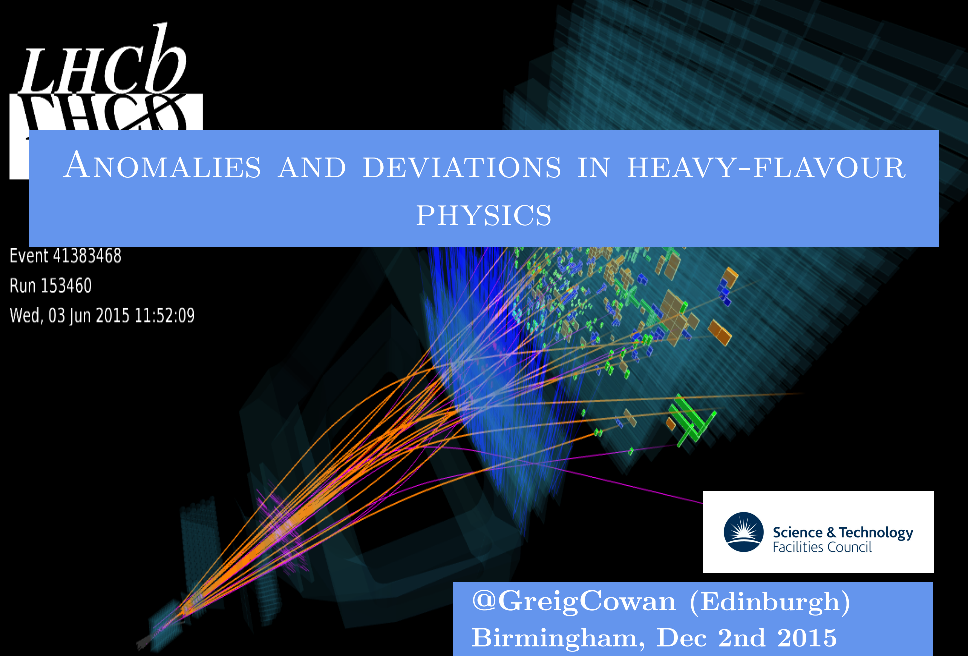
Anomalies and deviations in heavy-flavour physics

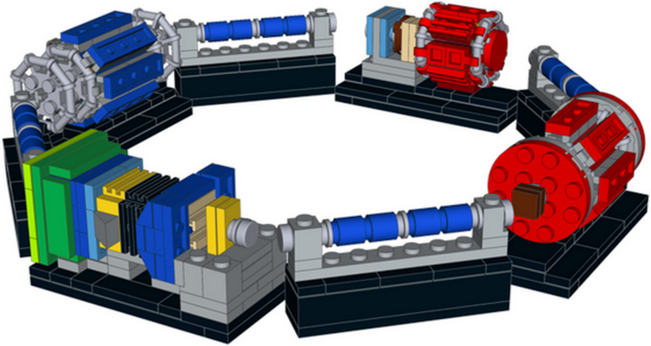


@GreigCowan (Edinburgh)
Birmingham, Dec 2nd 2015

- Introduction to the LHCb experiment

- $b \to sl^+l^-$ FCNC decays
- Lepton (non-)universality
- CP violation in the beauty + charm systems

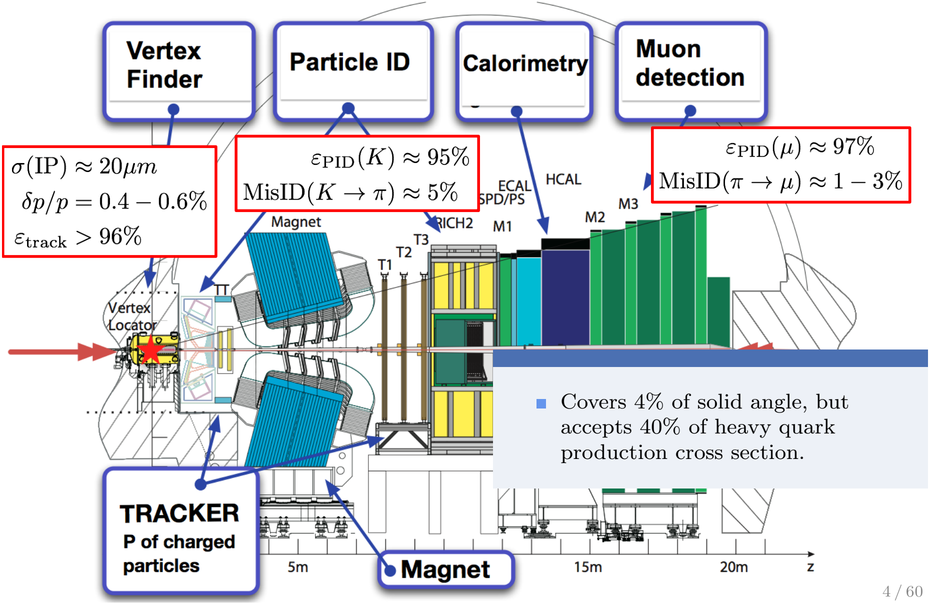
The LHC



https://ideas.lego.com/projects/94885

The LHCb detector

2008 JINST 3 S08005



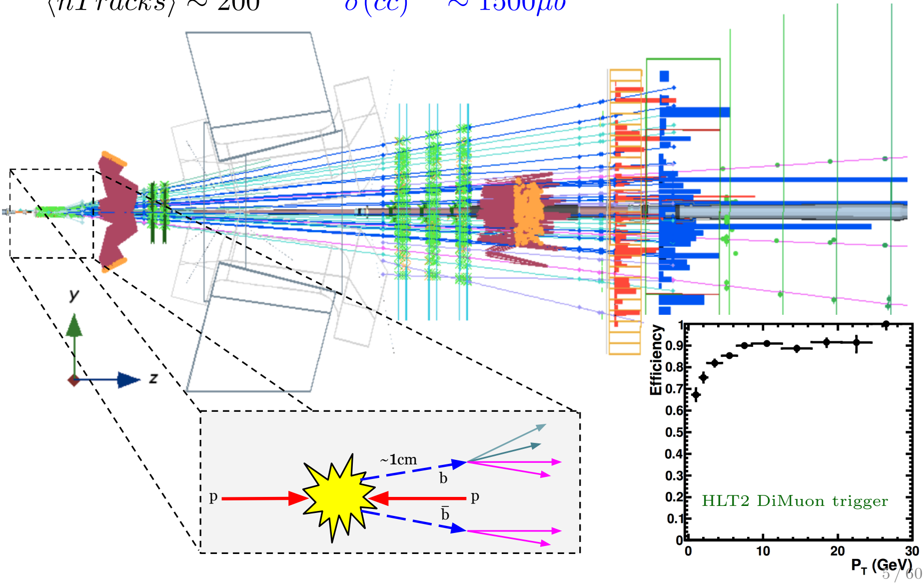
- Covers 4% of solid angle, but accepts 40% of heavy quark production cross section.

A typical LHCb event

[2008 JINST 3 S08005]

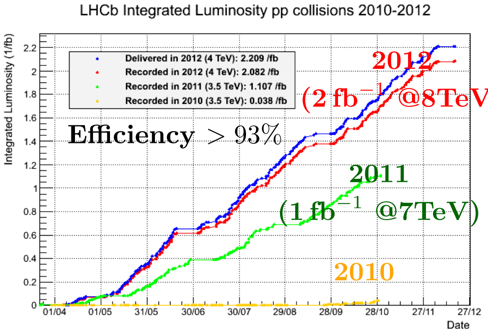
$\langle nPVs \rangle \sim 2.0$
$\langle nTracks \rangle \sim 200$

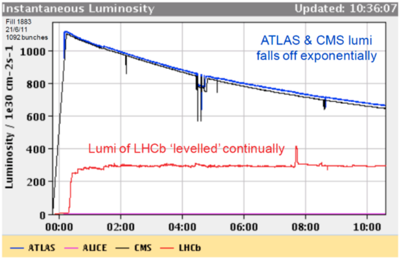
$\sigma(p\bar{p} \rightarrow b\bar{b}X) \sim 80\mu b$
$\sigma(c\bar{c}) \quad \sim 1500\mu b$



Run-1 data sample

- ~900 physicists from 64 universities/laboratories in 16 countries.
- $\mathcal{O}(100\text{k})$ $b\bar{b}$ pairs produced/sec.



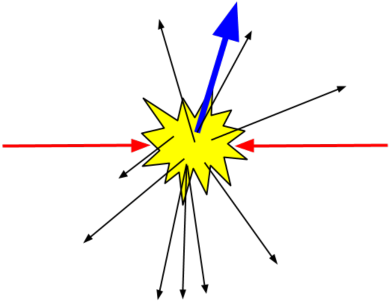


- LHCb designed to run at lower luminosity than ATLAS/CMS.
  - LHCb tracking/PID is sensitive to pile-up.
- LHC pp beams are displaced to reduce instantaneous luminosity - stable running conditions.
- $\langle\mathcal{L}\rangle_{2011} \sim 2.7 \times 10^{32} cm^{-2} s^{-1}$
- $\langle\mathcal{L}\rangle_{2012} \sim 4.0 \times 10^{32} cm^{-2} s^{-1}$

Searching for New Physics

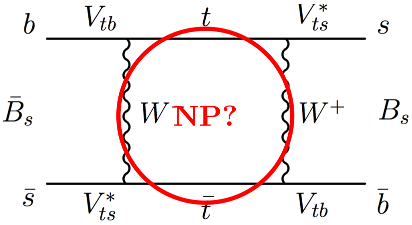
ON-SHELL

Cannot produce particles with $mc^2 > E$



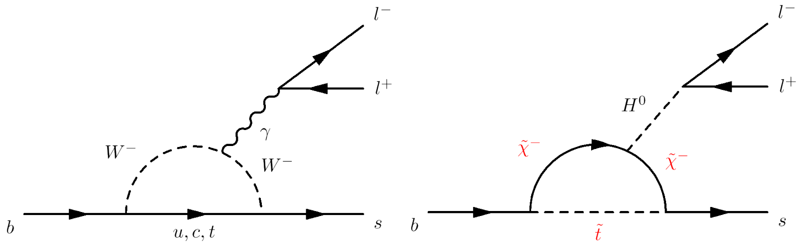
OFF-SHELL

Higher energy particles can appear virtually in quantum loops → flavour physics



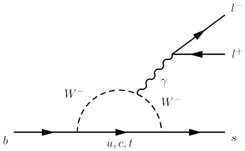
History: top quark mass predicted by quark mixing

Rare (FCNC) b-hadron decays

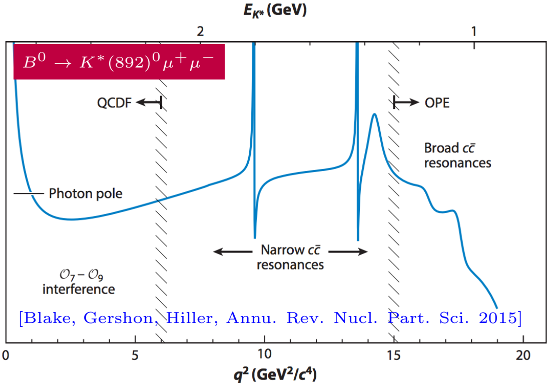


$b \to s$ TRANSITIONS

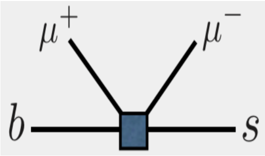
- $b \to s$ "penguin" decays are loop/CKM suppressed.
- FCNC can be crucial to finding out where to look for NP.
- Model independent effective Hamiltonian, where heavy degrees of freedom have been integrated out in short-distance Wilson coefficients, (C_i).



