Recent Theoretical Approaches Towards Understanding Jet Substructure

(and how it can be used to study QGP)

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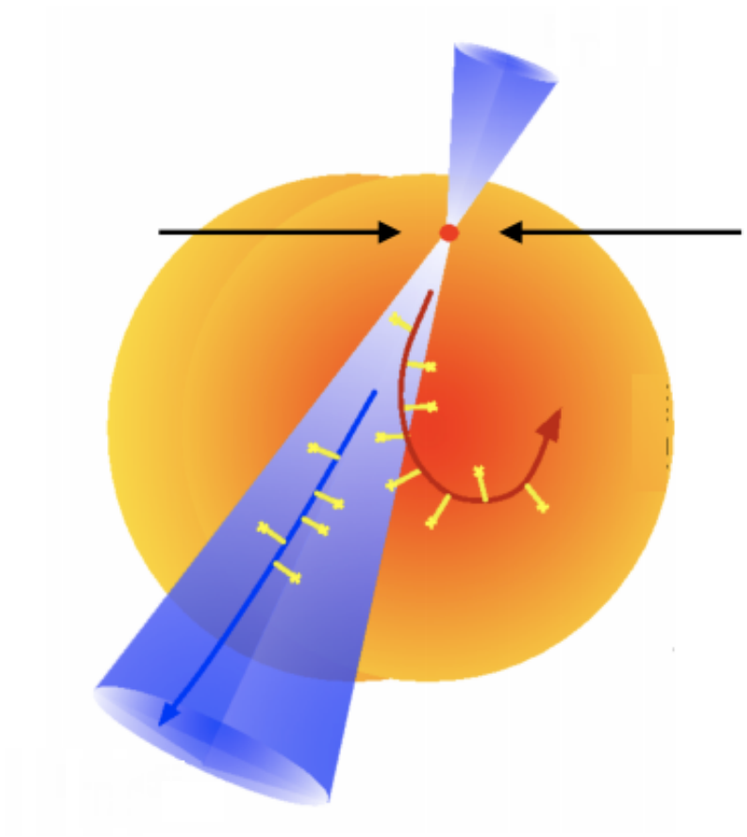
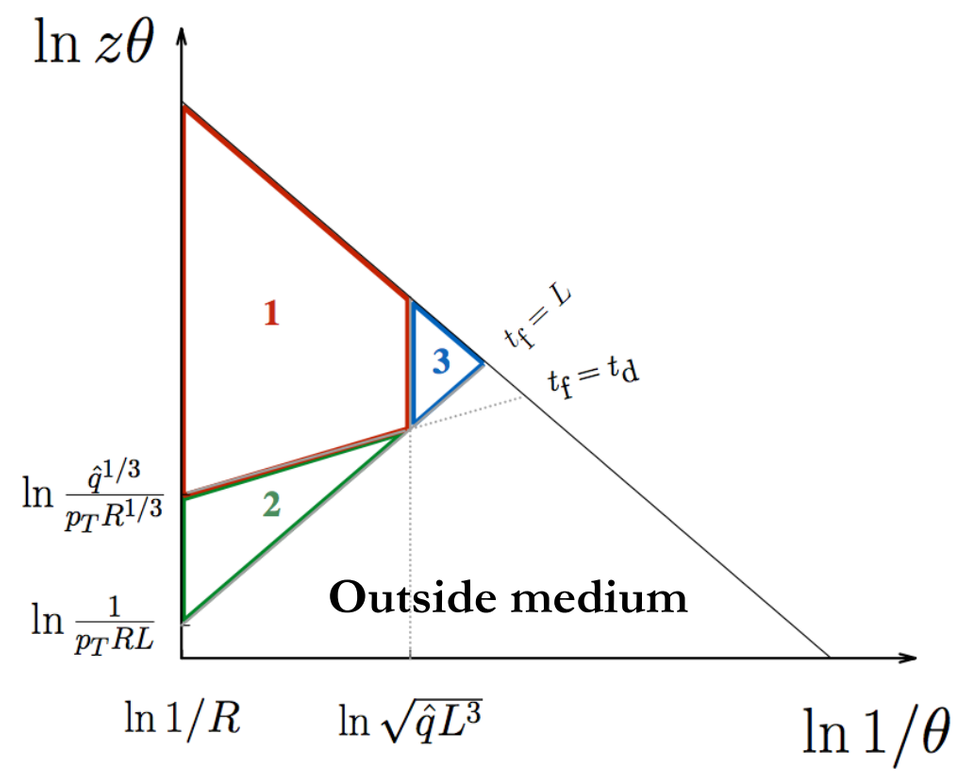
06/04/19 - 06/07/19

Jet as a probe of QGP



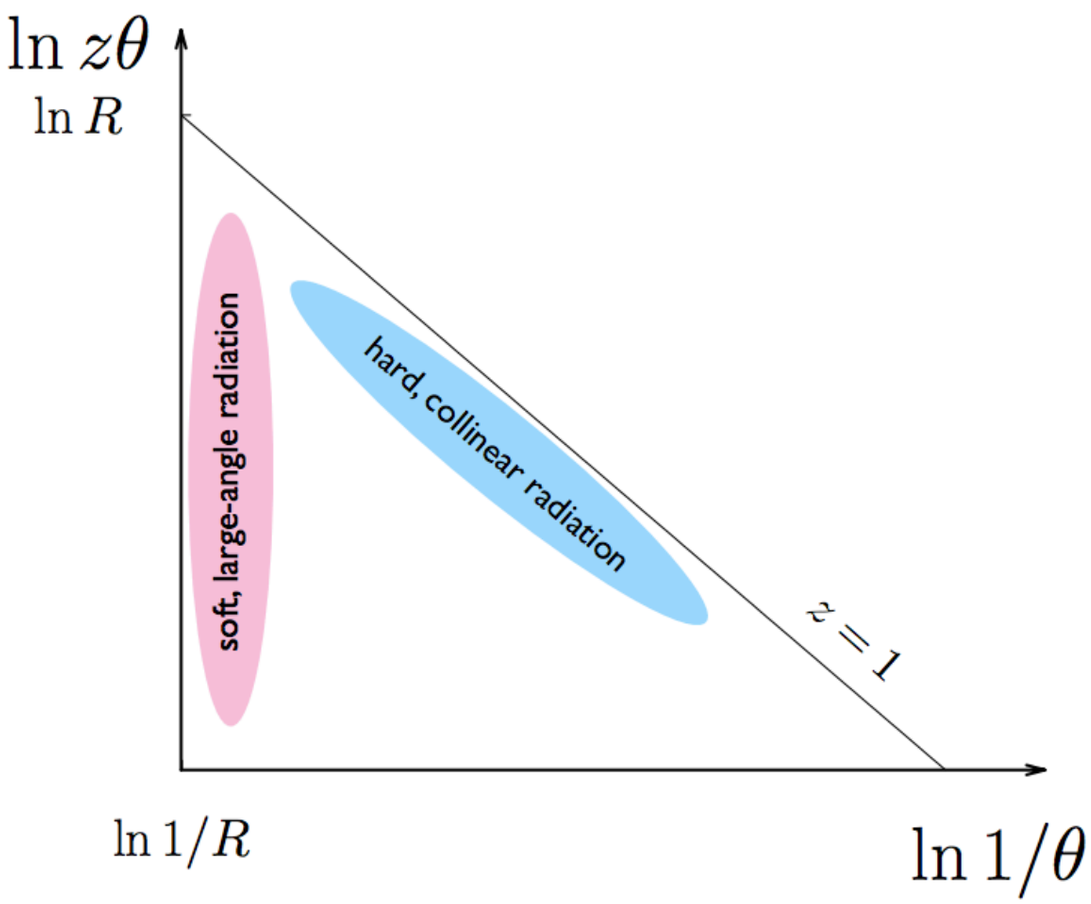
Lund diagram and splitting history



5th Heavy Ion Jet Workshop Report, 2018:

- **Devise jet substructure observables to probe different kinematical regions of QGP and discriminate different jet quenching models.**

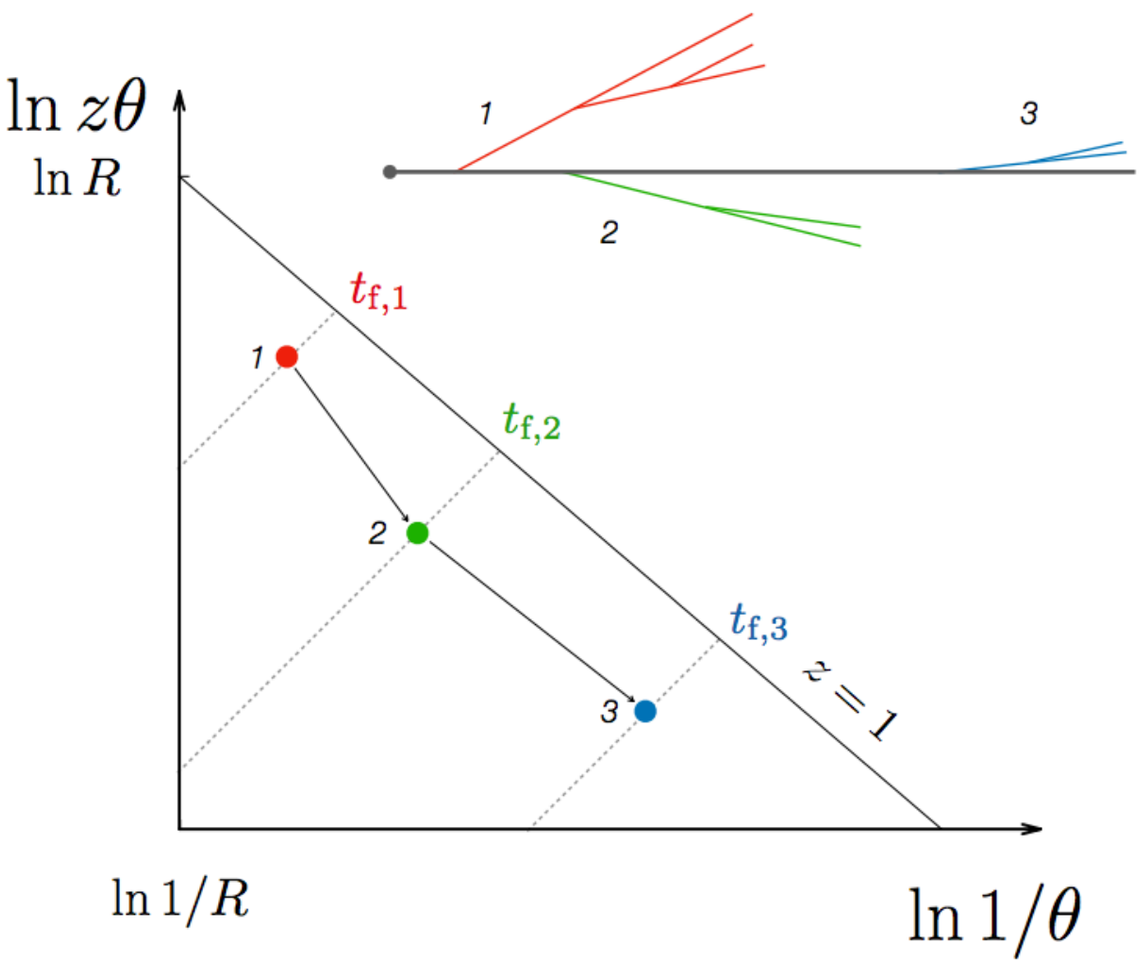
Lund diagram to map different splitting



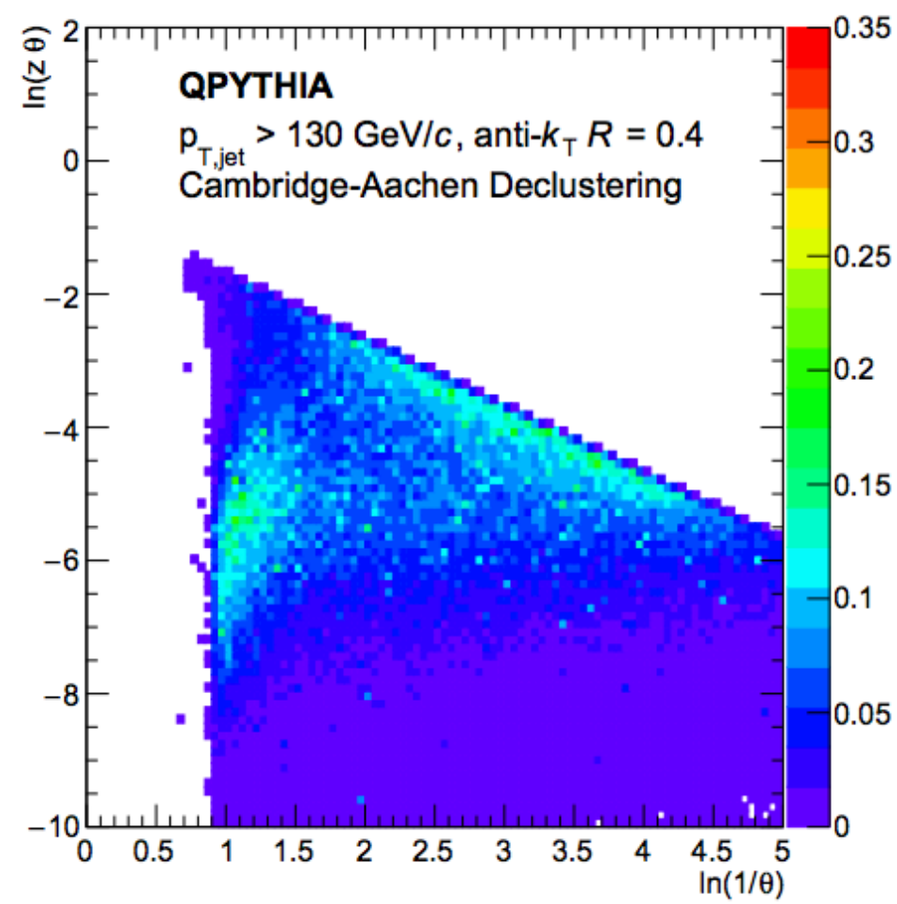
- **Lund diagram is useful to visualize collinear and soft splittings.**

5th Heavy Ion Jet Workshop Report, 2018

Lund diagram to map different splitting

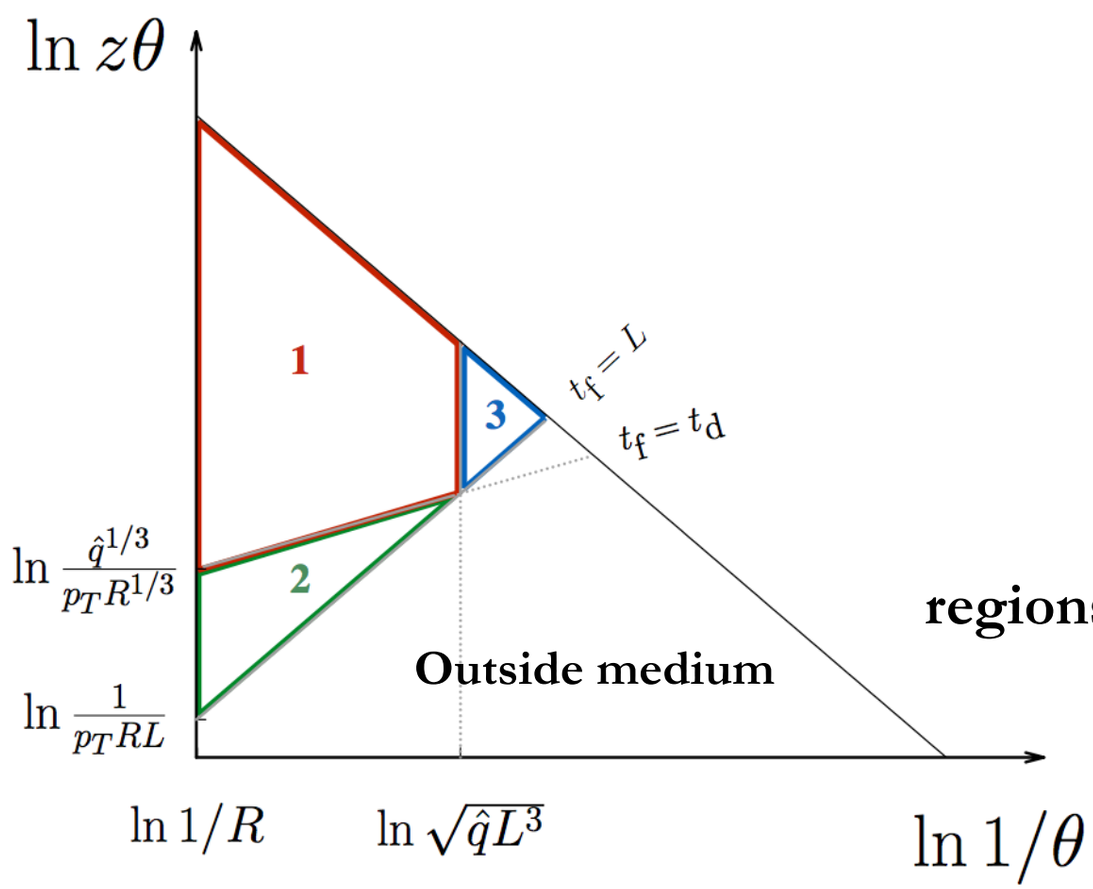


- **Lund diagram is useful to visualize collinear and soft splittings.**
- **Map splitting history into Lund Plane.**



5th Heavy Ion Jet Workshop Report, 2018

Lund diagram to map different splitting



- **Lund diagram is useful to visualize collinear and soft splittings.**
- **Map splitting history into Lund Plane.**
- **Identifies different kinematical regions when medium is introduced.**

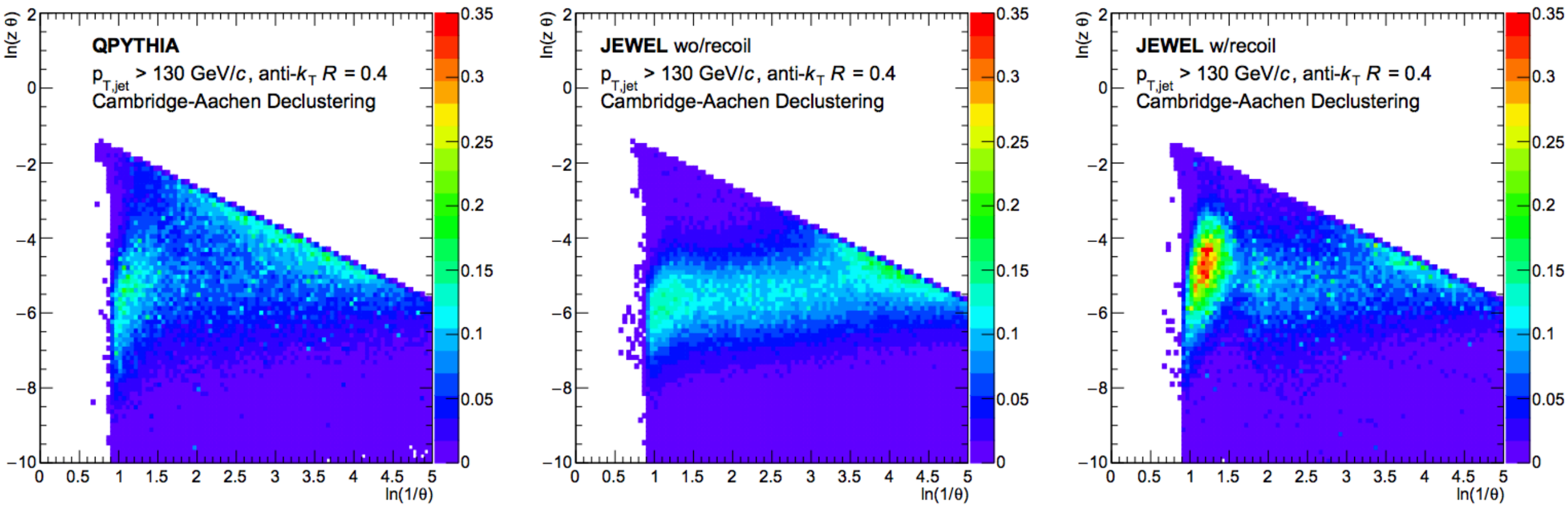
i.e. regions inside / outside medium (size L)
regions where medium resolves /does not resolve splitting
(broadening $\langle k_T^2 \rangle = \hat{q}t$)

5th Heavy Ion Jet Workshop Report, 2018:

- **Devise jet substructure observables to probe different kinematical regions of QGP and discriminate different jet quenching models.**

5th Heavy Ion Jet Workshop Report, 2018

Lund diagram to map different splitting



5th Heavy Ion Jet Workshop Report, 2018:

- **Devise jet substructure observables to probe different kinematical regions of QGP and discriminate different jet quenching models.**

