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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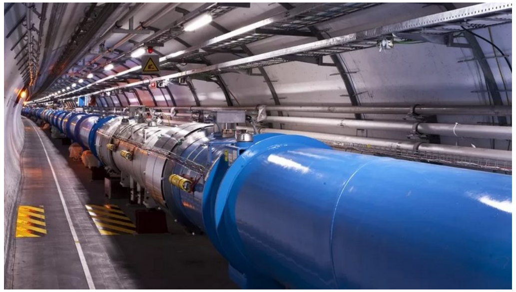
Outline

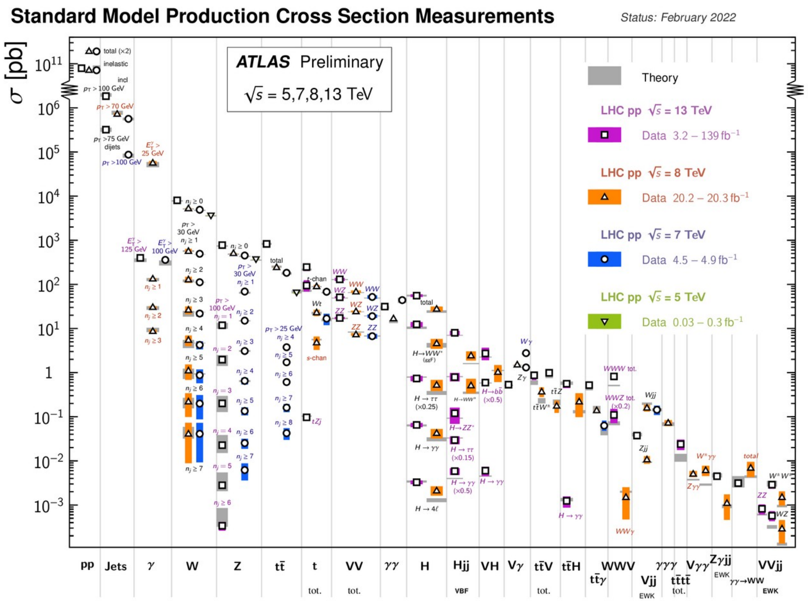
- → Phenomenological motivation
  - Vector bosons + flavoured jets
  - Infrared safety/sensitivity
- → NNLO QCD Phenomenology with W+c-jets
- → Flavoured (anti-kT) jet algorithms
  - Phenomenology
  - Comparisons → Les Houches effort

What are the fundamental building blocks of matter?

Scattering experiments

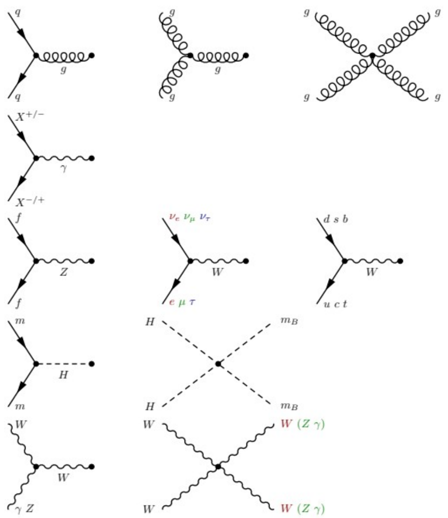


Credit: CERN



Credit: ATLAS

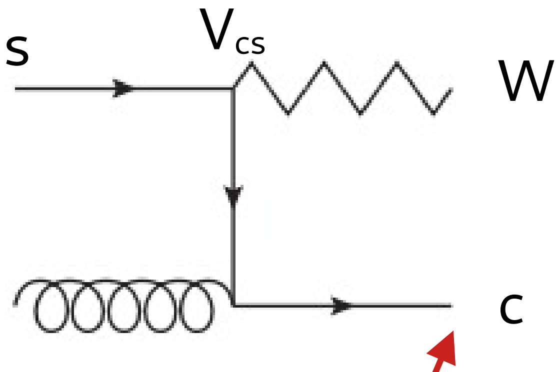
Theory/Model



Credit: Jack Lindon, CERN

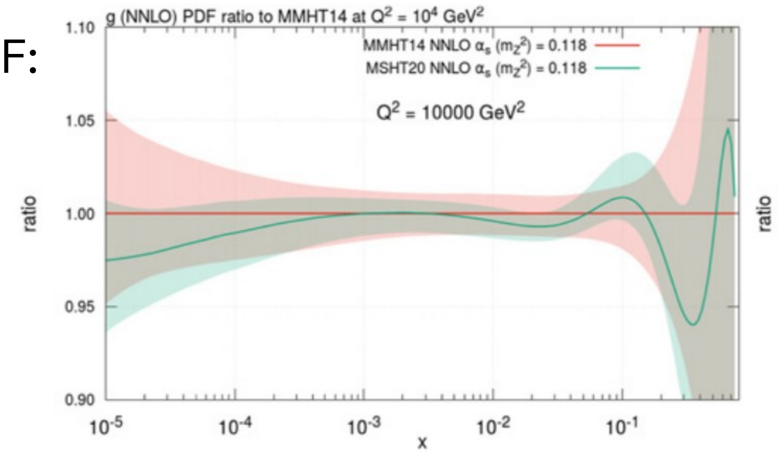
Looking into more exclusive observables ("flavoured jets") with more precision ("higher order corrections").

W + charm jet

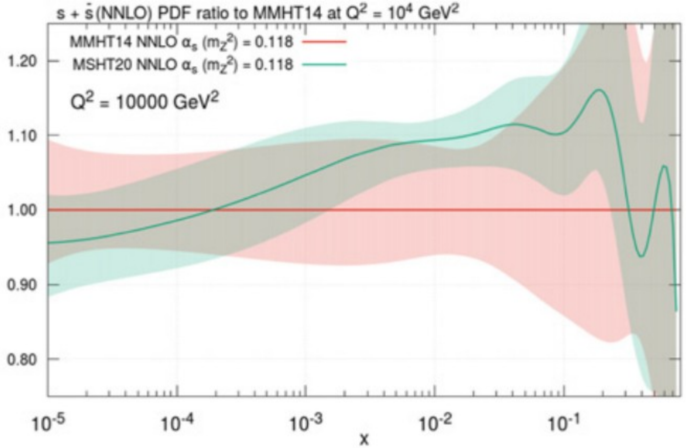


Tagging of charm jet to increase sensitivity to strange quark PDF

gluon PDF:

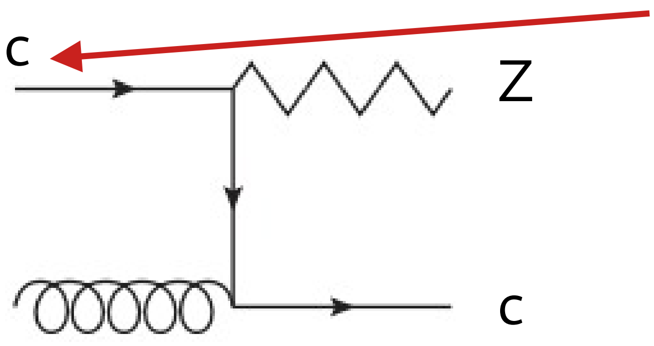


s+s PDF:

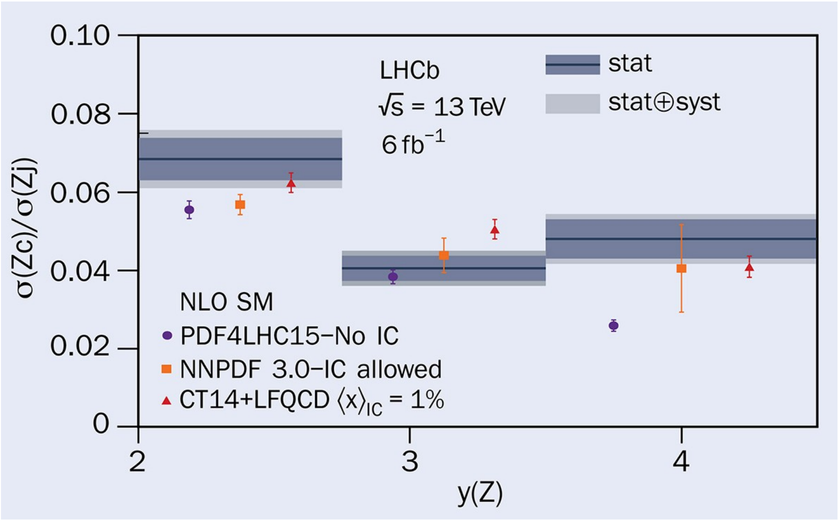


PDF4LHC22 [2203.05506]

Z + charm jet



Similar to W+charm but for charm PDF



CERN/LHCb 2109.08084

Intrinsic charm component?

Clarification needs

→ higher order corrections

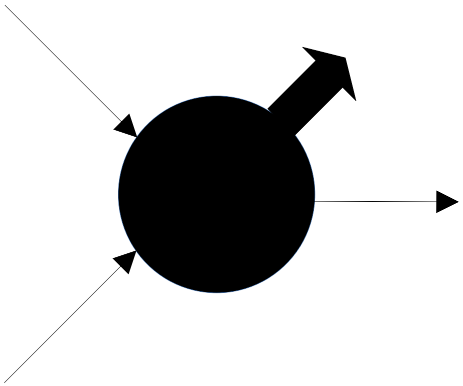
→ charm jet definition

Flavoured jets are everywhere

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

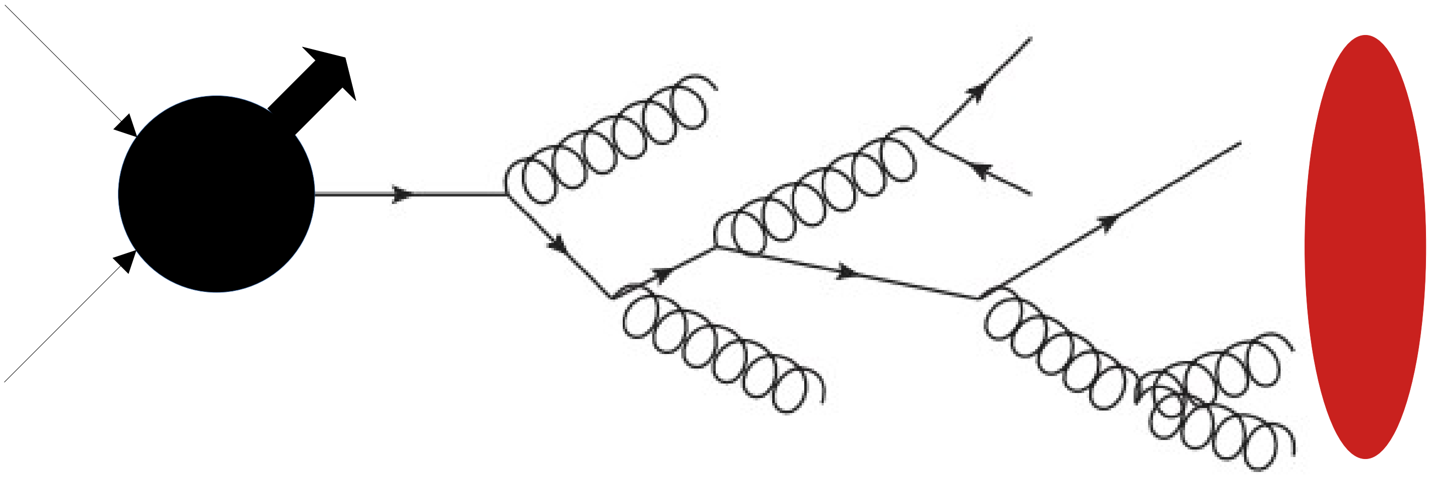
Rely on our capability to
→ identify flavoured jets
→ and interpret them

Heavy flavour production

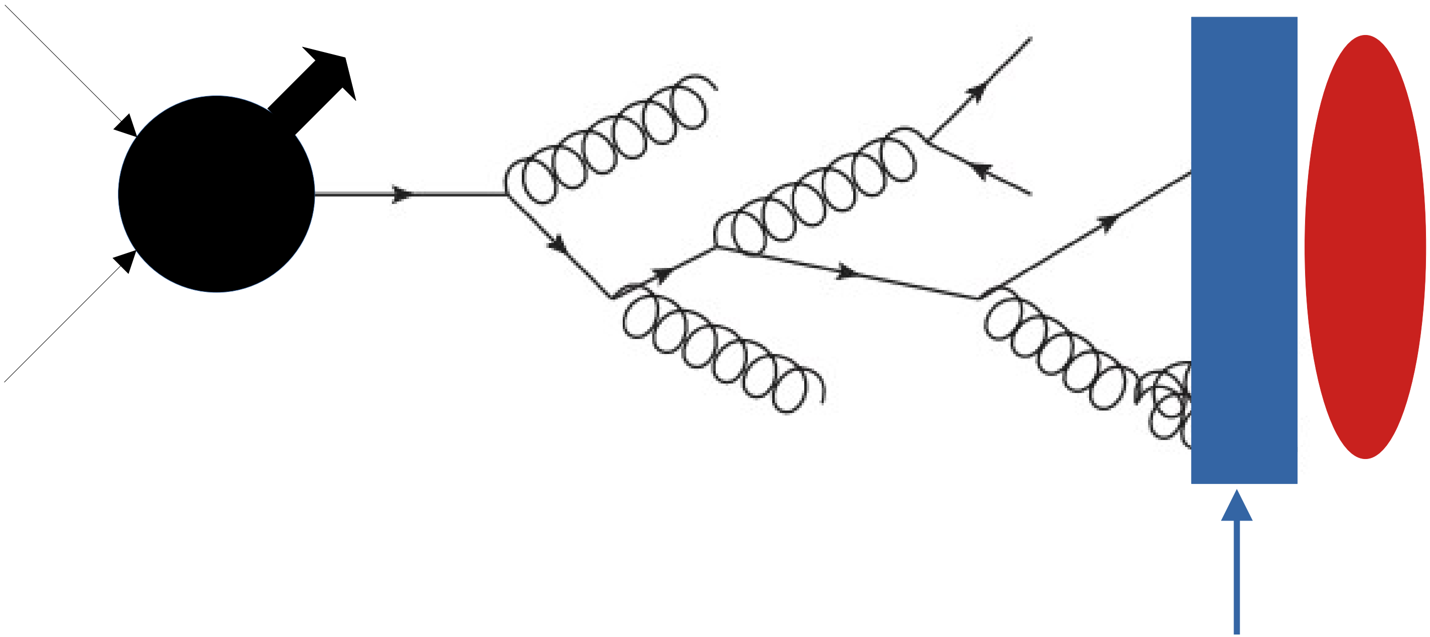


Setup for this talk:
Production of a massive quark(s)
with high transverse momentum: pT >> m

Partonic jet evolution

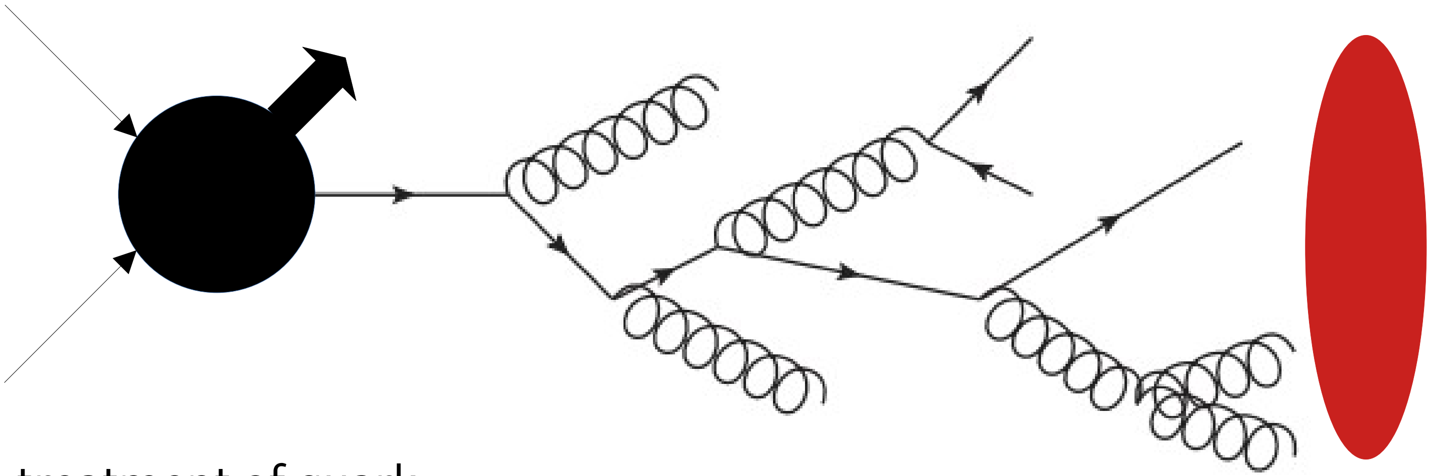


Partonic jet evolution



- 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

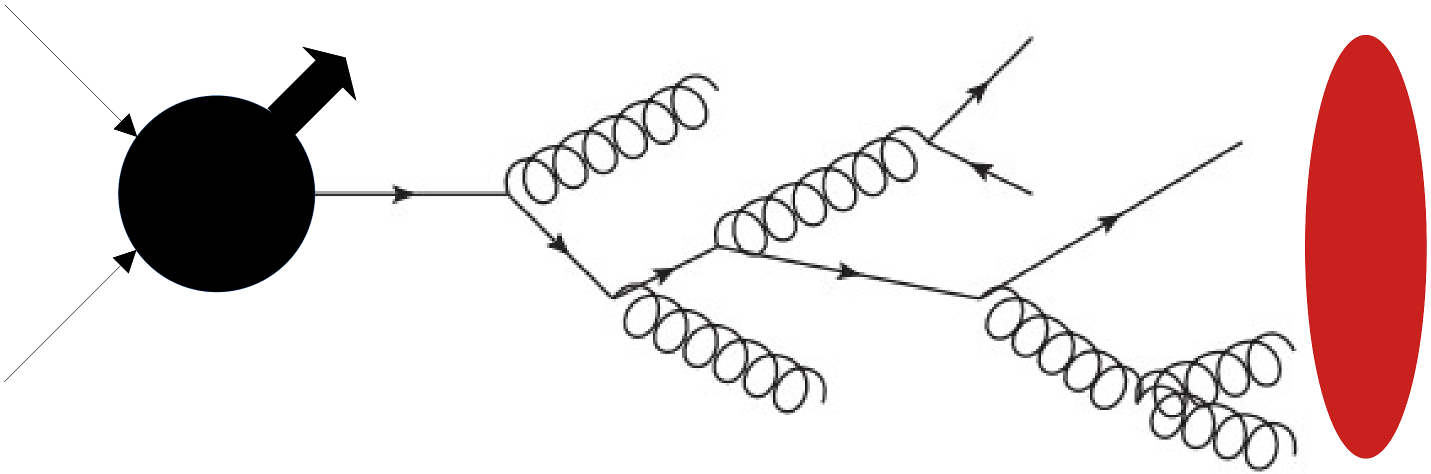


Massive treatment of quark

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

} NLO+PS

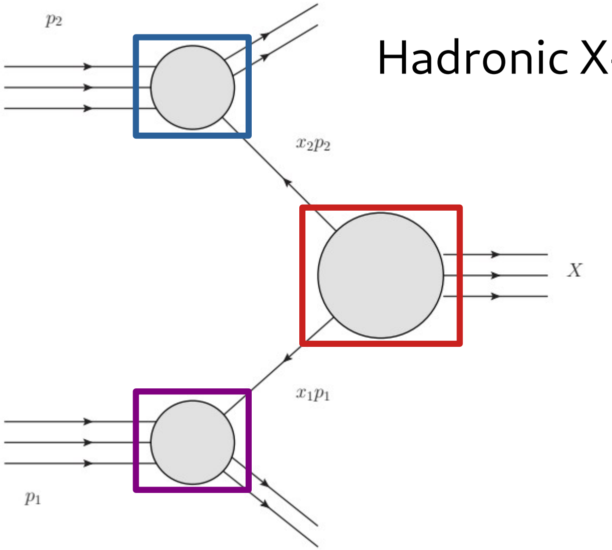
Partonic jet evolution



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

Parton distribution functions

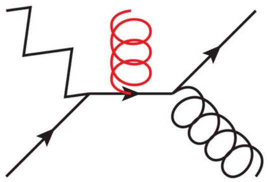
Perturbative expansion of partonic cross section:

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

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

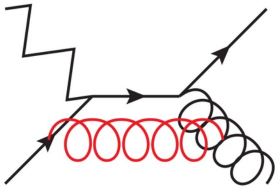
Real radiation

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$



Virtual correction

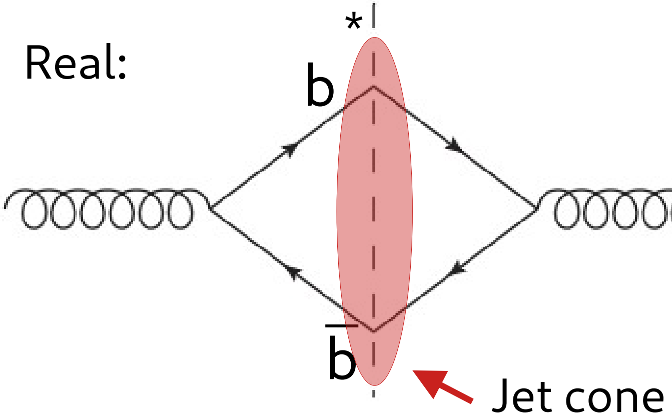
$$\hat{\sigma}^{\mathrm{V}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n}\, 2\mathrm{Re} \left\langle \mathcal{M}^{(0)}_{n} \middle| \mathcal{M}^{(1)}_{n} \right\rangle \mathrm{F}_{n}$$



IR safety issues starting from NLO QCD

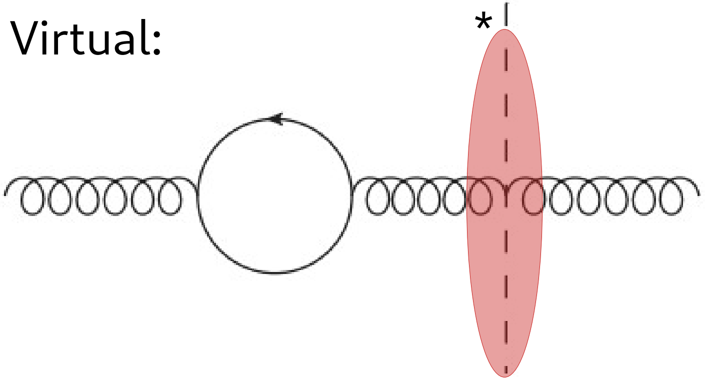
Massless QCD: Cancellation of IR divergences between real and virtual corrections

Real:



\+

Virtual:



= IR finite

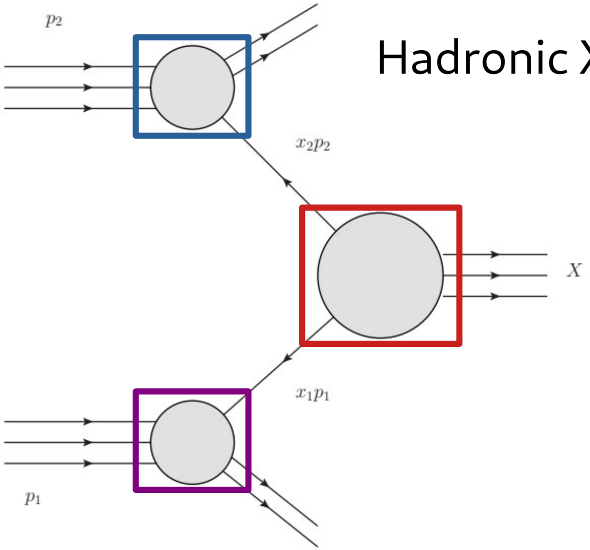
Flavoured?
(Keeping in mind quark-hadron duality)

Definitively not flavoured!

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

*: cut symbolises the “measured” final state

Hadronic cross section in collinear factorization – NNLO QCD



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Parton distribution functions

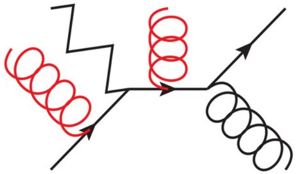
Perturbative expansion of partonic cross section:

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

The 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

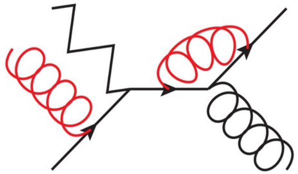
$$\hat{\sigma}^{\mathrm{RR}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2} \left\langle \mathcal{M}^{(0)}_{n+2} \middle| \mathcal{M}^{(0)}_{n+2} \right\rangle \mathrm{F}_{n+2}$$



These make massless calculations hard!

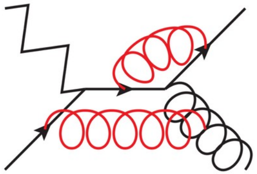
Real-Virtual correction

$$\hat{\sigma}^{\mathrm{RV}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1}\, 2\mathrm{Re} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(1)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$



Double virtual corrections

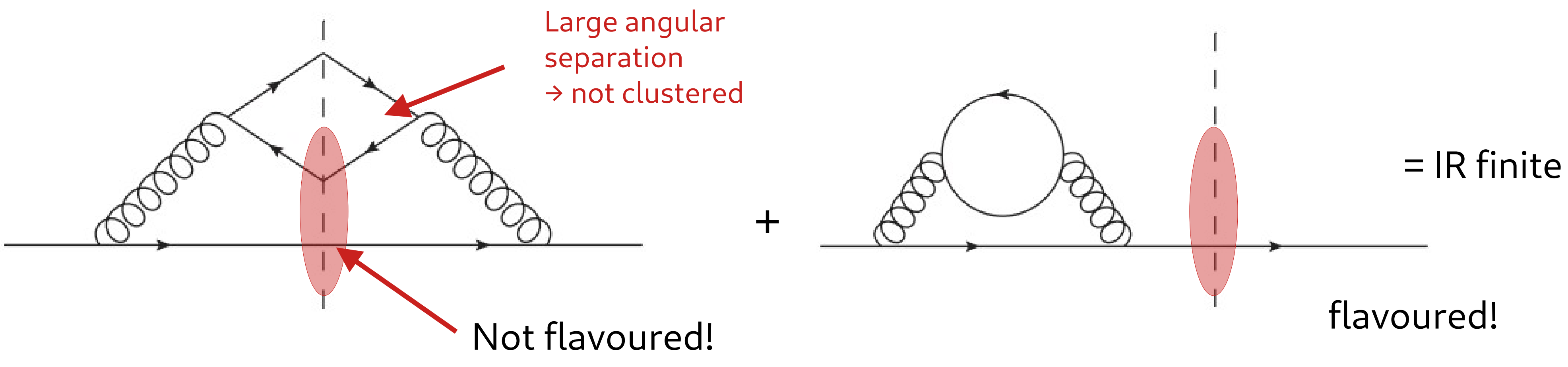
$$\hat{\sigma}^{\mathrm{VV}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n \left(2\mathrm{Re} \left\langle \mathcal{M}^{(0)}_n \middle| \mathcal{M}^{(2)}_n \right\rangle + |\mathcal{M}^{(1)}_n|^2 \right) \mathrm{F}_n$$



These make massive calculations hard!

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:

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

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

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

Theory approaches to heavy flavour

Massive
- FO more complicated
- Resummation of logs → PS
- Flavour-scheme/PDFs in high Q^2 processes?

Massless
- FO easier
- IR safety of jets?
- Useful for high pT regime
- Mass/Threshold effects at intermediate pT?

"FONLL"
- Matching between Massive/massless
- Useful for PDF fits? Flavour scheme?

Fragmentation
- Included in PS
- FO perturbative fragmentation → Resummation of mass effects
- Hadronic observables
- Non-perturbative input: Fragmentation functions?

Theory approaches to heavy flavour

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How does this compare to experiment?

"FONLL"
- Matching between Massive/massless
- Useful for PDF fits? Flavour scheme?

Fragmentation
- Included in PS
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- Hadronic observables
- Non-perturbative input: Fragmentation functions?

Experimental b/c-tagging

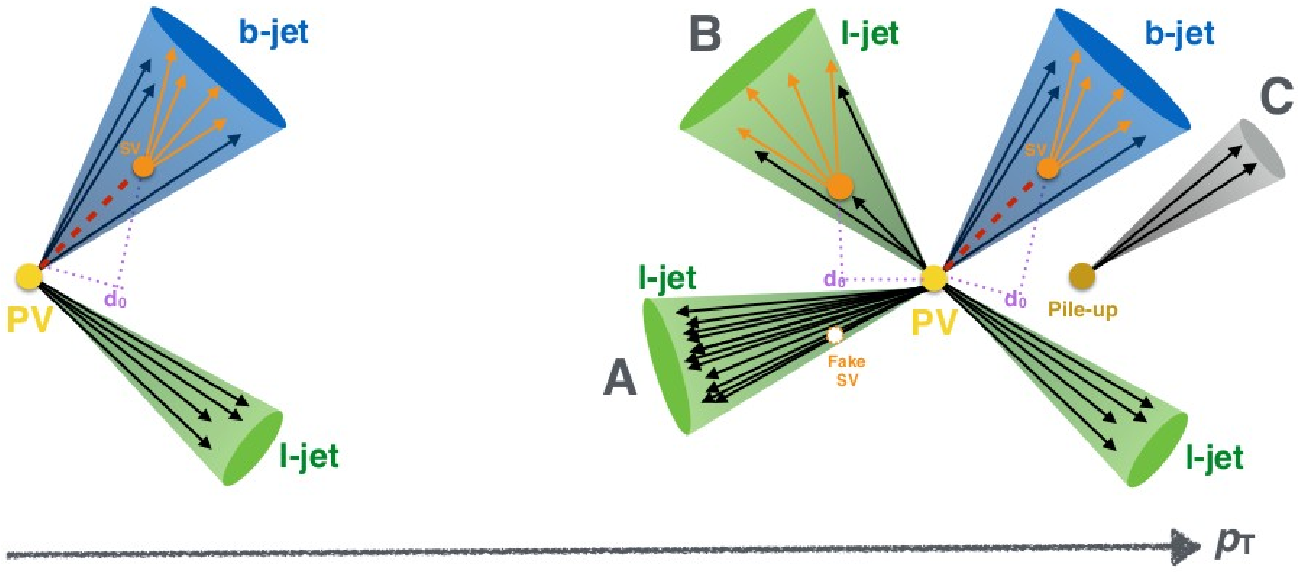
Credit: Arnaud Duperrin (DIS23 talk)

<u>Secondary vertex (SV) tagging</u>

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

<u>Challenges</u>

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



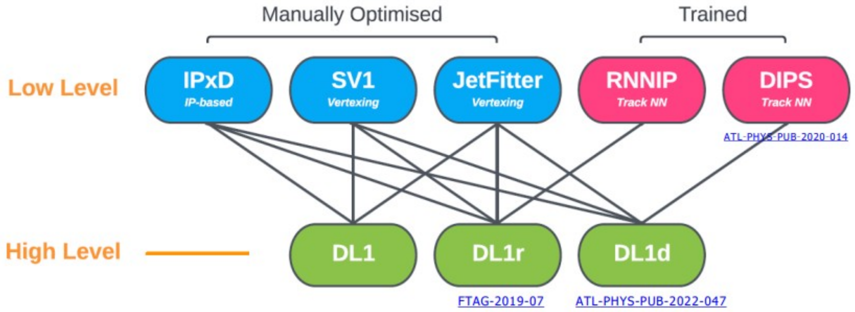
Experimental b/c-tagging with NN

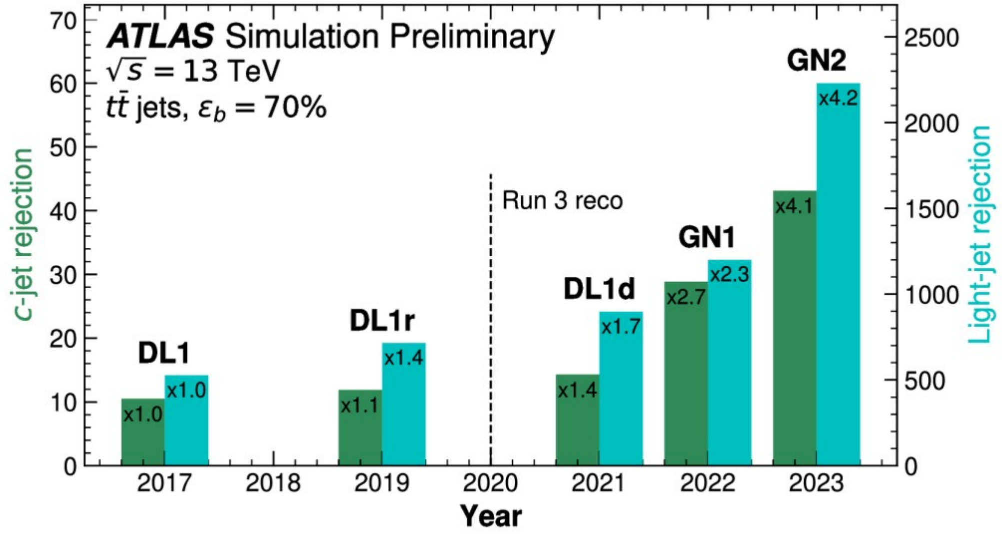
Credit: Arnaud Duperrin (DIS23 talk)

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





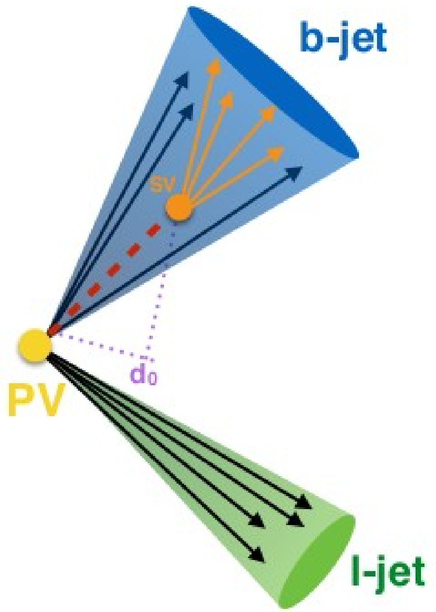
Experimental truth labels: Ghost tagging

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

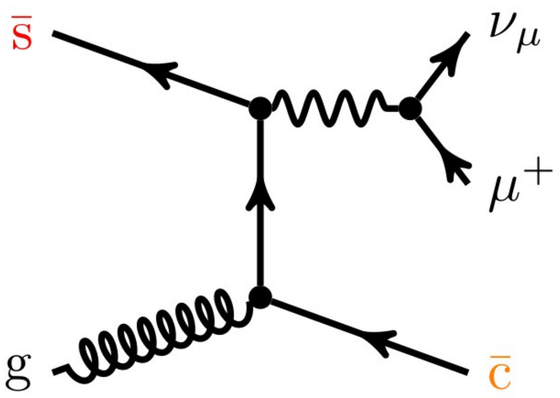
  2) Hadronisation/non-perturbative models

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

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:

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

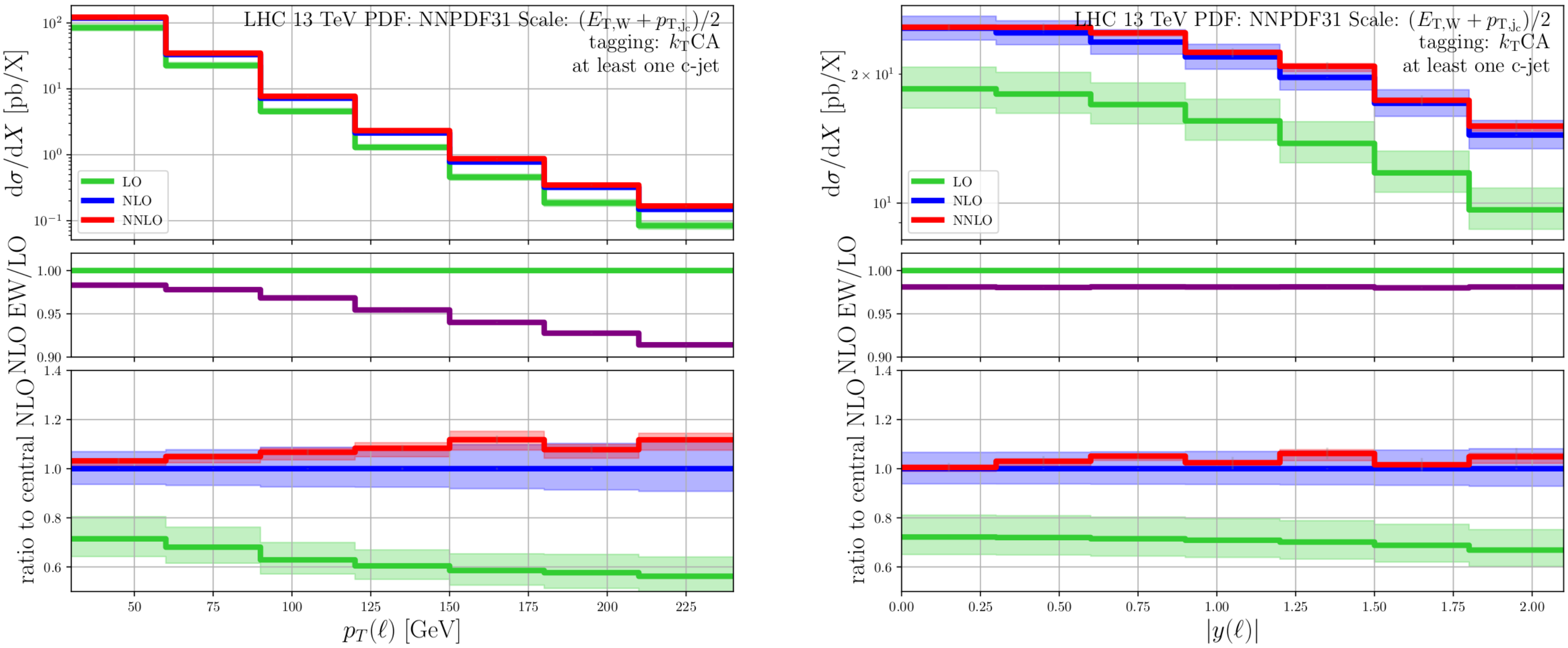
Various effects studied:

- NNLO QCD corrections
- Electroweak corrections
- Off-diagonal CKM matrix
- PDF sensitivity
- Tagging requirements
- Flavoured jet-algorithms

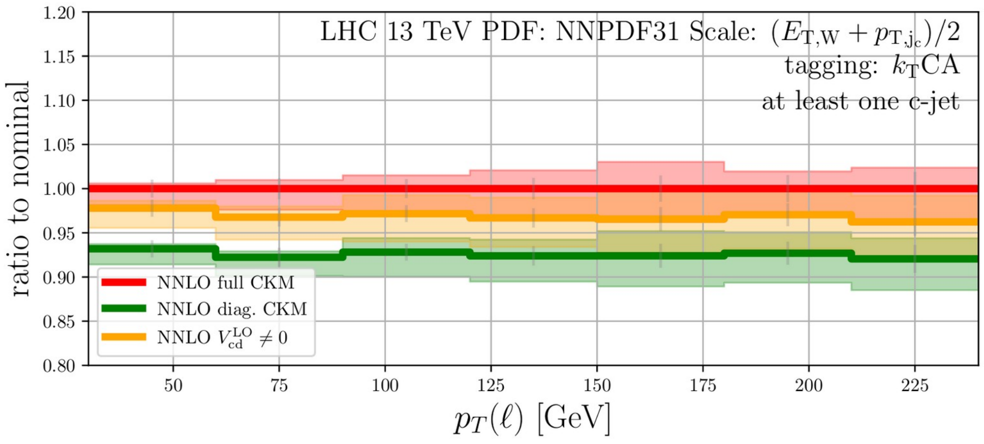
All ~5% effects

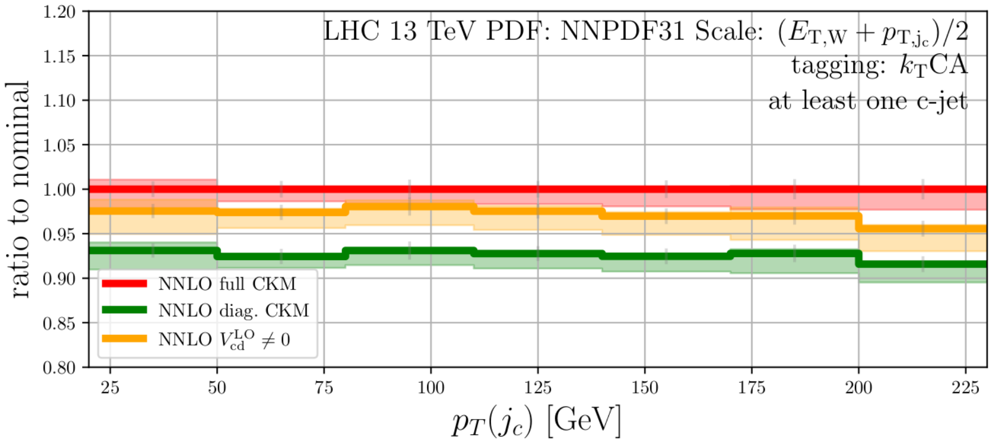
Perturbative corrections

Flavour-kT, inclusive c-jet requirements



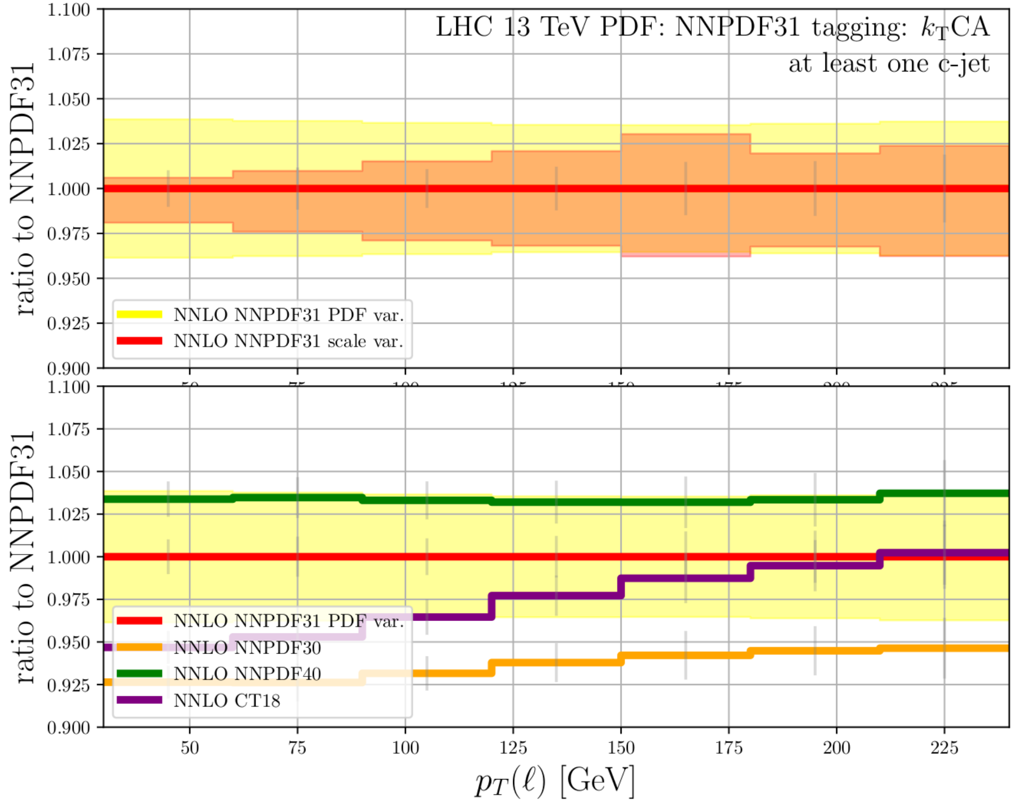
Off-diagonal CKM





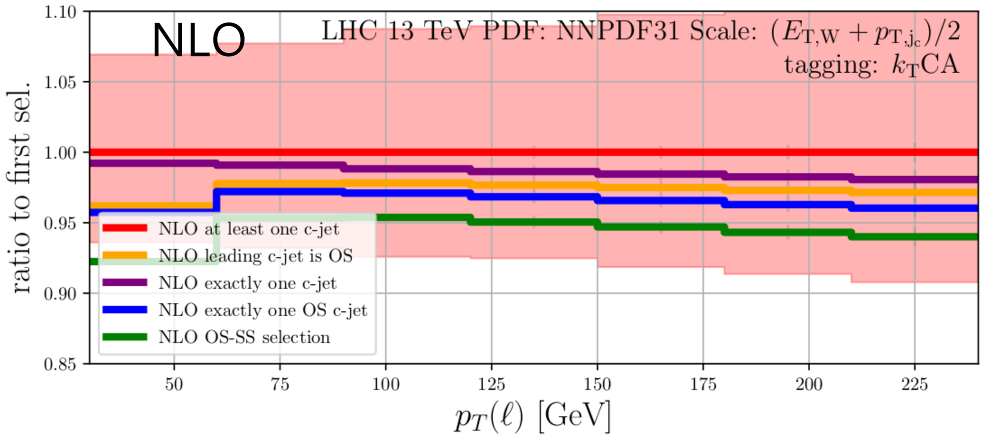
- Full CKM effects through NNLO QCD
- Sizeable with respect NNLO corrections!
- LO V_{cd} captures most of the full CKM

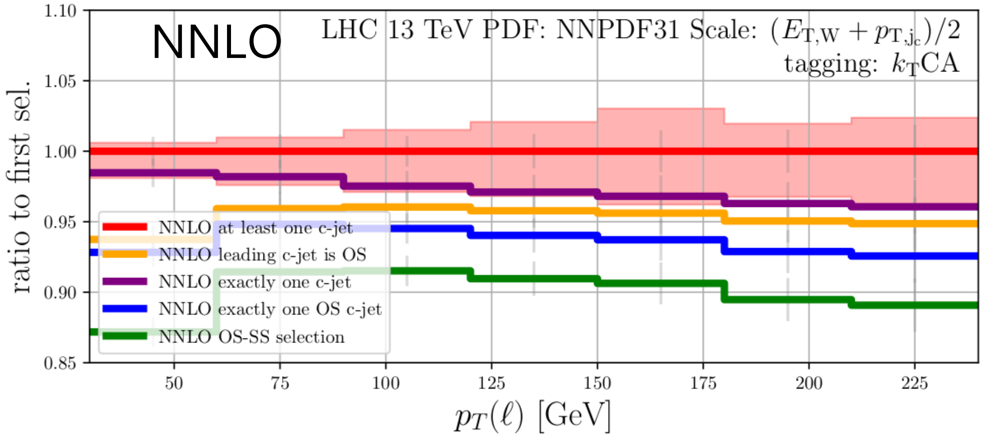
PDF dependence



- PDF uncertainty: ~5%
- PDF model variations: ~5-8%
  → different s-quark PDF treatment:
  - NNPDF asymmetric
  - CT18 symmetric
- Uncertainty > NNLO QCD uncertainty
  → Constraining power in PDF fits

Different tagging requirements





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

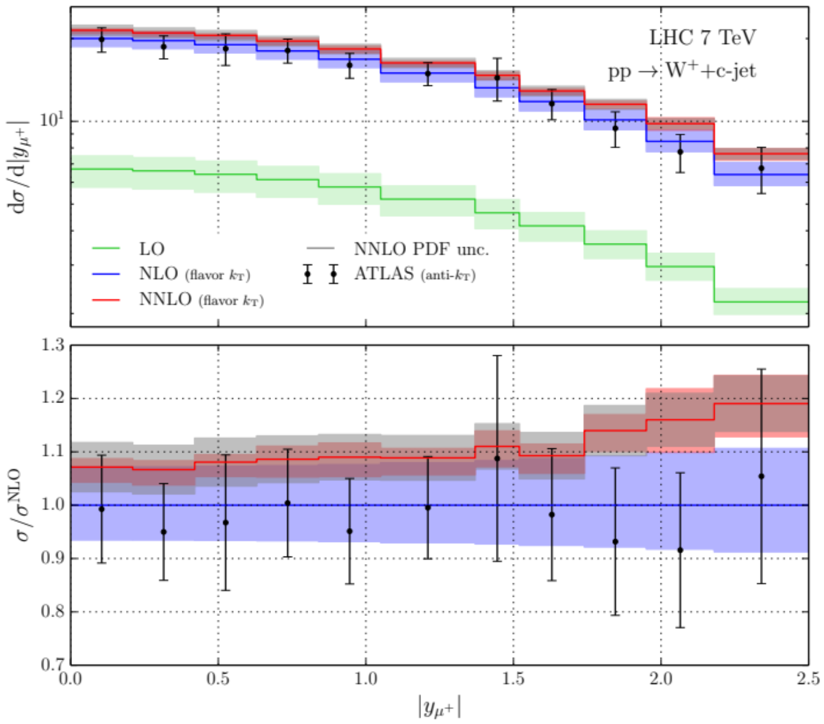
W+c-jet with flavour kT at NNLO QCD

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



Caveat: flavour-kT vs. anti-kT

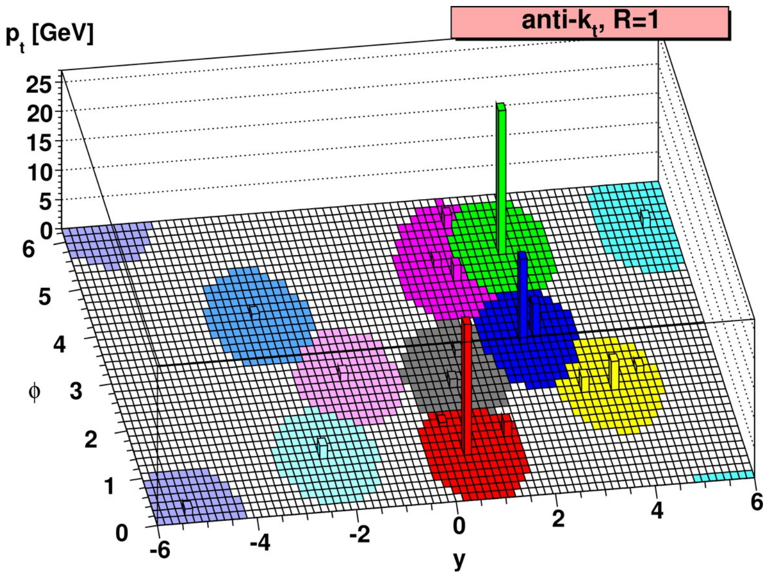
Flavour anti-kT?

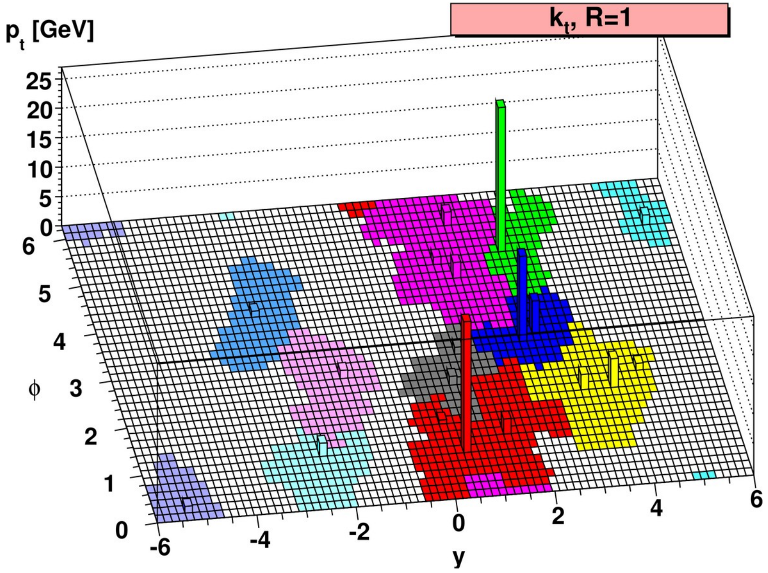
The standard algorithm for the LHC is the anti-kT:

→ nice geometric properties

→ less sensitive to soft physics, easy to subtract Pile-Up

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 — SDF
- Flavour anti-kT — **Infrared-safe flavoured anti-kT jets**, Czakon, Mitov, Poncelet 2205.11879 — CMP
- 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 — GHS
  - **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 — IFN
  - **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: $d_{ij} = \min(k_{T,i}^{-2}, k_{T,j}^{-2}) R_{ij}^2 \qquad d_i = k_{T,i}^{-2}$

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

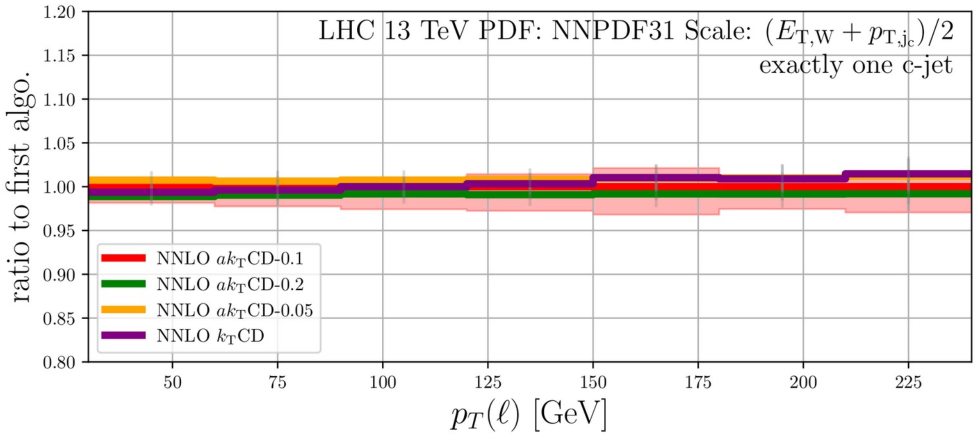
Variant: 2306.07314

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

W+charm - jet algorithm dependence

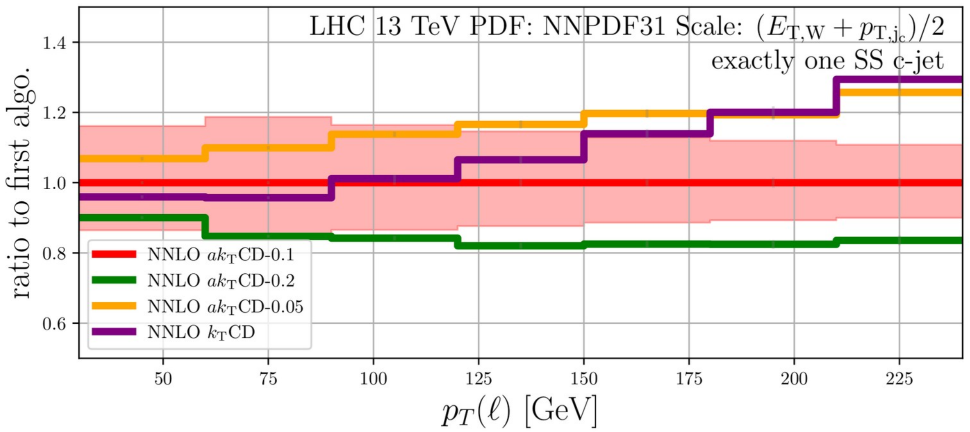
Exactly one c-jet requirement (OS+SS):

