technische universität dortmund

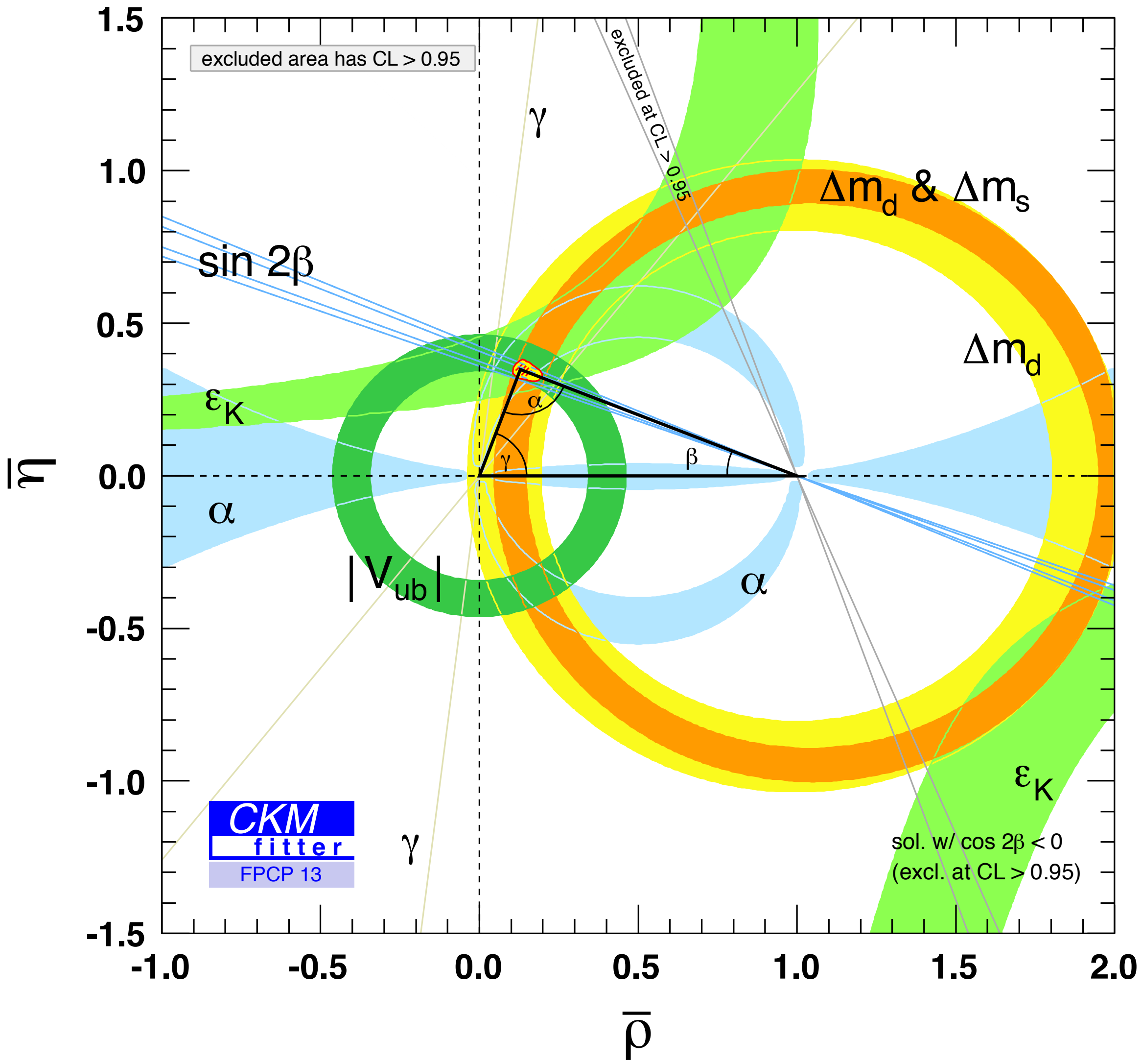

CC BY-NC-SA 2.0 peregrinari

CP violation in B decays at LHCb

Windows on the Universe (Inaugural Conference of ICISE)
11–17 August 2013 – Quy Nhon, Vietnam
Florian Kruse – on behalf of the LHCb collaboration

CP violation

- Violation of CP symmetry:
  - particles and antiparticles behave differently
  - well established in Standard Model (CKM matrix → unitarity triangles)
- Why CP violation?
  - tiny matter-antimatter asymmetry resulted in matter-dominated universe
  - CPV required to explain asymmetry
  - CPV in SM not enough
- Why measure CP violation?
  - test SM by over-constraining CKM parameters
  - find contributions of Physics Beyond the Standard Model (BSM)