5th Heavy Ion Jet Workshop Report, 2018

Jet substructures and characteristic scales

Single prong observables

- Jet angularities
- Energy-energy correlations
- Jet shape

Multi-prong observables

- N-subjettiness
- D_2

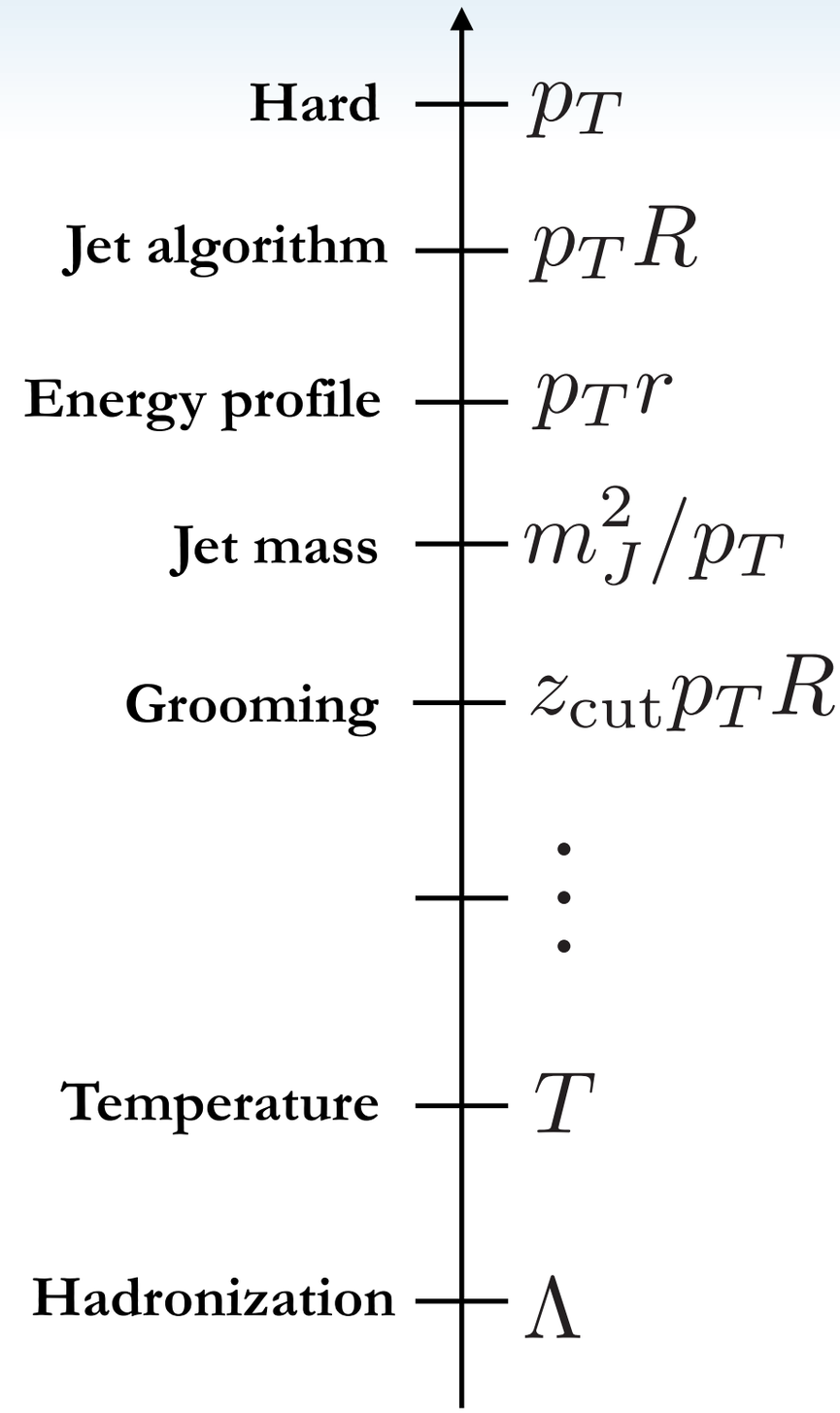
IRC unsafe observables

- Hadron in jet
- Multiplicities
- Jet charge

Groomed observables

- All of the above
- Observables characterizing grooming (SD): $z_g, \quad \theta_g = R_g/R$

and many more



Jet substructures and characteristic scales

Single prong observables

- Jet angularities
- Energy-energy correlations
-

Multi-prong ob

-
-

IRC unsafe obs

-
-
-

Groomed obs

-
-

grooming (SD): $z_g, \quad \theta_g = R_g/R$

Hard — p_T

Jet algorithm — $p_T R$

$_T r$

n_J^2/p_T

$_{\rm cut} p_T R$

Hadronization — Λ

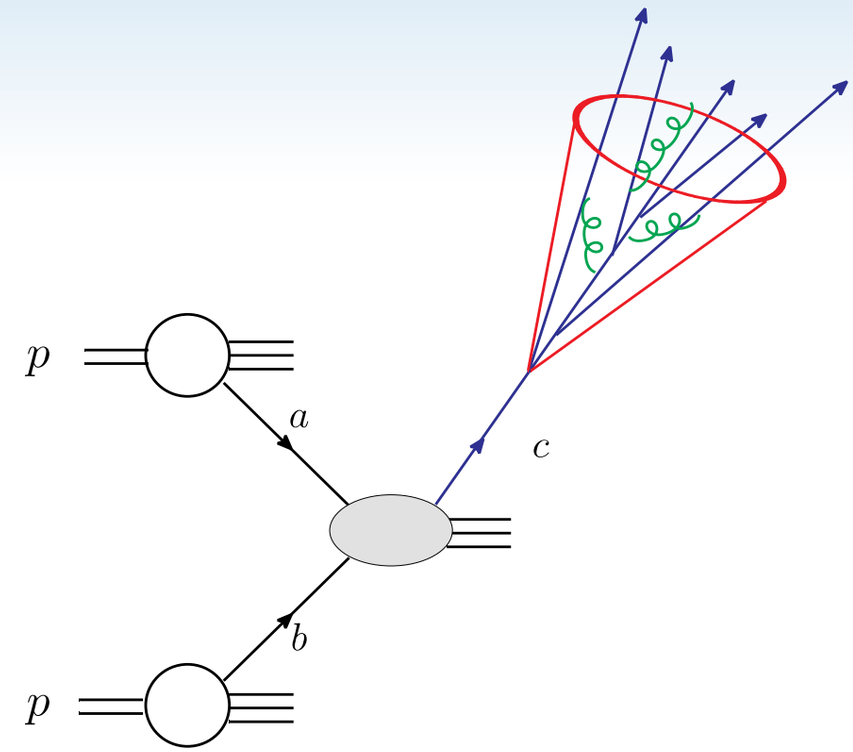
Jet substructures are perfect observables to probe different kinematical regimes of splitting.

Why we must study hadron-hadron collisions

- **Hadron-hadron collisions teach us valuable lessons:**

1. We need baseline to compare against vacuum predictions.

$$R_{AA} = \frac{dN_{AA}/dp_T^2 d\eta}{\langle T_{AA}\rangle d\sigma_{pp}/dp_T^2 d\eta}$$



2. Theoretical frameworks developed in pp can be insightful.

ex. QCD factorization, Lund diagrams, …

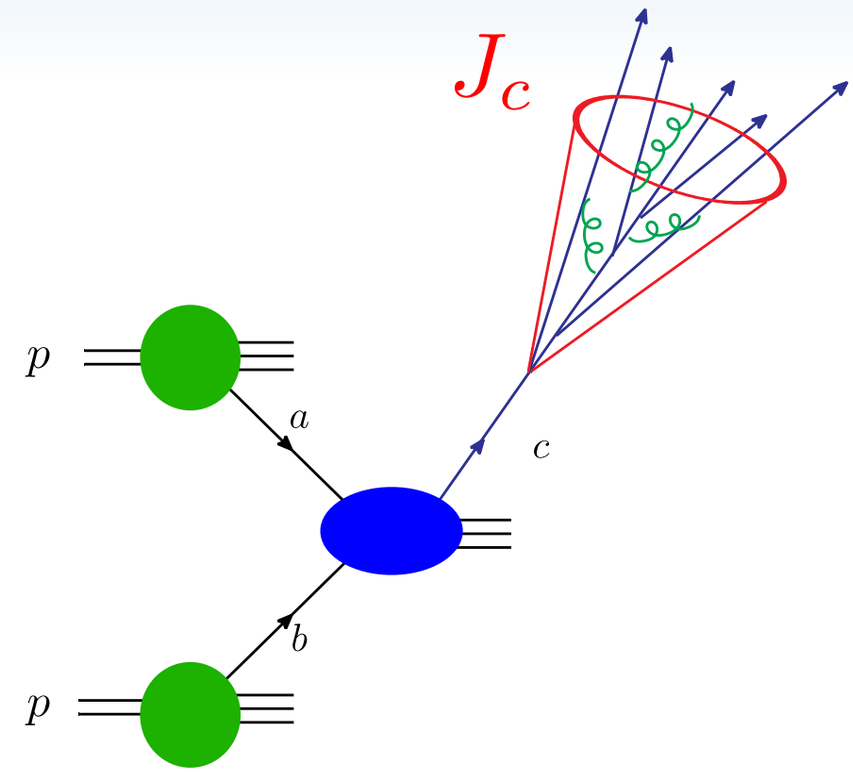
3. Useful place to develop new observables that may be useful in heavy ion collisions.

ex. Grooming, multi-prong observables, …

QCD factorization

Inclusive jet production $pp \to \text{jet} + X$

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} \underset{\Lambda_{\text{QCD}}}{f_a} \otimes \underset{\Lambda_{\text{QCD}}}{f_b} \otimes \underset{p_T}{H^c_{ab}} \otimes \underset{p_T R}{J_c}$$



Also exclusive processes and $pp \to Z/\gamma + \text{jet} + X$

Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16

QCD factorization

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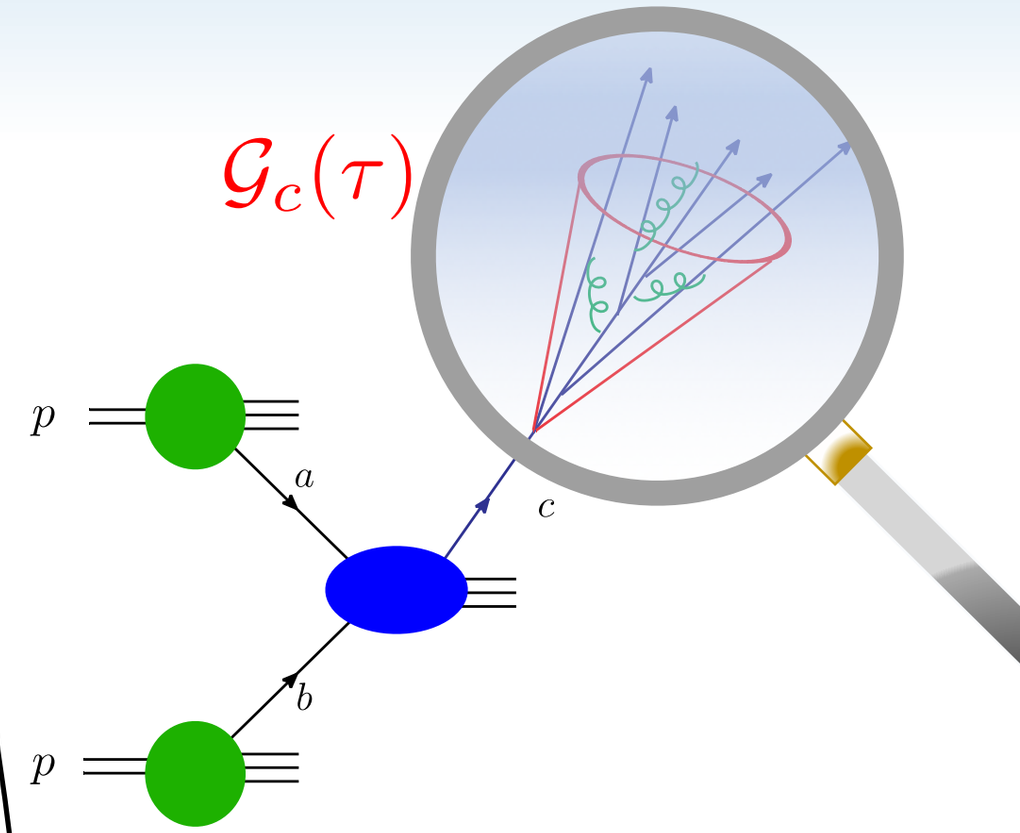


Jet substructure τ

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

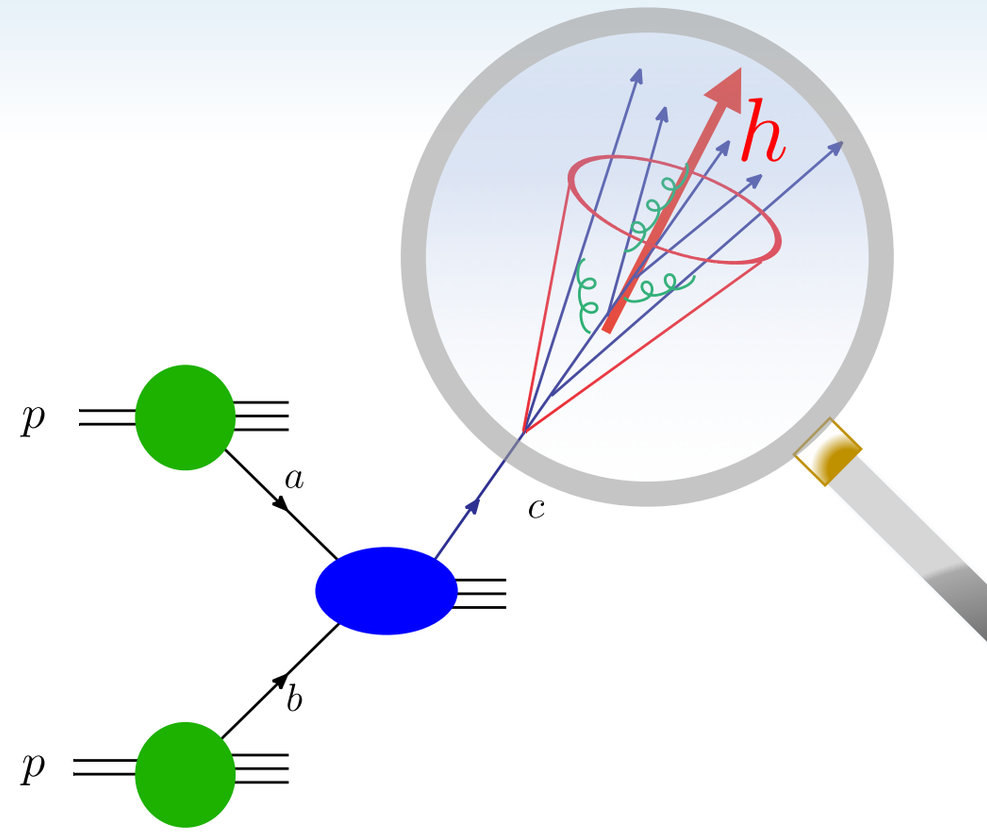
and other scale(s) depending on τ

Jet fragmentation function

$$\frac{d\sigma^{pp\to \mathrm{jet}(h)X}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes \mathcal{G}^h_c(z_h)$$

where $z = p_T^J / p_T^c$

$z_h = p_T^h / p_T^J$



IRC unsafe and require matching:

$$\mathcal{G}^h_c(z, z_h, p_T R, \mu) = \sum_j \mathcal{J}_{ij}(z, z_h, p_T R, \mu) \otimes D^h_j(z_h, \mu)$$

$p_T R$ Λ_{QCD}

matching coefficients **collinear FFs**

Procura, Stewart `10
Arleo, Fontannaz, Guillet, Nguyen `14
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16

Jet fragmentation function

- **Light charged hadrons**

  Arleo, Fontannaz, Guillet, Nguyen `14
  Kaufmann, Mukherjee, Vogelsang `15
  Kang, Ringer, Vitev `16
  Neill, Scimemi, Waalewijn `16

- **Photons**

  Kaufmann, Mukherjee, Vogelsang `16

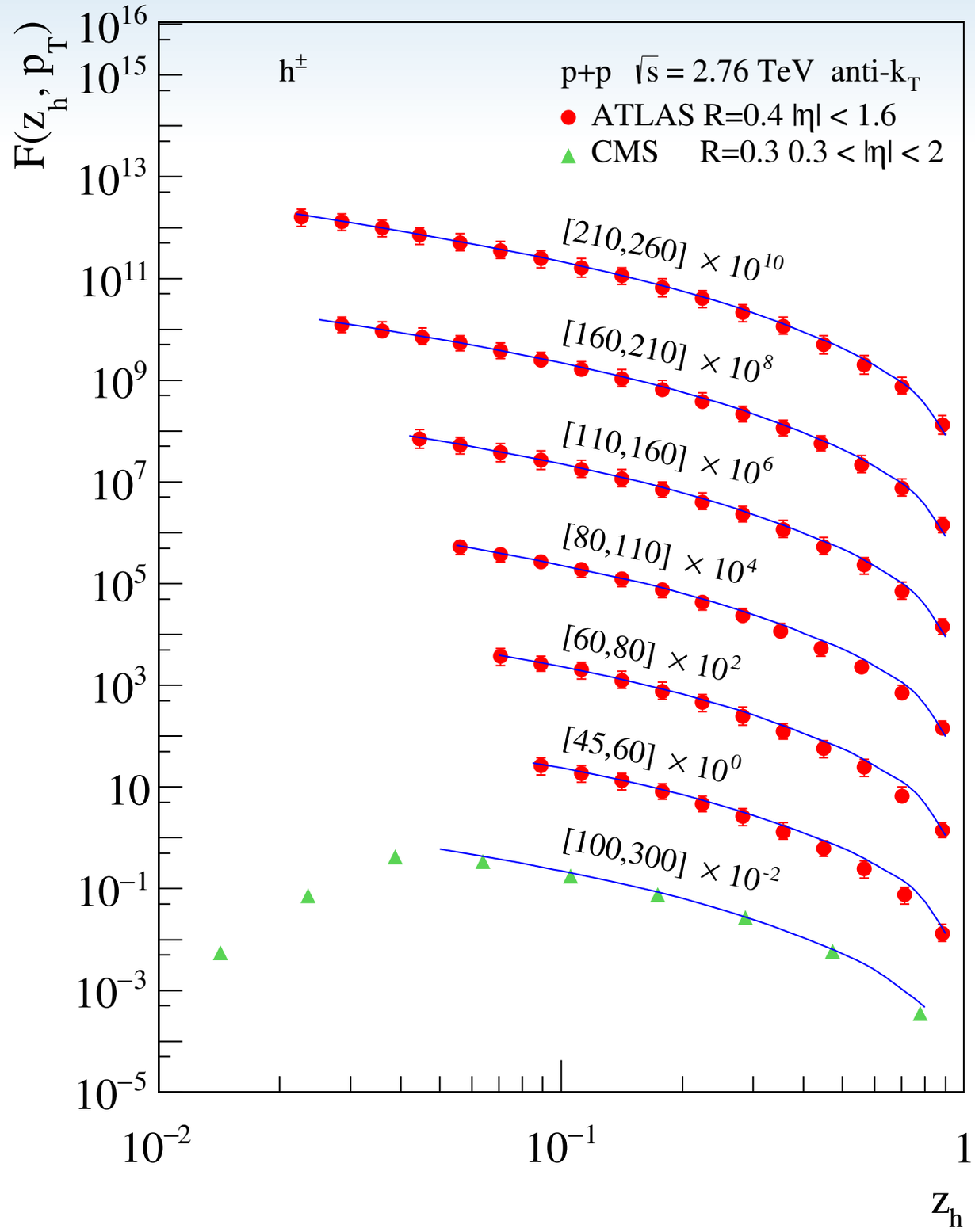
- **Heavy flavor mesons**

  Chien, Kang, Ringer, Vitev, Xing `15
  Bain, Dai, Hornig, Leibovich, Makris, Mehen `16
  Anderle, Kaufmann, Stratmann, Ringer, Vitev `17