- 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+SS ~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

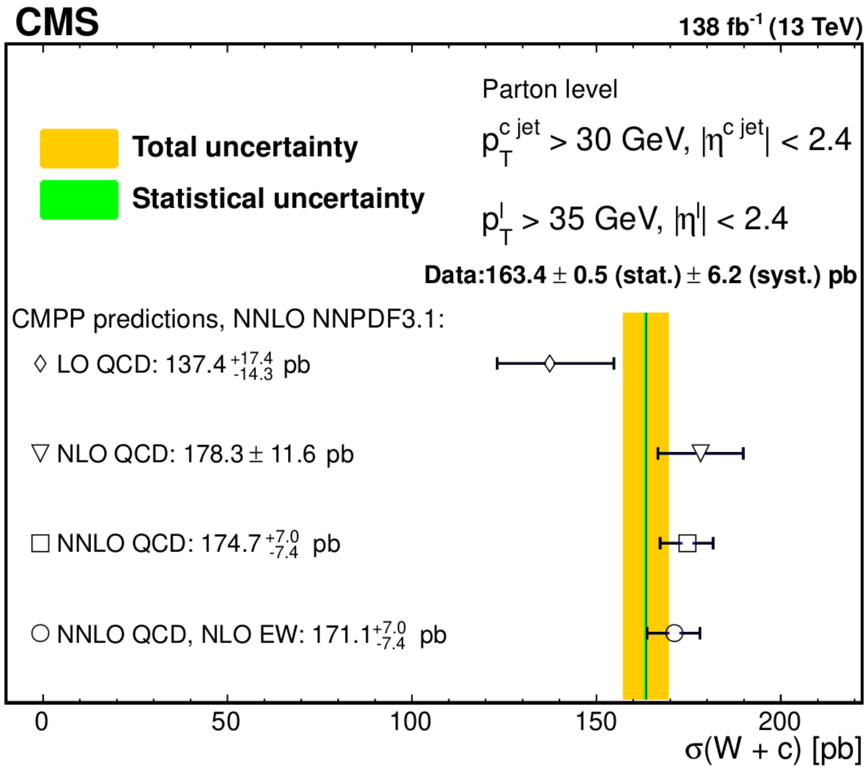
Similar phase space:

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

Measurement of OS – SS cross-section unfolded to parton-level (anti-kT algorithm)

→ hadronisation and fragmentation corr. ~ 10%

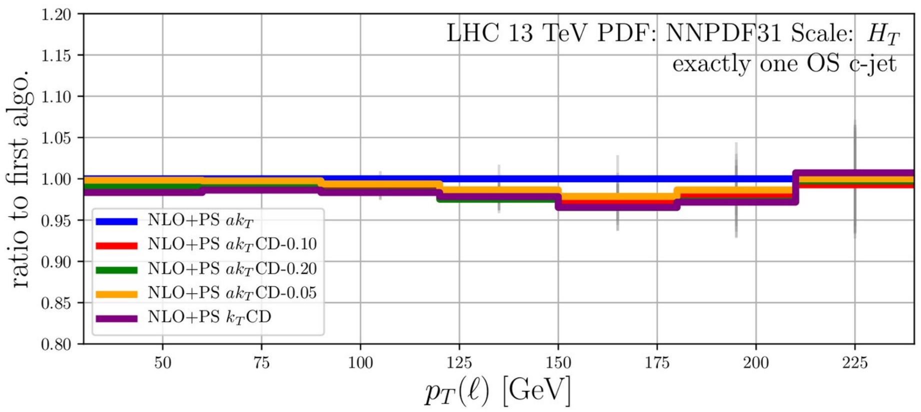
+ anti-kT → flv. Anti-kT correction on fixed-order

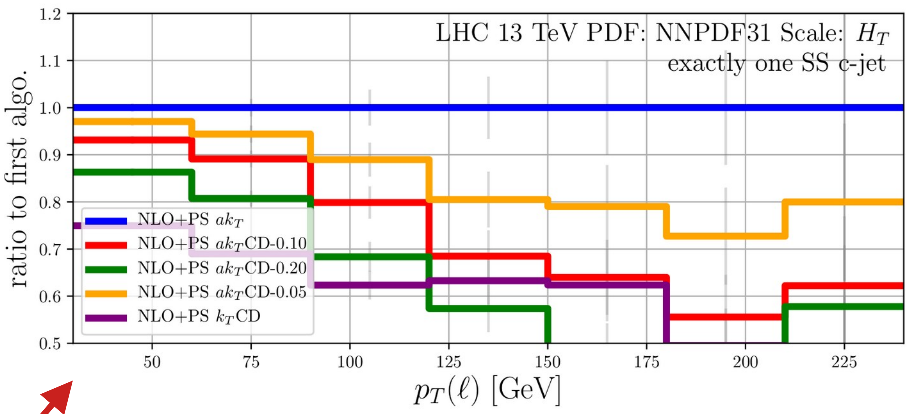


Not ideal but a full flv. Anti-kT unfolding was not feasible at that time…

Unfolding corrections

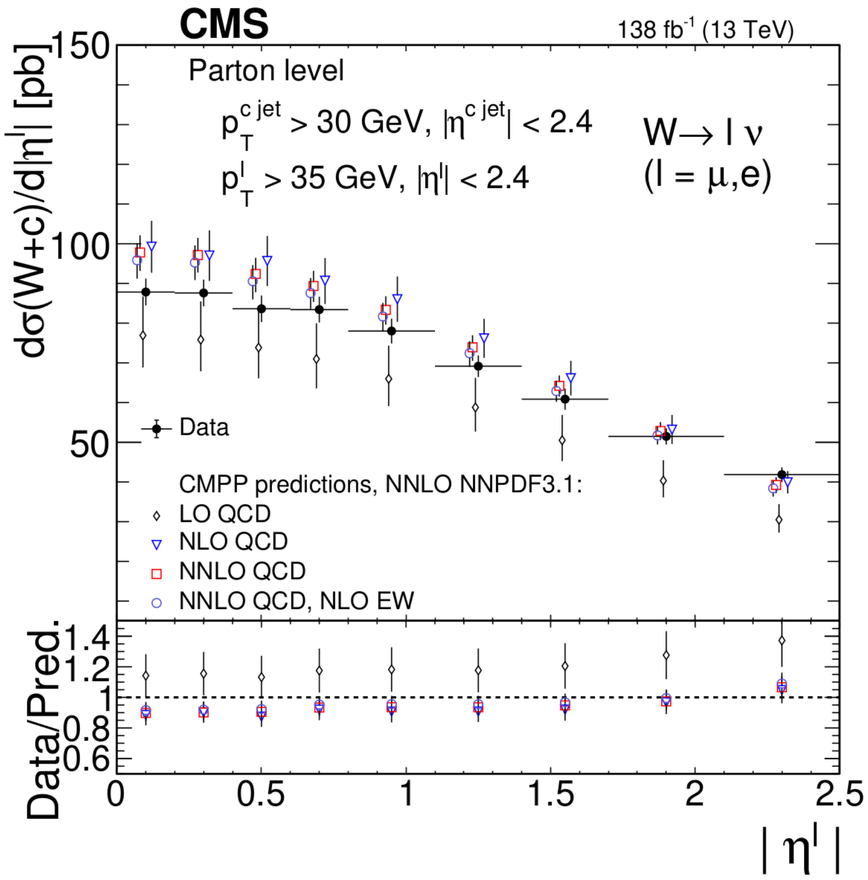
NLO+PS (fl. anti-kT) / NLO+PS (anti-kT)

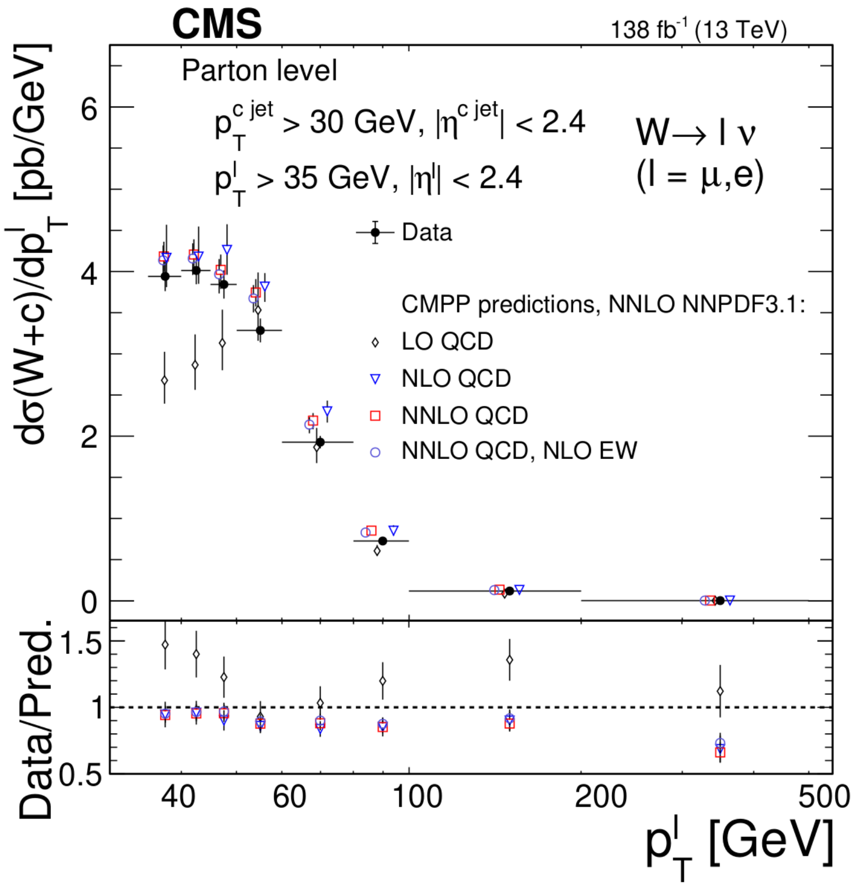




SS ~2-5% of OS
→ OS – SS unfolding corrections < 2%

Comparison to CMS data





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

Comparisons

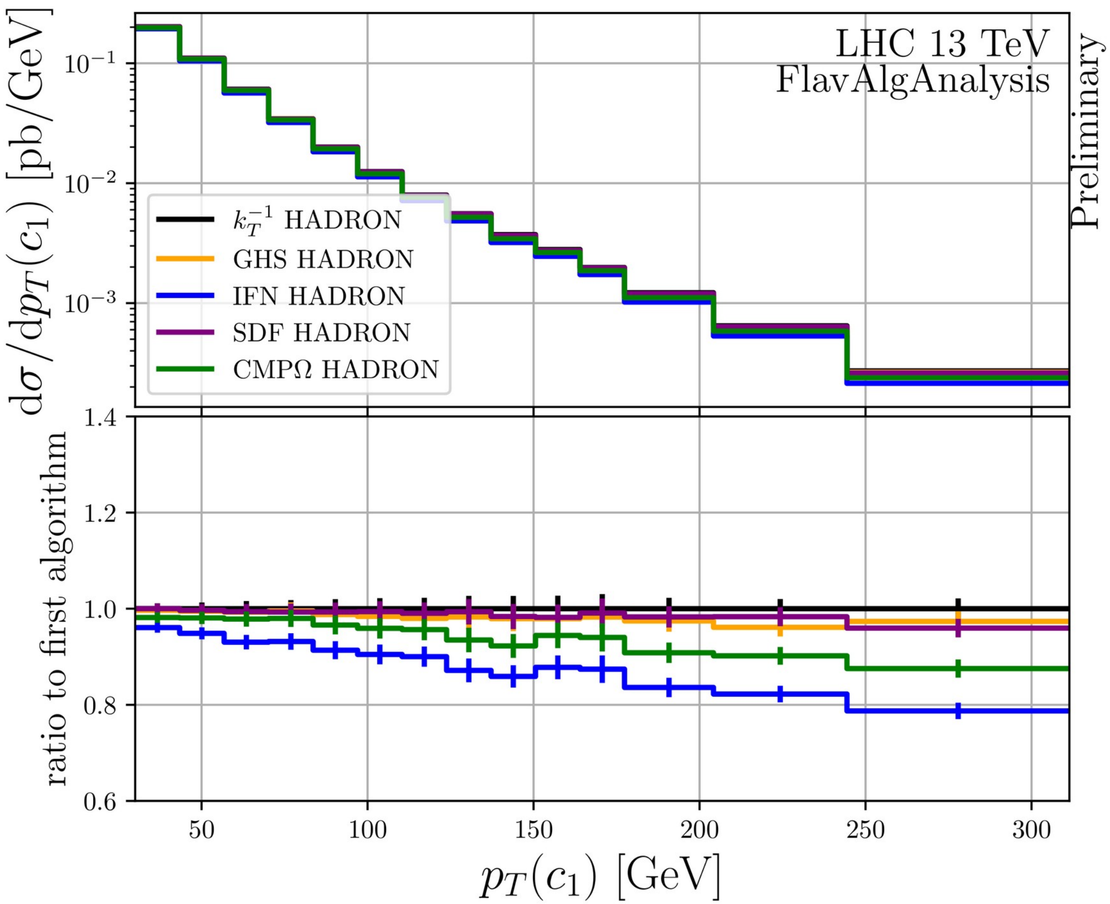
Les Houches effort

- Recommendation on the usage of these algorithms
- Recommendation for flavoured jet definitions for phenomenology
- Phenomenological comparisons of these algorithms
  NLO+PS + NNLO QCD where possible:
  - pp → Z + b-jet / Z + c-jet (LHCb and CMS/ATLAS phase space)
  - pp → W+charm
  - pp → WH(→ bb)
- Estimation of impact on experimental flavour tagging

Comparison with parton showers

Les Houches Jet Flavour WG

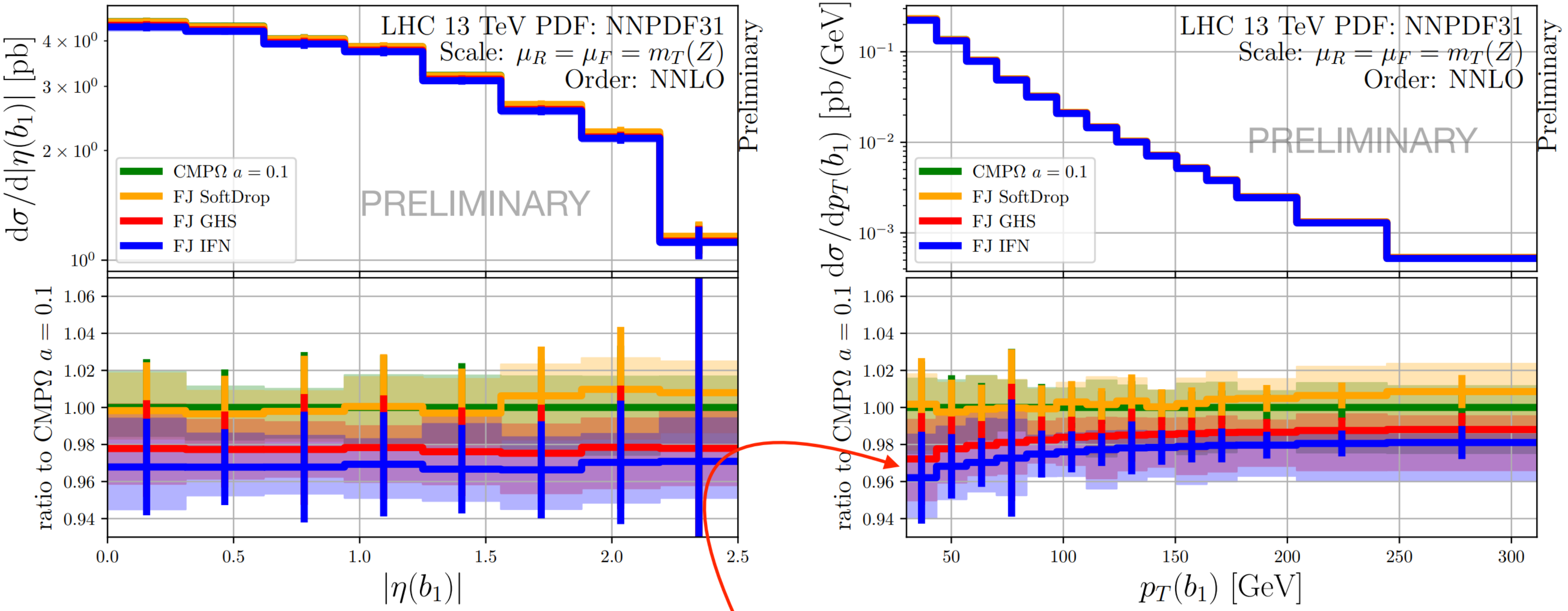
Benchmark:
pp → Z+charm



NNLO QCD comparisons

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

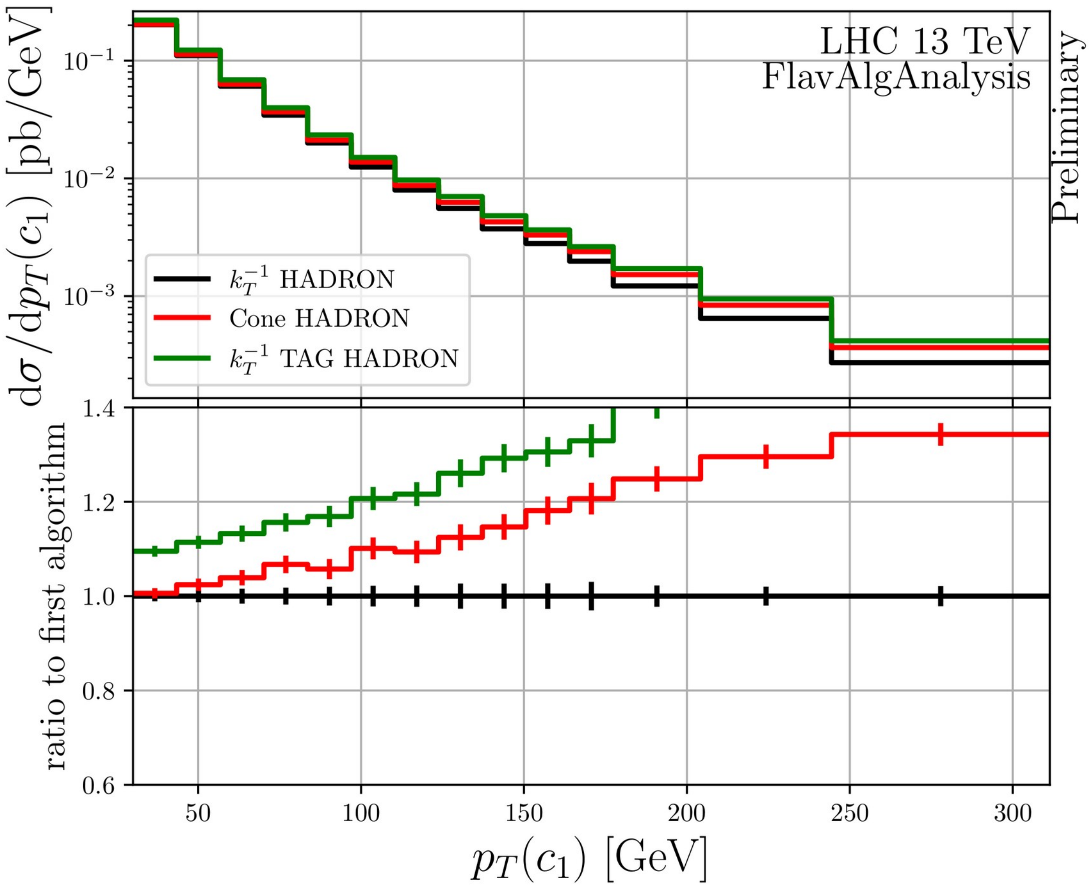
Les Houches Jet Flavour WG



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

Comparison to experimental truth tagging

- AKT (b $\bar{b}$ = g)
- CONE <=> ATLAS
- TAG <=> CMS



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

Associated production of a W boson and massive bottom quarks at next-to-next-to-leading order in QCD,
Buonocore, Devoto, Kallweit, Mazzitelli, Rottoli, Savoini, 2212.04954

