Theory aspects of jets & jet flavour definition

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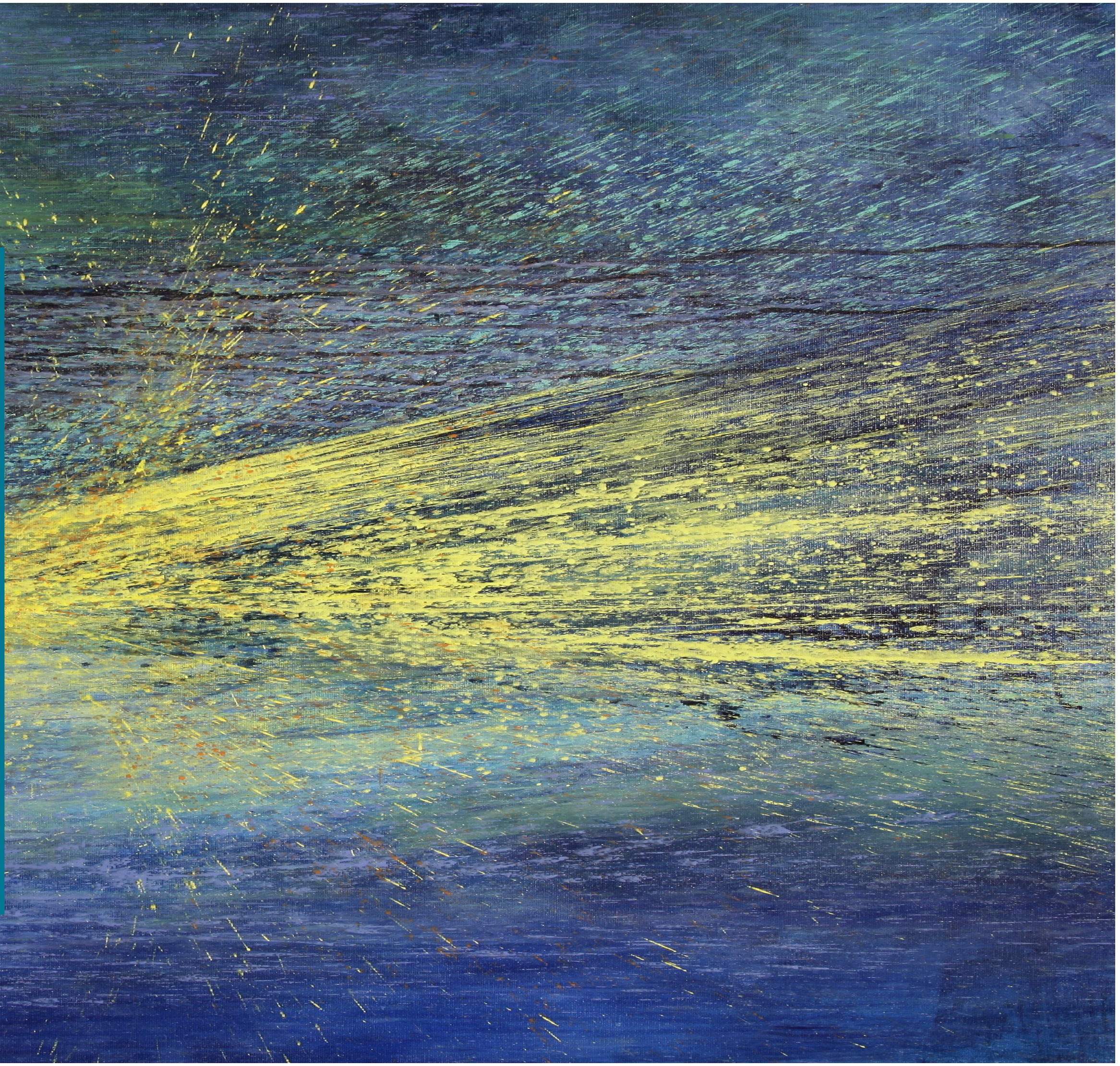
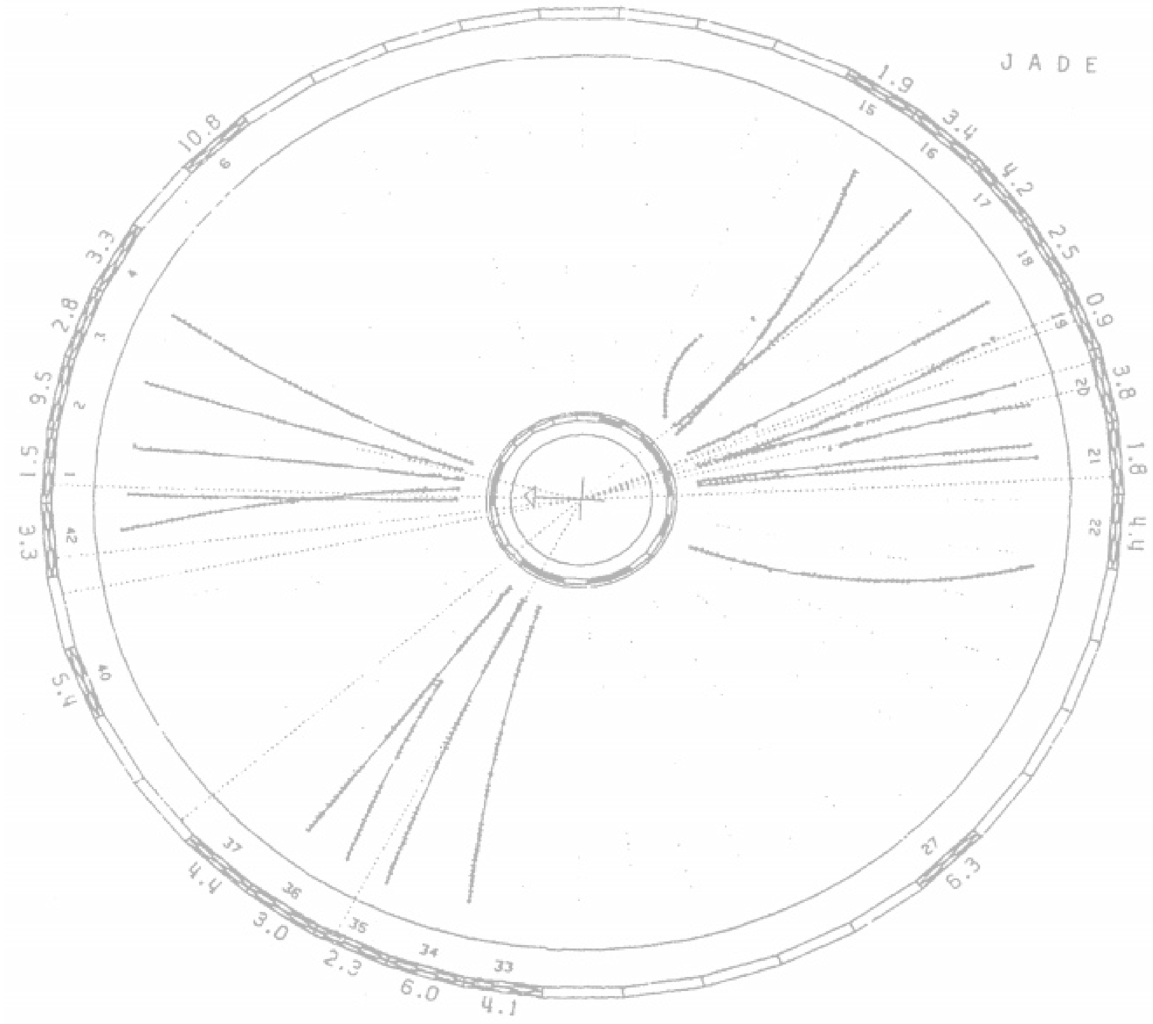
COMETA workshop on artificial intelligence
for multi-boson physics
01.10.2024, Amsterdam



Outline



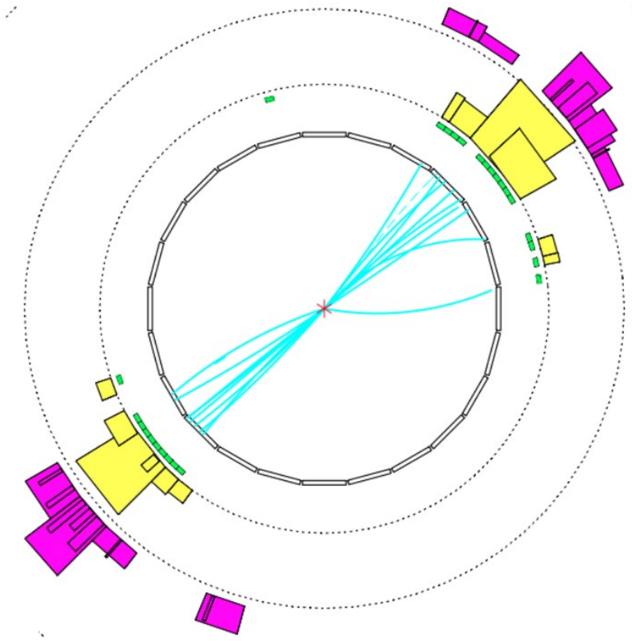
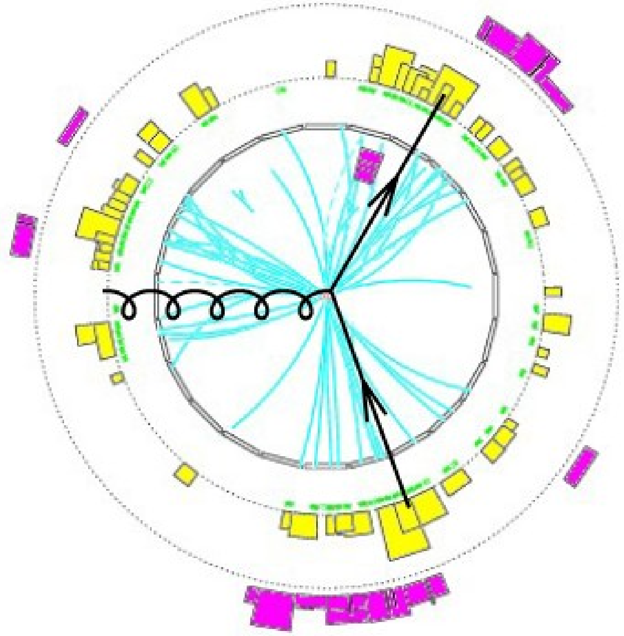
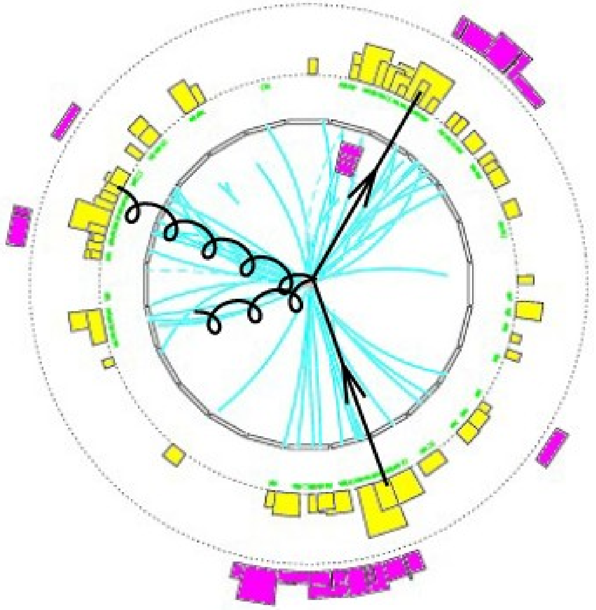
I. Introduction:
- hadronic jets
- the jet flavour problem

II. Jet flavour algorithms
- Flavour-kt
- Soft Drop Flavour
- Flavour anti-kt (CMP)
- Flavour dressing (GHS)
- Interleaved Flavour Neutralization (IFN)

III. Comparison between the algorithms

I. Introduction

Jets are probe of the underlying process

But we need to define what we call "jet".