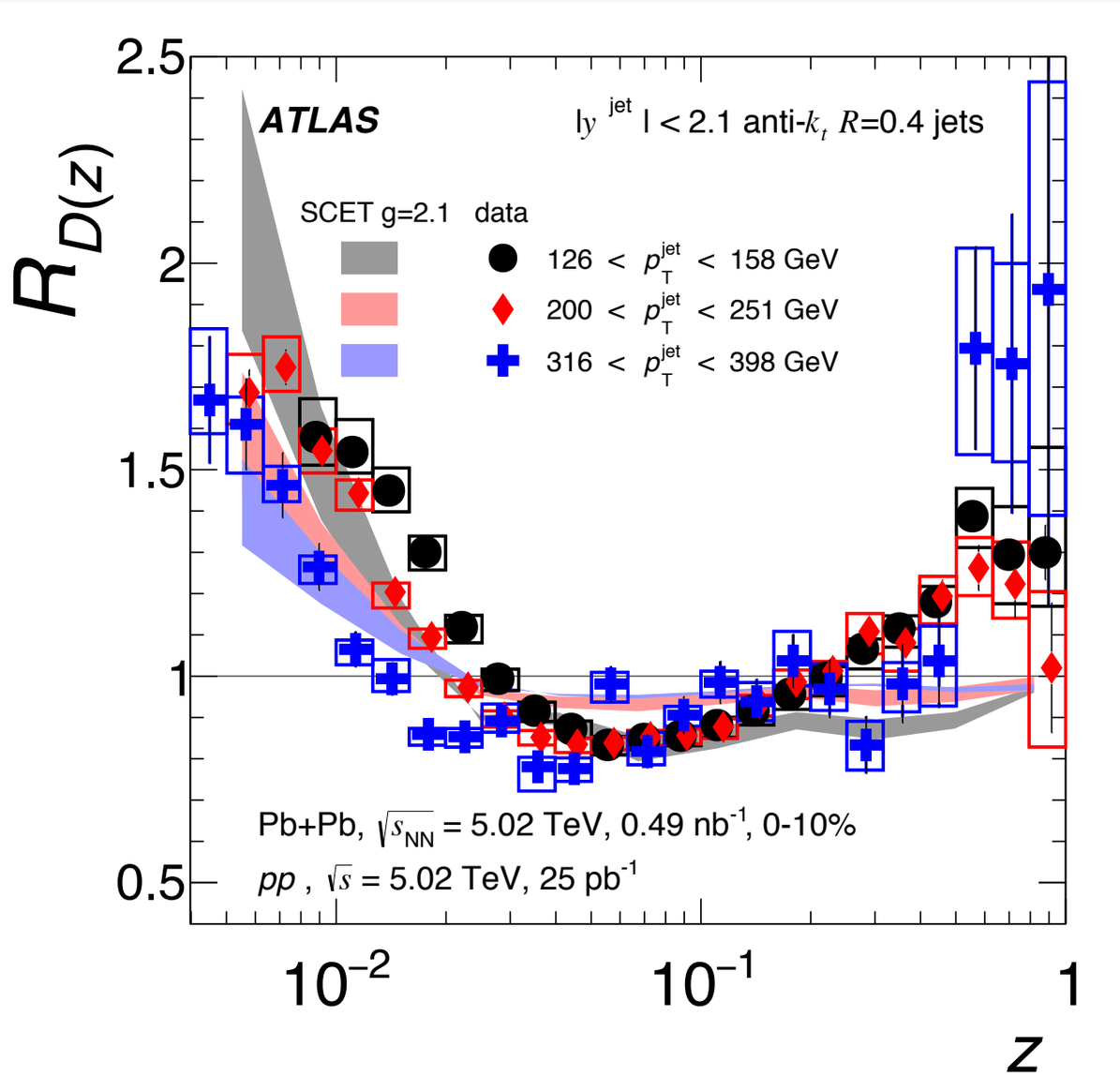
- **Quarkonia**

  Baumgart, Leibovich, Mehen, Rothstein `14
  Bain, Dai, Hornig, Leibovich, Makris, Mehen `16
  Kang, Qiu, Ringer, Xing, Zhang `17
  Bain, Dai, Leibovich, Makris, Mehen `17

$$F(z_h, p_T) = \frac{d\sigma^{pp\to(\mathrm{jet}h)X}}{dp_T d\eta dz_h} \Bigg/ \frac{d\sigma^{pp\to\mathrm{jet}X}}{dp_T d\eta}$$

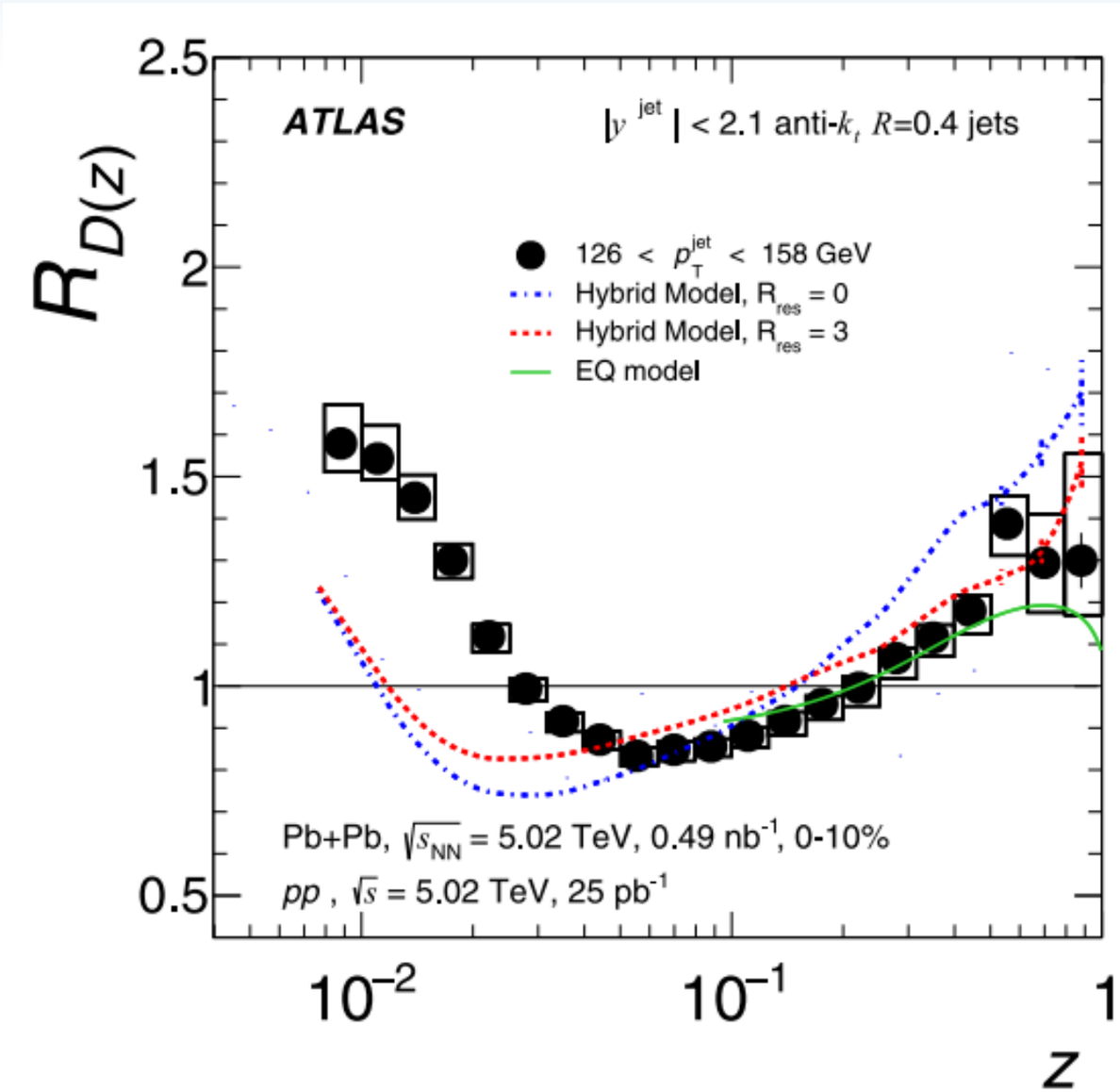


Jet fragmentation function



ATLAS, PRC 98 (2018) 024908

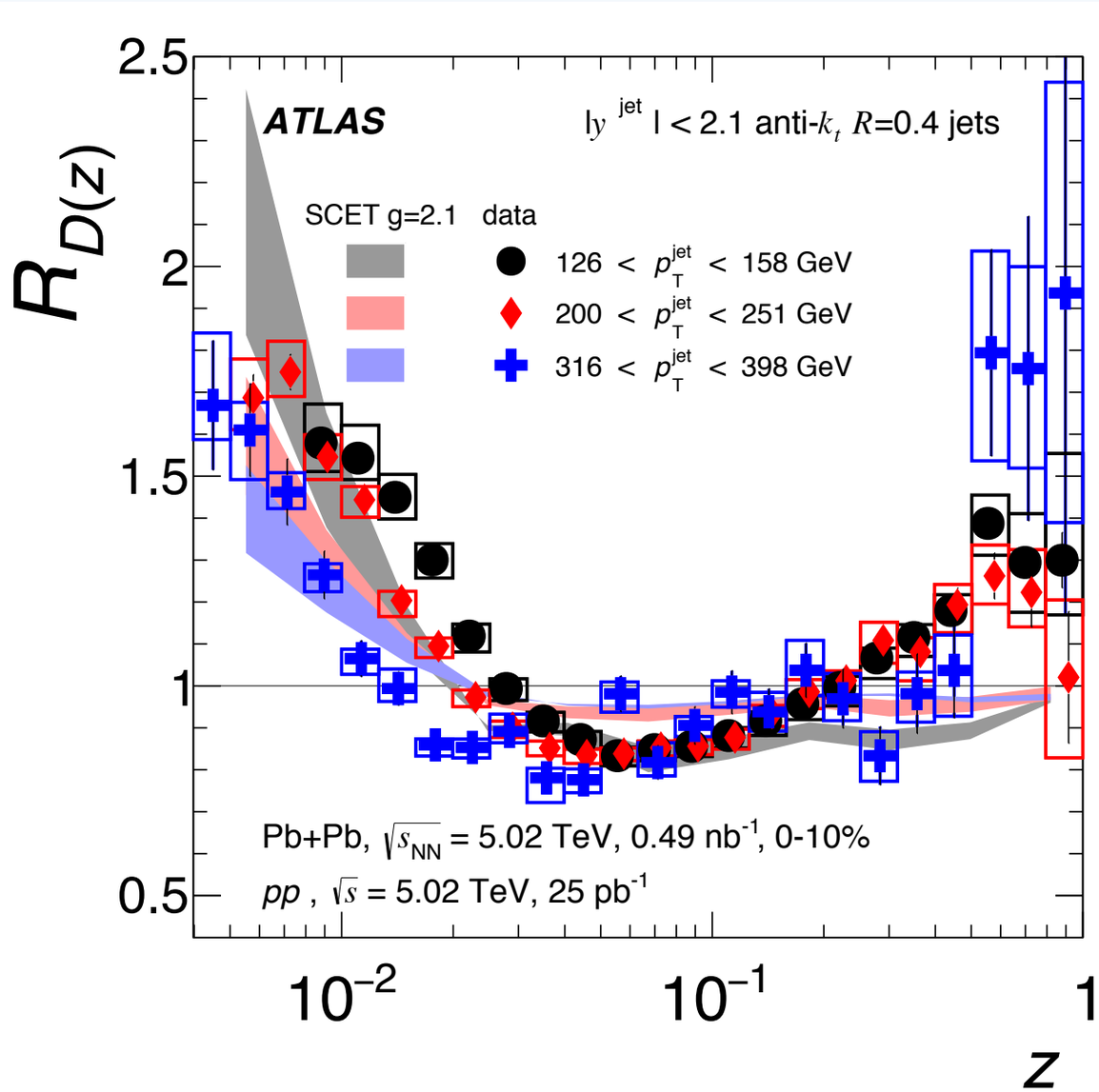
Chien, Kang, Ringer, Vitev, In preparation



Kang, Ringer, Vitev `17
Idilbi, Majumder `08
D'Eramo, Liu, Rajagopal `10
Ovanesyan, Vitev `12

Hulcher, Pablos, Rajagopal `17
Spousta, Cole `15

Jet fragmentation function



ATLAS, PRC 98 (2018) 024908

Chien, Kang, Ringer, Vitev, In preparation

$$\frac{d\sigma^{AA\to \mathrm{jet}(h)X}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes \mathcal{G}_c^{\mathrm{med},h}(z_h)$$

Include medium modified splitting functions from $\mathrm{SCET_G}$:

$$\mathcal{G}_q^{q,(1)}(z, z_h, \omega R, \mu) = D_q(z_h) \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P_{qq}(z, q_\perp) \right]_+ + \delta(1-z) \left[\int_{\mu_0}^{z_h(1-z_h)p_T R} dq_\perp P_{qq}(z_h, q_\perp) \right]_+ \otimes D_q(z_h)$$

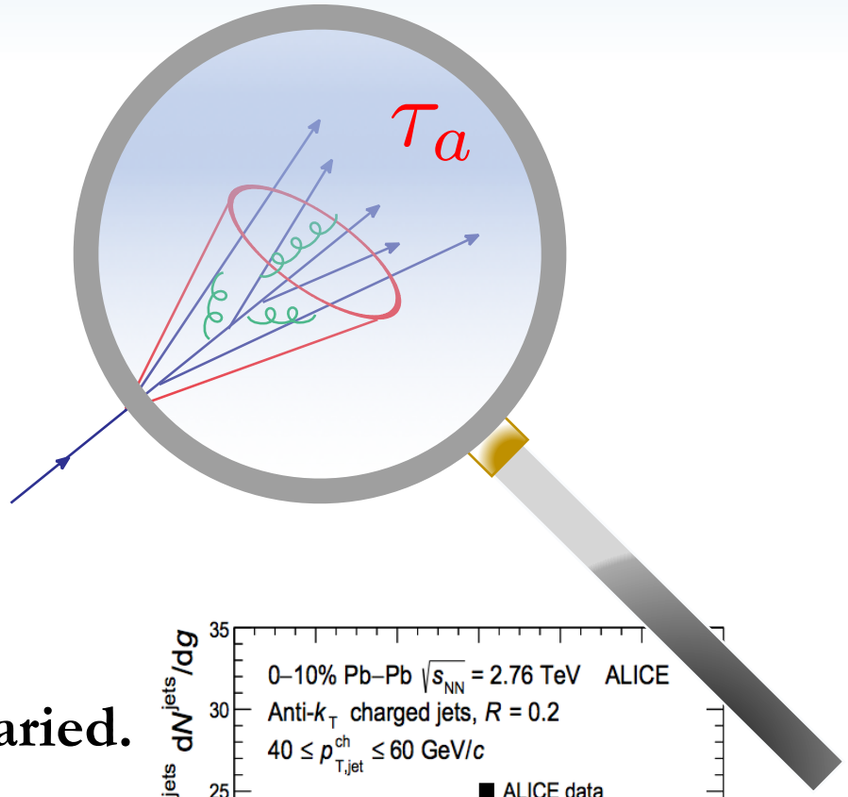
$$P_{ji}^{\mathrm{med}}(z, q_\perp) = P_{ji}(z, q_\perp)\, f_{ji}(z, q_\perp; \beta)$$

Kang, Ringer, Vitev `17
Idilbi, Majumder `08
D'Eramo, Liu, Rajagopal `10
Ovanesyan, Vitev `12

Jet angularity

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

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

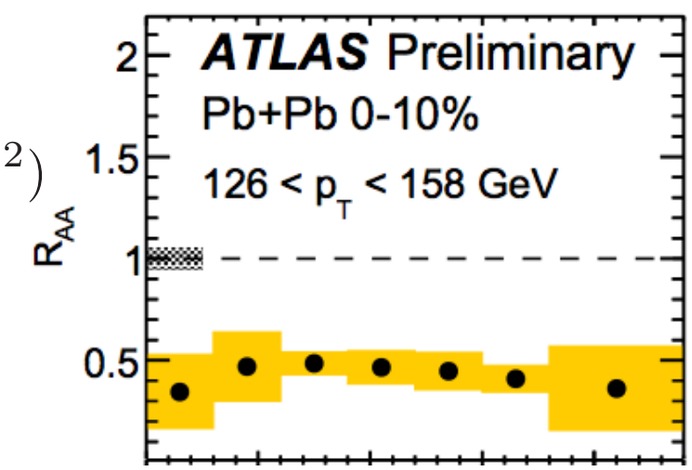


Sterman et al. `03, `08,
Hornig, C. Lee, Ovanesyan `09, Ellis, Vermilion, Walsh, Hornig, C.Lee `10,
Chien, Hornig, C. Lee `15, Hornig, Makris, Mehen `16, Kang, KL, Ringer `18

- **Varying sensitivity to collinear radiations as the parameter is varied.**

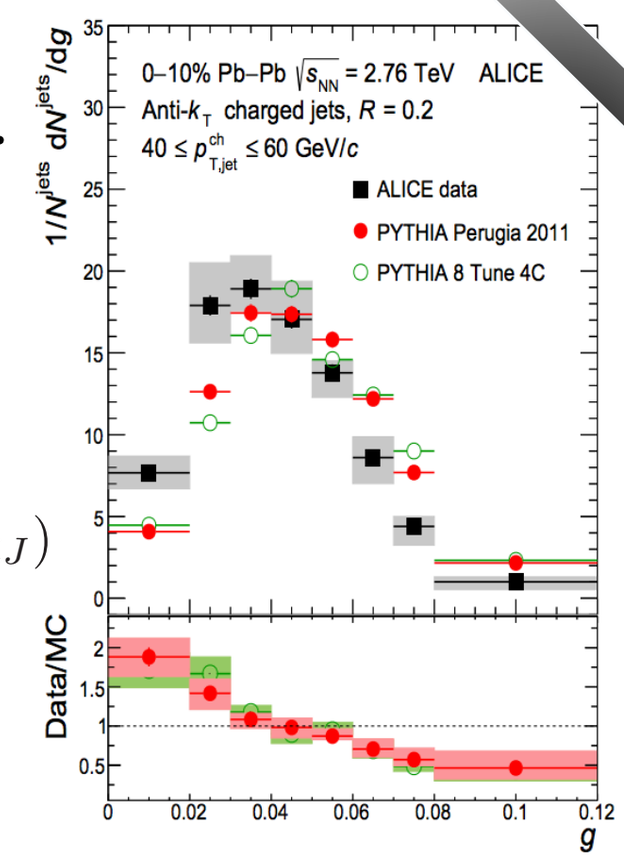
$a = 0$

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

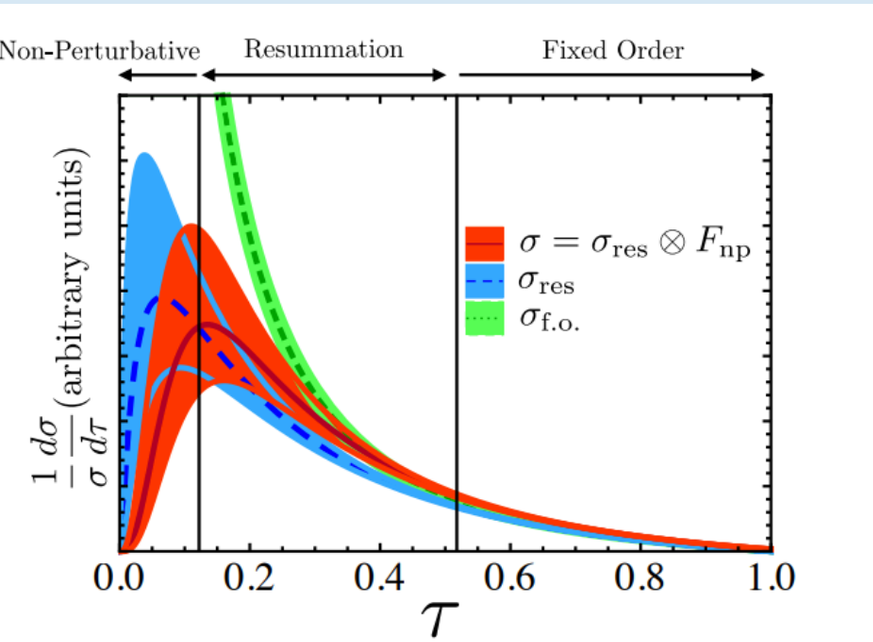


$a = 1$

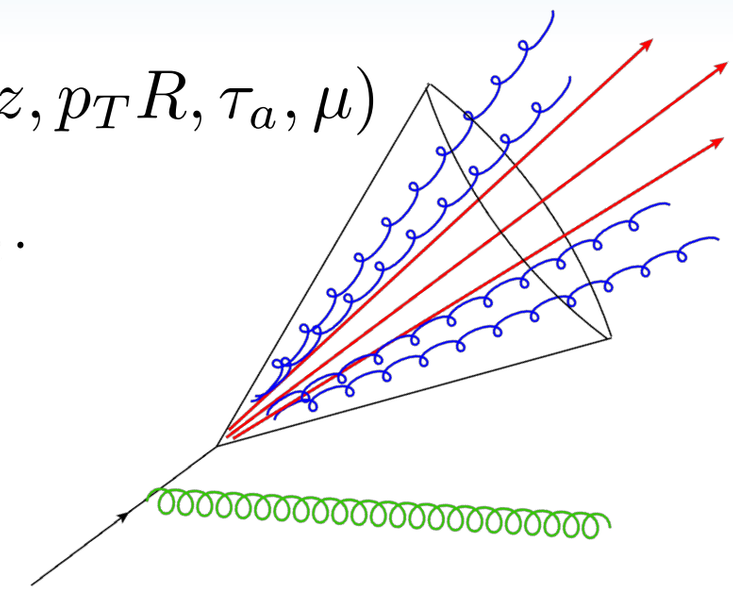
$$g(\text{girth}) = \frac{1}{p_T} \sum_{i \in J} p_{T,i} \, (\Delta R_{iJ})$$



