Precision QCD for jets and V+jets

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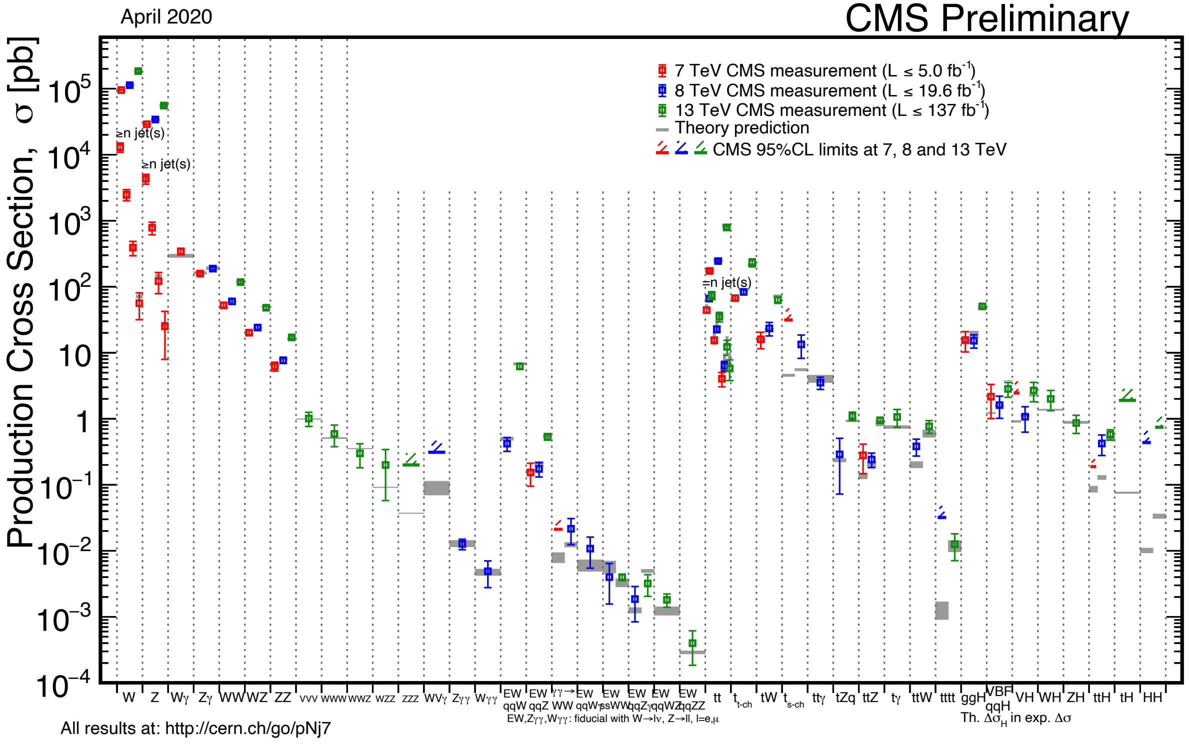
Precision jet physics at hadron colliders

- Precision tests of the Standard Model
  - Measurements of masses and couplings
- Interplay of calculations and measurements
  - Accuracy on most cross sections ≳5%
  - Limited by PDFs, QCD corrections
- Perturbative QCD as analysis tool
  - Data-driven background predictions, e.g. dark-matter+monojet [J.Lindert et al.]
  - Jet substructure techniques

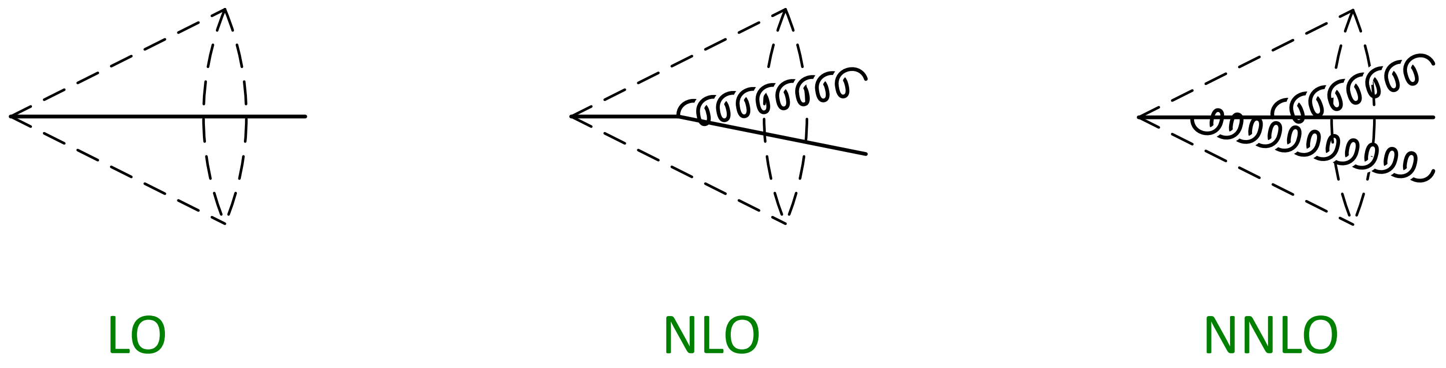


State-of-the-art

- Precise predictions: perturbation theory expansion of observables
- Automated tools for leading and next-to-leading order QCD and EW
  - infrastructure from event generator programs
    - HERWIG, SHERPA, aMC@NLO
  - standard interface to one-loop amplitude providers
    - BlackHat, GoSam, Recola, OpenLoops, NJet, MadLoop, CutTools
- Combined with parton shower
  - full event properties with NLO accuracy on differential cross sections

Jet observables in perturbation theory

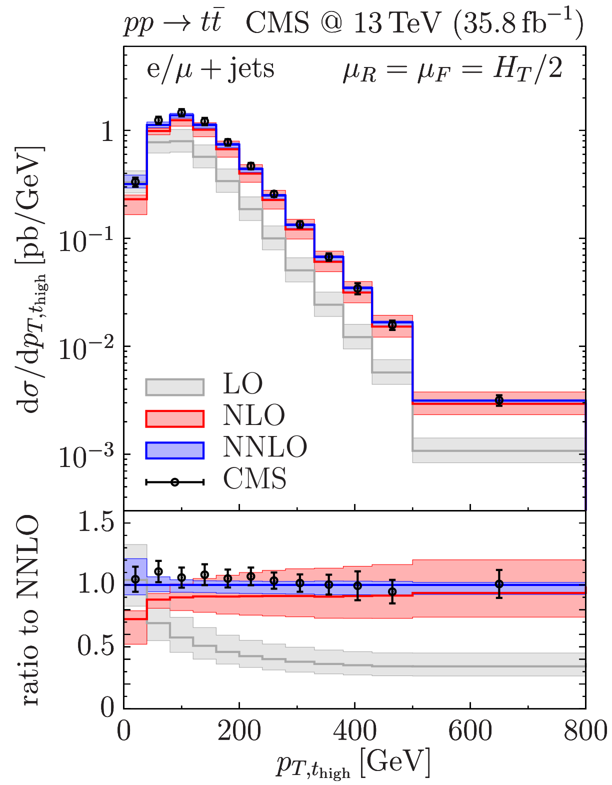
- Partons are combined into jets using same algorithm as in experiment



