QCD at the LHC

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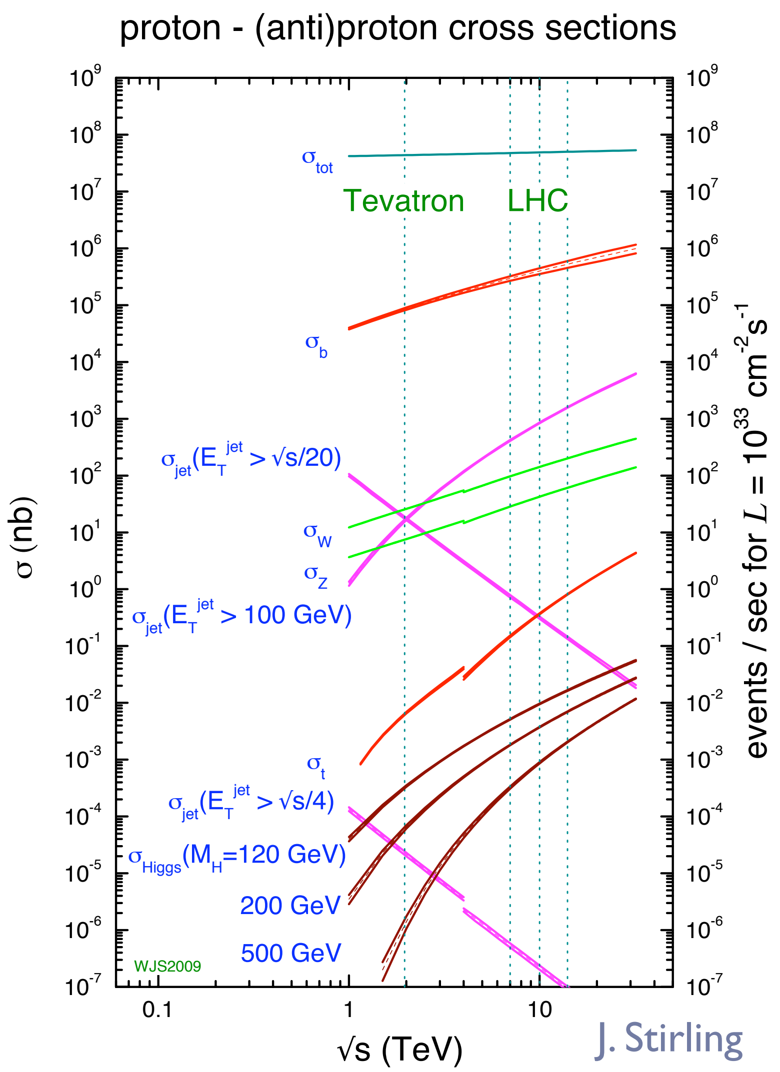
Benchmark processes at LHC

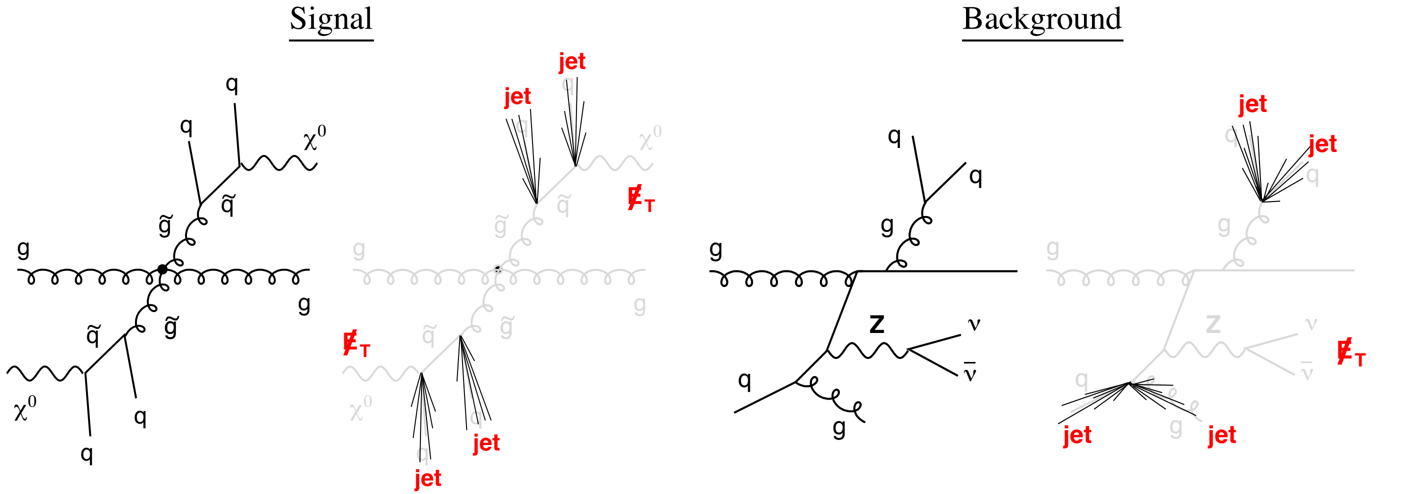
- Large production rates for Standard Model processes
  - jets
  - top quark pairs
  - vector bosons
- Allow precision measurements
  - masses
  - couplings
  - parton distributions
- Require precise theory



J. Stirling

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



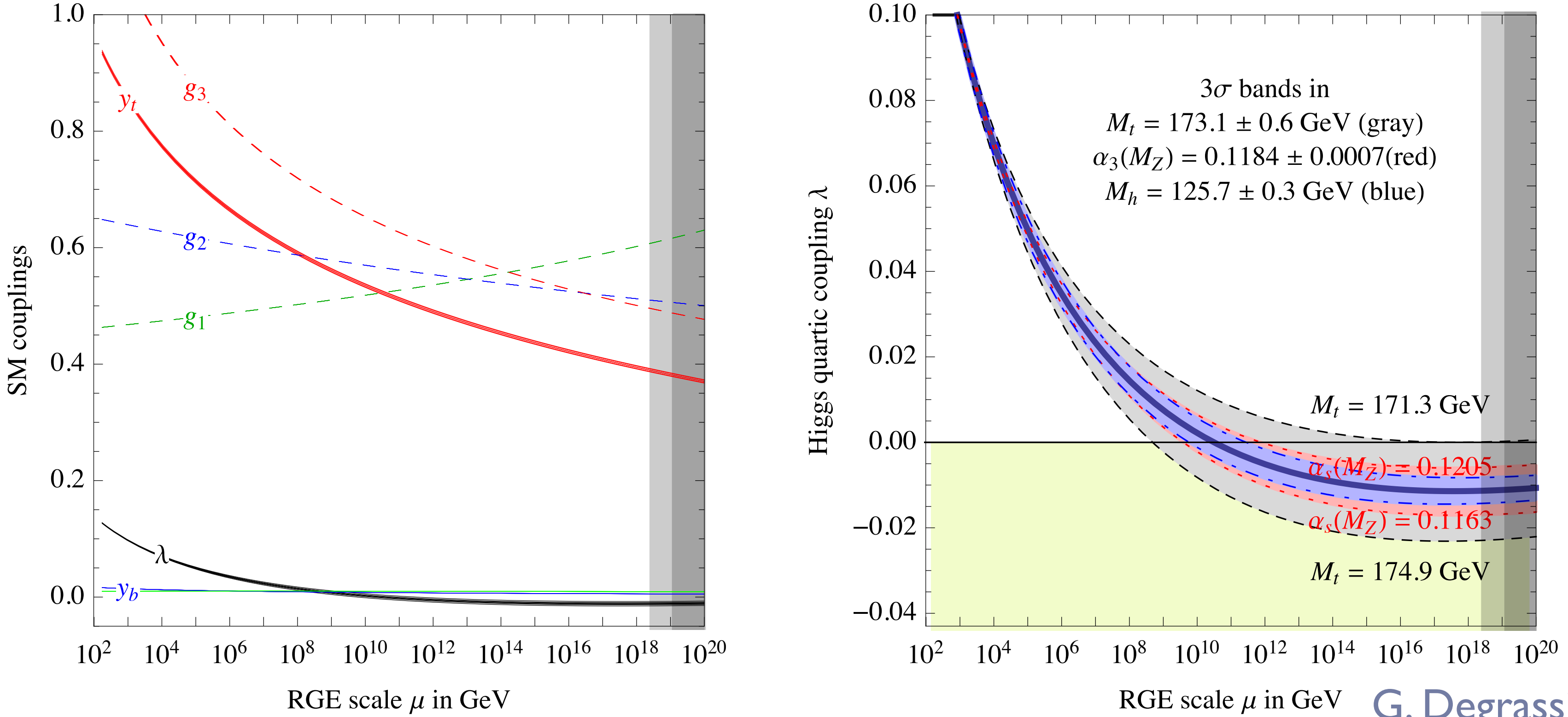
Example: SUSY signature 4j + $\not{E}_T$

The case for precision

- Implications of Higgs boson discovery at ATLAS and CMS
  - Higgs mechanism established
  - Higgs boson mass measured: $m_H = 125.7 \pm 0.3$ GeV
  - 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