Factorization for the jet angularity



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



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

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

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

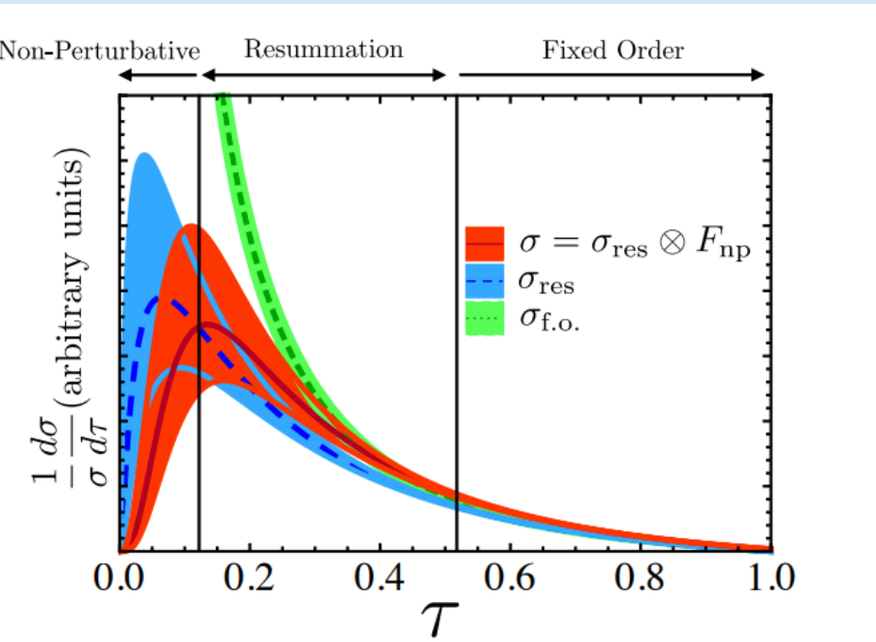
$\theta_s \sim R$ $\qquad z_{cs} \sim \dfrac{\tau_a}{R^{2-a}}$ $\qquad \mu_S \sim \dfrac{p_T \tau_a}{R^{1-a}}$

Hard-collinear

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

Kang, KL, Ringer, arXiv:1801.00790

Factorization for the jet angularity



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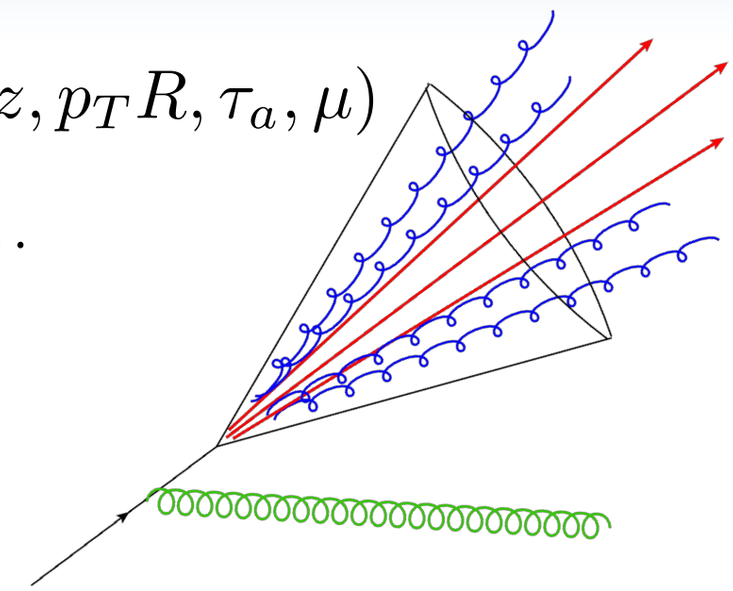


- **The ungroomed case ($\tau_a \ll R^{2-a}$)**

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

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

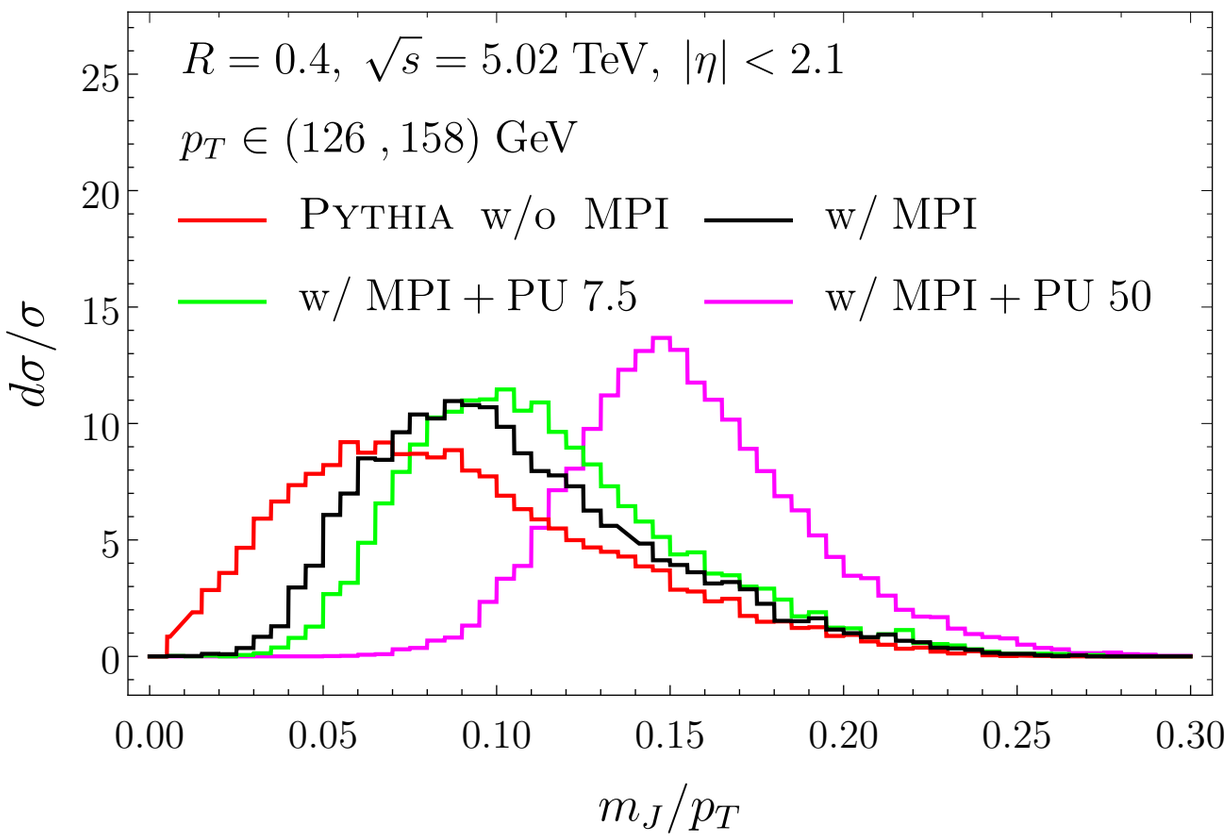
Kang, KL, Ringer, arXiv:1801.00790

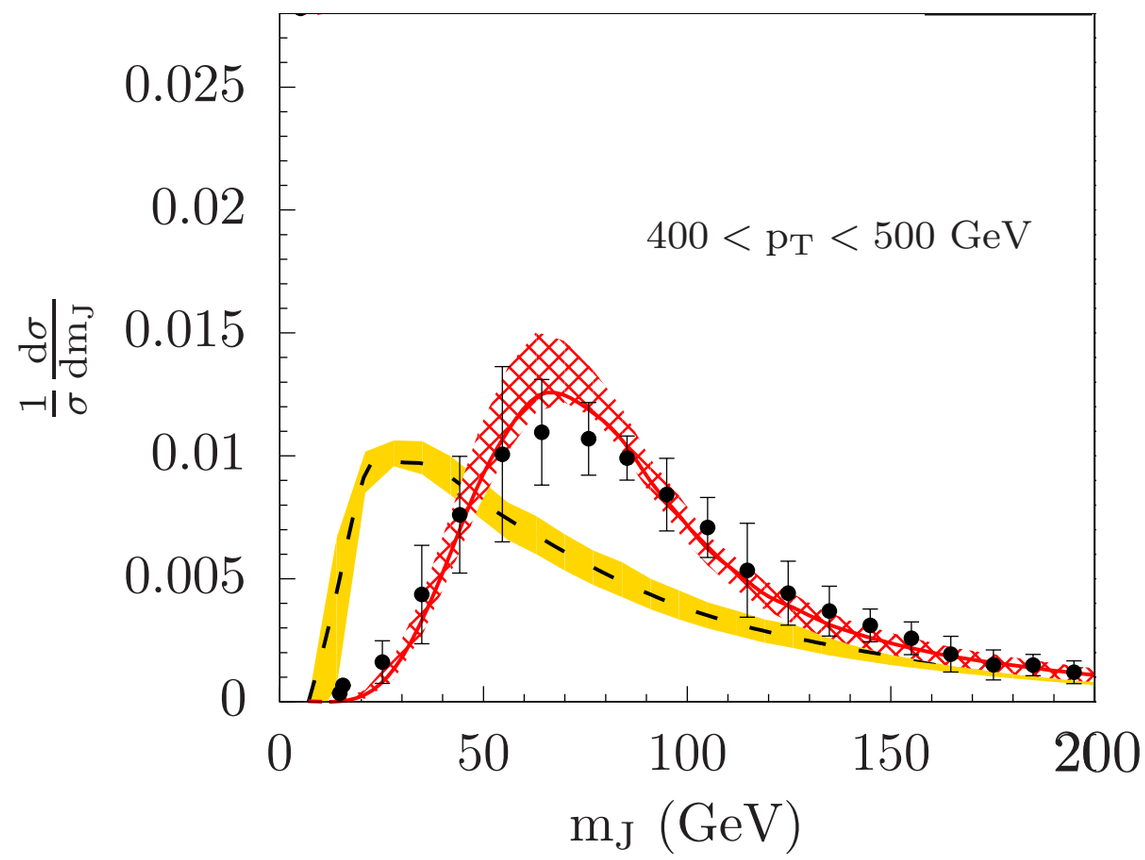
Non-perturbative Effects

$$\frac{d\sigma}{dp_T d\eta d\tau_a} = \frac{d\sigma^{\rm pert}}{dp_T d\eta d\tau_a} \otimes F_{\rm NP}$$

$$\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$$

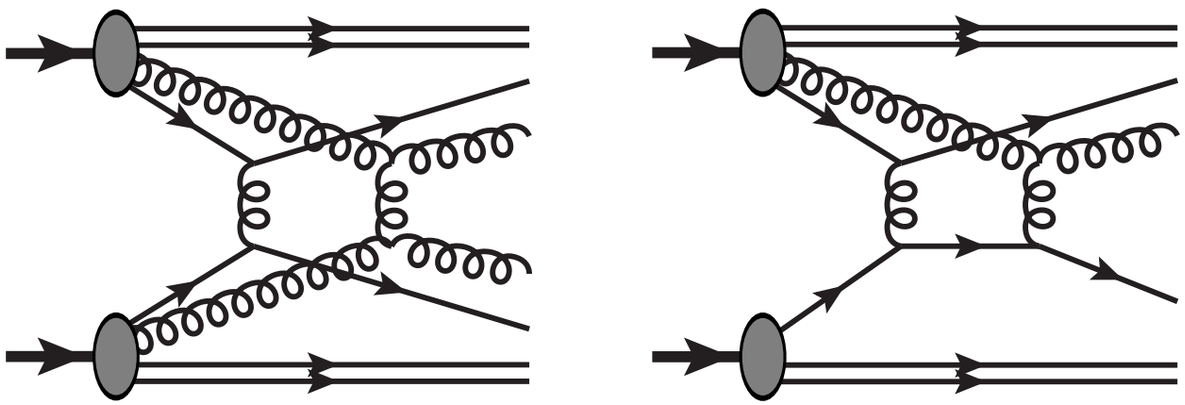
Large non-perturbative effects:



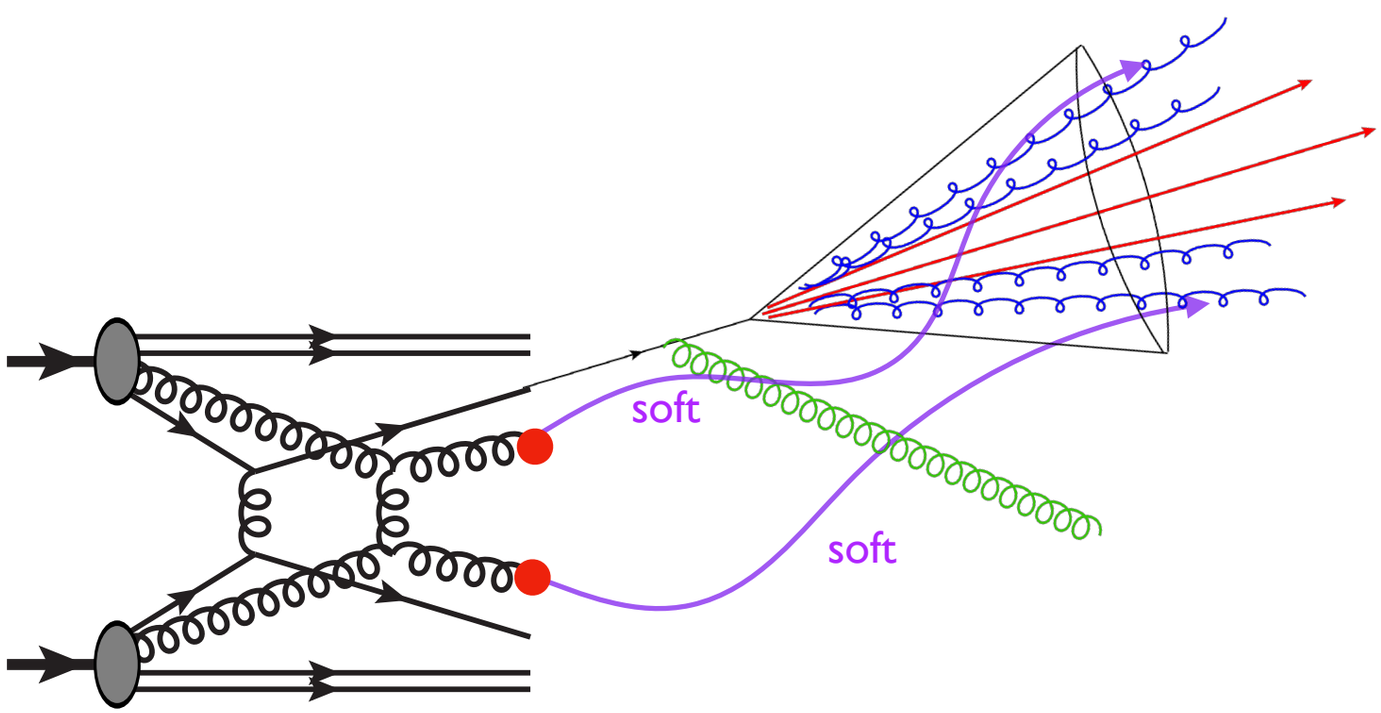


Non-perturbative Effects

- **Non-perturbative effects:**



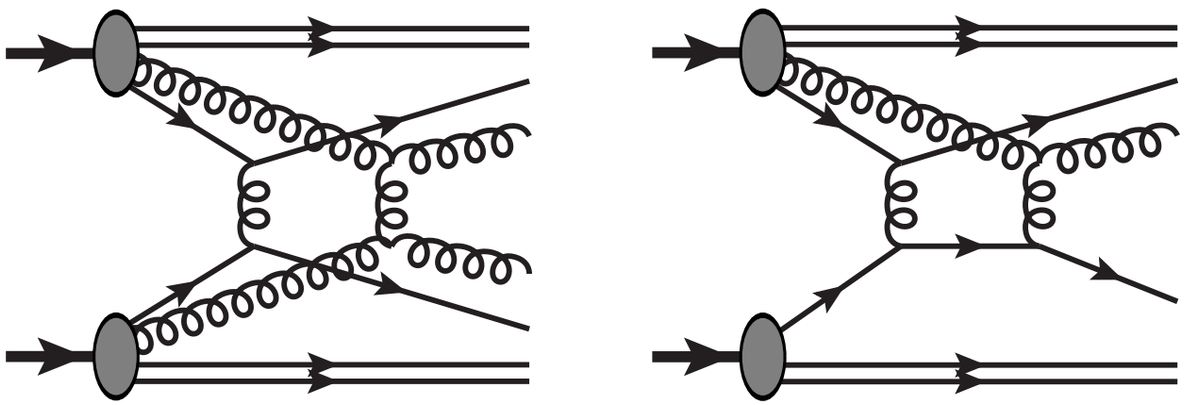
Figs from P. Bartalini et al. `11



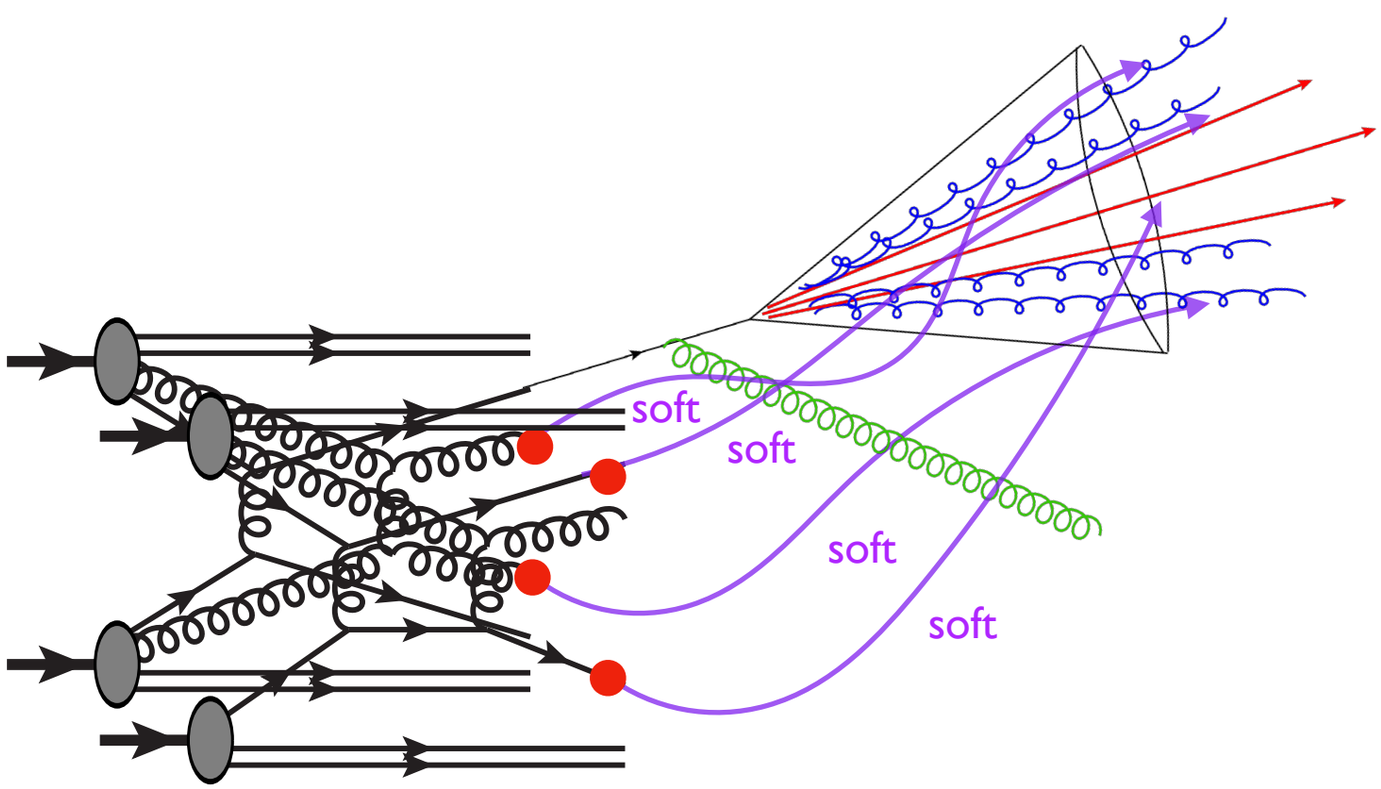
- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.

