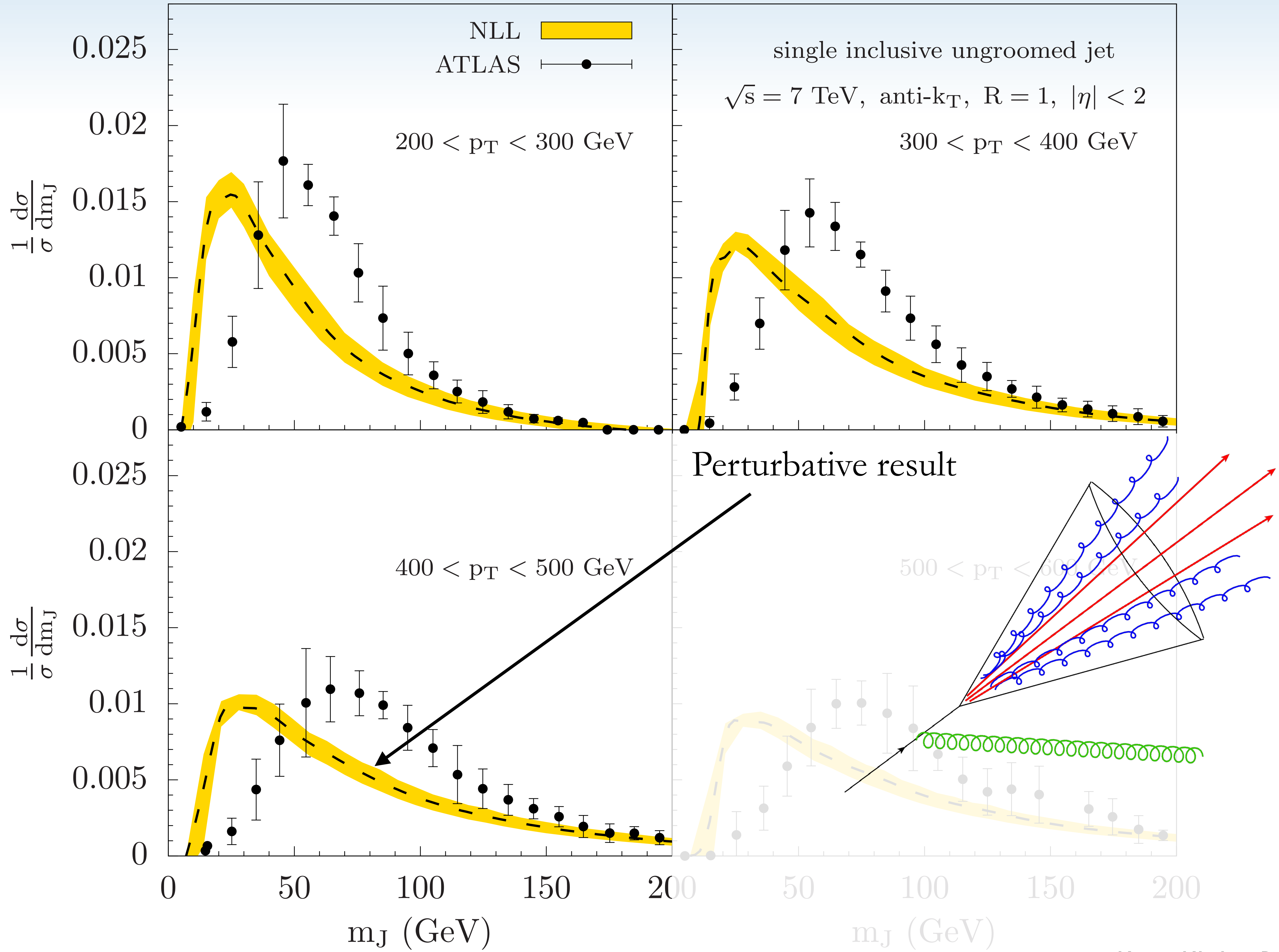
$\Omega_\kappa \sim \Lambda_{had} \sim 1\,\text{GeV}$ corresponds to non-perturbative effects coming primarily from the hadronization alone.

Phenomenology



Kang, KL, Liu, Ringer `18

Phenomenology



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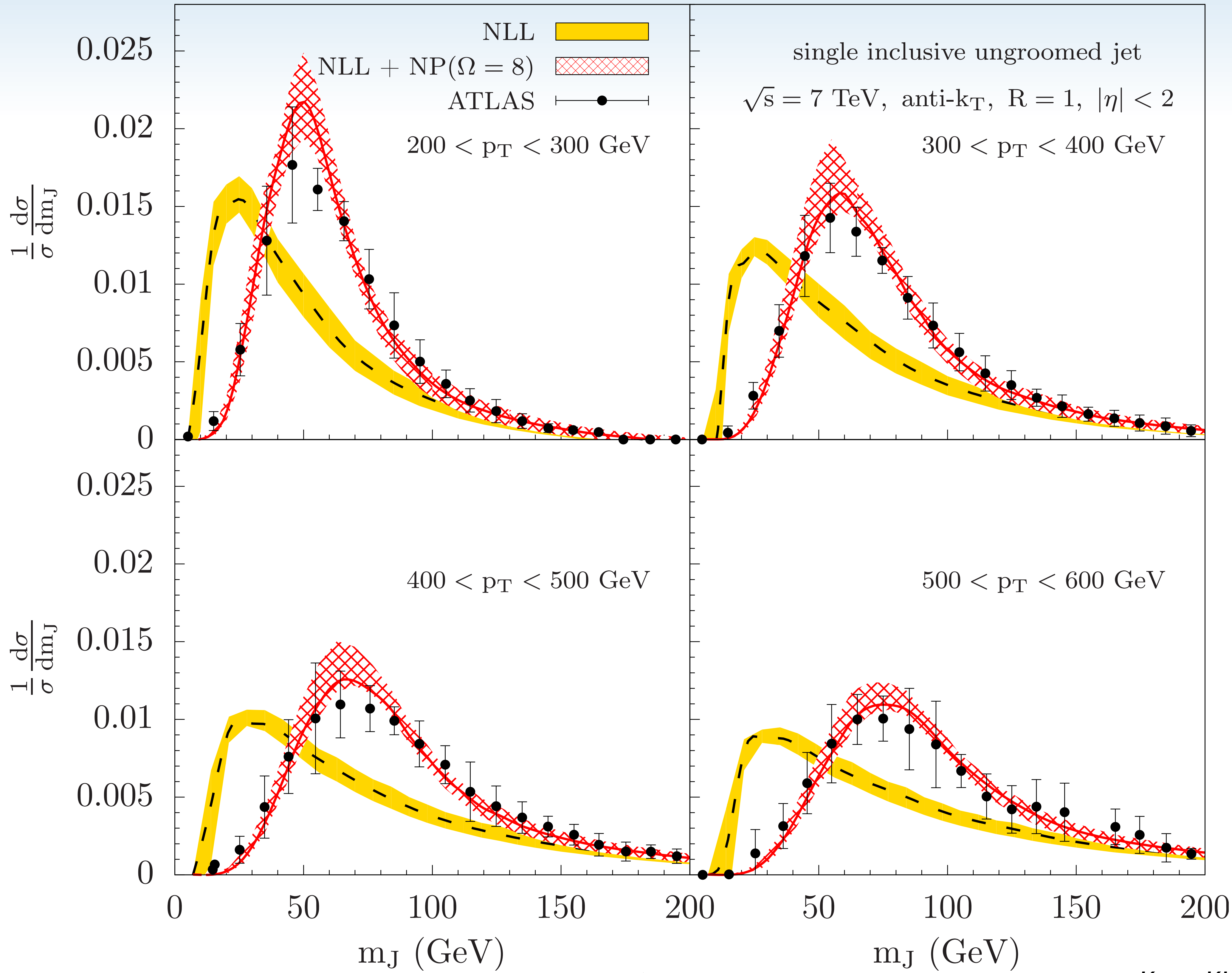

Kang, KL, Liu, Ringer `18

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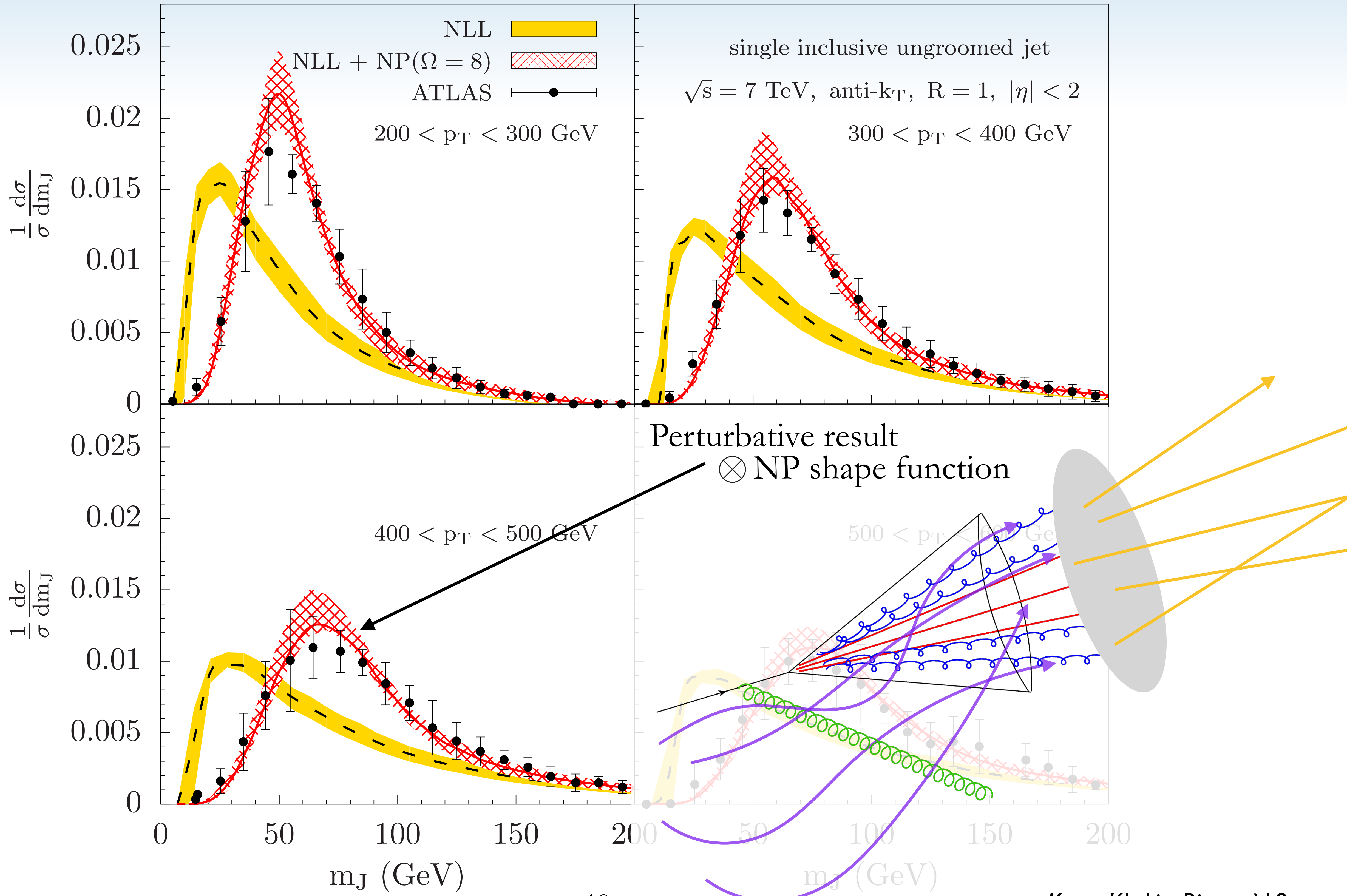


