Highlights from LHCb

Monica Pepe Altarelli (CERN)
On behalf of the LHCb collaboration

The Status of the SM, April 7-8 2014, Warsaw

Outline

- The LHCb experiment
- Rare decays
  - $B \rightarrow \mu^+\mu^-$
  - $B \rightarrow K^{(*)}\mu^+\mu^-$
  - Radiative decays
- Measurement of γ
- B^0_s mixing
  - Oscillation frequency
  - CPV in B^0_S mixing/decay ϕ_s
  - Semileptonic asymmetry a_{sl}
- Charm
  - D^0-$\overline{D}^0$ mixing
- Conclusions

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- Many other results not covered, e.g.
  - CPV and rare decays
    - Charmless B decays
    - Many rare exclusive decays
    - Electroweak Physics
    - W and Z production
  - Lepton flavour number violation
  - pA collisions
  - Production and spectroscopy
    - Fragmentation fractions
    - B_c decays and lifetimes
    - Quarkonia polarisation
    - XYZ states
    - Central exclusive production

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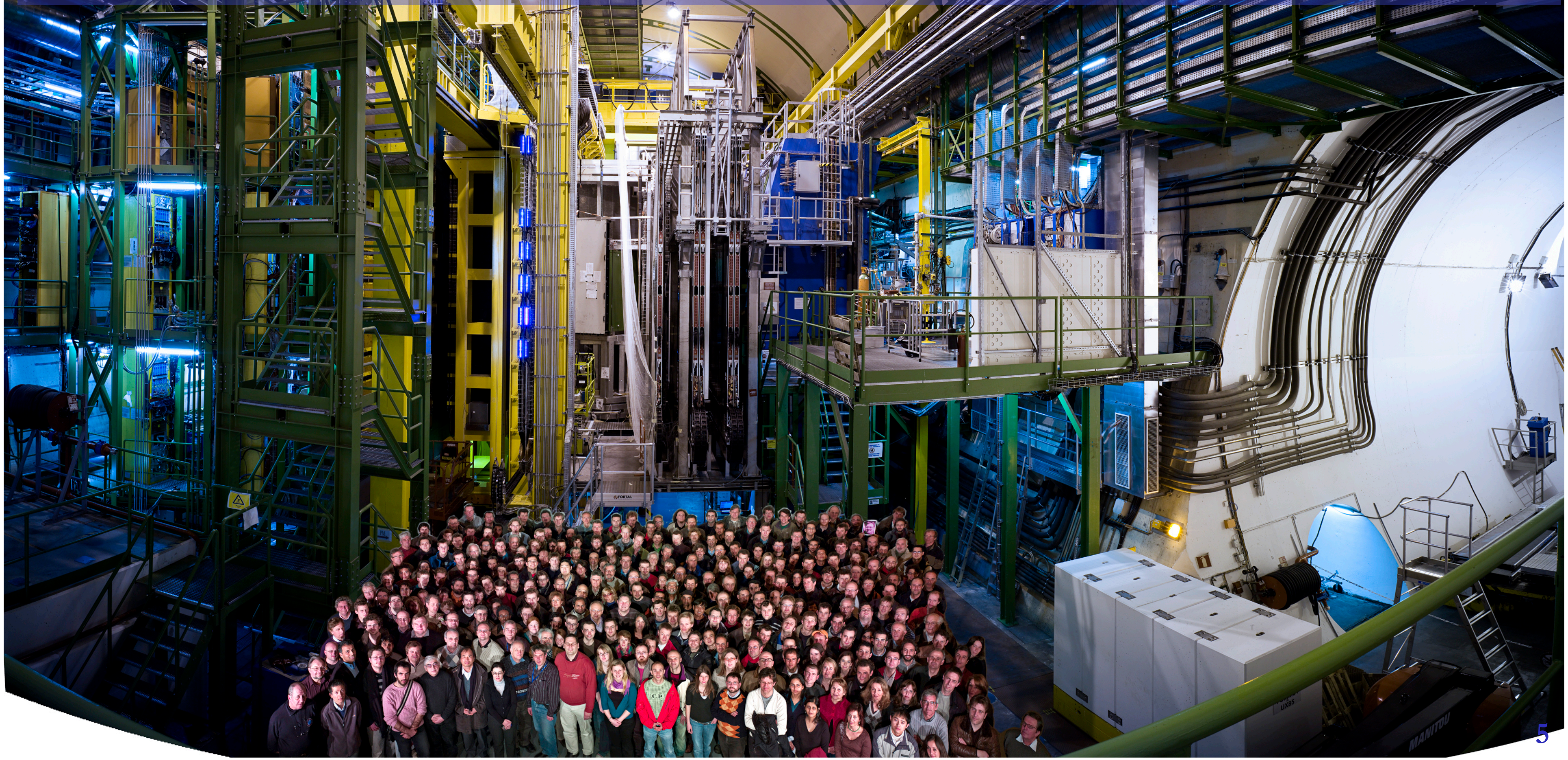
LHCb emerging as a general purpose, high-resolution spectrometer in the forward direction

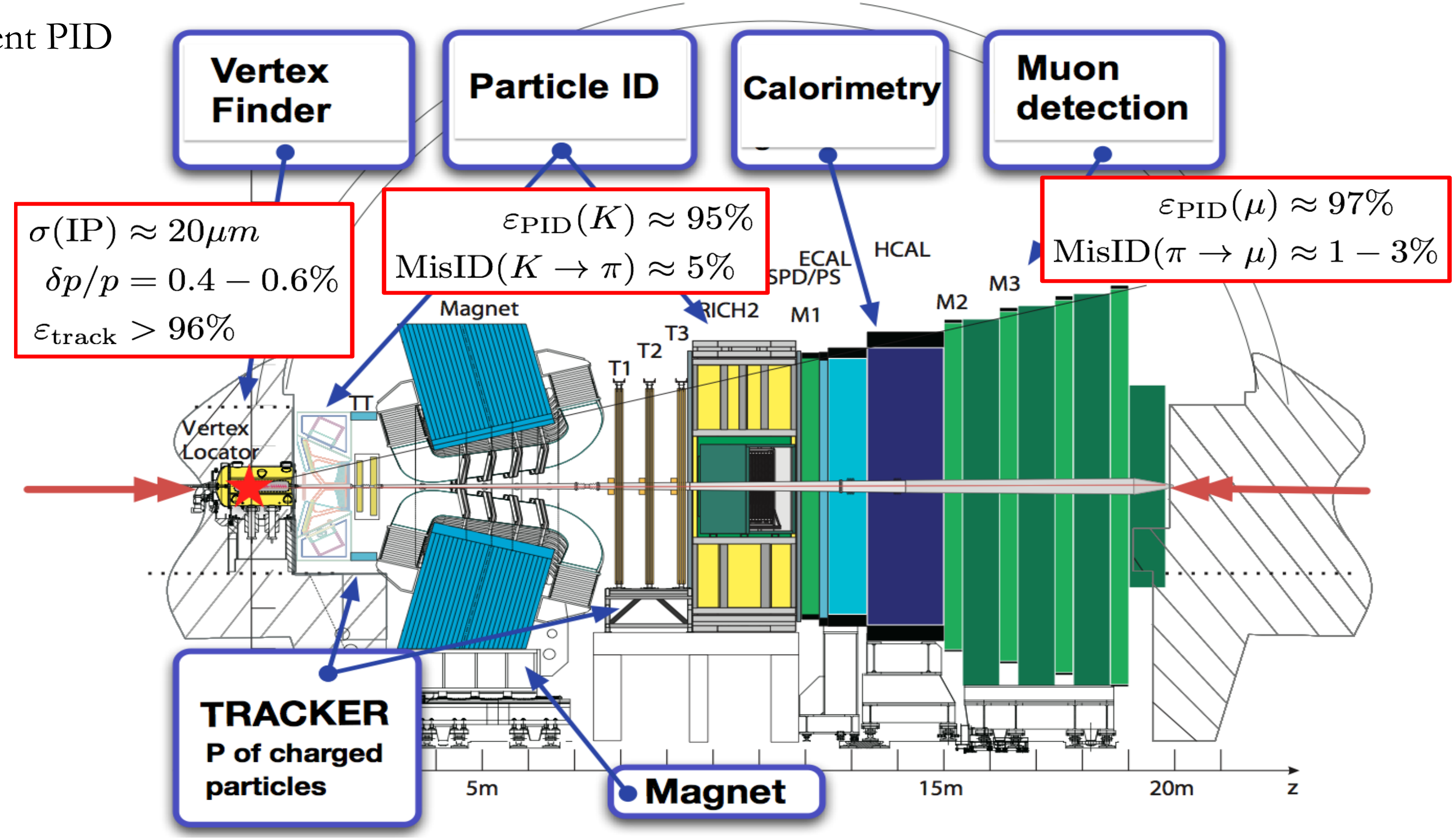
The LHCb collaboration

- 16 countries
- ~900 members from 67 universities/laboratories
- 178 publications, some of them with very high impact

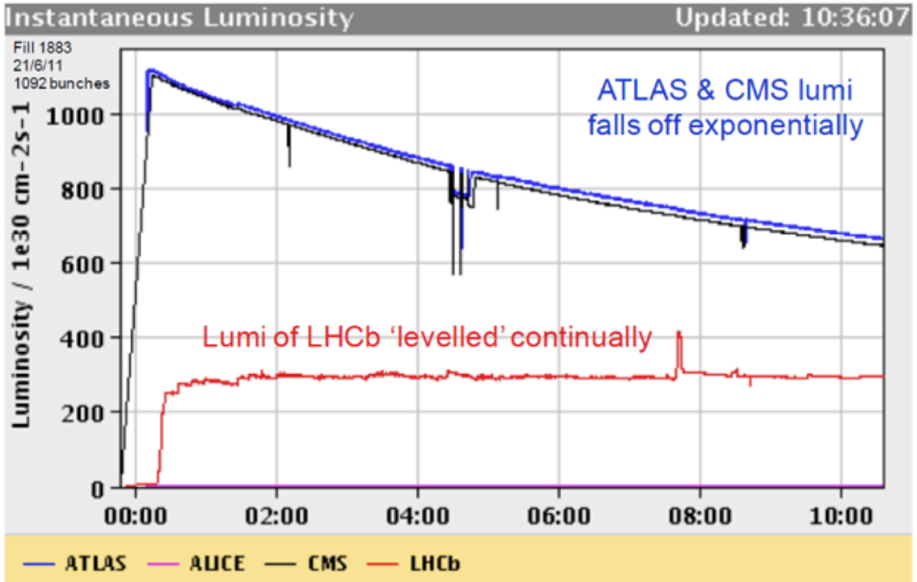


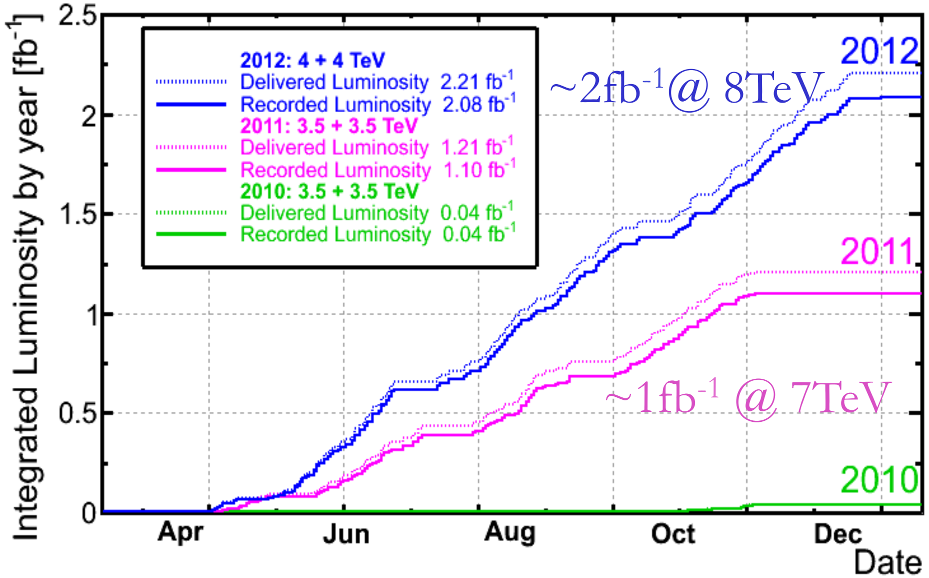
LHCb detector: the essentials

- Experiment optimized for heavy-flavour physics
  - Forward acceptance
  - Efficient trigger for hadronic and leptonic modes
  - Acceptance down to low p_T
  - Precision tracking and vertexing (VELO@7 mm from beam)
  - Excellent PID



Running conditions



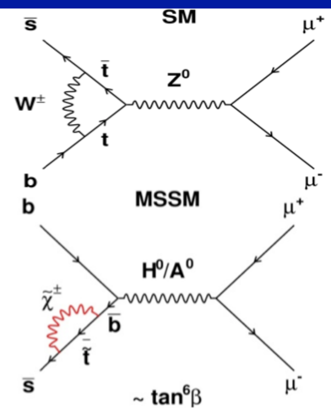


- LHCb designed to run at lower luminosity than ATLAS/CMS
  - Tracking, PID sensitive to pile-up
  - Mean number of interactions/bunch crossing ~2
- pp beams displaced to reduce instantaneous luminosity
- $\mathcal{L}_{2011} \sim 2.7\ 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\mathcal{L}_{2012} \sim 4.0\ 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Huge heavy quark production cross-sections
  - $\sigma_{bb} \sim 300\ \mu b$ @$\sqrt{s}$=7-8 TeV (~1nb in e^+e^-@ $\Upsilon(4s)$)
  - σ_{cc} is ~ 20 times larger!

