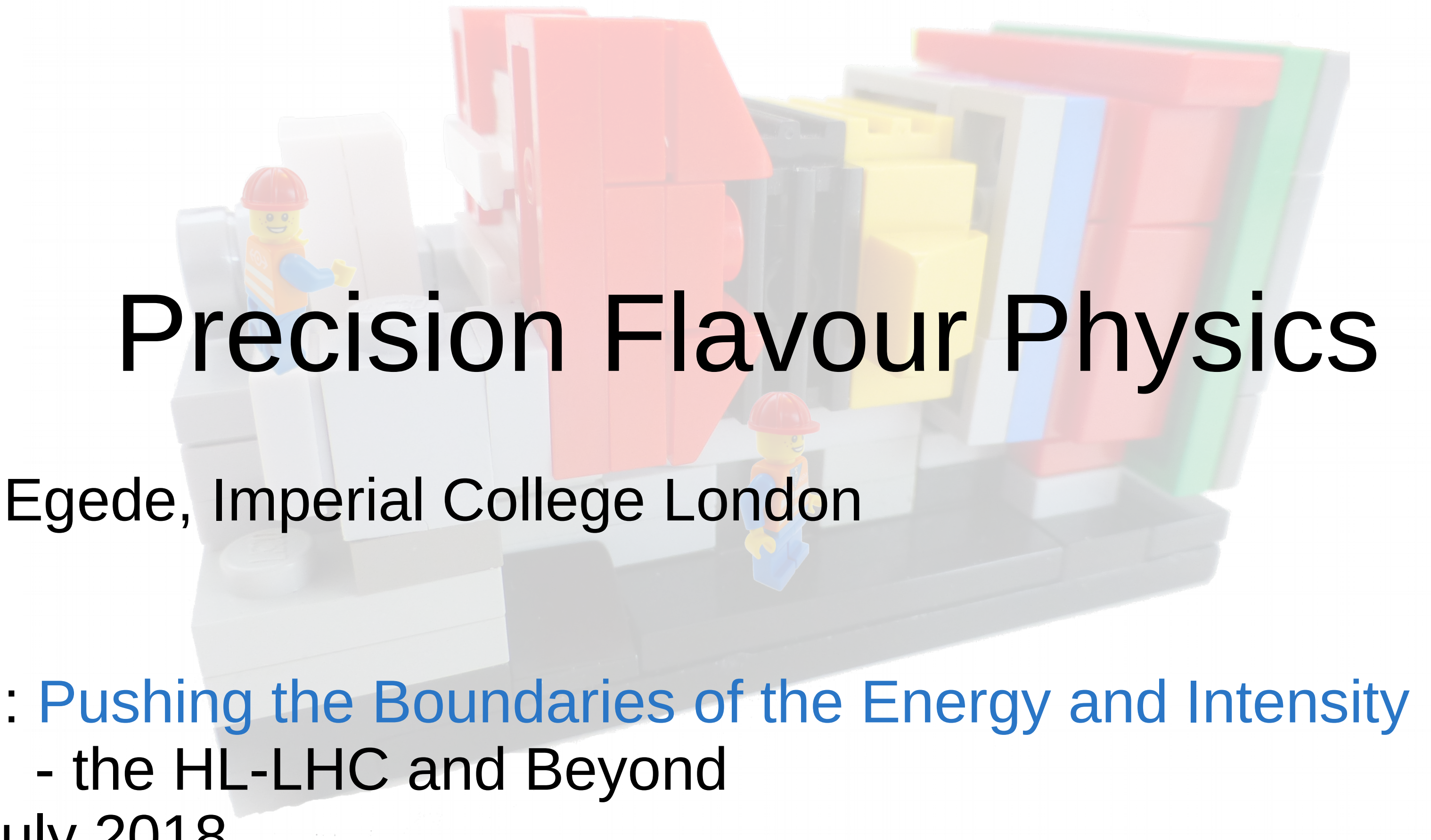


Precision Flavour Physics

Ulrik Egede, Imperial College London

IPPP: Pushing the Boundaries of the Energy and Intensity Frontiers
- the HL-LHC and Beyond

