Prospects for CP violation in $B_s^0 \to J/\psi\phi$ from first LHCb data

Basem Khanji

On behalf of the LHCb collaboration
CPPM, Aix-Marseille Université IN2P3 CNRS, France

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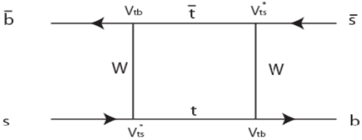
Outlines

1. Theoretical aspects
2. LHCb detector
3. $\phi_s^{J/\psi\phi}$ analysis
4. Conclusions and prospects

Mixing

- Neutral B mesons:
  - Mixing phenomena takes place via the weak interaction
  - B meson evolves as a superposition of B and $\overline{\mathrm{B}}$ states
    - Mass difference Δm_{q}
    - Width difference $\Delta\Gamma_{\mathrm{q}}$
    - phase $\phi_{SM}^{M/\Gamma} \sim (3.40^{+1.32}_{-0.77}) \times 10^{-3}\,\mathrm{rad.}$

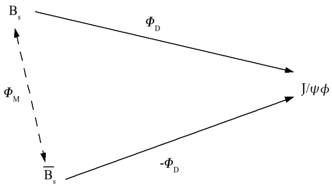


- Larger contribution $\phi_{\mathrm{s}}^{\Delta}$ from NP would change the predictions:

$$\phi^{M/\Gamma} \sim \phi_{SM}^{M/\Gamma} + \phi_{\mathrm{s}}^{\Delta} \sim \phi_{\mathrm{s}}^{\Delta}$$

CP violation in the interference

- CP violation in the interference between the decay and mixing
  - Tree-dominated decay diagram
  - $\phi_s^{J/\psi\phi} = \Phi_M - 2\Phi_D \sim -2\beta_s$
- $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
  - $-2\beta_s^{SM} \sim (-0.0360^{+0.0020}_{-0.0016})$ rad

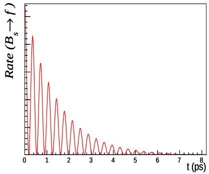


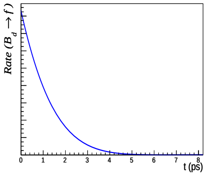
- Large NP contribution ϕ_s^{Δ} from NP would change the predictions:

$$-2\beta_s \sim -2\beta_s^{SM} + \phi_s^{\Delta} \sim \phi_s^{\Delta}$$

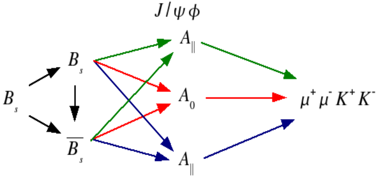
Challenges

- B_s^0 system has a fast oscillation
  - Need fine proper time resolution





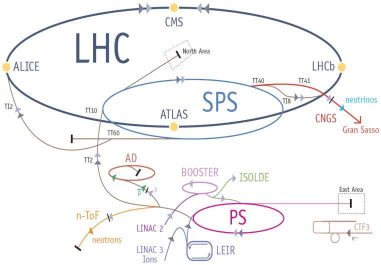
- $B_s^0 \to J/\psi\phi$ is a P→VV decay
  - $J/\psi\phi$ final state is a mixture of CP odd and CP even states.
  - Angular analysis to disentangle statistically these amplitudes

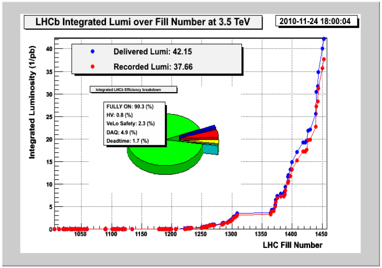


- $\Delta\Gamma_s >> \Delta\Gamma_d$
  - Correlation between proper time and angular variables

LHC

- LHC: the largest proton accelerator in the world
- Start end of 2009: @ 900 GeV
- 2010: collision @ 7 TeV
    - Increase number of interaction per crossing → collect Max. lumi.