- Cone algorithms
- Sequential recombination algorithms

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

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

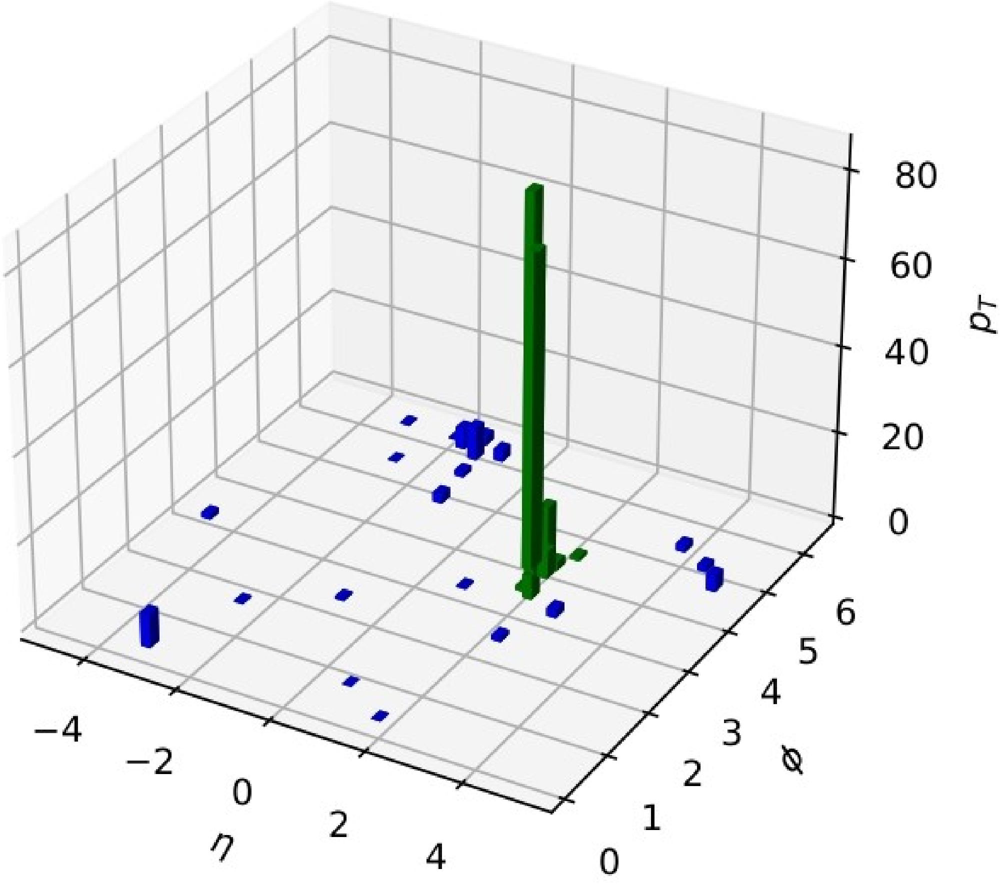
and the *beam distance* as

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

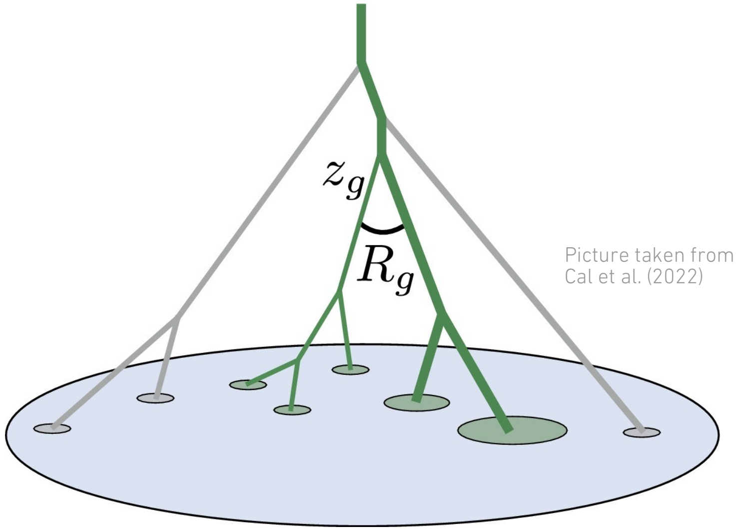
with R the jet radius.

- 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)



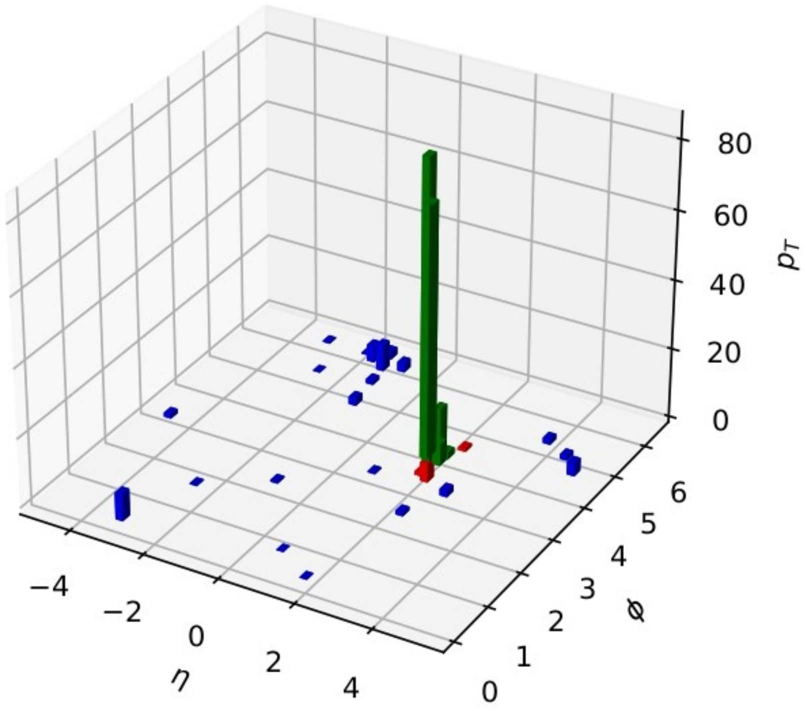
Grooming: Soft Drop



Picture taken from Cal et al. (2022)

Larkoski et al. (2014)

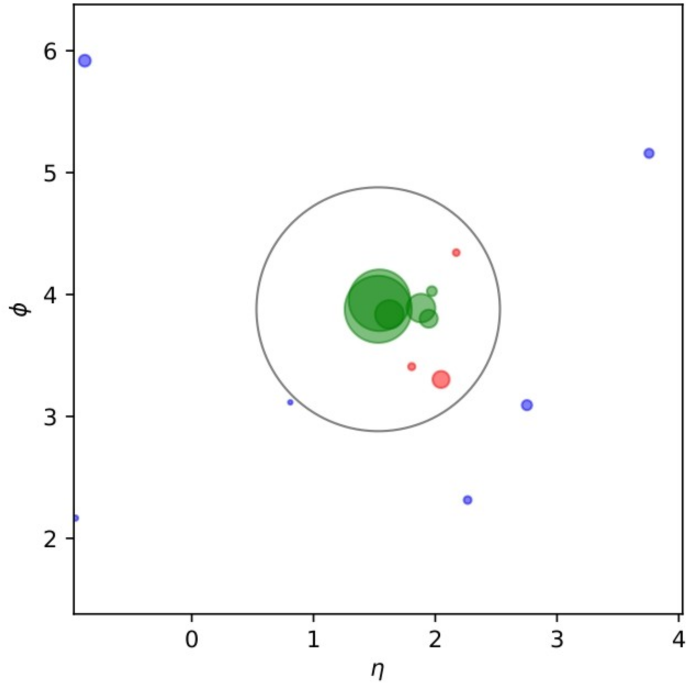
$$\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{\Delta_{ij}}{R} \right)^{\beta}$$



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

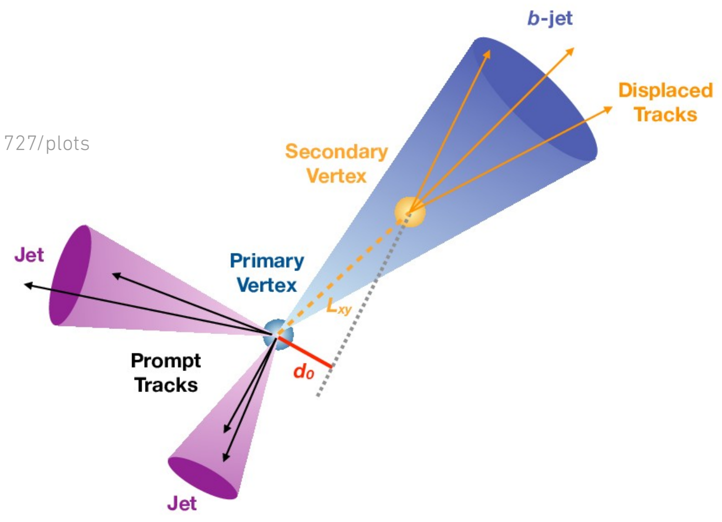
$$j = \max_{p_T}[j_1, j_2]$$

while(! SD)

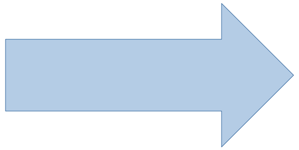


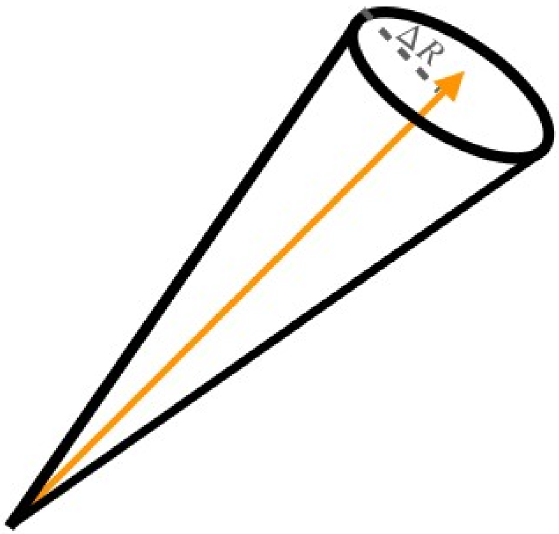
Experimental definition of flavoured jet

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



- Heavy-quark-initiated jets are experimentally identified exploiting B hadron lifetime, i.e. the display vertex.
- Jets are defined with anti-k_t.





- Take the 4-momenta of reconstructed anti-kt jets and B hadrons with pt > ptcut ~5GeV
- Assign a B to a jet if $\Delta R < R_0$ ~0.3
- If at least one B is assigned to jet J, then J is a b-jet

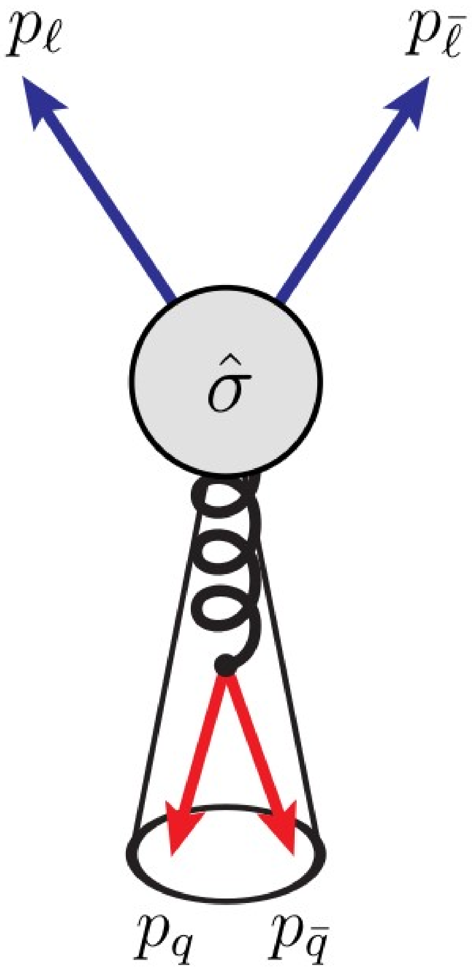
What can go wrong?