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i \left[C_i \mathcal{O}_i + C_i' \mathcal{O}_i'\right]$$

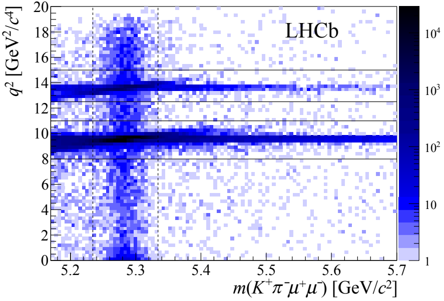


[Blake, Gershon, Hiller, Annu. Rev. Nucl. Part. Sci. 2015]



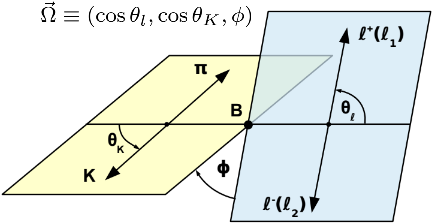
$$\mathcal{O}_{9(\prime)} = [\bar{s}\gamma_\mu P_{L(R)} b][\bar{l}\gamma^\mu l]$$

$$q^2 \equiv m(l^+l^-)^2$$



2398 ± 57 events, excluding the charmonia.

$\vec{\Omega} \equiv (\cos\theta_l, \cos\theta_K, \phi)$



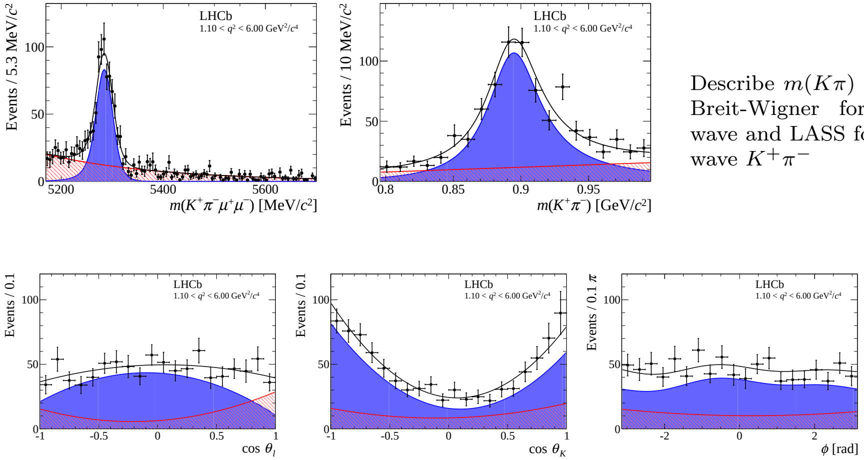
- Di-muon final state is experimentally clean signature, but BR $\sim 10^{-7}$.
- $P \to VV'$ decay, fully described by $q^2 \equiv m(\mu^+\mu^-)^2$ and 3 helicity angles.
- $B^0 \to K^*\mu^+\mu^-$ has rich system of observables (rates, angles, asymmetries) that are sensitive to NP.

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_{j=1}^{11} I_j(q^2) f_j(\vec{\Omega}), \quad I_j \to \bar{I}_j \text{ for } B^0$$

$$S_j = (I_j + \bar{I}_j) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right), \quad A_j = (I_j - \bar{I}_j) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

$B^0 \to K^*(892)^0 \mu^+ \mu^-$

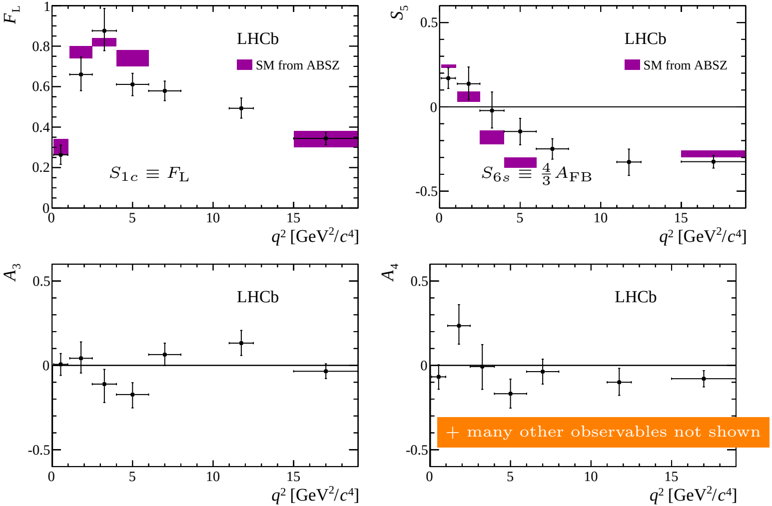
[LHCb-PAPER-2015-051]



Describe $m(K\pi)$ with Breit-Wigner for P-wave and LASS for S-wave $K^+\pi^-$

- S_i, A_i's extracted using a max likelihood fit.
- Example fits in $\pm 50\,\text{MeV}/c^2$ around $K^*(892)^0$.
- For the first time the $K\pi$ S-wave is accounted for.

$B^0 \to K^*(892)^0\mu^+\mu^-$: SOME OBSERVABLES [LHCb-PAPER-2015-051]

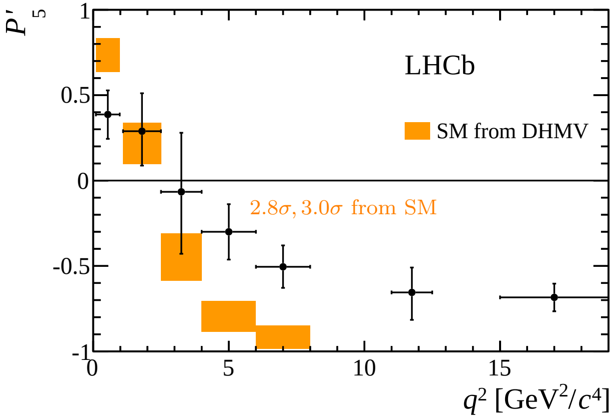


- Some observables have physical boundaries ⇒ use Feldman-Cousins for uncertainties.
- *CP*-asymmetries consistent with zero, as expected, but some deviations in *CP*-averaged observables (the S_j's).

$B^0 \to K^*(892)^0\mu^+\mu^-$: THE ANOMALY [LHCb-PAPER-2015-051]

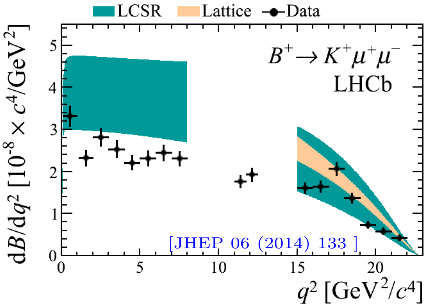
- "Theoretically clean" observables less dependent on hadronic form factors [Descotes-Genon et al JHEP 05 (2013) 137].
- These divide out the hadronic uncertainties to leading order.
- Tension from the $1\,\text{fb}^{-1}$ LHCb result remains.

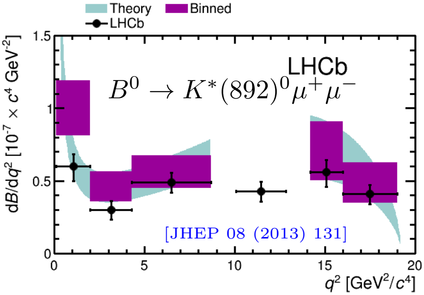
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

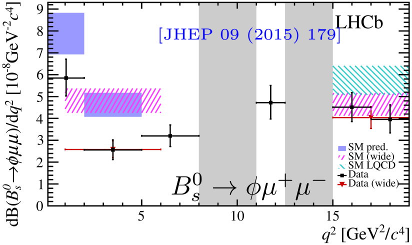


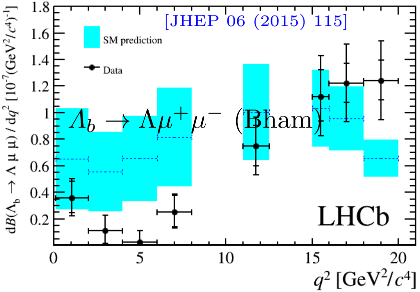
A χ^2 fit to all *CP*-averaged observables shows a 3.4σ shift from SM prediction

$b \to s\mu^+\mu^-$ branching fractions lower than predictions







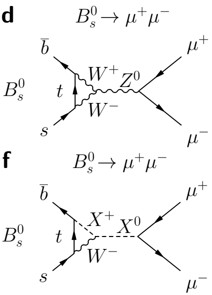


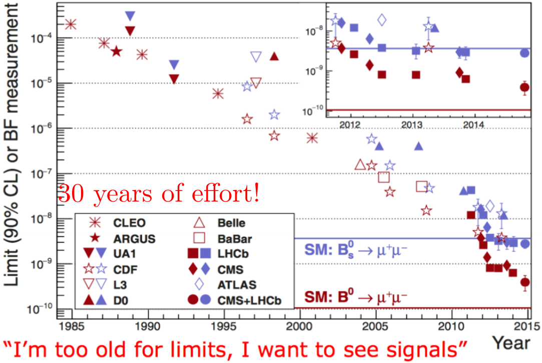
Observation of $B_s^0 \to \mu^+\mu^-$

- CKM suppressed and helicity suppressed ($(m_\mu/m_B)^2$).
  - $\mathcal{B}(B_s^0 \to \mu\mu)_{\text{SM}} = (3.66 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu\mu)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$
  - [PRL 112, 101801 (2014)]

Dominant uncertainty will be improved via refined Lattice QCD calcs.