Stability of the Higgs potential

- Renormalization group evolution of quartic coupling

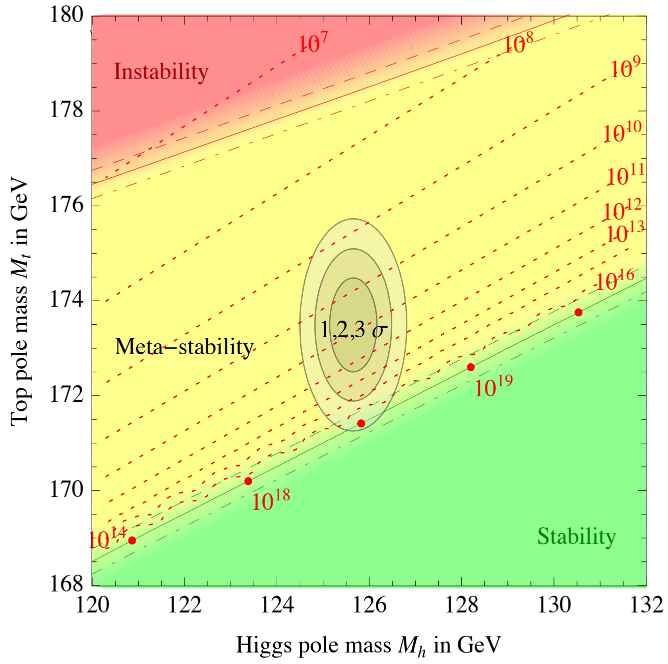


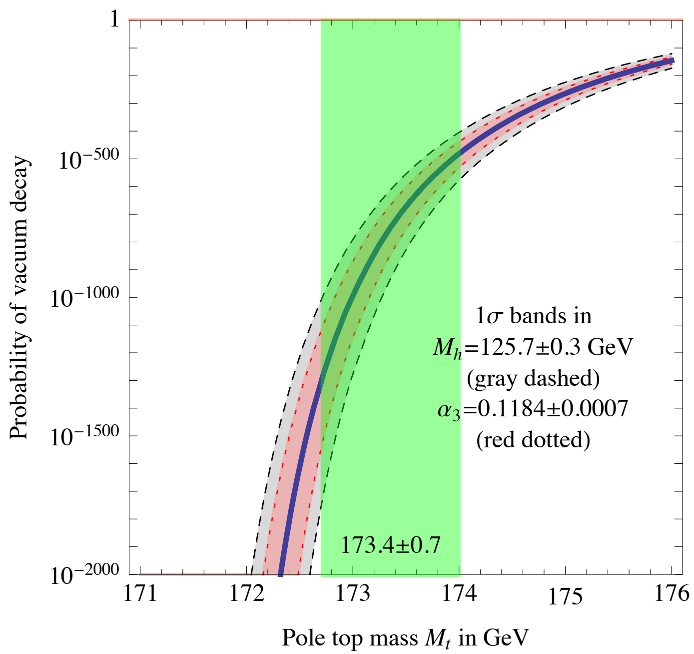
G. Degrassi et al.

- 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, results, directions
- Parton showers, resummation, matching
- NNLO: precision QCD
- Interpreting LHC data
- Precision frontier: aims and ideas

NLO: methods, results, directions

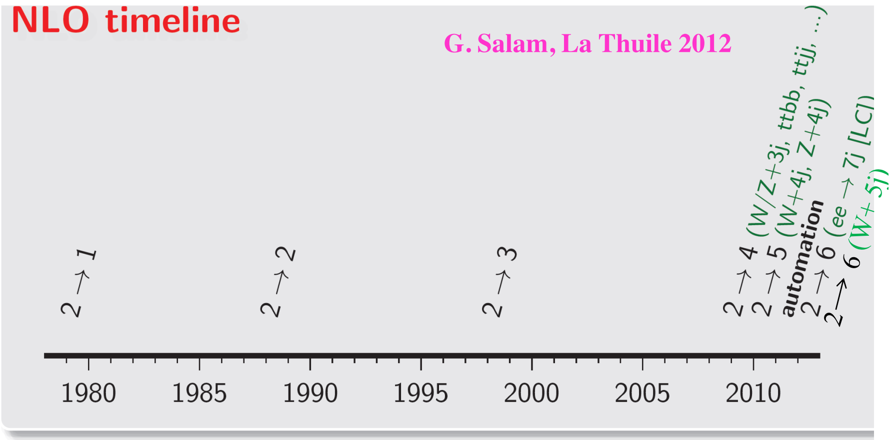
NLO multi-particle production

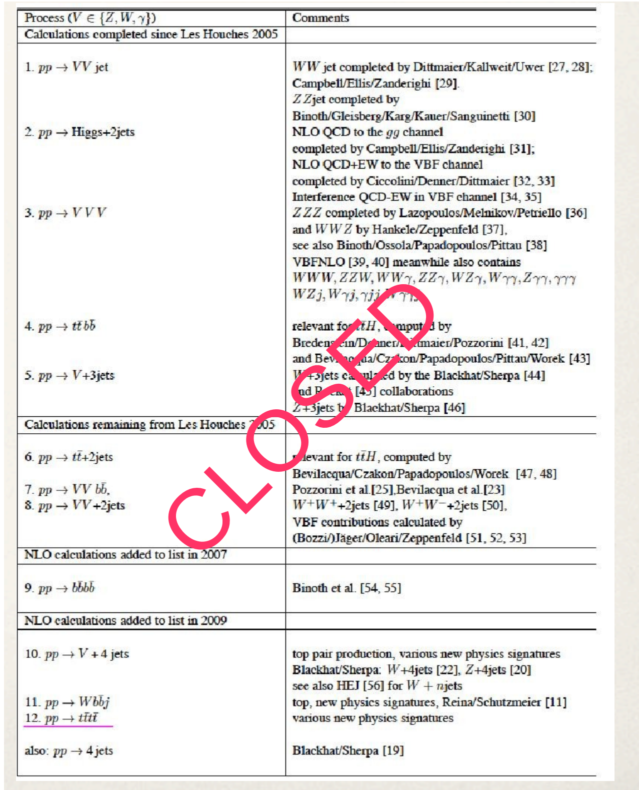
- Why NLO?
  - reduce scale uncertainty of LO theory prediction
  - reliable normalization and shape
  - accounts for effects of extra radiation
  - jet algorithm dependence

- 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





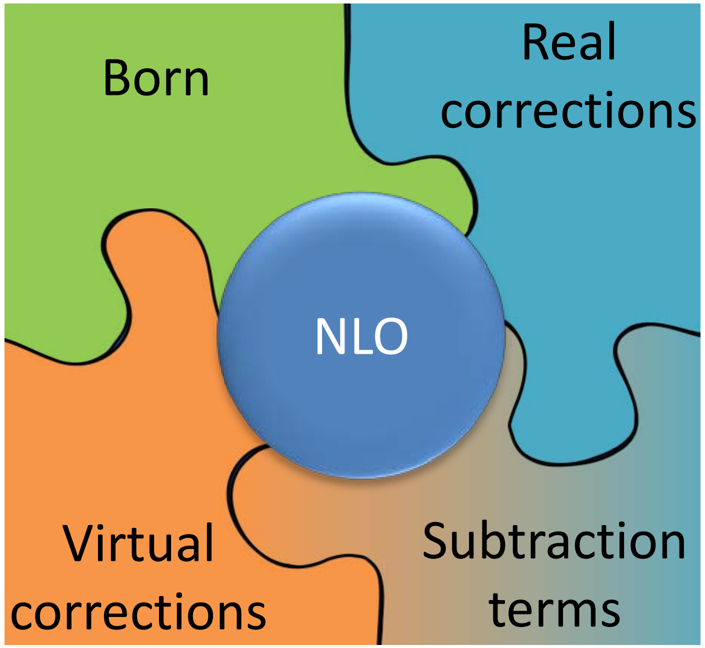
Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer [27, 28]; Campbell/Ellis/Zanderighi [29]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [30]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg 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 $WWW, ZZW, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma$ $WZj, W\gamma j, \gamma jj, W\gamma\gamma j$
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. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier [11]
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
also: $pp \to 4$ jets	Blackhat/Sherpa [19]

K. Melnikov, MITP, 2013

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

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)



Automation in NLO computations

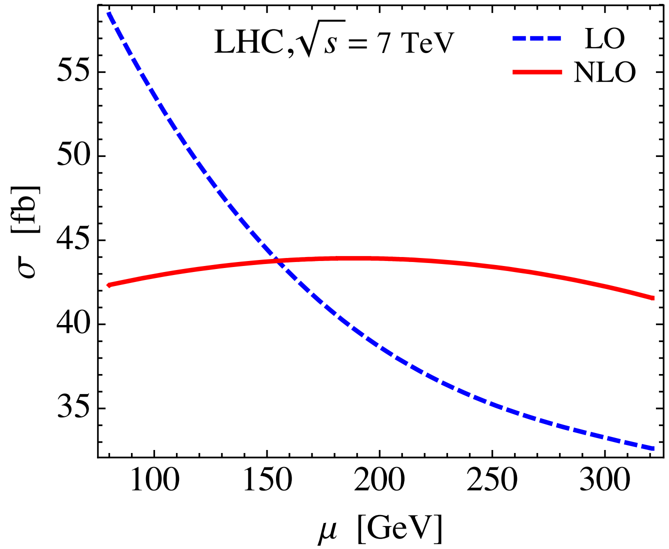
- Impressive list of results:
  - multiple jets (up to 4) (Blackhat + Sherpa; Njet)
  - gauge boson and up to 5 jets (Blackhat + Sherpa)
  - two gauge bosons with up to 2 jets (T. Melia et al.;VBFNLO: F. Campanario, M. Kerner, L.D. Ninh, D. Zeppenfeld; GoSam + MadEvent)
  - Three gauge bosons (VBFNLO: 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)
- Address rich phenomenology with few examples

