Precision QCD in the LHC era

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DIS 2014
Warsaw, April 28
LHC was incredibly successful at 7 & 8 TeV

Everything SM like (including Higgs)
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- New physics might be in the detail

Need to be precise on cross-sections and SM parameters

\[ m_H, \ m_t, \ \alpha_s, \ldots \]

**Vacuum stability in the SM at NNLO requires**

\[
m_H \geq 129.2 + 1.8 \times \left( \frac{m_t^{\text{pole}} - 173.2 \text{ GeV}}{0.9 \text{ GeV}} \right) - 0.5 \times \left( \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0 \text{ GeV}
\]

Degrassi et al; Bezrukov et al; Alekhin, Djouadi, Moch; Masina (2012)
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**SM Rules**

- LHC was incredibly successful at 7 & 8 TeV
- Everything SM like (including Higgs)
- New physics might be in the detail

**This Talk**

**Toolkit for precise TH predictions at the LHC**
In the LHC era, QCD is everywhere!

\[ d\sigma = \sum_{ab} \int dx_a \int dx_b \ f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2)) + O\left(\left(\frac{\Lambda}{Q}\right)^m\right) \]

\[ \text{non-perturbative parton distributions} \]

\[ \text{perturbative partonic cross-section} \]

Partonic cross-section: expansion in \( \alpha_s(\mu_R^2) \ll 1 \)

\[ d\hat{\sigma} = \alpha_s^n d\hat{\sigma}^{(0)} + \alpha_s^{n+1} d\hat{\sigma}^{(1)} + ... \]

 Require precision for perturbative and non-perturbative contribution
PDFs

- Several groups provide pdf fits + uncertainties
- Differ by: data input, TH/bias, HQ treatment, coupling, etc

<table>
<thead>
<tr>
<th>set</th>
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<tr>
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Luminosities with common $\alpha_s = 0.118$  

$$L_{ij}(\tau \equiv M_X^2 / S) = \frac{1}{S} \int_\tau^1 \frac{dx}{x} f_i(x, M_X^2) f_j(\tau / x, M_X^2)$$

gluon-gluon

- Good agreement for global fits but deviations as large as uncertainties
- Larger differences with “non-global” results
- 2x larger uncertainties for gluon
One main issue is the coupling constant

\[ \alpha_s(M_Z) = 0.1184 \pm 0.0007 \]

- Optimistic value for the uncertainty at the LHC
- DIS (PDFS) not well covered: some experiments pull value down

![Graph showing different measurements and their uncertainties for \( \alpha_s(M_Z) \)]
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**PDF4LHC recommendation**

- Compute pdfs uncertainties using MSTW & CT & NNPDF (68%cl)
- Obtain the envelope of all bands and use

\[ \Delta \alpha_s(M_Z) = \pm 0.0012 (\pm 0.002) \text{ at 68\% (90\%) c.l.} \]

- Precise LHC data will have important effect on validation & improvement
The perturbative toolkit for precision at colliders
Why NLO?

- Accurate Theoretical Predictions
  shape and normalization
  first error estimate
- Large Corrections: check PT
- Opening of new channels
- Effect of extra radiation
  jet algorithm dependence

Amazing progress in the last few years
The NLO revolution

Why NLO?

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Amazing progress in the last few years

Large multiplicities relevant for LHC
Revolution in calculation of 1-loop amplitudes

Bottleneck in the virtual contribution: large multiplicities

\[
\begin{align*}
&\sum_i d_i \quad + \quad \sum_i c_i \quad + \quad \sum_i b_i \quad + \quad \sum_i a_i \quad + \quad \frac{x}{y}
\end{align*}
\]

Feynmanian approach

- Improvements in decomposition and reduction
  - Denner, Dittmaier; Pozzorini; Binoth, Guillet, Heinrich, Pilon, Schubert + many others

Unitarian approach

- Use multi-particle cuts from generalized unitarity
  - Bern, Dixon, Dunbar, Kosower; Britto, Cachazo, Feng; Mastrolia; Forde; Badger; Ellis, Giele, Kunszt, Melnikov + many others

OPP Ossola, Papadopoulos, Pittau decomposition at the integrand level
This paper is organized as follows. In section II we summarize the basic setup of the processes and computation. In section III we present our results for cross sections. As the number of jets increases, production of a Q boson to leptons.

\[ \mu_R = \mu_F = \frac{\hat{H}_T}{2} = \frac{1}{2} \sum_m p_T^m + E_T^W \]

- **Dramatic reduction in scale dependence (~20%)**
- **Up to 50% correction (non-trivial in shape)**
Multi-jet production

\[ pp \rightarrow 5 \text{ jets at NLO} \]

