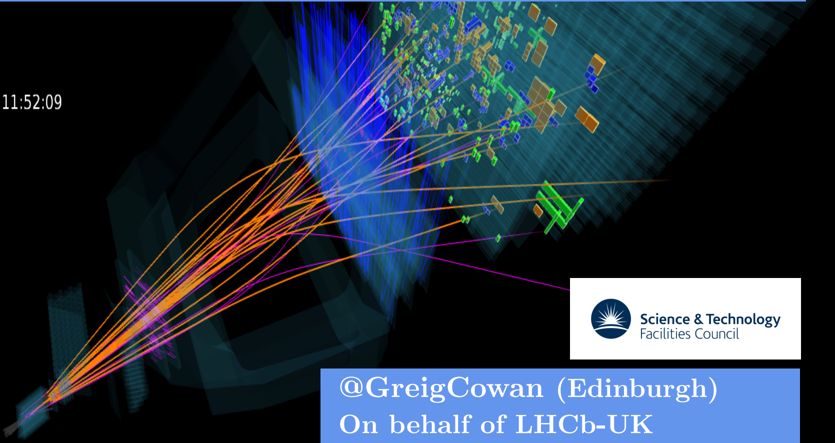
LHCb status report

Event 41383468
Run 153460
Wed, 03 Jun 2015 11:52:09

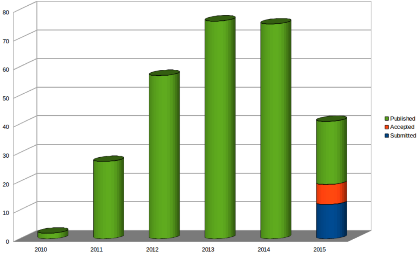


@GreigCowan (Edinburgh)
On behalf of LHCb-UK
PPAP, Sept 24th 2015

- **Detector status and plans for the upgrade**
- **Physics highlights from past year (70% UK-led):**
  - **CP violation in the beauty + charm systems**
  - **Lepton (non-)universality**
  - **Rare B decays**
  - **Pentaquarks and top physics**

279 papers published /accepted/submitted

c.f. $\sim$ 500 papers each from ATLAS/CMS.



LHCb in the UK

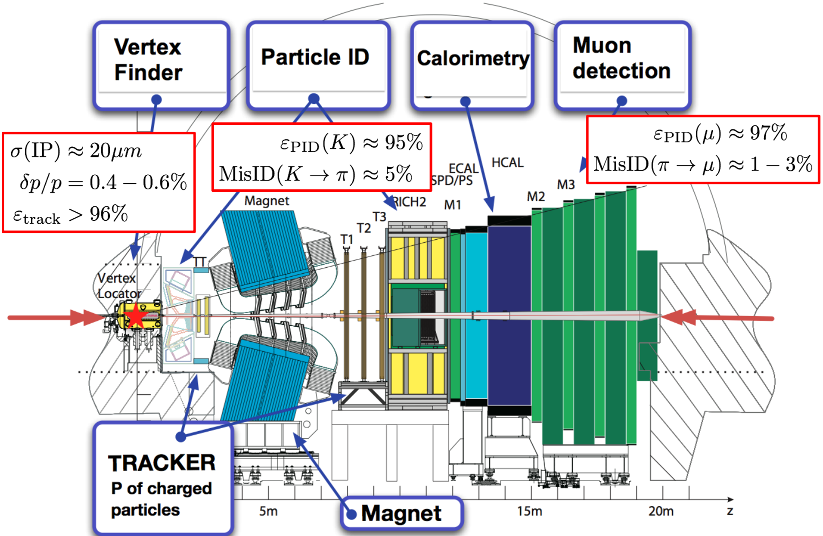
- ∼800 authors, ∼ 20% with UK affiliations
- LHCb spokesperson (Guy Wilkinson)
- Two previous physics coordinators (Tim Gershon, GW)
- EB, membership committee, operations chair, VELO and RICH project leaders.
- ∼ 25% of physics working-group convenors from UK
- UK responsibility for construction and M&O of VELO and RICH
- 30% (20%) of storage and compute provided by T1 (T2's).

http://www.lhcb.ac.uk
@LHCb_UK

Detector status and upgrade plans

The LHCb detector

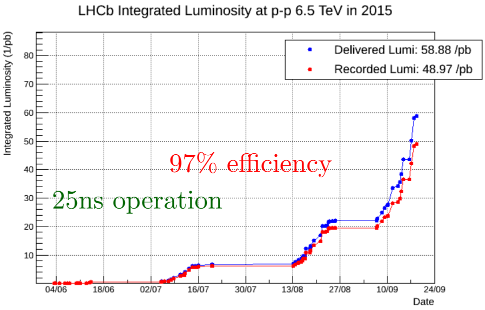
[JINST 3 S08005 (2008)]

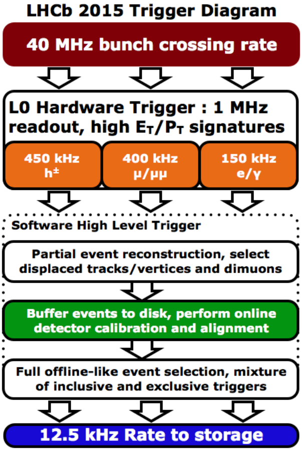


- $\langle \mathcal{L} \rangle_{2011} \sim 2.7 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow 1\,\mathrm{fb}^{-1}$ @7TeV
- $\langle \mathcal{L} \rangle_{2012} \sim 4.0 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow 2\,\mathrm{fb}^{-1}$ @8TeV

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

Run-2 status

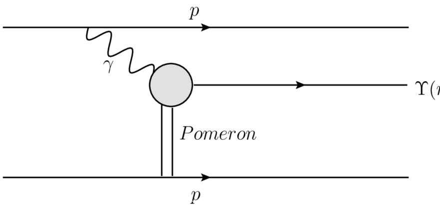


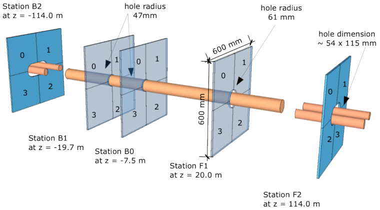


- Huge success so far!
- New trigger configuration commissioned.
  - Offline reconstruction in the trigger!
- **Online calibration + alignment allows physics analyses directly from the trigger.**
  - Only tracks and vertices that caused event to trigger are saved (no offline reco).
  - Used for high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

