Theory for the Terascale

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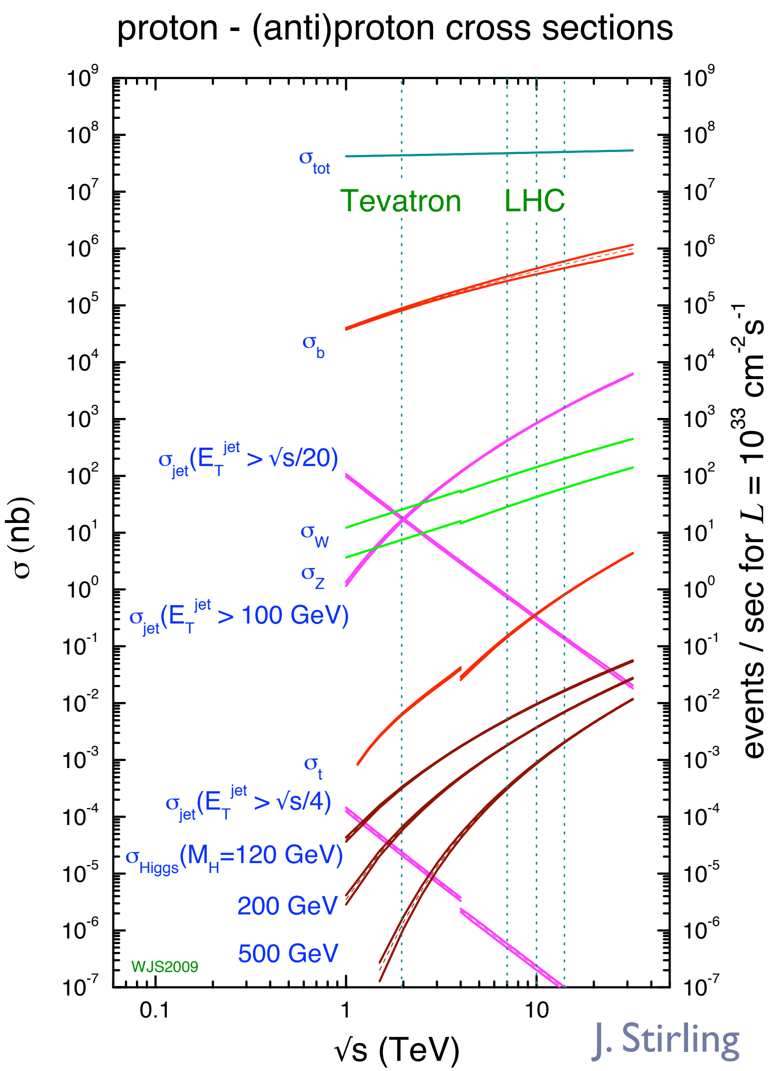
8th Annual Meeting of "Physics at the Terascale", DESY, 01.12.2014

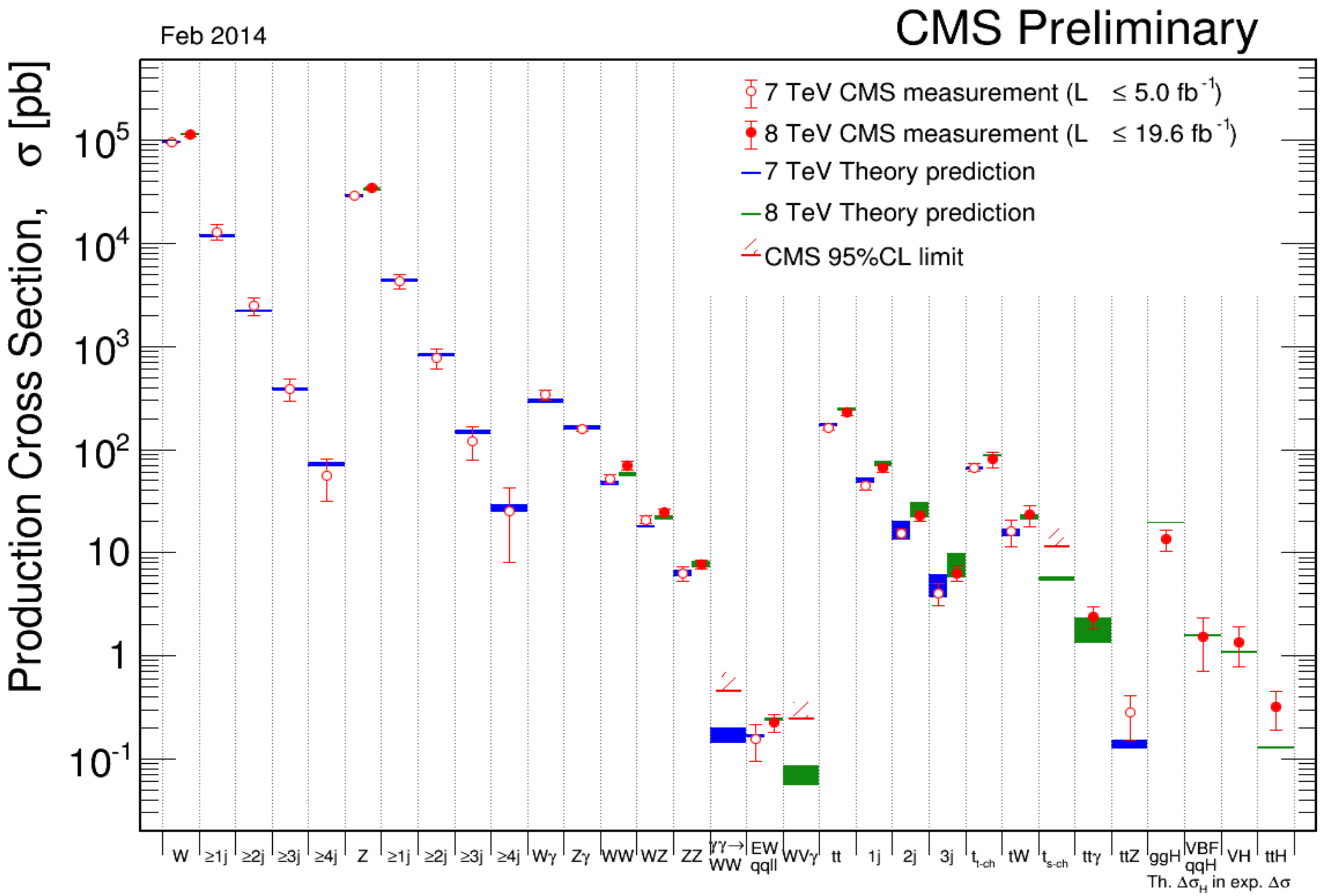
Benchmark processes at LHC

- Large production rates for Standard Model processes
  - jets
  - top quark pairs
  - vector bosons
- Allow precision measurements
  - masses
  - couplings
  - parton distributions
- Require precise theory



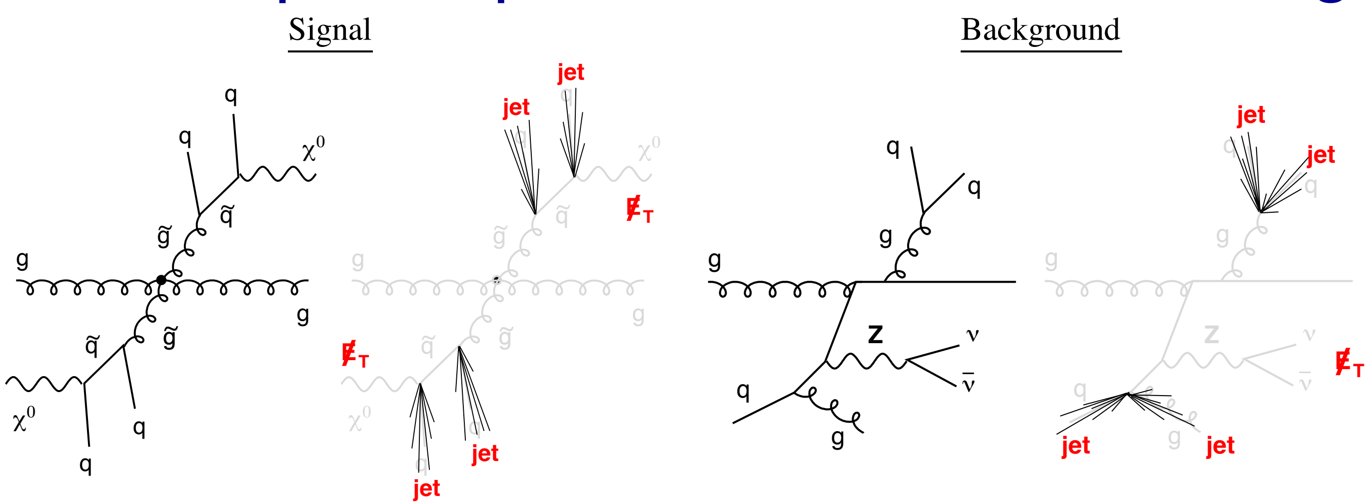
J. Stirling

Benchmark processes at LHC



Multi-particle production at LHC

- LHC brings new frontiers in energy and luminosity
- Production of short-lived heavy states (Higgs, top, SUSY…)
  - detected through their decay products
  - yield multi-particle final states involving jets, leptons, γ , $\not{E}_T$
- Search for new effects in multi-particle final states
- Need precise predictions for hard scattering processes



