Precision phenomenology with heavy-flavour jets at the LHC

Rene Poncelet

based on 2011.01011, 2205.11879, 2212.00467 and 2308.02285
and preliminary Les Houches studies

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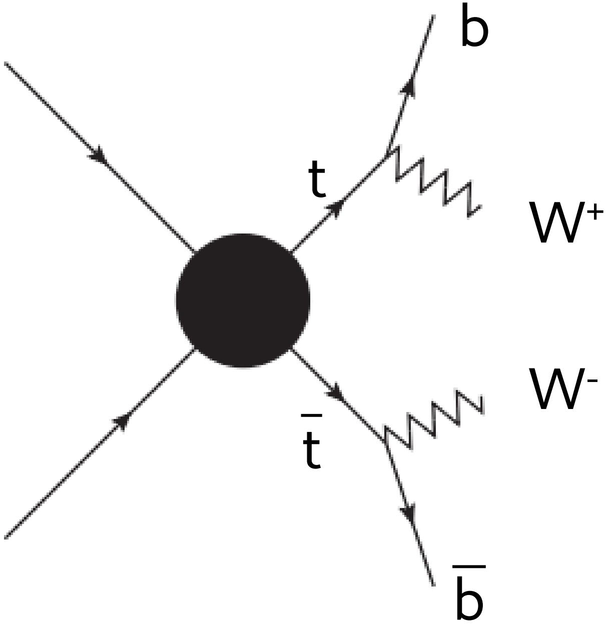
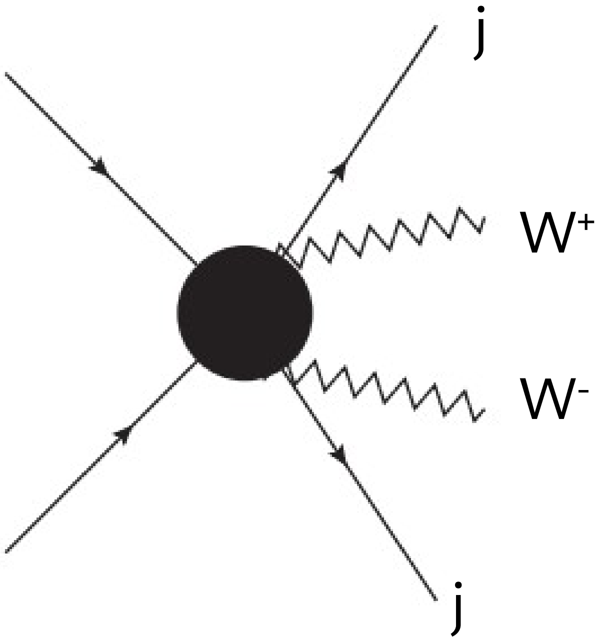
Outline

- Why are flavoured jets interesting for LHC physics?
  - Theory vs. Experimental point of view
  - Infrared safety/sensitivity
- Flavoured jet algorithms
  - Definition & Comparison
- NNLO QCD Phenomenology with flavour anti-kT algorithm
  - W+charm

Top-quark production

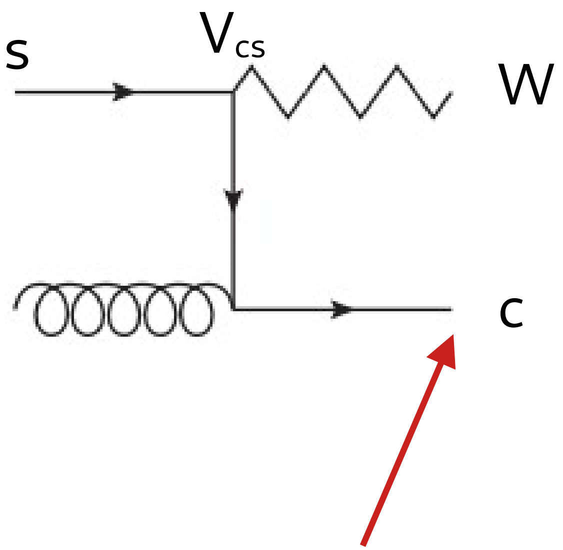


vs.



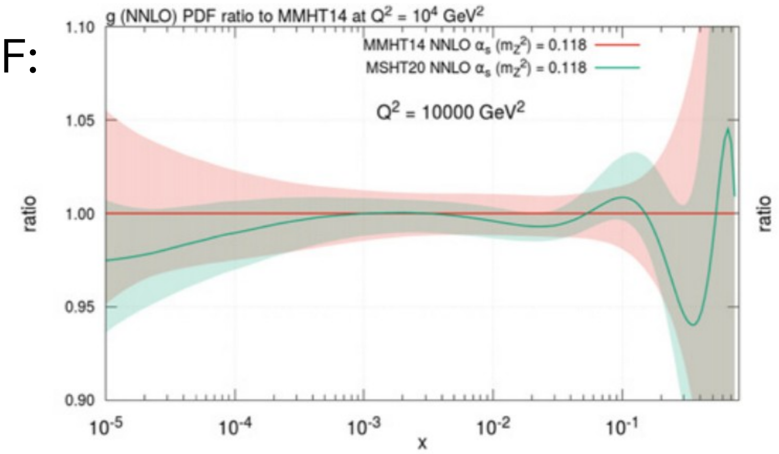
Top-quark pairs:
→ Experimental signature 2 – b-jets + WW
→ b-jet tagging reduces WW+QCD background dramatically.

W + charm jet

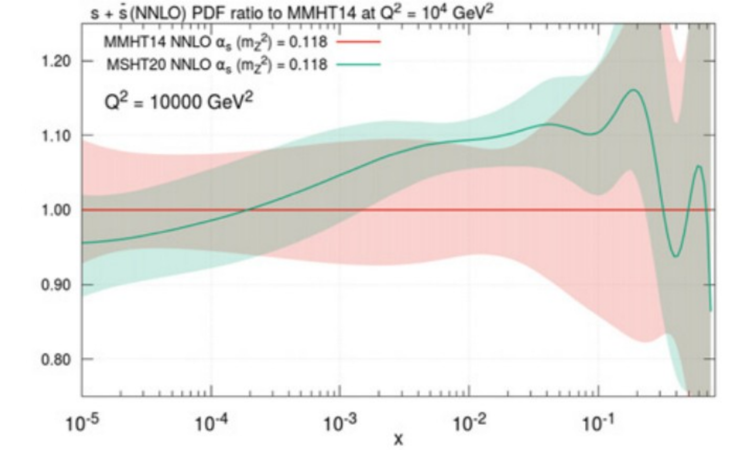


Tagging of charm jet
to increase sensitivity
to strange quark PDF

gluon PDF:



s+s PDF:



PDF4LHC22 [2203.05506]

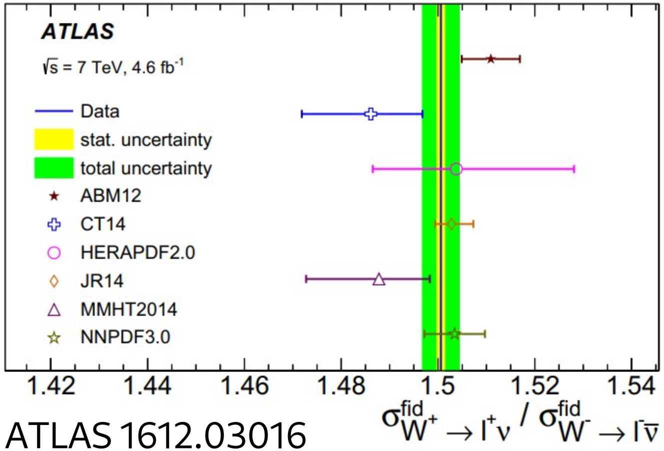
W + charm jet

Could solve long-standing puzzle:

Strange – anti – strange asymmetry

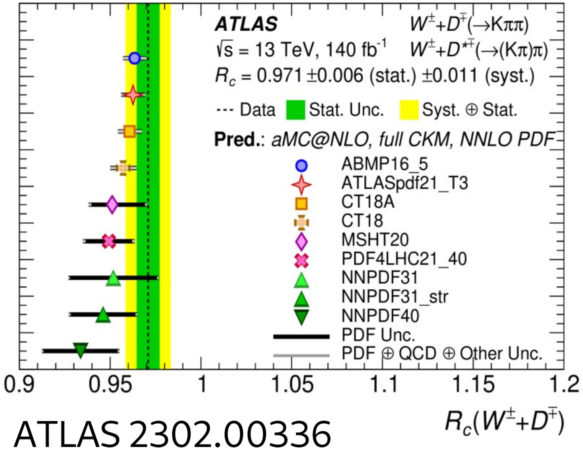
- pQCD: Three loop SM prediction q→ q' ≠ q → $\bar{q}$' small effect $\langle x(s-\bar{s})\rangle \sim 10^{-4}$
- Size of non-perturbative effect unknown

7 TeV analysis favours $s \neq \bar{s}$



ATLAS 1612.03016

13 TeV analysis favours $s = \bar{s}$

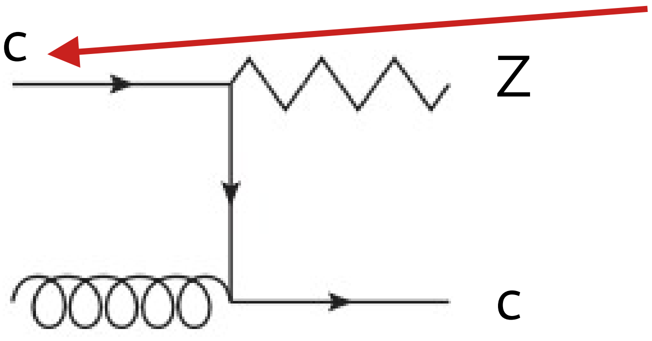


ATLAS 2302.00336

All at NLO QCD

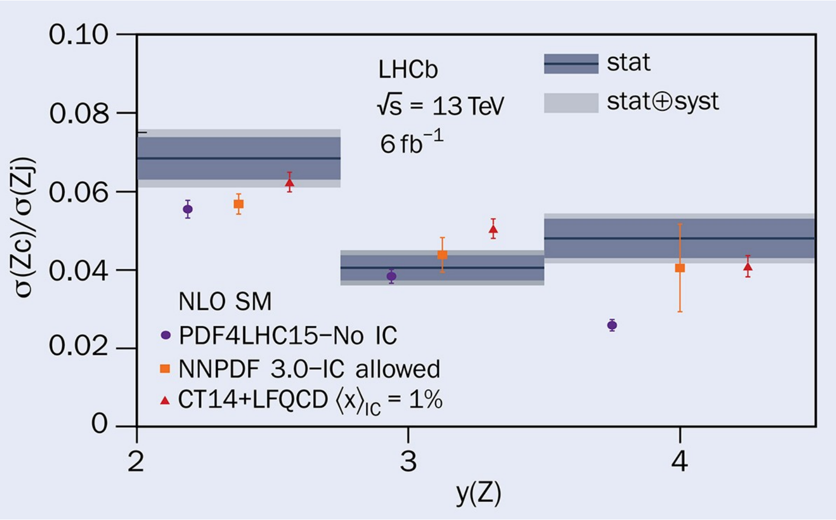
higher order corrections needed to fit properly the PDF

Z + charm jet



Similar to W+charm but for charm PDF

Intrinsic charm component?
Clarification needs
→ higher order corrections
→ charm jet definition

