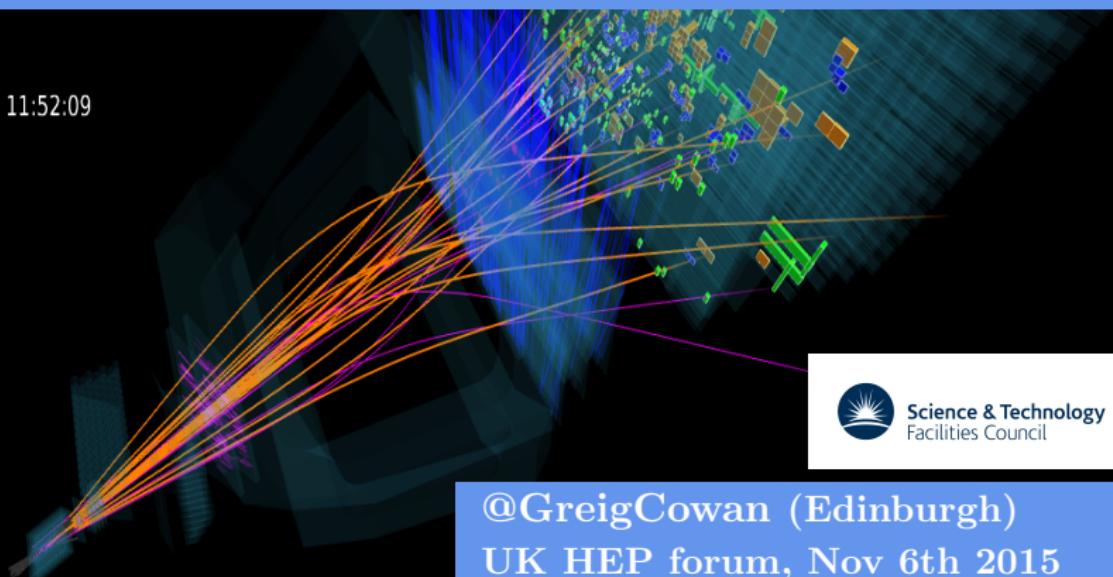


ANOMALIES AND DEVIATIONS IN HEAVY-FLAVOUR PHYSICS

Event 41383468

Run 153460

Wed, 03 Jun 2015 11:52:09



Science & Technology
Facilities Council

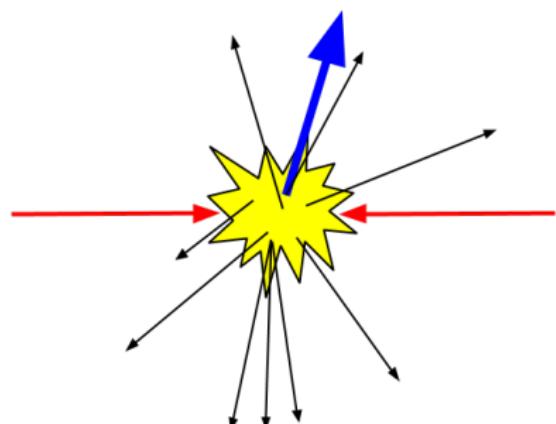
@GreigCowan (Edinburgh)
UK HEP forum, Nov 6th 2015

- $b \rightarrow sll$ FCNC decays
- Lepton (non-)universality
- CP violation in the beauty + charm systems

SEARCHING FOR NEW PHYSICS

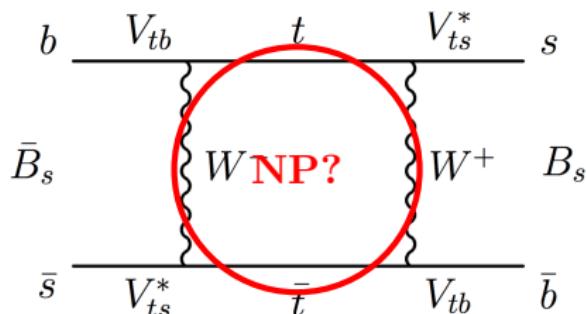
ON-SHELL

Cannot produce particles with $mc^2 > E$



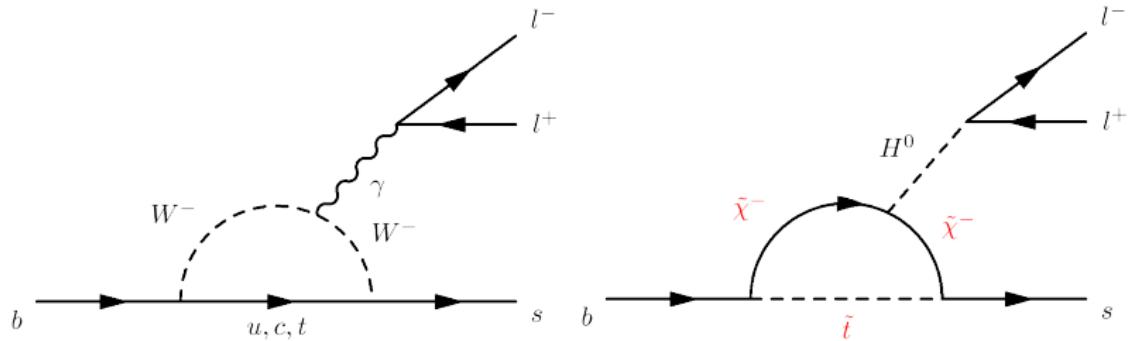
OFF-SHELL

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



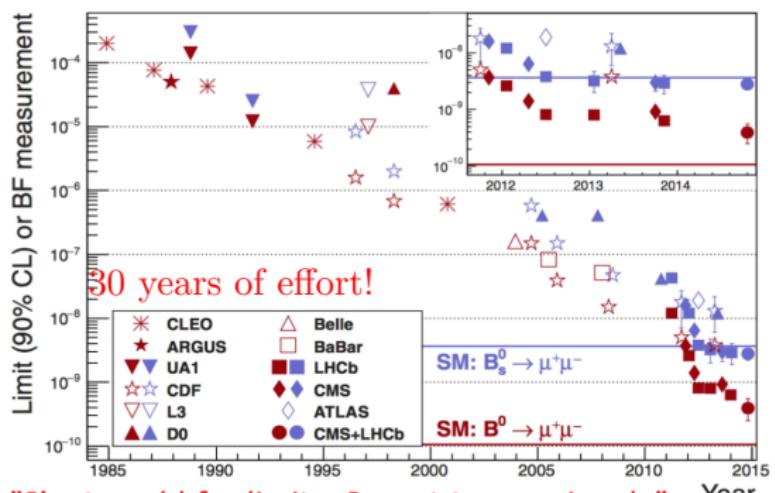
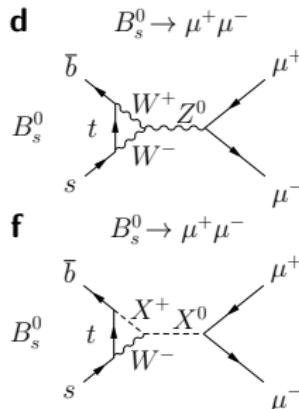
History: top quark mass predicted by quark mixing

Rare (FCNC) B meson decays



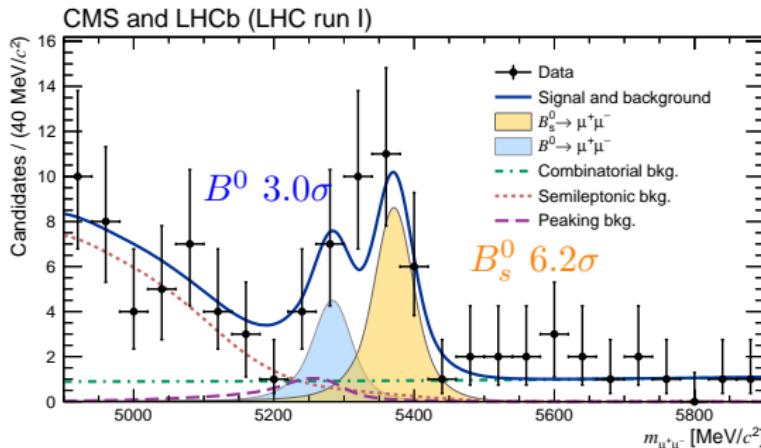
OBSERVATION OF $B_s^0 \rightarrow \mu^+ \mu^-$

- CKM suppressed and helicity suppressed ($(m_\mu/m_B)^2$).
- $\mathcal{B}(B_s^0 \rightarrow \mu\mu)_{\text{SM}} = (3.66 \pm 0.23) \times 10^{-9}$
- $\mathcal{B}(B^0 \rightarrow \mu\mu)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$
- [PRL 112, 101801 (2014)]
- Sensitive to scalar and pseudoscalar NP couplings, e.g., in MSSM $\mathcal{B} \propto (\tan \beta)^6$

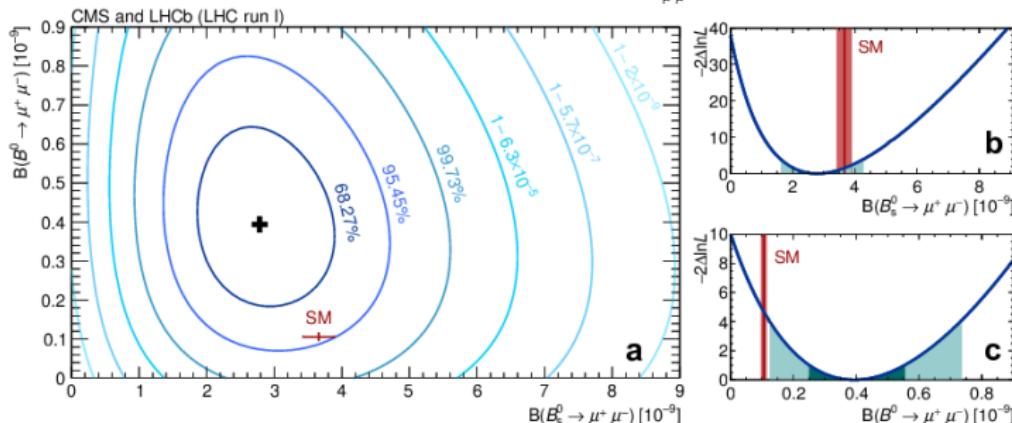


OBSERVATION OF $B_s^0 \rightarrow \mu^+ \mu^-$

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

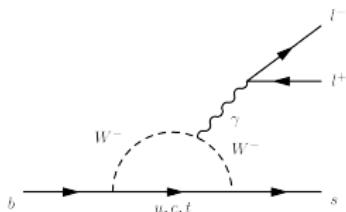


- Use multi-variate techniques to suppress background.
- Results consistent with SM at $\sim 2\sigma$.
- One to watch during LHC Run-2.

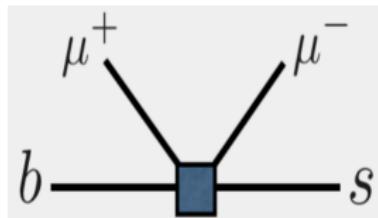
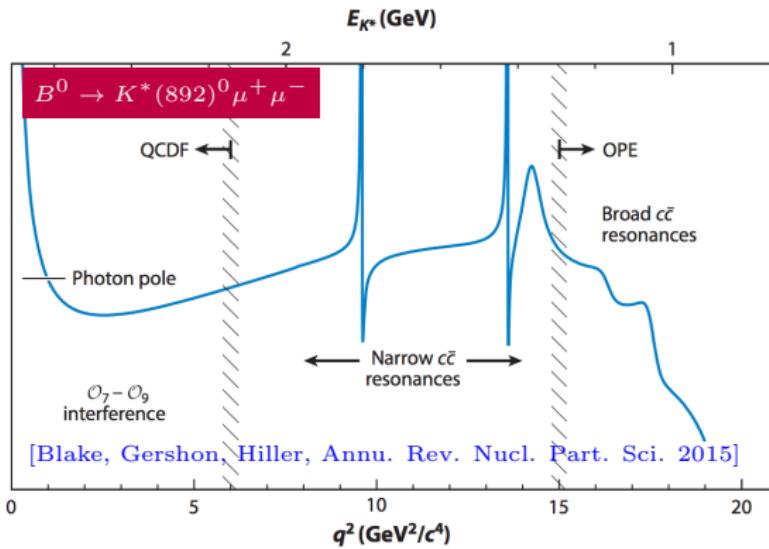


$b \rightarrow sll$ DECAYS

- $b \rightarrow s$ “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).

