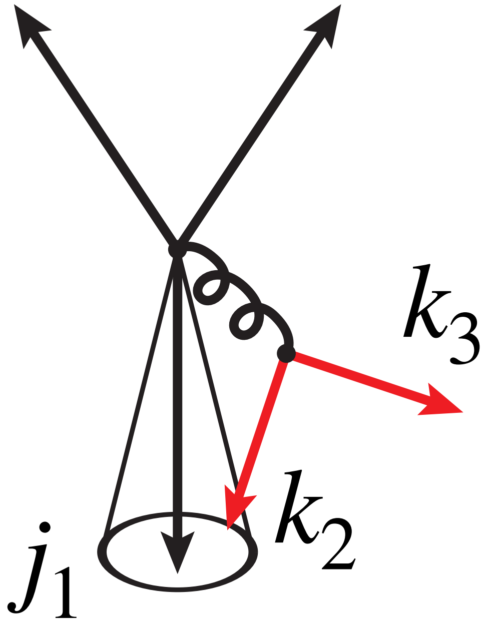


A dress of flavour to suit any jet

Rhorry Gauld

FCC-ee QCD Physics - jet flavour & tagging
CERN (13/12/22)

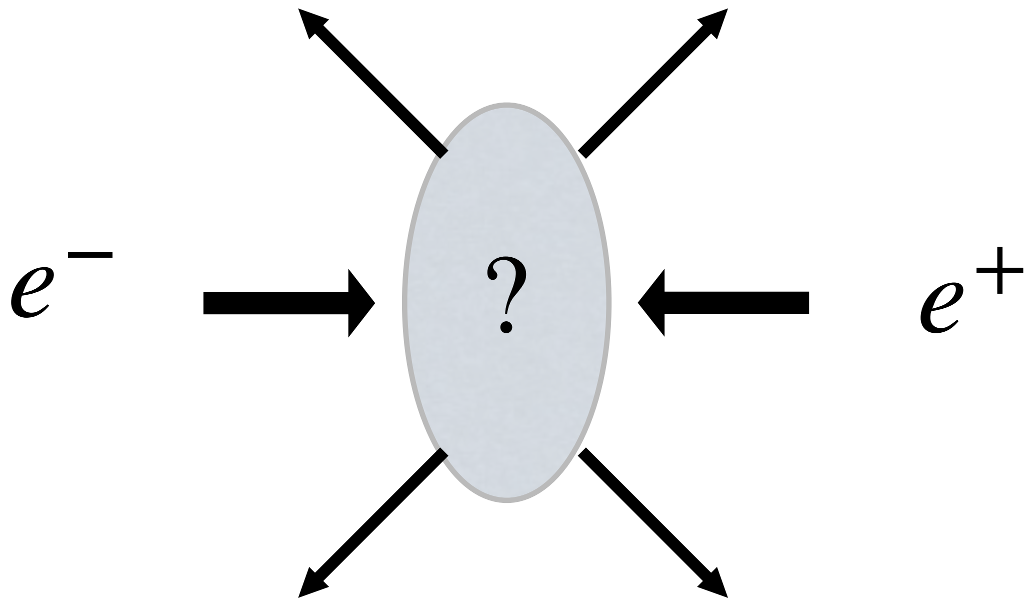
MAX-PLANCK-INSTITUT
FÜR PHYSIK

Overall goals of this talk:

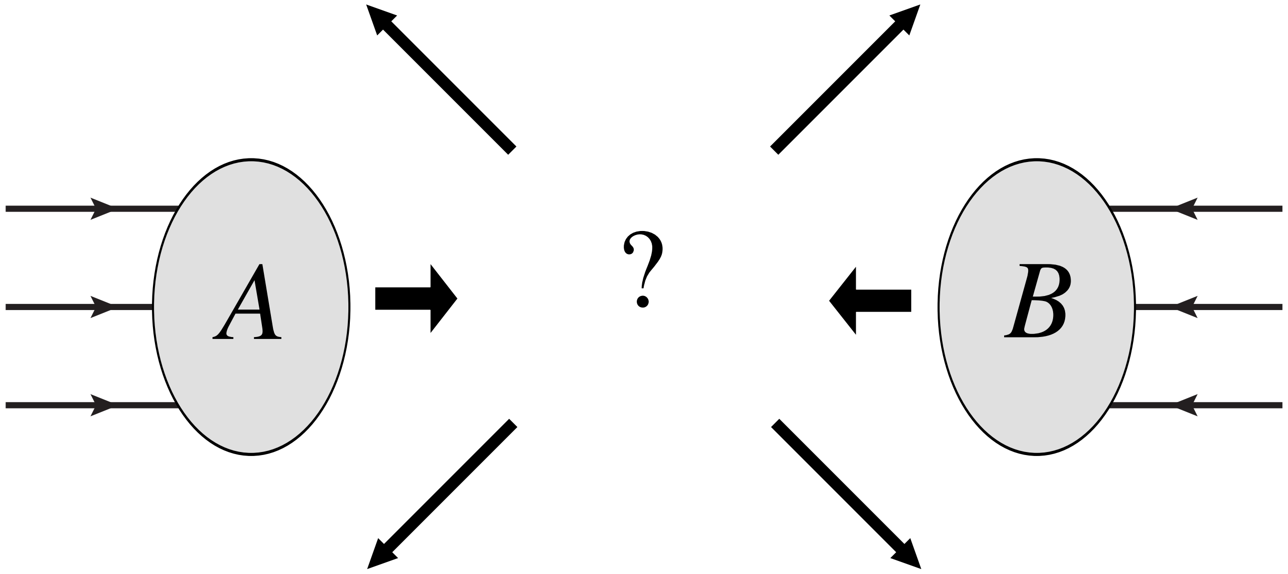
- Discuss recent (theoretical) progress on jet flavour

  … inevitably that will revolve around LHC physics

- Implications/relevance of this work for the FCC-ee



Threshold	$\sqrt{s}$
Z	~ 91 GeV
WW	~ 160 GeV
ZH	~ 240 GeV
$t\bar{t}$	~ 365 GeV



$$AB \rightarrow f + X$$

A, B may be e or p or …

f composed of :

- leptons
- hadrons
- photons
- missing E_T
- jets
- …

$$\boxed{\mathrm{d}\sigma^{\mathrm{meas.}}_{\mathrm{AB}\rightarrow\mathrm{f+X}} \quad \text{vs} \quad \mathrm{d}\sigma^{\mathrm{theory}}_{\mathrm{AB}\rightarrow\mathrm{f+X}}}$$

$$\boxed{d\sigma^{\text{meas.}}_{AB\to f+X} \quad \text{vs} \quad d\sigma^{\text{theory}}_{AB\to f+X}}$$

Focussing on IRC (InfraRed and Collinear) safe observables:

- Those not impacted by collinear splitting(s) or emission(s) of soft particles

➡ Can (reliably) use fixed-order perturbation theory

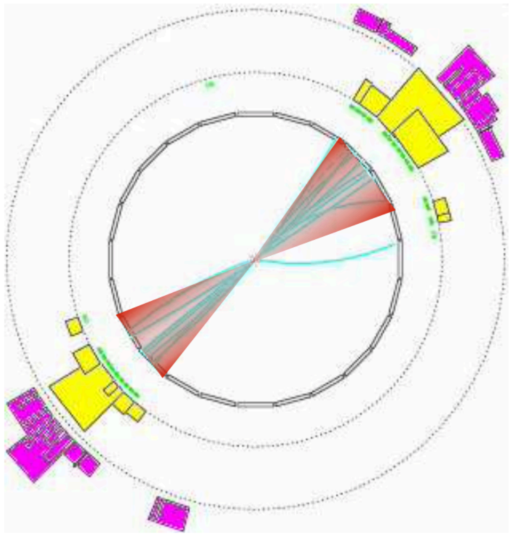
KLN theorem: (Kinoshita '62, Lee & Nauenberg '64)

- For such observables, a cancellation of IRC divergences between virtual and real emissions is ensured (order-by-order)

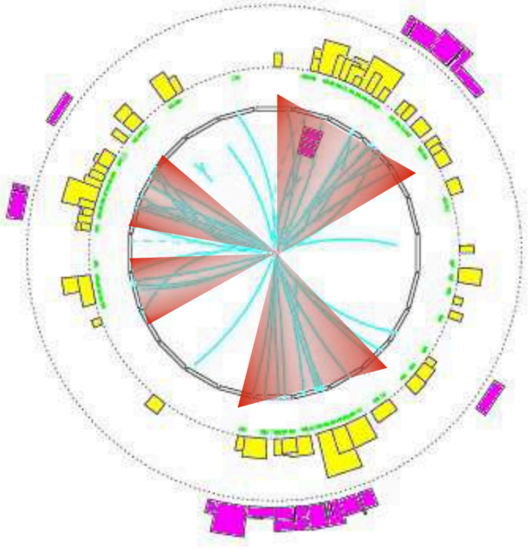
Comments:

- IRC unsafe observables can of course be defined, but then all order-resummation is required (e.g. PDF evolution, obs. dependent resummation)

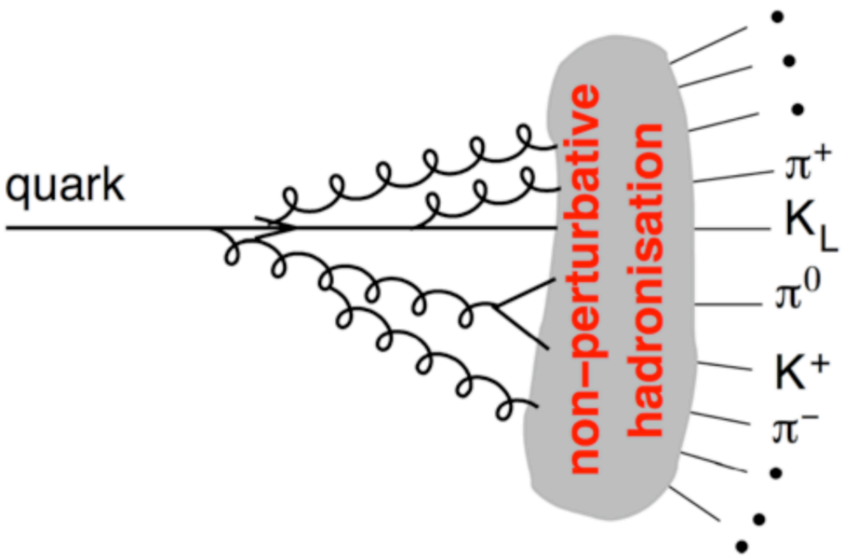
Jet algorithms



2 clear jets



3 jets?
or 4 jets?



