The success of the SM

Overall extremely good experiment-theory agreement
Differential SM measurements
Differential SM measurements

Complementarity at LHCb?
SM physics at HL-LHC/LHCb Upgrade II

- Precision EW/QCD
  - V+jets
    - differential measurements
- HF / top
  - charge asymmetries
- Rare processes
  - VBS
\[ |M|^2 \xrightarrow{\sigma} \]

Precision at the LHC
Precision at the LHC
Key: QCD factorization:

Short distance non-perturbative effects (PDFs)

\[ h_1 \]
\[ p_1 = x_1 P_1 \]
\[ p_2 = x_2 P_2 \]

\[ F(Q) \]

\[ d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{s}_{ij}(x_1 x_2 s) \]

Hard (perturbative) scattering process

\[ \n(\n(\text{N(N)LO QCD + EW}) \]

Precision at the LHC
Precision at the LHC

Hard (perturbative) scattering process

\[ N(N)\text{LO QCD} + \text{EW} \]

QCD Bremsstrahlung
- parton shower
- matched to NLO matrix elements

QED Bremsstrahlung
- parton shower
- matched to NLO matrix elements

Short distance non-perturbative effects (PDFs)

\[ d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{\sigma}_{ij}(x_1 x_2 s) \]

Key: QCD factorization:
Precision at the LHC

Key: QCD factorization:

Short distance non-perturbative effects (PDFs)

$$d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{\sigma}_{ij}(x_1 x_2 s)$$

PDFs

DGLAP fitting

- QCD Bremsstrahlung
  - parton shower
  - matched to NLO matrix elements

- QED Bremsstrahlung
  - parton shower
  - matched to NLO matrix elements

Hard (perturbative) scattering process

- N(N)LO QCD + EW

Hadronization/fragmentation/decay

- pheno models
Theoretical Predictions for the LHC

Hard (perturbative) scattering process:

\[ d\sigma = d\sigma_{\text{LO}} + \alpha_s d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}} \]
\[ + \alpha_s^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_s \alpha_{\text{EW}} d\sigma_{\text{NNLO QCD} \times \text{EW}} \]
Theoretical Predictions for the LHC

Hard (perturbative) scattering process:
\[
d\sigma = d\sigma_{\text{LO}} + \alpha_s d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}} + \alpha_s^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_s \alpha_{\text{EW}} d\sigma_{\text{NNLO QCDxEW}}
\]

\[
d\sigma_{\text{NLO}} = \frac{1}{2s} \int d\Phi_n \left[ |\mathcal{M}_{\text{LO}}|^2 + 2 \text{Re} \{ \mathcal{M}_{\text{LO}} \mathcal{M}^{\ast}_{\text{NLO,V}} \} \right] + \frac{1}{2s} \int d\Phi_{n+1} |\mathcal{M}_{\text{NLO,R}}|^2
\]

\[
\mathcal{M}_{\text{NLO,V}} \quad \text{virtual one-loop matrix element}
\]
\[
\mathcal{M}_{\text{NLO,R}} \quad \text{real tree-level matrix element}
\]

• UV renormalisation ⇒ reduction of \( \mu_R \) dependence
• soft/collinear cancellations + PDF renormalisation ⇒ reduction of \( \mu_F \) dependence
Theoretical Predictions for the LHC

Hard (perturbative) scattering process:

\[
d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}}
+ \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_S \alpha_{\text{EW}} d\sigma_{\text{NNLO QCDxEW}}
\]

\[
d\hat{\sigma}_{\text{NNLO}} = \frac{1}{2s} \int d\Phi_{n+1} \left[ |M_{\text{LO}}|^2 + 2\text{Re}\{M_{\text{LO}}M_{\text{NLO},V}^*\} + 2\text{Re}\{M_{\text{LO}}M_{\text{NLO},V}^*\} \right]
+ \frac{1}{2s} \int d\Phi_{n+2} |M_{\text{NNLO},RR}|^2
\]

\[
\int d\Phi_{n+1} \quad n, n+1, n+2 \text{ particle phase space}
\]

\[
\Delta_{\text{NLO}} \propto \alpha \quad \{ M_{\text{NLO},V} \text{ virtual one-loop matrix element} \}
\]

\[
\Delta_{\text{NNLO}} \propto \alpha^2 \quad \{ M_{\text{NNLO},V} \text{ double-virtual two-loop matrix element} \}
\]

\[
M_{\text{NLO,R}} \text{ real tree-level matrix element}
\]

\[
M_{\text{NNLO,R}} \text{ real-virtual one-loop matrix element}
\]

\[
M_{\text{NNLO,RR}} \text{ double-real tree-level matrix element}
\]
V+jets

- very important standard-candle (very clean and large x-sections)
- crucial background in many BSM searches
- allows for M_w and sin^2θ_eff measurements

