Jets at the LHC: a fixed order perspective

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Outline

→ Three jet observables at NNLO QCD

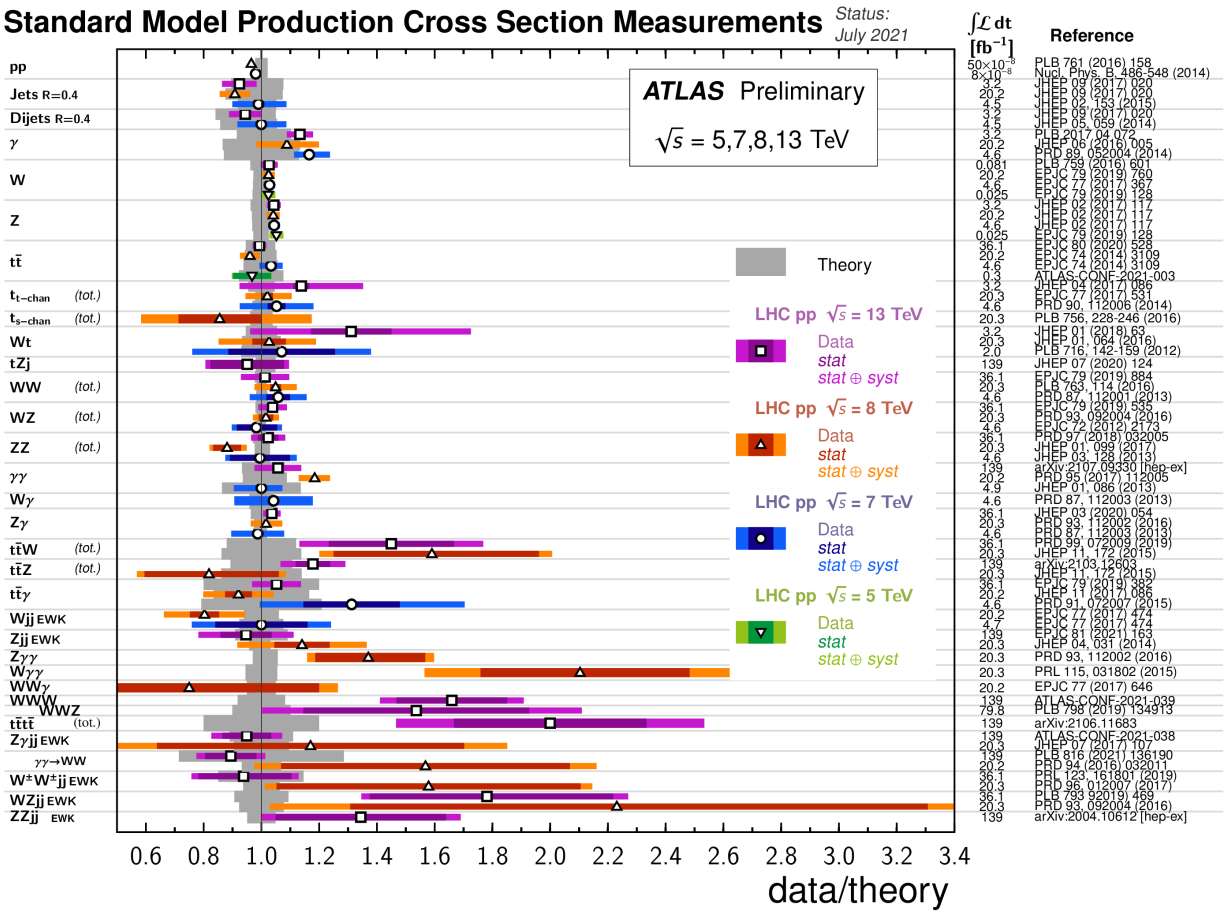
R32 ratios
Event-shapes

→ Flavoured jets

Infrared safe definition of jet flavour?
→ New proposal for a flavour safe algorithm.

→ Wrap-up and outlook

SM measurements at the LHC



New physics around the corner?

Precise measurements

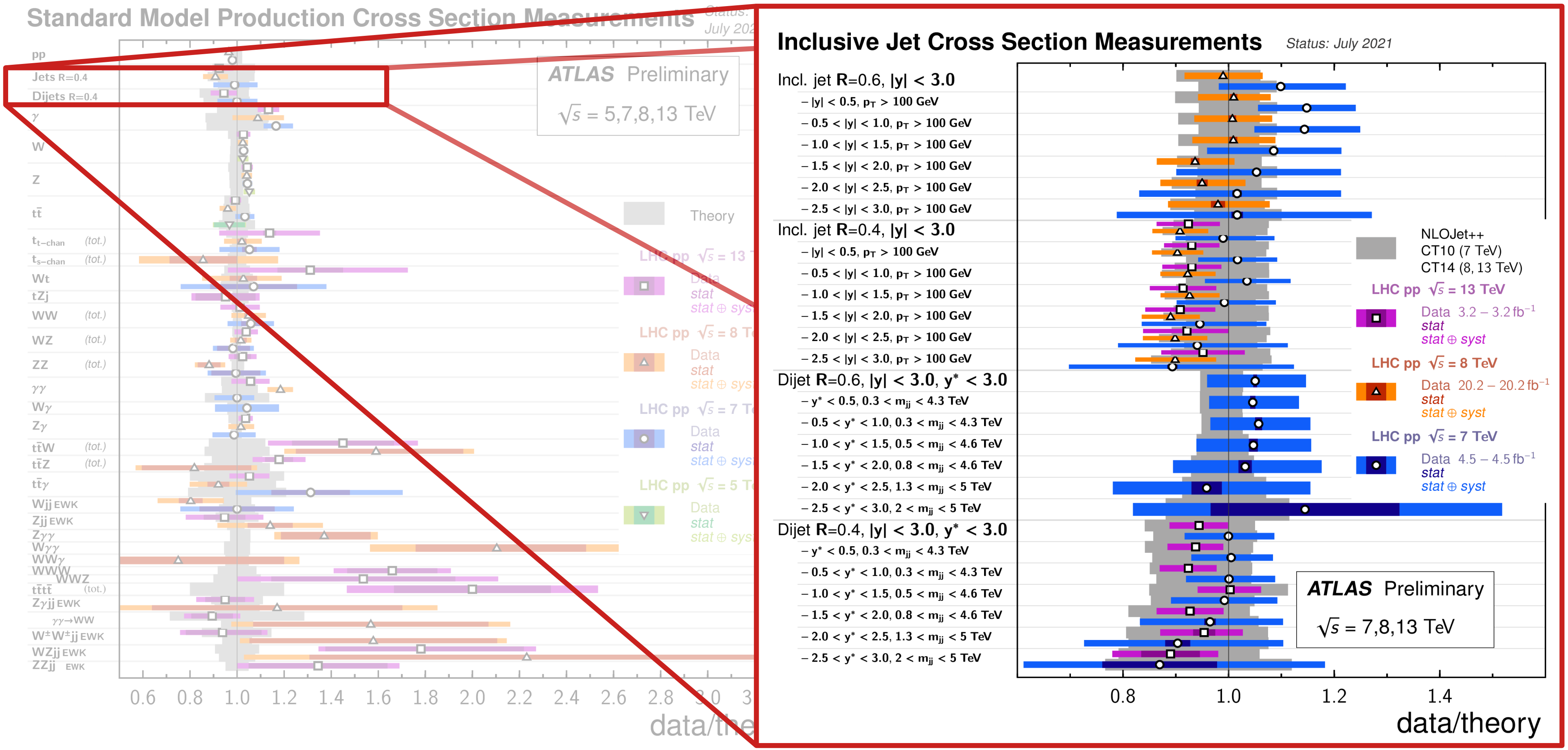
<->

Precise theory

Win-Win situation

- improved SM understanding
- possible indirect BSM signals

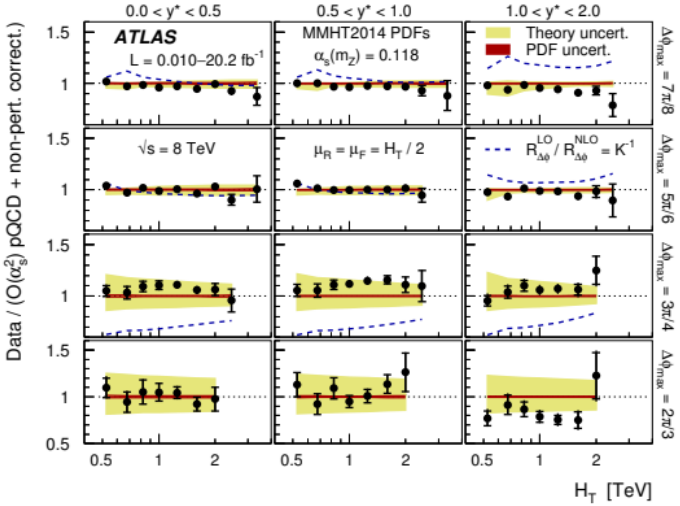
SM measurements at the LHC

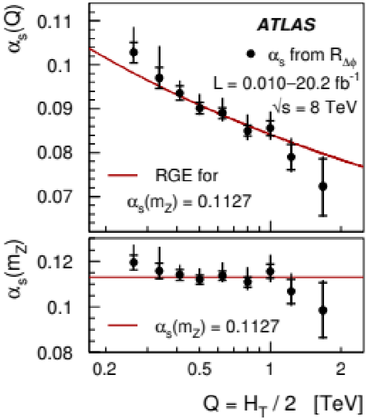


Jet observables at the LHC

The LHC produces jets abundantly → many phenomenological applications

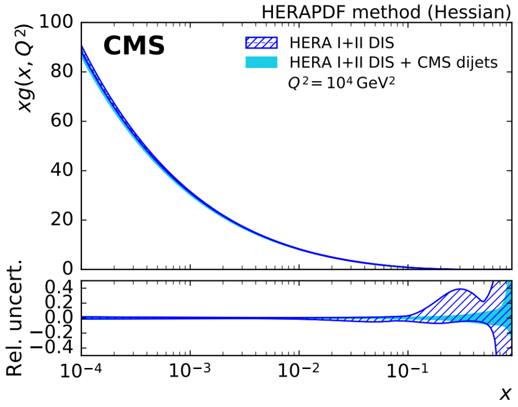
Tests of pQCD, α_s extraction:
R32 ratios, event-shapes





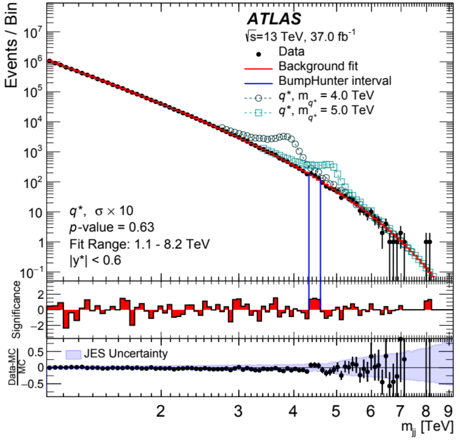
[1805.04691]

PDF determination:
Single inclusive,
Multi-differential dijet



[1705.02628]

BSM searches:
dijet mass



[1703.09127]

Precision theory required!

