Infrared-safe flavoured anti-kT jets

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Outline

- → Motivation: Flavoured jets
- → Fixed order flavoured jets beyond NLO
  - What is the issue?
  - Flavoured jet algorithms: flavour kT vs. flavour anti-kT
  - Tests IR safety of the proposed flavour anti-kT
- → Phenomenology
  - Benchmark process: pp → Z+b-jet
  - Preliminary: pp → W+ c-jet
- → Closing remarks

Flavoured jets

- Jets are a tool to connect QCD of quarks&gluons to actually strongly interacting particles, i.e. hadrons.
- They are defined by a suitable algorithm: experimentally and theoretically
- Jet-substructure reveals additional information:
  - Separation of quark and gluon initiated jets
  - Jets of definite flavour:

Experimentally	*Displayed vertices* of heavy intermediate particles: D/B mesons
MC Event Simulation	Similar objects due to hadronization and detector simulations
Partonic computations	• Impose relation between quarks and hadrons (quark model) • Massless quarks: emission of soft flavoured pairs → gluons → Implications for IR safety in FO computations beyond NLO

- Why are partonic computations for flavoured jets interesting?
  - Higher order perturbation theory (not necessarily available matched to PS)
  - Extraction of SM parameters or PDFs

Fixed order flavoured jets beyond NLO

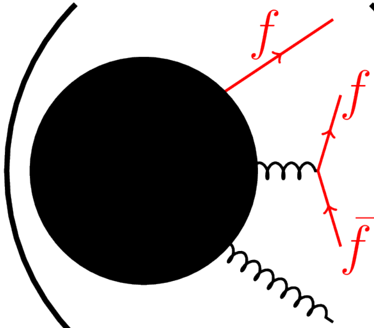
What is the problem with FO flavoured jets?

Example NNLO: double real radiation and subtraction

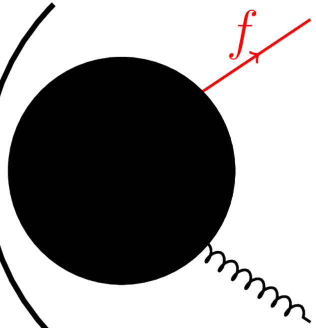
Double real matrix element

Double soft subtraction term:
Double soft function * tree ME

$$d\sigma \ni d\Phi_{n+2} \Bigg($$



$$\Bigg) F_{n+2} + \cdots + d\tilde{\Phi}_{n+2}\mathcal{S}_2 \Bigg($$



$$\Bigg) F_n$$

Flavour structure depends on the angular configuration

IR safety:
Have to match in double soft limit

Fixed flavour structure

- If F(n+2) does not treat the flavour pair appropriately:
  → double soft singularity not subtracted

➔ Implies correlated treatment of kinematics and flavour information

Solution: Modified jet algorithms

➔ Implies correlated treatment of kinematics and flavour information

Standard kT algorithm [Ellis'93]:

Pair distance:

$$d_{ij} = \min(k_{T,i}^2, k_{T,j}^2) R_{ij}^2$$

$$R_{ij}^2 = (\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2)/R^2$$

"Beam" distance for determination condition:

$$d_i = k_{T,i}^2$$

Flavour kT algorithm [Banfi'06]:

Pair distance:

$$d_{ij} = R_{ij}^2 \begin{cases} \max(k_{T,i}, k_{T,j})^\alpha \min(k_{T,i}, k_{T,j})^{2-\alpha} & \text{softer of i,j is flavoured} \\ \min(k_{T,i}, k_{T,j})^\alpha & \text{else} \end{cases}$$

Beam distance:

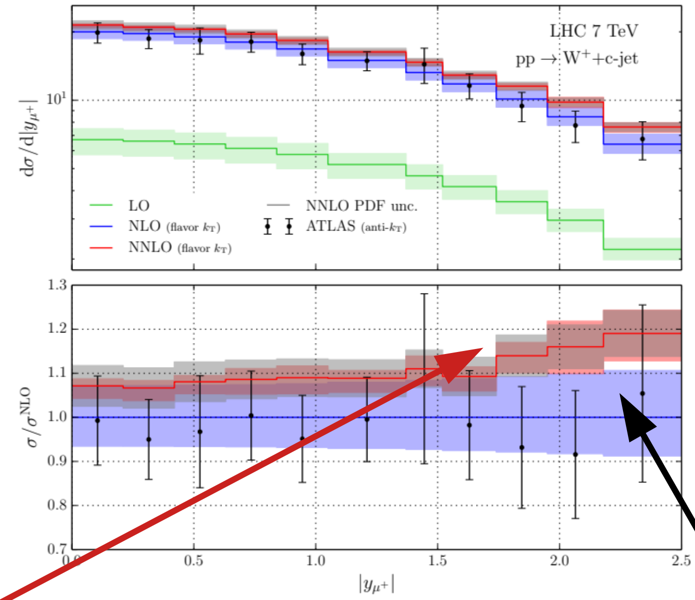
$$d_{i,B} = \begin{cases} \max(k_{T,i}, k_{T,B}(y_i))^\alpha \min(k_{T,i}, k_{T,B}(y_i))^{2-\alpha} & \text{i is flavoured} \\ \min(k_{T,i}, k_{T,B}(y_i))^\alpha & \text{else} \end{cases}$$

$$d_B(\eta) = \sum_i k_{T,i}(\theta(\eta_i - \eta) + \theta(\eta - \eta_i)e^{\eta_i - \eta}$$

$$d_{\bar{B}}(\eta) = \sum_i k_{T,i}(\theta(\eta - \eta_i) + \theta(\eta_i - \eta)e^{\eta - \eta_i}$$

Problem solved, isn't it?

