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
The corresponding cross section can be written as

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

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 \( Q_0 = 1 - 4 \text{ GeV} \)

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

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

- Evolve to desired \( Q^2 \) through DGLAP equation

\[
Q^2 \frac{\partial f_a(x, Q^2)}{\partial Q^2} = \int_x^1 \frac{d z}{z} P_{ab}(\alpha_s(Q^2), z) f_b(x/z, Q^2)
\]

\[
P_{ab}(\alpha_s, z) = \frac{\alpha_s}{2\pi} P^{(0)}_{ab}(z) + \left( \frac{\alpha_s}{2\pi} \right)^2 P^{(1)}_{ab}(z) + \left( \frac{\alpha_s}{2\pi} \right)^3 P^{(2)}_{ab}(z) + \ldots
\]

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

MMHT\(_{14}\) (CT\(_{14}\)) uses instead Chebyshev (Bernstein) polynomials

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

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

<table>
<thead>
<tr>
<th>set</th>
<th>data</th>
<th>errors</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMHT14</td>
<td>DIS+DY+jets+LHC</td>
<td>hessian</td>
<td>(\alpha_S) fixed</td>
</tr>
<tr>
<td>CT14</td>
<td>DIS+DY+jets+LHC</td>
<td>hessian</td>
<td>(\alpha_S) fixed</td>
</tr>
<tr>
<td>NNPDF3.0</td>
<td>DIS+DY+jets+LHC</td>
<td>Montecarlo</td>
<td>(\alpha_S) fixed</td>
</tr>
<tr>
<td>HeraPDF2.0</td>
<td>DIS</td>
<td>hessian</td>
<td>(\alpha_S) fixed</td>
</tr>
<tr>
<td>ABM12</td>
<td>DIS+DY+LHC</td>
<td>hessian</td>
<td>(\alpha_S) fitted</td>
</tr>
<tr>
<td>(G)JR</td>
<td>DIS+DY (ft) + some jets</td>
<td>hessian</td>
<td>valence-like (\alpha_S) fitted</td>
</tr>
</tbody>
</table>

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 $\alpha_S(m_Z) = 0.1185 \pm 0.0006$

- Recent reassessment of lattice result leads to $0.1184 \pm 0.0012$ (double error with respect to what used in the PDG)  
  - FLAG working group (2013)
- Determination from EW fit (at N3LO) 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 $\alpha_S(m_Z) = 0.1135 \pm 0.0011$
  - “Outliers” PDF+$\alpha_S$ fits lead to $\alpha_S(m_Z) \approx 0.113$
  
  - S. Alekhin et al. (2013, 2014)
  - P. Jimenez-Delgado, Reja (2014)

=&gt; **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 $\alpha_S$

$$\hat{\sigma} = \alpha_S^k \left( \hat{\sigma}^{(0)} + \frac{\alpha_S}{\pi} \hat{\sigma}^{(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \hat{\sigma}^{(2)} + \ldots \right)$$

Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions
- the scale of $\alpha_S$ is not defined
- jets $\leftrightarrow$ partons: jet structure starts to appear only beyond LO

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

$\Rightarrow$ NNLO allows to quantify uncertainties

Furthermore
- Resummation of the large logarithmic terms at phase space boundaries
- 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.

\[ \text{General one-loop amplitude expressed as a sum of known boxes, triangles and bubble integrals plus a remainder term} \]

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

For example, \( c_4 \) is a simple product of four tree-level amplitudes evaluated at complex momenta.

For many years the bottleneck has been the computation of the relevant one-loop amplitudes \( \rightarrow \) 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
  
  \( \text{A.Denner, S.Dittmaier (2006,2011)} \)

