Eidgenössische Technische Hochschule Zürich
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Perturbative QCD for the LHC

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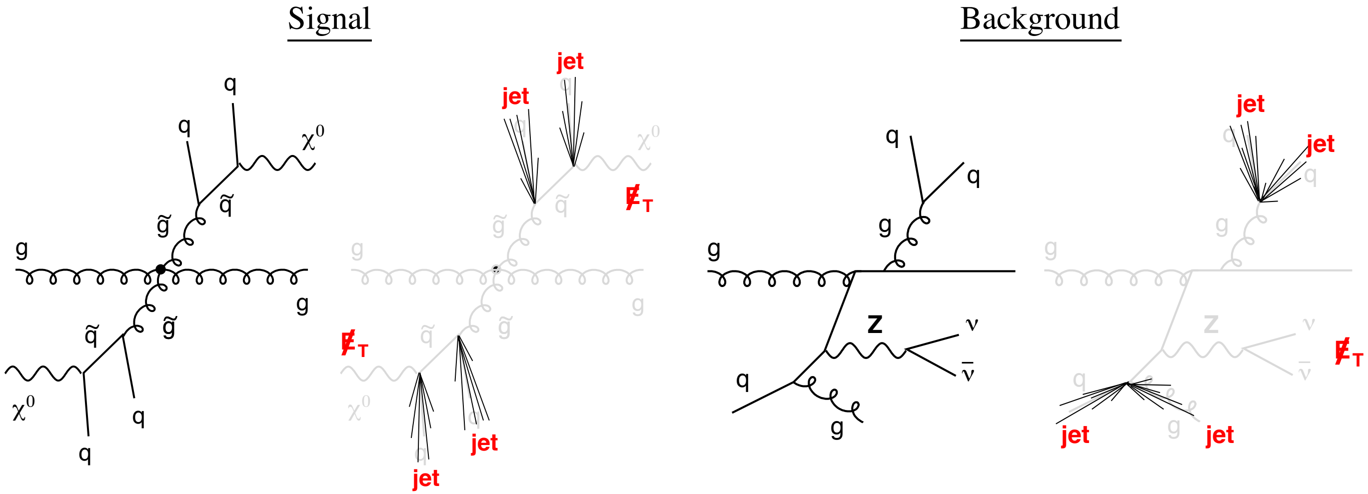
Brookhaven Forum 2013, Brookhaven National Laboratory, May 2013

Multi-particle production at LHC

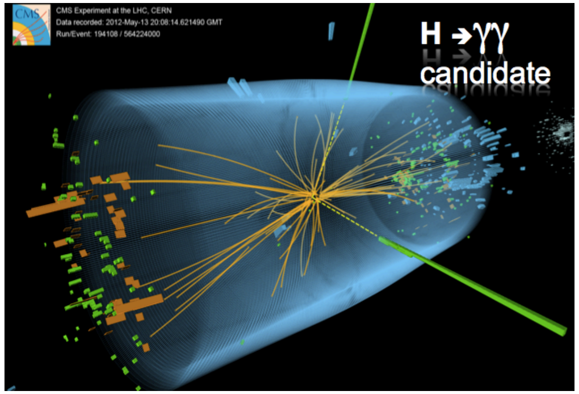
- LHC brings new frontiers in energy and luminosity
- Production of short-lived heavy states (Higgs, top, SUSY...)
  - detected through their decay products
  - yield multi-particle final states involving jets, leptons, γ , $\not{E}_T$
- Search for new effects in multi-particle final states
- Need precise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

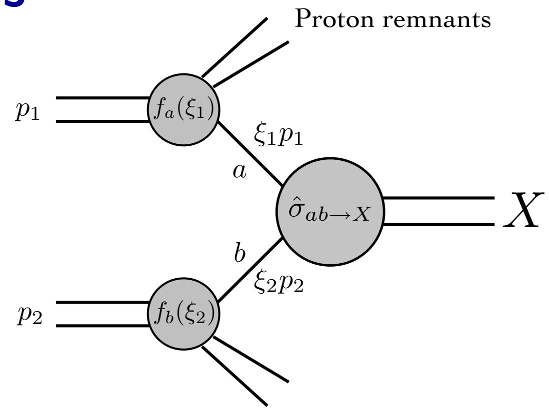


Example: SUSY signature 4j + $\not{E}_T$

QCD in hard scattering processes

- For processes with $Q^2 \gg M^2_{proton}$, factorization relates hadronic and partonic cross sections





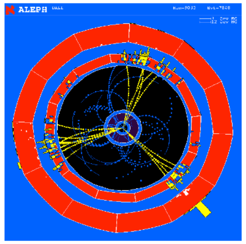
$$\sigma_{p_1 p_2 \to X} = \sum_{a,b=q,\bar{q},g} \int_0^1 \mathrm{d}\xi_1\, \mathrm{d}\xi_2\, f_a(\xi_1) f_b(\xi_2) \hat{\sigma}_{ab\to X}(\xi_1 p_1, \xi_2 p_2)$$

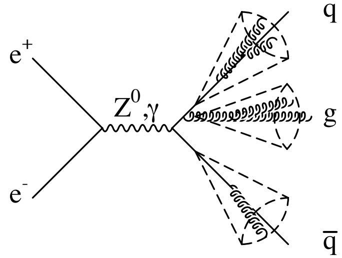
- PDFs: determined from data
  - MSTW08, CT10, NNPDF, ...

- Parton-level hard scattering cross section: $\hat{\sigma}_{ab\to X}$
  - calculable in perturbative QCD as expansion in α_s
  - Depends on scales: renormalization μ_R and factorization μ_F

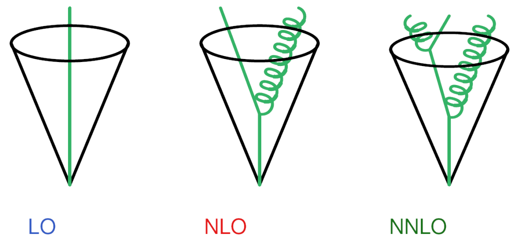
Jets

- Clusters of hadrons observed as jets
  - e.g. three-jet production at LEP





- Partons combined into jets using the same jet algorithm
  - Mostly used at LHC: anti-k_T clustering (M. Cacciari, G. Soyez, G. Salam)

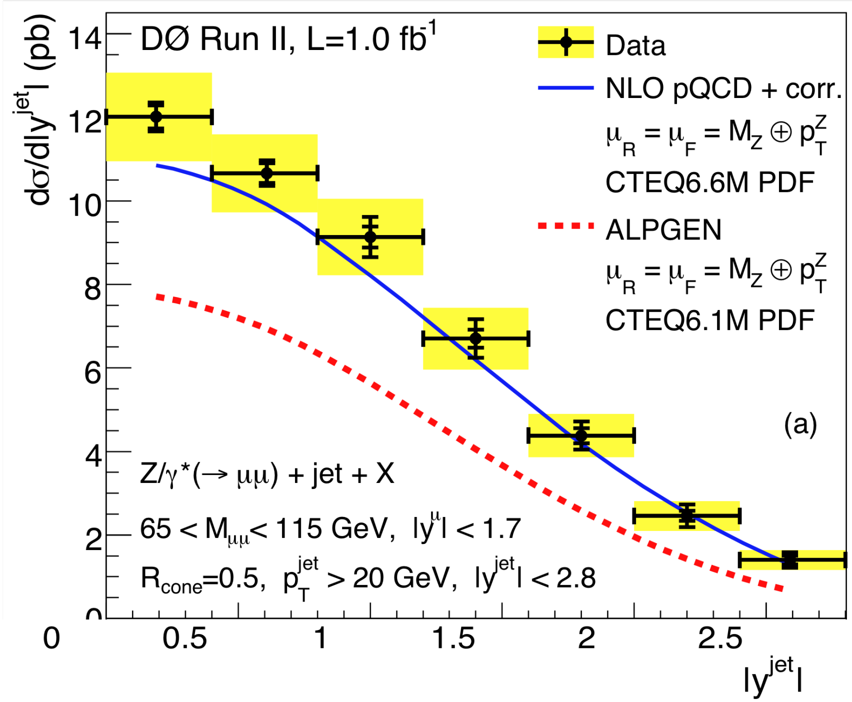


- Jets in perturbative QCD
  - No algorithm dependence at leading order
  - Theoretical description more accurate with increasing order
  - Current status: at most three partons in one jet