- No algorithm dependence at leading order
- Theoretical description more accurate with increasing order
- One extra parton per order in perturbation series
- Parton shower: multiple emissions, approximate description

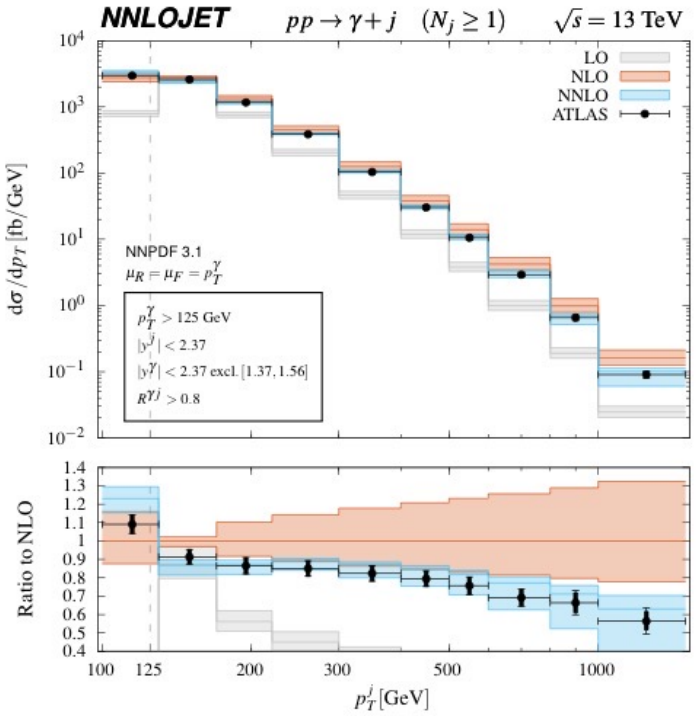
State-of-the-art: NNLO calculations

- Fully differential exclusive cross sections, various methods, process-by-process
- Sector decomposition
  - pp ⟶ H, pp ⟶ V [C.Anastasiou, K.Melnikov, F.Petriello]
- q_T subtraction
  - pp ⟶ H, pp ⟶ V,pp ⟶ γγ, pp ⟶ VH [S.Catani, L.Cieri, D.de Florian, G.Ferrera, M.Grazzini, F.Tramontano]
  - pp ⟶ VV [M.Grazzini et al.: MATRIX]
  - pp ⟶ tt, pp ⟶ bb [S.Catani, S.Devoto, M.Grazzini, S.Kallweit, J.Mazzitelli]
- Sector-improved residues
  - pp ⟶ tt [M.Czakon, P.Fiedler, A.Mitov]
  - pp ⟶ H+j [F.Caola, K.Melnikov, M.Schulze]
  - pp ⟶ 2j [M.Czakon, A.Van Hameren, A.Mitov, R.Poncelet]
  - pp ⟶ 3γ, pp ⟶ 2γ+j, pp ⟶ 3j [H.Chawdhry, M.Czakon, A.Mitov, R.Poncelet]



State-of-the-art: NNLO calculations

- Projection-to-Born
  - pp ⟶ H+2j, pp ⟶ HH+2j (VBF) [M. Cacciari, F. Dreyer, A. Karlberg, G. Salam, G. Zanderighi]
- N-Jettiness subtraction
  - pp ⟶ H, pp ⟶ V, pp ⟶ H+j, pp ⟶ V+j, pp ⟶ ɣ+j [R.Boughezal, J.Campbell, K.Ellis, C.Focke, W.Giele, X.Liu, F.Petriello, C.Williams: MCFM]
- Antenna subtraction
  - pp ⟶ H+j, pp ⟶ H+2j (VBF), pp ⟶ V+j, pp ⟶ ɣ+j, pp ⟶ 2j, pp ⟶ VH, ep ⟶ 2j [X.Chen, J.Cruz-Martinez, J.Currie, R.Gauld, A.Gehrmann-De Ridder, N.Glover, M.Höfer, A.Huss, I.Majer, J.Mo, T.Morgan, J.Niehues, J.Pires, D.Walker, J.Whitehead, TG: NNLOJET]
- Typically require HPC infrastructure: runtimes ~100’000 CPU hours
- Public codes available only for color singlet processes (MCFM, MATRIX)