W^+W^-+2 jet production at NLO

- Background to BSM searches and for H→WW decay
- Interplay with electroweak vector boson fusion process
  (VBFNLO: D. Zeppenfeld et al.)
- Two NLO QCD calculations completed recently
  (T. Melia, K. Melnikov, R. Rontsch, G. Zanderighi; N. Greiner, G. Heinrich, P. Mastrolia, G. Ossola, T. Reiter, F. Tramontano)
- Including W-boson decays:

$$pp \rightarrow W^+(\rightarrow \nu_e e^+)W^-(\rightarrow \mu^- \bar{\nu}_\mu) jj$$

- Scale variation : Use $\mu = \mu_F = \mu_{R,}$

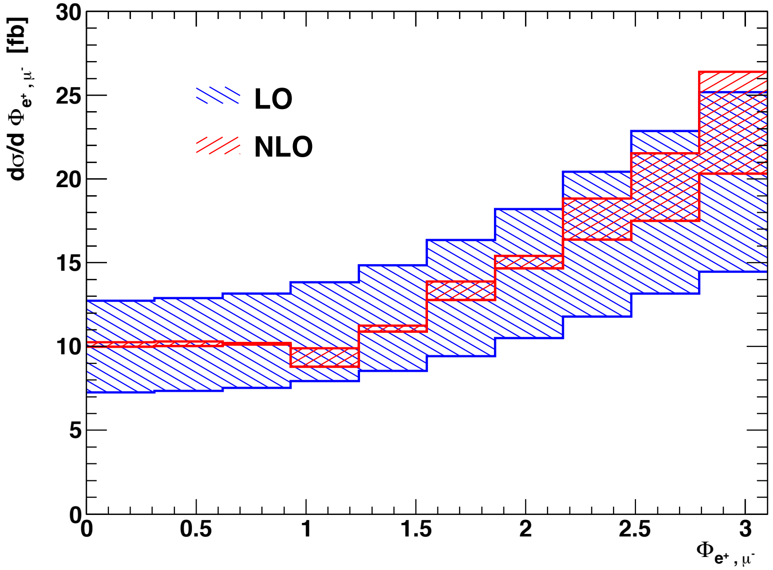


- Observe: NLO corrections stabilize scale dependence

W^+W^-+2 jet production at NLO

- Distribution in the lepton opening angle Φ_{e^+,μ^-}
- Vary $\mu = \mu_F = \mu_R$ in $M_W < \mu < 4\,M_W$

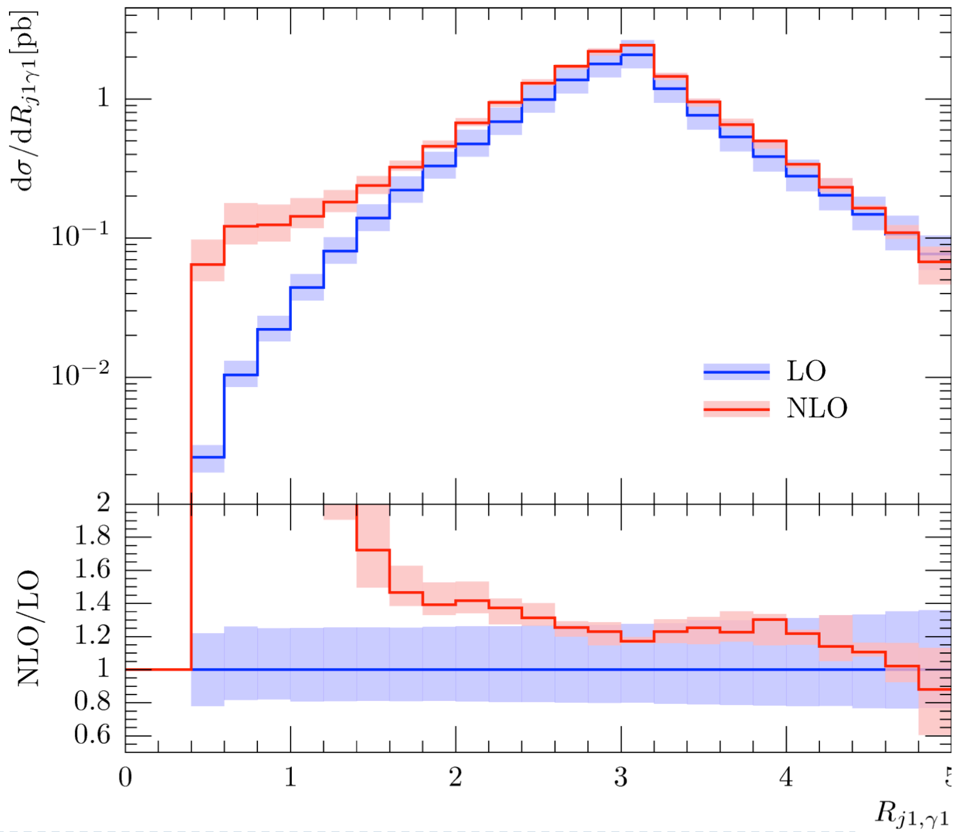
- NLO predictions within LO uncertainty band
- Relevant for designing cuts for the determination of HWW coupling
  - QCD process: peaked at π
  - Higgs signal: peaked at 0



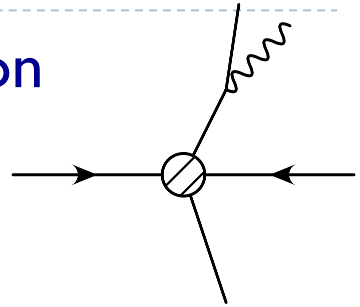
γγ + 2 jet production at NLO

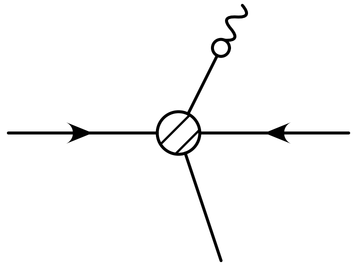
- Diphoton-plus-two-jet important Higgs background
- Currently determined from sideband data
- Insufficient for multiple differential measurements
- NLO: GoSam+MadEvent
  (G. Heinrich, N. Greiner, TG)
- Also: Blackhat+Sherpa
- Photon isolation: dynamical cone (S. Frixione)

$$E_{\rm had,max}(r_\gamma) = \epsilon\, p_T^\gamma \left(\frac{1-\cos r_\gamma}{1-\cos R}\right)^n$$



Photon production mechanisms





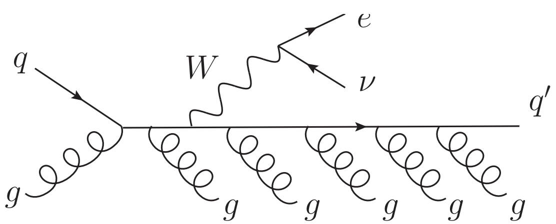
- Direct process: photon produced in hard interaction
  - perturbatively calculable
  - collinear quark-photon contributions present
- Fragmentation of parton into photon:
  - described by a non-perturbative parton-to-photon fragmentation function
  - absorbs collinear singularities from direct process
  - requires non-perturbative input
- Fixed cone isolation (used in experiment)
  - both processes contribute
  - fragmentation contributions reduced but not eliminated
- Smooth cone isolation (preferred by theorists)
  - no collinear nor fragmentation contributions
- Ongoing discussion (Les Houches 2013)

W+5 jets at NLO

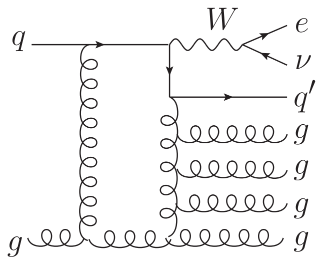
- First 2→6 NLO calculation at a hadron collider
- Using Blackhat + Sherpa

(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

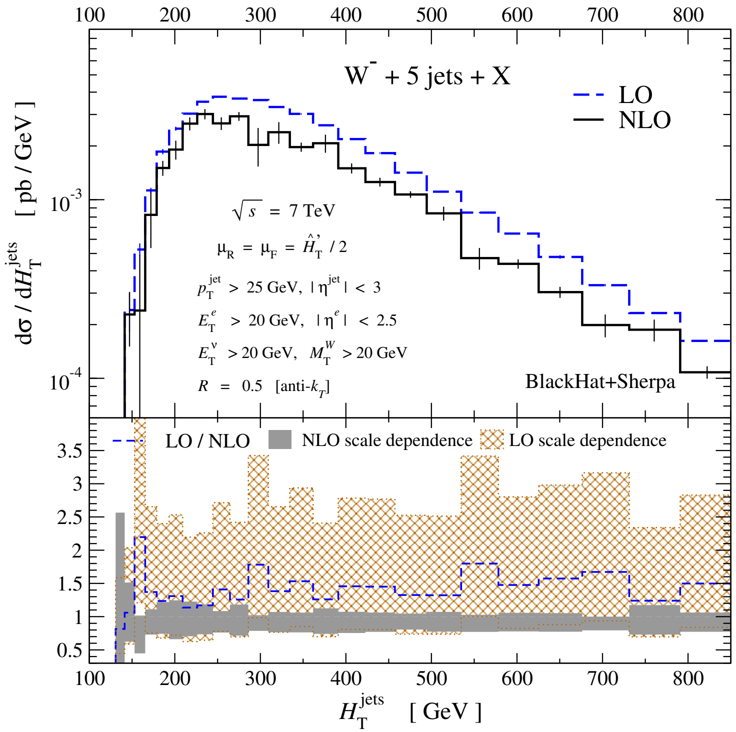
W+5 jets at NLO

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

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

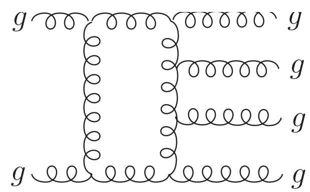
$$\hat{H}'_\mathrm{T} \equiv \sum_m p_\mathrm{T}^m + E_\mathrm{T}^W$$

