Physics at 10 % level
Higgs Boson Physics

The Future - 3000 fb^-1

Inclusive signal strength

- Luminosity at 1%
- Couplings better than 5%
- Differential Cross Sections get precise

<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>

ATLAS Simulation Preliminary

\( \sqrt{s} = 14 \text{ TeV}; \int L dt = 300 \text{ fb}^{-1} \); \( \int L dt = 3000 \text{ fb}^{-1} \)

- \( H \rightarrow \gamma \gamma \) (comb.)
- \( H \rightarrow ZZ \) (comb.)
- \( H \rightarrow WW \) (comb.)
- \( H \rightarrow Z \gamma \) (incl.)
- \( H \rightarrow b \bar{b} \) (comb.)
- \( H \rightarrow \tau \tau \) (VBF-like)
- \( H \rightarrow \mu \mu \) (comb.)
THE FUTURE – 3000 FB$^{-1}$

[Graph showing expected uncertainty vs. integrated luminosity (fb$^{-1}$)]

[Bar chart showing QCD scale uncertainty on total xsec prediction ggF (H4i)]

[$\Delta \mu / \Delta \mu_{\text{tot}}$]
HIGGS BOSON PHYSICS

THE FUTURE - 3000 $\text{fb}^{-1}$

Theory uncertainties!!

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: \( \alpha_S = 0.118 \)

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

- Resum and match where fixed order breaks down.
- Complement with other effects (electro-weak, masses, etc.).
Higher order 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]
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.
- $H \rightarrow b\bar{b}$ @ N3LO

[Duhr, Dulat, BM, arXiv:1904.09990]

[Mondini et al., arXiv:1904.08960]
Differential Cross Sections

Time of Differential Cross Sections Has Arrived

Transverse Momentum

Rapidity
Differential Cross Sections

**Small Transverse Momentum**

- Resummation for small $p_T$ is mandatory! **N3LL**

  ![Graphs showing differential cross sections](image)

  - [Neill et al., arXiv:1805.00736]
  - [Bizon et al., arXiv:1805.05916]

  **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]

  Forefront of fully differential 2->2 processes!

- **Top - bottom interference effects:**
  - [Caola et al., arXiv:1804.07632]

  Overall small, interesting to constrain couplings $Y_b$

- **Theoretical developments:**
  - Systematic expansion in small masses.
  - Resummation with small mass effects.
  - Large bottom quark mass scheme dependence.
CMS analysis of boosted Higgs production [CMS-HIG-17-010]

- Look at very boosted Higgs bosons recoiling against a jet.
  \[ p_T > 450 \text{GeV} \]
- 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!
  \[ p_T \gg m_t \]
DIFFERENTIAL CROSS SECTIONS

LARGE TRANSVERSE MOMENTUM

\[ p_T >> m_t \]

- NLO now available!
- Large K-factor similar to EFT.
### Large Transverse Momentum

All production modes become important.

Reasonable description by parton showers with LO top mass effects.

Mixed QCD Electro-Weak effects?

<table>
<thead>
<tr>
<th>$p_T^{cut}$</th>
<th>NNLO approximate quad. unc. [fb]</th>
<th>HJ-MINLO [fb]</th>
<th>MG5_MCG@NLO [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 GeV</td>
<td>$32.0^{+9.1%}_{-11.6%}$</td>
<td>$29^{+24%}_{-21%}$</td>
<td>$31.5^{+31%}_{-25%}$</td>
</tr>
<tr>
<td>430 GeV</td>
<td>$22.1^{+9%}_{-11.4%}$</td>
<td>-</td>
<td>$21.8^{+31%}_{-25%}$</td>
</tr>
<tr>
<td>450 GeV</td>
<td>$17.4^{+8.9%}_{-11.5%}$</td>
<td>$16.1^{+22%}_{-21%}$</td>
<td>$17.1^{+31%}_{-25%}$</td>
</tr>
</tbody>
</table>

![Graph showing fractional contributions](https://cds.cern.ch/record/2669113/files/LHCHXSWG-2019-002.pdf)
Precision QCD at N3LO.

Extension of analytic techniques from inclusive cross section.

Agreement with

[Cieri et al., arXiv:1807.11501]
**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

- 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?
  - ?
- ...
CONCLUSIONS

- 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!