Example: SUSY signature 4j + $\not{E}_T$

The case for precision

- Implications of Higgs boson discovery at ATLAS and CMS
  - Higgs mechanism established
  - Higgs boson mass measured
  - Standard Model of particle physics complete
- Beyond the Standard Model
  - Planck mass sets fundamental limit: $M_P \simeq 10^{19}$ GeV
  - Internal consistency of Standard Model
    - Hierarchy problem
    - Extrapolation to high energies
- Stability of the Higgs potential

H^0 $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ $(S = 1.2)$

$W W^* = 0.87^{+0.24}_{-0.22}$

$Z Z^* = 1.11^{+0.34}_{-0.28}$ $(S = 1.3)$

$\gamma\gamma = 1.58^{+0.27}_{-0.23}$

$b\bar{b} = 1.1 \pm 0.5$

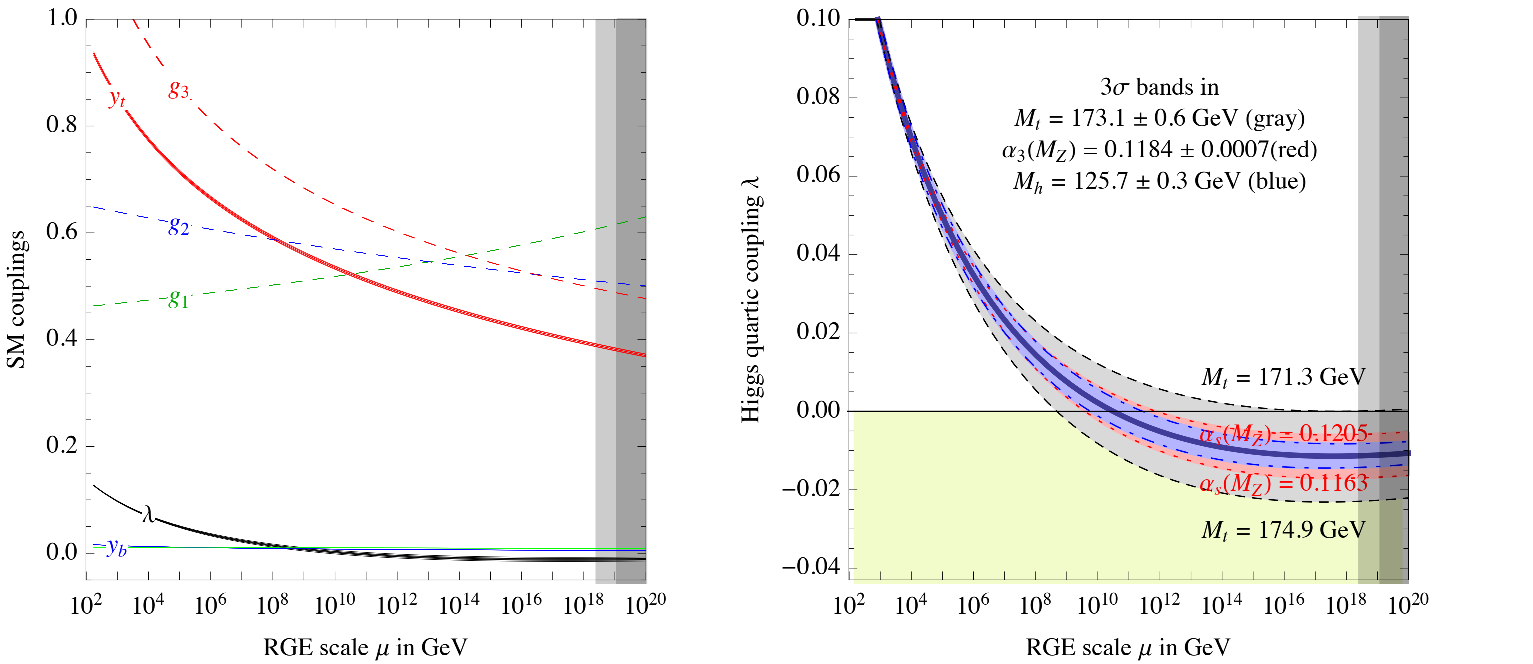
$\tau^+\tau^- = 0.4 \pm 0.6$

$Z\gamma <$ 9.5, CL = 95%

PDG 2014

Stability of the Higgs potential

- Renormalization group evolution of quartic coupling

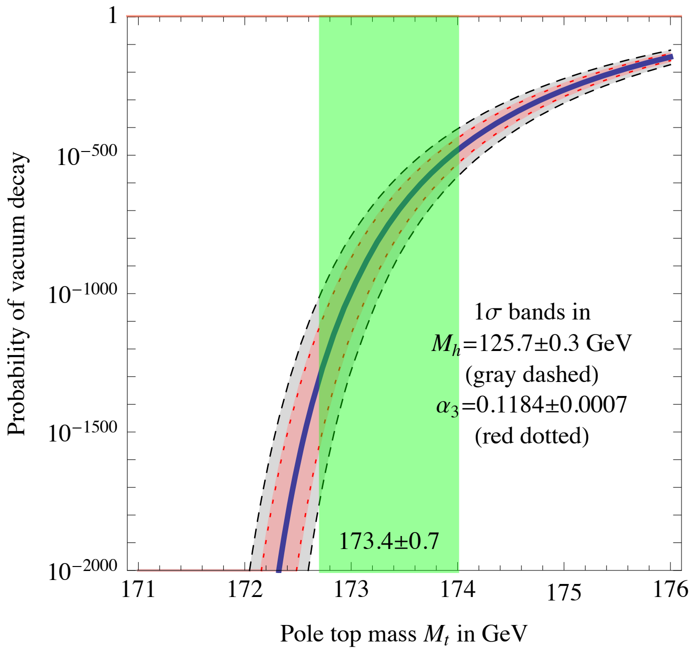


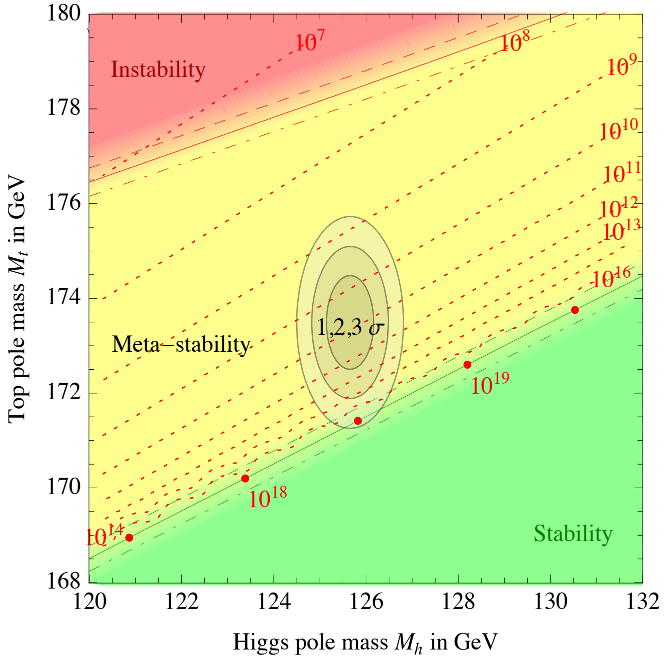
G. Degrassi et al., K. Chetyrkin, M. Zoller

- Propagation of errors on Standard Model parameters

Stability of the Higgs potential

- Determines vacuum stability
- Current data indicate metastable state
- Precision on parameters and for RGE evolution and matching crucial





F. Bezrukov, M. Kalmykov, B. Kniehl, M. Shaposhnikov;
J. Elias-Miro et al, G. Degrassi et al.;
F. Jegerlehner

QCD: precision physics at LHC

- NLO: methods and directions
- Parton showers, resummation, matching
- NNLO: precision QCD
- Precision frontier: aims and ideas