Experimentally (e.g. LHC):

- Apply an algorithm to particle flow objects (Kaons, Pions,…)
  (e.g. ATLAS arXiv:1703.10485, CMS arXiv:1706.04965, LHCb arXiv:1310.8197)

➡ Reconstruct a hadronic jet (~collimation of hadronic radiation)

Theoretically:

- If IRC safe, can be applied to parton-level fixed-order predictions

$$\boxed{d\sigma^{\text{meas.}}_{AB\to f+X} \quad \text{vs} \quad d\sigma^{\text{parton}}_{AB\to f+X}}$$

(i.e. physics of the hard-scattering)

The gen-k$_T$ algorithm

(Cacciari, Salam, Soyez arXiv:0802.1189)

Initialise a list of particles (pseudo jets)

Introduce distance measures between particles (pseudo jets) and a Beam:

$$d_{ij} = \min\left(k_{Ti}^{2p}, k_{Tj}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = k_{Ti}^{2p}$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

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$$d_{iB} = k_{Ti}^{2p}$$

(Inclusive) clustering proceeds by identifying the min. distance:

- If it is d_{ij} combine particles ij (update list to contain combined particle)
- If it is d_{iB} , identify i as a jet and remove from list (or a d_{cut} value, excl.)

[repeat until list is empty]

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[repeat until list is empty]

Special cases:

k$_T$ (p=1)
Cambridge/Aachen (p=0)
anti-k$_T$ (p=-1)

In e^+e^-, e.g. for $p = 1$:

$$d_{ij} = \frac{2\min\left(E_i^2, E_j^2\right)}{Q^2}\left(1 - \cos\theta_{ij}\right)$$

Durham / kT

The gen-k_T algorithm

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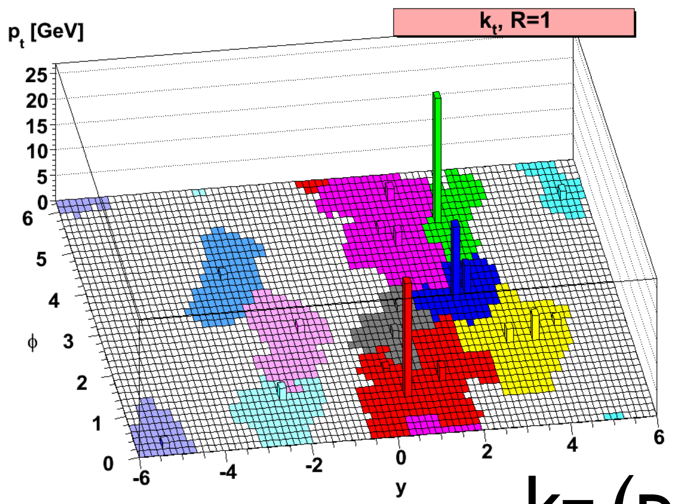
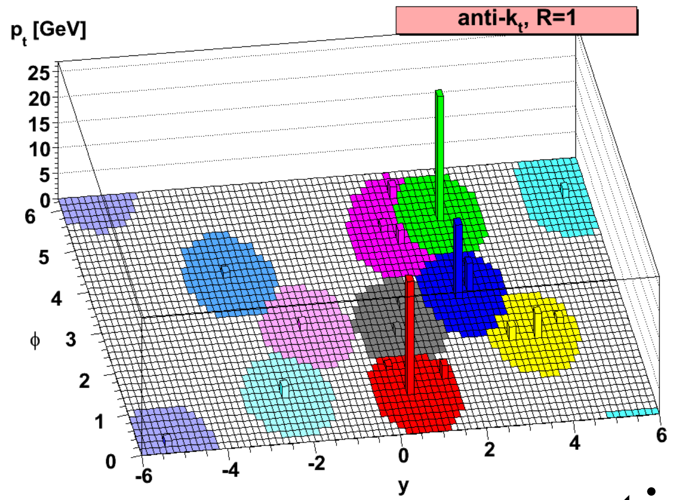
[repeat until list is empty]

Nice geometrical properties



k_T (p=1)



anti-k_T (p=-1)

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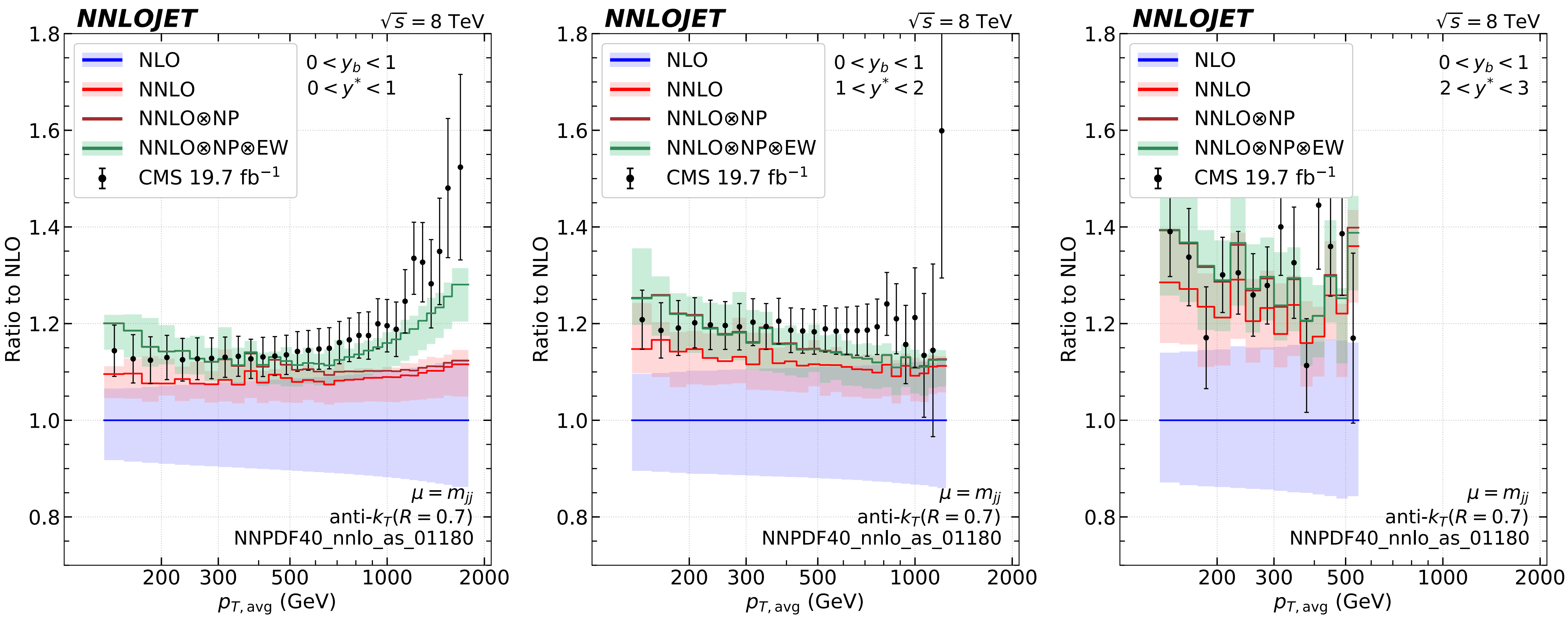
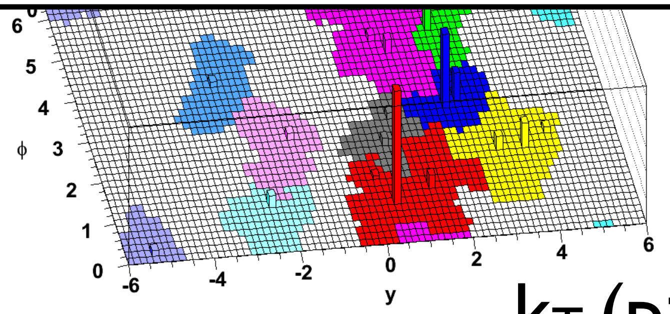
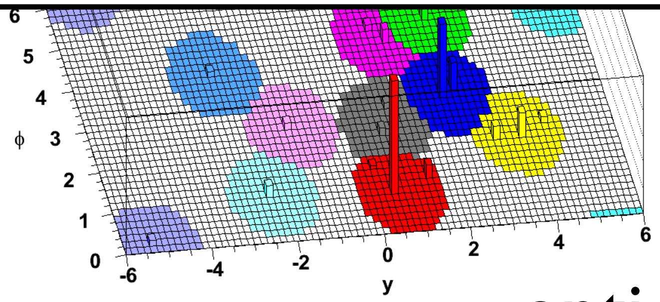


Example: dijet production at the LHC (CMS data) from Chen et al. arXiv:2204.10173



