Overview of the latest LHCb results

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on behalf of the LHCb collaboration

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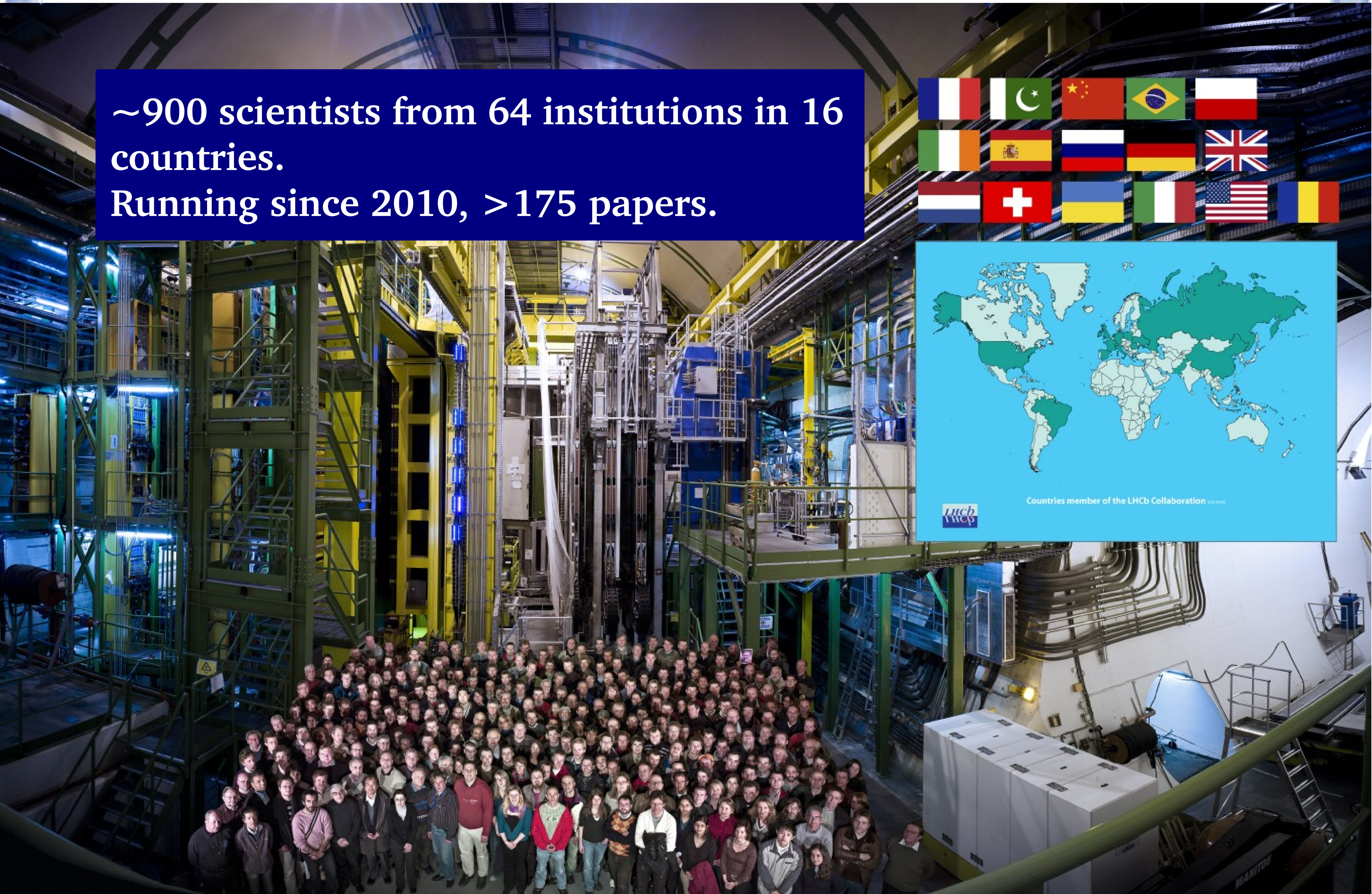
The LHCb collaboration

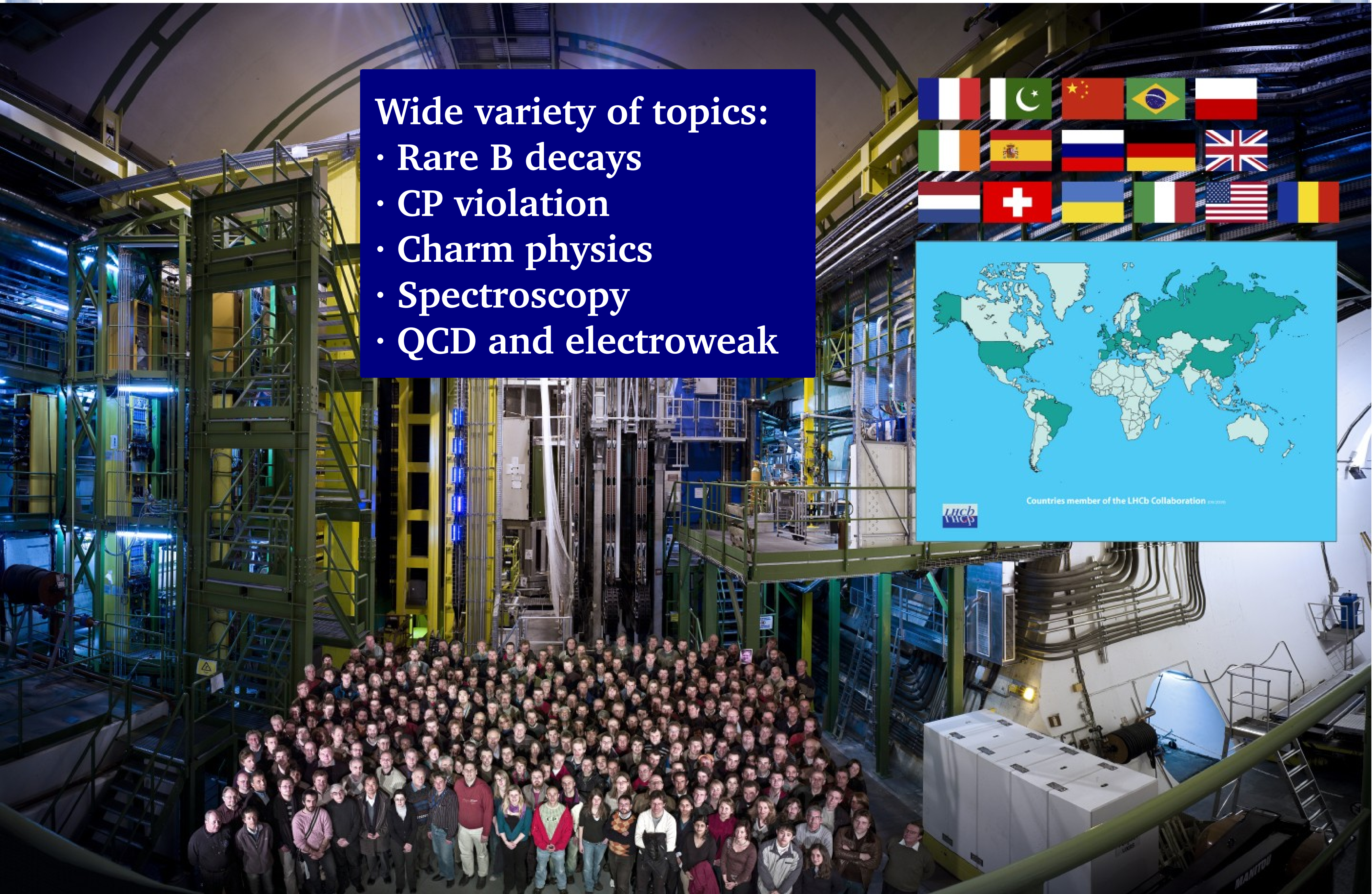
~900 scientists from 64 institutions in 16 countries.
Running since 2010, >175 papers.



The LHCb collaboration

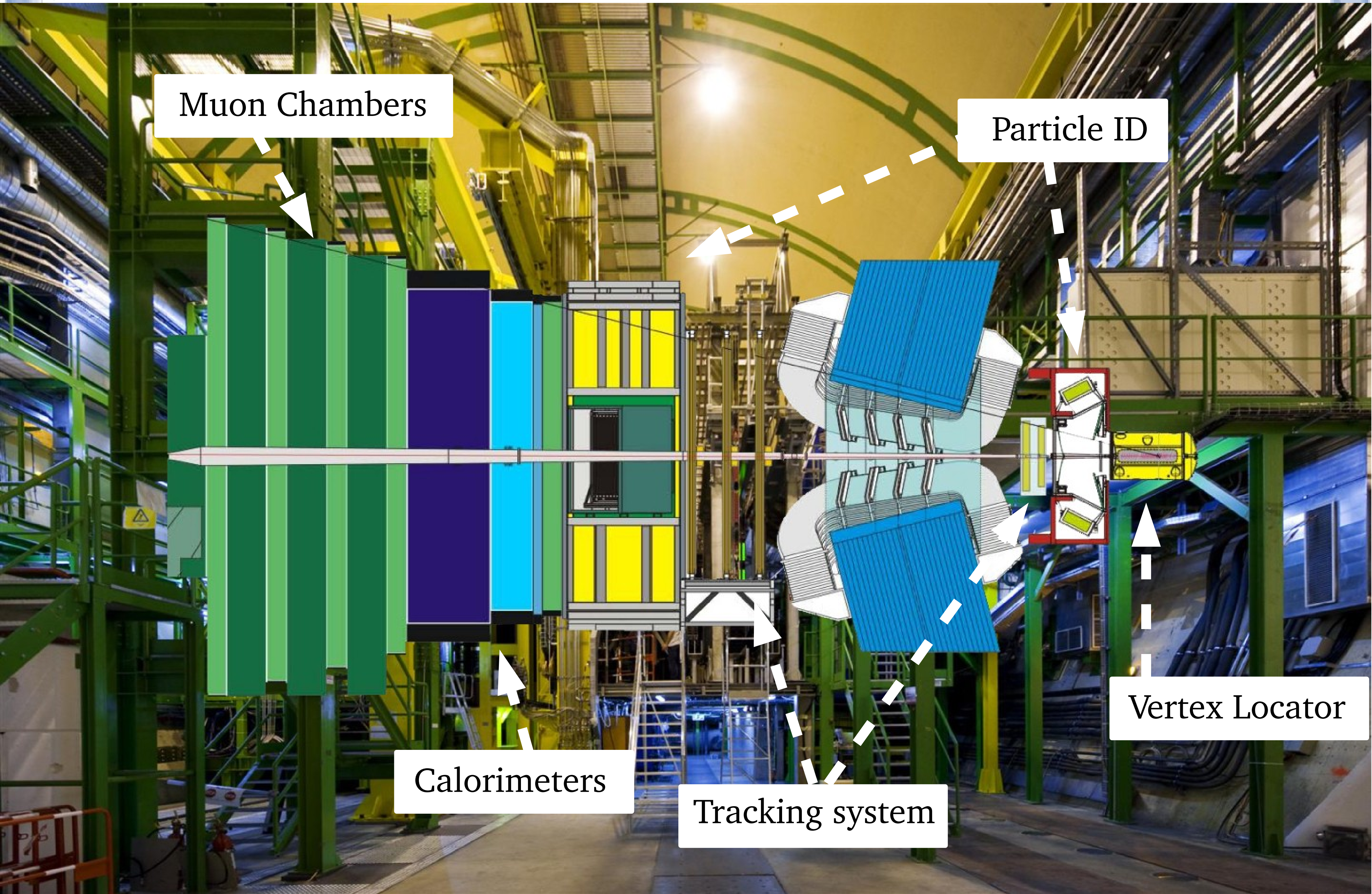
Wide variety of topics:

- Rare B decays
- CP violation
- Charm physics
- Spectroscopy
- QCD and electroweak



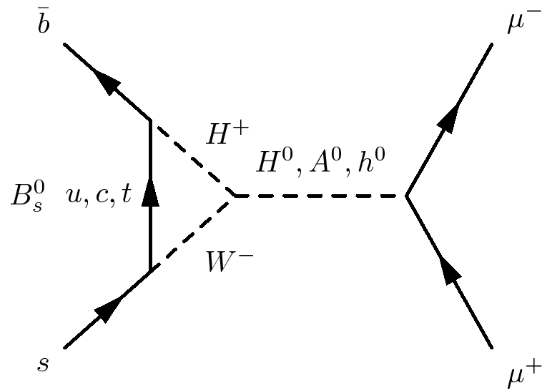
The LHCb detector

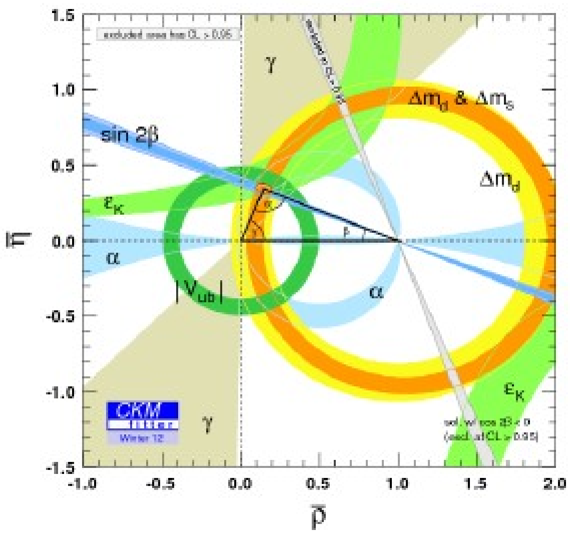
[2008 JINST 3 S08005]



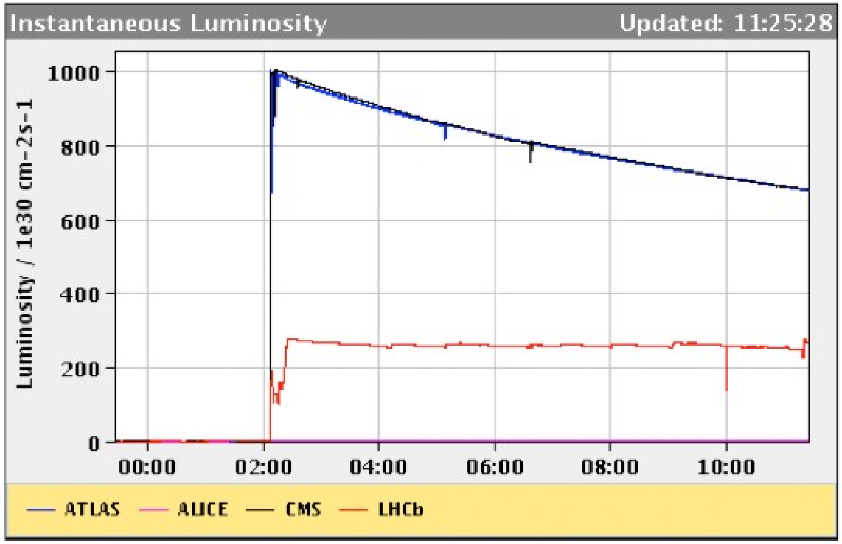
Searching for New Physics

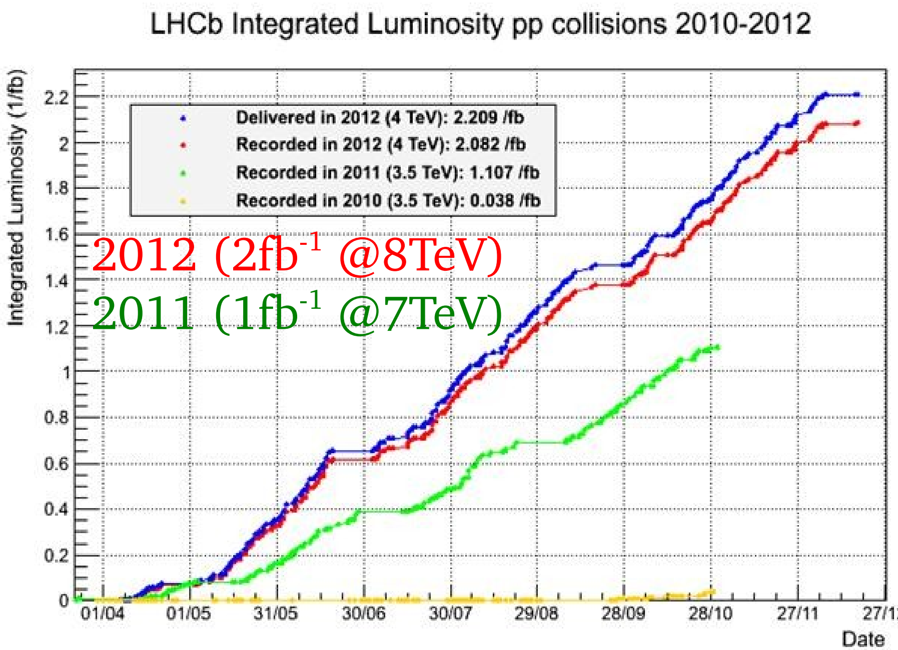
- Indirect way: higher energy particles can appear virtually in quantum loops.
- So far, no evidence of NP found from direct searches ~TeV.
- High-precision SM tests in flavour physics give constraints on scale of NP, > TeV.





