CPV in charm and b-decays at LHCb

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On behalf of the LHCb Collaboration

CAPRI 2012, 11-13 June 2012

Outline

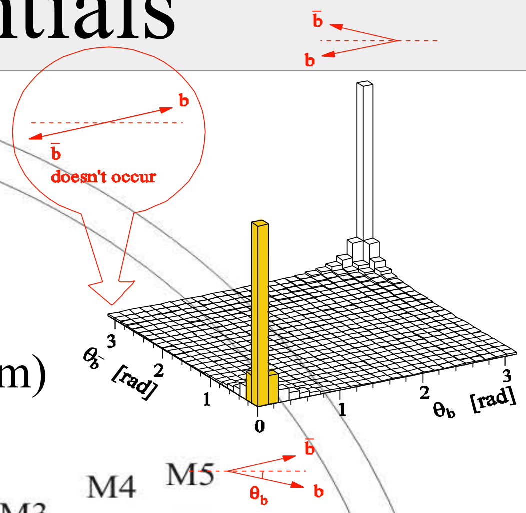
- Introduction
- Recent measurements of CPV in beauty and charm decays
    1. B_s decays (e.g. $B_s \to J/\psi\ \phi$)
    2. $B^\pm \to DK^\pm$
    3. $B \to h^+h'^-$ (where h and h' = π,K,p)
    4. ΔA_{CP} from $D^0 \to \pi^+\pi^-, K^+K^-$

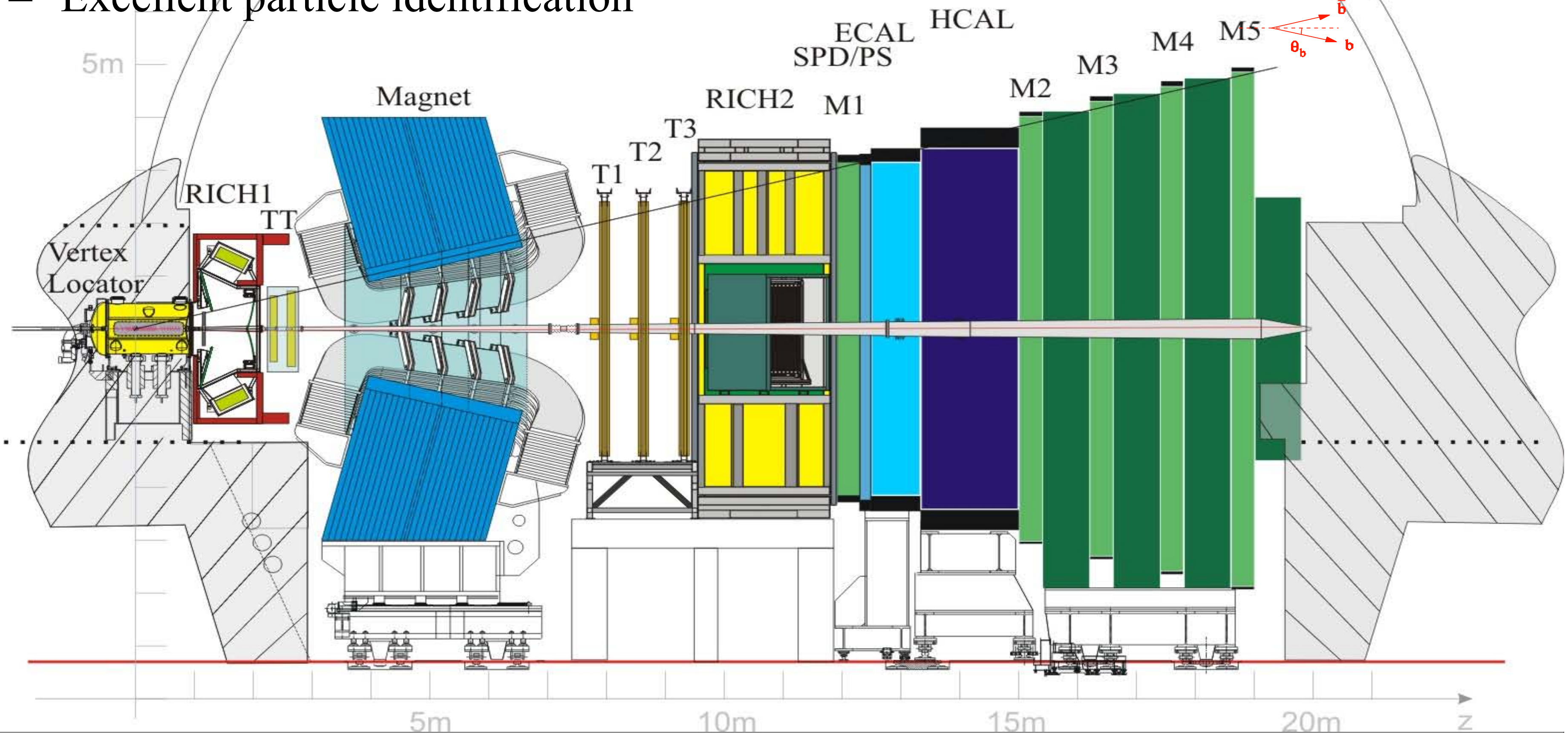
(Rare decays covered by J.Albrecht)

Many thanks to G.Wilkinson, G.Lanfranchi, P.Campana, MN.Minard and many others for (un)knowingly helping me!

LHCb detector: the essentials

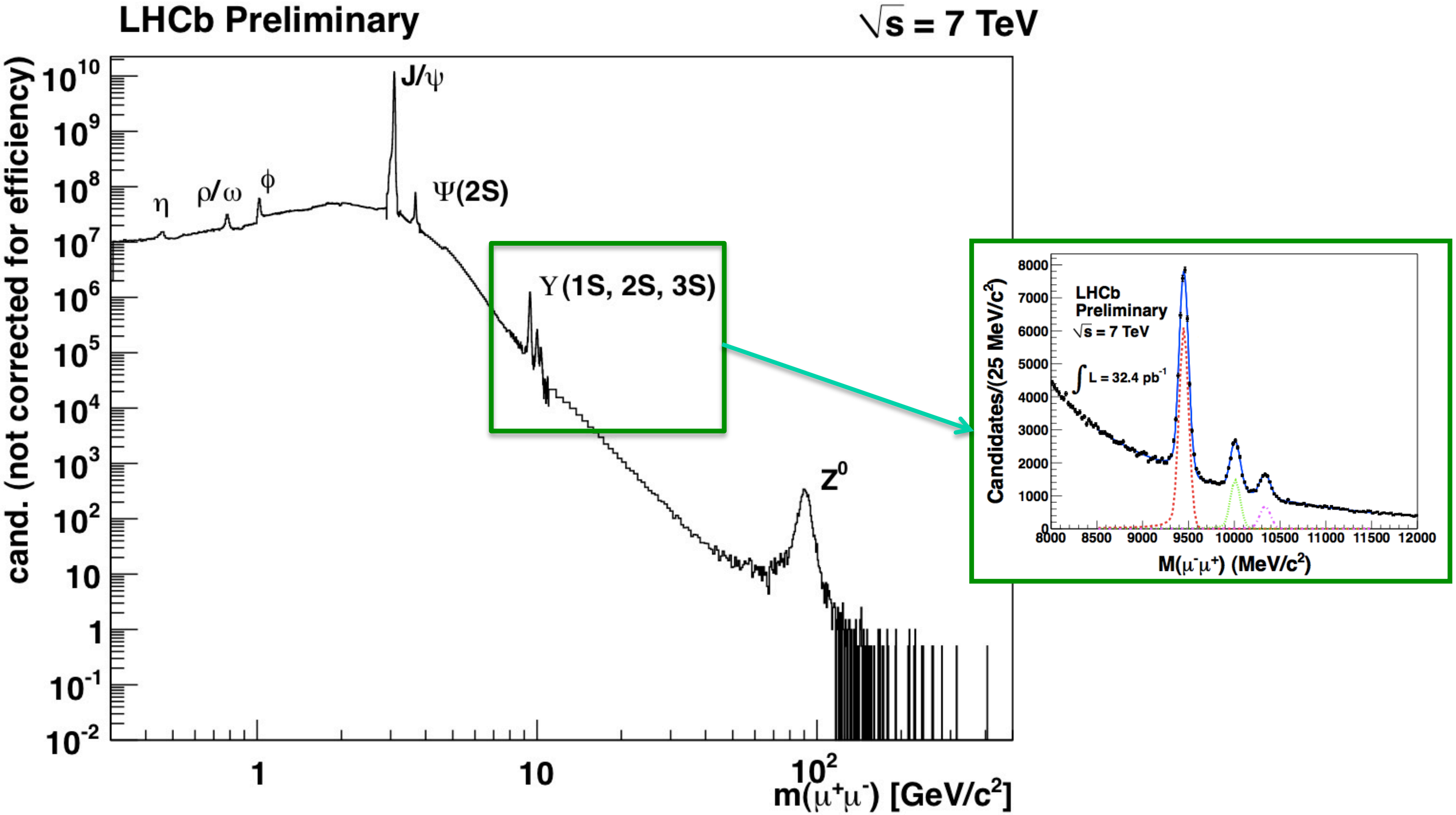
- Experiment optimized for heavy-flavour physics
  - Forward acceptance
  - Efficient trigger for hadronic and leptonic modes
  - Acceptance down to low p_T
  - Precision tracking and vertexing (VELO@7 mm from beam)
  - Excellent particle identification





LHCb detector

A general purpose, high resolution spectrometer in the forward direction



Running conditions

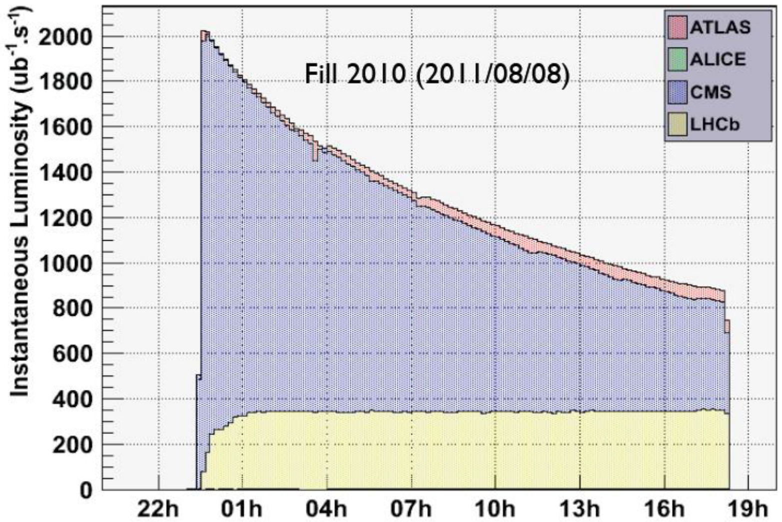
- LHCb running at ~4 10^{32} cm-^{2}s^{-1}

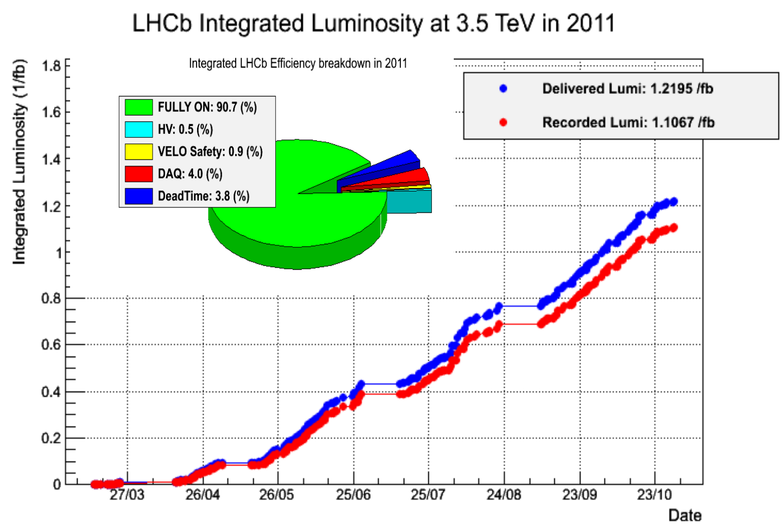
  i.e. factor of 2 above design value

- Luminosity is leveled through vertical beam displacement – operation in harmony with higher luminosity for ATLAS/CMS
- 2011: 1.2 fb^{-1} delivered

  1.1 fb^{-1} recorded (~91% efficiency)

