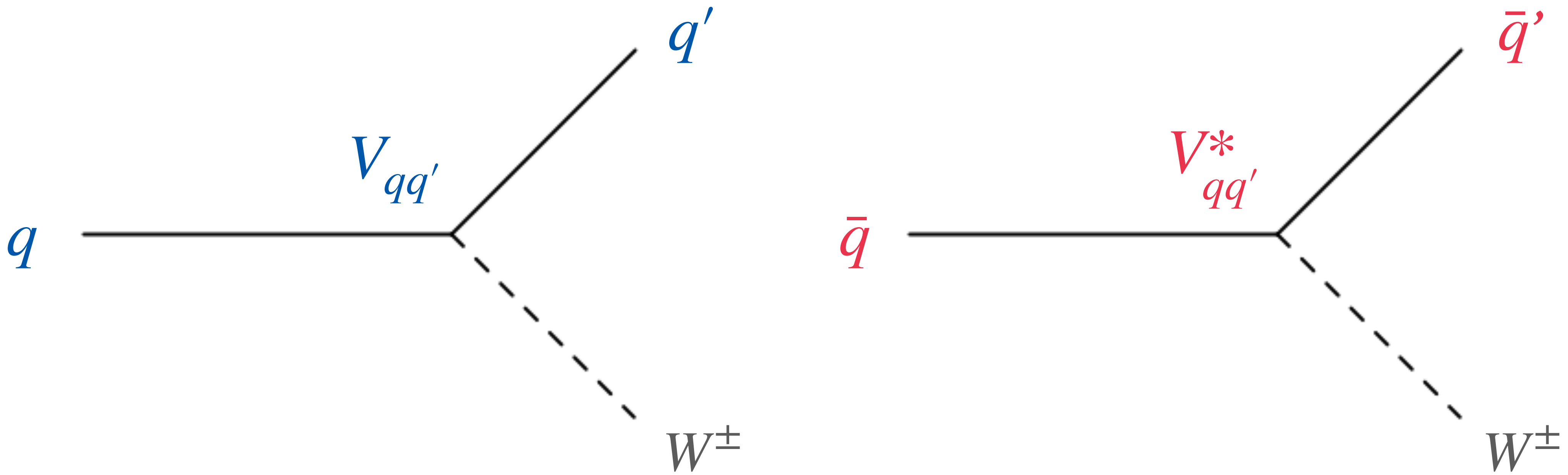
Measurement of the CP-violating phase ϕ_s at LHCb

Hilbrand Kuindersma

NNV annual meeting 01-11-2019

CKM MATRIX

- Quarks can change flavour through the emission of a W boson



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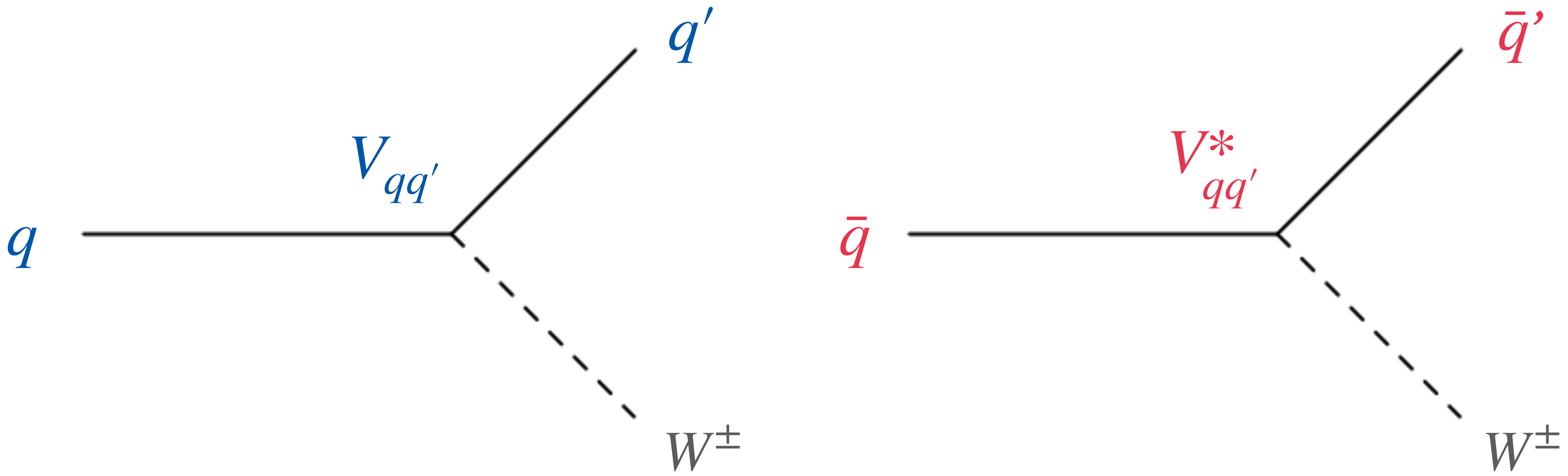

- The **CKM** matrix represents the coupling strength of quark transitions

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

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- Because the CKM matrix is a unitary matrix ($V_{CKM} \cdot V^{\dagger}_{CKM} = I$), this leads to the unitarity triangles:

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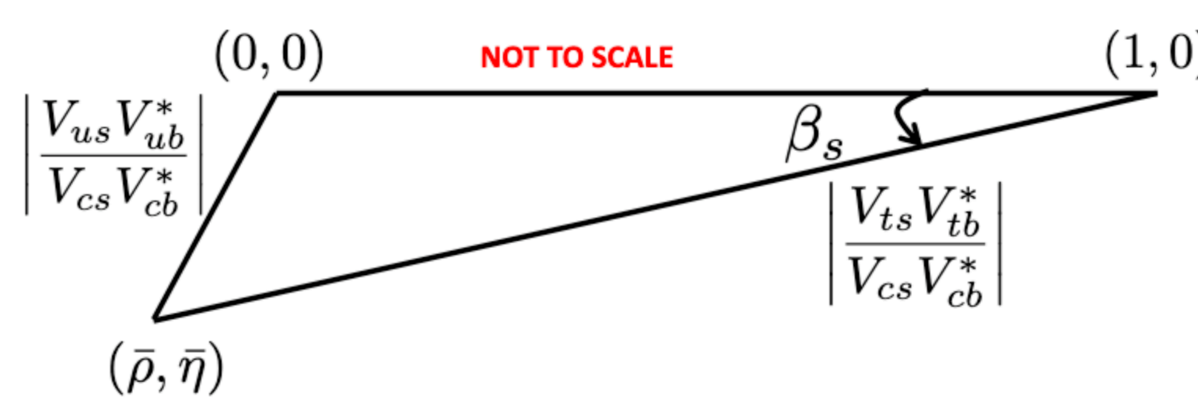
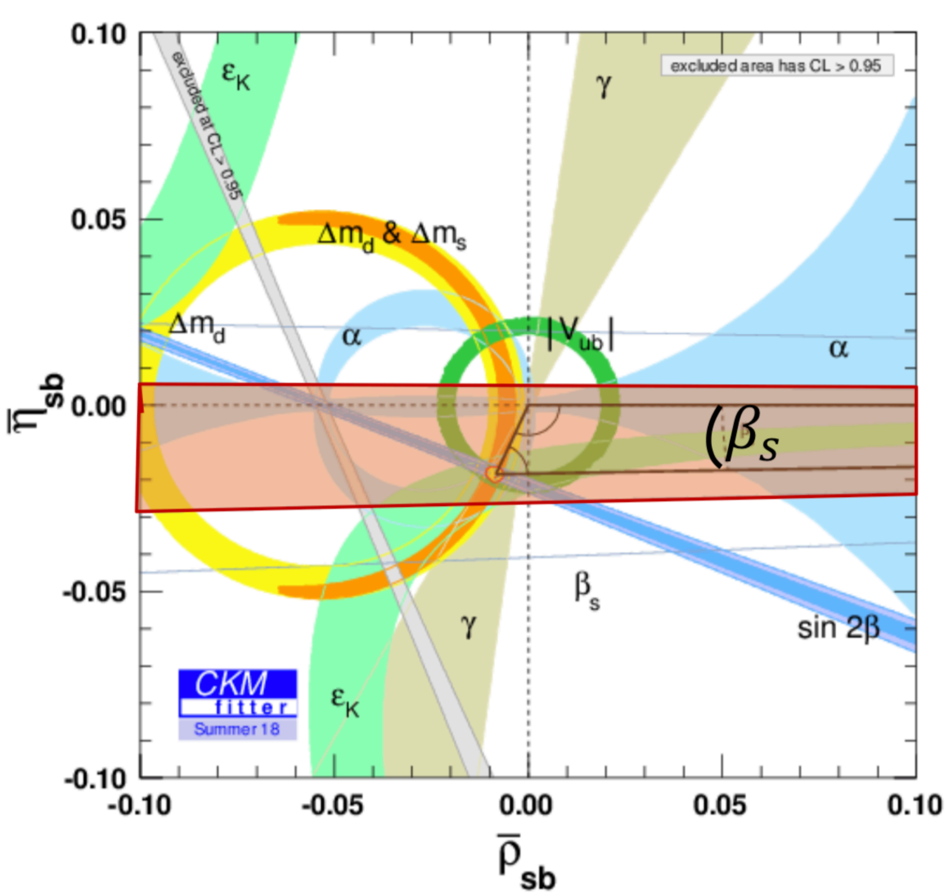
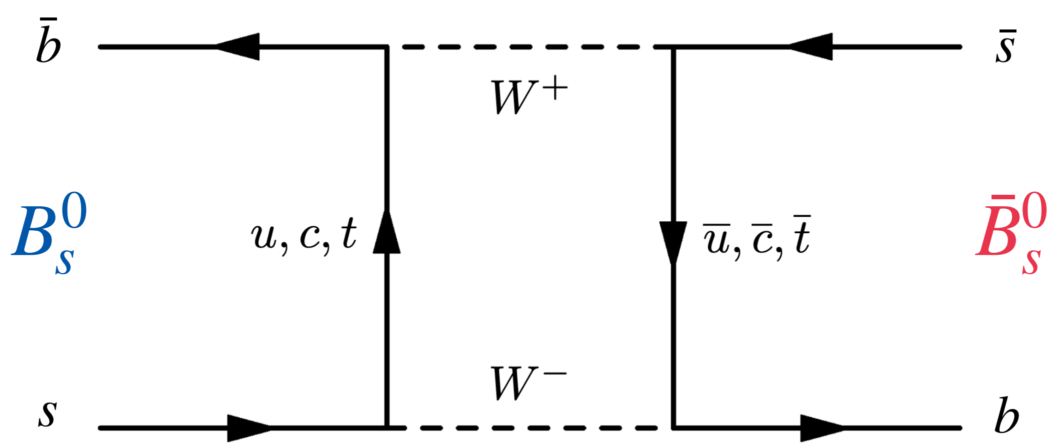
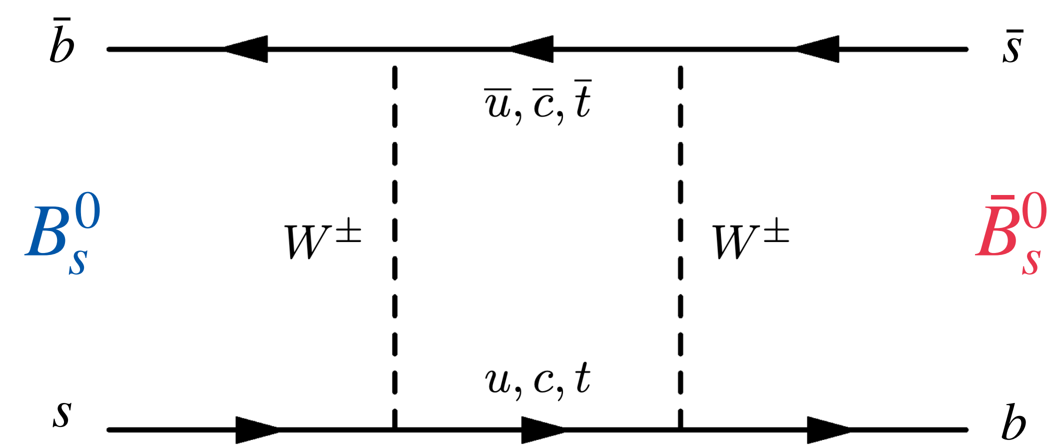




B MESON OSCILLATION





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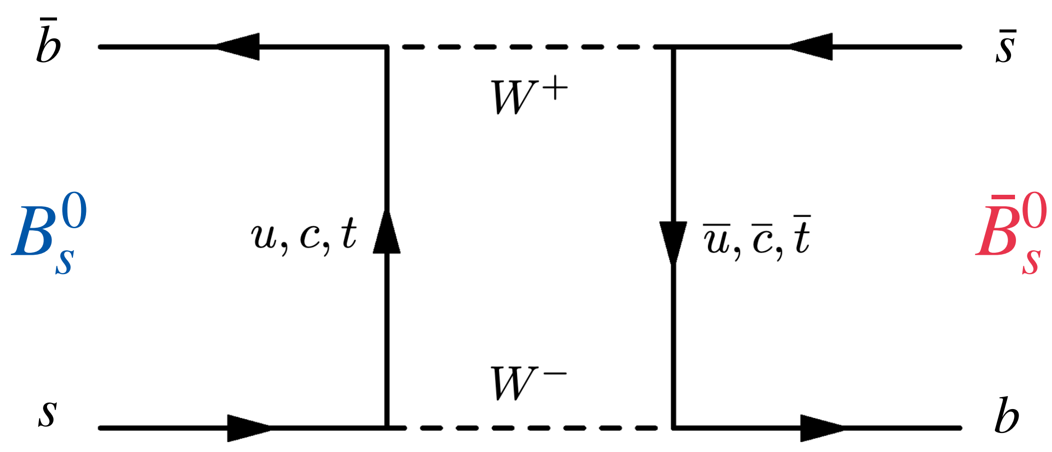

