北京師範大學
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Soft-Dropped Rg

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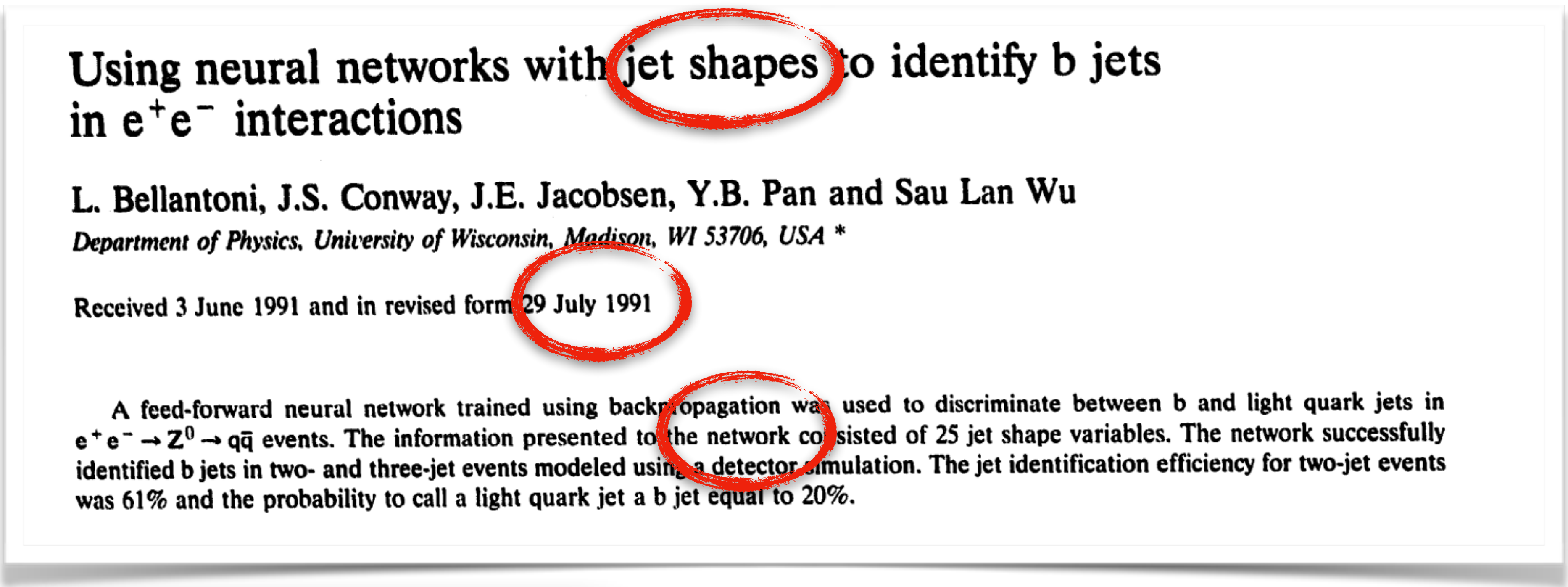
@IHEP 2019

Kang, Lee, XL, Neill and Ringer, 2019

Outline

- Status of jet substructure
- Soft Drop Rg-distribution
- Conclusions

A Long History



Using neural networks with jet shapes to identify b jets in e^+e^- interactions

L. Bellantoni, J.S. Conway, J.E. Jacobsen, Y.B. Pan and Sau Lan Wu
Department of Physics, University of Wisconsin, Madison, WI 53706, USA *

Received 3 June 1991 and in revised form 29 July 1991

A feed-forward neural network trained using backpropagation was used to discriminate between b and light quark jets in $e^+e^- \to Z^0 \to q\bar{q}$ events. The information presented to the network consisted of 25 jet shape variables. The network successfully identified b jets in two- and three-jet events modeled using a detector simulation. The jet identification efficiency for two-jet events was 61% and the probability to call a light quark jet a b jet equal to 20%.

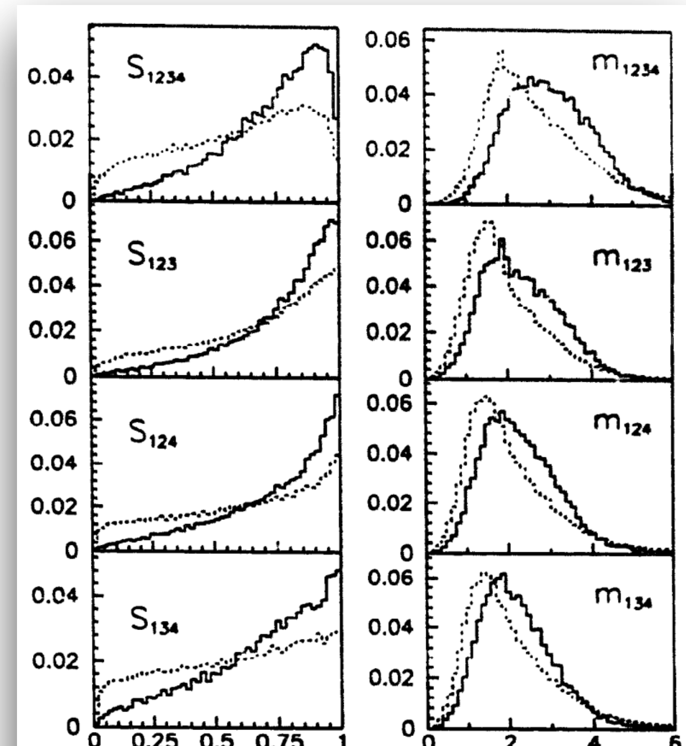


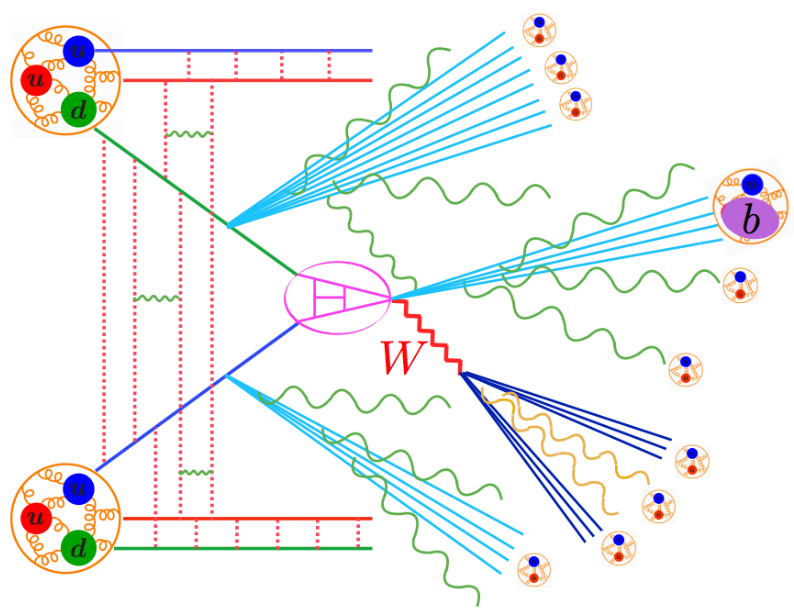
Fig. 2. Distribution of directed sphericity and mass for certain of the eleven track combinations used. Solid line is for b jets, dashed line is for light quark jets.

With all modern features:

- A clustering algorithm to construct jets
- Jet substructures instead of global event shapes
- Selected jet constitutes
- Use a " Modern" CS technique

A Long History

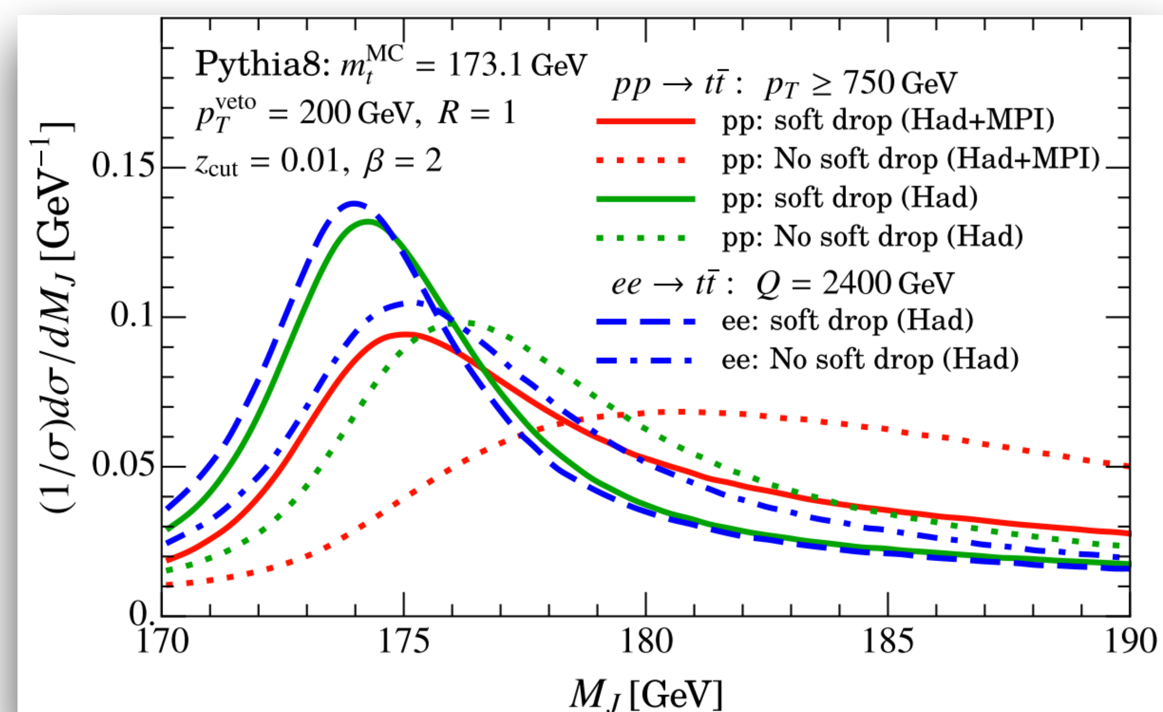
LHC is more complicated, probing regions from non-perturbative to TeV scales