- Infra-Red and Collinear Safety! IRC safety is mandatory to compute things beyond LO.
- An observable (or a jet definition) is IRC safe if, in the limit of a collinear splitting, or the emission of an infinitely soft particle, the observable (jet) does not change:

$$O(X; p_1, \ldots, p_n, p_{n+1} \to 0) \to O(X; p_1, \ldots, p_n)$$
$$O(X; p_1, \ldots, p_n \parallel p_{n+1}) \to O(X; p_1, \ldots, p_n + p_{n+1})$$

- An IRC-unsafe HF jet definition with massless partons, leads to divergent results in perturbation theory (and cannot be used)
- An IRC-unsafe HF jet definition with massive quarks, leads to finite but IRC-sensitive results in perturbation theory (large logs of m/pt)

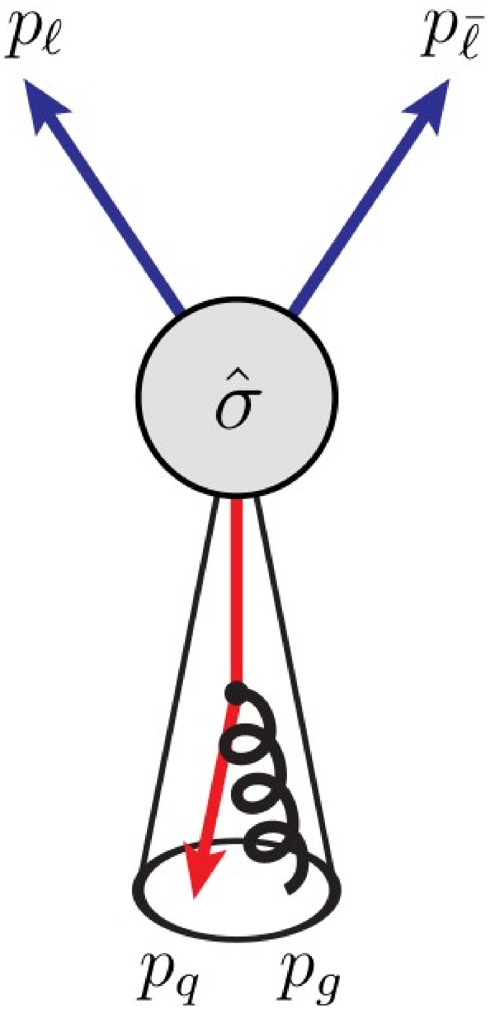
Issue n.1: NLO



Gauld et al. (2023)

- Consider the Z+b (or c) jet process
- Problematic configuration at NLO: g→ $b\bar{b}$ is collinear divergent (with zero mass).
- The corresponding singularity is canceled when we add the virtual correction, which **happens if and only if real and virtual are in the same flavour bin** (i.e. this is a gluon = no net flavour)
- This is particularly relevant for observables that are inclusive over the b-jet substructure, like the pt
- Important effects at high-pt

The ptcut on hadrons



Gauld et al. (2023)

- Furthermore, q → qg collinear splittings with a hard gluon leads to a flavourless jet because of the cut over the pt of the B hadron

- If we implement it at parton level, the soft quark may fail the cut, turning the jet into a gluon one → collinear unsafe!

- With ptcut it requires a fragmentation function, as we are identifying the particle.
  Without the ptcut, any IRC safe flavour agnostic algorithm will recombine the qg pair together.

Flavour recombination schemes

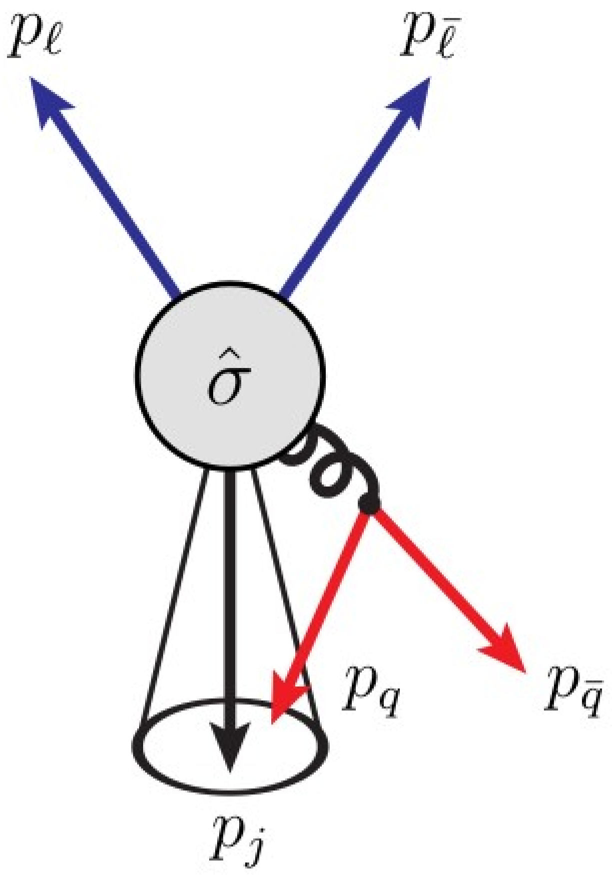
- However, the NLO issues can be easily fixed from the theory point of view using a different flavour recombination scheme

- This comes with large experimental baggage (reconstruction, mistag, etc.)

scheme \ jet contents	b	$b + \bar{b}$	$b + b$	
"any flavour"	b	b	b	simplest experimentally (but collinear unsafe for $m_b \to 0$)
net flavour	b	g	$2b$	theoretically "ideal" definition; but not robust wrt B–Bbar oscillations
flavour modulo 2	b	g	g	theoretically OK; robust wrt B–Bbar oscillations

From Gavin Salam's talk at Durham workshop

Issue n.2: NNLO



Gauld et al. (2023)

- Things are more complicated at NNLO, because soft large-angle g→ b$\bar{\text{b}}$ splittings can alter the flavour of the jet
- This leads to an IRC divergence for massless quarks
- Counting the net flavour is not enough and there is no way of fixing this with a flavour-agnostic jet algorithm. We need to reconsider the algorithm itself.

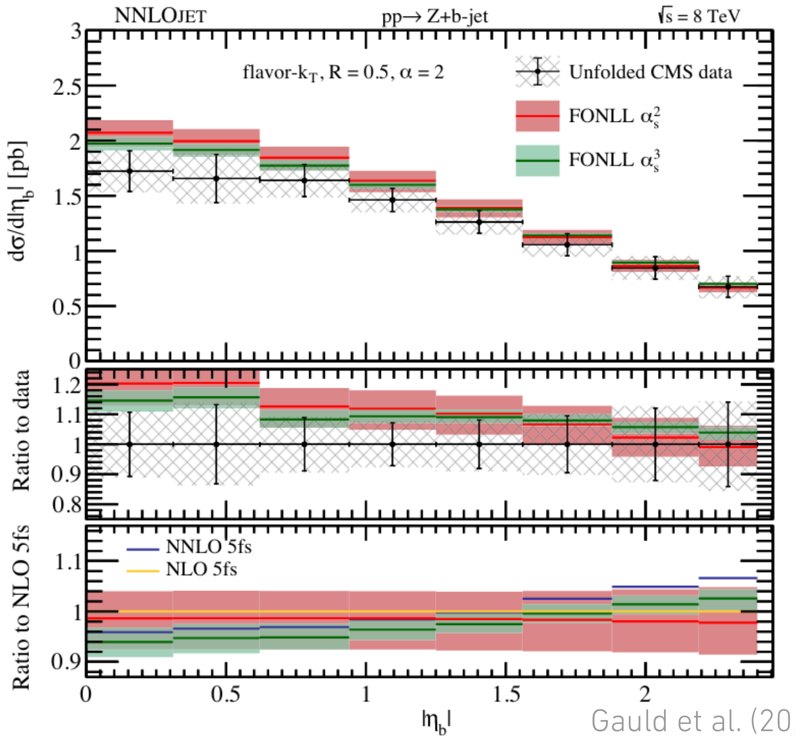
The first solution: flavour-kt

Introduce a flavour-sensitive metric that reflects the absence of soft quark singularities

$$d_{ij}^{\mathrm{BSZ}} = \left(\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2\right) \times \begin{cases} \max\left(k_{ti}^2, k_{tj}^2\right), & \text{if the softer of } i, j \text{ is flavored,} \\ \min\left(k_{ti}^2, k_{tj}^2\right), & \text{if the softer of } i, j \text{ is flavorless.} \end{cases}$$

Banfi et al. (2006)

- Flavour-kt is IRC safe, because it recombines together the problematic NNLO soft pair
- However, it is far from straightforward to implement in experimental analysis, because it is not anti-kt so the jets have a different kinematics and it requires a knowledge of the flavour at each step of the clustering procedure
- NNLO calculations have been performed with flavour-kt have been done in the past years, but they required an extra unfolding procedure to connect theory and experiment

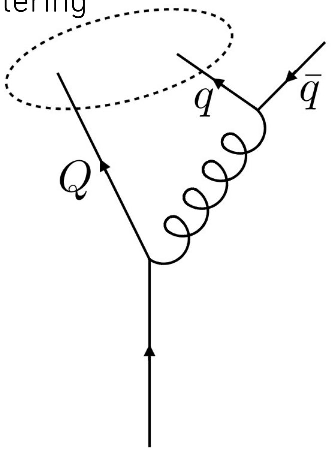


Gauld et al. (2020)

II. Jet Flavour Algorithms

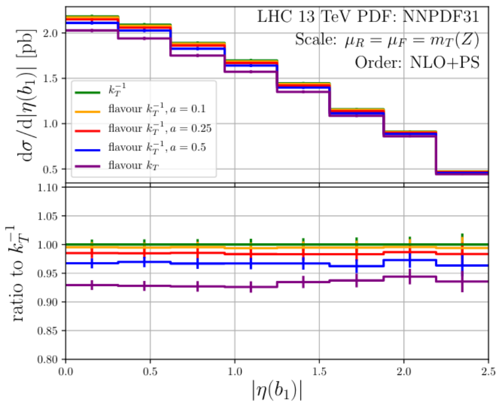
The “jet flavour gate”

- Groom jets with SD after JADE reclustering



Caletti, Reichelt, Larkoski, Marzani (2022)

- Define a flavor algorithm that resembles anti-k_T

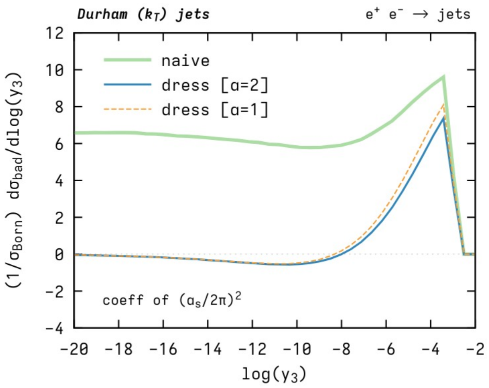


$$d_{ij}^{\mathrm{CMP}} = d_{ij} \times \begin{cases} \mathcal{S}_{ij}\,, & \text{if both } i \text{ and } j \text{ have non-zero flavor of opposite sign} \\ 1\,, & \text{otherwise} \end{cases}$$