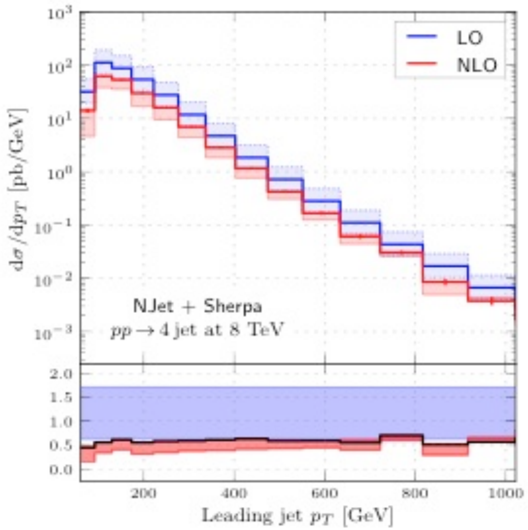
  - scale variation $\mu/2 \ldots 2\mu$
  - Observe:
    - Scale dependence reduced at NLO
    - ratio NLO/LO constant over full kinematical range
- NLO helps to motivate the scale choice



pp→4 jets at NLO

- Two calculations using on-shell methods for loop amplitudes
  - Blackhat+Sherpa (Z. Bern, L. Dixon, F. Febres Cordero, S. Höche, H. Ita, D. Kosower, D. Maitre, K. Ozeren)
  - NJET+Sherpa (S. Badger, B. Biedermann, P. Uwer, V. Yundin)

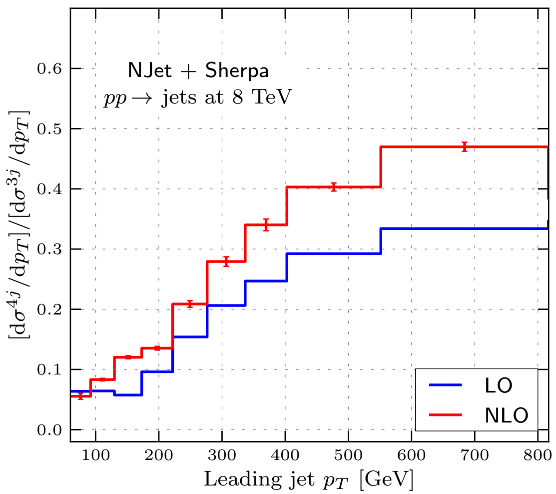




Dynamical scale:

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

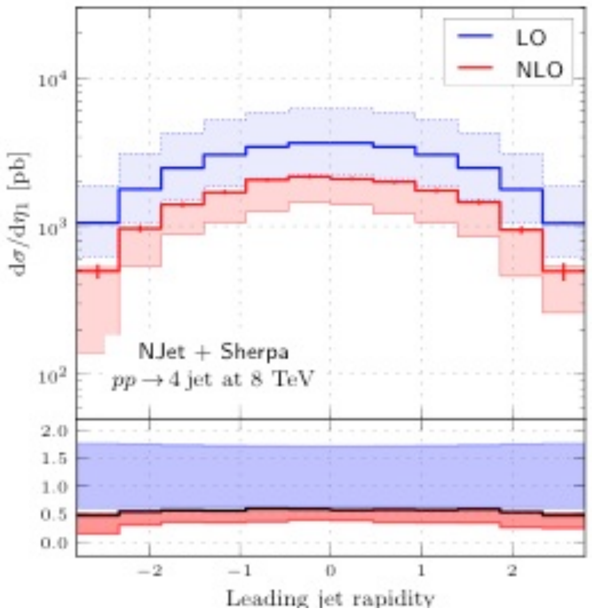
$$\hat{H}_T = \sum_{i=1}^{N_{\text{parton}}} p_{T,i}^{\text{parton}}.$$



- NLO prediction with central scale $\hat{H}_T/2$
- 4-to-3 jet ratio increases at NLO

pp →4 jets at NLO

- To disentangle NLO effects from parton distributions and genuine NLO corrections from hard scattering process
  - Use NLO partons for both NLO and LO predictions



Dynamical scale

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

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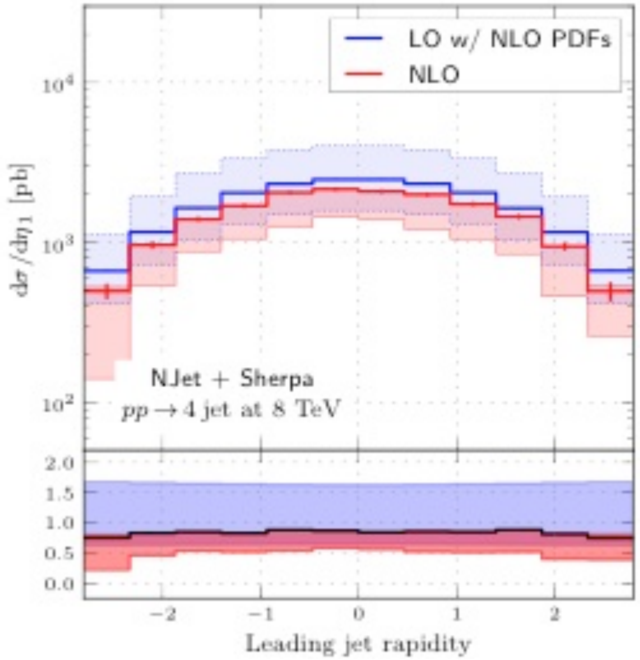
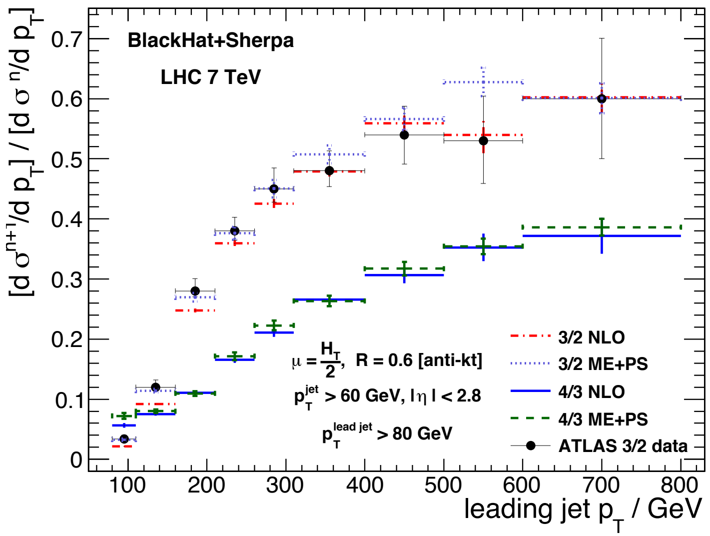


- LO with NLO partons closer to full NLO than pure LO

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

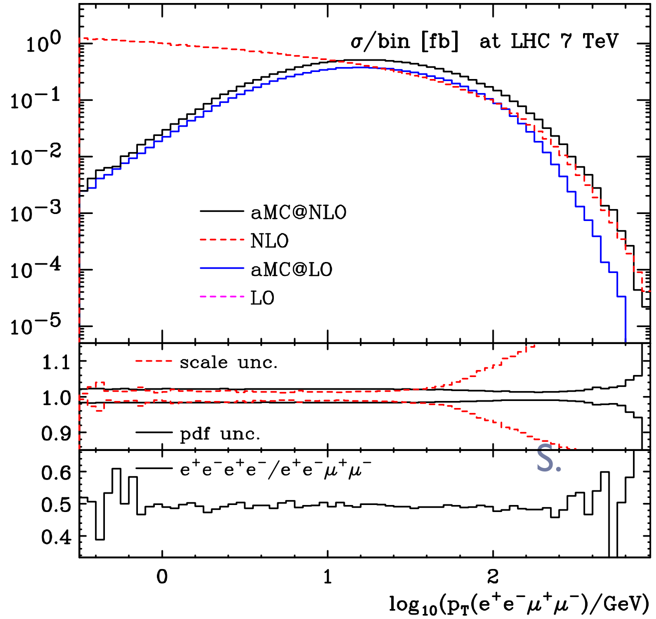
- Parton showers, resummation, matching

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

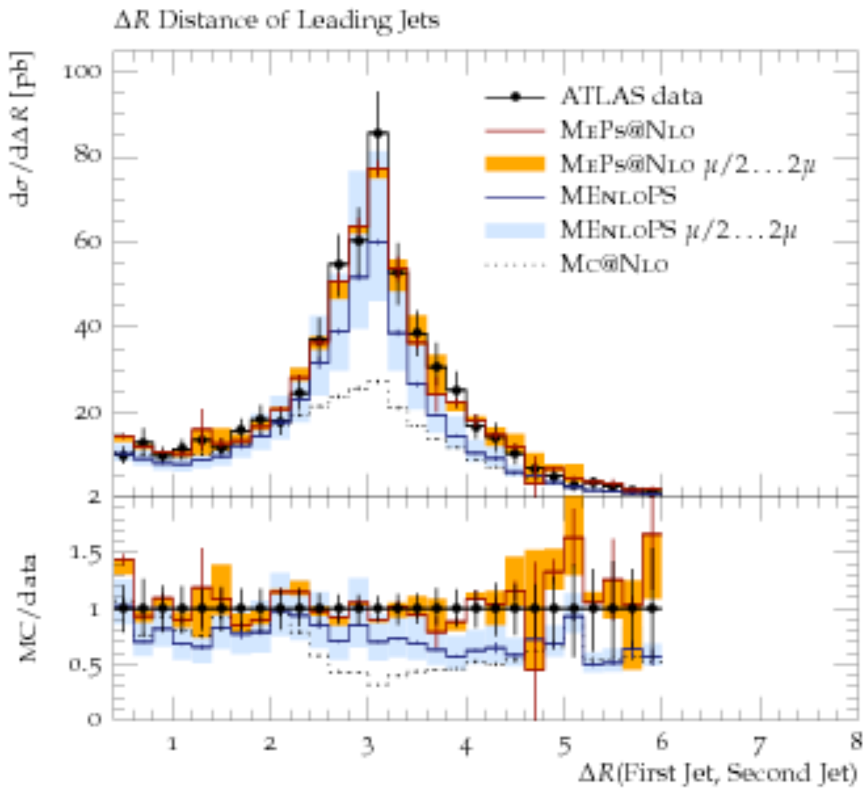
Merging of fixed order and parton shower

