Jet substructure with and without grooming

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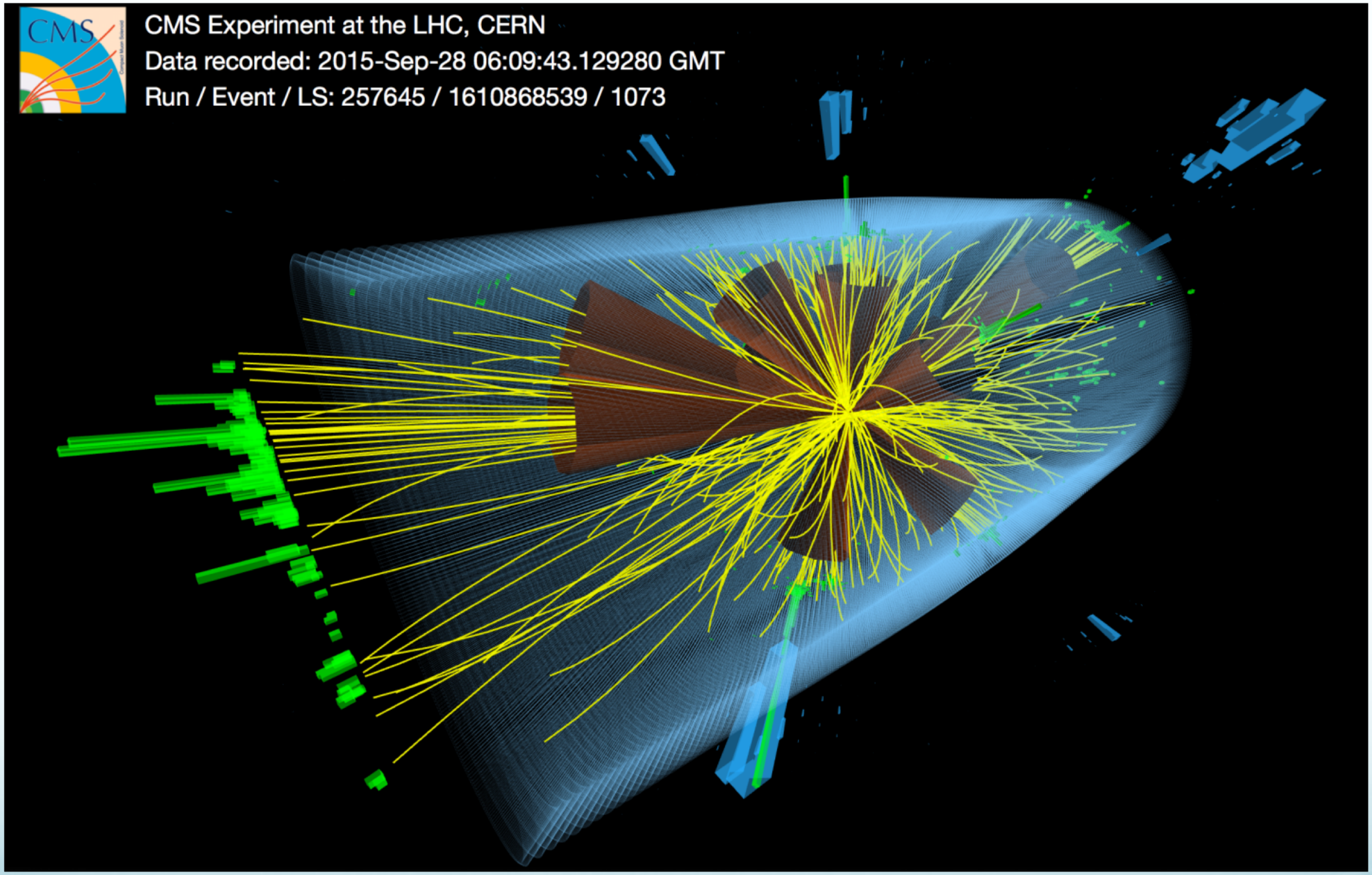
Jets are abundantly produced in both p+p and A+A

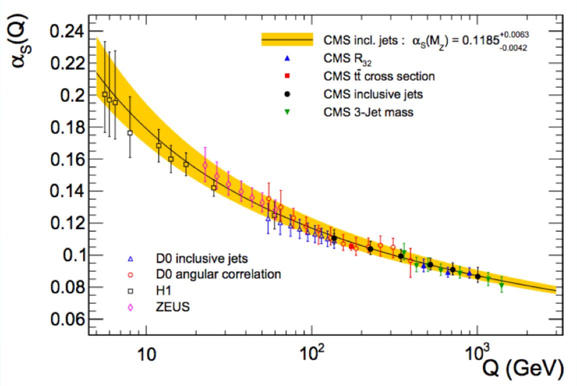
- Jets are everywhere

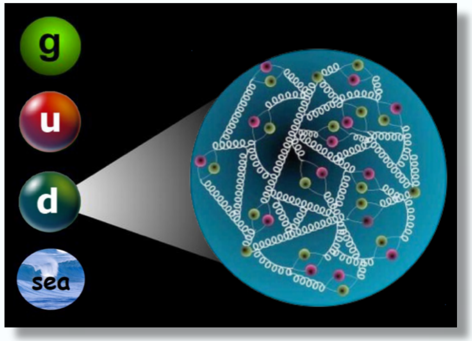


Why do we care about jets?

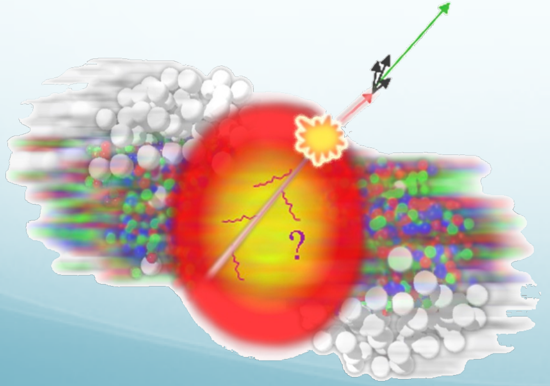
- Jets are inherently interesting
  - They are emergent phenomena and can teach us about QFT

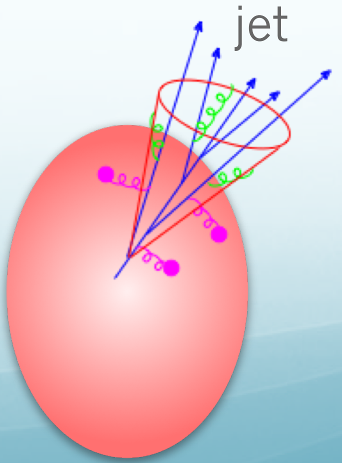
- Extract fundamental QCD parameters, constrain PDFs





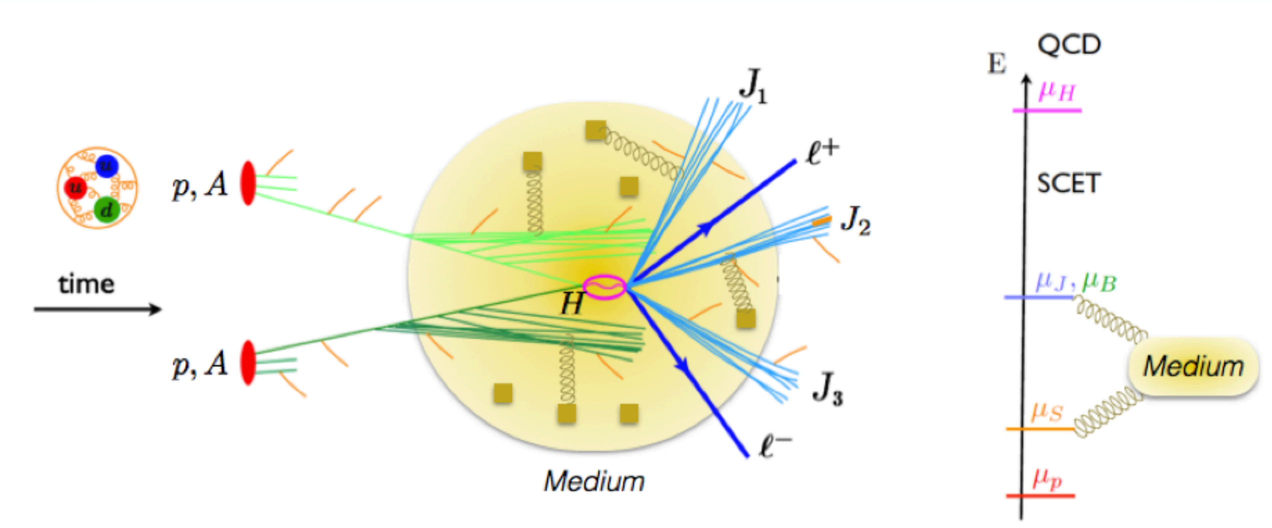
- Probing the properties of the hot and dense medium





Theory: jet substructure in p+p and A+A

- Studying jet substructure in QCD is generally a complicated problem, due to its multi-scale nature
  - Fixed-order computation usually fails



- Modern effective field theory (e.g., SCET) is here to rescue
  - Hard mode $p^\mu \sim Q(1,1,1)$
  - Collinear mode $p^\mu \sim Q(1,\lambda^2,\lambda)$ $\qquad p^\mu = (p^+, p^-, p_\perp)$
  - Soft mode $p^\mu \sim Q(\lambda,\lambda,\lambda)$