Data driven

Multi-jet observables at the LHC

Multi-jet final states:

- Tests of pQCD at high energy
- Tests of MC modelling of LHC events
- Search for new physics

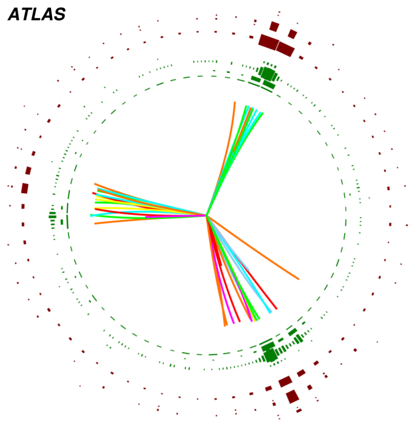
Study of perturbative QCD:

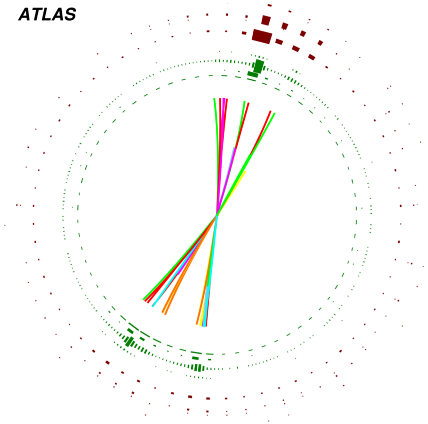
- R32 ratios

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

→ Extraction of the strong coupling constant

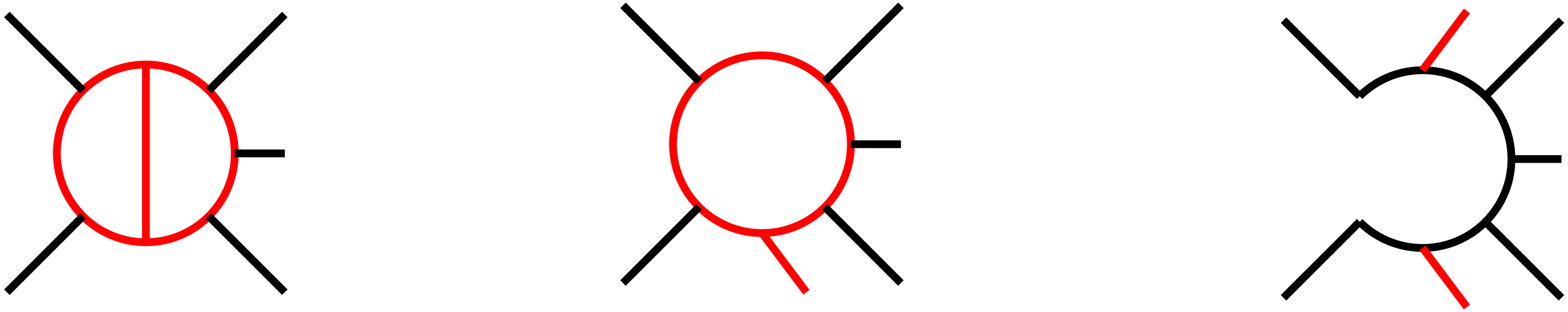
- Transverse Energy-Energy Correlator
- Event shapes





Credits: [ATLAS:2007.12600]

NNLO QCD prediction beyond 2 → 2



2 → 3 Two-loop amplitudes:

- Advances in amplitude techniques:

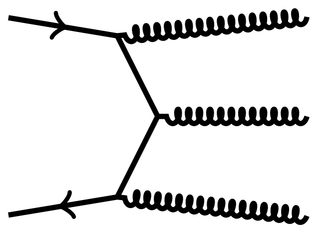
  IBPs, amplitude reconstruction and master integrals
- (Non-) planar 5 point massless amplitudes [Chawdry'19'20'21,Abreu'20'21,Agarwal'21, Badger'21]
  → triggered by efficient MI representation [Chicherin'20]

Cross-sections → Combination with real radiation

- Various NNLO subtraction schemes available:
  qT-slicing [Catain'07], N-jettiness slicing [Gaunt'15/Boughezal'15], Antenna [Gehrmann'05-'08], Colorful [DelDuca'05-'15], Projetction [Cacciari'15], Geometric [Herzog'18], Unsubtraction [Aguilera-Verdugo'19], Nested collinear [Caola'17], Sector-improved residue subtraction [Czakon'10-'14,'19]

Three-jet production

- Sector-improved residue subtraction [Czakon'10'14'19]
  - Efficient c++ implementation → STRIPPER
  - Highly automated to deal with enormous amount of channels in three-jet production → O(1k) sectors →O(1M) individual MC integrals
  - Still computationally very challenging! → O(1M CPUh)
- Many-leg, IR stable one-loop amplitudes → OpenLoops [Buccioni'19]
- Double virtual amplitudes in leading-colour approximation [Abreu'21]
  - Sub-leading colour corrections expected to be small
  - Analytical expressions challenging
  - Fast numerical evaluation → very small contribution to computational cost



$pp \to ggg + X$

Only Approximation made:

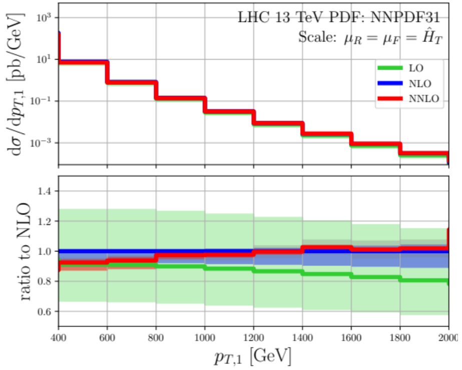
$$\mathcal{R}^{(2)}(\mu_R^2) = 2\,\mathrm{Re}\left[\mathcal{M}^{\dagger(0)}\mathcal{F}^{(2)}\right](\mu_R^2) + \left|\mathcal{F}^{(1)}\right|^2(\mu_R^2) \equiv \mathcal{R}^{(2)}(s_{12}) + \sum_{i=1}^{4} c_i \ln^i\left(\frac{\mu_R^2}{s_{12}}\right)$$

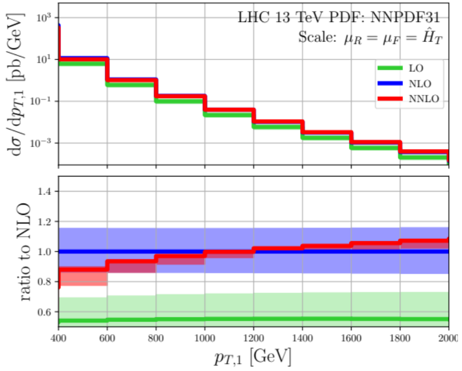
$$\mathcal{R}^{(2)}(s_{12}) \approx \mathcal{R}^{(2)l.c.}(s_{12})$$

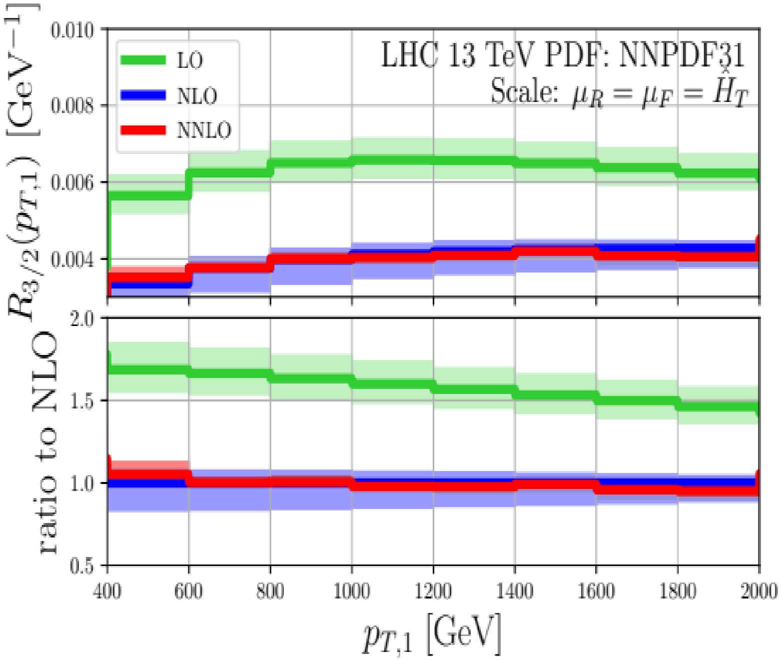
Three-jet production - R32(pT1)

- LHC @ 13 TeV, NNPDF31
- Require at least three (two) jets:
  - $p_T(j) > 60$ GeV and $|y(j)| < 4.4$
  - $H_{T,2} = p_T(j_1) + p_T(j_2) > 250$ GeV
- Scales:

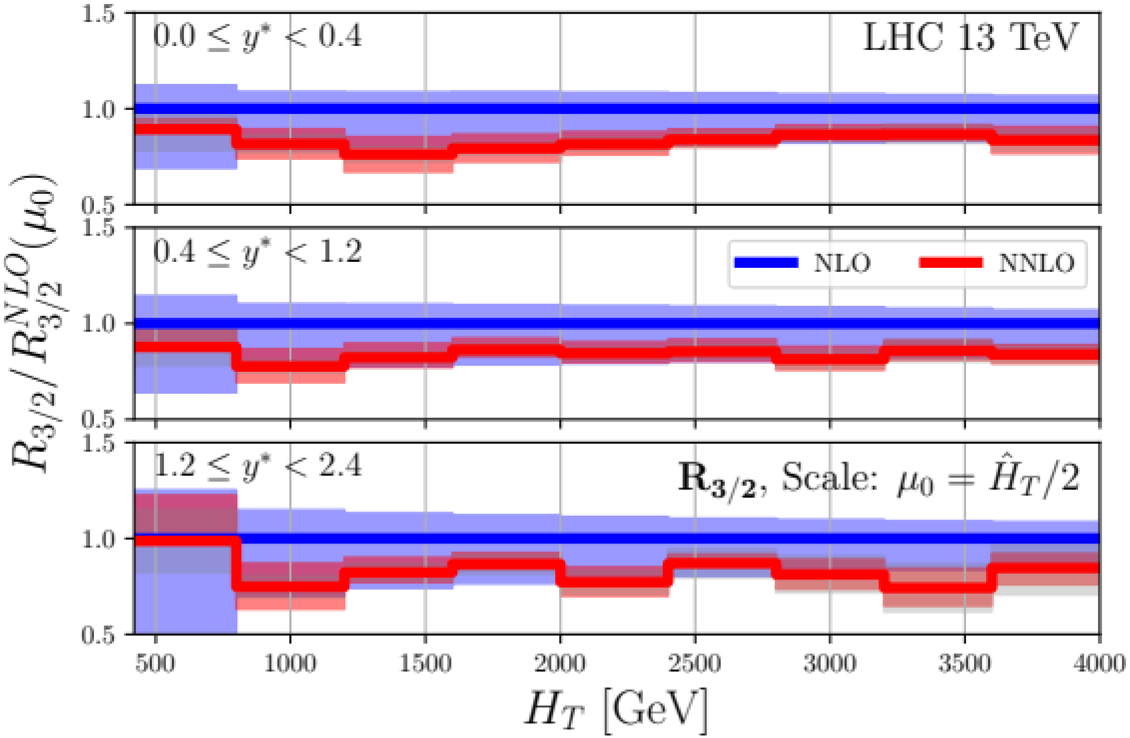
$$\mu_R = \mu_F = \hat{H}_T = \sum_{\text{partons}} p_T$$