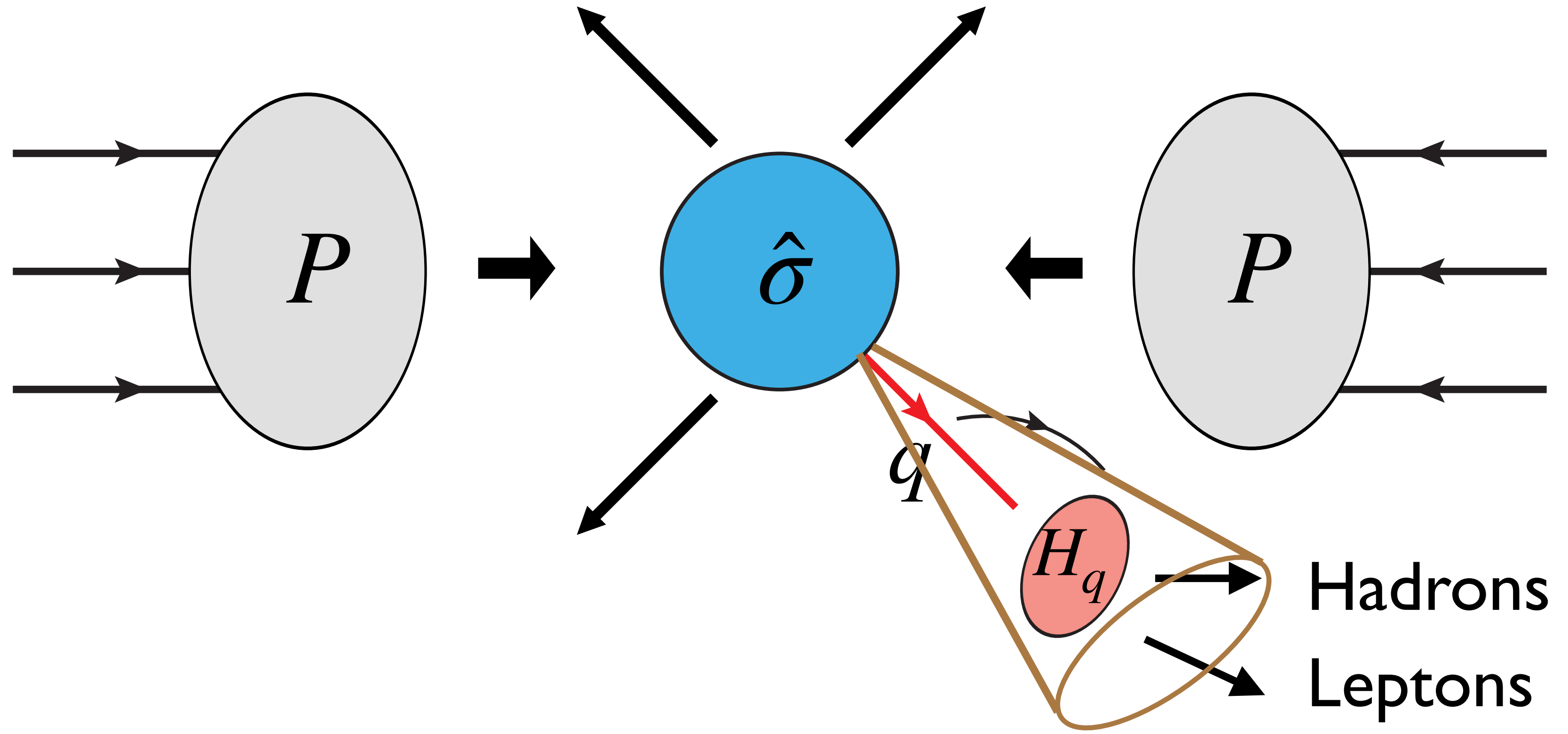
k_T (p=1)



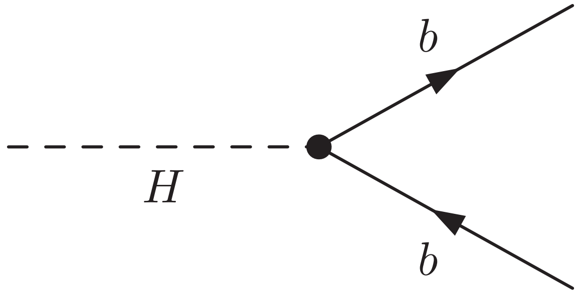
anti-k_T (p=-1)

Heavy-flavour jets at the LHC

(this has been the catalyst for progress on jet flavour)

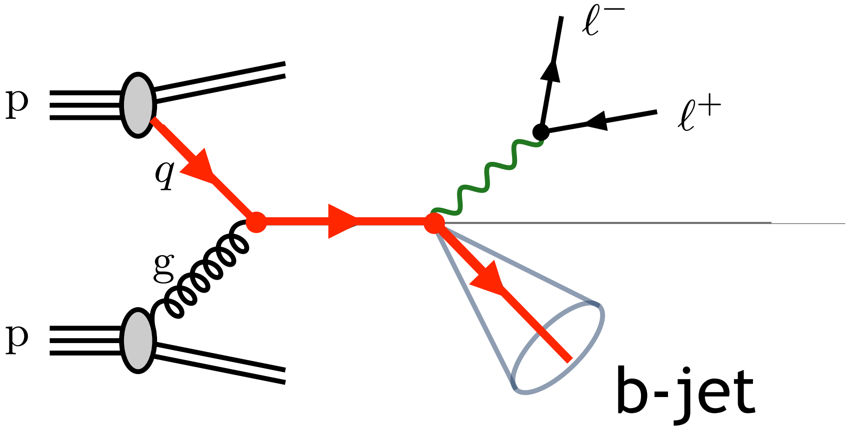


(i) Higgs physics (hadronic decays)



(ii) Top-quark physics ($|V_{tb}| \sim 1$)

(iii) New physics searches (f-jet $+E_T^{\text{miss}}$)



(iv) Gauge-boson + heavy-flavour

Heavy-flavour jets at the LHC

Examples of experimental approaches of defining jet flavour:

ATLAS arXiv:1504.07670, CMS arXiv:1712.07158, LHCb arXiv:1504.07670

Generally (at level of published data/truth level):

i) First identify flavour-blind anti-k_T jets in a fiducial region

ii) Tag these jets with flavour by the presence of 1 or more D/B hadrons

$$\Delta R(j, D/B) < 0.5$$

iii) [ATLAS/LHCb] Additionally make a p_T requirement on the D/B hadrons

$$p_T^{D/B} > 5 \text{ GeV}$$

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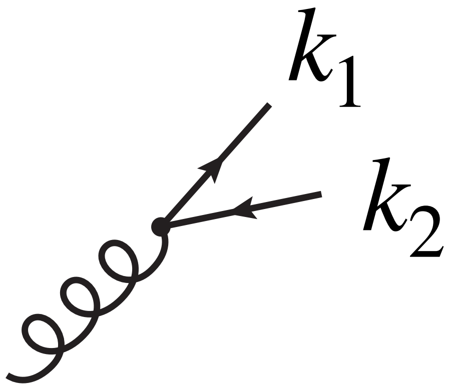
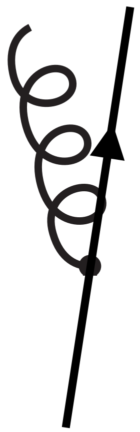
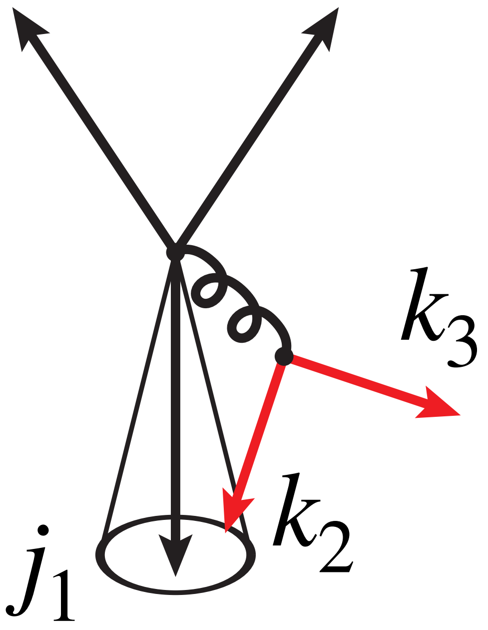
Many IRC problems…



the ‘even tag’



collinear ‘cutout’



soft ‘pollution’

An elegant solution (flavour k$_T$ algorithm)

(Banfi, Salam, Zanderighi hep-ph/0601139)

A flavour dependent jet algorithm (i.e. flavoured particle inputs)

1) Flavour number assignment:

$$q = +1\,, \qquad \bar{q} = -1$$

2) Flavour dependent distance measures (and hence clusterings)

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}, k_{tj})^{\alpha} \min(k_{ti}, k_{tj})^{2-\alpha} & \text{softer of } i, j \text{ is flavoured,} \\ \min(k_{ti}, k_{tj})^{\alpha} & \text{softer of } i, j \text{ is unflavoured} \end{cases}$$

3) Rapidity-dependent Beam distances (differentiates soft vs. initial collinear)

$$d_{fB} = \max\left(p_{T,f}\,, p_T^B(y)\right)^{\alpha} \min\left(p_{T,f}\,, p_T^B(y)\right)^{2-\alpha}$$

$$p_T^B(y) = \sum_i p_{T,i}\left(\Theta(y_i - y) + \Theta(y - y_i)e^{y_i - y}\right)$$

Note: the e^+e^- version, $p_T \to E\,, \quad \Delta R^2/R^2 \to 2\,(1-\cos\theta)/Q^2$

An elegant solution (flavour k_T algorithm)

(Banfi, Salam, Zanderighi hep-ph/0601139)

A flavour dependent jet algorithm (i.e. flavoured particle inputs)

However… this algorithm has never been adopted by experiment:

(1) Jet calibration / pileup subtraction better achieved with anti-k_T jets
(mainly a hadron collider issue)

(2) Flavour information of inputs particles required (i.e. modified inputs)
(modified inputs: D/B unstable, represented by secondary vertex SVs)

(3) Systematics due to probabilistic flavour of SVs
(every event will have many clustering histories / jet kinematics / flavour)

… Note, some issues less relevant in e^+e^- environment

Note: the e^+e^- version, $p_T \rightarrow E\,, \quad \Delta R^2/R^2 \rightarrow 2\,(1-\cos\theta)/Q^2$

An elegant solution (flavour k$_T$ algorithm)

(Banfi, Salam, Zanderighi hep-ph/0601139)

A flavour dependent jet algorithm (i.e. flavoured particle inputs)

Lots of activity from LHC community on this topic:

(i) Soft Drop grooming approach, Caletti et al. 2205.01109

(ii) Winner-Takes-All approach, Caletti et al. 2205.01117

(iii) Flavoured anti-k$_T$, Czakon et al. 2205.11879

(iv) Successive iterations of flavour-k$_T$ and anti-k$_T$, Caletti et al. 2108.10024

