Physics at 10 % level
Inclusive Production Cross Section of the Higgs Boson \textbf{AT 3000 \text{fb}^{-1}}

<table>
<thead>
<tr>
<th>Relative uncertainty</th>
<th>Total</th>
<th>Stat</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>3.5%</td>
<td>0.6%</td>
<td>1.6%</td>
</tr>
<tr>
<td>S2</td>
<td>2.4%</td>
<td>0.6%</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

- Luminosity at 1\%
- Couplings better then 5\%
- Differential cross sections get precise
FUTURE OF HIGGS BOSON PHYSICS

Inclusive Production Cross Section of the Higgs Boson AT $3000 \text{ fb}^{-1}$
Inclusive Production Cross Section of the Higgs Boson \textbf{AT 3000 FB}^{\text{-1}}

Theory uncertainties: \textbf{OPTIMISTIC} scenario!!!
THE WAY TO PRECISION LHC PREDICTIONS

\[ \sigma \sim \int dx dy f(x) f(y) \hat{\sigma} + \mathcal{O} \left( \frac{\Lambda}{Q} \right) \sim \%? \]

- Perturbative approach to computing partonic cross sections.
- QCD perturbation theory is dominant: \( \alpha_S = 0.118 \)
  
  \[
  \hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_S \hat{\sigma}^{(0)} + \alpha_S^2 \hat{\sigma}^{(2)} + \alpha_S^3 \hat{\sigma}^{(3)} \ldots
  \]

- Resum and match where fixed order breaks down.
- Complement with other effects (electro-weak, masses, etc.).
Higher order precision

GLUON FUSION AT N3LO

\[
\hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_S^1 \hat{\sigma}^{(0)} + \alpha_S^2 \hat{\sigma}^{(2)} + \alpha_S^3 \hat{\sigma}^{(3)} \ldots
\]

- Higher order corrections allow for precise predictions.
- Predicting high orders forces us to develop new tools / technology.

PHENOMENOLOGICAL COMPLEXITY

- It’s getting complicated!
- Many “minor” corrections have to be figured out in order to improve further.

[Dulat,Lazopoulos,BM, arXiv:1802.00827]
It’s getting complicated!

Many “minor” corrections have to be figured out in order to improve further.

HL-LHC

Pessimistic scenario
Optimistic scenario
THEORETICAL COMPLEXITY

- We can improve our algorithms:

<table>
<thead>
<tr>
<th>Order</th>
<th>Integrals</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>50000</td>
</tr>
<tr>
<td>3</td>
<td>517531178</td>
</tr>
</tbody>
</table>

- We can improve our mathematics:

  New classes of functions:
  Generalised Elliptic Integrals

- We can improve our understanding of QFT

  Systematic treatment of soft radiation.
**HIGHER ORDER PRECISION**

**BOTTOM QUARK FUSION AT N3LO**

- Coupling to bottom quarks.
- Clears up discrepancy between 4 / 5 flavour scheme.
- Further evidence for stability of series for certain scale choices.

\[ H \rightarrow b \bar{b} \text{ @ N3LO} \]

[Duhr, Dulat, BM, arXiv:1904.09990]

[Mondini et al., arXiv:1904.08960]
EWK CORRECTIONS

- EWK corrections start with 2 loops: difficult!
- How to combine them with QCD?

\[ \sigma = \sigma_{LO}(1 + \delta_{QCD} + \delta_{EWK}) \quad \sim \quad +2.5\% \]

vs.

\[ \sigma = \sigma_{LO}(1 + \delta_{QCD}) \times (1 + \delta_{EWK}) \quad \sim \quad +5\% \]
Various approximations of the full cross section.

- Clearly favouring the factorisation approach.

\[ \sigma = \sigma_{LO} (1 + \delta_{QCD} + \delta_{EWK}) \]

vs.

\[ \sigma = \sigma_{LO} (1 + \delta_{QCD}) \times (1 + \delta_{EWK}) \]

- Full, differential computation is desirable.
TIME OF DIFFERENTIAL CROSS SECTIONS HAS ARRIVED

Transverse Momentum

Rapidity

CMS Preliminary

137.1 fb⁻¹ (13 TeV)

Data (stat. ⊕ sys. unc.)
Systematic uncertainty
gg→H (NNLOPS) + XH
gg→H (POWHEG) + XH
XH = VBF + VH + ttH (POWHEG)
(LHC HXSWG YR4, mₜ=125.09 GeV)

ATLAS Preliminary

H→γγ, \(\sqrt{s} = 13\) TeV, 79.8 fb⁻¹

\(dσ_{\text{fid}}/dp_T^H\) (fb/GeV)

Ratio to NNLOPS

\(p_T^H\) (GeV)

Data, tot. unc.
syst. unc.
gg→H default MC + XH
gg→H SCETlib+MCFM8 + XH
XH = VBF+VH+ttH+bbH

\(dσ_{\text{fid}}/dy_{rr}\) (fb)

Ratio to default MC + XH

\(y_{rr}\)
DIFFERENTIAL CROSS SECTIONS

SMALL TRANSVERSE MOMENTUM

- Resummation for small $p_T$ is mandatory! N3LL

[Neill et al., arXiv:1805.00736]


Complementarity!