Three-jet production – R32(HT,y*)



Double differential w.r.t. $H_T = \sum_{\text{jets}} p_T$ and $y^* = |y(j_1) - y(j_2)|/2$

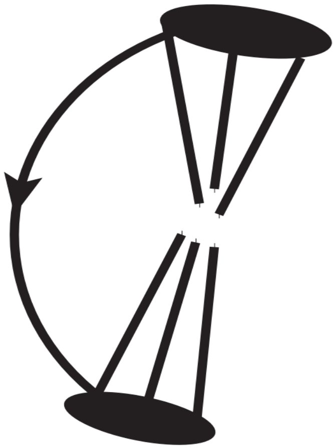
Central scale choice: $\hat{H}_T/2$

Three-jet production – azimuthal decorrelation

Kinematic constraints on the azimuthal separation between the two leading jets (ϕ_{12})

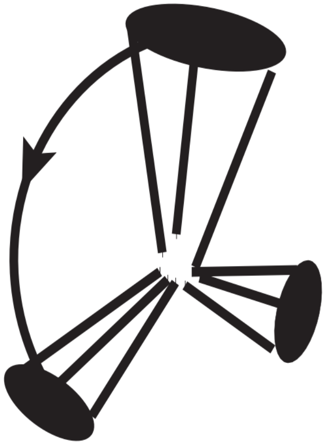
Dijet:

$\phi_{12} = \pi$



Trijet:

$\phi_{12} > \frac{2\pi}{3}$



φ12 sensitive to the jet multiplicity:

2j: $\phi_{12} = \pi$

3j: $\phi_{12} > \frac{2\pi}{3}$

4j: unconstrained

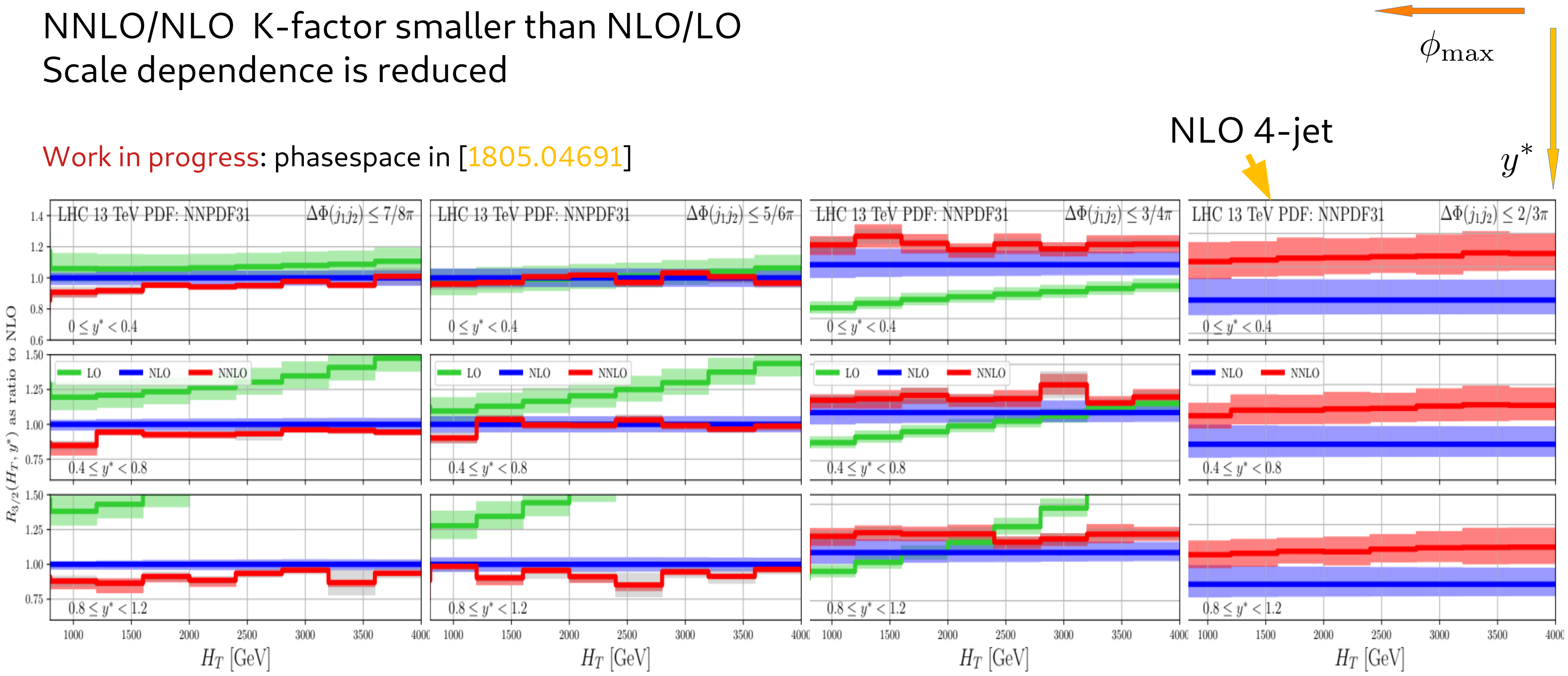
Study of the ratio:

$$R_{32}(H_T, y^*, \phi_{\max}) = \frac{\mathrm{d}\sigma_3(H_T, y^*, \phi_{12} < \phi_{\max})}{\mathrm{d}\sigma_2(H_T, y^*)}$$

Three-jet production - azimuthal decorrelation

NNLO/NLO K-factor smaller than NLO/LO
Scale dependence is reduced

Work in progress: phasespace in [1805.04691]



Outlook: Extraction of the strong coupling constant from multi-jet events at the LHC

→ Transverse Energy-Energy Correlator TEEC

→ Event shapes

Transverse Energy-Energy Correlator @ LHC

TEEC: Transverse Energy-Energy Correlation

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

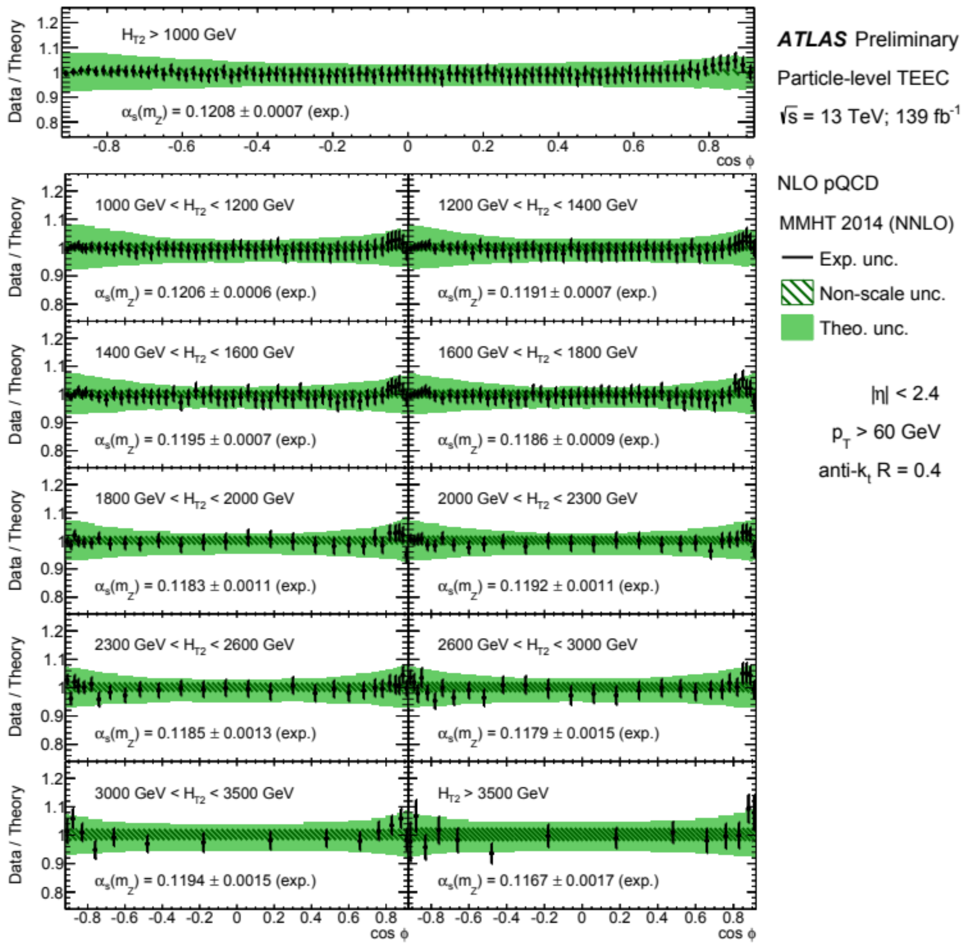
ATLAS measurement of the TEEC and ATEEC:

- @ 8 TeV [ATLAS:1707.02562]
- @ 13 TeV [ATLAS-CONF-2020-025]

TEEC in HT2 bins:

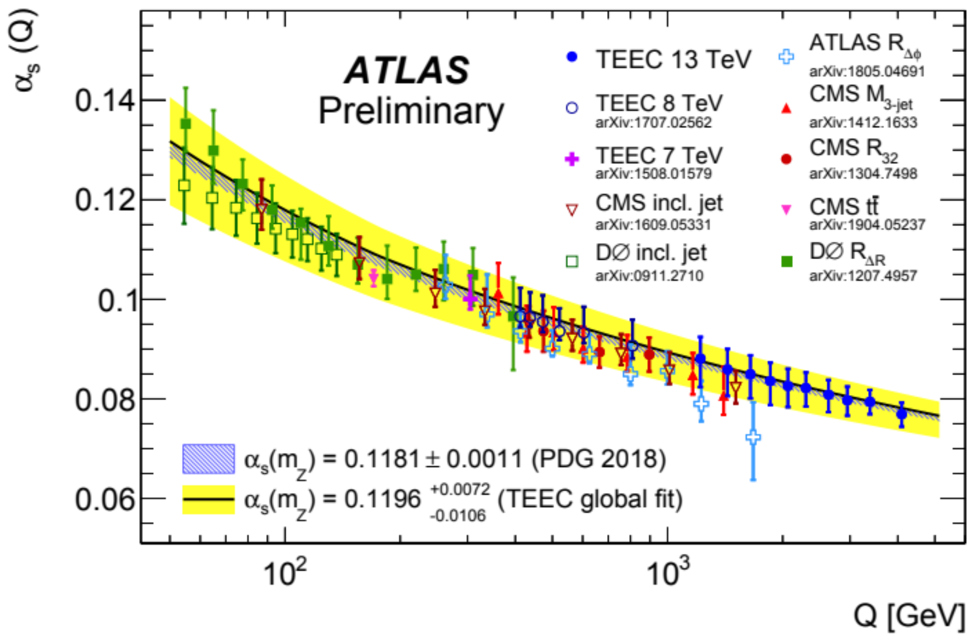
→ from 1000 GeV to 3500 GeV and above

→ sensitivity to different energy scales



Transverse Energy-Energy Correlator @ LHC

Extraction of alphas in different HT bins → test of SM running



$\langle Q \rangle$ [GeV]	$\alpha_s(m_Z)$ value (MMHT 2014)
Global	0.1195 ± 0.0002 (stat.) ± 0.0006 (syst.) $^{+0.0084}_{-0.0106}$ (scale) ± 0.0009 (PDF) ± 0.0003 (NP)
Inclusive	0.1198 ± 0.0002 (stat.) ± 0.0006 (syst.) $^{+0.0078}_{-0.0095}$ (scale) ± 0.0010 (PDF) ± 0.0002 (NP)
1219	0.1202 ± 0.0003 (stat.) ± 0.0006 (syst.) $^{+0.0079}_{-0.0098}$ (scale) ± 0.0010 (PDF) ± 0.0002 (NP)
1434	0.1184 ± 0.0003 (stat.) ± 0.0007 (syst.) $^{+0.0078}_{-0.0098}$ (scale) ± 0.0011 (PDF) ± 0.0002 (NP)
1647	0.1188 ± 0.0004 (stat.) ± 0.0007 (syst.) $^{+0.0073}_{-0.0087}$ (scale) ± 0.0012 (PDF) ± 0.0001 (NP)
1856	0.1177 ± 0.0006 (stat.) ± 0.0008 (syst.) $^{+0.0072}_{-0.0083}$ (scale) ± 0.0013 (PDF) ± 0.0006 (NP)
2064	0.1174 ± 0.0008 (stat.) ± 0.0009 (syst.) $^{+0.0069}_{-0.0078}$ (scale) ± 0.0013 (PDF) ± 0.0007 (NP)
2300	0.1185 ± 0.0009 (stat.) ± 0.0010 (syst.) $^{+0.0063}_{-0.0067}$ (scale) ± 0.0014 (PDF) ± 0.0005 (NP)
2636	0.1166 ± 0.0016 (stat.) ± 0.0012 (syst.) $^{+0.0062}_{-0.0066}$ (scale) ± 0.0015 (PDF) ± 0.0000 (NP)
2952	0.1141 ± 0.0029 (stat.) ± 0.0013 (syst.) $^{+0.0062}_{-0.0069}$ (scale) ± 0.0018 (PDF) ± 0.0003 (NP)
3383	0.1164 ± 0.0043 (stat.) ± 0.0015 (syst.) $^{+0.0050}_{-0.0044}$ (scale) ± 0.0017 (PDF) ± 0.0001 (NP)
4095	0.1029 ± 0.0163 (stat.) ± 0.0014 (syst.) $^{+0.0066}_{-0.0012}$ (scale) ± 0.0010 (PDF) ± 0.0003 (NP)

FO scale uncertainty limiting factor!

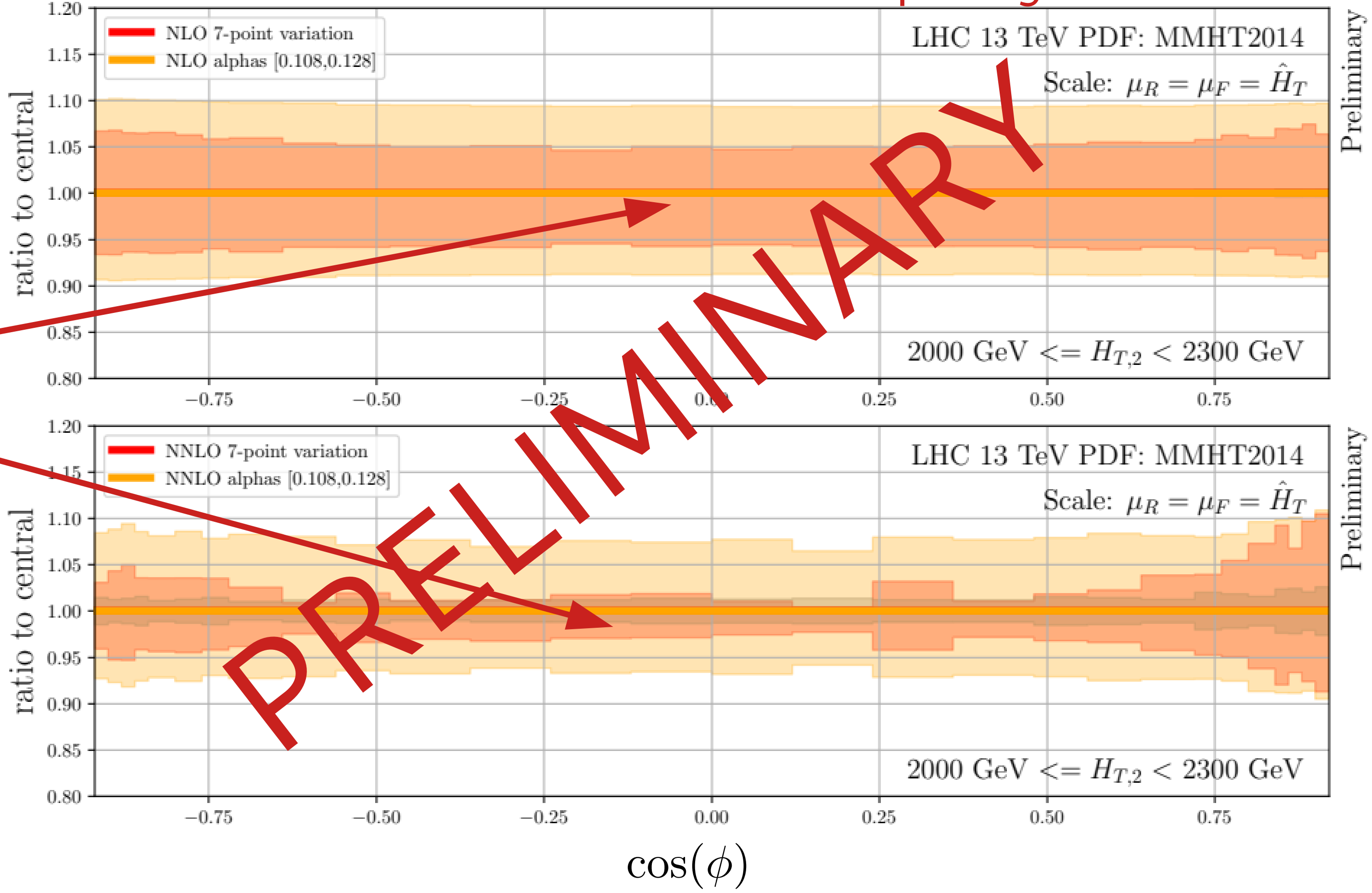
NNLO QCD corrections to TEEC @ LHC

Massive thanks to Manuel Alvarez and Javier Llorente for computing!

NLO

Reduction in scale dependence by factor 2-3

NNLO



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]

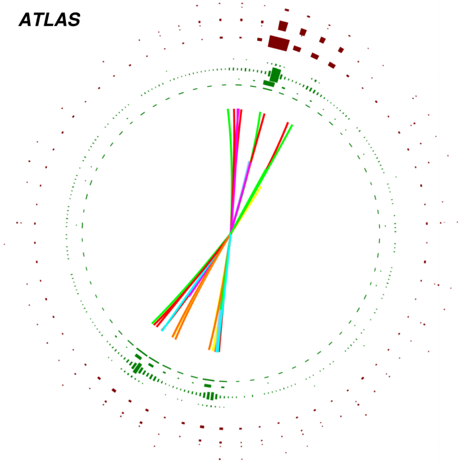
Transverse Thrust: $$\tau_T = 1 - \frac{\sum_i^{\text{jets}} |\vec{p}_{T,i} \cdot \hat{n}|}{\sum_i^{\text{jets}} |\vec{p}_{T,i}|}$$

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

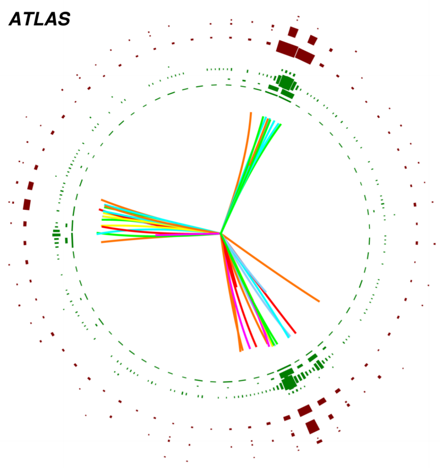
More quantities based on eigenvalues of (transverse) linearised sphericity tensor:

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

Back-to-Back

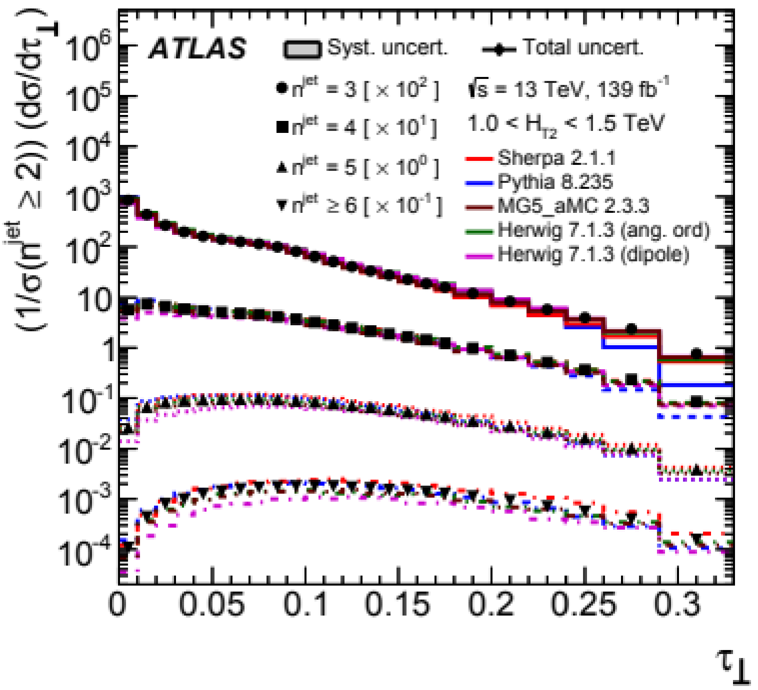


Spherical

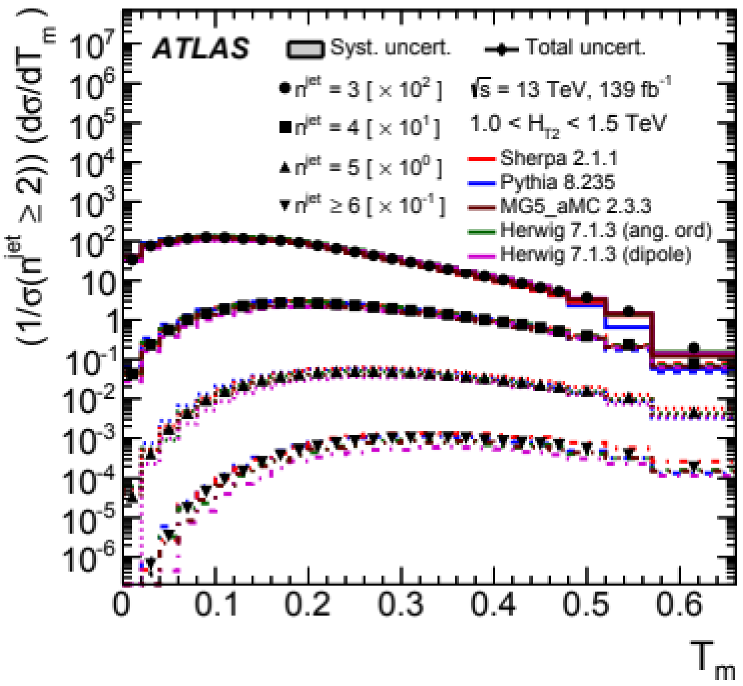


Event shapes at the LHC

Transverse thrust:



Transverse thrust minor:

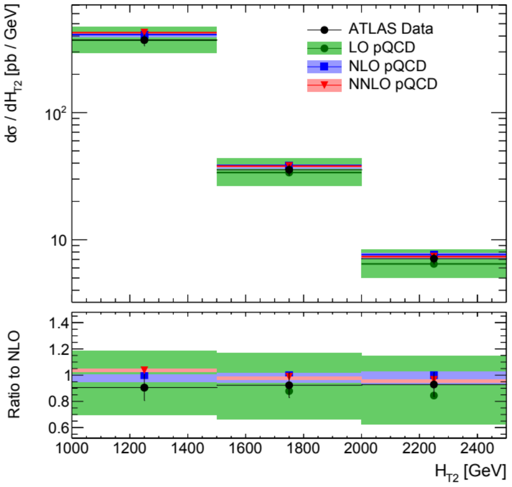


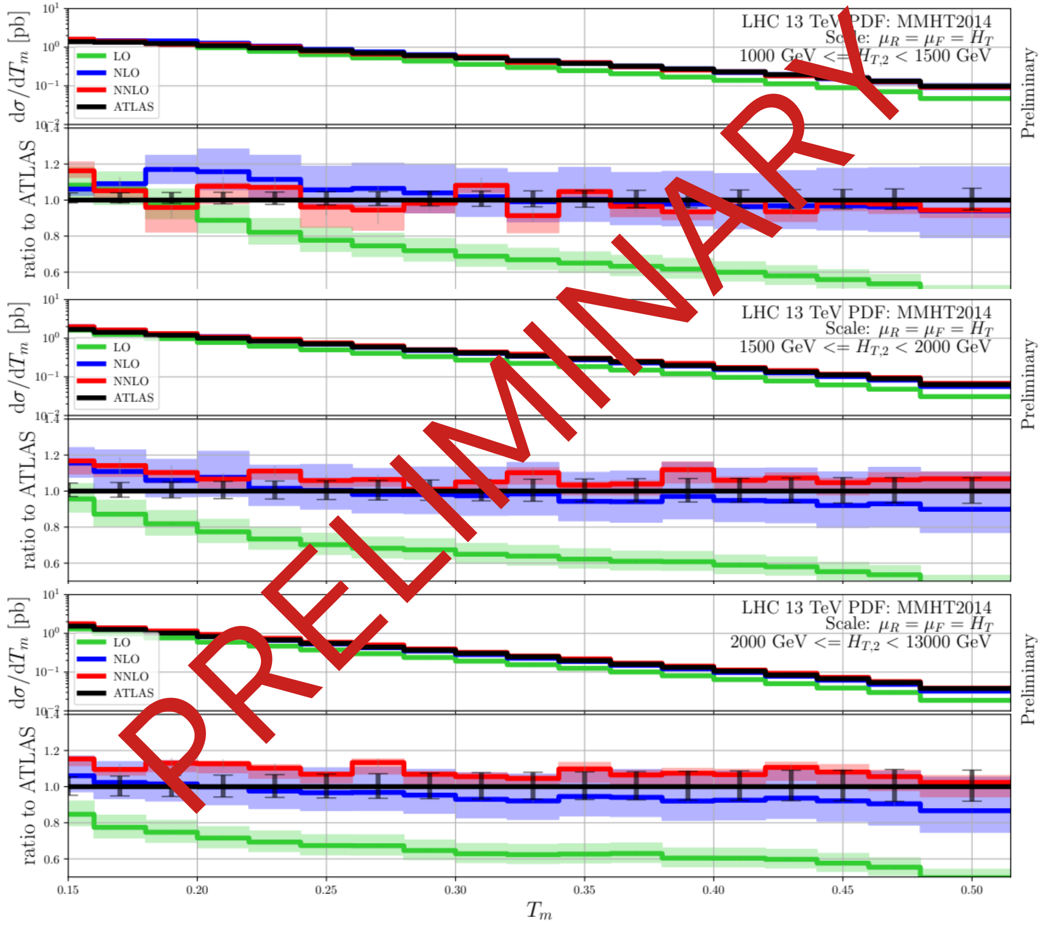
[ATLAS:2007.12600]

NNLO QCD corrections to event shapes

Comparison of public data from HEPdata

HT 2 denominator:





Credits:
Javier Llorente!

Example Thrust-Minor:

- Beautiful perturbative convergence
- Significant reduction of perturbative corrections

Flavoured Jets

Flavoured jets

- Jets are a tool to connect QCD of quarks&gluons to actually strongly interacting particles, i.e. hadrons.
- They are defined by a suitable algorithm: experimentally and theoretically
- Jet-substructure reveals additional information:
  - Separation of quark and gluon initiated jets
  - Jets of definite flavour:

Experimentally	*Displayed vertices* of heavy intermediate particles: D/B mesons
MC Event Simulation	Similar objects due to hadronization and detector simulations
Partonic computations	• Impose relation between quarks and hadrons (quark model) • Massless quarks: emission of soft flavoured pairs → gluons → Implications for IR safety in FO computations beyond NLO

- Why are partonic computations for flavoured jets interesting?
  - Higher order perturbation theory (not necessarily available matched to PS)
  - Extraction of SM parameters or PDFs

Fixed order flavoured jets beyond NLO

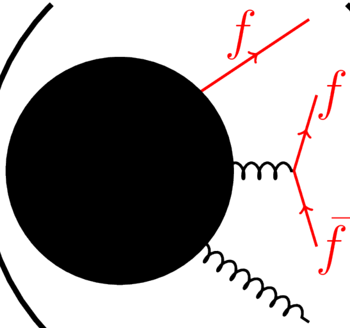
What is the problem with FO flavoured jets?

Example NNLO: double real radiation and subtraction

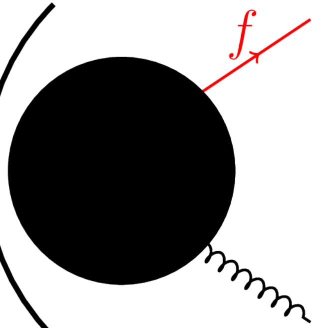
Double real matrix element

Double soft subtraction term:
Double soft function * tree ME

$$\mathrm{d}\sigma \ni \mathrm{d}\Phi_{n+2} \left(\right.$$



$$\left. \right) F_{n+2} + \cdots + \mathrm{d}\tilde{\Phi}_{n+2} \mathcal{S}_2 \left(\right.$$



$$\left. \right) F_n$$

Flavour structure depends on the angular configuration

IR safety:
Have to match in double soft limit

Fixed flavour structure

- If F(n+2) does not treat the flavour pair appropriately:
  → double soft singularity not subtracted

➔ Implies correlated treatment of kinematics and flavour information

Solution: Modified jet algorithms

➔ Implies correlated treatment of kinematics and flavour information

Standard kT algorithm [Ellis'93]:

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 [Banfi'06]:

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:

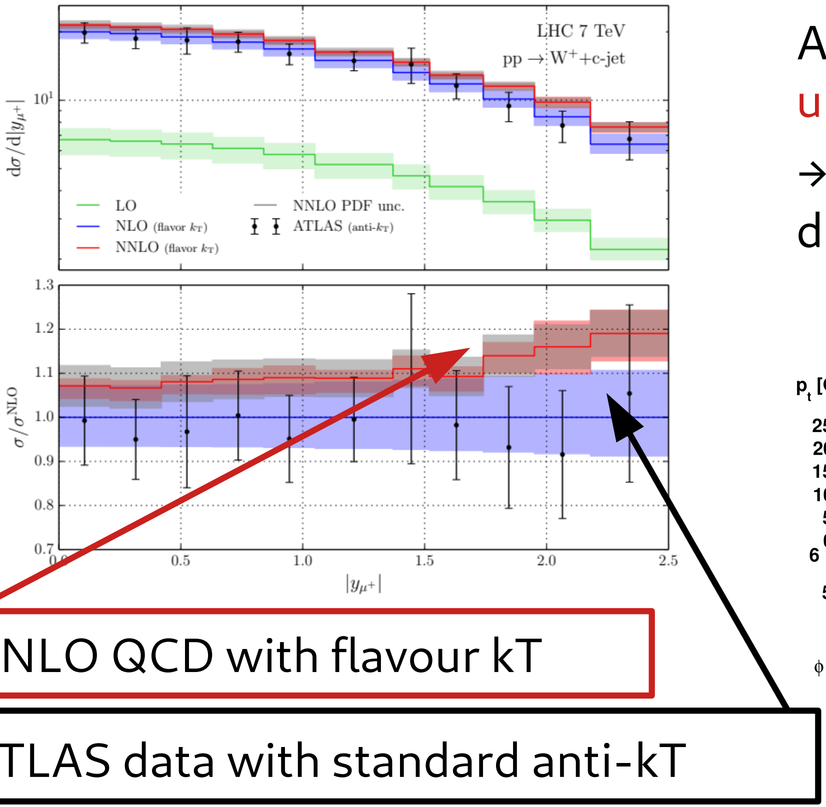
$$d_{i,B} = \begin{cases} \max(k_{T,i}, k_{T,B}(y_i))^\alpha \min(k_{T,i}, k_{T,B}(y_i))^{2-\alpha} & \text{i is flavoured} \\ \min(k_{T,i}, k_{T,B}(y_i))^\alpha & \text{else} \end{cases}$$

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

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

Problem solved, isn't it?

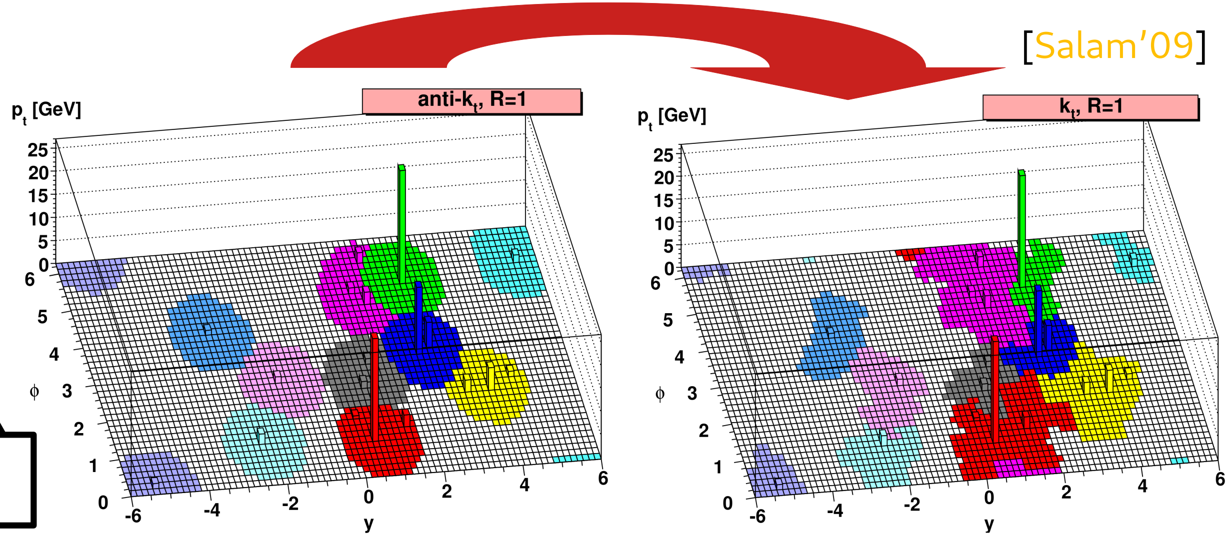
Real world example: W+c-jet at NNLO QCD with flavour-kT [Czakon'20]



A proper comparison would require to unfold experimental data

→ (flavour-) kT and anti-kT cluster partonic jets differently → Non-trivial procedure.