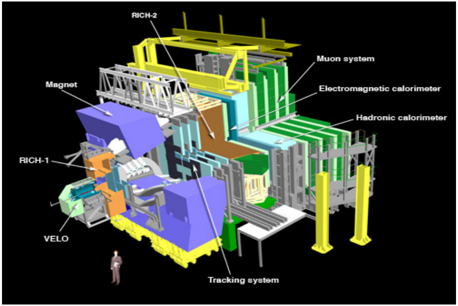




- LHCb recorded ∼ 37 pb^{-1}

LHCb detector

- LHCb physics' program:
  - CP violation (beauty/charm)
  - Rare decays
- Single-arm forward spectrometer:
  - VELO:
    reconstruct vertexes
    proper time measurement
  - Tracking system & magnet:
    reconstruct tracks & momentum
  - RICH system:
    $K - \pi$ identification
  - Calorimeter:
    Energy measurement, identify π^0,γ
  - Muon detector



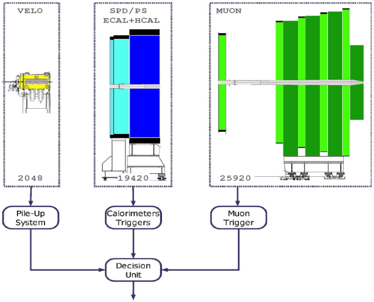
$\phi_s^{J/\psi\phi}$ measurement strategy

Analysis strategy to probe new physics at LHCb with the phase $\phi_s^{J/\psi\phi}$:

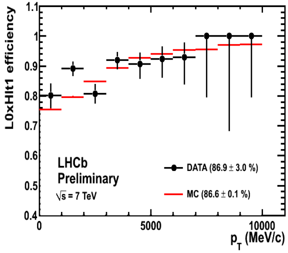
- Trigger & select $B_s^0 \to J/\psi\phi$ events
  - Avoid bias on the proper time distributions
    Crucial for the validation studies
    Understand systematics
- Measure mass, proper time & angular variables
  - Calibration & alignment of sub-detectors
- Tag initial flavor
  - Taggers' calibration using control channels
    ($B^0 \to J/\psi K^{*0}$, $B^+ \to J/\psi K^+$, $B_s^0 \to D_s^- \pi^+$)
- Fit the $\phi_s^{J/\psi\phi}$ phase

Trigger & select $B_s^0 \to J/\psi\phi$ events

- L0 hardware trigger:
  - Find lepton, hadron with high p_T
- HLT1 software trigger:
  - Finds vertexes in VELO
  - Tracks with high IP & p_T
- HLT2 software trigger:
  - Reconstruct all tracks in event
  - Select inclusive/exclusive B meson decays



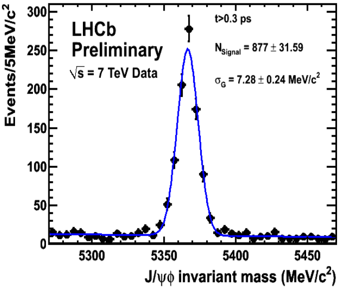
$J/\psi(\mu\mu)$



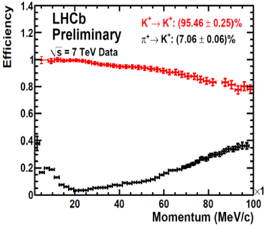
Trigger & select $B_s^0 \to J/\psi\phi$ events

- Selection is cut based, optimized against $S/\sqrt{S+B}$
- Unbiased selection
  - No cuts on IP, decay length, etc
  - Significant prompt background $B/S \sim 3$
  - Yield $\sim$ 30 k event per fb^{-1}
- Rely on kinematics & PIDs

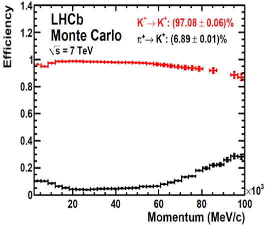
$\mathcal{L}_{\mathrm{int}} \sim 33\ \mathrm{pb}^{-1}$



