CP-violation measurements at LHCb

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CHIPP plenary, Sept 14th 2012

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1. **Time dependent CPV in $\bar{\mathrm{b}} \to \bar{\mathrm{c}}\mathrm{c}\bar{\mathrm{s}}$ transitions**
2. **Mixing induced CPV in B_s^0-system using semileptonics**
3. **Towards a measurement of γ**

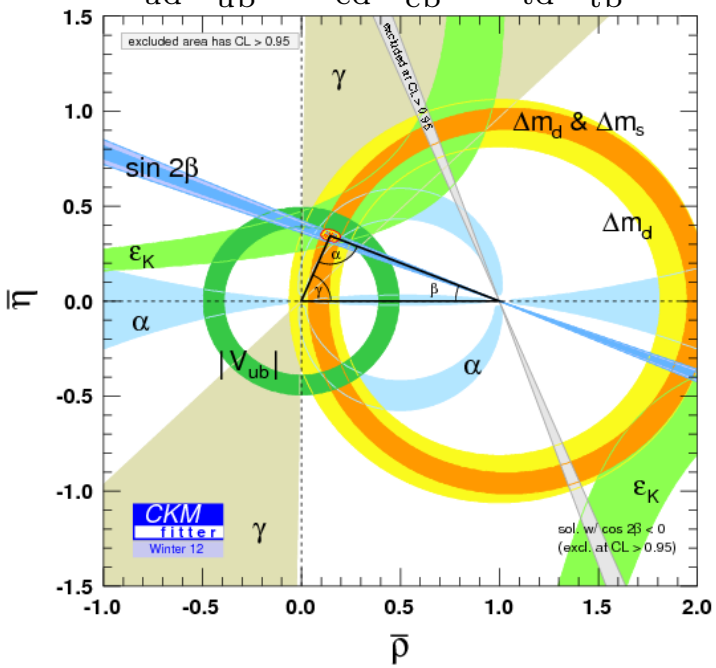
Unitarity+CKM $\Rightarrow$ triangles in the complex plane

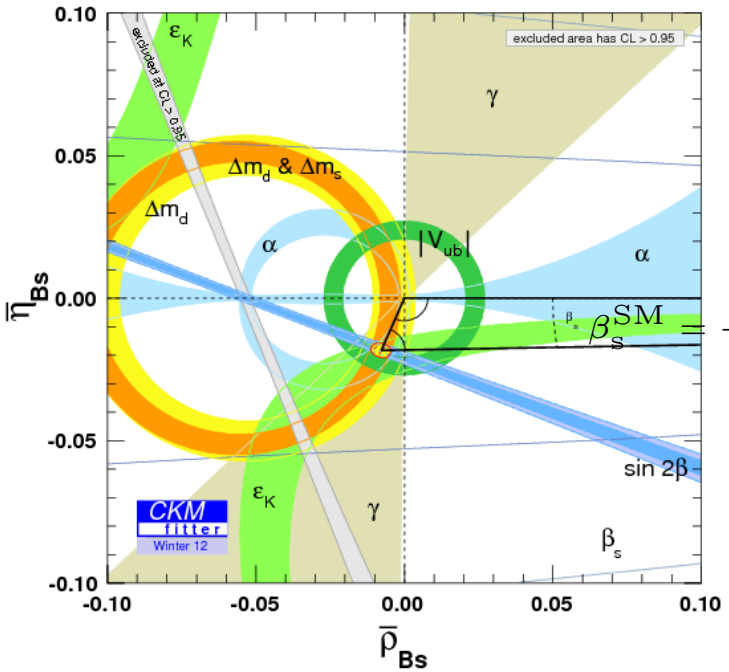
- SM allows quarks to change into each due to Yukawa mechanism.
- 3 generations + **1 phase** $\rightarrow$ only source of CP-violation in SM.

$$\mathrm{V_{CKM}} = \begin{pmatrix} \mathrm{V_{ud}} & \mathrm{V_{us}} & \mathrm{V_{ub}} \\ \mathrm{V_{cd}} & \mathrm{V_{cs}} & \mathrm{V_{cb}} \\ \mathrm{V_{td}} & \mathrm{V_{ts}} & \mathrm{V_{tb}} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & \mathrm{A}\lambda^3(\rho-\mathrm{i}\eta) \\ -\lambda & 1-\lambda^2/2-\lambda^4/8(1+4\mathrm{A}^2) & \mathrm{A}\lambda^2 \\ \mathrm{A}\lambda^3(1-\rho-\mathrm{i}\eta) & -\mathrm{A}\lambda^2+\mathrm{A}\lambda^4/2(1-2(\rho+\mathrm{i}\eta)) & 1-\mathrm{A}^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^5)$$

- $\mathrm{A} = 0.81 \pm 0.02$, $\lambda = 0.225 \pm 0.001$, $\rho = 0.145 \pm 0.027$, $\eta = 0.343 \pm 0.015$.

$$\mathrm{V_{ud}V_{ub}^*} + \mathrm{V_{cd}V_{cb}^*} + \mathrm{V_{td}V_{tb}^*} = 0$$

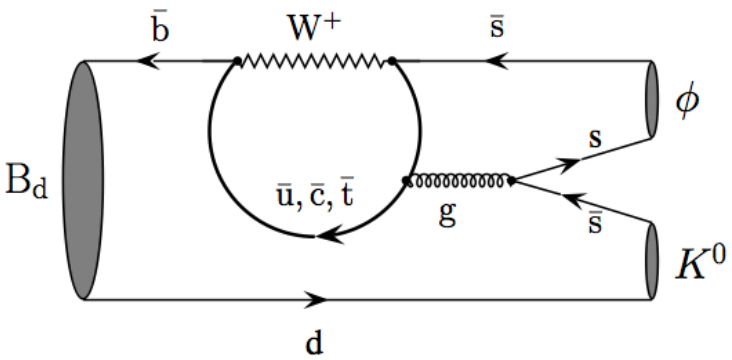




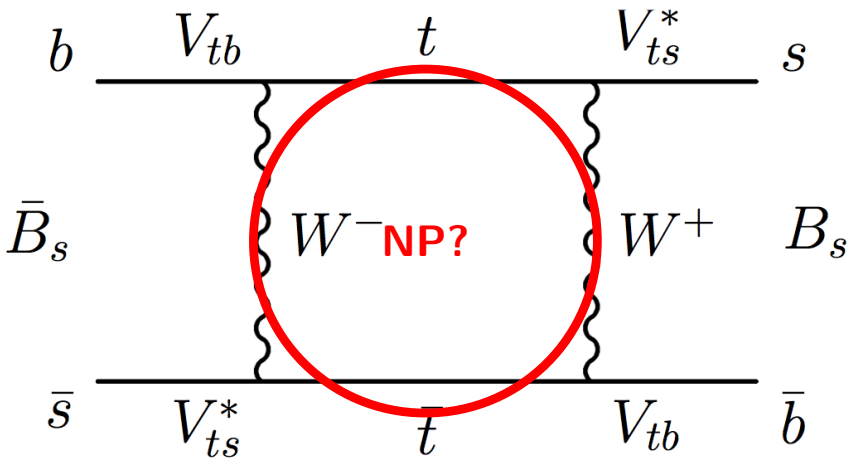
$$\beta_s^{\mathrm{SM}} = -\arg\left(\frac{\mathrm{V_{ts}V_{tb}^*}}{\mathrm{V_{cs}V_{cb}^*}}\right)$$

Searching for new physics using heavy flavour

Virtual particles appearing in FCNC loop diagrams



$\Delta F = 1$ **"penguin diagram"**



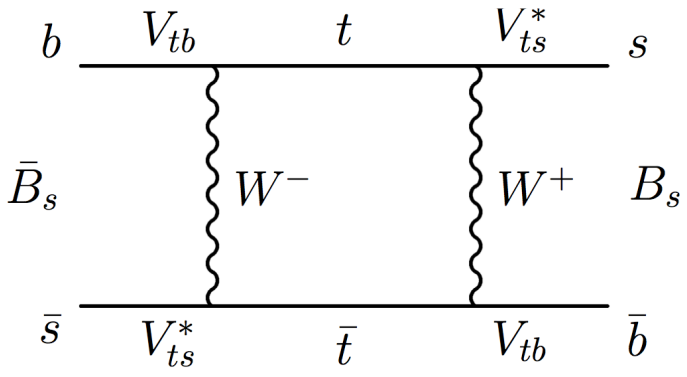
$\Delta F = 2$ **"box diagram"**

Indirect approach complements high-p_T searches

- Loop processes allows us to probe energies much higher than those of LHC!
- Specialised detector to make precision measurements
  $\Rightarrow$ find deviations from Standard Model predictions.
  $\Rightarrow$ give information about couplings and phases of new particles if they are visible at TeV scale.

Brief introduction to B_s^0-meson mixing and decay

$$\mathrm{i}\frac{\partial}{\partial \mathrm{t}}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \left(\mathbf{M} - \mathrm{i}\frac{\mathbf{\Gamma}}{2}\right)\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$



$$\begin{aligned} |B_{s,\mathrm{L}}^0\rangle &= p|B_s^0\rangle + q|\bar{B}_s^0\rangle \\ |B_{s,\mathrm{H}}^0\rangle &= p|B_s^0\rangle - q|\bar{B}_s^0\rangle \end{aligned}$$

Some relevant parameters

$$\mathrm{M}_{\mathrm{B_s^0}} = \frac{\mathrm{M_H} + \mathrm{M_L}}{2}, \qquad \Gamma_{\mathrm{s}} = \frac{\Gamma_{\mathrm{L}} + \Gamma_{\mathrm{H}}}{2}$$

$$\Delta \mathrm{m_s} = \mathrm{M_H} - \mathrm{M_L} \approx 2\mathrm{M_{12}}, \qquad \Delta\Gamma_{\mathrm{s}} = \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}} \approx 2\Gamma_{12}\cos\varphi_{12}$$

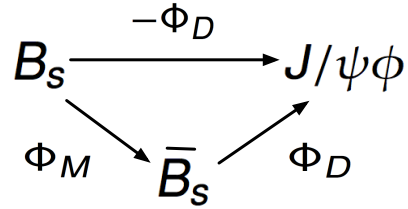
$$\varphi_{12} = \arg\left(-\frac{\mathrm{M_{12}}}{\Gamma_{12}}\right), \qquad \mathrm{a_{sl}^s} = \frac{\Gamma(\bar{\mathrm{B}}_{\mathrm{s}}^0(\mathrm{t}) \to \mathrm{f}) - \Gamma(\mathrm{B}_{\mathrm{s}}^0(\mathrm{t}) \to \bar{\mathrm{f}})}{\Gamma(\bar{\mathrm{B}}_{\mathrm{s}}^0(\mathrm{t}) \to \bar{\mathrm{f}}) + \Gamma(\mathrm{B}_{\mathrm{s}}^0(\mathrm{t}) \to \mathrm{f})} = \frac{\Delta\Gamma_{\mathrm{s}}}{\Delta \mathrm{m_s}}\tan\varphi_{12}.$$

