Kruger 2012

Workshop on Discovery Physics at the LHC

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CP Violation at LHCb

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on behalf of the LHCb collaboration

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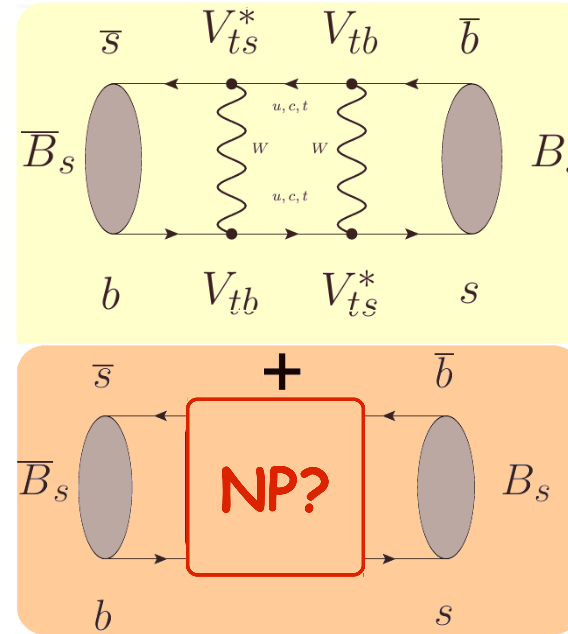
Sources of CP violation (I)



<u>CP violation in mixing</u> ("indirect" CP violation)

- **neutral meson systems ($K^0\overline{K}^0$, $D^0\overline{D}^0$, $B^0\overline{B}^0$, $B^0_s\overline{B}^0_s$): particle-antiparticle mixing due to box diagrams**
- **time evolution described by Schroedinger equation:**

$$i\frac{d}{dt}\begin{pmatrix} B^0_s \\ \overline{B}^0_s \end{pmatrix} = \begin{pmatrix} M^s_{11} - i\frac{\Gamma^s_{11}}{2} & M_{12} - i\frac{\Gamma^s_{12}}{2} \\ M^{s*}_{12} - i\frac{\Gamma^{s*}_{12}}{2} & M^s_{22} - i\frac{\Gamma^s_{22}}{2} \end{pmatrix} \cdot \begin{pmatrix} B^0_s \\ \overline{B}^0_s \end{pmatrix}$$

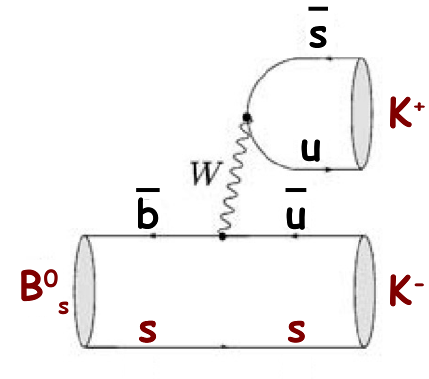
- **solution yields mass eigenstates (=** particles that propagate in vacuum**):**

$$|B_{s,L}\rangle = p\,|B^0_s\rangle + q\,|\overline{B}^0_s\rangle \qquad |B_{s,H}\rangle = p\,|B^0_s\rangle - q\,|\overline{B}^0_s\rangle$$

- **CP violation due to interference of Γ_{12} and M_{12} if $\phi^s_M = \arg\left(-M^s_{12}/\Gamma^s_{12}\right) \neq 0$**
  - **results in $|q/p| \neq 1$: mass eigenstates are not CP eigenstates**
  - **different transition rates for $B^0_s \rightarrow \overline{B}^0_s$ and $\overline{B}^0_s \rightarrow B^0_s$**
- **New Physics can enter through heavy new particles in box and affect ϕ^s_M**

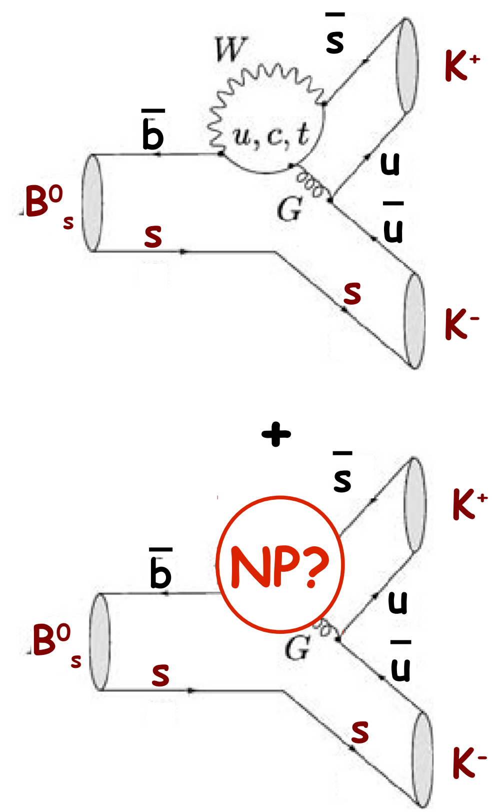
Sources of CP violation (II)

<u>CP violation in decay</u> ("direct" CP violation)



- due to interference of decay diagrams with different weak and strong phases
- causes different decay amplitudes for a process and its CP conjugate: $\left|\bar{A}_{\bar{f}}/A_f\right| \neq 1$
- measure time-integrated decay rate asymmetry

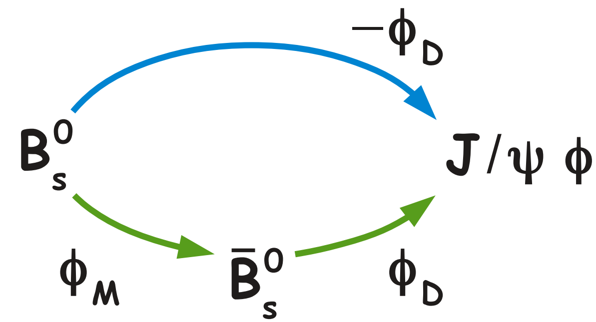
$$A_{\pm} = \frac{\Gamma(B^- \to f) - \Gamma(B^+ \to \bar{f})}{\Gamma(B^- \to f) + \Gamma(B^+ \to \bar{f})} \neq 0$$



- interfering amplitudes usually involve Penguin diagrams
  - New Physics can then enter through new heavy particles in Penguin loops
- challenge: disentangle weak phase from strong phase

Sources of CP violation (III)

CP violation due to the interferenc of mixing and decay



- if final state f accessible to both B^0_s and B^0_s:

  CP violated due to interference between direct decay and decay after mixing if

$$\mathrm{Im}\left(\frac{\bar{A}_f}{A_f}\cdot\frac{q}{p}\right) \neq 0$$

- measure time-dependent decay rate asymmetry:

$$A_{CP}(t) = \frac{\Gamma(B^0_s(t=0)\to f(t)) - \Gamma(\bar{B}^0_s(t=0)\to f(t))}{\Gamma(B^0_s(t=0)\to f(t)) + \Gamma(\bar{B}^0_s(t=0)\to f(t))} = \underbrace{S\sin(\Delta m_s t) + C\cos(\Delta m_s t)}_{\Delta m_s = m(B_{s,H}) - m(B_{s,L})}$$

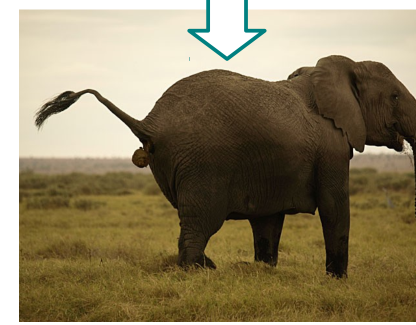
- most prominent example pre-LHCb:

  measurement of CKM angle 2β in $B^0 \to J/\psi\ K^0_s$ by Babar and Belle

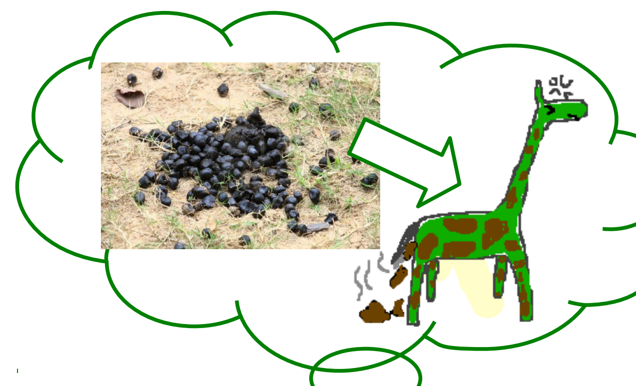
- NP can change phase of mixing (box diagram) and decay (if penguin)

- n.b. CP can be violated in this case even if $|q/p| = 1$ and $|\bar{A}_f/A_f| = 1$

CP Why?olation



- New Physics models usually predict new heavy particles
  - these can enter in <u>internal loops</u> (Box diagrams and Penguins), lead to sizeable modification of CP phases
- the comparison of <u>precise measurements</u> of CP phases with <u>precise predictions</u> from Standard Model can therefore reveal the presence of New Physics
- these <u>indirect searches</u> for New Physics make use of the appearance of virtual particles in loop diagrams
- are therefore sensitive to <u>higher mass scales</u> than direct searches for new particles

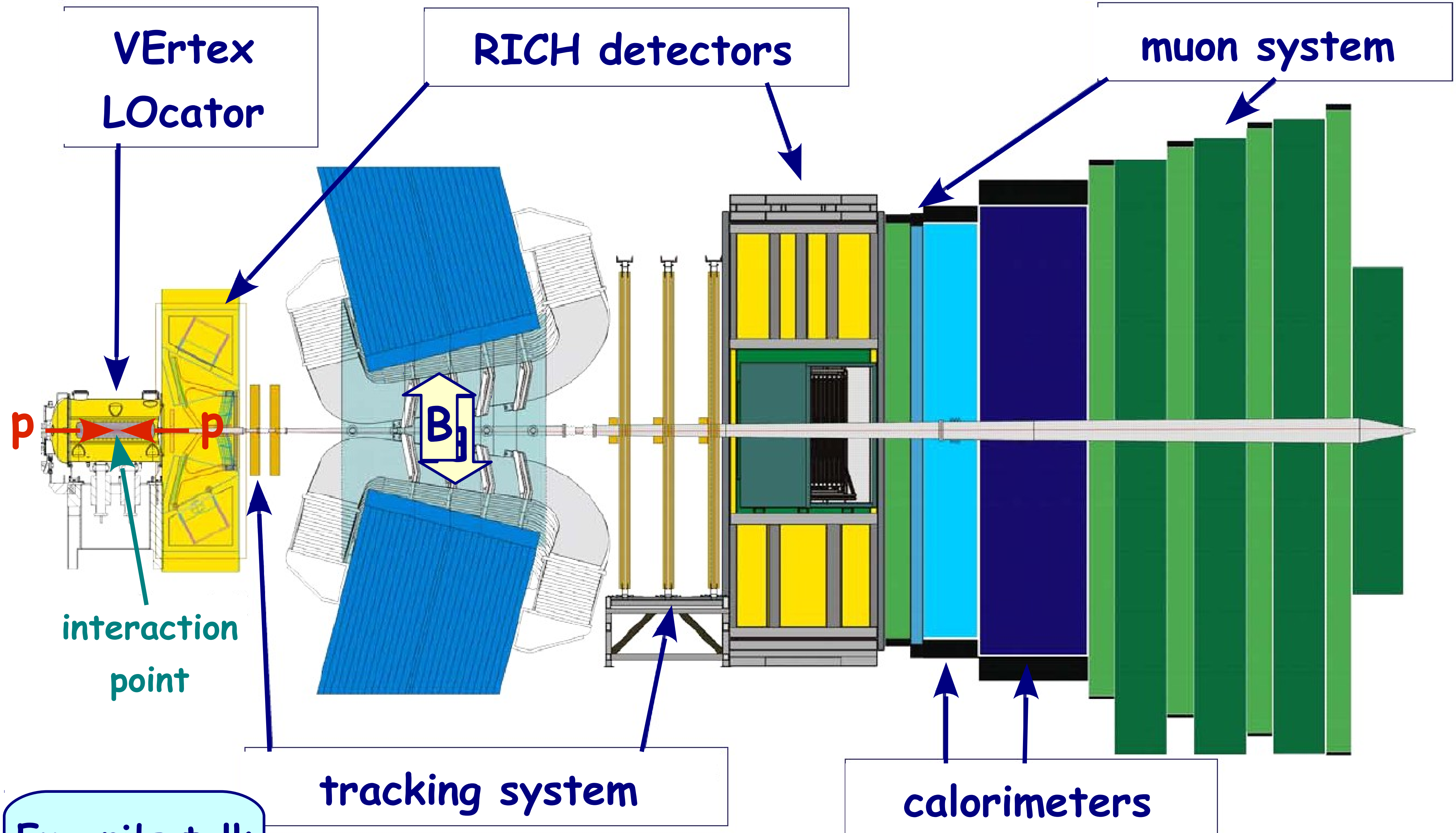


classic example: CP violation in $K^0\overline{K}^0$ (1964)

→ prediction of 3rd quark family (top direct discovery 1995)

- moreover, the <u>pattern of observed deviations</u> can hint at the <u>structure of the New Physics</u> at work

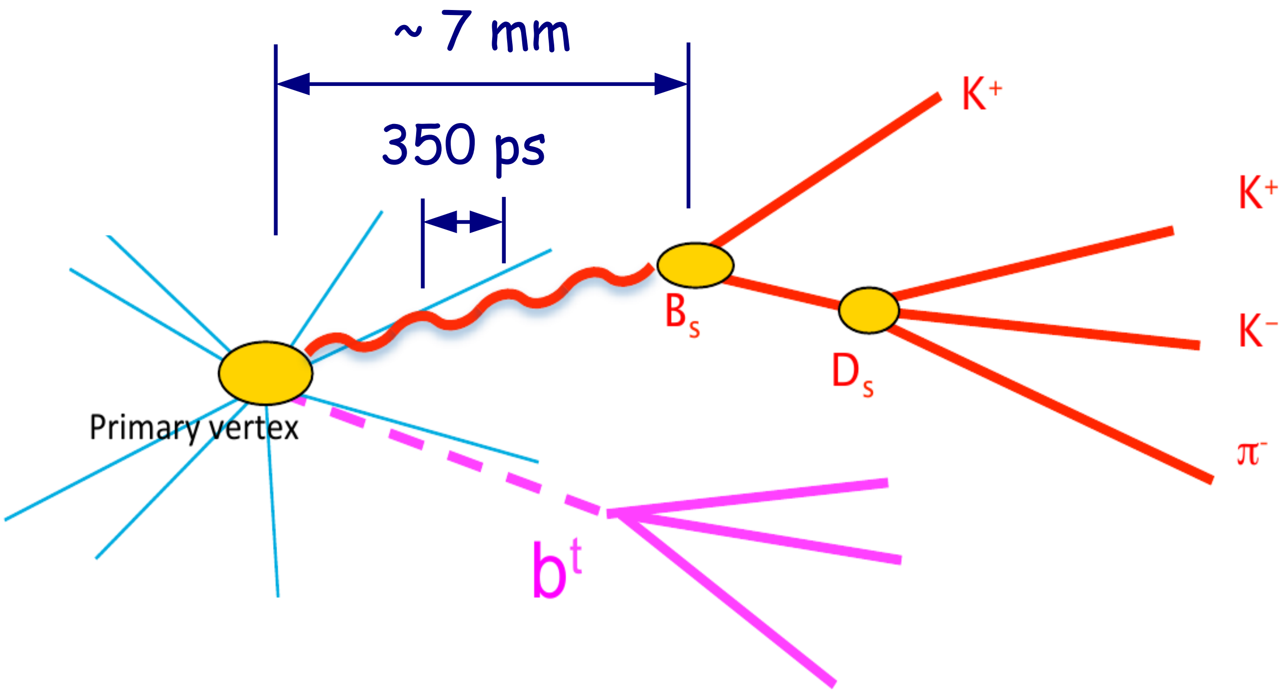
LHCb Apparatus



Eugeni's talk on Tuesday

[The LHCb Detector at the LHC, JINST 3 (2008) S08005]

Key Features

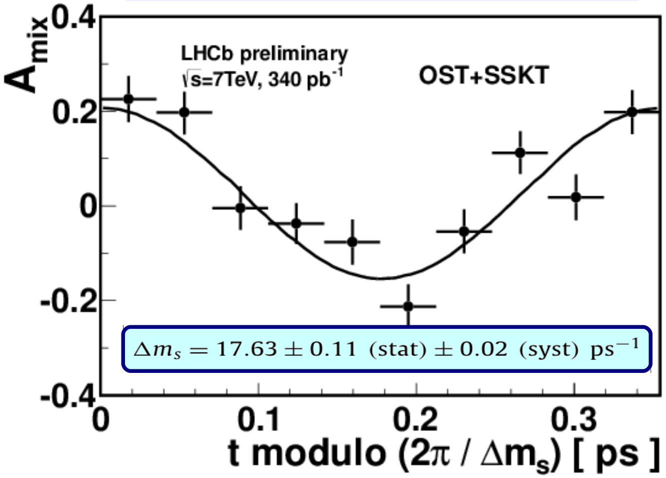


"B mesons are the elephants of the particle zoo – they are heavy and they live long."
(T. Schietinger)

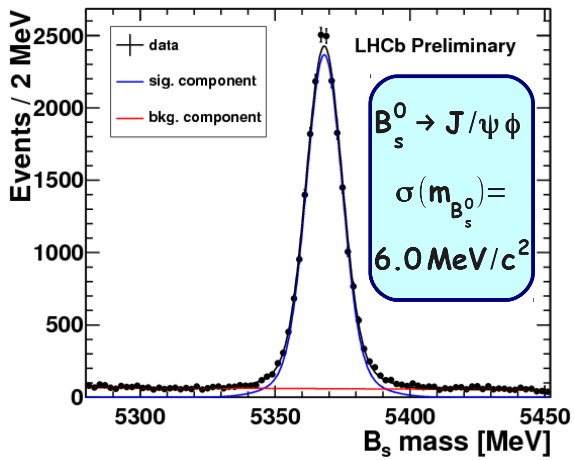
- **impact parameter resolution**
  - identify secondary vertices
- **proper time resolution**
  - resolve fast B^0_s-$\overline{B}^0_s$ oscillations
- **momentum, invariant mass resolution**
  - against combinatorial backgrounds
- **K/π separation**
  - against peaking backgrounds
  - flavour tagging
- **selective and efficient trigger, also for hadronic final states**
- **magnetic field reversed regularly to cancel detector asymmetries**