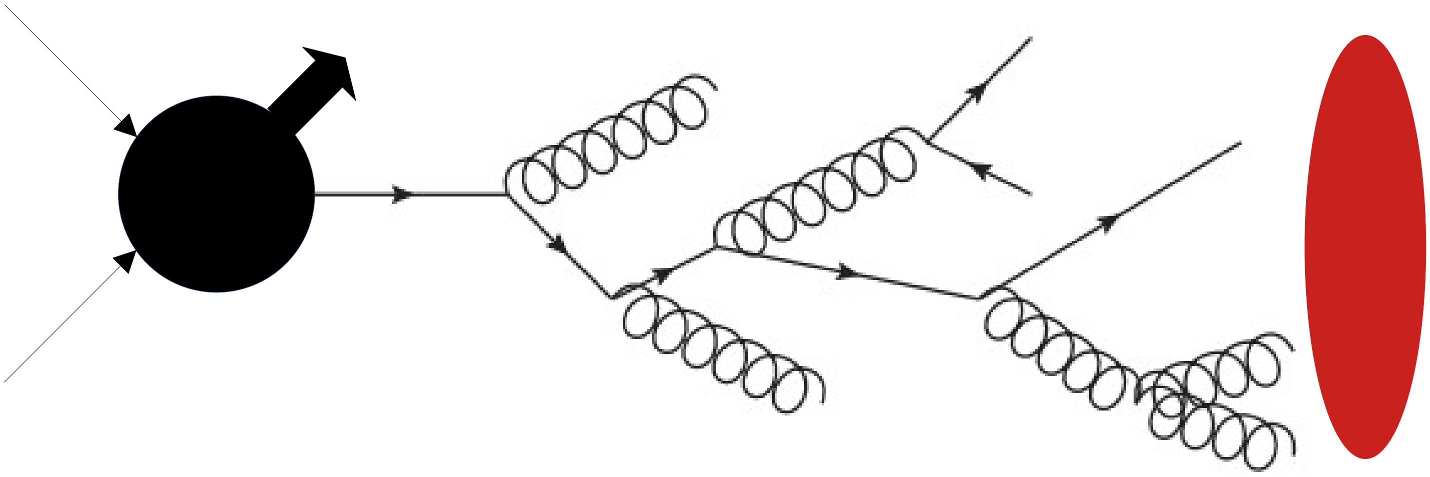


CERN/LHCb 2109.08084

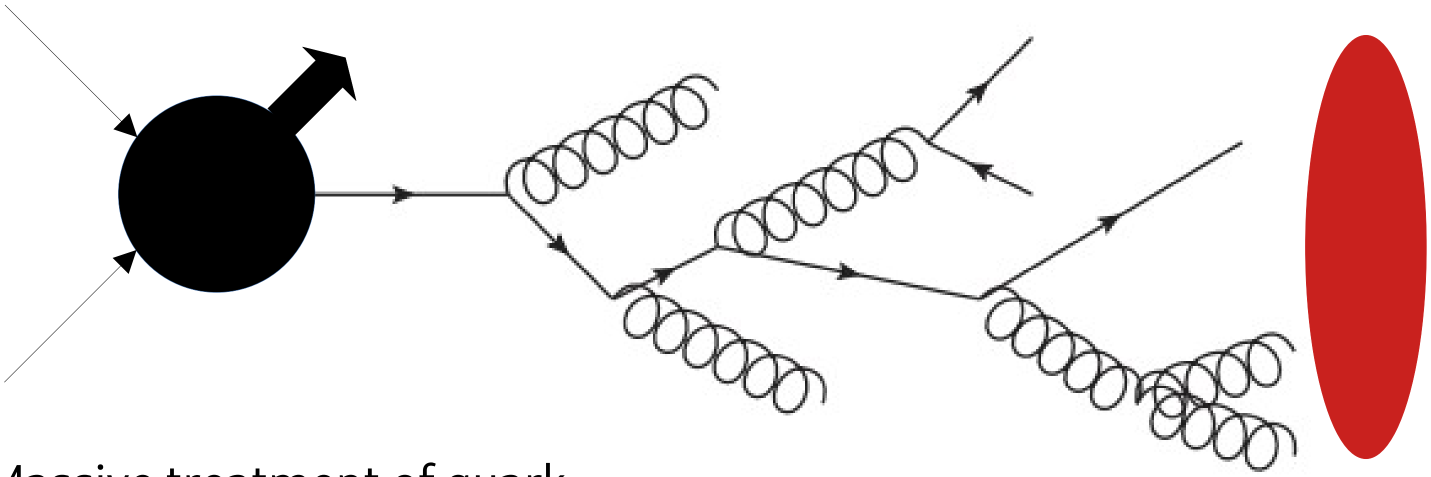
Flavoured jets are everywhere

- Top-quarks
- Vector+heavy flavour: pp → W/Z/A + c/b
- Higgs → charm, Higgs → bottom
- New physics searches
- ...

Partonic jet evolution



Partonic jet evolution



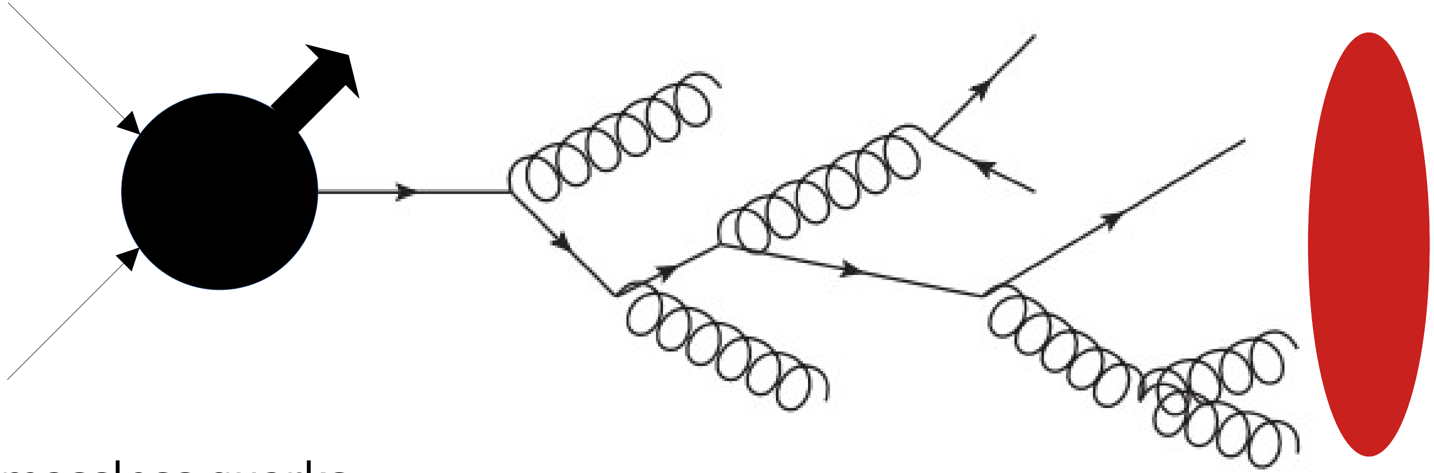
Case I: Massive treatment of quark

- Mass acts as IR regulator → no IR divergences from collinear splitting
- Price to pay: log(pT/m) will be important at high energy!
  → resummation needed for reliable predictions
- Parton-showers can do this but at low accuracy
- Higher order calculations more difficult

} NLO+PS

- Some applications (like PDF fits) need fixed order pQCD at higher orders

Partonic jet evolution

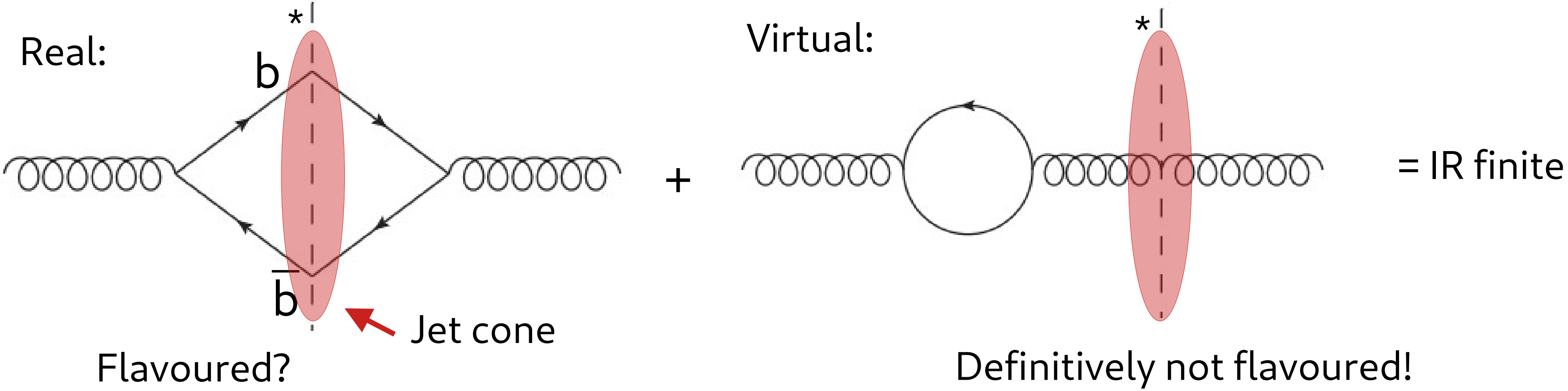


Case II: massless quarks

- Collinear divergences absorbed by renormalisation
- Consistent treatment in junction with PDFs
- Higher order calculations easier → NNLO QCD de-facto standard
- BUT: IR-safety more demanding due to collinear and soft flavoured particles

IR safety issues starting from NLO QCD

Massless QCD: Cancellation of IR divergences between real and virtual corrections

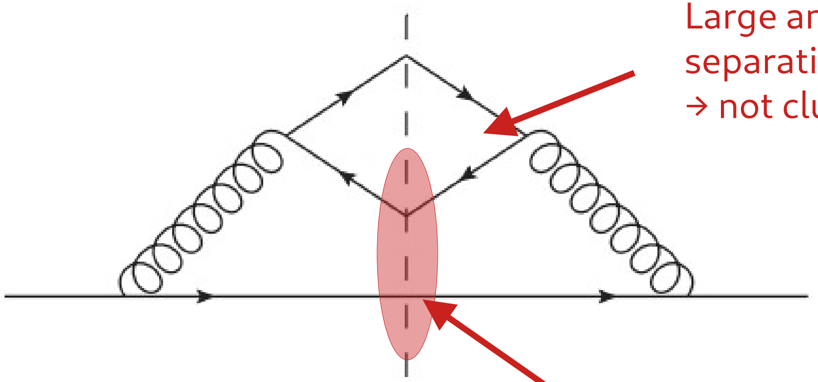


➡ $b\,\bar{b}$ has to count as a gluon!

*: cut symbolises the “measured” final state

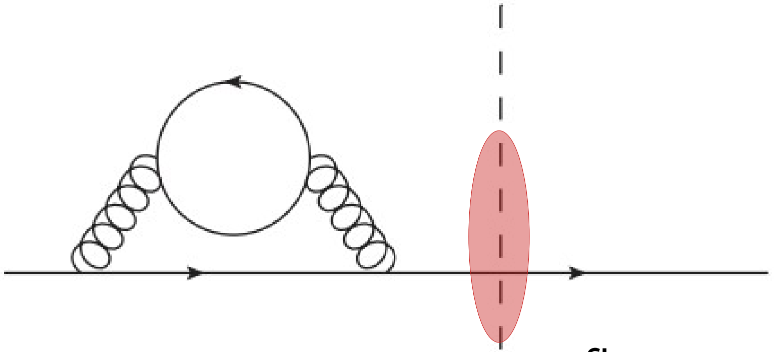
IR safety issues starting from NNLO QCD

Double soft limit of quark pairs



Large angular separation
→ not clustered

Not flavoured!



flavoured!

- These double soft splitting need to be captured
- Requires to interleave kinematics and flavour information!

Short summary - theory

- Massive:
  - Proper description near threshold
  - Identifiable objects → 4-momenta IR safe observables (mass is regulator)
  - Fixed-order perturbation theory: large logs at high pT → Resummation with PS
  - Higher-order corrections more challenging
- Massless:
  - Proper description at high energies, flavour takes part in PDFs/DGLAP
  - Higher-order corrections easier to compute
  - IR-safety requires modified jet algorithms → implications for phenomenology
- In-between solutions:
  - FONLL : matching of massive and massless computation
  - Perturbative fragmentation

How does this compare to experiment?