  – Huge production cross section:
    - σ_{inel} = 60 mb @ 7 TeV
    - σ_{cc} = 6 mb
    - σ_{bb} = 0.3 mb (~1nb @ Υ(4s))



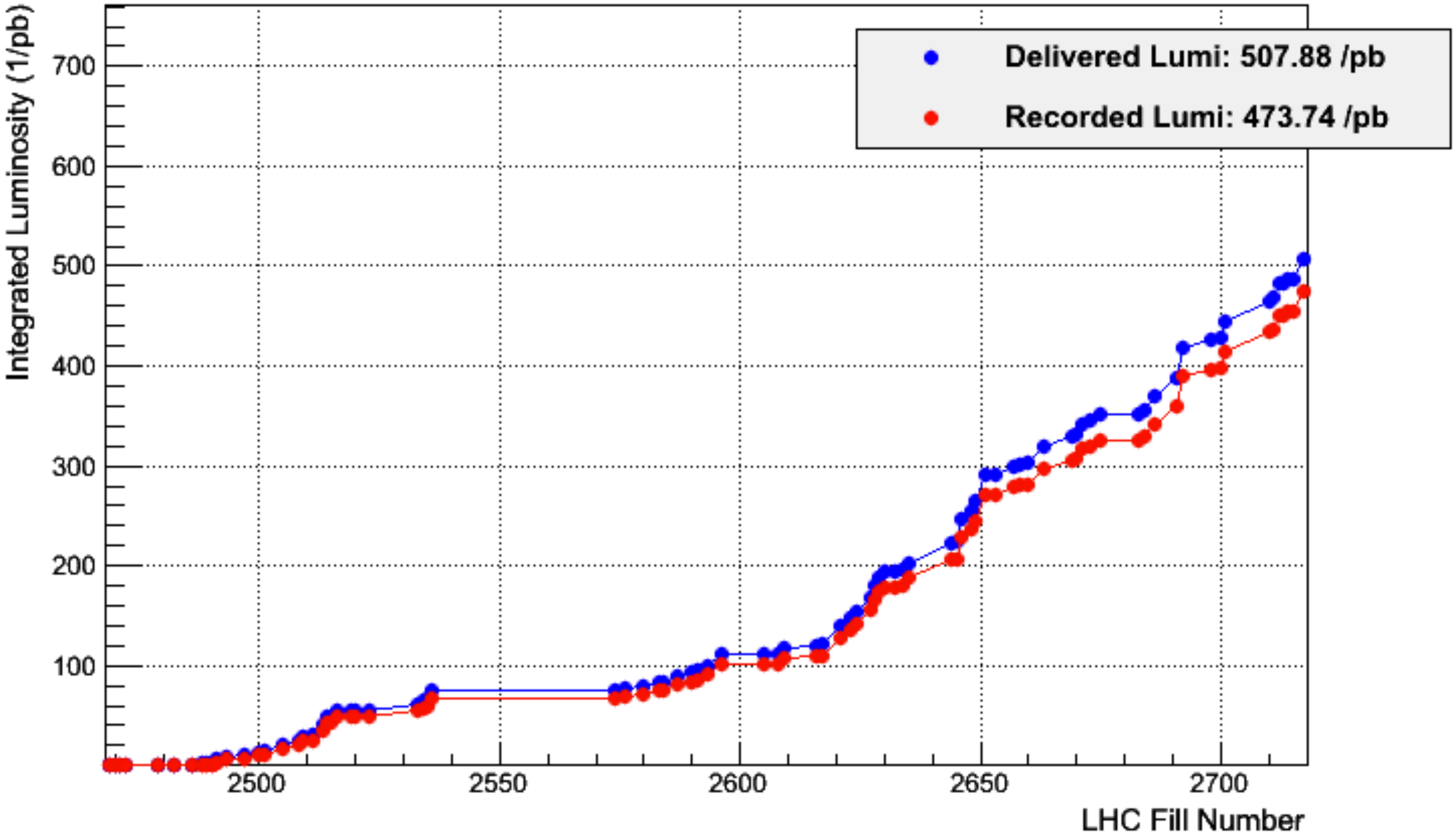


10^{11} b decays

10^{12} charm decays

in LHCb acceptance

2012 data taken so far (10-June)



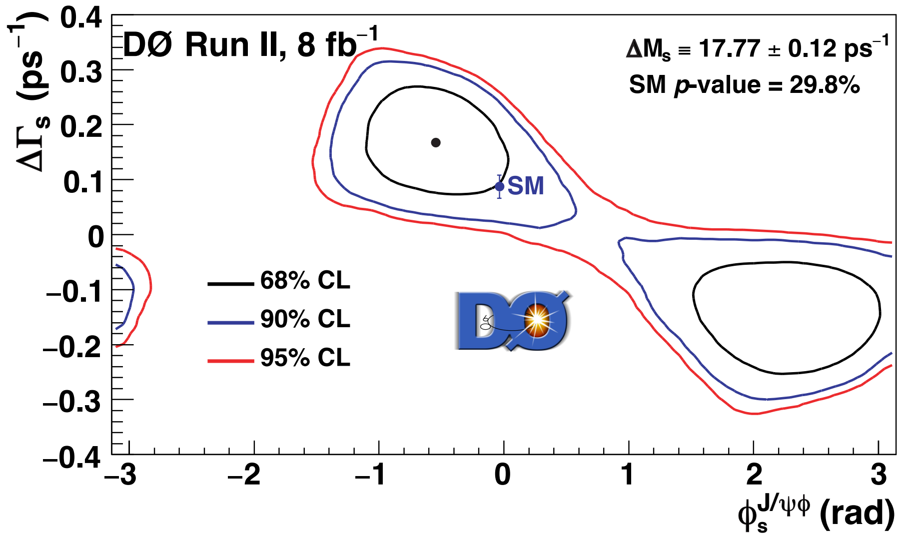
Target is 1.5 fb^{-1} recorded in 2012

CPV phase ϕ_s in B_s mixing-decay interference

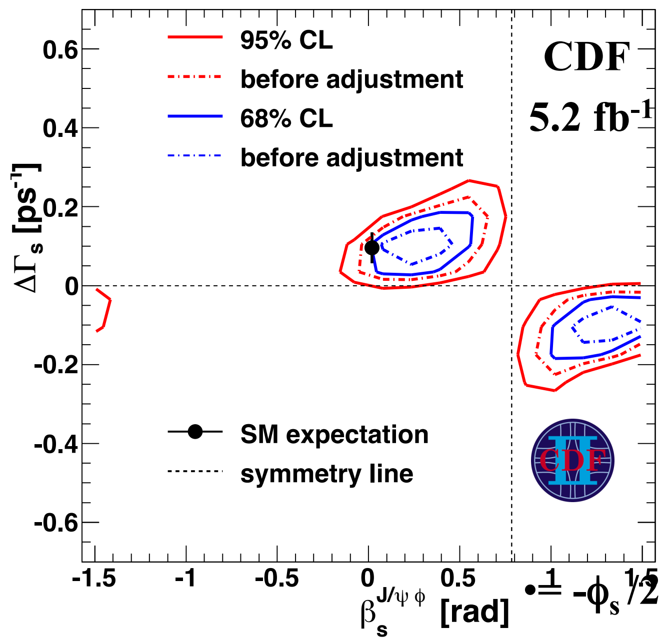
CPV phase ϕ_s in B_s mixing-decay interference

- Interesting Tevatron results with early data and intriguing with final sample

PRD 85 (2012) 032006



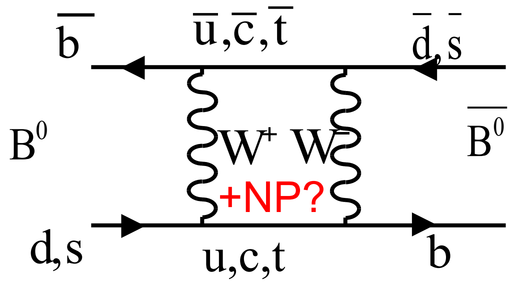
PRD 85 (2012) 072002



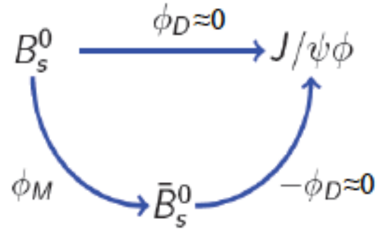
- Results are consistent, both ~1σ away from SM

What about LHCb?

Golden channel: $B_s \to J/\psi\ \phi$



- Measurement of B_s-$\bar{B}_s$ mixing phase ϕ_s in $B_s \to J/\psi\ \phi$ sensitive to NP effects in mixing
- The phase arises from interference between B decays with and without mixing



- ϕ_s is small in SM:

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

- NP can add large phases:

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

Golden channel: $B_s \rightarrow J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$

- Theoretically and experimentally clean
  - $b \rightarrow ccs$ tree dominance leads to precise prediction of ϕ_s in SM
  - Relatively large branching ratio and clean topology
  - Easy to trigger on muons from $J/\psi \rightarrow \mu^+\mu^-$

- Likelihood fit of proper time and angular decay rates for B_S^0 , $\overline{B}_S^0$
  - 6 observables:
    - invariant mass m_B, proper time, 3 angles of the decay products, B_S flavour
  - Needs flavour-tagged, time-dependent angular analysis to disentangle the CP-even and CP-odd components

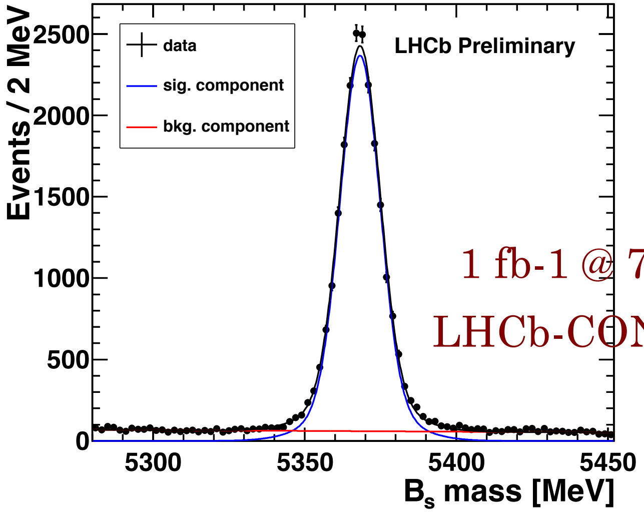
$$\mathrm{CP}\ \left|J/\psi\ \phi\right\rangle = (-1)^l \left|J/\psi\ \phi\right\rangle \qquad l = 0,1,2$$

- Determine 10 physics parameters:

  ϕ_s, $\Delta\Gamma_s$, Γ_s, ΔM_s, 3 amplitude ratios, 3 strong phase differences

$B_s \rightarrow J/\psi\ \phi$: key experimental ingredients

- Selection of signal and control channels

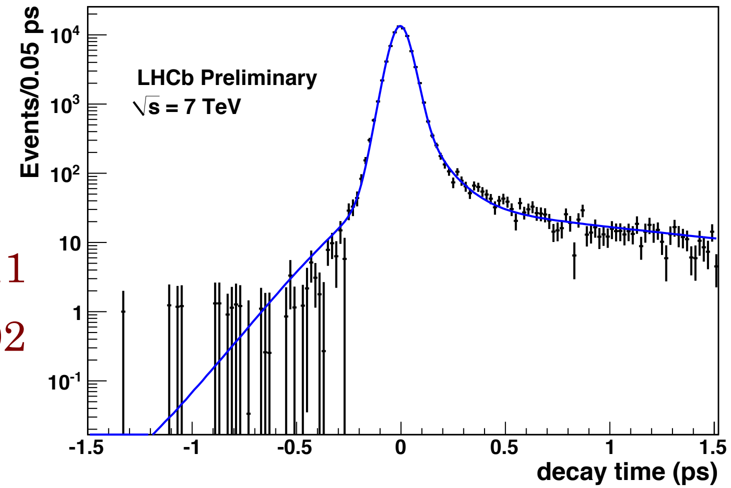


1 fb-1 @ 7TeV in 2011

LHCb-CONF-2012-002

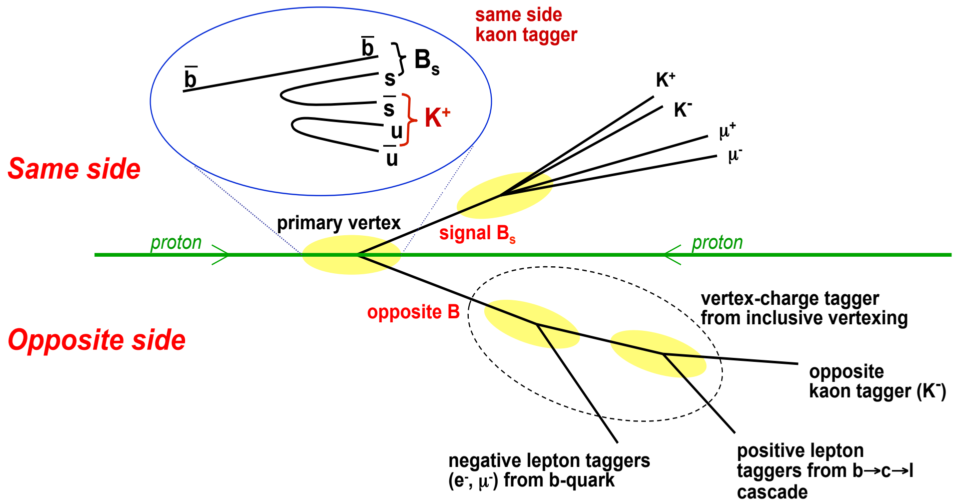
  - Very clean signal with ~21200 events (t>0.3 ps)
  - ~ 8 MeV mass resolution