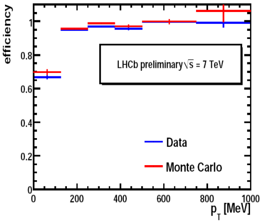
$K - \pi$ separation data



$K - \pi$ separation MC

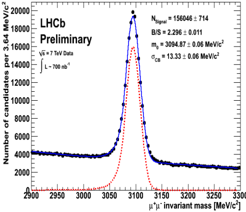


long tracks' efficiency comparison

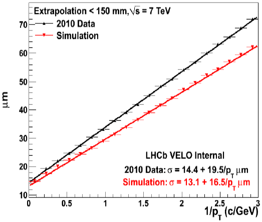


Measure mass, proper time & angular variables

- Excellent tracking system
  - very good mass resolutions ($\Delta P/P \sim 0.45\%$)
- Good proper time resolution
  - Yet performance still less than expected (30% worse in data)

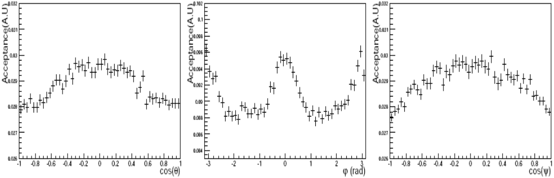


$J/\psi(\mu\mu)$ mass resolution



VELO IP_x resolution Vs $1/p_T$

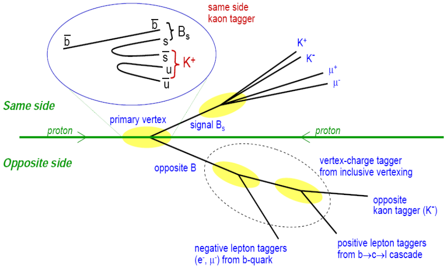
- Detector shape distorts angular variables' distributions
- Distortion's corrections (MC or real data using $B^0 \to J/\psi K^{*0}$ mode



LHCb angular distortions (MC expectations)

Tag initial flavor

- Determine the initial flavor of the B particle using tagging algorithm
- Precise estimation on: how often [tagging efficiency $\varepsilon_{\mathrm{eff}}$] and how good [mistag rate ω] you tag
    - Opposite-side tag: charge from leptons, K, inclusive vertex
    - Same-side tag: K from fragmentation quark
    - $\varepsilon_{\mathrm{tag}}(1-2\omega)^2 \sim 5.3\%$ for $\mathrm{B}_s^0 \to J/\psi\phi$ (MC expectations)

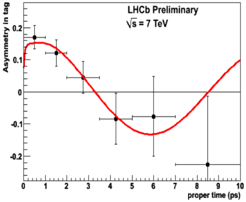


- Use signal-like channels to calibrate and control taggers
    - Select signal/control channels in a similar manner

Tag $B_s^0 \to J/\psi\phi$ events initial flavor

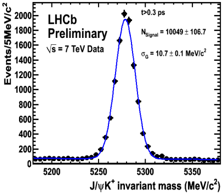
- Tagging optimization in $B^0 \to D^{*-}\mu^+\nu$
  - Fit for time evolution $\to$ extract mistag rate from oscillation $(\varepsilon_{tag}(1-2\omega)^2 \sim 60\%$ of MC expectations)

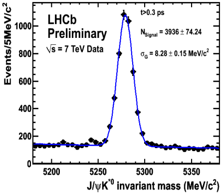
$\mathcal{L}_{int} \sim 2\ \text{pb}^{-1}$



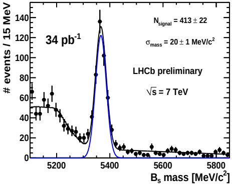
- Opposite side tagging's calibration:
  - Count the right/wrong tagged events in $B^+ \to J/\psi K^+$
  - Fit for time evolution in $B^0 \to J/\psi K^{*0}$ $\to$ extract mistag rate from oscillation

