LHCb, ATLAS AND CMS COMPLEMENTARITY

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On behalf of the LHCb, CMS, ATLAS Collaborations

Workshop on the physics of HL-LHC, and perspectives at HE-LHC, 18-20 June 2018
Where are we?

- After Higgs discovery, no more guarantees
- Situation may resemble around 1900 “... it seems probable that most of the grand underlying principles have been firmly established...” (Michelson 1894)

- LHC confirms that the SM is robust, but...
  - Hierarchy problem
  - Dark part of the Universe
  - Matter/Antimatter asymmetry
  - ...

- LHC will be our most powerful tool to address these challenges
Reasons to seek higher precision

Theoretical uncertainties?
- Under control in many key measurements and below experimental precision

What will the measurements teach us if deviations from the SM are [not] seen?
- FP data complementary with the high-$p_T$ part of the LHC program
- The synergy of measurements can teach us what the NP @ TeV scale is [not].

It is often said that what’s excluded at 300/fb cannot be discovered at 3000/fb…so why keep going?
- Not true for lighter/weakly coupled particles, Higgs couplings, flavour observables, maximal flavour violation (sensitive to NP at 100+ TeV)
- Statistics $\times 10$ can make $1.5\sigma \rightarrow \sim 5\sigma$, even without analysis improvements

Neubert, Beauty 2018
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Pulls for the SM global fit obtained by comparing the value of $\chi^2_{min}$ with and without including the meas.
Some anomalies

There are some areas of tension within the SM!
All need plausible explanations … or maybe first hints of NP?

- Lepton Flavor Universality
- Tensions in angular distribution, $P_5'$
- $V_{ub}$ and $V_{cb}$: Inclusive vs exclusive
- $B \to K\pi$ puzzle
- $\sin(2\beta)$ tension (direct vs CKM fit)
- Di-muon asymmetry

Need for more studies!
Two different(?) approaches

Complementary approaches of the energy and intensity frontier must be utilised in the search for physics beyond SM

Searching for direct signs of new physics:
- Supersymmetry
- Long-lived particles
- New heavy resonances
- Dark Matter and its nature

Searching for indirect signs of new physics:
- Couplings
- Cross sections
- Widths and branching ratios
- Differential distributions
- CP violation

All these approaches are far from exhausted

Europe’s top priority should be the exploitation of the full potential of the LHC (2013)
What you will (not) find in this presentation

- ATLAS and CMS focus mainly on direct searches for NP while LHCb looks for indirect effects of it.
  - Those approaches are already a definition of complementarity!

- Here, I want to focus on the complementarity in Flavour Physics and I will focus on the interplay of the different experiments on some key measurements that are performed by all of them.
  - In particular, the sensitivity that can be achieved by the different experiments in the HL-LHC is highlighted.
  - Some considerations on systematics.
The experimental scenario

LHCb may be the only large-scale flavour physics experiment operating in the HL-LHC era.

Pre-HL-LHC → Post-HL-LHC

- End Run 3 → End Run 5: \textbf{ATLAS/CMS}: 300/fb → 3000/fb, \textbf{LHCb}: 23/fb → 300/fb
- LHCb energy scale probed scales as $\propto \frac{4}{\sqrt{13}} \sim 1.9$

\textbf{Impact of Upgrade II comparable to moving from 14 TeV to 27 TeV for on-shell production!}
The CKM fit: a lot of room for NP

- It is safe to say that the era of HL-LHC (together with Belle II) will produce a much more precise picture of the physics of flavour.

- O(20%) NP contributions to most loop-level processes (FCNC) are still allowed:
  - See e.g. arXiv:1309.2293 [hep-ph]

- Interesting comparison of tree-level vs higher-order observables. In the latter, unknown particles could contribute.
CP violation in B mixing and decay, $\varphi_s$

CP-violating phase arising from interference between mixing and decay.