NLO Multiparticle production

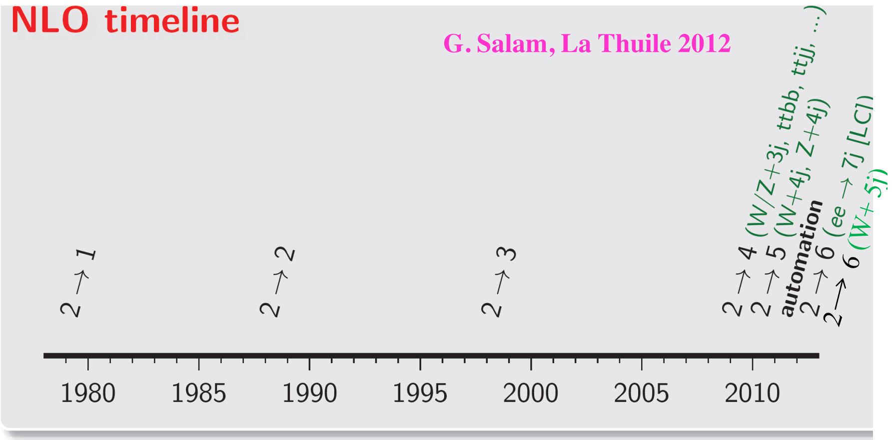
- Why NLO?
  - reduce scale uncertainty of LO theory prediction
  - reliable normalization and shape
  - accounts for effects of extra radiation
  - jet algorithm dependence

- Example: Z+j at Tevatron
  - NLO error: ~15%
  - substantial NLO effect
  - correction not constant



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 $WWW, ZZW, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma$ $WZj, W\gamma j, \gamma jj$ [illegible]
4. $pp \to t\bar{t}b\bar{b}$	relevant fo[illegible] $t\bar{t}H$, [illegible]mput[illegible] by Bredens[illegible]in/D[illegible]ner/[illegible]tmaier/Pozzorini [41, 42] and Bev[illegible]qua/Cz[illegible]kon/Papadopoulos/Pittau/Worek [43]
5. $pp \to V$+3jets	[illegible]+3jets ca[illegible]ul[illegible]ed by the Blackhat/Sherpa [44] [illegible]nd R[illegible] [4[illegible]] collaborations Z+3jets b[illegible] Blackhat/Sherpa [46]
Calculations remaining from Les Houches [illegible]05	
6. $pp \to t\bar{t}$+2jets	[illegible]levant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek [47, 48]
7. $pp \to VV\, b\bar{b}$,	Pozzorini et al.[25],Bevilacqua et al.[23]
8. $pp \to VV$+2jets	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]

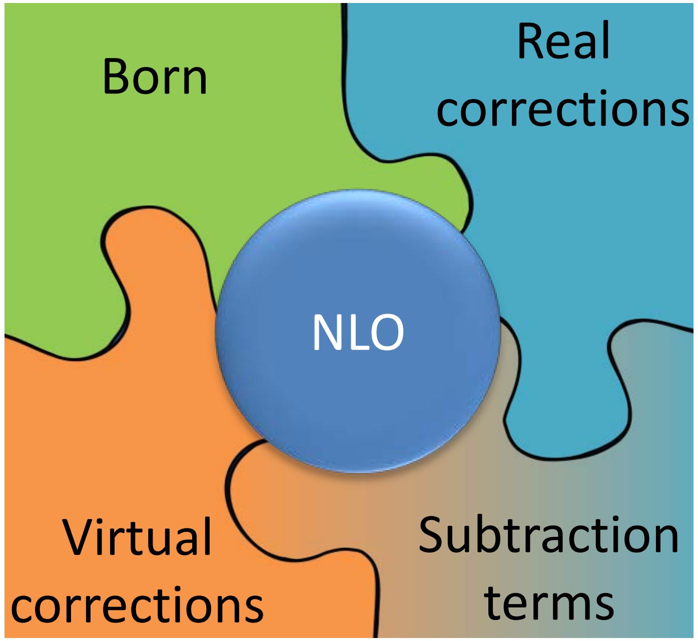
CLOSED

K. Melnikov, MITP, 2013

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

Automation in NLO computations

- NLO predictions obtained by combining numerical packages
- Currently implemented on process-by-process basis
- Impressive list of results:
  - multiple jets (up to 4)
  - gauge boson and up to 5 jets
  - two gauge bosons with up to 2 jets
  - Top quarks with jets (up to 2) or a gauge boson
  - Higgs and up to 2 jets



$$\sigma^{NLO}_{(m)} = \int_{\Phi_m} \left[d\sigma^{Born} + d\sigma^{V} + \int_{\Phi_1} d\sigma^{S} \right] + \int_{\Phi_{m+1}} \left[d\sigma^{R} - d\sigma^{S} \right]$$

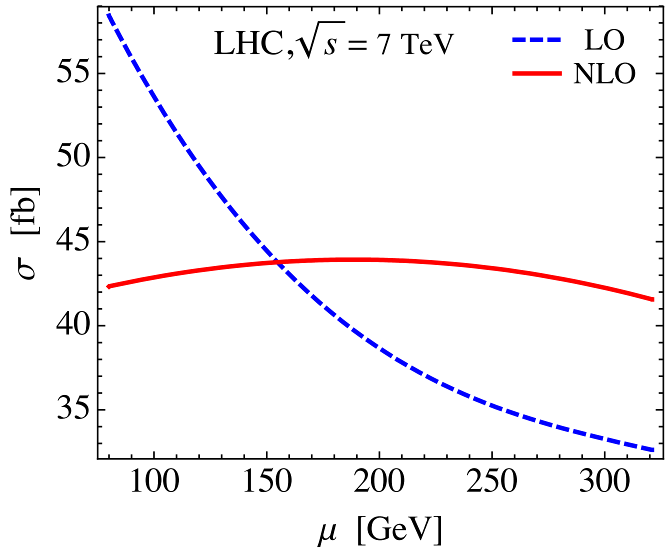
- Address rich phenomenology with few examples

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

- Background to BSM searches and for H→WW decay
- Two NLO 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:

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

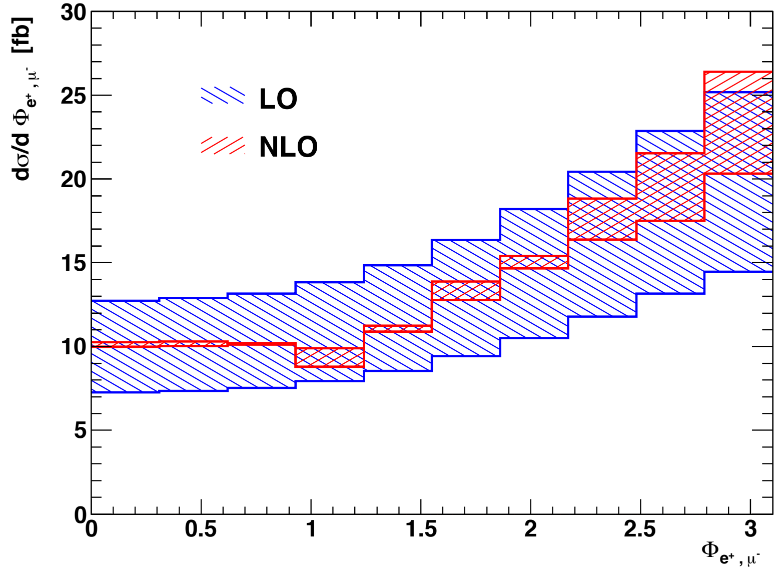
- Scale variation : Use $\mu = \mu_F = \mu_R$,



- 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 $M_W < \mu < 4\,M_W$



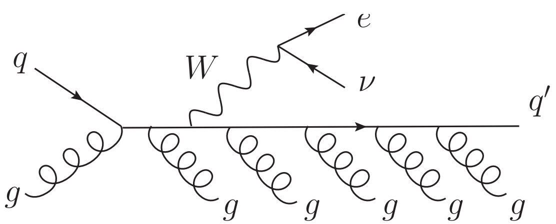
- NLO predictions within LO uncertainty band
- Relevant for designing cuts for the determination of HWW coupling
  - QCD process: peaked at π
  - Higgs signal: peaked at 0

