Precision predictions for jet rates

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In collaboration with Michal Czakon and Alexander Mitov
Based on: 1907.12911 and 21xx.xxxx

$pp \to j + X$

$pp \to jjj + X$

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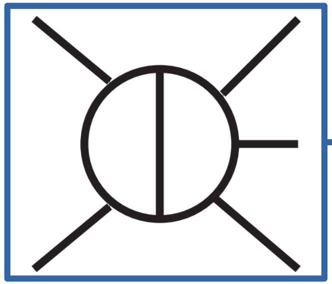
Jet rates at the LHC

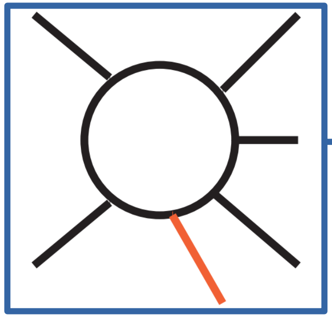
- Multi-jet rates provide an unique possibility to test (perturbative) QCD
- Parameter extraction:
  - Measurements of αS from event shapes and jet rate ratios (~αS)
    → energy scale dependence → test of αS running
  - PDF extraction → high-x gluon
- Multi-jet signatures are background for many SM signatures.
- Allow to probe broad ranges of energy scales for heavy new physics
- Large cross sections → large statistics
  In practice only limited by systematics!

  → Theory uncertainties: missing higher orders, resummation, NP-physics, …

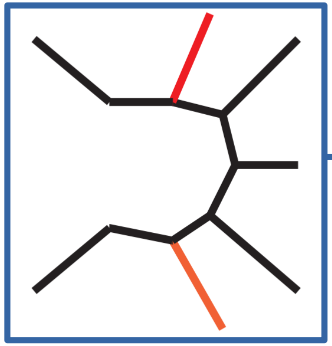
Ingredients for NNLO QCD jet rates



→ Double virtual

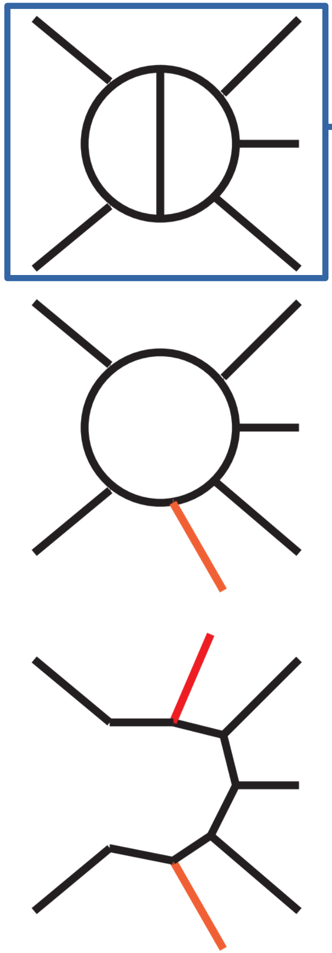


→ Real virtual



→ Double real

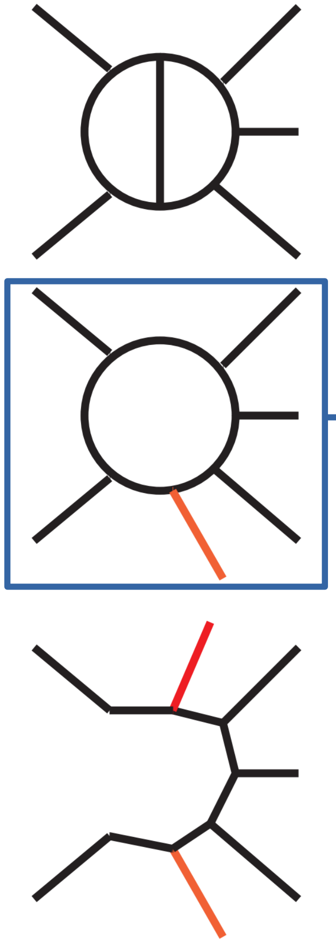
Ingredients for NNLO QCD jet rates



Double virtual corrections

- 2 → 2 Virtual amplitudes
  - Apart from special cases, most SM processes known
  - Di-jet amplitudes long known [Glover'01-'04]
- 2 → 3 Two-loop amplitudes:
  - (Non-) planar 5 point massless
    → fast progress recently [Abreu'20'21,Agarwal'21,Chawdhry'20'21]
    → triggered by efficient MI representation [Chicherin,Sotnikov'20]
  - Tri-jet amplitudes in leading colour [Abreu'21]
  - 5 point amplitudes with one external mass: [Badger'21,Abreu'20,Canko'20]
    → Needed for V/H+2jets