- Sensitive to scalar and pseudoscalar NP couplings, e.g., in MSSM $\mathcal{B} \propto (\tan\beta)^6$

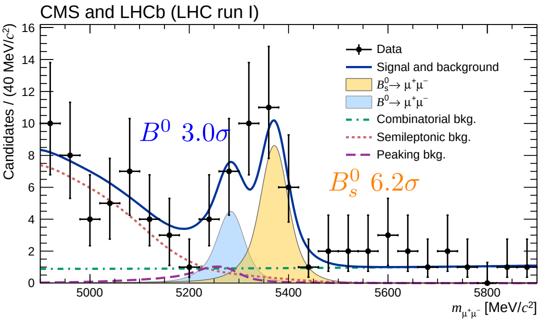


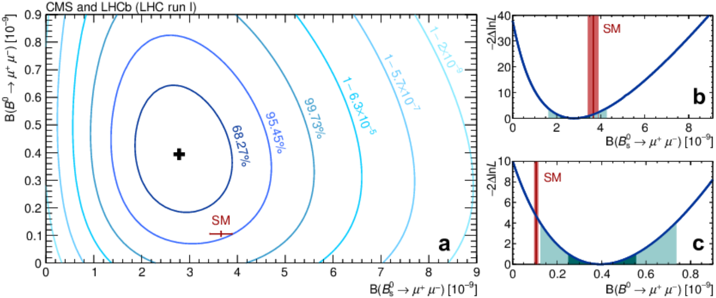


"I'm too old for limits, I want to see signals"
Francis Halzen (EPS '15)

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

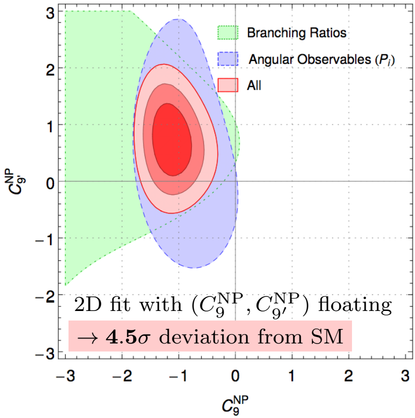
[CMS + LHCb, Nature 522, 68-72 (2015)]



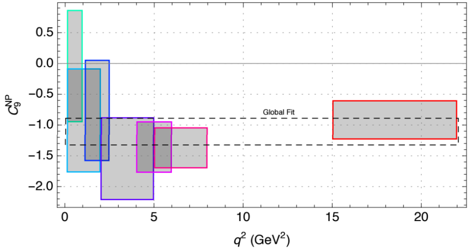


- Use multi-variate techniques to suppress background.
- Results consistent with SM at $\sim 2\sigma$.
- Constrains S and P contributions.
- One to watch during LHC Run-2.

Global fits for Wilson coeffs [Descotes-G et al, arXiv:1510.04239]



Other global fits exist!



- Inputs from branching fractions and angular observables from $b \rightarrow sll$ decays, $\mathrm{BR}(B \rightarrow X_s\gamma)$, $\mathrm{BR}(B_s^0 \rightarrow \mu^+\mu^-)$, ...

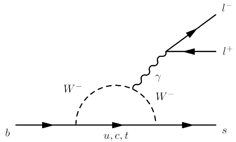
- Many fits performed with different subsets of the observables and different theoretical inputs (form factors, power corrections, charm loops).
- $C_9^{NP} < 0$ plays central role explaining many deviations seen in $b \rightarrow sll$ transitions.
- Possible Z'? Leptoquarks? [many authors]
- How well do we understand QCD-effects? [Lyon, Zwicky]

Lepton universality

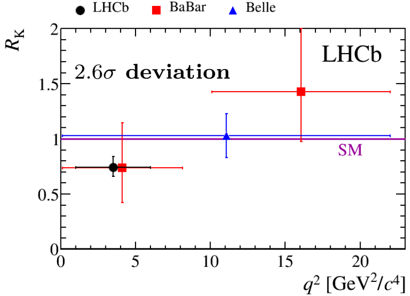
$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}, \ldots$$

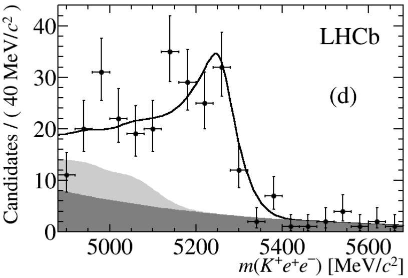
Lepton universality ($B^+ \to K^+ l^+ l^-$) [PRL 113,151601 (2014)]

- In the SM only the Higgs boson has non-universal lepton couplings.
- This results in SM predictions of $\sim$unity for various decay-rate ratios.



$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

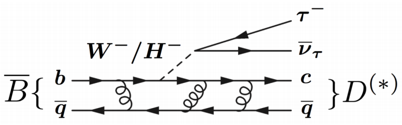




- Can be described assuming NP only in $b \to s\mu\mu$.
- Very interesting given indications of non-SM physics in other $b \to s\mu\mu$ FCNC decays and 2.4σ excess in $H \to \tau\mu$ at CMS [PLB 749 (2015) 337].
- Future: Make similar measurements using other decays - $R(\phi), R(K^*), R(\Lambda)$ (Bham).

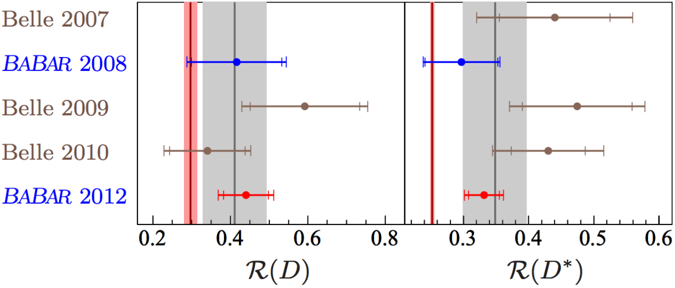
Lepton universality ($\overline{B^0} \to D^{*+} l\nu$)

- CKM mechanism well tested, but room for NP if coupling more to 3rd generation (e.g., charged Higgs).
- B-factories already reporting deviation from theoretically clean SM prediction.
- Form-factors cancel in the ratio.



Tree-level int., unlike $b \to sll$ FCNC

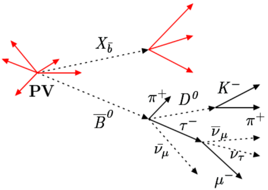
$$R(D^*) \equiv \frac{\mathcal{B}(\overline{B^0} \to D^{*+}\tau\nu_\tau)}{\mathcal{B}(\overline{B^0} \to D^{*+}\mu\nu_\mu)}$$

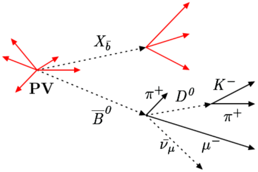


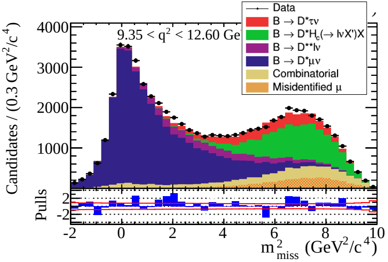
- Interesting given hints of non-universality in $B^+ \to K^+ l^+ l^-$ decays (R_K) and excl/incl measurements of V_{ub}, V_{cb}.

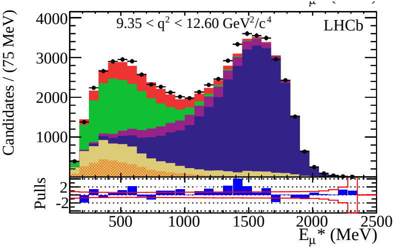
Lepton universality ($\overline{B^0} \to D^{*+} l\nu$) [PRL 115, 111803 (2015)]

- Very challenging measurement at hadron collider (no beam constraints and large backgrounds).
- $\mathcal{B}(\tau \to \mu\nu_\mu\nu_\tau) = (17.41 \pm 0.04)\%$
  - Signal and normalisation have same final state particles.
- Large samples of events, triggering on charm.
- Require significant B, D, τ flight distances. Use isolation MVA.
- Template fit to kinematic variables →





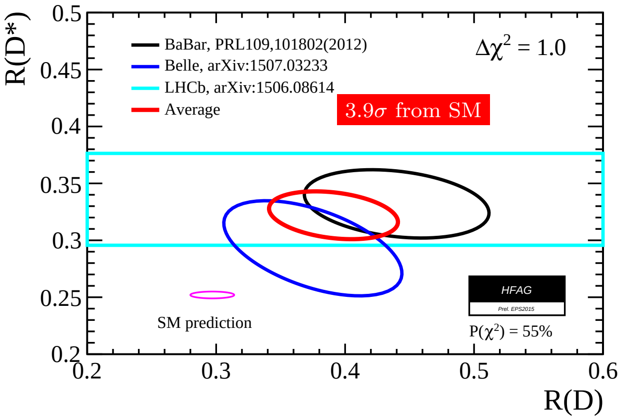




$$R(D^*) \equiv \frac{\mathcal{B}(\overline{B^0} \to D^{*+}\tau\nu_\tau)}{\mathcal{B}(\overline{B^0} \to D^{*+}\mu\nu_\mu)}$$

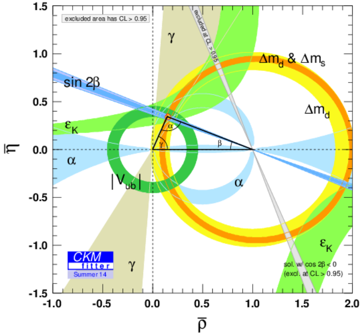
Lepton universality ($\overline{B^0} \to D^{*+} l \nu$) [PRL 115, 111803 (2015)]

- LHCb $R(D^*) = 0.336 \pm 0.027 \pm 0.030$ (2.1σ from SM)



- SM prediction from [PRD 85 (2012) 094025].
- Could be explained by enhancement of $b_L \to c_L \tau_L \nu_L$ amplitude.
- Now using other decay modes to make similar measurements ($R(D_{(s)})$, $R(\Lambda_c)$).

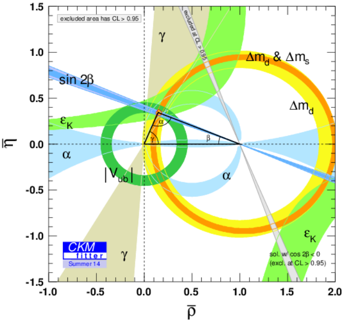
CP violation in the quark sector



CP violation in the quark sector

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

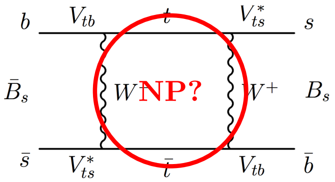
Wolfenstein parameterisation



- 3 generations + **1 phase** → $\bar\eta \neq 0$ is only source of CP violation in SM.
- CKM picture confirmed up to $\sim 20\%$.
- Couplings show strong hierarchy not seen in lepton sector ⇒ "*SM flavour puzzle*"

- New Physics should have flavour structure similar to SM...
- ...or the NP scale is very very large (~ 100TeV) ⇒ "*NP flavour puzzle*"
- Need more **precision measurements** to look for small deviations.

