Proving BSM physics with LHCb

Higgs and BSM physics in light of the LHC

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LHCb

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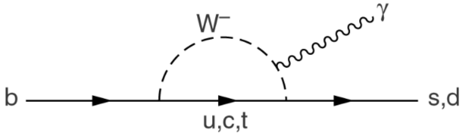
Indirect new physics

- Today present indirect searches for NP.
- These searches have been hugely successful in the past:
  - CPV in kaon system predicts $>=$ 3 quark families, $\sim$ 13 years before upsilon discovered.
  - Weak neutral current discovered by Gargamelle $\sim$ 10 years before Z at UA1/2.
  - Large B mixing rate at Argus suggests heavy top quark $\sim$ 8 years before direct discovery at TeVatron.

New physics at the LHC

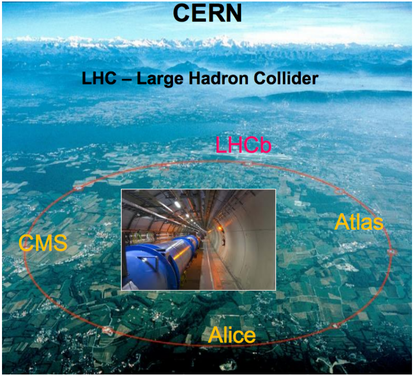
- If NP is round the corner, then wheres the hints from flavour physics?
- NP is either weakly coupled to flavour sector (MFV) or at a very high scale.
  - Important to probe energies beyond LHC.
- Do this by measuring processes suppressed or forbidden in the SM.



- Flavour-Changing-Neutral-Currents (FCNC), LFV decays etc ..

LHCb

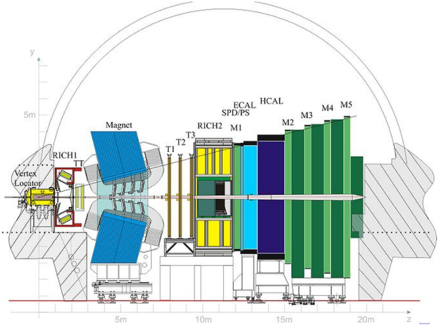
- LHCb is a single arm spectrometer designed for heavy flavour physics covering the pseudo-rapidity range 2-5.
- We collected $1\,\mathrm{fb}^{-1}$ of *pp* collision data in 2011 @ 7 TeV and $2\,\mathrm{fb}^{-1}$ in 2012 @ 8 TeV.



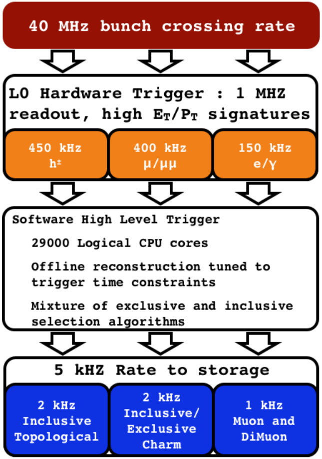
- We ran at $\sim$200% design luminosity during 2012.

LHCb

- Huge heavy flavour cross-section at LHC energies puts strain on detector.
- **IP resolution** : identify tracks from displaced vertex.
- **Decay time resolution** : crucial for B_s^0 mixing studies.
- **Momentum resolution** : narrow signal region $\rightarrow$ reduce background contamination.
- **Particle identification** : separating kaons and pions essential.



LHCb trigger



- $\sim 5(100) \times 10^{10}$ B (D) mesons decay inside our acceptance per fb^{-1}.
- Reduce 40MHz to 5KHz (2.5$\times$ nominal) via a three stage trigger.
- Saturated by signal, use multivariate techniques already to squeeze every last drop of physics out.