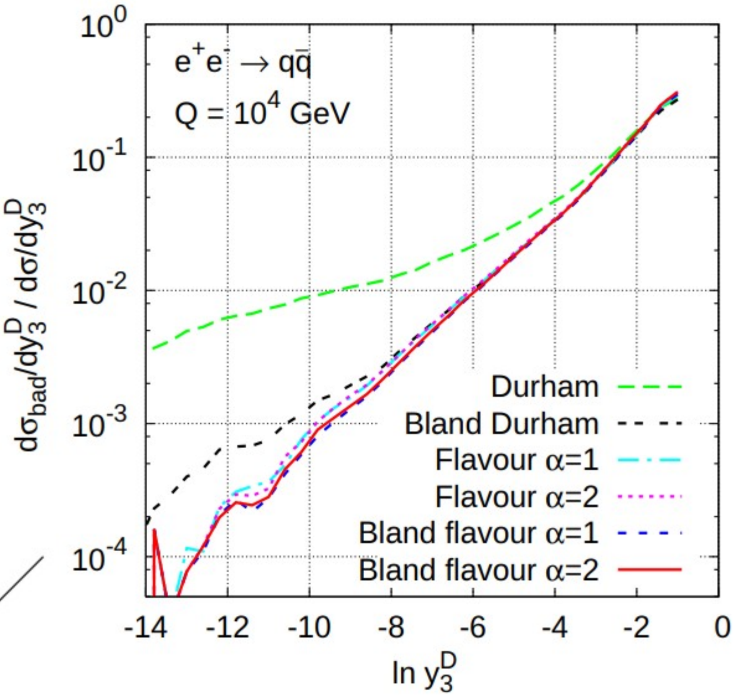
NNLO QCD predictions for Z-boson production in association with a charm jet within the LHCb fiducial region
Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, Stagnitto 2302.12844

Precise QCD predictions for W-boson production in association with a charm jets
Gehrmann-De Ridder, Gehrmann, Glover, Huss, Garcia, Stagnitto, 2311.14991

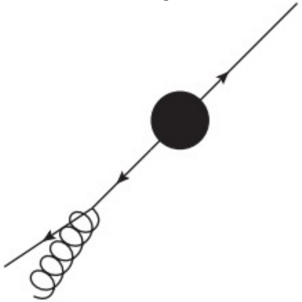
Tests of IR safety

Tests of IR safety

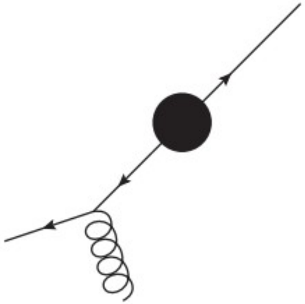
- Rate of bad-identified jet-flavour as a function of IR sensitive variable
- Parton-shower to model many emissions



Small y3

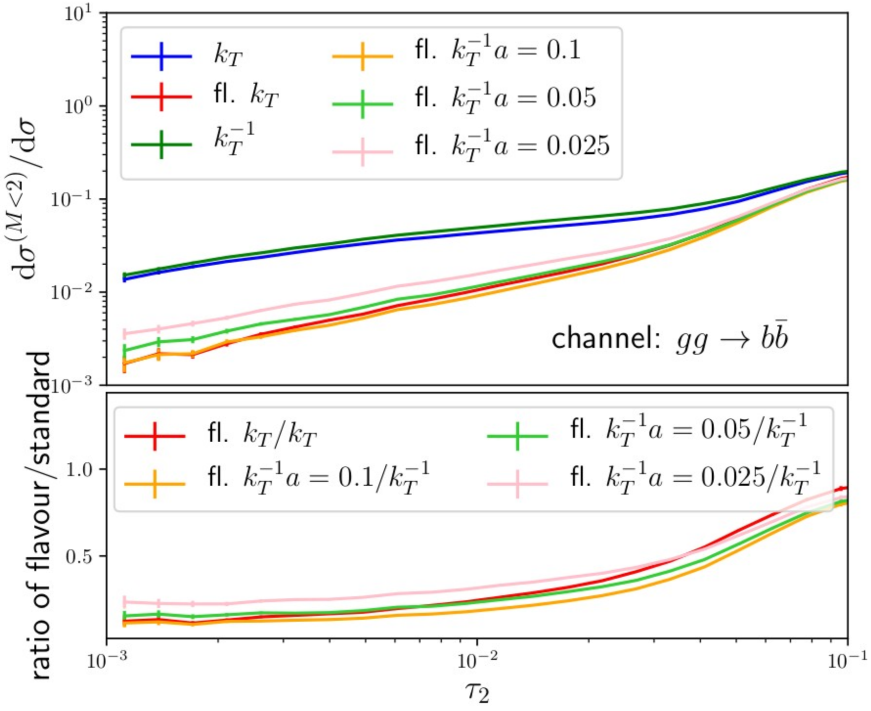


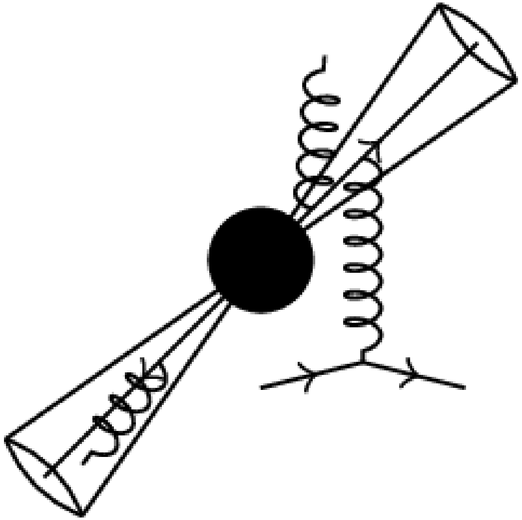
Large y3



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





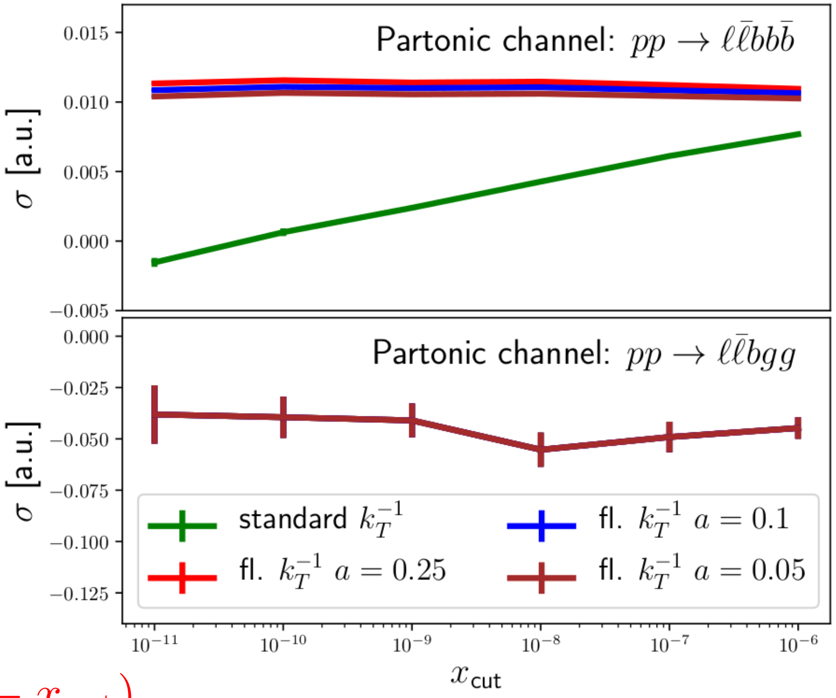
Tests of IR safety with NNLO FO computations

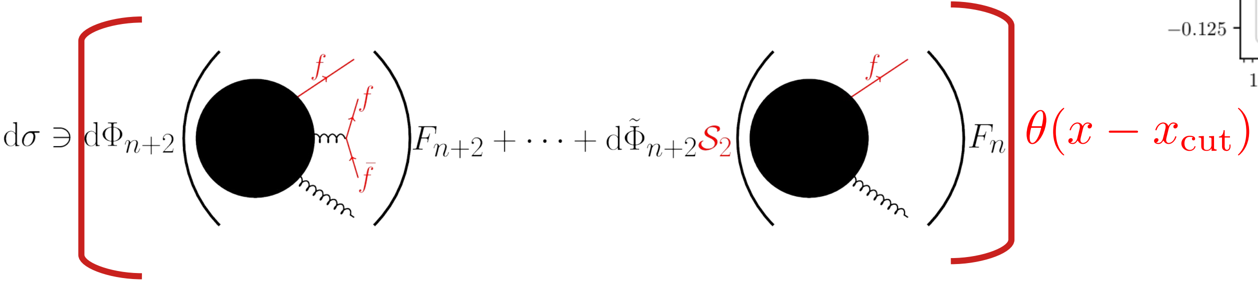
IR sensitivity of jet cross sections on (technical) IR regulating parameter x

In the limit x_cut → 0:

IR safe jet flavour → no dependence on x_cut

IR non-safe jet flavour → logarithmic divergent



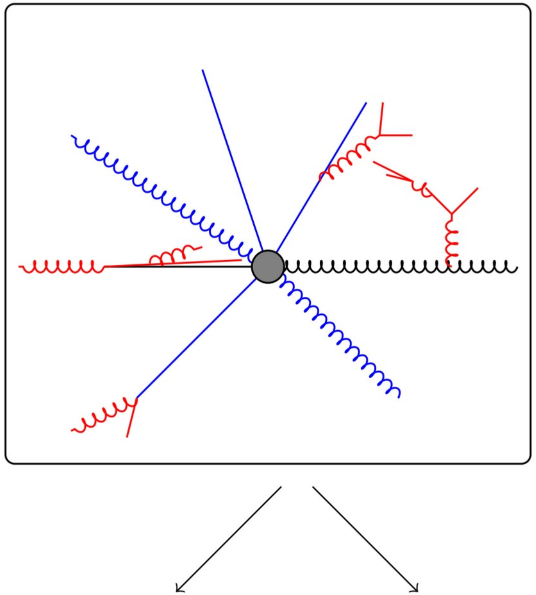


More tests...

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

- IRC safety testing suite:

Credit: Ludo Scyboz



Set of hard jets $\stackrel{!}{=}$ Set of hard+IRC jets

$\mathcal{J}_{\text{hard}} = \{(p_1, f_1), \ldots\} \stackrel{!}{=} \mathcal{J}_{\text{hard+IRC}} = \{(\tilde{p}_1, \tilde{f}_1), \ldots\}$

More tests...

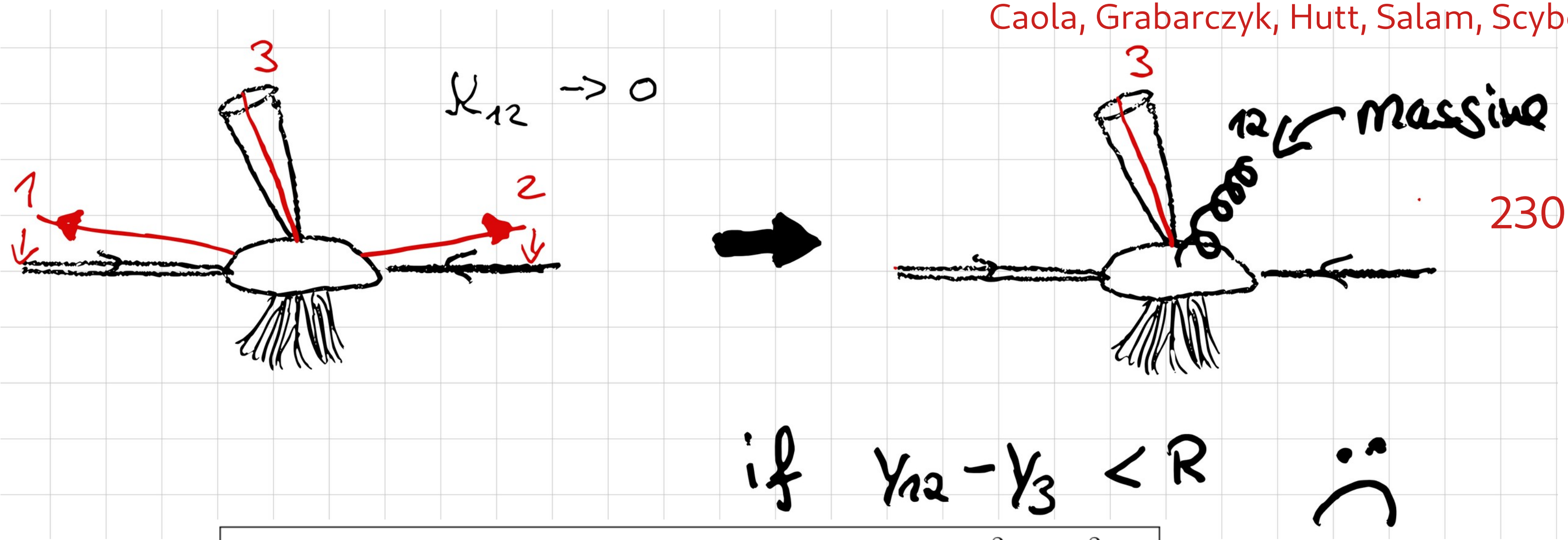
Flavoured jets with exact anti-kT kinematics and tests of infrared and collinear safety
Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler 2306.07314

order relative to Born		anti-k_t	flav-k_t ($\alpha = 2$)	CMP	GHS$_{\alpha,\beta}$ (2, 2)	anti-k_t+IFN$_\alpha$	C/A+IFN$_\alpha$
α_s	FHC	✓	✓	✓	✓	✓	✓
	IHC	✓	✓	✓	✓	✓	✓
α_s^2	FDS	✗ II B	✓	✓	✓	✓	✓
	IDS	✗ II B	✓	✓	✓	✓	✓
	FHC×IHC	✓	✓	✓	✓	✓	✓
	IHC^2	✓	✓	✗ C 2	✓	✓	✓
	FHC^2	✓	✓	✓	✗ C 4	✓	✓
α_s^3	IHC×IDS		~ C 1	✗ C 3	~ C 1	✓	✓
	rest					✓	✓
α_s^4	IDS×FDS				✗ C 5	✓	✓
	rest					✓	✓
α_s^5						✓	✓
α_s^6						✓	✓

Improved distance for CMP/flavour anti-kT

Issue for double collinear limits wrt. to initial states

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



2306.07314

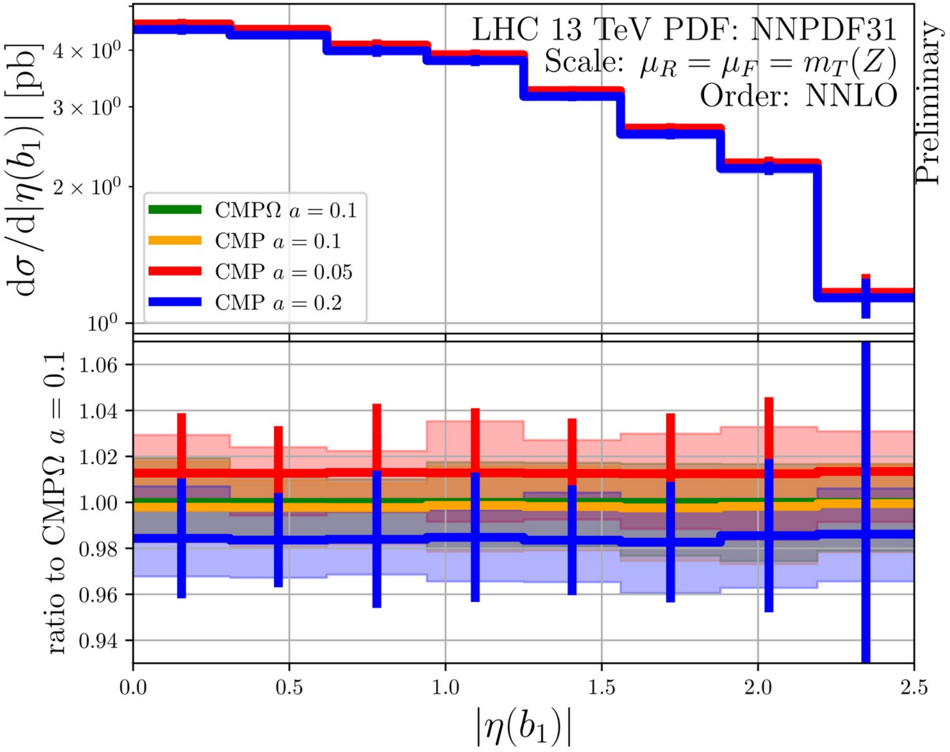
$$\mathcal{S}_{ij} \equiv 1 - \theta\left(1 - \kappa_{ij}\right) \cos\left(\frac{\pi}{2}\kappa_{ij}\right) \quad \text{with} \quad \kappa_{ij} \equiv \frac{1}{a} \frac{k_{T,i}^2 + k_{T,j}^2}{2k_{T,\max}^2} .$$