Experimental b/c-tagging

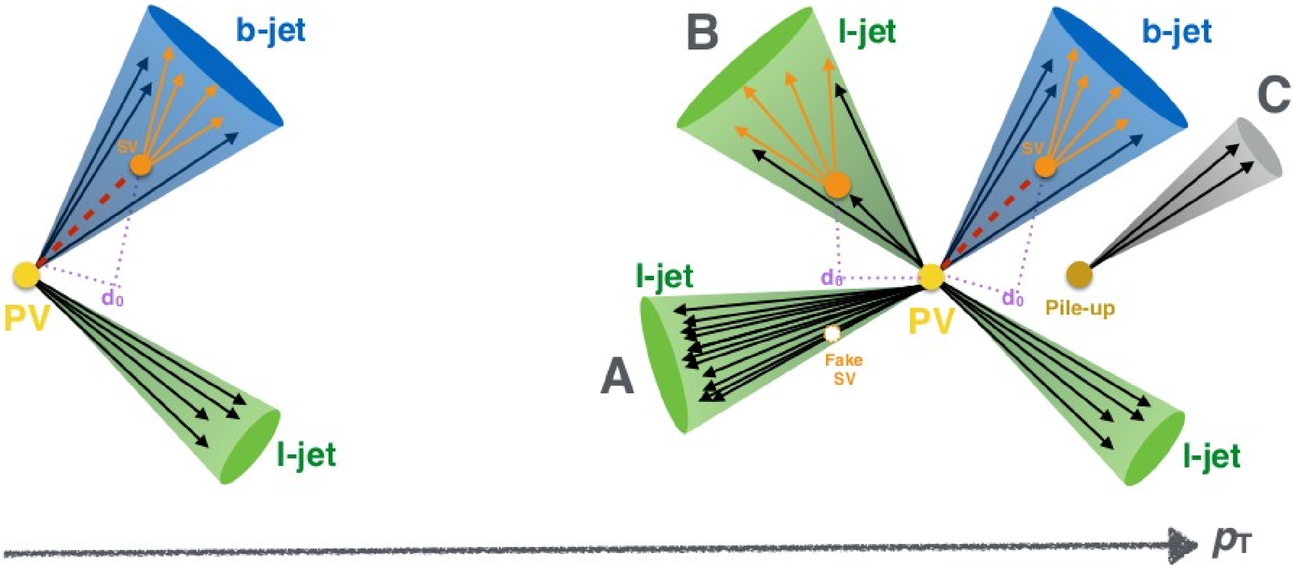
Credit: Arnaud Duperrin (DIS23 talk)

Secondary vertex (SV) tagging

- Long-life time
  → several mm flight
- Looking for the decay products of B-hadron decays forming SV

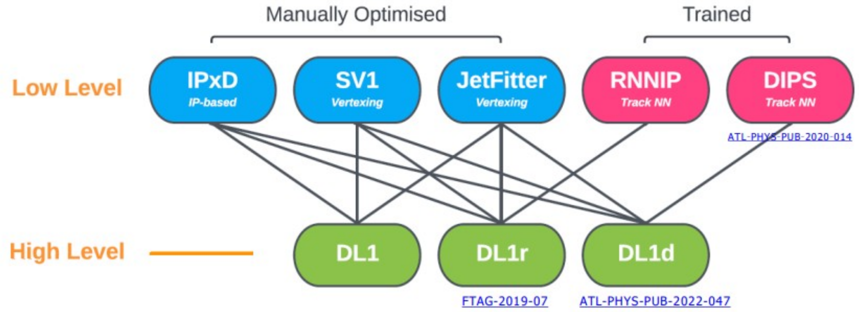
Challenges

- Fake SV from fragmentation
- Material interactions
- Pile-up



Experimental b/c-tagging with NN

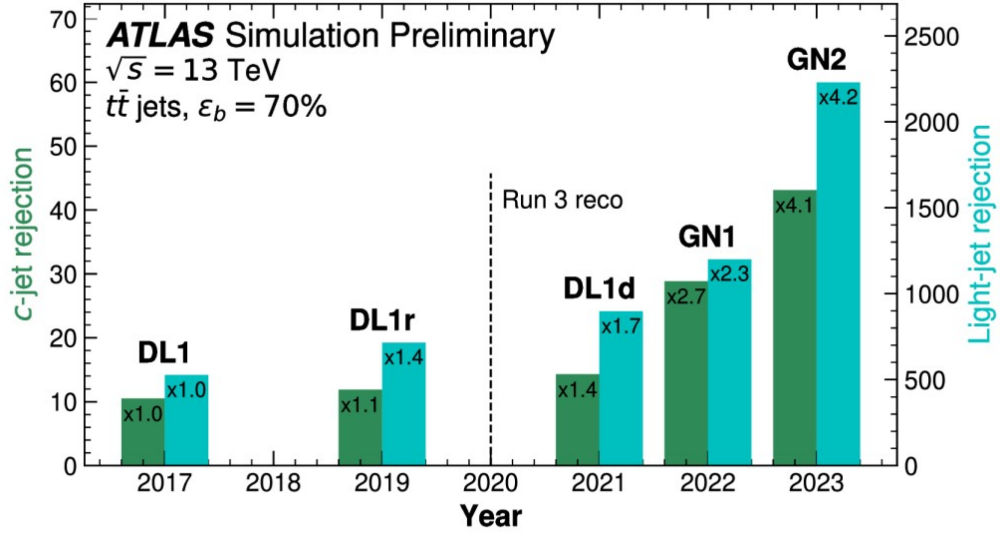
Credit: Arnaud Duperrin (DIS23 talk)



<u>Using NN to perform b-tagging</u>

- Many Run II/III analysis use already NN based taggers
- For example ATLAS: DL1
  → uses precomputed low-level infos
- Next generation will directly use hit, track and jet information
  → further performance boost

The truth level information comes from MC simulations

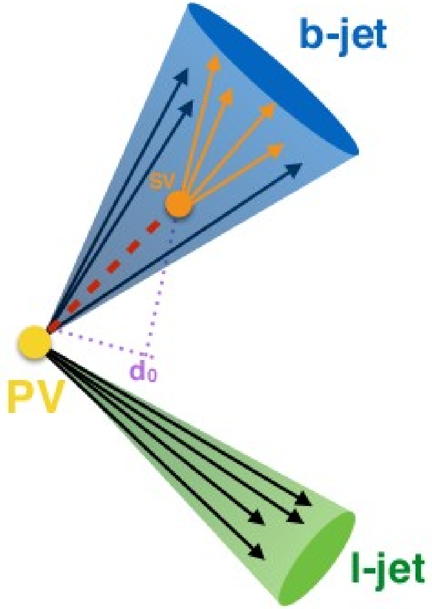


Ghost tagging

A jet is defined as flavoured if:

1) it contains at least one B/D hadron
   FO: IR-unsafe because of g → b $\bar{b}$ splitting
2) within dR < R of jet axis
   FO: IR-unsafe because soft wide angle emission
3) with pT > pT_cut
   FO: collinear unsafe b → b g splitting
   (okay in fragmentation approach)

“Truth” labelling used in Monte Carlo samples, used to train the NN



Technically okay for PS+hadronisation models
BUT
Unsatisfactory from theory point of view
(trading IR safety with sensitivity)

Issues for precision phenomenology

- The flavoured jet algorithms require detailed flavour information
  → flavour algorithms difficult to implement experimentally
  Limited by detector-resolution & efficiencies!

- For now: comparisons to higher order QCD partonic computations require corrections for the differences in tagging procedures! → Unfolding!

  1) g → b b splitting if both b's hadronise to B-hadrons
  (this is different to b $\bar{b}$ = g @ fixed order)

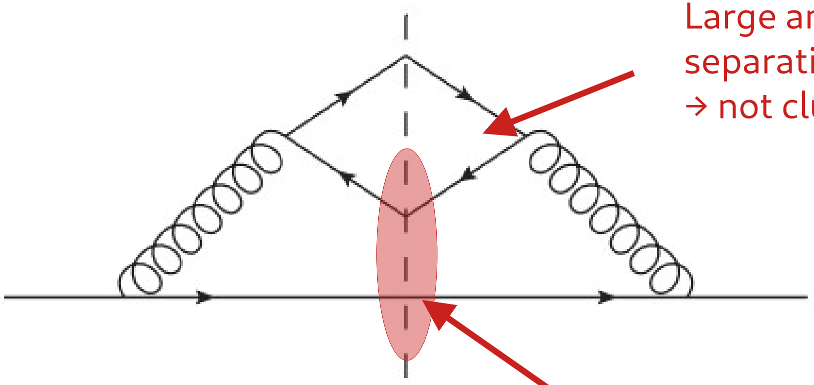
  2) Hadronisation/non-perturbative models

- Unfolding corrections can be sizeable O(5-10%)

Infrared safety of flavoured jet

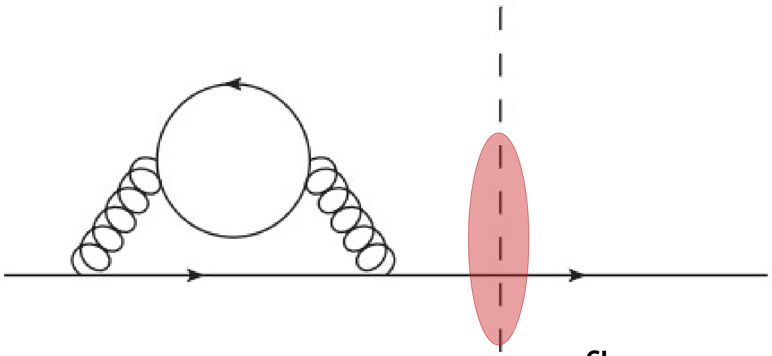
Flavoured jet algorithms

Double soft limit of quark pairs



Large angular separation
→ not clustered

Not flavoured!



flavoured!

- 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:

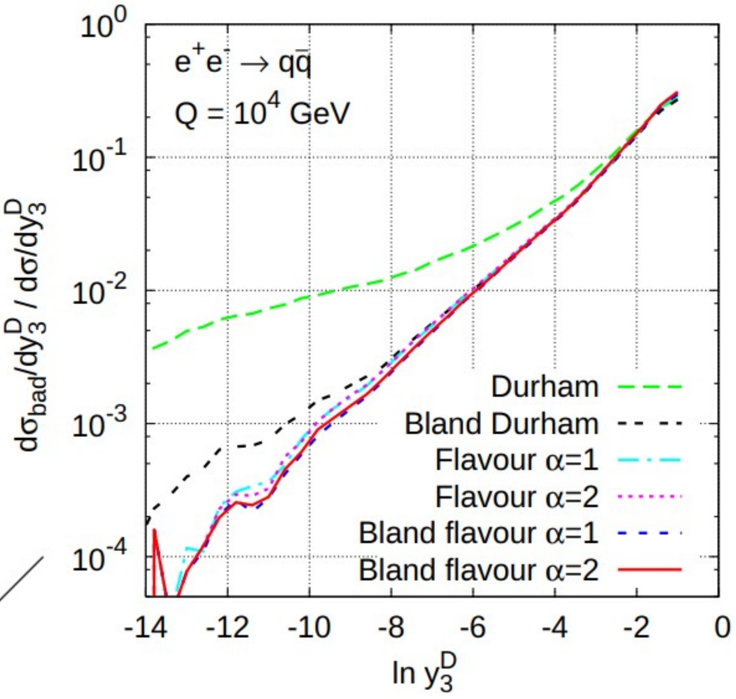
$$d_{i,B} = \begin{cases} \max(k_{T,i}, k_{T,B}(y_i))^\alpha \min(k_{T,i}, k_{T,B}(y_i))^{2-\alpha} & \text{i is flavoured} \\ \min(k_{T,i}, k_{T,B}(y_i))^\alpha & \text{else} \end{cases}$$

