NNLO QCD predictions for 2 to 3 processes

Rene Poncelet
In collaboration with Michal Czakon, Alexander Mitov and Herschel Chawdhry

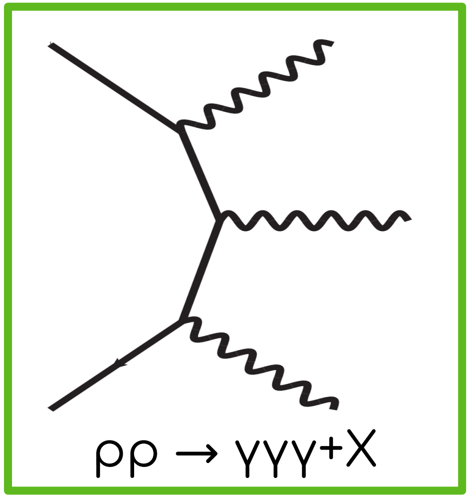
Based on: 2105.06940, 2103.04319, 2012.13553, 1911.00479

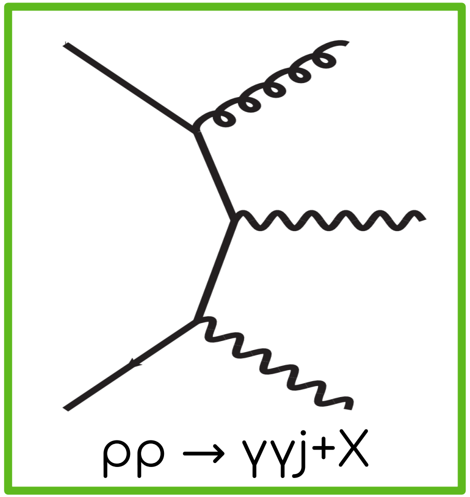
European Research Council
Established by the European Commission

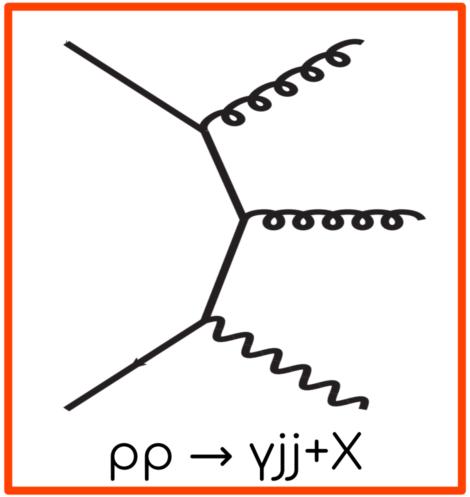
UNIVERSITY OF CAMBRIDGE

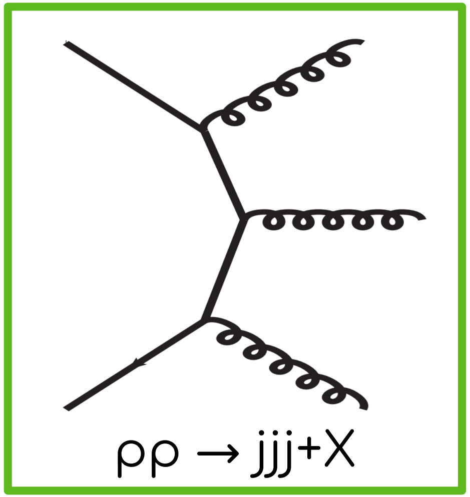
Outline

- Precision vs. Multiplicity @ the LHC
- NNLO QCD for 2 to 3 processes without masses:









- Summary

Precision vs. Multiplicity @ the LHC

Why are we interested in NNLO QCD for 2 → 3 processes? (8 talks this week)

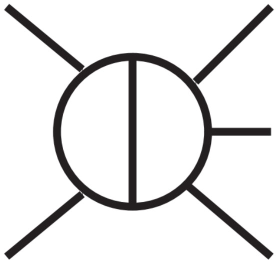
Phenomenological aspects:

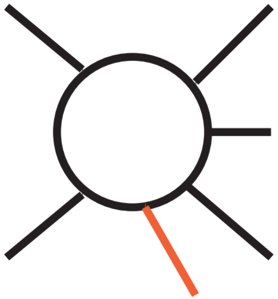
- For 2 → 2 NNLO QCD (+NLO EW) huge success for many measurements! In some cases N3LO on the wish list.
- Next phase of LHC → enough statistics to actually resolve 2→3 NNLO?!
  - Massless processes a clear case!
  - But also heavy processes H/V+2j,ttH, ttV, VVV, … call for NNLO predictions!

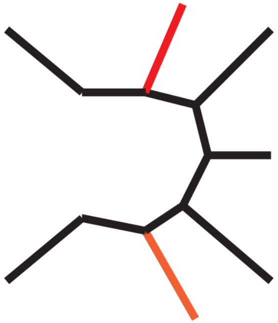
Theory aspects:

- Development of NNLO QCD technology (amplitudes&subtraction) crucial work on the road towards NNLO event simulation.
- Crucial ingredient for differential 2 → 2 N3LO QCD

NNLO QCD prediction beyond 2 → 2







2 → 3 Two-loop amplitudes:

- (Non-) planar 5 point massless → talk by Vasily, Herschel, Federico
  fast progress in the last half of year
  → triggered by efficient MI representation [Chicherin,Sotnikov'20]
- 5 point with one external mass
  → talk by Nikolaos, Ben, Konstantinos, Bayu

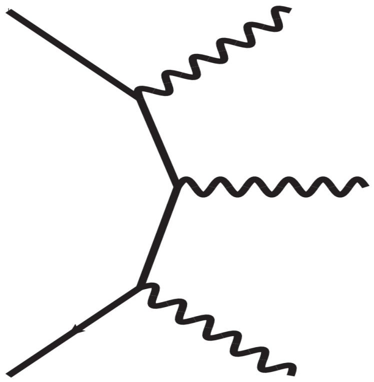
Many leg, IR stable one-loop amplitudes → OpenLoops [Buccioni'19]

