University of Chinese Academy of Sciences

中国物理学会高能物理分会
HIGH ENERGY PHYSICS BRANCH OF CPS

Time-dependent measurements of CP Violation at LHCb

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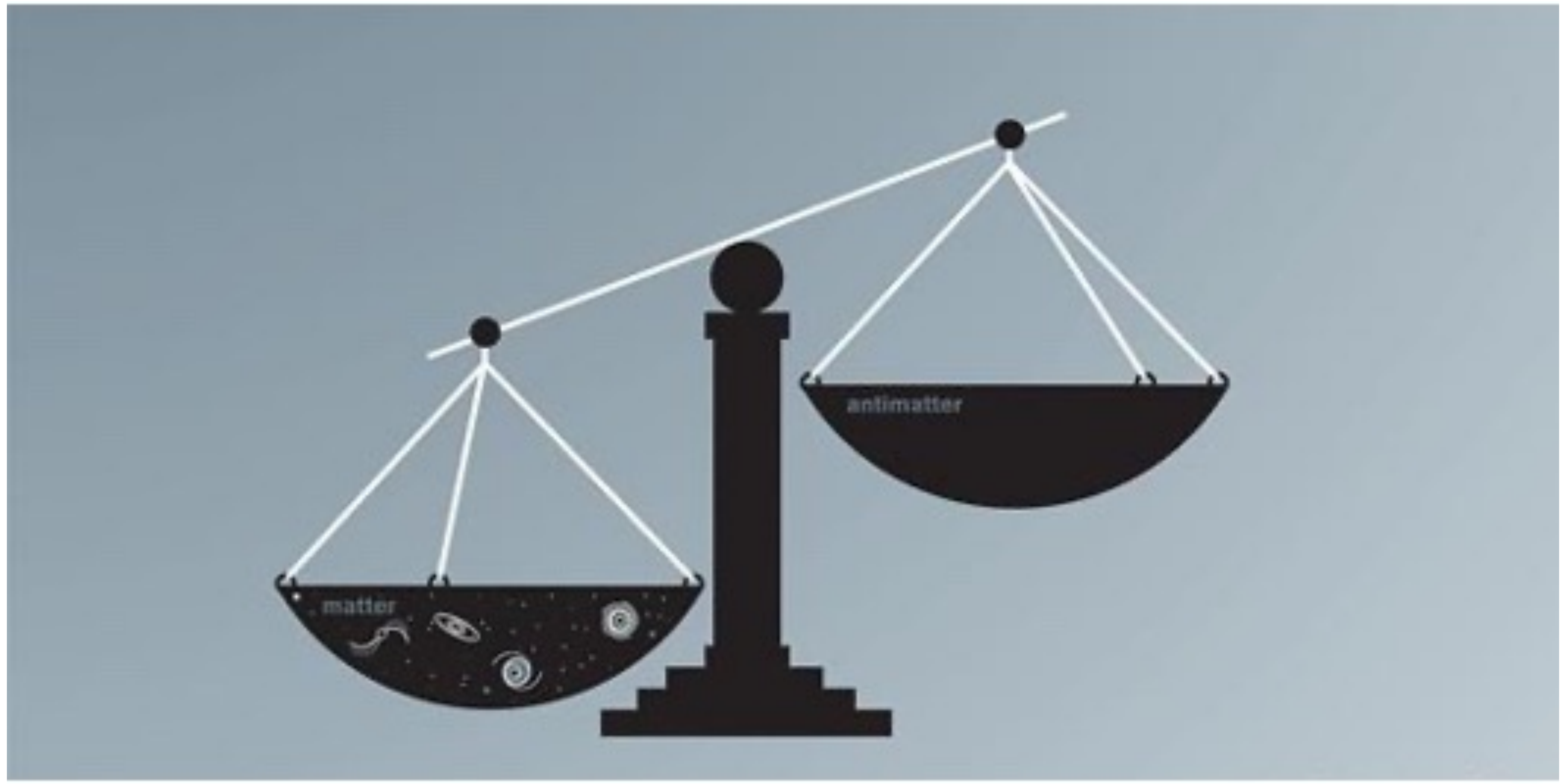
*on behalf of the LHCb collaboration

第十四届全国粒子物理大会

山东·青岛，2024-08-16

Outline

- Introduction
- Time-dependent CPV in B sector
- Time-dependent CPV in charm sector
- Summary

