Tasty jets at the LHC

Rene Poncelet

in collaboration with Michal Czakon and Alexander Mitov

and Mathieu Pellen, Andrei Popescu, Bayu Hartanto, Simone Zoia

LEVERHULME TRUST

UNIVERSITY OF CAMBRIDGE

Isaac Newton Trust

erc
European Research Council
Established by the European Commission

Outline

- Why are flavoured jets interesting?
- 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
  - Top-quark pair production and decay
  - pp → W+ 2 b-jets
  - pp → W+ c-jet
- Closing remarks & alternatives

Why are flavoured jets interesting?

- Study of microscopic physics → Standard Model (SM) → Scattering amplitudes
- We need to identify the final states to relate them to specific scattering processes
- Here flavour comes into play:

  Flavoured (partonic) final states allows to access specific "components" of the SM.

  Examples:

  - top-quark, Higgs (→ 2b-jets): using "b-tags" to identify candidate events
  - W/Z+flavoured jets: enhance sensitivity to certain PDFs
  - flavoured jet pairs: searches for new particles.
  - ...
- Precision measurements stress test theory and constrain parameters & content
  → Accurate and precise predictions for such final states required
  → higher order corrections essential (this talk: fixed order QCD (+PS) and a tiny bit fragmentation)
- We do not measure quarks and gluons in the detector → jets. We need to relate the partonic flavour structure to jet cross sections.

What are 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 • Massless quarks: emission of soft flavoured pairs → gluons → Implications for IR safety in FO computations beyond NLO → Special flavour jet algorithms solve this problem

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

The flavour kT algorithm

Problems with massless quarks:

1. Collinear gluon to f fbar splittings → count f (+1) and fbar (-1) in a jet ← NLO QCD
2. Soft gluon to f fbar → need to be recombined for arbitrary angles ← NNLO QCD

→ **Infrared safe definition of jet flavor**,
Banfi, Salam, Zanderighi hep-ph/0601139

Jets at hadron colliders

Accurate QCD predictions for heavy-quark jets at the Tevatron and LHC,
Banfi, Salam, Zanderighi 0704.2999

Muon decays

Muon decay spin asymmetry
Caola, Czarnecki, Liang, Melnikov, Szafron 1403.3386

e+e- eventshapes

The Forward-backward asymmetry at NNLO revisited
Weinzierl hep-ph/0609021

Phenomenology of event shapes at hadron colliders,
Banfi, Salam, Zanderighi 1001.4082

The two-jet rate in e+e- at next-to-next-to-leading-logarithmic order
Banfi, McAslan, Monni, Zanderighi 1607.03111

LHC precision computations with flavoured jets

Associated Higgs production + decays in b-quarks:

Associated production of a Higgs boson decaying into bottom quarks at the LHC in full NNLO QCD
Ferrera, Somogyi, Tramontano 1705.10304

NNLO QCD corrections to associated WH production and H → bbbar decay
Caola, Luisoni, Melnikov, Röntsch 1712.06954

Associated production of a Higgs boson decaying into bottom quarks and a weak vector boson decaying leptonically at NNLO in QCD
Gauld, Gehrmann-De Ridder, Glover, Huss, Majer 1907.05836

Bottom quark mass effects in associated WH production with the H → bbbar decay through NNLO QCD
Behring, Bizoń, Caola, Melnikov, Röntsch 2003.08321

VH + jet production in hadron-hadron collisions up to order \alpha_s^3 in perturbative QCD
Gauld, Gehrmann-De Ridder, Glover, Huss, Majer 2110.12992

+Partonshower:

NNLOPS accurate associated HZ production with H → bbbar decay at NLO
Astill, Bizoń, Re, Zanderighi 1804.08141

NNLOPS description of the H → bbbar decay with MiNLO
Bizoń, Re, Zanderighi 1912.09982

Next-to-next-to-leading order event generation for VH production with H → bbbar decay
Zanoli, Chiesa, Re, Wiesemann, Zanderighi 2112.04168

LHC precision computations with flavoured jets

Vector + flavoured jet(s) production:

NLO QCD predictions for Wbbbar production in association with up to three light jets at the LHC
Anger,Cordero, Ita, Sotnikov 1712.05721

Predictions for Z-Boson Production in Association with a b-jet at O(\alpha_s^3)
Gauld, Gehrmann-De Ridder, Glover, Huss, Majer 2005.03016

NNLO QCD predictions for W+c-jet production at the LHC,
Czakon, Mitov, Pellen, Poncelet 2011.01011

NNLO QCD corrections to Wbbbar production at the LHC,
Hartanto, Poncelet, Popescu, Zoia 2205.01687

Top-quark pair final state modelling:

Modeling uncertainties of ttbarW+- multilepton signatures
Bevilacqua, Bi, Cordero, Hartanto , Kraus, Nasufi, Reina, Worek 2109.15181

B-hadron production in NNLO QCD: application to LHC ttbar events with leptonic decays
Czakon, Generet, Mitov, Poncelet, 2102.08267

Fixed order flavoured jets beyond NLO

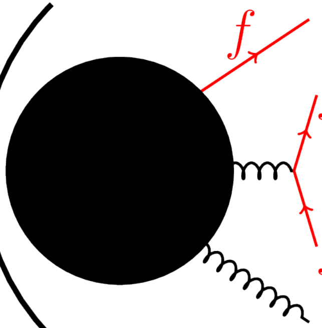
What is the problem with FO flavoured jets?

Example NNLO: double real radiation and subtraction

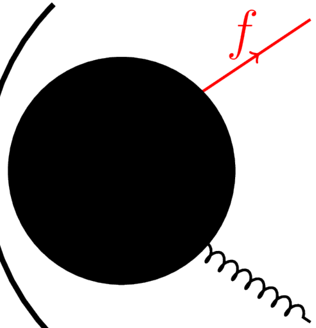
Double real matrix element

Double soft subtraction term:
Double soft function * tree ME

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



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



) 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:

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:

Infrared safe definition of jet flavor, Banfi, Salam, Zanderighi hep-ph/0601139

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?

