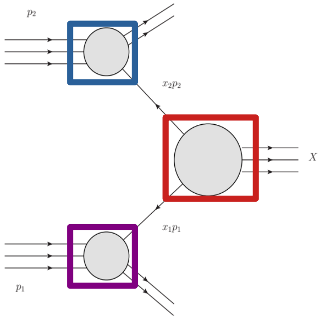
Jet calculations with the Sector-improved residue subtraction scheme

Rene Poncelet

Sector-improved residue subtraction scheme



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

PDFs

$$\boxed{\hat{\sigma}_{ab\to X} = \hat{\sigma}^{(0)}_{ab\to X} + \hat{\sigma}^{(1)}_{ab\to X} + \hat{\sigma}^{(2)}_{ab\to X} + \mathcal{O}(\alpha_s^3) \qquad \text{NNLO: } \hat{\sigma}^{(2)}_{ab} = \hat{\sigma}^{\mathrm{RR}}_{ab} + \hat{\sigma}^{\mathrm{RV}}_{ab} + \hat{\sigma}^{\mathrm{VV}}_{ab} + \hat{\sigma}^{\mathrm{C2}}_{ab} + \hat{\sigma}^{\mathrm{C1}}_{ab}}$$

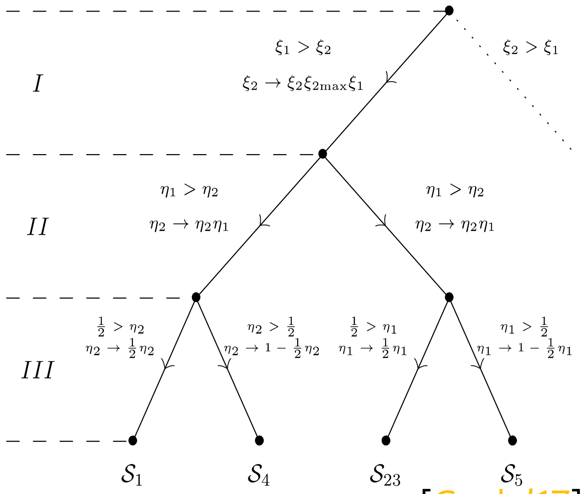
Divide and conquer IR singularities by sector decomposition:

[Czakon'10]

$$\hat{\sigma}^{\mathrm{RR}}_{ab} = \frac{1}{2\hat{s}}\int \mathrm{d}\Phi_{n+2}\sum_{i,j}\left[\sum_k \mathcal{S}_{ij,k} + \sum_{k,l}\mathcal{S}_{i,k;j,l}\right]\left\langle \mathcal{M}^{(0)}_{n+2}\middle|\mathcal{M}^{(0)}_{n+2}\right\rangle \mathrm{F}_{n+2}$$

Sector parameterization: $\hat{\eta}_i = \frac{1}{2}(1-\cos\theta_{ir}) \in [0,1] \qquad \hat{\xi}_i = \frac{u_i^0}{u_{\max}^0} \in [0,1]$

Overlapping triple collinear singularities: sub-sectors



[Caola'17]

Apply Master-formula: $$x^{-1-b\epsilon} = \underbrace{\frac{-1}{b\epsilon}}_{\text{pole term}} + \underbrace{\left[x^{-1-b\epsilon}\right]_+}_{\text{reg. + sub.}}$$

→ All contributions numerical finite integrals
→ Numerical ε – poles cancellation between real&virtual

Applications of sector-improved residue subtraction

Top-quark pairs + NWA decay

High-precision differential predictions for top-quark pairs at the LHC
Czakon, Heymes, Mitov 1511.00549

Higher order corrections to spin correlations in top quark pair production at the LHC
Behring, Czakon, Mitov, Papanastasiou, **Poncelet** 1901.05407
NNLO QCD corrections to leptonic observables in top-quark pair production and decay
Czakon, Mitov, **Poncelet** 2008.11133

Jets

Single-jet inclusive rates with exact color at $O(\alpha_s^4)$
Czakon, van Hameren, Mitov, **Poncelet** 1907.12911

Next-to-Next-to-Leading Order Study of Three-Jet Production at the LHC
Czakon, Mitov, **Poncelet** 2106.05331

Photons

NNLO QCD corrections to three-photon production at the LHC
Chawdhry, Czakon, Mitov, **Poncelet** 1911.00479

NNLO QCD corrections to diphoton production with an additional jet at the LHC
Chawdhry, Czakon, Mitov, **Poncelet** 2105.06940

Weak-bosons/Higgs

NNLO QCD study of polarised W+W- production at the LHC
Poncelet, Popescu 2102.13583

Exact Top-Quark Mass Dependence in Hadronic Higgs Production
Czakon, Harlander, Klappert, Niggetiedt 2105.04436

Weak-boson+jets

NNLO QCD predictions for W+c-jet production at the LHC
Czakon, Mitov, Pellen, **Poncelet** 2011.01011
Polarised W+j production at the LHC: a study at NNLO QCD accuracy
Pellen, **Poncelet**, Popescu 2109.14336
Angular coefficients in W+j production at the LHC with high precision
Pellen, **Poncelet**, Popescu, Vitos 2204.12394

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

NNLO QCD corrections to Wbb production at the LHC
Hartanto, **Poncelet**, Popescu, Zoia 2205.01687
Flavour anti-kT algorithm applied to Wbb production at the LHC
Hartanto, **Poncelet**, Popescu, Zoia 2209.03280

B-hadrons

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

NNLO QCD for three jets

Next-to-Next-to-Leading Order Study of Three-Jet Production at the LHC
Czakon, Mitov, **Poncelet** 2106.05331

NNLO QCD prediction for three jet rates and three-to-two jet ratios:

$$R_{3/2}(X,\mu_R,\mu_F) = \frac{\mathrm{d}\sigma_3(\mu_R,\mu_F)/\mathrm{d}X}{\mathrm{d}\sigma_2(\mu_R,\mu_F)/\mathrm{d}X} \sim \alpha_s$$

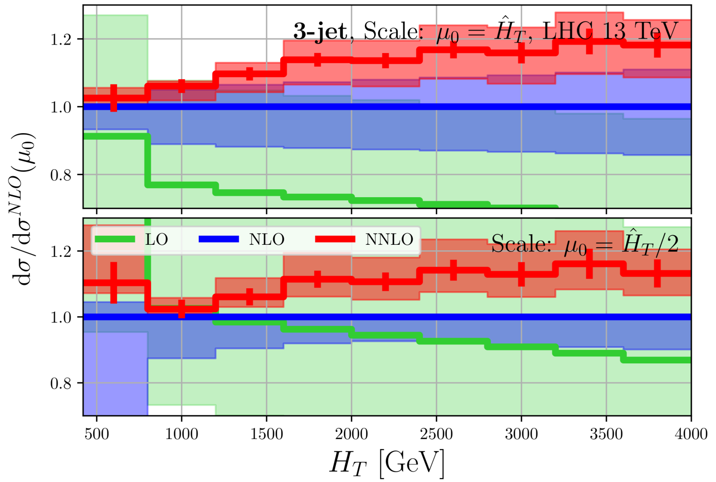
Full colour real radiation + LC double virtual