SCET based  Direct QCD based

- Resummation for fiducial xs? Jets? Multi-differential?
DIFFERENTIAL CROSS SECTIONS

MEDIUM TRANSVERSE MOMENTUM

- NNLO QCD!
  
  
  [Chen et al., arXiv:1408.5325]

New fully differential predictions become available!

\[ PP \rightarrow H + X \rightarrow 4l + X \]

[Chen et al., arXiv:1905.13738]

- Very challenging numerically.

- Overall agreement with CMS+ATLAS

Forefront of fully differential 2->2 processes!
MEDIUM TRANSVERSE MOMENTUM

- Top - bottom interference effects: Overall small, interesting to constrain couplings

- Theoretical developments:
  - Systematic expansion in small masses.
  - Resummation with small mass effects.
  - Large bottom quark mass scheme dependence.

[Caola, Tancredi et al., arXiv:1804.07632]
CMS analysis of boosted Higgs production

Look at very boosted Higgs bosons recoiling against a jet.

Decay to $b\bar{b}$

Sensitive to internal structure of the top quark loop!

Measured at $1.5\sigma$ at 36 fb^-1.

Excellent knowledge of $p_T$ - spectrum important!

$p_T > 450$ GeV

$p_T >> m_t$
DIFFERENTIAL CROSS SECTIONS

LARGE TRANSVERSE MOMENTUM

- $p_T \gg m_t$

- NLO now available!

- 2 methods!
  - [Lindert et al. arXiv:1801.08226]
  - [Jones et al. arXiv:1802.00349]

- Large K-factor similar to EFT.

[preliminary, credit: Jones,Kerner,Luisoni; Chen,Gehrmann,Glover,Huss]
Reasonable description by parton showers with LO top mass effects.

Mixed QCD Electro-Weak effects?

All production modes become important.
Higgs Boson Rapidity Distributions at N3LO

- Precision QCD at N3LO.
- Extension of analytic techniques from inclusive cross section.
- Agreement with [Cieri et al., arXiv:1807.11501]

\[ pp \to H + X \]
LHC@13 TeV
MMHT 2014 NNLO
\[ \mu_F = \mu_R = m_h / 2 \]

\[ d\sigma_n / dY \text{ [pb]} \]

[Dulat, BM, Pelloni, arXiv:1810.09462]
**Higgs Boson Rapidity - Ratio**

- Very compatible with rescaling of NNLO distribution
- Good news for current experimental usage!
  Re-weighted Parton-Shower MC.

[Dulat,BM,Pelloni, arXiv:1810.09462]
\[ H \rightarrow \gamma \gamma \]

- New methods for differential cross sections!
- Used for differential VBF at N3LO. [Cacciari et al. arXiv:1506.02660]
  [Dreyer, Karlberg, arXiv:1811.07906]
- Combination with H+J
- Validation at NNLO
- Fiducial Cross Sections for LHC Phenomenology!
- Extension to N3LO in progress
REQUIRED INGREDIENTS FOR PREDICTIONS

All the Rest!

- Better Virtual Diagrams
  H+2J, more numerical, ...

- Better Real Radiation Diagrams
  Slicing vs Subtraction, Improved Residue Subtraction, Colourful,…

- Parton Distribution Functions
  N3LO?, Theory Uncertainties, Small-x, Threshold, Non-pert., Flavour Thresholds, …

- Parton Showers
  Higher Log accuracy, hadronization, formal accuracy, matching to FO, merging, …

- Electro-Weak Corrections
  Mixed QCD-EWK, large pT, …

- Mass Effects
  Small mass expansions, resummation of small mass effects, …

- Uncertainty Estimates
  Theory definition, What beyond scale variation, bin-to-bin correlation, statistical basis?

- Perturbative Convergence?
  ?

- …
Incredibly precise measurements motivate us to push theoretical boundaries of perturbative QFT.

Improving theoretical precision to match demand of future LHC data is a challenge for years to come.

Main objective:
Describe experimental outcome as close as possible.

Rapidity distribution at N3LO:
Corner stone for future fully differential N3LO predictions.

Thank you!