Sensitivity to soft radiations

- Pile-ups/MPI···
- Non-Global Logarithms

distorts the (naive) expectations



A Long History

LHC is more complicated, probing regions from non-perturbative to TeV scales

kT type jet algorithms

$$d_{iB} = k_{i,T}^{2p} \qquad d_{ij} = \min(k_{i,T}^{2p}, k_{j,T}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2}$$

- If d_{iB} is the smallest, promote i as a jet and remove i from the event sample
- If d_{ij} is the smallest, merge i and j to ij
- Iterate

p=-1: anti-kT, p=1: kT, p=0 Cambridge/Archen

Smaller R less Pileups, less statistics

Larger R more Pileups, more statistics

Sensitivity to soft radiations

- Pile-ups/MPI$\cdots$
- Non-Global Logarithms

distorts the (naive) expectations

Grooming the Jet

- Re-cluster the jet
- Examine the jet list/clustering tree
- Groom the jet, remove evils!

Goals:

- Removing soft contaminations

Would be better if

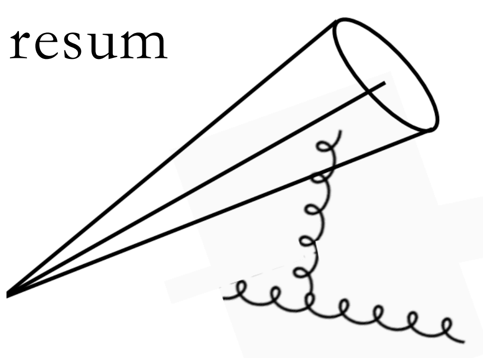
- First principle understanding
- Removing NGLs

Major theory tool for jet substructures: Res. but not FO

Wide angle soft only sees the overall direction of the collinear radiations, thus fully decoupled

NGLs due to the radiations near the jet boundary hard to resum

May not be wide any more for jet observables



Dasgupta, et al, hep-ph/0104277

Grooming the Jet

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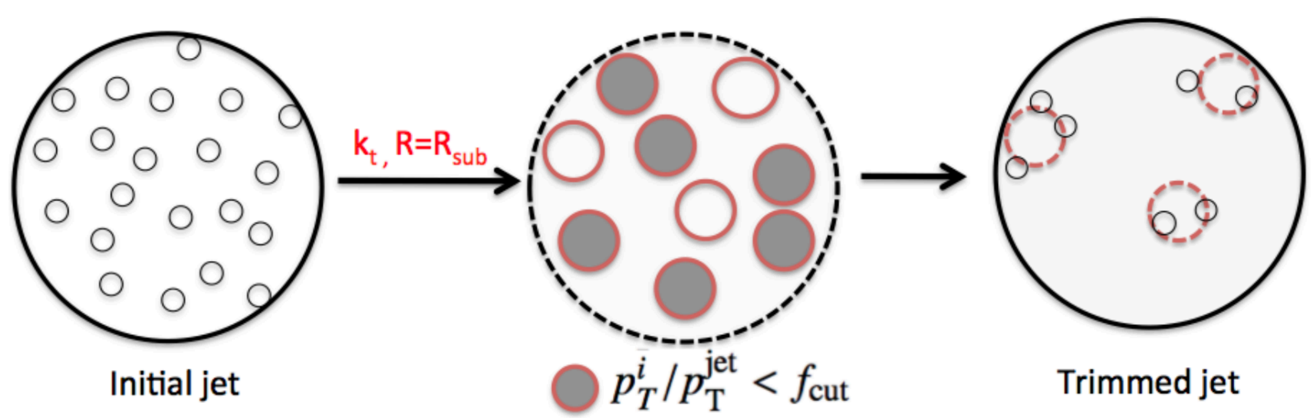
Trimming



- A pre-given angular parameter sets the boundary

Krohn et al. 0912.1342

Grooming the Jet

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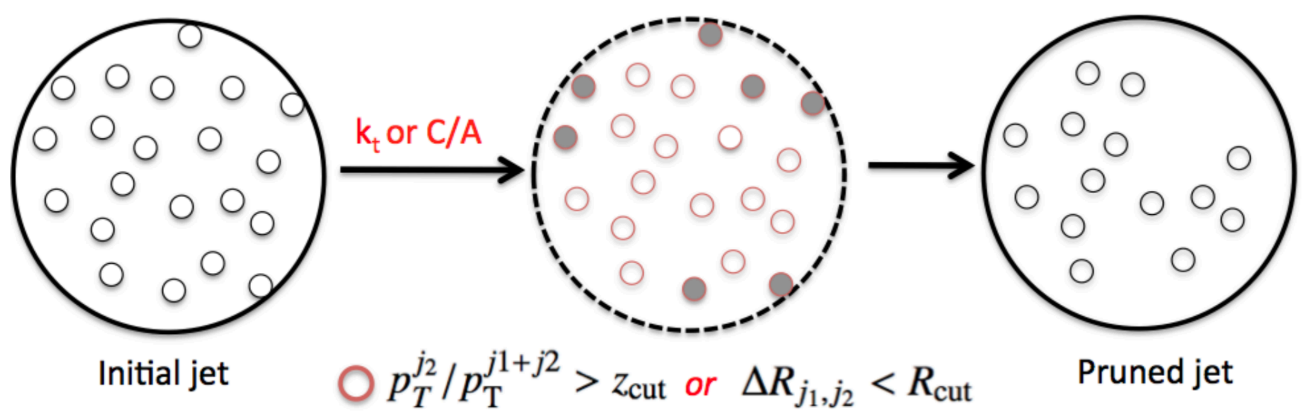
Pruning



- When merging, drop soft branches before clustering
- A pre-given angular parameter sets the boundary

Ellis et al. 0912.0033

Grooming the Jet

- Re-cluster the jet
- Examine the jet list/clustering tree
- Groom the jet, remove evils!

Goals:

- Removing soft contaminations

Would be better if

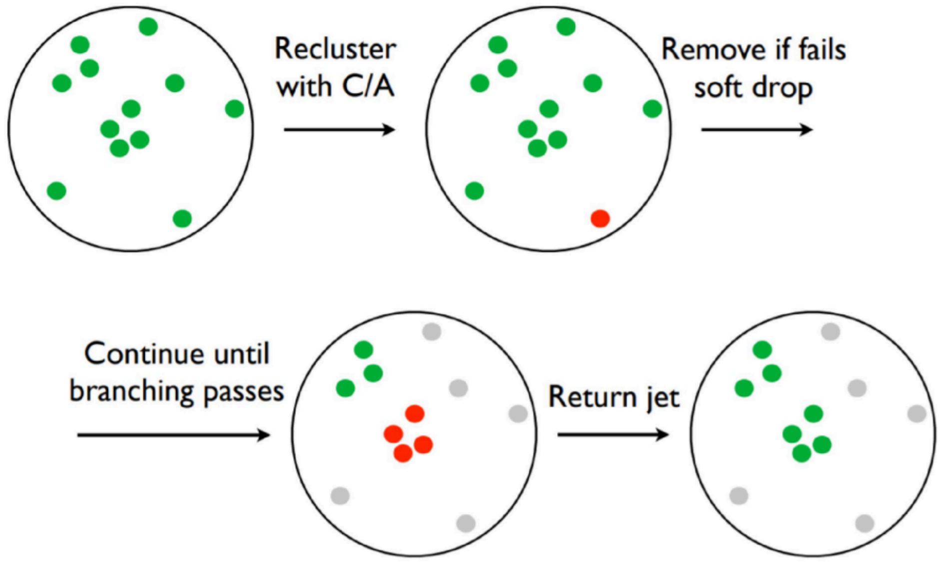
- First principle understanding ✓
- Removing NGLs

Soft Drop

- Reverse the clustering tree, dropping branches that are too soft.
- When both branches are hard enough, that is the groomed jet

$$z = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}}, \qquad \theta \equiv \frac{R_{12}}{R} \qquad z > z_{\rm cut}\theta^\beta$$

- Start with the largest angular separations, decreasing angular scale as we de-cluster
- No pre-given angular parameter (~ inclusive), but force an inclusive collinear limit dynamically



Larkoski, et al. 1402.2657

Grooming the Jet

- Re-cluster the jet
- Examine the jet list/clustering tree
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Goals:

- Removing soft contaminations

Would be better if

- First principle understanding ✓
- Removing NGLs ✓

Soft Drop

- Reverse the clustering tree, dropping branches that are too soft.
- When both branches are hard enough, that is the groomed jet

$$z = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}}, \qquad \theta \equiv \frac{R_{12}}{R} \qquad z > z_{\text{cut}}\theta^{\beta} \qquad \mathcal{M} \ll R$$ = norm. inclusive jet shape