2-4 July 2018

@UlrikEgede

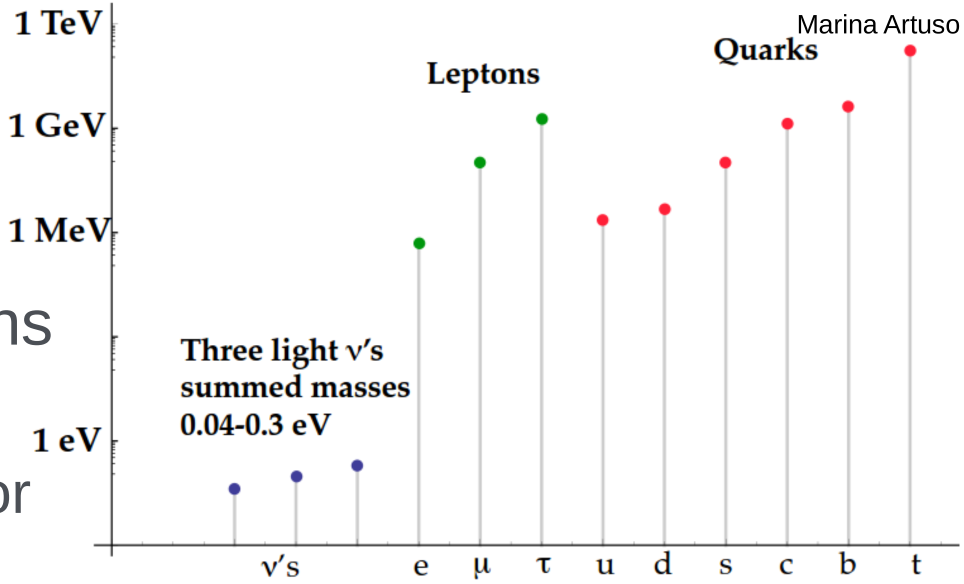
Why flavour physics?

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

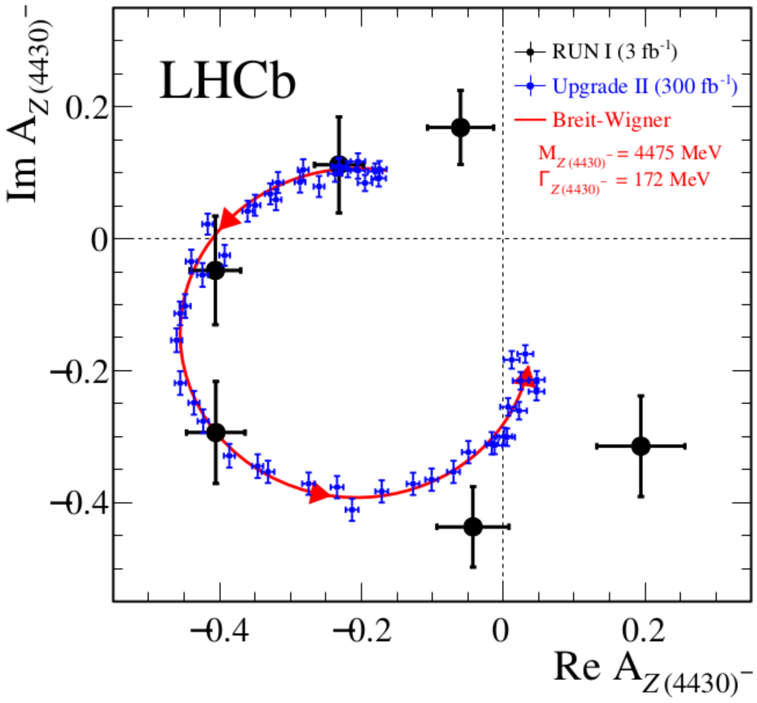
- What are the theoretical uncertainties and can they be reduced?
  - Push us to decays with leptons and search for CP violation
- Can we learn something from the measurement?
  - Need to have sensitivity to a high energy scale. Need to differentiate.
- What level of statistical accuracy is expected?
  - 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

- Majority of heavy flavour decays are hadronic
  - Predictions of branching fractions and phase space distribution of final state particles get huge QCD related uncertainties

As a side story there is a rich spectroscopy programme



Theoretical uncertainties

Solutions to “hadronic problem”