(v) Jet angularities & primary Lund jet plane, Fedkevych et al. 2202.05082

…

A dress of flavour to suit any jet

(**RG**, Huss, Stagnitto arXiv:2208.11138)

i

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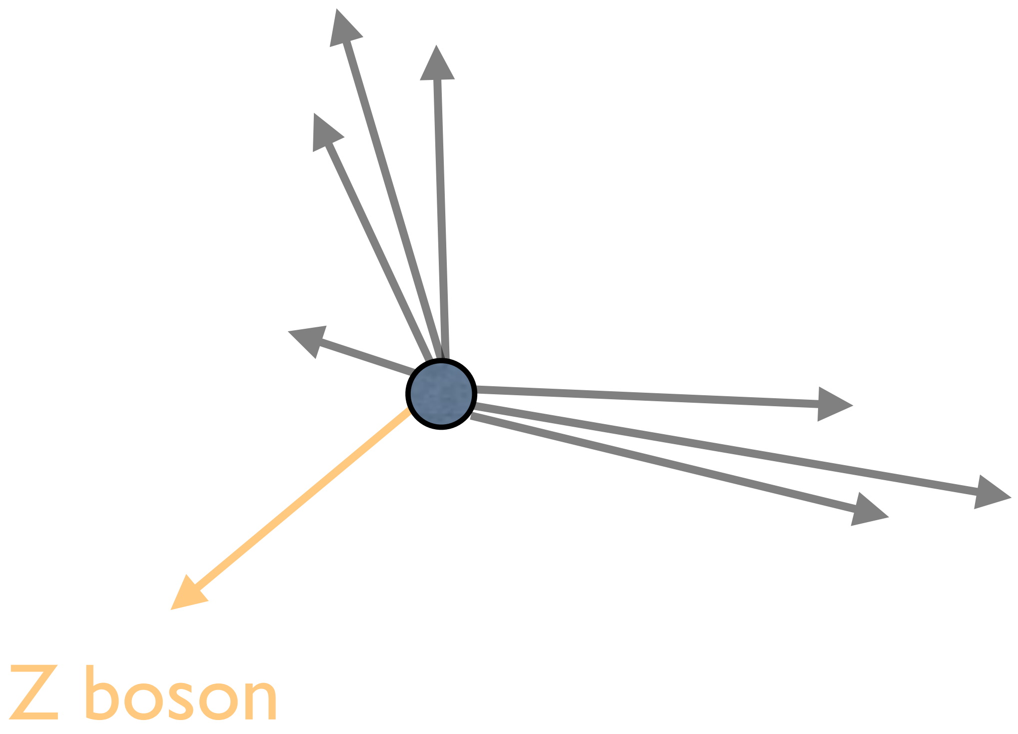
Our motivation: A well defined flavour algorithm applicable to anti-k_T jets

(actually, any jet)

Toy event



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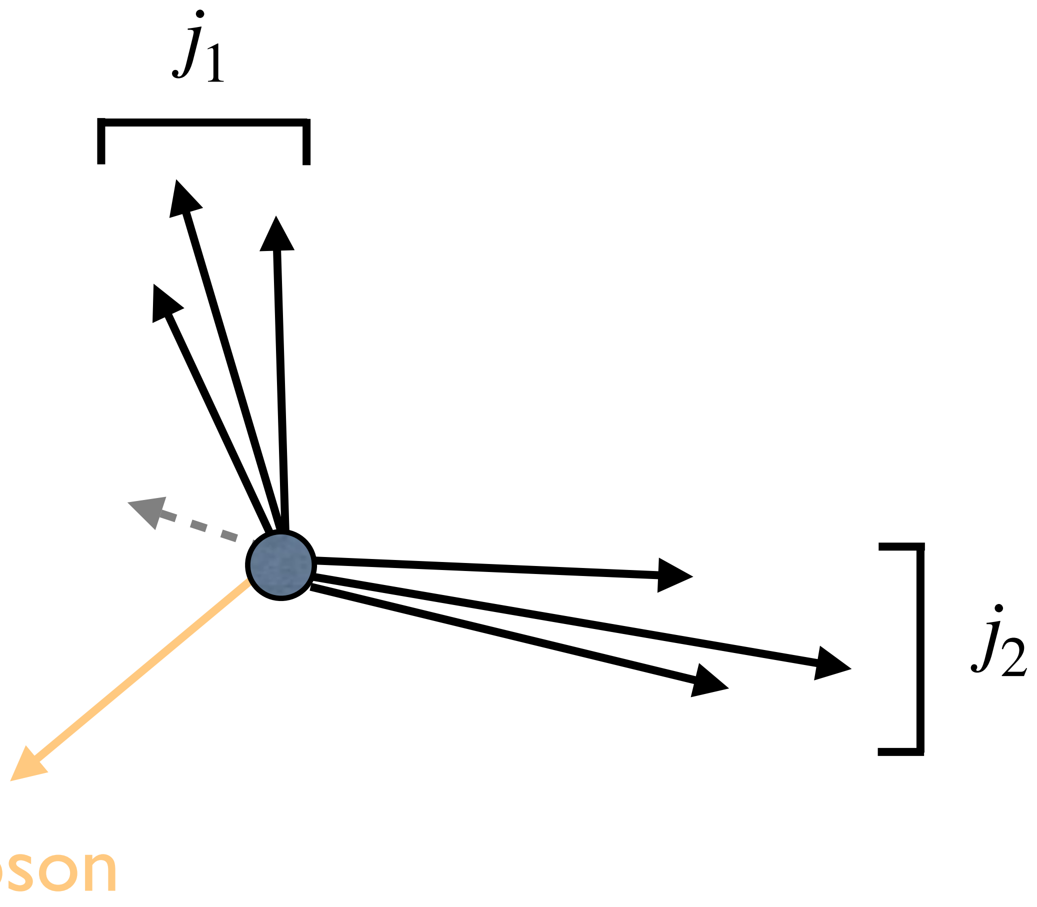

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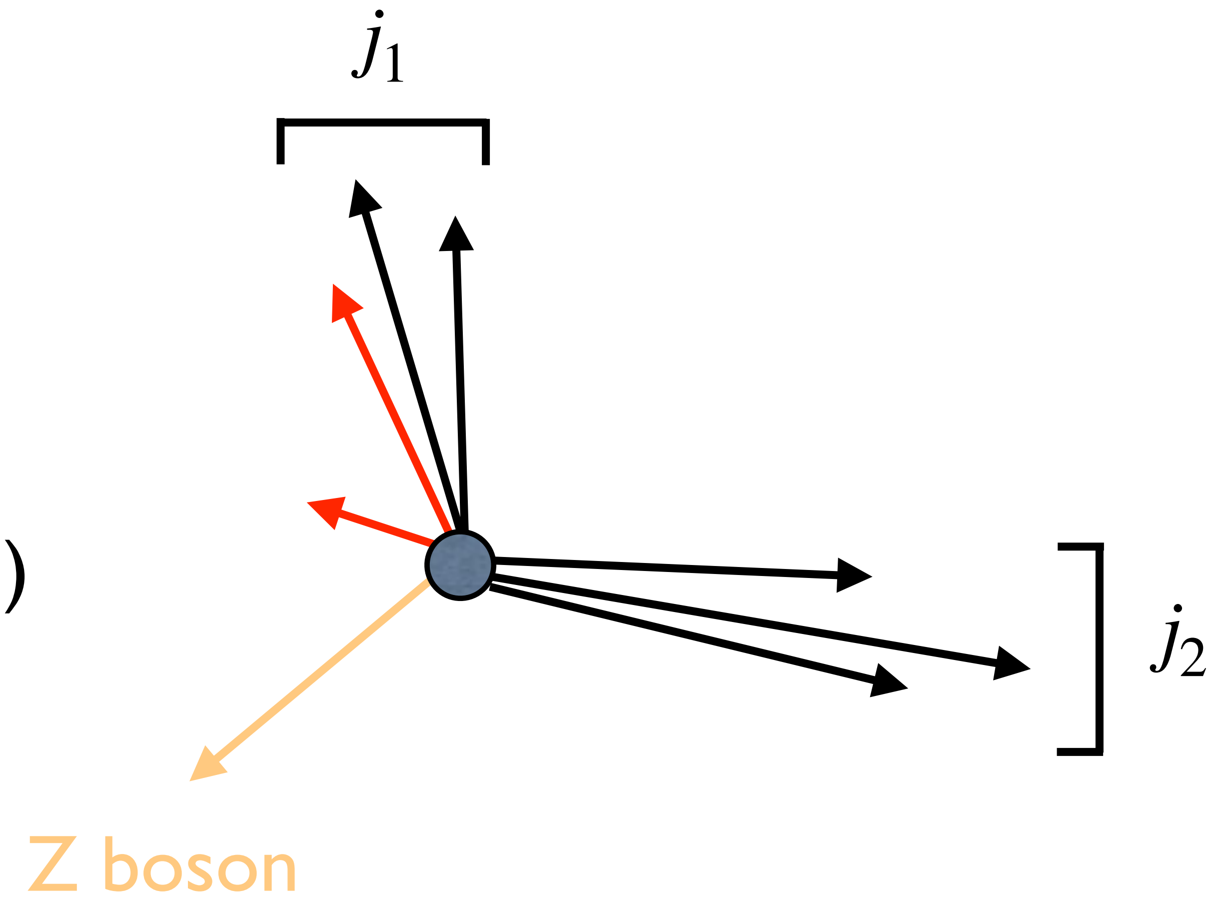

Flavoured particles

b-quark (theory)

secondary vertex (exp.)

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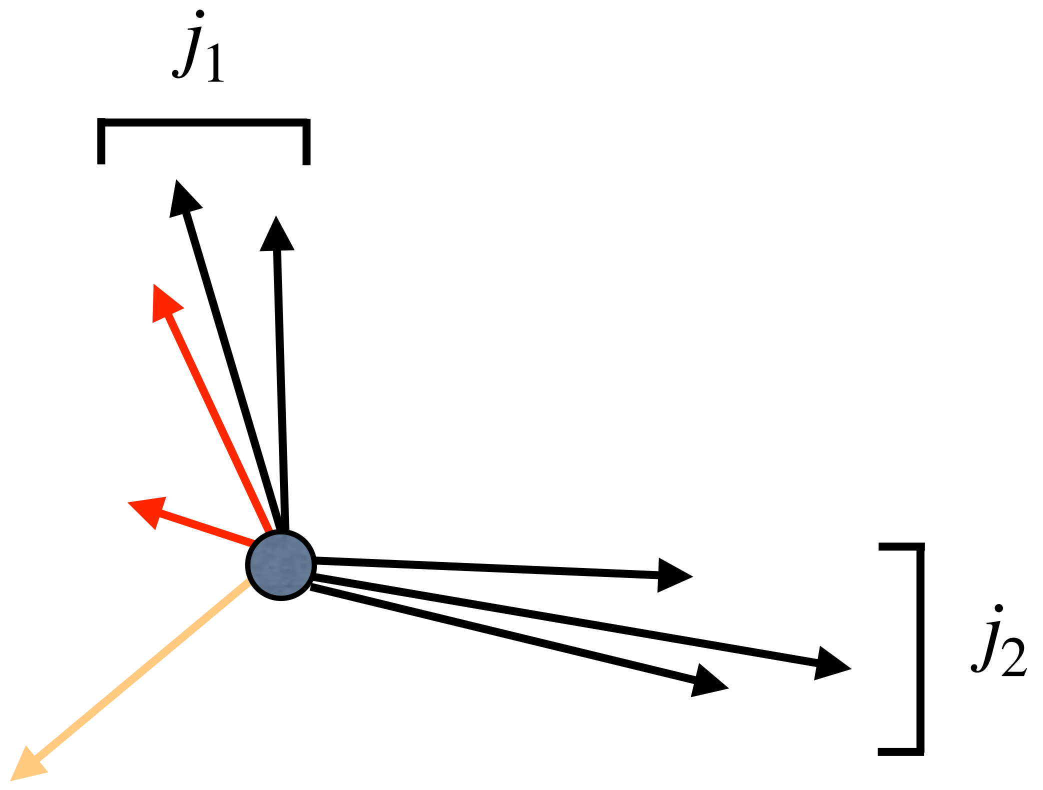

Flavoured particles
b-quark (theory)
secondary vertex (exp.)