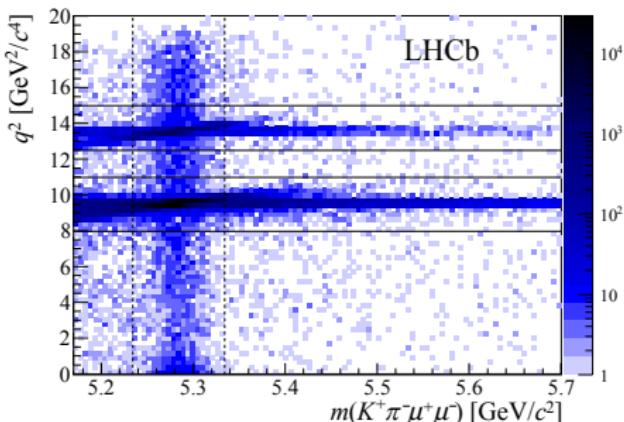


$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i [C_i \mathcal{O}_i + C'_i \mathcal{O}'_i]$$

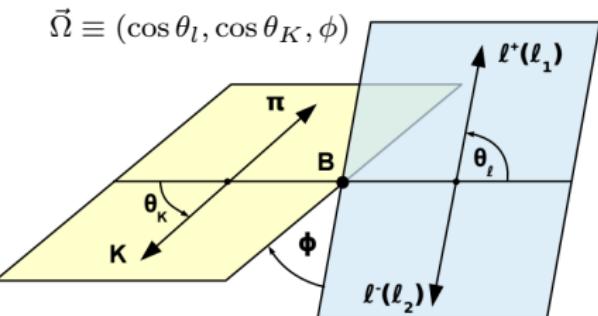


$$\mathcal{O}_{9(i)} = [\bar{s} \gamma^\mu P_{L(R)} b] [\bar{l} \gamma^\mu l]$$

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



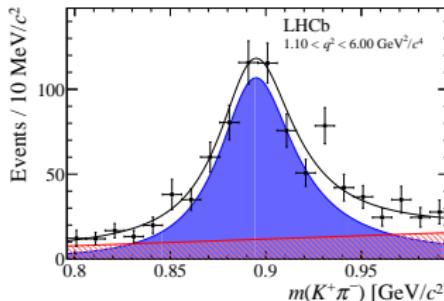
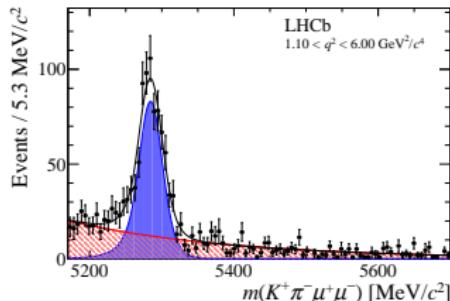
2398 ± 57 events, excluding the charmonia.



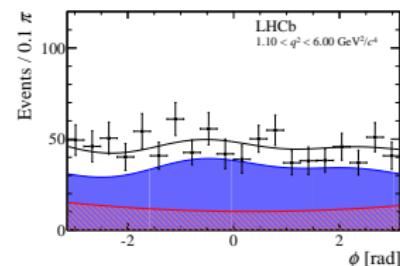
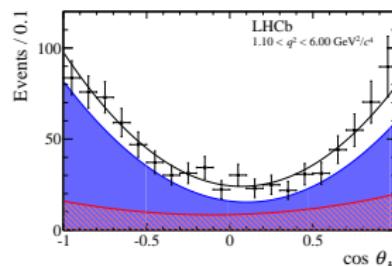
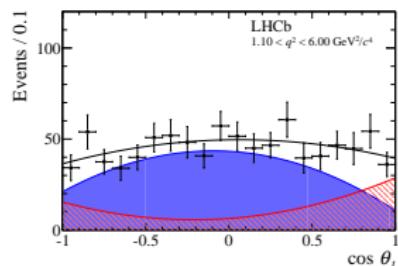
- Di-muon final state is experimentally clean signature, but BR $\sim 10^{-7}$.
- $P \rightarrow VV'$ decay, fully described by $q^2 \equiv m(\mu^+ \mu^-)^2$ and 3 helicity angles.
- $B^0 \rightarrow K^* \mu^+ \mu^-$ has rich system of observables (rates, angles, asymmetries) that are sensitive to NP.

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

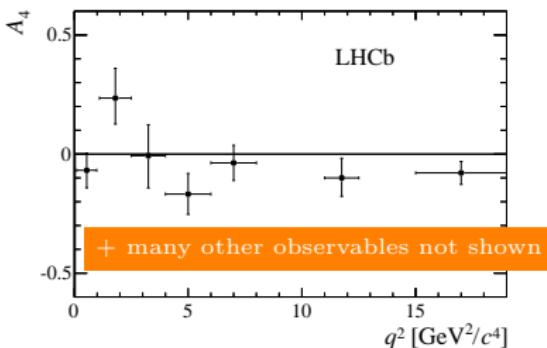
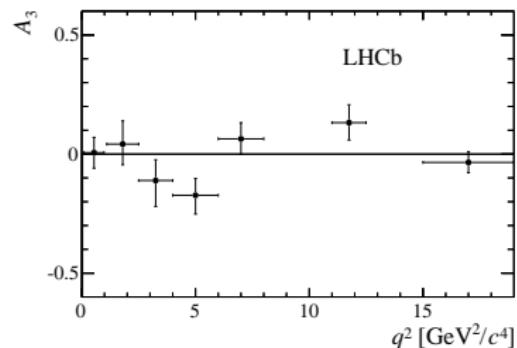
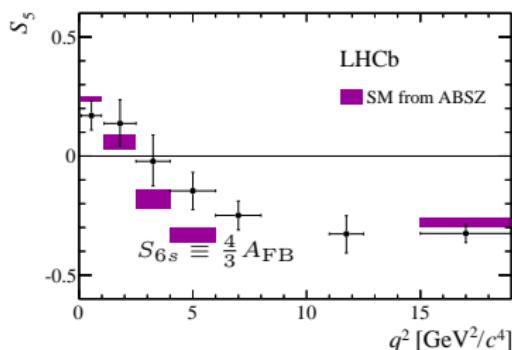
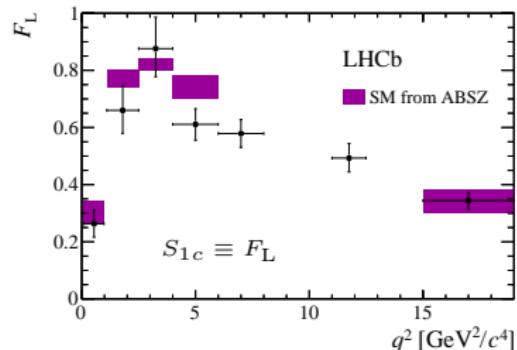
$$S_j = (I_j + \bar{I}_j) / \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2} \right), \quad A_j = (I_j - \bar{I}_j) / \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2} \right)$$



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



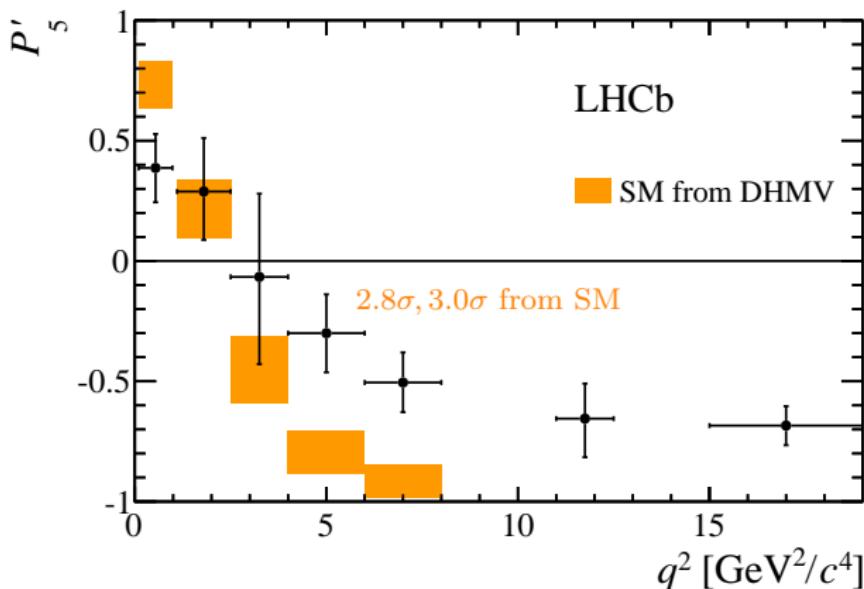
- S_i, A_i 's extracted using a max likelihood fit.
- Example fits in $\pm 50 \text{ MeV}/\text{c}^2$ around $K^*(892)^0$.
- For the first time the $K\pi$ S-wave is accounted for.



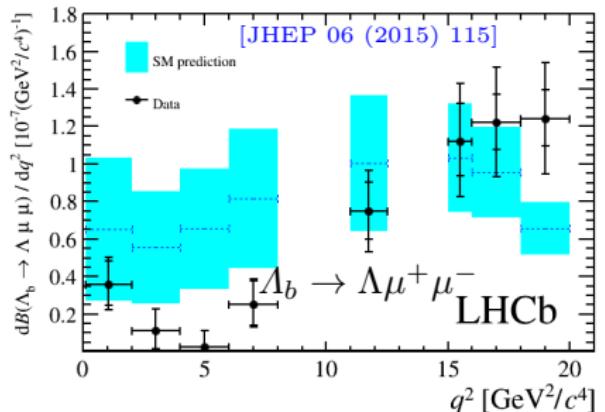
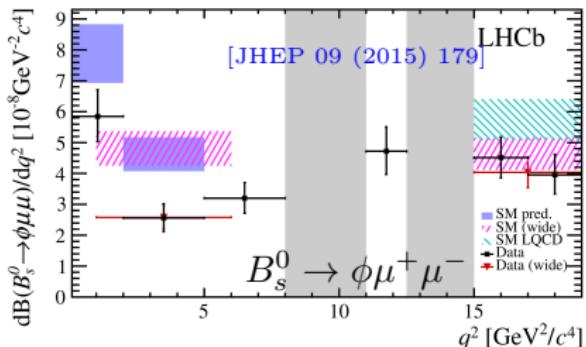
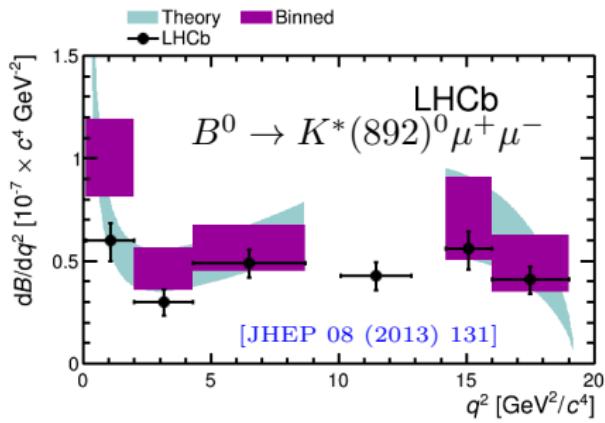
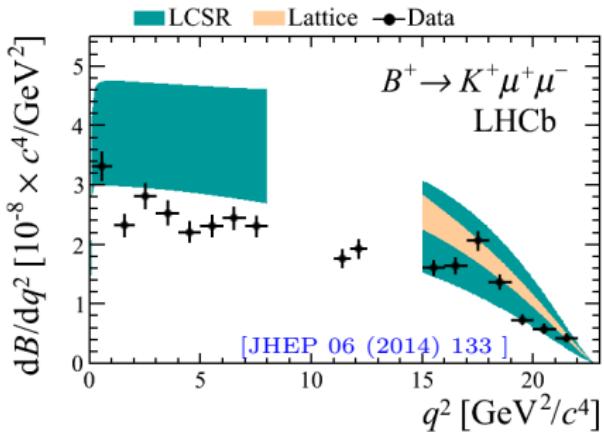
- Some observables have physical boundaries \Rightarrow use Feldman-Cousins for uncertainties.
- CP -asymmetries consistent with zero, as expected, but some deviations in CP -averaged observables (the S_j 's).