- fully numerical evaluation based on reduction at the integrand level

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

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

see also Van Hameren (2009)
## The NLO automation

<table>
<thead>
<tr>
<th>Process</th>
<th>Syntax</th>
<th>LO 13 TeV</th>
<th>Cross section (pb)</th>
<th>NLO 13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Higgs production</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g.1 ( pp \rightarrow H ) (HEFT)</td>
<td>( p p &gt; h )</td>
<td>1.593 ± 0.003 \cdot 10^1</td>
<td>+34.8% ± 1.2%</td>
<td>3.261 ± 0.010 \cdot 10^1</td>
</tr>
<tr>
<td>g.2 ( pp \rightarrow H j ) (HEFT)</td>
<td>( p p &gt; h j )</td>
<td>8.367 ± 0.003 \cdot 10^0</td>
<td>-26.0% ± 1.7%</td>
<td>1.422 ± 0.006 \cdot 10^1</td>
</tr>
<tr>
<td>g.3 ( pp \rightarrow Hjj ) (HEFT)</td>
<td>( p p &gt; h j j )</td>
<td>3.020 ± 0.002 \cdot 10^0</td>
<td>+39.4% ± 1.2%</td>
<td>5.124 ± 0.020 \cdot 10^0</td>
</tr>
<tr>
<td>g.4 ( pp \rightarrow Hjj ) (VBF)</td>
<td>( p p &gt; h j j ) ( w^+ w^- z )</td>
<td>1.987 ± 0.002 \cdot 10^0</td>
<td>+69.1% ± 1.4%</td>
<td>1.900 ± 0.006 \cdot 10^0</td>
</tr>
<tr>
<td>g.5 ( pp \rightarrow Hjjj ) (VBF)</td>
<td>( p p &gt; h j j j ) ( w^+ w^- z )</td>
<td>2.824 ± 0.005 \cdot 10^{-1}</td>
<td>+34.7% ± 1.7%</td>
<td>3.085 ± 0.010 \cdot 10^{-1}</td>
</tr>
<tr>
<td>g.6 ( pp \rightarrow HW^\pm )</td>
<td>( p p &gt; h w^m )</td>
<td>1.195 ± 0.002 \cdot 10^0</td>
<td>+3.5% ± 1.9%</td>
<td>1.419 ± 0.005 \cdot 10^0</td>
</tr>
<tr>
<td>g.7 ( pp \rightarrow HW^\pm j )</td>
<td>( p p &gt; h w^m j )</td>
<td>4.018 ± 0.003 \cdot 10^{-1}</td>
<td>+26.1% ± 0.8%</td>
<td>4.842 ± 0.017 \cdot 10^{-1}</td>
</tr>
<tr>
<td>g.8* ( pp \rightarrow HW^\pm jj )</td>
<td>( p p &gt; h w^m j j )</td>
<td>1.198 ± 0.016 \cdot 10^{-1}</td>
<td>-19.4% ± 0.6%</td>
<td>1.574 ± 0.014 \cdot 10^{-1}</td>
</tr>
<tr>
<td>g.9 ( pp \rightarrow HZ )</td>
<td>( p p &gt; h z )</td>
<td>6.468 ± 0.008 \cdot 10^{-1}</td>
<td>+3.5% ± 1.9%</td>
<td>7.674 ± 0.027 \cdot 10^{-1}</td>
</tr>
<tr>
<td>g.10 ( pp \rightarrow HZ j )</td>
<td>( p p &gt; h z j )</td>
<td>2.225 ± 0.001 \cdot 10^{-1}</td>
<td>+3.5% ± 1.9%</td>
<td>2.667 ± 0.010 \cdot 10^{-1}</td>
</tr>
<tr>
<td>g.11* ( pp \rightarrow HZ jj )</td>
<td>( p p &gt; h z j j )</td>
<td>7.262 ± 0.012 \cdot 10^{-2}</td>
<td>+26.2% ± 0.7%</td>
<td>8.753 ± 0.037 \cdot 10^{-2}</td>
</tr>
<tr>
<td>g.12* ( pp \rightarrow HW^\pm W^- ) (4f)</td>
<td>( p p &gt; h w^+ w^- )</td>
<td>8.325 ± 0.139 \cdot 10^{-3}</td>
<td>+0.0% ± 2.0%</td>
<td>1.065 ± 0.003 \cdot 10^{-2}</td>
</tr>
<tr>
<td>g.13* ( pp \rightarrow HW^\pm \gamma )</td>
<td>( p p &gt; h w^m a )</td>
<td>2.518 ± 0.006 \cdot 10^{-3}</td>
<td>-0.3% ± 1.6%</td>
<td>3.309 ± 0.011 \cdot 10^{-3}</td>
</tr>
<tr>
<td>g.14* ( pp \rightarrow HZW^\pm )</td>
<td>( p p &gt; h z w^m )</td>
<td>3.763 ± 0.007 \cdot 10^{-3}</td>
<td>+1.1% ± 2.0%</td>
<td>5.292 ± 0.015 \cdot 10^{-3}</td>
</tr>
<tr>
<td>g.15* ( pp \rightarrow HZZ )</td>
<td>( p p &gt; h z z )</td>
<td>2.093 ± 0.003 \cdot 10^{-3}</td>
<td>+6.0% ± 1.5%</td>
<td>2.538 ± 0.007 \cdot 10^{-3}</td>
</tr>
<tr>
<td>g.16 ( pp \rightarrow Htt )</td>
<td>( p p &gt; h t t \sim )</td>
<td>3.579 ± 0.003 \cdot 10^{-1}</td>
<td>+30.0% ± 1.7%</td>
<td>4.608 ± 0.016 \cdot 10^{-1}</td>
</tr>
<tr>
<td>g.17 ( pp \rightarrow Httj )</td>
<td>( p p &gt; h t t j )</td>
<td>4.994 ± 0.005 \cdot 10^{-2}</td>
<td>+9.3% ± 2.0%</td>
<td>6.328 ± 0.022 \cdot 10^{-2}</td>
</tr>
<tr>
<td>g.18 ( pp \rightarrow Hbb ) (4f)</td>
<td>( p p &gt; h b b \sim )</td>
<td>4.983 ± 0.002 \cdot 10^{-1}</td>
<td>+28.1% ± 1.5%</td>
<td>6.085 ± 0.026 \cdot 10^{-1}</td>
</tr>
<tr>
<td>g.19 ( pp \rightarrow Httj )</td>
<td>( p p &gt; h t t \sim j )</td>
<td>2.674 ± 0.041 \cdot 10^{-1}</td>
<td>-29.2% ± 2.9%</td>
<td>3.244 ± 0.025 \cdot 10^{-1}</td>
</tr>
<tr>
<td>g.20* ( pp \rightarrow Hbbj ) (4f)</td>
<td>( p p &gt; h b b \sim j )</td>
<td>7.367 ± 0.002 \cdot 10^{-2}</td>
<td>-29.1% ± 2.1%</td>
<td>9.034 ± 0.032 \cdot 10^{-2}</td>
</tr>
</tbody>
</table>

