NNLO QCD predictions for jet observables

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State of NNLO QCD at the LHC

NNLO QCD completed for 2 → 1, 2 → 2 SM processes:

- Colour singlet production: pp → H, pp → VV (available in MATRX [Grazzini'17], MCFM [Boughezal'16])
- Massive quark production: pp → ttbar (+decays) [Czakon'15], pp → bbar [Kallweit'20], single top [Campbell'17]
- Vector plus jet: pp → V+jet, pp → A + X, flavoured jets: pp → Z+b-jets, V+c-jets [NNLOJet '16-'20,Boughezal'15,Czakon'20]
- Di-jets: pp → j + X, pp → jj + X [NNLOJet '16-'20, Czakon'19]

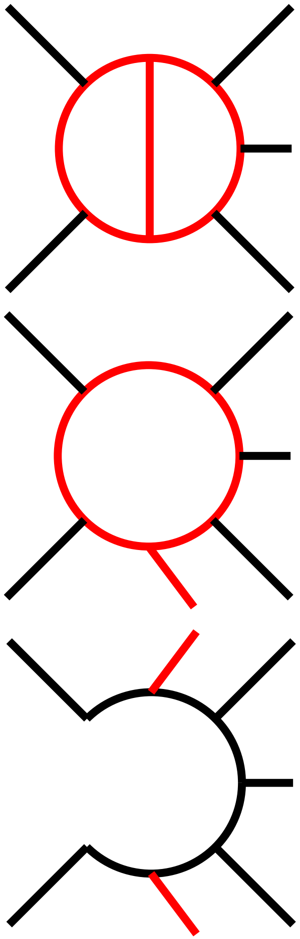
Recently first steps in the realm of 2 → 3 processes:

- Three photons [Chawdhry '19, Kallweit '20]
- Diphoton plus jet [Chawdhry '21] gg-induced @ N3LO [Badger'21]
- Three jets [Czakon '21]

Beyond fixed order:

- Dedicated resummation calculations for specific observables
- First NNLO + PS appear for colour singlet and ttbar: MiNNLOPS with MATRIX [Monni '20]
- Identified hadron production: B-hadrons in ttbar production [Czakon '21]
- Photon fragmentation [Gehrmann'21]

NNLO QCD prediction beyond 2 → 2



2 → 3 Two-loop amplitudes:

- (Non-) planar 5 point massless 'pheno ready' [Chawdry'19'20'21,Abreu'20'21,Agarwal'21,Badger'21]
  fast progress in the last half year
  → triggered by efficient MI representation [Chicherin'20]
- 5 point with one external mass [Abreu'20,Syrrakos'20,Canko'20,Badger'21]

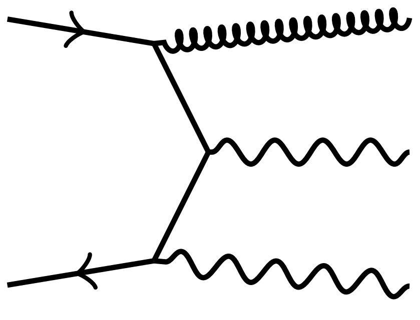
Many leg, IR stable one-loop amplitudes → OpenLoops [Buccioni'19]

Cross sections → Combination with real radiation

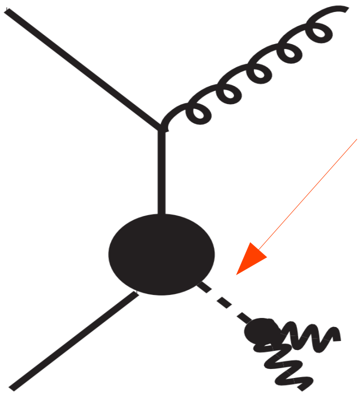
- Various NNLO subtraction schemes are available:
  qT-slicing [Catain'07], N-jettiness slicing [Gaunt'15/Boughezal'15], Antenna [Gehrmann'05-'08], Colorful [DelDuca'05-'15], Projection [Cacciari'15], Geometric [Herzog'18], Unsubtraction [Aguilera-Verdugo'19], Nested collinear [Caola'17], Sector-improved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

Diphoton plus jet production

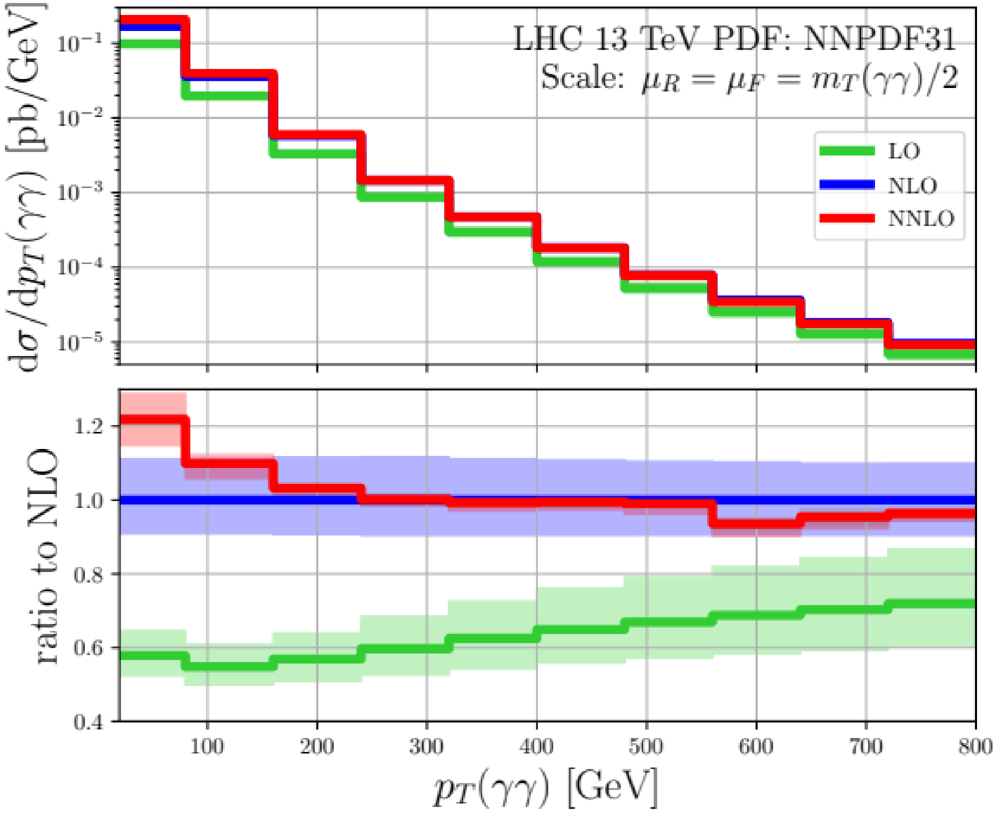
- Photon pair production @ LHC is of particular interest:
  - → Main background to cleanest Higgs decay channel
- Inclusive diphoton show large NNLO QCD corrections
  - → Perturbative convergence @ N3LO?
    First steps: [Chen's talk at RADCOR+Loopfest2021]
  - → Diphoton plus jet @ NNLO QCD ($p_T(\gamma\gamma)$→ 0 limit)
- $p_T(\gamma\gamma)$ spectrum itself interesting for Higgs → γγ :
  - → Higgs – p_T measurements resolve local Higgs couplings → BSM searches
  - → Angular diphoton observables → spin measurements