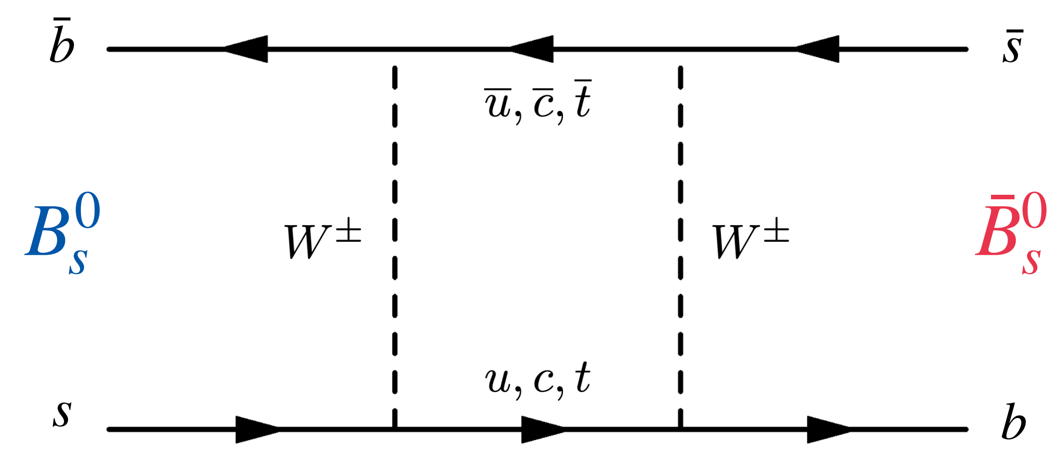

- Mass eigenstates are a mixture of weak eigenstates:

$$|B_L> = p\,|B_s^0> + q\,|\bar{B}_s^0>$$

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$$\Delta m_s = m_H - m_L$$

$$\Delta\Gamma_s = \Gamma_H - \Gamma_L$$

- Flavour at decay might be different from flavour at creation

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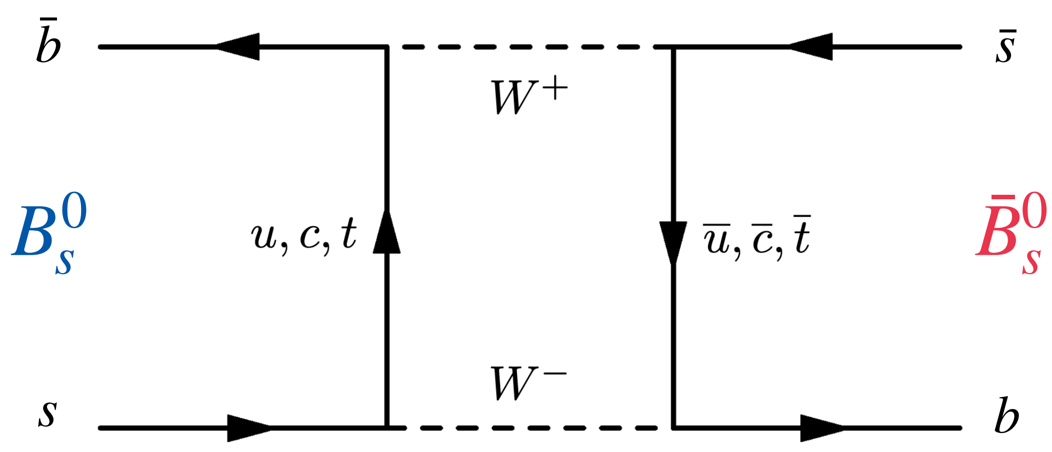

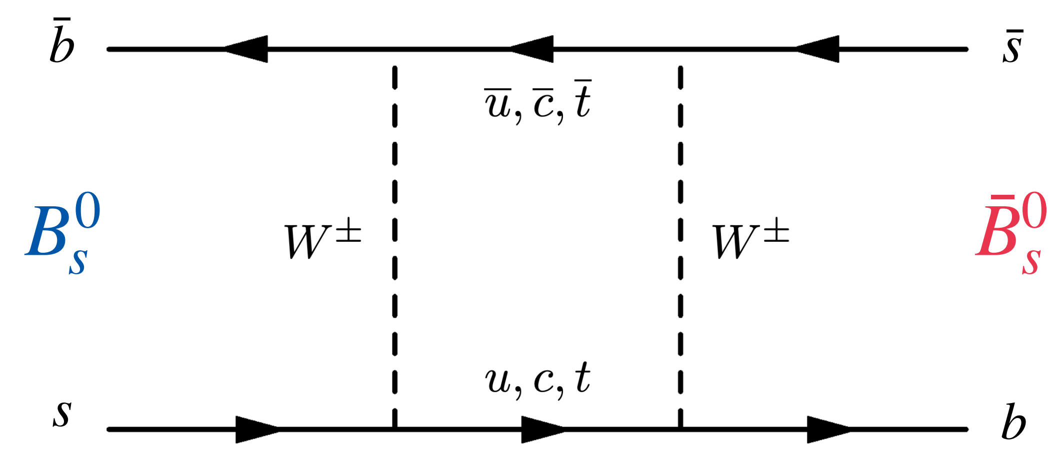

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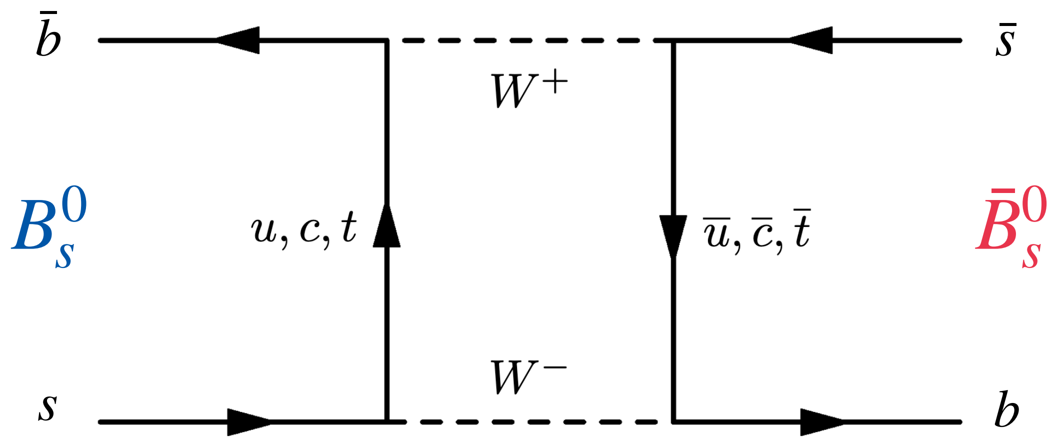

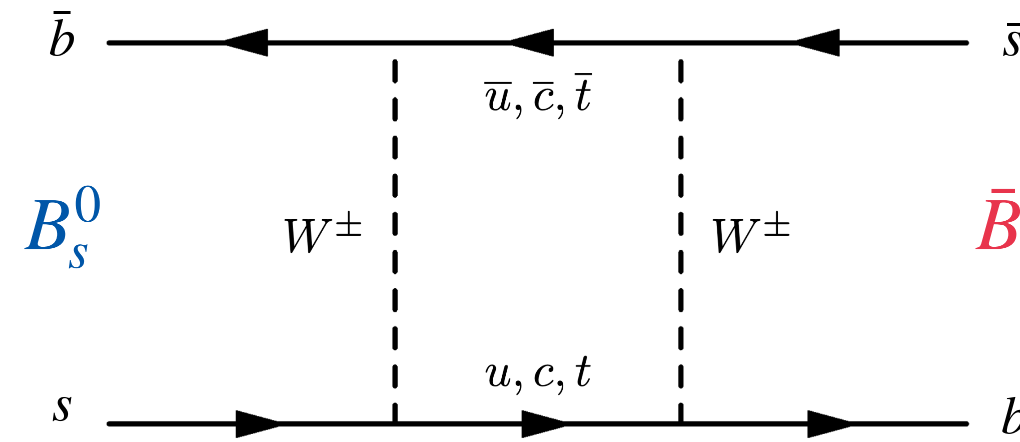

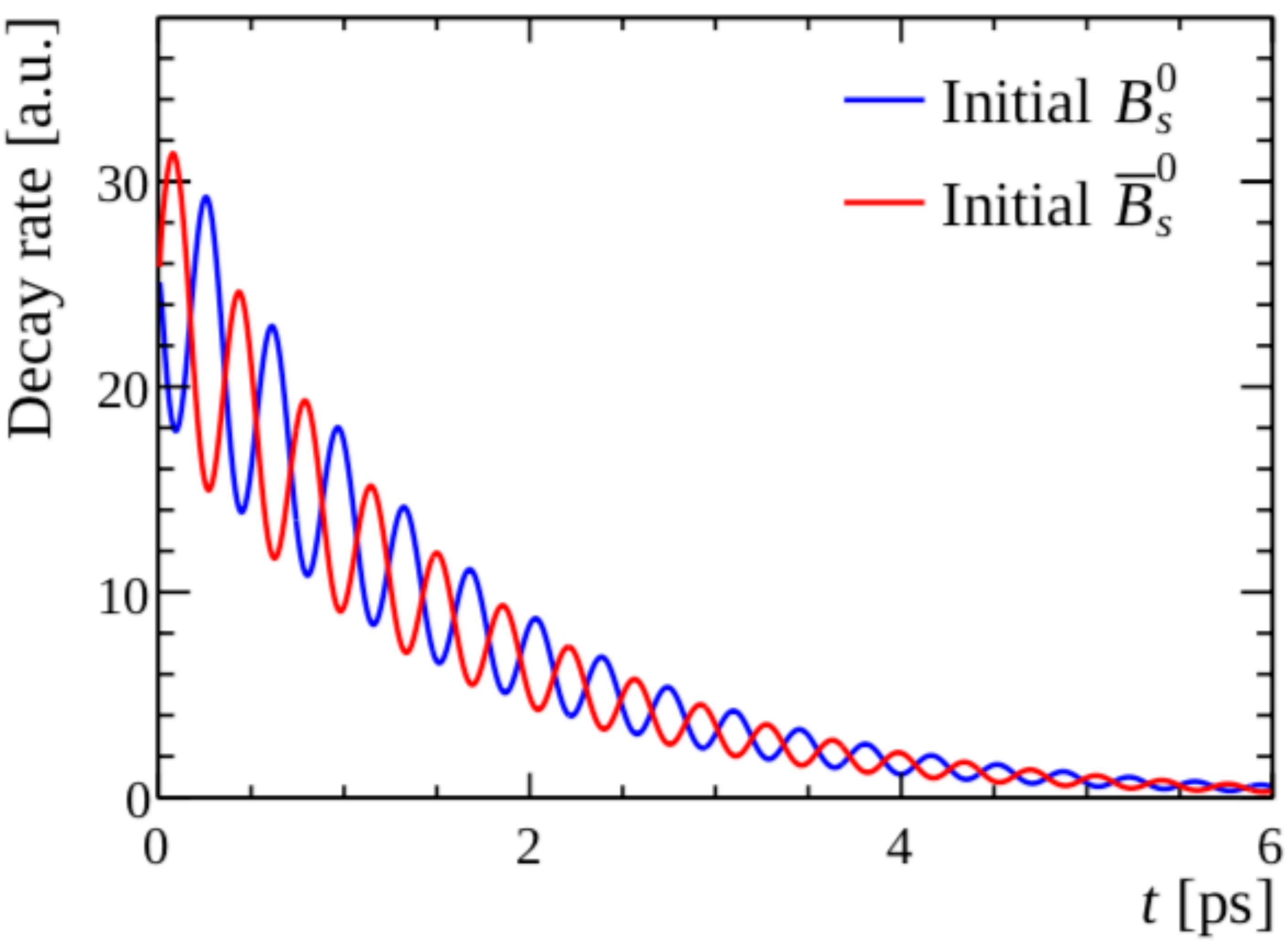

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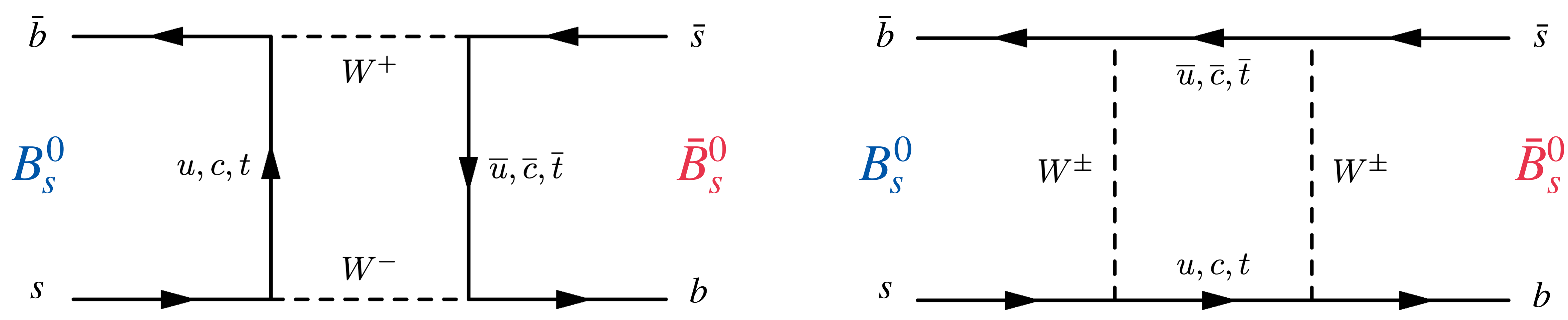