Luminosity levelling





LHCb is designed to run at lower luminosities that ATLAS/CMS.

- LHCb tracking / PID very sensitive to pile-up

LHC pp beams are displaced to reduce instantaneuos luminosity → stable running conditions.

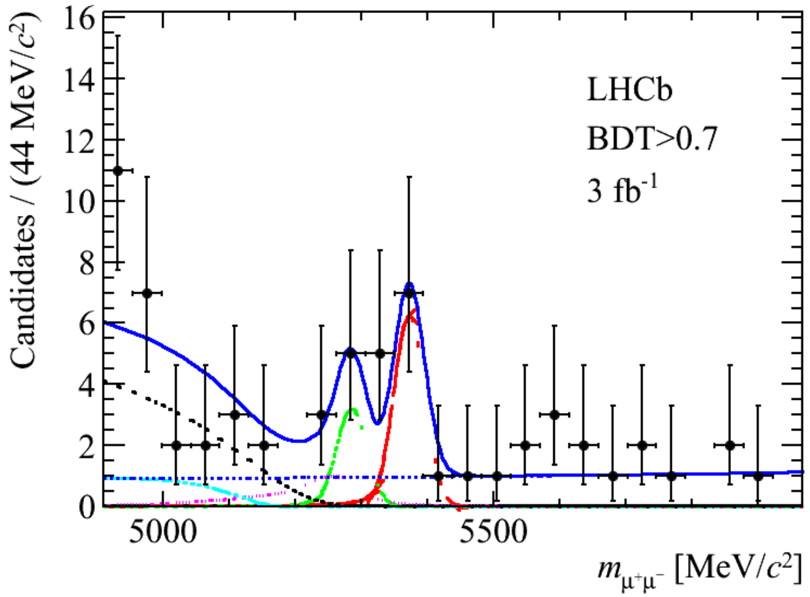
$$\langle \mathcal{L} \rangle_{2011} \sim 2.7 \times 10^{32} cm^{-2} s^{-1}$$
$$\langle \mathcal{L} \rangle_{2012} \sim 4.0 \times 10^{32} cm^{-2} s^{-1}$$

Beauty → ~75 μb [PLB 694 (2010) 209-216]
Charm → ~1419 μb [Nucl. Phys. B 871 (2013) 1-20]
Tau → ~80 μb [PLB 724 (2013) 36-45]

Rare B decays

Very rare decays: $B_{d,s} \to \mu^+\mu^-$

- Requires FCNC transition, an helicity suppressed by $(m_\mu/m_B)^2$



[PRL 08 (2013) 117]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9},$$ **4σ**

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$ **2σ**

In good agreement within uncertainties with the SM predictions.

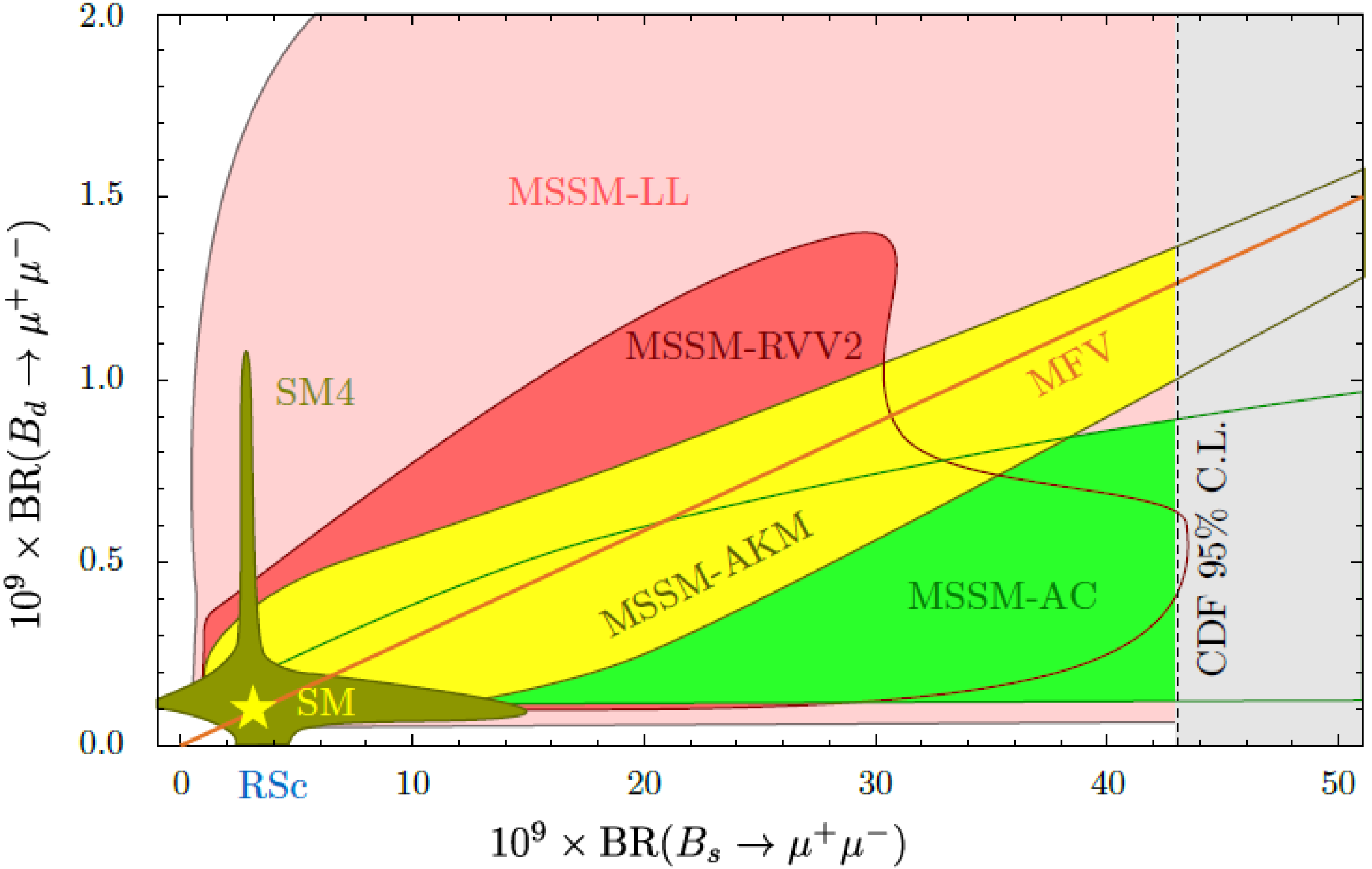
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.56 \pm 0.30) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.05) \times 10^{-10}$$

[Eur. Phys. J C72 (2012) 2172]
[PRL 109 (2012) 041801]

Constraints on BSM models

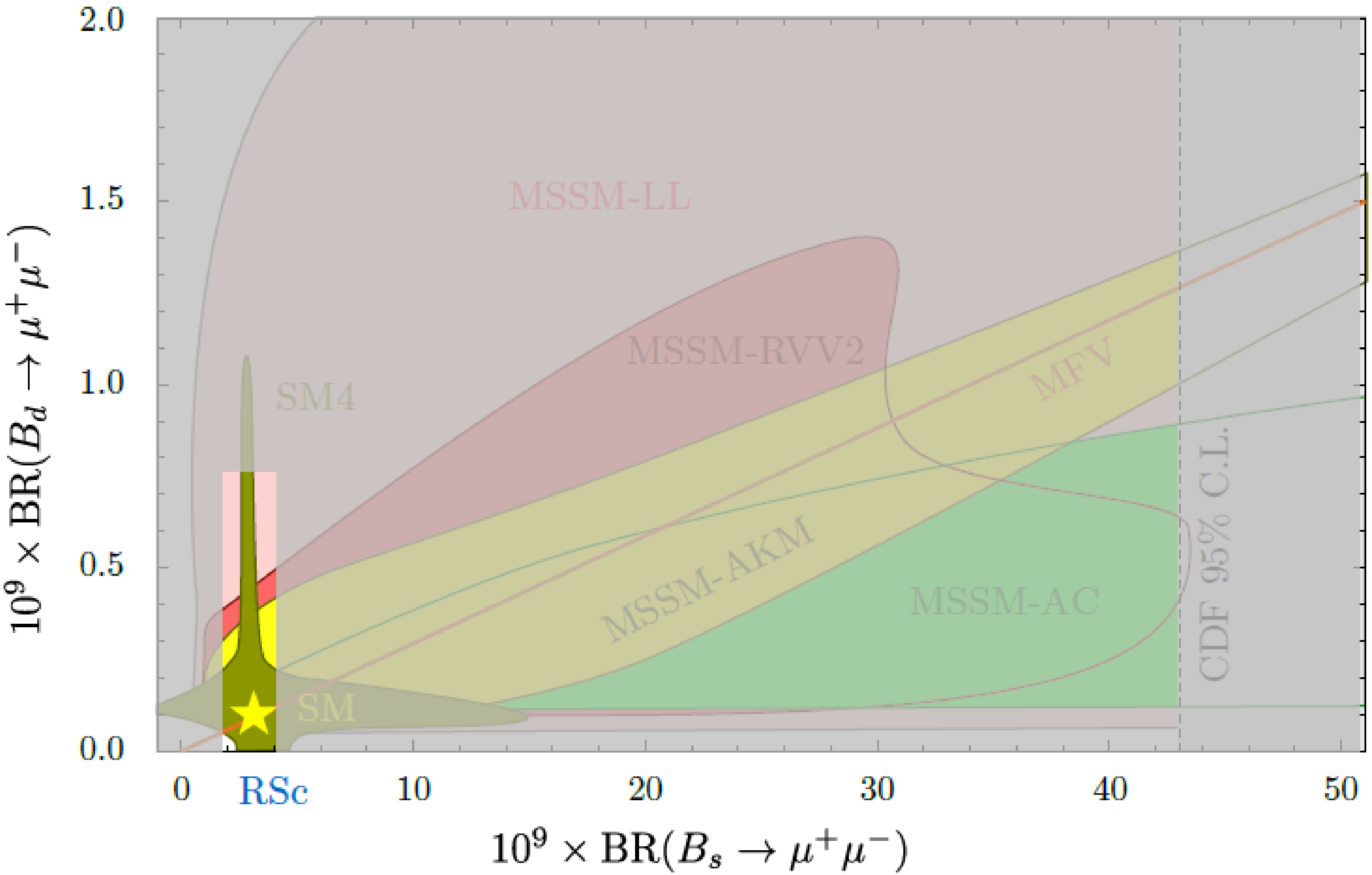
[arXiv:1012.3893]



Constraints on BSM models

- Strong constraints on the phase-space of NP models!

[arXiv:1012.3893]

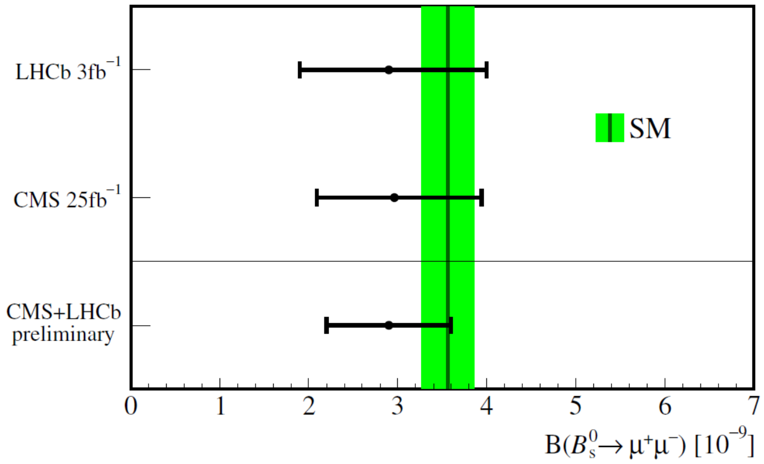


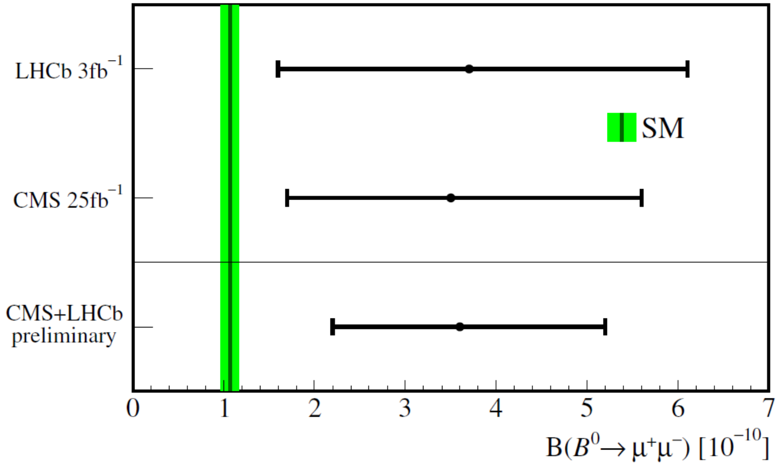
$B_{d,s}\to\mu^+\mu^-$ combination with CMS