3 types of CP violation

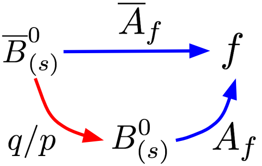


1. Mixing: $|q/p| \neq 1$
2. Decay: $|A_f/\overline{A}_f| \neq 1$
3. Interference between mixing and decay:

$$\phi_{d,s} \equiv -\arg(\lambda_f) \equiv -\arg\left(\frac{q}{p}\frac{A_f}{\overline{A}_f}\right) \neq 0$$

$$|B^0_{s,\mathrm{L}}\rangle = p|B^0_s\rangle + q|\overline{B}^0_s\rangle$$
$$|B^0_{s,\mathrm{H}}\rangle = p|B^0_s\rangle - q|\overline{B}^0_s\rangle$$

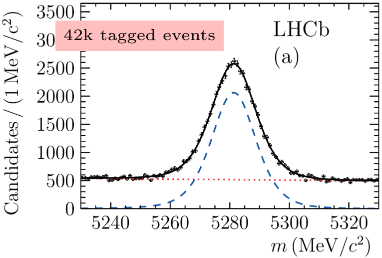
Expect $\quad |\lambda_f| \equiv \left|\frac{q}{p}\frac{A_f}{\overline{A}_f}\right| \approx 1$

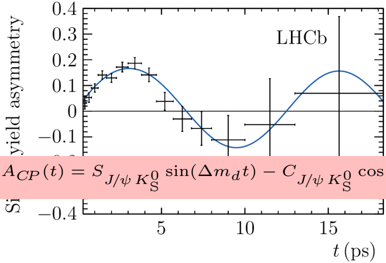


$$A_{CP}(t) \equiv \frac{\Gamma_{\overline{B}^0\to f} - \Gamma_{B^0\to f}}{\Gamma_{\overline{B}^0\to f} + \Gamma_{B^0\to f}} = \frac{S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma} \sinh(\Delta\Gamma\, t/2)}$$

CP violation in $B^0 \to J/\psi\, K^0_S$

[PRL 115 (2015) 031601]



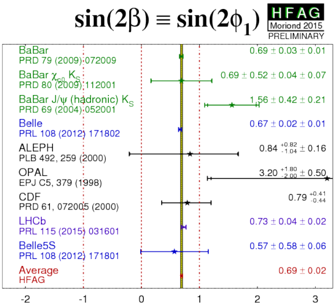


$$A_{CP}(t) = S_{J/\psi\, K^0_S} \sin(\Delta m_d t) - C_{J/\psi\, K^0_S} \cos(\Delta m_d t)$$

$$S_{J/\psi\, K^0_S} \approx \sin 2\beta$$

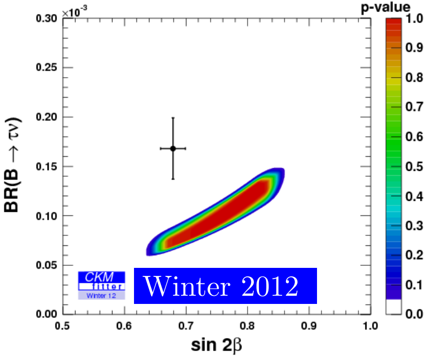
$$S_{J/\psi\, K^0_S} = +0.731 \pm 0.035 \pm 0.020$$

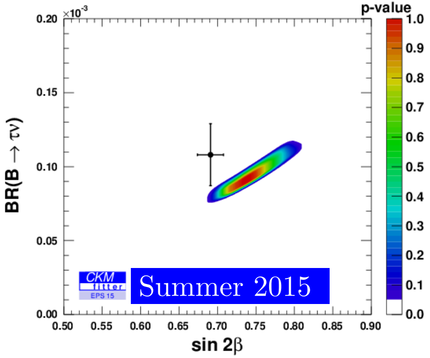
$$C_{J/\psi\, K^0_S} = -0.038 \pm 0.032 \pm 0.005$$



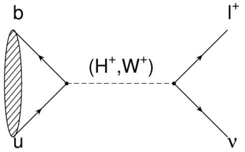
- Similar precision to B-factories, but LHCb measurement pulled WA up towards indirect determination from global fit.
- $\sin 2\beta^{\text{World Average}} = 0.691 \pm 0.017$
- $\sin 2\beta^{\text{CKMfitter}} = 0.748^{+0.030}_{-0.032}$

$B^+ \to \tau^+\nu_\tau$ vs. $\sin 2\beta$

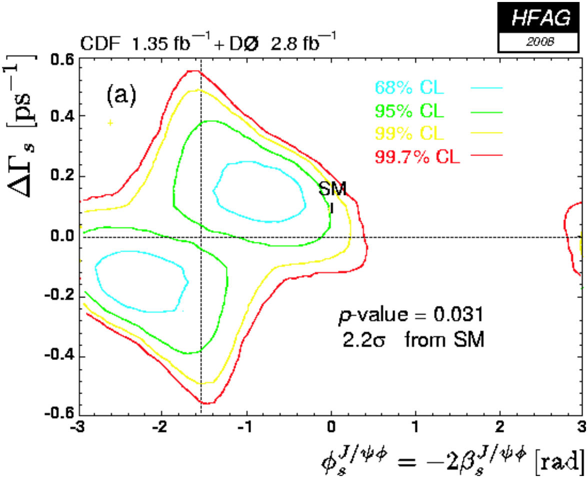


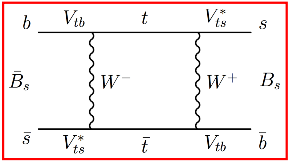


- Small tension reduced following:
  - Updated measurement of $\sin 2\beta$ and new measurement of $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ from Belle [arXiv:1503.05613].
  - CKM predictions also changed a bit.



CP violation in $B_s^0 \to J/\psi\,\phi$





$$|B^0_{s,\mathrm{L}}\rangle = p|B^0_s\rangle + q|\overline{B}^0_s\rangle$$

$$|B^0_{s,\mathrm{H}}\rangle = p|B^0_s\rangle - q|\overline{B}^0_s\rangle$$

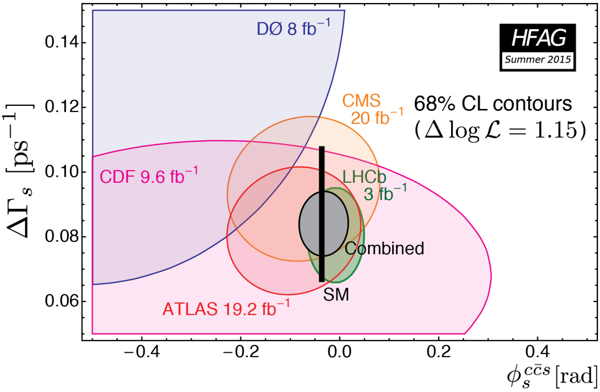
$$\Delta\Gamma_s \equiv \Gamma_\mathrm{L} - \Gamma_\mathrm{H}$$

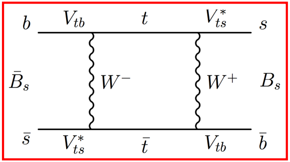
$$\phi_s \overset{\mathrm{SM}}{=} -0.0365 \pm 0.0012\,\mathrm{rad}$$

[CKMFitter]

$$\sigma(\phi_s) \sim \pm 0.4\ \mathrm{rad}$$

CP violation in $B_s^0 \to J/\psi\,\phi$





$$|B^0_{s,\mathrm{L}}\rangle = p|B^0_s\rangle + q|\overline{B}^0_s\rangle$$
$$|B^0_{s,\mathrm{H}}\rangle = p|B^0_s\rangle - q|\overline{B}^0_s\rangle$$

$$\Delta\Gamma_s \equiv \Gamma_\mathrm{L} - \Gamma_\mathrm{H}$$

$$\phi_s \overset{\mathrm{SM}}{=} -0.0365 \pm 0.0012\,\mathrm{rad}$$
[CKMFitter]

Combination

$\phi_s = -0.034 \pm 0.033$ rad
$\Delta\Gamma_s = 0.082 \pm 0.006\,\mathrm{ps}^{-1}$
Dominated by LHCb [PRL 114 (2015) 041801]

- New physics not large.

$\Rightarrow$ need to control SM effects (penguins).

- Also competitive in gluonic penguin decays ($B_s^0 \to \phi\phi$).

Penguin pollution in ϕ_s and $\sin 2\beta$

Controlling penguins pollution

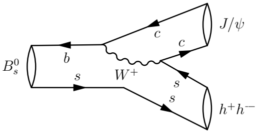
$$\phi_q^{\text{measured}} = \phi_q + \delta_{\text{Penguin}} + \delta_{\text{New Physics}}$$

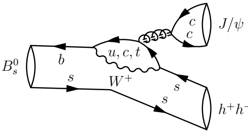
Enhancement could be caused by non-perturbative hadronic effects that are difficult to calculate in QCD.
[Nierste et al. arXiv:1503.00859], [Liu et al. PRD 89, 094010 (2014)]

1. Measure $\phi_s / \sin 2\beta$ for different polarisation states.
2. Measure δ_{Penguin} using decays where penguin/tree ratio is not suppressed.
   - Use SU(3)-flavour relations to link B_s^0 and B^0 (broken at 20-30% level).

$$A(B_s^0 \to (J/\psi\, \phi)_f) = (1 - \lambda^2/2)\mathcal{A}'_f \left[1 + \epsilon a'_f e^{i\theta'_f} e^{i\gamma}\right]$$

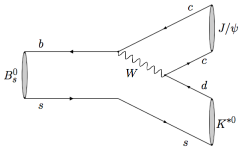
Penguin/tree suppressed by $\epsilon = \frac{|V_{us}|^2}{1 - |V_{us}|^2} = 0.05$

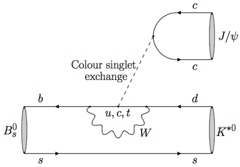




$$A(B_s^0 \to (J/\psi\, \overline{K^{*0}})_f) = -\lambda \mathcal{A}_f \left[1 - a_f e^{i\theta_f} e^{i\gamma}\right]$$

Penguin/tree not suppressed (but overall rate suppressed)

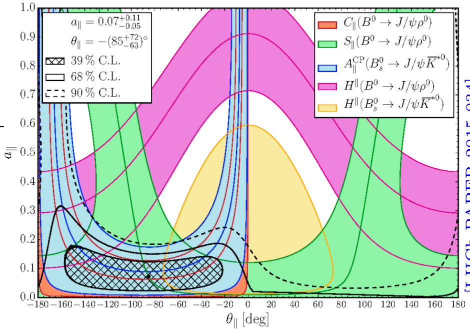




[Faller et al. PRD 79, 014005 (2009)] [De Bruyn, Fleischer, JHEP1503 (2015) 145]

Controlling penguins with $B_s^0 \to J/\psi\, \overline{K^{*0}}$ + $B^0 \to J/\psi\, \rho^0$

Parameter	Fitted value
$\Delta\phi_{s,0}^{J/\psi\,\phi}$	$0.000^{+0.009}_{-0.011}(\text{stat})^{+0.004}_{-0.009}(\text{syst})$
$\Delta\phi_{s,\parallel}^{J/\psi\,\phi}$	$0.001^{+0.010}_{-0.014}(\text{stat})^{+0.007}_{-0.008}(\text{syst})$
$\Delta\phi_{s,\perp}^{J/\psi\,\phi}$	$0.003^{+0.010}_{-0.014}(\text{stat})^{+0.007}_{-0.008}(\text{syst})$



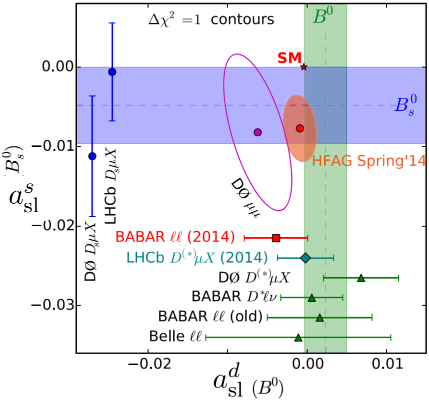
[LHCb-PAPER-2015-034]

- Penguin parameters effectively constrained from *CP* asymmetry measurements.
- Combined results dominated by $B^0 \to J/\psi\, \rho^0$ (access to mixing-induced asymmetry not available in flavour-specific $B_s^0 \to J/\psi\, \overline{K^{*0}}$ channel).

Penguins are small!

