The flavour dressing algorithm

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Infrared safe jet definitions

Infrared unsafe jet algorithms widely used at the Tevatron
[Infrared unsafe = the structure of the hard jets can be modified by very soft or collinear splittings in QCD]

Things changed at the LHC thanks seminal work which lead to the development of the fast-k_t, the SIScone and anti-kt algorithms

Cacciari & Salam hep-ph/0512210; Salam & Soyez 0704.0292; Cacciari, Salam, Soyez 0802.1189

This progress triggered considerable more work on jet-area, pileup subtraction and paved the way to the field of jet-substructure

Nobody, today, would use any old infrared unsafe jet-algorithm.
So, you will wonder, why I am talking about this at all here?

Because jet-algorithms specifying the flavour of jets are still a notable exception!

slide from Giulia Zanderighi @ LHCP 2023

The flavour dressing algorithm

Flavour assignment *factorised* from jet reconstruction:
we assign flavour to a set of flavour-agnostic jets
based on some flavour information about the event

Inputs:

- *Flavour agnostic jets* $\{j_k\}$
- *Flavoured clusters* $\{\hat{f}_i\}$
- *Association criterion*
- *Accumulation criterion*

The flavour dressing algorithm: inputs

- *Flavour agnostic jets* $\{j_k\}$*:*

  set of jets obtained with an IRC safe jet algorithm (e.g. gen-k_t family), possibly after a fiducial selection.

- *Flavoured clusters* $\{\hat{f}_i\}$

- *Association criterion*

- *Accumulation criterion*

The flavour dressing algorithm: inputs

- *Flavour agnostic jets* $\{j_k\}$
- *Flavoured clusters* $\{\hat{f}_i\}$*:*
  built out of quarks (e.g. c, b) or stable heavy-flavour hadrons (e.g. D, B), by dressing them with radiation close in angle (see in a minute)
  “Naked” flavoured objects are collinear unsafe
- *Association criterion*
- *Accumulation criterion*

The flavour dressing algorithm: inputs

- *Flavour agnostic jets* $\{j_k\}$
- *Flavoured clusters* $\{\hat{f}_i\}$
- *Association criterion:* whether $\hat{f}_i$ is "associated" to j_k
  At parton-level simply if $\hat{f}_i$ is a constituent of j_k
  Other options: $\Delta R(\hat{f}_i, j_k) < R_{\rm tag}$, ghost association, …
  Flavour assignment based only on the association is not IRC safe
- *Accumulation criterion*

The flavour dressing algorithm: inputs

- *Flavour agnostic jets* $\{j_k\}$
- *Flavoured clusters* $\{\hat{f}_i\}$
- *Association criterion*
- *Accumulation criterion:* how to "sum" flavours
  - sum flavoured if unequal number of f and $\bar{\mathrm{f}}$ (need charge information)
  - sum flavoured if odd number of f or $\bar{\mathrm{f}}$ (if no charge information)

Definition of flavoured cluster $\hat{f}_i$

1. Initialise a set with all the flavourless objects p_i (particles used as input to jets) and all the flavoured objects f_i (bare flavours), avoiding double counting if necessary.

2. Find the pair with the smallest angular distance ΔR_{ab}:
   — flavourless p_a, p_b: combine p_a and p_b into a flavourless p_{ab};
   — flavoured f_a, f_b: remove both from the set;
   — flavoured f_a, unflavoured p_b: remove p_b from the set and check a Soft Drop criterion

$$\frac{\min(p_{t,a}, p_{t,b})}{(p_{t,a} + p_{t,b})} > z_{\rm cut} \left(\frac{\Delta R_{ab}}{\delta R} \right)^{\beta}$$

   to **recombine collinear while preserving soft.** [default: $\delta R = 0.1$, $z_{\rm cut} = 0.1$, $\beta = 2$]
   If satisfied, combine f_a and p_b into a flavoured f_{ab}.

3. Iterate while there are at least two objects in the set until $\Delta R_{ab} > \delta R$.
   The momentum of $\hat{f}_i$ is given by the accumulated momentum into f_i.

The flavour dressing algorithm

1. Define tag_k = flavoured clusters assigned to jet j_k (initialised as empty for all jets) and populate set of distances:
   - $d(\hat{f}_i, \hat{f}_j)$ between flavoured clusters;
   - $d(\hat{f}_i, \hat{j}_k)$ if flavoured cluster $\hat{f}_i$ *associated* to jet j_k
   - $d_B(\hat{f}_i)$ if $\hat{f}_i$ not associated to any jet.

   Distances (including beam) inherited from the flavour-k_t algorithm:

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

$$d_{B\pm}(f) = \max\left(p_{t,f}^{\alpha}, p_{t,B_\pm}^{\alpha}(y_f)\right)\ \min\left(p_{t,f}^{2-\alpha}, p_{t,B_\pm}^{2-\alpha}(y_f)\right)$$