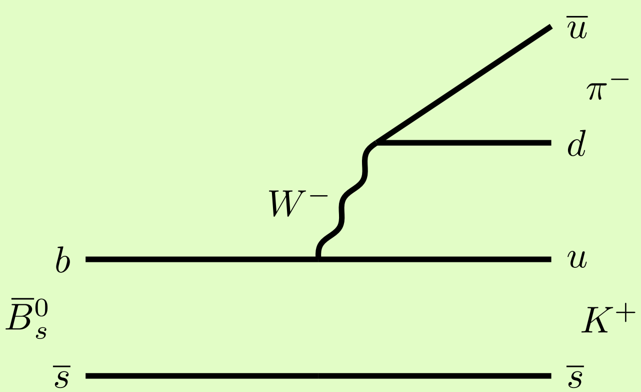


$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{ub} \end{pmatrix}$$

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

Sources of CP violation

DIRECT CPV

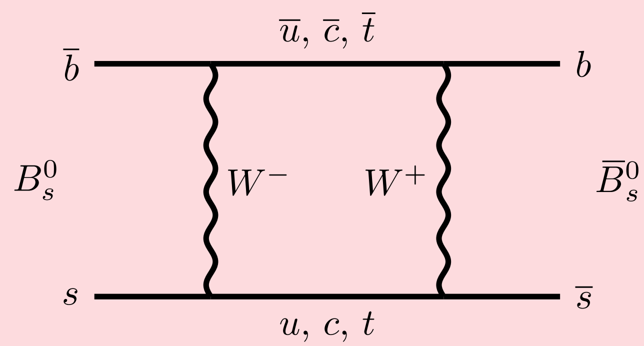


different decay rates for

$$\Gamma(B \to X) \neq \Gamma(\overline{B} \to \overline{X})$$

- $B_{(s)}$→Kπ
- γ in $B^{\pm}$→$Dh^{\pm}$

MIXING CPV

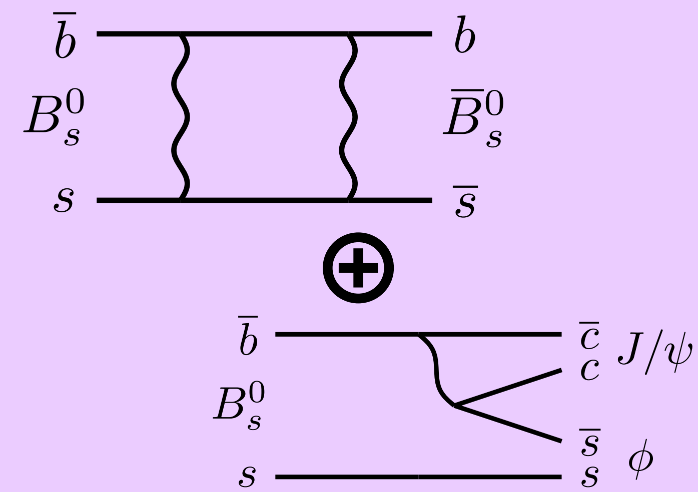


difference in mixing

$$\Gamma(B(t) \to \overline{X}) \neq \Gamma(\overline{B}(t) \to X)$$

- flavour-specific asymmetry a_{sl}

INTERFERENCE CPV

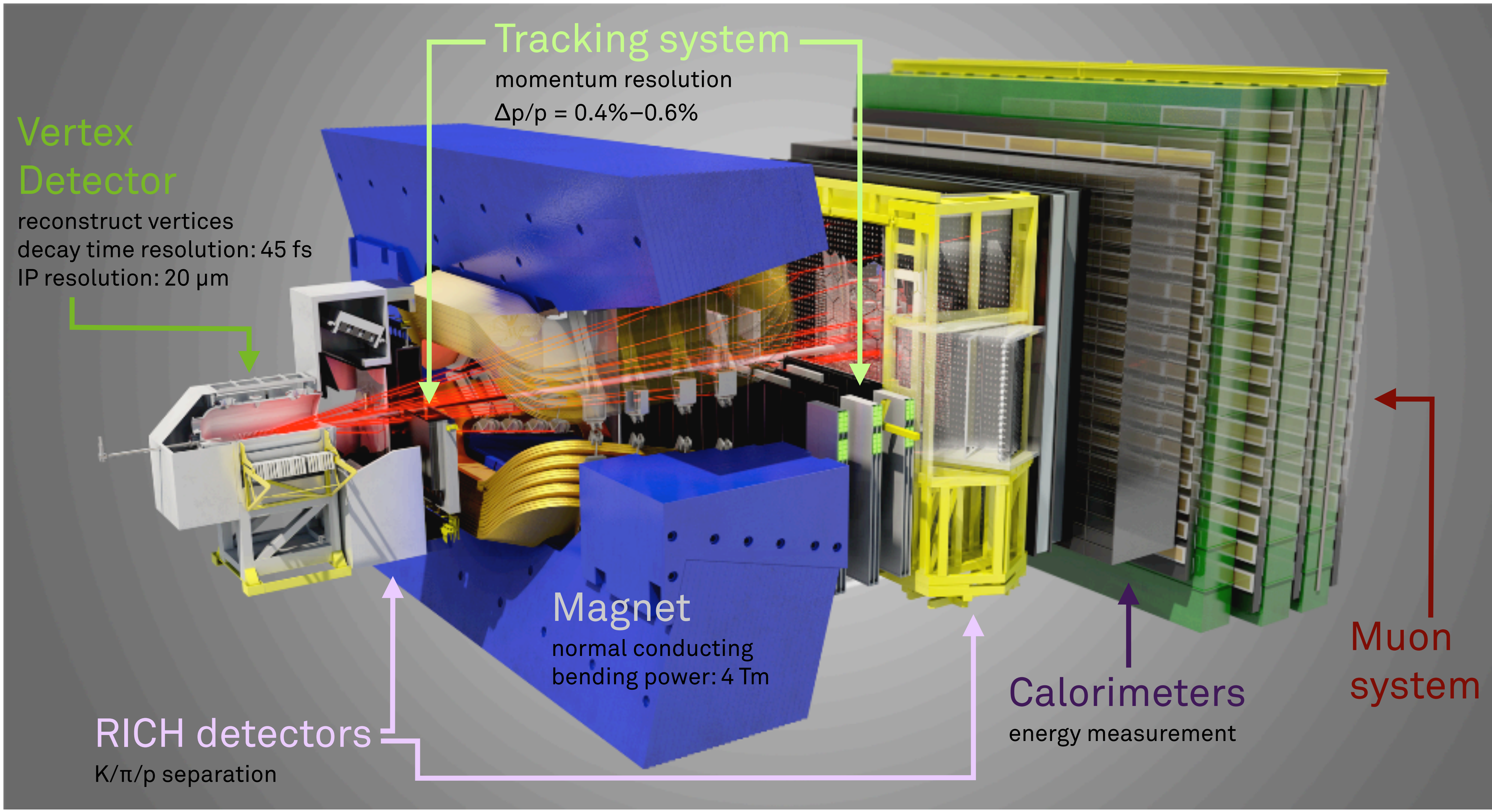


interference in mixing and decay

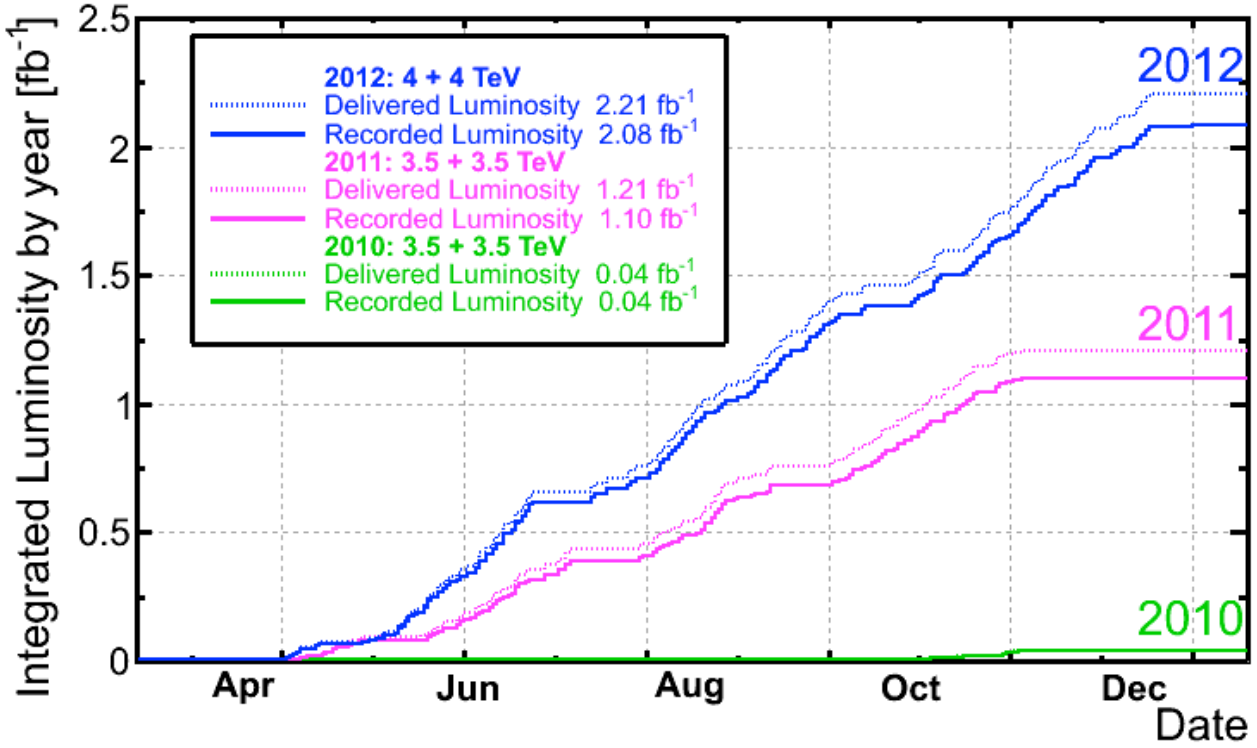
$$\Gamma(B(t) \to X_{CP}) \neq \Gamma(\overline{B}(t) \to X_{CP})$$

- B_d→J/ψK_S
- B_s→J/ψKK / J/ψππ

The LHCb detector



LHCb performance



- Total luminosity:
  - $L_{int} \approx 3\ fb^{-1}$
- Data taking efficiency: 93%
- Trigger:
  - reducing 20 MHz collision rate to 5 kHz output rate

Direct CPV

$B_{(s)} \to K\pi$
γ in $B^{\pm} \to Dh^{\pm}$

Direct CP violation in $B_{(s)} \to K\pi$, 1 fb^{-1}

- measure CP asymmetries:

$$A_{CP}(B^0 \to K^+\pi^-) = \frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

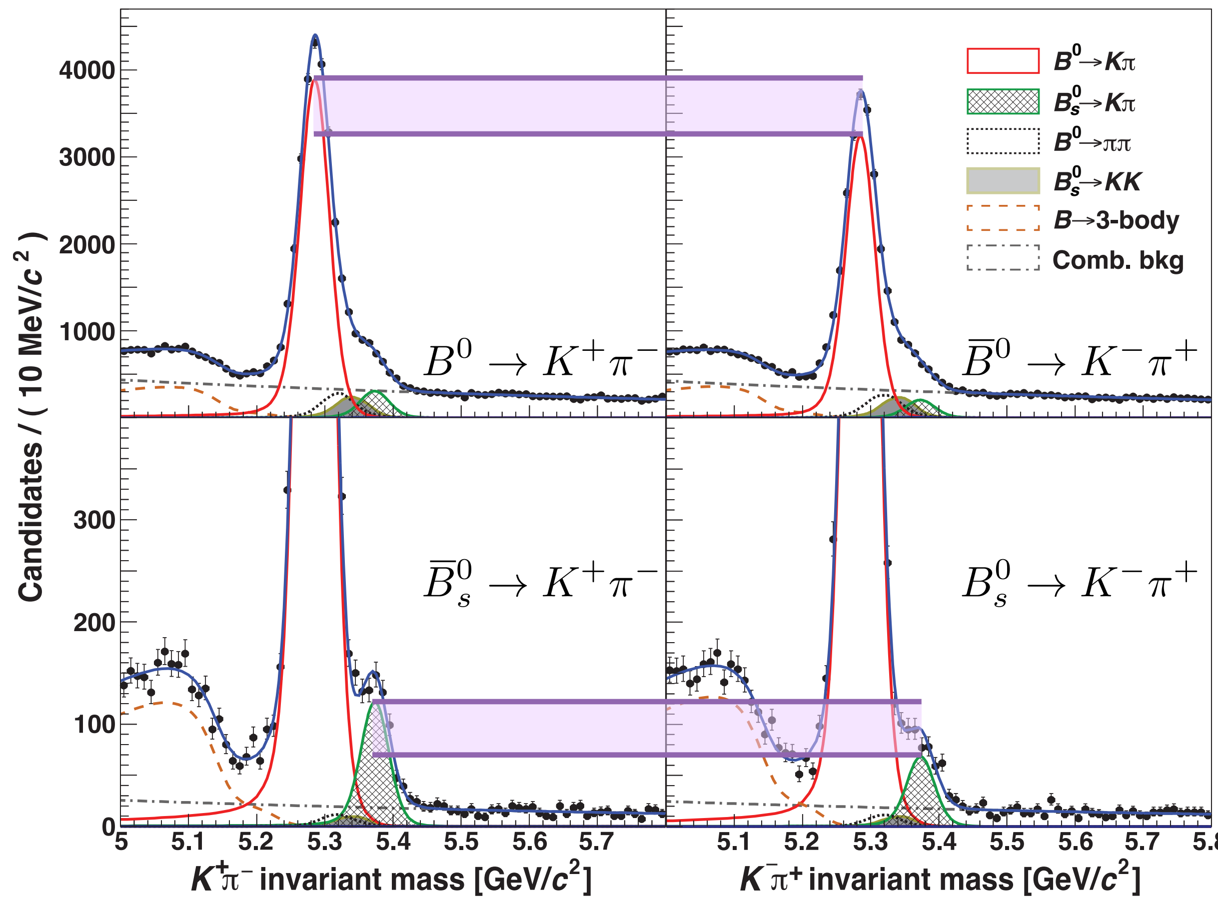
$$A_{CP}(B_s^0 \to K^-\pi^+) = \frac{\Gamma(\overline{B}_s^0 \to K^+\pi^-) - \Gamma(B_s^0 \to K^-\pi^+)}{\Gamma(\overline{B}_s^0 \to K^+\pi^-) + \Gamma(B_s^0 \to K^-\pi^+)}$$

- CPV through interference between tree and penguin contributions

Phys. Rev. Lett. 110 (2013) 221601

- measurement:
  - measure raw asymmetries from mass distribution fit
  - correct raw asymmetries for instrumental and production asymmetries

Direct CP violation in $B_{(s)} \to K\pi$, 1 fb^{-1}



Phys. Rev. Lett. 110 (2013) 221601

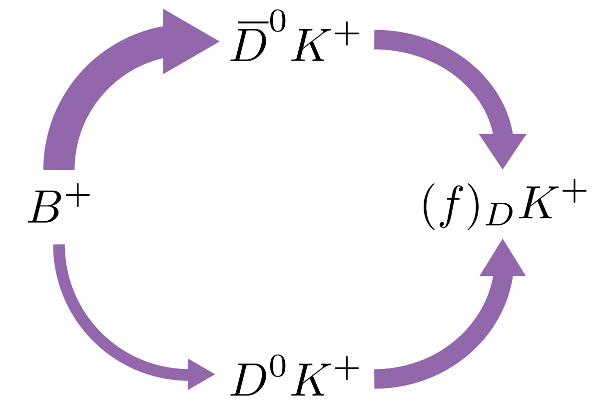
most precise!

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

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

first CPV in B_s (6.5σ)

γ in $B^{\pm}\to Dh^{\pm}$



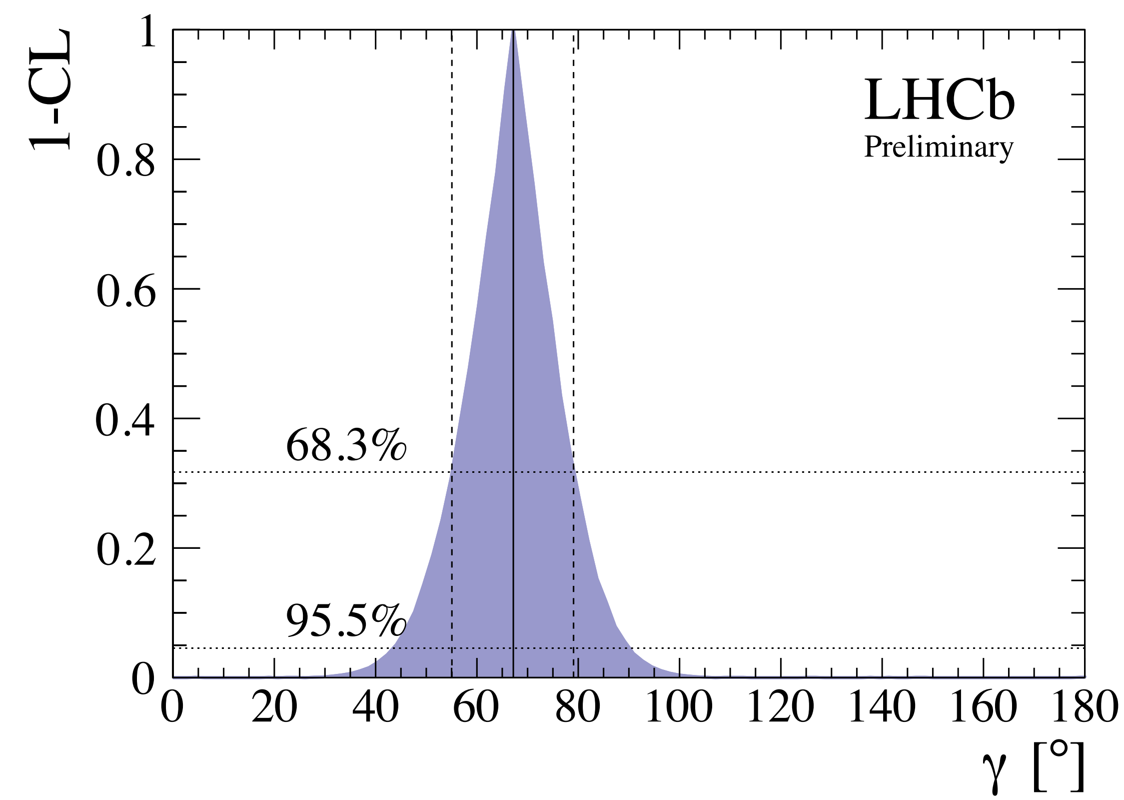
- determination of γ from tree level diagrams in $B^{\pm}\to Dh^{\pm}$
- combine various single measurements (not covered):
  - LHCb γ: GLW ($D\to KK/\pi\pi$), ADS ($D\to K\pi/K\pi\pi\pi$), GGSZ ($D\to K_S\pi\pi/K_S KK$)
  - additional LHCb/CLEO/HFAG inputs on D parameters (mixing, hadronic parameters, CP violation)
  - total of max. 38 observables (γ, phases, ratios, ...)
- use frequentist plugin approach:
  - combine all measurements into single likelihood
  - for nearly all observables: treat stat. + syst. fluctuations as Gaussian
  - correct for undercoverage