- Combination with CMS results for $B_{d,s}\to\mu\mu$ [PRL 111 (2013) 101804]
- Taking into account the common sources of uncertainties, the combined limits are

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}, > 5\sigma$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.6\,^{+1.6}_{-1.4}\right) \times 10^{-10}, < 3\sigma$$

[LHCb-CONF-2013-012, CMS-PAS-BPH-13-007]

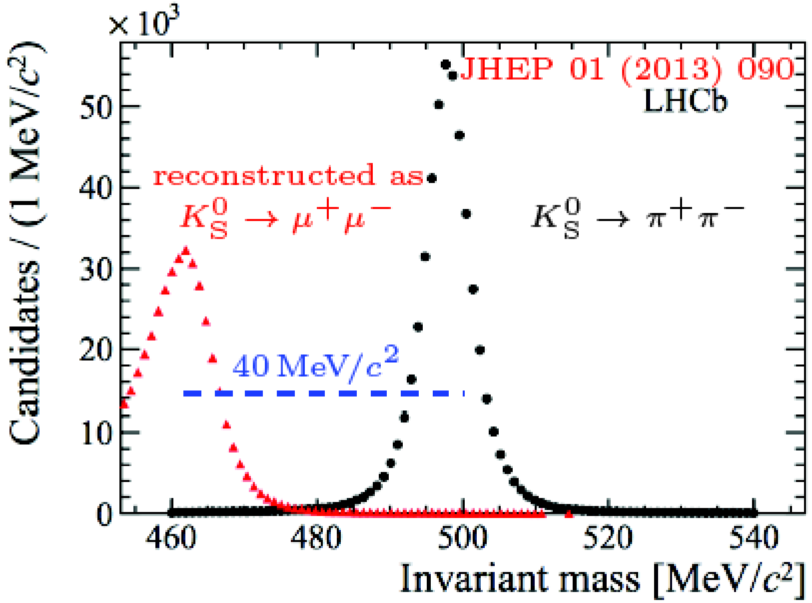




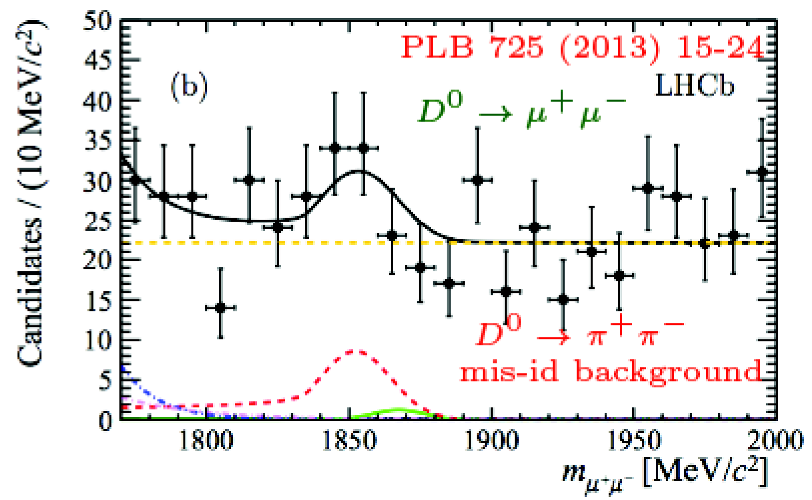
LHCb will now focus on measuring the ratio $BR(B_d\to\mu^+\mu^-)/BR(B_s\to\mu^+\mu^-)$

Other very rare decays: $K_s \to \mu^+\mu^-$, $D^0 \to \mu^+\mu^-$

- FCNC suppressed in the SM: $B_{SM}(K_s \to \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$
- $B(K_s \to \mu^+\mu^-) < 11 \times 10^{-9}$ @90% C.L.
- x30 better limit than previous result.

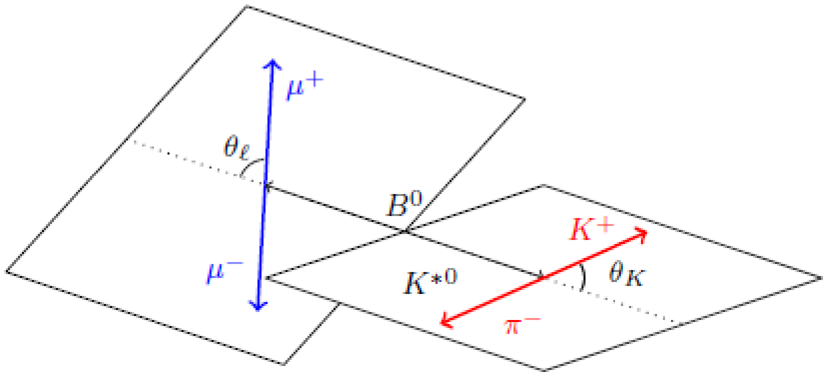


- FCNC, large GIM suppression due to absence of high-mass *d*-type quark and helicity suppression.
- $B_{SM}(D^0 \to \mu^+\mu^-) < \sim 6 \times 10^{-11}$
- $B(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ @90% C.L.
- x20 better limit than previous result.



FNCN b→sll transition: $B^0 \rightarrow K^{(*)}\mu^+\mu^-$

- Rich system of observables sensitive to NP.



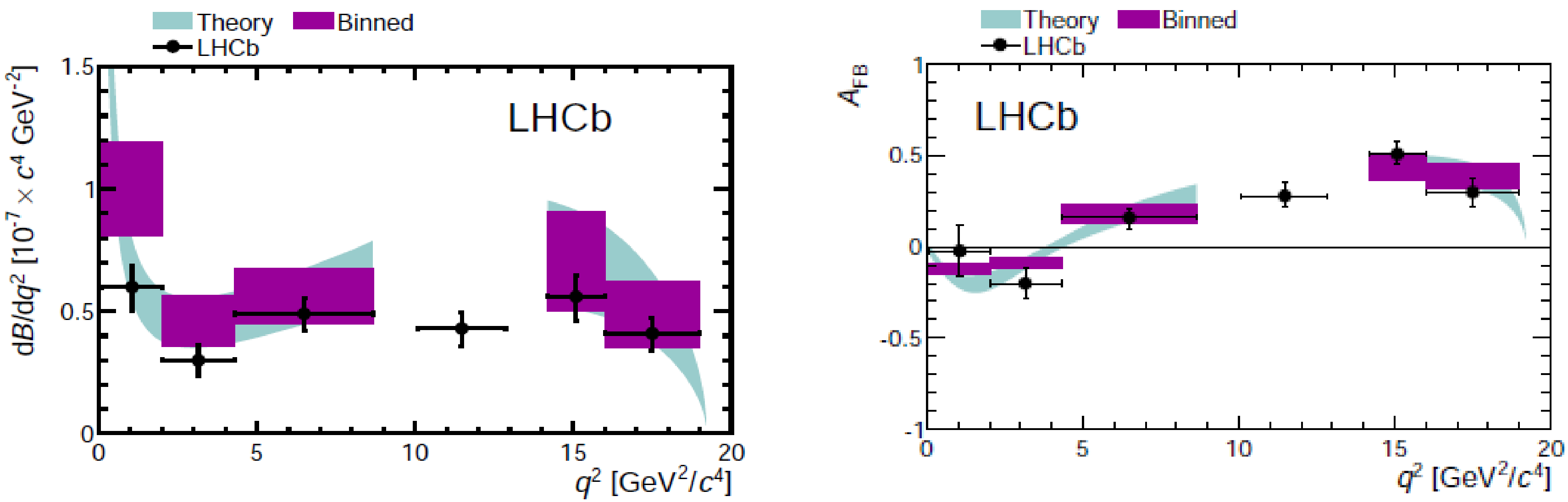
- Angular distribution depends on 3 angles, 12 coefficients that encode the contributions from NP (Wilson coefficients).

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+ S_5\sin2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin2\theta_K\sin2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big],$$

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

[JHEP 1308 (2013) 131]

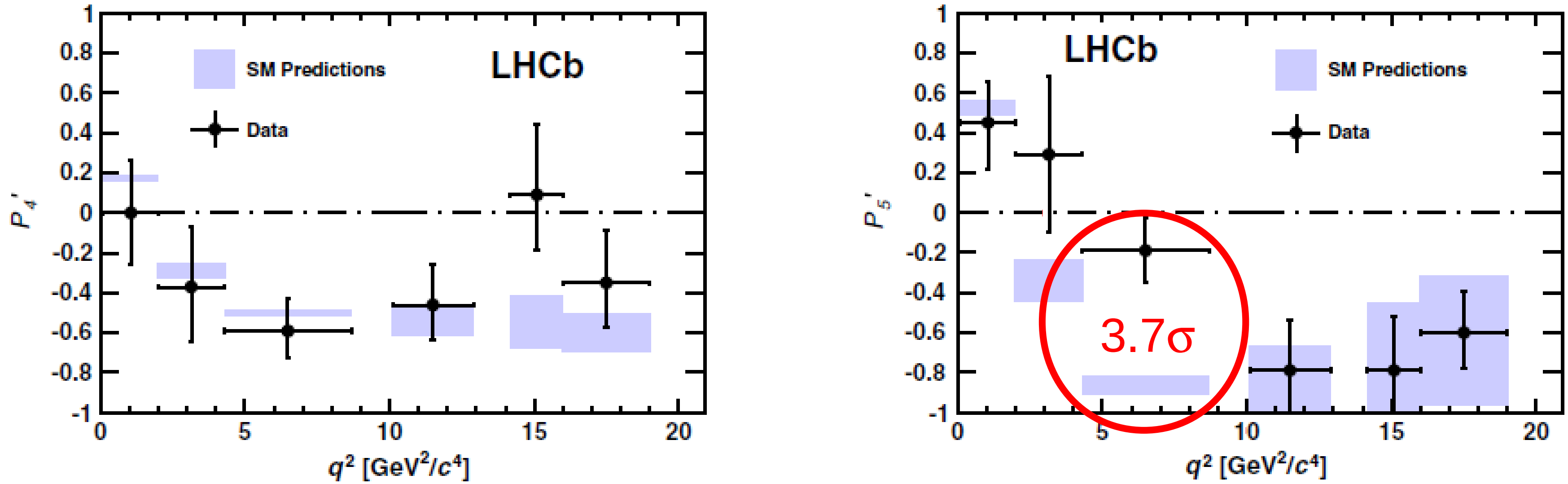
- Differential BR and forward-backward asymmetry as a function of di-muon invariant mass.
- Large theory uncertainties from hadronic form factors.



- In SM, A_{FB} changes sign at a well defined point q_0^2=[3.9-4.4] GeV^2
- First measurement of A_{FB} consistent with SM q_0^2=4.9±0.9 GeV^2

$B^0 \to K^*\mu^+\mu^-$ form-factor independent observables

- Combinations of obervables with reduced form factor dependency at low q^2 proposed [JHEP 1305 (2013) 137]
- New variables are $P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$.
- Repeat the analysis using the new basis [PRL 111 (2013) 191801]



- P'_6 and P'_8 are compatible with SM (close to zero). Significance of 2.8σ across the 24 bins.

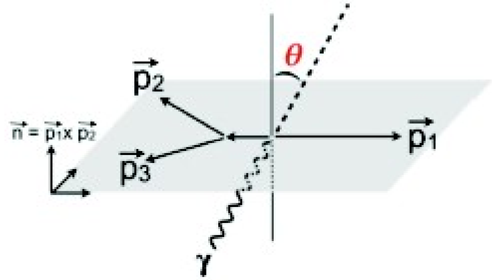
$B^0 \to K^* \mu^+ \mu^-$ "anomaly" interpretation

- Can be explained by a negative NP contribution to the C_9 Wilson coefficient, namely $C_9 = C_9$(SM)-1.5 [PRD 88 (2013) 074002, arXiv:1310.2478, arXiv:1308.1501]
- It can be due to the presence of Z' contribution [arXiv:1308.1959, arXiv:1310.1082, arXiv:1309.2466]
- It can be due to the the presence of exotic scalars [arXiv:1310.1937]
- Statistical fluctuation or underestimated theory uncertainties [JHEP 05 (2013) 043]

- Need to wait until the updated analysis (~summer) with the full dataset to shed some light.
- Also complement with other analysis $B_s \to \phi\mu\mu$, $B^+ \to K^+\mu\mu$

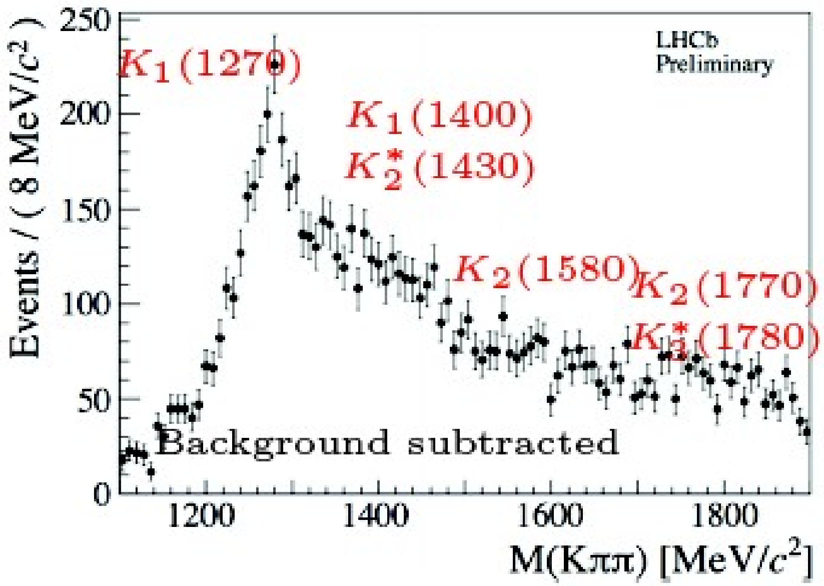
b→sγ FCNC: photon polarisation [arXiv:1402.6852]

- γ from B decays is left-handed, NP can modify it [PRL 79 (1997) 185, PRD 66 (2002) 054008, JHEP 12 (2013) 102]
- Measure the photon polarisation from 3-body decay of K_{res}: $B \to K_{res}\gamma$; $K_{res} \to K^+\pi^+\pi^-$



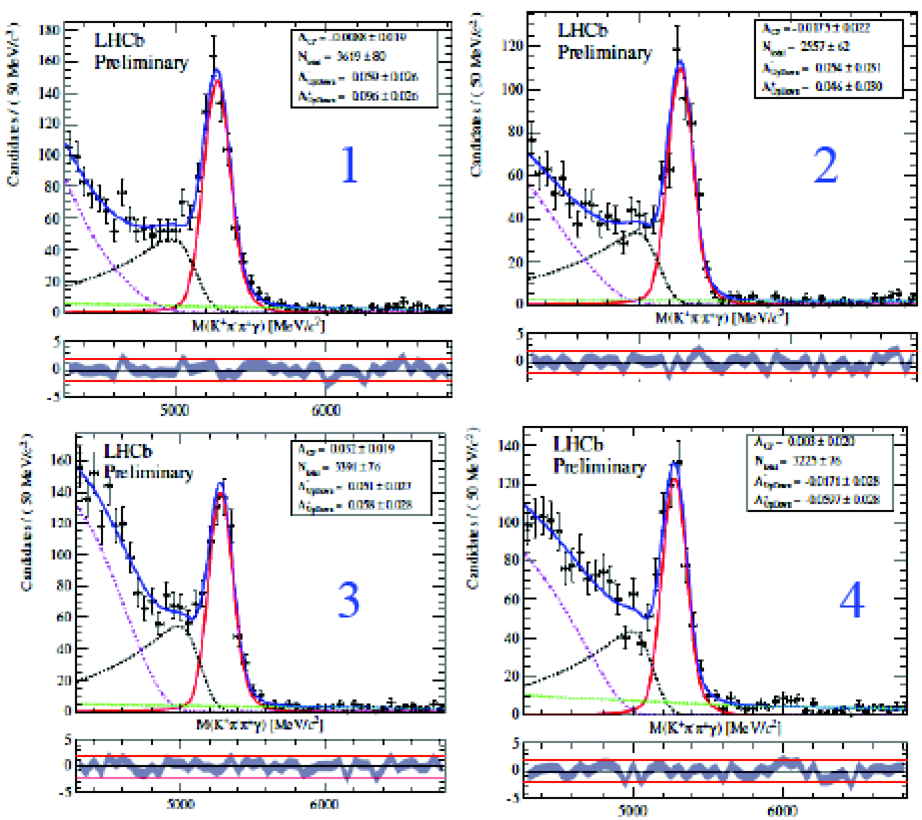
- Count the number of photons above of below the plane defined by the hadrons.

