Advances in QCD Predictions

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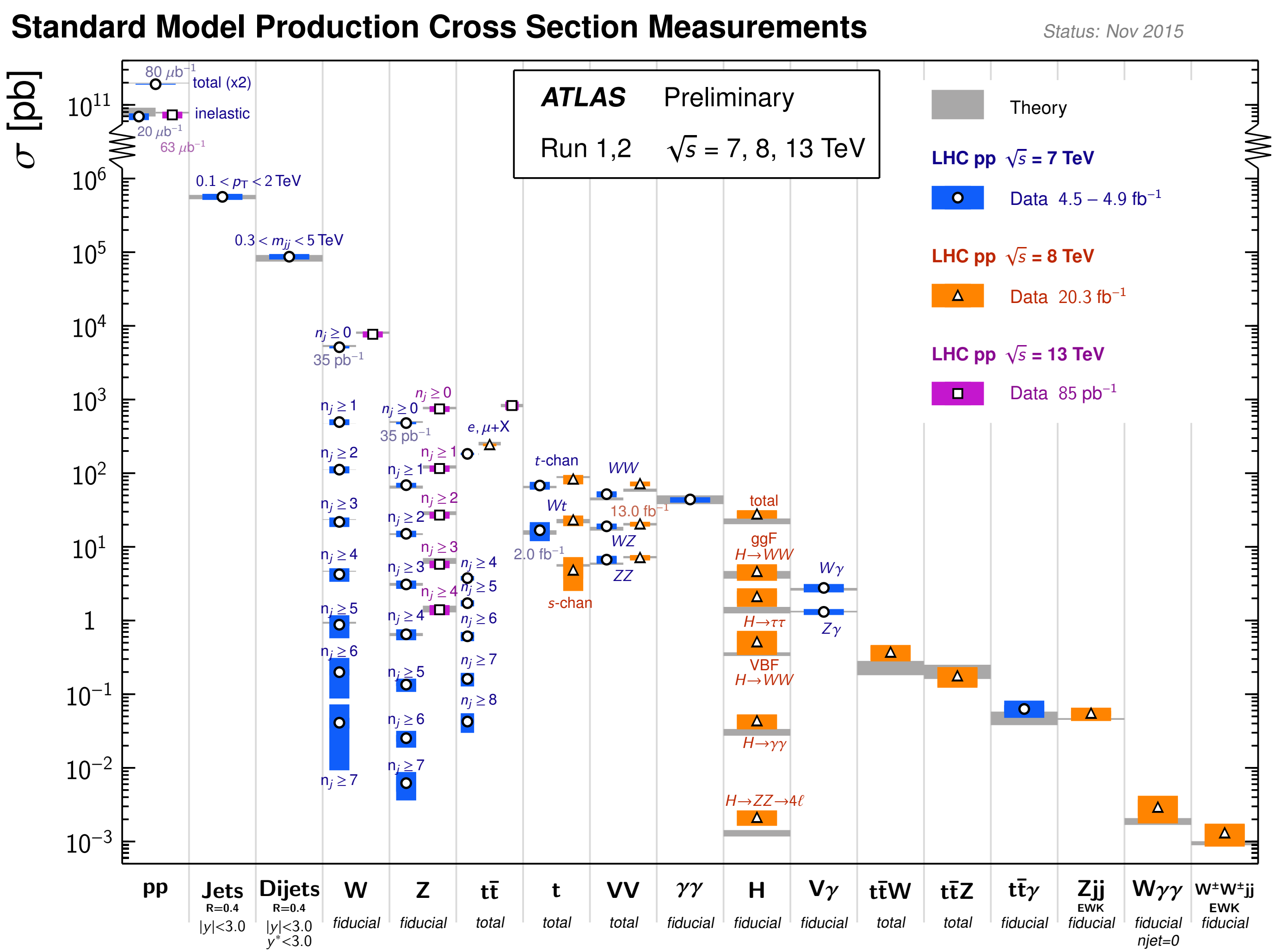
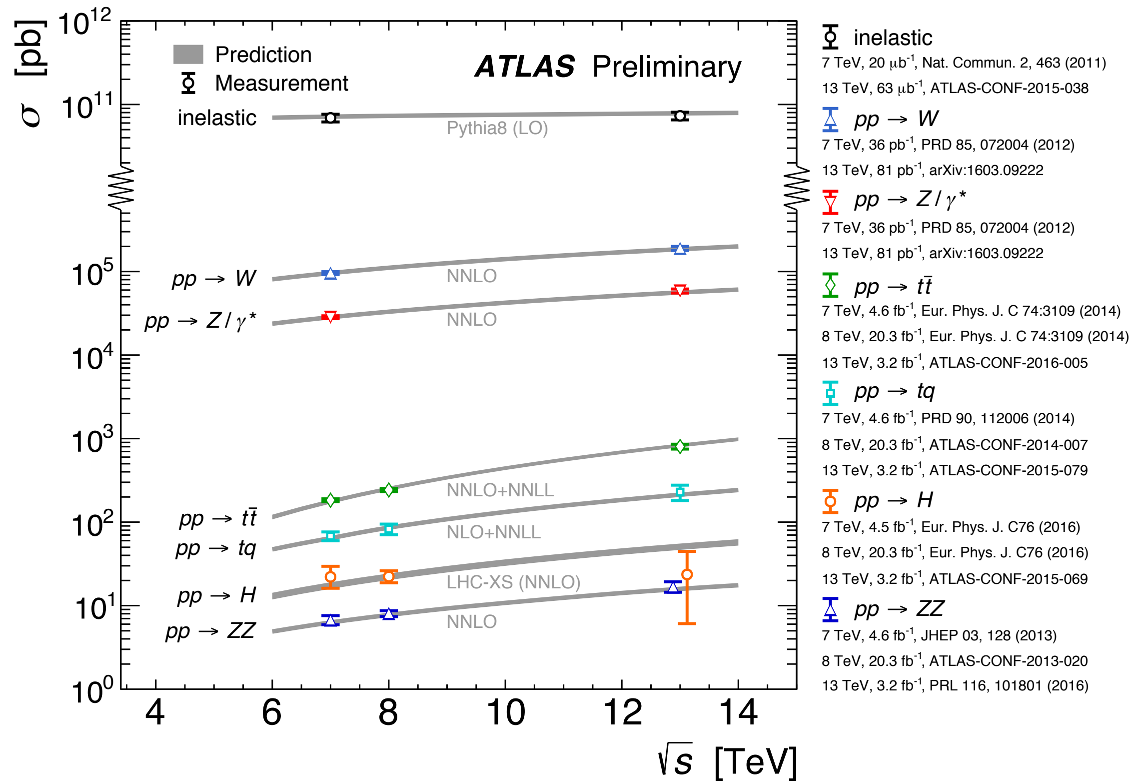
Standard Model processes at the LHC