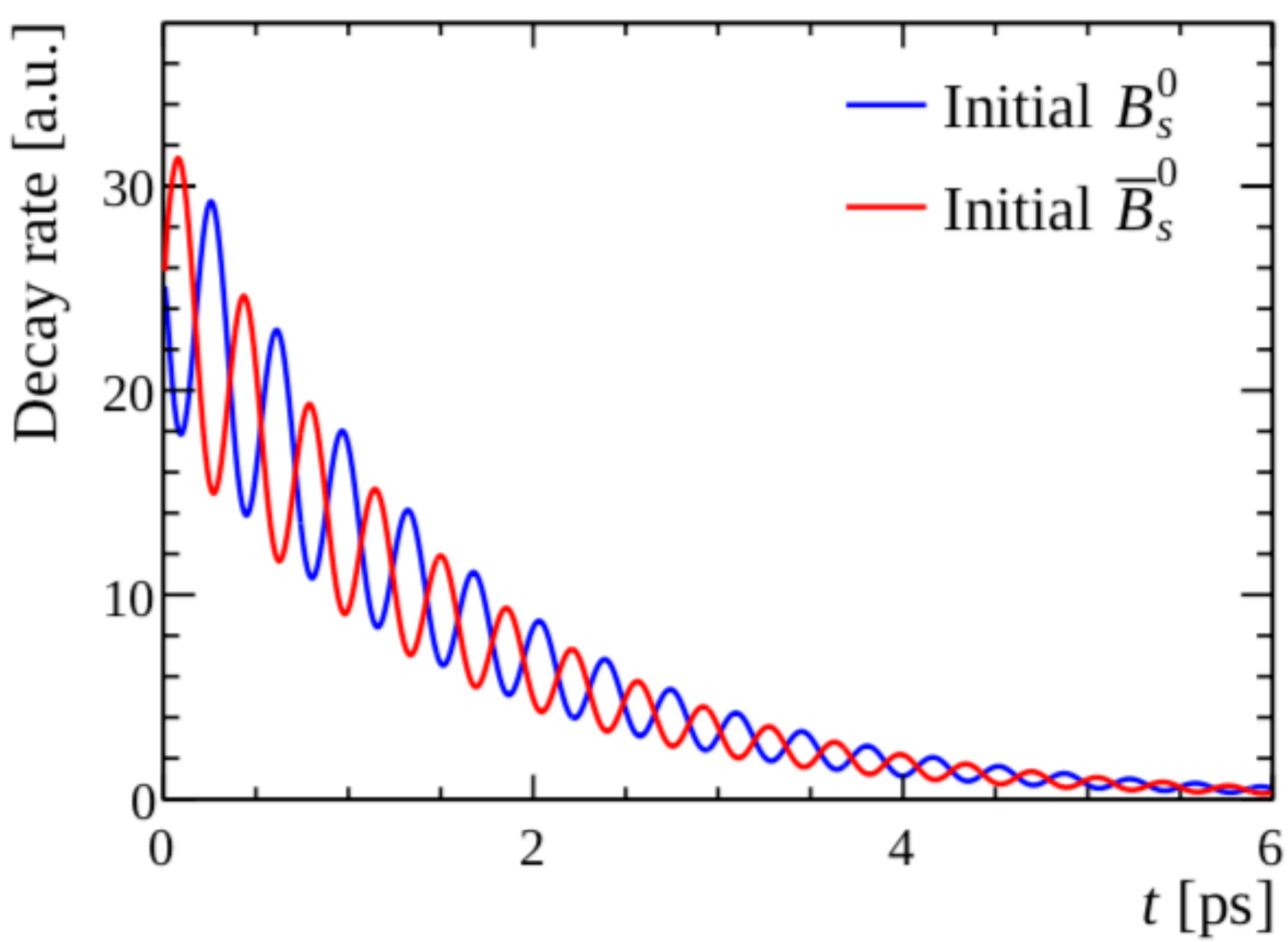

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CP VIOLATION

- CP violating effects of a B_s^0 decaying to a CP eigenstate depend on:

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

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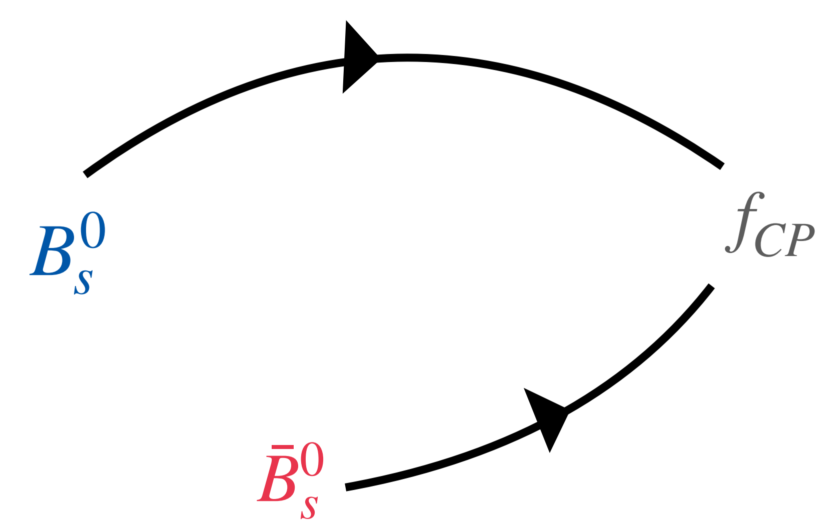
- Three types are usually distinguished; CP violation in:
  - 1. Decay

$$P(B_s^0 \to f) \neq P(\bar{B}_s^0 \to f)$$

$$|\bar{A}_f/A_f| \neq 1$$



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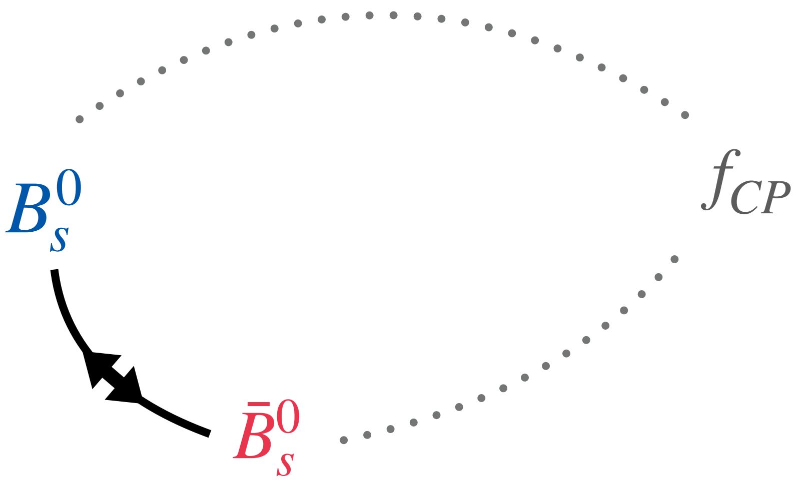

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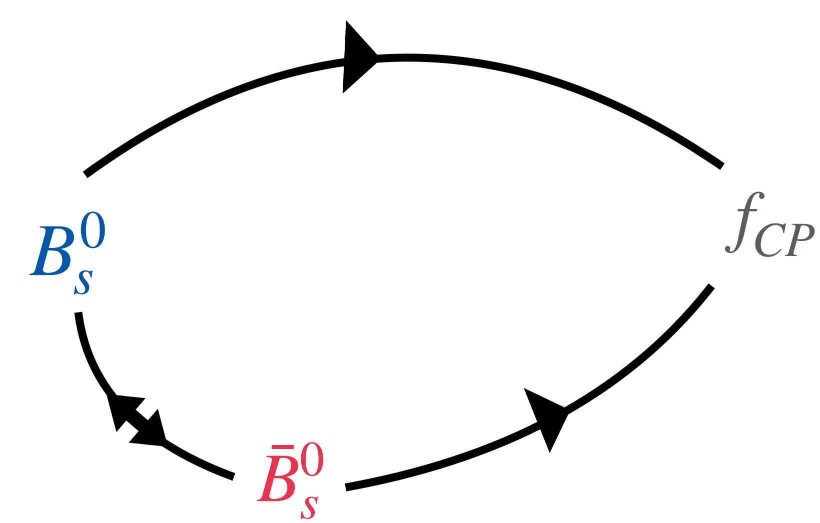
  - 3. The interference between mixing and decay

$$P(B_s^0 \to f) \neq P(B_s^0 \to \bar{B}_s^0 \to f)$$

$$arg(\lambda_f) \neq 0$$



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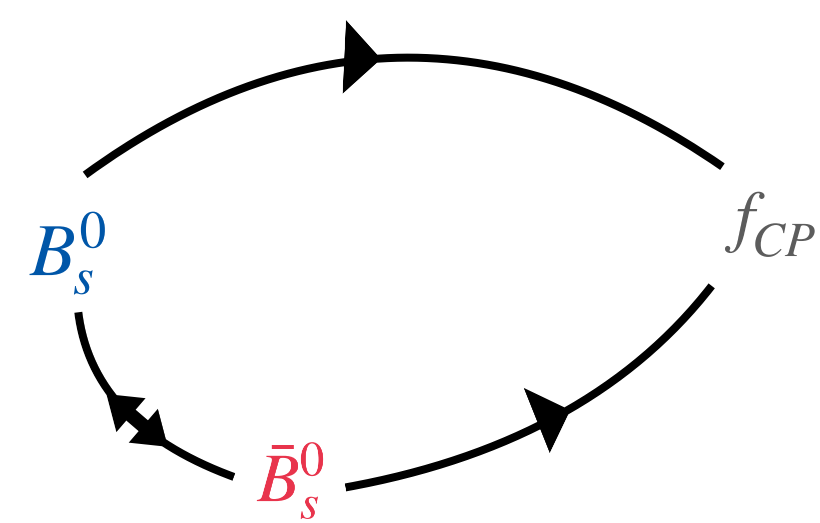

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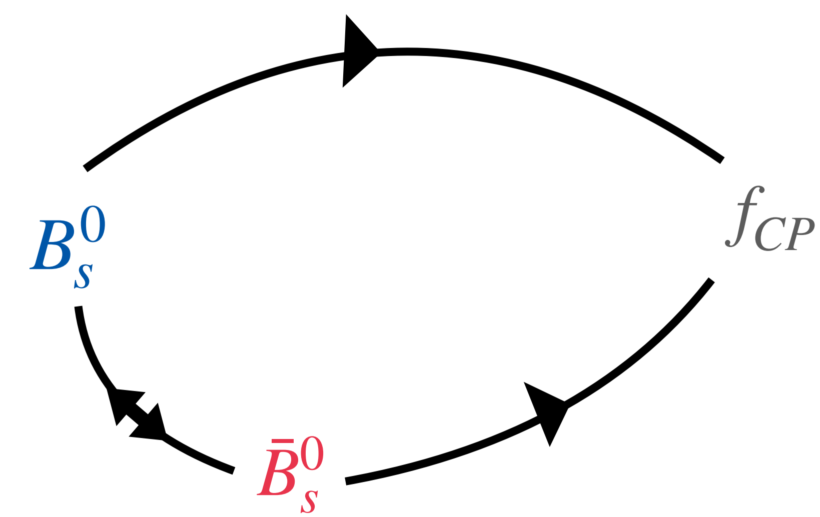


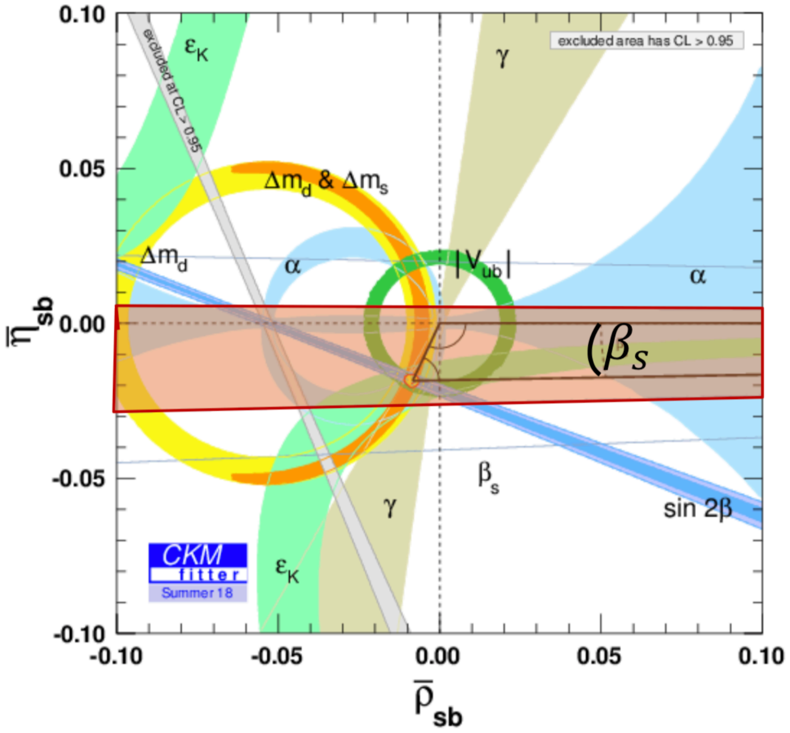
$$\phi_s = arg(\lambda_f)$$

WHY MEASURE ϕ_s?