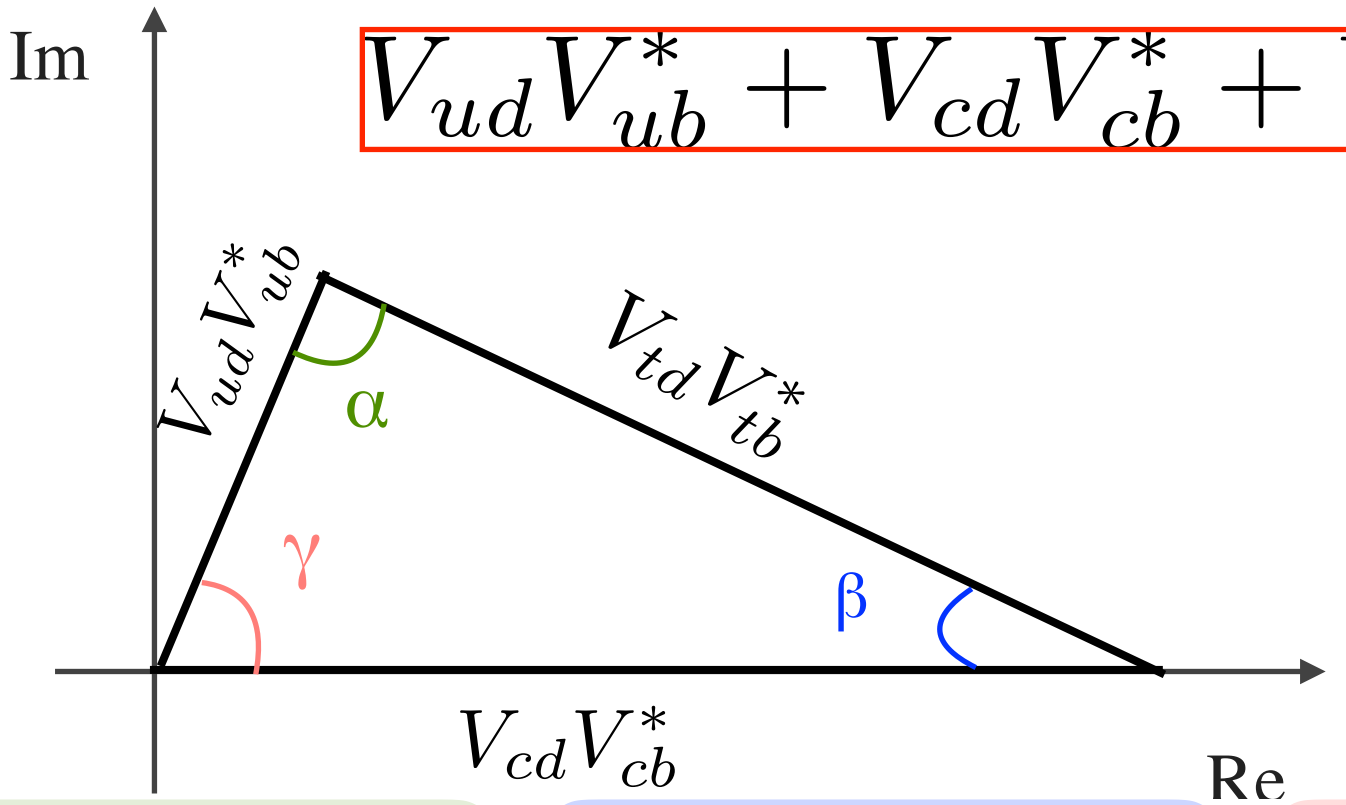


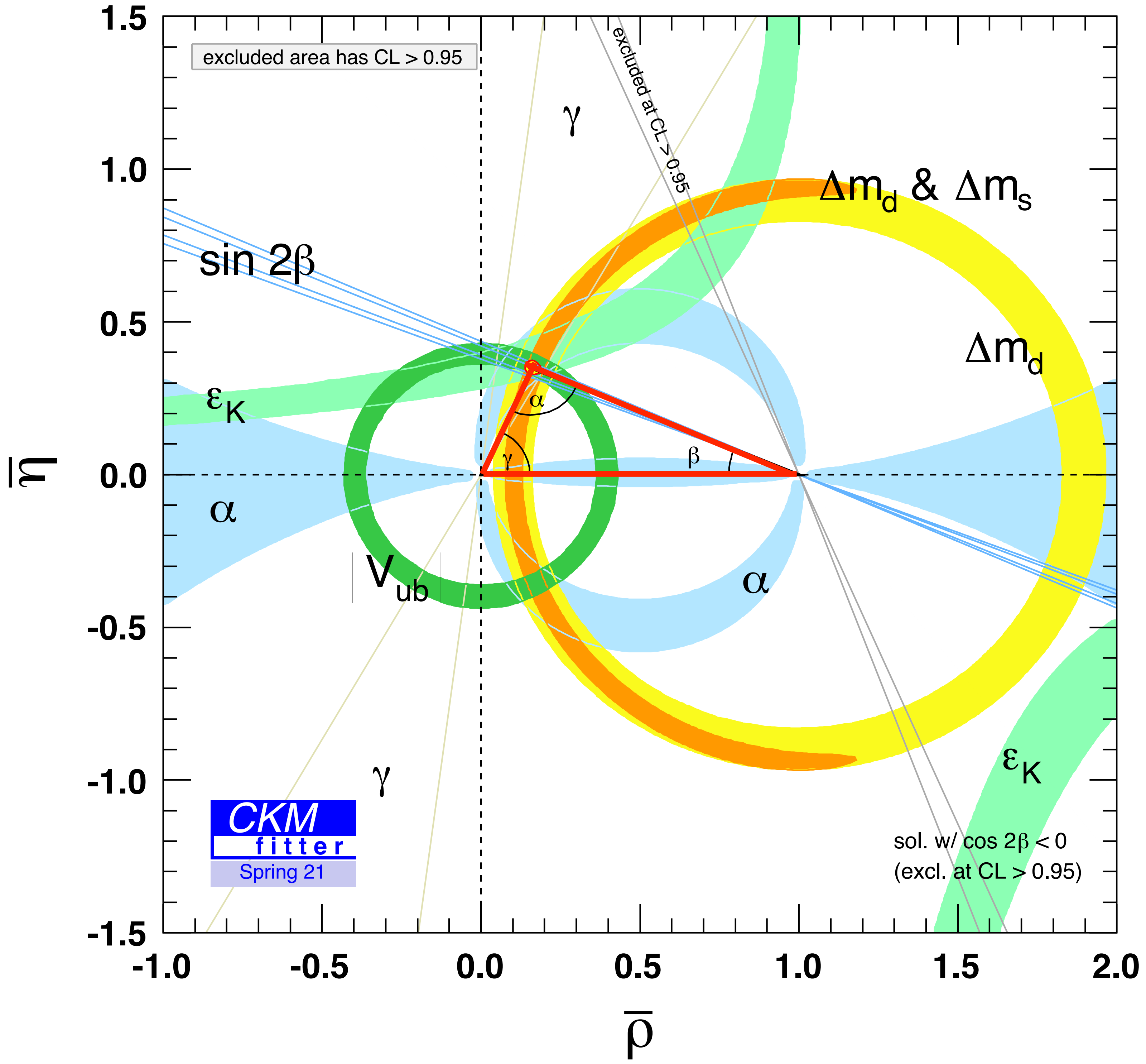
CKM matrix

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5) \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

- Key test of the SM: Verify unitarity of CKM matrix
  - Magnitudes: branching fractions or mixing frequencies
  - Phases: CP violation measurement
- Sensitive probe for new physics