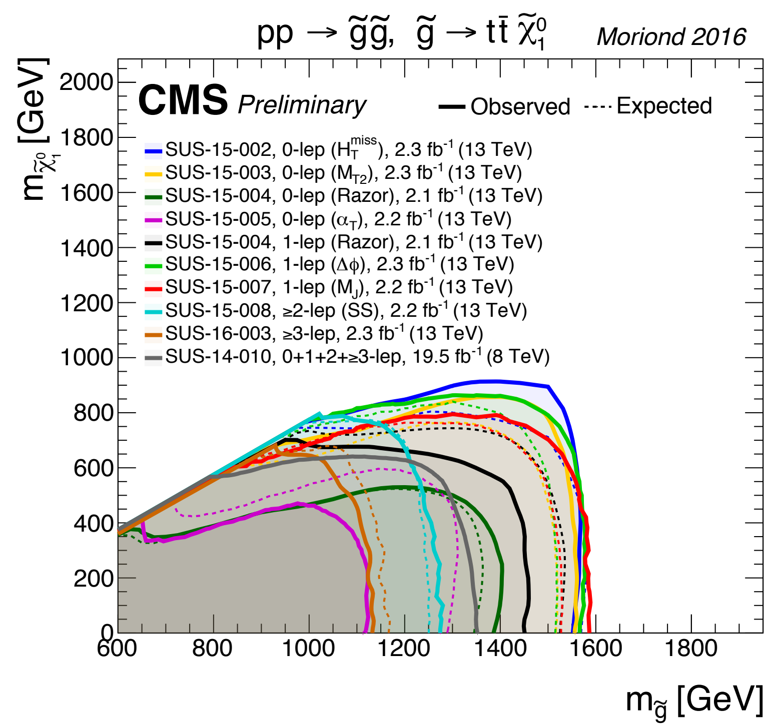
Benchmark processes

- Low multiplicity observables
- Enable precision measurements
  - Masses
  - Couplings
  - Parton distributions
- Precise theory
  - Higher orders
  - Resummation
  - Full event properties
- Indirect new physics searches



Multi-particle production

- Production of short-lived heavy states (new physics searches)
  - detected through their decay products
  - yield multi-particle final states involving jets, leptons, γ , $E_{T,miss}$
- Search for effects in many different multi-particle final states
- Need precise predictions for hard scattering processes
  - signal and background
  - often combine theory and data-driven approaches



Fixed order versus parton shower

- Fixed order calculations
  - Expansion in powers of the coupling constant
  - Correctly describes hard radiation pattern
  - Final states are described by single hard particles
  - NLO: up to two particles in a jet, NNLO: up to three..
  - Soft radiation poorly described, resummation needed
- Parton shower
  - Exponentiates multiple soft radiation (leading logarithms)
  - Describes multi-particle dynamics and jet substructure
  - Allows generation of full events (interface to hadronization)
  - Basis of multi-purpose generators (SHERPA, HERWIG, PYTHIA)
  - Fails to account for hard emissions
- Ideally: combine virtues of both approaches

NLO multi-particle production

- Why NLO?
  - reduce scale uncertainty of LO theory prediction
  - reliable normalization and shape
  - accounts for effects of extra radiation
  - jet algorithm dependence

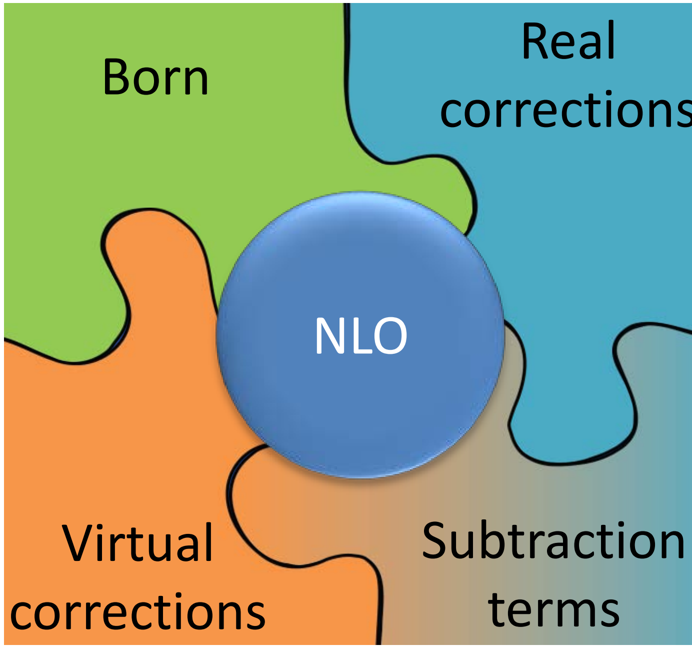
- Typical observations
  - sizable NLO corrections
  - corrections not constant, but kinematics-dependent
  - remaining uncertainty at NLO typically 10-20%

NLO multi-parton production

- Enormous progress in getting NLO predictions for 2→(4,5,6!) processes over the last years
- Made possible by
  - Improved techniques for loop amplitudes
  - Crucial: a high level of automation
- Well-defined interfaces (Binoth Les Houches accord)
  - combine different ingredients from different codes

NLO automation

- One-loop amplitudes
  - BlackHat (Z. Bern, L. Dixon, F. Febres Cordero, S. Höche, H. Ita, D. Kosower, D. Maitre, K. Ozeren)
  - GoSam (G. Cullen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, G. Ossola, T. Reiter, F. Tramontano)
  - OpenLoops (F. Cascioli, P. Maierhöfer, S. Pozzorini)
  - NJet (S. Badger, B. Biedermann, P. Uwer, V. Yundin)
  - MadLoop/aMC@NLO (R. Frederix et al.)
  - CutTools (G. Ossola, C. Papadopoulos, R. Pittau)
- Real radiation, subtraction terms and phase space (infrastructure)
  - From event generator programs



Tools for NLO calculations

- MCFM, VBFNLO (J. Campbell, K. Ellis, C. Williams; D. Zeppenfeld et al.)
  - Extensive libraries of NLO QCD processes
- MG5_aMC@NLO (F. Maltoni, S. Frixione et al.)
  - Full event generation program
  - Automation of one-loop amplitudes
  - Matching to parton shower (MC@NLO method)
- SHERPA (F. Kraus et al.)
  - Full event generation program
  - interfaces to automated one-loop codes (OpenLoops, BlackHat, Njet, GoSam)
  - Matching to parton shower (MC@NLO, POWHEG methods)
  - Matching of NLO multiplicities (MENLOPS)