~10^{11} b decays/fb in acceptance

~10^{12} c decays/fb

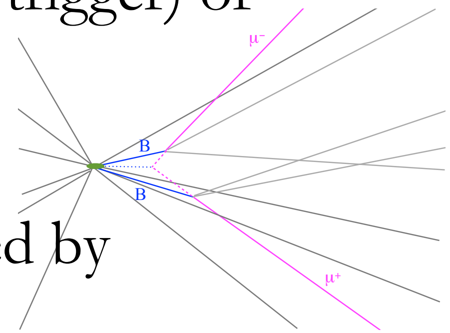
Rare decays: B→$\mu^+\mu^-$



- Highly suppressed in SM
  - FCNC
  - Helicity suppressed ~$(m_\mu/M_B)^2$
- Precisely predicted
  - $BR(B_s \to \mu^+\mu^-) = 3.35 \pm 0.28 \times 10^{-9}$ Buras et al, EPJ C72 (2012) 2172
    - Should be corrected up by few percent since measurement is of the time-integrated branching fraction De Bruyn, Fleischer et al, PRL 109 (2012) 041801→
    - $BR(B_s \to \mu^+\mu^-) = 3.56 \pm 0.30 \times 10^{-9}$ using $\Delta\Gamma_s/(2\Gamma_s) = 0.0615 \pm 0.0085$
  - $BR(B_d \to \mu^+\mu^-) = 1.07 \pm 0.10 \times 10^{-10}$
- Sensitive to NP
  - in MSSM $BR \sim \tan^6\beta$
- Very clean signature
  - studied by all high-energy hadron collider experiments

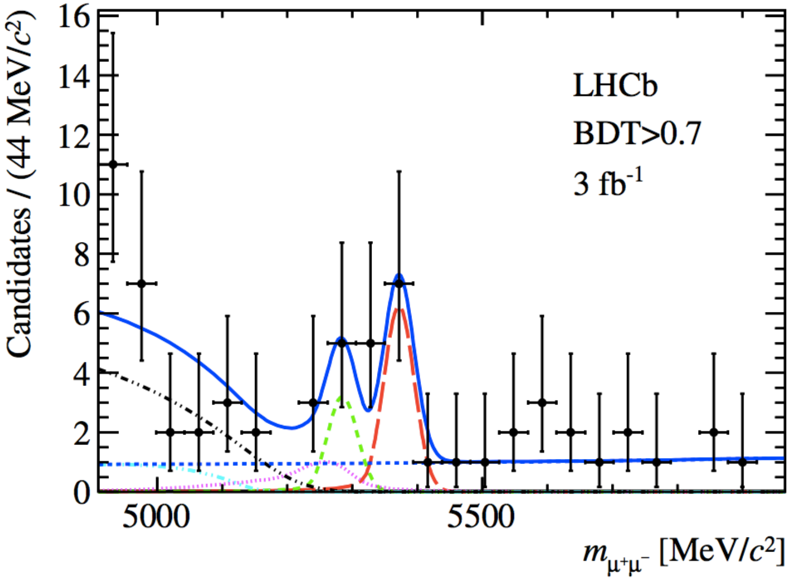
$B \rightarrow \mu^+\mu^-$: Analysis features

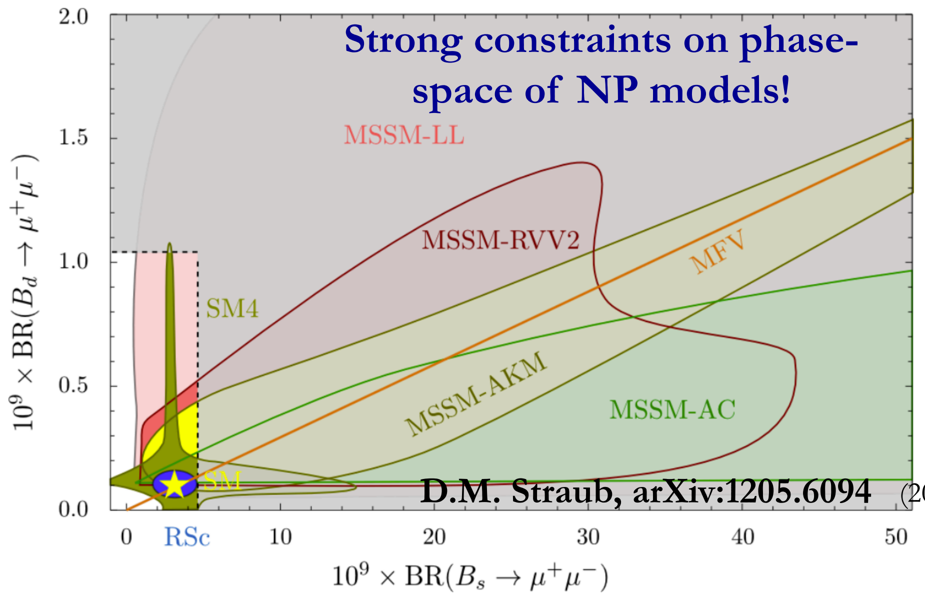
- Use of control channels to calibrate selection avoiding dependence on simulation
- Use of multi-variant discriminants trained on data whenever possible (e.g. B candidate decay time, IP and p_T, isolation, etc)
- Use of normalisation channels with well-known BRs, same topology and/or trigger. Cancel uncertainties in ratios.
  - Normalise to large sample of $B^+ \rightarrow J/\psi K^+$ (same trigger) or $B^0 \rightarrow K^+\pi$ (same topology)
- Full data set of 3/fb analysed
  - Main issue is rejection of background, dominated by $B \rightarrow \mu^+X$, $B \rightarrow \mu^-X$ decays
  - Mass resolution crucial (σ_B~23 MeV for LHCb)
  - CMS: σ_B from ~32 MeV for $\eta_{\mu\mu}$~0 to ~75 MeV for $|\eta_{\mu\mu}|$>1.8



$B \to \mu^+\mu^-$: First evidence

	$\mathcal{B}(B_s^0 \to \mu\mu) \times 10^{-9}$	$\mathcal{B}(B^0 \to \mu\mu) \times 10^{-9}$	
LHCb	$2.9^{+1.1+0.3}_{-1.0-0.1}$	$3.7^{+2.4+0.6}_{-2.1-0.4}$	PRL 111 101805 (2013)
CMS	$3.0^{+1.0}_{-0.9}$	$3.5^{+2.1}_{-1.8}$	PRL 111 101804 (2013)
Combined Preliminary	2.9 ± 0.7	$3.6^{+1.6}_{-1.4}$	LHCb-CONF-2013-012 CMS-PAS-BPH-13-007

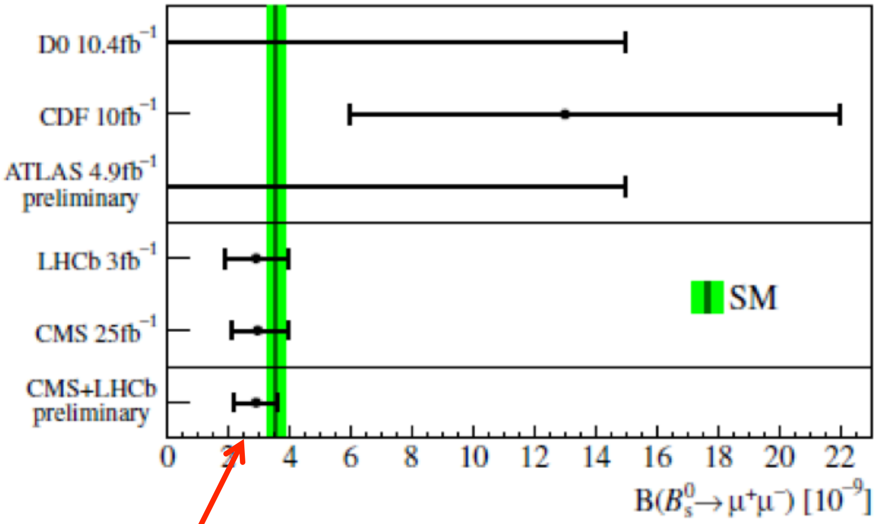




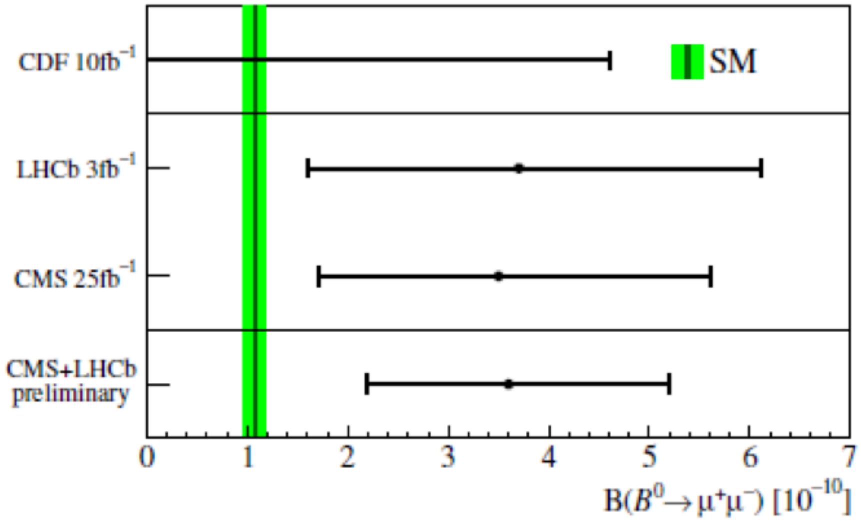
- Background to $B_d \to K\pi$ with double misID relevant for $B_d \to \mu^+\mu^-$

$B \to \mu^+\mu^-$: First evidence

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



$B_d \to \mu^+\mu^-$



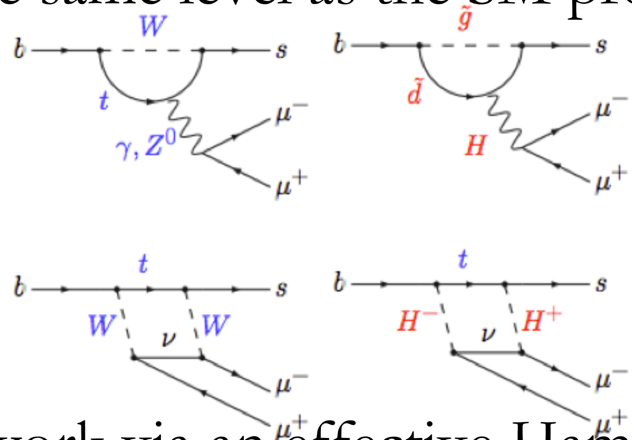
Measured with 25% precision

- From theory : BRs known to ~10% (can be improved with refined lattice QCD calculations)
- Additional handle on NP through $B_s \to \mu^+\mu^-$ effective lifetime (i.e. fitting a single exponential to this rate) feasible at upgrades of LHC detectors

Buras, Fleischer et al
arXiv:1303.3820

FCNC $b \rightarrow s$ transitions: $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\mu^+\mu^-$

- $B^0 \rightarrow K^{*0}\mu^+\mu^-$ is a FCNC decay that only proceed via loops and boxes
- Rich phenomenology, plethora of observables
- NP can enter at the same level as the SM processes



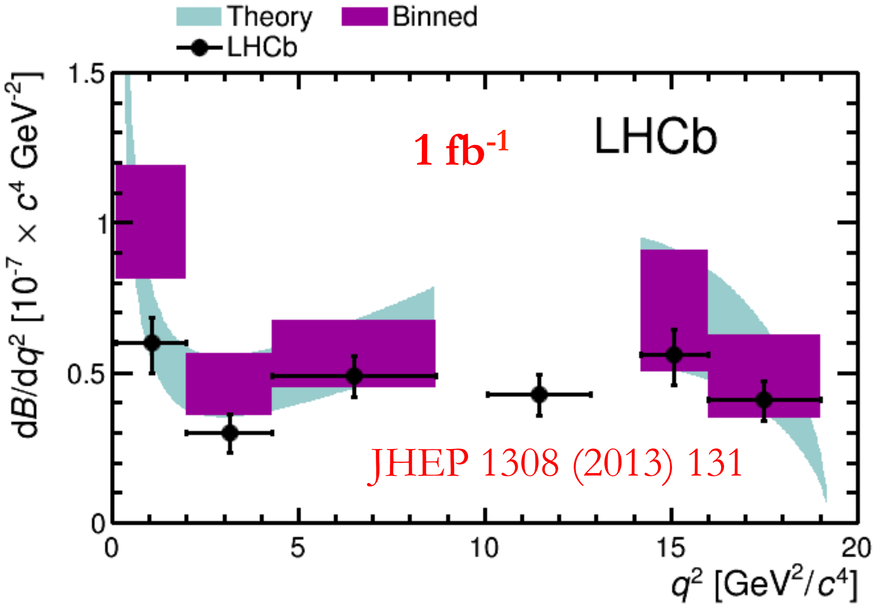
- Theoretical framework via an effective Hamiltonian :
  - Wilson coefficients (C_i) describing short distance interactions, sensitive to NP
  - Operators (O_i) describing long distance interactions