Huge superposition of interfering resonances



b→sγ FCNC: photon polarisation [arXiv:1402.6852]

- Perform the analysis in 4 independent bins of 3-body mass: [1.1-1.3],[1.3-1.4],[1.4-1.6] and [1.6-1.9] GeV.



Significance of A_{ud} been different from zero

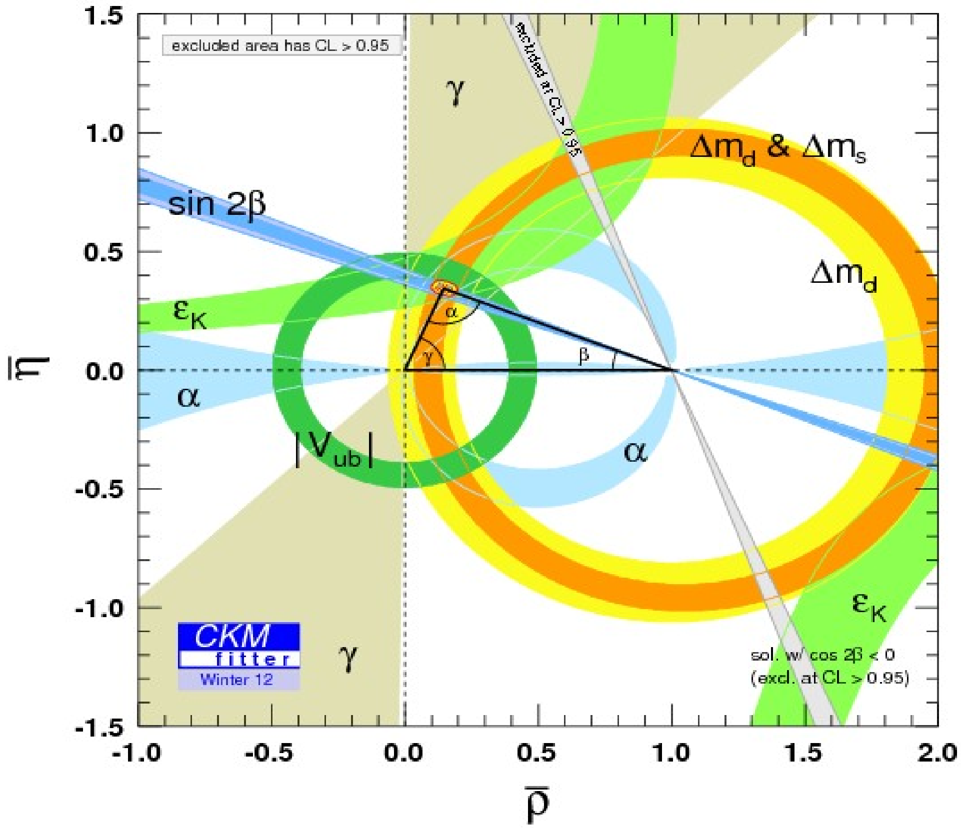
	[1.1, 1.3]	[1.3, 1.4]	[1.4, 1.6]	[1.6, 1.9]
c_1	6.3±1.7	5.4±2.0	4.3±1.9	−4.6±1.8
c_2	31.6±2.2	27.0±2.6	43.1±2.3	28.0±2.3
c_3	−2.1±2.6	2.0±3.1	−5.2±2.8	−0.6±2.7
c_4	3.0±3.0	6.8±3.6	8.1±3.1	−6.2±3.2
$\mathcal{A}_{ud}$	6.9±1.7	4.9±2.0	5.6±1.8	−4.5±1.9

4 independent experiments with results distributed as a χ^2 variable with p-value 1.7x10^{-7}.

This translates into 5.2σ significance for the photon to be polarised.

CKM γ angle

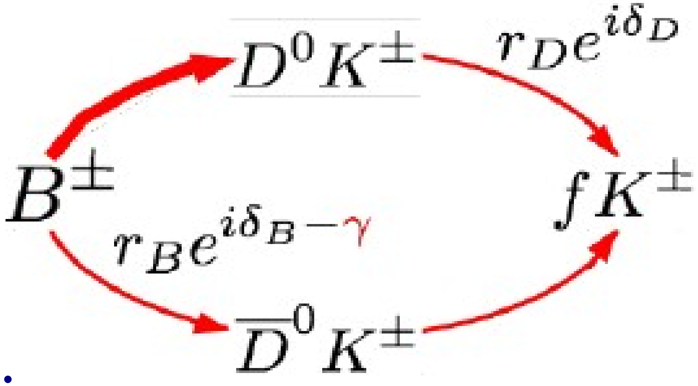
γ state of the art



- γ is the least well measured angle
- Tree-level decays ↔ SM benchmark since no NP contributions!

Measurement of γ from $B^{\pm}\to D^{0}K^{\pm}$

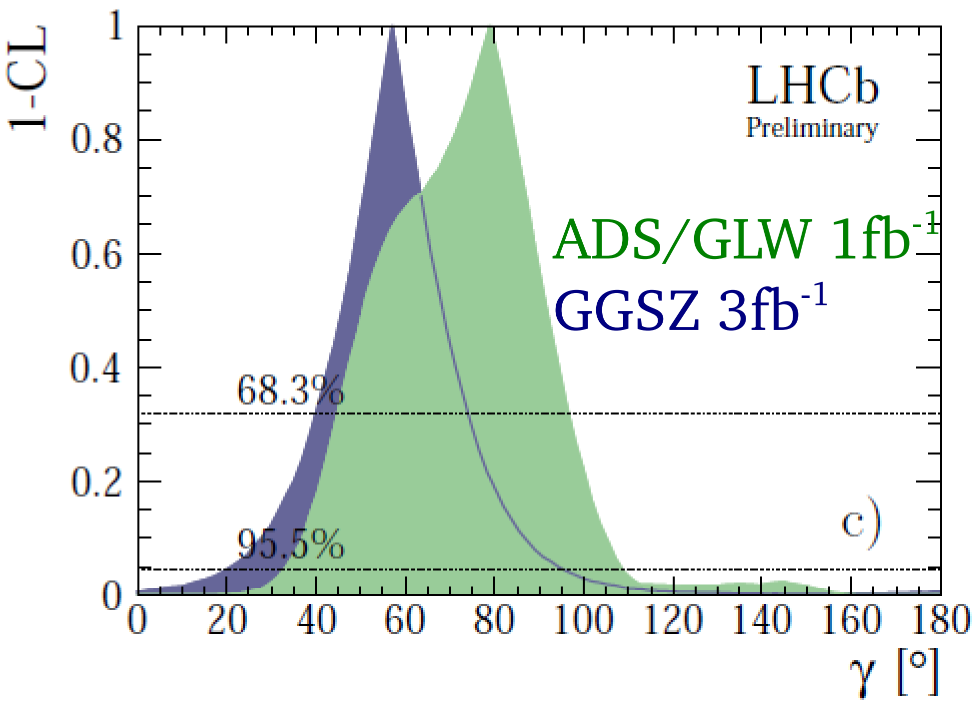
- Same D/$\overline{\text{D}}$ final states.
  - Sensitivity to γ via interference

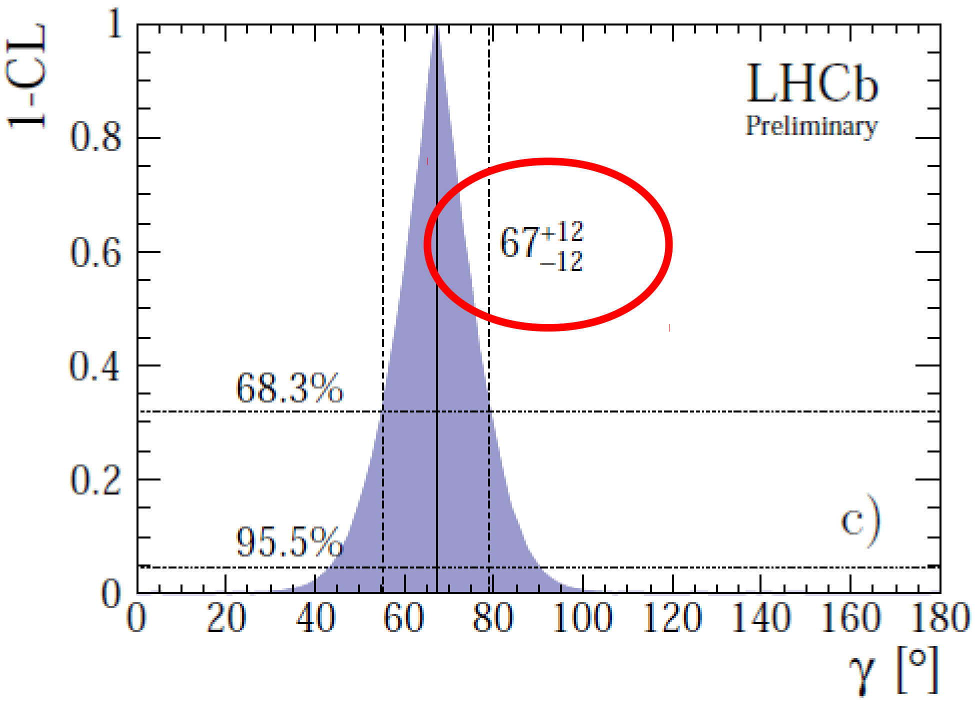


- 3 methods (no flavour tagging needed):
  - **A**twood **D**unietz **S**ony: common flavour states, e.g. Kπ, Kπππ
    - Lower rate, higher interference [PLB 723 (2013) 44, PLB 712 (2012) 203]
  - **G**ronau **L**ondon **W**yler: CP eigenstates, e.g. KK, ππ
    - Large rate, small interference [PLB 712 (2012) 203]
  - **G**iri **G**rossmas **S**offer **Z**upan: self-conjugate, e.g. $K_s$hh
    - Requires Dalitz analysis [PLB 718 (2012) 43]

Measurement of γ: LHCb combination

- $B^{\pm} \rightarrow D^0 K^{\pm}$ results are combined into a single confidence interval. [LHCb-CONF-2013-006]





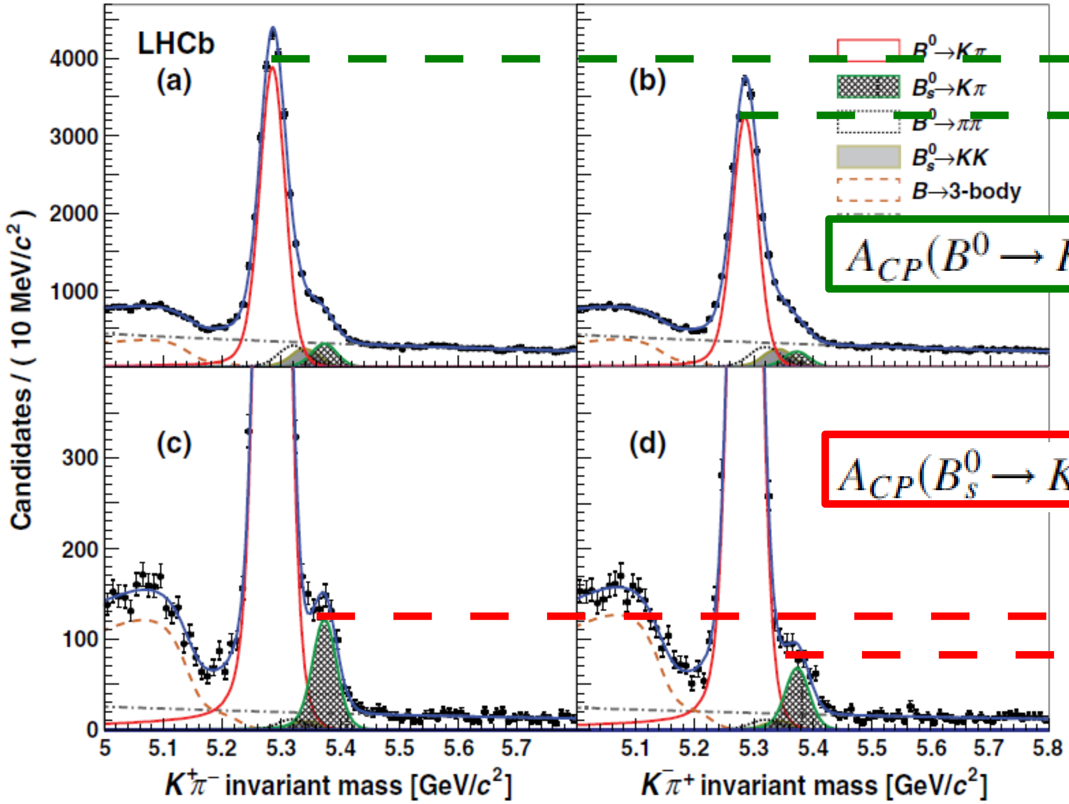
- Single best measurement in agreement with B-factories.
- Work to combine $B^{\pm}$, B_s tree decays. Expected accuracy ~7° with run-I data.