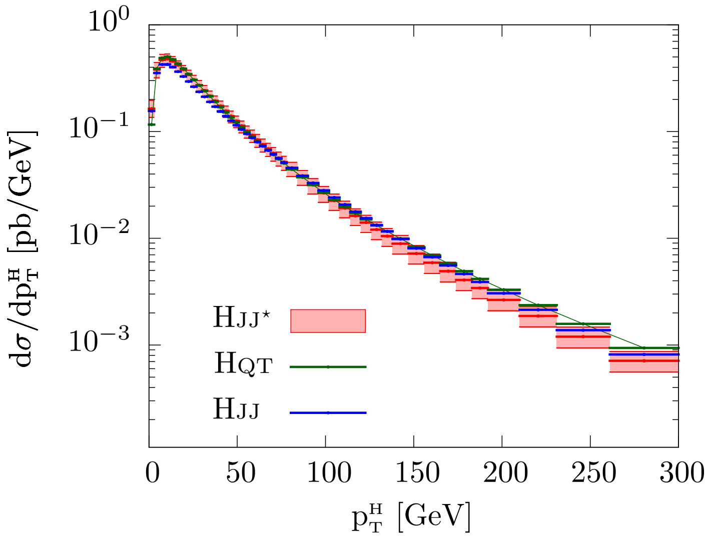
Automation in NLO computations

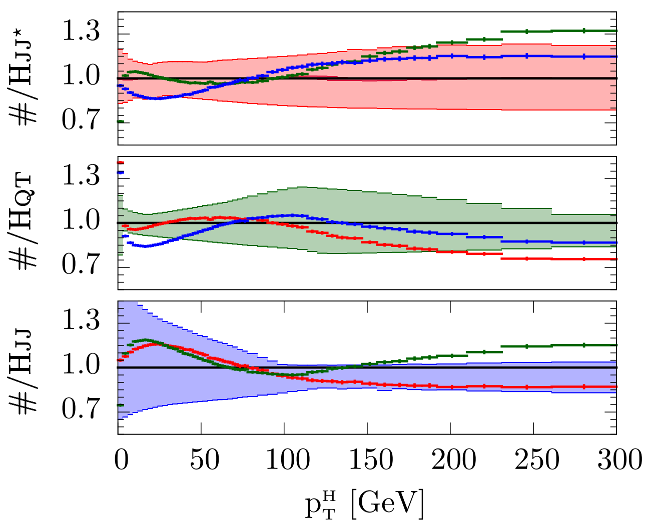
- Impressive list of results during past years, e.g.:
  - multiple jets (up to 4) (Blackhat + Sherpa; Njet)
  - gauge boson and up to 5 jets (Blackhat + Sherpa)
  - two gauge bosons with up to 2 jets (T. Melia et al.;VBFNLO: F. Campanario, M. Kerner, L.D. Ninh, D. Zeppenfeld; GoSam + MadEvent)
  - three gauge bosons (VBFNLO: G. Bozzi, F. Campanario, C. Englert, M. Rauch, D. Zeppenfeld)
  - top quarks with jets (up to 2) (A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini; G. Bevilacqua, M. Czakon, C. Papadopoulos, M. Worek)
  - top quarks with a gauge boson (A. Lazopoulos, K. Melnikov, F. Petriello; K. Melnikov, M. Schulze, A. Scharf; HelacNLO: A. Kardos, Z. Trocsanyi, C. Papadopoulos; MCFM: J. Campbell, K. Ellis)
  - Higgs with a top quark pair and one jet (GoSam + Sherpa + MadEvent: H. van Deurzen, G. Luisoni, P. Mastrolia, E. Mirabella, G. Ossola, T. Peraro)
  - Higgs and up to 3 jets (GoSam + Sherpa + Madevent: G. Cullen, H. van Deurzen, N. Greiner, G. Luisoni, P. Mastrolia, E. Mirabella, G. Ossola, T. Peraro, F. Tramontano)

- Broad implications for precision phenomenology

Merging of fixed order and parton shower

- Combining NLO computations for different multiplicities and interfacing with parton showers
  - SHERPA (S. Höche, F. Krauss, M. Schönherr, F. Siegert)
  - MINLO (K. Hamilton, P. Nason, C. Oleari, G. Zanderighi)
  - UNLOPS (L. Lönnblad, S. Prestel)
- Applications: V+jets, H+jets, tt+jets

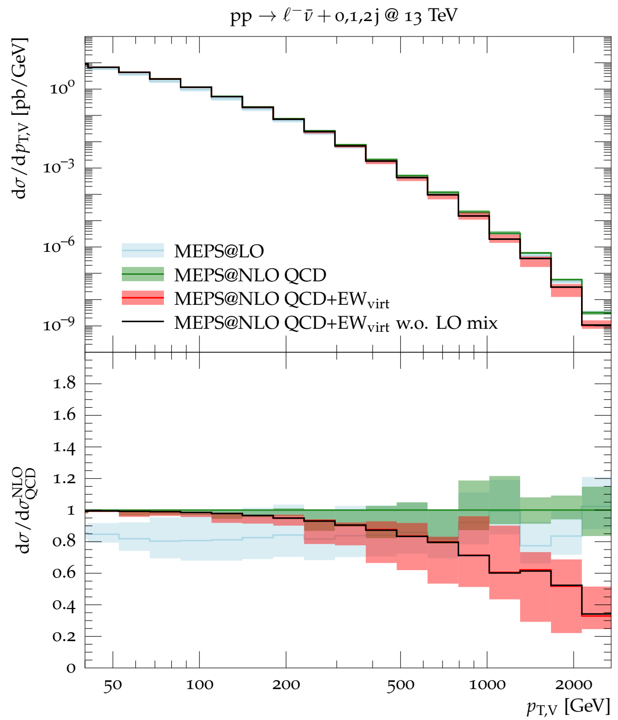




MiNLO:
R. Frederix,
K. Hamilton

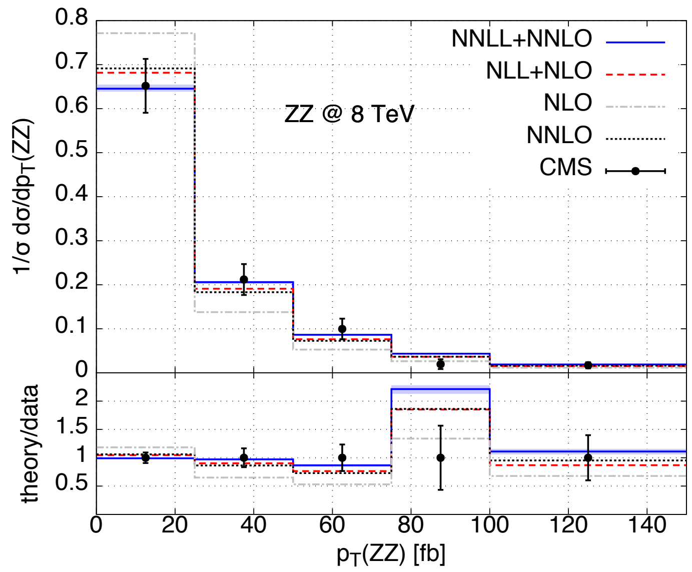
NLO QCD+EW

- Extension of automated NLO codes to include electroweak corrections
  - OpenLoops (S. Kallweit, J. Lindert, P. Maierhöfer, S. Pozzorini, M. Schönherr)
  - MG5_aMC@NLO (S. Frixione, V. Hirschi, D. Pagani, H. Shao, M. Zaro)
  - Issue of ordering of corrections: QCDxEW or QCD+EW
- Applications
  - Top pair production (MG5_aMC@NLO)
  - Vector boson plus multijet (OpenLoops+Sherpa)