- NLO: methods, results, directions

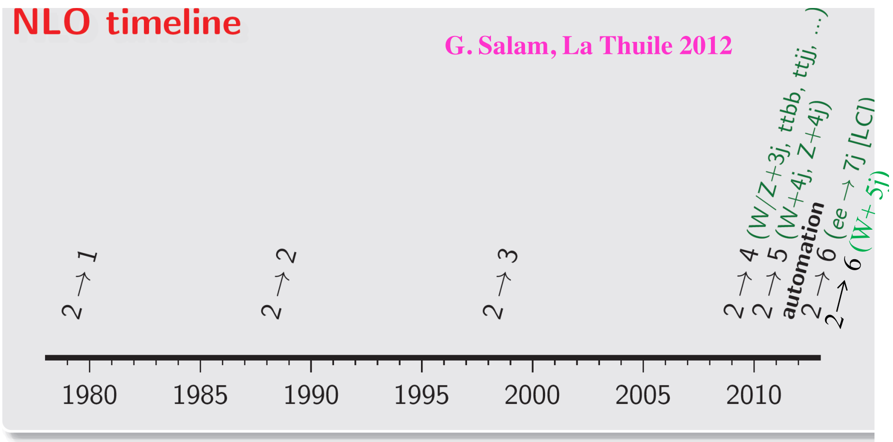
NLO multi-particle production

- 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



Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer [27, 28]; Campbell/Ellis/Zanderighi [29]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [30]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [31]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [32, 33] Interference QCD-EW in VBF channel [34, 35]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [36] and WWZ by Hankele/Zeppenfeld [37], see also Binoth/Ossola/Papadopoulos/Pittau [38] VBFNLO [39, 40] meanwhile also contains $WWW, ZZW, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma$ $WZj, W\gamma j, \gamma jj$ ...
4. $pp \to t\bar{t}\, b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini [41, 42] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [43]
5. $pp \to V$+3jets	W+3jets calculated by the Blackhat/Sherpa [44] and Rocket [45] collaborations Z+3jets by Blackhat/Sherpa [46]
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek [47, 48]
7. $pp \to VV\, b\bar{b}$, 8. $pp \to VV$+2jets	Pozzorini et al.[25],Bevilacqua et al.[23] W^+W^++2jets [49], W^+W^-+2jets [50], VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [51, 52, 53]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al. [54, 55]
NLO calculations added to list in 2009	
10. $pp \to V + 4$ jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets [22], Z+4jets [20] see also HEJ [56] for $W + n$jets
11. $pp \to Wb\bar{b}j$ 12. $pp \to t\bar{t}t\bar{t}$	top, new physics signatures, Reina/Schutzmeier [11] various new physics signatures
also: $pp \to 4$ jets	Blackhat/Sherpa [19]

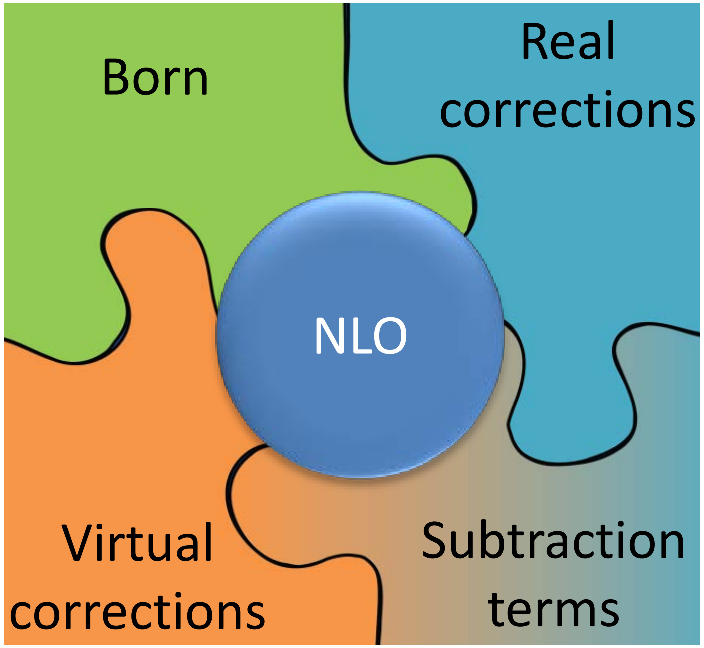
CLOSED

- Made possible by
  - Improved techniques for loop amplitudes
  - Crucial: a high level of automation

K. Melnikov, MITP, 2013

NLO automation

- Well-defined interfaces (Binoth Les Houches accord)
  - combine different ingredients from different codes
- 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)
  - Sherpa (F. Kraus et al.)
  - Madgraph/MadEvent (F. Maltoni et al.)
  - HelacNLO (G. Bevilacqua, C. Papadopoulos et al.)
  - MCFM (J. Campbell, K. Ellis, C. Williams)
  - VBFNLO (D. Zeppenfeld et al.)



Automation in NLO computations

- Impressive list of recent results:
  - 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)

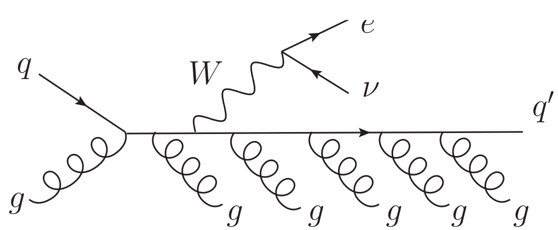
- Broad implications for precision phenomenology

W+5 jets at NLO

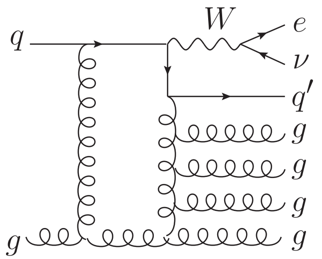
- First 2→6 NLO calculation at a hadron collider
- Using Blackhat + Sherpa

(Z. Bern, L. Dixon, F. Febres Cordero, S. Höche, H. Ita, D. Kosower, D. Maitre, K. Ozeren)

  - Blackhat: virtual one-loop corrections using on-shell methods
  - Sherpa: real emission, subtraction, phase space integration



Example diagram for real emission (2→8) at tree level



Example diagram for virtual emission (2→7) at one-loop (octogon)

- Computation at the actual frontier of NLO complexity
  - Considered impossible until few years ago

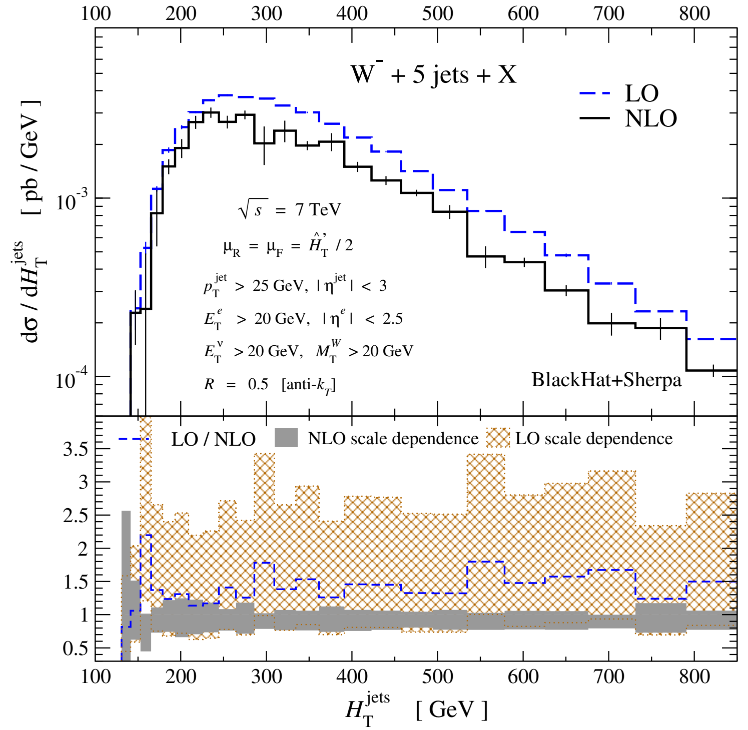
W+5 jets at NLO

- Distribution in H_T^{jets} (sum of jet transverse energies)
  - Dynamical scale choice

$$\mu_R = \mu_F = \hat{H}'_T/2$$

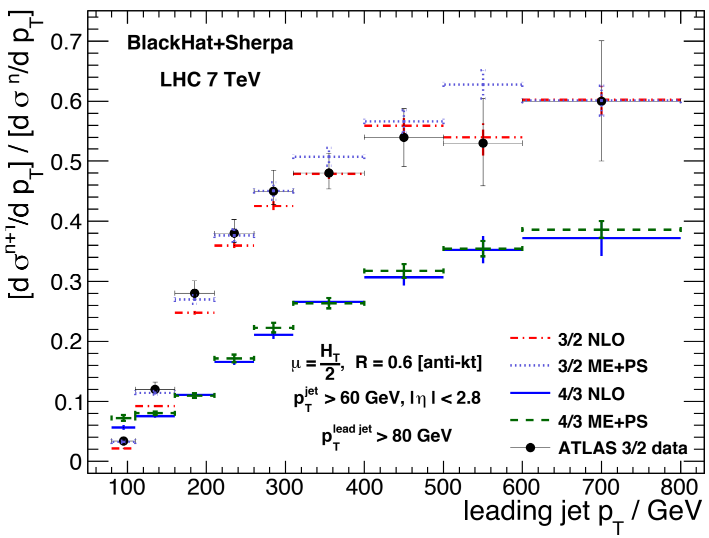
$$\hat{H}'_{\mathrm{T}} \equiv \sum_m p_{\mathrm{T}}^m + E_{\mathrm{T}}^W$$