Z boson

set of jets $\{j_1, \ldots, j_m\}$

set of flavoured objects $\left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$

an assignment of the flavoured objects to these jets

(collinear safe) flavoured objects

(**RG**, Huss, Stagnitto arXiv:2208.11138)

flavoured particles (quarks, hadrons) not collinear safe. Define new objects:

Non-technical version:

We dress the flavoured particles with collinear radiation

(altering momenta but not flavour)

$$\{f_1, \ldots, f_n\} \to \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$$

flavoured particles → flavoured 'clusters'

(collinear safe) flavoured objects

(**RG**, Huss, Stagnitto arXiv:2208.11138)

flavoured particles (quarks, hadrons) not collinear safe. Define new objects:

i) Initialise a list of all particles

ii) Add to the list all flavoured particles, removing any overlap

iii) Calculate the distances $d_{ij} = \Delta R_{ij}^2$ between all particles

iv) If $d_{ij}^{\min} > \Delta R_{\mathrm{cut}}^2$ terminate the clustering. Otherwise:

1. (i & j flavourless) replace i & j in the list with combined object ij
2. (i & j flavoured) remove flavoured objects i & j from the list
3. (i or j flavoured) combine i and j if the criterion:

$$\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{ij}}{R_{\mathrm{cut}}} \right)^{\beta}$$

[Soft-drop]

(Larkoski et al. arXiv:1402.2657)

Otherwise remove flavourless of i/j from list

[Repeat until list empty, or no flavoured particles left]

The flavour dressing algorithm

(**RG**, Huss, Stagnitto arXiv:2208.11138)

We now have have $\{j_1, \ldots, j_m\}, \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$

We introduce an **Association criterion** for $\hat{f}_a$ and j_b (some possibilities):

- the flavoured particle f_a is a constituent of jet j_b (applicable to unstable f_a)
- or $\Delta R(\hat{f}_a, j_b) < R_{\text{tag}}$
- or Ghost association of $\hat{f}_a$ (include direction of $\hat{f}_a$ in anti-k$_T$ clustering)

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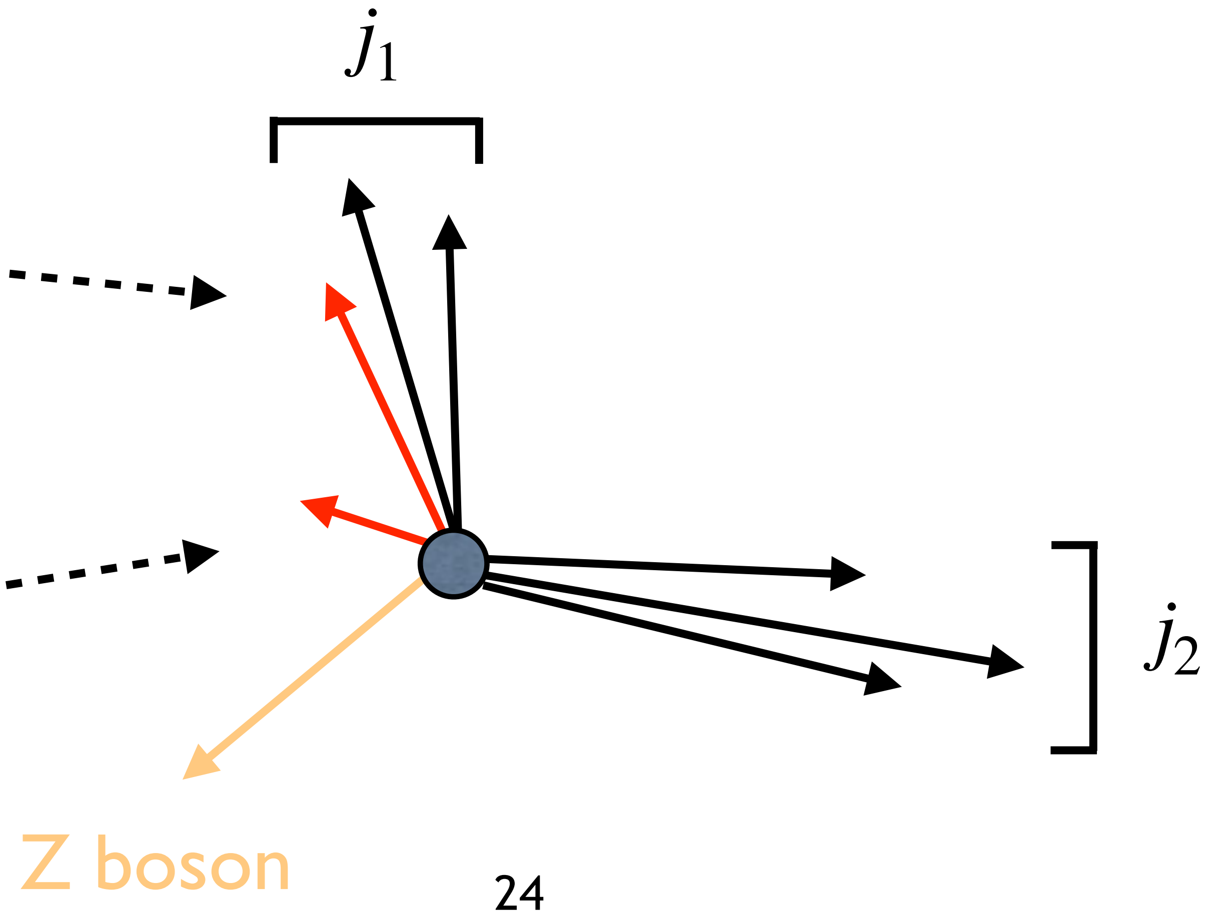

Here, $f \sim j_1$

No association for this f

The flavour dressing algorithm

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- or Ghost association of $\hat{f}_a$ (include direction of $\hat{f}_a$ in anti-k$_T$ clustering)

Introduce a **Counting** or **Accumulation** for flavour:

- with charge info. (q vs $\bar{q}$), then $q = +1$ and $\bar{q} = -1$ (net flavour is sum)
- if one cannot (e.g. experiment), $q = \bar{q} = 1$ (net flavour is sum modulo 2)
  [i.e. jets with even number of $q_i + \bar{q}_j$ are NOT flavoured]

The flavour dressing algorithm

(**RG**, Huss, Stagnitto arXiv:2208.11138)

We now have have $\{j_1, \ldots, j_m\}, \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$, association, and counting rules

The flavour dressing algorithm

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We now have have $\{j_1, \ldots, j_m\}, \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$, association, and counting rules

Dressing algorithm:

- Calculate a set of distances between the flavoured objects, jets and beam:
  - [ff] d_{ab} between all all flavoured objects $\hat{f}_a$ and $\hat{f}_b$
    - [fj] d_{ab} between $\hat{f}_a$ and j_b ONLY if there is an association
    - [fB] d_{aB} for all $\hat{f}_a$ without a jet association

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- Find the minimum distance of all entries in the list
  - if it is an [fj] assign $\hat{f}_a$ to j_b (removing entries involving $\hat{f}_a$ from list)
  - otherwise just remove $\hat{f}_a$ [fB] or $\hat{f}_a$ and $\hat{f}_b$ [ff] from the list

[repeat until list empty]

- The flavour of each jet is then just the accumulation of its flavour

The flavour dressing algorithm

(**RG**, Huss, Stagnitto arXiv:2208.11138)

We now have have $\{j_1, \ldots, j_m\}, \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$, association, and counting rules

Dressing algorithm:

Here we use the distance measures proposed in flavour-k$_T$

(Banfi, Salam, Zanderighi hep-ph/0601139)

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

$$d_{aB\pm} = \max\left(p_{T,a}^{\alpha}, p_{T,B_\pm}^{\alpha}(y_{\hat{f}_a})\right) \ \min\left(p_{T,a}^{2-\alpha}, p_{T,B_\pm}^{2-\alpha}(y_{\hat{f}_a})\right)$$

Note: the e^+e^- version, $p_T \to E\,,\quad \Delta R^2/R^2 \to 2\,(1-\cos\theta)/Q^2$

Another viable option is Jade:
(directly suitable for e^+e^-)

$$d_{ab} = 2p_a \cdot p_b$$

- The flavour of each jet is then just the accumulation of its flavour

Tests of the algorithm (e^+e^-)

(**RG**, Huss, Stagnitto arXiv:2208.11138)

Consider the process $e^+e^- \to 2$ jets at fixed-order using k$_T$ algorithm

Look at 'bad' events (i.e. where we do not find 2 flavoured jets, $e^+e^- \to q\bar{q}$)

The 'bad' cross-section should vanish in the $y_3 \to 0$ limit

(y_3 defines the distance measure at which the event goes from 2 jet → 3 jet)

($y_3 \to 0$ corresponds to limit of extremely soft and/or collinear emissions)

These tests originally proposed/shown in the original flavour-k$_T$ study

(Banfi, Salam, Zanderighi hep-ph/0601139)