- ϕ_s for $c(\bar{c}s)$ transitions:

$$\phi_s^{SM} = arg(\lambda_f^{c\bar{c}s}) \approx -2\ arg\left[\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] = -2\beta_s$$

$$\phi_s^{SM} = -0.03686^{+0.00096}_{-0.00068}\ rad$$ [CKM fitter]



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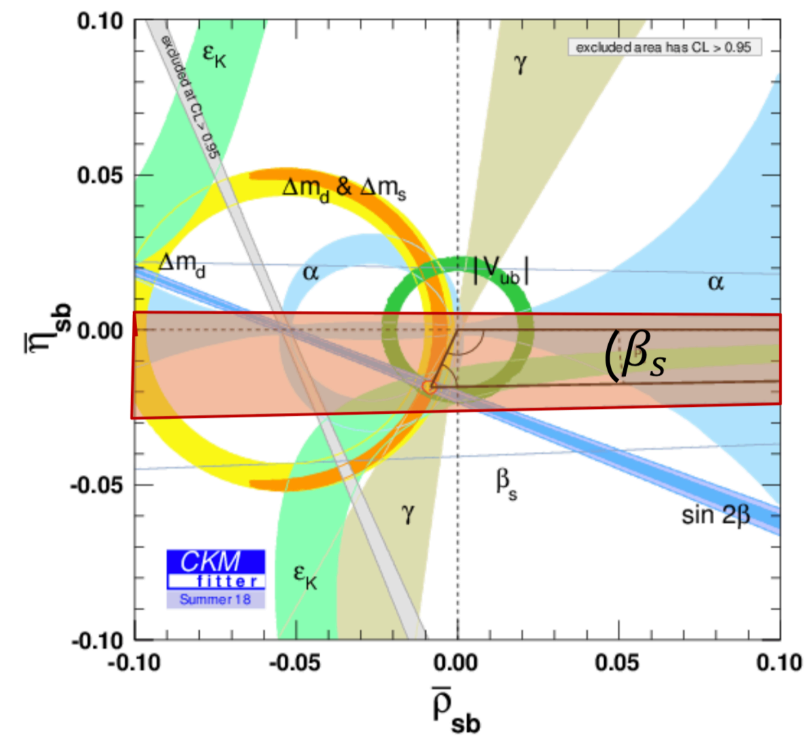

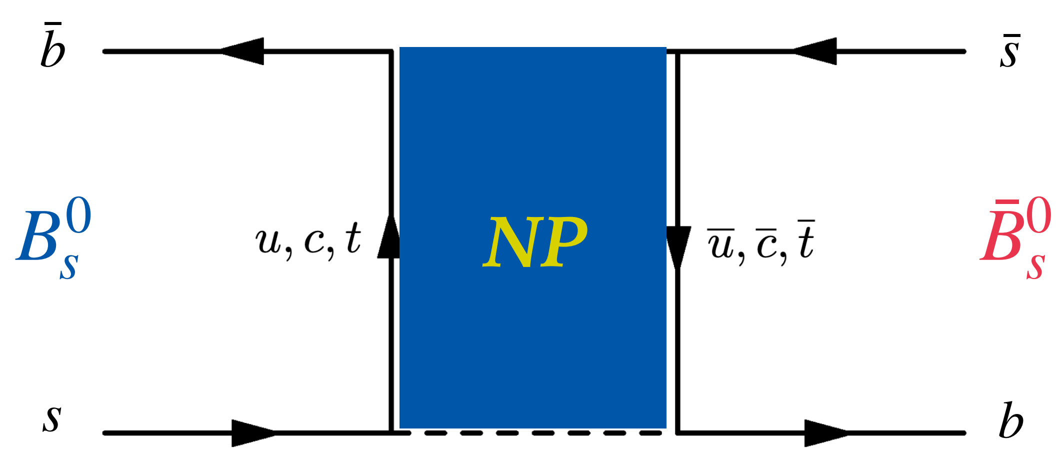

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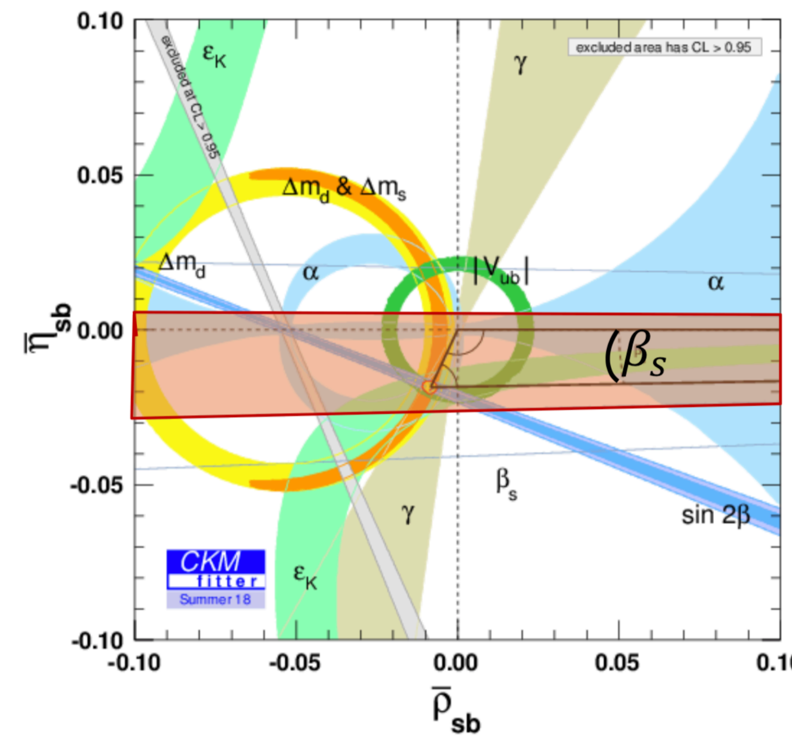

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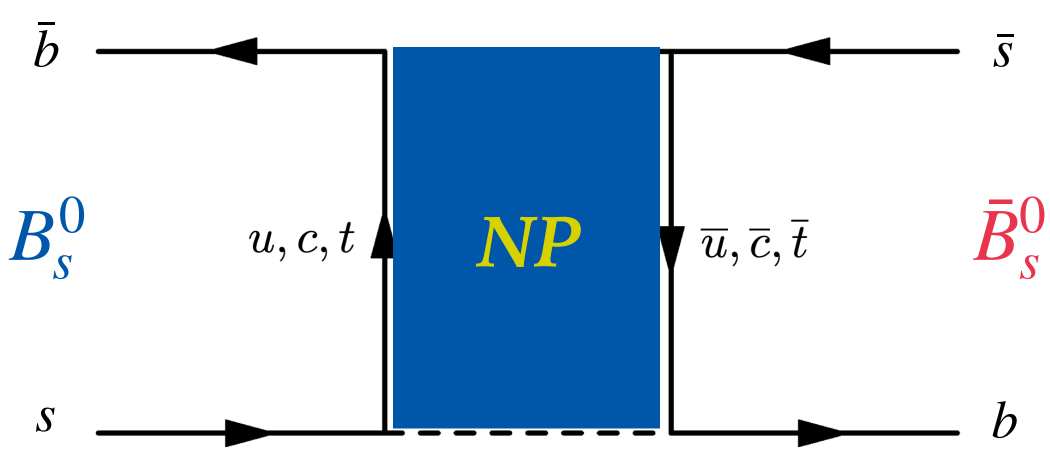

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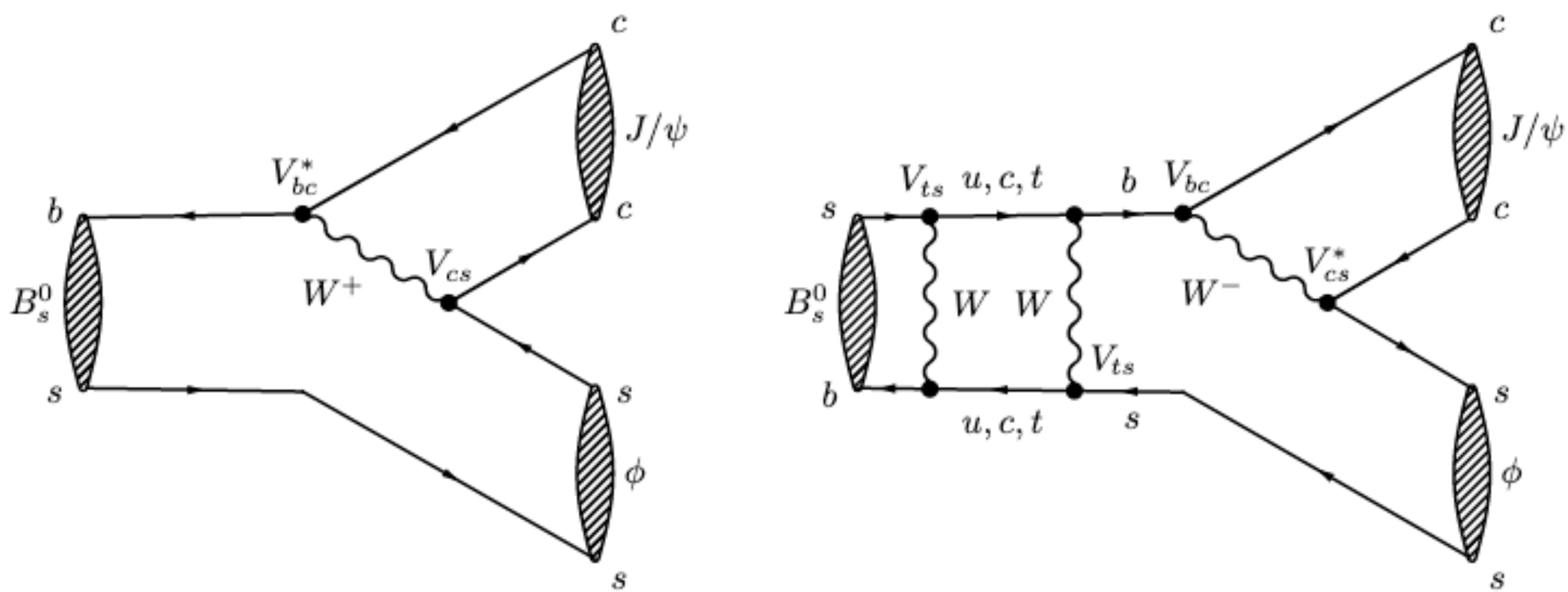
$$\phi_s^{exp} \neq \phi_s^{SM}$$

New physics!

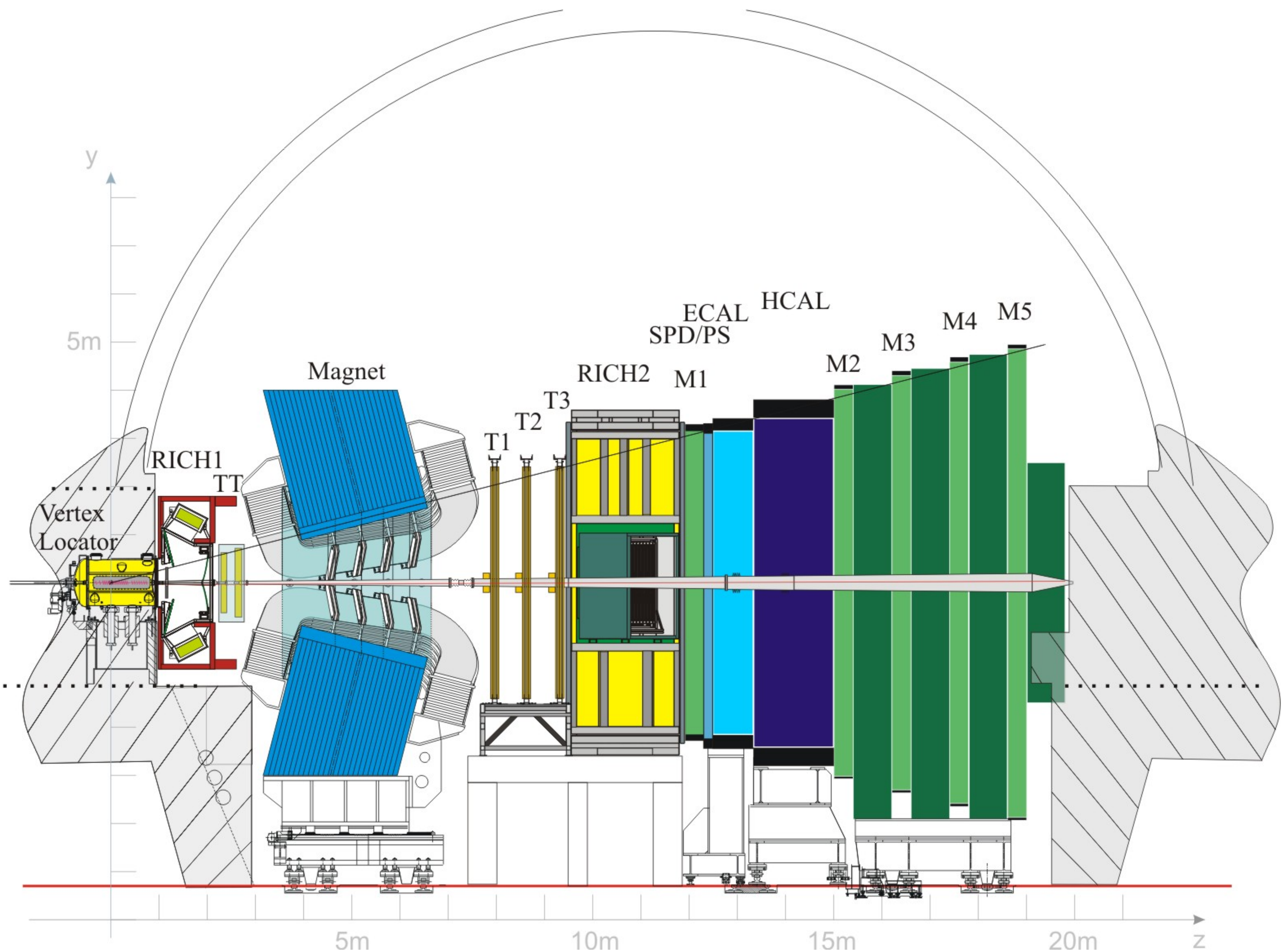
$B_s^0 \to J/\psi\ K^+K^-$ ($b \to c\bar{c}s$ TRANSITION)

