technische universität dortmund

CP-Violation Measurements at LHCb

Ramon Niet on behalf of the LHCb collaboration

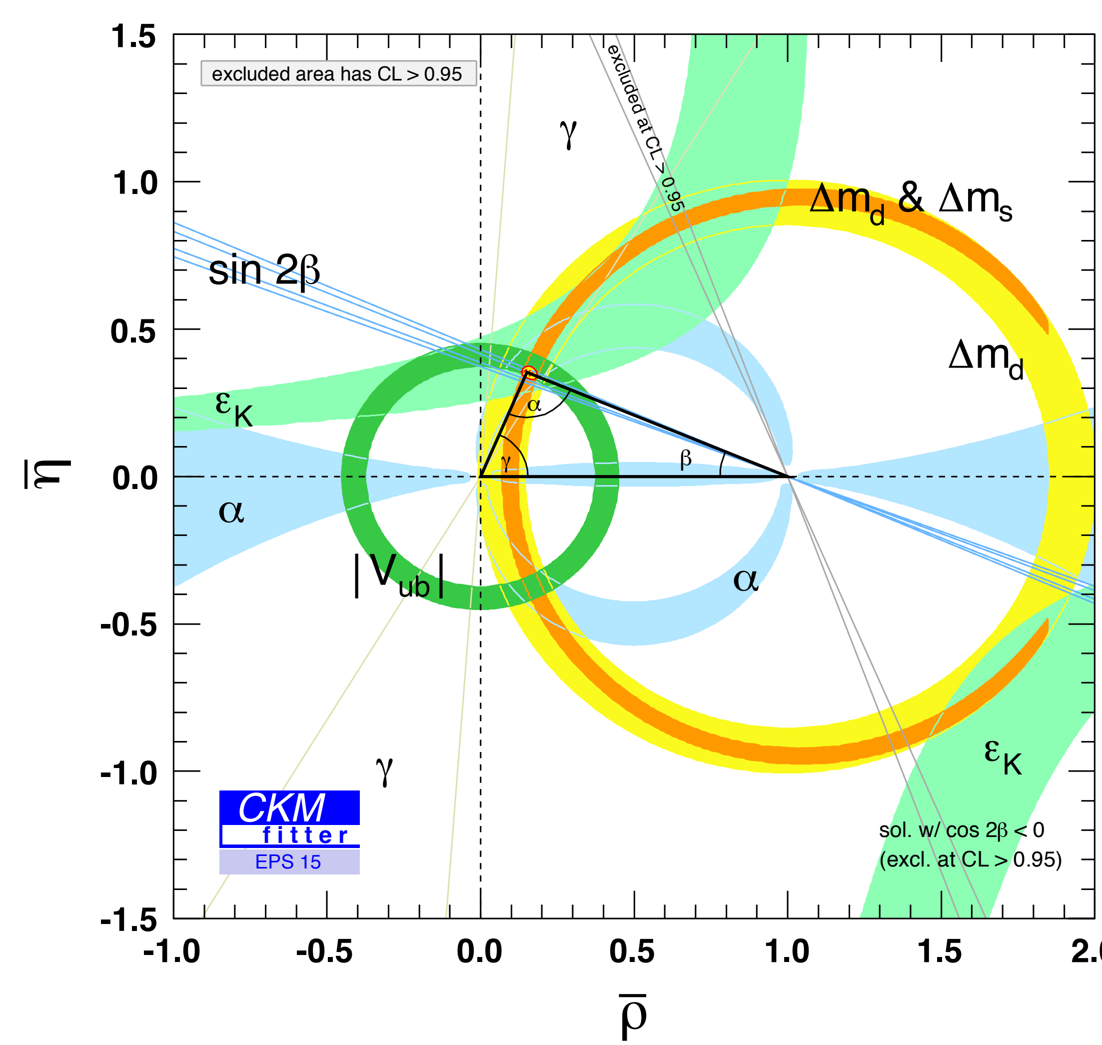
SUSY 2015 Lake Tahoe, California — 24/8/2015

Introduction to CP Violation (CPV)

- **What** CPV is
  - different behaviour of particles and antiparticles
  - necessary ingredient to explain observed baryon asymmetry
- **Why** CPV is studied
  - CPV in SM not sufficient
  - expect contributions from Physics Beyond the Standard Model
- **How** CPV is studied
  - SM: complex phase of CKM matrix
  - measure phases in interfering amplitudes
  - over-constrain CKM parameters and look for contradictions

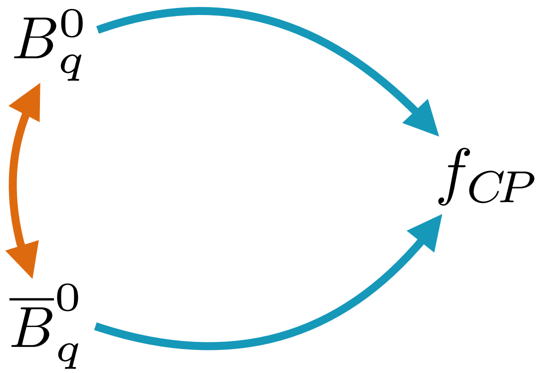
$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{ub} \end{pmatrix}$$

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



Measurements of mixing induced CPV

- need final state both B flavours can decay to
- interference of direct decay and decay after mixing



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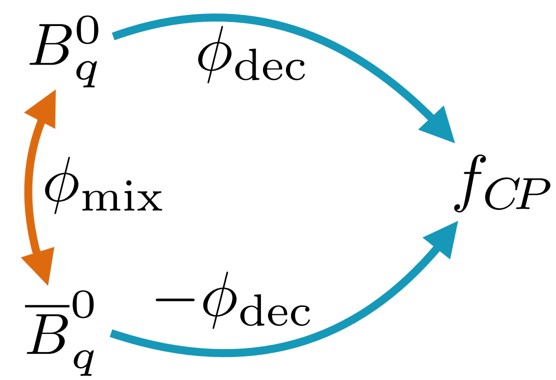
- interference of direct decay and decay after mixing
- partial decay widths are sensitive to $\phi_q = \phi_{\text{mix}} - 2\,\phi_{\text{dec}}$
- decay-time dependent CP asymmetry:



$$a_{CP}(t) \equiv \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to f)} = \frac{S\sin(\Delta m\, t) - C\cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)}$$

- *CP* observables $S, C, A_{\Delta\Gamma}$ *m*ixing parameters Δm, $\Delta\Gamma$

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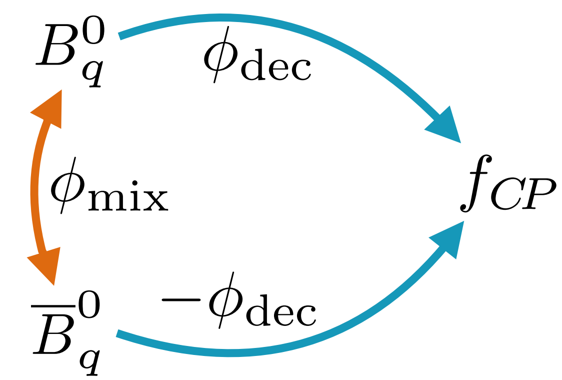

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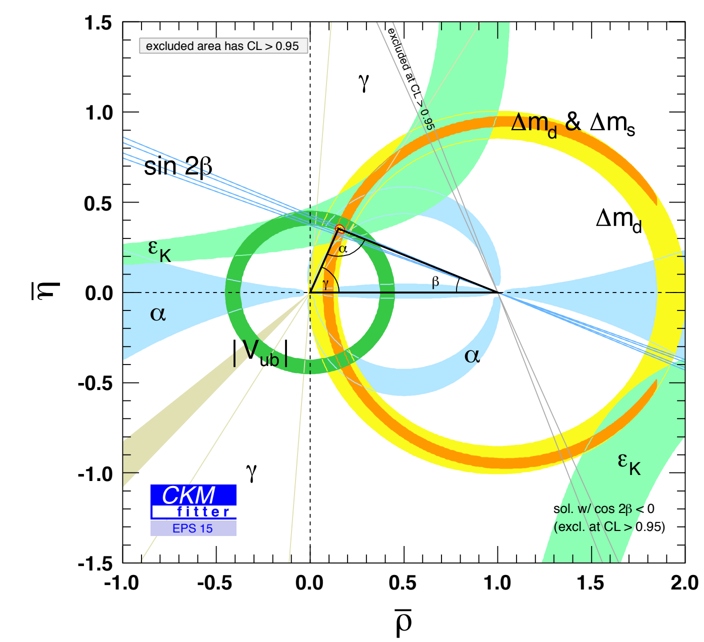
- *CP* observables $S, C, A_{\Delta\Gamma}$ mixing parameters Δm, $\Delta\Gamma$

- golden modes provide direct match to CKM angle
  - $B^0 \to J/\psi K_S$ ($\phi_d = 2\beta$) $\sin 2\beta = 0.748^{+0.030}_{-0.032}$
  - $B_s \to J/\psi hh$ ($\phi_s = -2\beta_s$) $\sin 2\beta_s = 0.03761^{+0.00073}_{-0.00082}$

CKMFitter EPS2015



probing precise predictions from other measurements!

Asymmetry measurement

- Experimentally determine number of B's with
  - production flavour B
  - decay time of B

$$a_{\text{meas}}(t) = \frac{N_{\bar{B}_q^0}(t) - N_{B_q^0}(t)}{N_{\bar{B}_q^0}(t) + N_{B_q^0}(t)}$$

Asymmetry measurement

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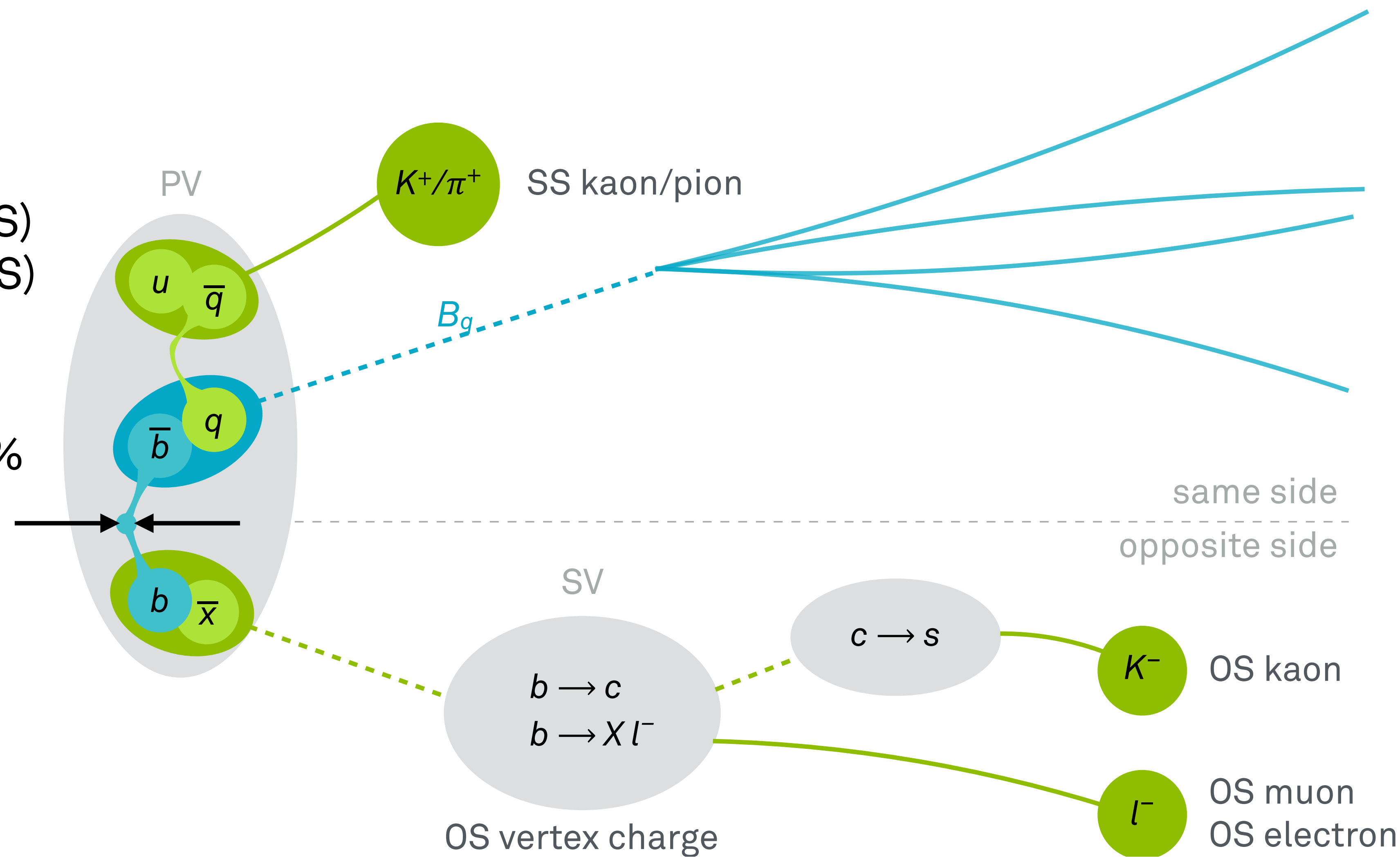
- production flavour inferred from tagging algorithms
  - exploit pair production (OS) hadronization of signal (SS)
  - wrong tag rate $\omega \approx 38\%$
  - tagging power $\varepsilon(1-2\omega)^2 \approx 3\%$

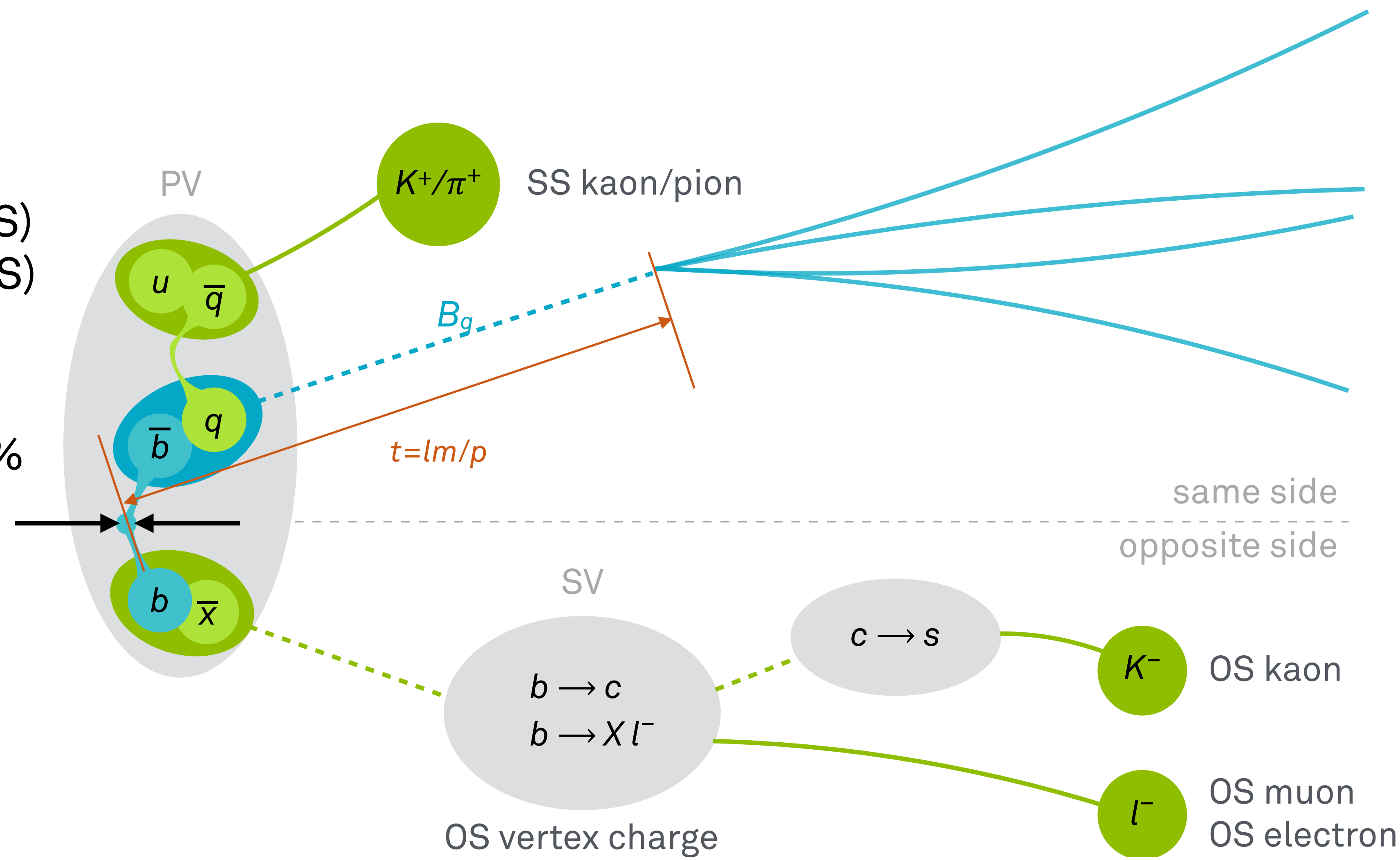


Asymmetry measurement

- Experimentally determine number of B's with
  - production flavour B
  - decay time of B