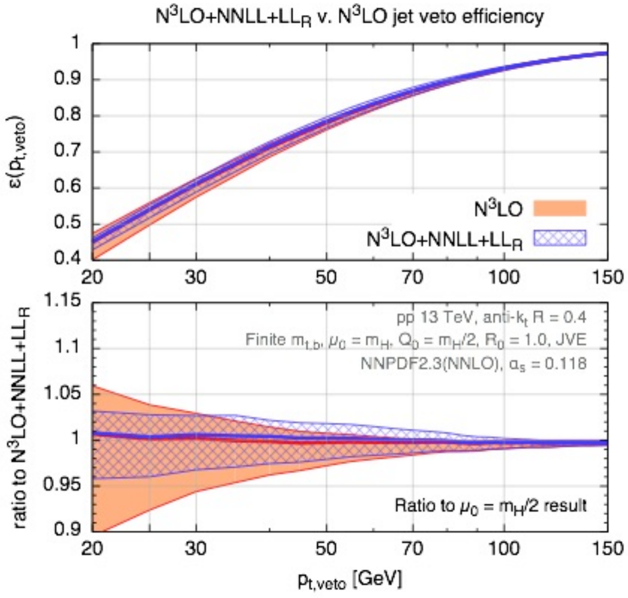
Resummation

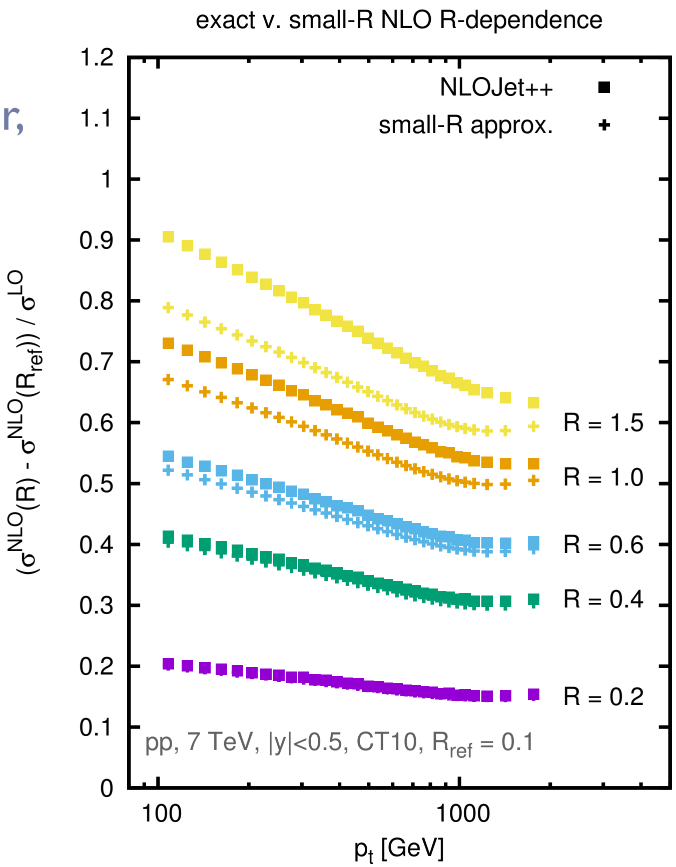
- Parton shower: leading logarithmic accuracy (LL)
- Resummation of higher-order logarithms
  - threshold, transverse momentum, jet size
- Recent results
  - Generic N3LL threshold resummation (S. Catani, L. Cieri, D. de Florian, G. Ferrera, M. Grazzini; T. Ahmed, N. Rana, V. Ravindran)
  - Generic NNLL transverse momentum resummation (S. Catani et al.; M. Grazzini, S. Kallweit, D. Rathlev, M. Wiesemann)
  - Development of N3LL transverse momentum resummation (H.X. Zhu, Y. Li)



Resummation

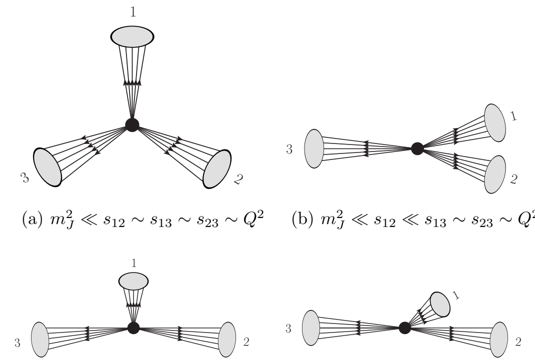
- Resummation for small jet radius (LL_R)
  (M. Dasgupta, F. Dreyer, G. Salam, G. Soyez)
- Application to jet veto in Higgs production (A. Banfi, F. Caola, F. Dreyer, F. Dulat, P. Monni, G. Salam, G. Zanderighi)





Resummation

- Soft-collinear effective theory (SCET) for resummation
  - Effective field theory for jet process
    (T. Becher, M. Neubert, L. Rothen, D. Shao)
  - XCONE: N-jettiness as jet algorithm
    (I. Stewart, F. Tackmann, C. Vermilion, T. Wilkason)
  - Multi-scale hierarchies between jets
    (P. Pietrulewicz, F. Tackmann, W. Waalewijn)
  - Endpoint NNLL resummation for event shapes
    (T. Becher, G. Bell; X. Garcia i Tormo, J. Piclum)



(a) $m_J^2 \ll s_{12} \sim s_{13} \sim s_{23} \sim Q^2$ (b) $m_J^2 \ll s_{12} \ll s_{13} \sim s_{23} \sim Q^2$

(c) $m_J^2 \ll s_{12} \sim s_{13} \ll s_{23} \sim Q^2$ (d) $m_J^2 \ll s_{12} \ll s_{13} \ll s_{23} \sim Q^2$

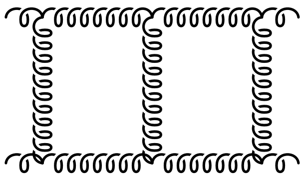
- Systematic perturbative expansion of ingredients
  - Soft functions (Y. Li, H.X. Zhu; R. Boughezal, X. Liu, F. Petriello)
  - Beam functions (J. Gaunt, M. Stahlhofen, F. Tackmann; T. Lübbert, L.L. Yang, TG)

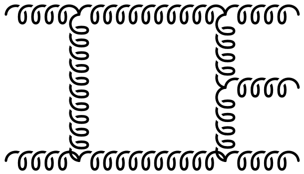
NNLO observables at hadron colliders

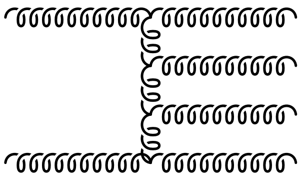
- NNLO predictions
  - expected to have a per-cent level accuracy
  - yielding first reliable estimate of theoretical uncertainty
- For processes measured to few per cent accuracy
  - jet production
  - vector boson (+jet) production
  - vector boson pair prodcution
  - top quark pair production
- For processes with potentially large perturbative corrections
  - New channels and/or phase space regions open up
    - Higgs or vector boson pair production

NNLO calculations

- Require three principal ingredients
  - two-loop matrix elements
    - explicit infrared poles from loop integral
      - known for all massless 2 → 2 processes
  - one-loop matrix elements
    - explicit infrared poles from loop integral
    - and implicit poles from single real emission
      - usually known from NLO calculations
  - tree-level matrix elements
    - implicit poles from double real emission
      - known from LO calculations







- Infrared poles cancel in the sum
- Challenge: combine contributions into parton-level generator
  - Need a method to extract implicit infrared poles

Real radiation at NNLO: methods

- Sector decomposition (T. Binoth, G. Heinrich; C. Anastasiou, K. Melnikov, F. Petriello)
  - pp → H, pp → V, including decays (C. Anastasiou, K. Melnikov, F. Petriello; S. Bühler, F. Herzog, A. Lazopoulos, R. Müller)
- Sector-improved residues (M. Czakon; R. Boughezal, K. Melinkov, F. Petriello)
  - pp → tt (M. Czakon, P. Fiedler, A. Mitov)
  - pp → H+j (R. Boughezal, F. Caola, K. Melnikov, F. Petriello, M. Schulze)
  - pp → t+j (M. Brucherseifer, F. Caola, K. Melnikov)
- Antenna subtraction (A. Gehrmann-De Ridder, E.W.N. Glover, TG)
  - e^+e^- → 3j (A. Gehrmann-De Ridder, E.W.N. Glover, G. Heinrich, TG; S. Weinzierl)
  - pp → H+j (X. Chen, E.W.N. Glover, M. Jaquier, TG)
  - pp → Z+j (A. Gehrmann-De Ridder, E.W.N. Glover, A. Huss, T. Morgan, TG)
- q_T subtraction (S. Catani, M. Grazzini)
  - pp → H, pp → V, pp → $\gamma\gamma$, pp → VH (S. Catani, L. Cieri, D. de Florian, G. Ferrera M. Grazzini, F. Tramontano)
  - pp → Vγ (M. Grazzini, S. Kallweit, D. Rathlev)
  - pp → ZZ, pp → WW (M. Grazzini et al.)