- Decay time resolution



  - Effective time resolution ~45 fs from prompt events (B_S oscillation period ~350 fs)

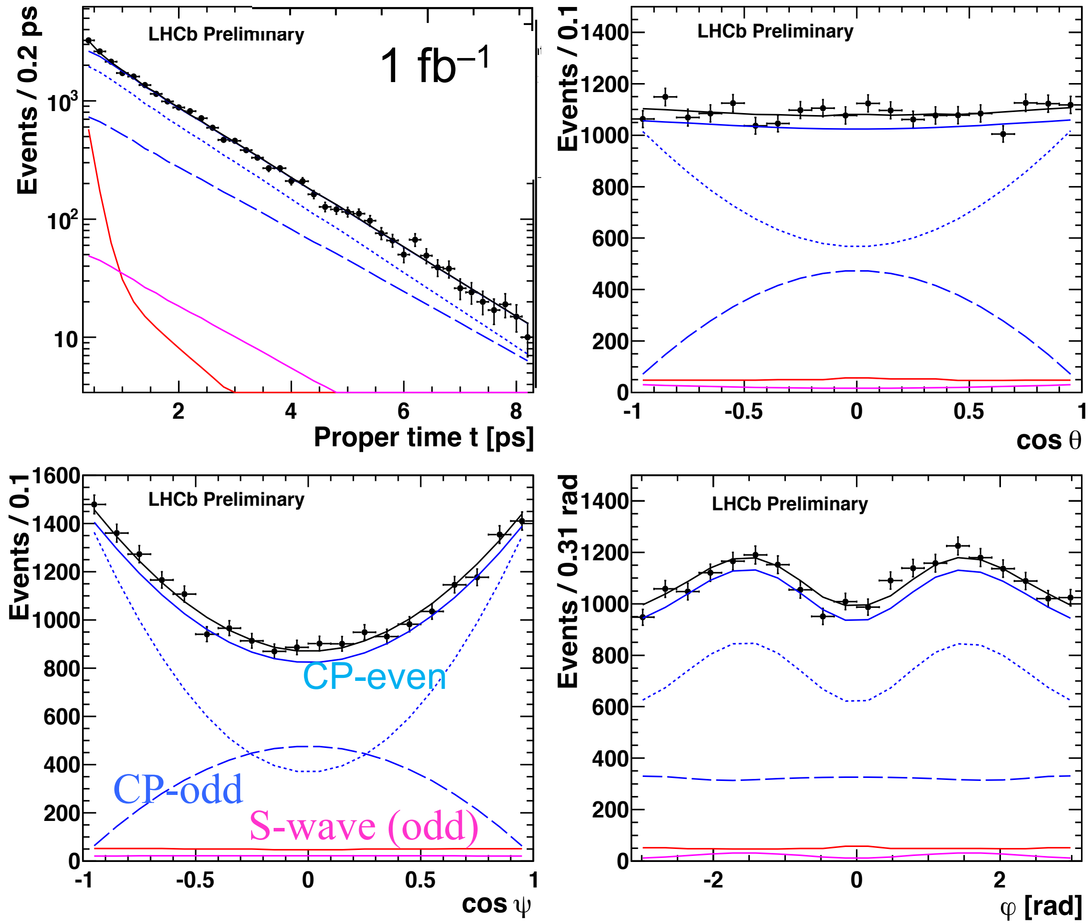
- Tagging of the initial flavour
  - Effective tagging efficiency ~2.3% from Opposite Side Tagging (exploits the decay of the other b-hadron in the event)
  - Calibrated with $B^+ \rightarrow J/\psi\ K^+$



$B_s \rightarrow J/\psi\ \phi$: fit projections

- Maximum likelihood fit using angular information used to statistically separate different CP eigenstates

LHCb-CONF-2012-002

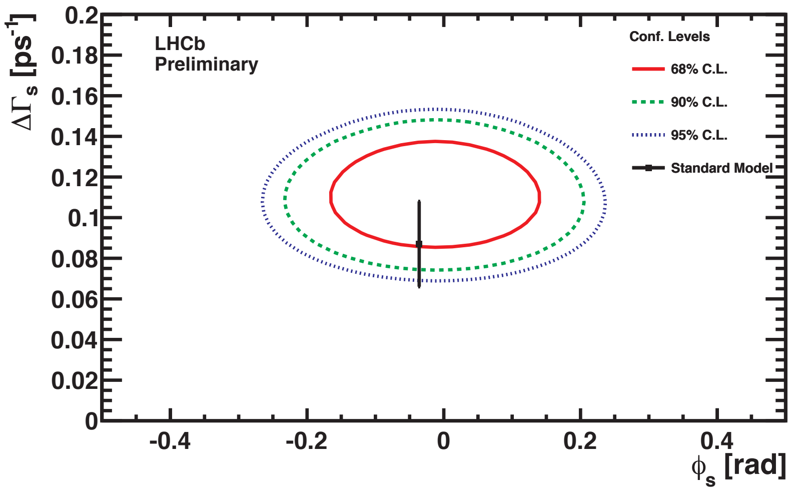


$B_s \to J/\psi\ \phi$: preliminary results

- Fit of the tagged and untagged rates as a function of B_s mass, proper time and angles

LHCb-CONF-2012-002 (1/fb)

Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.6580	0.0054	0.0066
$\Delta\Gamma_s$ [ps^{-1}]	0.116	0.018	0.006
$\lvert A_\perp(0)\rvert^2$	0.246	0.010	0.013
$\lvert A_0(0)\rvert^2$	0.523	0.007	0.024
F_S	0.022	0.012	0.007
$\delta_\perp$ [rad]	2.90	0.36	0.07
$\delta_\parallel$ [rad]	[2.81, 3.47]		0.13
δ_s [rad]	2.90	0.36	0.08
ϕ_s [rad]	-0.001	0.101	0.027

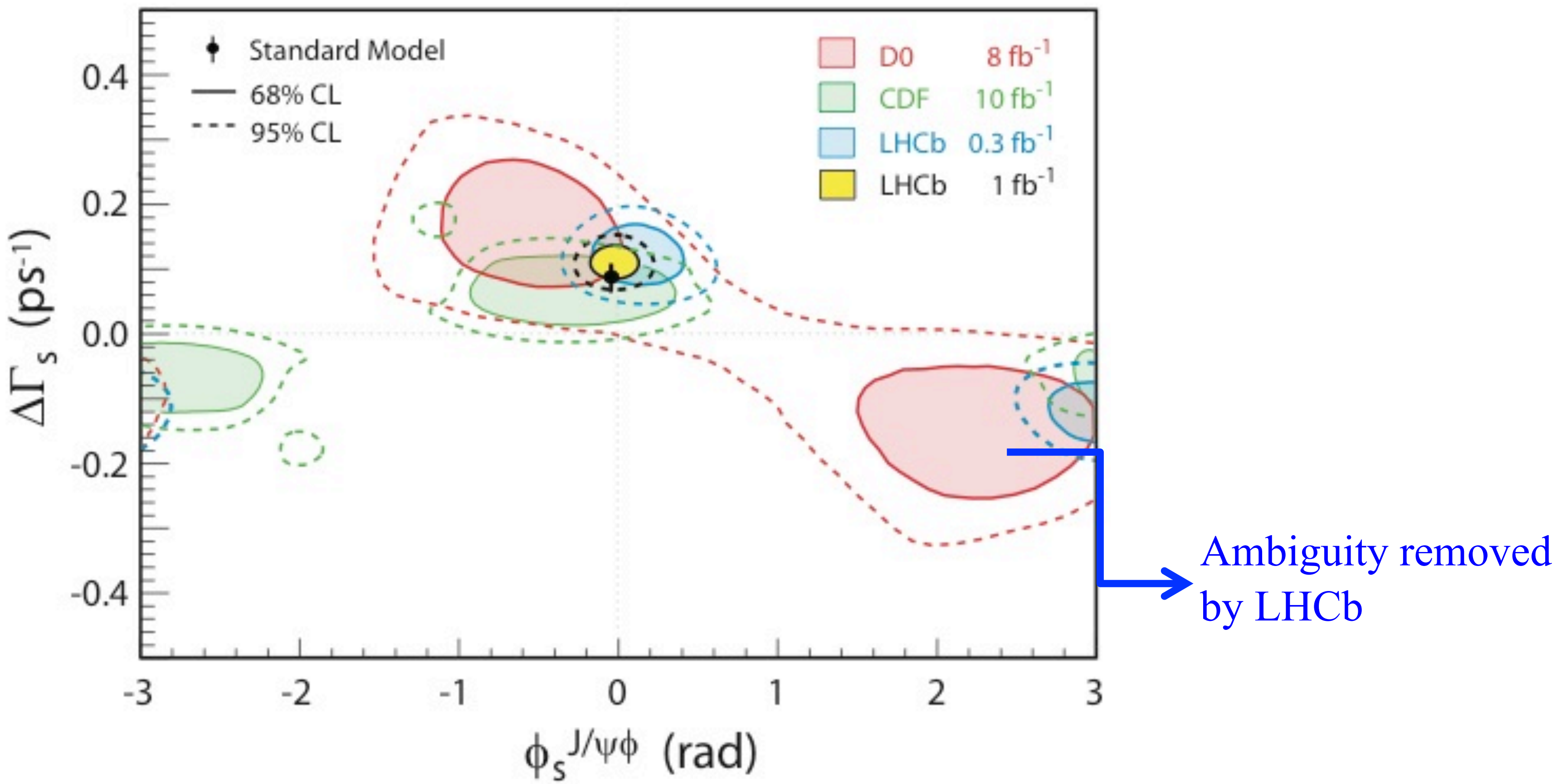


ΔM_s constrained to LHCb measurement: $\Delta M_s = (17.63 \pm 0.11\ \text{ps}^{-1})$ Phys. Lett. B 709 (2012) 177

- World's most precise measurement of ϕ_s
- First direct observation for a non-zero value for $\Delta\Gamma_s$
- ϕ_s and $\Delta\Gamma_s$ compatible with SM predictions

