Precision Flavour Physics

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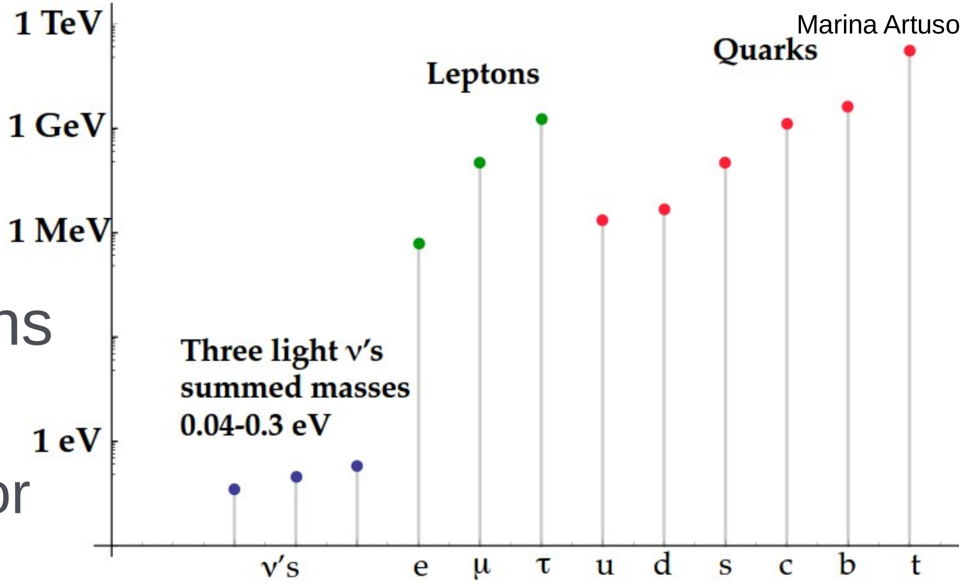
Why flavour physics?

In SM flavour structure arise through the Yukawa couplings to the Higgs field and the weak force

- Misalignment of these gives structure of CKM matrix

Any NP model with new flavoured particles or flavour breaking interactions must “hide” behind SM interactions

- NP mass scale very large >~100 TeV or
- NP mimics Yukawa couplings



Potential for discovery of NP

For a set of prospective measurements, we need to ask the questions

- What are the theoretical uncertainties and can they be reduced?
- Can we learn something from the measurement?
- What level of statistical accuracy is expected?
- How will experimental systematic uncertainties be controlled?

Potential for discovery of NP

For a set of prospective measurements, we need to ask the questions

- What are the theoretical uncertainties and can they be reduced?
  - Push us to decays with leptons and search for CP violation
- Can we learn something from the measurement?
  - Need to have sensitivity to a high energy scale. Need to differentiate.
- What level of statistical accuracy is expected?
  - Need high luminosity and high trigger efficiency
- How will experimental systematic uncertainties be controlled?
  - Need to access many control channels

Theoretical uncertainties

In order to see a NP signature, we need to understand the SM

QCD or the “hadronic problem” is the big challenge

- Make (part of the) final state insensitive to QCD
  - Move to leptonic, semileptonic, rare semileptonic decays
- Exploit that we know that there is no (significant) CP violation in QCD
  - Measure CP violation in b- and c-hadron decays
- Test symmetries or forbidden transitions in SM
  - Lepton non-universality, lepton number violation, baryon number violation

