High-precision calculations for W+charm at the LHC

Rene Poncelet

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

THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

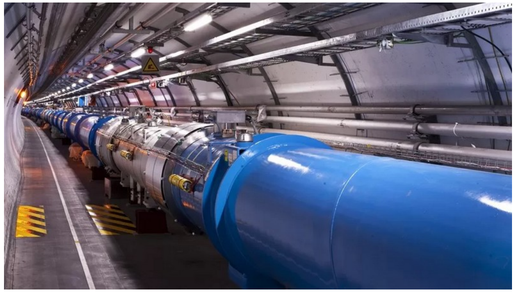
Presented research received funding from:
LEVERHULME TRUST
Isaac Newton Trust

Outline

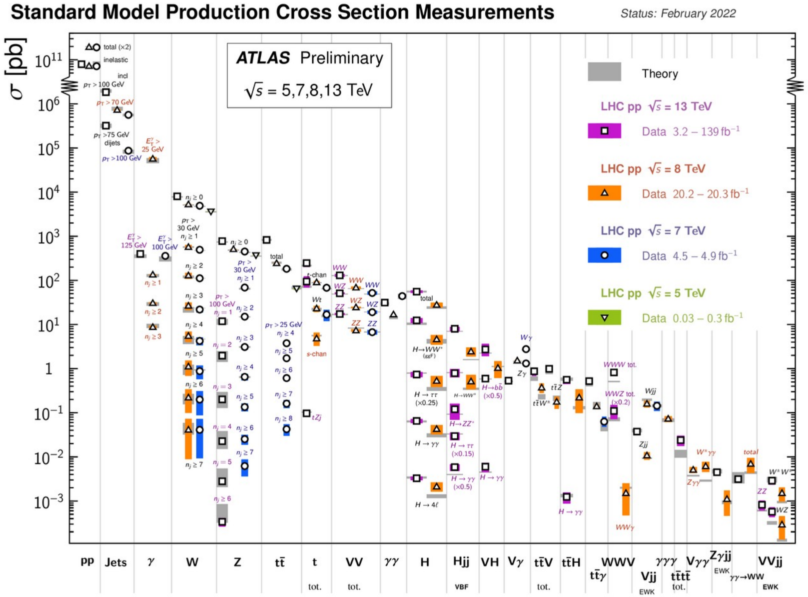
- Phenomenological motivation
  - Vector bosons + flavoured jets
  - Infrared safety/sensitivity
- NNLO QCD Phenomenology with W+c-jets
- Flavoured (anti-kT) jet algorithms
  - Definition & Comparison

What are the fundamental building blocks of matter?

Scattering experiments

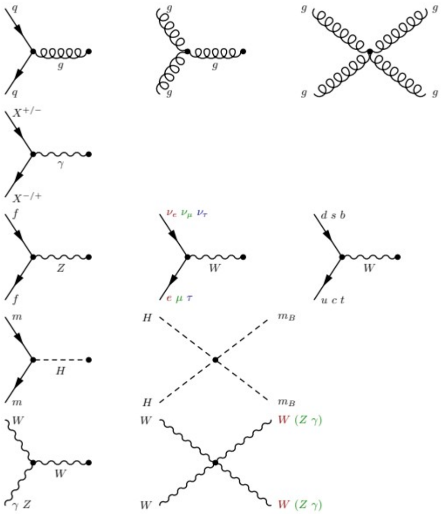


Credit: CERN



Credit: ATLAS

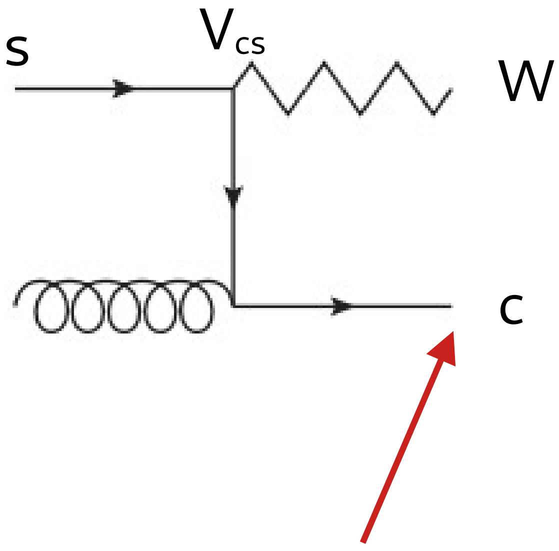
Theory/Model



Credit: Jack Lindon, CERN

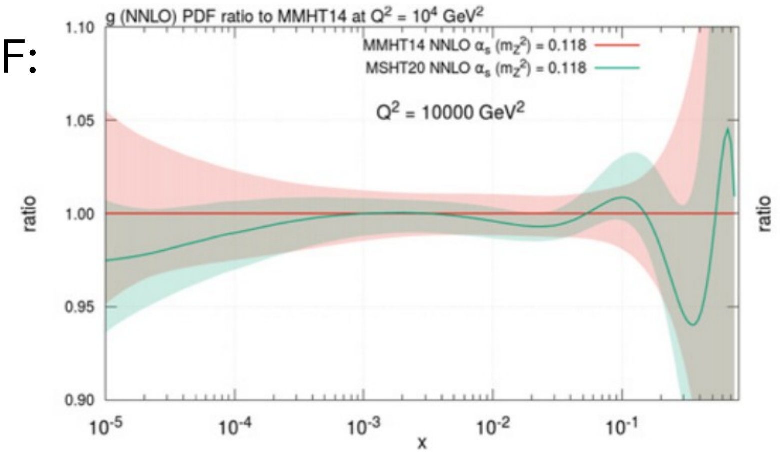
Looking into more exclusive observables (“flavoured jets”) with more precision (“higher order corrections”).

W + charm jet

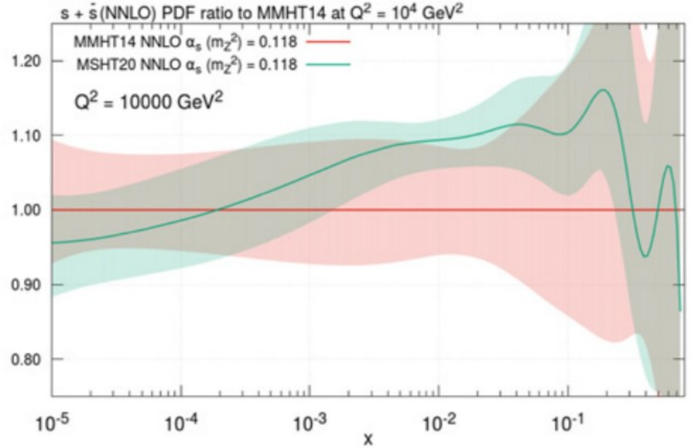


Tagging of charm jet
to increase sensitivity
to strange quark PDF

gluon PDF:



s+s PDF:



PDF4LHC22 [2203.05506]

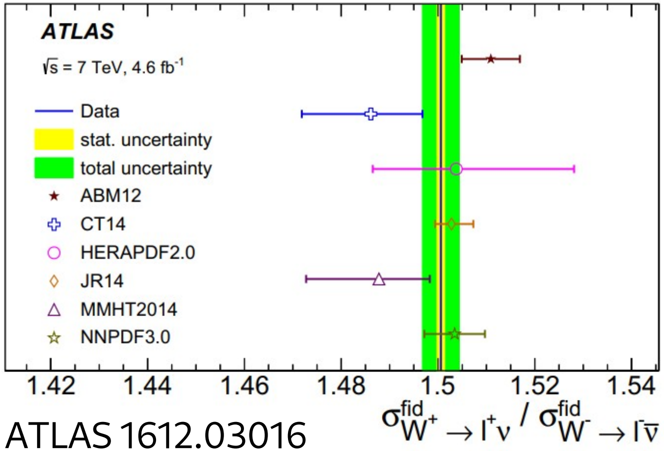
W + charm jet

Could solve long-standing puzzle:

Strange – anti – strange asymmetry

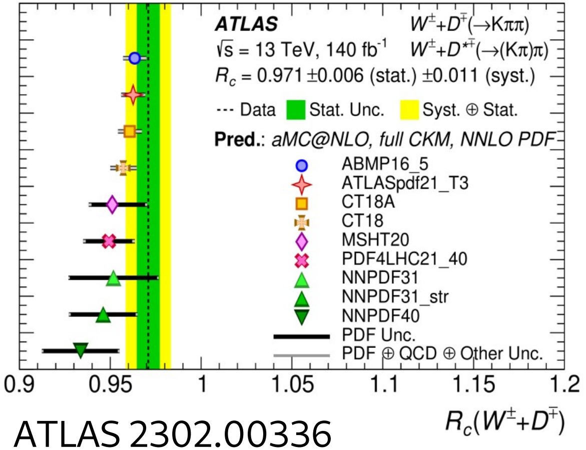
- pQCD: Three loop SM prediction q→ q' ≠ q → $\bar{q}$' small effect $\langle x(s-\bar{s})\rangle \sim 10^{-4}$
- Size of non-perturbative effect unknown

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



ATLAS 1612.03016

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

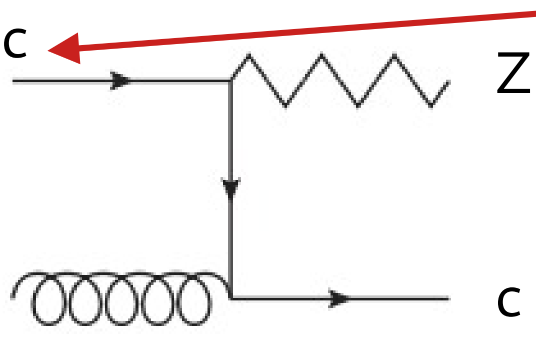


ATLAS 2302.00336

All at NLO QCD

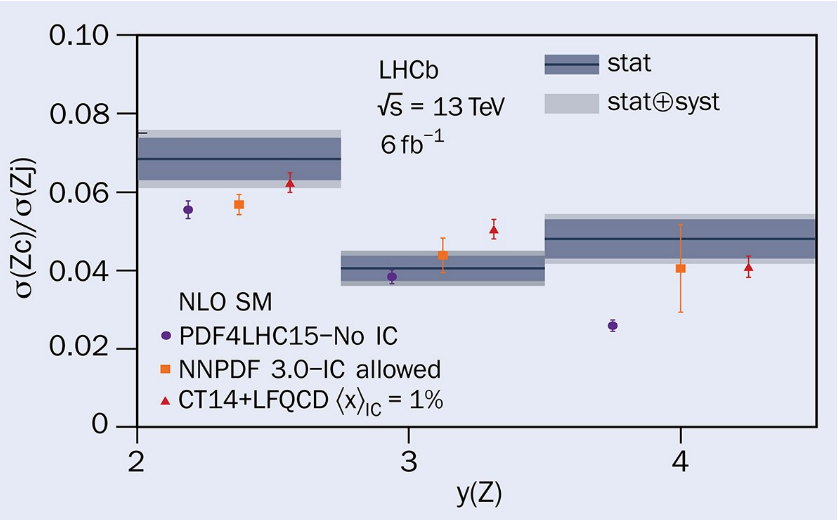
higher order corrections needed to fit properly the PDF