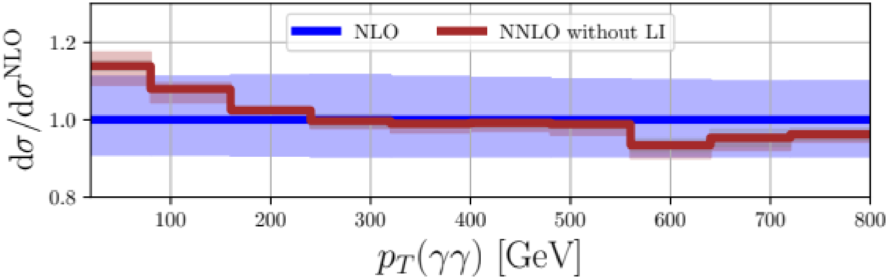
$pp \to g\gamma\gamma + X$



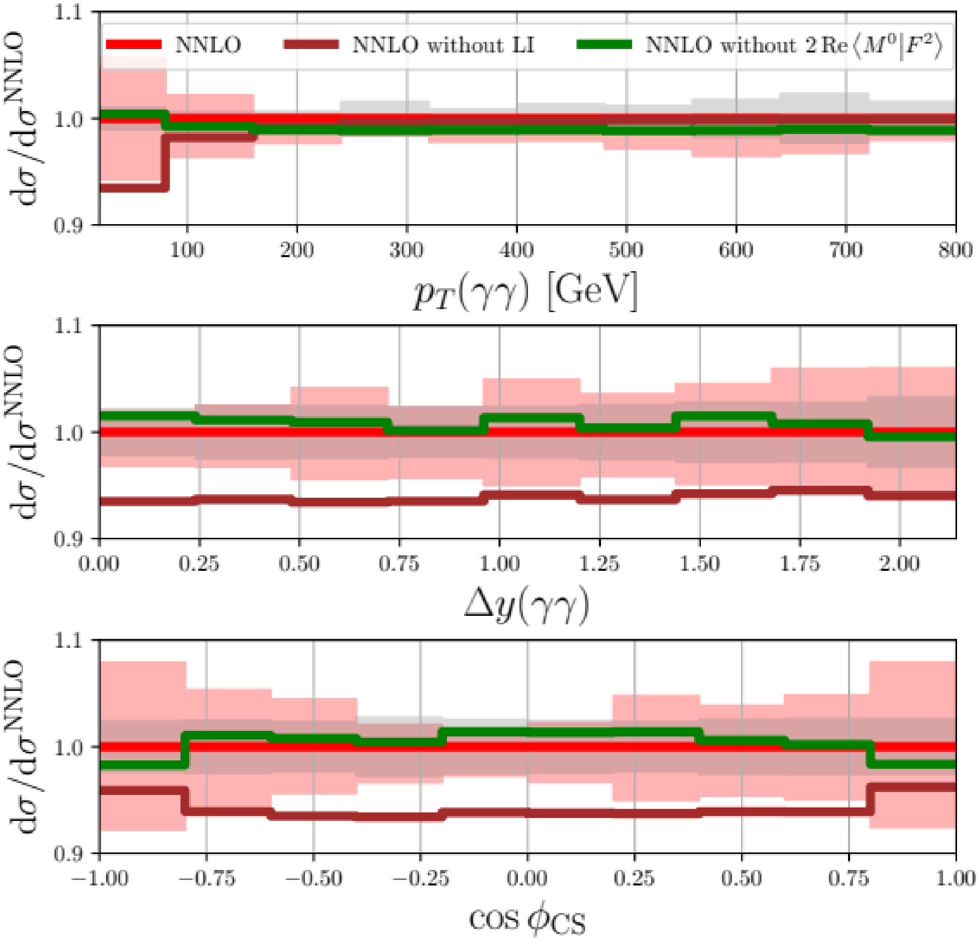
Diphoton plus jet – pT spectrum



- Beautiful perturbative convergence
- Scale dependence:
  NLO: ~10%
  NNLO: ~1-2%
- Low p_T region:
  - ? Resummation for $p_T(\gamma\gamma)/m(\gamma\gamma) \ll 1$
  - Strong effect from the loop induced!

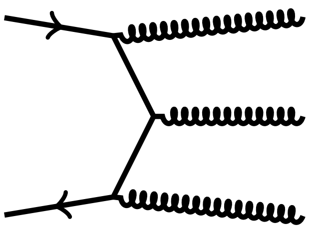


Diphoton plus jet – two-loop contribution



- Two-loop contribution (green line) <~1%,
- Loop induced contribution:
  - sizeable effects for low p_T vanishes for high p_T
  - flat effect in 'bulk' observables
  - Dominant source of scale dependence
  - NLO QCD correction (formally N3LO) relevant,
    ~~missing piece~~: $gg \to g\gamma\gamma$ two-loop [Badger'21]

Three jet production



Advances in perturbative QCD allow to tackle the most complicated 2→3 process

Bottlenecks:

- Handling of real radiation:
  - Sector-improved residue subtraction [Czakon'10'14'19]
  - Computationally very challenging! → O(1M CPUh)
- Double virtual amplitudes in leading colour approximation [Abreu'21]
  - Fast numerical evaluation → very small contribution to computational cost

Only Approximation made:

→ taken from [Abreu'21]

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

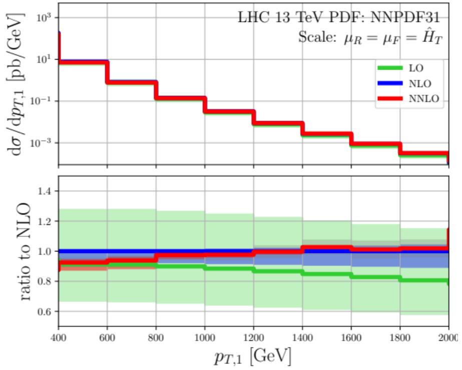
$$\mathcal{R}^{(2)}(s_{12}) \approx \mathcal{R}^{(2)l.c.}(s_{12})$$

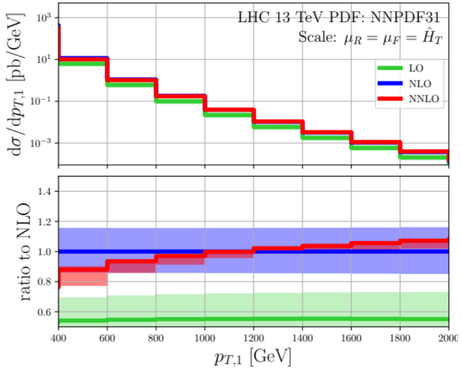
Three jet production - R32(pT1)