The flavour dressing algorithm

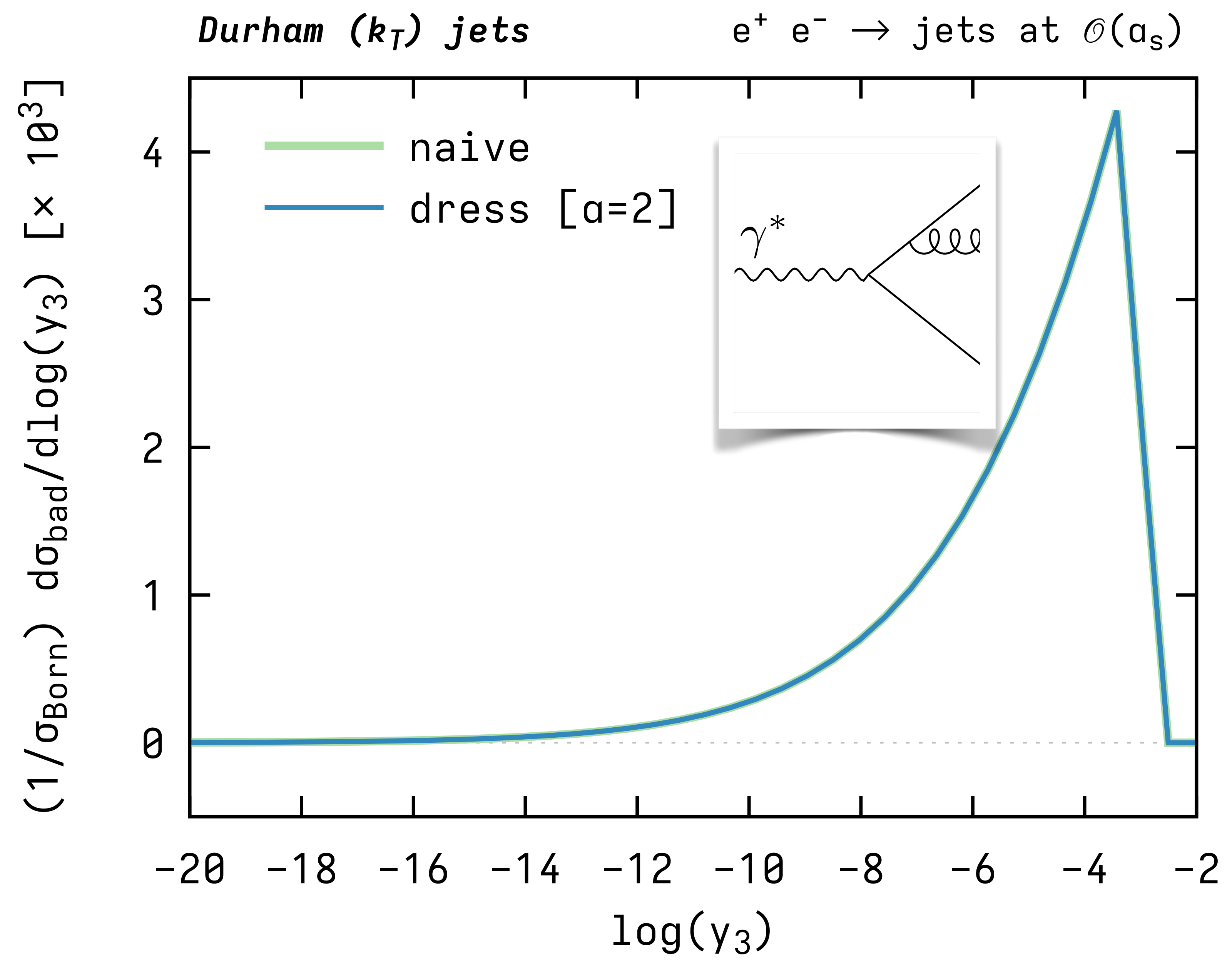
2. While the set of distances is not empty, select the smallest distance:
   $\rightarrow d(\hat{f}_i, \hat{f}_j)$:
   the two flavours "annihilate", hence remove distances that involve $\hat{f}_i$ or $\hat{f}_j$;
   $\rightarrow d(\hat{f}_i, \hat{j}_k)$:
   update $\mathrm{tag}_k = \mathrm{tag}_k \cup \{f_i\}$, then remove distances that involve $\hat{f}_i$.
   $\rightarrow d_B(\hat{f}_i)$:
   discard flavour $\hat{f}_i$ and remove all entries that involve $\hat{f}_i$.

3. Assign flavour to jet j_k according to tag_k and *accumulation* criterion.

IRC safety test in $e^+e^- \to$ jets

Vanishing mis-identification of flavours in the fully unresolved regime = IRC safety

only soft and/or collinear radiation



Any gen-k_t algo is safe!

IRC safety test in $e^+e^- \to$ jets

Vanishing mis-identification of flavours in the fully unresolved regime = IRC safety