Njet+Sherpa (Badger, Biedermann, Uwer, Yundin)

- Better stability
- NLO in very good agreement with data!
### Experimenter’s wish-list

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<tr>
<th>Process (V \in {Z,W,\gamma})</th>
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7. $pp \rightarrow VV b\bar{b}$ | relevant for VBF $\rightarrow H \rightarrow VV$, $ttH$.
8. $pp \rightarrow V+2$ jets | relevant for VBF $\rightarrow H \rightarrow VV$.
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DIS 2012 Theory Developments in QCD Daniel de Florian
Final goal: Really automatic NLO calculations
• Specify the process (input card)
• Input parameters
• Define final cuts

Automatic NLO calculation “conceptually” solved
• in a few years a number of codes (among others)

Blackhat+Sherpa
MadLoop+MadFKS
CutTools
✓
compete on precision, flexibility, speed, stability, ...
✓ many features : uncertainties, ...

GoSam + Sherpa/MadGraph
OpenLoops+Sherpa

Best solution still to emerge, but not more NLO wish-list, do it yourself!

Individual calculations still relevant! ✓ open the way to new methods
Resummation

- **QCD based on convergence of perturbative expansion**
  \[ \sigma = C_0 + \alpha_s C_1 + \alpha_s^2 C_2 + \alpha_s^3 C_3 + \ldots \]
  requires \( \alpha_s \ll 1 \), \( C_n \sim \mathcal{O}(1) \)

In the boundaries of phase space → soft and collinear emission
unbalance cancellation of infrared singularities
between real and virtual contributions

- **Convergence spoiled when two scales are very different**
  \( L = |\log \frac{E_1}{E_2}| \gg 1 \)
  \( C_m \sim L^n \quad n \leq 2m \)
  low transverse momentum \( \log \frac{q_T}{Q} \)

Higgs

- **LO:** \( \frac{d\sigma}{dq_T} \to +\infty \) as \( q_T \to 0 \)
- **NLO:** \( \frac{d\sigma}{dq_T} \to -\infty \) as \( q_T \to 0 \)
Resummation achieved by exponentiation of large logs in Sudakov factor

Most recently: jet vetos
Jet veto in Higgs @ NNLL

Banfi, Monni, Salam, Zanderighi (2012)
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Stewart, Tackmann, Walsh, Zuberi (2013)

Revised Figure 4: (Left) Comparison between the matched efficiency at NNLL+NNLO accuracy and the NNLO fixed-order result, both results include mass effects. (Right) Zero-jet cross section computed in the large-\(m_t\) limit (green dot-dashed curve), including full \(m_t\) dependence (blue dashed curve), and including full \(m_t\) and \(m_b\) dependence (red solid band). The lower panel shows the ratio to the central value of the band.

Figure 5: Comparison between the match efficiency at NNLL+NNLO accuracy in the large-\(m_t\) limit (dashed blue), including \(m_t\) only (dot-dashed green) and both \(m_t\), \(m_b\) effects (solid red). The lower panel shows the ratio to the central value of the band.

Below we provide tables with numerical results for cross-sections and efficiencies for...

\[ \frac{\epsilon(p_{T,veto})}{\epsilon_{\text{central}}(p_{T,veto})} \]

\[ \sigma_{0}(p_{T,veto}) \ [\text{pb}] \]

\[ gg \rightarrow H, m_H = 125 \text{ GeV} \]

\[ pp, 8 \text{ TeV} \]

\[ m_H/4 < \mu_R, \mu_F \text{, scheme a,b,c} \]

MSTW2008 NNLO PDFs

anti-\(k_t\), \(R = 0.5\)

\(m_t, m_b\) corrections

\(\mu_H = \mu_{FO} = m_H/2\)

STWZ

NNLL'_{pT} + NNLO

NNLO (ST)

\[ 0 < m_H/4 < \mu_R, \mu_F < m_H \]

schemes a,b,c

\[ pp, 8 \text{ TeV} \]

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Reduction in uncertainty
Validation of tools

Stewart, Tackmann, Walsh, Zuberi (2013)

efficiency 0-jet “QCD”

Recover fixed order at large transverse momentum
Merging NLO with Parton Showers

- Resummation to NLL accuracy + realistic final states
- Allow to carry NLO precision to all aspects of experimental analysis
  - **MC@NLO** Frixione, Webber
  - **POWHEG** Nason; Frixione, Nason, Oleari
- Can be interfaced to different tools: Herwig, Phytia, Sherpa
- Treat radiation differently but formally same NL accuracy
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- NNLOPS (Higgs)  
  Hamilton, Nason, Re, Zanderighi