- 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:

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

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





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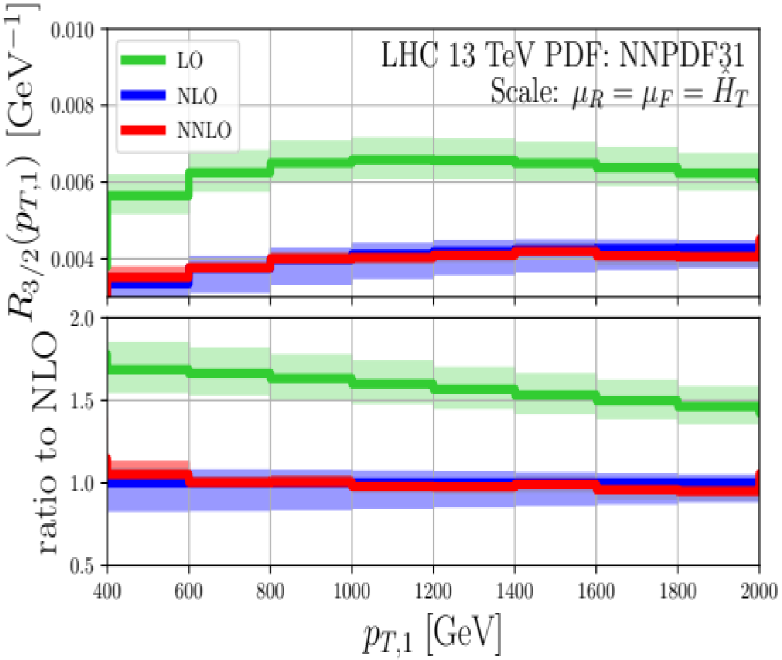
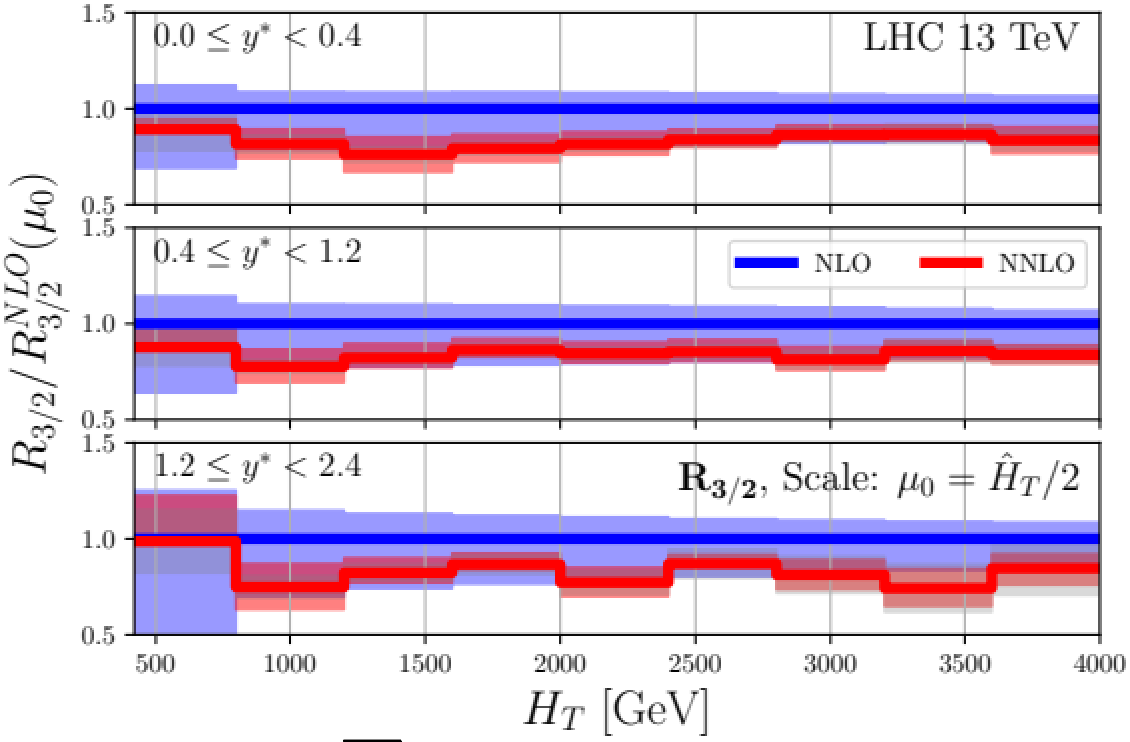


Three jet production – R32(HT,y*)



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

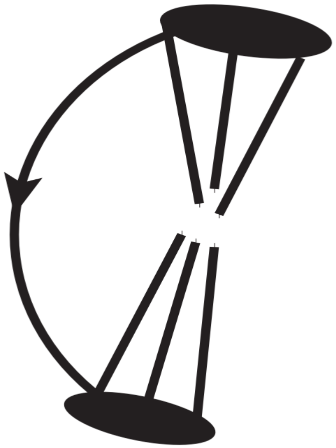
Central scale choice: $\hat{H}_T/2$

Three jet production – azimuthal decorrelation

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

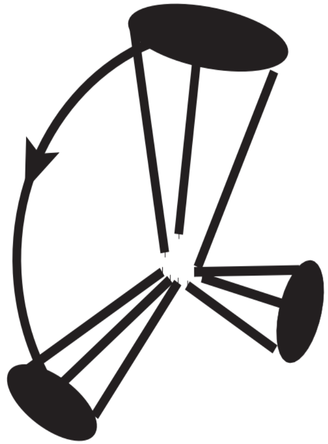
Dijet:

$$\phi_{12} = \pi$$



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

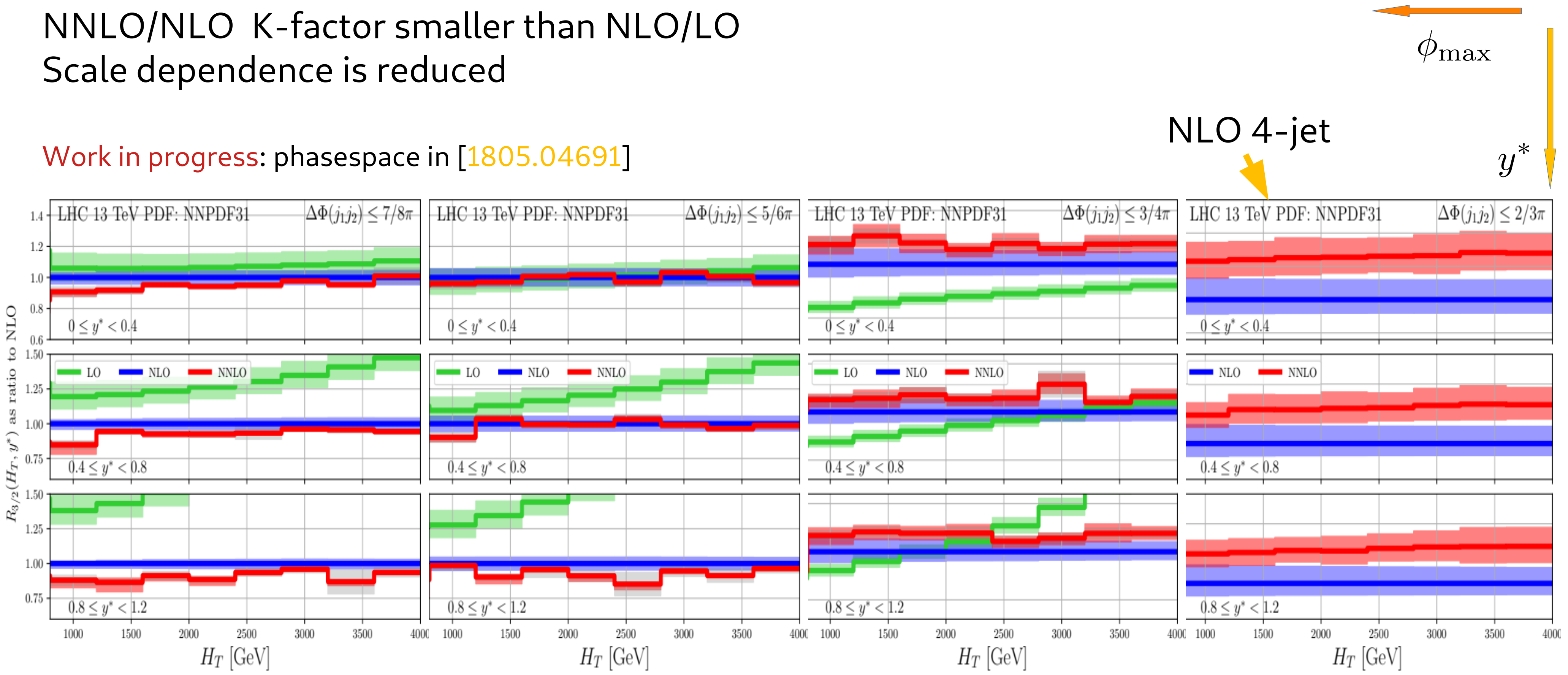
Study of the ratio:

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

Three jet production - azimuthal decorrelation

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

Work in progress: phasespace in [1805.04691]

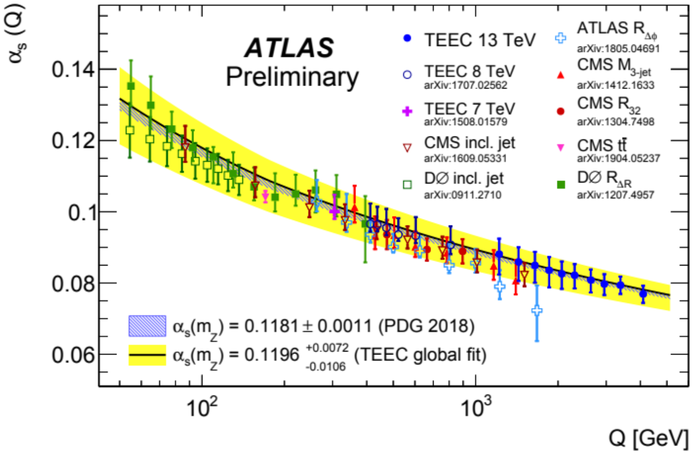


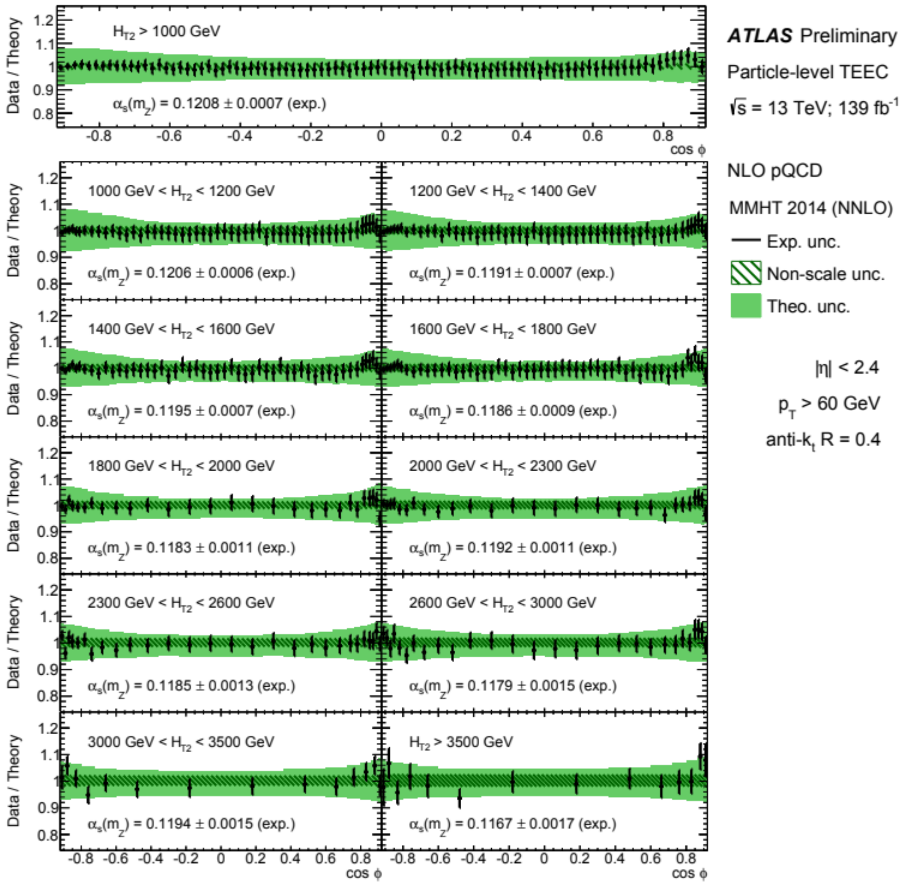
Energy correlators at the LHC

In collaboration with ATLAS group:
Strong coupling measurement in TEEC
→ three jet is leading contribution
→ normalization through dijet rates

