Flavour jet algorithms in fixed-order calculations

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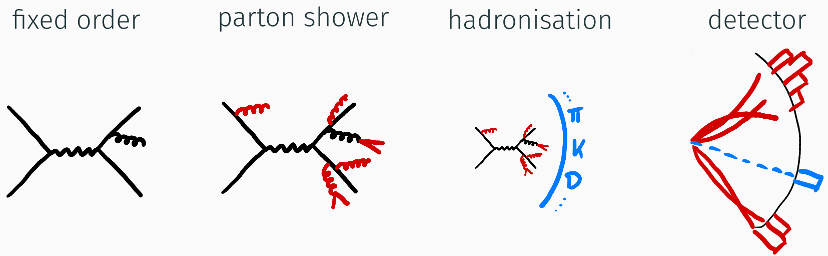
June 12, 2024 – Flavoured Jets at the LHC – IPPP, Durham, UK

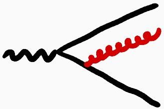
Jets: A leap of faith



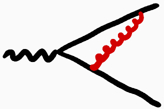
- Expect jets to be “stable concepts” across different stages of description
- Well motivated leap(s) of faith between levels for energy / four momentum
- What about flavour?

What is the problem in fixed-order calculations?

real

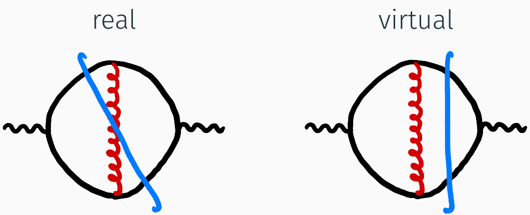


virtual



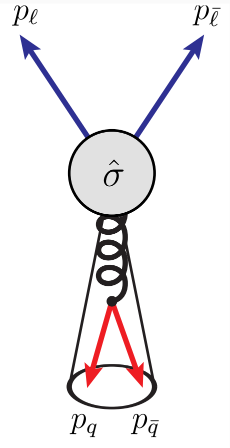
- Collinear or soft emissions cannot be distinguished from non-emission configurations
- Singularities occur in real and virtual contributions

What is the problem in fixed-order calculations?



- Consider squared matrix elements
- Real and virtual contributions correspond to different cuts of the same diagrams
- Singularities cancel in sum *if the observable agrees in singular limits*
  $\rightarrow$ IRC safety
- We have to make sure that the flavour definition of the jets does not spoil this

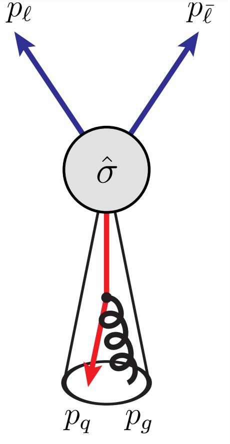
(Some of the) subtleties of defining jet flavour



Diagrams: [Gauld et al. '22]

- Collinear splitting $g \to b\bar{b}$
- Causes problem if b tag applies if *any* b parton / B hadron is present
- Can be fixed by using *net* or *mod 2* flavour recombination

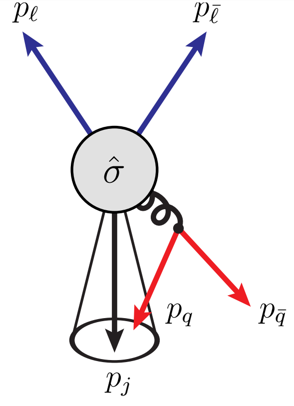
(Some of the) subtleties of defining jet flavour



Diagrams: [Gauld et al. '22]

- Collinear $b \to bg$ splitting
- Causes logarithmic sensitivity if B hadron must pass, e.g., $p_{T,\mathrm{cut}} > 5\,\mathrm{GeV}$ cut
- Such a cut cannot be implemented on parton level $\to$ would require hadronisation or fragmentation function

(Some of the) subtleties of defining jet flavour

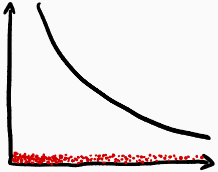


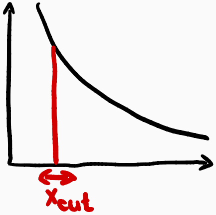
- Soft $g \to b\bar{b}$ splitting
- Problematic because soft b quarks can change flavour label of flavourless jets
- Cannot be fixed without an improved jet flavour definition

Diagrams: [Gauld et al. '22]

How does it show up?