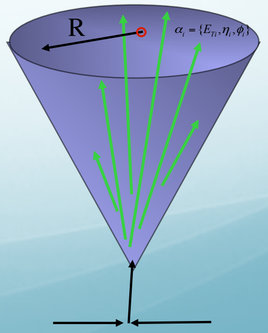
$$\sigma = H \otimes S \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j$$

Poor theorist review: status

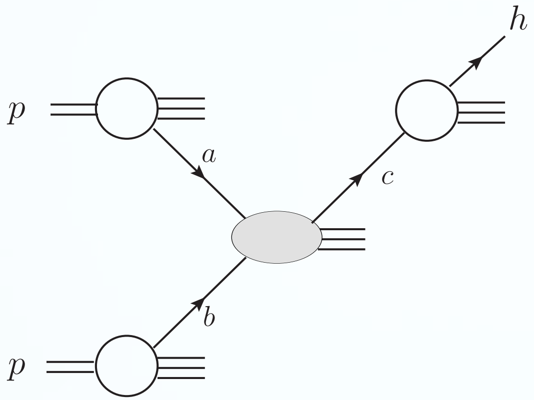
- P+P: a lot of work are still needed to develop the theory formalism for jet substructure

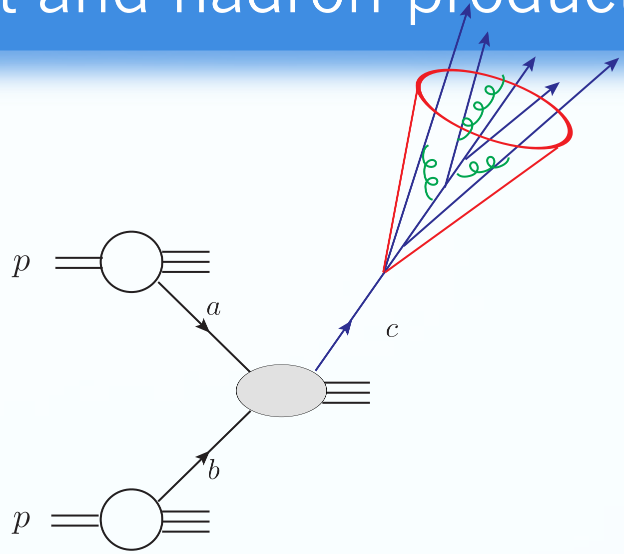
- A+A: the interaction between collinear modes (jet) and the medium is captured by Glauber gluons $q \sim (\lambda^2, \lambda^2, \lambda)$
  - How soft modes coupled to the medium is not explored yet
  - In general soft background is much more complicated in heavy ion environment, which could obscure the comparison between p+p and A+A

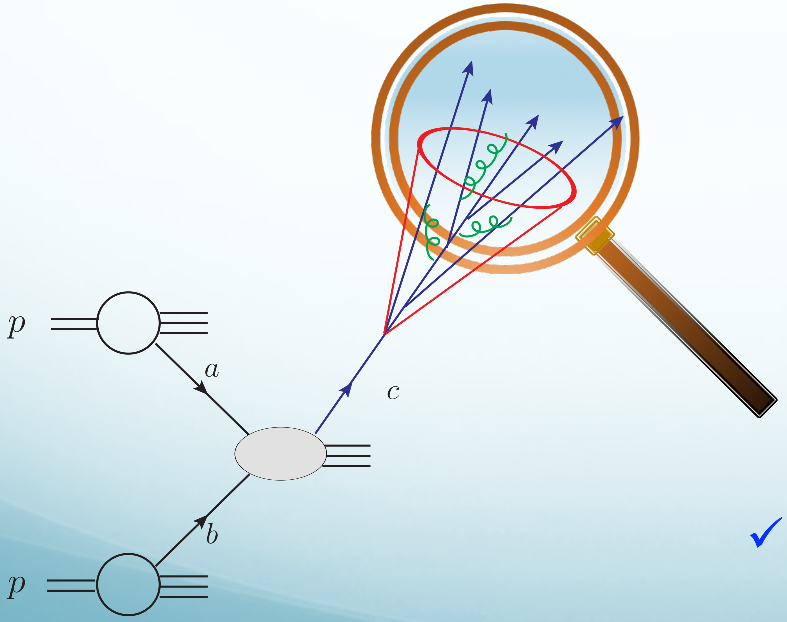
- Initial strategy??
  - Try to reduce sensitivity to soft modes: soft drop grooming
  - Try to rely on collinear physics, e.g., using winner-take-all jet axis (instead of standard jet axis)



A unified framework for jet and hadron production







$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h(z,\mu)$$

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(z,p_T R,\mu)$$

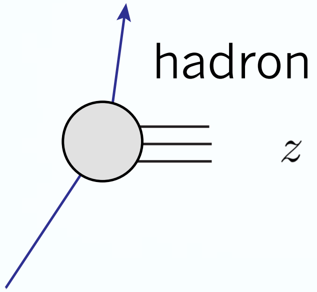
$$\frac{d\sigma^{pp\to \mathrm{jet}(\tau)X}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c(z,p_T R,\tau,\mu)$$

✓ Same hard functions, telling us the quark and gluon jet ratios order by order in pQCD

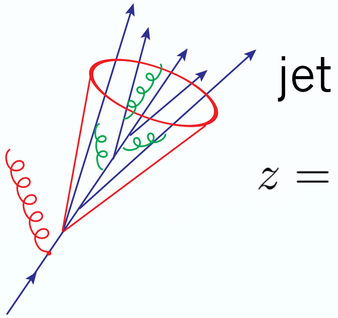
Kang, Ringer, Vitev, 1606.06732, 1606.07063, Dai, Kim, Leibovich, 1606.07411, see also, Kaufmann, Mukherjee, Vogelsang, 1506.01415

What are these jet functions?

- They are usually referred to as “semi-inclusive jet function”



$$z = \frac{p_{\mathrm{h}}^+}{p_{\mathrm{parton}}^+}$$



$$z = \frac{p_{\mathrm{jet}}^+}{p_{\mathrm{parton}}^+}$$

- They follow DGLAP evolution equation
  - All jet substructures are contained in these functions

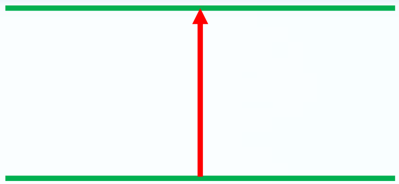
$$\mu\frac{d}{d\mu}D_i^h(z,\mu) = \sum_j P_{ji} \otimes D_j^h(z,\mu)$$

$$\mu\frac{d}{d\mu}J_i(z,p_T R,\mu) = \sum_j P_{ji} \otimes J_j(z,p_T R,\mu)$$

$$\mu\frac{d}{d\mu}\mathcal{G}_i(z,p_T R,\tau,\mu) = \sum_j P_{ji} \otimes \mathcal{G}_j(z,p_T R,\tau,\mu)$$

Ln(R) resummation

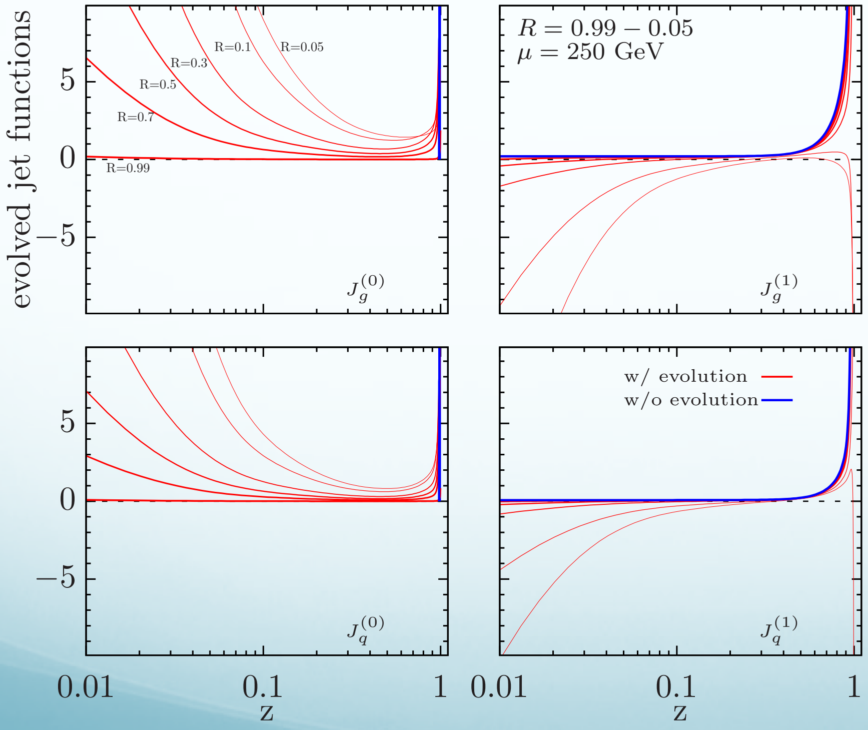
- Natural scale for jet functions: p_T*R
- Jet radius resummation: $(\alpha_s \ln R)^n$