W+5 jets at NLO

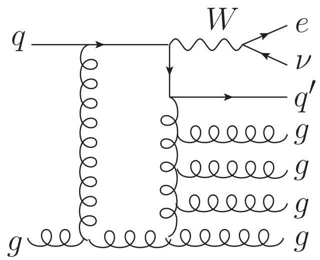
- First 2→6 NLO calculation at a hadron collider
- Using Blackhat + Sherpa

(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

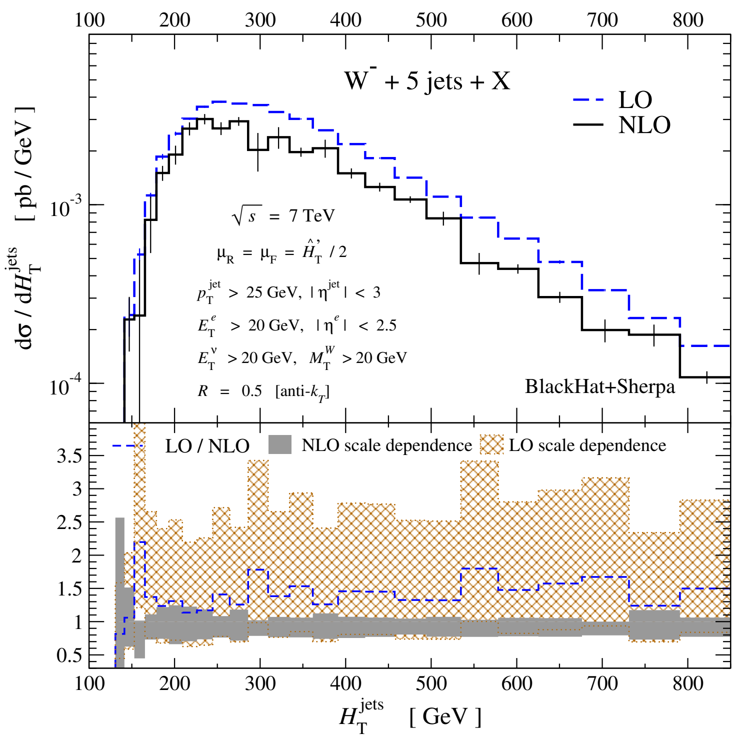
W+5 jets at NLO

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

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

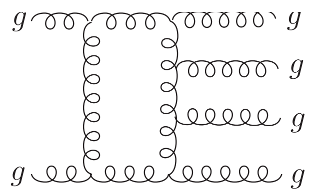
$$\hat{H}'_{\mathrm{T}} \equiv \sum_m p_{\mathrm{T}}^m + E_{\mathrm{T}}^W$$

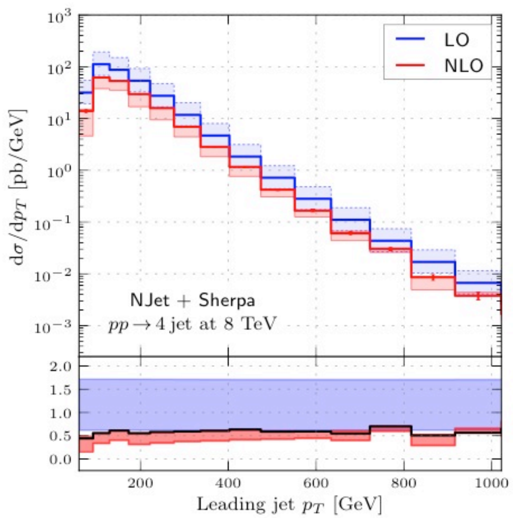
  - scale variation $\mu/2 \ldots 2\mu$
  - Observe:
    - Scale dependence reduced at NLO
    - ratio NLO/LO constant over full kinematical range
- NLO helps to motivate the scale choice



pp→4jets 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)

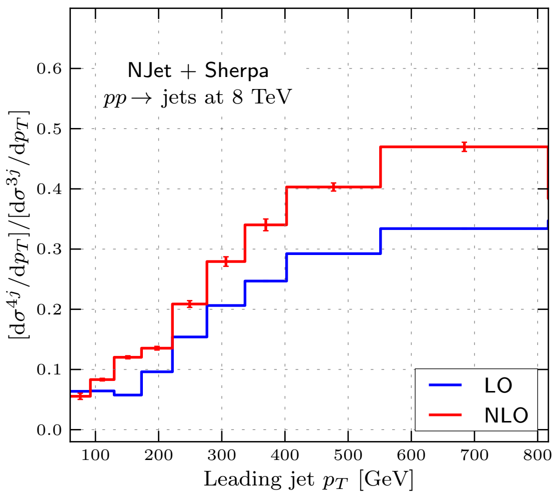




Dynamical scale:

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

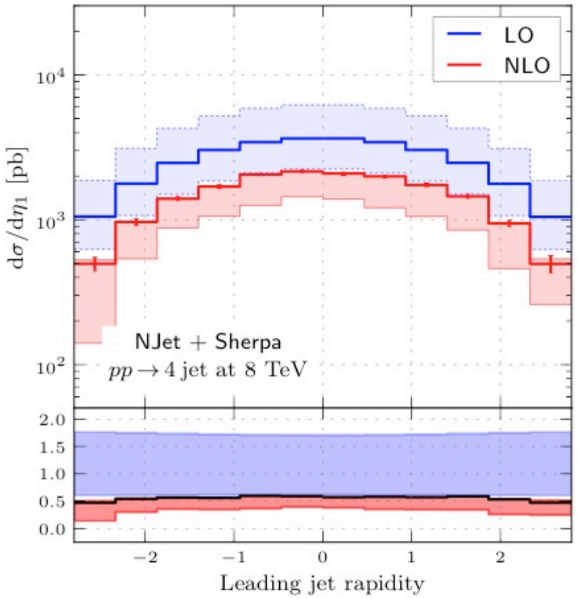
$$\hat{H}_T = \sum_{i=1}^{N_{\text{parton}}} p_{T,i}^{\text{parton}}.$$



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

pp →4jets at NLO

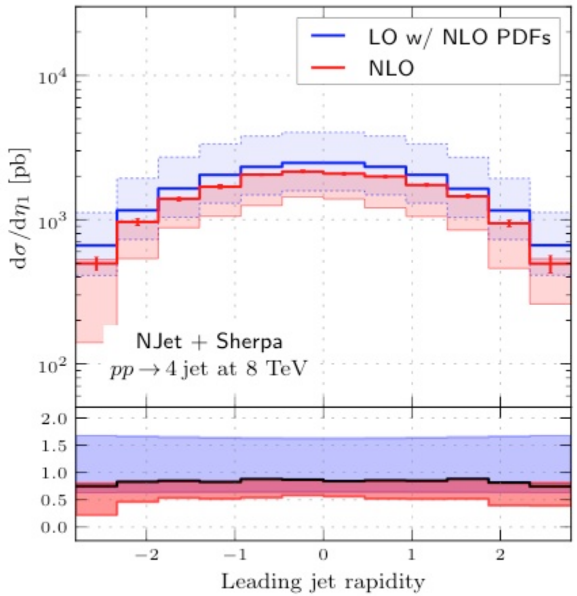
- To disentangle NLO effects from parton distributions and genuine NLO corrections from hard scattering process
  - Use NLO partons for both NLO and LO predictions



Dynamical scale

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

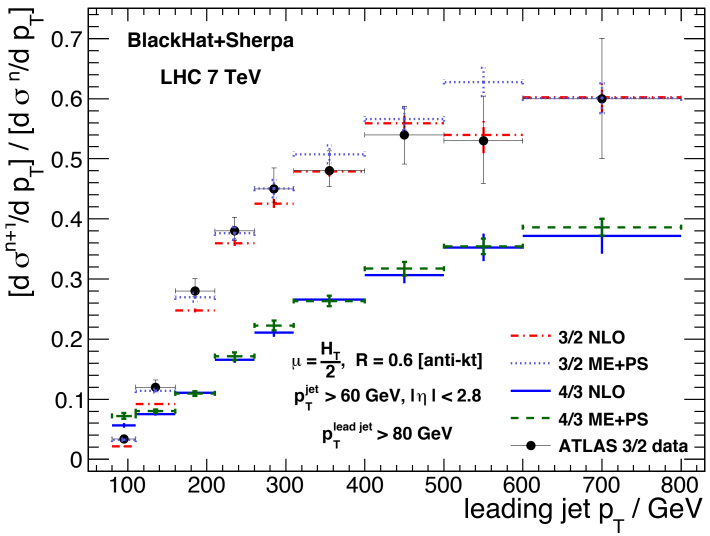
$$\hat{H}_T = \sum_{i=1}^{N_{\text{parton}}} p_{T,i}^{\text{parton}}.$$



