Progress on precision QCD calculations

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N3LO computations

2→3 NNLO QCD

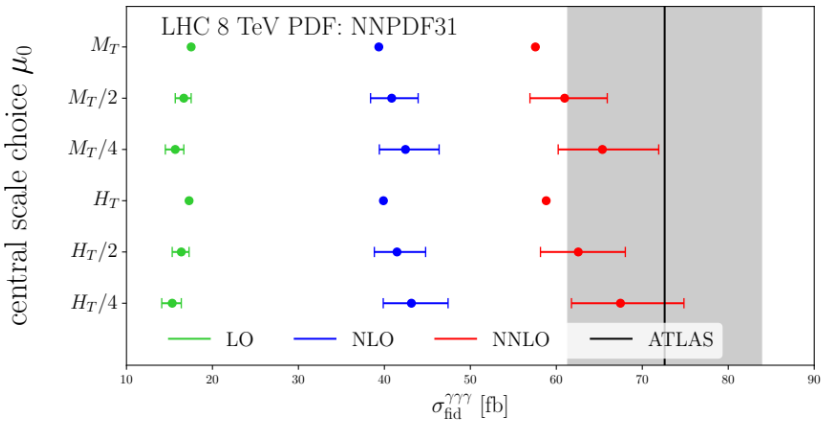
NNLO QCD + PS

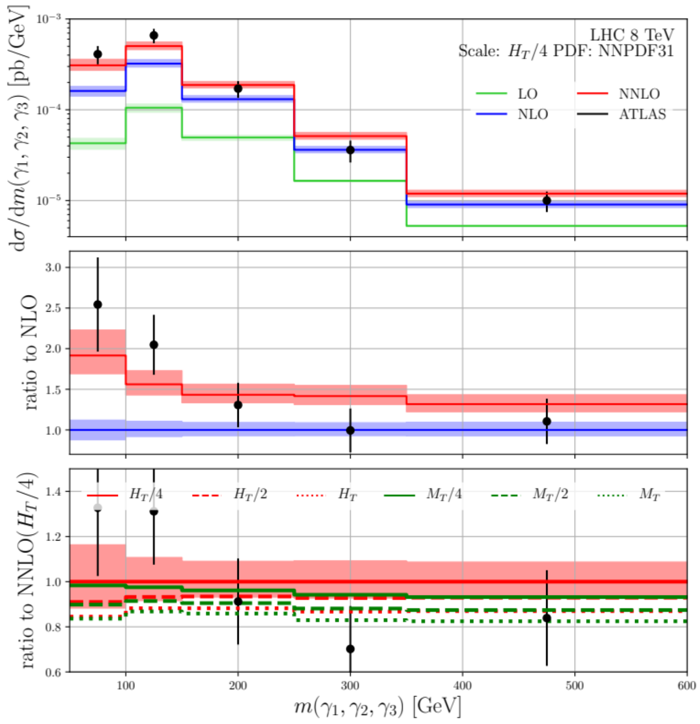
Fragmentation

Mixed EW-QCD

Three photon production

- First NNLO QCD 2 → 3 cross sections:
  NNLO QCD corrections to three-photon production at the LHC, Chawdhry, Czakon, Mitov and Poncelet, 1911.00479
  Triphoton production at hadron colliders in NNLO QCD, Kallweit, Sotnikov and Wiesemann, 2010.04681
- Simplest among the 2→3 massless cases: colour singlet
- Approximation in two-loop virtuals: only planar diagrams
  → overall small contribution
- Large NNLO/NLO K-factors
- NNLO QCD corrections essential for theory/data comparison
  Here: ATLAS