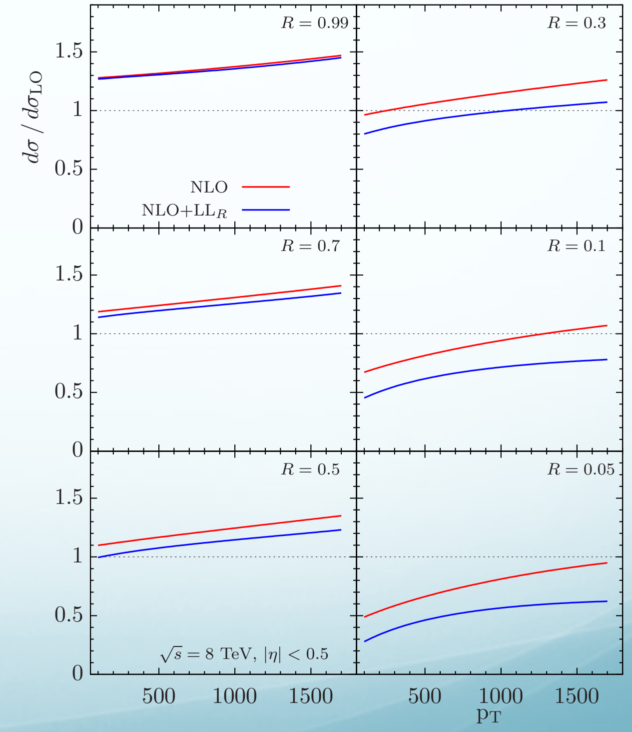


$\mu \sim p_T$

$\mu_J \sim p_T \times R$

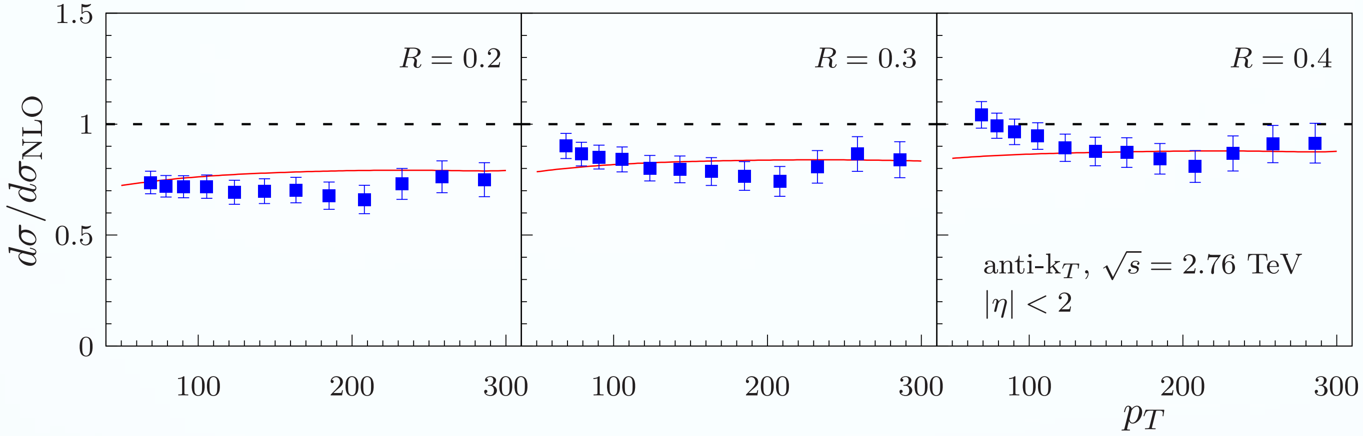
Kang, Ringer, Vitev, 1606.06732





Effect of ln(R) resummation

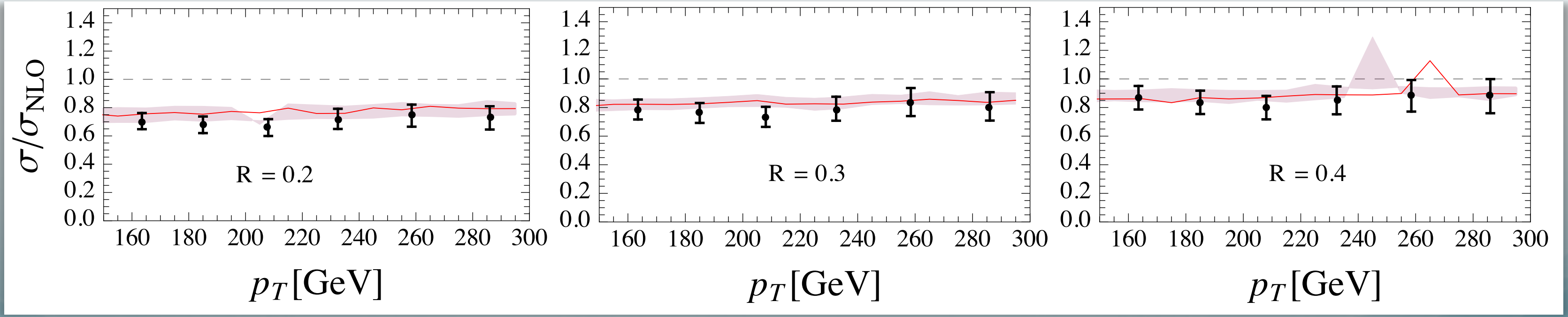
- The ln(R) is the main source for the discrepancy:



CMS, 1609.05383

Kang, Ringer, Vitev, PLB 2017

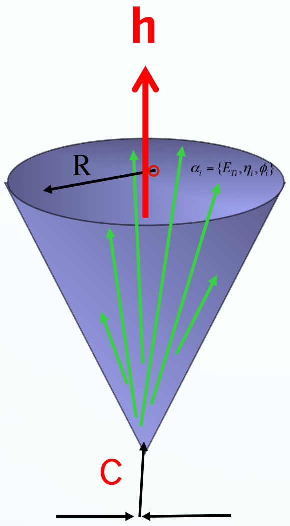
- Threshold resummation further improve the agreement



Liu, Moch, Ringer, PRL 2017

Jet fragmentation function

- First produce a jet, and then further look for a hadron inside the jet



$$F(z_h, p_T) = \frac{d\sigma^h}{dy\,dp_T\,dz_h} \Big/ \frac{d\sigma}{dy\,dp_T}$$

$$z_h = p_T^h / p_T$$

$$z = p_T / p_T^c$$

Kang, Ringer, Vitev, JHEP 2016

- Just like the single inclusive jet production, we have
  - Semi-inclusive fragmenting jet function

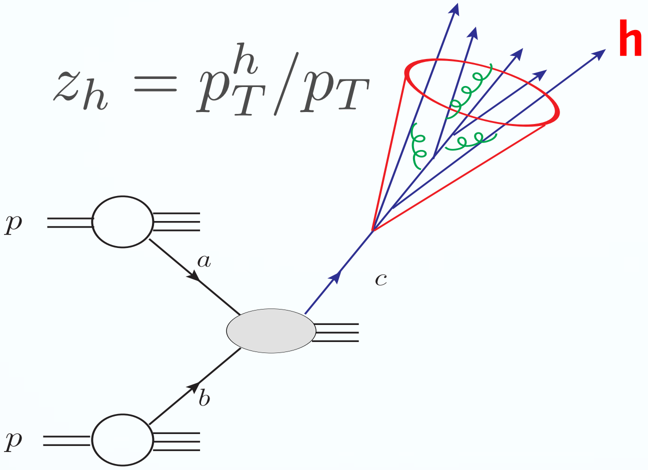
$$\frac{d\sigma}{dy\,dp_T\,dz_h} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, R, \mu)$$

Semi-inclusive fragmenting jet function

- One needs a more complicated jet function

Kang, Ringer, Vitev, 1606.07063, JHEP 16

$$z_h = p_T^h / p_T$$

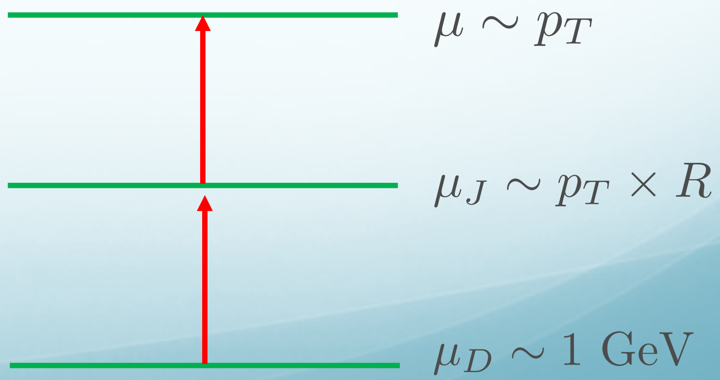


$$J_c(z, p_T R, \mu) \to \mathcal{G}_c^h(z, z_h, p_T R, \mu)$$

- Two DGLAPs:

$$\mu \frac{d}{d\mu} \mathcal{G}_i^h(z, z_h, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}\right) \mathcal{G}_j^h(z', z_h, \mu)$$

$$\mathcal{G}_i^h(z, z_h, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}\left(z, z_h', \mu\right) D_j^h\left(\frac{z_h}{z_h'}, \mu\right)$$



