Heavy flavour JSS with SoftDrop

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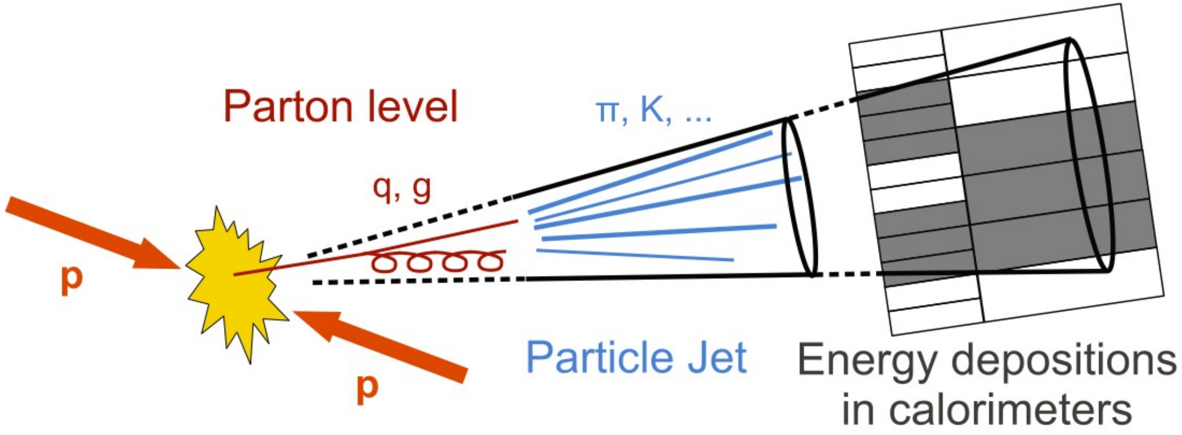
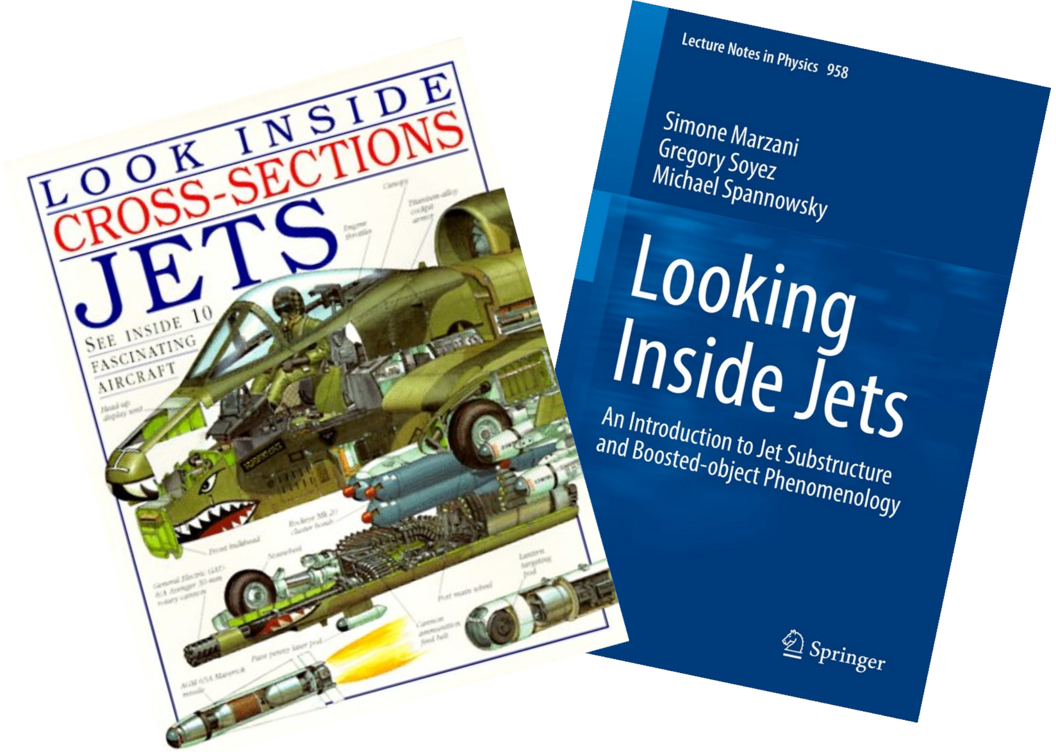
What's a jet?

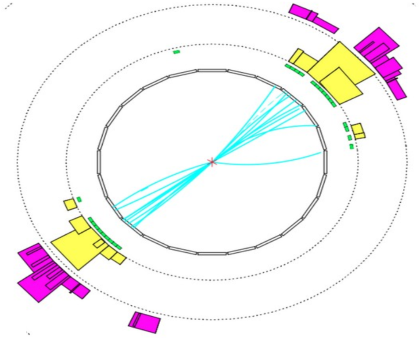




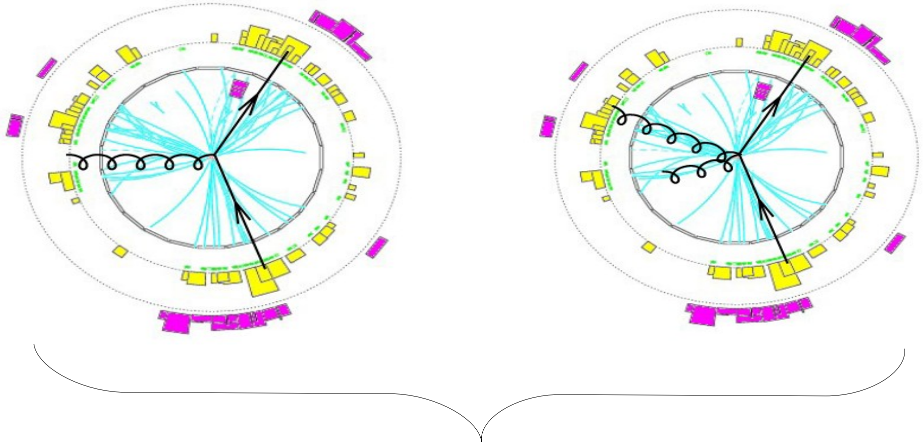
Naive definition: **collimated spray of hadrons**, ubiquitous in collider experiments, associated with the production of elementary particles that carries color charge

> *The design of good jet algorithms is therefore more a craft than a deductive science.*

Banfi, Salam, Zanderighi (flavour-kt paper)



clearly a 2-jet event



3-jet or 4-jet event?

Gen-k_t recombination algorithms

- Take the particles in the events as our initial list of objects.
- From this list build the *inter-particle distance* as

$$d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right)\Delta_{ij}^2$$

where we introduced

$$\Delta_{ij} = \sqrt{(\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2}$$

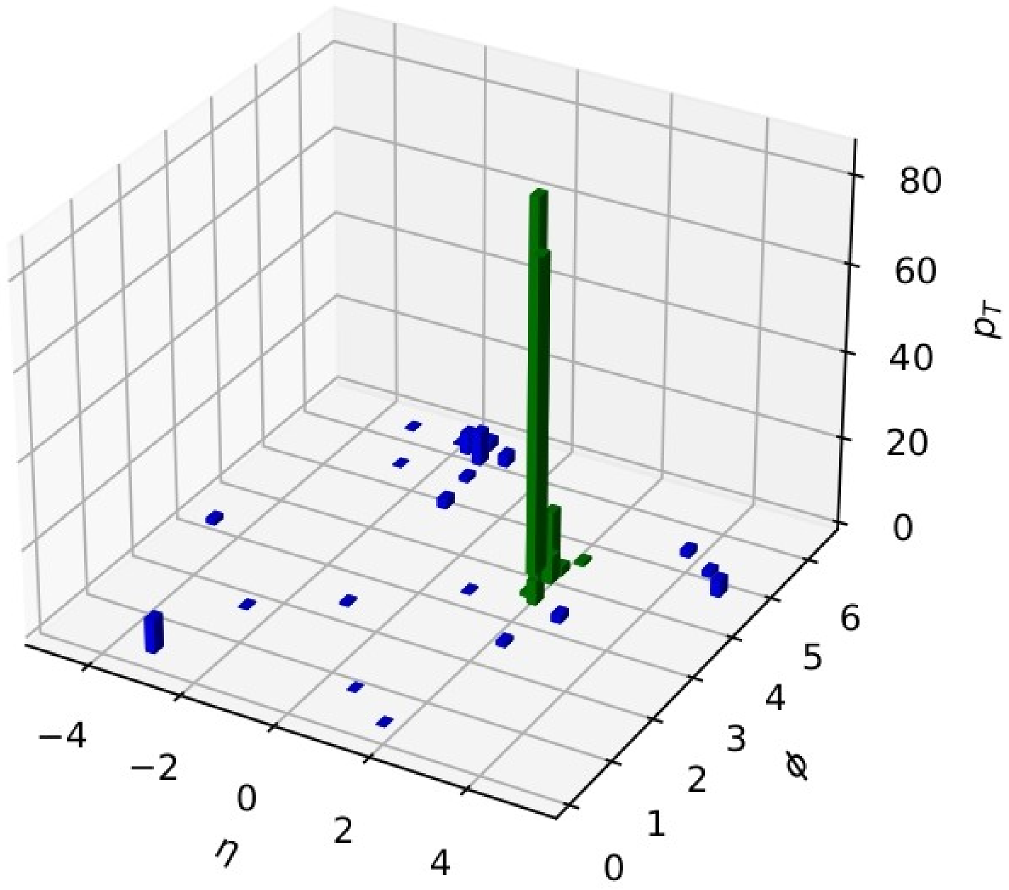
and the *beam distance* as

$$d_{B,i} = p_{T,i}^{2p} R^2$$

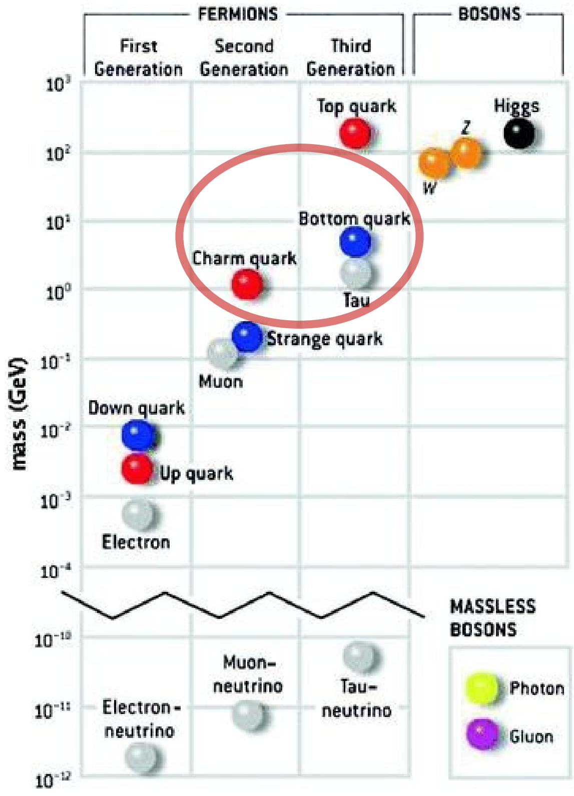
with R the jet radius.

- Iteratively find the smallest among all the two distances:
  - If $d_{ij} < d_{B,i}$ then remove i and j and recombine them into a new object k which is added to the new list.
  - If $d_{B,i} < d_{ij}$ then it is called a *jet* and removed from the list.

while(! list is empty)



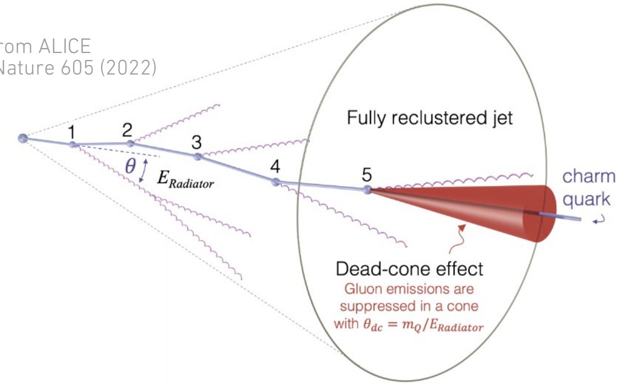
Why Heavy Flavour? Why JSS?