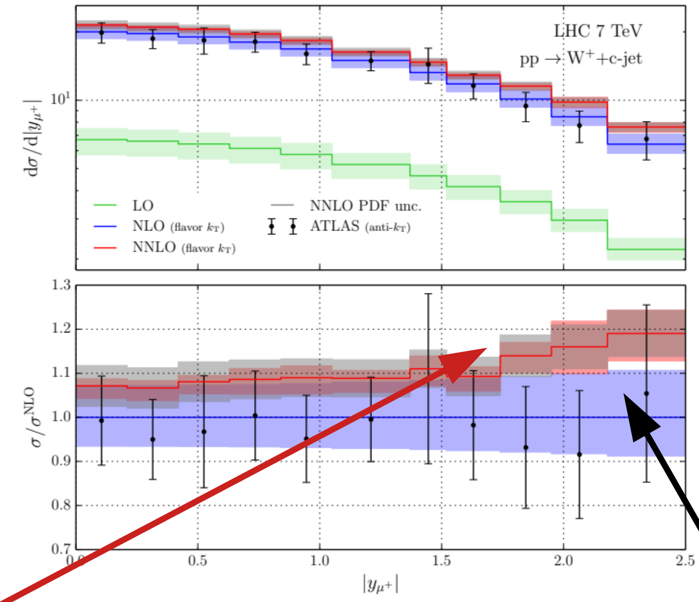
Real world example: W+c-jet at NNLO QCD with flavour-kT

NNLO QCD predictions for W+c-jet production at the LHC,
Czakon, Mitov, Pellen, Poncelet 2011.01011

A proper comparison would require to
unfold experimental data

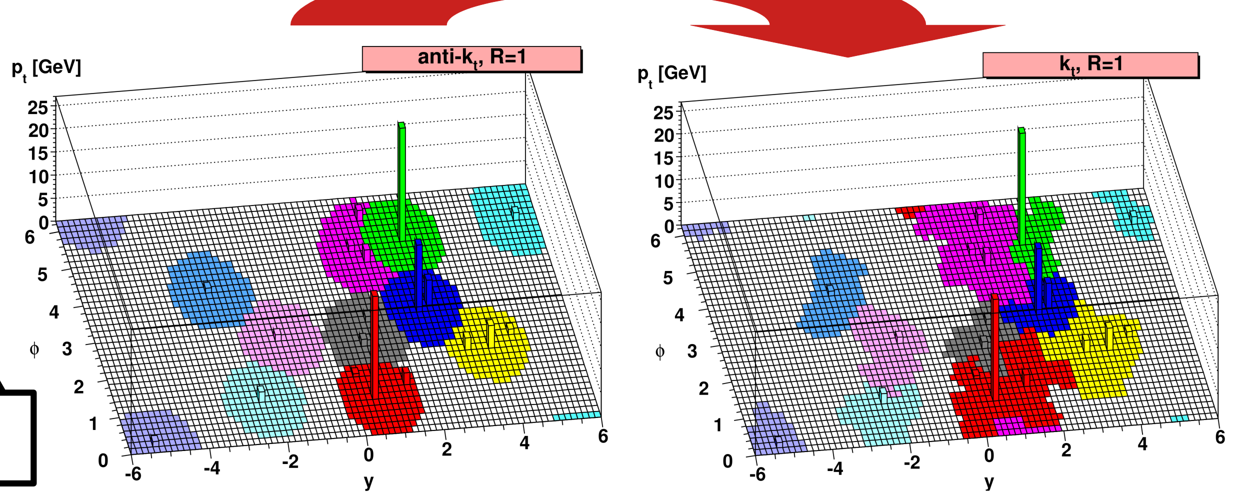
→ (flavour-) kT and anti-kT cluster partonic jets differently → Non-trivial procedure.

Towards Jetography
Salam 0906.1833



NNLO QCD with flavour kT

ATLAS data with standard anti-kT



What about flavour anti-kT?

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

Infrared-safe flavoured anti-kT jets, Czakon, Mitov, Poncelet 2205.11879

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

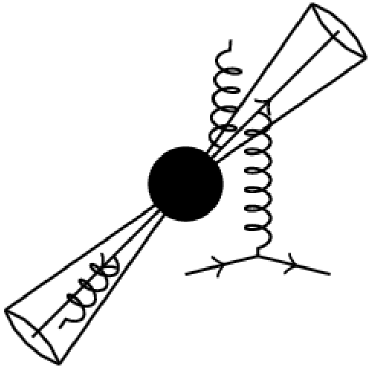
Proposed modification:

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

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

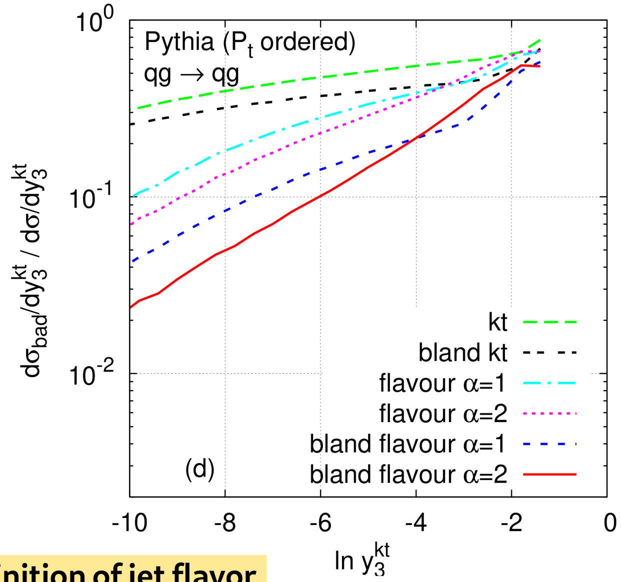
$$\mathcal{S}_{ij} = 1 - \theta(1-x)\cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_{T,i}^2 + k_{T,j}^2}{2ak_{T,\max}^2}$$