- 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

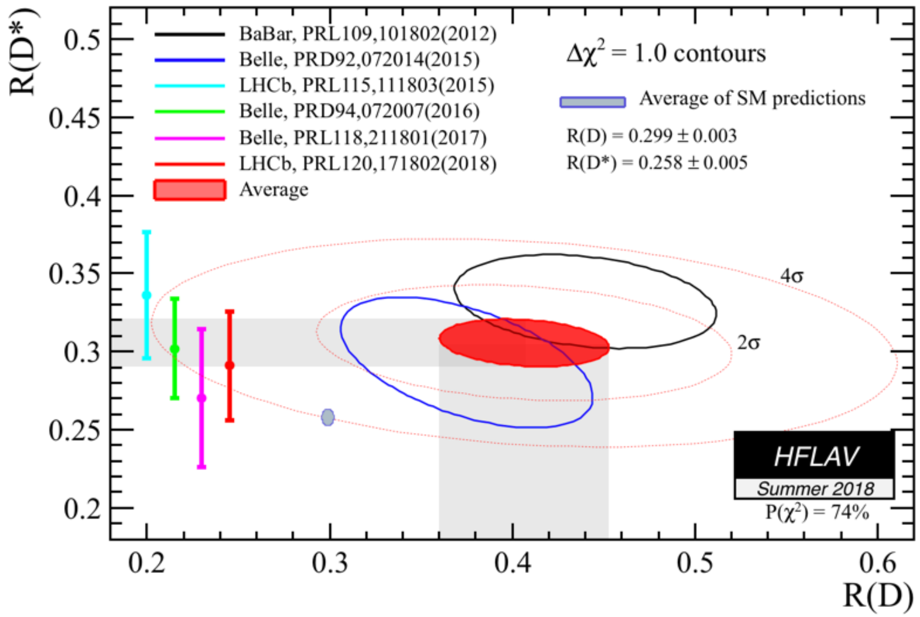
Theoretical uncertainties

Make (part of the) final state insensitive to QCD

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

Angular analysis of $B^0 \to D^{*+}\tau^-\nu$ the next step for semileptonic analysis

- Will require huge data samples due to poor S/N for τ channel

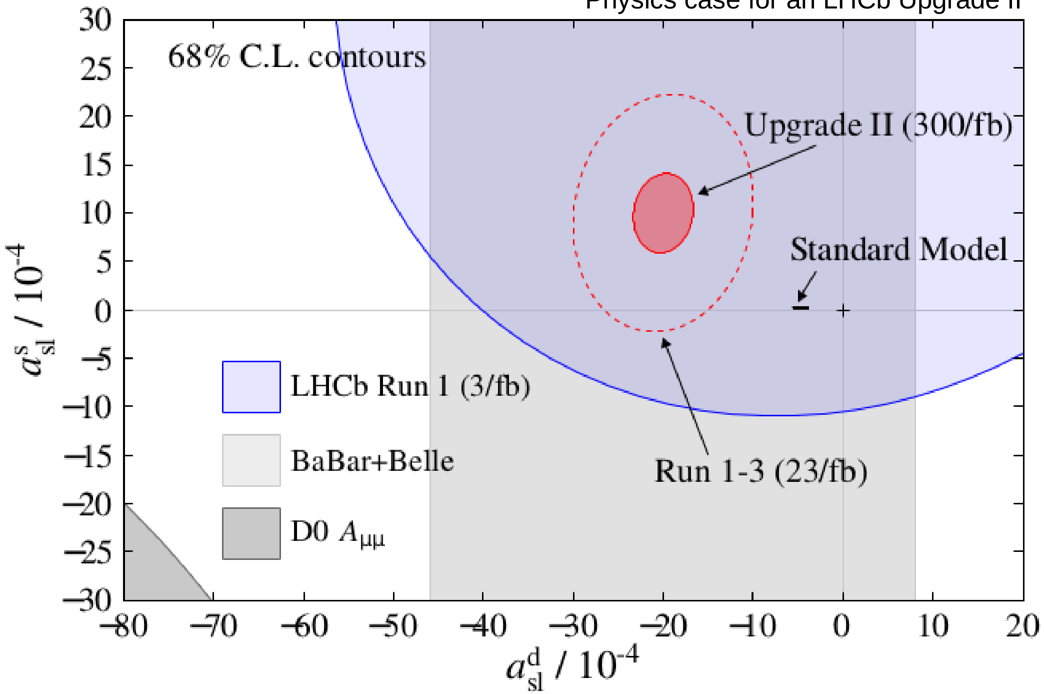


Theoretical uncertainties

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?

Concentrating on the BSM physics, the quest is to be able to reach for high mass scales

Look at features that are forbidden or heavily suppressed in SM

- Rare decays like $B^0_{(s)} \to \mu^+\mu^-$
- CP violation where there is little or none in SM
  - $B^0_s \to J/\psi\ \varphi$, Charm decays, B mixing

Closure tests

- Unitarity of CKM matrix

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?