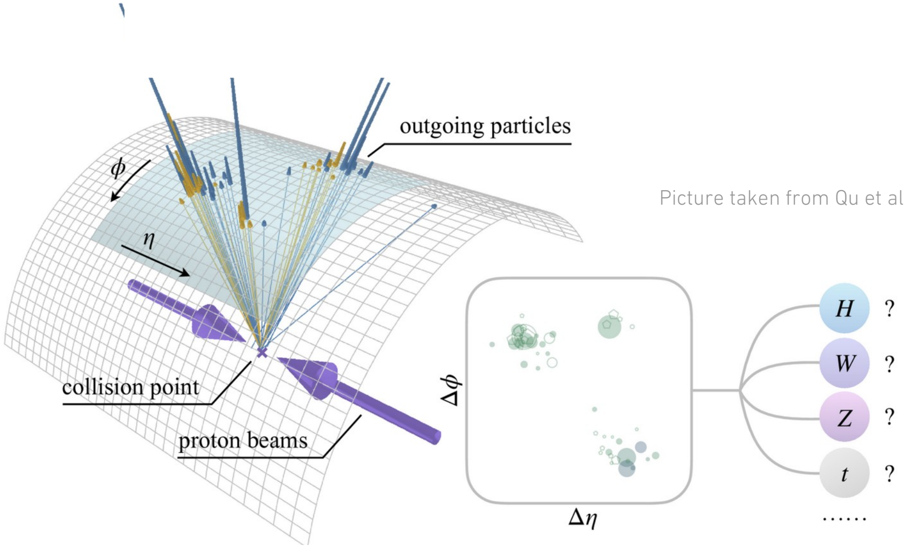
We can study heavy quark properties:

- looking at SD z_g we can directly probe HQ splitting functions
- looking at SD ϑ_g we can directly see the dead-cone effect

Picture taken from ALICE Collaboration, Nature 605 (2022) 440-446



$$\alpha_S \int \frac{d\theta^2}{\theta^2 + \frac{m^2}{Q^2}} \sim \alpha_S \log \frac{m^2}{Q^2}$$



Picture taken from Qu et al (2024)

Processes with HQ allow to:

- probe intrinsic flavour components of the proton, mostly charm [NNPDF collaboration (2022)]
- Explore physics of hadronization processes at an intermediate scale between the top quark (no hadronization) and light quarks.
- Constraint s-quark PDF in W+c-jet production at the LHC

Grooming: Soft Drop

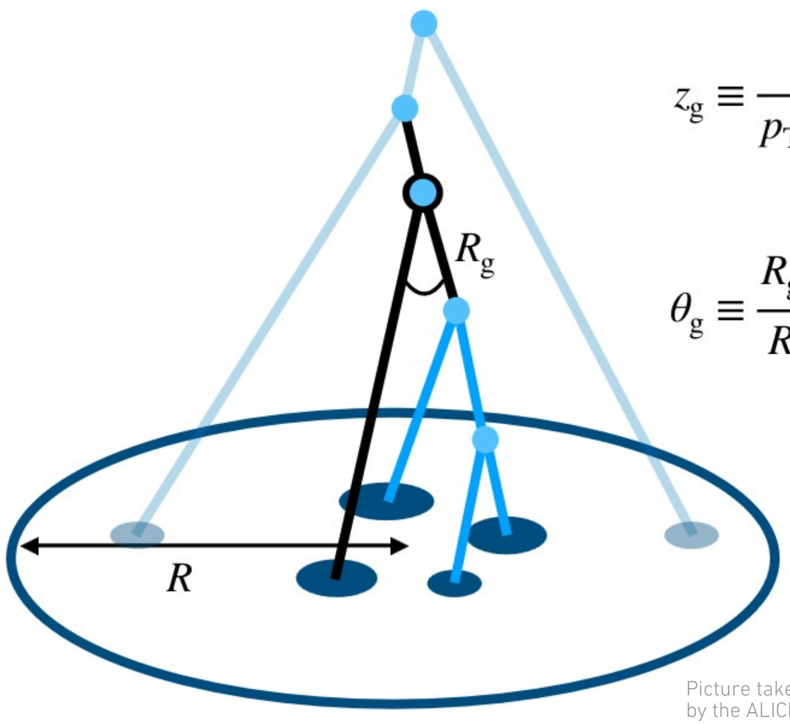
Larkoski et al. (2014)

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

1. Break the jet j into two subjets by undoing the last stage of C/A clustering and label them as j1 and j2.
2. If j1 and j2 pass the SD condition then deem j to be the final soft-drop jet.
3. Else: redefine

$$j = \max_{p_T}[j_1, j_2]$$

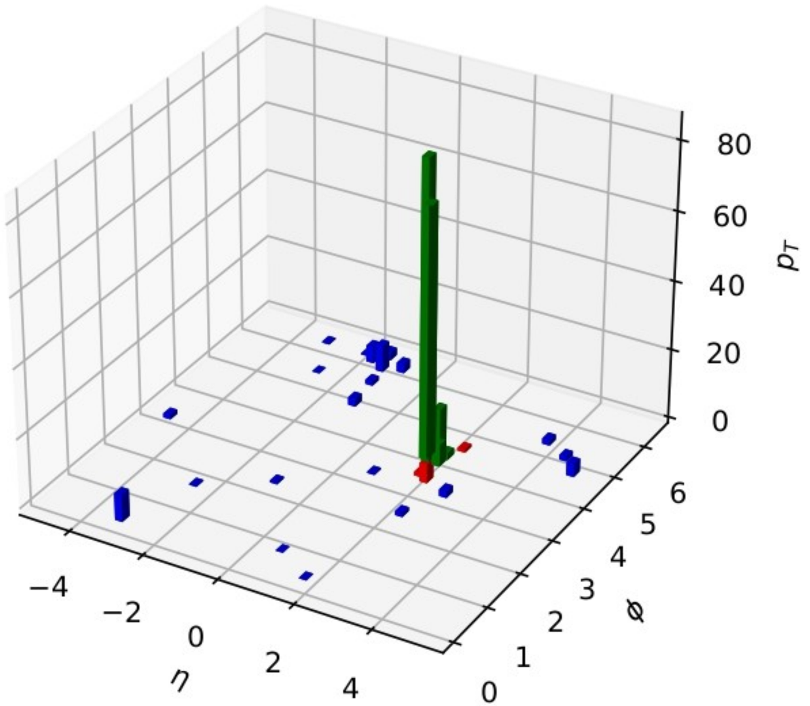
while(! SD)



$$z_g \equiv \frac{p_{\text{T,subleading}}}{p_{\text{T,leading}} + p_{\text{T,subleading}}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

Picture taken from 2204.10246
by the ALICE collaboration



The Lund Plane (light jets)

The cumulant distribution for the observable $\mathcal{V}$ can be written as

$$\Sigma(v) = \frac{1}{\sigma_0} \int_0^v dv' \frac{d\sigma}{dv'}$$

Almost all the observable of interest have the following infrared and collinear behavior

$$\mathcal{V}(p_1, p_2, k) \to V_1(k_t, \eta_1) = d_i \left(\frac{k_t}{Q}\right)^{a_i} e^{-b_i \eta_i}$$

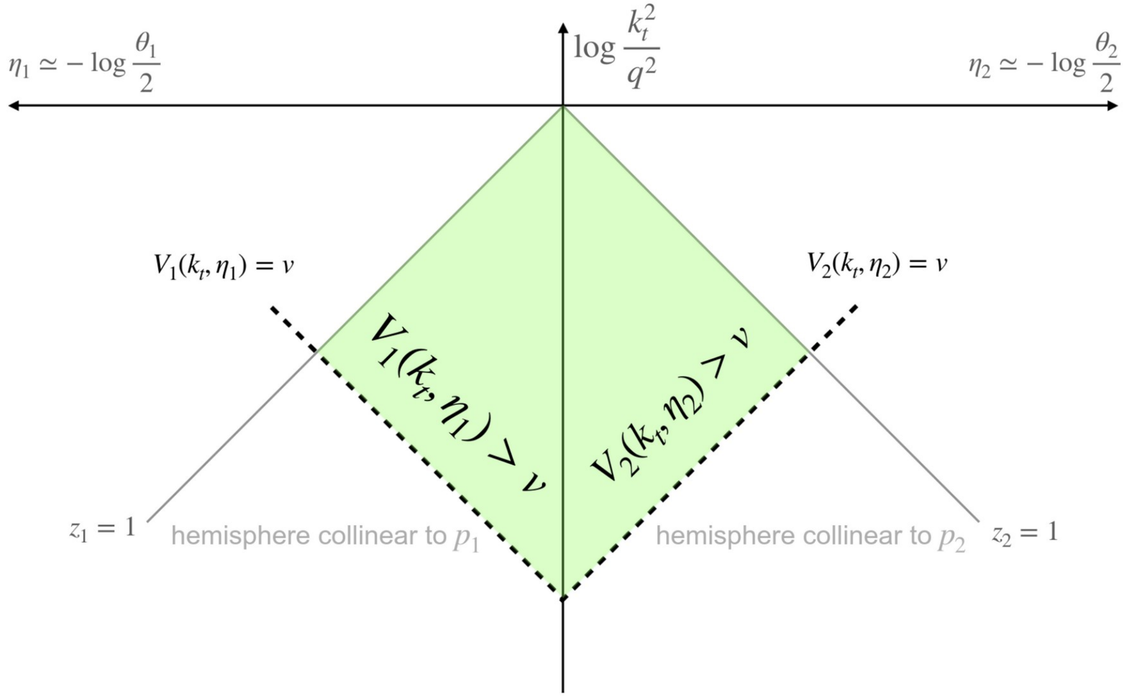
NLL resummation is known for this class of observables [Banfi, Salam, Zanderighi (2004)]

$$\Sigma(v) = \mathcal{S}\mathcal{F} e^{-\mathcal{R}(v)}$$

Non-global effects [Dasgupta, Salam (2001)]

Multiple emissions

On Lund jet plane QCD radiation is uniformly distributed in the soft and collinear limit



Real emissions cannot take place everywhere in the PS but they are constrained in the above the shaded area by $V_i(k_t, \eta_i) < v$

Thus, the Sudakov form factor (radiator) is given by the no-emission probability

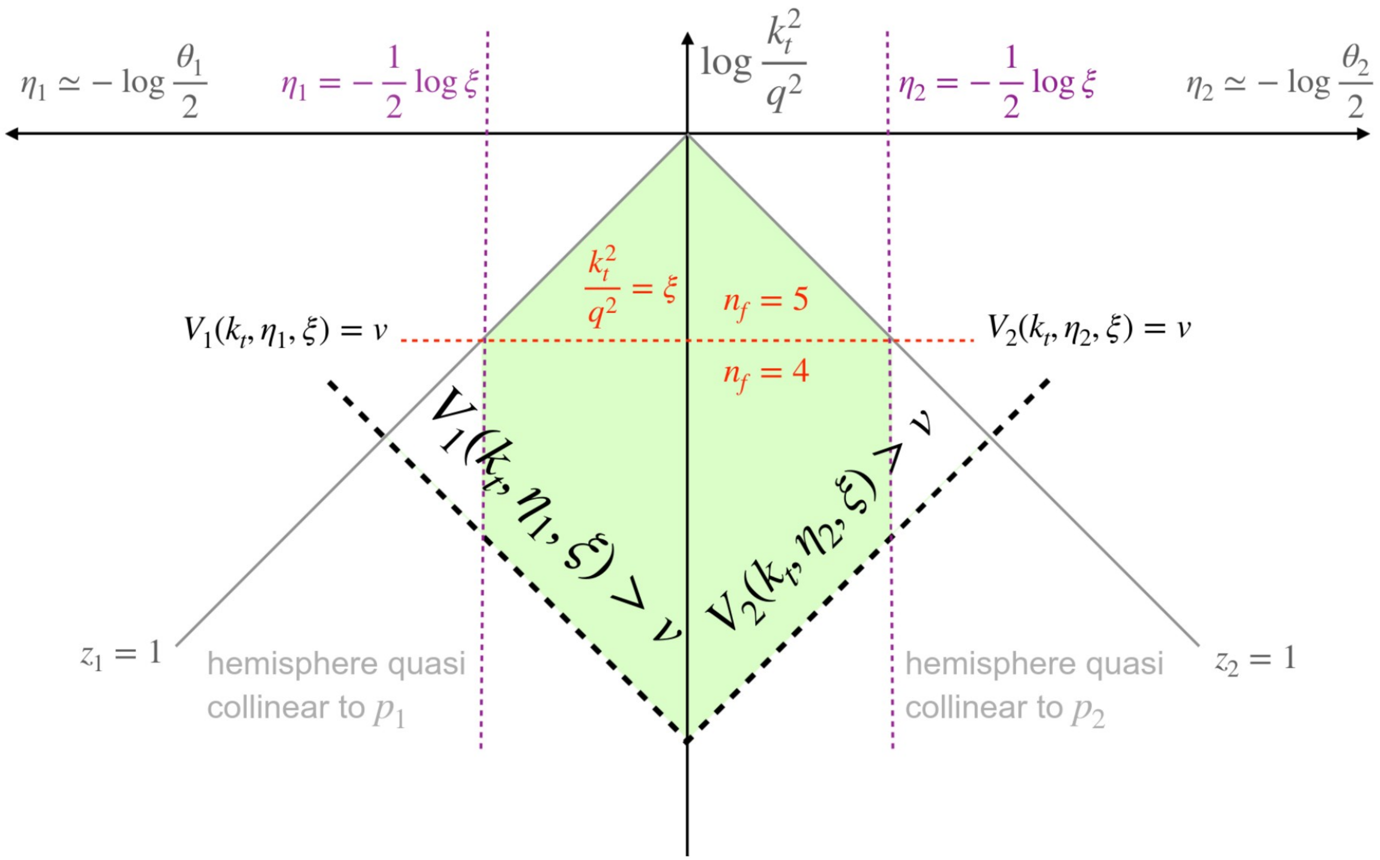
$$\mathcal{R}(v) = \sum_{i \in \text{legs}} \int_0^{Q^2} \frac{dk_t^2}{k_t^2} \int_0^1 dz P_{qg\leftarrow q}(z) \frac{\alpha_S^{CMW}(k_t^2)}{2\pi} \Theta(\mathcal{V}_i(k_t^2, \eta_i) - v)$$

Lund Plane for massive particles

[Ghira, Marzani, Ridolfi (2309.06139)]

In the massive case the following we have

- to consider the quasi-collinear splitting function $P_{Qg \leftarrow Q}$
- to modify the PS (aka the Lund Plane) introducing a new boundary (dead cone effect)
  ➞ new vertical lines
- to introduce boundaries corresponding to 4 and 5 active flavour treshold (or 3 and 4)
  ➞ new horizontal lines
- to take into account that the observable might explicitly depends on the HQ mass
  ➞ dashed lines are deformed



Observables studied (or under investigation) exploiting this framework:

θ_g z_g — this talk

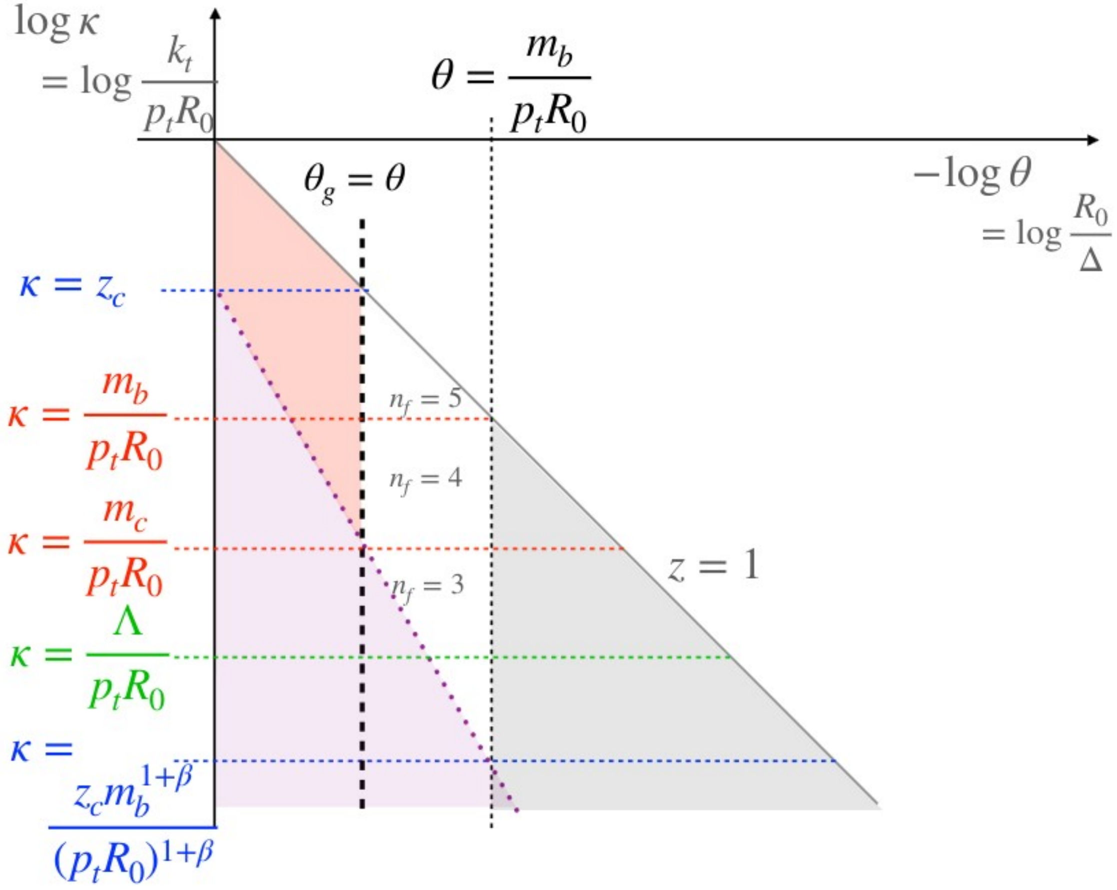
λ_α — see Andrea's talk

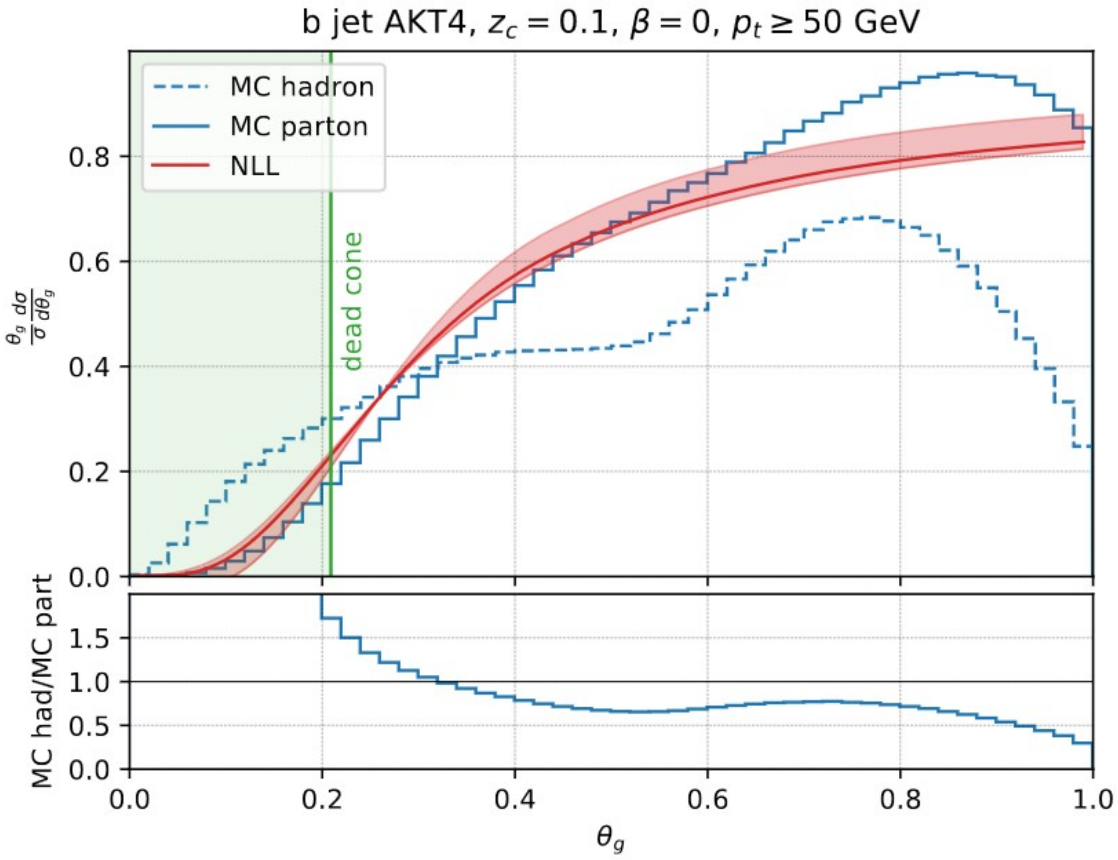
ECF

SoftDrop ϑ_g at NLL

[SC, Ghira, Marzani (2312.11623)]

Heavy quark jets allow to explore the dead-cone effect and to study heavy-quark fragmentation.





HERWIG 7.2.2 at LO+PS

13 TeV c.o.m. energy
Jets are AKT with R = 0.4
$p_{t,jet}$ > 50, 150 or 300 GeV and $|\eta_{jet}|$ < 2.4
$p_{t,mu}$ > 26 GeV and $|\eta_{mu}|$<2.4

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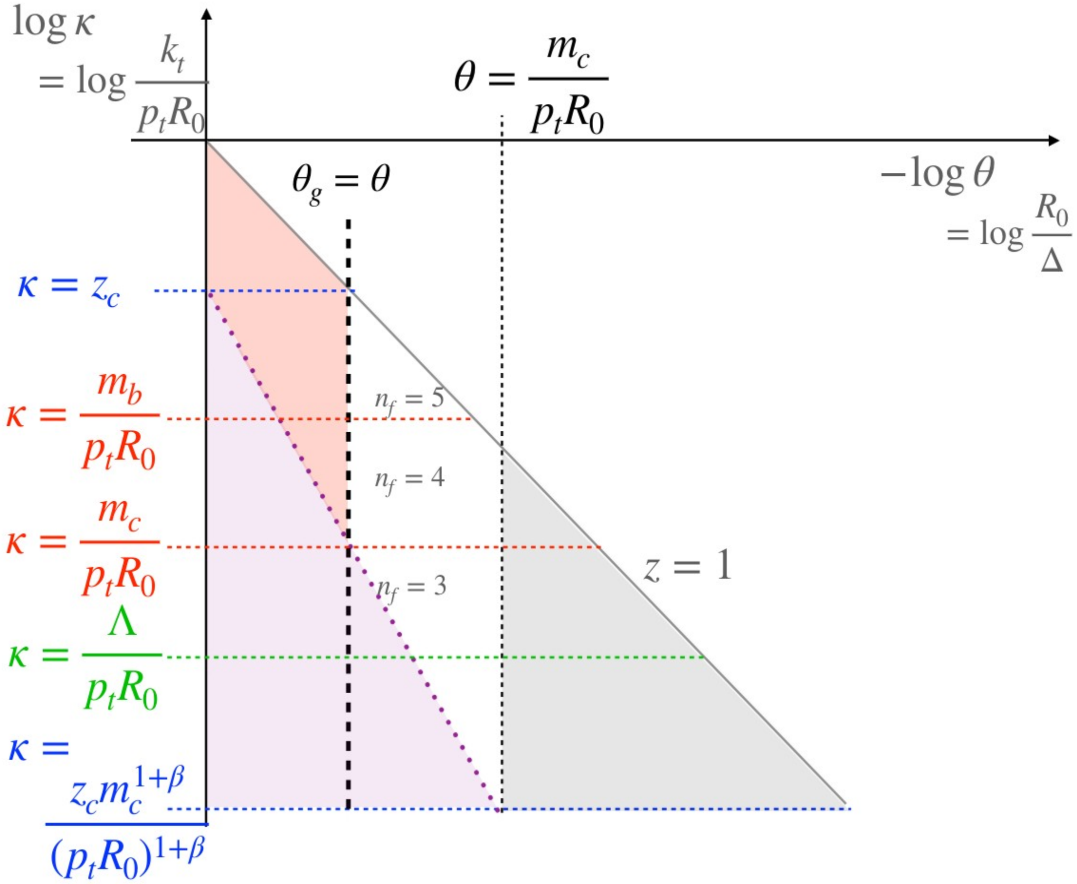

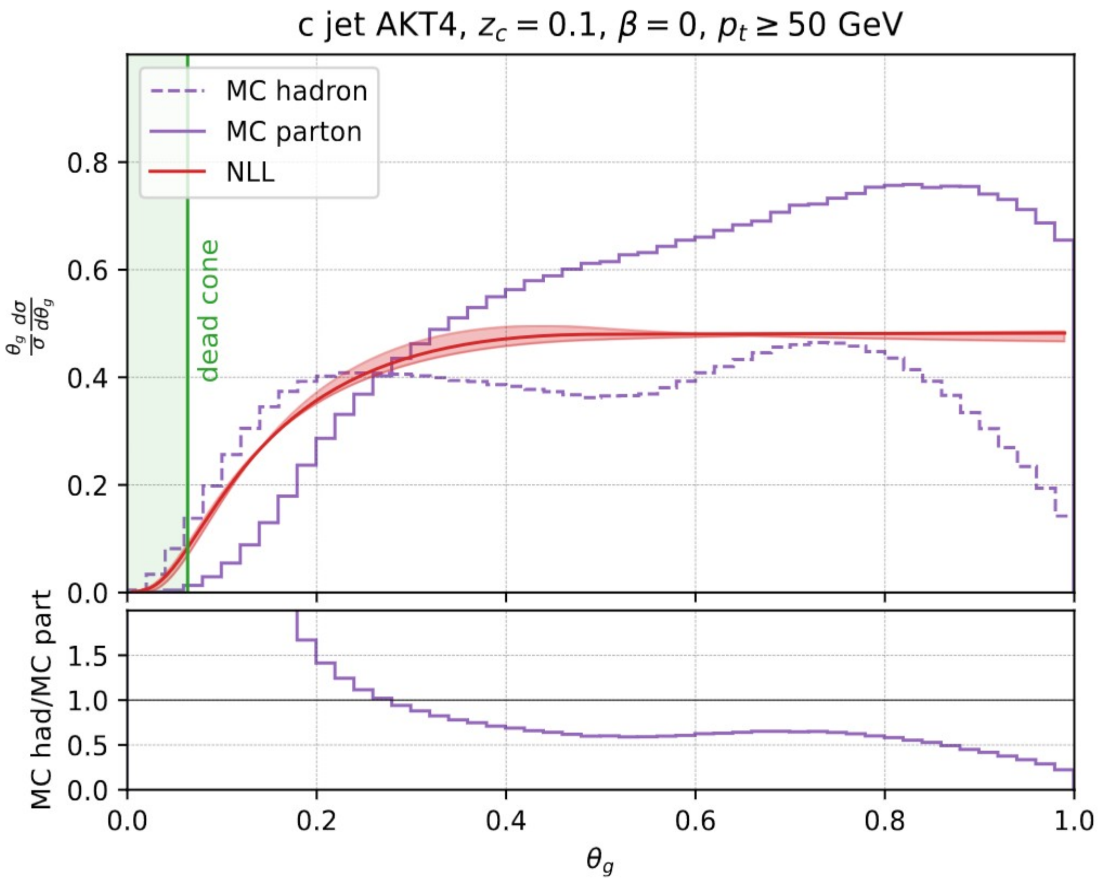

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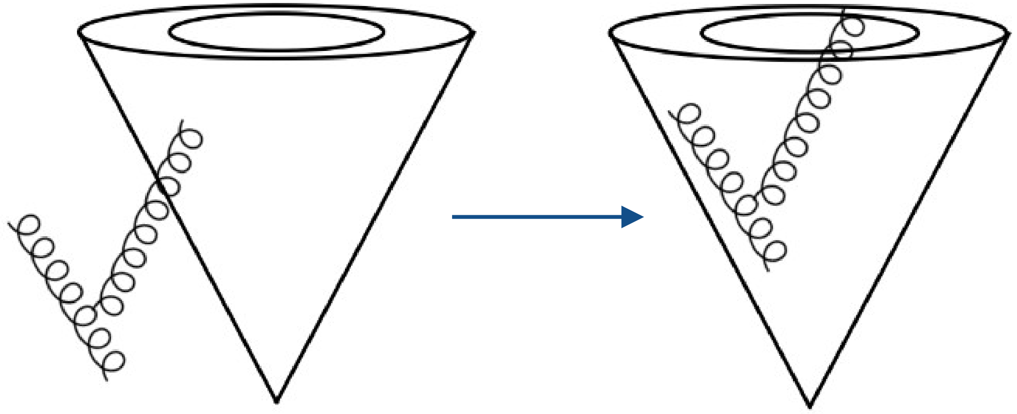
NGL structure for SoftDrop ϑ_g