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



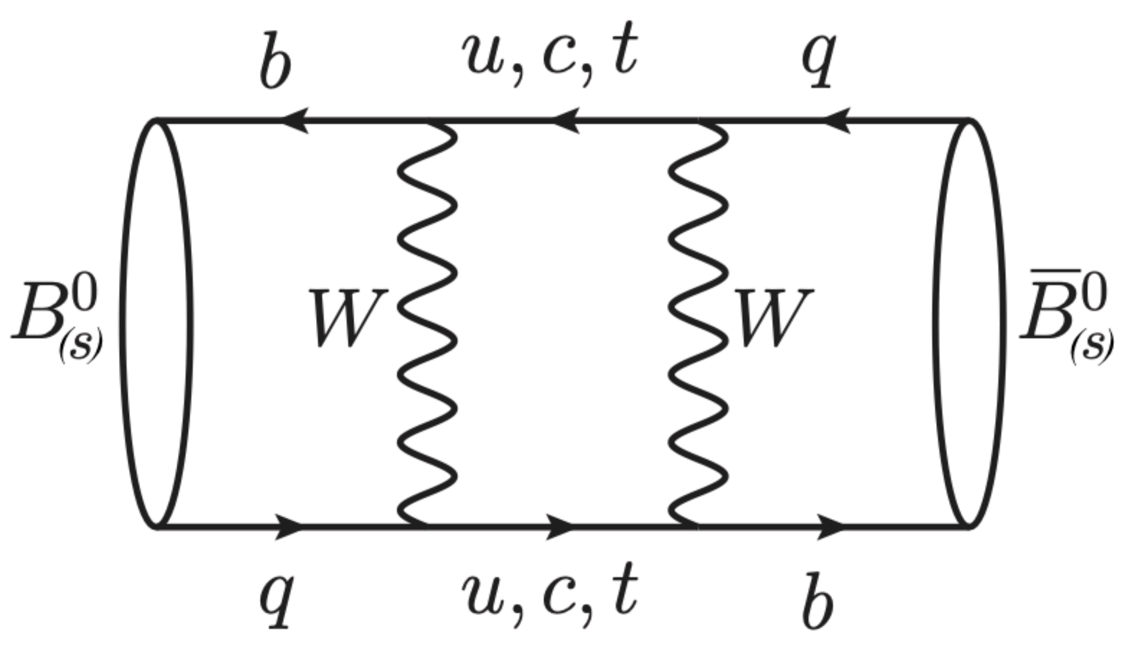


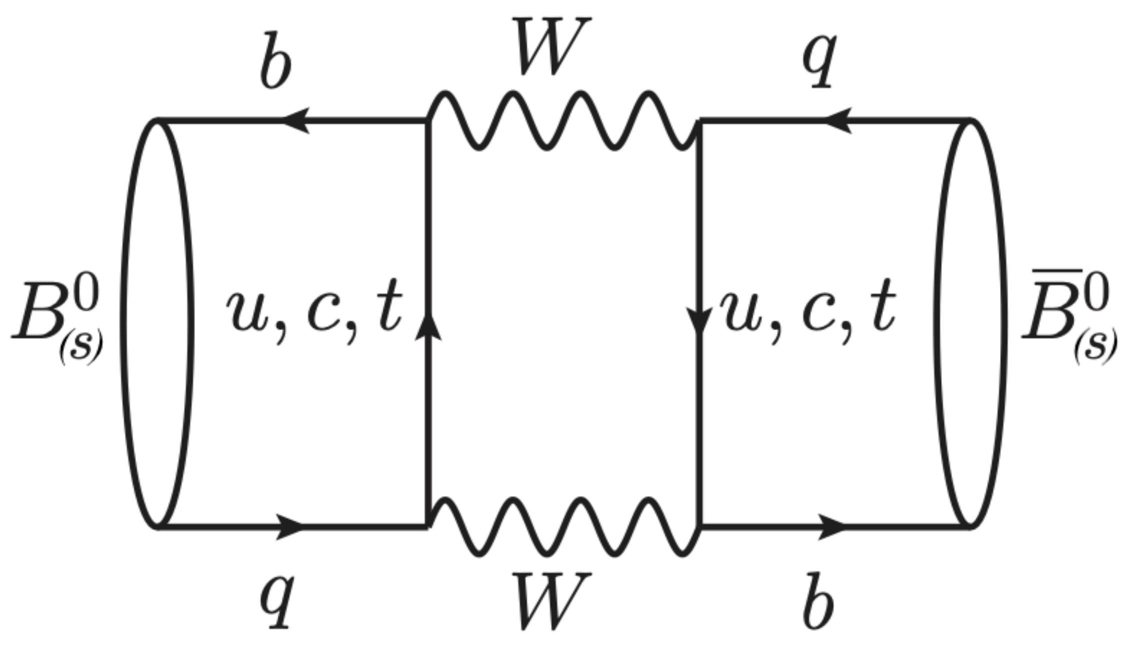
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

see Xiaokang Zhou's talk later

Neutral meson oscillation

- Neutral $B^0_{(s)}$ mesons can oscillate through box diagrams