Physics menu

- LHCb has a huge BSM physics program, ranging from Majorana neutrino searches to precision charm measurements.
- Today, concentrate on:
  - Rare FCNC/LFV decays, e.g: $B_s^0 \to \mu^+\mu^-$,
  - CPV in B_s^0 mixing, e.g: $B_s^0 \to J/\psi\,\phi$
  - CKM angle γ, e.g: $B \to DK$
  - CPV in charm, e.g: $\Delta(\mathcal{A}^{\mathrm{CP}})(D^0 \to hh)$

Rare decays

Wilson Coefficients

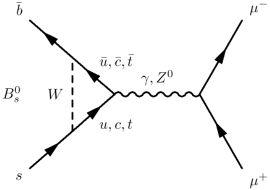
- Rare decays phenomenology based on effective field theory.
- Write effective Hamiltonian as

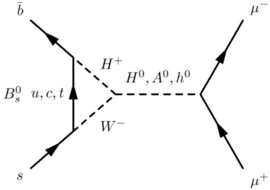
$$H_{\text{eff}} \propto \sum_i (\mathcal{C}_i \mathcal{O}_i + \mathcal{C}_i^{'} \mathcal{O}_i^{'}) + h.c.$$

- Where the Wilson coefficients, $\mathcal{C}_i$ encapsulate short distance physics above some energy scale, μ.
- Form a complete basis, can put all the NP/SM physics operators in here.
- Allows a model independent interpretation.
- If NP found at by direct searches, can study gauge structure using rare decays.

$B_s^0 \to \mu^+\mu^-$

- The decay $B_s^0 \to \mu^+\mu^-$ a helicity suppressed FCNC, making it an incredibly rare decay.
- Large enhancement possible in NP scenarios, especially to extended Higgs sector.





SM prediction: [JHEP 1010:009,2010] + [Phys. Rev. D 86, 014027 (2012)]

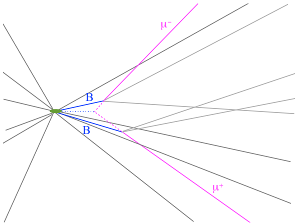
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{<t ave>}} = 3.5 \pm 0.3 \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 1.0 \pm 0.1 \times 10^{-10}$$

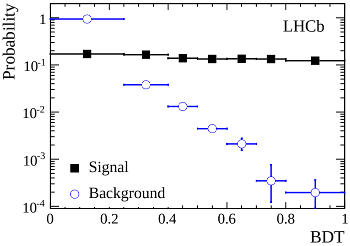
$B^0 \to \mu^+\mu^-$ suppressed by $|V_{td}/V_{ts}|^2$ in SM $\to$ test non-MFV.

$B_s^0 \to \mu^+\mu^-$

Background dominated by real muons from different b decays.

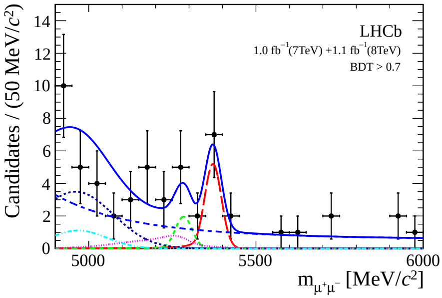


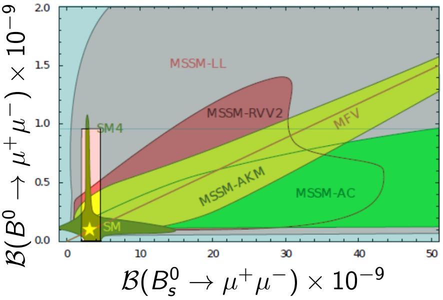
Reduce using a Boosted Decision Tree, using kinematic and geometric information.



$B_s^0 \to \mu^+\mu^-$

Find first evidence for $B_s^0 \to \mu^+\mu^-$, at 3.5 σ significance.





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10} \text{ @ } 95\% \text{ CL}$$

Another $1\,\text{fb}^{-1}$ of data in hand ready to analyse.