Ingredients for NNLO QCD jet rates

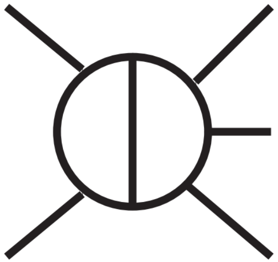


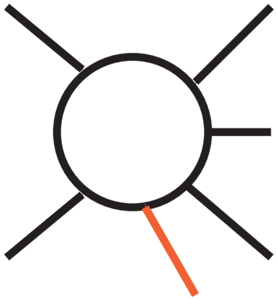
Real-virtual corrections

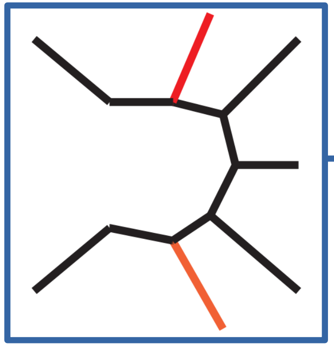
- Multi-leg one-loop amplitudes automated in many codes:
  → MadGraph [Alwall'14]
  → OpenLoops [Buccioni'19]
  → Recola [Denner'17]
  → HELAC[Bevilacqua'11]
  …
  Jet amplitudes: Njet [Badger'13]
- Nowadays part of any NLO MC
- IR-stability crucial for NNLO

  → OpenLoops 2 [Buccioni'19]