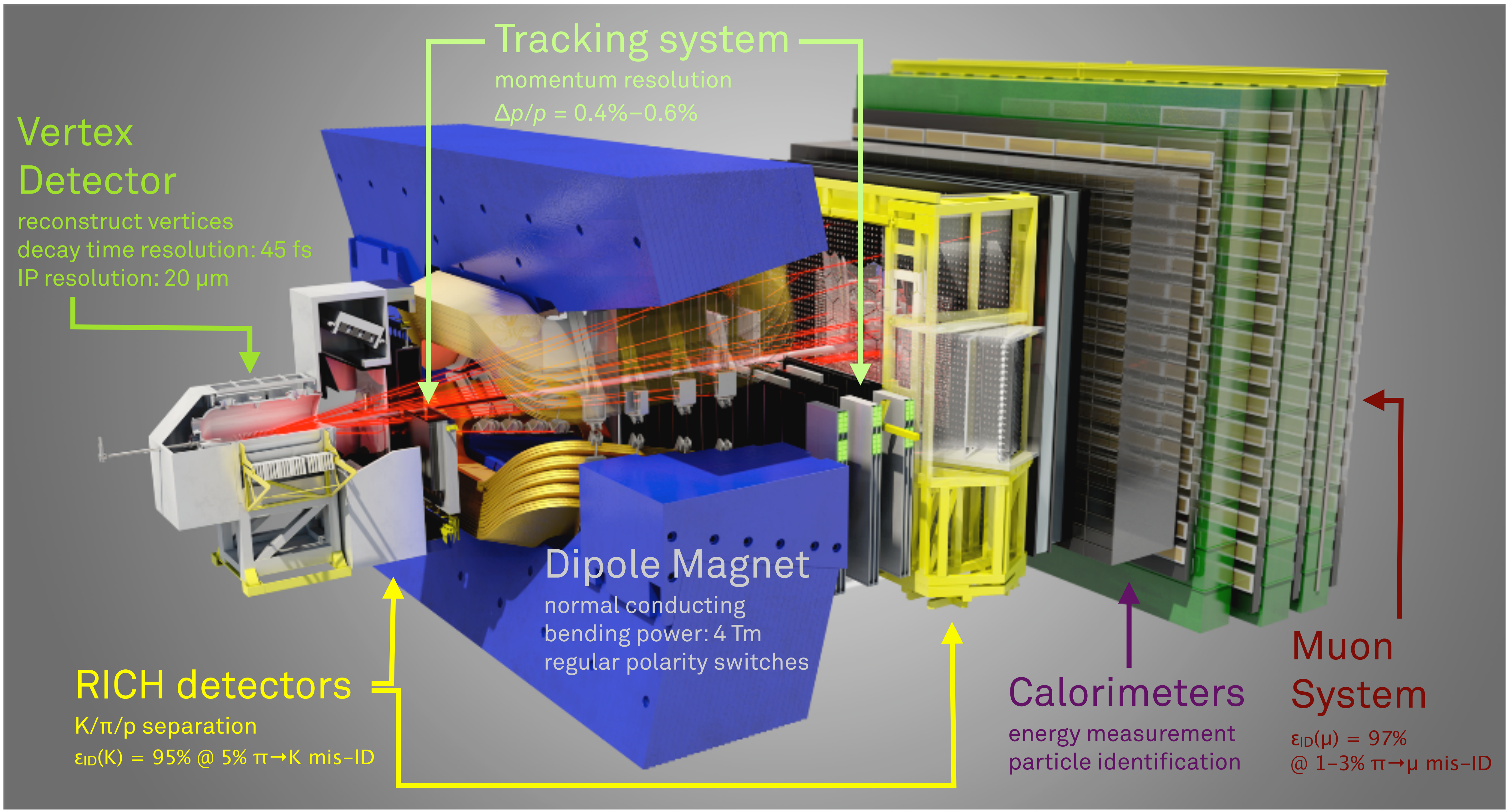
$$a_{\text{meas}}(t) = \frac{N_{\bar{B}^0_q}(t) - N_{B^0_q}(t)}{N_{\bar{B}^0_q}(t) + N_{B^0_q}(t)}$$

- production flavour inferred from tagging algorithms
  - exploit pair production (OS) hadronization of signal (SS)
  - wrong tag rate $\omega \approx 38\%$
  - tagging power $\varepsilon(1-2\omega)^2 \approx 3\%$
- decay time from flight distance
  - highly boosted B's are great for this!
  - flight distance O(cm)



The LHCb experiment

- 20 m long single arm forward spectrometer covering $2 < \eta < 5$



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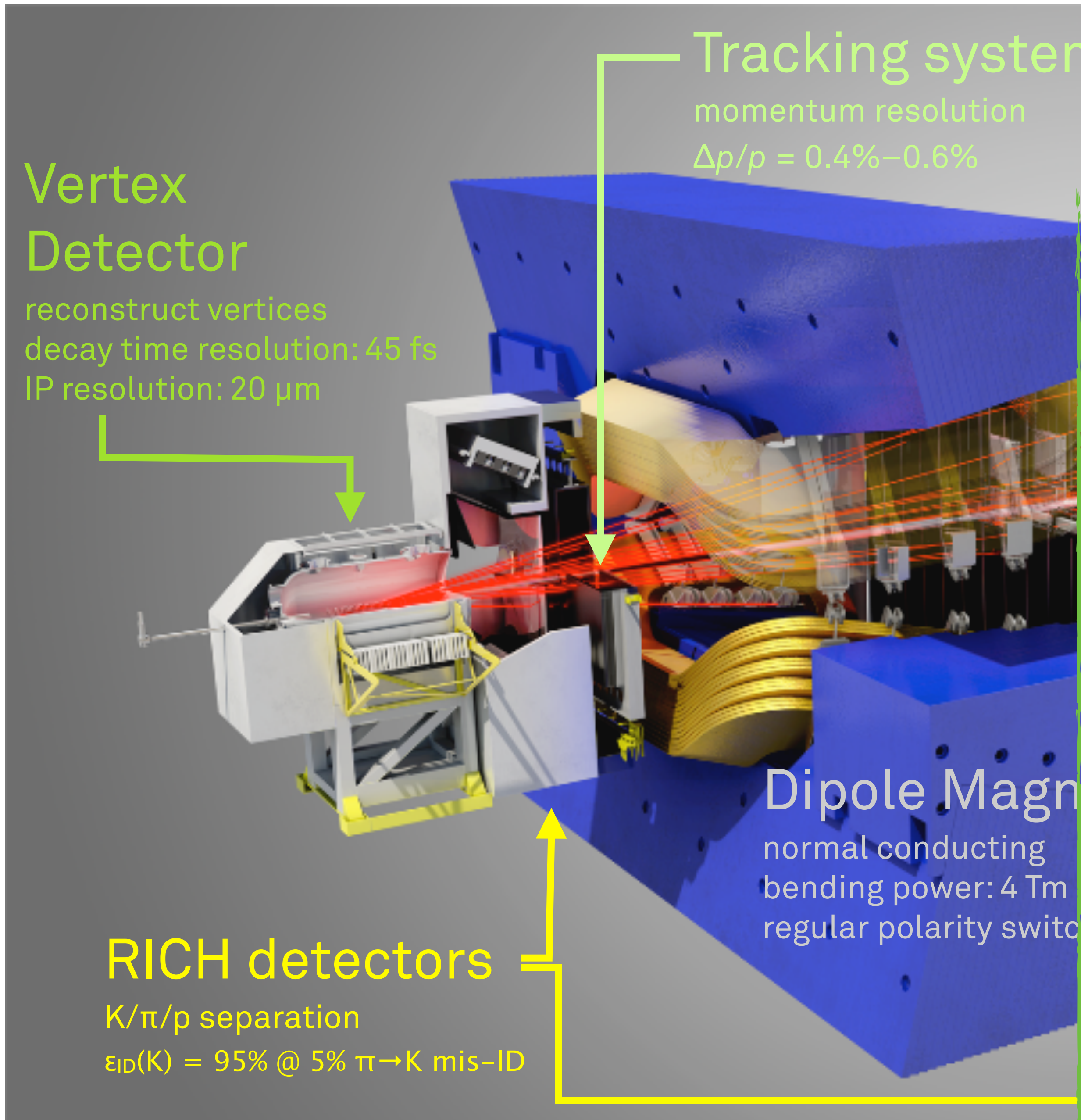


- recorded:
  - $1fb^{-1}$ data @7TeV
  - $2fb^{-1}$ data @8TeV
- huge cross sections (@7TeV):
  - $\sigma(c\bar{c}) = 1419 \pm 133\ \mu b$
  - $\sigma(b\bar{b}) = 75.3 \pm 14\ \mu b$

excellent conditions for flavour physics

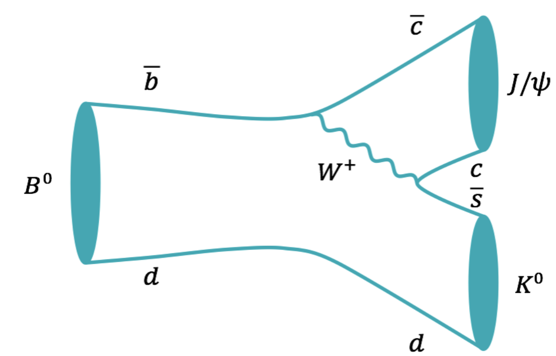
Beauty CPV Measurements

$B^0 \to J/\psi K_S$ $B_s \to J/\psi K_S$

$B_s \to J/\psi hh$ $B_s \to J/\psi K^*$

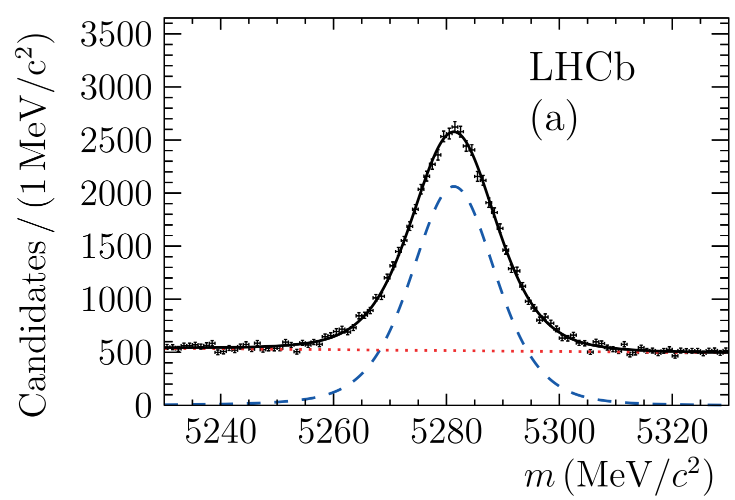
PRL 115, 031601 (2015)

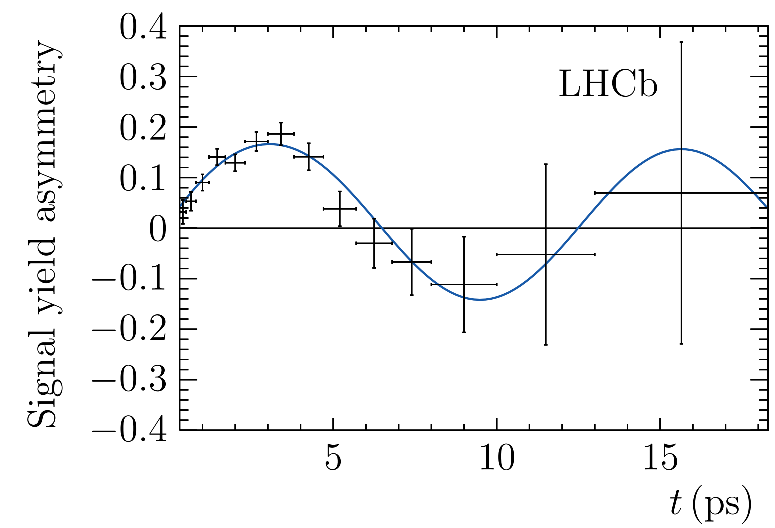
sin(2β) with $B^0 \rightarrow J/\psi K_S$ ($3fb^{-1}$)

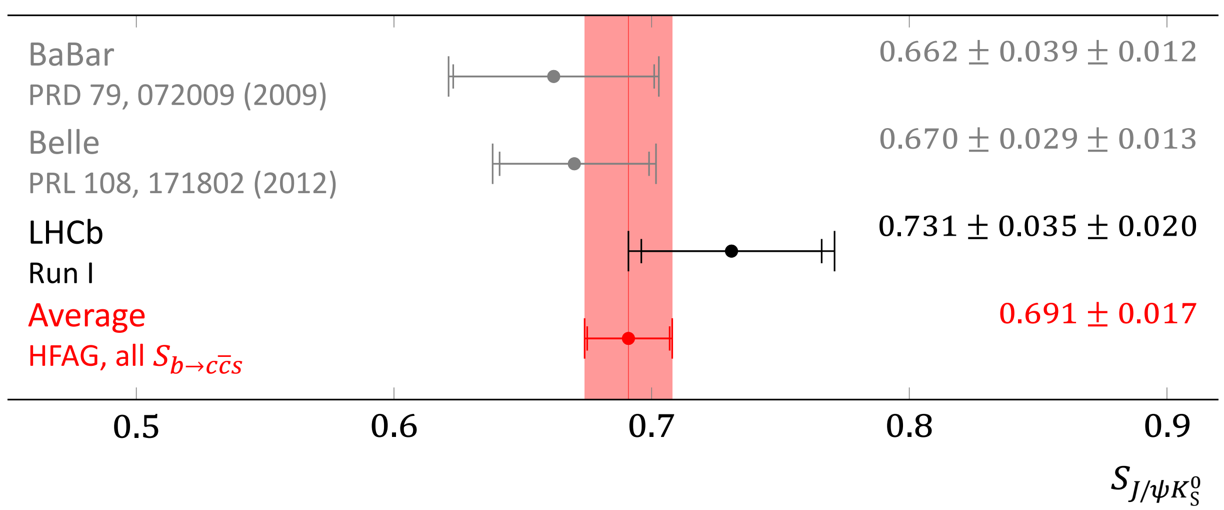


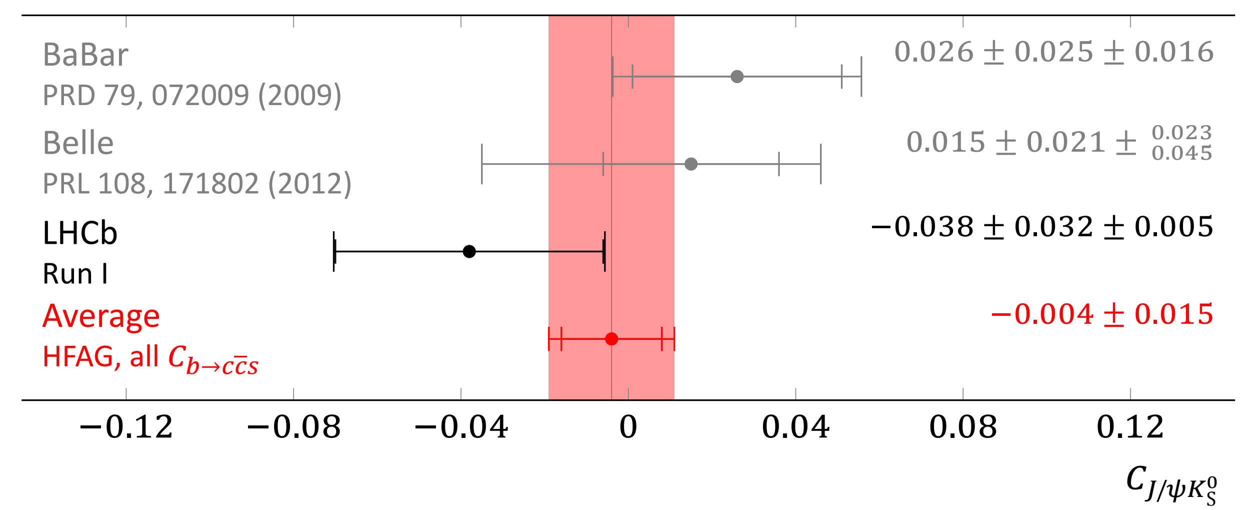
- 114000 signal candidates (41560 tagged)
- multi-dimensional unbinned maximum likelihood fit to extract CP observables
- analysis accounts for
  - tagging / production asymmetries

$$S = 0.731 \pm 0.035\,(\text{stat}) \pm 0.020\,(\text{syst})$$
$$C = -0.038 \pm 0.032\,(\text{stat}) \pm 0.005\,(\text{syst})$$