Statistical accuracy

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

A proposed LHCb upgrade phase-II will take data after 2030

- ~ factor 200

Statistical accuracy

The upgrades of CMS and ATLAS will take place after Run 3 (2025)

- Primary design consideration is not flavour physics
- With ~200 pp collisions per bunch crossing, flavour physics will be constrained in signatures or limited to special runs
- Trigger would have to be a dedicated trigger like what CMS is doing this year

From detector technology point of view, both detectors capable of flavour physics

Experimental systematic uncertainty

The hardest of all limitations to predict

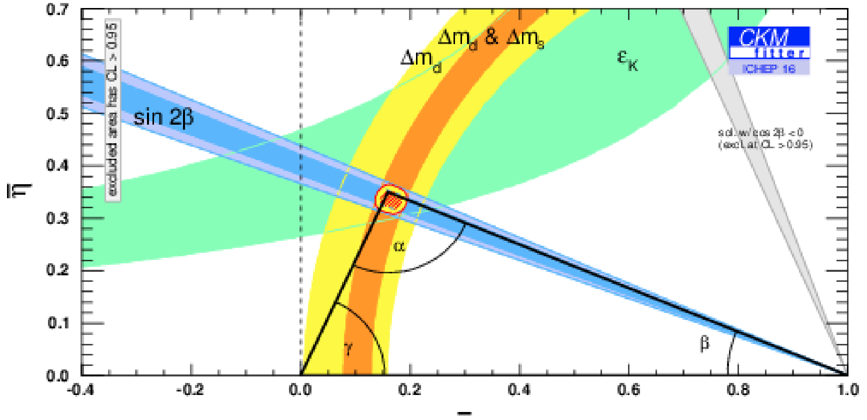
- Angular acceptance in $B^0 \to K^{*0}\mu^+\mu^-$
  - Use of $B^0 \to J/\psi\, K^{*0}$ as control channel and more efficient simulation
- Understand penguin pollution in CP violation measurements
  - There is a need to understand exactly what we measure CPV of
- Relative efficiency of different lepton species
  - For e/μ this will turn easier with higher resolution calorimeter
  - For τ/μ the improved vertex detector will aid differentiation and modelling

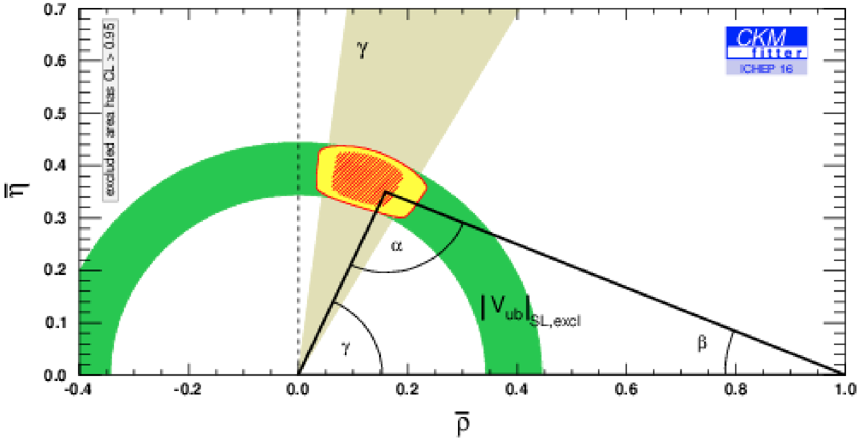
Unitarity triangle

We have very detailed knowledge of constraints on unitarity triangle

- Still allows for NP amplitudes at the 20% level on SM
- Perfectly compatible with NP at the TeV level