Toy example: $\int_0^1 \frac{f(x)}{x} \mathrm{d}x$





Naive expectation:

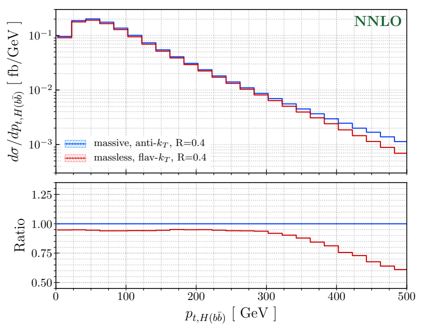
- Monte Carlo integral diverges
- "Finite" result for finite n_{points}
- Result depends on n_{points}
- Diverges for $n_{\text{points}} \to \infty$

More realistically:

- Monte Carlo integral diverges
- Technical cut-off necessary to prevent numerical instabilities
- Result depends on x_{cut}
- Diverges for $x_{\text{cut}} \to 0$

Taking the high road: making the quark massive

- Sometimes it is feasible to keep $m_b \neq 0$
- Enables use of conventional jet algorithms (e.g., anti-k_T)
- We did this for $pp \to WH(\to b\bar{b})$ in [Bizon, AB, Caola, Melnikov, Röntsch '20]
- Comparison to $m_b = 0$ with flavour-k_T: large differences in some distributions



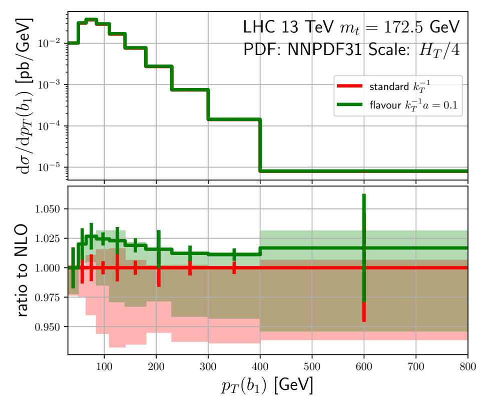
[Bizon, AB, Caola, Melnikov, Rönsch '20]

Also the high road has muddy patches

- Questions about potentially large mass logarithms
- PDFs in $n_f = 4$ vs. $n_f = 5$ flavour scheme
- ...

The heretic answer: ignoring the problem

- Sometimes one can get away with ignoring the problem
- Accept cut-off dependence if the singular contribution (if treated properly) is much smaller than everything else
- Example: $pp \to t\bar{t}$ with leptonic decays at NNLO in QCD
  [AB, Czakon, Mitov, Poncelet, Papanastasiou '19] [Czakon, Mitov, Poncelet '20]



[Czakon, Mitov, Poncelet '22]

Flavour-sensitive jet algorithms

- Several proposals for flavour-sensitive jet algorithms:
  - flavour-k_T [Banfi, Salam, Zanderighi '06]
  - SDF (soft drop flavour) [Caletti, Larkoski, Marzani, Reichelt '22]
  - CMP (flavour anti-k_T) [Czakon, Mitov, Poncelet '22]
  - GHS (flavour dressing) [Gauld, Huss, Stagnitto '22]
  - IFN (interleaved flavour neutralisation) [Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler '23]
- SDF, CMP, GHS and IFN all aim for (approximate) anti-k_T kinematics
- All of them achieve this in quite different ways
- Comparison between algorithms would be interesting

Plan for the rest of this talk

- Algorithms have been used in fixed-order calculations
  - CMP: $pp \to Wb\bar{b}$ [Hartanto, Poncelet, Popescu, Zoia '22]
  - CMP: $pp \to W + c$ jet [Czakon, Mitov, Pellen, Poncelet '22]
  - GHS: $pp \to Z + c$ jet [Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, Stagnitto '23]
  - GHS: $pp \to W + c$ jet [Gehrmann-De Ridder, Gehrmann, Glover, Huss, Rodriguez Garcia, Stagnitto '23]

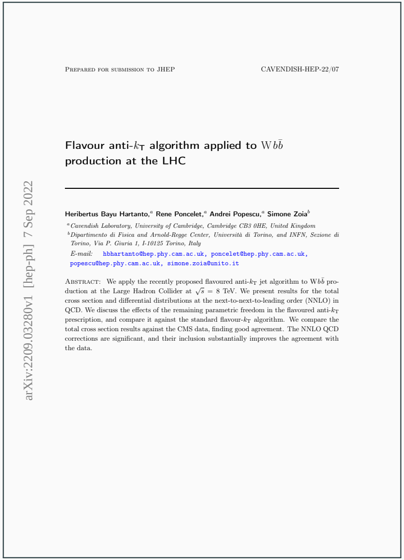
  $\to$ Discuss some examples
- Les Houches study compared algorithms on both PS and fixed-order calculations
  $\to$ Show some very preliminary plots for $pp \to WH(\to b\bar{b})$ at NNLO in QCD
  (further processes ($Z + b$ jet, $Z + c$ jet) are planned but not done yet)