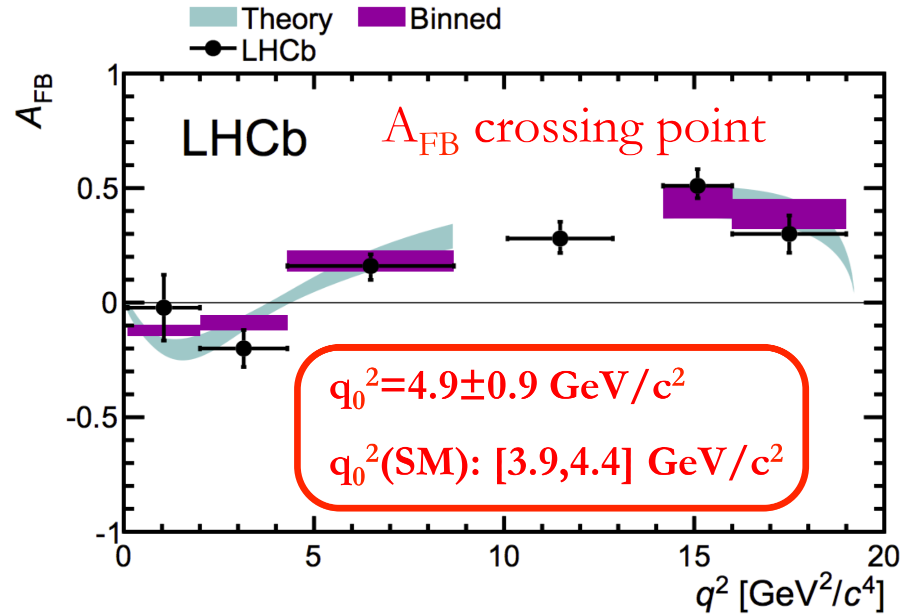
$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} (C_i^{SM} + \Delta C_i^{NP})\ O_i$$

  - In SM, leading contributions from O_7, O_9, O_{10}

FCNC $b \to s$ transitions: $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

- Rates, angular distributions and asymmetries sensitive to NP
- Kinematics described by three angles and $q^2=m(\mu^+\mu^-)^2$
  - dB/dq^2: differential branching fraction
  - A_{FB}: $\mu^+\mu^-$ forward-backward asymmetry (flavour self-tagged through K charge)



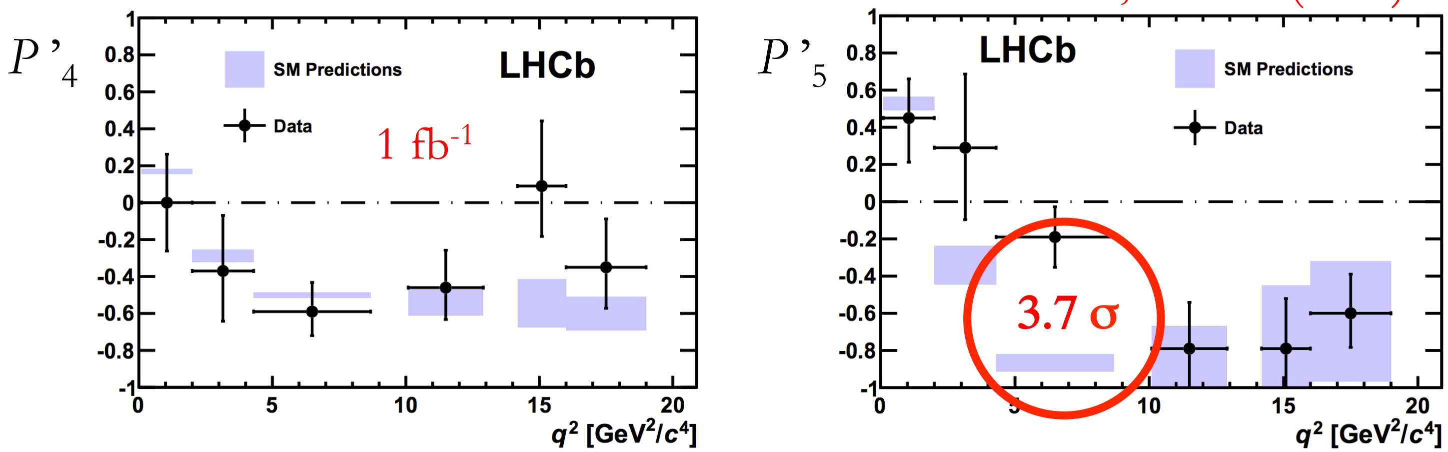


- Large theory uncertainties in part due to large contributions from hadronic form factors
- In SM, A_{FB} changes sign at a very well defined value of q^2, q_0^2
- First measurement of q_0^2, consistent with SM

Form-factor independent observables in $B^0 \rightarrow K^{*0}\mu^+\mu^-$

- Combinations of observables with reduced form-factor uncertainties at large recoil (low-q^2) proposed by several authors
  - combinations of F_L and S_i (bilinear combinations of K^{*0} decay amplitudes, F_L is K^{*0} longitudinal polarisation fraction) $$P'_{i=4,5,6,8} = \frac{S_{i=4,5,6,8}}{\sqrt{F_L(1-F_L)}}$$ (Matias et al, arXiv: 1303.5794)
- 'Folding technique' used by LHCb to simplify differential decay rate without losing experimental sensitivity
- P'_6 and P'_8 close to SM predictions (close to zero) over full q^2 range

PRL 111, 191801 (2013)



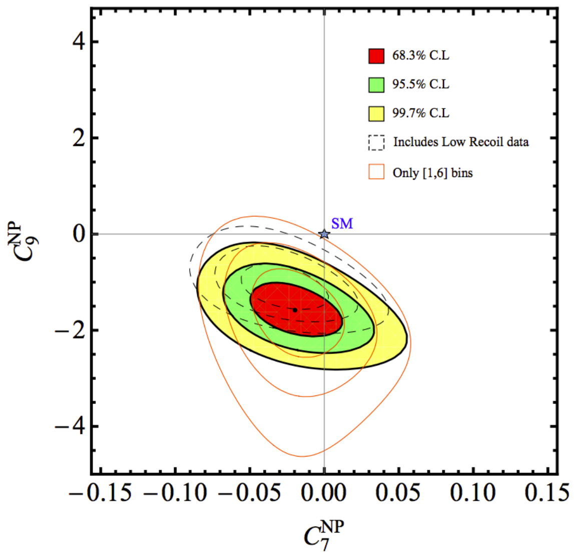
- Across 24 bins, significance drops to 2.8 σ
- Most likely scenario: statistical fluctuation or underestimated theory uncertainties (see e.g. Jäger & Camalich, JHEP 05 (2013) 043)

Form-factor independent observables in $B^0 \to K^{*0}\mu^+\mu^-$

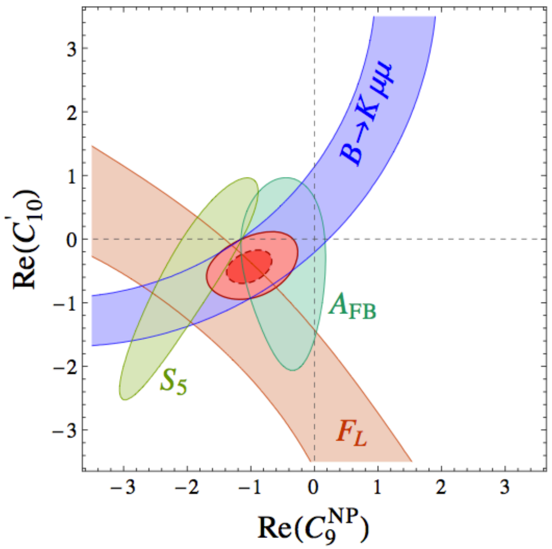
- Interest from theory community as NP contributing to C_9 could provide a better fit to the data, and still be compatible with other measurements
  - $C_9 = C_9^{SM} + C_9^{NP}$, where $C_9^{SM} \sim 4$ and $C_9^{NP} \sim -1.5$
- Smaller value of C_9 Wilson coefficient through a Z' of few TeV ?

Gauld et al arXiv:1308.1959
Buras et al arXiv:1309.2466

Descotes-Genon et al
PRD 88 (2013) 074002



Altmannshofer & Straub
arXiv:1308.1501



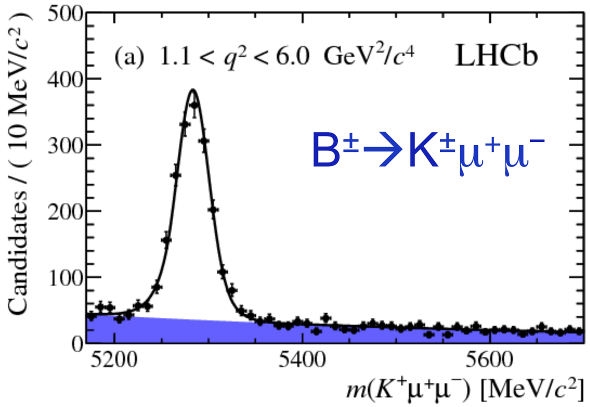
- Next steps: - Analyse full data set (3/fb analysis in preparation)
  - Provide complementary constraints (e.g. $B_s \to \phi\mu^+\mu^-$, $B \to K\mu^+\mu^-$)

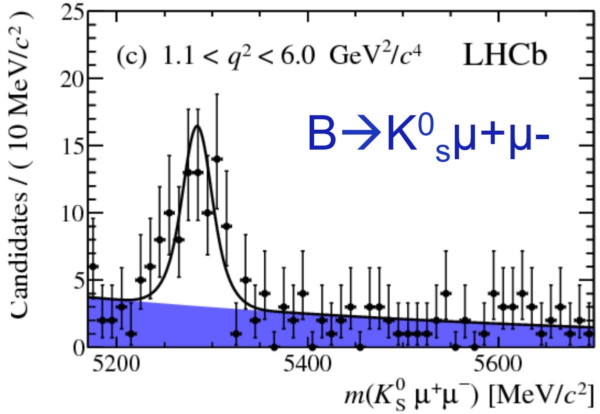
Other B→K$\mu^+\mu^-$ decays

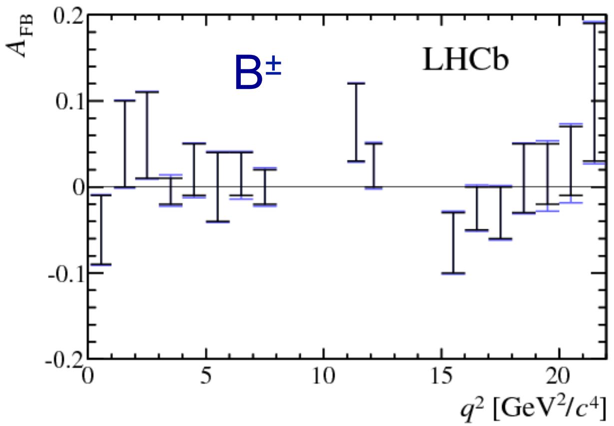
- Angular analysis of $B^\pm \to K^\pm\mu^+\mu^-$ and $B \to K^0_s\mu^+\mu^-$ decays
- Able to isolate clean signal events in full q^2 (3/fb)
  - ~4750 $B^\pm \to K^\pm\mu^+\mu^-$
  - ~180 $B^0 \to K^0_s\mu^+\mu^-$ (ε_{rec}~0.2%)
- Results expressed in terms of A_{FB} and F_H
  - e.g., for the $B^\pm$ $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_l) + \frac{1}{2}F_H + A_{FB}\cos\theta_l$
- SM: $A_{FB} \approx 0$, $F_H \approx 0$ in in every q^2 bin but could be enhanced by new (pseudo)scalar or tensor couplings contributions