[SC, Ghira, Marzani (2312.11623), Kang at al. (1908.01783)]

- Clustering Logarithms from C/A reclustering

  → might cluster 2 soft gluons together first, if close in angle (instead of clustering them with the hard quark)

- Pure Non-global Logarithms contribution modified by the re-clustering condition



Massless case

$$\mathcal{S} = 1 + \left(\frac{\alpha_S}{\pi}\right)^2 \log^2\left(z_c \theta_g^\beta\right) \frac{\pi^2}{108}(C_F^2 - 4C_F C_A)$$

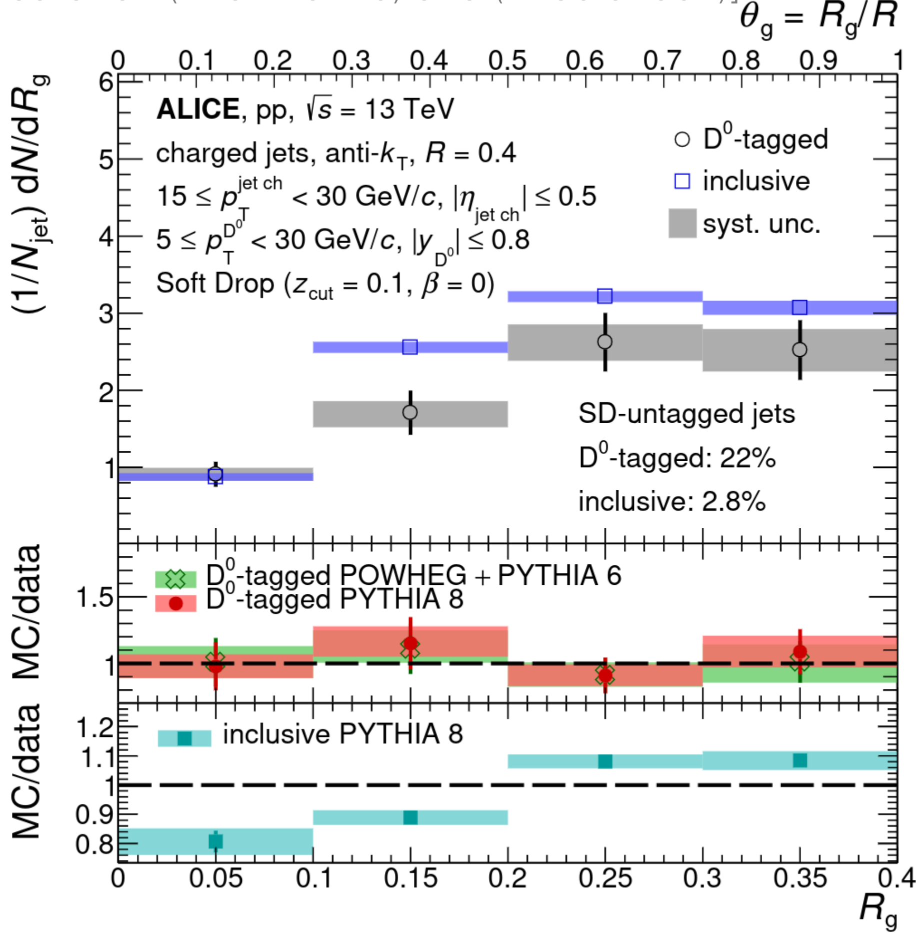
Massive case

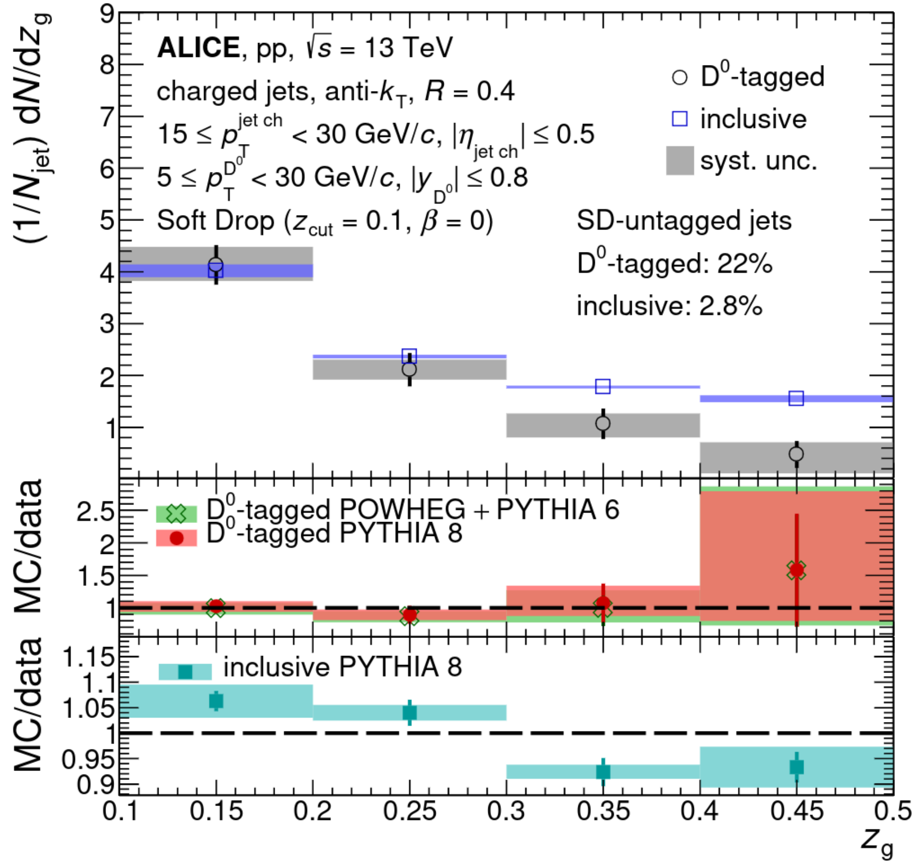
$$\lim_{\theta_i^2/\theta_g^2 \to 0} \mathcal{F}_{\text{Abelian}} = \frac{\pi^2}{108} \qquad \lim_{\theta_i^2/\theta_g^2 \to 0} \mathcal{F}_{\text{Non Abelian}} = -\frac{\pi^2}{27}$$

$$\lim_{\theta_g^2/\theta_i^2 \to 0} \mathcal{F}_{\text{Abelian}} = \lim_{\theta_g^2/\theta_i^2 \to 0} \mathcal{F}_{\text{Non Abelian}} = 0$$

Heavy-flavour JSS measurements

[ALICE Collaboration (2204.10246) and (2208.04857)]





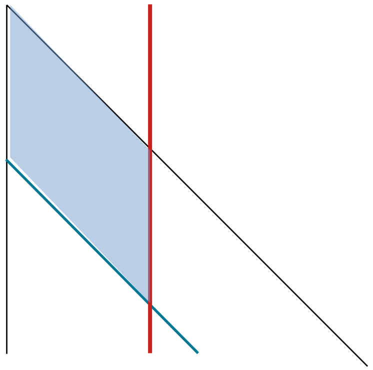
- Measurements of the SD radius for charmed jets.
- The charm and inclusive-jet distributions are consistent at small R_g. Possible interplay between the dead-cone effect from the charm quark, and the more abundant emissions from quarks compared with gluons at small angles.

- First direct experimental constraint on the charm-quark splitting function obtained via the measurement of the groomed shared momentum fraction of the first splitting.
- The z_g distributions show that charm-tagged jets have significantly fewer symmetric splittings compared with inclusive jets. This is consistent with the role of mass effects in the QCD splitting function.

SoftDrop z_g and Sudakov safety

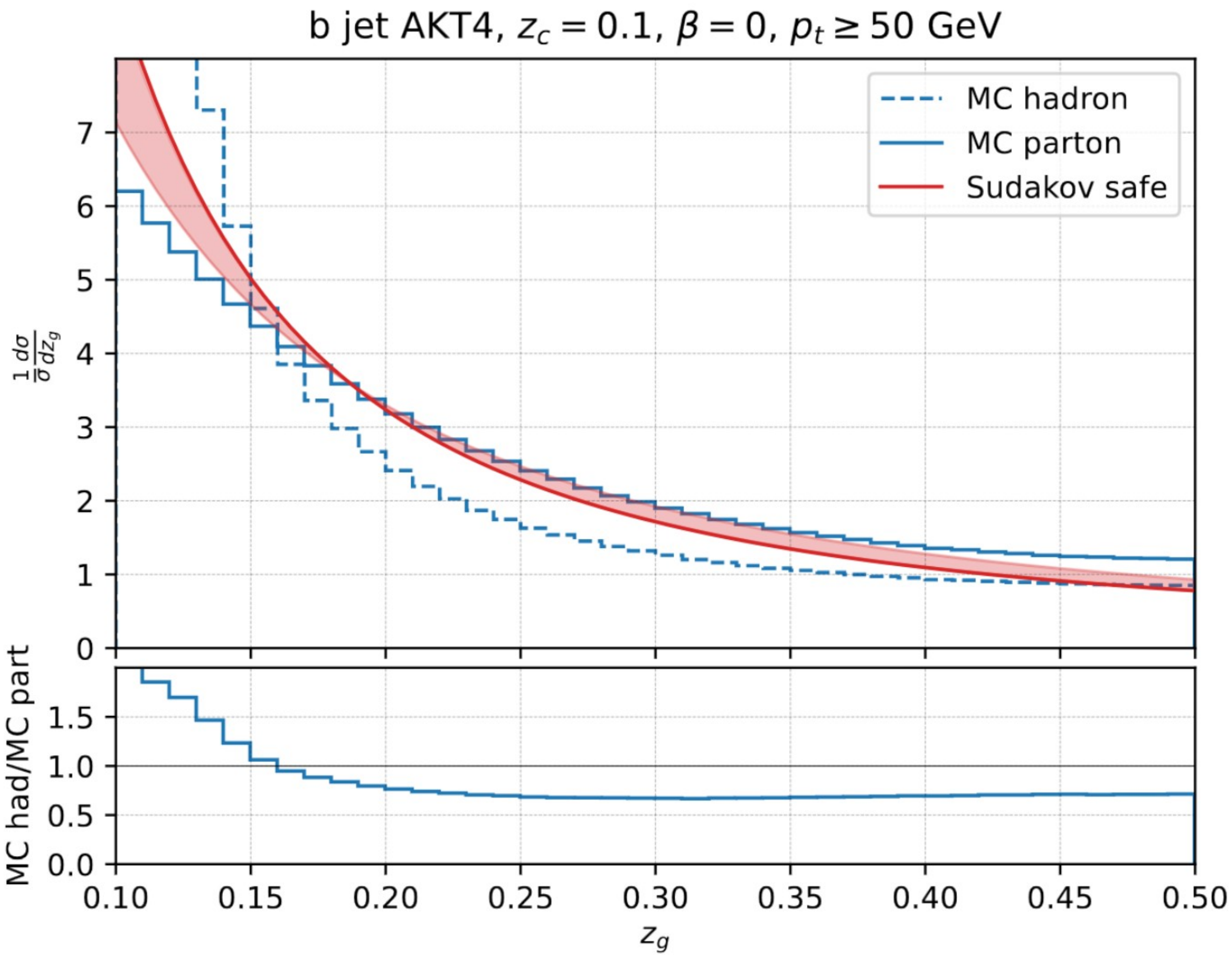
[SC, Ghira, Marzani (2312.11623)]

z_g is **not** IRC safe in the massless case for $\beta \geq 0$ and it has been computed using the Sudakov safety prescription



$$\frac{1}{\sigma_0}\frac{d\sigma}{dz_g} = \int_0^1 d\theta_g \overbrace{p(\theta_g)}^{\frac{1}{\sigma_0}\frac{d\sigma}{d\theta_g}} p(z_g|\theta_g)$$

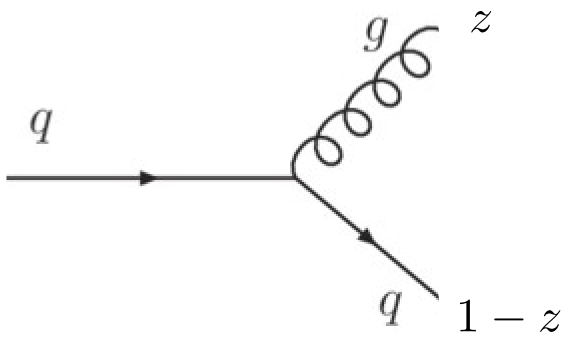
Where the conditional probability is evaluated at fixed order and $p(\theta_g)$ is resummed. This way the Sudakov form factor regulates the θ_g singularity of the integrand.