Ingredients for NNLO QCD jet rates





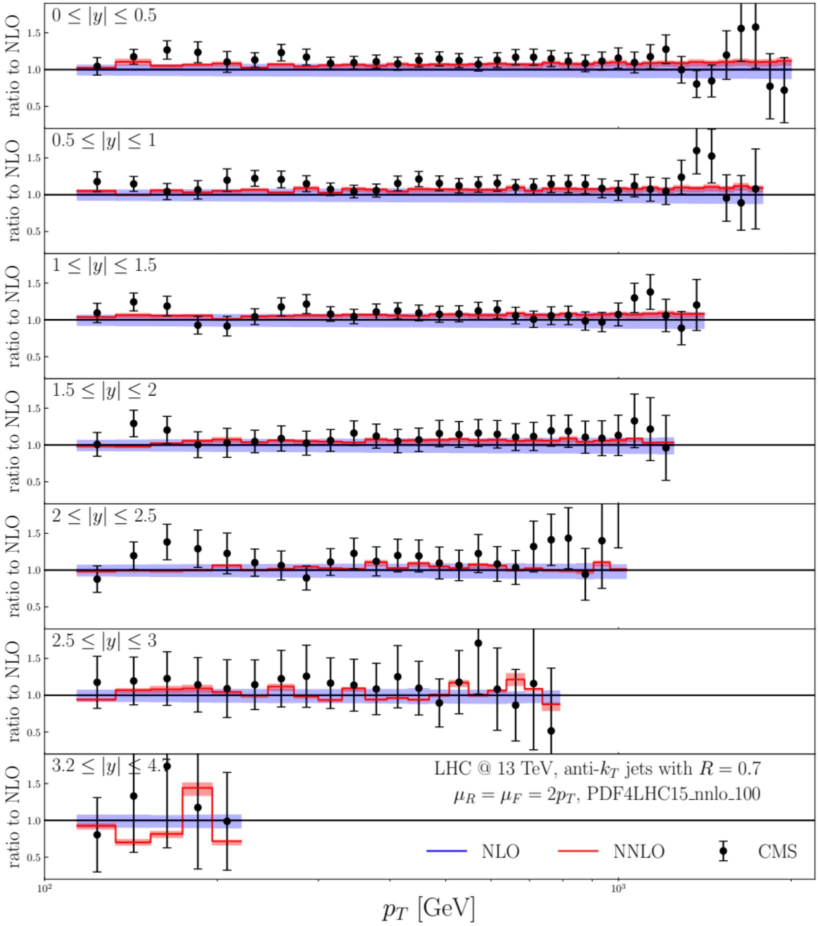


Double real corrections

- 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], Projetction [Cacciari'15], Geometric [Herzog'18], Unsubtraction [Aguilera-Verdugo'19], Nested collinear [Caola'17],
  Sector-improved residue subtraction [Czakon'10-'14,19] → STRIPPER C++ code
- NNLO QCD di-jet production known:
  - Gluons only [Gehrmann-De Ridder'13]
  - Partially leading colour[Currie'16]
    → studies of single inclusive, di-jet production [NNLOJet '16-...]
  - STRIPPER: complete colour [Czakon'19]
  - → All ingredients for NNLO QCD three jets → first results

Single inclusive jet production

- Well studied observable:
  - NNLOJet [Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Pires '16-19]
  - NNLO QCD provides very good description of experimental data
- Full colour [Czakon'19]:
  - Technically very challenging
  - Tests all possible IR subtraction terms
  - Comparison to NNLOJet results:
    - Found full agreement
    - Missing sub leading colour terms small ~1-2 %



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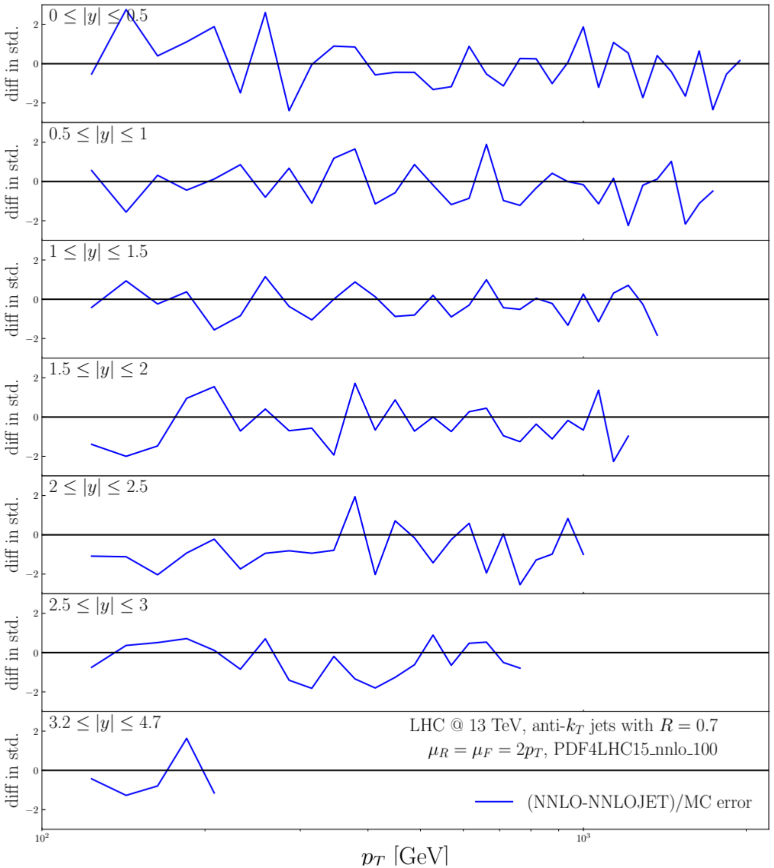


NNLO QCD three jet production

- Current status:
  - NLO QCD [Nagy'03] and NLO EW [Dittmaier'12]
    → complete NLO predictions [Frederix'16,Reyer'19]
- Bottlenecks for NNLO QCD:
  - double virtual amplitudes:
    → recently published in leading colour approximation [Abreu'21]
    → expected to be a good approximation of full colour amplitudes
  - handling of real radiation in STRIPPER:
    → Sector-improved residue subtraction conceptually capable
    → no approximations necessary:
    all channels, all limits, all contributions
    → Tour-de-force → preliminary results

Three jet production - Setup

Setup:

- LHC @ 13 TeV, NNPDF31
- Require at least three (two) jets with:
  - $p_T > 60$ GeV, $|y| < 4.4$
  - $HT2 = p_{T1}+p_{T2} > 250$ GeV
- Scales: $\mu_R = \mu_F = \text{HThat} = \Sigma\, p_T$ partons

R32 ratios:

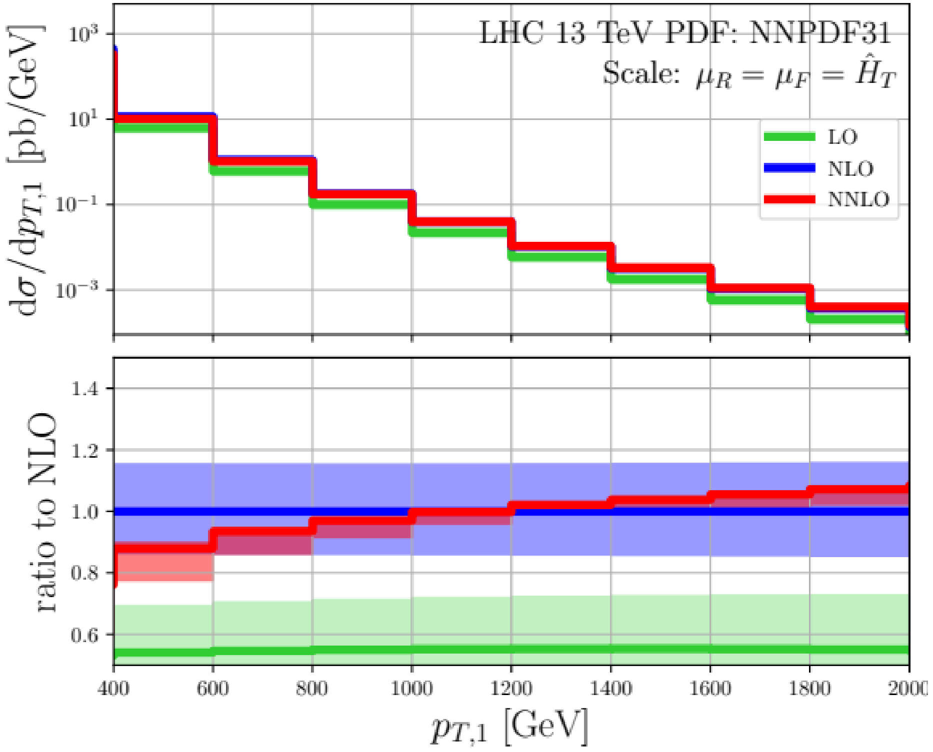
- Two jet rate = $\sigma 2$
  Three jet rate = $\sigma 3$
- $R32 = \sigma 3/\sigma 2$
- Differentially in X:
  $R32(X) = (d\sigma 3/dX)/(d\sigma 2/dX)$
- Scale dependence of R32(X) is determined by correlated variation in $\sigma 3$ and $\sigma 2$

Only Approximation made: $R2 = F0*F2 + F1*F1 \approx (F0*F2 + F1*F1)|_{\text{leading color}}$

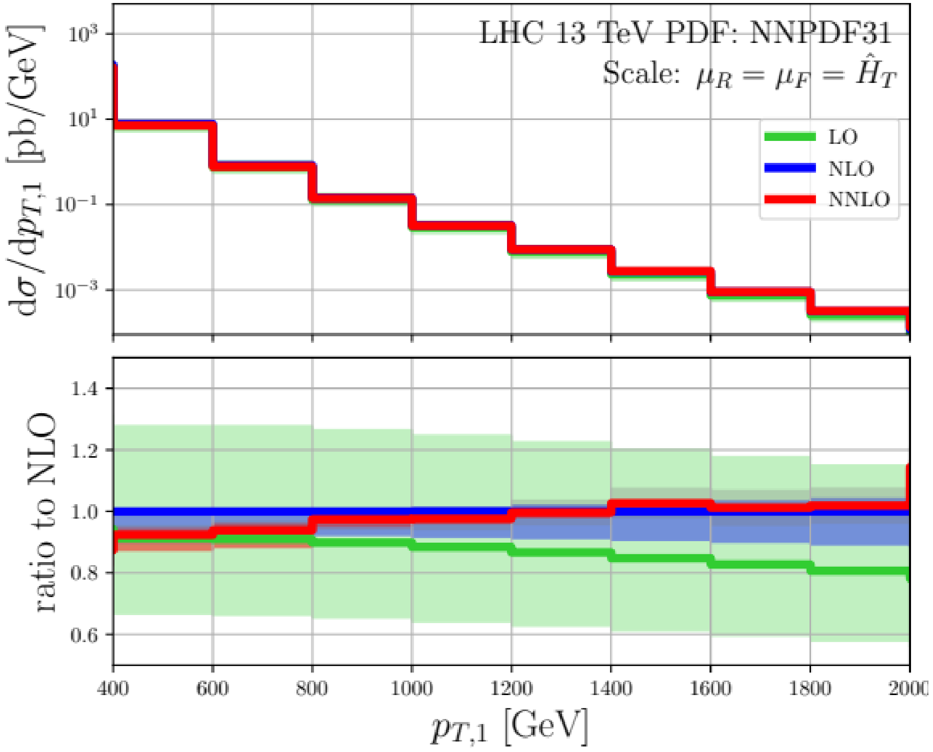
→ taken from [Abreu'21]