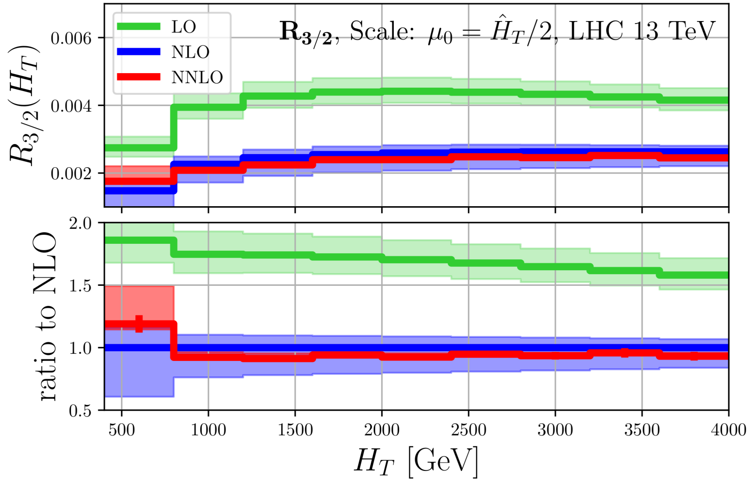
$$\mathcal{R}^{(2)}(\mu_R^2) = 2\,\mathrm{Re}\left[\mathcal{M}^{\dagger(0)}\mathcal{F}^{(2)}\right](\mu_R^2) + \left|\mathcal{F}^{(1)}\right|^2(\mu_R^2) \equiv \mathcal{R}^{(2)}(s_{12}) + \sum_{i=1}^{4} c_i \ln^i\left(\frac{\mu_R^2}{s_{12}}\right)$$

$$\mathcal{R}^{(2)}(s_{12}) \approx \mathcal{R}^{(2)l.c.}(s_{12})$$

Leading-color two-loop QCD corrections for three-jet production at hadron colliders
Abreu, Cordero, Ita, Page, Sotnikov 2102.13609

Updated plots due to missing colour factor in VV:
→ VV sizable contribution ~10% → naive sub-leading ~1%





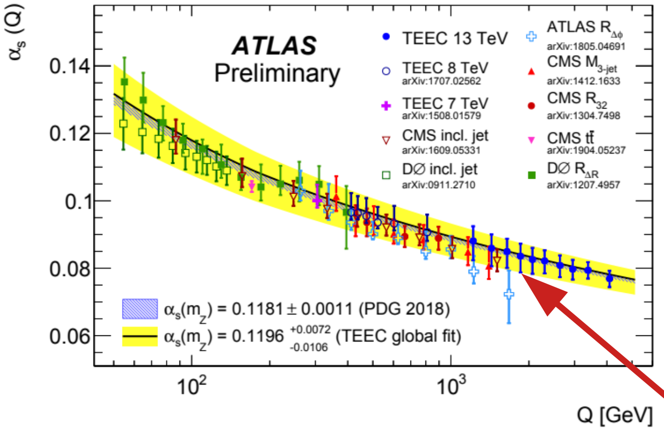
Transverse Energy-Energy Correlator @ LHC

TEEC: Transverse Energy-Energy Correlation

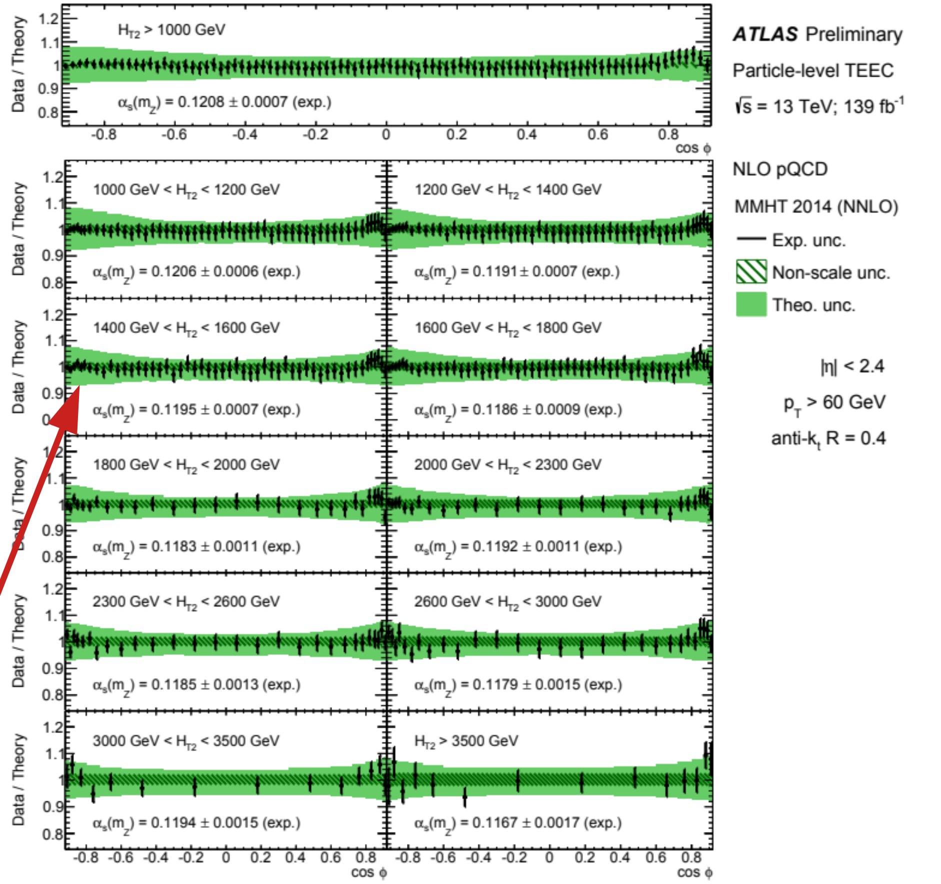
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\perp,i}E^A_{\perp,j}}{\left(\sum_k E^A_{T,k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

HT2 bins from 1000 GeV to 3500 GeV

→ α_s sensitivity at different energy scales



ATLAS @ 13 TeV [ATLAS-CONF-2020-025]



FO scale uncertainty limiting factor!