Kang, KL, Liu, Ringer `18

Jet angularity

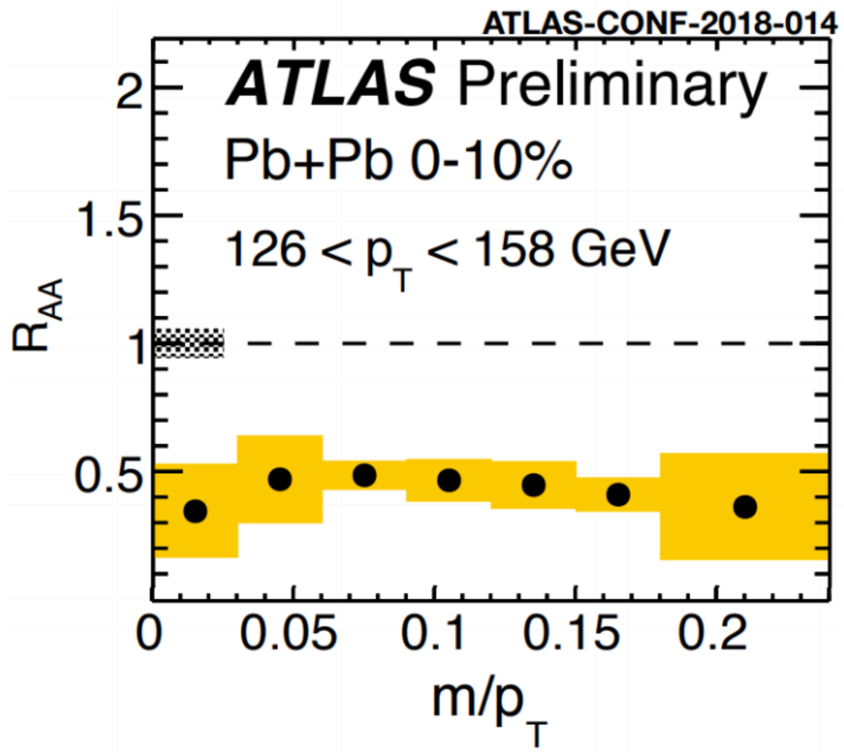
- A generalized class of IR safe observables, angularity (applied to jet):

$$\tau_a^{e^+e^-} = \frac{1}{E_J}\sum_{i\in J} E_i \theta_{iJ}^{2-a}$$

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

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

- a=0 related to thrust (jet mass)



- General observables that includes jet mass to test medium modifications.

Kang, KL, Ringer `18

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?

- **Define observables less sensitive to MPI.**

  1. **Subtracted jet mass moments**
  2. **Grooming**

Subtracted jet mass moments

- Experiments often done with several bins of p_T range.
- Define normalized moments corresponding to the n-th bin by

$$[\tau]^{(n)} = \frac{1}{\sigma^{(n)} \langle \frac{1}{p_T} \rangle^{(n)}} \int^{(n)} dp_T \, d\tau \, \tau \frac{d\sigma}{d\tau dp_T}$$

- Then from

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

we get

$$[\tau]^{(n)} = [\tau]^{(n)}_{\rm pert} + \langle k \rangle_F$$

from MPI and hadronization.

Chien, Kang, KL, Makris, In Preparation

Subtracted jet mass moments

- Experiments often done with several bins of p_T range.
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$$[\tau]^{(n)} = [\tau]^{(n)}_{\rm pert} + \langle k \rangle_F$$

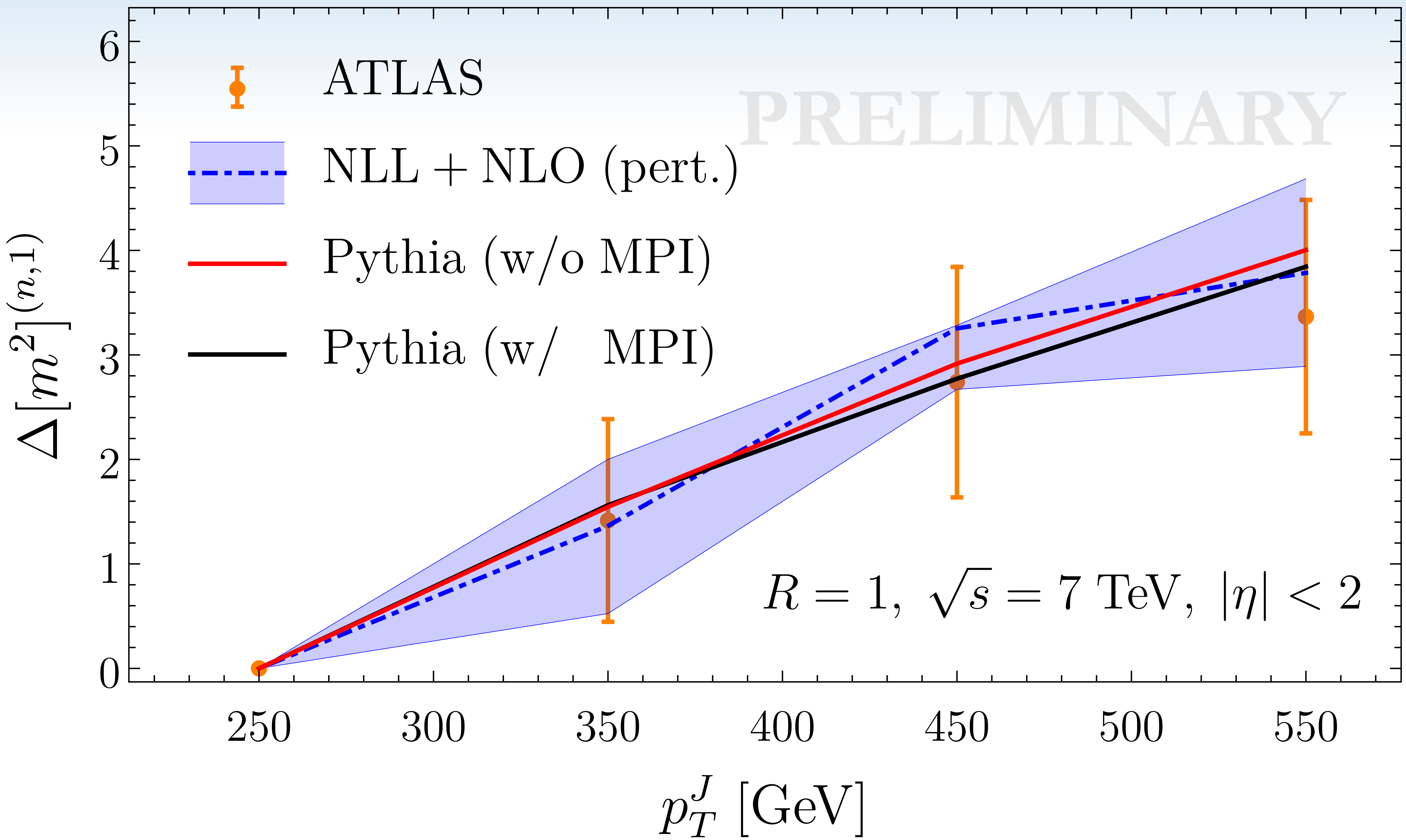
- Choosing the 'n-th' bin as the reference, taking difference with the moments of 'm-th' bin,

$$\Delta\tau^{(m,n)} \equiv [\tau]^{(m)} - [\tau]^{(n)} = [\tau]^{(m)}_{\rm pert} - [\tau]^{(n)}_{\rm pert} \equiv \Delta\tau^{(m,n)}_{\rm pert}$$

we find a quantity independent of uncorrelated radiations.