Three jet production – leading pT

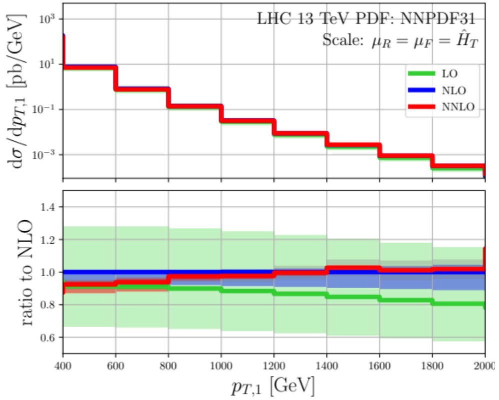
Two jets:

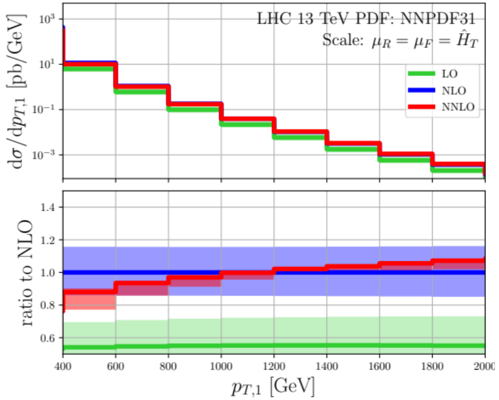


Three jets:



Three jet production - R32(pT1)