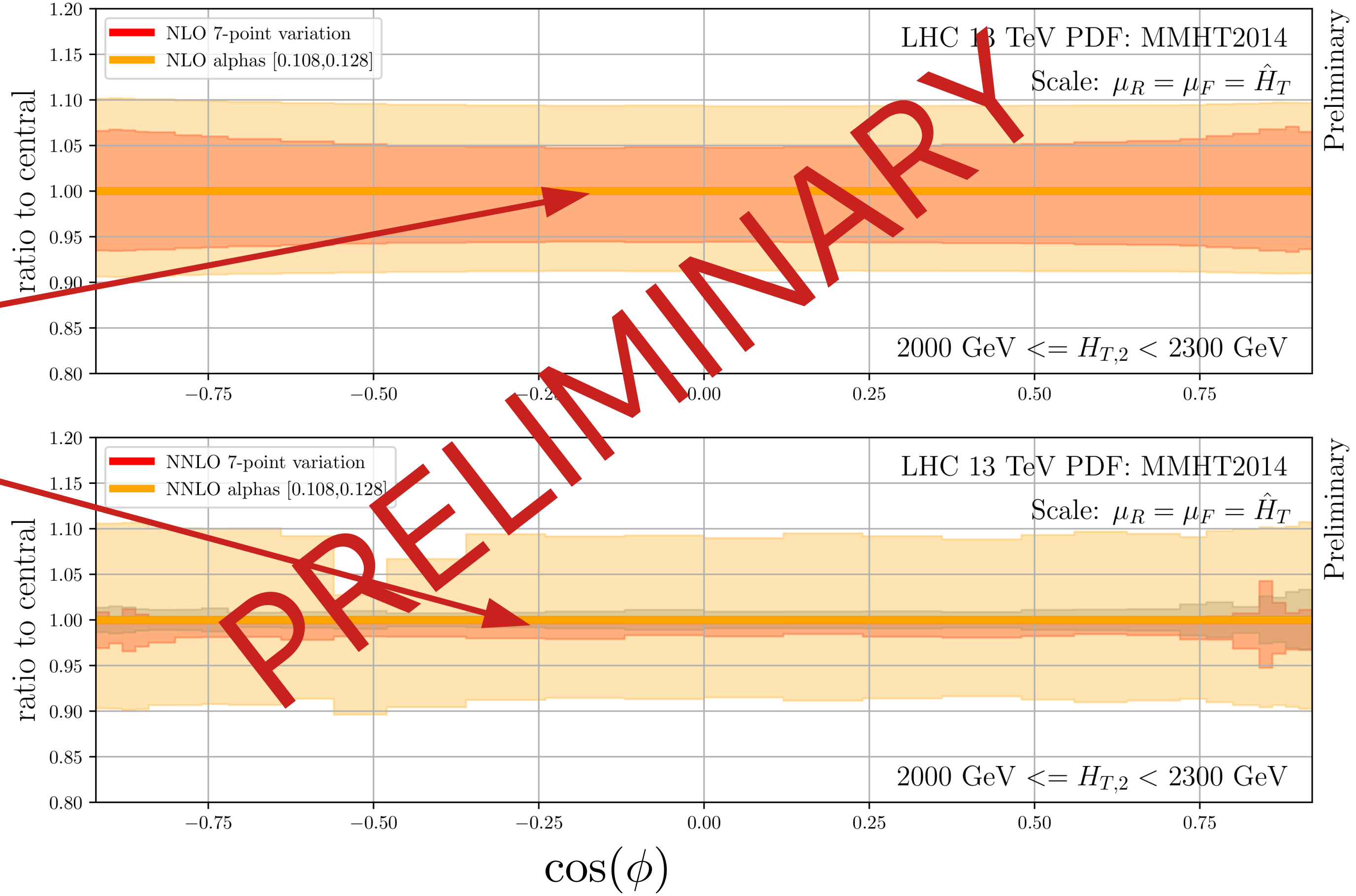
NNLO QCD corrections to TEEC @ LHC

Massive thanks to Manuel Alvarez and Javier Llorente for computing support!

NLO

NNLO

Reduction in scale dependence by factor 3-4



Event shapes at the LHC

ATLAS measurement of event shapes @ 13 TeV using multi-jet events (139fb^{-1}) in HT2 bins and high pT jets (> 100 GeV): [ATLAS:2007.12600]

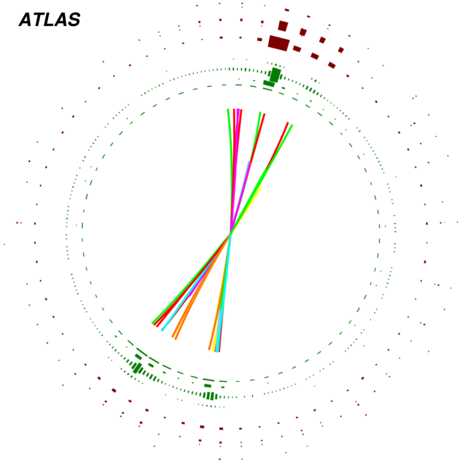
Jet-based
Transverse Thrust: $$\tau_T = 1 - \frac{\sum_i^{\text{jets}} |\vec{p}_{T,i} \cdot \hat{n}|}{\sum_i^{\text{jets}} |\vec{p}_{T,i}|}$$

Jet-based
Thrust Minor: $$T_m = \frac{\sum_i^{\text{jets}} |\vec{p}_{T,i} \times \hat{n}|}{\sum_i^{\text{jets}} |\vec{p}_{T,i}|}$$

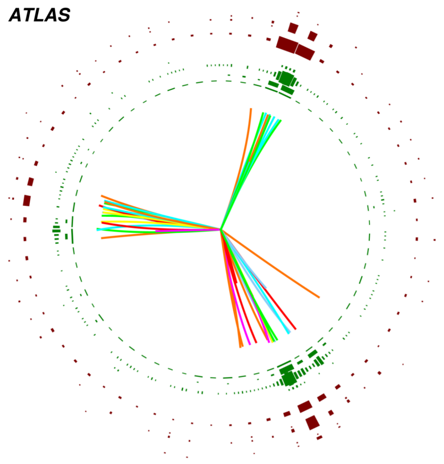
More quantities based on eigenvalues of (transverse) linearised sphericity tensor:

$$\mathcal{M}_{xyz} = \frac{1}{\sum_i^{\text{jets}} |\vec{p}_i|} \sum_i^{\text{jets}} \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} & p_{x,i}p_{z,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 & p_{y,i}p_{z,i} \\ p_{z,i}p_{x,i} & p_{z,i}p_{y,i} & p_{z,i}^2 \end{pmatrix}$$