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

Jet ratios at NLO

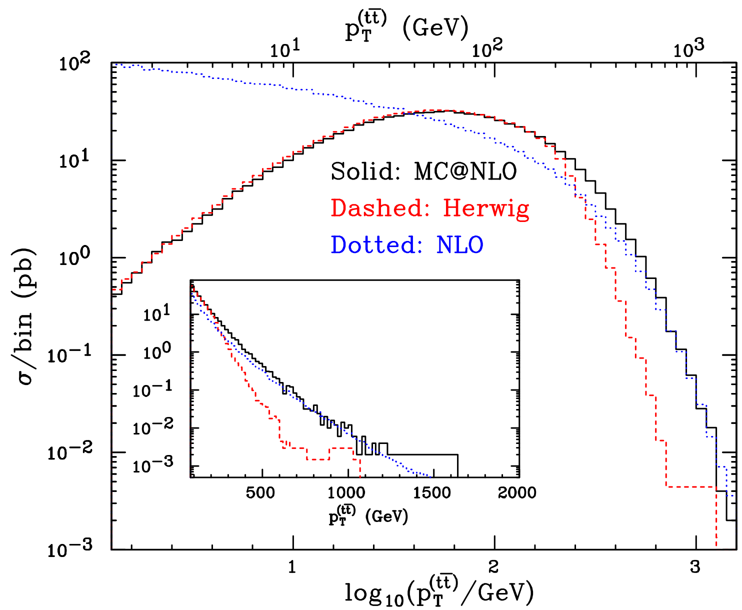
- Systematic uncertainties (th. and exp.) cancel in ratios
  - Predictions more reliable
  - Can be used in data-driven background estimation
- Jet ratio as function of leading jet p_T
  - NLO and parton shower both agree with data for large p_T
  - Parton shower (multiple emission) better at low p_T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



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

How to improve NLO predictions? Merging with parton showers

- Add multiple radiation from parton shower(PS) to NLO prediction (NLO) for a specific hard process
- Challenge: avoid double counting
- Two established methods
  - MC@NLO (S. Frixione, B. Webber)
  - POWHEG (P. Nason, C. Oleari)
- Combines NLO accuracy for hard radiation with multiple soft emissions
  - High-p_T: described by NLO
  - Low-p_T: described by the parton shower
- Ever increasing number of NLO predictions combined with PS



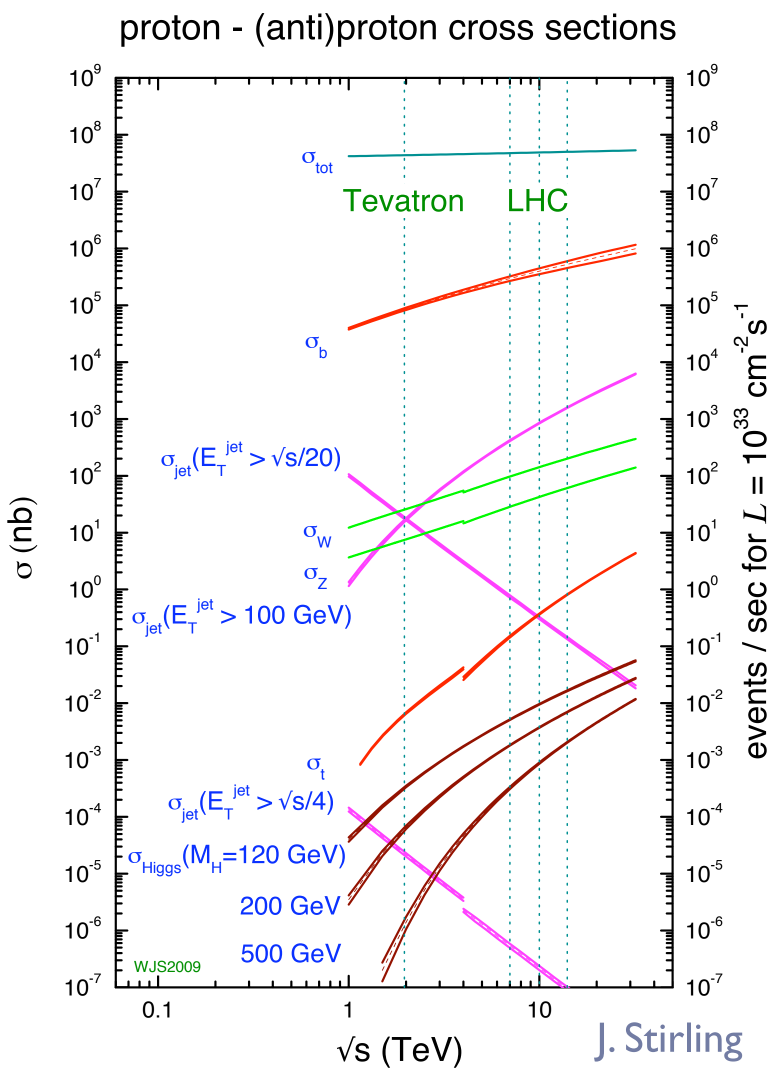
p_T-distribution in top quark pair production at Tevatron
(S. Frixione, P.Nason, B. Webber)

Next frontiers with NLO

- Full automation (well in progress)
  - 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)
  - MadLoop/aMC@NLO (R. Frederix et al.)
  - CutTools (G. Ossola, C. Papadopoulos, R. Pittau)
- 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)
- Work in progress

How to improve NLO predictions?
NNLO corrections

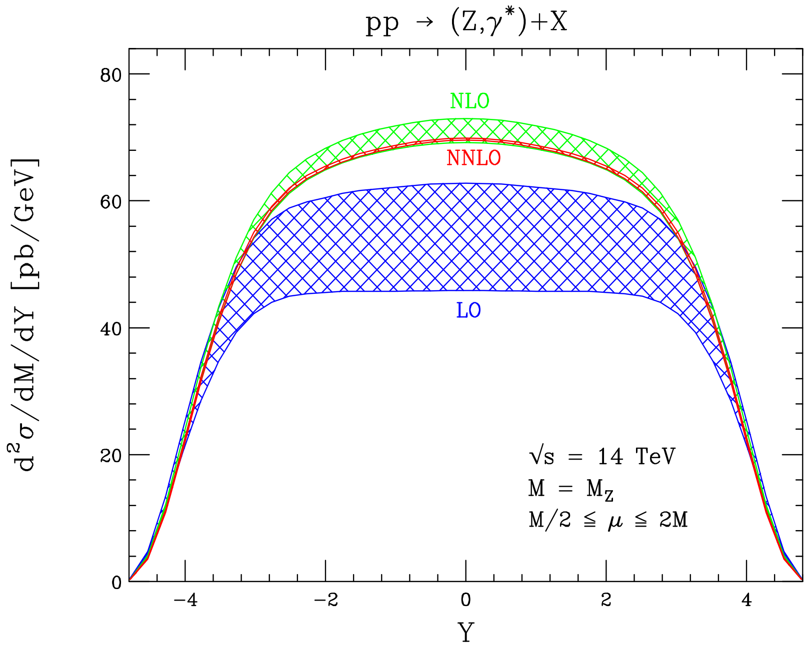
- Expectations at LHC: Large production rates for low multiplicity processes with
  - Jets
  - Top-quark pairs
  - Vector bosons
- Allow precise determinations
  - coupling constants
  - parton distributions
- Require precise theory description: NNLO