CP violation in B system

Direct CPV in 2-body B decays

- B_s mode, first observation

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



After correcting for production and detection asymmetries

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst})$$

10.5σ significance

$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst})$$

6.5σ significance

[PRL 110 (2013) 221601]

In SM, $\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0,$

$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

[PLB 621 (2005) 126]

Large direct CP violation in 3-body B decays

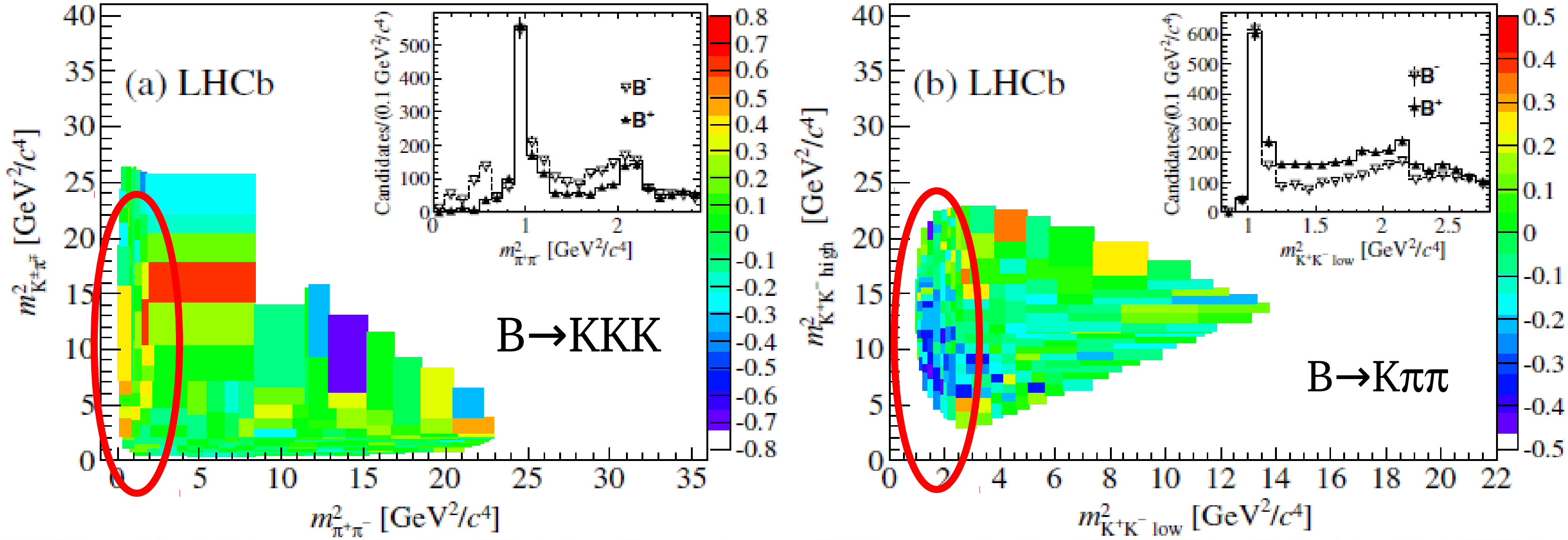
- Source of strong phase difference in 2-b decays, not well understood
- Inclusive measurement (across the Dalitz plane) [PRL 111 (2013) 101801]

$$\mathcal{A}_{CP}(B^\pm \to K^\pm K^+ K^-) = -0.043 \pm 0.009\,(stat) \pm 0.003\,(syst) \pm 0.007\,(J/\psi K^\pm)$$ **3.7σ**

$$\mathcal{A}_{CP}(B^\pm \to K^\pm \pi^+ \pi^-) = 0.032 \pm 0.008\,(stat) \pm 0.004\,(syst) \pm 0.007\,(J/\psi K^\pm)$$ **2.8σ**

Unexpected local asymmetry observed (>50%) with opposite sign at low $m^2_{\pi\pi}$ and m^2_{KK}. Not associated with any ressonance.

Compound CP violation [PRD 71 (2005) 014030] or interference between intermediate states?



Large direct CP violation in 3-body B decays

- Similar analysis with other 3-body decays. [PRL 112 (2014) 011801]

$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = 0.117 \pm 0.021(stat) \pm 0.009(syst) \pm 0.007(J/\psi K^\pm)$$ **4.9σ**

$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.141 \pm 0.040(stat) \pm 0.018(syst) \pm 0.007(J/\psi K^\pm)$$ **3.2σ**

Unexpected local asymmetry observed (>50%) with opposite sign at low $m^2_{\pi\pi}$ and m^2_{KK}. Not associated with any ressonance.

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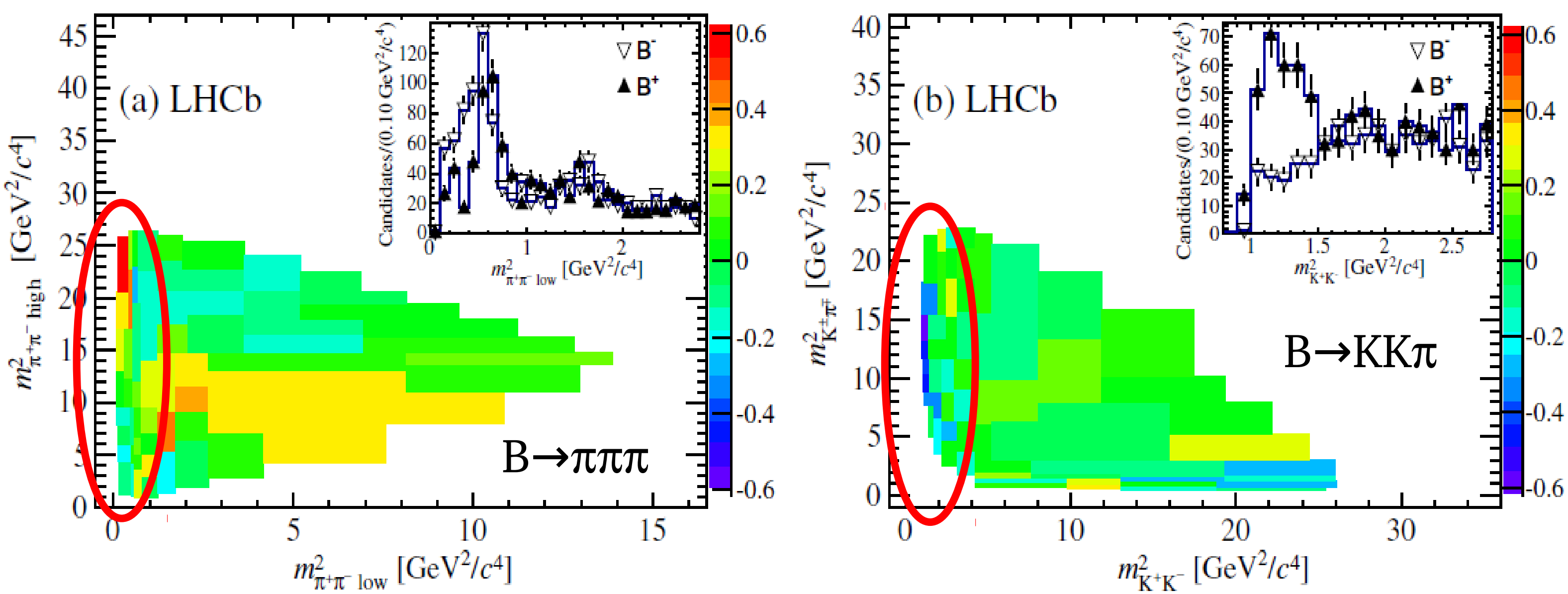


Large direct CP violation in 3-body B decays

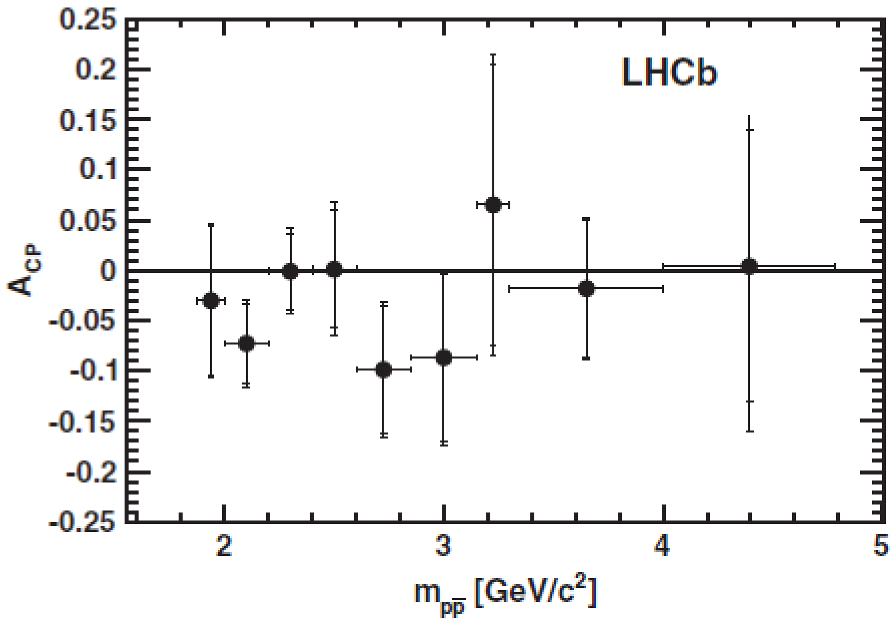
- Check in $B^+ \to p\bar{p}K^+$, same short distance dynamics.
- $hh \leftrightarrow p\bar{p}$ rescattering suppressed.

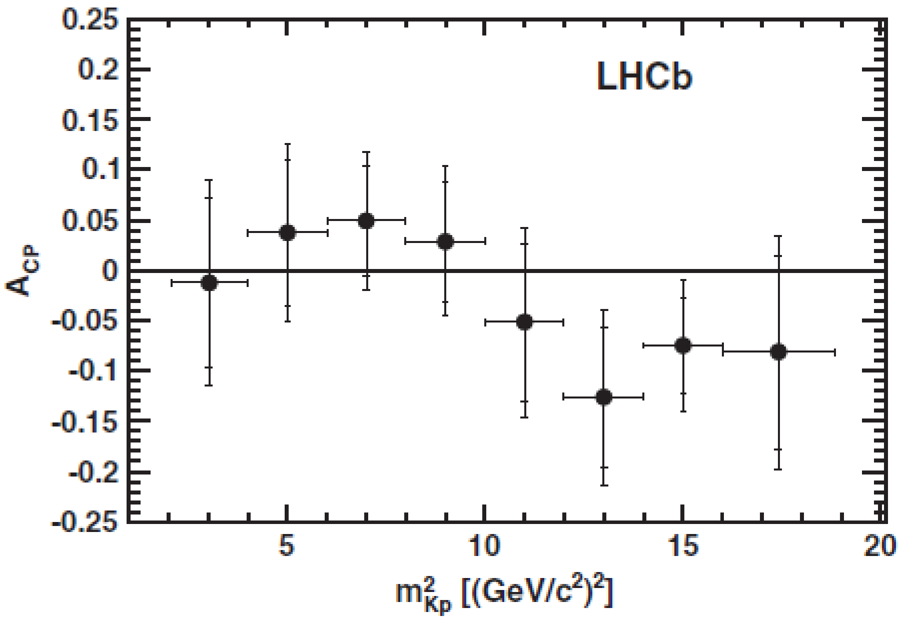
[PRD 88 (2013) 052015]

$$\mathcal{A}_{CP} = -0.022 \pm 0.031(stat) \pm 0.007(syst)$$

Compatible with 0

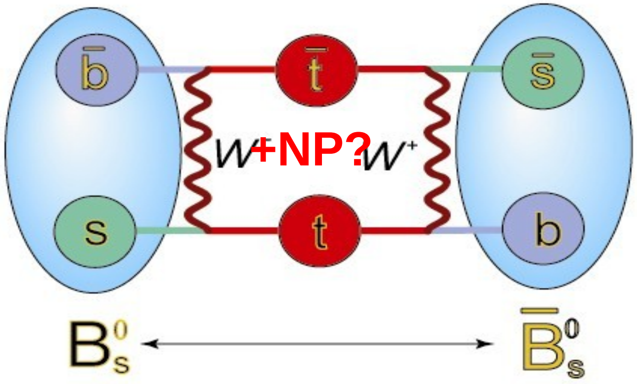
No significance asymmetry in any bin of the Dalitz plot!!
Different long-range behaviour in $B \to hhh$ and $B \to p\bar{p}h$



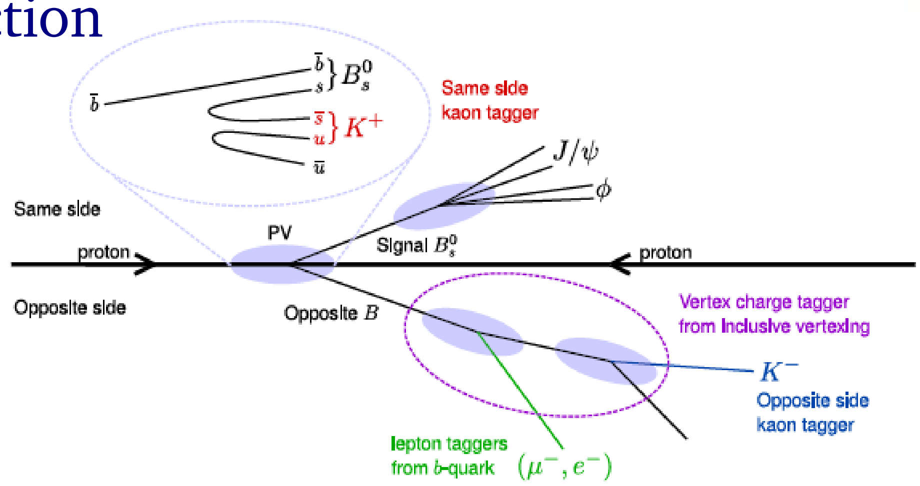


B_s mixing: oscillation frequency

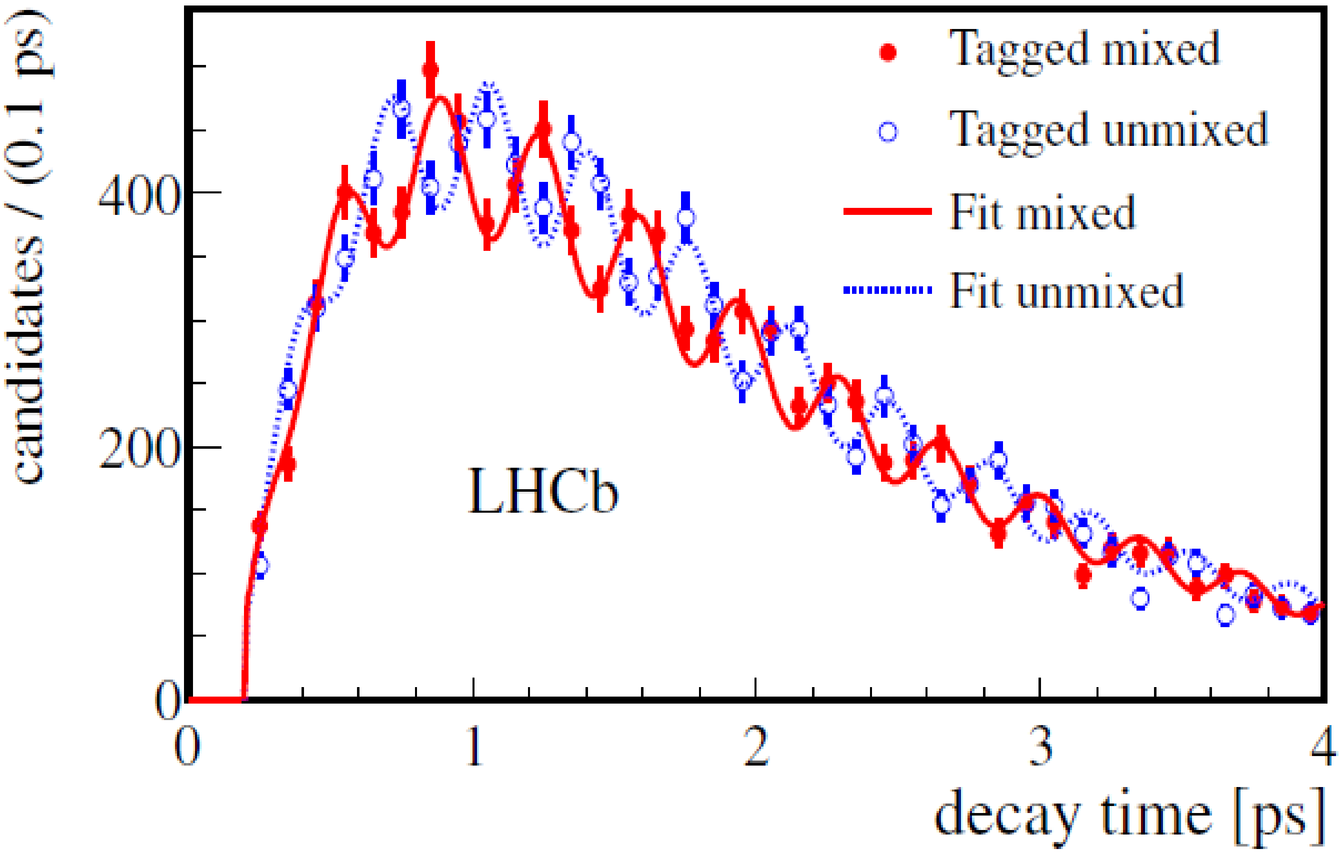
- $B_s - \overline{B}_s$ mixing highly sensitive to NP
- On average, Bs changes flavour 9 times between production and decay → measure the oscillation frequency is challenging.