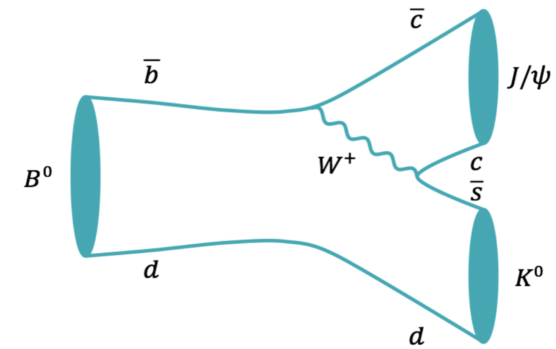


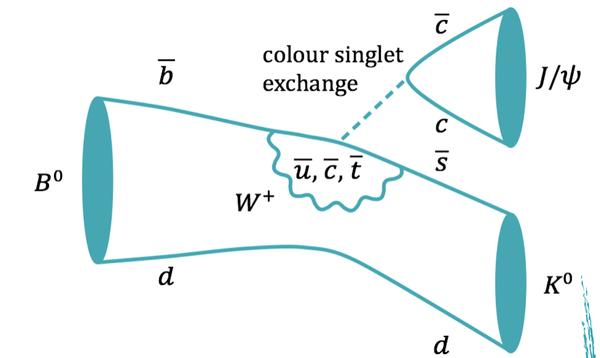




PRL 115, 031601 (2015)

sin(2β) with $B^0 \to J/\psi K_S$ ($3fb^{-1}$)





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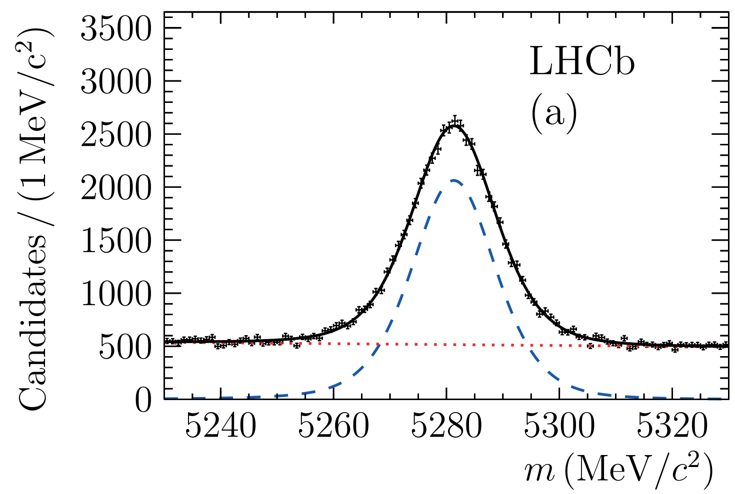
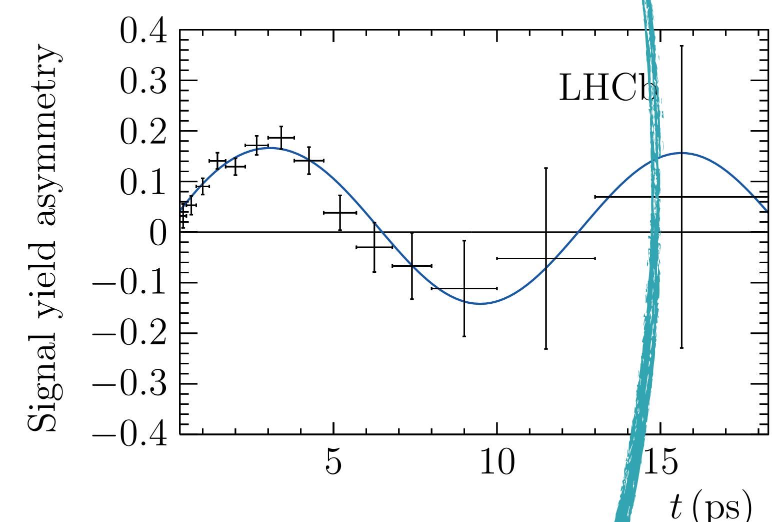
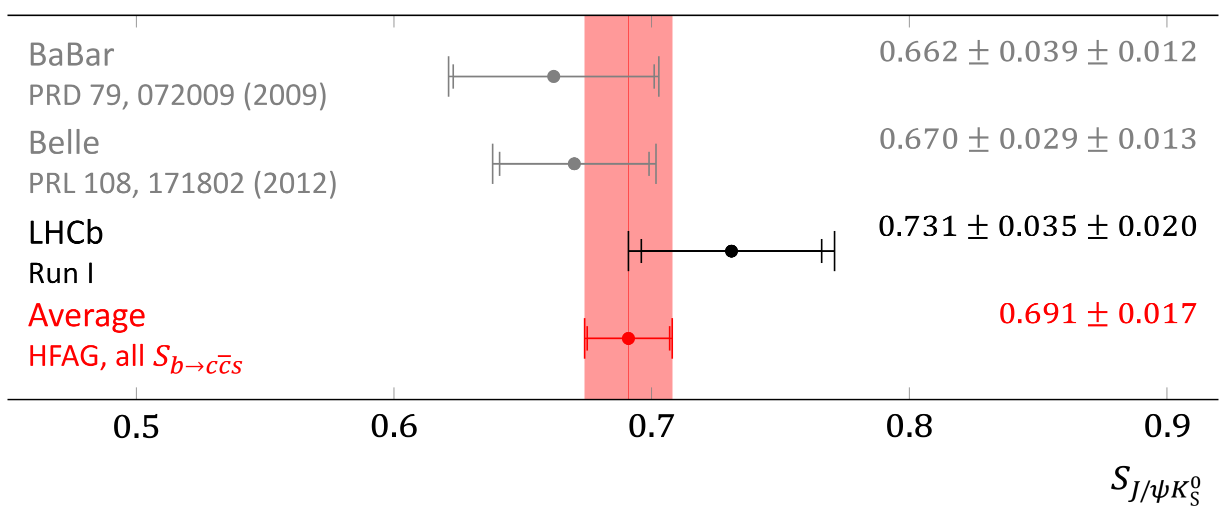
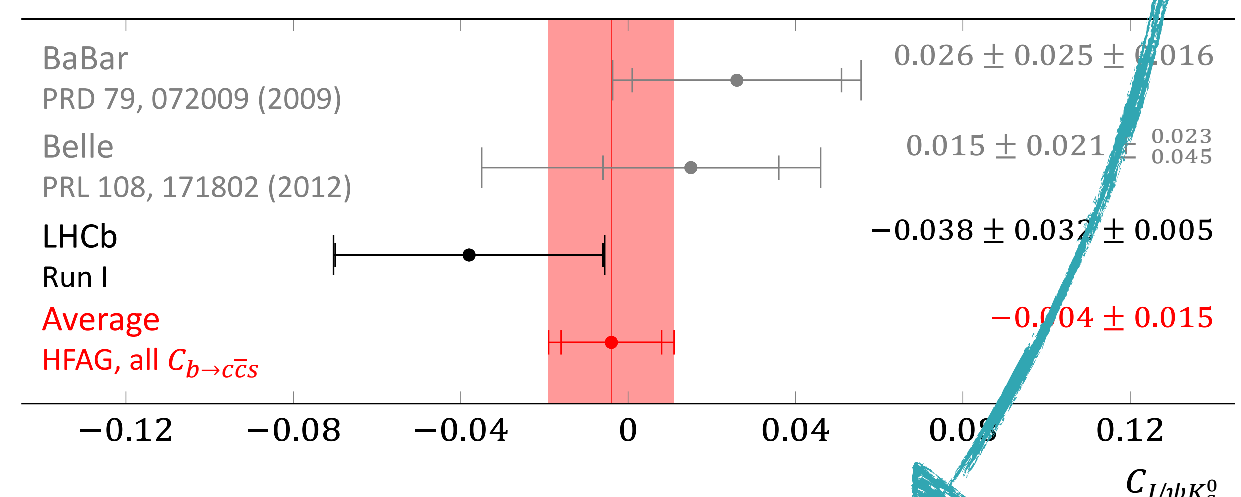




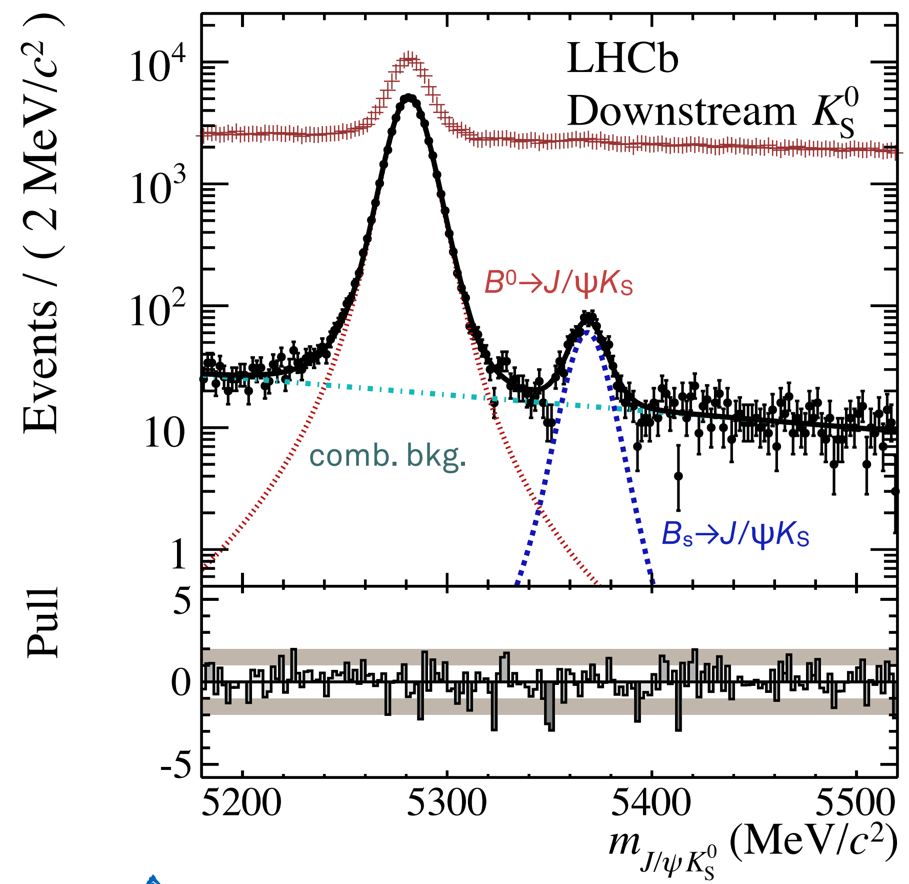




- need handle on penguin pollution: $\sin 2\beta_{B^0\to J/\psi K^0_S} = \frac{S}{\sqrt{1-C^2}} = \sin(2\beta + \Delta\phi_d + \phi_d^{\rm NP})$

Penguins from $B_s \to J/\psi K_S$ (3fb^{-1})

- related via d ↔ s exchange
- CKM suppression of tree topology
  - extraction of penguin parameters possible
  - 900 B_s candidates
- use B^0 component as proxy



Results for the CP coefficients

$$\mathcal{A}_{\Delta\Gamma}\left(B_s^0 \to J/\psi K_S^0\right) = 0.49 \pm^{0.77}_{0.65} \text{(stat)} \pm 0.06 \text{(syst)}$$
$$C\left(B_s^0 \to J/\psi K_S^0\right) = -0.28 \pm 0.41 \text{(stat)} \pm 0.08 \text{(syst)}$$
$$S\left(B_s^0 \to J/\psi K_S^0\right) = -0.08 \pm 0.40 \text{(stat)} \pm 0.08 \text{(syst)}$$

World's First

successful proof of concept!
but no constraint on penguins yet

Φ_s measurements (3fb^{-1})

PRL 114, 041801 (2015)

- Analysis of $B_s \rightarrow J/\psi K^+K^-$
  - time dependent angular analysis
  - disentangle CP even and CP odd
  - 95690 signal candidates

$$\phi_s = -0.058 \pm 0.049 \pm 0.006\,\mathrm{rad}$$

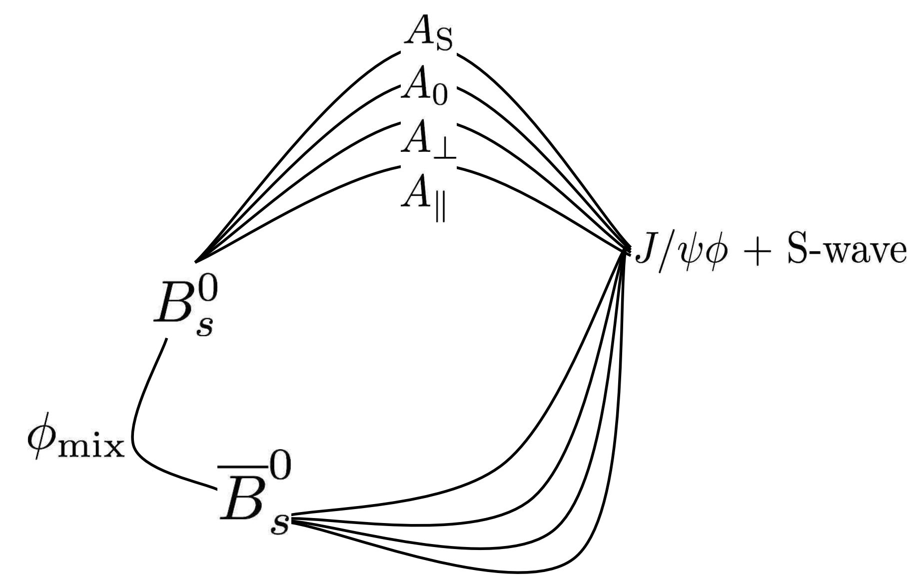
  - no evidence for polarisation-dependent CPV
  - Combined result with $B_s \rightarrow J/\psi\pi^+\pi^-$