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{M}} = \sum_{ijk} f_i f_j\, H_{ij}^k[Q, R, z_{cut}] \otimes \mathcal{J}_k[\mathcal{M}, p_T, z_{cut}, \beta]$$

~ Collinear factorization just like a fragmentation function

Soft Drop

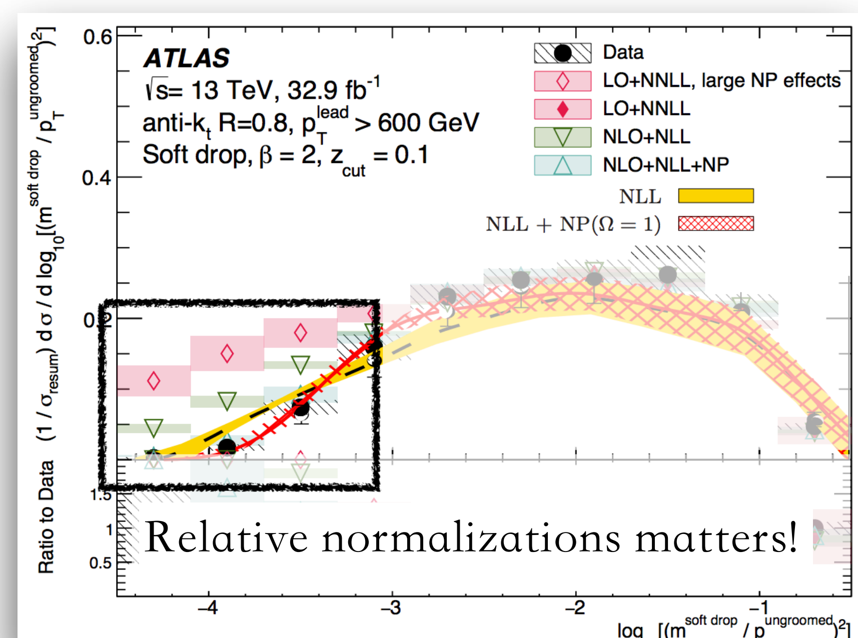
- Reducing soft contaminations
- First principle understanding
- Absence of NGLs (claim)
  - Precision physics using jet!
  - e.g. NNLO + N^{X}LL v.s. LHC data for α_s extraction? removing NP by soft drop?

$$\frac{d\sigma}{d\mathcal{M}} = \sum_{ijk} f_i f_j H_{ij}^k[Q, R, z_{cut}] \otimes \mathcal{J}_k[\mathcal{M}, p_T, z_{cut}, \beta]$$

NGLs　　　no NGLs

Too optimistic ?

- NGLs in the normalizations for individual partonic channels
- Make it hard to go beyond NLL



Frye et al, '16 (global soft drop, restrictedly dijet)

Marzani, et al '17 (restrictedly dijet, NLO normalization from matching)

Kang, Lee, XL, Ringer, '18 (inclusive jet, NLO normalization encoded)

Nachman, Boost 18

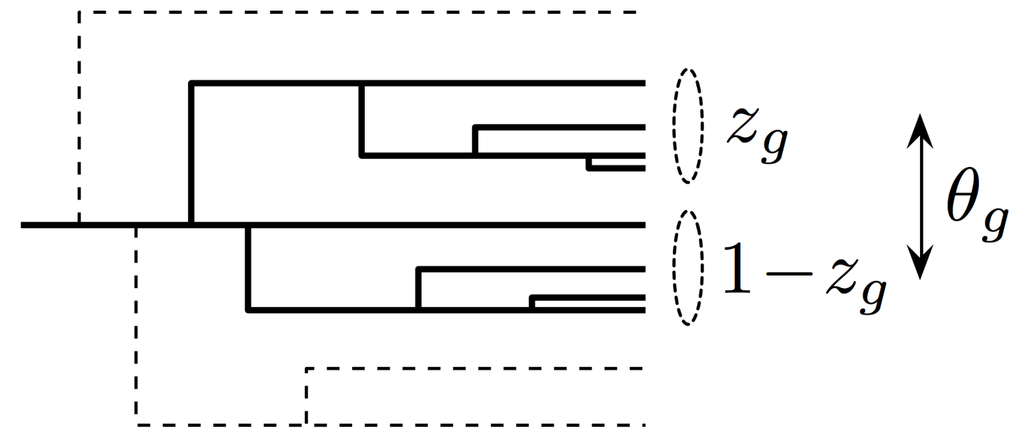
Soft Drop

- R_g and z_g
- z_g probes the splitting kernel
- R_g is a necessary input for z_g
  - Both will shed lights on the modification of jets in heavy ions

$$p(z_g) = \frac{1}{\sigma}\frac{d\sigma}{dz_g} = \int dr_g\, p(r_g)\, p(z_g|r_g)$$

$$p(z_g|r_g) = \frac{\overline{P}_i(z_g)}{\int_{z_{\rm cut} r_g^\beta}^{1/2} dz\, \overline{P}_i(z)} \Theta(z_g - z_{\rm cut} r_g^\beta)$$

$$\overline{P}_i(z) = \sum_{j,k} \left[P_{i\to jk}(z) + P_{i\to jk}(1-z)\right].$$



$$z_g = \frac{\min[p_{T1}, p_{T2}]}{p_{T1}+p_{T2}}, \qquad \theta_g = \frac{\Delta R_{12}}{R}$$

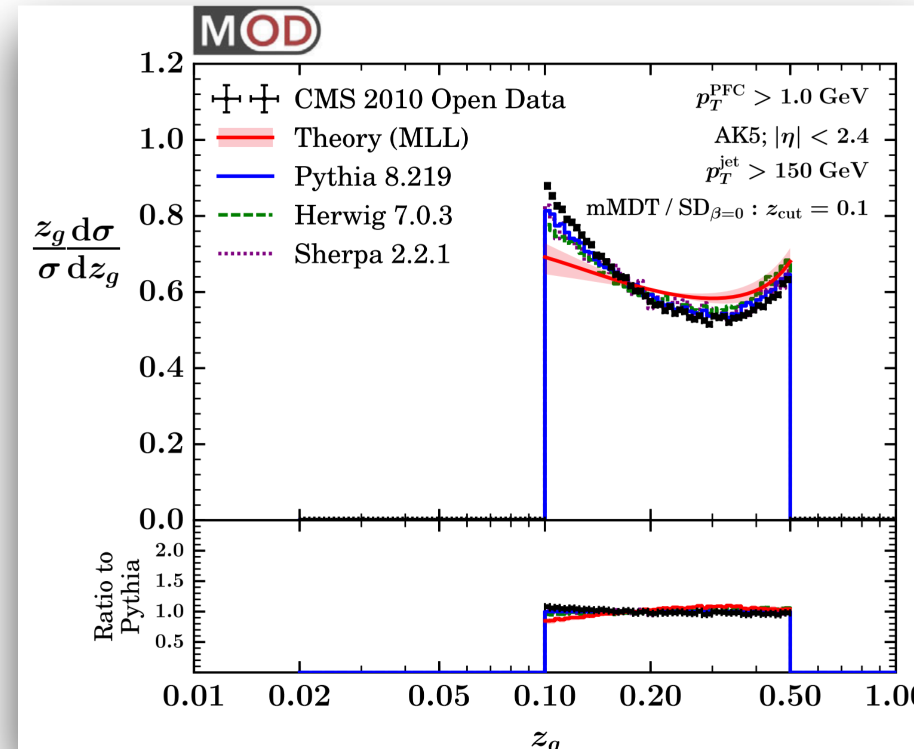
z_g is not well-defined for 1-prong, i.e. Rg = 0, uncanceled poles in FO.

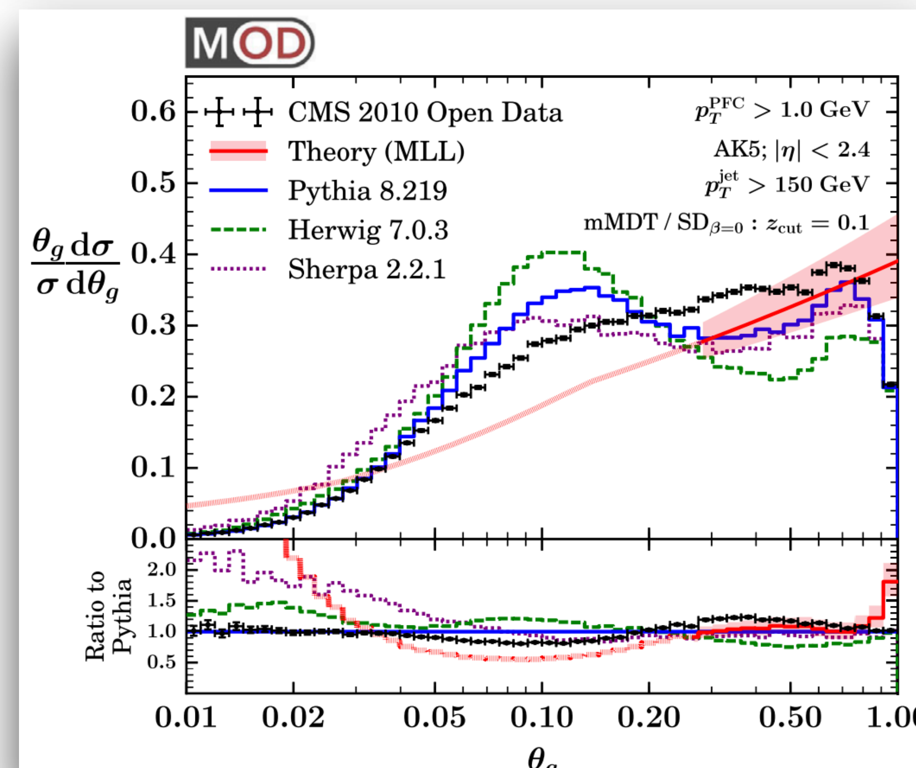
Use Resummed R_g distribution, which vanishes as $R_g > 0$, to regulate the poles.