  - scale variation $\mu/2 \ldots 2\mu$
  - Observe:
    - Scale dependence reduced at NLO
    - ratio NLO/LO constant over full kinematical range
- NLO helps to motivate the scale choice



Jet ratios at NLO

- Systematic uncertainties (th. and exp.) cancel in ratios
  - Predictions more reliable
  - Can be used in data-driven background estimation
- Jet ratio as function of leading jet p_T
  - NLO and parton shower both agree with data for large p_T
  - Parton shower (multiple emission) better at low p_T
    - Large uncertainty on parton shower not shown



Observe: 3/2 ratio below the data at small p_T

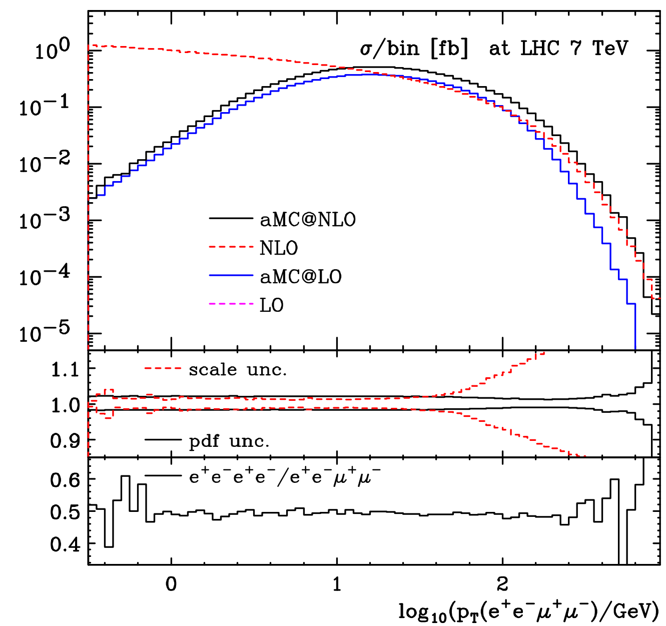
- Parton showers, resummation, matching

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
- 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

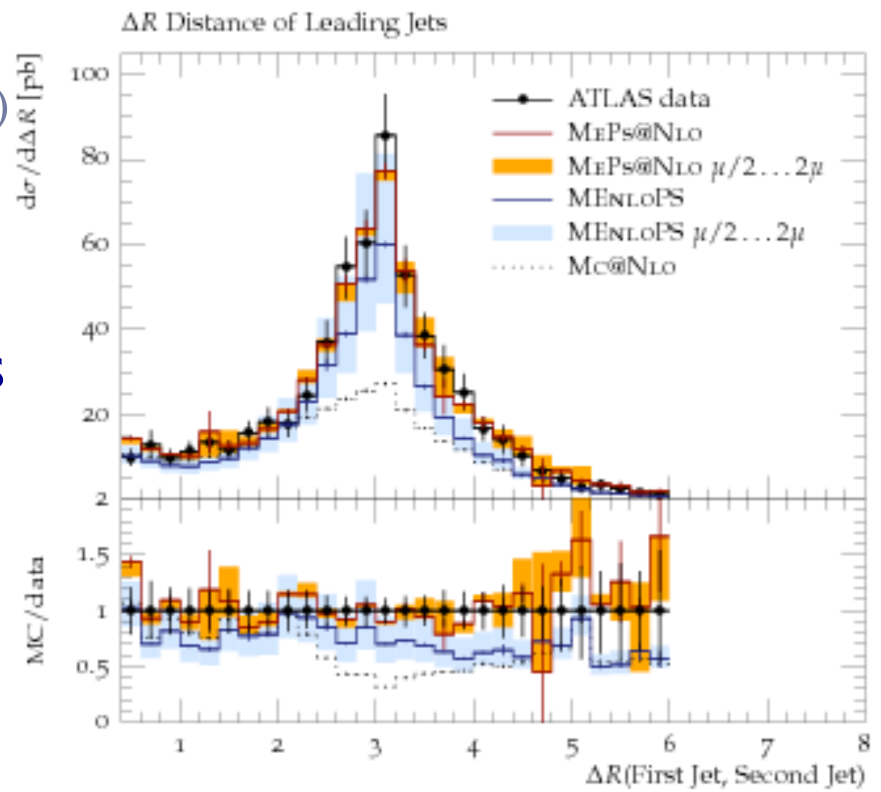
Merging of fixed order and parton shower

- Merging multiplicities
  - Combine fixed-order matrix elements at different multiplicity with vetoed shower
  - Leading order prescriptions: CKKW (S. Catani, F. Krauss, R. Kuhn, B. Webber) and MLM (M. Mangano)
  - Has become standard for parton shower simulations
- Merging NLO with parton shower
  - Combine fixed-multiplicity NLO calculation with parton shower
  - Accomplished for many processes (MC@NLO: S. Frixione, B. Webber; POWHEG: P. Nason, C. Oleari et al.)
  - Automation: aMC@NLO (R. Frederix, S. Frixione, V. Hirschi, F. Maltioni, R. Pittau, P. Torrielli)



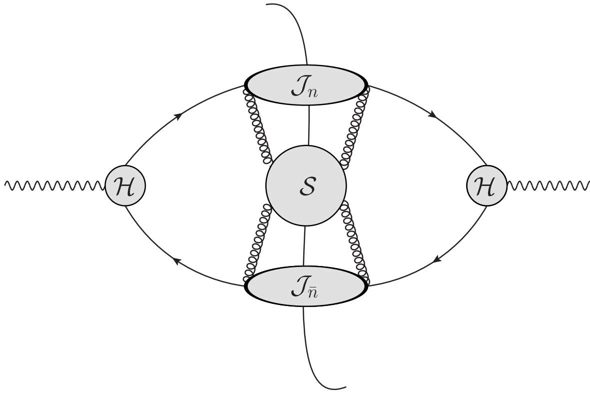
Merging of fixed order and parton shower

- Combining NLO computations for different multiplicities and interfacing with parton showers (proof-of-principle)
  - SHERPA (S. Höche, F. Krauss, M. Schönherr, F. Siegert)
  - MINLO (K. Hamilton, P. Nason, C. Oleari, G. Zanderighi)
  - UNLOPS (L. Lönnblad, S. Prestel)
  - FxFx (S. Frixione, R. Frederix)
- Yields combined event samples
- Improves especially jet-jet correlations
- Work in progress



Resummation

- Parton shower: leading logarithmic accuracy (LL)
- Resummation of higher-order logarithms
  - NLL: largely automated (CAESAR: A. Banfi, G. Salam, G. Zanderighi)
  - NNLL and beyond: process-by-process calculations
- Methods
  - Laplace-space resummation (CSS: J. Collins, D. Soper, G. Sterman)
  - Soft-collinear effective theory (SCET: C. Bauer, S. Fleming, D. Pirjol, I. Rothstein, I. Stewart; M. Beneke, A. Chapovsky, M. Diehl, T. Feldmann)
  - Systematic extension beyond NLL



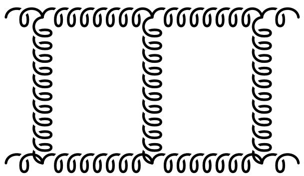
- NNLO: towards precision QCD

NNLO observables at hadron colliders

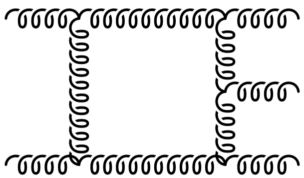
- NNLO predictions
  - expected to have a per-cent level accuracy
  - yielding first reliable estimate of theoretical uncertainty
- For processes measured to few per cent accuracy
    - jet production
    - vector boson (+jet) production
    - top quark pair production
- For processes with potentially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

NNLO calculations

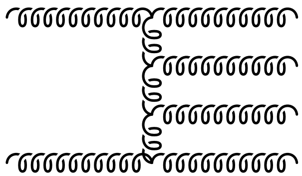
- Require three principal ingredients (here: pp $\rightarrow$ 2j)
  - two-loop matrix elements
    - explicit infrared poles from loop integral
      - known for all massless 2 $\rightarrow$ 2 processes



  - 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

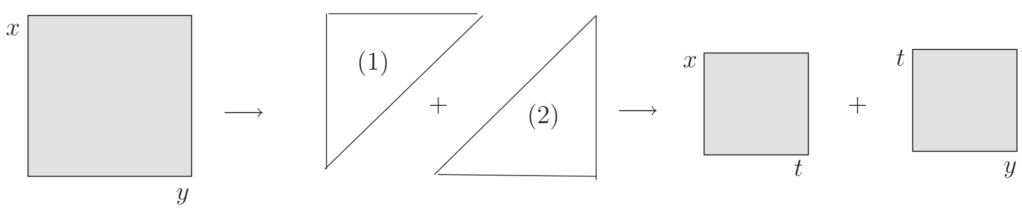


- Infrared poles cancel in the sum
- Challenge: combine contributions into parton-level generator
  - Need a method to extract implicit infrared poles