Diphoton plus jet production

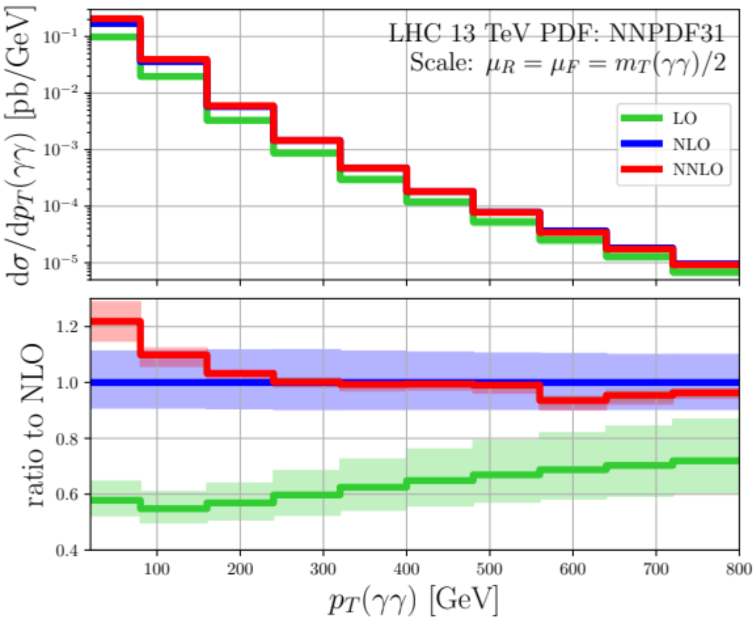
Photon pair production @ LHC is of particular interest:

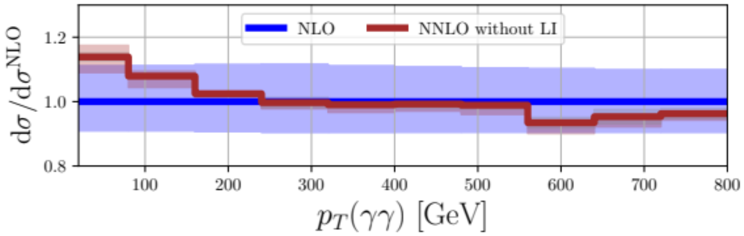
- ➔ Main background to cleanest Higgs decay channel
- ➔ Large NNLO QCD corrections!
  Perturbative convergence @ N3LO?
- ➔ Diphoton plus jet @ NNLO QCD (pT(AA) → 0 limit)
- ➔ pT(γγ) spectrum itself interesting for Higgs → γγ

First NNLO QCD for pp → AAj

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

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

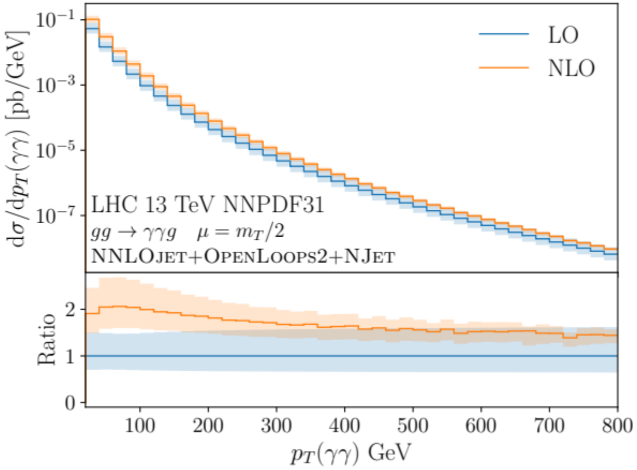




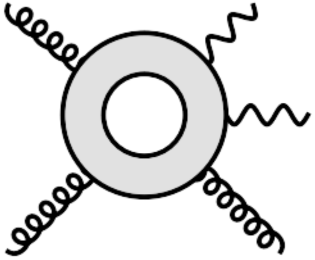
Diphoton plus jet – gg fusion

Next-to-leading order QCD corrections to diphoton-plus-jet production through gluon fusion at the LHC, Badger, Gehrmann, Marcoli and Moodie, 2109.12003

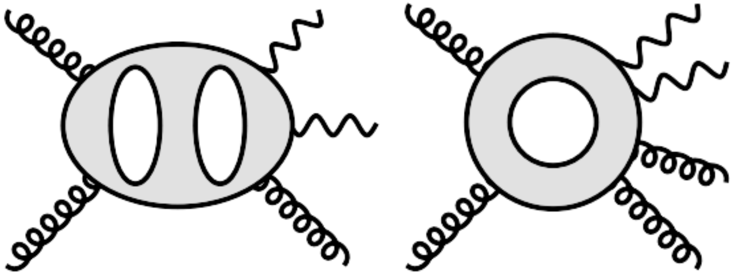
- NLO QCD to gg → γγg (formally N3LO for pp→γγj)
- Challenging double virtual matrix element
- Large corrections of up to 100% → relate to 5% in full pp → γγj
- Reduction of scale dependence at high transverse momentum