Measurements of CP angle γ are statistical limited even in long term future

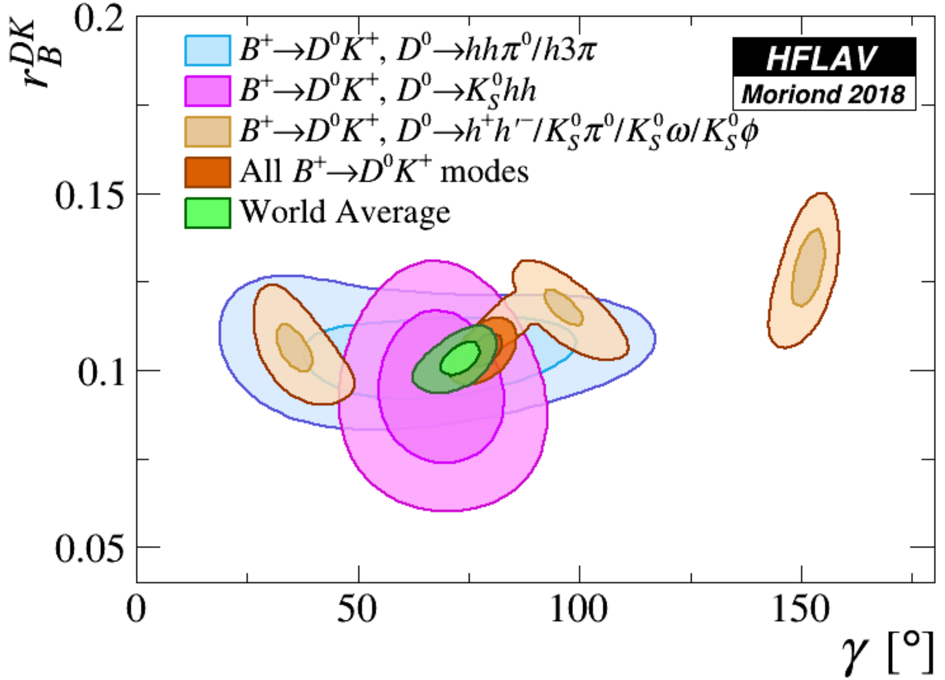




Other searches for New Physics

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

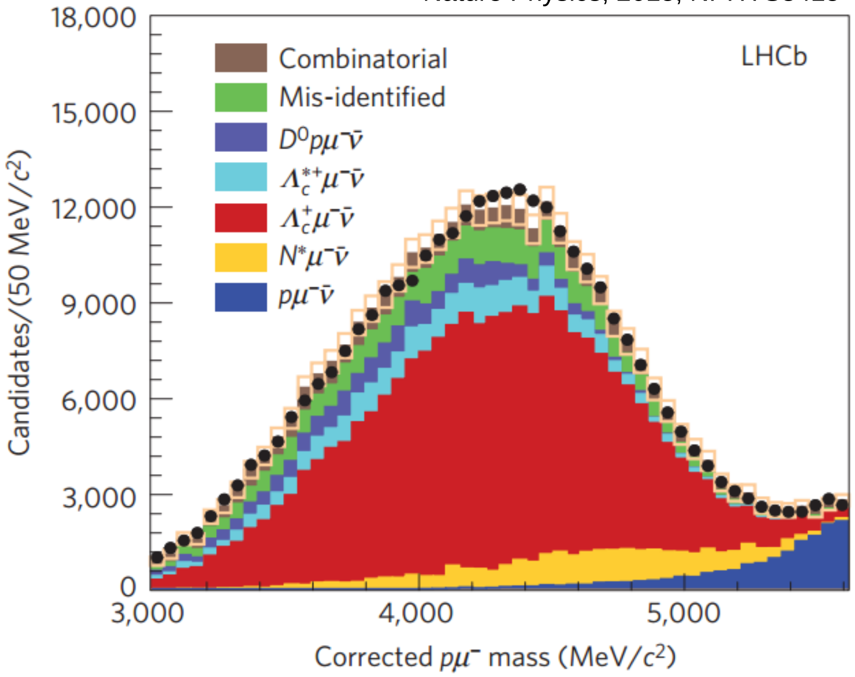
LHCb has proven with the $\Lambda_b \rightarrow p\mu\nu$ that precision measurements can be made of $|V_{ub}|/|V_{cb}|$

With semileptonic decays there is no signal peak as such

Use direction of flight of Λ_b to construc a "corrected mass"

