Standard Model Theory for Collider Physics

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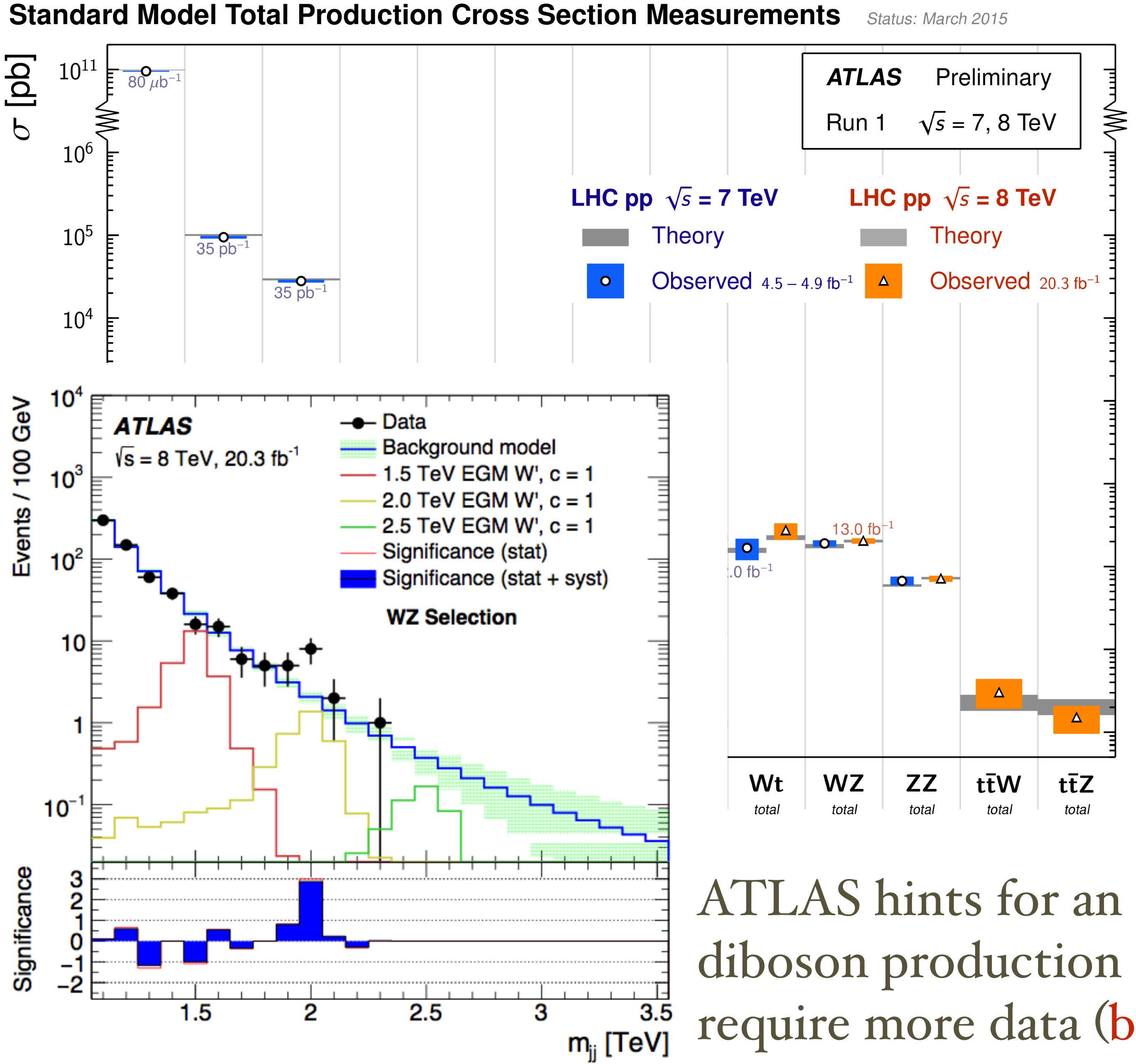
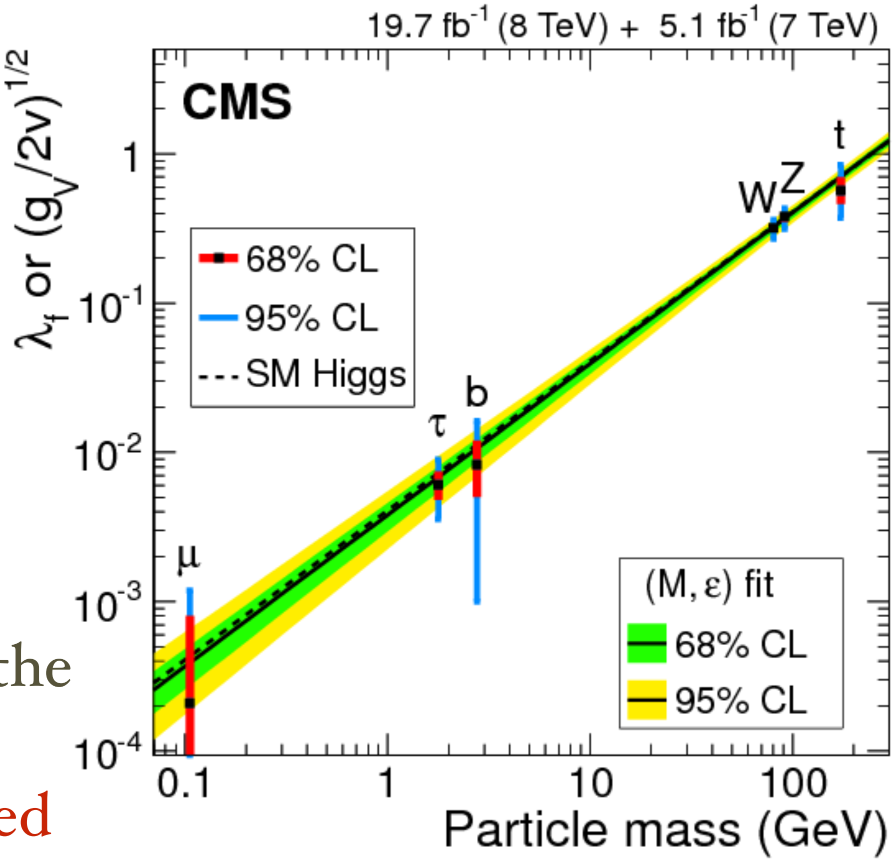
Introduction

Run 1 at the LHC was a great success for the Standard Model (SM)

No evidence for a new physics signal has been observed



The newly discovered Higgs particle appears SM like

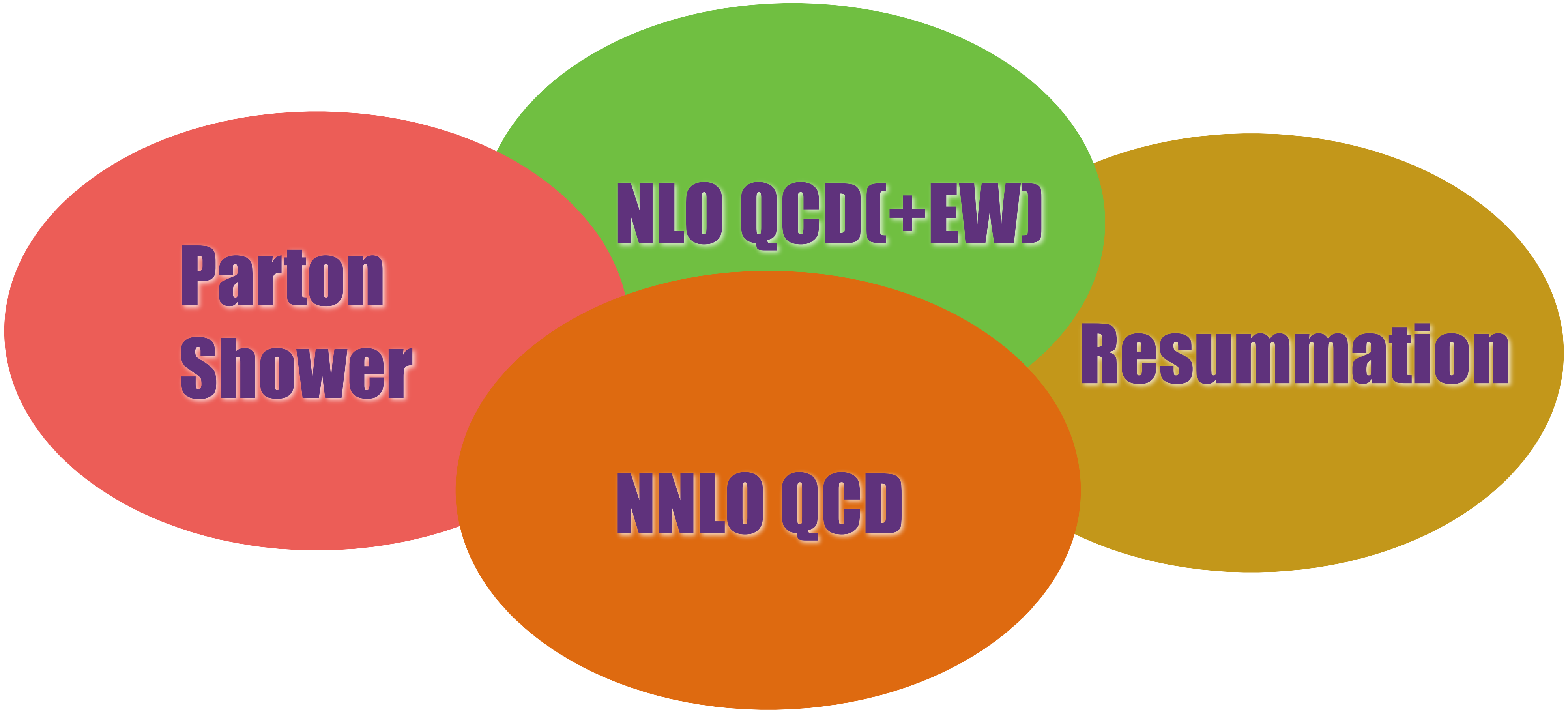


ATLAS hints for an excess in the diboson production at 2 TeV require more data (but triggered more than 30 TH papers !)

Introduction

Precise theoretical predictions maybe not crucial for Higgs discovery but essential to interpret the Higgs signal in the SM

→ this talk: quick overview of the progress and tools used in SM physics



Parton Shower

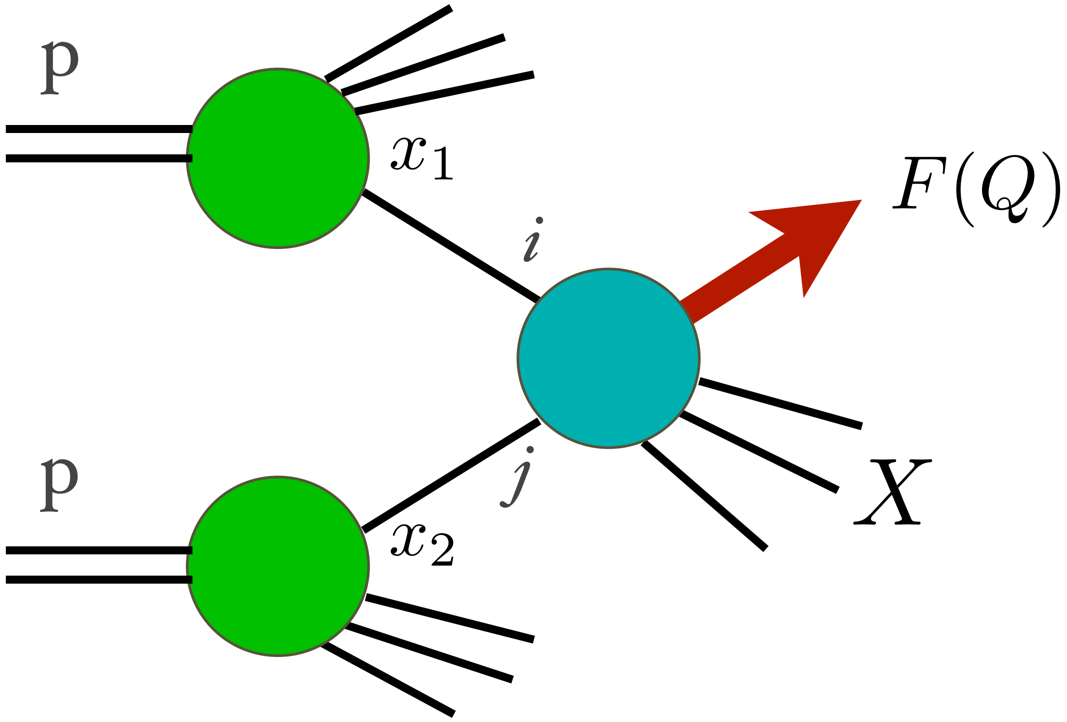
NLO QCD(+EW)

Resummation

NNLO QCD

\+ **Automation**

Theoretical framework



High-p_T interactions are characterised by the presence of a hard scale Q (invariant mass of a lepton pair, high-p_T jet, heavy-quark....)

→ They can be controlled through the factorisation theorem

The corresponding cross section can be written as

Partonic cross section

$$\sigma(P_1,P_2) = \sum_{i,j}\int dx_1 dx_2\, f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2) \times \hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2;\mu_F^2,\mu_R^2) + \left(\frac{\Lambda}{Q}\right)^p$$

Parton distributions (PDFs)

Power suppressed terms

Accurate predictions for hadronic cross section depend on good knowledge of both $f_{i,h}(x,\mu_F^2)$ and $\hat{\sigma}_{ij}$

PDFs

Determined by global fits to different data sets

Standard procedure:

- Parametrise at input scale $Q_0 = 1 - 4\ \mathrm{GeV}$

$$xf(x, Q_0^2) = Ax^{\alpha}(1-x)^{\beta}(1+\epsilon\sqrt{x}+\gamma x + ...)$$

MMHT14 (CT14) uses instead Chebyshev (Bernstein) polynomials

NNPDF generates replicas of the data and fits using a set of neural networks on each replica

- Impose momentum sum rule: $\sum_a \int_0^1 dx\, x f_a(x, Q_0^2) = 1$

- Evolve to desired Q² through DGLAP equation

$$Q^2 \frac{\partial f_a(x,Q^2)}{\partial Q^2} = \int_x^1 \frac{dz}{z} P_{ab}(\alpha_{\mathrm{S}}(Q^2), z) f_b(x/z, Q^2)$$

$$P_{ab}(\alpha_S, z) = \frac{\alpha_S}{2\pi} P_{ab}^{(0)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ab}^{(1)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^3 P_{ab}^{(2)}(z) + ...$$

LO (1974) NLO (1980) NNLO (2004: Moch et al.)

- Compute observables and then fit to data to obtain the parameters

PDFs

set	data	errors	comments
MMHT14	DIS+DY+jets+LHC	hessian	α_S fixed
CT14	DIS+DY+jets+LHC	hessian	α_S fixed
NNPDF3.0	DIS+DY+jets+LHC	Montecarlo	α_S fixed
HeraPDF2.0	DIS	hessian	α_S fixed
ABM12	DIS+DY+LHC	hessian	α_S fitted
(G)JR	DIS+DY (ft) +some jets	hessian	valence-like α_S fitted

} global fits

"outliers"

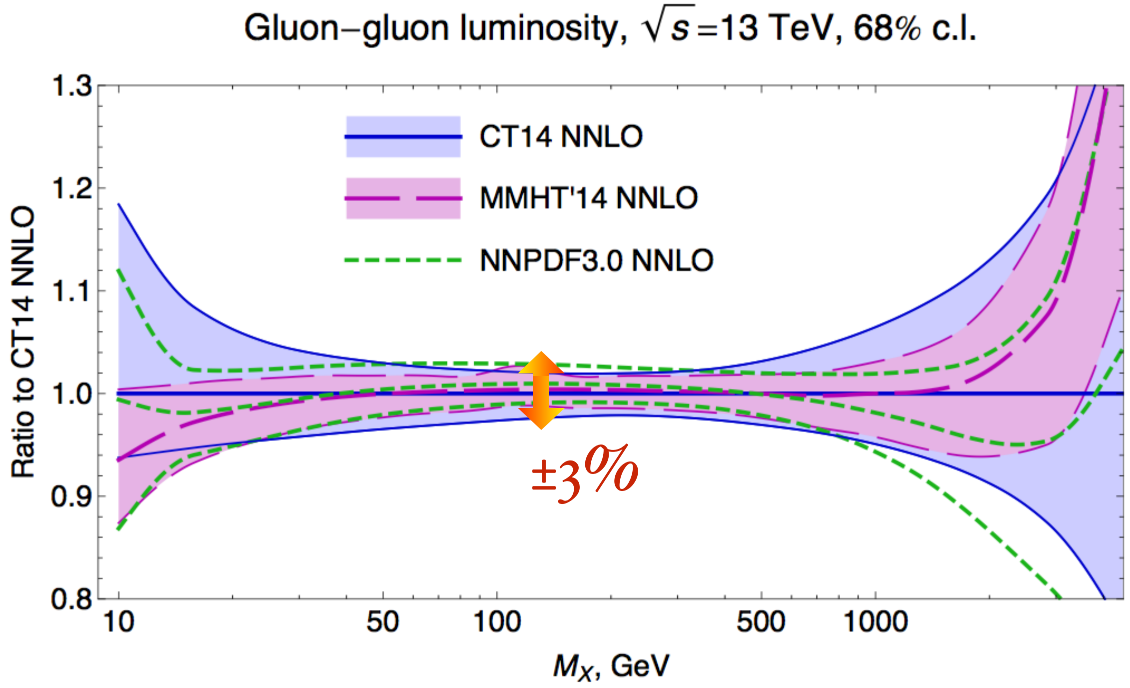
→ $\alpha_S(m_Z)$=0.1132 ± 0.0011

→ $\alpha_S(m_Z)$=0.1136 ± 0.0004

All fits now up to NNLO

Latest PDF sets from global fits display a nice agreement for the gluon luminosity

→ Good news for Higgs production !