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

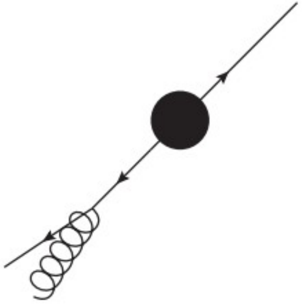
$$d_{\bar{B}}(\eta) = \sum_i k_{T,i}(\theta(\eta - \eta_i) + \theta(\eta_i - \eta) e^{\eta - \eta_i}$$

Tests of IR safety

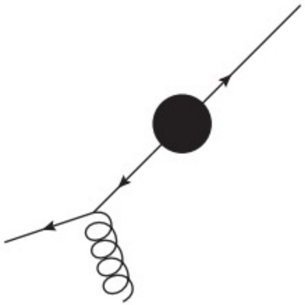
- Rate of bad-identified jet-flavour as a function of IR sensitive variable
- Parton-shower to model many emissions



Small y3



Large y3



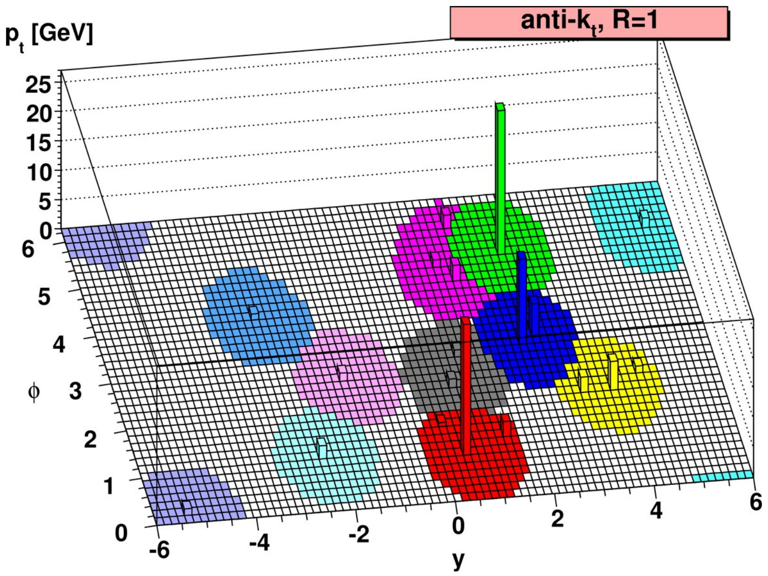
Flavour anti-kT?

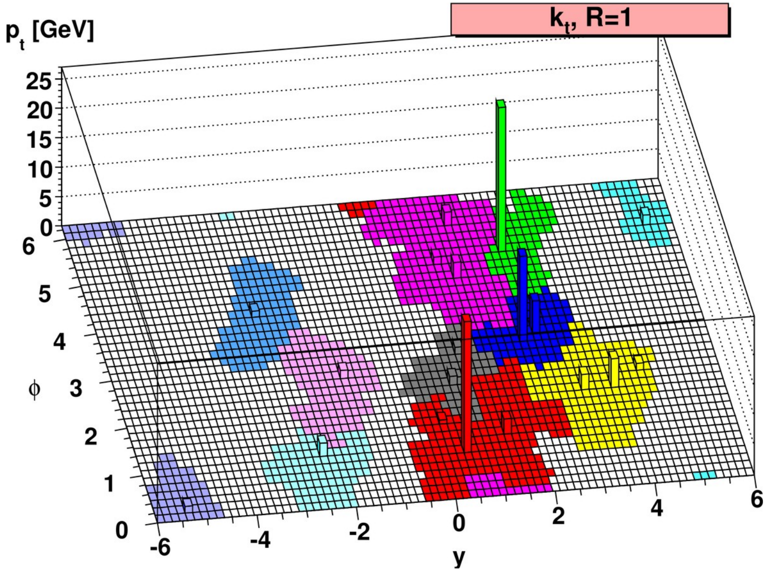
The standard algorithm for the LHC is the anti-kT:

→ nice geometric properties

→ less sensitive to soft physics

Towards Jetography
Salam 0906.1833





New proposals for flavour-safe anti-kT jets

- Flavour with Soft-drop

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

- Flavour anti-kT

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

- Fragmentation approach

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

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

- Flavour dressing → standard anti-kT + flavour assignment

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

A dress of flavour to suit any jet
Gauld, Huss, Stagnitto 2208.11138

- Interleaved flavour neutralisation

Flavoured jets with exact anti-kT kinematics and tests of infrared and collinear safety
Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler 2306.07314

- TBC...

Flavour anti-kT

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

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

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

Proposed modification:

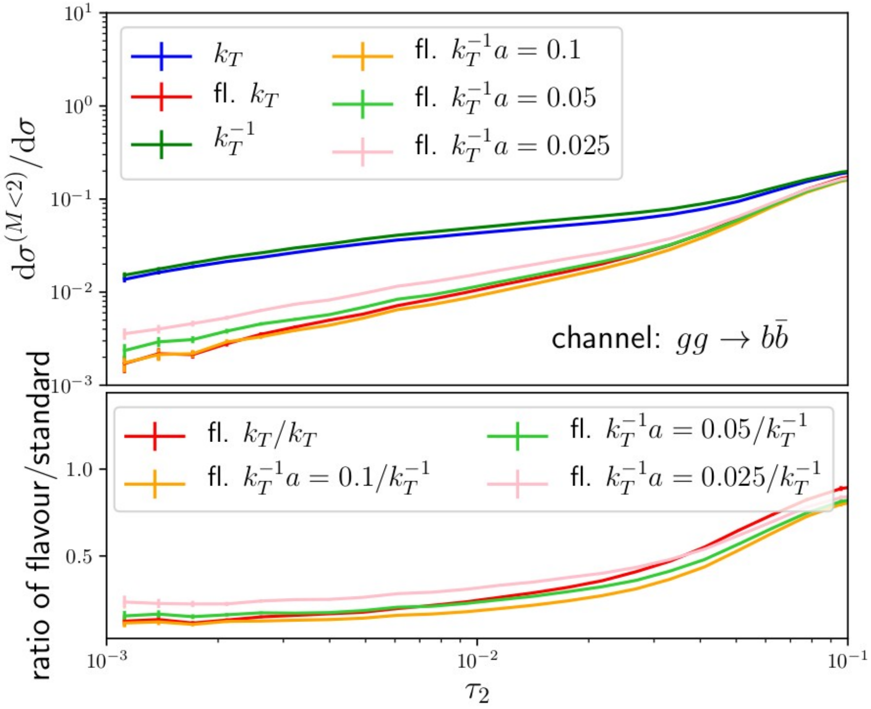
A soft term designed to modify the distance of flavoured pairs.

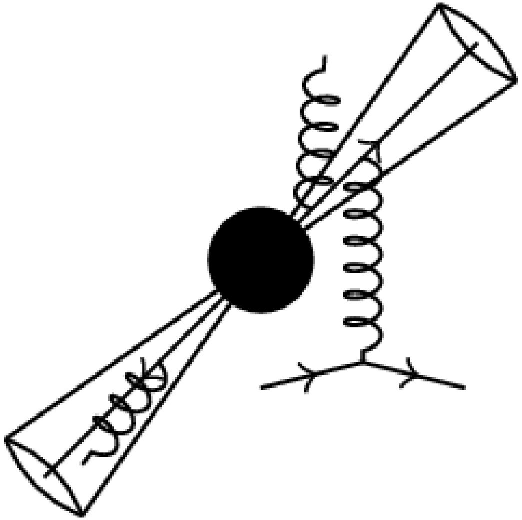
$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases}$$

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

Tests of IR safety with parton showers

In the di-jet limit the flavour needs to correspond to tree level flavours
→ misidentification rate needs to vanish in di-jet back-to-back limit
→ IR sensitive observable 2-jettiness



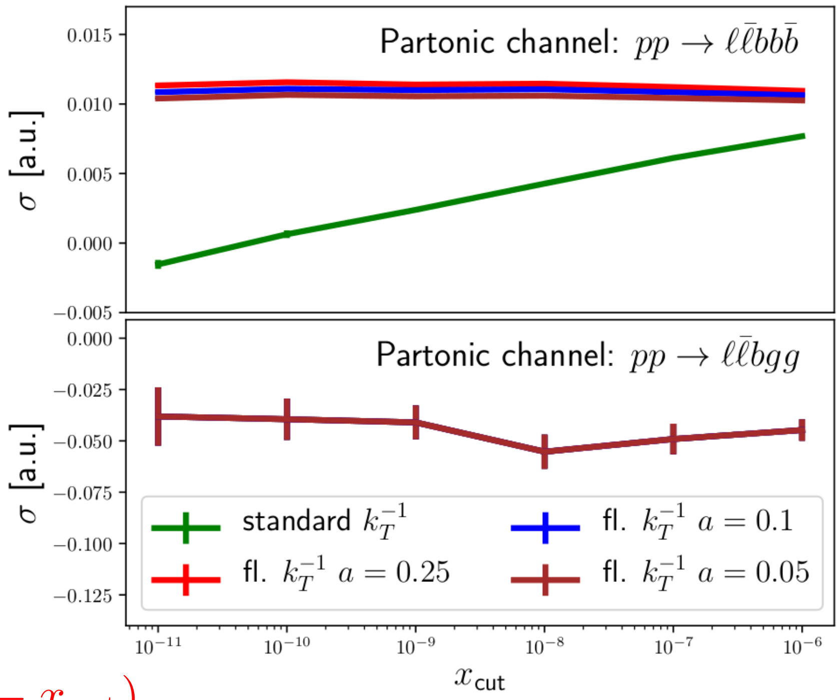


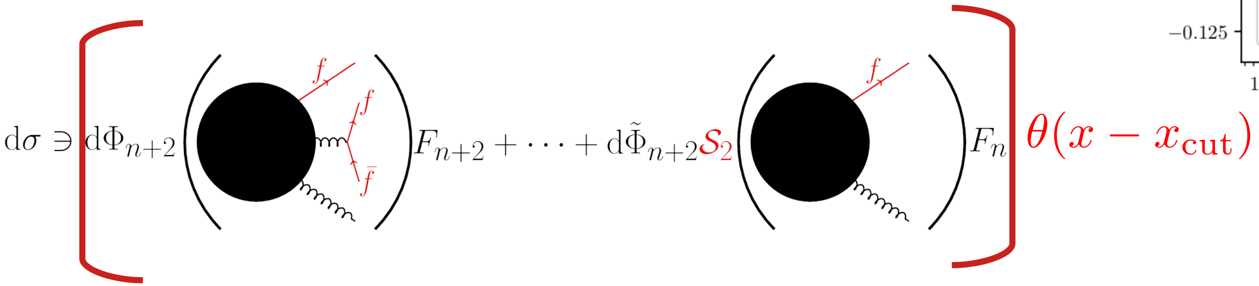
Tests of IR safety with NNLO FO computations

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





Remarks to the flavour anti-kT

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

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

- 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.