Real radiation at NNLO: methods

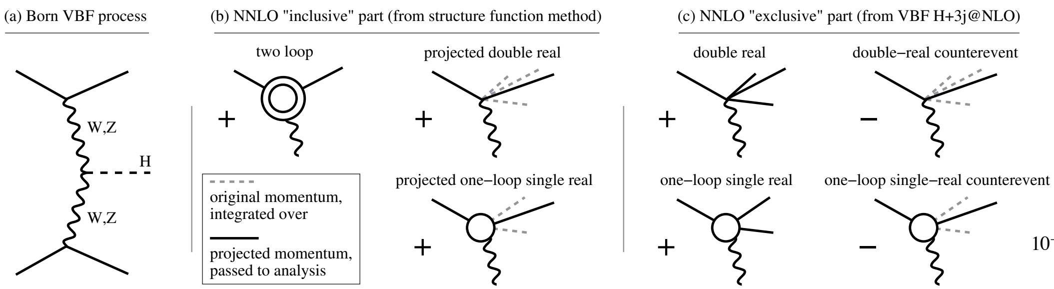
- N-Jettiness subtraction
  (R. Boughezal, X. Liu, F. Petriello; J. Gaunt, M. Stahlhofen, F. Tackmann, J.R. Walsh)
  - $pp \rightarrow H+j$ (R. Boughezal, C. Focke, W. Giele, X. Liu, F. Petriello)
  - $pp \rightarrow W+j$ (R. Boughezal, C. Focke, X. Liu, F. Petriello)
  - $pp \rightarrow Z+j$ (R. Boughezal, J. Campbell, K. Ellis, C. Focke, W. Giele, X. Liu, F. Petriello)
- N-Jettiness variable: distance from N-parton configuration
  (I. Stewart, F. Tackmann, W. Waalewijn)

$$\mathcal{T}_N(\Phi_M) = \sum_{k=1}^{M} \min_i \left\{ \frac{2 q_i \cdot p_k}{Q_i} \right\}$$

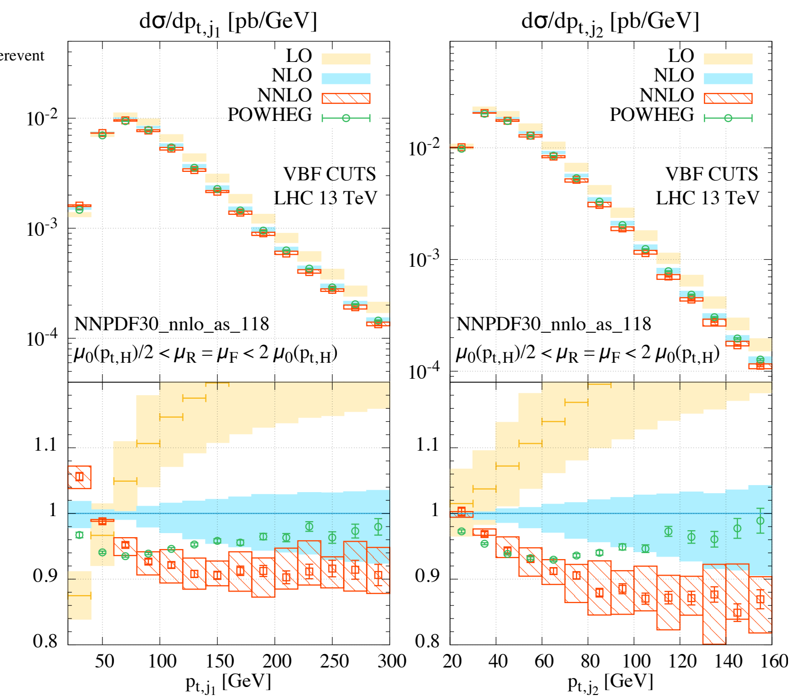
  - Universal behaviour at small T_N from SCET resummation
  - Implementation: N+1jet calculation at NLO with cut-off on T_N

Vector boson fusion at NNLO

- New method: projection to Born process
  (M. Cacciari, F. Dreyer, A. Karlberg, G. Salam, G. Zanderighi)

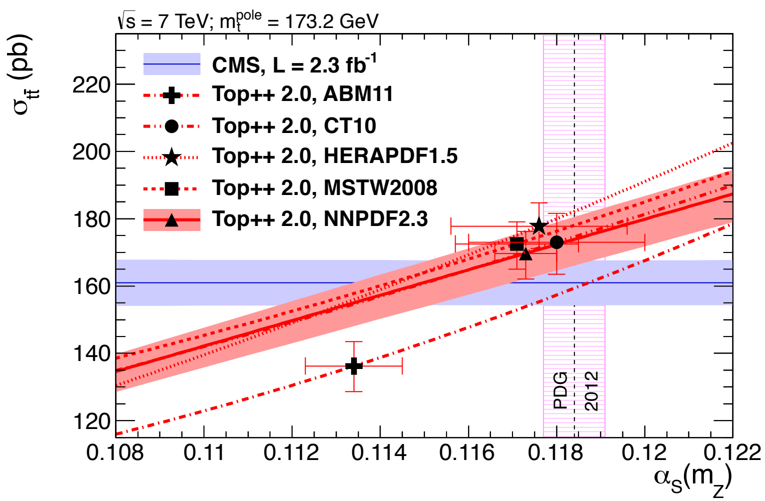


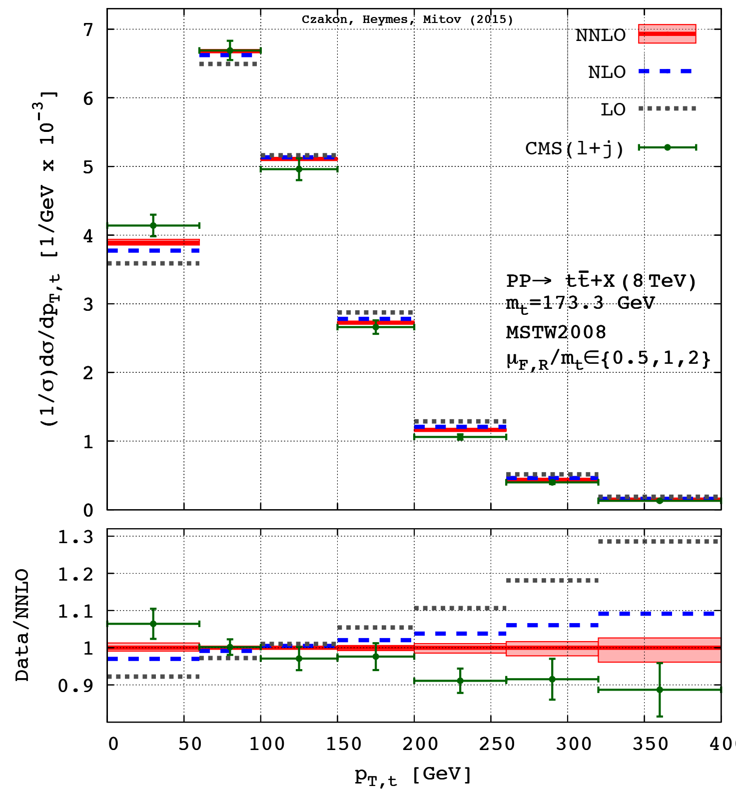
- Corrections small for total cross section
- Sizable effects in fiducial cross sections and distributions
- Not accounted for by NLO+PS