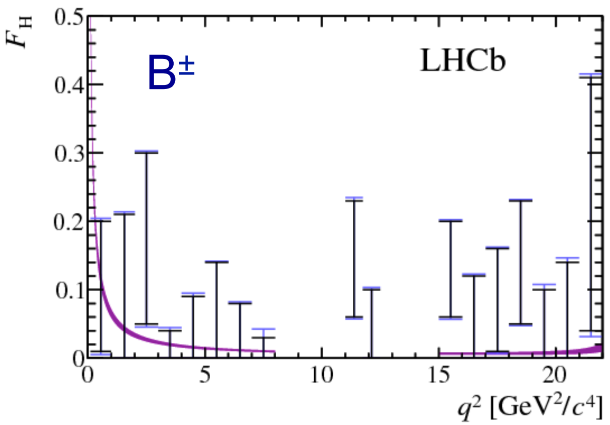
arXiv:1403.8045

→ No evidence for new (pseudo)scalar or tensor couplings







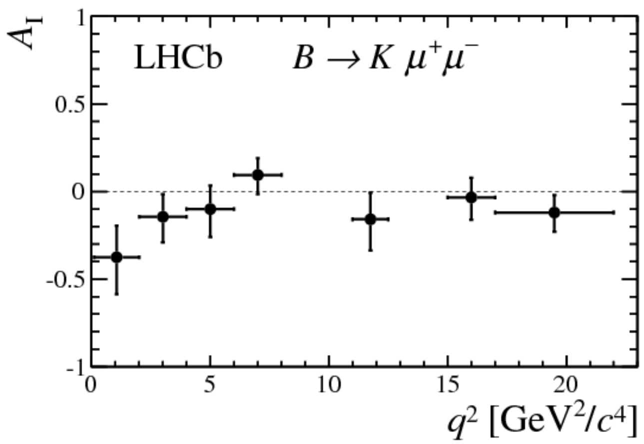


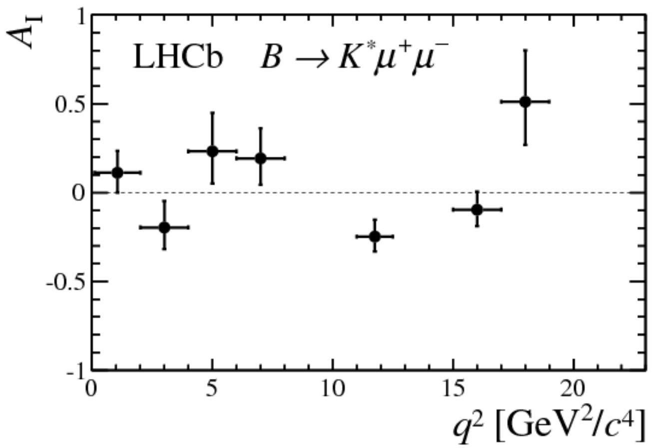
Isospin asymmetry in $B \to K^{(*)}\mu^+\mu^-$

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

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

- A_I more precisely predicted than branching fractions; expected close to zero in SM
  - $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^0_S\mu^+\mu^-$
  - $B^+ \to K^{*+} (\to K^0_S\pi^+)\mu^+\mu^-$, $B^0 \to K^{*0} (\to K^+\pi^-)\mu^+\mu^-$
- **A_I results based on 3/fb consistent with SM** (arXiv:1403.8044)
  – Analysis of $1 fb^{-1}$ (2011): A_I for K^* modes consistent with zero, for K modes 4.4 σ from zero! [JHEP 07 (2012) 133]

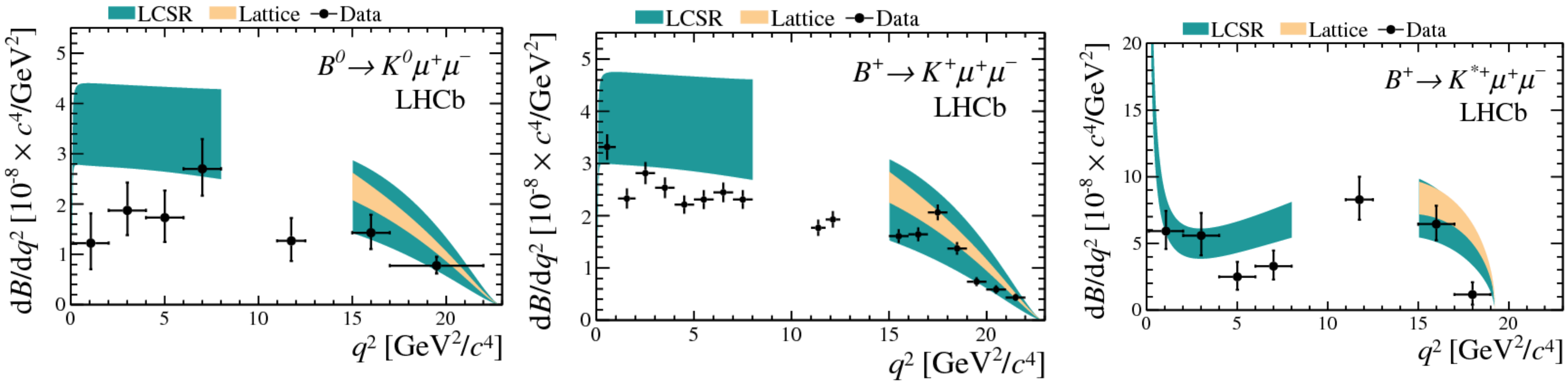




arXiv:1403.8044

3/fb

Differential Branching Fractions in $B \to K^{(*)}\mu^+\mu^-$

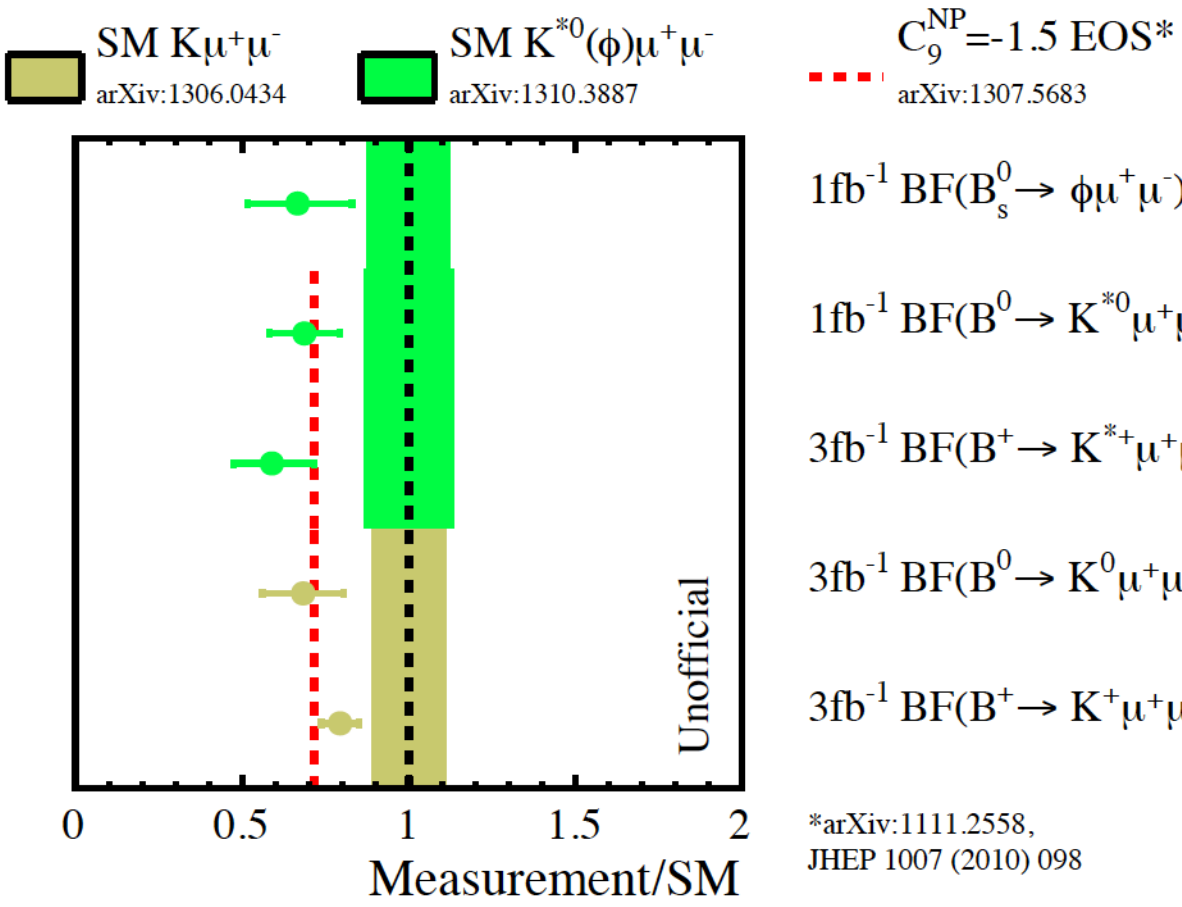


- Each mode normalised wrt its corresponding $B \to J/\psi\ K^{(*)}$ channel
- Although consistent with SM, results tend to be below theory
- Extrapolate underneath charmonium resonances assuming q^2 distribution from [Ali et al., Phys. Rev. D61 (2000) 074024]→
  - $B(B^+ \to K^+\mu^+\mu^-) = (4.29 \pm 0.07 \pm 0.21)\ 10^{-7}$
  - $B(B^0 \to K^0_S\mu^+\mu^-) = (3.27 \pm 0.34 \pm 0.17)\ 10^{-7}$
  - $B(B^+ \to K^{*+}\mu^+\mu^-) = (9.24 \pm 0.93 \pm 0.67) 10^{-7}$

arXiv:1403.8044, 3/fb

- Theory predictions: [Ball, Zwicky Phys. Rev. D71 (2005) 014029; A. Khodjamirian et al., JHEP 09(2010) 089, M. Beneke et al., Nucl. Phys. B612 (2001) 25, Eur. Phys. J. C41 (2005) 173; C. Bobeth et al., JHEP 12(2007) 040, B. Grinstein and D. Pirjol, Phys. Rev. D70 (2004) 114005, U. Egede et al., JHEP 11 (2008) 032]
- Lattice predictions : [C. Bouchard et al., Phys. Rev. D88 (2013) 054509; R. R. Horgan et al., arXiv:1310.3722]

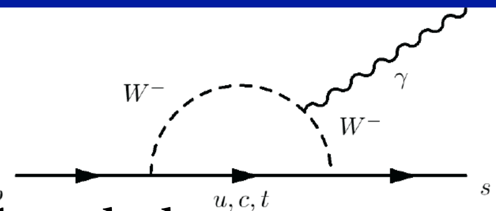
Branching Fractions at high q^2



Mitesh Patel
Moriond EW '14

- High-q^2 branching fraction measurements are below the latest lattice SM predictions
- Better consistency with C_9^{NP}=-1.5 suggested by (low q^2) anomalous angular data
- Stat. fluctuations, experimental or theory problems?

FCNC in radiative decays

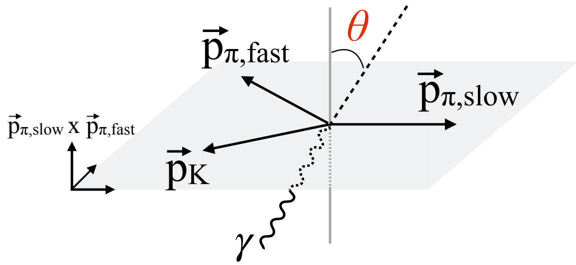


- b → s γ transition, through a penguin diagram
- In SM photon left-handed, but could acquire right-handed components through NP
- Photon polarisation λ_γ as test of SM
- Measure λ_γ from decay :

  $B^+ \rightarrow K^+\pi^+\pi^-\gamma$ (~10^{-5} BF)

- Count γ emitted above/below plane defined by momenta of final-state hadrons in their centre-of-mass frame

$$A_{ud} \equiv \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}} \propto \lambda_\gamma$$