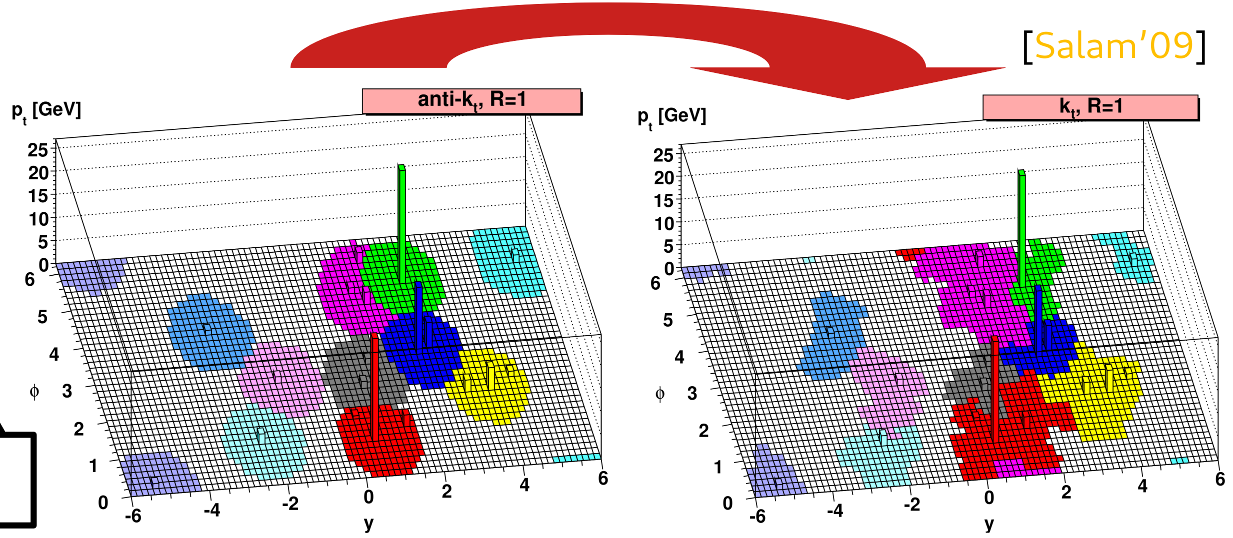
Real world example: W+c-jet at NNLO QCD with flavour-kT [Czakon'20]



A proper comparison would require to unfold experimental data

→ (flavour-) kT and anti-kT cluster partonic jets differently → Non-trivial procedure.

[Salam'09]



NNLO QCD with flavour kT

ATLAS data with standard anti-kT

What about flavour anti-kT?

Anti-kT: $d_{ij} = \min(k_{T,i}^{-2}, k_{T,j}^{-2})R_{ij}^2 \qquad d_i = k_{T,i}^{-2}$

The energy ordering in anti-kT prevents correct recombination of flavoured pairs in the double soft limit.

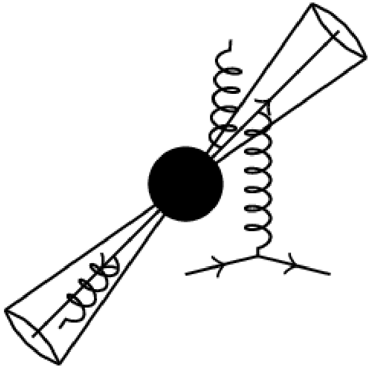
Proposed modification:

A soft term designed to modify the distance of flavoured pairs.

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases}$$

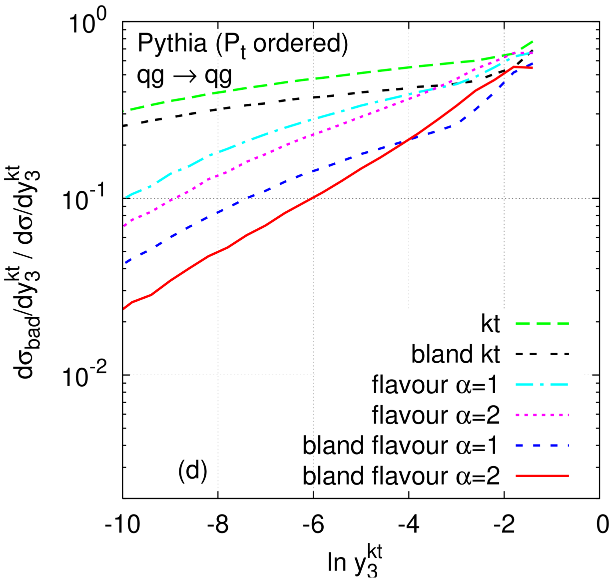
$$\mathcal{S}_{ij} = 1 - \theta(1-x)\cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_{T,i}^2 + k_{T,j}^2}{2ak_{T,\max}^2}$$