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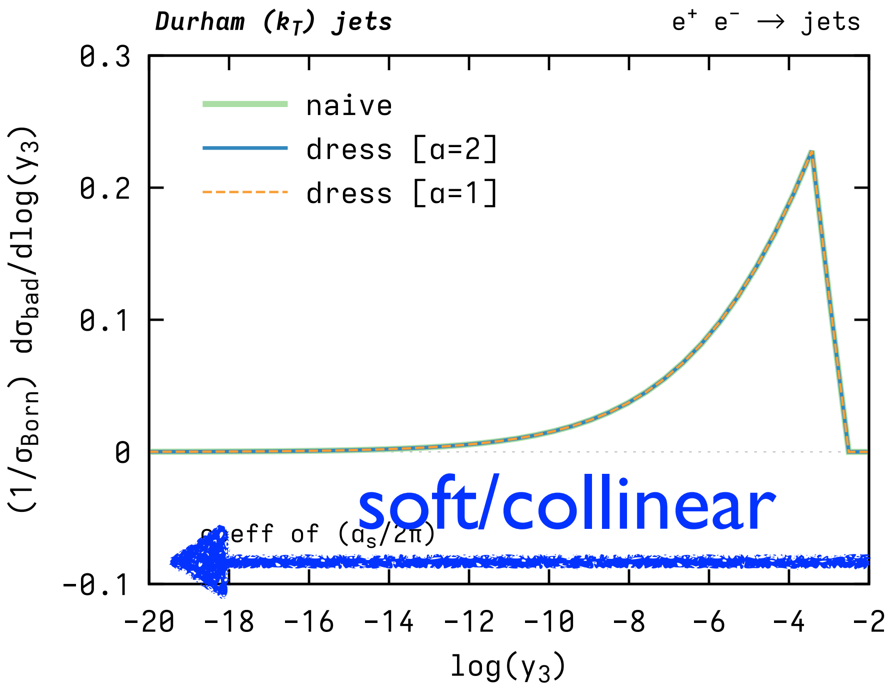
$\mathcal{O}(\alpha_s)$



These tests originally proposed/shown in the original flavour-k$_T$ study

(Banfi, Salam, Zanderighi hep-ph/0601139)

Tests of the algorithm (e^+e^-)

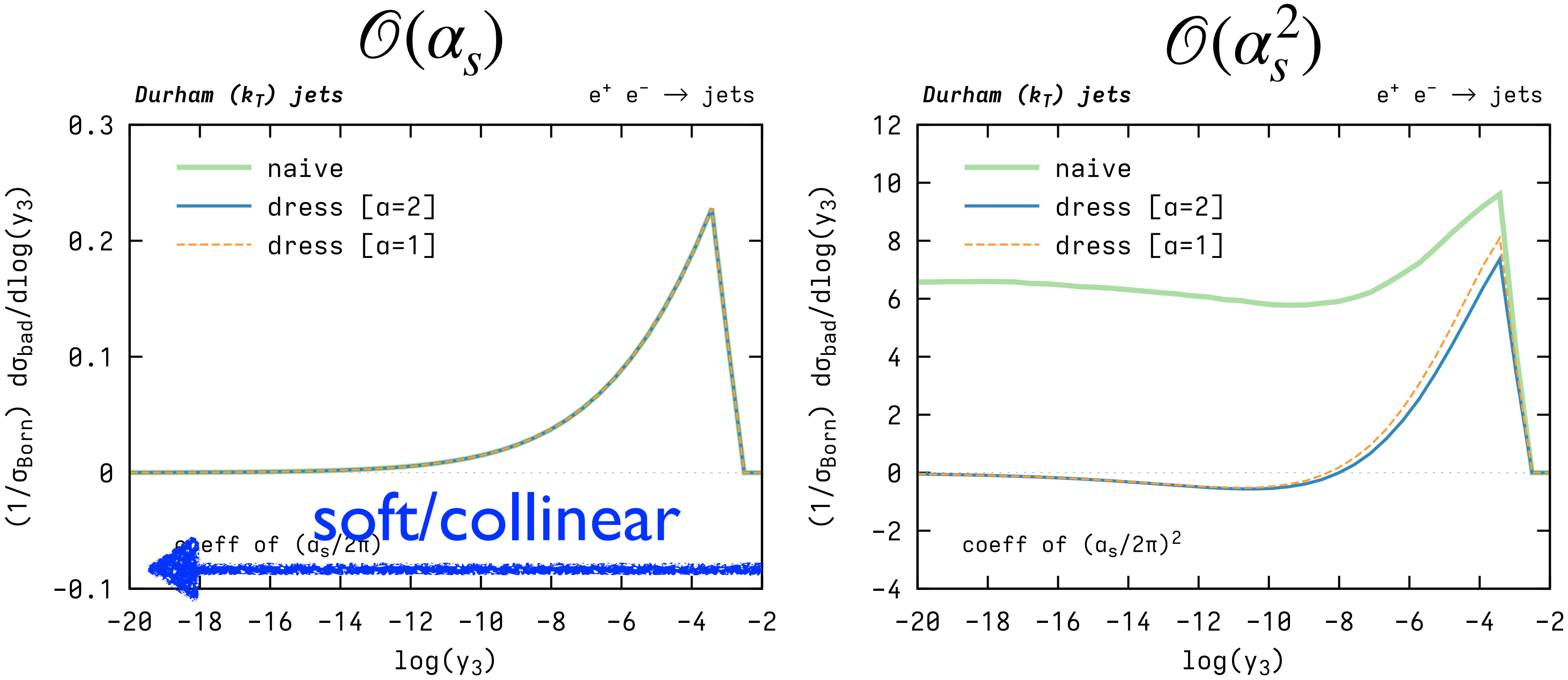
(**RG**, Huss, Stagnitto arXiv:2208.11138)

Consider the process $e^+e^- \rightarrow 2$ jets at fixed-order using k$_T$ algorithm

Look at 'bad' events (i.e. where we do not find 2 flavoured jets, $e^+e^- \rightarrow q\bar{q}$)

The 'bad' cross-section should vanish in the $y_3 \rightarrow 0$ limit
(y_3 defines the distance measure at which the event goes from 2 jet → 3 jet)
($y_3 \rightarrow 0$ corresponds to limit of extremely soft and/or collinear emissions)

$\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha_s^2)$



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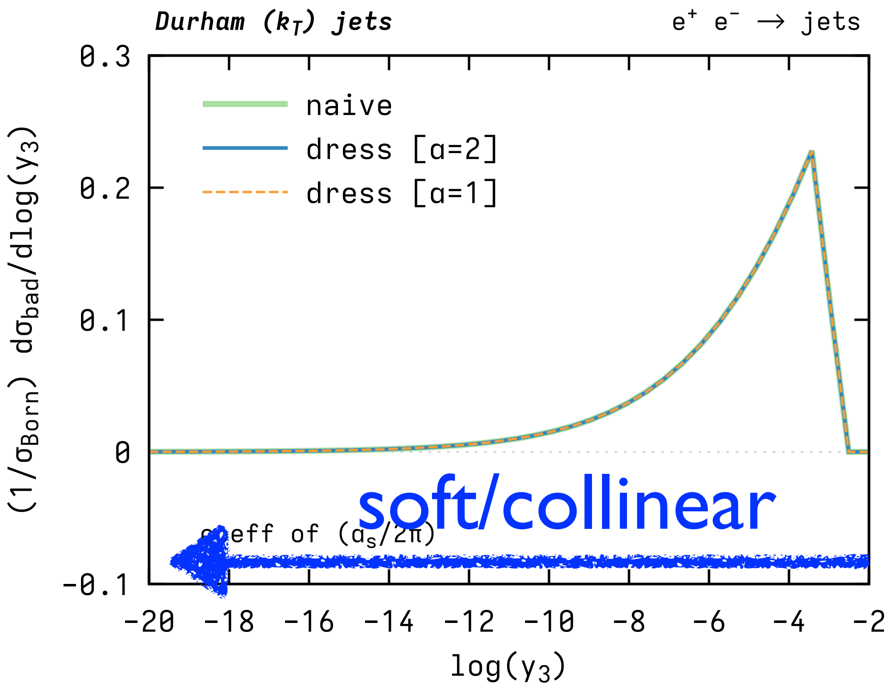
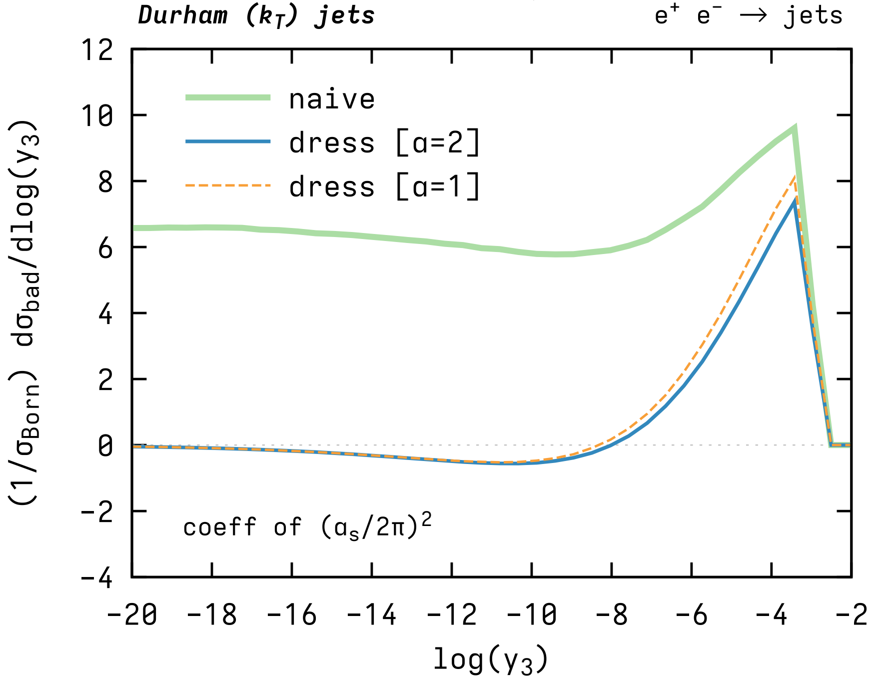
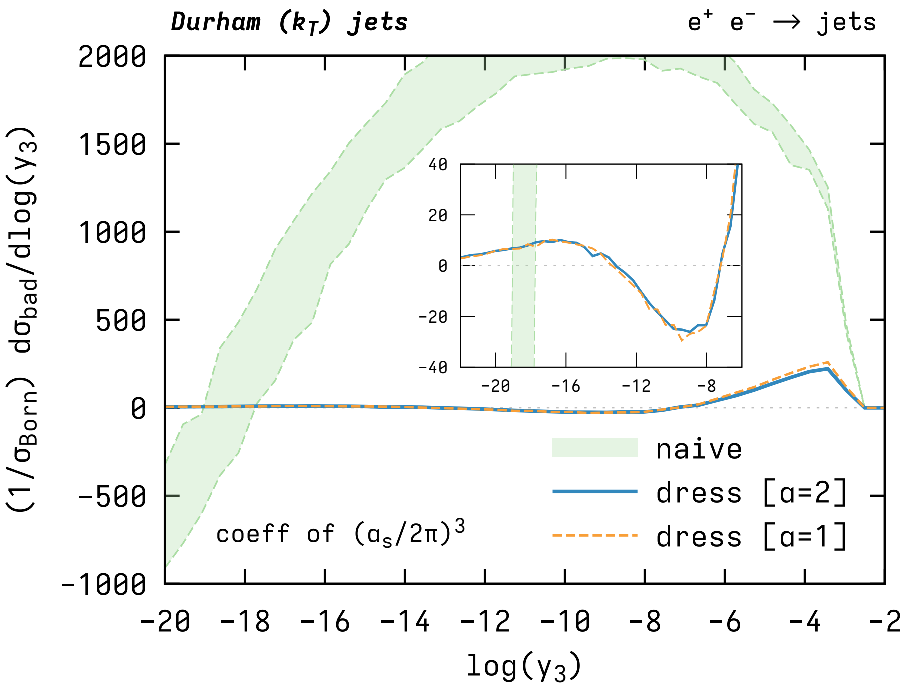
$\mathcal{O}(\alpha_s)$