Z + charm jet



Similar to W+charm but for charm PDF

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



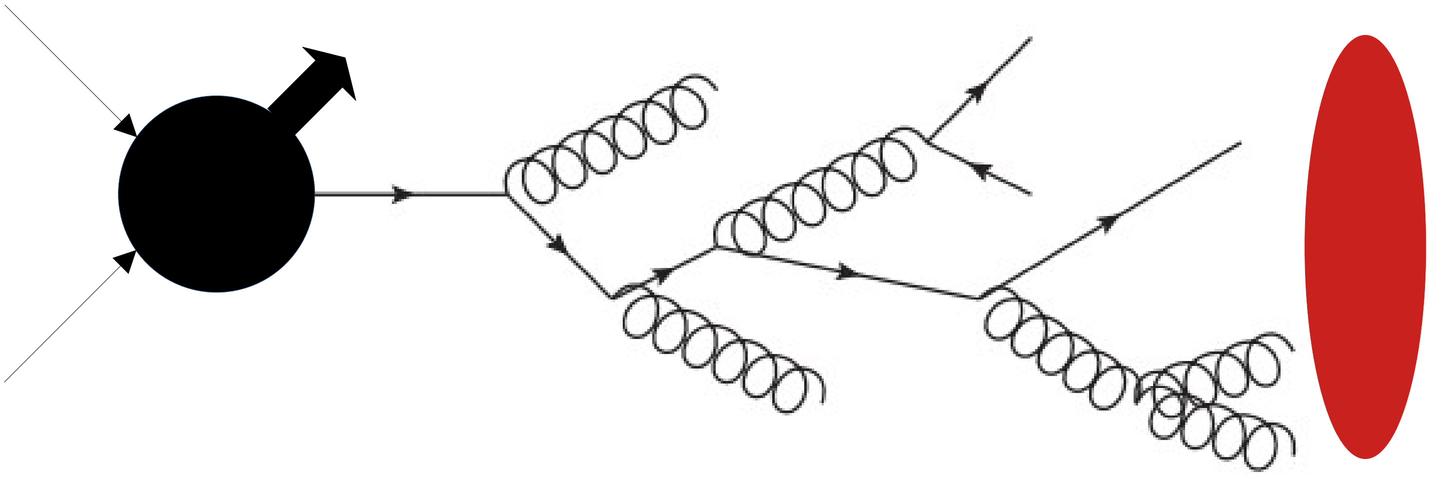
CERN/LHCb 2109.08084

Flavoured jets are everywhere

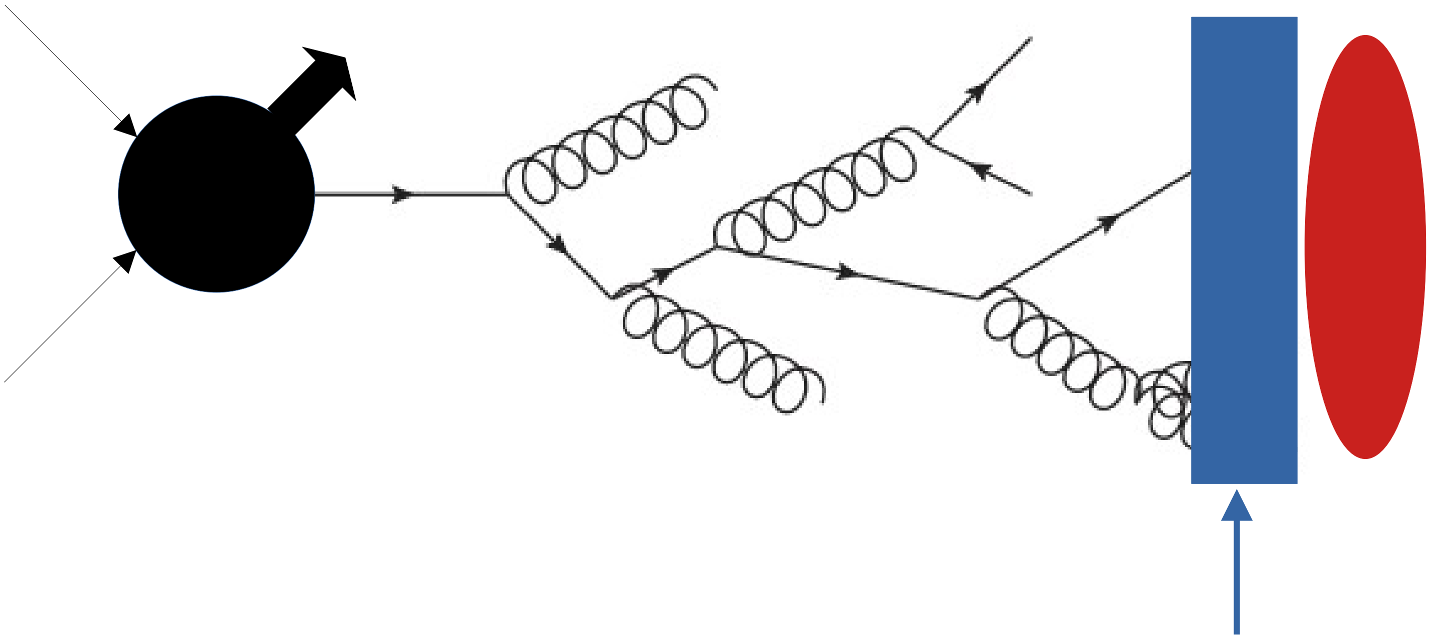
V+heavy-flavour as benchmark for flavour tagging

- Heavy-quark evolution: fragmentation and hadronisation
- IR safety/sensitivity
- Flavoured jets as signature:
  - Top-quarks
  - Vector+heavy flavour: pp → W/Z/A + c/b
  - Higgs → charm, Higgs → bottom
  - New physics searches

Partonic jet evolution

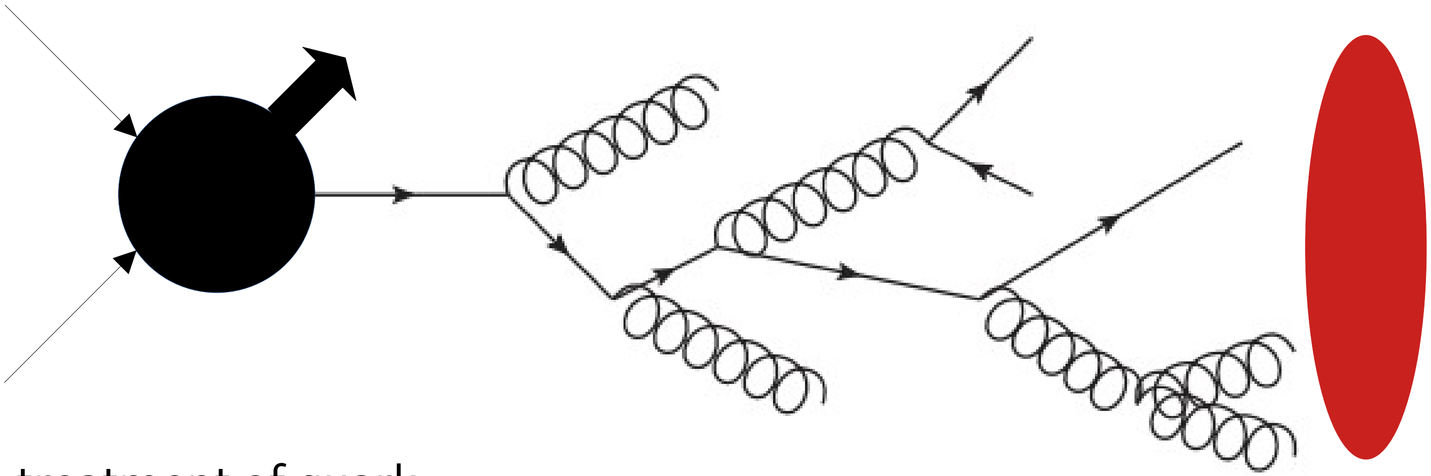


Partonic jet evolution



- Fragmentation/Hadronisation
- Partonic jet flavour: Quark-Hadron Duality
- Heavy B/D – hadron's long life time: experiment signature (displaced vertices) → distinguishable from "light" jets

Partonic jet evolution

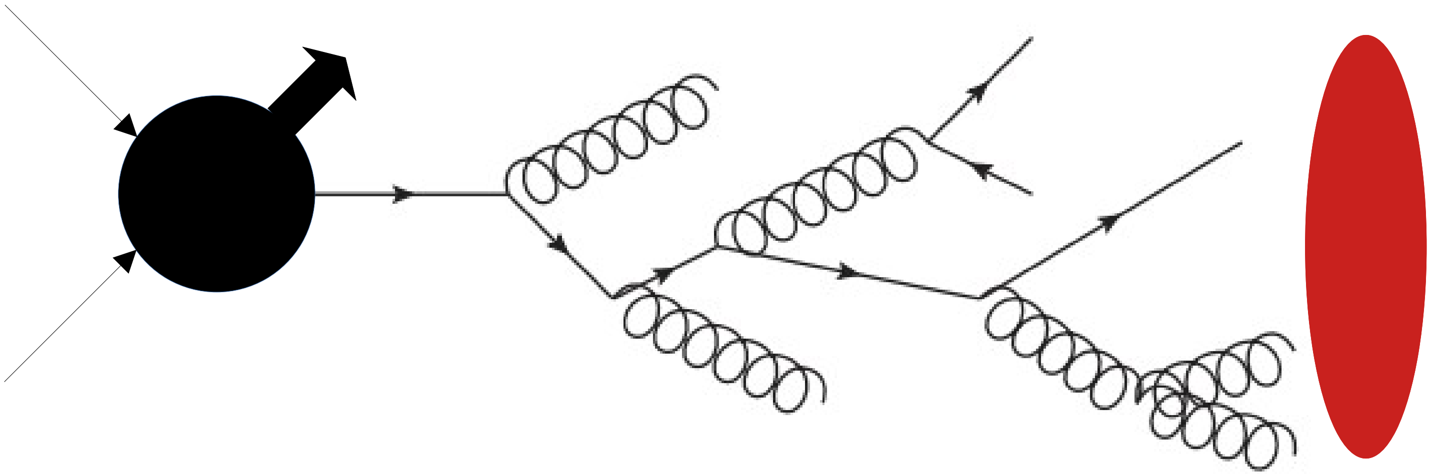


Massive treatment of quark

- Mass acts as IR regulator → no IR divergences from collinear splitting
- Price to pay: log(pT/m), how to treat PDFs (high Q^2 process due to V-boson)?
  → Resummation for reliable predictions
  → Parton-showers (at low accuracy)
- But Higher order calculations more difficult
  → some applications (like PDF fits) need fixed order pQCD at higher orders

} NLO+PS

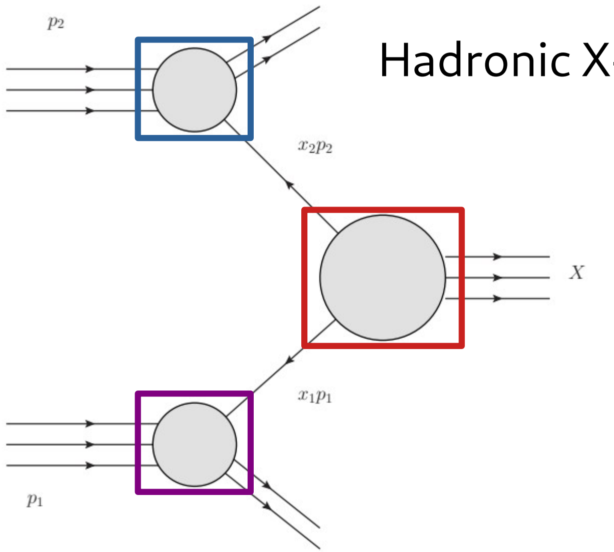
Partonic jet evolution



High transverse momentum → massless quarks

- Collinear (mass) divergences absorbed by renormalisation
- Consistent treatment with PDFs (high Q^2 → c/b quarks in DGLAP)
- Bonus: higher order calculations easier → NNLO QCD de-facto standard
- BUT: IR-safety more demanding due to collinear and soft flavoured particles

Hadronic cross section in collinear factorization – NNLO QCD



Hadronic X-section: $\sigma_{h_1h_2\to X} = \sum_{ij}\int_0^1\int_0^1 \mathrm{d}x_1\mathrm{d}x_2\phi_{i,h_1}(x_1,\mu_F^2)\phi_{j/h_2}(x_2,\mu_F^2)\hat{\sigma}_{ij\to X}(\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2)$

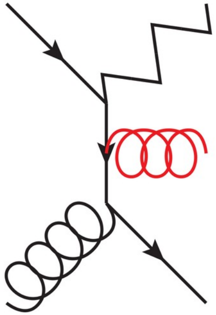
Parton distribution functions

Perturbative expansion of partonic cross section:

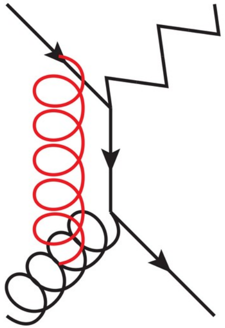
$$\hat{\sigma}_{ab\to X} = \hat{\sigma}^{(0)}_{ab\to X} + \hat{\sigma}^{(1)}_{ab\to X} + \hat{\sigma}^{(2)}_{ab\to X} + \mathcal{O}(\alpha_s^3)$$

The NLO bit: $\hat{\sigma}^{(1)}_{ab} = \hat{\sigma}^{\mathrm{R}}_{ab} + \hat{\sigma}^{\mathrm{V}}_{ab} + \hat{\sigma}^{\mathrm{C}}_{ab}$

Real radiation



Virtual correction



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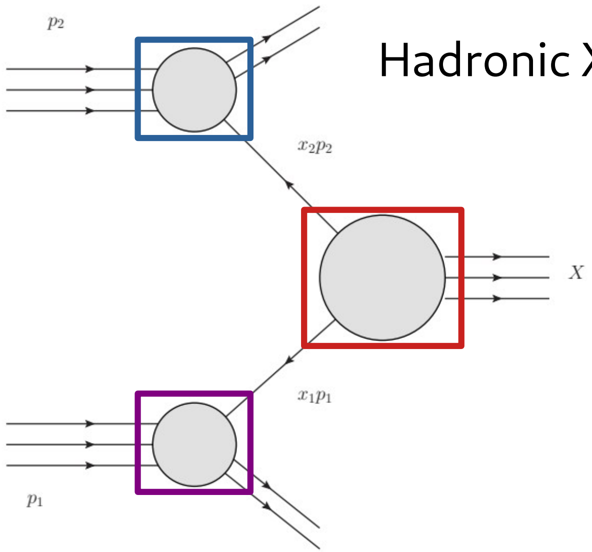