Chien, Kang, KL, Makris, In Preparation

Subtracted jet mass moments



- **Independent of model, i.e. shape function.**
- **Useful to test modifications by medium with reduced sensitivity to uncorrelated radiations.**

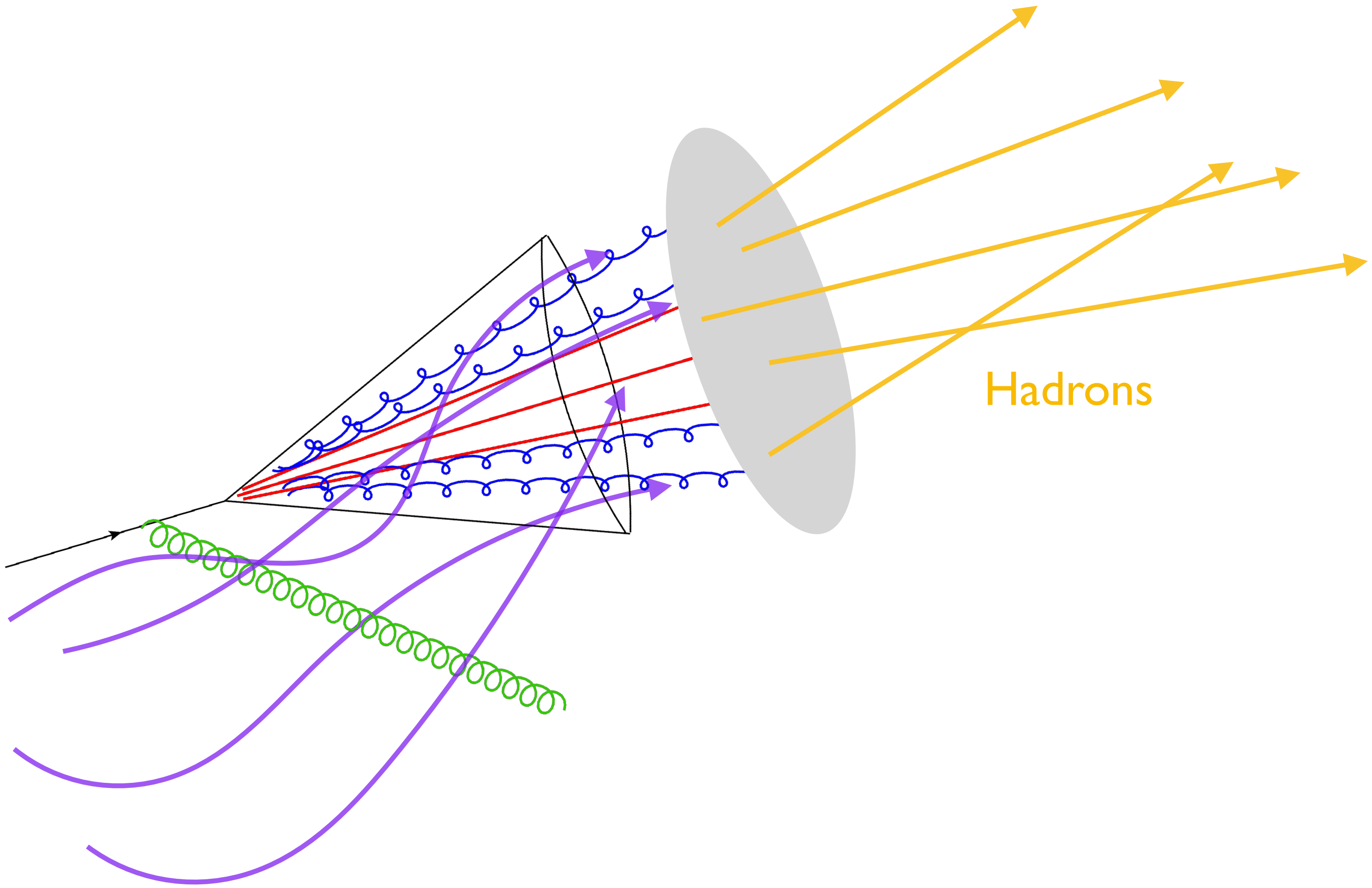
Chien, Kang, KL, Makris, In Preparation

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.



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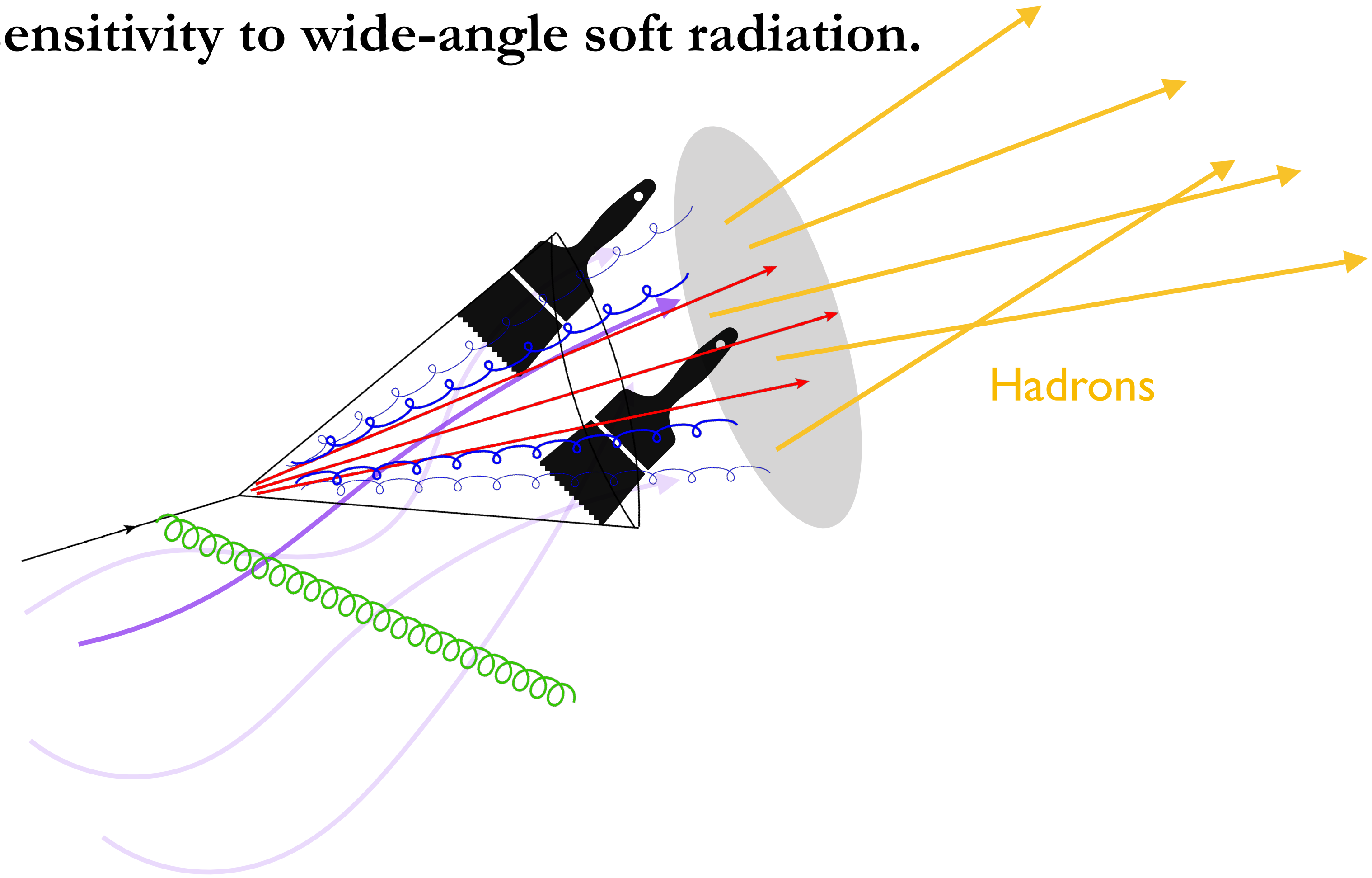
  Groom jets to reduce sensitivity to wide-angle soft radiation.



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.

Figure from Ian Moult's slide from UCLA Nov, 2017

- **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:

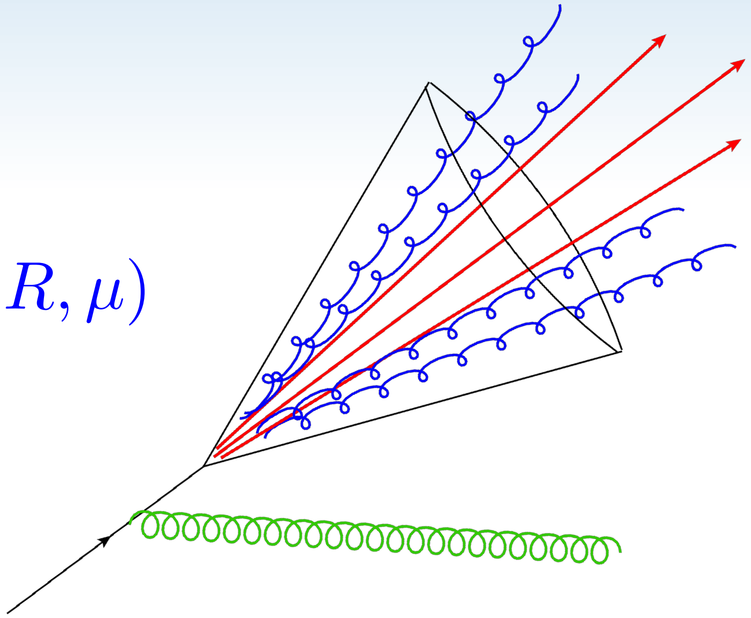
$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{\rm cut} \left(\frac{R_{ij}}{R}\right)^{\beta}$$