Back-to-Back



Spherical

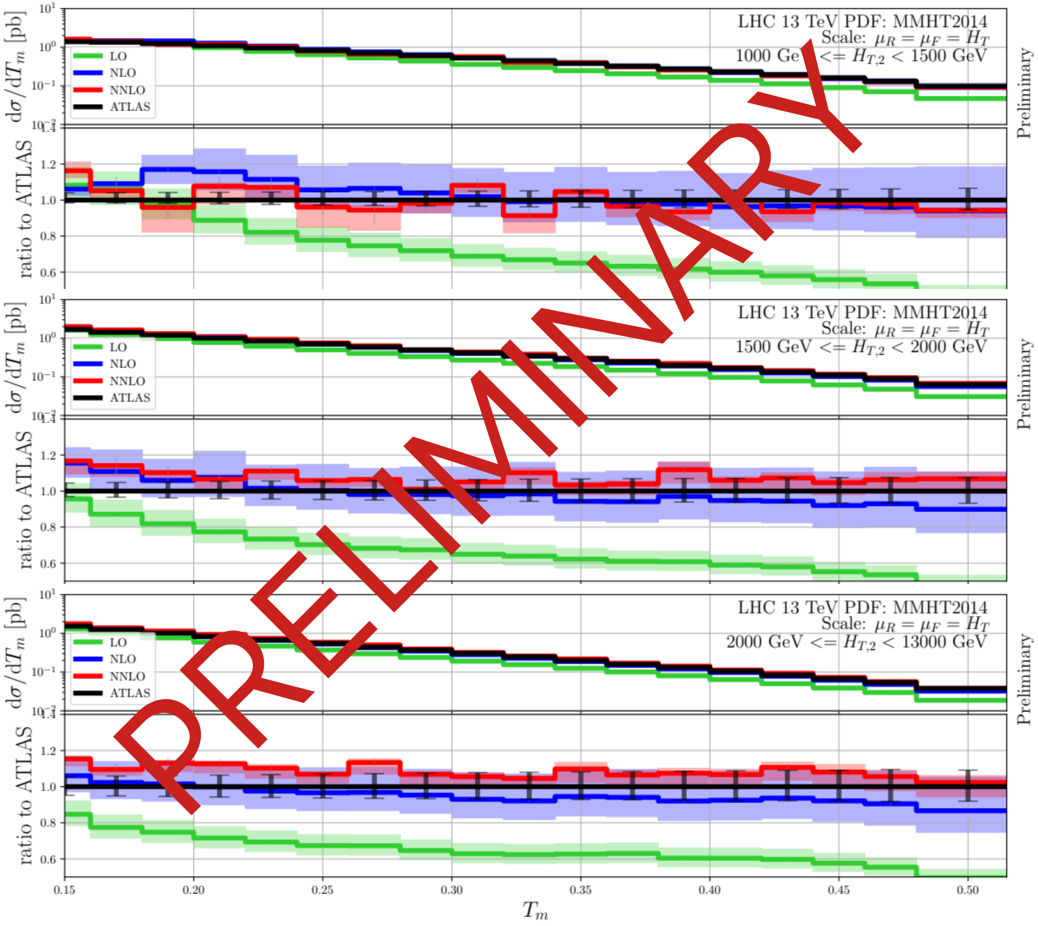


NNLO QCD corrections to event shapes

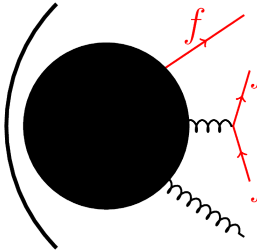
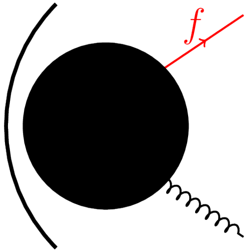
Comparison of public data from HEPdata

Example Thrust-Minor:
- Beautiful perturbative convergence
- Significant reduction of perturbative corrections

Question to be addressed:
- Resummation effects
- Non-perturbative corrections



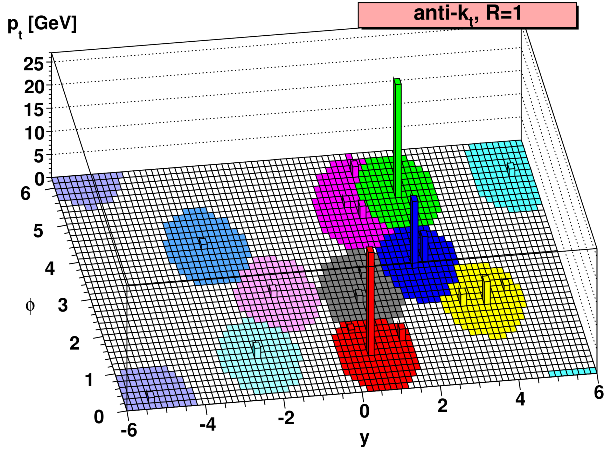
IR-safety of flavour observables

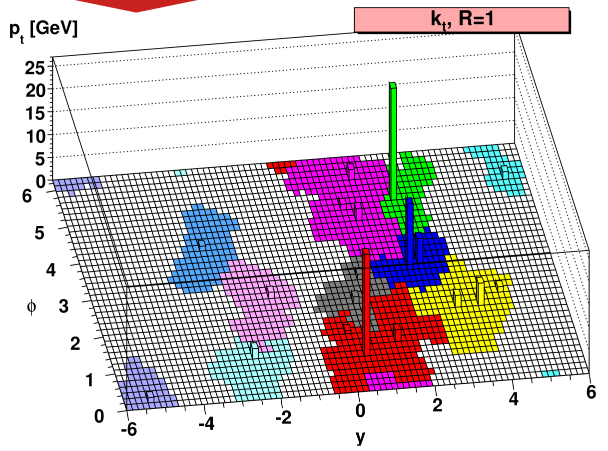
NNLO QCD: $\mathrm{d}\sigma \ni \mathrm{d}\Phi_{n+2}$ () $F_{n+2} + \cdots + \mathrm{d}\tilde{\Phi}_{n+2}\mathcal{S}_2$ () F_n

IR safety implies correlated treatment of kinematics and flavour information:

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

Towards Jetography
Salam 0906.1833





Open issues:

→ Requires flavour-information

→ (flavour-) kT and anti-kT cluster partonic jets differently

A proper comparison requires to unfold experimental data

Old problem, new approaches

Renewed interest:

- Anti-kT + flv.-kT flavour matching:

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

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

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

- Fixed-order fragmentation:

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

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

- Modified anti-kT algorithm:

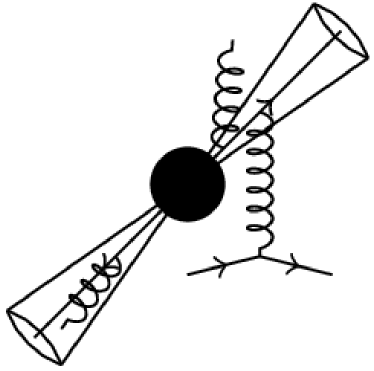
  Infrared-safe flavoured anti-kT jets, Czakon, Mitov, Poncelet 2205.11879