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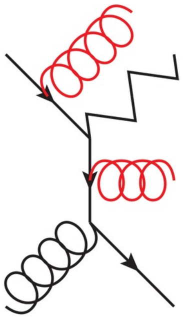
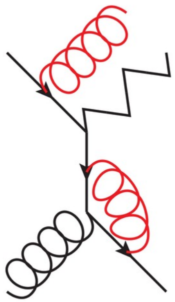
The NNLO bit: $\hat{\sigma}^{(2)}_{ab} = \hat{\sigma}^{\mathrm{RR}}_{ab} + \hat{\sigma}^{\mathrm{RV}}_{ab} + \hat{\sigma}^{\mathrm{VV}}_{ab} + \hat{\sigma}^{\mathrm{C2}}_{ab} + \hat{\sigma}^{\mathrm{C1}}_{ab}$

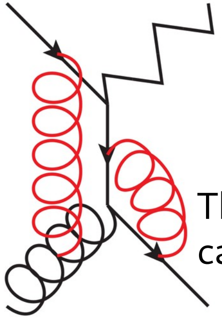
Double real radiation



Real/Virtual correction

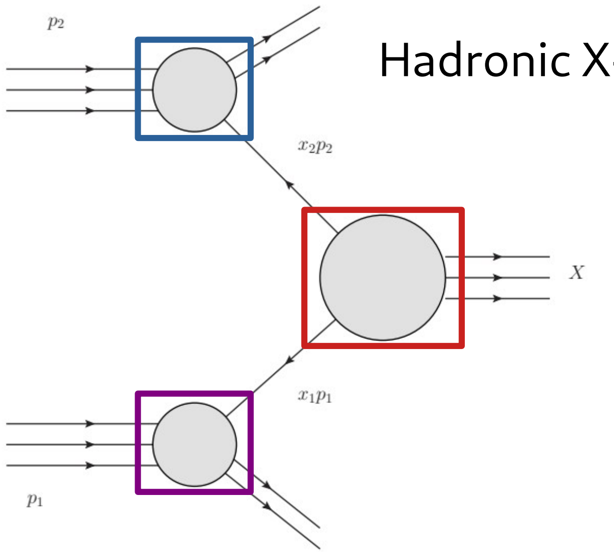


Double virtual corrections



These make massive calculations hard!

Hadronic cross section in collinear factorization – NNLO QCD



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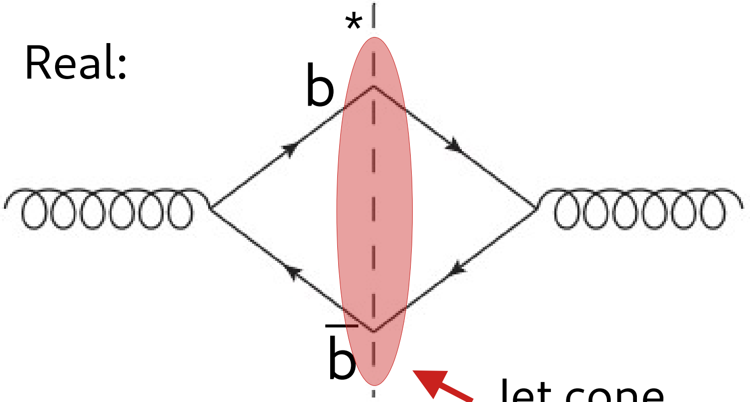
Calculations performed with sector-improved residue subtraction scheme
1408.2500 & 1907.12911

IR safety issues starting from NLO QCD

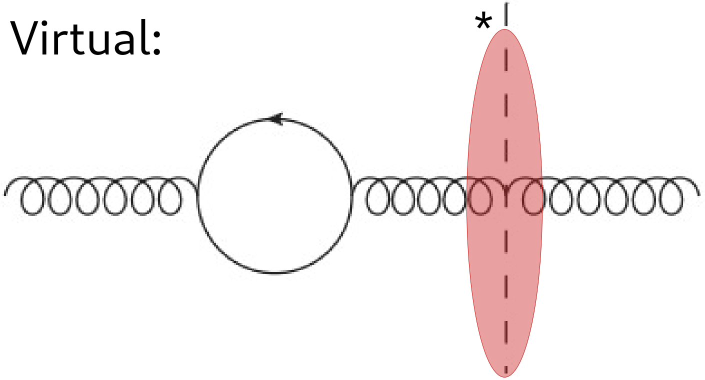
Massless QCD: Cancellation of IR divergences between real and virtual corrections

Real:



+

Virtual:



= IR finite

Flavoured?
(Keeping in mind quark-hadron duality)

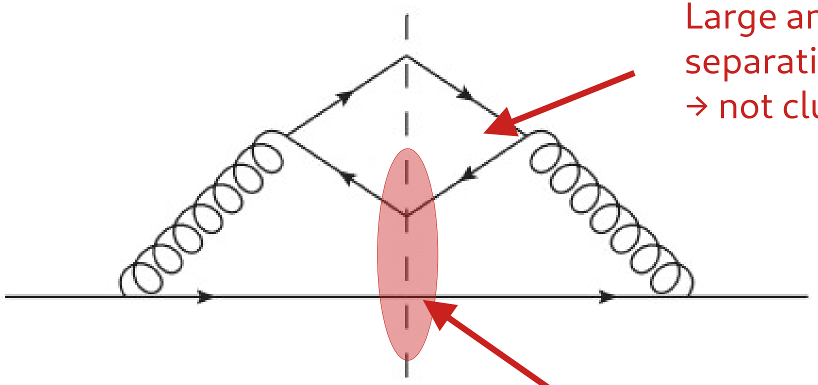
Definitively not flavoured!

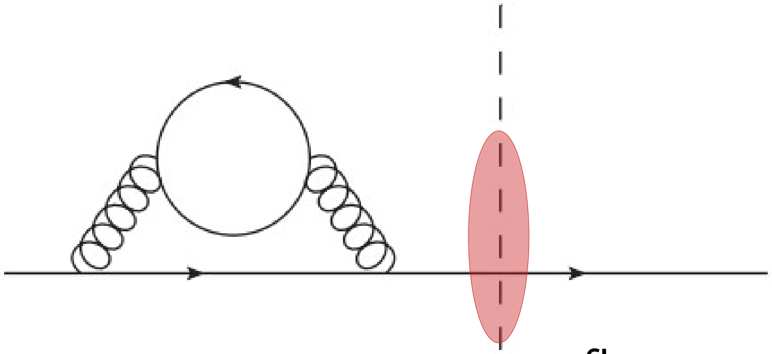
$b\,\bar{b}$ has to count as a gluon/light jet!

*: cut symbolises the "measured" final state

IR safety issues starting from NNLO QCD

Double soft limit of quark pairs





- These double soft splitting need to be captured
- Requires to interleave 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:

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

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

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

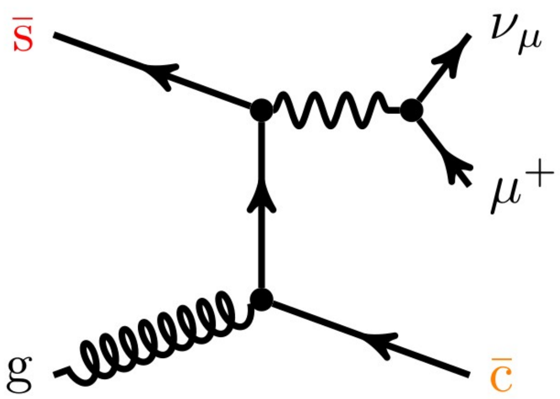
Short summary

- 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?

NNLO QCD W+c-jet

W+charm production



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

Simple phase space:

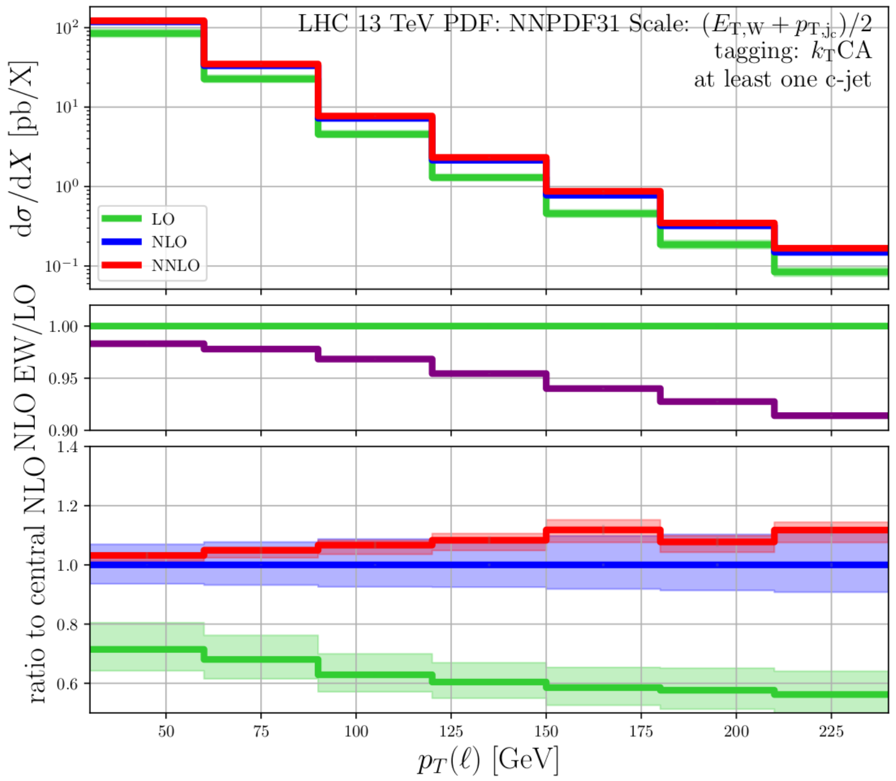
$$p_{T,\ell} > 30\,\text{GeV}, \qquad |\eta_\ell| < 2.5$$
$$p_{T,j_c} > 20\,\text{GeV}, \qquad |\eta_{j_c}| < 2.5$$

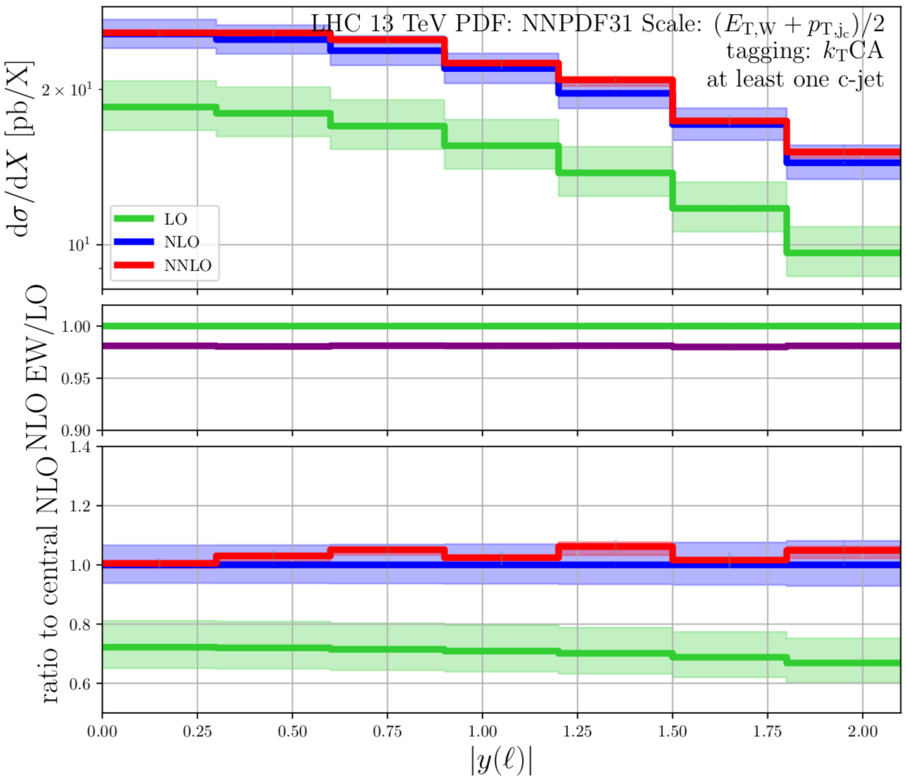
Various effects studied:
- EW corrections
- Off-diagonal CKM
- Jet-algorithms: fl. kT & fl. anti-kT

- 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 $c\bar{c}$ pairs from gluon splittings
  - OS–SS ("OS *minus* SS") cross section.