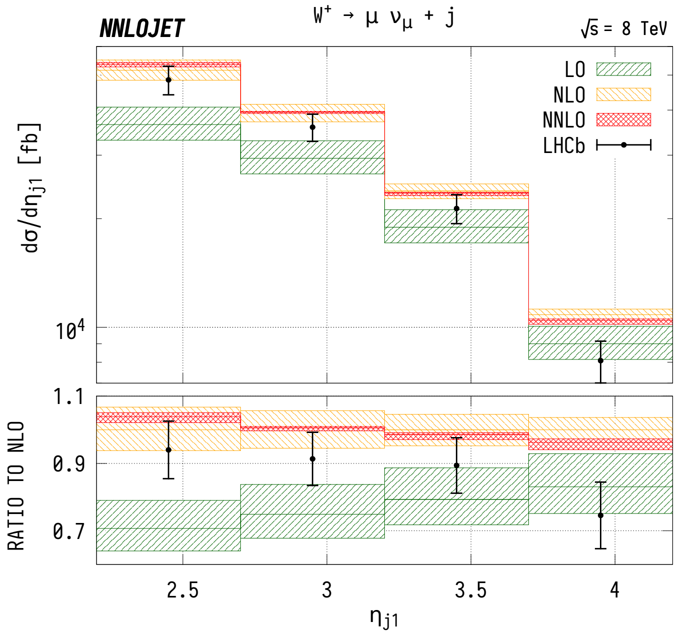
NNLOJET code

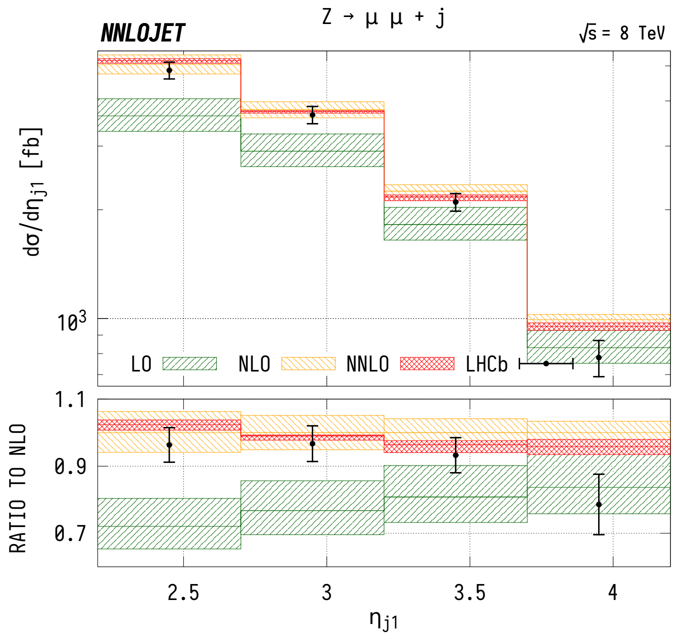
- NNLO parton level event generator
  - Based on antenna subtraction
- Provides infrastructure
  - Process management
  - Phase space, histogram routines
  - Validation and testing
  - Parallel computing (MPI) support for warm-up and production
  - ApplGrid/fastNLO interfaces in development
- Processes implemented at NNLO
  - Z+(0,1)jet, H+(0,1)jet, W+(0,1)jet, ɣ+1jet H+2jet (VBF)
  - DIS-2j, LHC-2j
  - Typical runtimes: 60’000-250’000 core-hours

NNLOJET project:
X. Chen, J. Cruz-Martinez, J, Currie,
A. Gehrmann-De Ridder, E.W.N. Glover,
M. Höfer, A. Huss, I. Majer, J. Mo,
T. Morgan, J. Niehues, J. Pires,
R. Schürmann, M. Sutton, D. Walker, TG

V+jet at NNLO

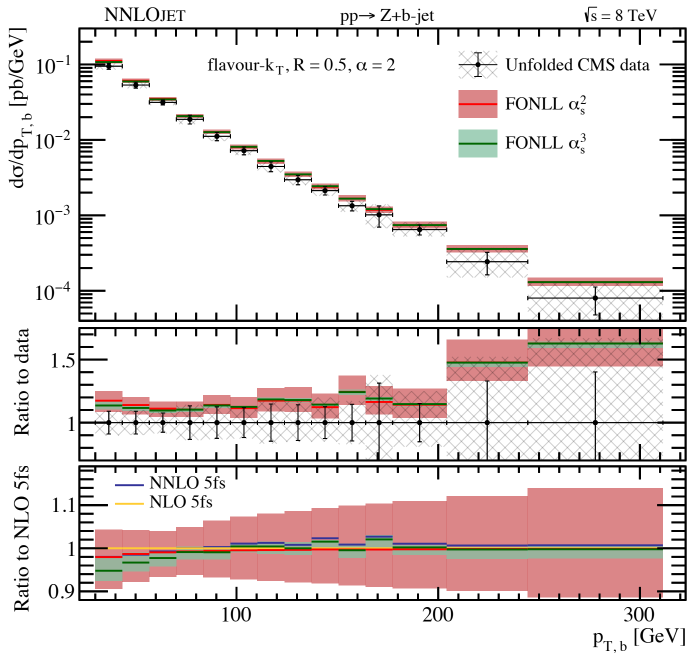
- Application: forward V+jet production at LHCb (8TeV)
  [NNLOJET: A.Gehrmann-De Ridder, E.W.N.Glover, A. Huss, D.Walker, TG]
  - NNLO corrections small; residual theory uncertainty ~2%
  - Potential impact on parton distributions

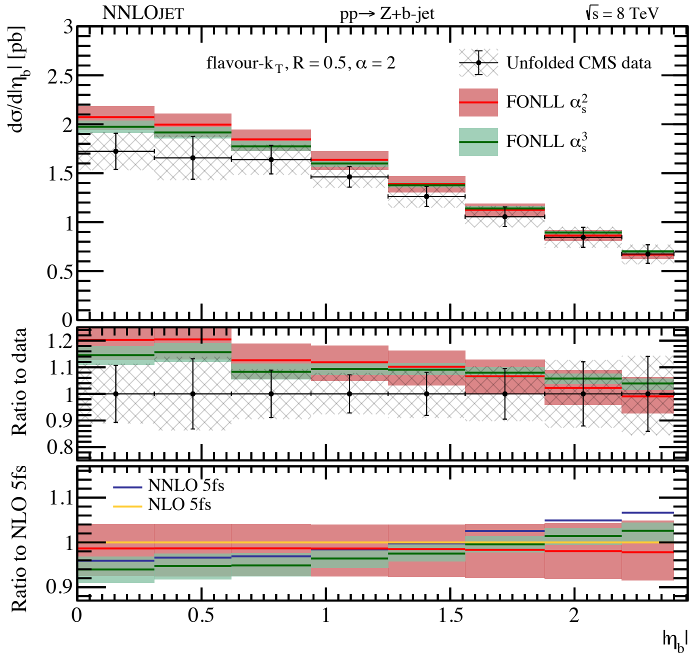




Z+b-jet at NNLO

- Identified-flavour jets
  - signature top precision physics and in many BSM searches
  - probe specific quark-parton distributions
- Require infrared-safe definition jet-flavour
  - flavour-k_T algorithm [A.Banfi, G.Salam, G.Zanderighi]
- NNLO calculation for Z+b-jet production
  [NNLOJET: R.Gauld, A.Gehrmann-De Ridder, N.Glover, A.Huss, I.Majer]
  - experimental measurement: anti-k_T jets with flavour tag (not IR-safe)
  - massive variable-flavour number scheme
  - data/theory comparison requires data unfolding to flavour-k_T