CMP: $pp \to Wb\bar{b}$

- Background to other important processes in SM ($pp \to WH(\to b\bar{b})$, $pp \to t(\to Wb)\bar{b}$, ...) and BSM searches
- Testing ground for new jet algorithms
- [Hartanto, Poncelet, Popescu, Zoia '22] compared mainly flavour-k_T and CMP

Setup:

- Jets clustered with $R = 0.5$
- $p_{T,\ell} > 30$ GeV, $|\eta_\ell| < 2.1$
  $p_{T,j} > 25$ GeV, $|\eta_j| < 2.4$
  $p_{T,b} > 25$ GeV, $|\eta_b| < 2.4$
- inclusive (≥ 2 b jets) vs exclusive ($= 2$ b jets)


Prepared for submission to JHEP CAVENDISH-HEP-22/07

arXiv:2209.03280v1 [hep-ph] 7 Sep 2022

Flavour anti-k_T algorithm applied to $Wb\bar{b}$ production at the LHC

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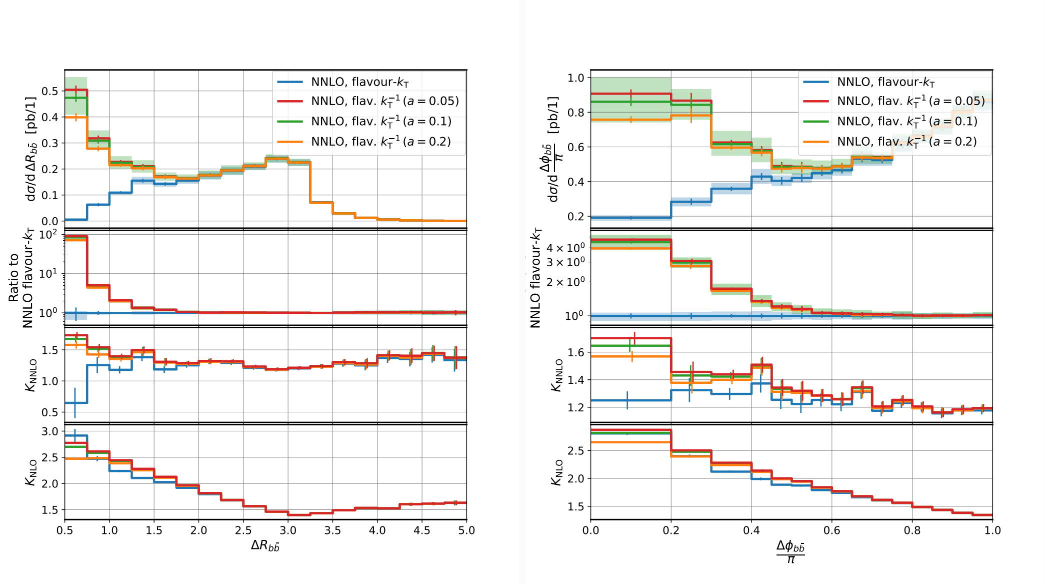
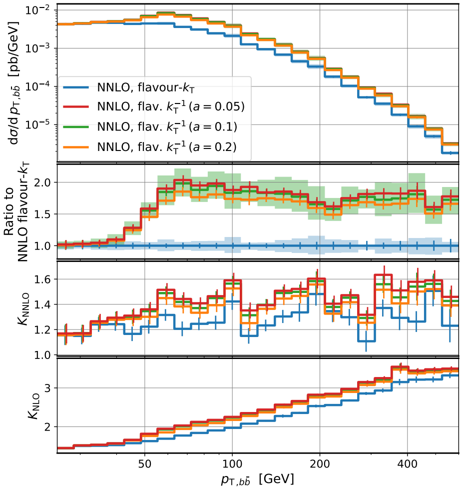
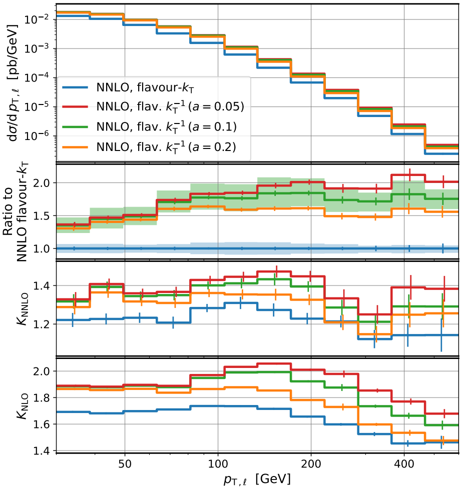
Abstract: We apply the recently proposed flavoured anti-k_T jet algorithm to $Wb\bar{b}$ production at the Large Hadron Collider at $\sqrt{s} = 8$ TeV. We present results for the total cross section and differential distributions at the next-to-next-to-leading order (NNLO) in QCD. We discuss the effects of the remaining parametric freedom in the flavoured anti-k_T prescription, and compare it against the standard flavour-k_T algorithm. We compare the total cross section results against the CMS data, finding good agreement. The NNLO QCD corrections are significant, and their inclusion substantially improves the agreement with the data.