Key Features

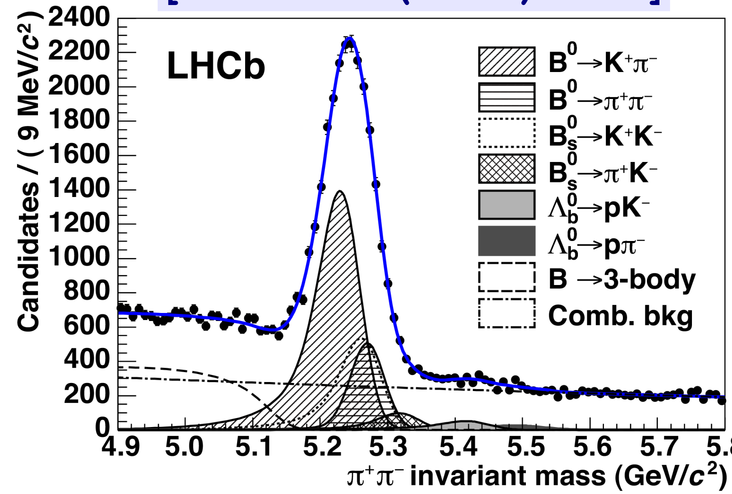
[LHCb-CONF-2011-050]



[LHCb-CONF-2012-002]



[JHEP 10 (2012) 037]



- **impact parameter resolution**
  - identify secondary vertices
- **proper time resolution**
  - resolve fast B^0_s-$\overline{B}^0_s$ oscillations
- **momentum, invariant mass resolution**
  - against combinatorial backgrounds
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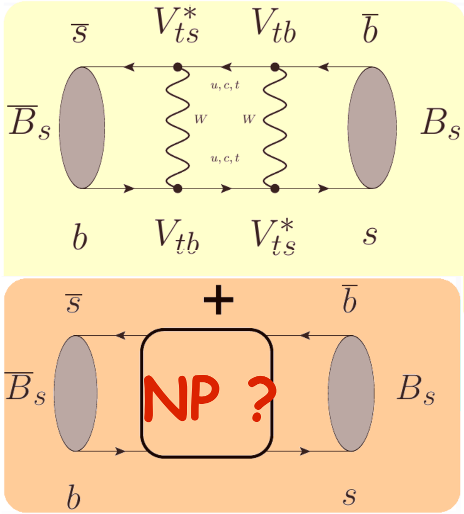
Overview

- Short introduction ✔
- CP violation in $B^0_s \overline{B}^0_s$ mixing from semileptonic decays
- CP phase ϕ_s from $B^0_s \rightarrow J/\psi\, \phi$ and $B^0_s \rightarrow J/\psi\, \pi^+\pi^-$
- CKM phase γ from $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D\pi^\pm$ Tree decays
- CP violation in charmless B decays ("γ from loops")
- Summary and outlook: LHCb upgrade

CP violation in B^0_s-$\overline{B}^0_s$ mixing

Semileptonic Asymmetry



- remember, CP violated in B^0_s-$\bar{B}^0_s$ mixing if

$$\phi_M = \arg\left(-M^s_{12} / \Gamma^s_{12}\right) \neq 0$$

- can be measured in semileptonic decay asymmetry

$$a^s_{sl} = \frac{\Gamma(B^0_s \to D^-_s \mu^+ X) - \Gamma(\bar{B}^0_s \to D^+_s \mu^- X)}{\Gamma(B^0_s \to D^-_s \mu^+ X) + \Gamma(\bar{B}^0_s \to D^+_s \mu^- X)} = \frac{\Delta\Gamma_s}{\Delta m_s} \tan\phi_M$$

($\Delta\Gamma_s$, Δm_s: lifetime and mass difference between the two mass eigenstates)

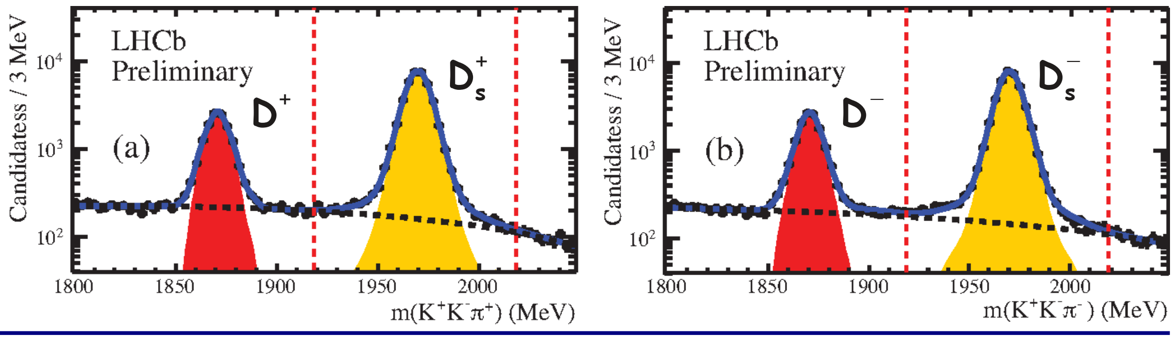
- predicted to be very small in Standard Model

$$a^s_{sl} = (1.9 \pm 0.3) \times 10^{-5}$$

[A.Lenz, arXiv:1205.1444]

- very sensitive to possible New Physics contributions in box diagram
- LHCb analyis of 1.0 fb^{-1}
  - 193k signal events
  - very low backgrounds

[LHCb-CONF-2012-022]



Semileptonic Asymmetry

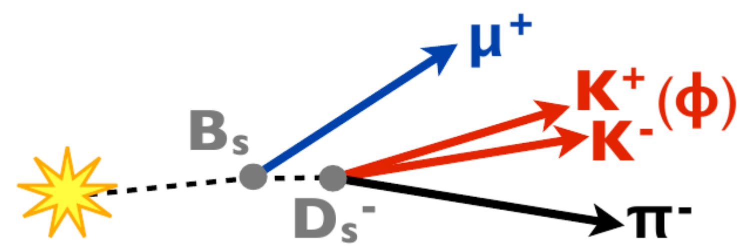
- LHC collides protons on protons
  - $B^0_s \bar{B}^0_s$ production asymmetry, $a_p \sim 1$ %

so B^0_s mesons are NOT like elephants – they forget !

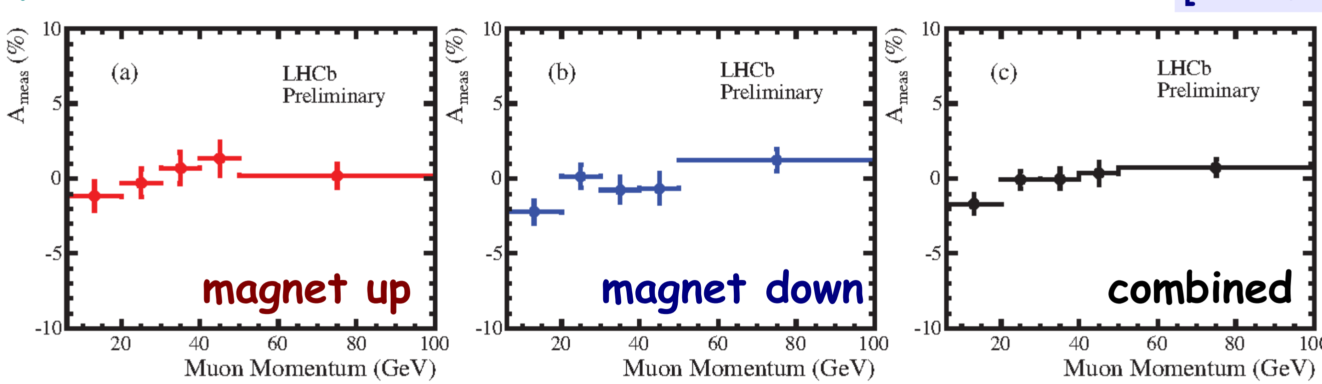
- but: a_p steongly diluted by the very rapid B^0_s-$\bar{B}^0_s$ oscillation

$$A_{raw} = \frac{N(D_s^-\mu^+)-N(D_s^+\mu^-)}{N(D_s^-\mu^+)+N(D_s^+\mu^-)} = \frac{a_{sl}^s}{2} + \left[a_p - \frac{a_{sl}^s}{2}\right] \times \underbrace{\frac{\int e^{-\Gamma_s t}\cos(\Delta m_s t)\,\varepsilon(t)\,dt}{\int e^{-\Gamma_s t}\cosh(\Delta\Gamma_s t/2)\,\varepsilon(t)\,dt}}_{=2\times 10^{-3}\ \text{for LHCb acceptance}\ \varepsilon(t)}$$

- detection asymmetries: measured from data using various control channels
- also: look at data separately for the two magnet polarities



[LHCb-CONF-2012-022]



Semileptonic Asymmetry

- LHCb result

$$a^s_{sl} = \left(-0.24 \pm 0.54\,(\text{stat}) \pm 0.33\,(\text{syst})\right)\,\%$$

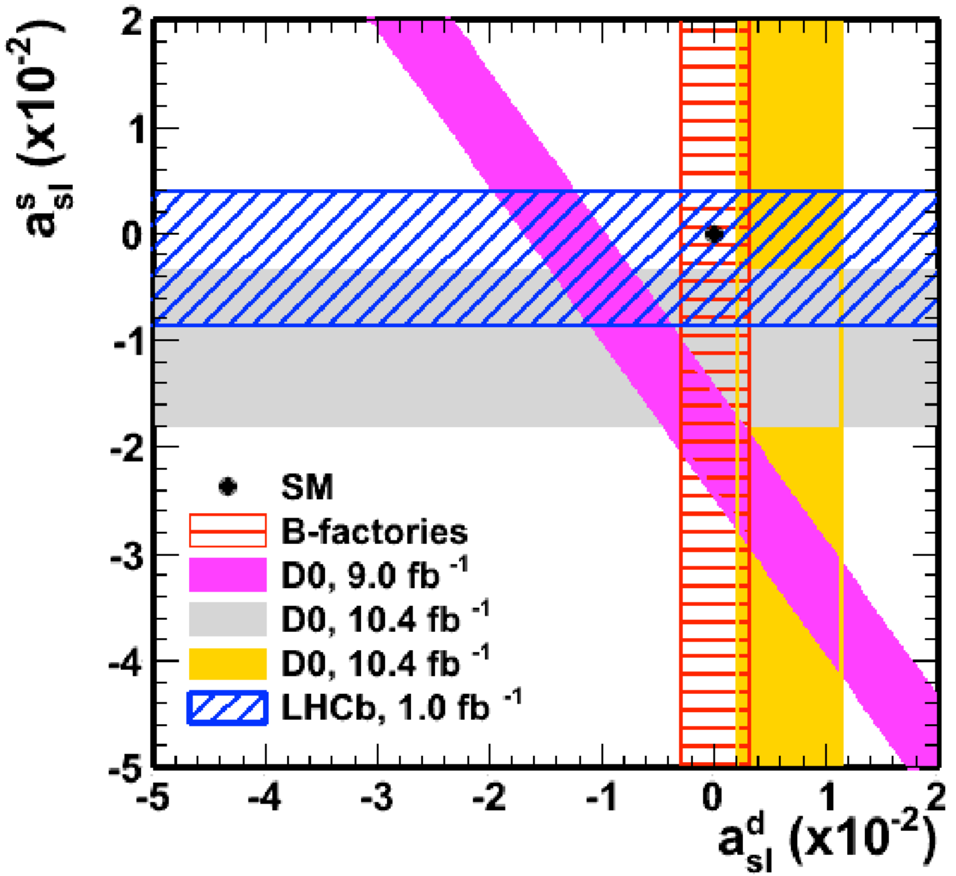
[LHCb-CONF-2012-022]
preliminary

- most precise measurement to date
- consistent with Standard Model
- remember: D0 reports 2.9 σ deviation from Standard Model in measurement of like-sign dimuon asymmetry

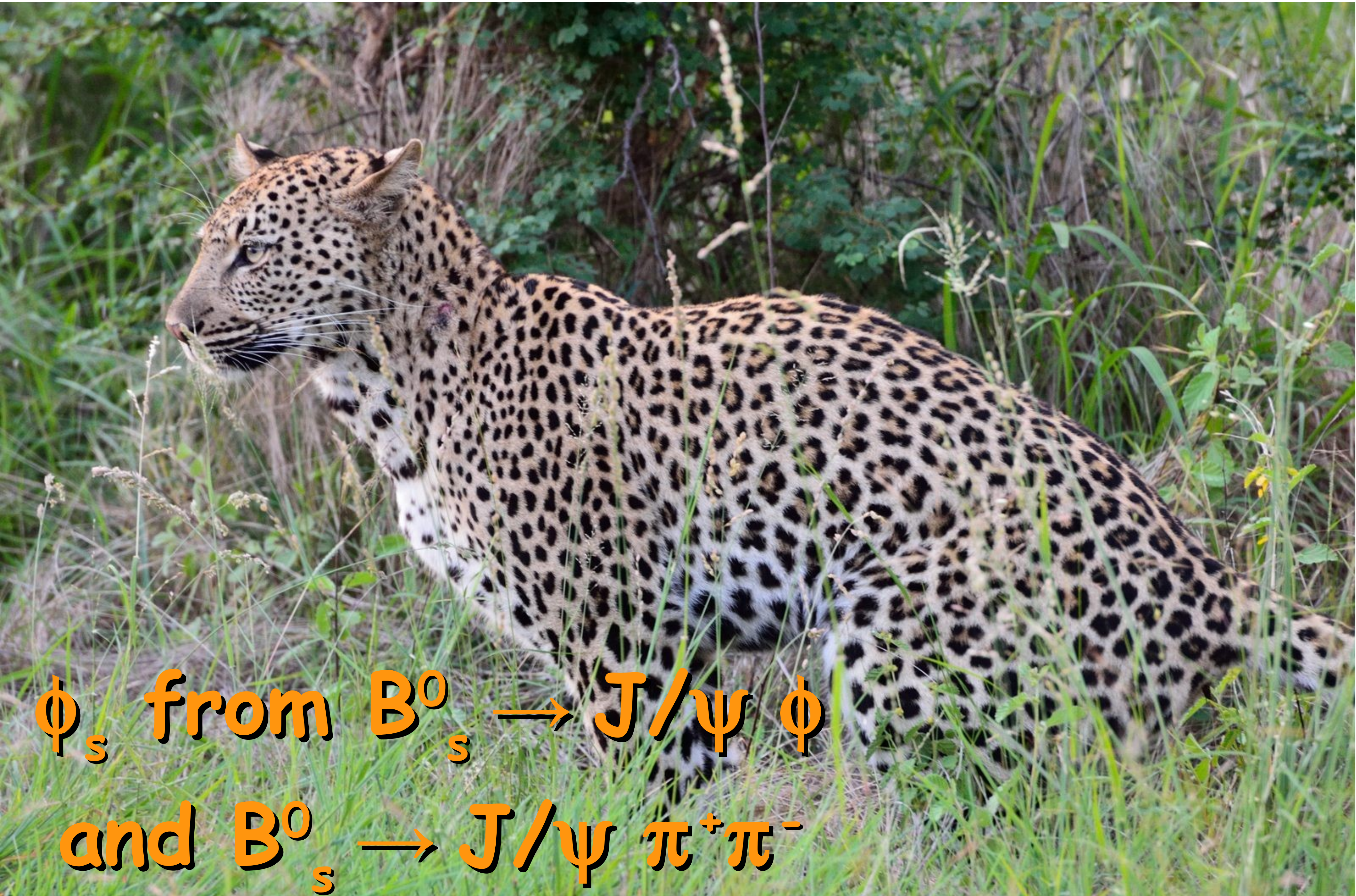
$$A_{\mu\mu} = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} \approx 0.6\, a^s_{sl} + 0.4\, a^d_{sl}$$

for D0

[D0 collaboration, arXiv:1208.5813]

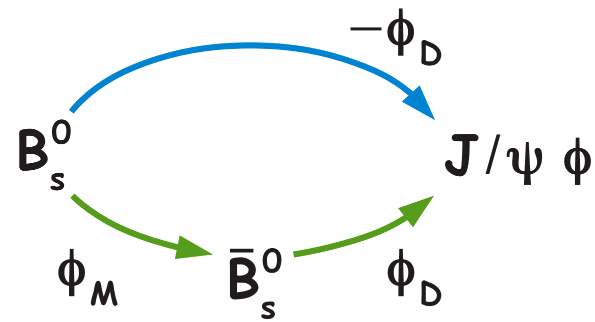


- LHCb and D0 results compatible with each other at < 2 σ level


ϕ_s from $B^0_s \rightarrow J/\psi\ \phi$
and $B^0_s \rightarrow J/\psi\ \pi^+\pi^-$

CP violation in $B^0_s \to J/\psi\,\phi$

- example for CP violation in interference between mixing and decay
- CP violating phase