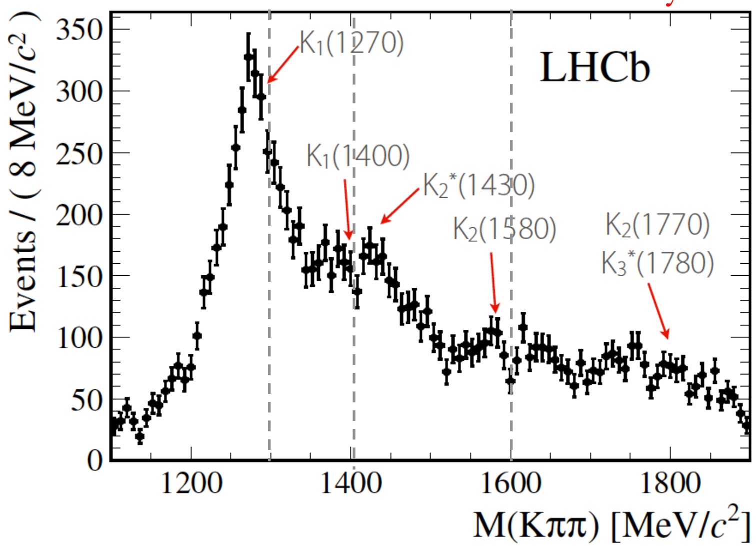


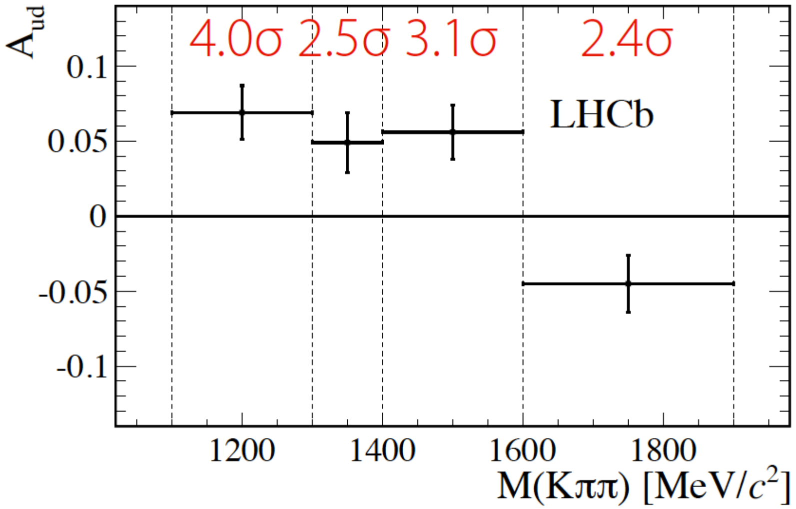
Radiative decays – results

- Full data set of 3/fb analysed

arXiv:1402.6852

Inclusive analysis

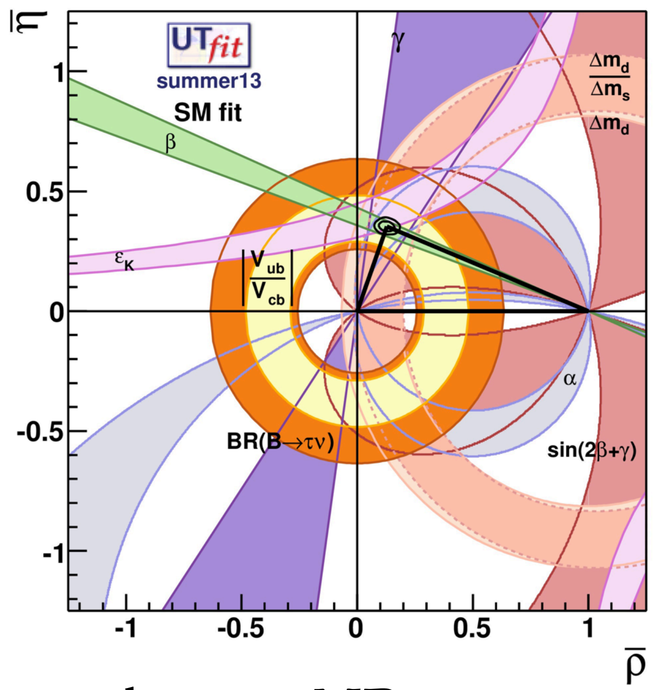




- Use 4 independent measurements up-down asymmetries to extract combined significance wrt $\lambda_\gamma=0$ scenario
- Up-down asymmetry different from zero at 5.2 σ
- First observation of photon polarization in b → s γ transitions!
- Each resonance contributes differently and one needs to resolve them to turn the observation into a measurement of λ_γ
- More work is needed from theory and experiment!

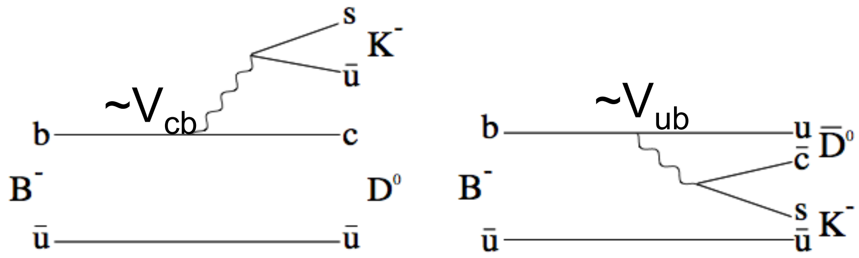
γ: State of the art

- Very precise picture of CKM parameters has emerged (see e.g. Utfit, CKMfitter)
- $\gamma = \arg(-V_{ud}V_{ub}^{*} / V_{cd}V_{cb}^{*})$ is least well measured angle
- γ measurable in both tree-level processes and ones with loops

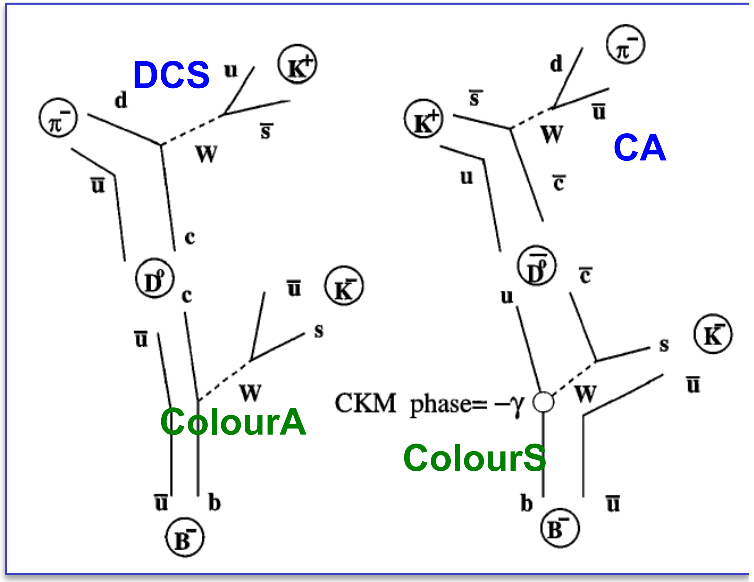


- Tree level decays are good test of SM and are robust to NP
- Theoretically very clean: $\delta\gamma/\gamma \sim 10^{-7}$ (Brod & Zupan, arXiv:1308.5663)
- BUT.. measuring γ at tree level is hard: for $B^{\pm} \rightarrow Dh^{\pm}$, small BFs
- Combining measurements is key to precise determination of γ

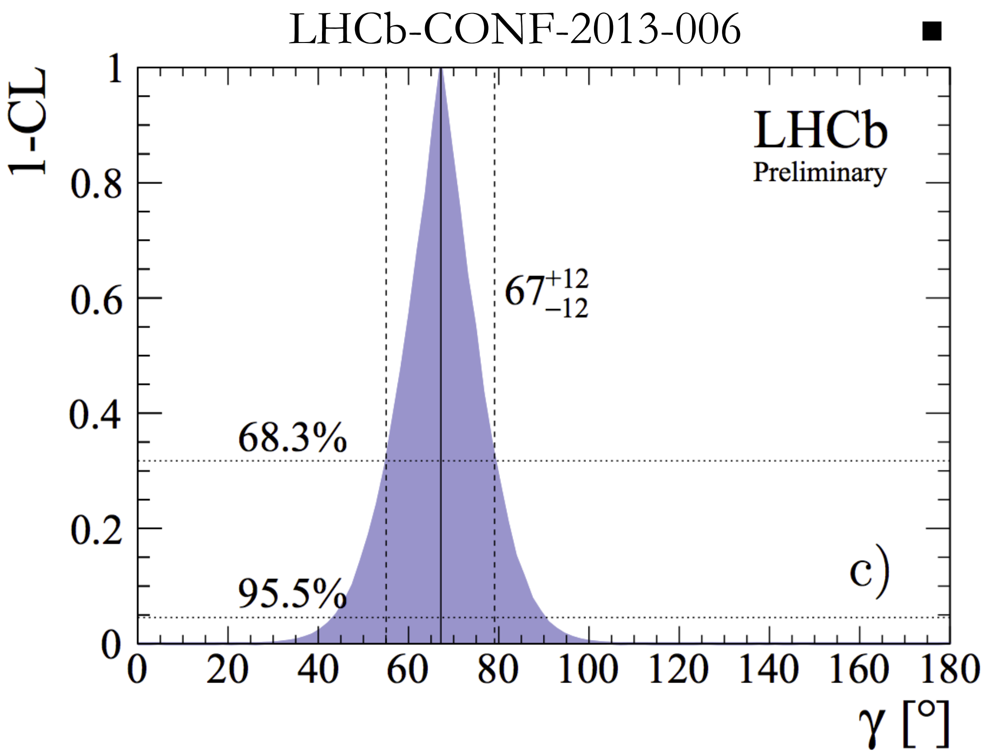
Measurement of γ from $B^{\pm} \rightarrow D^0 K^{\pm}$



- Sensitivity to γ through final states accessible to both D^0 and $\overline{D}^0$ leading to interference
  - D decays to CP eigenstates, e.g. $\pi^+\pi^-$, K^+K^- ("**G**ronau **L**ondon **W**yler")
    - Large rate, small interference
  - D decays to flavour specific states, e.g. $K^+\pi^-$ ("**A**twood **D**unietz **S**oni")
    - Reverse suppression between B and D decays results in comparable interfering amplitudes → Lower rate, but high sensitivity to γ
  - D decays to common multi-body decay, e.g. $K_sK^+K^-$, $K_s\pi^+\pi^-$ (**G**iri **G**rossman **S**offer **Z**upan)
    - Requires Dalitz analysis



γ: Results



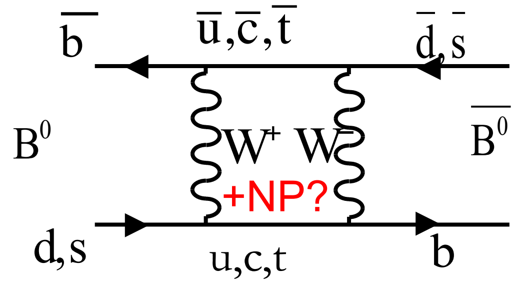
- Combination: B→DK modes only
  - 1 fb^{-1} 2011 ADS/GLW
    $B^{\pm} \to DK^{\pm}$, with $D \to K^+K^-$, $\pi^+\pi^-$, $K\pi$, $K3\pi$
    - PLB 712 (2012) 203
  - 3 fb^{-1} 2011 GGSZ
    $B^{\pm} \to DK^{\pm}$, with $D \to K^0{}_S\pi^+\pi^-$, $K^0{}_S K^+K^-$
    - LHCb-CONF-2013-004
    - PLB 718 (2012) 43

$\gamma = (67 \pm 12)^o$ Preliminary

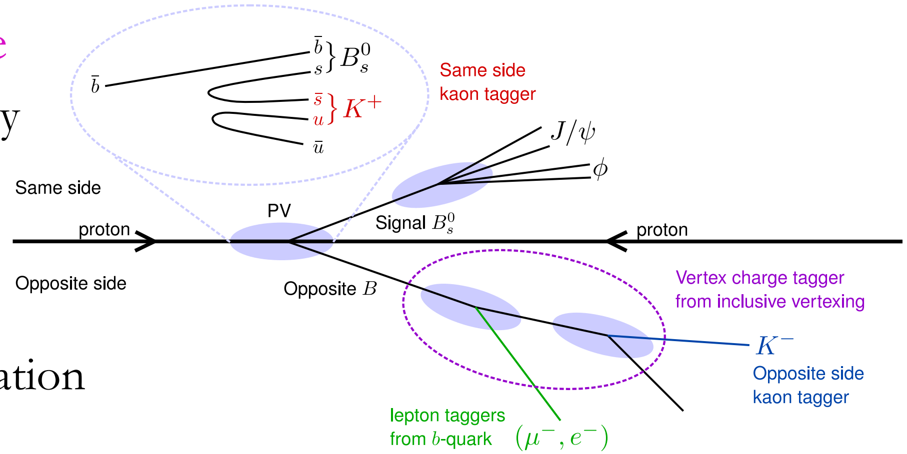
  - LHCb sensitivity already comparable to B-factory combinations

- Updates including this result:
  - CKMFitter $\gamma = 68.0^{+8.0}_{-8.5}{}^o$ (FPCP 2013)
  - UTFit $\gamma = 70.1 \pm 7.1^o$ (EPS 2013)
- Anticipated LHCb sensitivity by 2018 ~ 4^o

B^0_s mixing – Oscillation frequency



- B^0_s - $\bar{B}^0_s$ mixing highly sensitive to NP
- On average, B^0_s changes its flavour nine times between production and decay → measuring oscillation frequency is an experimental challenge
- LHCb average decay time resolution : ~ 44 fs << 350 fs, B^0_s oscillation period
- Use $B^0_s \to D^-_s\pi^+$, to tag flavour at decay time
  - Flavour specific decay, i.e. B^0_s flavour given by charges of final state particles
- Tagging identifies flavour at production
  - Both Opposite side (exploits b and $\bar{b}$ pair production) and Same side (exploits hadronization → extra s-quark often leading to charged K):
  - (2.6±0.4)% tagging power OST
  - (1.2±0.3)% tagging power SST