- “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 fb^{-1} LHCb result remains.

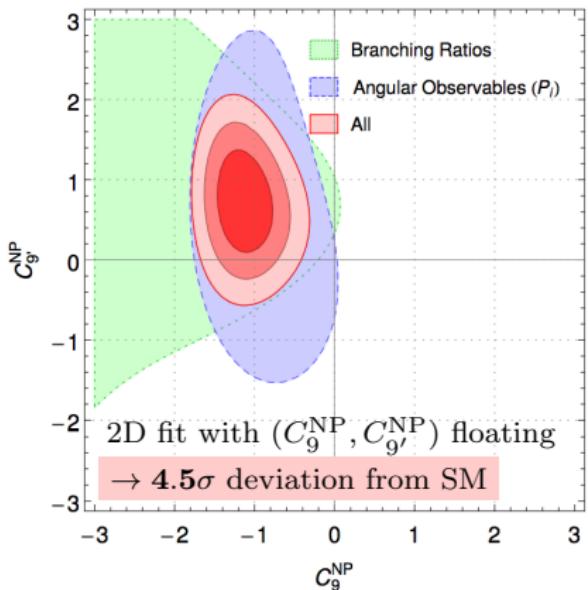
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}$$



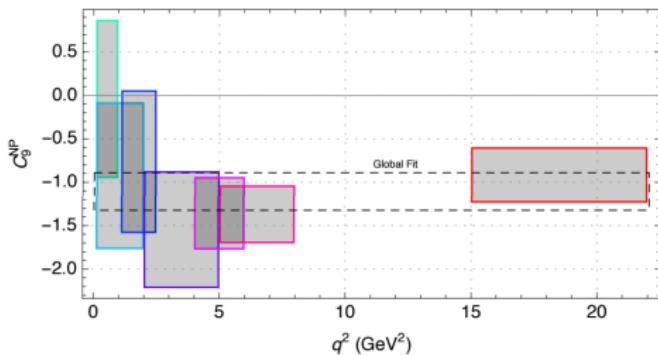
$b \rightarrow s\mu^+\mu^-$ BRANCHING FRACTIONS LOWER THAN PREDICTIONS



GLOBAL FITS FOR WILSON COEFFFS [DESCOTES-G ET AL, ARXIV:1510.04239]



Other global fits exist!



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

- Many fits performed with different subsets of the observables and different theoretical inputs (form factors, power corrections, charm loops).
- $C_9^{\text{NP}} < 0$ 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]

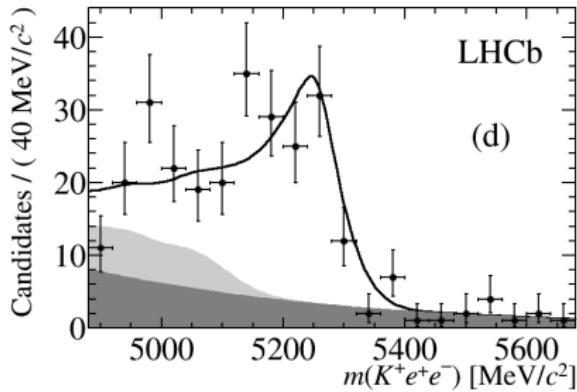
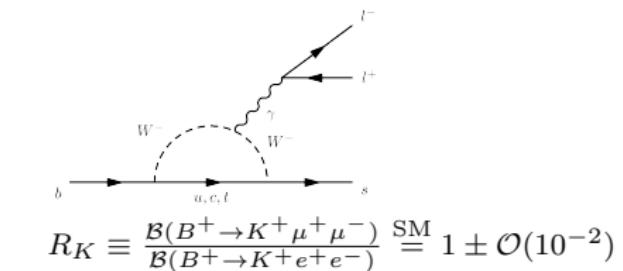
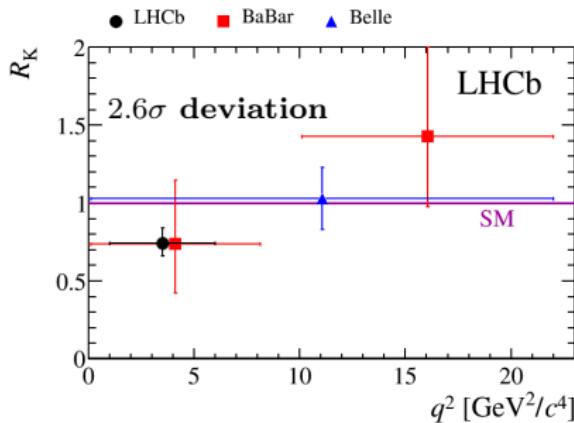
Lepton universality

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

LEPTON UNIVERSALITY ($B^+ \rightarrow K^+ l^+ l^-$)

[PRL 113, 151601 (2014)]

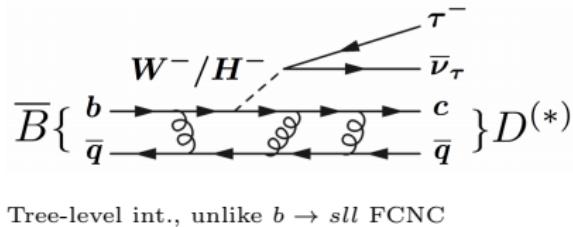
- In the SM only the Higgs boson has non-universal lepton couplings.
- This results in SM predictions of \sim unity for various decay-rate ratios.



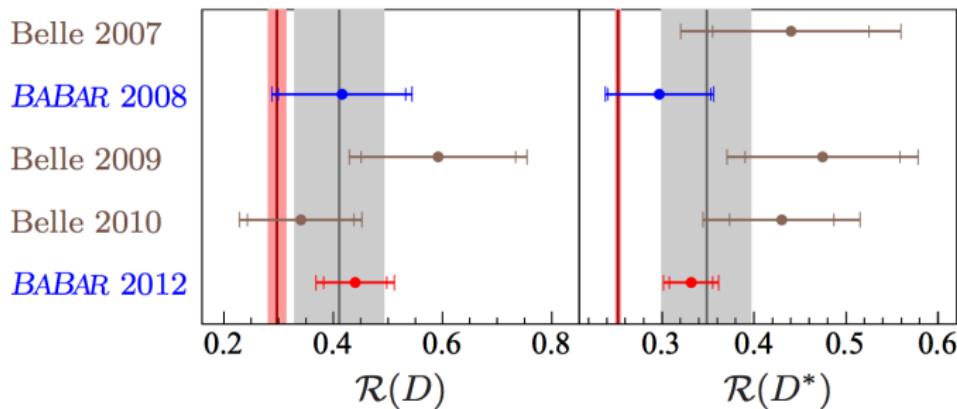
- Can be described assuming NP only in $b \rightarrow s\mu\mu$.
- Very interesting given indications of non-SM physics in other $b \rightarrow s\mu\mu$ FCNC decays and 2.4 σ excess in $H \rightarrow \tau\nu$ at CMS [PLB 749 (2015) 337].
- Future: Make similar measurements using other decays - $R(\phi)$,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

LEPTON UNIVERSALITY ($\overline{B^0} \rightarrow D^{*+} l \nu$)

- 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.



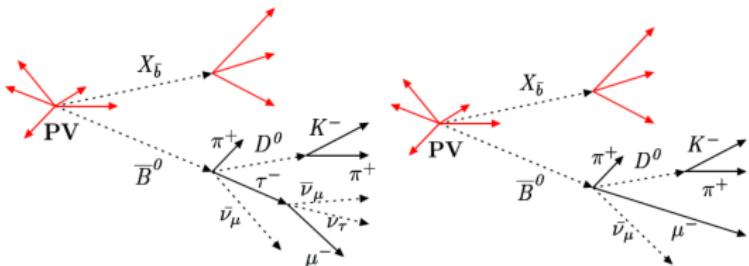
$$R(D^*) \equiv \frac{\mathcal{B}(\overline{B^0} \rightarrow D^{*+} \tau \nu_\tau)}{\mathcal{B}(\overline{B^0} \rightarrow D^{*+} \mu \nu_\mu)}$$



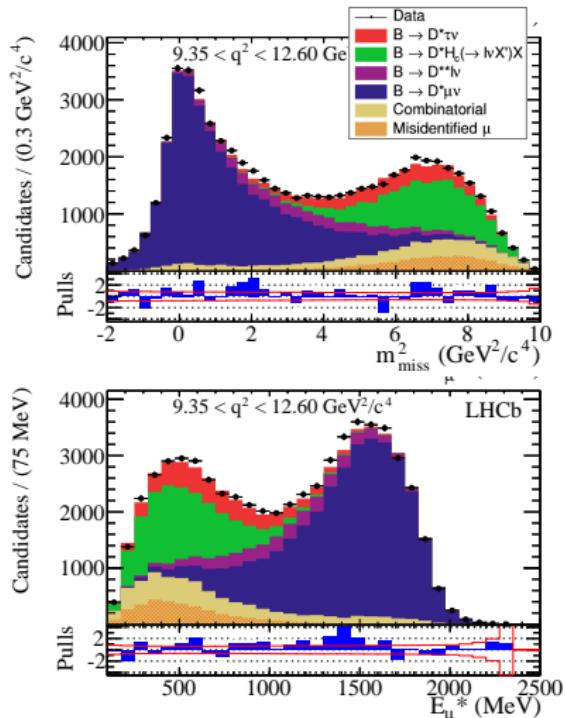
- Interesting given hints of non-universality in $B^+ \rightarrow K^+ l^+ l^-$ decays (R_K) and excl/incl measurements of V_{ub} , V_{cb} .