Tests of IR safety with parton showers

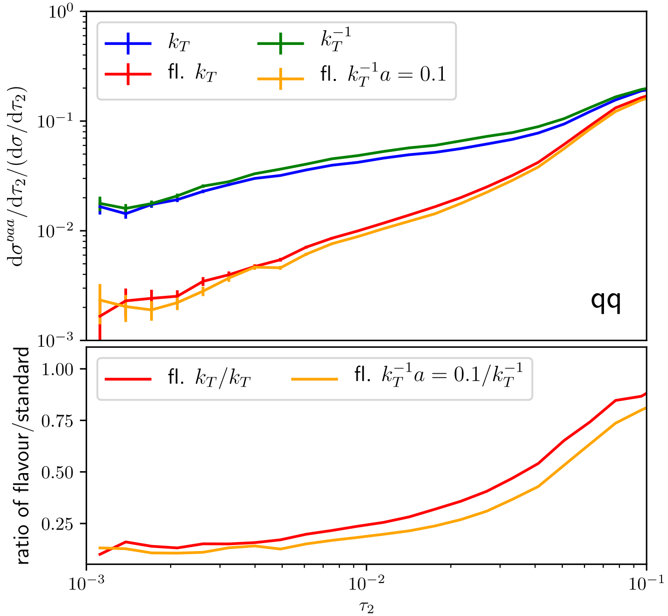


Dress tree-level di-jet events (definite flavour structure: "qq", "qg" or "gg") with radiation and study jet flavour (q or g) as function of kinematics.
In the di-jet limit the flavour needs to correspond to tree level flavours
→ misidentification rate needs to vanish in dijet back-to-back limit

Flavour kT vs. kT:



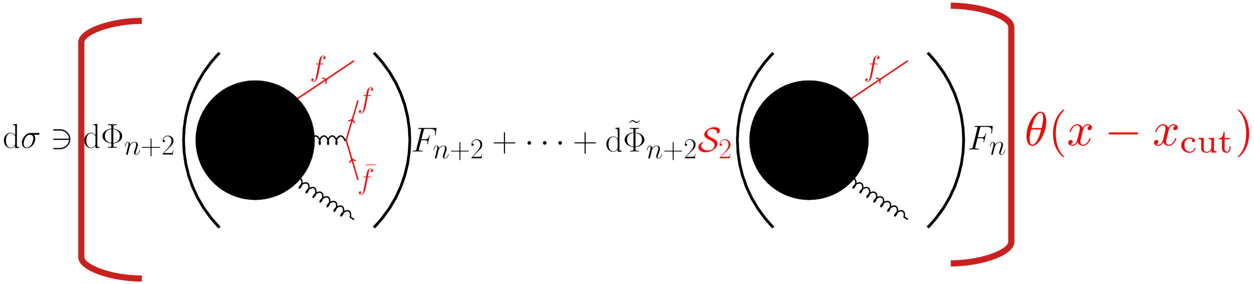
Flavour anti-kT:



Infrared safe definition of jet flavor,
Banfi, Salam, Zanderighi hep-ph/0601139

Tests of IR safety with NNLO FO computations

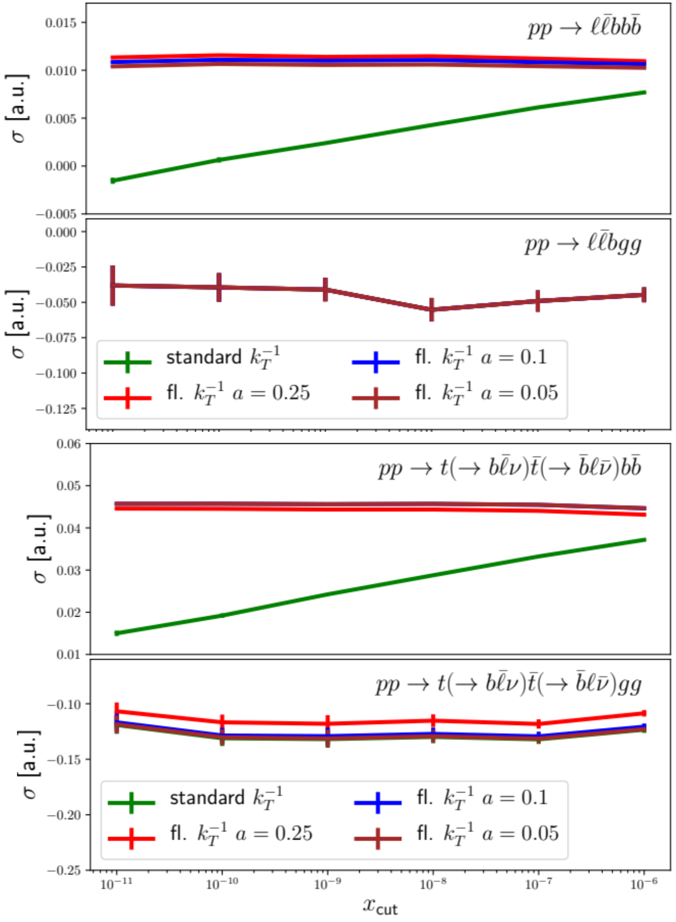
IR sensitivity of jet cross sections on (technical) IR regulating parameter x



In the limit x_cut → 0:

IR safe jet flavour → no dependence on x_cut

IR non-safe jet flavour → logarithmic divergent



IR–Safe? Yes. But is it useful?

↓

Phenomenology

Processes:

- pp → Z + b-jet
- top-quark pair production and decay
- pp → W + c-jet
- pp → W + 2 bjets

Benchmark process: Z+b-jet

Well studied up to $\mathcal{O}(\alpha_s^3)$:

Predictions for Z-Boson Production in Association with a b-jet at O(a_s^3), Gauld, Gehrmann-De Ridder, Glover, Huss, Majer 2005.03016

- Flavour-kT algorithm
- Unfolding of experimental data (RooUnfold,bin-by-bin unfolding)
- Matching between four- and five-flavour schemes (FONLL)

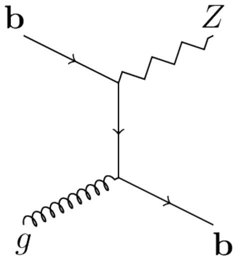
$$\mathrm{d}\sigma^{\mathrm{FONLL}} = \mathrm{d}\sigma^{5\mathrm{fs}} + (\mathrm{d}\sigma^{4\mathrm{fs}}_{m_b} - \mathrm{d}\sigma^{4\mathrm{fs}}_{m_b\to 0})$$

- CMS measurement @ 8 TeV

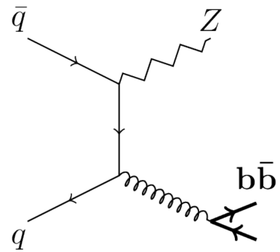
Measurements of the associated production of a Z boson and b jets in pp collisions at \sqrt{s} = 8 TeV}, CMS 1611.06507