How to retain full differential information on the leptons in measurements?

**lepton kinematics in the Z/γ^* (lepton-pair) rest frame:**

\[ k_{1,2}^\mu = \sqrt{q^2_2} \left( 1, \pm \sin \theta \cos \phi, \pm \sin \theta \sin \phi, \pm \cos \theta \right)^\text{T} \]

**Decomposition in terms of spherical harmonics:**

\[
\frac{d\sigma}{d^4q \, d\cos \theta \, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{\text{unpol.}}}{d^4q} \left\{ \left(1 + \cos^2 \theta \right) + \frac{1}{2} A_0 \left(1 - 3 \cos^2 \theta \right) \\
+ A_1 \sin(2\theta) \cos \phi + \frac{1}{2} A_2 \sin^2 \theta \cos(2\phi) \\
+ A_3 \sin \theta \cos \phi + A_4 \cos \theta + A_5 \sin^2 \theta \sin(2\phi) \\
+ A_6 \sin(2\theta) \sin \phi + A_7 \sin \theta \sin \phi \right\},
\]

**Dominant angular coefficients:**

- parity even: \( A_{0,1,2} \)
- parity odd: \( A_{3,4} \)

\( \sim \) probed by \( \gamma^* \) & Z exchange

\( \sim \) sensitive to \( \sin^2 \theta_w \), \( A_4 \leftrightarrow A_{FB} \)
V+jets

Lam–Tung relation: \( A_0 - A_2 = 0 \)

✓ \( @ \mathcal{O}(\alpha_s^0) \) spin-\( \frac{1}{2} \) nature of quarks ↔ Callan–Gross \( (F_2 = 2xF_1) \)
✓ \( @ \mathcal{O}(\alpha_s^1) \) vector coupling of spin-1 gluon
✗ \( @ \mathcal{O}(\alpha_s^2) \) ↔ DY @ NNLO only LO prediction in \( (A_0 - A_2) \)!

V+jet @ NNLO yields \( \mathcal{O}(\alpha_s^3) \), i.e. \( (A_0-A_2) \) at NLO

[Gauld, Gehrmann-De Ridder, Gehrmann, Glover, Huss, 1708.00008]
HF hadroproduction

- Dominant uncertainty = Scale variation +/- 10%
For both bottom- and charm-quark production, the weak corrections are negligibly small. Corrections to the LO QCD process are negative and more important in the case of charm-becomes relevant (reaching roughly 10%) in the region of (labelled as ISR only). Have also displayed the result when including only initial-state radiation (ISR) from QCD

- QCD always dominant
- EW and QCD-EW contributions typically (1-10)%
- Proper treatment of FSR corrections important

HF hadroproduction

[Gauld, Haisch, Pecjak, 1901.0757]
HF hadroproduction: ratio

[Gauld, Haisch, Pecjak, 1901.0757]

Figure 5. Ratio between the differential cross section of $c$- and $b$-jet pair production at the 13 TeV LHC. Left: LO and NLO distributions for $\mu_0 = m_{\bar{Q}Q}$, as well as the NLO distribution obtained without the $O(\alpha^2)$ corrections. Right: NLO distribution obtained with $\mu_0 = m_{\bar{Q}Q}$, where an additional uncertainty due to photon-induced contributions has been included as explained in the main text. The central value of the LO distribution is also shown for reference.

3.2 Cross-section ratios

In addition to the measurements of the $b\bar{b}$ and $c\bar{c}$ cross sections discussed in the last section, it is also of interest to perform measurements of the cross-section ratio between the different heavy-quark types. As the theoretical predictions for the cross-section ratios are very precise, these measurements will provide an important experimental benchmark for testing and validating the (charged) flavour-tagging efficiency and mis-tag rates.