CPV in $B_s \to J/\psi\ \varphi$

Pictorial representation



- No big NP effects in ϕ_s !! → must increase precision

Sign of $\Delta\Gamma_s = \Gamma_L - \Gamma_H$

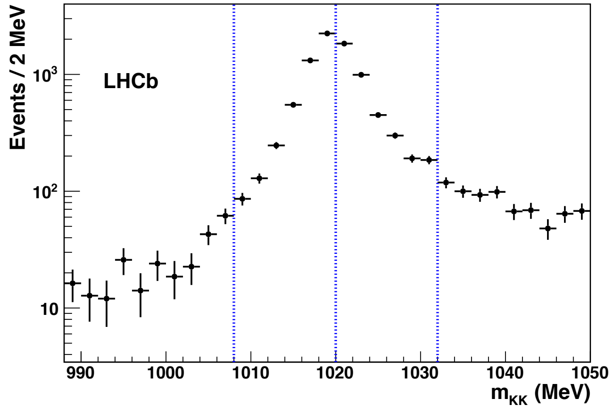
LHCb, arXiv:1202.4717

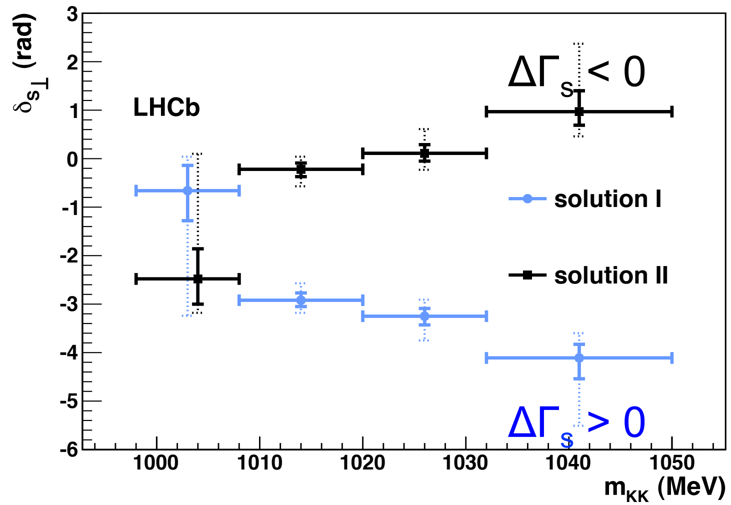
PRL 108.241801

- Two ambiguous solutions because decay rates invariant under transformation $(\phi_s, \Delta\Gamma_s) \rightarrow (\pi - \phi_s, -\Delta\Gamma_s)$ (plus strong phase changes)
- Remove ambiguity through P-wave ⇔ S-wave interference
  - S-wave K^+K^- contribution to dominant P–wave $\phi \rightarrow K^+K^-$ decay
  - Measure strong phase difference between S-wave and P-wave amplitudes as function of K^+K^- invariant mass
  - Expect
    - P-wave phase to rise through the $\phi(1020)$ region
    - S-wave is expected to vary slowly
    - Hence strong phase to decrease for physical solution
  - Solution I is selected:

    $\Gamma_L - \Gamma_H > 0$ at the 4.7σ level

Heavier B_s meson lives longer!

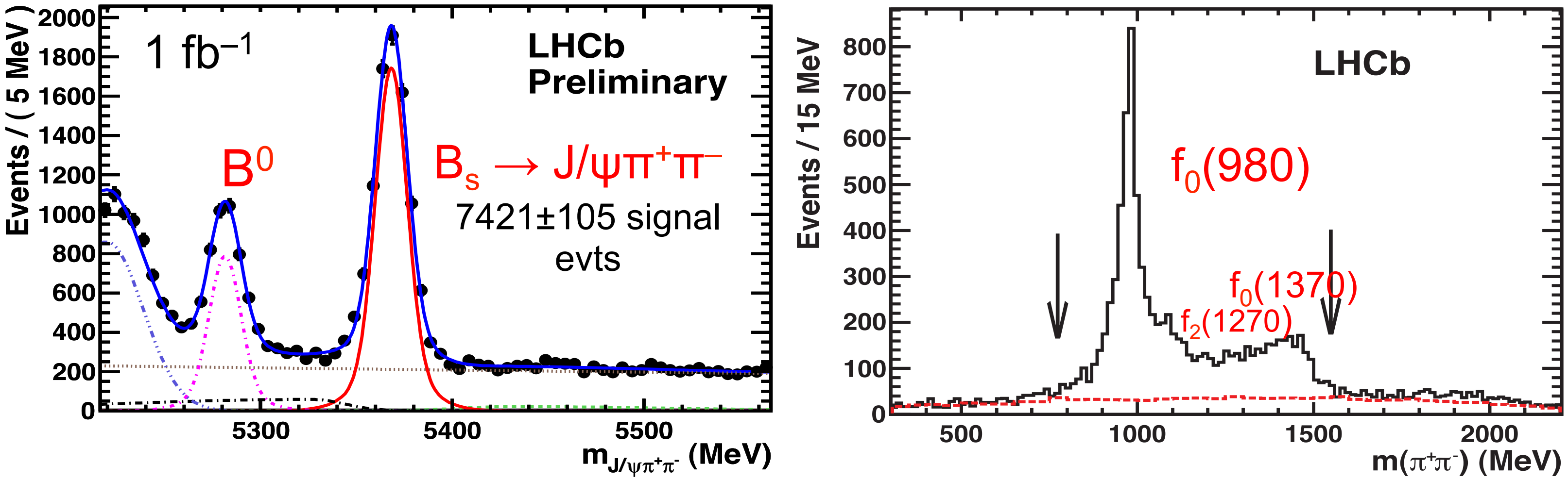




$B_s \to J/\psi\ \pi^+\pi^-$

LHCb-PAPER-2012-006
arXiv 1204.5675
submitted to PLB

- ϕ_s also measured in $B_s \to J/\psi\pi^+\pi^-$
  - Previous analysis was $B_s \to J/\psi f_0(980)$ [PLB 707 (2012) 497]
    - This is CP eigenstate → no need of angular analysis
  - Mass window extended to 775 < m(ππ) <1550 MeV/c²
  - Angular analysis shows CP-odd fraction > 97.7% at 95% C.L.
  - Smaller BR ~20% wrt $B_s \to J/\psi\ \phi$ ~ 7400 events in signal region
  - $\phi_s = -0.02 \pm 0.17 \pm 0.02$ rad



- $B_s \to J/\psi\phi$ and $B_s \to J/\psi\pi\pi$ <u>combined preliminary result</u>
  $\phi_s = -0.002 \pm 0.083(\text{stat.}) \pm 0.027(\text{syst.})$ rad LHCb-CONF-2012-002

The semi-leptonic asymmetry

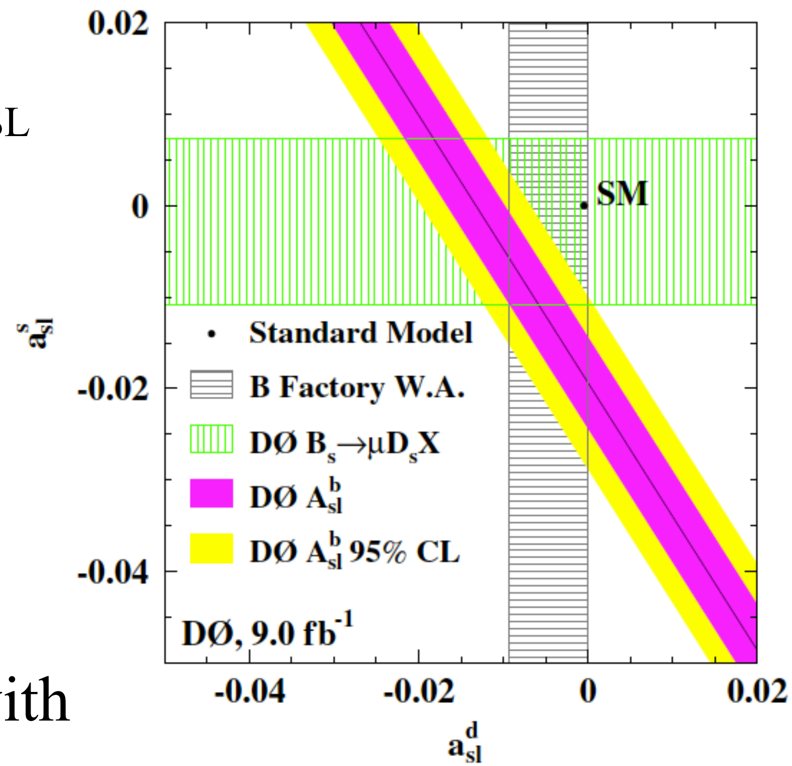
- D0 measurement, with dileptons, measures a superposition of a^d_{SL} and a^s_{SL}

$$A^b_{sl} = \frac{N^{++}_{b\bar{b}} - N^{--}_{b\bar{b}}}{N^{++}_{b\bar{b}} + N^{--}_{b\bar{b}}} = C_d a^d_{sl} + C_s a^s_{sl}$$

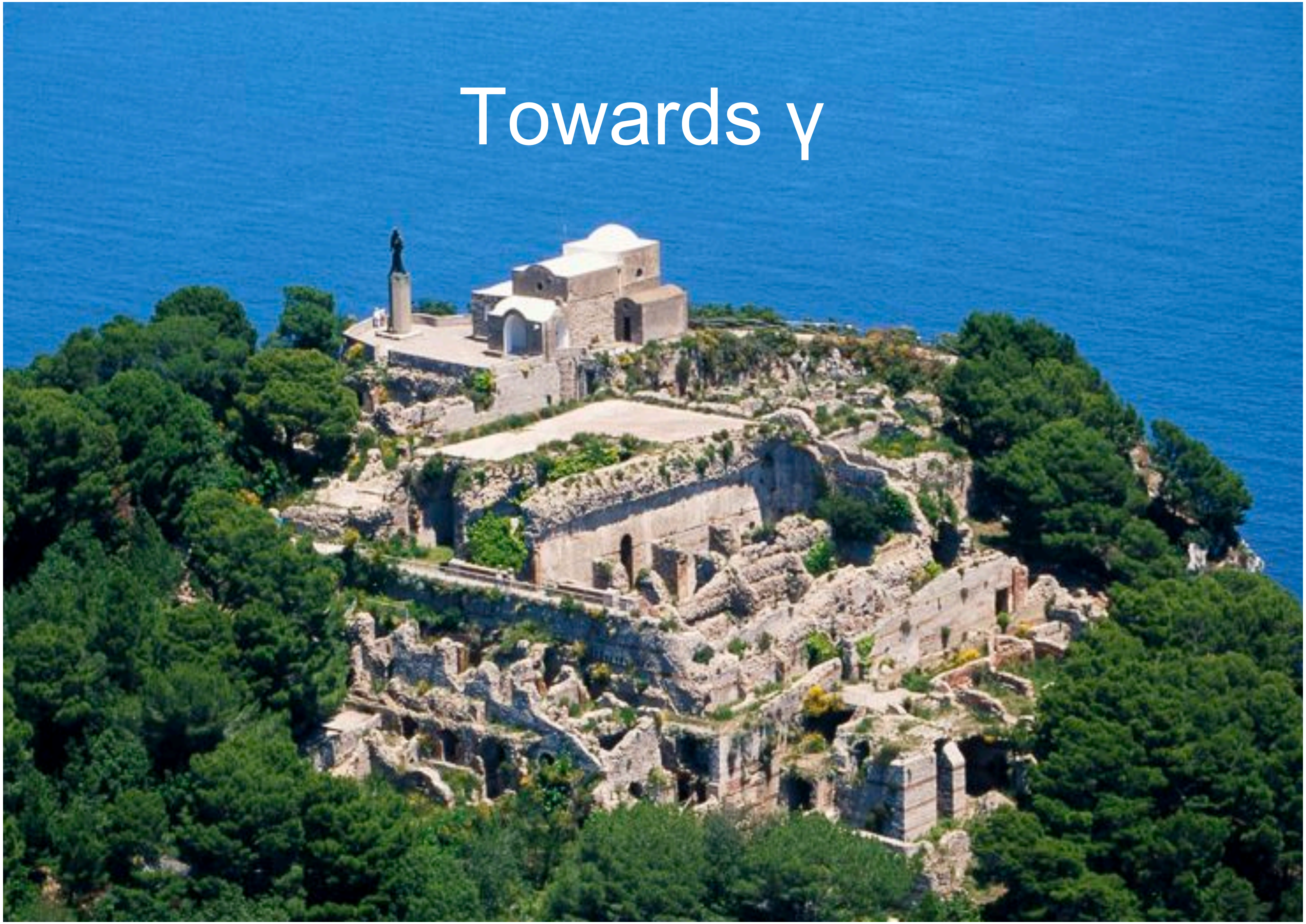
- Result 3.9 σ away from SM !