- Excellent time resolution 44fs << 350fs, B_s oscillation period.
- Use $B_s \to D_s^- \pi^+$, to tag flavour at decay
  - Flavour is given by charge of final state particles
- Tagging identifies flavour at production
  - Opposite side (2.6±0.4)%
  - Same side (1.2±0.3)%



B_s mixing: oscillation frequency



Use $B_s \to D_s^- \pi^+$ with:

$D_s^- \to \phi\pi^-$

$D_s^- \to K^{*0}K^-$

$D_s^- \to K^-K^+\pi^-$

$D_s^- \to K^-\pi^+\pi^-$

$D_s^- \to \pi^-\pi^+\pi^-$

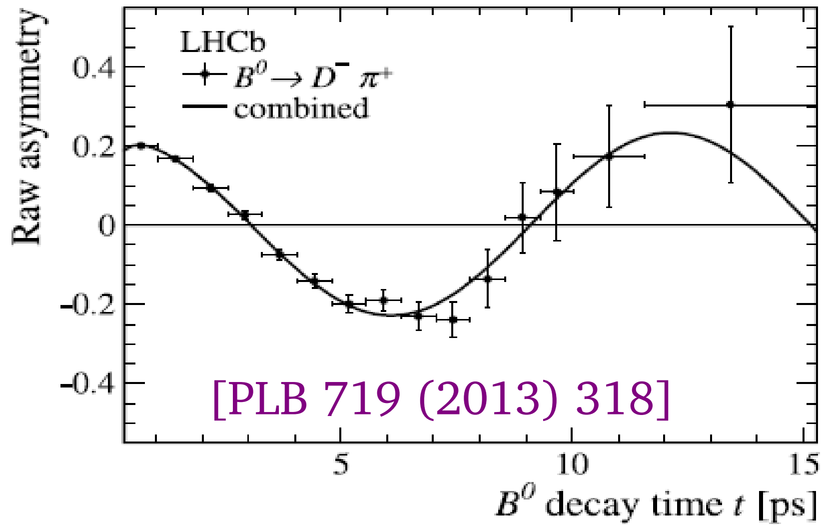
[New J Phys. 15 (2013) 053201]

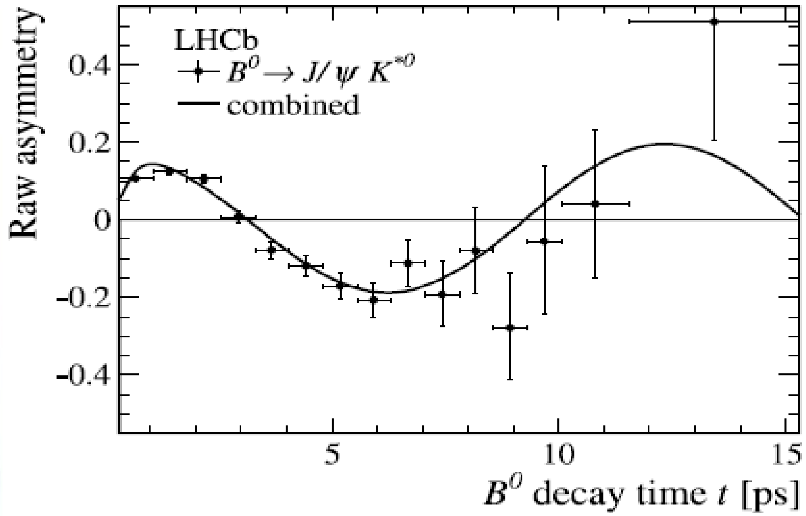
$$\Delta m_s = 17.768 \pm 0.023\,(\text{stat}) \pm 0.006\,(\text{syst})\ \text{ps}^{-1}$$

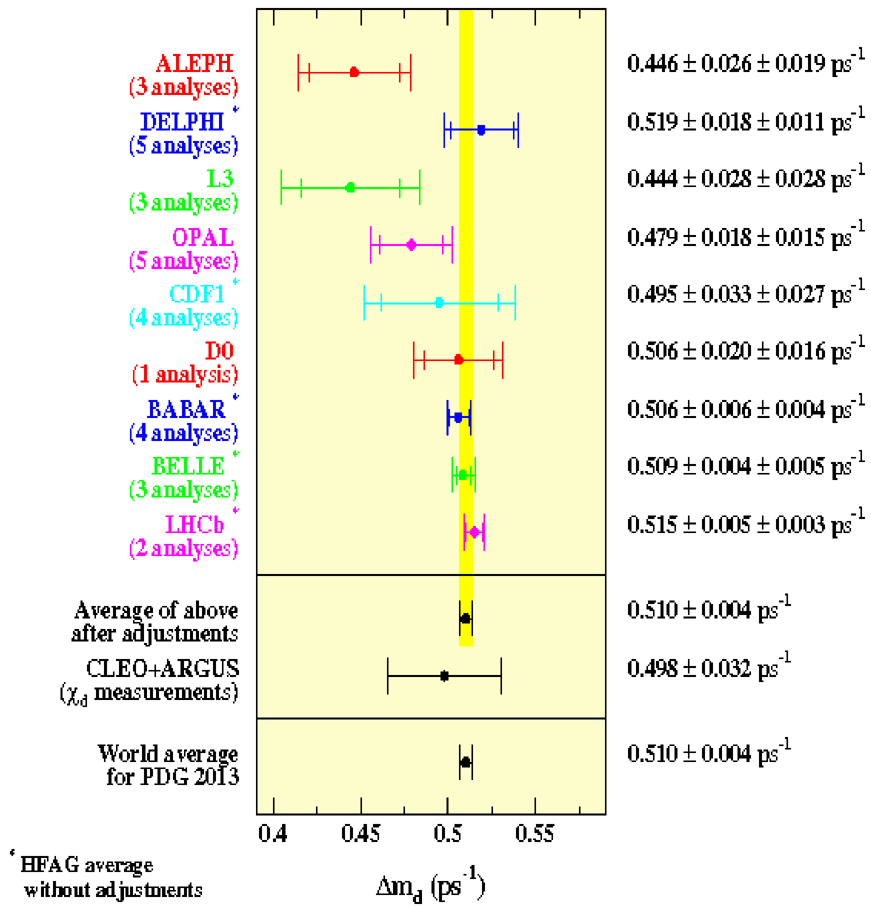
Most precise results to date with 1fb^{-1}. Key in time dependent CPV

B^0 mixing: using $B^0 \to D^-\pi^+$, $B^0 \to J/\psi K^{*0}$

$$A_{mix}(t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} \propto \frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)}$$







$\Delta m_d = 0.5156 \pm 0.0051\,(\text{stat.}) \pm 0.0033\,(\text{syst.})\ \text{ps}^{-1}$

CP violation in $B_{(s)}$ mixing

- CP violation in mixing is very small

Lenz + Nierste, 2011
$$a_{sl}^{d}(B^0) = (-4.1 \pm 0.6) \times 10^{-4}$$
$$a_{sl}^{s}(B_s^0) = (+1.9 \pm 0.3) \times 10^{-5}$$

- a_{sl}: CP asymmetry in flavour specific (semileptonic) decays.
- Final state: $D_s^+\mu^-\bar{\nu}X$ and $D_s^-\mu^+\nu X$
- Experimentally, measure time integrated asymmetry

$$A_{CP}^{measured} = \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]} = \frac{a_{sl}^s}{2} + \left[a_P - \frac{a_{sl}^s}{2}\right] \frac{\int e^{-\Gamma_s t}\cos(\Delta m_s t)\varepsilon(t)dt}{\int e^{-\Gamma_s t}\cosh(\Delta\Gamma_s/2t)\varepsilon(t)dt}$$

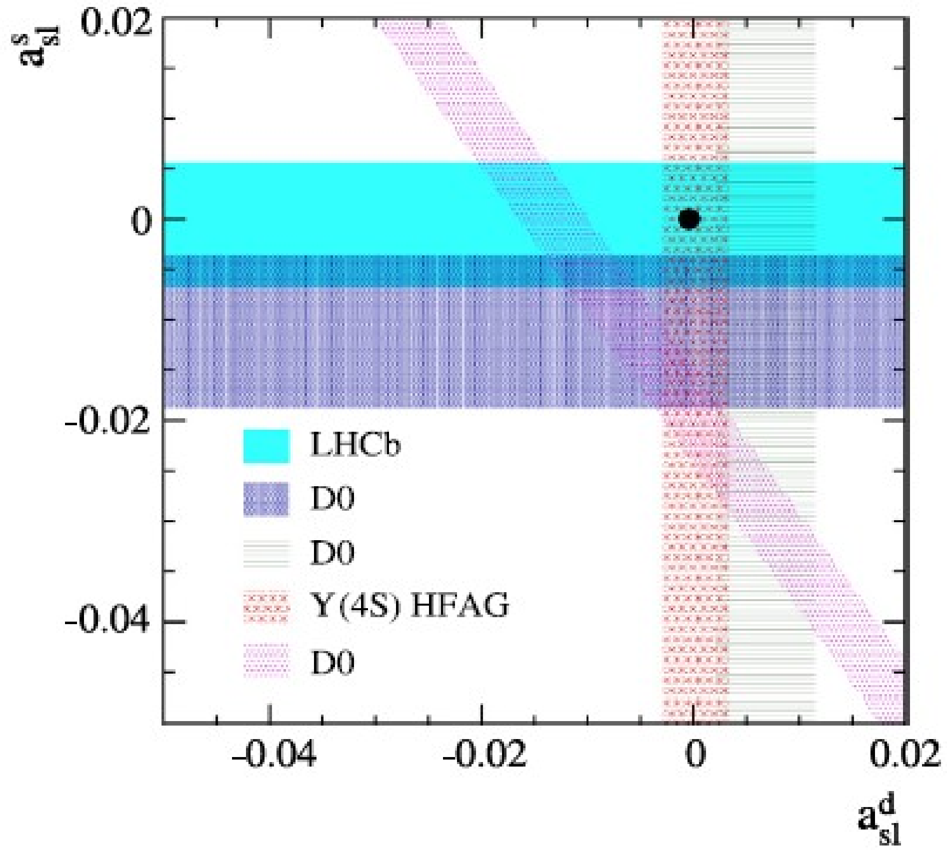
The fast B_s oscillation dilutes the integral ratio to ~0.2%

Use the LHCb result: $\Delta m_s = 17.768 \pm 0.023\,(\mathrm{stat}) \pm 0.006\,(\mathrm{syst})\,\mathrm{ps}^{-1}$

a_P is the B_s production asymmetry ~10^{-4}

CP violation in $B_{(s)}$ mixing

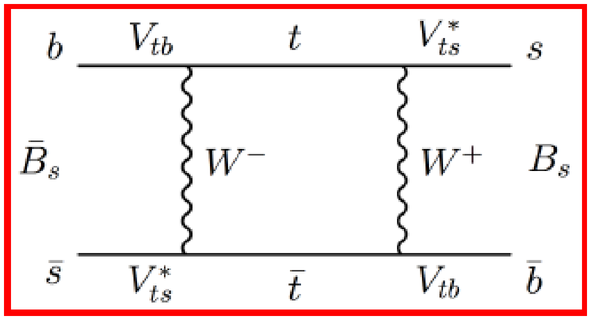
- Result based on $1fb^{-1}$ of data: $a_{sl} = [-0.06 \pm 0.50(stat) \pm 0.36(syst)]\%$
- ~3σ tension of D0 result not confirmed or excluded by LHCb



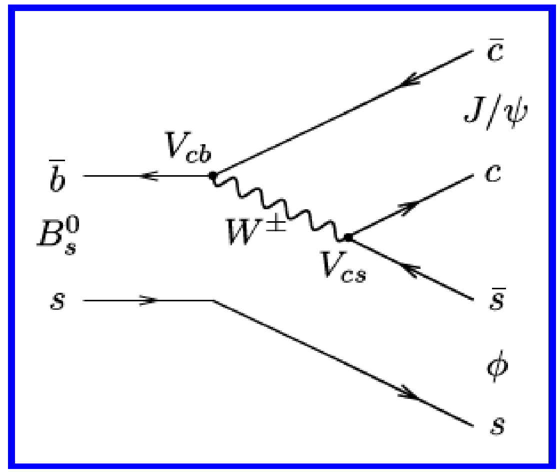
[PLB 728C (2014) 607]

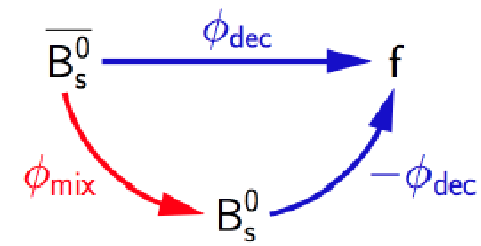
CP violation in $B_{(s)}$ mixing/decay

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



$$\phi_{dec} = \arg(V_{cs}V^*_{cb})$$





$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}^0 \to f) + \Gamma(B^0 \to f)} = \mathcal{D}\eta_f \sin\phi_f \sin(\Delta m t)$$

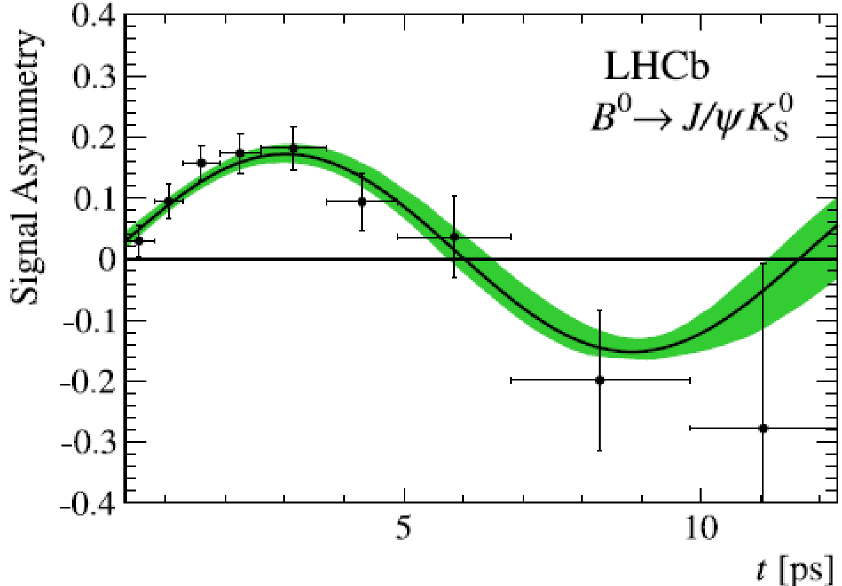
- Use the intereference between **mixing** and **decay** to measure CP-violating phase.
- Use a final CP-eigenstate.
- Contributions from NP in the penguin diagram.

