ETH zürich

COMETA

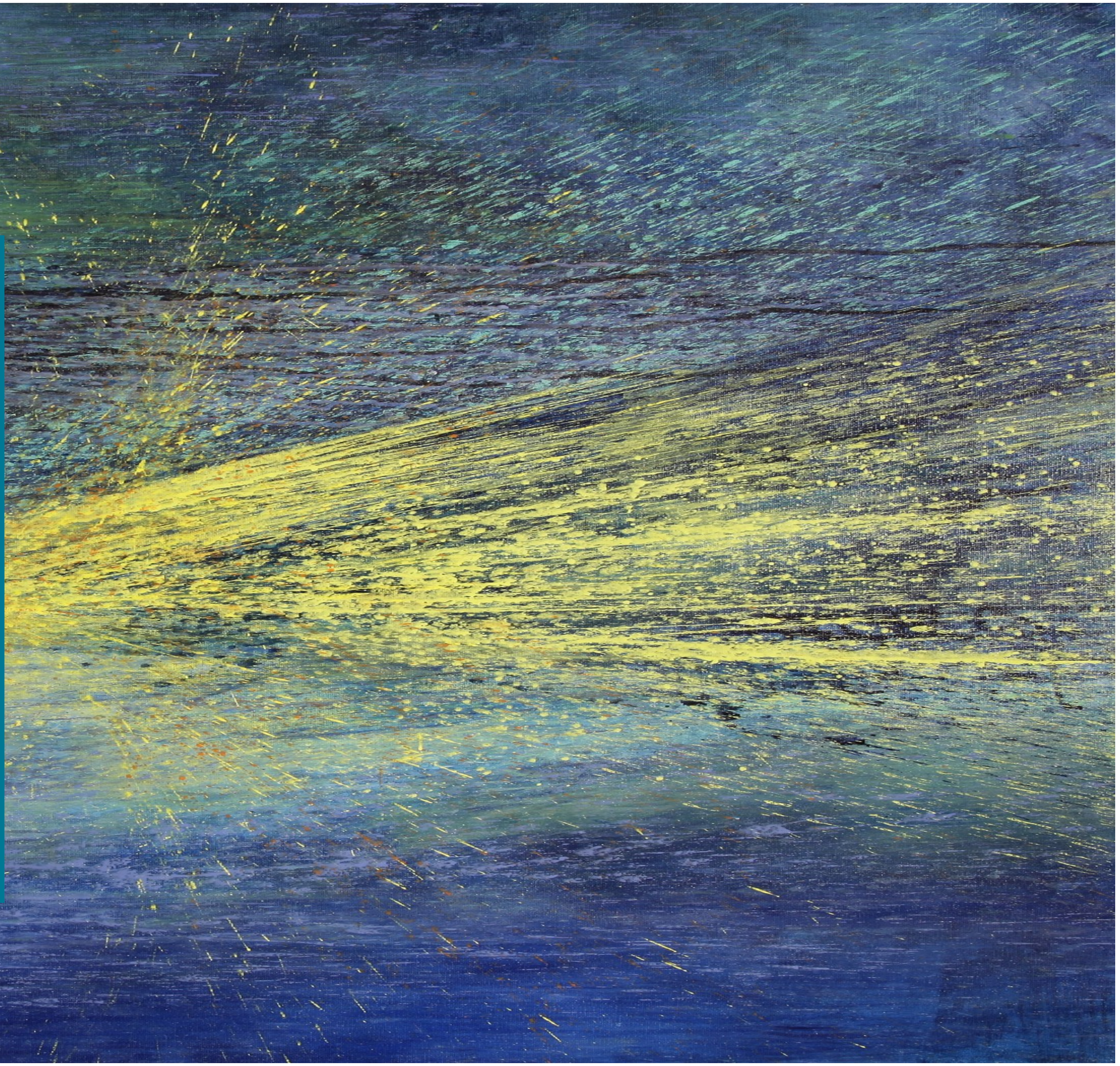
Jets and Substructure

Simone Caletti

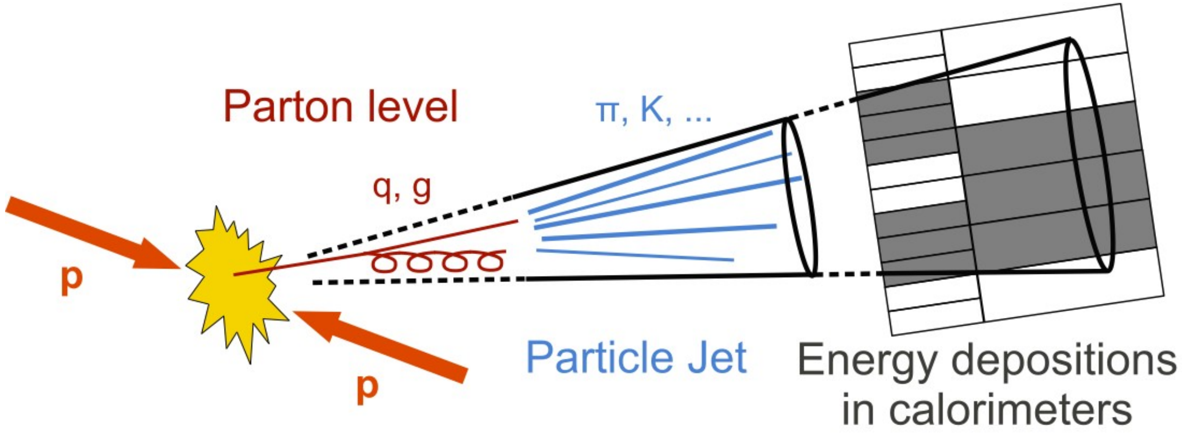
LHCP2024

June 3rd – 7th, 2024

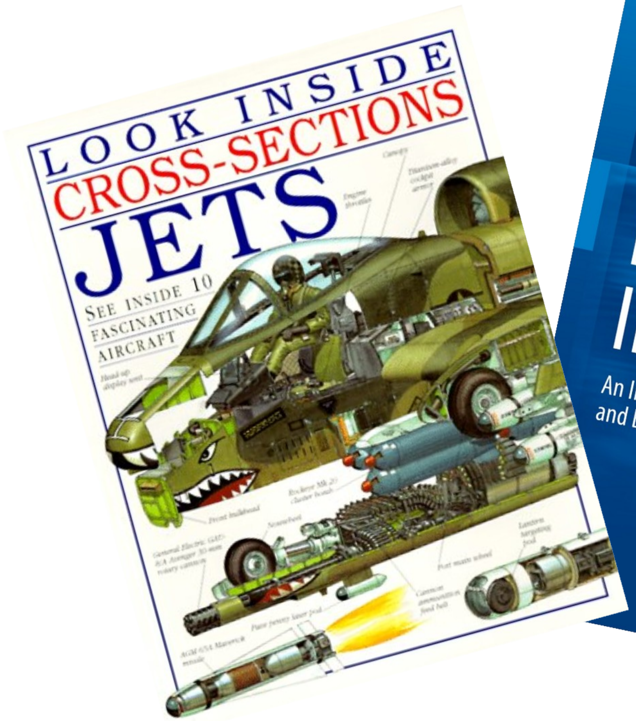
Boston, USA

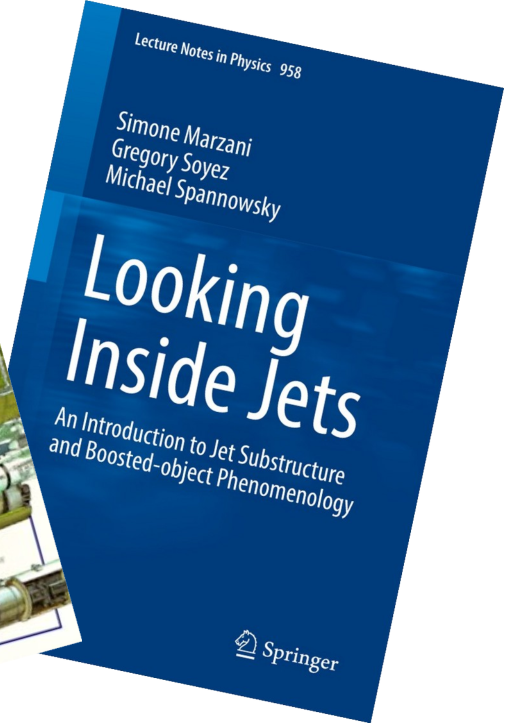


What’s a jet?



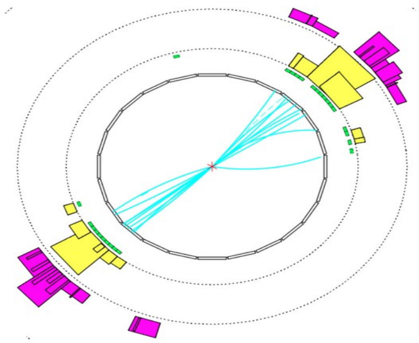
Naive definition: **collimated spray of hadrons**, ubiquitous in collider experiments, associated with the production of elementary particles that carries color charge



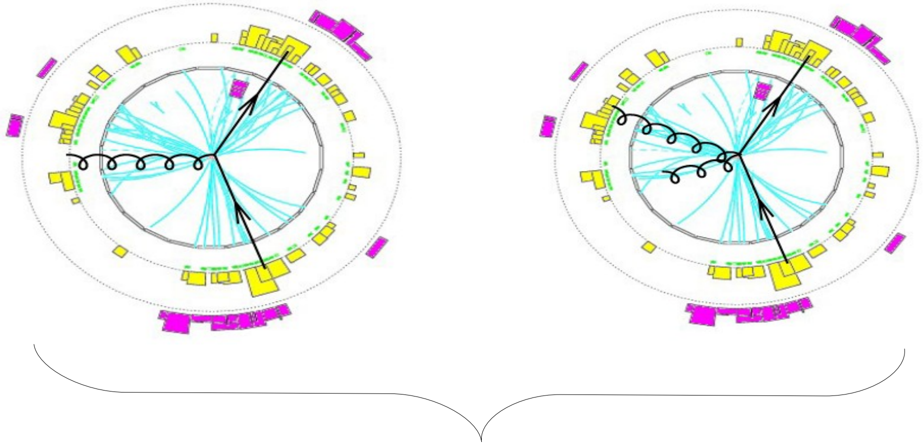


> *The design of good jet algorithms is therefore more a craft than a deductive science.*

Banfi, Salam, Zanderighi (0601139)



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

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

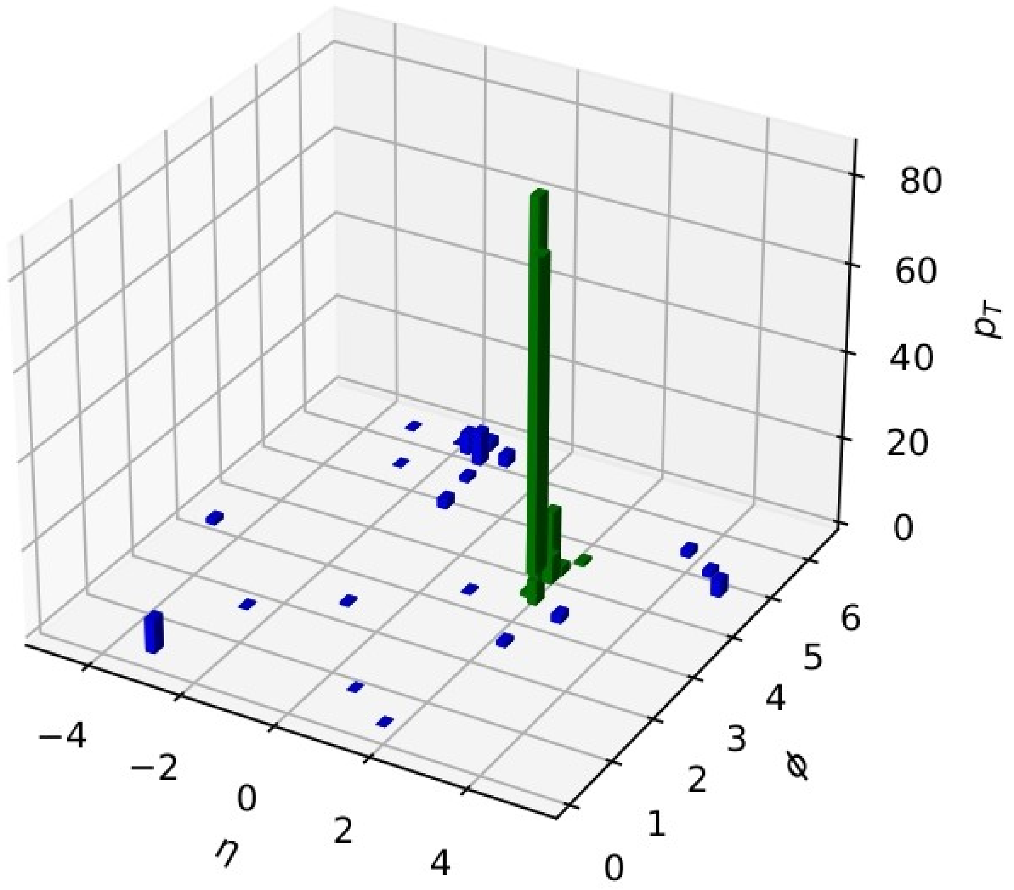
and the *beam distance* as

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

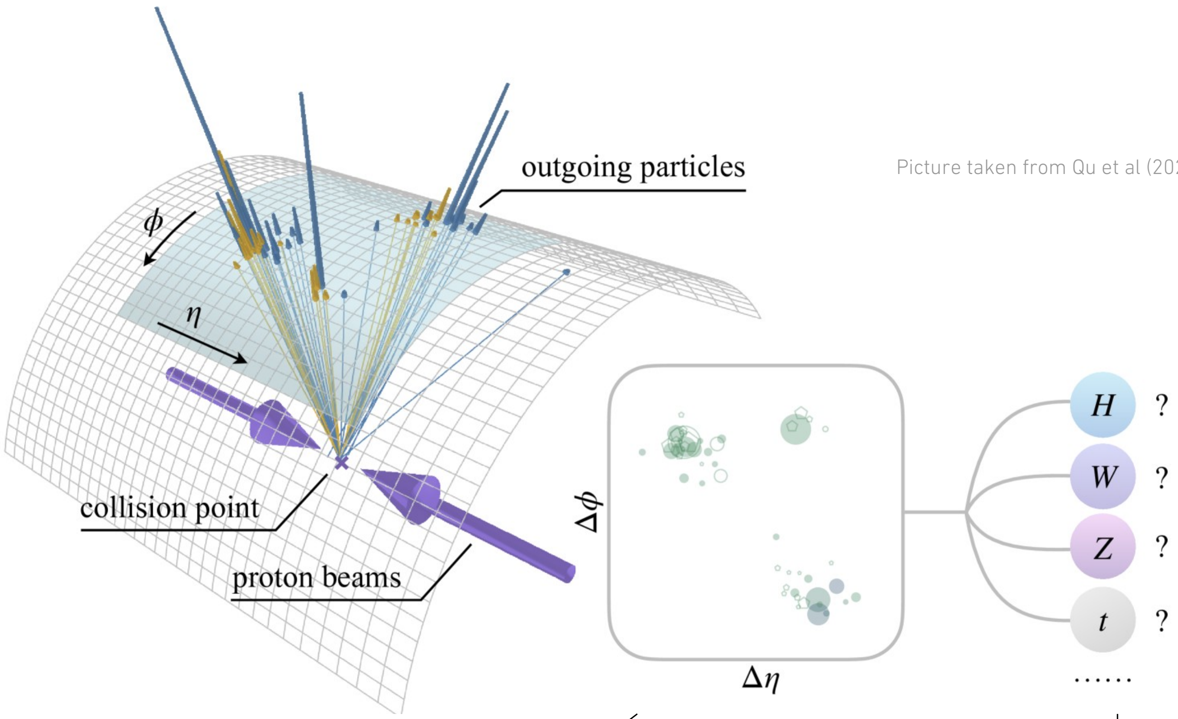
with R the jet radius.