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

Groomed jet mass factorization

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

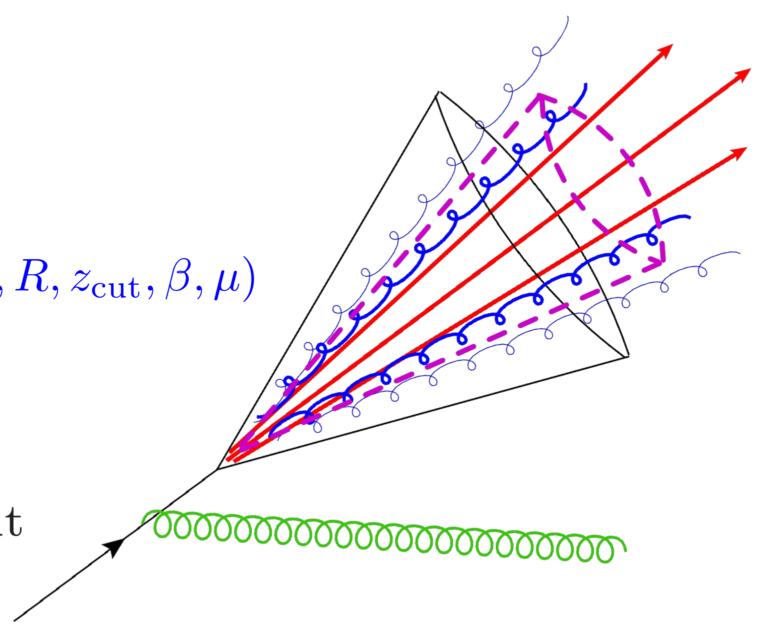
$$\mathcal{G}_i(z, p_T R, \tau, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) C_j(\tau, p_T, \mu) \otimes S_j(\tau, p_T, R, \mu)$$



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

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

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



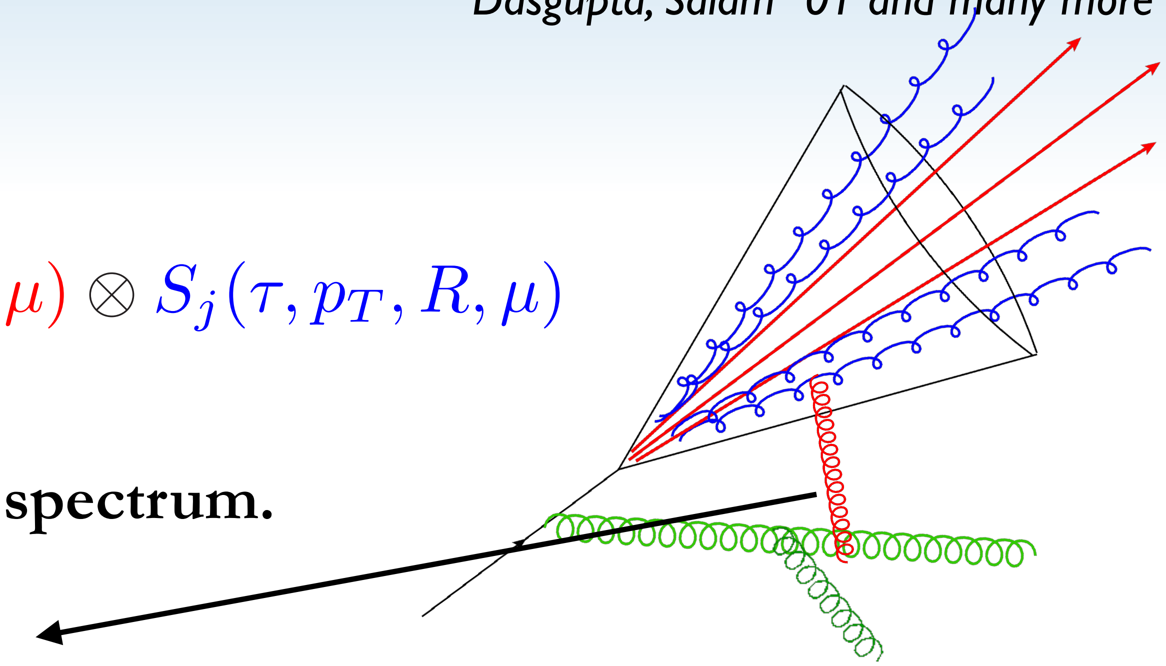
- Resums global logs $\alpha_s^n \ln^n R$, $\alpha_s^n \ln^{2n} \tau/R^2$, and $\alpha_s^n \ln^{2n} z_{\rm cut}$

Non-global Logarithms

Dasgupta, Salam `01 and many more

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

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

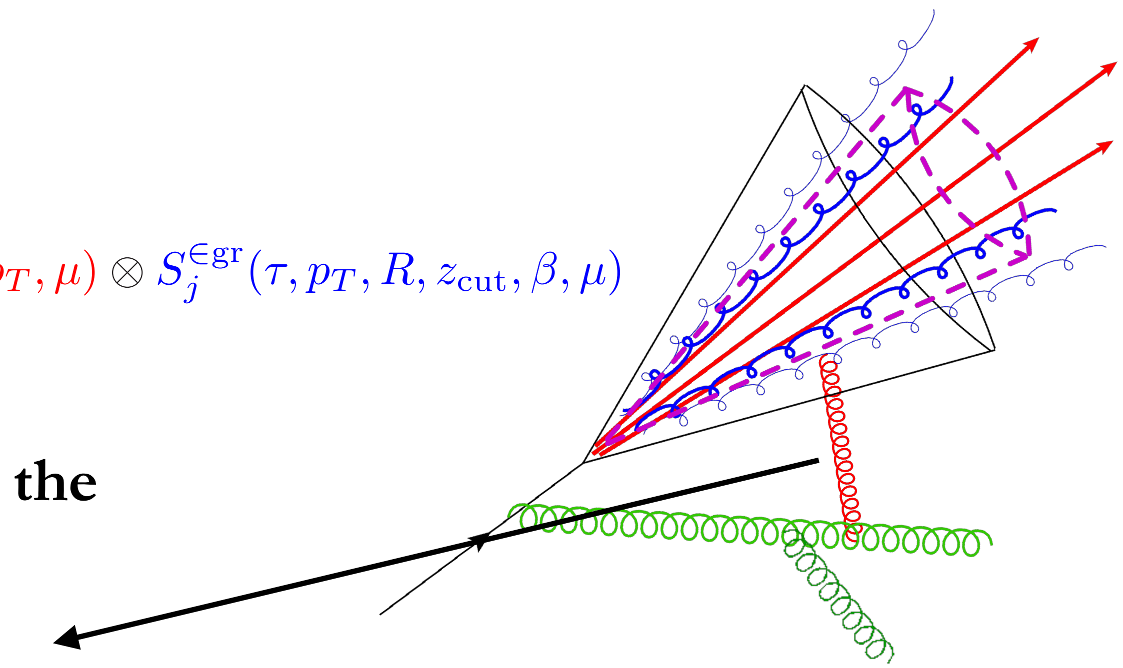


- **Non-global logs directly affect the jet mass spectrum.**

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

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

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



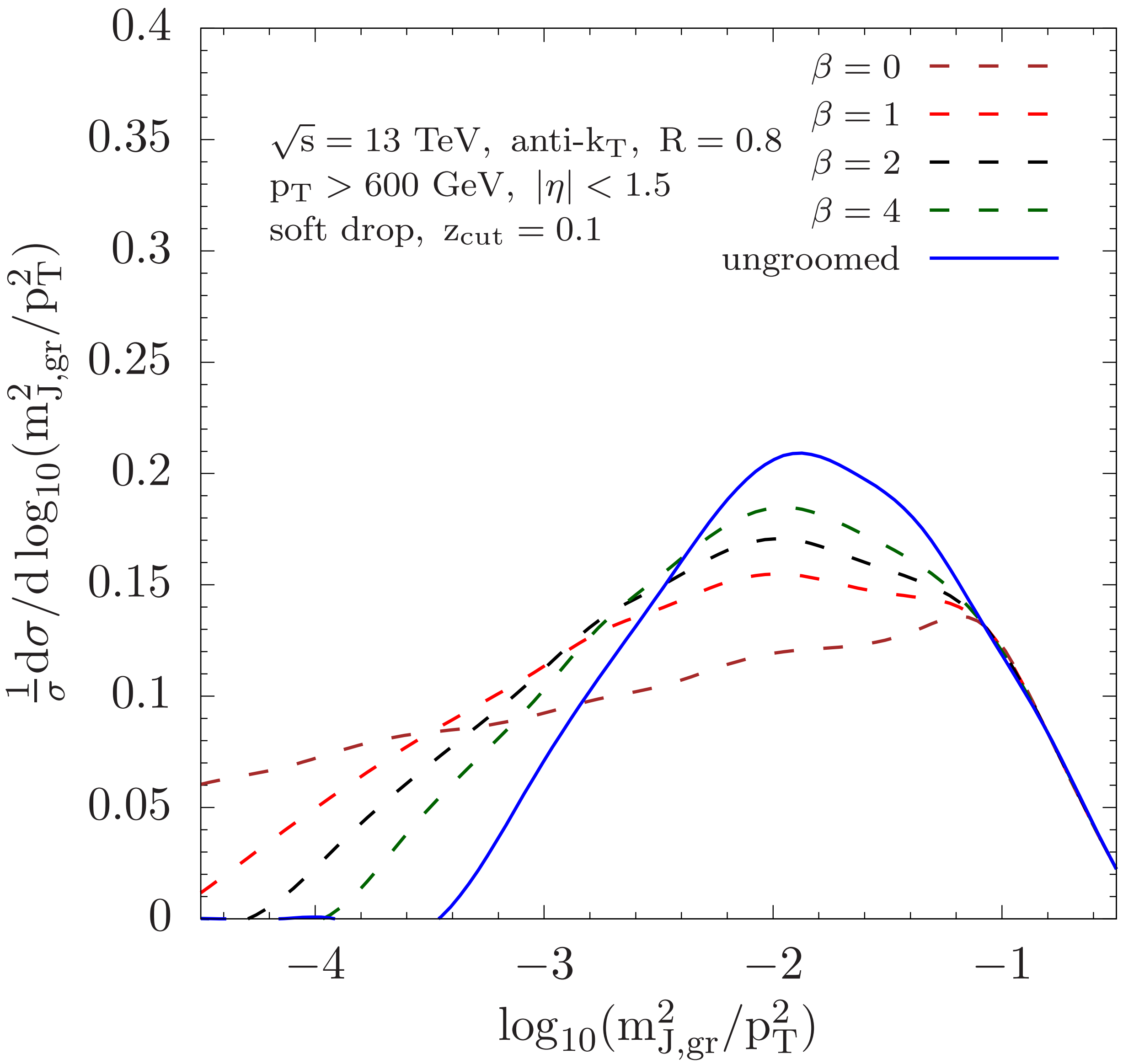
- **Non-global logs affects only indirectly affects the jet mass spectrum through normalization.**