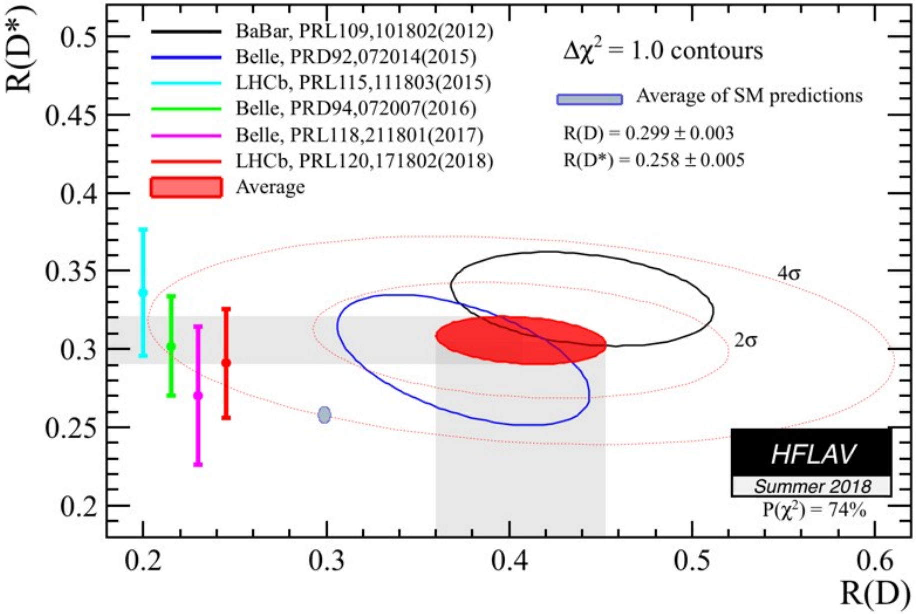
Theoretical uncertainties

Make (part of the) final state insensitive to QCD

- Move to leptonic, semileptonic, rare semileptonic decays
- Theory uncertainties are very small

Futher developments required

- Analysis with $\Lambda_b \to \Lambda_c \tau\nu$ and $B_c \to J/\psi\tau\nu$ have different theory uncertainties
- Angular analysis $B^0 \to D^{*+}\tau^-\nu$ and B

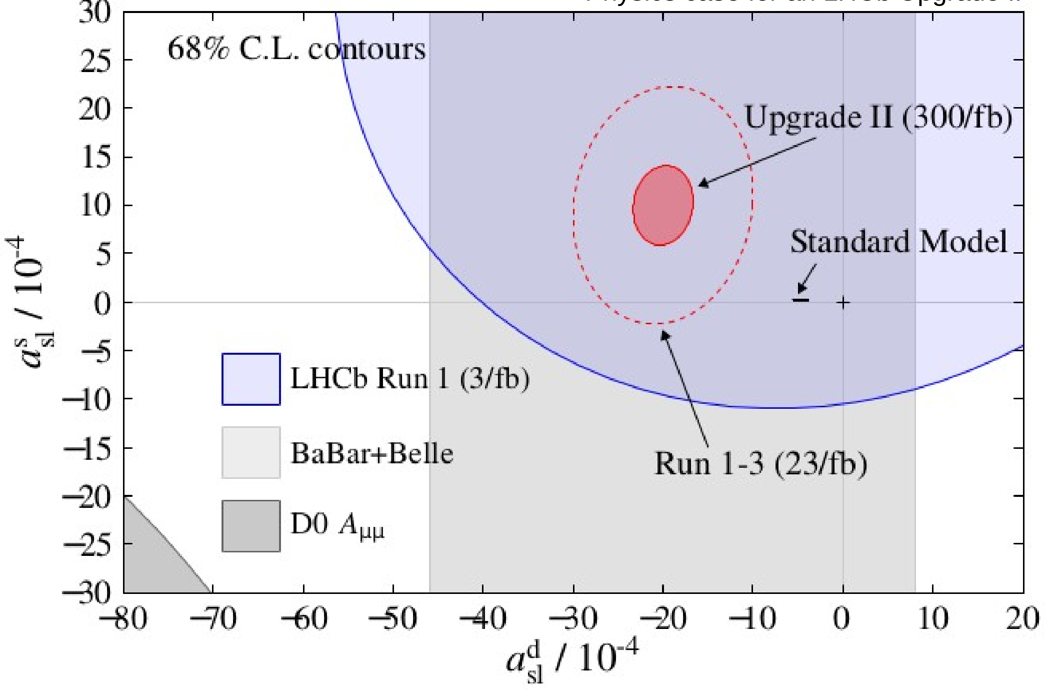


Theoretical uncertainties

Exploit that we know that there is no (significant) CP violation in QCD

As example, the CP violation in B^0 and B^0_s mixing has theory uncertainty far below even 300 fb^{-1} sensitivity

Physics case for an LHCb Upgrade II



Can we learn something from the measurement?