Measuring $\Gamma_s, \Delta\Gamma_s$ and ϕ_s

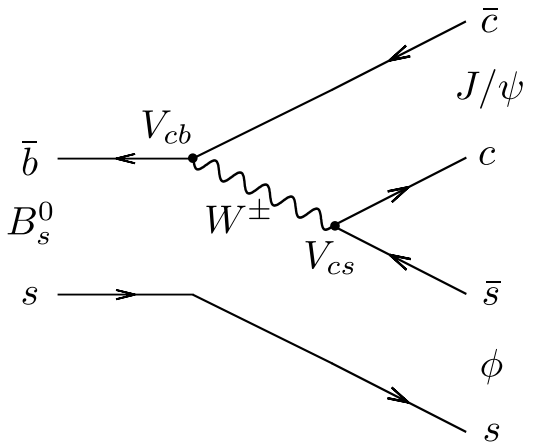
- Interference between $\bar{b} \to \bar{c}c\bar{s}$ either directly or via mixing gives rise to a *CP*-violating phase

$$\phi_s^{SM} = -2\beta_s + \delta P = -0.036 \pm 0.002\,\text{rad} + \delta P$$

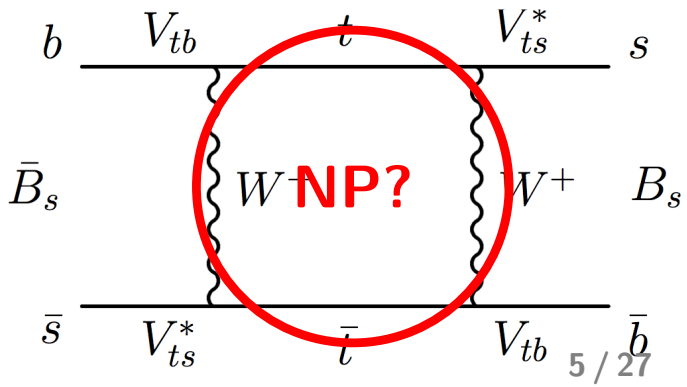
$\phi_s = \Phi_M - 2\Phi_D$



- $\bar{b} \to \bar{c}c\bar{s}$ dominated by tree-level transitions, $\Phi_D = \arg(V_{cs}V_{cb}^*)$.
  - Small penguin pollution, $\delta P \sim 10^{-3} - 10^{-4}$.



- Mixing phase $\Phi_M = 2\arg(V_{ts}V_{tb}^*) \approx -2\beta_s$.
  - New physics can modify: $\phi_s \to \phi_s^{SM} + \phi_s^{NP}$.

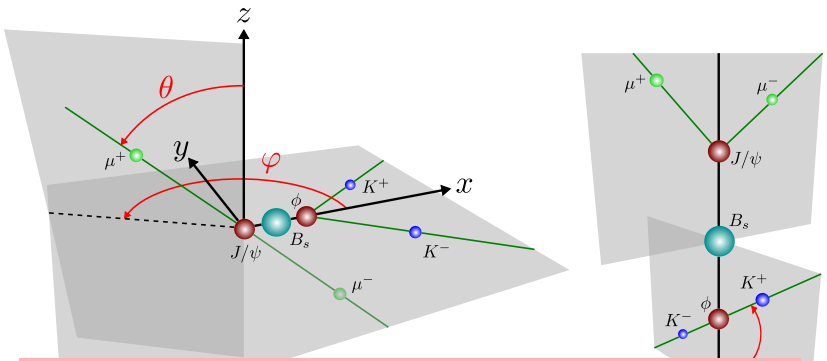


The GOLDEN mode: $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

- $P \to VV$: final state is admixture of CP-odd ($\ell = 1$) and CP-even ($\ell = 0, 2$) with different lifetimes.
- 3 K^+K^- P-wave, 1 S-wave

$$\begin{aligned} \mathrm{CP}|\,J/\psi\phi\rangle_\ell &= \eta_f |\,J/\psi\phi\rangle_\ell \\ &= (-1)^\ell |\,J/\psi\phi\rangle_\ell \end{aligned}$$

- Unbinned log-likelihood fit to statistically disentangle final states.



Angular analysis $\Omega = (\theta,\ \varphi,\ \psi)$

$$\mathcal{S}(\lambda, \mathrm{m}, \mathrm{t}, \Omega) = \mathcal{G}(\mathrm{m}) \cdot \epsilon(\mathrm{t}, \Omega) \cdot \left(\frac{1 + \mathrm{qD}}{2} \cdot \mathrm{s}(\lambda, \mathrm{t}, \Omega) + \frac{1 - \mathrm{qD}}{2} \cdot \bar{\mathrm{s}}(\lambda, \mathrm{t}, \Omega) \right) \otimes \mathrm{R_t}$$

- Acceptance, flavour tagging, time resolution.
- **Physics**: $\boxed{\lambda = (\phi_\mathrm{s},\ \Gamma_\mathrm{s},\ \Delta\Gamma_\mathrm{s},\ \Delta\mathrm{m_s},\ \delta_\parallel,\ \delta_\perp,\ \delta_\mathrm{S},\ |\mathrm{A}_\parallel|^2,\ |\mathrm{A}_\perp|^2,\ \mathrm{F_S})}$

$B_s^0 \to J/\psi\phi$ analysis of $1\,\text{fb}^{-1}$

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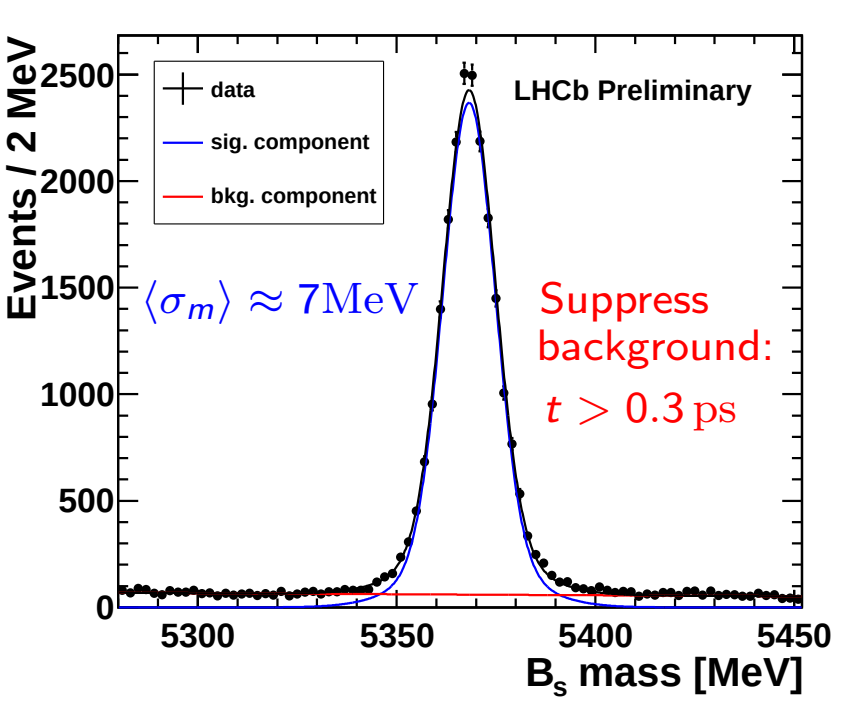
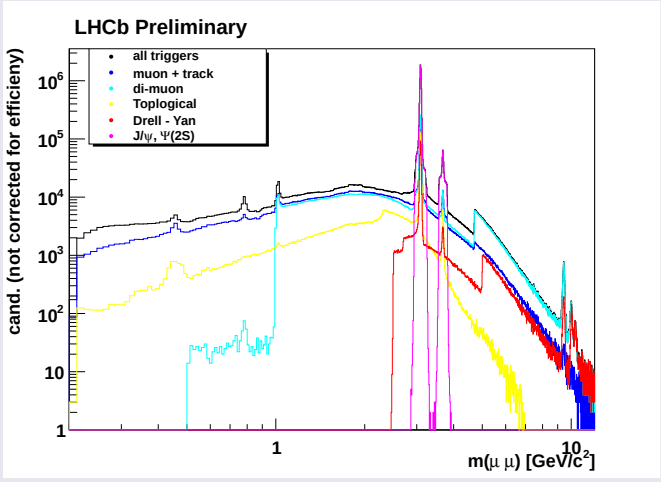
Selection

- Simple kinematic selection: $\sim$ 21200 candidates

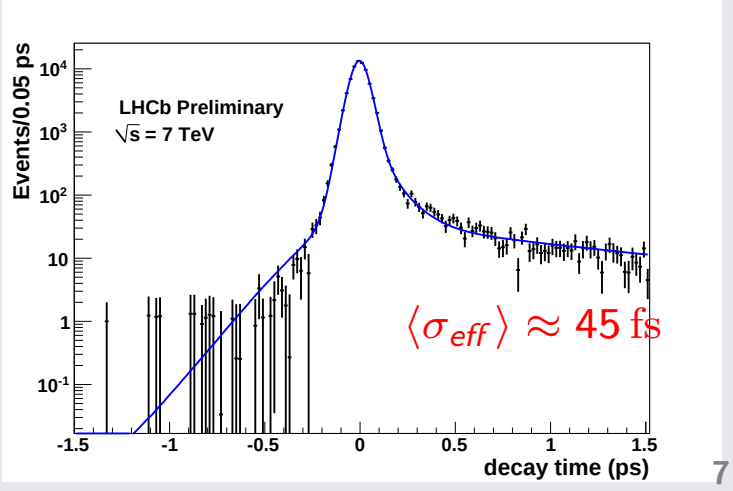


Di-muon trigger: $p_T > 0.5\,\text{GeV}/c$



Decay time resolution

- Use prescaled sample of prompt-J/ψ events to extract resolution scale factor.