**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

- **MEPS@NLO (UNLOPS)**: merge two NLO+PS simulations with different multiplicities
  - R.Frederix, S.Frixione (2011)

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

- **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 \( t\bar{t} \)**)
  - \( qq \rightarrow qq \) evolution matrix elements
  - M.Czakon et al. (2015)
  - S.Platzer (2013)

- **NLO+PS EW implementation in \( H \rightarrow ZZ \rightarrow 4 \) 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.

Resummed $p_T$ spectra at full NNLL+NNLO:

WW (and ZZ)

Z (and W) including leptonic cuts


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

Resummation

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

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

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

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

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

Jet and beam functions computed to NNLO

Soft function for $\tau_1$ to NNLO


The NNLO revolution

NNLO calculations important at least for the following cases:

1) Benchmark processes measured with high accuracy
   - $e^+e^\rightarrow 3$ jets
   - $pp \rightarrow W, Z$
   - $pp \rightarrow t\bar{t}$
   - $pp \rightarrow 2$ jets towards completion

2) Processes with large NLO corrections
   - $pp \rightarrow H$
   - $pp \rightarrow H+jet$
   - $pp \rightarrow HH$
   - even $N^3LO$ known now

3) Important backgrounds for Higgs and NP searches
   - $pp \rightarrow \gamma\gamma$
   - $pp \rightarrow W\gamma, Z\gamma$
   - $pp \rightarrow WW$
   - $pp \rightarrow ZZ$
   - $pp \rightarrow WZ$
   - $pp \rightarrow W(Z)+jet$
   - NNLO reduces tension with ATLAS data