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], Projetction [Cacciari'15], Geometric [Herzog'18], Unsubtraction [Aguilera-Verdugo'19], Nested collinear [Caola'17], Sector-improved residue subtraction [Czakon'10-'14]

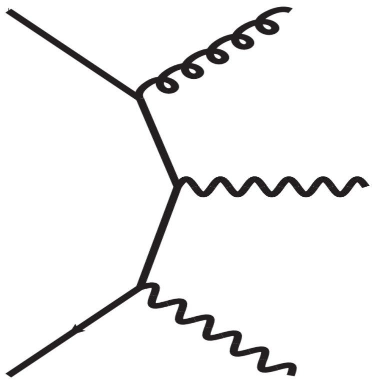
Phenomenological applications

Three photons



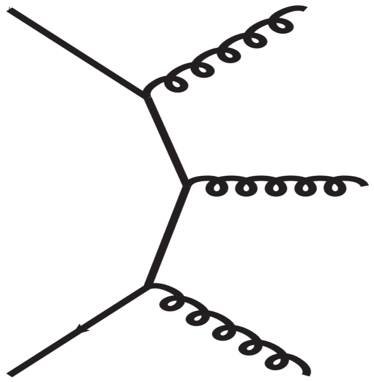
$pp \to \gamma\gamma\gamma+X$

Two photons plus jet



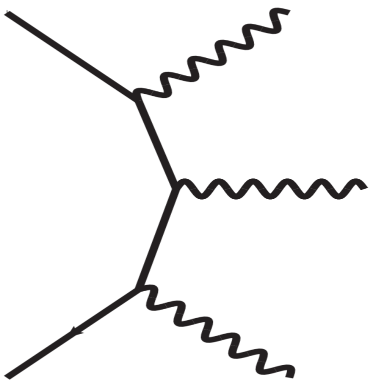
$pp \to \gamma\gamma j+X$

Three jets



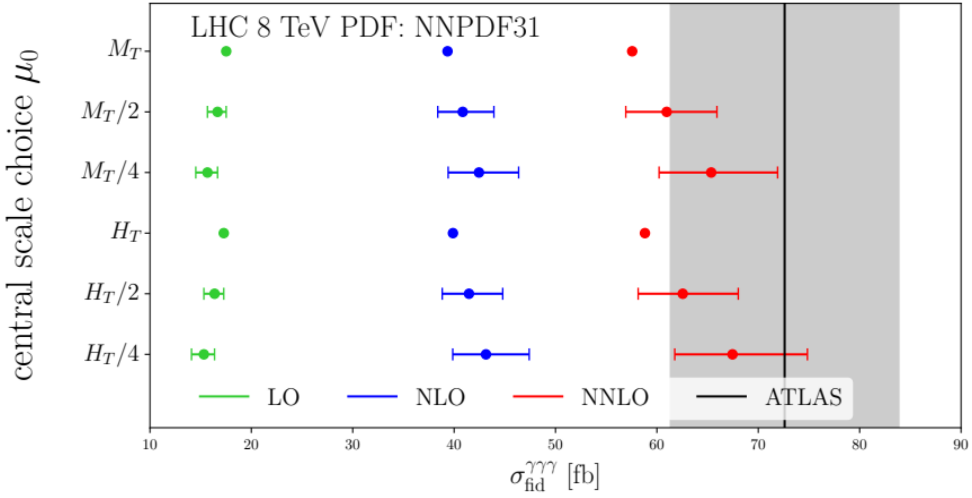
$pp \to jjj+X$

Three photon production



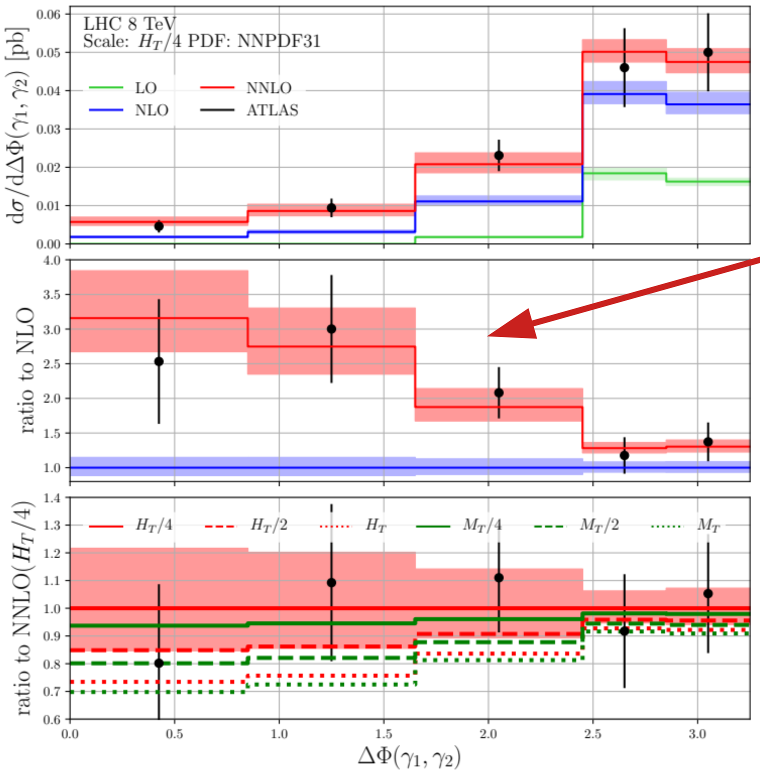
$pp \to \gamma\gamma\gamma + X$

- First NNLO QCD 2 → 3 cross sections: [Chawdhry'19],[Kallweit'20]
- Simplest among the 2→3 massless cases: colour singlet
- Planar Two-loop virtuals:
  2*Re(M0*F2) with 'original' pentagon functions [Henn'18]
  → Fast helicity amplitudes: [Abreu'20],[Chawdhry'20]