$D^0 \to \mu^+\mu^-$

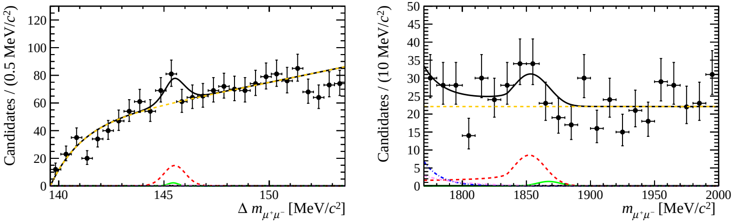
- FCNC with up type quarks complementary to beauty and strange sector.
- The decay $D^0 \to \mu^+\mu^-$ is even rarer than $B_s^0 \to \mu^+\mu^-$ (GIM mechanism more exact).
- SM limit from $D^0 \to \gamma\gamma$ [arXiv:1110.6480].

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6 \times 10^{-11} @\ 90\ \mathrm{CL}$$

- Previous best limit set by BELLE, 1.4×10^{-7} at 90% CL.

$D^0 \to \mu^+\mu^-$

- Main challenge is dealing with backgrounds via $h \to \mu$ mis-identification.



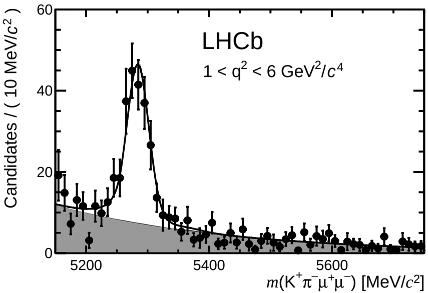
- LHCb limit a factor 20 better than previous measurements [arXiv:1305.5059].

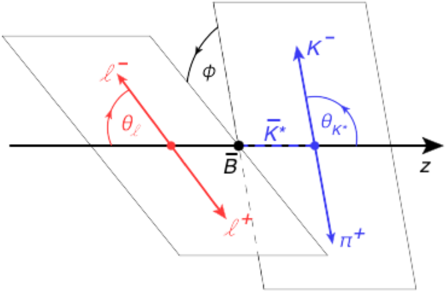
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9} \text{ @ } 90\% \text{ CL}$$

- Still plenty of room for NP to appear ($2\,\text{fb}^{-1}$ of data to add).

$B^0 \to K^{*0}\mu^+\mu^-$

- $B^0 \to K^{*0}\mu^+\mu^-$ is a $b \to s\ \mu^+\mu^-$ process at the level of $\sim 10^{-6}$
- Have $\sim$ 900 signal candidates across full q^2 range with $1\,\text{fb}^{-1}$ of data.

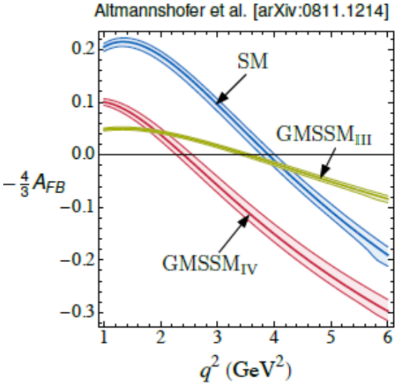


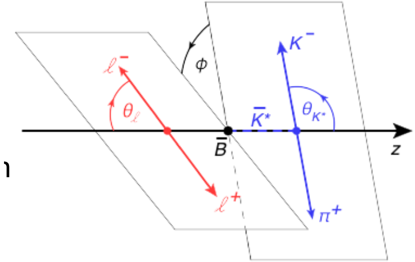


- It can be described by three angles θ_l, θ_k, ϕ and the invariant mass squared of the dimuon system, q^2.
- Angular observables theoretically cleaner than rates.

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular distribution

- Angular observables are sensitive to various NP models.



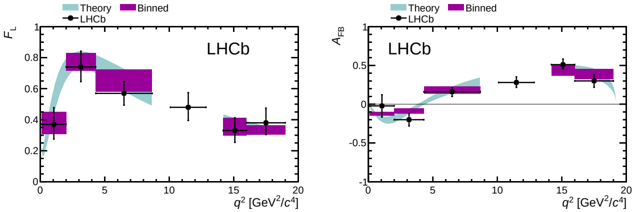


- Apply “folding“ trick with angular distribution to cancel some angular terms.