$\mathcal{L}_{int} \sim 33\ \text{pb}^{-1}$



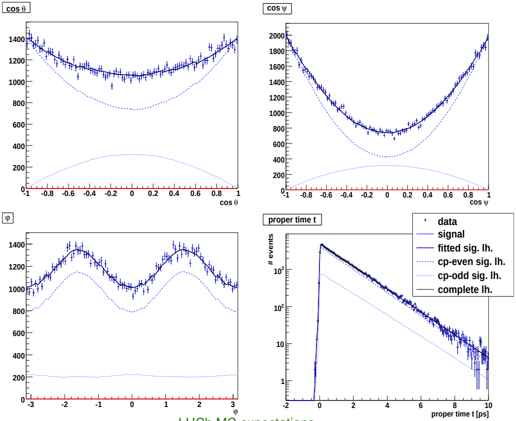


- Same side tagging's calibration:
  - Fit for time evolution in $B_s^0 \to D_s^-\pi^+$ $\to$ extract mistag rate from oscillation



Fit the $\phi_s^{J/\psi\phi}$ phase (MC)

- Unbinned likelihood :
  $\mathcal{L} = \prod_e^N \mathcal{P}(X_e; \lambda)$
  - X_e : proper time t, decay angles Ω, B mass m and initial B flavor tag q.
  - $\lambda_{\rm phys} = \{\Gamma_s, \Delta\Gamma_s, R_\perp, R_0, \delta_\perp, \delta_\parallel, \Delta m_s, \phi_s\}$
  - $\lambda_{\rm det}$ mass resolution σ_m, proper time resolution σ_t, mistag rate ω, background properties
  - Angular distortion corrections

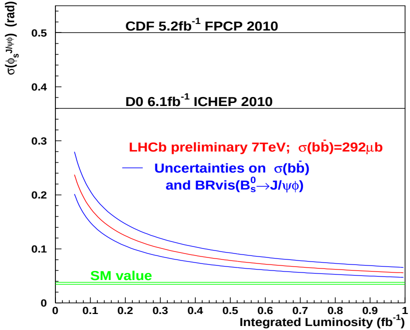


LHCb MC expectations

$$\sigma(\phi_s^{J/\psi\phi})_{stat} \sim 0.08\,\mathrm{rad\ for\ 1\ fb^{-1}}$$

LHCb sensitivity to $\phi_s^{J/\psi\phi}$ phase

- Expectation on the $\phi_s^{J/\psi\phi}$ sensitivity
  - Based on $b\bar{b}$ cross-section measured in LHCb.
  - MC expectations for tagging and proper time used



- Use realistic MC to study systematics
- Systematic errors' level $< 10\%$

Parameter	Variation	$\lvert\phi_s^{wrong} - \phi_s^{true}\rvert / \phi_s^{true}$
Angular distortions	$\pm 5\%$	7%
Proper time resolution	± 5 fs	6%
Mistag	1%	7%

Summary

- $B_s^0 \to J/\psi\phi$ is the golden mode to probe $\phi_s^{J/\psi\phi}$
- Challenges:
  - LHC running with high pile-up scheme
    - Efforts to cope in trigger, tracking and tagging
    - Very good performance on detector level
  - Challenging measurement:
    - Time and Angular analysis
    - Flavor tagging
    - Understanding background, angular distortions and proper time resolution
- $\sim$ 1000 $B_s^0 \to J/\psi\phi$ in $\sim$ 33 pb^{-1} of integrated luminosity
  - Very good mass and proper time resolution
  - Encouraging tagging performance
- LHCb is sensitive to NP in $\phi_s^{J/\psi\phi}$ ($\sigma(\phi_s^{J/\psi\phi})_{stat} \sim 0.08\,\mathrm{rad}$ for 1 fb^{-1})
- LHCb will soon deliver the news on $\phi_s^{J/\psi\phi}$, stay tuned

Backups

$B_s^0 \to J/\psi\phi$ decay rates (1)