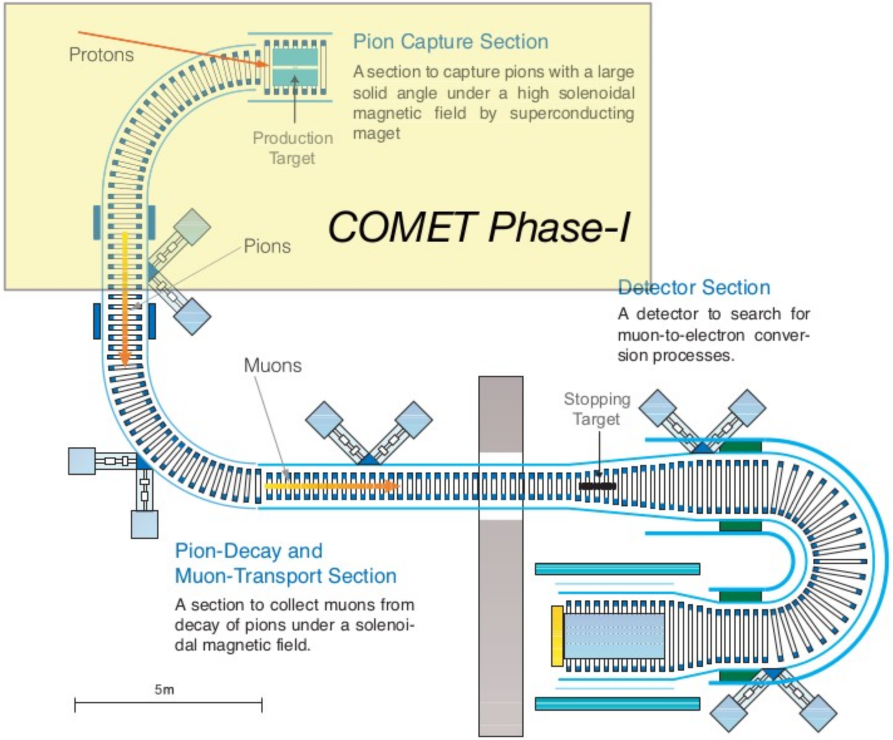
- Just to know there is something new is not good enough
  - We need to differentiate
  - Measurement of single branching, e.g. $B^0_s \rightarrow \mu^+\mu^-$ not useful for this
- How does NP fit in with the quark sector?
  - Look at Cabibbo suppressed transitions
- And the lepton sector?
  - Lepton flavour violation in addition to lepton non-universality?

Lepton flavour violation

The COMET experiment is looking for LFV in the process $\mu^- N \rightarrow e^- N$