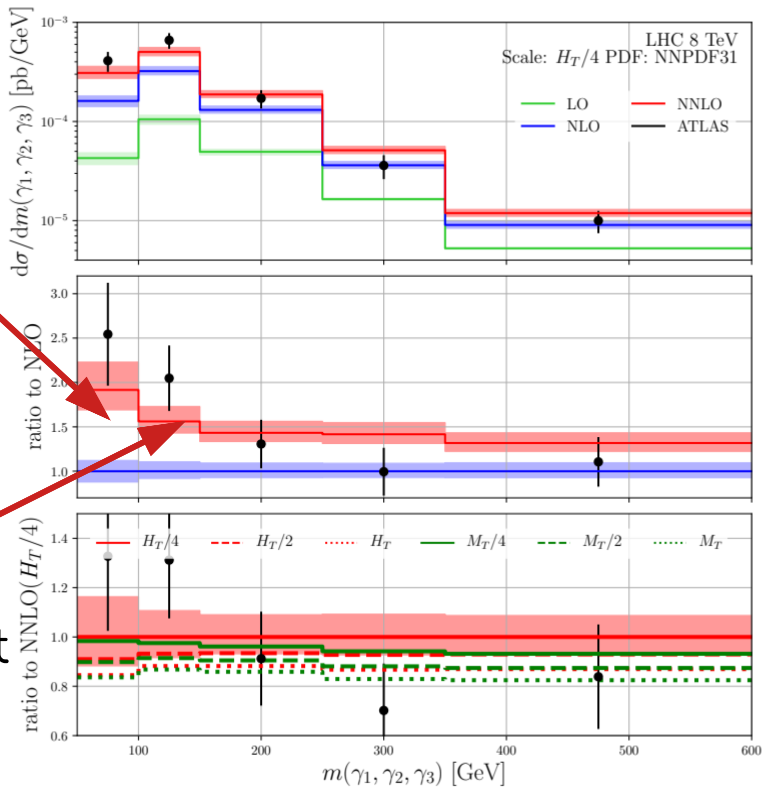
- Large NNLO/NLO K-factors
- Similar behaviour as $pp \to \gamma\gamma$
- NNLO QCD corrections essential for theory/data comparison
- Contribution of 2l amps small ≈ 1%

Three photon production



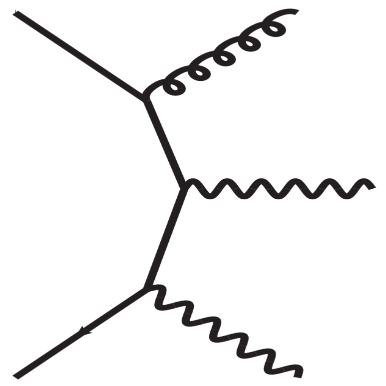
Corrections to shape and normalization

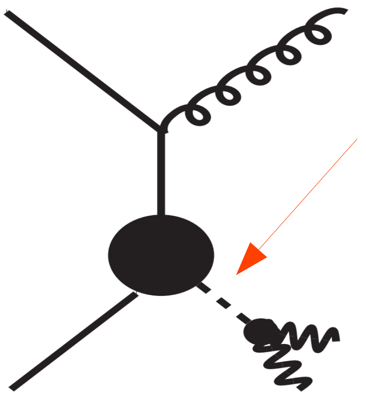
Typical for colour singlets: Scale uncertainty stays large. Very different for pp→γγj, pp→jjj



Diphoton plus jet production

- Photon pair production @ LHC is of particular interest:
  - Main background to cleanest Higgs decay channel
- Inclusive diphoton shows large NNLO QCD corrections
  - Perturbative convergence @ N3LO?
    First steps: Talks by Xuan, Lorenzo
  - Diphoton plus jet @ NNLO QCD (pT(AA) → 0 limit)
- pT(γγ) spectrum itself interesting for Higgs → γγ :
  - Higgs – pT measurements at large pT resolves local Higgs couplings → BSM searches
  - Angular diphoton observables → spin measurements





Diphoton plus jet - setup

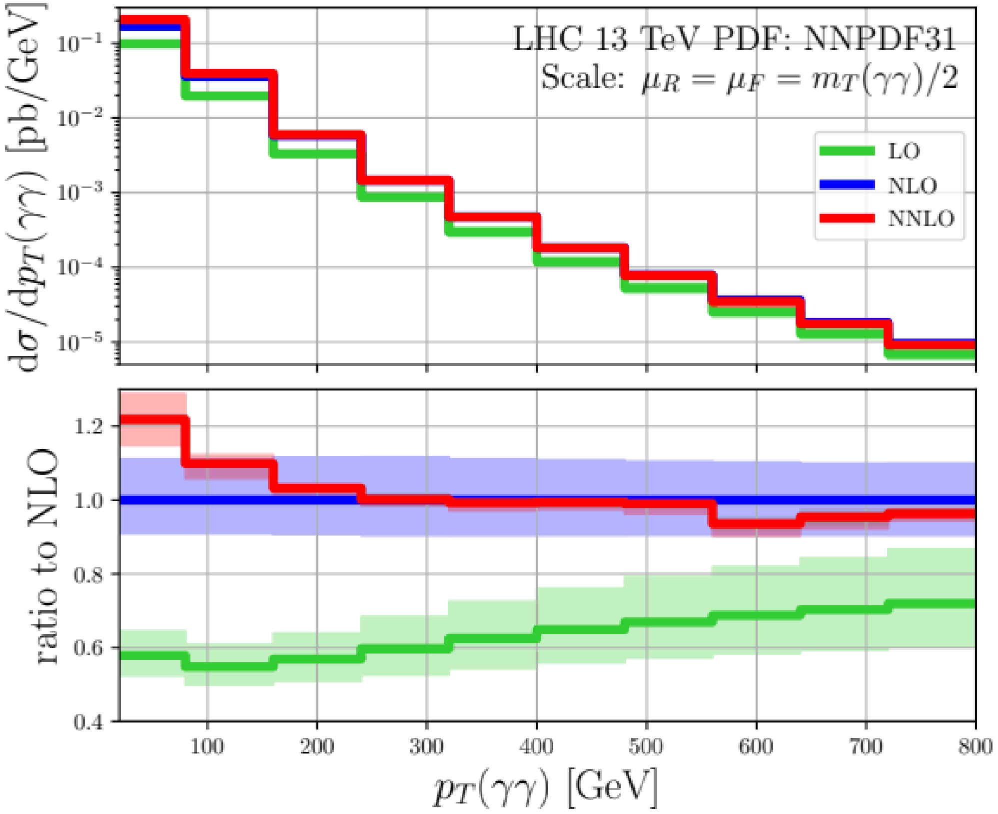
2105.06940: Inspired by Higgs → γγ measurement phase spaces