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Projection of time dependent angular fit

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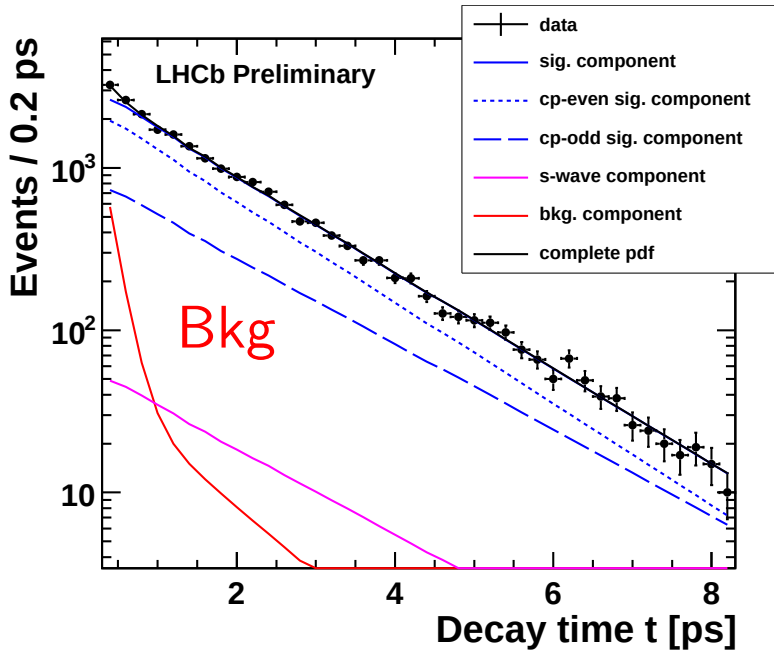

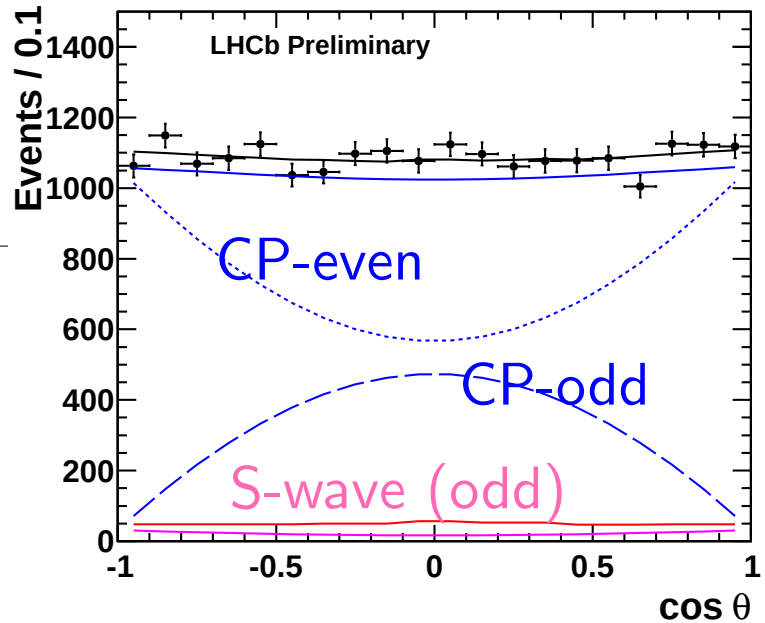

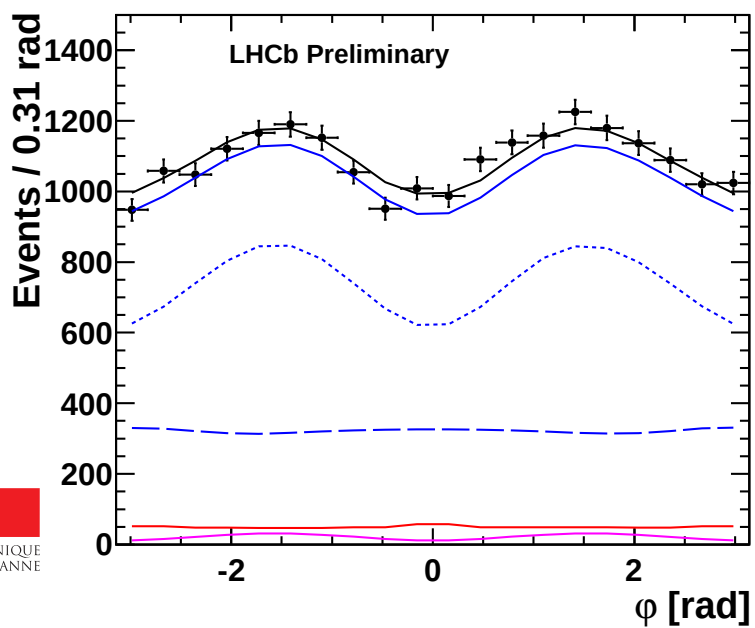

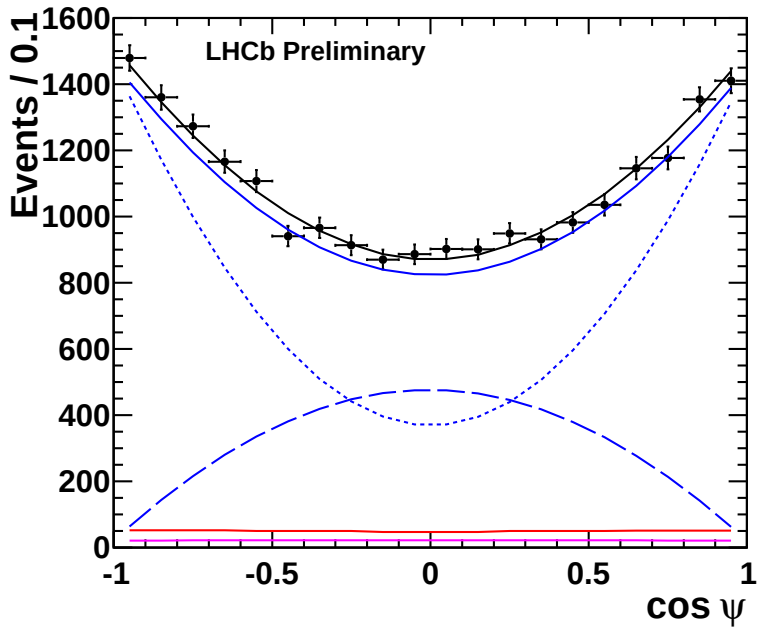

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B_s^0-mixing results

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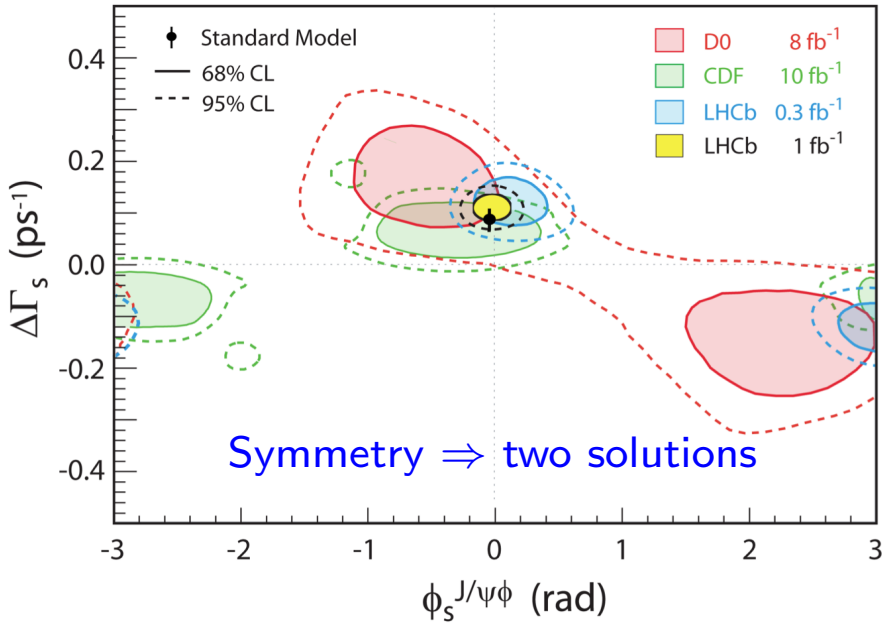
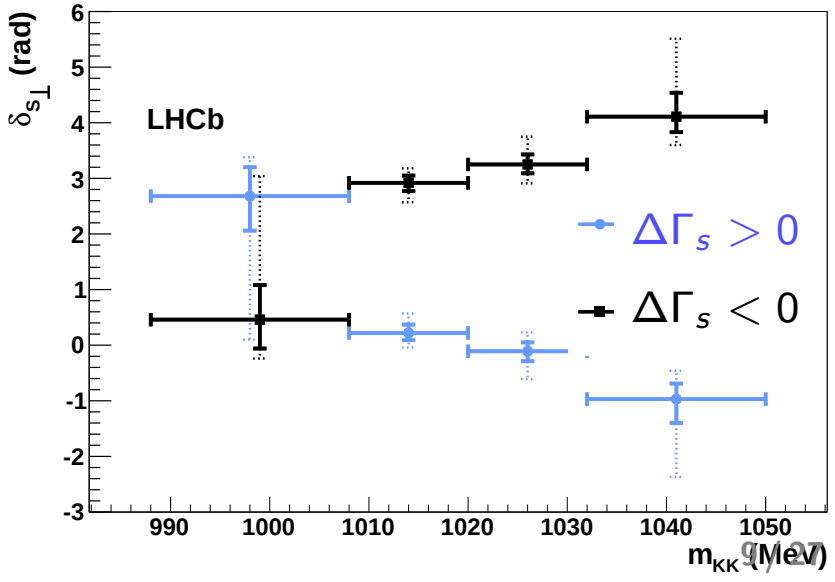
Preliminary			
Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.6580	0.0054	0.0066
$\Delta\Gamma_s$ [ps^{-1}]	0.116	0.018	0.006
$\lvert A_\perp(0)\rvert^2$	0.246	0.010	0.013
$\lvert A_0(0)\rvert^2$	0.523	0.007	0.024
F_S	0.022	0.012	0.007
$\delta_\perp$ [rad]	2.90	0.36	0.07
$\delta_\parallel$ [rad]	[2.81,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



Resolving the ambiguity

Phys. Rev. Lett. 108 (2012) 241801

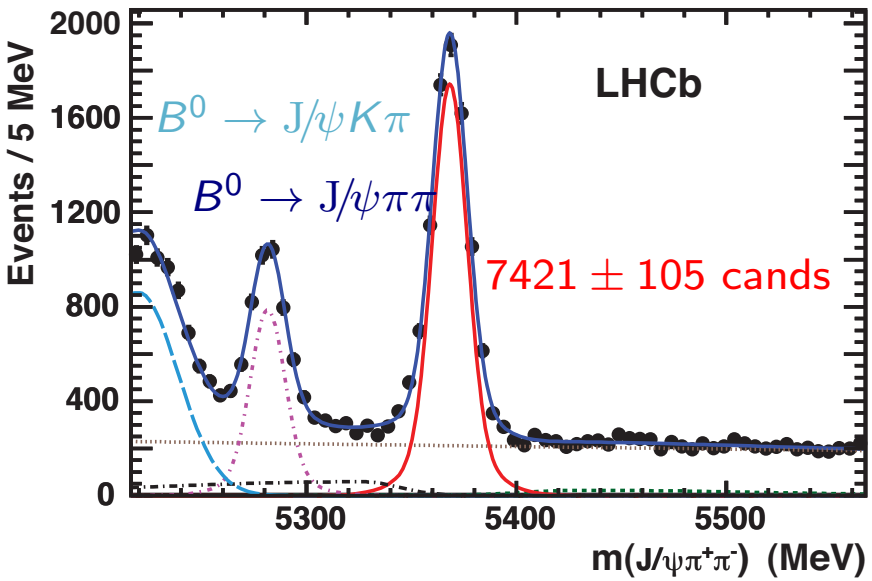
LHCb showed which is the physical solution:
$\Delta\Gamma_s > 0$
$\Rightarrow$ the heavy B_s^0 eigenstate lives longer than the light one!