$$\phi \rightarrow \phi + \pi \text{ for } \phi > 0$$

$B^0 \to K^{*0}\mu^+\mu^-$ results

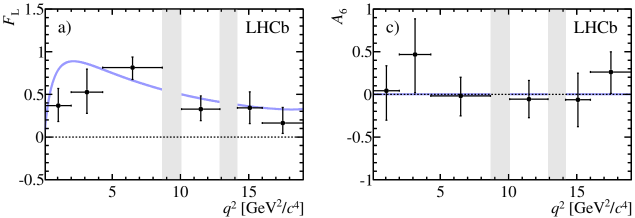
- Results for $\mathrm{F_L}$ and $\mathrm{A_{FB}}$ with $1\,\mathrm{fb}^{-1}$ of 2011 data [arXiv:1304:6325]:



- Measurements agree amazingly well with SM predictions (from [JHEP 1107:067,2011]).

$B_s^0 \to \phi\mu^+\mu^-$ results

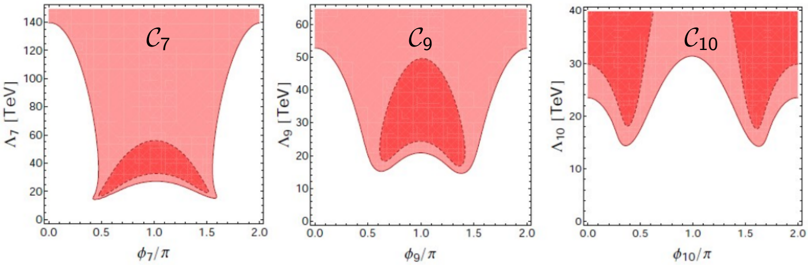
- Also can do similar analysis with B_s^0 mesons (1/4 statistics) [arXiv:1305.2168]
- Here not self tagging so cannot access full set of variables.



- Again, measurements agree well with SM predictions [arXiv:0811.1214].

Constraints on new physics

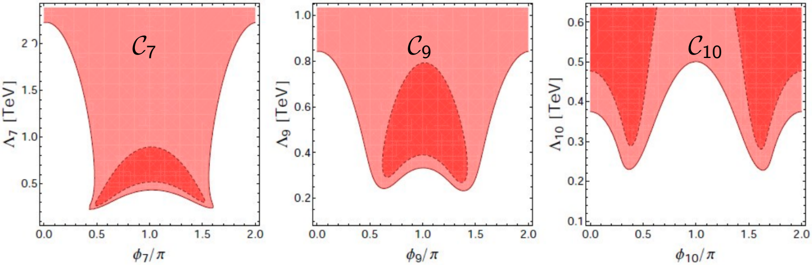
- BSM physics with $\mathcal{O}(1)$ flavour couplings must be $>\sim 15\,TeV$.



Constraints based on [JHEP 1208:121, 2012].

Constraints on new physics

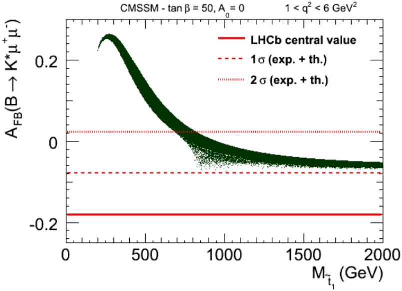
- If one inserts SM like flavour couplings, limit reduces to ∼300MeV - 2TeV.



- Limits with MFV lower, but still competitive with direct searches.

Constraints on CMSSM

- Can try scanning across a particular SUSY model (CMSSM), to see comparison with direct searches.



- Complimentary constraints compared with direct searches.
- See [arXiv:1205.1845] for more detail on model.