POWHEG+MINLO

H+jet at NLO
Inclusive H reweighthed to NNLO

Figure 4. Comparison of the $N_{nlops}$ (red) with the NNLL+NNLO prediction of $H_{qT}$ (green) for the Higgs transverse momentum. In $H_{qT}$ we choose $\mu_R = \mu_F = \frac{1}{2} m_H$ as the central scales, and keep the resummation scale always fixed to $\frac{1}{2} m_H$. On the left (right) the $N_{nlops}$ ($H_{qT}$) uncertainty band is shown. In the lower panel, the ratio to the $N_{nlops}$ central prediction is displayed.

Figure 5. A similar but with $\mu = \frac{1}{2}$ in the profile function.

In figures 4 and 5, we compare the $N_{nlops}$ (see eq. (3.2)) with the $H_{qT}$ [55, 56] result for two choices of the parameter in the profile function. The uncertainty band is the envelope of the 21-point scale variation illustrated in section 3. We used the 'switched' output of $H_{qT}$, forming the related uncertainty band from the envelope of the seven results obtained by independent variations of $\mu_R$ and $\mu_F$, by a factor of two, symmetrically, about $\mu_R = \mu_F = \frac{1}{2} m_H$, while keeping the resummation scale always fixed to $\frac{1}{2} m_H$.

Pleasingly, we see that the $N_{nlops}$ and $H_{qT}$ results are almost completely contained within each other’s uncertainty band in the region of moderate transverse momenta. We have verified that at high transverse momentum the $H_{qT}$ prediction agrees identically with that of $H_{nnlo}$, since the ‘switched’ output in the former uses the fixed order result in this region. It follows that here we see the $H_{qT}$ spectrum falling less rapidly than that of the $N_{nlops}$ simulation at large $p_H^T$. As was seen in fig. 3 and remarked upon in the related discussion, in the case of $\mu = 1$, the $N_{nlops}$ result is very well approximated by that of $H_{j-Minlo}$ multiplied by a uniform NNLO-to-NLO $K$-factor of 1.5, leaving the slope of the distribution unchanged. On the other hand, for $\mu = \frac{1}{2}$ (fig. 5) the $K$-factor enhancement is $\approx 1.3$.
Automation and more

- Provide large library of processes or different degree of automation

- aMC@NLO: full automation of NLO and PS in MC@NLO framework
  Frederix, Frixione, Hirschi, Pittau, Maltoni, Torrelli

- POWHEG-BOX framework
  Aioli, Nason, Oleari, re

- Sherpa: real matrix elements matching MC@NLO and POWHEG
  Krauss, Höche, Siegert, Schönher

- POWHEL: automation of ME from HELAC with POWHEG-Box
  Papadopoulos, Garzelli, Kardos, Trocsanyi

- POWHEG Box + Madgraph4
  Campbell, Ellis, Frederix, Nason, Oleari, Williams

- MINLO
  Hamilton, Nason, Oleari, Zanderighi

- UNLOPS
  Lönnblad, Prestel

- GENEVA
  Aioli et al

+ many others
NNLO the new frontier

- Some measurements to few percent accuracy
  - $e^+e^- \rightarrow 3\text{ jets}$
  - $e^- p \rightarrow (2 + 1)\text{ jets}$

- Some processes with still (potentially) large NNLO corrections
  - $pp \rightarrow H$
  - $pp \rightarrow HH$
  - $pp \rightarrow \gamma\gamma$
  - $pp \rightarrow Z\gamma$
  - $pp \rightarrow VH$
  - $pp \rightarrow VV$
  - $pp \rightarrow H + \text{jets}$

$O(\alpha_s^2)$
Match experimental accuracy
Extract accurate information
Meaningful comparison
Solid estimate of uncertainties
\[ pp \rightarrow Z\gamma \]

M.Grazzini, S.Kallweit, D.Rathlev, A.Torre (2013)

- Triple gauge boson couplings
- OpenLoops for amplitude generation
- First step towards automation

\( NNLO \sim 16\% \) at LHC

Improvement in data/TH

\( p_T^\gamma \) distribution of the photon, and we present a comparison of the invariant mass distribution in Fig. 3. With 0

**References**

[1] T. Aaltonen


[3] V. M. Abazov

\[ pp \rightarrow t\bar{t} \]

- Very relevant observable at colliders
- LHC will reach better than 5% accuracy
- top mass, pdfs, new physics