CMP: $pp \to Wb\bar{b}$



[Hartanto, Poncelet, Popescu, Zoia '22]





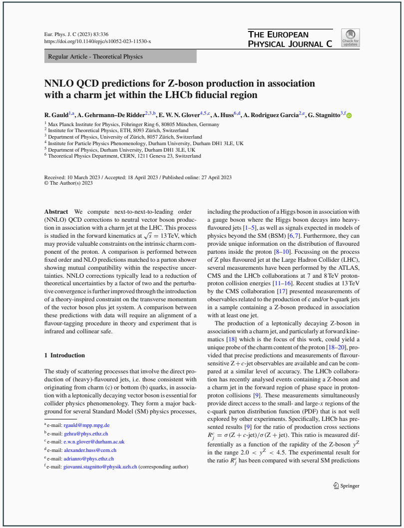
[Hartanto, Poncelet, Popescu, Zoia '22]

GHS: $pp \to Z + c$ jet

- [Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, Stagnitto '23] investigates $pp \to Z + c$ jet in LHCb fiducial region
- Interesting for constraining intrinsic charm in proton PDFs
- Jets: anti-k_T, $R = 0.5$, with GHS flavour dressing

Cuts:

- $p_{T,j} \in [20, 100]$ GeV, $\eta_j \in [2.2, 4.2]$
- $p_{T,\ell} > 20$ GeV, $y_\ell \in [2.0, 4.5]$
- $M_{\ell\bar{\ell}} \in [60, 120]$ GeV, $\Delta R(j, \ell) > 0.5$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The European Physical Journal C
Regular Article - Theoretical Physics

NNLO QCD predictions for Z-boson production in association with a charm jet within the LHCb fiducial region

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Abstract We compute next-to-next-to-leading order (NNLO) QCD corrections to neutral vector boson production in association with a charm jet at the LHC. This process is studied in the forward kinematics at $\sqrt{s} = 13$ TeV, which may provide valuable constraints on the intrinsic charm component of the proton. A comparison is performed between fixed order and NLO predictions matched to a parton shower showing mutual compatibility within the respective uncertainties. NNLO corrections typically lead to a reduction of theoretical uncertainties by a factor of two and the perturbative convergence is further improved through the introduction of a theory-inspired constraint on the transverse momentum of the vector boson plus jet system. A comparison between these predictions with data will require an alignment of a flavour-tagging procedure in theory and experiment that is infrared and collinear safe.

1 Introduction

The study of scattering processes that involve the direct production of (heavy)-flavoured jets, i.e. those consistent with originating from charm (c) or bottom (b) quarks, in association with a leptonically decaying vector boson is essential for collider physics phenomenology. They form a major background for several Standard Model (SM) physics processes, including the production of a Higgs boson in association with a gauge boson where the Higgs boson decays into heavy-flavoured jets [1–5], as well as signals expected in models of physics beyond the SM (BSM) [6,7]. Furthermore, they can provide unique information on the distribution of flavoured partons inside the proton [8–10]. Focussing on the process of Z plus flavoured jet at the Large Hadron Collider (LHC), several measurements have been performed by the ATLAS, CMS and the LHCb collaborations at 7 and 8 TeV proton-proton collision energies [11–16]. Recent studies at 13 TeV by the CMS collaboration [17] presented measurements of observables related to the production of c and/or b-quark jets in a sample containing a Z-boson produced in association with at least one jet.