- **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)



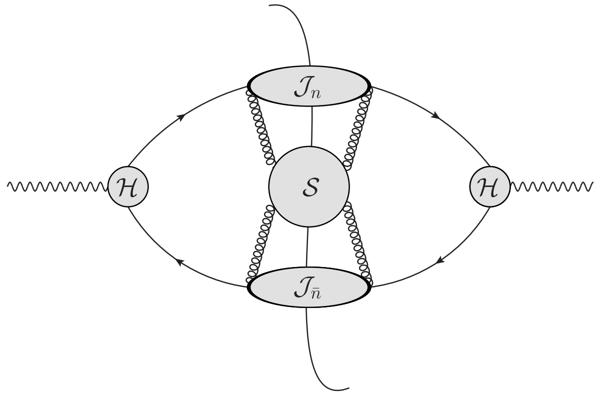
Merging of fixed order and parton shower

- 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



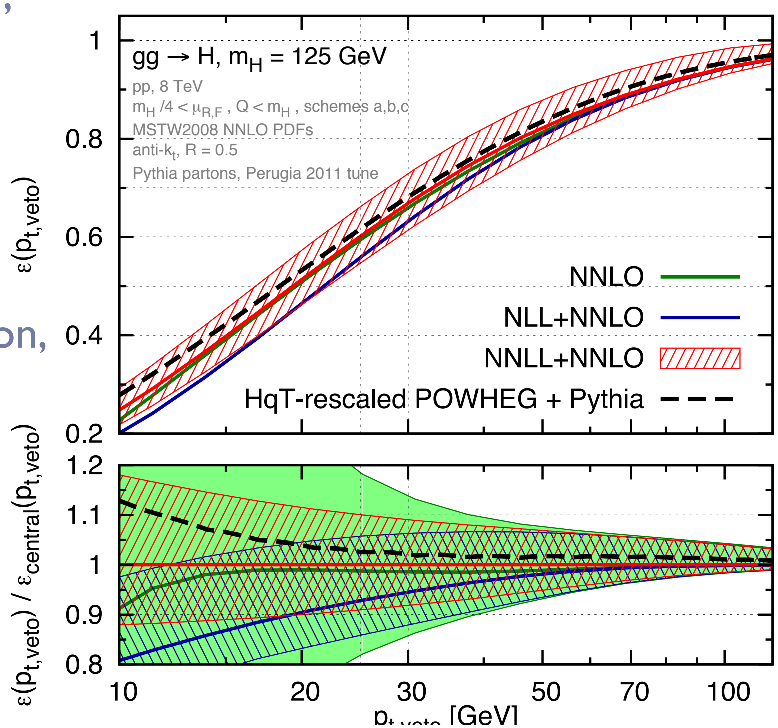
Resummation

- 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



Resummation

- Recent NNLL results
  - Higgs boson p_T distribution (D. de Florian, G. Ferrera, M. Grazzini, D. Tommasini; V. Ahrens, T. Becher, M. Neubert, L.L. Yang)
  - Jet veto cross sections (A. Banfi, P.F. Monni, G. Salam, G. Zanderighi; T. Becher, M. Neubert)
  - Jet-p_T distributions in Higgs events (I. Stewart, F. Tackmann, J. Walsh, S. Zuberi)
  - Top quark pair production (M. Beneke, P. Falgari, S. Klein, C. Schwinn, M. Cacciari, M. Czakon, M. Mangano, A. Mitov, P. Nason, V. Ahrens et al.)
- Impact of NNLL
  - extended range of theory prediction
  - reduction of scale uncertainty



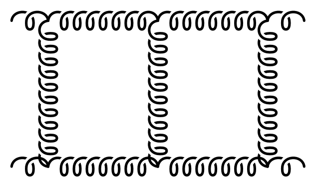
- NNLO: towards precision QCD

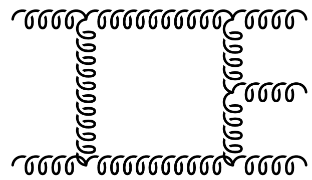
NNLO observables at hadron colliders

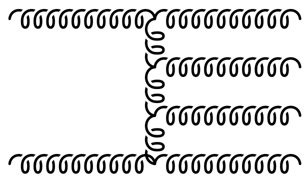
- NNLO predictions
  - expected to have a per-cent level accuracy
  - yielding first reliable estimate of theoretical uncertainty
- For processes measured to few per cent accuracy
  - jet production
  - vector boson (+jet) production
  - top quark pair production
- For processes with potentially large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

NNLO calculations

- Require three principal ingredients (here: pp → 2j)
  - 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







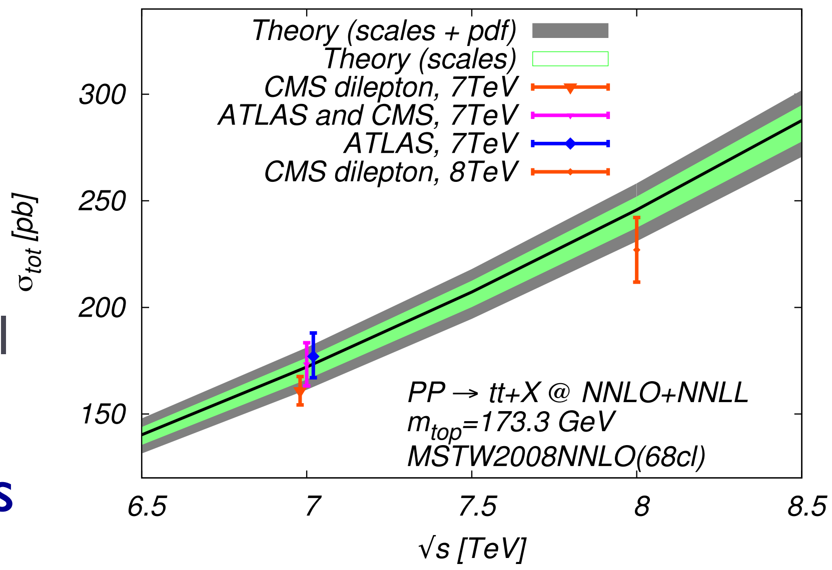
- Infrared poles cancel in the sum
- Challenge: combine contributions into parton-level generator
  - Need a method to extract implicit infrared poles

Real radiation at NNLO: methods

- Sector decomposition
  (T. Binoth, G. Heinrich; C. Anastasiou, K. Melnikov, F. Petriello)
  - $pp \to H$, $pp \to V$, including decays
    (C. Anastasiou, K. Melnikov, F. Petriello; S. Bühler, F. Herzog, A. Lazopoulos, R. Müller)
- 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)
- 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)
- 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)
  - $pp \to 2j$ (A. Gehrmann-De Ridder, E.W.N. Glover, J. Pires, TG)

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)
  - From a purely numerical code
  - based on sector-improved subtraction
    - numerical cancellation of infrared poles
  - Observe: theoretical and experimental uncertainties comparable (% level)
- Differential distributions in progress



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 inclusive H production known at NNLO
    (C. Anastasiou, K. Melnikov, F. Petriello; S.Catani,M. Grazini)
  - H+1jet and H+2jet known at NLO
  - H+0jet and H+1jet samples of comparable sizes
- 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

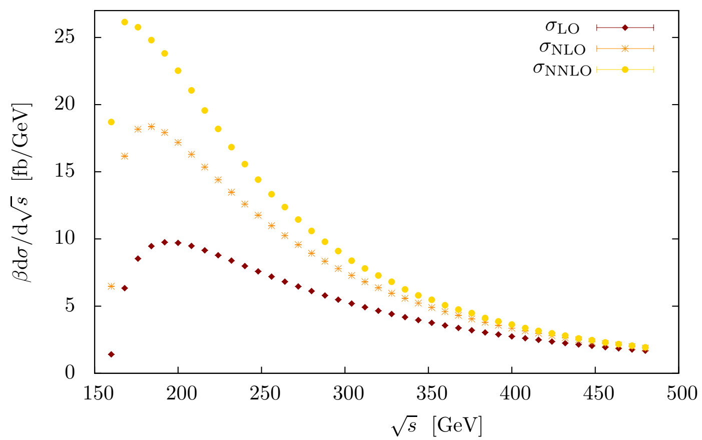
Higgs+jet production at NNLO

- First results for H+jet total cross section (gluons only)
  (R. Boughezal, F. Caola, K. Melnikov, F. Petriello, M. Schulze)
  - using a purely numerical code
    - Based on sector-improved subtraction
    - numerical cancellation of infrared singularities
  - cross section multiplied by gluon luminosity

$$\beta\frac{d\sigma_{\rm had}}{d\sqrt{s}} = \beta\frac{d\sigma(s,\alpha_s,\mu_R,\mu_F)}{d\sqrt{s}} \times \mathcal{L}\left(\frac{s}{s_{\rm had}},\mu_F\right),$$