NEW SUB-DETECTOR: HERSCHEL

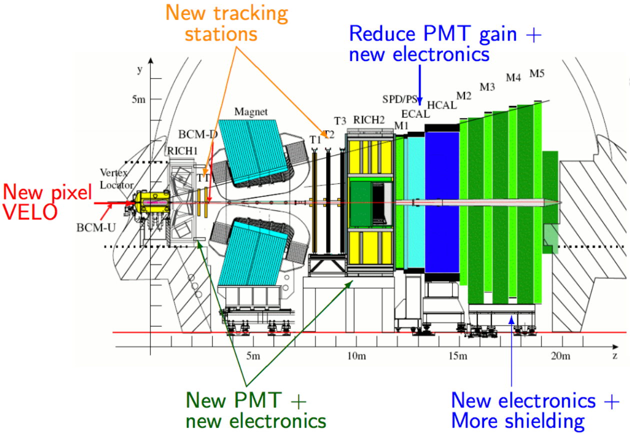
- Opportunity to advance the study of Central Exclusive Production in Run-2.
  - Already started work in Run-1 (e.g., [arXiv:1505.08139]).
- Need to tag background at very high rapidity ($5 < |\eta| < 8$).

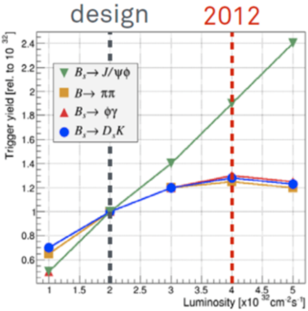




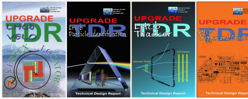
- Herschel is series of forward shower counters, some > 100m from *pp* interaction.
- Detector installed and working.
- Now commissioning read-out electronics and integration with LHCb trigger system.

Beyond Run-2: the LHCb upgrade

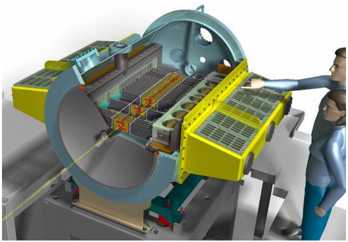




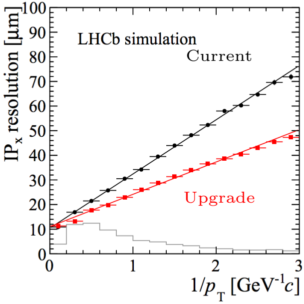
- Aim: significant increase in event statistics.
- Increase $\mathcal{L}$ to 2×10^{33} cm^{-2}s^{-1}.
- Improve detector readout from 1MHz $\to$ 40MHz. Use full software trigger.
- Will have big impact for hadronic decays (e.g., $10\times$ charm).



UPGRADED VELO [LHCB-TDR-013] (UK LED)



- Pixel detector: 55 μm × 55 μm pixels.
- Radiation dose of 10^{16} protons/cm^2.
- Detector will be 5 mm from LHC beam.
- New 250 μm aluminium RF foil but re-use as many components as possible.



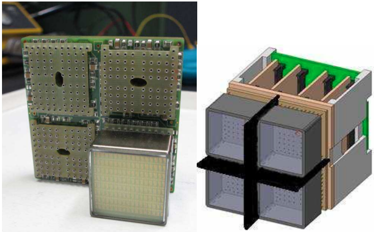
UK ACTIVITIES

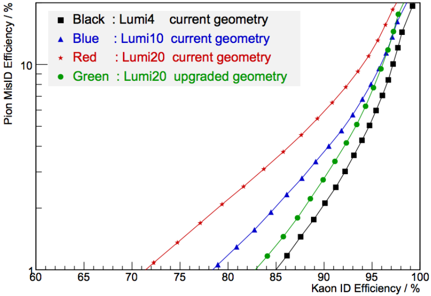
- Pixel detectors, hybrids, cables and readout electronics.
- Micro-channel channel cooling.
- Assembly and testing of modules.
- Assembly of the detector.

- Excellent track reconstruction efficiency and decay time resolution will be maintained in upgrade.

Upgraded RICH [LHCB-TDR-014] (UK led)

- High-occupancy environment in Run-3.
- RICH-1 layout optimized ⇒ new mirrors and mechanics.
- New MAPMT photodetectors (R11265 + H12700 from Hamamatsu) replace HPDs.
- New readout electronics and magnetic shielding.
- Maintain excellent charged particle PID.





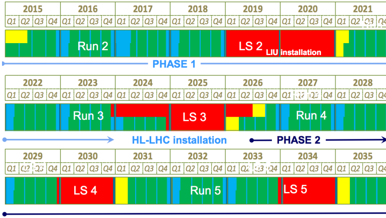
UK activities

- Photon-detector testing.
- Electronics and firmware.
- Mechanics and mirrors.
- Assembly of the detector.

- Maintain excellent charged particle PID.

LHCb in the high-luminosity LHC era

- LHCb-upgrade will be installed in LS2 and operate during Run-3.
- **Initial ideas** to consolidate LHCb-upgrade in LS3 so that it can operate in Run-4 (HL-LHC operation).
  - ⇒ Stations in the magnet (to improve reconstruction of multi-body final states).
  - ⇒ Improvements to PID via time-of-flight (UK-led project)

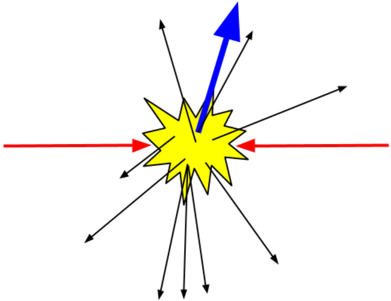


- ECFA flavour working group investigating if there is a physics case to continue operating LHCb in HL-LHC era (Run-5).
  - This would only make sense with further upgrades to allow higher luminosity.
  - Discussions started with LHC about operating IP8 at $\mathcal{L} = 1\text{-}2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$.