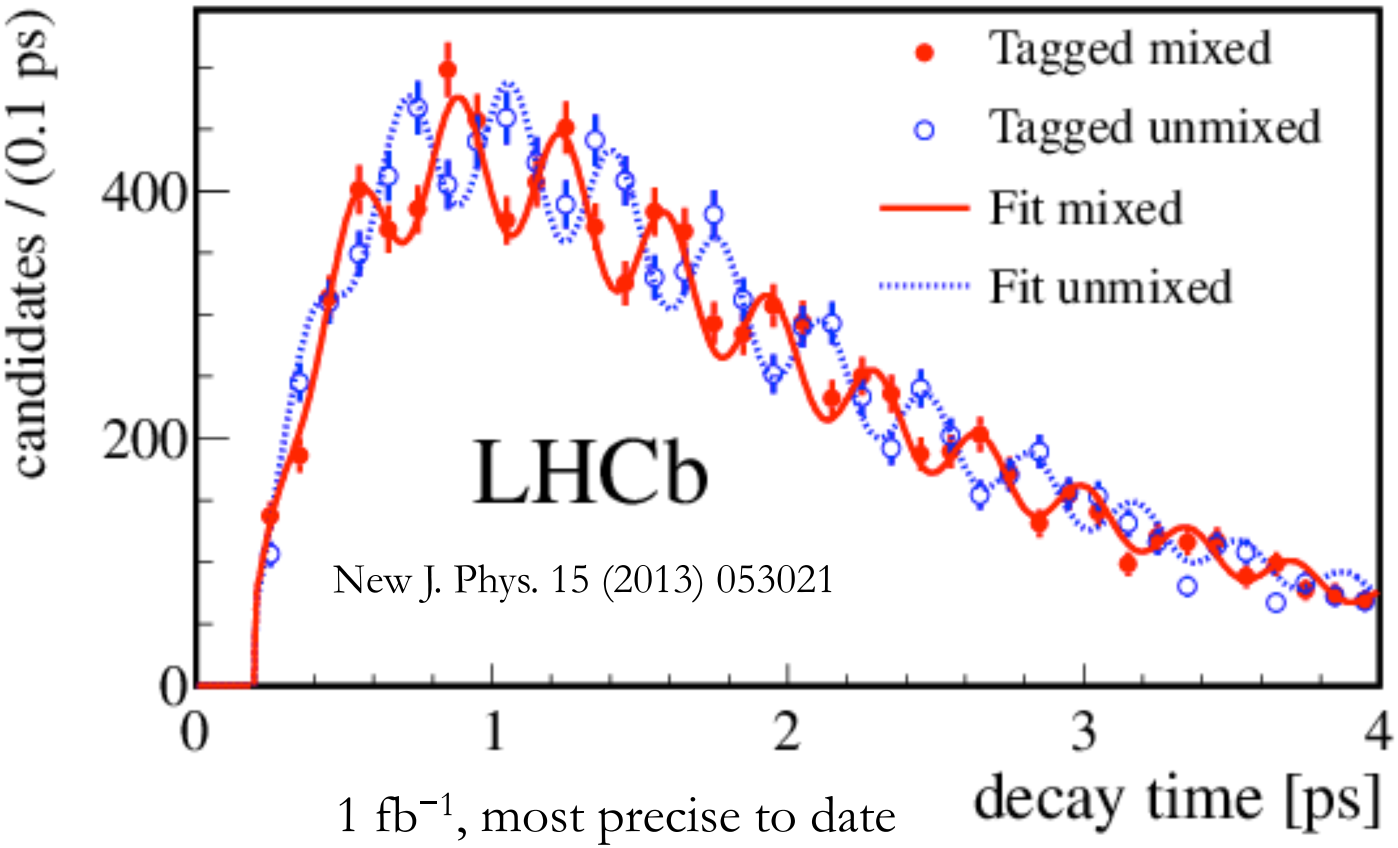


New J. Phys. 15 (2013) 053021

B^0_s mixing – Oscillation frequency

$B_s^0 \to D_s^- \pi^+$

with $D_s^- \to \phi(K^+K^-)\pi^-,\ K^{*0}(K^+\pi^-)K^-,\ K^+K^-\pi^-,\ K^-\pi^+\pi^-,\ \pi^-\pi^+\pi^-$



different flavour at decay and production

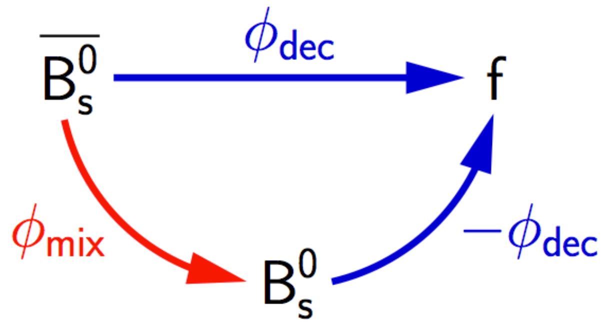
same flavour at decay and production

1 fb^{-1}, most precise to date

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ ps^{-1}$

CPV in B^0_s mixing/decay

- Phase ϕ_s arises from interference between B^0_S decays with and without mixing



- Measurement of B^0_s-$\overline{B}^0_s$ mixing phase ϕ_s sensitive to NP effects in mixing
- Golden channel: $B^0_s \rightarrow J/\psi\ \phi$
- ϕ_s is small in SM:

$$\phi_s^{SM} = \phi_s^M - 2\phi_s^D \simeq -2\beta_s = -2\arg\left(-\frac{\overbrace{V_{ts}V_{tb}^*}^{\text{mixing}}}{\underbrace{V_{cs}V_{cb}^*}_{\text{decay}}}\right) = -(2.1 \pm 0.1)^\circ$$

CKMfitter
PRD 84 (2011) 033005

- NP can add large phases:

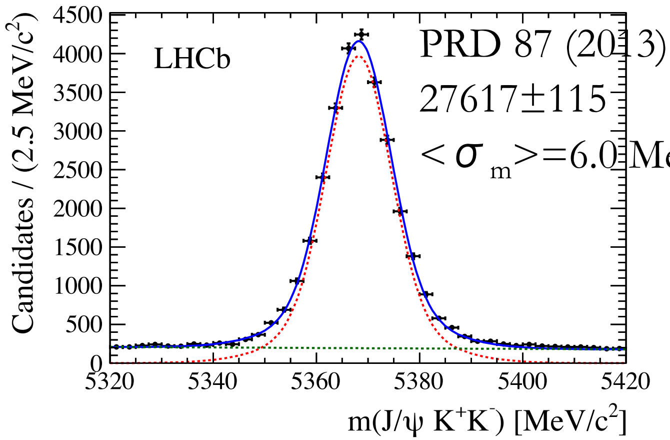
$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

CPV in B^0_s mixing/decay

- Mixing phase ϕ_s measured in
  - $B^0_s \to J/\psi\ \phi$ (PRD 87 (2013) 112010)
    - Superposition of CP-even and CP-odd states → Needs flavour-tagged, time-dependent angular analysis
    - Same final state can also be produced with K^+K^- in S-wave → both P- and S-wave decays explicitly included
    - 27617 events selected with 1 fb^{-1}

$$\mathrm{CP}\,|J/\psi\ \phi\rangle = (-1)^l\,|J/\psi\ \phi\rangle \qquad l = 0,1,2$$

$$\phi_s = 0.07 \pm 0.09 \pm 0.01\ \mathrm{rad}$$
$$\Gamma_S \equiv (\Gamma_L + \Gamma_H)/2 = 0.663 \pm 0.005 \pm 0.006\ \mathrm{ps}^{-1}$$
$$\Delta\Gamma_S \equiv \Gamma_L - \Gamma_H = 0.100 \pm 0.0016 \pm 0.003\ \mathrm{ps}^{-1}$$



  - $B^0_s \to J/\psi\ \pi^+\pi^-$ (PLB 713 (2012) 378, updated in PRD 87 (2013) 112010)
    - CP-odd fraction >97.7%
    - 2936 events selected with 1 fb^{-1}

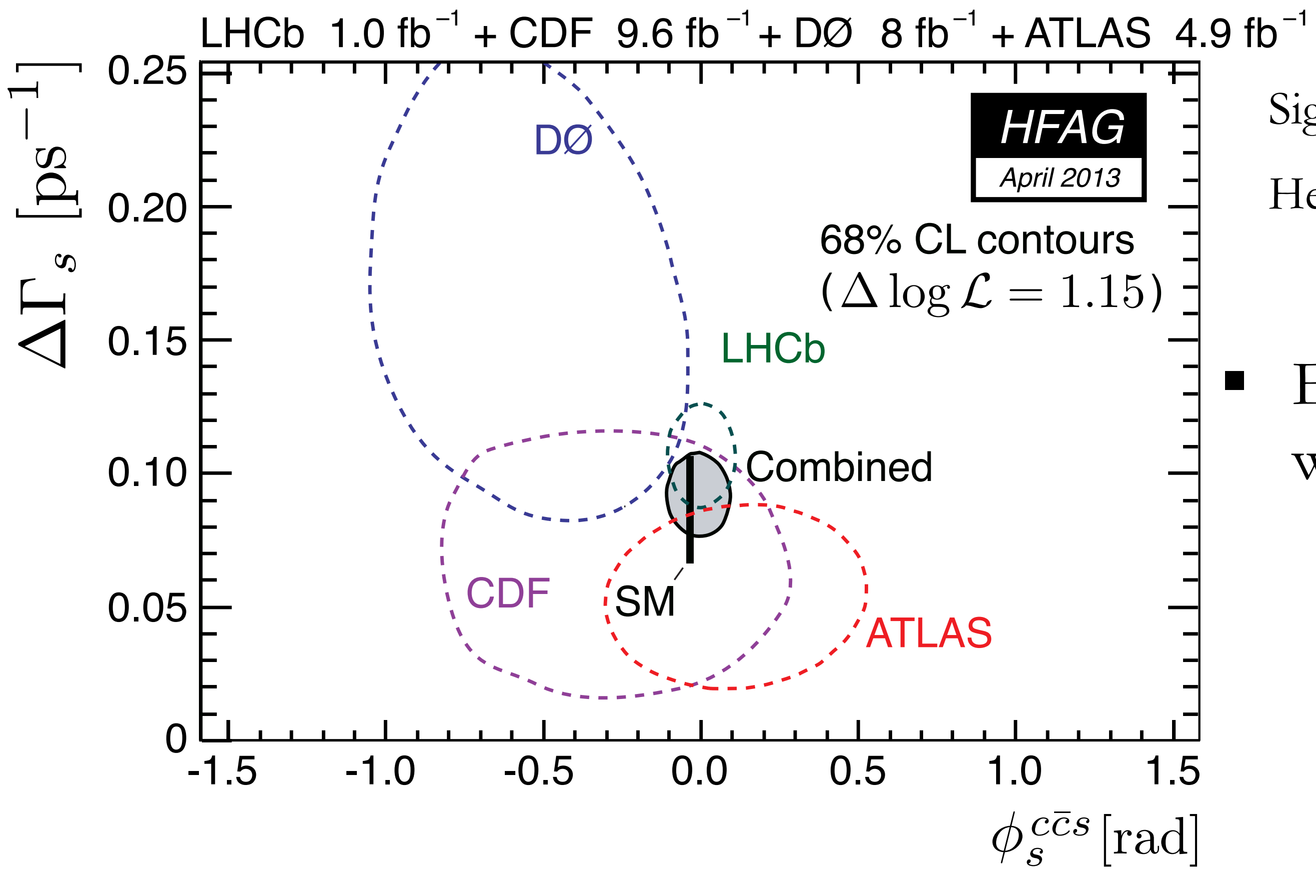
$$\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01\ \mathrm{rad}$$

CPV in B^0_s mixing/decay

- Performing a combined fit of $B^0_s \rightarrow J/\psi\,\phi$ and $B^0_s \rightarrow J/\psi\,\pi^+\pi^-$:

PRD 87 (2013) 112010

$$\phi_s = 0.01 \pm 0.07 \pm 0.01 \text{ rad}$$
$$\Gamma_S = 0.661 \pm 0.004 \pm 0.006 \text{ ps}^{-1}$$
$$\Delta\Gamma_S = 0.106 \pm 0.011 \pm 0.007 \text{ ps}^{-1}$$



Sign of $\Delta\Gamma_S$ established

Heavier B_s meson lives longer!

- Excellent agreement with SM

Flavour-specific CPV asymmetry in B^0_s decays

- a_{sl}: CP asymmetry in flavour specific (semileptonic) decays

- Final state : $D_s^+\mu^-\bar{\nu}X$ and $D_s^-\mu^+\nu X$, with $D_s^\pm \to \phi\pi^\pm$

- $$a_{sl} \equiv \frac{\Gamma(\bar{B}(t)\to f) - \Gamma(B(t)\to \bar{f})}{\Gamma(\bar{B}(t)\to f) + \Gamma(B(t)\to \bar{f})} \cong \frac{\Delta\Gamma}{\Delta M}\tan\phi_{12},\ \text{with}\ \phi_{12} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

Nierste 2009
arXiv:0904.1869v1

$$a_{sl}^{s,SM} = (1.9 \pm 0.3)\cdot 10^{-5}$$
$$a_{sl}^{d,SM} = -(4.1 \pm 0.6)\cdot 10^{-4}$$

Lenz & Nierste 2011
arXiv:1102.4274v1

$$A_{\text{meas}} \equiv \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]} = \frac{a_{\text{sl}}^s}{2} + \left[a_{\text{P}} - \frac{a_{\text{sl}}^s}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s\, t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s\, t}{2})\epsilon(t)dt}$$