- Precisely predicted by the SM: $\varphi_s^{SM} = 36.4 \pm 1.2$ mrad
- Golden channel exploited by LHCb, ATLAS, CMS: $B_s^0 \rightarrow J/\psi\phi$
- LHCb also measured many other channels

$\varphi_s^{HFLAV} = -21 \pm 31$ mrad

CP violation in B mixing and decay, $\varphi_s$

- Include gain in trigger for $B_s^0 \to D_s^- D_s^+$ after Upgrade 1
- Same performances as in Run II
- Planning new modes: $J/\psi \to ee, \eta' \to \rho^0 \gamma$ or $\eta' \to \eta \pi \pi$

300/fb: $\sigma^{STAT} (\varphi_s) \sim 4 \text{ mrad}$ from $B_s^0 \to J/\psi \phi$ only

- Include gain in trigger after Upgrade 1
- 300/fb: $\sigma^{STAT} (\varphi_s) \sim 11 \text{ mrad}$ from $B_s^0 \to \phi \phi$
- 300/fb: $\sigma^{STAT} (\varphi_s) \sim 9 \text{ mrad}$ from $B_s^0 \to K\pi K\pi$
- $B_s^0 \to \phi \phi$ will remain stat. limited, limiting syst for $B_s^0 \to K\pi K\pi <30 \text{ mrad}$ (MC, modelling resonances)
CP violation in B mixing and decay, $\varphi_s$  

Better decay time resolution:
- Run 2 30% better than Run 1 (IBL)
- Additional gain expected from Itk at high $p_T$ and from analogue instead of digital pixel clustering.

\[ HL - LHC: \sigma^{\text{STAT}}(\varphi_s) \sim 22 \text{ mrad} \quad \text{[ATL-PHYS-PUB-2013-010]} \]
\[ \sigma^{\text{SYST}}(\varphi_s) < 40 \text{ mrad} \quad \text{[ATL-PHYS-PUB-2013-010]} \quad \text{(conservative)} \]

+ Statistics x~3 by topological $\mu$ trigger
  (lower $p_T$ thresholds, same bandwidth) \[ \text{[ATL-PHYS-PUB-2013-010]} \]

ATLAS is also studying the possibility to trigger on hadronic final states, $B_s^0 \to \varphi\varphi$ will become possible!
Better decay time resolution will improve the sensit. to $\varphi_s$

Introducing tracking information in the L1 trigger:
- improve the $p_T$ resolution of various objects at L1
- contribute to the mitigation of pileup
- allow the exploitation of information on track isolation

Test bed: $B_s^0 \rightarrow \phi\phi$ identified already at L1
- oppositely charged tracks from the same vertex
- application of topological cuts at L1 to reduce background
- very soft $p_T$ of the lowest- $p_T$ kaon (close to 2 GeV)
- Improvements required to keep a low trigger rate (e.g. displaced vertex finding tool)
Rare decays

Clean probes for New Physics, strong constraints (or evidence) for new flavour structures beyond the SM. E.g. $B^0_s \rightarrow \mu^+\mu^-$:

<table>
<thead>
<tr>
<th>$\mathcal{B}(B_s \rightarrow \mu\mu)$</th>
<th>$\mathcal{B}(B^0 \rightarrow \mu\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>$(3.66\pm 0.23) \times 10^{-9}$</td>
</tr>
<tr>
<td>Run I (CMS)</td>
<td>$(3.0^{+0.9}_{-0.9}) \times 10^{-9}$</td>
</tr>
<tr>
<td>Run I (CMS+LHCb)</td>
<td>$(2.8^{+0.7}_{-0.6}) \times 10^{-9}$</td>
</tr>
<tr>
<td>Run I (ATLAS)</td>
<td>$(0.9^{+1.0}_{-0.8}) \times 10^{-9}$</td>
</tr>
<tr>
<td>Run I + Run II (LHCb)</td>
<td>$(3.0\pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$</td>
</tr>
</tbody>
</table>

[arXiv:1311.0903]

PRL 111 (2013) 101804

Nature 522 (2015) 68

EPJ. C 76 (2016) 513


Upgrade will allow

- Meaningful measurements of new observables, e.g. effective lifetime
- Time dependent CP-asymmetry of $B^0_s \rightarrow \mu^+\mu^-$ decays
- Search for other (semi-)leptonic B and D decays
Rare decays

- $B^0 \to \mu^+\mu^-$ statistically limited also with 300/fb
- 300/fb: $\sigma^{STAT}(B^0_s \to \mu^+\mu^-) \sim 1.8\%$
- 300/fb: $\sigma^{SYST}(B^0_s \to \mu^+\mu^-) \sim 4\%$
- Large part of MSSM models will be covered

- Ratio $R = \mathcal{B}(B^0_s \to \mu^+\mu^-)/\mathcal{B}(B^0 \to \mu^+\mu^-)$ limited only by statistics 300/fb: $\sigma^{STAT}(R) \sim 10\%$, cf. 5-10% theory uncertainty.