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

Limit to the ungroomed case

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

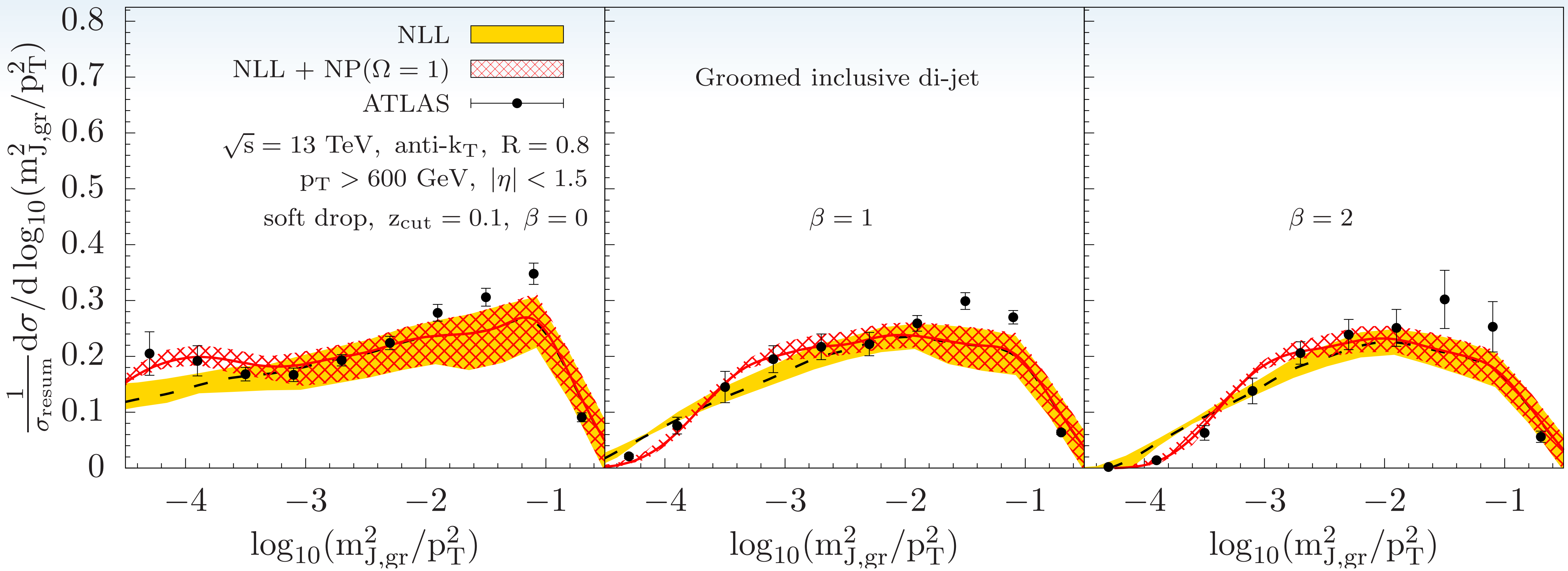
$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{R_{ij}}{R}\right)^{\beta} \to 0 \quad \textbf{when} \quad \beta \to \infty$$



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.

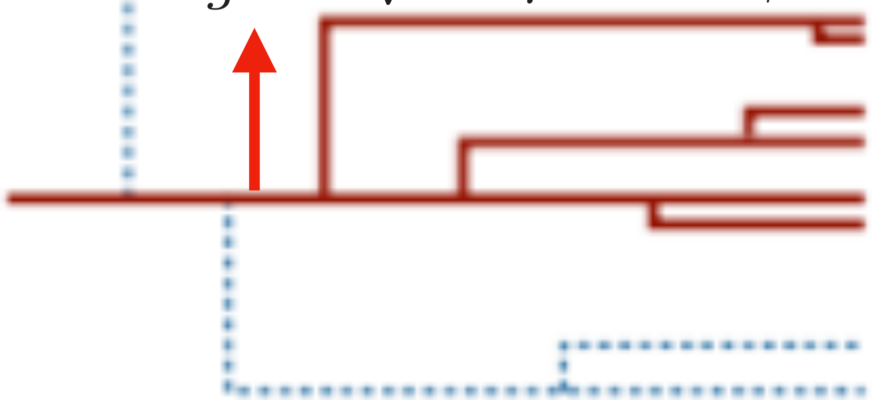
See also
ATLAS, arXiv:1711.08341
Larkoski, Marzani, Soyez, Thaler `14
Frye, Larkoski, Schwartz, Yan `16

Kang, KL, Liu, Ringer `18

NLL factorization of θ_g

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

$$R_g = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



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

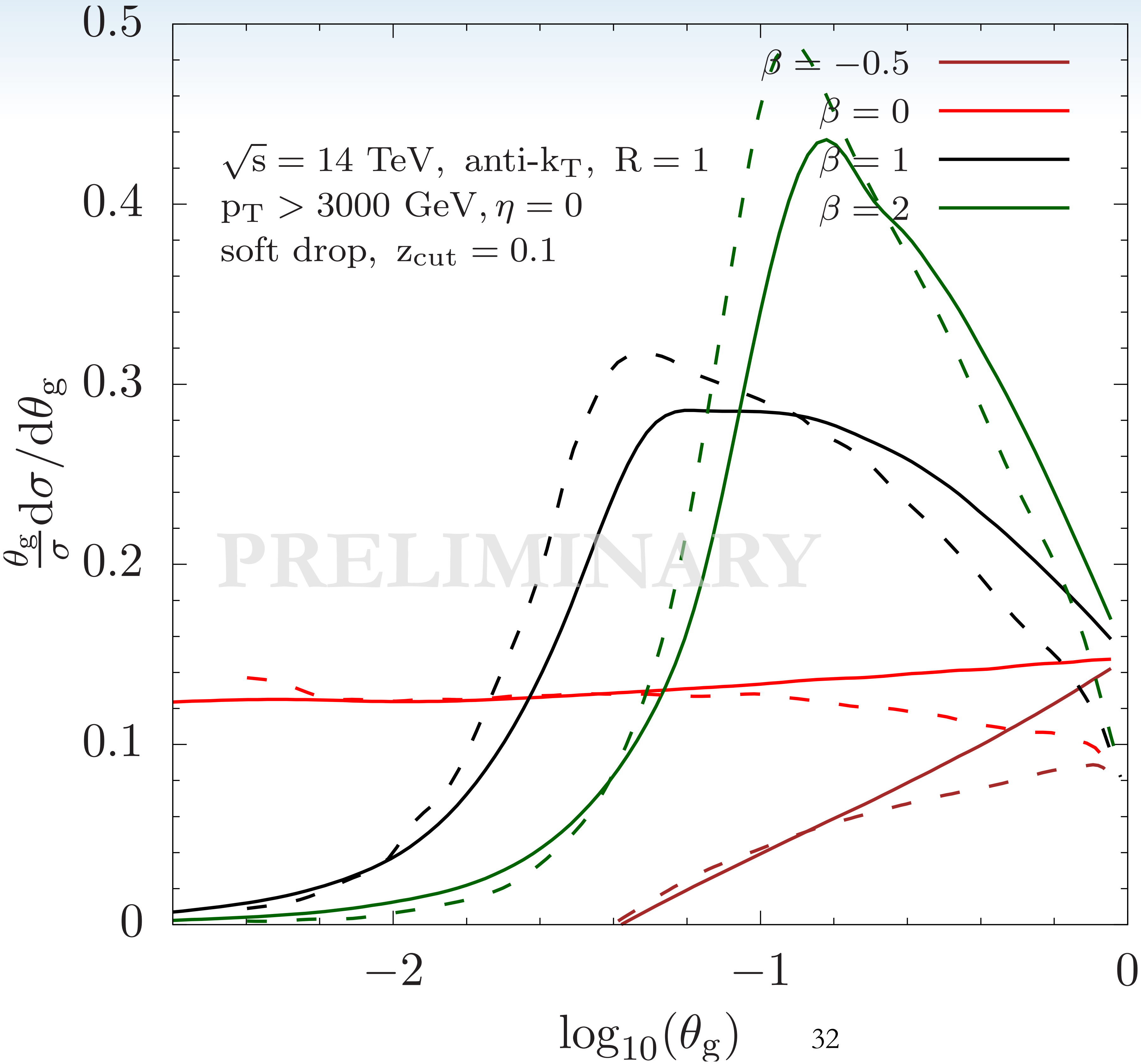
- **Distance between the two branches that passes the soft drop condition.**
- **Groomed jet area is approximately** $\approx \pi R_g^2$
- **Proxy for the sensitivity to contamination from pileup.**
- **Write factorization for cumulative distribution.**

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

$$\mathcal{G}_c(z,p_T,\theta_g,\mu;z_{\rm cut},\beta) = \sum_i \mathcal{H}_{c\to i}(z,p_T R,\mu)\, C_i\left(\theta_g R, p_T,\mu\right) S_i^{\in \rm gr}(\theta_g, R, p_T,\mu;z_{\rm cut},\beta)$$
$$\times\, S_i^{\notin \rm gr}\left(p_T, R, \mu; z_{\rm cut},\beta\right)$$