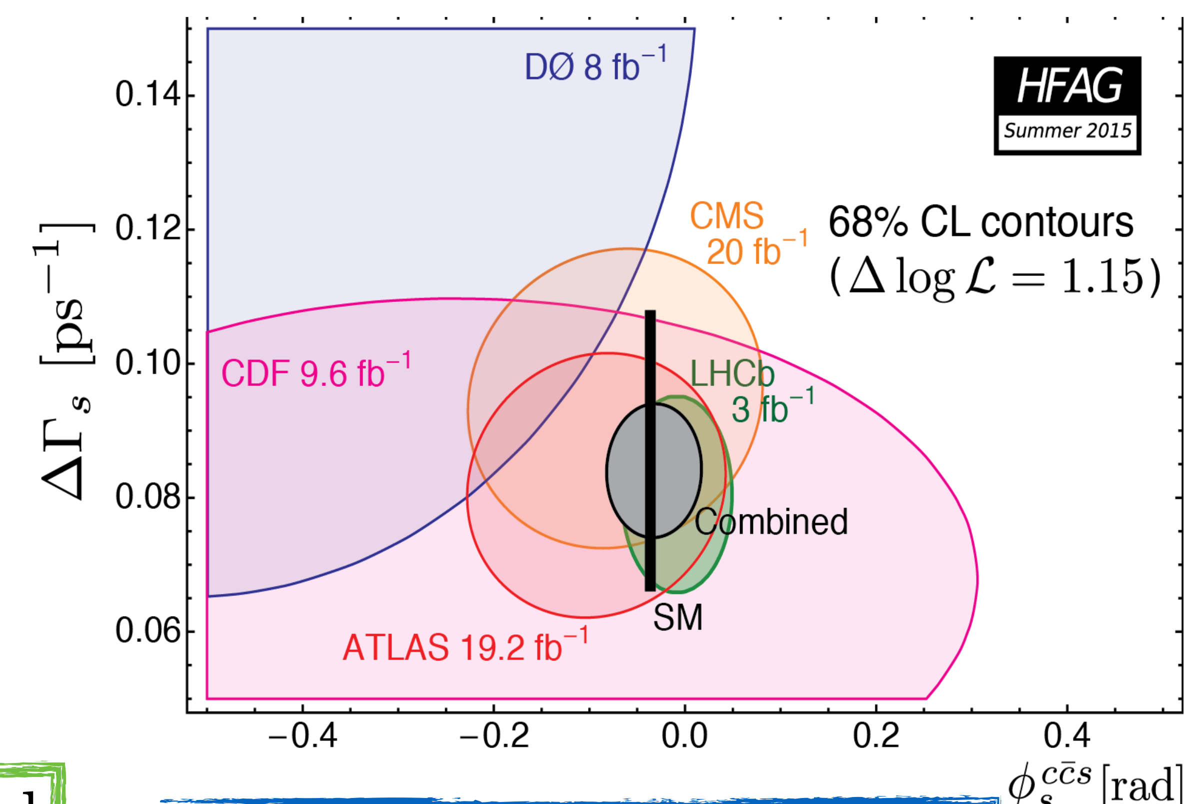
$$\phi_s = -0.010 \pm 0.039\,\mathrm{rad}$$

- Analysis of $B_s \rightarrow D_s^+D_s^-$

$$\phi_s = 0.02 \pm 0.17\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})\,\mathrm{rad}$$

PRL 113, 211801 (2014)





$$\phi_s = -0.034 \pm 0.033\,\mathrm{rad}$$

(World Average) HFAG preliminary

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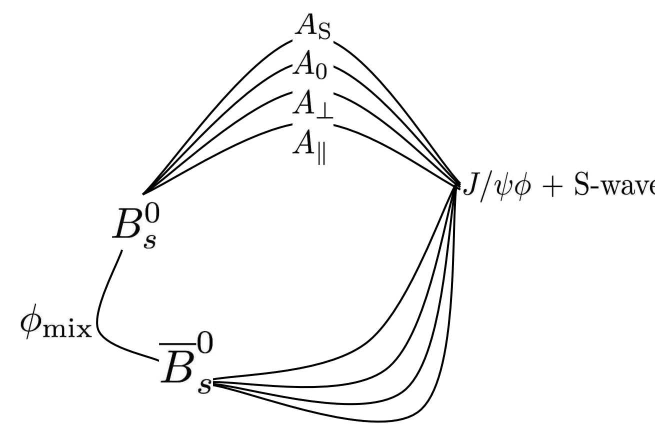
PRL 113, 211801 (2014)



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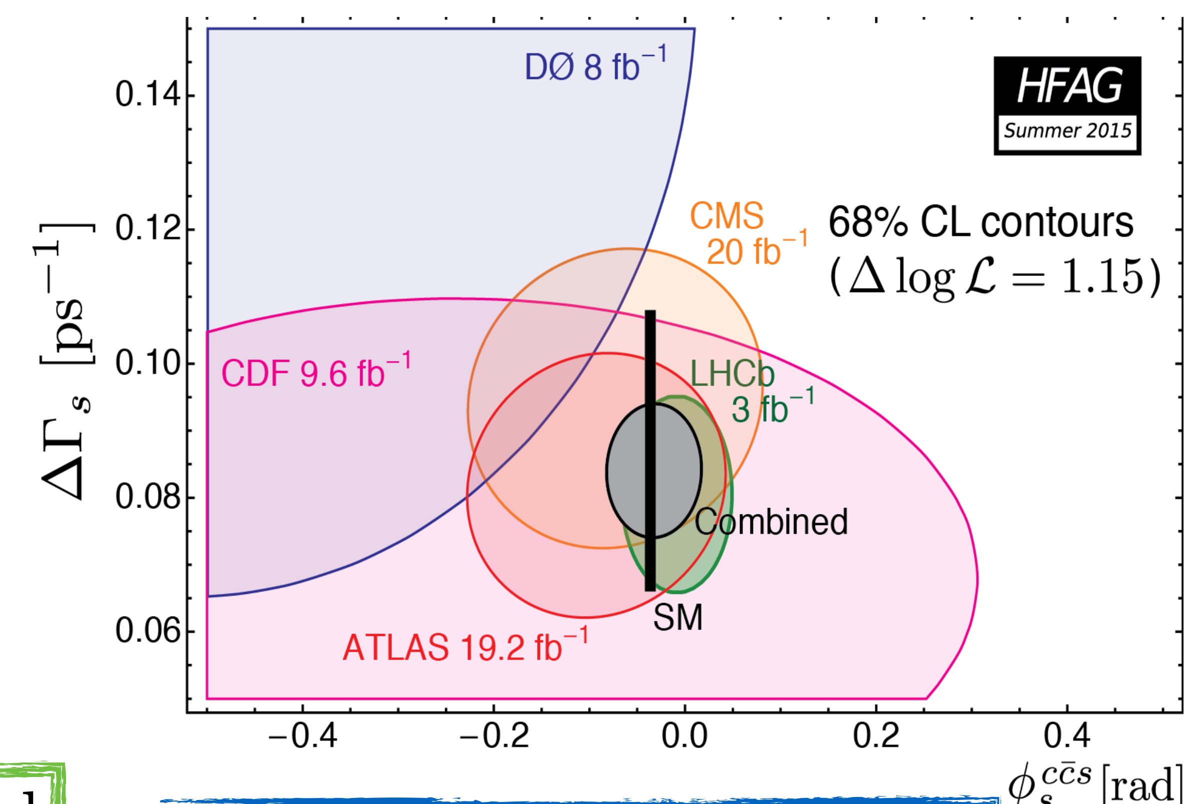
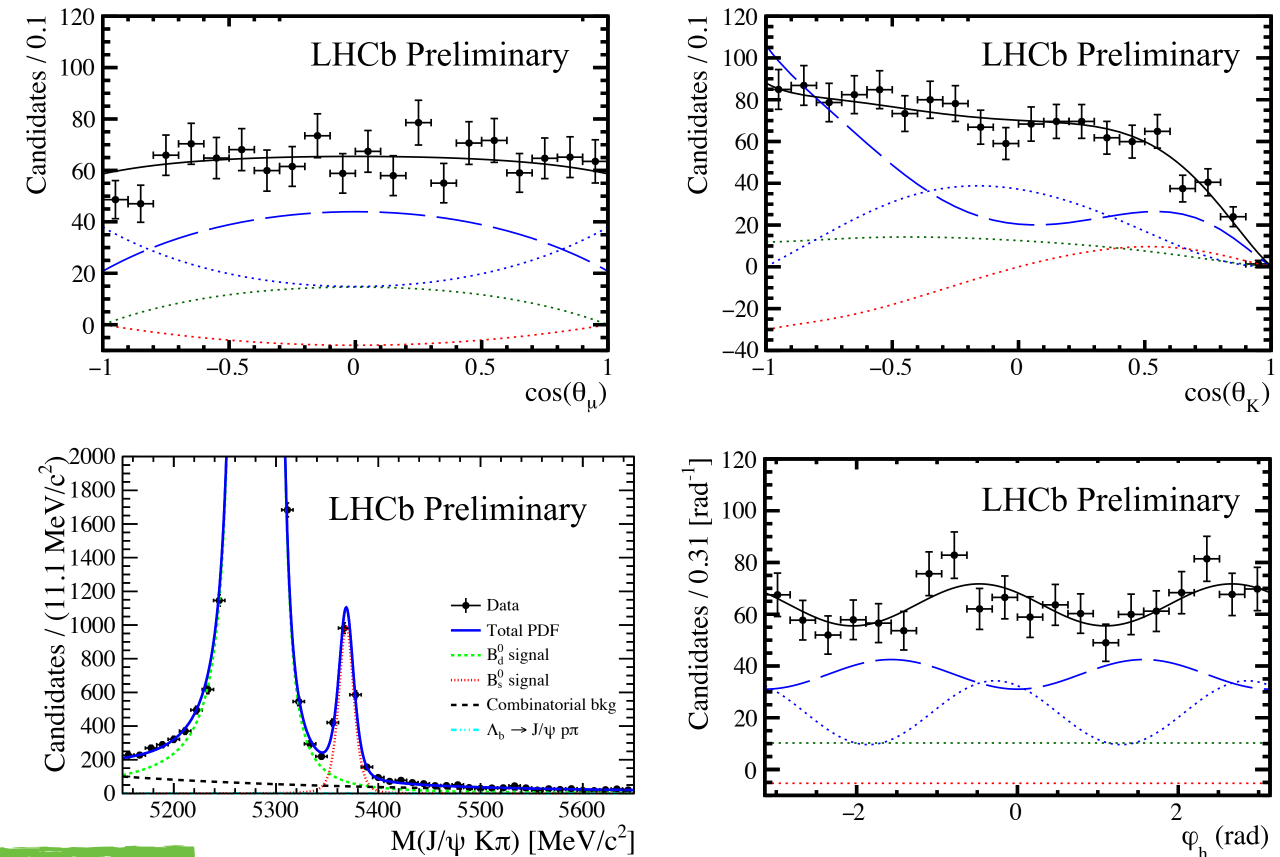


$$\phi_s = -0.034 \pm 0.033\,\text{rad}$$

(World Average) HFAG preliminary

Penguins from $B_s \to J/\psi K^{*0}$ ($3 fb^{-1}$)

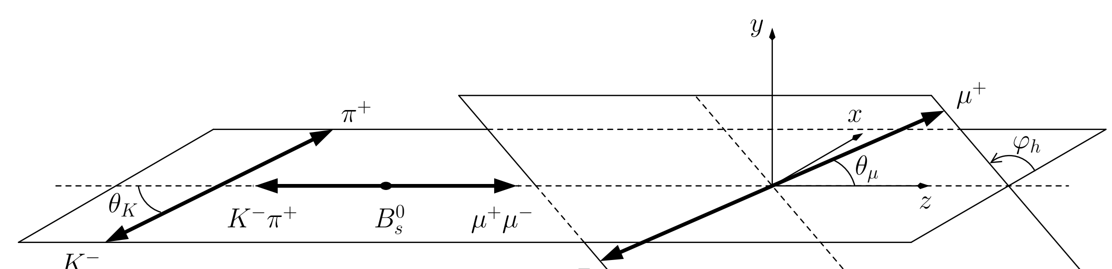
- flavour specific final state
- measurement of direct CPV ($J/\psi K^+\pi^-$ vs. $J/\psi K^-\pi^+$)
  - time integrated
  - polarization dependent
- 208700 B^0 and 1800 B_s decays



Preliminary Results

$$
\begin{aligned}
f_0 &= 0.497 \pm 0.025\ (\text{stat}) \pm 0.025\ (\text{syst})\\
f_\parallel &= 0.179 \pm 0.027\ (\text{stat}) \pm 0.013\ (\text{syst})\\
A_0^{CP}(B_s^0 \to J/\psi\, \overline{K}^{*0}) &= -0.048 \pm 0.057\ (\text{stat}) \pm 0.020\ (\text{syst})\\
A_\parallel^{CP}(B_s^0 \to J/\psi\, \overline{K}^{*0}) &= 0.171 \pm 0.152\ (\text{stat}) \pm 0.028\ (\text{syst})\\
A_\perp^{CP}(B_s^0 \to J/\psi\, \overline{K}^{*0}) &= -0.049 \pm 0.096\ (\text{stat}) \pm 0.025\ (\text{syst})
\end{aligned}
$$

$$
\mathcal{B}(B_s^0 \to J/\psi\, \overline{K}^{*0}) = \left(4.13 \pm 0.16\,(\text{stat}) \pm 0.25\,(\text{syst}) \pm 0.24\,(f_d/f_s)\right) \times 10^{-5}
$$



definition of helicity angles

LHCB-PAPER-2015-034 in preparation
to be submitted to JHEP

Penguins from $B_s \to J/\psi K^{*0}$ ($3fb^{-1}$)

- result combined with $B^0 \to J/\psi\rho^0$ PLB742, 38-49 (2015)

Preliminary

$$\Delta\phi_{s,0}^{J/\psi\,\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})^{+0.004}_{-0.009}\,(\text{syst})$$

$$\Delta\phi_{s,\parallel}^{J/\psi\,\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat})^{+0.007}_{-0.008}\,(\text{syst})$$

$$\Delta\phi_{s,\perp}^{J/\psi\,\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat})^{+0.007}_{-0.008}\,(\text{syst})$$

absolute shift on ϕ_s smaller is found smaller than 19 mrad

no need to worry yet

$$\phi_s = -0.034 \pm 0.033\,\text{rad}$$

(World Average) HFAG preliminary

Charm CPV Measurements

Looking for anything ...