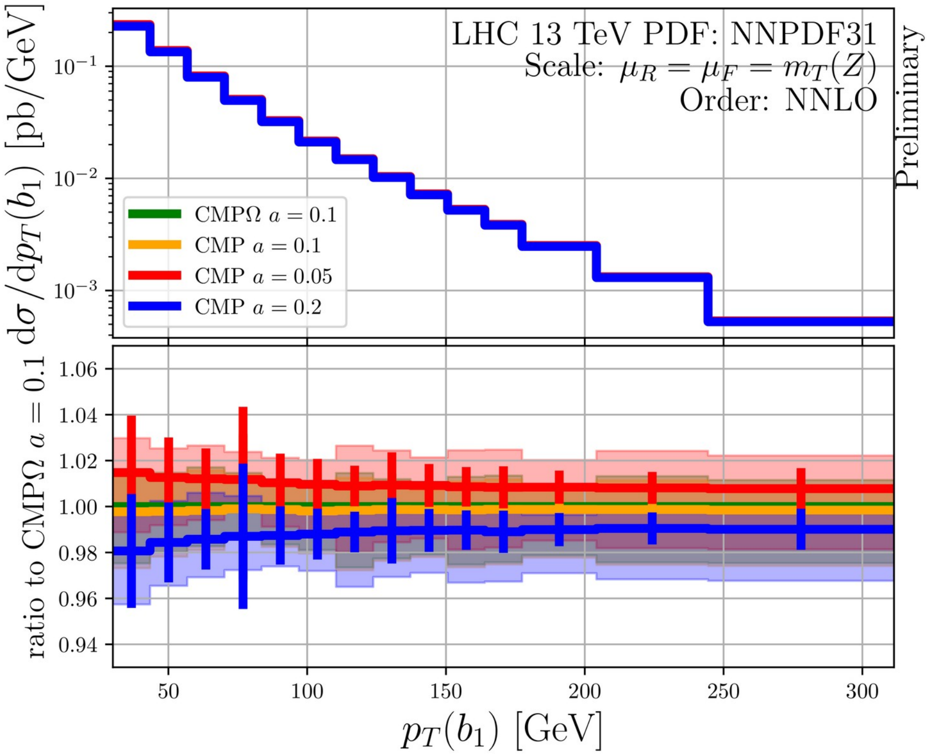
Their proposal: $$\mathcal{S}_{ij} \to \overline{\mathcal{S}}_{ij} = \mathcal{S}_{ij} \frac{\Omega_{ij}^2}{\Delta R_{ij}^2} \qquad \Omega_{ik}^2 \equiv 2\left[\frac{1}{\omega^2}\left(\cosh(\omega \Delta y_{ik}) - 1\right) - \left(\cos\Delta\phi_{ik} - 1\right)\right]$$

Flavour anti-kT: impact of Ω_ij

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

Les Houches Jet Flavour WG



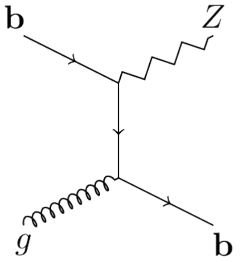


Negligible difference between CMPΩ and CMP

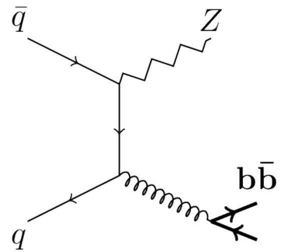
Benchmark process: Z+b-jet

pp → Z(ll) + b-jet

5fs:



4fs:



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

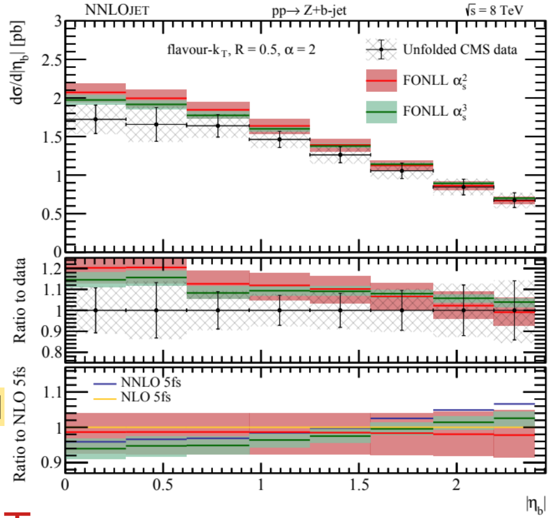
Predictions for Z-Boson Production in Association with a b-jet at O(a_s^3), Gauld, Gehrmann-De Ridder, Glover, Huss, Majer 2005.03016

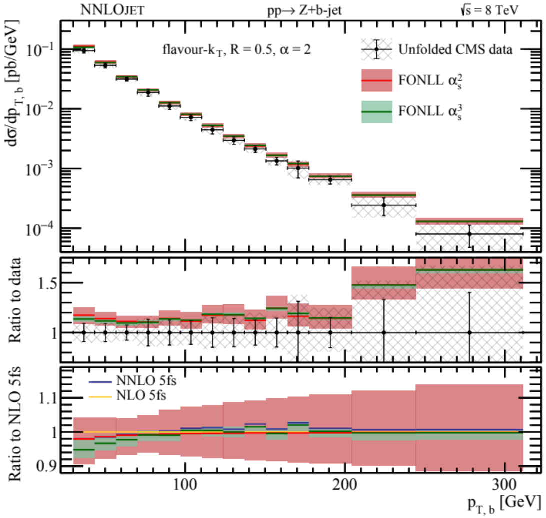
- Flavour-kT algorithm
- Unfolding of experimental data (RooUnfold, bin-by-bin unfolding)
- Matching between four- and five-flavour schemes (FONLL)

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

- 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



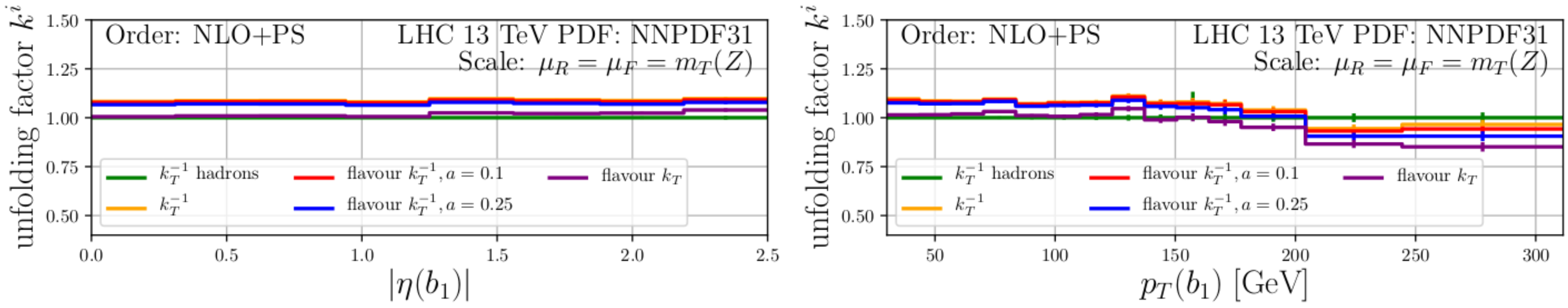


→ Ideal testing ground for flavour anti-kT

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)



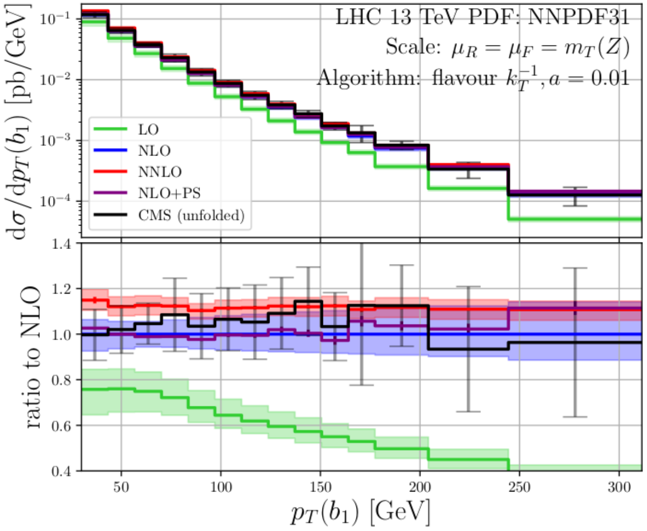
Z+b-jet Phenomenology: Tunable parameter

Benchmark process: pp → Z(ll) + b-jet

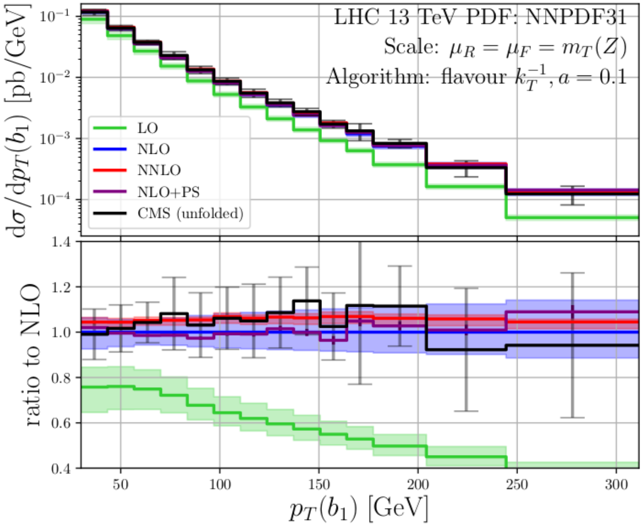
Tunable parameter a:

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

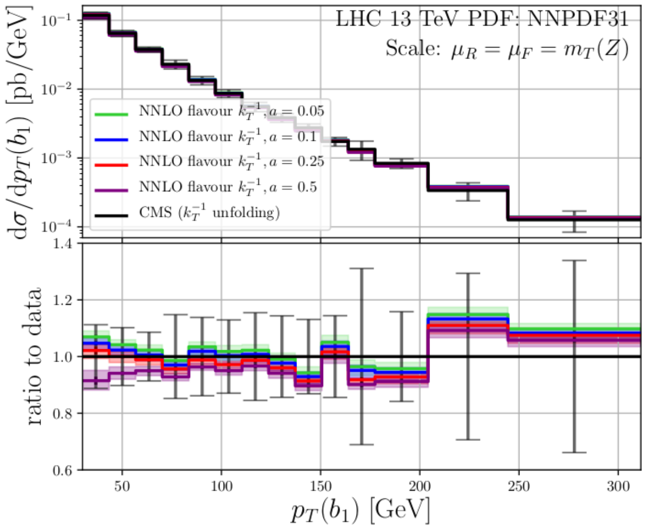
Flavour anti-kT (a=0.01):



Flavour anti-kT (a=0.1):

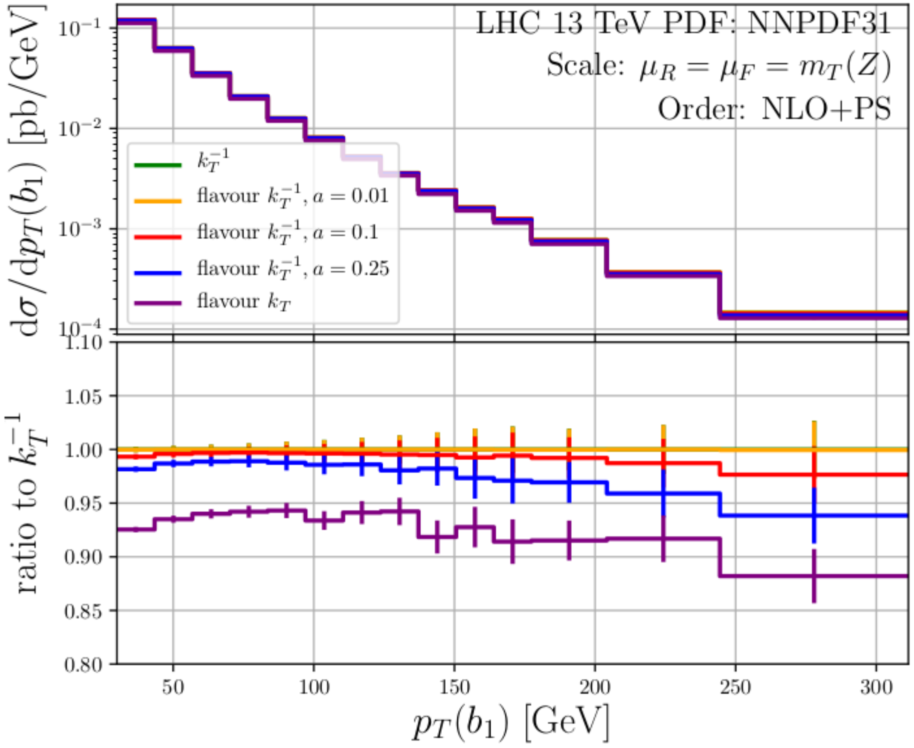


Comparison of different parameter a to data:



Z+b-jet Phenomenology: Tunable parameter II

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



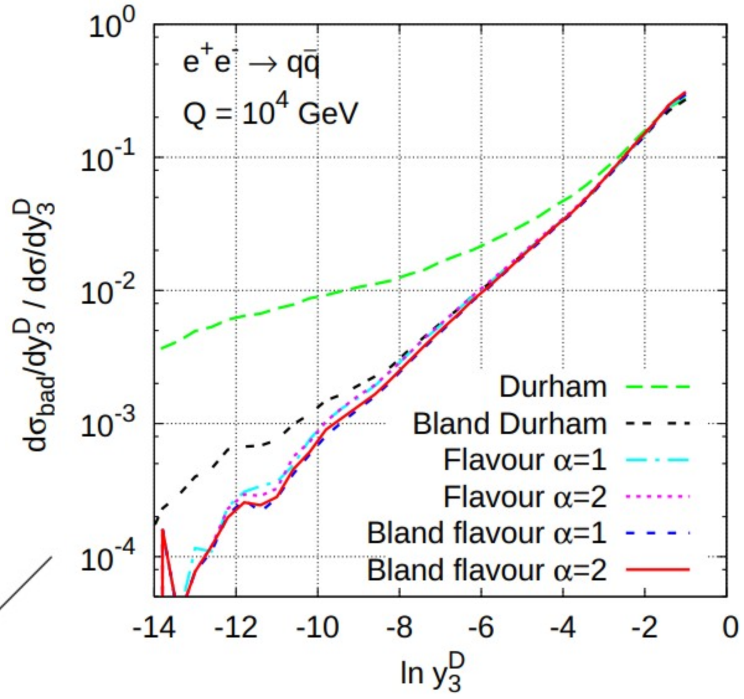
Tunable parameter a:

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

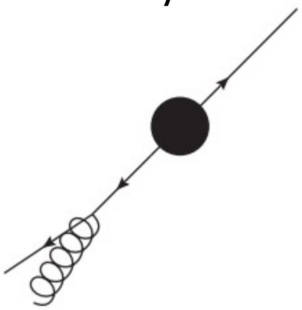
Good FO perturbative convergence + Small difference to standard anti-kT → a~0.1 is a good candidate

Tests of IR safety

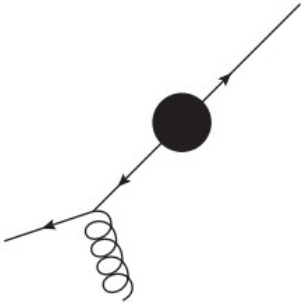
- Rate of bad-identified jet-flavour as a function of IR sensitive variable
- Parton-shower to model many emissions



Small y3



Large y3



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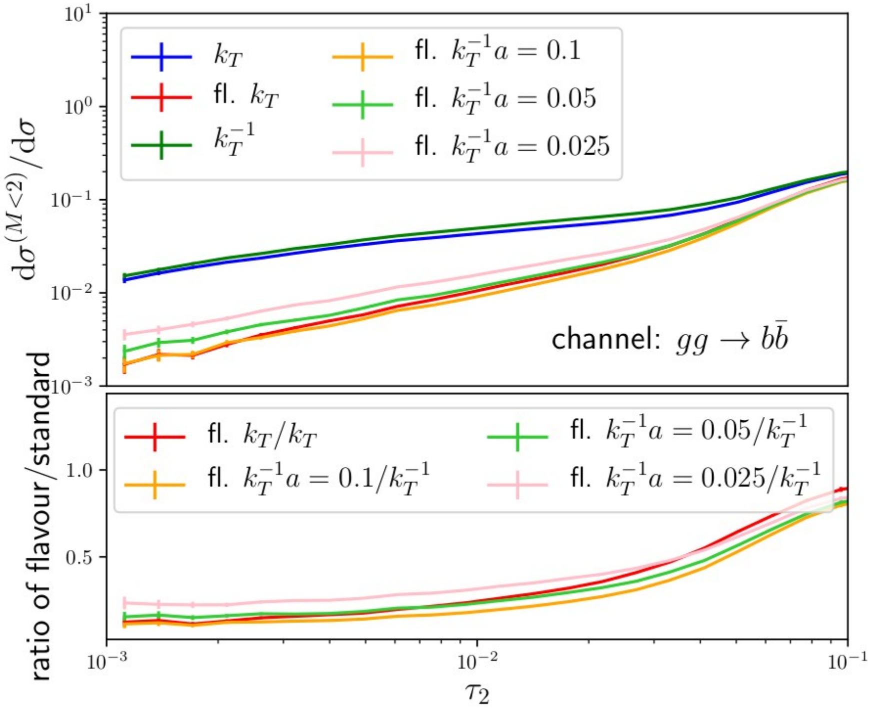