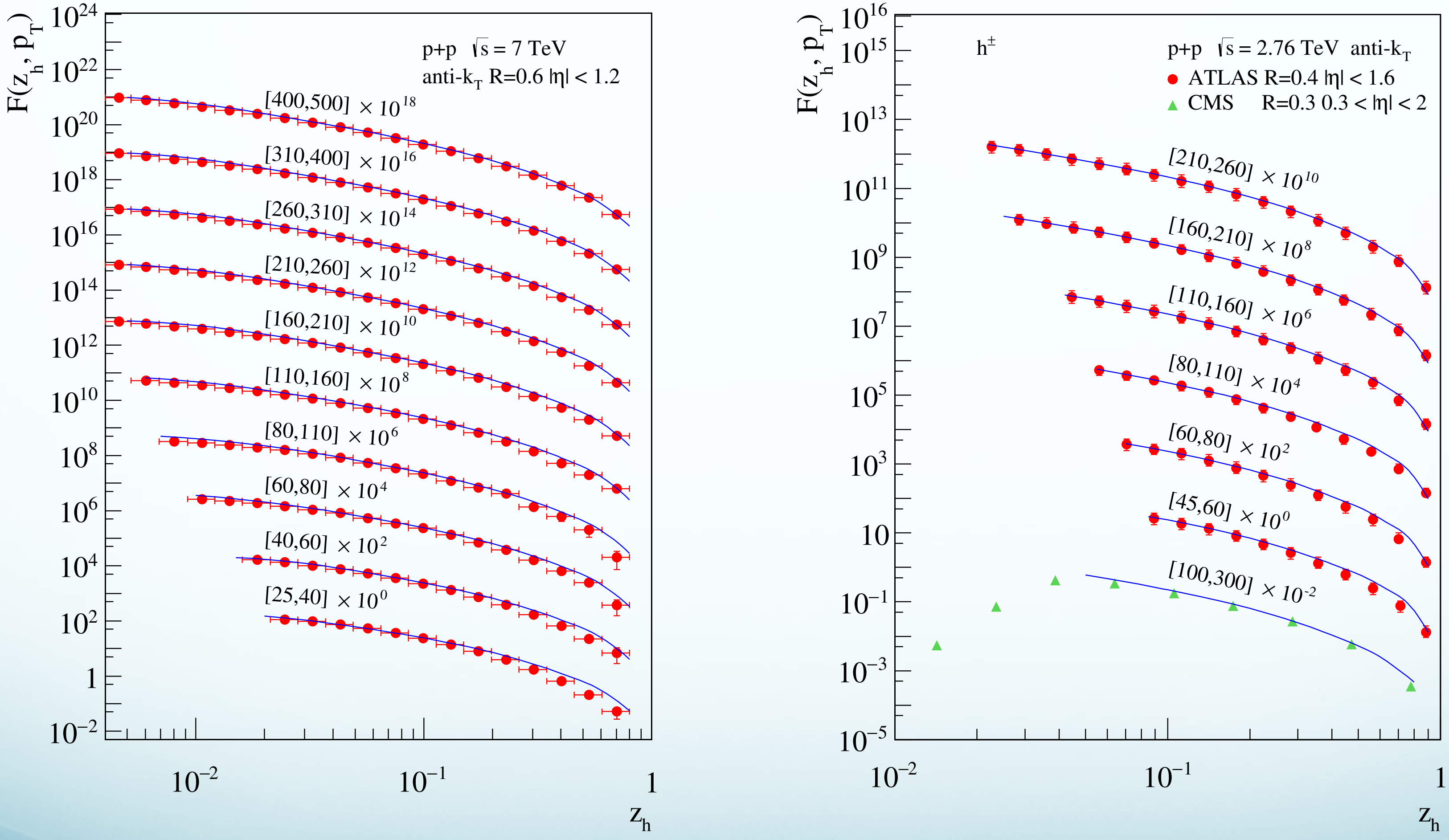
$\mu \sim p_T$

$\mu_J \sim p_T \times R$

$\mu_D \sim 1 \text{ GeV}$

Some interesting phenomenology

- Works pretty well in comparison with experimental data

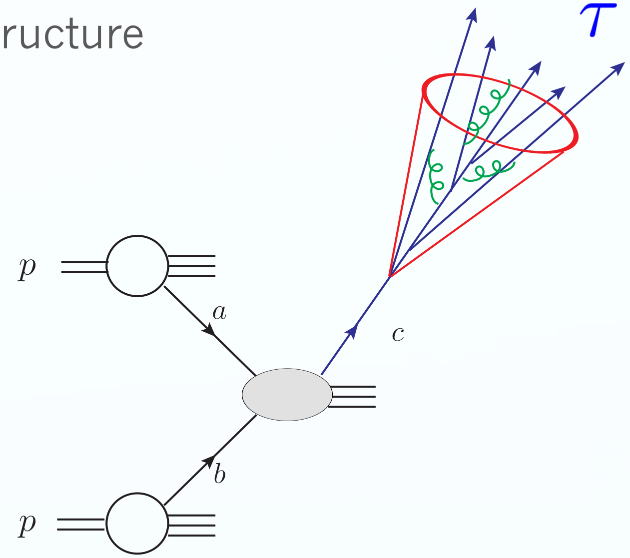


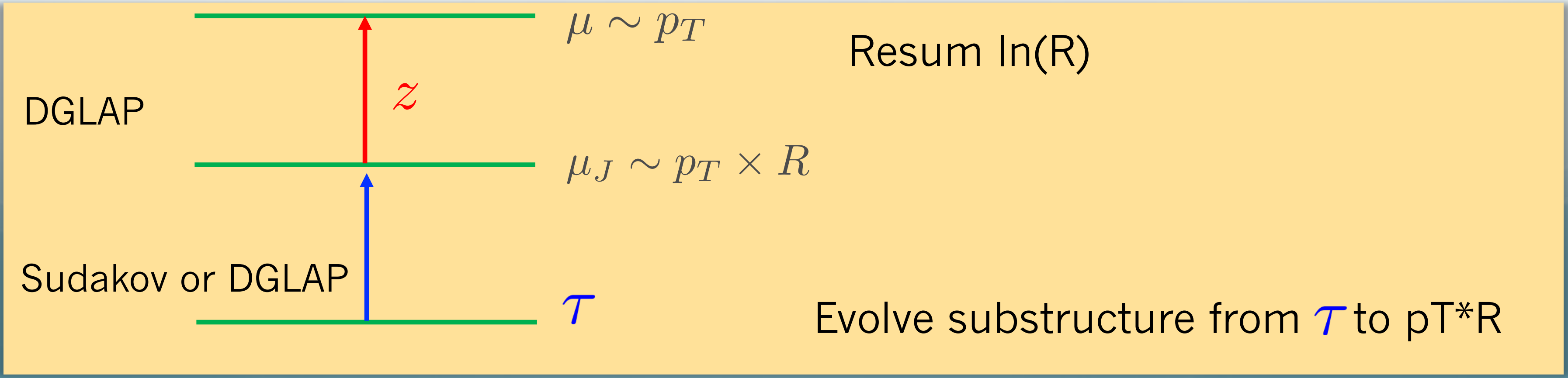
Kang, Ringer, Vitev, arXiv:1606.07063

Evolution structure for jet substructure

- Jet substructure: two-layer QCD factorization
  - Producing the jet
  - Concentrating on the internal substructure

$$\frac{d\sigma}{d\eta\, dp_T\, {\color{blue}d\tau}}$$





DGLAP

$\mu \sim p_T$

Resum ln(R)

z

$\mu_J \sim p_T \times R$

Sudakov or DGLAP

τ

Evolve substructure from τ to pT*R

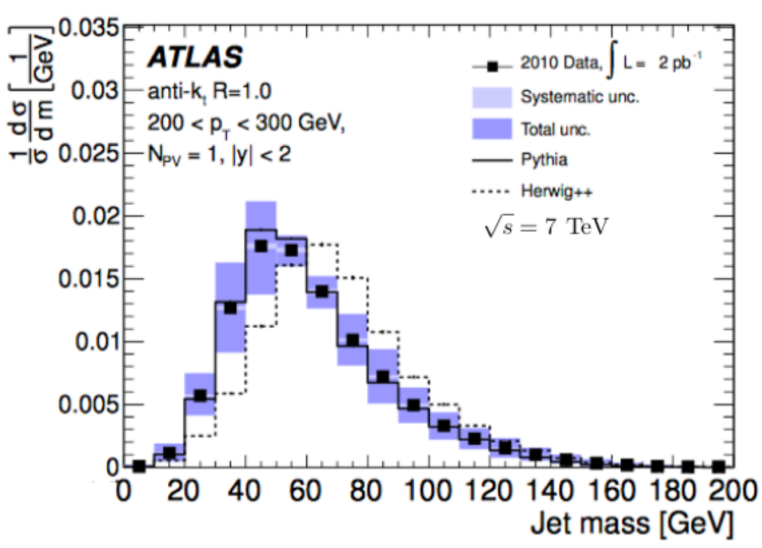
Measuring mass of a jet

- Jet mass for single inclusive jet production: $pp \to \text{jet} + X$

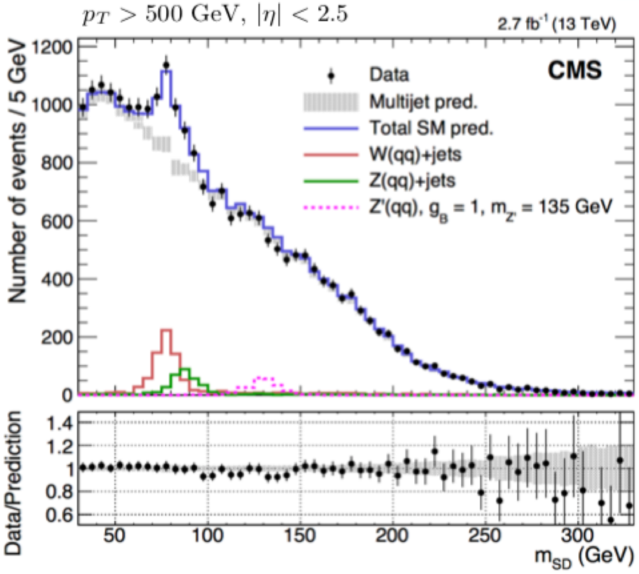
$$m_J^2 = \left(\sum_{i \in J} p_i \right)^2$$