	LHC era			HL-LHC era	
$\int \mathcal{L}\, dt$	2010-12 (Run-1)	2015-18 (Run-2)	2021-23 (Run-3)	2026-29 (Run-4)	2031++ (Run-5)
ATLAS, CMS	$25\,\text{fb}^{-1}$	$100\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$	$\rightarrow$	$3000\,\text{fb}^{-1}$
LHCb	$3\,\text{fb}^{-1}$	$8\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$46\,\text{fb}^{-1}$	$100\,\text{fb}^{-1}$

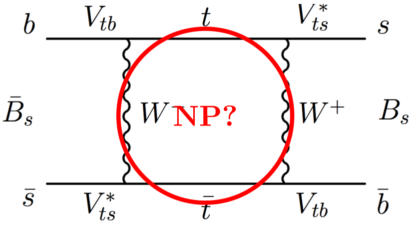
ON-SHELL

Cannot produce particles with $mc^2 > E$



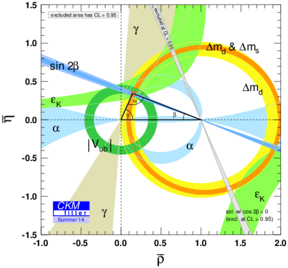
OFF-SHELL

Higher energy particles can appear virtually in quantum loops $\rightarrow$ flavour physics



History: top quark mass predicted by quark mixing

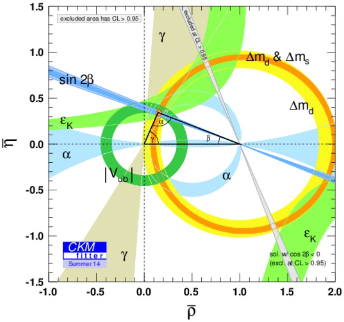
CP violation in the quark sector



CP violation in the Standard Model

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

Wolfenstein parameterisation

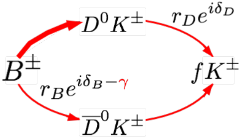


- 3 generations + **1 phase** → $\bar\eta \neq 0$ is only source of CP violation in SM.
- CKM picture confirmed up to ∼ 20%.
- Couplings show strong hierarchy not seen in lepton sector ⇒ "*SM flavour puzzle*"

- 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.

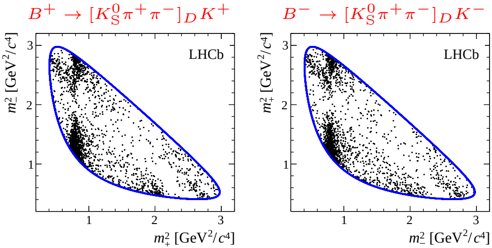
Tree-level measurement of γ

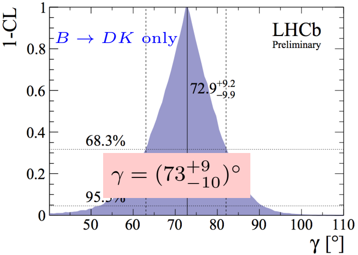
- Least well known of the CKM angles.
- Can be measured entirely from tree decays where there is small residual theory uncertainty $|\delta\gamma| \leq \mathcal{O}(10^{-7})$ [Brod, Zupan JHEP 1401 (2014) 051]
- Use interference between $B^{\pm} \to D^0 K^{\pm}$, $D^0 \to f$ decay amplitudes.
- Time-independent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



[LHCb-CONF-2014-004]

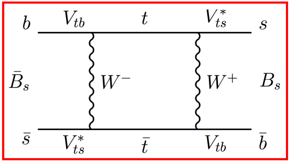
[JHEP 10 (2014) 097]



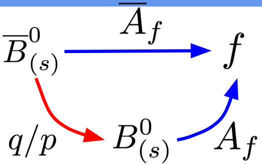


- Best precision comes from combining many independent decay modes.
- B-factories: $\sigma(\gamma) \sim 15^\circ$; **Final LHCb Run-1: $\sigma(\gamma) \sim 7^\circ$.**

CP violation in $b \to c\bar{c}s$ decay + mixing

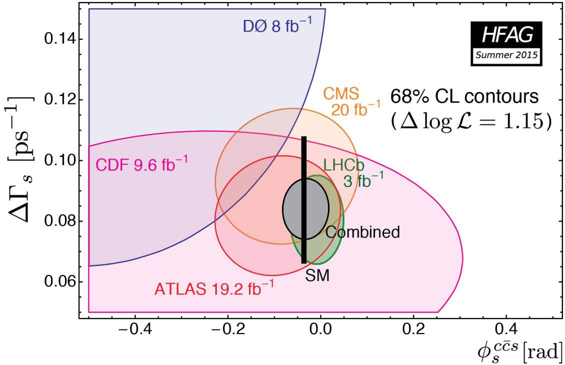


$$\phi_{mix} = 2\arg(\mathrm{V_{tb}V_{ts}^*})$$
$$\phi_{decay} = \arg(\mathrm{V_{cb}V_{cs}^*})$$



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

Precise prediction for ϕ_s from global fit [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.

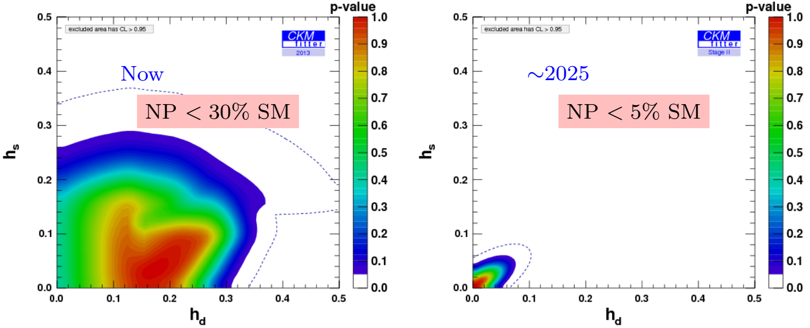
⇒ need to control SM effects (penguins).

- Also competitive in B^0 system ($\sin 2\beta$) and in gluonic penguin decays ($B_s^0 \to \phi\phi$).

New physics prospects

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

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



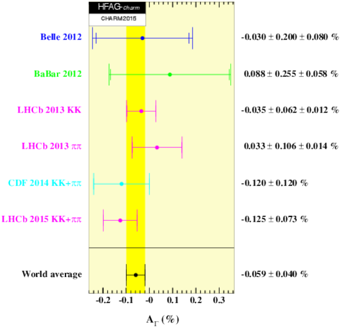
$$h \approx \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\frac{4.5\ \text{TeV}}{\Lambda}\right)^2$$

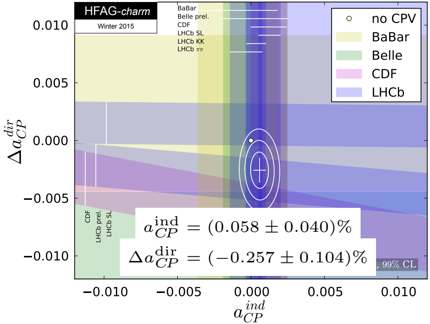
Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

Charm physics

- Only way to study FCNC with u-type quarks. Allows to probe higher energy scales than b decays.
- Huge event yields have led to huge progress in CP violation in charm mixing and rare decays.
  - Will take advantage of higher cross-section and new trigger configuration in Run-2.