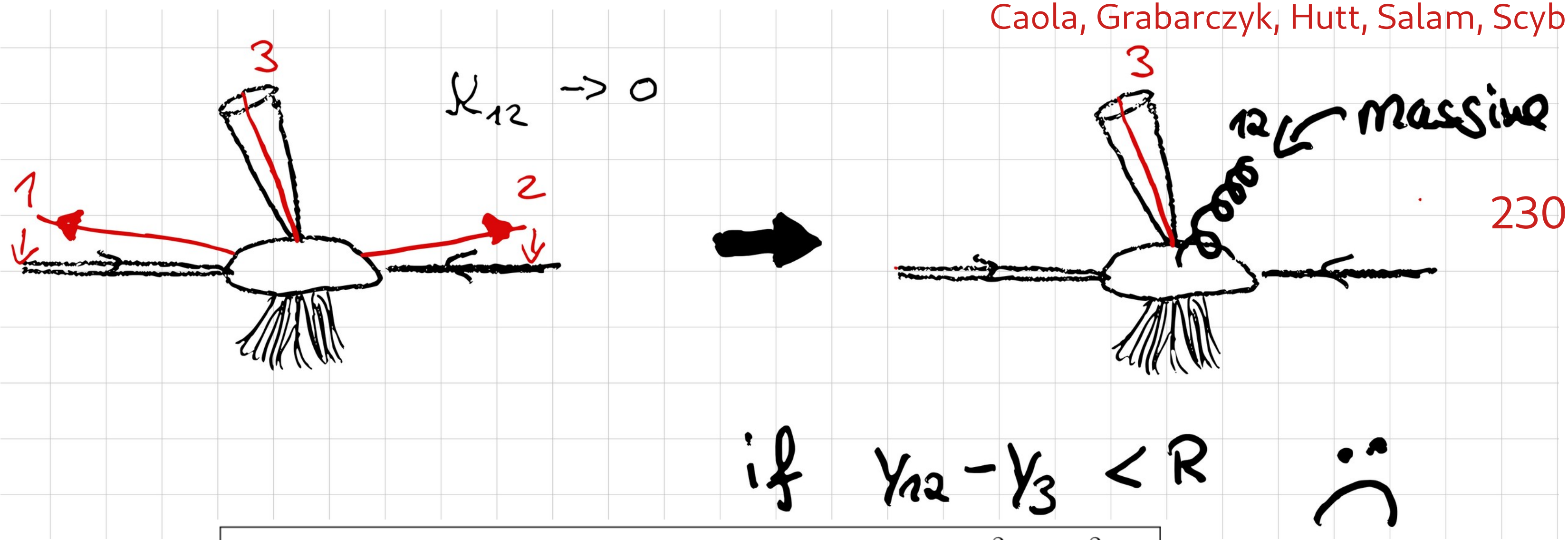
  → The choice impacts the clustering.

New developments...

Issue for double collinear limits wrt. to initial states

Many thanks to
Caola, Grabarczyk, Hutt, Salam, Scyboz,Thaler

2306.07314



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

Their proposal: $\mathcal{S}_{ij} \to \overline{\mathcal{S}}_{ij} = \mathcal{S}_{ij}\dfrac{\Omega_{ij}^2}{\Delta R_{ij}^2}$

$$\Omega_{ik}^2 \equiv 2\left[\frac{1}{\omega^2}\left(\cosh(\omega\Delta y_{ik}) - 1\right) - \left(\cos\Delta\phi_{ik} - 1\right)\right]$$

Solves also an issue at α_s^3

Comparisons

Les Houches 23 workshop aka FlavourFest :)

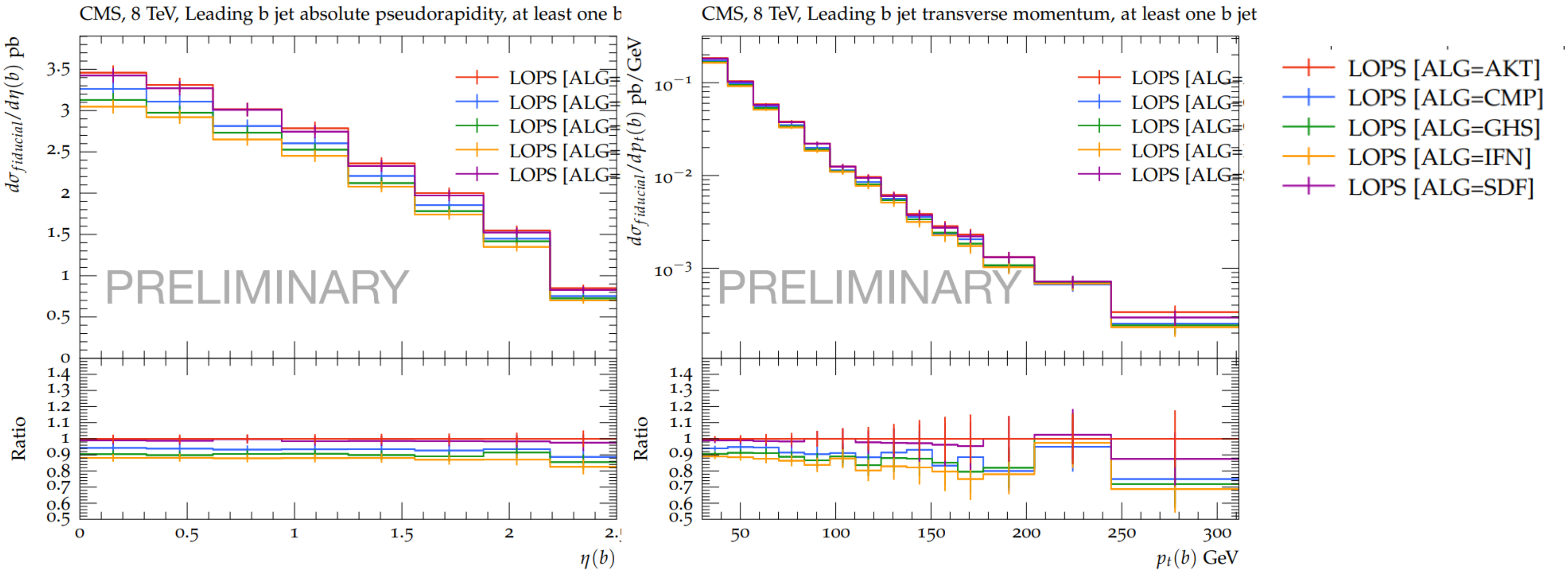
- CMPΩ: Flavour anti-kT (with fixed S_ij)
- SDF: Flavour with Soft-drop
- GHS: Flavour dressing → standard anti-kT + flavour assignment
- IFN: Flavour neutralisation

Implementation in FastJet package

Comparison with parton showers

Les Houches Jet Flavour WG

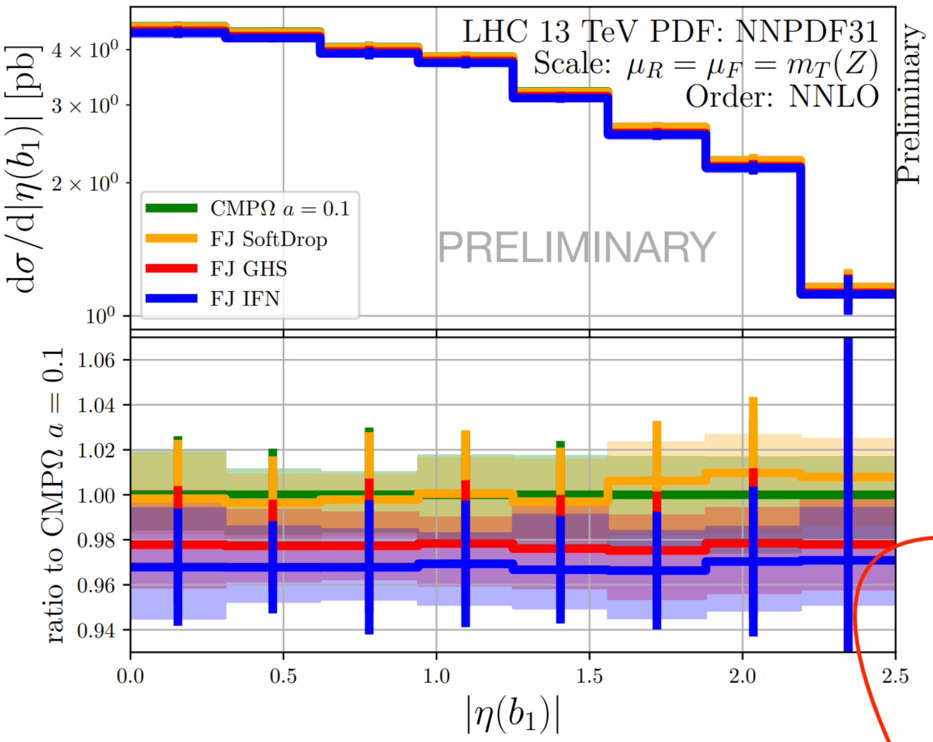
HERWIG LO PS

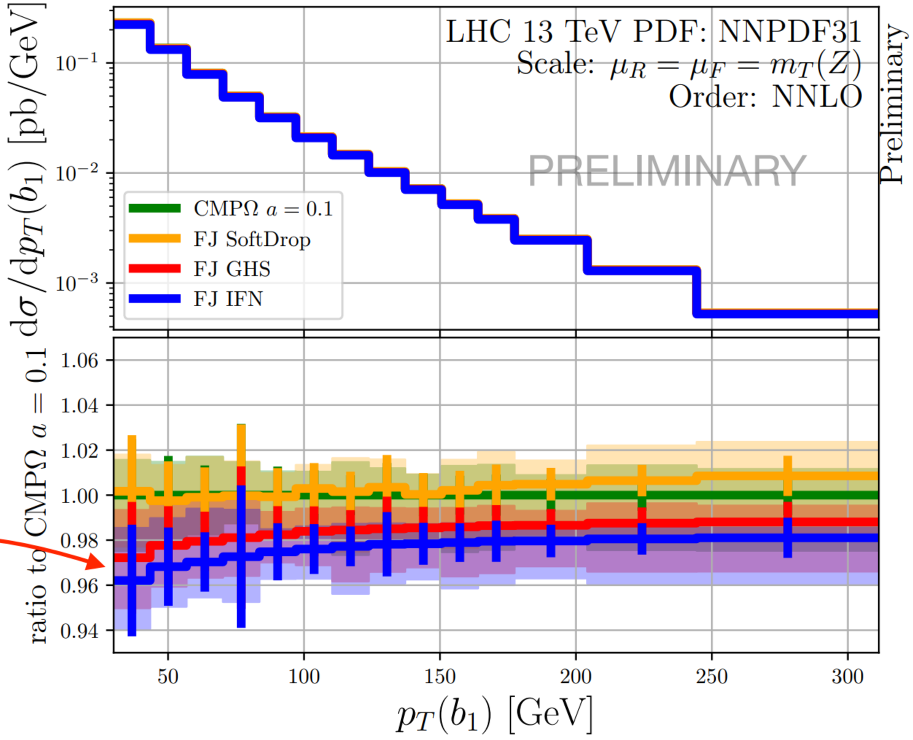


NNLO QCD comparisons

Calculations performed with sector-improved residue subtraction scheme
1408.2500 & 1907.12911