Top quark pair production at LHC

- Total cross section at NNLO (M. Czakon, P. Fiedler, A. Mitov)
  - Observe: theoretical and experimental uncertainties comparable (% level)
  - Input to precision phenomenology
  - Explain forward-backward asymmetry at Tevatron

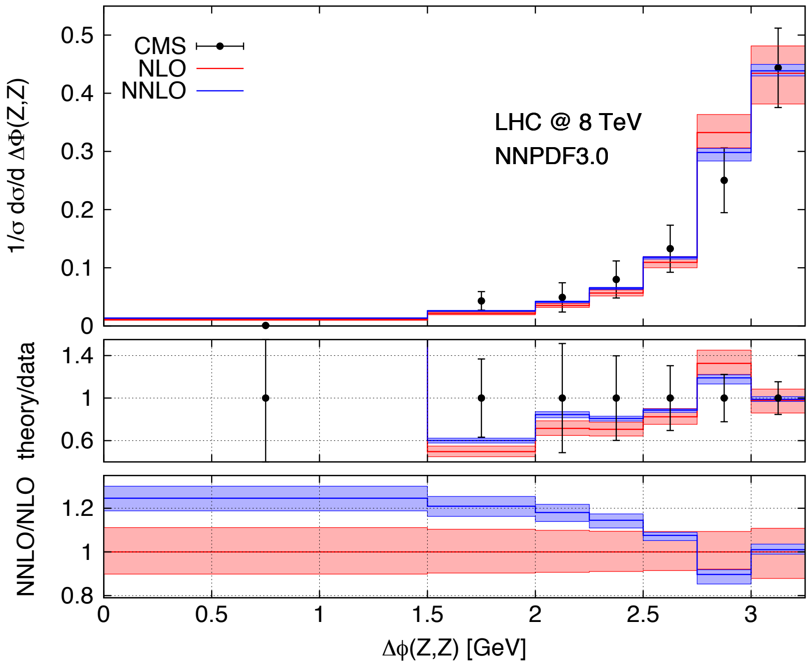




- Differential distributions (M. Czakon, D. Heymes, A. Mitov)

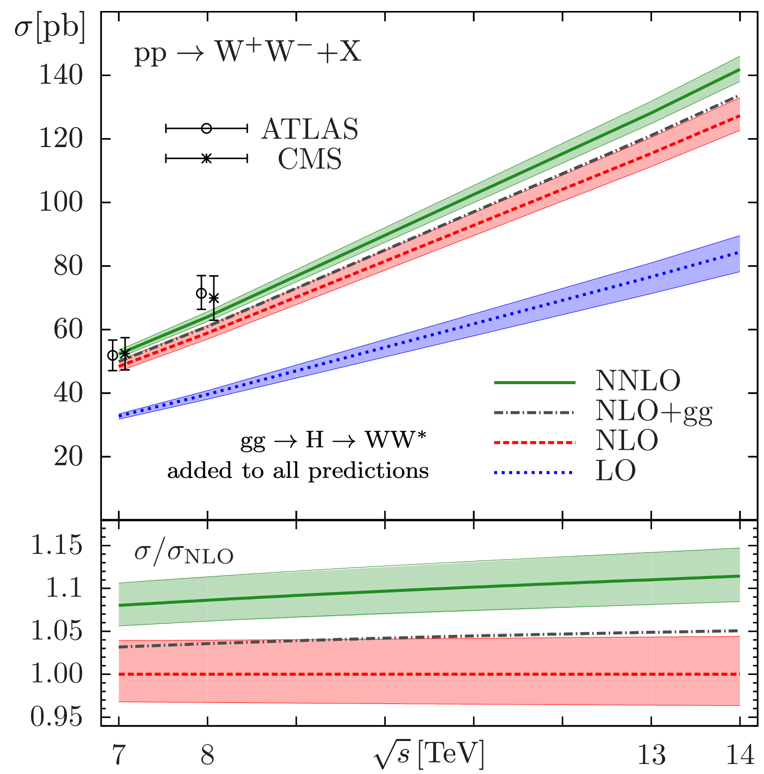
pp → VV at NNLO

- Vector boson pair production
  - Test standard model coupling structure (anomalous couplings)
  - Final state configurations similar to beyond-SM signatures
- Fully exclusive results
  - Fiducial cross sections
  - Differential distributions
  - pp → Z Z, pp → V γ
    (M. Grazzini, S. Kallweit, D. Rathlev)



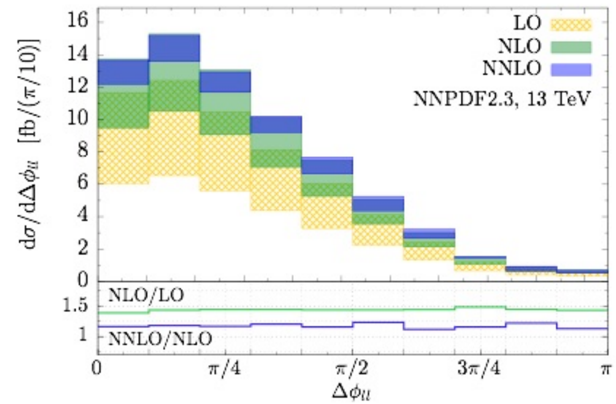
$pp \to W^+W^-$ at NNLO

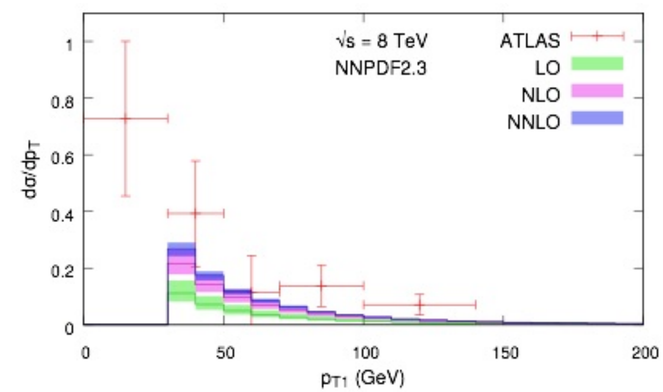
- Total cross section for W pair production
  - $pp \to WW$ (M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, TG)
- Total cross section in 4FNS
  - Improved description of data
  - Data based on interpolation from fiducial region
  - Calls for fully differential description, including vector boson decays and off-shell effects



Higgs+jet production at NNLO

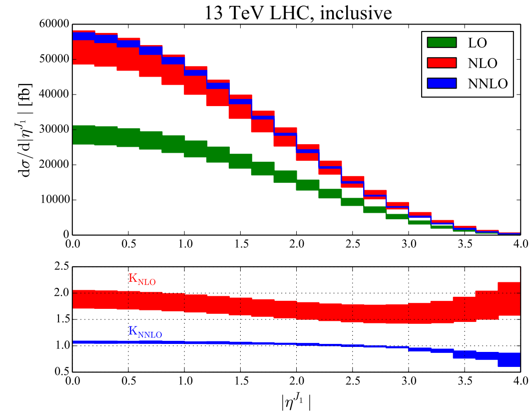
- Essential to establish the properties of the newly discovered Higgs boson
- Three independent NNLO calculations
  - Sector-improved subtraction
    (F. Caola, K. Melnikov, M. Schulze)
  - N-Jettiness subtraction
    (R. Boughezal, C. Focke, W. Giele, X. Liu, F. Petriello)
  - Antenna subtraction
    (X. Chen, E.W.N. Glover, M. Jaquier, TG)
- Including Higgs decays
  - Fiducial cross sections
  - Preparing precision Higgs studies