- Search for $B^0_{(s)} \to \tau^+\tau^-$ at LHCb allowed to put the most stringent limits: $\mathcal{B}(B^0_{(s)} \to \tau^+\tau^-) < 2.1(6.8) \times 10^{-3}$ @95% C. L.
- NP models needed to explain LFU anomalies predict an enhancement of these BF.
- For $B_s^0$ factor 5 to $1.3 \times 10^{-3}$ improvements end of Upgrade I and another 2.6 to $5 \times 10^{-4}$ by the Upgrade II.
Rare decays

Projections available for two scenarios:
- **Phase-I scenario**: expected performance for Run II and III (300 fb-1 @14 TeV)
- **Phase-II upgrade scenario**: expected performance after full detector upgrade & 3000 fb-1

Inputs from:
- L1 trigger: $\mu^+\mu^-$ with $p_T > 3$ GeV, $|\eta| < 2$ from the same PV and invariant mass between 3.9 and 6.9 GeV
- Improved momentum resolution in barrel
- Large Pile-up will limit usage of isolation and implies tighter cuts to reduce fakes
- Larger syst from semilept. decays: $\sim 20\%$

Evaluating to include also a study on $T_{\mu\mu}^{\text{eff}}$ for the Yellow Report

<table>
<thead>
<tr>
<th>L (fb$^{-1}$)</th>
<th>$\delta R(B_s \rightarrow \mu\mu)$</th>
<th>$\delta R(B^0 \rightarrow \mu\mu)$</th>
<th>$B^0$ sign.</th>
<th>$\delta [\delta R(B^0 \rightarrow \mu\mu) / \delta R(B_s \rightarrow \mu\mu)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>14%</td>
<td>63%</td>
<td>0.6–2.5$\sigma$</td>
<td>66%</td>
</tr>
<tr>
<td>300</td>
<td>12%</td>
<td>41%</td>
<td>1.5–3.5$\sigma$</td>
<td>43%</td>
</tr>
<tr>
<td>300 (barrel)</td>
<td>13%</td>
<td>48%</td>
<td>1.2–3.3$\sigma$</td>
<td>50%</td>
</tr>
<tr>
<td>3000 (barrel)</td>
<td>11%</td>
<td>18%</td>
<td><strong>5.6–8.0$\sigma$</strong></td>
<td><strong>21%</strong></td>
</tr>
</tbody>
</table>
Rare decays

ATLAS Run 1 result lower in both BRs compared to combined CMS&LHCb result.

Expected Upgrade improvement:

- **Better mass separation** wrt Run I: Barrel $1.4\sigma \rightarrow 2.3\sigma$, End-caps $0.85\sigma \rightarrow 1.3\sigma$ [ATL-PHYS-PUB-2016-026]

Three trigger scenarios for HL-LHC:

- $2\text{MU10} \rightarrow 15 \times \text{NRun1}$
- $\text{MU6}_\text{MU10} \rightarrow 60 \times \text{NRun1}$
- $2\text{MU6} \rightarrow 75 \times \text{NRun1}$
- Main syst: $(fs/fd) \sim 8.3\%$ “conservative” [ATL-PHYS-PUB-2018-005]
Rare decays: lepton flavour violation

- LFV branching fractions enhanced to $10^{-11}$ in certain models of leptoquarks, $Z'$ [Medeiros Varzielas, Hiller, JHEP 06 (2015) 072]
- LHCb was the first experiment to search for LFV $\tau$ decays in a hadron collider

<table>
<thead>
<tr>
<th></th>
<th>$B(B^0(s) \rightarrow e\mu)$</th>
<th>$B(B \rightarrow \tau\mu)$</th>
<th>$B(\tau \rightarrow \mu\mu\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run I @ 90 C.L.</td>
<td>$&lt; 1.0 \ (5.4) \times 10^{-9}$</td>
<td>Soon</td>
<td>$&lt; 4.6 \times 10^{-8}$</td>
</tr>
<tr>
<td>HL-LHC @ 90 C.L.</td>
<td>$&lt; 3 \ (9) \times 10^{-10\ (11)}$</td>
<td>$&lt; 3 \times 10^{-6}$</td>
<td>$&lt;\mathcal{O}(10^{-9})$</td>
</tr>
</tbody>
</table>