- Several modes can be used to measure ϕ_s at LHCb

- "Golden mode": $B_s^0 \to J/\psi\ K^+K^-$
  - Relatively large branching fraction (high yield)
  - Clean experimental signature



LHCb DETECTOR



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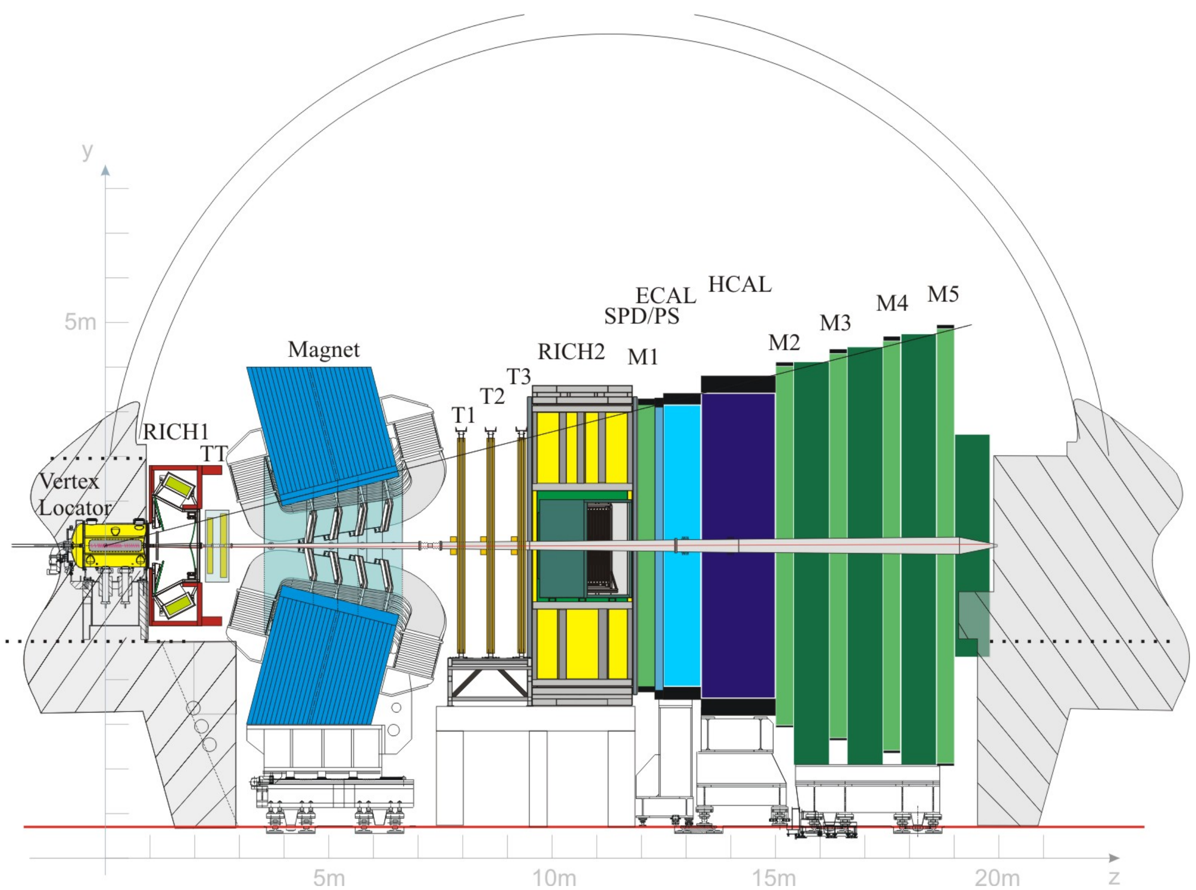

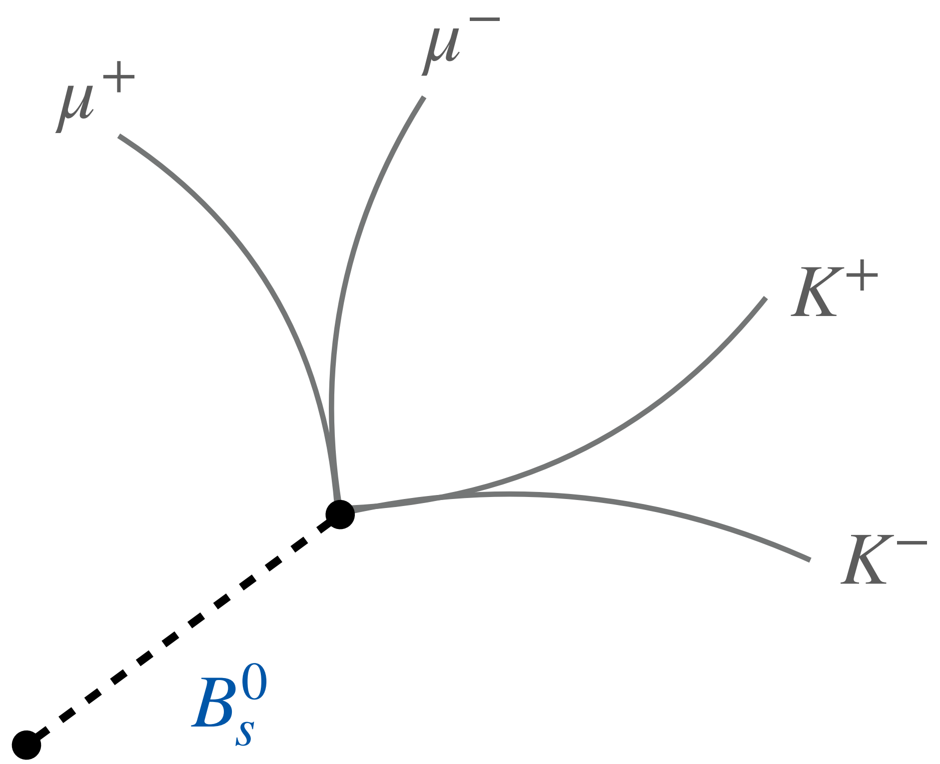

MEASURING ϕ_s

- Time dependent CP asymmetry given as:

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

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- Experimentally this becomes:

$$A_{CP}(t) = \underline{e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2}} \cdot \underline{(1 - 2\omega)} \cdot \eta_f \cdot sin(\phi_s) \cdot sin(\Delta m_s t)$$

σ_t : *Decay time resolution*

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- Furthermore, decay time efficiency and angular efficiency need to be taken into account

CP EIGENVALUE, $\eta_f = \pm 1$

- $J/\psi K^+K^-$ is an admixture of CP even and CP odd components (due to angular momentum conservation)

- To determine η_f, an angular distribution is used to disentangle the CP eigenstates
  - CP even: $A_0, A_{||}$ $\eta_f = +1$
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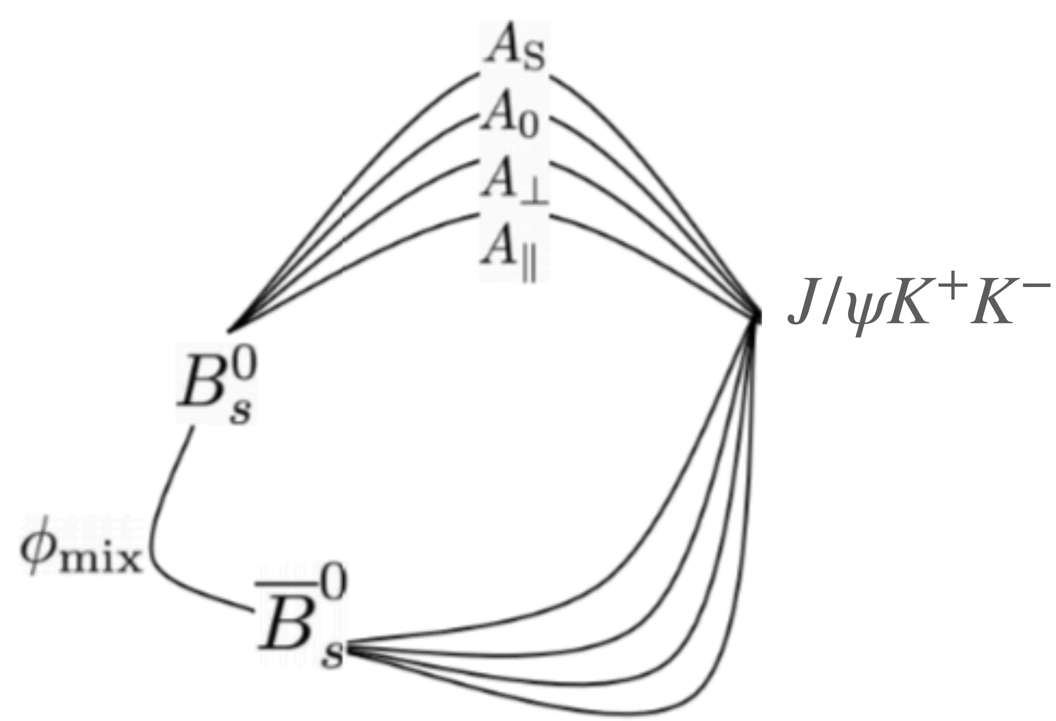

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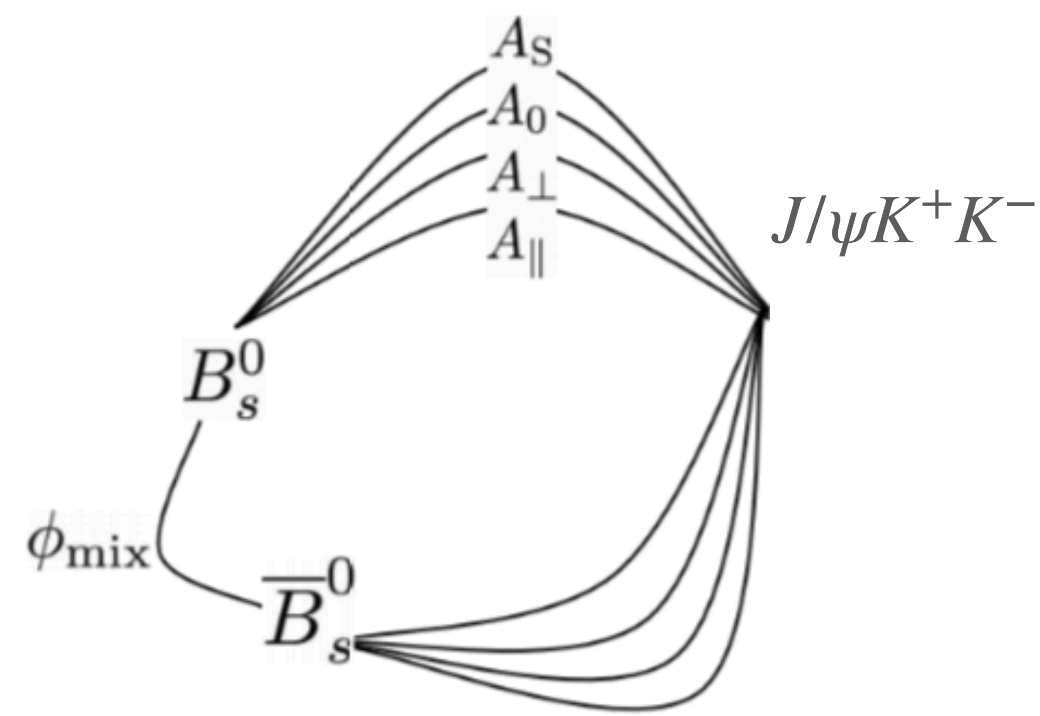