- Quark-gluon discrimination

- Tagging of boosted objects



ATLAS, JHEP 1205 (2012) 128

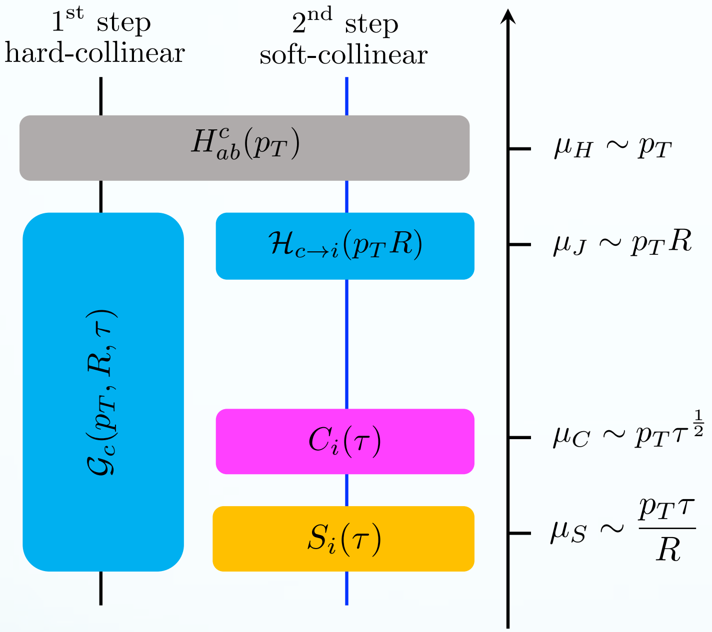


CMS, PRL 119 (2017) 111802

Factorization formalism

- Standard (ungroomed) jet mass distribution

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



1st step
hard-collinear

2nd step
soft-collinear

$H^c_{ab}(p_T)$

$\mathcal{H}_{c\to i}(p_T R)$

$\mathcal{G}_c(p_T, R, \tau)$

$C_i(\tau)$

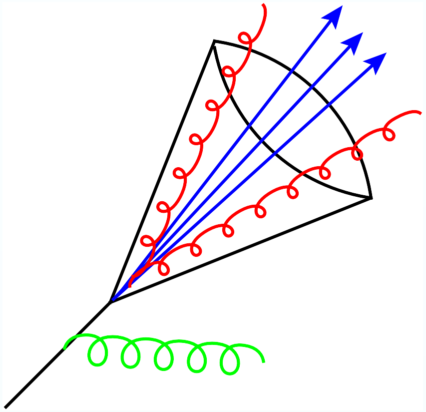
$S_i(\tau)$

$\mu_H \sim p_T$

$\mu_J \sim p_T R$

$\mu_C \sim p_T \tau^{\frac{1}{2}}$

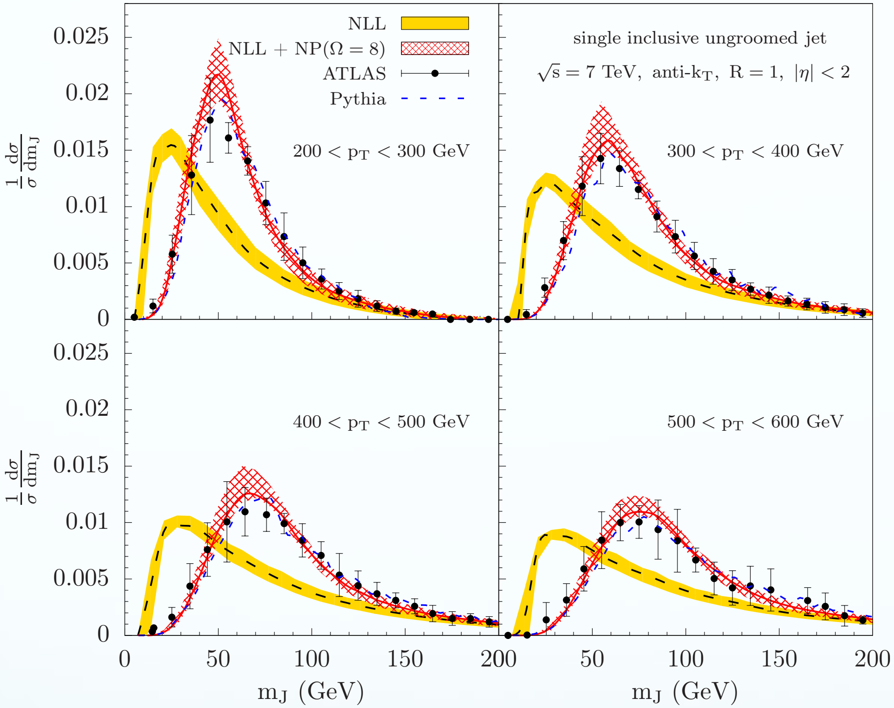
$\mu_S \sim \frac{p_T \tau}{R}$



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

Jet mass

- Comparison with jet mass measurements at the LHC



$$\Omega = 8\mathrm{GeV}$$

Kang, Lee, Liu, Ringer, 1803.03645

- Non-perturbative effect is modeled by a single parameter shape function

Stewart, Tackmann, Waalewijn, 15

Non-perturbative effect

- Non-perturbative contribution mainly from soft momentum *k*

$$m_{J,\text{tot}}^2 = \sum (p_\text{jet} + k)^2 = p_\text{jet}^2 + 2p_\text{jet} \cdot k + \mathcal{O}(k^2)$$

$$p_\text{jet} \sim p_T R$$

$$\text{shift in jet mass} \sim 2p_T R k$$

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

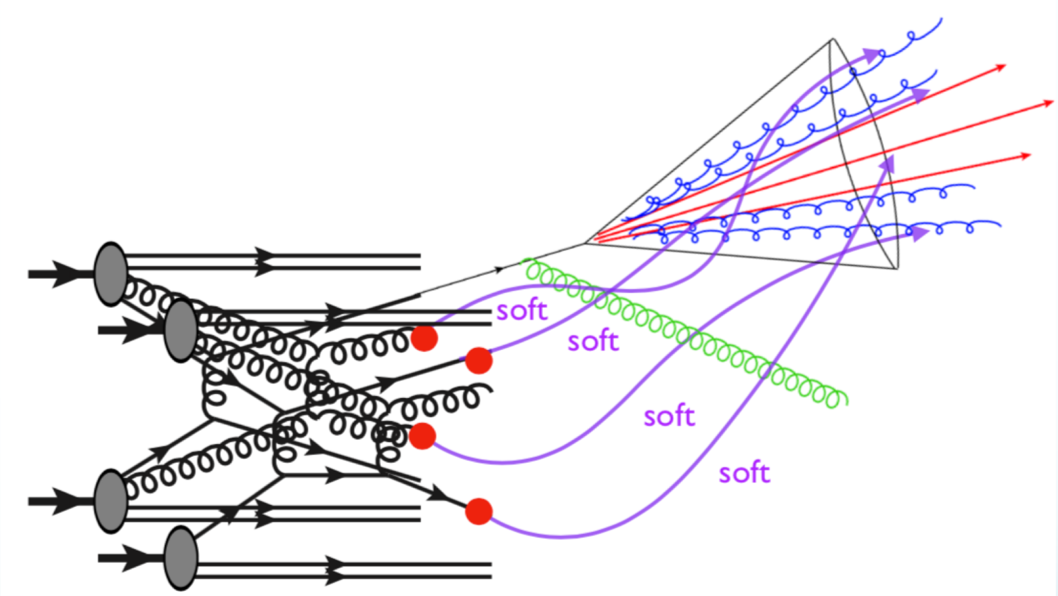
$$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right) \exp\left(-\frac{2k}{\Omega_\kappa}\right)$$