Les Houches Jet Flavour WG



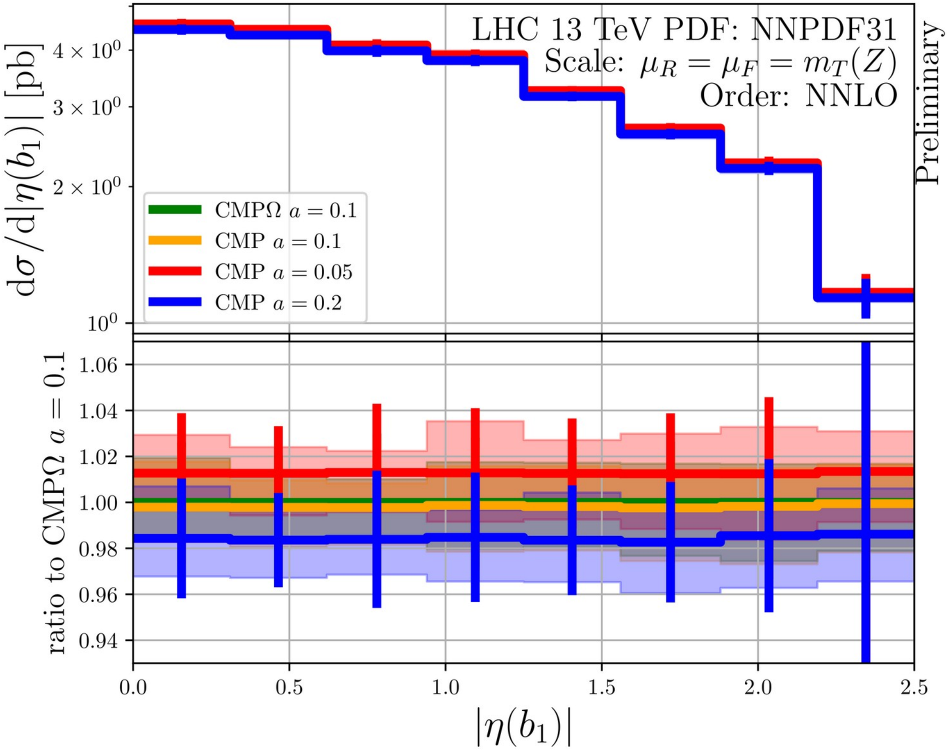


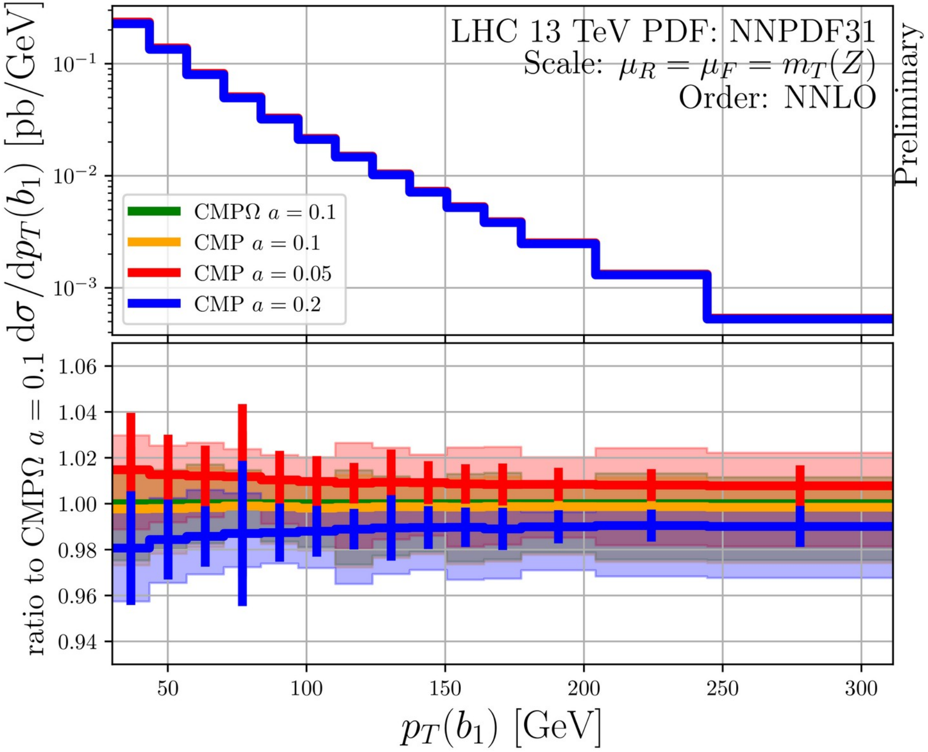
interesting shape difference at low p_t: it deserves further investigation!

Flavour anti-kT: impact of Ω_ij

Calculations performed with sector-improved residue subtraction scheme
1408.2500 & 1907.12911

Les Houches Jet Flavour WG

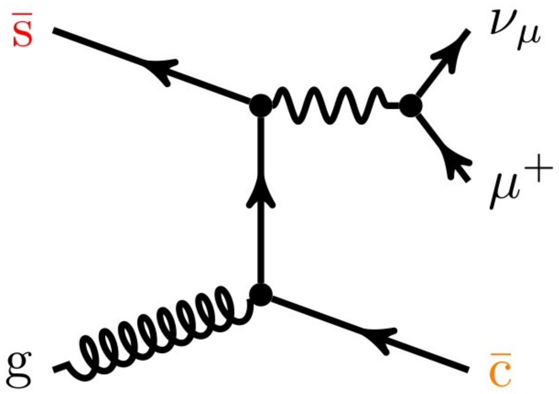




Negligible difference between CMPΩ and CMP

NNLO QCD Phenomenology with flavour anti-kT

W+charm production



A detailed investigation of W+c-jet at the LHC, Czakon, Mitov, Pellen, Poncelet 2212.00467

Simple phase space:

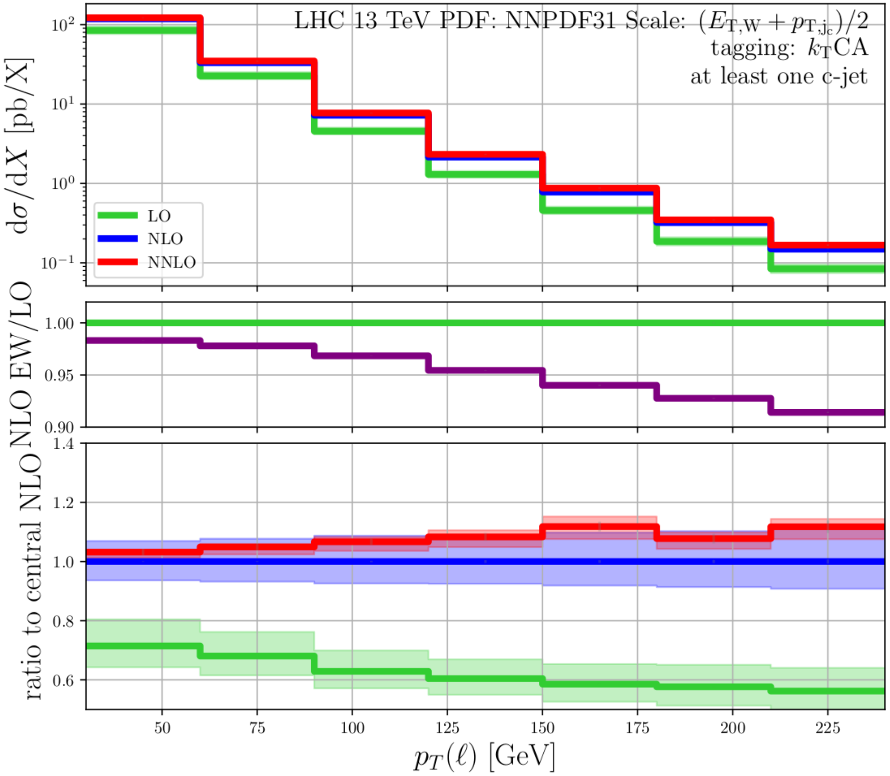
$$p_{T,\ell} > 30\,\text{GeV}, \qquad |\eta_\ell| < 2.5$$
$$p_{T,j_c} > 20\,\text{GeV}, \qquad |\eta_{j_c}| < 2.5$$

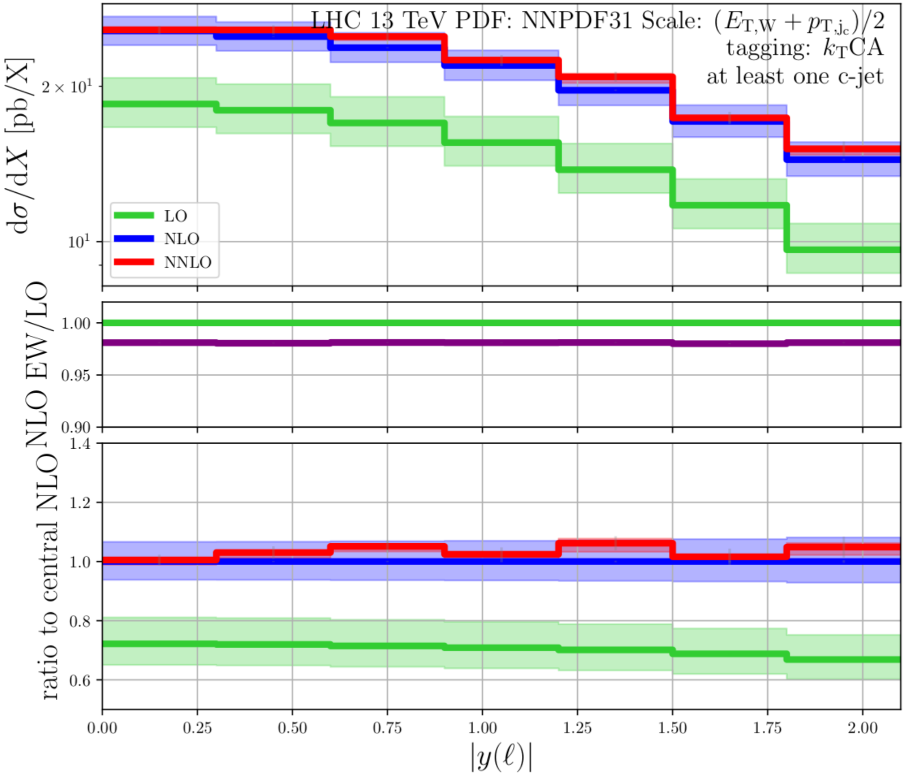
Various effects studied:
- EW corrections
- Off-diagonal CKM
- Jet-algorithms: fl. kT & fl. anti-kT

- Different tagging requirements:
  - The leading c-jet (based on its transverse momentum) is of OS type, no requirement on c-jet multiplicity,
  - One and only one c-jet is required, no requirement on c-jet charge,
  - One and only one c-jet of OS type,
  - One and only one c-jet of SS type, ← Sensitive to cc pairs from gluons splittings
  - OS–SS ("OS *minus* SS") cross section.

Perturbative corrections

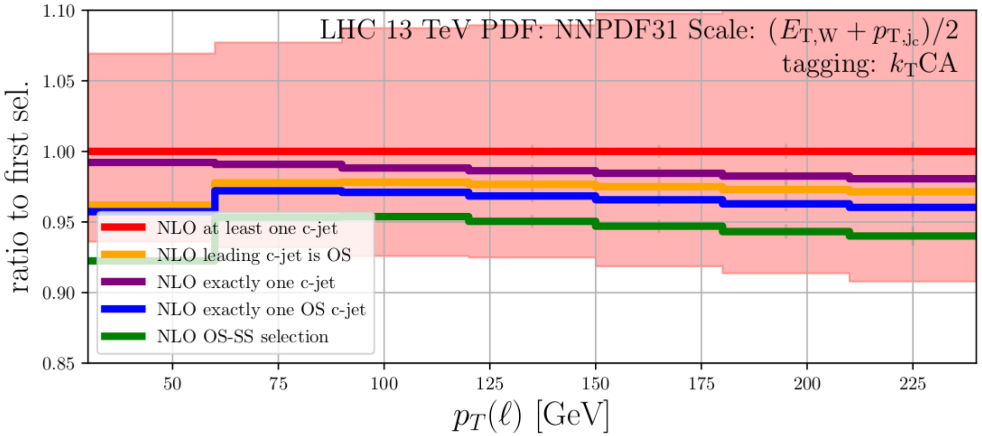
Flavour-kT, inclusive c-jet requirements