$\mathcal{O}(\alpha_s^2)$



$\mathcal{O}(\alpha_s^3)$



These tests originally proposed/shown in the original flavour-k$_T$ study

(Banfi, Salam, Zanderighi hep-ph/0601139)

I have presented a new algorithm for assigning flavour to jets:

- The approach is IRC safe (at least until N4LO, maybe more)
- It can be applied to any set of (IRC safe) jets
  (and can be applied in any collider environment pp, e^+e^-, … etc.)
- It does **not** require flavoured particles to be part of the initial jet reco.
  (i.e. it can be applied to heavy flavour tagging at an experiment!)
- The algorithm can be applied to general processes with flavoured jets
  (e.g. run the algorithm for u,d,s,c,b flavours, or for q flavour)

Obvious use cases (where precise theory critical): $A_{fb}^{b}, \quad A_{fb}^{c}, \quad \ldots$

continued…

- Experimental detectors are not ideal (Particle Identification not perfect)
  (obviously critical here, when tracking flavour quantum numbers)

- There are many interesting measurements of the IRC-unsafe contr.
  (e.g. double-tagged jet events, critical for PS tunes and fragmentation)

Thank you!

(more pp results in backups)

Whiteboard

Whiteboard

Tests of the algorithm (pp)

(**RG**, Huss, Stagnitto arXiv:2208.11138)

Can also perform all-order 'sensitivity' tests using Parton Shower framework

In this case study, also use resolution variable to probe IRC sensitive regions (here we study the behaviour, rather than the bad cross-section vanishing)

Here consider dijet events (exclusive k_T algorithm) with $E_T \geq 1\ \mathrm{TeV}$

We use the resolution variable: $y_3^{\mathrm{k_T}} = d_3^{\mathrm{k_T}}/(E_{T,1} + E_{T,2})$

(Buonocore et al. arXiv:2201.11519)

These tests originally proposed/shown in the original flavour-$\mathrm{k_T}$ study

(Banfi, Salam, Zanderighi hep-ph/0601139)

Tests of the algorithm (pp)

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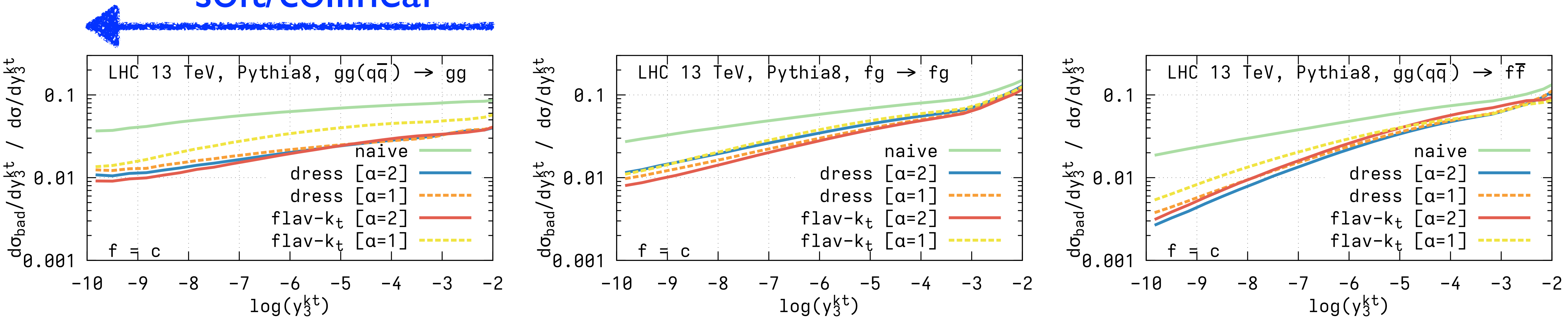
soft/collinear



These tests originally proposed/shown in the original flavour-k$_T$ study

(Banfi, Salam, Zanderighi hep-ph/0601139)

Application of the algorithm (pp)

(**RG**, Huss, Stagnitto arXiv:2208.11138)

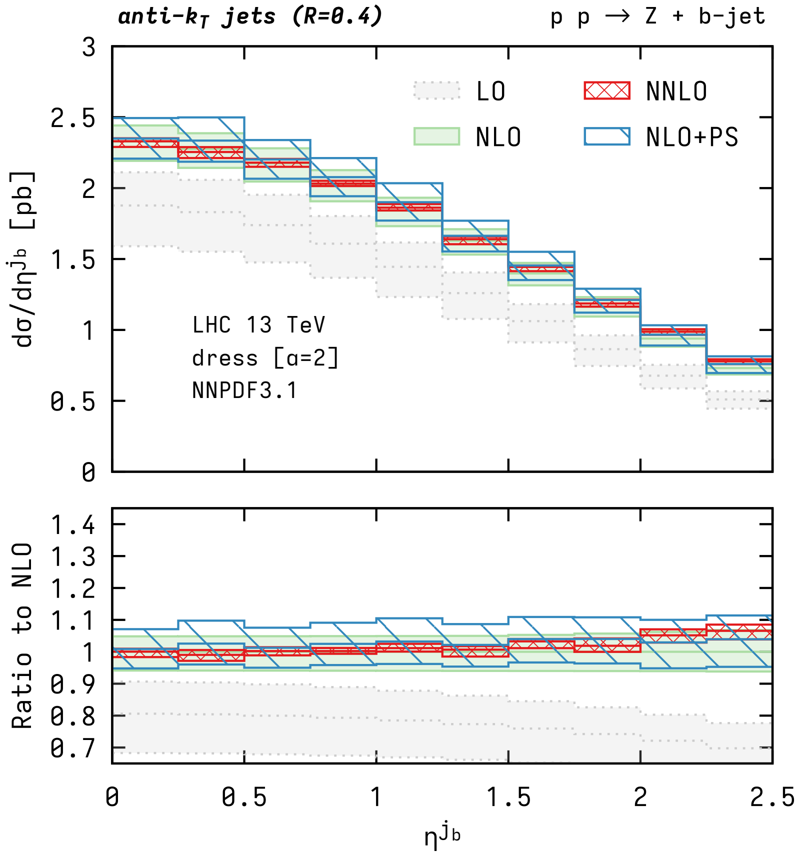
Now consider the process $pp \to Z + b - \text{jet}$ in Fiducial region (13 TeV, CMS-like)

(N)NLO at fixed-order w/ NNLOJET, **RG** et al. arXiv:2005.03016

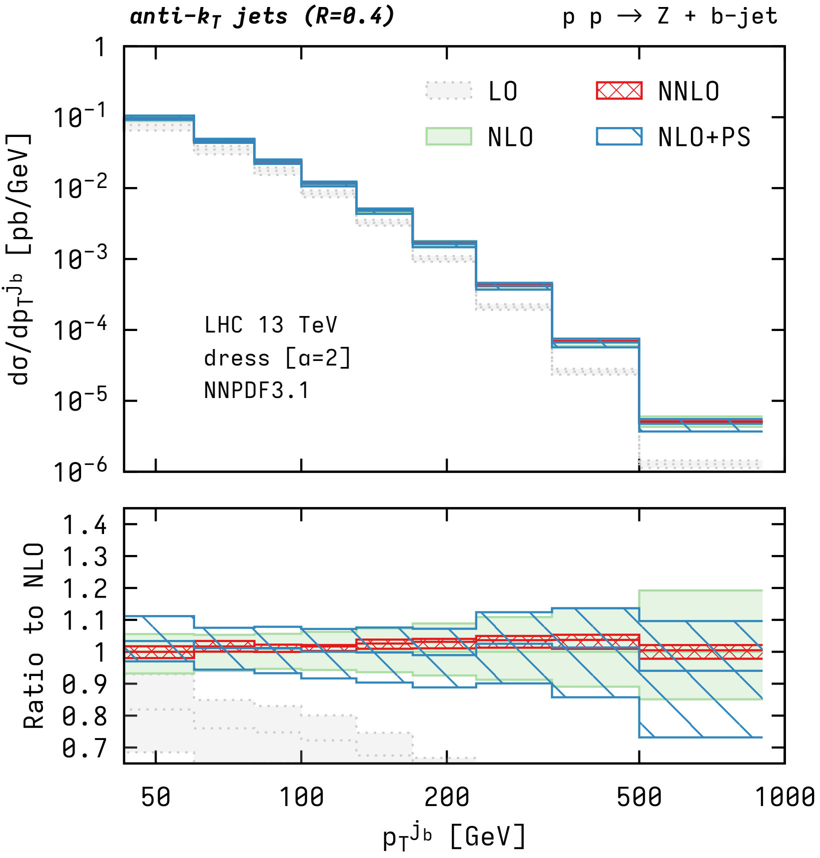
NLO+PS Hadron-level with aMC@NLO interfaced to Pythia8

Tests sensitivity to: all-order effects, hadronisation (also FO IRC safety in pp)