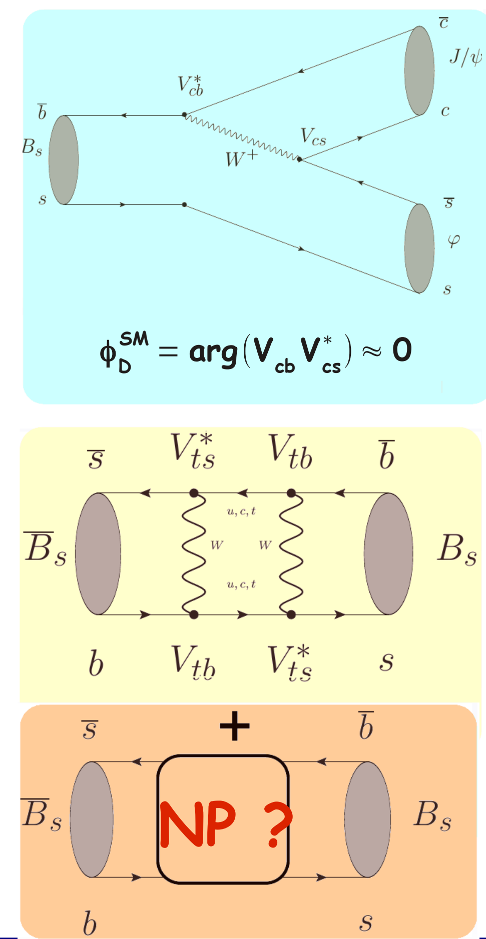
$$\phi_s = \phi_M - 2\phi_D$$

- ϕ_s predicted to be very small in Standard Model
  - B^0_s-B^0_s mixing phase ϕ_M expected to be very small
  - decay dominated by Tree diagram with ϕ_D ~ 0, only small contamination from Penguin

$$\phi_s = 0.036 \pm 0.002 \text{ rad}$$

[Phys.Rev.D 84 (2011) 033005]

- highly sensitive to New Physics contributions in B^0_s-$\bar{B}^0_s$ mixing



CP violation in $B^0_s \to J/\psi\, \phi$

- time-dependent CP asymmetry for CP eigenstate f with eigenvalue $\eta_f = \pm 1$

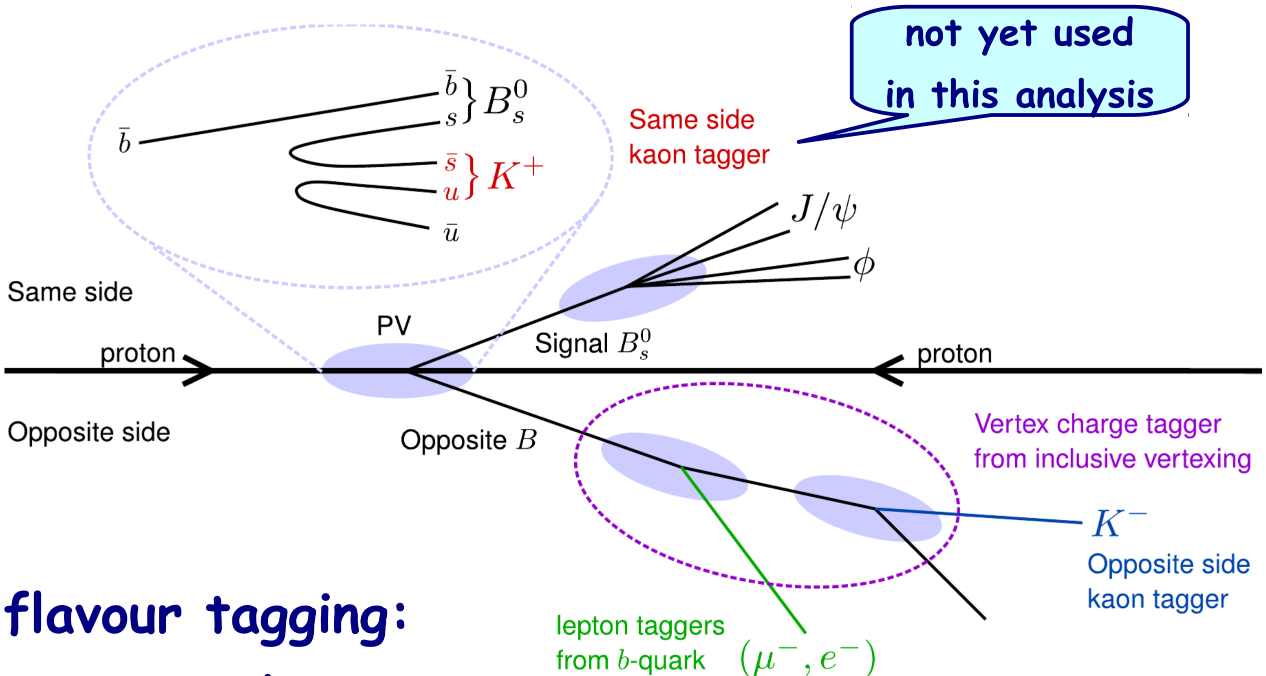
$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0_s(t=0) \to f) - \Gamma(B^0_s(t=0) \to f)}{\Gamma(\bar{B}^0_s(t=0) \to f) + \Gamma(B^0_s(t=0) \to f)} = \eta_f \boxed{\sin\phi_s} \sin(\Delta m_s t)$$

- need to determine flavour of B_s meson at t=0 → mis-tag fraction $\boxed{\omega_{tag}}$
- need to resolve B^0_s-$\bar{B}^0_s$ oscillations → finite proper time resolution $\boxed{\sigma_t}$

$$A_{CP}(t) \approx (1 - \boxed{2\omega_{tag}})\, e^{-\frac{1}{2}\Delta m_s^2 \boxed{\sigma_t^2}}\, \eta_f \boxed{\sin\phi_s} \sin(\Delta m_s t)$$

- final state in $B^0_s \to J/\psi\, \phi$ is a mix of CP even and odd ($L_{J/\psi\, \phi}$ = 0,1,2)
  - three polarisation amplitudes, plus contribution from S-wave K^+K^-
  - time-dependent angular analysis to disentangle these and determine ϕ_s
- finite lifetime difference $\Delta\Gamma_s$ between CP eigenstates in $B^0_s\bar{B}^0_s$ system
  - not well measured yet, needs to be determined simultaneously with ϕ_s

CP violation in $B^0_s \to J/\psi\ \phi$



- opposite-side flavour tagging: imply B^0_s flavour at production from decay properties of the associated b hadron produced
  - neural net algorithm using charge of lepton, kaon, inclusive vertex
- calibrated on flavour-specific decays such as $B^\pm \to J/\psi\ K^\pm$
- effective tagging power:

$$\varepsilon_{tag} \times (1 - 2\,\overline{\omega}_{tag})^2 = (2.35 \pm 0.06(stat))\ \%$$

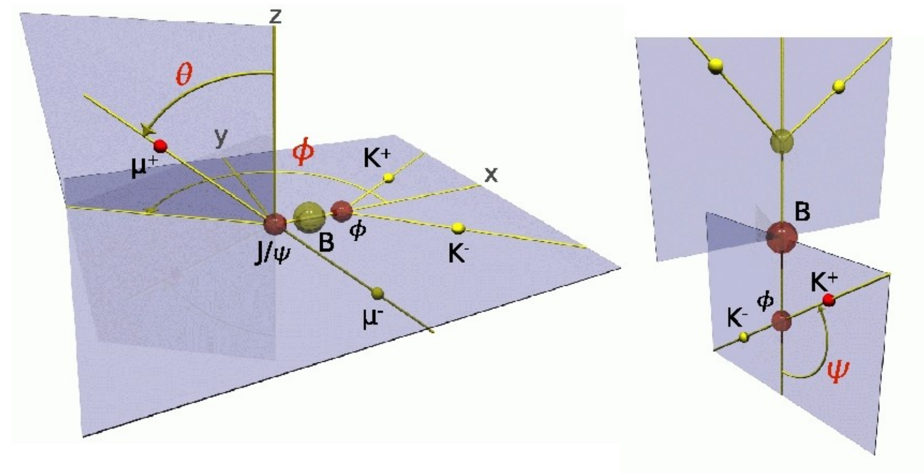
[LHCb-CONF-2012-026] preliminary

- same-side tagging (charge of $K^\pm$ from hadronisation chain) not yet used

CP violation in $B^0_s \to J/\psi\,\phi$

- time-dependent angular fit using transversity angles

  $\Omega = (\theta=\theta_\mu,\ \phi=\phi_\mu,\ \psi=\theta_K)$



- full fit function:

$$\frac{\mathrm{d}^4\Gamma(B^0_s \to J/\psi\,\phi)}{\mathrm{d}t\ \mathrm{d}\Omega} \propto \sum_{k=1}^{10} h_k(t)\ f_k(\Omega)$$

$$h_k(t) = N_k e^{-Gt}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

k	$f_k(\theta_\mu, \theta_K, \phi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\cos^2\phi_h\right)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\sin^2\phi_h\right)$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K\sin^2\theta_\mu\sin 2\phi_h$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\cos\phi_h$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\sin\phi_h$	$\lvert A_0(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_s(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\cos\phi_h$	$\lvert A_s(0)A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\sin\phi_h$	$\lvert A_s(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K\sin^2\theta_\mu$	$\lvert A_s(0)A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

- physics parameters:

$$S \approx -\sin\phi_s\ ;\ D \approx -\cos\phi_s\ ;\ \Delta m_s\ ;\ \Delta\Gamma_s\ ;\ \lvert A_\perp\rvert\ ;\ \lvert A_\parallel\rvert\ ;\ \lvert A_0\rvert\ ;\ \delta_\perp\ ;\ \delta_\parallel\ ;\ \delta_0$$

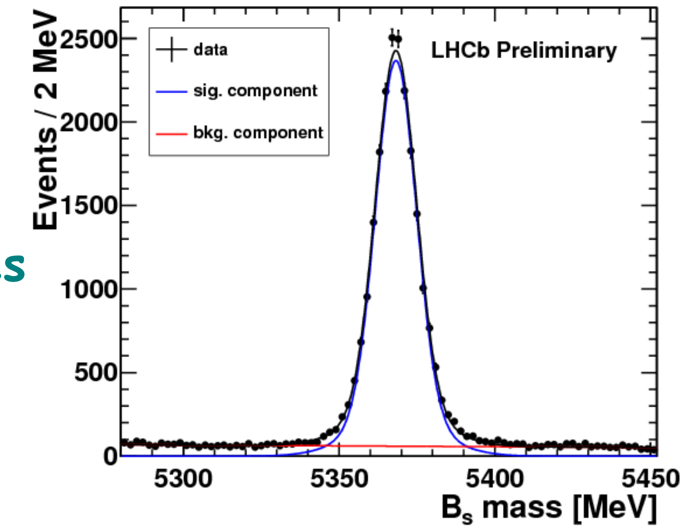
- two-fold ambiguity in solution: fit function invariant under transformation

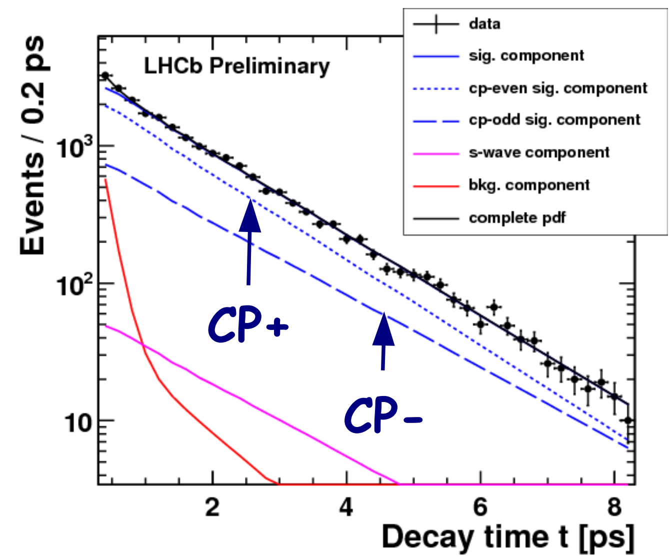
$$(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_\parallel, -\delta_\perp)$$

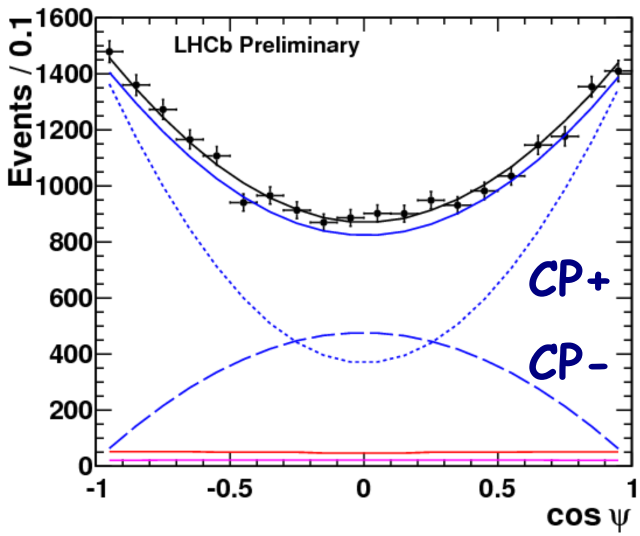
CP violation in $B^0_s \to J/\psi\ \phi$

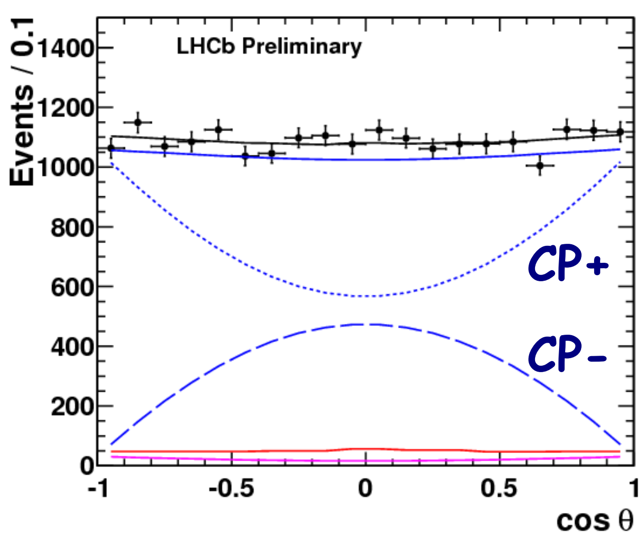
[LHCb-CONF-2012-002]

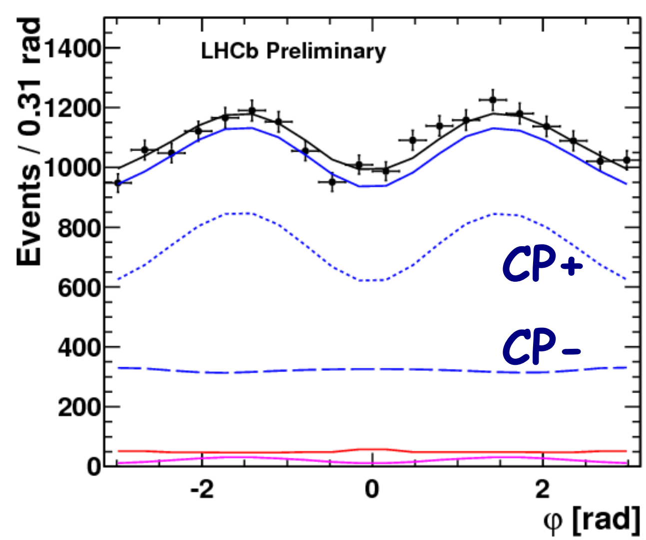
- LHCb analysis based on 1.0 fb^{-1}
- 21k signal events
  - world's largest sample
- only few % background
- angular fit cleanly separates CP even/odd components
- different lifetimes clearly visible in fit projection



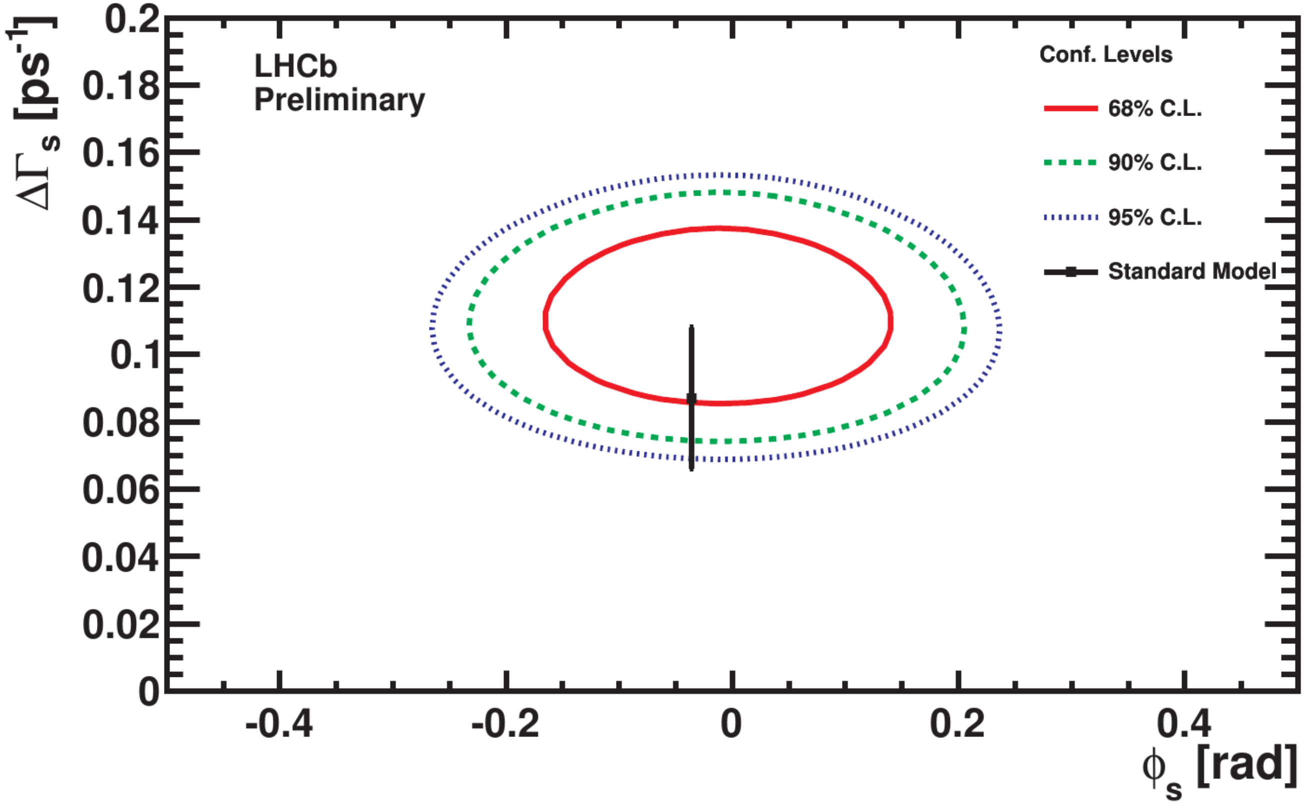








CP violation in $B^0_s \to J/\psi\ \phi$



- result consistent with Standard Model prediction

$$\phi_s = -0.001 \pm 0.101(\text{stat}) \pm 0.027(\text{syst})\ \text{rad}$$

[LHCb-CONF-2012-002]
preliminary

- first observation (> 5 σ significance) of $\Delta\Gamma_s \neq 0$

$$\Delta\Gamma_s = 0.116 \pm 0.018(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1}$$

