Standard Model Theory for Collider Physics

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HEP 2013
Stockholm, July 22
- LHC was incredibly successful at 7 & 8 TeV
- Everything SM like (including Higgs)
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LHC was incredibly successful at 7 & 8 TeV

Everything SM like (including Higgs)

New physics might be in the detail

Need to be precise on cross-sections and SM parameters

\[ \begin{align*}
\mathcal{L} &= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
&+ i \bar{f} \gamma^\mu D_\mu f \\
&+ \lambda_1 y_{ij} x_j \phi^i \phi \phi \phi \\
&+ \frac{1}{2} |\mathbf{D}\phi|^2 - V(\phi)
\end{align*} \]

SM Rules

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)
LHC was incredibly successful at 7 & 8 TeV

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Need to be precise on cross-sections and SM parameters

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

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This Talk

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

\[
\frac{d\sigma}{d^4p_T} = \sum_{ab} \int dx_a \int dx_b f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2)) + O\left(\left(\frac{\Lambda}{Q}\right)^n\right)
\]

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

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

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>
<th>H.O.</th>
<th>data</th>
<th>$\alpha_s(M_Z)$@NNLO</th>
<th>uncertainty</th>
<th>HQ</th>
<th>Comments</th>
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<tbody>
<tr>
<td>MSTW 2008</td>
<td>NNLO</td>
<td>DIS+DY+Jets</td>
<td>0.1171</td>
<td>Hessian (dynamical</td>
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<td>old HERA DIS</td>
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<tr>
<td>NNPDF 2.3</td>
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<td>(G)JR</td>
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<td></td>
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- Differ by: data input, TH/bias, HQ treatment, coupling, etc

**up to 5%! >15% in Higgs cross section**

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Luminosities with common $\alpha_s = 0.118$

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

**Figure 6:** The gluon-gluon (upper plots) and quark-gluon (lower plots) luminosities, Eq. (2), for the production of a final state of invariant mass $M_X$ (in GeV) at LHC 8 TeV. The left plots show the comparison between NNPDF2.3, CT10 and MSTW08, while in the right plots we compare NNPDF2.3, HERAPDF1.5 and MSTW08. All luminosities are computed at a common value of $\alpha_s = 0.118$.

- 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

PDG S. Bethke \(\alpha_s(M_Z) = 0.1184 \pm 0.0007\)

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

**PDH4LHC recommendation**

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

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

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

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

Large multiplicities relevant for LHC

‣ Improved techniques for loop
‣ High level of automation

Table 1: The updated experimenter’s wishlist for LHC processes

<table>
<thead>
<tr>
<th>Process $(V + {Z, W, \gamma})$</th>
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<tr>
<td>Calculations completed since Les Houches 2005</td>
<td></td>
</tr>
<tr>
<td>1. $pp \rightarrow VV$jet</td>
<td>$WW$jet completed by Dittmaier/Kallweit/Uwer [4,5]; Campbel/Ellis/Zanderlith [6]; $ZZ$jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]</td>
</tr>
<tr>
<td>2. $pp \rightarrow Higgs+2jets$</td>
<td>NLO QCD to the $gg$ channel completed by Campbel/Ellis/Zanderlith [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9, 10]</td>
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| 3. $pp \rightarrow VVV$ | $ZZ$ completed by Loupoulos/Melinks/Mertiolo/Pol 
| | (see also Binoth/Disd/Dad/Papadopoulo/Pittau [13]) |
| 4. $pp \rightarrow t\bar{t}b\bar{b}$ | relevant for tH computed by Bredenstein/Denner/Dittmaier/Pozzorini [14,15] and Bekvoc/Czakon/Papadopoulo/Pittau/Worek [16] |
| 5. $pp \rightarrow V+3jets$ | calculated by the Blackhat/Shiira [17] and Rocket [18] collaborations |