The production of a leptonically decaying Z-boson in association with a charm jet, and particularly at forward kinematics [18] which is the focus of this work, could yield a unique probe of the charm content of the proton [18–20], provided that precise predictions and measurements of flavour-sensitive $Z + c$-jet observables are available and can be compared at a similar level of accuracy. The LHCb collaboration has recently analysed events containing a Z-boson and a charm jet in the forward region of phase space in proton-proton collisions [9]. These measurements simultaneously provide direct access to the small- and large-x regions of the c-quark parton distribution function (PDF) that is not well explored by other experiments. Specifically, LHCb has presented results [9] for the ratio of production cross sections $R_j^c = \sigma(Z + c\text{-jet})/\sigma(Z + \text{jet})$. This ratio is measured differentially as a function of the rapidity of the Z-boson y^Z in the range $2.0 < y^Z < 4.5$. The experimental result for the ratio R_j^c has been compared with several SM predictions

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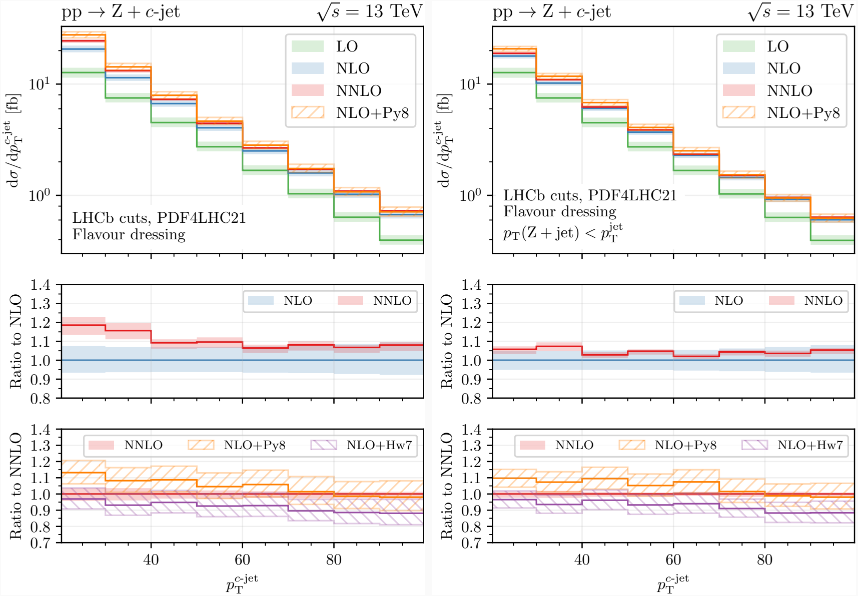
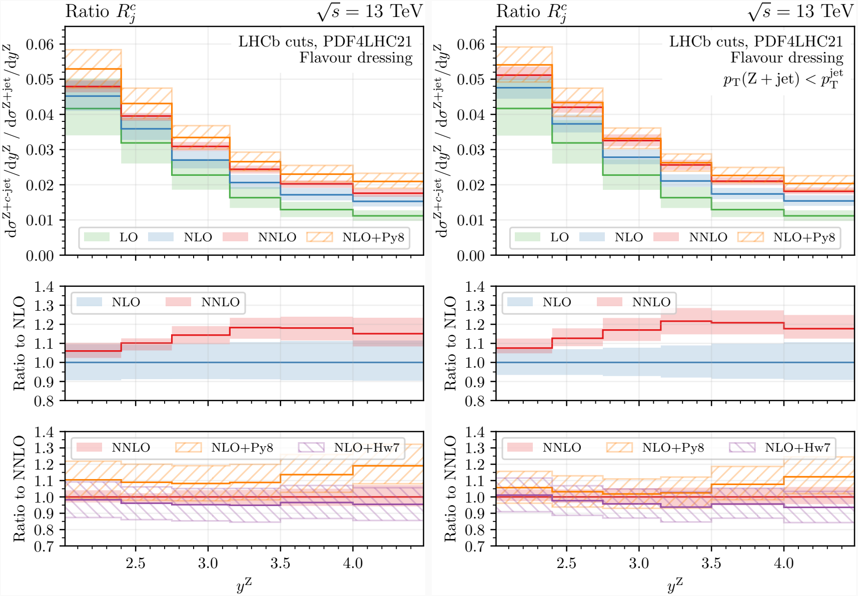
GHS: $pp \to Z + c$ jet



[Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, Stagnitto '23]

GHS: $pp \to Z + c$ jet



[Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, Stagnitto '23]

CMP & GHS: $pp \to W + c$ jet

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A detailed investigation of W+c-jet at the LHC

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Regular Article - Theoretical Physics