Isospin asymmetry in $B \to K^{(*)}\mu^+\mu^-$ decays

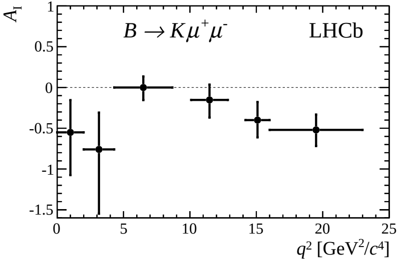
The isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$, A_I, is defined as:

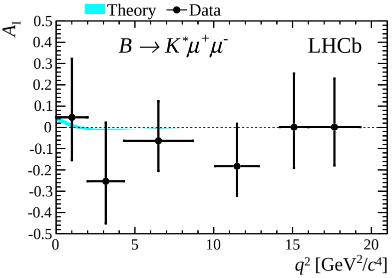
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

- A_I expected to be $\mathcal{O}(1\%)$ in the SM [JHEP 0301:074,2003],[JHEP 1302:010,2013].
- In 2009, BABAR measured a surprising $3.9\,\sigma$ deviation from zero at low q^2 [Phys. Rev. Lett. 102, 091803] .
- Now significance down to $\sim 2\ \sigma$ and only in the $B \to K\mu^+\mu^-$ mode.

Isospin asymmetry results

- A_I for $B \to K\mu^+\mu^-$ is over 4σ away from the SM prediction.
- For $B^0 \to K^{*0}\mu^+\mu^-$, things are consistent with zero.

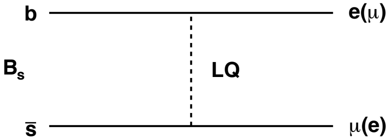




[arXiv:1205.3422]

$B_s^0 \to e^+ \mu^-$

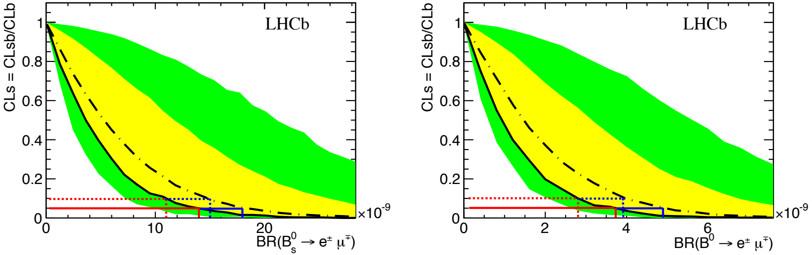
- Lepton flavour violating decays occur at $\sim< 10^{-50}$ in the SM.
- The decay $B_s^0 \to e^+ \mu^-$ is allowed in models with a local gauge symmetry with leptons and quarks.



- So-called lepto-quarks have been directly searched for at the LHC, with limits of around 0.5-1 TeV/c^2 (no mixing assumed).

$B_s^0 \to e^+ \mu^-$

- Search for $B_s^0 \to e^+ \mu^-$ at LHCb using 2011 dataset. [LHCb-PAPER-2013-030]



Solid black line: observed, dashed black line: expected

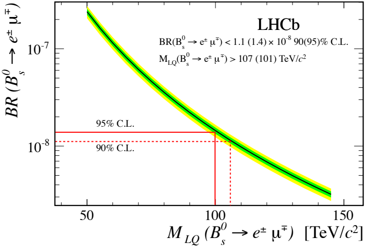
- No significant signal observed, set limits,

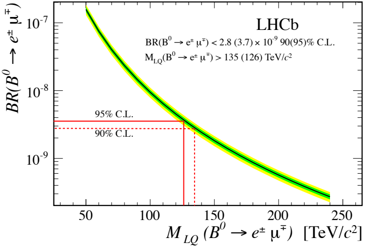
$$\mathcal{B}(B_s^0 \to e^+\mu^-) < 1.4 \times 10^{-8} \text{ @ } 95\% \text{ CL}$$

$$\mathcal{B}(B^0 \to e^+\mu^-) < 3.7 \times 10^{-9} \text{ @ } 95\% \text{ CL}$$

$B_s^0 \to e^+ \mu^-$

- Convert branching fraction limits into lepto-quark masses using formula from [arXiv:hep-ph/9409201].