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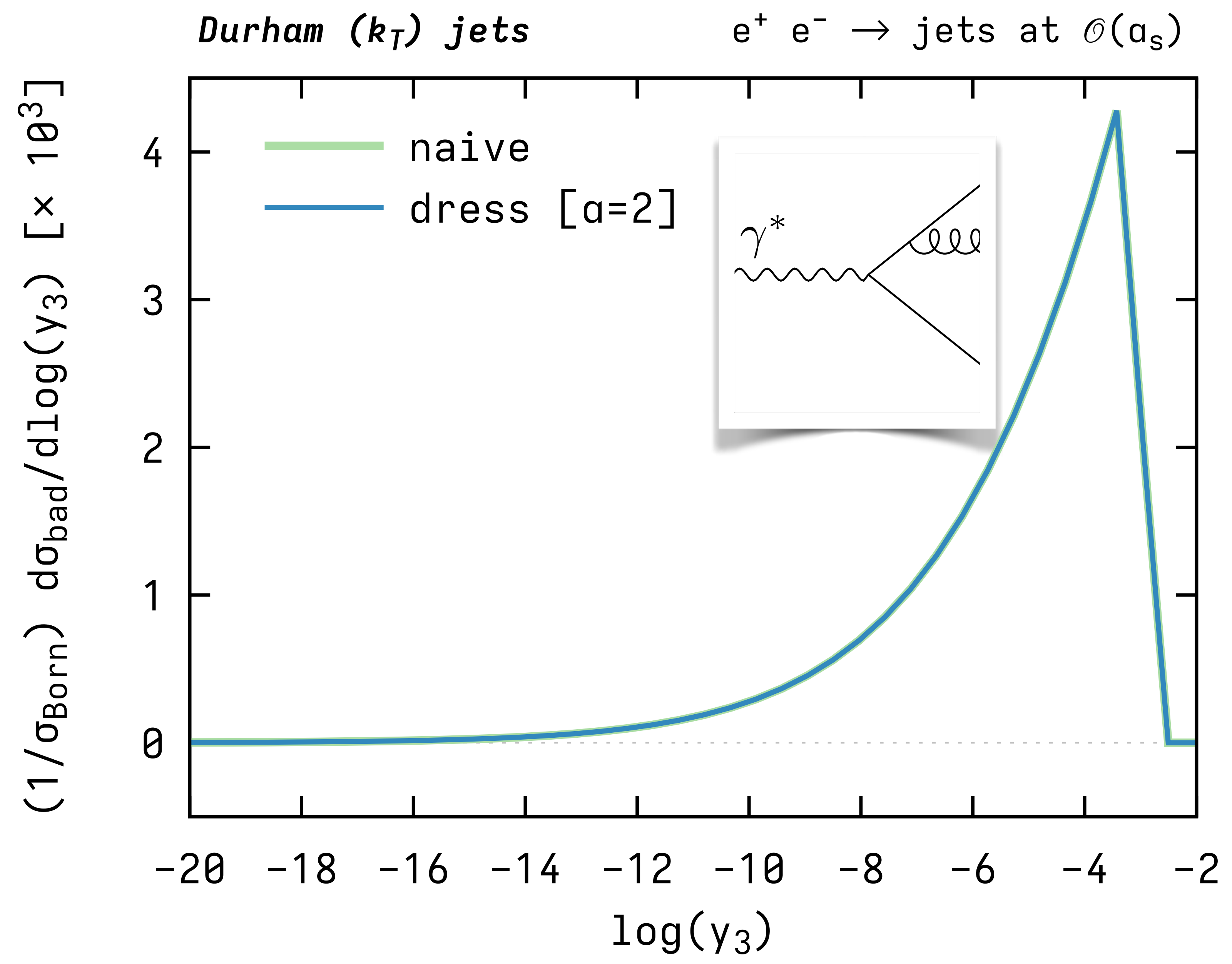