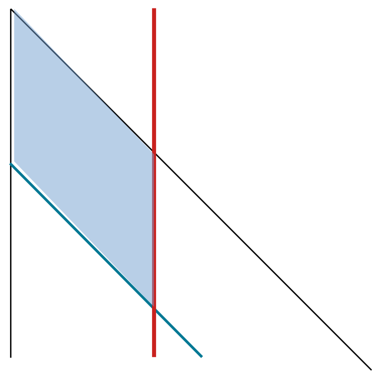


→ in the high- z_g region we undershoot the MC prediction because we used unsymmetrized splitting functions

z_g vs fragmentation – LO picture

[SC, Ghira, Marzani (2312.11623)]





The SoftDrop z_g and the fragmentation variable $\zeta = 1 - \frac{p_{T,b}}{p_{T,\text{jet}}}$ are the same at $\mathcal{O}(\alpha_S)$ for $\zeta > z_c$

$$\frac{1}{\sigma_0}\frac{d\sigma_i^{(f.c.)}}{dz_g} = \frac{\alpha_S}{2\pi}\int_{\theta_i^2}^{1}\frac{d\bar{\theta}^2}{\bar{\theta}^2}\mathcal{P}_{gi}(z_g,\bar{\theta}^2)\Theta(z_g - z_c)$$

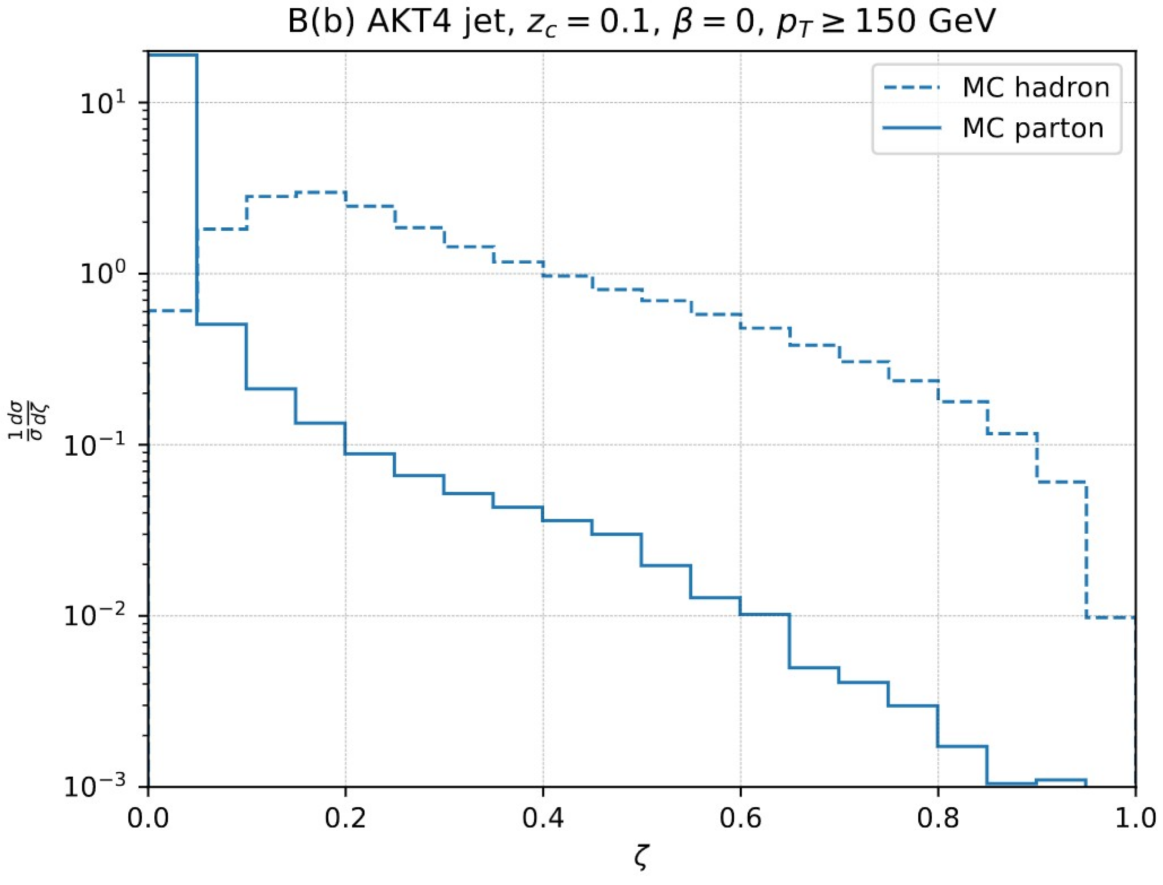
$$\frac{1}{\sigma_0}\frac{d\sigma_i^{(f.c.)}}{d\zeta} = \frac{\alpha_S}{2\pi}\int_{\theta_i^2}^{1}\frac{d\bar{\theta}^2}{\bar{\theta}^2}\mathcal{P}_{gi}(\zeta,\bar{\theta}^2)$$

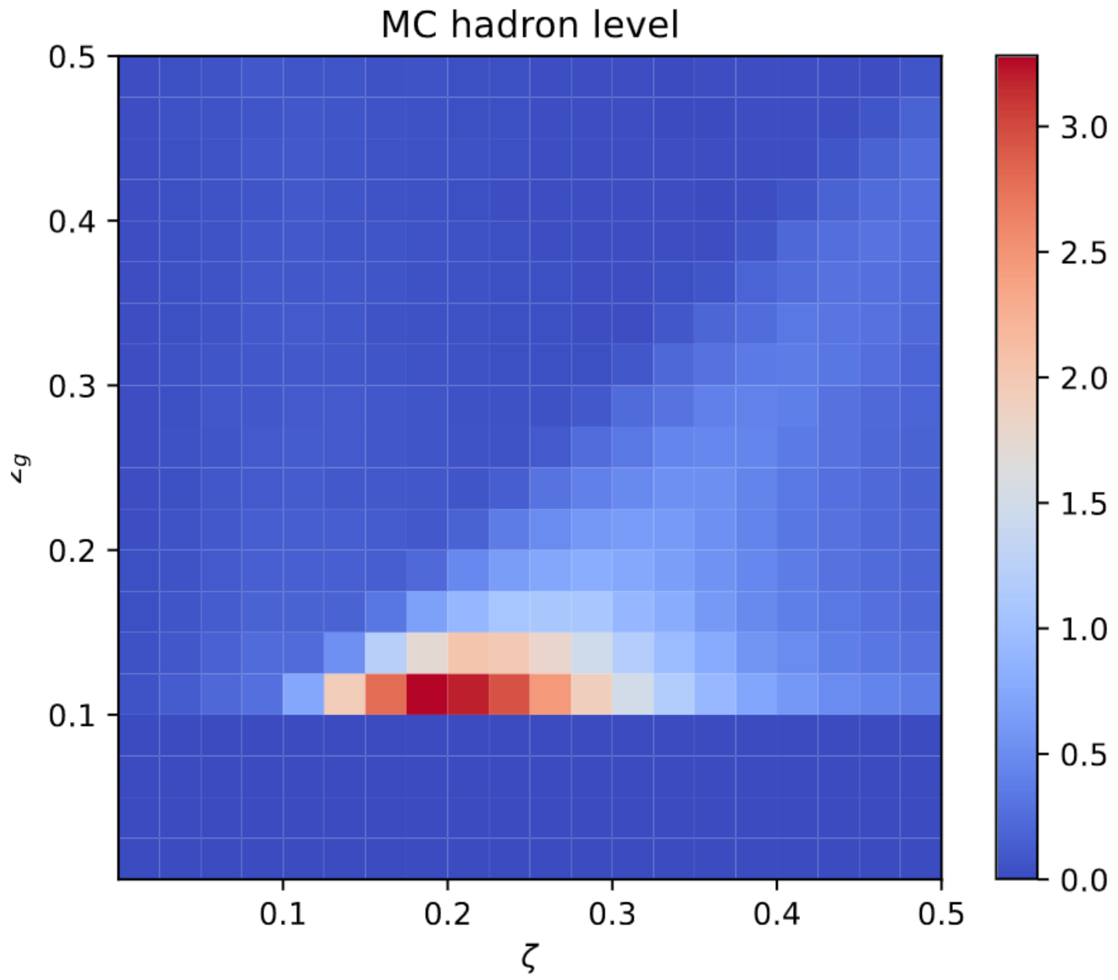
- Already at LL in the f. c. approximation, one can see that the $\vartheta_i \to 0$ limit is not smooth and the massless result is not recovered.
  → related to non-commutativity of the soft and massless limits

- Using Sudakov safety we correctly recover the massless limit

z_g vs fragmentation – PS + HAD corrections

[SC, Ghira, Marzani (2312.11623)]





- Non-perturbative effects are large.
- Fragmentation functions are under better perturbative control than Soft Drop observables, but the latter seem to be more robust against non-perturbative corrections.

- The $\mathcal{O}(\alpha_S)$ correlation between the two observables is not maintained when higher-order corrections and non-perturbative effects are included.
- Thus z_g and ζ offer different handles to study heavy-flavor dynamics.

Conclusions

- Heavy flavour jet substructure is an interesting subject for phenomenology:
  → to explore dead-cone effect, heavy quark splitting functions, etc.

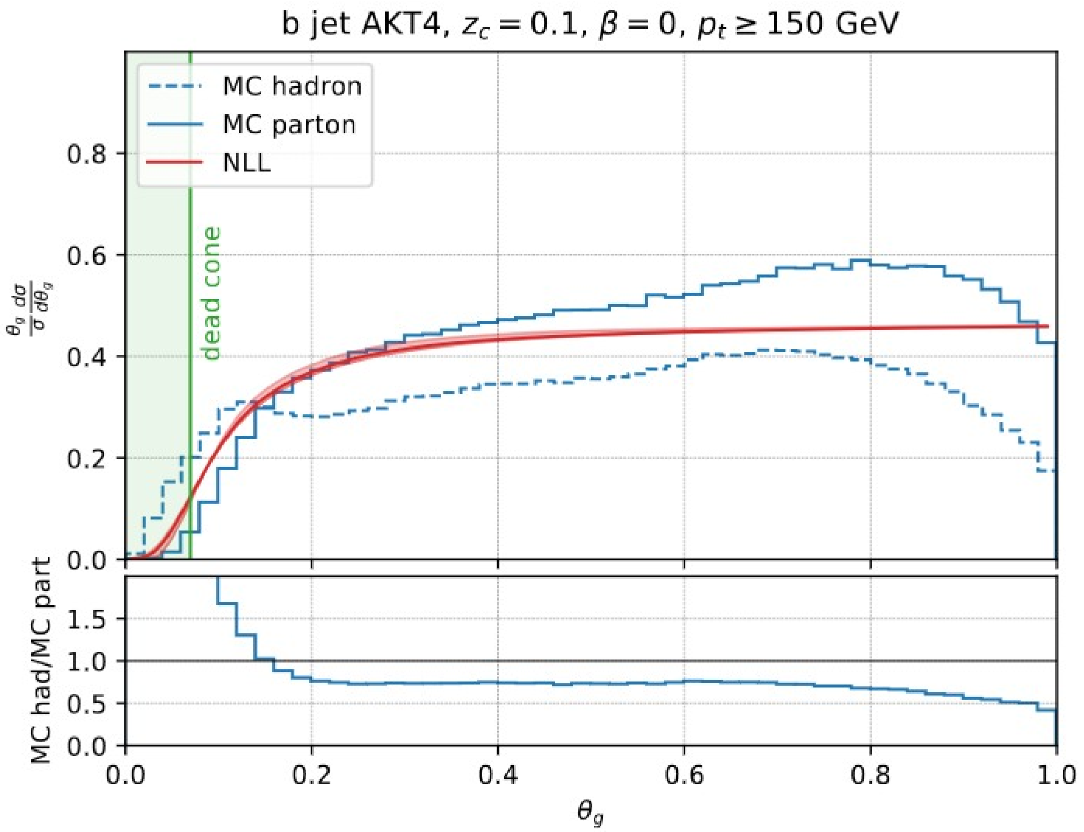
- Lund Plane techniques can be exploited for resummed calculations also with heavy quarks, with some measures.

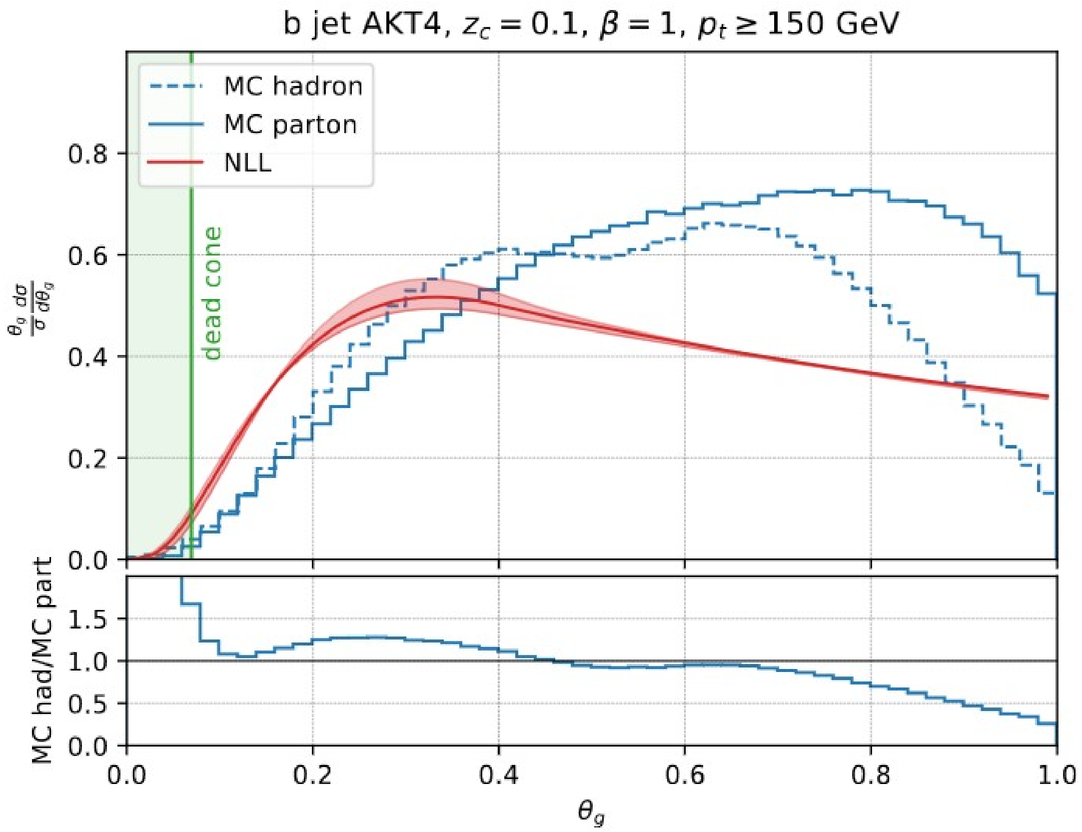
- In conjuction with IRC safe flavour algorithms, this will open up a wide range of possible interesting applications.