Translate BR limits into limits on leptoquark mass

Searches for $B \rightarrow K e\mu, B \rightarrow K^0\tau(\rightarrow \pi\pi\nu)\mu, B \rightarrow K \tau(\rightarrow \pi\pi\nu)\mu$ and $\Lambda_b^0 \rightarrow \Lambda^0 e\mu$ are ongoing

- Using Run1 + Run2 data expects limits $\mathcal{O}(10^{-9})$ and $\mathcal{O}(10^{-6})$ for $B \rightarrow K e\mu$ and $B \rightarrow K^0\tau\mu$, respectively
- Complementary as charged lepton FV couplings among different families are expected to be different
- Multi-body final states: allow the measurement of more observables

Similar to what is expected from Belle II
Rare decays: $\tau \to \mu\mu\mu$

- Main source of $\tau$ leptons in $pp$ collisions is $D_s \to \tau\nu$
  - final state $\mu$ have very low $p$ and are mainly produced in the forward region
  - only $\sim13\%$ of signal events have all there $\mu$ within $2<\eta<4$ and $p_T > 2.5$ GeV
  - will benefit from the extended $\eta$ coverage of the muon system and the improved trigger resolution at low $p_T$

- Events split in two categories based on $\eta$ of the most forward muon
  - Dedicated L1 trigger and dedicated muon ID, targeting low momentum muons

| $|\eta|$ most forward muon | Cat. 1 | Cat. 2 |
|---------------------------|--------|--------|
|                            | $< 2.4$ | $> 2.4$ |
| Average $3\mu$ mass resolution | 18 MeV | 31 MeV |
| L1 trigger efficiency      | 80%    | 50%    |
| $B(\tau \to 3\mu)$ limit per category | $4.3 \times 10^{-9}$ | $7.0 \times 10^{-9}$ |
| Combined limit              | $3.7 \times 10^{-9}$ |

CMS also plans to measure $B \to e\mu$, $B \to \tau\mu$ and $B \to \tau\tau$
Rare decays: $\tau \rightarrow \mu\mu\mu$

- Current ATLAS limit: $3.7 \times 10^{-7}$ [EPJC 76, 232 (2016)], Run-1 analysis using $\tau$’s originating from $W \rightarrow \tau \nu$ decays
- New analysis will exploit $\tau$’s from $D_s \rightarrow \tau \nu$ (production of $D_s$ one order of magnitude larger than $W$)

- Many improvements from Run-1
  - **Improved reconstruction efficiency** for close-by low $p_T$ muons
  - **Improved trigger acceptance** by more efficient algorithms and topological selection at level-1 (L1Topo)
  - **New methods for jet flavour tagging** (c-tagging) became available to separate signal and background

**Prospects for HL-LHC**
- Increase statistics by more than a factor of 30
- Assuming acceptance×efficiency can be maintained at similar level branching ratios up to $\mathcal{O}(8 \times 10^{-9})$ can be obtained
- Critical component ensure sufficiently low threshold triggers
- **ATLAS also plans to measure** $B^0_s \rightarrow e\mu$
Hints of lepton flavour anomalies

- Intriguing hints of anomalies in B decays entered the stage in 2012 ($R_D, R_{D^*}, P_5', R_K, R_{K^*}, \mathcal{B}(B \rightarrow X\mu^+\mu^-)$)

$$R_{D(*)} = \frac{\Gamma(\bar{B} \rightarrow D(*)\tau\bar{\nu})}{\Gamma(\bar{B} \rightarrow D(*)\ell\bar{\nu})} \ \ell = e, \mu \ \ \ \text{TREE} \ (b \rightarrow c\ell\bar{\nu})$$

$$R_{K(*)} = \frac{\Gamma(\bar{B} \rightarrow K(*)\mu^+\mu^-)}{\Gamma(\bar{B} \rightarrow K(*)e^+e^-)} \ \ \ \text{FCNC} \ (b \rightarrow s\ell^+\ell^- \ \text{and} \ b \rightarrow d\ell^+\ell^-)$$

Both Belle2 and LHCb experiments could individually confirm or rule out the current flavour anomaly by 2026 (arXiv:1709.10308)

If true, hugely important for the future development of high-energy particle physics, providing a clear target for future searches at energy frontier… exactly what’s missing right now!