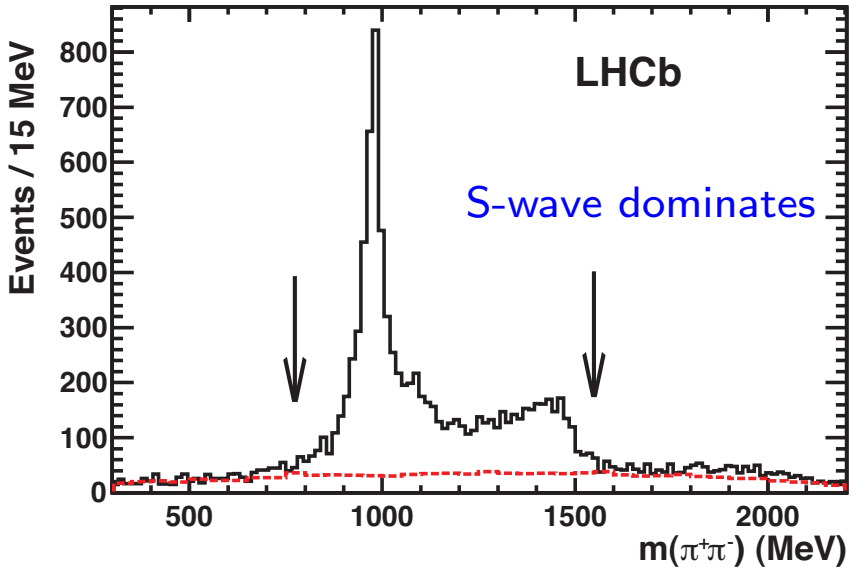


ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$

arXiv:1204.5675v3, submitted to Phys. Lett. B

- $B_s^0 \to J/\psi\pi^+\pi^-$ is another $\bar{b} \to \bar{c}c\bar{s}$.
- Not vector-vector final state $\Rightarrow$ no complex angular analysis!
- $\pi^+\pi^-$ is $> 97.7\%$ CP-odd @ 95% Conf. Level.





Simultaneous fit of $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$

$$\phi_s = -0.002 \pm 0.083 \pm 0.027\,\text{rad}$$

Semileptonic asymmetries

LHCb-CONF-2012-022

- Asymmetry between $\mathrm{D_s^+ X}\mu^-\bar{\nu}_\mu$ and $\mathrm{D_s^-}\,\mathrm{X}\mu^+\nu_\mu$:

$$\mathrm{A^s_{measured}} = \frac{\Gamma[\mathrm{D_s^-}\,\mu^+] - \Gamma[\mathrm{D_s^+}\,\mu^-]}{\Gamma[\mathrm{D_s^-}\,\mu^+] + \Gamma[\mathrm{D_s^+}\,\mu^-]} = \frac{\mathrm{a^s_{sl}}}{2} + \left[\mathrm{a_p} - \frac{\mathrm{a^s_{sl}}}{2}\right]\kappa_\mathrm{S}$$

- $\mathrm{a_p}$ is production asymmetry - difference in number of $\mathrm{b} - \bar{\mathrm{b}}$ at LHC.
- Fast B_s^0 mixing dilutes second term below precision of this measurement.
- Untagged and time-integrated analysis.
- Detection asymmetries: cancel using flip of magnetic field.

Systematics are important

- Asymmetries can bias result.
- Use $\mathrm{D_s^-} \to \phi(\mathrm{K^+K^-})\pi^+$, so worry about π and μ detection/reconstruction asymmetries.
- Swap magnetic field to help cancel effects.
- Obtain any corrections from data/control samples.

Semileptonic asymmetries

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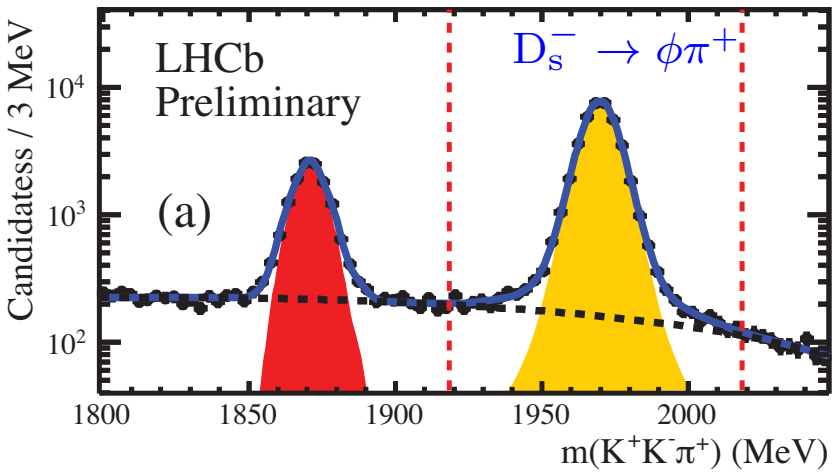
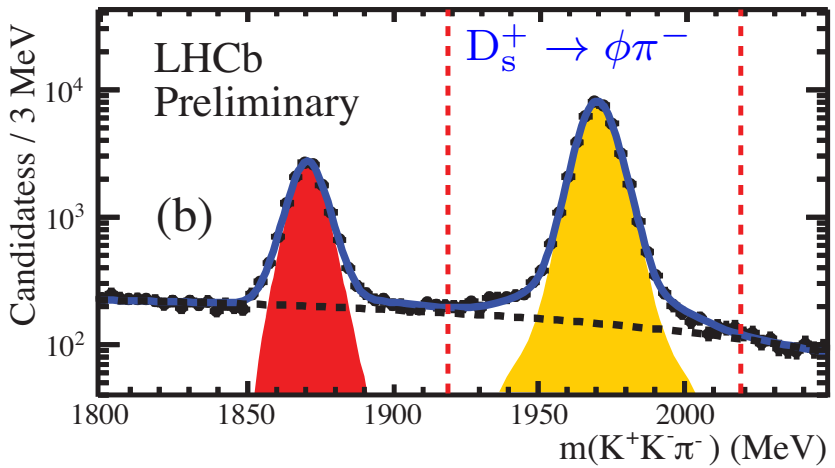
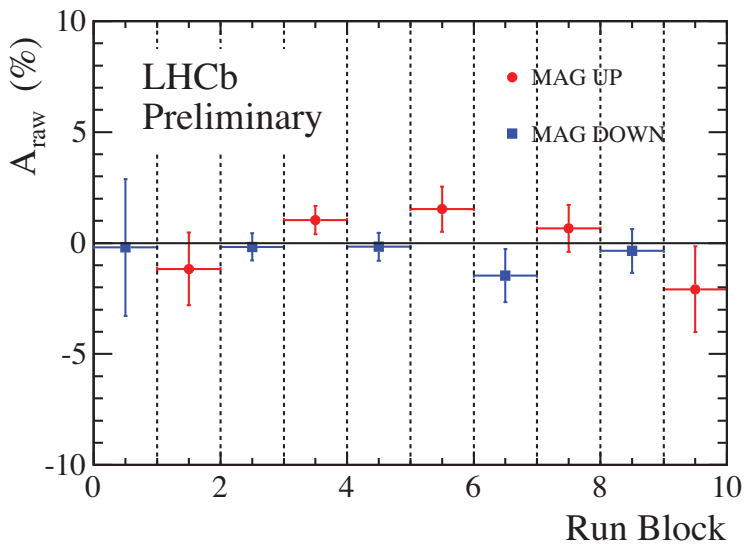
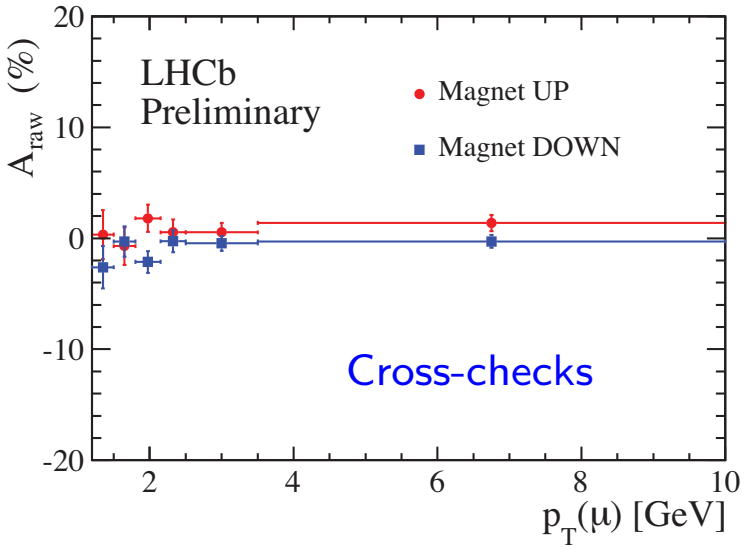
- 190k B_s^0 signal candidates in magnetic up and down.