The value of $\alpha_S(m_Z)$

The current world average from PDG2014 is $\alpha_S(m_Z)=0.1185 \pm 0.0006$

quoted error is 0.5 % !

- Recent reassessment of lattice result leads to 0.1184± 0.0012 (double error with respect to what used in the PDG)

FLAG working group (2013)

- Determination from EW fit (at N^3LO) gives $\alpha_S(m_Z)=0.1197 \pm 0.0028$

- Some (maybe controversial) extractions point to much lower $\alpha_S(m_Z)$
    - See e.g. thrust distribution $\alpha_S(m_Z)=0.1135\pm0.0011$
    - "Outliers" PDF+α_S fits lead to $\alpha_S(m_Z) \sim 0.113$

R.Abbate et al (2010)

S.Alekhin et al. (2013,2014)
P. Jimenez-Delgado, Reja (2014)

➡ **A more conservative error estimate on $\alpha_S(m_Z)$ is desirable**

New PDF4LHC agreement: PDFs all evaluated at the same $\alpha_S(m_Z)=0.118$

Uncertainty for Higgs cross sections evaluated in steps of $\Delta\alpha_S(m_Z)=0.001$-$0.0015$

Combined PDF4LHC15 sets close to be released

S.Forte, HXSWG meeting, july 2015

Theoretical uncertainties ?

Partonic cross section

The partonic cross section for high-p_T processes can be computed as a series expansion in the QCD coupling α_S

$$\hat{\sigma} = \alpha_S^k \left(\underset{\substack{\uparrow \\ \text{LO}}}{\hat{\sigma}^{(0)}} + \frac{\alpha_S}{\pi} \underset{\substack{\uparrow \\ \text{NLO}}}{\hat{\sigma}^{(1)}} + \left(\frac{\alpha_S}{\pi}\right)^2 \underset{\substack{\uparrow \\ \text{NNLO}}}{\hat{\sigma}^{(2)}} + \ldots \right)$$

Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions

- the scale of α_S is not defined
- jets ⟺ partons: jet structure starts to appear only beyond LO

To obtain reliable predictions at least next-to leading order (NLO) is needed

➡ NNLO allows to quantify uncertainties

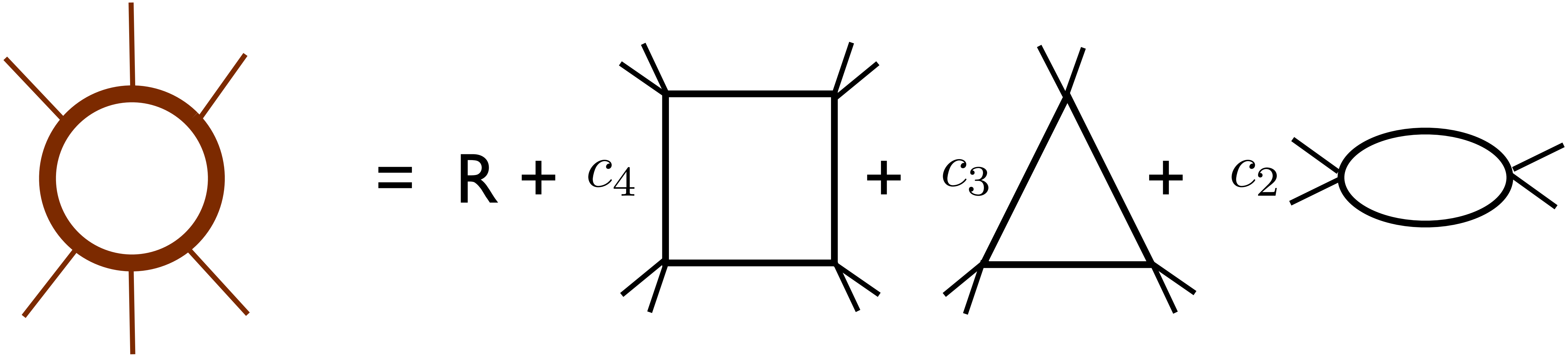
Furthermore ↗ Resummation of the large logarithmic terms at phase space boundaries

Furthermore ↘ NLO Electroweak corrections

The NLO automation

For many years the bottleneck has been the computation of the relevant one-loop amplitudes → Enormous progress in the last 10 years

The traditional approach based on Feynman diagrams is now complemented with new powerful methods based on recursion relations and unitarity



General one-loop amplitude expressed as a sum of known boxes, triangles and bubble integrals plus a remainder term

Coefficient of these integrals can be computed by taking suitable multiple cuts

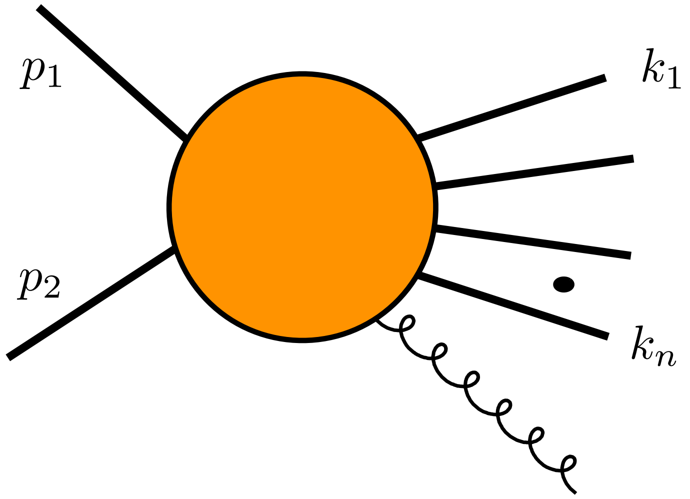
For example c_4 → Simple product of four tree-level amplitudes evaluated at complex momenta

R.Britto, F.Cachazo, B.Feng (2004)

The NLO automation

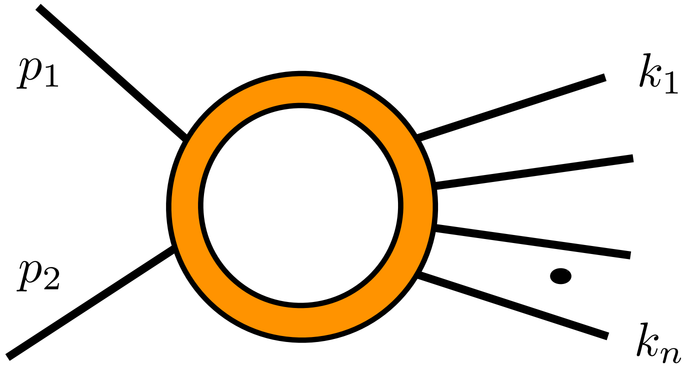
For many years the bottleneck has been the computation of the relevant one-loop amplitudes ➡ Enormous progress in the last years

Automation of NLO corrections



Combine available methods to compute real corrections.....

with most efficient techniques for virtual corrections:



- "traditional" methods to evaluate tensor and scalar integrals

A.Denner, S.Dittmaier (2006,2011)

- fully numerical evaluation based on reduction at the integrand level

G.Ossola, C.Papadopoulos, R.Pittau (2007)
K.Ellis, W.Giele, Z.Kunszt (2007)

The NLO automation

- Unitarity and on-shell methods

MadGraph5_aMC@NLO   BlackHat+Sherpa   NJet

GoSam+Sherpa   Helac-NLO

- Numerical off-shell methods

Combine efficiency of the numerically stable tensor-integral reduction with the automation made possible by a completely recursive approach

OpenLoops+Sherpa   Recola

see also Van Hameren (2009)

The final goal is really automatic NLO calculations

Specify process (input card),
define cuts/distributions → run and get the results

The problem is “in principle” solved

The NLO automation

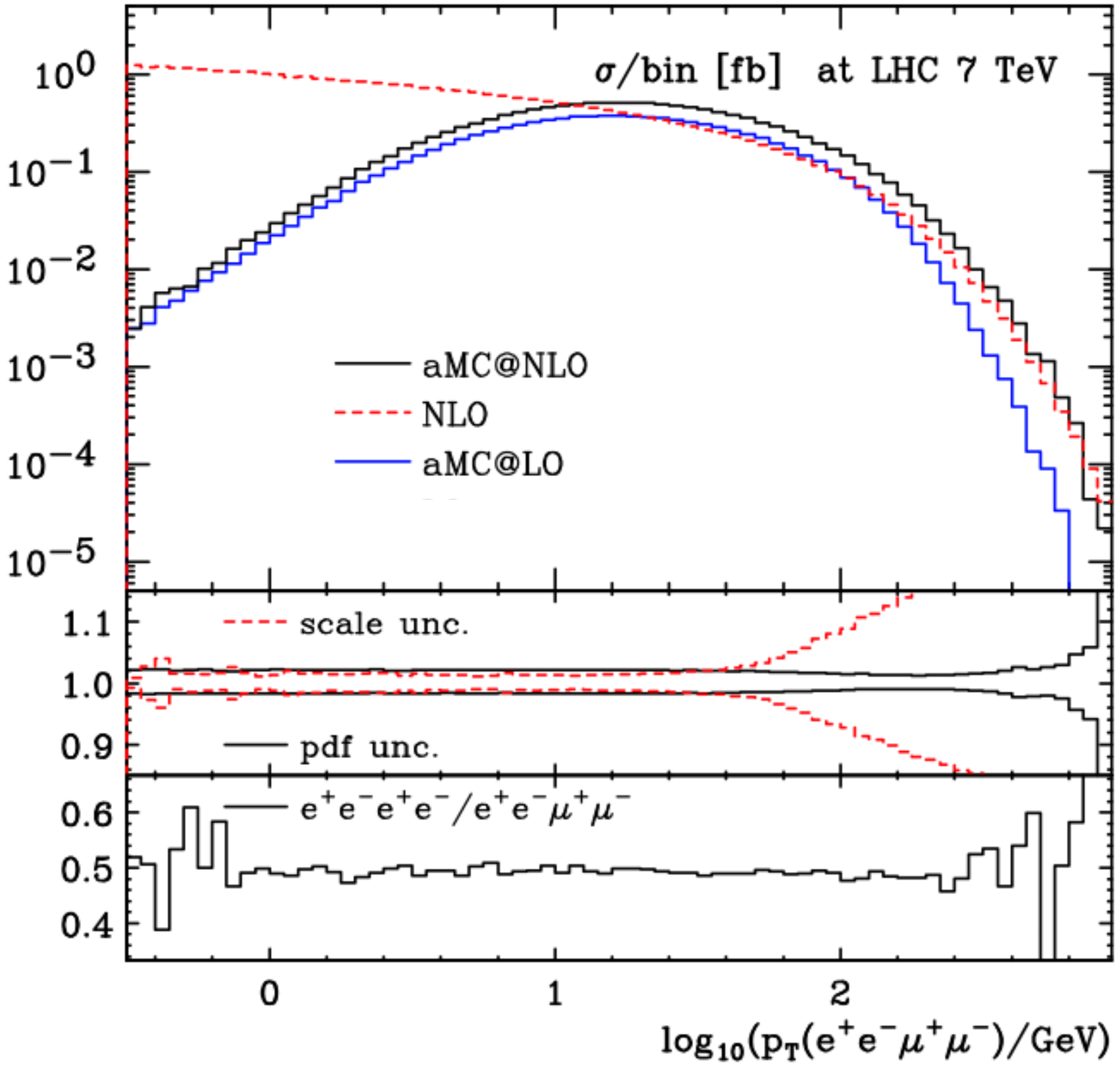
Process		Syntax	Cross section (pb)			
Single Higgs production			LO 13 TeV		NLO 13 TeV	
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 \pm 0.003 \cdot 10^{1}$	$^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1}$	$^{+20.2\%}_{-17.9\%}$ $^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 \pm 0.003 \cdot 10^{0}$	$^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$	$^{+18.5\%}_{-16.6\%}$ $^{+1.1\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 \pm 0.002 \cdot 10^{0}$	$^{+59.1\%}_{-34.7\%}$ $^{+1.4\%}_{-1.7\%}$	$5.124 \pm 0.020 \cdot 10^{0}$	$^{+20.7\%}_{-21.0\%}$ $^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$	$^{+1.7\%}_{-2.0\%}$ $^{+1.9\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$	$^{+0.8\%}_{-0.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$	$^{+15.7\%}_{-12.7\%}$ $^{+1.5\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$	$^{+2.0\%}_{-3.0\%}$ $^{+1.5\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$	$^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.419 \pm 0.005 \cdot 10^{0}$	$^{+2.1\%}_{-2.6\%}$ $^{+1.9\%}_{-1.4\%}$
g.7	$pp \to HW^{\pm}j$	`p p > h wpm j`	$4.018 \pm 0.003 \cdot 10^{-1}$	$^{+10.7\%}_{-9.3\%}$ $^{+1.2\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$	$^{+3.6\%}_{-3.7\%}$ $^{+1.2\%}_{-1.0\%}$
g.8*	$pp \to HW^{\pm}jj$	`p p > h wpm j j`	$1.198 \pm 0.016 \cdot 10^{-1}$	$^{+26.1\%}_{-19.4\%}$ $^{+0.8\%}_{-0.6\%}$	$1.574 \pm 0.014 \cdot 10^{-1}$	$^{+5.0\%}_{-6.5\%}$ $^{+0.9\%}_{-0.6\%}$
g.9	$pp \to HZ$	`p p > h z`	$6.468 \pm 0.008 \cdot 10^{-1}$	$^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$	$7.674 \pm 0.027 \cdot 10^{-1}$	$^{+2.0\%}_{-2.5\%}$ $^{+1.9\%}_{-1.4\%}$
g.10	$pp \to HZj$	`p p > h z j`	$2.225 \pm 0.001 \cdot 10^{-1}$	$^{+10.6\%}_{-9.2\%}$ $^{+1.1\%}_{-0.8\%}$	$2.667 \pm 0.010 \cdot 10^{-1}$	$^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$
g.11*	$pp \to HZjj$	`p p > h z j j`	$7.262 \pm 0.012 \cdot 10^{-2}$	$^{+26.2\%}_{-19.4\%}$ $^{+0.7\%}_{-0.6\%}$	$8.753 \pm 0.037 \cdot 10^{-2}$	$^{+4.8\%}_{-6.3\%}$ $^{+0.7\%}_{-0.6\%}$
g.12*	$pp \to HW^{+}W^{-}$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$	$^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$	$^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$	$^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$	$^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$	$^{+1.1\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$	$^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 \pm 0.003 \cdot 10^{-3}$	$^{+0.1\%}_{-0.6\%}$ $^{+1.9\%}_{-1.5\%}$	$2.538 \pm 0.007 \cdot 10^{-3}$	$^{+1.9\%}_{-1.4\%}$ $^{+2.0\%}_{-1.5\%}$
g.16	$pp \to Ht\bar{t}$	`p p > h t t~`	$3.579 \pm 0.003 \cdot 10^{-1}$	$^{+30.0\%}_{-21.5\%}$ $^{+1.7\%}_{-2.0\%}$	$4.608 \pm 0.016 \cdot 10^{-1}$	$^{+5.7\%}_{-9.0\%}$ $^{+2.0\%}_{-2.3\%}$
g.17	$pp \to Htj$	`p p > h tt j`	$4.994 \pm 0.005 \cdot 10^{-2}$	$^{+2.4\%}_{-4.2\%}$ $^{+1.2\%}_{-1.3\%}$	$6.328 \pm 0.022 \cdot 10^{-2}$	$^{+2.9\%}_{-1.8\%}$ $^{+1.5\%}_{-1.6\%}$
g.18	$pp \to Hb\bar{b}$ (4f)	`p p > h b b~`	$4.983 \pm 0.002 \cdot 10^{-1}$	$^{+28.1\%}_{-21.0\%}$ $^{+1.5\%}_{-1.8\%}$	$6.085 \pm 0.026 \cdot 10^{-1}$	$^{+7.3\%}_{-9.6\%}$ $^{+1.6\%}_{-2.0\%}$
g.19	$pp \to Ht\bar{t}j$	`p p > h t t~ j`	$2.674 \pm 0.041 \cdot 10^{-1}$	$^{+45.6\%}_{-29.2\%}$ $^{+2.6\%}_{-2.9\%}$	$3.244 \pm 0.025 \cdot 10^{-1}$	$^{+3.5\%}_{-8.7\%}$ $^{+2.5\%}_{-2.9\%}$
g.20*	$pp \to Hb\bar{b}j$ (4f)	`p p > h b b~ j`	$7.367 \pm 0.002 \cdot 10^{-2}$	$^{+45.6\%}_{-29.1\%}$ $^{+1.8\%}_{-2.1\%}$	$9.034 \pm 0.032 \cdot 10^{-2}$	$^{+7.9\%}_{-11.0\%}$ $^{+1.8\%}_{-2.2\%}$

MadGraph5_aMC@NLO: sample from 172 processes

NLO+PS matching

Parton Shower Monte Carlo provide a simulation of all the stages of the hadronic collision: merge QCD matrix element + shower in the soft collinear approximation +hadronization model

The MC@NLO and POWHEG methods allow us to combine NLO calculations with existing MC like PYTHIA, HERWIG, SHERPA....