[Salam'09]



What about flavour anti-kT?

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:

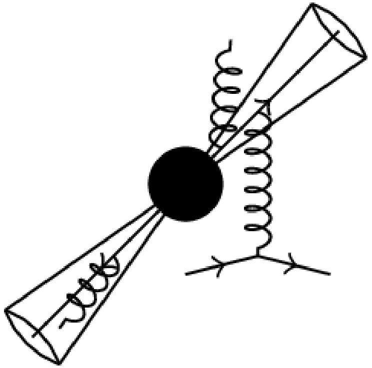
A soft term designed to modify the distance of flavoured pairs.

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

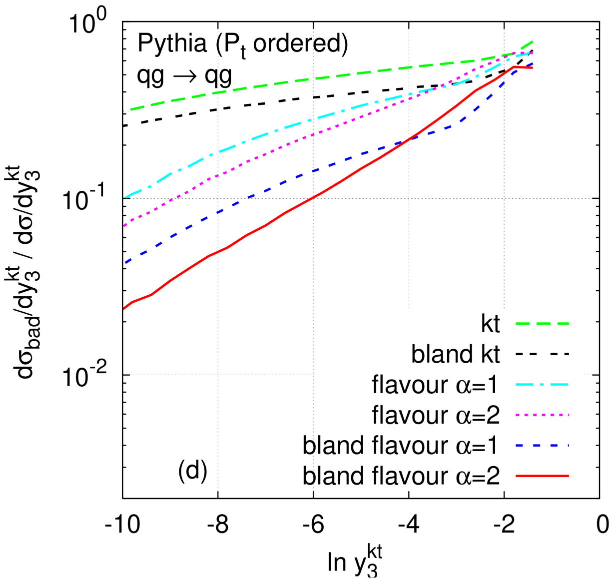
$$\mathcal{S}_{ij} = 1 - \theta(1-x)\cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_{T,i}^2 + k_{T,j}^2}{2a k_{T,\max}^2}$$

Tests of IR safety with parton showers

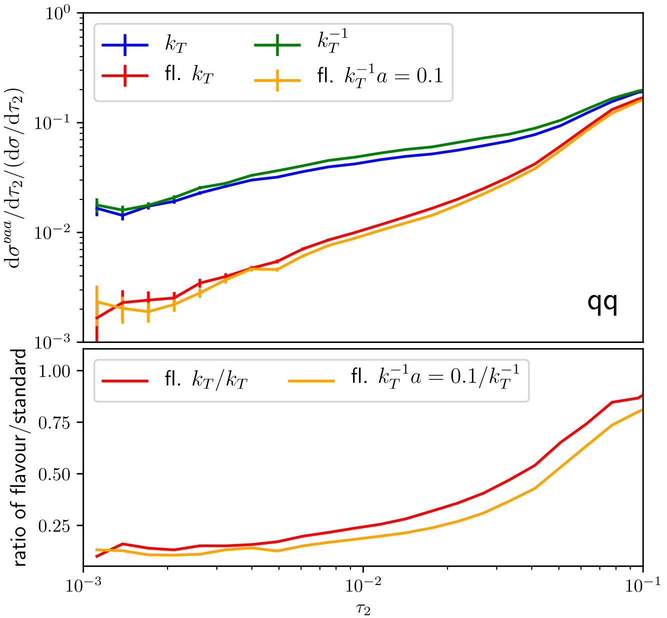
Dress tree-level di-jet events (definite flavour structure: “qq”, “qg” or “gg”) with radiation and study jet flavour (q or g) as function of kinematics.
In the di-jet limit the flavour needs to correspond to tree level flavours
→ misidentification rate needs to vanish in dijet back-to-back limit



Flavour kT vs. kT [Banfi’06]:

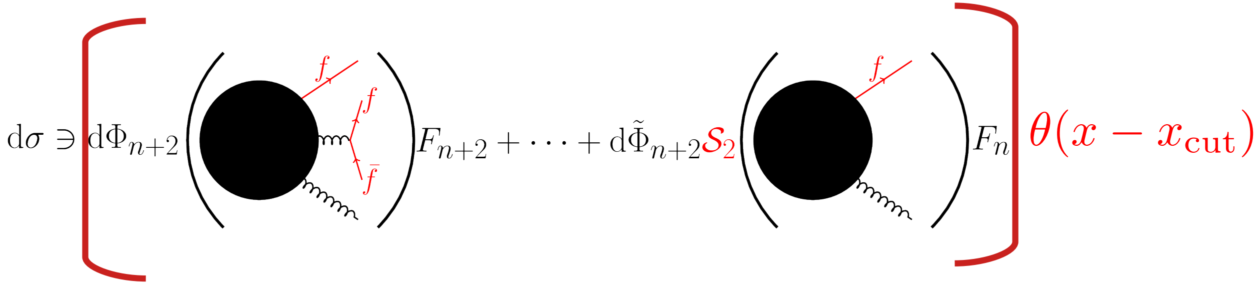


Flavour anti-kT



Tests of IR safety with NNLO FO computations

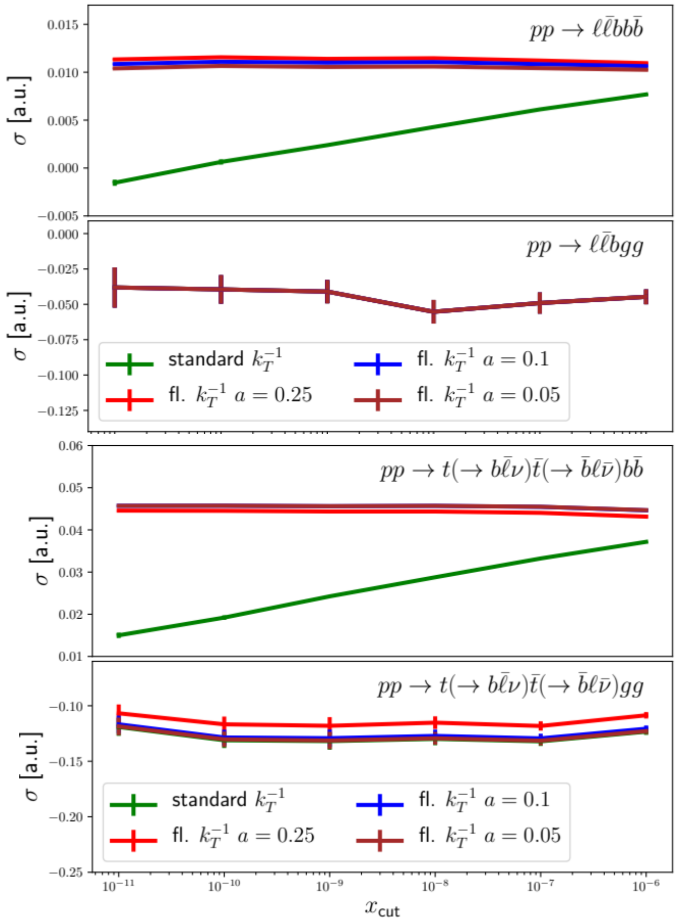
IR sensitivity of jet cross sections on (technical) IR regulating parameter x



In the limit x_cut → 0:

IR safe jet flavour → no dependence on x_cut

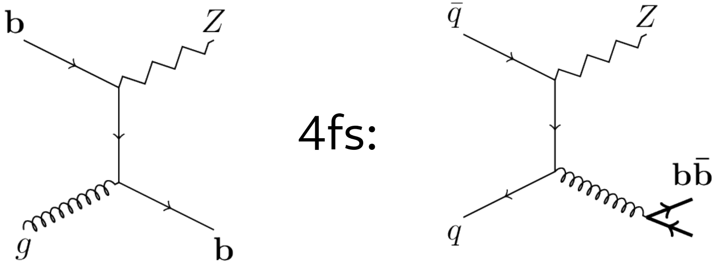
IR non-safe jet flavour → logarithmic divergent



Phenomenology: Z+b-jet

Benchmark process: pp → Z(ll) + b-jet

5fs: 4fs:

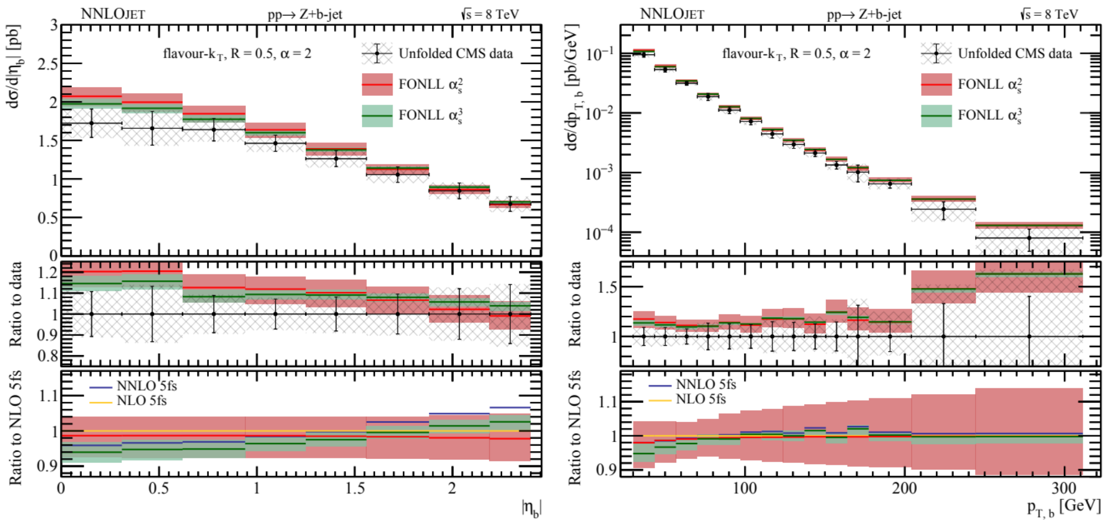


Well studied up to $\mathcal{O}(\alpha_s^3)$ [Gauld'20]:

- Defined with flavour-kT algorithm
- Unfolding of experimental data (RooUnfold,bin-by-bin unfolding)
- Matching between four- and five-flavour schemes (FONLL) [Gauld'21]

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

- CMS measurement @ 8 TeV [CMS 1611.06507]