- No significant signal observed , set limits,

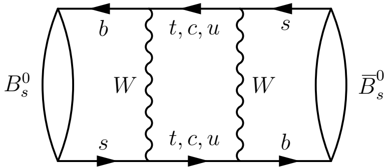
$$m_{LQ}(B_s^0 \to e^+\mu^-) > 101\,TeV/c^2 \text{ @ 95\% CL}$$
$$m_{LQ}(B^0 \to e^+\mu^-) > 135\,TeV/c^2 \text{ @ 95\% CL}$$

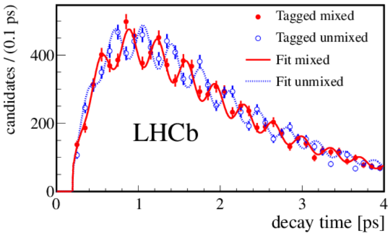
[LHCb-PAPER-2013-030]

CPV in B_s^0 mixing

CPV in B_s^0 mixing

- B_s^0 oscillations studied at high precision at LHCb [arXiv:1304.4741].

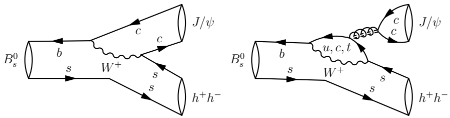




- BSM physics can enter into the mixing amplitude, accessible via interference.

CP mixing angle ϕ_s

- Find decay common to both B_s^0 and $\bar{B}_s^0$ decays: e.g. $B_s^0 \to J/\psi\,\phi$.



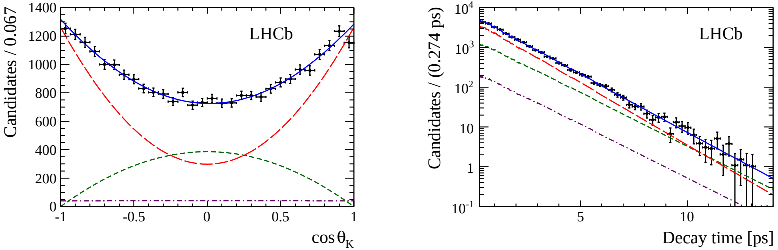
- Weak phase difference between B_s^0 mixing and B_s^0 decay, ϕ_s, is predicted to be very small in the SM.

$\phi_s = -2\mathrm{arg}(\mathrm{V_{ts}V^*_{tb}/V_cV^*_{cb}}) = 0.036 \pm 0.002\mathrm{rad}$, [arXiv : 1106.4041].

$B_s^0 \to J/\psi\,\psi$ analysis

- PS $\to$ VV decay, separate CP-odd (red), CP-even (green) and S-wave (purple) final states with angular analysis.

[arXiv:1304.2600]

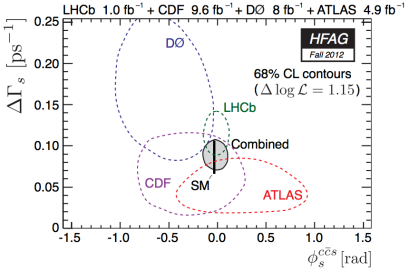


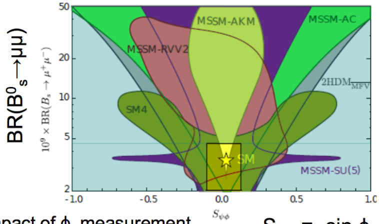
- Simultaneously fit angular distribution, lifetime and flavour to determine ϕ_s.

ϕ_s results

- Determine 68% contour with ψ_s and difference in lifetimes of B_s^0 eigenstates:

based on [arXiv:1107.0266]





Impact of ϕ_s measurement (together with BR($B^0_s \to \mu\mu$))

$S_{\psi\varphi} = -\sin \phi_s$

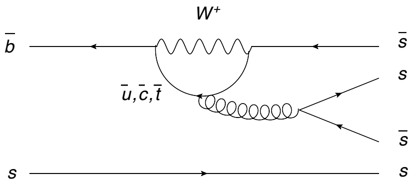
Combined results with $B_s^0 \to J/\psi \pi^+\pi^-$ [arXiv:1304.2600]:

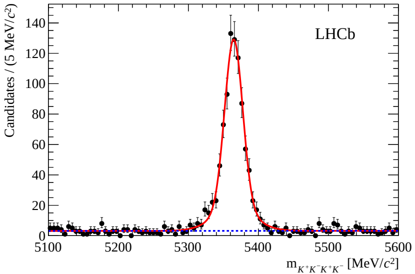
$$\phi_s = 0.01 \pm 0.07 \pm 0.01 \text{ rad}$$

- So far results show good agreement with SM prediction.