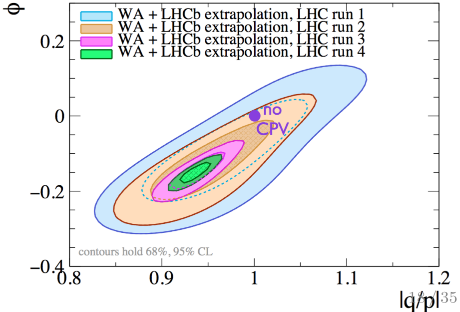
$$A_{\Gamma} \equiv \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} = -a_{CP}^{\text{ind}} - a_{CP}^{\text{dir}} y_{CP}$$





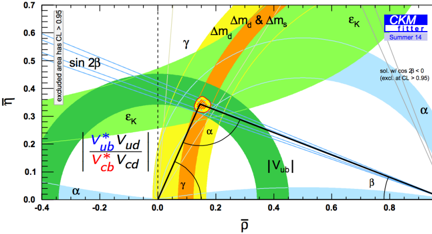
$a_{CP}^{\text{ind}} = (0.058 \pm 0.040)\%$

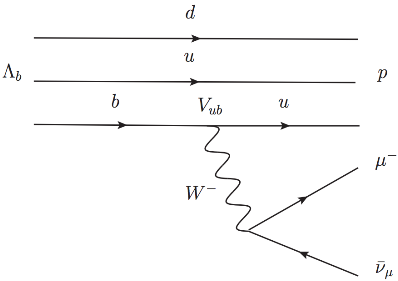
$\Delta a_{CP}^{\text{dir}} = (-0.257 \pm 0.104)\%$

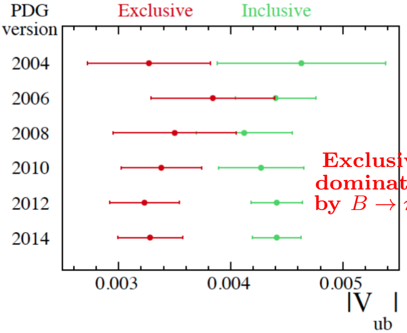


$|V_{ub}|$ USING $\Lambda_b \to p\mu\overline{\nu}_\mu$

- Long-standing discrepancy between inclusive + exclusive measurements of $|V_{ub}|$.
- **Thought to be impossible for LHCb.**
  - 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.







Exclusive dominated by $B \to \pi l\nu$

nature physics
ARTICLES
PUBLISHED ONLINE: 27 JULY 2015 | DOI: 10.1038/NPHYS3415
OPEN

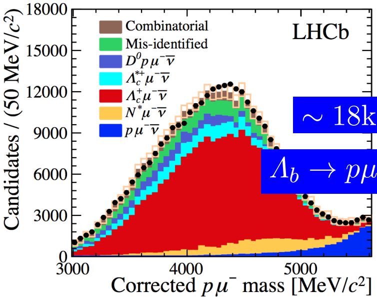
Determination of the quark coupling strength $|V_{ub}|$ using baryonic decays

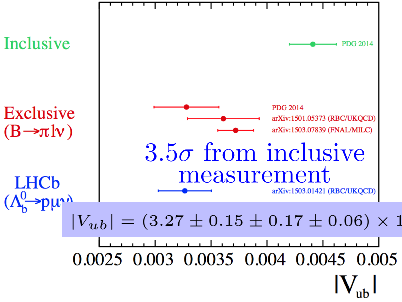
- Normalise to the V_{cb} decay, $\Lambda_b \to \Lambda_c \mu\nu$ and use world average $|V_{cb}|$ value.

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

- Fit corrected mass (peaks at mass of Λ_b):

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





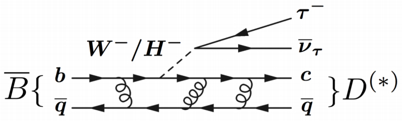
$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$$

- Interpretation of inclusive/exclusive discrepancy in terms of RHC now disfavoured.

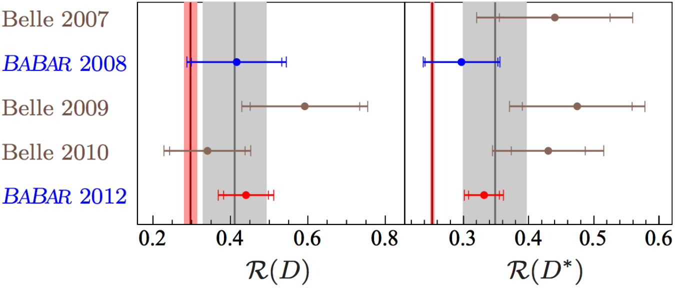
Lepton universality

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

- 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.



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

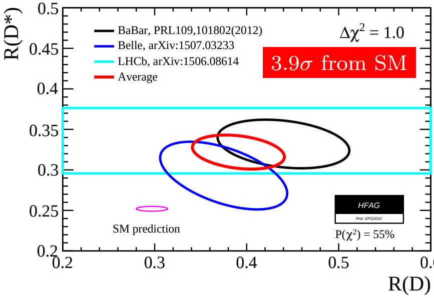


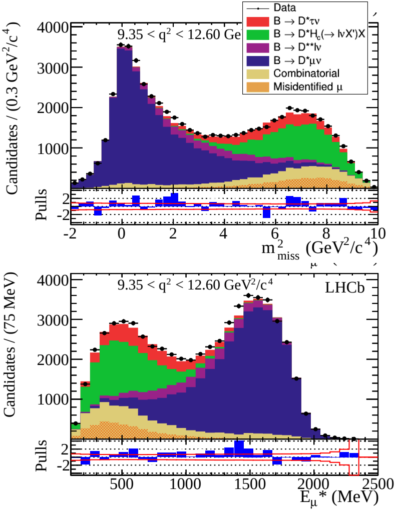
- Interesting given the hints of non-universality in $B^+ \to K^+ l^+ l^-$ decays (R_K) and excl/incl measurements of V_{ub}, V_{cb}.