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d\Omega} \propto \sum_{k=1}^{6} h_k(t) f_k(\Omega)\,, \quad \text{and} \quad \frac{d^4\Gamma(\overline{B}_s^0 \to J/\psi\phi)}{dt\, d\Omega} \propto \sum_{k=1}^{6} \bar{h}_k(t) f_k(\Omega)\,.$$

B_s^0 time and angular terms:

k	$h_k(t)$	$\bar{h}_k(t)$	$f_k(\theta, \psi, \varphi)$
1	$\lvert A_0(t)\rvert^2$	$\lvert \bar{A}_0(t)\rvert^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\lvert A_{\vert\vert}(t)\rvert^2$	$\lvert \bar{A}_{\vert\vert}(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
2	$\lvert A_{\vert\vert}(t)\rvert^2$	$\lvert \bar{A}_{\vert\vert}(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\lvert \bar{A}_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A_{\vert\vert}^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_{\vert\vert}^*(t)\bar{A}_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\{A_0^*(t)A_{\vert\vert}(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_{\vert\vert}(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

$B_s^0 \to J/\psi\phi$ decay rates (2)

Time dependent amplitude for B_s^0:

$$|A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\phi_s \sin(\Delta m_s t)\right],$$

$$|A_{||}(t)|^2 = |A_{||}(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\phi_s \sin(\Delta m_s t)\right],$$

$$|A_{\perp}(t)|^2 = |A_{\perp}(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\phi_s \sin(\Delta m_s t)\right],$$

$$\Re\{A_0^*(t)A_{||}(t)\} = |A_0(0)||A_{||}(0)|e^{-\Gamma_s t}\cos\delta_{||}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\phi_s \sin(\Delta m_s t)\right]$$

$$\Im\{A_{||}^*(t)A_{\perp}(t)\} = |A_{||}(0)||A_{\perp}(0)|e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_{||})\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin(\delta_\perp - \delta_{||})\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_{||})\cos\phi_s \sin(\Delta m_s t)\right],$$

$$\Im\{A_0^*(t)A_{\perp}(t)\} = |A_0(0)||A_{\perp}(0)|e^{-\Gamma_s t}\left[-\cos\delta_\perp \sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\delta_\perp \cos(\Delta m_s t) - \cos\delta_\perp \cos\phi_s \sin(\Delta m_s t)\right].$$

- For $\overline{B}_s^0$: change sign
  $\to$ loose sensitivy if no tagging

New physics effects

General parametrization of new physics effects in mixing

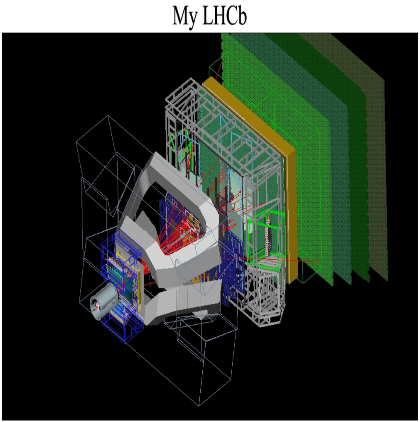
$$\Gamma_{12,s} = \Gamma_{12,s}^{\mathrm{SM}}\,, \qquad M_{12,s} = M_{12,s}^{\mathrm{SM}} \cdot \Delta_s\,; \qquad \Delta_s = |\Delta_s| e^{i\phi_s^{\Delta}}$$

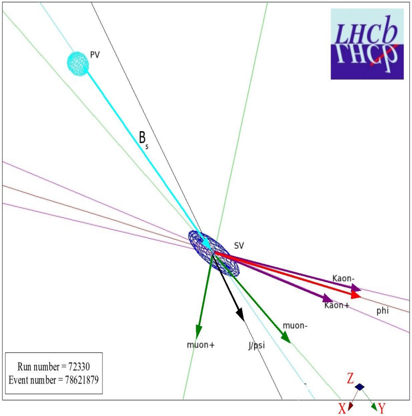
leads to the following relations for observables