γ in $B^\pm \to Dh^\pm$

- using $B^\pm \to DK^\pm$ only, with 2012 data:
  - GLW/ADS with 1 fb^{-1} + GGSZ with 3 fb^{-1} LHCb-CONF-2013-006
  - no D mixing

most precise!

$$\gamma = (67 \pm 12)^\circ$$



- combining $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$:
  - GLW/ADS/GGSZ with 1 fb^{-1}
  - incl. D mixing

$$\gamma = (72.6^{+9.7}_{-17.2})^\circ$$

arXiv:1305.2050

Mixing CPV

Flavour-specific asymmetry a_{sl} in B_s

Flavour-specific asymmetry a_{sl} in B_s

- flavour-specific asymmetry:

$$a_{\mathrm{sl}}^{s} = \frac{\Gamma(\overline{B}{}_s^0(t) \to f) - \Gamma(B_s^0(t) \to \bar{f})}{\Gamma(\overline{B}{}_s^0(t) \to f) + \Gamma(B_s^0(t) \to \bar{f})} \quad \text{with } f : D_s^- X \mu^+ \nu_\mu$$

NEW!

  - $B_s(t)$: time evolution of particle produced as B_s at t=0
  - *f*: flavour-specific final state only B_s can decay into
  - decays only possible via B mixing

arXiv:1308.1048

- measured quantity (time-integrated):

$$A_{\mathrm{meas}} = \frac{\Gamma(D_s^- \mu^+) - \Gamma(D_s^+ \mu^-)}{\Gamma(D_s^- \mu^+) + \Gamma(D_s^+ \mu^-)} = \frac{a_{\mathrm{sl}}^s}{2}$$

  - corrected for reconstruction and background asymmetries

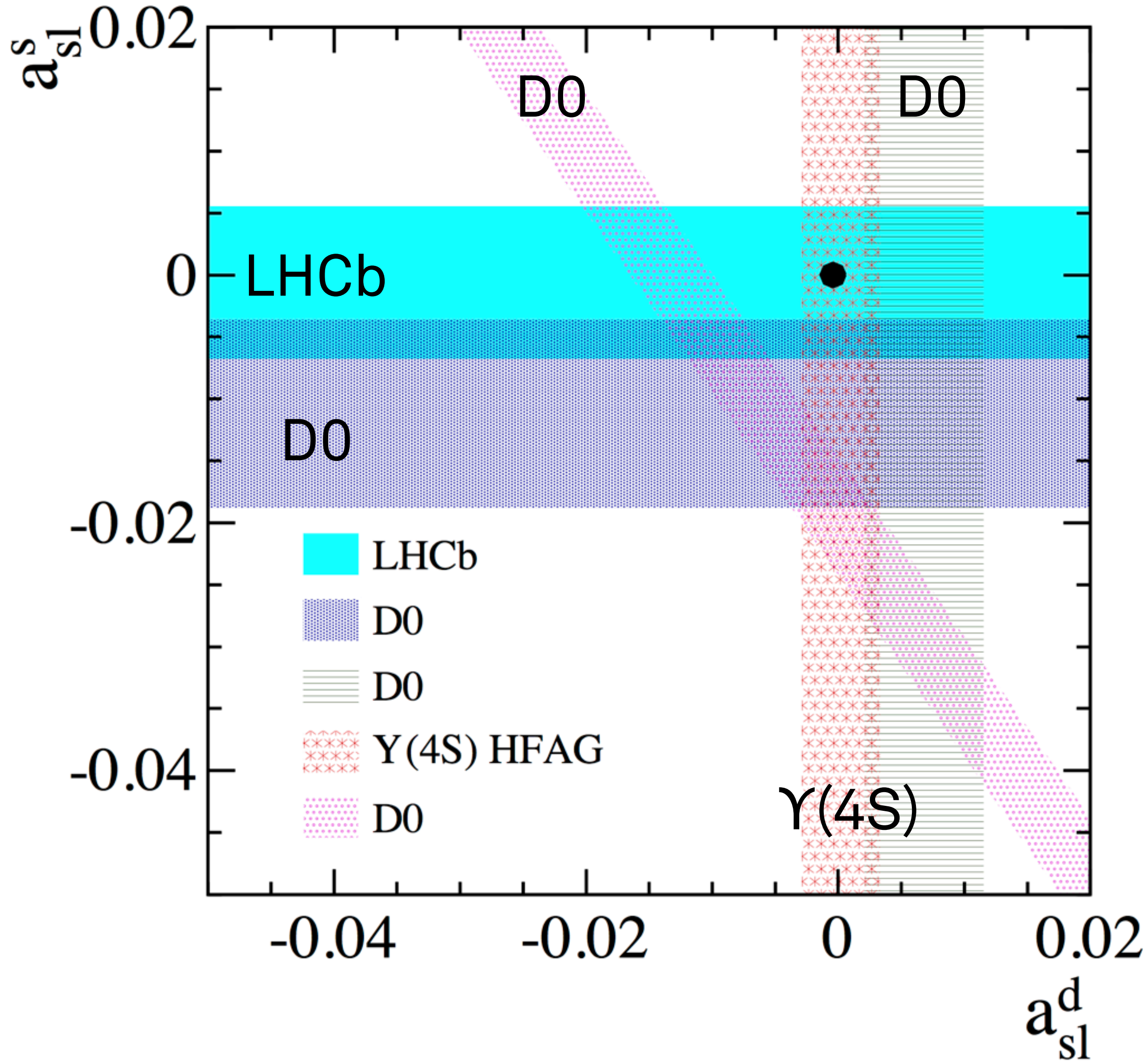
- measurement on 1 fb^{-1}

Flavour-specific asymmetry a_{sl} in B_s

$$a_{\rm sl}^s = (-0.06 \pm 0.50\,({\rm stat}) \pm 0.36\,({\rm syst}))\%$$

most precise!

NEW!



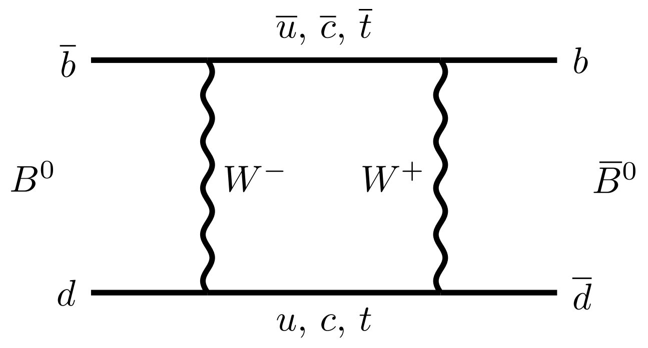
arXiv:1308.1048

Interference CPV

$B_d \to J/\psi K_S$
$B_s \to J/\psi KK$ / $J/\psi \pi\pi$

CP violation in interference between mixing and decay

- neutral B mesons mix through box diagrams



- light and heavy mass eigenstate: B_L, B_H
  - mass difference $\Delta m_{s,d}$ ⇒ oscillation frequency
  - decay width difference $\Delta\Gamma_{s,d}$
- interference CPV:
  - both flavour eigenstates (B/$\overline{\text{B}}$) can decay into common final state f
  - measure time-dependent asymmetry

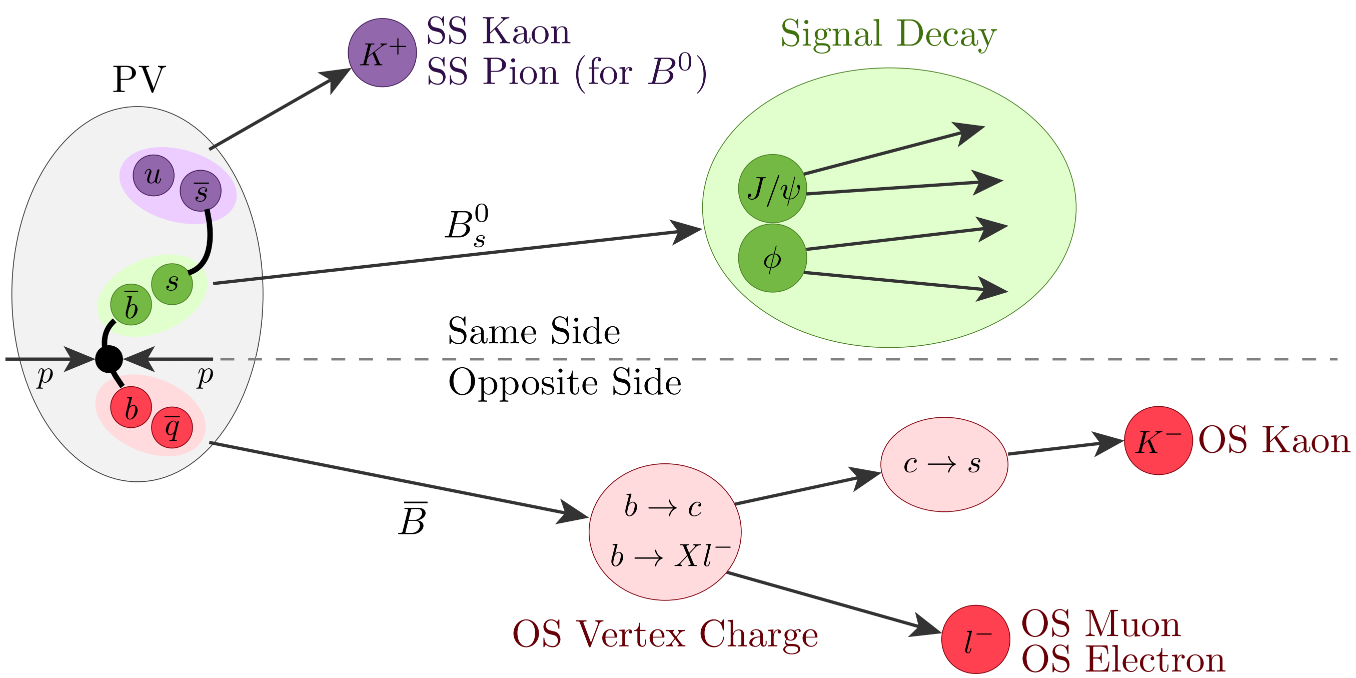
$$A_{CP}(t) = \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to f)}$$

  - B(t): time evolution of particle produced as B at t=0

CP violation in interference between mixing and decay

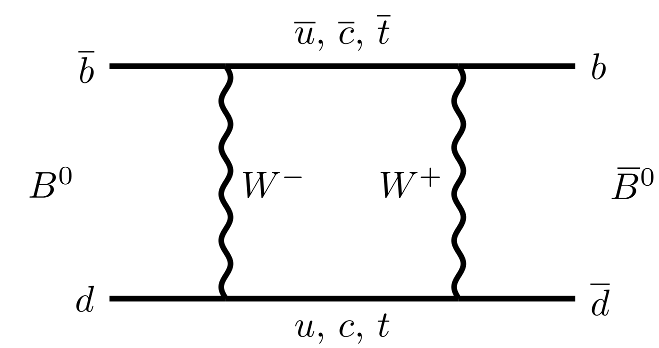
- ingredients to measure interference CPV:
  - B production flavour ⇒ Flavour Tagging
  - B decay time
  - wrong-tag rate
  - decay time resolution

$$A_{CP}(t) = \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to f)}$$



CP asymmetry in $B_d \to J/\psi K_S$

- measurement of time-dependent asymmetry:



$$A_{J/\psi K^0_S}(t) = \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t)$$