Our predictions for the cross-section ratio of $c\bar{c}$- and $b\bar{b}$-jet pairs at the 13 TeV LHC in the phase-space region ($m_{Q\bar{Q}}$) are shown in Figure 5. These distributions are obtained with $\mu_0 = m_{\bar{Q}Q}$, and the uncertainty has been evaluated by correlating the scale variations between the charm- and bottom-quark predictions. In the considered $m_{Q\bar{Q}}$ range, the ratio between the $c\bar{c}$ and $b\bar{b}$ cross sections is below 1. The observed deviation of the ratio from 1 can be attributed to the mass dependence of the LO cross section — see Figure 1 (left) — and also to the different EW charges of up- and down-type quarks which affect the ratio both close to and away from the $Z$ peak. In Figure 5 (left), the NLO ratio is also displayed for the case that the $O(\alpha^2)$ corrections have been removed. These corrections arise dominantly in the form of QED corrections to the $gg\rightarrow Q\bar{Q}X$ subprocess. They are negative and amount to effects of the order of $e_Q \cdot 1\%$ on the spectra, where $e_Q$ denotes the electric charge of the heavy quark $Q$.

While the $O(\alpha^2)$ contributions thus have a negligible impact at the level of the cross sections, they have a visible effect on the ratio of the symmetric rates.

As discussed in Section 2, we have chosen to use PDFs that do not include a photon PDF, and as a result photon-initiated contributions are not included in our computations. To assess the potential uncertainty due to these missing contributions, we have recomputed the ratio of the $c\bar{c}$ and $b\bar{b}$ spectra at LO with the LUXqed15 PDF set. An uncertainty is

Continuum

- Mass effects ($m_b = 4.75$ GeV, $m_c = 1.5$ GeV)
- QED effects ($Q_c = 2/3$, $Q_b = 1/3$)

Z-boson Resonance

- Weak effects ($Z_{bb}$ vs $Z_{cc}$ couplings)
HF hadroproduction: asymmetry

\[ \frac{dA}{dm_{QQ}} = \left( \frac{d\sigma}{dm_{QQ}} \right)^{-1} \left( \frac{d\sigma_A}{dm_{QQ}} \bigg|_{\Delta y>0} - \frac{d\sigma_A}{dm_{QQ}} \bigg|_{\Delta y<0} \right) \]

\[ \Delta y = y_Q - y_{\bar{Q}} \]
HF hadroproduction: asymmetry

[Gauld, Haisch, Pecjak, 1901.0757]

Figure 7. Differential asymmetry for $b\bar{b}$- (left) and $c\bar{c}$-jet (right) pairs within the LHCb fiducial region ($\mathcal{F}$) at $p_{\text{S}} = 13$ TeV. The shown NLO distributions are obtained with the scale choice $\mu_0 = m_{b\bar{b}}$, and the estimated statistical sensitivity of a future measurement at LHCb with 5 fb$^{-1}$ of integrated luminosity has been indicated.

We conclude this Section by returning to the choice of the angular cut $Q_{\bar{b}b}$ used in defining the fiducial region ($\mathcal{F}$). As mentioned in Section 3, the motivation for introducing this cut is to increase the sensitivity to the asymmetry by enhancing "non-$gg$ production mechanisms". To assess this statement, we study the impact of the choice of $\min Q_{\bar{b}b}$ on the observable $A/\bar{S}$, where $S$($A$) is the (a)symmetric production cross section. The motivation behind this definition is that the significance of a statistically limited measurement of the asymmetry is approximately $A/A_{\text{stat}}$. Our definition is therefore useful as it estimates the overall statistical sensitivity to the asymmetry measurement itself, rather than just the asymmetry. This is relevant because, while the value of the asymmetry may increase as the value of the cut $\min Q_{\bar{b}b}$ is increased, the number of analysed events simultaneously decreases. Our predictions for $A/\bar{S}$ as a function of $\min b\bar{b}$ are shown in Figure 8. The two different sets of predictions correspond to the results restricted to the invariant mass bins $m_{b\bar{b}} \in [75, 105]$ GeV and $m_{b\bar{b}} \in [105, 300]$ GeV. The obtained distributions are close to flat as $\min b\bar{b}$ increases, indicating that from a statistical point of view the sensitivity to the asymmetry is not improved by requiring larger $\min b\bar{b}$ values. We have therefore chosen to provide predictions for $\min b\bar{b} = 2.6$, which matches the original value advocated in [4].