Real radiation at NNLO: methods

- Sector decomposition
  (T. Binoth, G. Heinrich; C. Anastasiou, K. Melnikov, F. Petriello)
  - pp $\rightarrow$ H, pp $\rightarrow$ V, including decays
    (C. Anastasiou, K. Melnikov, F. Petriello; S. Bühler, F. Herzog, A. Lazopoulos, R. Müller)
- Split final state phase space into different singular sectors

$$I = \int_0^1 dx \int_0^1 dy\, x^{-1-a\epsilon}\, y^{-b\epsilon} \Big(x + (1-x)\, y\Big)^{-1}$$



- Expand phase space integral in distributions

$$I_j = -\frac{1}{b_j\epsilon}\mathcal{I}_j(0,\{t_{i\neq j}\},\epsilon) + \int\limits_0^1 dt_j\, t_j^{-1-b_j\epsilon}\Big(\mathcal{I}(t_j,\{t_{i\neq j}\},\epsilon) - \mathcal{I}_j(0,\{t_{i\neq j}\},\epsilon)\Big)$$

Real radiation at NNLO: methods

- Sector-improved subtraction schemes
  (M. Czakon; R. Boughezal, K. Melinkov, F. Petriello)
  - $pp \to t\bar{t}$ (M. Czakon, P. Fiedler, A. Mitov)
  - $pp \to H+j$ (R. Boughezal, F. Caola, K. Melnikov, F. Petriello, M. Schulze)
  - $pp \to t+j$ (M. Brucherseifer, F. Caola, K. Melnikov)
- Construct subtraction term in each unresolved sector
  - Using universal factorization properties of QCD matrix elements
  - Fully local subtraction terms
- Expand subtraction terms in distributions
  - Numerically integrate subtraction terms

Real radiation at NNLO: methods

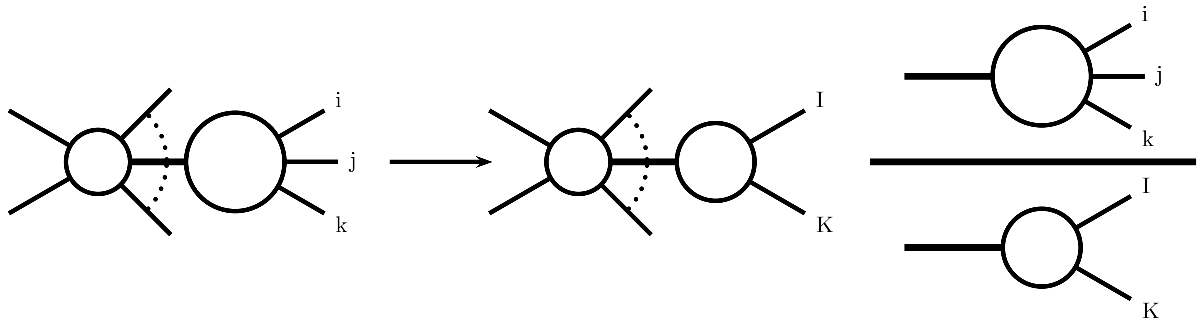
- q_T-subtraction (S. Catani, M. Grazzini)
  - $pp \to H$, $pp \to V$, $pp \to \gamma\gamma$, $pp \to VH$
    (S. Catani, L. Cieri, D. de Florian, G. Ferrera M. Grazzini, F. Tramontano)
  - $pp \to Z\gamma$ (M. Grazzini, S. Kallweit, D. Rathlev, A. Torre)
  - $pp \to ZZ$, $pp \to WW$ (F. Cascioli, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, E. Weihs, TG)
- Production of colourless final states at hadron colliders
  - Universal behaviour in the limit of small transverse momentum, known from resummation
  - Use small-q_T limit to construct subtraction term (non-local)

$$d\sigma^{F}_{NNLO} = \mathcal{H}^{F}_{NNLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+\mathrm{jet}}_{NLO} - d\sigma^{CT}_{NLO} \right]$$

  - Implementation based on NLO calculation for F+jet

Real radiation at NNLO: methods

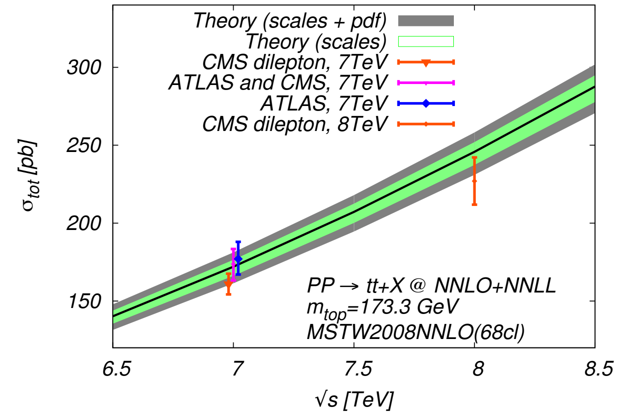
- Antenna subtraction (A. Gehrmann-De Ridder, E.W.N. Glover, TG)
  - $e^+e^- \to 3j$ (A. Gehrmann-De Ridder, E.W.N. Glover, G. Heinrich, TG; S. Weinzierl)
  - $pp \to 2j$ (J. Currie, A. Gehrmann-De Ridder, E.W.N. Glover, J. Pires, TG)
  - $pp \to H+j$ (X. Chen, E.W.N. Glover, M. Jaquier, TG)
  - $pp \to t\bar{t}$ (G. Abelof, A. Gehrmann-De Ridder, P. Maierhöfer, S. Pozzorini)
- Construct subtraction terms from antenna functions
  - Encapsulate all unresolved limits between a pair of hard partons

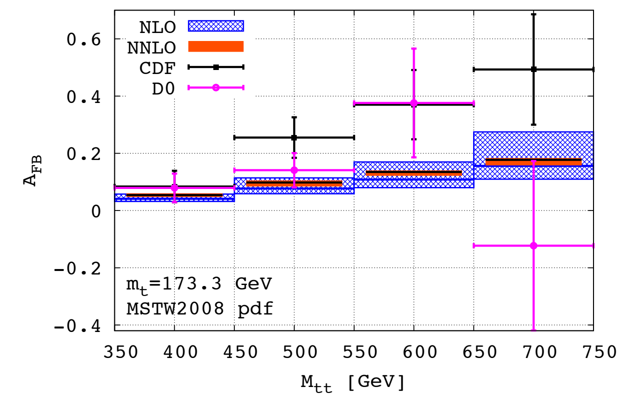


  - Ensure analytical cancellation of poles

Top quark pair production at LHC

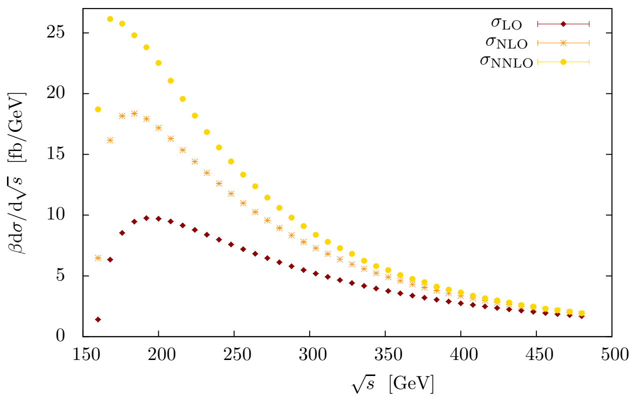
- Large production cross section at the LHC (~250pb at 8TeV)
  - Expected experimental error of ~5% for $\sigma_{t\bar{t}}$
  - NLO+NLL predictions yield an uncertainty of ~10%
- NNLO accuracy of theory needed
- Calculation for the total cross section completed (M. Czakon, P. Fiedler, A. Mitov)
  - based on sector-improved subtraction
    - numerical cancellation of infrared poles
  - Observe: theoretical and experimental uncertainties comparable (% level)
- Differential distributions in progress
  - Forward-backward asymmetry at the Tevatron explained