- 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)



Jet Substructure in a nutshell



Picture taken from Qu et al (2024)

Jet Substructure
- Angularities
- Soft Drop radius for Heavy-Quark jets

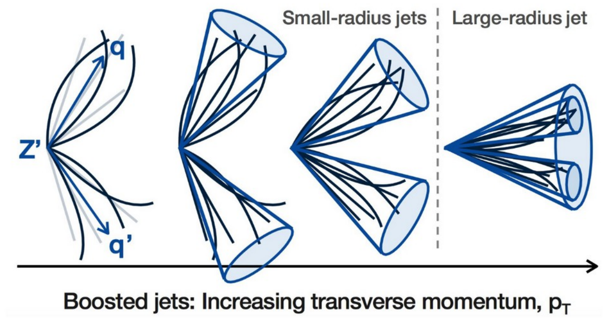
Jet tagging, flavor algorithms

THIS TALK

Main LHC goals

Search of new particles	Characterization of known particles

- Jets can be formed by QCD particles or by the decay of massive particles in a boosted regime. Is it required to distinguish between signal and background.
- Looking to the internal structure of jets can give us an insight on the originating splitting
- The picture is obscured by many effects such as: hadronization, Underlying Events, Pileup
- Useful tools are
  - Grooming → clean the jet removing soft radiation
  - Tagging → identify the feature of the hard radiation and select event looking to them



Grooming: Soft Drop

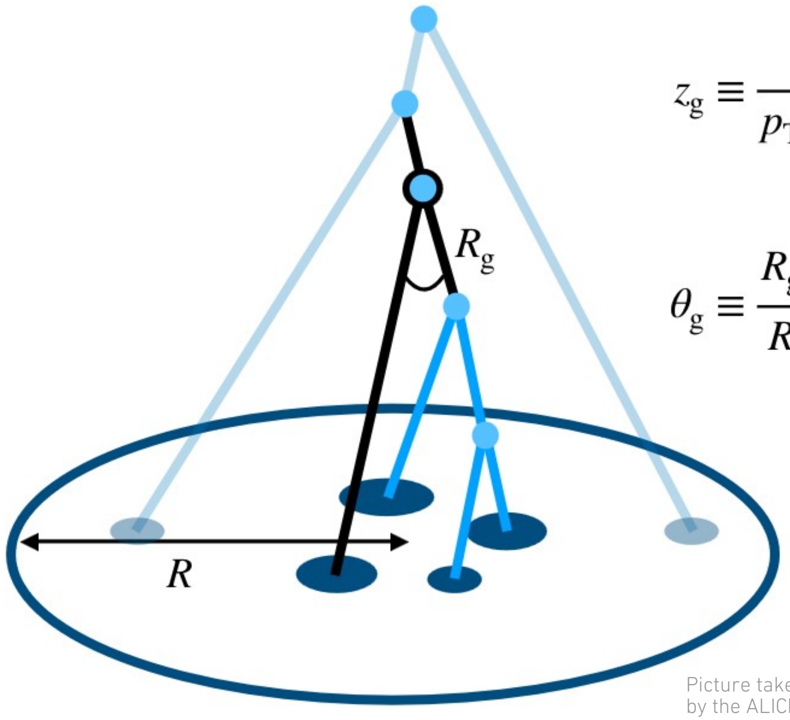
Larkoski et al. (2014)

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

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

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

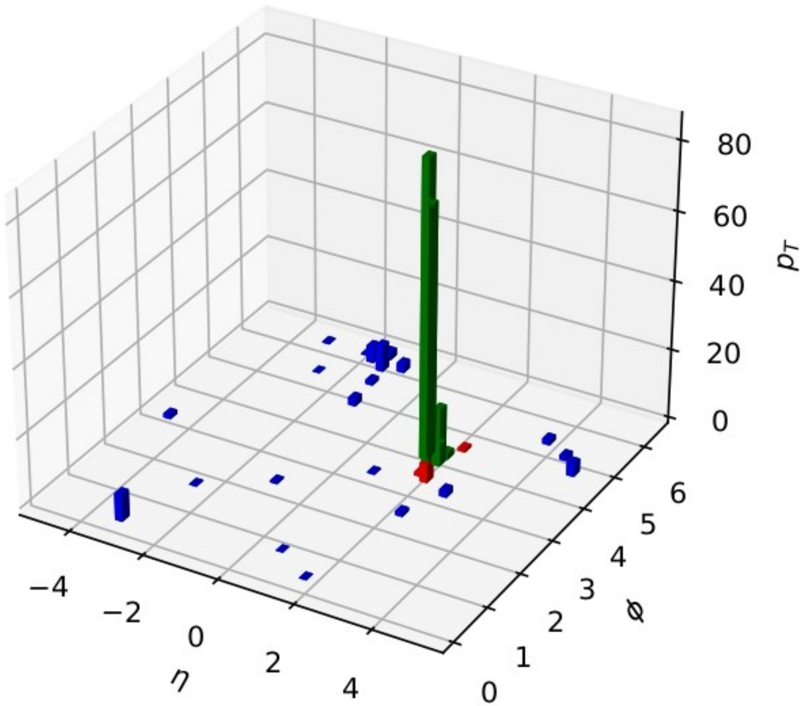
while(! SD)



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

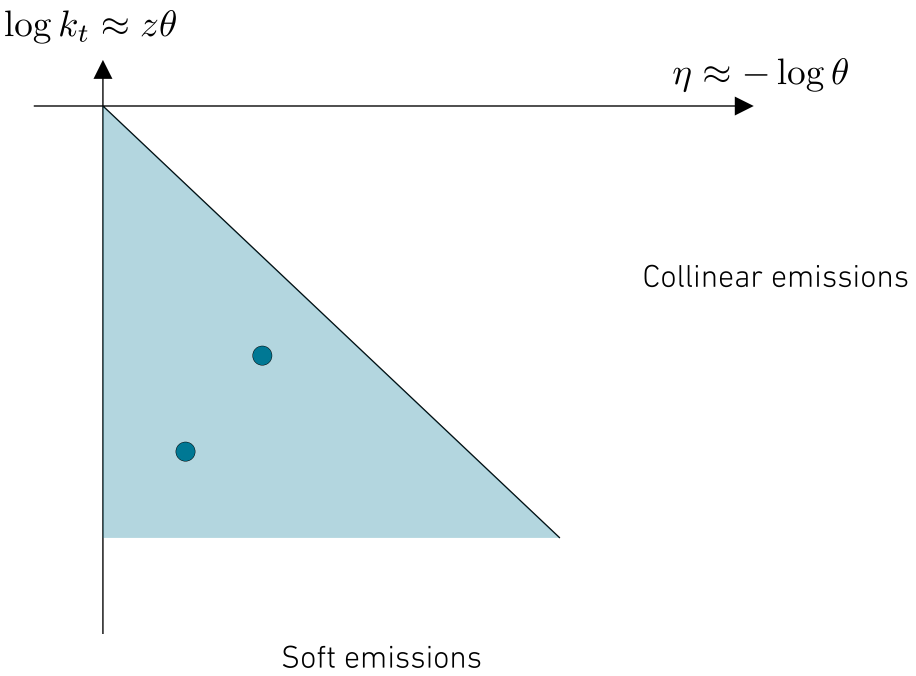
$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

Picture taken from 2204.10246
by the ALICE collaboration



The Lund Plane

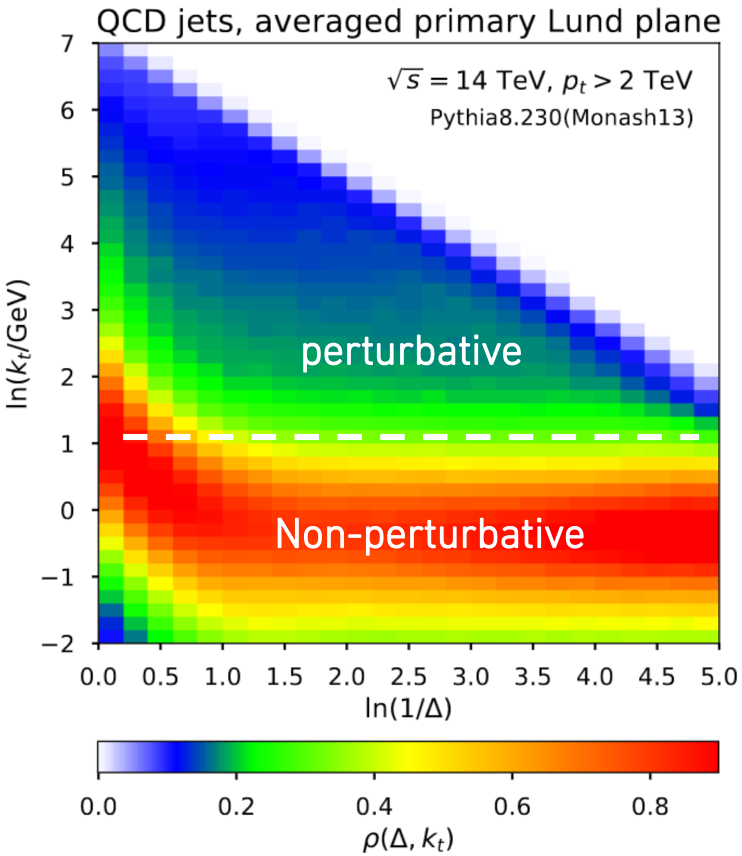
The Lund jet plane is a way to represent QCD radiation inside a jet or in the whole event and it is extremely useful in a wide range of applications.



Soft-collinear emissions are uniformly distributed among the Lund plane in a LL picture

$$\rho \simeq \frac{2\alpha_S C_F}{\pi} \approx 0.16$$

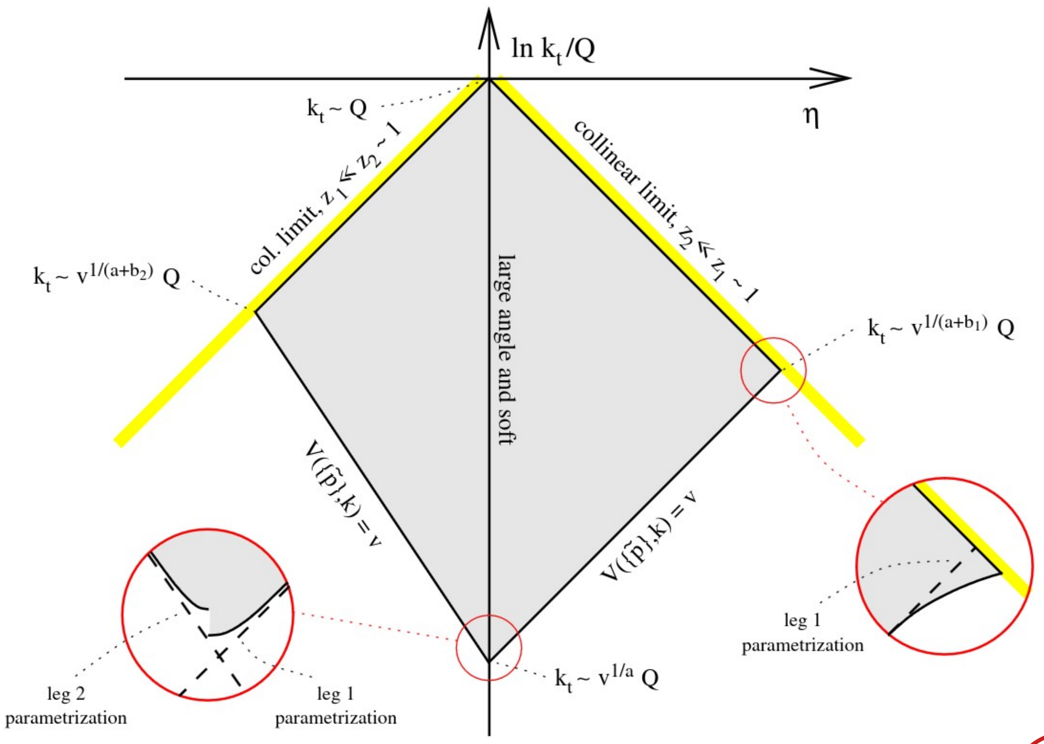
Taken from Dreyer et al (2018)



Different kinematic regimes are clearly separated

Automated resummation up to NLL

[Banfi, Salam, Zanderighi (0407286)]



$$a = 1$$

$$b_\ell = b = \alpha - 1$$

$$g_\ell d_\ell = \left(\frac{2\cosh\eta_{\rm jet}}{R}\right)^{\alpha-1}\frac{\mu_Q}{p_{T,\rm jet}R}$$

For observables that can be parameterized as

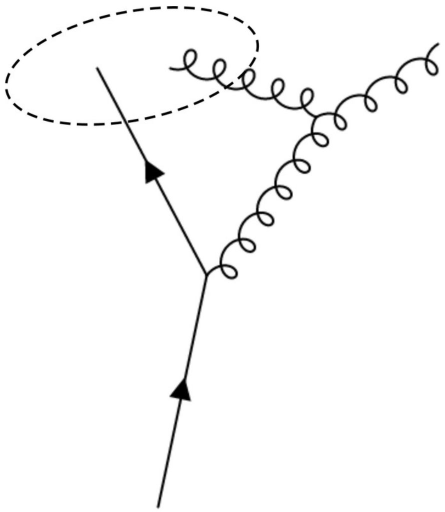
$$V(\{\tilde p\},k) = d_\ell(\mu_Q)\left(\frac{k_t^{(\ell)}}{\mu_Q}\right)^a e^{-b_\ell\eta^{(\ell)}} g_\ell(\phi^{(\ell)})$$

we have

$$\Sigma^{\rm NLL}(v) = \mathcal{M}\,\mathcal{S}\,e^{-\mathcal{R}} \quad \text{with} \quad \mathcal{M}(v) = \frac{e^{-\gamma_E\mathcal{R}'(v)}}{\Gamma(1+\mathcal{R}'(v))}$$