- Most easily interpreted as a B_s driven effect, however difficult to reconcile with other measurements such as $B_s \rightarrow J\psi\phi$

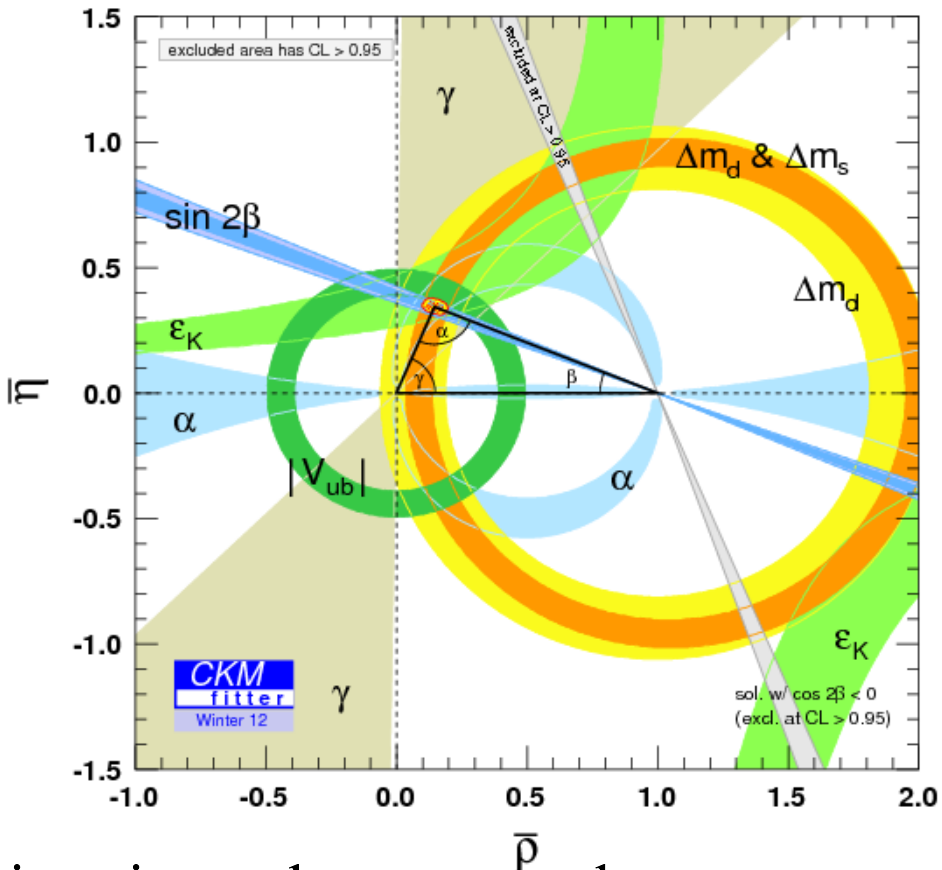
- LHCb finalising a time integrated study of $B_s \rightarrow D_s(\phi\pi)\mu\upsilon$ decays to measure a^s_{SL}



Towards γ



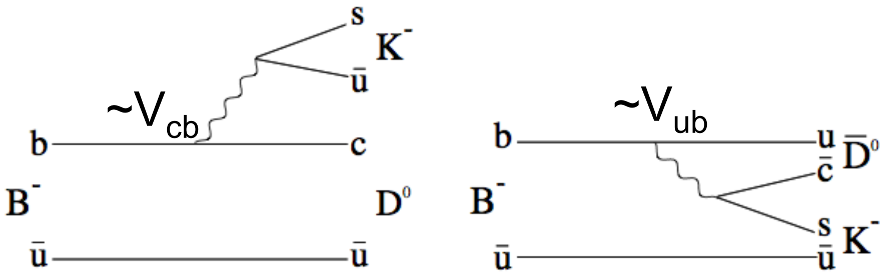
State of the art



CKMfitter, S.Descotes-Genon
UTFit, M.Bona

- Very precise picture has emerged
- γ is least well measured angle
- Current measurement error ~10-12°; indirect (through loops) is ~4°

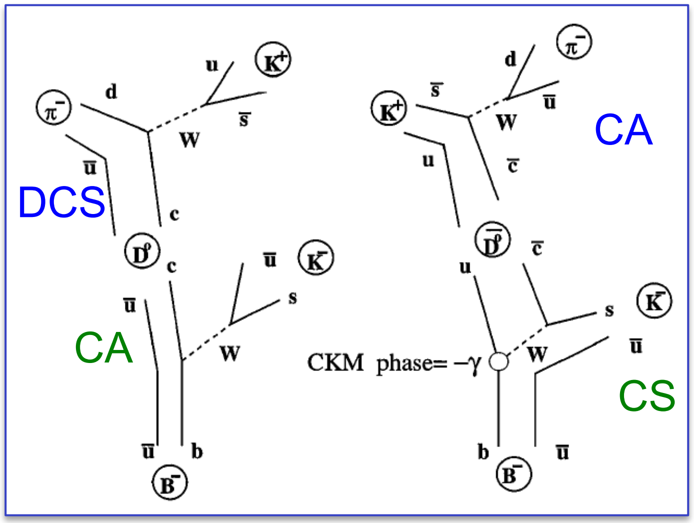
CPV in $B^{\pm} \rightarrow DK^{\pm}$



- Sensitivity to γ through final states accessible to both D^0 and $\bar{D}^0$ leading to interference
- No "pollution" from penguin loops

1. D decays to CP eigenstates, e.g. $\pi^+\pi^-$, K^+K^- ("**G**ronau **L**ondon **W**yler")
2. 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 similar amplitudes → high sensitivity to γ



CPV in $B^{\pm} \rightarrow DK^{\pm}$

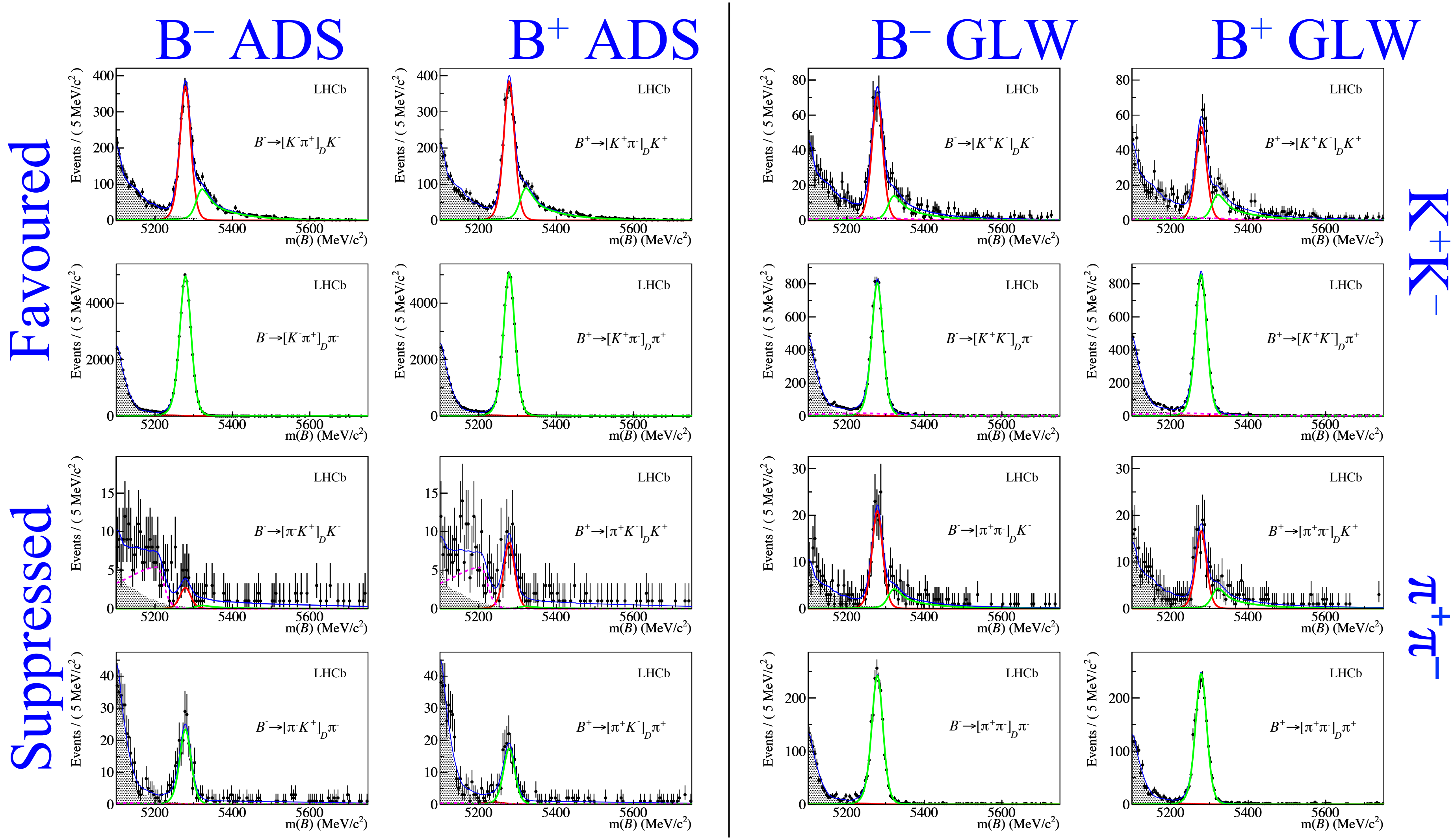
LHCb, arXiv:1203.3662
Submitted to PLB

- Recent LHCb analysis towards measurement of γ:
  - Combines "GLW" and "ADS"
  - Measures 16 decay rates:
    - $B^{-} \rightarrow Dh^{-}$ and $B^{+} \rightarrow Dh^{+}$ ($h=K$ or π) and $D \rightarrow K^{-}\pi^{+}$, $K^{+}\pi^{-}$, $\pi^{+}\pi^{-}$, $K^{+}K^{-}$
  - Extracts 3 ratios of partial widths, 6 CP asymmetries, 4 ratios of ADS to favoured partial widths

CPV in $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$

LHCb, arXiv:1203.3662
Submitted to PLB

1 fb^{-1}



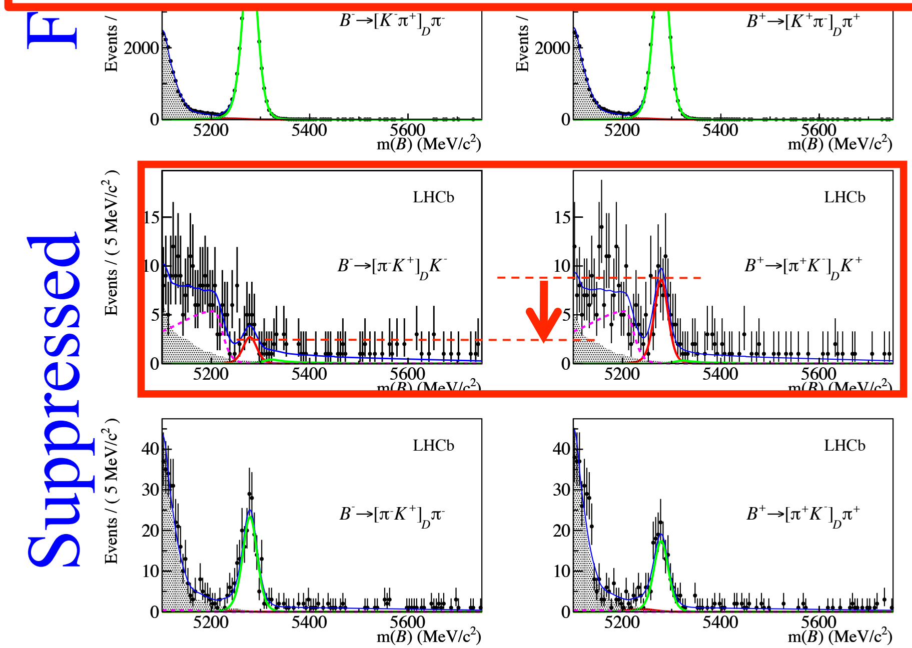
CPV in $B^{\pm} \rightarrow DK^{\pm}$ and $B^{\pm} \rightarrow D\pi^{\pm}$