- Time evolution:

$$-i\frac{d}{dt}\begin{pmatrix}|B^0_s(t)>\\|\bar{B}^0_s(t)>\end{pmatrix} = (\mathbf{M} - \frac{i}{2}\Gamma)\begin{pmatrix}|B^0_s(t)>\\|\bar{B}^0_s(t)>\end{pmatrix}$$

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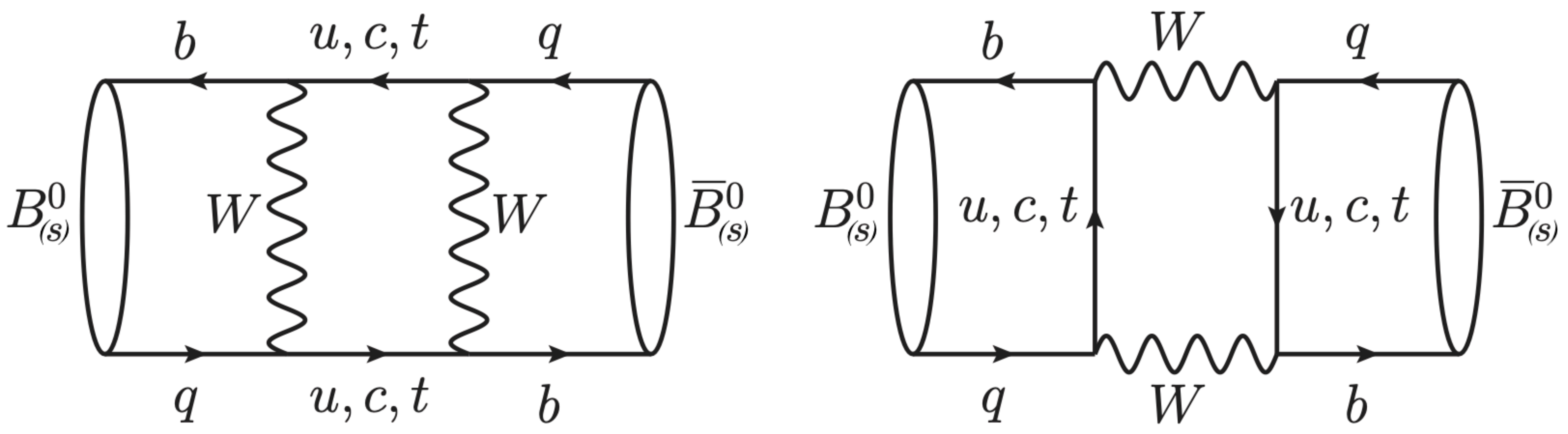