- The interplay/complementarity between hadron fragmentation and heavy quark JSS should further be explored and might give interesting insight on non-perturbative QCD dynamics.

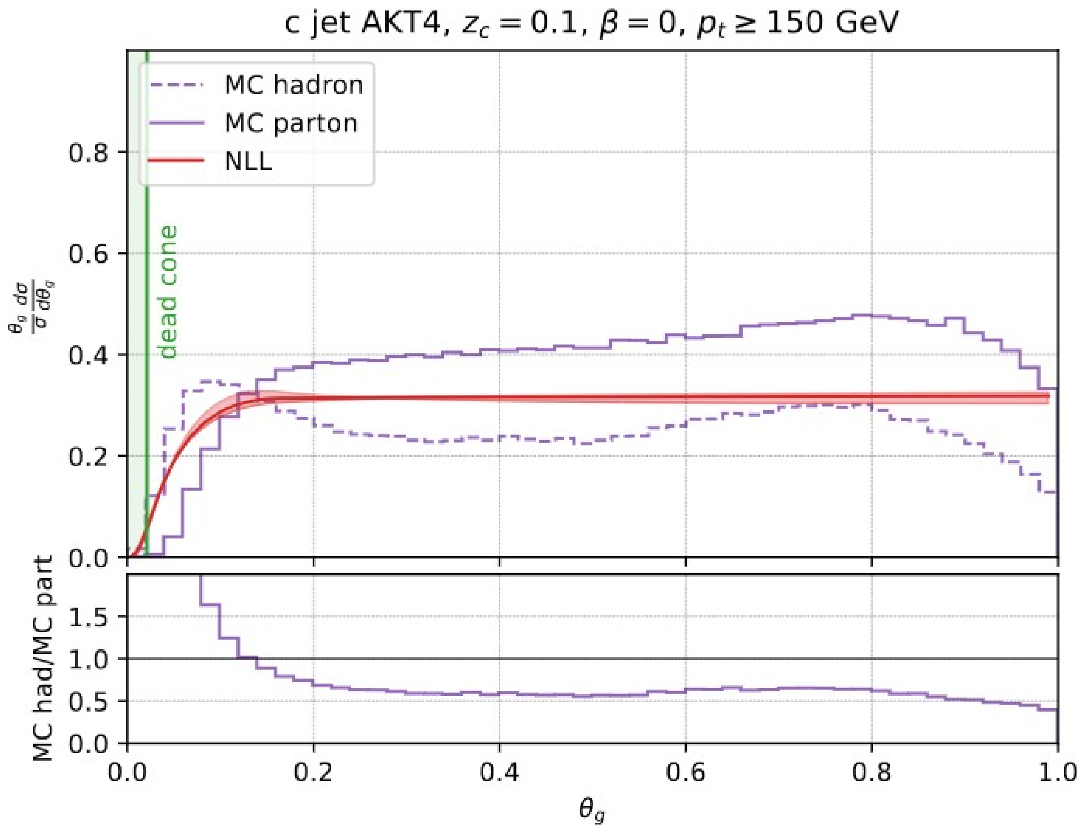
BACKUP SLIDES

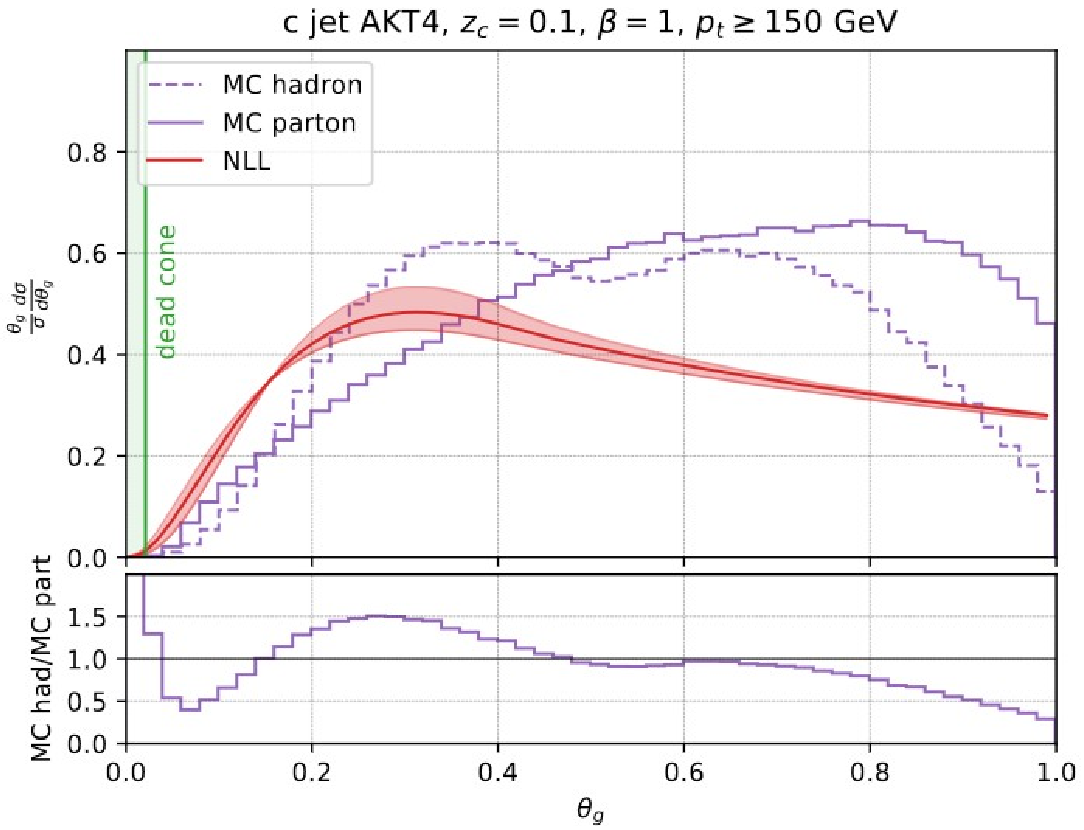
ϑ_g b-jets with p_t>150 GeV



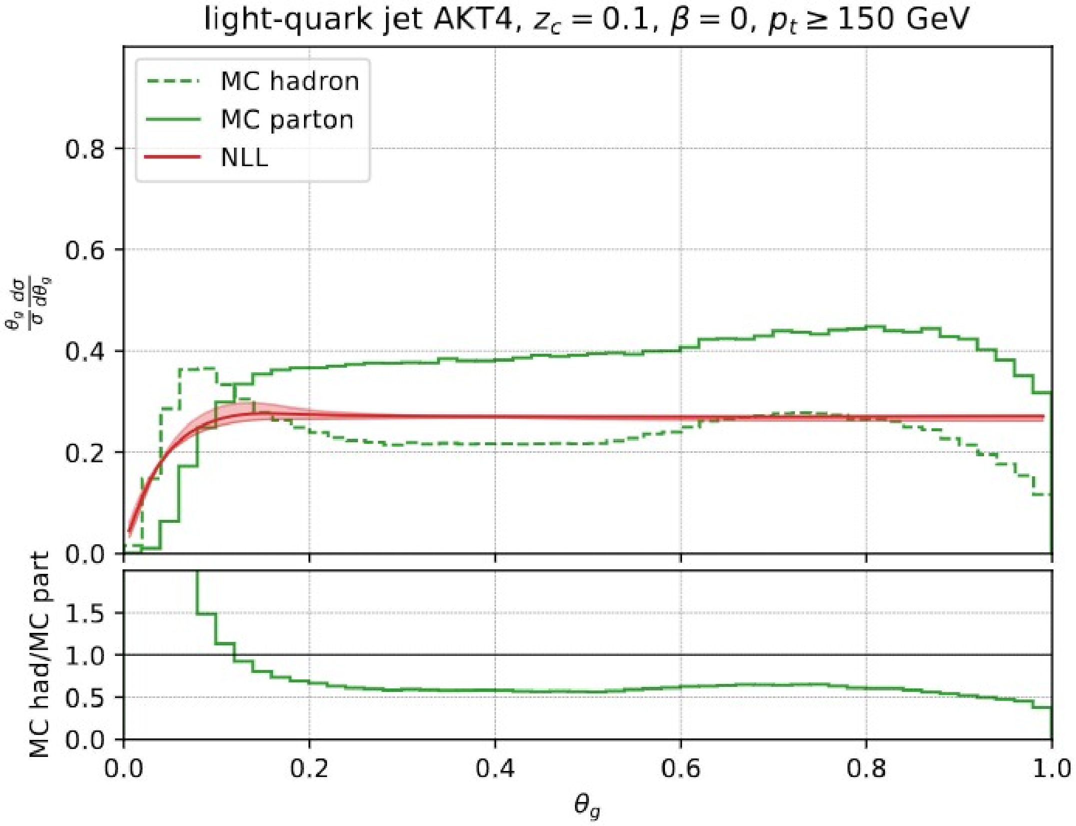


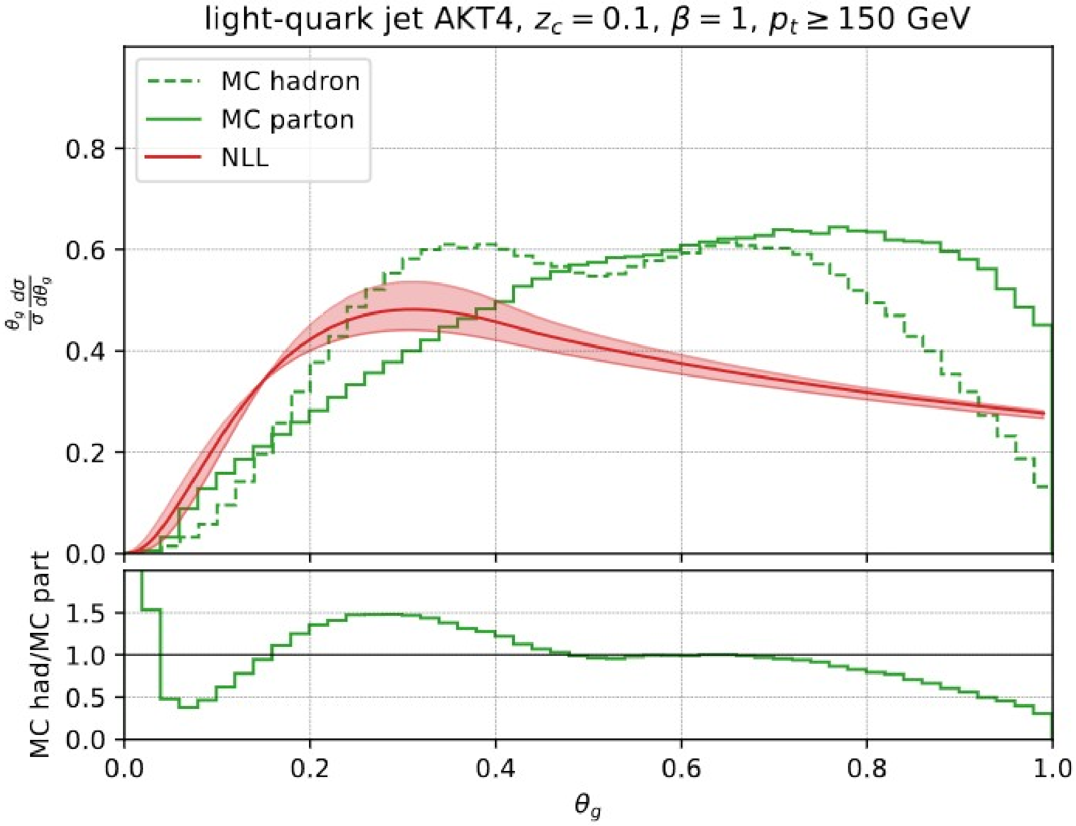
ϑ_g c-jets with p_t>150 GeV



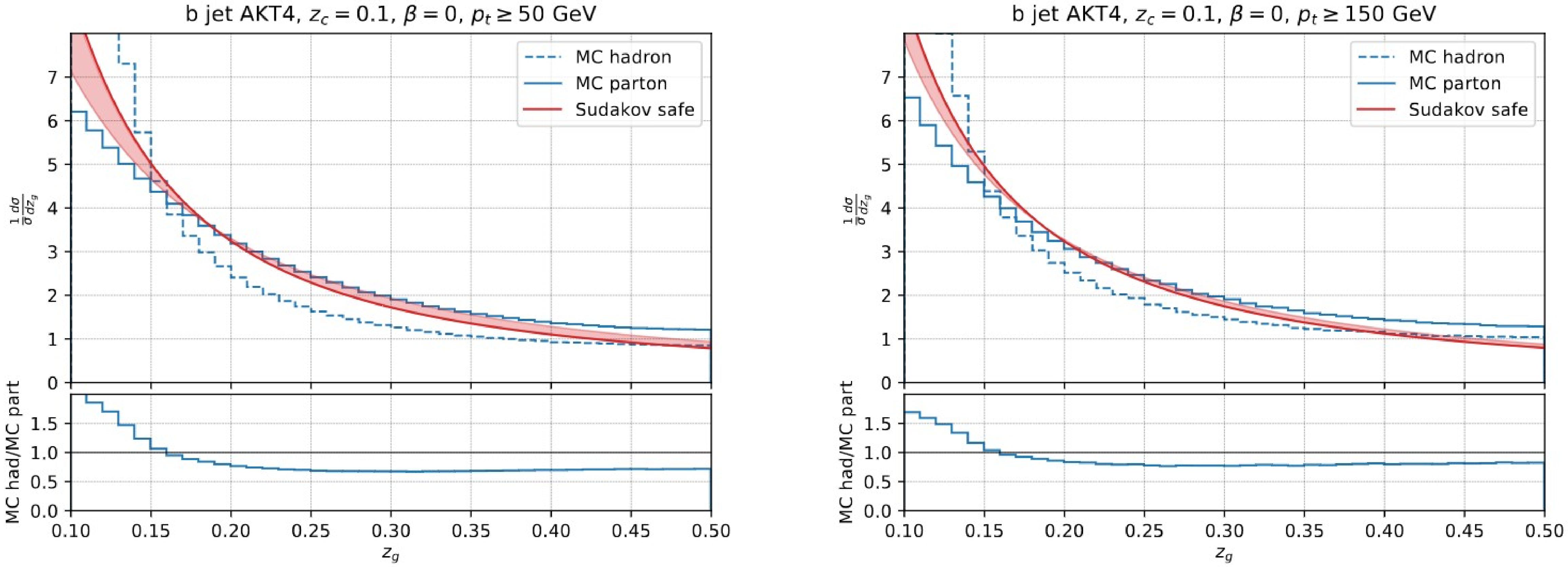


ϑ_g light-jets with p_t>150 GeV

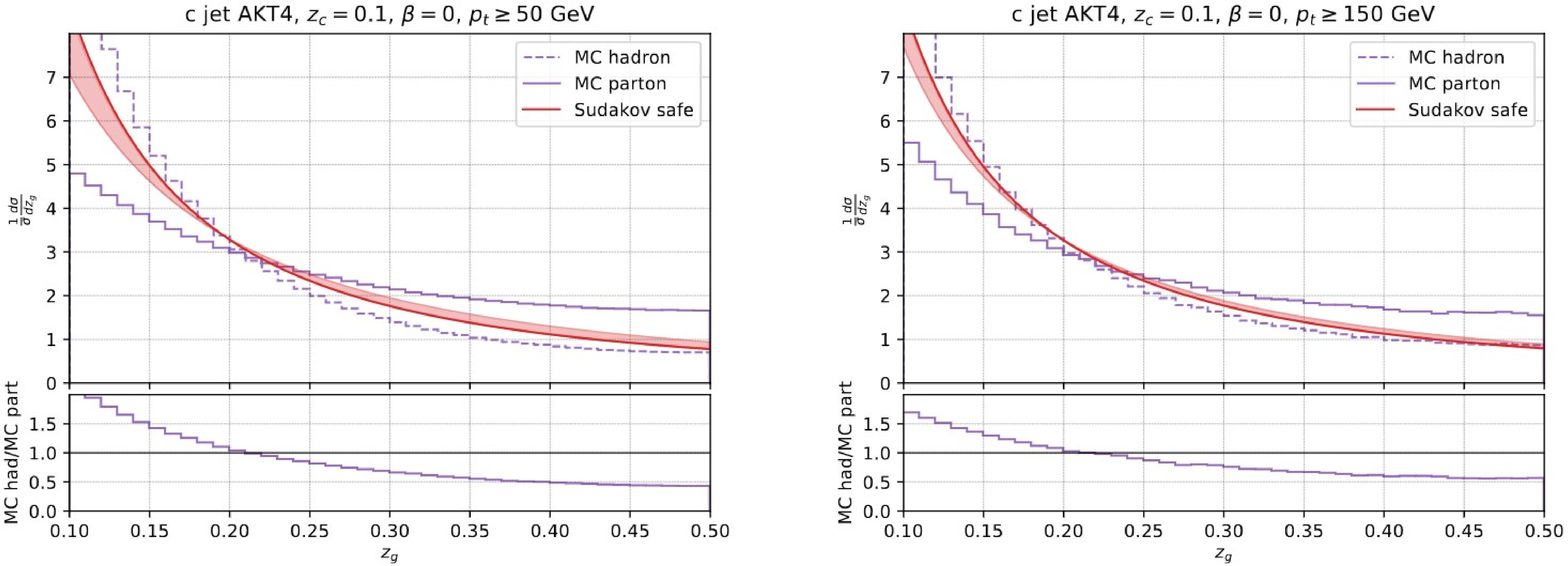




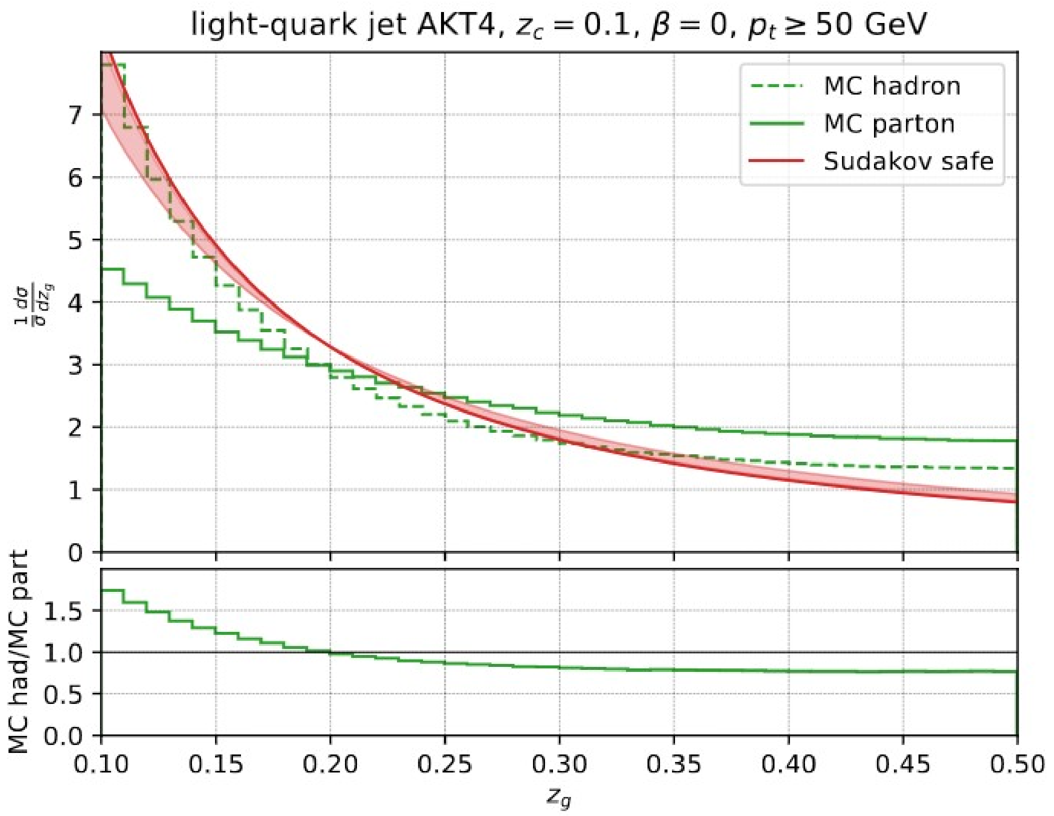
z_g b-jets with β=0

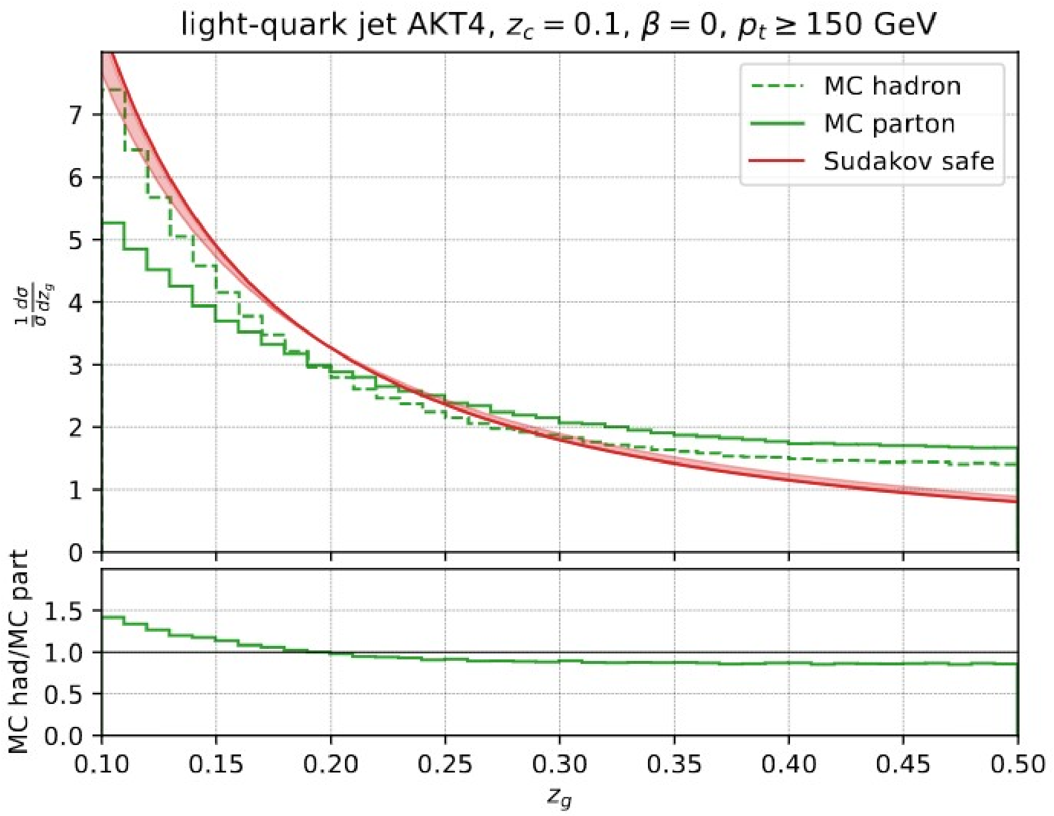


z_g c-jets with β=0



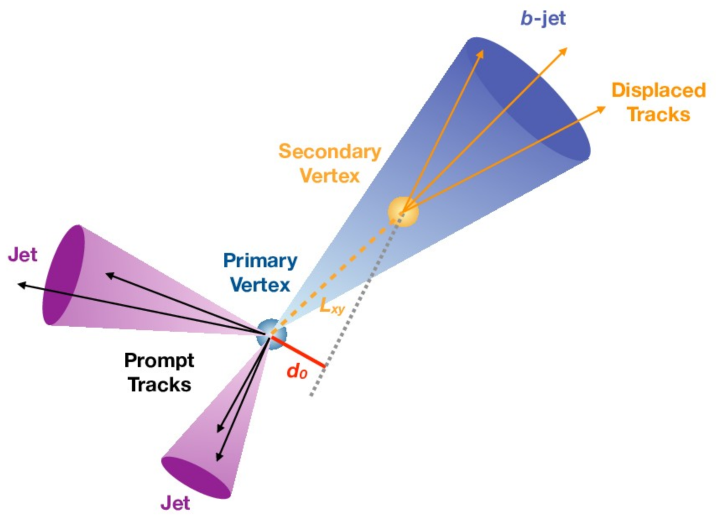
z_g light-jets with β=0



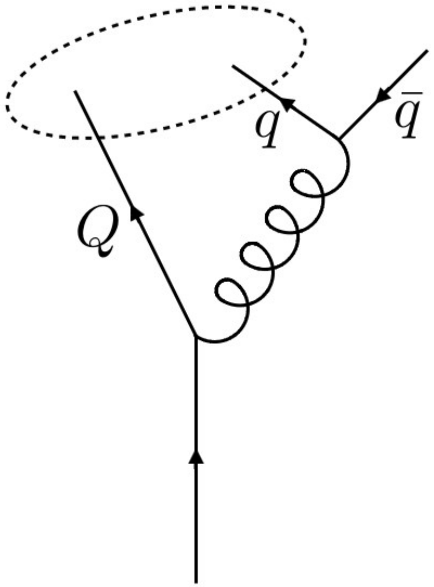