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<tr>
<td>6. $pp \rightarrow t\bar{t}+2jets$</td>
</tr>
<tr>
<td>7. $pp \rightarrow Vb\bar{b}$, $pp \rightarrow V+2jets$</td>
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<tr>
<td>8. $pp \rightarrow V+4jets$</td>
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<td>9. $pp \rightarrow b\bar{b}b\bar{b}$</td>
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<td>10. $pp \rightarrow V+4 jets$</td>
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<tr>
<td>11. $pp \rightarrow Wb\bar{b}$</td>
</tr>
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<td>12. $pp \rightarrow t\bar{t}t$</td>
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<td>13. $gg \rightarrow W^+W^-\gamma (\nu^{\pm}\nu_{\bar{\nu}}) \rangle$</td>
</tr>
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<td>14. NNLO $pp \rightarrow t\bar{t}$</td>
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<td>15. NNLO to VBF and $Z/\gamma+jet$</td>
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<td>16. NNLO QCD+NLO EW for $W/Z$</td>
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  - shape and normalization
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- Large Corrections: check PT
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- Effect of extra radiation
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Experimenter’s wish-list

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<td>3. pp → VVV</td>
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<td>6. pp → tt+2jets</td>
<td>relevant for tH computed by Bozzi/Jager/Oleari/Zeppenfeld [20–22]</td>
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<td>7. pp → VVbb</td>
<td>relevant for VBF → H → VV; tH</td>
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<td>8. pp → VV+2jets</td>
<td>relevant for VBF → H → VV; VBF contributions calculated by Bozzi/Jager/Oleari/Zeppenfeld [20–22].</td>
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<td>9. pp → Vbb</td>
<td>q+q channel calculated by Golem collaboration [23].</td>
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<tr>
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<tr>
<td>10. pp → V+4 jets</td>
<td>top pair production, various new physics signatures</td>
</tr>
<tr>
<td>11. pp → W+bj</td>
<td>top, new physics signatures</td>
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<tr>
<td>12. pp → tth</td>
<td>various new physics signatures</td>
</tr>
<tr>
<td>Calculations including electroweak effects</td>
<td></td>
</tr>
<tr>
<td>13. gg → W+W+O(α²α°s)</td>
<td>backgrounds to Higgs</td>
</tr>
<tr>
<td>14. NNLO pp → tt</td>
<td>normalization of a benchmark process</td>
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<td>15. NNLO to VBF and Z+/+jet</td>
<td>Higgs couplings and SM benchmark</td>
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Experimenter’s wish-list

Amazing progress in the last few years

- Large multiplicities relevant for LHC

Improved techniques for loop

High level of automation

talk by Zvi Bern
A very recent example: $W+5$ jets !!

BlackHat Collaboration, Z.Bern et al

Real $2 \rightarrow 8$ SHERPA

Virtual $2 \rightarrow 7$ BlackHat

Dynamical Scale choice \[ \mu_R = \mu_F = \frac{\hat{H}_T'}{2} \equiv \frac{1}{2} \sum_m p^m_T + E^W_T \]

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

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

in perfect agreement with previous calculation by BlackHat (Z.Bern et al)

$pp \to 5$ jets at NLO

- Preliminary results for 5 jets in good agreement with data!
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
- GoSam + Sherpa/MadGraph
- MadLoop+MadFKS
- CutTools
- OpenLoops+Sherpa

✓ compete on precision, flexibility, speed, stability, ...
✓ many features : uncertainties, ...

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

Higgs transverse momentum

dElf, Ferrera, Grazzini, Tommasini (2012)

Large logarithmic corrections spoil convergence in boundaries of phase space

State of the art: NNLL

Jet veto in Higgs @ NNLL

Banfi, Monni, Salam, Zanderighi (2012)

Stewart, Tackmann, Walsh, Zuberi (2013)

- Reduction in uncertainty \(\sim 10-13\%\)
- Validation of tools

"Exclusive jet fractions"

Scale variation in fixed-order exclusive n-jet cross sections can underestimate the theory uncertainty

Recently resummed predictions for the 0-jet and (part of) the 1-jet cross section were made available. They provide us with a more reliable assessment of the error

We need a flexible and general prescription to treat uncertainties in all jet bins which allows one to include resummed results whenever they are available.
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

**MC@NLO** and **POWHEG** treat radiation differently but formally same NL accuracy

Differences usually small

Higgs counterexample addressed by **POWHEG**
Automation

- 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

+ many others
**NNLO the new frontier**

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

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

\[ O(\alpha_s^2) \]

Match experimental accuracy
Extract accurate information

Meaningful comparison
Solid estimate of uncertainties
NNLO the new frontier

- Some measurements to few percent accuracy
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$O(\alpha_s^2)$