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

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

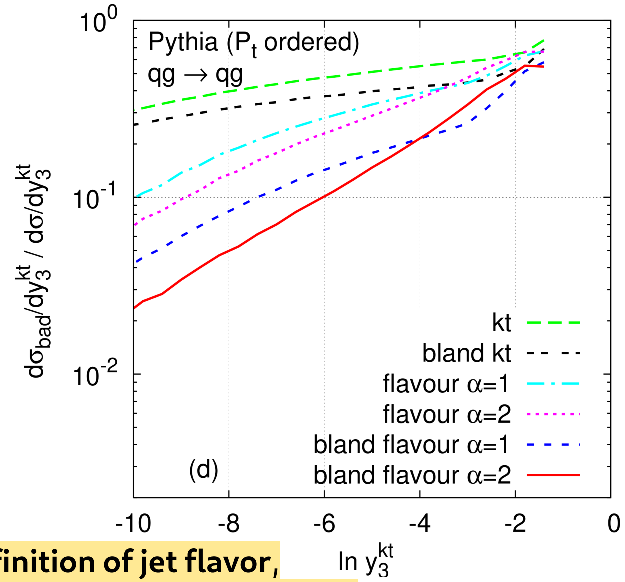
$$\mathcal{S}_{ij} = 1 - \theta(1-x)\cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_{T,i}^2 + k_{T,j}^2}{2ak_{T,\max}^2}$$

Tests of IR safety with parton showers

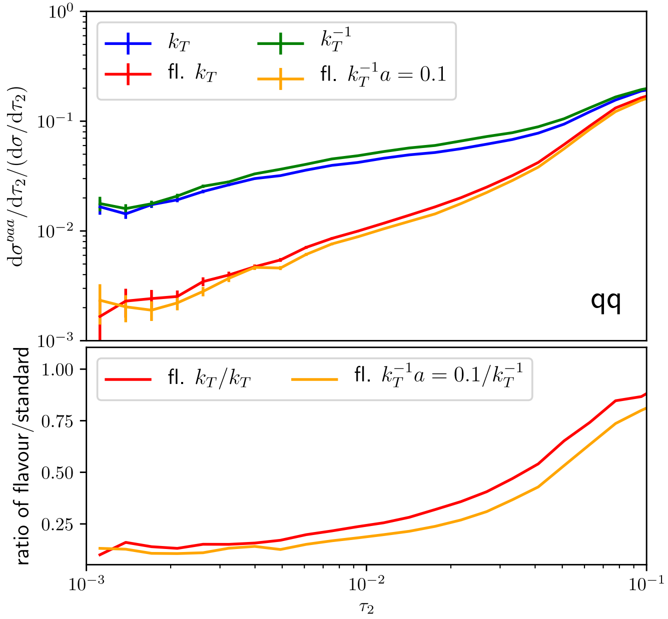


Dress tree-level di-jet events (definite flavour structure: “qq”, “qg” or “gg”) with radiation and study jet flavour (q or g) as function of kinematics.
In the di-jet limit the flavour needs to correspond to tree level flavours
→ misidentification rate needs to vanish in di-jet back-to-back limit

Flavour kT vs. kT:



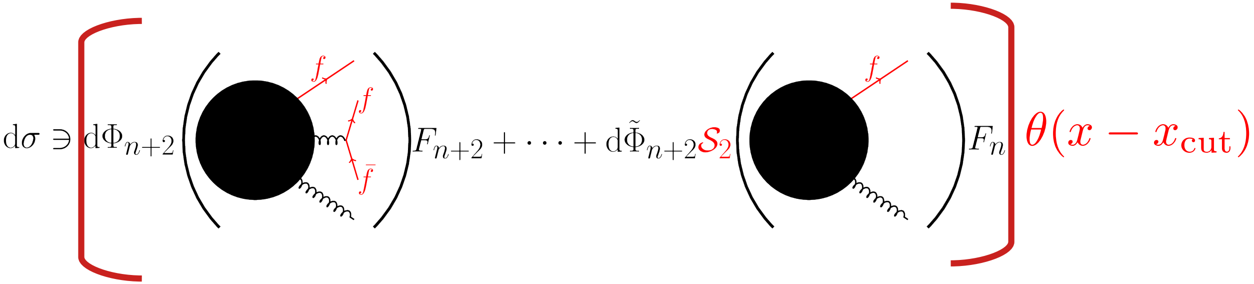
Flavour anti-kT:



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

Tests of IR safety with NNLO FO computations

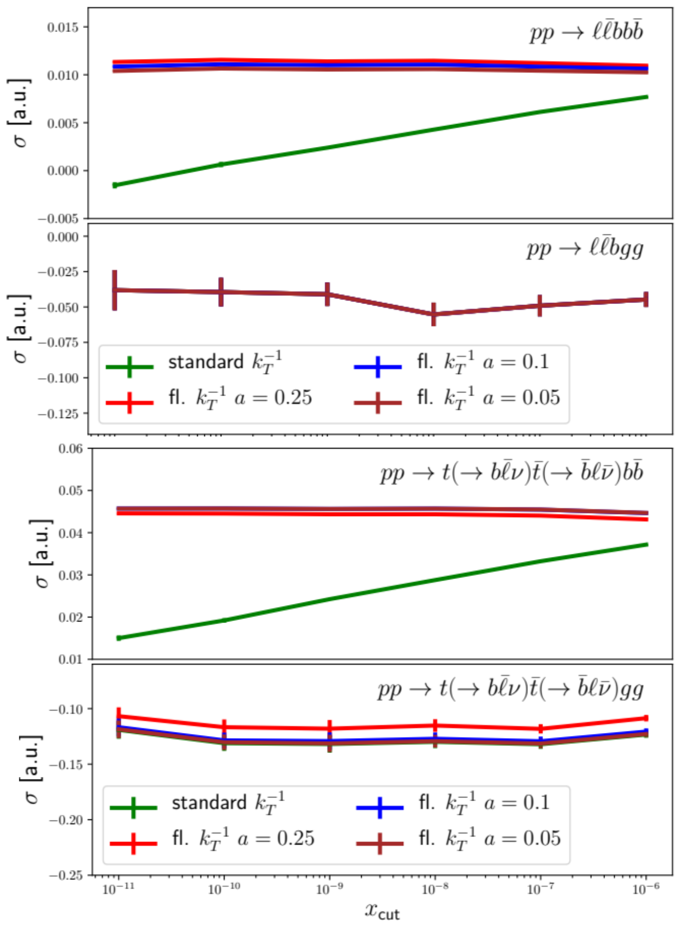
IR sensitivity of jet cross sections on (technical) IR regulating parameter x



In the limit x_cut → 0:

IR safe jet flavour → no dependence on x_cut

IR non-safe jet flavour → logarithmic divergent



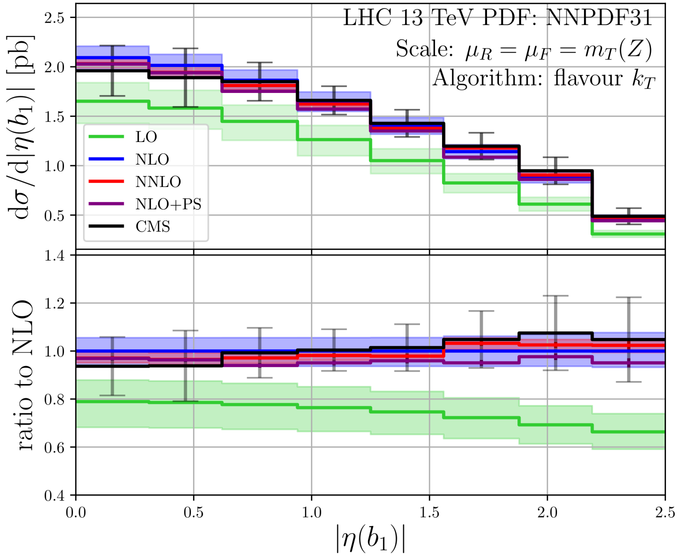
Z+b-jet Phenomenology: Tunable parameter