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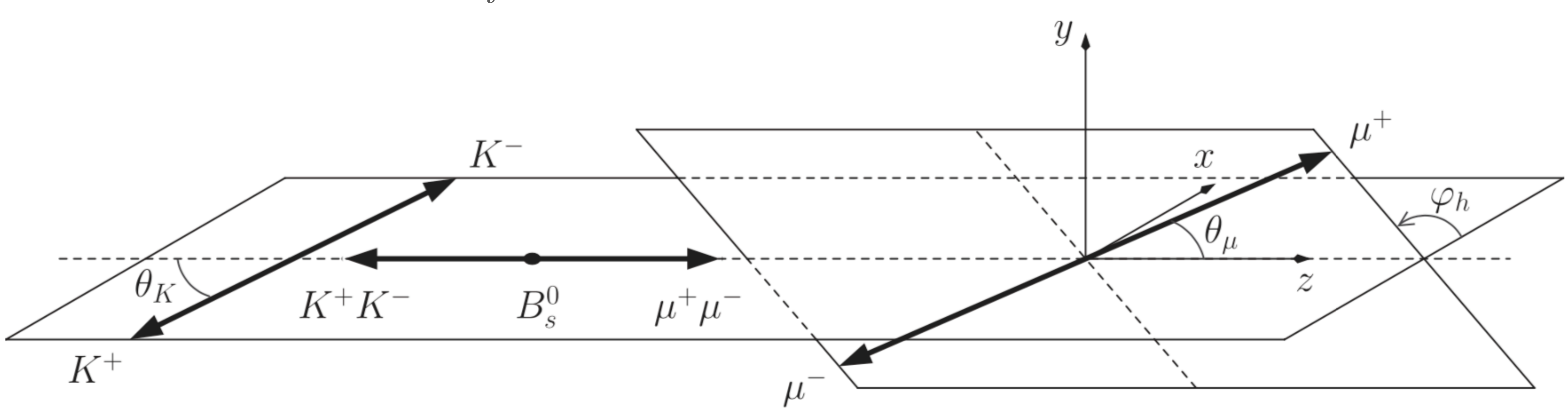

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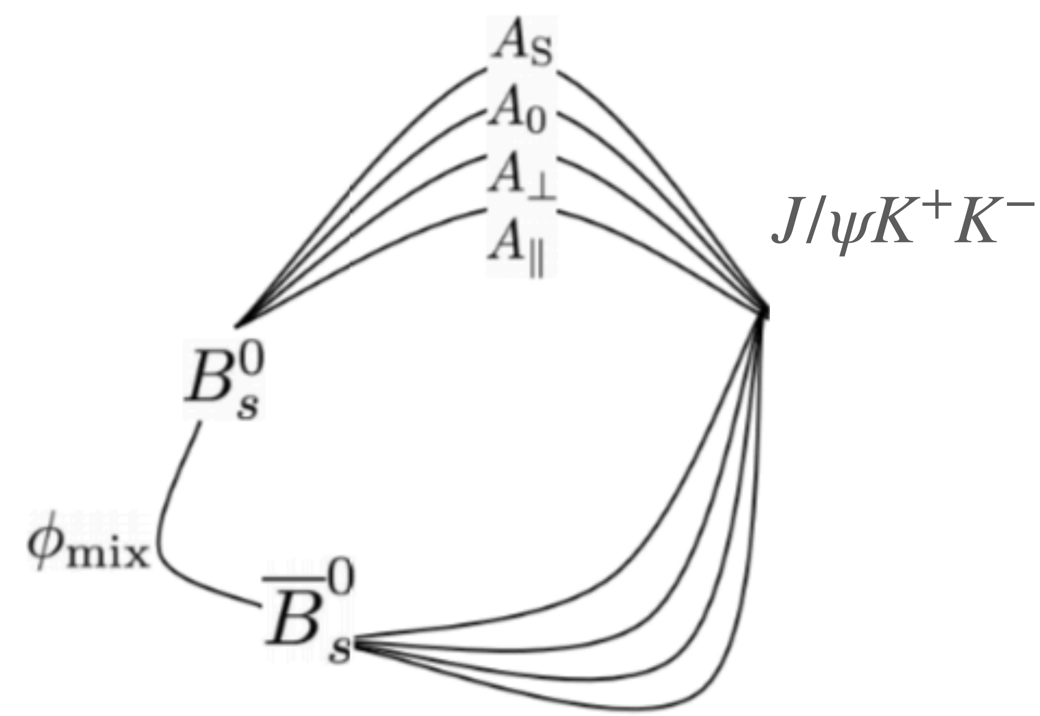

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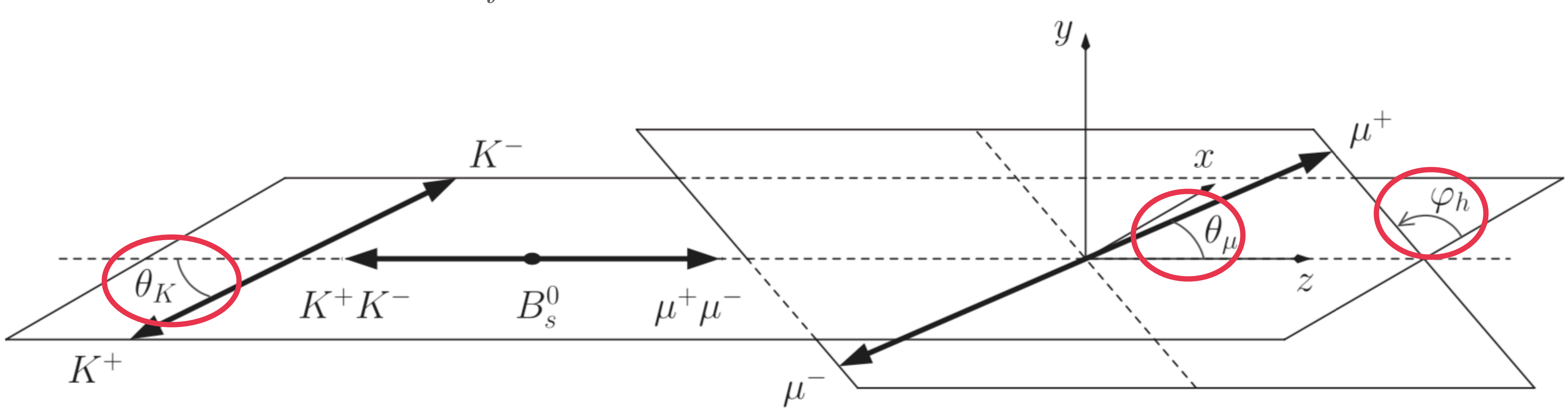
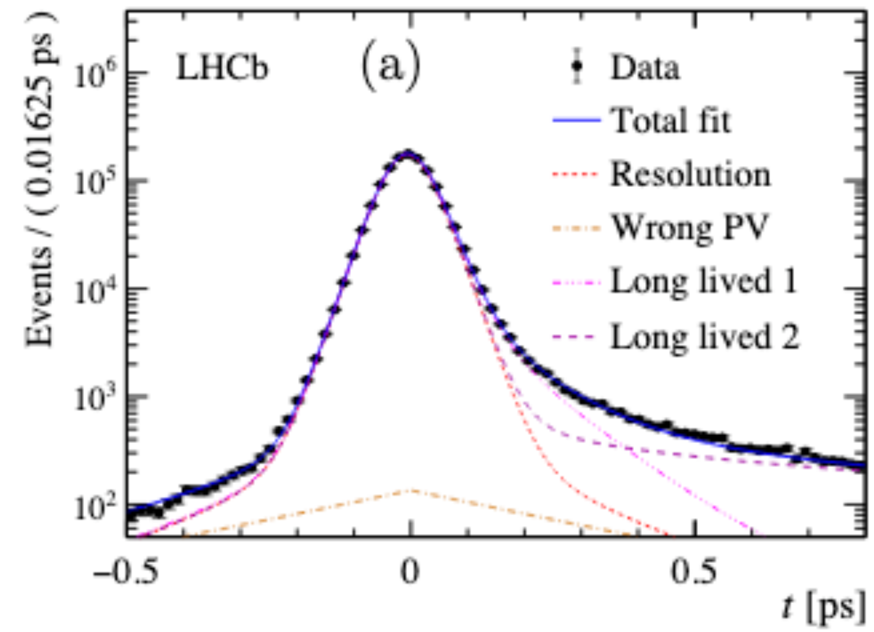


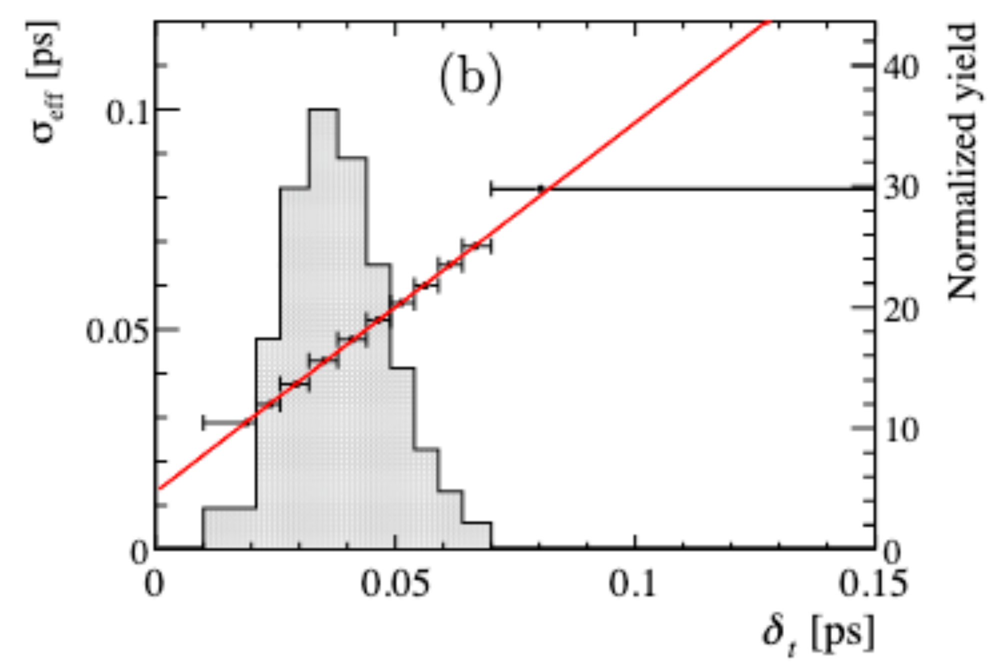
DECAY TIME RESOLUTION

[arXiv: 1906.08356]

- Essential for resolving fast B meson oscillations

- Determined on data using prompt sample of reconstructed $J/\psi(\to \mu\mu)$ + 2 random kaons $(t = 0 \pm \sigma_t)$





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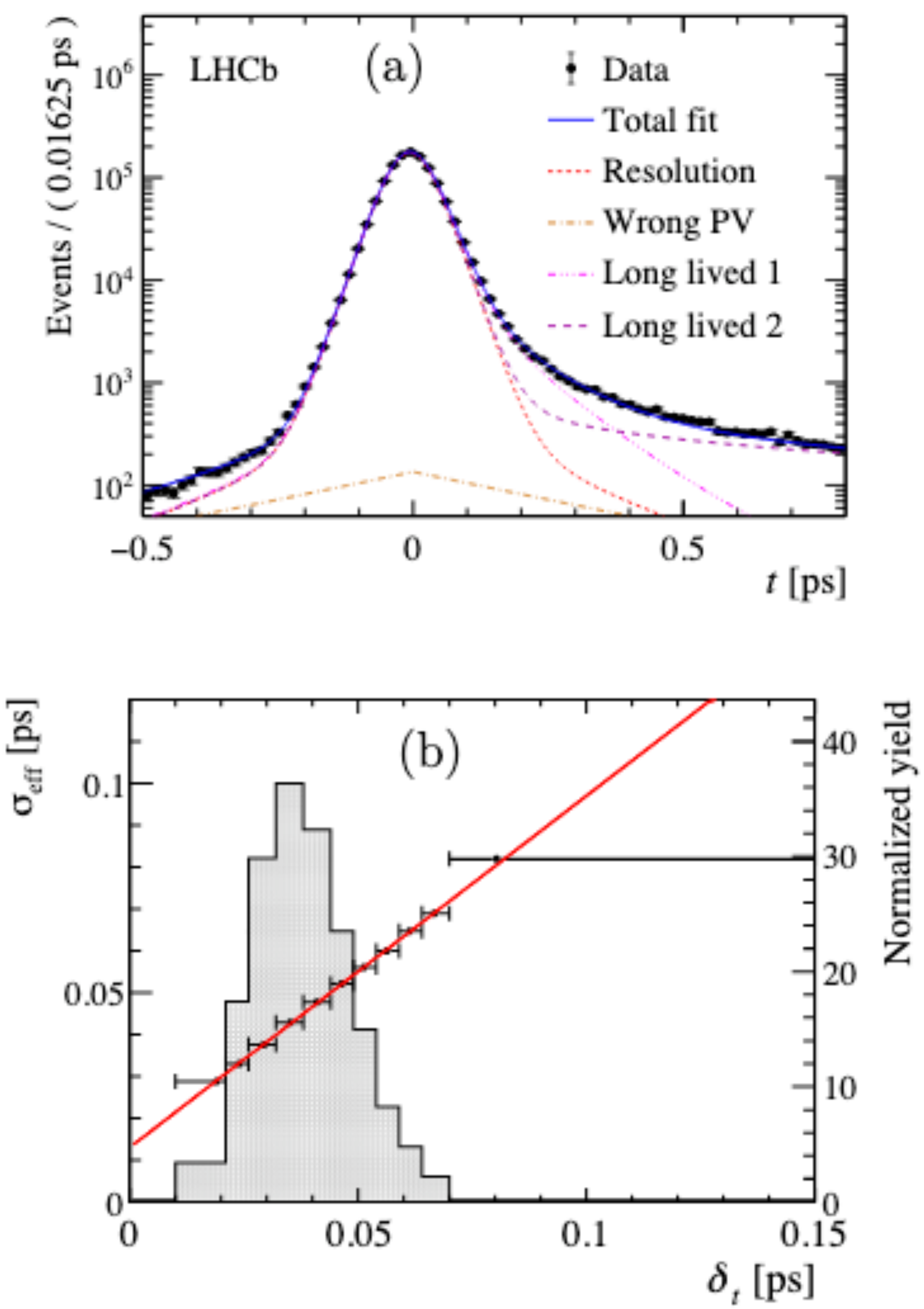
- $\sigma_{eff} \approx 45.5\ fs$ (sufficiently narrower than one oscillation period $\sim 354\ fs$)
- D ~ 0.72 $\quad D = e^{-\sigma_i^2 \Delta m_s^2/2}$