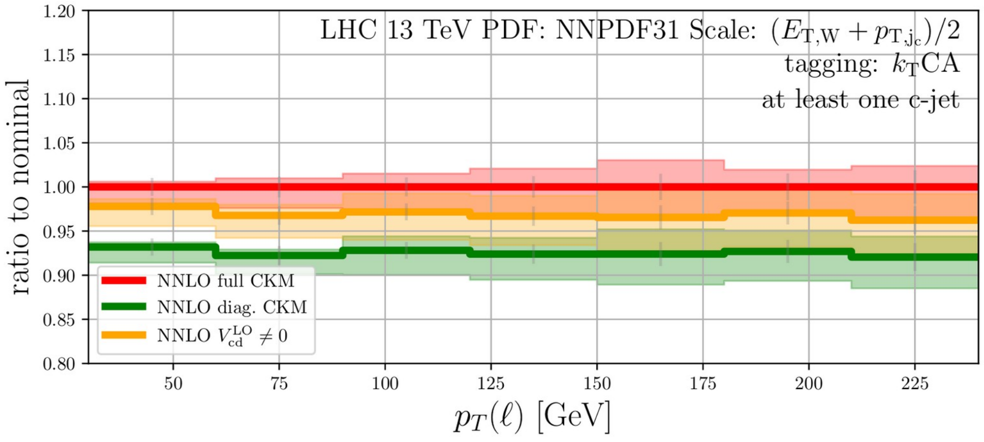
Perturbative corrections

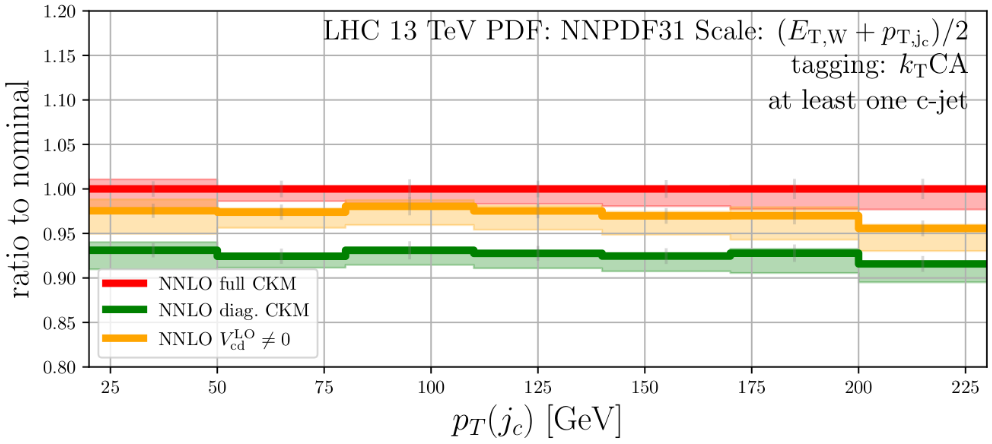
Flavour-kT, inclusive c-jet requirements





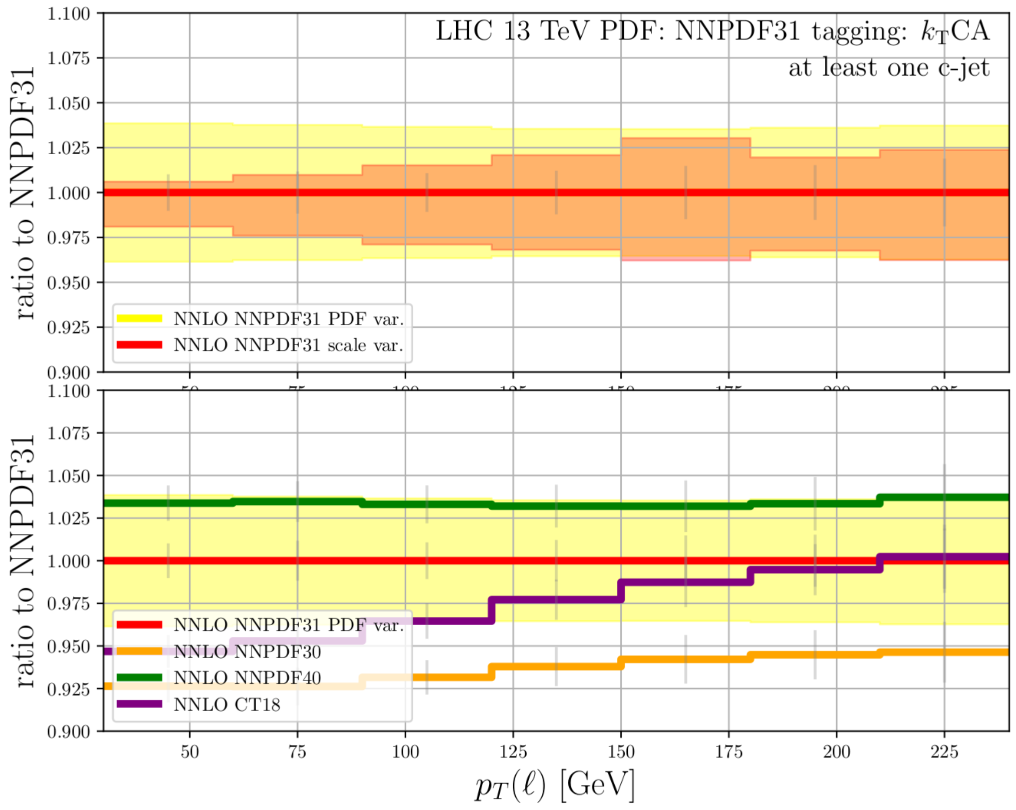
Off-diagonal CKM





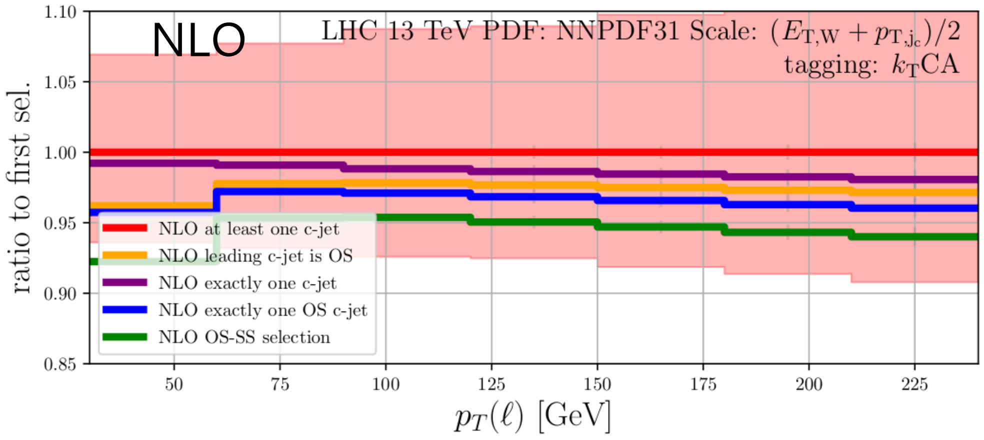
- Full CKM effects through NNLO QCD
- Sizeable with respect NNLO corrections!
- LO V_{cd} captures most of the full CKM

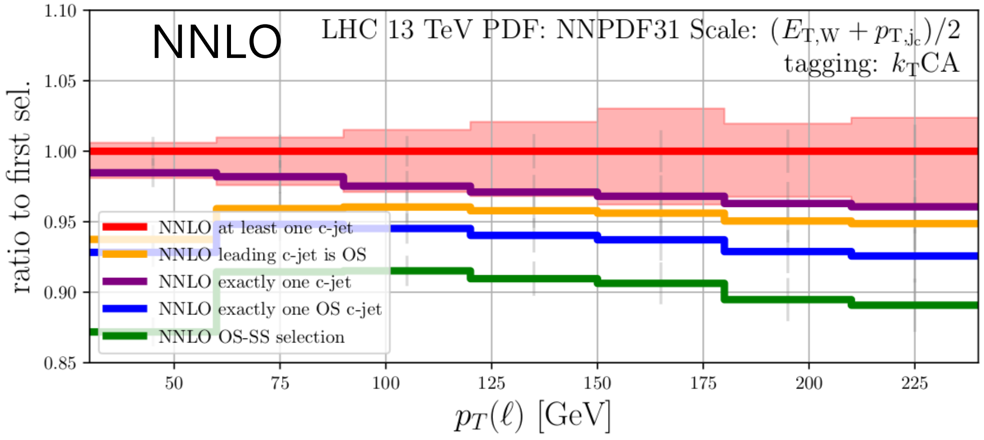
PDF dependence



- PDF uncertainty: ~5%
- PDF model variations: ~5-8%

Different tagging requirements





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- OS–SS ("OS *minus* SS") cross section.

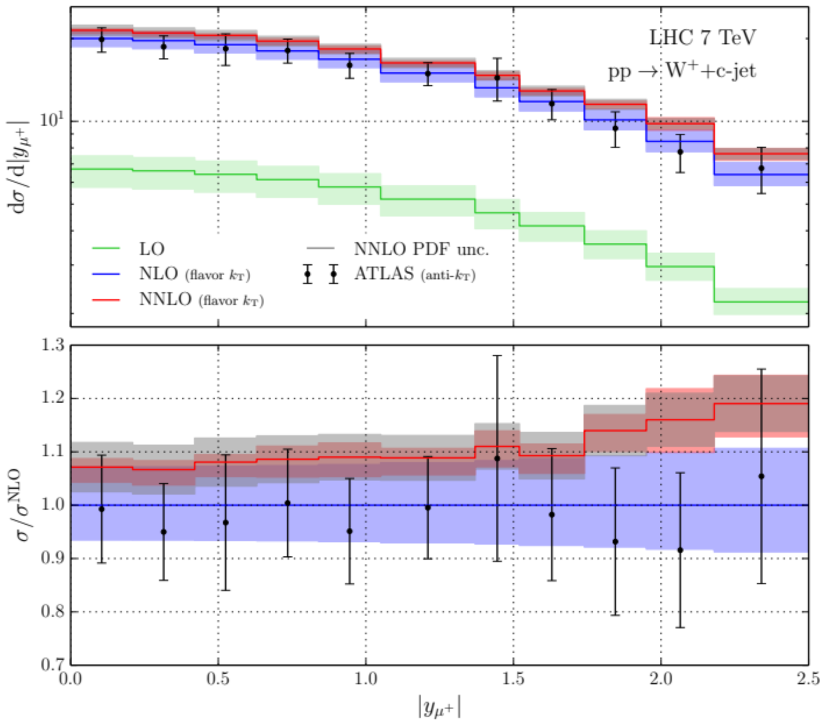
W+c-jet with flavour kT at NNLO QCD

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

NNLO QCD 7 TeV results:

- 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



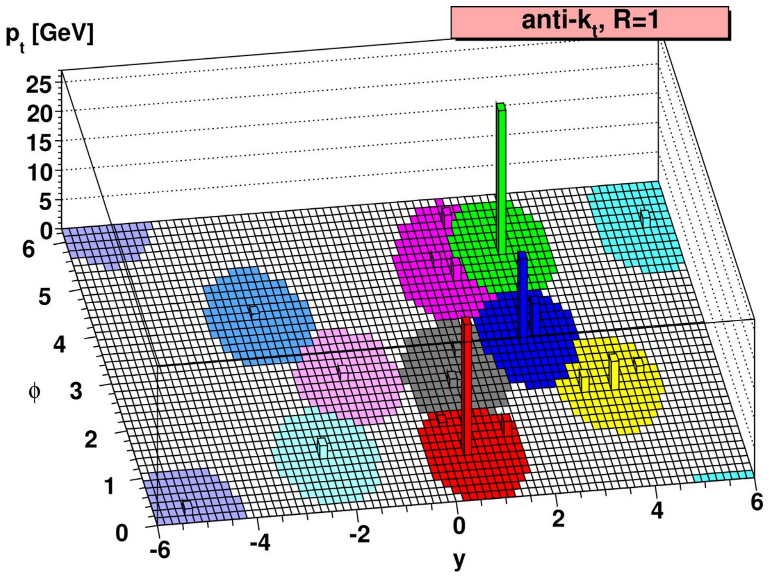
Flavour anti-kT?