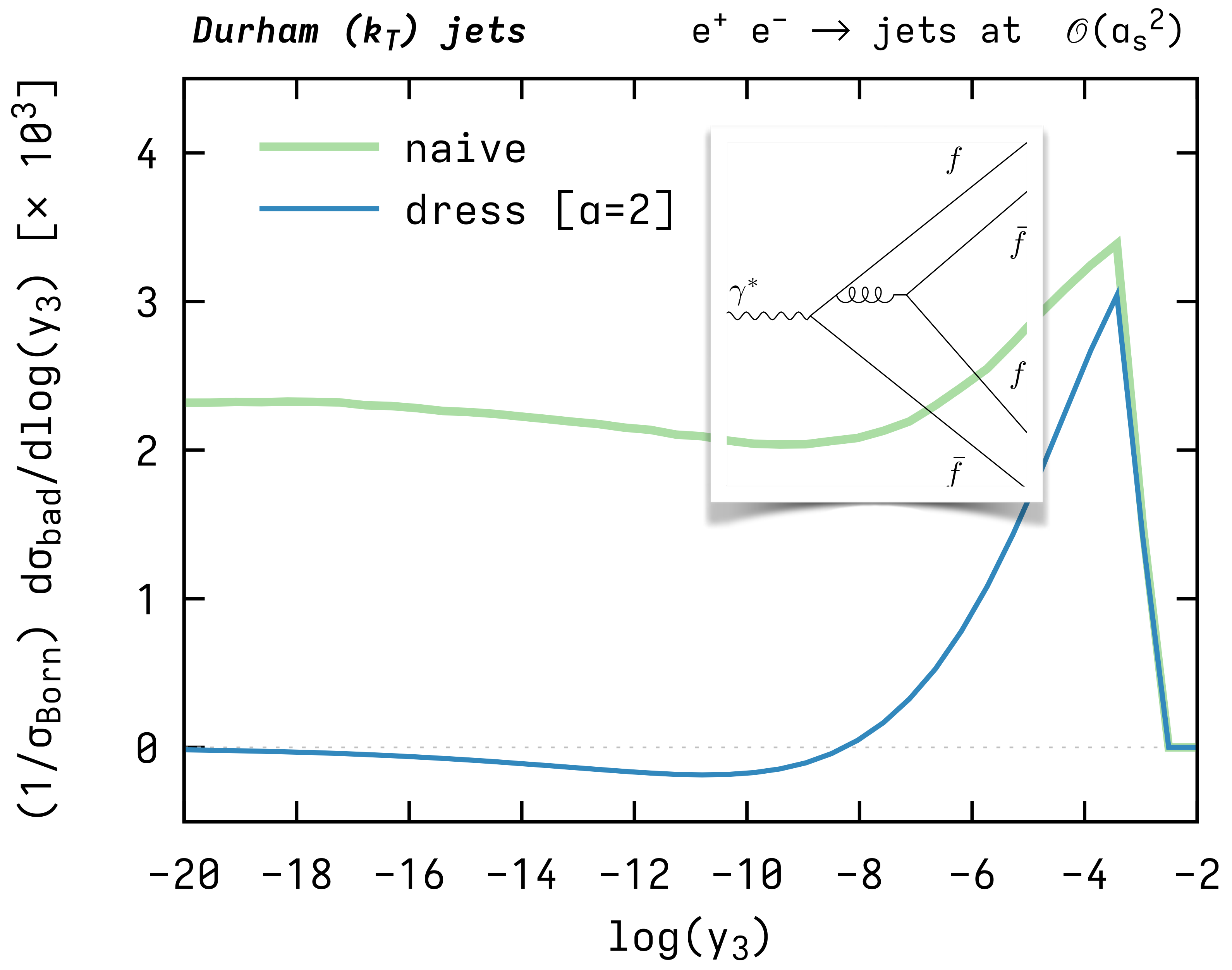

Any gen-k_t algo is safe!

Naive dressing unsafe, flavour dressing safe!