CP VIOLATION IN $B^0_{(s)}$ MIXING $(|B^0_{\rm L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle)$

[PRL 114, 081801 (2015)]



Use semileptonic B^0, B^0_s decays

$$a_{\rm sl} \equiv \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \overline{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \overline{f})}$$

$$a_{\rm meas}(t) = \frac{N(f,t) - N(\overline{f},t)}{N(f,t) + N(\overline{f},t)} = \frac{a_{\rm sl}}{2}\left(1 - \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}\right)$$

[Lenz arXiv:1205.1444] - tiny in SM

$a^d_{\rm sl} = (-4.1 \pm 0.6) \times 10^{-4}$

$a^s_{\rm sl} = (+1.9 \pm 0.3) \times 10^{-5}$

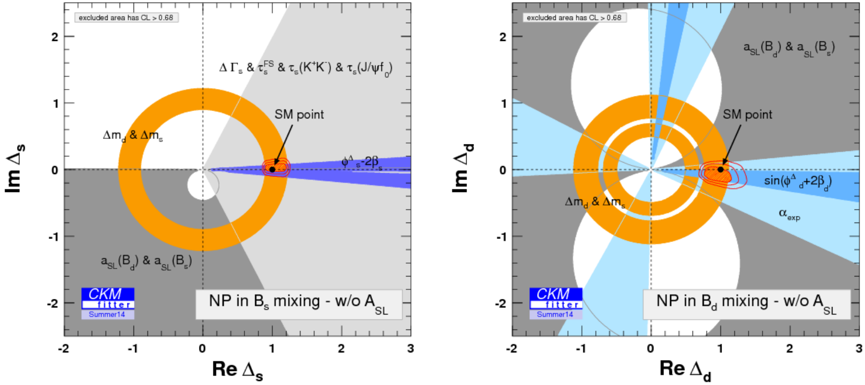
$a^d_{\rm sl} = -0.0015 \pm 0.0017$ [HFAG]

$a^s_{\rm sl} = -0.0075 \pm 0.0041$ [HFAG]

- No tagging needed. Typically time-dep. measurement for B^0 system, indep. for B^0_s.
- Crucial to control production and detection asymmetries using control samples.
- **$\sim 3\sigma$ tension with SM from D0 dimuon asymmetry not confirmed or excluded by other experiments.**
- Explanation of D0 dimuon could be due to deviation in value of $\Delta\Gamma_d$ [PRD 87 074020 (2013)].

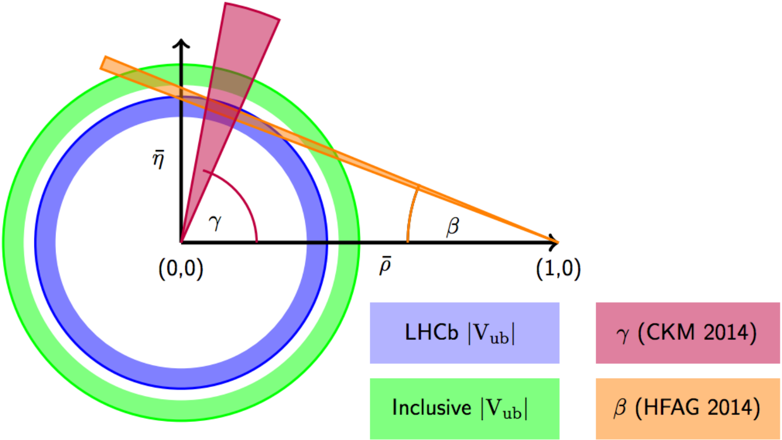
New physics in B mixing

[Lenz et al. arXiv:1203.0238v2 + updates]



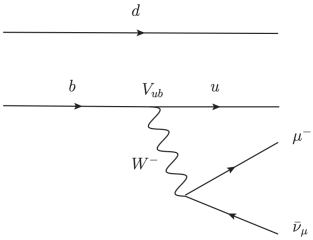
- Introduce generic NP through complex parameter Δ_q: $M_{12}^{\mathrm{NP},q} = M_{12}^{\mathrm{SM},q}\Delta_q$
- NP contribution to B_s^0 mixing is limited to $< 30\%$ at 3σ.
- But beware of **hadronic uncertainties** that could mimic small NP.
- **Take-home message:** will significantly shrink these contours with Run-2 data and probe BSM contributions @ few % of SM.

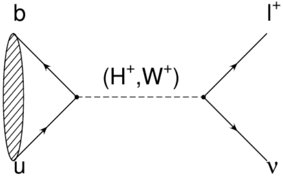
$|V_{ub}|$ from the CKM unitarity triangle



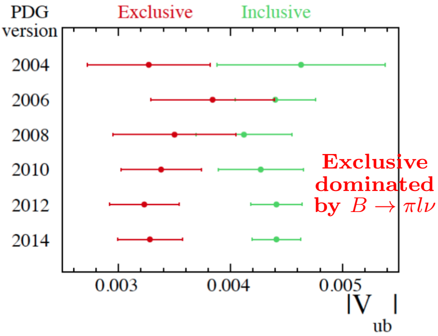
- $|V_{ub}|$ indispensible in CKM unitarity fits.
- Excellent test of unitarity (and/or NP) by comparing $|V_{ub}|$ (tree-level process) with $\sin 2\beta$ (B^0-mixing, loop process).

$|V_{ub}|$



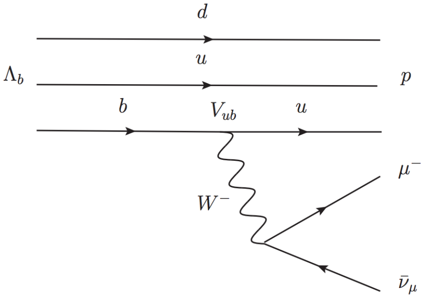


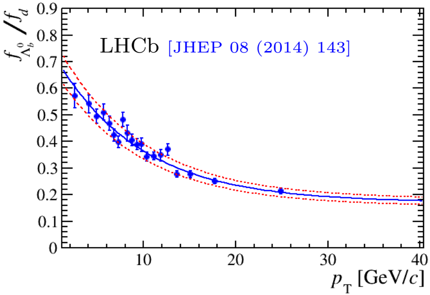
- Measure exclusive branching fraction ($B^0 \to \pi l \nu$, $B^+ \to \tau \nu_\tau$).
- Or inclusive sum of states ($b \to u l \nu$).
- Each method relies on different theoretical inputs.
- Long-standing discrepancy between these two approaches using results from BaBar/Belle.



$|V_{ub}|$ USING $\Lambda_b \to p\mu\overline{\nu}_\mu$

- Challenging at hadron collider to separate $b \to u\mu\nu$ and $b \to c\mu\nu$ processes without beam energy constraint of e^+e^- machine.
- Large production of Λ_b baryons at LHC. Cleaner than $B \to \pi l\nu$ due to protons in final state.





Aside on b-baryons:

- No *CP* violation in the baryon system observed.
- This is an area where only LHC experiments (particularly LHCb) can contribute.

$|V_{ub}|$ using $\Lambda_b \to p\mu\bar{\nu}_\mu$

[Nature Physics 10 (2015) 1038]

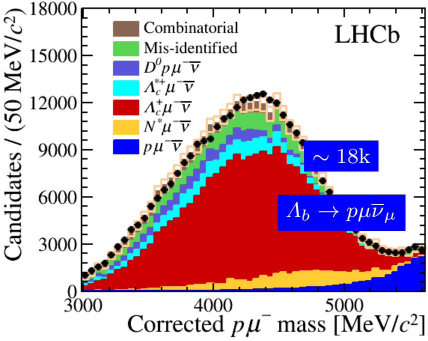
- To cancel many systematic uncertainties we measure the branching ratio relative to $\Lambda_b \to \Lambda_c\mu\bar{\nu}_\mu$, $\Lambda_c \to pK\pi$.

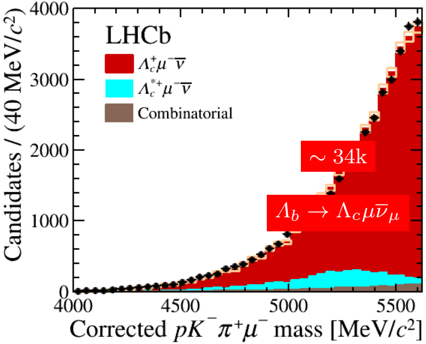
$\Rightarrow$ Must use global $|V_{cb}|$ average as input.

- Lattice QCD input is **crucial** [Meinel arXiv:1503.01421].
- Fit corrected mass (peaks at $m(\Lambda_b)$)

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)_{q^2>15\,\mathrm{GeV}}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}}} R_{\mathrm{FF}}$$

$$m_{\mathrm{corr}} = \sqrt{m_{h\mu}^2 + p_{\mathrm{T}}^2} + p_{\mathrm{T}}$$

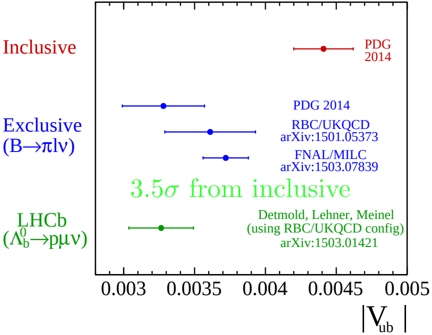


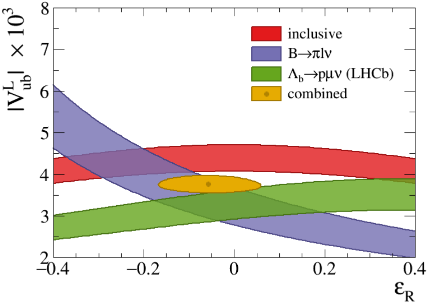


$$|V_{ub}| = (3.27 \pm 0.15(stat) \pm 0.17(syst) \pm 0.06(theory)) \times 10^{-3}$$

$|V_{ub}|$ using $\Lambda_b \rightarrow p\mu\overline{\nu}_\mu$

[Nature Physics 10 (2015) 1038]





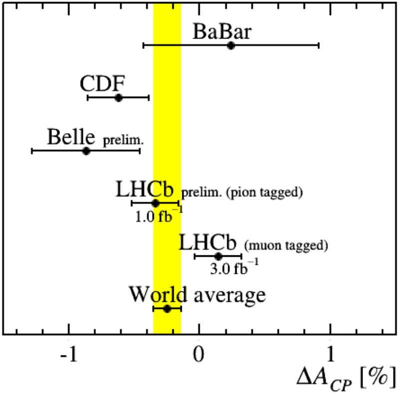
- **Syst. limited** from Lattice QCD calc. of Λ_b form-factor (more precise at high q^2).
- $\Lambda_b \rightarrow p\mu\nu$ has different dependence on right-handed currents than other modes.
- Combination starts to disfavour interpretation of discrepancy in terms of quantity of RHC (ϵ_R).

Charm physics

- Only way to study FCNC with u-type quarks. Allows to probe higher energy scales than b decays.
- Look at time-integrated CP asymmetries. Expect to be small.
- LHCb measurement of $\Delta A_{CP} \neq 0$ in 2012 [PRL 108 (2012) 111602]. Wow!
- Situation now less certain following updates - stay tuned...