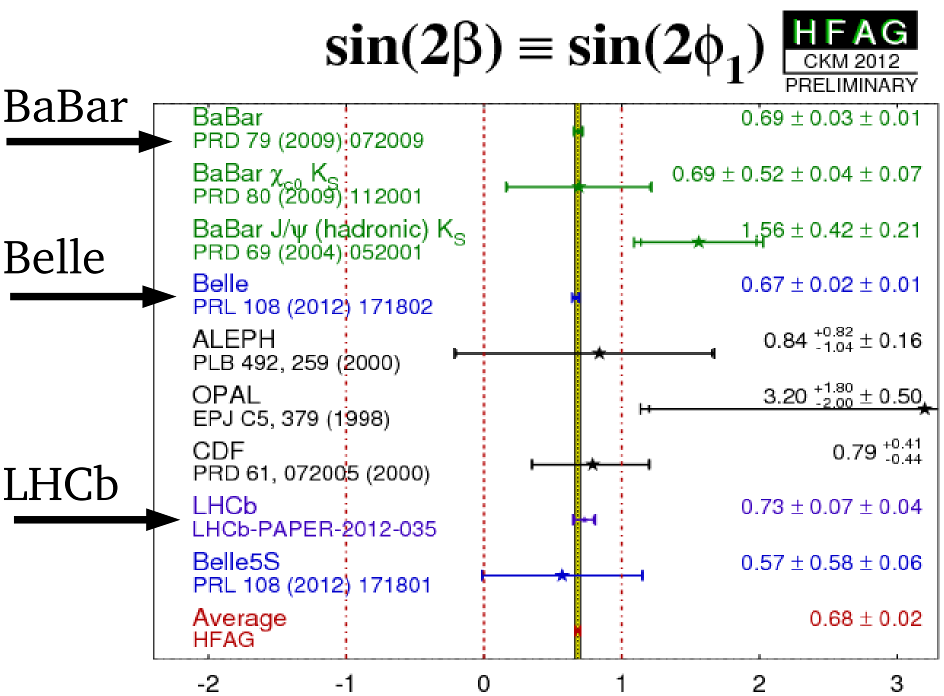
sin2β using $B^0 \to J/\psi K_S$

[PLB 721 (2013) 24-31]

- ~8200 signal candidates in $1 fb^{-1}$
- From the time dependent CP asymmetry

$$A_{CP}(t) \equiv \frac{\Gamma_{B^0 \to f} - \Gamma_{\overline{B}^0 \to f}}{\Gamma_{B^0 \to f} + \Gamma_{\overline{B}^0 \to f}} = S_{J/\psi K^0_S} \sin(\Delta m\, t) + C_{J/\psi K^0_S} \cos(\Delta m\, t)$$



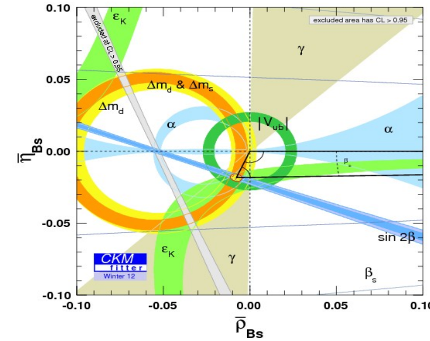


$$S_{J/\psi K^0_S} = 0.73 \pm 0.07 \pm 0.04$$

$$C_{J/\psi K^0_S} = 0.03 \pm 0.09 \pm 0.01$$

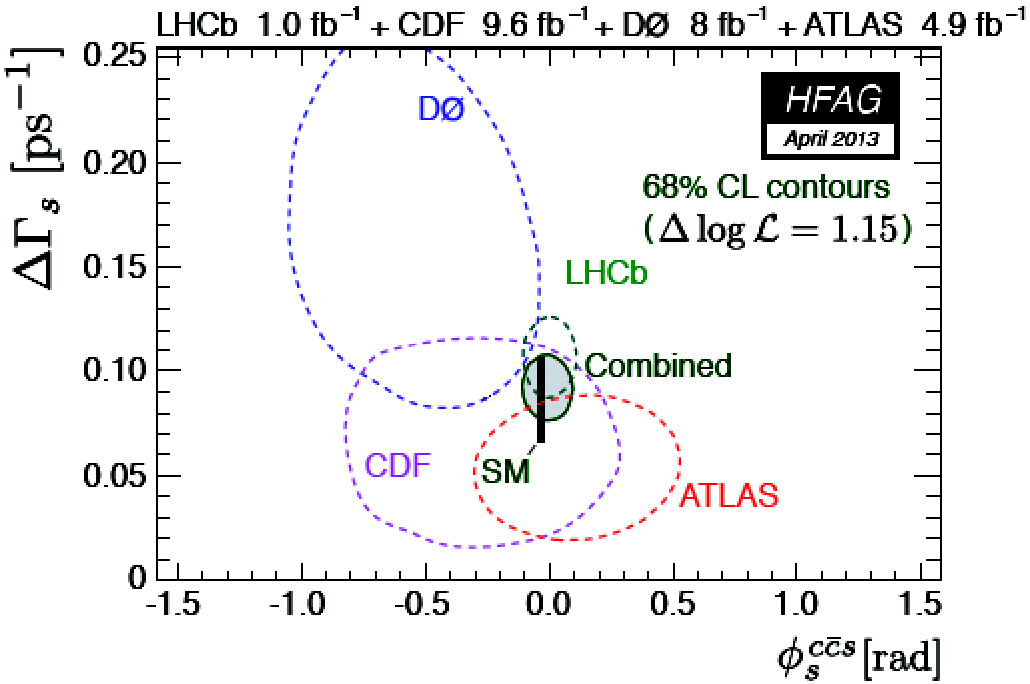
Measurement of ϕ_s

- Φ_s is small in SM ($\Phi_s^{SM} = -2.1 \pm 0.1)^o$ [arXiv:1203.0238]
- Combine fit of $B_s \rightarrow J\psi\phi$ and $B_s \rightarrow J\psi\pi^+\pi^-$



$$\phi_s = 0.01 \pm 0.07(\text{stat}) \pm 0.01(\text{syst})\ \text{rad},$$
$$\Gamma_s = 0.661 \pm 0.004(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1},$$
$$\Delta\Gamma_s = 0.106 \pm 0.011(\text{stat}) \pm 0.007(\text{syst})\ \text{ps}^{-1}.$$

[PRD 87 (2013) 112010]



Sign of $\Delta\Gamma_s$ establish

Heavier meson lives longer

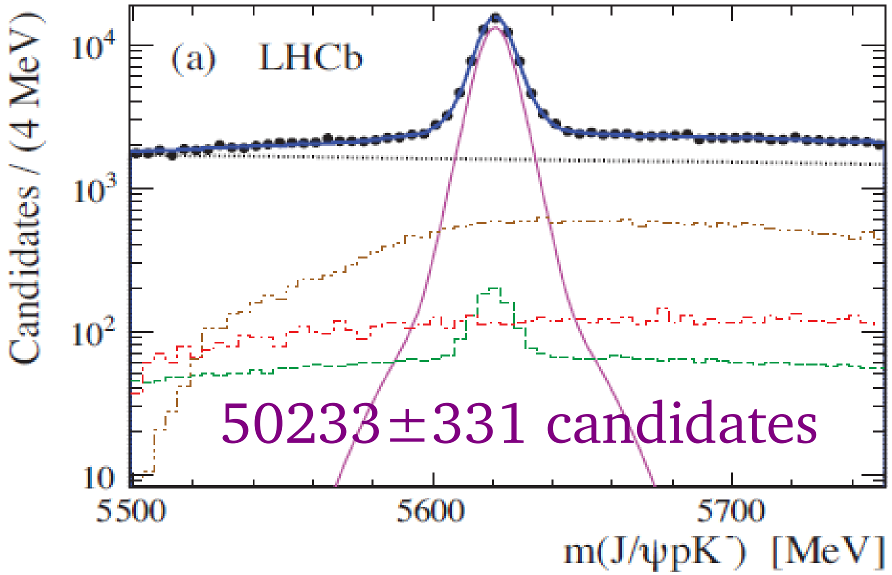
NP contributions to B_s mixing is limited to <30%

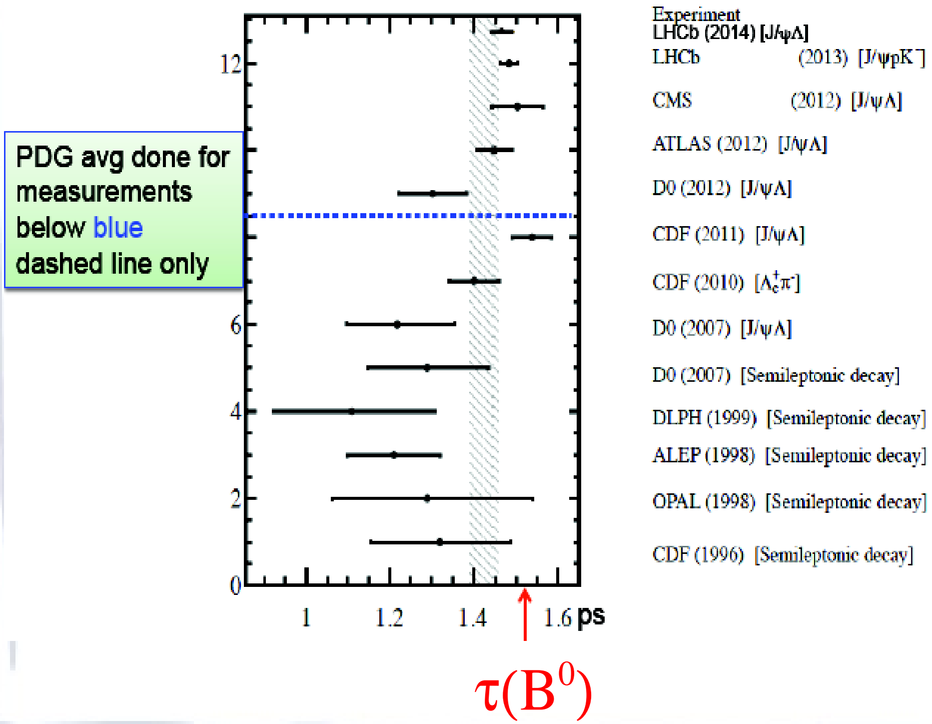
[arXiv:1203.0238]

b-baryon physics

Λ_b lifetime measurement [arXiv:1402.6242]

- HQE: $\frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.98 + \mathcal{O}(1/m_b^3)$
- Test of HQE: use for inclusive prediction of V_{ub} and V_{cb}
- Update with full dataset $3fb^{-1}$
- Normalise to $B^0 \to J/\psi K^{*0}$





$$\frac{\tau_{\Lambda_b^0}}{\tau_{\overline{B}^0}} = 0.974 \pm 0.006 \pm 0.004$$

Good agreement with HQE prediction

Charm physics

D^0 mixing and CPV

- Expect small CPV in charm mixing and decays → sensitive null test of CKM.
- Mixing dominated by long-distance effects not easy to compute.
- Classify as right-sign or wrong-sign $D^{*+} \to D^0(K\pi)\pi^+$ using flavour at production.
  - RS: Cabibbo Favoured $D^{*+} \to D^0(K^-\pi^+)\pi^+$ (54M candidates)
  - WS: DCS, mixing+CF $D^{*+} \to D^0(K^+\pi^-)\pi^+$ (0.23M candidates)
- WS/RS vs time separates suppressed decay from oscillation

$$R(t) \equiv \frac{N_{\rm ws}(t)}{N_{\rm rs}(t)} \approx R_D + \sqrt{R_D}y't + \frac{1}{4}(x'^2 + y'^2)t^2$$

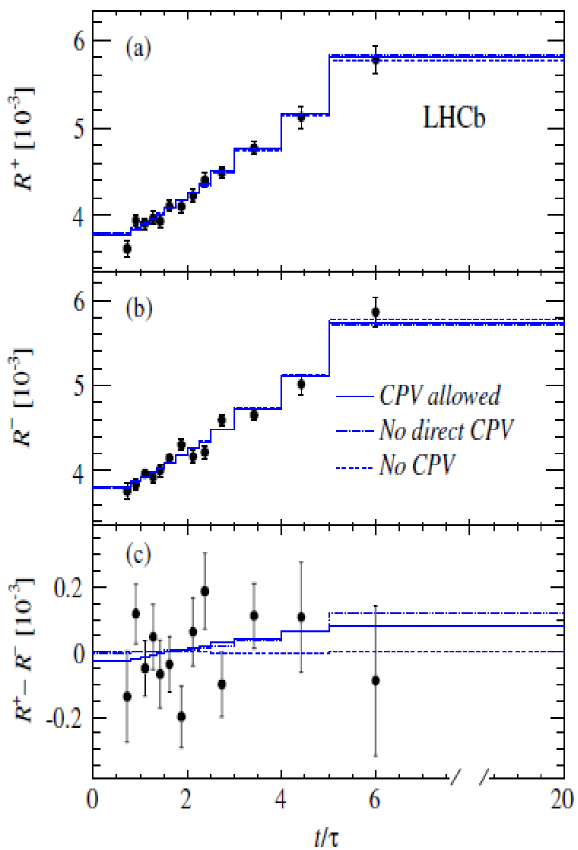
Direct CPV, DCS — Interference — Mixing

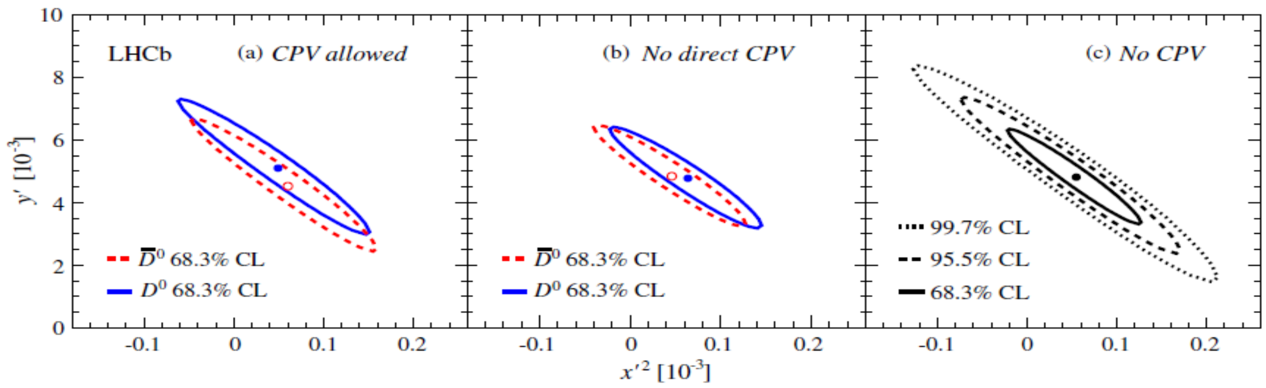
- Fit D^0 / $\overline{D}^0$ separately to search for CPV