When β = 0, probes directly the splitting kernels

Soft Drop

- R_g and z_g
- z_g probes the splitting kernel
- R_g is a necessary input for z_g
    - Both will shed lights on the modification of jets in heavy ions





MLL = $\alpha_s^n L^{2n-q}$, q=0,1

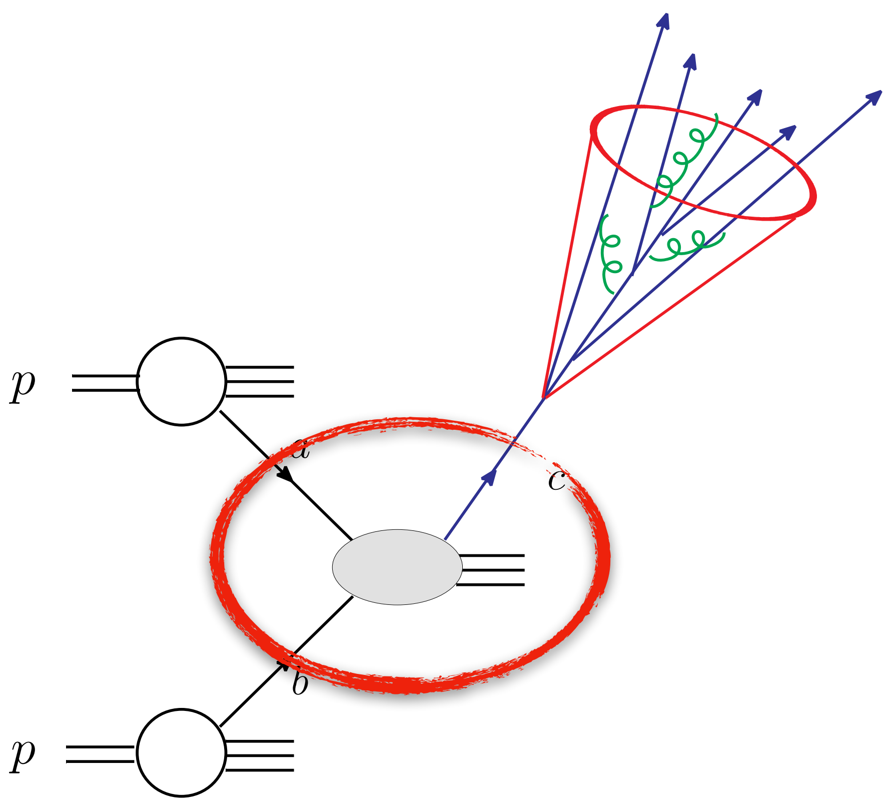
MLL is not good in describing the data nor the Monte Carlo simulation

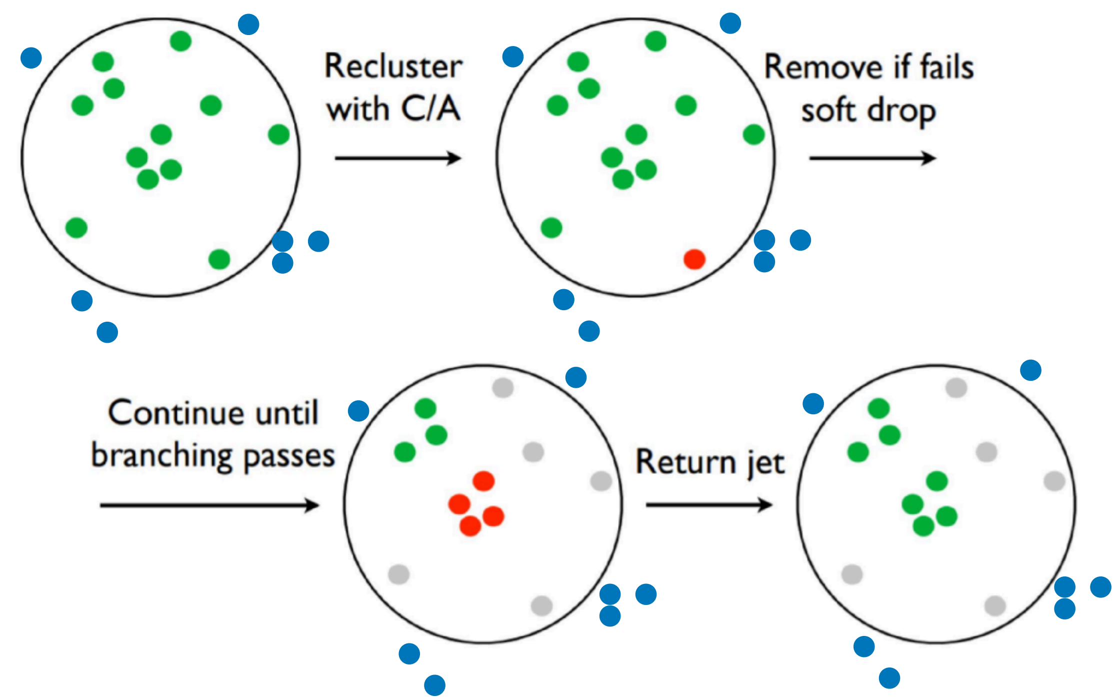
We need to go beyond

MB. Data with detector effects

Soft Dropped R_g @ NLL

Determine the modes (inclusive jet production with $R << 1$, $R_g << R$, $z_{cut} << 1$)