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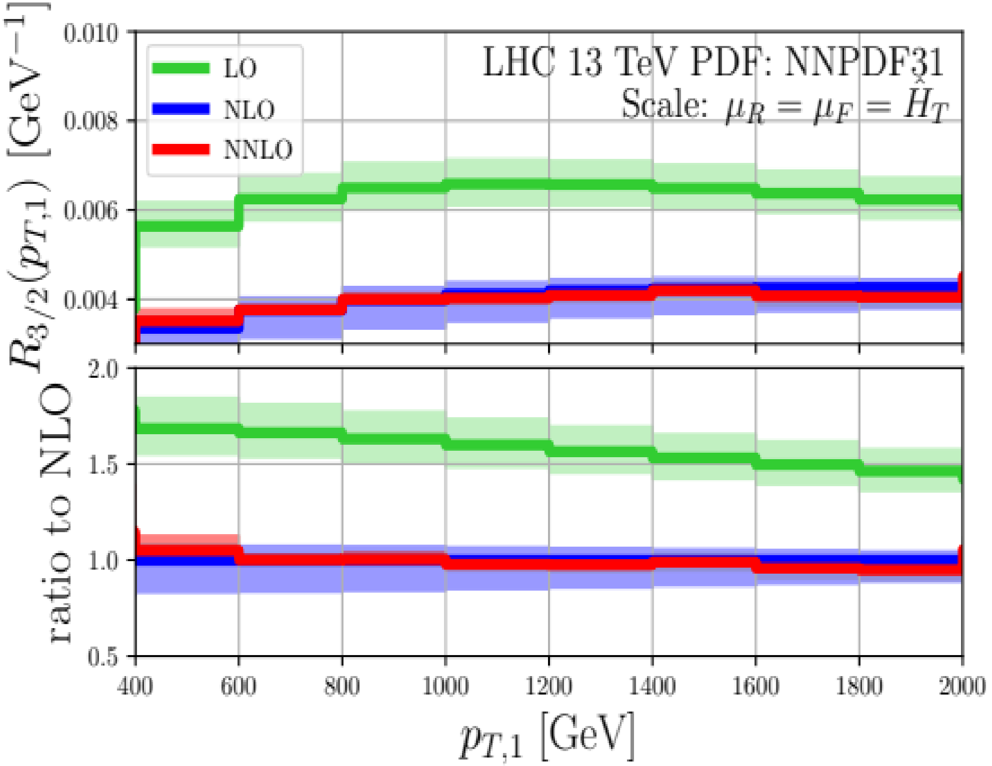
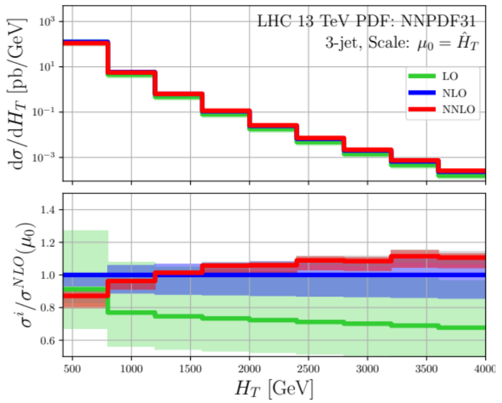
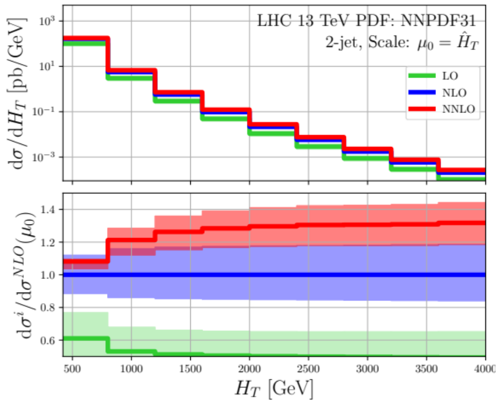
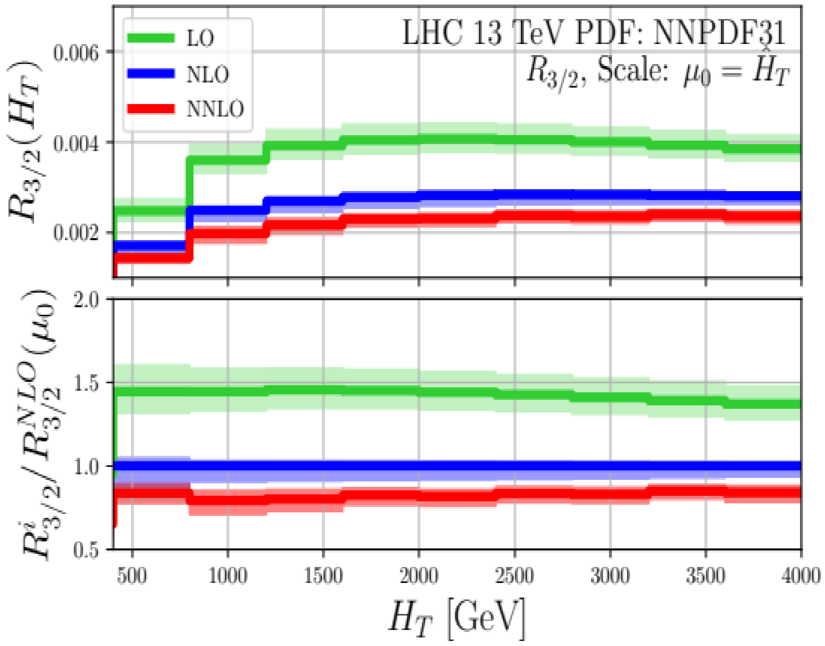


Three jet production - R32(HT)





HT = Σ pT(jet)