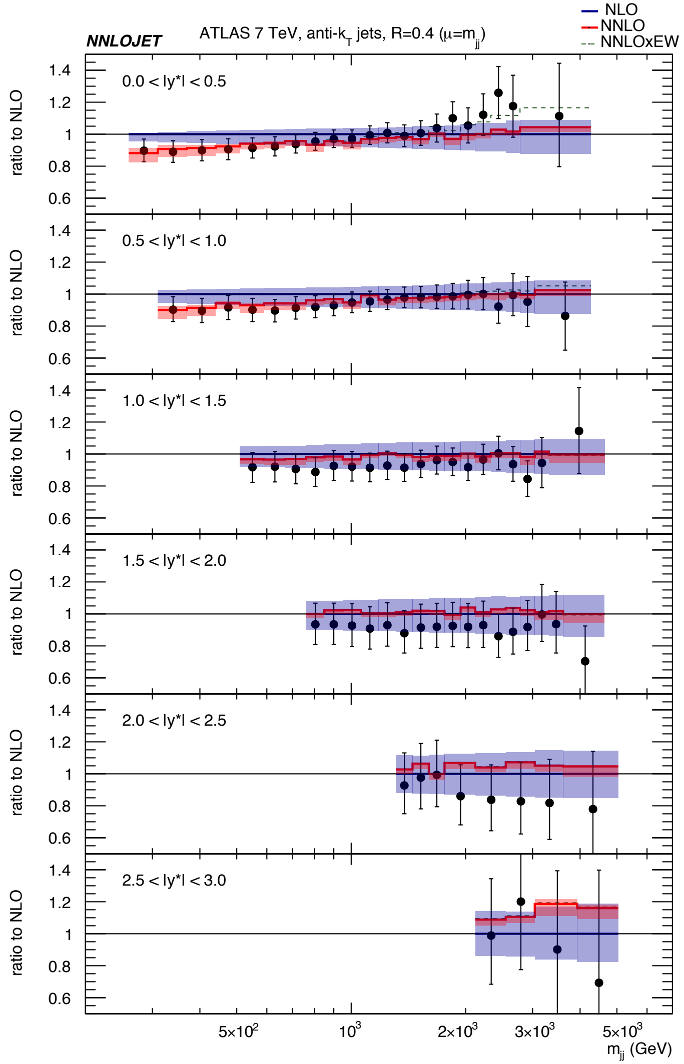


NNLO corrections to jet production

- Four QCD partons at tree level
  - Most complicated process so far
  - Larger number of unresolved limits than in V+jet
- NNLO corrections at leading color N and leading N_F
  - Subleading corrections: below 2% of cross section at NLO
    (M. Czakon, A. van Hameren, A. Mitov, R. Poncelet)
- Current parton distributions fit to single jet inclusive data
  - Consistent in NLO fit
  - In NNLO fit: used so far coefficient functions at NLO+resummation
  - Di-jet data not used in fit
- Full NNLO corrections potentially feed back on fits

NNLO corrections to di-jet production

- Impact of NNLO terms
  [NNLOJET: J.Currie, A.Gehrmann-De Ridder, E.W.N.Glover, A.Huss, J.Pires, TG]
  - Improved description of shape
  - Eliminate NLO ambiguity on central scale choice in di-jet production (m_{JJ} versus $\langle p_T \rangle$)
  - Remaining uncertainty ~3%
- Expose problems in single-jet inclusive observables
  - each jet in event enters observable independently
  - large NLO and NNLO corrections in second-jet distribution
  - ambiguity on scale setting remains at NNLO
    - event-based (H_T) versus jet-based (p_T)

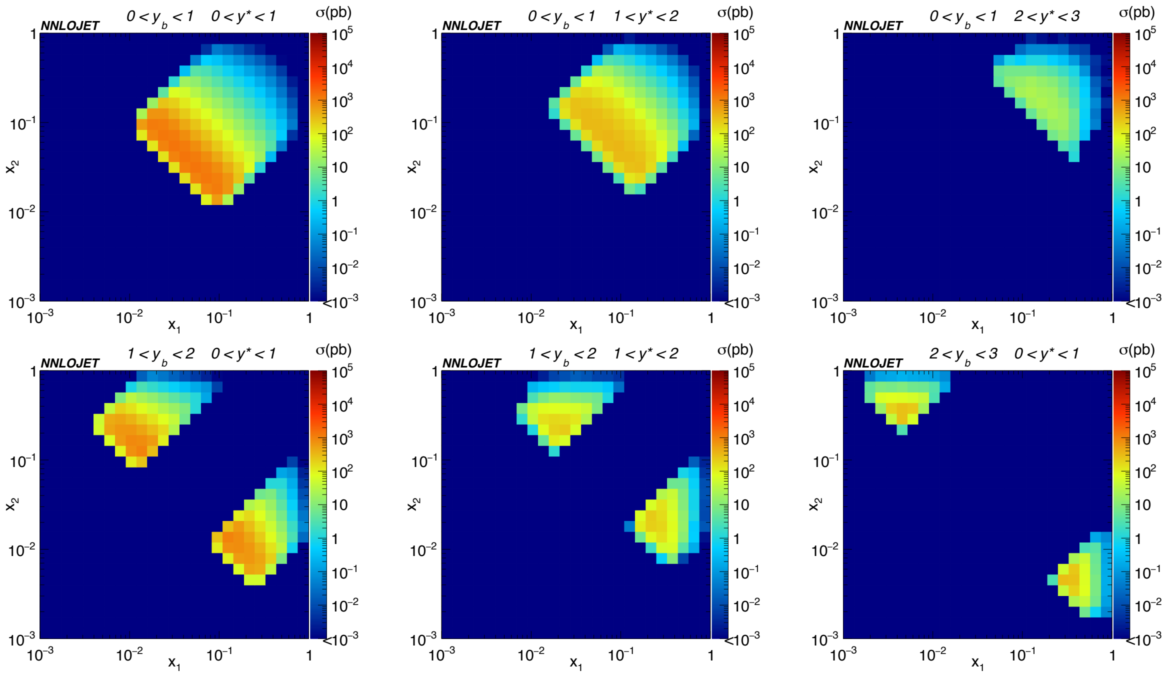


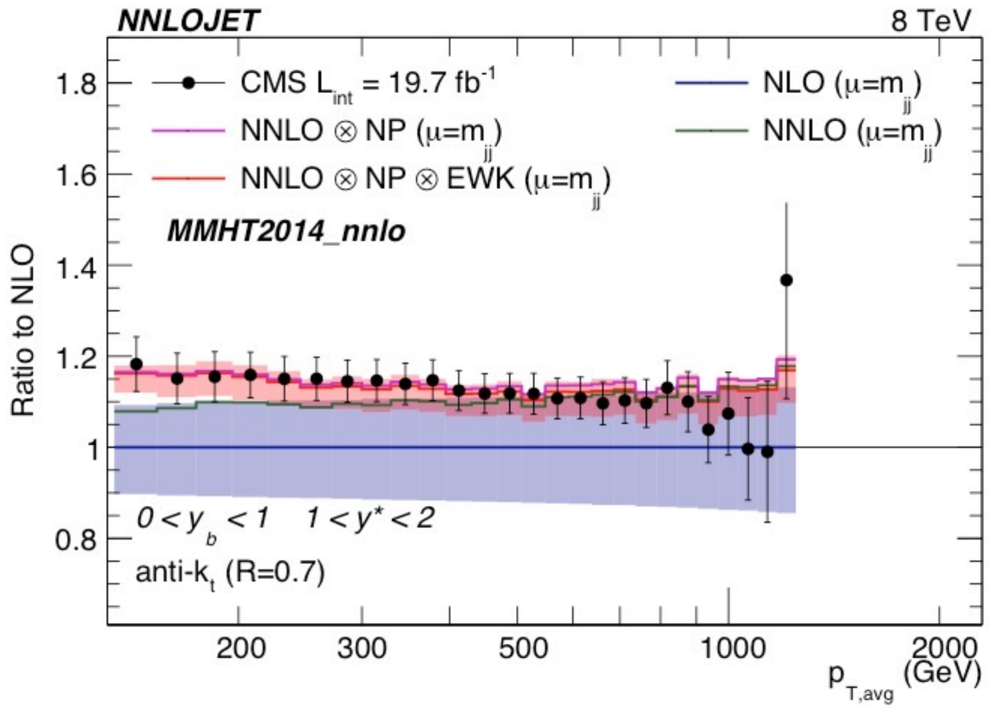
Triple differential di-jet cross section