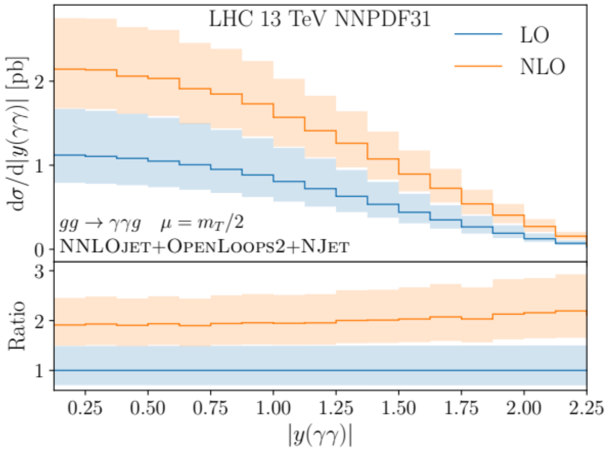


LO:



NLO:





Three-jet production

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

Computational challenges:

- Sector-improved residue subtraction for real radiation
  - 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
- Many-leg, IR stable one-loop amplitudes → OpenLoops 2
- Double virtual amplitudes in leading-colour approximation
  - Sub-leading colour corrections expected to be small
  - Analytical expressions challenging
  - Fast numerical evaluation → very small contribution to computational cost
- The pure gluonic process evaluated within the NNLOJet framework:

A novel subtraction scheme for double-real radiation at NNLO, Czakon, 1005.0274
Four-dimensional formulation of the sector-improved residue subtraction scheme, Czakon and Heymes, 1408.2500
Single-jet inclusive rates with exact color at O(as^4) Czakon, van Hameren, Mitov and Poncelet, 1907.12911

OpenLoops 2, Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller, 1907.13071

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

Automation of antenna subtraction in colour space: gluonic processes,
Chen, Gehrmann, Glover, Huss and Marcoli, 2203.13531

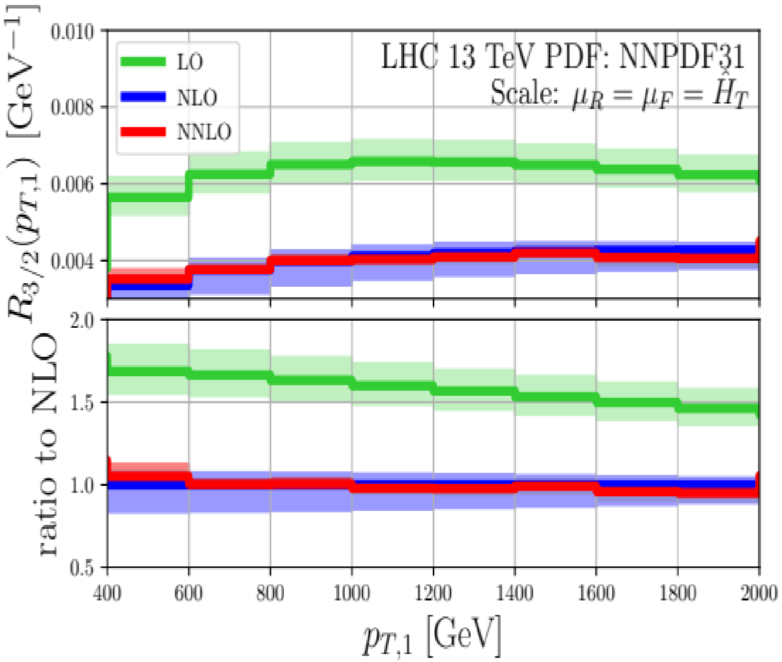
Three-jet production - R32

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

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

Interesting phenomenological applications:

- Extraction of alphaS, tests of SM running and tests of QCD matrix elements
  R32, event-shapes, TEEC, azimuthal decorrelation