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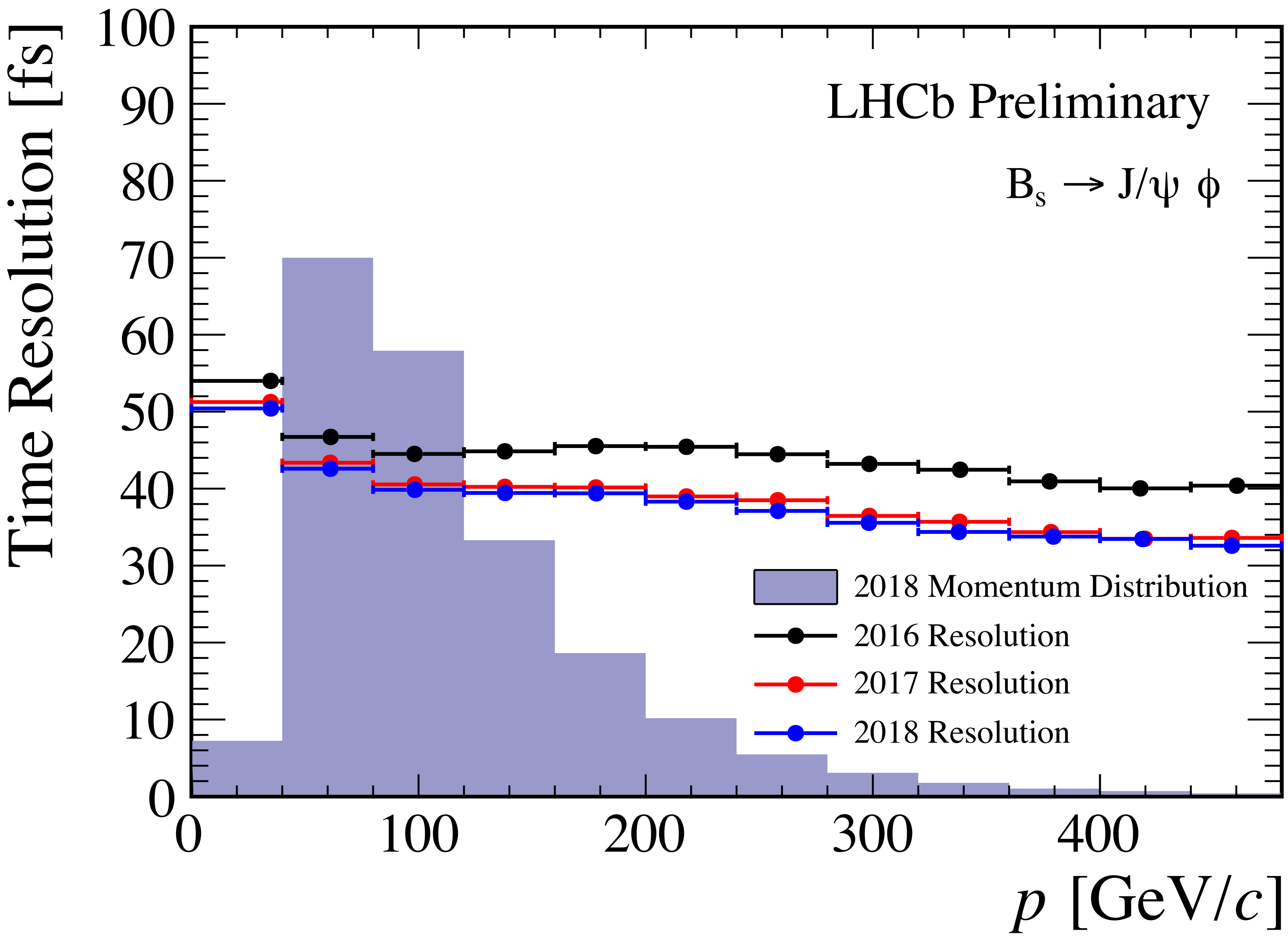
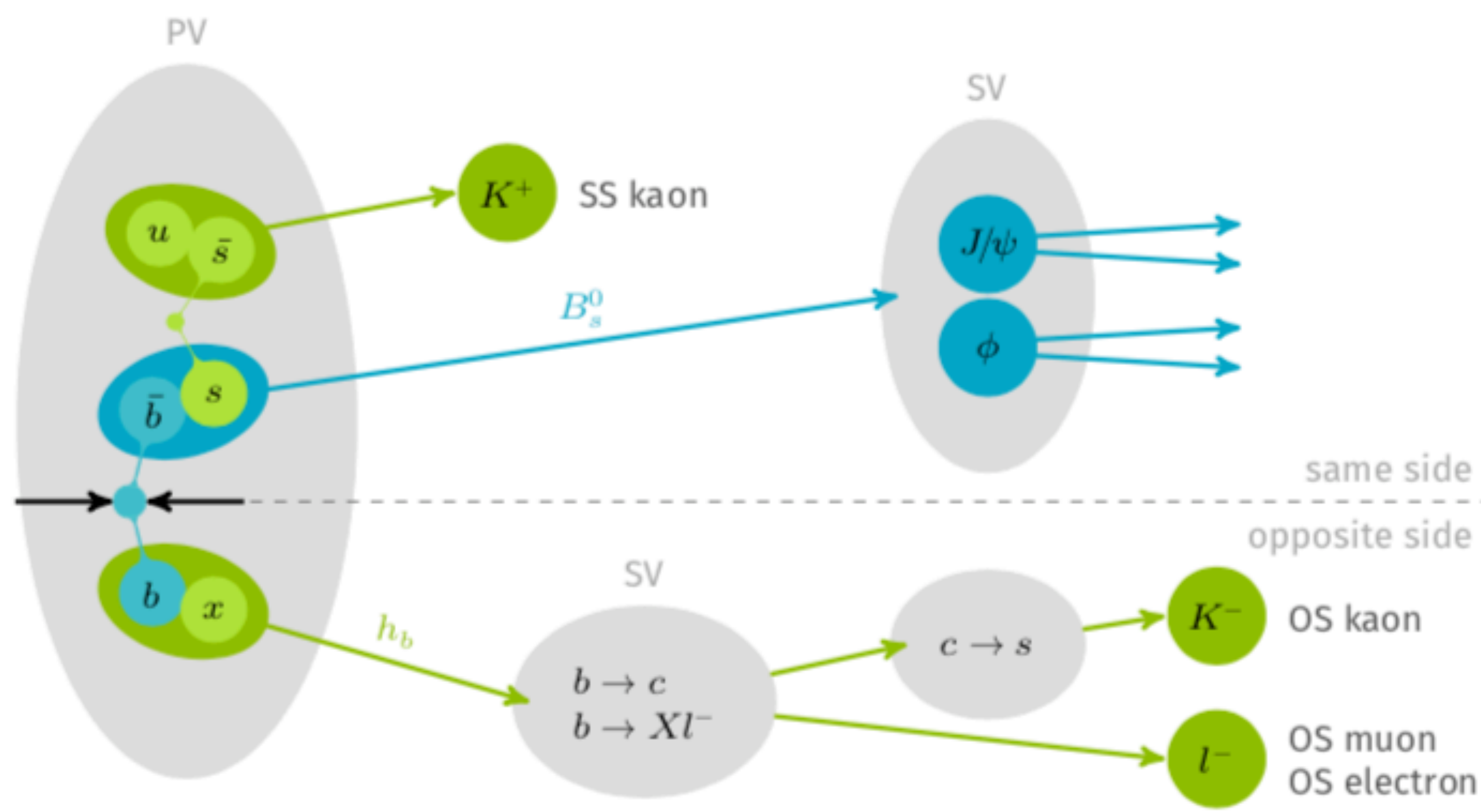


FLAVOUR TAGGING

- Two different algorithms used:
  - Same side (SS)
  - Opposite side (OS)



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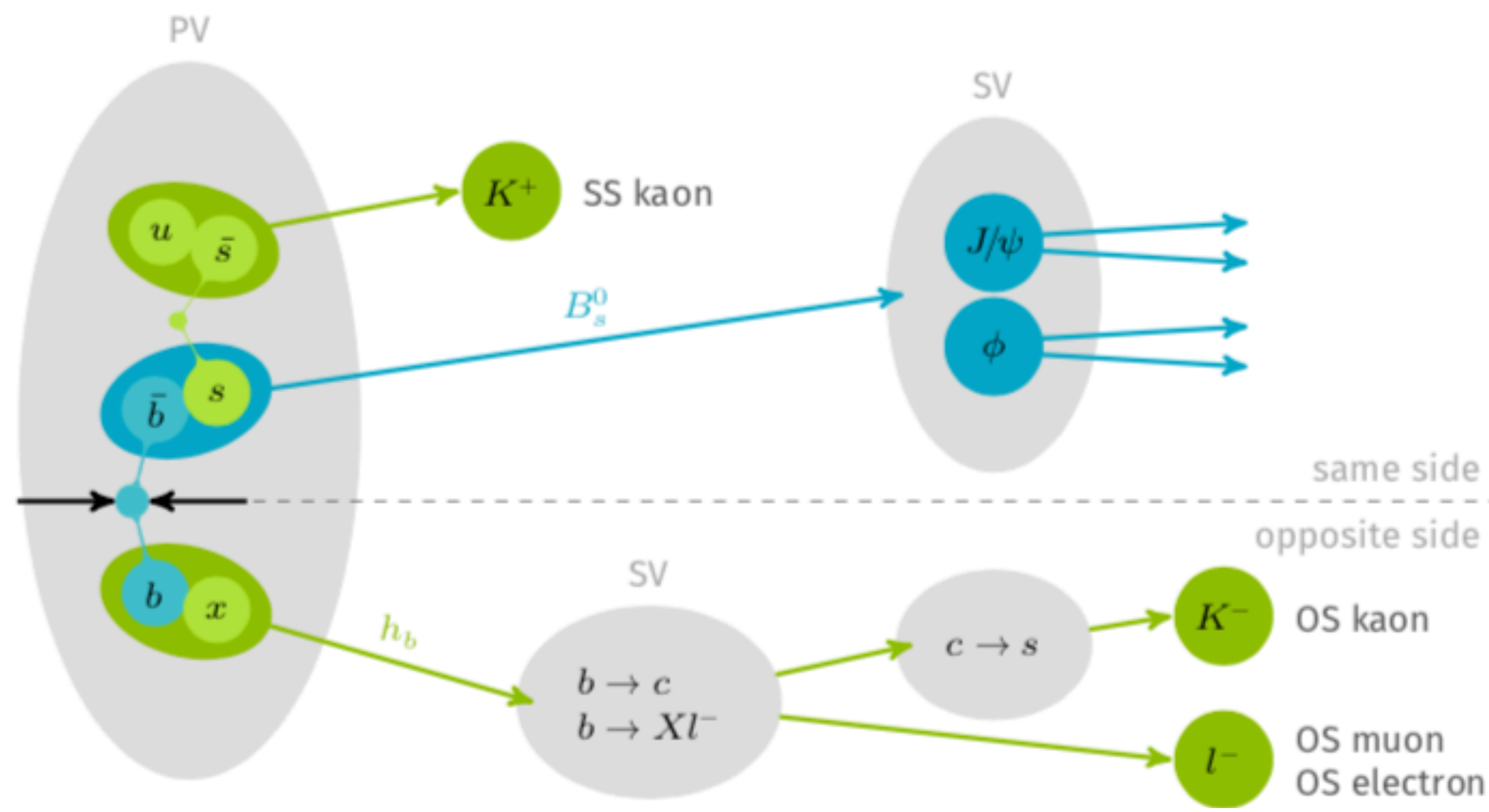
  - Same side (SS)
  - Opposite side (OS)



- Tagging power expressed as: $\epsilon_{tag}D^2$, where $D = (1 - 2\omega)$ and ω is mistag probability
- $\epsilon_{tag}D^2 \sim 4.73 \pm 0.34\,\%$ (Run 1: 3.73 %)