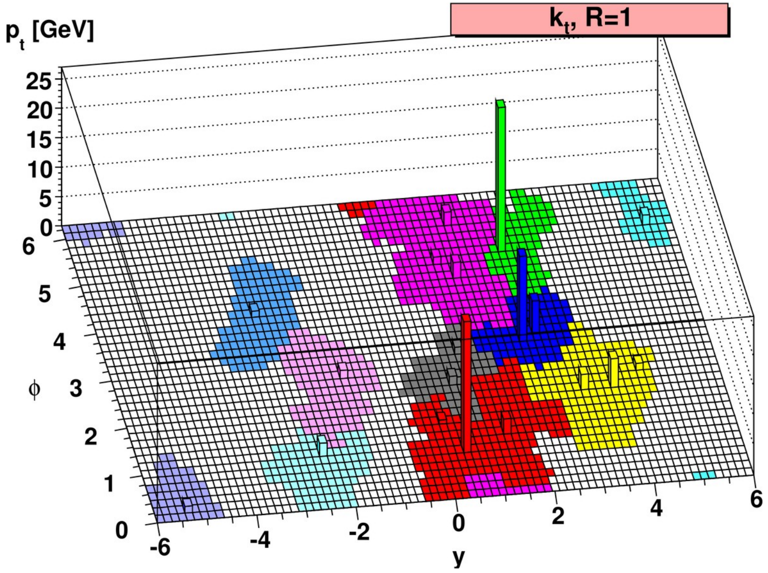
The standard algorithm for the LHC is the anti-kT:

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

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.

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

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

A scale to define "soft"
→ Can be any hard scale

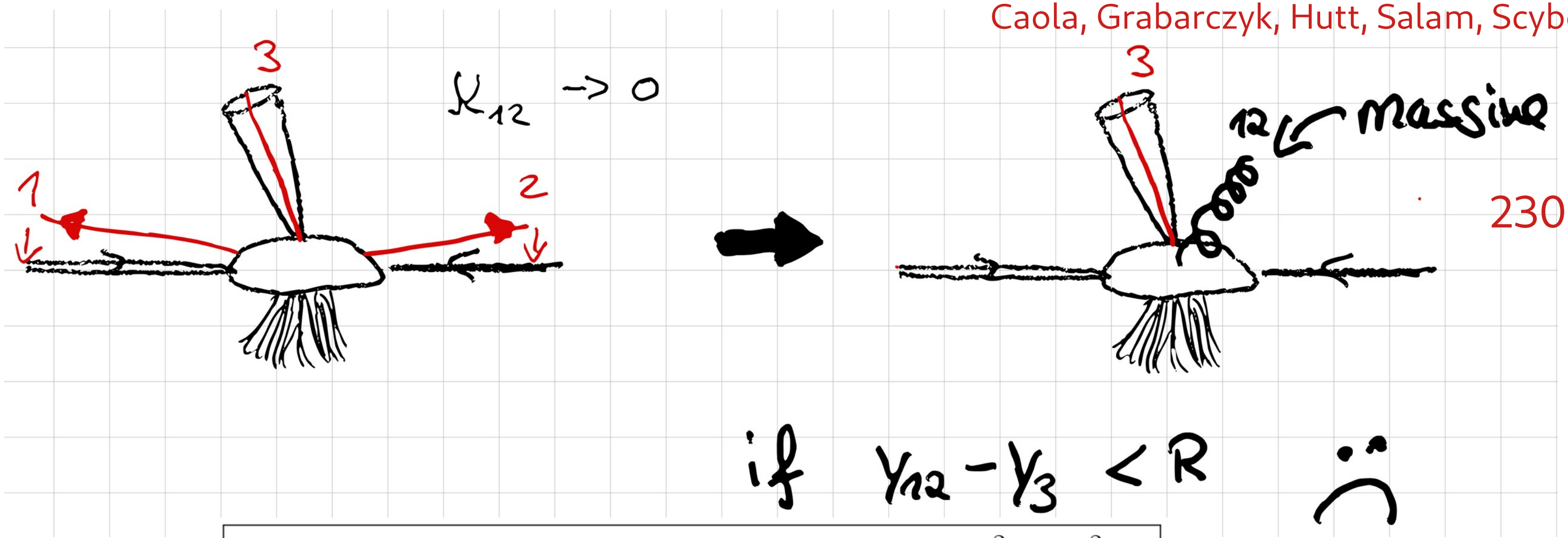
Allow systematic variations

New developments...

Issue for double collinear limits wrt. to initial states

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

2306.07314



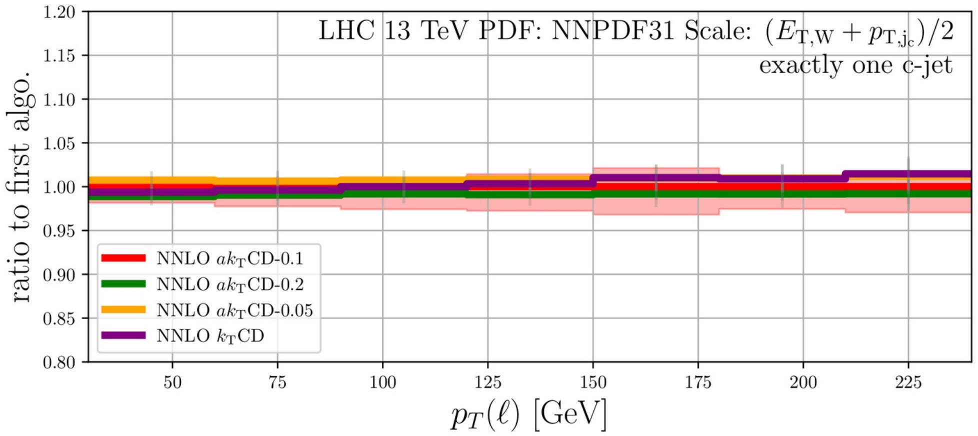
$$\mathcal{S}_{ij} \equiv 1 - \theta(1-\kappa_{ij}) \cos\left(\frac{\pi}{2}\kappa_{ij}\right) \quad \text{with} \quad \kappa_{ij} \equiv \frac{1}{a}\frac{k_{T,i}^2 + k_{T,j}^2}{2k_{T,\max}^2}\,.$$

Their proposal: $\mathcal{S}_{ij} \to \overline{\mathcal{S}}_{ij} = \mathcal{S}_{ij}\frac{\Omega_{ij}^2}{\Delta R_{ij}^2}$ $\qquad \Omega_{ik}^2 \equiv 2\left[\frac{1}{\omega^2}(\cosh(\omega\Delta y_{ik})-1) - (\cos\Delta\phi_{ik} - 1)\right]$

W+charm - jet algorithm dependence

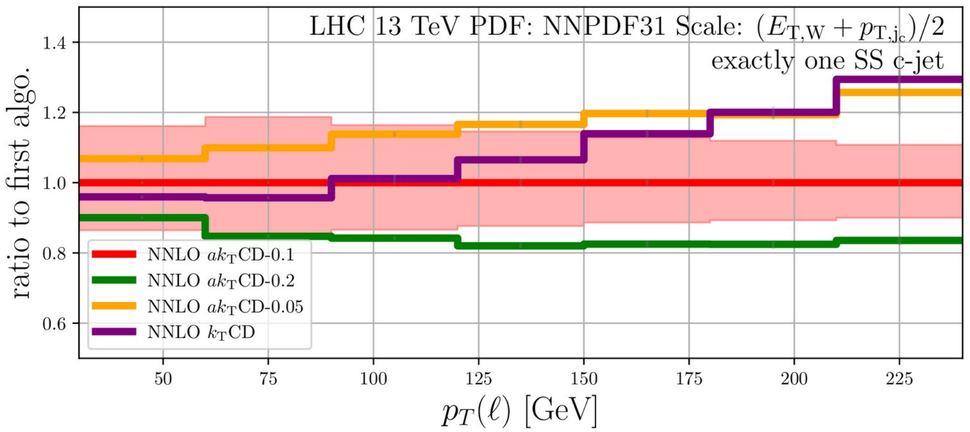
Exactly one c-jet requirement (OS+SS):

- 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



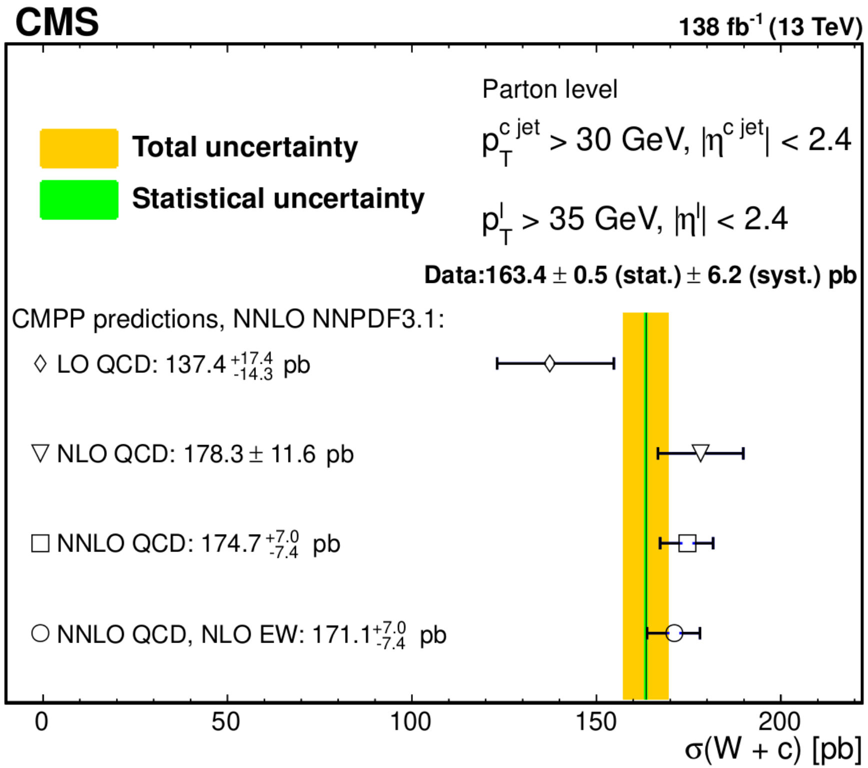
Comparison to CMS data

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

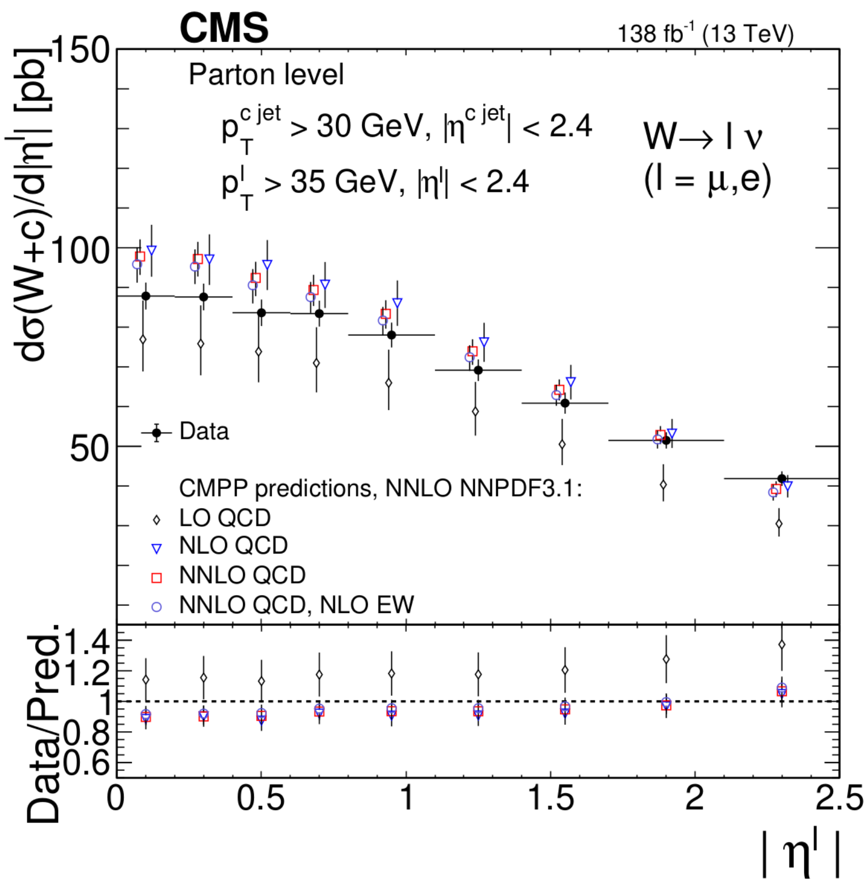
Similar phase space:

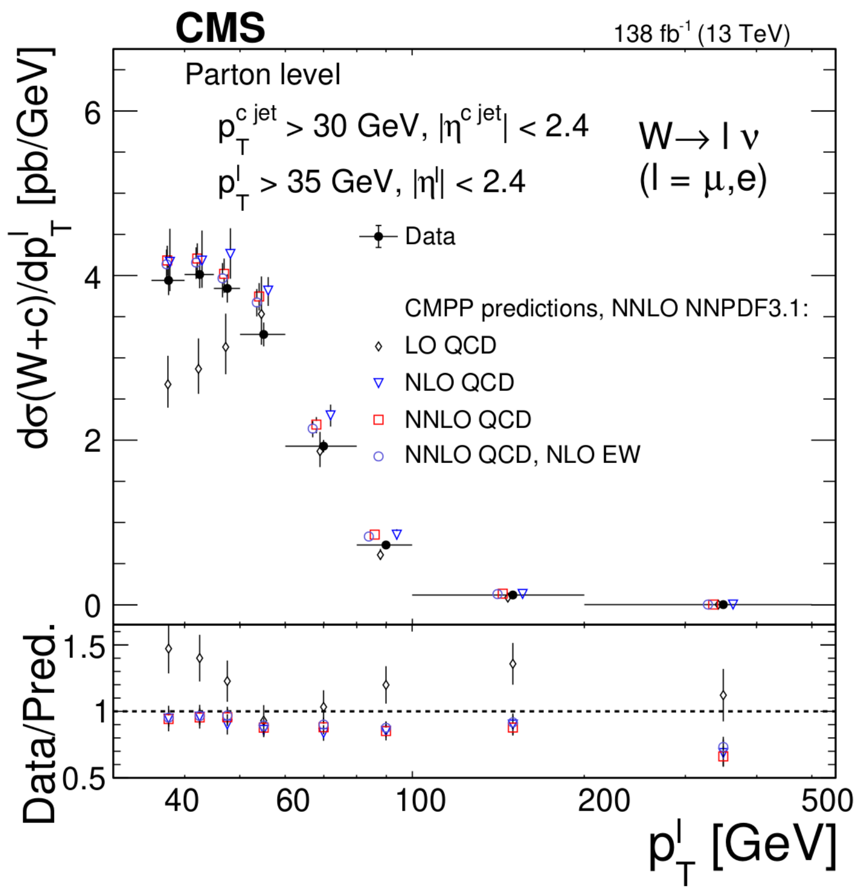
$$p_T^\ell > 35\,\text{GeV},\ |\eta^\ell| < 2.4,\ p_T^{\text{c jet}} > 30\,\text{GeV}$$
$$|\eta^{\text{c jet}}| < 2.4,\ \Delta R(\text{jet},\ell) > 0.4$$

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



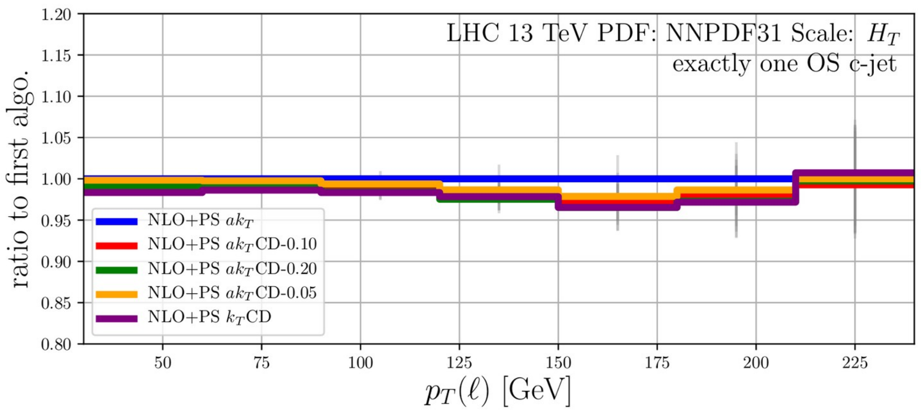
Comparison to CMS data

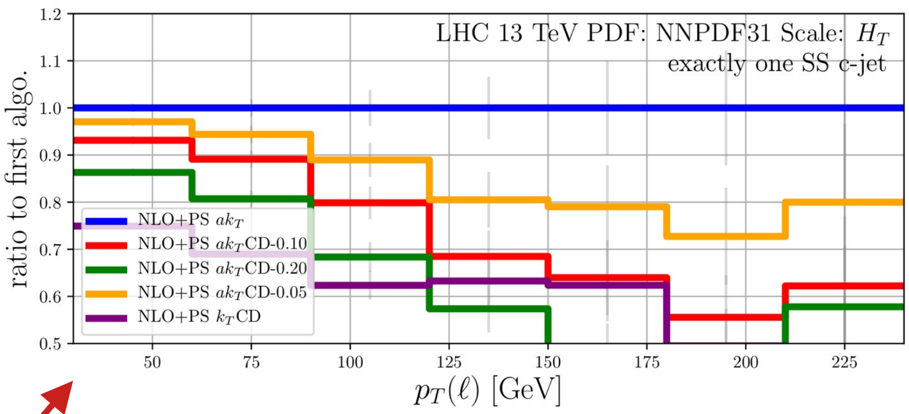




Unfolding corrections

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





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

Comparison of flavoured jet algorithms

Comparisons

Les Houches 23 workshop (aka FlavourFest :))

- CMPΩ: Flavour anti-kT (with fixed $\mathcal{S}_{ij}$)
- SDF: Flavour with Soft-drop (only IR-safe up to α_s^2 corrections)
- GHS: Flavour dressing → standard anti-kT + flavour assignment
- IFN: Interleaved flavour neutralisation

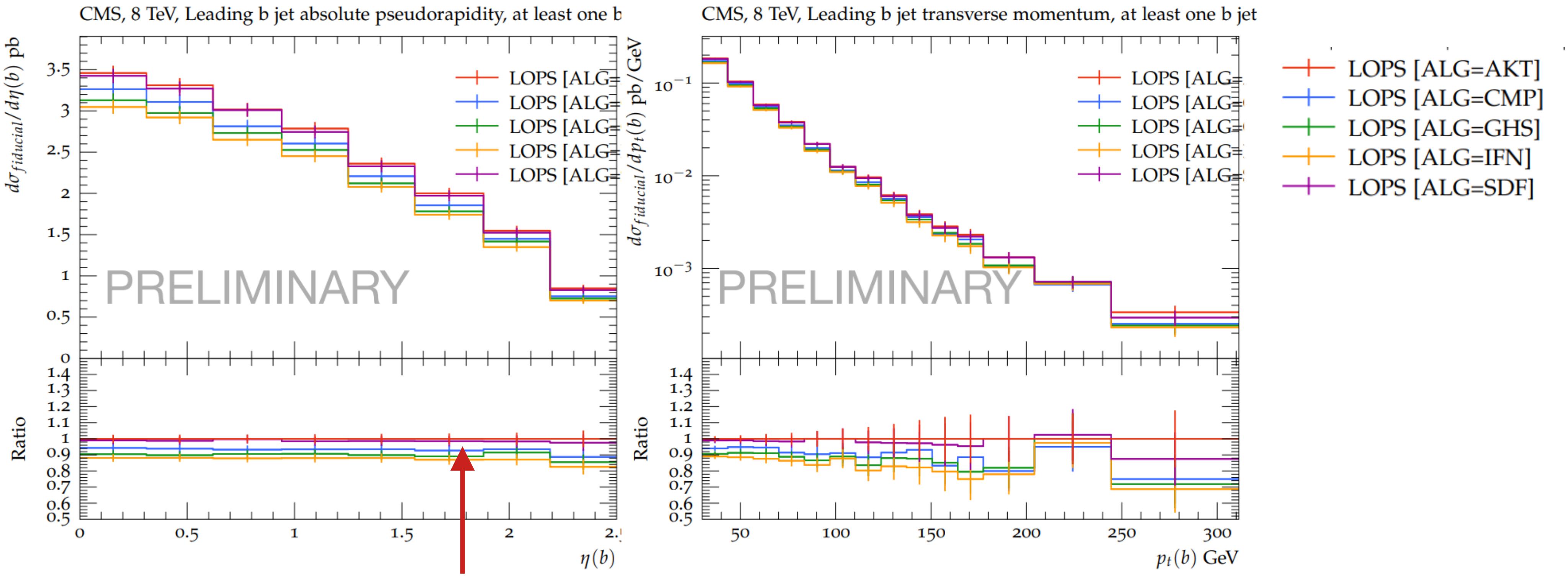
} Implementation in FastJet package

Benchmark process: Z+b-jet following CMS analysis 1611.06507

Comparison with parton showers

Les Houches Jet Flavour WG

HERWIG LO PS

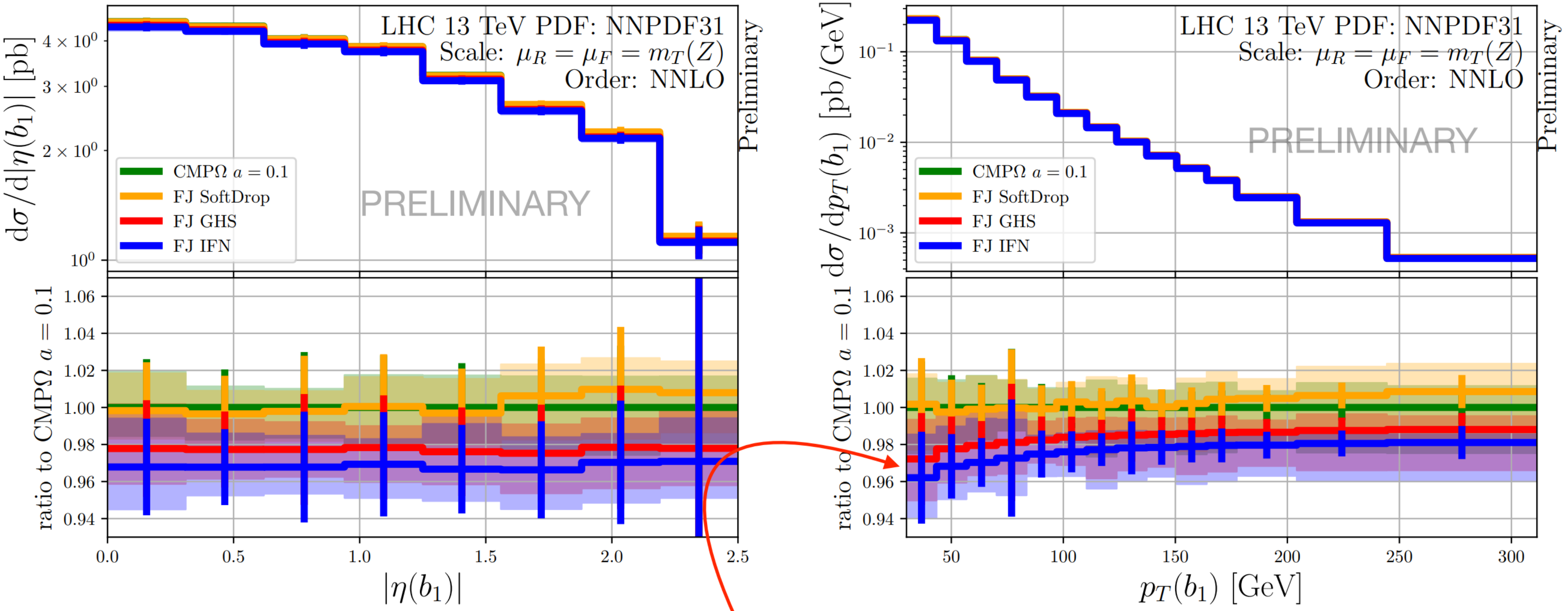


SDF ~ anti-kT → consequence of IR unsafety at higher orders?