- in SM: direct and mixing CPV negligible:

$$C_{J/\psi K^0_S} \approx 0 \Rightarrow S_{J/\psi K^0_S} = \sin 2\beta$$

- “golden mode” for sin2β, world averages:

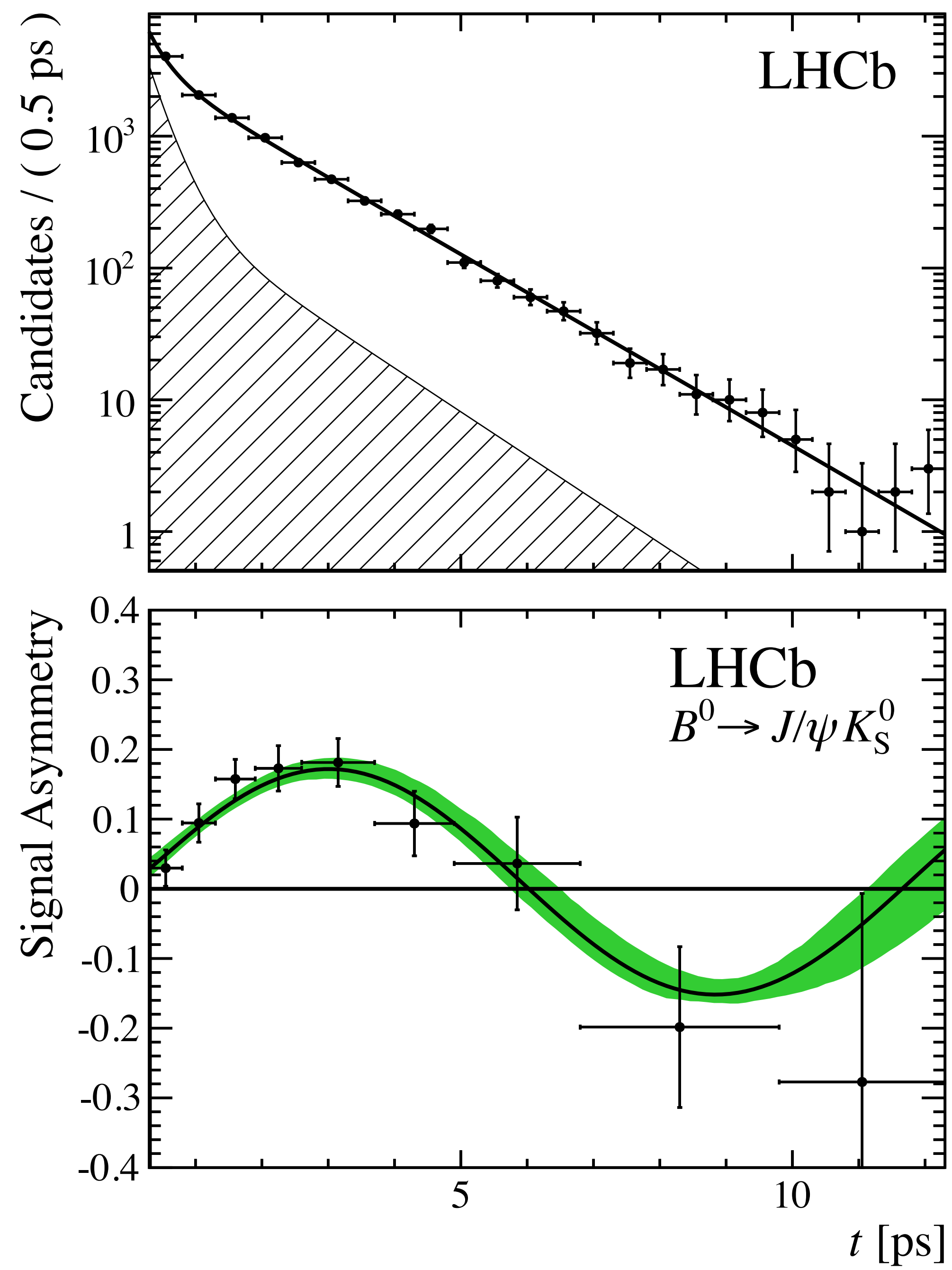
$$S_{J/\psi K^0_S} = 0.665 \pm 0.024 \quad C_{J/\psi K^0_S} = 0.024 \pm 0.026$$

CP asymmetry in $B_d \to J/\psi K_S$

- result on 1 fb^{-1} data:

$$S_{J/\psi K^0_S} = 0.73 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{syst})$$
$$C_{J/\psi K^0_S} = 0.03 \pm 0.09\,(\text{stat}) \pm 0.01\,(\text{syst})$$

- first significant CPV measurement in $B_d \to J/\psi K_S$ at hadron collider
- only OS tagging used



Phys. Lett. B 721 (2013) 24-31

CP violation in $B_s \to J/\psi K^+K^-$ / $J/\psi\pi^+\pi^-$

- CP violating phase ϕ_s, standard model prediction:

$$\phi_s^{\rm SM} = -0.036 \pm 0.002\,{\rm rad}$$

- possible new physics (NP) in box diagrams:

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

- challenges:
  - $\Delta m_s = 17.8\ \mathrm{ps}^{-1}$ ($\Delta m_d = 0.510\ \mathrm{ps}^{-1}$)
  - LHCb decay time resolution: 45 fs
  - precise resolution description essential
  - K^+K^- via P-wave ($\phi(1020)$) or non-resonant S-wave
  - disentanglement via angular analysis

can fit for $\Delta\Gamma_s$!

CP violation in $B_s \to J/\psi K^+K^-$ / $J/\psi \pi^+\pi^-$

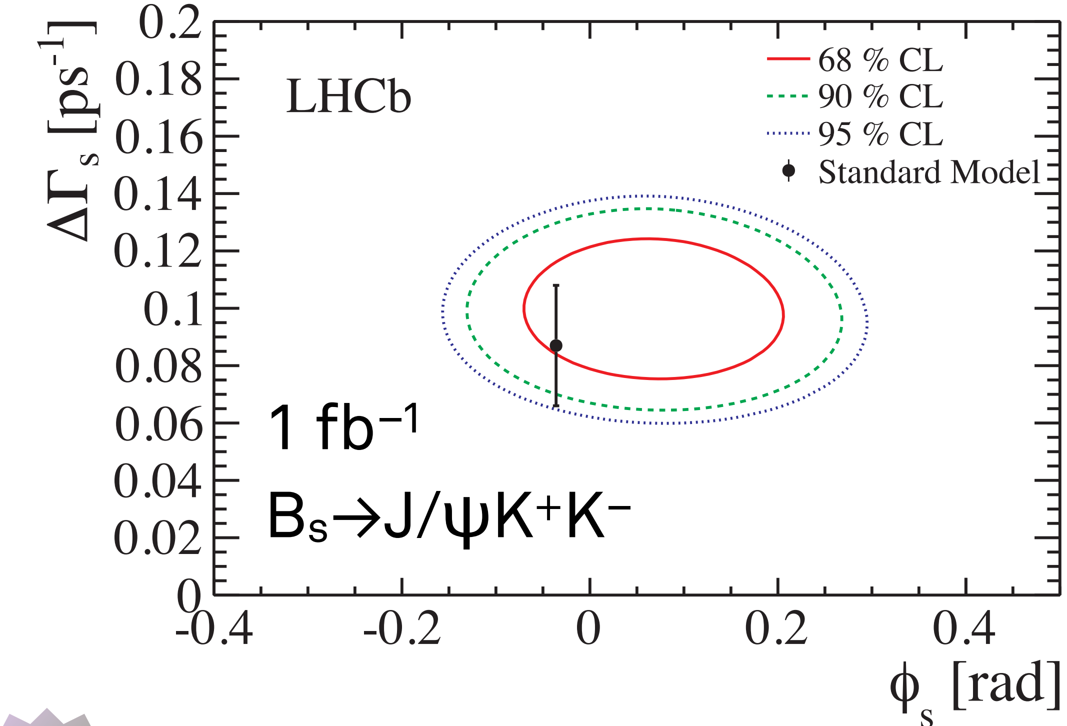
- using only $B_s \to J/\psi K^+K^-$, $1 fb^{-1}$:

$$\phi_s = 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst) rad}$$
$$\Gamma_s = 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}$$
$$\Delta\Gamma_s = 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst) ps}^{-1}$$

- $B_s \to J/\psi K^+K^-$ + $B_s \to J/\psi \pi^+\pi^-$, $1 fb^{-1}$:

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

most precise!



- combining OS+SS tagging
- data split in six bins of invariant K^+K^- mass
  - higher statistical precision
  - resolve ambiguity in ϕ_s and $\Delta\Gamma_s$

Phys. Rev. D 87, 112010 (2013)

Conclusions

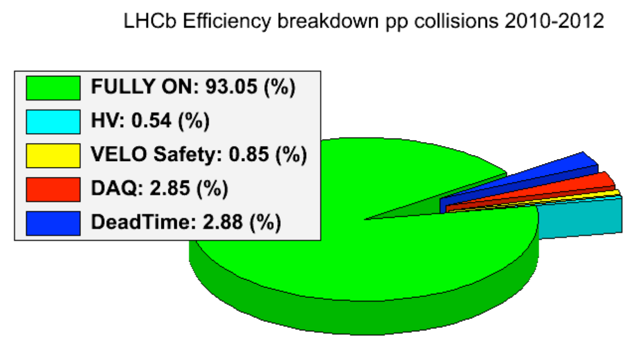
- with 1 fb^{-1} of data:
  - ϕ_s, $\Delta\Gamma_s$, Γ_s: most precise single measurement
  - $S_{J/\psi KS}$, $C_{J/\psi KS}$: most precise and first significant CP violation at a hadron collider
  - γ: LHCb competitive
  - $B_{(s)} \to K\pi$: first observation of CP violation in B_s decays
- new analyses with 3 fb^{-1} expected soon:
  - Standard Model tests and searches for new physics ongoing

Backup

LHCb facts

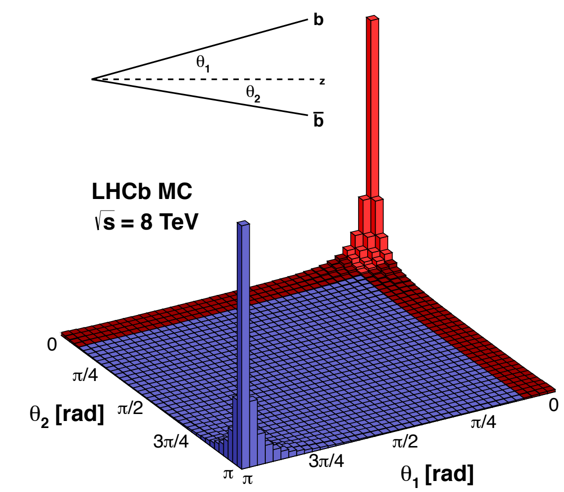
Integrated luminosity

2010:
37 pb^{-1}
2011:
1.0 fb^{-1}
2012:
2 fb^{-1} (note number of digits)