- MC@NLO method
  - MadGraph5_aMC@NLO
  - Sherpa+OpenLoops
  - Herwig++Matchbox+Openloops/Gosam
- Powheg method
  - Madgraph4+Powheg+MCFM/Gosam
  - Herwig++Matchbox+Openloops/Gosam

POWHEG and MC@NLO implementations have same formal accuracy but differ in the amount of radiation that is exponentiated ➡ Main issue now is to assess uncertainties

NLO and PS: what else ?

- MENLOPS: Start from a definite NLO+PS and add higher multiplicities tree level ME

K.Hamilton, P.Nason (2010)

- MEPS@NLO (UNLOPS) merge two NLO+PS simulations with different multiplicities

R.Frederix, S.Frixione (2011)
S.Hoeche, F.Krauss, M.Schonherr, F.Siegert (2012)
L.Lonnblad, S.Prestel (2012), S.Platzer (2012)

- MINLO, Geneva Merge two NLO+PS without merging scale (improving Sudakov form factor)

K.Hamilton, P.Nason, G.Zanderighi (2012)
S.Alioli et al (2012)

- Alternative NLO+PS scheme: KrKNLO
  (requires PDFs in a dedicated scheme)

S.Jadach et al. (2015)

- Attempts to go beyond Leading Color approximation
  - Deductor (talk by M.Kraus for application to $t\bar{t}$)
  - qq→qq evolution matrix elements

Z.Nagy, D.Soper (2012,2015)
M.Czakon et al. (2015)

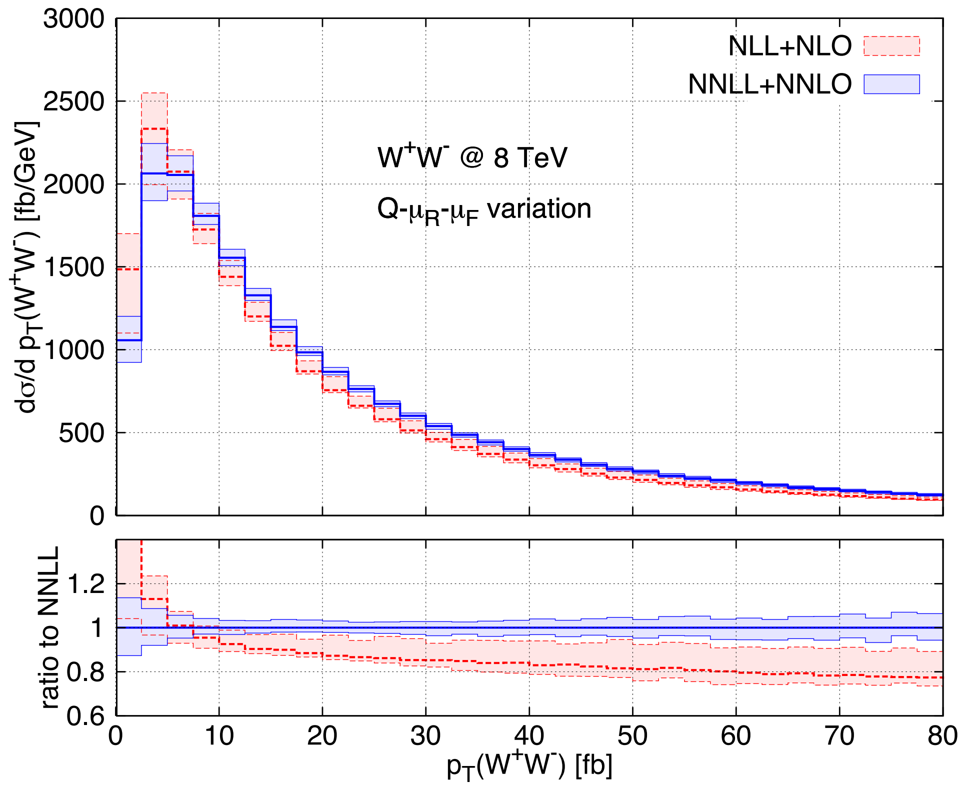
S.Platzer (2013)

- NLO+PS EW implementation in H→ZZ→4 leptons

S.Boselli et al. (2015)

Resummation

For specific observables, analytic resummation provides predictions with higher logarithmic accuracy and an important validation of MC tools

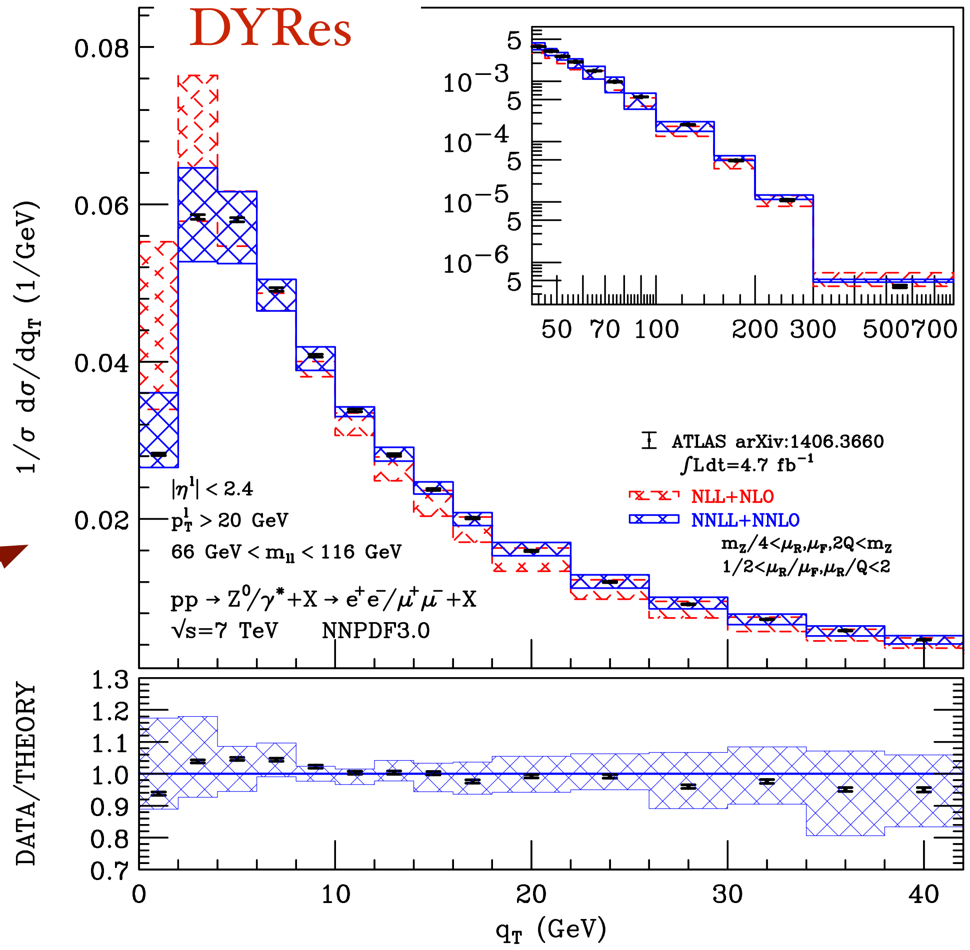


S.Kallweit,D.Rathlev,M.Wiesemann,MG (2015)

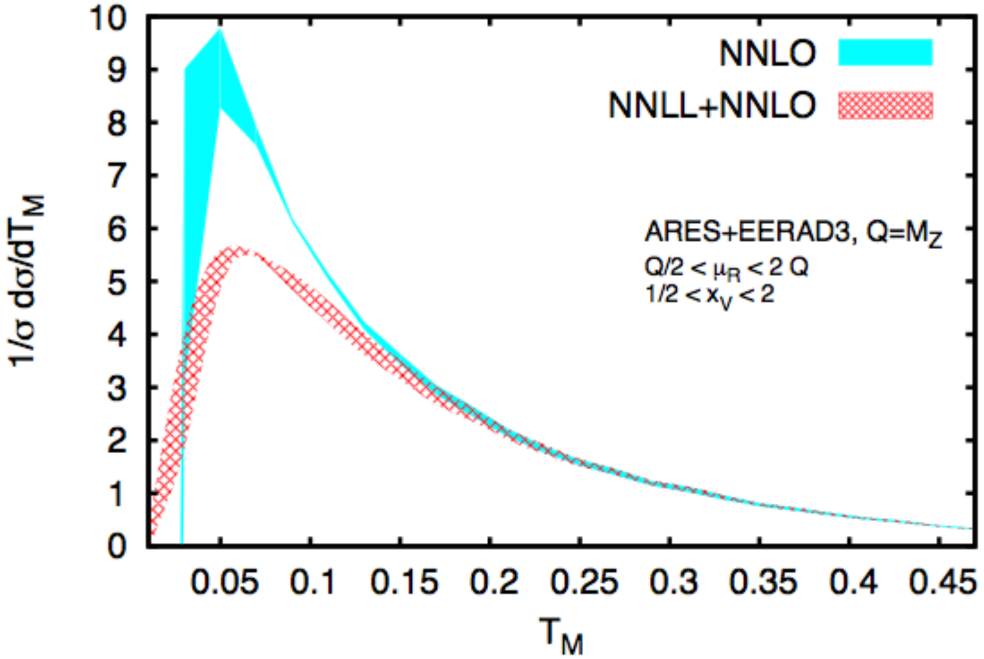
Resummed p_T spectra at full NNLL+NNLO:

WW (and ZZ)

Z (and W) including leptonic cuts



S.Catani, D. de Florian, G.Ferrera, MG (2015)



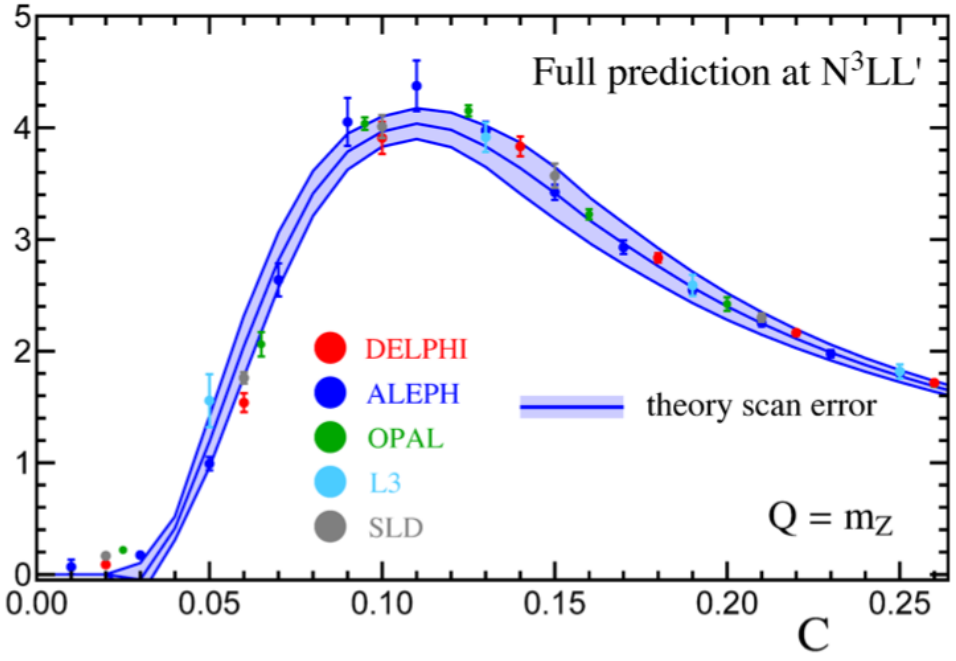
Automatic resummation for event-shape variables in e^+e^- annihilation at NNLL

Valid for a specific class of IR safe observables (recursive IR safe): method potentially applicable to hadron collisions

P.Monni, A.Banfi, G.Zanderighi (2015)

Resummation

Soft collinear effective theory (SCET) complements traditional QCD approach to derive new interesting results



A.Hoang et al (2015)

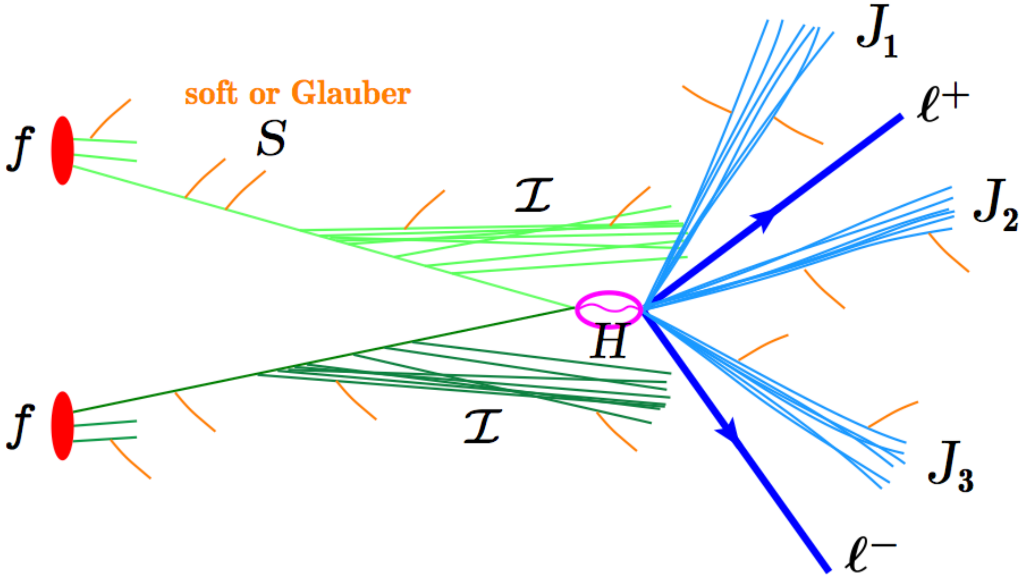
- Resummation for the C-parameter and fit to $\alpha_S(m_Z)$

  Result for $\alpha_S(m_Z)$=0.1123 ± 0.0015 consistent with analogous fit from Thrust