- both results dominated by statistical uncertainties

Sign of $\Delta\Gamma_s$

- resolve two-fold ambiguity

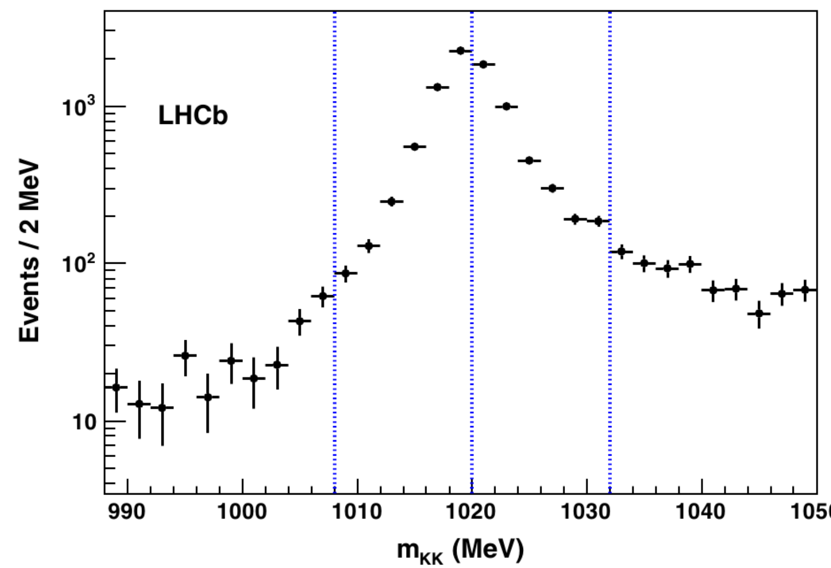
[PRL 108 (2012) 241801]

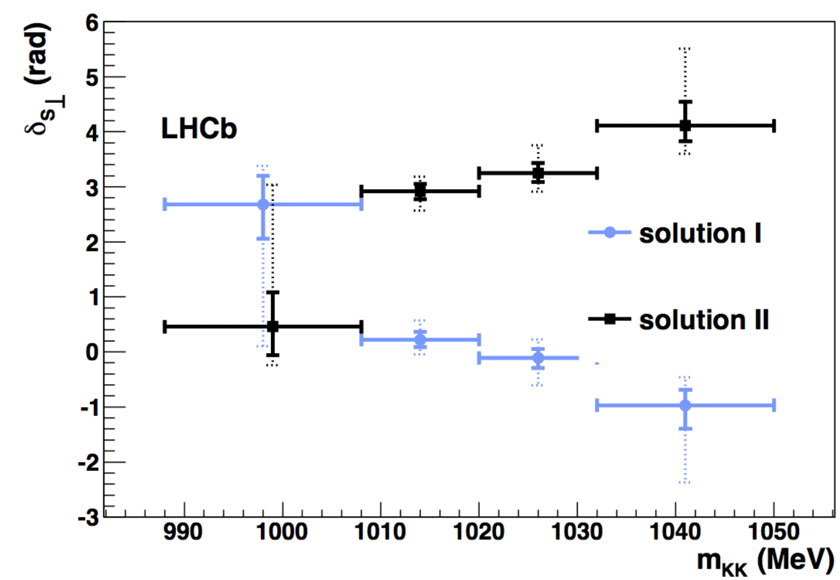
$$(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_\parallel, -\delta_\perp)$$

("solution I") ("solution II")

looking at strong phase difference $\delta_{s\perp} = \delta_s - \delta_\perp$ between K^+K^- P-wave and S-wave amplitudes as a function of $m(K^+K^-)$ around the $\phi(1020)$

- P-wave: going through $\phi(1020)$ resonance
  → expect rapid positive phase shift
- S-wave: non-resonant + tail from $f_0(980)$
  → expect no significant variation of phase

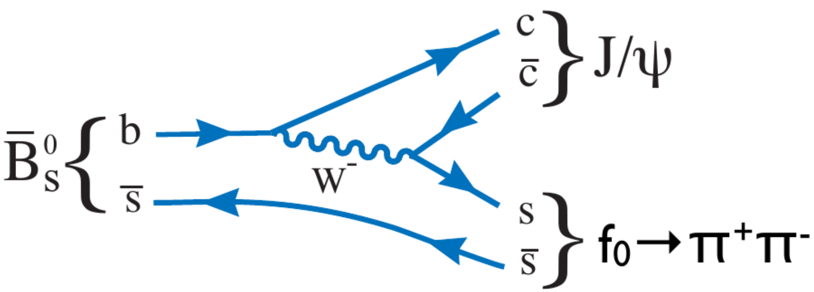




- LHCb analysis based on 0.37 fb^{-1}
  - determine $\delta_{s\perp}$ in four K^+K^- mass bins

solution corresponding to $\Delta\Gamma_s > 0$
selected with 4.7 σ significance

ϕ_s from $B^0_s \to J/\psi\, \pi^+\pi^-$

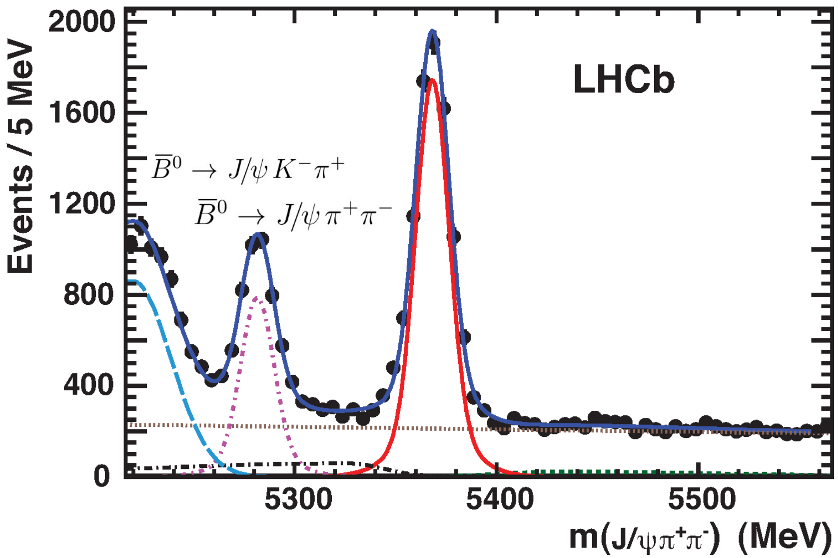


- dominated by $f_0(980) \to \pi^+\pi^-$
- from modified Dalitz-plot analysis:

> 99.7 % CP odd at 95 % C.L.
> in $775 < m(\pi^+\pi^-) < 1550$ MeV/c²

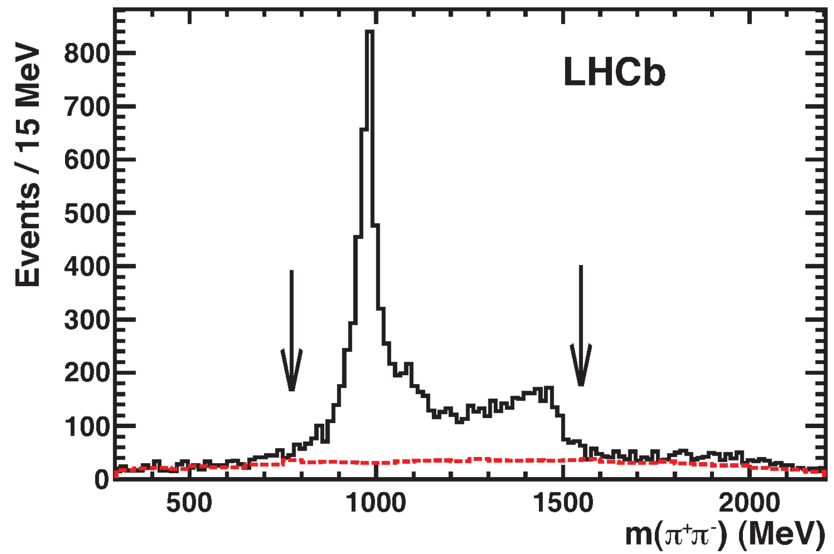
[arxiv 1204.5643]

[arxiv 1204.5675]



- ϕ_s measurement in $B^0_s \to J/\psi\, \pi^+\pi^-$ based on ~7400 candidates from 1.0 fb⁻¹
  - lower BF than $B^0_s \to J/\psi\, \phi$
  - but no angular analysis required

$$\phi_s = -0.019\,^{+0.173}_{-0.174}\,(\text{stat})\,^{+0.004}_{-0.003}\,(\text{syst})\ \text{rad}$$



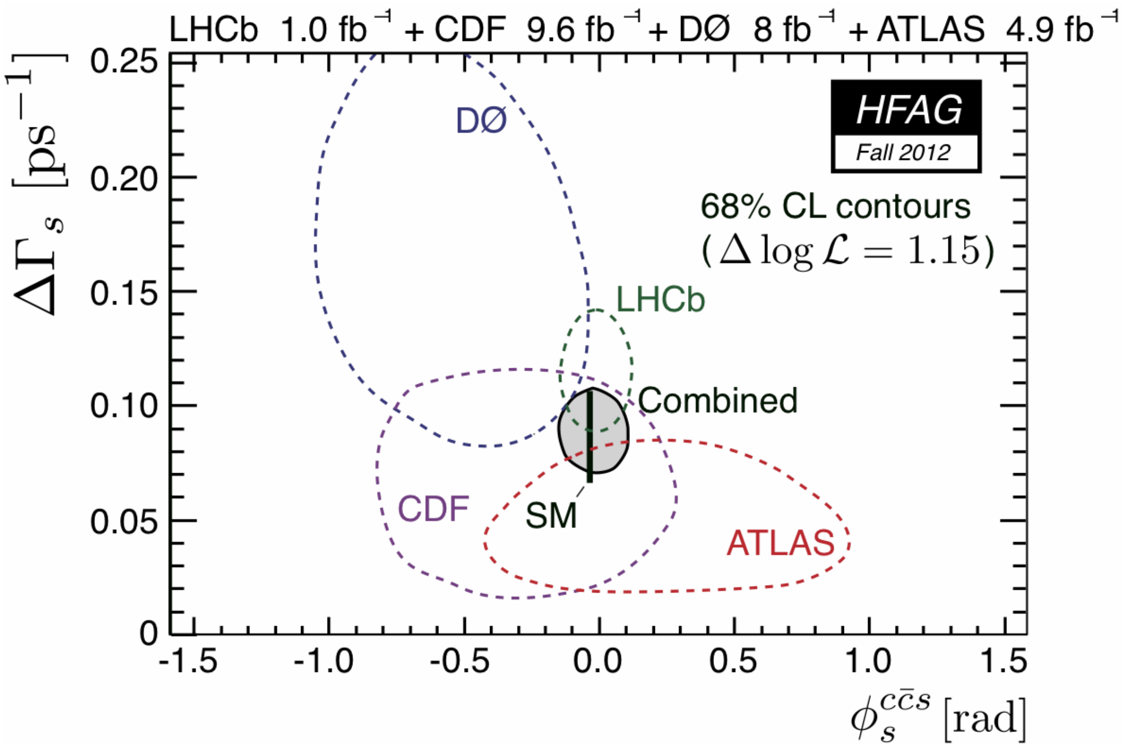
ϕ_s Combination and Comparison

- simultaneous fit of $B^0_s \to J/\psi\, \phi$ and $B^0_s \to J/\psi\, \pi^+\pi^-$

$$\phi_s = -0.002 \pm 0.083\,(\text{stat}) \pm 0.027\,(\text{syst})\ \text{rad}$$

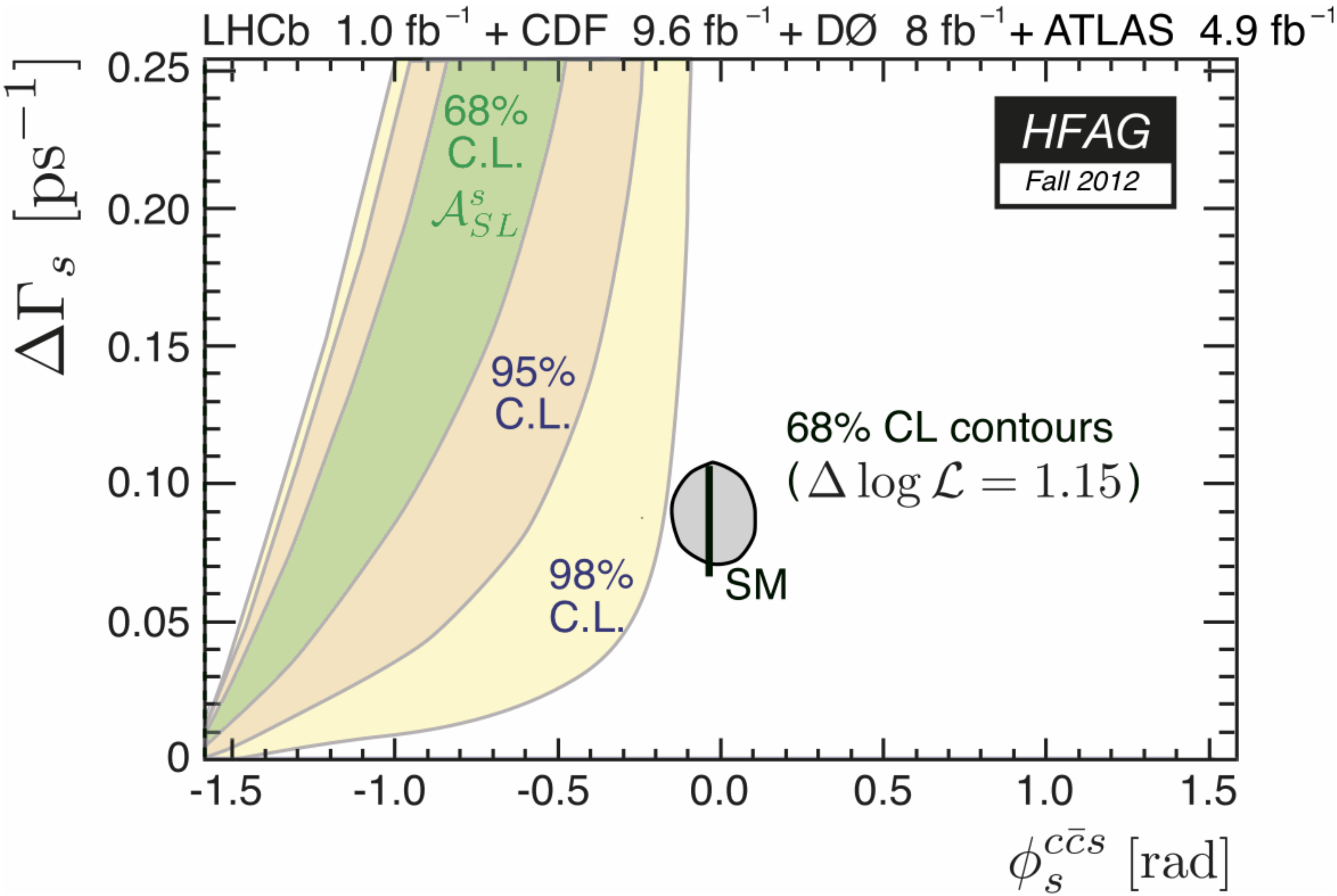
[LHCb-CONF-2012-002]
preliminary

- most precise measurement to date
- excellent agreement with Standard Model prediction
- but still space for possible contribution from New Physics
- precision completely dominated by statistical uncertainty
  - expect significant improvement with more data



ϕ_s Combination and Comparison

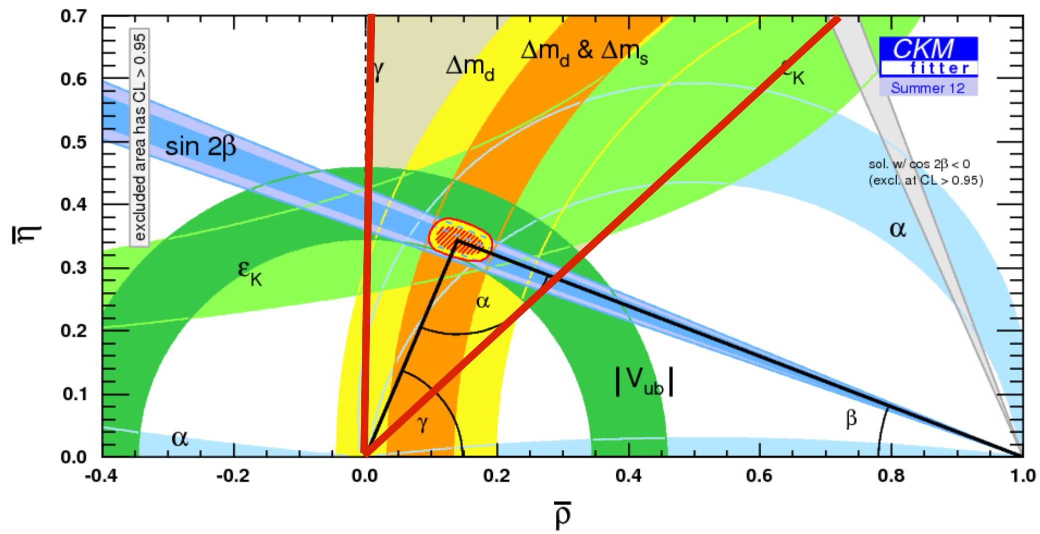
- some tension between ϕ_s measurements and dimuon asymmetry from D0