- Measure two jet production differential in

$$p_{T,\text{avg}} = (p_{T,1} + p_{T,2})/2 \qquad y^\star = |y_1 - y_2|/2 \qquad y_b = |y_1 + y_2|/2$$

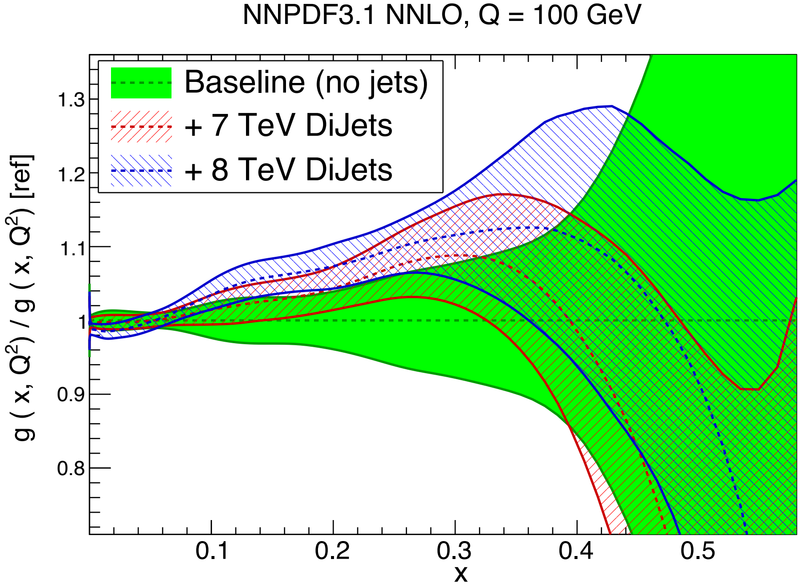
- scan parton distributions in (x_1,x_2)

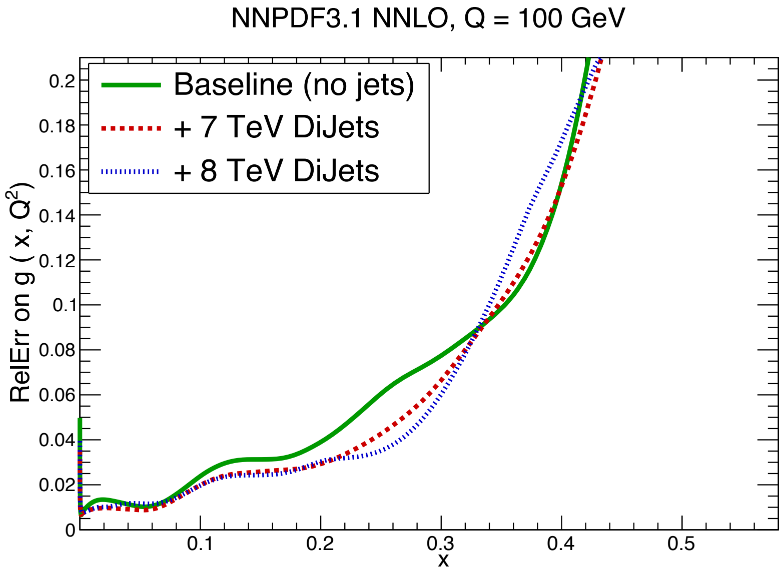




Impact on parton distributions

- Use single inclusive jet and di-jet data in global NNLO PDF fit
  [NNLOJET and NNPDF: R.Abdul Khalek, S. Forte, T. Gianni, E. Nocera, J. Rojo, G. Stagnitto]
  - increase in gluon distribution at for x≈0.1...0.3 (M_X ≈ 200...1500 GeV)
  - decreased uncertainty in this region