Semileptonic asymmetries

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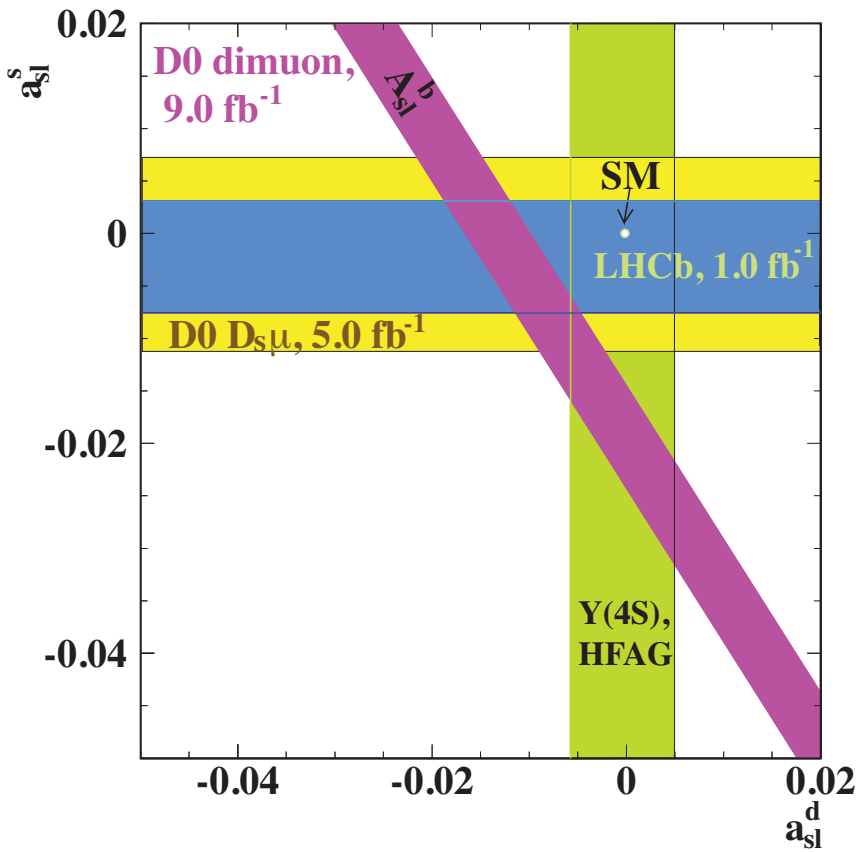
$$a^s_{sl} = [-0.24 \pm 0.54(\text{stat}) \pm 0.33(\text{syst})]\%$$

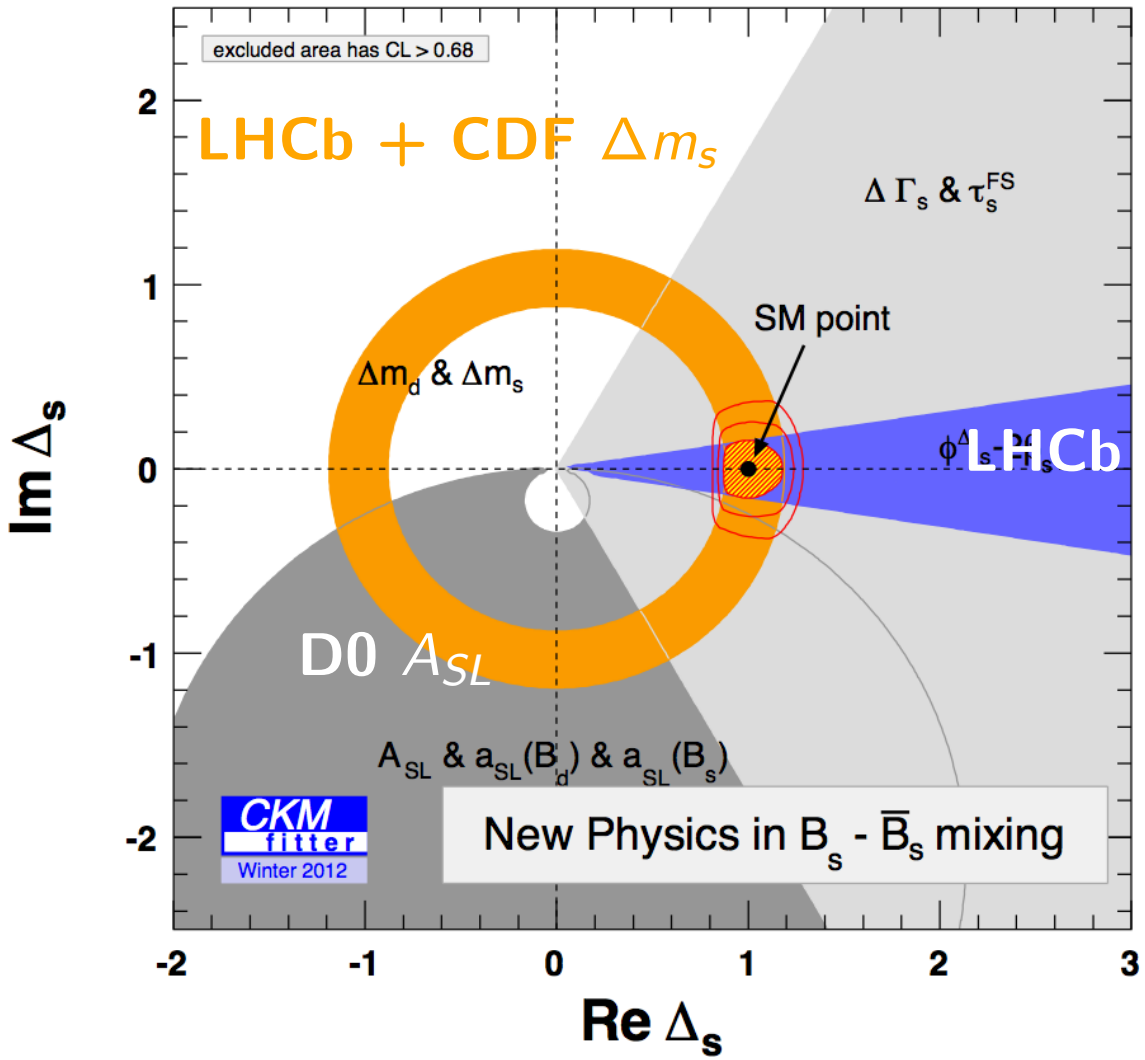


- Dominant systematic is from limited statistics in control sample.
- 3σ **tension with SM in the D0 result, not confirmed or excluded by LHCb.**
- More data needed and addition of B_d mode!

Impact on New Physics

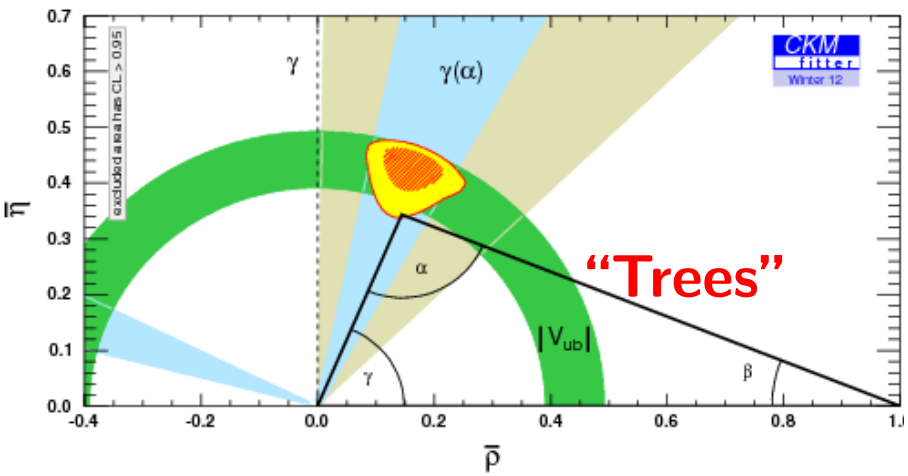
Lenz et al. arXiv:1203.0238v2 [hep-ph]

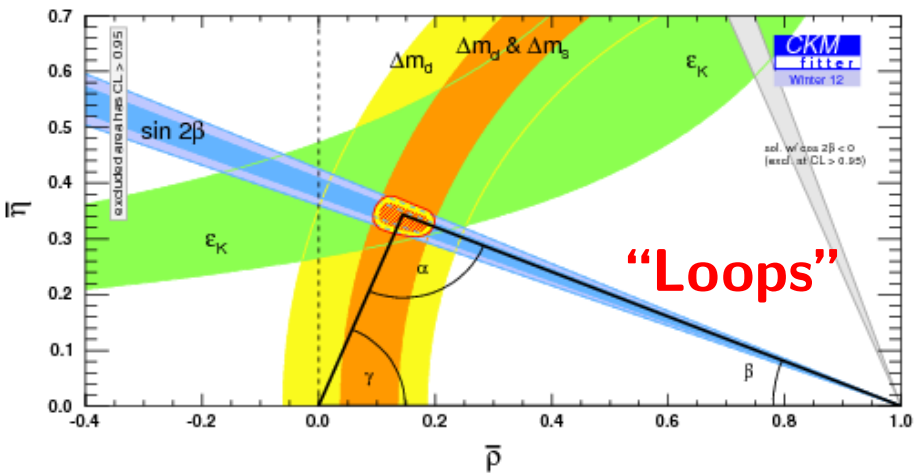
- Model independent analysis places strong constraints on size of NP in M_{12}.
- **Need** increased precision on ϕ_s and a_{sl}.



Towards a precision γ measurement

- Key LHCb objective: precision measurement of $\gamma = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$.
- Typically done using "tree"-level processes which are not sensitive to new physics.
- Need precision $\mathcal{O}(1\%)$ on γ to determine if new physics is hiding in the loops!