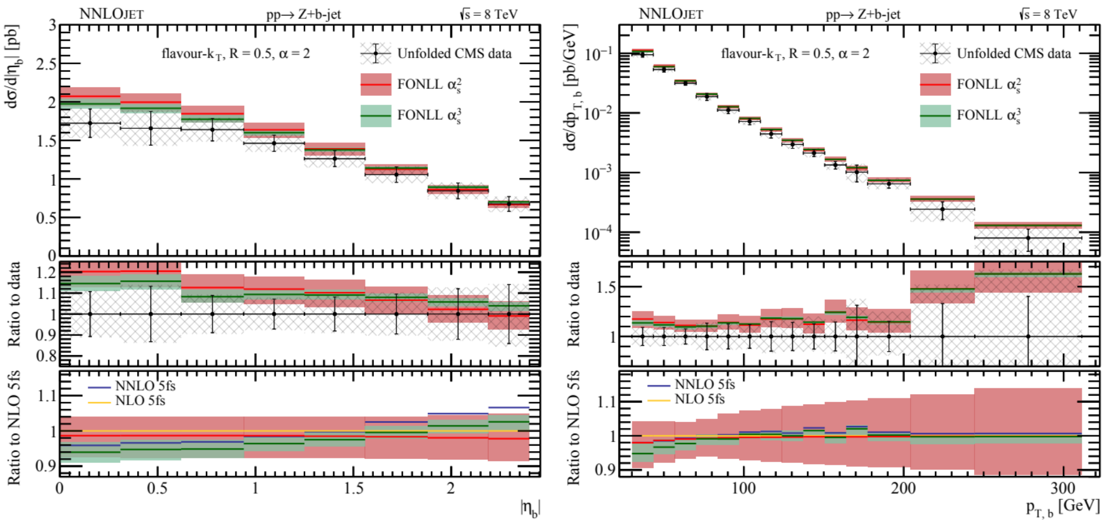
pp → Z(ll) + b-jet

5fs:



4fs:





Z+b-jet Phenomenology: Tunable parameter

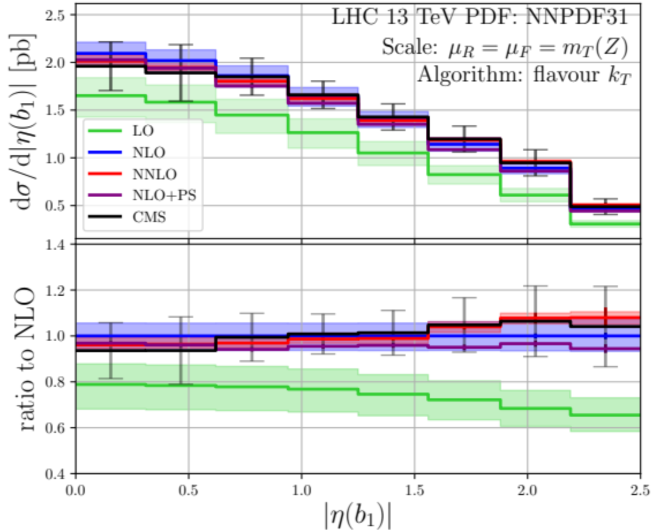
Benchmark process: pp → Z(ll) + b-jet

Tunable parameter a:

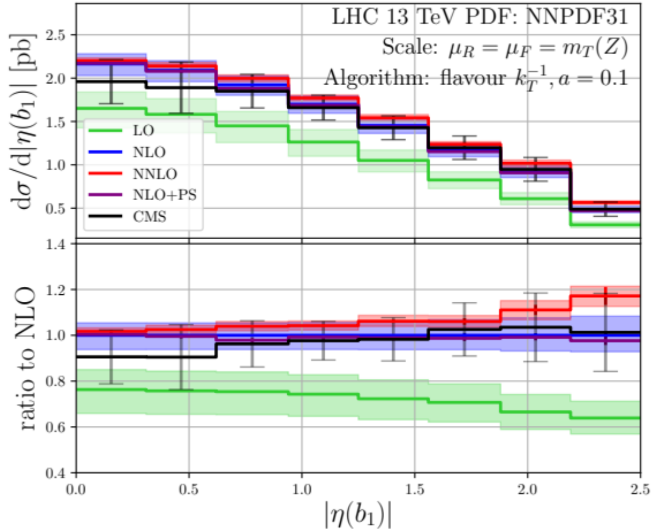
- Limit a → 0 <=> original anti-kT (IR unsafe)
- Large a <=> large modification of cluster sequence

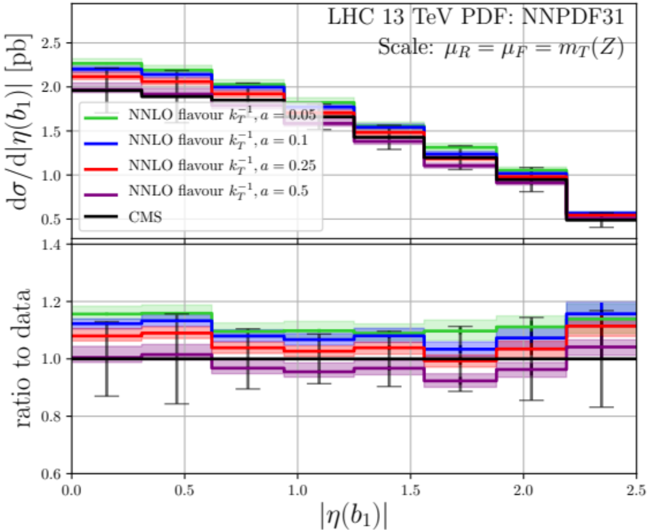
Comparison of different parameter a to data:

Flavour kT:



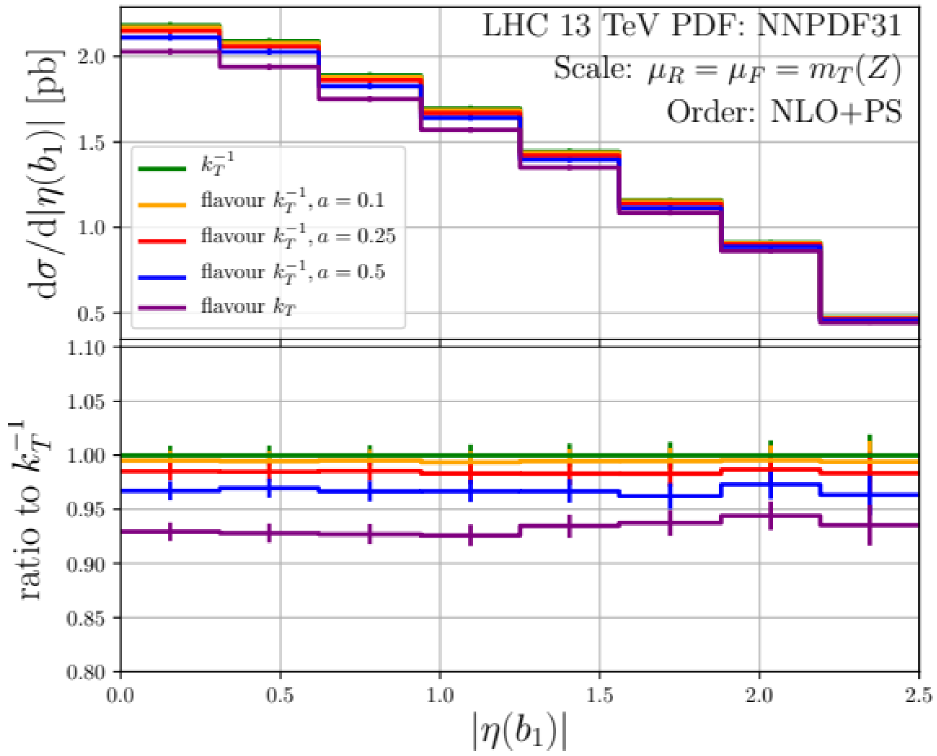
Flavour anti-kT: $a = 0.1$





Z+b-jet Phenomenology: Tunable parameter II

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

b-jets in top-pair production & decay

NNLO QCD corrections to leptonic observables in top-quark pair production and decay, Czakon, Mitov, Poncelet 2008.11133

$$pp \to t(\to b\bar{\ell}\nu)\bar{t}(\to \bar{b}\ell\bar{\nu}) + X$$

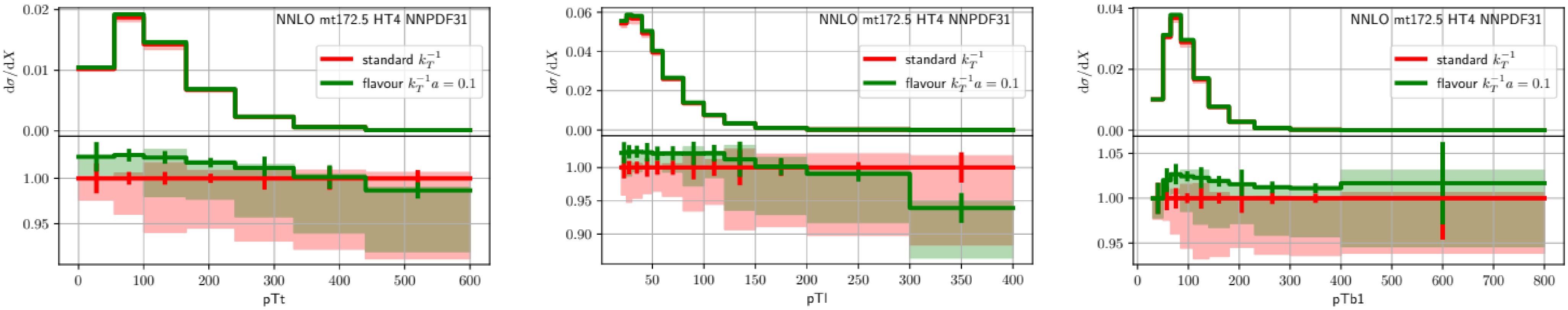
Flavour sensitive channels like: $pp \to t\bar{t}b\bar{b} \to \bar{\ell}\nu\ell\bar{\nu}\,b\bar{b}b\bar{b}$

Small numerical impact from extra bbar emissionsin pp → bbarand single-top production
→ naive treatment via cut-off procedure

Bottom-quark production at hadron colliders: fully differential predictions in NNLO QCD, Catani, Devoto, Grazzini, Kallweit, Mazzitelli 2010.11906

Differential Distributions for t-channel Single Top-Quark Production and Decay at Next-to-Next-to-Leading Order in QCD, Berger,Gao, Zhu 1708.0940

Single-top-quark production in the t-channel at NNLO, Campbell, Neumann, Sullivan 2012.01574