Phenomenology: Tunable parameter

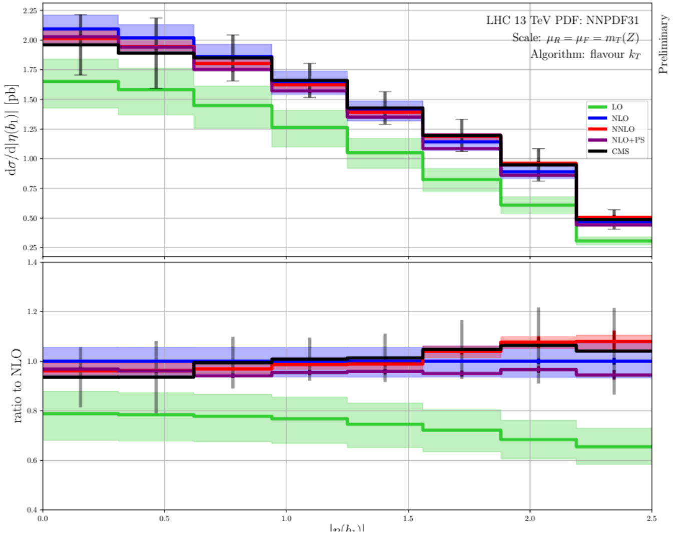
Preliminary

Benchmark process: pp → Z(ll) + b-jet

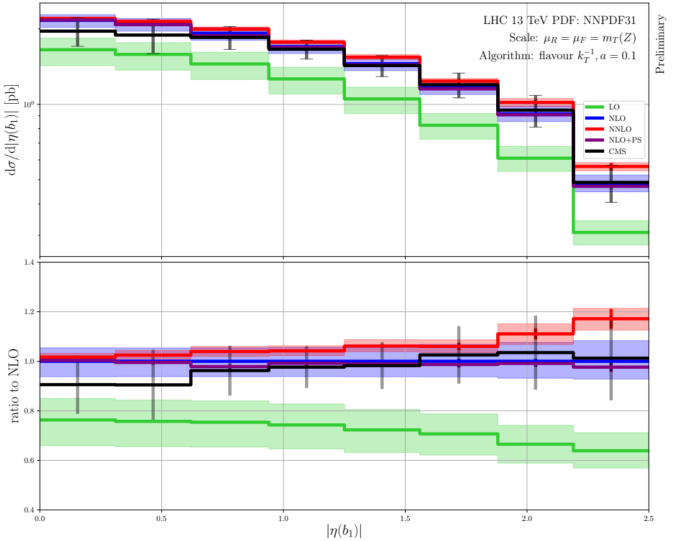
Tunable parameter a:

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

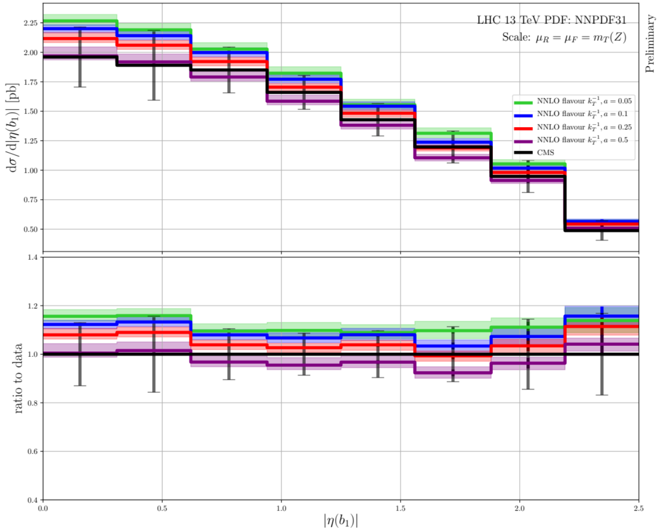
Flavour kT:



Flavour anti-kT: $a = 0.1$



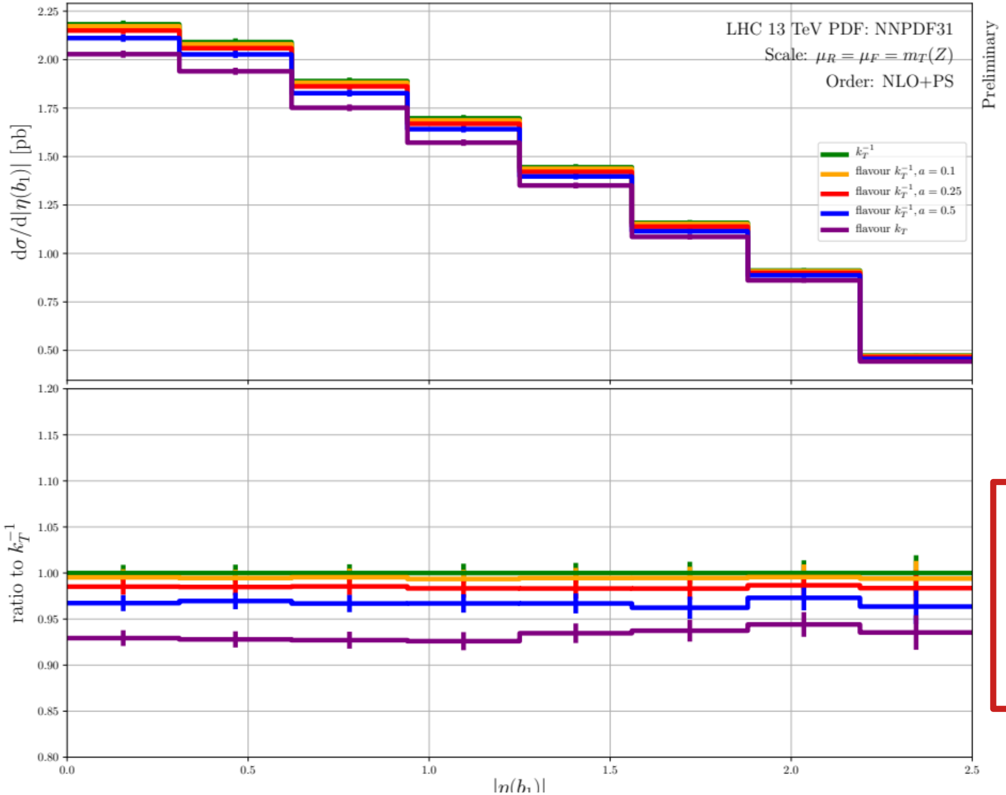
Comparison of different parameter a to data:



Phenomenology: Tunable parameter II

Preliminary

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



Tunable parameter a:

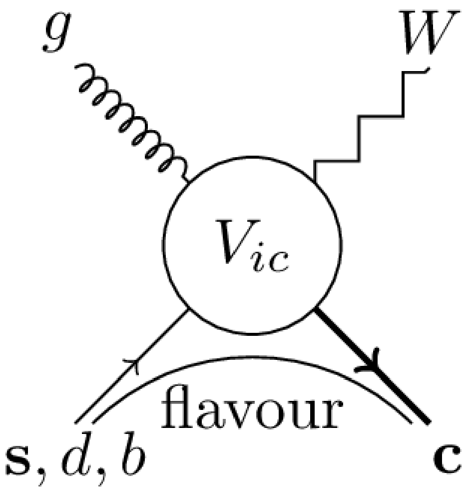
- Small a: Flavour anti-kT results are more similar to standard anti-kT → small unfolding factors
- Larger a: Larger modification of clustering

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

W+c-jet

Idea: Identify final state c-quarks to access s-quark PDFs.
→ Reduction of PDF uncertainties
→ Shed light on $s\bar{s}$ asymmetry

- Non-diagonal CKM and g → $c\bar{c}$ reduce s-PDF sensitivity
- Large NLO corrections → higher order corrections?
- Theoretical treatment:
  - Massive c (3-flavour scheme):
    - Resummation of mass logs at high pT → PS
    - Higher order predictions?
  - Massless c:
    - c-quark part of the PDFs
    - NNLO QCD available
    - **Jet definition?**



Vsc > Vdc >> Vbc

W+c-jet with flavour kT at NNLO QCD

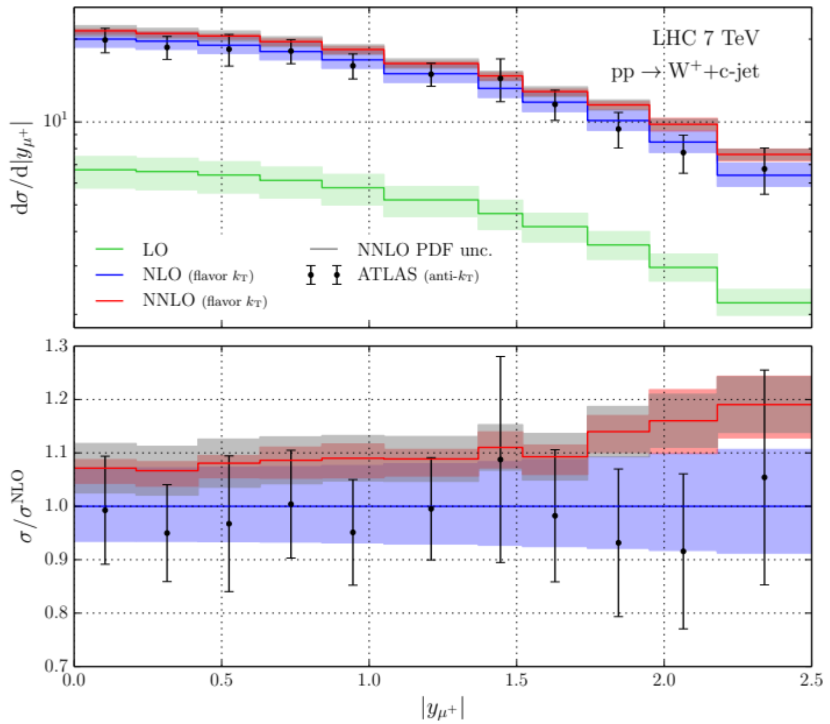
In collaboration with: Czakon, Mitov, Pellen

NNLO QCD 7 TeV results [2011.01011]:

- Full NNLO corrections for Vcs contribution
- Off-diagonal CKM only LO QCD
- Comparison flv. kT results vs. ATLAS [1402.6263]

Update for 13 TeV measurement:

- Full CKM through NNLO QCD
- Study of different jet-algorithms:
  - Impact of beam-function d_iB in flv kT
  - New anti-kT algorithm
- Study of different flavour tag definitions/setups:
  - Modulus vs. absolute flv tag definition
  - OS minus SS
  - "Inclusive c-jet" rates