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- Mass eigenstates (*H*, *L*) are admixtures of the flavor eigenstates

$$|B^0_{q,L/H}\rangle = p|B^0_q\rangle \pm q|\bar{B}^0_q\rangle \;\; (p, q \in \mathbb{C},\ |p|^2 + |q|^2 = 1)$$

$\rightarrow$ $|p/q| = 1$ if CP conserved in mixing

- Mass difference $\Delta m_{(s)} = M_H - M_L = 2|M_{12}|$ $\rightarrow$ oscillation frequency!
- Decay-width difference $\Delta\Gamma_{(s)} = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|cos\phi_{\text{mixing}}$

Measurement of $B_s^0 - \bar{B}_s^0$ oscillations

- Flavour at production (*t=0*) could be difference from flavour at decay time *t*

$$|B^0_{s,H/L}(t)\rangle = e^{-iM_{H/L}t - \Gamma_{H/L}t/2}|B^0_{s,H/L}\rangle$$

- $\Delta m_s = (17.7656 \pm 0.0057)\ \mathrm{ps}^{-1}$, most precise measurement to date!

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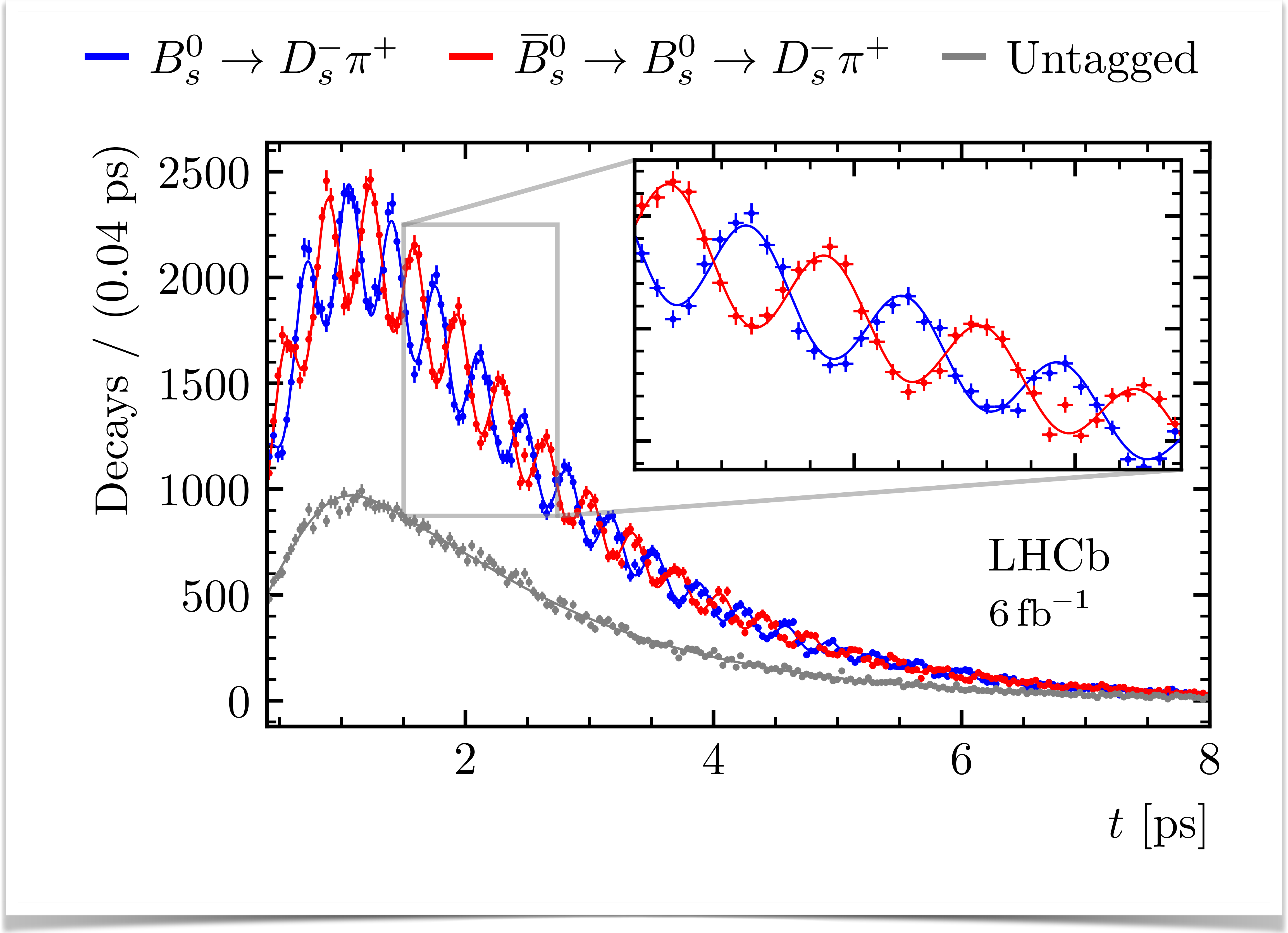