Match experimental accuracy
Extract accurate information

meaningful comparison
solid estimate of uncertainties

Keep Theorists employed after all the automatic machinery at NLO...
Invariant mass : 40-50 % corrections

\[ p\bar{p} \rightarrow \gamma\gamma \]

- \( q\bar{q} \)
- \( qg \)
- \( gg \)

\[ \alpha_s^0 \]
\[ \alpha_s^1 \]
\[ \alpha_s^2 \]

Open new channel at NLO,NNLO

Azimuthal difference

\[ \alpha_s^2 \]
Needed to understand LHC data

(effectively NLO)

large discrepancy between NLO and Data

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

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

(inclusive) Full NNLO (+NNLL) available <5% TH uncertainties

### Czakon, Fiedler, Mitov (2013)

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<tr>
<th>Collider</th>
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<tr>
<td>Tevatron</td>
<td>7.164</td>
<td>+0.110(1.5%)</td>
<td>+0.169(2.4%)</td>
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<td>-0.200(2.8%)</td>
<td>-0.122(1.7%)</td>
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<td>LHC 7 TeV</td>
<td>172.0</td>
<td>+4.4(2.6%)</td>
<td>+4.7(2.7%)</td>
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<td>-5.8(3.4%)</td>
<td>-4.8(2.8%)</td>
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<td>+6.2(2.8%)</td>
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<td>LHC 14 TeV</td>
<td>953.6</td>
<td>+22.7(2.4%)</td>
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<td>-33.9(3.6%)</td>
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- **Precision for mass**
- **Precision for gluon pdf**
$pp \rightarrow 2 \text{jets}$


- Pure gluon (leading colour) using antenna subtraction: NNLOJET

- $\sqrt{s}=8$ TeV
- $\text{anti-}k_T \ R=0.7$
- MSTW2008nnlo
- $\mu_R=\mu_F=\mu_{T1}$

• 15-25% increase
• K-factor ~flat

Similar results expected for other partonic channels
\[ pp \rightarrow H + \text{jet} \]


- 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 \( \sim 4\% \)
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

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<td>precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries</td>
</tr>
<tr>
<td>$t\bar{t} + j$</td>
<td>$\delta r_{(t\bar{t} + j)} @ NLO QCD$</td>
<td>$\delta r_{(t\bar{t} + j)} @ NLO QCD$</td>
<td>precision top/QCD, top asymmetries</td>
</tr>
<tr>
<td>single-top</td>
<td>$\sigma_{tot} @ NLO QCD$</td>
<td>$\sigma_{tot} @ NLO QCD$</td>
<td>precision top/QCD, $V_{t\bar{t}}$</td>
</tr>
<tr>
<td>dijet</td>
<td>$\sigma @ NLO QCD$</td>
<td>$\sigma @ NLO QCD$</td>
<td>Obs.: incl. jets, dijet mass $\rightarrow$ PDF fits (gluon at high $x$) $\rightarrow$ $\alpha_s$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$\sigma @ NLO QCD$</td>
<td>$\sigma @ NLO QCD$</td>
<td>Obs.: $R_{t\bar{t}}/2$ or similar $\rightarrow$ $\alpha_s$ at high scales dom. uncertainty: scales</td>
</tr>
<tr>
<td>$W + j$</td>
<td>$\sigma_{tot} (VBF) @ NLOQCD$</td>
<td>$\sigma_{tot} (VBF) @ NLOQCD$</td>
<td>$\delta r_{g(t)} @ NLO QCD$</td>
</tr>
<tr>
<td>$H + V$</td>
<td>$\delta r @ NLO QCD$</td>
<td>$\delta r @ NLO QCD$</td>
<td>$H$ branching ratios and couplings</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>$\delta r_{(t\bar{t}H)} @ NLO QCD$</td>
<td>$\delta r_{(t\bar{t}H)} @ NLO QCD$</td>
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</tr>
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<td>$H$</td>
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<td>$\delta r @ NLO QCD$</td>
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</tr>
</tbody>
</table>

For more details on the processes and corrections, please refer to the Standard Model Theory for Collider Physics by Daniel de Florian.
Electroweak corrections at large energies