- Smooth photon isolation criteria (ET = 10GeV, R = 0.4), dR(γγ) > 0.4 GeV
- pT(γ1) > 30 GeV, pT(γ2) > 18 GeV and |y(γ)| < 2.4
- m(γγ) > 90 GeV and pT(γγ) > 20 GeV, below resummation important
- No further restrictions on jets (IR safety from pT(γγ) cut)

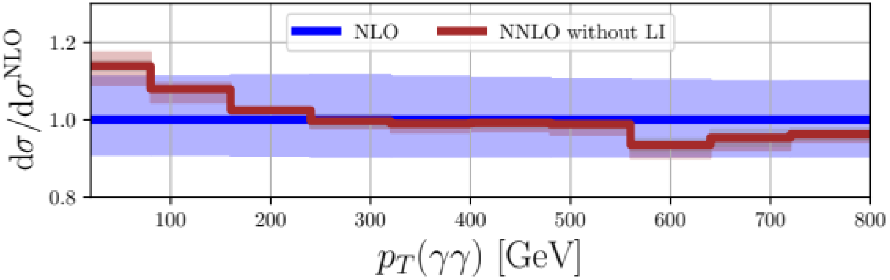
Technicalities:

- LHC 13 TeV, PDF: NNPDF31, Scale: μR^2 = μF^2 = ¼(m(γγ)^2 + pT(γγ)^2)
- 5 massless flavours and top-quarks (in all one-loop amps)
- Approximation of two-loop amps:
  2Re(M0*F2) + F1*F1 without top-quark loops
  and 2Re(M0*F2) in leading colour limit [Chawdhry'21]
  → Update to full colour planed [Agarwal'21]