(inclusive) Full NNLO available

<5% TH uncertainties

**Precision for mass**

<table>
<thead>
<tr>
<th>Collider</th>
<th>( \sigma_{\text{tot}} ) [pb]</th>
<th>scales [pb]</th>
<th>pdf [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>7.164</td>
<td>+0.110(1.5%)</td>
<td>+0.169(2.4%)</td>
</tr>
<tr>
<td>LHC 7 TeV</td>
<td>172.0</td>
<td>+4.4(2.6%)</td>
<td>+4.7(2.7%)</td>
</tr>
<tr>
<td>LHC 8 TeV</td>
<td>245.8</td>
<td>+6.2(2.5%)</td>
<td>+6.2(2.5%)</td>
</tr>
<tr>
<td>LHC 14 TeV</td>
<td>953.6</td>
<td>+22.7(2.4%)</td>
<td>+16.2(1.7%)</td>
</tr>
</tbody>
</table>

M. Czakon, P. Fiedler, A. Mitov, J. Rojo (2013)

Precision QCD in the LHC era  Daniel de Florian
**Precision for gluon pdf**

\[ pp \rightarrow t\bar{t} \]

\[ \alpha_s = 0.118 \]

\[ Q^2 = 100 \text{ GeV}^2 \]

M. Czakon, M. Mangano, A. Mitov, J. Rojo (2013)

\(~20\%\) reduction \( x=0.1 \) to \( 0.5 \)

- data used in ABM 2013

\[ g^{(new)}(x, Q^2)/g^{(old)}(x, Q^2) \]
• Precision for gluon pdf

\[ pp \rightarrow t\bar{t} \]

M. Czakon, M. Mangano, A. Mitov, J. Rojo (2013)

\(~20\%\) reduction \(x=0.1\) to 0.5

data used in ABM 2013

• Even higher precision: threshold resummation

\[ Q^2 = 100 \text{ GeV}^2 \]


**pp → 2 jets**


- Pure gluon using antenna subtraction: NNLOJET

- **15-25% increase**

Similar results expected for other partonic channels (gg dominant at low \( p_T \))

- Amazing reduction in scale dependence: precision for LHC

- But NNLO can not be predicted by NLO scale variations..
\[ pp \rightarrow H + \text{jet} \]


- Pure gluon only \( p_T^{\text{jet}} > 30 \text{ GeV} \)

\[
\begin{align*}
\sigma_{\text{LO}}(pp \rightarrow Hj) &= 2713_{-776}^{+1216} \text{ fb}, \\
\sigma_{\text{NLO}}(pp \rightarrow Hj) &= 4377_{-738}^{+760} \text{ fb}, \\
\sigma_{\text{NNLO}}(pp \rightarrow Hj) &= 6177_{-242}^{+204} \text{ fb}.
\end{align*}
\]

+60% NLO
+30-40% NNLO

- Another case of significantly reduced scale dependence \( \sim 4\% \)
\[ pp \rightarrow HH \]

- Triple Higgs coupling: Higgs potential
- Expect large corrections (single Higgs)
- Use large top mass limit

\[ M_H = 126 \text{ GeV} \]

\[ \sigma_{\text{LO}} = 17.8^{+5.3}_{-3.8} \, \text{fb} \]

\[ \sigma_{\text{NLO}} = 33.2^{+5.9}_{-4.9} \, \text{fb} \]

\[ \sigma_{\text{NNLO}} = 40.2^{+3.2}_{-3.5} \, \text{fb} \]

\[ K = 1.86 \]

\[ \sigma(\pm 20\%) \text{ at NLO.} \]
Many of them doable in the next few years

More realistic final states (V, top with decays)

Larger multiplicities not possible yet

Automation far away

Shower requires increase in accuracy

NLO EW corrections needed
Electroweak corrections at large energies

- **Sudakov logarithms** induced by soft gauge-boson exchange

\[ \delta_{LL}^{1\text{-loop}} \sim -\frac{\alpha}{\pi s_W^2} \ln^2 \left( \frac{s}{M_W^2} \right) \approx -26\% \]
\[ \delta_{LL}^{2\text{-loop}} \sim +\frac{\alpha^2}{2\pi^2 s_W^4} \ln^4 \left( \frac{s}{M_W^2} \right) \approx 3.5\% \]

- still sizable at 2-loops

\[ s, |t|, |u| \gg M_W^2 \]

**Dijet production**

Dittmaier, Huss, Speckner

**Tree EW**

\[ u \gamma, Z d \]

**I-loop EW**

\[ \times \]

\[ \delta_{\text{tree}} + \delta_{1\text{-loop}} \]

\[ \delta_\% \]

\[ k_{T,1} [\text{GeV}] \]

\[ 0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \quad 1400 \]
Higgs Boson