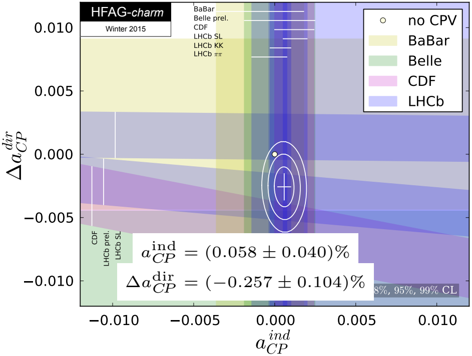
$$A_{CP} = \frac{\Gamma(\overline{D}^0 \to f) - \Gamma(D^0 \to f)}{\Gamma(\overline{D}^0 \to f) + \Gamma(D^0 \to f)}$$

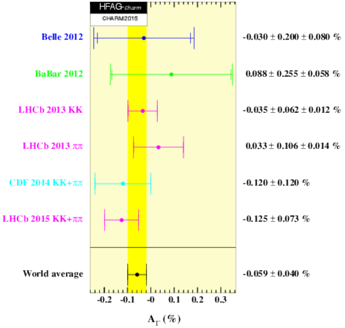
$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$



Charm physics

- Huge event yields have led to huge progress in *CP* violation in charm mixing and rare decays.
- LHCb will take advantage of higher cross-section and new trigger configuration in Run-2.





$$A_\Gamma \equiv \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} \approx -a_{CP}^{\text{ind}} - a_{CP}^{\text{dir}} y_{CP}$$

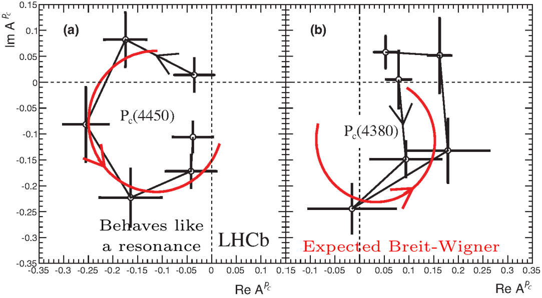
$$\Delta A_{CP} \approx \left(1 + \frac{\langle t \rangle}{\tau} y_{CP}\right) \Delta a_{CP}^{\text{dir}} + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{rmind}$$

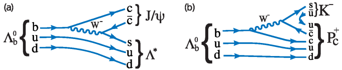
Pentaquarks

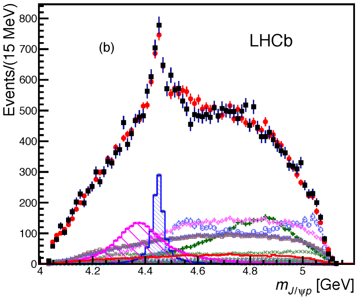
[PRL 115 (2015) 072001]

- Two pentaquark states observed in $\Lambda_b \to J/\psi\, pK^-$
- 6D amplitude fit performed (coherent sum of resonant states).
- Fit quality insufficient if only using $\Lambda^* \to pK$ resonances.
- Need two P_c states of opposite parity.

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ



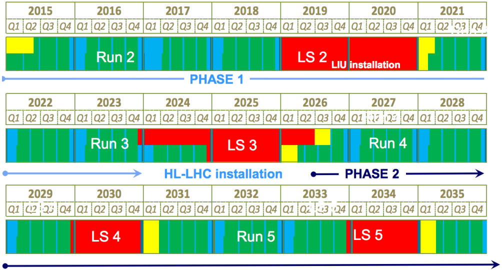


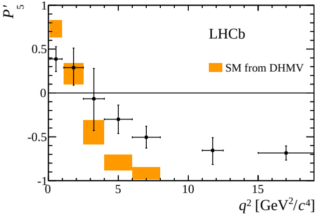


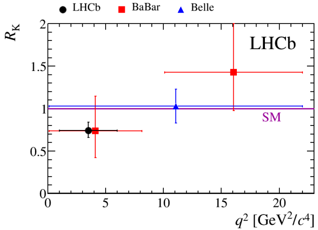
- Prospect first raised 50 years ago by Gell-Mann, Zweig.
- LHCb states have quark content $c\bar{c}uud$

Summary

- Exciting indications of non-SM physics in B physics.
- Crucially, these are in related channels:
  - $R(D^*), R_K, P_5', b \to s$ penguin branching ratios, $(H \to \tau\mu)$.
- More measurements and theory developments needed to interpret what we are seeing.
- CKM mechanism holding up to scrutiny, need more precision.
- Most results statistically limited $\to$ looking forward to Run-2 of LHC and start-up of Belle-II ~2018.







Visualising the P_5' discrepancy

The observable S_5 also corresponds to the asymmetry between the regions labelled *up* and *down* in Fig. 107. The distribution of candidates in $m(K^+\pi^-\mu^+\mu^-)$ in the range $4.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$ in these two regions is also shown in Fig. 107. The asymmetry due to S_5 is clearly visible. The best-fit asymmetry from the likelihood fit to the data and the predicted SM asymmetry are also shown.

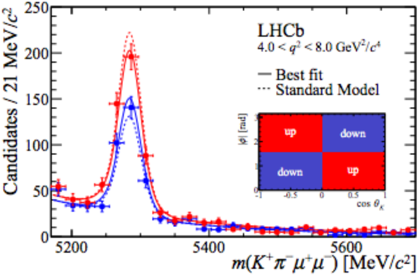
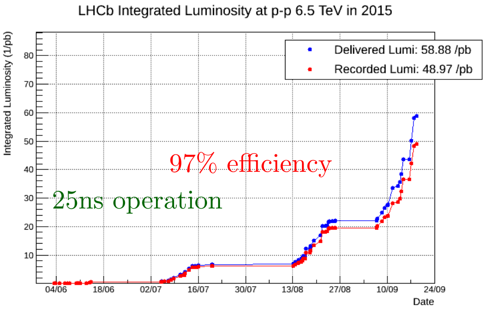
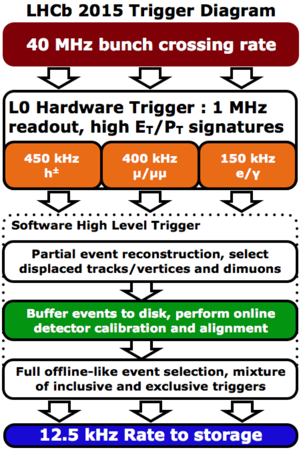


Figure 107: Visualisation of the asymmetry of the data due to S_5. The inset illustrates the two regions in $\cos\theta_K$ and ϕ that can be used to compute S_5. The two histograms show the distribution of candidates in $m(K^+\pi^-\mu^+\mu^-)$ in the dataset for the *up* and *down* regions. The data are overlaid with predictions for the signal yield given the best-fit (solid line) and SM (dashed line) values of S_5.

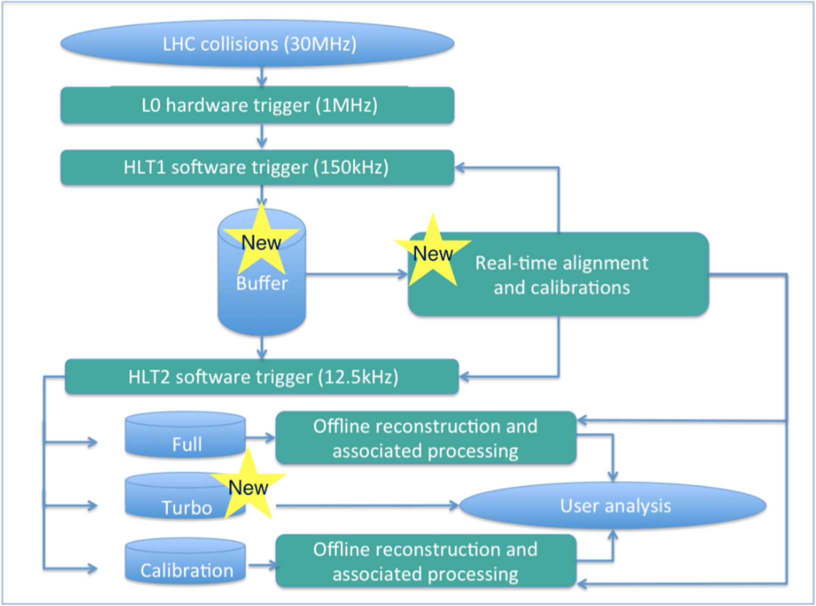
Run-2 status



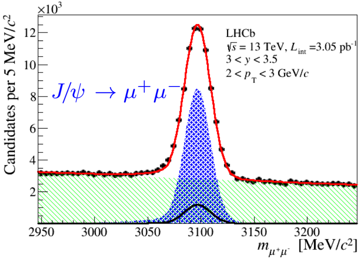


- Huge success so far!
- New trigger configuration commissioned.
  - Offline reconstruction in the trigger!
- **Online calibration + alignment allows physics analyses directly from the trigger.**
  - Only tracks and vertices that caused event to trigger are saved (no offline reco).
  - Used for high yield samples (J/ψ, D^0, D^+ ...)

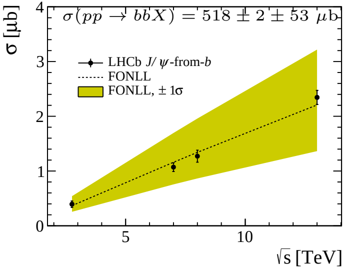
Run-2 data flow

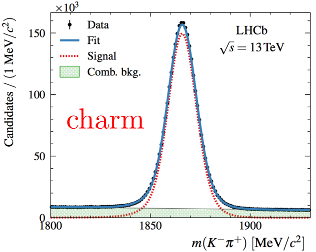


First results at $\sqrt{s} = 13$ TeV



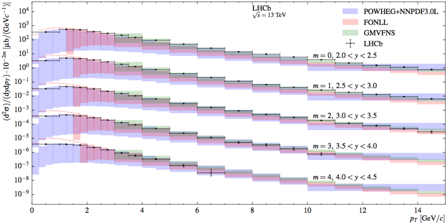
[arXiv:1509.00771]





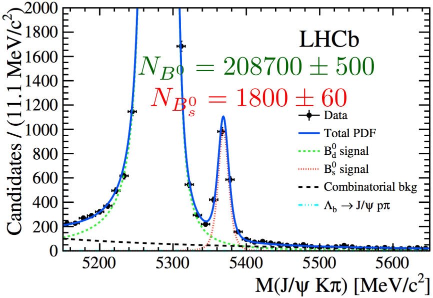
[LHCB-PAPER-2015-041]

$\sigma(pp \to c\bar{c}X) = 2.72 \pm 0.01 \pm 0.18 \pm 0.14$ mb (in LHCb)

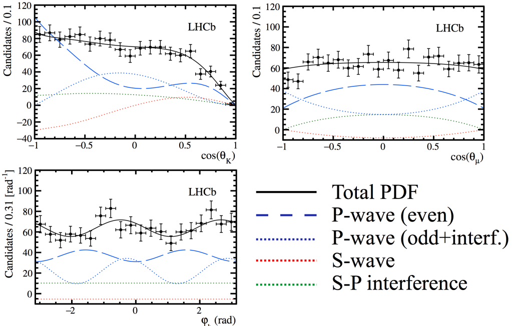


- New trigger and automatic calibration/alignment validated with early measurements (mainly 50ns ramp).
- First results with Run-2 data! J/ψ and charm cross-sections agree with expectations.