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
  - antenna subtraction
  - “colourful” subtraction *(talk by Z. Trocsanyi)*
  - joint use of subtraction and sector decomposition

- **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
  - “$N$-jettiness” method
  - recently introduced “Born projection” method for VBF *(talk by A. Karlberg)*

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

- M. Czakon (2010, 2011)
- S. Catani, MG (2007)
- F. Tackmann et al. (2015)
- 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

  \[
  p_T^{jet} > 30 \text{ GeV}, |\eta_{jet}| < 2.4
  \]

  - Leading order: 533\(^{+39}_{-38}\) pb
  - Next-to-leading order: 798\(^{+63}_{-48}\) pb
  - Next-to-next-to-leading order: 775\(^{+10}_{-8}\) pb

  Small NNLO effect and significant reduction of scale uncertainties

- **Z+jet**

  Similar effects for Z+jet: antenna subtraction (large N\(_C\) approximation for the dominant channels)

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

Consider pp→ZZ→4 leptons at 8 TeV

Use ATLAS cuts to define fiducial region:

- $p_T > 7 \text{ GeV}$
- $|\eta| < 2.7$
- $\Delta R(l,l) > 0.2$
- $66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma_{LO}$ (fb)</th>
<th>$\sigma_{NLO}$ (fb)</th>
<th>$\sigma_{NNLO}$ (fb)</th>
<th>$\sigma_{exp}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-e^+e^-$</td>
<td>$3.547(1)^{+2.9%}_{-3.9%}$</td>
<td>$5.047(1)^{+2.8%}_{-2.3%}$</td>
<td>$5.79(2)^{+3.4%}_{-2.6%}$</td>
<td>$4.6^{+0.8}<em>{-0.7}(\text{stat})^{+0.4}</em>{-0.4}(\text{syst.})^{+0.1}_{-0.1}(\text{lumi.})$</td>
</tr>
<tr>
<td>$\mu^+\mu^-\mu^+\mu^-$</td>
<td>$6.950(1)^{+2.9%}_{-3.9%}$</td>
<td>$9.864(2)^{+2.8%}_{-2.3%}$</td>
<td>$11.31(2)^{+3.2%}_{-2.5%}$</td>
<td>$5.0^{+0.6}<em>{-0.5}(\text{stat})^{+0.2}</em>{-0.2}(\text{syst.})^{+0.2}_{-0.2}(\text{lumi.})$</td>
</tr>
</tbody>
</table>

+15% (60% comes from gg fusion)

NNLO corrections improve agreement with ATLAS data in the 2e2\(\mu\) channel but make the agreement worse in the other channels (but experimental uncertainties still large)

Done with new code \textbf{MATRIX}: $q_T$ subtraction +Munich+amplitudes from Openloops
ZZ at NNLO: lepton decays and off-shell effects

Now CMS cuts:
\[ 60 \, \text{GeV} < m_{ll} < 120 \, \text{GeV} \]
\[ p_{T1} > 20 \, \text{GeV} \quad p_{T2} > 10 \, \text{GeV} \quad m_{ll} > 4 \, \text{GeV} \]
\[ p_T^e > 7 \, \text{GeV} \quad | \eta_e | < 2.5 \]
\[ p_T^\mu > 5 \, \text{GeV} \quad | \eta_\mu | < 2.4 \]

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)

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

2) **UN²LOPS**: use S-MC@NLO + UNLOPS + q_T slicing

   - 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 $O(\alpha) \sim O(\alpha_s^2)$ we expect NLO EW $\sim$ 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

......and in MG5_aMC@NLO
- $t\bar{t}$+heavy bosons

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

S. Frixione et al. (2015)

N³LO for Higgs production


Full calculation for the gg → H completed through the evaluation of 30 terms in the soft-expansion: first complete calculation at N³LO in hadronic collisions!