- Resummation as a way to get further insight into fixed order calculations

  Example: N-jettiness: $\tau_N \to 0$ when exactly N jets

I.Stewart,F.Tackmann,W.Waalewijn (2010)



$$\tau_N = \frac{2}{Q^2}\sum_k \min\{q_a\cdot p_k,\, q_b\cdot p_k,\, q_1\cdot p_k,\, \ldots,\, q_N\cdot p_k\}$$

Jet and beam functions computed to NNLO

T.Becher, M.Neubert (2006); T.Becher, M.Neubert, G.Bell (2010)
J.Gaunt, M.Stahlhofen,F.Tackmann (2014)

Soft function for τ_1 to NNLO

R.Boughezal, X.Liu, F.Petriello (2015)

The NNLO revolution

NNLO calculations important at least for the following cases:

1) Benchmark processes measured with high accuracy

- ✅ $e^+e^- \to$ 3 jets
- ✅ $pp \to W, Z$
- ✅ $pp \to t\bar{t}$
- (✅) $pp \to$ 2 jets

towards completion

2) Processes with large NLO corrections

- ✅ $pp \to H$

even N^{3}LO known now

- ✅ $pp \to H$+jet
- ✅ $pp \to HH$

3) Important backgrounds for Higgs and NP searches

- ✅ $pp \to \gamma\gamma$
- ✅ $pp \to W\gamma, Z\gamma$
- ✅ $pp \to WW$

NNLO reduces tension with ATLAS data

- ✅ $pp \to ZZ$
- ❌ $pp \to WZ$
- ✅ $pp \to W(Z)$+jet

It is essential to provide fiducial cross sections and distributions with which the data can be directly compared

(for more processes see also Les Houches 2013 NNLO wish list)

NNLO methods

Broadly speaking there are two approaches that we can follow:

- Organise the calculation from scratch so as to cancel all the singularities

  - sector decomposition

    T. Binoth, G.Heinrich (2000,2004)
    C.Anastasiou, K.Melnikov, F.Petriello (2004)

  - antenna subtraction

    A. & T. Gehrmann, N. Glover (2005)

  - "colourful" subtraction (talk by Z.Trocsanyi)

    G, Somogyi, Z. Trocsanyi,
    V. Del Duca (2005, 2007)

  - joint use of subtraction and sector decomposition

    M.Czakon (2010,2011)
    R.Boughezal, K.Melnikov, F.Petriello (2011)

- Start from an inclusive NNLO calculation (sometimes obtained through resummation) and combine it with an NLO calculation for n+1 parton process

  - q_T subtraction

    S.Catani, MG (2007)

  - "N-jettiness" method

    R.Boughezal, C.Focke,X.Liu, F.Petriello (2015)
    F.Tackmann et al. (2015)

  - recently introduced "Born projection" method for VBF (talk by A. Karlberg)

    M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)

...and then we need the relevant two-loop amplitudes !

C.Anastasiou, F.Caola, M.Czakon, T.Gehrmann, N.Glover, M.Jaquier, A. Koukoutsakis
C.Oleari, K.Melnikov, L.Tancredi, M.E. Tejeda-Yeomans, A. von Manteuffel and many others

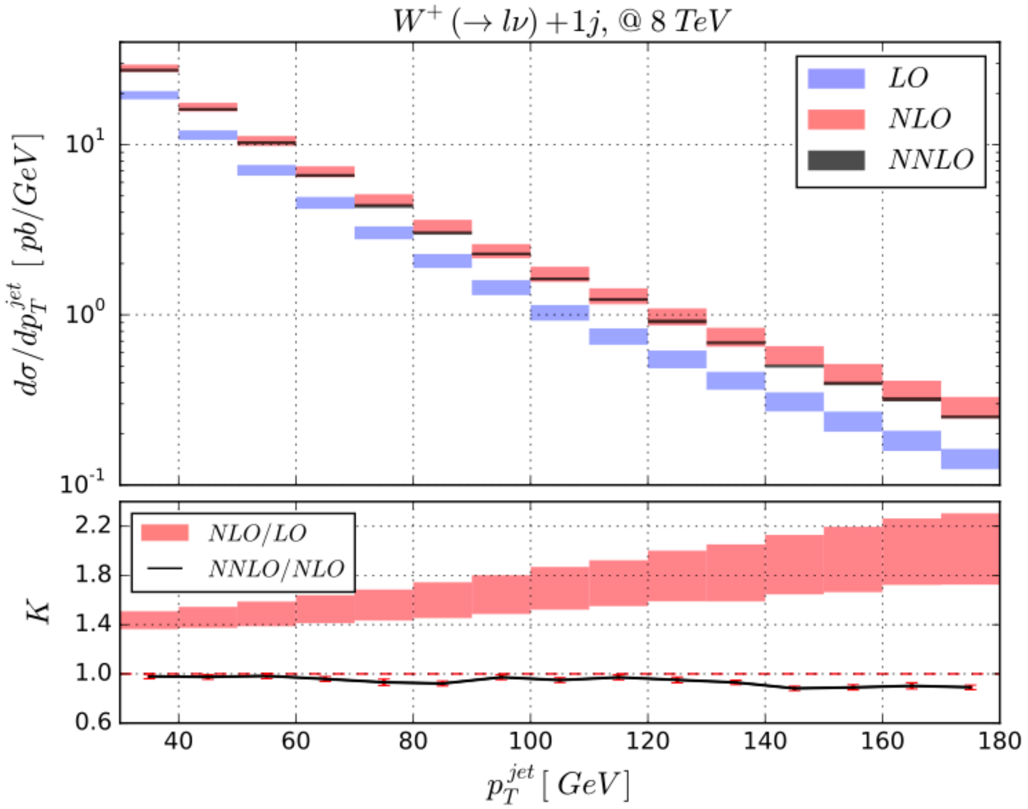
W and Z+jet at NNLO

- W+jet

First application of new "*N-jettiness*" method: relatively flat NNLO correction

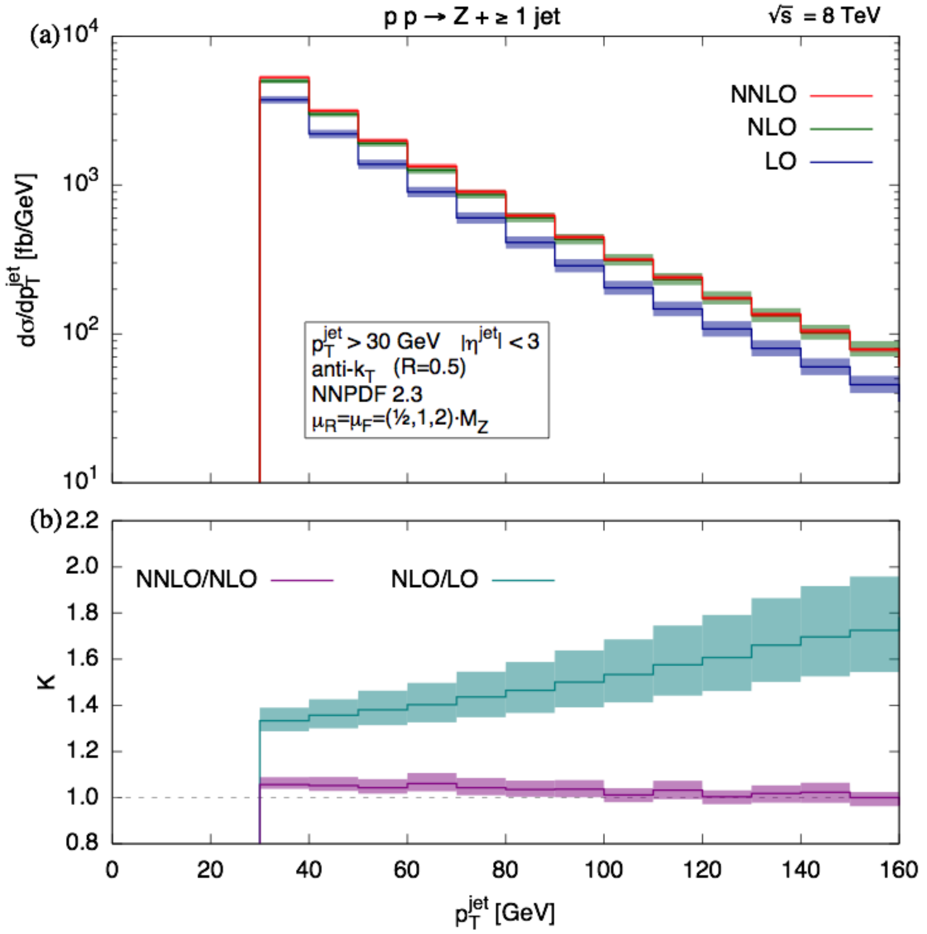
$p_T^{jet} > 30$ GeV, $\lvert\eta_{jet}\rvert < 2.4$	
Leading order:	533^{+39}_{-38} pb
Next-to-leading order:	798^{+63}_{-48} pb
Next-to-next-to-leading order:	775^{+0}_{-8} pb

Small NNLO effect and significant reduction of scale uncertainties



R.Boughezal, C.Focke,X.Liu, F.Petriello (2015)

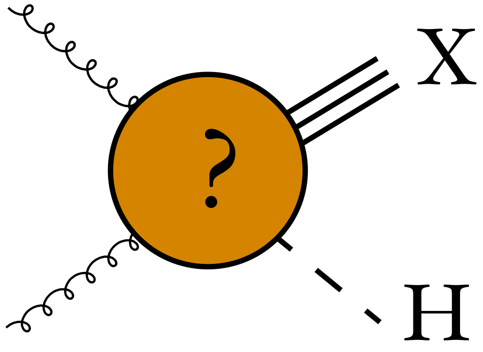
- Z+jet



Similar effects for Z+jet: *antenna subtraction* (large N_C approximation for the dominant channels)

A and T. Gehrmann, N. Glover, T.Morgan, A.Huss (2015)

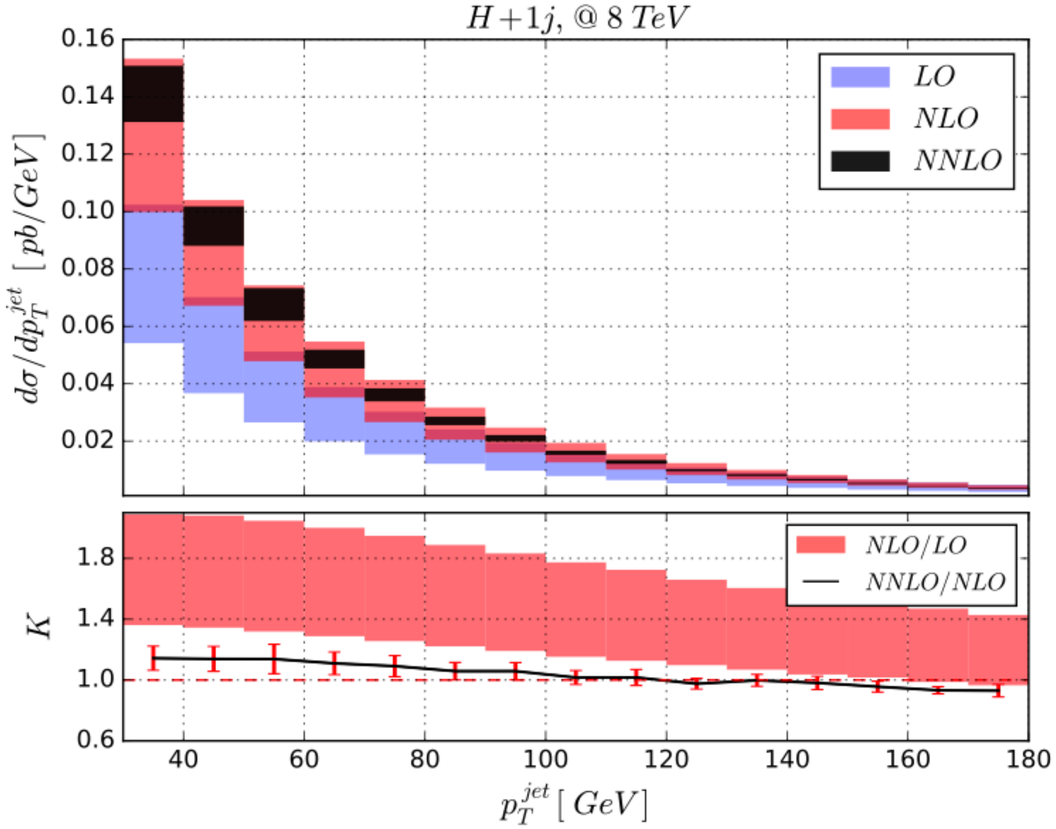
H+jet at NNLO

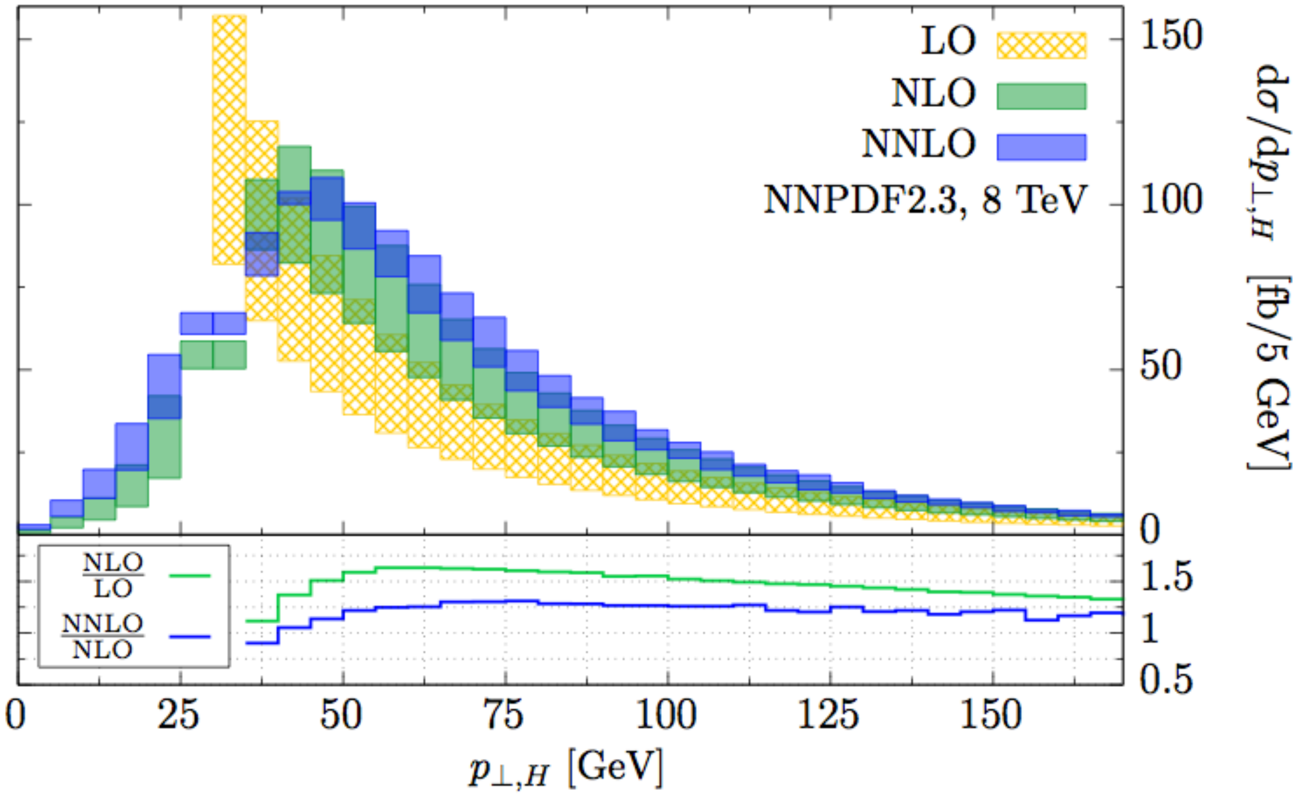


X. Chen, T. Gehrmann, N. Glover, M. Jaquier (2014)
R.Boughezal, F.Caola, K.Melnikov, ,F.Petriello, M.Schulze (2015)
R.Boughezal, C.Focke, W.Giele ,X.Liu, F.Petriello (2015)

Higgs production at high-p_T is useful to test new physics scenarios and better resolve the structure of the heavy-quark loop

NNLO calculation carried out with three independent methods (*antenna subtraction, subtraction+sector, N-jettiness*) !