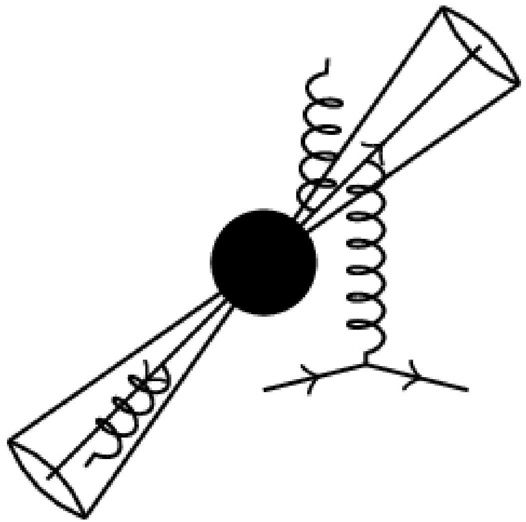

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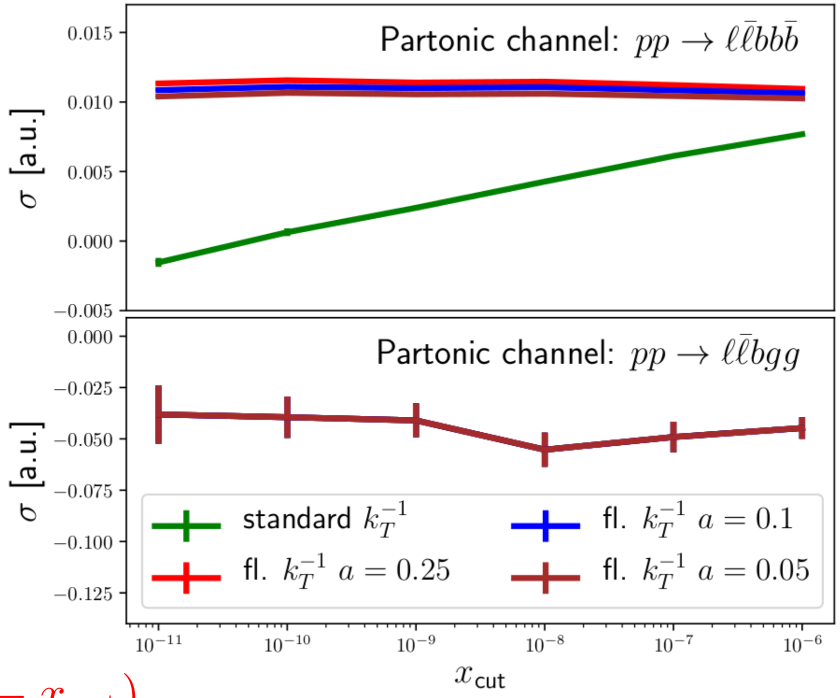

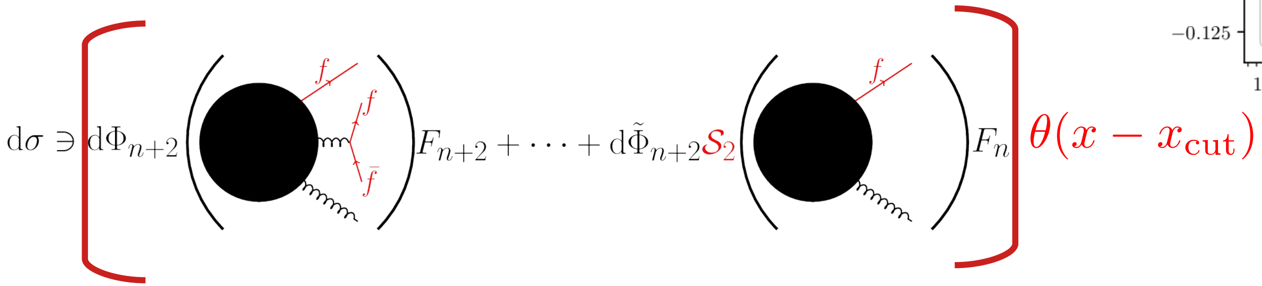

New developments...

Issue for double collinear limits wrt. to initial states

Many thanks to
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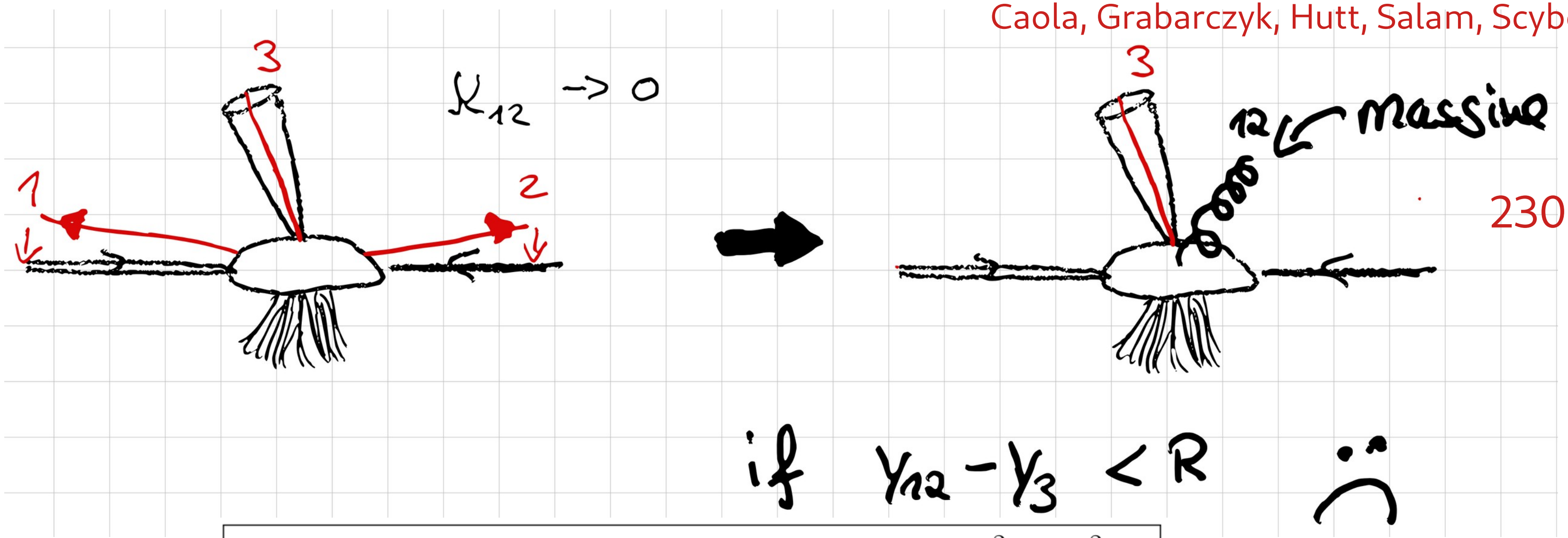

2306.07314

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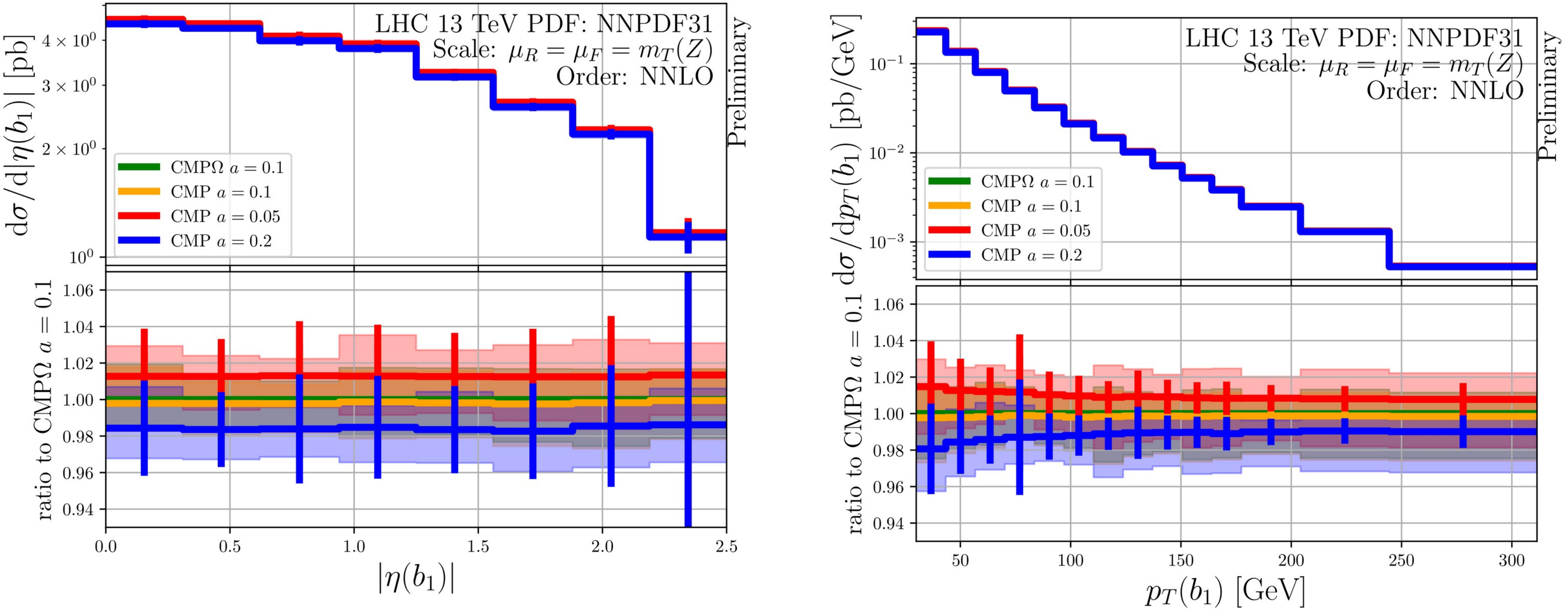
1408.2500 & 1907.12911

Les Houches Jet Flavour WG



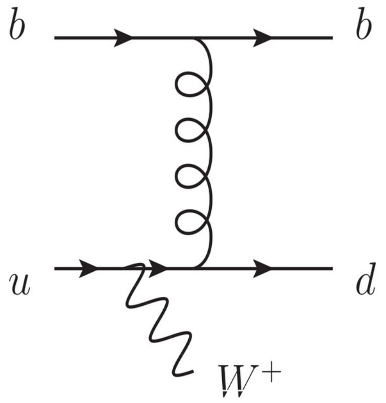
Negligible difference between CMPΩ and CMP

W + bottom-pairs

W + b - jets

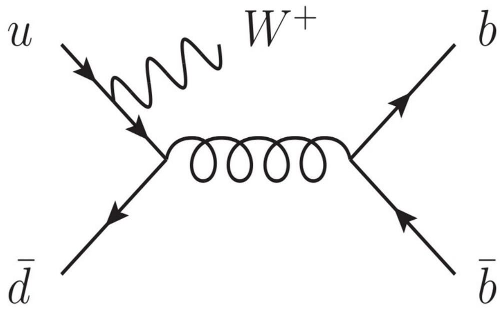
Motivation: → testing perturbative QCD: large NLO QCD corrections, 4FS vs. 5 FS
→ modelling of flavoured jets

W + 1b-jet



→ probe b quark PDFs

W + 2b-jet



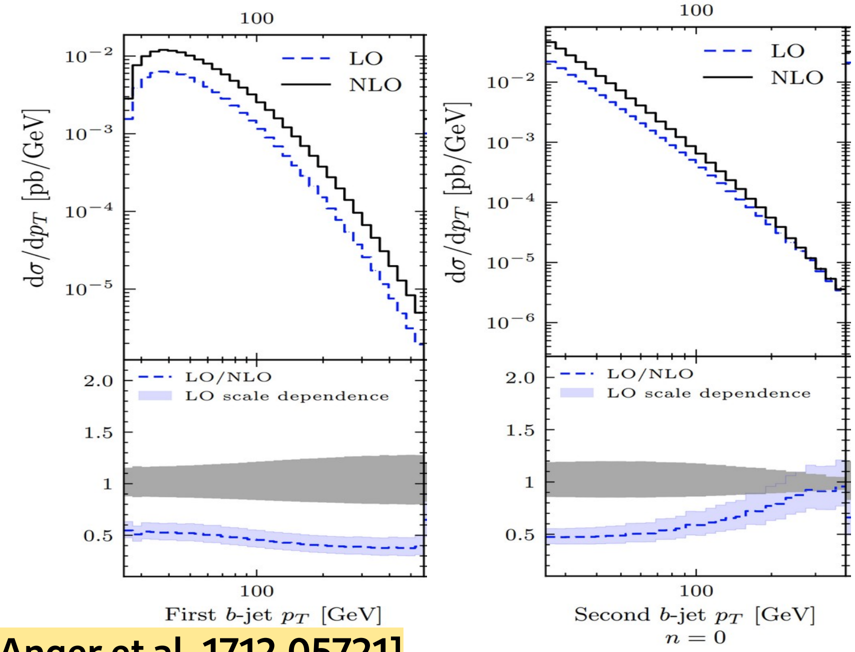
background for:
→ WH(H→ bb)
→ single top

NLO QCD corrections

Experiment: **[D0,1210.0627,0410062] [ATLAS,1109.1470,1302.2929][CMS,1312.6608,1608.07561]**

Theory W+1 b-jet: **[Campbell et al,0611348,0809.3003][Caola et.al.,1107.3714]**

Theory W+2 b-jet: mb=0 **[Ellis et al,9810489]** onshell W: **[Cordero et al,0606102]**W(lv)bb: **[Campbell et al,1011.6647]**
NLO+PS: **[Oleari et al,1105.4488][Frederix et al,1110.5502]** W(lv)bb: **[Luisoni et al,1502.01213]**
W(lv)bb+≤3j: **[Anger et al, 1712.05721]**



[Anger et al, 1712.05721]

- Large NLO QCD corrections + scale dependence
- Opening of qg-channel

- NNLO QCD corrections required!
  Main challenges:
  - Twoloop amplitudes [Bager'21,Hartanto'22]
  - Subtraction for high-multiplicity processes → Stripper [Czakon'10'14'19]

Setup

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

- LHC @ 8 TeV in 5 FS, NNPDF31, scale: $H_T = E_T(l\nu) + pT(b1) + pT(b2)$
- Phasespace definition to model **[CMS, 1608.07561]:**
  $pT(l) \geq 30$ GeV $|y(l)| < 2.1$ $pT(j) \geq 25$ GeV, $|y(j)| < 2.4$
- Inclusive (at least 2 b-jets) and exclusive (exactly 2 b-jets, no other jets) jet phase spaces (defined by the flavour-kT jet algorithm [Banfi'06])

	inclusive [fb]	$\mathcal{K}_{\rm inc}$	exclusive [fb]	$\mathcal{K}_{\rm exc}$
$\sigma_{\rm LO}$	$213.2(1)^{+21.4\%}_{-16.1\%}$	-	$213.2(1)^{+21.4\%}_{-16.1\%}$	-
$\sigma_{\rm NLO}$	$362.0(6)^{+13.7\%}_{-11.4\%}$	1.7	$249.8(4)^{+3.9(+27)\%}_{-6.0(-19)\%}$	1.17
$\sigma_{\rm NNLO}$	$445(5)^{+6.7\%}_{-7.0\%}$	1.23	$267(3)^{+1.8(+11)\%}_{-2.5(-11)\%}$	1.067

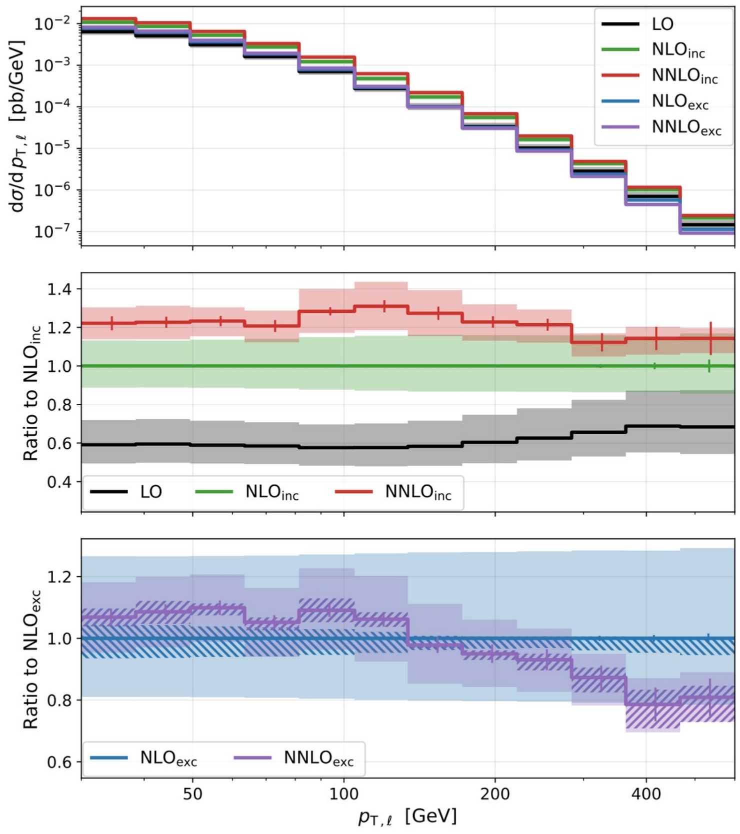
- Inclusive :
  ~ +20% corrections
  ~ 7% scale dependence
- Exclusive:
  ~ + 6% corrections
  ~ 2.5% scale dependence (7-pt)
  Compare decorrelated model: [Steward'12]
  ~ 11% scale dependence

$$\sigma_{Wb\bar{b},\text{excl.}} = \sigma_{Wb\bar{b},\text{incl.}} - \sigma_{Wb\bar{b}j,\text{incl.}}$$

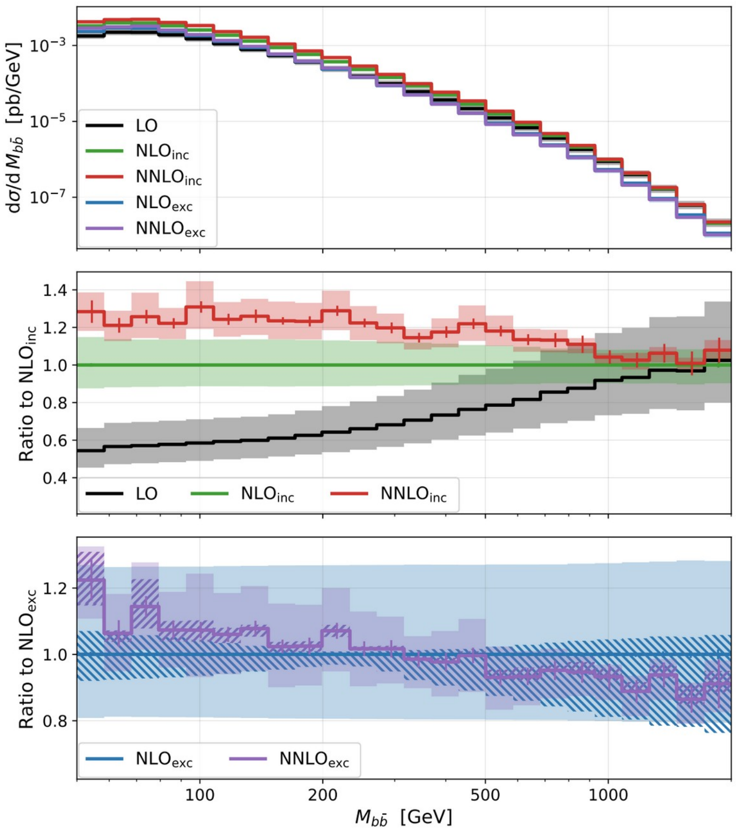
$$\Delta\sigma_{Wb\bar{b},excl.} = \sqrt{(\Delta\sigma_{Wb\bar{b},incl.})^2 + (\Delta\sigma_{Wb\bar{b}j,incl.})^2}$$