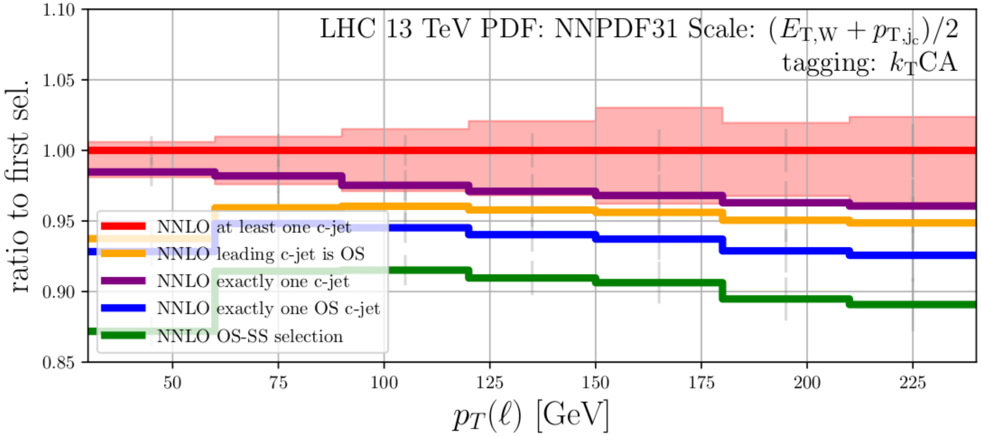


Different tagging requirements

NLO



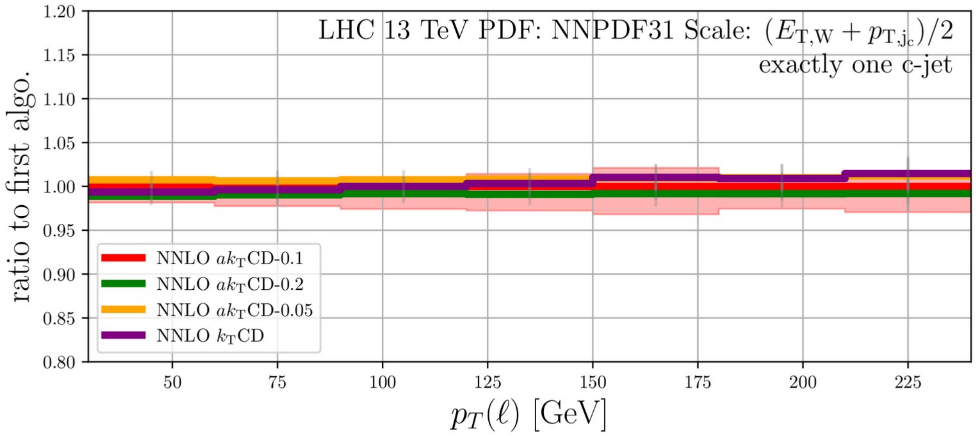
NNLO



Dependence on the jet algorithm

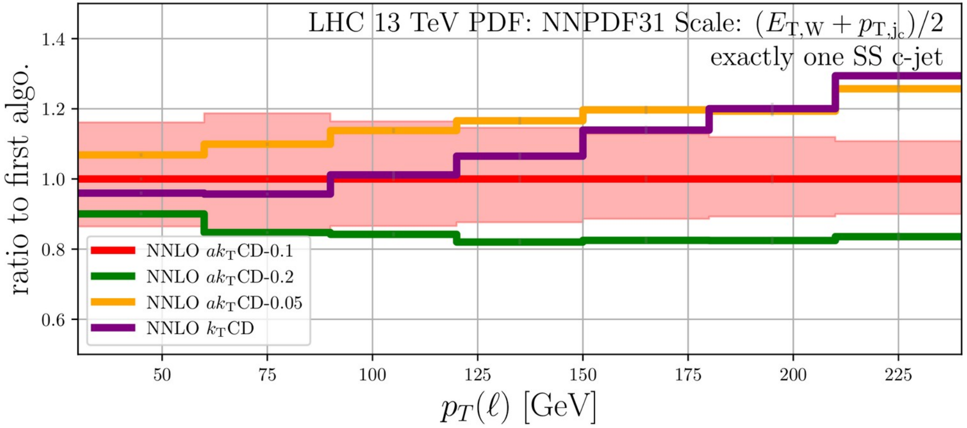
Exactly one c-jet requirement (OS+SS):

- 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



Comparison to CMS data

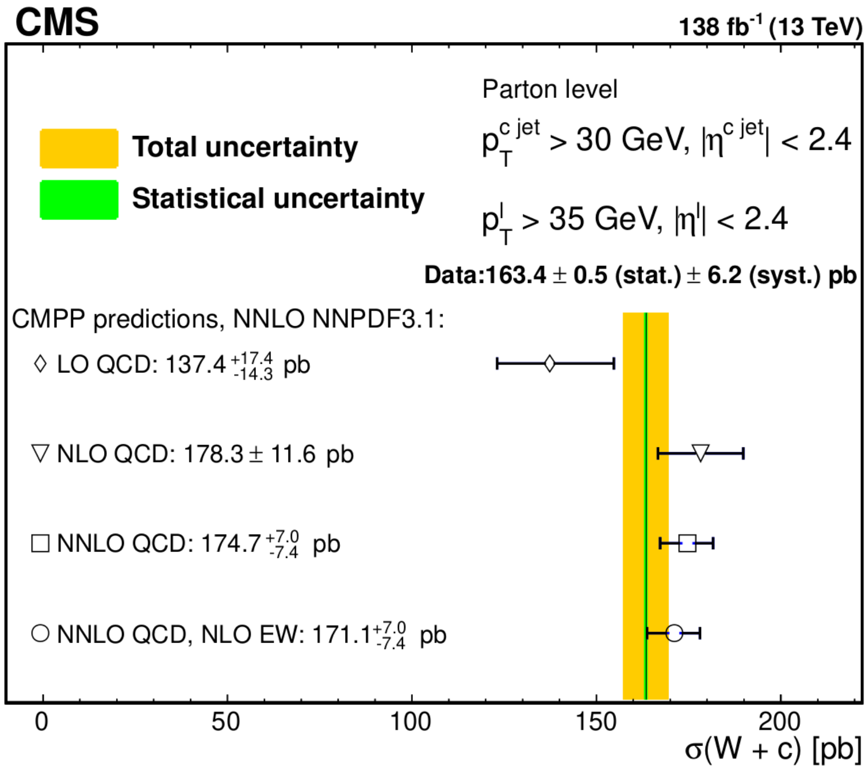
Measurement of the production cross section for a W boson in association with a charm quark in proton-proton collisions at Sqrt(s) = 13 TeV
CMS 2308.02285

Similar phasespace:

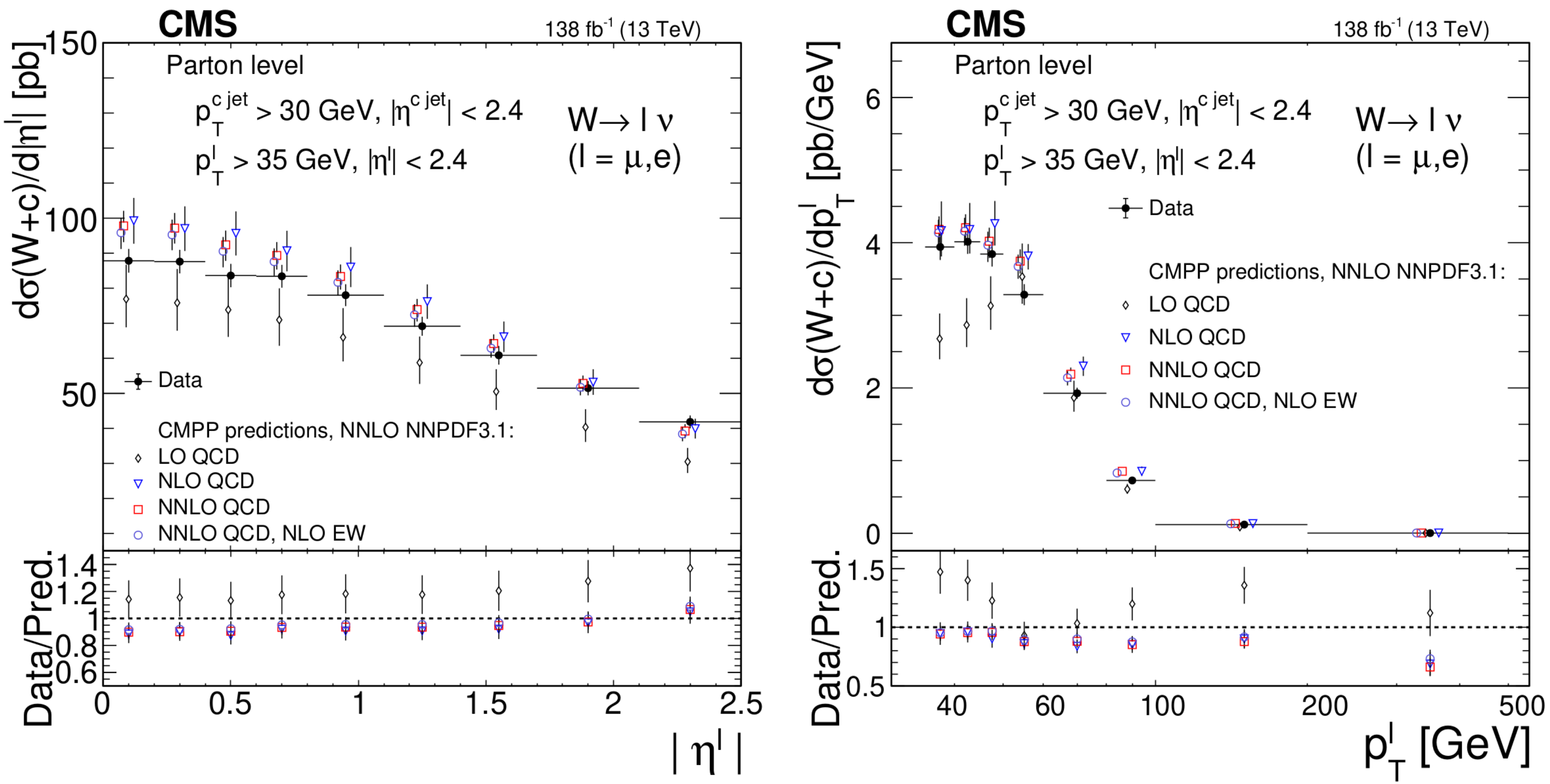
$$p_T^\ell > 35\,\text{GeV},\ |\eta^\ell| < 2.4,\ p_T^{\text{c jet}} > 30\,\text{GeV}$$

$$|\eta^{\text{c jet}}| < 2.4,\ \Delta R(\text{jet},\ell) > 0.4$$

Measurement of OS – SS cross-section unfolded to parton-level
→ hadronisation and fragmentation corr. ~ 10%

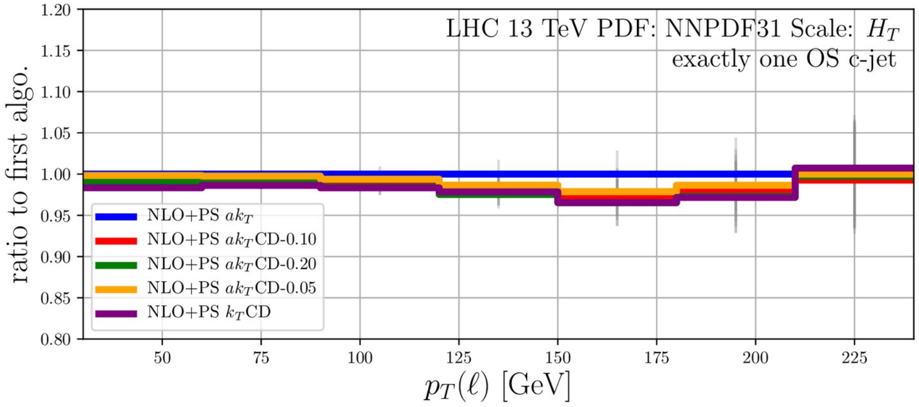


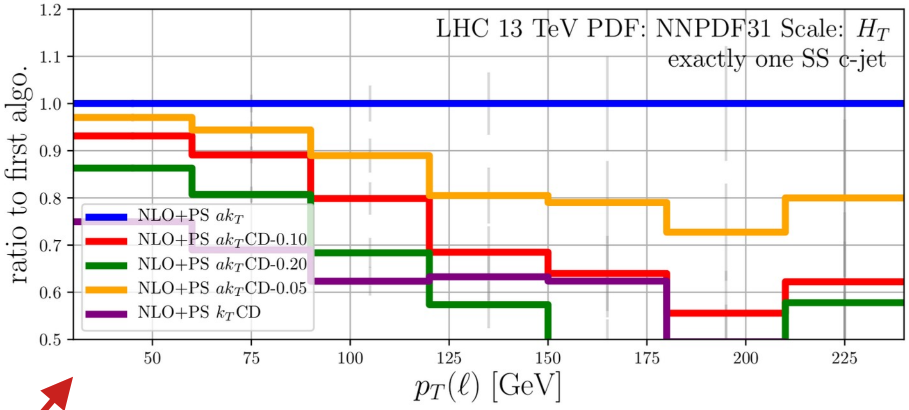
Comparison to CMS data



Unfolding corrections: anti-kT vs. fl. anti-kT

NLO+PS (fl. anti-kT) / NLO+PS (anti-kT)





SS ~2-5% of OS
→ OS – SS unfolding corrections < 2%

Summary

Take home messages

1) Flavoured Jets require modified jet algorithms to avoid IR safety/sensitivity issues

2) Solutions exists for anti-kT jets and are implemented in FastJet:
   SDF, CMP, GHS, IFN, …
   → phenomenological applications @ NNLO QCD

3) Still open question regarding the best way of comparing state-of-the-art predictions and measurements:
   → Unfolding? How do the different algorithms compare?
   → Which flavoured jet algorithm has the most favourable properties?