CKM angle γ
from Tree Decays

CKM angle γ from Tree Decays

- CKM fits so far a huge success story for the Standard Model
- need more precise measurements to test for subtle effects from New Physics



- least well constrained CKM parameter by direct measurement:

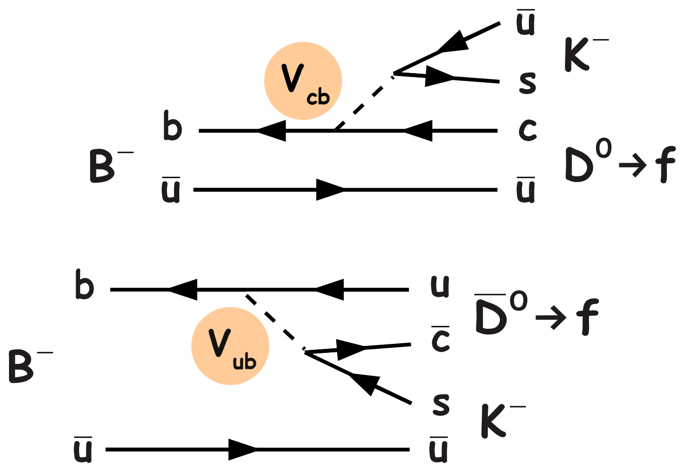
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

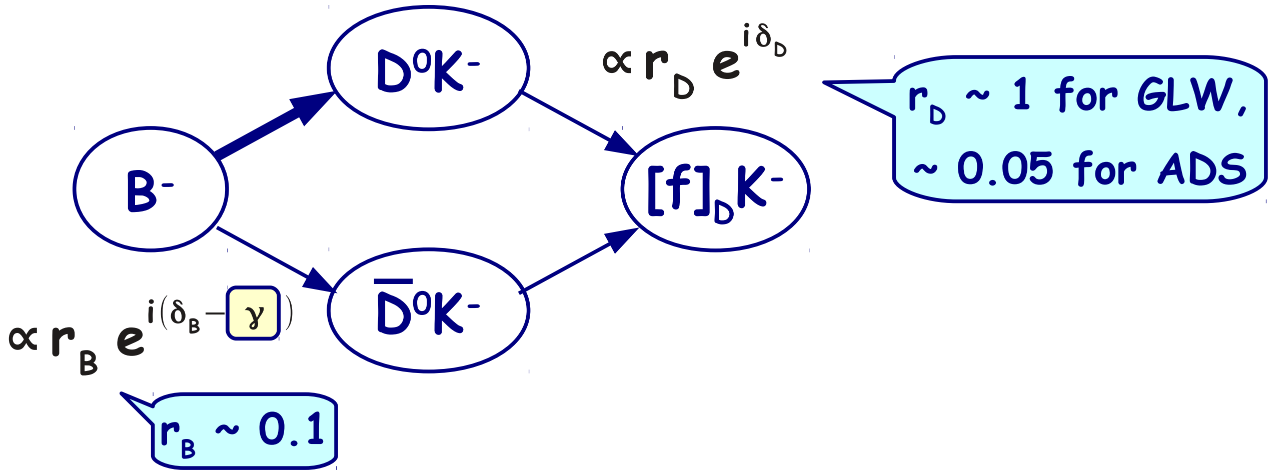
$\gamma = (66 \pm 12)^\circ$ [CKMfitter]

$\gamma = (72 \pm 9)^\circ$ [UTfit]

- Tree-level B decays: theoretically "clean" measurement of γ
  - no loops → largely unaffected by possible effects from New Physics
- but experimentally very challenging
  - purely hadronic final states (→ trigger, K/π separation)
  - small branching fractions (→ need large number of B's)

CKM angle γ from Tree Decays





- time-integrated methods: exploit interference of

$$B^\pm \to D^0K^\pm \to [f]_D\,K^\pm \quad \text{and} \quad B^\pm \to \bar{D}^0\,K^\pm \to [f]_D\,K^\pm,$$

  where final state $[f]_D$ is accessible to D^0 and $\bar{D}^0$

- GLW: CP eigenstates $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$
  [PLB 253 (1991) 483, PLB 265 (1991) 172]

- ADS: favoured $D^0 \to K^+\pi^-$ / suppressed $D^0 \to K^-\pi^+$
  [PRL 78 (1997) 257, PRD 63 (2001) 036005]

- GGSZ: Dalitz-plot analysis of 3-body $D^0 \to K^0_s\pi^+\pi^-$
  [PRD 68 (2003) 054018] [PRD 70 (2004) 072003]

combined analysis of all modes to extract γ and hadronic parameters r_B, δ_B, r_D, δ_D

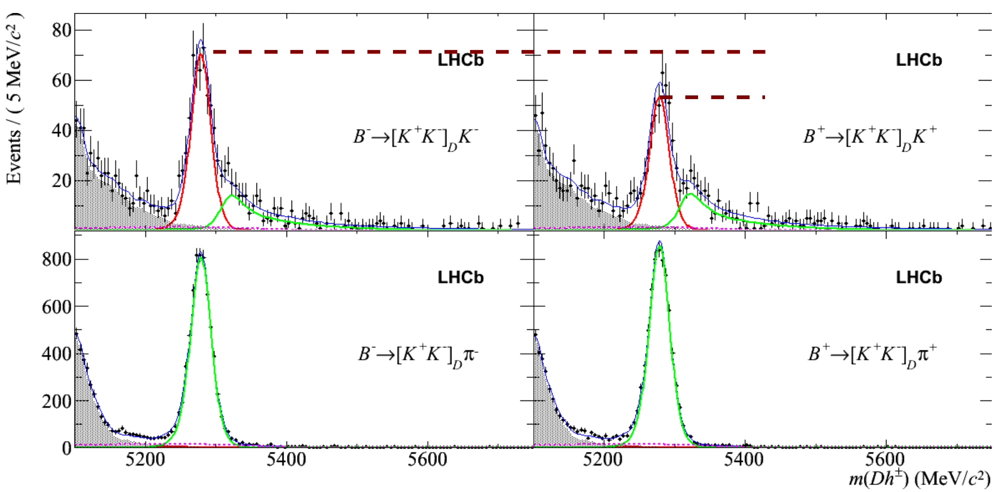
γ from Trees: GLW modes

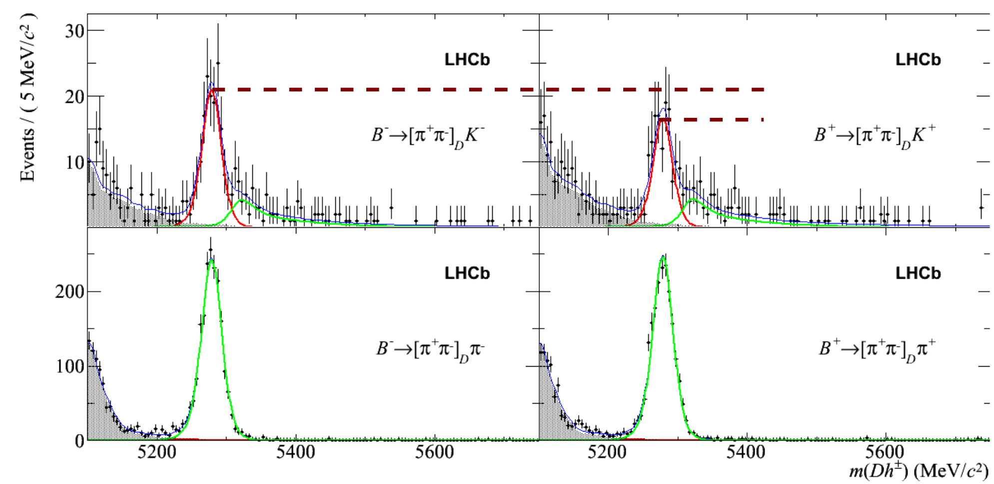
- form ratios and asymmetries of decay rates → cancellation of systematics

$$R_{CP+} = \frac{\Gamma(B^- \to [h^+h^-]_D K^-) + \Gamma(B^+ \to [h^+h^-]_D K^+)}{1/2 \cdot \left[\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)\right]} = 1 + r_B^2 + 2 \cdot r_B \cdot \cos\delta_B \cdot \cos\gamma$$

$$A_{CP+} = \frac{\Gamma(B^- \to [h^+h^-]_D K^-) - \Gamma(B^+ \to [h^+h^-]_D K^+)}{\Gamma(B^- \to [h^+h^-]_D K^-) + \Gamma(B^+ \to [h^+h^-]_D K^+)} = + \frac{2 \cdot r_B \cdot \cos\delta_B \cdot \cos\gamma}{R_{CP+}}$$

- LHCb analysis of 1.0 fb^{-1} [PLB 713 (2012) 351]
- clear asymmetry in $B^\pm \to DK^\pm$ and (as expected) no asymmetry in $B^\pm \to D\pi^\pm$





$A_{CP+}(KK) = (-14.8 \pm 3.7 \pm 1.0)\ \%$

$A_{CP+}(\pi\pi) = (-13.5 \pm 6.6 \pm 1.0)\ \%$

γ from Trees: ADS modes

- ratios and asymmetries of decay rates to flavour-specific final states

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 \cdot r_B r_D \cdot \cos(\delta_B + \delta_D) \cdot \cos\gamma$$

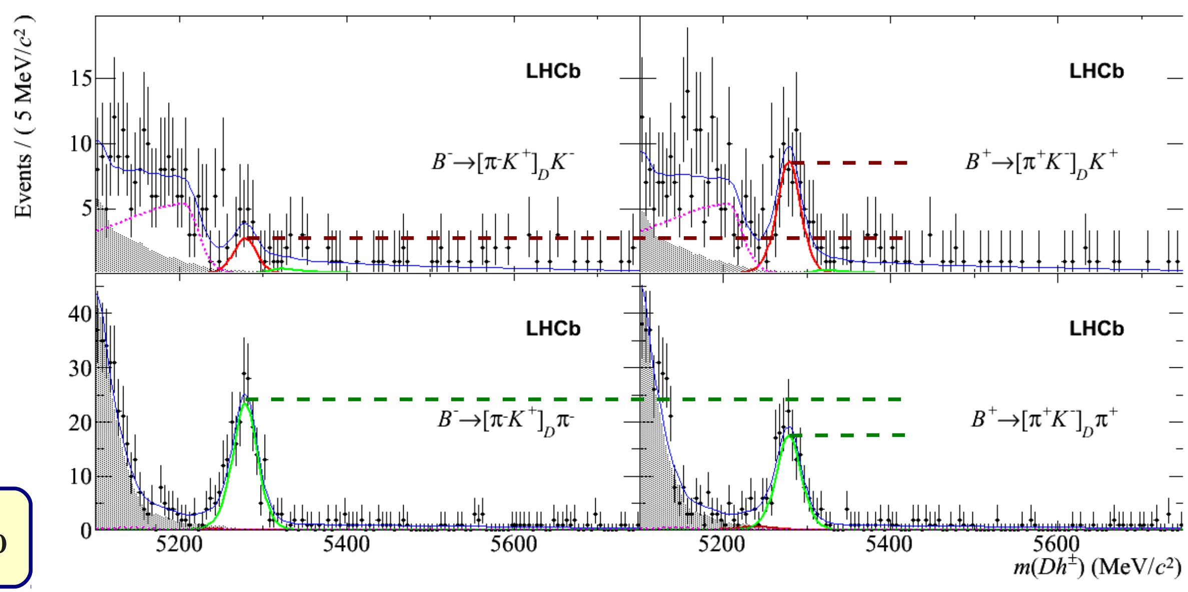
$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2 \cdot r_B r_D \cdot \sin(\delta_B + \delta_D) \cdot \sin\gamma}{R_{ADS}}$$

- LHCb analysis of 1.0 fb^{-1} [arxiv 1203.3362]
- first observation of the rare ADS decay (10 σ significance)
- evidence for asymmetry in $B^\pm \to DK^\pm$ (4 σ significance)

$$A_{ADS}(DK) = (-52 \pm 15 \pm 2)\ \%$$

- hint for asymmetry also in $B^\pm \to D\pi^\pm$ (2.4 σ significance)

$$A_{ADS}(D\pi) = (-14.3 \pm 6.2 \pm 1.1)\ \%$$



γ from Trees: $D \rightarrow \pi K \pi \pi$

- similar to 2-body ADS, but different values of r_D and δ_D
  - add statistics but also new information

[LHCb-CONF-2012-030]
preliminary

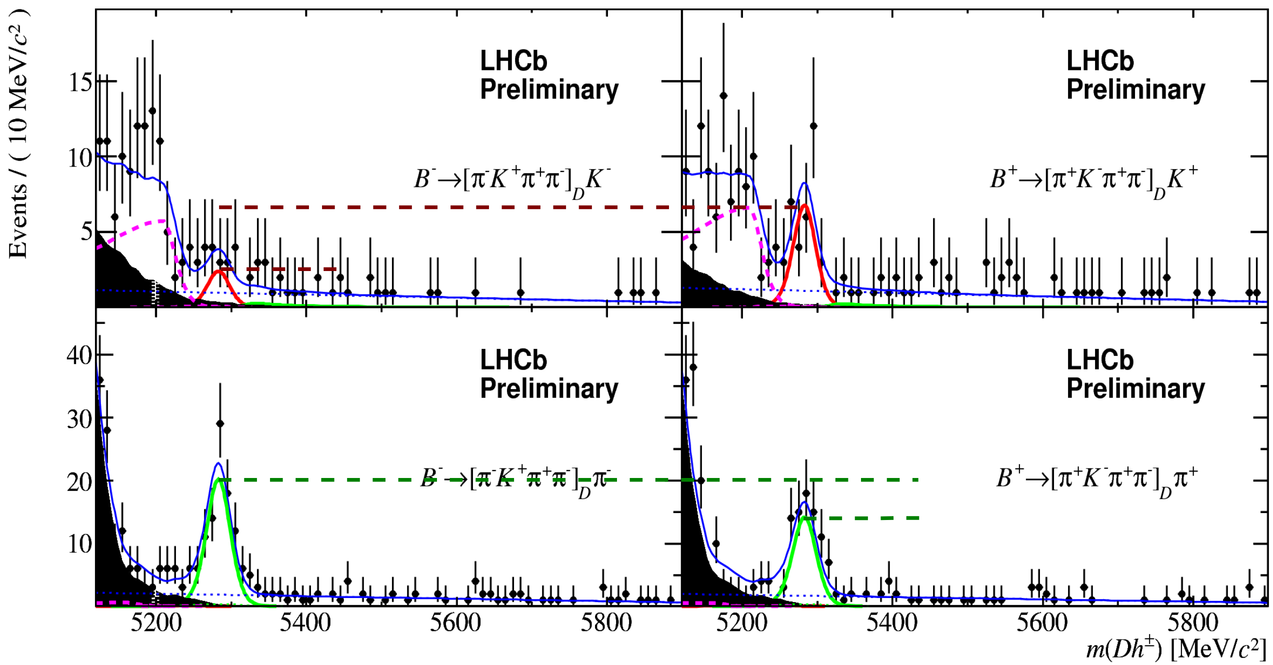
- LHCb analysis of 1.0 fb^{-1}:
- first observation of rare ADS decays (10 σ in $B^{\pm} \rightarrow D\pi^{\pm}$, 5.1 σ in $B^{\pm} \rightarrow DK^{\pm}$)

$$R_{ADS}(DK) = (1.24 \pm 0.27)\ \%$$

$$A_{ADS}(DK) = (4.2 \pm 2.2)\ \%$$

$$R_{ADS}(D\pi) = (0.369 \pm 0.036)\ \%$$

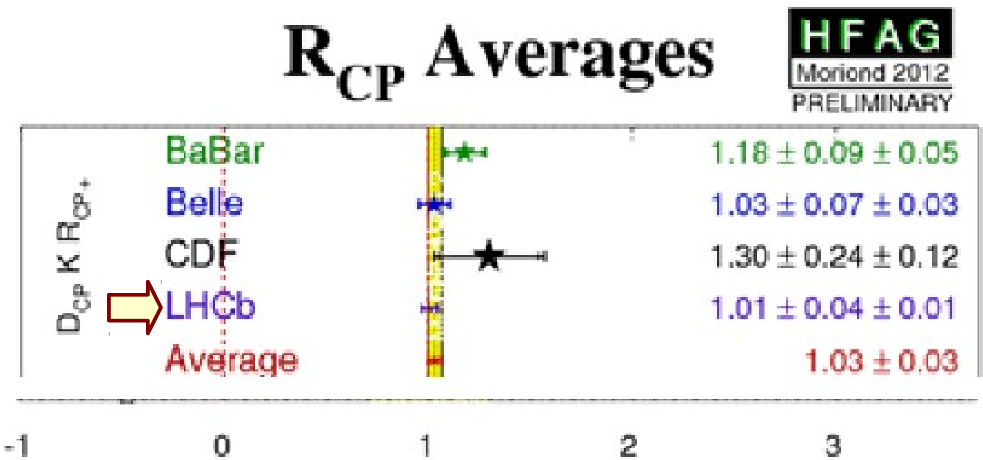
$$A_{ADS}(D\pi) = (13 \pm 10)\ \%$$

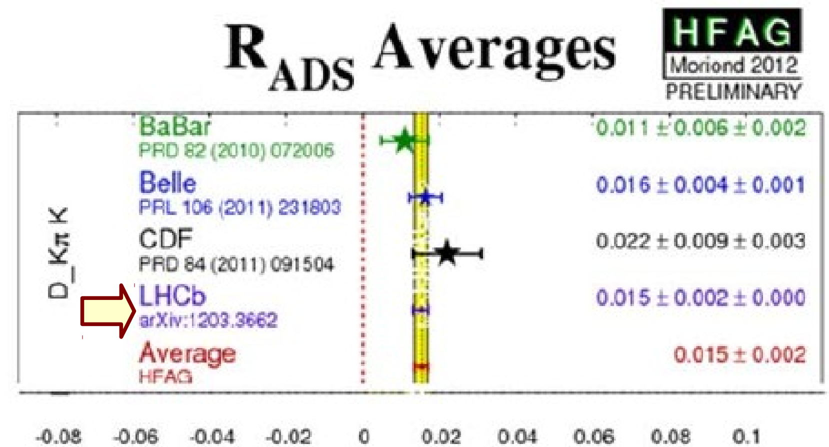


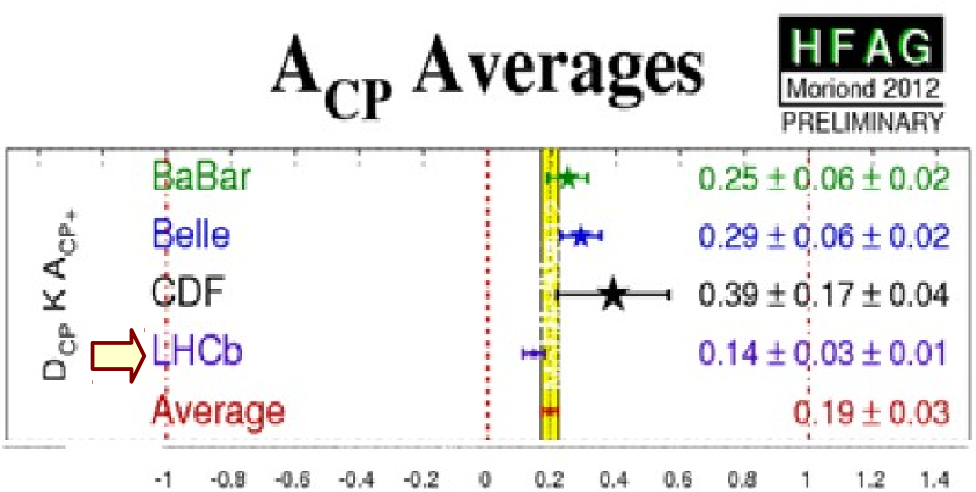
- systematics small, dominated by
  - particle identification (R)
  - production, interaction, detection asymmetries (A)