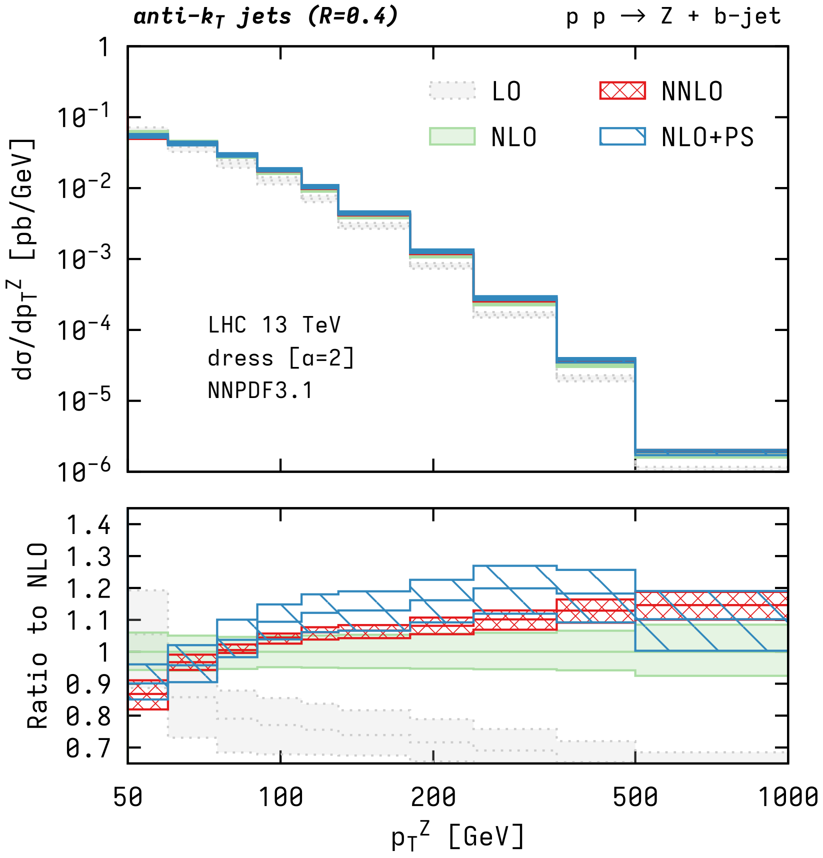
$\eta_{\text{b-jet}}$



$p_{T,\text{b-jet}}$



$p_{T,Z}$



Massive calculation (IRC unsafe def.)

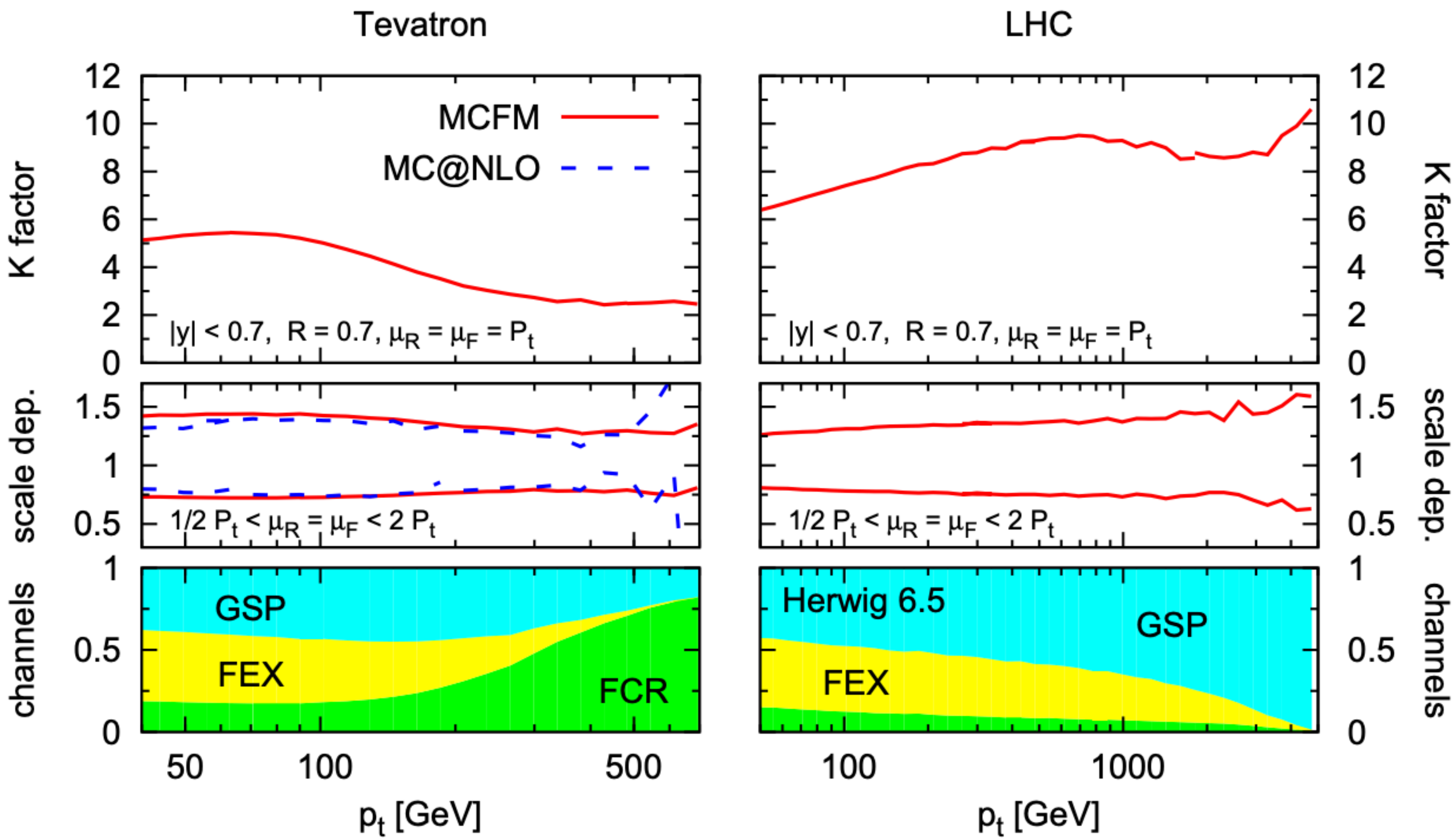


Figure 2: Top: K-factor for inclusive b-jet spectrum as computed with MCFM [10], clustering particles into jets using the k_t jet-algorithm [9] with R=0.7, and selecting jets in the central rapidity region ($|y| < 0.7$). Middle: scale dependence obtained by simultaneously varying the renormalisation and factorisation scales by a factor two around p_t, the transverse momentum of the hardest jet in the event. Bottom: breakdown of the Herwig [11] inclusive b-jet spectrum into the three major hard underlying channels cross sections (for simplicity the small $bb \to bb$ is not shown).

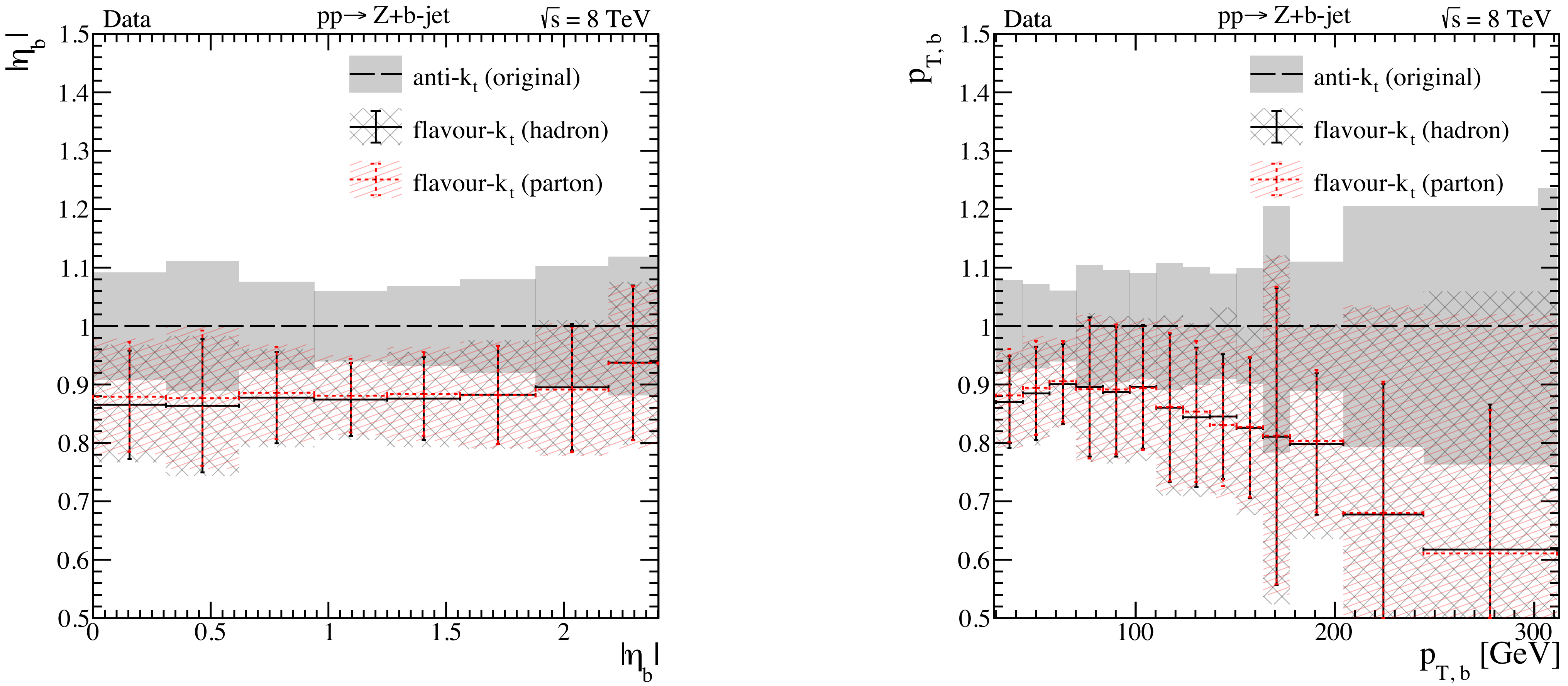
arXiv:0704.2999 BSZ

Unfolding for Z+b-jet

How to account for theory-experiment mismatch?

Use an NLO + Parton Shower prediction (which can evaluate both)
1) Prediction at parton-level, flavour-k_T algorithm **(Theory)**
2) Prediction at hadron-level, anti-k_T algorithm **(Experiment)**

Calculate an "Unfolding" correction from 2) Experiment → 1) Theory



We use RooUnfold (following the procedure used in the exp. analyses)