- **Gluon-gluon fusion dominates due to large gluon luminosity**

- **QCD corrections are huge!**

\[ K = \frac{\sigma^{NNLO(NLO)}}{\sigma^{LO}} \]

- **NLO**
  Dawson (1991); Djouadi, Spira, Zerwas (1991)
  Graudenz, Spira, Zerwas (1993)

- **NNLO**
  Harlander, Kilgore (2002)
  Anastasiou, Melnikov (2002)
Improved Higgs Cross-section @ LHC

- NNLL Resummation 9% at 7 TeV  \(^{Catani, \text{de}F., \text{Grazzini, Nason}} \text{(2003)}\)
- Two loop EW corrections not negligible \(\sim 5\%\)  \(^{Aglieotti, \text{Bonciani, Degrassi, Vicini}} \text{(2004)}\),  \(^{Degrassi, \text{Maltoni}} \text{(2004)}\),  \(^{Actis, \text{Passarino, Sturm, Uccirati}} \text{(2008)}\)
- Mixed EW-QCD effects evaluated in EFT approach  \(^{Anastasiou et al} \text{(2008)}\)
- + Mass effects, Line-shape, interferences, ...  \(^{Higgs \text{ Cross-Section WG}}\)

\[
\sigma(m_H = 125 \text{ GeV}) = 19.27^{+7.2\%}_{-7.8\%}^{+7.5\%}_{-6.9\%} \text{ pb}
\]

- Still sizable uncertainties but great improvement over the last years
- And more precise results just arriving!!
Improved Higgs Cross-section @ LHC

- NNLL Resummation 9% at 7 TeV  
  Catani, deFl., Grazzini, Nason (2003)

- Two loop EW corrections not negligible ~ 5%  
  Aglietti, Bonciani, Degrassi, Vicini (2004)  
  Degrassi, Maltoni (2004)  
  Actis, Passarino, Sturm, Uccirati (2008)

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  Higgs Cross-Section WG

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def, Grazzini

- Still sizable uncertainties but great improvement over the last years

- And more precise results just arriving!!
Even Higher orders: $N^3LO$

- **3 loop form factor**
  - Baikov et al (2009)
  - Lee, Smirnov, Smirnov (2010)

- **Triple real emission: threshold expansion**
  - Anastasiou, Duhr, Dulat, Mistlberger (2013)

- **2 loop + single emission**
  - Duhr, Gehrmann (2013); Li, Zu (2013); Gehrmann, Jaquier, Glover, Koukoutsakis (2012)

- **1 loop + double emission**
  - Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2013)

- **Subtraction terms**
  - Höschele, Hoff, Pak, Steinhauser, Ueda (2013)
  - Buehler, Lazopoulos (2013)

- **NNNLO Soft-Virtual approximation**
  - Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger (2014)

New era in precision
Further improvements expected
Precision in data sensitive to NNLO effects

TH vs EXP: detailed comparison just began at LHC
DATA vs TH : DiPhotons  \( pp \rightarrow \gamma\gamma \)

**ATLAS**

\( \sqrt{s} = 7 \text{ TeV} \)

- **Data 2011, \( \int L dt = 4.9 \text{ fb}^{-1} \)**
- **DIPHOX+GAMMA2MC (CT10)**
- **2\(γ\)NNLO (MSTW2008)**

**FIG. 8.** Invariant mass distribution of the leading photon pairs \( m_{\gamma\gamma} \) [GeV].

**FIG. 7.** The measured di-photon system (right) [22]. Black dots correspond to data with error bars for their total uncertainties. The data are compared using the different predictions shown by a dashed line: a

- **Data 2010 (PDF: CT10)**
- **Data 2011 (PDF: MSTW2008)**
- **Data 2010 (PDF: MSTW2008)**

- **DIPHOX+GAMMA2MC (CT10)**
- **2\(γ\)NNLO (MSTW2008)**

The uncertainty on the cross sections predicted by LO MC generators include only statistical uncertainties, while the theoretical uncertainty added in quadrature) and the hatched band represents the theoretical uncertainty.

The measured cross section. The inner (outer) error bars represent the statistical uncertainties (the statistical and systematic uncertainties added in quadrature).
Conclusions

Amazing work in the last few years direct consequence of LHC

- PDFs: precision and uncertainties
- NLO : multileg processes and automatic!
- NNLO finally reaching $2 \to 2$ processes
- Resummation setting NNLL as new standard
- Improvements for NLO+PS and high degree of automation
- Higgs moving towards N3LO
- + many other issues not discussed (including jet structure)!
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Thanks!