Non-perturbative Effects

- **Non-perturbative effects:**



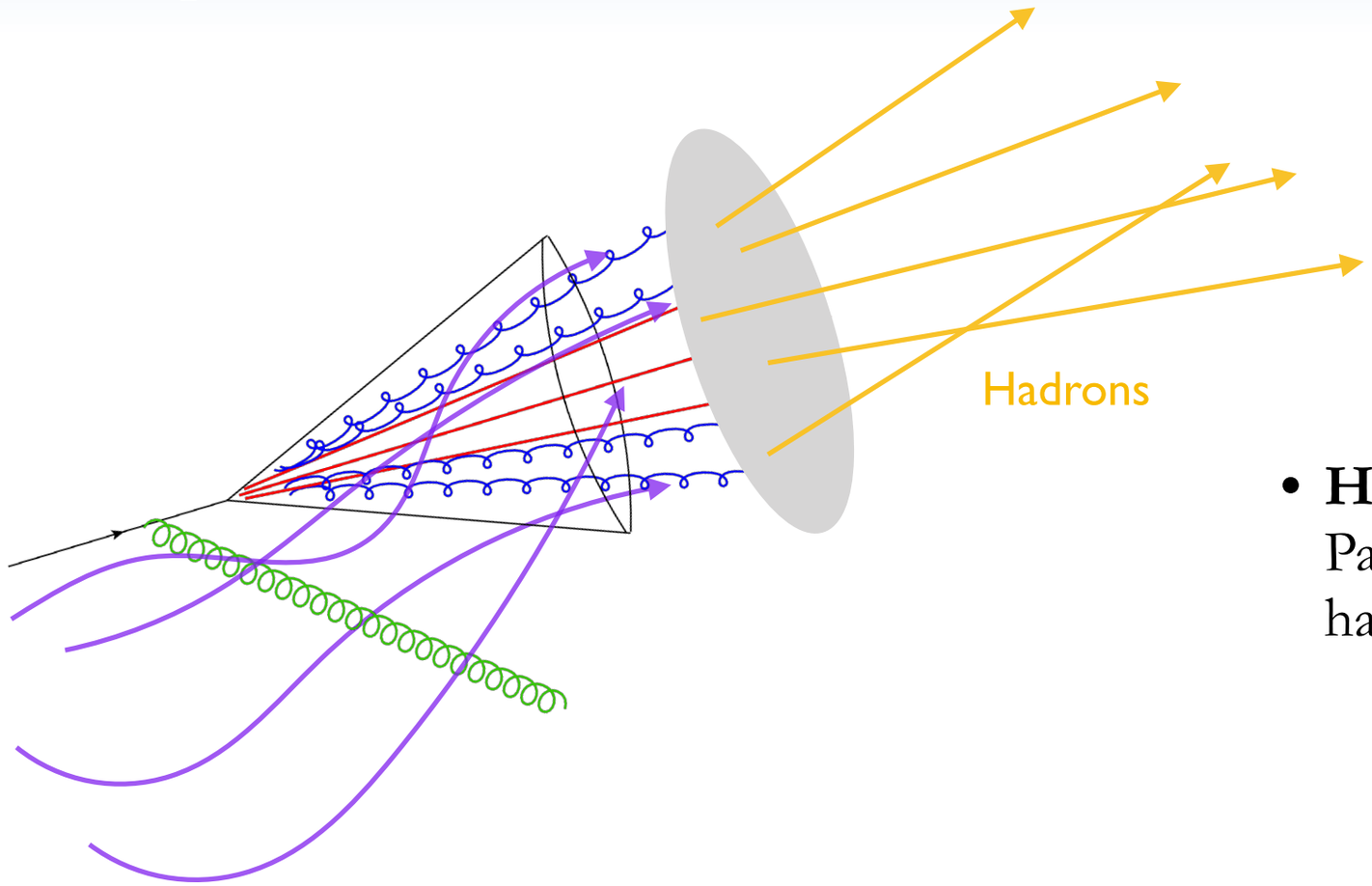
Figs from P. Bartalini et al. `11



- **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

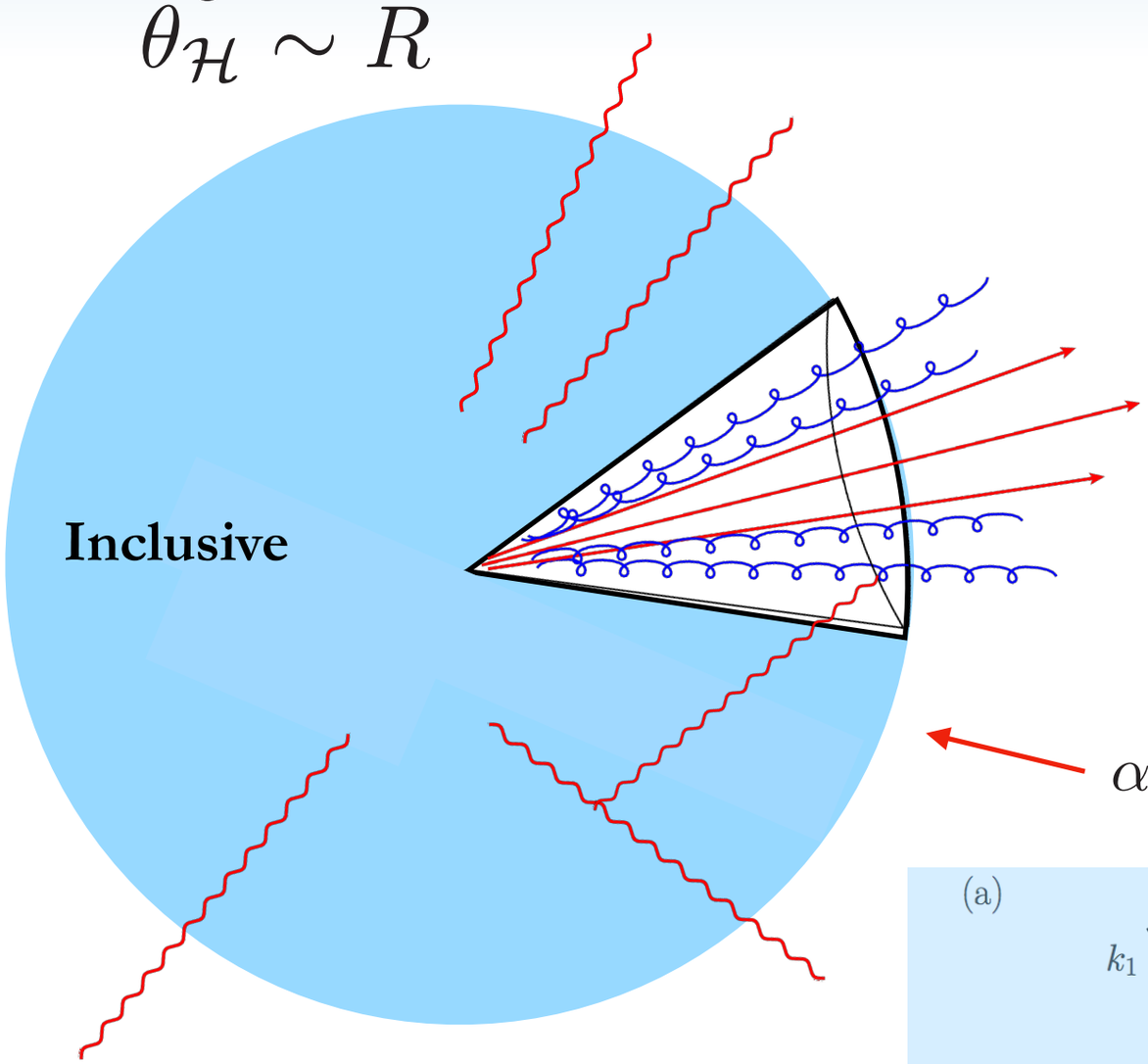
- **Non-perturbative effects:**



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

Appearance of the NGLs

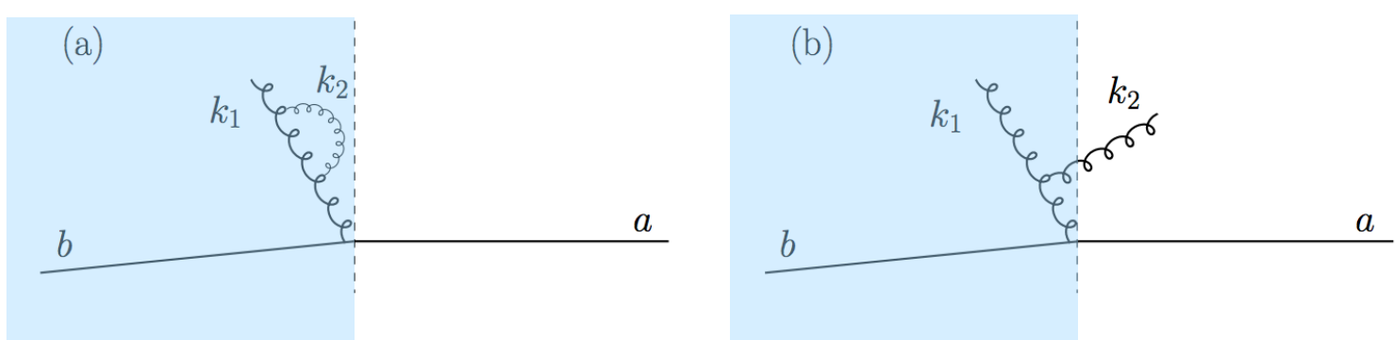
$$\theta_s \sim R$$
$$\theta_{\mathcal{H}} \sim R$$



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

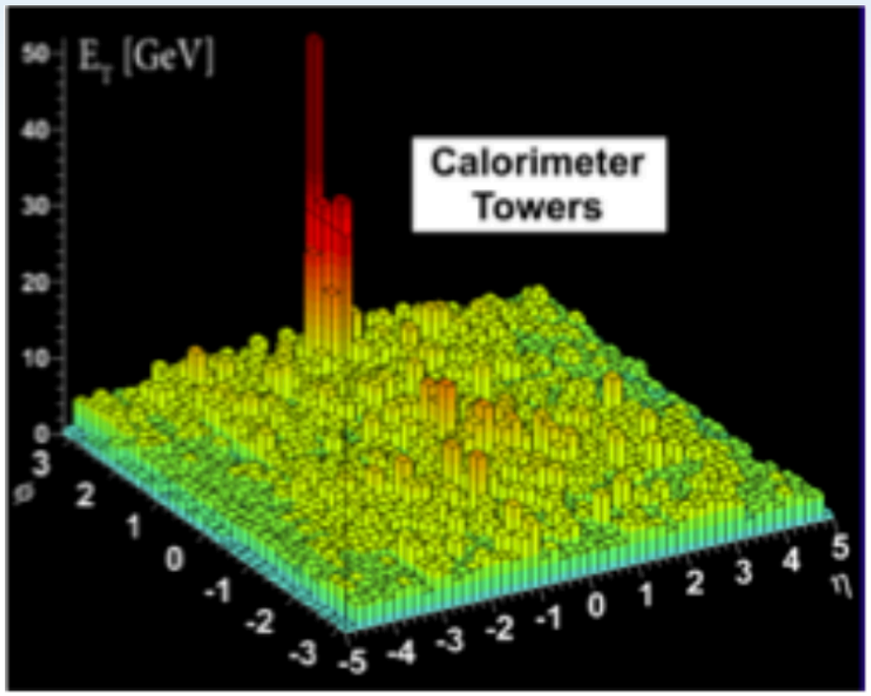
- **Non-global logarithms (NGLs): arises from the correlation between the in-jet and the out-of-jet radiation.**

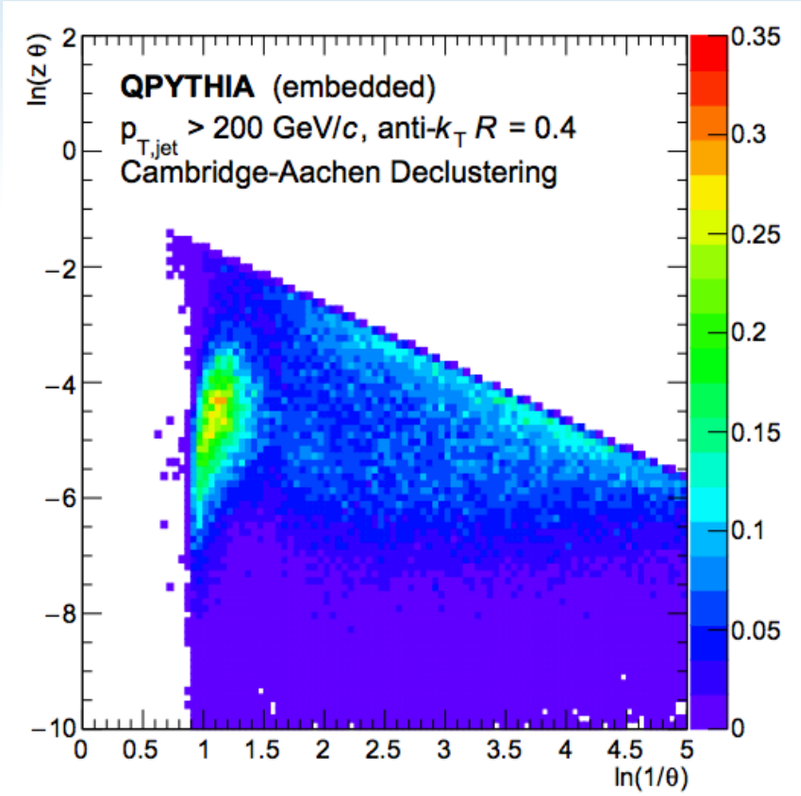
$$\alpha_s^n \ln^n(\tau_a/R^{2-a})$$



Dasgupta, Salam `01

Large uncorrelated background in QGP





- **Heavy ion collisions produce large number of uncorrelated soft particles in the background contaminating the jet.**

1. **Develop a background subtraction techniques to identify true compositions of the jets.**

or

2. **Define an observable less sensitive to the uncorrelated background.**
   a. **Subtracted cumulants**
   b. **Grooming (recursive algorithm)**

Subtracted cumulants (moments)

$$\frac{d\sigma}{dp_T d\tau_0} = \frac{d\sigma^{\rm pert}}{dp_T d\tau_0} \otimes F_{\rm NP}$$

Moments of the distribution can be separated into contribution from signal and background:

$$\langle \tau_0 \rangle = \frac{1}{\sigma} \int d\tau_0 \, \tau_0 \, \frac{d\sigma}{d\tau_0 dp_T} = \langle \tau_{0,\rm pert} \rangle + \frac{2}{p_T} \Omega_F$$

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

signal

uncorrelated emissions

Chien, Kang, KL, Makris, `18

Subtracted cumulants (moments)

$$\frac{d\sigma}{dp_T d\tau_0} = \frac{d\sigma^{\rm pert}}{dp_T d\tau_0} \otimes F_{\rm NP}$$

Moments of the distribution can be separated into contribution from signal and background:

$$\langle \tau_0 \rangle = \frac{1}{\sigma} \int d\tau_0 \, \tau_0 \, \frac{d\sigma}{d\tau_0 dp_T} = \langle \tau_{0,\rm pert} \rangle + \frac{2}{p_T} \Omega_F$$

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

- Experiments often done with several bins of p_T range.
- The binned version would give:

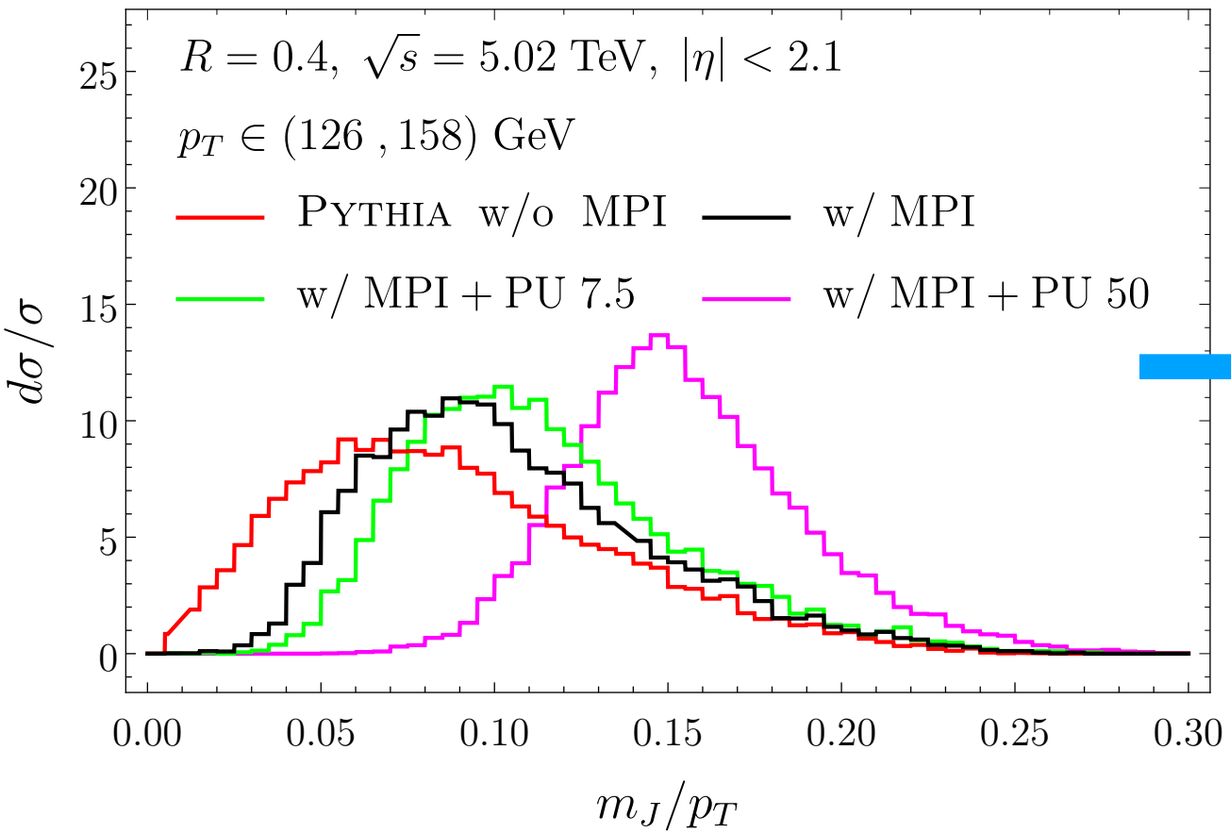
$$\langle \tau_0 \rangle^{[n]} = \langle \tau_{0,\rm pert} \rangle^{[n]} + 2\Omega_F \langle p_T^{-1} \rangle^{[n]}$$

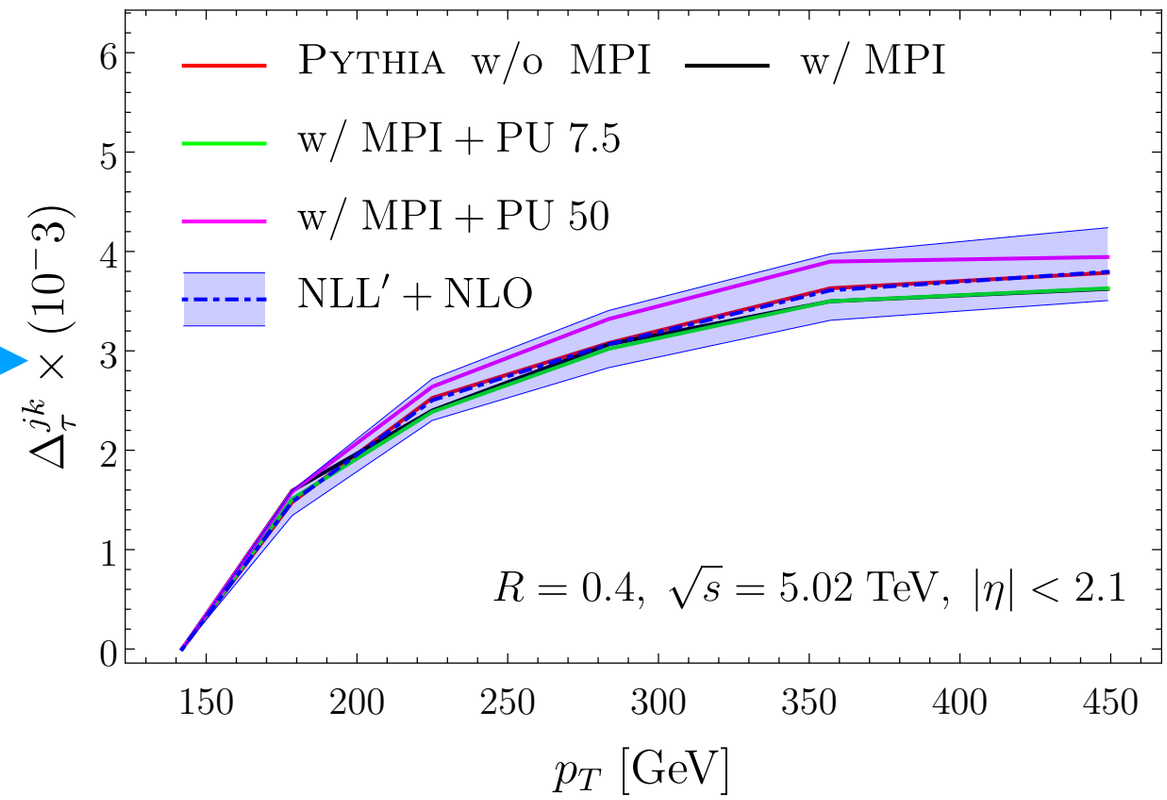
Subtracted cumulants (independent of contribution from SUEs) :

$$\Delta_{\tau_0}^{jk} = \langle \tau_0 \rangle^{[j]} - \langle \tau_0 \rangle^{[k]} \frac{\langle p_T^{-1} \rangle^{[j]}}{\langle p_T^{-1} \rangle^{[k]}} = \langle \tau_{0,\rm pert} \rangle^{[j]} - \langle \tau_{0,\rm pert} \rangle^{[k]} \frac{\langle p_T^{-1} \rangle^{[j]}}{\langle p_T^{-1} \rangle^{[k]}}$$

Chien, Kang, KL, Makris, `18

Testing limit of SUE independence





- **Even at 50 pile ups, the subtracted cumulants of τ_0 gives same subtracted moments!**

Chien, Kang, KL, Makris, `18

Soft Drop Grooming

- **Taming wide angle soft radiations, giving sensitivity to UE, PU, and NGLs directly changing distribution.**

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

- **Soft drop grooming algorithms:**

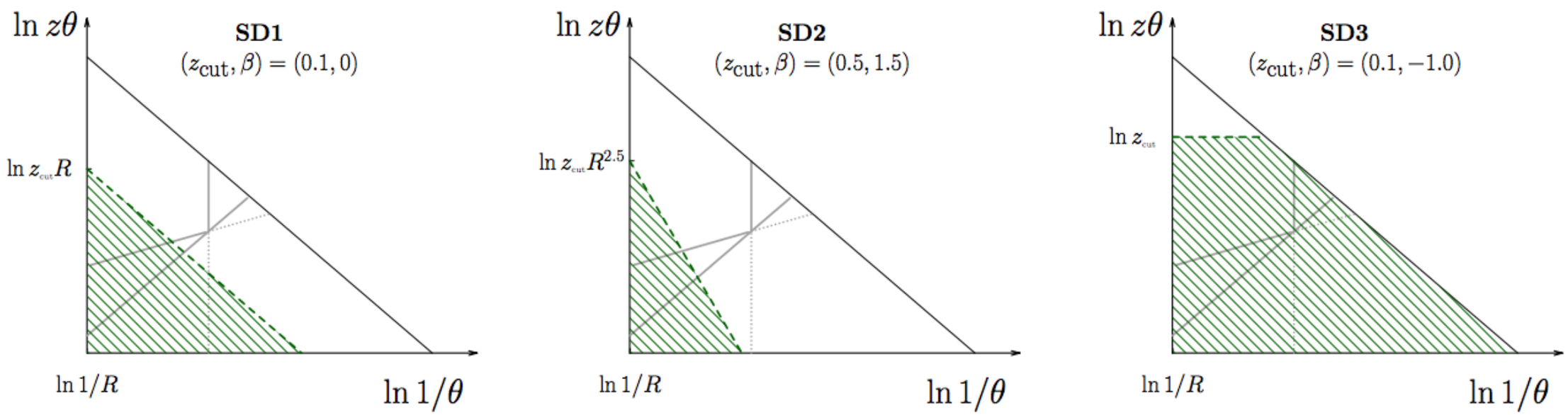
1. Reorder emissions in the identified jet according to their relative angle using C/A jet algorithm.