Benchmark process: pp → Z(ll) + b-jet

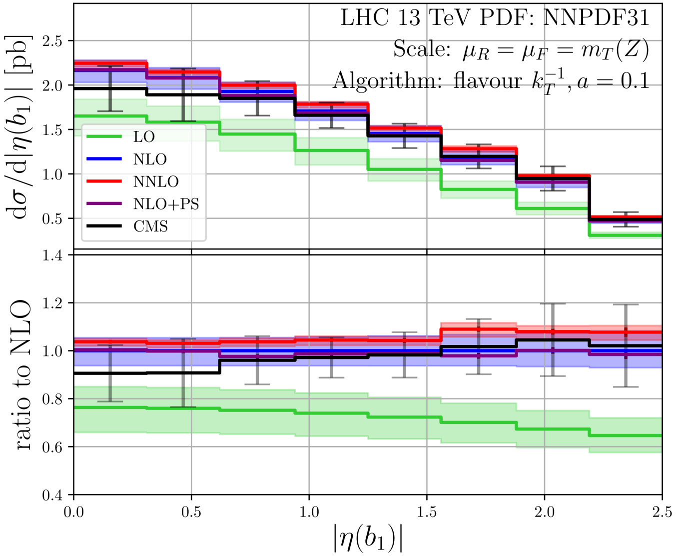
Tunable parameter a:

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

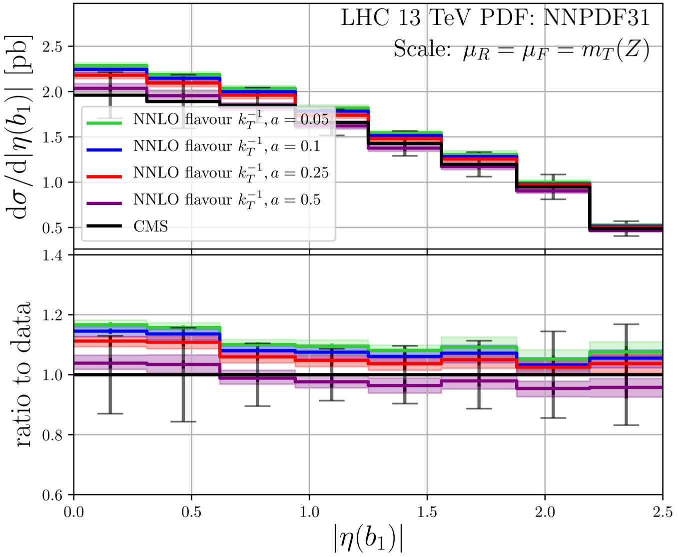
Flavour kT:



Flavour anti-kT: $a = 0.1$

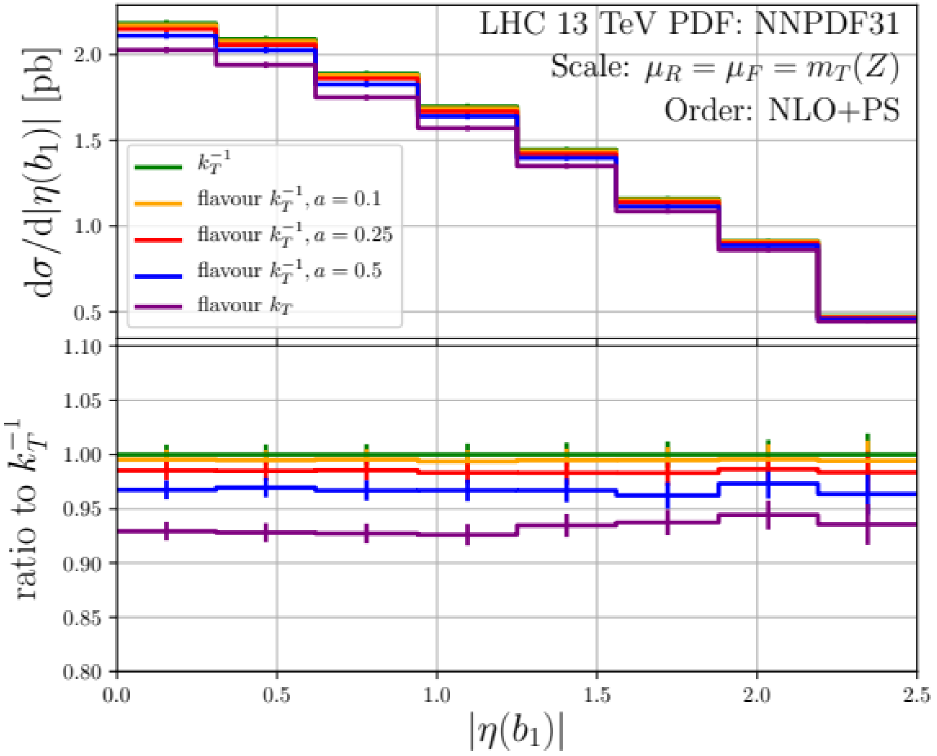


Comparison of different parameter a to data:



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 → small unfolding factors
- Larger a: Larger modification of clustering