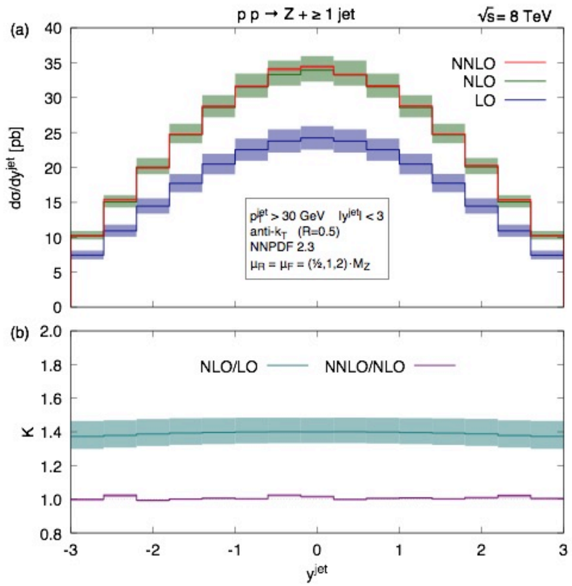




V+jet production at NNLO

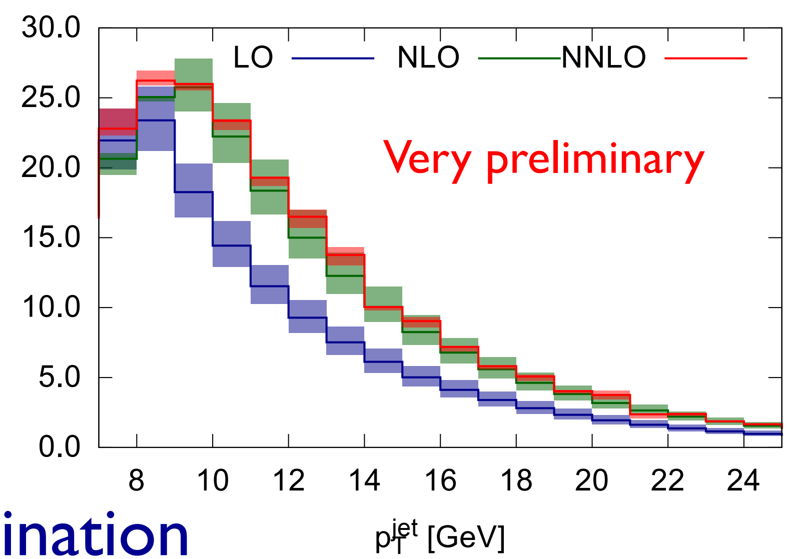
- Benchmark process
  - Parton distributions
  - Strong coupling
  - Energy calibration
- NNLO calculations
  - Including leptonic decay
  - pp → W+j (R. Boughezal, C. Focke, X. Liu, F. Petriello)
  - pp → Z+j (A. Gehrmann-De Ridder, E.W.N. Glover, A. Huss, T. Morgan, TG)
  - pp → Z+j (R. Boughezal, J. Campbell, K. Ellis, C. Focke, W. Giele, X. Liu, F. Petriello)
- Precision phenomenology upcoming
  - NNLO error at 1% level





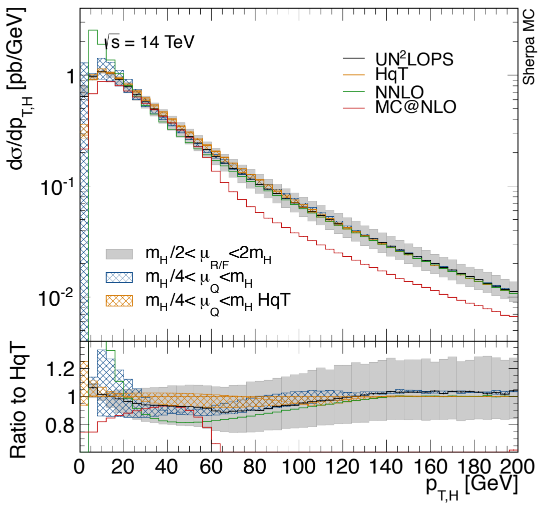
Di-jet production at NNLO

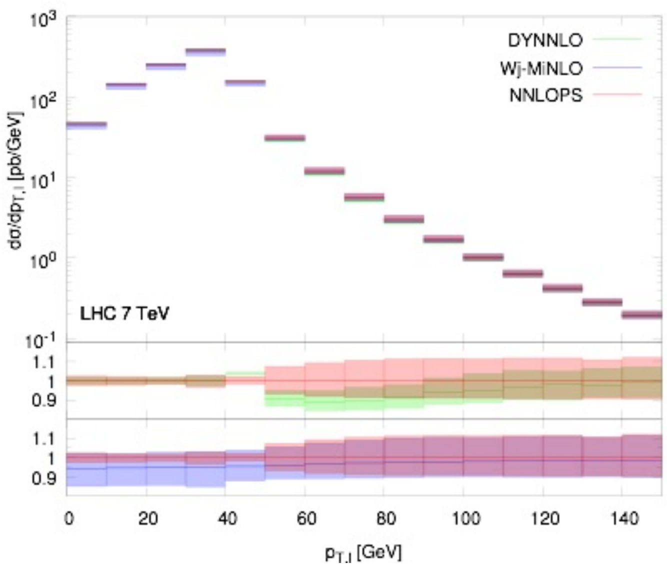
- Inclusive jet and di-jet production
  - Important constraints on gluon distribution
  - Determination of α_s
- Hadron collider
  - Precision data from Tevatron, CMS, ATLAS
  - NNLO calculation ongoing
    (J. Currie, E.W.N. Glover, J. Pires)
- Deep inelastic scattering
  - Precision data from H1, ZEUS
  - NNLO calculation completed
    (J. Currie, J. Niehues, TG)
    - Leading jet distribution in dijet events
- Prepare interfaces to PDF determination



NNLO + parton shower

- Approaches: build upon NLO multiplicity merging
  - UN2LOPS (S Höche, Y. Li, S. Prestel)
  - NNLOPS (K. Hamilton, P. Nason, E. Re, G. Zanderighi)
- Frist applications
  - Higgs production (UN2LOPS, NNLOPS)
  - Drell-Yan process (UN2LOPS, A. Karlberg, E. Re, G. Zanderighi)
  - WH production (W. Astill, W. Bizon, E. Re, G. Zanderighi)





Towards NNLO automation

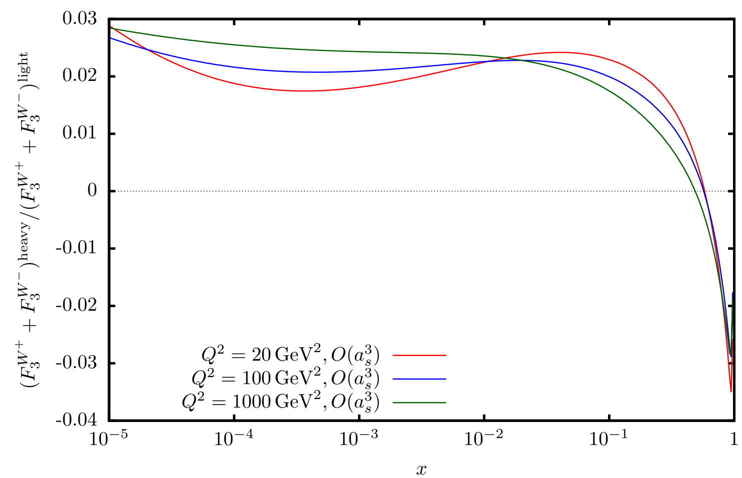
- Methods for real radiation at NNLO becoming mature
  - q_T subtraction
  - N-Jettiness subtraction
  - Sector-improved schemes
  - Antenna subtraction
- Issues
  - Automation of code generation
  - Numerical efficiency and stability
  - Availability of two-loop amplitudes