IRC safety test in $e^+e^- \to$ jets

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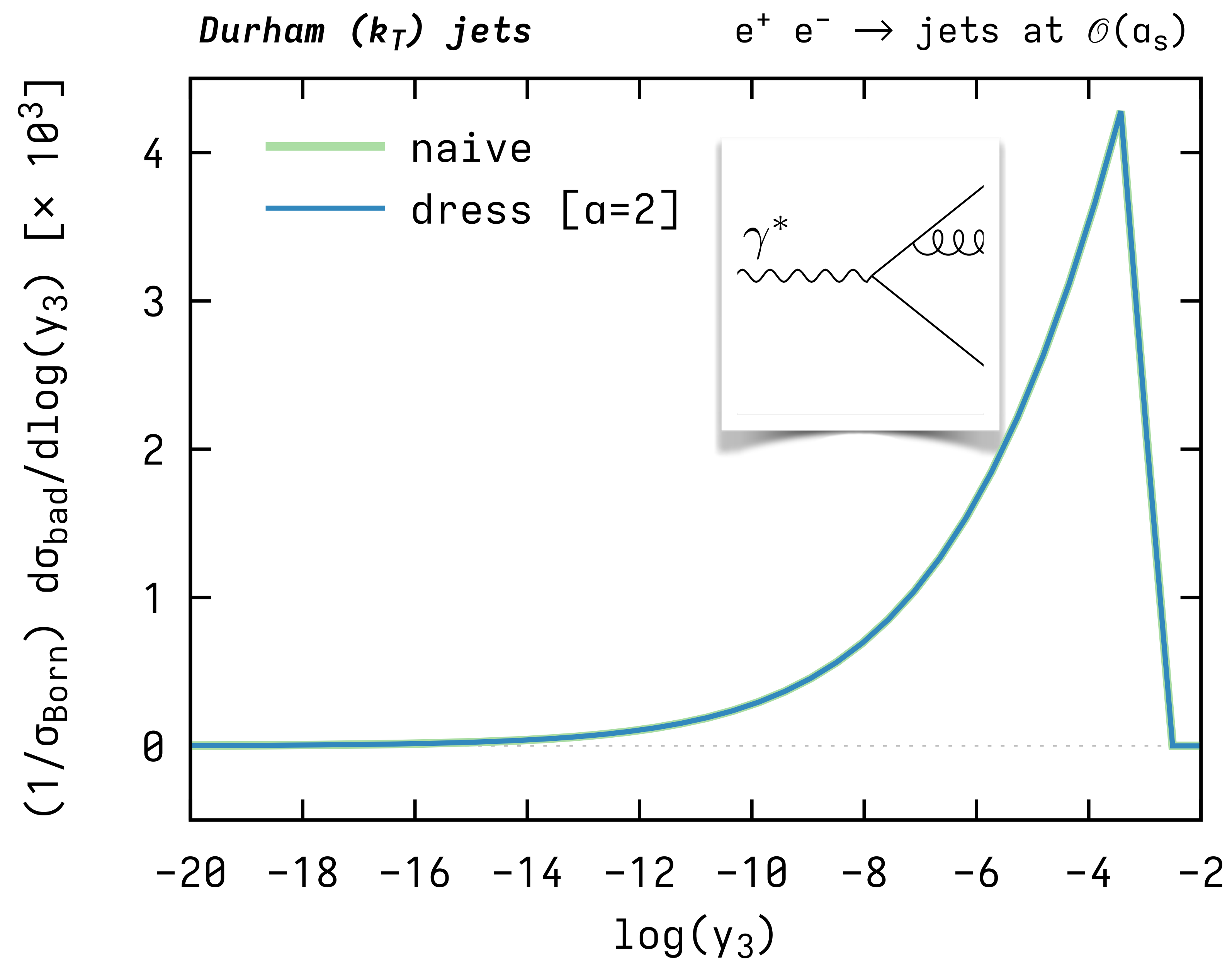
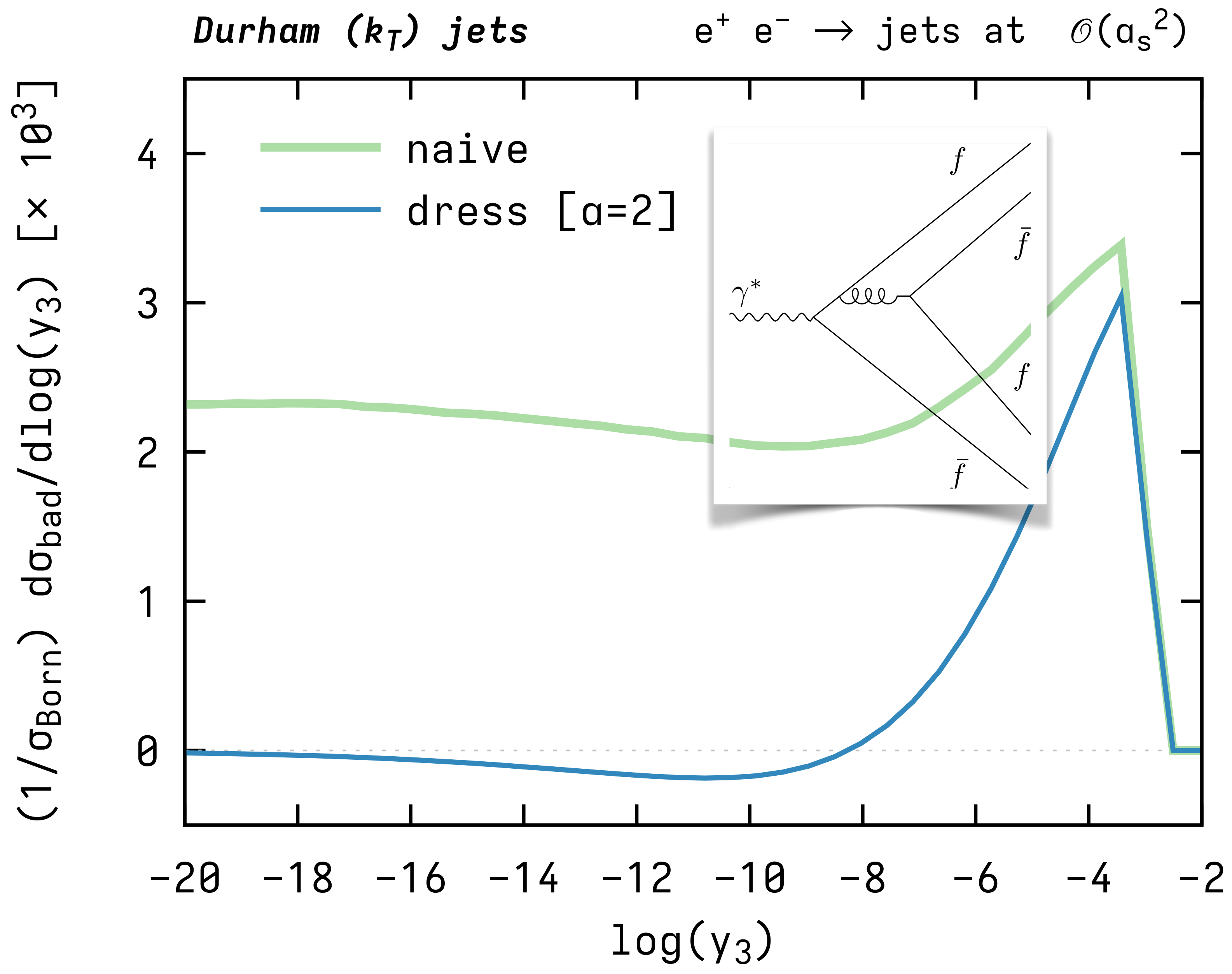
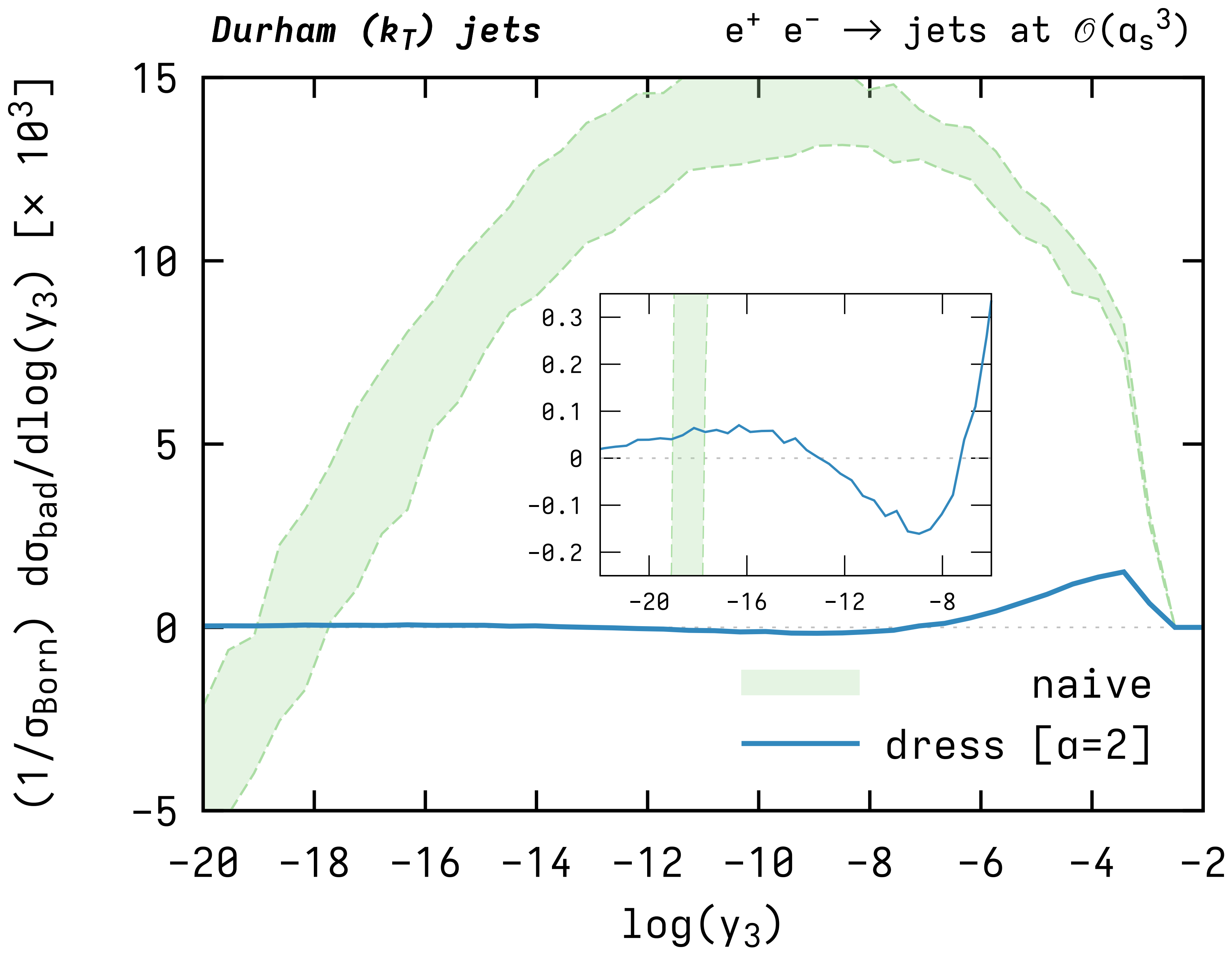