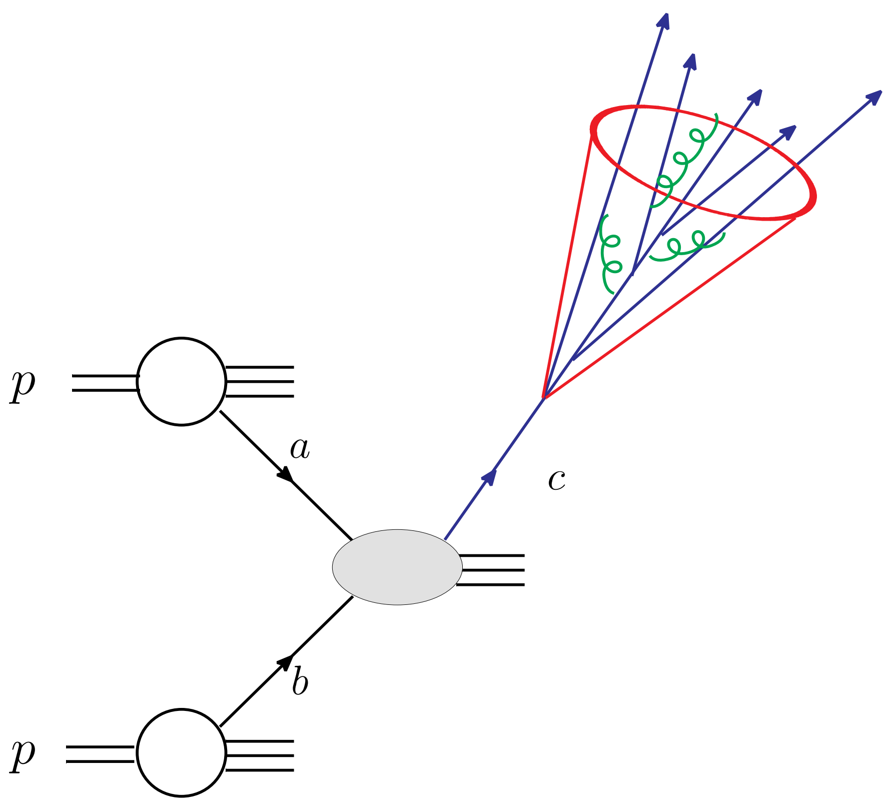


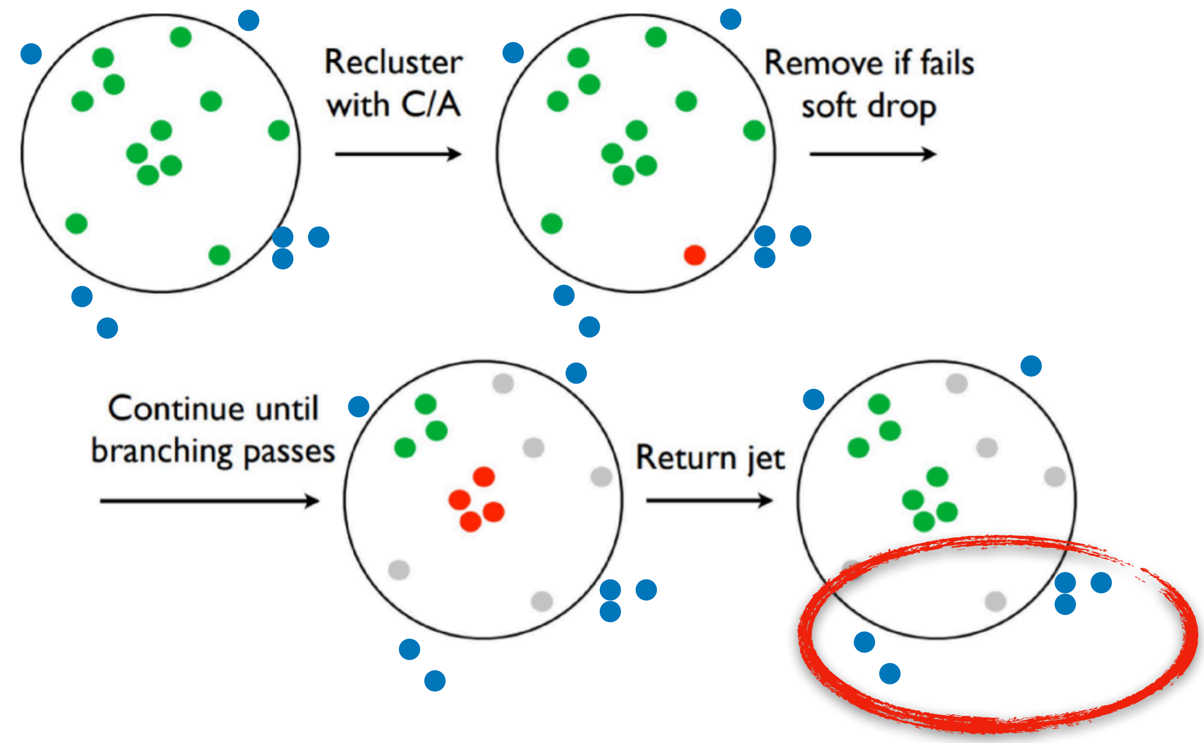
Hard mode: $m^2 \sim p_T^2$, x-sec to produce a parton = partonic x-sec for hardon

Different from di-jet, not only loops but real emissions encoded

Soft Dropped R_g @ NLL

Determine the modes (inclusive jet production with $R << 1$, $R_g << R$, $z_{cut} << 1$)



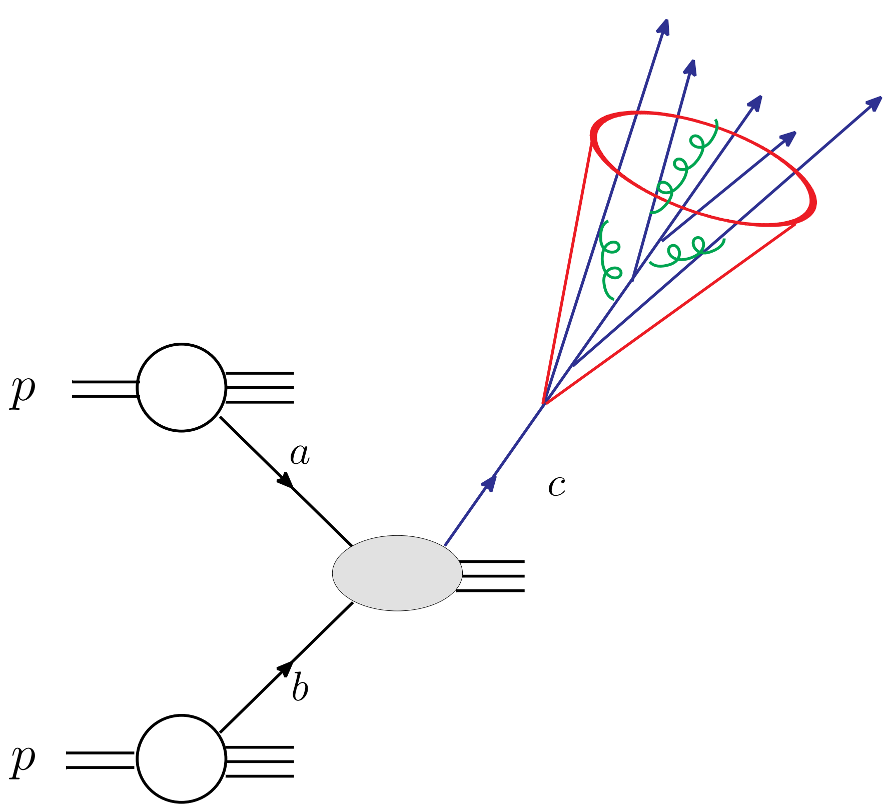


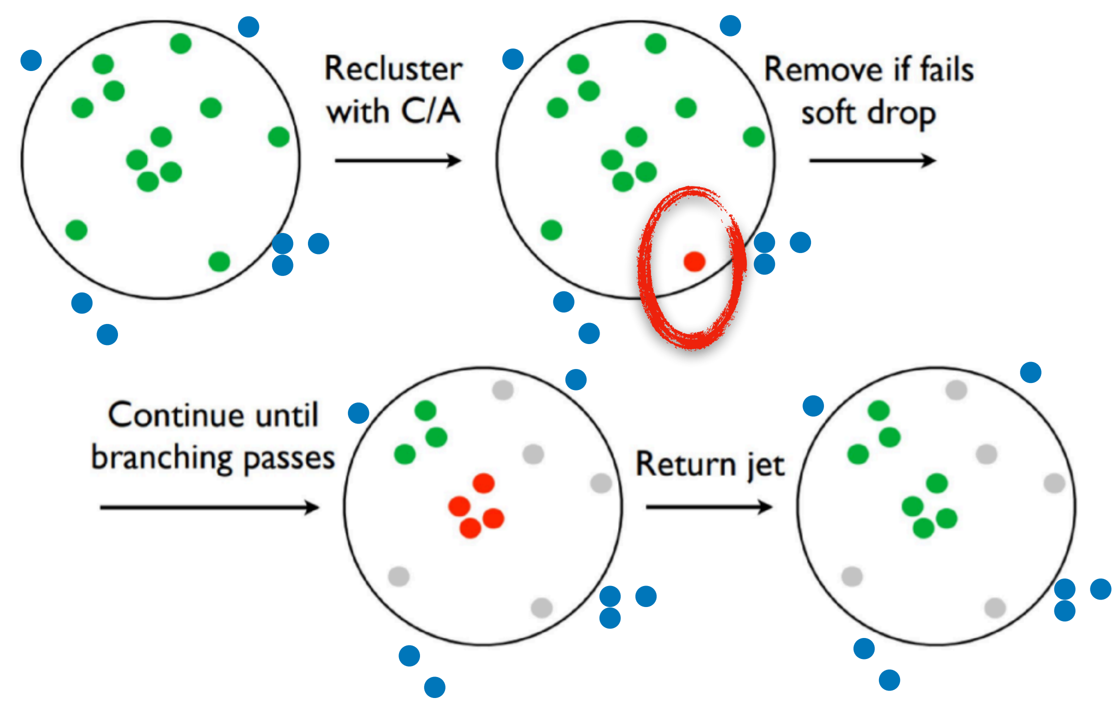
Hard mode: $m^2 \sim p_T^2$, x-sec to produce a parton = partonic x-sec for hardon

Hard Collinear mode: $m^2 \sim (p_T R)^2$, out-side the jet but near the jet boundary

Soft Dropped R_g @ NLL

Determine the modes (inclusive jet production with $R << 1$, $R_g << R$, $z_{cut} << 1$)





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Hard Collinear mode: $m^2 \sim (p_T R)^2$, out-side the jet but near the jet boundary

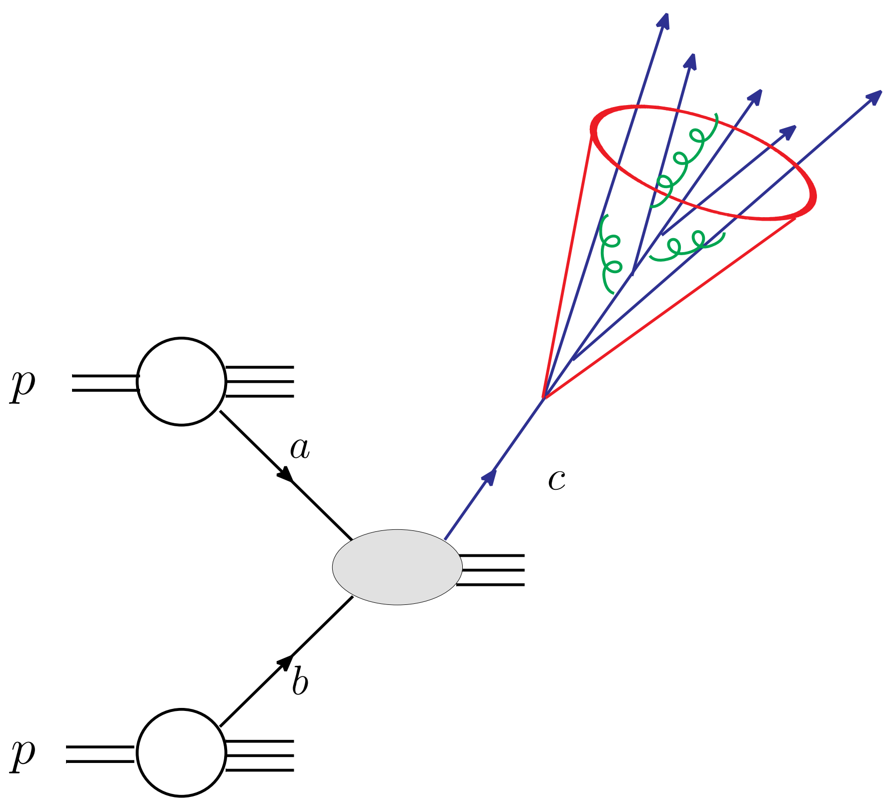
Groomed-soft mode: $p \sim z_{cut}\, p_T\, (1,R,R^2)$, always fails the soft drop, can not resolve R_g