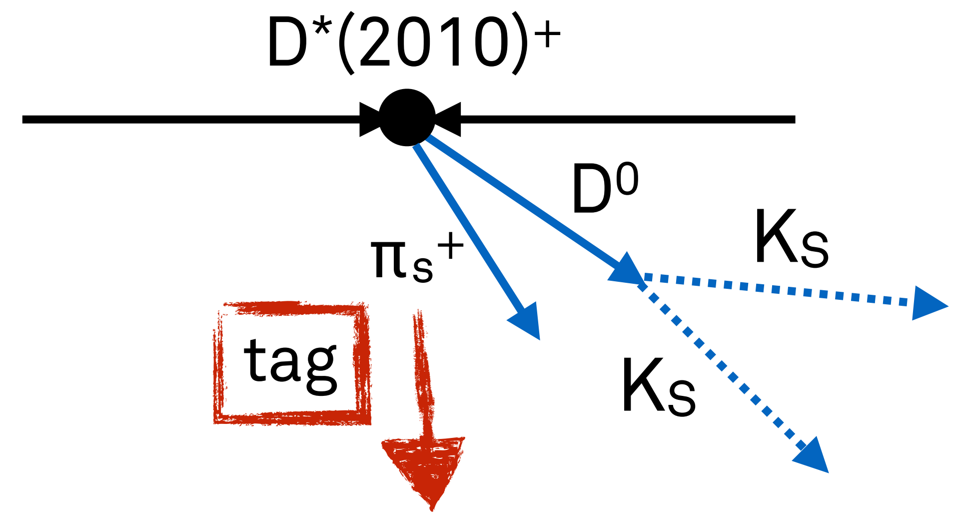
Time integrated CPV
- $D^0 \rightarrow K_S K_S$

Amplitude Analysis of
- $D^0 \rightarrow K_S K^{\pm} \pi^{\mp}$

LHCB-PAPER-2015-030 in preparation
to be submitted to JHEP

Time integrated CPV in $D^0 \to K_S K_S$

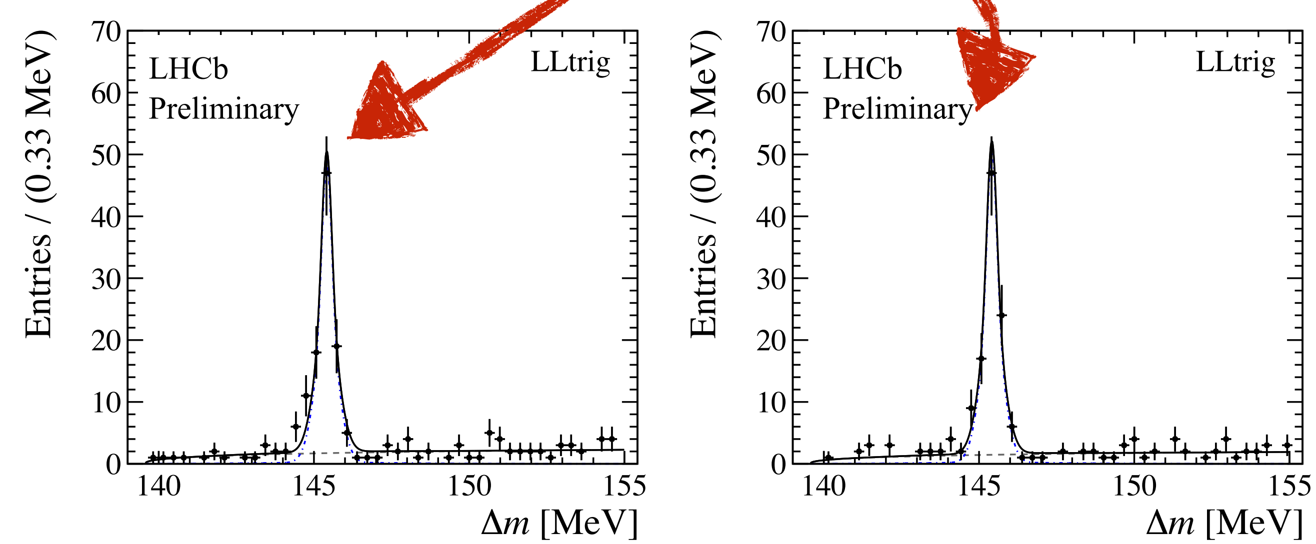
- CPV could be as big as O(1%)
- vertexing two long lived neutrals
- tagged by charged π_s from prompt D^*
- systematics from $D^0 \to K^- \pi^+$
  - charged $\pi_s^{\pm}$ detection asymmetry
  - background model



$$A_{CP} = \frac{N^+ - N^-}{N^+ + N^-}$$

$$A_{CP} = -0.029 \pm 0.052 \pm 0.022$$

No evidence of CPV

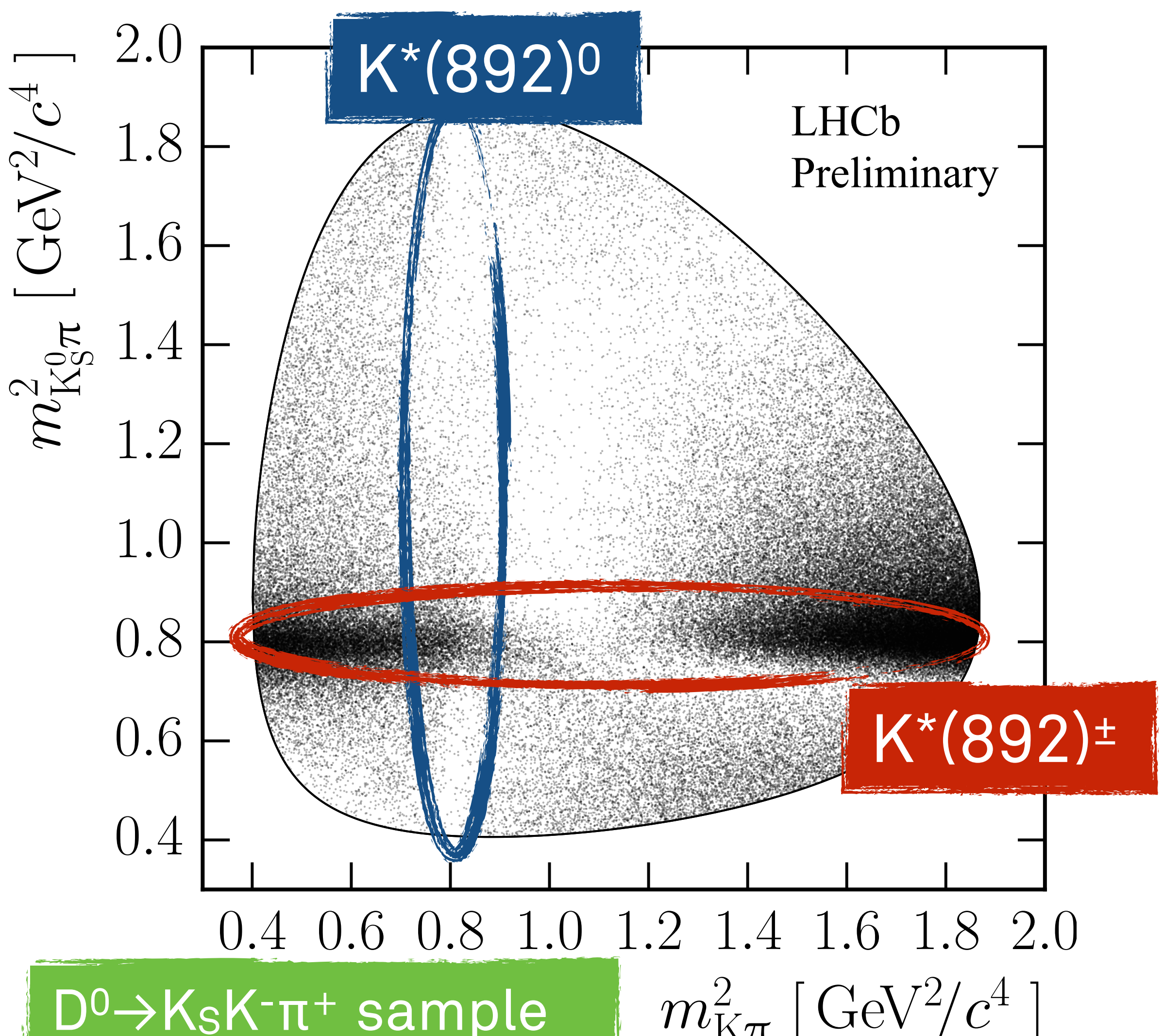


- not as sensitive as other charm CPV searches yet:

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\%$$
$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$ JHEP 07 (2014) 041

Amplitude Analysis of $D^0 \to K_S K^\pm \pi^\mp$

- 190K signal candidates
- final state reached by various resonances



$D^0 \to K_S K^- \pi^+$ sample
+ charge conjugated

- description via „isobar models"

$$A = \sum_R a_R e^{i\Phi_R} A_R$$

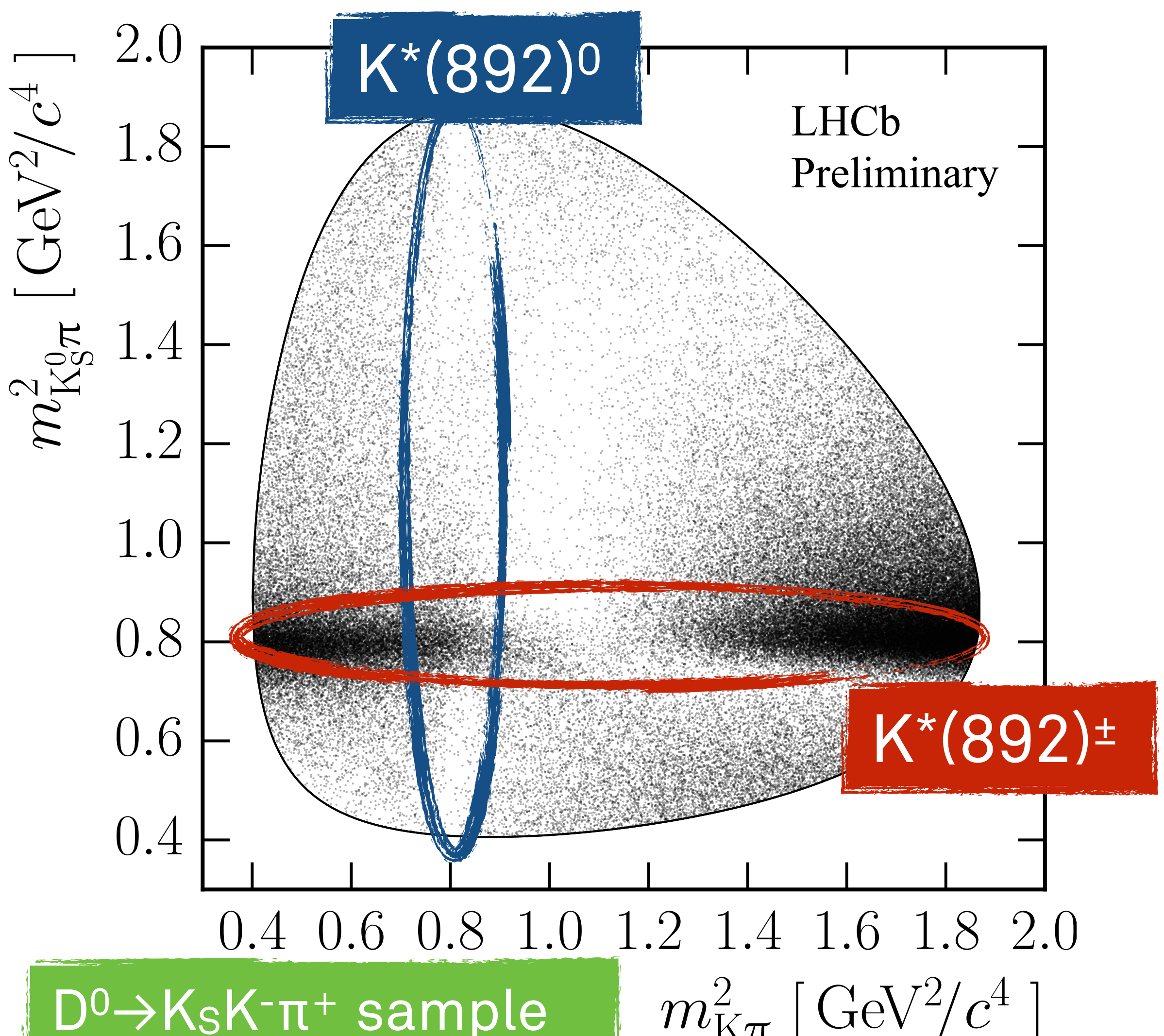
useful input for other analyses

LHCB-PAPER-2015-026 in preparation
to be submitted to PRD

Amplitude Analysis of $D^0 \to K_S K^\pm \pi^\mp$

- 190K signal candidates
- final state reached by various resonances

Model dependent CPV search!



$D^0 \to K_S K^- \pi^+$ sample
\+ charge conjugated

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$$A = \sum_R a_R e^{i\Phi_R} A_R$$

useful input for other analyses

- for CPV: refit best model using

$$A = \sum_R (a_R \pm \Delta a_R) e^{i(\Phi_R \pm \Delta\Phi_R)} A_R$$

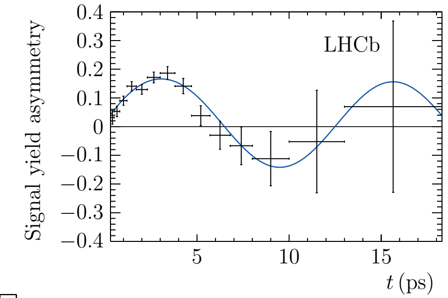
  - χ^2 test of $\Delta a_R = 0, \Delta\Phi_R = 0$
  - p-value of 0.45 → not rejected

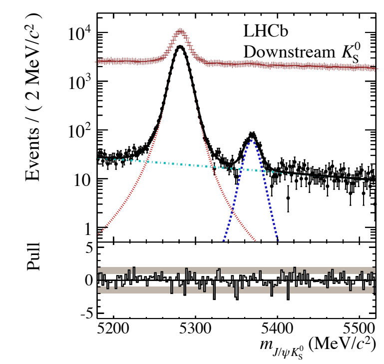
signs from π_s tag

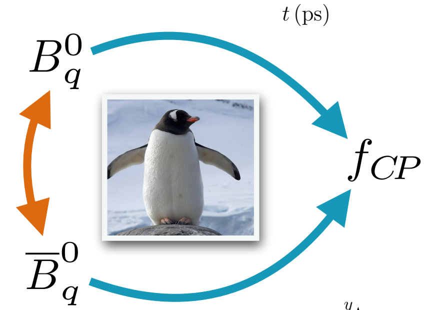
No evidence of CPV

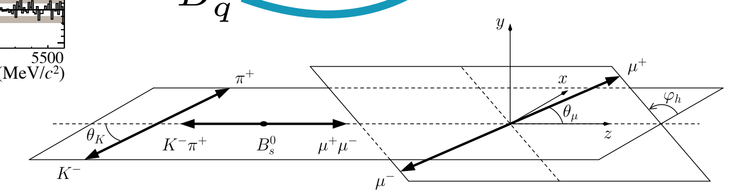
Conclusions

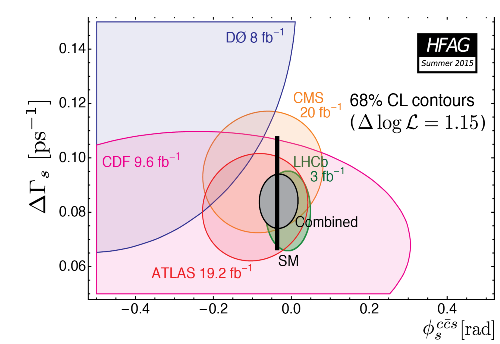
- colorful program of beauty & charm CPV analyses at LHCb
  (I've shown you only a tiny selection of its freshest)
- if present new physics in CPV searches must be small
- penguin contributions are under control
- no evidence of charm CPV yet
- analyses are mostly statistically limited
  - stay tuned for Run II - exciting results to come from LHCb!