Kang, KL, Liu, Ringer, In Preparation

NLL factorization of θ_g



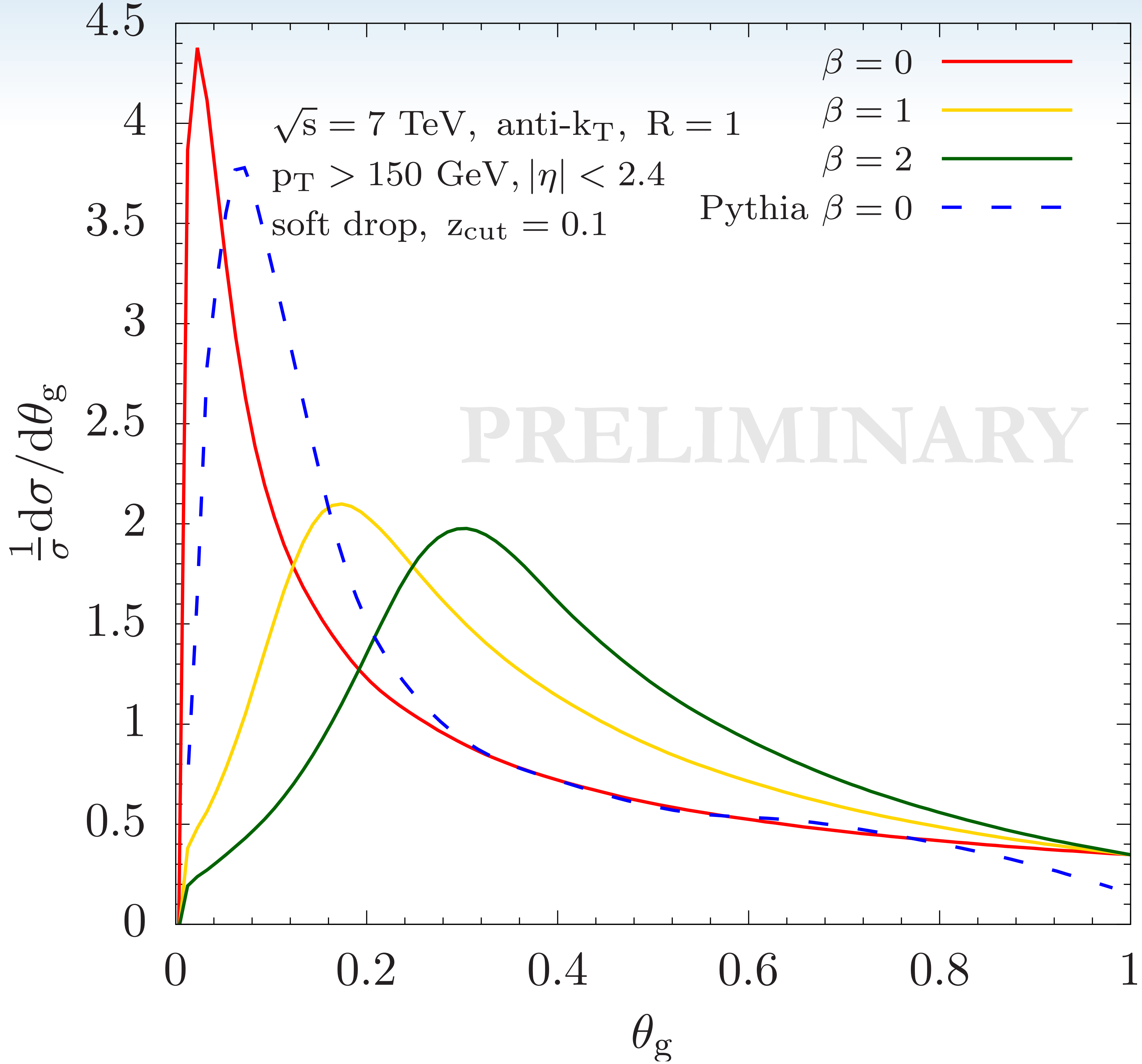
$$\frac{d\sigma}{d\eta dp_T d\theta_g} = \frac{d}{d\theta_g}\frac{d\Sigma(\theta_g)}{d\eta dp_T}$$

Dashed - Pythia
Solid - NLL (pert)

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

Kang, KL, Liu, Ringer, In Preparation

NLL factorization of θ_g



$$\frac{d\sigma}{d\eta dp_T d\theta_g} = \frac{d}{d\theta_g}\frac{d\Sigma(\theta_g)}{d\eta dp_T}$$

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

Kang, KL, Liu, Ringer, In Preparation

Photoproduction at the EIC

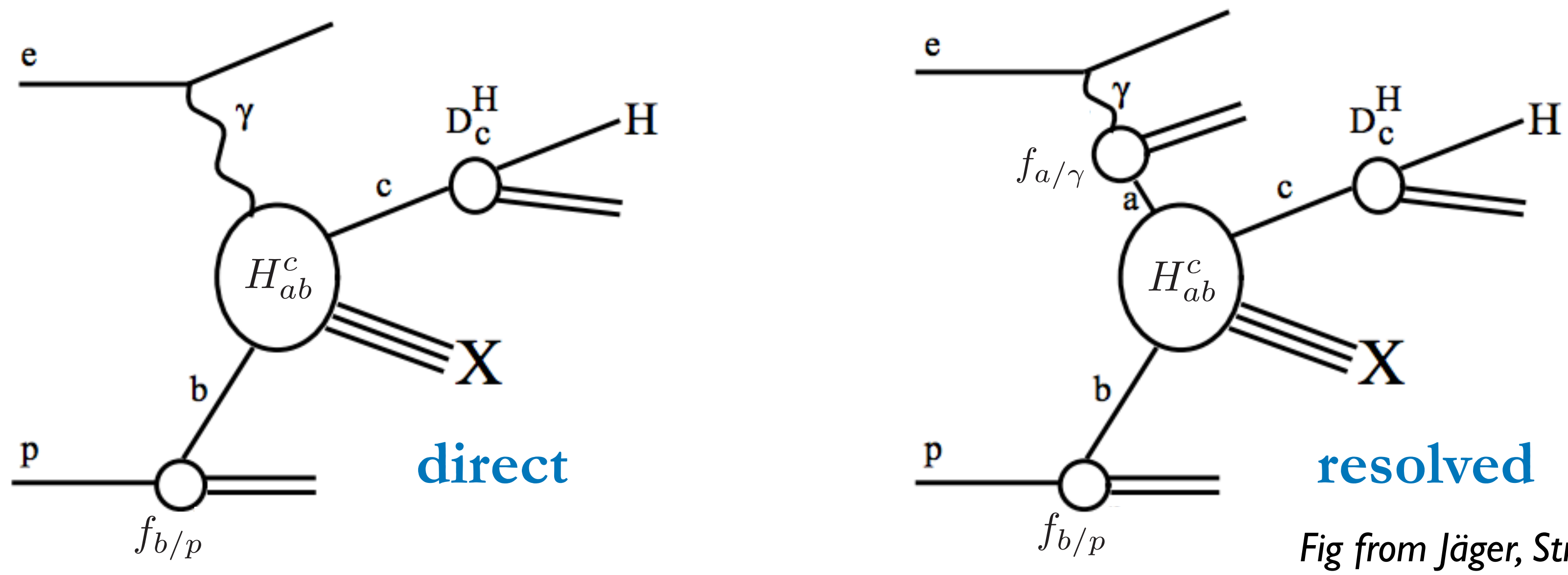


Fig from Jäger, Stratmann, Vogelsang `03

hadron $$\frac{d\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes D^h_c$$

Weizsäcker-Williams spectrum

$$f_{a/l} = P_{\gamma l} \otimes f_{a/\gamma}$$

- For the direct process, $f_{a/\gamma} = \delta(1 - x_\gamma)$.
- Observe outgoing lepton to tag Q^2
- Require high p_T and $Q^2 < 0.1$ GeV^2 (near on-shell photon)