ANGULAR ANALYSIS OF $B_s^0 \to J/\psi \overline{K^{*0}}$ NEW!



- Angular analysis performed in 4 bins around $K^*(892)^0 \to K^+\pi^-$ mass, for B_s^0 and $\overline{B}_s^0$.
- Use simulation to get angular efficiency correction (+ correction for lack of S-wave in MC).
- Account for production and detection asymmetries [PRL 114 (2015) 041601],[PLB 739 (2014) 218], [JHEP 07 (2014) 041].



Parameter	Fitted value
f_0	$0.497 \pm 0.025 \pm 0.025$
$f_\parallel$	$0.179 \pm 0.027 \pm 0.013$
A_0^{CP}	$-0.048 \pm 0.057 \pm 0.020$
$A_\parallel^{CP}$	$0.171 \pm 0.152 \pm 0.028$
$A_\perp^{CP}$	$-0.049 \pm 0.096 \pm 0.025$

$$\mathcal{B}(B_s^0 \to J/\psi \overline{K^{*0}}) = (4.13 \pm 0.16 \pm 0.25 \pm 0.24(f_s/f_d)) \times 10^{-5}$$

[LHCb-PAPER-2015-034]

Controlling penguins with $B_s^0 \to J/\psi \overline{K^{*0}}$ NEW!

- Use results from **angular analysis** and **branching fraction** of $B_s^0 \to J/\psi \overline{K^{*0}}$ to measure $\Delta\phi_{s,i}^{J/\psi\,\phi}$ for each polarisation $i \in (0, \perp, \parallel, S)$.

$$H_i \propto \frac{1}{\epsilon}\left|\frac{\mathcal{A}_i'}{\mathcal{A}_i}\right|^2 \frac{\mathcal{B}(B_s^0 \to \mathrm{J}/\psi \overline{K^{*0}})}{\mathcal{B}(B_s^0 \to \mathrm{J}/\psi\phi)} \frac{f_i}{f_i'} = \frac{1 - 2a_i\cos\theta_i\cos\gamma + a_i^2}{1 + 2\epsilon a_i'\cos\theta_i'\cos\gamma + \epsilon^2 a_i'^2}$$

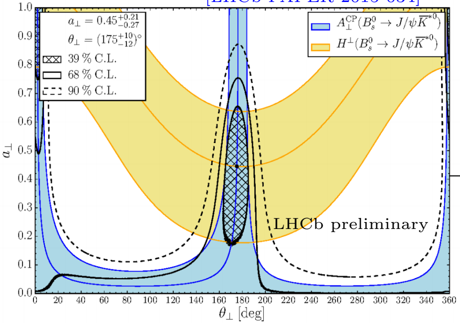
$$A_i^{CP} = -\frac{2a_i\sin\theta_i\sin\gamma}{1 - 2a_i'\cos\theta_i'\cos\gamma + a_i'^2}$$

$SU(3)$: $a_i = a_i'$, $\theta_i = \theta_i'$

$\left|\frac{\mathcal{A}_i'}{\mathcal{A}_i}\right|$ computed with LCSR [Barucha et al, arXiv:1503.05534]

$\gamma = 73 \pm 7^\circ$ [CKM]

[LHCb-PAPER-2015-034]



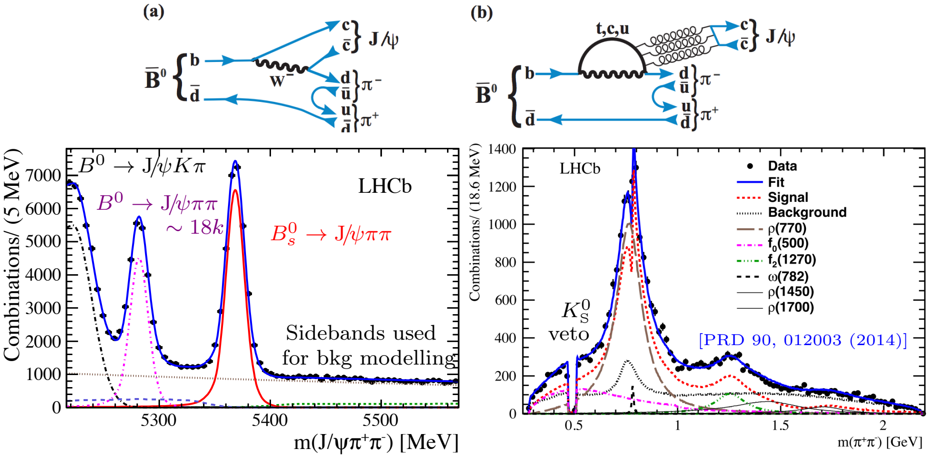
- Extract penguin parameters from χ^2 fit to H_i and A_i^{CP} information for each polarisation $i \in (0, \perp, \parallel, S)$.
- Translate to penguin phase shift:

Param.	Value	± (stat)	± (syst)	$\pm(\lvert\mathcal{A}_i'/\mathcal{A}_i\rvert)$
$\Delta\phi_{s,0}^{J/\psi\,\phi}$	0.001	$^{+0.087}_{-0.011}$	$^{+0.013}_{-0.008}$	$^{+0.048}_{-0.030}$
$\Delta\phi_{s,\parallel}^{J/\psi\,\phi}$	0.031	$^{+0.049}_{-0.038}$	$^{+0.013}_{-0.013}$	$^{+0.031}_{-0.033}$
$\Delta\phi_{s,\perp}^{J/\psi\,\phi}$	-0.046	$^{+0.012}_{-0.012}$	$^{+0.007}_{-0.008}$	$^{+0.017}_{-0.024}$

Compare to current experimental precision: $\sigma(\phi_s) = \pm 0.035\,\mathrm{rad}$, $\sigma(\phi_d) = \pm 0.028\,\mathrm{rad}$

CP violation in $B^0 \to J/\psi\,\rho^0(770)$

PLB 742 (2015) 38-49

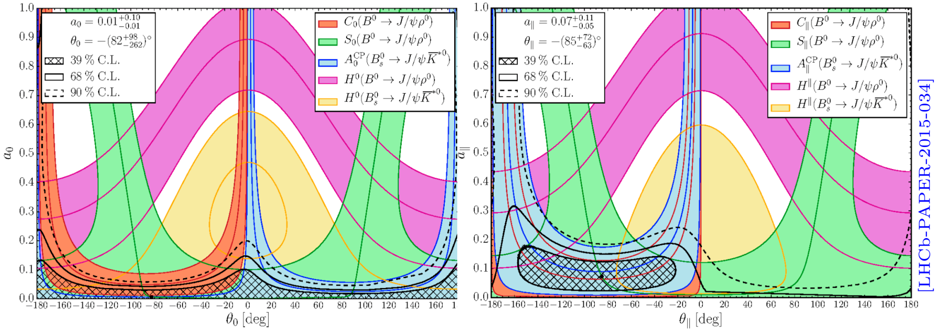


- Use $\rho^0(770)$ component to measure:

$$\phi_d^{\mathrm{eff}} = (41.7 \pm 9.6^{+2.8}_{-6.3})^\circ,\ \alpha_{CP} \equiv \frac{1-|\lambda_f|}{1+|\lambda_f|} = (-32 \pm 28^{+9}_{-7}) \times 10^{-3}$$

$$\Rightarrow \Delta\phi_d = (-0.9 \pm 9.7^{+2.8}_{-6.3})^\circ$$ (equivalent to $0.016 \pm 0.169^{+0.049}_{-0.110}$ rad)

Controlling penguins with $B_s^0 \to J/\psi\,\overline{K^{*0}}$ + $B^0 \to J/\psi\,\rho^0$ **NEW!**



- Now fit for $|\mathcal{A}_i'/\mathcal{A}_i|$ to limit sensitivity to hadronic uncertainties.
- Assume $|\mathcal{A}_i'/\mathcal{A}_i|(B_s^0 \to J/\psi\,\overline{K^{*0}}) = |\mathcal{A}_i'/\mathcal{A}_i|(B^0 \to J/\psi\,\rho^0)$

Parameter	Fitted value
$\Delta\phi_{s,0}^{J/\psi\,\phi}$	$0.000^{+0.009}_{-0.011}(\text{stat})^{+0.004}_{-0.009}(\text{syst})$
$\Delta\phi_{s,\parallel}^{J/\psi\,\phi}$	$0.001^{+0.010}_{-0.014}(\text{stat})^{+0.007}_{-0.008}(\text{syst})$
$\Delta\phi_{s,\perp}^{J/\psi\,\phi}$	$0.003^{+0.010}_{-0.014}(\text{stat})^{+0.007}_{-0.008}(\text{syst})$

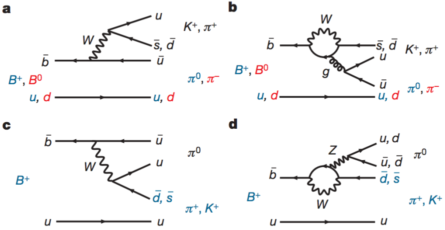
- Penguin parameters effectively constrained from *CP* asymmetry measurements.
- Combined results dominated by $B^0 \to J/\psi\,\rho^0$ (access to mixing-induced asymmetry not available in flavour-specific $B_s^0 \to J/\psi\,\overline{K^{*0}}$ channel).

Penguins are small!

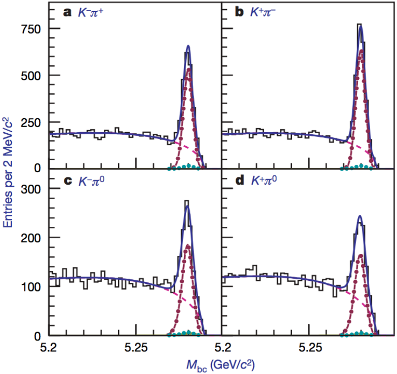
THE "$K\pi$ PUZZLE"

$$\Delta A_{CP} \equiv A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.12 \pm 0.02$$

- Naively expect $\Delta A_{CP} = 0$. NP in electroweak penguin loop or QCD effect?
- Need isospin analysis to understand what is going on (e.g., sum rule proposed by [Gronau, PLB 627 (2005) 82-88]).
- $B^0 \to K^+\pi^-$ measured at BaBar, Belle, CDF, LHCb. $B^+ \to K^+\pi^0$ at BaBar/Belle.
- $B^+ \to K^+\pi^0$ challenging at LHCb (no secondary vertex + photons in final state) but possible [LHCb-CONF-2015-001].
- Expect Belle-II to make significant improvements here (including $B^0 \to K^0\pi^0$).