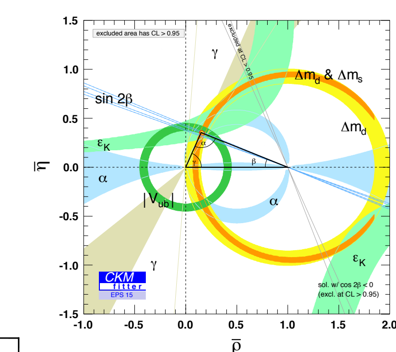


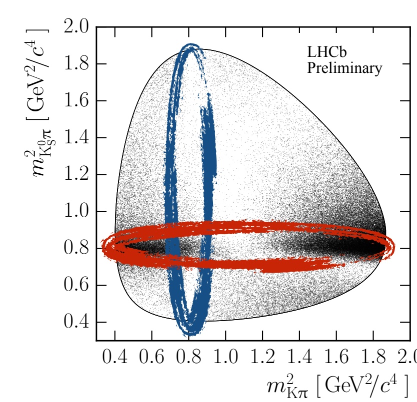






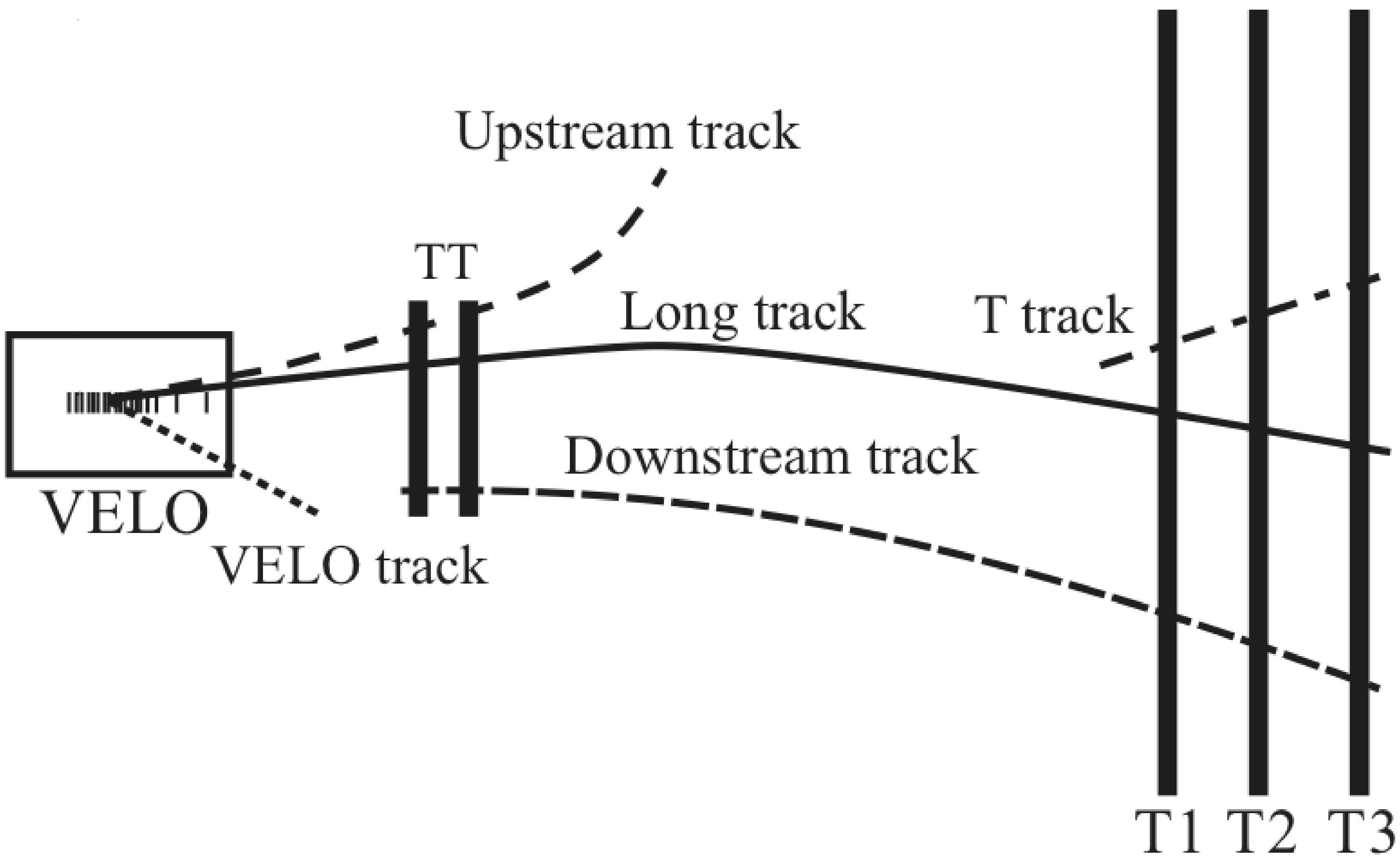






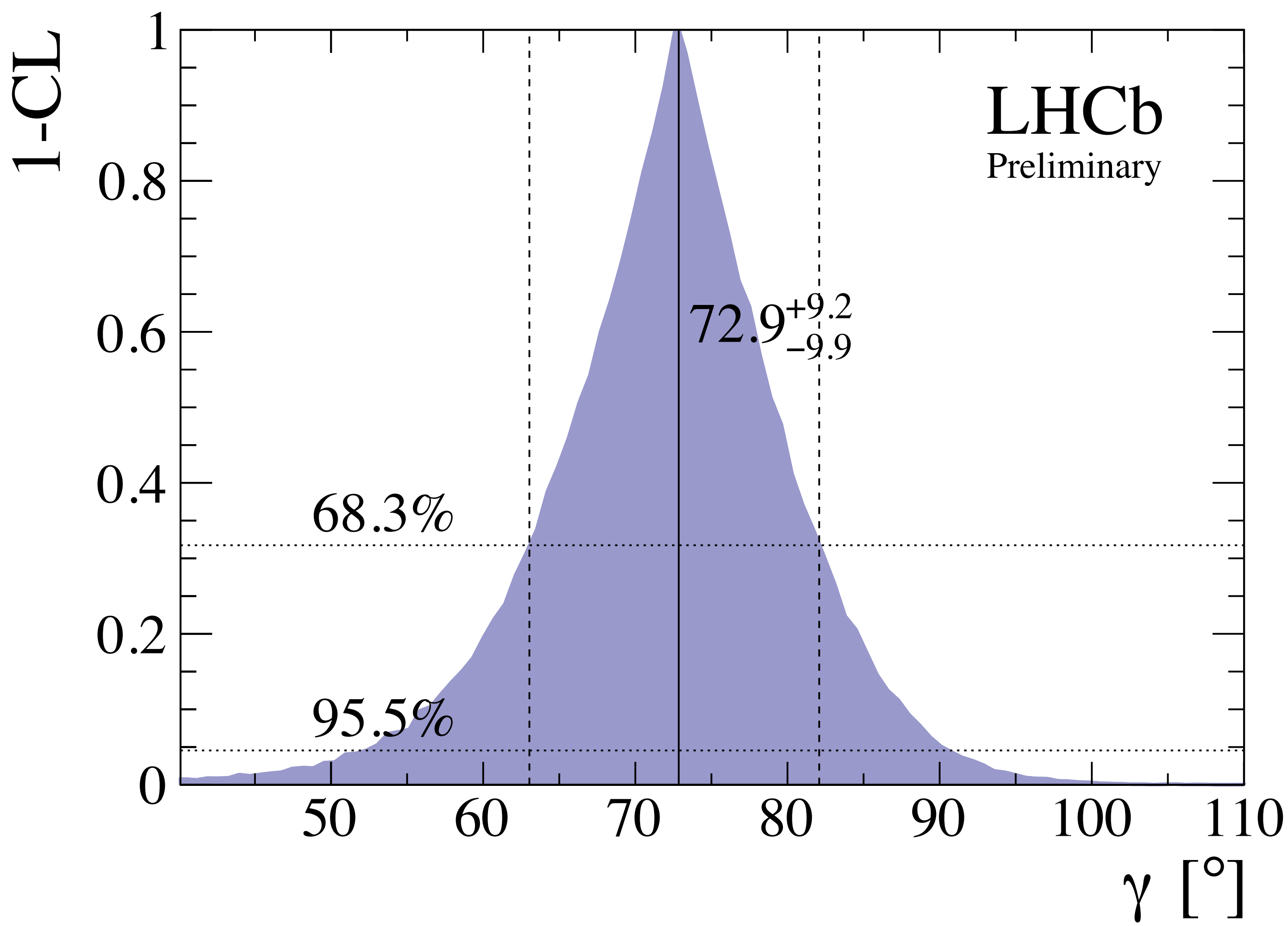
Backup

Candidate classification



γ Combination

- mixture of $3fb^{-1}$ and $1fb^{-1}$ measurements

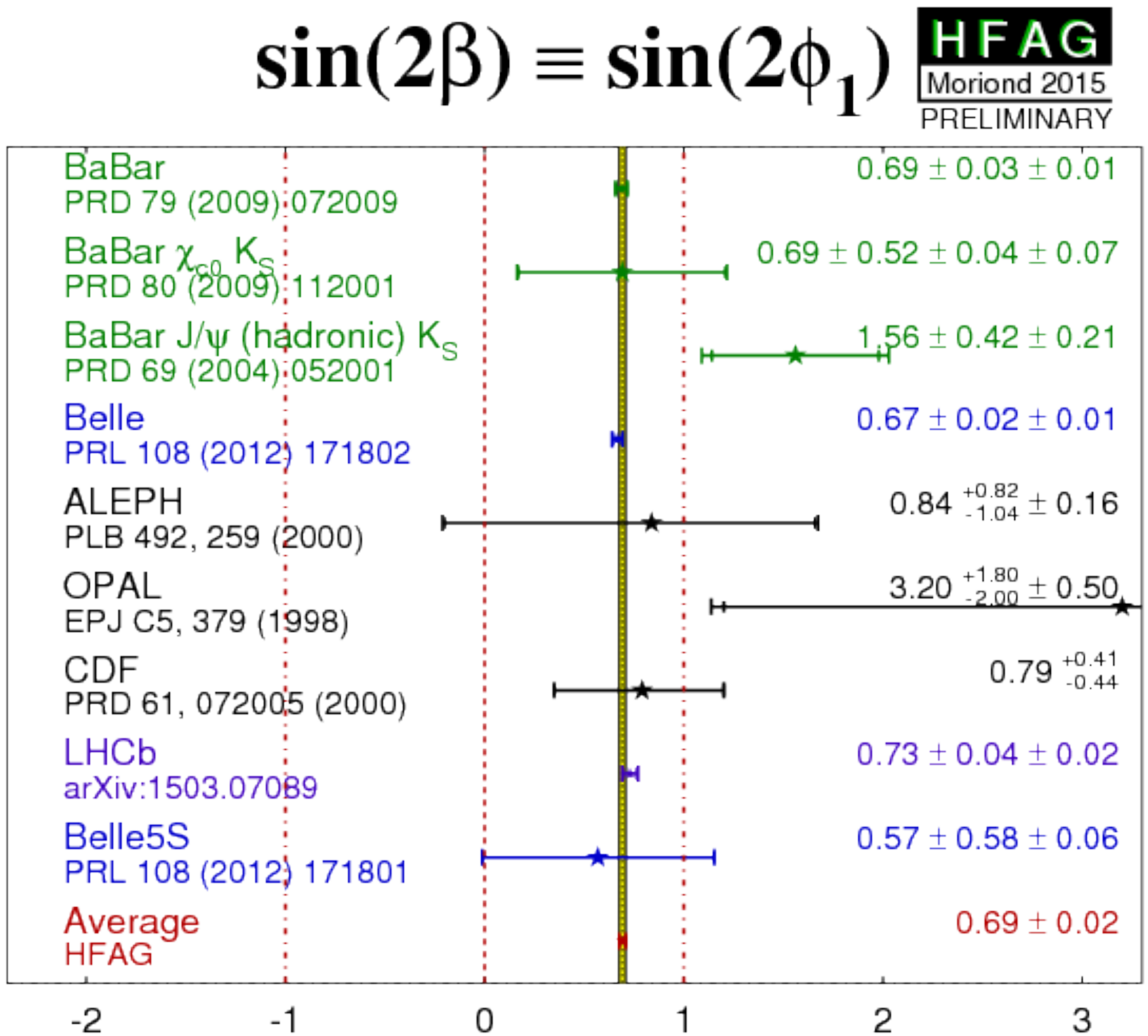


LHCb Analysis
$B^+ \to DK^+$, $D \to hh$, GLW/ADS
$B^+ \to DK^+$, $D \to K\pi\pi\pi$, ADS
$B^+ \to DK^+$, $D \to K^0_S hh$, model-independent GGSZ
$B^+ \to DK^+$, $D \to K^0_S K\pi$, GLS
$B^0 \to DK^{*0}$ GLW/ADS
$B^0_s \to D^\mp_s K^\pm$

sin(2β) with $B^0 \to J/\psi K_S$ ($3fb^{-1}$)

- systematic uncertainties

Origin	σ_S	σ_C
Background tagging asymmetry	0.0179 (2.5 %)	0.0015 (4.5 %)
Tagging calibration	0.0062 (0.9 %)	0.0024 (7.2 %)
$\Delta\Gamma$	0.0047 (0.6 %)	—
Fraction of wrong PV component	0.0021 (0.3 %)	0.0011 (3.3 %)
z-scale	0.0012 (0.2 %)	0.0023 (7.0 %)
Δm	—	0.0034 (10.3 %)
Upper decay time acceptance	—	0.0012 (3.6 %)
Correlation between mass and decay time	—	—
Decay time resolution calibration	—	—
Decay time resolution offset	—	—
Low decay time acceptance	—	—
Production asymmetry	—	—
Sum	0.020 (2.7 %)	0.005 (15.2 %)



$\sin(2\beta)_{b\to c\bar{c}s,\text{HFAG}} = 0.691 \pm 0.017 (0.016_{\text{stat-only}})$

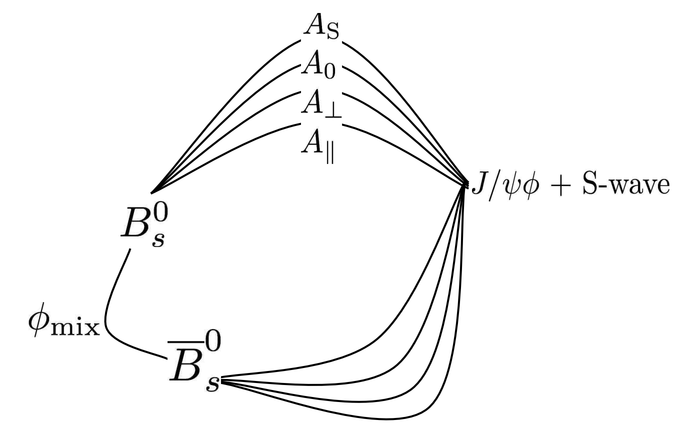
$C_{b\to c\bar{c}s,\text{HFAG}} = -0.004 \pm 0.015 (0.012_{\text{stat-only}})$

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

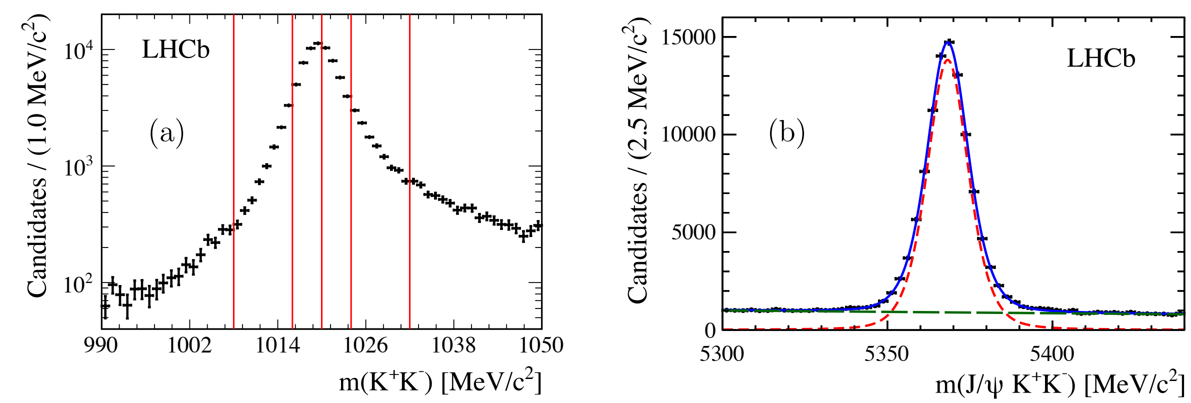
- systematic uncertainties

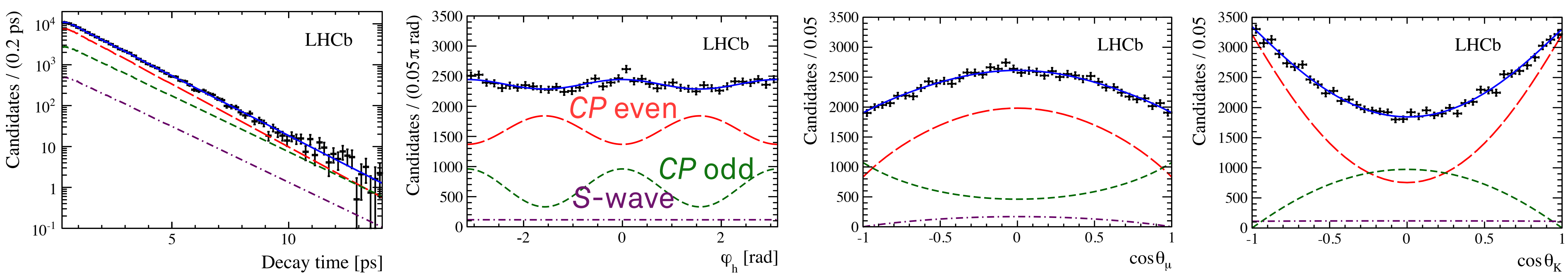
Source	$\mathcal{A}_{\Delta\Gamma}$	C_{dir}	S_{mix}	Long $R \times 10^5$	Downstream $R \times 10^5$
Mass modelling	0.045	0.009	0.009	15.5	17.2
Decay-time resolution	0.038	0.066	0.070	0.6	0.3
Decay-time acceptance	0.022	0.004	0.004	0.6	0.5
Tagging calibration	0.002	0.021	0.023	0.1	0.2
Mass resolution	0.010	0.005	0.006	12.6	8.0
Mass–time correlation	0.003	0.037	0.036	0.2	0.1
Total	0.064	0.079	0.083	20.0	19.0