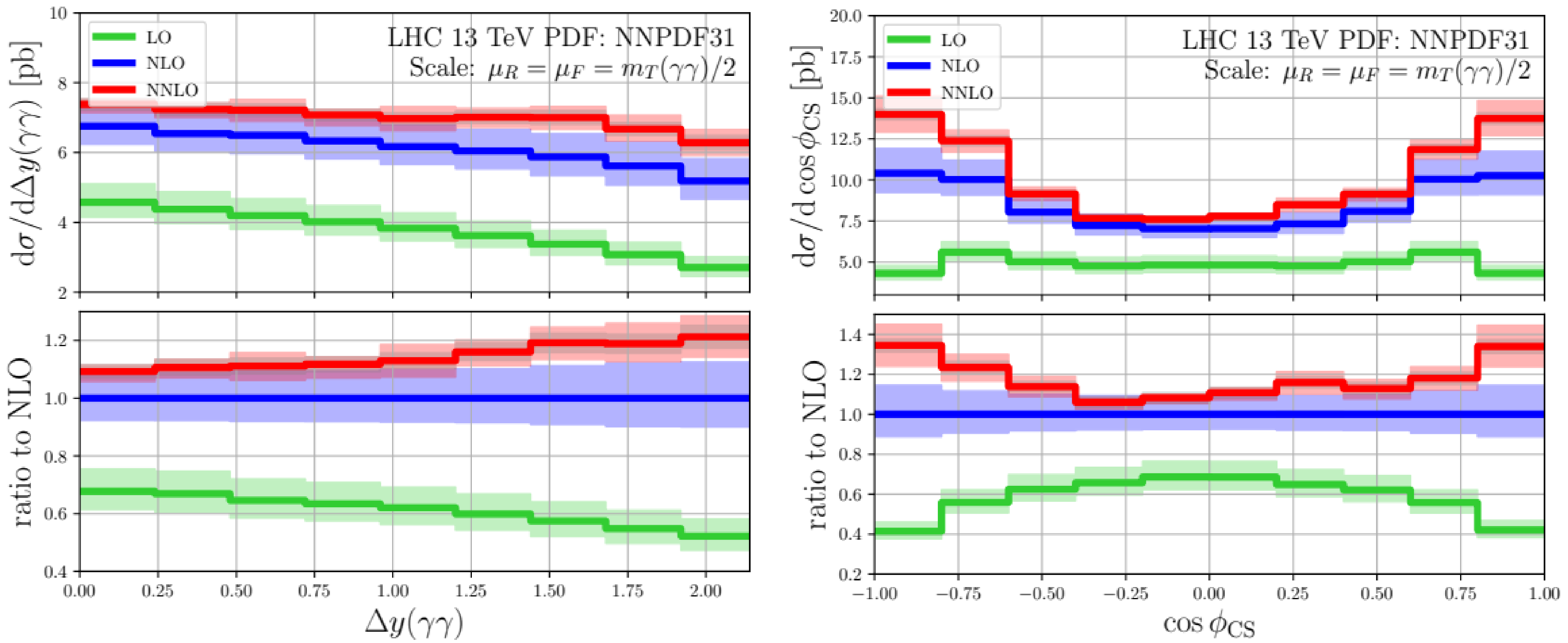
Diphoton plus jet – pT spectrum



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

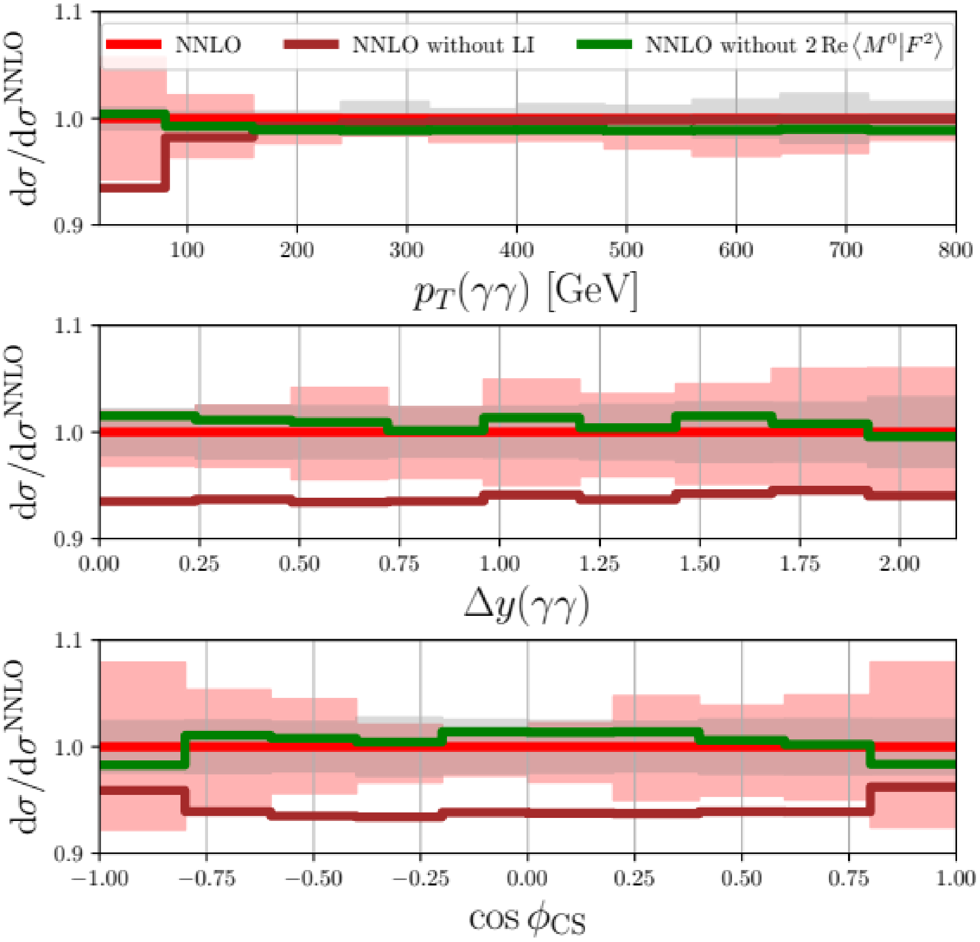


Diphoton plus jet – Angular observables



Note: Normalization effected by low pT behaviour

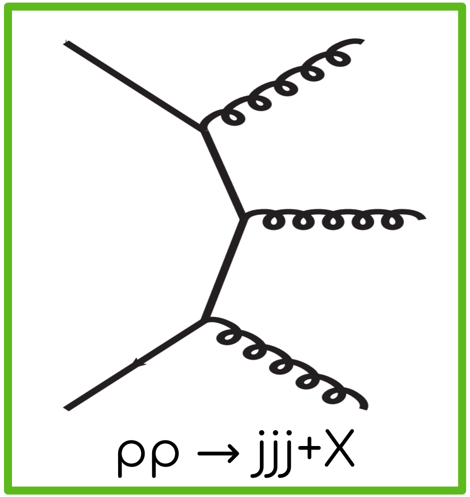
Diphoton plus jet – two-loop contribution



- Two-loop contribution (green line) <~1%,
- Loop induced contribution:
  - sizeable effects for low pT, vanishes for high pT
  - flat effect in 'bulk' observables
  - Dominant source of scale dependence
  - NLO QCD correction (formally N3LO) relevant,
    missing piece: gg → γγg two-loop

Three jet production

- Multi-jet rates provide an unique possibility to test (perturbative) QCD at the LHC
- Measurements of αS from event shapes and jet rate ratios (~αS)
- Test of αS running
- Multi-jet signatures are background for many LHC signatures.
- Allow to probe broad ranges of energy scales for heavy new physics
- Large cross sections → large statistics, in practice only limited by systematics!



Three jet production

Advances in perturbative QCD allow precision predictions for multi-jet rates

Here: NNLO QCD predictions for two and three jet rates

- NNLO QCD di-jet production known:
  - Gluons only [Gehrmann-De Ridder'13], partially leading colour [Currie'16]
  - Complete [Czakon'18] → sub-leading colour effects < 1-2%
- NNLO QCD tri-jet production:
  - Bottleneck double virtual amplitudes: recently published in leading colour approximation [Abreu'21]
  - Handling of real radiation:
    - Sector-improved residue subtraction conceptually capable → Tour-de-force (~4000 sectors for RR) → preliminary results

Three jet production - Setup

Setup:

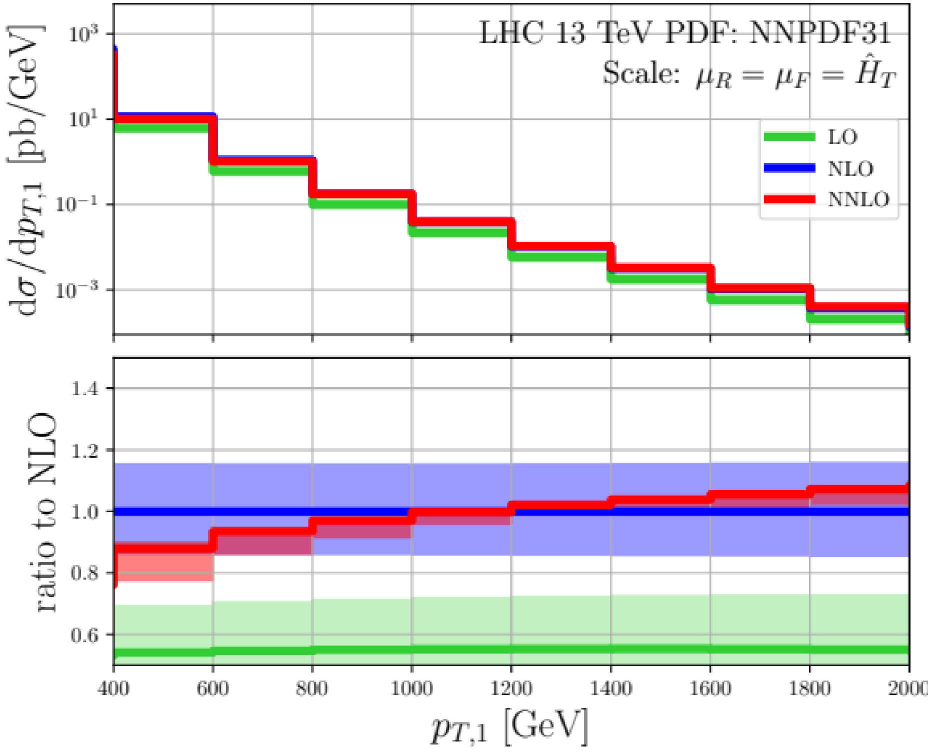
- LHC @ 13 TeV, NNPDF31
- Require at least three (two) jets with:
  - $pT > 60$ GeV, $|y| < 4.4$
  - $HT2 = pT1+pT2 > 250$ GeV
- Scales: $\mu R = \mu F = Hhat = \Sigma\ pT$ partons

R32 ratios:

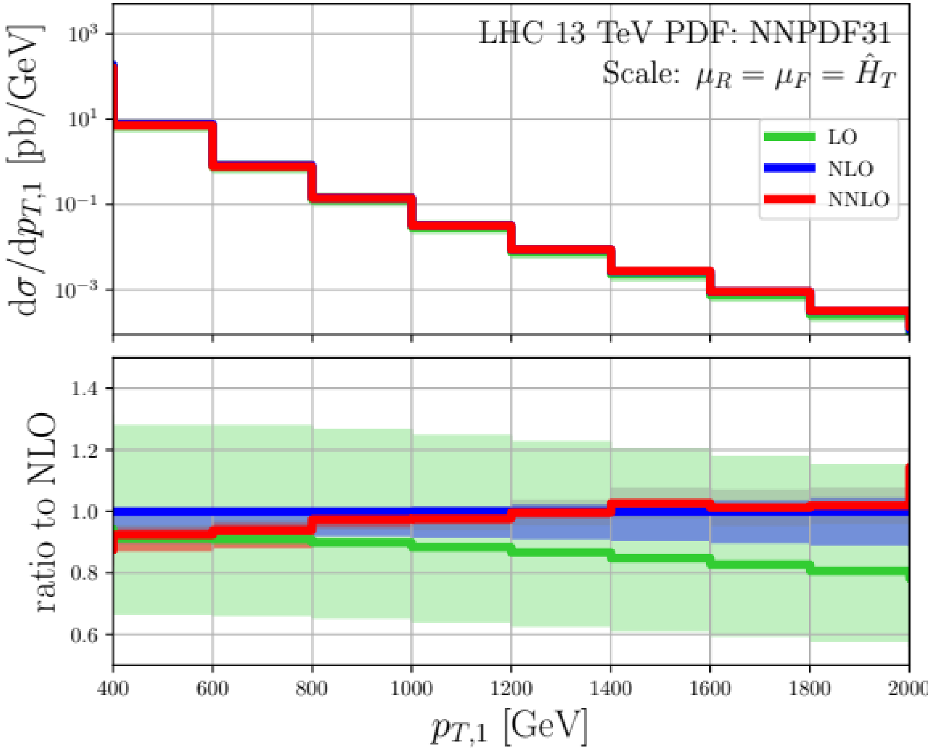
- Two jet rate = $\sigma 2$
  Three jet rate = $\sigma 3$
- $R32 = \sigma 3/\sigma 2$
- Differentially in X:
  $R32(X) = (d\sigma 3/dX)/(d\sigma 2/dX)$
- Scale dependence of R32(X) is determined by correlated variation in $\sigma 3$ and $\sigma 2$

Three jet production – leading pT

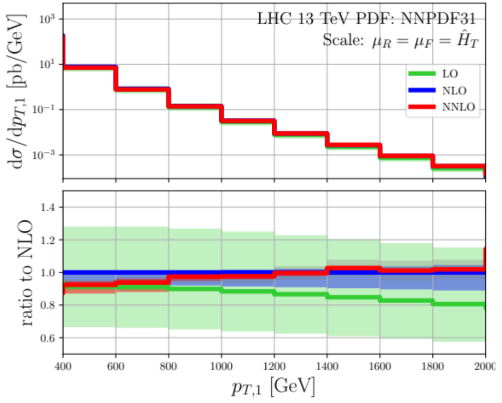
Two jets:

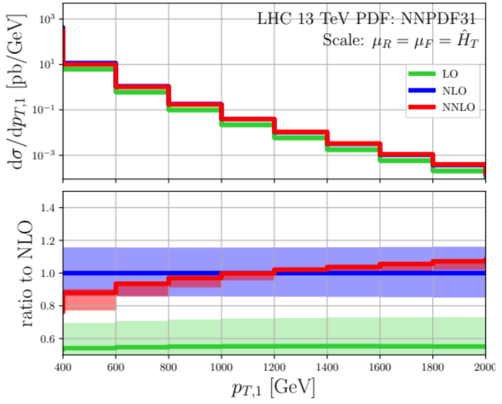


Three jets:

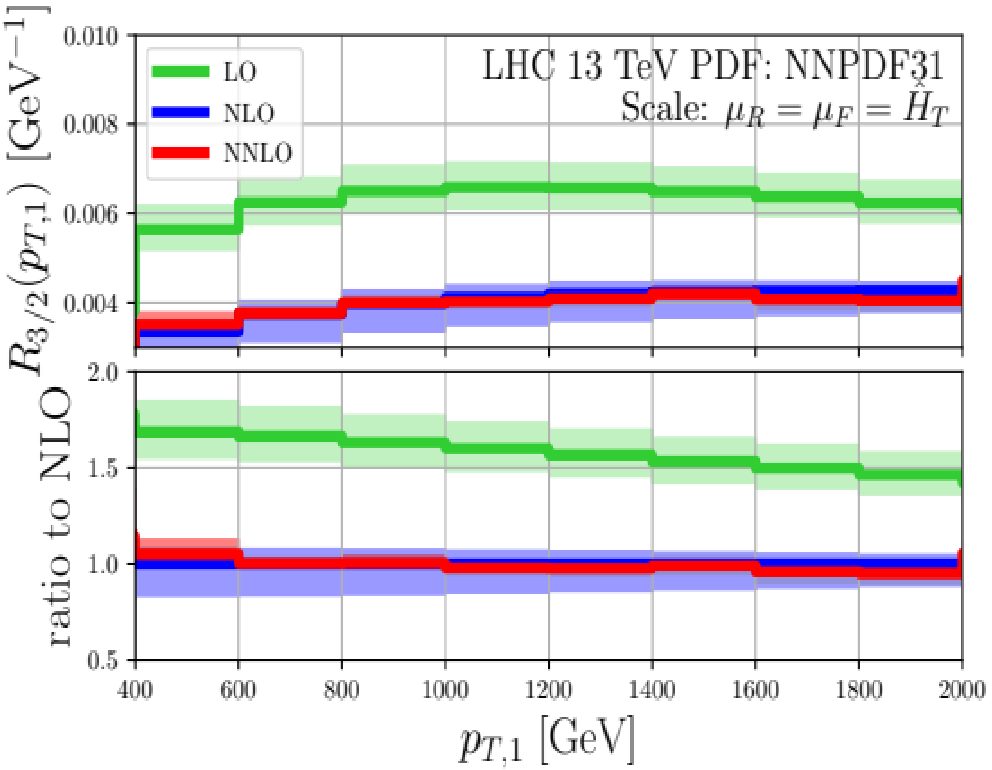


Three jet production - R32(pT1)

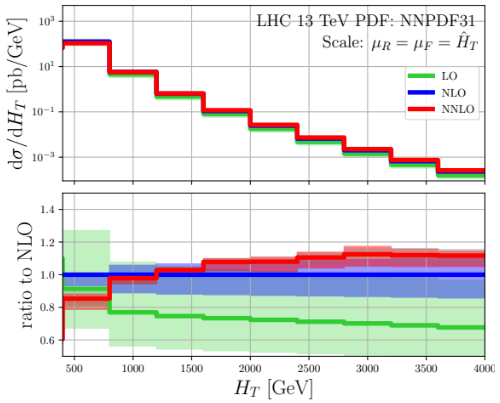


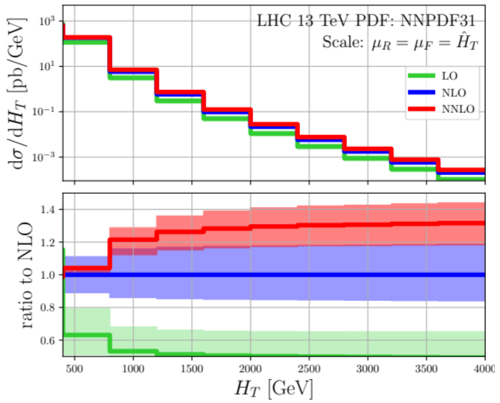


=



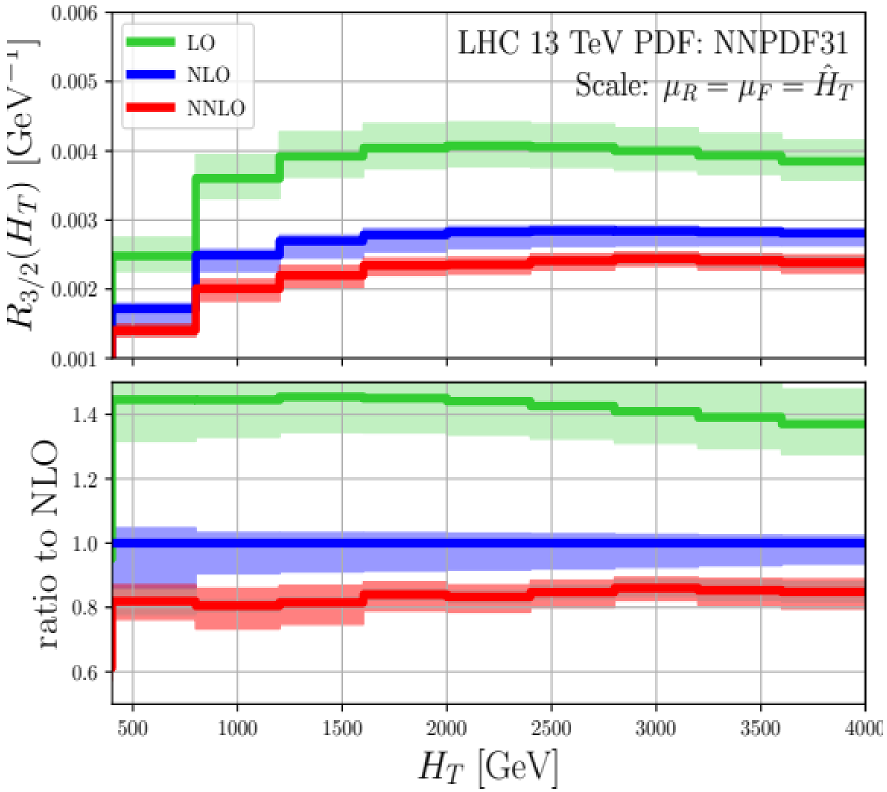
Three jet production - R32(HT)