Even if not confirmed, they serve as a good example of the potential of FP at Upgrade II to probe beyond the energy frontier.

Neubert, Beauty 2018
FCNC transitions

- LFU will play a large role in Upgrade II physics case
- Improvements: Reduce the material (e.g. RF-foil), improve ECAL granularity, better Brem recovery algorithms
- Upgrade II: 440k fully reconstructed $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ will allow a $q^2$-unbinned approach ⇒ probe the SM contributions, NP expected to have no $q^2$ dependence
- Compare angular distr. $B^0 \rightarrow K^{*0} e^+ e^- / B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Upgrade will provide thousands of $b \rightarrow d \ell^+ \ell^-$ decays (e.g. 4300 $B_s^0 \rightarrow K^{*0} \mu^+ \mu^-$), angular analysis possible
- 45k $B^+ \rightarrow K^+ e^+ e^-$ and 20k $B^0 \rightarrow K^{*0} e^+ e^-$ in the Upgrade II → Ultimate precision on $R_{K^{(*)}} < 1\%$
- $R_\varphi, R_{pK}, R_\pi, \ldots$ will be possible un Upgrade II

All four NP scenarios could be distinguished at more than 5$\sigma$ in Upgrade II!
Semileptonic decays

LHCb measured $R_{D^{(*)}}$ using muonic ($\tau \rightarrow \mu \nu \nu$) and hadronic ($\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \nu$) decays

Upgrade II: new observables beyond the BF ratio
- Kinematics of $\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}$ fully described by dilepton mass, and three angles, $\chi, \theta_L$ and $\theta_d$ (better resolution)

Upgrade II: measurements in other b-hadron species
- $B_S^0 \rightarrow D_S^{(*)} \tau^- \bar{\nu}$: 6% (2.5%) relat. unc. after Run 3 (Upgrade II)
- Semitauonic decays of b-baryons and of $B_c^+$ mesons
  - $R(\Lambda_c^+)$ 4% (2.5%) relat. unc. after Run 3 (Upgrade II)

HFLAV
Connections with high-$p_T$

- ATLAS plans to perform $B^0 \rightarrow K^{*0} e^+ e^- / B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- CMS will include an estimate with expected uncertainties for $P_5'(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$ in the YR [Run I: Phys.Lett. B781 (2018) 517] + studying $B^{0(+)} \rightarrow K^{*0(+)} e^+ e^- / B^0 \rightarrow K^{*0(+)} \mu^+ \mu^-$
- Moreover, connection with high- $p_T$ must be fully exploited:

**In the SM**
- Loop, CKM, and GiM suppression

- $C_9^{SM} \approx -C_{10}^{SM} \approx 4.2$

**New Physics**
- e.g. pure V-A scenario:
  - $\Delta C_9^{\text{NP}} = -\Delta C_{10}^{\text{NP}} = -0.61 \pm 0.12$
  - implies $\Lambda / g_s \approx 32^{+4}_{-3} \text{ TeV}$

**Tree-level, unsuppressed ($g_s \sim 1$)**
- $\sim 30 \text{ TeV}$

**Tree-level, MFV ($g_s^2 = V_{tb}$)**
- $\sim 6 \text{ TeV}$

**Loop-generated ($g_s = 1/4\pi$)**
- $\sim 2.5 \text{ TeV}$

**Loop-generated, MFV**
- $\sim 0.5 \text{ TeV}$

**Flavour structure drives the direct searches phenomenology**

From $b \rightarrow s \ell^+ \ell^-$

- Tree-level process
- Mild CKM suppression

**From $b \rightarrow c \ell \bar{\nu}$**

- Large NP contribution required
  - [Presumably tree-level generated]

**Tree-level, unsuppressed ($g_s \sim 1$)**
- $\sim 3.5 \text{ TeV}$

**Tree-level, MFV ($g_s^2 = V_{cb}$)**
- $\sim 0.7 \text{ TeV}$

**Perturbative unitarity constraint:** NP scale $\leq 9 \text{ TeV}$

[Di Luzio and Nardecchia, 2017, 01668]
Connections with high-$\rho_T$

- Importance to search for $Z'$ and Leptoquarks if anomalies are confirmed.