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

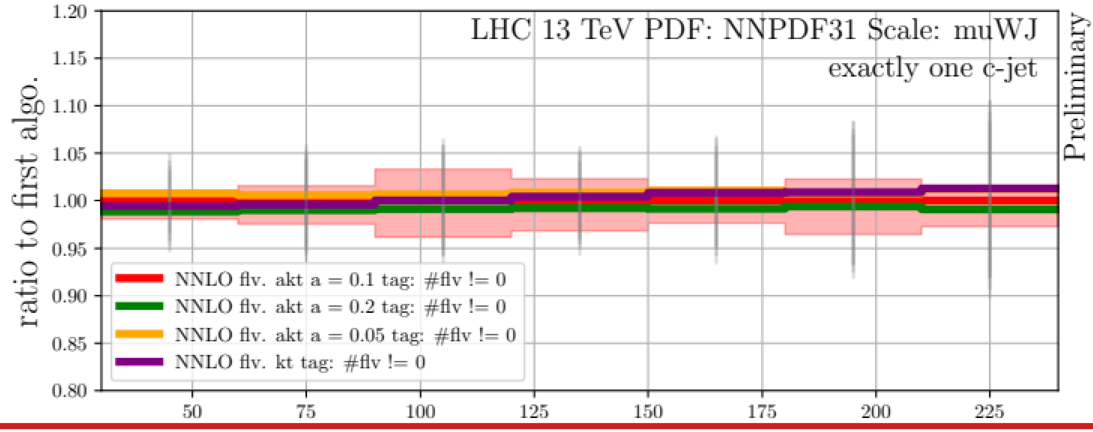
W+c-jet with flavour anti-kT

In collaboration with: Czakon, Mitov, Pellen

Preliminary

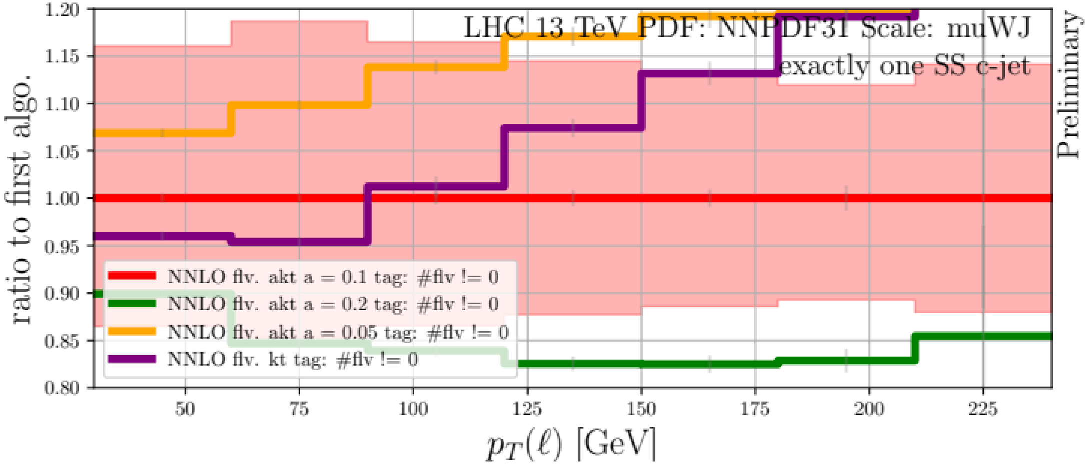
Exactly one c-jet requirement:

- Comparison of parameters a:
  → small dependence < 2%
- Comparison to flv kT:
  → small dependence @ NNLO < 2%



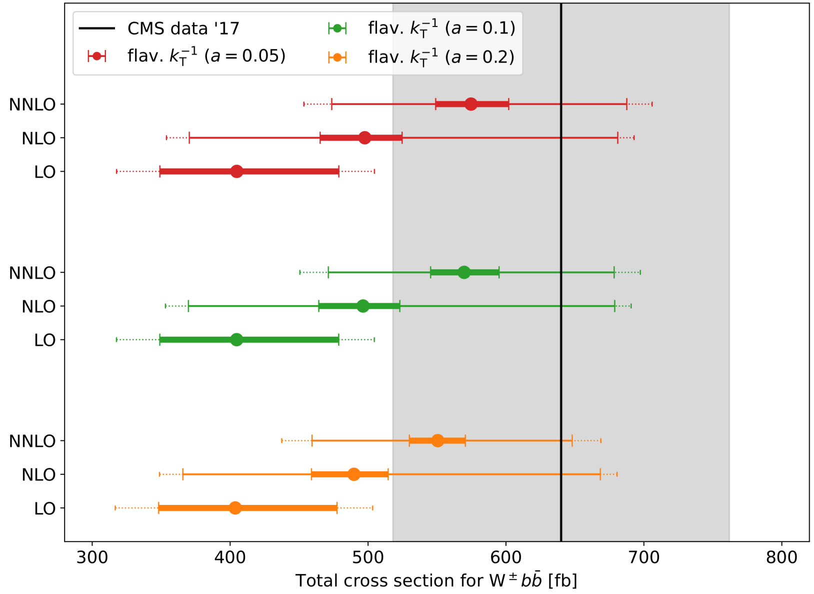
ONLY large effect in SS contribution

- Exactly one c-jet of SS type:
  Larger dependence ~15%
  (roughly size of NNLO scale band)
- BUT: SS contribution ~2-5%
- => OS ~0.2-0.5% dependence



W+2 bjets: flavour anti-kT

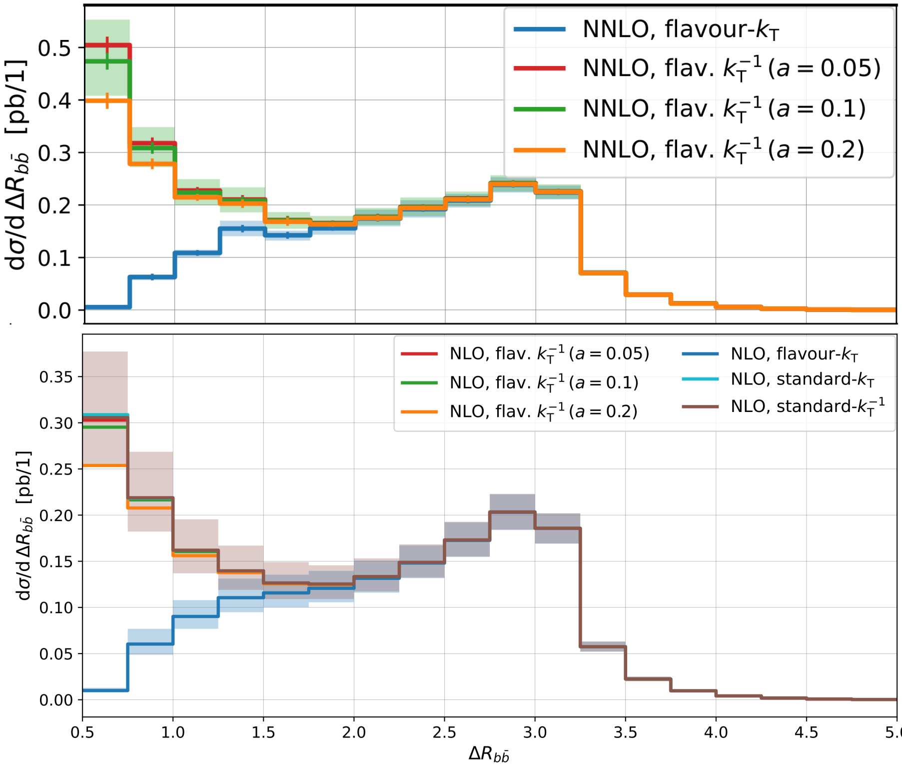
Flavour anti-kT algorithm applied to Wbb production at the LHC
Hartanto, **Poncelet**, Popescu, Zoia 2209.03280



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)