LEPTON UNIVERSALITY ($\overline{B^0} \rightarrow D^{*+} l \nu$) [PRL 115, 111803 (2015)]

- Very challenging measurement at hadron collider (no beam constraints and large backgrounds).
- $\mathcal{B}(\tau \rightarrow \mu \nu_\mu \nu_\tau) = (17.41 \pm 0.04)\%$
 - 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 →

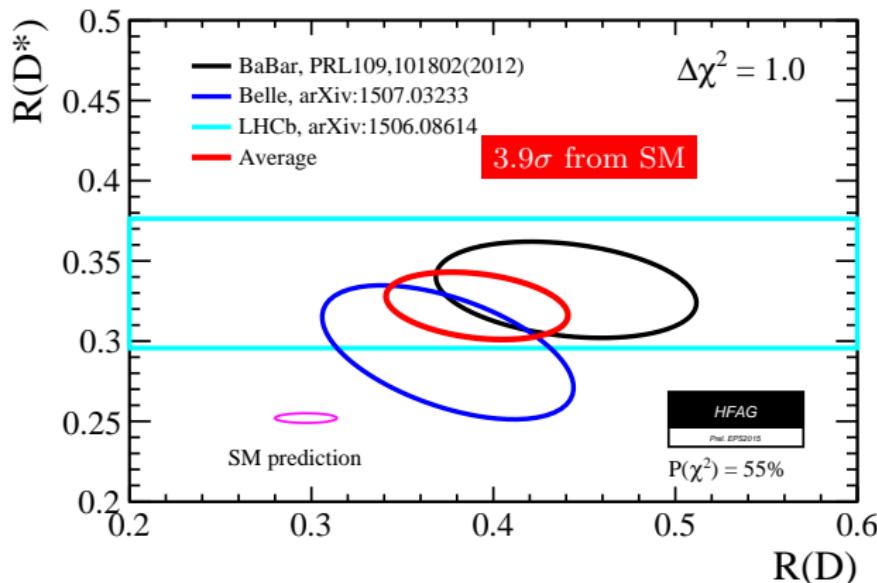


$$R(D^*) \equiv \frac{\mathcal{B}(\overline{B^0} \rightarrow D^{*+} \tau \nu_\tau)}{\mathcal{B}(\overline{B^0} \rightarrow D^{*+} \mu \nu_\mu)}$$



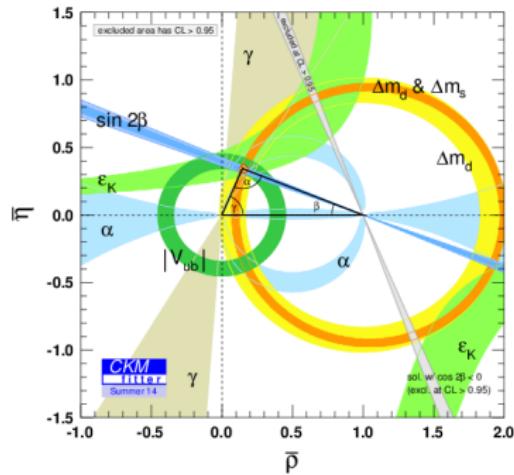
LEPTON UNIVERSALITY $(\overline{B^0} \rightarrow D^{*+} l \nu)$ [PRL 115, 111803 (2015)]

- 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 $b_L \rightarrow c_L \tau_L \nu_L$ amplitude.
- Now using other decay modes to make similar measurements ($R(D_{(s)})$, $R(\Lambda_c)$).

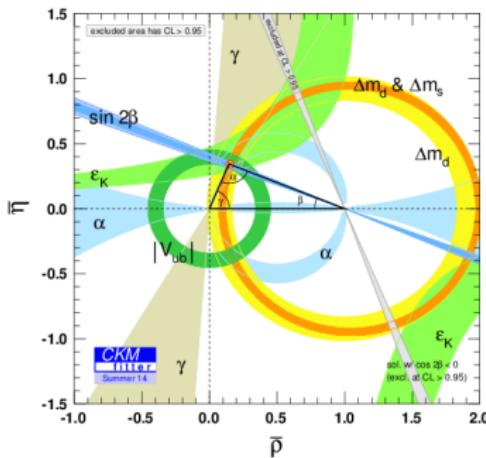
CP violation in the quark sector



CP VIOLATION IN THE QUARK SECTOR

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

Wolfenstein parameterisation



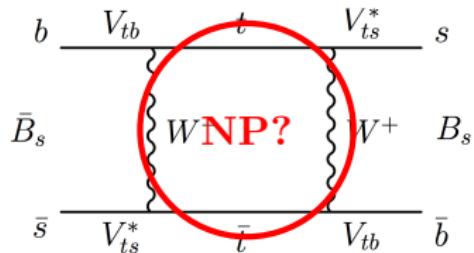
- 3 generations + **1 phase** $\rightarrow \bar{\eta} \neq 0$ is only source of CP violation in SM.
- CKM picture confirmed up to $\sim 20\%$.
- Couplings show strong hierarchy not seen in lepton sector
 \Rightarrow “*SM flavour puzzle*”
- New Physics should have flavour structure similar to SM...
- ... or the NP scale is very very large ($\sim 100\text{TeV}$) \Rightarrow “*NP flavour puzzle*”
- Need more **precision measurements** to look for small deviations.

3 TYPES OF CP VIOLATION

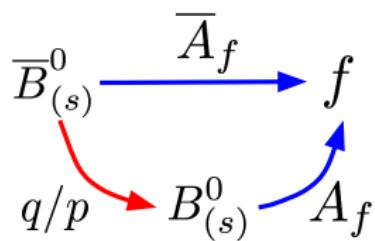
- 1 Mixing: $|q/p| \neq 1$
- 2 Decay: $|A_f/\bar{A}_f| \neq 1$
- 3 Interference between mixing and decay:

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

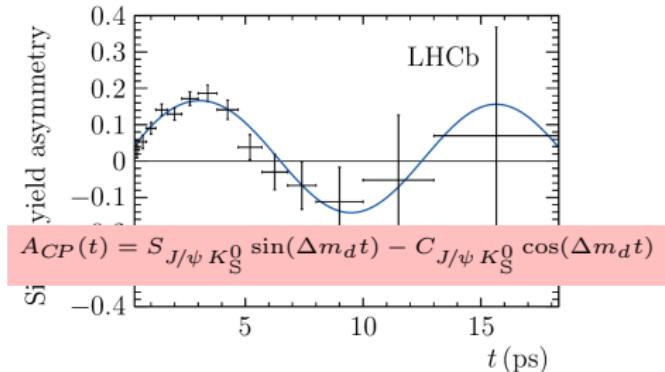
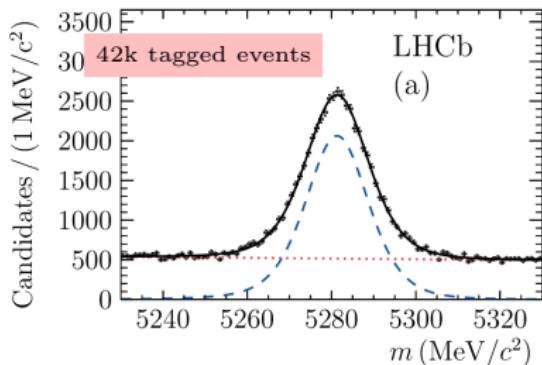
Expect $|\lambda_f| \equiv \left|\frac{q}{p}\frac{A_f}{\bar{A}_f}\right| \approx 1$



$$\begin{aligned} |B_{s,L}^0\rangle &= p|B_s^0\rangle + q|\bar{B}_s^0\rangle \\ |B_{s,H}^0\rangle &= p|B_s^0\rangle - q|\bar{B}_s^0\rangle \end{aligned}$$

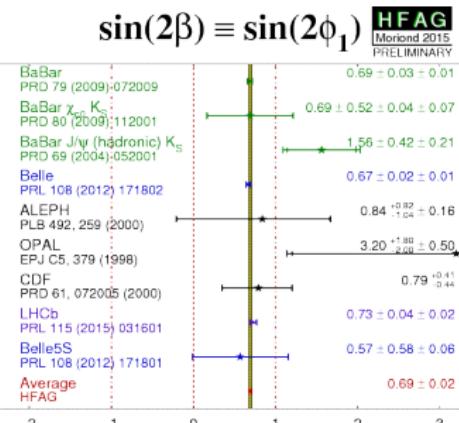


$$A_{CP}(t) \equiv \frac{\Gamma_{\bar{B}^0 \rightarrow f} - \Gamma_{B^0 \rightarrow f}}{\Gamma_{\bar{B}^0 \rightarrow f} + \Gamma_{B^0 \rightarrow f}} = \frac{S_f \sin(\Delta m t) - C_f \cos(\Delta m t)}{\cosh(\Delta \Gamma t/2) + A_{\Delta \Gamma} \sinh(\Delta \Gamma t/2)}$$

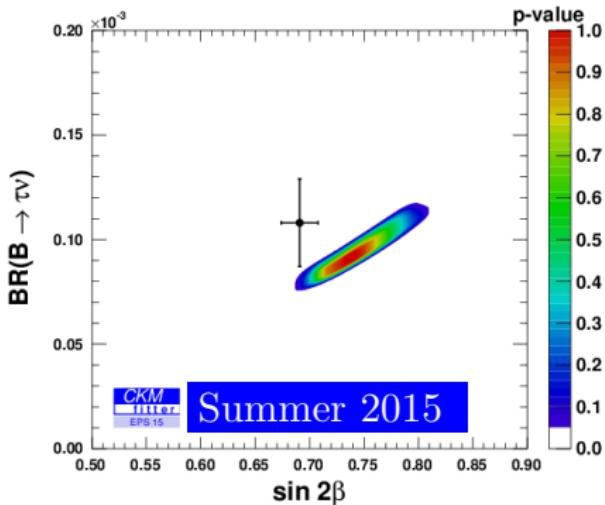
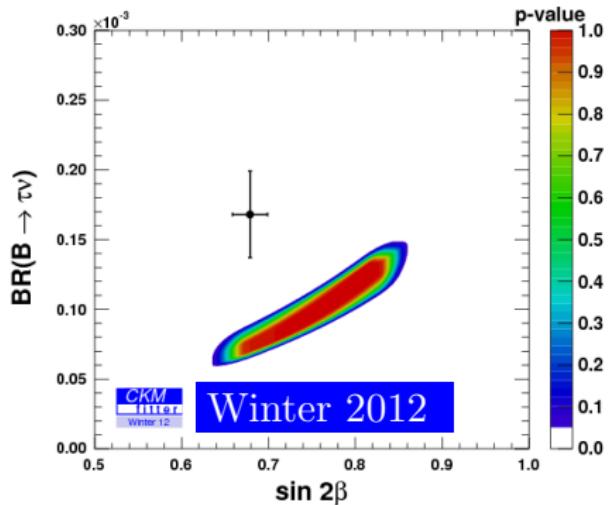


$$\begin{aligned} S_{J/\psi K_S^0} &\approx \sin 2\beta \\ S_{J/\psi K_S^0} &= +0.731 \pm 0.035 \pm 0.020 \\ C_{J/\psi K_S^0} &= -0.038 \pm 0.032 \pm 0.005 \end{aligned}$$

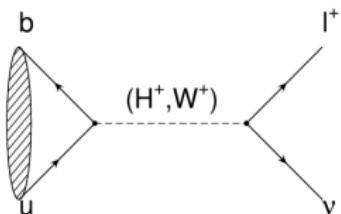
- Similar precision to B-factories, but LHCb measurement pulled WA up towards indirect determination from global fit.
- $\sin 2\beta$ World Average = 0.691 ± 0.017
- $\sin 2\beta$ CKMfitter = $0.748^{+0.030}_{-0.032}$