Flavor algorithms

[SC, Larkoski, Marzani, Reichelt (2205.01117) and (2205.01109)]

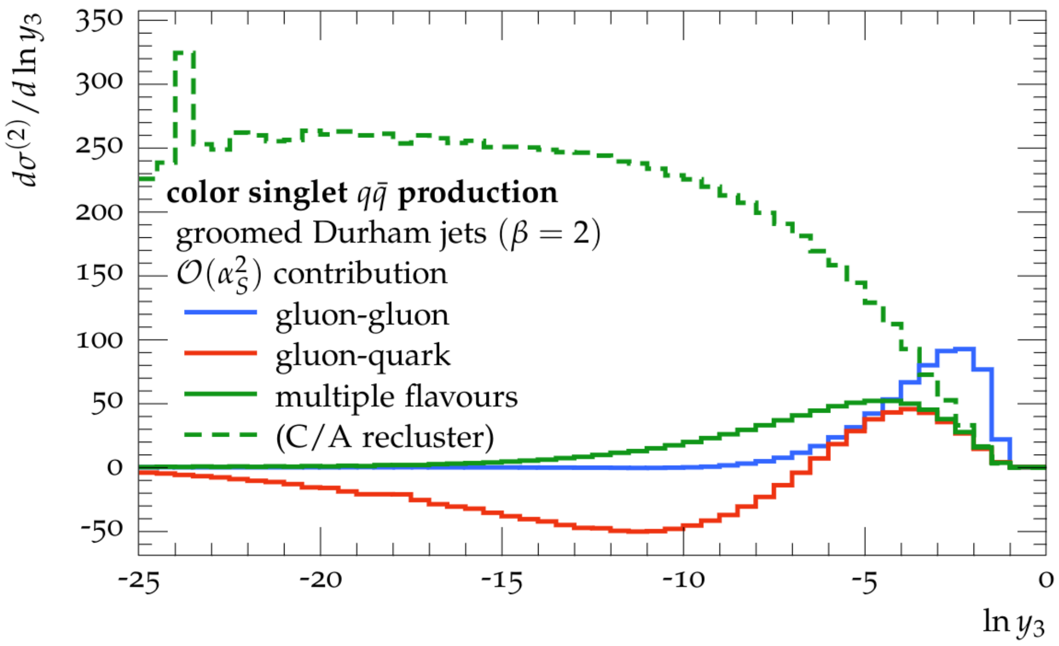


https://cds.cern.ch/record/2771727/plots



1. Cluster jets with any IRC safe clustering algorithm
2. Recluster the jet with JADE
3. At each stage require that particles i and j pass the SD condition for β>0.
4. Return the net flavor of the groomed jet as the flavor of the initial jet

- Heavy-quark-initiated jets are experimentally identified exploiting B hadron lifetime, i.e. the display vertex of **anti-kt** jets.
- From the theory perspective, the **partonic net flavor** of anti-kt jets is **not** IRC safe at NNLO.
- **Flavor-kt** can be used from theory point of view, but then we cannot directly compare with experiment.