Tests of IR safety with parton showers

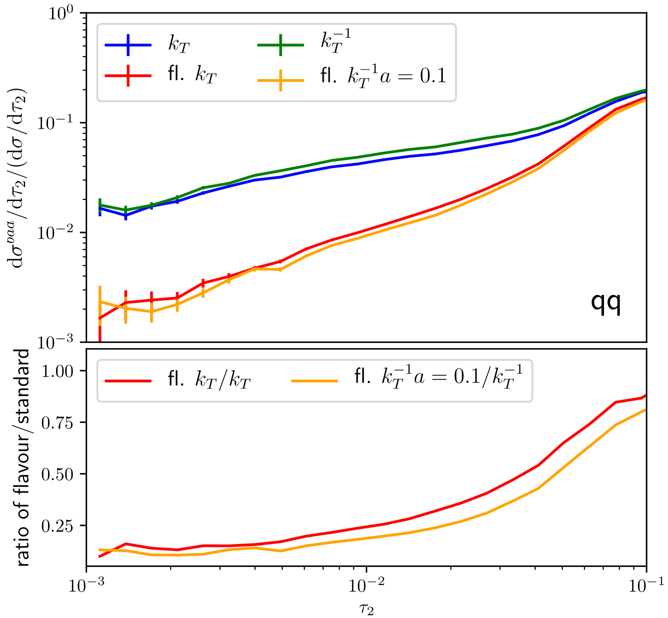


Dress tree-level di-jet events (definite flavour structure: “qq”, “qg” or “gg”) with radiation and study jet flavour (q or g) as function of kinematics.
In the di-jet limit the flavour needs to correspond to tree level flavours
→ misidentification rate needs to vanish in dijet back-to-back limit

Flavour kT vs. kT [Banfi’06]:

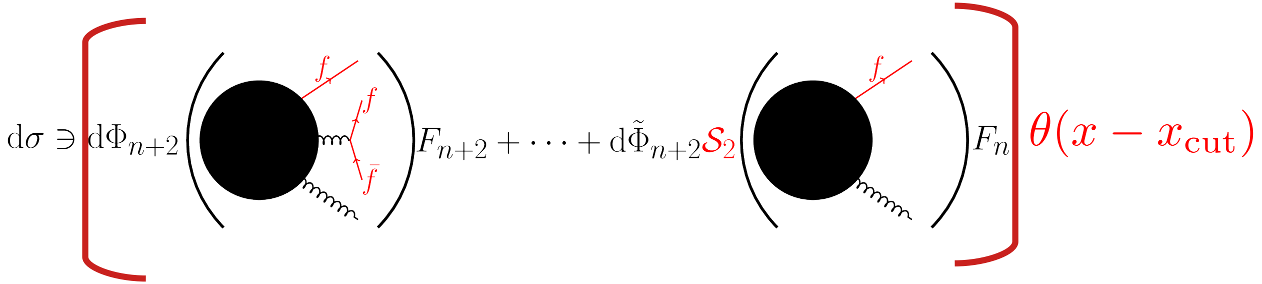


Flavour anti-kT



Tests of IR safety with NNLO FO computations

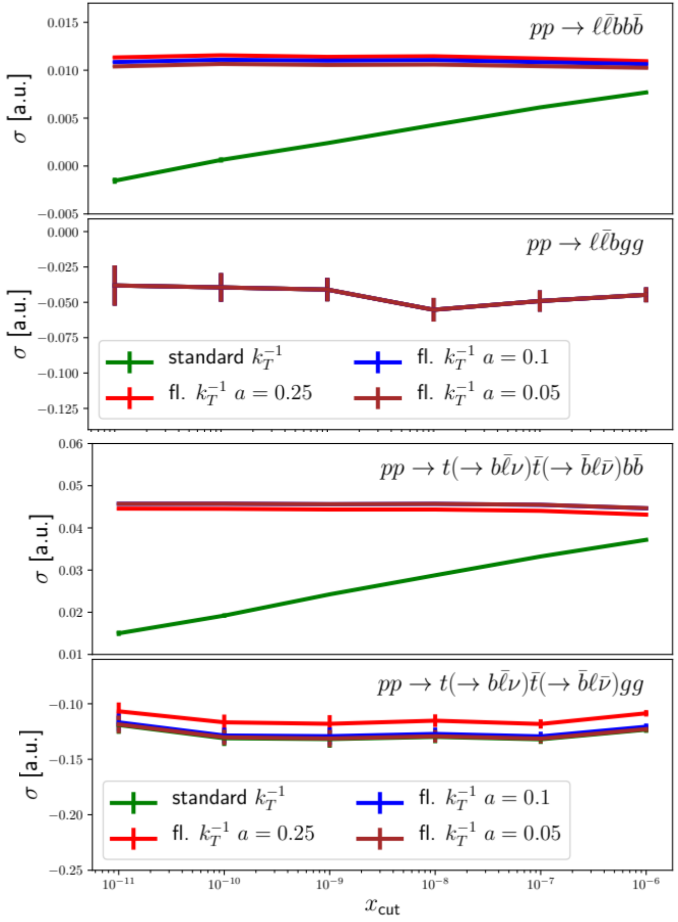
IR sensitivity of jet cross sections on (technical) IR regulating parameter x



In the limit x_cut → 0:

IR safe jet flavour → no dependence on x_cut

IR non-safe jet flavour → logarithmic divergent



Phenomenology

Phenomenology: Z+b-jet

Benchmark process: pp → Z(ll) + b-jet

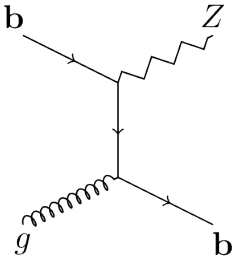
Well studied up to $\mathcal{O}(\alpha_s^3)$ [Gauld'20]:

- Defined with flavour-kT algorithm
- Unfolding of experimental data (RooUnfold,bin-by-bin unfolding)
- Matching between four- and five-flavour schemes (FONLL) [Gauld'21]

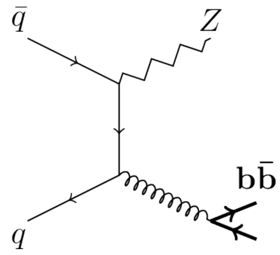
$$\mathrm{d}\sigma^{\mathrm{FONLL}} = \mathrm{d}\sigma^{5\mathrm{fs}} + \left(\mathrm{d}\sigma^{4\mathrm{fs}}_{m_b} - \mathrm{d}\sigma^{4\mathrm{fs}}_{m_b \to 0}\right)$$

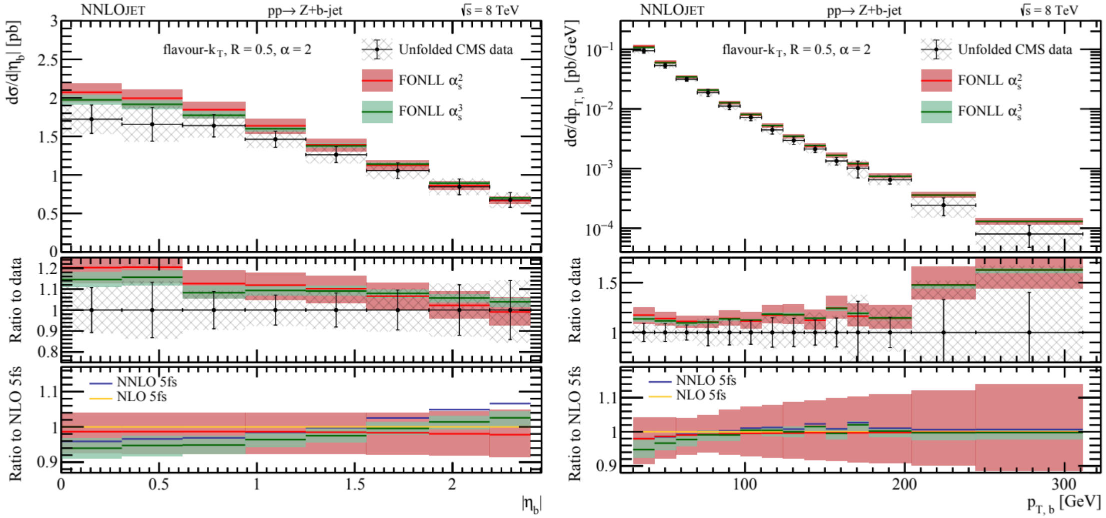
- CMS measurement @ 8 TeV [CMS 1611.06507]

5fs:



4fs:





Phenomenology: Tunable parameter

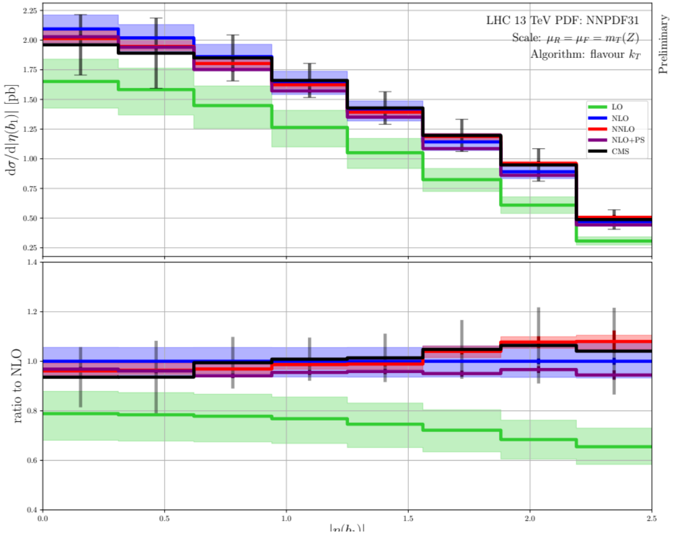
Preliminary

Benchmark process: pp → Z(ll) + b-jet

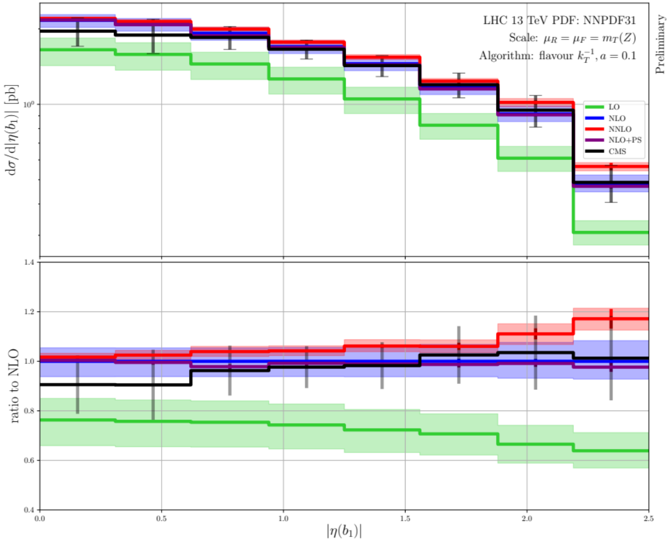
Tunable parameter a:

- Limit a → 0 <=> original anti-kT (IR unsafe)
- Large a <=> large modification of cluster sequence

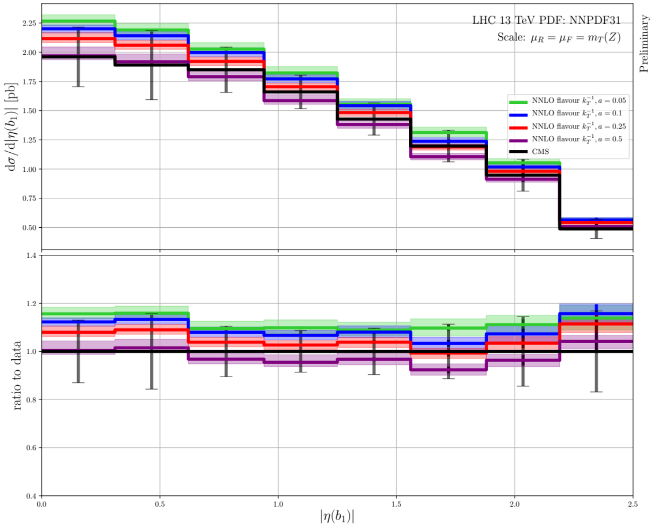
Flavour kT:



Flavour anti-kT: $a = 0.1$



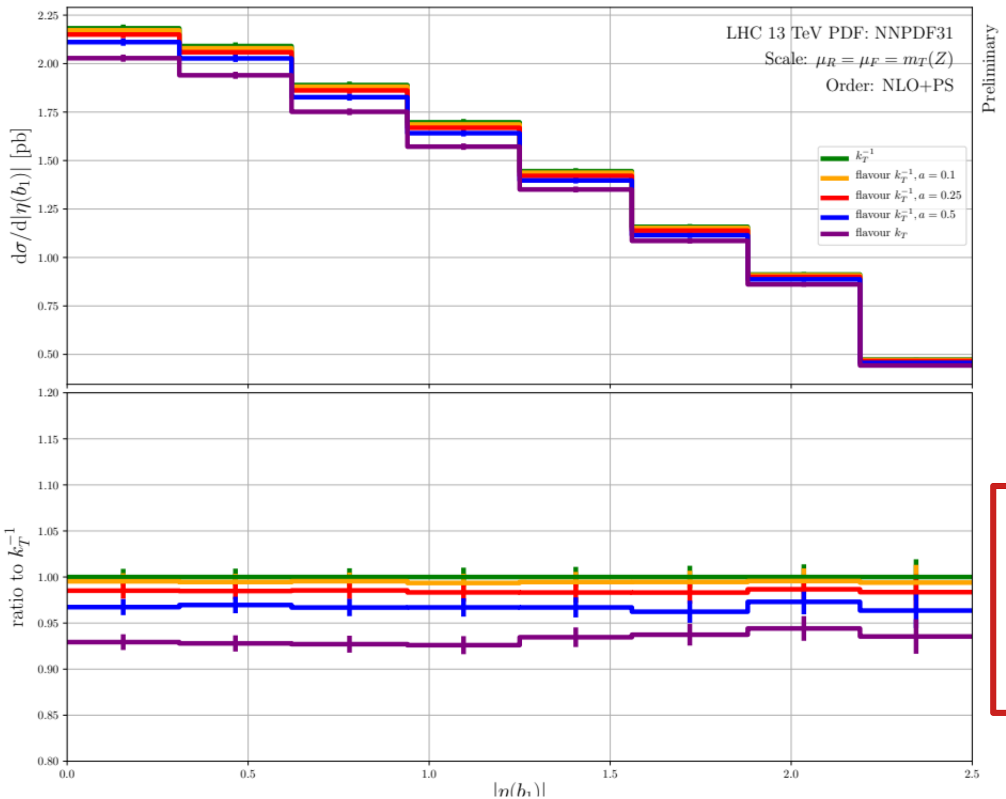
Comparison of different parameter a to data:



Phenomenology: Tunable parameter II

Preliminary

What happens in the presence of many flavoured partons? → NLO PS



Tunable parameter a:

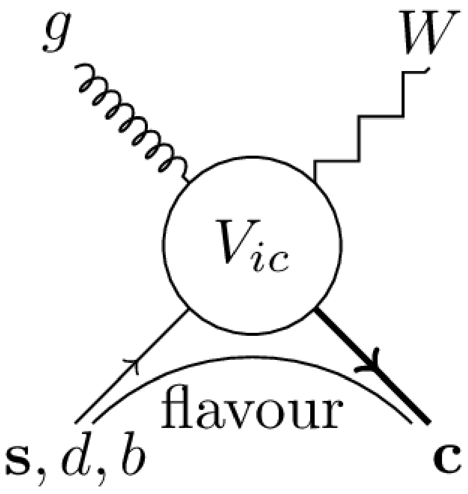
- Small a: Flavour anti-kT results are more similar to standard anti-kT → small unfolding factors
- Larger a: Larger modification of clustering