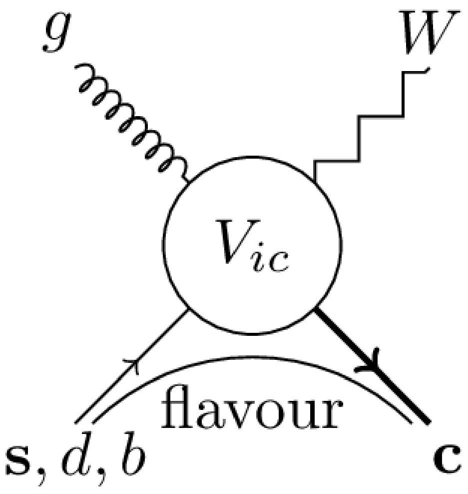


Naive ‘cut-off’ treatment vs. proposed IR safe flavour anti-kT

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?**



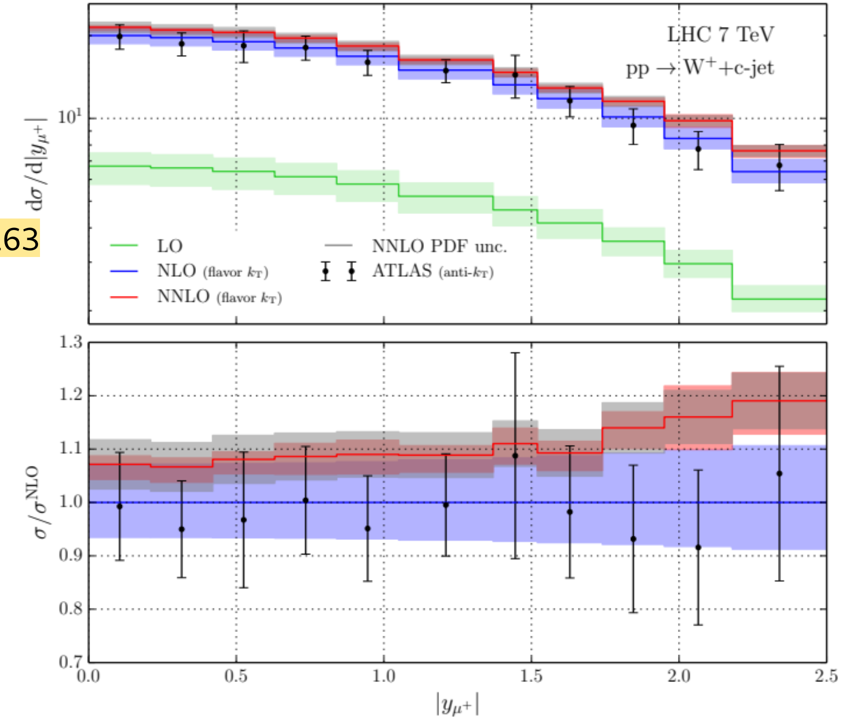
Vsc > Vdc >> Vbc

W+c-jet with flavour kT at NNLO QCD

NNLO QCD 7 TeV results: **NNLO QCD predictions for W+c-jet production at the LHC**, Czakon, Mitov, Pellen, Poncelet 2011.01011

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

Measurement of the production of a W boson in association with a charm quark in pp collisions at \sqrt{s} = 7 TeV with the ATLAS detector, 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

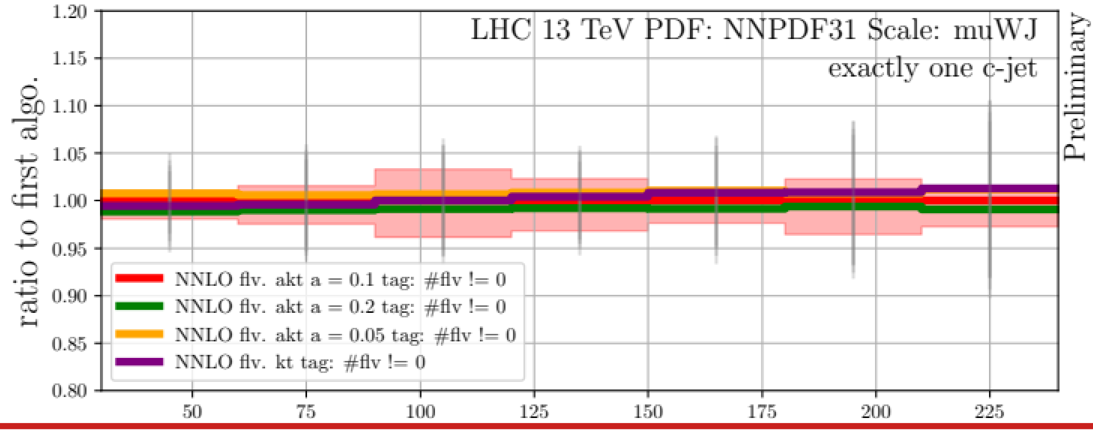
W+c-jet with flavour anti-kT

In collaboration with: Czakon, Mitov, Pellen

Preliminary

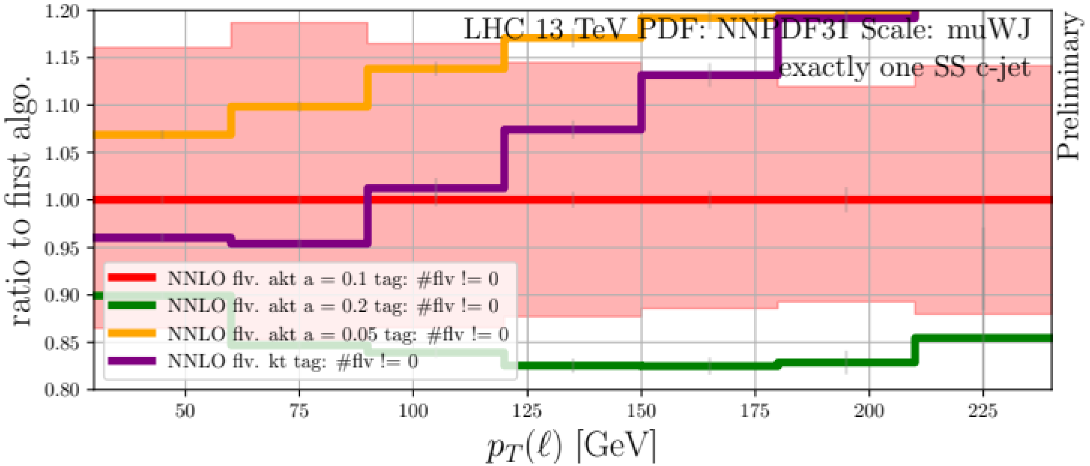
Exactly one c-jet requirement:

- 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



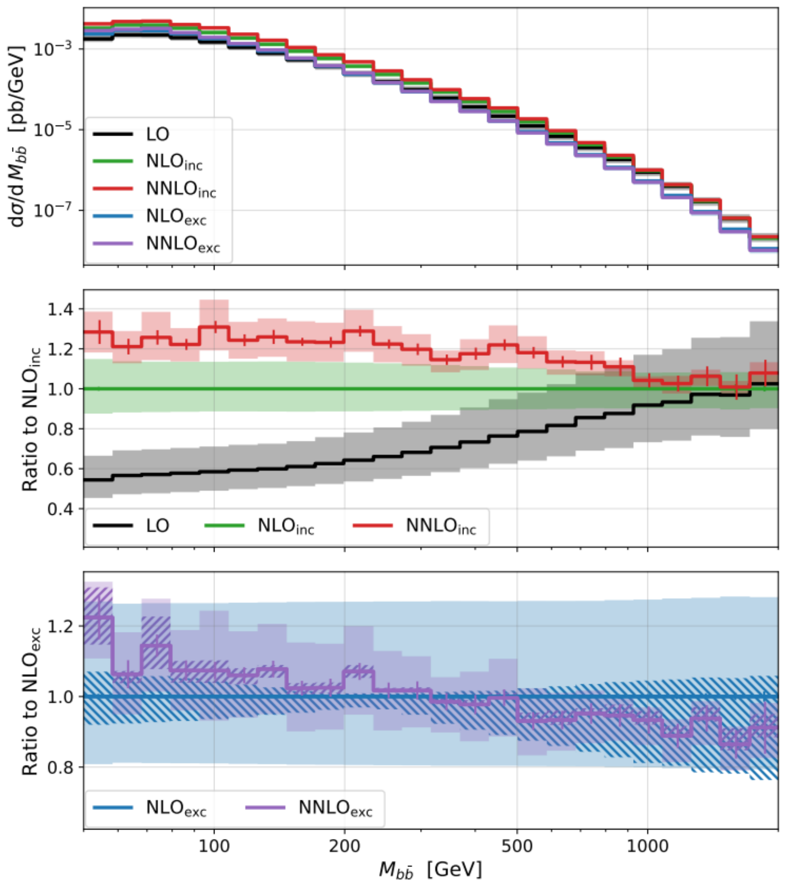
pp → W + 2 b-jets

First NNLO QCD computation with a massive leg

$$pp \to \ell\bar{\nu}b\bar{b} + X$$

NNLO QCD corrections to Wbbbar production at the LHC, Hartanto, Poncelet, Popescu, Zoia, 2205.01687

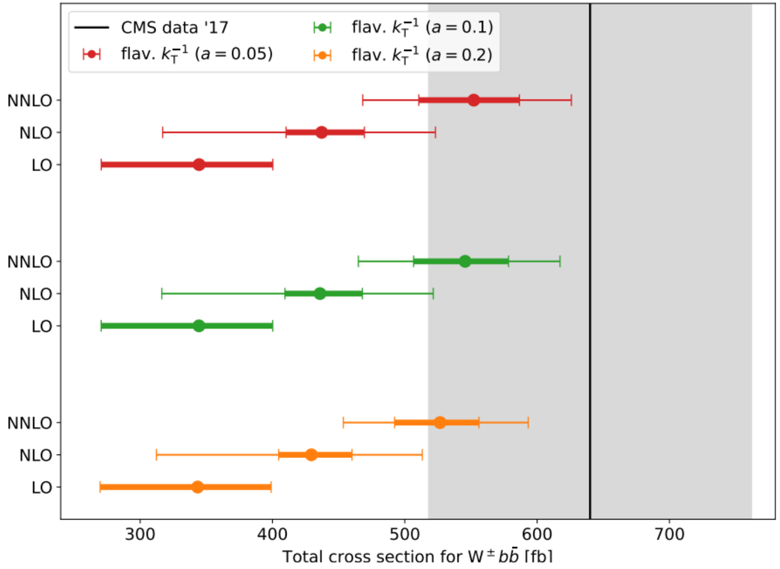
- Leading colour approximation for 2-loop amplitudes
- Massless b-quark → flavour kT algorithm for IR safety



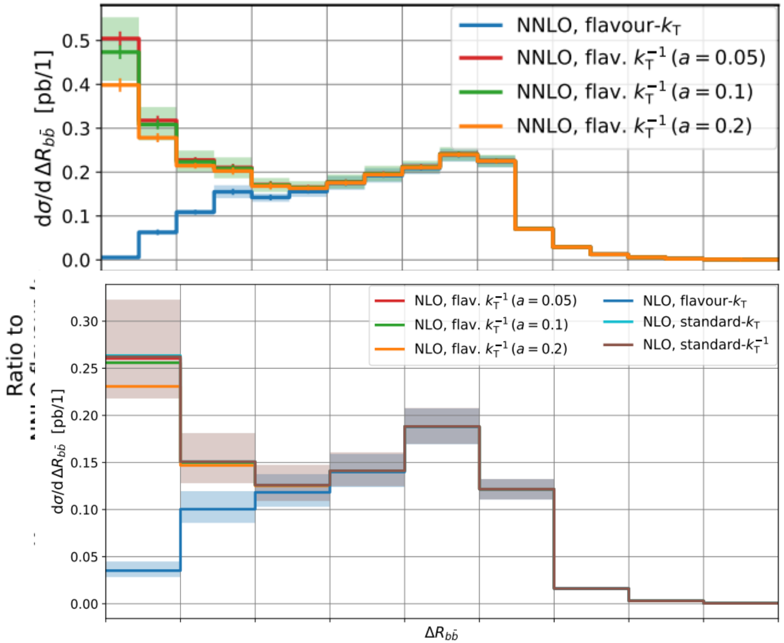
W+2bjets: flavour anti-kT

Fiducial cross section W+ and W- + 2 b-jets

Preliminary



Measurement of the production cross section of a W boson in association with two b jets in pp collisions at \sqrt{s} = 8 TeV, CMS 1608.07561



Significant differences between kT and anti-kT
In small DeltaR(bb) region? Maybe Beam-function?

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.

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

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

- 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 ??
- Is it realizable in experiment? → Would require detailed experimental flavour information… :/
- Alternatives:
  - Reclustering with flavour safe algorithm + matching:

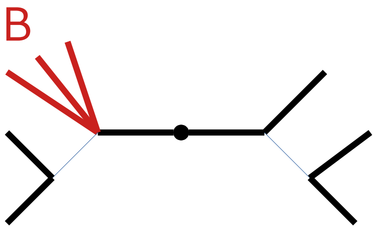
QCD-aware partonic jet clustering for truth-jet flavour labelling
Buckley, Pollard 1507.00508