Still in the large m_{top} approximation

quantitative effect smaller than previously anticipated from gg only: at the 20% level ($\mu=m_H$)

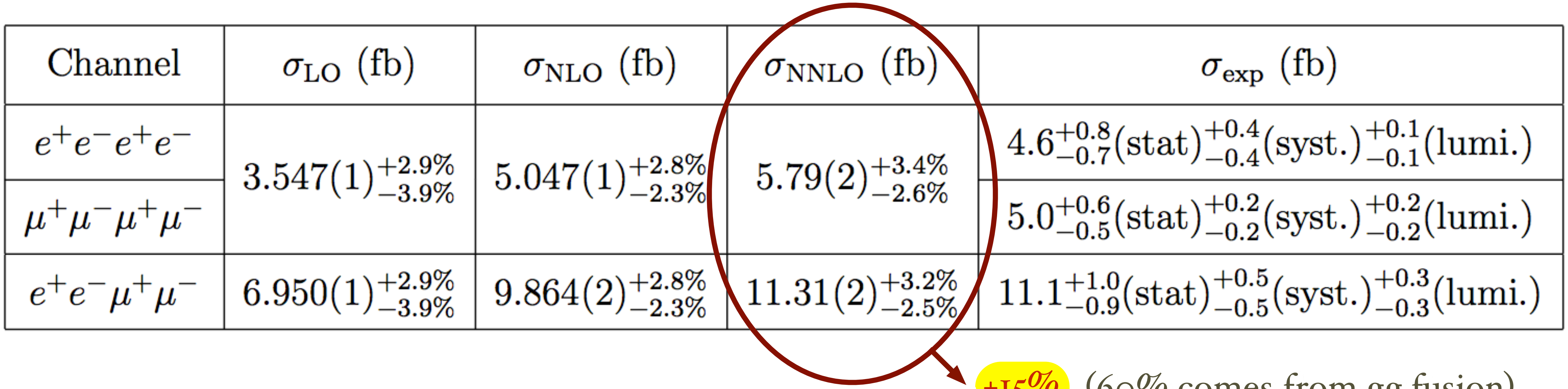
ZZ at NNLO: lepton decays and off-shell effects

S. Kallweit, D. Rathlev, MG (2015)

Consider pp→ZZ→4 leptons at 8 TeV

Use ATLAS cuts to define fiducial region:

$p_{Tl} > 7$ GeV $|\eta_l| < 2.7$ $\Delta R(l,l)>0.2$
66 GeV < m_{ll} < 116 GeV



Channel	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)	σ_{exp} (fb)
$e^+e^-e^+e^-$	$3.547(1)^{+2.9\%}_{-3.9\%}$	$5.047(1)^{+2.8\%}_{-2.3\%}$	$5.79(2)^{+3.4\%}_{-2.6\%}$	$4.6^{+0.8}_{-0.7}(\mathrm{stat})^{+0.4}_{-0.4}(\mathrm{syst.})^{+0.1}_{-0.1}(\mathrm{lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}(\mathrm{stat})^{+0.2}_{-0.2}(\mathrm{syst.})^{+0.2}_{-0.2}(\mathrm{lumi.})$
$e^+e^-\mu^+\mu^-$	$6.950(1)^{+2.9\%}_{-3.9\%}$	$9.864(2)^{+2.8\%}_{-2.3\%}$	$11.31(2)^{+3.2\%}_{-2.5\%}$	$11.1^{+1.0}_{-0.9}(\mathrm{stat})^{+0.5}_{-0.5}(\mathrm{syst.})^{+0.3}_{-0.3}(\mathrm{lumi.})$

+15% (60% comes from gg fusion)

NNLO corrections improve agreement with ATLAS data in the 2e2μ channel but make the agreement worse in the other channels (but experimental uncertainties still large)

Done with new code MATRIX: q_T *subtraction* +Munich+amplitudes from Openloops

ZZ at NNLO: lepton decays and off-shell effects

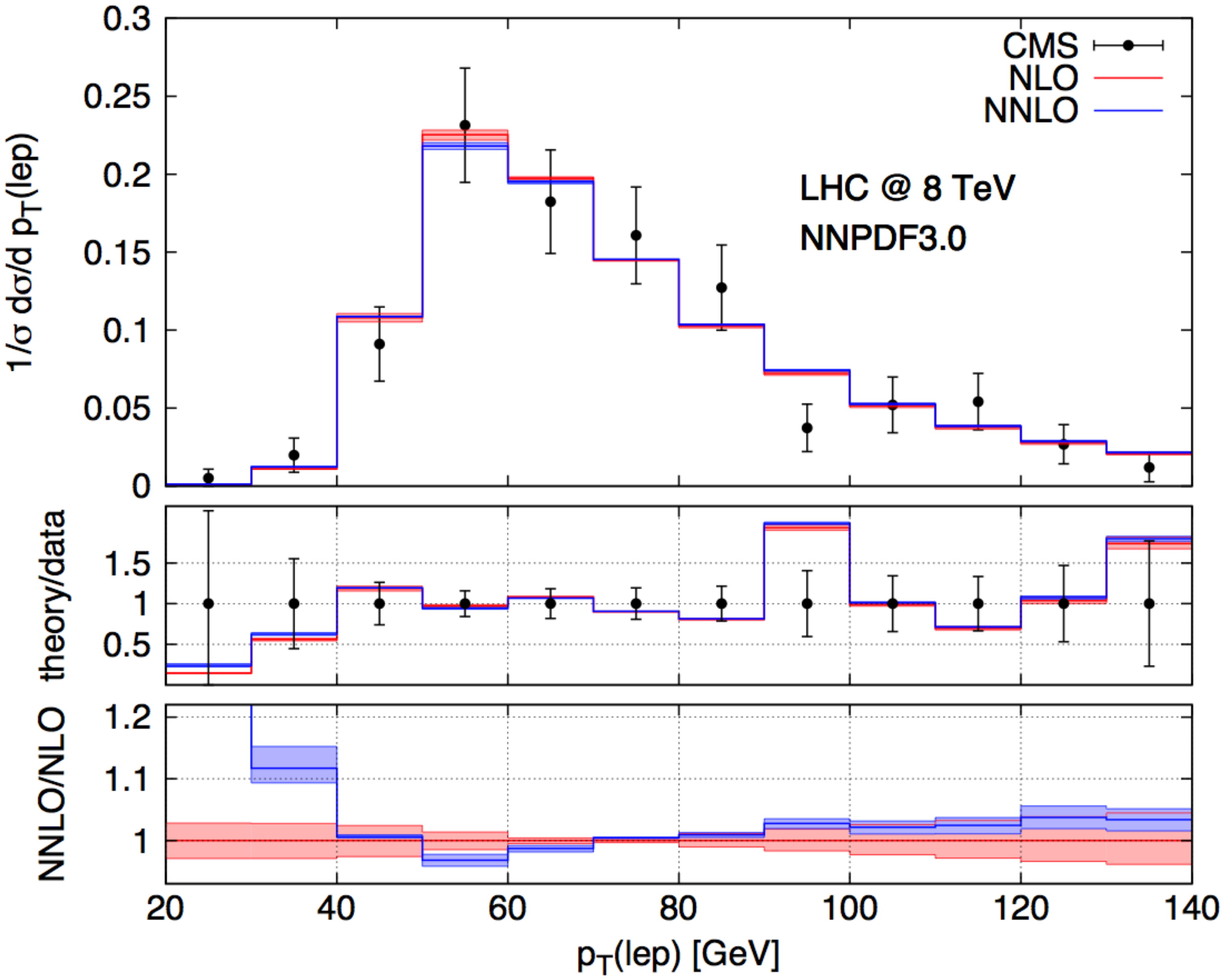
S. Kallweit, D. Rathlev, MG (2015)

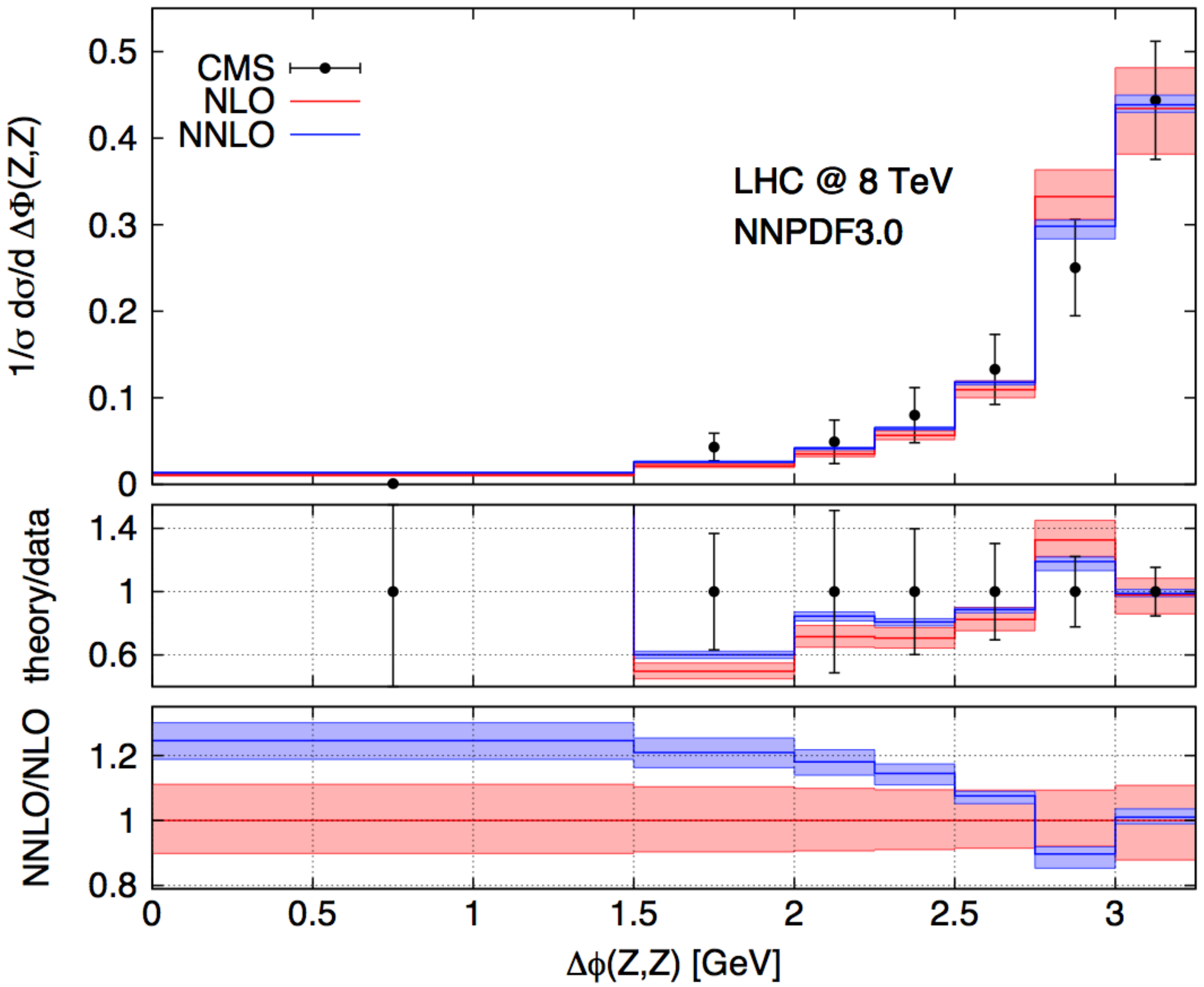
Now CMS cuts: $60\ \text{GeV} < m_{ll} < 120\ \text{GeV}$

$p_{T1} > 20$ GeV $p_{T2} > 10$ GeV $m_{ll} > 4$ GeV

$p_{Te} > 7$ GeV $|\eta_e| < 2.5$

$p_{T\mu} > 5$ GeV $|\eta_\mu| < 2.4$





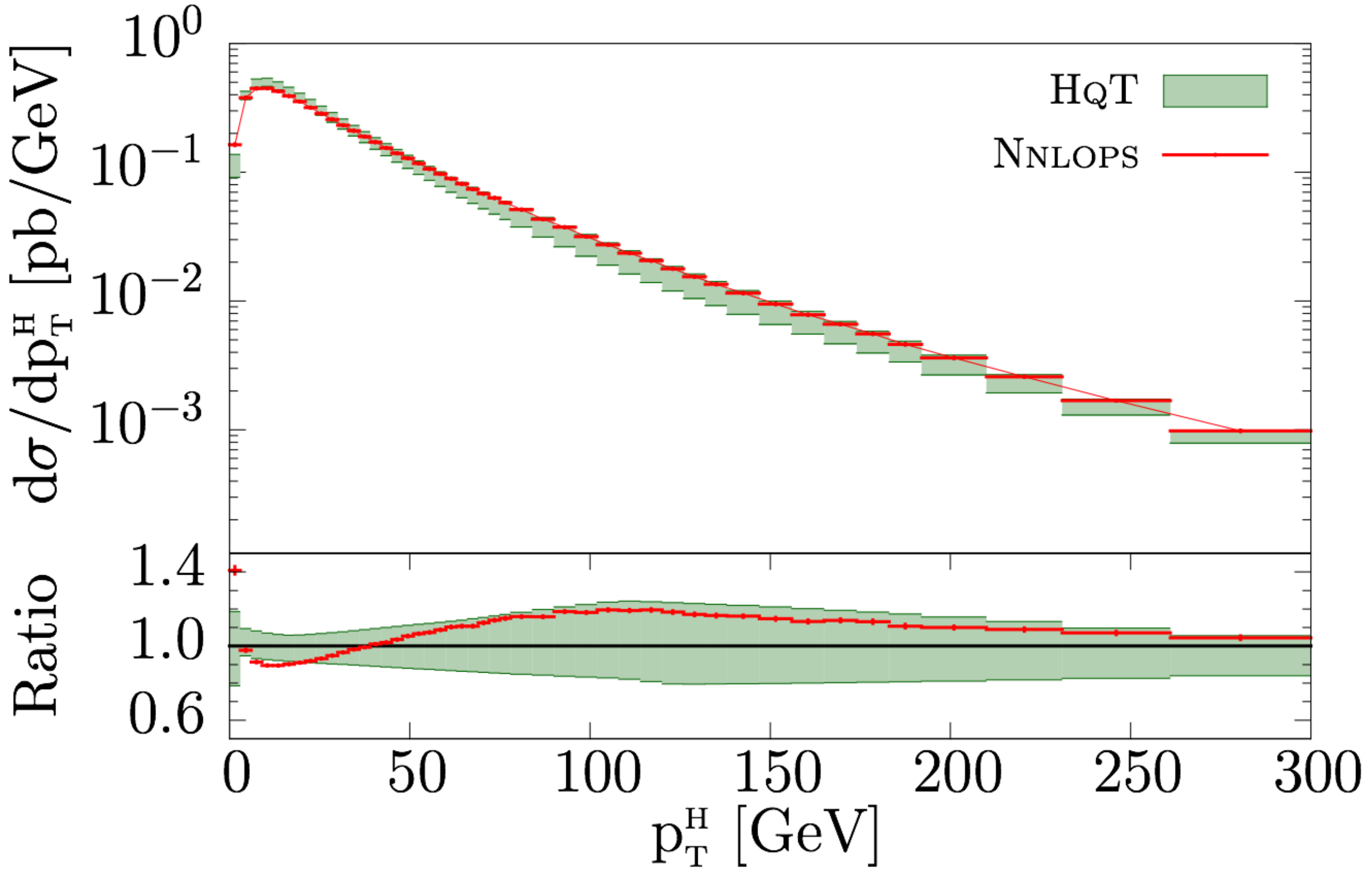
NNLO effects improve agreement with data for the $\Delta\phi$ distribution