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

$$\frac{\min[p_{T,1}, p_{T,2}]}{p_{T,1}+p_{T,2}} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

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

Grooming to probe different kinematical regions



$\beta = 0$

Grooming only on energy fraction

$\beta > 0$

Stronger grooming on large angles

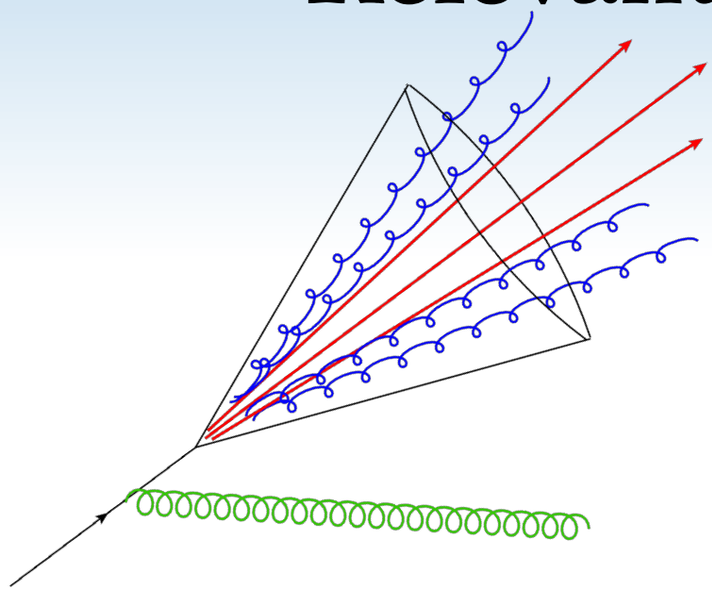
$\beta < 0$

Only hard radiations

- **By varying grooming parameter, specific regions of phase space can be isolated.**
- **Appropriate isolation can be used to study regions with enhanced or suppressed medium effects.**

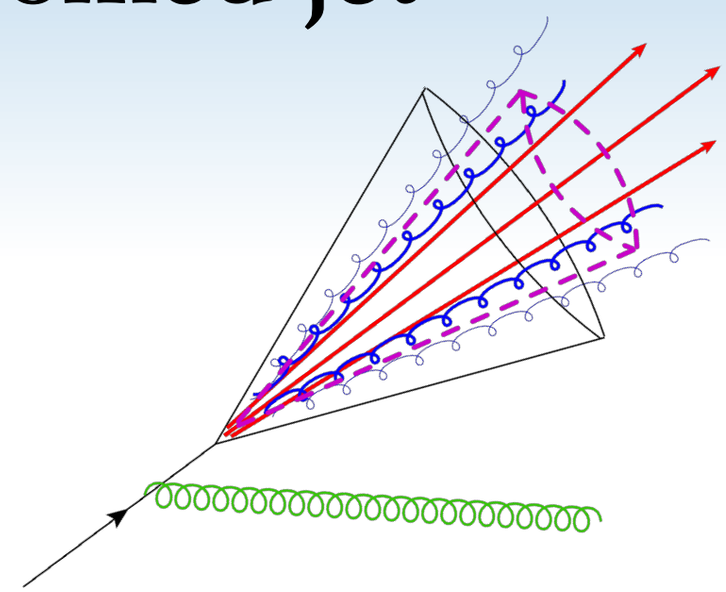
5th Heavy Ion Jet Workshop Report, 2018

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)

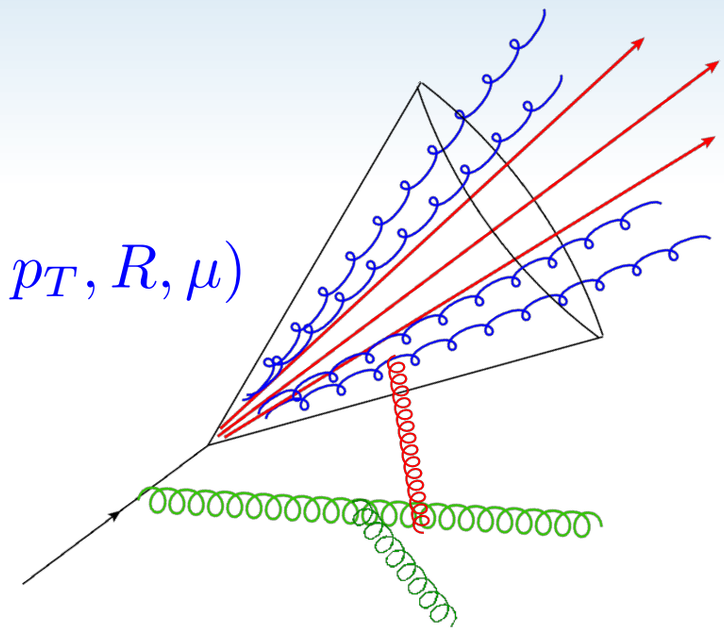
$$z_{\in \rm gr} \sim z_{\rm cut}\left(\frac{\theta}{R}\right)^{\beta} = z_{\rm cut}^{\frac{2-a}{2-a+\beta}}\left(\frac{\tau_a}{R^{2-a}}\right)^{\frac{\beta}{2-a+\beta}} \qquad \theta_{\in \rm gr} \sim \left(\frac{\tau_a R^{\beta}}{z_{\rm cut}}\right)^{\frac{1}{2-a+\beta}}$$

Factorization for the groomed jet angularity

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

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

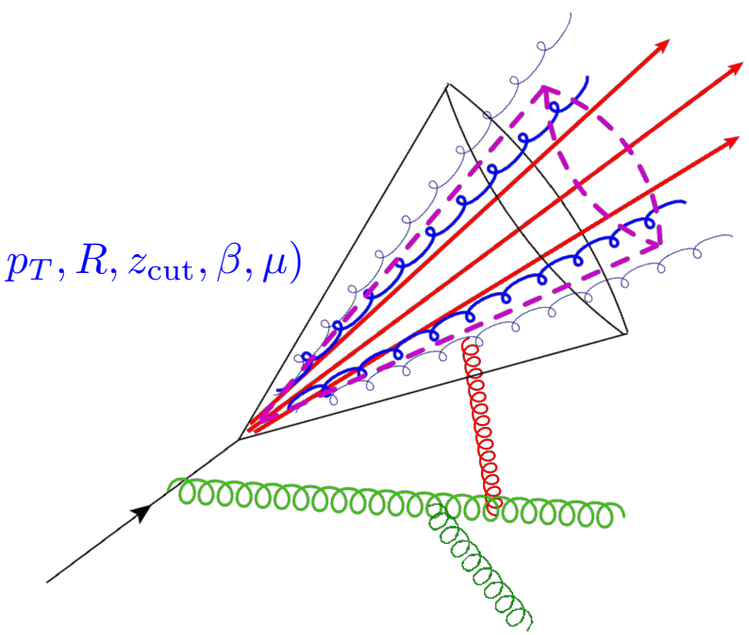
$$\mathcal{G}_i(z, p_T R, \tau_a, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) C_j(\tau_a, p_T, \mu) \otimes S_j(\tau_a, p_T, R, \mu)$$



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

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

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



Kang, KL, Liu, Ringer `18

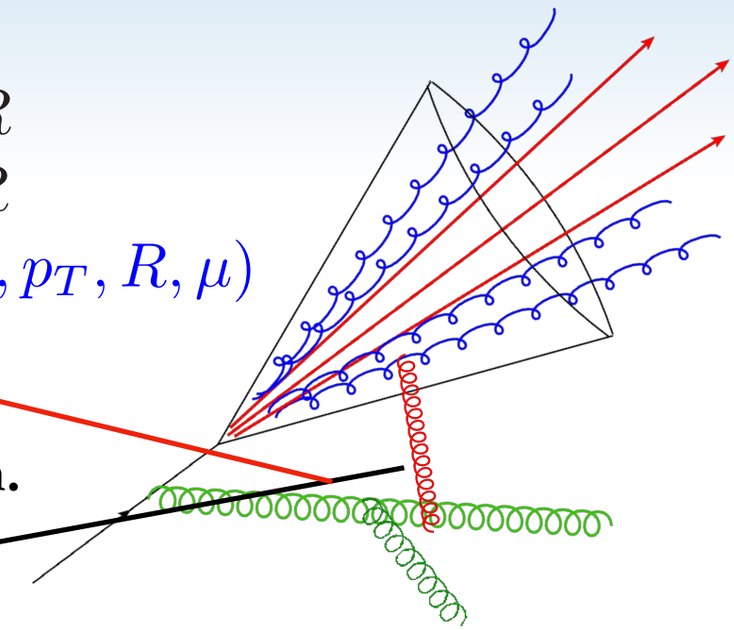
Factorization for the groomed jet angularity

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

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

$$\theta_{\mathcal{H}} \sim R$$
$$\theta_s \sim R$$

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



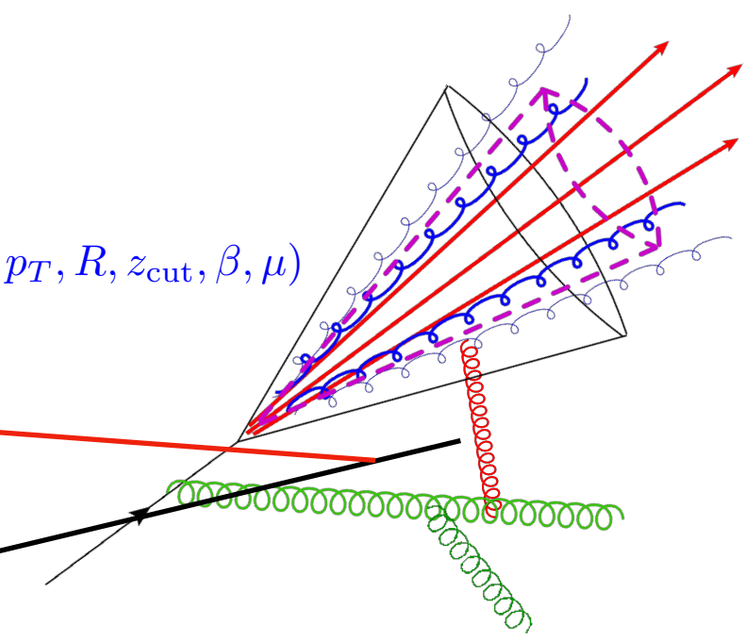
- **Non-global logs directly affect the jet angularity spectrum.**

$$\alpha_s^n \ln^n(\tau_a/R^{2-a}) \qquad n \geq 2$$

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

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

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

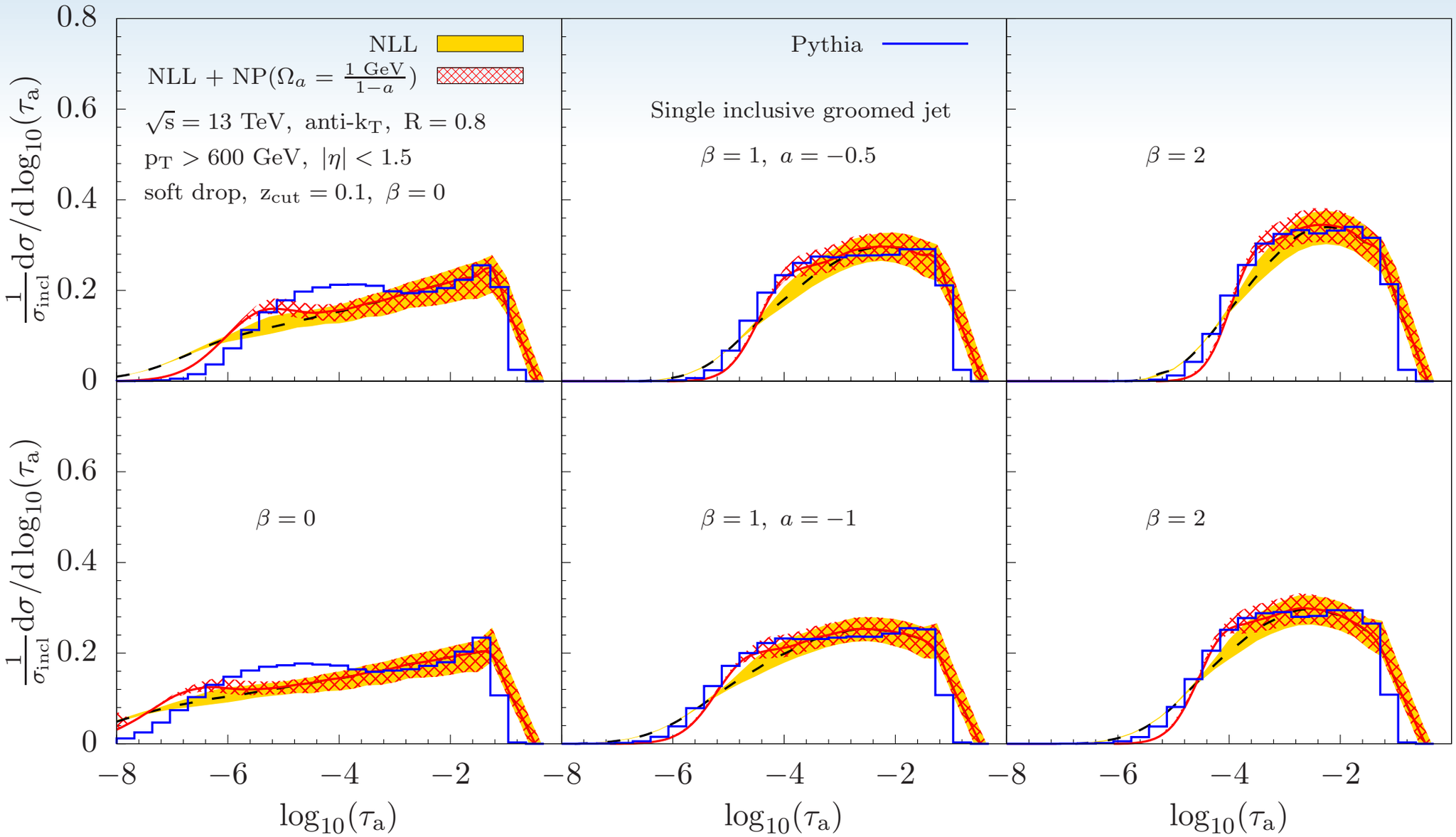


- **Non-global logs only indirectly affects the jet angularity spectrum through normalization.**

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

Kang, KL, Liu, Ringer `18

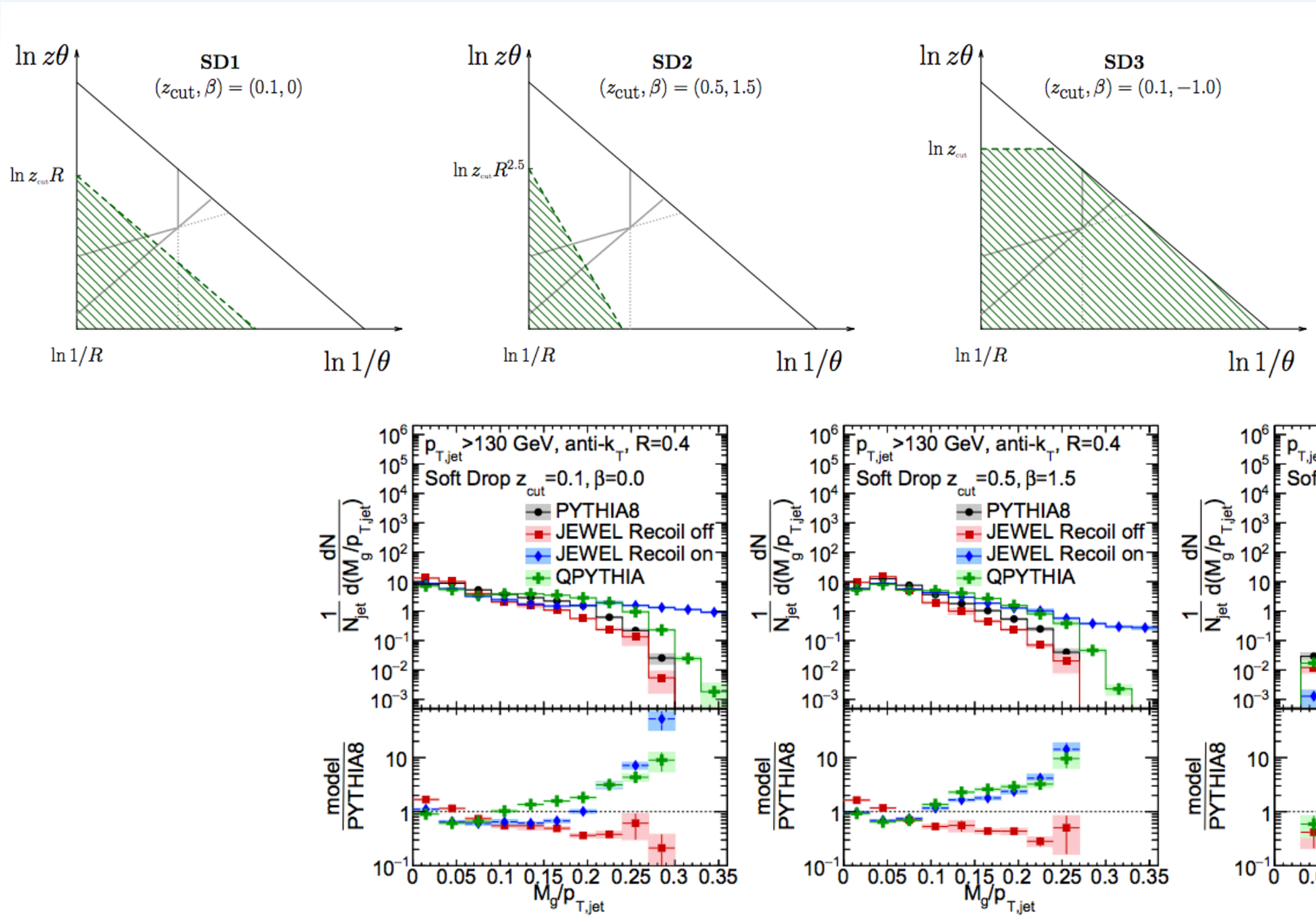
Phenomenology



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

Kang, KL, Liu, Ringer `18

Groomed jet mass in the medium $(a = 0)$



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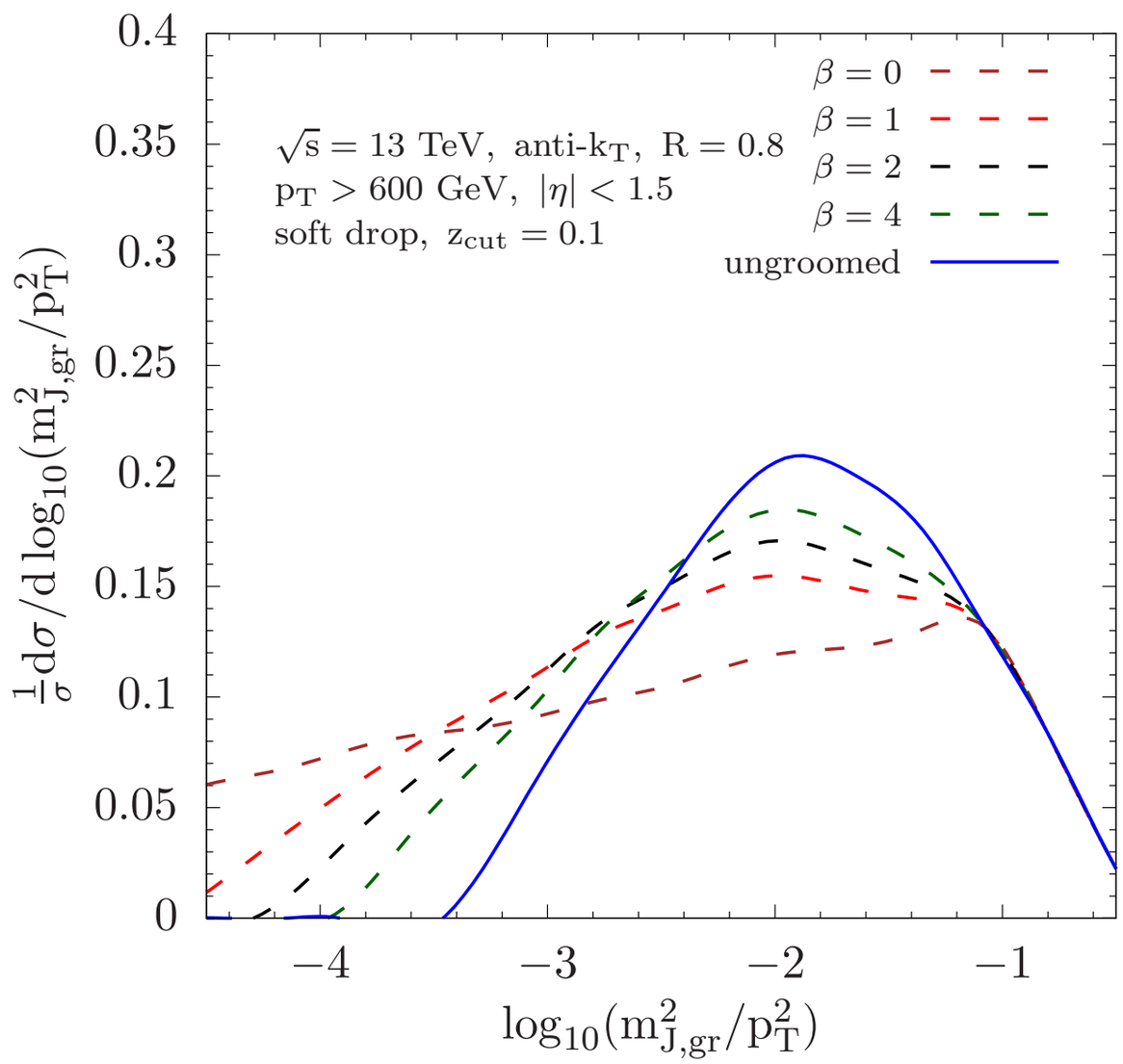
Limit to the ungroomed case

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

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



Checked both numerically and analytically.