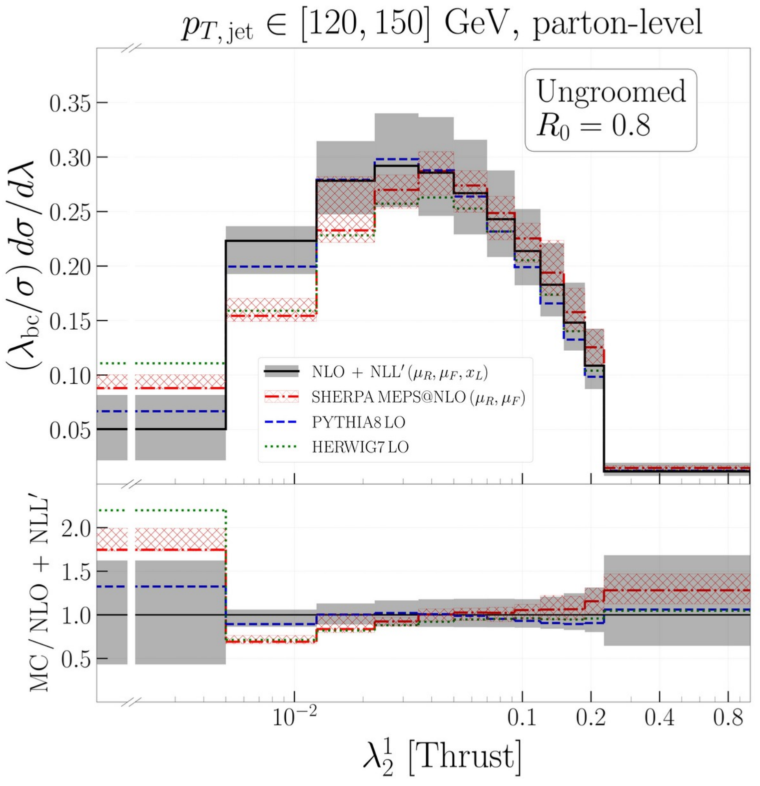
ANGULARITY

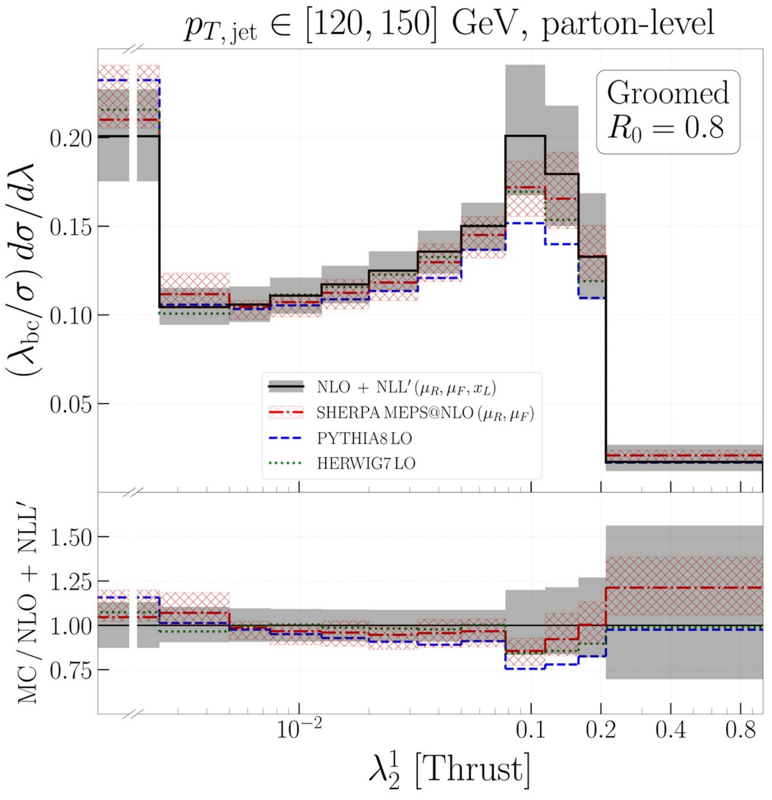
$$\lambda_\alpha^\kappa = \sum_{j\in{\rm Jet}}\left(\frac{p_{T,j}}{\sum_{j\in{\rm Jet}}p_{T,j}}\right)^\kappa\left(\frac{\Delta_j}{R}\right)^\alpha \simeq \sum_{j\in{\rm Jet}} z_j^\kappa\theta_j^\alpha$$

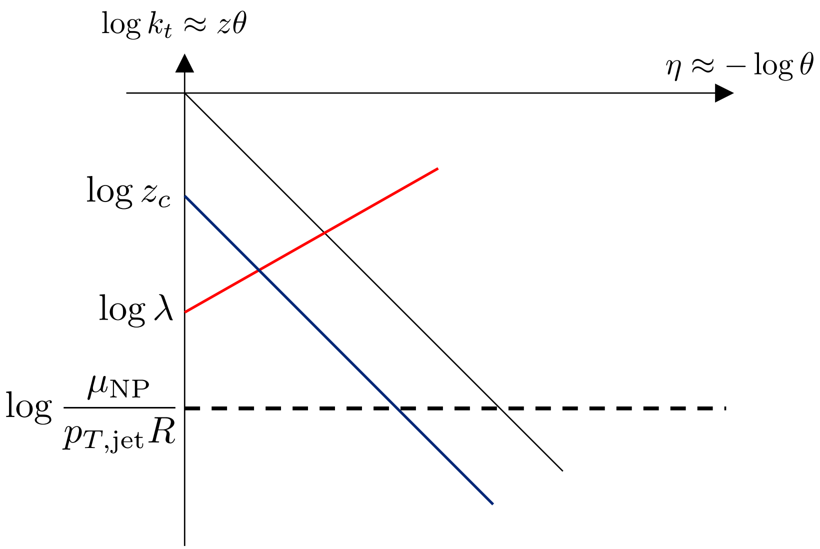


Jet Angularities in Z+jet at LHC

[SC, Fedkevych, Marzani, Reichelt, Schumann, Soyez, Theeuwes (2104.06920)]







Perturbative domain:

$\alpha > 1$

$$v > \frac{\mu_{\text{NP}}}{p_{T,\text{jet}} R} \left(\frac{\mu_{\text{NP}}}{z_{\text{cut}} p_{T,\text{jet}} R} \right)^{\frac{\alpha-1}{\beta+1}}$$

$\alpha \leq 1$ or ungroomed

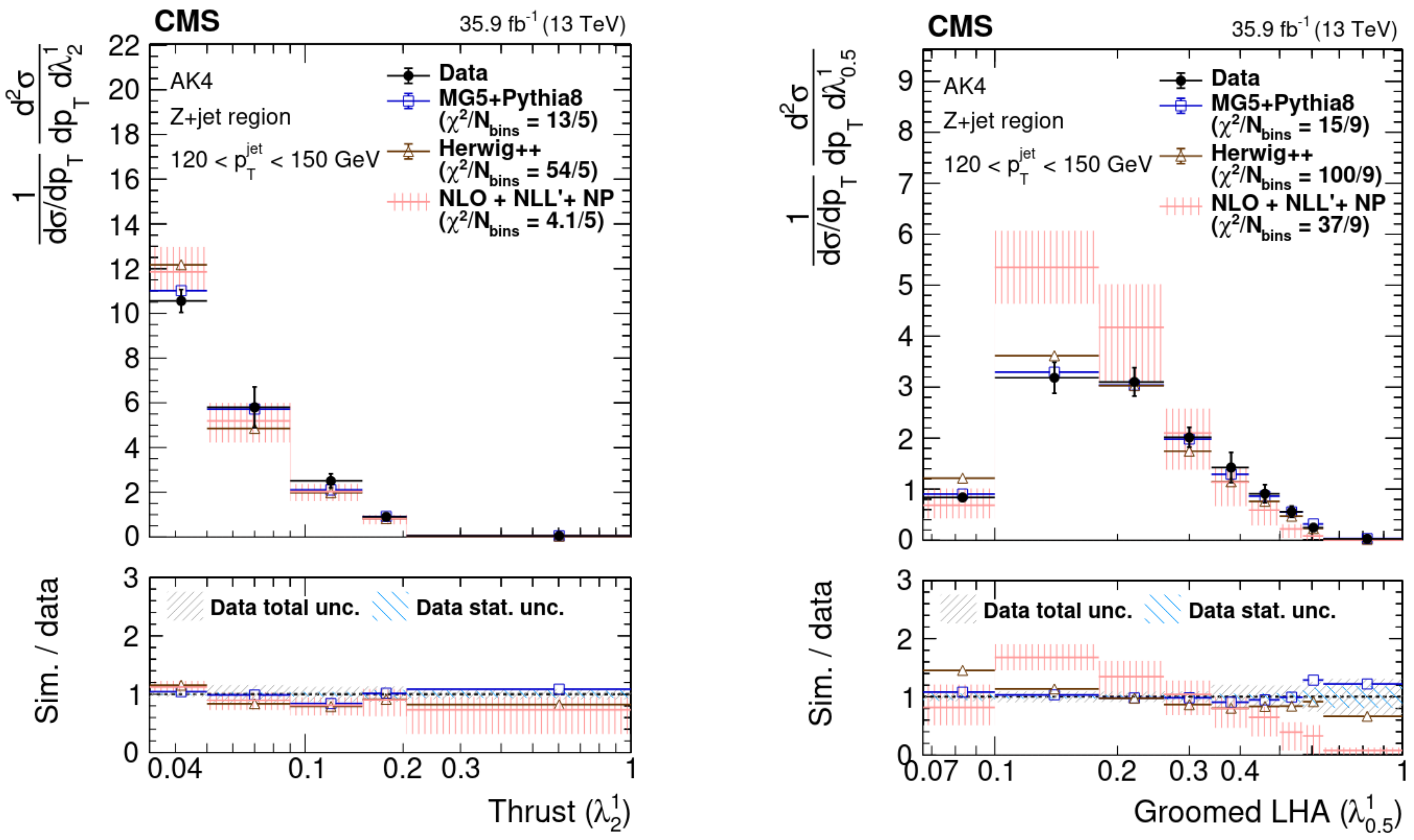
$$v > \left(\frac{\mu_{\text{NP}}}{p_{T,\text{jet}} R} \right)^{\min[\alpha,1]}$$

- Good agreement between MC and analytical predictions
- Visible NP transition point for the ungroomed case at ~0.01
- Visible SD transition point for the groomed case at ~0.1
- SD extends the perturbative domain and removes NGL

Jet Angularities in Z+jet at LHC

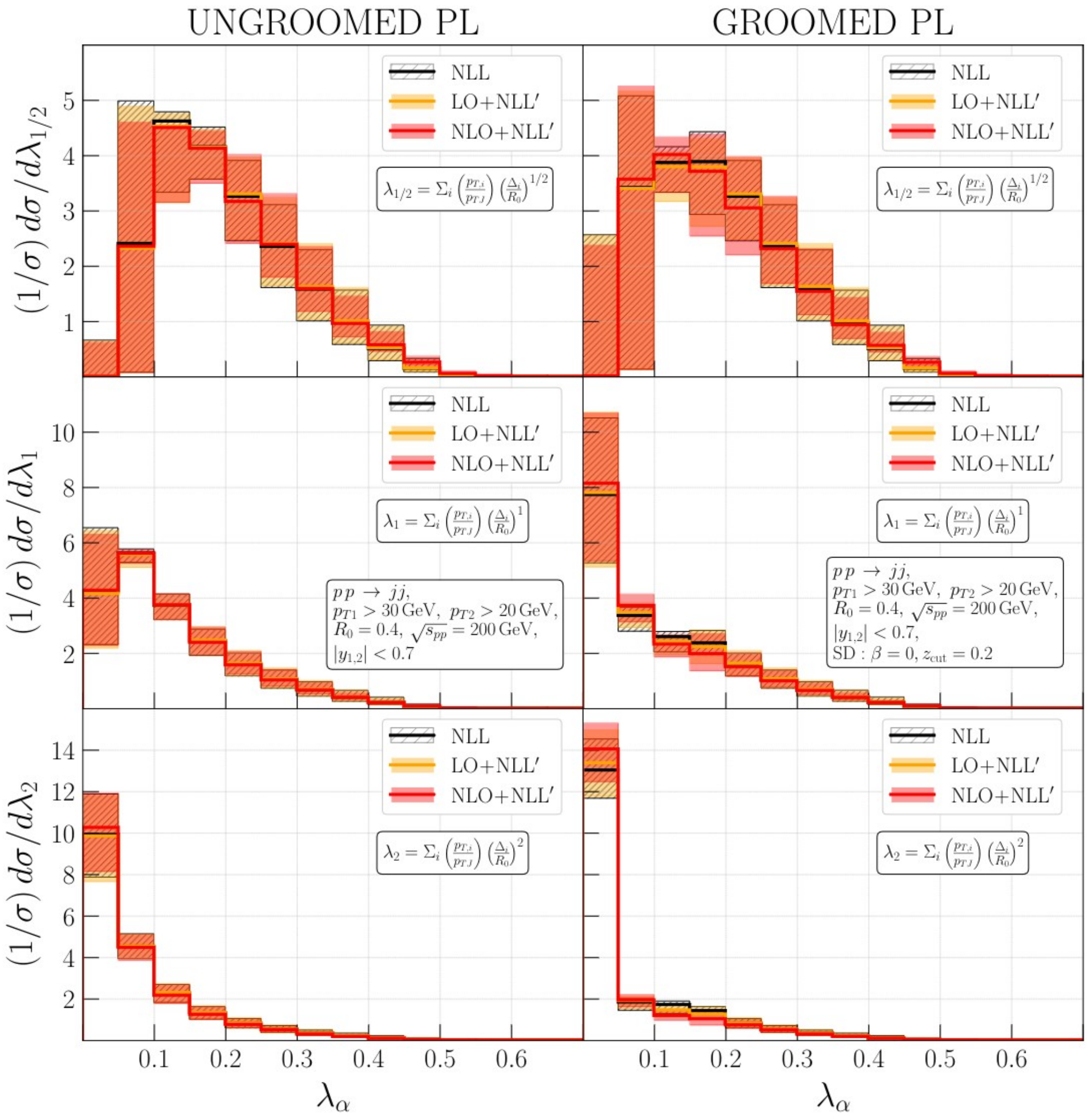
[SC, Fedkevych, Marzani, Reichelt, Schumann, Soyez, Theeuwes (2104.06920)]
[CMS Collaboration (2109.03340)]