NNLO+PS matching

NLO matching well established, while NNLO matching still in its infancy

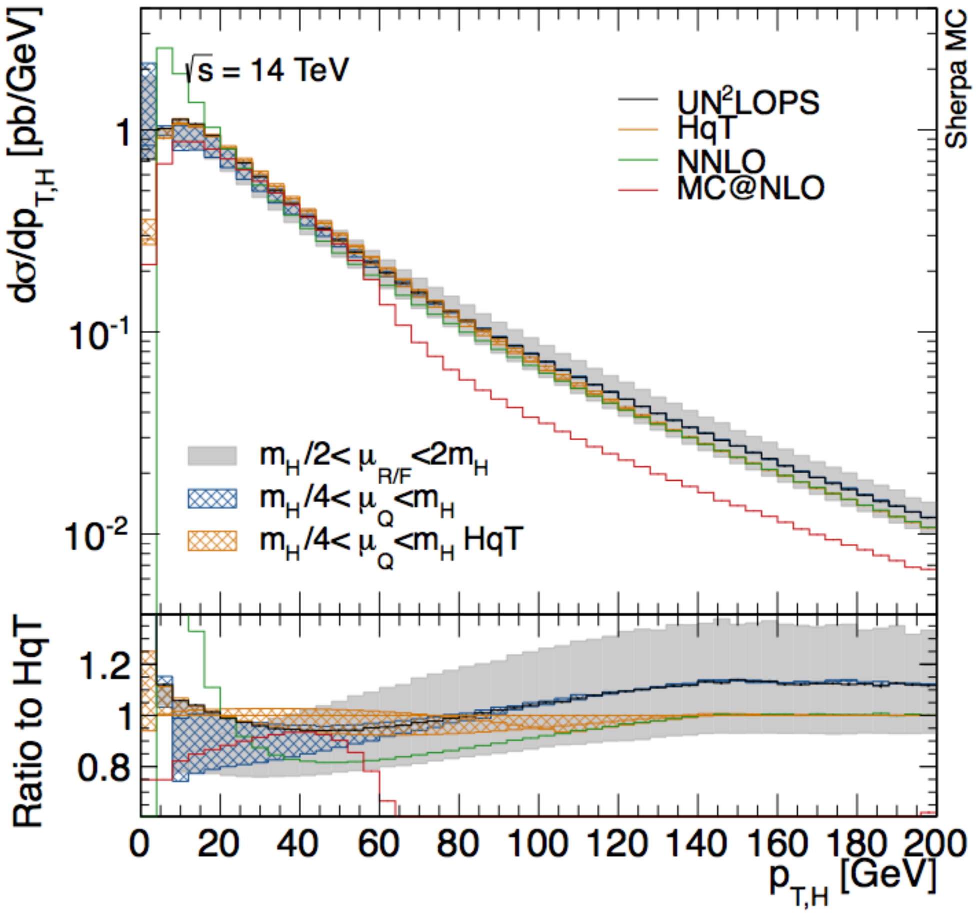
1) **NNLOPS:** use MINLO to obtain a NLO generator for both H and H+jet(s)

K.Hamilton, P.Nason, G.Zanderighi (2014,2015)



2) **UN^{2}LOPS:** use S-MC@NLO + UNLOPS + q_T slicing

N.Lavesson, L.Lonnblad (2008)
S.Hoeche, Y.Li, S.Prestel (2014)



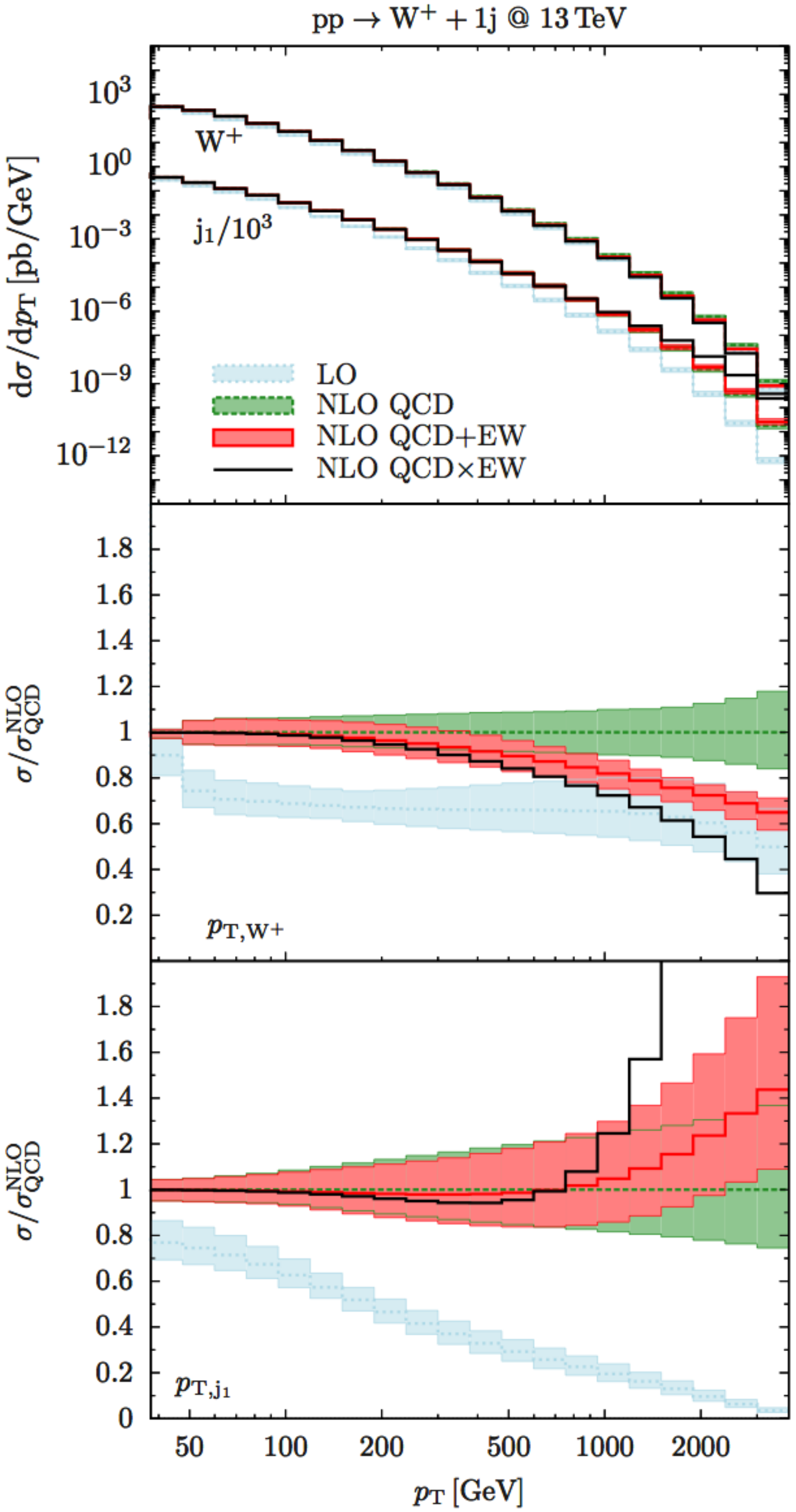
Enforce correct NNLO normalisation by reweighing the inclusive rapidity distribution to the NNLO calculation

NNLO virtual corrections confined in the low p_T region while in the POWHEG-MINLO approach they are spread over the whole p_T region

Current applications limited to vector and Higgs boson production

Electroweak corrections

Since O(α) ~ O(α_S^2) we expect NLO EW ~ NNLO QCD but enhancements due to



- EW Sudakov logs: important at high p_T
- photon emission from “bare” leptons

NLO EW corrections automation in Openloops+Munich+Sherpa.......

- W+multijet

S. Kallweit, J.Lindert, P.Maierhofer, S.Pozzorini M.Shonherr (2014)

.....and in MG5_aMC@NLO

- $t\bar{t}$+heavy bosons

S. Frixione et al. (2015)

See also Gosam, Recola...

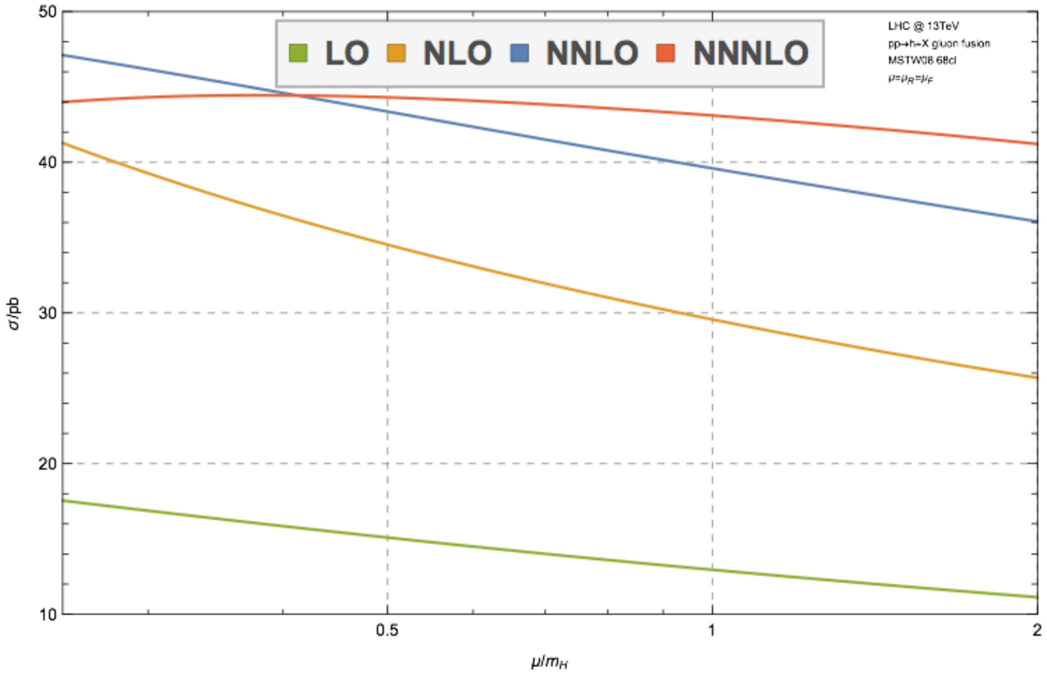
Progress in the computation of mixed QCD-EW O($\alpha\alpha_S$) corrections for the Drell-Yan process: important for a precise W mass measurement

S.Dittmaier, A.Huss, C.Schwinn (2014)

N^{3}LO for Higgs production

C.Anastasiou, C.Duhr, F.Dulat, F.Herzog, B.Mistlberger (2015)

Full calculation for the gg →H completed through the evaluation of 30 terms in the soft-expansion: first complete calculation at N^{3}LO in hadronic collisions !



Nice stabilisation of scale dependence around $\mu = m_H/2$

σ/pb	2 TeV	7 TeV	8 TeV	13 TeV	14 TeV
$\mu = \frac{m_H}{2}$	$0.99^{+0.43\%}_{-4.65\%}$	$15.31^{+0.31\%}_{-3.08\%}$	$19.47^{+0.32\%}_{-2.99\%}$	$44.31^{+0.31\%}_{-2.64\%}$	$49.87^{+0.32\%}_{-2.61\%}$
$\mu = m_H$	$0.94^{+4.87\%}_{-7.35\%}$	$14.84^{+3.18\%}_{-5.27\%}$	$18.90^{+3.08\%}_{-5.02\%}$	$43.14^{+2.71\%}_{-4.45\%}$	$48.57^{+2.68\%}_{-4.24\%}$

results in the large m_{top} approximation

N^{3}LO effect +2.2% at $\mu = m_H/2$

Corresponding new results for the Higgs cross section including mass effects at NLO and the other known corrections at 13 TeV expected soon

Significant reduction of uncertainties from missing higher orders and PDF+α_S

Together with H+jet at NNLO will help improve predictions in jet categories

Summary

- The first run at the LHC has been a triumph for the Standard Model, with the discovery of its last missing ingredient, the Higgs boson
- Accurate theoretical predictions are essential to further sharpen our picture of the Higgs boson and to control SM backgrounds in new physics searches
- The last 10 years have witnessed a revolution in NLO calculations that are now the standard and have reached a high level of automation
- NLO matching and merging to parton shower well established: main issue now is to properly assess uncertainties
- In the last 2 years an enormous progress in NNLO calculations has been achieved with many $2 \to 2$ computations completed
- First NNLO+PS matched applications for Higgs and vector boson production
- The automation of NLO EW corrections is following

➡ We are doing our best to be ready for the LHC Run 2 !

Thanks for your attention !

Many thanks to:

Stefano Catani , Daniel de Florian, Stefano Forte, Stefano Frixione, Thomas Gehrmann, Pier Monni, Stefano Pozzorini, Gavin Salam, Marek Schonherr

for various useful discussions on the topics presented here....

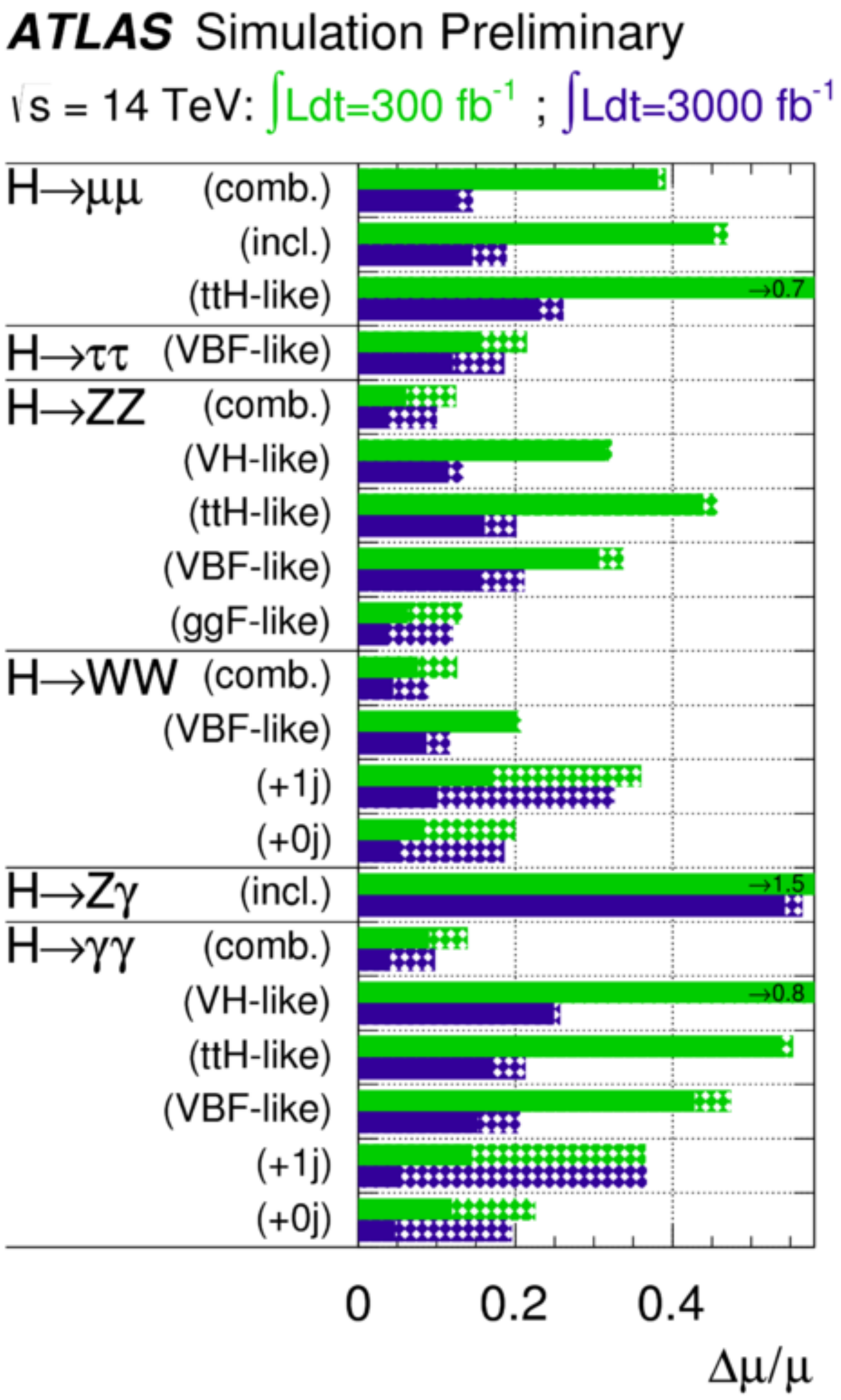
....and apologies for having left out many important results !