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

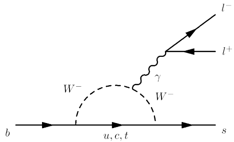
- Very challenging measurement at hadron collider (no beam constraints and large backgrounds).
- Use $\tau \to \mu\nu_\mu\nu_\tau$ $(BF = 17.41 \pm 0.04\%)$
  - Signal and normalisation have same final state particles.
- Large samples of events, triggering on charm.
- Template fit to kinematic variables →
- $R(D^*) = 0.336 \pm 0.027 \pm 0.030$ (2.1σ from SM)

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

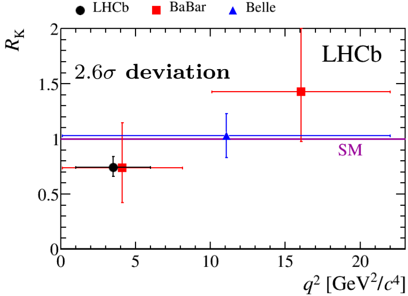


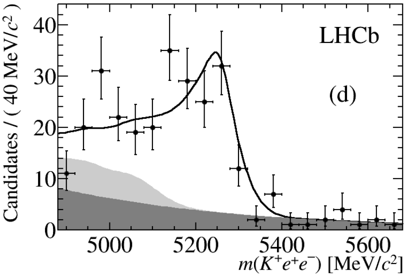


- In the SM only the Higgs boson has non-universal lepton couplings.
- This results in SM predictions of nearly unity for various decay-rate ratios

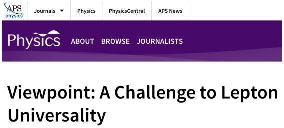


$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} \stackrel{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-3})$$

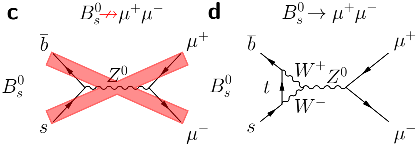




- Interesting given the indications of non-SM physics in other $b \to s$ penguin decays (see later).

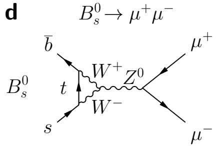


Rare (FCNC) B meson decays

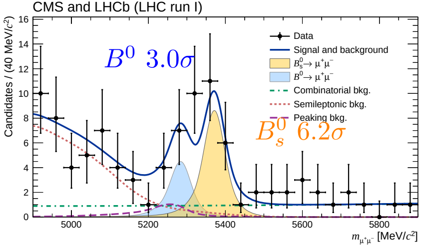


Observation of $B_s^0 \to \mu^+\mu^-$ [CMS + LHCb, Nature 522, 68-72 (2015)]

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



- Sensitive to scalar and pseudoscalar NP couplings, e.g., in MSSM $\mathcal{B} \propto (\tan\beta)^6$
- $\mathcal{B}(B^0 \to \mu\mu)/\mathcal{B}(B_s^0 \to \mu\mu)$ consistent with SM at $\sim 2\sigma$.

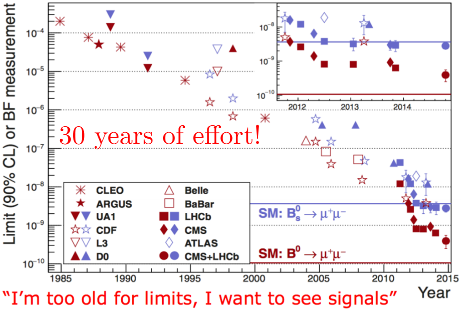



LETTER

OPEN

doi:10.1038/nature14474

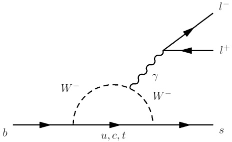
Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

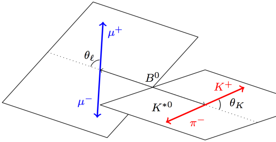


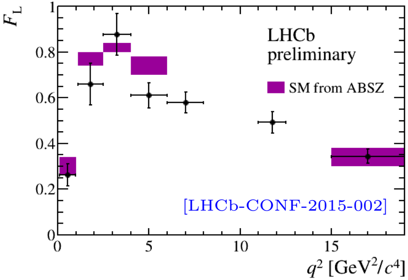
"I'm too old for limits, I want to see signals"
Francis Halzen (EPS '15)

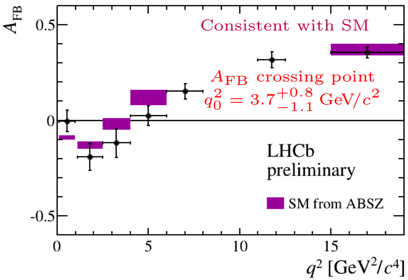
$B^0 \to K^*\mu^+\mu^-$ AND FRIENDS

- $b \to s$ "penguin" decays are loop/CKM suppressed.
- $B^0 \to K^*\mu^+\mu^-$ has rich system of observables (rates, angles, asymmetries) that are sensitive to NP.
- $q^2 \equiv m(\mu^+\mu^-)^2$



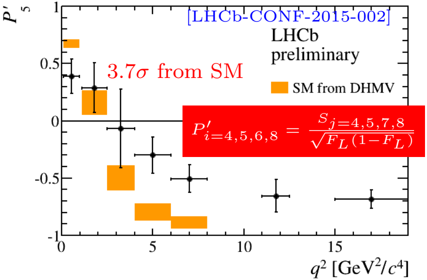




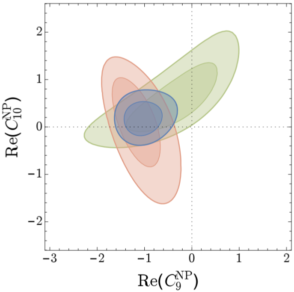


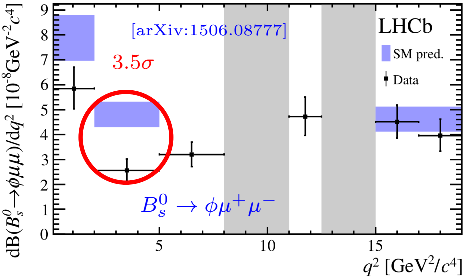
$B^0 \to K^*\mu^+\mu^-$ AND FRIENDS

- Alternative observables less dependent on hadronic form factors [Descotes-Genon et al arXiv:1303.5794].
- Also BR of many other $b \to s\mu^+\mu^-$ transitions are lower than expected.
- Global fit to all $b \to s\mu^+\mu^-$ data prefers NP scenario with negative C_9 Wilson coefficient at 3.7σ.
  - Possible Z'? Leptoquarks? [many authors]



[Altmannshofer, Straub] [arXiv:1503.06199]