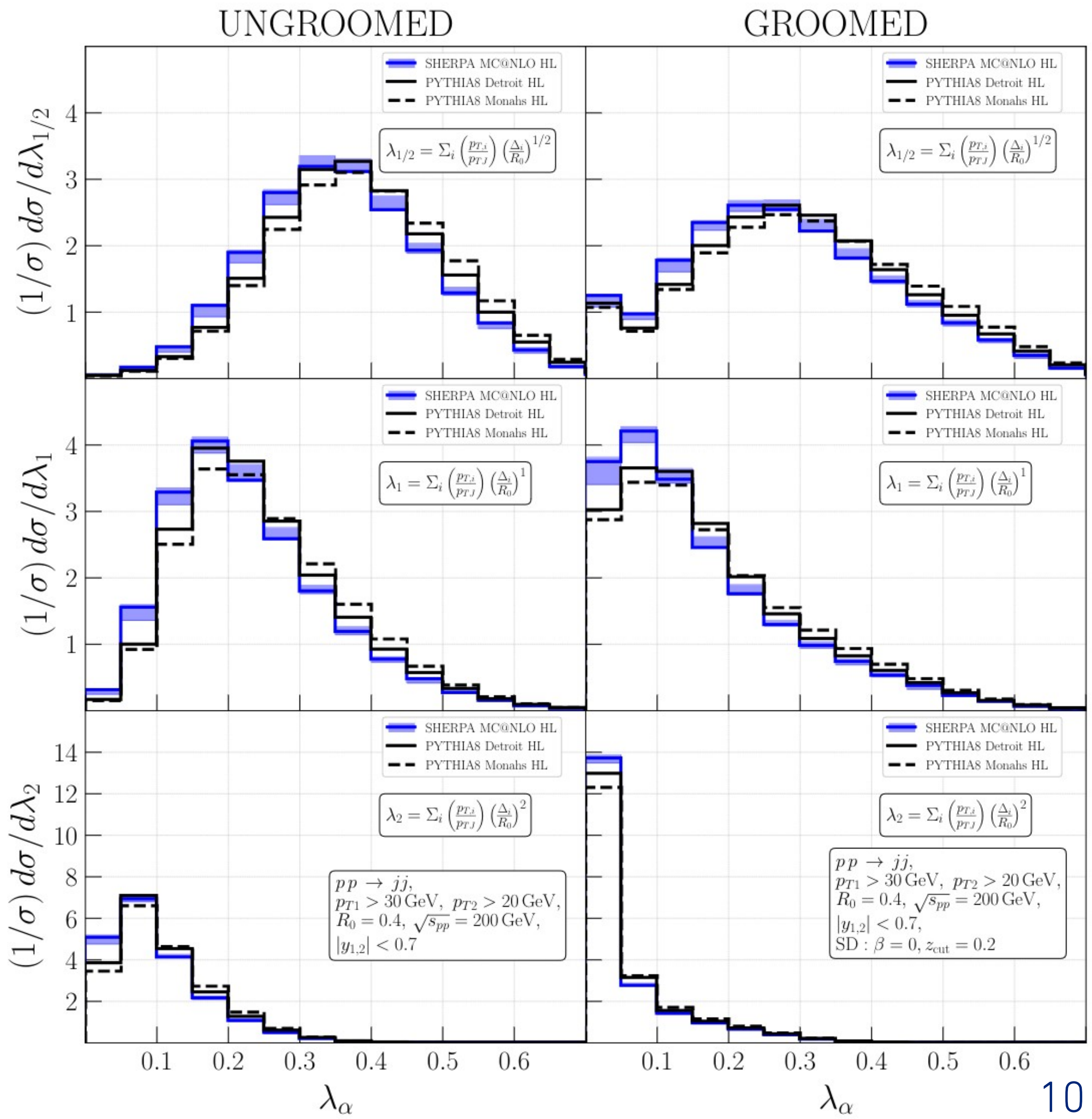
- NLL resummation with NLO matching is automated within a SHERPA plugin
- This allows to easily produce predictions for pheno studies



Jet Angularities in dijet at RHIC

[Chien, Fedkevych, Reichelt, Schumann (2404.04168)]





Non-perturbative corrections

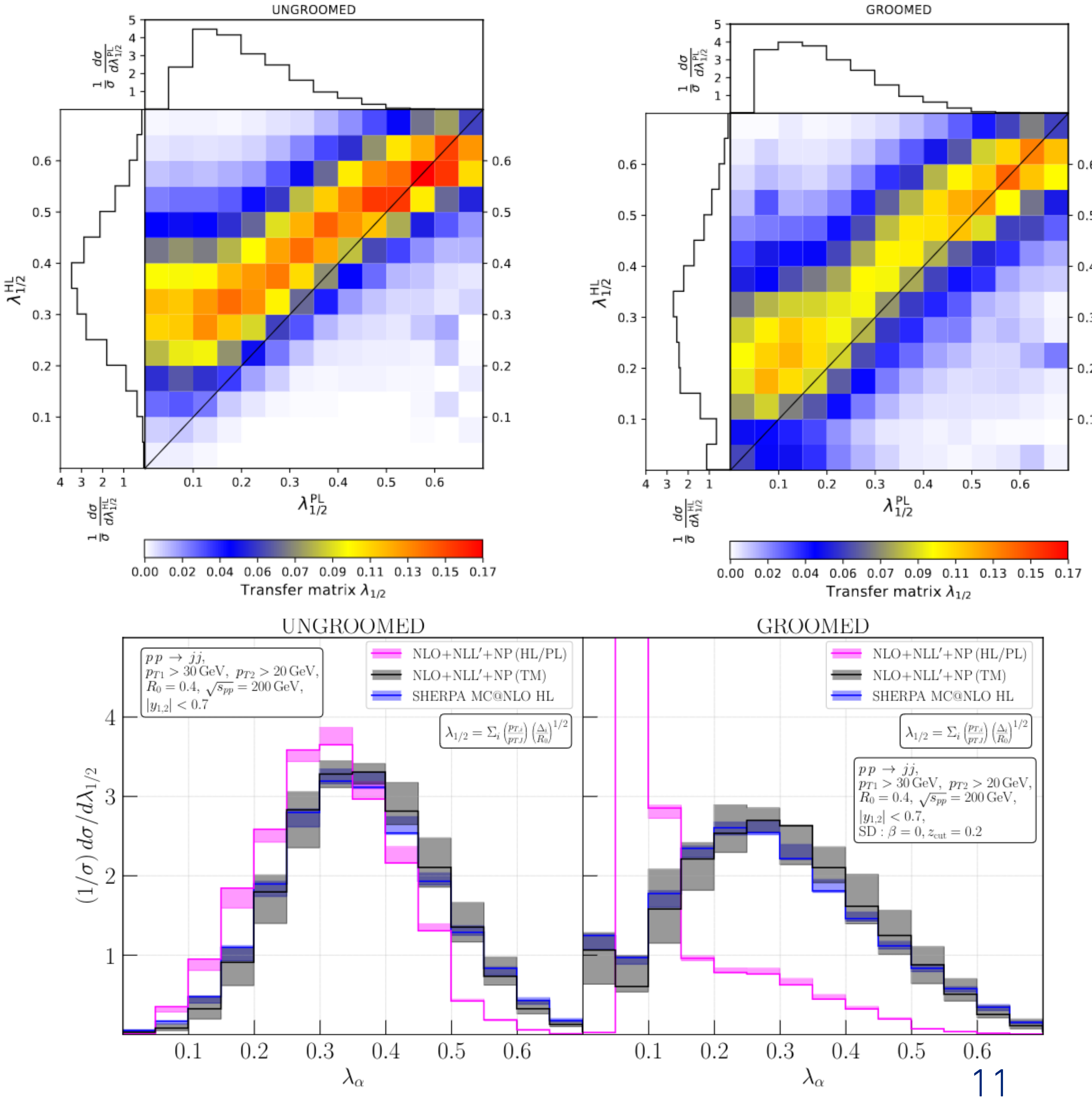
[Chien, Fedkevych, Reichelt, Schumann (2404.04168)]

$$\mathcal{T}(\vec{v}_h|\vec{v}_p) = \frac{\int d\mathcal{P} \frac{d\sigma}{d\mathcal{P}} \delta^{(m)}\left(\vec{v}_p - \vec{V}(\mathcal{P})\right) \delta^{(n)}\left(\vec{v}_h - \vec{V}(\mathcal{H}(\mathcal{P}))\right)}{\int d\mathcal{P} \frac{d\sigma}{d\mathcal{P}} \delta^{(m)}\left(\vec{v}_p - \vec{V}(\mathcal{P})\right)}$$

$$\frac{d^m \sigma^{\mathrm{HL}}}{dv_{h,1}\dots dv_{h,m}} = \int d^m \vec{v}_p \mathcal{T}(\vec{v}_h|\vec{v}_p) \frac{d^m \sigma^{\mathrm{PL}}}{dv_{p,1}\dots dv_{p,m}}$$

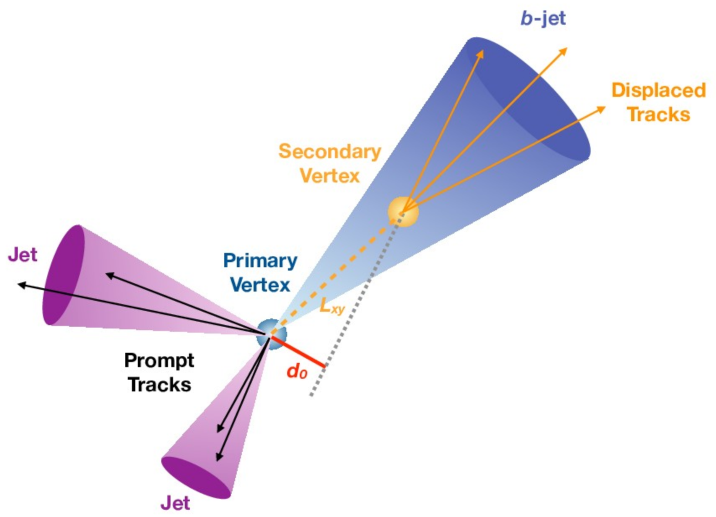
- The element of the transfer matrix can be extracted from MC event generator if individual events are accessible at different stages of their evolution in the simulation process.

- Transfer matrix corrections are very compatible with pure MC predictions, especially for the groomed case.



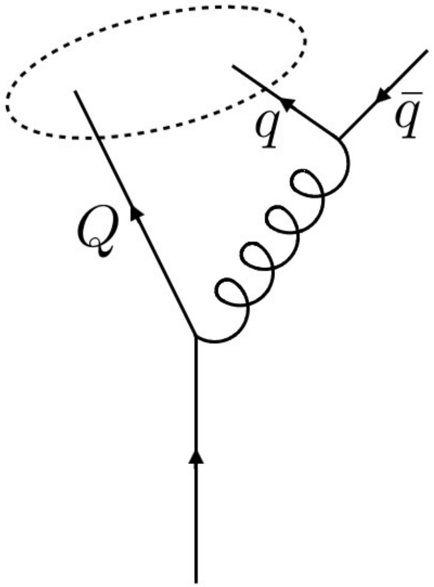
Flavor algorithms

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

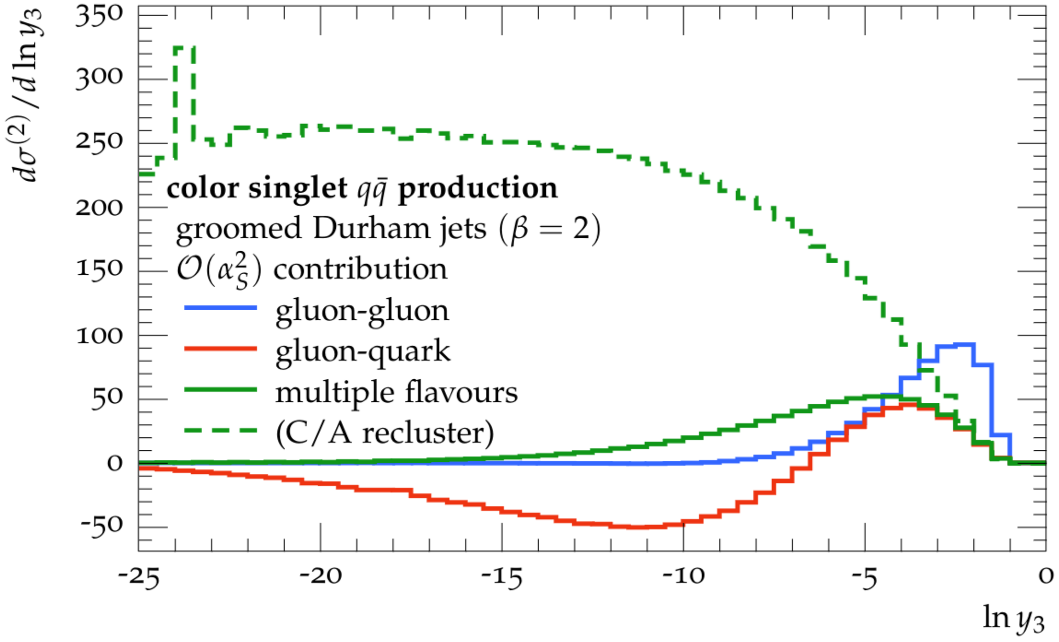


https://cds.cern.ch/record/2771727/plots

- 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.