Backup

Motivations for accurate SM predictions

ATL-PHYS-PUB-2013-014

Estimated uncertainty on the total signal strength μ for all Higgs final states in the different experimental categories used in the combination, assuming a SM Higgs boson with a mass of 125 GeV



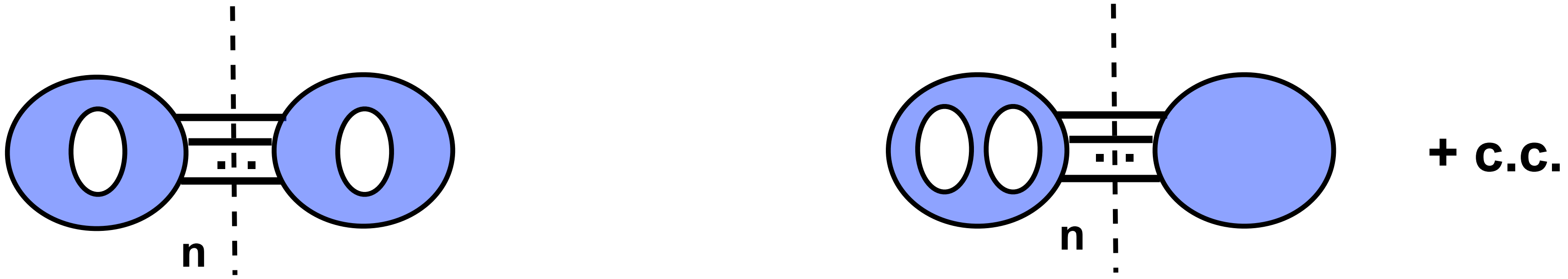
Hashed areas show the impact of theory uncertainties

➡ NNLO Les Houches 2013 wishlist includes processes with Higgs, vector bosons, heavy quarks and jets

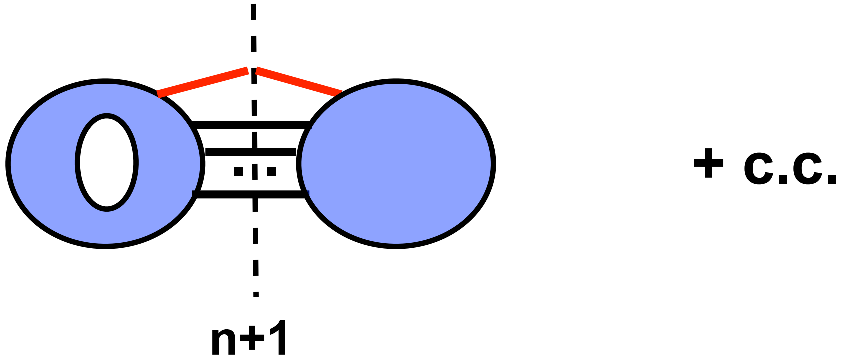
Ingredients of NNLO calculations

Let us assume that the process involves n partons at LO ➡ we need:

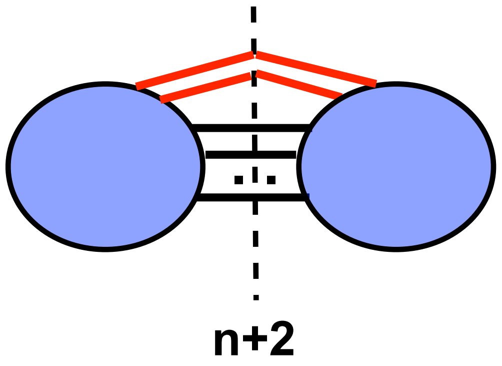
- Double virtual contribution with n resolved partons



- Real-virtual contribution with 1 unresolved parton



- Double-real contribution with 2 unresolved partons

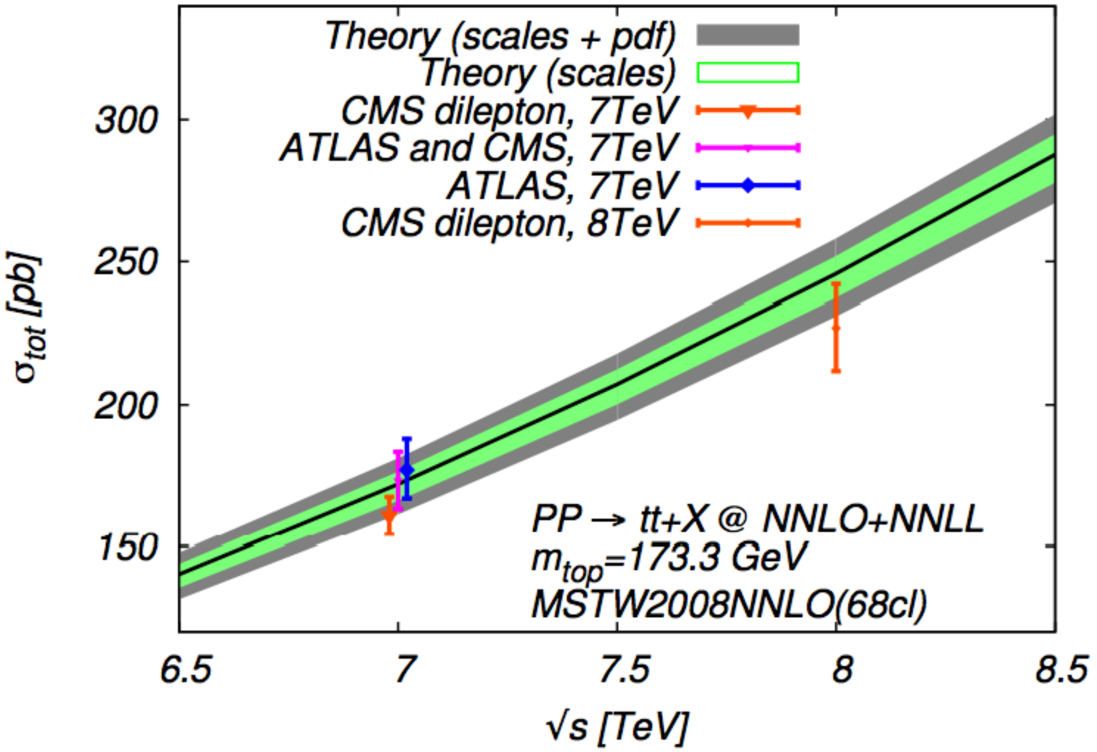


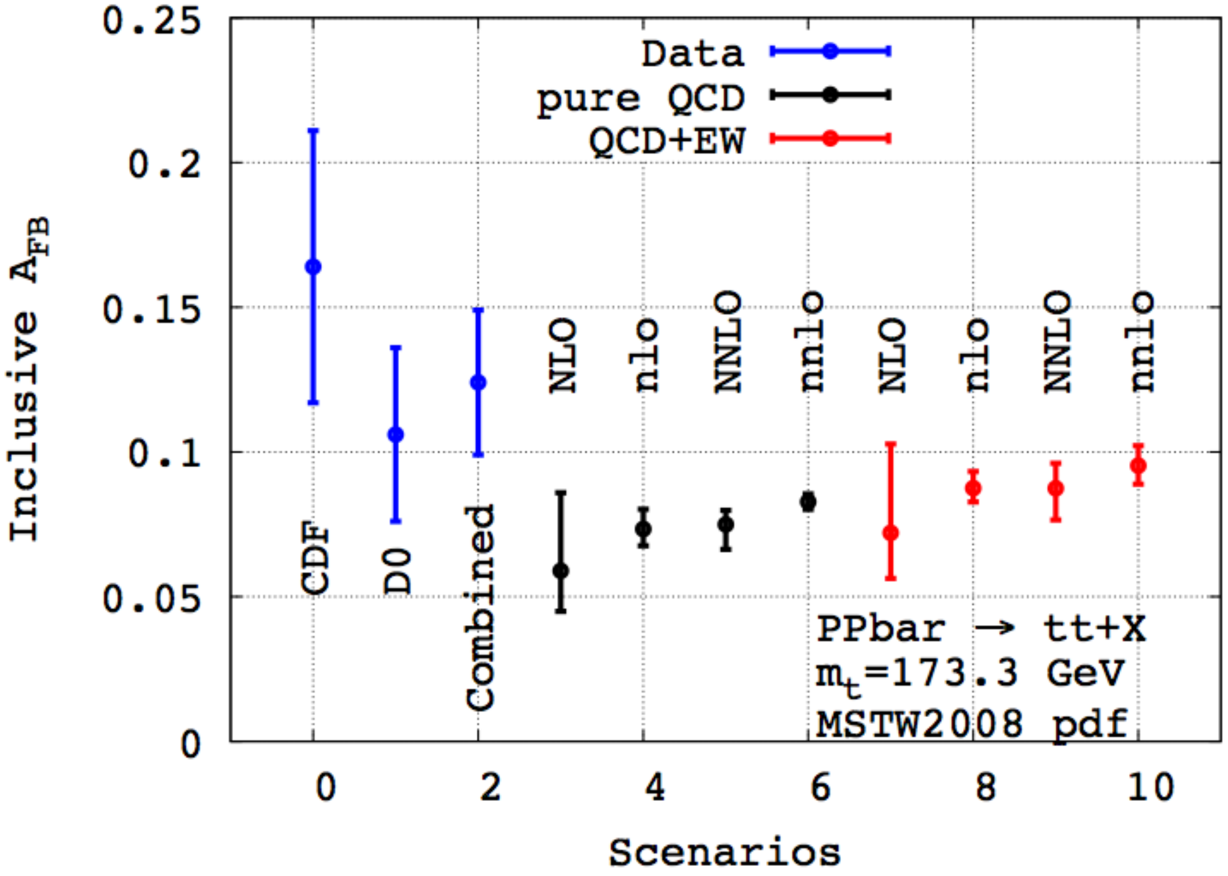
All the three contributions are divergent: how can we handle IR singularities ?

Top production at NNLO

NNLO calculation for $t\bar{t}$ supplemented with soft-gluon resummation: residual scale uncertainties at the few % level (*subtraction+sector decomposition*)

P.Bernreuther, M.Czakon,A.Mitov (2012)
M.Czakon, A.Mitov; M.Czakon, P.Fielder, A.Mitov (2013)

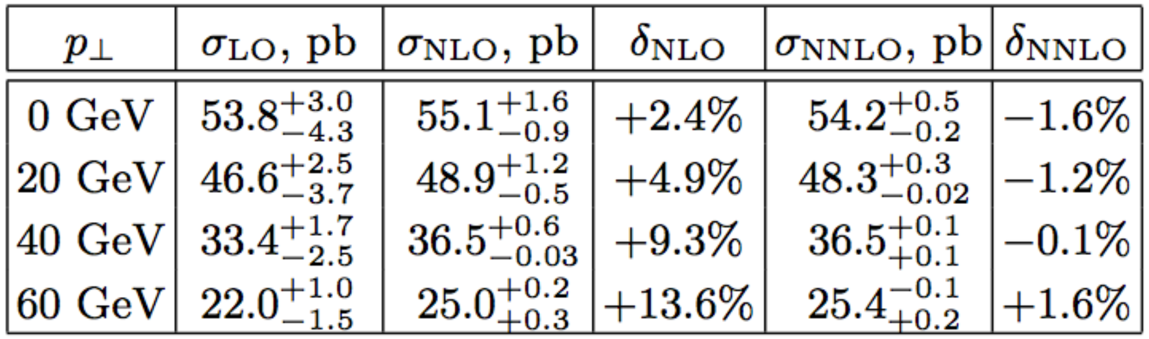




Forward-backward asymmetry at NNLO

M.Czakon, P.Fielder, A.Mitov (2014)

Single top



$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

M.Brucherseifer, F.Caola,K.Melnikov (2014)

Further results expected soon

Parallel work done with antenna subtraction

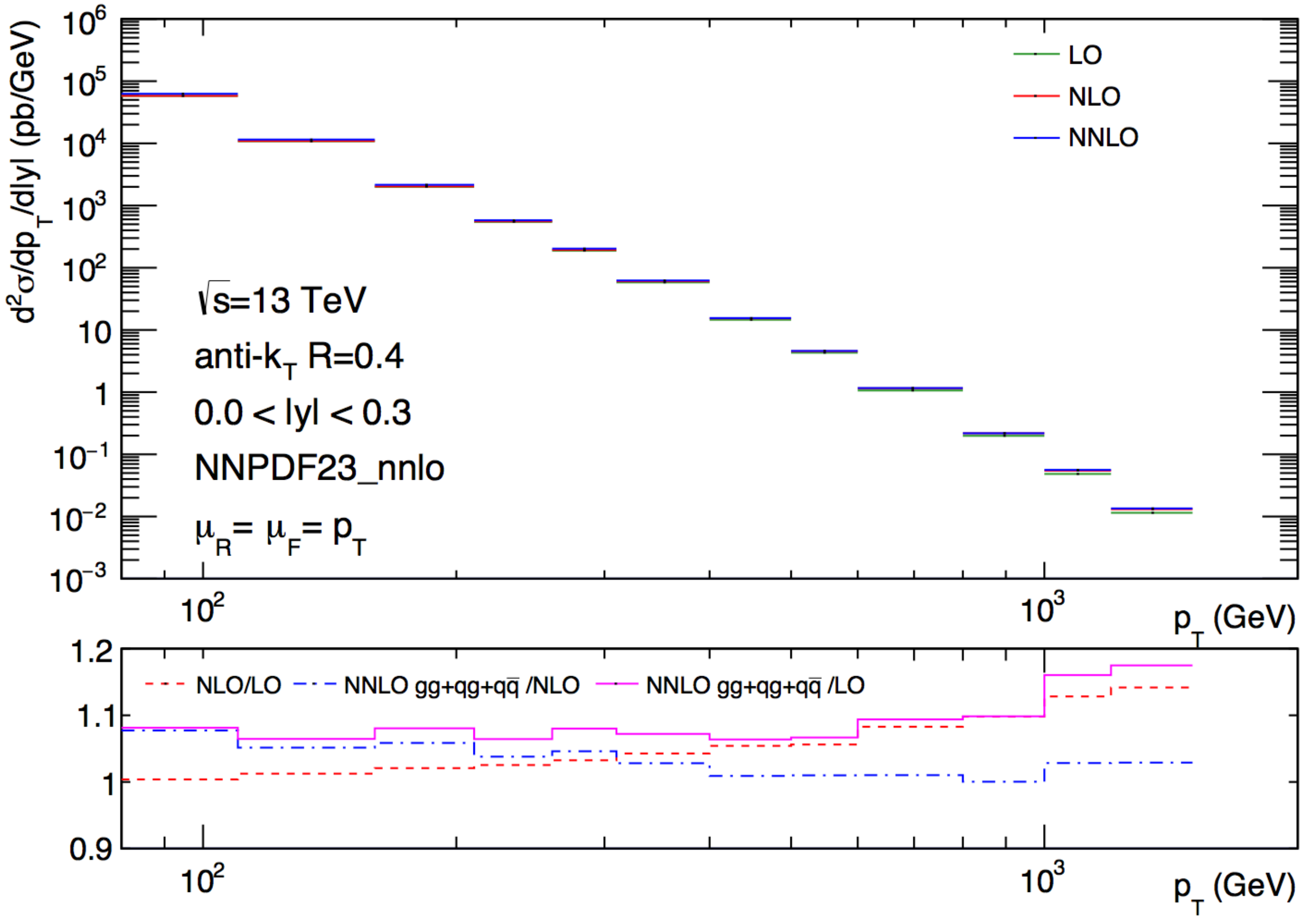
A.Gehrmann et al. (2014,2015)