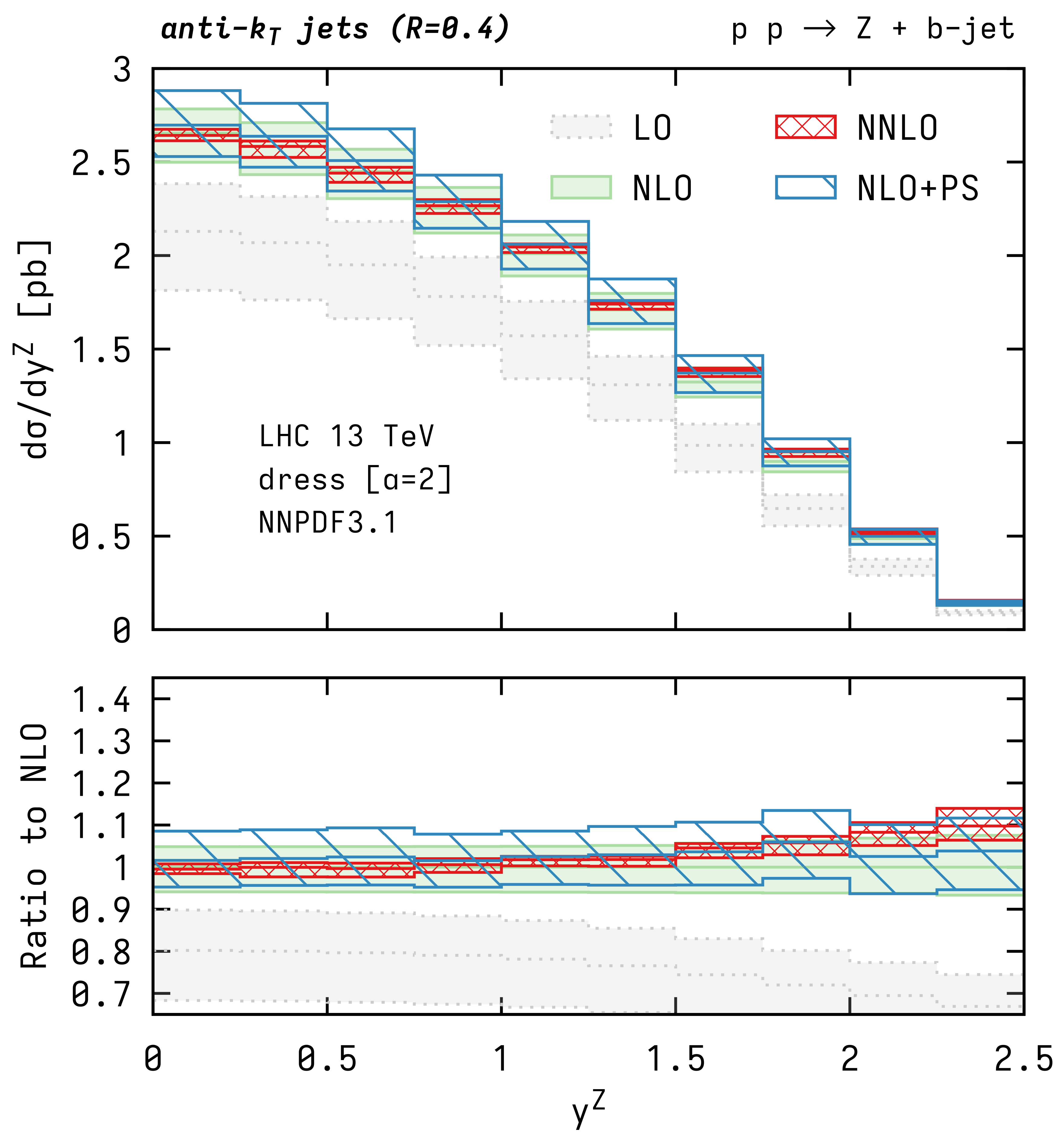


Any gen-k_t algo is safe!

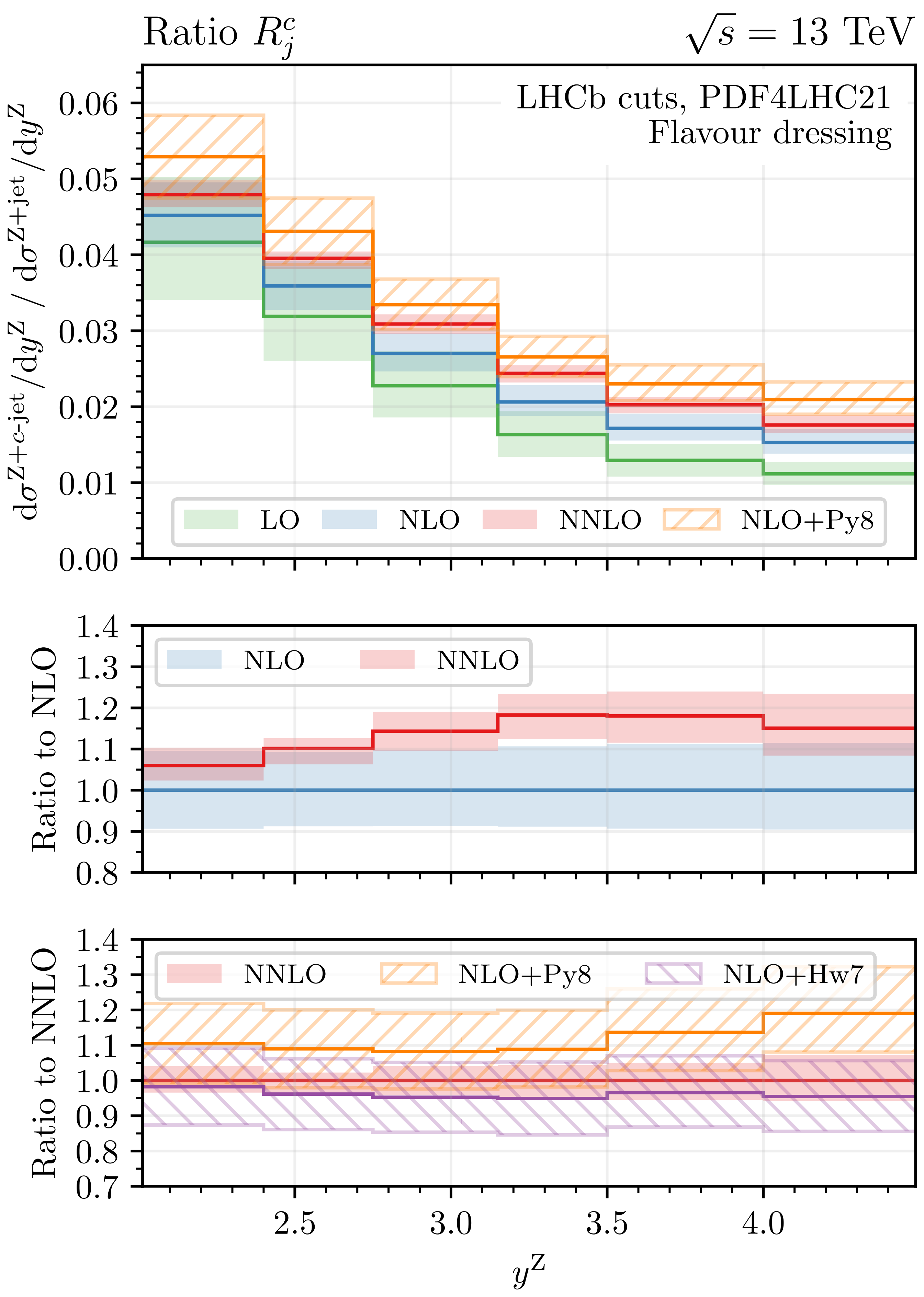
Naive dressing unsafe, flavour dressing safe!

Naive dressing unsafer, flavour dressing still safe!

Test in phenomenological applications



$Z + b$-jet @ ATLAS/CMS [2208.11138]



$Z + c$-jet @ LHCb [2302.12844]

“All-order” IRC safety? Spoiler!