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

  at $\sqrt{s} \sim 1$ TeV

  \[
  \delta^{1-\text{loop}}_{\text{LL}} \sim -\frac{\alpha}{\pi s^2_W} \ln^2 \left( \frac{s}{M^2_W} \right) \approx -26\%
  \]

  \[
  \delta^{2-\text{loop}}_{\text{LL}} \sim +\frac{\alpha^2}{2\pi^2 s^4_W} \ln^4 \left( \frac{s}{M^2_W} \right) \approx 3.5\%
  \]

  • still sizable at 2-loops

  S. Dittmaier

Dijet production

Dittmaier, Huss, Speckner

\begin{itemize}
  \item tree EW
  \item I-loop EW
\end{itemize}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{dijet_production}
\caption{Dijet production}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{dijet_corrections}
\caption{Dijet corrections}
\end{figure}
Higgs Boson

- Gluon-gluon fusion dominates due to large gluon luminosity

- QCD corrections are huge!

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

**LHC, \( \sqrt{s} = 7 \text{ TeV} \)**

**MSTW2008**

**K**

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

- **NLO**
  - Harlander, Kilgore (2002)
  - Anastasiou, Melnikov (2002)

**m_H (GeV)**

- \( M_H/2 < \mu_F, \mu_R < 2 M_H \)
- \( 1/2 < \mu_F/\mu_R < 2 \)
Improved Higgs Cross-section @ LHC

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

- Two loop EW corrections not negligible ~ 5%  
  Aglietti, Bonciani, Degrassi, Vicini (2004)
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- + Mass effects, Line-shape, interferences, ...  
  Higgs 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 possible in near future
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  deF, Grazzini

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Even Higher orders $N^3$LO

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

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

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

- Missing
  - 2 loop + single emission
  - 1 loop + double emission
  - work in progress

- Possible to reach Soft-Virtual approx. (and beyond) in near future

- Resummation at $N^3LL$ : soft contributions
Conclusions

Amazing work in the last few years → direct consequence of LHC

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

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Thanks to Eric Laenen, Sven Moch, Thomas Gehrmann, Aude Gehrmann-De Ridder, Nigel Glover, Stefan Dittmaier, Massimiliano Grazzini and Joey Huston for discussions
Thanks!
Backup Slides
Effect of top cross section in gluon determination

- Top quark cross-section data discriminates between PDF sets
- In addition, it can also be used to reduce the PDF uncertainties within a single PDF set
- Included the most precise top quark data into the NNPDF2.3 global PDF analysis

- Effect of top cross section in gluon determination
  - 20% reduction in uncertainty at large x (where correlation is most significant)
  - Czakon, Mangano, Mitov, Rojo (2013)

Effect of prompt photons in gluon determination

- Moderate reduction of uncertainties in region relevant for Higgs production
- Large $p_T$ gauge boson production also relevant
- Need more precise data for photon+jet

Czakon, Mangano, Mitov, Rojo (2013)
Comparison to LHC jet data (Atlas 2010)

Reasonable agreement
Still large systematic uncertainties

No NNLO calculation available yet
Use NLO or NLO+threshold corrections

Larger impact expected with full data set

J. Rojo, DIS2013

Ball et al (2012)
First NNLO calculations achieved using different methods

- **Sector decomposition**
  - Anastasiou, Melnikov, Petriello
  - Czakon
  - Boughezal, Melnikov, Petriello
  - Anastasiou, Herzog, Lazopoulos ...

- **$qT$ - subtraction**
  - Catani, Grazzini
  - Catani, Cieri, deF., Ferrera, Grazzini

- **Antenna subtraction**
  - Gehrmann-De Ridder, Glover, Gehrmann;
  + Daleo, Luisoni, Boughezal, Ritzmann, Monni, ...

- Bottleneck in virtual amplitudes with many legs but do not underestimate numerical/stability issues in real contributions

- Automation in NNLO still far away

- Matching NNLO with Shower will require increase in logarithmic accuracy of shower (NLL in all emissions?)
Higgs: Improvements over NNLO

- QCD corrections dominated by soft and virtual gluon radiation

Threshold NNLL (+NNLO) Resummation
9% at 7 TeV, 13% at Tevatron

Catani, deF, Grazzini, Nason (2003)

- Two loop EW corrections not negligible ~ 5%

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