Czakon, Mitov, Poncelet (2022)

Applied to W+c-jet and Wbb production

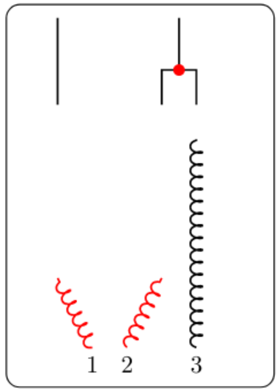
- Construct a flavor dressing and associate the flavour to a given jet



Gauld, Huss, Stagnitto (2022)

Applied to W+c-jet production

- Introduce a neutralization distance

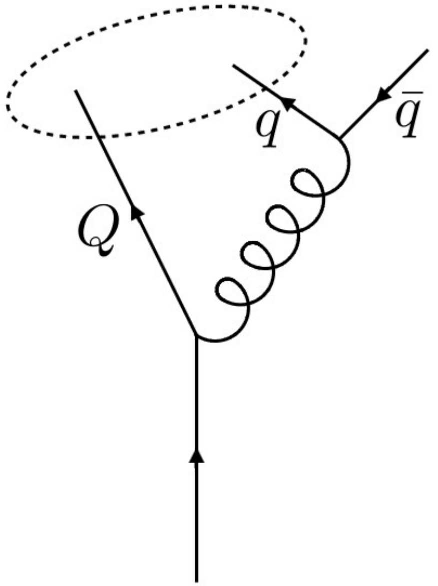


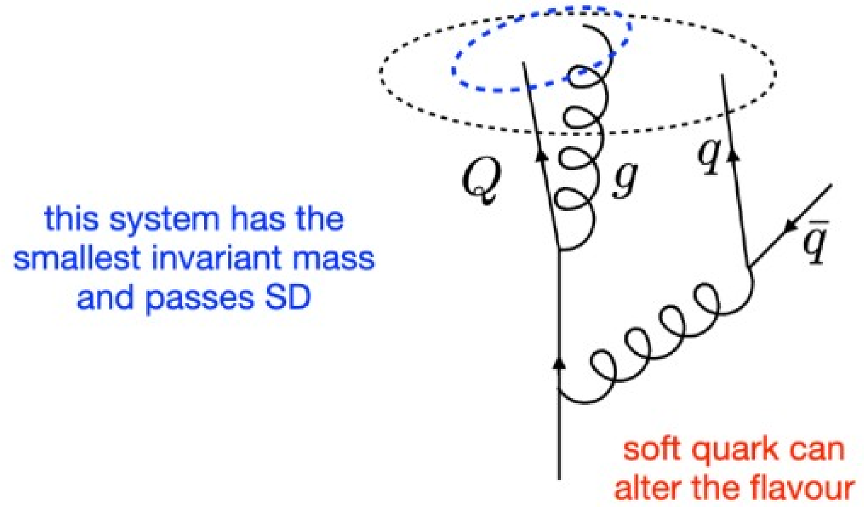
Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2023)

- All of them implemented as a contrib in Fastjet and soon available (goal of the LH23 workshop)

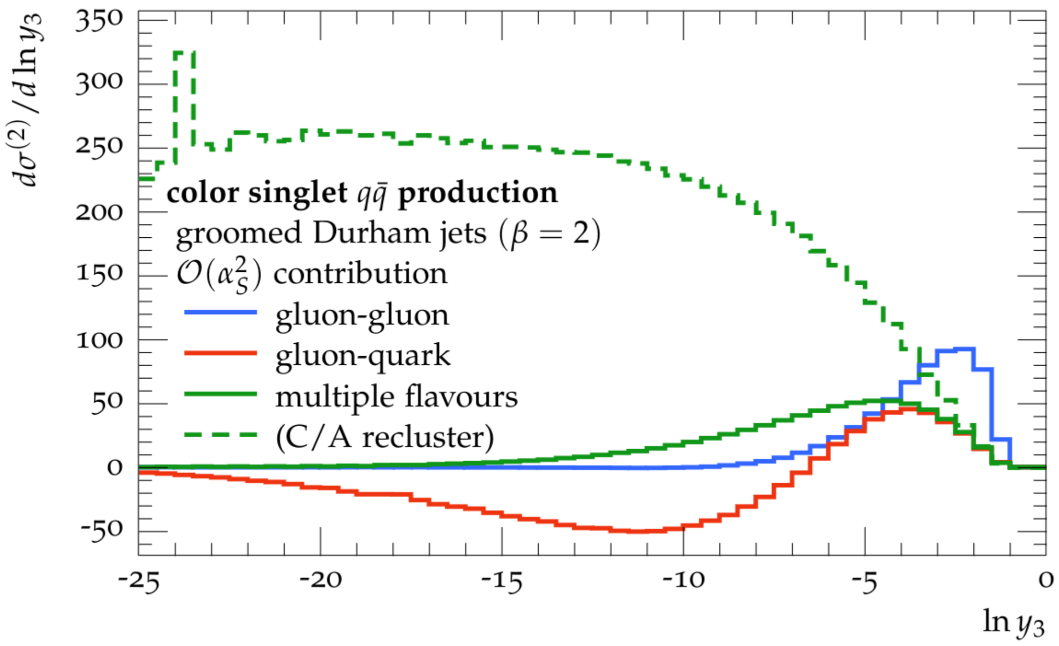
Soft Drop Flavour (SDF)

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





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

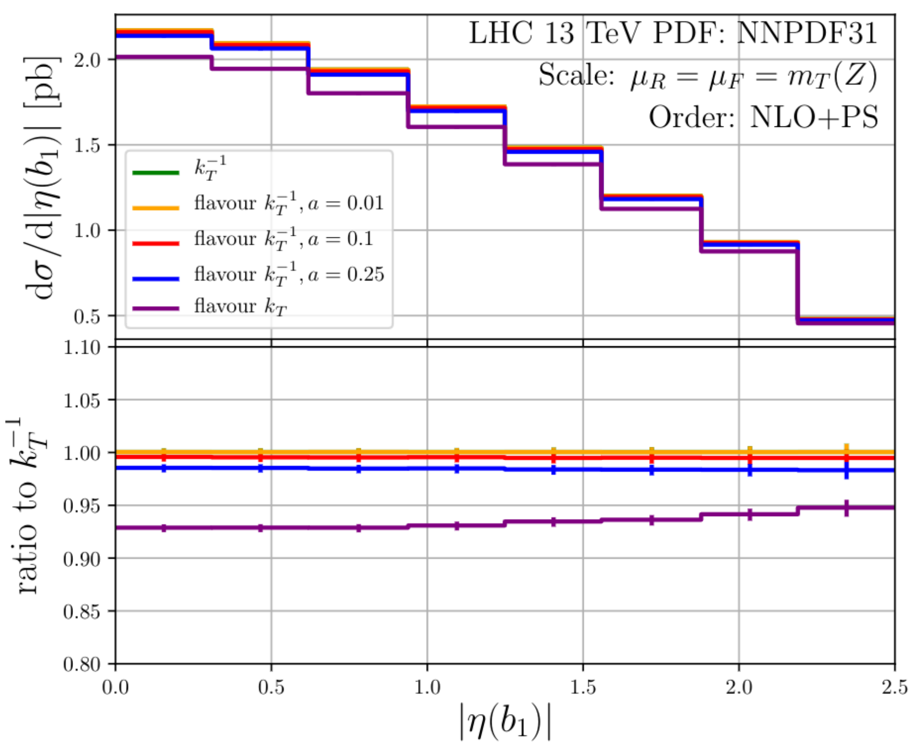


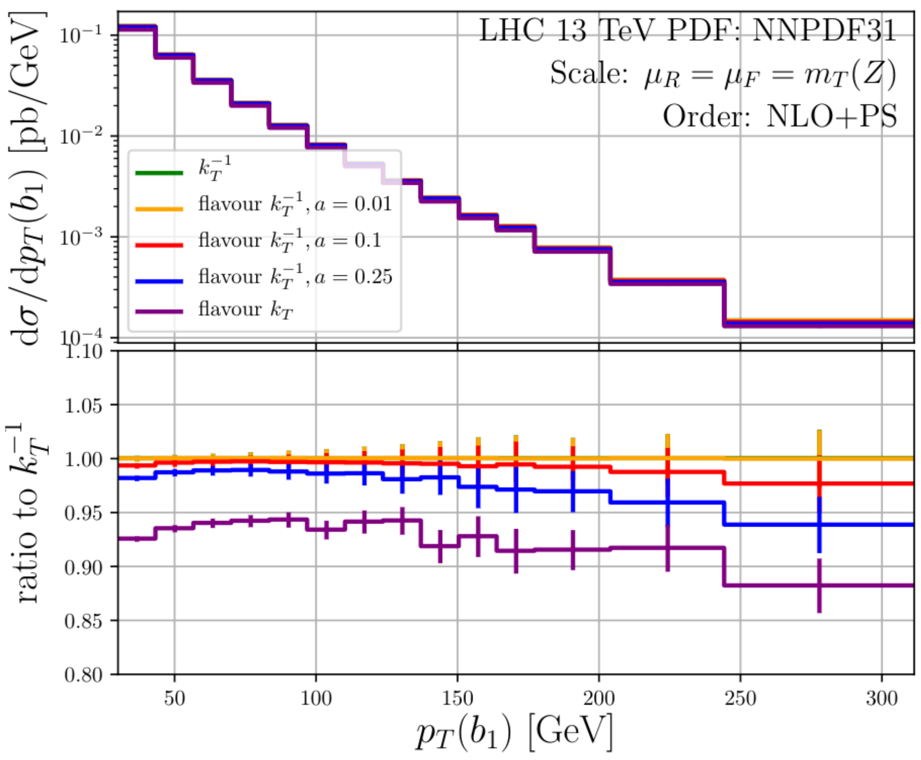
Flavour anti-kt (CMP)

[Czakon, Mitov, Poncelet (2205.11879)]

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

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

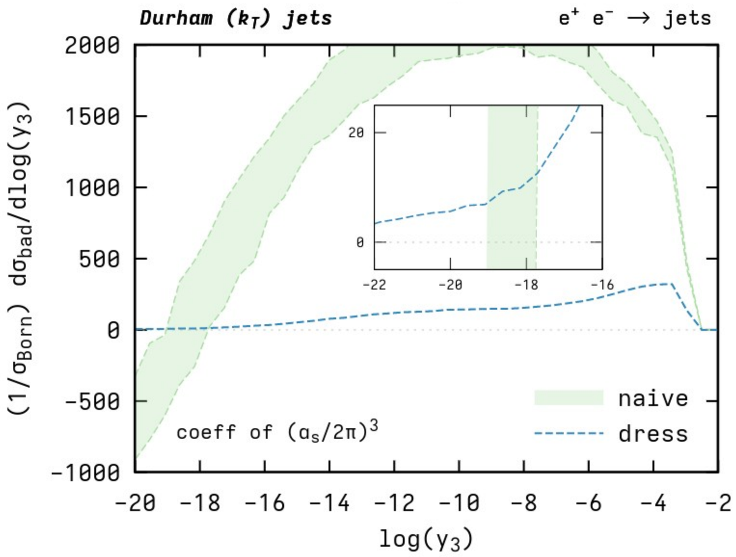


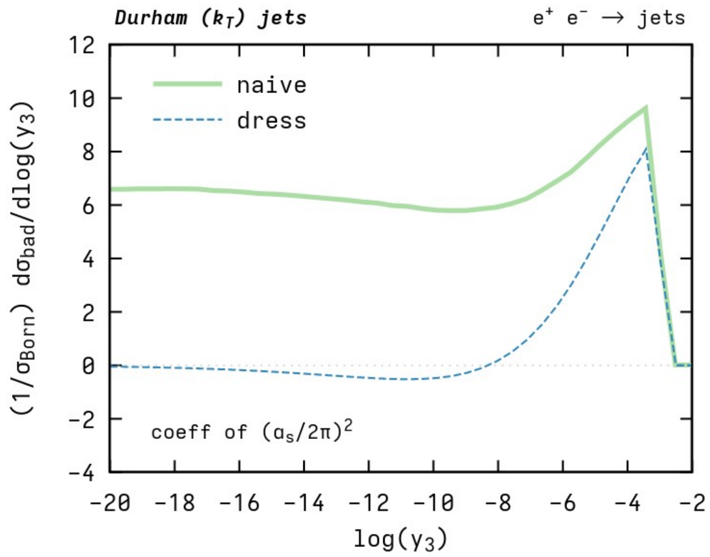


Flavour dressing (GHS)