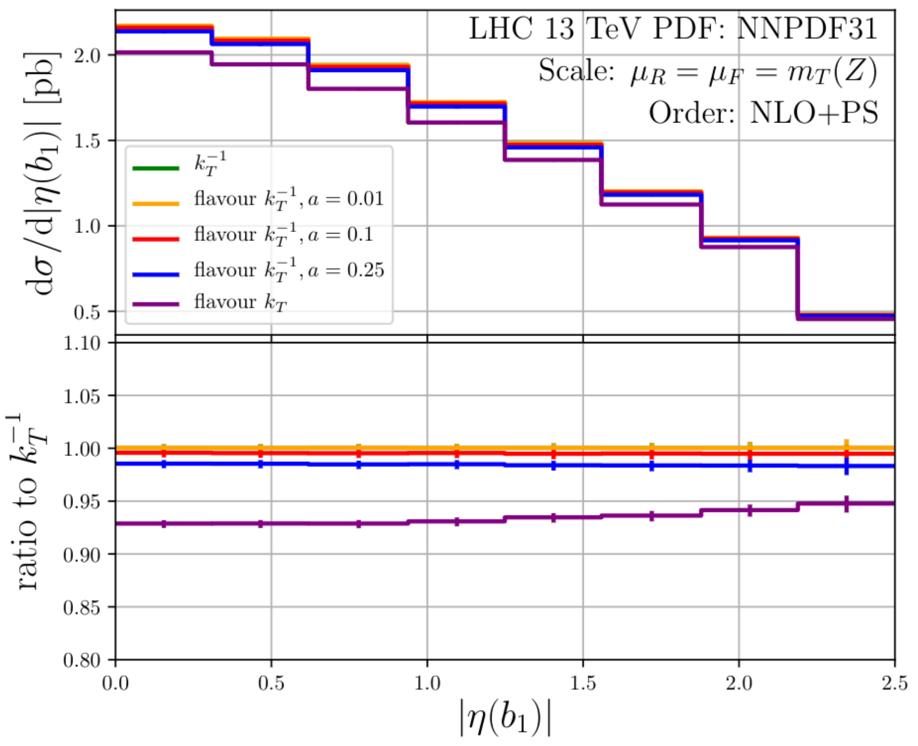


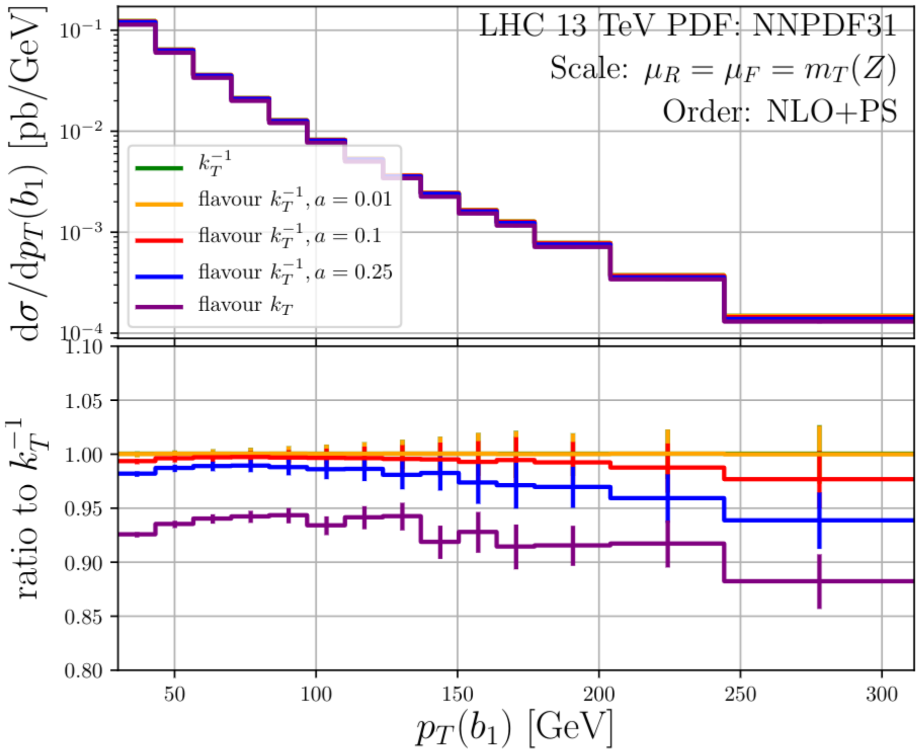
Flavor algorithms

[Czakon, Mitov, Poncelet (2205.11879)]

$$d_{ij}^{(F)} = \overbrace{\left(\frac{\Delta_{ij}}{R}\right)^2 \min(k_{T,i}^{-2}, k_{T,j}^{-2})}^{\text{standard anti-}k_t\text{ measure}} \begin{cases} \mathcal{S}_{ij}, & \text{if both } i \text{ and } j \text{ have non-zero flavor of opposite sign} \\ 1, & \text{otherwise} \end{cases}$$

$$\mathcal{S}_{ij} = 1 + \Theta(1-\kappa_{ij}) \cos\left(\frac{\pi}{2}\kappa_{ij}\right) \quad \text{with} \quad \kappa_{ij} \equiv \frac{1}{a}\frac{k_{T,i}^2 + k_{T,j}^2}{2k_{T,\max}^2}$$





Flavor algorithms

[Gauld, Huss, Stagnitto (2208.11138)]

1. Initialize empty sets tag_k for each jet j_k to accumulate all flavored particles assigned to it

2. Populate a set $\mathcal{D}$ of distance measures based on all allowed pairings:

   (a) For each unordered pair p_i and p_j add the distance measure d_{p_i,p_j}, if either both particles are flavored or at least one particle is unflavored and p_i and p_j are associated with the same jet.

   (b) If p_i is associated to jet j_k, add the distance measure d_{p_i,j_k} At hadron colliders, add the beam distance $d_{p_i,B_\pm}$

3. While the set $\mathcal{D}$ is not empty, select the pairings with the smallest distance measure:

   (a) d_{p_i,p_j} is the smallest. Merge the two particles into a new particle k_{ij} carring the sum of the four-momenta and flavor. All entries in $\mathcal{D}$ involving p_i or p_j are removed and new distances for k_{ij} are added to $\mathcal{D}$.

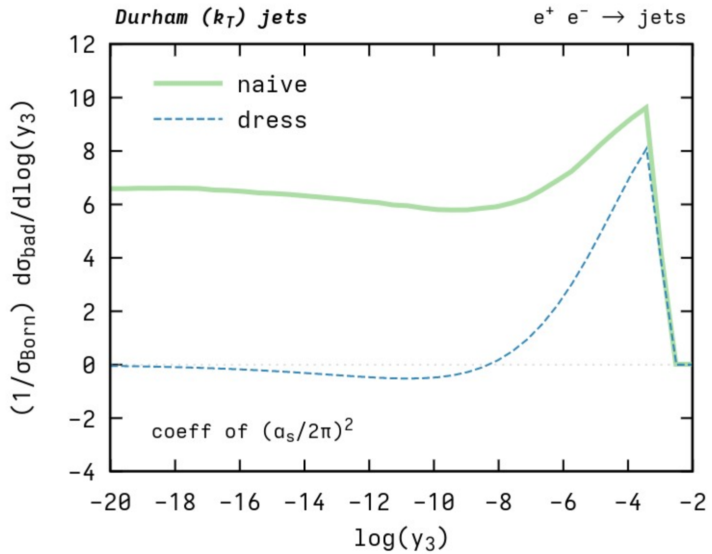
   (b) d_{p_i,j_k} is the smallest. Assign the particle p_i to the jet j_k, $\mathrm{tag}_k \to \mathrm{tag}_k \cup \{p_i\}$ and remove all entries in $\mathcal{D}$ that involve p_i.

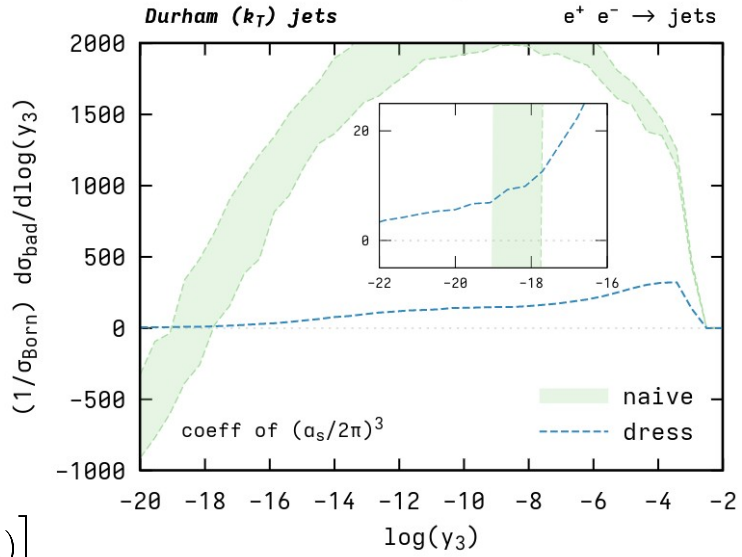
   (c) $d_{p_i,B_\pm}$ is the smallest. Discard particle p_i and remove all entries in $\mathcal{D}$ that involve p_i.

4. The flavor assignment for the jet j_k is determined according to the accumulated flavors in tag_k.

$$d_{ab} = \Omega_{ab}^2 \max(p_{T,a}^{\alpha}, p_{T,b}^{\alpha}) \min(p_{T,a}^{2-\alpha}, p_{T,b}^{2-\alpha})$$

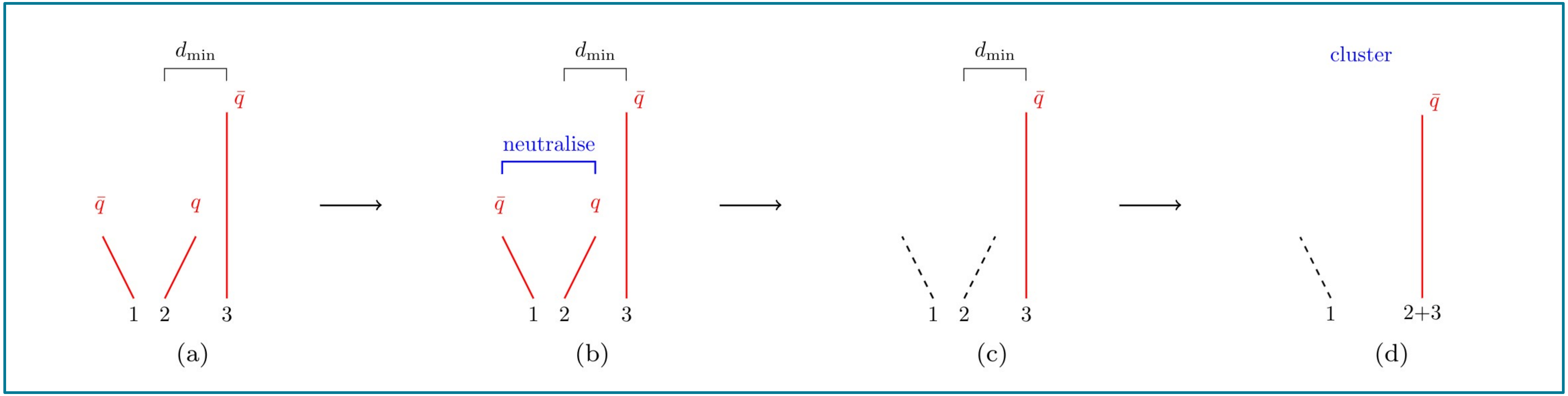
$$\Omega_{ab}^2 = 2\Big[\frac{1}{\omega^2}\big(\cosh(\omega\Delta y_{ab}) - 1\big) - (\cos\Delta\phi - 1)\Big]$$





Flavor algorithms

[Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2306.07314)]



Consider a soft $q\bar{q}$ pair (particles 1 and 2) and a hard $\bar{q}$ (particle 3) with

$$p_{T,1} \sim p_{T,2} \ll p_{T,3}$$

We have that $\Delta R_{23} < R$

while $\Delta R_{12} > R$

Before the 2+3 clustering, the flavor of 1 is used to neutralized the flavor of 2.

Now 2 is clustered with 3 into a 2+3 object with the flavor of 3.

$$u_{ik} = \max(p_{T,i}^{\alpha}, p_{T,j}^{\alpha}) \min(p_{T,i}^{2-\alpha}, p_{T,j}^{2-\alpha}) \times \Omega_{ij}^2$$

The neutralization metric is given by

$$\Omega_{ij}^2 = 2\left[\frac{1}{\omega^2}(\cosh(\omega \Delta y_{ij}) - 1) - (\cos \Delta\phi_{ij} - 1)\right]$$