Effective lifetime measurements in $B_s^0 \to J/\psi\eta'$

- Simultaneous analysis of CP-even decay $B_s^0 \to J/\psi(\mu^+\mu^-)\eta'(\pi^+\pi^-\gamma)$ and CP-odd decay $B_s^0 \to J/\psi\rho^0$ to determine $\Delta\Gamma_s$
- Fit to the ratio of decay time $R(t)$ in 8 bins

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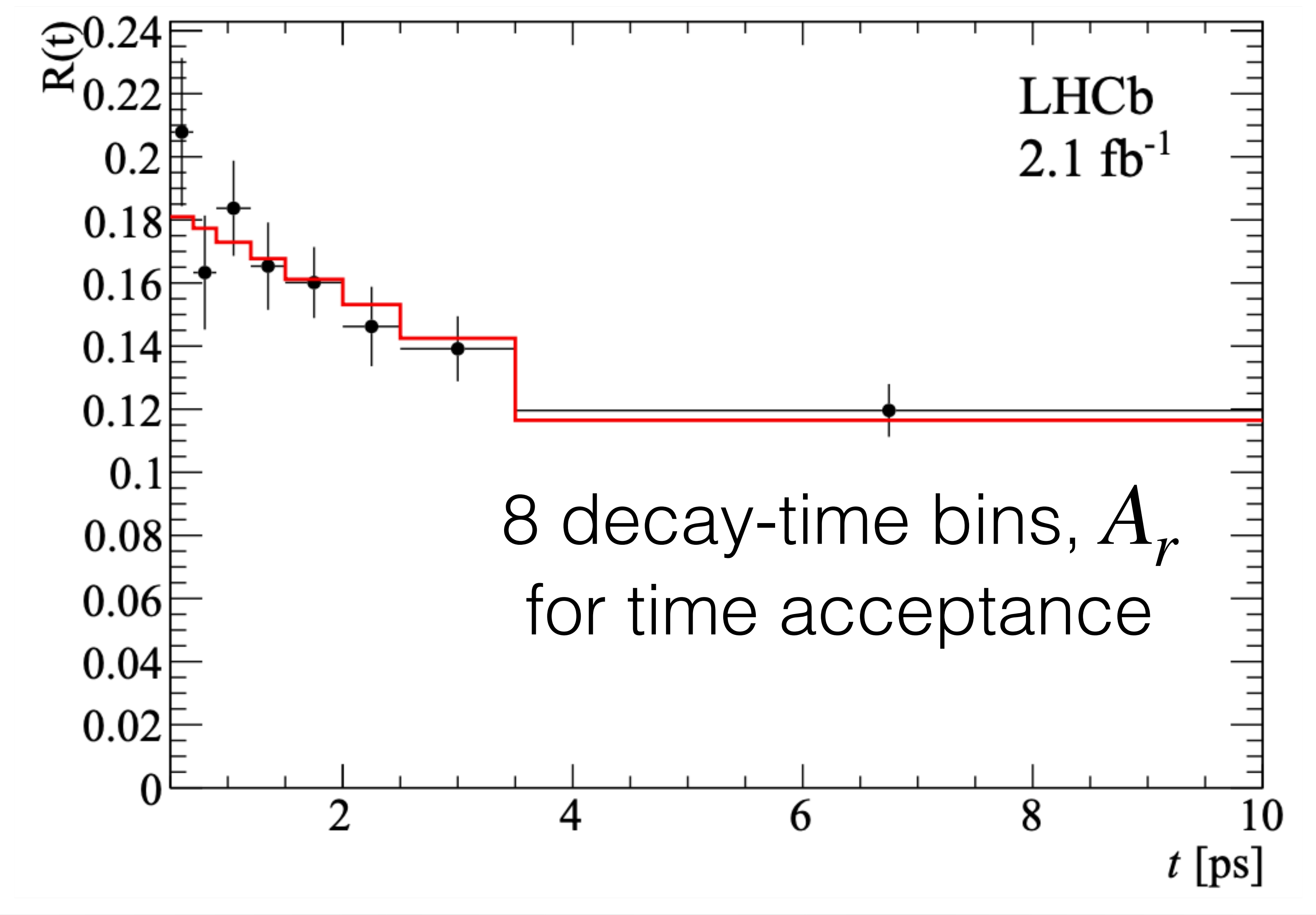
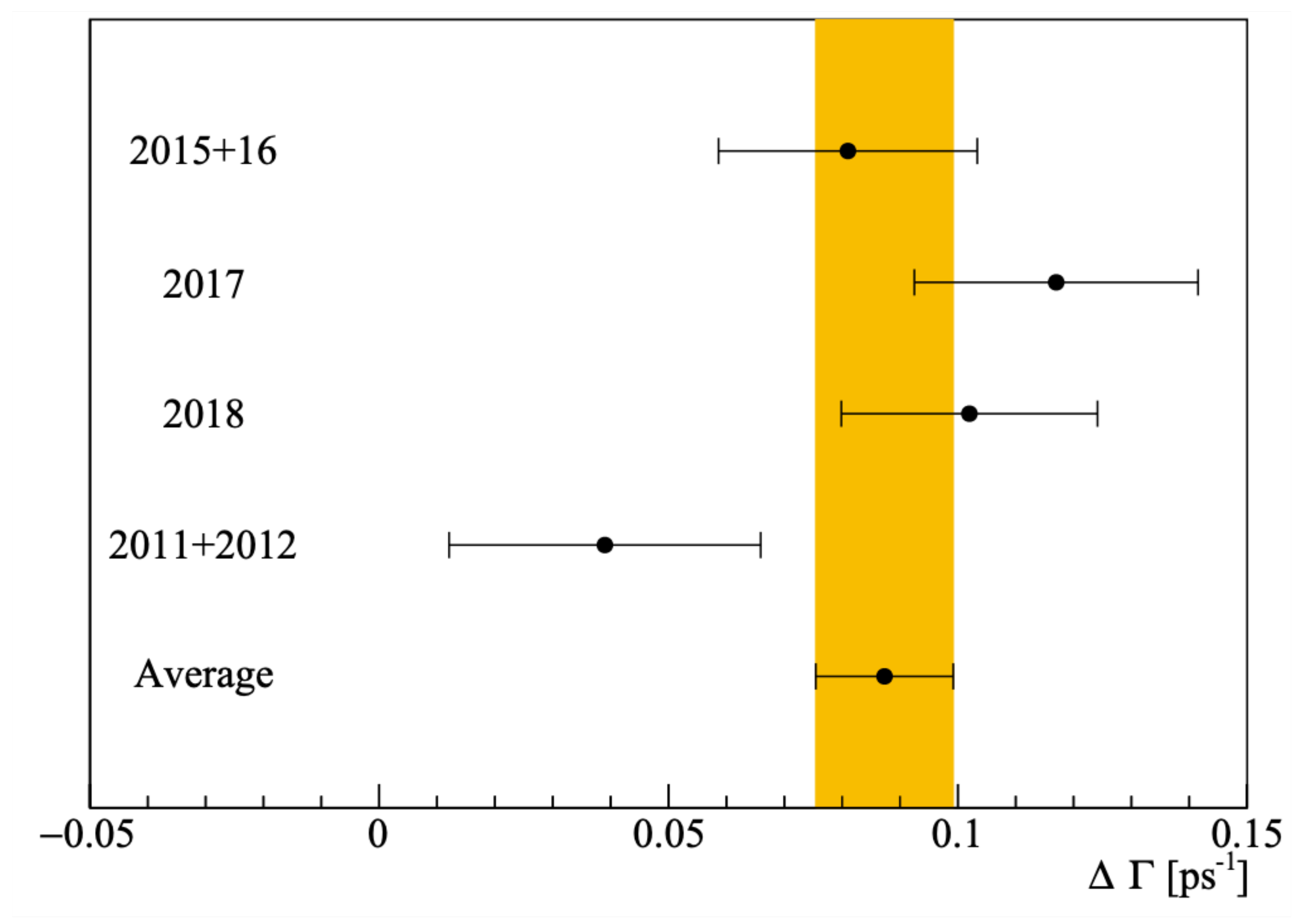
$$R(t) = A_r(t) \cdot \frac{N_{\rm L}}{N_{\rm H}}$$