Good FO perturbative convergence + Small difference to standard anti-kT → a~0.1 is a good candidate

W+c-jet

Idea: Identify final state c-quarks to access s-quark PDFs.
→ Reduction of PDF uncertainties
→ Shed light on $s\bar{s}$ asymmetry

- Non-diagonal CKM and g → $c\bar{c}$ reduce s-PDF sensitivity
- Large NLO corrections → higher order corrections?
- Theoretical treatment:
  - Massive c (3-flavour scheme):
    - Resummation of mass logs at high pT → PS
    - Higher order predictions?
  - Massless c:
    - c-quark part of the PDFs
    - NNLO QCD available
    - **Jet definition?**



Vsc > Vdc >> Vbc

W+c-jet with flavour kT at NNLO QCD

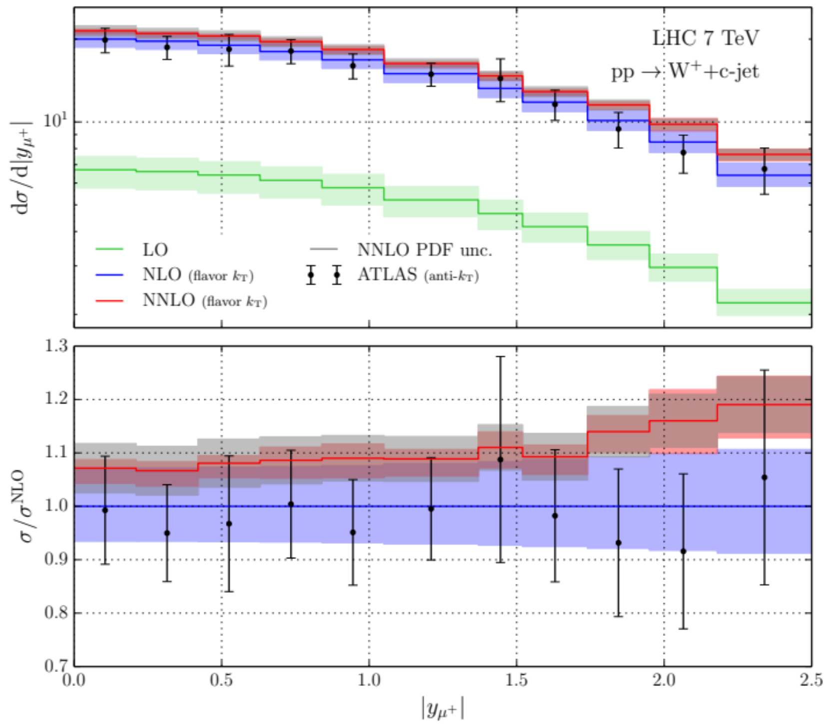
In collaboration with: Czakon, Mitov, Pellen

NNLO QCD 7 TeV results [2011.01011]:

- Full NNLO corrections for Vcs contribution
- Off-diagonal CKM only LO QCD
- Comparison flv. kT results vs. ATLAS [1402.6263]

Update for 13 TeV measurement:

- Full CKM through NNLO QCD
- Study of different jet-algorithms:
  - Impact of beam-function d_iB in flv kT
  - New anti-kT algorithm
- Study of different flavour tag definitions/setups:
  - Modulus vs. absolute flv tag definition
  - OS minus SS
  - “Inclusive c-jet” rates