Final states: $\tau\tau, \mu\mu, tt, bb, ...$

- QCD pair production
- Single LQ + lepton production
- Dilepton production

Final states: $b\tau b\tau, b\mu b\mu, b\tau b\mu, t\nu t, ...$

E.g. $pp \rightarrow \mu\mu$
- Bump hunt
- Non resonant deviations in the tail
Forward and high-$p_T$ physics

The flexible data collection has and will allow the physics progr. to be expanded in ways that were completely unforeseen!

**Higgs decay to $c\bar{c}$**

- Powerful heavy-flavour jet-tagging procedure with clear separation between b- and c- jets.
  - Efficiency to identify b- and c-jets is $\sim$65% and 25%, respectively.
  - 0.3% mis-id probability between a jet initiated by a light-parton or heavy-flavour.

**Run I**

**Upgrade II**

- VH production cross section increases by a factor of $\sim$7 within LHCb from 8 to 14 TeV.
- Improved VELO is expected to increase the c-jet tag efficiency to 30%
- Looser di-c-jet tagging efficiency wrt Run I, with a small impact on overall background.
- Electron reconstruction expected to improve
- Deep-learning algo following CMS and ATLAS to improve separation from c-jet backgrounds.

Potential to make the most stringent constraint!
### Ex. of systematics @ HL-LHC

<table>
<thead>
<tr>
<th>LHCb</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varphi_s$</td>
<td>Statistically dom.</td>
<td>Tagging scales with size, rest (modelling, $B^0 \to J/\psi K^*$, trigger eff., alignment) stays the same. 40 mrad very conserv. (~Run I).</td>
</tr>
<tr>
<td>$B^0_s \to \mu^+\mu^-$</td>
<td>4%. Current dominated by knowledge of $f_s/f_d$, BR of normaliz. modes, 2% PID and 2% track reconstruction</td>
<td>Main syst: $(f_s/f_d) \sim 8.3%$ “conservative” as same for Run I</td>
</tr>
</tbody>
</table>

**Take home messages:**

- Flavour WG should define a similar strategy for main and common systematics (being optimistic or not, how to scale them)
- Importance to list the main syst. expected in any future document to pin down complementarity between the experiments!
Complementarity of the experiments

To what extent our main systematics on some of these measurements could be complementary?

Time measurements (e.g. $\Gamma_s/d$) will be critical to keep statistically dominated in Upgrade II (sub-fs precision):

- LHCb suffer from an upper decay time acceptance introduced mainly in the VELO reconstruction
  - Must be of course re-determined with the pixel-VELO foreseen in Run III
  - What about CMS and ATLAS? If different sources exists there could be a global benefit.

Measurements like $\Delta \Gamma_d$ don’t need tagging, CMS and ATLAS already proved to have great performances:

- Extremely precise measurements foreseen for Upgrade II
- To reduce systematics, important to rely as less as possible on MC to model decay-time acceptance. Plans?

Can we be smarter with the combination of unique and overlap regions for $f_s/f_d$?

E.g. if LHCb can pin down the absolute normalisation in the overlap region using semileptonic decays, then CMS and ATLAS can use any decay to port this to the rest of their acceptance.

.... and so on...just some random thoughts to start the discussion!
Outlook

◦ The Upgrade II of LHCb will enable a very wide range of flavour observables to be measured to unprecedented precision (see table in backup).

◦ Focused on measurements with overlap btw experiments, but LHCb flavour program is very rich!
  ◦ Comprehensive measurement programme of **observables to test LFU**, many not accessible in Upgrade I
  ◦ Precise measurement of **Unitary Triangle parameters**, e.g. $\varphi_s$ at 3 mrad.
  ◦ Precise measurement of **rare decays**, e.g. $R = B(B_s^0 \rightarrow \mu^+\mu^-)/B(B^0 \rightarrow \mu^+\mu^-)$ with 10% uncert.
  ◦ **Complementarity with some of the high-$p_T$ searches** performed by ATLAS and CMS
  ◦ CP-violation studies in **charm** with $10^{-5}$ precision
  ◦ Huge data-sets available for **spectroscopy**

◦ The B-physics capabilities of ATLAS and CMS will be enhanced by their Phase II Upgrades. These improvements, together with the very large data sets that are foreseen, will allow for **precise measurements** to be performed, **in particular for final states including dimuons**.
  ◦ $\sim 10^{15} b\bar{b}$ produced in 3000 fb$^{-1}$, 0.7% of recorded minbias is $b\bar{b}$: big gain with lower pt thresholds