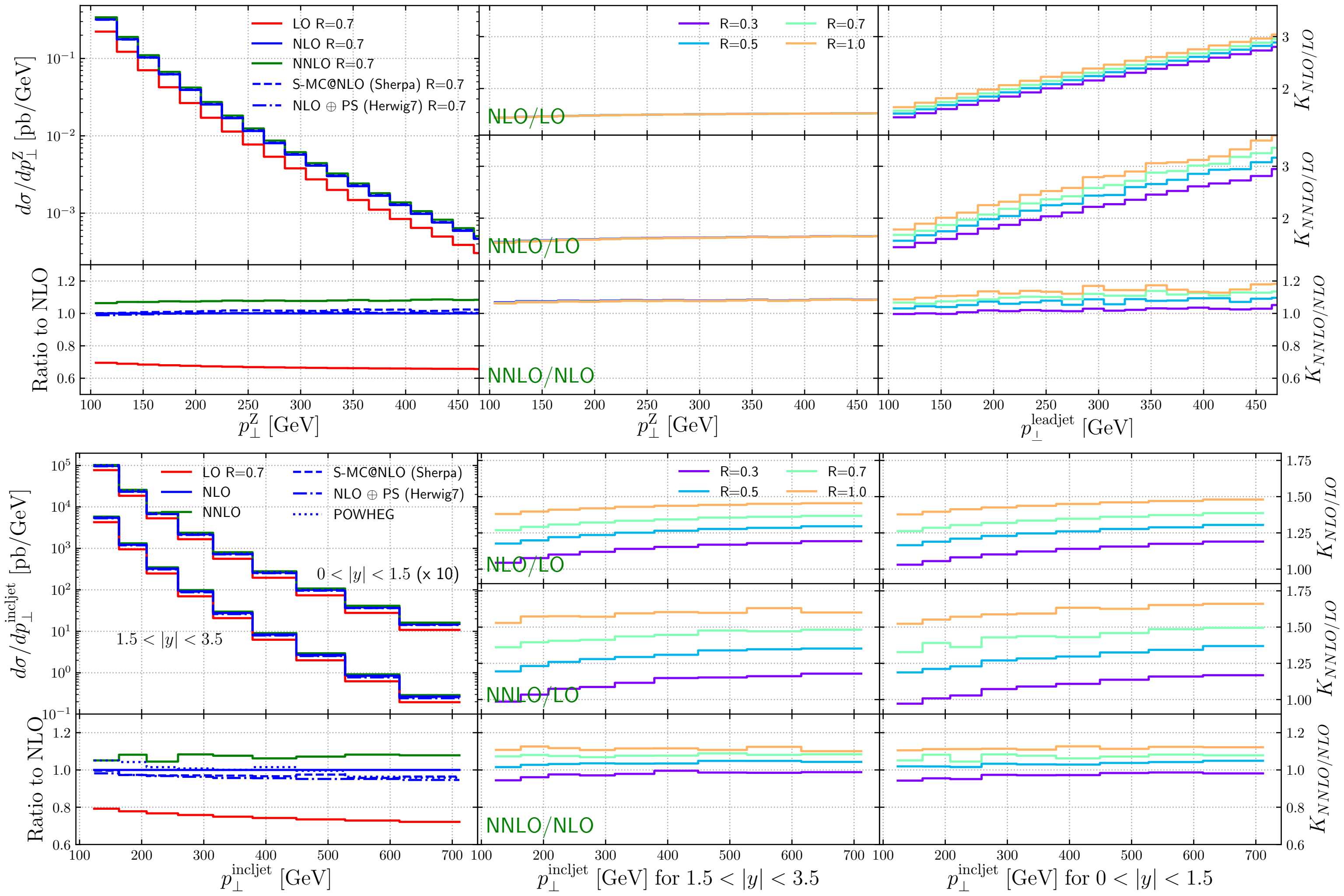




- Suggests to replace single-inclusive jets by di-jets for PDF fit

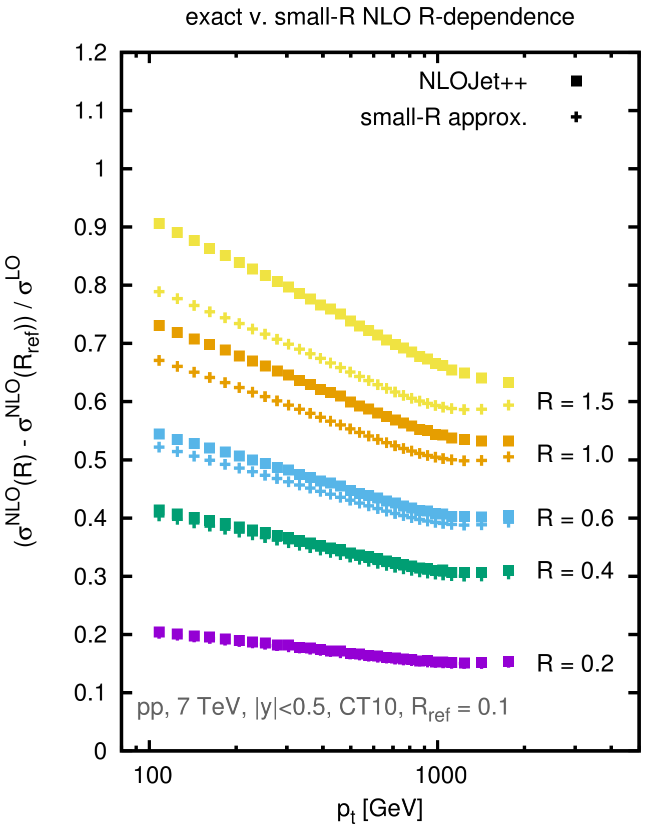
Fixed-order vs. resummation for QCD jets

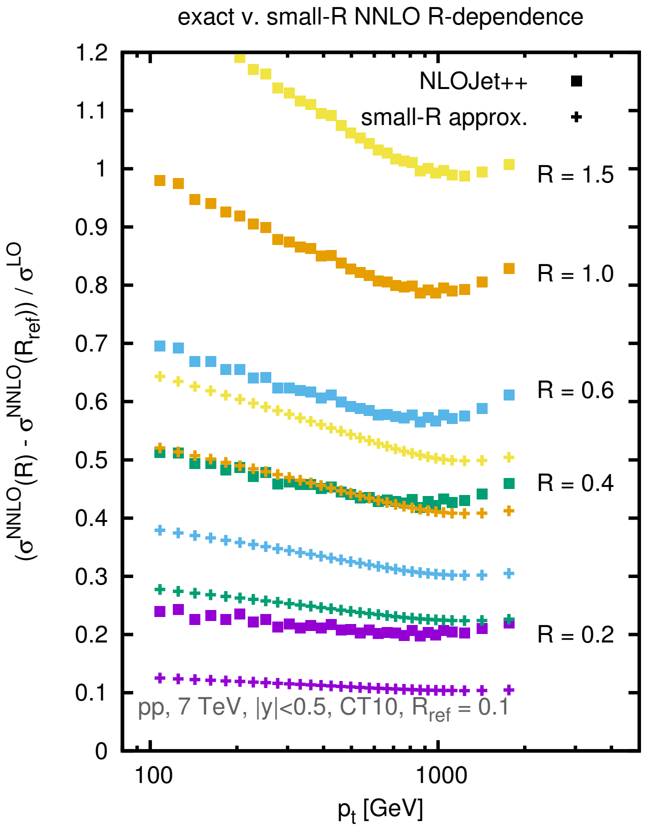
- Detailed comparative study of Sherpa, Herwig, Powheg, NNLOJET [J.Bellm et al.]
- NLO+PS does not capture NNLO effects
- Jet-size dependence of NNLO corrections
- Follow-up: VBF Higgs production [A. Buckley et al.]



Fixed-order vs. resummation for QCD jets

- Dependence on jet algorithm/jet resolution only through real radiation
  - NNLO variations can be studied using NLO calculation for higher multiplicity
    [M. Dasgupta, F. Dreyer, G. Salam, G. Soyez]
  - invalidates small-R approximation





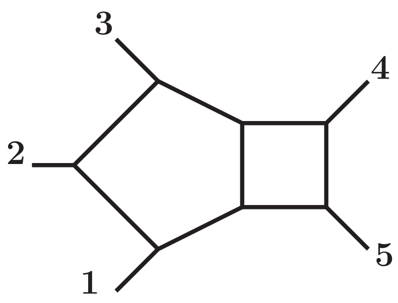
Directions and challenges in precision QCD

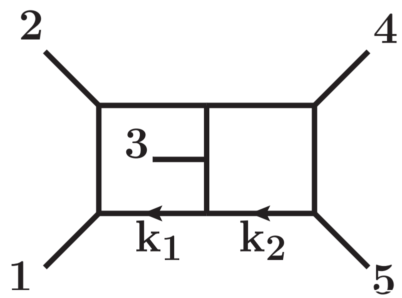
- NNLO for higher multiplicities (beyond $2 \longrightarrow 2$)
  - virtual two-loop amplitudes and integrals largely unknown
  - methods for handling infrared singularities becoming unpractical
  - much room for conceptual and technical progress
- Matching NNLO and parton showers
  - obtain predictions for fully exclusive final states
- N3LO for benchmark processes