[Gauld, Huss, Stagnitto (2208.11138)]

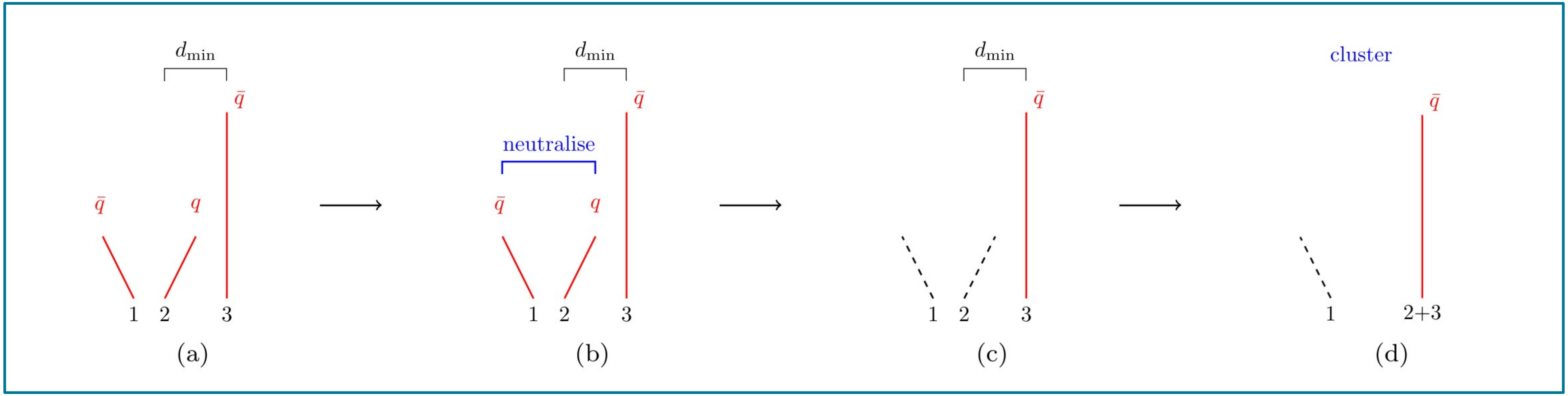
- Input flavour-agnostic jets (e.g. anti-kt) and fl,avour information (e.g. b or c quarks, stable heavy flavour hadrons, etc)
- **Preliminary step:** build flavour clusters recombining flavour inputs with radiation close in angle, but without touching the soft particles (thanks to the Soft Drop condition)
- **Dressing step:** in order to assign flavour to jets, run a sequential recombination algorithm with flavour-kt like distances between jets and flavour clusters.





Interleaved Flavour Neutralization (IFN)

[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.

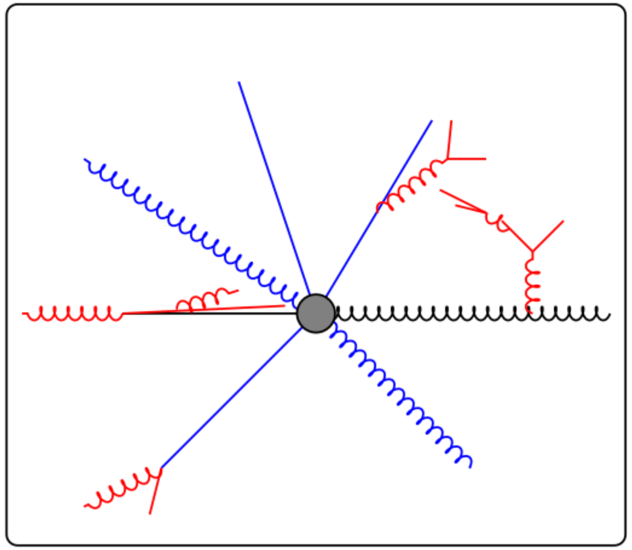
$$u_{ik} = \max(p_{T,i}^{\alpha}, p_{T,j}^{\alpha}) \min(p_{T,i}^{2-\alpha}, p_{T,j}^{2-\alpha}) \times \Omega_{ij}^2$$

The neutralization metric is given by

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

Systematic IRC safety tests

Numerical framework developed by the IFN group has allowed to discover potentially problematic configurations at higher orders



FSR-DS = double-soft
ISR-DS
FC = FS hard-collinear
IC = IS hard-collinear

possibly nested

		CMP	GHS	FN1	FN2	anti-k_t
α_s^2	FSR-DS					
	ISR-DS					
	FC IC					
	FC FC					
	IC IC					

From Ludovic Scyboz slides at Moriond QCD 2023

Pros and cons of massive calculations

In principle, massive calculations do not require an IRC safe flavour algorithm (screening effect due to m_q).

However, presence of large logarithms $\log(Q^2/m_q^2)$, spoiling the convergence of the perturbative series ($\alpha_s \log(m_Z^2/m_c^2) \sim 1$).

Benefits of massless calculations with IRC safe jet tagging:

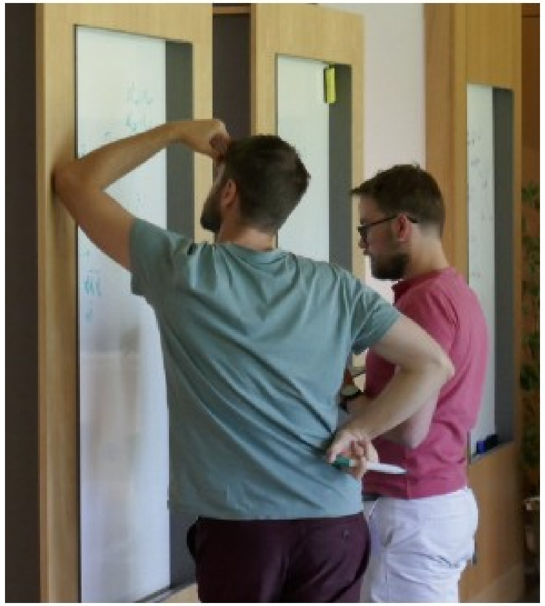
- in the initial-state, a massless calculation allows for a resummation of $\log(Q^2/m_q^2)$ by PDF evolution (crucial in some cases e.g. when probing non-perturbative charm PDF)
- in the final-state, an IRC safe prescription implies a suppressed sensitivity on $\log(Q^2/m_q^2)$, both in fixed order and resummed calculations / parton showers.

Stolen from Giovanni Stagnitto's slides at Durham

III. Comparison between the algorithms

Disclaimer: all results presented here are preliminary
Particular credits to all the member of the LH23 working group for this plots

Les Houches2023



A lot of discussions (and headaches) around flavoured jets…

(Thank you Giovanni for the collage)

Les Houches2023

PART 1
Les Houches, there's a place you can go
I said, Les Houches, when you're short on ideas
You can stay there, and I'm sure you will find
Many ways to have a good time!

PART 2
Les Houches, where we all can discuss
I said, Les Houches, in the beautiful Alps
You can stay there, and then try to combine
truth and reco, then go drink wine!

CHORUS A
We want jet's flavour to be I. R. C. Safe
We want jet's flavour to be I. R. C. Safe
Cannot just count the b's, of an anti-kt
because even a soft gluon splits

PART 1
Les Houches, there's a place you can go
I said, Les Houches, when you're short on ideas
You can stay there, and I'm sure you will find
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PART 2
Les Houches, where we all can discuss
I said, Les Houches, in the beautiful Alps
You can stay there, and then try to combine
truth and reco, then go drink wine!

CHORUS B
We should reduce the ne-ga-tive weights
and compute processes at N3LO
This is our wishlist, to make Joey in peace
and then make the best of stats

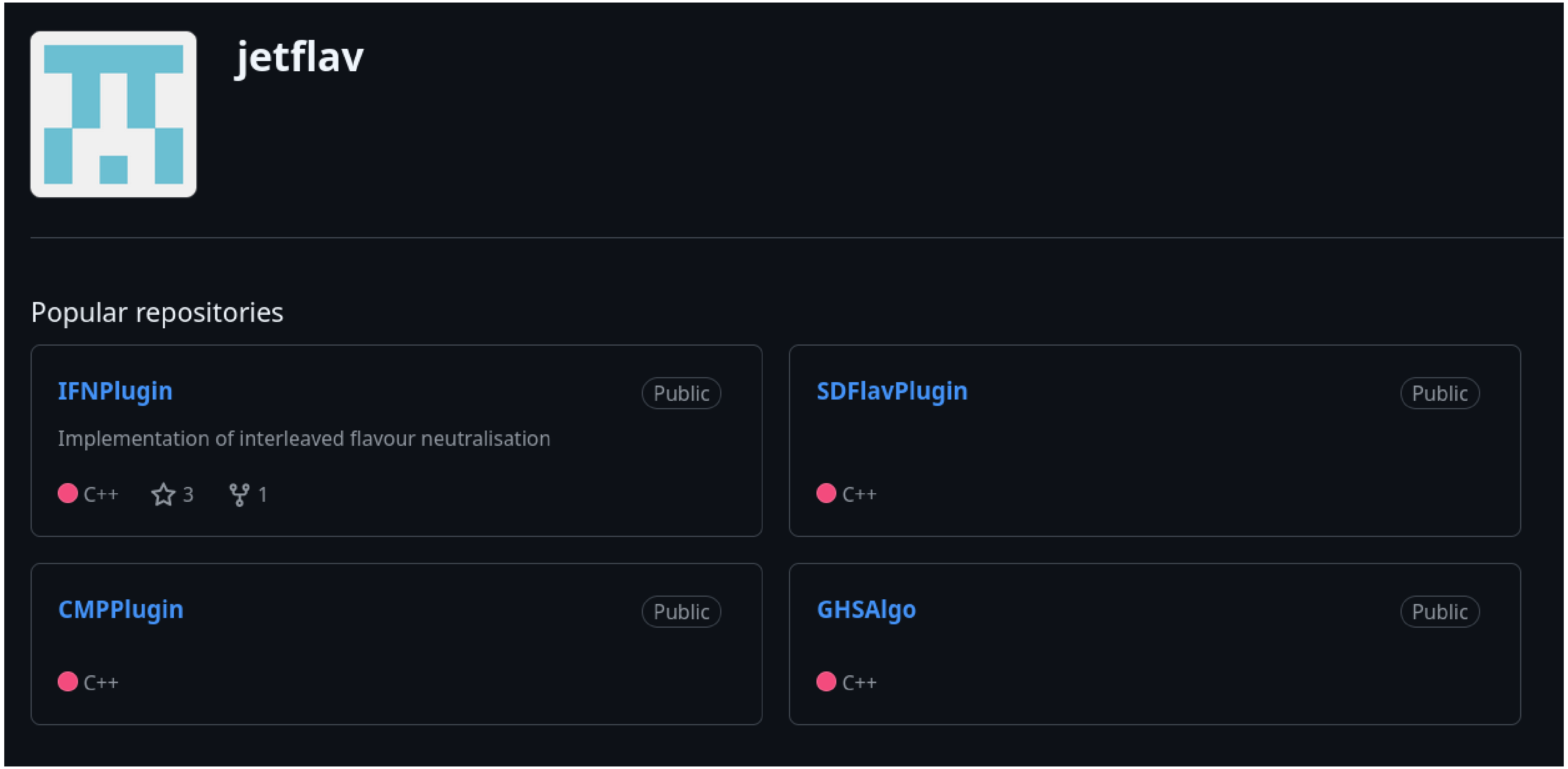
CHORUS A x2
We want jet's flavour to be I. R. C. Safe
We want jet's flavour to be I. R. C. Safe
Cannot just count the b's, of an anti-kt
because even a soft gluon splits