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**Essential in searching for, and characterising, NP in HL-LHC era!**

**Most of measurements are exclusive of LHCb!**

**ATLAS & CMS provide complementarity for some key measurements**
"And if someone dares to yawn during your presentation, this pointer easily transforms from a laser to a taser!"
Prospects for selected flavour observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb</th>
<th>LHCb 2025</th>
<th>Belle II</th>
<th>Upgrade II</th>
<th>GPDs Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EW Penguins</strong></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>$R_K$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2$)</td>
<td>$0.1 , ^{+0.255}_{-0.07}$</td>
<td>$0.022$</td>
<td>$0.036$</td>
<td>$0.006$</td>
<td></td>
</tr>
<tr>
<td>$R_{K^*}$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2$)</td>
<td>$0.1 , ^{+0.254}_{-0.029}$</td>
<td>$0.029$</td>
<td>$0.032$</td>
<td>$0.008$</td>
<td></td>
</tr>
<tr>
<td>$R_{\phi}$, $R_{\phi K}$, $R_{\pi}$</td>
<td>$-0.07, 0.04, 0.11$</td>
<td>$-0.02, 0.01, 0.03$</td>
<td></td>
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<td></td>
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<tr>
<td><strong>CKM tests</strong></td>
<td></td>
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</tr>
<tr>
<td>$\gamma$, with $B^0 \to D_s^+ K^-$</td>
<td>$^{+15\circ}_{-22\circ}$</td>
<td>$4\circ$</td>
<td>$-1\circ$</td>
<td>$-1\circ$</td>
<td></td>
</tr>
<tr>
<td>All modes</td>
<td>$^{+5.5\circ}_{-6.8\circ}$</td>
<td>$1.5\circ$</td>
<td>$1.5\circ$</td>
<td>$0.35\circ$</td>
<td></td>
</tr>
<tr>
<td>$\sin 2\beta$, with $B^0 \to J/\psi K^0_s$</td>
<td>$0.04 , ^{+0.569}_{-0.011}$</td>
<td>$0.01$</td>
<td>$0.005$</td>
<td>$0.003$</td>
<td></td>
</tr>
<tr>
<td>$\phi$, with $B^0 \to J/\psi \phi$</td>
<td>$49 , ^{+32}_{-32}$</td>
<td>$14 , ^{+32}_{-32}$</td>
<td>$-4 , ^{+32}_{-32}$</td>
<td>$22 , ^{+32}_{-32}$</td>
<td>$570\circ$</td>
</tr>
<tr>
<td>$\phi$, with $B^0 \to D^+_s D_s^-$</td>
<td>$170 , ^{+37}_{-37}$</td>
<td>$35 , ^{+37}_{-37}$</td>
<td>$-9 , ^{+37}_{-37}$</td>
<td>$-9 , ^{+37}_{-37}$</td>
<td></td>
</tr>
<tr>
<td>$\phi^\ast$, with $B^0 \to \phi \phi$</td>
<td>$150 , ^{+571}_{-571}$</td>
<td>$60 , ^{+571}_{-571}$</td>
<td>$-17 , ^{+571}_{-571}$</td>
<td>$-17 , ^{+571}_{-571}$</td>
<td>Under study $572\circ$</td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>$3 \times 10^{-4}$</td>
<td>$10 \times 10^{-4}$</td>
<td>$-3 \times 10^{-4}$</td>
<td>$-3 \times 10^{-4}$</td>
<td>$-3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>$</td>
<td>$6% , ^{+186}_{-186}$</td>
</tr>
<tr>
<td>$B^0_s, B^0 \to \mu^+ \mu^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B^0 \to \mu^+ \mu^-)/B(B^0_s \to \mu^+ \mu^-)$</td>
<td>$90% , ^{+244}_{-244}$</td>
<td>$34%$</td>
<td>$-10%$</td>
<td>$21% , ^{+573}_{-573}$</td>
<td></td>
</tr>
<tr>
<td>$\gamma_{B^0 \to \mu^+ \mu^-}$</td>
<td>$22% , ^{+244}_{-244}$</td>
<td>$8%$</td>
<td>$-2%$</td>
<td>$-2%$</td>
<td></td>
</tr>
<tr>
<td>$S_{\mu \mu}$</td>
<td>$-0.2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b \to c\ell^- \bar{\nu}_\ell$ LUV studies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>$9% , ^{+199}_{-202}$</td>
<td>$3%$</td>
<td>$2%$</td>
<td>$1%$</td>
<td></td>
</tr>
<tr>
<td>$R(J/\psi)$</td>
<td>$25% , ^{+202}_{-202}$</td>
<td>$8%$</td>
<td>$-2%$</td>
<td>$-2%$</td>
<td></td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta A_{CP}(K^- \pi^+)$</td>
<td>$8.5 \times 10^{-4}$</td>
<td>$574%$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$5.4 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$A_{CP}(\approx x \sin \phi)$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$222%$</td>
<td>$4.3 \times 10^{-5}$</td>
<td>$3.5 \times 10^{-5}$</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$x \sin \phi$ from $D^0 \to K^+ \pi^-$</td>
<td>$13 \times 10^{-4}$</td>
<td>$210%$</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$4.6 \times 10^{-4}$</td>
<td>$8.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$x \sin \phi$ from multibody decays</td>
<td>$- (K3\pi) 4.0 \times 10^{-5}$</td>
<td>$(K3\pi) 1.2 \times 10^{-4}$</td>
<td>$(K3\pi) 8.0 \times 10^{-5}$</td>
<td>$- (K3\pi) 8.0 \times 10^{-6}$</td>
<td>$- (K3\pi) 8.0 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Based on extrapolations from current measurements, and take no account of detector improvements apart from an approximate factor two increase in efficiency for hadronic modes, coming from the full software trigger that will be deployed from Run 3 onwards.
Similar challenges