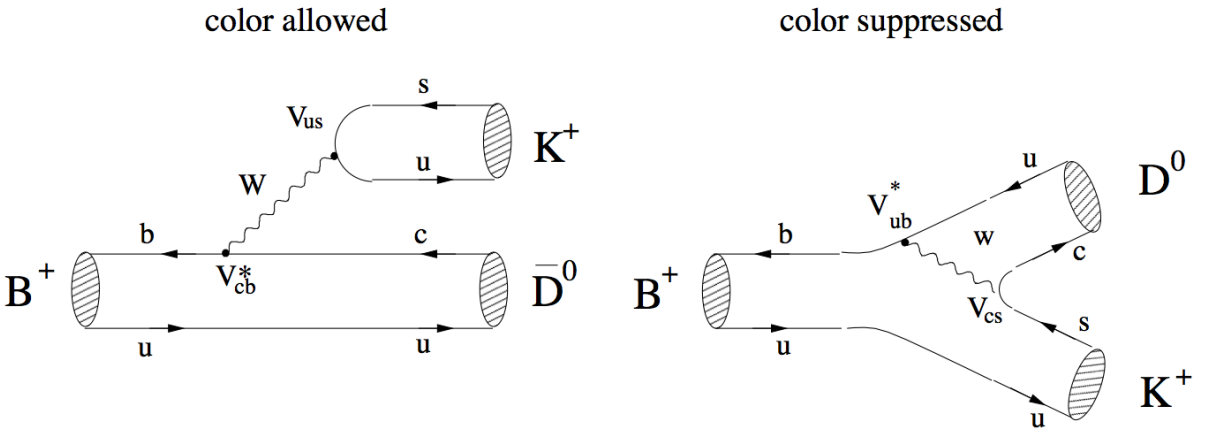


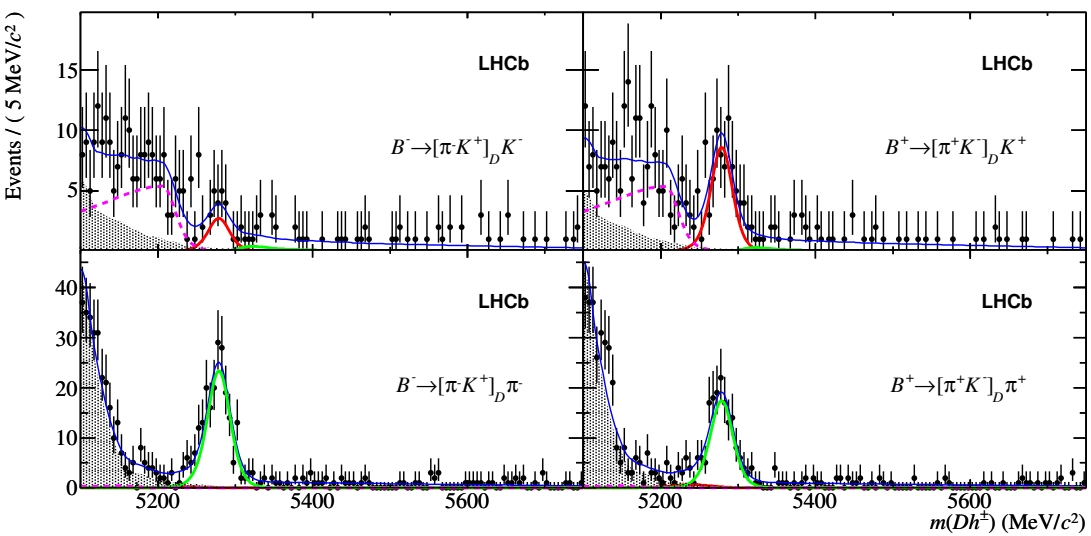
CPV in $B^{\pm} \to DK^{\pm}$

Physics Letters B 712 (2012), pp. 203-212

- Use interference between processes where the D-meson final state is the same for both D^0 and $\bar{D}^0$, i.e., $D \to K^+K^-, \pi^+\pi^-, K^{\pm}\pi^{\mp}$.

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



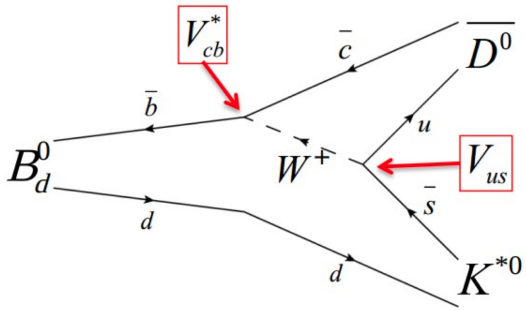


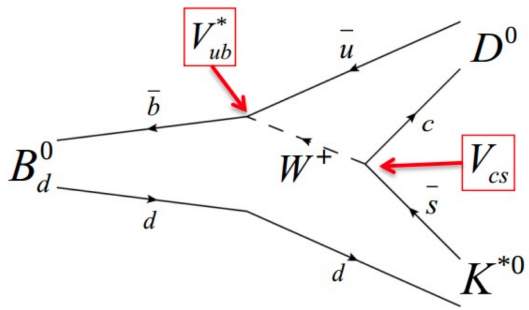
- CP violation in $B^{\pm} \to DK^{\pm}$ is observed with 5.8σ signficance.
- $B^{\pm} \to D(\pi K)_{suppressed} K^{\pm}$ mode observed at $\sim 10\sigma$.
- Gives great sensitivity to γ.

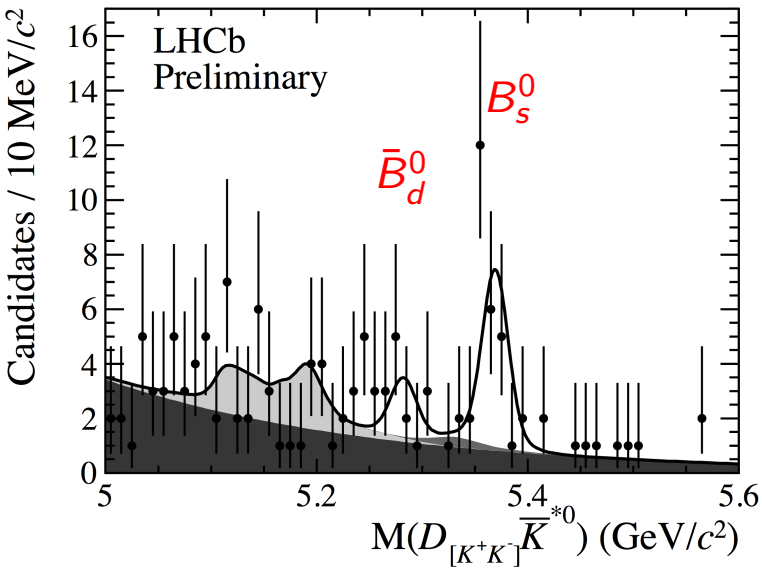
CPV in $B^0 \to DK^{*0}$

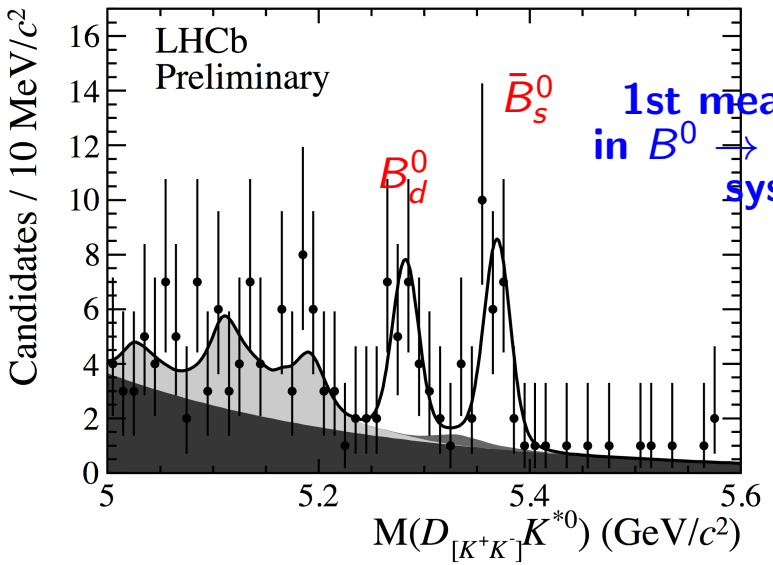
LHCb-CONF-2012-024

- Both decays colour suppressed $\Rightarrow$ enhanced interference $\Rightarrow$ improved sensitivity to γ.
- Select signal using kinematic and vertexing cuts.









1st measurement in $B^0 \to D(KK)K^{*0}$ system

$$\mathcal{A}_{\rm d}^{\rm KK} = -0.47^{+0.24}_{-0.25}(stat) \pm 0.02(syst)$$
$$\mathcal{A}_{\rm s}^{\rm KK} = 0.04 \pm 0.17(stat) \pm 0.01(syst)$$

CPV in other modes

1. Observation of $B^0 \to \bar{D}^0 K^+ K^-$ and evidence for $B_s^0 \to \bar{D}^0 K^+ K^-$

   `arXiv:1207.5991, Phys. Rev. Lett.`

   - Dalitz analysis could have significant impact on γ extraction.

2. First obs. of CPV in charmless 3-body B decays ($B \to K^\pm \pi^+ \pi^-$, $B \to K^\pm K^+ K^-$)

   `LHCb-CONF-2012-018`

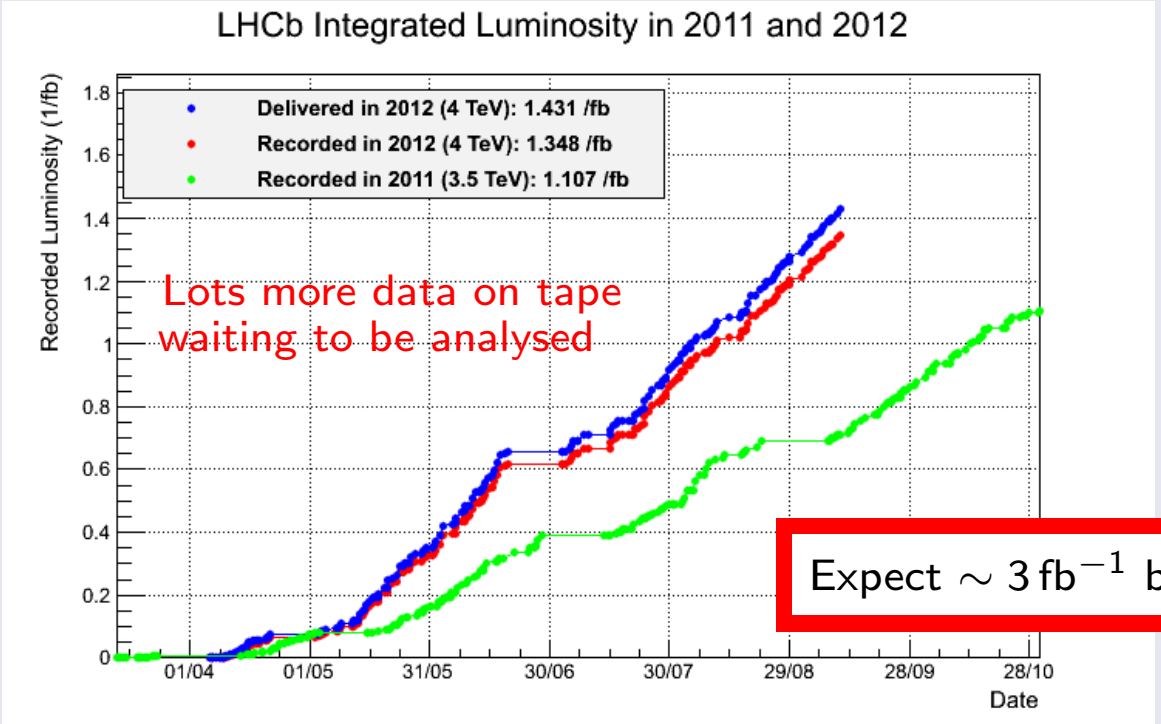
3. First evidence of CPV in charm sector

   `PRL 108 (2012) 111602`

4. ...