Multi-loop amplitudes

- Key ingredient to higher order QCD corrections
- Two challenges
  - Expression of amplitude in terms of master integrals
  - Calculation of master integrals
- Integral reduction techniques
  - Integration-by-parts (K. Chetyrkin, F. Tkachev; S. Laporta)
  - Unitarity-based methods
  - Integrand reduction
- Calculation of integrals
  - Direct evaluation (numerical: sector decomposition)
  - Differential equations (A. Kotikov; E. Remiddi, TG; J. Henn)

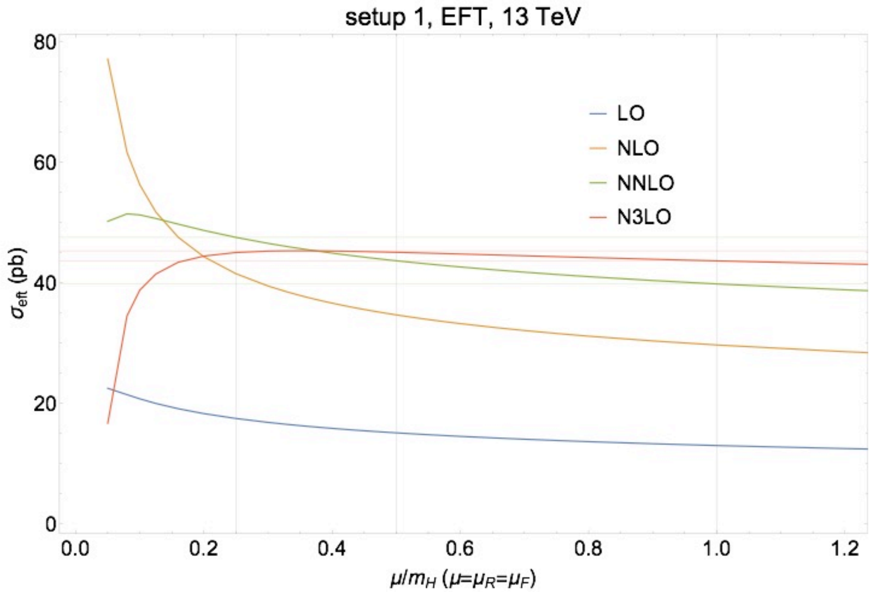
Multi-loop amplitudes

- Limit in complexity at two loops: $2 \to 2$
  - Up to two external masses, one internal mass
    - pp $\to V_1 V_2$, pp $\to$ tt available
    - $2 \to 3$ ongoing: gg $\to$ ggg (S. Badger, G. Mogull, A. Ochirov, D. O'Connell; J. Henn. A. Lo Presti, TG; C. Papadopoulos, D. Tomassini, C. Wever)
- Limit in complexity at three loops: $2 \to 1$ (or equivalent)
  - DIS three loop splitting and coefficient functions (S. Moch, A. Vogt, J. Vermaseren)
  - Heavy quark DIS coefficient functions at NNLO (J. Ablinger, A. Behring, J. Blümlein, A. Hasselhuhn, A. von Manteuffel, C.G. Raab, M. Round, C. Schneider, F. Wissbrock)



Higgs production in gluon fusion at N3LO

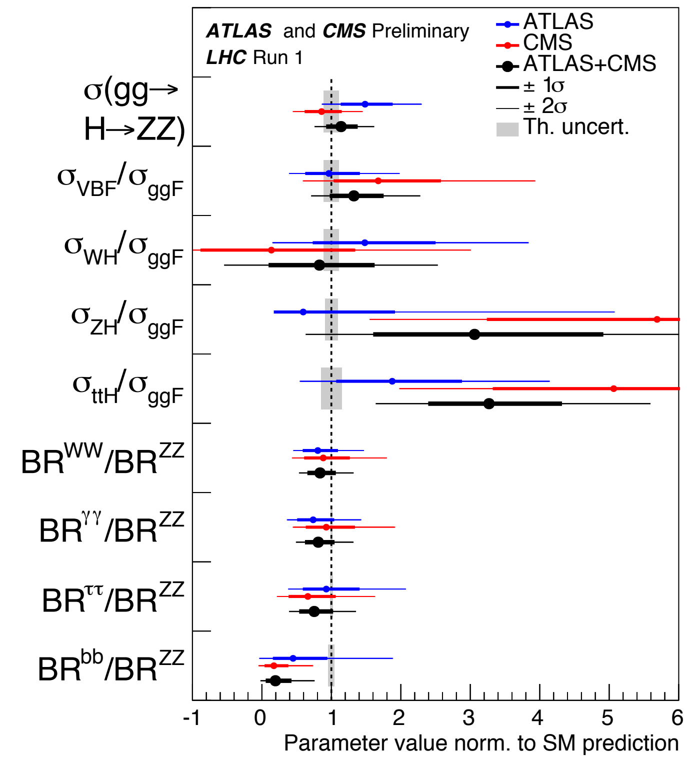
- **N3LO contributions to Higgs production** (P. Baikov, K. Chetyrkin, V. Smirnov, A. Smirnov, M. Steinhauser; N. Glover, T. Huber, N. Ikizlerli, C. Studerus, M. Jaquier, A. Koukoutsakis, C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger, E. Furlan, Y. Li, A. von Manteuffel, R. Schabinger, H.X. Zhu, C. Anzai, A. Hasselhuhn, M. Hoschele, J. Hoff, W. Kilgore, M. Steinhauer, T. Ueda, TG)
  - Three-loop form factor
  - Two-loop single real
  - One-loop double real
  - Tree-level triple real
- **Coefficient function** (C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger)
  - From high-order expansion around threshold



Higgs production in gluon fusion

- Precise prediction mandatory for coupling extraction
- N3LO coefficient function plus
  - Quark mass corrections at NLO
  - Electroweak corrections
- Sources of uncertainty
  - PDF and strong coupling
  - Resummation effects
  - Truncation error
- Prediction for 13 TeV

(C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, F. Herzog, A. Lazopoulos, B. Mistlberger, TG)



$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\;(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\;(\text{PDF}+\alpha_s)$$

Where do we stand?

- Witnessed an NLO revolution
  - Previously unthinkable NLO QCD+EW multi-particle calculations now feasible due to technological breakthroughs
  - High-level of automation
  - Standarization of interfaces: combine different codes (providers)
  - Interface to experiment (codes, ntuples, histograms,..)?
- NLO and parton showers
  - Matching of individual processes (MC@NLO, POWHEG)
- Substantial progress on NNLO calculations
  - Several different methods available
  - Close interplay with resummation
  - Calculations on process-by-process basis
  - Codes typically require HPC infrastructure

Future Directions

- NLO+PS as new standard for event generation
  - Fully automated public codes
  - Consistent matching to parton shower
  - Matching of different multiplicities at NLO
  - Monte Carlo with NLO-accurate event samples
  - NNLO+PS emerging
- NNLO automation
  - Uncover analytical structures to organize calculation
  - Develop standard interfaces
  - Interface to experiment ?
- Beyond NNLO
  - N^3LO precision for benchmark processes