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

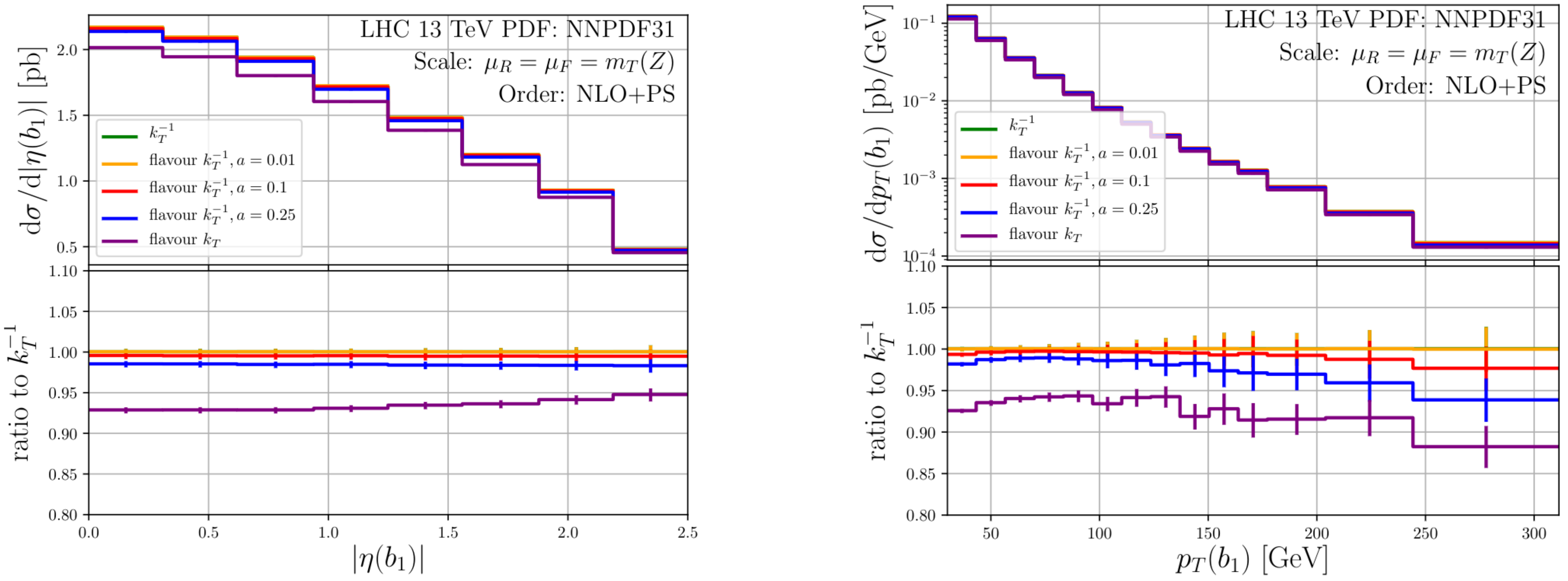


Flavor algorithms

[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:

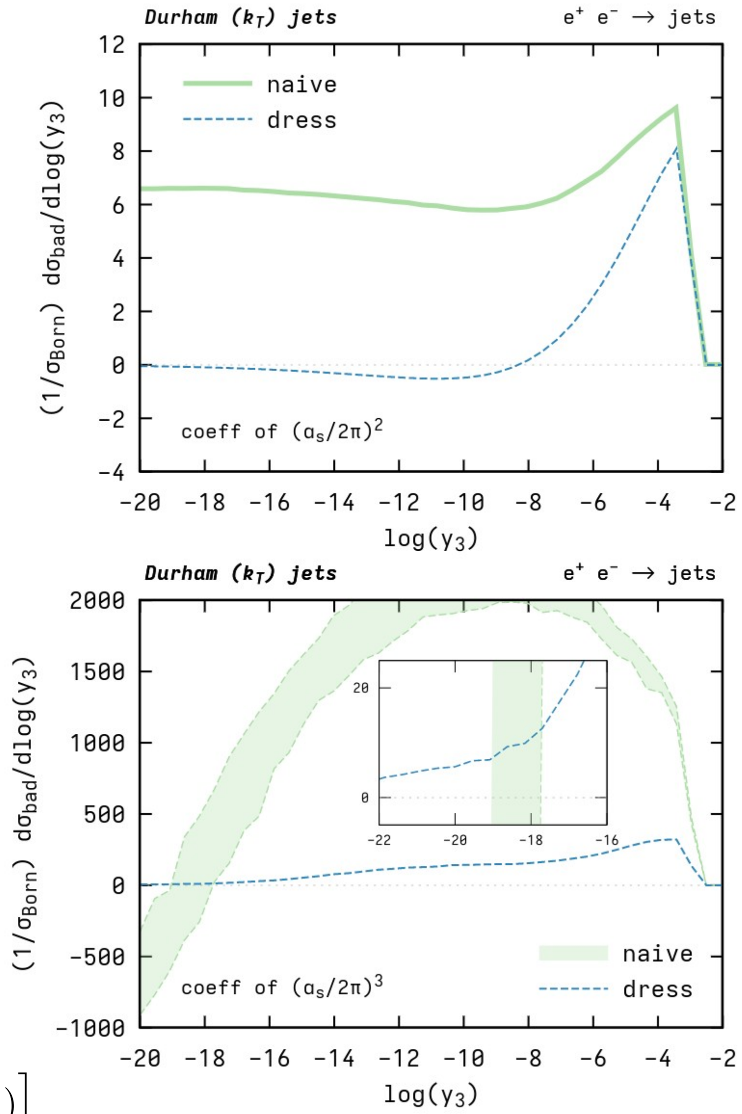
   (a) d_{p_i,p_j} is the smallest. Merge the two particles into a new particle k_{ij} carring the sum of the four-momenta and flavor. All entries in $\mathcal{D}$ involving p_i or p_j are removed and new distances for k_{ij} are added to $\mathcal{D}$.

   (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.

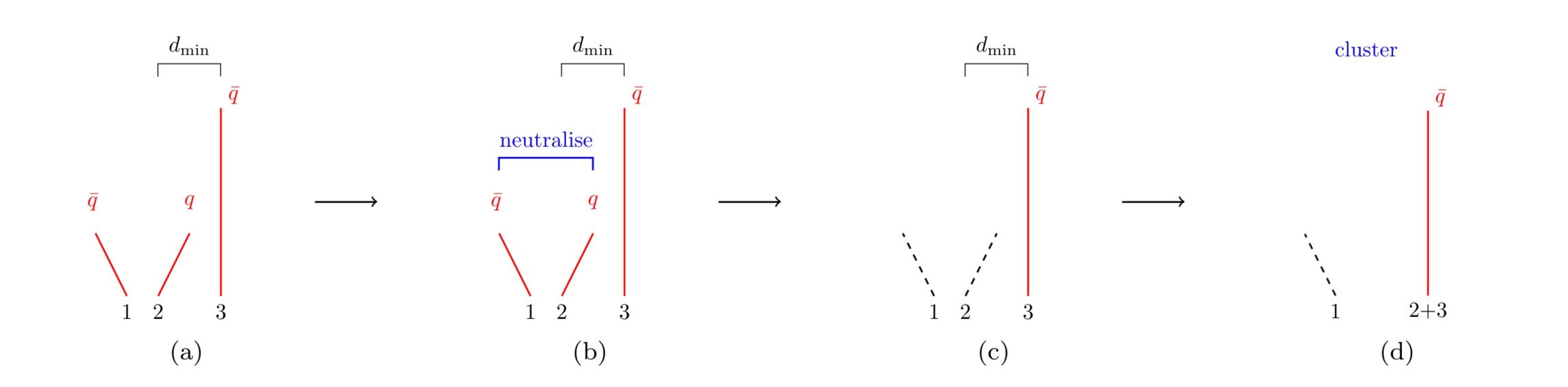
4. The flavor assignment for the jet j_k is determined according to the accumulated flavors in tag_k.

$$d_{ab} = \Omega_{ab}^2 \max(p_{T,a}^{\alpha}, p_{T,b}^{\alpha}) \min(p_{T,a}^{2-\alpha}, p_{T,b}^{2-\alpha}) \qquad \Omega_{ab}^2 = 2\left[\frac{1}{\omega^2}\left(\cosh(\omega \Delta y_{ab}) - 1\right) - (\cos\Delta\phi - 1)\right]$$



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.

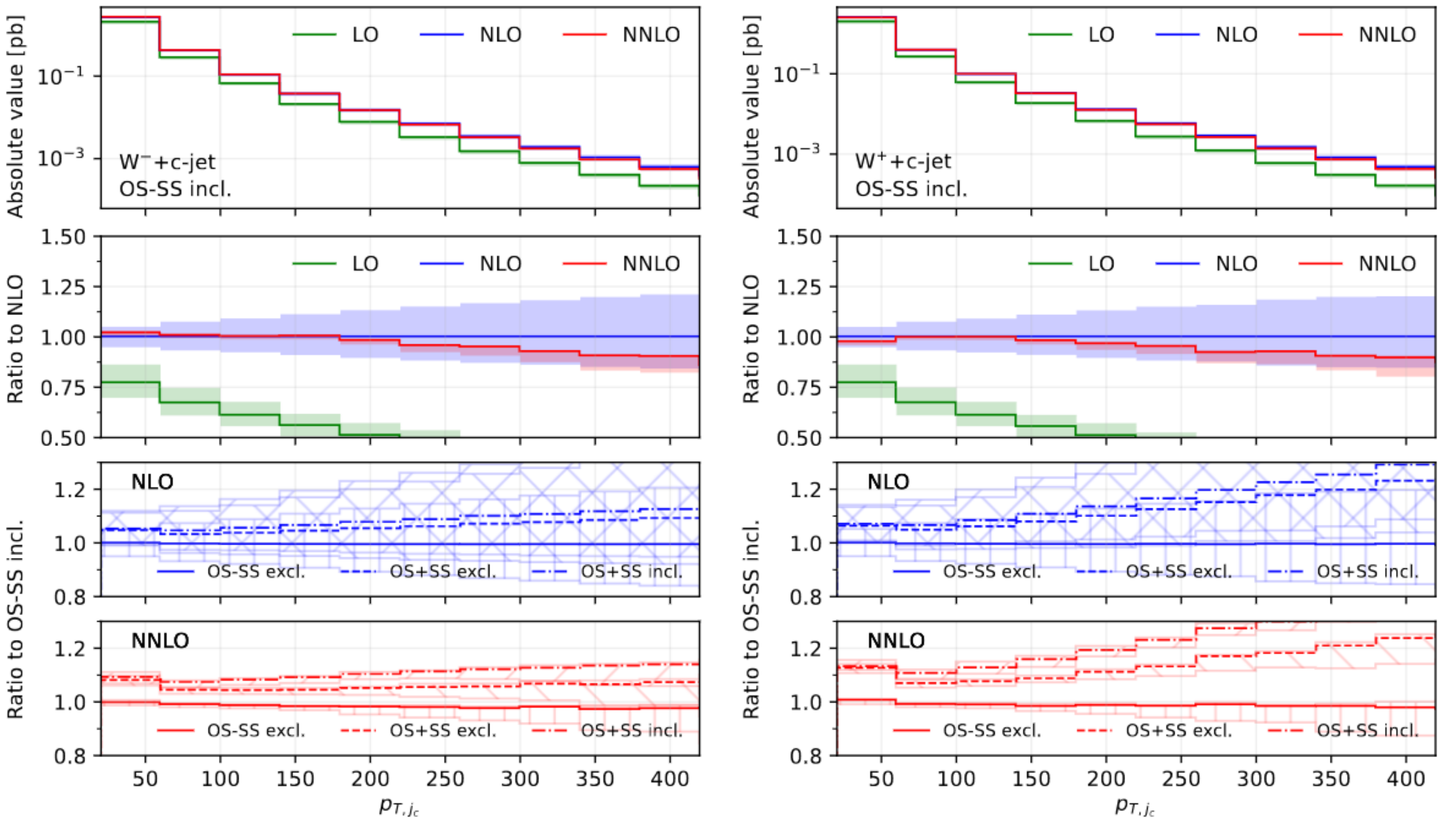
$$u_{ik} = \max(p_{T,i}^{\alpha}, p_{T,j}^{\alpha}) \min(p_{T,i}^{2-\alpha}, p_{T,j}^{2-\alpha}) \times \Omega_{ij}^2$$

The neutralization metric is given by

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

W+c-jet @ NNLO

[Gehrmann-De Ridder, Gehrmann, Glover., Huss, Rodriguez Garcia, Stagnitto (2311.14991)]
[Czakon, Mitov, Pellen, Poncelet (2212.00467)]



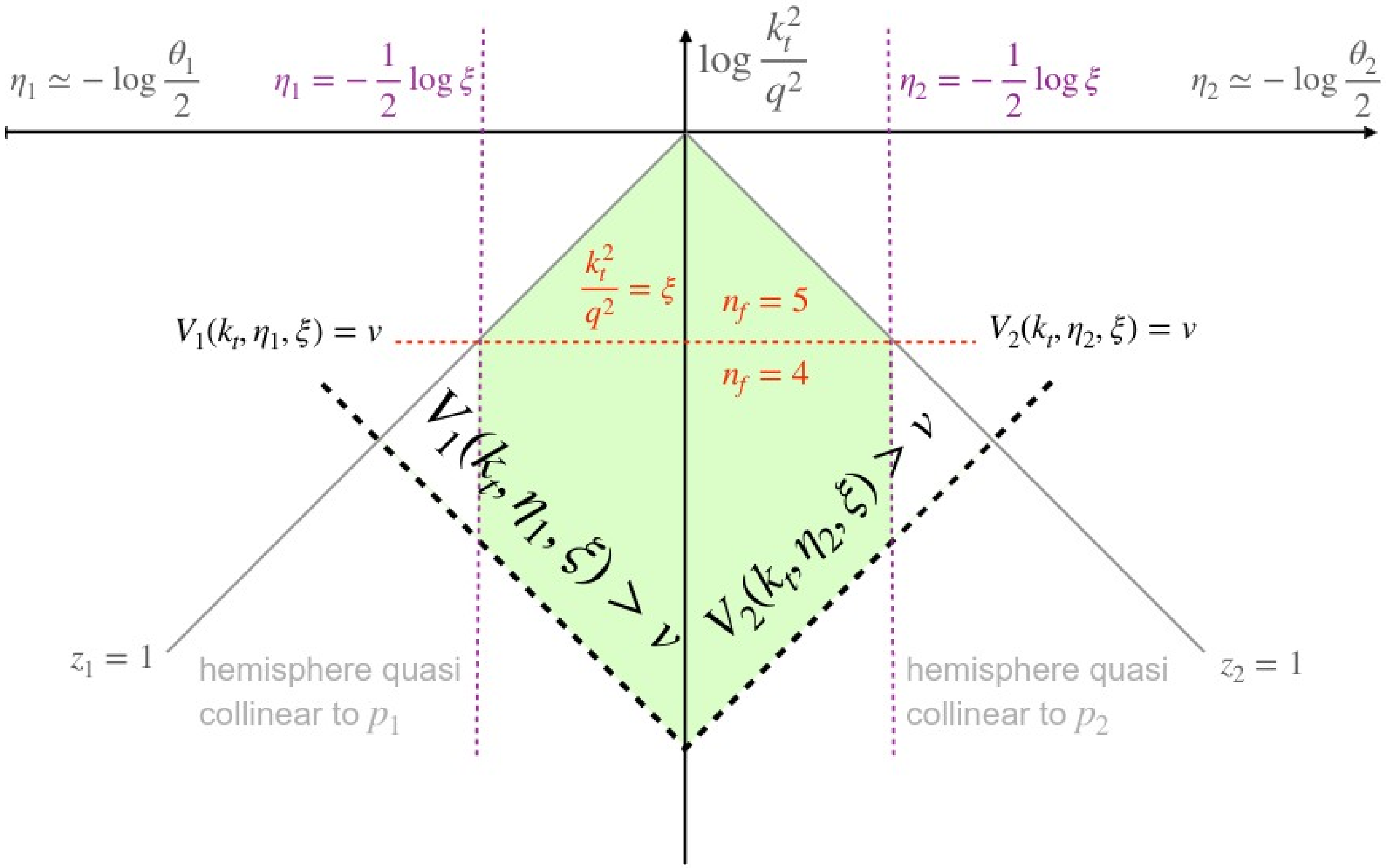
- First calculations employing IRC safe flavor algorithms for V+h processes are available.
- Last Les Houches workshop played a central role in implementing all the flavor algorithm within the fastjet contrib framework (hopefully available soon).