Precise QCD predictions for W-boson production in association with a charm jet

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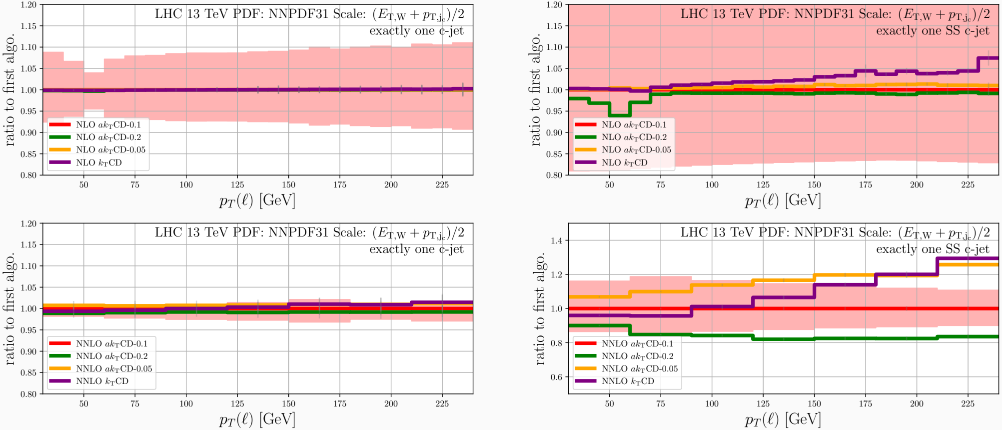
Abstract The production of a W-boson with a charm quark jet provides a highly sensitive probe of the strange quark dis- ... The resulting PDFs do not have uniform uncertainties across the different quark flavours, since only some flavour combi-

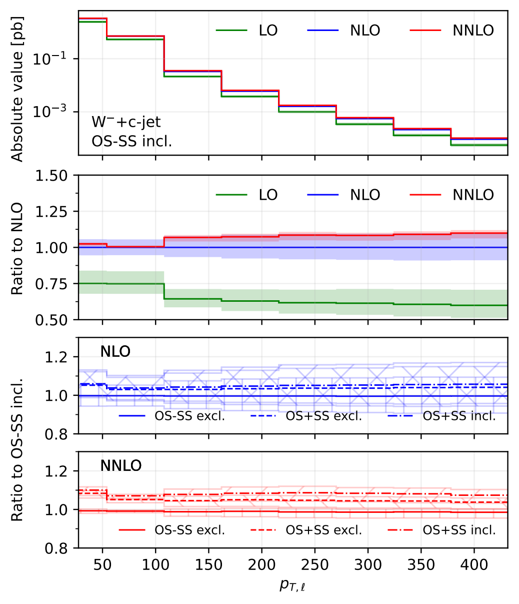
- $pp \to W + c$ jet was investigated by both [Czakon, Mitov, Pellen, Poncelet '22] and [Gehrmann-De Ridder, Gehrmann, Glover, Huss, Rodriguez Garcia, Stagnitto '23]
- Interesting due to sensitivity to strange quark PDF
- Czakon et al.: compare flavour-k_T vs CMP, investigate NLO EW corrections, off-diagonal CKM effects, PDF dependence and scale setting, …
- Gehrmann-De Ridder et al.: provide also a partonic channel breakdown

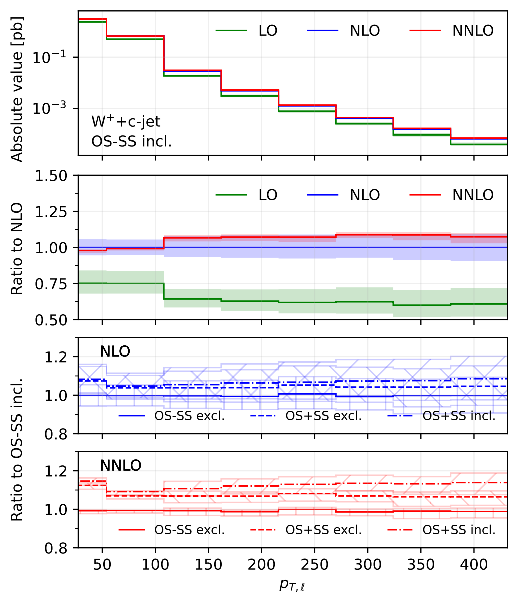
CMP: $pp \to W + c$ jet



[Czakon, Mitov, Pellen, Poncelet '22]