…and even the LH2023 song
"I.R.C. safe" (to the tune of YMCA)
was dedicated to flavoured jets

(Thank you Giovanni for the collage)

Les Houches2023

A common framework with FastJet implementation of the four algorithms was required



A FastJet contrib is in preparation

LHCb fiducial cuts

[ATLAS 2024 (2109.08084)]

Z bosons	$p_T(\mu) > 20\,\text{GeV},\ 2.0 < \eta(\mu) < 4.5,\ 60 < m(\mu^+\mu^-) < 120\,\text{GeV}$
Jets	$20 < p_T(j) < 100\,\text{GeV},\ 2.2 < \eta(j) < 4.2$
Charm jets	~~$p_T(c\text{ hadron}) > 5\,\text{GeV},\ \Delta R(j, c\text{ hadron}) < 0.5$~~
Events	$\Delta R(\mu, j) > 0.5$

→ Replace by the respective flavour algorithms

Flavoured Jet algorithms

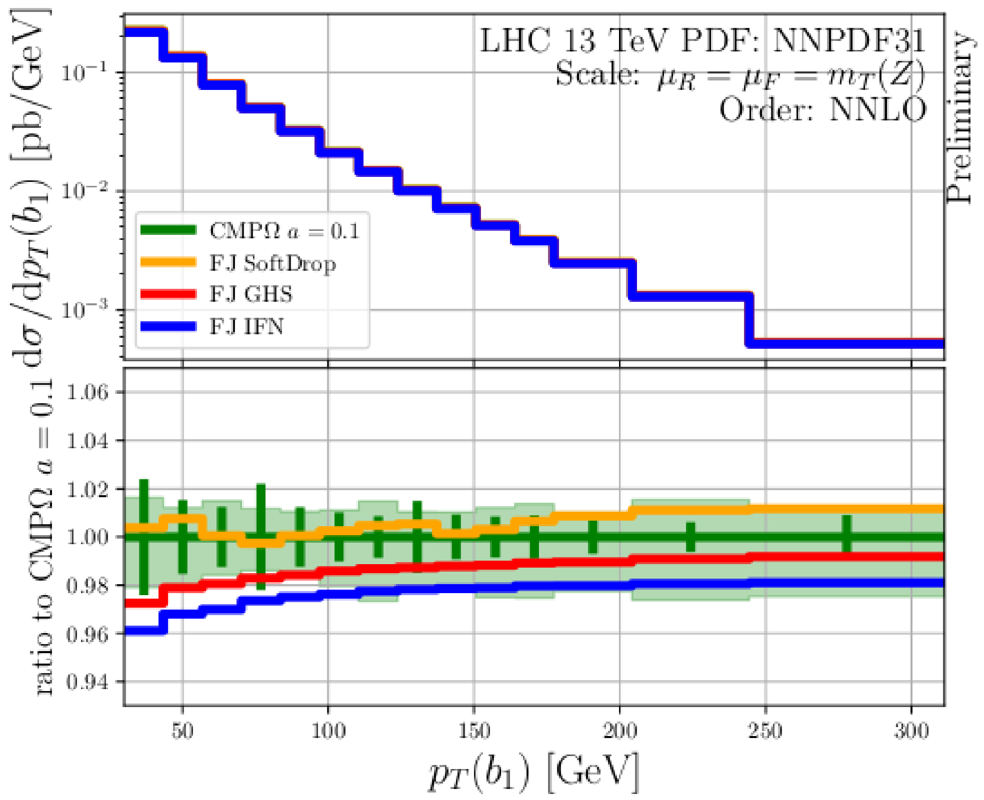
- SDF (beta = 1, zcut = 0.1)
- GHS (omega = 2, alpha = 1, ptcut = 15 GeV)
- IFN (alpha = 2, omega = 3 – alpha)
- CMP (a = 0.1)
- All with |#b/B| mod 2 == 1 flavour tag

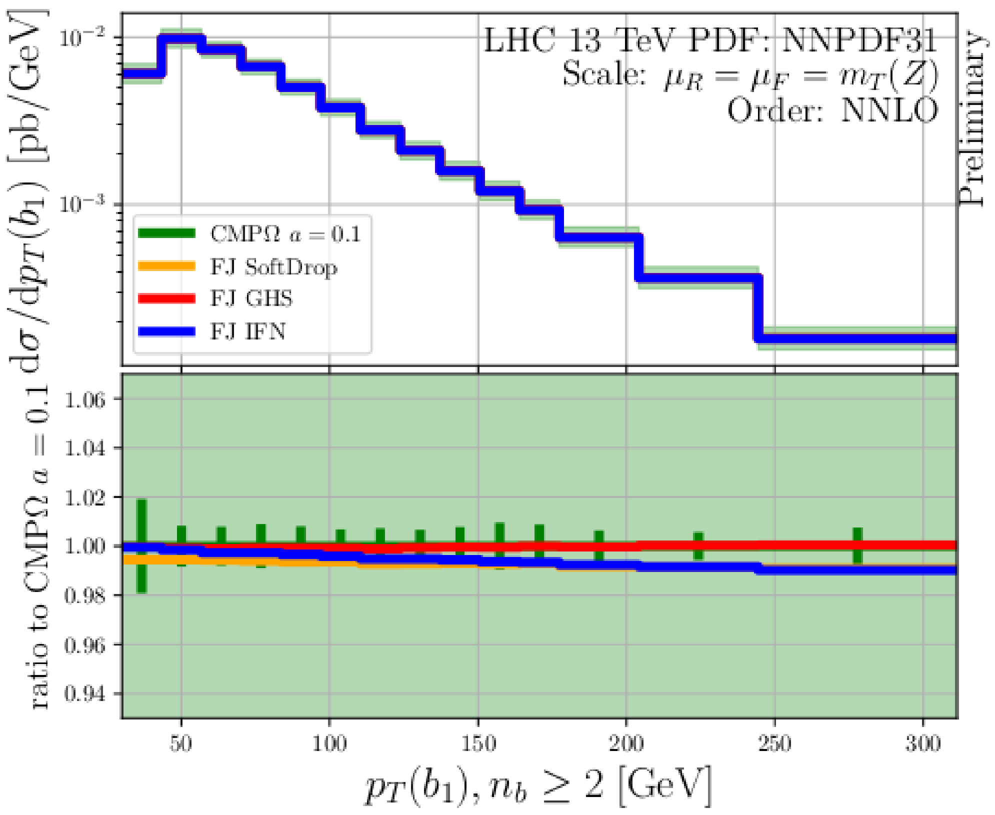
Anti-kT for comparison:

- ATLAS style truth-level ghost-tagging → CONE
- Anti-kT CMS truth level tag → TAG
- Anti-kT odd #B-hadron tag → AKT

Z+b-jet @ NNLO (central rapidity)

Plots from René Poncelet



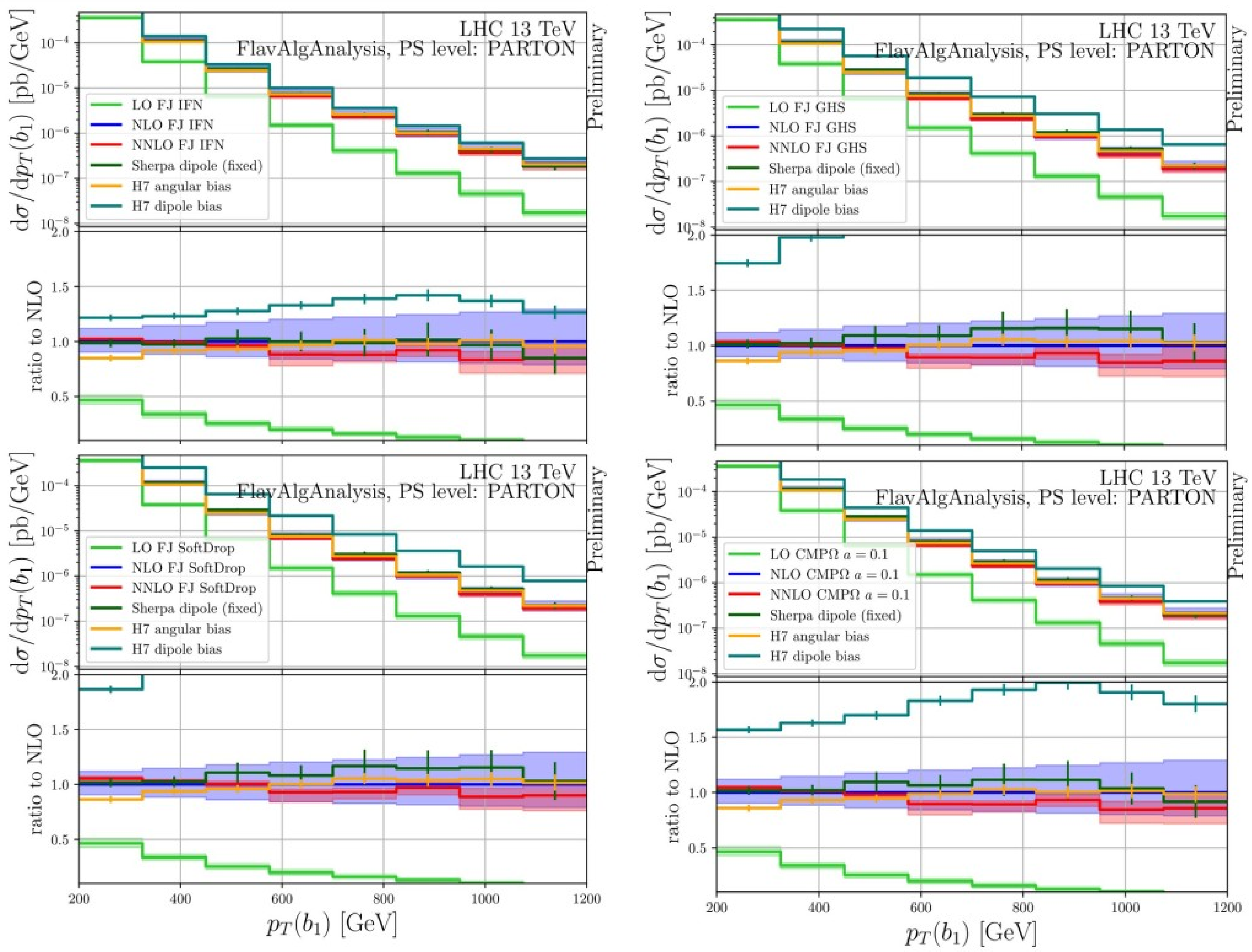


- New algorithms agree at the percent level for most distributions

- More b-tags reduce the differences, this because there is less freedom for the algorithms

Z+b-jet @ NLO+PS parton level (central rapidity)