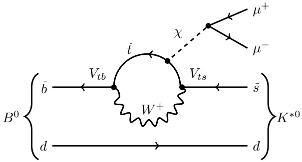


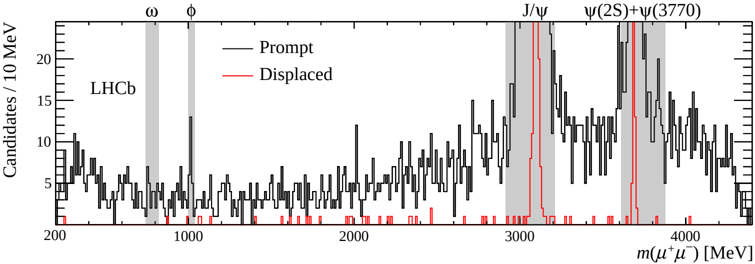


- How well do we understand QCD-effects? [Lyon, Zwicky]

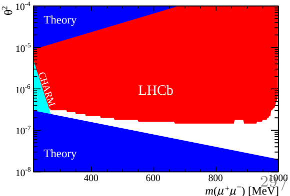
Dark bosons

- $b \to s$ penguins are an excellent lab to search for low-mass hidden-sector particles (e.g., anything that mixes with the Higgs sector).
- Search for $B \to K^* \chi, \chi \to \mu\mu$ by scanning $m(\mu\mu)$ and allowing non-zero $\tau(\mu\mu)$.





- No evidence for χ-boson, so set model-independent limits on BR of $10^{-7} \to 10^{-9}$, depending on $\tau(\mu\mu)$.
- Very strong constraints placed on theories that invoke mixing with the Higgs sector.



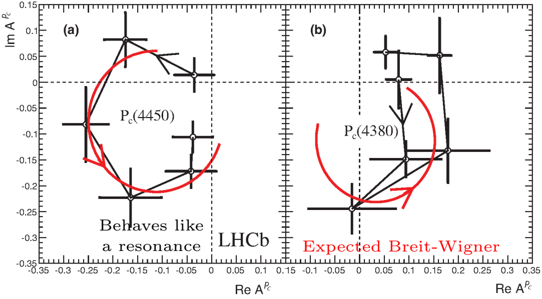
Exotic spectroscopy, top physics and Run-2 data

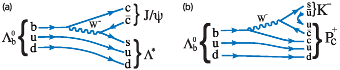
Pentaquarks

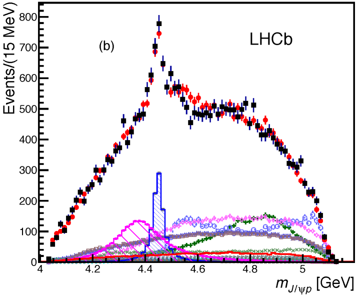
[PRL 115 (2015) 072001]

- 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.

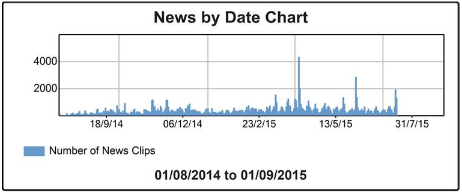
	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ





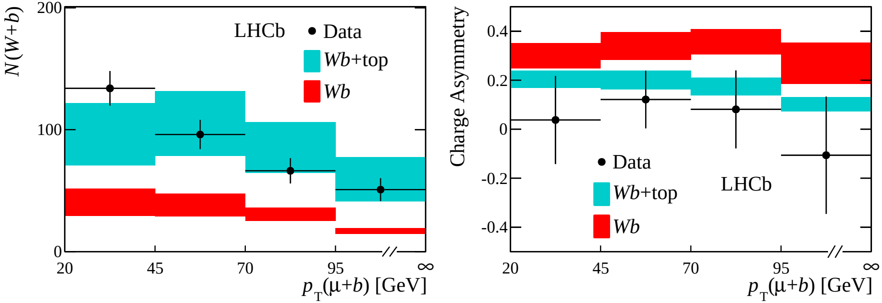


- Prospect first raised 50 years ago by Gell-Mann, Zweig.
- LHCb states have quark content $c\bar{c}uud$



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

- Forward $t\bar{t}$ production used to constrain gluon PDFs at large x and test NNLO.
- Use highest yield mode: $t \to W + b$-jet, with $W \to \mu\nu$.
- Jet reco using particle flow approach (anti-k_T).
- Developed b, c-jet taggers (ε =65,25%), with low light-jet mistag rate (0.3%) [arXiv:1505.04051]

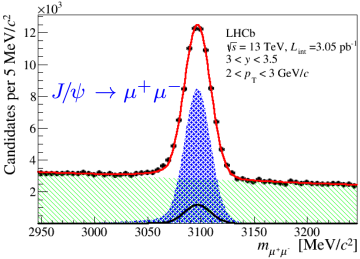


- Data cannot be described by only $W + b$-jet. 5.4σ observation.
- Use excess above $W + b$-jet to measure inclusive production in fiducial region.

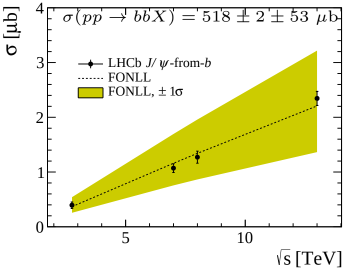
$$\sigma(t\bar{t} + t + \bar{t}) = 239 \pm 53 \pm 38 \text{ fb [7TeV]}$$
$$\sigma(t\bar{t} + t + \bar{t}) = 289 \pm 43 \pm 46 \text{ fb [8TeV]}$$

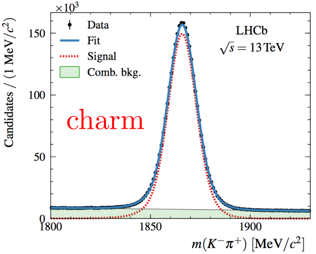
- Both agree with SM prediction.

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



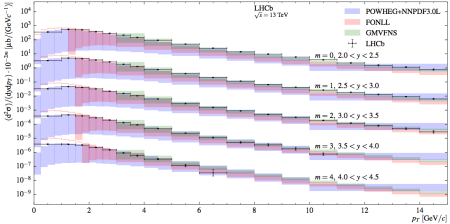
[arXiv:1509.00771]





[LHCB-PAPER-2015-041]

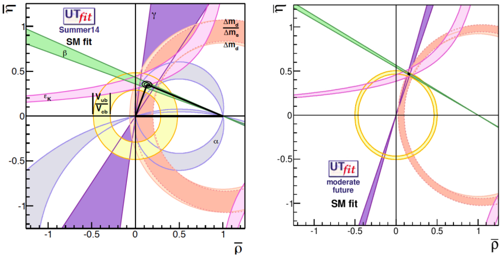
$\sigma(pp \to c\bar{c}X) = 2.72 \pm 0.01 \pm 0.18 \pm 0.14$ mb (in LHCb)



- 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.