Acceptance

pseudorapidity:
$2 < \eta < 5$



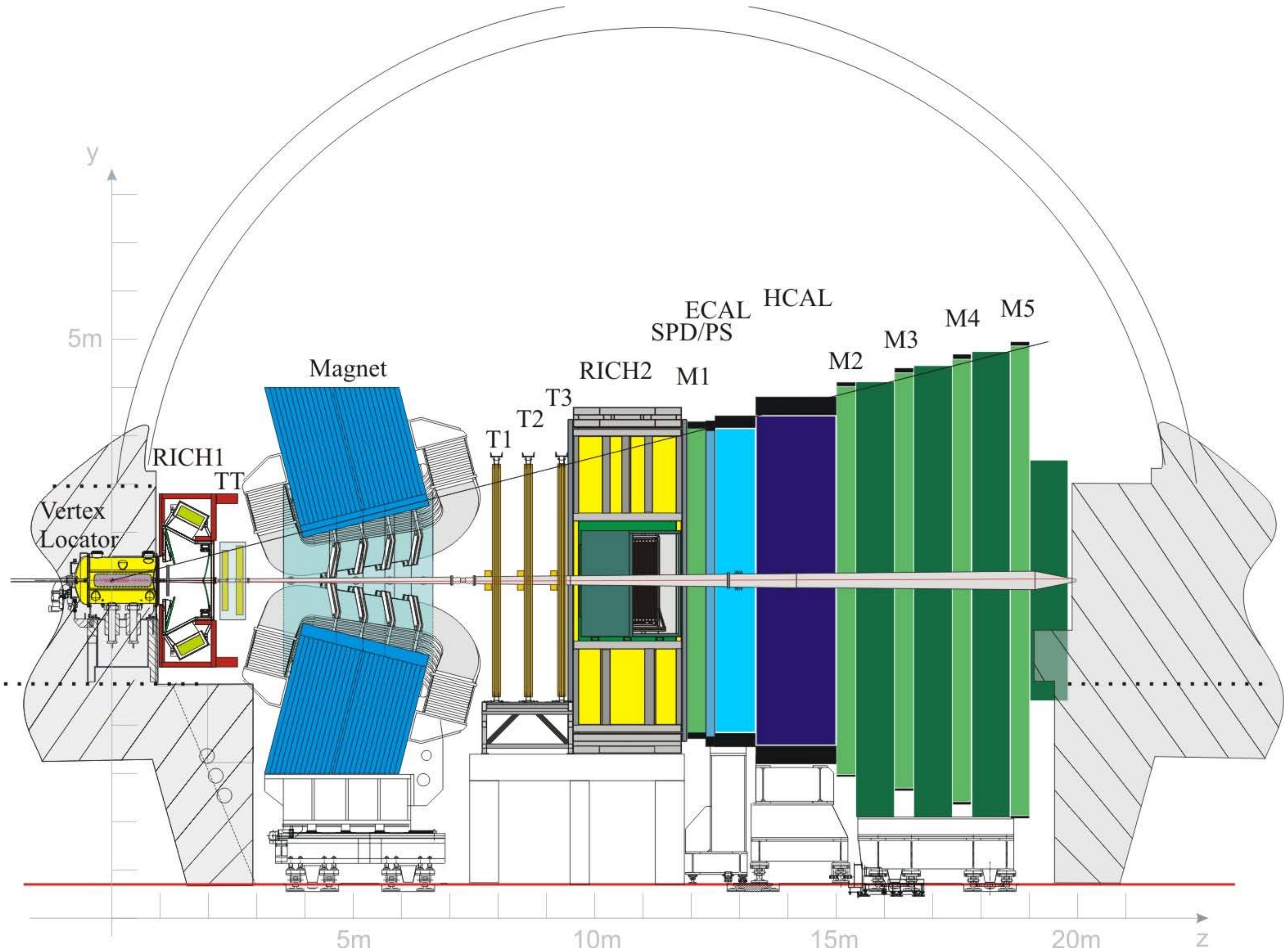
Resolutions

momentum resolution:
$\Delta p / p$ = 0.4 % at 5 GeV/c to 0.6 % at 100 GeV/c
ECAL resolution (nominal):
1 % + 10 % / √(E[GeV])
impact parameter resolution:
20 µm for high-pT tracks
invariant mass resolution:
~8 MeV/c^2 for $B \to J/\psi X$ decays with constraint on J/ψ mass
~22 MeV/c^2 for two-body B decays
~100 MeV/c^2 for $B_s \to \varphi \gamma$, dominated by photon contribution
decay time resolution:
45 fs for $B_s \to J/\psi \varphi$ and for $B_s \to D_s \pi$

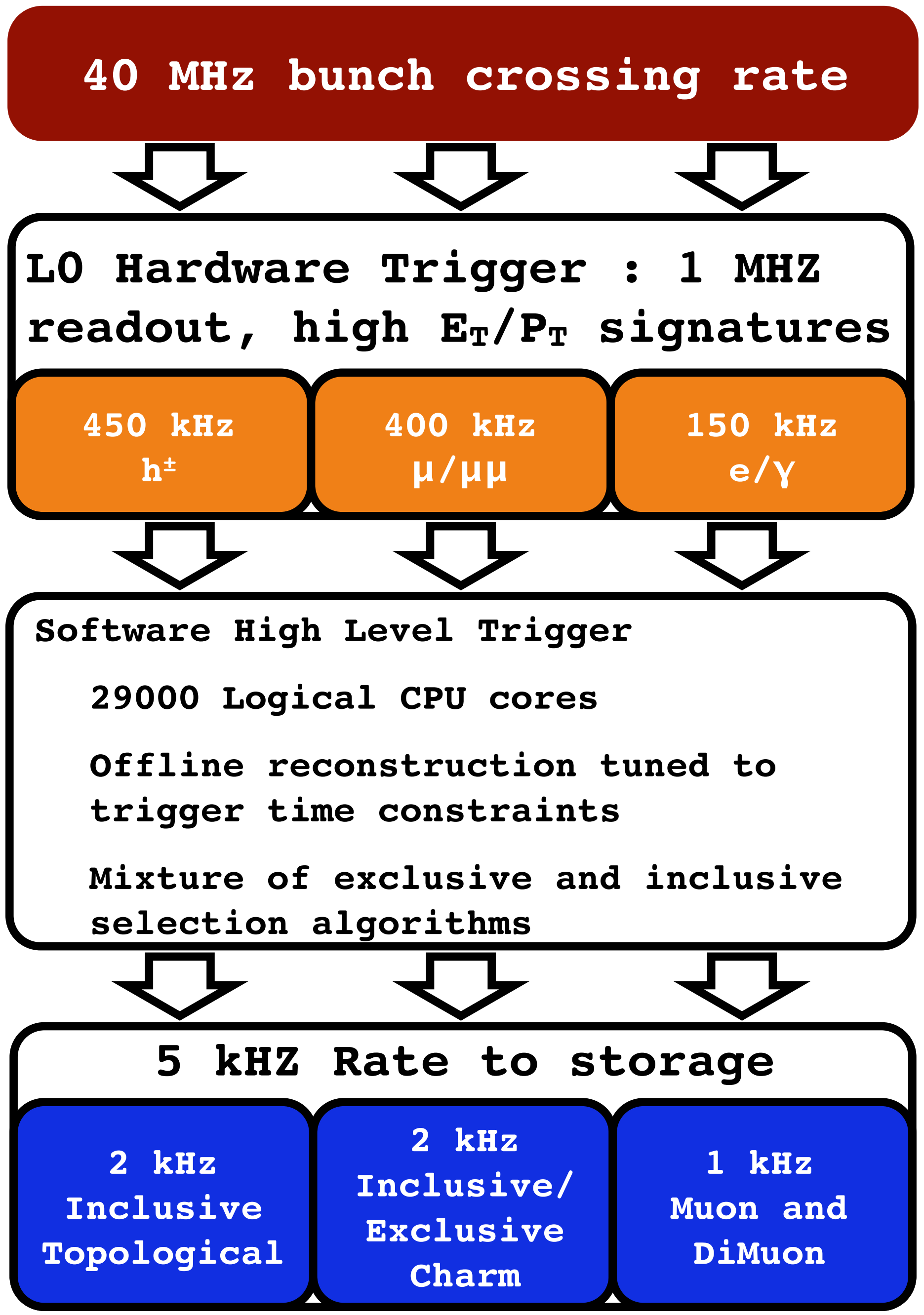
Efficiencies

percentage of working detector channels:
~ 99 % for all sub-detectors
data taking efficiency:
> 90 %
data good for analyses:
> 99 %
trigger efficiencies:
~ 90 % for dimuon channels
~ 30 % for multi-body hadronic final states
track reconstruction efficiency:
> 96 % for long tracks
electron ID efficiency:
~ 90 % for ~ 5 % $e \to h$ mis-id probability
kaon ID efficiency:
~ 95 % for ~ 5 % $\pi \to K$ mis-id probability
muon ID efficiency:
~ 97 % for 1-3 % $\pi \to \mu$ mis-id probability

LHCb schematics



LHCb Trigger



- two stage trigger
  - L0 Trigger (Hardware)
  - High Level Trigger (Software)

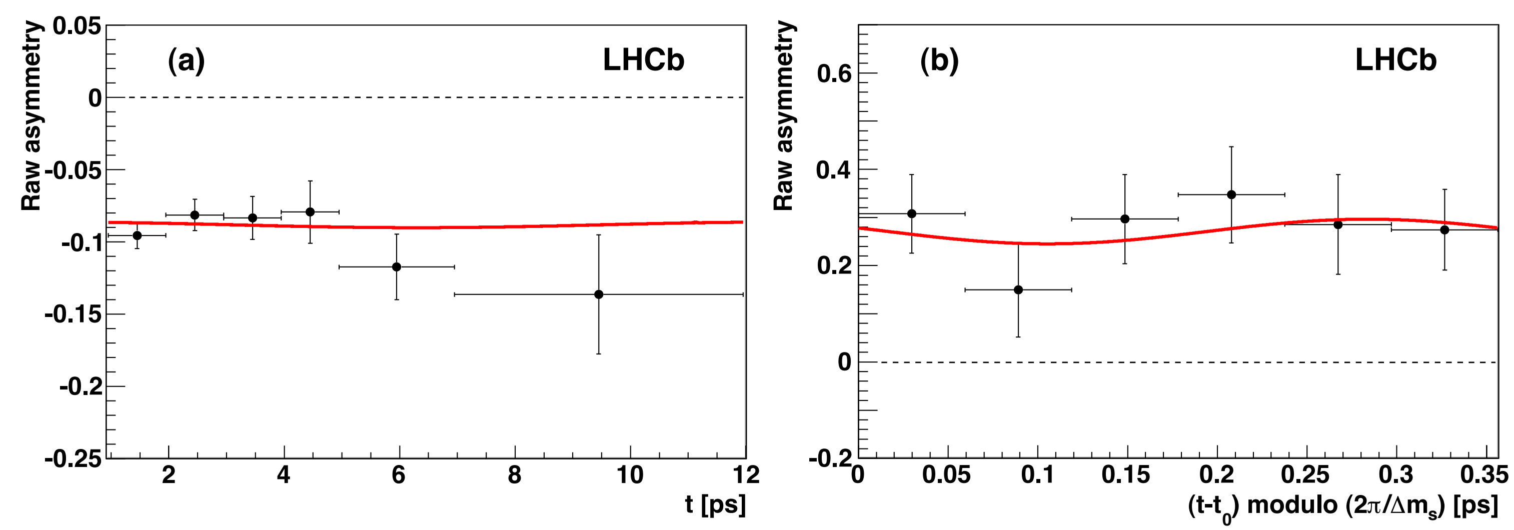
Direct CPV in $B_{(s)} \to K\pi$: Correction

- Correction from raw to CP asymmetry:

$$A_{CP} = A_{\mathrm{raw}} - \zeta_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^0_{(s)})$$

$\zeta_d = +1, \zeta_s = -1$ — instrumental asymmetry — mixing dilution — production asymmetry

- A_D: measured with $D^{*+} \to D^0(K^-\pi^+)\pi^+ / D^0(K^-K^+)\pi^+$ decays (incl. $D^0 \to K^-K^+$ CP asymmetry)
- A_P: measured from time-dependent raw asymmetries



Phys. Rev. Lett. 110 (2013) 221601

a_{sl} in B_s: systematics

Table 3: Sources of systematic uncertainty on A_{meas}.