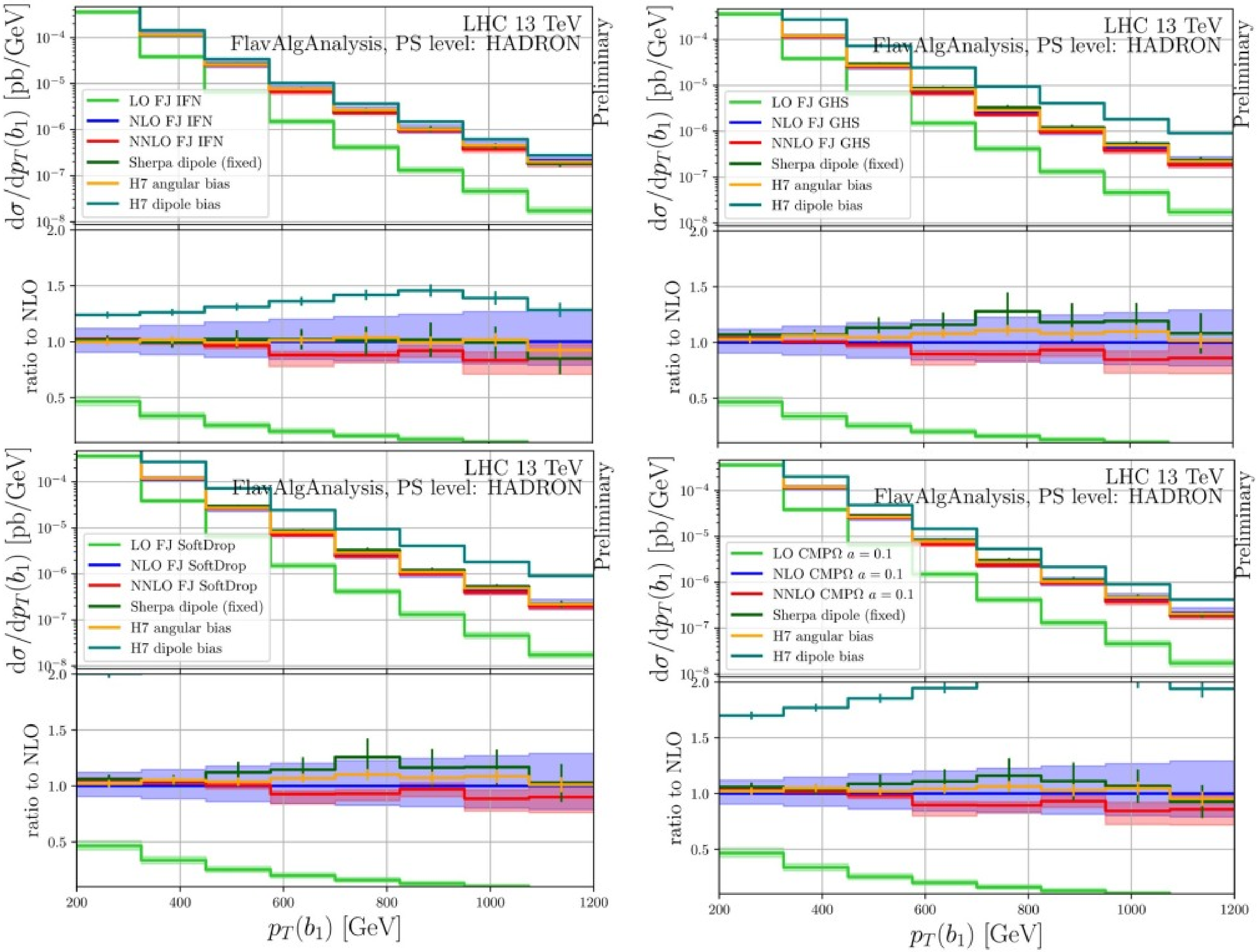
Plots from René Poncelet and Daniel Reichelt



- We find consistent results at parton level for all the algorithms, even at high b-jet pt (where more bb pairs are emitted)
- We observe a good perturbative convergence
- FO and PS provides a consistent pictures
- Note: H7 AO and SHERPA keep massive b-quarks in the shower, while H7 dipole is with massless b-quarks.

Z+b-jet @ NLO+PS hadron level (central rapidity)

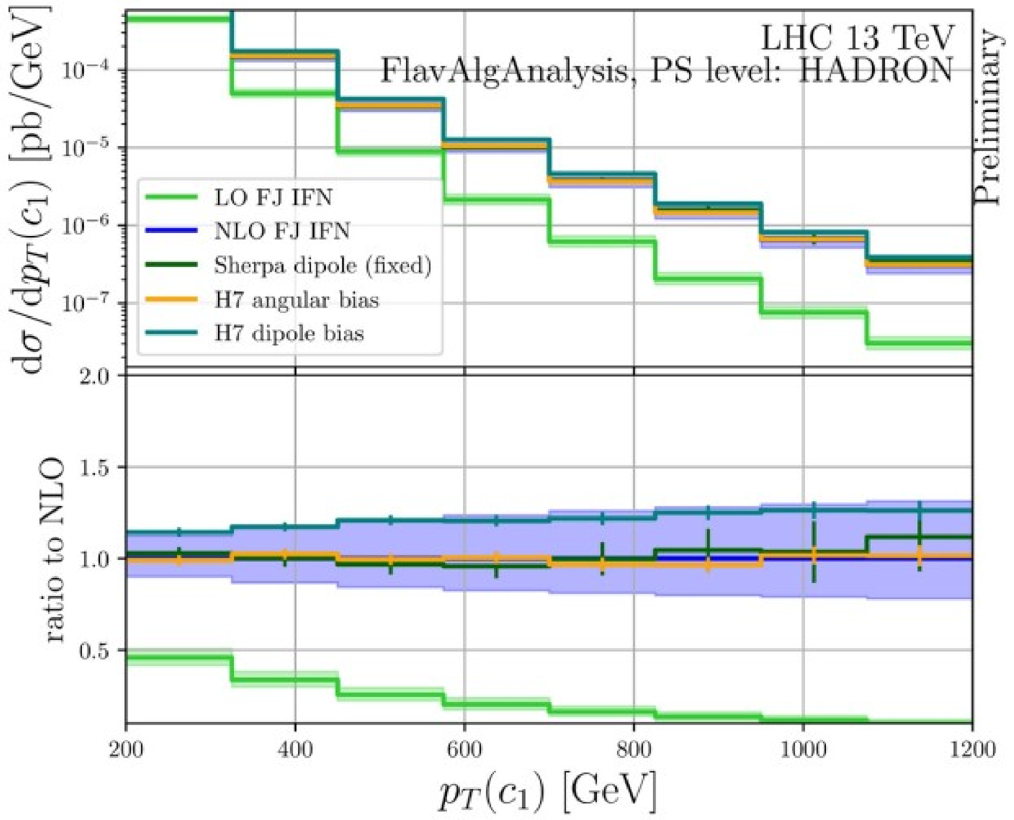
Plots from René Poncelet and Daniel Reichelt

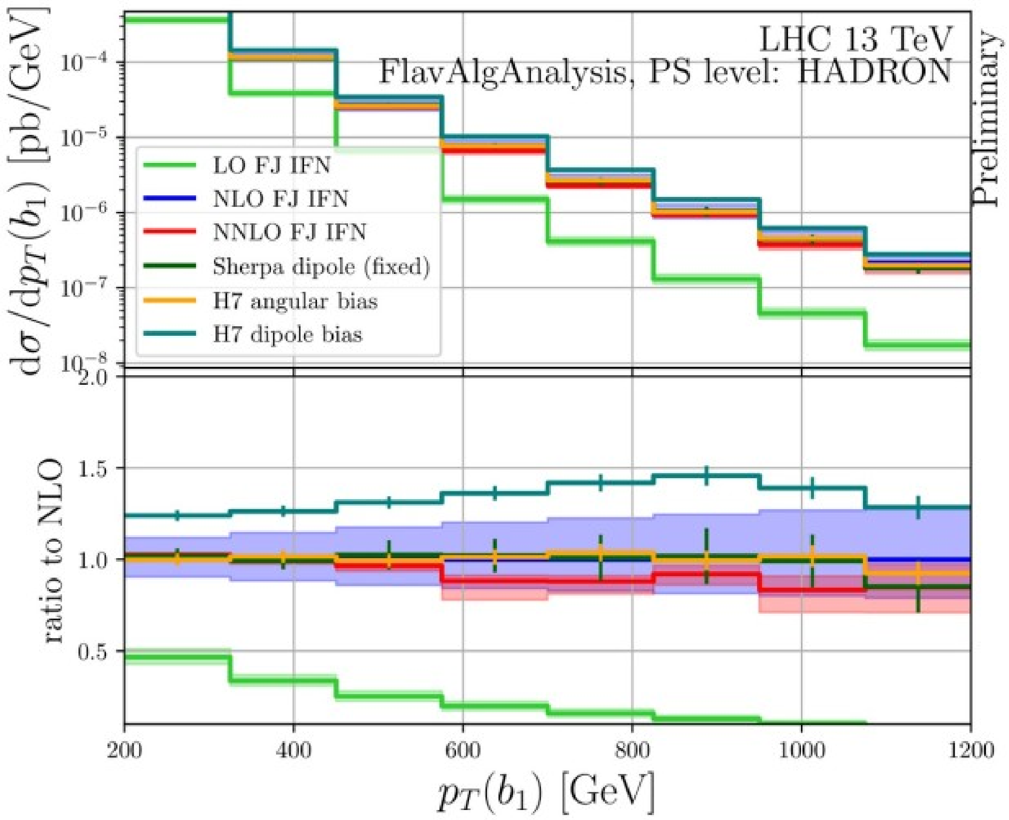


- Differences are slightly larger at hadron level
- Massless H7 dipole close only with IFN
- From these plots it seems that the differences between NLOPS and FO is
  IFN < CMP < GHS ~ SDF

Charm VS Beauty

Plots from René Poncelet and Daniel Reichelt





- Pictures for c-jets are similar to the b-jet ones. Massless H7 dipole shower is closer to the massive one (as expected)

Comparison to experimental strategies

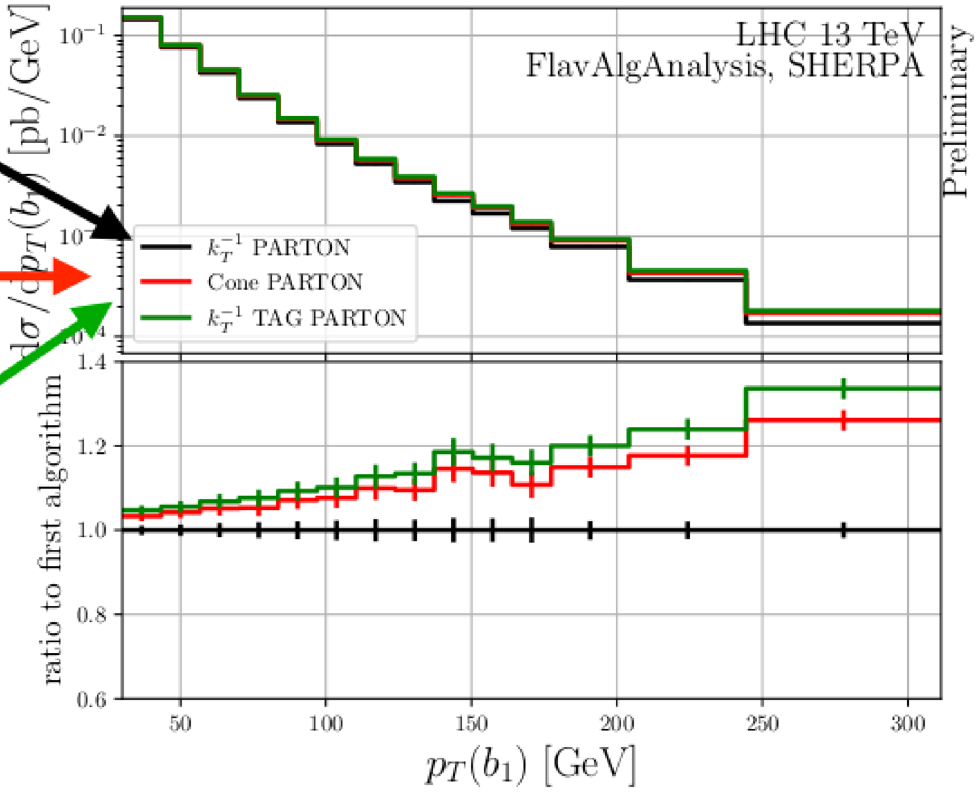
Plots from René Poncelet and Daniel Reichelt