Summary

- Outstanding physics performance from LHCb at Run-1.
- Many unexpected results as we expand from core *CP* violation and rare decay programme:
    - studying modes involving ν, electrons, π^0, photons
    - pentaquarks, top physics, heavy ions, central exclusive production...
- Exciting indications of non-SM physics in related channels:
    - $R(D^*), R_K, P_5', b \to s$ penguin branching ratios.
    - Looking forward to more data in Run-2 and beyond!
- Run-2 start-up successful and results starting to come out.
- LHCb-upgrade on track for installation in 2019.

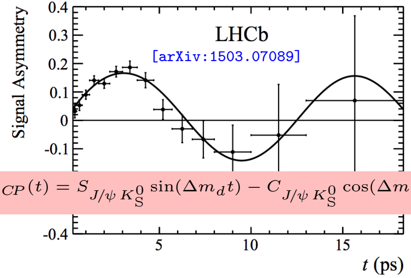


Sensitivity prospects LHCb-PUB-2014-040

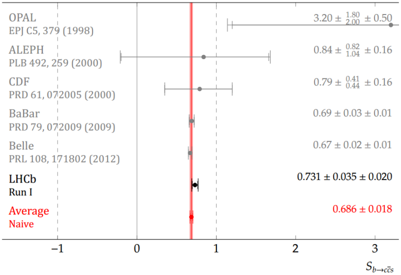
Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (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.

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



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

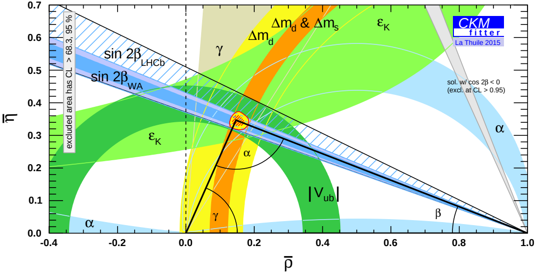


$$S_{J/\psi\, K^0_S} \approx \sin 2\beta$$

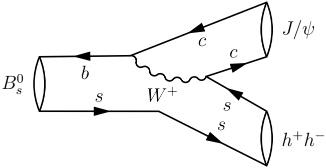
$$S_{J/\psi\, K^0_S} = +0.731 \pm 0.035 \pm 0.020$$

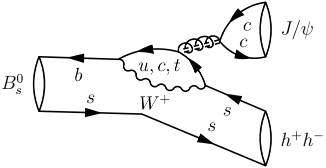
$$C_{J/\psi\, K^0_S} = -0.038 \pm 0.032 \pm 0.005$$

- Consistent with world average and similar precision to B-factories.
- **HL-LHC**: expect $\sigma(S_{J/\psi\, K^0_S}) \sim 0.005$, similar from Belle-II.



Controlling penguin pollution in ϕ_s





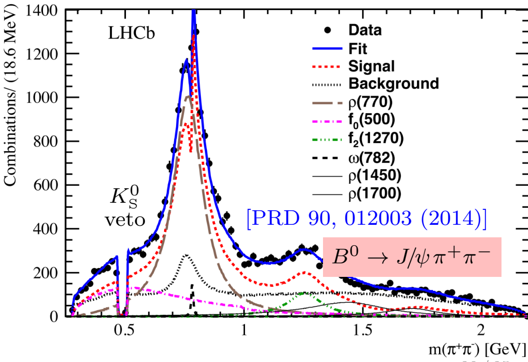
Penguin-to-tree suppression:

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

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

- 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. $\sigma(\phi_s) = \pm 2.0°$, $\sigma(\phi_d) = \pm 1.4°$

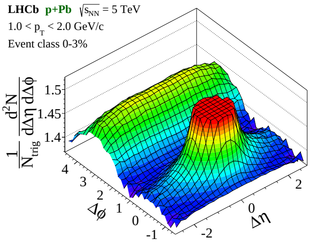


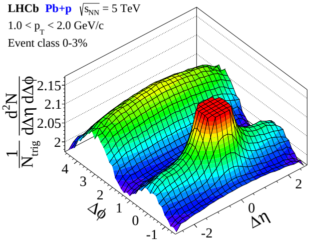
[PRD 90, 012003 (2014)]

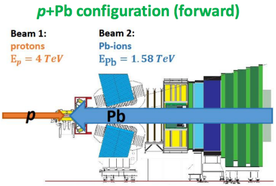
$B^0 \to J/\psi \pi^+\pi^-$

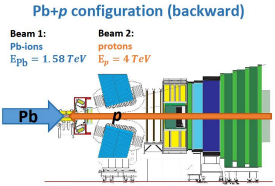
Heavy ion physics - the ridge

- Study of two-charged-particle correlation in $\Delta\eta$ and $\Delta\phi$ allows the study QCD and collective effects in collisions.
  - $\mathcal{L} = 0.46\text{nb}^{-1}$ (p+Pb); $\mathcal{L} = 0.30\text{nb}^{-1}$ (Pb+p)
  - $2.5 < |y| < 4$ and $\sqrt{S_{NN}} = 5$ TeV
- A long-range correlation on the near side (the ridge at $\Delta\phi \approx 0$) is observed in both p+Pb and Pb+p.
- Most pronounced for $1 < p_{\mathrm{T}} < 2$ and high event activity (many VELO hits).
- In common activity regions, ridges are compatible for p+Pb and Pb+p.