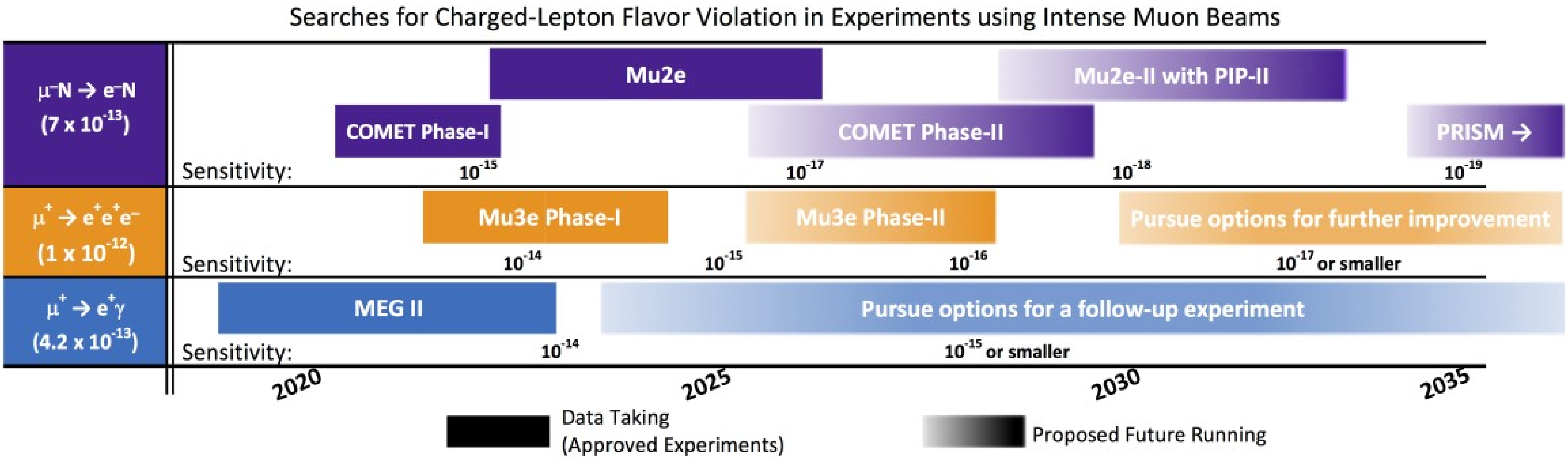
- The signal is electrons with momentum corresponding to the muon mass (no neutrinos)
- Dominant background from “normal” muon decays

Phase-I aims to reduce single event sensitivity to 3×10^{-15}, a factor 100 below the current one



COMET timeline

The technology of COMET has the potential for improvements in sensitivity that go much further



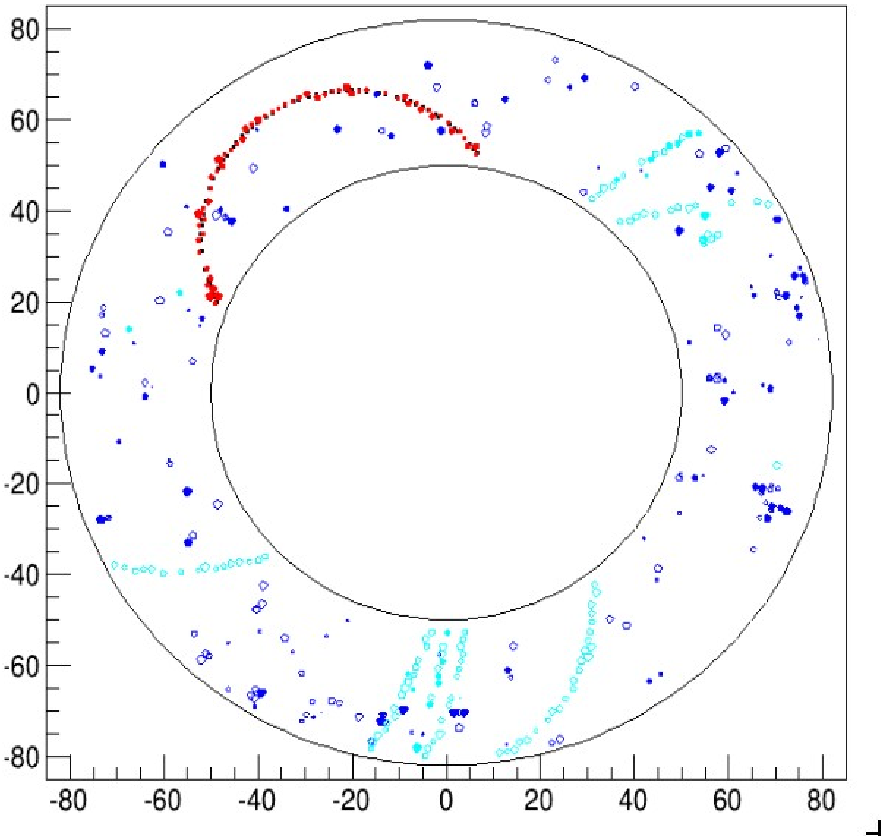
COMET involvement

Due to the extremely high data rate of incoming muons, the trigger is essential

Part of trigger based on tracking

The involvement in COMET is on the the FPGA based tracking algorithm

- Will use machine learning to identify possible signal electrons at the full repetition rate of ~1μs