J. Stirling

NNLO observables at hadron colliders

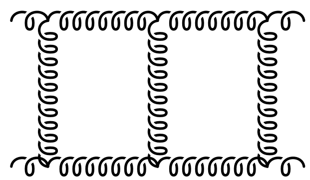
- NNLO predictions:
  - expected to have a per-cent level accuracy
  - yielding first reliable estimate of theoretical uncertainty
- For processes measured to few per cent accuracy
  - jet production
  - vector boson (+jet) production
  - top quark pair production
- For processes with potentially large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



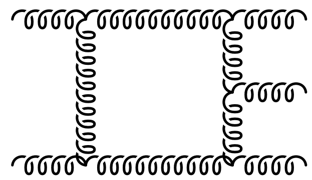
Rapidity distribution in Z production
(C. Anastasiou, L. Dixon, K. Melnikov, F. Petriello)

NNLO calculations

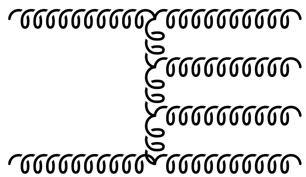
- Require three principal ingredients (here: pp → 2j)
  - two-loop matrix elements
    - explicit infrared poles from loop integral
      - known for all massless 2 → 2 processes



  - 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



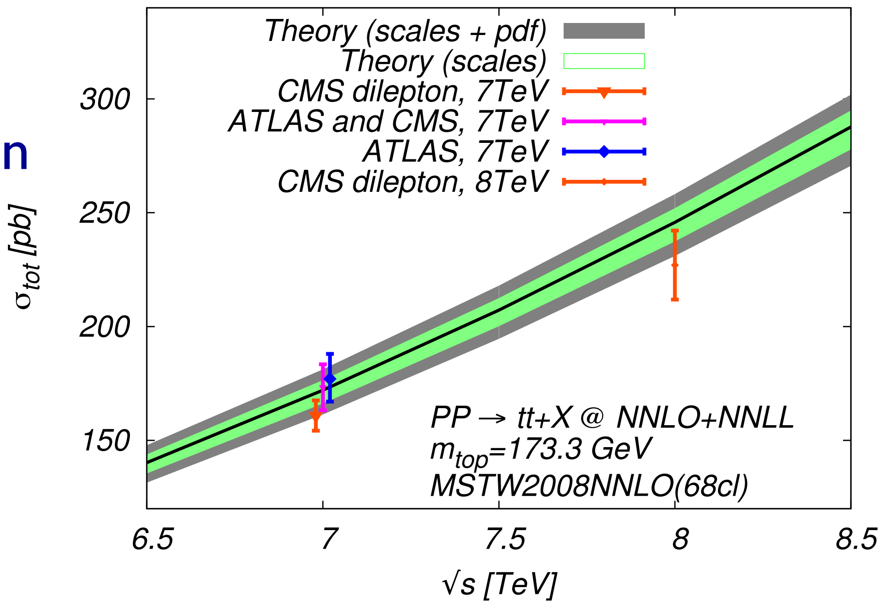
- Infrared poles cancel in the sum
- Challenge: combine contributions into parton-level generator
  - Need a method to extract implicit infrared poles

Real radiation at NNLO: methods

- Sector decomposition
  (T. Binoth, G. Heinrich; C. Anastasiou, K. Melnikov, F. Petriello)
  - pp → H, pp → 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 → $t\bar{t}$ (M. Czakon, P. Fiedler, A. Mitov, 2013)
  - pp → H+j (R. Boughezal, F. Caola, K. Melnikov, F. Petriello, M. Schulze, 2013)
- 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)
- Antenna subtraction (T. Gehrmann, E.W.N. Glover, AG)
  - e^+e^- → 3j (T. Gehrmann, E.W.N. Glover, G. Heinrich, AG; S. Weinzierl)
  - pp → 2j (T. Gehrmann, E.W.N. Glover, J. Pires, AG, 2013)

Top quark pair production at LHC

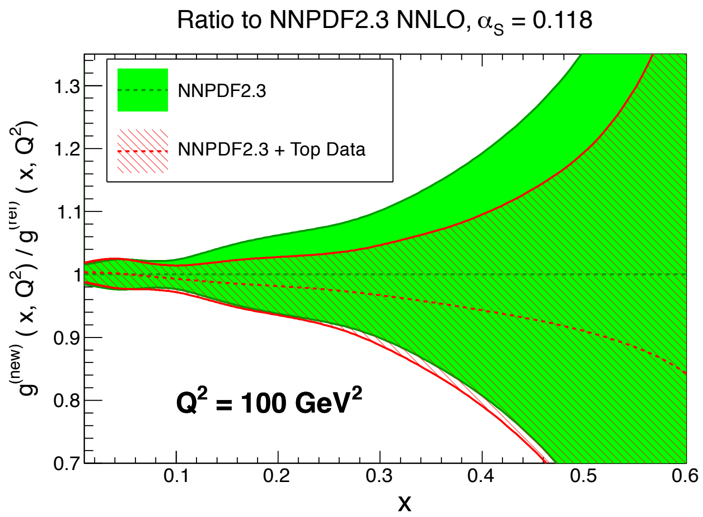
- Large production cross section at the LHC (~250pb at 8TeV)
  - Expected experimental error of ~5% for $\sigma_{t\bar{t}}$
  - NLO+NLL predictions yield an uncertainty of ~10%
- NNLO accuracy of theory needed
- Calculation for the total cross section completed (M. Czakon, P. Fiedler, A. Mitov)
  - From a purely numerical code
  - based on sector-improved subtraction
    - numerical cancellation of infrared poles

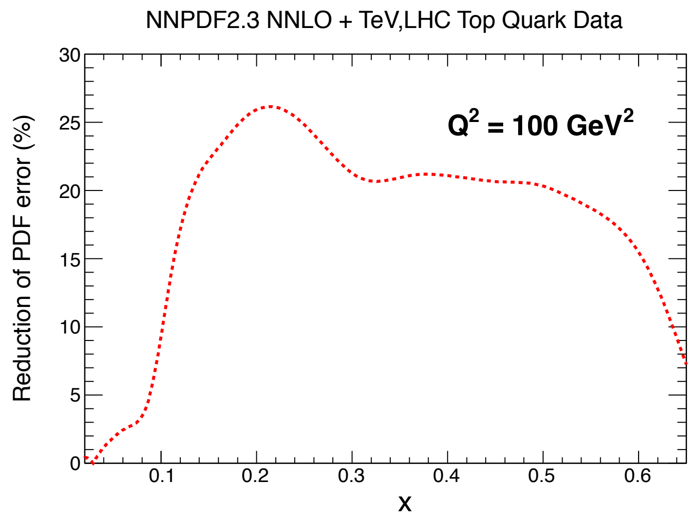


  - Observe: theoretical and experimental uncertainties comparable (% level)
- Differential distributions in progress

Top quark pair production at NNLO

- Impact on the determination of parton distributions
  - Top production at LHC mainly from qg and gg processes
  - Total cross section sensitive on gluon distribution
  - Inclusion into NNLO global parton distribution fit
    (M. Czakon, M. Mangano, A. Mitov, J. Rojo)





- Observe: reduced uncertainty on gluon at large x

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) (→see R. Boughezal parallel talk)
  - Full calculation and differential distributions in progress