Stewart, Tackmann, Waalewijn, 15

- Higher pT jet leads to a bigger shift in mass

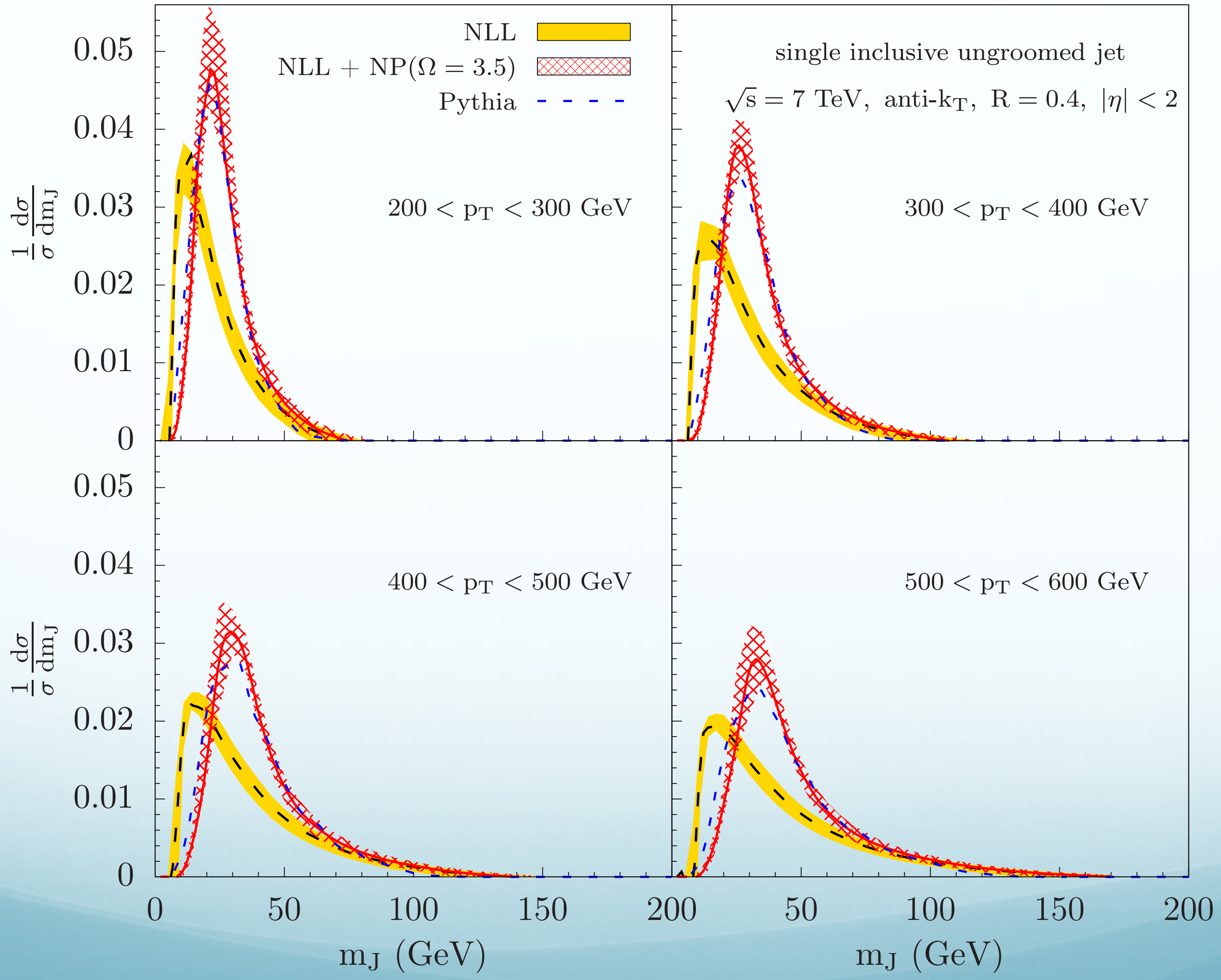
Very large non-perturbative contribution

- What are the sources of non-perturbative physics?
  - Underlying event (multi parton interactions)
  - Pile up
  - Hadronization effect: parton to hadron



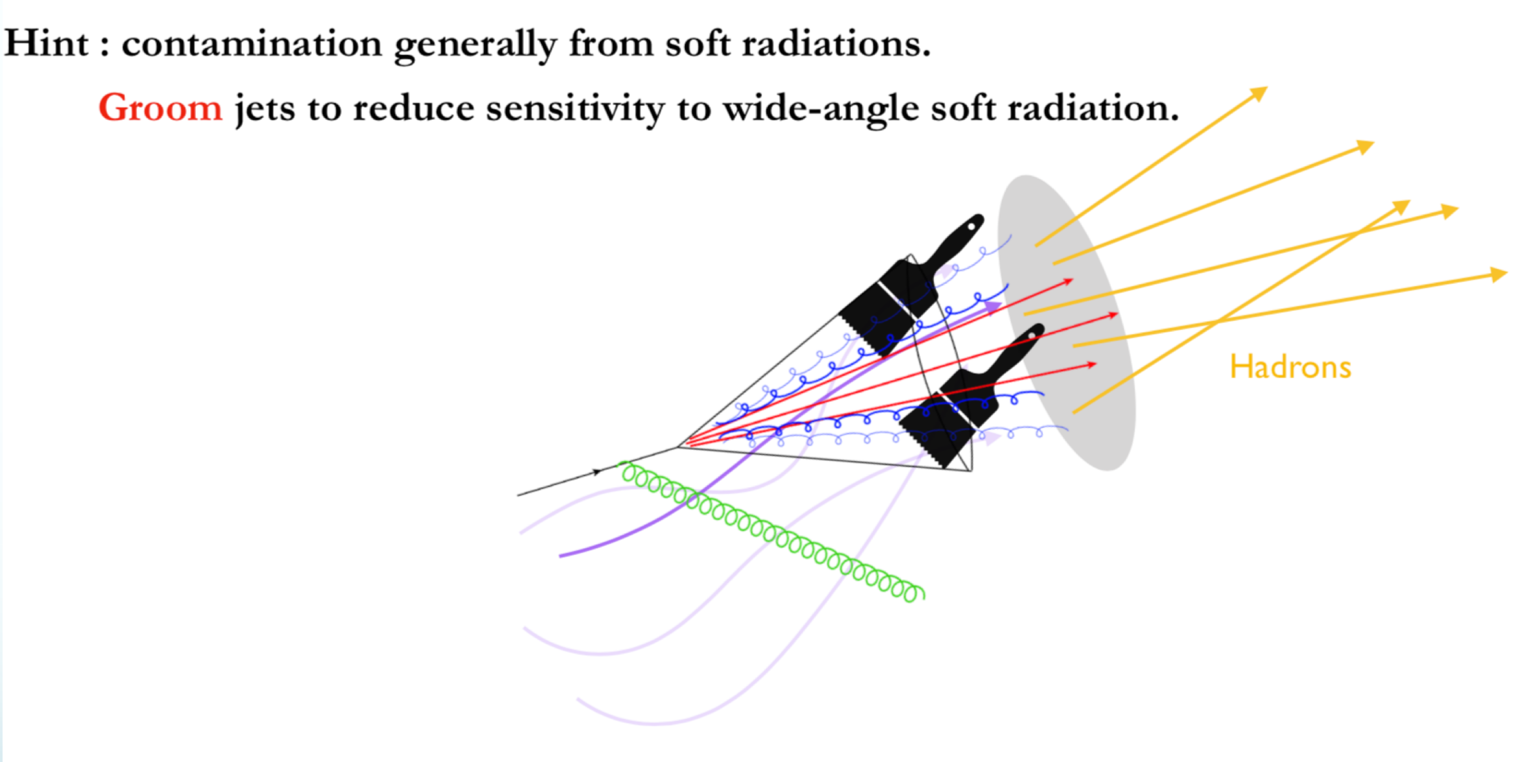
Likely: MPI is suppressed for small radius jets

- Non-perturbative parameter: $\Omega = 3.5\text{GeV}$



Reduce soft sensitivity

- Underlying Events are difficult to understand, maybe try to get rid of them somehow to our observables



Hint : contamination generally from soft radiations.

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

Soft drop grooming

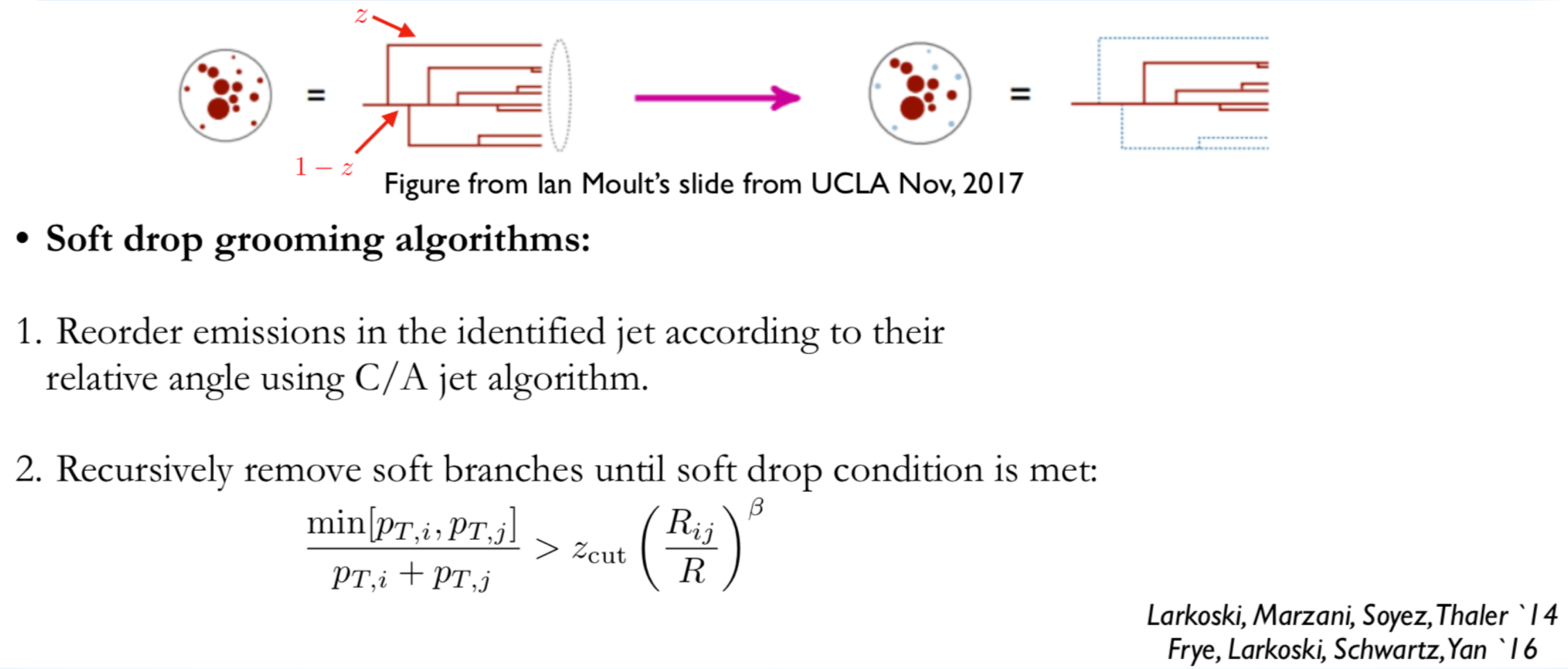


Figure from Ian Moult's slide from UCLA Nov, 2017

- **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:

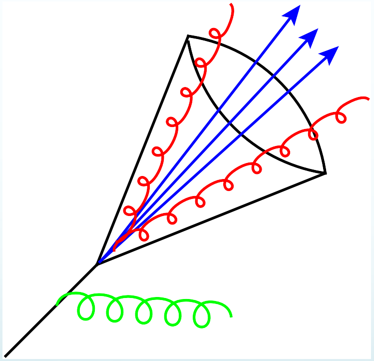
$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{R_{ij}}{R} \right)^{\beta}$$

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

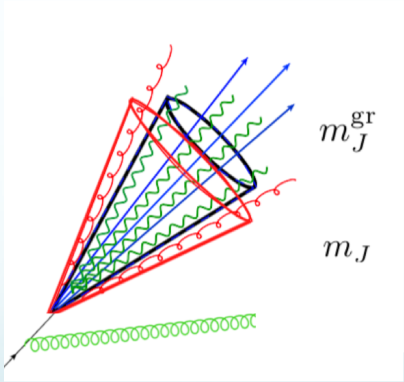
- C/A jet: branches with smallest angle are clustered first
  - Clustering from right to left
- Soft drop: check the soft drop condition from largest angle first
  - Declustering from left to right

What does soft drop grooming do?

- If treated z_{cut} as a soft scale, the large angle soft radiation will fail the soft drop condition
  - Thus soft drop grooming removes “wide/large angle soft radiation”
- Soft drop grooming
  - Does not affect “small angle soft radiation” (collinear soft modes)
  - Does not affect “small angle collinear radiation” inside the jet (collinear modes)
  - Does not affect anything outside the jet



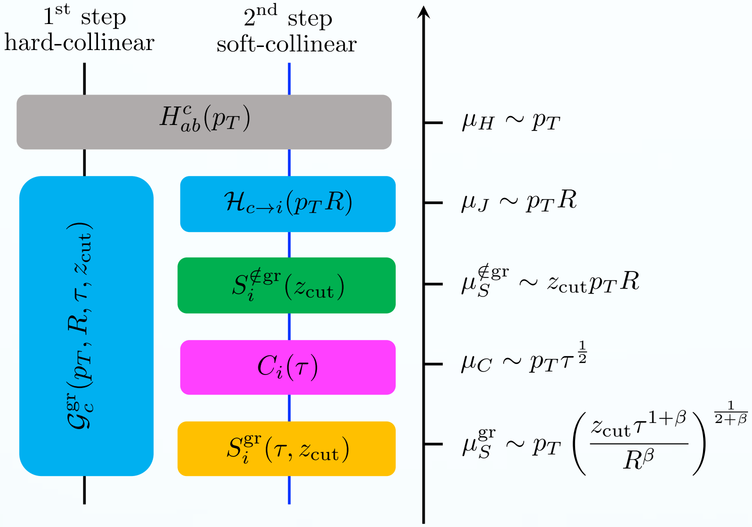
ungroomed



groomed

Factorization formalism

- Groomed jet mass distribution



1st step
hard-collinear

2nd step
soft-collinear

$H_{ab}^{c}(p_T)$

$\mathcal{G}_c^{\rm gr}(p_T, R, \tau, z_{\rm cut})$

$\mathcal{H}_{c\to i}(p_T R)$

$S_i^{\notin{\rm gr}}(z_{\rm cut})$

$C_i(\tau)$

$S_i^{\rm gr}(\tau, z_{\rm cut})$

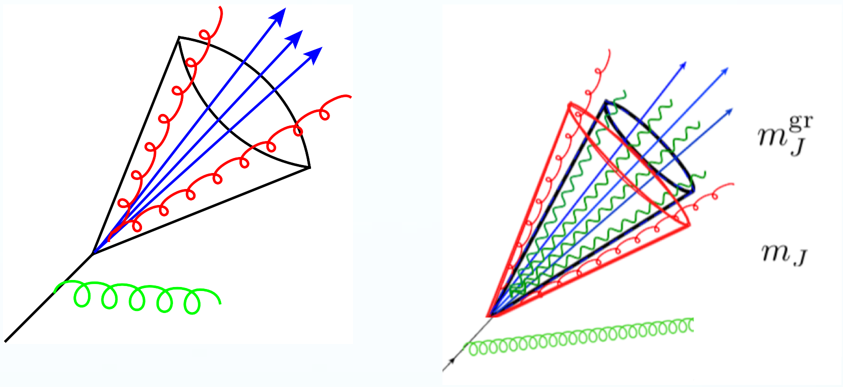
$\mu_H \sim p_T$

$\mu_J \sim p_T R$

$\mu_S^{\notin{\rm gr}} \sim z_{\rm cut} p_T R$

$\mu_C \sim p_T \tau^{\frac{1}{2}}$

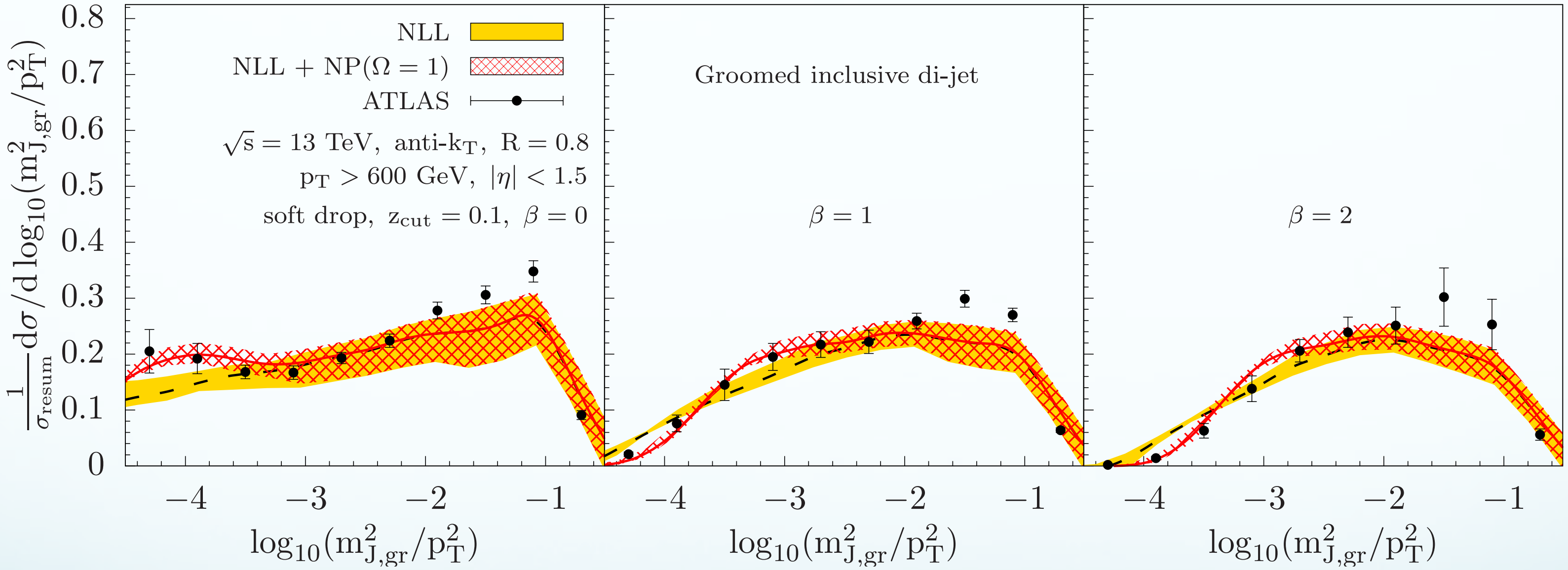
$\mu_S^{\rm gr} \sim p_T \left(\frac{z_{\rm cut}\tau^{1+\beta}}{R^\beta}\right)^{\frac{1}{2+\beta}}$