LHCb upgrades

The current LHCb detector configuration will be used until end of Run-2 (2018)

- ~ factor 5 on Run-1 yield

The LHCb upgrade will take data for 6 years from 2021

- ~ factor 25
- This ignores trigger improvements

The proposed LHCb upgrade-II will take data after 2030

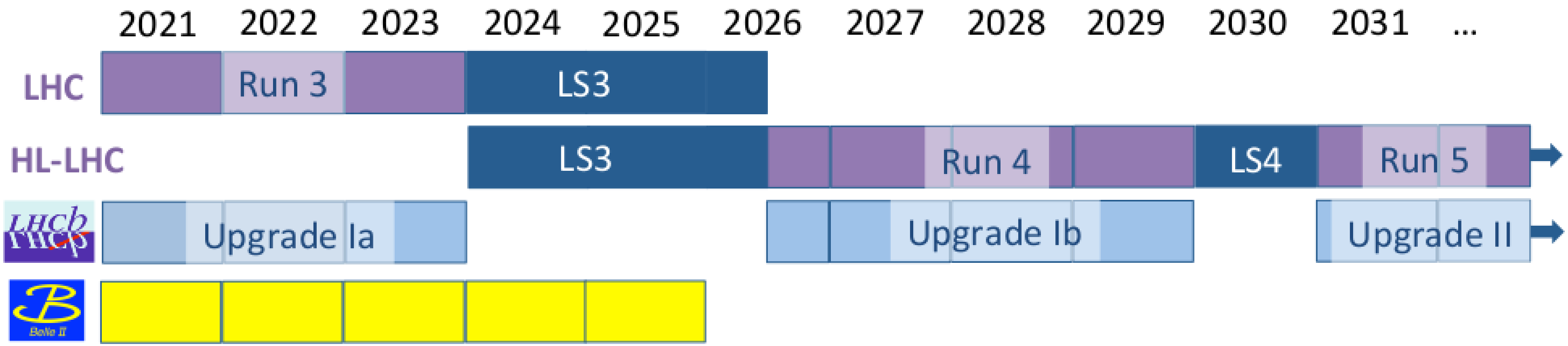
- ~ factor 200

LHCb upgrade timeline

The current Upgrade-Ia is taking place right now

Upgrade Ib and Upgrade II are after currently scheduled end-time of BELLE-II

- There is a rich opportunity for Australia to be involved in the long-term future of heavy-flavour physics