Higgs+jet production at the LHC

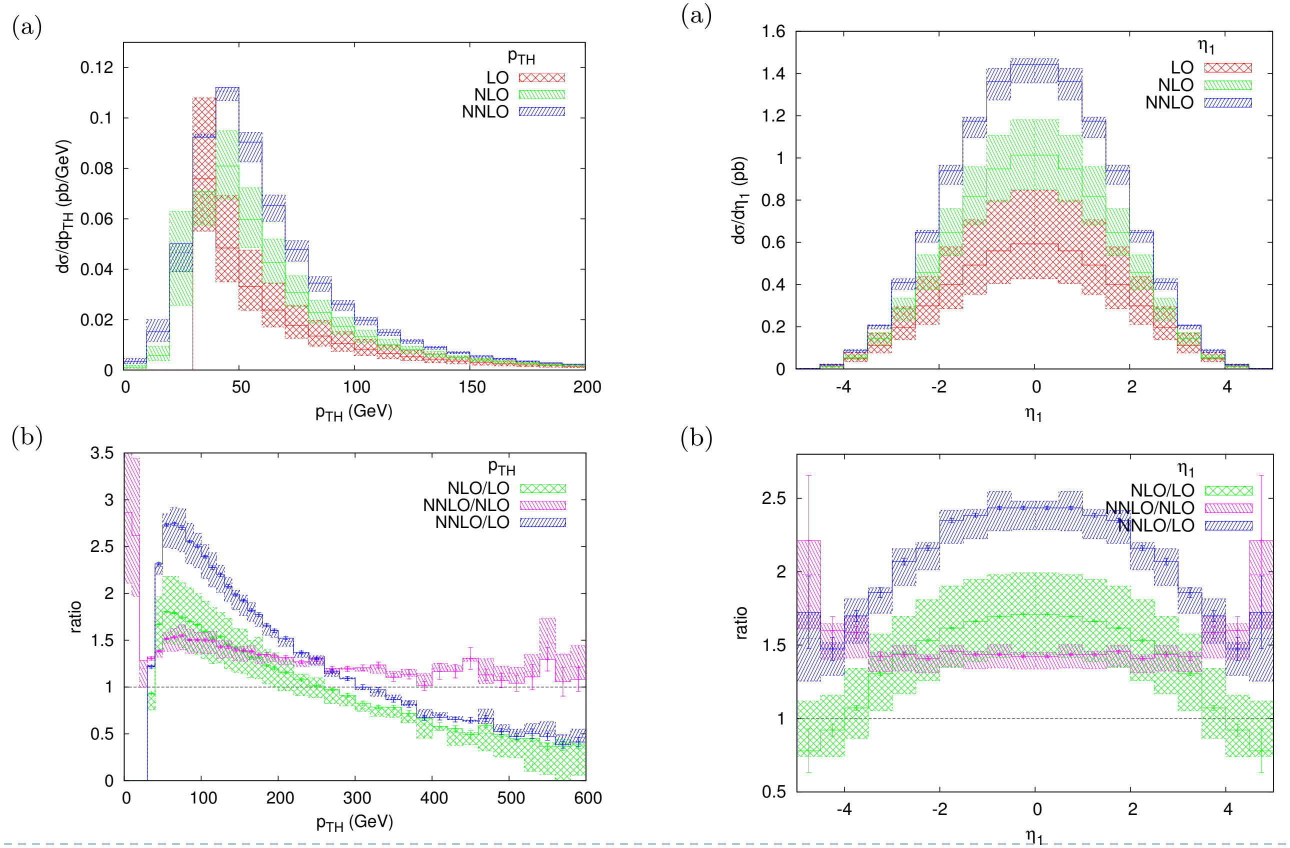
- Essential to establish the properties of the newly discovered Higgs boson
- Experiments select events according to number of jets
  - Different backgrounds for different jet multiplicities
  - H+0jet and H+1jet samples of comparable sizes
  - H+0jet and inclusive H production known at NNLO
    (C. Anastasiou, K. Melnikov, F. Petriello; S. Catani, M. Grazini)
  - H+1jet and H+2jet known at NLO
- NNLO for H+1jet needed
  - gluons-only total cross section completed
    (R. Boughezal, F. Caola, K. Melnikov, F. Petriello, M. Schulze)
  - Full calculation and differential distributions in progress
    (X. Chen, T. Gehrmann, E.W.N. Glover, M. Jaquier)



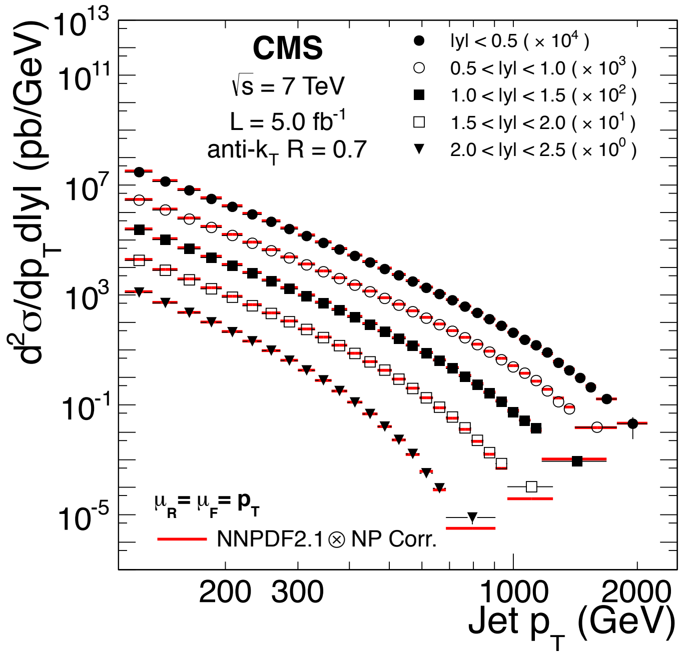
Higgs+jet production at NNLO

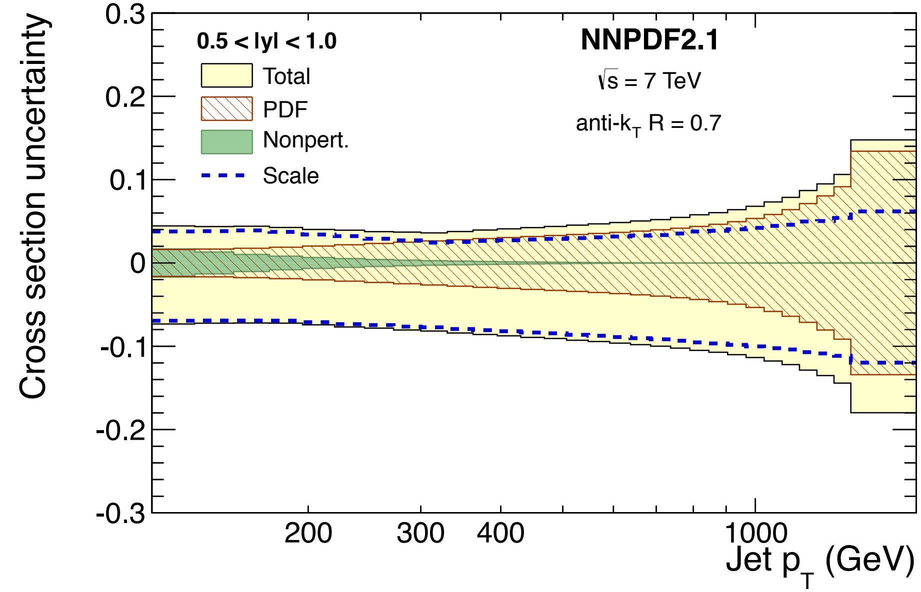
- Distributions for H+jet total cross section (gluons only)
  (X. Chen, E.W.N. Glover, M. Jaquier, TG)
  - Using antenna subtraction

p_{tj}> 30 GeV, k_T-alg., R=0.5



Jet cross sections at LHC

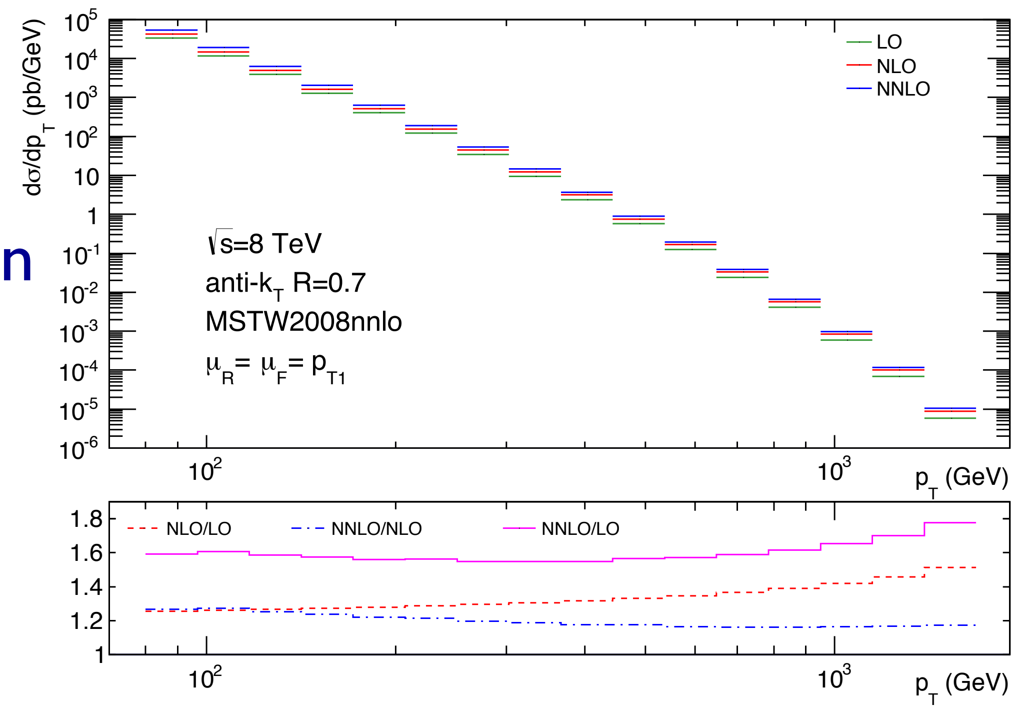




- Jet data can be used to constrain parton distributions
- Scale and PDF uncertainties on NLO prediction of comparable size
- Need improved theory (NNLO)