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

Kang, KL, Liu, Ringer `18

R_g and z_g

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

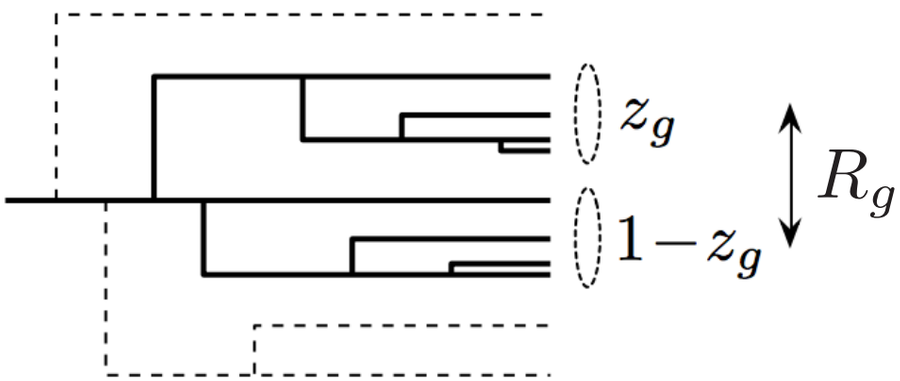


fig. from Tripathee, Xue, Larkoski, Marzani, Thaler`17

- **Two characteristic variables that describe soft drop groomed jet:**

$$z_g = \frac{\min[p_{T,1}, p_{T,2}]}{p_{T,1} + p_{T,2}} \qquad R_g = \Delta R_{12}$$

when soft drop condition is met

$$\frac{\min[p_{T,1}, p_{T,2}]}{p_{T,1} + p_{T,2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

Kang, KL, Liu, Ringer, In Preparation

Groomed jet radius R_g

- $z_{\rm cut} \ll 1$ and $R_g \ll R$

Hard-collinear

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

correlation

$\notin gr$ **soft**

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

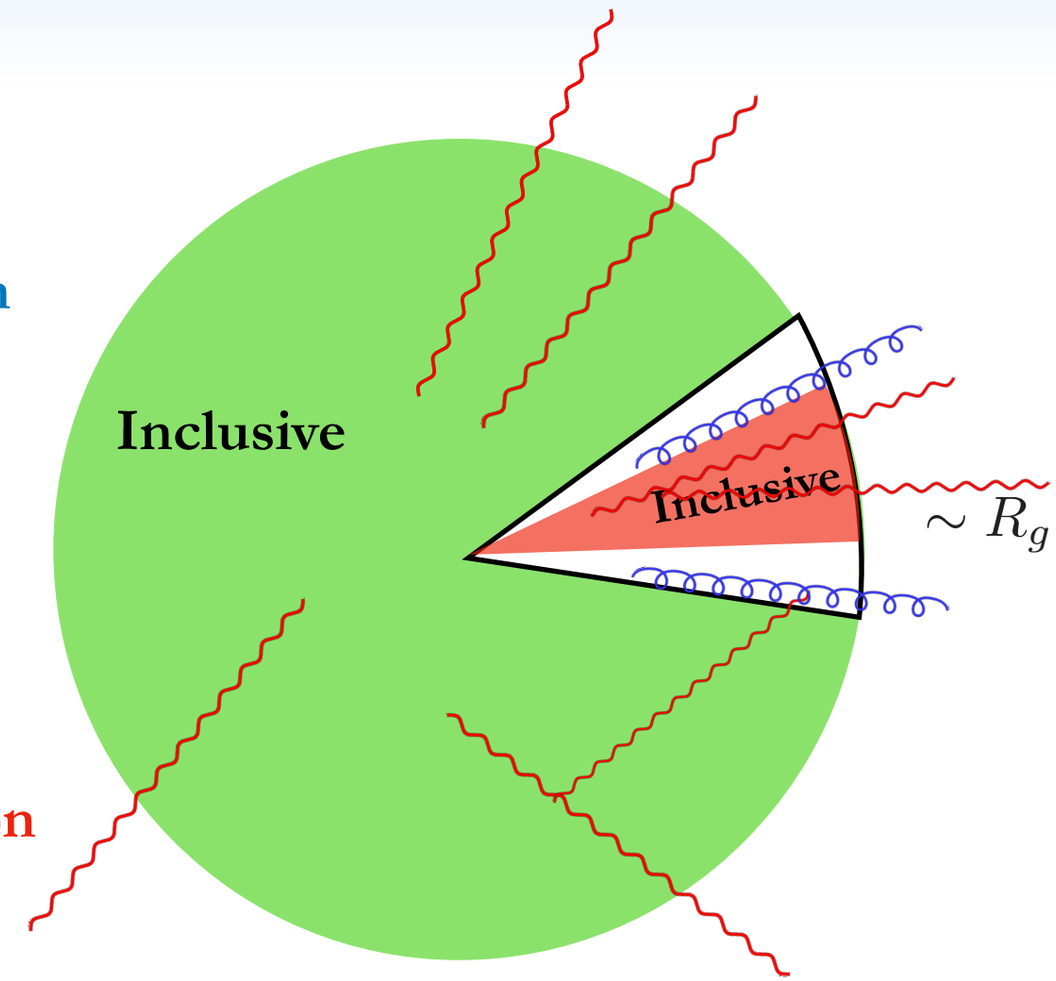
Collinear

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

correlation

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

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



Kang, KL, Liu, Ringer, In Preparation

Factorization of R_g

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

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

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

- $z_{\rm cut} \ll 1$ and $R_g \ll R$

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

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

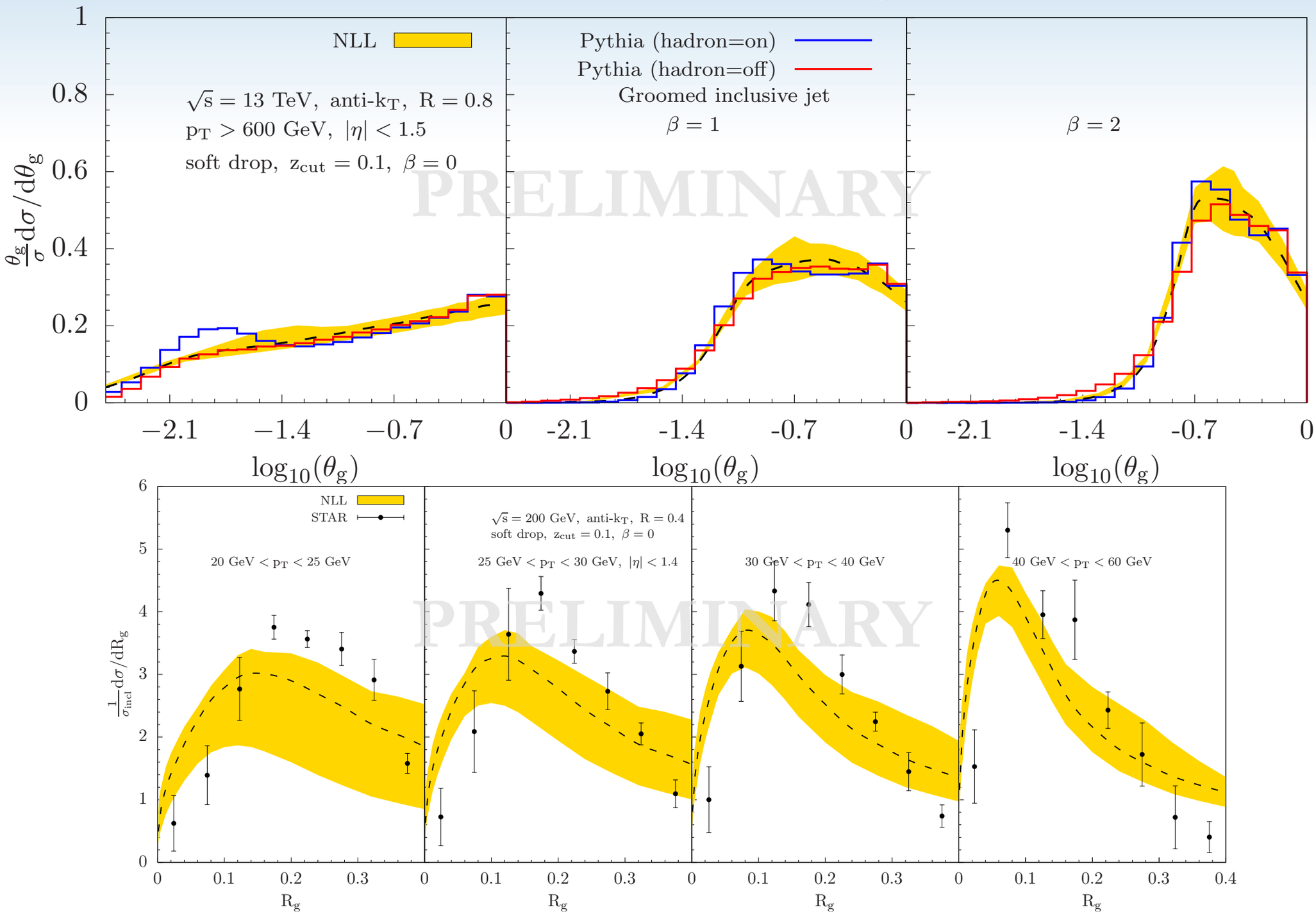
correlation

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

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

Kang, KL, Liu, Ringer, In Preparation

Phenomenology

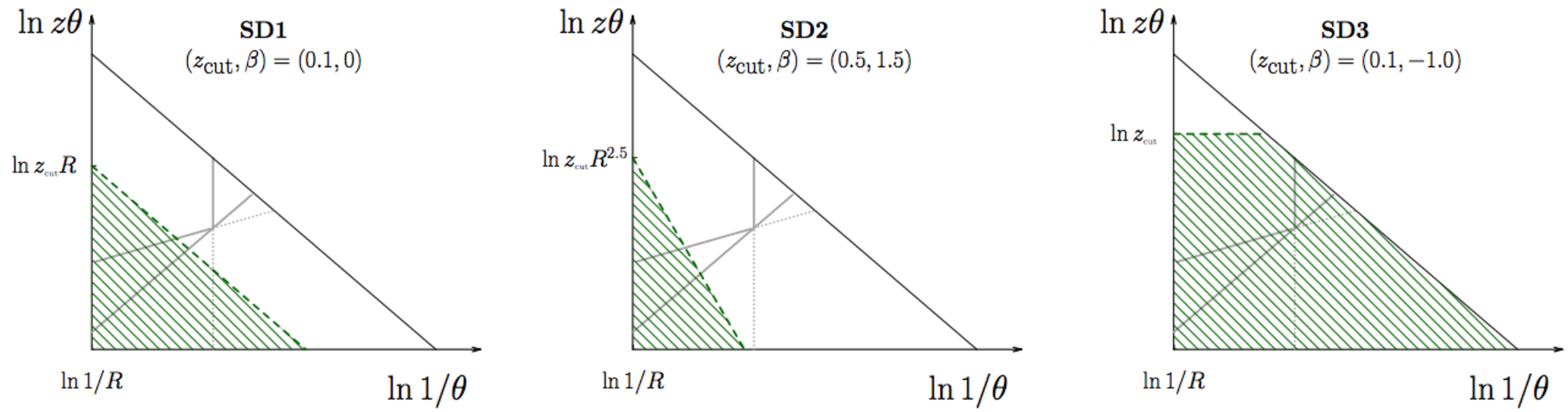


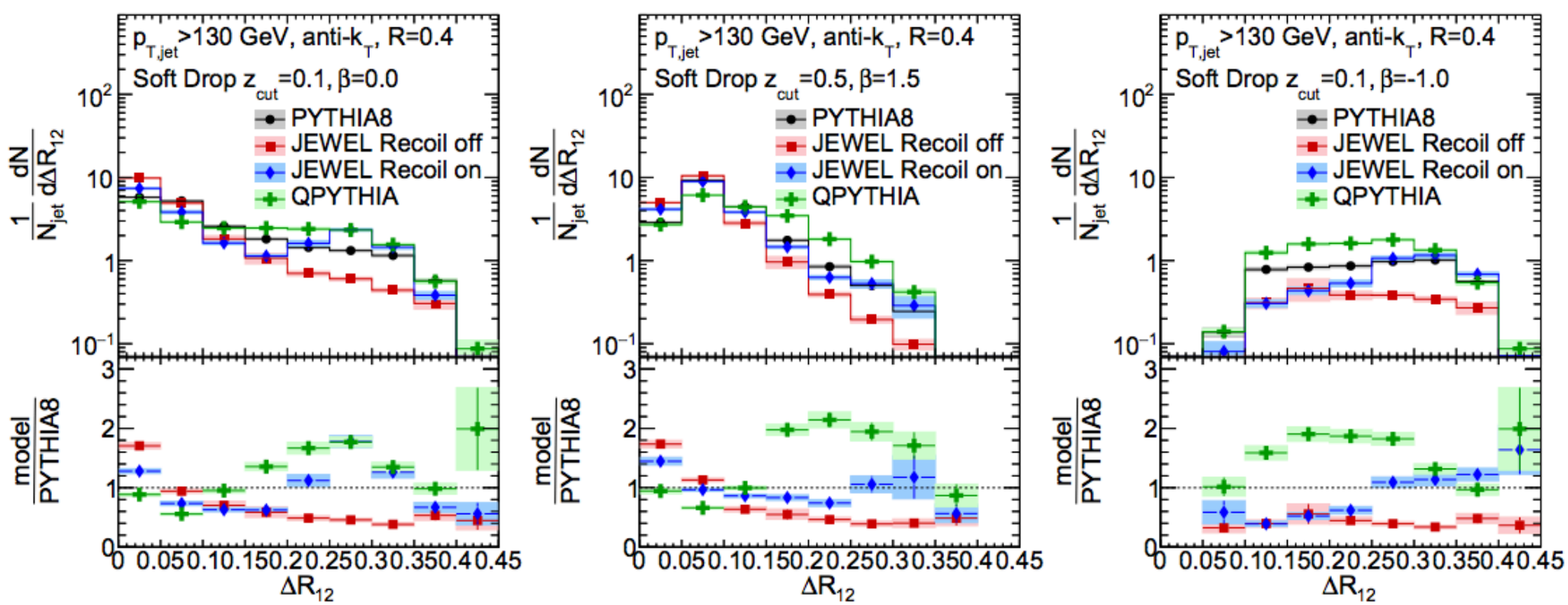
- **Shows agreement for both LHC and STAR kinematics.**

Kang, KL, Liu, Ringer, In Preparation
STAR Preliminary data

R_g in the medium

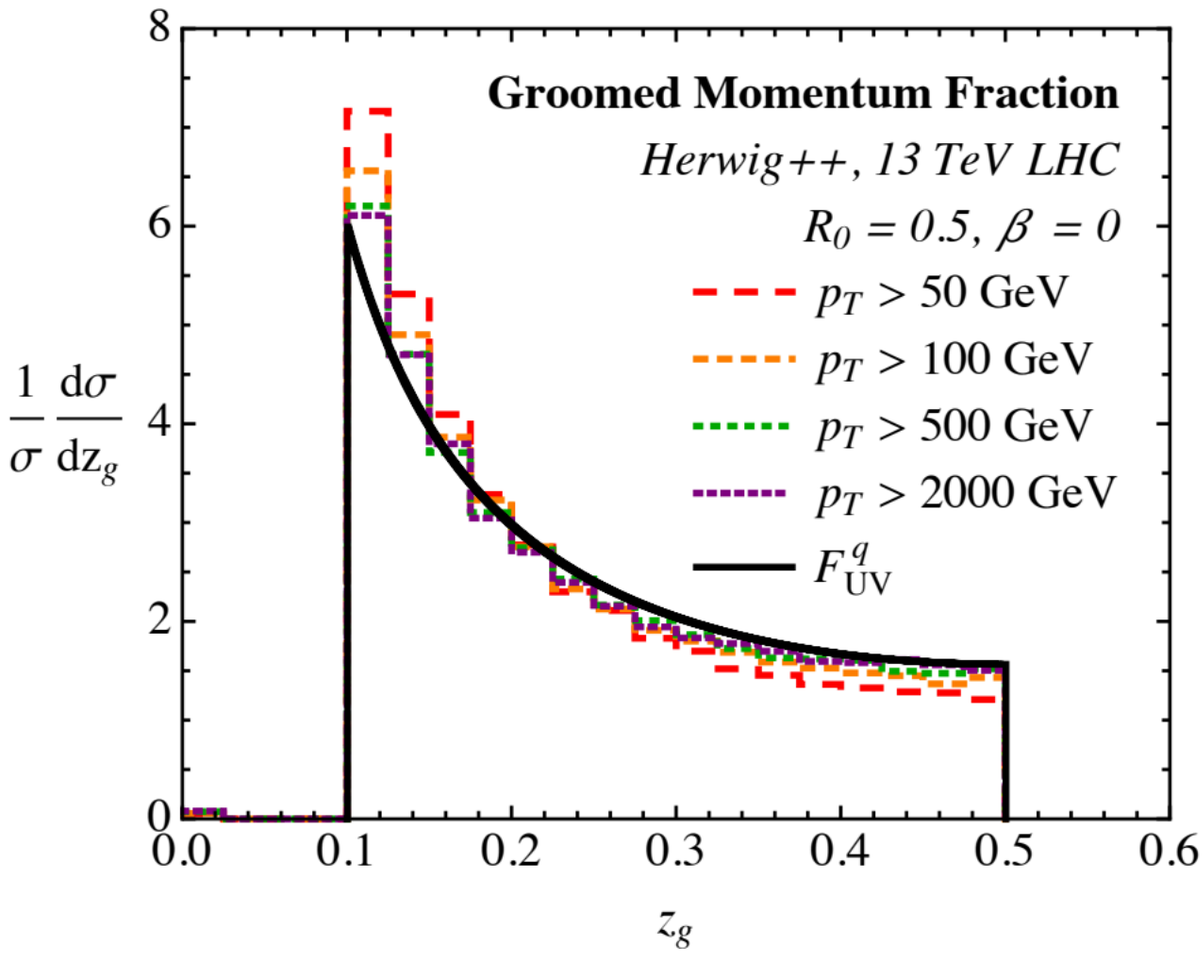
- Are substructures quenched differently as a function of their angular separation?