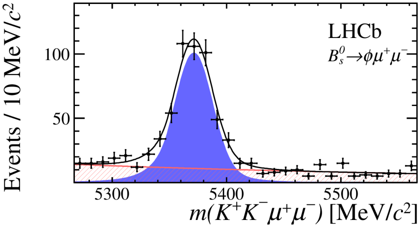


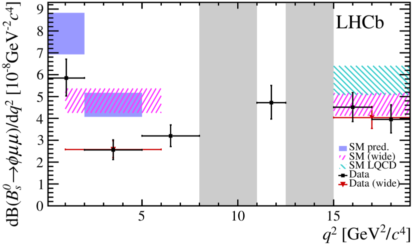
[Belle, Nature 452, 332-335 (2008)]



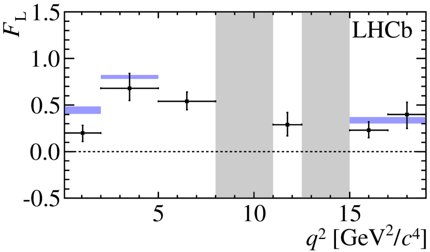
$B_s^0 \to \phi\mu^+\mu^-$ $(\phi \to K^+K^-)$

[JHEP 09 (2015) 179]





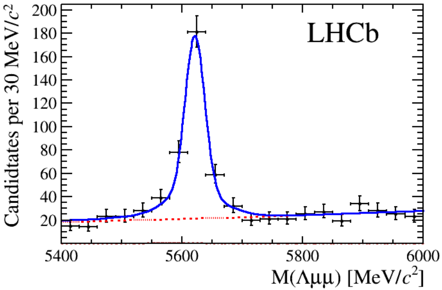
- Differential branching fraction and angular analysis (using max likelihood fit).
- Angular observables in good agreement with SM.
- $d\mathcal{B}/dq^2$ in $q^2 \in [1, 6]$ GeV/c^2 lower than SM by 3.2σ.
  - Similar story in $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$.

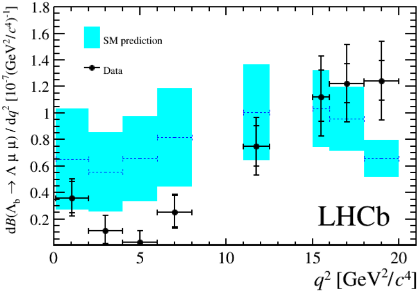


- SM pred. and wide from [arXiv:1503.05534]
- SM LQCD from [PRL112(2014)21200

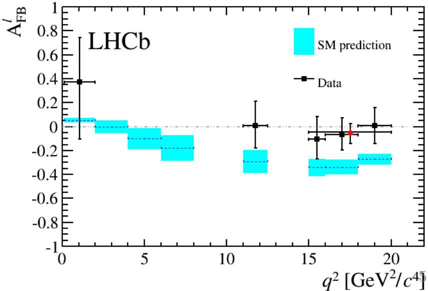
$\Lambda_b \to \Lambda\mu^+\mu^-$ $(\Lambda \to p\pi^-)$

[JHEP 06 (2015) 115]





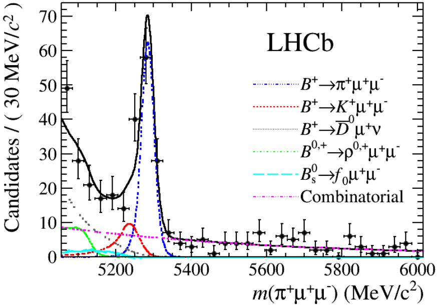
- Differential branching fraction and first angular analysis (using max likelihood fit).
- Evidence for decay in first q^2 bin, but not in $q^2 \in [1.1, 6]\,\text{GeV}/c^2 \Rightarrow$ lower than SM.
- Some angular observables in good agreement with SM, others not. e.g. $\rightarrow$

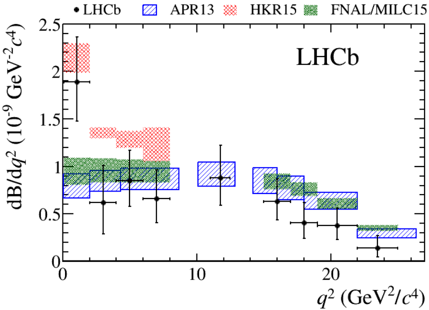


- SM prediction [PRD87(2013)074502]

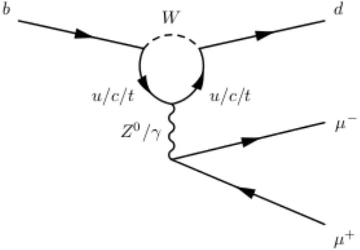
$B^+ \to \pi^+\mu^+\mu^-$

[JHEP 10 (2015) 034]





- First measurement of differential branching fraction and CP asymmetry in $b \to dll$ transition.
- $d\mathcal{B}/dq^2$ compatible with SM but on the low side.



- APR13 [PRD89(2014)094021]
- HKR15 [arXiv:1506.07760]
- FNAL/MILC15 [arXiv:1507.01618]

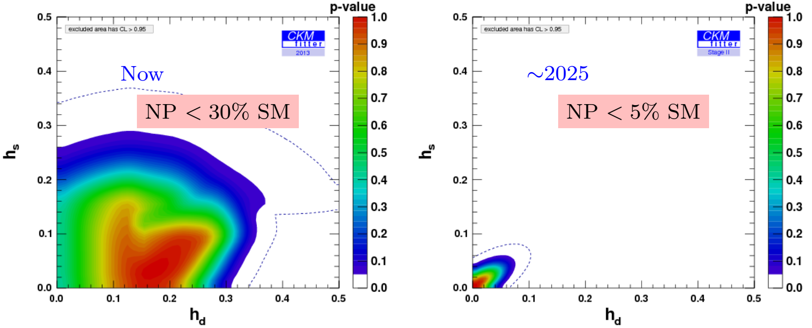
Sensitivity prospects LHCb-PUB-2014-040

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\ K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

- Before upgrade.
- After upgrade.
- Current theory uncertainty.

[J. Charles et al. PRD 89, 033016 (2014)]

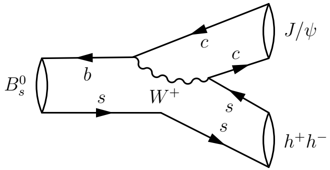
- Assume that NP only enters B^0 and B_s^0 mixing: $M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM}(1 + h_{d,s}e^{2i\sigma_{d,s}})$.

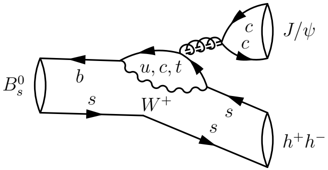


$$h \approx \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2}\left(\frac{4.5\ \text{TeV}}{\Lambda}\right)^2$$

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

Controlling penguin pollution in ϕ_s



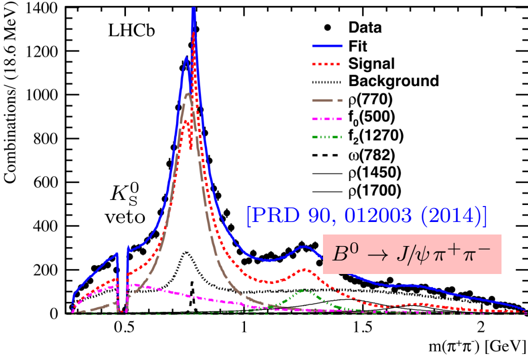


Penguin-to-tree suppression:

$$\epsilon = \frac{|V_{us}|^2}{1-|V_{us}|^2} = 0.05$$

$$\phi_s^{\text{measured}} = \phi_s + \delta_{\text{Penguin}} + \delta_{\text{New Physics}}$$

- Difficult-to-calculate non-perturbative hadronic effects could lead to big enhancement.
- Measure δ_{Penguin} using decays where penguin/tree ratio is enhanced.
  [Faller et al. arXiv:0810.4248, De Bruyn & Fleischer, arXiv:1412.6834]
- Use SU(3) relations to link B_s^0 and B^0 (broken at level of 20-30%).
- $|\delta_P| < 1.8°$
  c.f. $\sigma(\phi_s) = \pm 2.0°$, $\sigma(\phi_d) = \pm 1.4°$



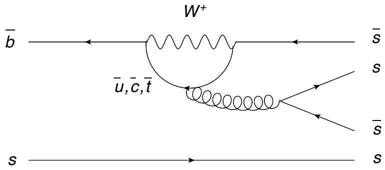
[PRD 90, 012003 (2014)]

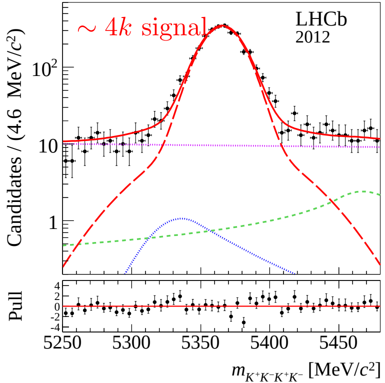
$B^0 \to J/\psi \pi^+\pi^-$

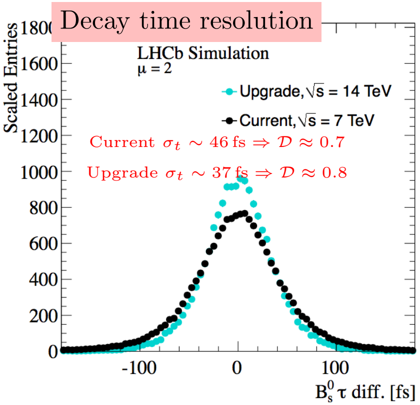
CP VIOLATION IN CHARMLESS B_s^0 DECAYS [PRD 90 (2014) 052011]

- $B_s^0 \to \phi\phi$: $b \to s$ penguin decays sensitive to NP in the loops.
- $\phi \to KK$: 5 different polarisation amplitudes $\Rightarrow$ angular analysis.
- $\phi_s = -0.17 \pm 0.15 \pm 0.03$ rad.
- $|\lambda| = 1.04 \pm 0.07 \pm 0.03 \Rightarrow$ **no direct CPV**.

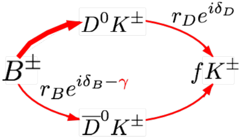
SM: $|\phi_s| < 0.02\,\mathrm{rad}$



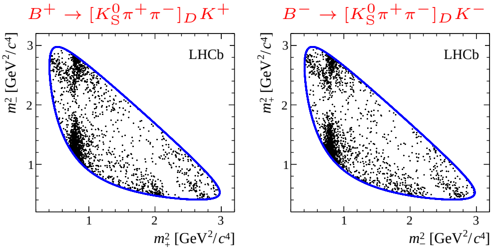




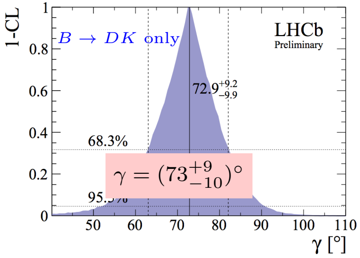
- Least well known of the CKM angles.
- Can be measured entirely from tree decays where there is small residual theory uncertainty $|\delta\gamma| \leq \mathcal{O}(10^{-7})$ [Brod, Zupan JHEP 1401 (2014) 051]
- Use interference between $B^{\pm} \to D^0 K^{\pm}$, $D^0 \to f$ decay amplitudes.
- Time-independent $B^{\pm} \to D^0 K^{\pm}$ and $B^0 \to D K^{*}$ ...
- ...or time-dependent $B_s^0 \to D_s^{\mp} K$ $(\gamma - 2\beta_s)$



[JHEP 10 (2014) 097]



[LHCb-CONF-2014-004]



- Best precision comes from combining many independent decay modes.
- B-factories: $\sigma(\gamma) \sim 15^{\circ}$; **Final LHCb Run-1: $\sigma(\gamma) \sim 7^{\circ}$.**