- This is NLO+PS with just anti-kt jets and different strategies to assign flavour label

anti-k_t with net flavour (OK at NLO but not at NNLO)

cone with any flavour (proxy to ATLAS)

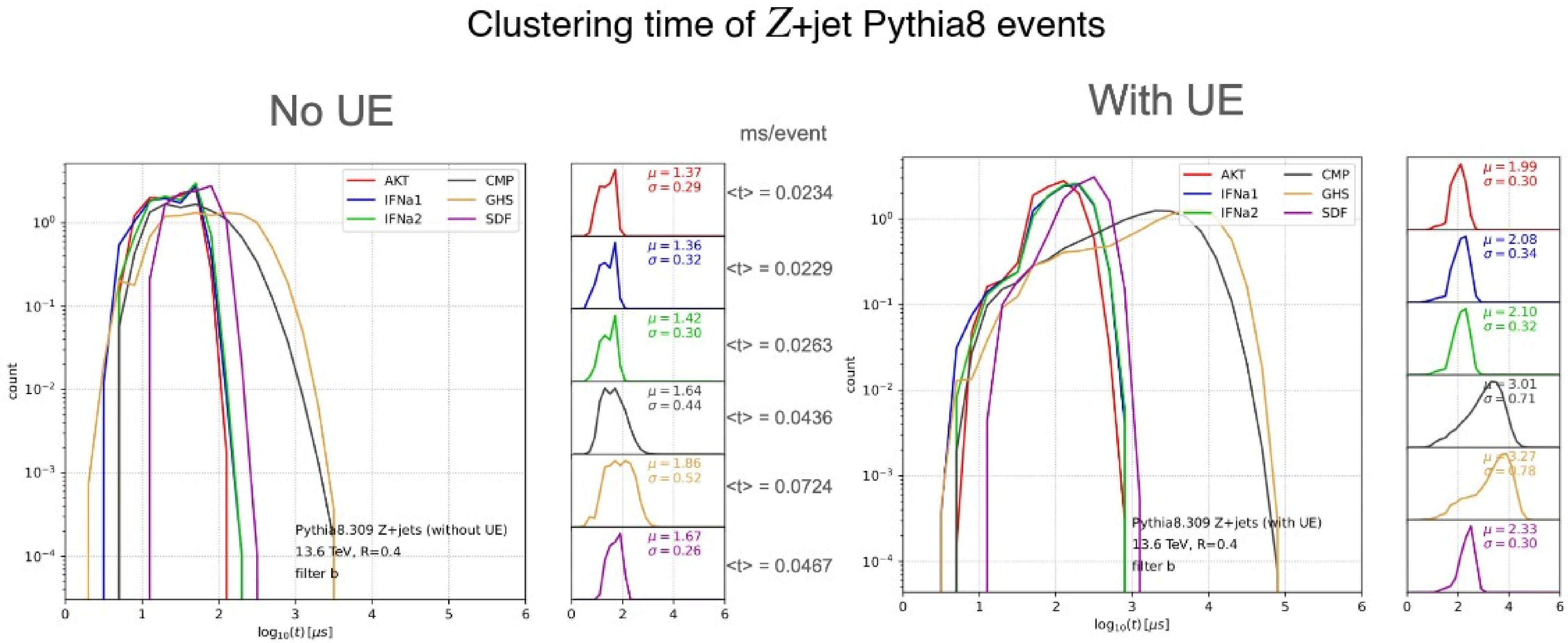
Rivet b-tagging with any flavour (proxy to CMS)



- Large differences between current experimental strategies, likely due to net-flavour VS any-flavour

Performance studies of FastJet implementation

From Giovanni Stagnitto's talk in Durham. Plots performed by Ludovic Scyboz.

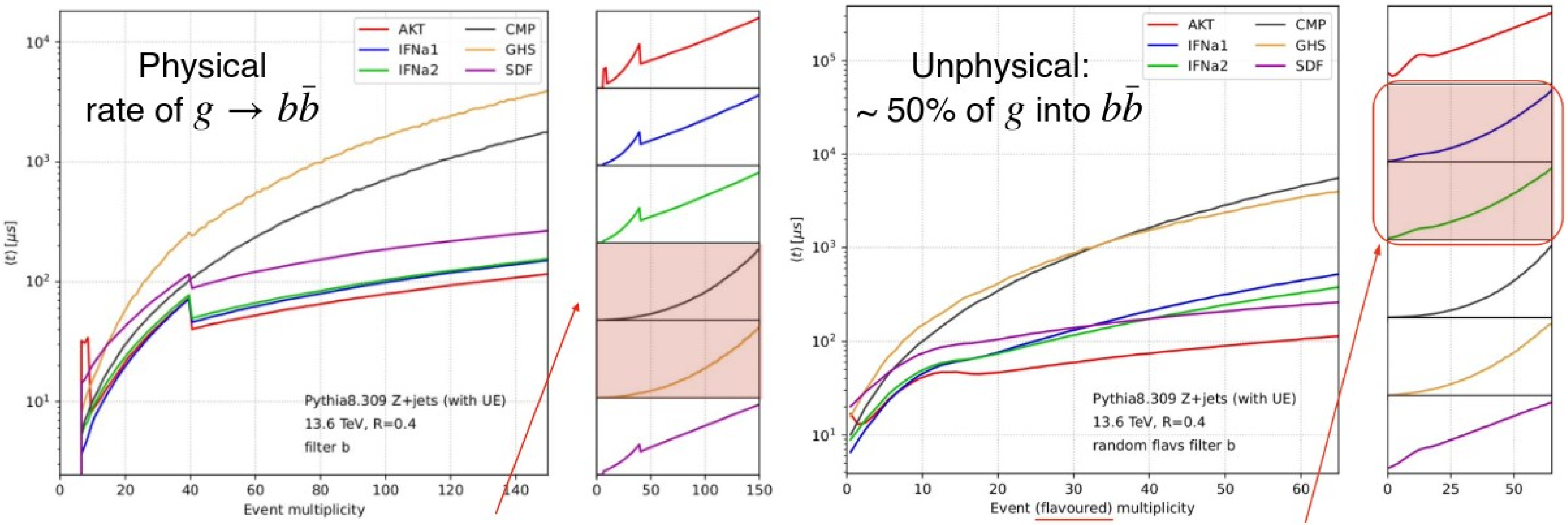


- GHS and CMP are slower with higher multiplicities, some optimization are currently ongoing
- IFN has already been optimized, while SDF is basically using the SD algorithm already implemented in FastJet

Performance studies of FastJet implementation

From Giovanni Stagnitto's talk in Durham. Plots performed by Ludovic Scyboz.

Clustering time of Z+jet Pythia8 events

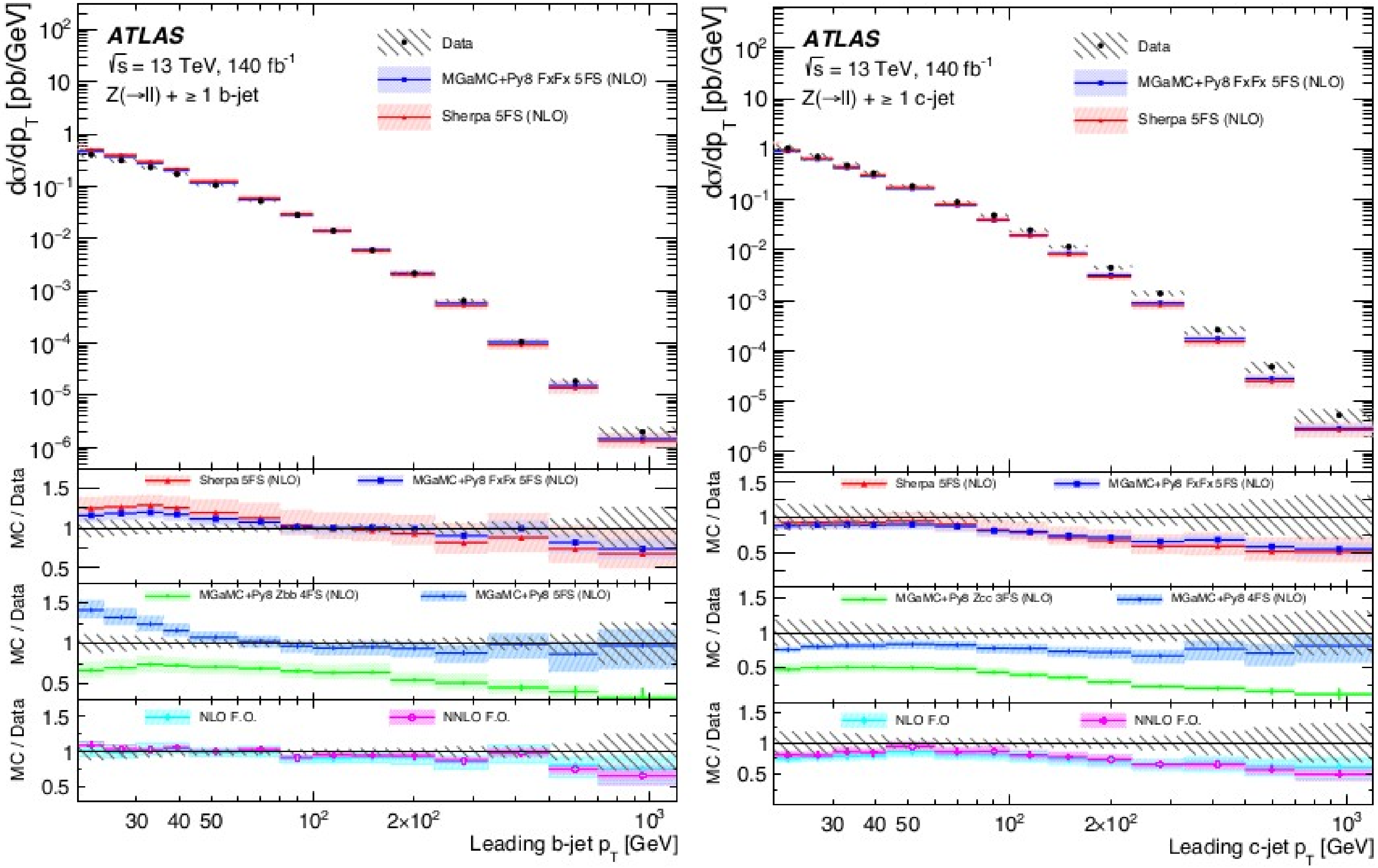


Current implementations of GHS/CMP scale like N^2

Also IFN scaling is worsening with many flavoured particles

Conclusion: does all of this matter?

[ATLAS 2024 (2109.08084)]



- At large pt non-perturbative corrections are small and comparison to fixed-order makes sense.
- However, unfolding to IRC safe algorithms can be sizable (sometimes bigger than the NNLO correction)
- Most of the effect is likely due to any-flavour vs net-flavour

We must do better if we want to do NNLO phenomenology!

Thank you for your attention!