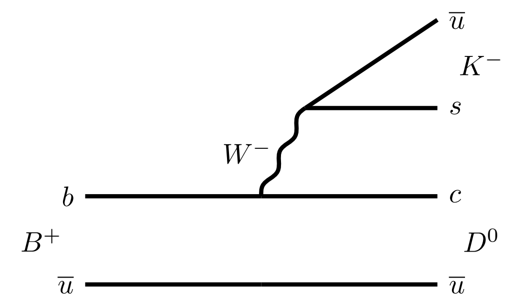
Source	$\sigma(A_{\text{meas}})[\%]$
Signal modelling and muon correction	0.07
Statistical uncertainty on the efficiency ratios	0.08
Background asymmetry	0.05
Asymmetry in track reconstruction	0.13
Field-up and field-down run conditions	0.01
Software trigger bias (topological trigger)	0.05
Total	0.18

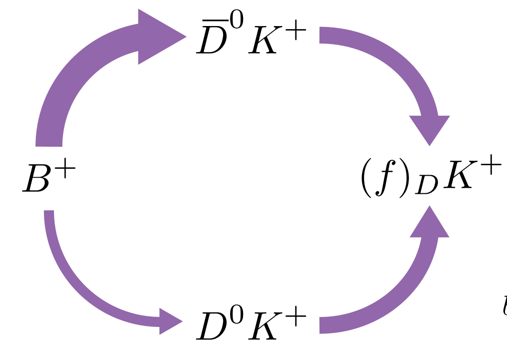
Table 2: Muon efficiency ratio corrected asymmetry A^c_μ. The errors account for the statistical uncertainties in the B^0_s signal yields.

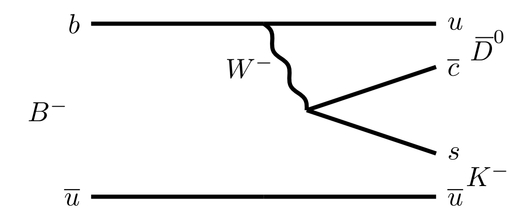
A^c_μ [%]	KS muon correction		MS muon correction		Average
Magnet	$p_x p_y$	$p_\text{T}\phi$	$p_x p_y$	$p_\text{T}\phi$	
Up	$+0.38 \pm 0.38$	$+0.30 \pm 0.38$	$+0.64 \pm 0.37$	$+0.63 \pm 0.37$	$+0.49 \pm 0.38$
Down	-0.17 ± 0.32	-0.25 ± 0.32	-0.60 ± 0.32	-0.62 ± 0.32	-0.41 ± 0.32
Avg.	$+0.11 \pm 0.25$	$+0.02 \pm 0.25$	$+0.02 \pm 0.24$	$+0.01 \pm 0.24$	$+0.04 \pm 0.25$

γ in B±→Dh±

- interference between two tree diagrams
- methods differ in D decay products







- measure charge asymmetries and yield ratios (GLW/ADS):

$$A_h^f = \frac{\Gamma(B^- \to D[\to f]h^-) - \Gamma(B^+ \to D[\to \overline{f}]h^+)}{\Gamma(B^- \to D[\to f]h^-) + \Gamma(B^+ \to D[\to \overline{f}]h^+)} \qquad R_{K/\pi}^f = \frac{\Gamma(B^- \to D[\to f]K^-) + \Gamma(B^+ \to D[\to \overline{f}]K^+)}{\Gamma(B^- \to D[\to f]\pi^-) + \Gamma(B^+ \to D[\to \overline{f}]\pi^+)}$$

$$R_h^\pm = \frac{\Gamma(B^\pm \to D[\to f_{\text{sup}}]h^\pm)}{\Gamma(B^\pm \to D[\to f]h^\pm)}$$

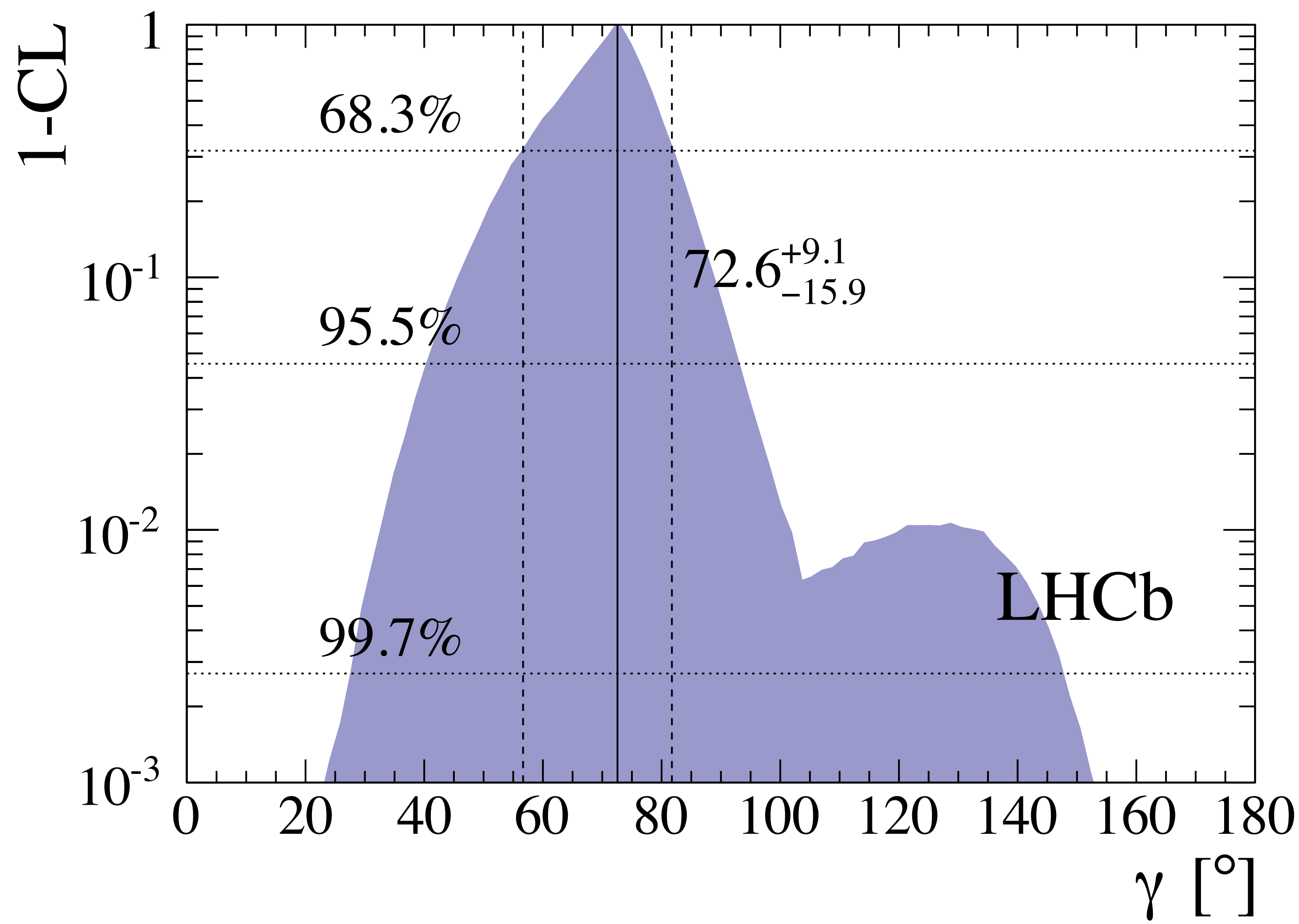
- cartesian coordinates from Dalitz plane (GGSZ)

γ in $B^{\pm}\to Dh^{\pm}$, 1 fb^{-1}

arXiv:1305.2050

- Combining $B^{\pm}\to DK^{\pm}$ and $B^{\pm}\to D\pi^{\pm}$:
  - GLW/ADS/GGSZ with 1 fb^{-1}
  - incl. D mixing

$$\gamma = (72.6^{+9.7}_{-17.2})^{\circ}$$



γ in B±→Dh±: plugin method

- plugin method similar to Feldman-Cousins:

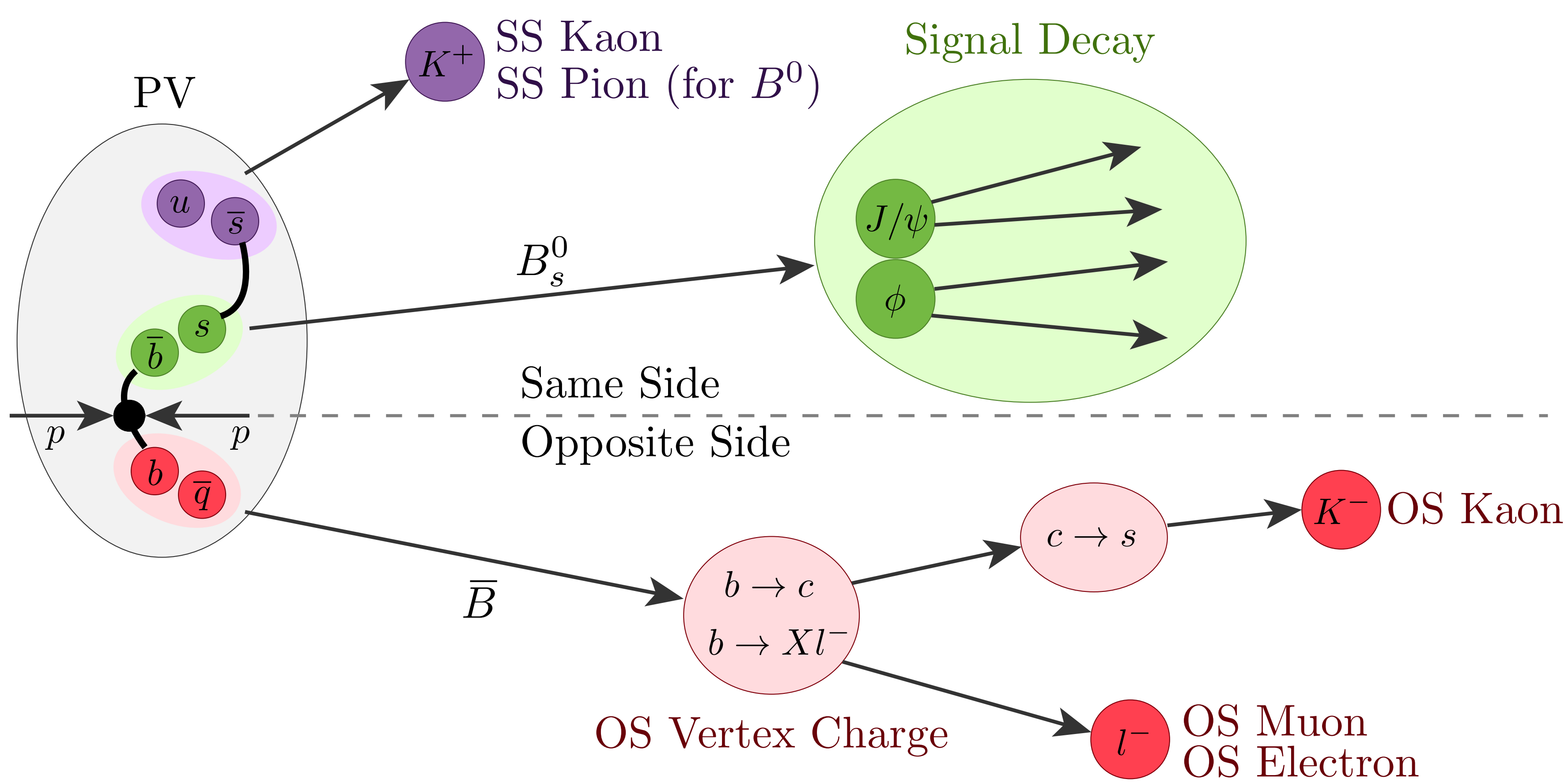
The evaluation of this combination follows a frequentist approach. A χ^2-function is defined as $\chi^2(\vec{\alpha}) = -2\ln\mathcal{L}(\vec{\alpha})$, where $\mathcal{L}(\vec{\alpha})$ is defined in Eq. 1. The best-fit point is given by the global minimum of the χ^2-function, $\chi^2(\vec{\alpha}_{\text{min}})$. To evaluate the confidence level for a given value of a certain parameter, say $\gamma = \gamma_0$ in the following, the value of the χ^2-function at the new minimum is considered, $\chi^2(\vec{\alpha}'_{\text{min}}(\gamma_0))$. This also defines the profile likelihood function $\hat{\mathcal{L}}(\gamma_0) = \exp(-\chi^2(\vec{\alpha}'_{\text{min}})/2)$. Then a test statistic is defined as $\Delta\chi^2 = \chi^2(\vec{\alpha}'_{\text{min}}) - \chi^2(\vec{\alpha}_{\text{min}})$. The p-value, or $1 - \text{CL}$, is calculated by means of a Monte Carlo procedure, described in Ref. [29] and briefly recapitulated here. For each value of γ_0:

1. $\Delta\chi^2$ is calculated;
2. a set of pseudoexperiments $\vec{A}_j$ is generated using Eq. 1 with parameters $\vec{\alpha}$ set to $\vec{\alpha}'_{\text{min}}$ as the PDF;
3. $\Delta\chi^{2\prime}$ of the pseudoexperiment is calculated by replacing $\vec{A}_{\text{obs}} \to \vec{A}_j$ and minimising with respect to $\vec{\alpha}$, once with γ as a free parameter, and once with γ fixed to γ_0;
4. $1 - \text{CL}$ is calculated as the fraction of pseudoexperiments which perform worse ($\Delta\chi^2 < \Delta\chi^{2\prime}$) than the measured data.

This method is sometimes known as the "$\hat{\mu}$", or the "plug-in" method. Its coverage cannot be guaranteed [29] for the full parameter space, but is verified for the best-fit point. The reason is, that at each point γ_0, the nuisance parameters, *i.e.* the components of $\vec{\alpha}$ other than the parameter of interest, are set to their best-fit values for this point, as opposed to computing an n-dimensional confidence belt, which is computationally very demanding.

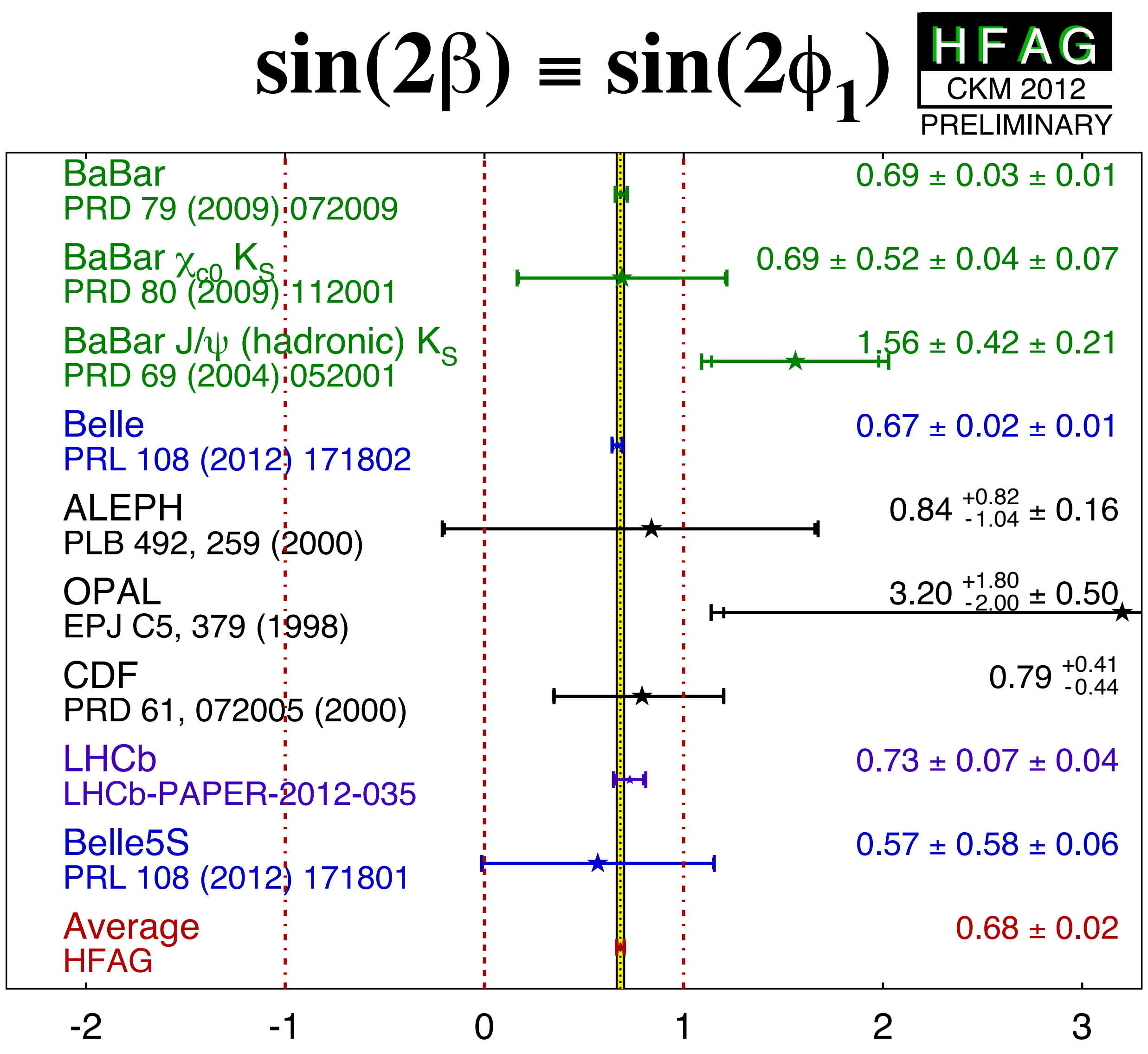
Flavour Tagging

- infer B production flavour
- Opposite Side algorithms:
  charge of leptons/hadrons of other B meson
- Same Side algorithms:
  Kaon/Pion charge from fragmentation
- mistag probability ω
  - dilution D=(1−2ω) of CP asymmetry
- calibration of taggers necessary



CPV in $B_d \to J/\psi K_S$: comparison

- LHCb not yet competitive with B factories
- measurement on 3 fb^{-1} data expected soon



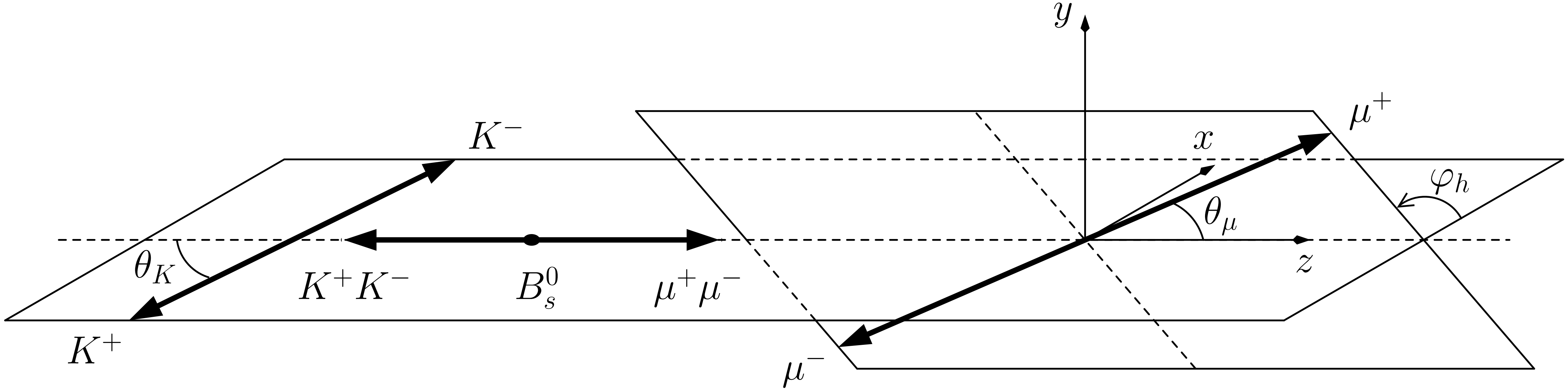
CPV in $B_d \to J/\psi K_S$: systematics/tagging

Table 1
Summary of systematic uncertainties on the *CP* parameters.

Origin	$\sigma(S_{J/\psi K^0_S})$	$\sigma(C_{J/\psi K^0_S})$
Tagging calibration	0.034	0.001
Tagging efficiency difference	0.002	0.002
Decay time resolution	0.001	0.002
Decay time acceptance	0.002	0.006
Background model	0.012	0.009
Fit bias	0.004	0.005
Total	0.036	0.012

$$\varepsilon_{\rm tag}\mathcal{D}^2 = (2.38 \pm 0.27)\%$$
$$\varepsilon_{\rm tag} = (32.65 \pm 0.31)\%$$
$$\omega = (36.5 \pm 0.8)\%$$