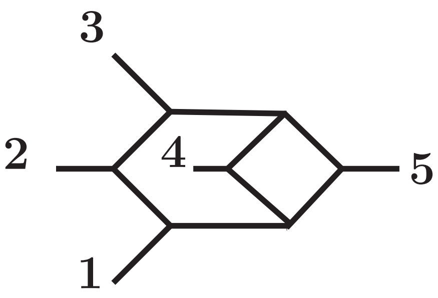
Directions: loop amplitudes

- One-loop amplitudes computable for arbitrary processes
  - automation relies on finite set of known one-loop Feynman integrals
- Multi-loop integrals only known for special cases
  - main techniques: differential equations, sector decomposition
  - often mix of analytical and numerical techniques
  - massless propagators: 2-loop 2→(2,3), 3-loop 2→(1,2), 4-loop 1 →(1,2)

    [D.Chicherin, J.Henn, A.Lo Presti, P.Wasser, Y.Zhang, S.Zoia, TG; S.Abreu, L.J.Dixon, E.Herrmann, B.Page, M.Zeng; C.Papadopoulos, D.Tomassini, C.Wever; S.Abreu, H.Ita, F.Moriello, B.Page, W.Tschernow, M.Zeng; J.Henn, B.Mistlberger, V.Smirnov, P.Wasser; A.von Manteuffel, R.Schabinger, E.Panzer; K.Chetyrkin, P.Baikov]

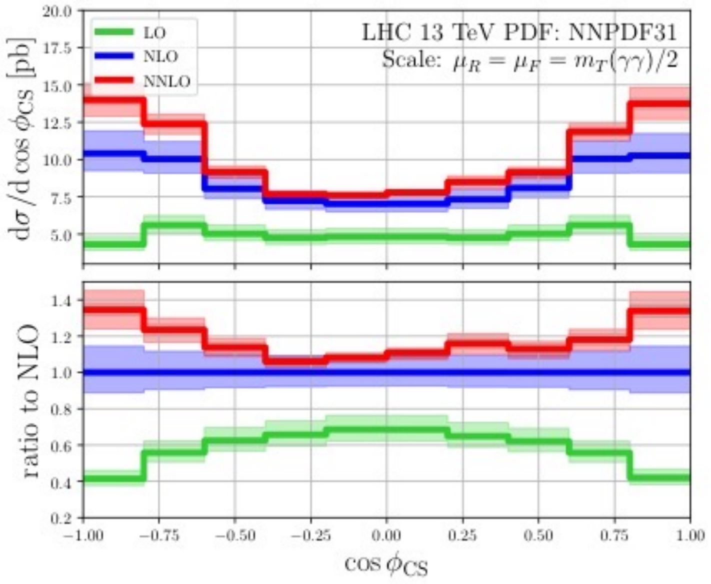






Directions: loop amplitudes

- Multi-loop amplitudes
  - require determination of integral coefficients (reduction to master integrals)
  - purely symbolic integration-by-parts techniques limited by complexity
  - alternative: finite-field reconstruction (multiple evaluations for integer values of kinematics) [FinRed: A.von Manteuffel, R.Schabinger; FiniteFlow: T.Peraro]
- Recent QCD results
  - 5 partons: pp → 3j, pp → γ+2j, pp → 2γ+j, pp → 3γ
    [S.Abreu, J.Dormans, F.Febres Cordero, H.Ita, B.Page, V.Sotnikov; H.A.Chawdhry, M.Czakon, A.Mitov, R.Poncelet]
  - V+4 partons: pp → W+bb
    [S.Badger, C.Borrnum-Hansen, H.B.Haranto, T.Peraro]
- Applications: pp → 2γ+j, pp → 3γ
  [H.A.Chawdhry, M.Czakon, A.Mitov, R.Poncelet]

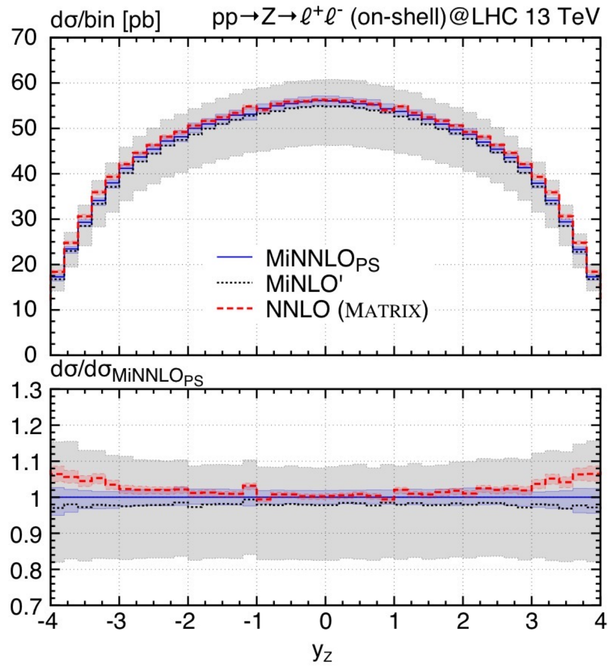


Directions: NNLO for higher multiplicities

- Matrix elements: issues
  - availability of two-loop amplitudes
  - stability of (auto-generated) one-loop amplitudes in unresolved limits
- Real radiation at NNLO: issues and developments
  - methods scale poorly with multiplicity (complexity, efficiency, ingredients)
  - pragmatic approach: residue subtraction with sector decomposition, gradual replacement with analytic integrals [M.Czakon; F.Caola, K.Melnikov, R.Röntsch]
  - ideas in search for generic methods: factorization, colour-kinematics relations [G.Bevilacqua, A.Kardos, G.Somogyi, Z.Trocsanyi, Z.Tulipant; L.Magnea, L.Maina, G.Pelliccioli, C.Signorile-Signorile, P.Torrielli, S.Uccirati]

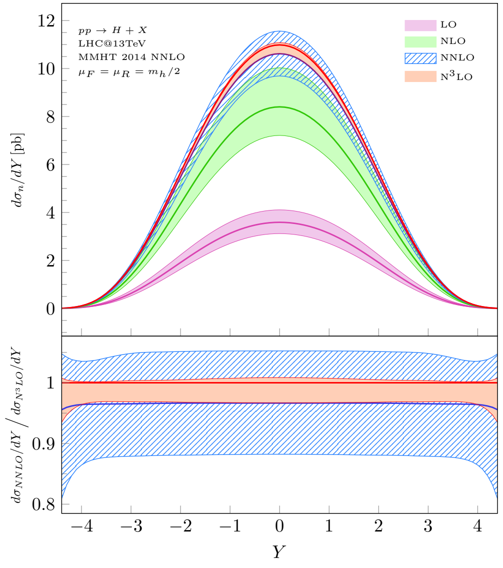
Directions: matching NNLO & parton showers