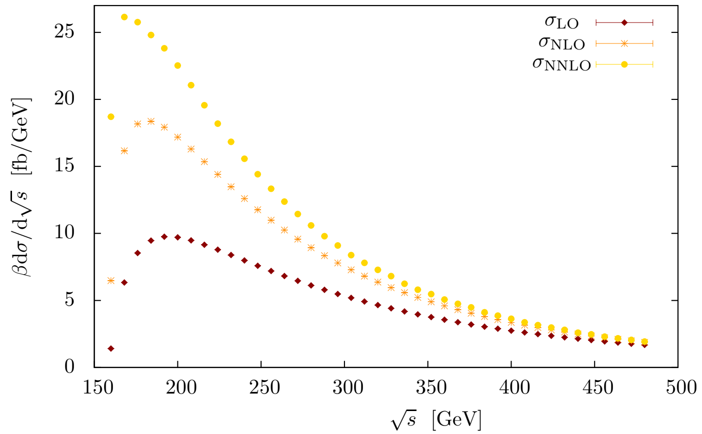
Higgs+jet production at NNLO

- 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

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

  - 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

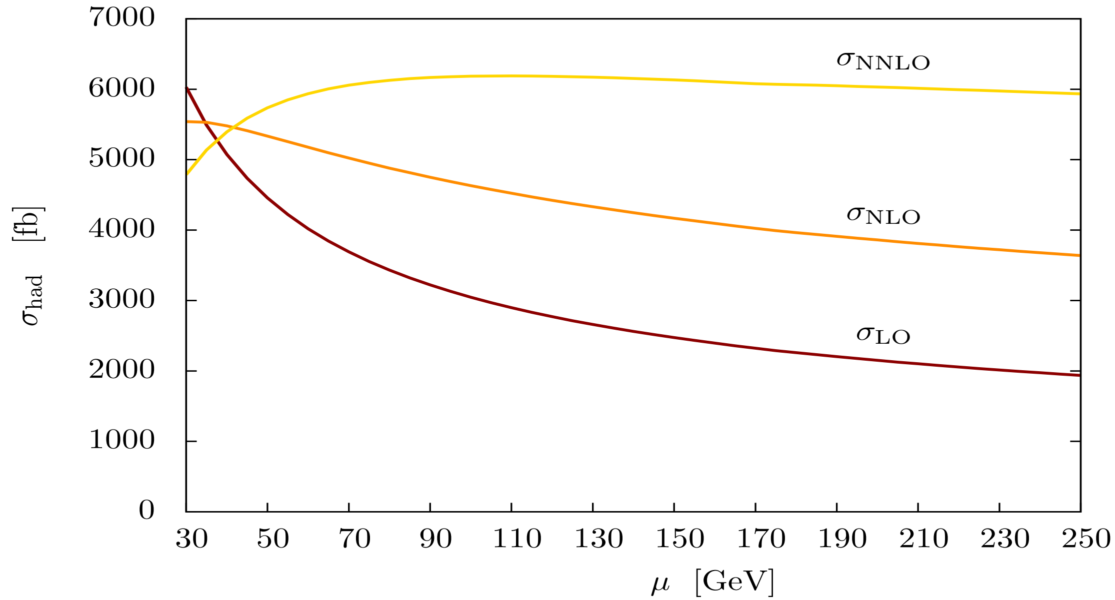


- Observe large NNLO effects close to partonic threshold region

Higgs+jet production at NNLO

- Scale dependence of the integrated total cross section

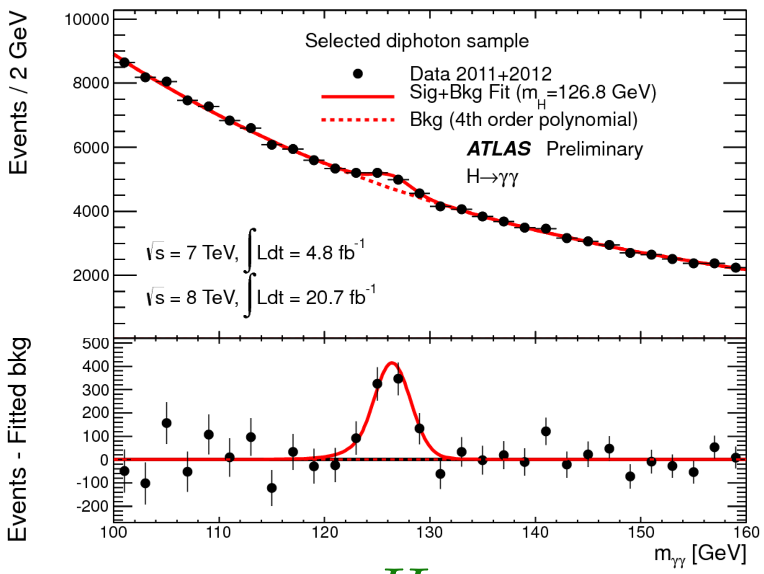
  $\mu = \mu_F = \mu_R$



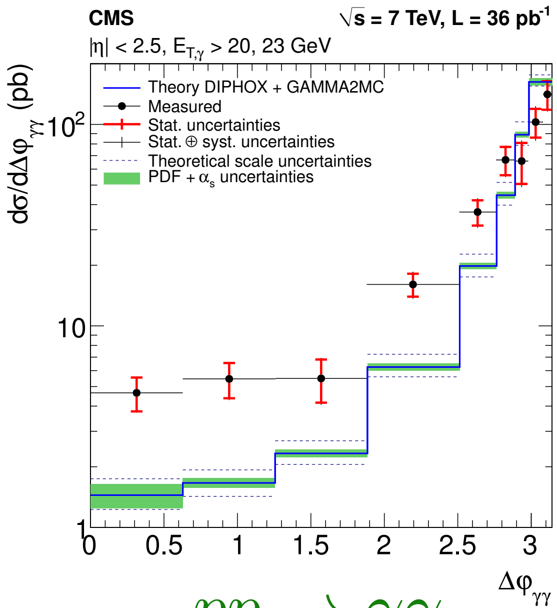
- Considerable stabilization at NNLO
- Corrections smallest for $\mu = M_H/2$ as in inclusive case

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



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



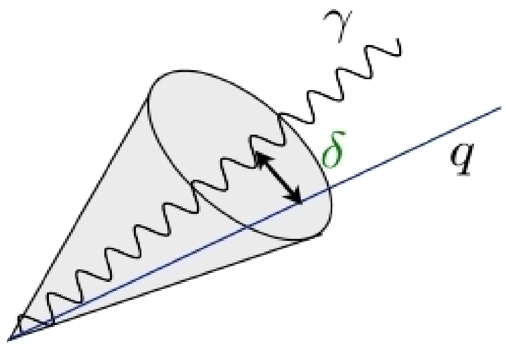
$pp \to \gamma\gamma$

- Require precise theoretical predictions (NNLO)

Photon isolation

- Photons need to be isolated from hadrons in events
  - Suppress secondary photons from hadron decays
  - Complete isolation not infrared safe, nor exp. well-defined
- Isolation criteria
  - Fixed cone isolation

$$\sum_{\delta<R} E_T^h < E_T^{max}$$



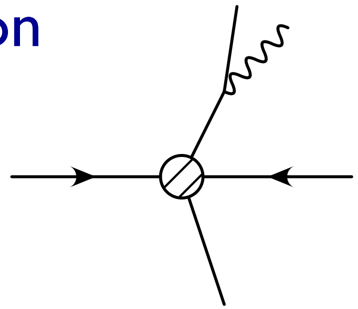
  - Smooth cone isolation (S.Frixione)

$$\sum_{\delta<R} E_T^h < E_T^{max} \left(\frac{1-\cos(\delta)}{1-\cos(R)} \right)^n$$

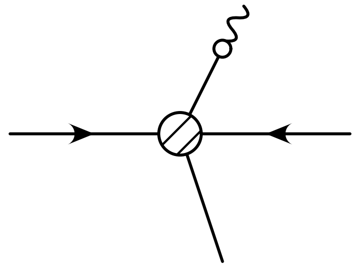
    - only soft radiation allowed close to photon
    - experimental implementation difficult (finite detector resolution)

Photon production mechanisms

- Direct process: photon produced in hard interaction
  - perturbatively calculable
  - collinear quark-photon contributions present



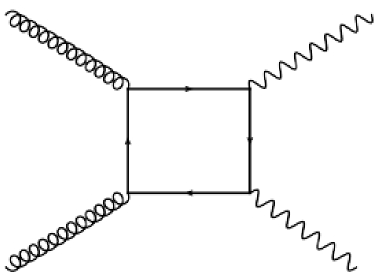
- Fragmentation of parton into photon:
  - described by a non-perturbative parton-to-photon fragmentation function
  - absorbs collinear singularities from direct process
  - requires non-perturbative input

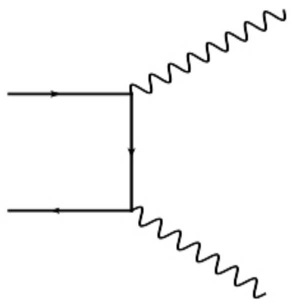


- Fixed cone isolation
  - both processes contribute
  - fragmentation contributions reduced but not eliminated
- Smooth cone isolation
  - no collinear nor fragmentation contributions