Pileup in HL-LHC: ~200 for ATLAS/CMS, ~50 for LHCb
Common themes: timing, granularity and radiation hardness
Forward and high-$p_T$ physics

- The flexible data collection has and will allow the physics progr. to be expanded in ways that were completely unforeseen!

### Top physics in the forward region

- Three measurements already performed exploiting $\mu b$, $\ell bb$, and $\mu eb$ final states.
- Upgrade II: precision measurement of top production and charge asymmetry.
  - Rises from $\sim 1\%$ in the central region to as high as $8\%$ within the LHCb acceptance.

### Gauge-boson production

- LHCb already performed inclusive & associated production measurements of $W$ and $Z$ at different pp energies.
- Upgrade II: differential measurements in more dimensions and in association with heavy-flavour/ high-p jets.
  - LHCb probe a unique region of the phase-space associated with parton distribution functions.

### Measurement of the eff. weak mixing angle

- At higher Z rapidities @ LHCb the forward-backward asymm. is larger and easier to measure + better prediction.
- Run I: $\sin^2(\theta_W^{\text{eff}}) = 0.23142 \pm 0.00073 \pm 0.00056$
- Upgrade II samples can enable an impressive sensitivity.
  - Understand the discrepancy ($\sim 3\sigma$) among LEP and SLD determination.

### Measurement of the W mass

- Highly desirable due to the complementary lepton acceptance $2 < \eta < 5$,
  - Partial anti-correlation between the PDF uncertainties as compared to ATLAS and CMS.
- Upgrade II would allow a precision of few MeV.
Forward and high-$p_T$ physics

- The flexible data collection has and will allow the physics program to be expanded in ways that were completely unforeseen!

**Higgs decay to $c\bar{c}$**
- Run 1: powerful heavy-flavour jet-tagging procedure with clear separation between $b$- and $c$-jets.
- Upgrade II: improved VELO and electron reconstruction and deep-learning algorithm to separate $b$- and $c$-jets.

  Potential to make the most stringent constraint!

**Decays of long-lived particles (LLP)**
- Run 1: neutralinos decaying semilept. into high-$p_T \mu^+$, Hidden Valley and $\pi'$s decaying to pair of jets
- Upgrade II: LHCb will test most of phase space left from ATLAS and CMS

  Low mass and low lifetime region of LHCb unexplored by other experiments

**Search for prompt and detached dark photons**
- Current limits (gray fills), current LHCb limits (black bands), and possible LHCb future reach (coloured bands).
- LHCb can explore significant portions of unconstrained $A'$ parameter space.

  LHCb will either confirm or reject the presence of a dark photon for nearly all relevant parameter space.