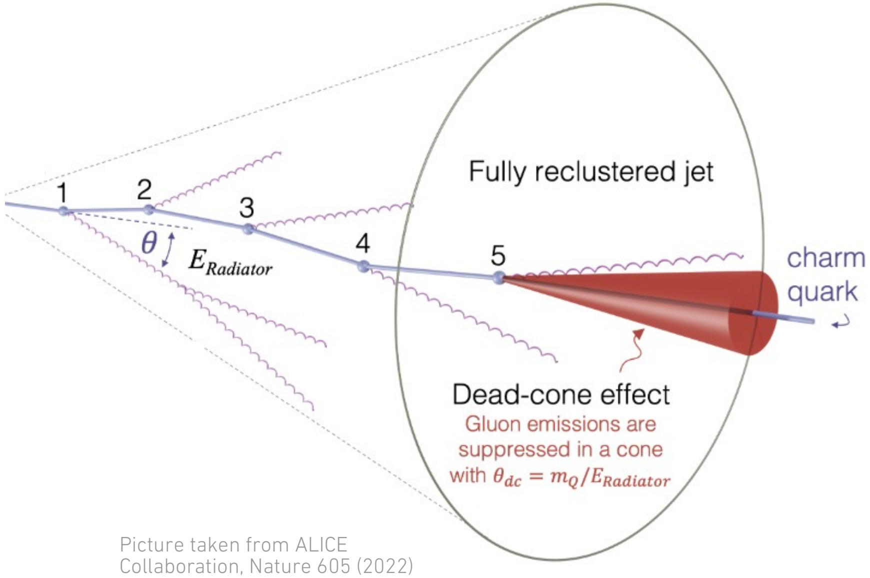
What about JSS for heavy-quark-initiated jets?

→ Also, see talk by Matthew yesterday

Lund Plane for massive particles

[Ghira, Marzani, Ridolfi (2309.06139)]





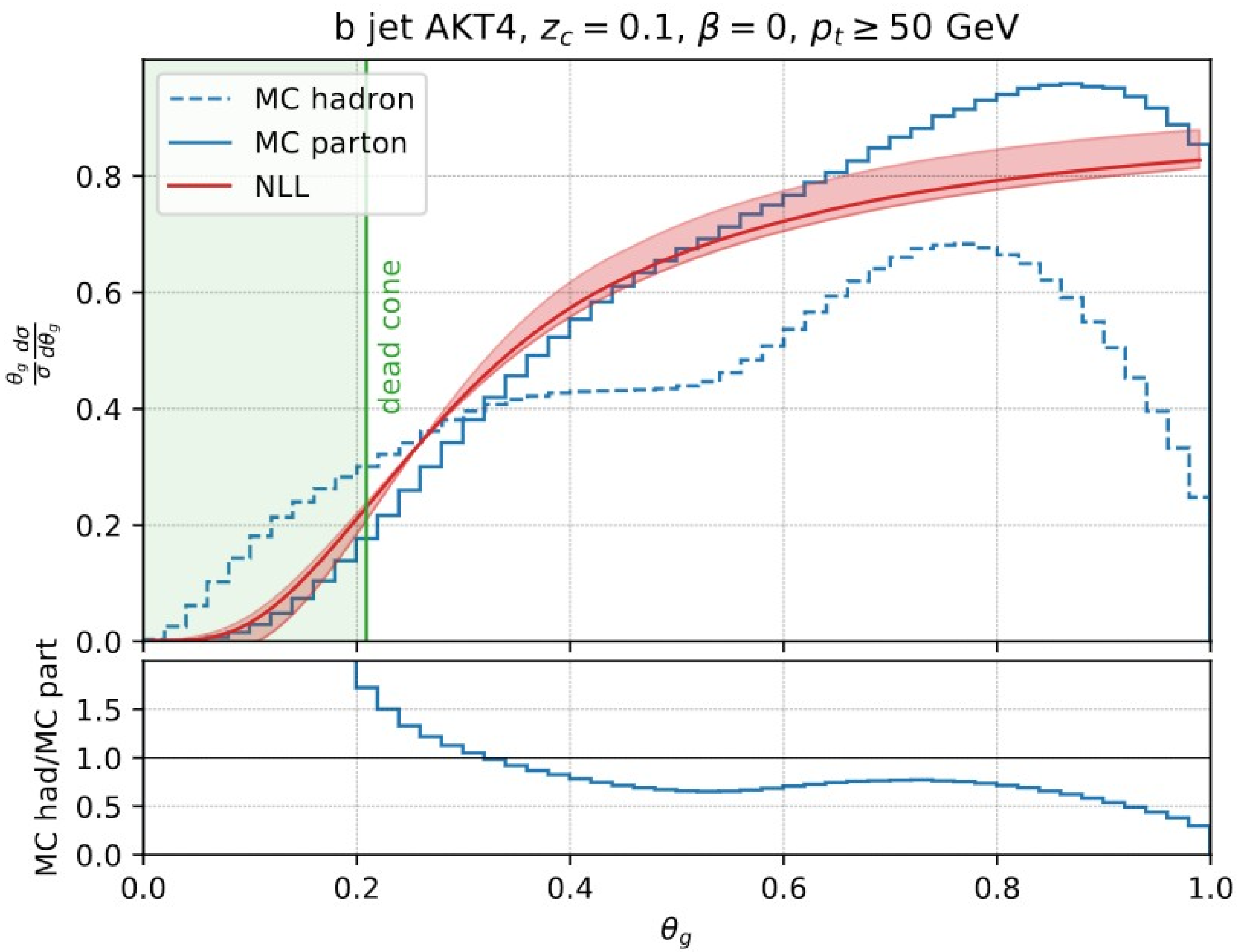
Picture taken from ALICE Collaboration, Nature 605 (2022) 440-446

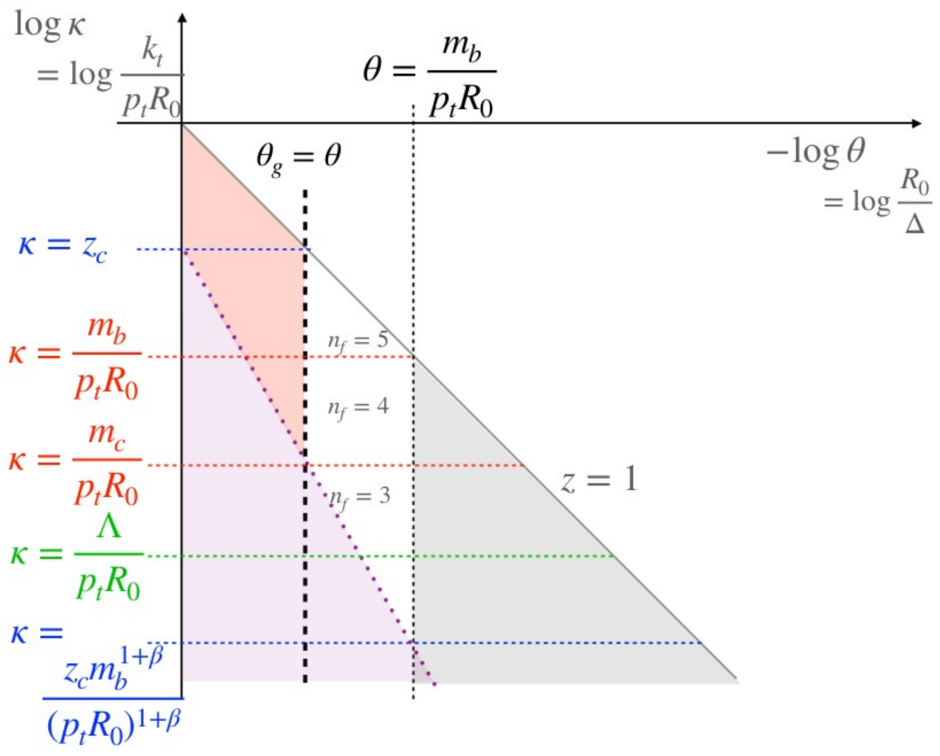
$$\alpha_S \int \frac{d\theta^2}{\theta^2 + \frac{m^2}{Q^2}} \sim \alpha_S \log \frac{m^2}{Q^2}$$

- When jets are initiated by a heavy flavor quark , the quark mass shields the collinear singularity → dead-cone effect
- In the massive case, we can still employ the Lund plane technique to compute the Sudakov form factor, provided that we reduce the available phase-space introducing two vertical lines set by the quark mass.

Heavy-flavor jets substructure

[SC, Ghira, Marzani (2312.11623)]





- Heavy quark jets allow to explore the dead-cone effect and to study heavy-quark fragmentation.
- First jet substructure resummed calculations with mass effects are available. Still to work on automatization, matching, etc. in order to provide full phenomenology.
- It would be interesting to compare heavy quark jet measurements with in-jet hadron fragmentation.

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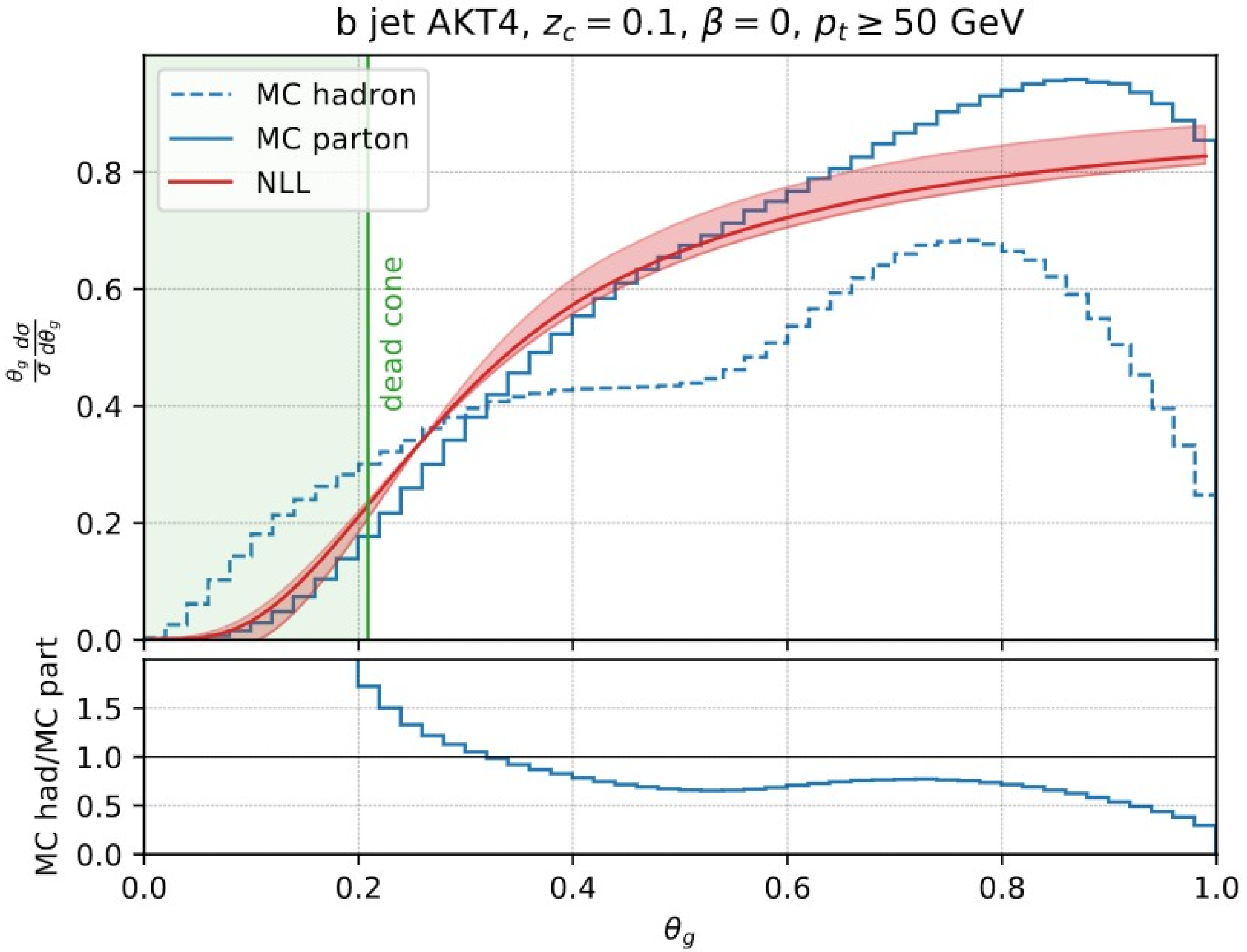