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

Comparison with data

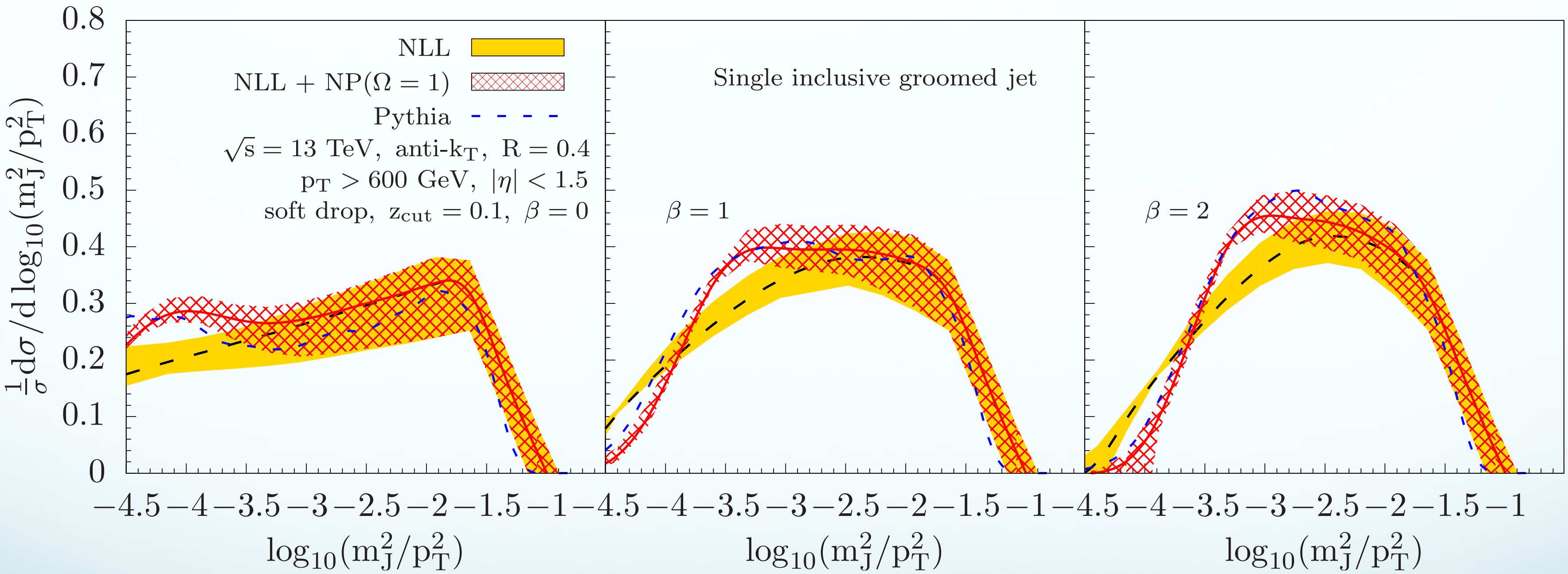
- Non-perturbative parameter: $\Omega = 1\mathrm{GeV}$
- Non-pertubative contribution is much reduced: only hadronization effect



Kang, Lee, Liu, Ringer, 1803.03645

Much reduced sensitivity of MPI

- Jets with different R: still same non-perturbative parameter



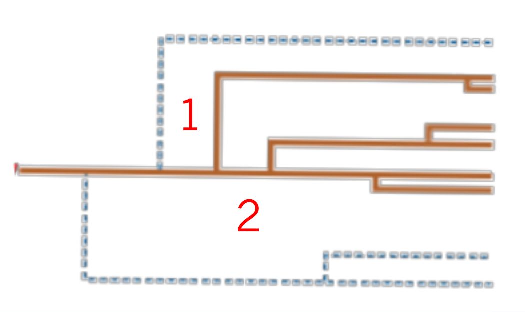
Groomed jet characteristics

- To characterize the groomed jet
  - Momentum sharing

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

  - Angular separation: groomed jet radius

$$R_g = \sqrt{(\Delta\eta_{12})^2 + (\Delta\phi_{12})^2}$$

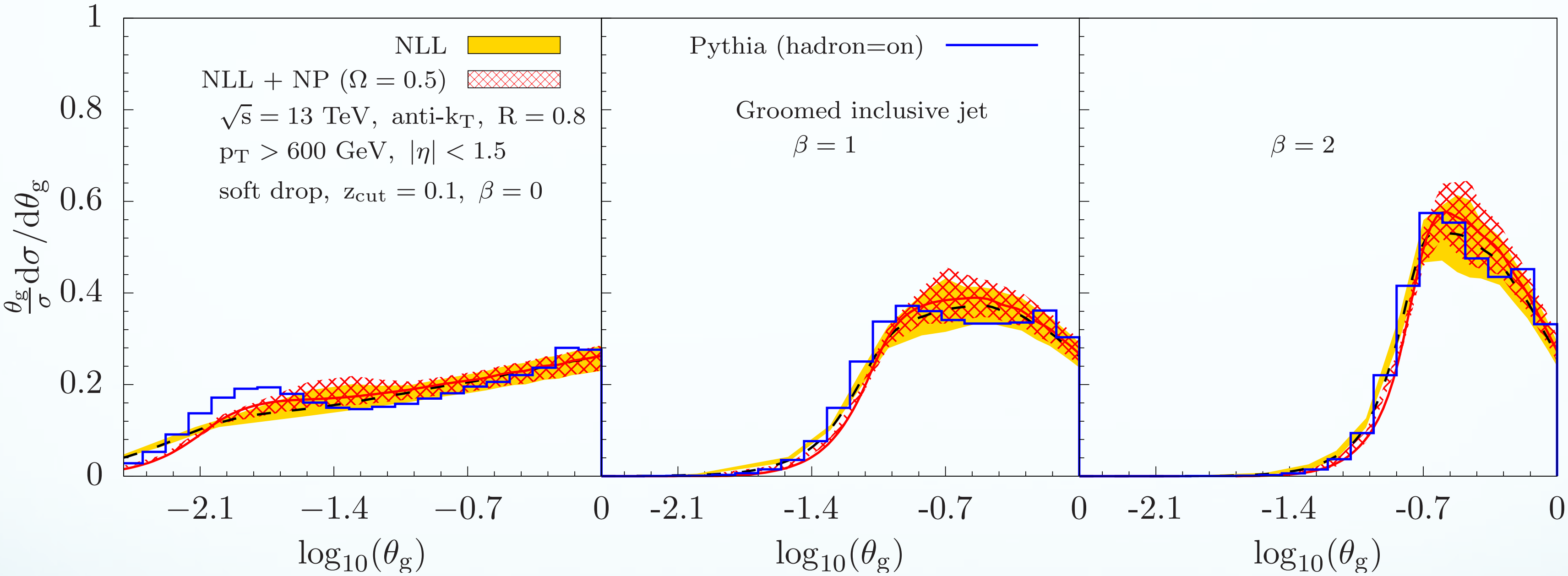


- Factorization for Rg distribution
  - Realizing Rg is the largest angular separation for groomed jet
  - Derive a factorization for cumulative distribution (any value below Rg contributes)
  - The distribution differential in Rg can be obtained through

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

Preliminary prediction at the LHC

- Compared with Pythia

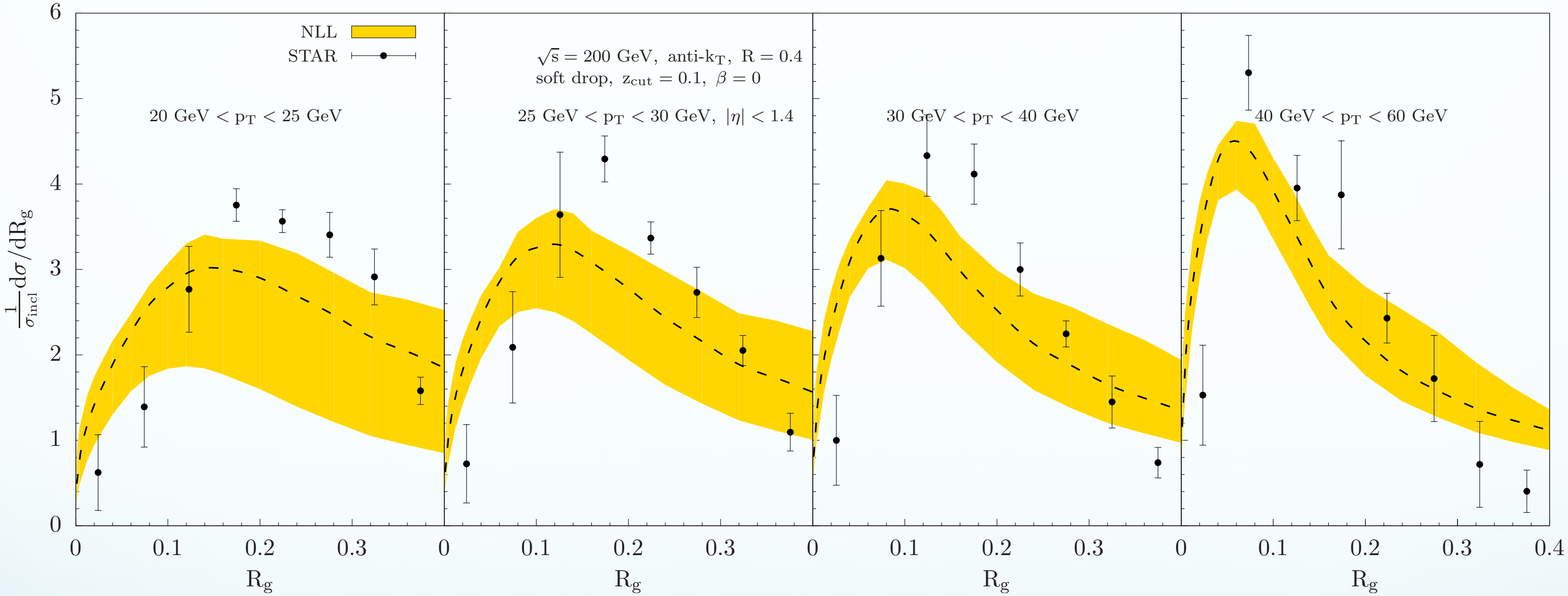


$$\theta_g = \frac{R_g}{R}$$

Kang, Lee, Liu, Ringer, 1903.xxxxx

Comparison with STAR data

- Preliminary comparison with STAR data (see Raghav’s talk)
  - Very promising
  - Smaller jet pT, thus larger uncertainty from scale variations



- Purely perturbative results (above), still testing non-perturbative contributions
  - For STAR, smaller jet pT, thus larger non-perturbative contributions

Summary

- A unified factorization formalism for study inclusive jets and jet substructure is introduced, through so-called semi-inclusive jet functions
    - Precision phenomenology using resummation
    - Jet substructure calculations from first principles
    - (un)groomed jet observables: jet fragmentation function, jet mass, groomed radius

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Thank you!