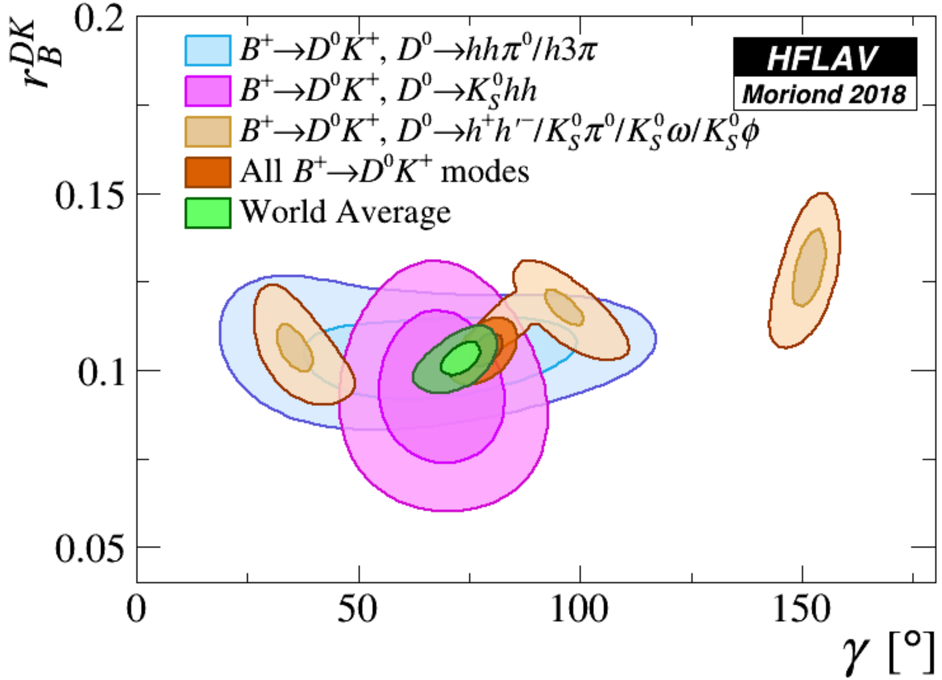
LHCb upgrade opportunities

- The calorimeter of LHCb will require a major upgrade for Upgrade-II
  - More radiation resistent – radiation level of 200 Mrad
  - Faster timing to avoid spillover – to reduce occupancy
  - Timing information at the ps level for clusters – to allow for clustering to separate individual pp collisions in same bunch crossing
  - Clustering to take place prior to trigger
    - FPGA technology as for COMET is a very favourable route for this. So far unexplored
- Other countries involved in calorimeter upgrade are China, Russia and France

Other searches for New Physics

Measurement of CP angle γ

- LHCb is providing the dominant measurements at the moment and will continue to dominate
- Ambiguities are resolved by measurements in multiple channels
- With 300 fb^{-1}, LHCb will reach resolution of 0.35°



Unitarity triangle

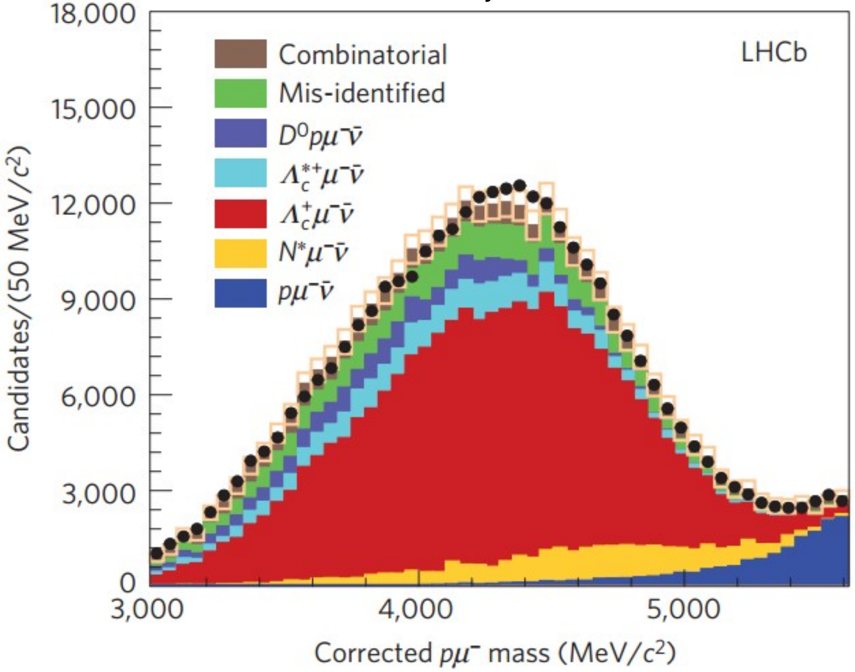
LHCb has proven with the $\Lambda_b \rightarrow p\mu\nu$ that precision measurements can be made of $|V_{ub}|/|V_{cb}|$

With semileptonic decays there is no signal peak as such

Use direction of flight of Λ_b to construct a “corrected mass”