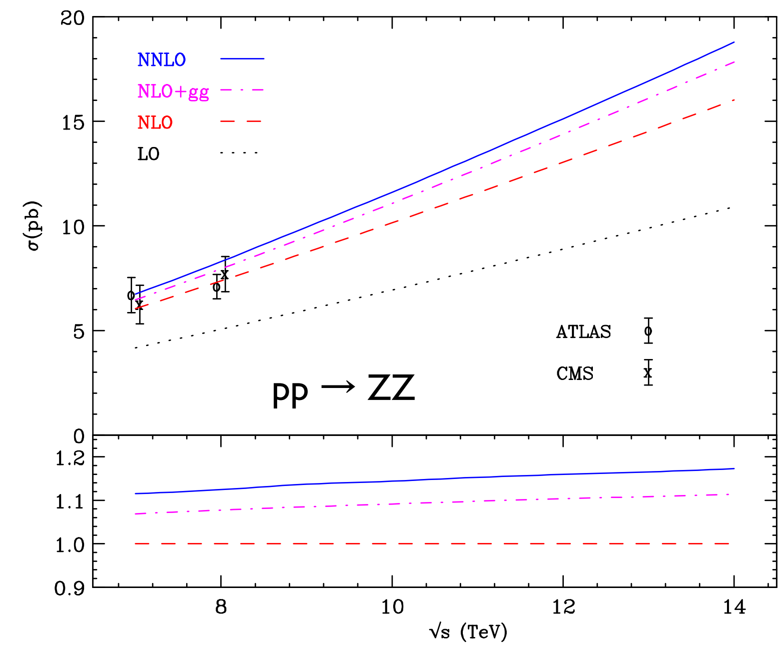
pp → 2 jets at NNLO

- First results at NNLO available
  - gg → gg and $q\bar{q}$ → gg subprocess
    (J. Currie, A. Gehrmann-De Ridder, E.W.N. Glover, J. Pires, TG)
  - Developed a new parton-level event generator NNLOJET
  - using antenna subtraction
    - analytic cancellation of infrared poles
- Inclusive jet p_T distribution
  - NNLO/NLO differential K-factor flat over the whole p_T range



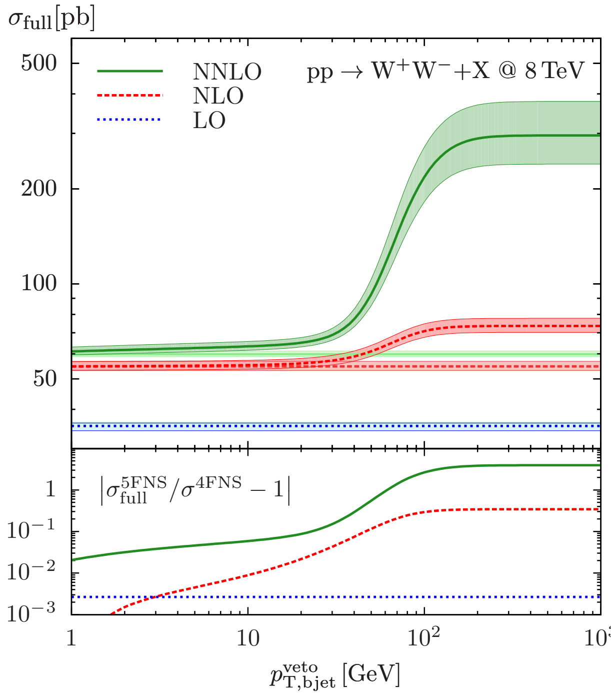
pp → VV at NNLO

- Vector boson pair production
  - Test standard model coupling structure (anomalous couplings)
  - Final state configurations similar to beyond-SM signatures
- Recently completed using q_T-subtraction
  - pp → Z γ, pp → W γ
    (M. Grazzini, S. Kallweit, D. Rathlev, A. Torre)
  - pp → Z Z (F. Cascioli et al.)
    - Moderate NNLO corrections, about half from gg → ZZ



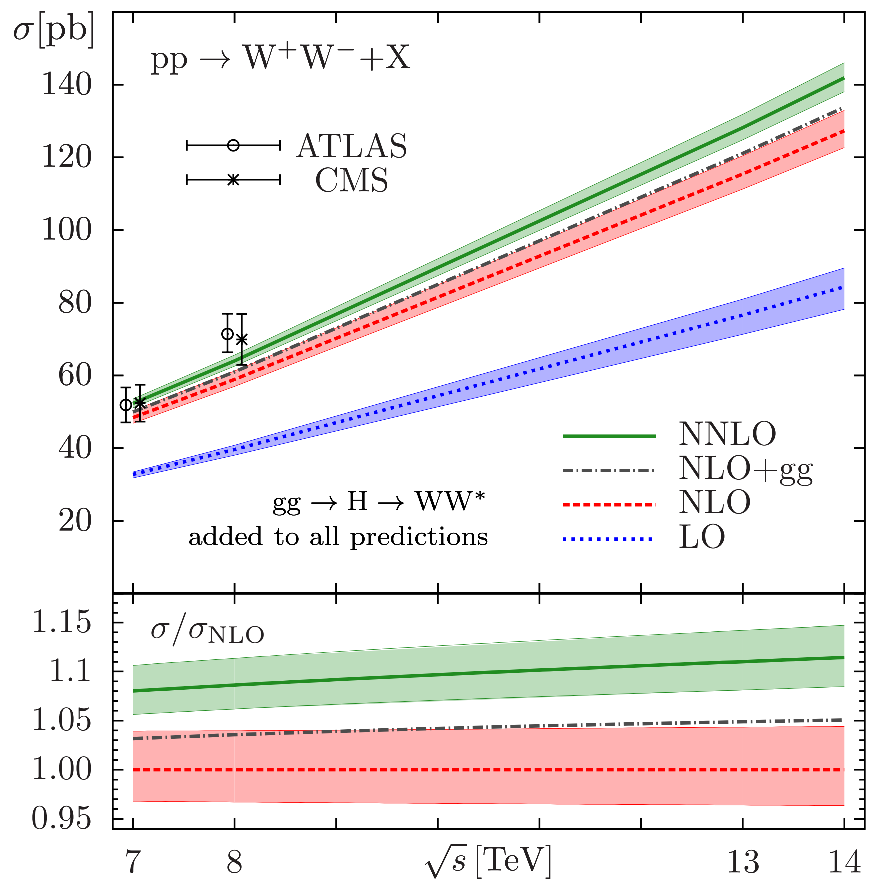
pp → W^+W^- at NNLO

- Total cross section for W pair production
  - pp → WW (M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, TG)
- At higher orders: pp → WW not well defined
  - NLO: contribution from gb → WWb
  - NNLO: contribution from $q\bar{q}$/gg → WW$b\bar{b}$
  - Can not be removed consistently in 5FNS
  - Define 5FNS contribution from scaling behaviour with top quark width
  - Good agreement of 4FNS and 5FNS



pp → W^+W^- at NNLO

- 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



- Precision frontier: aims and ideas

Towards NNLO automation

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

Towards NNLO automation

- Virtual two-loop amplitudes: analytically process-by-process
  - Current stockpile
    - pp $\to$ 2j (C. Anastasiou, N. Glover, C. Oleari, M. Tejeda-Yeomans; Z. Bern, L. Dixon, A. De Freitas)
    - pp $\to$ V+j (L. Garland, N. Glover, A. Koukoutsakis, E. Remiddi, TG)
    - pp $\to$ V+ γ (L. Tancredi, E. Weihs, TG)
    - pp $\to$ H+j (N. Glover, M. Jaquier, A. Koukoutsakis, TG)
    - pp $\to$ tt (P. Bärnreuther, M. Czakon, P. Fiedler; R. Bonciani, A. Ferroglia, A. von Manteuffel, C. Studerus, TG)
    - pp $\to$ VV (L. Tancredi, E. Weihs, TG; F. Caola, J. Henn, K. Melnikov, V. Smirnov, A. Smirnov)
- Research directions: towards different masses and 2 $\to$ 3
  - Systematic techniques to compute master integrals (J. Henn)
  - Semi-numerical approaches (P. Bärnreuther, M. Czakon, P. Fiedler)
  - Classification of integral basis (H. Johansson, D. Kosower, K. Larsen)
  - Unitarity-based methods (P. Mastrolia, E. Mirabella, G. Ossola, T. Peraro)