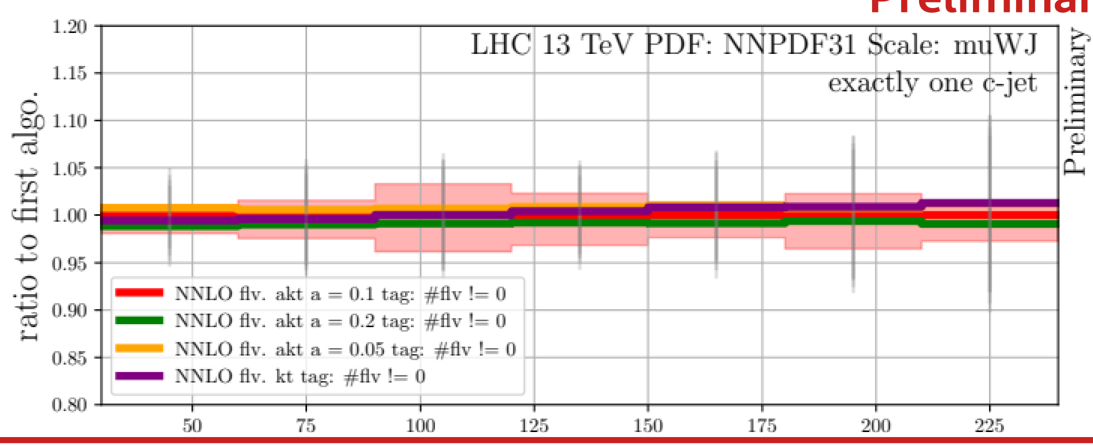
W+c-jet with flavour anti-kT

In collaboration with: Czakon, Mitov, Pellen

Preliminary

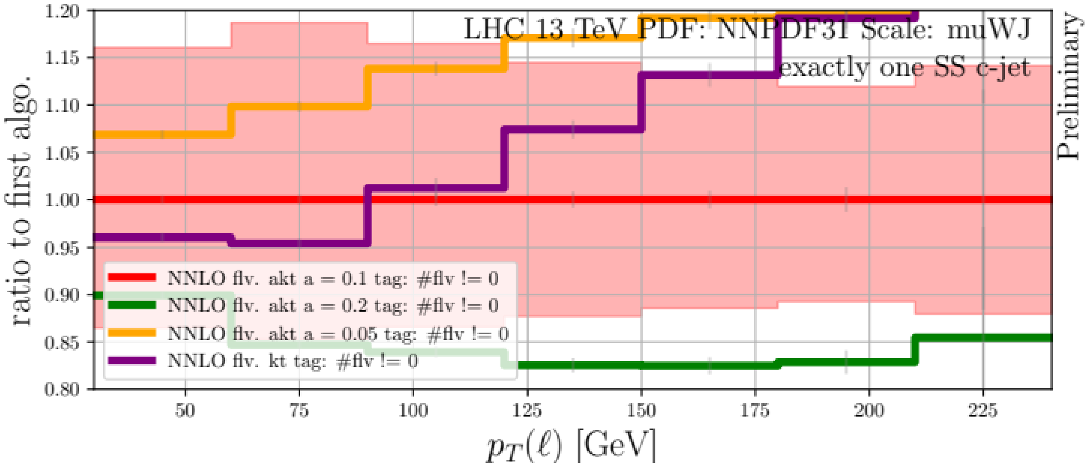
Exactly one c-jet requirement:

- Comparison of parameters a:
  → small dependence < 2%
- Comparison to flv kT:
  → small dependence @ NNLO < 2%



ONLY large effect in SS contribution

- Exactly one c-jet of SS type:
  Larger dependence ~15%
  (roughly size of NNLO scale band)
- BUT: SS contribution ~2-5%
- => OS ~0.2-0.5% dependence



Flavour tags: OS - SS

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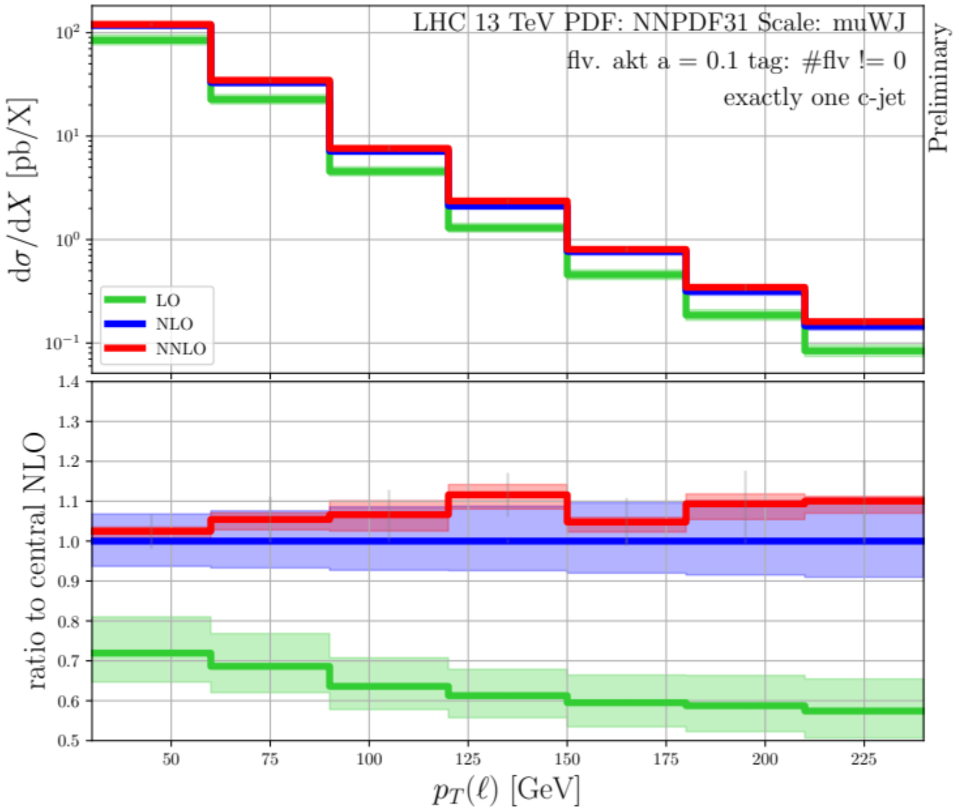
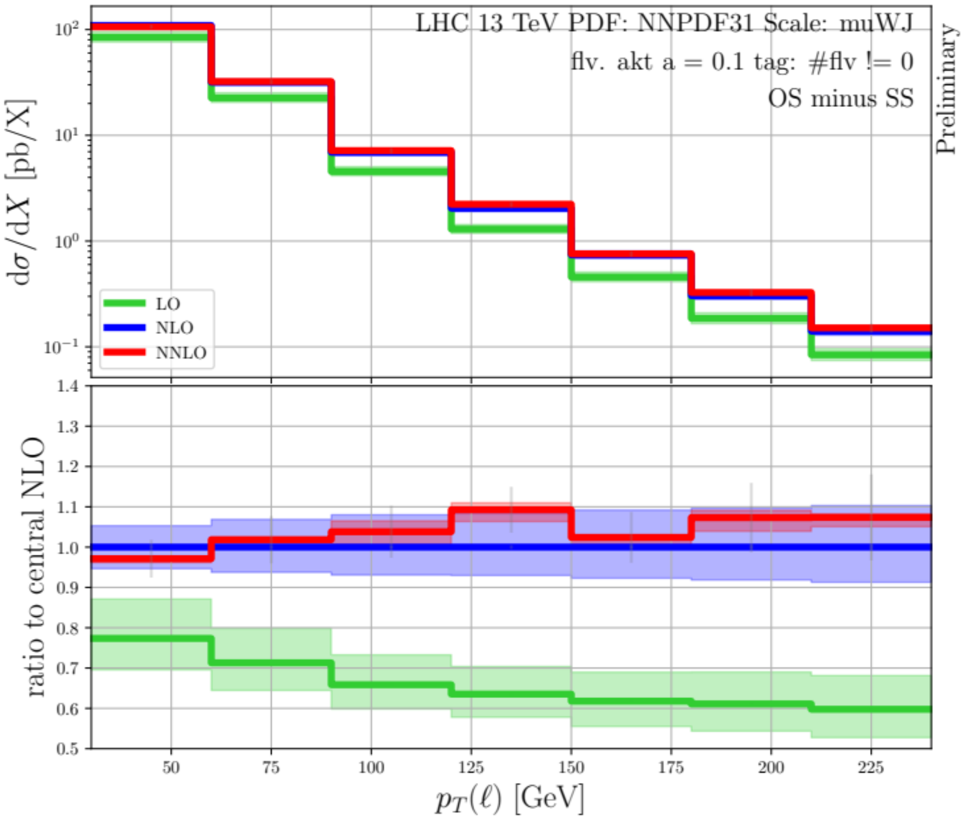
Preliminary