- Methods to subtract double-counted terms: NNLOPS, UNNLOPS
- Applications: colour-neutral final states: no jets
  [S.Höche, Y.Li, S.Prestel; P.Monni, K.Hamilton, A.Karlberg, E.Re, G.Zanderighi]
  - Higgs production
  - Drell-Yan process
  - W^+W^- production: rearrange NNLOPS to avoid expensive tabulation [E.Re, M.Wiesemann, G.Zanderighi]
- Optimised scale-setting: MiNNLO_{PS}
  [D.Lombardi, M.Wiesemann, G.Zanderighi]
  - no re-weighting
  - applicable to generic final states



Ultimate QCD precision: N3LO calculations

- Inclusive coefficient functions
  - Deep inelastic scattering [S.Moch, J.Vermaseren, A.Vogt]
  - Higgs production [C.Anastasiou, C.Duhr, F.Dulat, F. Herzog, B.Mistlberger]
  - Higgs rapidity distribution [F.Dulat, B.Mistlberger, A.Pelloni]
  - VBF Higgs production [F.Dreyer, A.Karlberg]
  - Drell-Yan process [C.Duhr, F.Dulat, B.Mistlberger]



- Exclusive differential observables: methods
  - Projection to Born [M.Cacciari, F.Dreyer, A.Karlberg, G.Salam, G.Zanderighi]

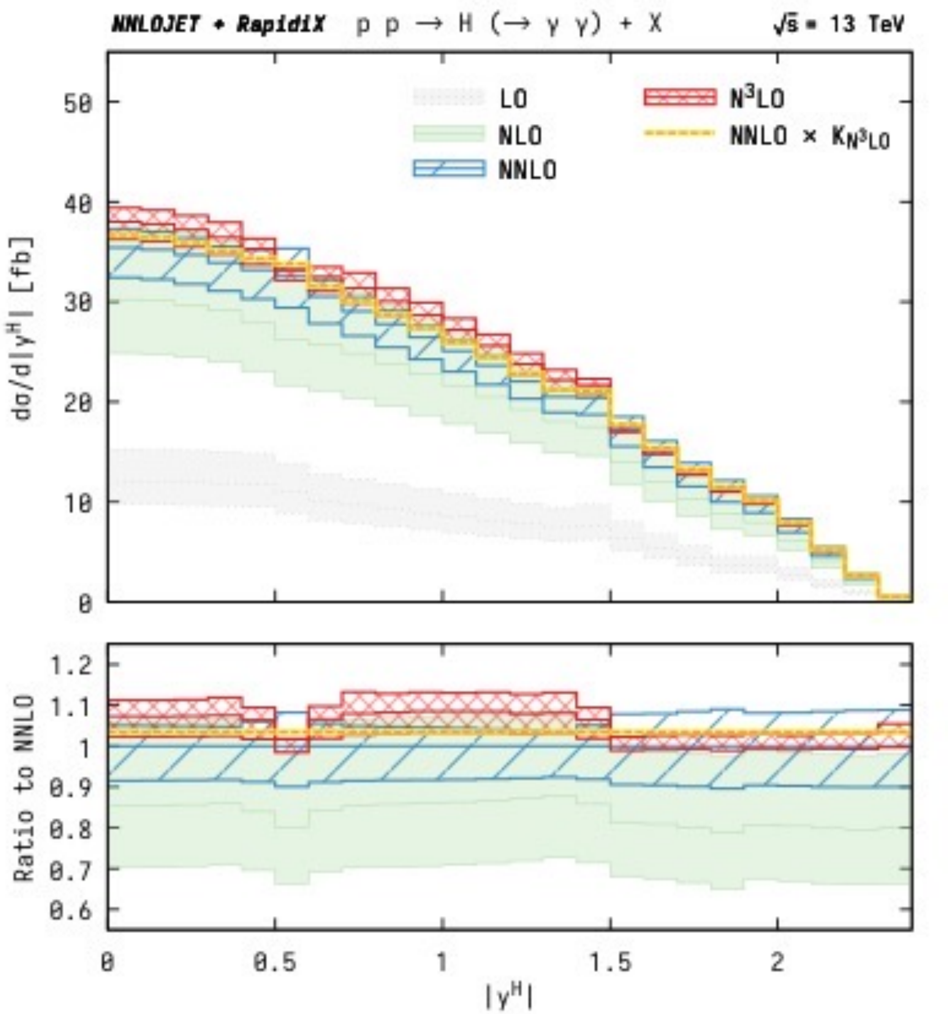
$$\frac{d\sigma_X^{N3LO}}{dO} = \frac{d\sigma_{X+j}^{NNLO}}{dO} - \frac{d\sigma_{X+j}^{NNLO}}{dO_B} + \frac{d\sigma_X^{N3LO,incl}}{dO_B}$$

  - q_T subtraction [S.Catani, M.Grazzini]

$$\frac{d\sigma_X^{N3LO}}{dO} = \mathcal{H}_{N3LO} \otimes \frac{d\sigma_X^{LO}}{dO} + \left[\int_{q_{T,X}} \frac{d\sigma_{X+j}^{NNLO}}{dO} - \frac{d\sigma_{X,CT}^{NNLO}}{dO}(q_T)\right]$$

Ultimate QCD precision: towards N3LO

- Jet production in deep inelastic scattering
  [J.Currie, N.Glover, A.Huss, J.Niehues, A.Vogt, D.Walker TG]
  - Projection to Born method
  - exploits special Born-level kinematics in DIS
- Higgs boson production with H→γγ
  [X. Chen, E.W.N. Glover, A. Huss, B. Mistlberger, A. Pelloni]
  - Projection to Born method
  - Fully differential in decay products
- Jet structure observables
  - dependence on algorithm and resolution
  - jet profiles
  - require (only) NNLO at higher multiplicity



Precision theory for jet observables

- Crucial for full exploitation of HL-LHC precision data
  - determination of parton distributions and SM parameters
  - new physics searches and data driven background methods
- Predict fiducial multi-differential cross sections
  - NLO automated, NNLO case-by-case
  - Require new computational paradigms: automation and efficiency
  - high-multiplicity $2 \to 3$ at NNLO becoming feasible
- NNLO real radiation effects often not captured by parton showers
  - jet structure, algorithm and resolution dependence
- Ultimate precision: NNLO+PS, N3LO