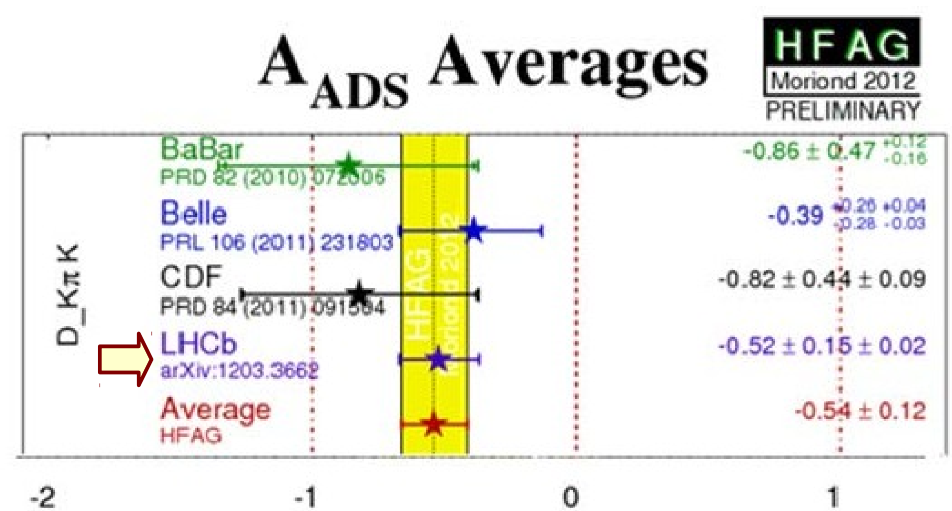
} for all "γ from Trees" analyses

γ from Trees: LHCb Impact





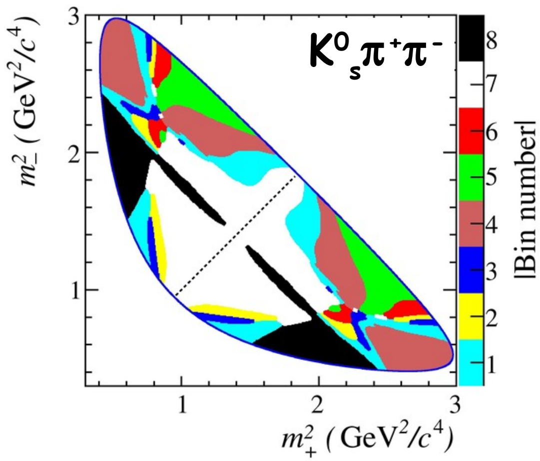


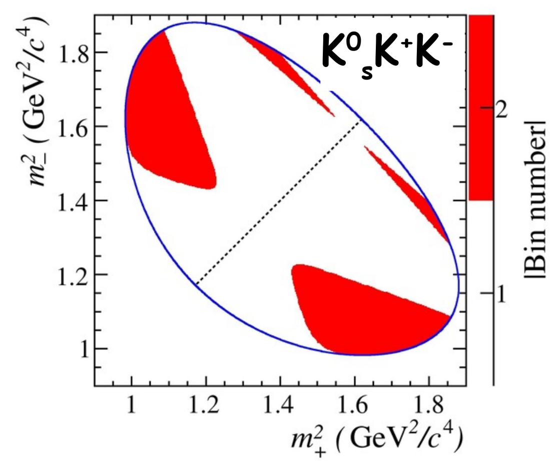


γ from Trees: GGSZ

- **exploit interference patterns in $D^0 \to K^0_s h^+ h^-$ Dalitz plot ($h=\pi,K$)**
  - powerful method, dominates precision on γ from B factories
- **complication: strong phase difference δ_D varies across Dalitz plot**
  - rich resonance structure, difficult to model correctly
- **model-independent approach chosen to minimize systematics:**
- **divide Dalitz plot into regions of ~ constant δ_D using input from CLEO measurements**

  [PRD82 (2010) 112006]





- **determine B^+ and B^- event yields in each region i:**

$$N_i(B^\pm) = K_{\mp,i} + (x_\pm^2 + y_\pm^2) K_{\pm,i} + 2\sqrt{K_{+,i}K_{-,i}} \left\{ x_\pm \langle\cos\delta_D\rangle_i \mp y_\pm \langle\sin\delta_D\rangle_i \right\}$$

asymmetries measured in flavour-specific D decays

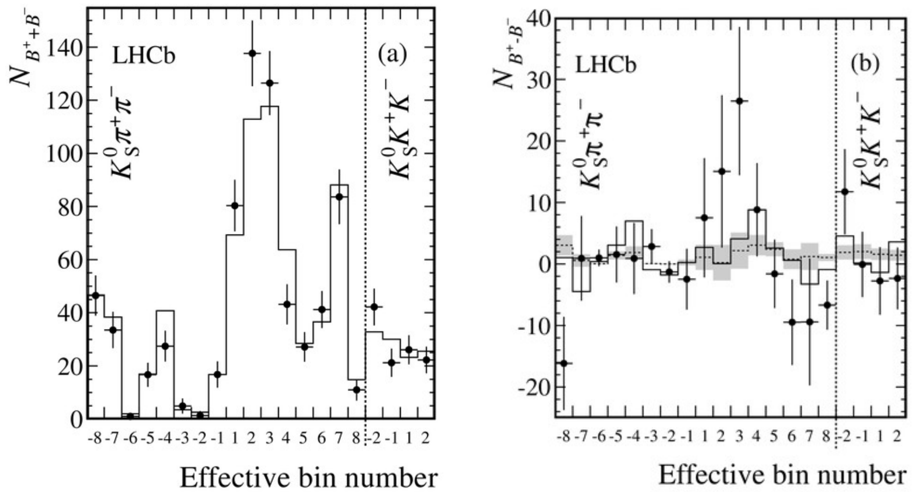
$$x_\pm = r_B \cdot \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \cdot \sin(\delta_B \pm \gamma)$$

measured by CLEO

γ from Trees: GGSZ

[PLB 718 (2012) 43]

- LHCb analysis of 1.0 fb^{-1}
  - ~ 650 $B^{\pm} \to [K^0_s \pi^+ \pi^-]_D K^{\pm}$ candidates
  - ~ 100 $B^{\pm} \to [K^0_s K^+ K^-]_D K^{\pm}$ candidates
- precision on $x_{\pm}$, $y_{\pm}$ similar to B factories
- systematic uncertainty dominated by assumption of no CPV in $B \to D\pi$ (used to determine efficiencies)



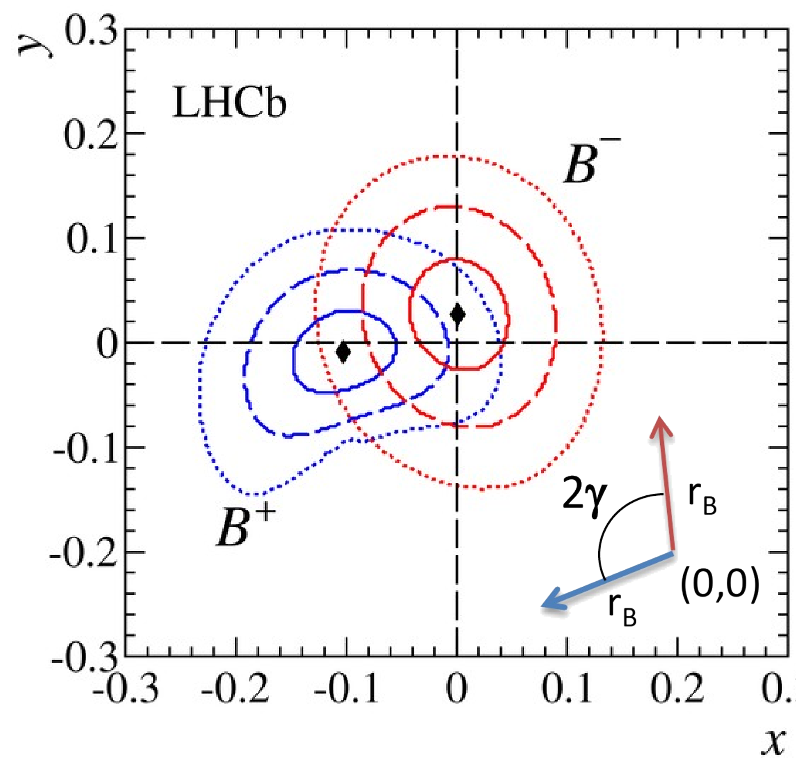
$$x_- = (0.0 \pm 4.3 \pm 1.5 \pm 0.6)\ \%$$

$$y_- = (2.7 \pm 5.2 \pm 0.8 \pm 2.3)\ \%$$

$$x_+ = (-10.3 \pm 4.4 \pm 1.8 \pm 1.4)\ \%$$

$$y_+ = (-0.9 \pm 3.7 \pm 0.8 \pm 3.0)\ \%$$

stat | syst | CLEO inputs

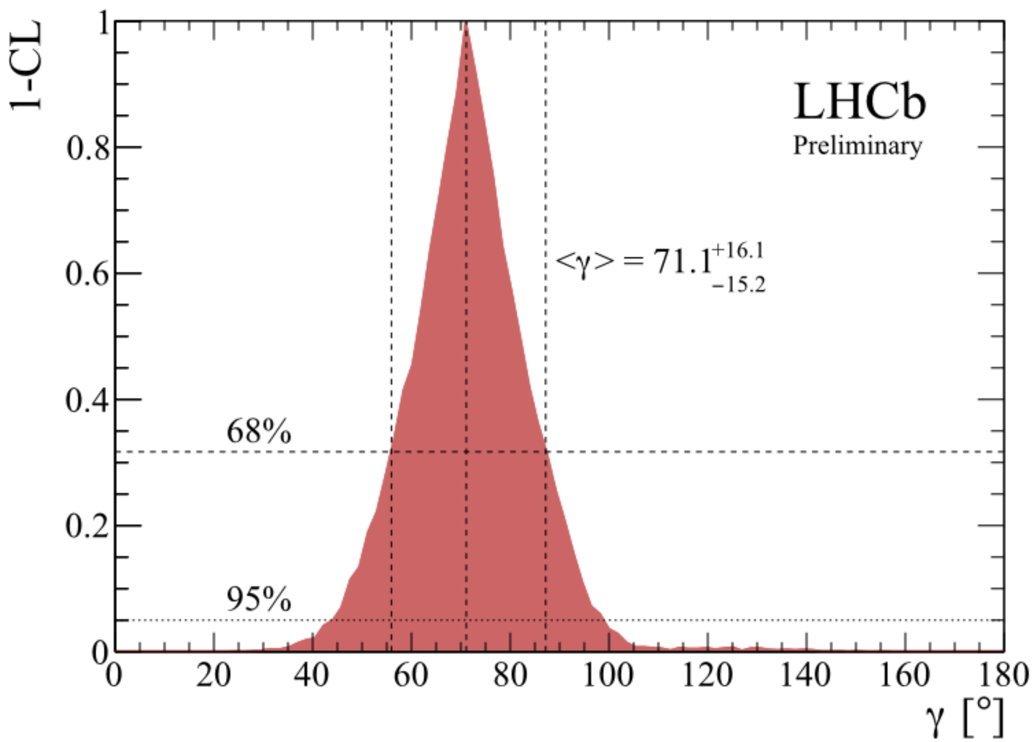


γ from Trees: LHCb Combination

- LHCb γ average from combination of $B^\pm \to DK^\pm$
- using frequentist approach to combine the shown results from
  - GLW/ADS $B^\pm \to [h^+h^-]_D K^\pm$ [PLB 713 (2012) 351]
  - ADS 4-body $B^\pm \to [\pi K\pi\pi]_D K^\pm$ [LHCb-CONF-2012-030]
  - GGSZ $B^\pm \to [K^0_s h^+h^-]_D K^\pm$ [PLB 718 (2012) 43]

$$\langle \gamma \rangle = \left(71\,^{+16}_{-15}\right)^\circ$$

[LHCb-CONF-2012-032] preliminary



[43.9° - 98.8°] @ 95% C.L.

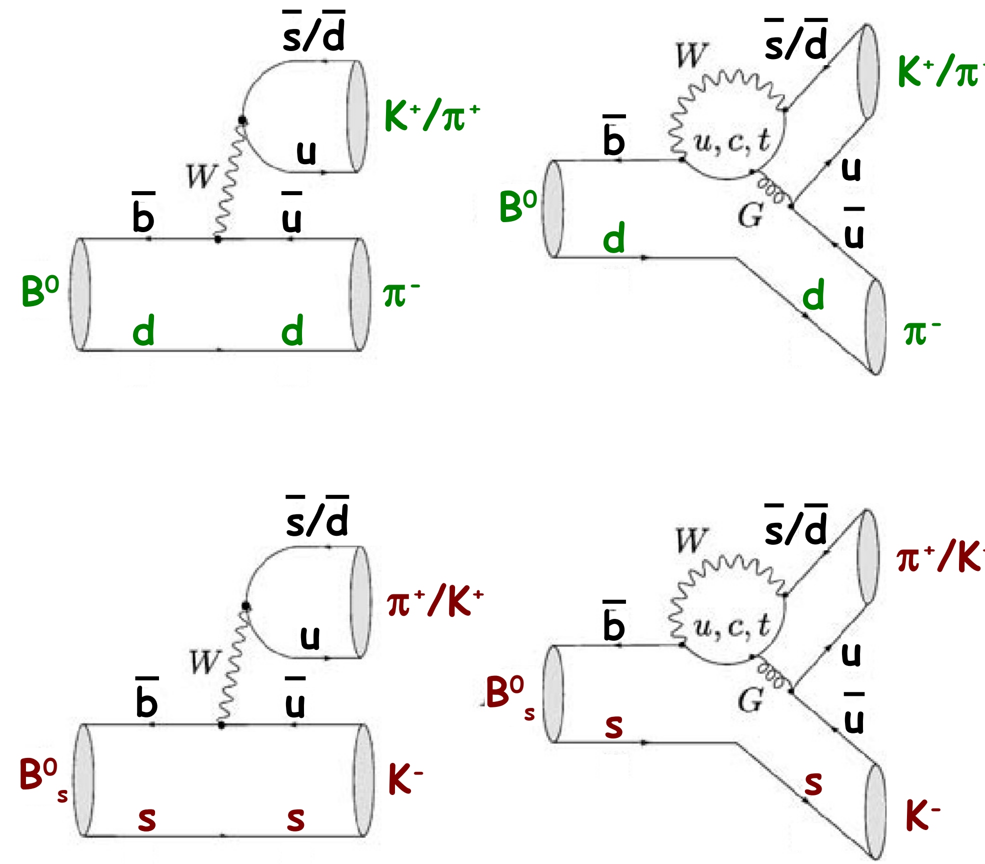
- precision already comparable with γ averages from B factories
  - Babar: $\gamma = \left(69\,^{+17}_{-16}\right)^\circ$
  - Belle: $\gamma = \left(68\,^{+15}_{-14}\right)^\circ$


Charmless B decays:
towards γ from Loops

γ from Loops

- 2-body charmless B decays: γ from interference of $b \to u$ Tree diagrams and $b \to s(d)$ Penguin diagrams
  - sensitive to possible New Physics contribution in Penguin loops
- hadronic uncertainties can be controlled using U-Spin symmetry between B^0 and B^0_s decays

  [Fleischer, EPJC 52 (2007) 267]