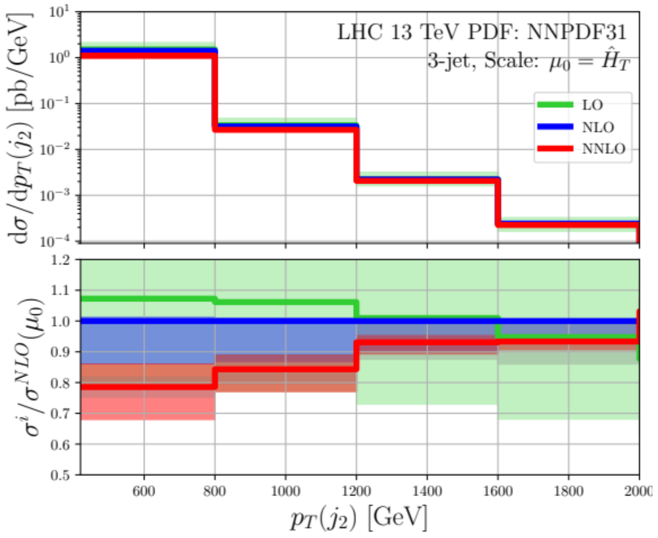
Scale dependence correlated in ratio

→ reduction of scale dependence

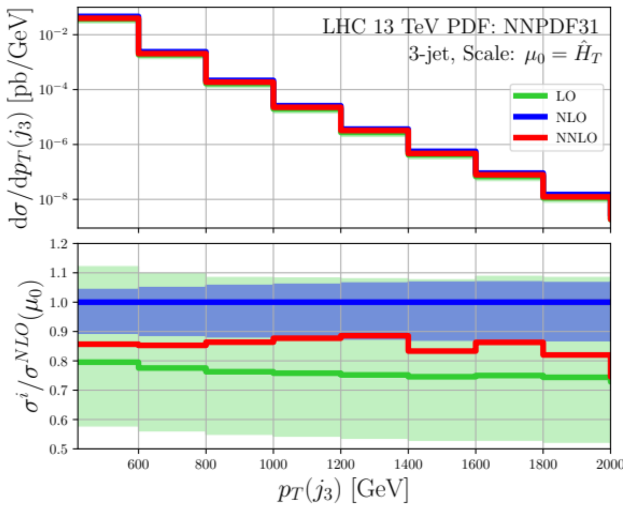
→ flat k-factor

→ scale bands in ratio barely overlap

Three jet production – sub-leading jet pTs



- PT2:
  → suffers from slow MC convergence, larger binning
  → shows reasonable perturbative convergence
- PT3:
  → fast MC convergence
  → flat k-factor



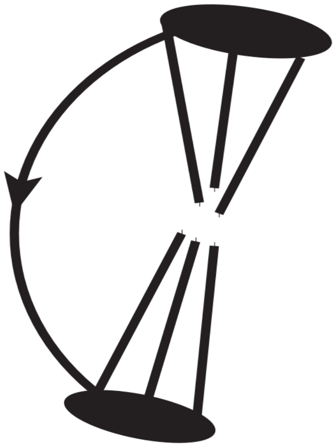
Caveat:
→ Scale choice based on full event
→ reasonable for pT1 and pT2
→ pT3 << pT1+pT2 → potentially large hierarchy
→ investigation with 'jet-based' scale would be useful

Three jet production – azimuthal decorrelation

Kinematic constraints on the azimuthal separation between the two leading jets ($\varphi12$)

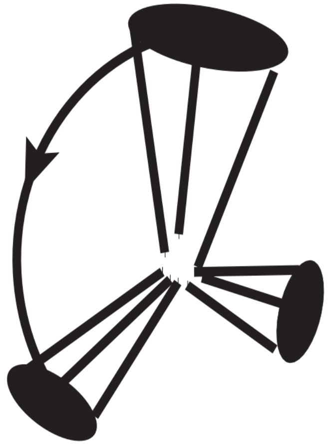
Dijet:

$\varphi12 = \pi$



Trijet:

$\varphi12 > 2/3\pi$



$\varphi12$ sensitive to the jet multiplicity:

2j: $\varphi12 = \pi$

3j: $\varphi12 > 2/3\pi$

4j: unconstrained

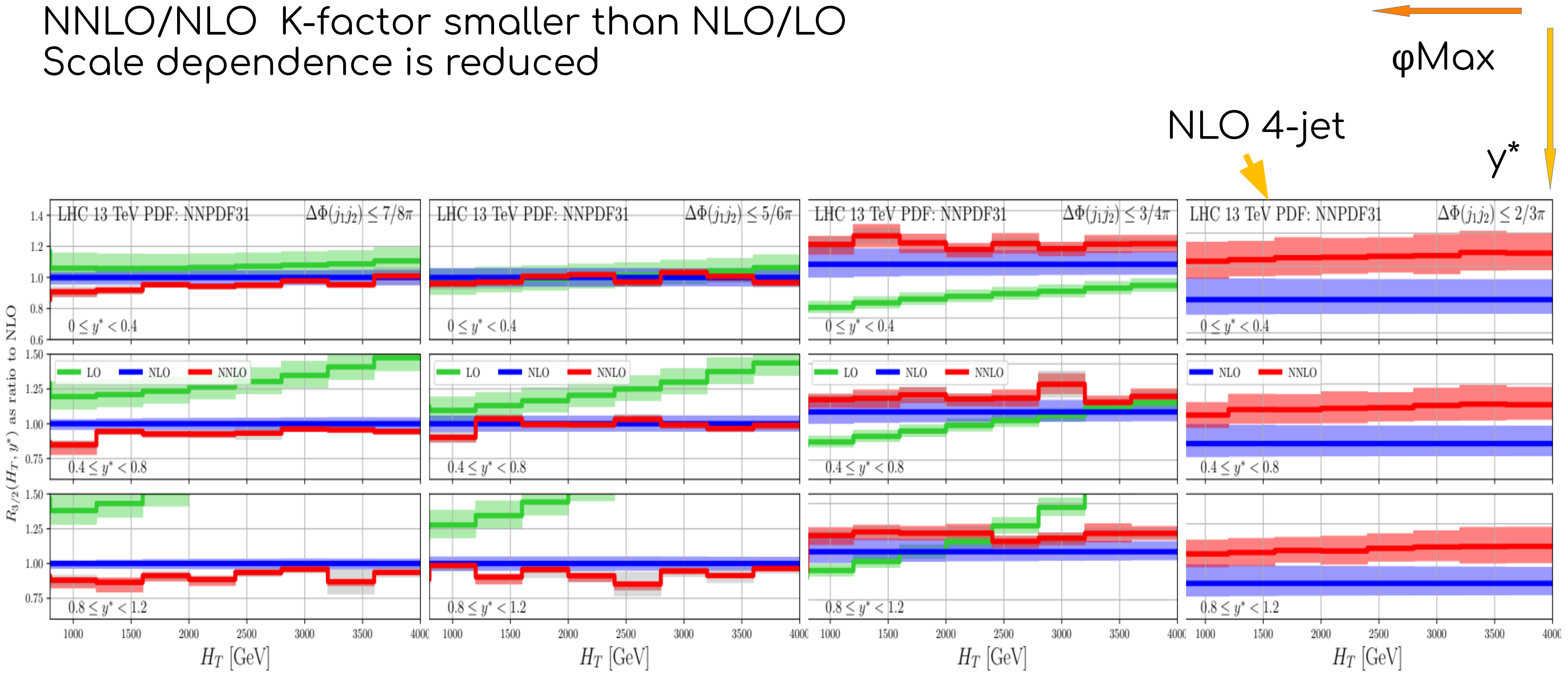
Study of the ratio

$R32(HT,y^*,\varphi Max) = (d\sigma3(\varphi<\varphi Max)/dHT/dy^*)/(d\sigma2/dHT/dy^*)$

With $y^* = |y1-y2|/2$

Three jet production – R32(HT,y*,φMax)

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



Summary and Outlook

Jet rates with the sector-improved residue subtraction framework

- Full NNLO QCD predictions for di-jet production available
  → sub-leading colour contributions small
- Three jets @ the LHC:
  - First predictions available with approximate two-loop contribution!
    → improved scale dependence and stabilized K-factors
    → pT spectra, HT
  - Real radiation for 2→3 can be handled.
    But efficiency is a concern and needs some attention!
  - Many interesting applications ahead! Stay tuned!

Thank you for your attention!