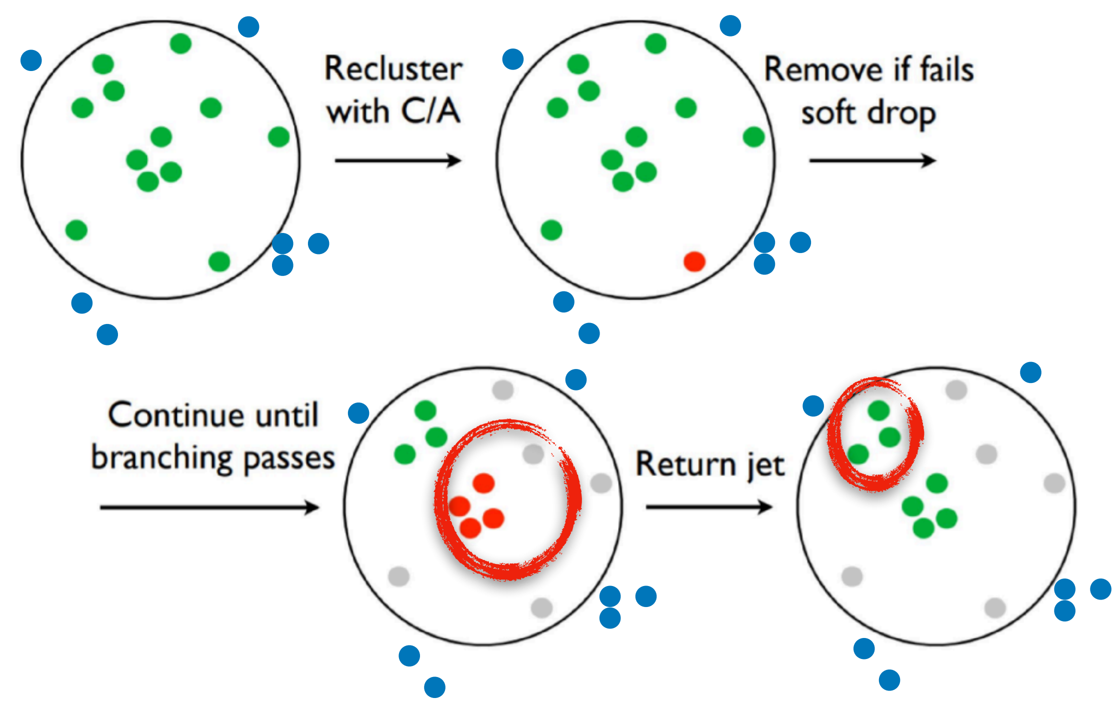
All these modes contribute to the normalization only

Universal, NGLs in H-C + G-S

Soft Dropped R_g @ NLL

Determine the modes (inclusive jet production with $R << 1$, $R_g << R$, $z_{cut} << 1$)





Collinear mode: $p \sim p_T\,(1, R_g, R_g^2)$, always pass the soft drop

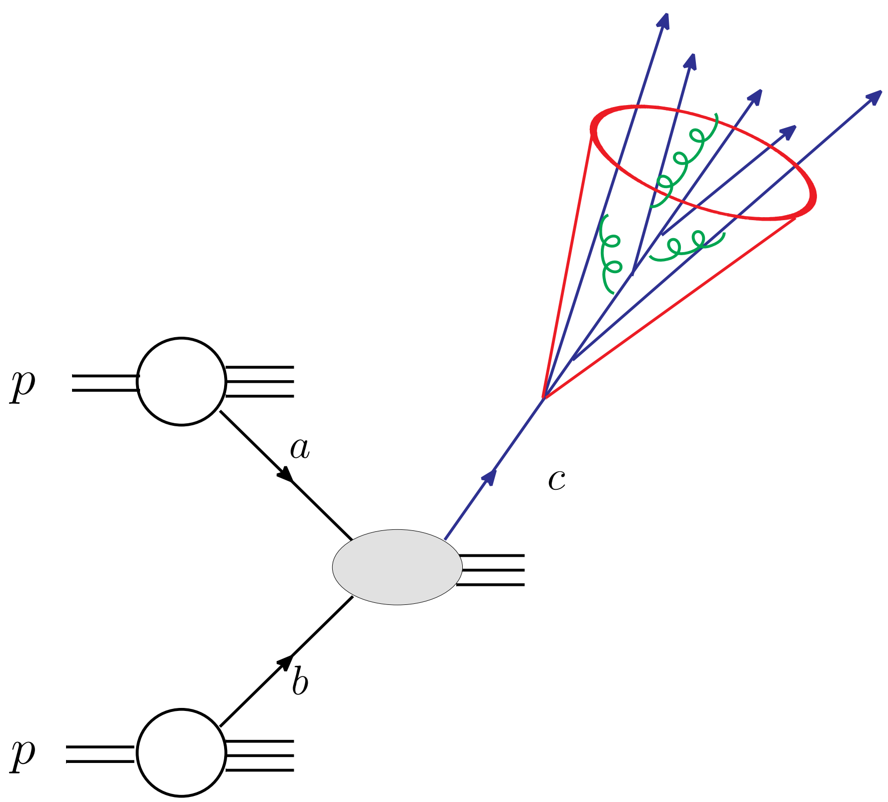
Collinear-soft mode: $p \sim z_{cut}\, p_T\,(1, R_g, R_g^2)$, may or may not pass the soft drop

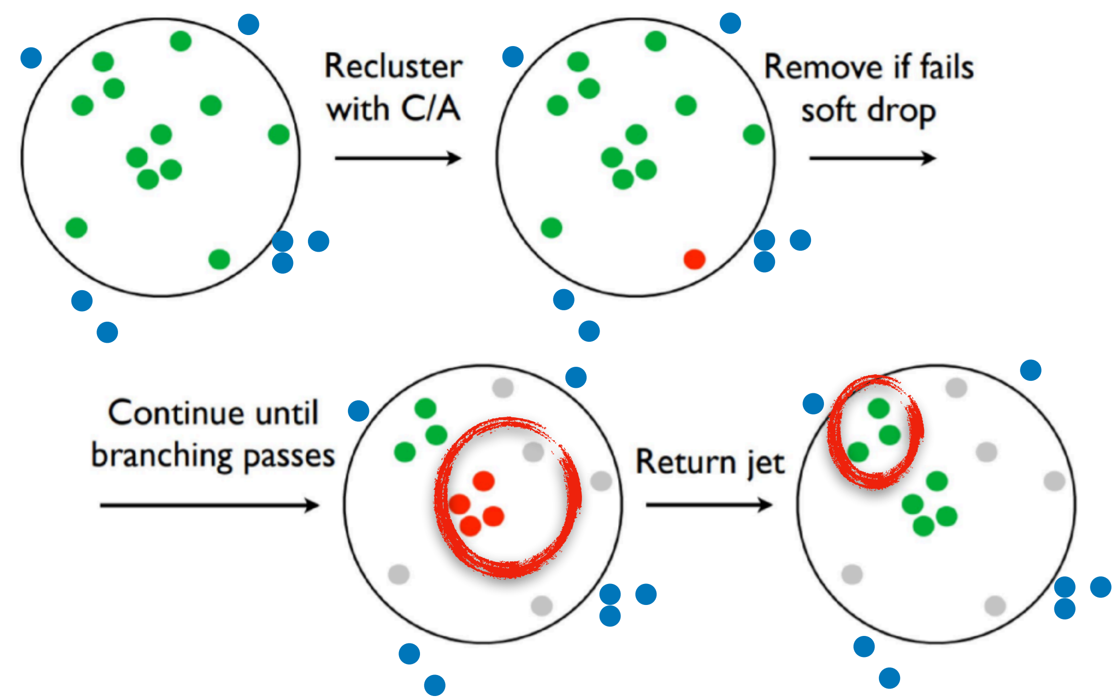
Modes contribute to the distribution

For R_g, C-S and C modes have the same angular separation

Soft Dropped R_g @ NLL

Determine the modes (inclusive jet production with $R << 1$, $R_g << R$, $z_{cut} << 1$)





Collinear mode: $p \sim p_T\,(1, R_g, R_g^2)$, always pass the soft drop

Collinear-soft mode: $p \sim z_{cut}\, p_T\,(1, R_g, R_g^2)$, may or may not pass the soft drop

Only the C-S mode will test against the Soft Drop criterion
But it can be shown equivalent to jet veto

Soft Dropped R_g @ NLL

Measurements for c-soft mode

$$z = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}}, \qquad \theta \equiv \frac{R_{12}}{R} \qquad z > z_{\rm cut}\theta^\beta$$