GHS: $pp \to W + c$ jet



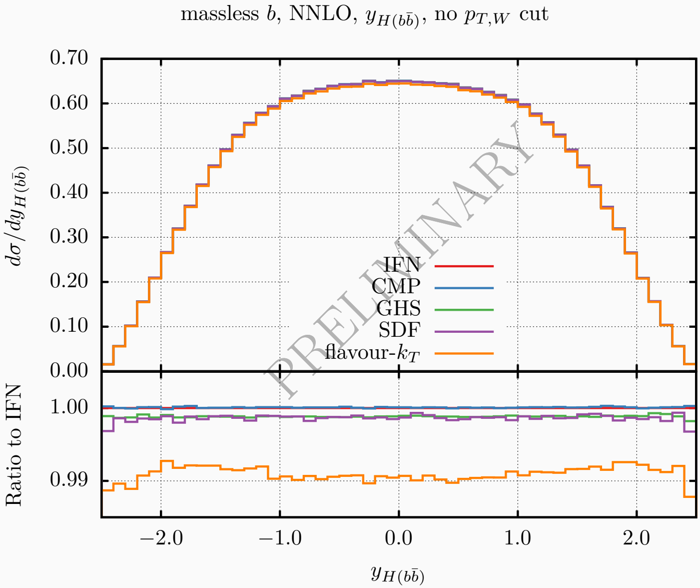


[Gehrmann-De Ridder, Gehrmann, Glover, Huss, Rodriguez Garcia, Stagnitto '23]

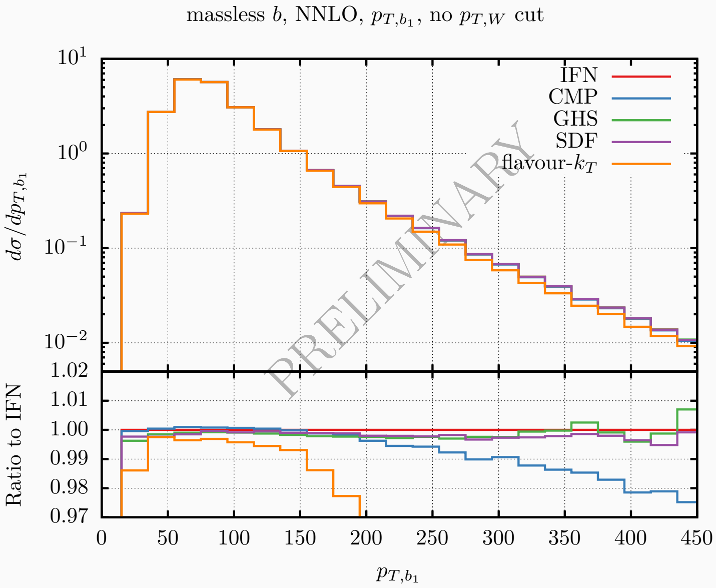
Associate Higgs production with b decays

- Les Houches flavour jet study includes fixed-order NNLO QCD calculations to compare jet algorithms
- Here: use $pp \to W^+(\to e^+\nu_e)H(\to b\bar{b})$,
  based on [Behring, Bizon, Caola, Melnikov, Röntsch '20]
- Interesting feature: both $m_b = 0$ and $m_b \neq 0$ calculations are available
- Setup:
  $p_{T,\ell} > 15\,\text{GeV}$, $|\eta_\ell| < 2.5$
  $p_{T,b} > 25\,\text{GeV}$, $|\eta_b| < 2.5$
  $p_{T,j} > 25\,\text{GeV}$
  ≥ 2 b jets
- Caveat: what follows are *very preliminary* plots!