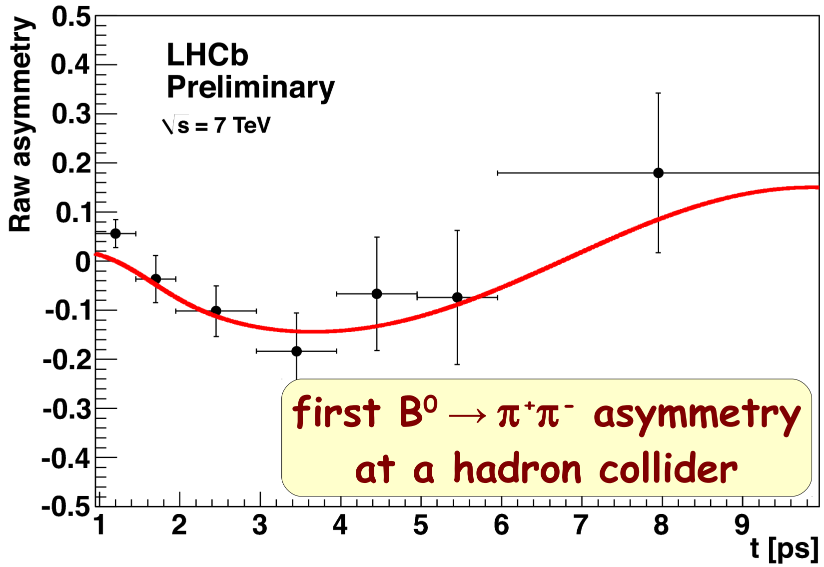
- two approaches:
  - time-dependent CP asymmetry in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$
  - time-integrated CP asymmetry in $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$
- also: time-integrated CP asymmetry in 3-body charmless $B^\pm$ decays

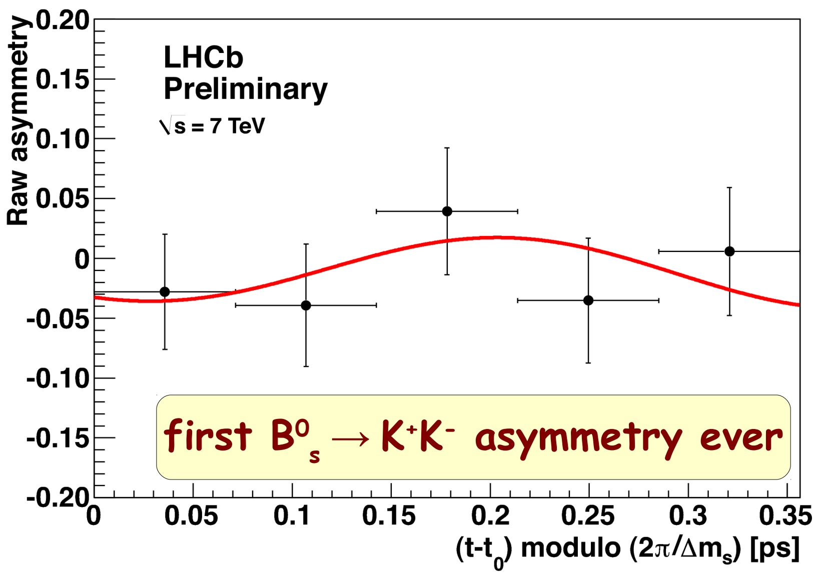
Time-dependent CPV in $B^0_{(s)} \to h^+h^-$

- measure time-dependent asymmetry of decay rates

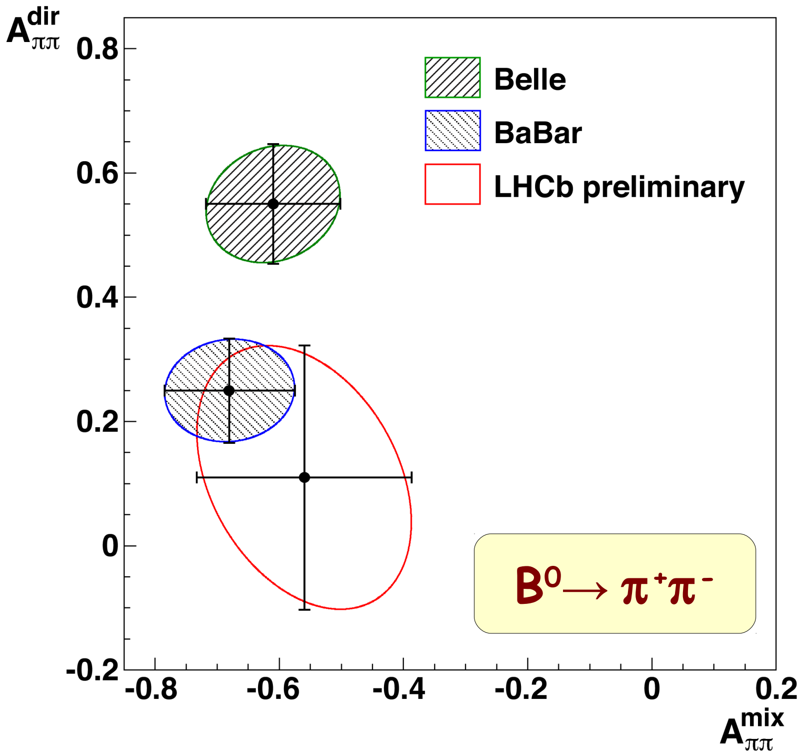
$$A_{CP}(t) = \frac{\Gamma(B^0_{(s)}(t=0)\to f) - \Gamma(\bar{B}^0_{(s)}(t=0)\to f)}{\Gamma(B^0_{(s)}(t=0)\to f) + \Gamma(\bar{B}^0_{(s)}(t=0)\to f)} = \frac{A_f^{dir}\cos(\Delta m_{(s)} t) + A_f^{mix}\cos(\Delta m_{(s)} t)}{\cosh(\frac{\Delta\Gamma_{(s)}}{2}t) - A_f^{\Delta\Gamma}\sinh(\frac{\Delta\Gamma_{(s)}}{2}t)}$$

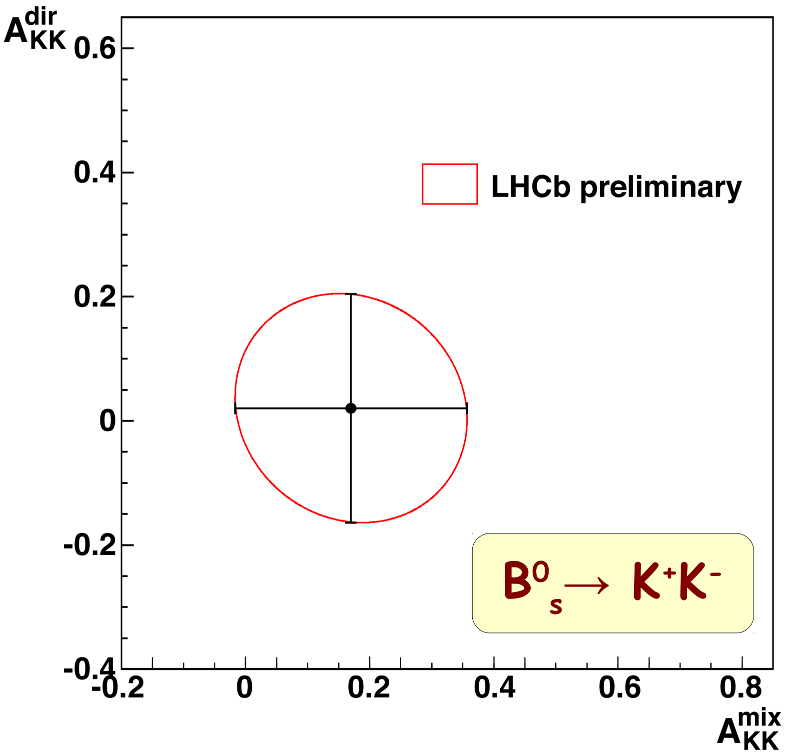
- use flavour tagging algorithms to determine flavour of $B^0_{(s)}$ at production
- LHCb analysis of 0.69 fb^{-1} [LHCb-CONF-2012-007]
- fix values of Δm_d and Δm_s and sign of $\Delta\Gamma_s$ to previous LHCb measurements
- use $B^0 \to K^+\pi^-$ to calibrate tagging and determine mis-tag probability





Time-dependent CPV in $B^0_{(s)} \to h^+h^-$





$$A^{dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$$
$$A^{mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$$

$$A^{dir}_{KK} = 0.02 \pm 0.18 \pm 0.04$$
$$A^{mix}_{KK} = 0.17 \pm 0.18 \pm 0.05$$

[LHCb-CONF-2012-007]
preliminary

- $A^{dir}_{\pi\pi}$ **result favours Babar** [arXiv:0807.4226] **over Belle** [PRL 98 (2007) 211801]

Direct CP Violation in $B^0_{(s)} \to K\pi$

- time-integrated asymmetry of decay rates to flavour-specific final states

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

- LHCb analysis of 0.35 fb^{-1}

[PRL 108 (2012) 201601]

- $B^0 \to K^+\pi^-$ / $\bar{B}^0 \to K^-\pi^+$

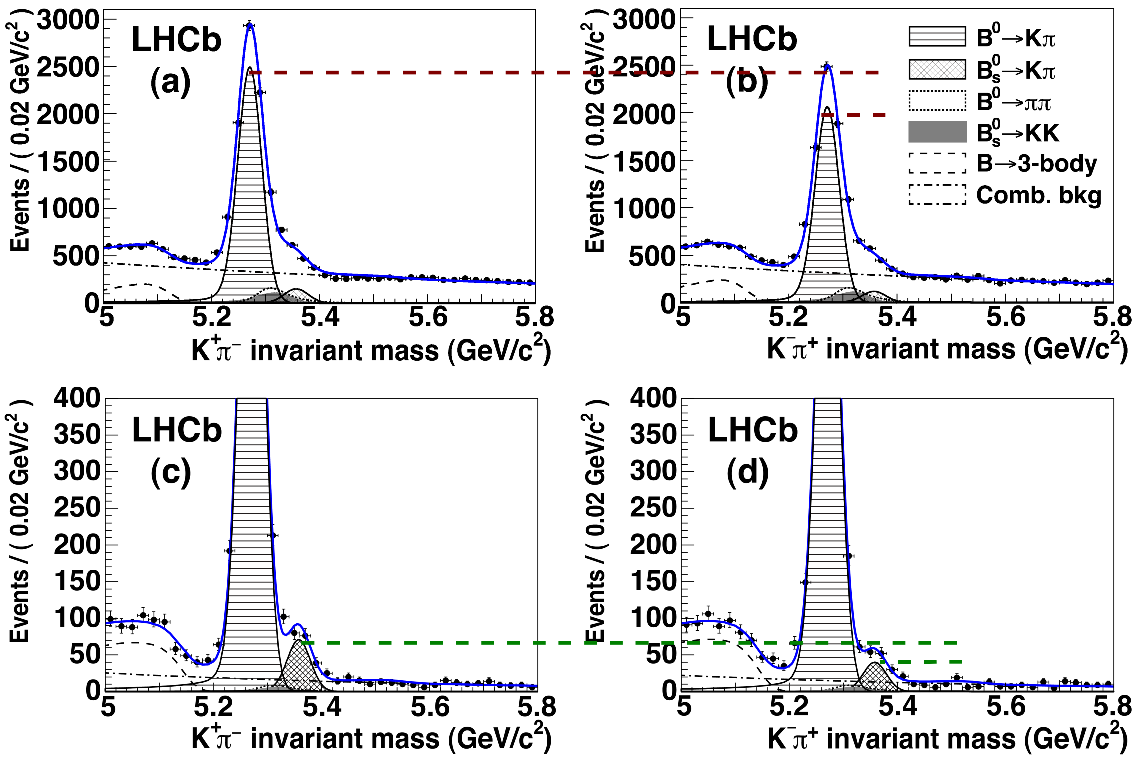
$$A_{CP} = (-0.088 \pm 0.011 \pm 0.008)$$

> 6 σ: first observation of CP violation at a hadron collider

- $B^0_s \to K^-\pi^+$ / $\bar{B}^0_s \to K^+\pi^-$

$$A_{CP} = (0.27 \pm 0.08 \pm 0.02)$$

3.2 σ: first evidence for CP violation in the B^0_s system



- production/detection asymmetries small, corrected using control channels
- dominating systematic: different K^+/K^- interaction cross-sections

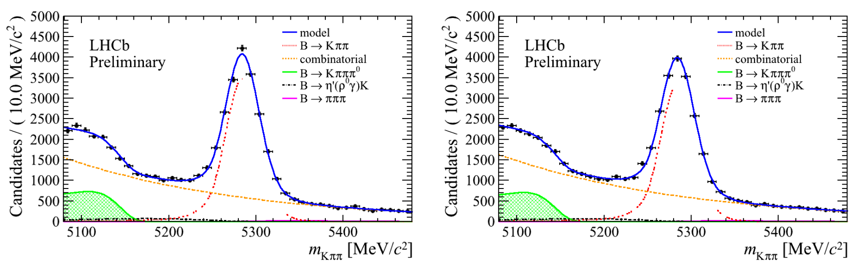
CP Violation in 3-body $B^{\pm}$ decays

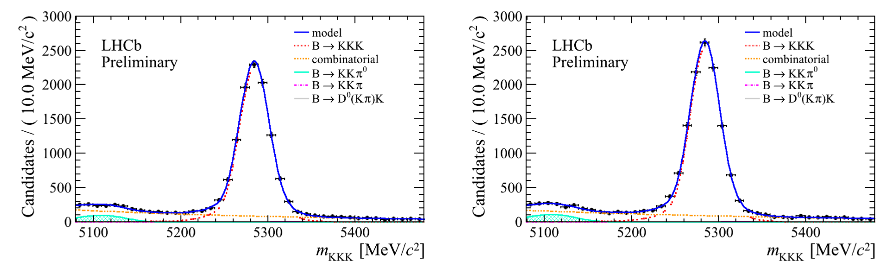
- again, interference of $b \to u$ Tree transitions and $b \to s(d)$ Penguins

$$A_{CP} = \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to \overline{f^+})} \qquad f^{\pm} = \begin{cases} K^{\pm}\pi^{+}\pi^{-}\ ,\ K^{\pm}K^{+}K^{-} \\ \pi^{\pm}\pi^{+}\pi^{-}\ ,\ K^{+}K^{-}\pi^{\pm} \end{cases}$$

[LHCb-CONF-2012-018]
[LHCb-CONF-2012-028]
preliminary

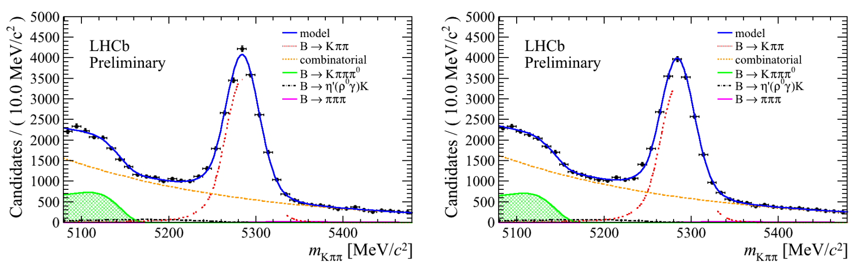
- LHCb analyses using 1.0 fb^{-1}
- measure production and detection asymmetries from $B^{\pm} \to J/\psi K^{\pm}$

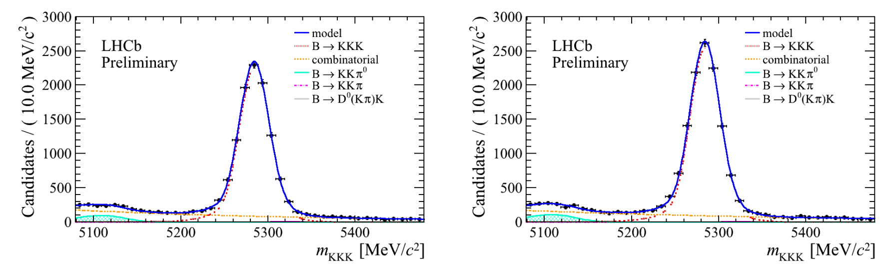




$A_{CP}(K^{\pm}\pi^{+}\pi^{-}) = 0.034 \pm 0.009 \pm 0.004 \pm 0.007$

$A_{CP}(K^{\pm}K^{+}K^{-}) = -0.046 \pm 0.009 \pm 0.005 \pm 0.007$





$A_{CP}(\pi^{+}\pi^{-}\pi^{\pm}) = 0.120 \pm 0.020 \pm 0.019 \pm 0.007$

$A_{CP}(K^{+}K^{-}\pi^{\pm}) = -0.153 \pm 0.046 \pm 0.019 \pm 0.007$

stat

syst

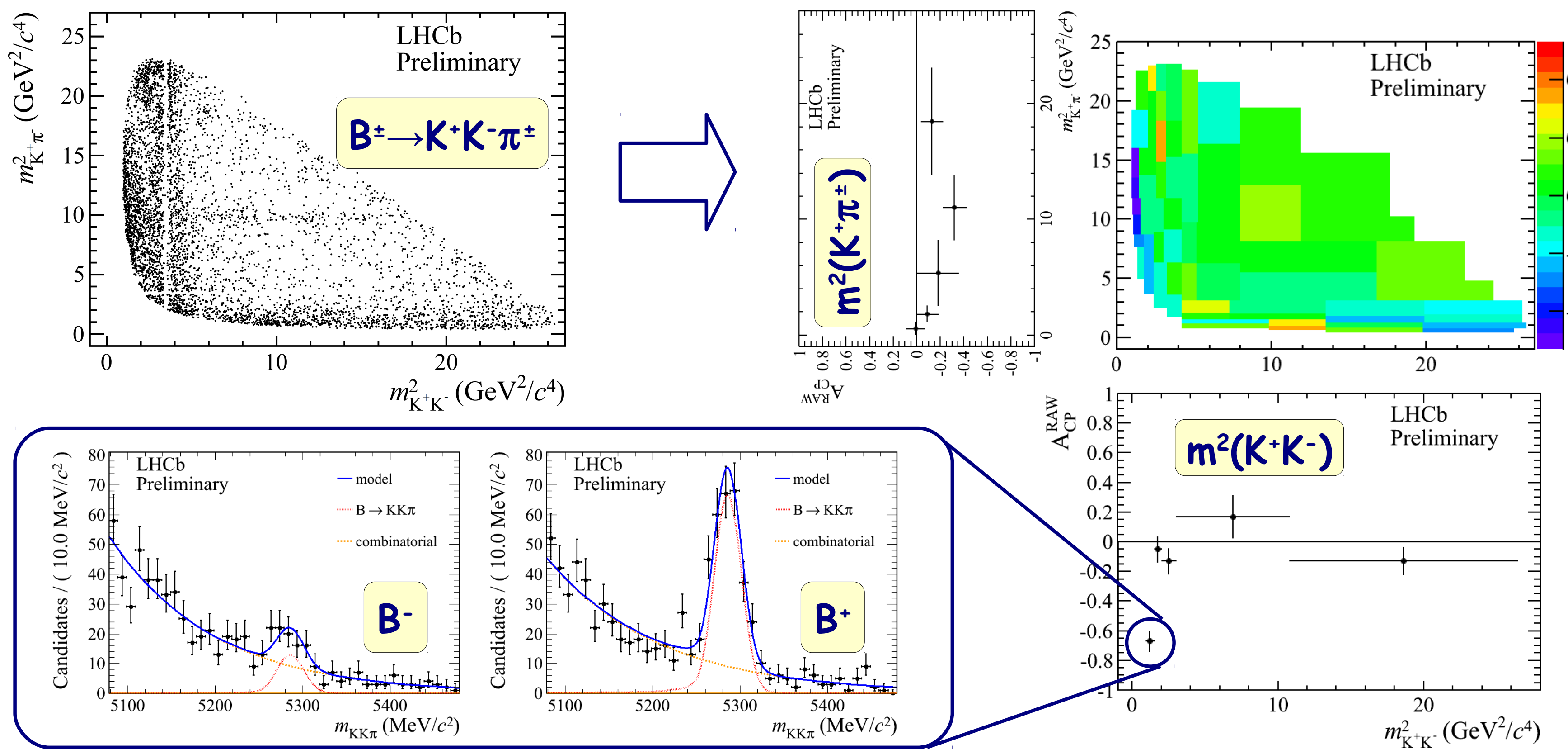
knowledge of CP asymmetry in $B^{\pm} \to J/\psi K^{\pm}$