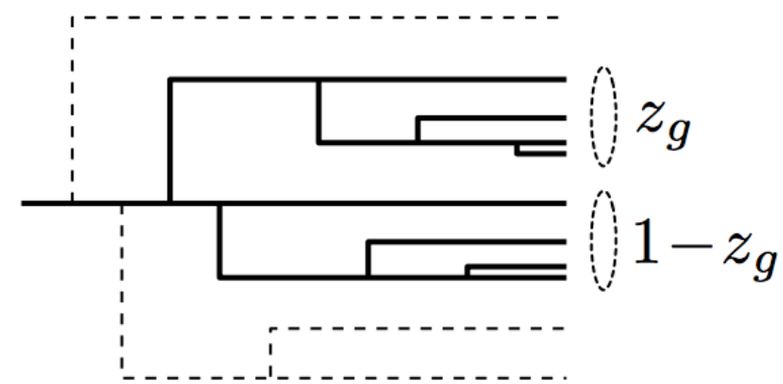
5th Heavy Ion Jet Workshop Report, 2018

Momentum sharing fraction z_g



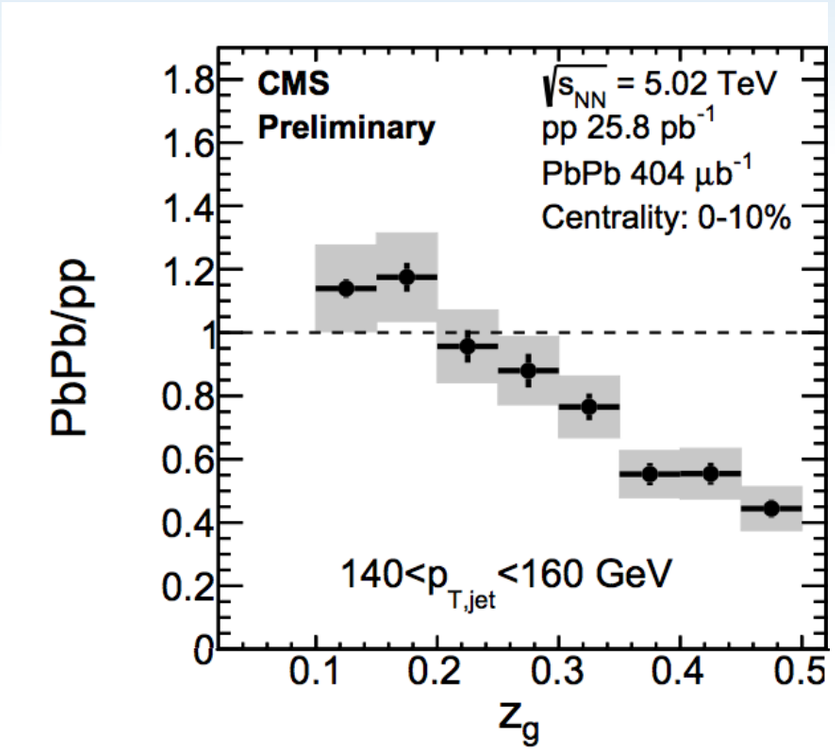
Larkoski, Marzani, Thaler `15
Tripathee, Xue, Larkoski, Marzani, Thaler `17

- **Sudakov safe observable**

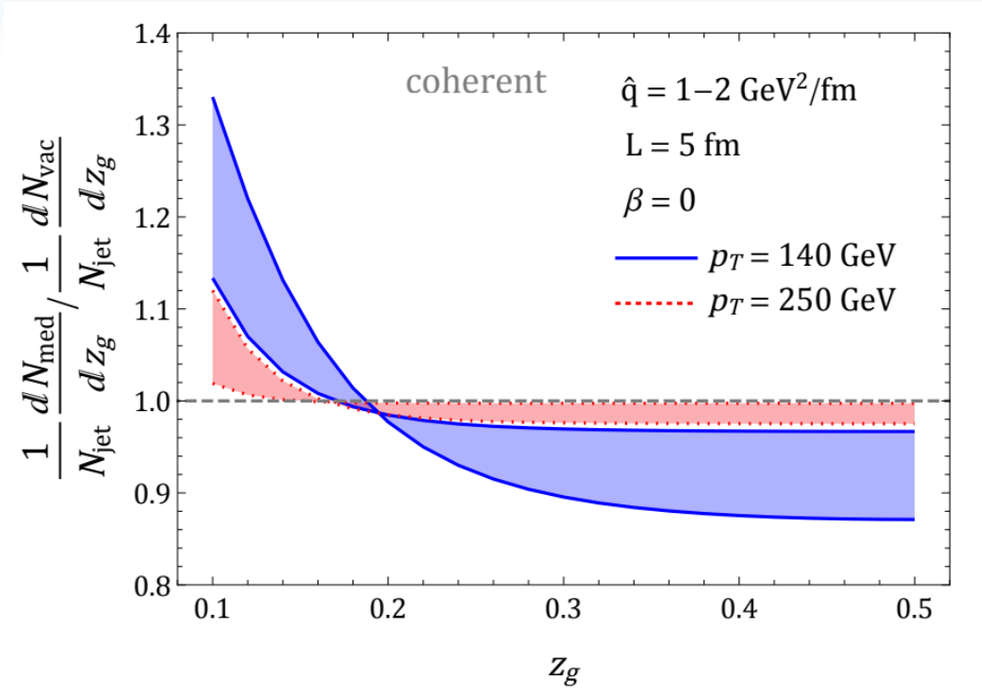


- **Identifies collinear-splitting and give direct access to the splitting functions.**

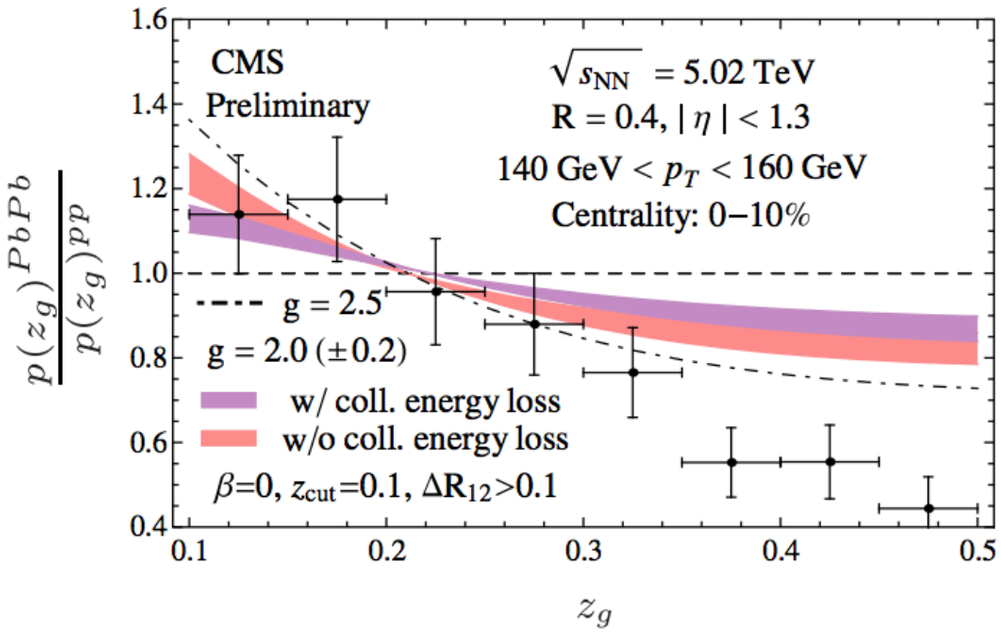
Momentum sharing fraction z_g



CMS(2016) PAS HIN-16-006



Mehtar-Tani, Tywoniuk `17

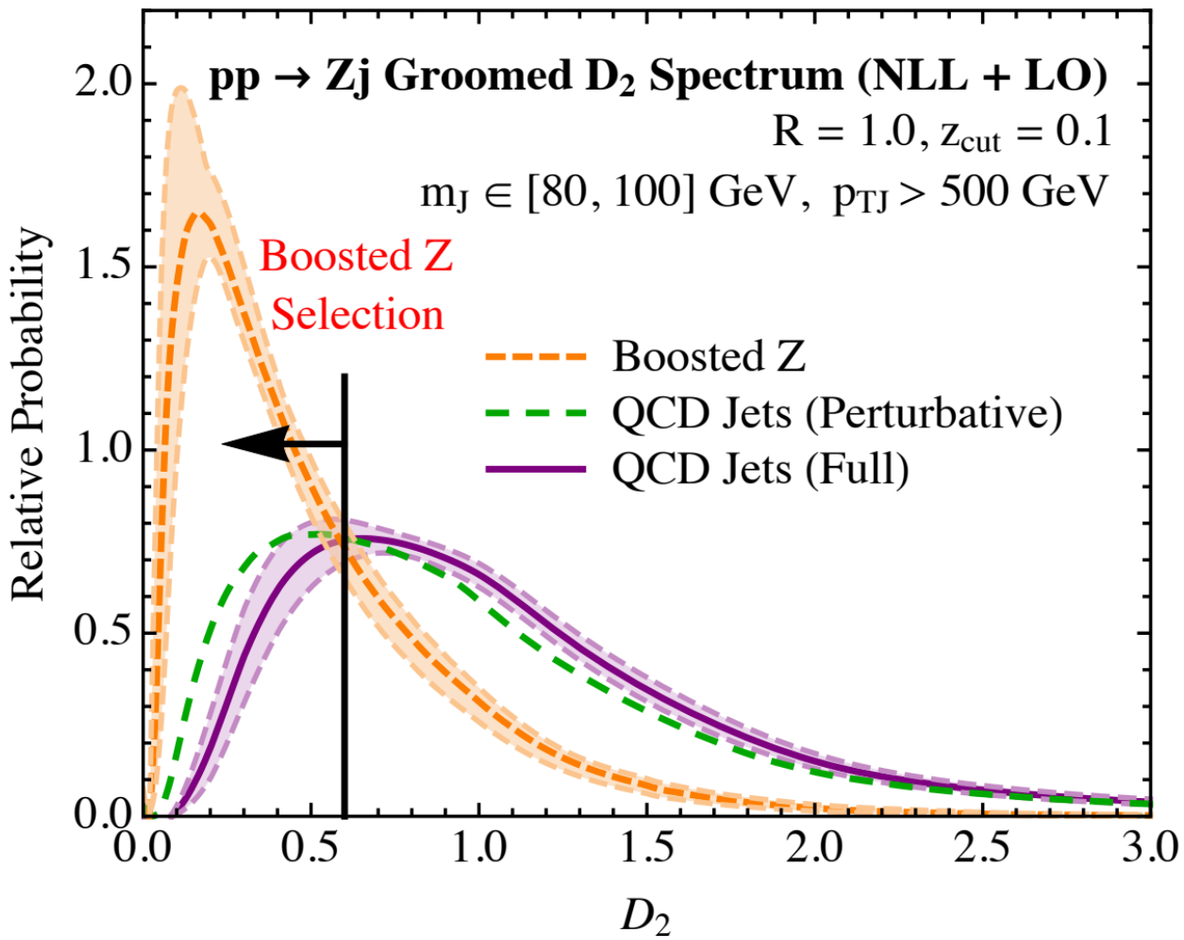


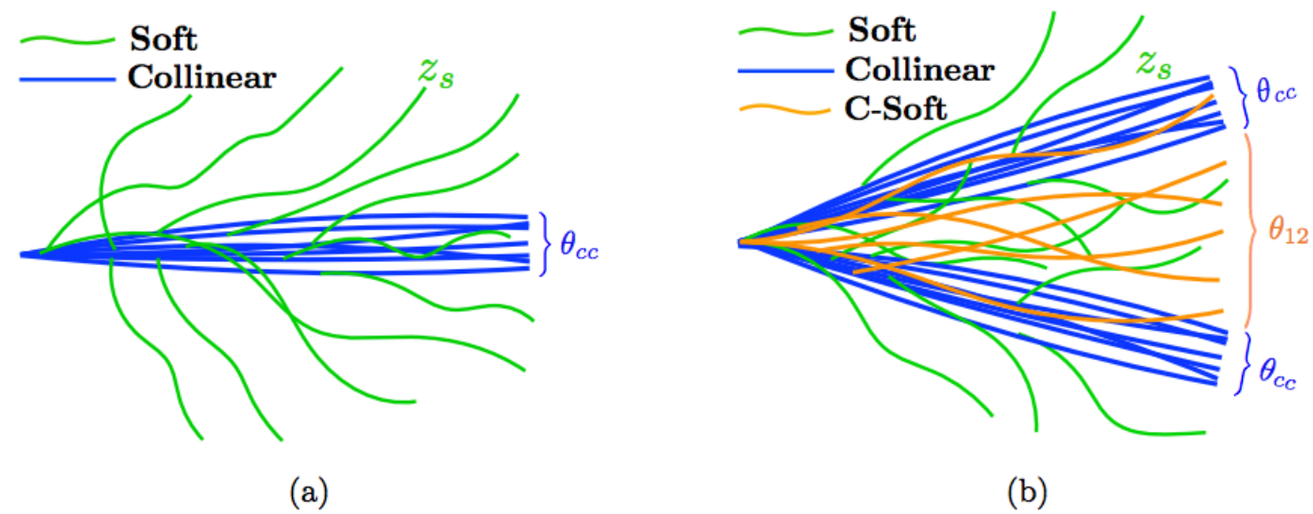
Chien, Vitev `17

$$P^{\text{tot}} = P^{\text{vac}} + \Delta P^{\text{med}}$$

- **Can give access modification of splitting due to the presence of medium.**

Multi-prong observables





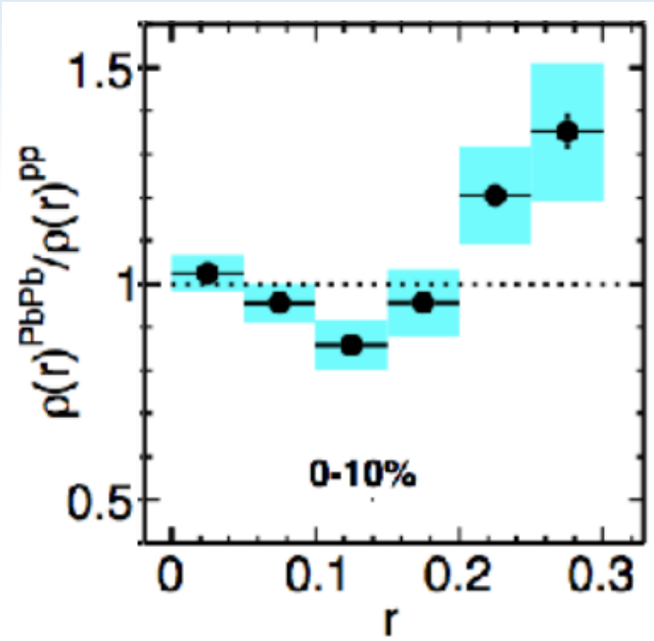
- **Designed to discriminate one-prong QCD jets and multi-prong boosted heavy objects.**

- **May be used in heavy-ion collisions to discriminate jets with single or several hard cores. May be used to test color decoherence.**

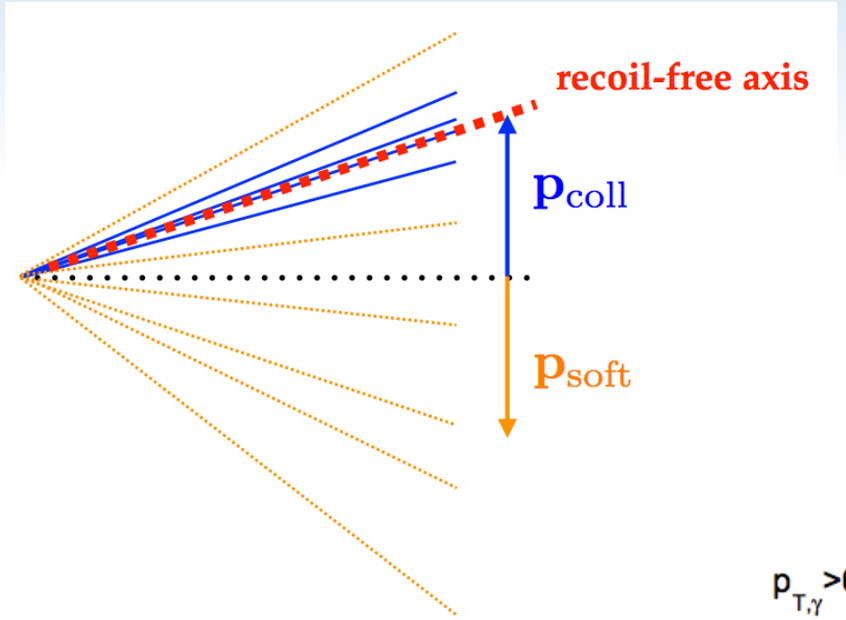
Larkoski, Moult, Neill `16-17
Stewart, Tackmann, Waalewijn `10
and more …

Many more …

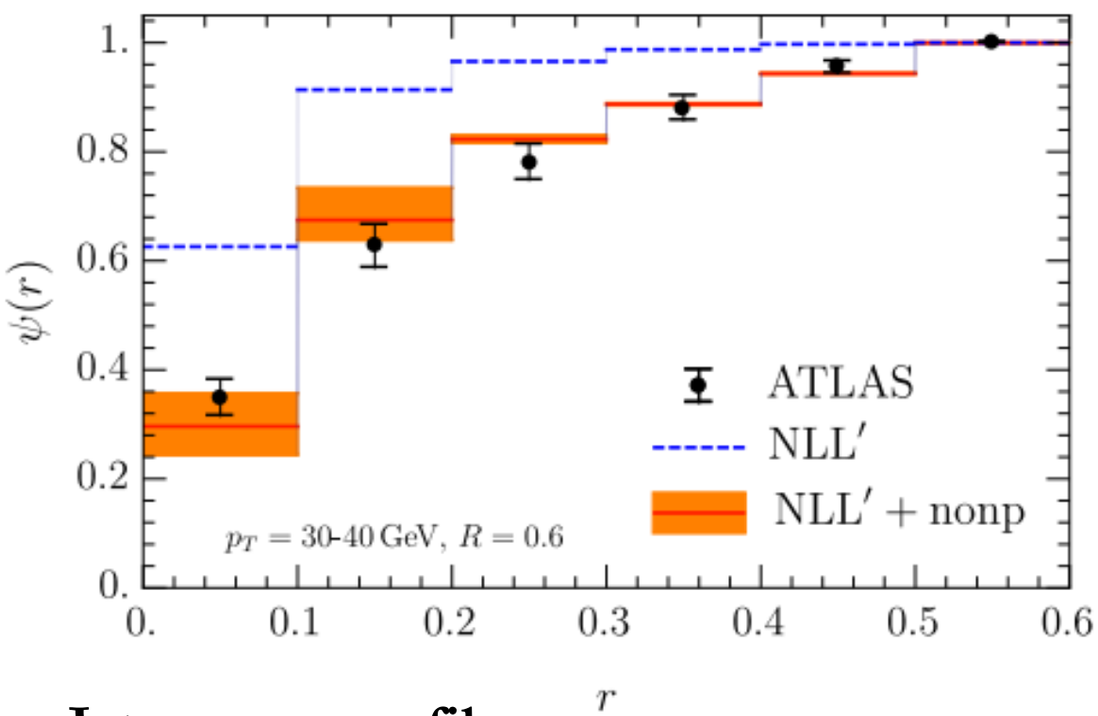
Larkoski, Neill, Thaler `14
5th Heavy Ion Jet Workshop Report `18
Cal, Ringer, Waalewijn `19
Neill, Papaefstathiou, Waalewijn, Zoppi `19
and more…



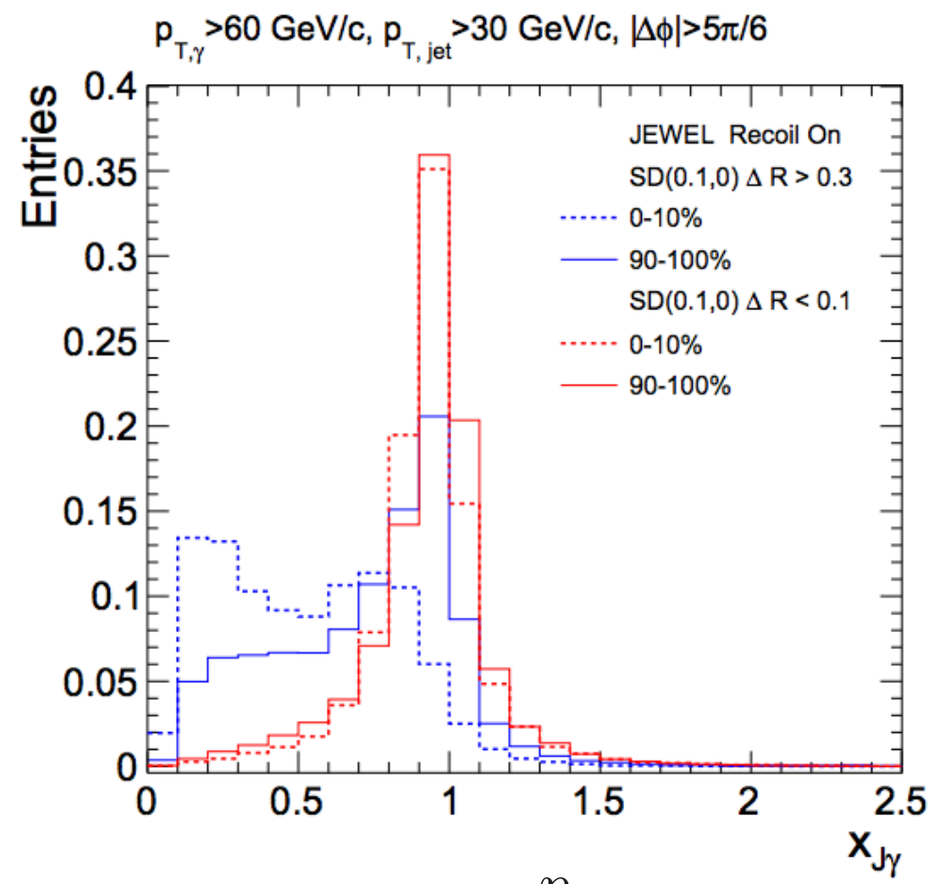
CMS, PLB 730 (2014) 243



Jet axis



Jet energy profile



$$x_{J\gamma} = \frac{p_{T,\mathrm{jet}}}{p_{T,\gamma}}$$