See Jäger, Stratmann, Vogelsang `03

Photoproduction at the EIC

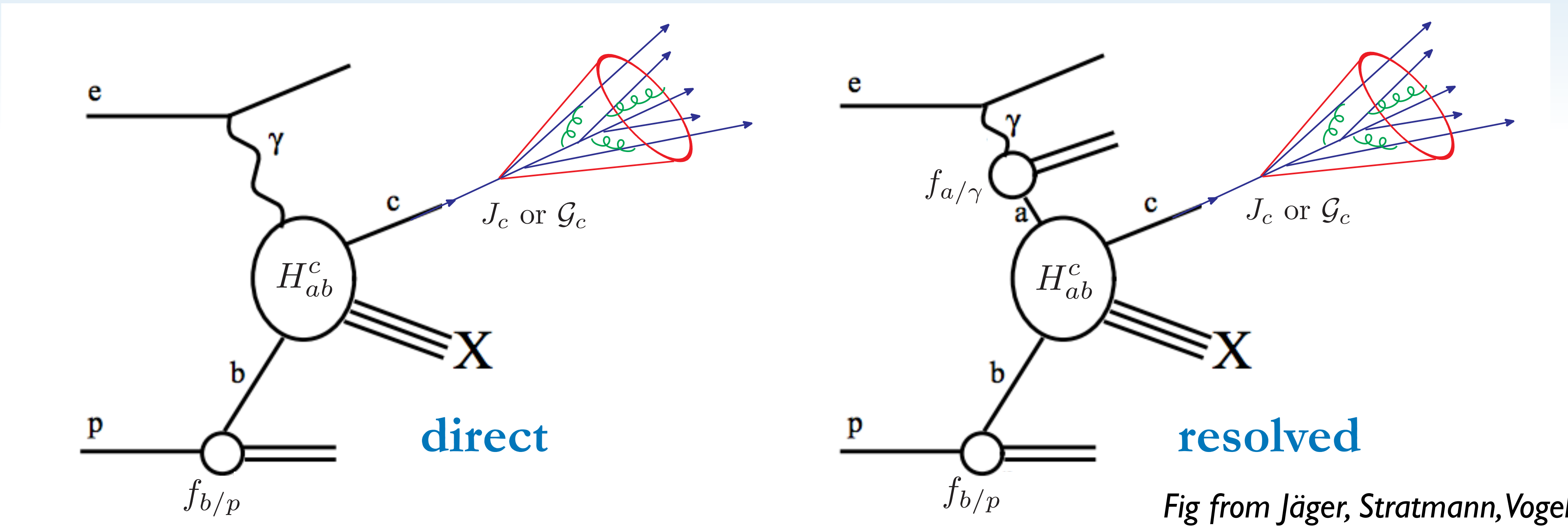


Fig from Jäger, Stratmann, Vogelsang `03

hadron $$\frac{d\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes D^h_c$$

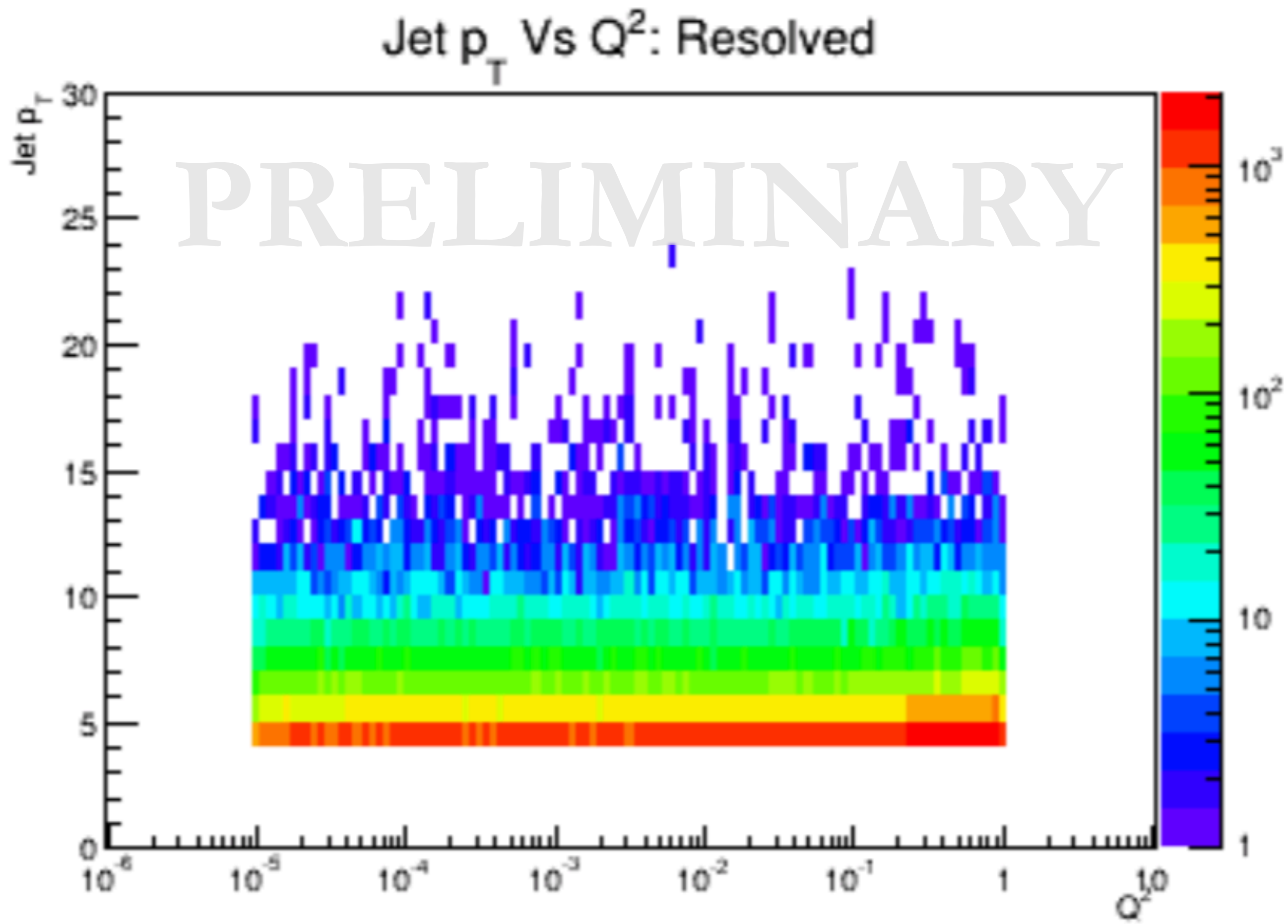
Inclusive Jet $$\frac{d\sigma^{ep\to e\text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes J_c + \mathcal{O}(R^2)$$

Jet mass $$\frac{d\sigma^{ep\to e\text{jet}(m_J)X}}{dp_T d\eta dm_J} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes \mathcal{G}_c(m_J) + \mathcal{O}(R^2)$$

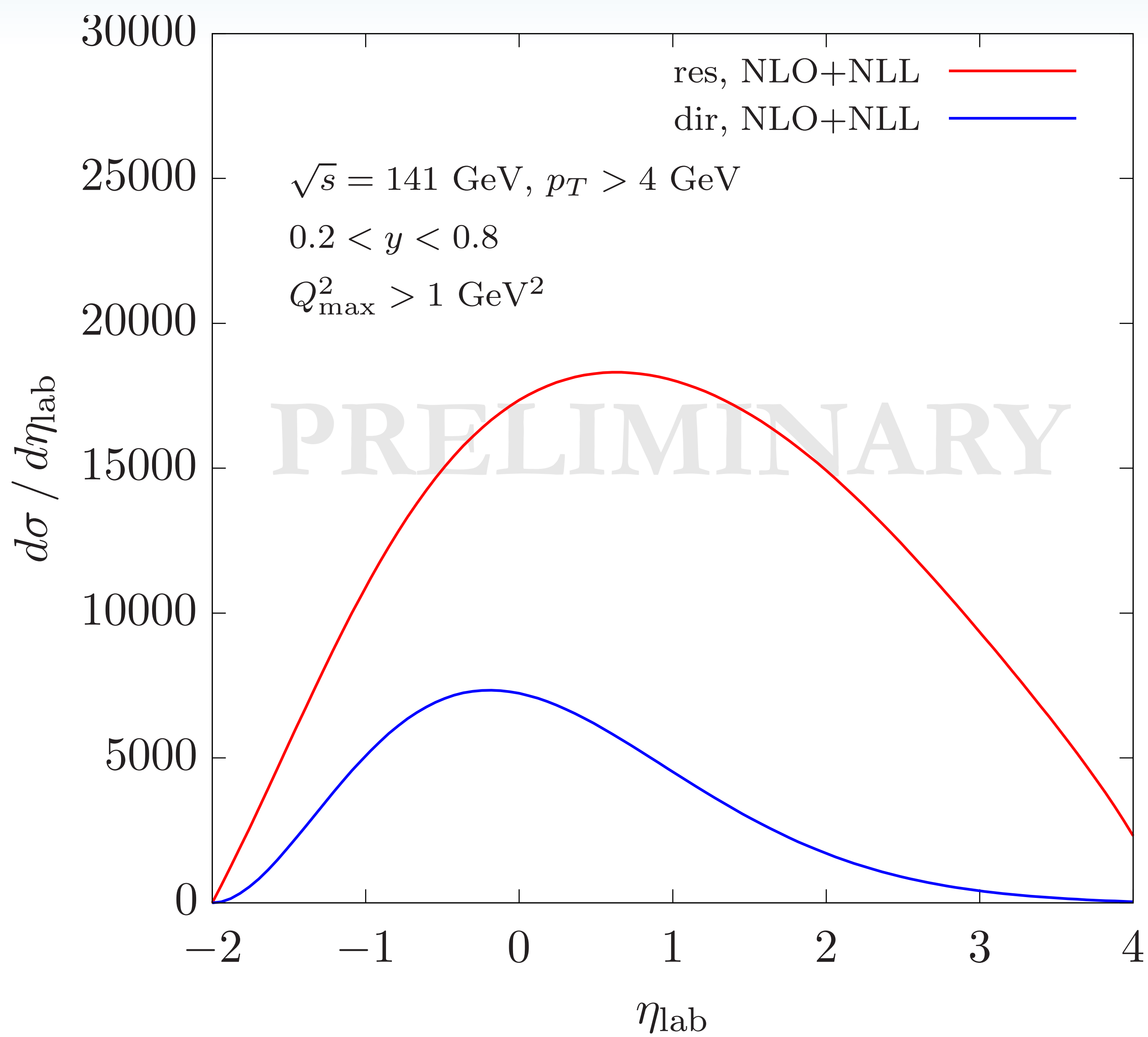
- Sensitivity to the photon pdfs. Can be done for polarized and unpolarized case.
- Quark and gluon discrimination with jet mass observed.
- Role of NP physics?

Jäger, Stratmann, Vogelsang `03
Chu, Aschenauer, Lee, Zheng `17
In collaboration with Elke Aschenauer and Brian Page

p_T distribution for the jets in the EIC



$E_e = 20$ GeV
$E_p = 250$ GeV



- $5\text{ GeV} < p_T < 15\text{ GeV}$ for $Q^2 < 1\text{ GeV}$, contribution mostly from resolved.