Differential cross sections

Transverse momentum of lepton

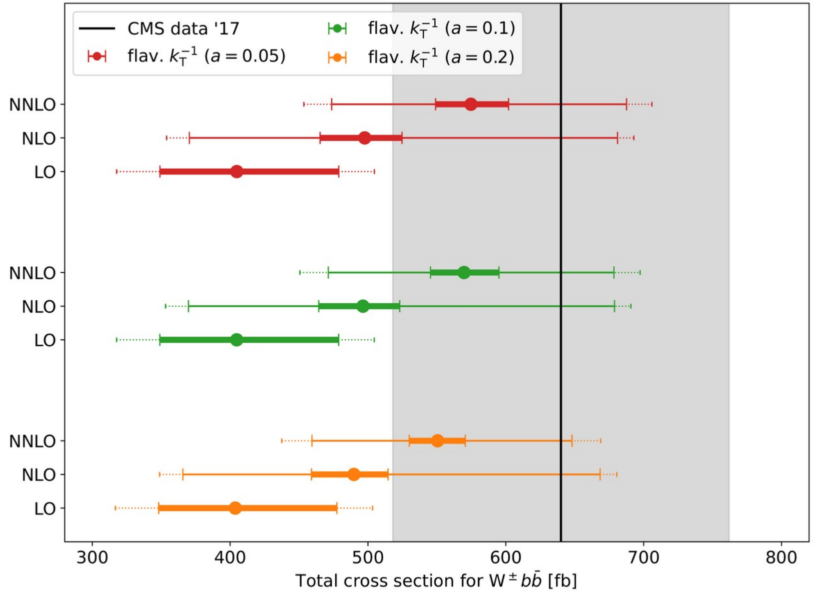


Invariant mass b-jet pair



W+2 bjets: flavour anti-kT

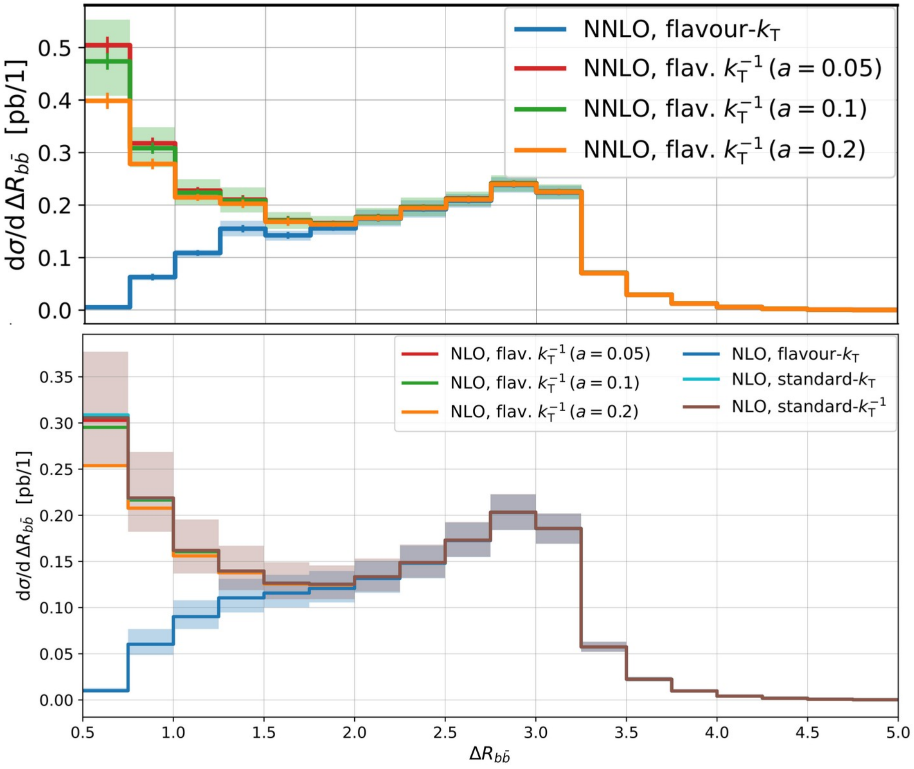
Flavour anti-kT algorithm applied to Wbb production at the LHC
Hartanto, **Poncelet**, Popescu, Zoia 2209.03280



Comparison to data

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

(assumes small unfolding corrections → wip)



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

Computation in 4FS

Associated production of a W boson and massive bottom quarks at next-to-next-to-leading order in QCD,
Buonocore, Devoto, Kallweit, Mazzitelli, Rottoli, Savoini, 2212.04954

Credit: Luca Buonocore
RadCor23

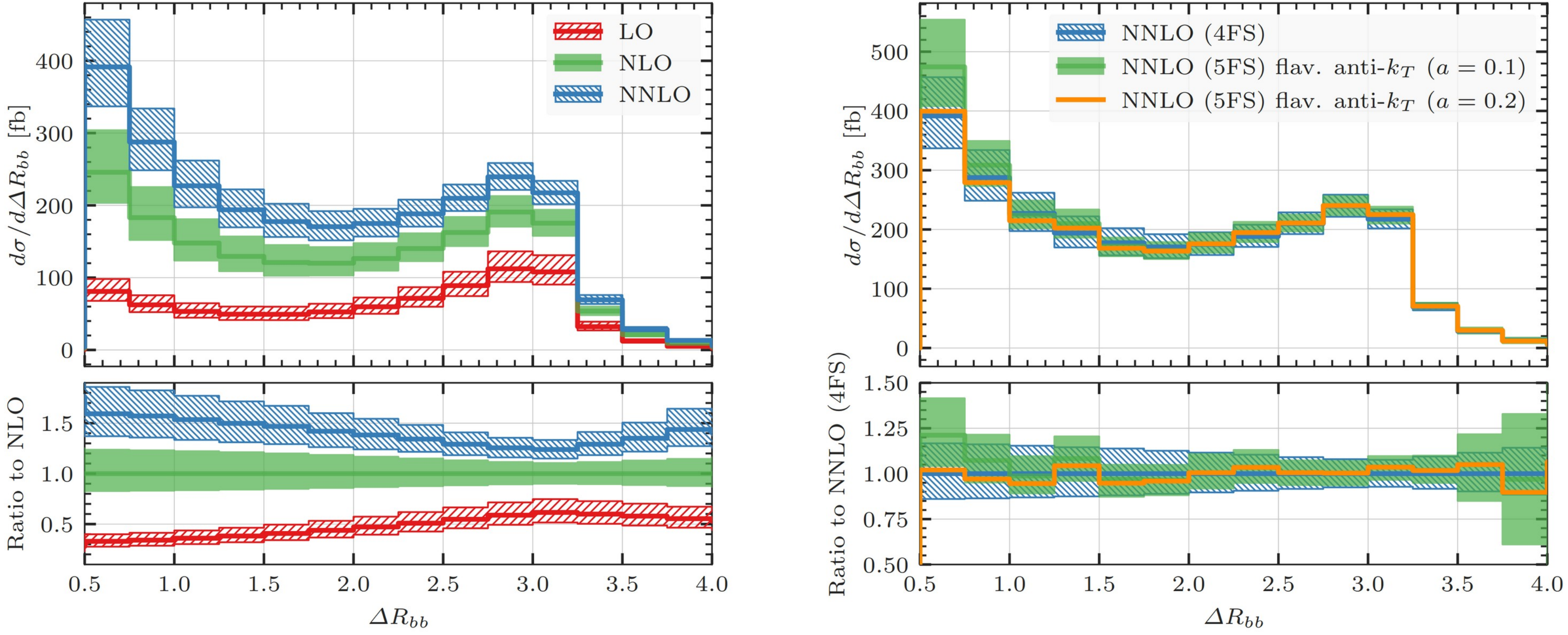
	2209.03280	2212.04954
α_s and PDF scheme	5FS	4FS
Jet clustering algorithm	flavour k_T and flavour anti-k_T algorithm (R=0.5)	k_T and anti-k_T algorithm (R=0.5)
pdf sets	NNPDF31_as_0118 (LO, NLO, NNLO)	NNPDF30_as_0118_nf_4 (LO) NNPDF31_as_0118_nf_4 (NLO, NNLO)

Simplification of massive 2-loop amplitude (Massification) [Mitov, Moch '07]:

$$|\mathcal{M}^{[p],(m)}> = \prod_i \left[Z_{[i]}\left(\frac{m^2}{\mu^2}, \alpha_s(\mu^2), \epsilon\right)\right]^{1/2} \times |\mathcal{M}^{[p]}> + \mathcal{O}\left(\frac{m^2}{Q^2}\right)$$

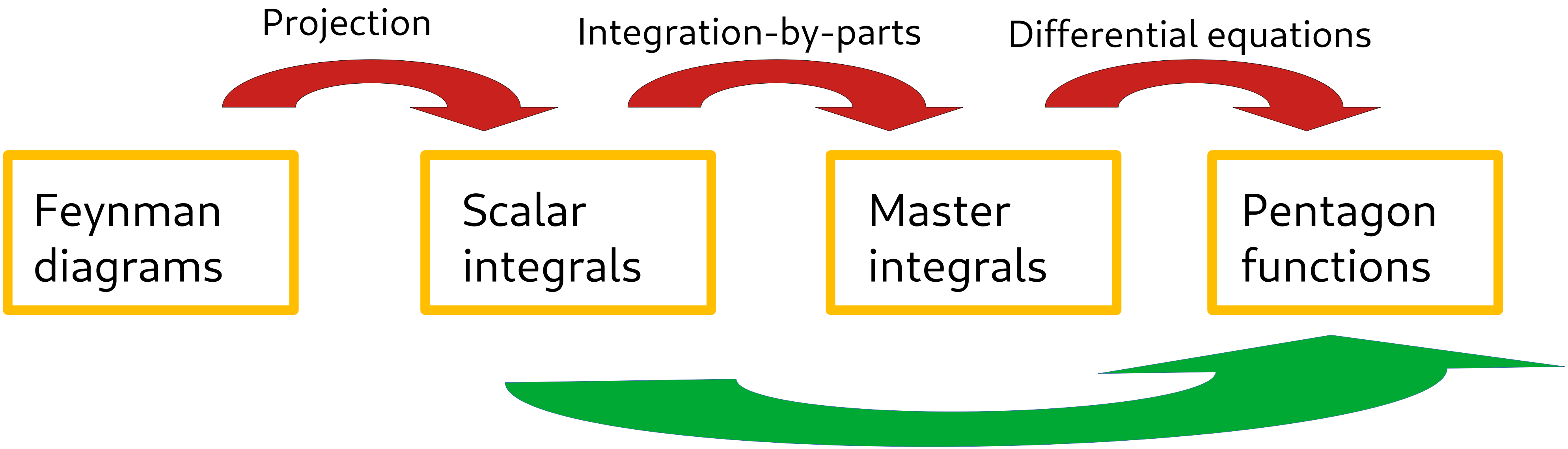
Comparison 4FS(+PS) vs 5FS

Associated production of a W boson and massive bottom quarks at next-to-next-to-leading order in QCD,
Buonocore, Devoto, Kallweit, Mazzitelli, Rottoli, Savoini, 2212.04954



Overview

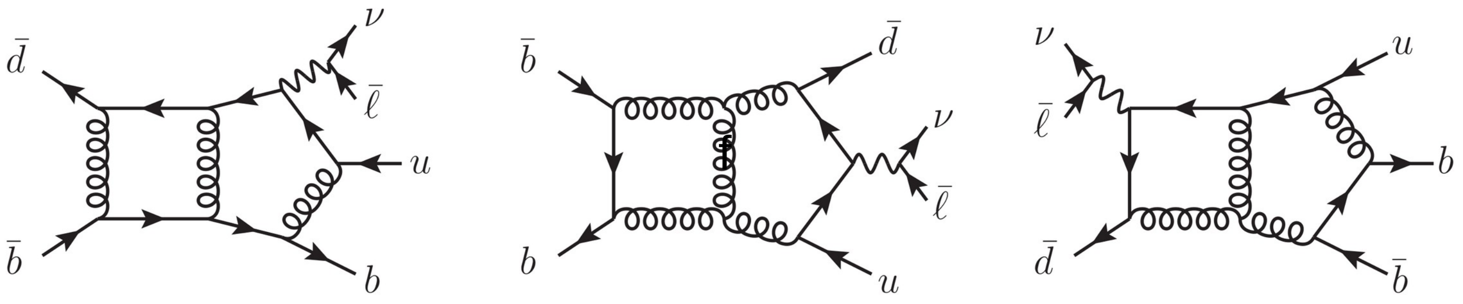
Old school approach:



Automated framework using finite fields to avoid expression swell based on FiniteFlow [Peraro'19]

Projection to scalar integrals

Generate diagrams (contributing to leading-colour) with QGRAF



Factorizing decay: $A_6^{(L)} = A_5^{(L)\mu} D_\mu P$ $\qquad$ $M_6^{2(L)} = \sum_{\text{spin}} A_6^{(0)^*} A_6^{(L)} = M^{(L)\mu\nu} D_{\mu\nu} |P|^2$

Projection on scalar functions (FORM+Mathematica):
→ anti-commuting γ_5 + Larin prescription

$$M_5^{(L)} = \sum_{i=1}^{16} a_i^{(L)} v_i^{\mu\nu}$$

$$a_i^{(L)} = a_i^{(L),\text{even}} + \text{tr}_5 a_i^{(L),\text{odd}} \qquad a_i^{(L),p} = \sum_i c_{j,i}(\{p\},\epsilon)\mathcal{I}(\{p\},\epsilon)$$

Integration-By-Parts reduction

$$a_i^{(L),p} = \sum_i c_{j,i}(\{p\},\epsilon)\mathcal{I}(\{p\},\epsilon)$$

Prohibitively large number of integrals

$$\mathcal{I}_i(\{p\},\epsilon) \equiv \mathcal{I}(\vec{n_i},\{p\},\epsilon) = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d}\prod_{k=1}^{11} D_k^{-n_{i,k}}(\{p\},\{k\})$$

Integration-By-Parts identities connect different integrals → system of equations
→ only a small number of independent “master” integrals

$$0 = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d} l_\mu \frac{\partial}{\partial l^\mu}\prod_{k=1}^{11} D_k^{-n_{i,k}}(\{p\},\{k\}) \quad \text{with} \quad l \in \{p\} \cap \{k\}$$

LiteRed (+ Finite Fields)

$$a_i^{(L),p} = \sum_i d_{j,i}(\{p\},\epsilon)\mathrm{MI}(\{p\},\epsilon)$$

Master integrals & finite remainder

Differential Equations: $\mathrm{d}\vec{\mathrm{MI}} = \mathrm{d}A(\{p\},\epsilon)\vec{\mathrm{MI}}$

Canonical basis: $\mathrm{d}\vec{\mathrm{MI}} = \epsilon\mathrm{d}\tilde{A}(\{p\})\vec{\mathrm{MI}}$

[Remiddi, 97]
[Gehrmann, Remiddi, 99]
[Henn, 13]

Simple iterative solution

$$\mathrm{MI}_i = \sum_w \epsilon^w \tilde{\mathrm{MI}}_i^w \quad \text{with} \quad \tilde{\mathrm{MI}}_i^w = \sum_j c_{i,j} m_j$$

Chen-iterated integrals
"Pentagon"-functions

[Chicherin, Sotnikov, 20]
[Chicherin, Sotnikov, Zoia, 21]

Putting everything together (and removing of IR poles):

$$f_i^{(L),p} = a_i^{(L),p} - \text{poles} \qquad f_i^{(L),p} = \sum_j c_{i,j}(\{p\}) m_j + \mathcal{O}(\epsilon)$$

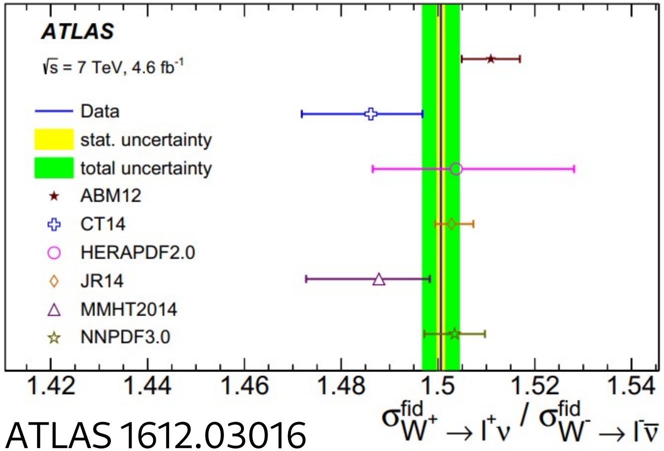
W + charm jet

Could solve long-standing puzzle:

Strange – anti – strange asymmetry

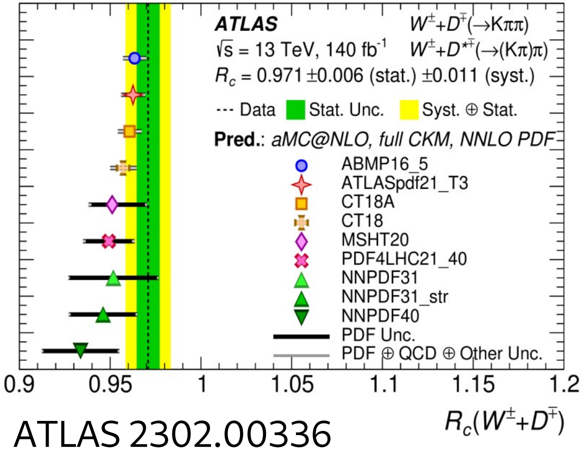
- pQCD: Three loop SM prediction q→ q' ≠ q → $\bar{q}$' small effect $\langle x(s-\bar{s})\rangle \sim 10^{-4}$
- Size of non-perturbative effect unknown

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