Backup

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

A detailed investigation of W+c-jet at the LHC,
Czakon, Mitov, Pellen, Poncelet 2212.00467

NNLO QCD predictions for Z-boson production in association with a charm jet within the LHCb fiducial region
Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, Stagnitto 2302.12844

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

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)

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

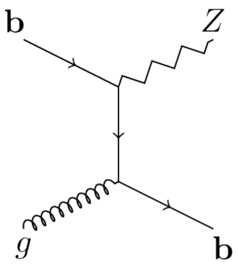
- CMS measurement @ 8 TeV

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

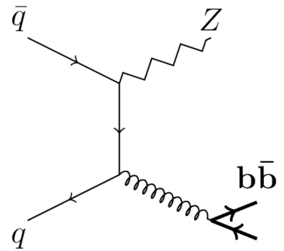
→ Ideal testing ground for flavour anti-kT

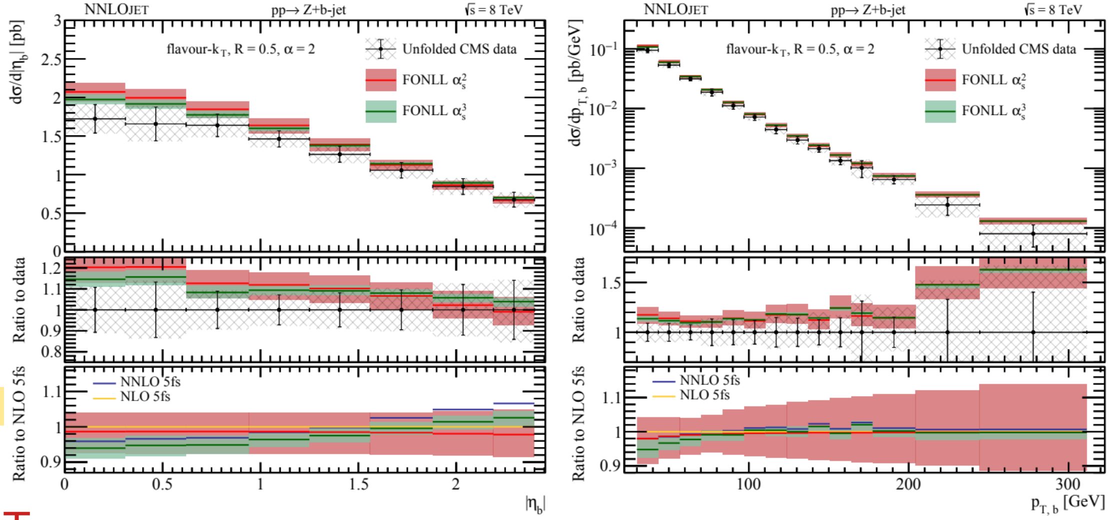
pp → Z(ll) + b-jet

5fs:



4fs:

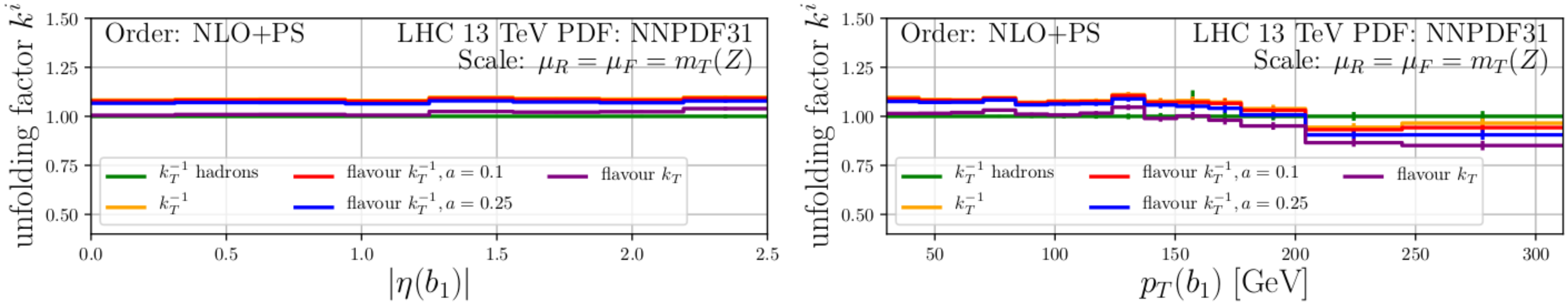




Bin-by-bin unfolding

Estimation of hadronisation and experimental tagging corrections
→ NLO + PS (Madraph+Pythia8)

Unfolding factor = NLO+PS (had = Off) / NLO+PS (had = On)



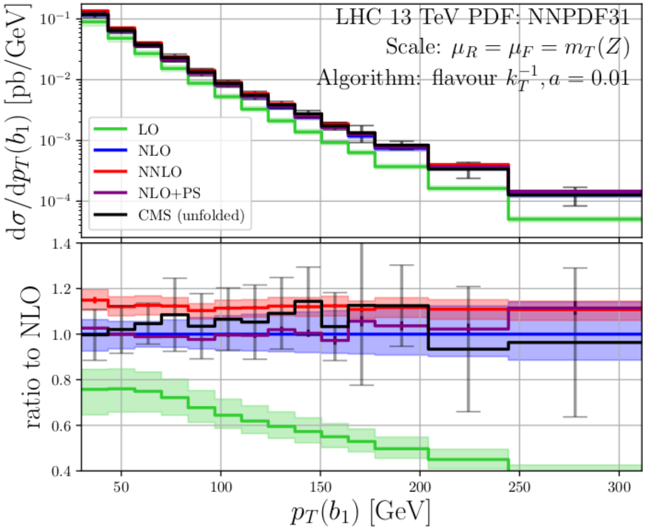
Z+b-jet Phenomenology: Tunable parameter

Benchmark process: pp → Z(ll) + b-jet

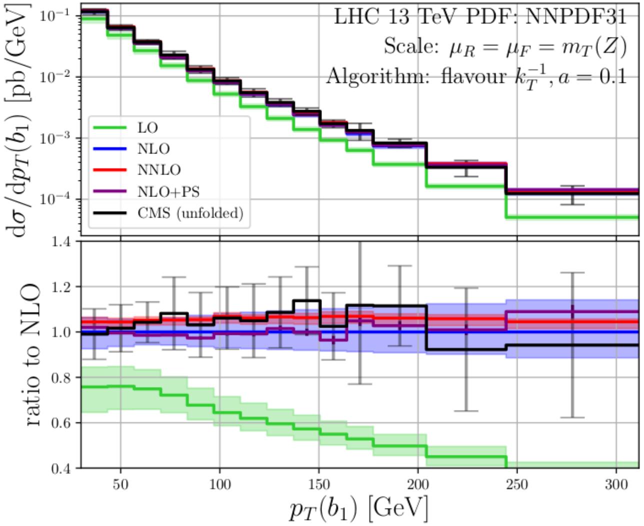
Tunable parameter a:

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

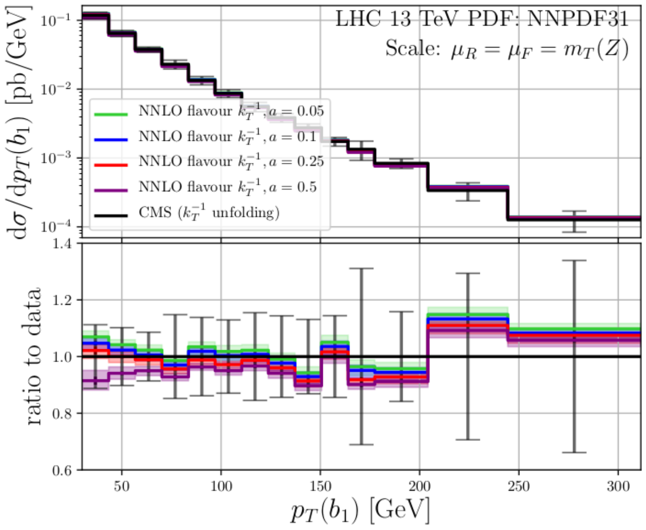
Flavour anti-kT (a=0.01):



Flavour anti-kT (a=0.1):

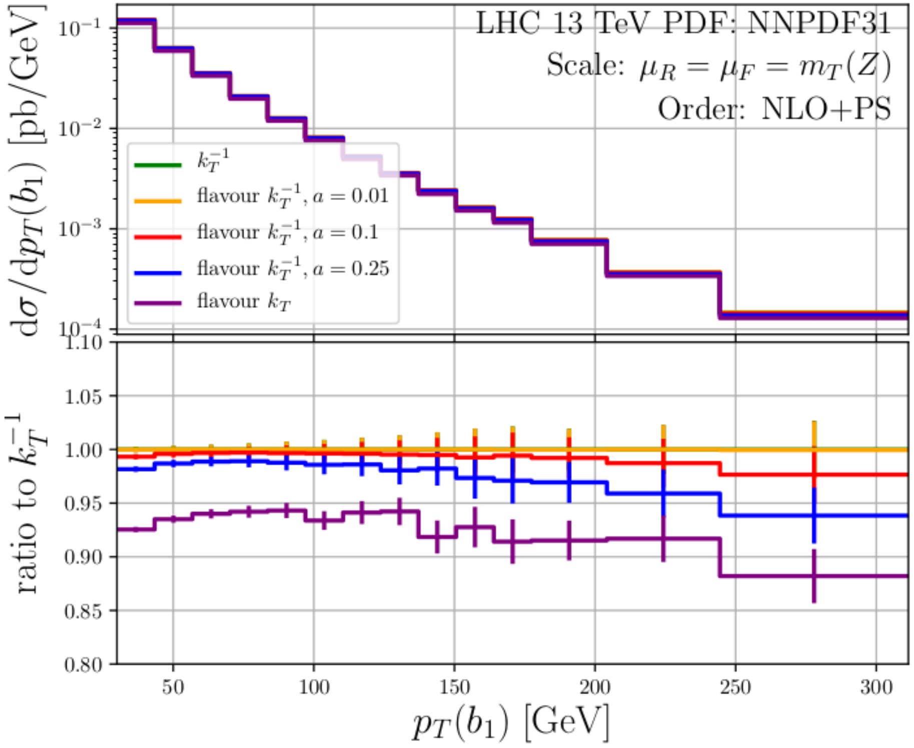


Comparison of different parameter a to data:



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
- Larger a: Larger modification of clustering

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