$\Delta M_S = 17.768 \pm 0.24\ \text{ps}^{-1}$

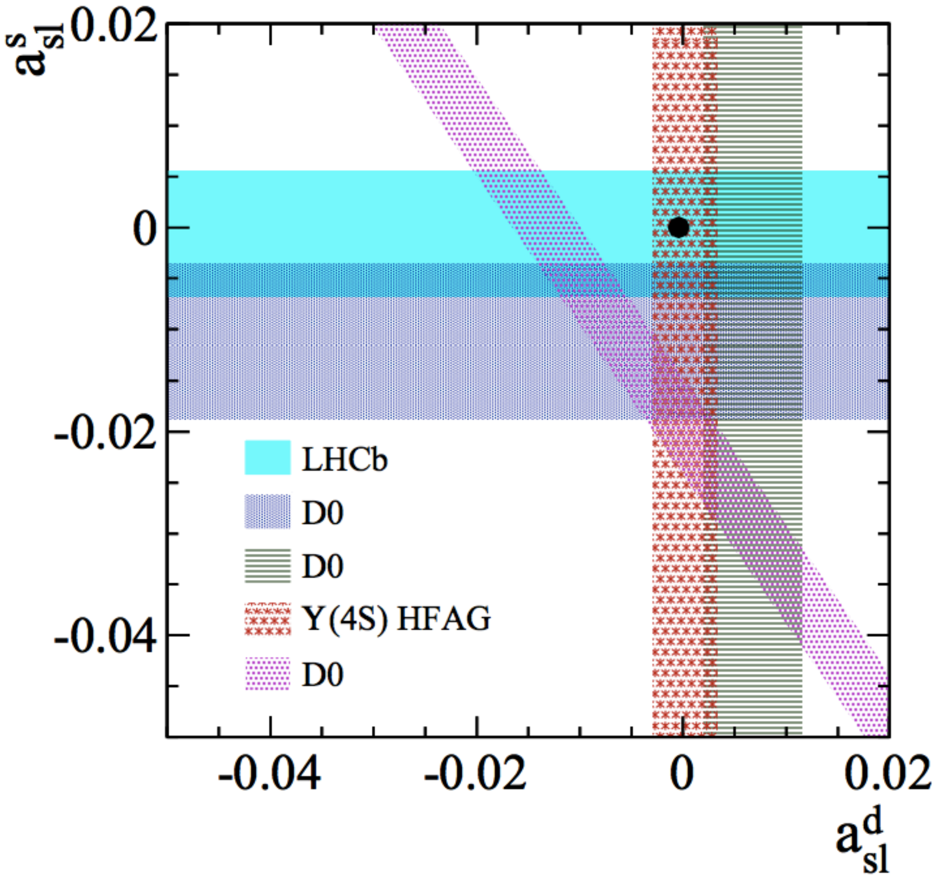
Integral ratio ~0.2%

$$a_p \equiv \frac{N(B) - N(\bar{B})}{N(B) + N(\bar{B})}$$ at most a few percent

- Effect of a_p reduced to ~10^{-4} level for B_S
- Target precision ~10^{-3}
- $$A_{meas} = \frac{a_{sl}^s}{2}$$

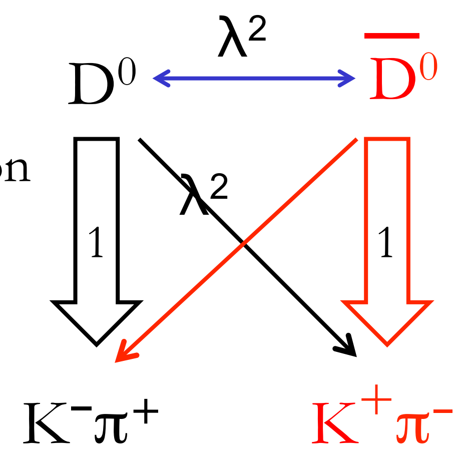
Flavour-specific CPV asymmetry in B^0_s decays

- Result based on 1fb^{-1} $a^s_{sl} = (-0.06 \pm 0.50 \pm 0.36)\%$ (PLB 728C (2014) 607)
- In agreement with SM
- ~3σ tension of D0 result not confirmed or excluded



Measurement of D^0–$\overline{D}^0$ mixing & CPV

- Extremely small level of CPV expected in charm mixing and in decays offers the opportunity for very sensitive null tests of CKM
- Mixing dominated by long-distance effects not easily calculable
  – **Charm as a discovery tool , not as a precision probe!**
- Reconstruct neutral D in $K\pi$ mode
- Classify as RS or WS using $D^{*\pm}$ to identify flavour at production



  – **RS**: $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\,\pi^+$
    - (Cabibbo favoured - 54M events in 3 fb^{-1})

  – **WS**: $D^{*+} \to D^0\pi^+ \to (K^+\pi^-)\,\pi^+$
    - (DCS, mixing + CF 0.23M events in 3 fb^{-1})

- WS/RS vs time separates suppressed decay from oscillation

$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_D + \sqrt{R_D}\,y'\,t + \frac{1}{4}(x'^2 + y'^2)\cdot t^2$$

Direct CPV, DCS

Interference

Mixing

$x \equiv \Delta m / \Gamma,\ y \equiv \Delta\Gamma / 2\Gamma$

$x' \equiv x\cos\delta + y\sin\delta \quad y' \equiv y\cos\delta - x\sin\delta$

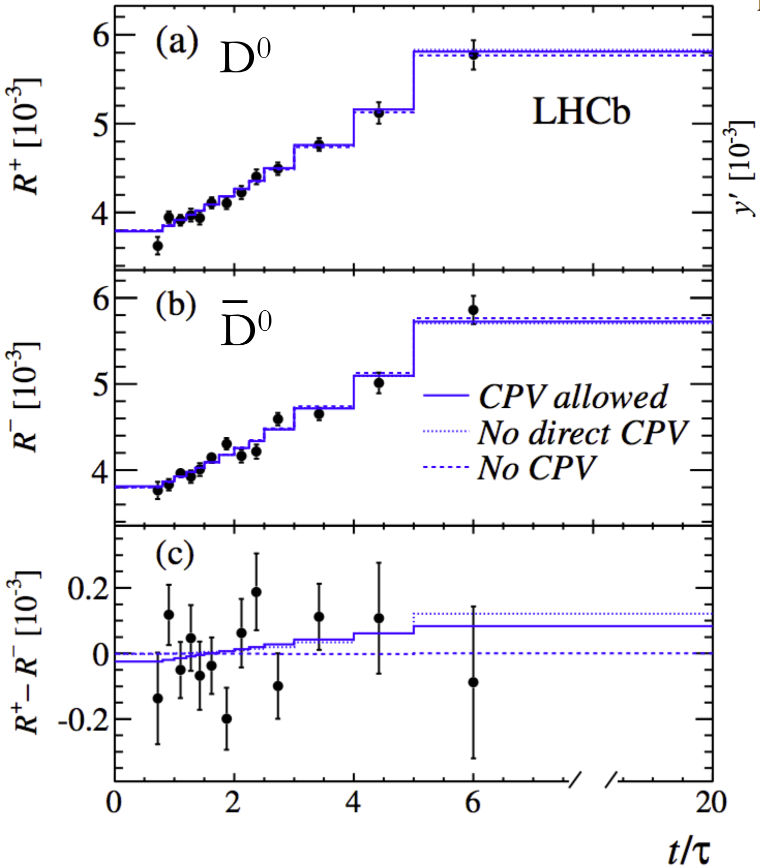
R_D ratio suppressed-to-favoured rates

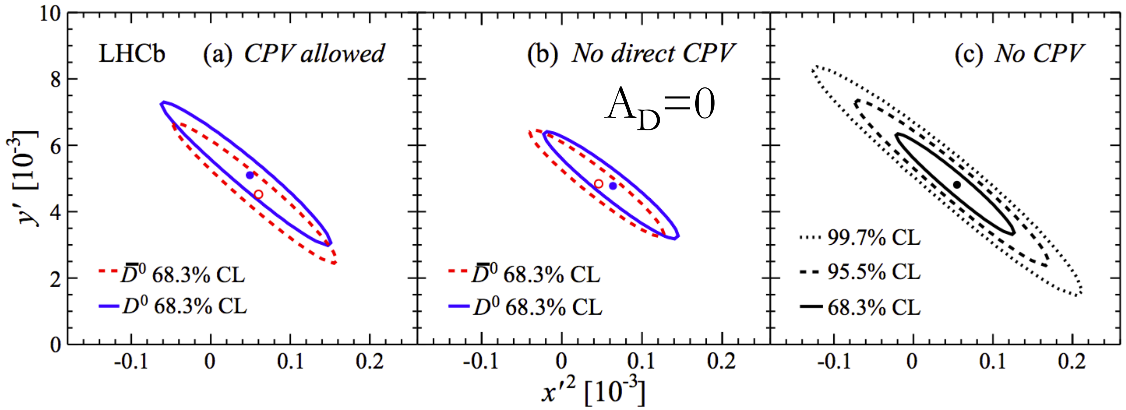
$$\left(R^+, R^-, A_D = \frac{R^+ - R^-}{R^+ + R^-}\right)$$

- Fit D^0 / $\overline{D}^0$ time evolution independently to search for CPV

Measurement of D^0–$\overline{D}^0$ mixing & CPV

PRL 111 (2013) 251801





- From full sample of 3 fb^{-1} :

$$x'^2 = (5.5 \pm 4.9)\cdot 10^{-5}$$
$$y' = (4.8 \pm 1.0)\cdot 10^{-3}$$
$$R_D = (3.568 \pm 0.066)\cdot 10^{-3}$$
$$0.75 < |q/p| < 1.24 \text{ @ } 68\% \text{ CL}$$
$$A_D = (-0.7 \pm 1.9)\%$$

- No evidence for CPV
- Best determination of mixing parameters
  - First single-experiment measurement >5 σ significance

Effective-lifetime asymmetry

- Study of indirect CP asymmetry in $D^0 \to K^+K^- / \pi^+\pi^-$ via flavour-tagged lifetime asymmetry

$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\bar{\Gamma}}}{\hat{\Gamma} + \hat{\bar{\Gamma}}} \approx \eta_{CP}\left(\frac{A_m + A_d}{2} y\cos\phi - x\sin\phi\right)$$

$$A_m \equiv \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}, \quad A_d \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}, \quad \lambda_f \equiv \frac{q\bar{A}_f}{pA_f} = -\eta_{CP}\frac{q}{p}\left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$$

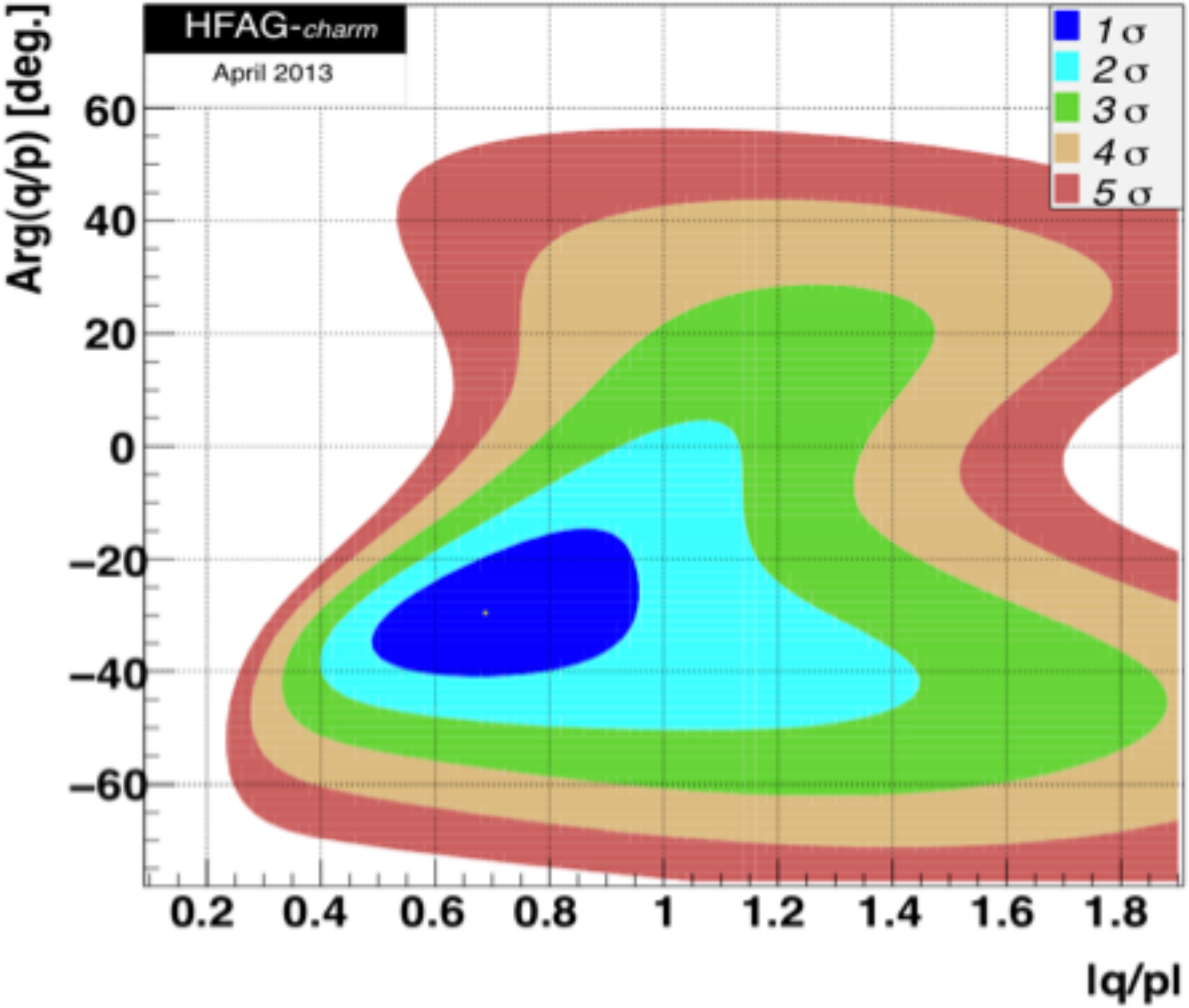
- Non-zero if CPV in mixing occurs (A_d small for current precision)
- D* to tag D flavour at production; measure D and $\bar{D}$ yields as function of decay-time
- Acceptance vs decay-time for each candidate taken from data
  - Slide each decay along D flight path to determine the pattern of accepted/rejected times for that decay
- >90% pure samples of 3M $D^0 \to KK$ and 1M $D^0 \to \pi\pi$ ($1\,fb^{-1}$)