=

HT = Σ ρT(jet)



Scale dependence correlated in ratio

→ reduction of scale dependence

→ flat k-factor

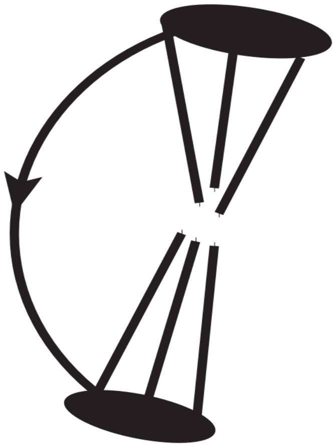
→ scale bands in ratio barely overlap

Three jet production – azimuthal decorrelation

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

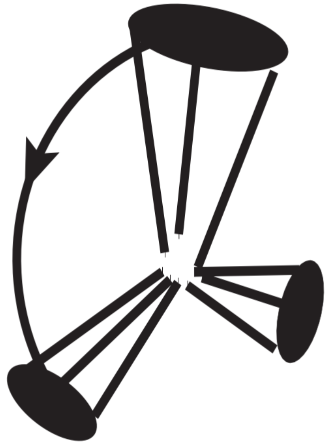
Dijet:

$\varphi_{12} = \pi$



Trijet:

$\varphi_{12} > 2/3\pi$



φ_{12} sensitive to the jet multiplicity:

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

3j: $\varphi_{12} > 2/3\pi$

4j: unconstrained

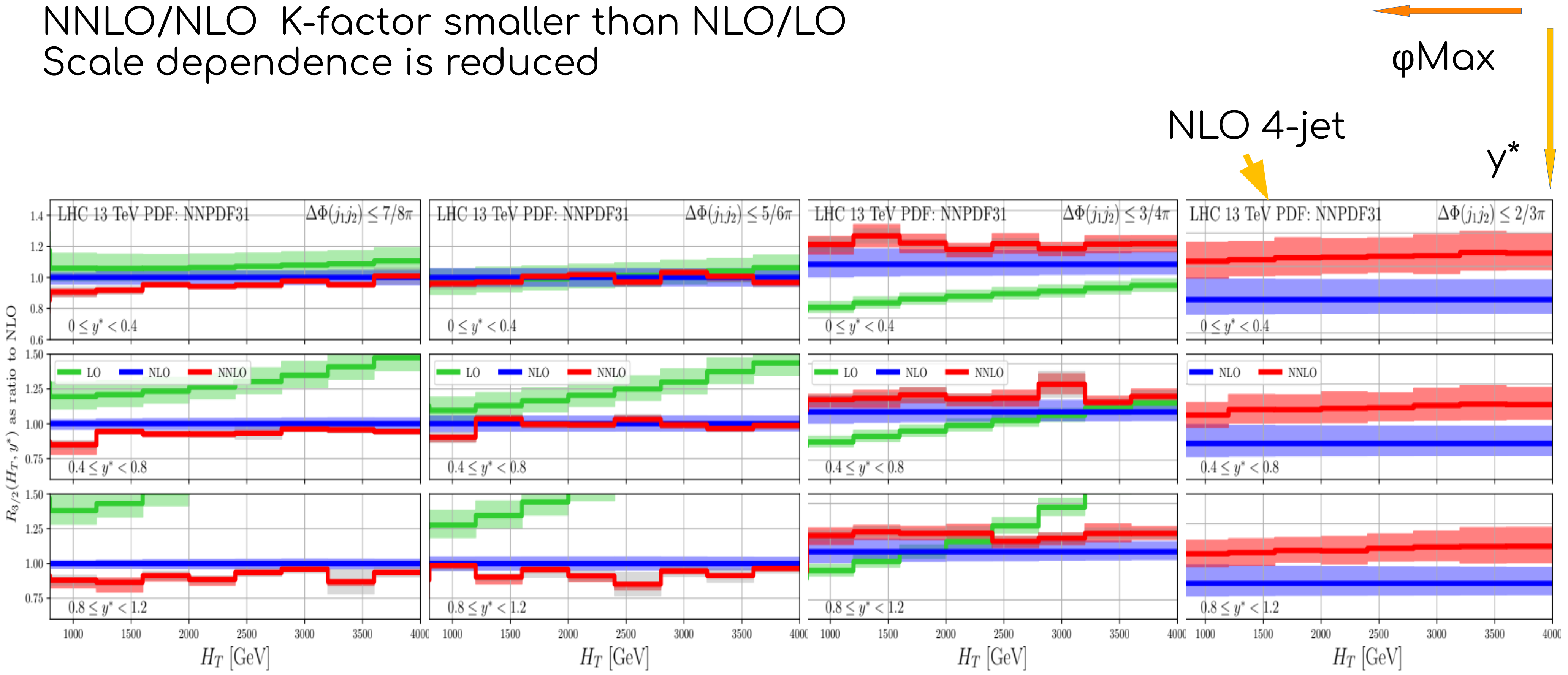
Study of the ratio

$R32(HT, y^*, \varphi Max) = (d\sigma 3(\varphi < \varphi Max)/dHT/dy^*)/(d\sigma 2/dHT/dy^*)$

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

- NNLO QCD predictions for 2 to 3 processes will be essential part of precision phenomenology at the LHC
- Results for:
  - Three photons
  - Diphoton plus jet
  - Three jet production
- Virtual matrix elements with high multiplicity and many scales are the bottleneck!
- 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!