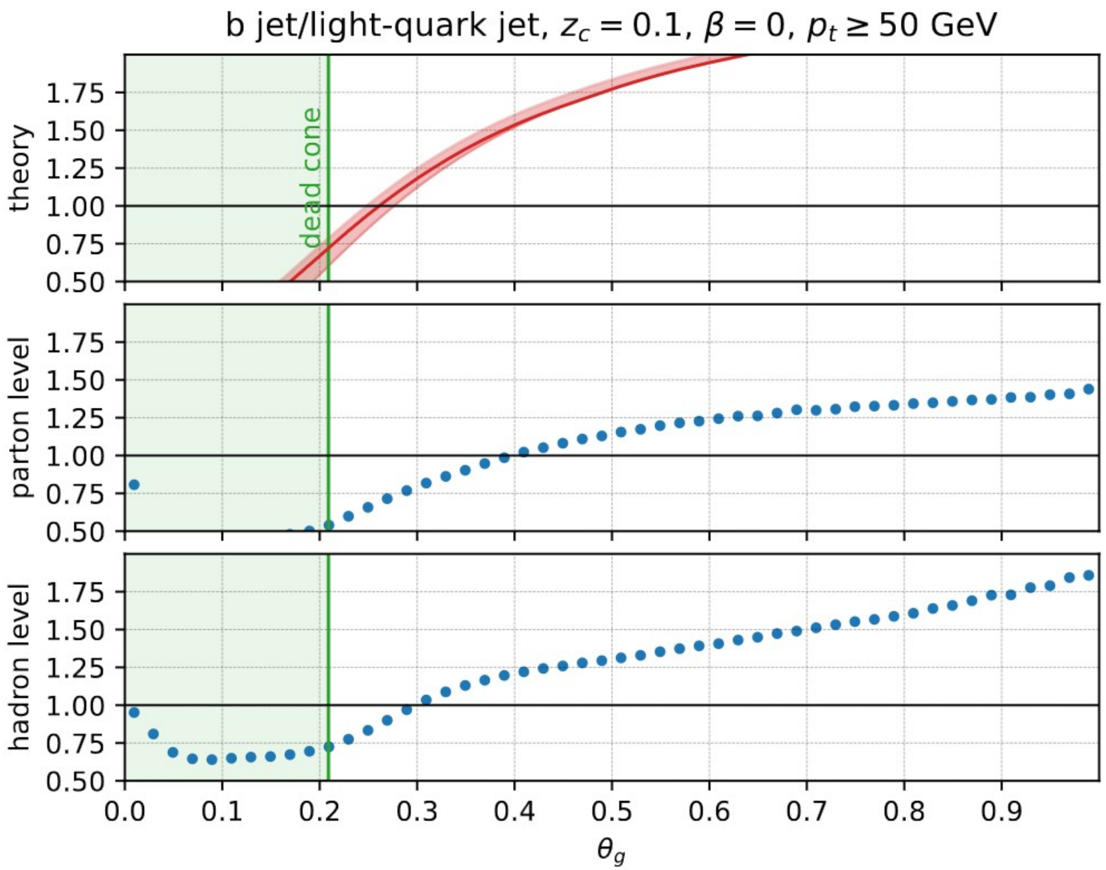

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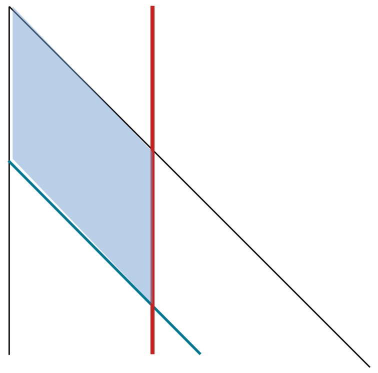
Heavy-flavor jets substructure

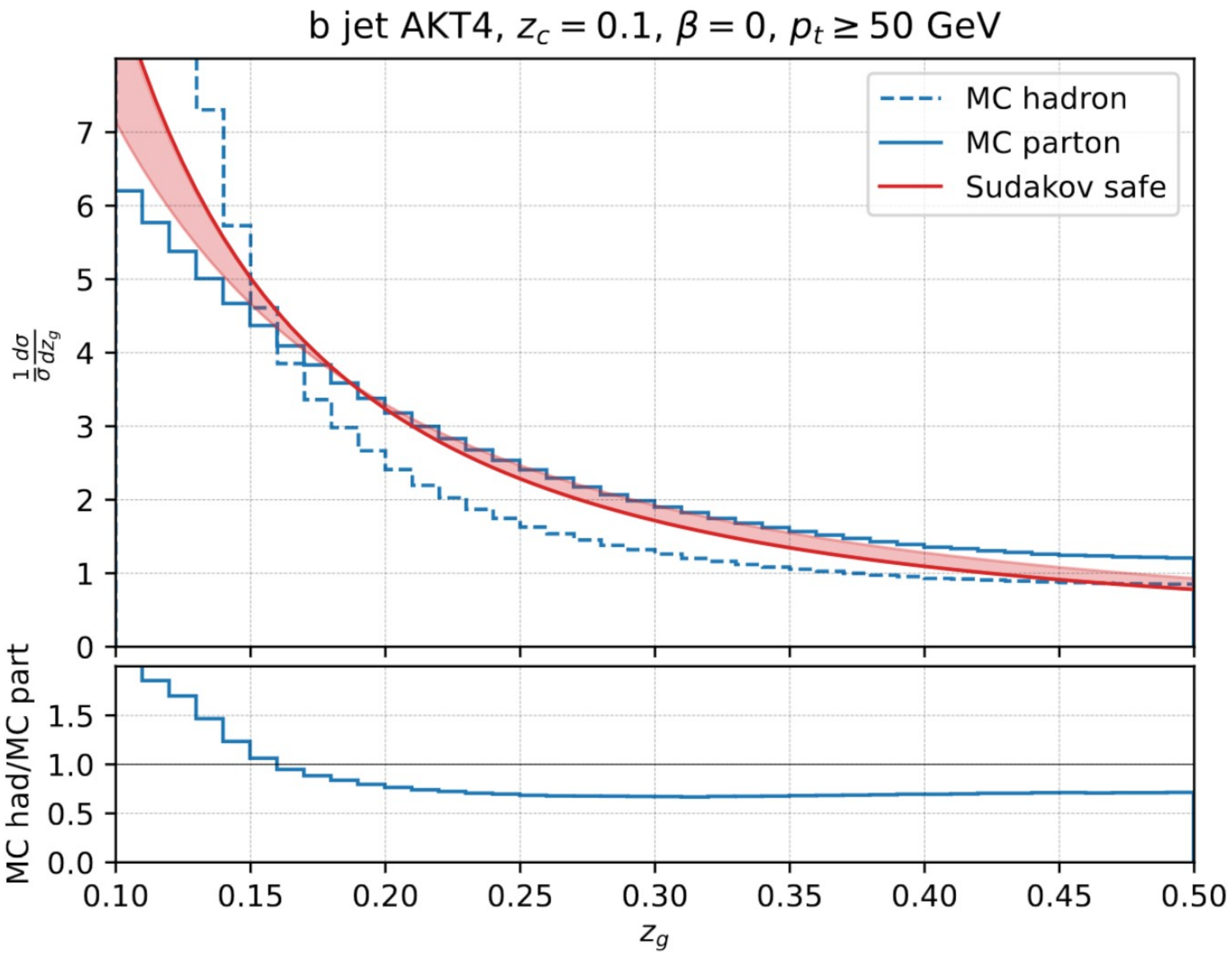
[SC, Ghira, Marzani (2312.11623)]

z_g is **not** IRC safe in the massless case for β≥0.
It can be computed using the Sudakov safety prescription, also in the massive case



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

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.



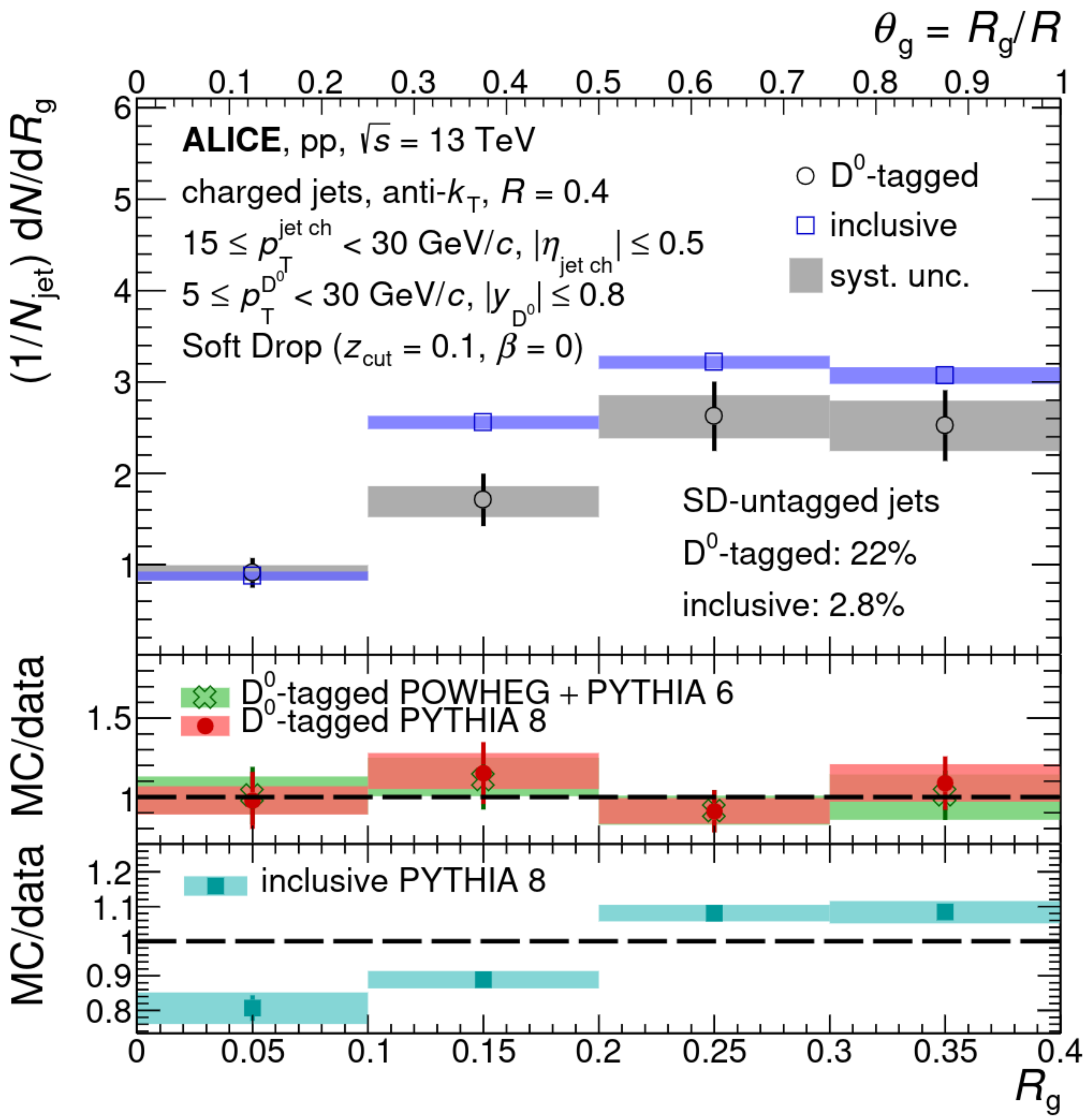
→ in the high-z_g region we undershoot the MC prediction because we used unsymmetrized splitting functions

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

Heavy-flavor jets substructure

[ALICE Collaboration (2204.10246) and (2208.04857)]

- Measurements of the SD radius for charm jets.
- 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 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.