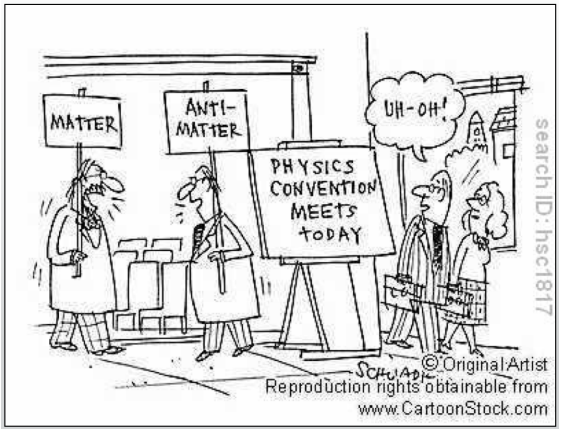
Summary

- Performing precision measurements of CP-violation in the heavy-flavour sector is essential as we search for new physics.
  - Indirect searches are complimentary to those of high-p_{T} programme.
- LHCb detector performance is excellent (clean signals, good decay time resolution).
- LHCb has performed many World's best measurements of CP-violation parameters and asymmetries.
- Working hard to improve the precision of the CKM angle γ.



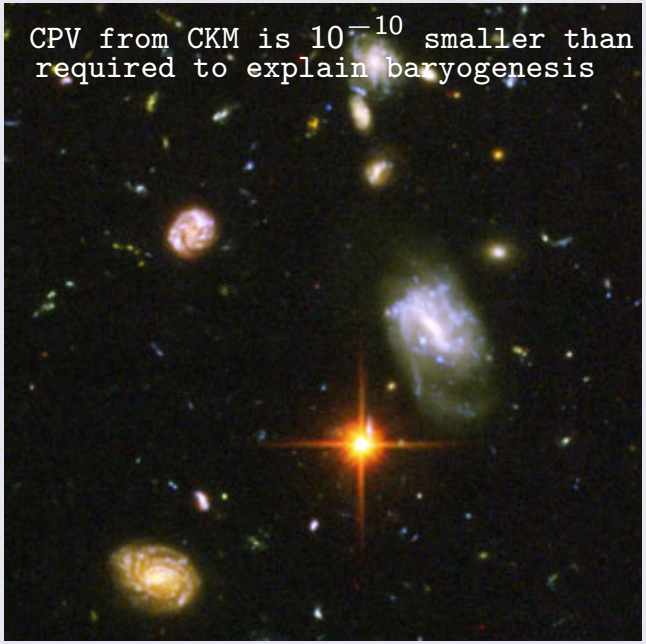
Backup

CP-violation



2001: experimental evidence of *CP*-violation in B-system by BELLE & BaBar

Matter-antimatter asymmetry



Symmetries of nature

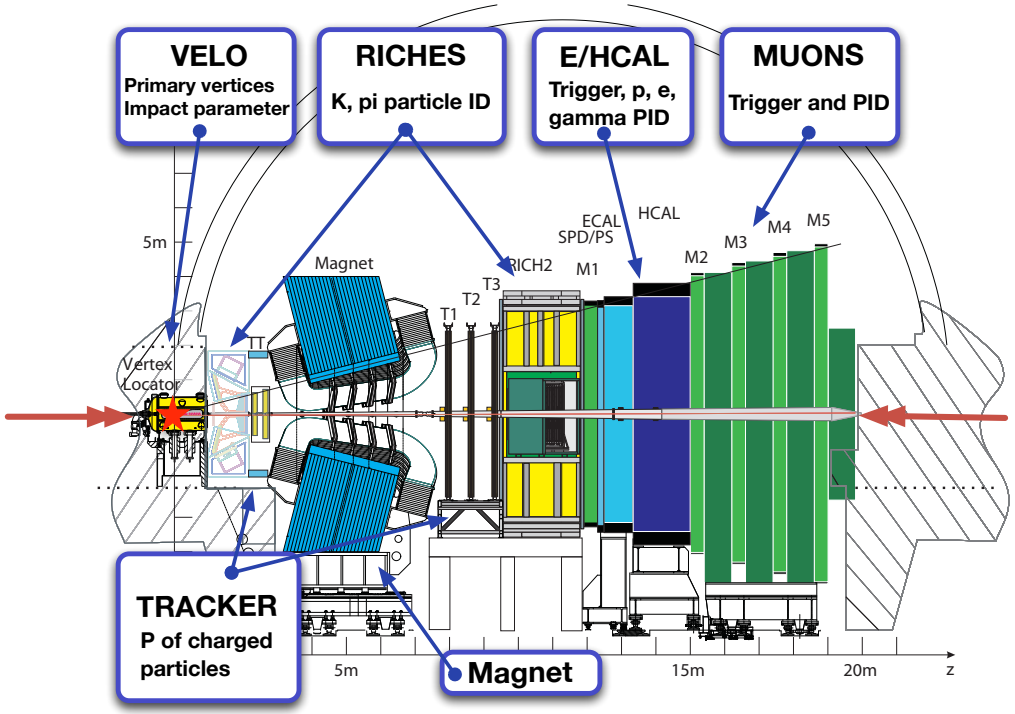
- **C**harge-symmetry converts particles $\leftrightarrow$ antiparticles.
- **P**arity-symmetry converts left $\leftrightarrow$ right.
- *CP*-symmetry is broken in nature!

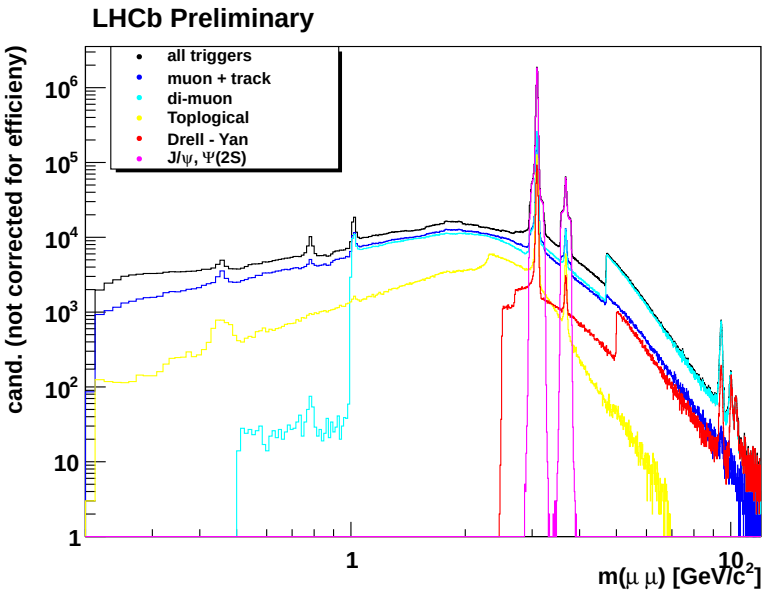
Race for the prize

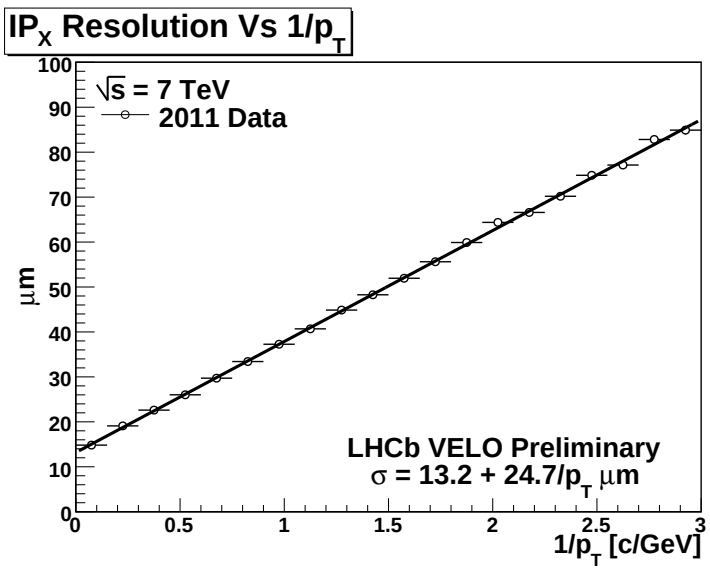
- 2008 Nobel prize in physics to Kobayashi and Maskawa for discovery of theoretical mechanism for *CP*-violation in the Standard Model.

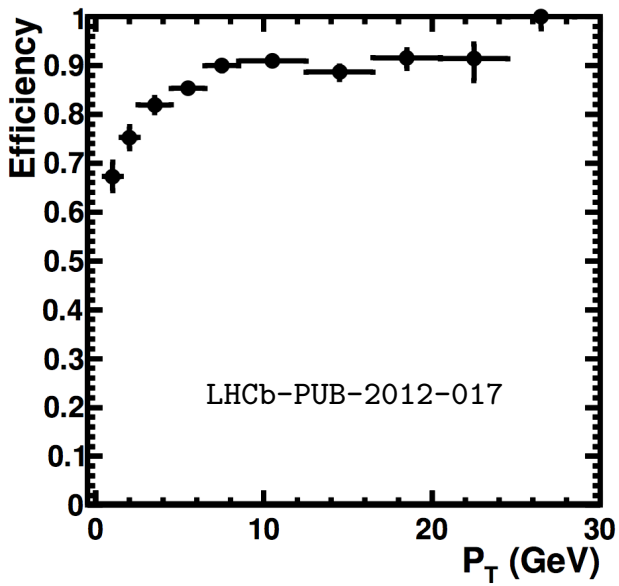
LHC*b* detector

2008 JINST 3 S08005









Systematics

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$A_\perp^2$	A_0^2	F_S	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	δ_s [rad]	ϕ_s [rad]
Description of background	0.0010	0.004	-	0.002	0.005	0.04	0.04	0.06	0.011
Angular acceptances	0.0018	0.002	0.012	0.024	0.005	0.12	0.06	0.05	0.012
t acceptance model	0.0062	0.002	0.001	0.001	-	-	-	-	-
z and momentum scale	0.0009	-	-	-	-	-	-	-	-
Prod. asymmetry ($\pm$ 10%)	0.0002	0.002	-	-	-	-	-	-	0.008
CPV mixing & decay ($\pm$ 5%)	0.0003	0.002	-	-	-	-	-	-	0.020
Fit bias	-	0.001	0.003	-	0.001	0.02	0.02	0.01	0.005
Quadratic sum	0.0066	0.006	0.013	0.024	0.007	0.13	0.07	0.08	0.027

ϕ_s

1. Neglecting potential CPV in mixing and decay.
   - Fit for $|\lambda|$ shows that $\Delta(|\lambda|^2) = \pm 5\%$ is a reasonable variation.
   - Evaluate using toys generating with $|\lambda|^2 = 0.95, 1.05$ and fitting with $|\lambda|^2 = 1$.
2. Knowledge of angular acceptance.