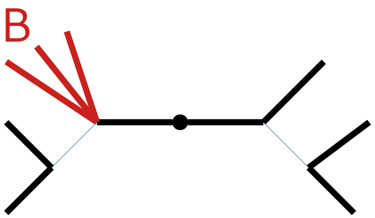


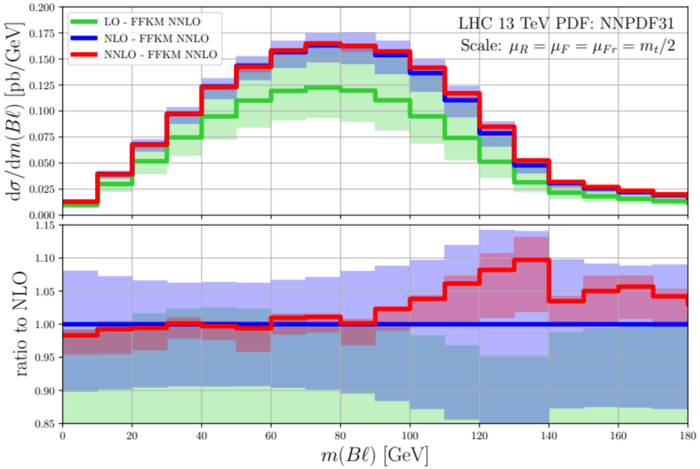
Significant differences between kT and anti-kT
In small DeltaR(bb) region? Beam-function?!

Flavour tagging and fixed order fragmentation

- Fixed order QCD predictions with a final state hadron
- Partonic computation + transition of parton to hadron (collinear fragmentation of massless partons)
- Non-perturbative fragmentation function (similar to PDFs): Probability to find a hadron with a fraction x of a parton
- Advantage is that the hadrons momentum is measurable → usage as b-tag?
- Implementation in the STRIPPER framework through NNLO QCD:
  B-hadron production in NNLO QCD: application to LHC ttbar events with leptonic decays, Czakon, Generet, Mitov and Poncelet, 2102.08267

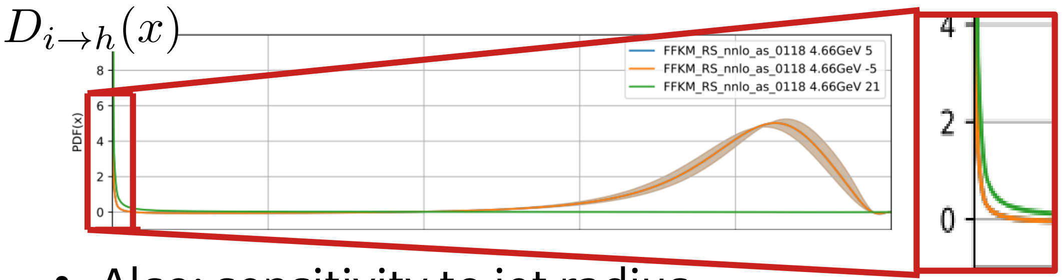
$$pp \to t\bar{t} \to B\ell\bar{\ell}\nu\bar{\nu}b + X$$





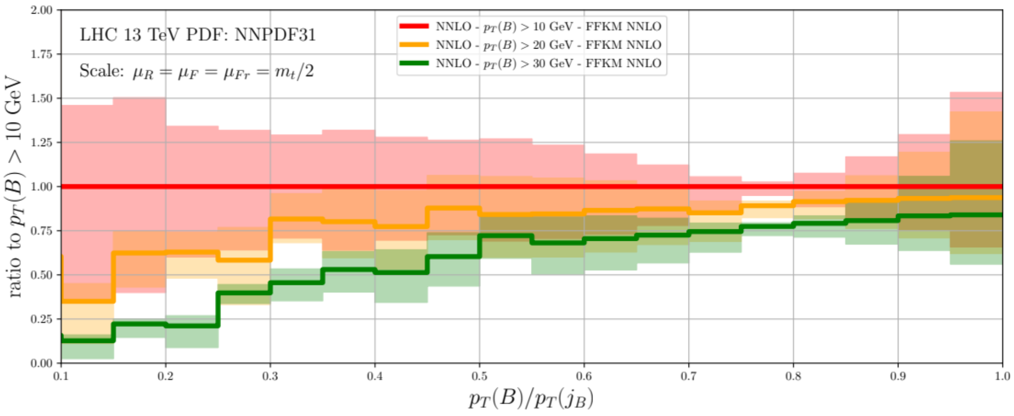
Subtleties

- pT(B) requirement necessary since NNLO fragmentation function divergent for x → 0 due to g → bbar splitting:

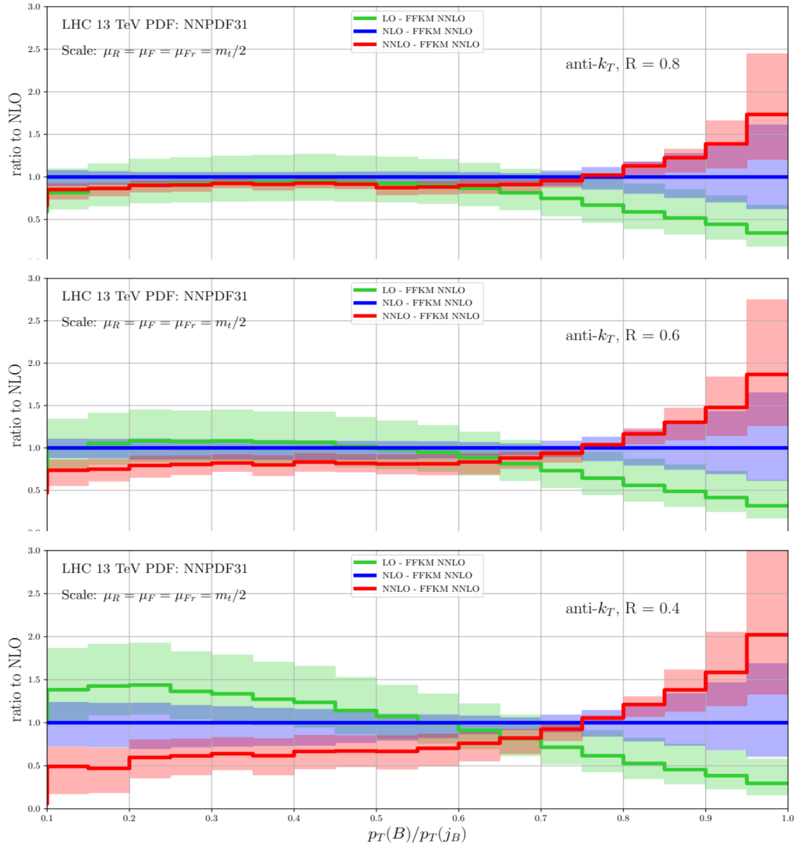


- Also: sensitivity to jet radius

→ Usage as b-tag needs tuning



Jet radius variation R = 0.8,0.6,0.4



Summary & Outlook

Summary:

- Many phenomenological applications of the sector-residue subtraction scheme
- NNLO QCD predictions for three-jet observables
- Flavoured jets → proposal for modified anti-kT algorithm

Outlook:

- More three jet pheno results: TEEC, eventshapes
- More applications to 2 → 3 processes with 1 external mass
- More studies of flavoured jet algorithms