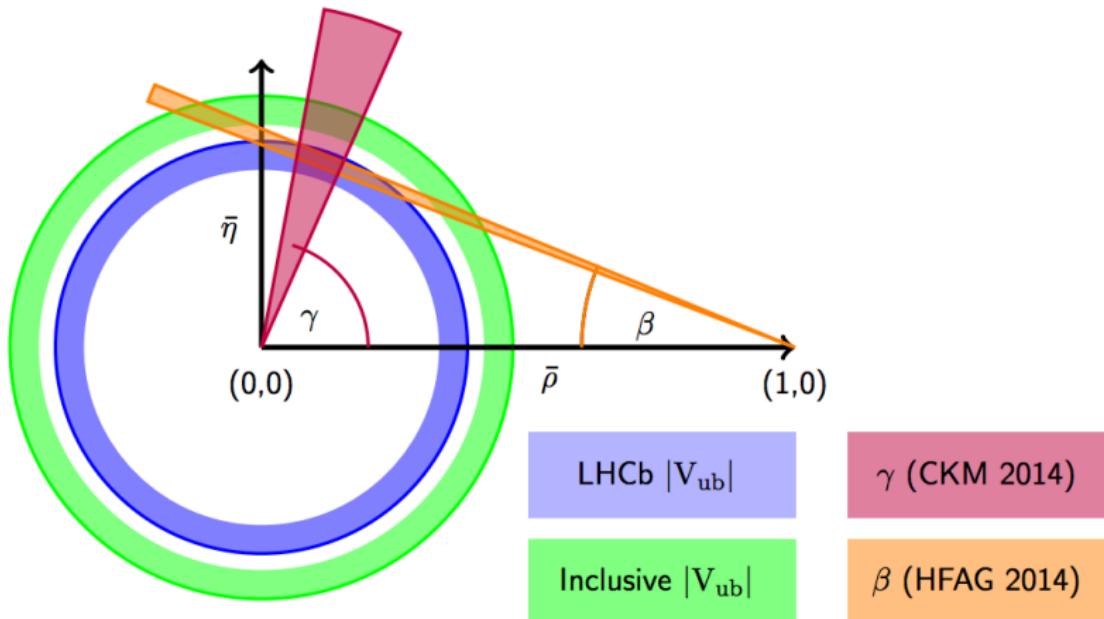
$B^+ \rightarrow \tau^+ \nu_\tau$ VS. $\sin 2\beta$



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

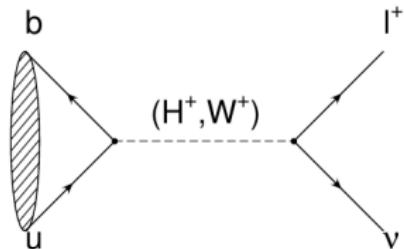
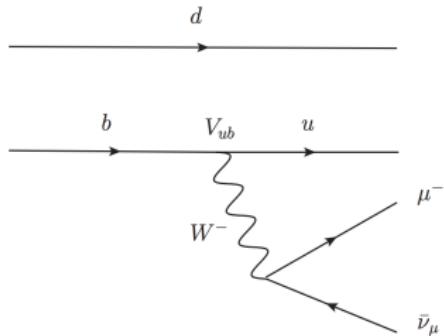


$|V_{ub}|$ FROM THE CKM UNITARITY TRIANGLE

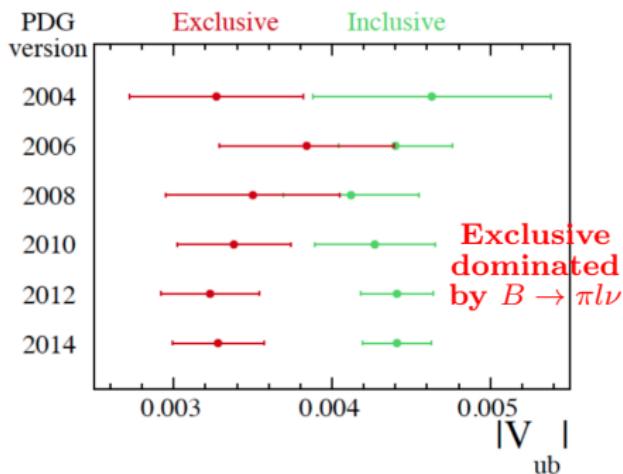


- $|V_{ub}|$ indispensable in CKM unitarity fits.
- Excellent test of unitarity (and/or NP) by comparing $|V_{ub}|$ (tree-level process) with $\sin 2\beta$ (B^0 -mixing, loop process).

$|V_{ub}|$

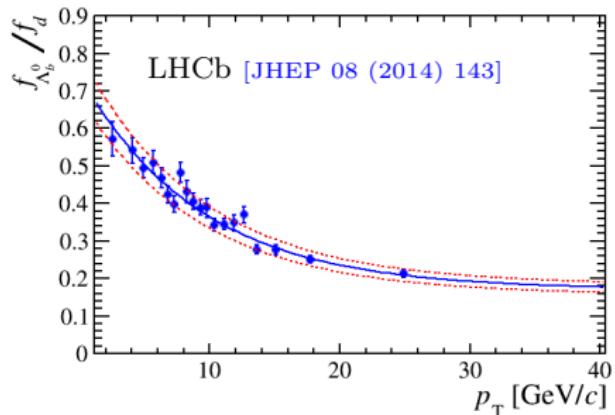
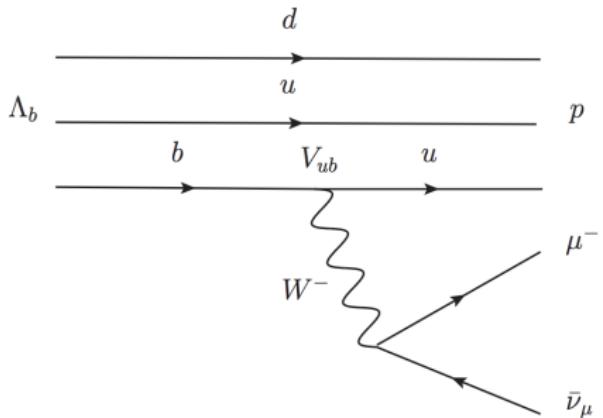


- Measure exclusive branching fraction ($B^0 \rightarrow \pi l \nu$, $B^+ \rightarrow \tau \nu_\tau$).
- Or inclusive sum of states ($b \rightarrow ul\nu$).
- Each method relies on different theoretical inputs.
- Long-standing discrepancy between these two approaches using results from BaBar/Belle.



$|V_{ub}|$ USING $\Lambda_b \rightarrow p\mu\bar{\nu}_\mu$

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



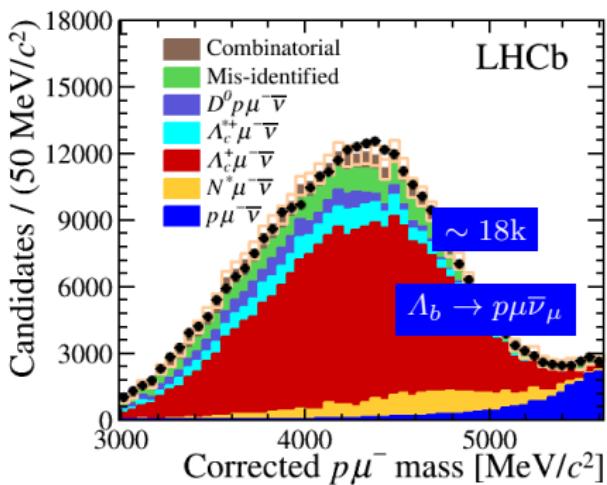
ASIDE ON b -BARYONS:

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

$|V_{ub}|$ USING $\Lambda_b \rightarrow p\mu\bar{\nu}_\mu$

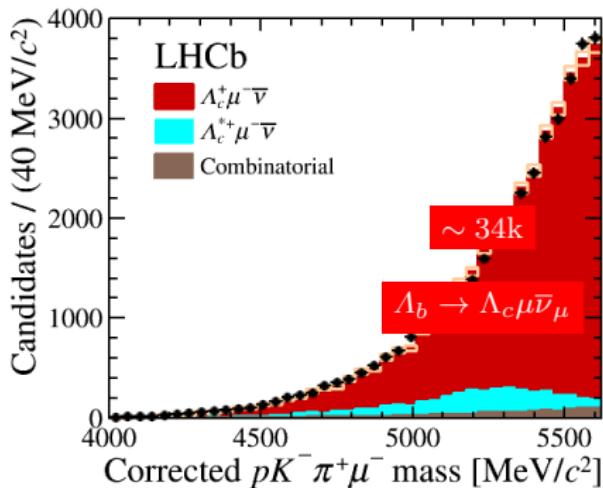
[NATURE PHYSICS 10 (2015) 1038]

- To cancel many systematic uncertainties we measure the branching ratio relative to $\Lambda_b \rightarrow \Lambda_c\mu\bar{\nu}_\mu$, $\Lambda_c \rightarrow pK\pi$.
- Must use global $|V_{cb}|$ average as input.
- Lattice QCD input is **crucial** [Meinel arXiv:1503.01421].
- Fit corrected mass (peaks at $m(\Lambda_b)$)



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

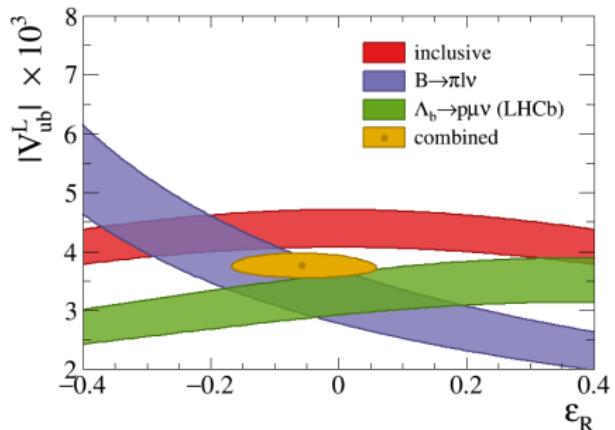
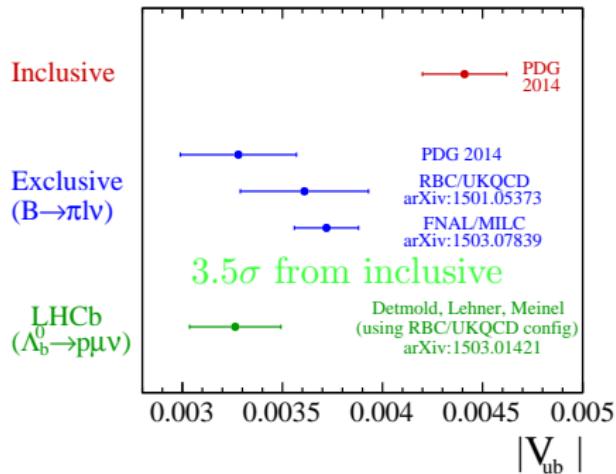
$$m_{\text{corr}} = \sqrt{m_{h\mu}^2 + p_T^2} + p_T$$



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

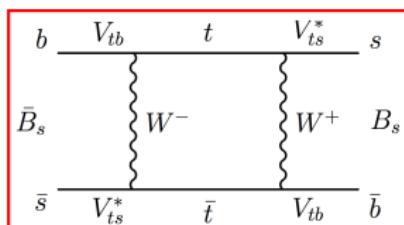
$|V_{ub}|$ USING $\Lambda_b \rightarrow p\mu\bar{\nu}_\mu$

[NATURE PHYSICS 10 (2015) 1038]



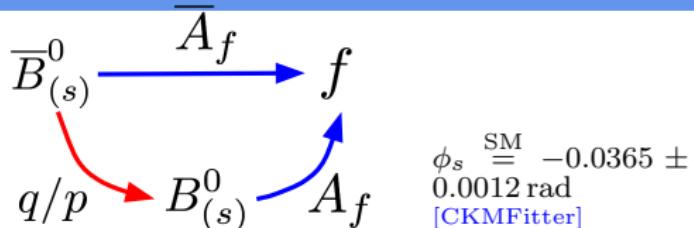
- **Syst. limited** from Lattice QCD calc. of Λ_b form-factor (more precise at high q^2).
- $\Lambda_b \rightarrow p\mu\nu$ has different dependence on right-handed currents than other modes.
- Combination starts to disfavour interpretation of discrepancy in terms of quantity of RHC (ϵ_R).