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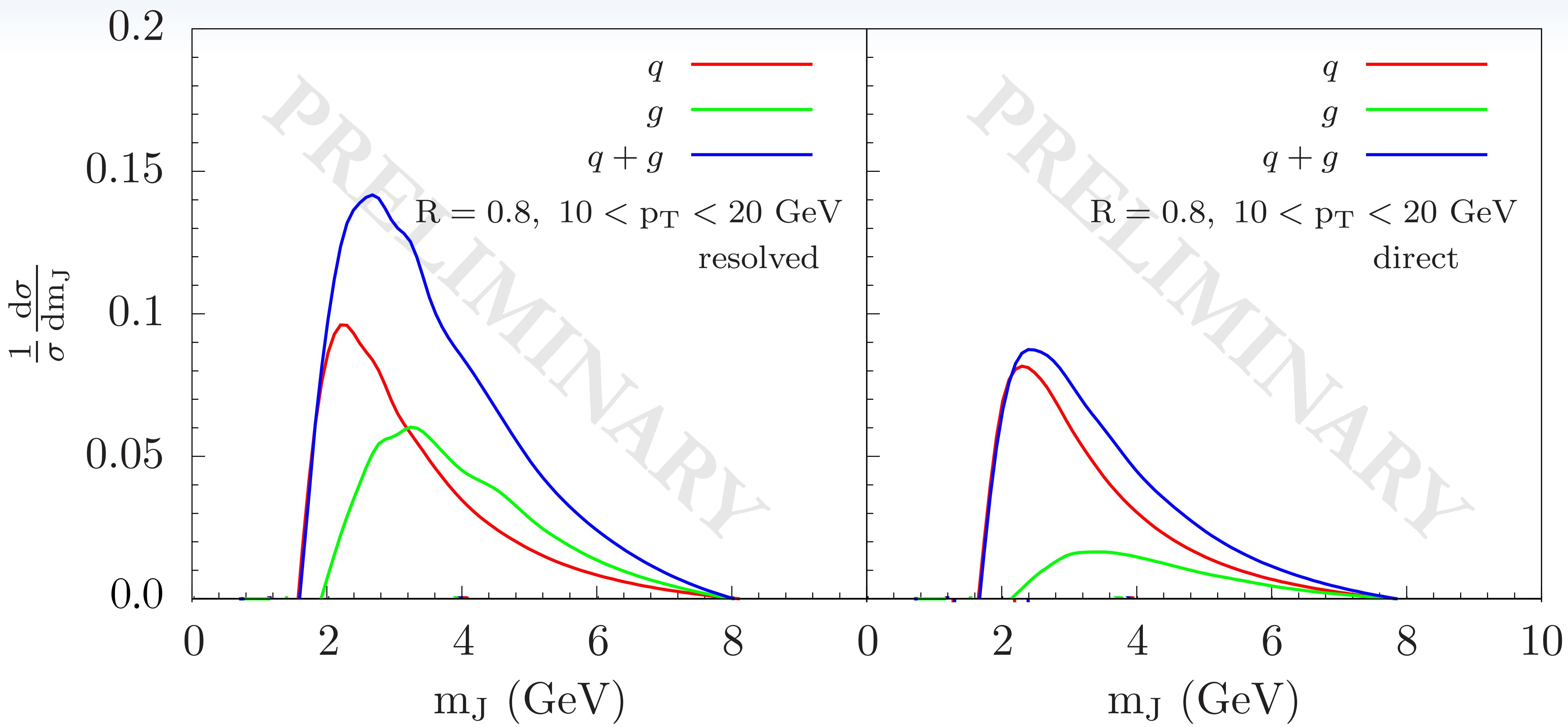
Preliminary Plots



- **Fraction of gluon contribution is reduced for the direct process relative to the resolved process.**

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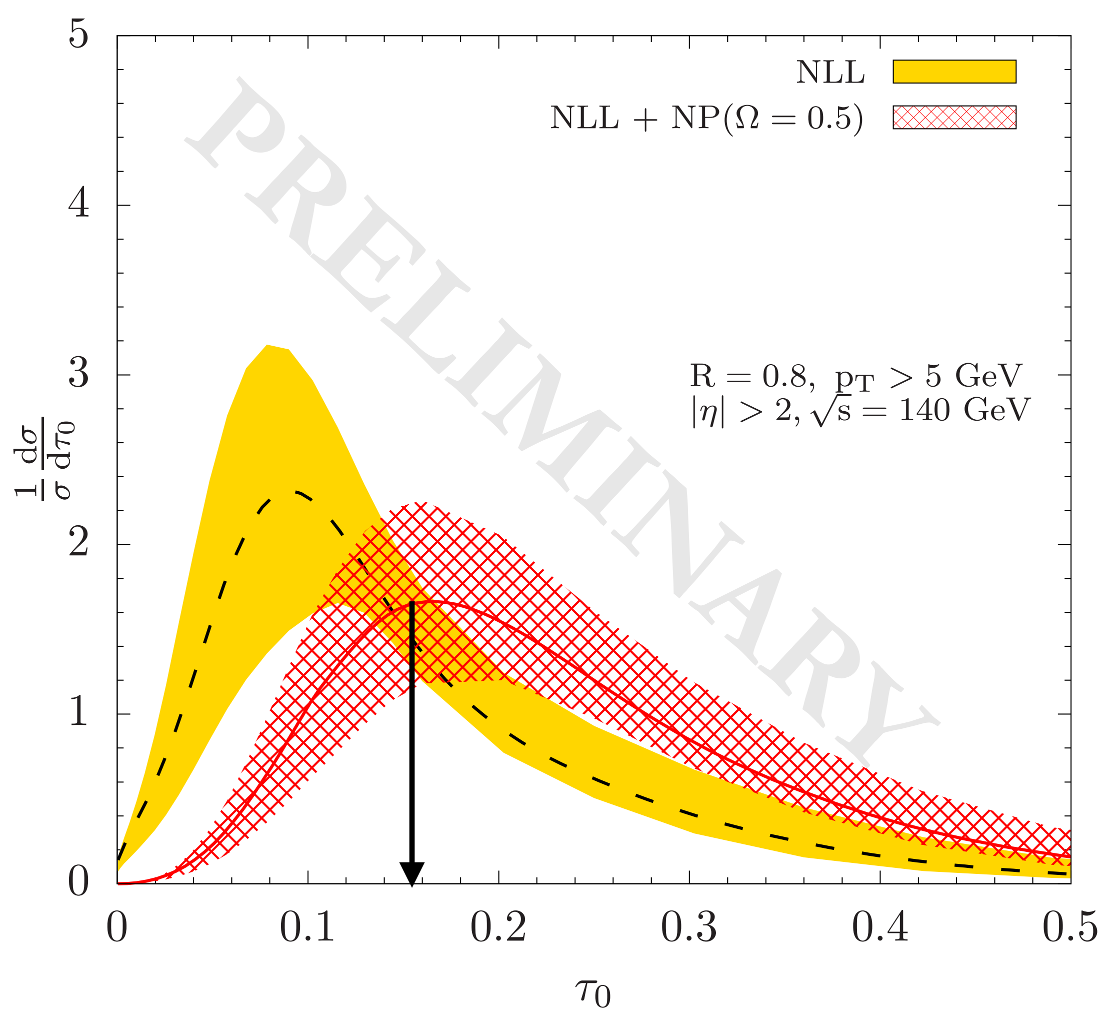
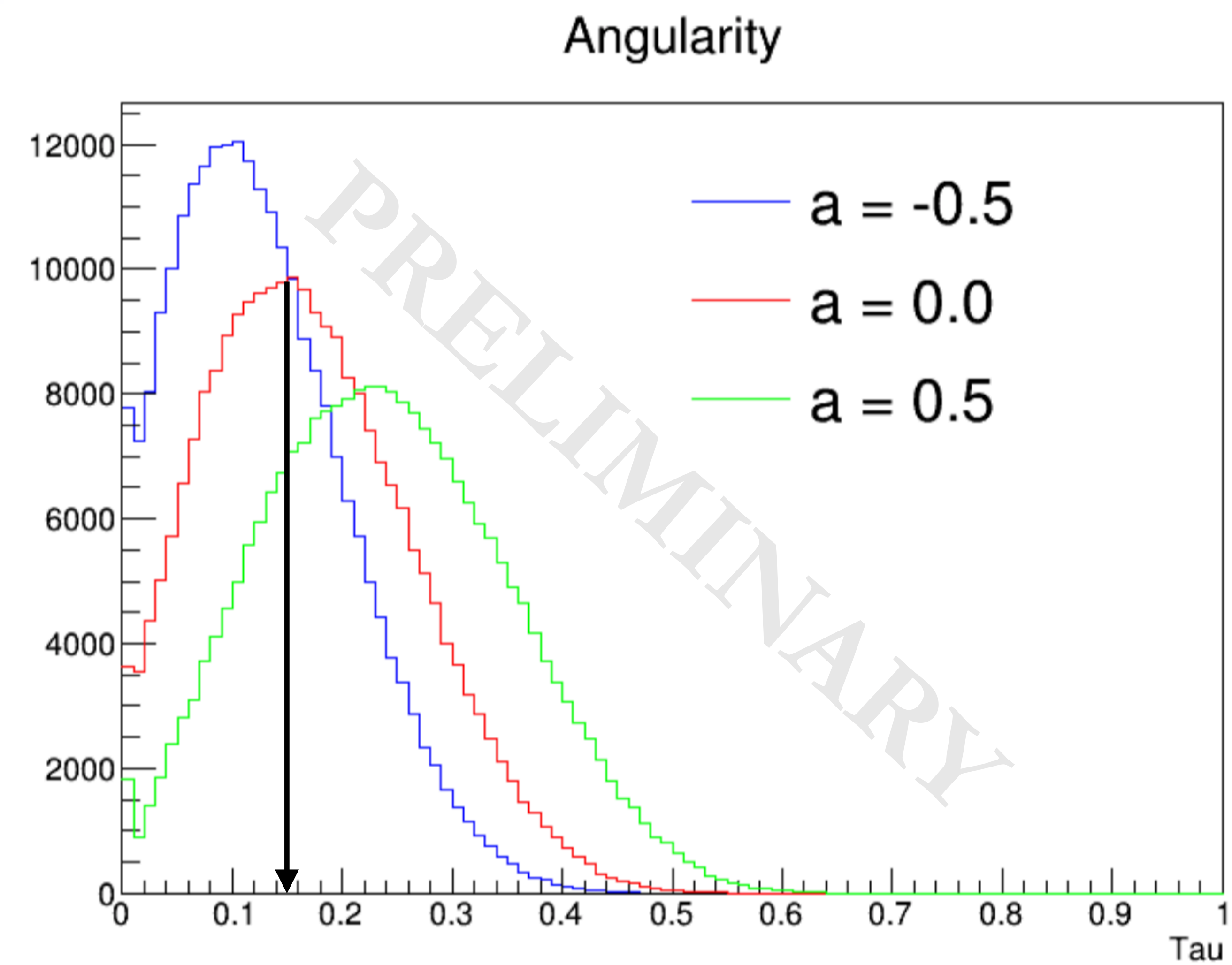
Preliminary Plots





- **Monte Carlo**

- $\Omega_\kappa = 0.5$ GeV, **assumption that NP effects only come from the hadronization gives the right peak value $\Longrightarrow$ less contamination from UE than LHC**

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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 subtracted jet mass moments and grooming which reduce contaminations from the uncorrelated radiations.
- Discussed phenomenology of groomed jet mass and groomed jet radius.
- Formalisms were extended to the photoproduction case at the EIC and was shown that EIC has a cleaner environment than the LHC.