Exactly 1 c-jet:



OS-SS:



Remarks & Summary

Some final remarks

- What is that kT_max parameter?

  Some scale to define what soft means.

  Examples:

  1. pT of hardest pseudo jet or lepton
     at a clustering step
  2. Some fixed dynamical scale, e.g. pT(Z), pT(lep), …
  3. Some fixed hard scale: m_top, m_Z etc.

  → The choice impacts the clustering.

$$d_{ij}^{(F)} = d_{ij}\begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases}$$

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

- Besides c/b jets: What about gluon/quark jet identification?

  Conceptually not a problem. Not yet studied in detail.

  But might introduce some more sensitivity to actual form of S_ij ??

- More complicated examples: pp → W bbar ! LO sensitivity to flv jet algorithm

Summary and Outlook

New proposal for flavour safe anti-kT algorithm

- Numerical checks of IR safety
- Introduction of tunable parameter a
- New phenomenological studies:
  - pp → Z+b-jet
  - pp → tt + decays
  - pp → W+c-jet

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases}$$

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

pp → W+c -jet @ NNLO @ 13 TeV

- Full CKM dependence
- Small differences at FO between algorithms
  → NLO+PS shower study necessary to confirm.

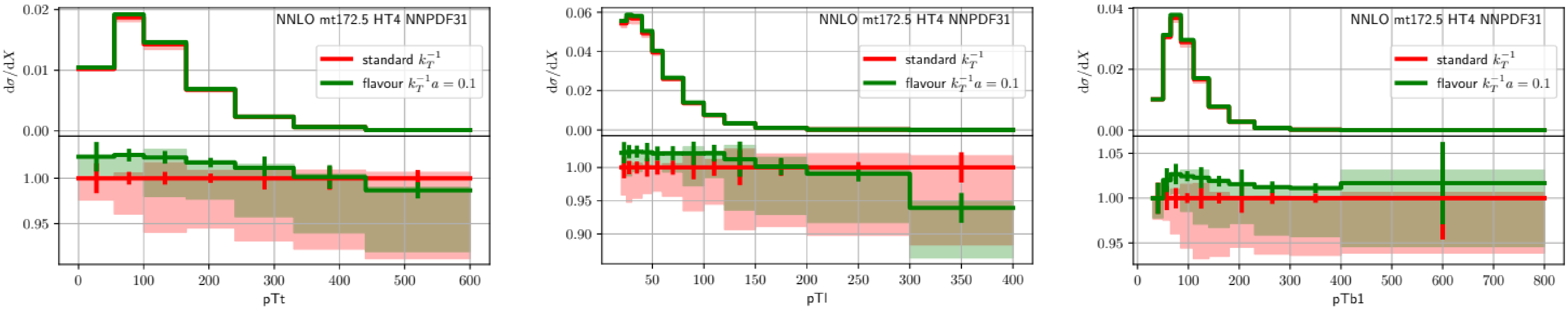
Backup

b-jets in top-pair production&decay

NNLO QCD corrections [Czakon'20] to: $pp \to t(\to b\bar{\ell}\nu)\bar{t}(\to \bar{b}\ell\bar{\nu}) + X$

Flavour sensitive channels like: $pp \to t\bar{t}b\bar{b} \to \bar{\ell}\nu\ell\bar{\nu}\, b\bar{b}b\bar{b}$

Small numerical impact from extra bbar emissions
in pp → bbar [Catani'20] and single-top production [Berger '17'18, Campbell '20]
→ naive treatment via cut-off procedure



Naive 'cut-off' treatment vs. proposed IR safe flavour anti-kT