Φ_s with $B_s \rightarrow J/\psi K^+K^-$ ($3 fb^{-1}$)



- **tagged time-dependent** analysis, but...
- K^+K^- reached dominantly via ϕ resonance (P-Wave)
  - **P2VV decay** CP even (L=0,2) and CP odd (L=1) final state
- takes S-Wave contribution into account
  - analysis is performed in bins of $m(K^+K^-)$
- angular analysis to statistically disentangle
- also studies polarization dependence of CPV
- ≈ 96000 signal candidates





$$\phi_s = -0.058 \pm 0.049\,(\text{stat}) \pm 0.006\,(\text{syst})$$

No evidence for polarisation dependent CP violation

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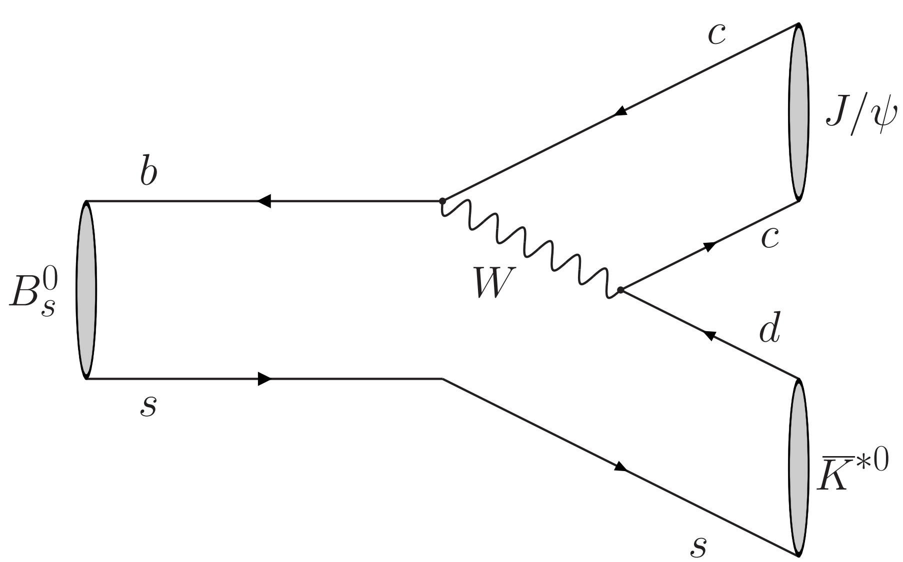
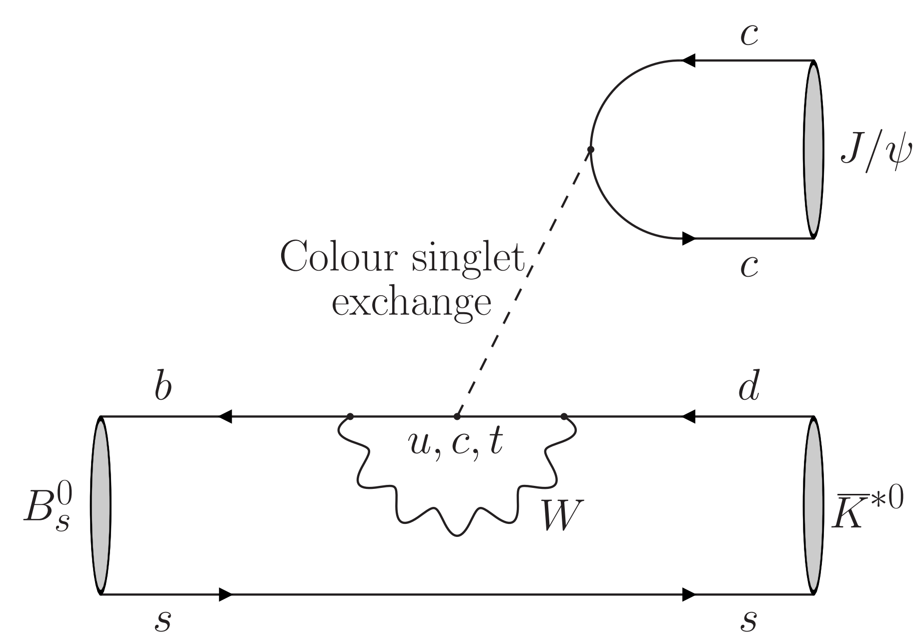
CPV in $B_s \to J/\psi K^{*0}$

- Feynman diagrams





- Definition of direct CP asymmetry:

$$A^i_{CP}(B^0_{(s)} \to f_{(s)}) = \frac{\Gamma(\overline{B}^0_{(s)} \to \overline{f}_{(s),i}) - \Gamma(B^0_{(s)} \to f_{(s),i})}{\Gamma(\overline{B}^0_{(s)} \to \overline{f}_{(s,),i}) + \Gamma(B^0_{(s)} \to f_{(s),i})}$$

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$B_s \to J/\psi K^{*0}$ systematics (P-Wave)

	f_0	$f_\parallel$	$\delta_\parallel$	$\delta_\perp$	A_0^{CP}	$A_\parallel^{CP}$	$A_\perp^{CP}$
Fitted value	0.497	0.179	−2.70	0.01	−0.048	0.171	−0.049
Statistical uncertainties	$^{+0.024}_{-0.025}$	$^{+0.027}_{-0.026}$	$^{+0.15}_{-0.16}$	0.11	0.057	0.152	$^{+0.095}_{-0.096}$
Angular acceptance (MC stat)	0.018	0.008	0.02	0.01	0.009	0.017	0.008
Angular acceptance (data–MC corrections)	0.015	0.007	0.17	0.10	0.007	—	0.015
C_{SP} factors	—	0.001	—	—	0.001	0.002	0.002
D–wave contribution	0.004	0.003	—	—	0.002	0.015	0.002
Background angular model	$^{+0.004}_{-0.003}$	0.002	0.02	0.01	$^{+0.003}_{-0.004}$	$^{+0.012}_{-0.004}$	0.002
Mass parameters and B^0 contamination	—	—	—	—	0.001	0.001	—
Mass—$\cos(\theta_\mu)$ correlations	0.007	0.006	0.07	$^{+0.02}_{-0.04}$	0.014	$^{+0.009}_{-0.012}$	0.016
Fit bias	—	—	0.01	0.12	0.003	0.003	0.005
Detection asymmetry	—	—	—	—	0.005	0.005	$^{+0.005}_{-0.006}$
Production asymmetry	—	—	—	—	—	—	—
Quadratic sum of systematics	0.025	0.013	0.19	0.16	$^{+0.019}_{-0.020}$	$^{+0.028}_{-0.027}$	0.025
Total uncertainties	0.035	$^{+0.030}_{-0.029}$	$^{+0.24}_{-0.25}$	0.20	$^{+0.063}_{-0.062}$	0.163	$^{+0.098}_{-0.099}$

$B_s \to J/\psi K^{*0}$ systematics (S-Wave)

	A_S^{CP}	$m_{K\pi}^{\text{bin0}}$ F_S	$m_{K\pi}^{\text{bin0}}$ δ_S	$m_{K\pi}^{\text{bin1}}$ F_S	$m_{K\pi}^{\text{bin1}}$ δ_S	$m_{K\pi}^{\text{bin2}}$ F_S	$m_{K\pi}^{\text{bin2}}$ δ_S	$m_{K\pi}^{\text{bin3}}$ F_S	$m_{K\pi}^{\text{bin3}}$ δ_S
Fitted value	0.167	0.475	0.54	0.080	−0.53	0.044	−1.46	0.523	−1.76
Statistical uncertainties	$^{+0.113}_{-0.114}$	$^{+0.108}_{-0.112}$	0.16	$^{+0.031}_{-0.025}$	$^{+0.25}_{-0.21}$	$^{+0.042}_{-0.029}$	$^{+0.22}_{-0.19}$	$^{+0.109}_{-0.112}$	$^{+0.13}_{-0.14}$
Angular acceptance (MC stat)	0.028	0.039	0.03	0.012	0.065	0.015	0.10	0.065	0.06
Angular acceptance (data–MC corrections)	0.015	0.058	0.08	0.019	0.18	0.027	0.27	0.006	0.04
C_{SP} factors	—	0.002	0.01	0.001	—	0.002	—	0.001	0.01
D–wave contribution	0.008	0.010	0.02	0.005	0.03	0.008	0.08	0.002	0.04
Background angular model	0.001	0.002	0.01	$^{+0.000}_{-0.001}$	0.01	—	$^{+0.03}_{-0.02}$	$^{+0.002}_{-0.000}$	$^{+0.07}_{-0.04}$
Mass parameters and B^0 contamination	0.001	0.001	$^{+0.00}_{-0.01}$	—	—	—	—	—	—
Mass—$\cos(\theta_\mu)$ correlations	$^{+0.023}_{-0.029}$	$^{+0.040}_{-0.028}$	0.05	0.003	0.04	$^{+0.006}_{-0.016}$	0.02	$^{+0.009}_{-0.011}$	$^{+0.02}_{-0.03}$
Fit bias	0.001	0.005	0.01	0.001	0.01	0.004	0.03	0.013	—
Detection asymmetry	0.005	—	—	—	—	—	—	—	—
Production asymmetry	—	—	—	—	—	—	—	—	—
Quadratic sum of systematics	$^{+0.040}_{-0.044}$	$^{+0.081}_{-0.076}$	.10	0.023	0.20	$^{+0.033}_{-0.036}$	0.30	0.067	$^{+0.10}_{-0.09}$
Total uncertainties	$^{+0.120}_{-0.122}$	0.135	0.19	$^{+0.038}_{-0.031}$	$^{+0.32}_{-0.29}$	$^{+0.053}_{-0.046}$	$^{+0.36}_{-0.35}$	$^{+0.128}_{-0.131}$	0.17

Penguins from $B_s \to J/\psi K^{*0}$

- Relation between amplitudes:

$$A\left(B_s^0 \to (J/\psi\,\overline{K}^{*0})_i\right) = -\lambda \mathcal{A}_i \left[1 - a_i e^{i\theta_i} e^{i\gamma}\right]$$

$$A\left(B_s^0 \to (J/\psi\,\phi)_i\right) = \left(1 - \frac{\lambda^2}{2}\right) \mathcal{A}'_i \left[1 + \epsilon a'_i e^{i\theta'_i} e^{i\gamma}\right]$$

$$a'_i = a_i \qquad \theta'_i = \theta_i$$

SU(3) Flavour Symmetry

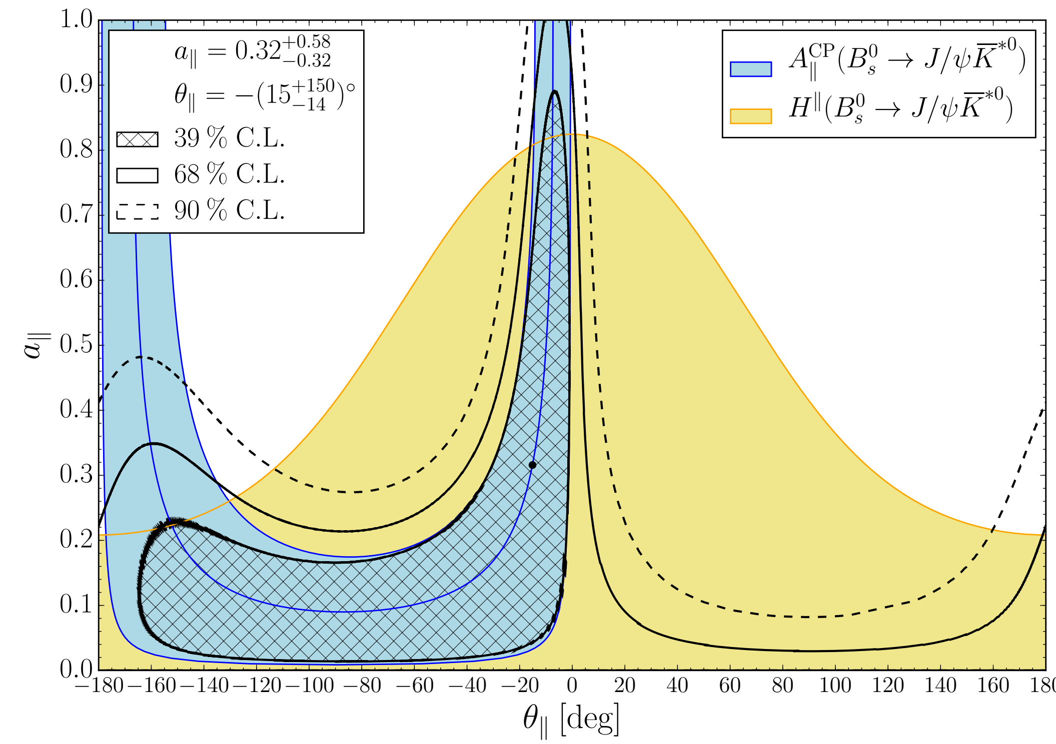
- Observables for extraction:

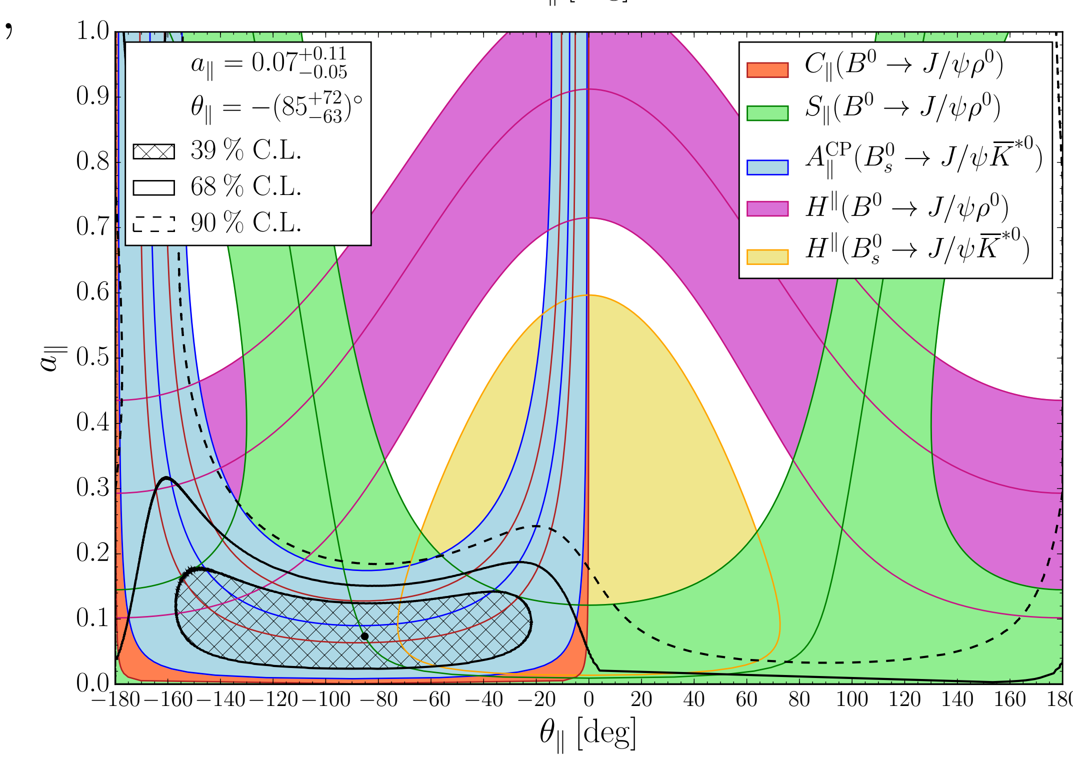
$$H_i \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'_i}{\mathcal{A}_i}\right|^2 \frac{\Phi(m_{J/\psi}/m_{B_s^0}, m_\phi/m_{B_s^0})}{\Phi(m_{J/\psi}/m_{B_s^0}, m_{\overline{K}^{*0}}/m_{B_s^0})} \frac{\mathcal{B}(B_s^0 \to J/\psi\,\overline{K}^{*0})_{\text{theo}}}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)_{\text{theo}}} \frac{f_i}{f'_i},$$

$$= \frac{1 - 2a_i \cos\theta_i \cos\gamma + a_i^2}{1 + 2\epsilon a'_i \cos\theta'_i \cos\gamma + \epsilon^2 a'^2_i},$$

$$A_i^{CP} = -\frac{2a_i \sin\theta_i \sin\gamma}{1 - 2a_i \cos\theta_i \cos\gamma + a_i^2}$$

$$\tan(\Delta\phi_{s,i}^{J/\psi\,\phi}) = \frac{2\epsilon a'_i \cos\theta'_i \sin\gamma + \epsilon^2 a'^2_i \sin(2\gamma)}{1 + 2\epsilon a'_i \cos\theta'_i \cos\gamma + \epsilon^2 a'^2_i \cos(2\gamma)}$$