- Resolution dominated by secondary vertex resolution

Nature Physics, 2015, NPHYS3415

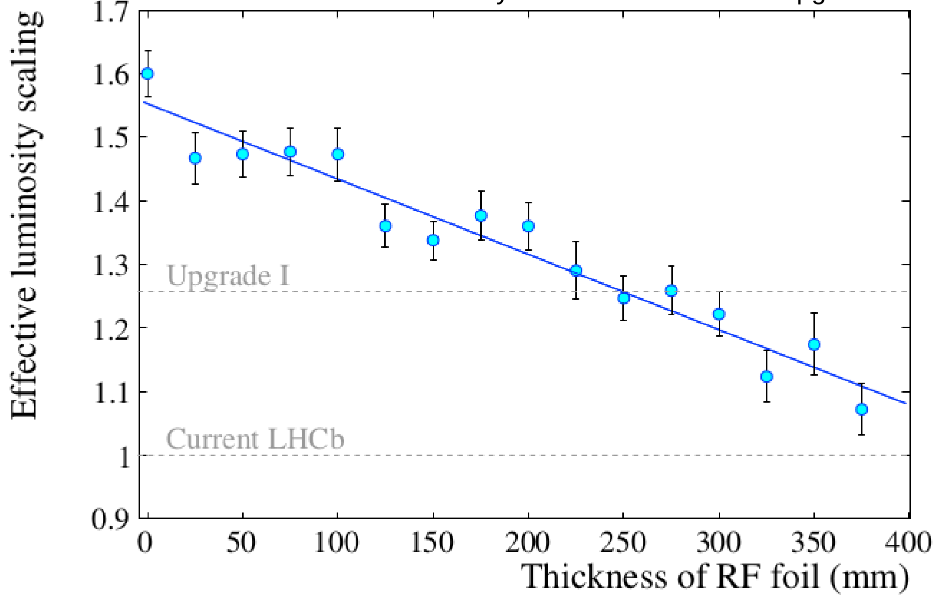


Unitarity triangle

For ultimate precision will need to go to $B^0_s \rightarrow K^- \mu^+ \nu$ to get heavier spectator and thus improve Lattice QCD

Combined drive of more data, detector improvements and lattice QCD improvements will give resolution in $|V_{ub}|/|V_{cb}|$ of 1%

Physics case for an LHCb Upgrade II



Anomalies persist: When is enough enough?

If NP is there, we need to understand its properties

- $B^0 \to \rho^0\mu^+\mu^-$ angular analysis compared to $B^0 \to K^{*0}\mu^+\mu^-$
  - Can help us understand if NP observes minimal flavour violation
- Search for $B^+ \to K^+e^+\mu^-$, $B^+ \to K^+\tau^+\mu^-$
  - Is NP flavour diagonal in lepton sector?
- Measure dilepton “R” in $b \to d$ transitions, $B \to \pi/\rho/p\bar{p}\ l^+l^-$
  - Does lepton non-universality depend on quark sector?

None of these measurements are systematic limited at 300 fb^{-1}

Anomalies gone: When is enough enough?

The reach in terms of mass and couplings in EFT scales as

$$\#\ \text{events} = \left(\frac{\lambda^2}{M^2}\right)^2 \quad \Rightarrow \quad M \propto \sqrt[4]{\#\ \text{events}}$$

That is a factor 2.5 between now and end of HL-LHC

- More than the factor 2 jump from HL-LHC to hypothetical HE-LHC for direct searches!

As 300 fb^{-1} does not hit systematic limit for many analyses this is for sure worth while

- An x100 increase in #events will increase energy reach by x3

Performance summary

Table 10.1: Summary of prospects for future measurements of selected flavour observables. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. Unless indicated otherwise the Belle-II sensitivities are taken from Ref. [568].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [186]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%	21% [573]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [244]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c l^- \bar{\nu}_l$ **LUV studies**					
$R(D^*)$	9% [199, 202]	3%	2%	1%	–
$R(J/\psi)$	25% [202]	8%	–	2%	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [574]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [222]	4.3×10^{-5}	3.5×10^{-5}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [210]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Conclusion

If NP is there for discovery in Flavour Physics, there is a rich programme ahead of us to understand it!

Flavour physics will be a competitive NP search tool for at least another generation

Both COMET and LHCb have very promising upgrade paths with possibilities for Australia