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 $\to \gamma\gamma$
  - First fully consistent inclusion of the Box contribution



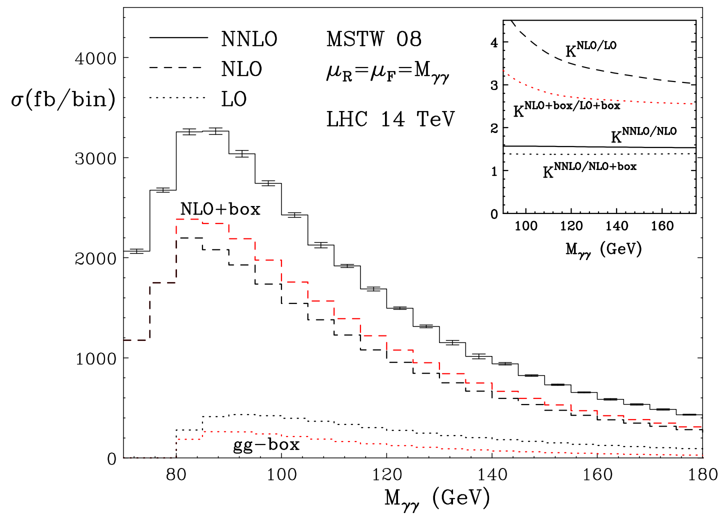


O(α_s^2), gluon luminosity comparable size to O(α_s^0), qq luminosity

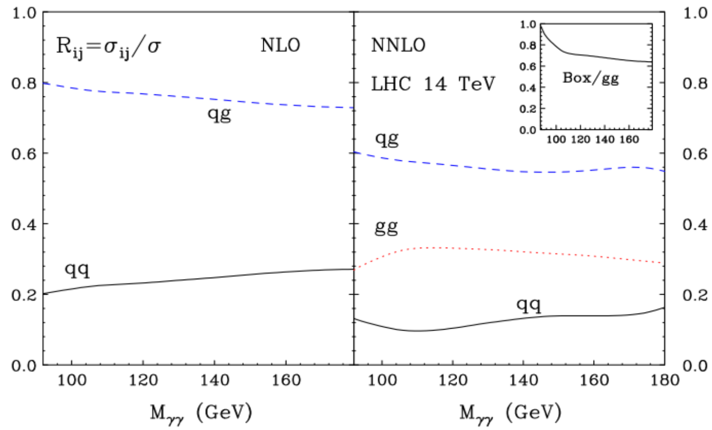
- Box also included in NLO-type codes (DIPHOX+gamma2MC, MCFM)
  (T. Binoth, J.P. Guillet, E. Pilon, M. Werlen; Z. Bern, L. Dixon, C. Schmidt; J. Campbell et al.)

Di-photon production with 2γNNLO

- Invariant-mass distribution with staggered photon cuts



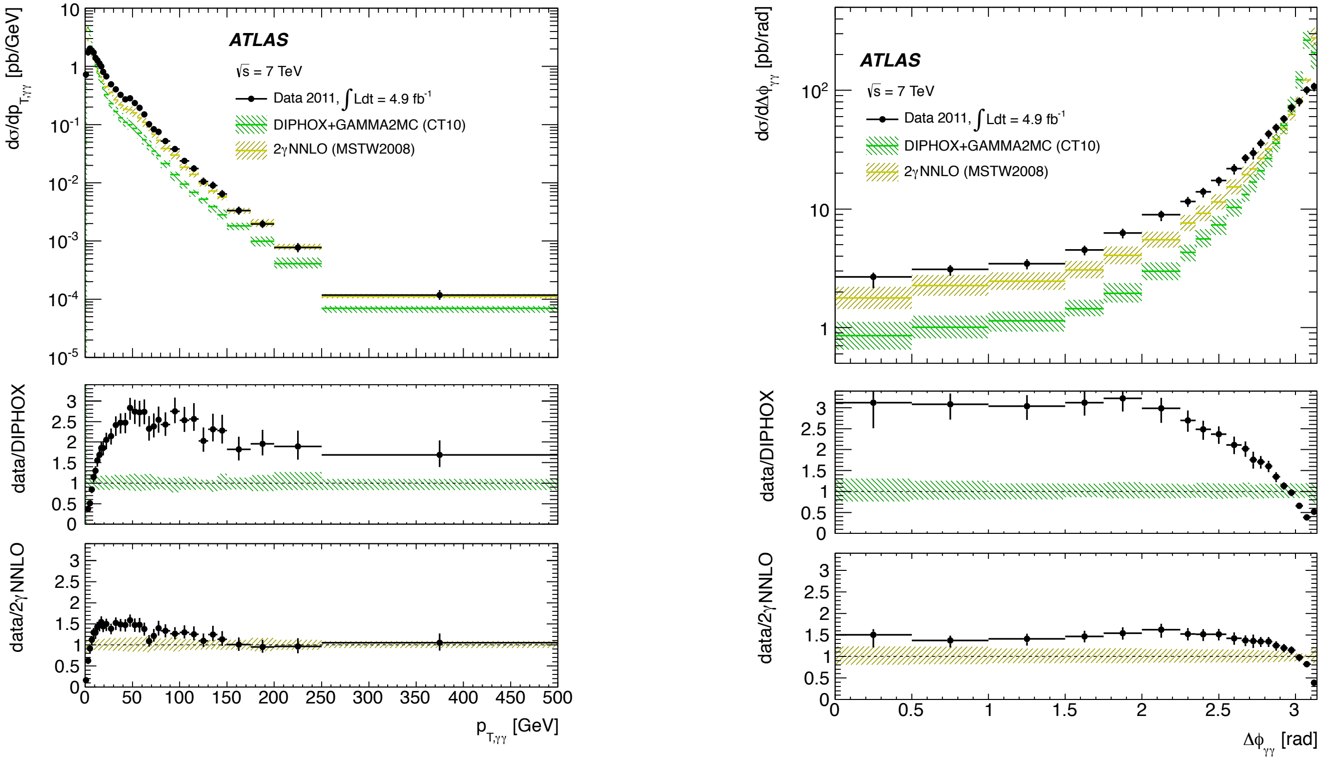
$$p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV}$$
$$p_T^{\gamma\,soft} \geq 25\,\mathrm{GeV}$$
$$|\eta^\gamma| \leq 2.5$$
$$20\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 250\,\mathrm{GeV}$$



L. Cieri, La Thuile, March 2013

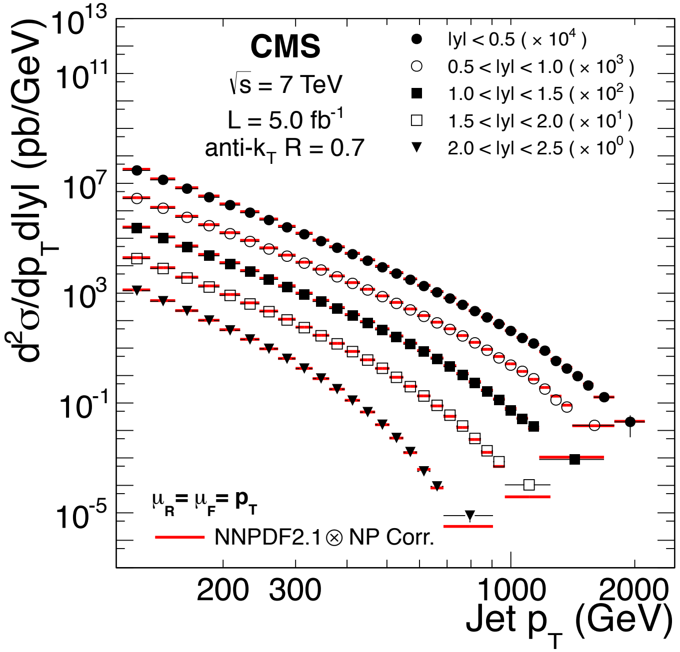
- NNLO corrections large in low $M_{\gamma\gamma}$ region
  - Main contribution from qg channel (dominant channel at NLO)