LHCB-PAPER-2015-034 in preparation
to be submitted to JHEP

Penguins from $B_s \to J/\psi K^{*0}$

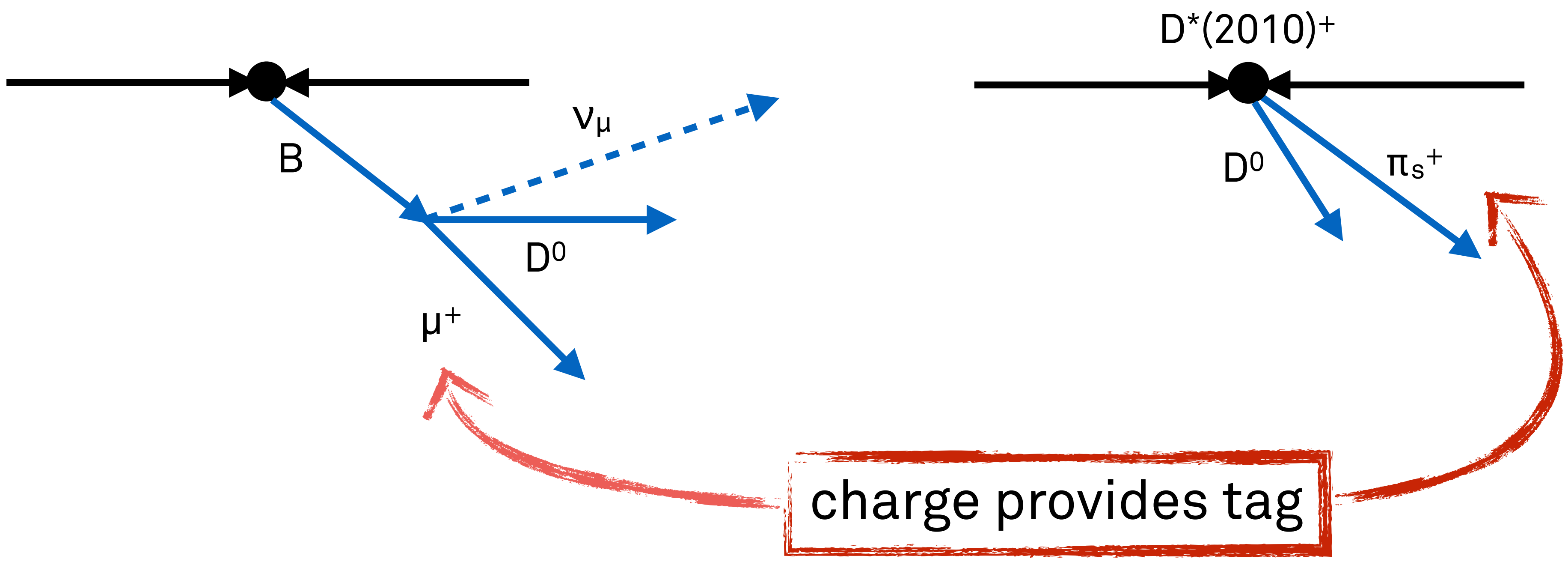
- Observables in $B^0 \to J/\psi\rho^0$ that relate to penguin parameters:

$$C_i = \frac{2\, a_i \sin\theta_i \sin\gamma}{1 - 2\, a_i \cos\theta_i \cos\gamma + a_i^2}\,,$$

$$S_i = -\eta_i \left[\frac{\sin\phi_d - 2\, a_i \cos\theta_i \sin(\phi_d + \gamma) + a_i^2 \sin(\phi_d + 2\gamma)}{1 - 2\, a_i \cos\theta_i \cos\gamma + a_i^2}\right]$$

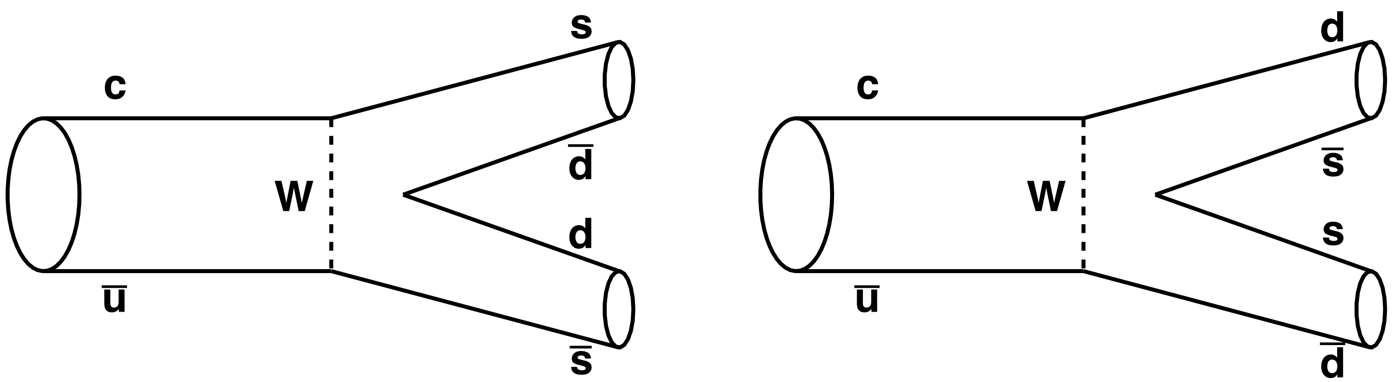
CPV Measurements Charm at LHCb

- O(5 x 10^{12}) cc pairs produced during 2011-2012 in LHCb
  - Worlds best sensitivity to many Charm CPV observables
  - Highly boosted D mesons great for time-dependent studies
- At LHCb two methods to tag charm
  - semi-leptonic B decays

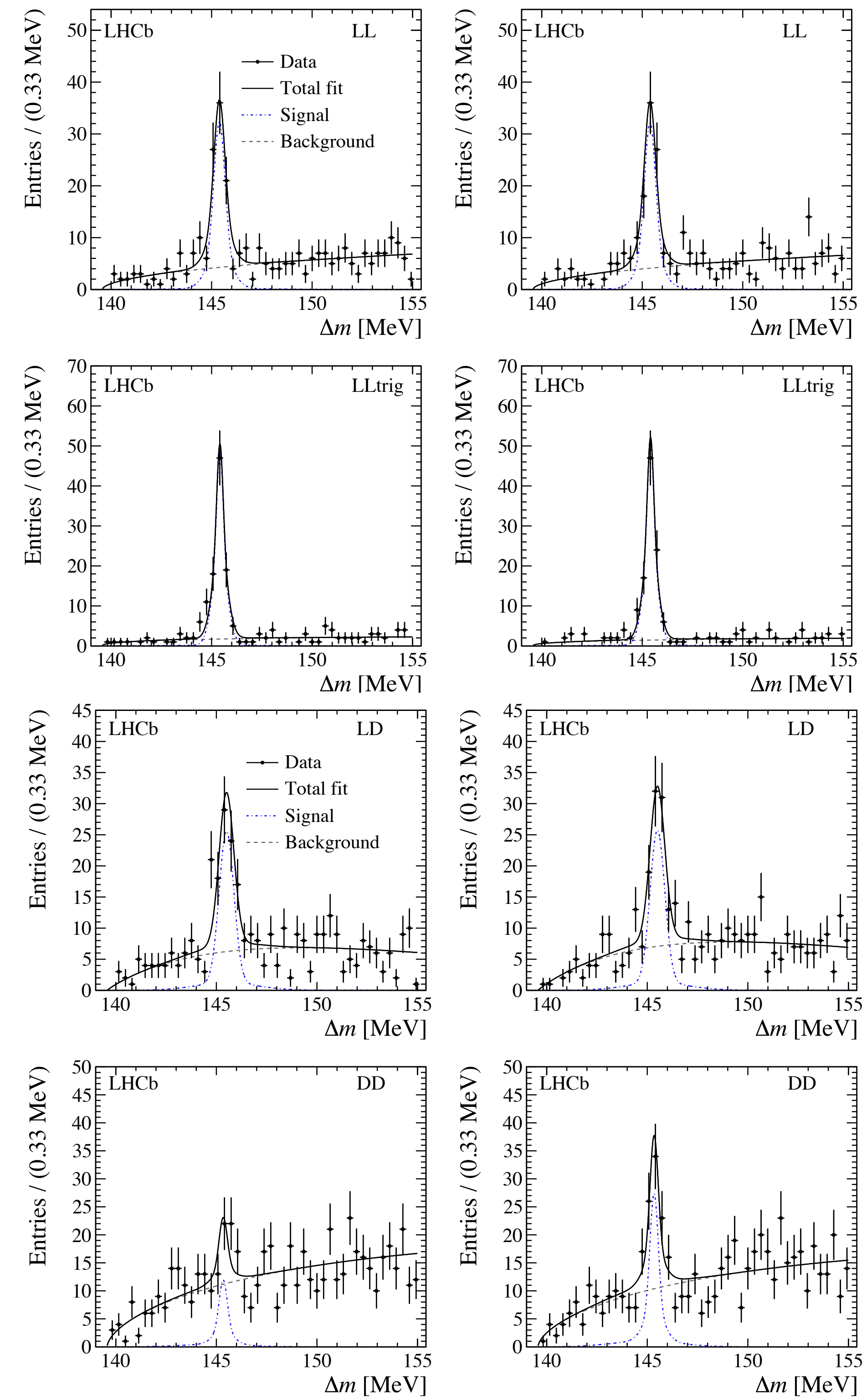


Time integrated CPV in $D^0 \rightarrow K_S K_S$

- dominant processes largely cancel



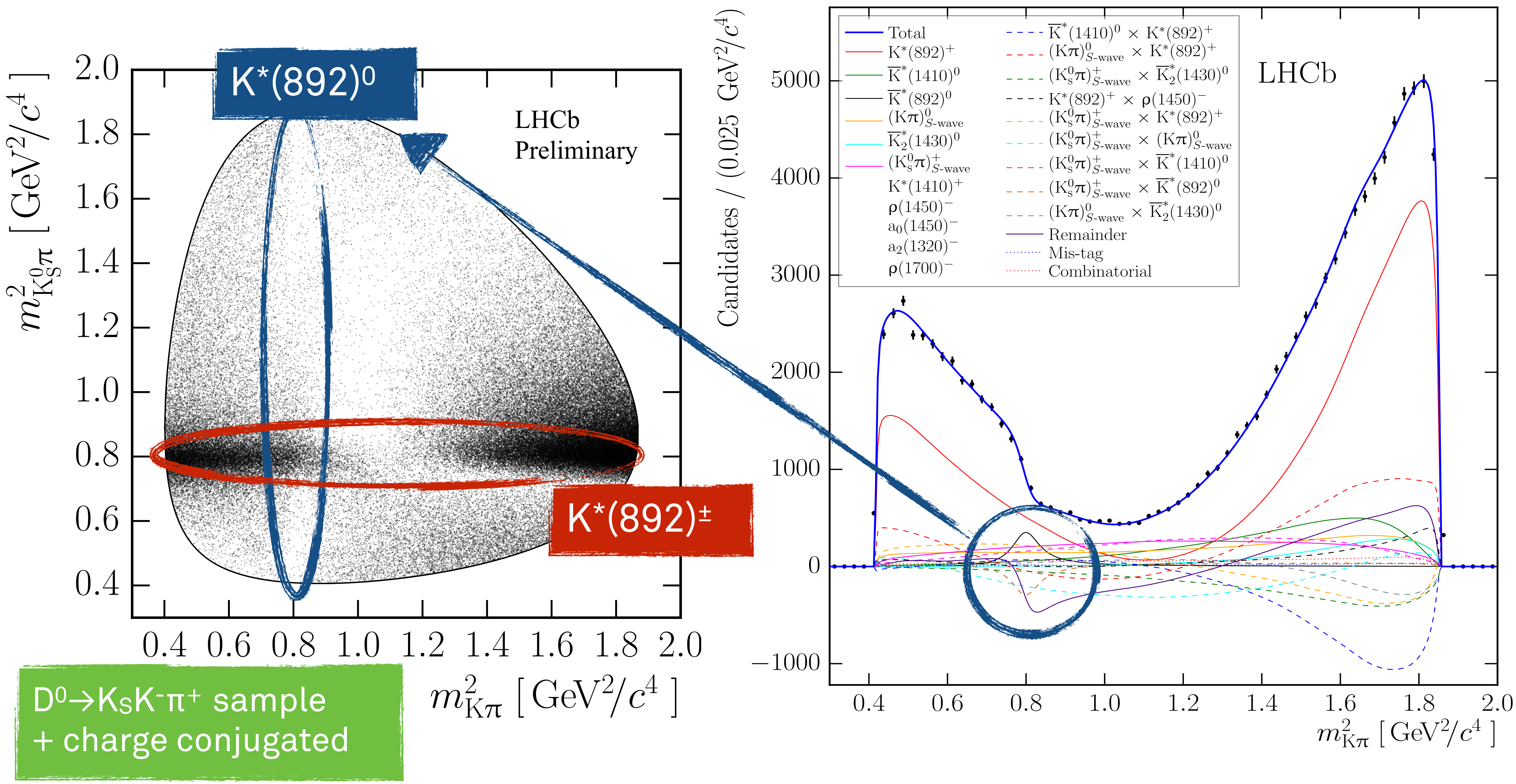
- 3 different track categories (LL, DD, LD)
- dedicated trigger line during 2012 running period
- systematics assessed from $D^0 \rightarrow K^- \pi^+$
  - charged pion detection asymmetry
  - background model



LHCB-PAPER-2015-026 in preparation
to be submitted to PRD

Amplitude Analysis of $D^0 \to K_S K^\pm \pi^\mp$

- Destructive Interference of $K_S\pi$ S-Wave



Wolfenstein & Angles

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

$$V_{\text{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$+\begin{pmatrix} -\frac{1}{8}\lambda^4 & 0 & 0 \\ \frac{1}{2}A^2\lambda^5\,[1-2(\rho+i\eta)] & -\frac{1}{8}\lambda^4(1+4A^2) & 0 \\ \frac{1}{2}A\lambda^5(\rho+i\eta) & \frac{1}{2}A\lambda^4\,[1-2(\rho+i\eta)] & -\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$$+\mathcal{O}(\lambda^6).$$

$A \approx 0.82 \quad \lambda \approx 0.22 \quad \rho \approx 0.13$

$\eta \approx 0.26$

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \quad \beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$