CP VIOLATION IN $b \rightarrow c\bar{c}s$ DECAY + MIXING

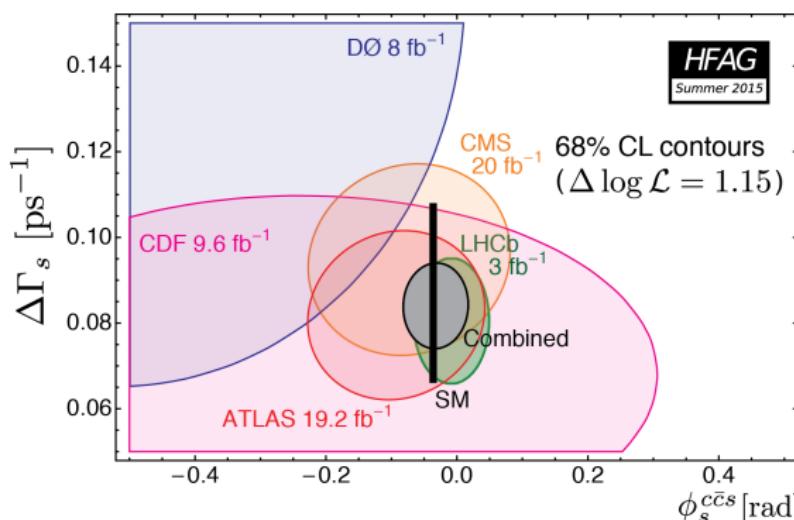


$$\phi_{mix} = 2 \arg(V_{tb} V_{ts}^*)$$

$$\phi_{decay} = \arg(V_{cb} V_{cs}^*)$$



$$\phi_s \equiv -\arg\left(\frac{q}{p} \frac{A_f}{\bar{A}_f}\right)$$



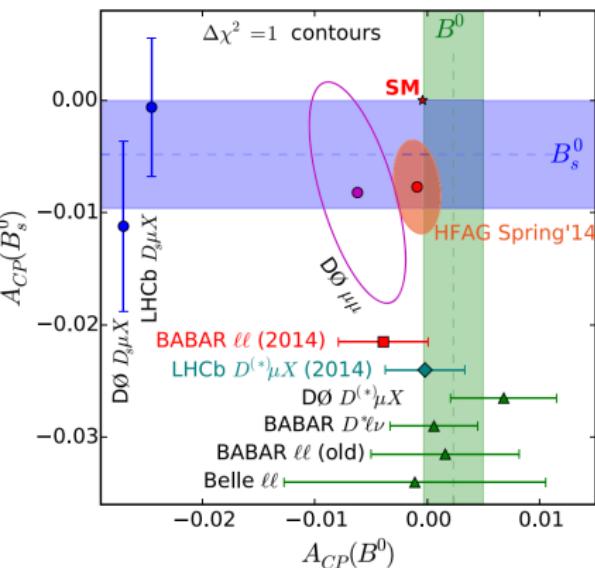
COMBINATION

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

- New physics not large.
- ⇒ need to control SM effects (penguins).
- Also competitive in gluonic penguin decays ($B_s^0 \rightarrow \phi\phi$).

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

[PRL 114, 081801 (2015)]



Use semileptonic B^0 , B_s^0 decays

$$a_{\text{sl}} \equiv \frac{\Gamma(\bar{B} \rightarrow B \rightarrow f) - \Gamma(B \rightarrow \bar{B} \rightarrow \bar{f})}{\Gamma(\bar{B} \rightarrow B \rightarrow f) + \Gamma(B \rightarrow \bar{B} \rightarrow \bar{f})} \equiv A_{CP}$$

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

[Lenz arXiv:1205.1444] - tiny in SM

$$\begin{aligned} a_{\text{sl}}^d &= (-4.1 \pm 0.6) \times 10^{-4} \\ a_{\text{sl}}^s &= (+1.9 \pm 0.3) \times 10^{-5} \end{aligned}$$

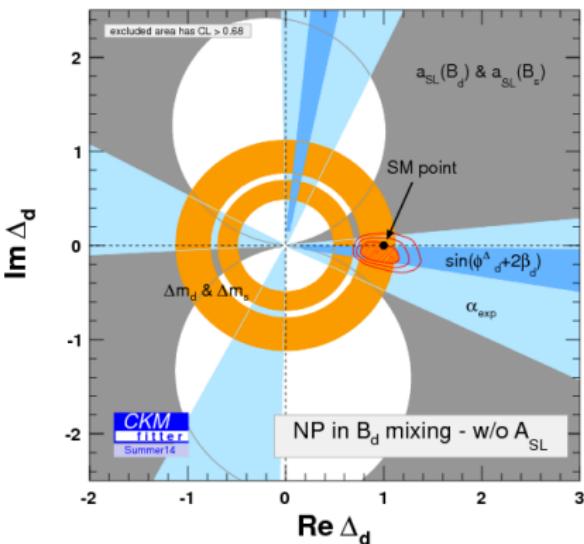
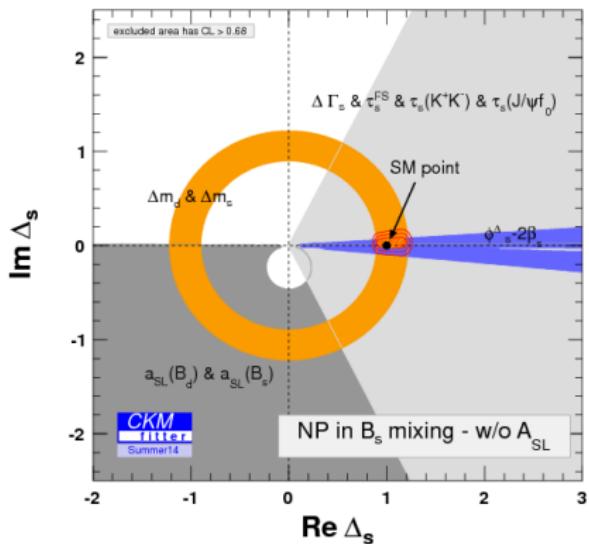
$$a_{\text{sl}}^s = -0.0075 \pm 0.0041 \text{ (HFAG)}$$

$$a_{\text{sl}}^d = -0.0015 \pm 0.0017 \text{ (HFAG)}$$

- No tagging needed. Typically time-dep. measurement for B^0 system, indep. for B_s^0 .
- Crucial to control production and detection asymmetries using control samples.
- **~3 σ 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]



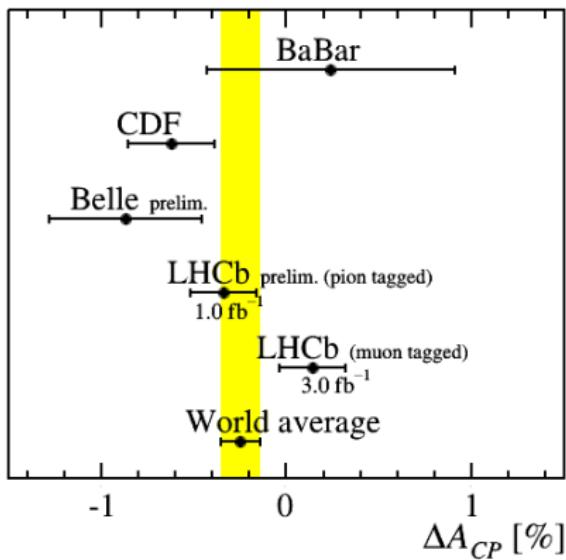
- Introduce generic NP through complex parameter Δ_q :
$$M_{12}^{\text{NP},q} = M_{12}^{\text{SM},q} \Delta_q$$
- NP contribution to B_s^0 mixing is limited to $< 30\%$ at 3σ .
- But beware of **hadronic uncertainties** that could mimic small NP.
- **Take-home message:** will significantly shrink these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

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...

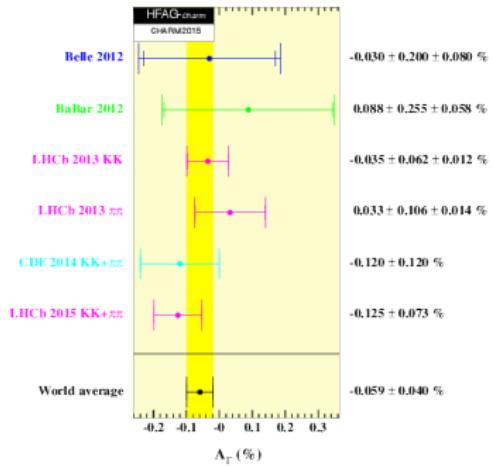
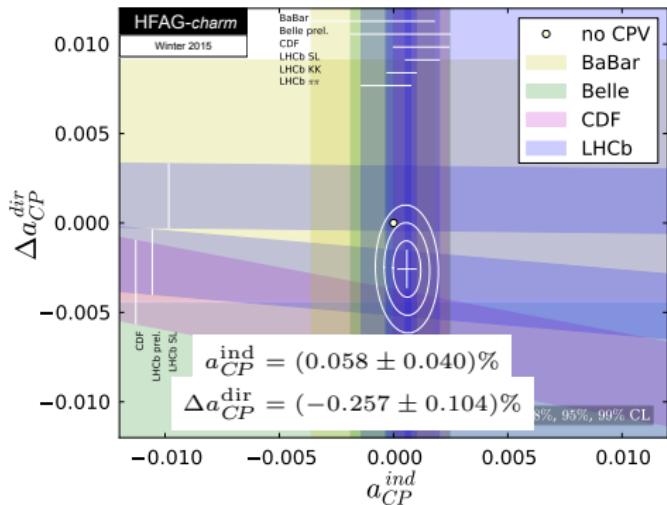
$$A_{CP} = \frac{\Gamma(\overline{D}^0 \rightarrow f) - \Gamma(D^0 \rightarrow f)}{\Gamma(\overline{D}^0 \rightarrow f) + \Gamma(D^0 \rightarrow f)}$$

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



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.

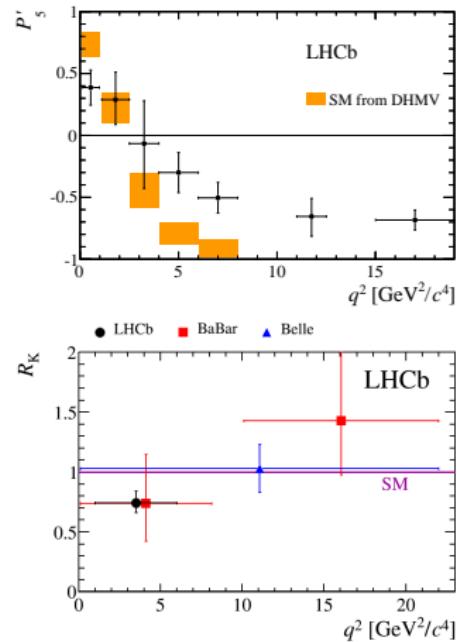
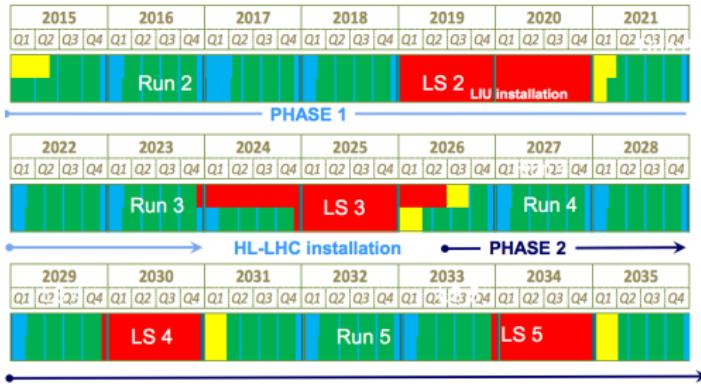


$$A_\Gamma \equiv \frac{\tau(\bar{D}^0 \rightarrow h^+ h^-) - \tau(D^0 \rightarrow h^+ h^-)}{\tau(\bar{D}^0 \rightarrow h^+ h^-) + \tau(D^0 \rightarrow h^+ h^-)} \approx -a_{CP}^{ind} - a_{CP}^{dir} y_{CP}$$

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

SUMMARY

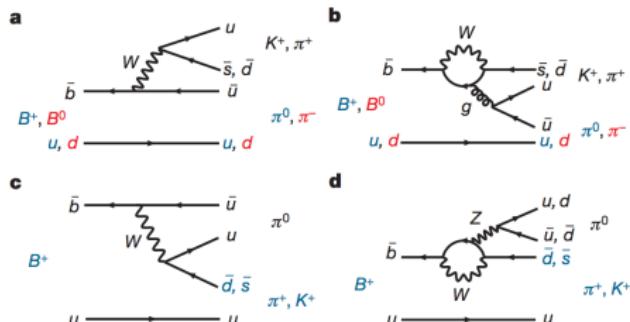
- Exciting indications of non-SM physics in B physics.
- Crucially, these are in related channels:
 - $R(D^*), R_K, P'_5, b \rightarrow s$ penguin branching ratios, ($H \rightarrow \tau\mu$).
- More measurements and theory developments needed to interpret what we are seeing.
- CKM mechanism holding up to scrutiny, need more precision.
- Most results statistically limited → looking forward to Run-2 of LHC and start-up of Belle-II ~ 2018 .