NNLO QCD comparisons

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

Les Houches Jet Flavour WG

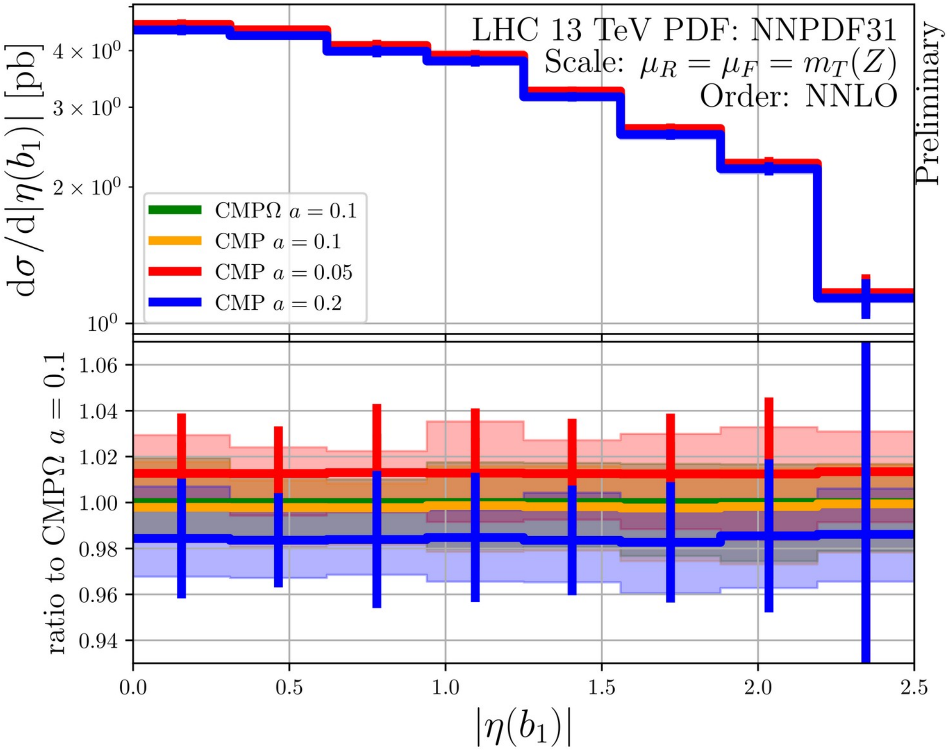


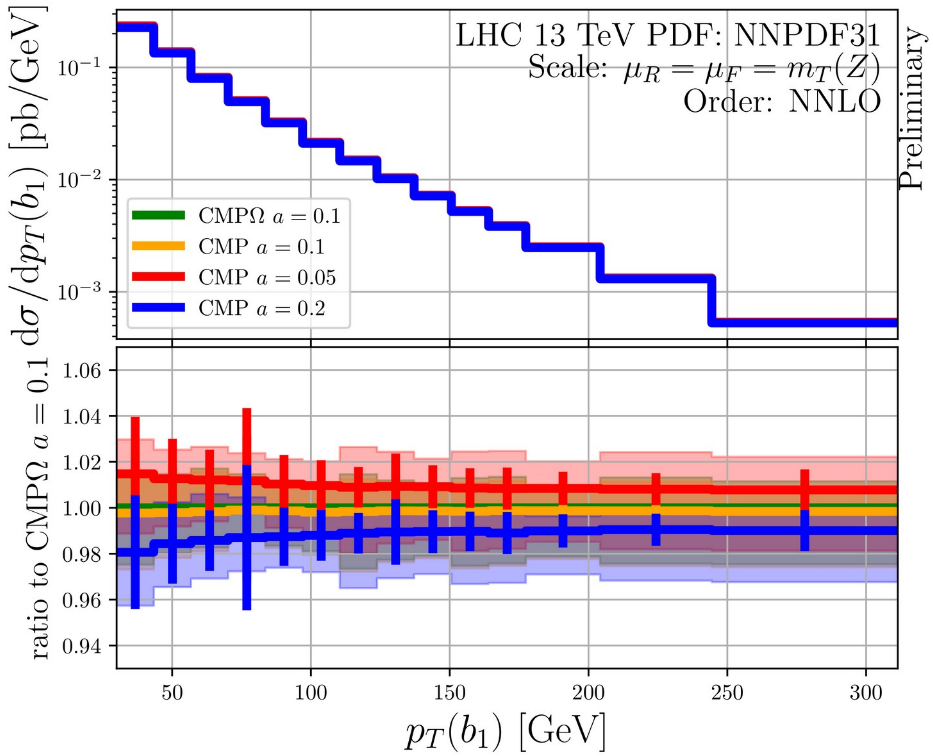
interesting shape difference at low p_t: it deserves further investigation!

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

Some remarks concerning exp. b-tagging

Experimental b/c-tagging

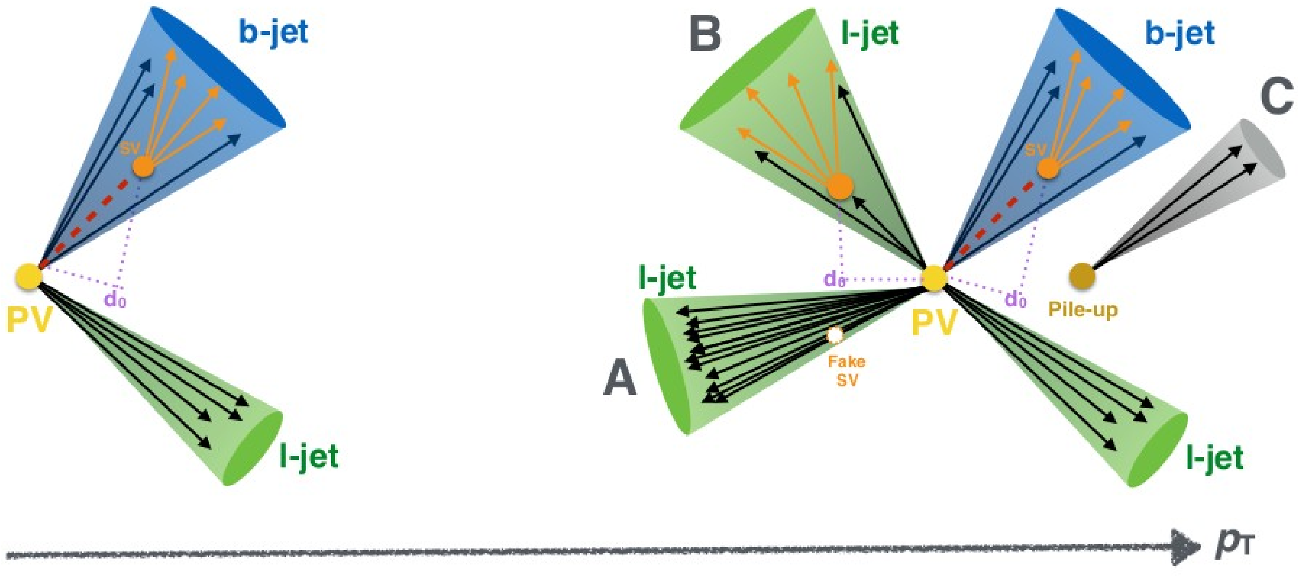
Credit: Arnaud Duperrin (DIS23 talk)

Secondary vertex (SV) tagging

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

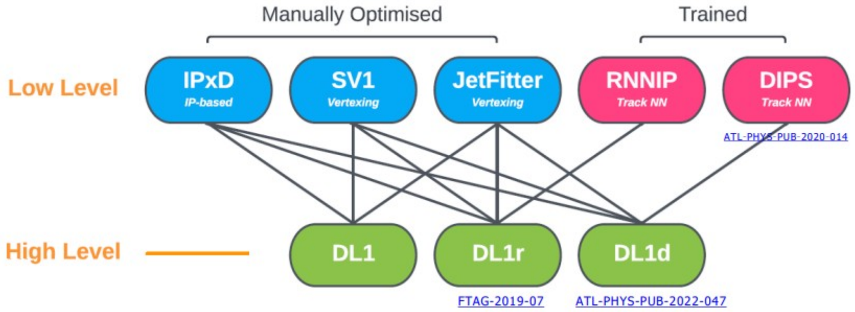
Challenges

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



Experimental b/c-tagging with NN

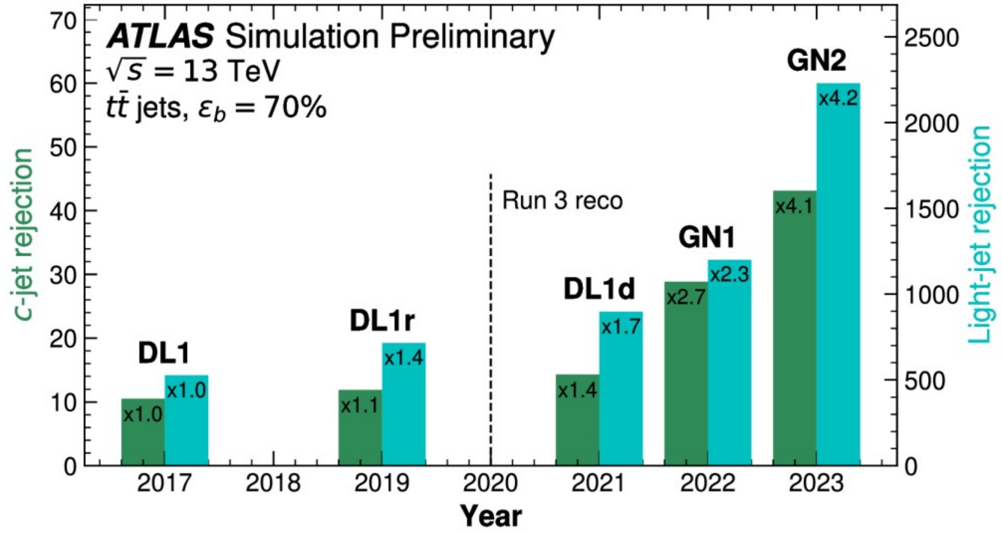
Credit: Arnaud Duperrin (DIS23 talk)



Using NN to perform b-tagging

- 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



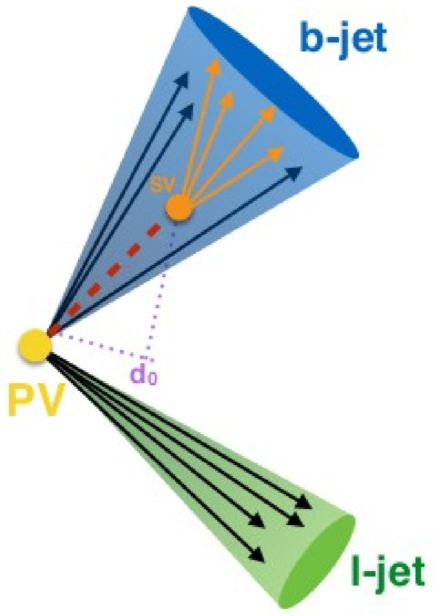
Ghost tagging

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%)

Summary

Take home messages

1) NNLO QCD effects in W+charm largely understood.
   First comparisons to data → steps towards W+charm in PDF fits

2) Flavoured jets require modified jet algorithms to avoid IR safety/sensitivity issues.
   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 with flavoured jets:
   → 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

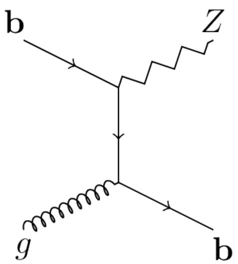
pp → Z(ll) + b-jet

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

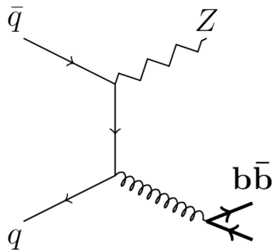
Predictions for Z-Boson Production in Association with a b-jet at O(a_s^3), Gauld, Gehrmann-De Ridder, Glover, Huss, Majer 2005.03016

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

5fs:



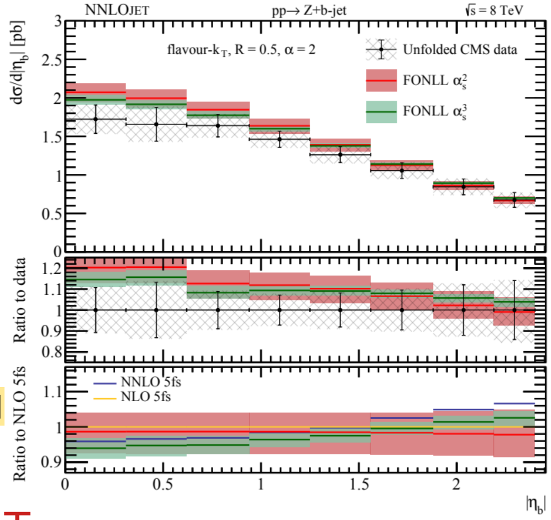
4fs:

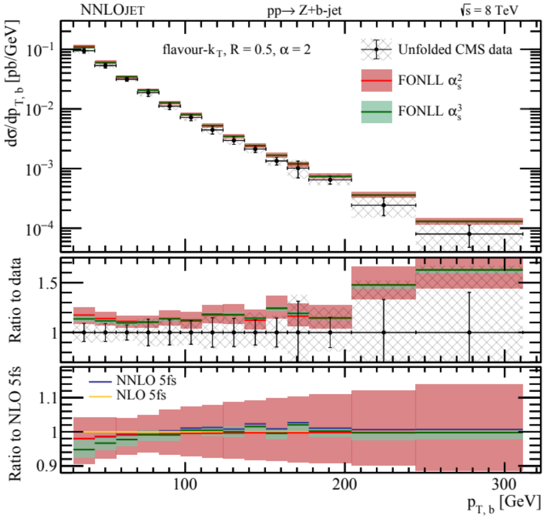


$$d\sigma^{\text{FONLL}} = d\sigma^{5\text{fs}} + (d\sigma^{4\text{fs}}_{m_b} - d\sigma^{4\text{fs}}_{m_b \to 0})$$