$B_s^0 \to \phi\phi$

- Can also do the same analysis with a penguin decay, $B_s^0 \to \phi\phi$.



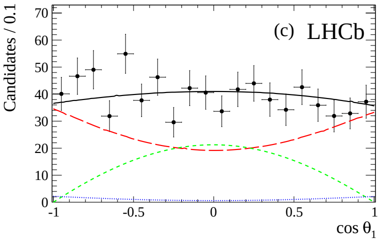


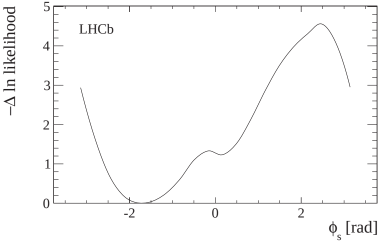
[arXiv:1303.7125]

- Less stats than $B_s^0 \to J/\psi\,\phi$, but suppressed decay offers additional sensitivity.

$B_s^0 \to \phi\phi$

- ϕ_s not the same as $B_s^0 \to J/\psi\,\phi$ as its different decay.





[arXiv:1303.7125]

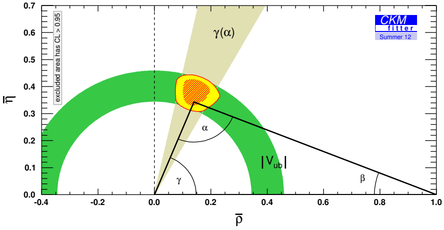
- Use Feldman-Cousins technique to determine 68% CL region: [-2.46, 0.76] rad.
- p-value with SM is 16%.

CKM angle γ

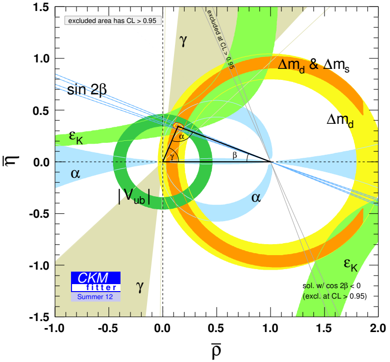
The CKM angle, γ

- CKM picture consistent so far

Trees



Trees + loops



- New measurements on γ could poke holes in this picture.

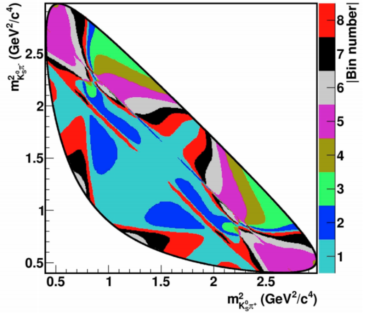
γ via $B \to DK$ decays

- Use interference between $b \to u\bar{c}s$ and $b \to c\bar{u}s$ decays.

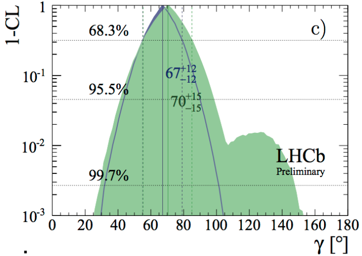
  - B⁻ can decay into both D^0 and $\overline{D^0}$, diagrams very different amplitudes

  - Decays of D^0, $\overline{D^0}$ to same final state gives access to interference

- Many analyses, latest update uses $B^+ \to (D^0 \to K^0_S hh)K^+$ decays with $3\,\mathrm{fb}^{-1}$. [LHCb-CONF-2013-004].
- Model independent analysis, with strong phase variation across phase-space taken from CLEO data.
- Analysis yields $\gamma = (57 \pm 16)^o$ (already competitive).