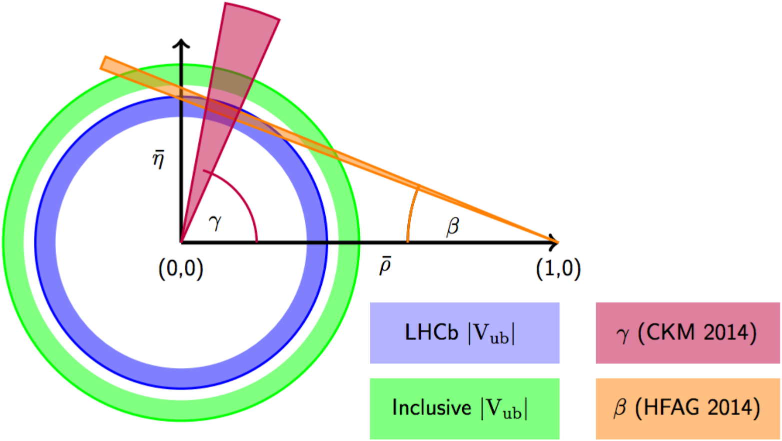






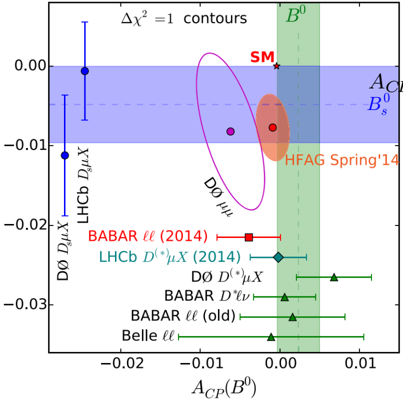


Impact of $|V_{ub}|$ on unitarity triangle



- LHCb $|V_{ub}|$ result consistent with world average value of $\sin 2\beta$.

[PRL 114, 081801 (2015)]



$$A_{CP} = a_{\rm sl} = \frac{\Gamma(\overline{B}\to B\to f) - \Gamma(B\to\overline{B}\to\overline{f})}{\Gamma(\overline{B}\to B\to f) + \Gamma(B\to\overline{B}\to\overline{f})} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

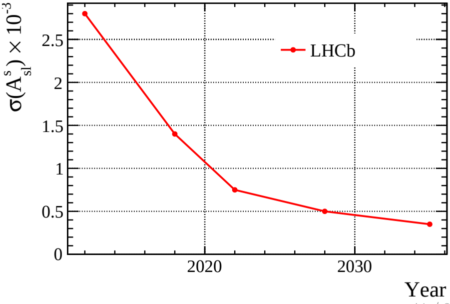
[Lenz arXiv:1205.1444] - tiny in SM

$$a^d_{\rm sl} = (-4.1 \pm 0.6) \times 10^{-4}$$
$$a^s_{\rm sl} = (+1.9 \pm 0.3) \times 10^{-5}$$

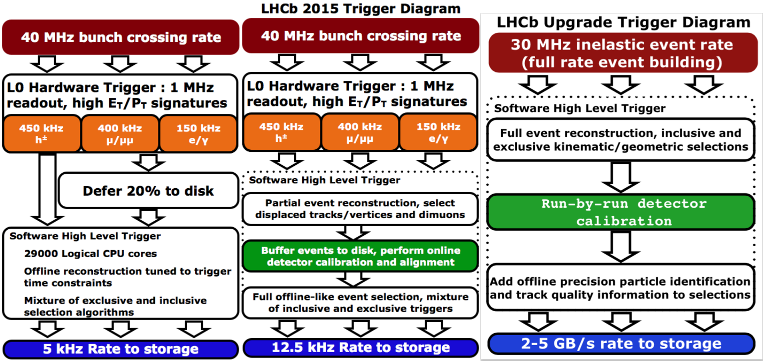
$$a^s_{\rm sl} = [-0.06 \pm 0.50 \pm 0.36]\% \ (\text{LHCb, } 1\,\text{fb}^{-1})$$
$$a^d_{\rm sl} = [-0.02 \pm 0.19 \pm 0.30]\% \ (\text{LHCb, } 3\,\text{fb}^{-1})$$

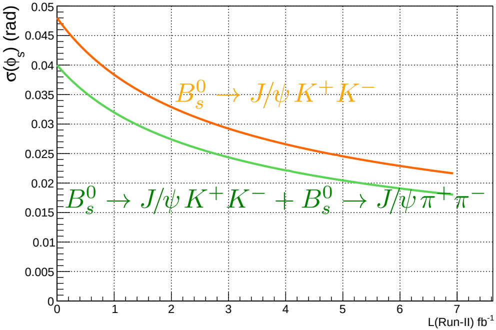
[PLB 728 (2014) 607, PRL 114 (2014) 041601]

- **$\sim 3\sigma$ tension with SM from D0 not confirmed or excluded by LHCb.**



LHCb trigger





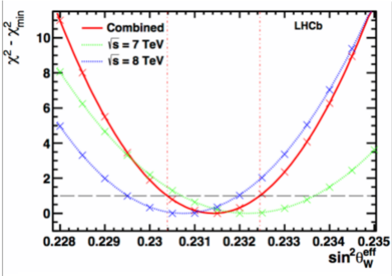
- In future, use other channels:
  - $B_s^0 \to \psi(2S)\phi$
  - $B_s^0 \to J/\psi \eta$
  - $B_s^0 \to J/\psi (ee)\phi$
  - $B_s^0 \to J/\psi K^+K^-$ (high K^+K^- mass)
- Control of penguins essential!
  - $B_s^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi K^*$, $B^0 \to J/\psi \rho^0$ [NPB 873 (2013) 275-292, PRD 86 (2012) 071102]

ϕ_s error (rad)	Run 1 (2010–12) $3\,fb^{-1}$	Run 2 (2015–18) $8\,fb^{-1}$	Upgrade (2019–??) $50\,fb^{-1}$	Theory
$B_s^0 \to J/\psi K^+K^-$	0.049	0.025	0.009	~ 0.003
$B_s^0 \to J/\psi \pi^+\pi^-$	0.068	0.035	0.012	~ 0.01
$B_s^0 \to \phi\phi$	0.15	0.10	0.018	< 0.02

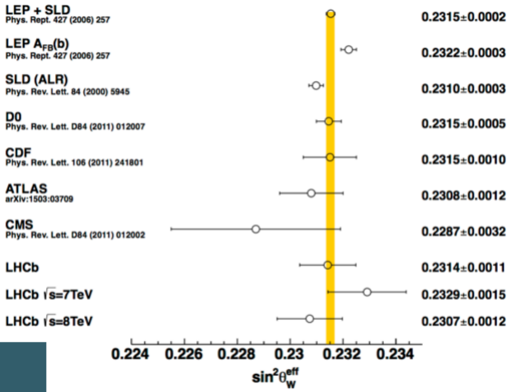
- Upgraded detector will be read out at 40MHz.
- Factor-10 increase signal yields.
- Existing design will saturate at higher luminosities.

$\sin^2\theta_W$

[LHCB-PAPER-2015-039]



$\sin^2\theta_W^{\text{eff}} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056$



- A_{FB} generated with a range of $\sin^2\theta_W$ using POWHEG-BOX.
- χ^2 with data calculated for each.
- Fit to the distribution of χ^2 to determine minimum and error.

Largest syst. uncertainties from PDFs renormalisation and factorisation scales