It is worth noting that the choice of this cut may also be important for background rejection (i.e. from light jets). In the far future, if the asymmetry measurements becomes systematically limited, it may be worthwhile to perform a dedicated experimental study of this issue.

5 Applications

In this Section we present two applications of our calculations of heavy-quark production. We will first discuss the model-independent constraints that future LHCb measurements of the ratio of the $b\bar{b}$ and $c\bar{c}$ asymmetry may allow to set on the couplings of the $Z$ boson to bottom- and charm-quark pairs. We will compare the results of our sensitivity studies – Sensitivity on $Z_{bb}$ and $Z_{cc}$ couplings!

Could this even compete with $A_{bb,\text{LEP}}$ (long-lasting $3\sigma$ deviation)?

Percent level precision required….

This requires NNLO QCD and good control of exp. systematics.

Feasible!
Top quark production in the forward region

- Only partial reconstruction of decay products possible
- Complementary information to ATLAS and CMS

<table>
<thead>
<tr>
<th>Final state</th>
<th>300 fb⁻¹</th>
<th>&lt;x&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>ℓb</td>
<td>830k</td>
<td>0.295</td>
</tr>
<tr>
<td>ℓbb</td>
<td>130k</td>
<td>0.368</td>
</tr>
<tr>
<td>μeb</td>
<td>12k</td>
<td>0.348</td>
</tr>
<tr>
<td>μebb</td>
<td>1.5k</td>
<td>0.415</td>
</tr>
</tbody>
</table>

- Measurements at sub-percent level feasible
- Measurements at percent level feasible

- Significant constraints on gluon PDF in forward region possible
Top quark charge asymmetries at LHCb

Signal:

Background:

- Enhanced sensitivity in forward region due to increased quark content

![Diagram](image)

\[ A(\ell b) \text{ [%]} \]

- Sufficient sensitivity for non-zero charge asymmetry at HL-LHC

- LHCb 23 fb\(^{-1}\)
- LHCb 300 fb\(^{-1}\)
- aMC@NLO + Pythia
- NNPDF3.1, \( m_t = 172.5 \) GeV

[HL/HE Report '19]
Rare EW processes: VBS

- Direct access to quartic EW gauge couplings
- VBS: longitudinal gauge bosons at high energies
- Window to electroweak symmetry breaking via off-shell Higgs exchange
Note: severe QCD background to VBS signatures + interference:

\[
d\sigma = d\sigma(\alpha_s^2\alpha^4) + d\sigma(\alpha_s\alpha^5) + d\sigma(\alpha^6) + \ldots
\]

QCD-background    interference    VBS-signal

VBS
VBS

Note: severe QCD background to VBS signatures + interference:

\[ d\sigma = d\sigma(\alpha_S^2 \alpha^4) + d\sigma(\alpha_S \alpha^5) + d\sigma(\alpha^6) + \ldots \]  

QCD-background interference VBS-signal

\[ \cdots + d\sigma(\alpha_S^3 \alpha^4) + d\sigma(\alpha_S^2 \alpha^5) + d\sigma(\alpha_S \alpha^6) + \sigma(\alpha^7) \]  

NLO
Note: severe QCD background to VBS signatures + interference:

\[ d\sigma = d\sigma (\alpha_S^2 \alpha^4) + d\sigma (\alpha_S \alpha^5) + d\sigma (\alpha^6) + \ldots \]  

QCD-background \( O(\alpha_s) \) interference \( O(\alpha) \) VBS-signal

\[ \cdots + d\sigma (\alpha_S^3 \alpha^4) + d\sigma (\alpha_S^2 \alpha^5) + d\sigma (\alpha_S \alpha^6) + \sigma (\alpha^7) \]  