2 → 3 with massive legs: Wbbar

First NNLO QCD computation with a massive leg

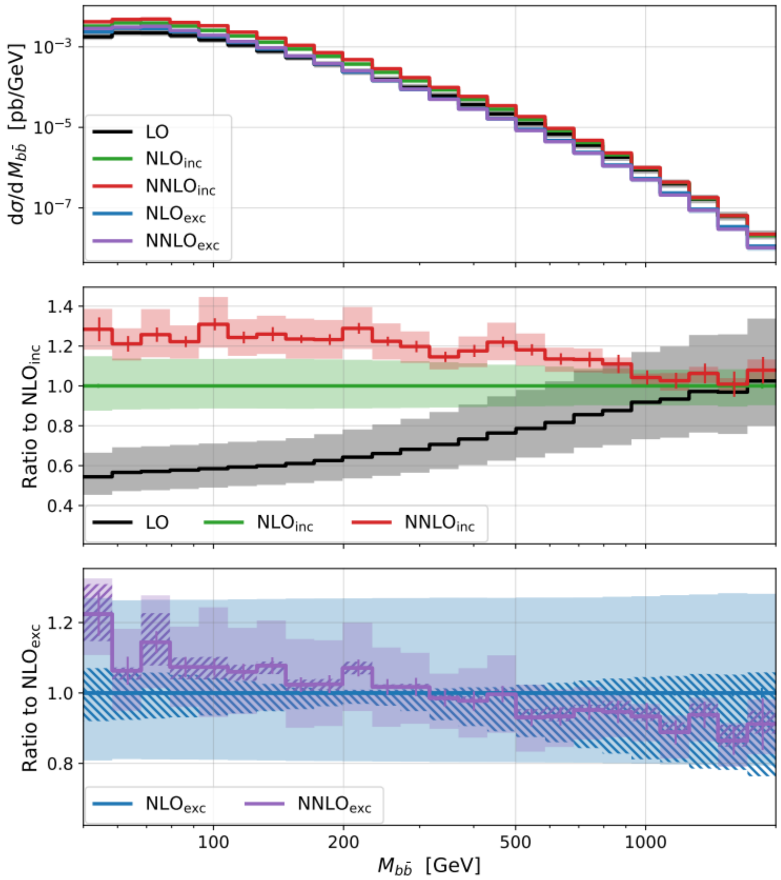
$$pp \to \ell\bar{\nu}b\bar{b} + X$$

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

- Leading colour approximation for 2-loop amplitudes
- Massless b-quark → flavour kT algorithm for IR safety
- Study of scale uncertainty in jet-veto phase space:

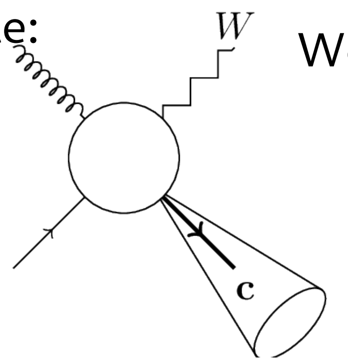
	inclusive [fb]	$\mathcal{K}_{\text{inc}}$	exclusive [fb]	$\mathcal{K}_{\text{exc}}$
σ_{LO}	$213.2(1)^{+21.4\%}_{-16.1\%}$	-	$213.2(1)^{+21.4\%}_{-16.1\%}$	-
σ_{NLO}	$362.0(6)^{+13.7\%}_{-11.4\%}$	1.7	$249.8(4)^{+3.9(+27)\%}_{-6.0(-19)\%}$	1.17
σ_{NNLO}	$445(5)^{+6.7\%}_{-7.0\%}$	1.23	$267(3)^{+1.8(+11)\%}_{-2.5(-11)\%}$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

7-point scale variation vs. uncorrelated prescription

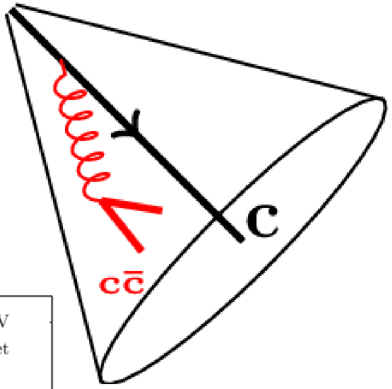


IR safe jet flavour

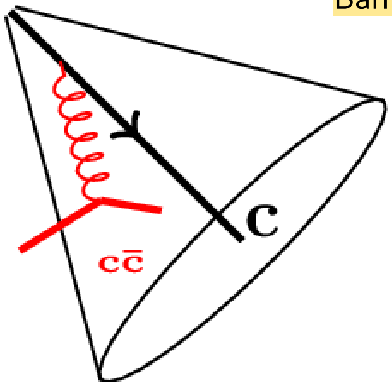
Example:



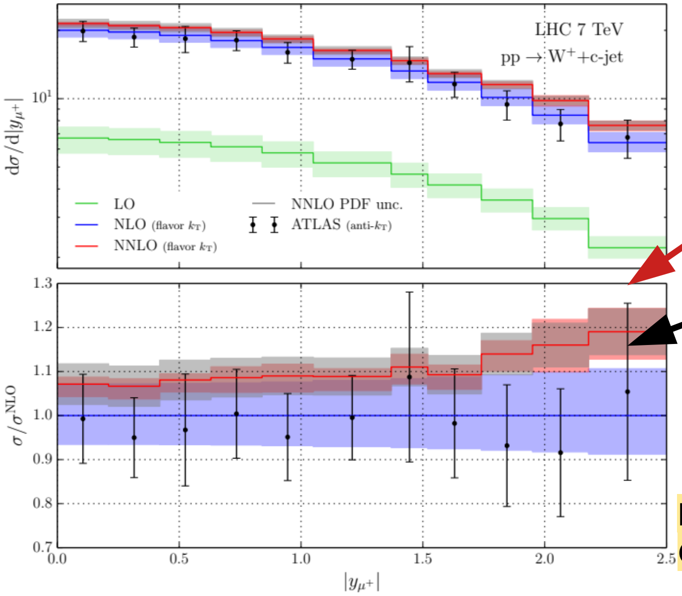
Well known problem in massless NNLO QCD: **Infrared safe definition of jet flavor**, Banfi, Salam, Zanderighi, hep-ph/0601139



vs.



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



NNLO QCD with flavour kT

ATLAS data with standard anti-kT

A proper comparison would require to unfold experimental data

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

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.

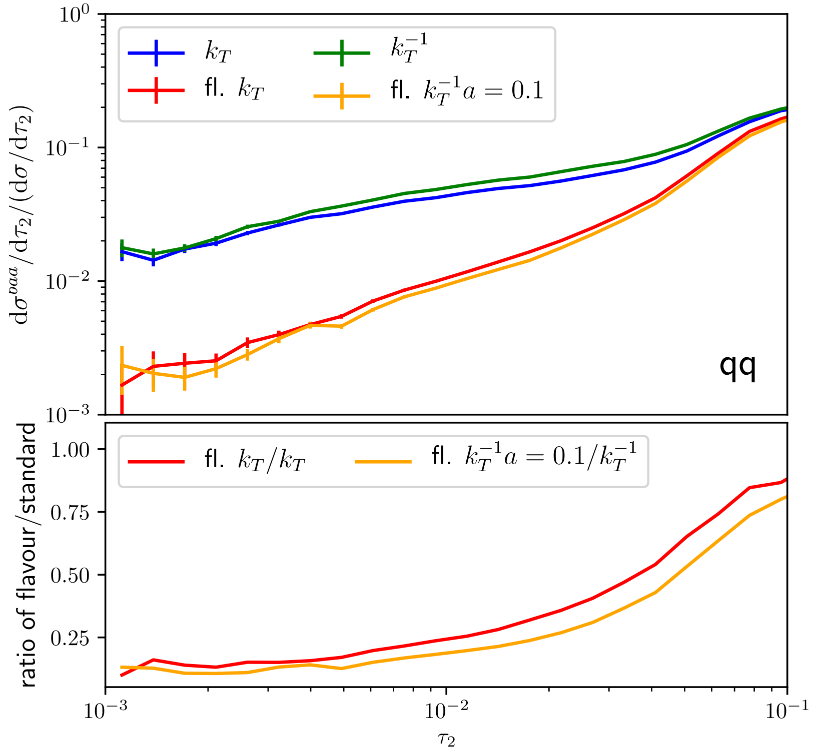
Proposed modification [to be published soon]:

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

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

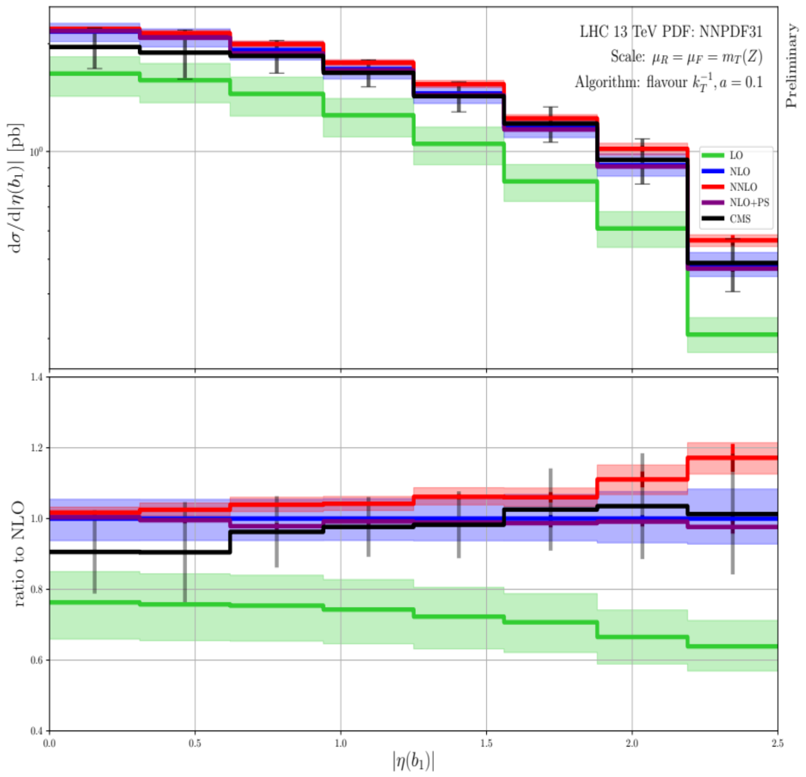
$$\mathcal{S}_{ij} = 1 - \theta(1-x)\cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_{T,i}^2 + k_{T,j}^2}{2ak_{T,\max}^2}$$

IR safety check:

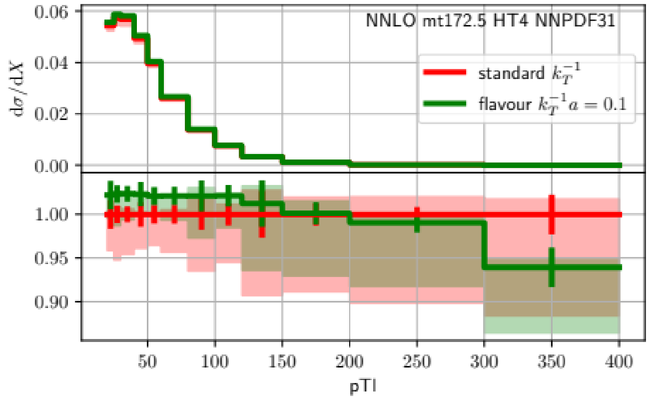


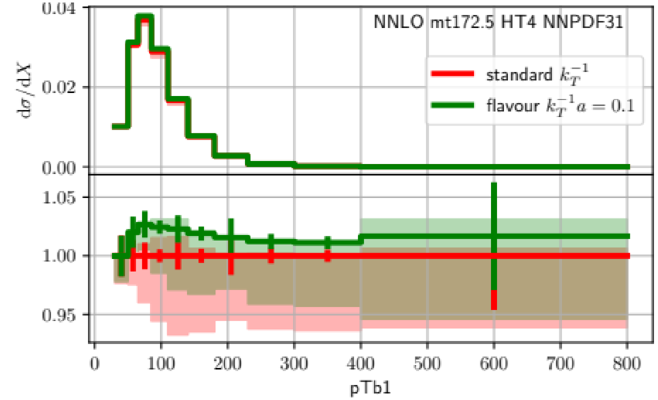
Flavour anti-kT: phenomenology

pp → Z(→ ll) + b-jet @ 8 TeV



pp → t(→ lνb) $\bar{t}$(→ lν$\bar{b}$) @ 13 TeV





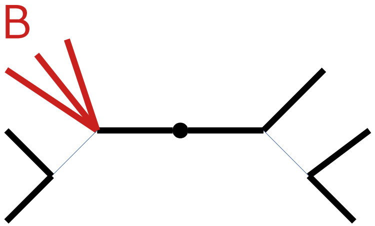
Fixed-order Fragmentation

- Fixed order QCD predictions with a final state hadron/photon
- Considering partonic computation + transition of parton to hadron/photon (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 through NNLO QCD
  B-hadron production in NNLO QCD: application to LHC ttbar events with leptonic decays,
  Czakon, Generet, Mitov and Poncelet, 2102.08267
- Photon fragmentation in NNLOJet
  Photon Fragmentation in the Antenna Subtraction Formalism,
  Gehrmann and Schürmann, 2201.06982
  Single Photon Production at Hadron Colliders at NNLO QCD with Realistic Photon Isolation,
  Chen, Gehrmann, Glover, Hoefer, Huss, Schuermann, 2205.01516

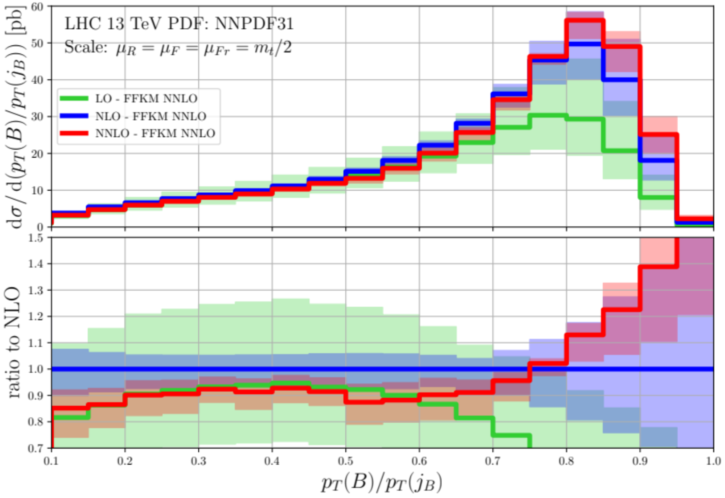
B-hadrons in ttbar production

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

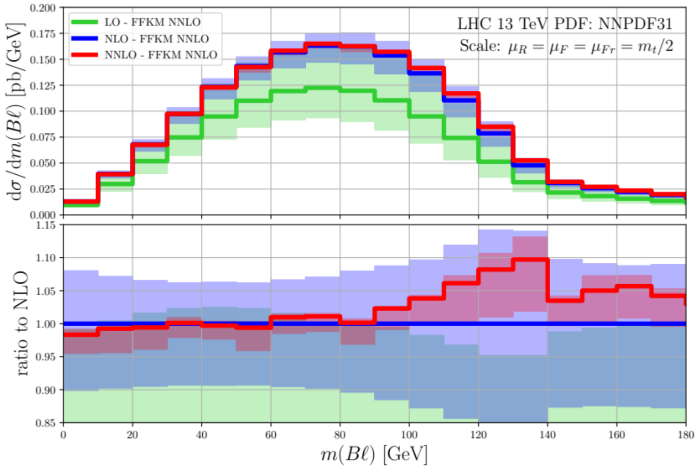
$$pp \to t\bar{t} \to B\ell\bar{\ell}\nu\bar{\nu}b + X$$