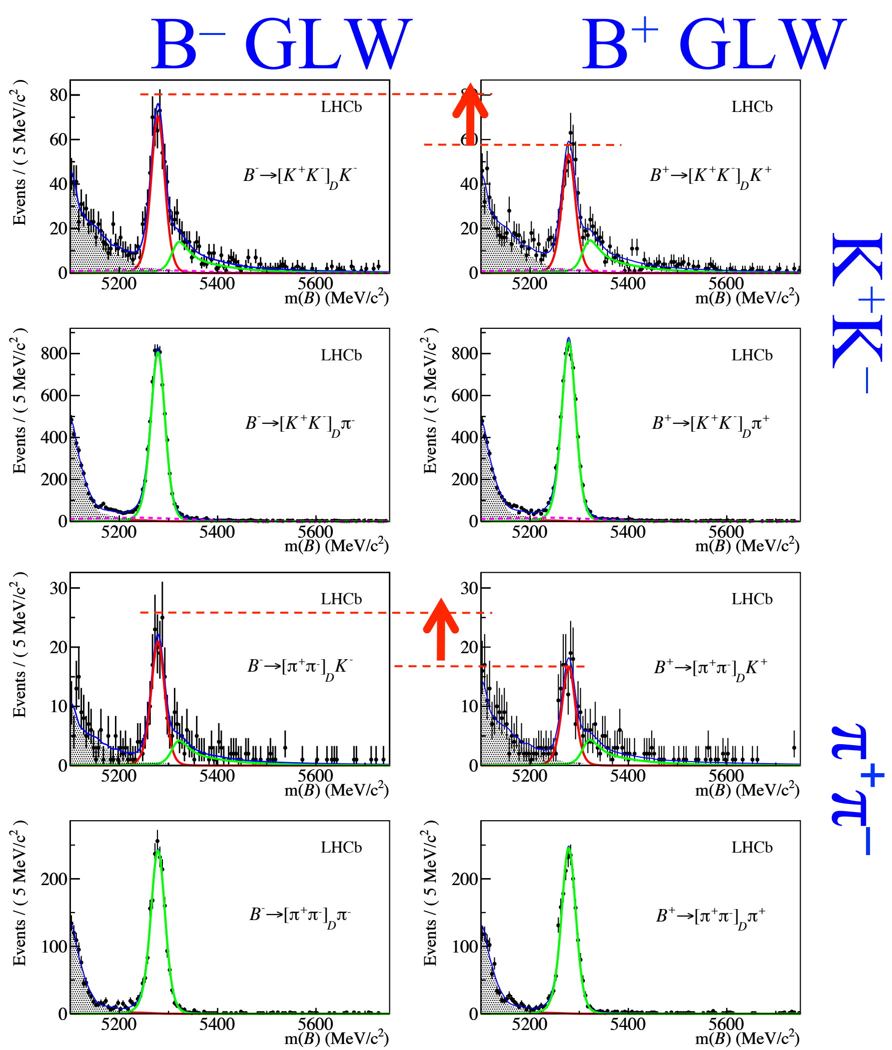
LHCb, arXiv:1203.3662
Phys Lett B 712 (2012) 203

First observation of $B^{\pm} \rightarrow DK^{\pm}$ ADS mode (~10 σ)

Evidence of a large negative asymmetry in DK: $A_{ADS}(K) = (-52 \pm 15 \pm 2)\%$ (4 σ)

With KK, ππ, CPV in $B^{\pm} \rightarrow DK^{\pm}$ observed with 5.8 σ significance

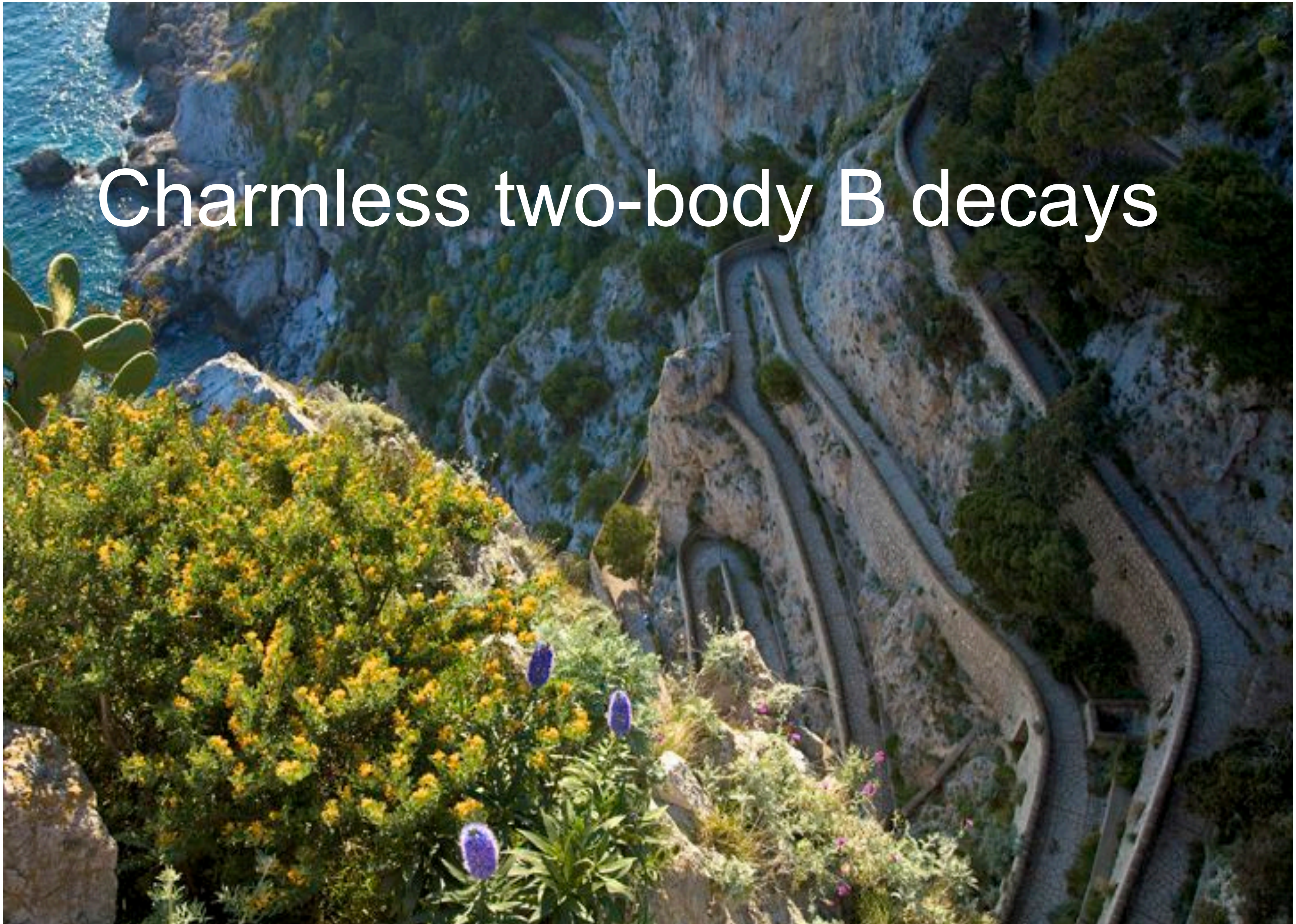




Towards γ

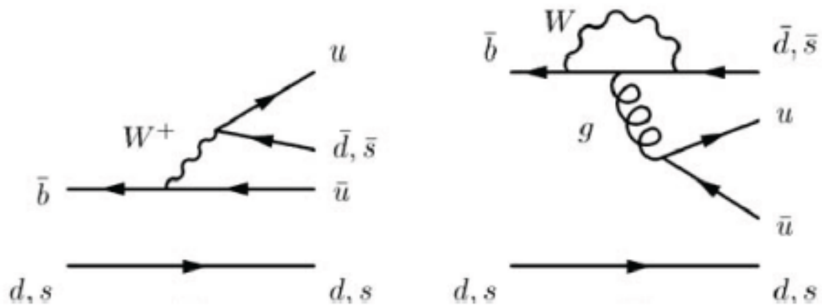
- LHCb is on-track to make a combined measurement of γ using $B^{\pm}$, B^0, B_s tree decays, to an accuracy of 5~8° with the 2011+2012 data
- Anticipated LHCb sensitivity by 2018 ~ 4^o (i.e. matching current indirect precision)

Charmless two-body B decays



Charmless two-body B decays

B → $h^+h'^-$ (where h and h' = π,K,p)



…plus other diagrams

- Interesting class of decays
- Sensitive to V_{ub} so to CKM angle γ
- 'Simple' interpretation of measurements in terms of CKM phases not possible (penguin pollution, etc)
- NP can contribute to penguin loops
- Important interplay among the various B → $h^+h'^-$ channels
  - e.g. assuming U-spin symmetry (d – s interchange)

Charmless two-body B decays

- Very large yields at LHCb
  - e.g. [1/fb] ~ 41k ($B^0 \rightarrow K\pi$); 7k ($B^0 \rightarrow \pi\pi$); 2k ($B_s \rightarrow K\pi$); 11k ($B_s \rightarrow KK$)
- PID capability with RICH detectors to isolate clean samples of $B \rightarrow h^+h^-$ ($h = \pi, K, p$)
- Direct CP asymmetries in $K\pi$ modes $\Gamma(B^0 \rightarrow f) \neq \Gamma(\bar{B}^0 \rightarrow \bar{f})$
  - Detection asymmetries (acceptance, reconstruction, interaction in material)
    - Studied with high stat. D* and D^0 samples with inversion of magnet field polarity
  - B-$\bar{B}$ production asymmetries
    - Studied with $B^0 \rightarrow J/\psi K^{*0}$ (No CPV in $b \rightarrow c\bar{c}s$)
- Time-dependent CPV in $\pi\pi$ and KK modes
  - Needs flavour tagging (tagging power ~ 2.3%)

Direct CPV in $B_{(s)} \rightarrow K\pi$

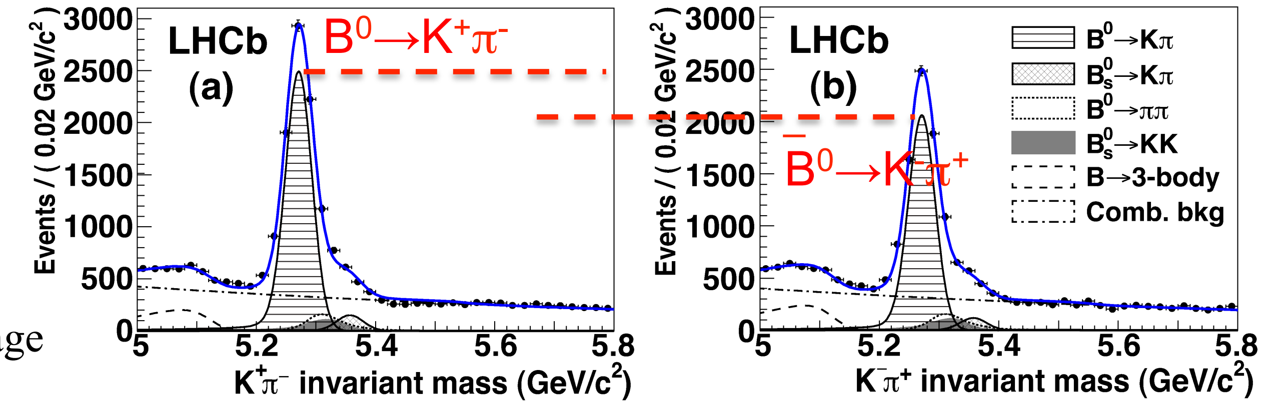
LHCb, arXiv:1202.6251
Accepted by PRL

- With 0.35 fb^{-1}

$A_{CP}(B^0 \rightarrow K\pi) =$

$-0.088 \pm 0.011 \pm 0.008$

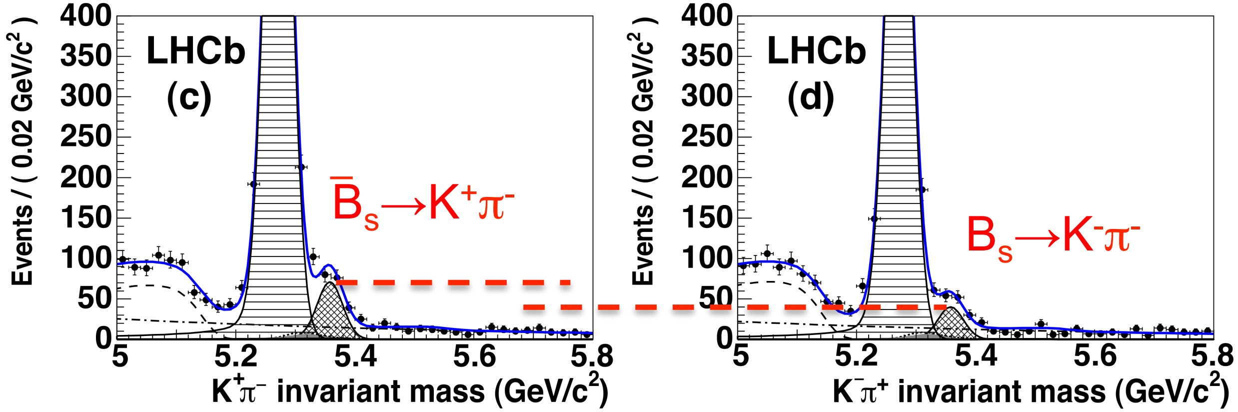
Good agreement with HFAG average



First observation (>6σ) of direct CPV in B decays at a hadron collider

$A_{CP}(B_s \rightarrow K\pi) =$

$+0.27 \pm 0.08 \pm 0.02$



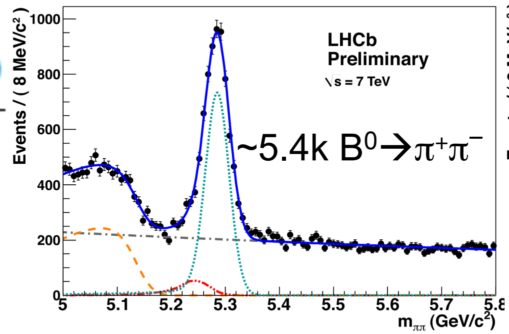
First evidence (3.3 σ) of direct CPV in B_S decays