$$\begin{aligned}
\Delta M_s &= 2|M_{12,s}^{\mathrm{SM}}| \cdot |\Delta_s| \\
\Delta\Gamma_s &= 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{\mathrm{SM}} + \phi_s^{\Delta}\right) \\
a_{fs}^{s} &= \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\mathrm{SM}}|} \cdot \frac{\sin\left(\phi_s^{\mathrm{SM}} + \phi_s^{\Delta}\right)}{|\Delta_s|} \\
\phi_s^{J/\Psi\phi} &= -2\beta_s + \phi_s^{\Delta} + \delta_{\mathrm{Peng.}}^{\mathrm{SM}} + \delta_{\mathrm{Peng.}}^{\mathrm{NP}}
\end{aligned}$$

Remember: $\phi_{\mathrm{s}}^{\mathrm{SM}} = \arg(-M_{12}^{s}/\Gamma_{12}^{s}) = (0.0042 \pm 0.0014)\,\mathrm{rad}$ and $\beta_{\mathrm{s}} = \arg\left(-V_{\mathrm{ts}} V_{\mathrm{tb}}^{*} / V_{\mathrm{cs}} V_{\mathrm{cb}}^{*}\right)$; $2\beta_{\mathrm{s}} = (0.036 \pm 0.0017)\,\mathrm{rad}$

First $B_s^0 \to J/\psi\phi$ @ LHCb....

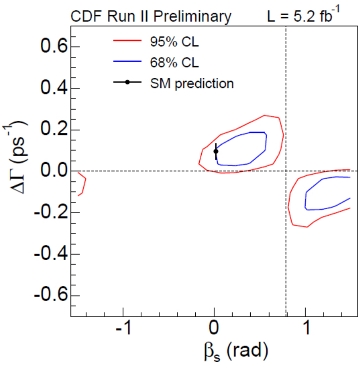




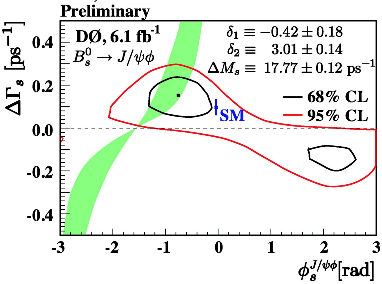
- One of the first $B_s^0 \to J/\psi\phi$ candidates (flight distance $\sim$ 2 cm!)

Reminder: Tevatron results

CDF, FPCP'2010



D0, ICHEP'2010



	Signal yield (lumi)	$\phi_s^{J/\psi\phi}$ (rad)	Ref.
CDF	6 500 (5.2 pb^{-1})	$-0.54 \pm 0.50^{(*)}$	CDF Note 10206
D0	3 400 (6.1 fb^{-1})	$-0.76^{+0.38}_{-0.36}(\text{stat}) \pm 0.02(\text{syst})$	D0 6098-CONF

(*) CDF quotes $\beta_s \in [0.02, 0.52] \cup [1.08, 1.55]$ rad at 68%CL. "-0.54 ± 0.50" is my estimate.

Selection table

Decay mode	Cut
$J/\psi(\mu\mu)$	$\Delta \ln \mathcal{L}_{\mu\pi} > 0$ muons $\chi^2_{\mathrm{track}}/\mathrm{nDoF} < 4$ $\min(p_T\mu^+, p_T\mu^-) > 500\,\mathrm{MeV}/c$ $\chi^2_{\mathrm{vtx}}/\mathrm{nDoF}(J/\psi) < 11$ $\lvert M(\mu\mu) - M^{\mathrm{fitted}}(J/\psi)\rvert/\sigma(M(\mu\mu)) < \pm 4.2$
$\phi \to K^+K^-$	$\Delta \ln \mathcal{L}_{K\pi} > 0$ kaons $\chi^2_{\mathrm{track}}/\mathrm{nDoF} < 4$ $\chi^2_{\mathrm{vtx}}/\mathrm{nDoF}(\phi) < 20$ $p_T(\phi) > 1\,\mathrm{GeV}/c$ $\lvert M(K^+K^-) - M(\phi)\rvert < \pm 12\,\mathrm{MeV}/c^2$
$B^0_s \to J/\psi\phi$	$\chi^2_{\mathrm{vtx}}/\mathrm{nDoF} < 5$ B^0_s min IP χ^2 wrt PV < 25