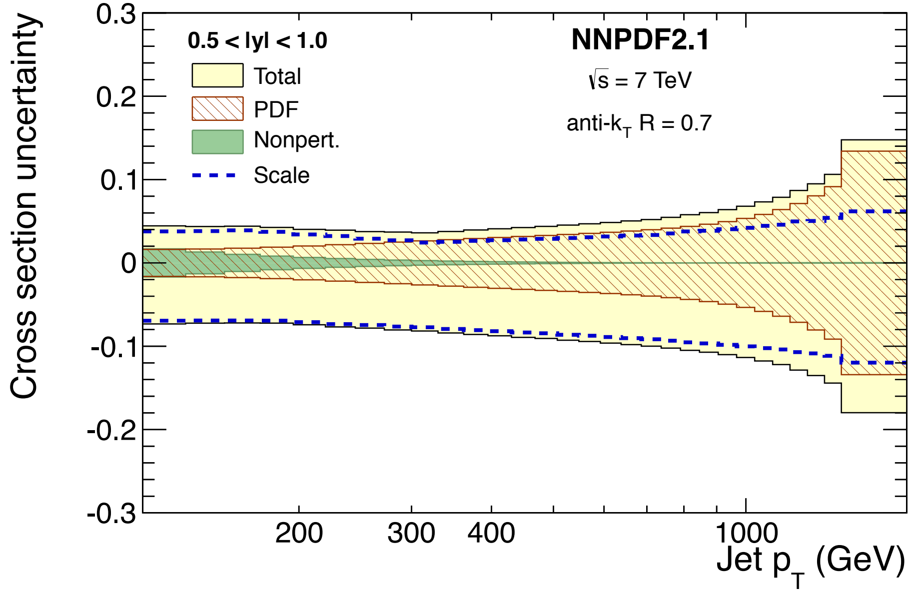
ATLAS di-photon results



- 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

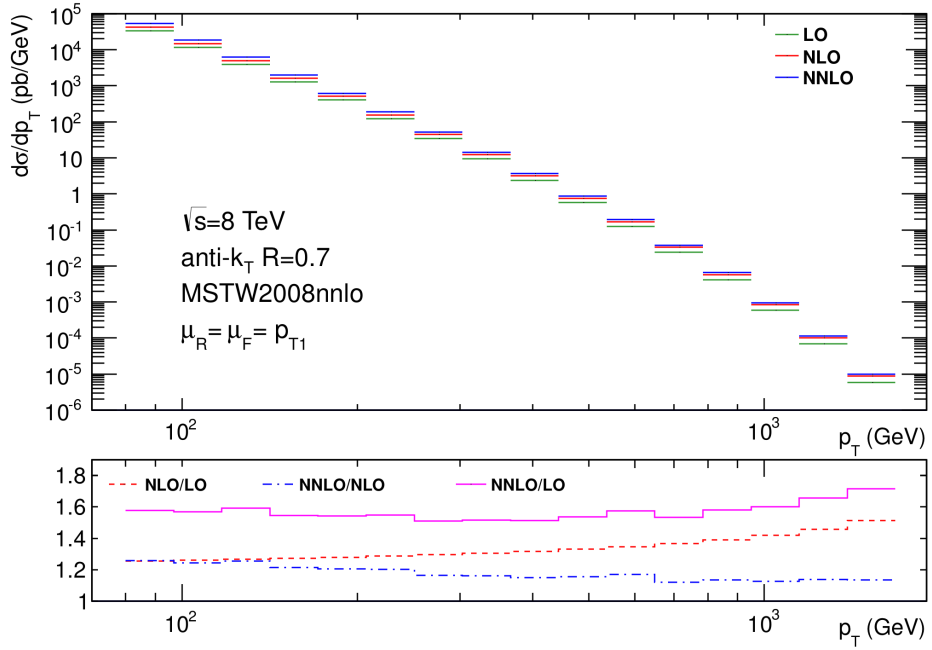




- Jet data can be used to constrain parton distributions
- Scale and PDF uncertainties on NLO prediction of comparable size
- Need improved theory (NNLO)

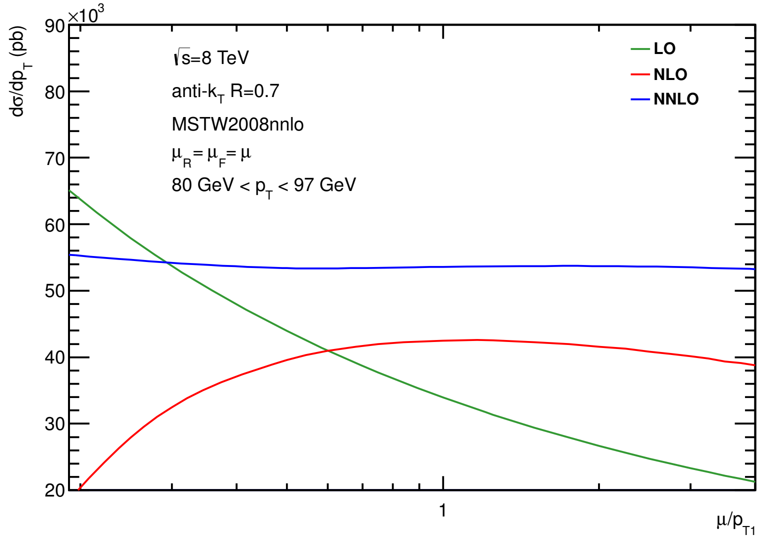
pp → 2jets at NNLO

- First results at NNLO available
  - gg → gg subprocess at leading colour (LC) (AG, T. Gehrmann, E.W.N. Glover, J. Pires)
  - 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

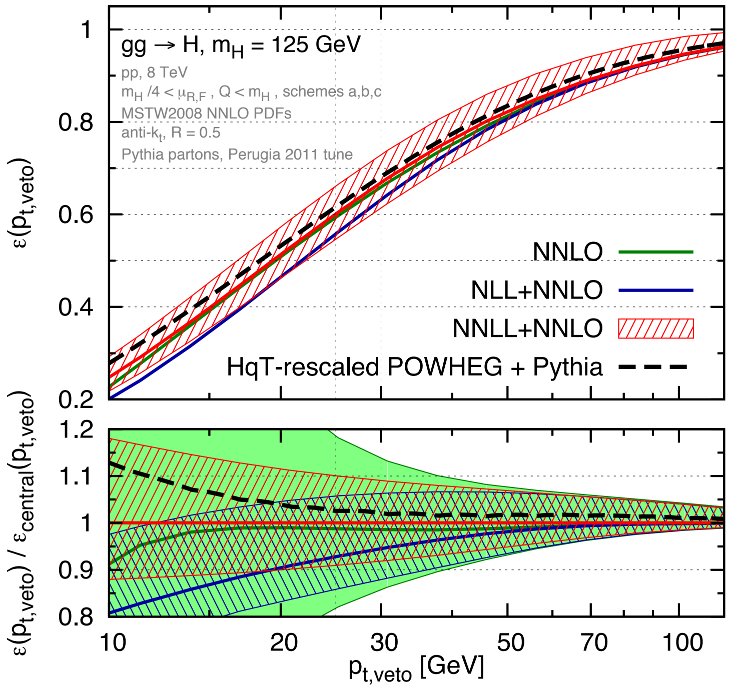
- **Inclusive jet p_T distribution: scale dependence** (gluons only, LC)
  (AG, T. Gehrmann, E.W.N. Glover, J. Pires)
  - Dynamical scale choice: leading jet p_T
  - Same PDF for all fixed order predictions



- **Stabilization at NNLO**

Improving NNLO with resummation

- Combining NNLO with analytic resummation
  - Fixed order becomes unreliable if large ratios of scales are involved, e.g. $p_T \ll M$
  - Perform all-order resummation of large logarithms
  - Combine with NLO or NNLO
  - State-of-the-art: NNLL
    (D. de Florian, G. Ferrera, M. Grazzini, D. Tomassini; M. Beneke, P. Falgari, S. Klein, C. Schwinn; V. Ahrens, A. Ferroglia, M. Neubert, B. Pecjak, L.L. Yang)
  - Jet-vetoed cross section in Higgs production at NNLL+NNLO
    (A. Banfi, P.F. Monni, G. Salam, G. Zanderighi; T. Becher, M. Neubert)
    - Observe substantial reduction of uncertainty



Conclusions and Outlook

- Apologises for all important contributions not covered in this 40 minutes talk
- Be prepared for exciting times ahead with the LHC