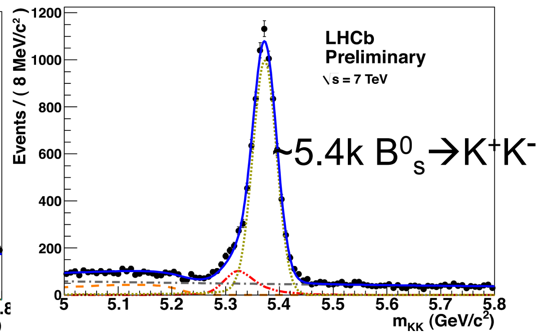
Time dependent CPV in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$

LHCb-CONF-2012-007 0.69 fb-1

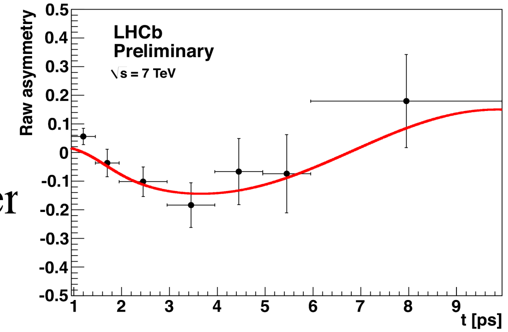
$$A_{CP}(t) = \frac{A_f^{dir}\cos(\Delta m t) + A_f^{mix}\sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) - A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t\right)}$$

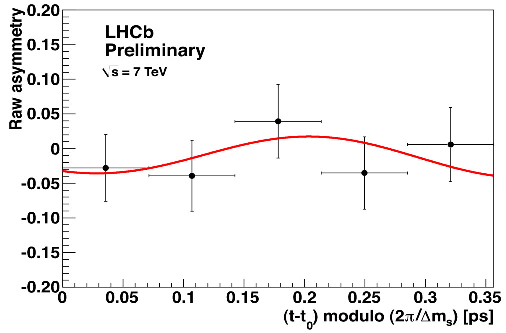
→ A^{dir}_f and A^{mix}_f



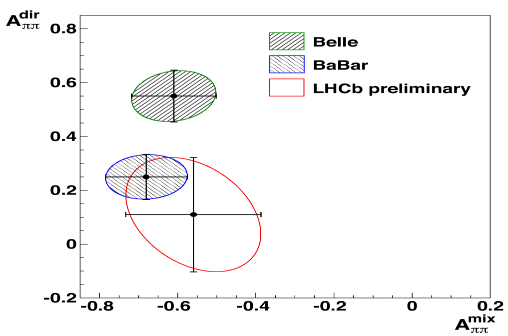


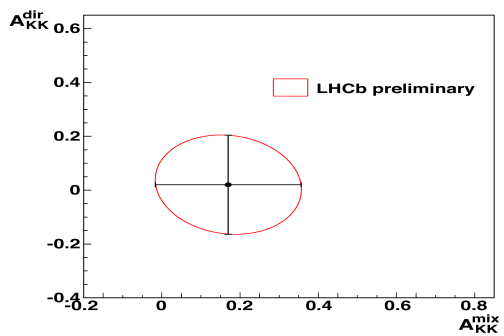
- $B^0 \to \pi^+\pi^-$
  - $A^{dir}_{\pi\pi} = 0.11 \pm 0.2 \pm 0.03$
  - $A^{mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$
  - First measurement at a hadron collider
  - Compatible with B factories





- $B^0_s \to K^+K^-$
  - $A^{dir}_{KK} = 0.02 \pm 0.18 \pm 0.04$
  - $A^{mix}_{KK} = 0.17 \pm 0.18 \pm 0.05$
  - First measurement

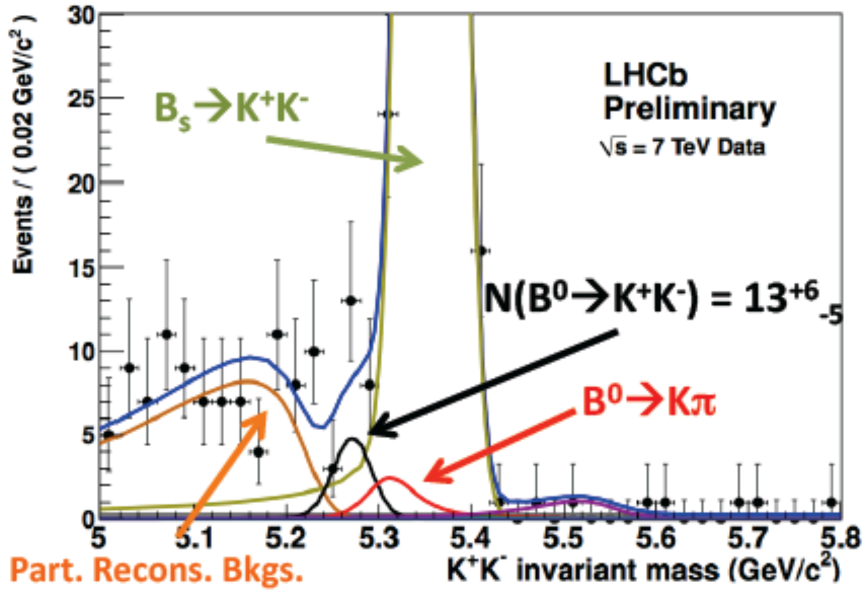


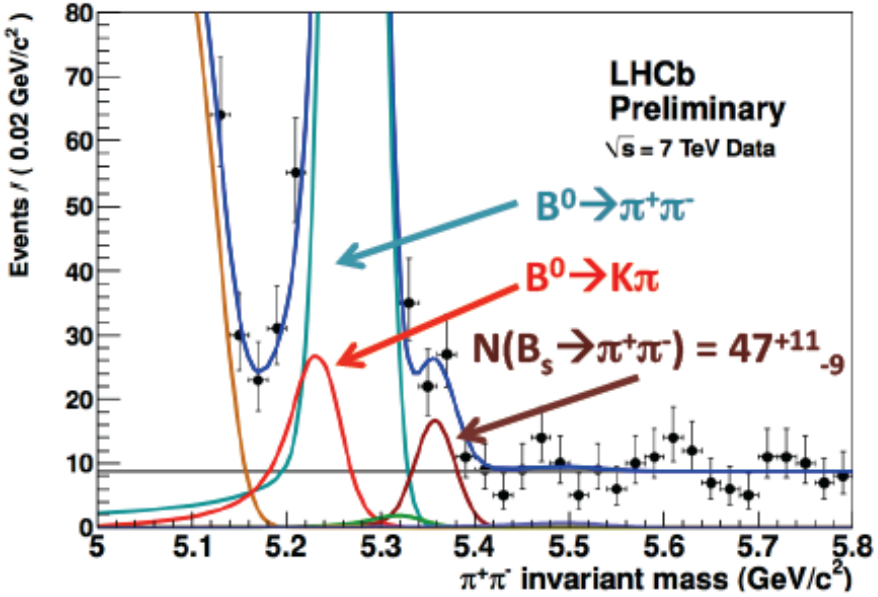


Very rare topologies in B→h⁺h⁻

LHCb-CONF-2011-042

32 fb^{-1}



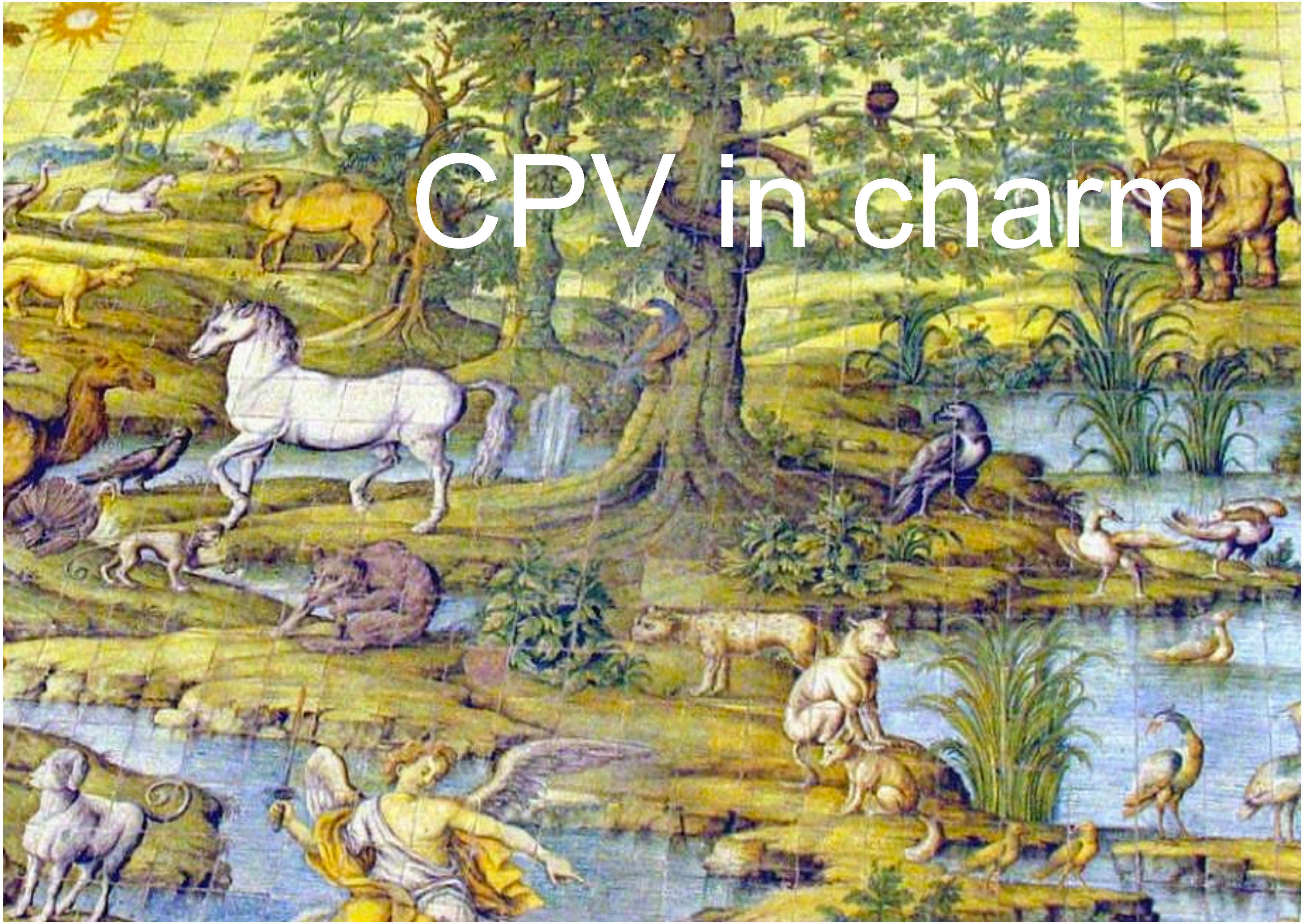


$$BR(B^0 \to K^+K^-) = (0.13^{+0.06}_{-0.05} \pm 0.07)\cdot 10^{-6}$$

$$BR(B^0_S \to \pi^+\pi^-) = (0.98^{+0.23}_{-0.19} \pm 0.11)\cdot 10^{-6}$$

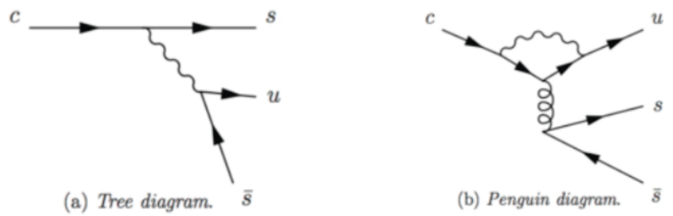
First observation of $B_S \to \pi^+\pi^-$ with 5.3σ significance