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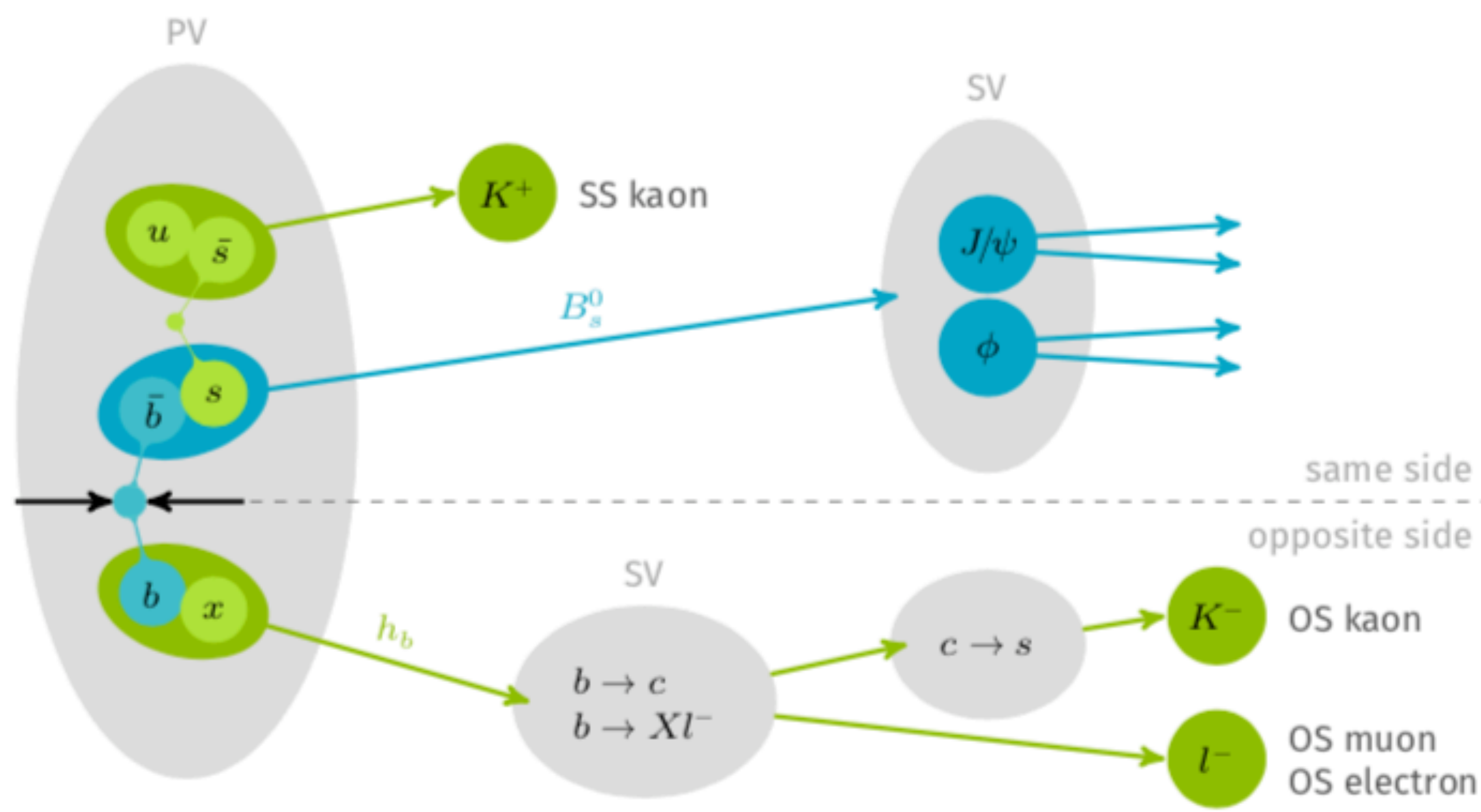

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- $\epsilon_{tag}D^2 \sim 4.73 \pm 0.34\,\%$ (Run 1: 3.73 %)
- Higher tagging power means a better exploitation of available data

RESULT

$$A_{CP}(t) = \eta_f \cdot e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \cdot (1 - 2\omega) \cdot sin(\phi_s) \cdot sin(\Delta m_s t)$$

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- Latest result by LHCb, based on 2015 + 2016 data (0.3 + 1.6 fb^{-1}):

$$\phi_s^{exp} = -0.080 \pm 0.041 \pm 0.006 \ rad$$

[arXiv: 1906.08356]

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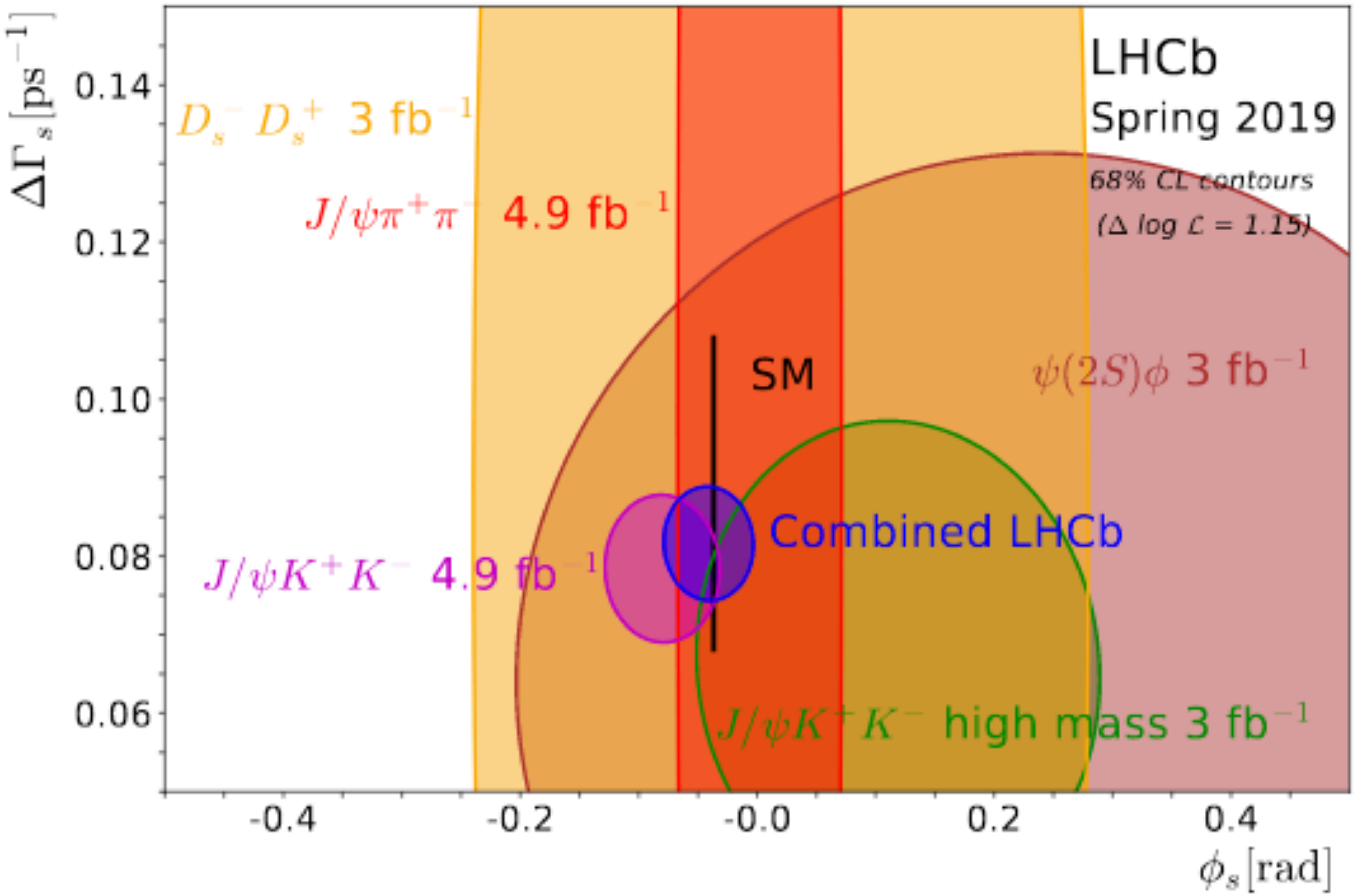
$$\phi_s^{SM} = -\,0.03686^{+0.00096}_{-0.00068} \; rad$$

RESULT



LHCb
Spring 2019
68% CL contours
(Δ log ℒ = 1.15)
$D_s^- D_s^+$ 3 fb^{-1}
$J/\psi\pi^+\pi^-$ 4.9 fb^{-1}
SM
$\psi(2S)\phi$ 3 fb^{-1}
Combined LHCb
$J/\psi K^+K^-$ 4.9 fb^{-1}
$J/\psi K^+K^-$ high mass 3 fb^{-1}
$\Delta\Gamma_s\,[\mathrm{ps}^{-1}]$
0.14
0.12
0.10
0.08
0.06
-0.4
-0.2
-0.0
0.2
0.4
$\phi_s\,[\mathrm{rad}]$

SUMMARY (TAKE-AWAY MESSAGES)

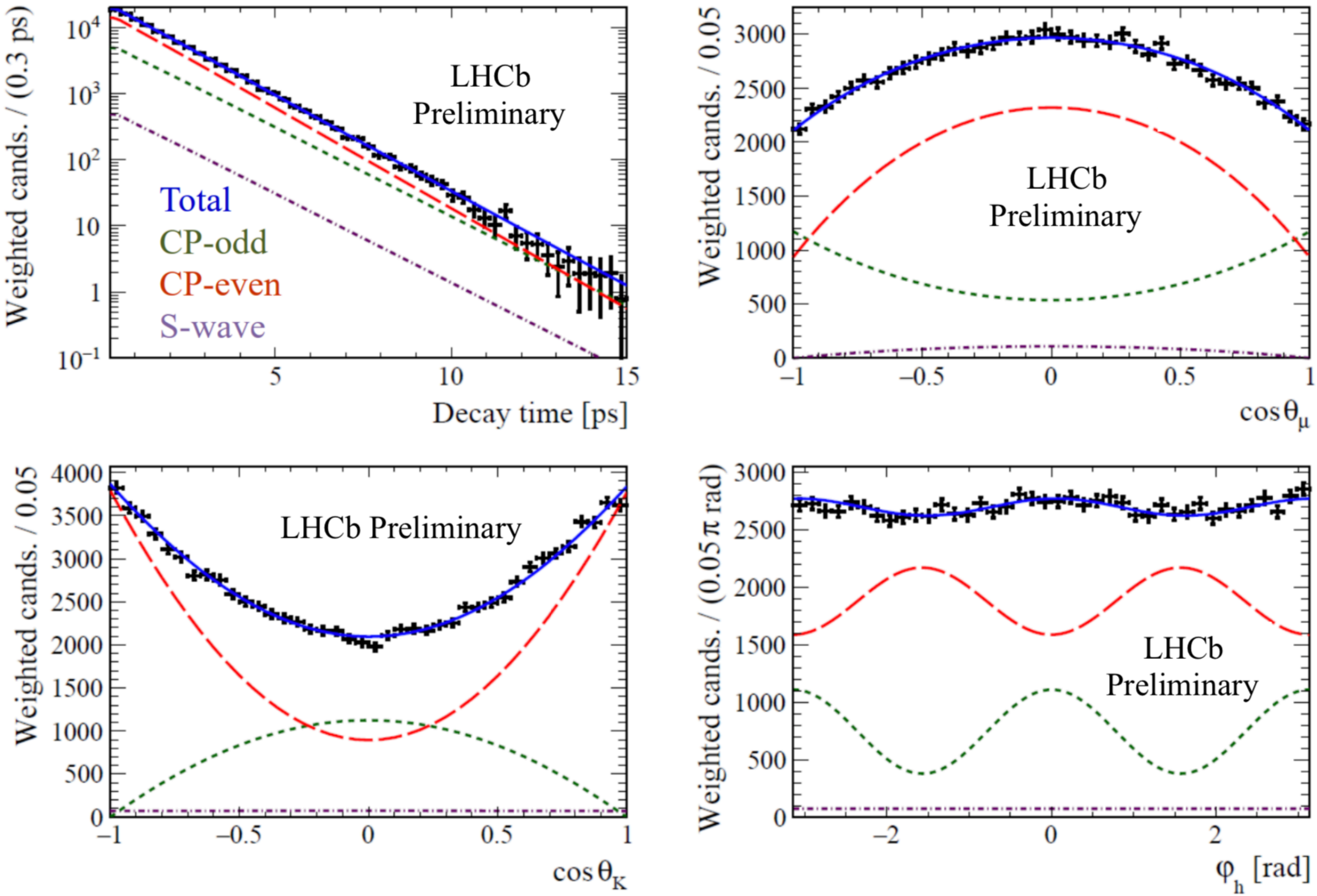
- ϕ_s is a measure of CP violation caused by the interference of the mixing and decay of the B_s^0 meson

- Its SM value can be inferred and true value can be measured with high precision, making it an excellent probe for NP

- Latest result by LHCb, using 2015 and 2016 data ($1.9\ fb^{-1}$) , is in agreement with SM prediction

$$\phi_s^{exp} = -0.080 \pm 0.041 \pm 0.006\ rad$$

- 2017 and 2018 ($3.8\ fb^{-1}$) data currently being analysed, stay tuned!



Weighted cands. / (0.3 ps)
LHCb
Preliminary
Total
CP-odd
CP-even
S-wave
Decay time [ps]
Weighted cands. / 0.05
LHCb
Preliminary
cos θ_μ
Weighted cands. / 0.05
LHCb Preliminary
cos θ_K
Weighted cands. / (0.05π rad)
LHCb
Preliminary
φ_h [rad]