Dijets

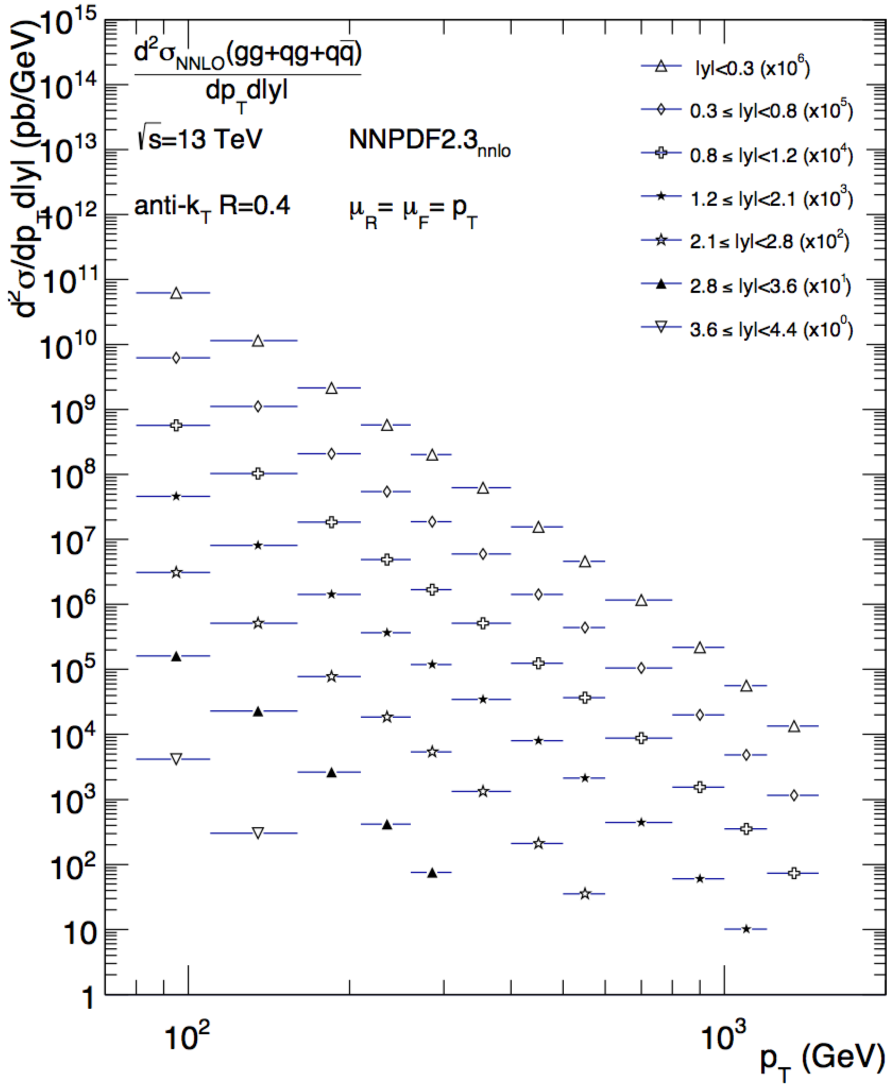
A. & T. Gehrmann, N. Glover,
J.Currie,J.Pires (2013,2014)

gg channel completed in 2013

new results include qg and qqbar channel at leading color



J.Currie, Radcor 2015



This should be already a good approximation for not too large jet p_T

The NNLO impact seems relatively small

The qq channel becomes important at $p_T > 1$ TeV

WW at NNLO

T. Gehrmann, S. Kallweit, P. Maierhofer, A. von Manteuffel,
S. Pozzorini, D. Rathlev, L. Tancredi, MG (2014)

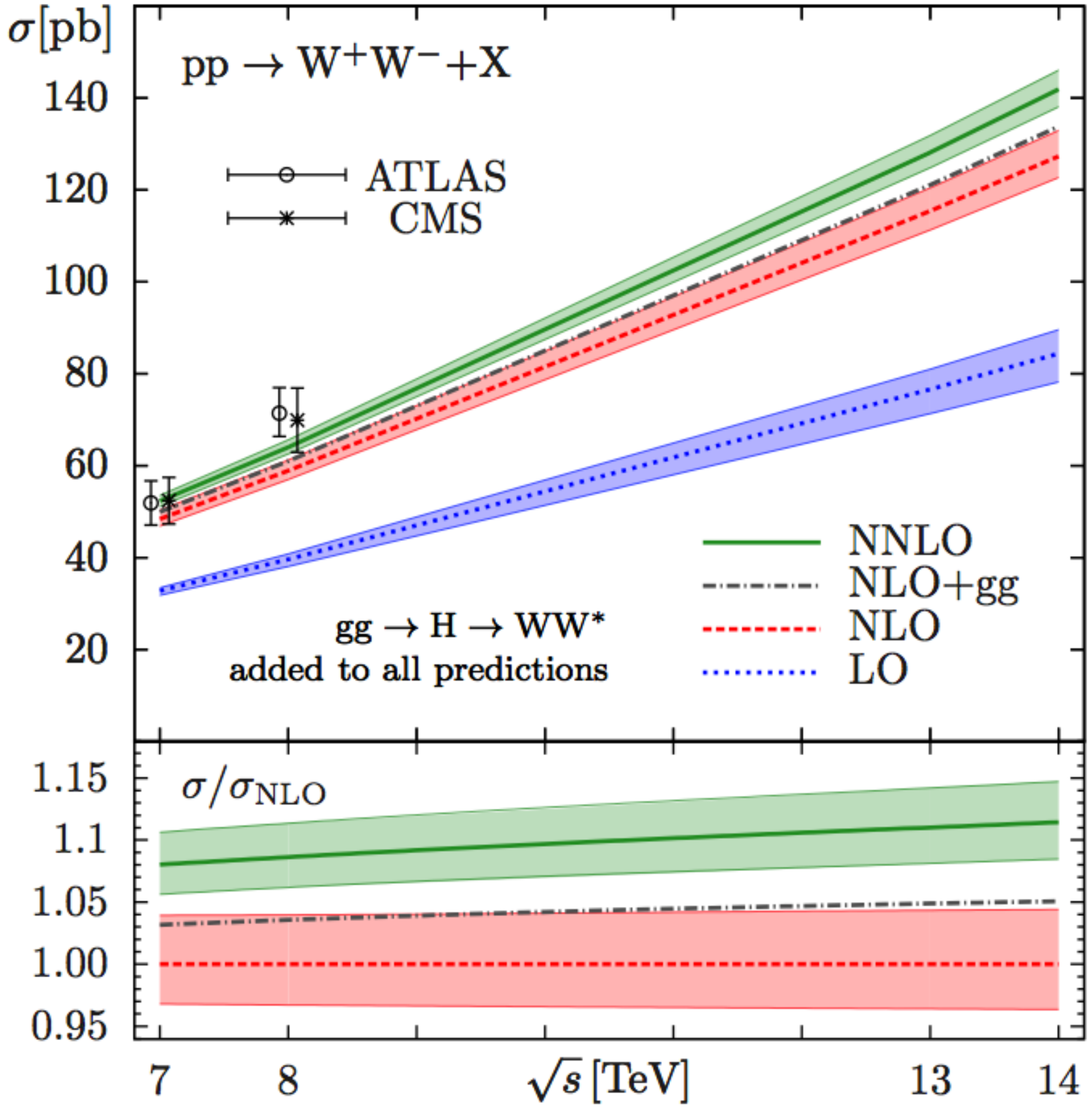
The NNLO effect in the 4FS ranges from 9 to 12 % when √s varies from 7 to 14 TeV

gg contribution 35% of the full NNLO effect

Comparing with 5FS with subtraction of tt and Wt contribution we find agreement at the 1(2)% level

NNLO result significantly reduces the tension with the ATLAS measurement and is in good agreement with recent result from CMS

Done with *q_T subtraction* +Munich+tree and one-loop amplitudes from Openloops



Scale uncertainties computed by varying μ_F and μ_R simultaneously and independently with
$1/2\ m_W < \mu_F, \mu_R < 2m_W$ and $1/2 < \mu_F/\mu_R < 2$

Wγ at NNLO

S.Kallweit,D.Rathlev, MG (2015)

ATLAS cuts (arXiv:1302.1283)

photon isolation: $\varepsilon = 0.5$
smooth cone $R = 0.4$

+19%

$p^{\gamma}_T > 15$ GeV $p^{l}_T > 25$ GeV $\Delta R(l/\gamma,\text{jet}) > 0.3$

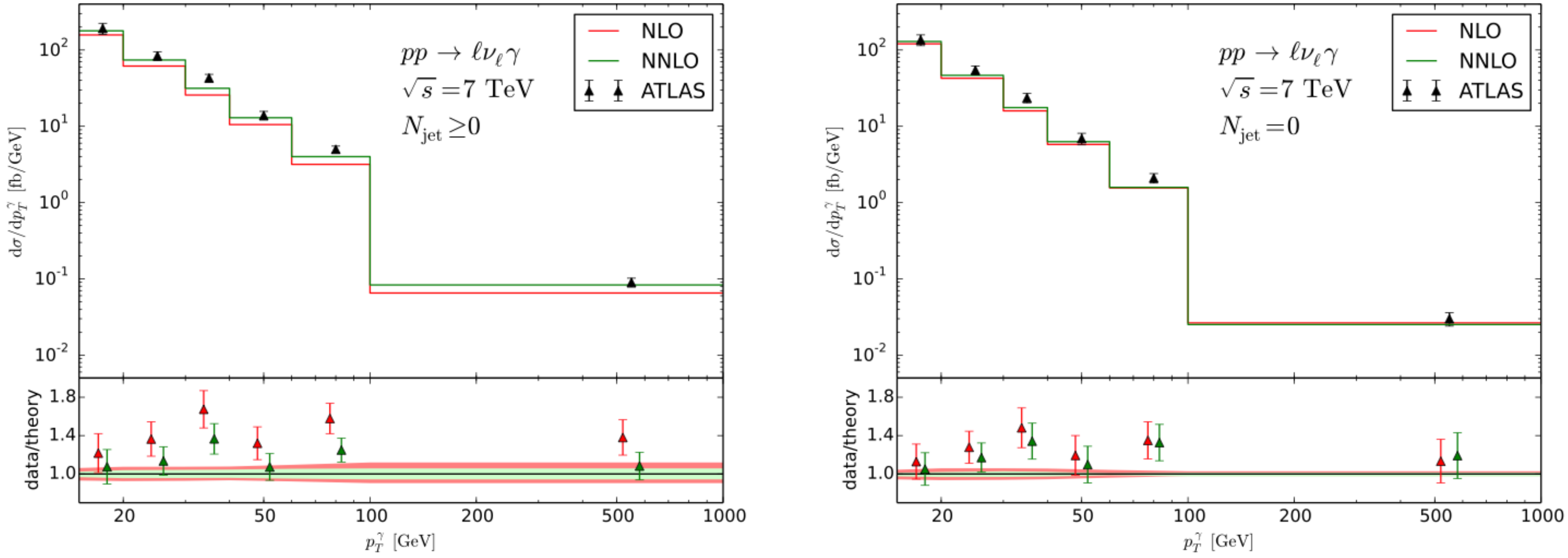
$|\eta^{\gamma}| < 2.37$ $|\eta^{l}| < 2.47$ $\Delta R(l,\gamma) > 0.7$

$p_T^{\text{miss}} > 35$ GeV

jets: anti-kt with D=0.4

$p_T^{\text{jet}} > 15$ GeV $|\eta^{\text{jet}}| < 2.47$

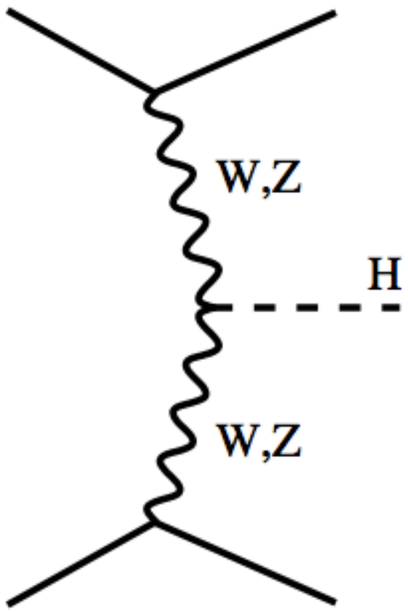
	σ_{NLO} [pb]	σ_{NNLO} [pb]	σ_{ATLAS} [pb]
$N_{\text{jet}} \geq 0$	$2.058^{+6.8\%}_{-6.8\%}$	$2.453^{+4.1\%}_{-4.1\%}$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)
$N_{\text{jet}} = 0$	$1.395^{+5.2\%}_{-5.8\%}$	$1.493^{+1.7\%}_{-2.7\%}$	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi)



$q_T$subtraction +Munich+tree and one-loop amplitudes from Openloops

VBF Higgs production

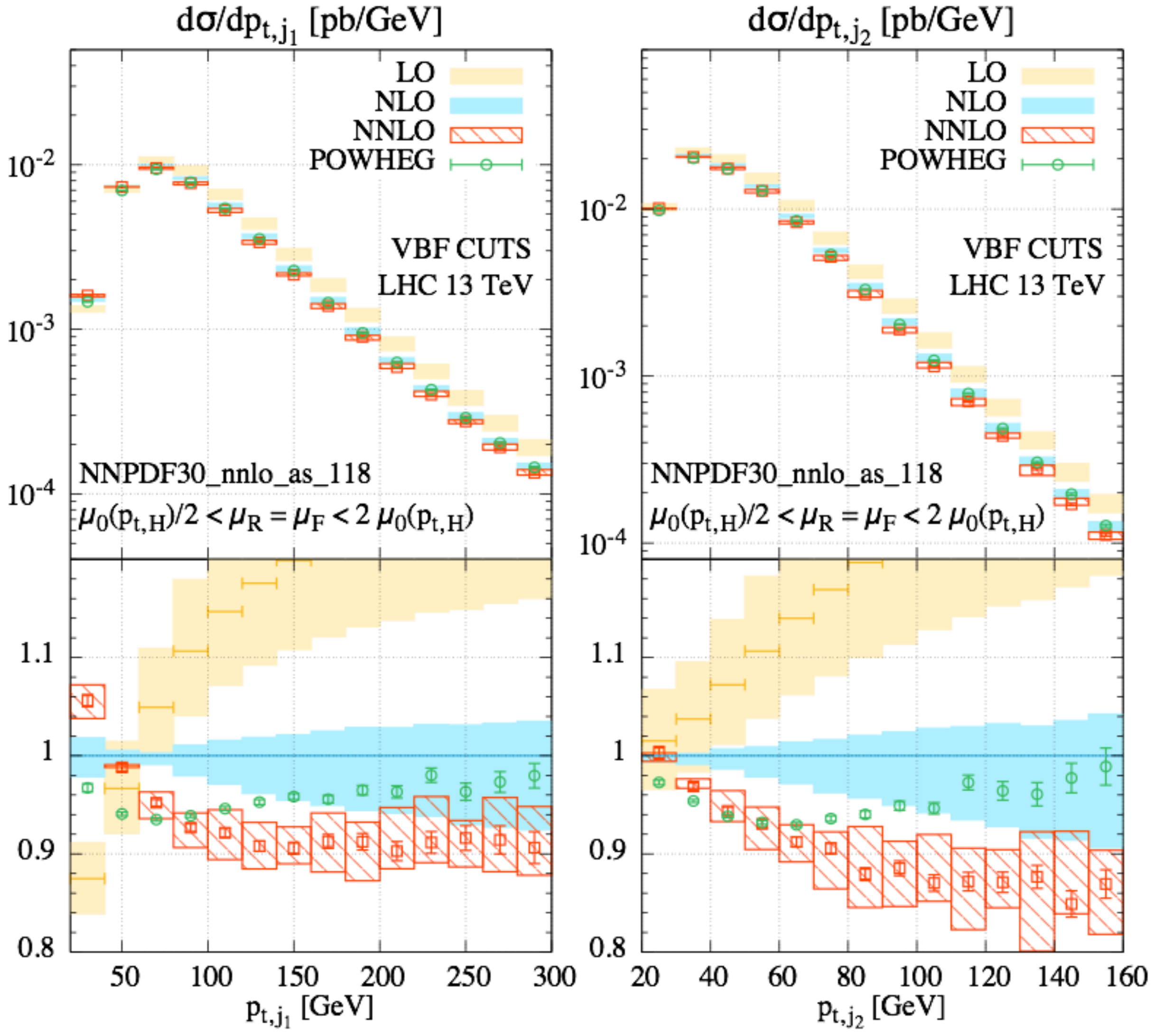
M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)



Vector boson fusion (VBF) is an important production channel for the Higgs boson: distinctive signature with little jet activity in the central rapidity region

Fully inclusive NNLO corrections known since quite some time in the structure function approach: O(1%) effect

P.Bolzoni, F.Maltoni,S.Moch,M.Zaro (2010)



Fully exclusive NNLO computation recently completed (still neglecting color exchanges between quark lines)

NNLO corrections make p_T spectra softer ➡ larger impact when VBF cuts are applied

	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032\,^{+0.057}_{-0.069}$	$0.957\,^{+0.066}_{-0.059}$
NLO	$3.929\,^{+0.024}_{-0.023}$	$0.876\,^{+0.008}_{-0.018}$
NNLO	$3.888\,^{+0.016}_{-0.012}$	$0.826\,^{+0.013}_{-0.014}$

-1% -6%