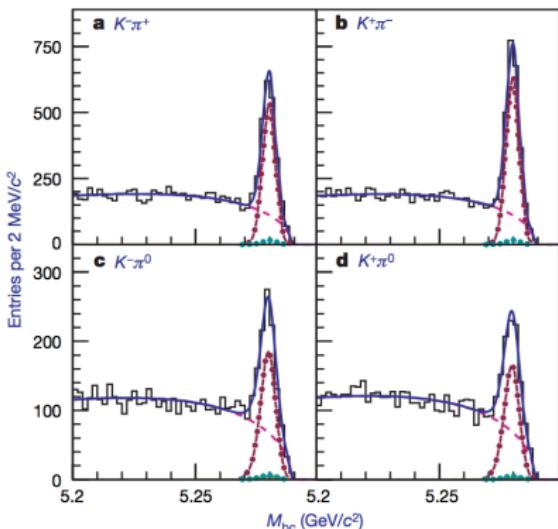
THE “ $K\pi$ PUZZLE”

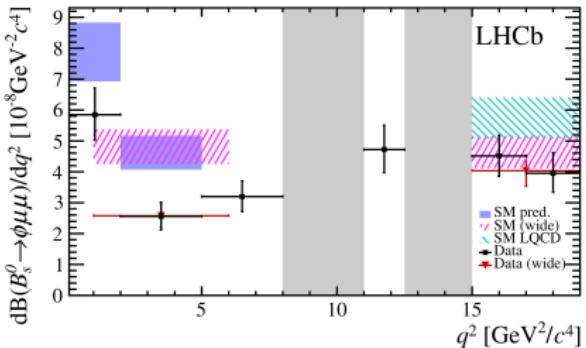
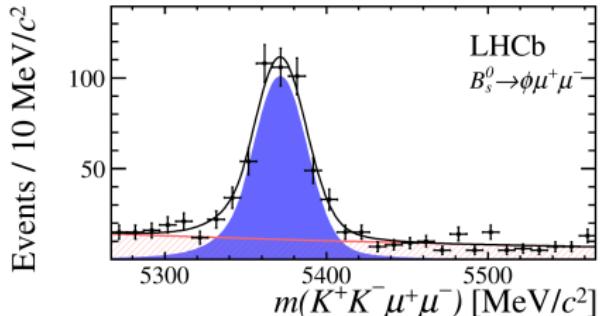
$$\Delta A_{CP} \equiv A_{CP}(B^+ \rightarrow K^+\pi^0) - A_{CP}(B^0 \rightarrow K^+\pi^-) = 0.12 \pm 0.02$$

- 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]).
- $B^0 \rightarrow K^+\pi^-$ measured at BaBar, Belle, CDF, LHCb. $B^+ \rightarrow K^+\pi^0$ at BaBar/Belle.
- $B^+ \rightarrow K^+\pi^0$ 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 $B^0 \rightarrow K^0\pi^0$).

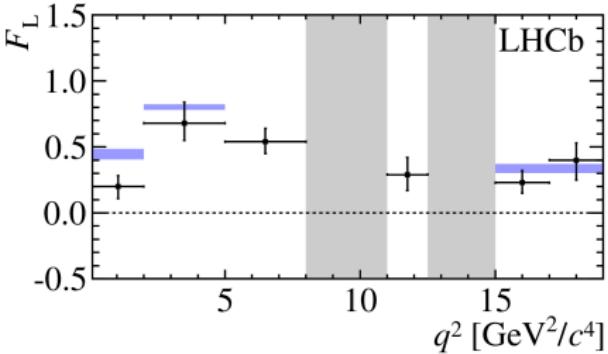


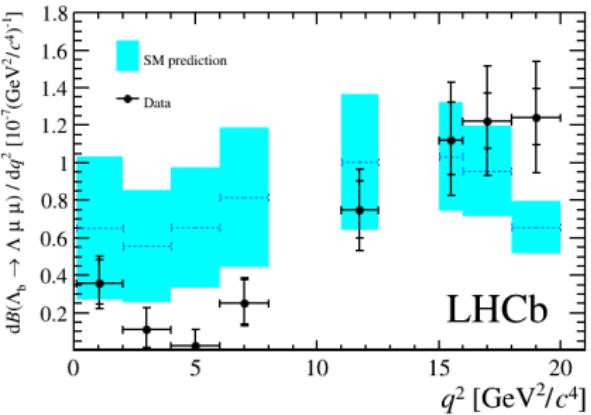
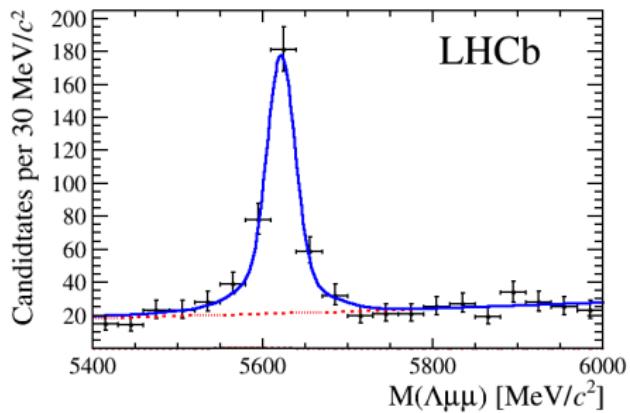
[Belle, Nature 452, 332-335 (2008)]



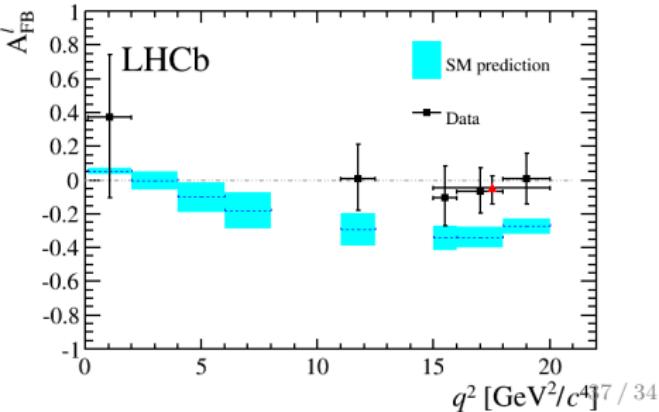


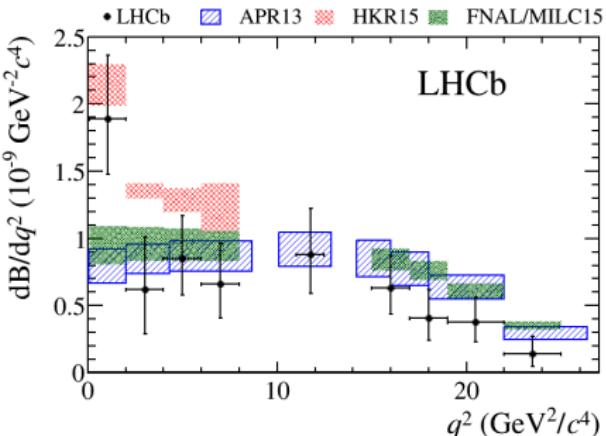
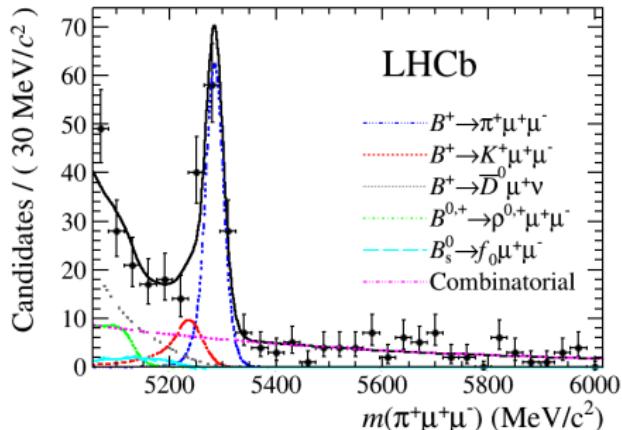
- Differential branching fraction and angular analysis (using max likelihood fit).
- Angular observables in good agreement with SM.
- $d\mathcal{B}/dq^2$ in $q^2 \in [1, 6] \text{ GeV}/c^2$ lower than SM by 3.2σ .
 - Similar story in $B^+ \rightarrow K^+ \mu^+ \mu^-$ and $B^0 \rightarrow K^{*0} \mu^+ \mu^-$.
- SM pred. and wide from [arXiv:1503.05534]
- SM LQCD from [PRL112(2014)21200]



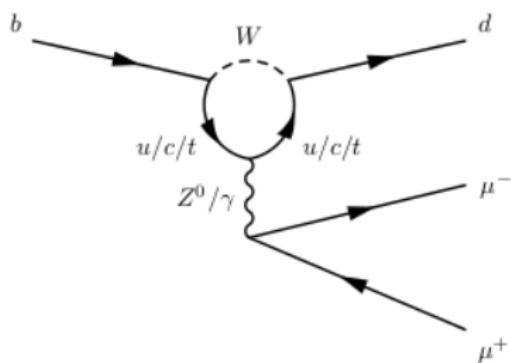


- Differential branching fraction and first angular analysis (using max likelihood fit).
- Evidence for decay in first q^2 bin, but not in $q^2 \in [1.1, 6] \text{ GeV}/c^2 \Rightarrow$ lower than SM.
- Some angular observables in good agreement with SM, others not. e.g. \rightarrow
- SM prediction [PRD87(2013)074502]





- First measurement of differential branching fraction and CP asymmetry in $b \rightarrow d\bar{d}$ 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

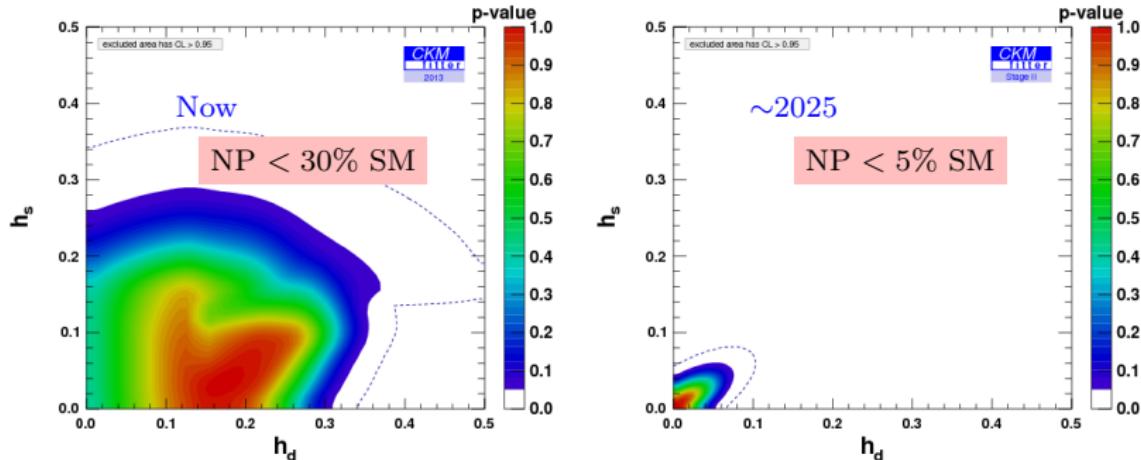
Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \rightarrow J/\psi \phi)$ (rad)	0.049	0.025	0.009	~ 0.003
	$\phi_s(B_s^0 \rightarrow J/\psi f_0(980))$ (rad)	0.068	0.035	0.012	~ 0.01
	$A_{sl}(B_s^0) (10^{-3})$	2.8	1.4	0.5	0.03
Gluonic penguin	$\phi_s^{\text{eff}}(B_s^0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