- Resolution dominated by secondary vertex resolution

Nature Physics, 2015, NPHYS3415

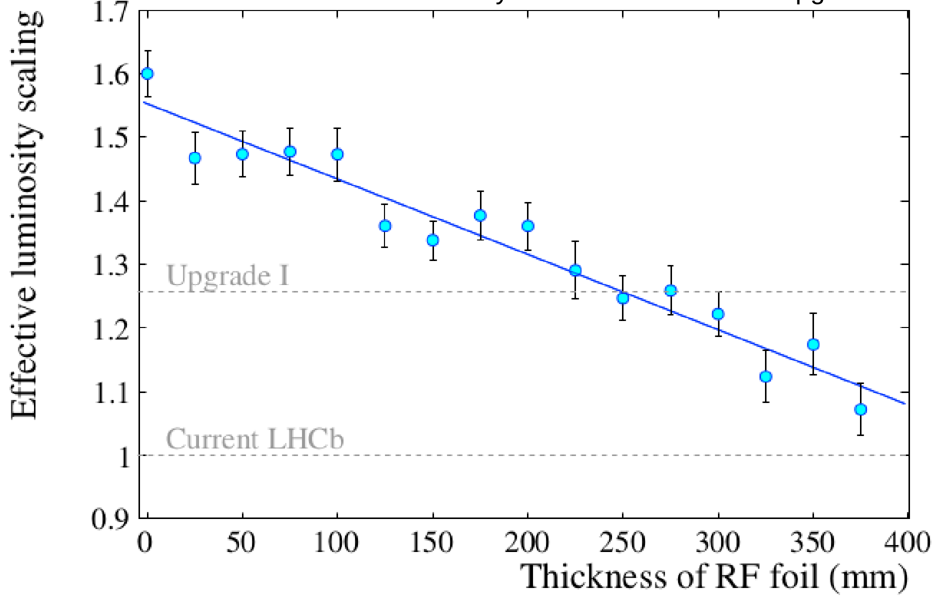


Unitarity triangle

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%

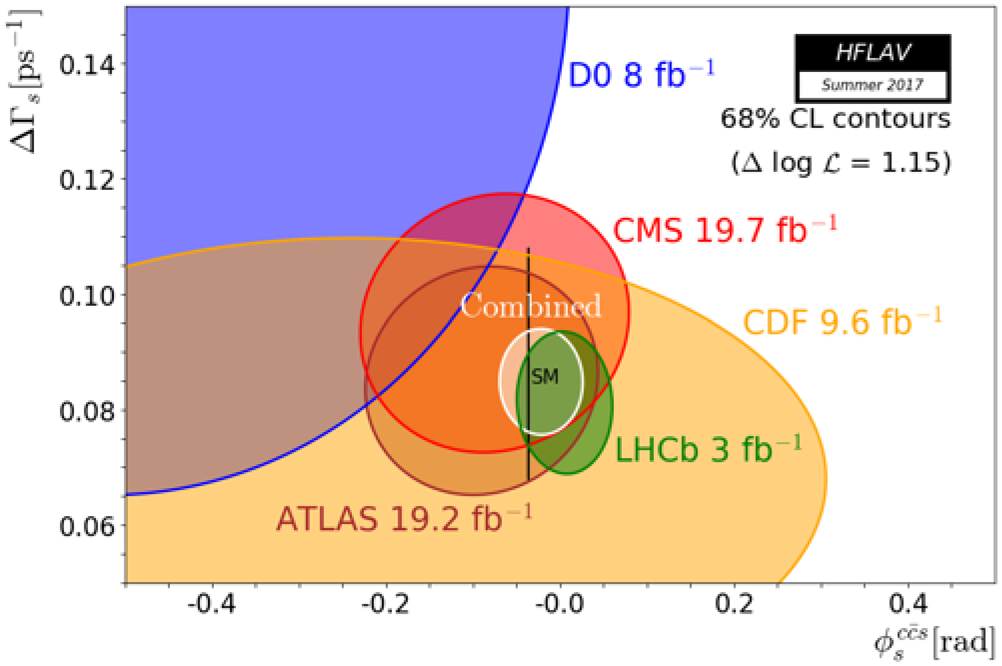
Physics case for an LHCb Upgrade II



Measurement of φ_s

CP violation in interference between mixing and decay in B^0_s system is small and with tiny uncertainty in SM

Clean signature of $B^0_s \rightarrow J/\psi\ \varphi$ decay means that ATLAS and CMS has input here as well

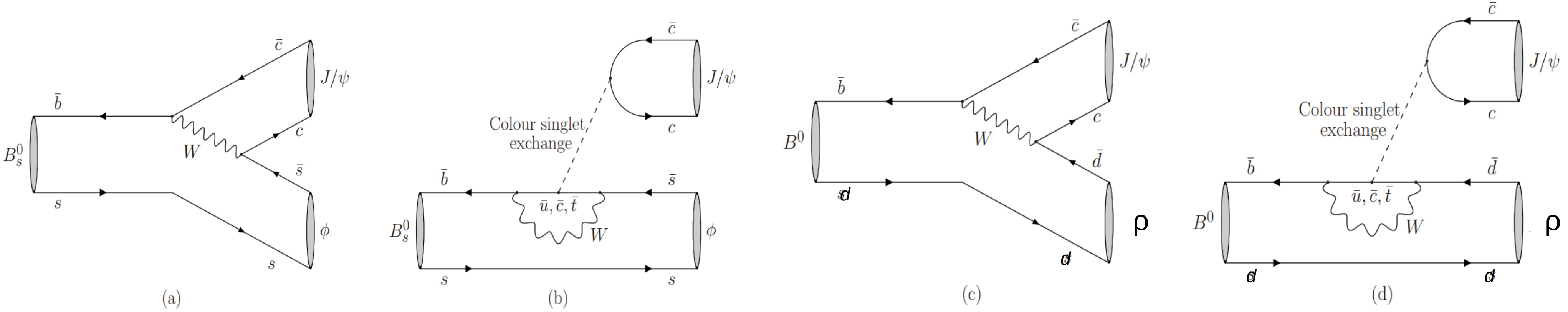


Measurement of φ_s

"Penguin pollution" arises from gluonic and EW penguin amplitudes

- Measure these using SU(3) flavour symmetry in $B^0 \to J/\psi\ \rho$

$$\Delta\phi_s^{c\bar{c}s} \approx -\epsilon \left({\phi_d}^{J/\psi\,\rho^0} - 2\beta \right)$$