Systematics

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$A_\perp^2$	A_0^2	F_S	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	δ_s [rad]	ϕ_s [rad]
Description of background	0.0010	0.004	-	0.002	0.005	0.04	0.04	0.06	0.011
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t acceptance model	0.0062	0.002	0.001	0.001	-	-	-	-	-
z and momentum scale	0.0009	-	-	-	-	-	-	-	-
Prod. asymmetry ($\pm$ 10%)	0.0002	0.002	-	-	-	-	-	-	0.008
CPV mixing & decay ($\pm$ 5%)	0.0003	0.002	-	-	-	-	-	-	0.020
Fit bias	-	0.001	0.003	-	0.001	0.02	0.02	0.01	0.005
Quadratic sum	0.0066	0.006	0.013	0.024	0.007	0.13	0.07	0.08	0.027

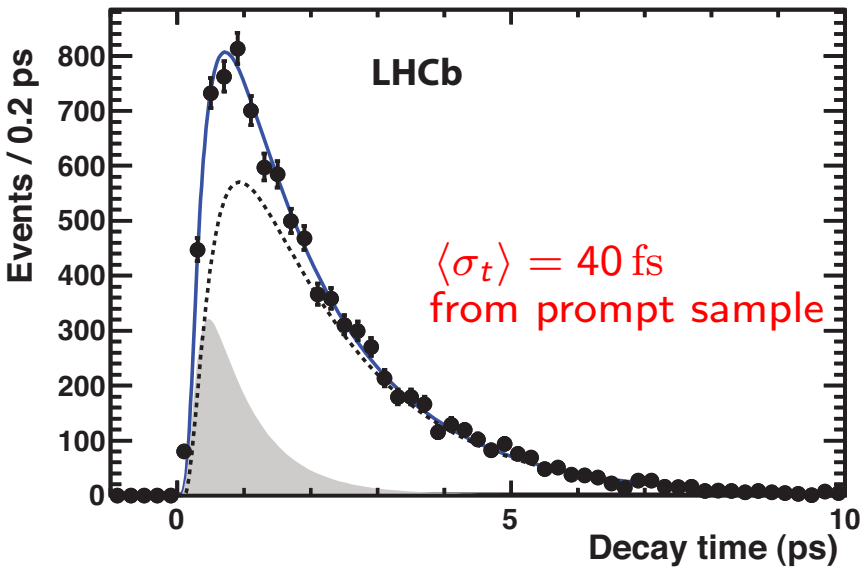
$\Delta\Gamma_s, \Gamma_s$

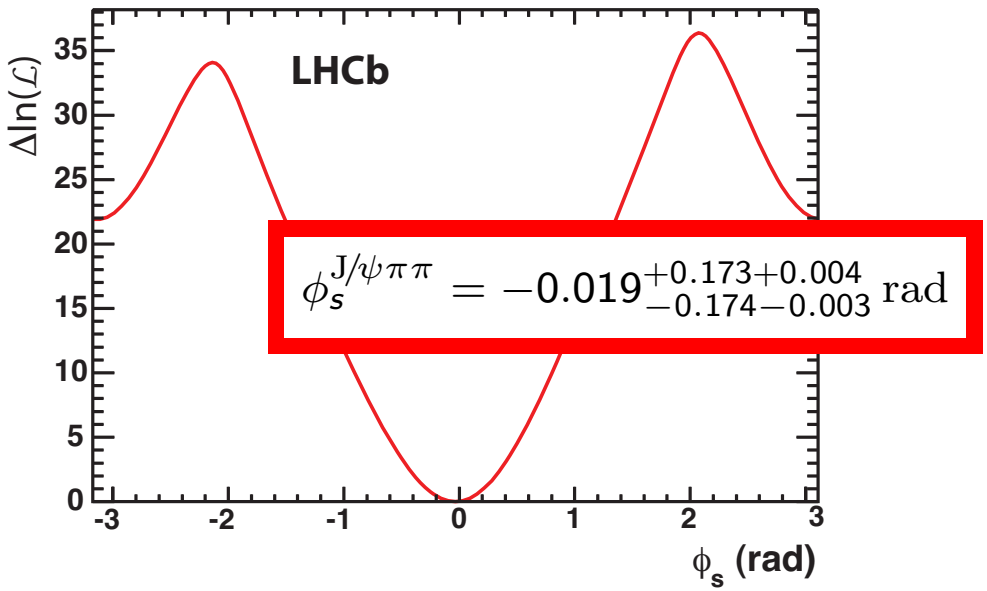
1. Background description.
2. Upper decay time acceptance affects Γ_s.
3. Trigger acceptance affects $\Delta\Gamma_s$, amplitudes.

ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$

arXiv:1204.5675v3, submitted to Phys. Lett. B

- $\Gamma_s, \Delta\Gamma_s$ constrained from $B_s^0 \to J/\psi\phi$ analysis (see talk from A. Phan on B_s^0 lifetimes)
- Δm_s from LHCb (Phys. Lett. B709 (2012) 177).



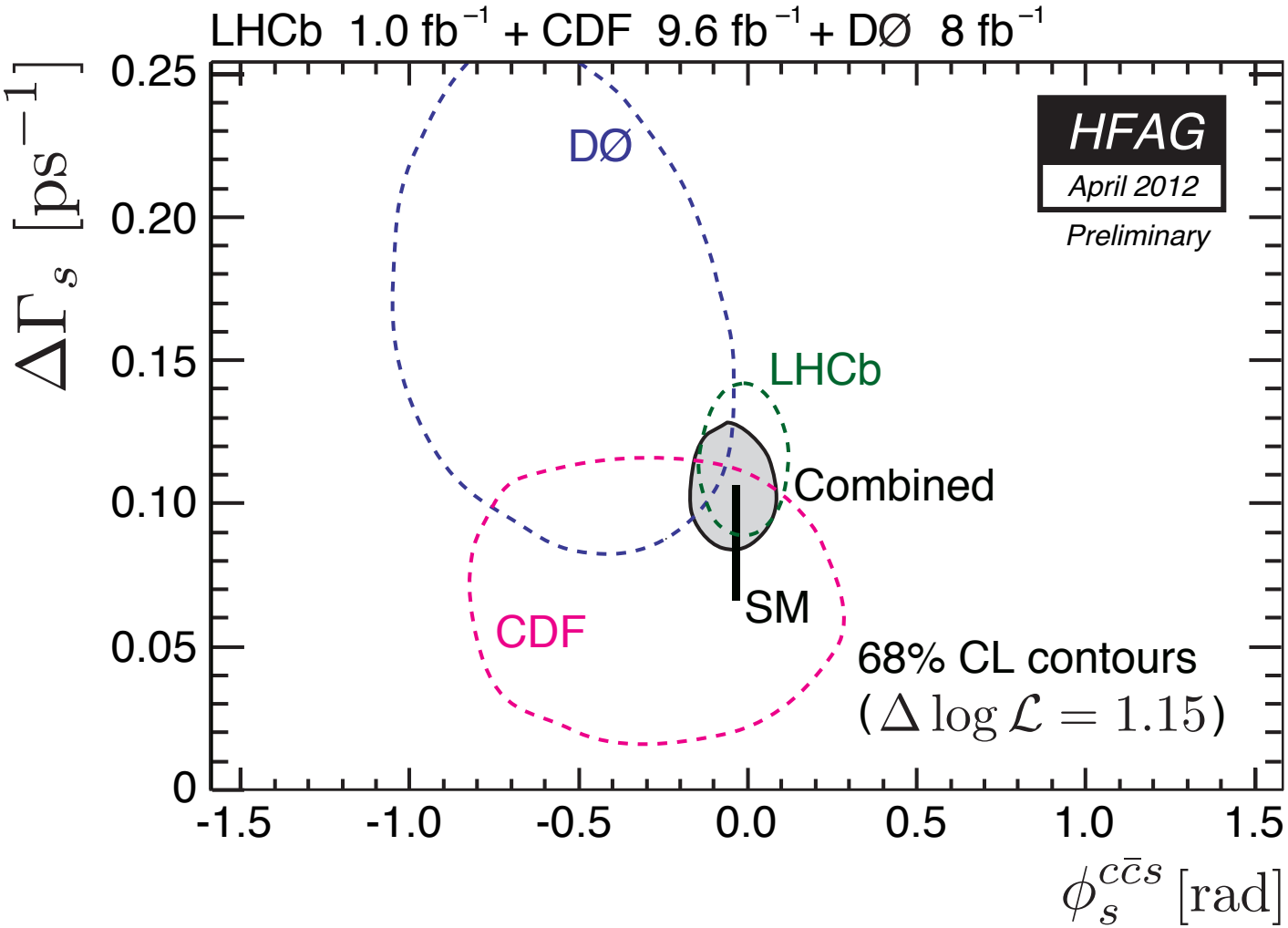


Simultaneous fit of $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$

$$\phi_s = -0.002 \pm 0.083 \pm 0.027\,\text{rad}$$

Latest ϕ_s combination

arXiv:1207.1158



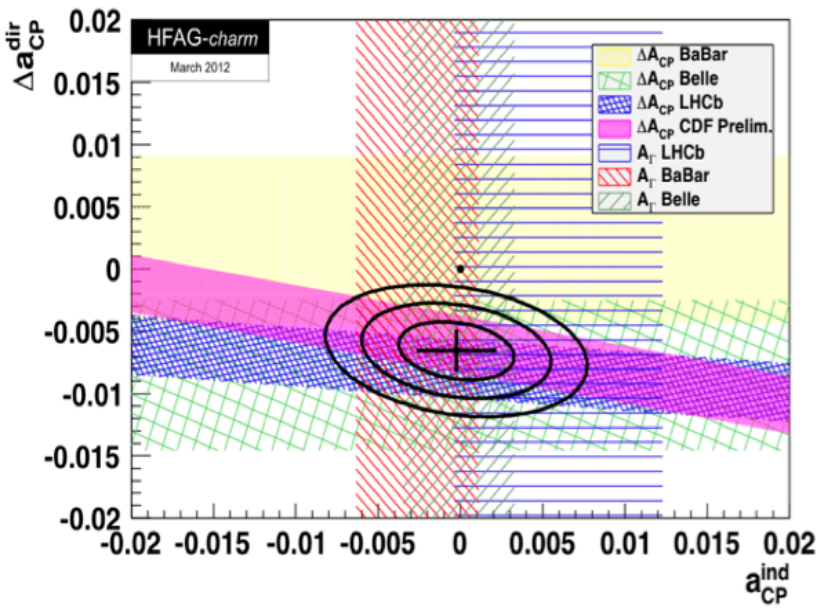
$$\phi_s = -0.044^{+0.090}_{-0.085}\,\text{rad}, \qquad \Delta\Gamma_s = +0.105 \pm 0.015\,\text{ps}^{-1}$$

First evidence of CPV in charm sector

PRL 108 (2012) 111602

- Select $D^{*+} \to D^0 \pi_s^+$ and tag initial flavour of D^0 or $\bar{D}^0$ using π_s.

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

- ΔA_{CP} should be small in the SM, although precise prediction is difficult.
- Taking the difference allows us to cancel some systematics:
  1. D^* production asymmetry
  2. slow pion reco efficiency asymmetry

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