1 c-soft prong:

$$\mathcal{M}_1(J_1) = \Theta(\theta_{J_1,J} < R_g)\Theta(J_1 p) + \Theta(J_1 f)$$

$$= \Theta(\theta_{J_1,J} < R_g) + \Theta(\theta_{J_1,J} > R_g)\Theta(J f)$$

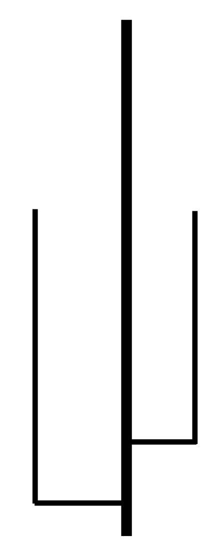
2 c-soft prongs:

$$\mathcal{M}_2 = \sum_{\rm perm.} \Theta(J_2)\left[\mathcal{M}_1(J_1)\,\mathcal{M}_1(J_2 f) + \mathcal{M}_1(J_2 p)\right]$$

$$= \sum_{\rm perm.} \Theta(J_2)\left[\mathcal{M}_1(J_1)\,\mathcal{M}_1(J_2) + \mathcal{M}_1(J_2 p)(1 - \mathcal{M}_1(J_1))\right]$$

$$= \mathcal{M}_1(J_1)\,\mathcal{M}_1(J_2)\,,$$

$$1 - \mathcal{M}_1 = \Theta(\theta_{J_1,J} > R_g)\Theta(J_1 p)$$



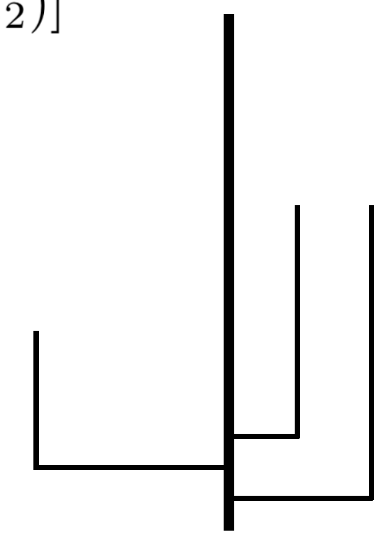
Soft Dropped R_g @ NLL

Measurements for c-soft mode

$$z = \frac{\min[p_{T1}, p_{T2}]}{p_{T1}+p_{T2}}, \qquad \theta \equiv \frac{R_{12}}{R} \qquad z > z_{\rm cut}\theta^\beta$$

3 c-soft prongs:

$$\begin{aligned}\mathcal{M}_3 &= \sum_{\text{perm.}} \Theta(J_3)\,[\mathcal{M}_2\,\mathcal{M}_1(J_3 f) + \mathcal{M}_1(J_3 p)] \\ &= \sum_{\text{perm.}} \Theta(J_3)\,[\mathcal{M}_2\,\mathcal{M}_1(J_3) \;+\; \mathcal{M}_1(J_3 p)(1-\mathcal{M}_2)] \\ &= \mathcal{M}_1(J_1)\,\mathcal{M}_1(J_2)\mathcal{M}_1(J_3)\,,\end{aligned}$$



N c-soft prongs:

$$\mathcal{M}_N = \prod_i^N \mathcal{M}_1(J_i)$$

Soft drop ~ jet veto within the jet, if R_g is measured

Soft Dropped R_g @ NLL

Soft drop ~ jet veto within the jet, if R_g is measured

We know how to do NLL resummation

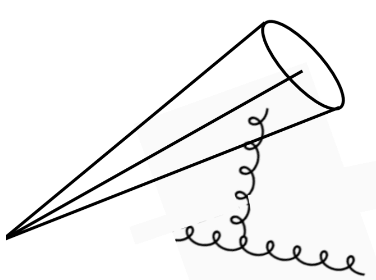
$$\frac{d\sigma}{d\mathcal{M}} = \sum_{ijk} f_i f_j \, H_{ij}^k[Q, R, z_{cut}] \otimes \mathcal{J}_k[\mathcal{M}, p_T, z_{cut}, \beta]$$

$$\Sigma(R_g) \sim f_i f_j \, \hat{\sigma}_{ij}^c \, \mathcal{H}_{c\to k}(p_T R) \, S_k^{\notin gr}(z_{cut} p_T R) \, C_k(p_T R_g) \, S_{Coll,k}(\text{soft drop jet veto})$$

by solving RGE for each function

NGL + Clustering effects by Monte Carlo simulation

NGLs in the distribution now



$\sim \alpha_s^2 \log^2(z_{cut})$

C/A clustering effect breaks the (naive) factorization

$$\Theta_1(k) + [\Theta(\theta_{k,n_2} - \theta_{k,n_1})\Theta(\theta_{n_1,n_2} - \theta_{k,n_1}) + \Theta(\theta_{k,n_1} - \theta_{k,n_2})\Theta(\theta_{n_1,n_2} - \theta_{k,n_2})]\,[1 - \Theta_1(k)]$$