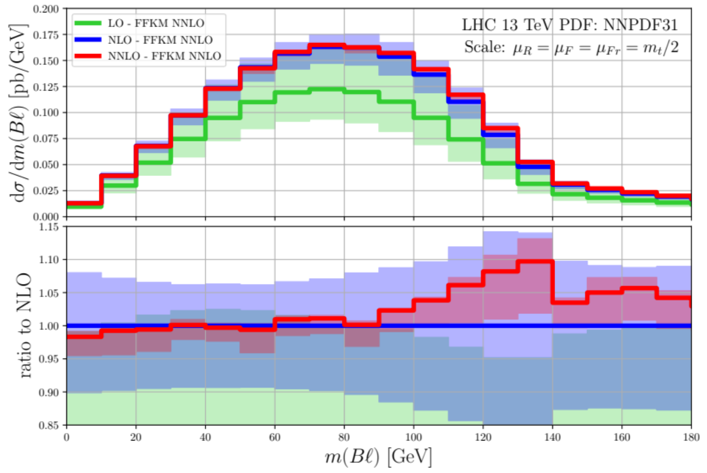
Practical Jet Flavour Through NNLO
Caletti, Larkoski, Marzani, Reichelt 2205.01109

  - Using fixed order fragmentation for jet-tagging

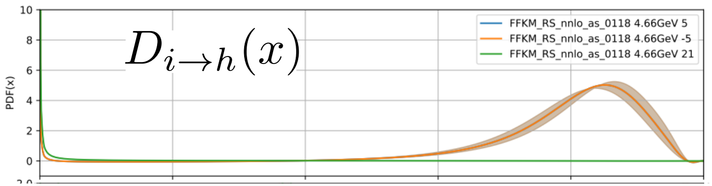
A Fragmentation Approach to Jet Flavor
Caletti, Larkoski, Marzani, Reichelt 2205.01117

$$pp \to t\bar{t} \to B\ell\bar{\ell}\nu\bar{\nu}b + X$$





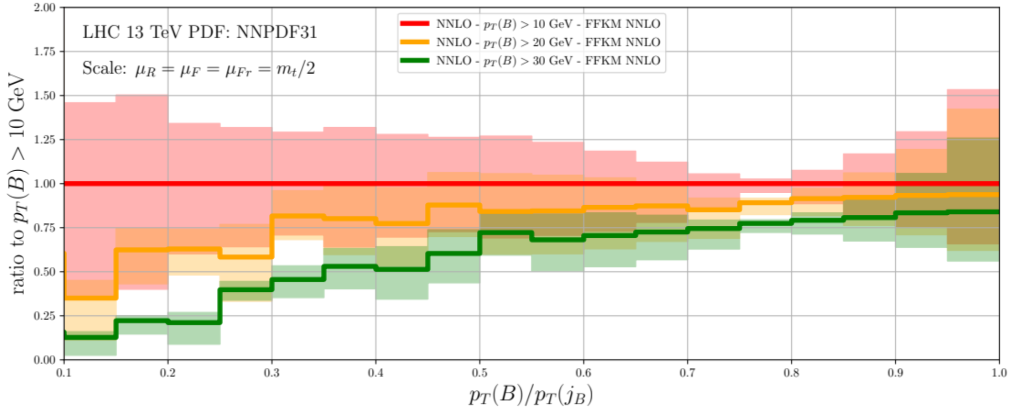
- Fixed order QCD predictions with a final state hadron
- Considering partonic computation
  + transition of parton to hadron
  (collinear fragmentation of massless partons)
- Advantage is that the hadrons momentum is measurable while the quark's is not
- Fragmentation function (similar to PDFs): Probability to find a hadron with a fraction x of the quarks momentum:

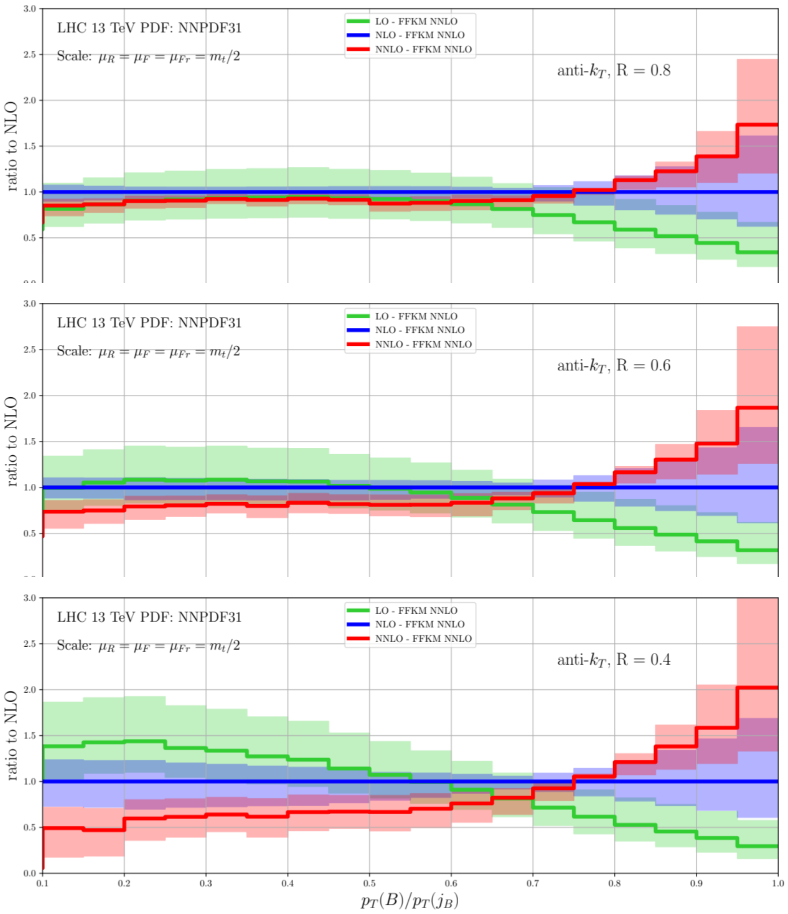


- No Parton-shower needed
- Implementation in the STRIPPER framework through NNLO QCD
  B-hadron production in NNLO QCD: application to LHC ttbar events with leptonic decays, Czakon, Generet, Mitov and Poncelet, 2102.08267

- pT(B) requirement necessary since NNLO fragmentation function divergent for x→0 due to g → bbar splitting
- Predictions depend on this choice!
- Also: sensitivity to jet radius

→ Usage as b-tag needs tuning





Summary and Outlook

New proposal for flavour safe anti-kT algorithm

- Numerical checks of IR safety
- Introduction of tunable parameter a
- Phenomenological studies:
  - pp → Z+b-jet
  - pp → tt + decays
  - pp → W+c-jet
  - pp → W+2 b-jets

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

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

Thank you for your attention :)