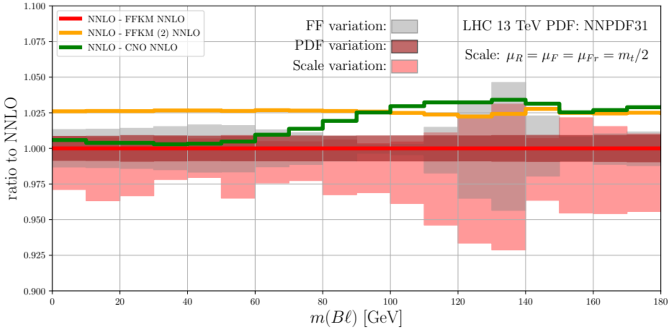


pT(B)/pT(jB): sensitive to B-hadron fraction x



m(lB): sensitive to top-quark mass





Photon fragmentation

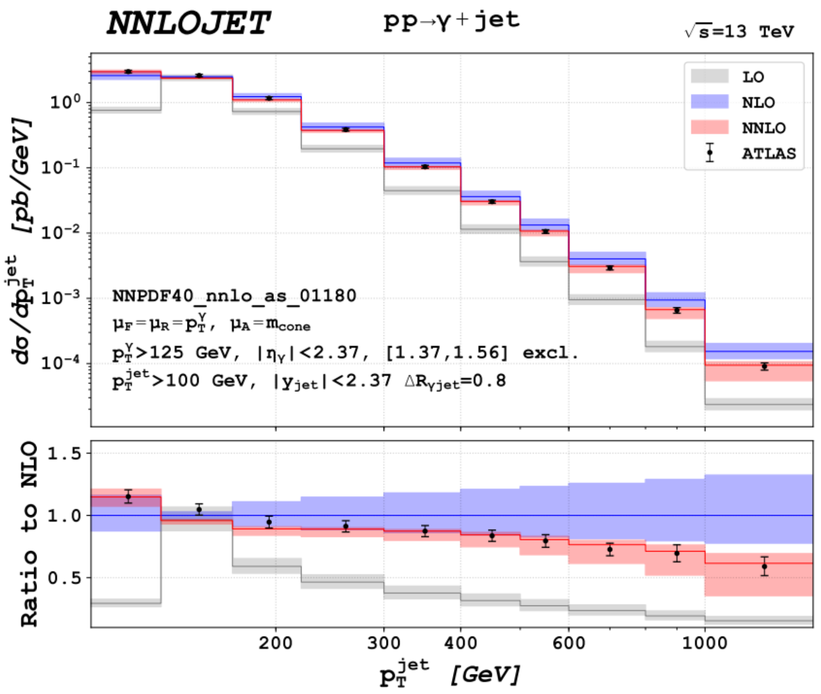
Single Photon Production at Hadron Colliders at NNLO QCD with Realistic Photon Isolation,
Chen, Gehrmann, Glover, Hoefer, Huss, Schuermann, 2205.01516

Photon plus jet production

- Direct and fragmentation component

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{dir}} + \mathrm{d}\sigma_{\mathrm{frag}}$$

- Smooth cone isolation minimizes $\mathrm{d}\sigma_{\mathrm{frag}}$ but is experimentally cumbersome
- Experimentally fixed cones are used
- New: fragmentation up to NNLO in inclusive photon and photon+jet production



What’s next?

New processes in NNLO QCD → what two-loop amplitudes are or will be available soon?

- 2 → 3 massless: pp → AAA (LC), pp → AAj (FC), pp → jjj (LC) , pp → Ajj ?
  → All ingredients available for the complete set → at most technical challenges
- 2 → 3 one-mass:
  - Progress on master integrals:
    Analytic representation of all planar two-loop five-point Master Integrals with one off-shell leg, Canko, Papadopoulos, Syrrakos, 2009.13917
    Pentagon functions for one-mass planar scattering amplitudes, Chicherin, Sotnikov and Zoia, 2110.10111
    Two-loop hexa-box integrals for non-planar five-point one-mass processes, Abreu, Ita, Page and Tschernow, 2107.14180
  - pp → W/Z/H jj (planar/LC):
    Two-Loop QCD Corrections to Wbb Production at Hadron Colliders, Badger, Hartanto and Zoia, 2102.02516
    Leading-Color Two-Loop Amplitudes for Four Partons and a W Boson in QCD, Abreu, Cordero, Ita,Klinkert, Page, Sotnikov, 2110.07541
- 2 → 3 two-mass and beyond ???

Summary

- NNLO QCD covers more or less all 2 → 1 and 2 → 2 processes
- First 2 → 3 processes become available: pp → 3y, pp → yyj, pp→jjj, pp->Wbbar
  - Double virtual amplitudes for 2 → 3 one-mass processes start to appear but virtual amplitudes are the main bottleneck for extending the portfolio → automation of numerical two-loop amplitudes?
- Flavoured jets in fixed order predictions: flavour anti-kT algorithm
- Fragmentation at NNLO QCD
- And many other exciting applications!

Further interesting topics

- Mixed QCD-EW
- New FastNLO tables @ NNLO by the NNLOJet group for DIS, single inclusive jets, pp → Zj
- NNLO + PS for colour singlets and ttbar
- N3LO predictions for colour singlet production