NNLO and beyond: techniques

- Seemingly simple task: check equality of two expressions
  - Becomes very tricky if complicated functions involved
    - e.g. Abel relation (1855)

$$\ln(1-x)\ln(1-y) = \mathrm{Li}_2\left(\frac{x}{1-y}\right)+\mathrm{Li}_2\left(\frac{y}{1-x}\right)-\mathrm{Li}_2(x)-\mathrm{Li}_2(y)-\mathrm{Li}_2\left(\frac{xy}{(1-x)(1-y)}\right)$$

- Systematic procedure for iterated rational integrals
  - Symbol and coproduct (A. Goncharov, M. Spradlin, A. Volovich, C. Vergu; C. Duhr)
  - Often allows huge simplifications (many pages → few lines)
- starts to get used for loop integrals
  - simplification
  - analytical continuation
  - automated derivation of relations

Beyond NNLO: observables

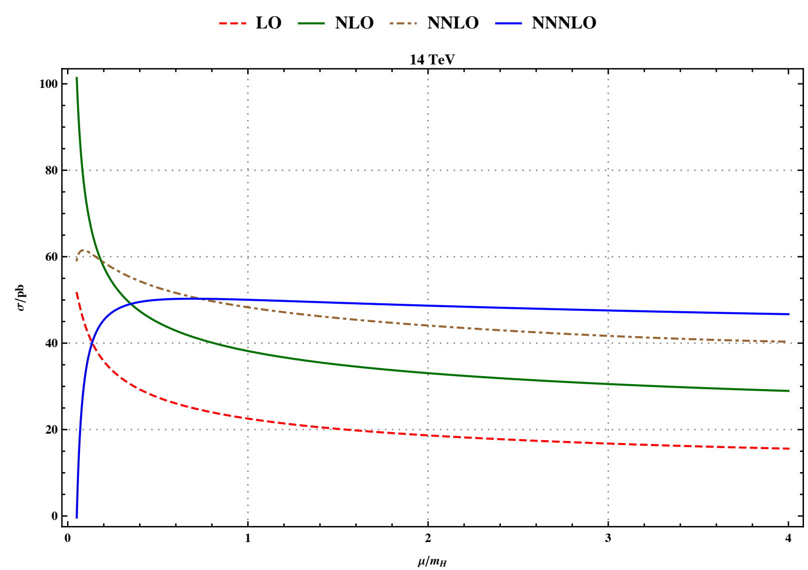
- Hadronic R-ratio in e^+e^-
  - Most precise QCD observable in Z and τ decays
  - Known to $O(\alpha_s^4)$ (P. Baikov, K. Chetyrkin, H. Kühn, J. Rittinger)
  - Produces most precise $\alpha_s(M_Z) = 0.1198 \pm 0.0015$

- Gluon-fusion Higgs cross section at hadron colliders
  - Large NLO and NNLO corrections
  - Ultimate precision on Higgs couplings may require N^3LO
  - Ingredients
    - Three-loop vertex functions (P. Baikov, K. Chetyrkin, A. Smirnov, V. Smirnov, M. Steinhauser; N. Glover, T. Huber, N. Ikizlerli, C. Studerus, TG)
    - Counterterms and lower-order expansions (C. Anastasiou, S. Bühler, C. Duhr, F. Herzog; M. Höschele, J. Hoff, A. Pak, M. Steinhauser, T. Ueda)
    - Triple real radiation (C. Anastasiou, C. Duhr, F. Dulat, B. Mistlberger)
    - Interplay of real and virtual corrections at N^3LO (C. Duhr et al.)
  - Major work in progress

Towards gg → H at N³LO

- **Expand coefficient function around production threshold**
  (C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, F. Herzog, B. Mistlberger, TG)
  - Reliable prediction: need further terms in threshold expansion

$$\begin{aligned}
\hat{\eta}^{(3)}(z) = {}& \delta(1-z)\Big\{ C_A^3 \Big(-\frac{2003}{48}\zeta_6 + \frac{413}{6}\zeta_3^2 - \frac{7579}{144}\zeta_5 + \frac{979}{24}\zeta_2\zeta_3 - \frac{15257}{864}\zeta_4 - \frac{819}{16}\zeta_3 + \frac{16151}{1296}\zeta_2 + \frac{215131}{5184}\Big) \\
& + N_F\Big[C_A^2\Big(\frac{869}{72}\zeta_5 - \frac{125}{12}\zeta_3\zeta_2 + \frac{2629}{432}\zeta_4 + \frac{1231}{216}\zeta_3 - \frac{70}{81}\zeta_2 - \frac{98059}{5184}\Big) \\
& \quad + C_A C_F\Big(\frac{5}{2}\zeta_5 + 3\zeta_3\zeta_2 + \frac{11}{72}\zeta_4 + \frac{13}{2}\zeta_3 - \frac{71}{36}\zeta_2 - \frac{63991}{5184}\Big) + C_F^2\Big(-5\zeta_5 + \frac{37}{12}\zeta_3 + \frac{19}{18}\Big)\Big] \\
& + N_F^2\Big[C_A\Big(-\frac{19}{36}\zeta_4 + \frac{43}{108}\zeta_3 - \frac{133}{324}\zeta_2 + \frac{2515}{1728}\Big) + C_F\Big(-\frac{1}{36}\zeta_4 - \frac{7}{6}\zeta_3 - \frac{23}{72}\zeta_2 + \frac{4481}{2592}\Big)\Big]\Big\} \\
& + \Big[\frac{1}{1-z}\Big]_+ \Big\{ C_A^3\Big(186\,\zeta_5 - \frac{725}{6}\zeta_3\zeta_2 + \frac{253}{24}\zeta_4 + \frac{8941}{108}\zeta_3 + \frac{8563}{324}\zeta_2 - \frac{297029}{23328}\Big) + N_F^2 C_A\Big(\frac{5}{27}\zeta_3 + \frac{10}{27}\zeta_2 - \frac{58}{729}\Big) \\
& \quad + N_F\Big[C_A^2\Big(-\frac{17}{12}\zeta_4 - \frac{475}{36}\zeta_3 - \frac{2173}{324}\zeta_2 + \frac{31313}{11664}\Big) + C_A C_F\Big(-\frac{1}{2}\zeta_4 - \frac{19}{18}\zeta_3 - \frac{1}{2}\zeta_2 + \frac{1711}{864}\Big)\Big]\Big\} \\
& + \Big[\frac{\log(1-z)}{1-z}\Big]_+ \Big\{ C_A^3\Big(-77\zeta_4 - \frac{352}{3}\zeta_3 - \frac{152}{3}\zeta_2 + \frac{30569}{648}\Big) + N_F^2 C_A\Big(-\frac{4}{9}\zeta_2 + \frac{25}{81}\Big) \\
& \quad + N_F\Big[C_A^2\Big(\frac{46}{3}\zeta_3 + \frac{94}{9}\zeta_2 - \frac{4211}{324}\Big) + C_A C_F\Big(6\,\zeta_3 - \frac{63}{8}\Big)\Big]\Big\} \\
& + \Big[\frac{\log^2(1-z)}{1-z}\Big]_+ \Big\{ C_A^3\Big(181\,\zeta_3 + \frac{187}{3}\zeta_2 - \frac{1051}{27}\Big) + N_F\Big[C_A^2\Big(-\frac{34}{3}\zeta_2 + \frac{457}{54}\Big) + \frac{1}{2}C_A C_F\Big] - \frac{10}{27}N_F^2 C_A\Big\} \\
& + \Big[\frac{\log^3(1-z)}{1-z}\Big]_+ \Big\{ C_A^3\Big(-56\,\zeta_2 + \frac{925}{27}\Big) - \frac{164}{27}N_F C_A^2 + \frac{4}{27}N_F^2 C_A\Big\} \\
& + \Big[\frac{\log^4(1-z)}{1-z}\Big]_+ \Big(\frac{20}{9}N_F C_A^2 - \frac{110}{9}C_A^3\Big) + \Big[\frac{\log^5(1-z)}{1-z}\Big]_+ 8\,C_A^3 .
\end{aligned}$$



- Instead of a summary: Outlook

Where do we stand?

- Witnessed an NLO revolution
  - Previously unthinkable NLO 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
  - 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 automation
  - Uncover analytical structures to organize calculation of real and virtual corrections
  - Develop standard interfaces
  - Interface to experiment ?
- Beyond NNLO
  - N^3LO precision for benchmark processes

- Progress on precision physics on many frontiers
- Be prepared for exciting times at the Terascale