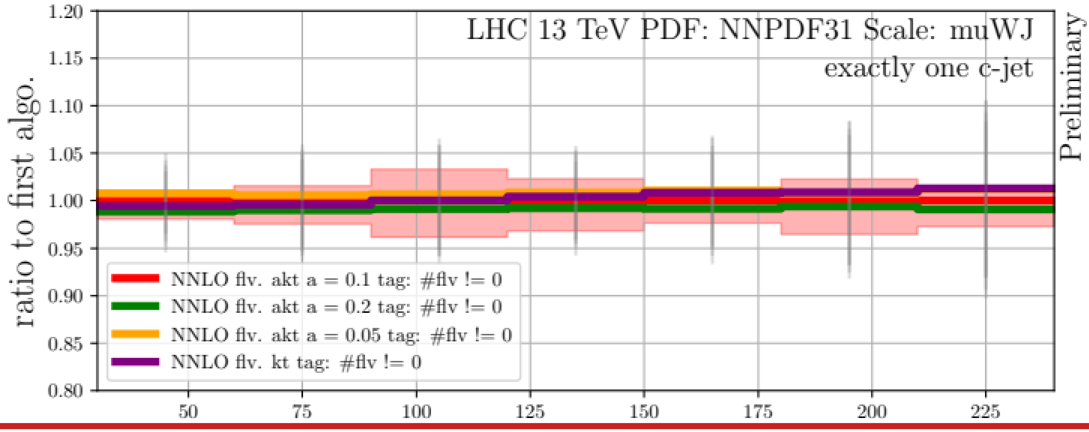
W+c-jet with flavour anti-kT

In collaboration with: Czakon, Mitov, Pellen

Preliminary

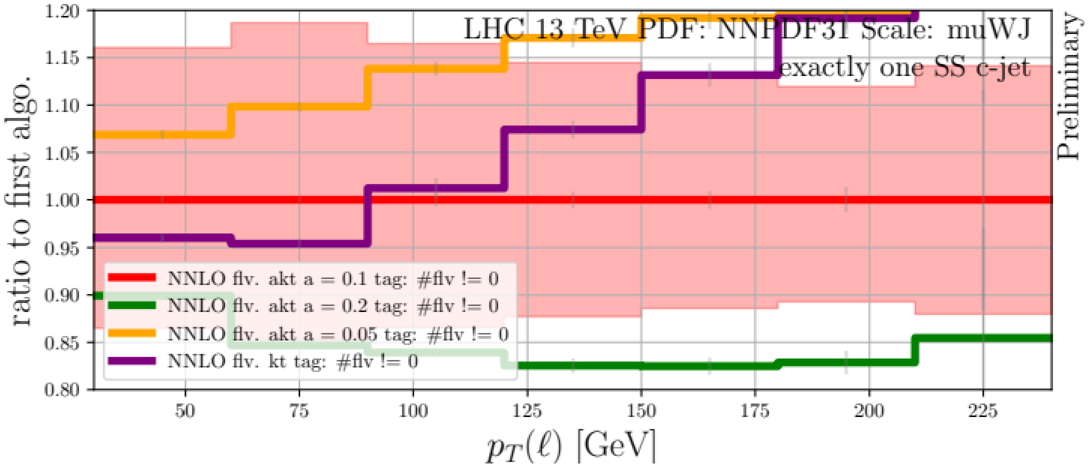
Exactly one c-jet requirement:

- 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

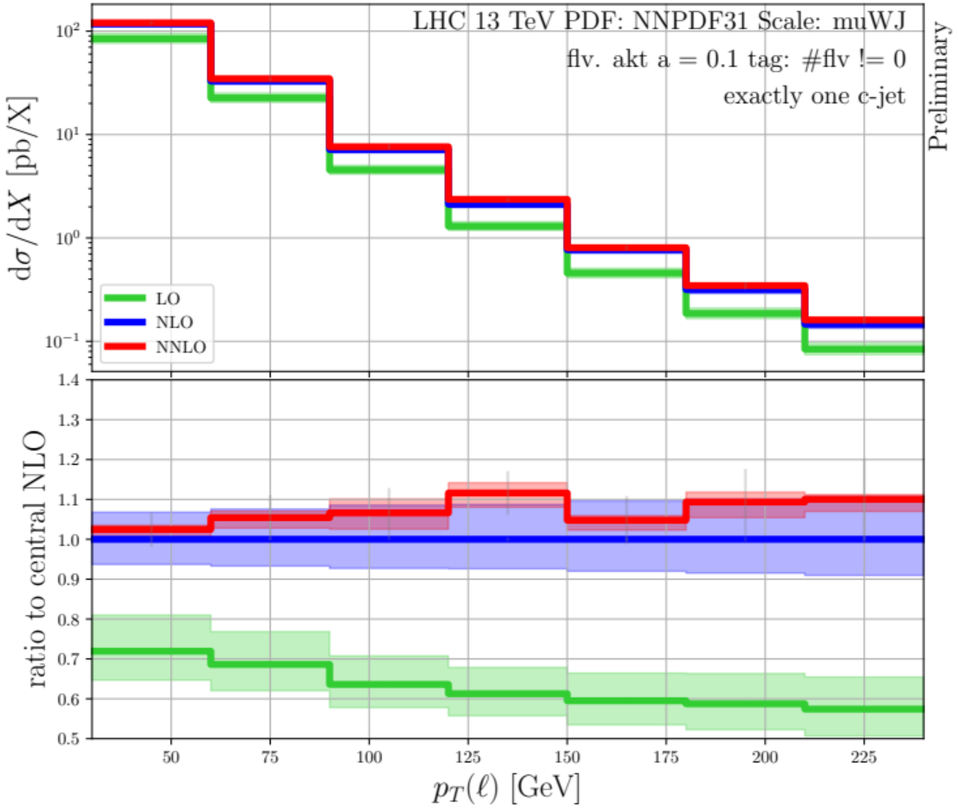


Flavour tags: OS - SS

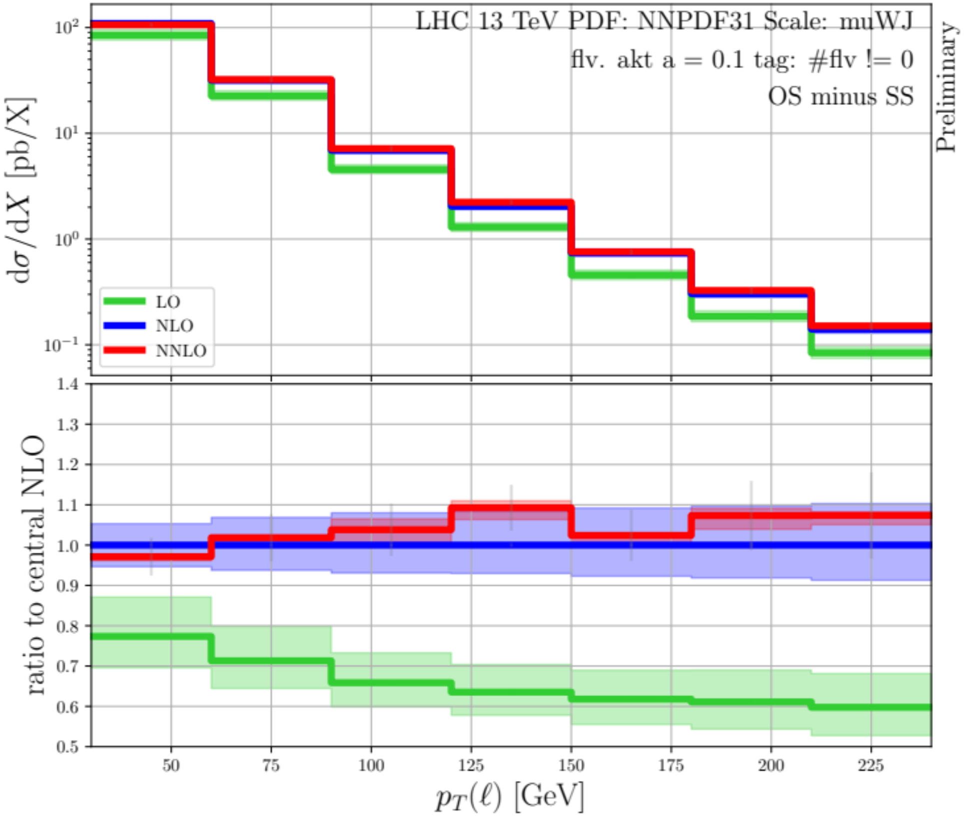
In collaboration with: Czakon, Mitov, Pellen

Preliminary

Exactly 1 c-jet:



OS-SS:



Some final remarks

- What is that kT_max parameter?

  Some scale to define what soft means.

  Examples:

  1. pT of hardest pseudo jet or lepton at a clustering step
  2. Some fixed dynamical scale, e.g. pT(Z), pT(lep), …
  3. Some fixed hard scale: m_top, m_Z etc.

  → The choice impacts the clustering.

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

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

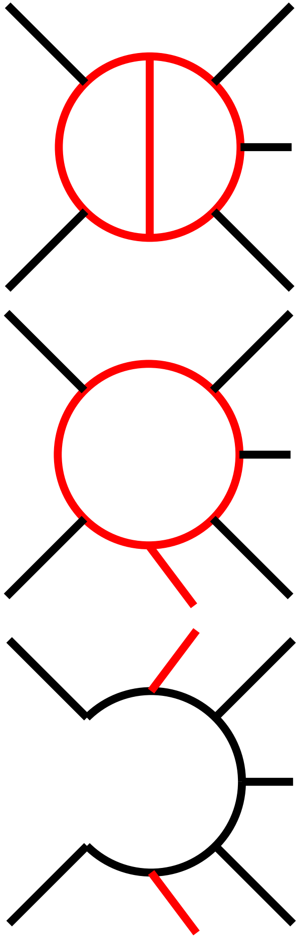
- Besides c/b jets: What about gluon/quark jet identification?

  Conceptually not a problem. Not yet studied in detail.

  But might introduce some more sensitivity to actual form of S_ij ??

- More complicated examples: pp → W bbar ! LO sensitivity to flv jet algorithm

Summary and Outlook



Precision jet observables allow for many pheno applications!

- First NNLO QCD phenomenology results for three jet production
  R32 ratios, azimuthal decorrelation, event-shapes
- Future application to alphaS extraction

Flavoured jet observables

- New proposed flavour safe version of anti-kT
- Phenomenological applications to Z+b-jet, W+c-jet, top-quark pairs
- Many more applications ahead: open-b's,...

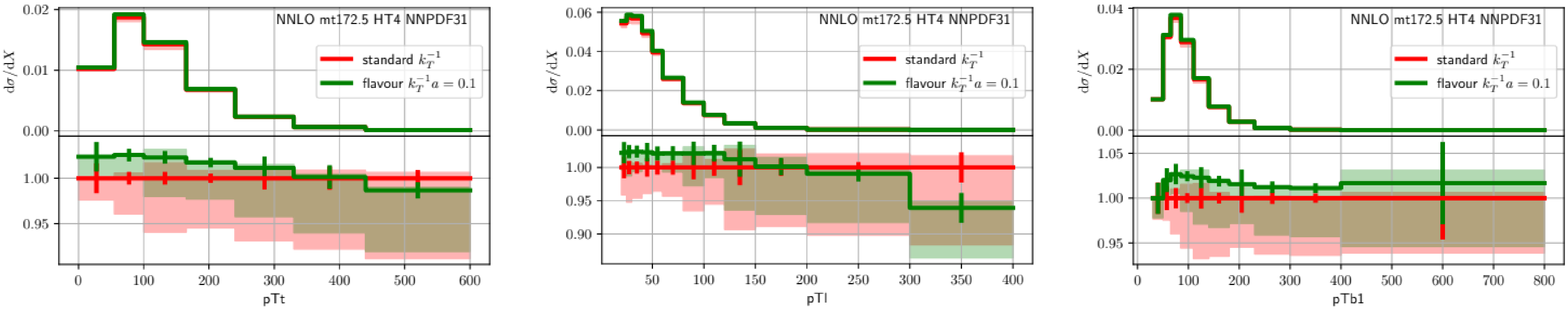
Backup

b-jets in top-pair production&decay

NNLO QCD corrections [Czakon'20] to: $pp \to t(\to b\bar{\ell}\nu)\bar{t}(\to \bar{b}\ell\bar{\nu}) + X$

Flavour sensitive channels like: $pp \to t\bar{t}b\bar{b} \to \bar{\ell}\nu\ell\bar{\nu}\, b\bar{b}b\bar{b}$

Small numerical impact from extra bbar emissions
in pp → bbar [Catani'20] and single-top production [Berger '17'18, Campbell '20]
→ naive treatment via cut-off procedure



Naive 'cut-off' treatment vs. proposed IR safe flavour anti-kT