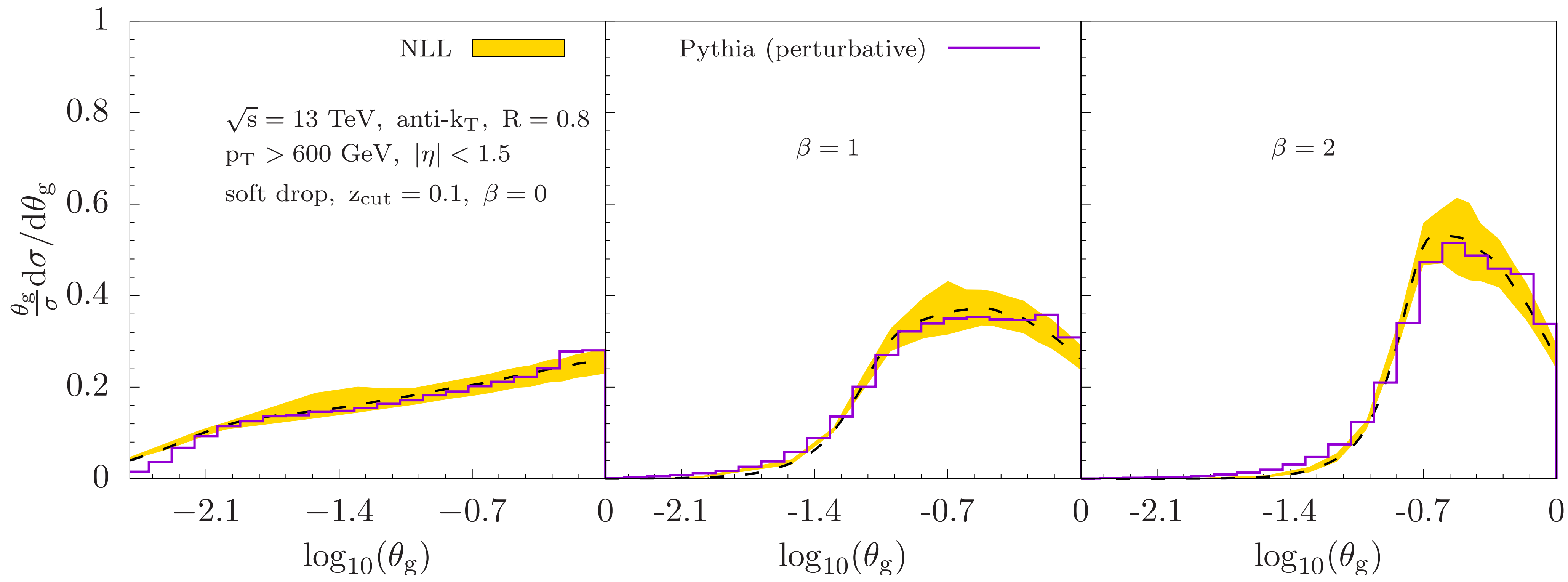
SD on a c-s radiation k

Corrections due to clustering

$\sim \alpha_s^2 \log^2(z_{cut})$

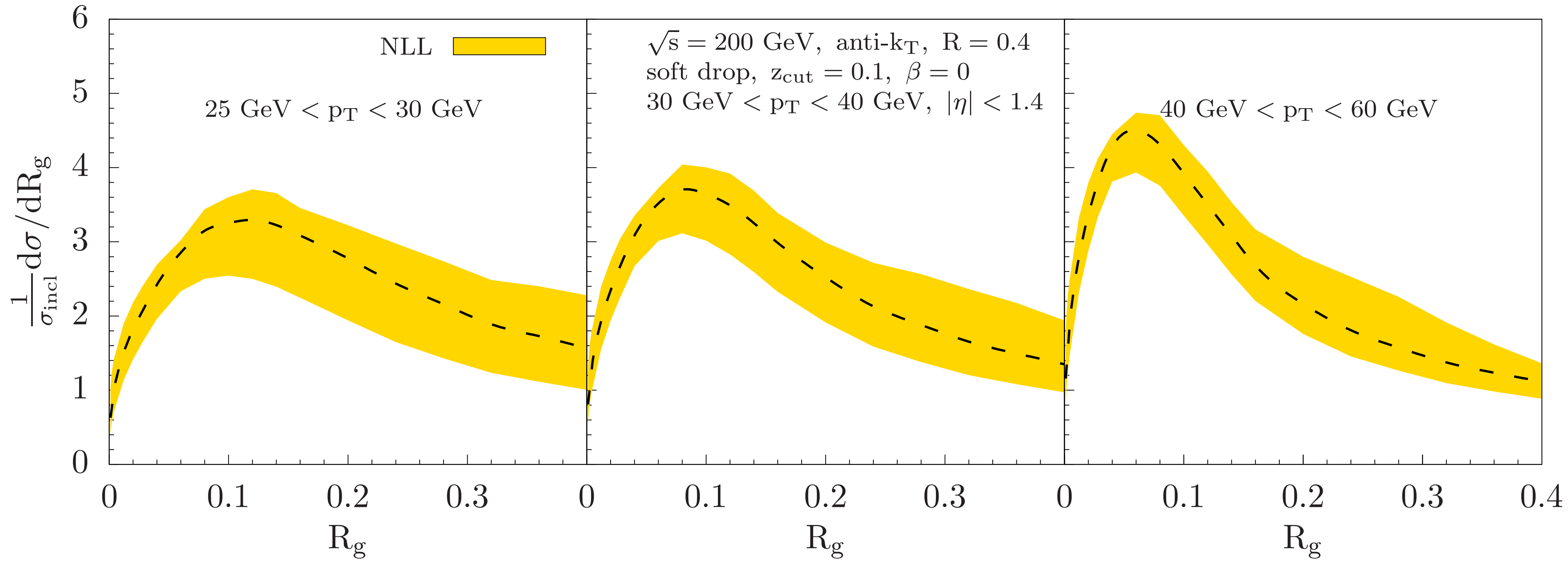
Small coefficient due to limited space

Soft Dropped R_g @ NLL



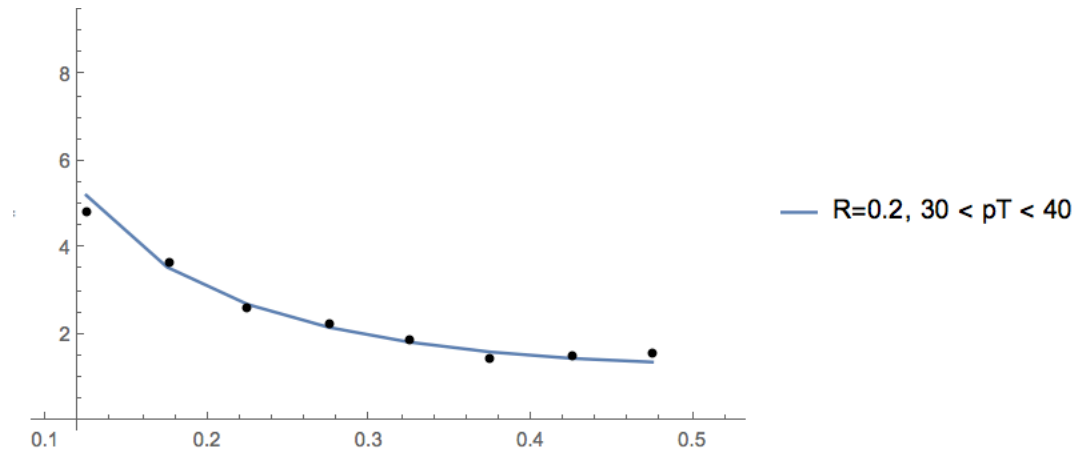
Comparison with Pythia

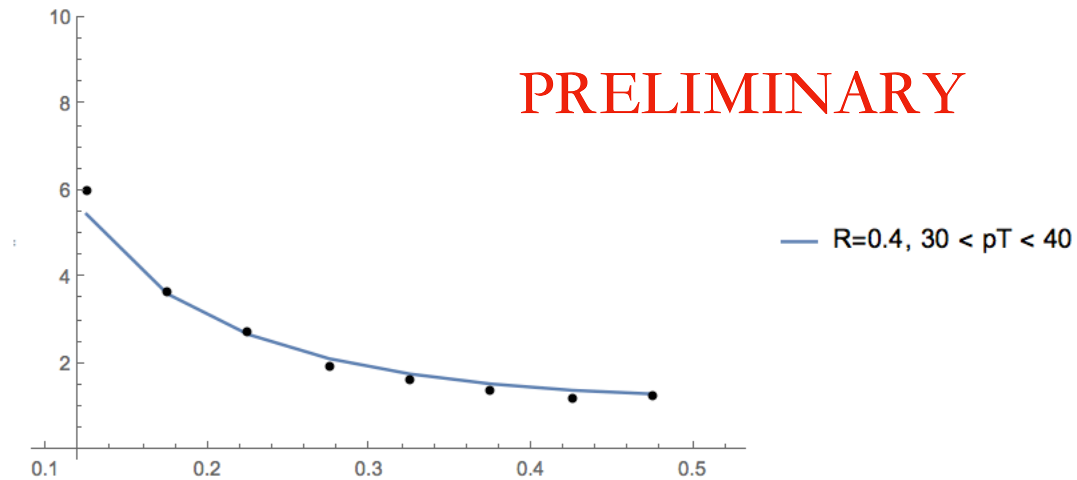
Soft Dropped R_g @ NLL

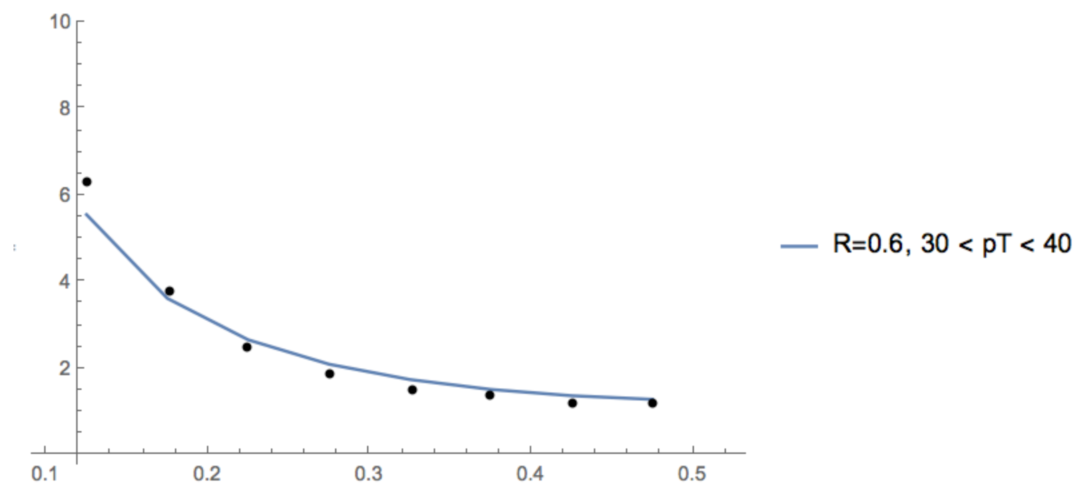


Predictions for STAR

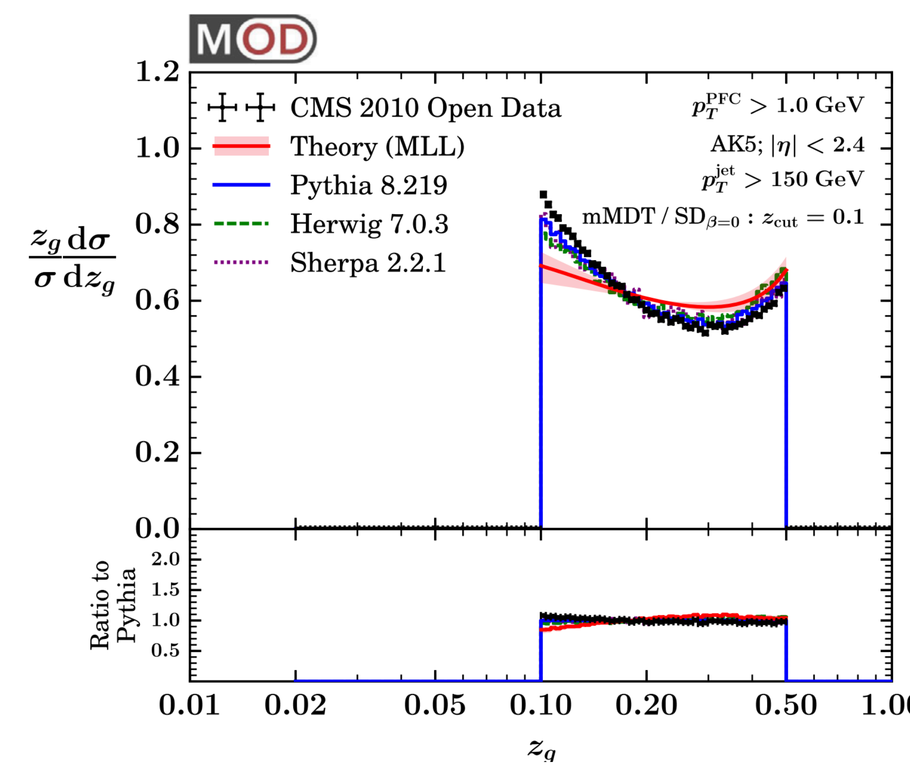
Soft Dropped R_g @ NLL







z_g distribution with STAR data



Conclusions

- Soft drop grooming draws extensive attentions
- MLL does not agree well with the data and the Monte Carlo simulations
- NLL improves the agreement with Pythia and data. Expect to see more comparisons with the data in the near future
- Go beyond for future LHC precision measurements

Thanks