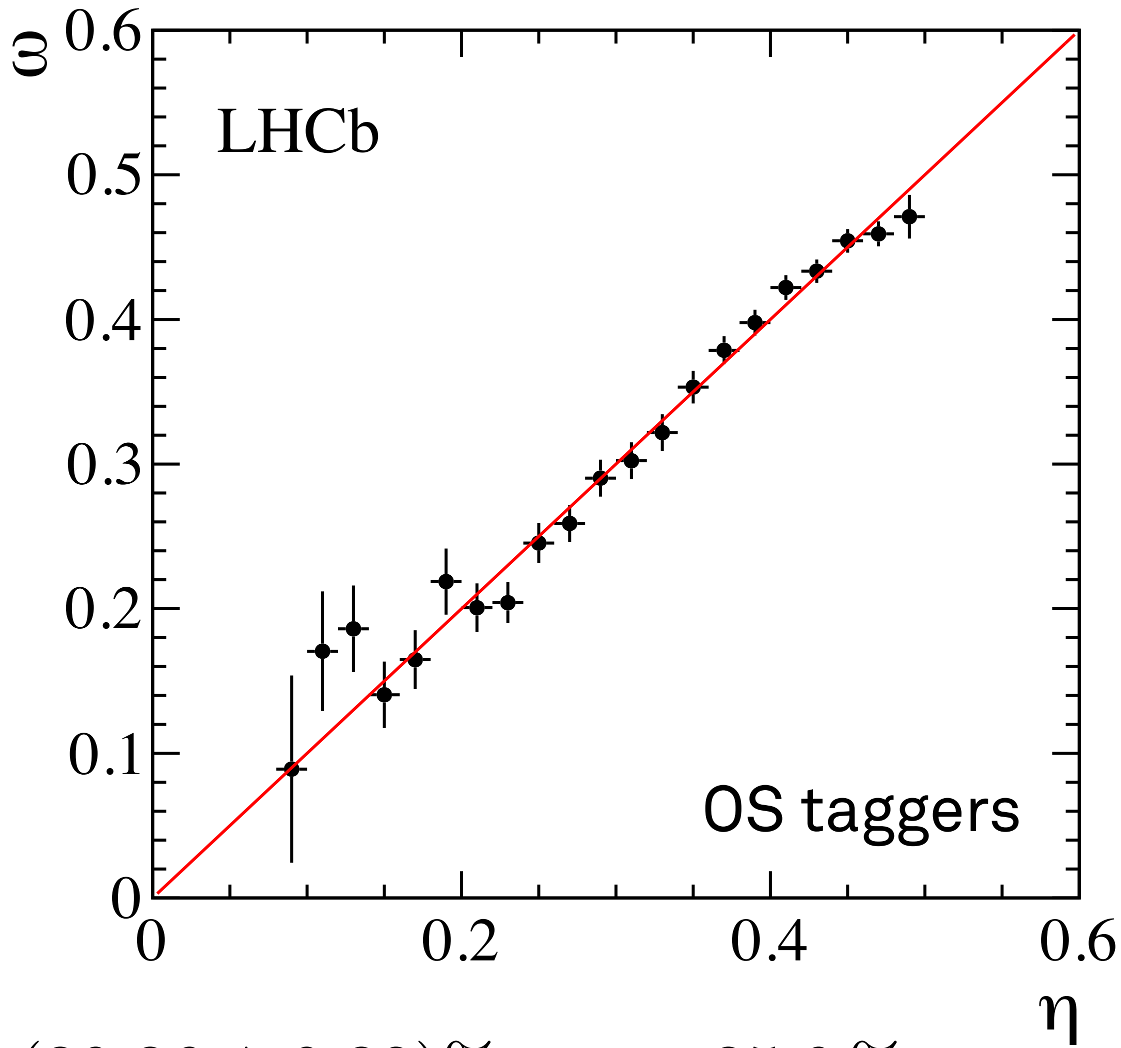
CPV $B_s \to J/\psi K^+K^-$ / $J/\psi \pi^+\pi^-$: angles



Flavour Tagging calibration

- predicted wrong-tag probability η transformed:

$$\omega(\eta) = p_0 \pm \frac{\Delta p_0}{2} + p_1(\eta - \langle\eta\rangle)$$



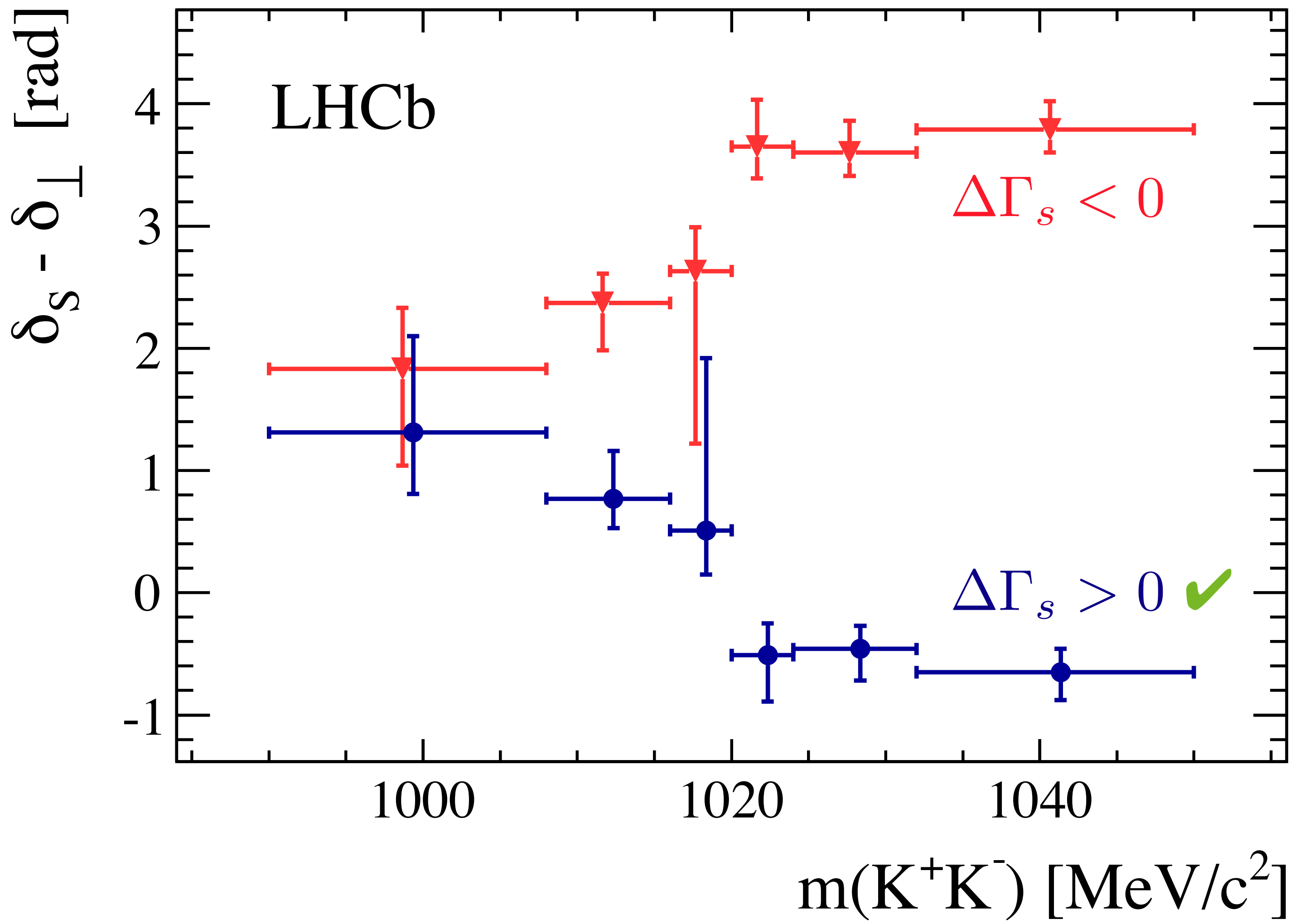
Phys. Rev. D 87, 112010 (2013)

$$\varepsilon_{\text{tag}}\mathcal{D}^2 = (3.13 \pm 0.12 \pm 0.20)\% \quad \varepsilon_{\text{tag}} = (39.36 \pm 0.32)\% \quad \omega = 35.9\,\%$$

Calibration	p_0	p_1	$\langle\eta\rangle$	Δp_0
OS	$0.392 \pm 0.002 \pm 0.008$	$1.000 \pm 0.020 \pm 0.012$	0.392	0.011 ± 0.003
SSK	$0.350 \pm 0.015 \pm 0.007$	$1.000 \pm 0.160 \pm 0.020$	0.350	-0.019 ± 0.005

CPV $B_s \to J/\psi K^+K^-$ / $J/\psi\pi^+\pi^-$: ambiguity

- measure phase difference between S- and P-wave amplitudes
- physical solution:
  - decreasing trend with $m(K^+K^-)$



Phys. Rev. D 87, 112010 (2013)

Phys. Rev. Lett. 108, 241801 (2012)

CPV $B_s \to J/\psi K^+K^-$ / $J/\psi\pi^+\pi^-$: systematics

Table 9: Statistical and systematic uncertainties.

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp\rvert^2$	$\lvert A_0\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$
Stat. uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	–	0.0031	0.03	0.02	0.003	0.003
$B^0 \to J/\psi K^{*0}$ background	–	0.001	0.0030	0.0001	0.01	0.02	0.004	0.005
Ang. acc. reweighting	0.0007	–	0.0052	0.0091	0.07	0.05	0.003	0.020
Ang. acc. statistical	0.0002	–	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay time acc. model	0.0023	0.002	–	–	–	–	–	–
Upper decay time acc. model	0.0040	–	–	–	–	–	–	–
Length and mom. scales	0.0002	–	–	–	–	–	–	–
Fit bias	–	–	0.0010	–	–	–	–	–
Decay time resolution offset	–	–	–	–	–	0.04	0.006	–
Quadratic sum of syst.	0.0063	0.003	0.0064	0.0097	0.08	0.08	0.011	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.092	0.038

Table 10: Statistical and systematic uncertainties for S-wave fractions in bins of $m(K^+K^-)$.

Source	bin 1 F_S	bin 2 F_S	bin 3 F_S	bin 4 F_S	bin 5 F_S	bin 6 F_S
Stat. uncertainty	$^{+0.081}_{-0.073}$	$^{+0.030}_{-0.027}$	$^{+0.014}_{-0.007}$	$^{+0.012}_{-0.009}$	$^{+0.027}_{-0.025}$	$^{+0.043}_{-0.042}$
Background subtraction	0.014	0.003	0.001	0.002	0.004	0.006
$B^0 \to J/\psi K^{*0}$ background	0.010	0.006	0.001	0.001	0.002	0.018
Angular acc. reweighting	0.004	0.006	0.004	0.005	0.006	0.007
Angular acc. statistical	0.003	0.003	0.002	0.001	0.003	0.004
Fit bias	0.009	–	0.002	0.002	0.001	0.001
Quadratic sum of syst.	0.020	0.009	0.005	0.006	0.008	0.021
Total uncertainties	$^{+0.083}_{-0.076}$	$^{+0.031}_{-0.029}$	$^{+0.015}_{-0.009}$	$^{+0.013}_{-0.011}$	$^{+0.028}_{-0.026}$	$^{+0.048}_{-0.047}$

CPV $B_s \to J/\psi K^+K^-$ / $J/\psi \pi^+\pi^-$: correlations

Table 6: Results of the maximum likelihood fit for the principal physics parameters. The first uncertainty is statistical and the second is systematic. The value of Δm_s was constrained to the measurement reported in Ref. [38]. The evaluation of the systematic uncertainties is described in Sect. 10.

Parameter	Value
Γ_s [ps^{-1}]	$0.663 \pm 0.005 \pm 0.006$
$\Delta\Gamma_s$ [ps^{-1}]	$0.100 \pm 0.016 \pm 0.003$
$\|A_\perp\|^2$	$0.249 \pm 0.009 \pm 0.006$
$\|A_0\|^2$	$0.521 \pm 0.006 \pm 0.010$
$\delta_\parallel$ [rad]	$3.30\,^{+0.13}_{-0.21} \pm 0.08$
$\delta_\perp$ [rad]	$3.07 \pm 0.22 \pm 0.08$
ϕ_s [rad]	$0.07 \pm 0.09 \pm 0.01$
$\|\lambda\|$	$0.94 \pm 0.03 \pm 0.02$

Table 7: Correlation matrix for the principal physics parameters.

	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\|A_\perp\|^2$	$\|A_0\|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\|\lambda\|$
Γ_s [ps^{-1}]	1.00	−0.39	0.37	−0.27	−0.09	−0.03	0.06	0.03
$\Delta\Gamma_s$ [ps^{-1}]		1.00	−0.68	0.63	0.03	0.04	−0.04	0.00
$\|A_\perp\|^2$			1.00	−0.58	−0.28	−0.09	0.08	−0.04
$\|A_0\|^2$				1.00	−0.02	−0.00	−0.05	0.02
$\delta_\parallel$ [rad]					1.00	0.32	−0.03	0.05
$\delta_\perp$ [rad]						1.00	0.28	0.00
ϕ_s [rad]							1.00	0.04
$\|\lambda\|$								1.00