Carlos Vazquez Sierra, CERN-THESIS-2016-281

The up quark sector

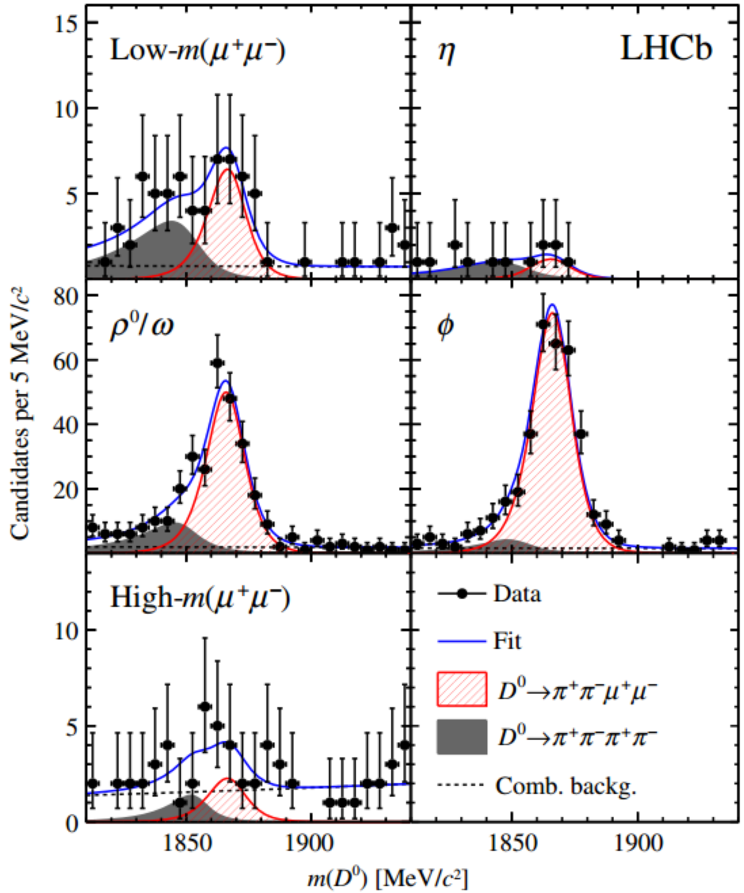
Phys. Rev. Lett. 119, 181805

Focus has been on the b quark so far as charm is viewed as theoretically too difficult

Discovery of $D^0 \to \pi^+\pi^-\mu^+\mu^-$

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$

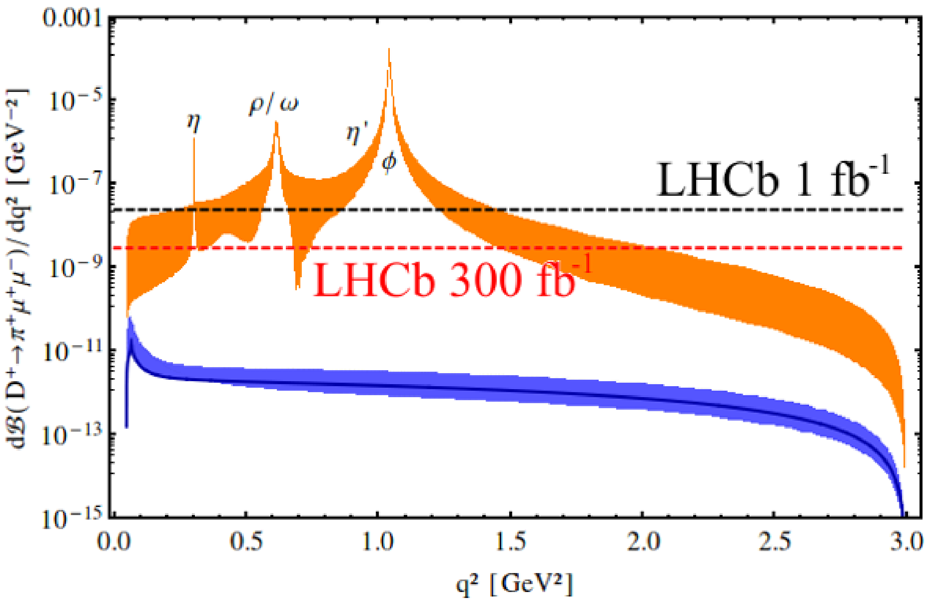
Dominated by long range effects so can not in itself be used to probe for NP