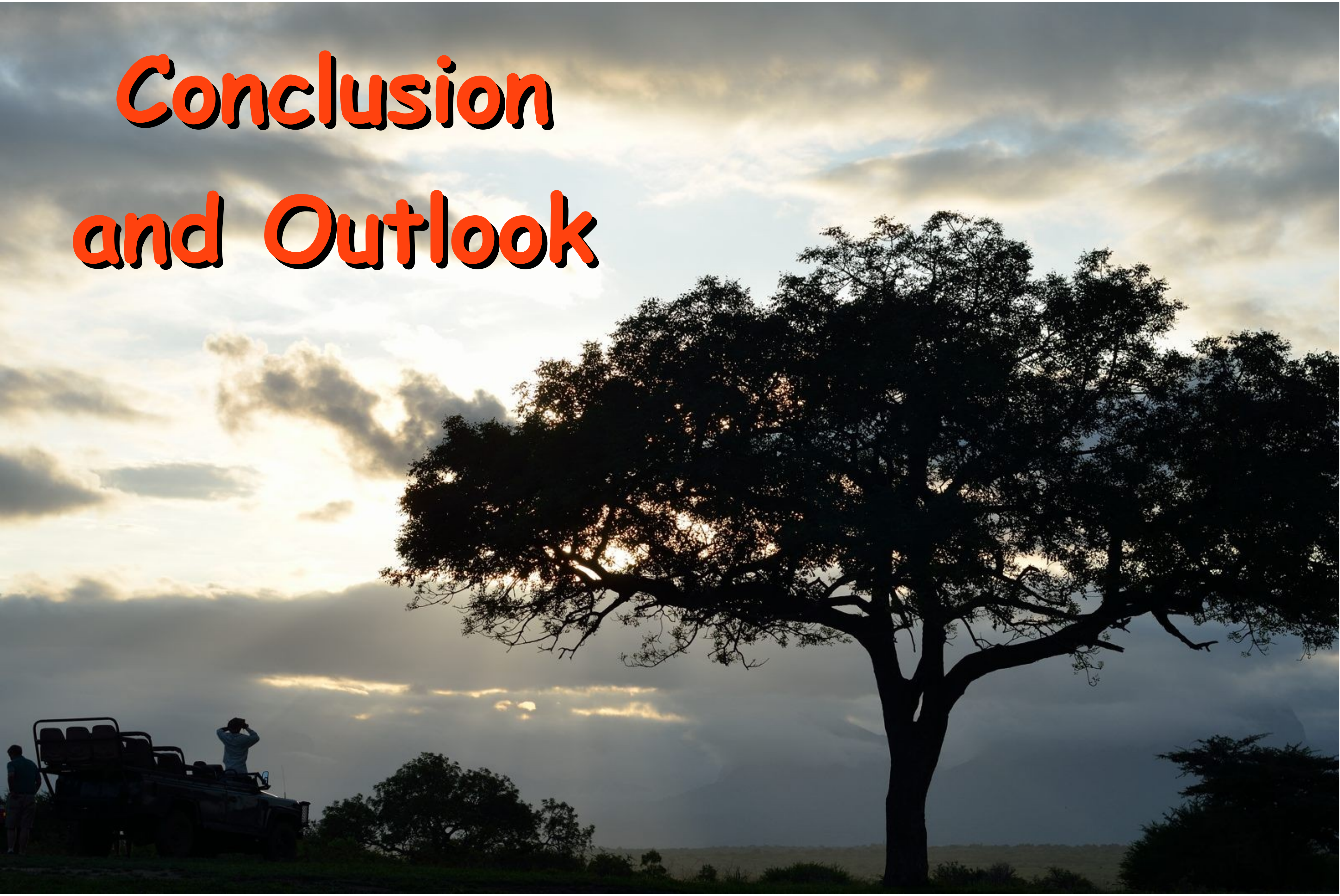
CP Violation in 3-body $B^\pm$ decays

- analyses also performed as a function of phase space
  - subdivide Dalitz plots into bins of ~ equal population
  - determine asymmetry in each bin

[LHCb-CONF-2012-018]
[LHCb-CONF-2012-028]
preliminary

- observe large local asymmetries in all four channels
- interpretation pending (not related to intermediate resonances)




Conclusion
and Outlook

Conclusion

- LHC and LHCb are a spectacular success
- so is the Standard Model

  … up to now

- but current precision of measurements still leaves lots of room for sub-dominant contributions from New Physics

Outlook: LHCb Upgrade

- LHC and LHCb are a spectacular success
- so is the Standard Model

  … still

- current precision of measurements still leaves lots of room for sub-dominant contributions from New Physics
- almost all LHCb results are completely dominated by statistical uncertainties
- leading systematic uncertainties will also decrease with increasing statistics

2010	0.037 fb^{-1} @ 7 TeV
2011	1 fb^{-1} @ 7 TeV
2012	2 fb^{-1} @ 8 TeV
2013 2014	LHC LS1
2015 2016 2017	5 fb^{-1} @ 13 TeV
2018 2019	LHC LS2, LHCb upgrade
2020 2021 2022	5 fb^{-1} per year

NEED MORE STATISTICS

$\Rightarrow$

THE LHCb UPGRADE !

LHCb Upgrade

- goal: reach measurement precision that matches theory uncertainties

[CERN-LHCC-2012-007]

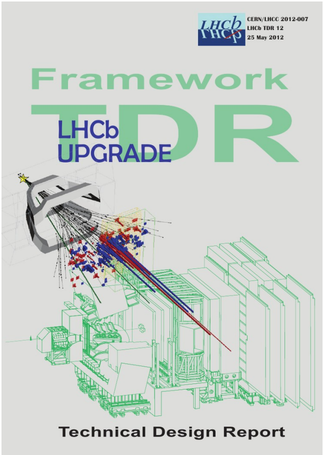
Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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 ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	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}	–

Upgrade

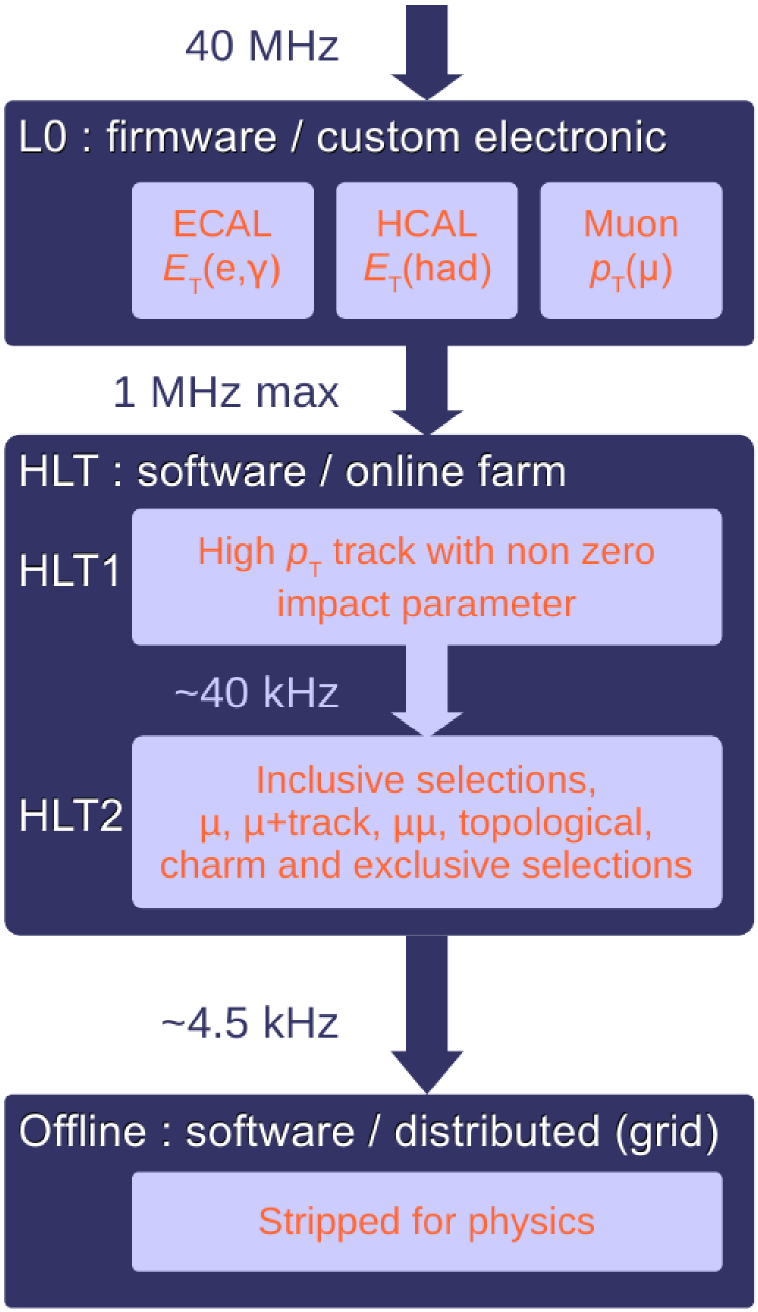
- two lines of attack
  - increase trigger efficiencies for hadronic final states
    - read out the full detector at the LHC bunch-crossing frequency
  - operate the detector at up to x 5 higher luminosity
    - new main tracker to cope with increase in particle densities

expected increase in rate (compared to 2011):
x 10 for channels involving final-state muons
x 20 for channels to fully hadronic final states

- details are described in
  - Letter of Intent [CERN-LHCC-2011-001]
  - Framework TDR [CERN-LHCC-2012-007]
- endorsed by the LHCC



Reminder: Current LHCb Trigger



Hardware level (L0):

- maximum output rate 1 MHz
- typical thresholds 2012:

  $E_T(e/\gamma) > 2.7$ GeV

  $E_T(h) > 3.6$ GeV

  $p_T(\mu) > 1.4$ GeV

Software level (HLT):

~ 30000 tasks in parallel on ~ 1500 nodes

Combined efficiency (L0+HLT):

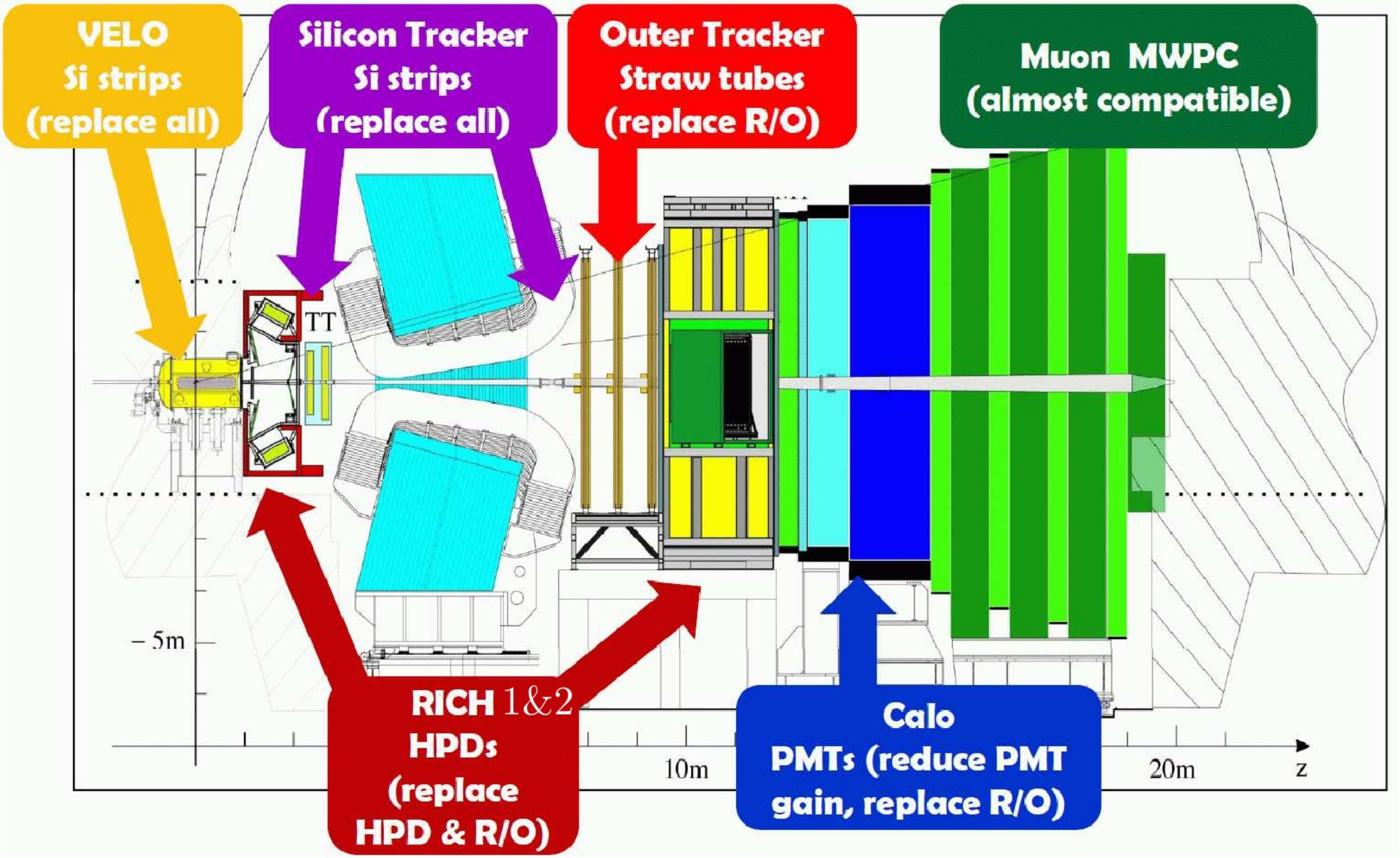
~ 90 % for di-muon channels

~ 30 % for multi-body hadronic final states

Offline processing:

~ 10^{10} events, 700 TB recorded per year

Upgrade



- **2012/2013: R&D, technology choices, preparation of sub-system TDRs**
- **2014: funding, procurements**
- **2015-2019: construction and installation**


819 members
60 Institutes
16 countries
(October 1st, 2012)
?
Countries member of the LHCb Collaboration
The engine is running,
the safari has
only just begun
fetch your binoculars
and join the party

Not Mentioned …

- $B^0_s \to K K$ effective lifetime [PLB 716 (2012) 393]
- $B^0_s \to J/\psi\, f_0$ effective lifetime [PRL 109 (2012) 152002]
    - both sensitive to new physics in B^0_s-$\bar{B}^0_s$ mixing
- BF ($B^0_s \to J/\psi\, \eta'$) [arXiv:1210.2631]
    - another channel to measure ϕ_s
- BF ($B^0_s \to J/\psi\, K^{0*}$) [PRD 86 (2012) 071102]
    - to estimate penguin contamination in J/psi phi
- GLW-type analysis of $B^0 \to D\, K^{*0}$ [LHCb-CONF-2012-024]
- Time-dependent CP violation in $B^0_s \to D_s K^{\pm}$ [LHCb-CONF-2012-029]
    - other channels to measure gamma from Trees
- BF ($B^0_s \to D_{(s)} D_{(s)}$) [LHCb-CONF-2012-009]
- CP violation in $B_0 \to K^{*0} \mu^+ \mu^-$ [arXiv:1210.4492]
- CP violation in $B_0 \to K^{*0} \gamma$ [Nucl Phys B 867 (2013) 1]
- ΔA_{CP} (CP violation in $D \to h^+ h^-$) [PRL 108 (2012) 111602]

Eugeni's talk on Tuesday