CPV in charm



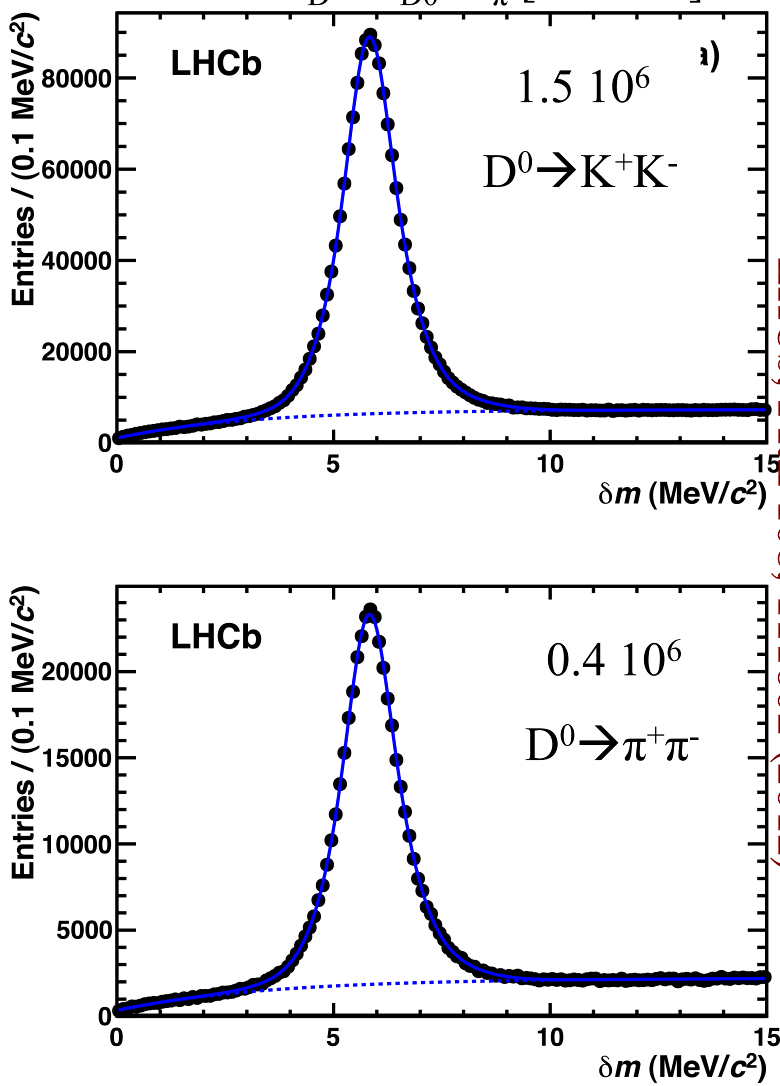
Search for direct CPV in SCS charm decays

- Direct CPV in charm expected to be small in SM
- In Singly Cabibbo Suppressed (SCS) decays, interference between tree and penguin diagrams gives possibility to NP to manifest itself



- LHCb has very large samples (e.g. statistics in $D^0 \rightarrow hh$ for 2011 data alone are order of magnitude higher than total B-factory yields)
- Clear opportunity for NP search!

LHCb $m_{D*}-m_{D0}-m_{\pi}$ [0.6 fb-1]

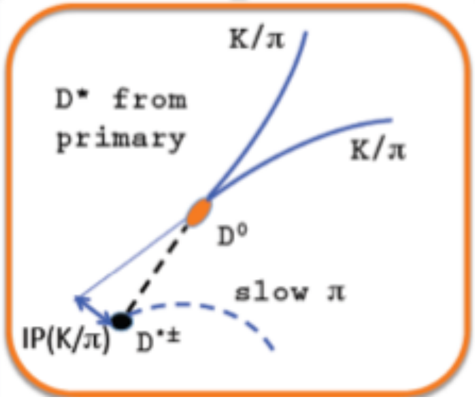


LHCb, PRL 108, 111602 (2012)

CPV in time-integrated $D^o \rightarrow h^+h^-$ decay rates

- Raw asymmetry for tagged D^0 to final state f ($\pi^+\pi^-$ or K^+K^-):

$$A_{raw}(f) = \frac{N(D^{*+} \rightarrow D^0(f)\pi_s^+) - N(D^{*-} \rightarrow \overline{D}^0(\overline{f})\pi_s^-)}{N(D^{*+} \rightarrow D^0(f)\pi_s^+) + N(D^{*-} \rightarrow \overline{D}^0(\overline{f})\pi_s^-)}$$



- First order Taylor Expansion:

$$A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

physics CP asymmetry

Detection asymmetry of D^0

Detection asymmetry of soft pion

Production asymmetry

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

$A_D(\pi^+\pi^-) = A_D(K^+K^-) = 0$

Independent of f

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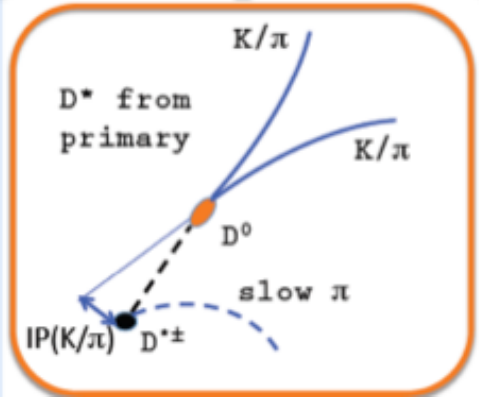

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Independent of f

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

Nice bonus: in U-spin limit $A_{CP}(KK) = -A_{CP}(\pi\pi)$ for any direct CPV, so effect amplified by taking difference

LHCb, PRL 108, 111602 (2012)

Evidence of CPV in time-integrated $D^o \rightarrow h^+h^-$ decay rates

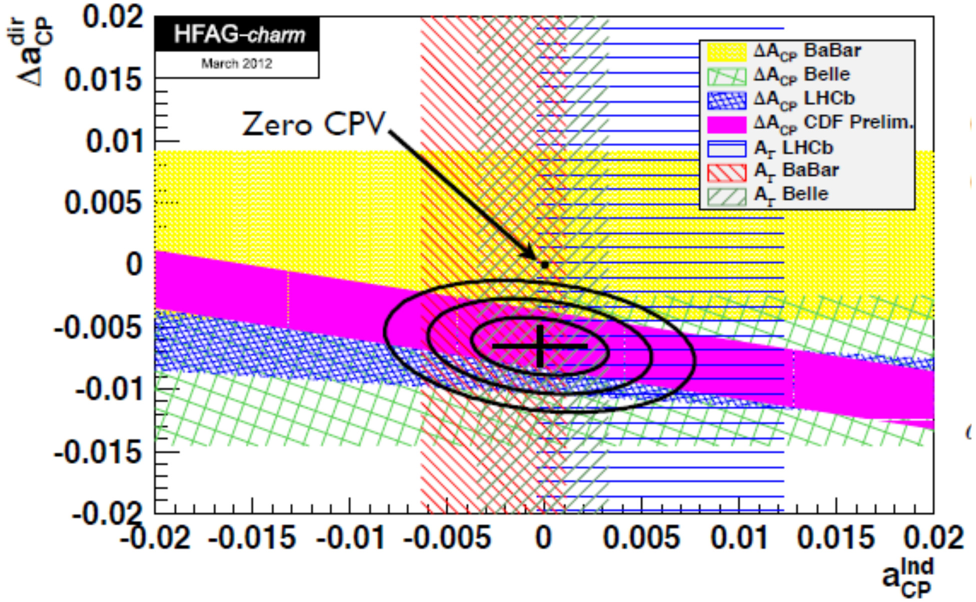
LHCb, PRL 108, 111602 (2012)

- ΔA_{CP} mainly related to direct CP violation. a_{CP}^{ind} is to a good approx. universal. Contribution from indirect CPV remains if time acceptance is different for $\pi^+\pi^-$ and K^+K^- final states:

$$\Delta A_{CP} = \left[a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{ind}$$

- Result, based on 0.62/fb of 2011 data is

$$\Delta A_{CP} = (-0.82 \pm 0.21_{stat} \pm 0.11_{syst})\%$$



(Note also recent preliminary CDF result: [-0.62 +- 0.21 +- 0.10]% [CDF note 10784])

Evidence of CPV in time-integrated $D^o \rightarrow h^+h^-$ decay rates

- Prospects
  - Analysis of remainder of 2011 data is ongoing (~0.4/fb)
  - Published analysis selects prompt charm → only ~3% of total yield is charm from B
  - Alternative analysis ongoing in which D^0 flavour is tagged using charge of μ in semileptonic B decays → completely different systematics, interesting experimental cross-check
  - Precision study of other SCS modes

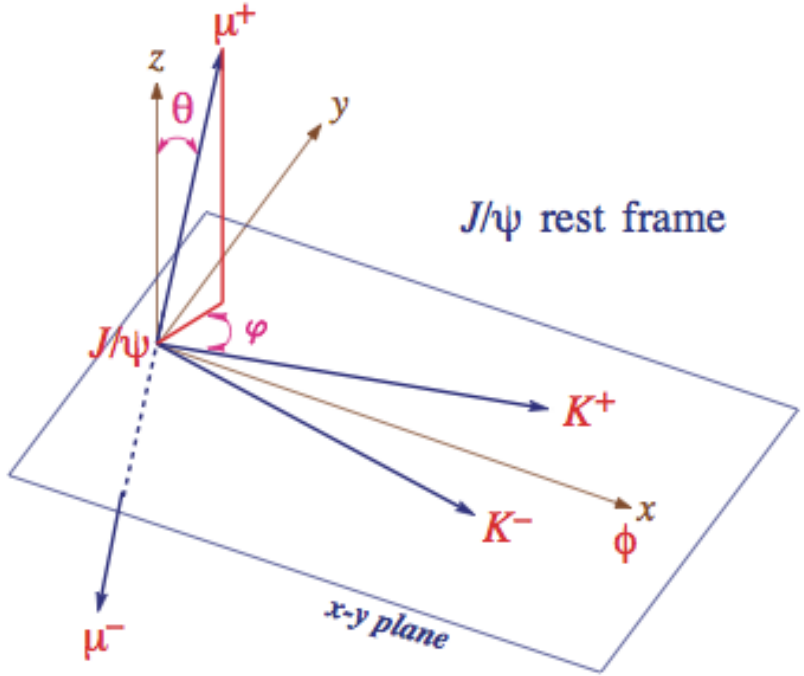
Conclusions

- Wealth of LHCb results with the first 1/fb collected in 2001 at "CERN's flavour factory"
  - Everything works (LHC, luminosity leveling, detector, trigger, collaboration, data analysis, ..)
  - World record results on $B_s \rightarrow J/\Psi\phi$, $B_s \rightarrow \mu\mu$, $B_d \rightarrow K^* \mu\mu$ and charm physics. For some topics we are moving from exploration to precision measurements.
  - Many other analyses ongoing (not only in b and c physics)
- Some new territory already explored but SM still depressingly uncracked
- We'll keep on looking….
- More than double the statistics in 2012
- Working hard to prepare for the future (LHCb Upgrade)

Statistical sensitivities for LHCb Upgrade

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.13 %	0.03 %	0.02 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	8 %	2.5 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	$\sim 20°$ [19]	4°	0.9°	negligible
	γ ($B_s^0 \to D_sK$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\mathrm{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-neglible for the most precisely measured quantities.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J/ψ
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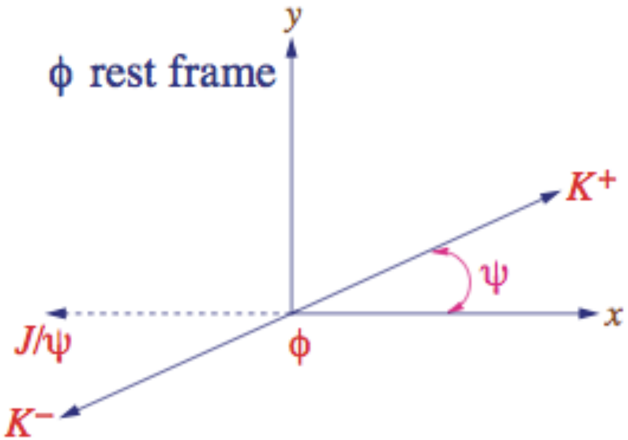
y
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J/ψ
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K−