  - with $\beta = \sqrt{1-\frac{E_{th}^2}{s}}, \quad E_{th} \approx 158 GeV$

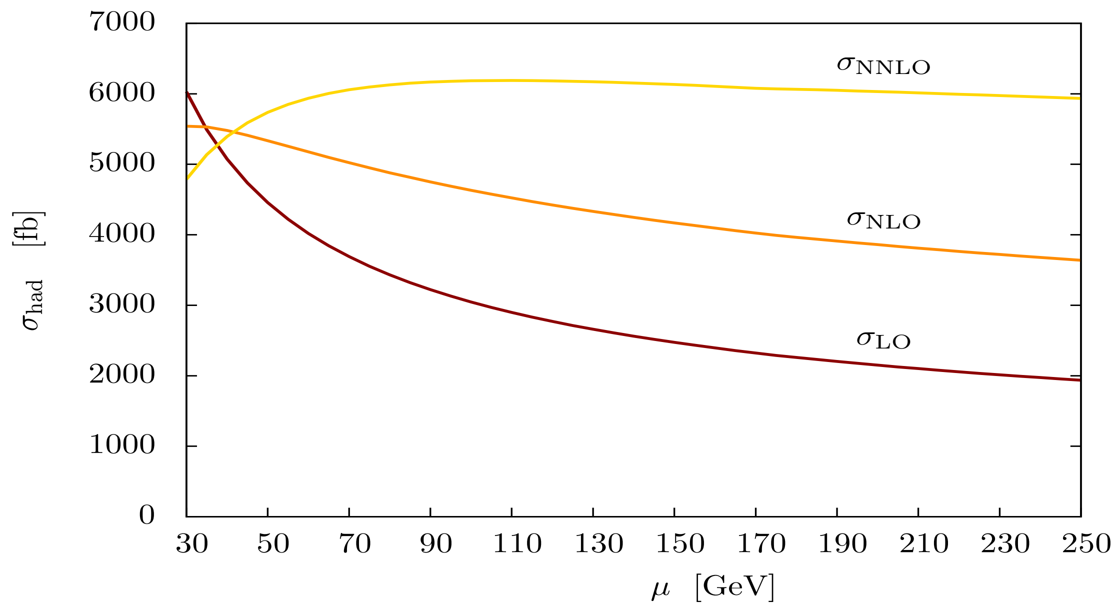
p_{tj}> 30 GeV, k_T-alg., R=0.5



- Observe large NNLO effects close to partonic threshold region

Higgs+jet production at NNLO

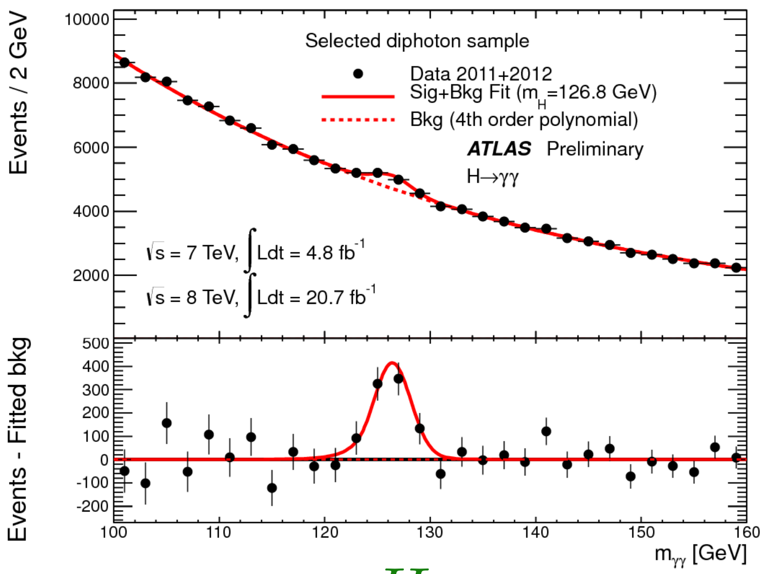
- Scale dependence of the integrated total cross section
  $\mu = \mu_F = \mu_R$



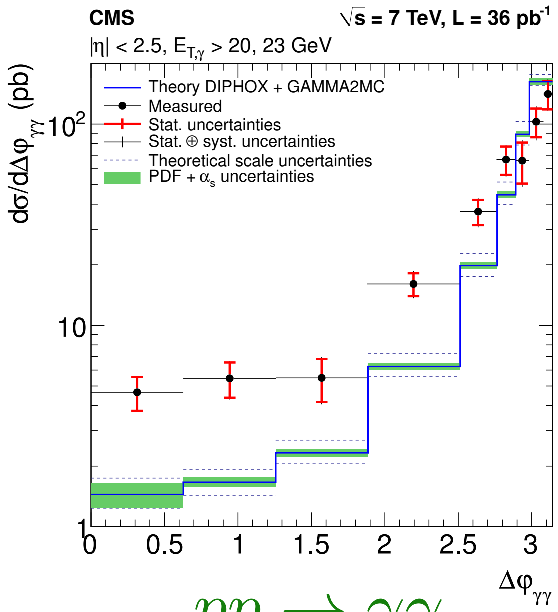
- Considerable stabilization at NNLO
- Corrections smallest for $\mu = M_H/2$ as in inclusive case

Di-photon production at the LHC

- Di-photon production: irreducible background for $H \to \gamma\gamma$
  - at present determined from sideband data fits
- Discrepancy between NLO theory and data in some distributions



$pp \to H \to \gamma\gamma$

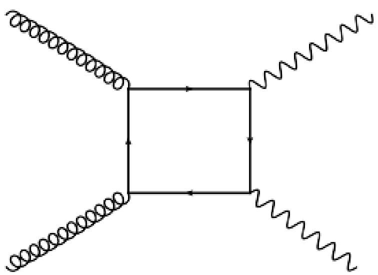


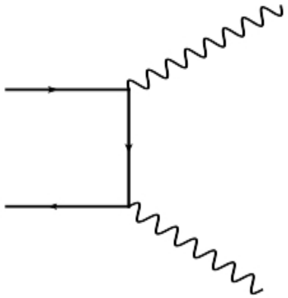
$pp \to \gamma\gamma$

- Require precise theoretical predictions (NNLO)

Di-photon production at the LHC

- New NNLO calculation: 2γNNLO
  (S. Catani, L. Cieri, D. de Florian, G. Ferrera, M. Grazzini)
  - parton-level event generator, based on q_T-subtraction
    - Analytic cancellation of infrared poles
  - using a smooth isolation criterion to define photons
  - includes all O(α_s^2) corrections to direct photon production pp $\rightarrow \gamma\gamma$
  - First fully consistent inclusion of the Box contribution