![Graph showing N³LO effects](image)

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

<table>
<thead>
<tr>
<th>$\sigma / \text{pb}$</th>
<th>2 TeV</th>
<th>7 TeV</th>
<th>8 TeV</th>
<th>13 TeV</th>
<th>14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu = m_H/2$</td>
<td>0.99$^{+0.43%}_{-4.65%}$</td>
<td>15.31$^{+0.31%}_{-3.08%}$</td>
<td>19.47$^{+0.32%}_{-2.99%}$</td>
<td>44.31$^{+0.31%}_{-2.64%}$</td>
<td>49.87$^{+0.32%}_{-2.61%}$</td>
</tr>
<tr>
<td>$\mu = m_H$</td>
<td>0.94$^{+4.87%}_{-7.35%}$</td>
<td>14.84$^{+3.18%}_{-5.27%}$</td>
<td>18.90$^{+3.08%}_{-5.02%}$</td>
<td>43.14$^{+2.71%}_{-4.45%}$</td>
<td>48.57$^{+2.68%}_{-4.24%}$</td>
</tr>
</tbody>
</table>

N³LO 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+$\alpha_S$

Together with H+jet at NNLO will help improve predictions in jet categories
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 $2 \rightarrow 2$ 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 $\mu$ 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

<table>
<thead>
<tr>
<th>Process</th>
<th>Category</th>
<th>(comb.)</th>
<th>(incl.)</th>
<th>(ttH-like)</th>
<th>(VBF-like)</th>
<th>(ggF-like)</th>
<th>(VH-like)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H\rightarrow \mu\mu$</td>
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<tr>
<td>$H\rightarrow \tau\tau$</td>
<td>(VBF-like)</td>
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<td>$H\rightarrow ZZ$</td>
<td>(comb.)</td>
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<td>$H\rightarrow WW$</td>
<td>(comb.)</td>
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<tr>
<td>$H\rightarrow Z\gamma$</td>
<td>(incl.)</td>
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<td>$H\rightarrow \gamma\gamma$</td>
<td>(comb.)</td>
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</tbody>
</table>

Hashed areas show the impact of theory uncertainties

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

\[ \Delta \mu/\mu \]
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)

Further results expected soon

Parallel work done with antenna subtraction

A. Gehrmann et al. (2014, 2015)

Forward-backward asymmetry at NNLO

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

Single top

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


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

The NNLO impact seems relatively small

The qq channel becomes important at $p_T > 1$ TeV
The NNLO effect in the 4FS ranges from 9 to 12 % when $\sqrt{s}$ varies from 7 to 14 TeV.

gg contribution 35% of the full NNLO effect

Comparing with 5FS with subtraction of $t\bar{t}$ 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 $\mu_F$ and $\mu_R$ 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)**

- $p_T^\gamma > 15$ GeV
- $p_T^l > 25$ 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 $D=0.4$ and $p_T^{\text{jet}} > 15$ GeV
- $|\eta^{\text{jet}}| < 2.47$
- $N_{\text{jet}} \geq 0$
- $N_{\text{jet}} = 0$

**Photon isolation:**
- $\varepsilon = 0.5$
- Smooth cone $R = 0.4$

**Table:**

<table>
<thead>
<tr>
<th>$\sigma_{\text{NLO}}$ [pb]</th>
<th>$\sigma_{\text{NNLO}}$ [pb]</th>
<th>$\sigma_{\text{ATLAS}}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.058 $^{+6.8%}_{-6.8%}$</td>
<td>2.453 $^{+4.1%}_{-4.1%}$</td>
<td>2.77 $^{+0.03\text{ (stat)}}_{-0.33\text{ (syst)}}$</td>
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<tr>
<td>$1.395^{+5.2%}_{-5.8%}$</td>
<td>1.493 $^{+1.7%}_{-2.7%}$</td>
<td>1.76 $^{+0.03\text{ (stat)}}_{-0.21\text{ (syst)}}$ $^{+0.08\text{ (lumi)}}$</td>
</tr>
</tbody>
</table>

**Graphs:**

- $pp \rightarrow \ell \nu \gamma$
- $\sqrt{s} = 7$ TeV
- $N_{\text{jet}} \geq 0$
- $N_{\text{jet}} = 0$

$q_T^{\text{subtraction}} + $ Munich + tree and one-loop amplitudes from Openloops
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: $O(\alpha^2)$ effect

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

NNLO corrections make $p_T$ spectra softer $\Rightarrow$ larger impact when VBF cuts are applied