a_{fs} at LHCb

- Flavor-specific : Decay to a given state which cannot be reached by anti-flavor state(at tree level).
- CP violating asymmetry in the mixing
  - Physical asymmetry :

$$a_{\rm fs} = \frac{\Delta\Gamma_{\rm s}}{\Delta m_{\rm s}} \tan(\phi^{M/\Gamma})$$

$$a^d_{\rm fs}(SM) = (-4.8^{+1.0}_{-1.2}) \times 10^{-4} \quad , \quad a^s_{\rm fs}(SM) = (2.1 \pm 0.6) \times 10^{-5}$$

  - Measuered asymmetry :

$$A_{\rm fs} = \frac{\Gamma(f)-\Gamma(\bar{f})}{\Gamma(f)+\Gamma(\bar{f})}$$

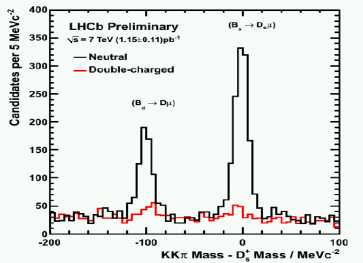
$$A_{\rm fs} = \frac{a_{\rm fs}}{2} - \frac{\delta^q_c}{2} - \left(\frac{a_{\rm fs}}{2} + \frac{\delta^q_P}{2}\right)\frac{\cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2)} + \frac{\delta_b}{2}$$

- Difficult in LHCb:
  - Detector asymmetry $\delta^q_c \sim 10^{-2}$
    - Matter detector $\rightarrow$ hadronic interaction asymmetric
    - At LHCb: reduced by swapping the B field
  - Production asymmetry $\delta^q_P \sim 10^{-2}$
    - LHC is a proton-proton collidor
  - Background asymmetry $\delta_b \sim 10^{-3}$
    - Calculated using sidebands

a_{fs} at LHCb

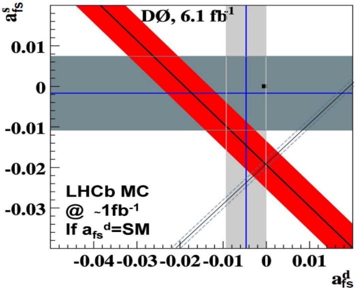
- Using hadronic modes e.g: $\mathrm{B_s^0} \to \mathrm{D_s^-}\pi^+$
  - small detector asymmetry, excellent proper time resolution (35 fs)
  - fit a_{fs} and δ_P^s, fix δ_c^s
- Subtraction methode in semi-leptonic modes
  - $\mathrm{B_s^0} \to \mathrm{D_s^-}\mu^+\nu$ and $\mathrm{B^0} \to \mathrm{D^-}_{\mathrm{q}}\mu^+\nu$, smae final state $K^+K^-\pi^-\mu^+$ $\to$ same detector asymmetry δ_c for this modes.
  - Measure the difference between $\mathrm{B_s^0}$ and $\mathrm{B^0}$:

$$\Delta A_{fs}^{s,d} \sim \frac{a_{\mathrm{fs}}^s - a_{\mathrm{fs}}^d}{2}$$



a_{fs} at LHCb Vs D0

D0	LHCb
$A^b \sim \frac{a^s_{fs}+a^d_{fs}}{2}$	$A^{s,d}_{fs} \sim \frac{a^s_{fs}-a^d_{fs}}{2}$
$\Delta A^b = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$	$\Delta A^{s,d}_{fs} = (2.5^{+0.5}_{-0.6}) \times 10^{-4}$
$\delta_P = 0$	δ_P fitted/discarded
δ_c compensated with MC	δ_c cancelled in data



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