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

NEW PHYSICS PROSPECTS

[J. CHARLES ET AL. PRD 89, 033016 (2014)]

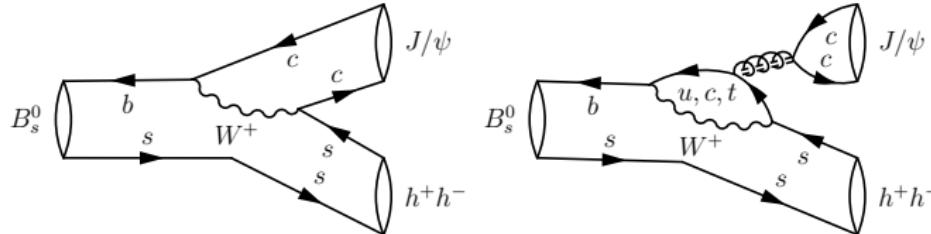
- Assume that NP only enters B^0 and B_s^0 mixing: $M_{12}^{d,s} = (M_{12}^{d,s})_{\text{SM}}(1 + h_{d,s}e^{2i\sigma_{d,s}})$.



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

Couplings	NP loop order	Scales (in TeV) probed by	
		B_d mixing	B_s mixing
$ C_{ij} = V_{ti} V_{tj}^* $ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$ C_{ij} = 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:

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

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

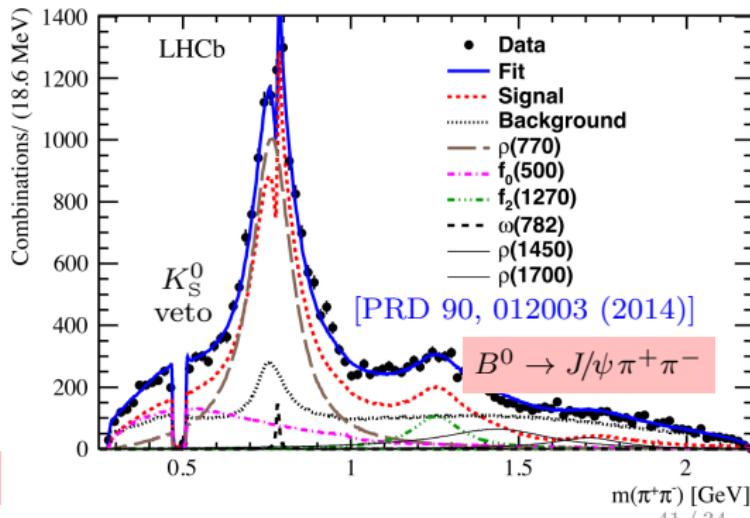
- Difficult-to-calculate non-perturbative hadronic effects could lead to big enhancement.
- Measure δ_{Penguin} using decays where penguin/tree ratio is enhanced.

[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%).

- $|\delta_P| < 1.8^\circ$

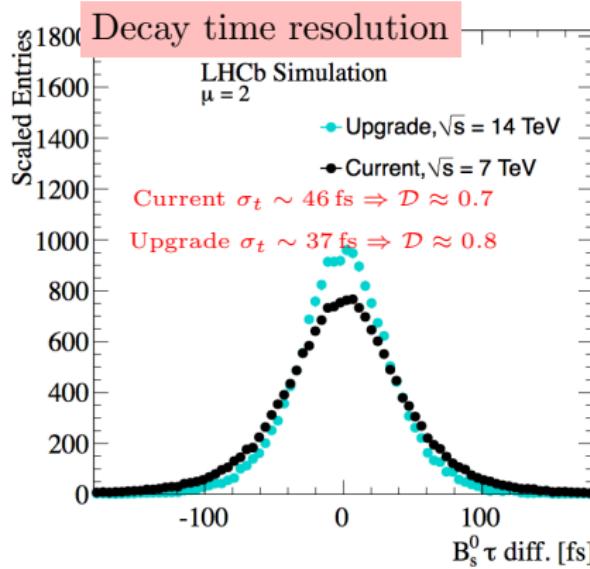
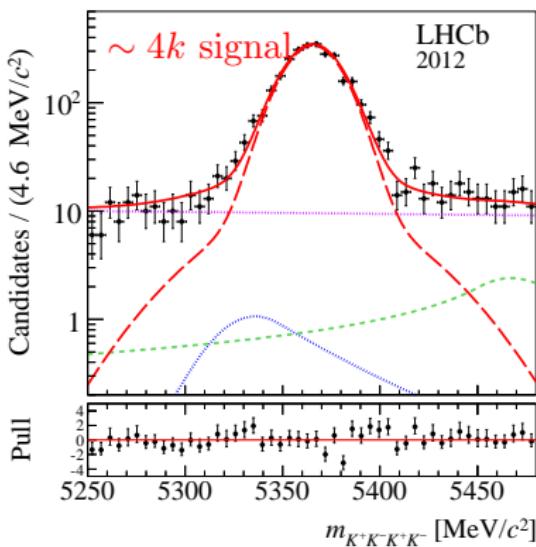
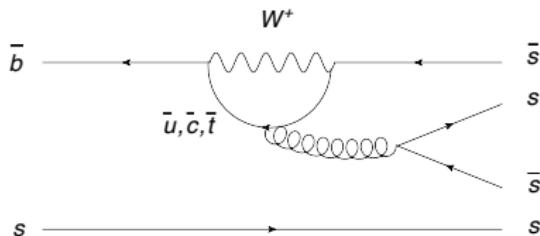
c.f. $\sigma(\phi_s) = \pm 2.0^\circ$, $\sigma(\phi_d) = \pm 1.4^\circ$



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

- $B_s^0 \rightarrow \phi\phi$: $b \rightarrow s$ penguin decays sensitive to NP in the loops.
- $\phi \rightarrow KK$: 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: $|\phi_s| < 0.02$ rad



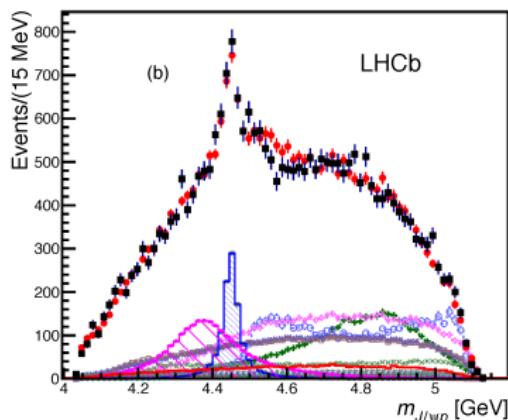
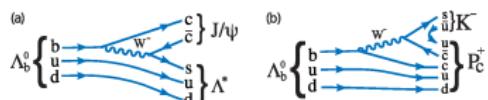
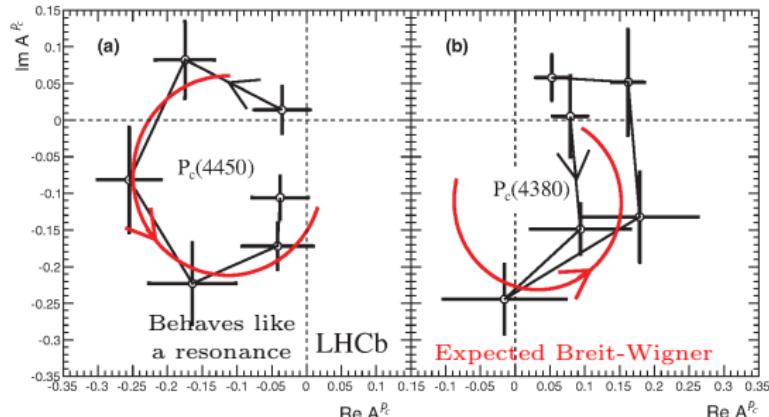
Exotic spectroscopy, top physics and Run-2 data

PENTAQUARKS

[PRL 115 (2015) 072001]

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

J^P	$P_c(4380)^+$	$P_c(4450)^+$
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

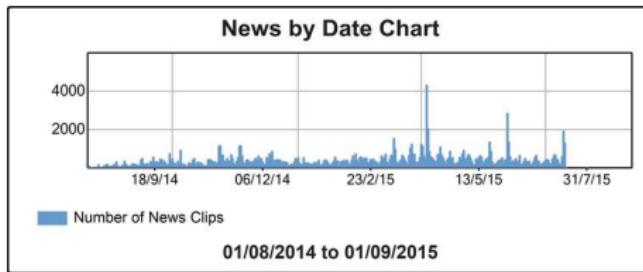


- Prospect first raised 50 years ago by Gell-Mann, Zweig.
- LHCb states have quark content $c\bar{c}uud$



PENTAQUARKS

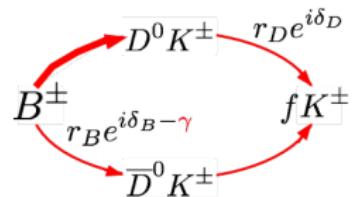
[PRL 115 (2015) 072001]



Largest CERN physics news story this year! (others were LHC start-up)
Generated huge interest in community.

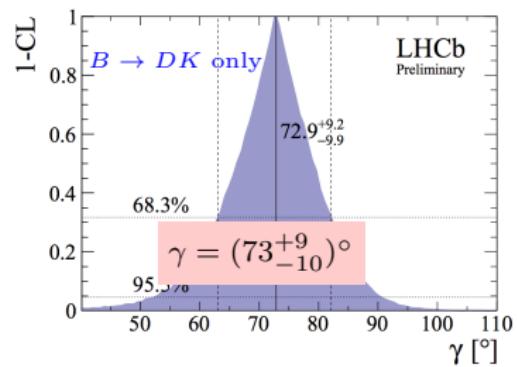
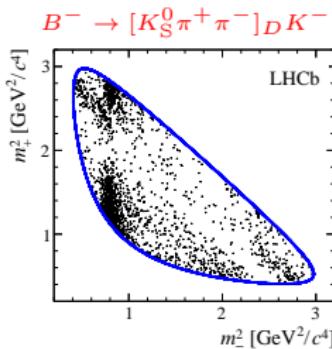
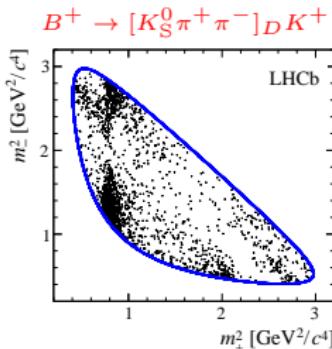
TREE-LEVEL MEASUREMENT OF γ

- 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 $B^\pm \rightarrow D^0 K^\pm$, $D^0 \rightarrow f$ decay amplitudes.
- Time-independent $B^\pm \rightarrow D^0 K^\pm$ and $B^0 \rightarrow DK^*$...
- ... or time-dependent $B_s^0 \rightarrow D_s^+ K^-$ ($\gamma - 2\beta_s$)



[LHCb-CONF-2014-004]

[JHEP 10 (2014) 097]



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