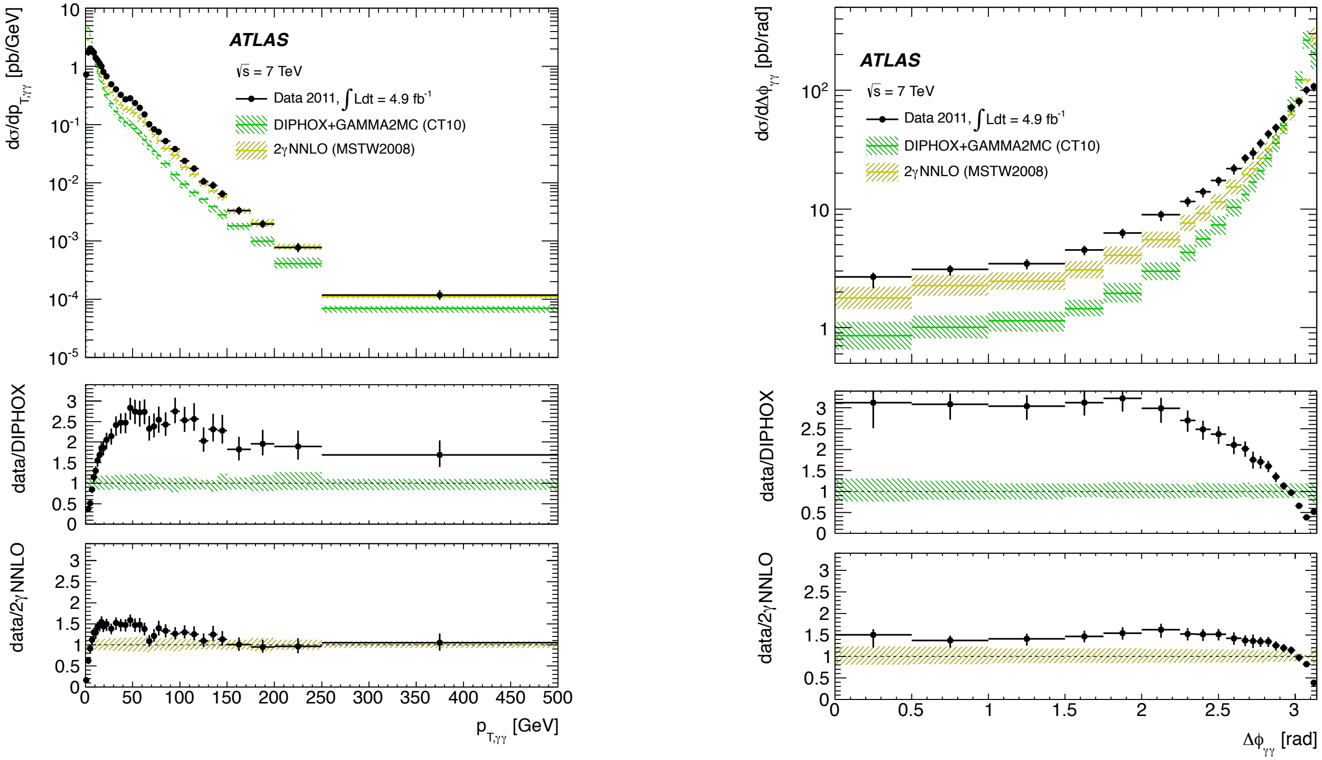




O(α_s^2), gluon luminosity   comparable size to   O(α_s^0), qq luminosity

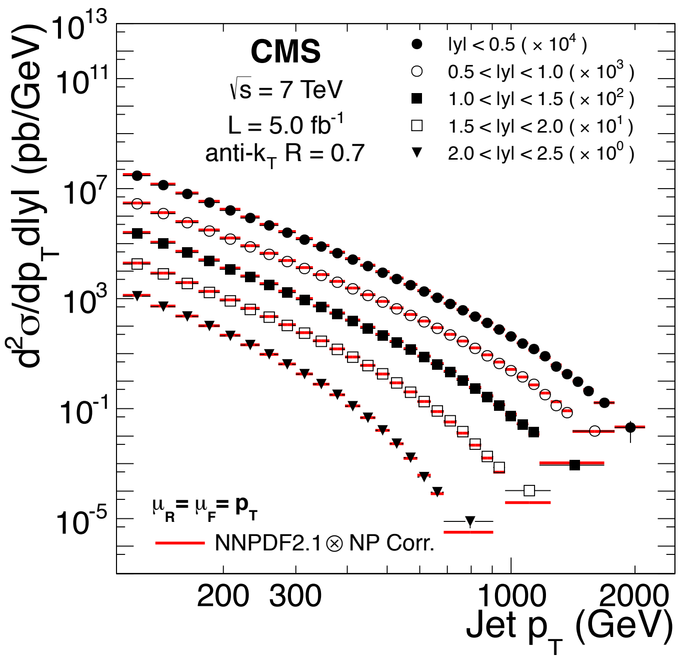
  - Box also included in NLO-type codes (DIPHOX+gamma2MC, MCFM)
    (T. Binoth, J.P. Guillet, E. Pilon, M. Werlen; Z. Bern, L. Dixon, C. Schmidt; J. Campbell et al.)

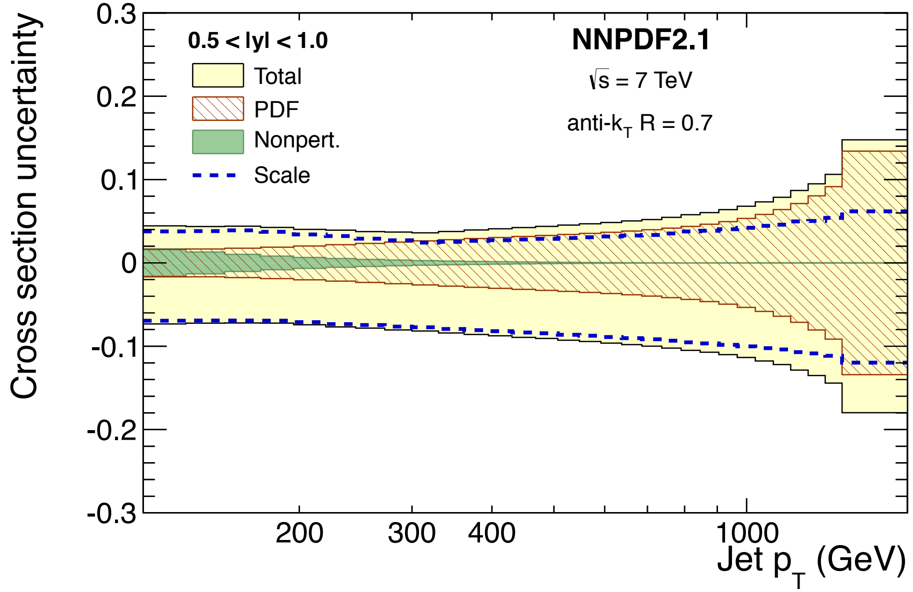
ATLAS di-photon results



- Inclusion of NNLO corrections resolves discrepancy between NLO-type prediction and data
  - Despite the use of slightly different cone isolation criteria

Jet cross sections at LHC

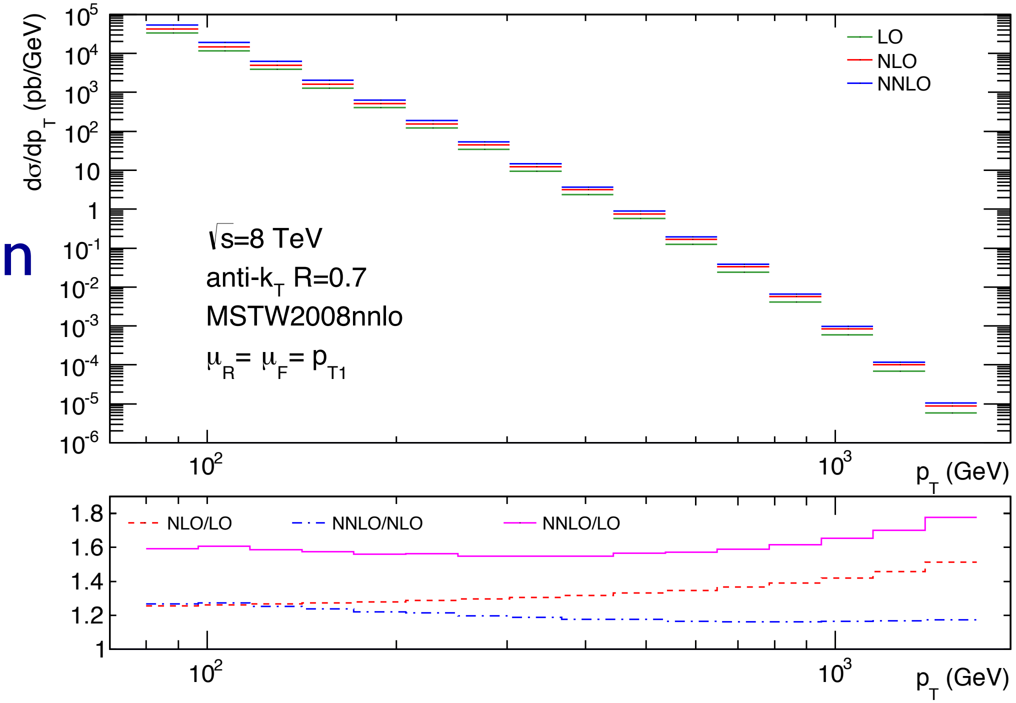




- Jet data can be used to constrain parton distributions
- Scale and PDF uncertainties on NLO prediction of comparable size
- Need improved theory (NNLO)

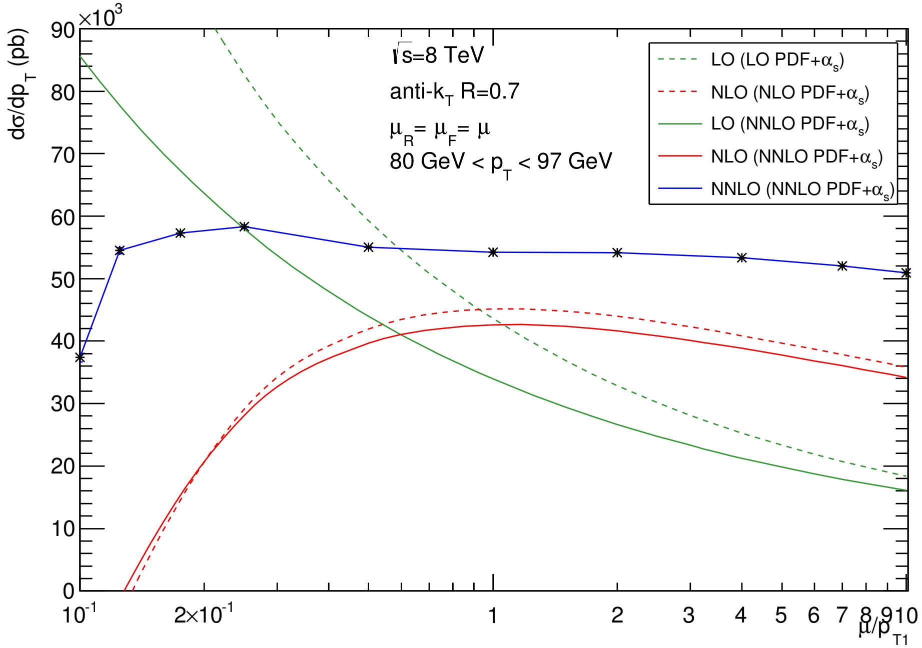
pp → 2jets at NNLO

- First results at NNLO available
  - gg → 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 → 2jets at NNLO

- Inclusive jet p_T distribution: scale dependence (gluons only)
  (J. Currie, A. Gehrmann-De Ridder, E.W.N. Glover, J. Pires, TG)
  - Dynamical scale choice: leading jet p_T