- 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



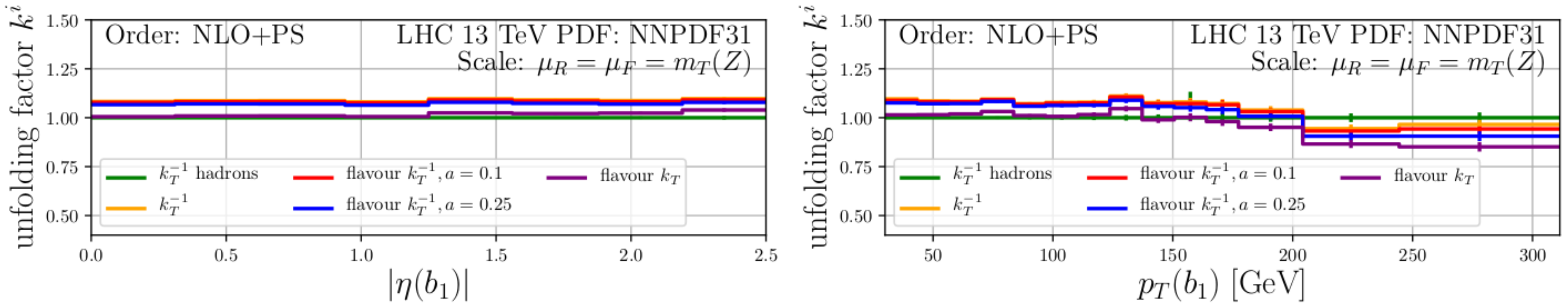


→ Ideal testing ground for flavour anti-kT

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)



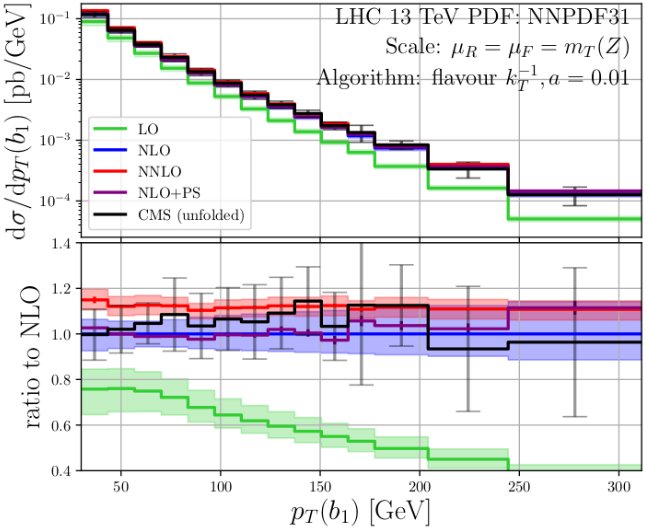
Z+b-jet Phenomenology: Tunable parameter

Benchmark process: pp → Z(ll) + b-jet

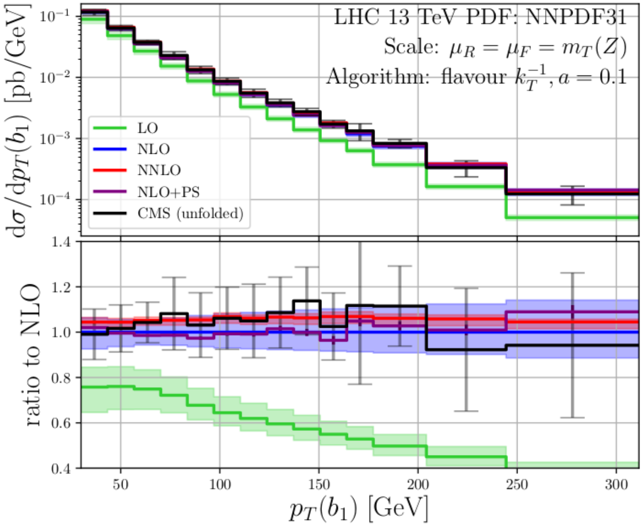
Tunable parameter a:

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

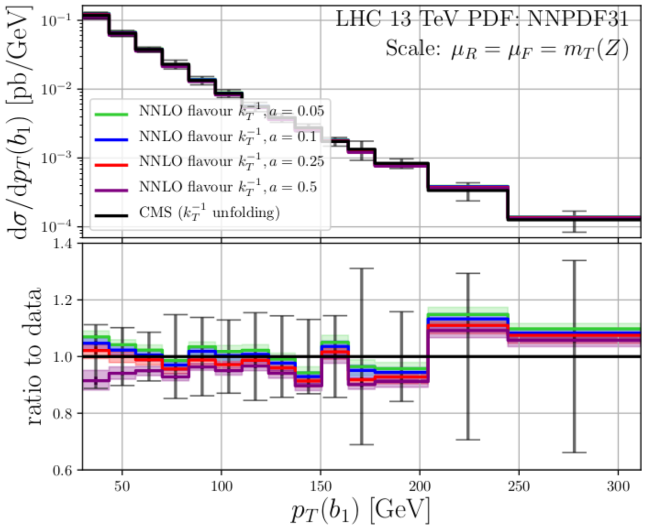
Flavour anti-kT (a=0.01):



Flavour anti-kT (a=0.1):

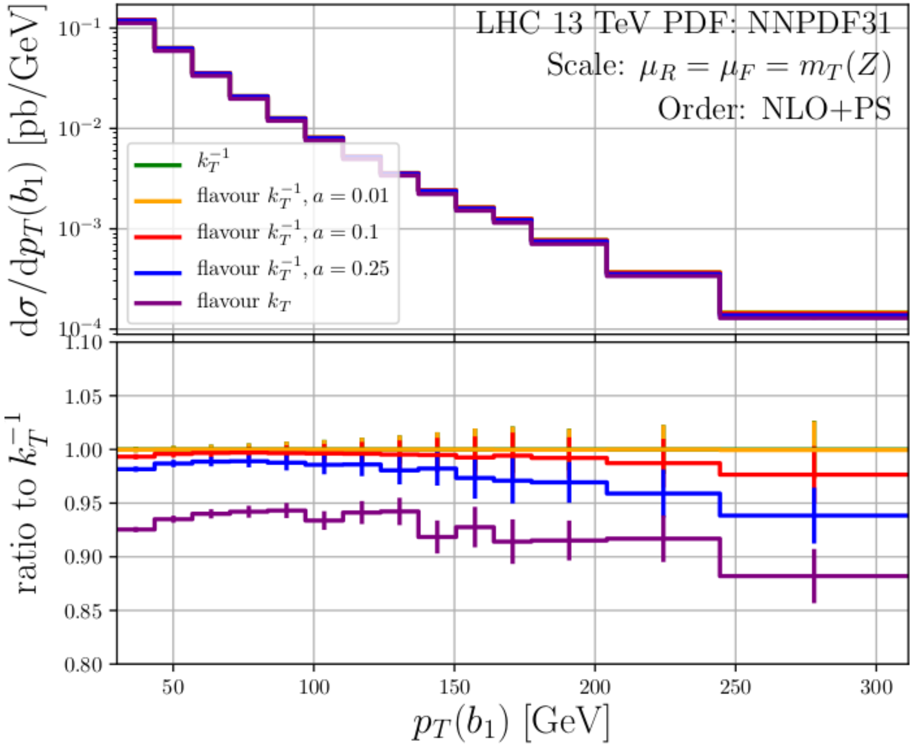


Comparison of different parameter a to data:



Z+b-jet Phenomenology: Tunable parameter II

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



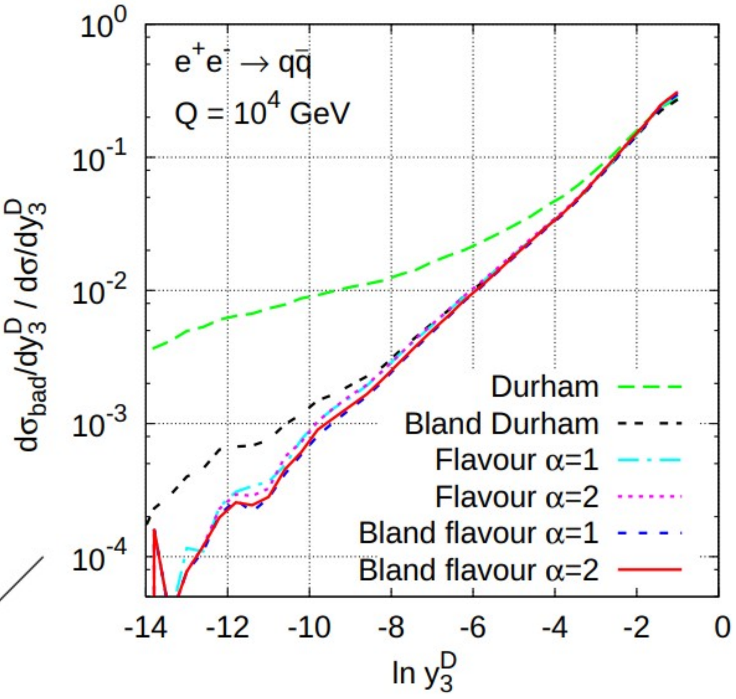
Tunable parameter a:

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

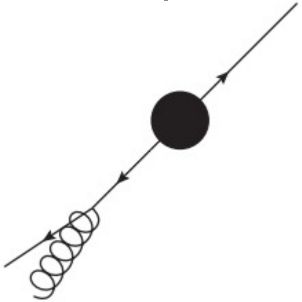
Good FO perturbative convergence +
Small difference to standard anti-kT
→ a~0.1 is a good candidate

Tests of IR safety

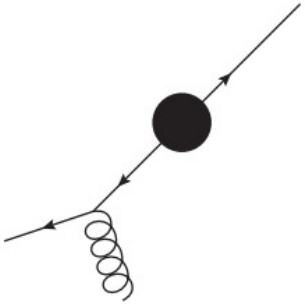
- Rate of bad-identified jet-flavour as a function of IR sensitive variable
- Parton-shower to model many emissions



Small y3

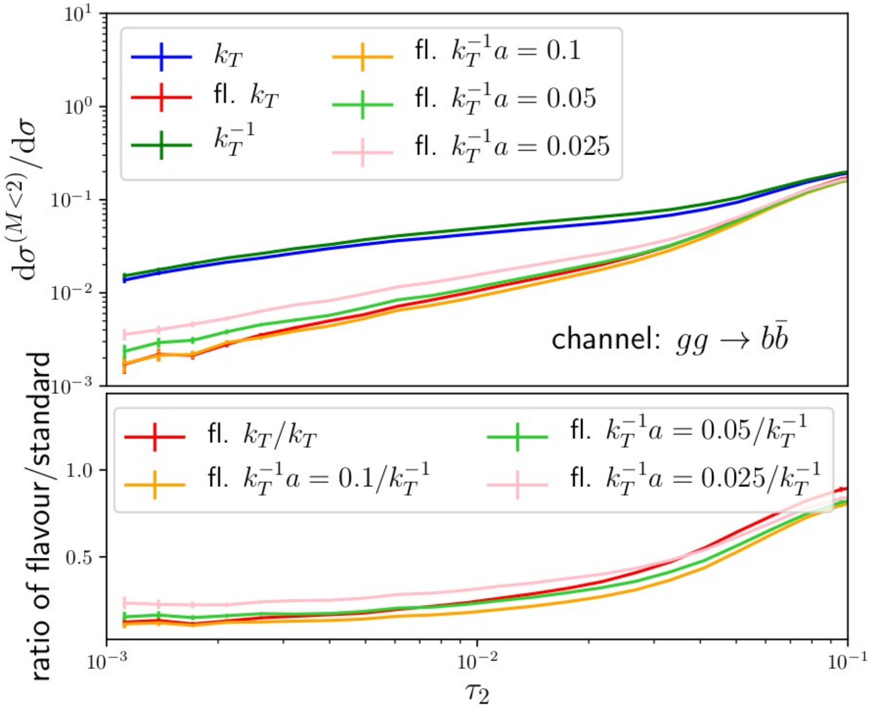


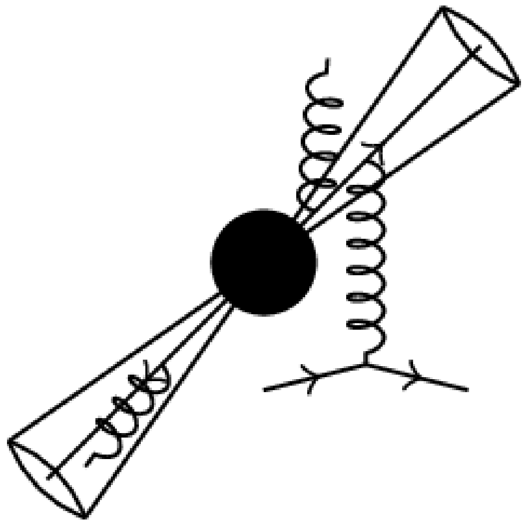
Large y3



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