D^0 mixing and CPV

[PRL 111 (2013) 251801]

Ratio WS/RS vs time





No evidence of CP violation when studying D^0 / $\overline{D}^0$ separately

$$x'^2 = (5.5 \pm 4.9) \times 10^{-5}$$
$$y' = (4.8 \pm 1.0) \times 10^{-3}$$
$$A_D \equiv \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.7 \pm 1.9)\%$$
$$|q/p| = 1.00 \pm 0.25$$

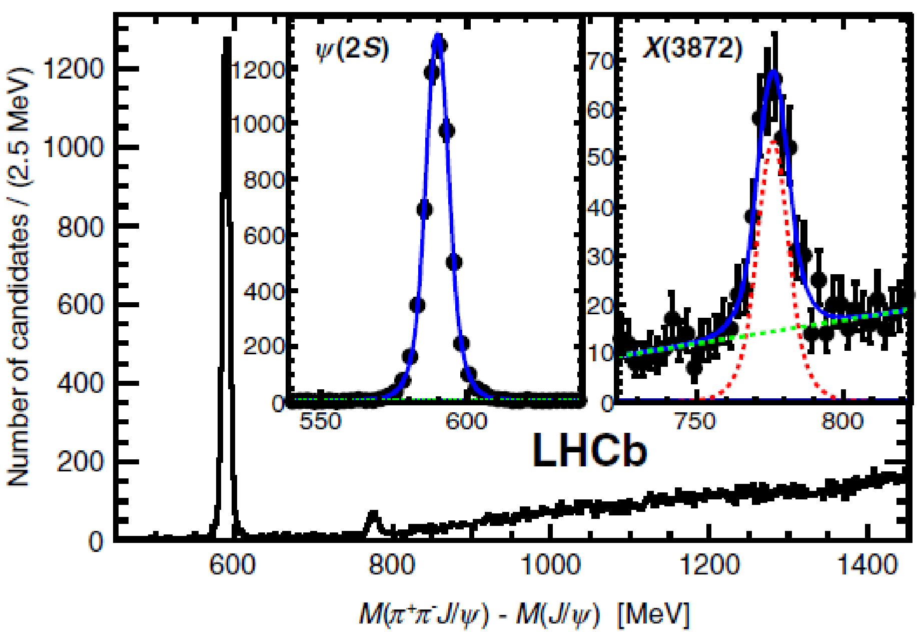
Best determination of mixing parameters with 3fb^{-1}

Exotica, QCD and EW physics

Exotic spectroscopy: X(3872) [PRL 110 (2013) 222001]

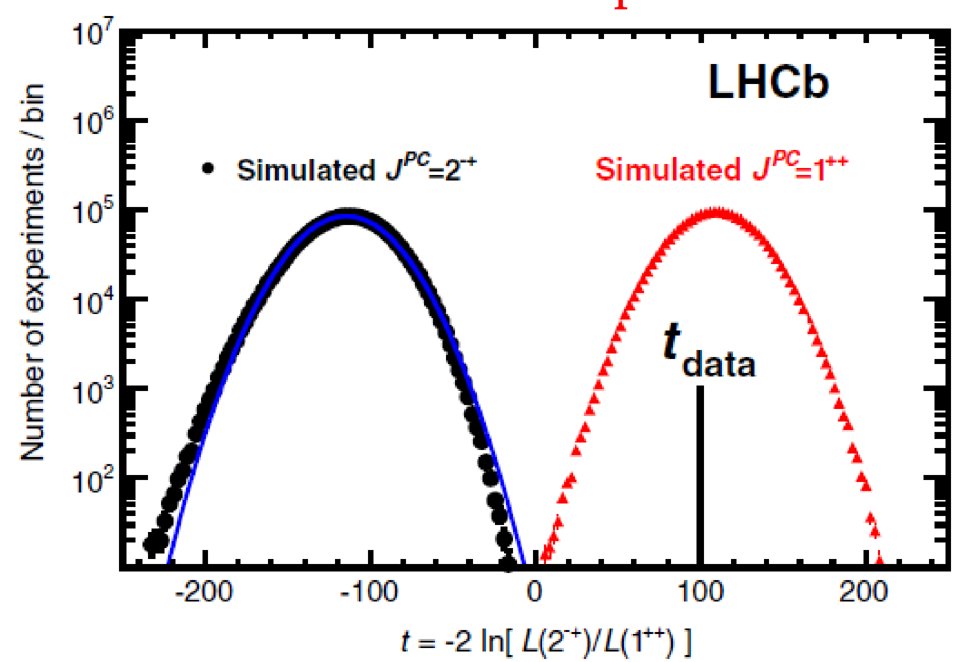
- What is the nature of this state (tetra-quark or DD* molecule, or...?)
- Must be C = +, since $X(3872) \to J/\psi\gamma$ has been observed by Belle.
- CDF previosuly rules out all J^{PC} except 1^{++} and 2^{-+}

$B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$



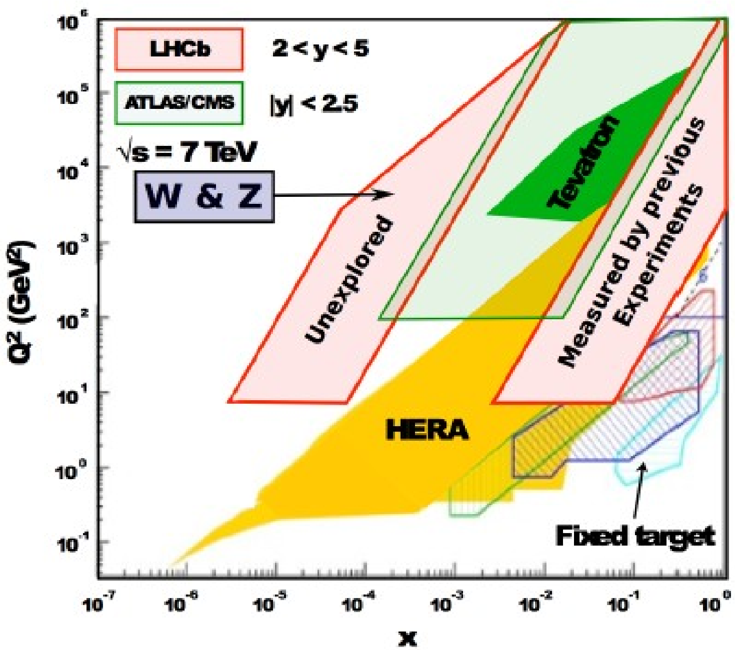
.Cb.

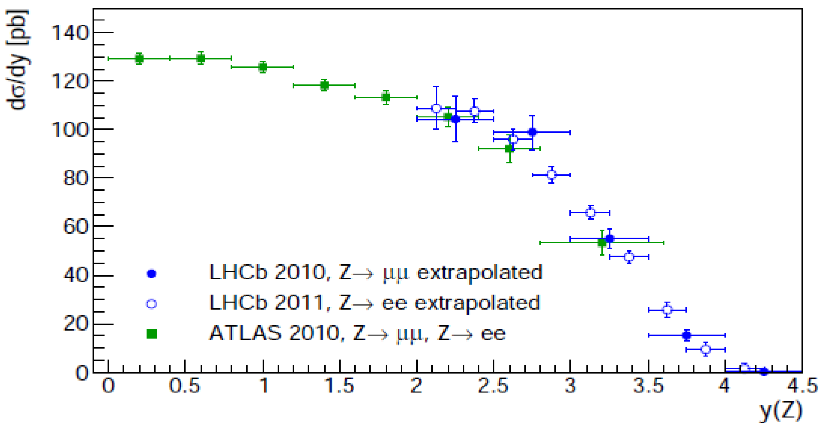
From 5D angular fit. $J^{PC} = 1^{++}$ established at 8.4σ significance. Favours exotic interpretation.

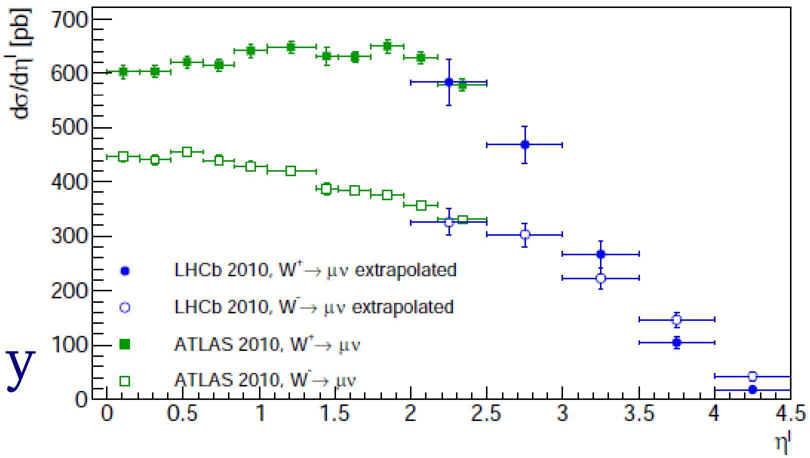


QCD and EW measurements

- LHCb tests low Björken x – high Q^2 previously unexplored.
- Comparison possible in overlap regions with ATLAS/CMS



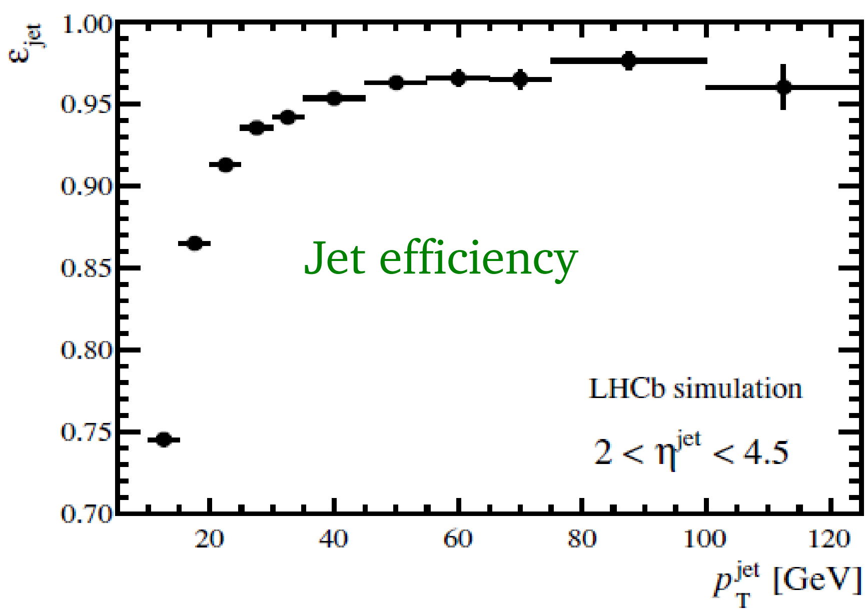


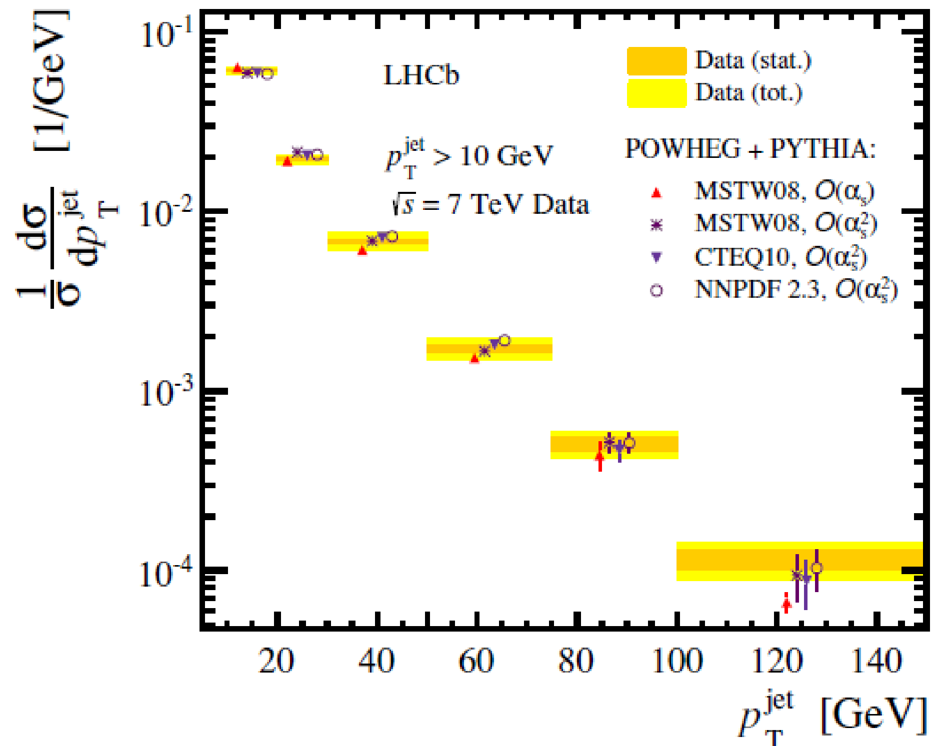


Good agreement as a function of y
[LHCb-CONF-2013-005]

QCD and EW measurements: Z+jets

- Z + jets production cross-section measured. Test of jet capabilities in LHCb. [JHEP 01 (2014) 033]
- Sensitive to the gluon content of the proton.





Good agreement with $O(\alpha^2)$ calculations

Summary

- LHCb provides a unique laboratory for the precision study of heavy flavour.
  - But not only that. LHCb is emerging as a general purpose, high resolution spectrometer in the forward direction.
- Many results and world best measurements with the first $3fb^{-1}$ of data.
- The SM is still healthy. No excepcional signs of NP spotted, but few anomalies appear.
- Expect new results to appear in the near future (e.g. Moriond EW and QCD)