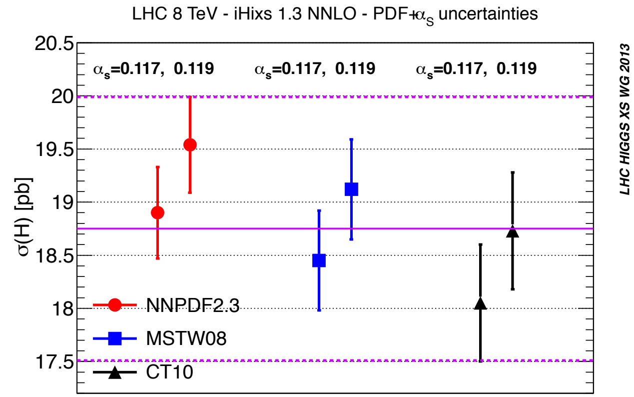


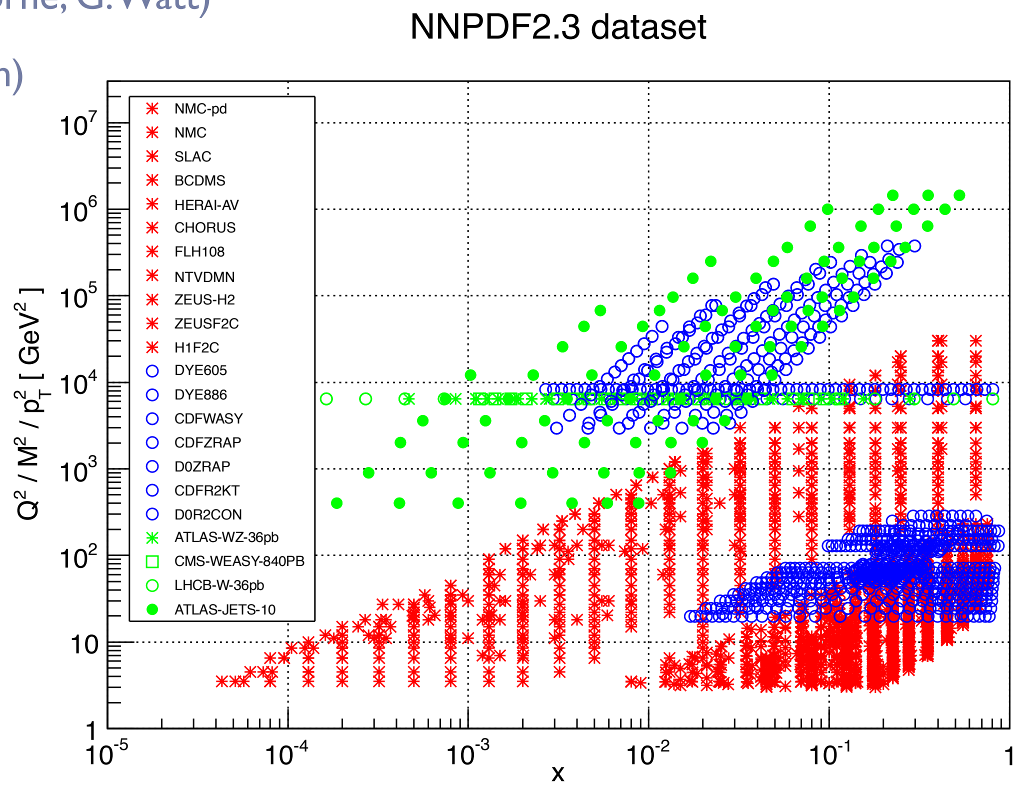
- Stabilization at NNLO

- Precision physics with LHC data

Parton distributions from the LHC

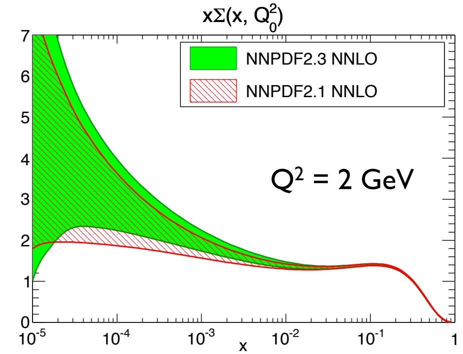
- Parton distributions determined from global fit to data
  - MSTW (A. Martin, J. Stirling, R. Thorne, G. Watt)
  - ABM (S. Alekhin, J. Blümlein, S. Moch)
  - CTEQ (J. Huston et al.)
  - NNPDF (R. Ball, S. Forte et al.)
  - JR (P. Jimenez-Delgado, E. Reya)
- Enter all predictions of cross sections

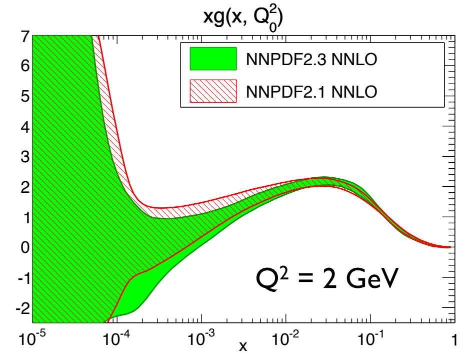


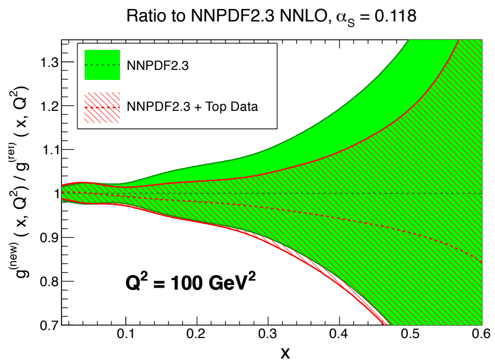


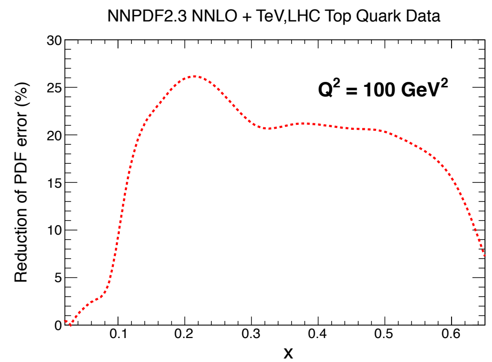
Parton distributions from the LHC

- LHC data starting to impact (NNPDF)
  - High-E_T jets
  - Vector bosons
  - Low-x at LHCb
- Top cross section
  - Dominated by gluon fusion
  - Total cross section at NNLO included in fit
    (M. Czakon, M. Mangano, A. Mitov, J. Rojo)
  - Improved knowledge at large x



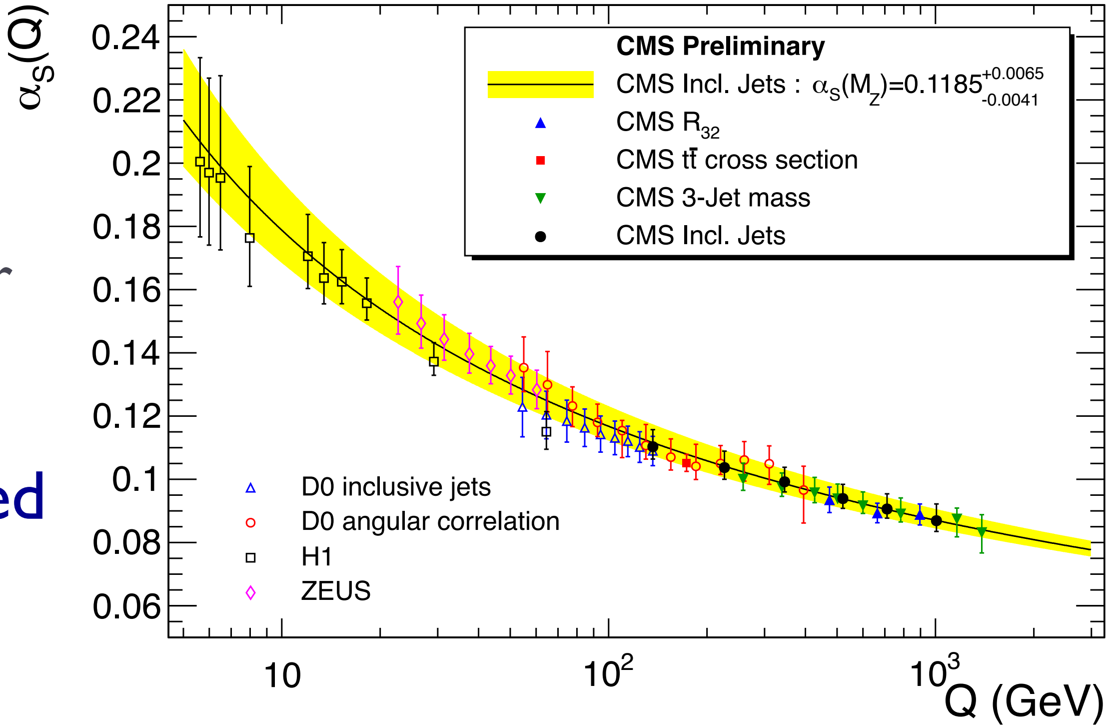






Strong coupling constant at the LHC

- Inclusive jet production
  - Correlation between α_s and gluon distribution
- Jet ratios
  - $R_{3/2}$ particularly sensitive
- Event shapes
  - Classical observable at e^+e^- colliders
  - Under development for hadron colliders, e.g. 3-jet mass
- Precision theory-limited
  - NNLO needed



- 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 → 2j (C. Anastasiou, N. Glover, C. Oleari, M. Tejeda-Yeomans; Z. Bern, L. Dixon, A. De Freitas)
    - pp → V+j (L. Garland, N. Glover, A. Koukoutsakis, E. Remiddi, TG)
    - pp → V+ γ (L. Tancredi, E. Weihs, TG)
    - pp → H+j (N. Glover, M. Jaquier, A. Koukoutsakis, TG)
    - pp → tt (P. Bärnreuther, M. Czakon, P. Fiedler; R. Bonciani, A. Ferroglia, A. von Manteuffel, C. Studerus, TG)
  - In progress
    - pp → VV (L. Tancredi, E. Weihs, TG; J. Henn, V. Smirnov)
- Research directions: towards different masses and 2 → 3
  - 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

- 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 ahead with the LHC