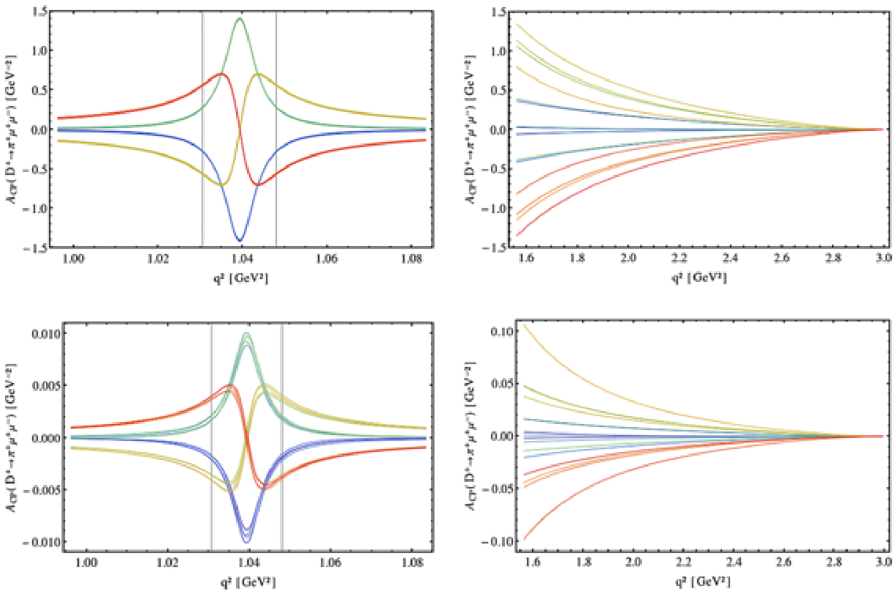
The up quark sector

First step towards looking for CP violation between short and long-range amplitudes

- Such a measurement has NP sensitivity



Physics case for an LHCb Upgrade II



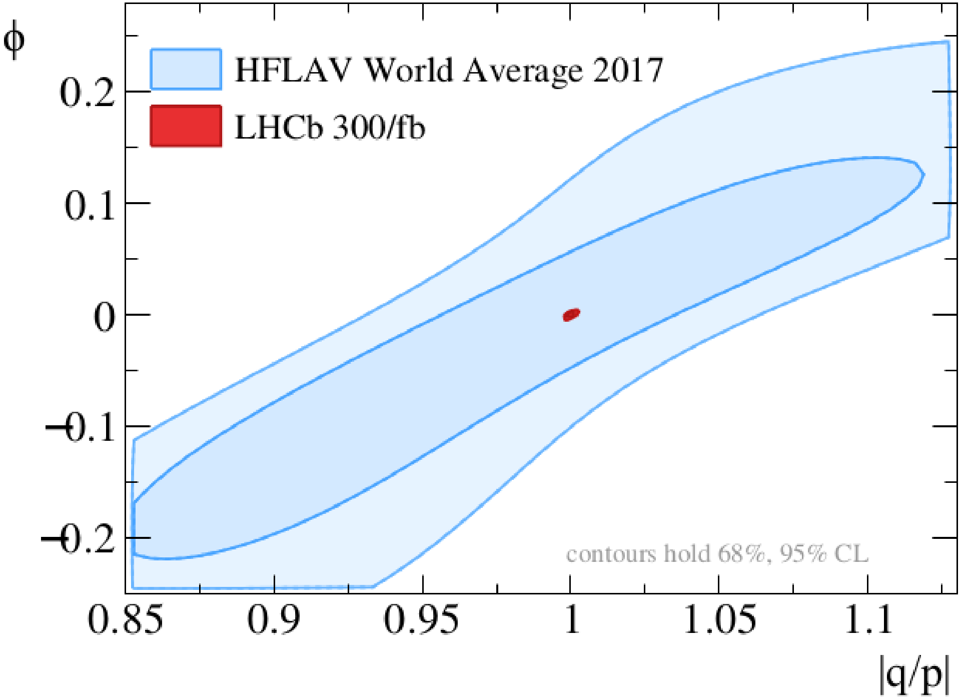
CPV in charm

Looking for CPV in charm is essentially a null test for NP

- Change in trigger for LHCb allows for higher trigger efficiency
- Tracking extended to low momentum allows for higher tracking efficiency

Gain demonstrated here for sensitivity to CPV in mixing

Physics case for an LHCb Upgrade II



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 sensitivies 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%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%	21% [573]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [244]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c l^- \bar{\nu}_l}$ **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}	–

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}

- Any new facility should include a flavour physics programme

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 HE-LHC for direct searches

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

Any new facility should include a flavour physics programme

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

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