WHbb: $y_{H(b\bar{b})}$

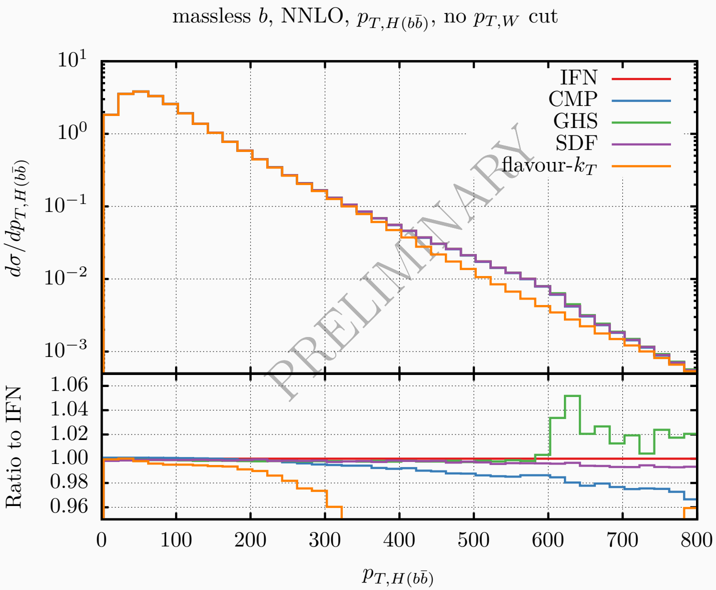


WHbb: p_{b_1}

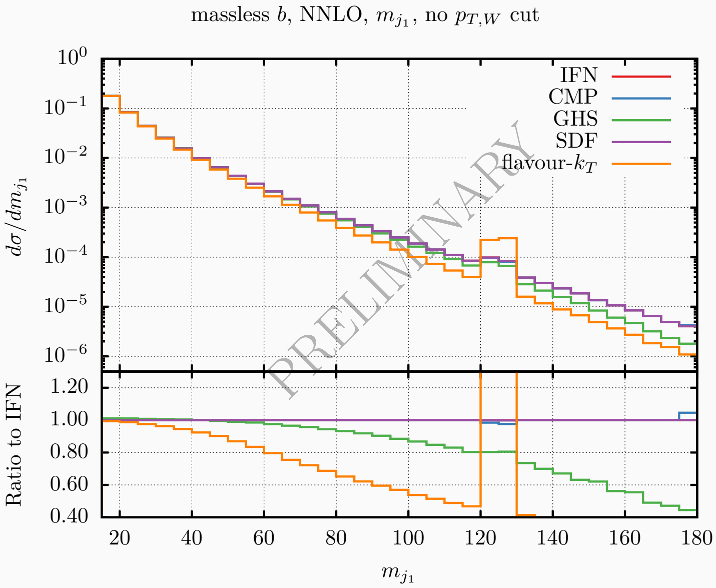


massless b, NNLO, p_{T,b_1}, no $p_{T,W}$ cut
IFN
CMP
GHS
SDF
flavour-k_T
PRELIMINARY
$d\sigma/dp_{T,b_1}$
Ratio to IFN
p_{T,b_1}
10^1
10^0
10^{-1}
10^{-2}
1.02
1.01
1.00
0.99
0.98
0.97
0
50
100
150
200
250
300
350
400
450

WHbb: $p_{T,H(b\bar{b})}$

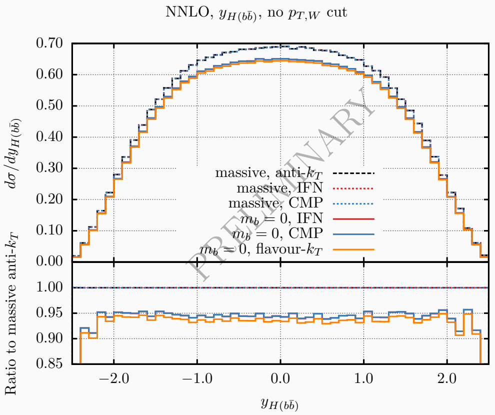


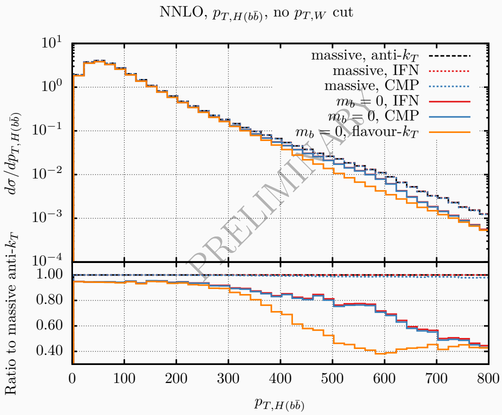
WHbb: m_{j_1}



massless b, NNLO, m_{j_1}, no $p_{T,W}$ cut
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$d\sigma/dm_{j_1}$
IFN
CMP
GHS
SDF
flavour-k_T
PRELIMINARY
Ratio to IFN
1.20
1.00
0.80
0.60
0.40
20
40
60
80
100
120
140
160
180
m_{j_1}

WHbb: massive vs massless calculations





Conclusions

- IRC safety of jet flavour definition is very important for fixed-order calculations
- New flavour jet algorithms allow for closer correspondence between theory calculation and experimental measurements
- New algorithms have been used in interesting NNLO QCD fixed-order calculations
- Les Houches flavour jet study includes comparisons on NNLO fixed-order calculations
- For most distributions the different algorithms agree very well
- Work in progress: better understanding and add more processes to comparison