Numerical framework developed in 2306.07314
has allowed to discover potentially problematic configurations at higher orders
(CMP = “flavour anti-k_t”; GHS = “flavour dressing”, IFN = see Ludovic’s talk)
→ as for GHS, work in progress to fix them

order relative to Born		anti-k_t	flav-k_t ($\alpha = 2$)	CMP	GHS$_{\alpha,\beta}$ $(2,2)$	anti-k_t+IFN$_\alpha$	C/A+IFN$_\alpha$
α_s	FHC	✓	✓	✓	✓	✓	✓
	IHC	✓	✓	✓	✓	✓	✓
α_s^2	FDS	×II B	✓	✓	✓	✓	✓
	IDS	×II B	✓	✓	✓	✓	✓
	FHC×IHC	✓	✓	✓	✓	✓	✓
	IHC^2	✓	✓	×C 2	✓	✓	✓
	FHC^2	✓	✓	✓	×C 4	✓	✓
α_s^3	IHC×IDS		~C 1	×C 3	~C 1	✓	✓
	rest					✓	✓
α_s^4	IDS×FDS				×C 5	✓	✓
	rest					✓	✓
α_s^5						✓	✓
α_s^6						✓	✓

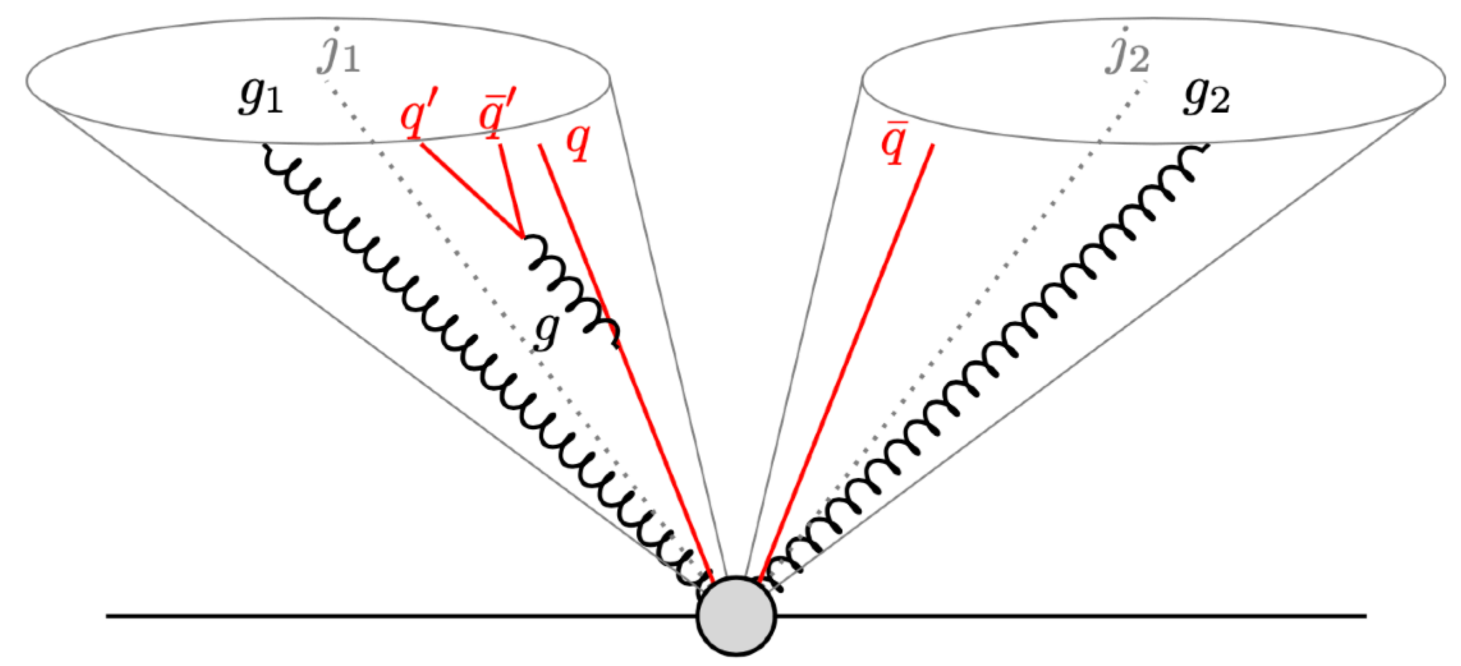


FIG. 20. Example $\mathcal{O}(\alpha_s^2)$ configuration that yields an issue for the GHS algorithm. There are four hard particles (that one can imagine recoiling against a hard gluon or electroweak system on the other side of the event), a collinear emission of a hard gluon g from one of the flavoured particles (the q), which then splits collinearly to a flavoured pair $q'\bar{q}'$.

e.g. $Zb\bar{b}$ @ N4LO

Final remarks

- **IRC-safe flavour assignment** allows for massless fixed-order calculations (and a suppressed sensitivity on mass logarithms). In particular, a massless calculation is crucial to resum mass logarithms in the initial-state.

- Main **strength of flavour dressing**: flavour assignment *factorised* from the initial jet reconstruction, hence it can be combined with any flavour-agnostic jet definition. Very flexible algorithm.

- WIP towards a ***fastjet-contrib*** with a public implementation of flavour dressing (possibly a joint contribution with the other proposals in order to have a common interface to access flavour info of the event?)