“NLO QCD” “NLO EW” “NLO QCD” “NLO EW”
Note: severe QCD background to VBS signatures + interference:

\[ \sigma = \sigma(\alpha_s^2\alpha^4) + \sigma(\alpha_s\alpha^5) + \sigma(\alpha^6) + \ldots \]

QCD-background \( \mathcal{O}(\alpha_s) \) \( \xrightarrow{\text{interference}} \) VBS-signal \( \mathcal{O}(\alpha) \)

\[ \cdots + \sigma(\alpha_s^3\alpha^4) + \sigma(\alpha_s^2\alpha^5) + \sigma(\alpha_s\alpha^6) + \sigma(\alpha^7) \]

“NLO QCD” \( \rightarrow \) “NLO EW” \( \rightarrow \) “NLO QCD” \( \rightarrow \) “NLO EW”

⇒ separation meaningless at NLO
Signature: \( \ell^+ \ell^+ j \)

VBS at LHCb

[\textit{Pellen, 1908.06805}]

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \sigma_{\text{EW}} ) [fb]</th>
<th>( \sigma_{\text{QCD}} ) [fb]</th>
<th>( \sigma_{\text{EW}}/\sigma_{\text{QCD}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ss WW</td>
<td>0.0185(1)</td>
<td>0.0104(1)</td>
<td>1.78</td>
</tr>
<tr>
<td>WZ</td>
<td>0.0071(1)</td>
<td>0.2952(4)</td>
<td>0.02</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.0003(1)</td>
<td>0.0161(1)</td>
<td>0.02</td>
</tr>
<tr>
<td>Sum</td>
<td>0.0258(1)</td>
<td>0.3217(4)</td>
<td>0.08</td>
</tr>
</tbody>
</table>

\( p_{T,j} > 20 \text{ GeV}, \ 2.2 < \eta_j < 4.2, \)  
\( p_{T,\ell^+} > 20 \text{ GeV}, \ 2.0 < \eta_{\ell^+} < 4.5, \)  
\( \Delta R_{\ell^+} > 0.5. \)

\[ \sigma_{\ell^+\ell'^+} \approx 1.3 \text{ fb} \]

\( \rightarrow \) VBS @ LHCb might be feasible!
Conclusions

- SM is in excellent shape
- High-precision (Theo + Exp) allows to push limits to unprecedented levels (LHC completes LEP)
- Important complementarity in phase-space accessible by LHCb
- (N)NLO QCD + NLO EW is the new standard: V+jets, tt, HF, VBS
- Explore the unknown

Possible technical developments towards HL/HE-LHC
- NNLO QCD + PS
- PS matching and multi-jet merging @ NLO QCD+EW
- NNLO QCD for 2→3(4)
- NNLO QCDxEW & NNLO EW
- N3LO QCD for 2→2

New theoretical, mathematical, and computational concepts

precision for HL-LHC
Backup
Relevance of EW higher-order corrections I

Numerically \( \mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \) ⇒ \textbf{NLO EW \sim NNLO QCD}

I. Possible large (negative) enhancement due to soft/collinear \textit{logs} from virtual EW gauge bosons:

\[ pp \to W^+ j \]

\[
\begin{array}{c}
\text{NLO/LO - 1} \\
\text{NNLO/LO - 1} \\
\text{NLL/LO - 1} \\
\text{NNLL/LO - 1}
\end{array}
\]

Universality and factorisation: [Denner, Pozzorini; '01]

\[
\delta \mathcal{M}^\text{LL+NNLL}_{\text{LL+NNLL}} = \frac{\alpha}{4\pi} \sum_{k=1}^{n} \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma,Z,W^\pm} I^a(k) I^a(l) \ln^2 \frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{EW}}(k) \ln \frac{\hat{s}}{M^2} \right\} \mathcal{M}_0
\]

⇒ overall large effect in the tails of distributions: \( p_T, m_{\text{inv}}, H_T, \ldots \) (relevant for BSM searches!)
Relevance of EW higher-order corrections II

2. Possible large enhancement due to soft/collinear logs from photon radiation $\sim \alpha \log \left( \frac{m_T^2}{Q^2} \right)$ in sufficiently exclusive observables.

$\Rightarrow$ Important for various precision observables, e.g. for determination of $M_W$ in DY