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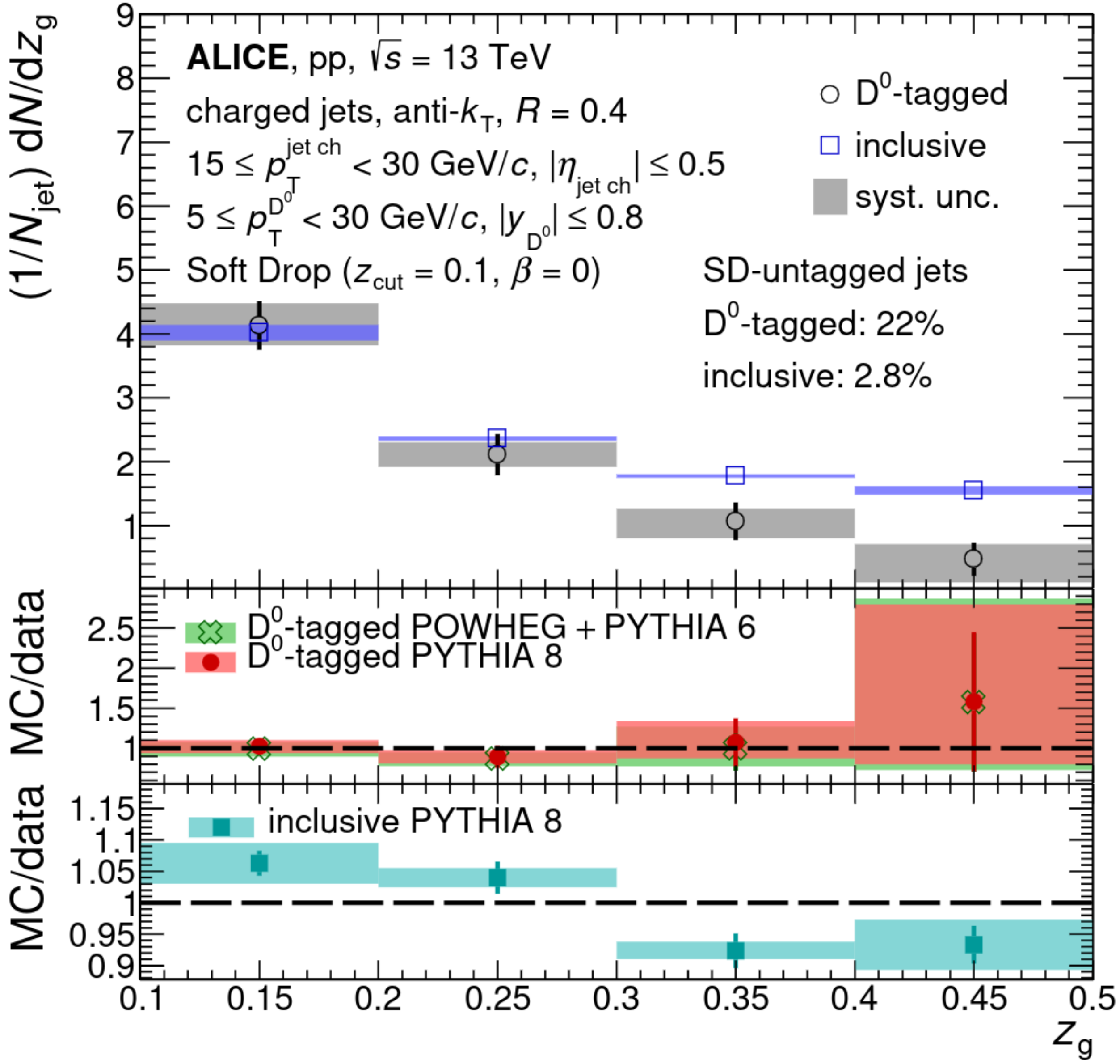
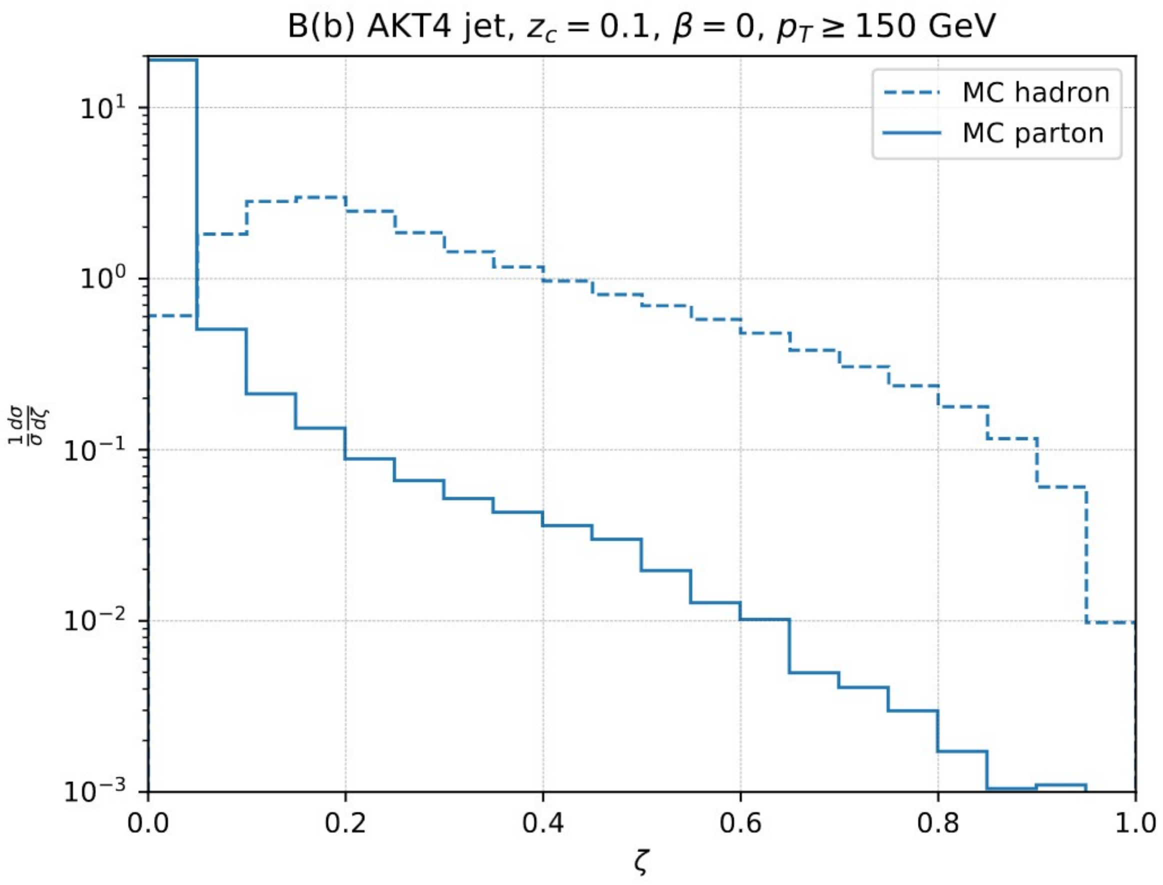
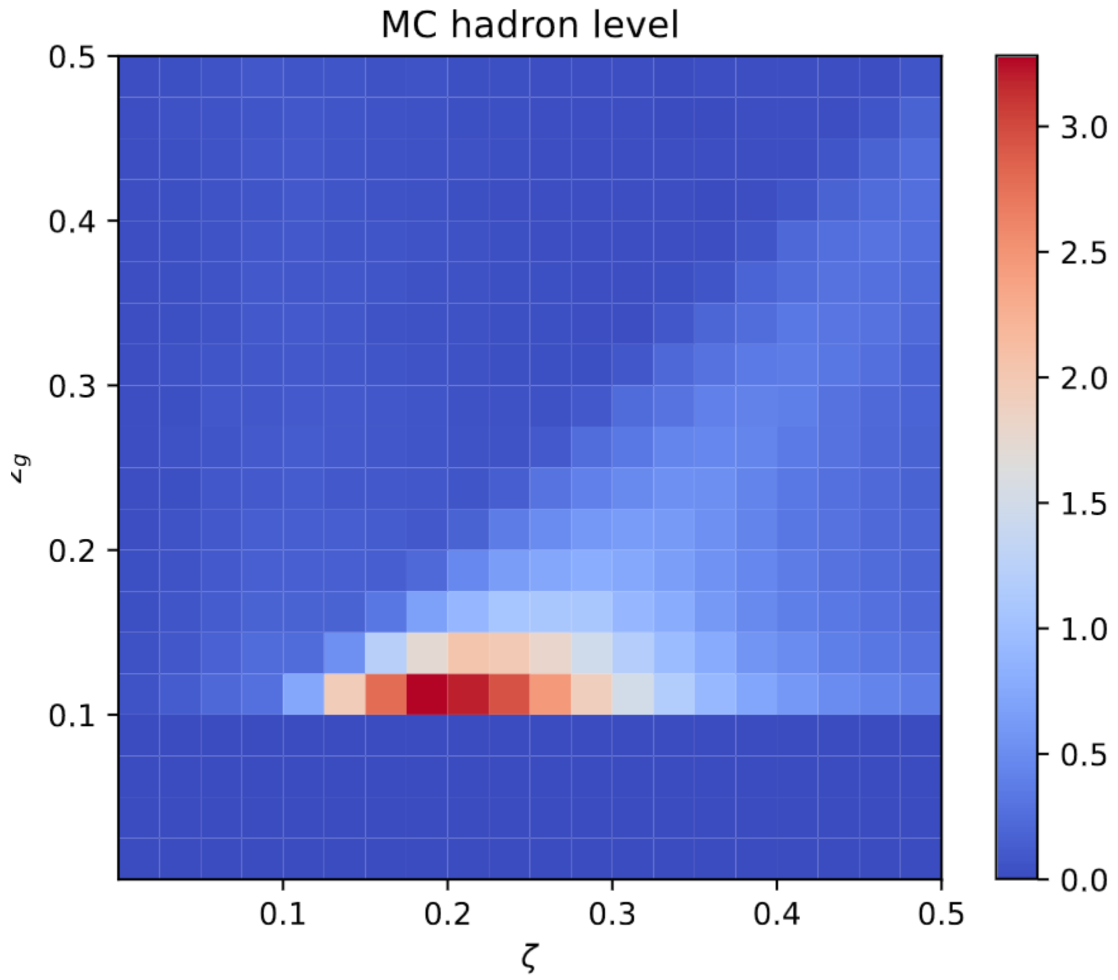
- First direct experimental constraint on the charm-quark splitting function obtained via the measurement of the groomed shared momentum fraction of the first splitting.
- The charm and inclusive-jet distributions are consistent at small R_g. Possible interplay between the dead-cone effect from the charm quark, and the more abundant emissions from quarks compared with gluons at small angles.
- 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.



Heavy-flavor jets substructure

[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.

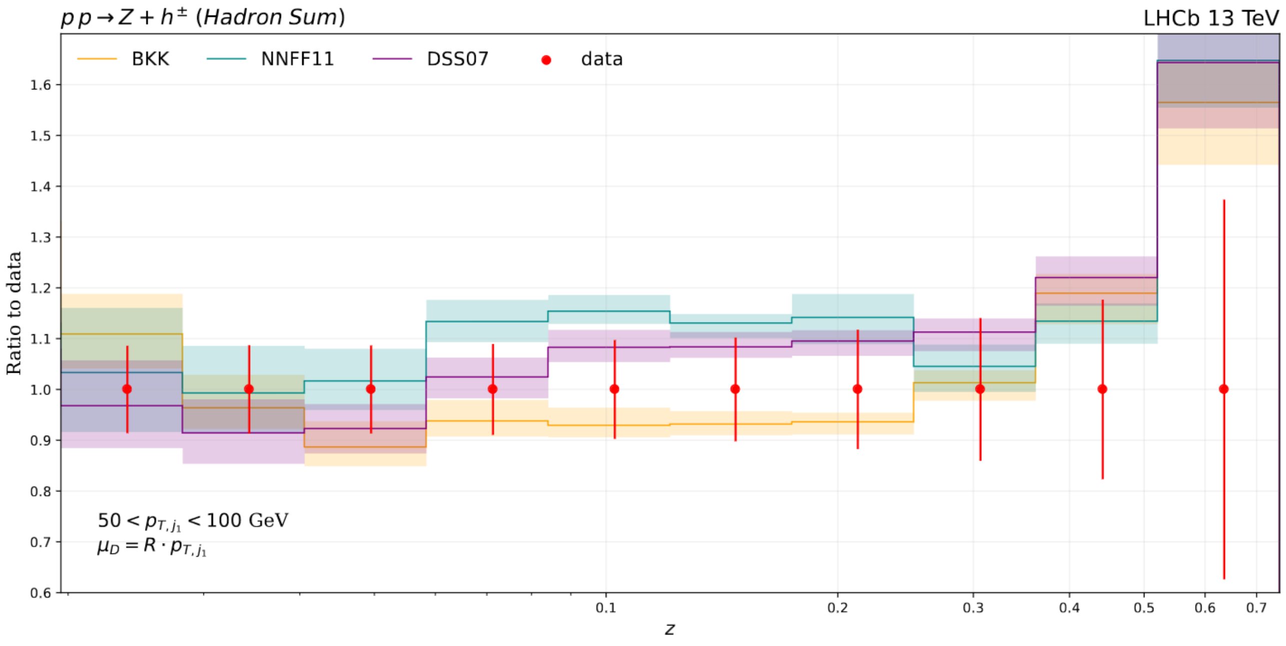
- The $\mathcal{O}(\alpha_S)$ correlation between the two observables is not maintained when higher-order corrections and non-perturbative effects are included.
- Thus z_g and ζ offer different handles to study heavy-flavor dynamics.

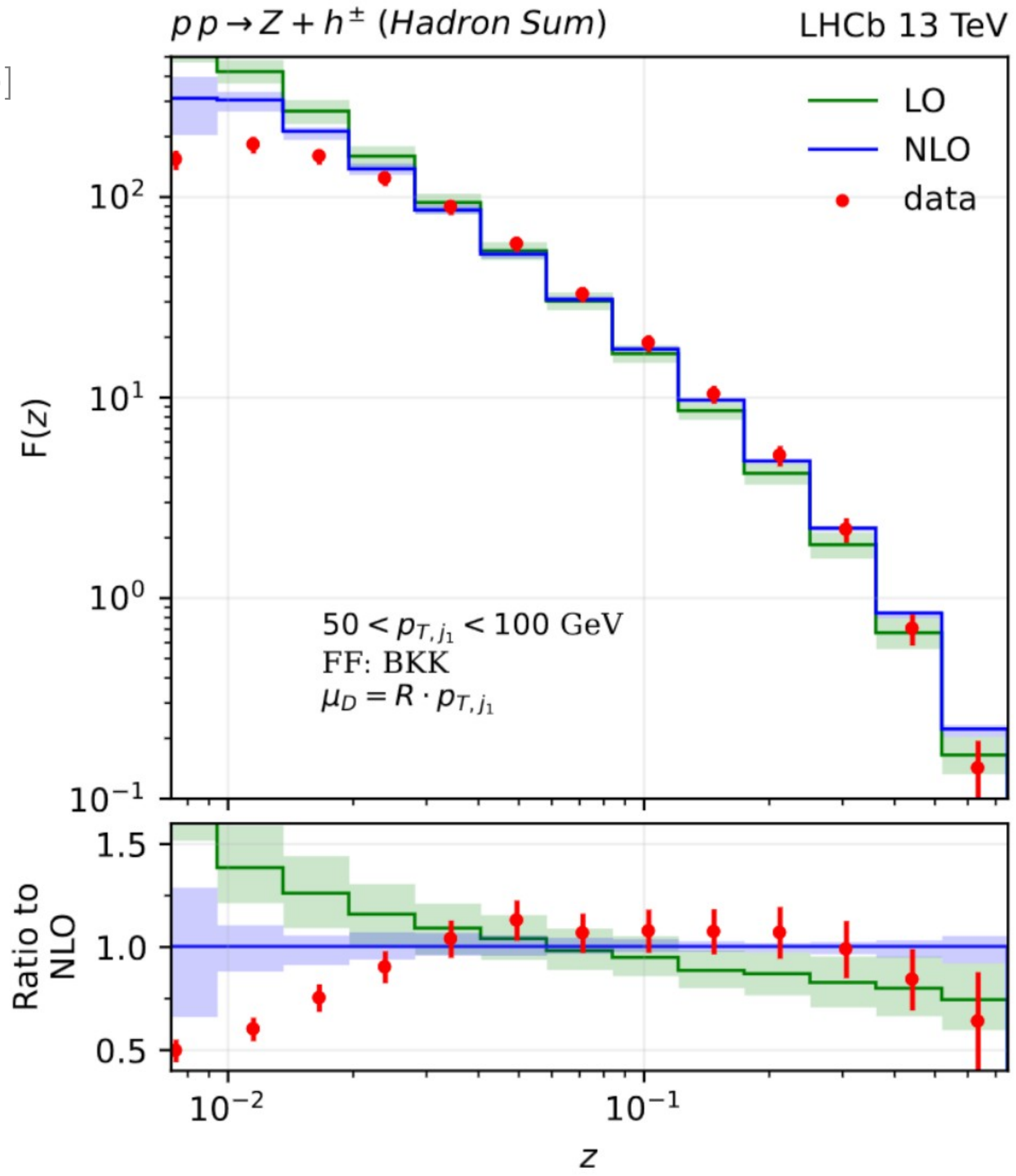
Hadron-in-jet fragmentation

[SC, Gehrmann-De Ridder, Huss, Rodriguez Garcia, Stagnitto (2405.17540)]
[LHCb Collaboration (2109.08084)]

- It is likely that this dataset is able to offer important constraints on FFs when included in global fits.

$$z = \frac{\mathbf{p}_h \cdot \mathbf{p}_{j_1}}{|\mathbf{p}_{j_1}|^2} \qquad F(z) = \frac{1}{\sigma_{Z+\text{jet}}} \frac{d\sigma_{Z+h}}{dz}$$





Conclusions

- Jet substructure is a very active field and gives an insight on the jet evolution.
- A detailed study of non-perturbative contributions is important to provide high-quality predictions.
- A continuous communication between theorist and experimentalist is crucial to develop useful tools that can have an impact on what we compute and measure.
- Flavor algorithms allow to look at heavy-quark-initiated jet dynamics. The study of heavy-quark jets gives us the opportunity to observe important property of QCD, like the dead-cone effect.
- The interplay/complementarity between hadron fragmentation and heavy-jet substructure should further explored and might give interesting insight on non-perturbative QCD dynamics.