Gamma combination



- Tightest combination uses $B^+ \to D^0 K^+$ modes with $B^+ \to (D^0 \to K^0_S hh) K^+$ update [LHCb-CONF-2013-006].
- LHCb measurement already most precise:
  - LHCb: $(67 \pm 12)^o$
  - BELLE: $(69^{+17}_{-16})^o$ [arXiv:1301.2033]
  - BaBar: $(68^{+15}_{-14})^o$ [arXiv:1301.1029]
- So far consistent with indirect measurements ($(67 \pm 5)^o$), but still plenty of room left for NP to appear.
- More measurements to be added/updated $\to$ expect a much improved measurement soon.

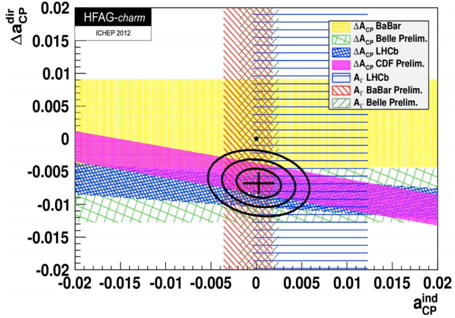
CPV in charm

CPV in charm

- Direct CPV in charm expected to be $\mathcal{O}(10^{-4})$ -$\mathcal{O}(10^{-3})$.
- With $0.6\,\mathrm{fb}^{-1}$ of data, LHCb found 3.5σ evidence for direct CPV by measuring

$$\Delta(\mathcal{A}^{\mathrm{CP}}) = \mathcal{A}^{\mathrm{CP}}(D^0 \to K^+K^-) - \mathcal{A}^{\mathrm{CP}}(D^0 \to \pi^+\pi^-)$$

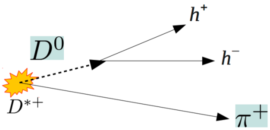
$$= [-0.82 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})]\%$$



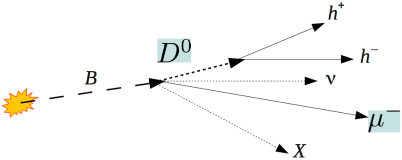
- Led to discussion whether $\mathcal{O}(\%)$ CPV could be SM or NP.

$\Delta(\mathcal{A}^{\mathrm{CP}})$ update

- Two independent analyses, using $1\,\mathrm{fb}^{-1}$ of data.



[LHCb-CONF-2013-003]



[arXiv:1303.2614]

- Prompt mode tagged with slow pion, semi-leptonic mode tagged with muon.
- Orthogonal systematics → complementary measurements.

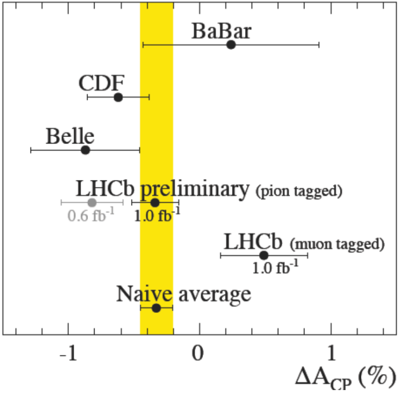
$\Delta(\mathcal{A}^{\mathrm{CP}})$ update with $1\,\mathrm{fb}^{-1}$

Results with 2011 data, [LHCb-CONF-2013-003], [arXiv:1303.2614]:

$$\Delta(\mathcal{A}^{\mathrm{CP}})_{\mathrm{prompt}} = [-0.34 \pm 0.15(stat) \pm 0.10(syst)]\%$$

$$\Delta(\mathcal{A}^{\mathrm{CP}})_{\mathrm{semilep}} = [0.49 \pm 0.30(stat) \pm 0.14(syst)]\%$$

- Previous evidence not confirmed with update.
- More precise/complementary measurements coming soon.



Outlook

- LHCb is probing BSM physics in various different ways
  - Rare decays.
  - CPV in B_s^0 mixing.
  - Direct measurement of γ.
  - High precision direct CP measurements.
- Most results are consistent with the SM.
  - The isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$ being an exception, but no model can accommodate it so far.
- Most of the results shown today use $1\,\text{fb}^{-1}$, another $2\,\text{fb}^{-1}$ in hand.