TEEC: Transverse Energy-Energy Correlation

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





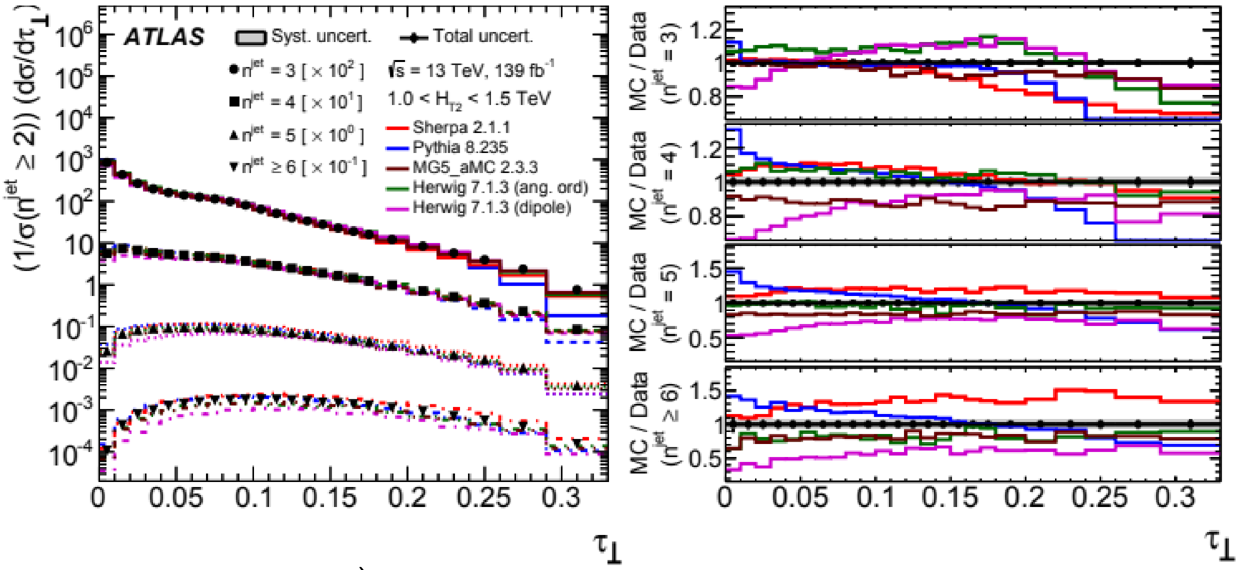
[ATLAS-CONF-2020-025]

Event-shapes at the LHC

ATLAS measurement of event shapes [2007.12600]

Transverse Thrust:

$$\tau_T = 1 - \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}|}{\sum |\vec{p}_{T,i}|}$$

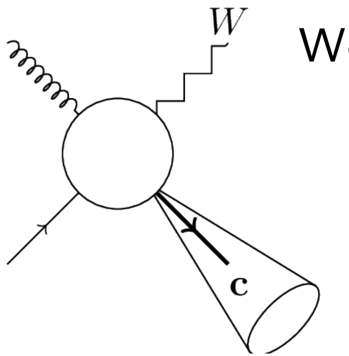


Linearised sphericity tensor:

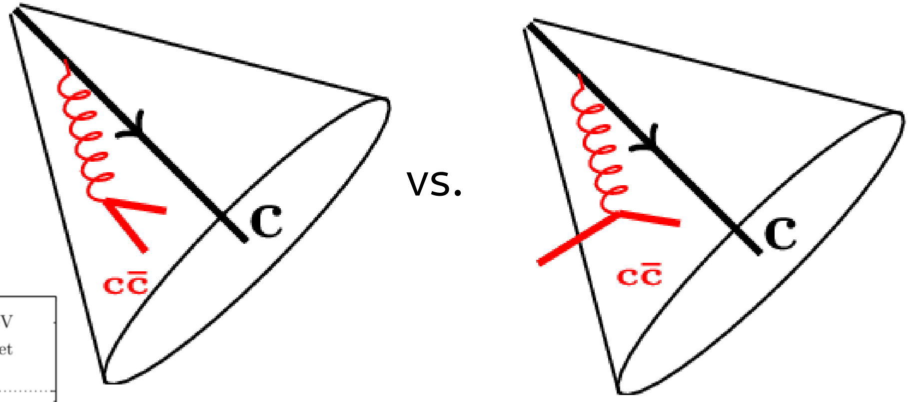
$$\mathcal{M}_{xyz} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} & p_{x,i}p_{z,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 & p_{y,i}p_{z,i} \\ p_{z,i}p_{x,i} & p_{z,i}p_{y,i} & p_{z,i}^2 \end{pmatrix}$$

Flavoured jets and fragmentation

IR safe jet flavour

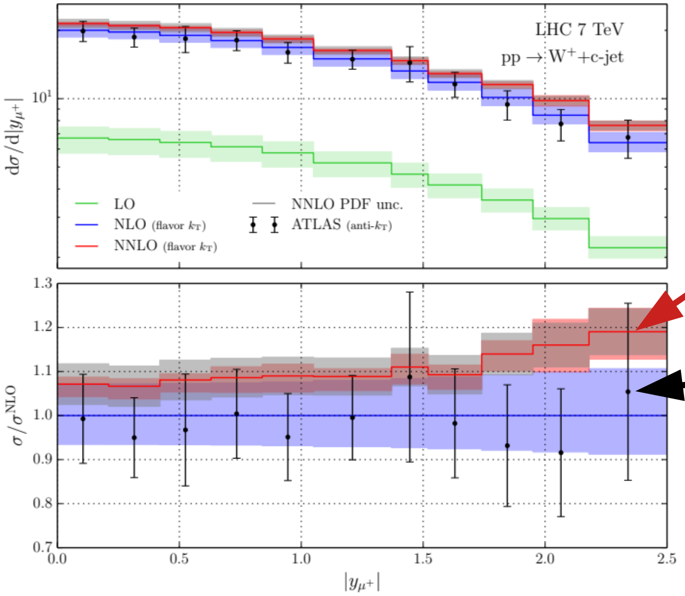
Example: 

Well known problem in massless NNLO QCD [Banfi'06]:



A possible solution:
change the clustering
→ Flavour – KT algorithm

[Czakon'20]



NNLO QCD with flavour kT

ATLAS data with standard anti-kT

A proper comparison would require to unfold experimental data

What about flavour anti-kT?

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

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

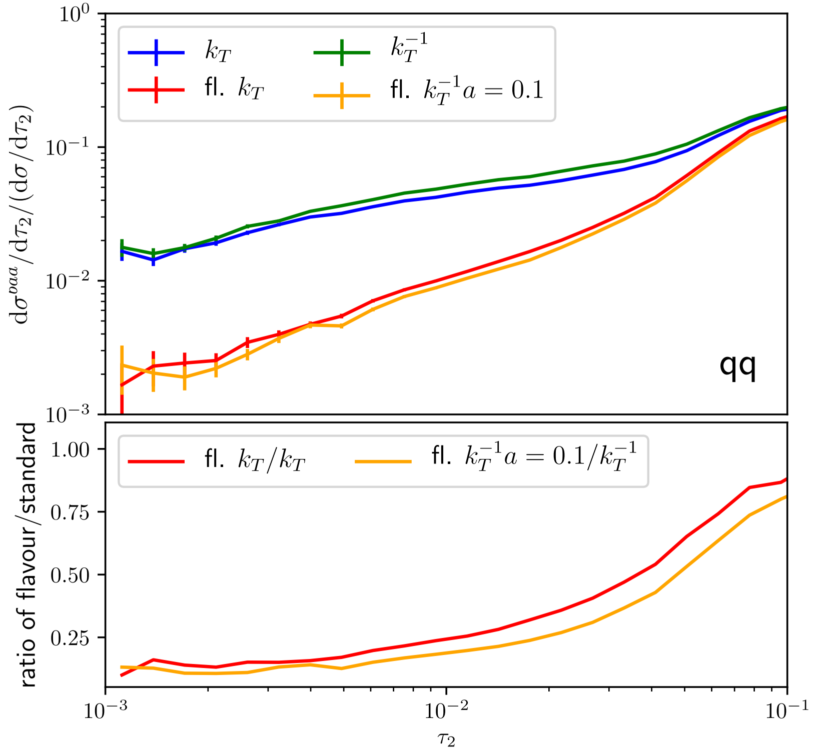
Proposed modification [to be published soon]:

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

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

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

IR safety check:



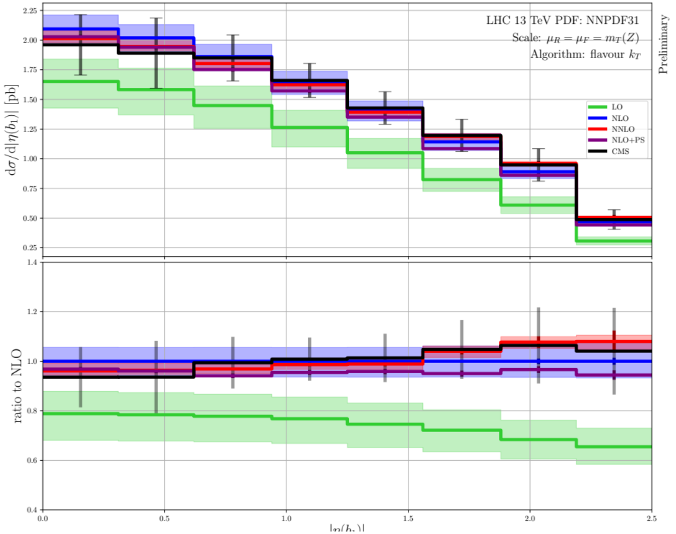
Phenomenology: Tunable parameter

Benchmark process: pp → Z(ll) + b-jet

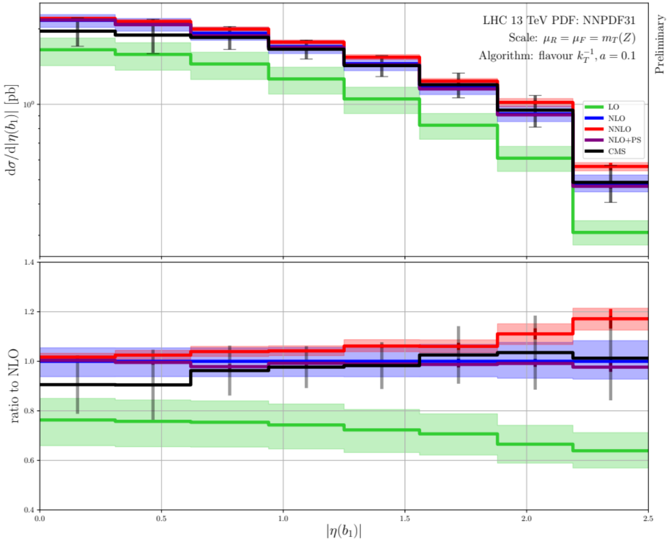
Tunable parameter a:

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

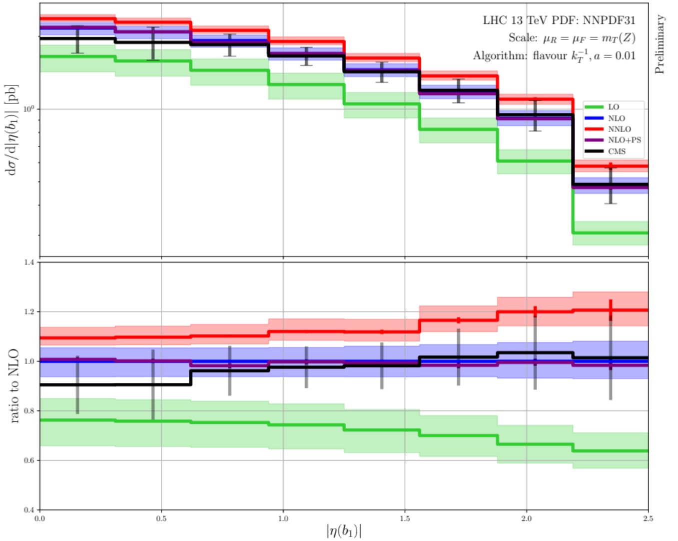
Flavour kT:



Flavour anti-kT: $a = 0.1$

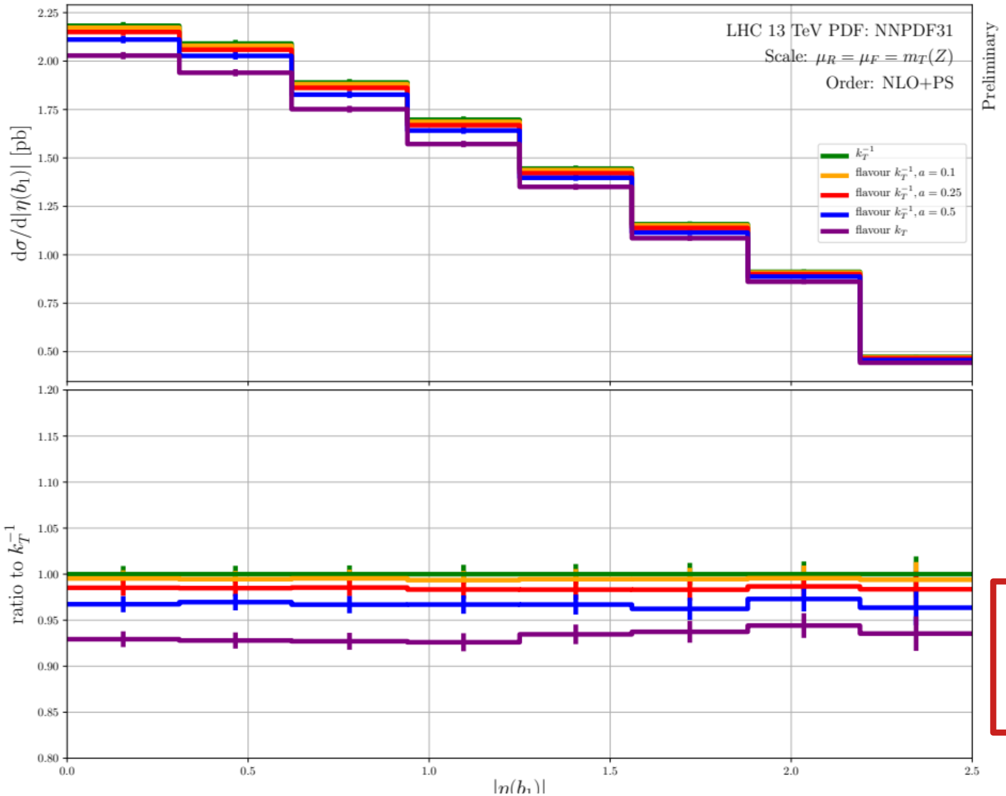


Flavour anti-kT: $a = 0.01$



Phenomenology: Tunable parameter II

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



Tunable parameter a:

- Flavour anti-kT results are similar to standard anti-kT
  → small unfolding factors
- Flavour-kT has larger difference

Combine with perturbative convergence:
→ a~0.1 is a good candidate

Fixed-order Fragmentation

Fixed order QCD predictions with a final state hadron

Considering partonic computation
+ transition of parton to hadron (collinear fragmentation of massless partons)

Advantage is that the hadrons momentum is measurable while the quark's is not

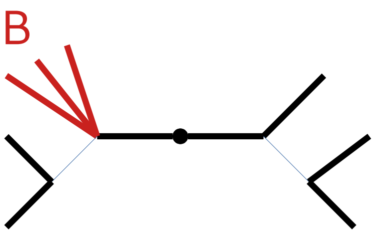
Fragmentation function (similar to PDFs)
Probability to find a hadron with a fraction x of the quarks momentum: $D_{i \to h}(x)$

No Parton-shower needed

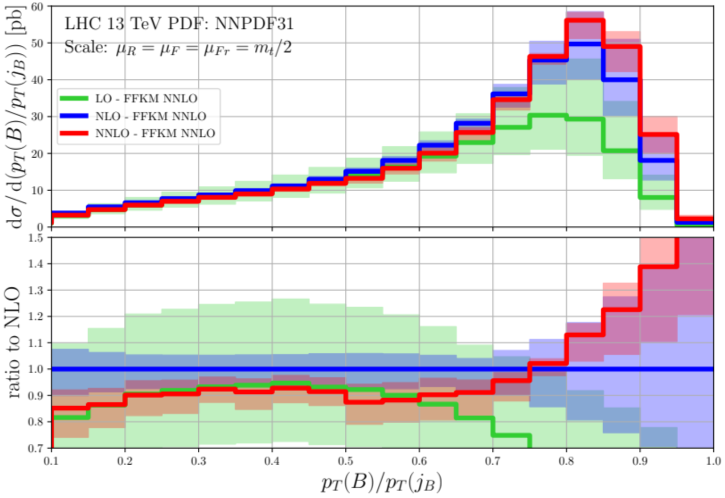
Implementation in the STRIPPER framework

B-hadrons in ttbar production

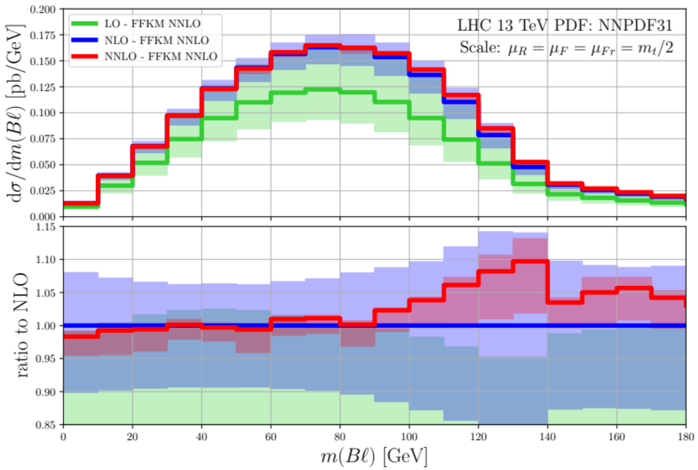
$$pp \to t\bar{t} \to B\ell\bar{\ell}\nu\bar{\nu}\bar{b} + X$$

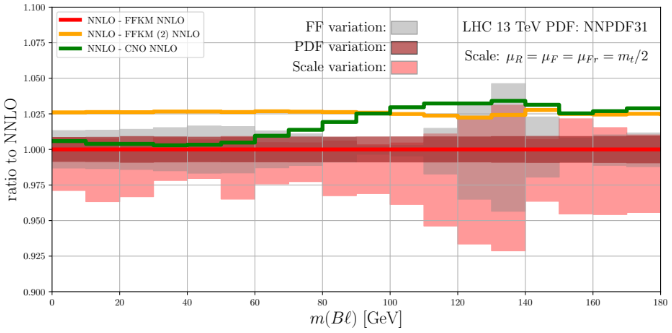


pT(B)/pT(jB): sensitive to B-hadron fraction x



m(lB): sensitive to top-quark mass





Applications

Exploration of applications:

→ Measurement of fragmentation functions at the LHC (so far mostly data from LEP)?

→ What observables? pT(B)/pT(jB) and similar look promising.

→ Using the B-hadron to tag jets in partonic computation? → flavoured jets

Fragmentation implementation not limited to ttbar:

→ Open b

→ V + hadron

Work in progress: fragmentation function fits with the right conventions

Summary and Outlook

NNLO predictions with the sector-improved residue subtraction framework

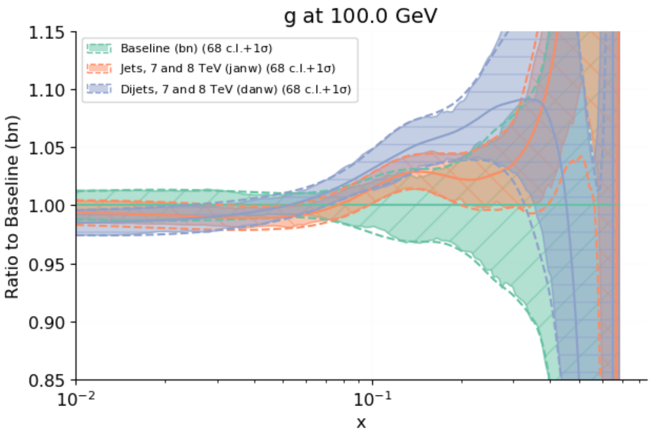
- First computations of 2 → 3 processes: 3 photon, 2photon+jet and three jet production
- Three jets @ the LHC:
  - R32 ratios → reduction of scale uncertainties, stabilization of K-factors
  - Planned applications: alphaS extractions from R32 ratios, event-shapes & TEEC
- Flavoured jet observables: new ideas for flavoured jet definitions with anti-kT
- Identified hadron production in fixed-order fragmentation:
  - Applications: measurement of fragmentation functions, top-quark mass measurements,…

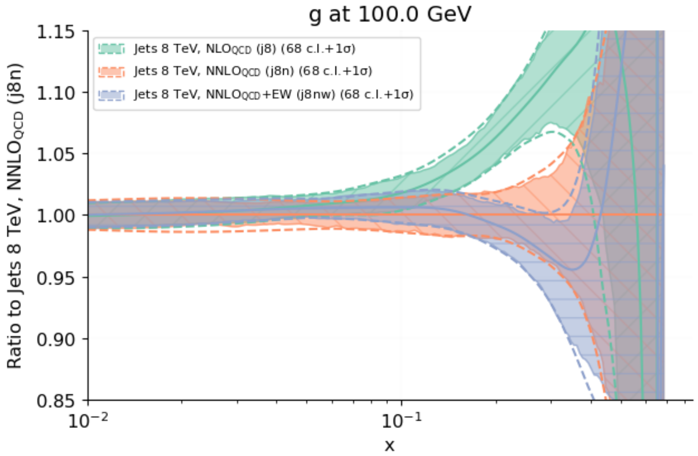
Many interesting applications ahead!
Stay tuned!