$$A_\Gamma(K^+K^-) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$$

PRL 112 (2014) 041801

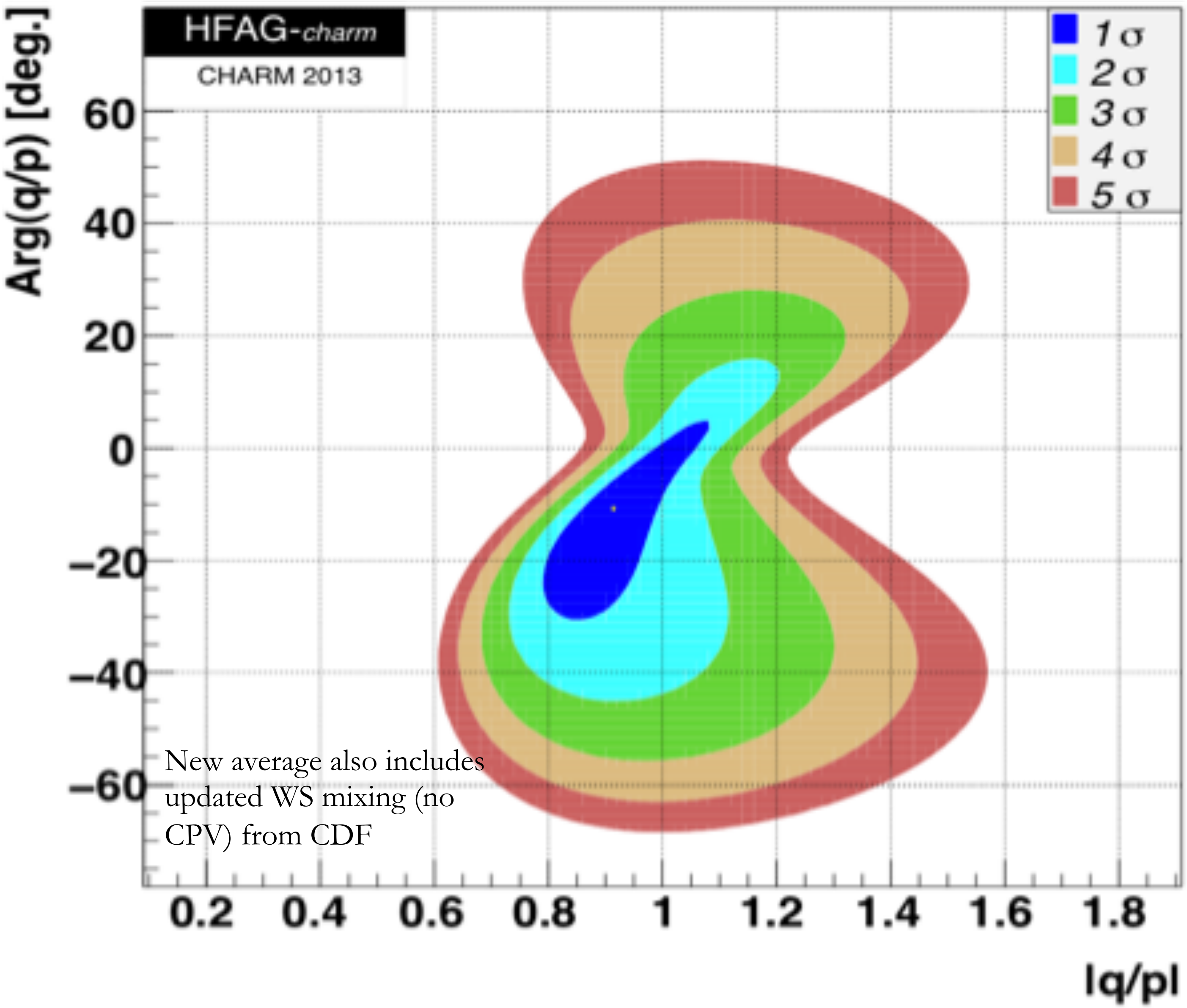
- World's best result with 1/3 of the statistics!

Impact



HFAG-charm
April 2013
1σ
2σ
3σ
4σ
5σ
Arg(q/p) [deg.]
60
40
20
0
−20
−40
−60
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
|q/p|

Impact



New average also includes updated WS mixing (no CPV) from CDF

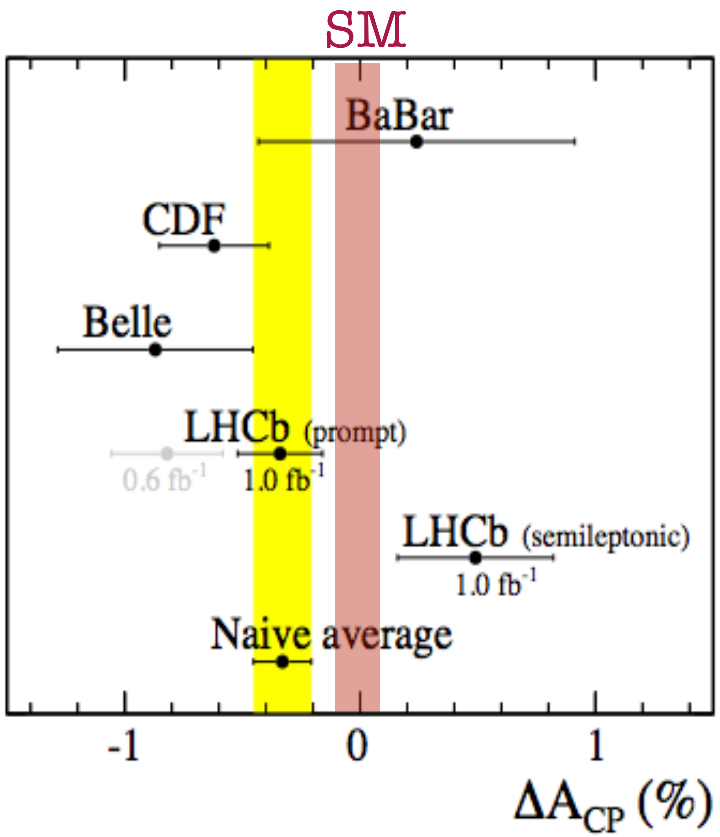
Search for direct CPV in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays (ΔA_{CP})

- Intriguingly large difference in CP asymmetry between D^0 decays to K^+K^- and $\pi^+\pi^-$, at odds with expectations
  - $\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$

- Two methods:
  - Use $D^{*+} \to D^0\pi^+$ as source of D^0 samples, flavour tagged by the emitted pion
    - PRL 108 (2012) 111602
    - LHCb-CONF-2013-003 (1fb^{-1})
  - Use D^0 produced in semileptonic b-hadron decays, flavour tagged by accompanying charged lepton
    - PLB 723 (2013) 33 (1fb^{-1})

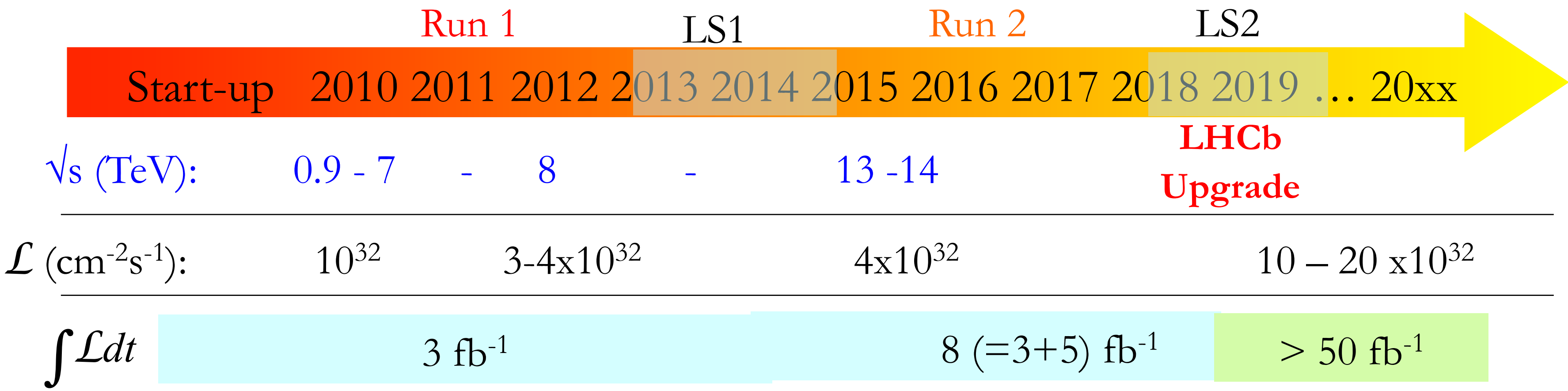
- Experimental and theoretical picture still blurry

- Measurement with full LHCb data set in progress (semileptonic analysis already passed Collaboration-wide review)



Looking forward: LHCb upgrade

- By the end of Run2, LHCb will have accumulated ~>8fb^{-1} (at $\mathcal{L} = 4\ 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- Without modifications data doubling time after Long Shutdown 2 (LS2) would become too long → need significant increase in instantaneous luminosity.
- LHCb will be upgraded during LS2 to run at higher luminosity ($\mathcal{L} \geq 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

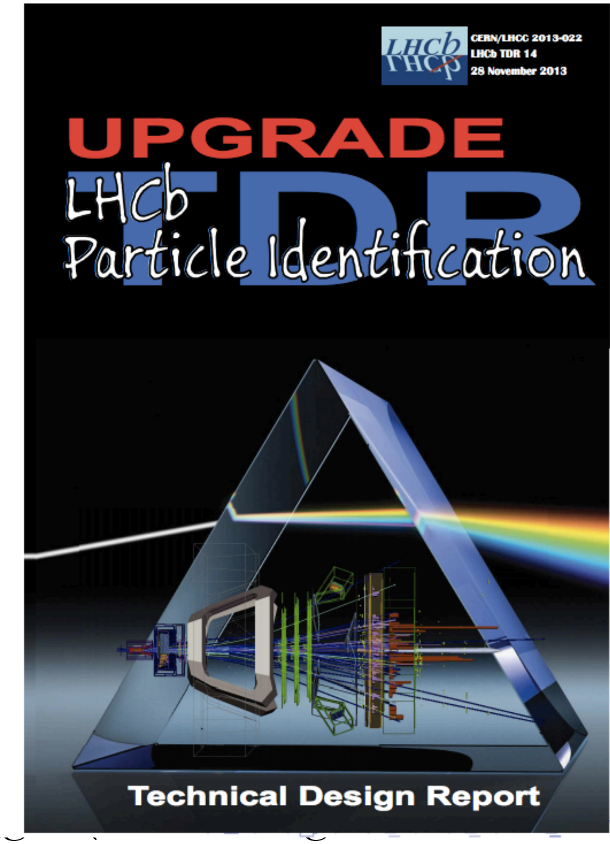


- Read-out whole detector at every bunch-crossing (40 MHz)
- Move to fully software-based flexible trigger (factor ~2 gain for hadronic triggers)
- The upgraded experiment is expected to collect > 50 fb^{-1} (~5 fb^{-1}/year)
- Detector TDRs being submitted to LHC Experiments Committee

Looking forward: LHCb upgrade

- By the end of Run2, LHCb will have accumulated ~>8fb^{-1} (at $\mathcal{L}$ = 4 10^{32}cm^{-2}s^{-1})
- Without modifications data doubling time after Long Shutdown 2 (LS2) would become t… …ity.
- LHCb wi… …$)^{33}$cm^{-2}s^{-1})

Sta…	…) … 20xx
√s (TeV…	…e
$\mathcal{L}$ (cm^{-2}s^{-1})	…) – 20 x10^{32}
$\int \mathcal{L} dt$	…> 50 fb^{-1}



- Read-out …
- Move to f… …nic triggers)
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Sensitivities to key observabls

LHCb-PUB-2013-015

Type	Observable	LHC Run 1 ($\int L\,dt = 3\ fb^{-1}$)	LHCb 2018 (End of Run2, $\int L\,dt = 8\ fb^{-1}$)	**LHCb upgrade** ($\int L\,dt = 50\ fb^{-1}$)	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 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)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	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%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 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°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	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	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Conclusions

- Wealth of LHCb results with the first 3/fb collected at "CERN's flavour factory"
  - Everything worked beautifully (LHC, luminosity leveling, detector, trigger, collaboration, data analysis, ..)
  - Many world record results. For some topics we are moving from exploration to precision measurements.
  - Many other analyses ongoing on full data set (not only in b and c physics) …
- Some new territory already explored but SM still depressingly uncracked
- We'll keep on looking….
- Working hard to prepare for the future (LHCb Upgrade)