Thank you for your attention!

Backup

Higher order pQCD: PDF fits with jets





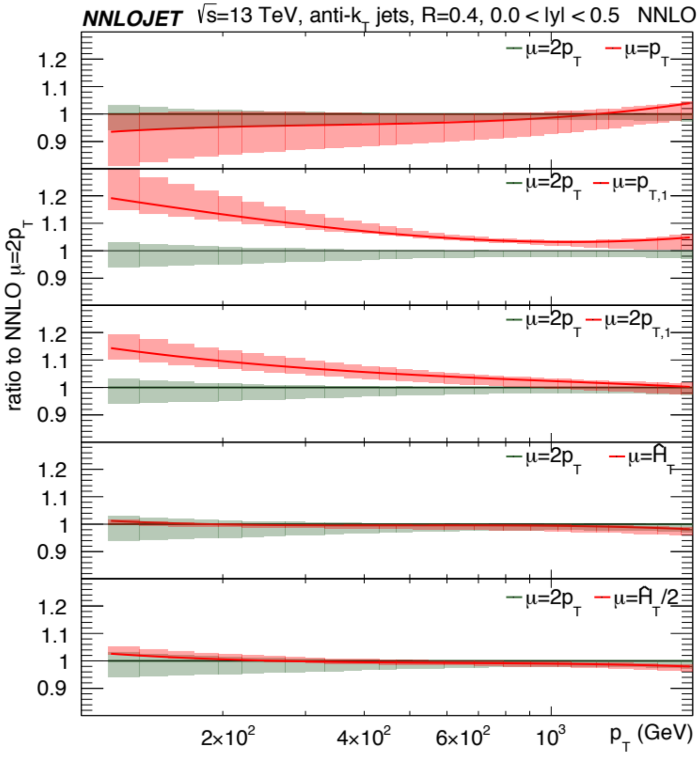
Idea (quite old actually [Giele'94]):

Here by a collaboration of NNLOJet and NNPDF [Khalek'20]:

Combine single inclusive and dijet triple differential measurements by ATLAS and CMS to constrain the large gluon-x

- Reduced uncertainty in large-x gluon PDF
- NNLO QCD corrections crucial to obtain consistent results between data sets
- NLO EW [Dittmaier'12] or
  full NLO corrections [Frederix'17,Reyer'19]

Higher order pQCD: lessons from dijet



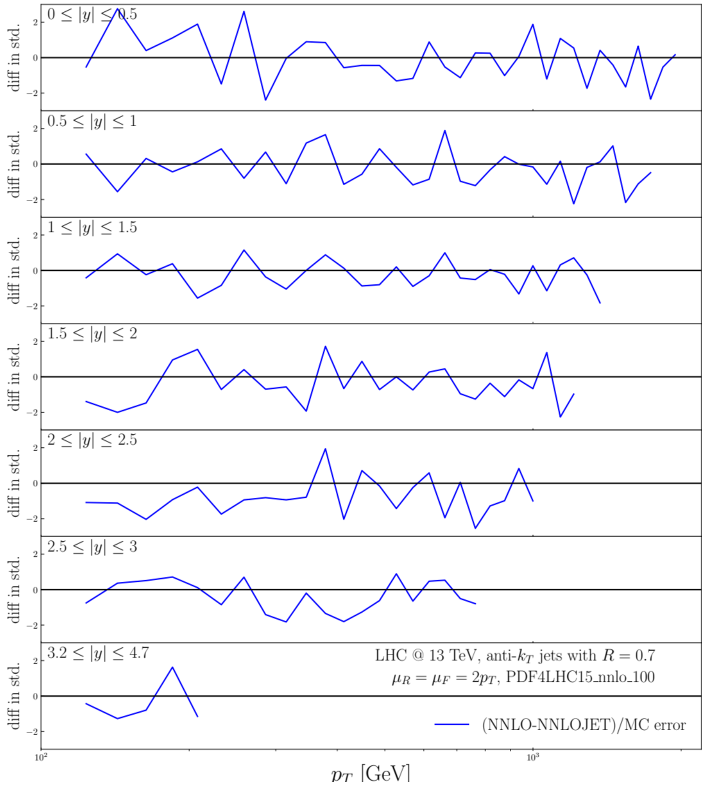
Detailed studies of scale dependence:

Event-based choices vs. single jet choices

[Currie'18]

Study of sub-leading colour effects in quark channels: smaller than O(1%)

[Czakon'19]



Diphoton plus jet - setup

[Chawdry'21]: Inspired by Higgs → γγ measurement phase spaces

- Smooth photon isolation criteria: $E_T = 10\ \mathrm{GeV}, R_\gamma = 0.4, \Delta R(\gamma,\gamma) > 0.4$
- $p_T(\gamma_1) > 30\ \mathrm{GeV}, p_T(\gamma_2) > 18\ \mathrm{GeV}$ and $|y(\gamma)| < 2.4$
- $m(\gamma\gamma) > 90\ \mathrm{GeV}$ and $p_T(\gamma\gamma) > 20\ \mathrm{GeV}$, below resummation important
- No further restrictions on jets (IR safety from $p_T(\gamma\gamma)$ cut)

Technicalities:

- LHC 13 TeV, PDF: NNPDF31, Scale: $\mu_R^2 = \mu_F^2 = \frac{1}{4} m_T^2(\gamma\gamma) = \frac{1}{4}(m(\gamma\gamma)^2 + p_T(\gamma\gamma)^2)$
- 5 massless flavours and top-quarks (in all one-loop amps)
- Approximation of two-loop amps:
  $2\,\mathrm{Re}(\mathcal{M}^{(0)^\dagger}\mathcal{F}^{(2)}) + \mathcal{F}^{(1)^\dagger}\mathcal{F}^{(1)}$ without top-quark loops
  and $2\,\mathrm{Re}(\mathcal{M}^{(0)^\dagger}\mathcal{F}^{(2)})$ in leading colour limit [Chawdhry'21]
  → Update to full colour planned [Agarwal'21]

Solution: Modified jet algorithms

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: $$d_i = k_{T,i}^2$$

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:

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

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

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

Numerical check in 2jet events: Misidentification rate as a function of y3kt