$$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009\ {\rm ps}^{-1}$$



Agree with the World Average: $0.074 \pm 0.006\ {\rm ps}^{-1}$

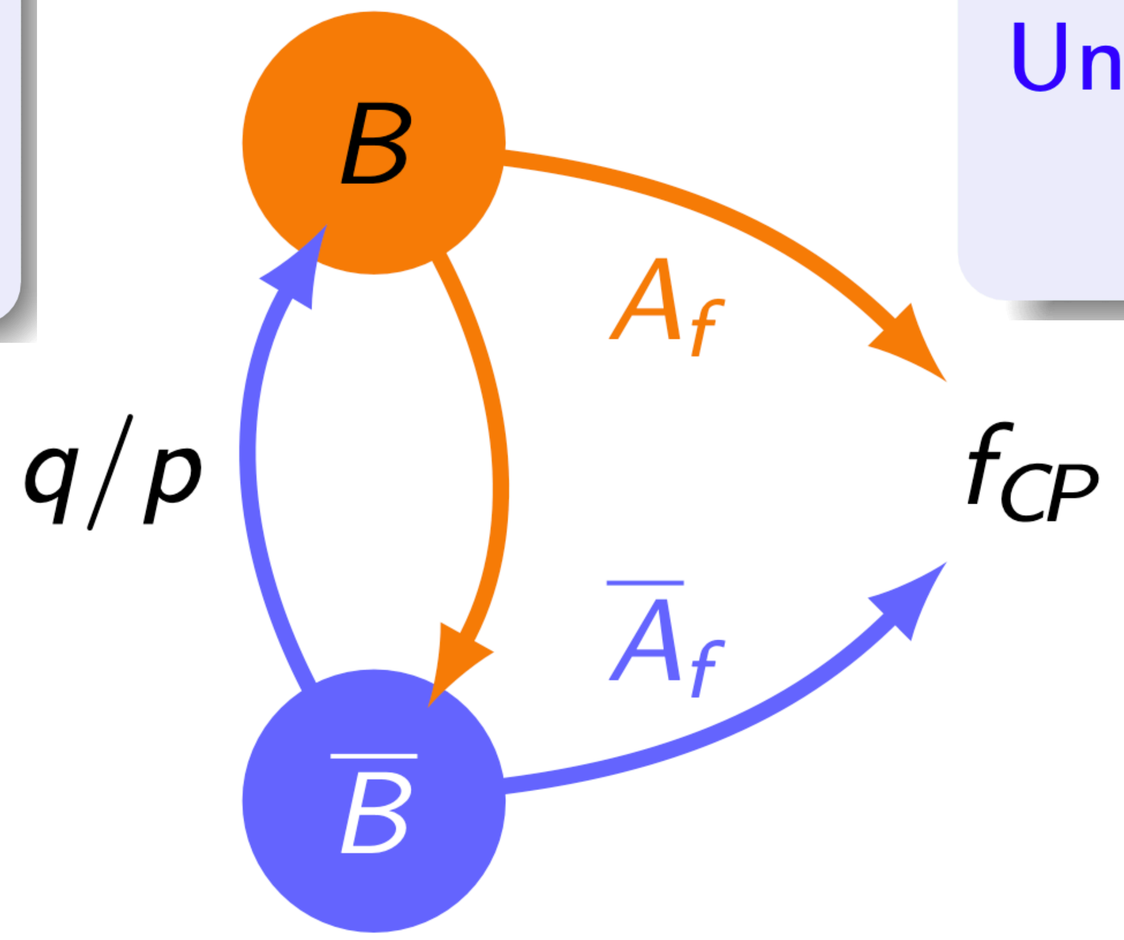
CP violation in $B^0_{(s)}$ system

- CP-violating nature of weak interaction has multiple manifestations
- Requires two interfering amplitudes with different strong and weak phases

CP violation in mixing

Unequal transition probabilities between flavour eigenstates

$$P(B \to \overline{B}) \neq P(\overline{B} \to B)$$



CP violation in decay

Unequal CP-conjugated decay rates

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

CP violation in interference of decays with/without mixing

Time-dependent or time-integrated difference of decay rates of initial flavour eigenstates

$$\Gamma(B_{(\rightsquigarrow \overline{B})} \to f_{CP})(t) \neq \Gamma(\overline{B}_{(\rightsquigarrow B)} \to f_{CP})(t)$$

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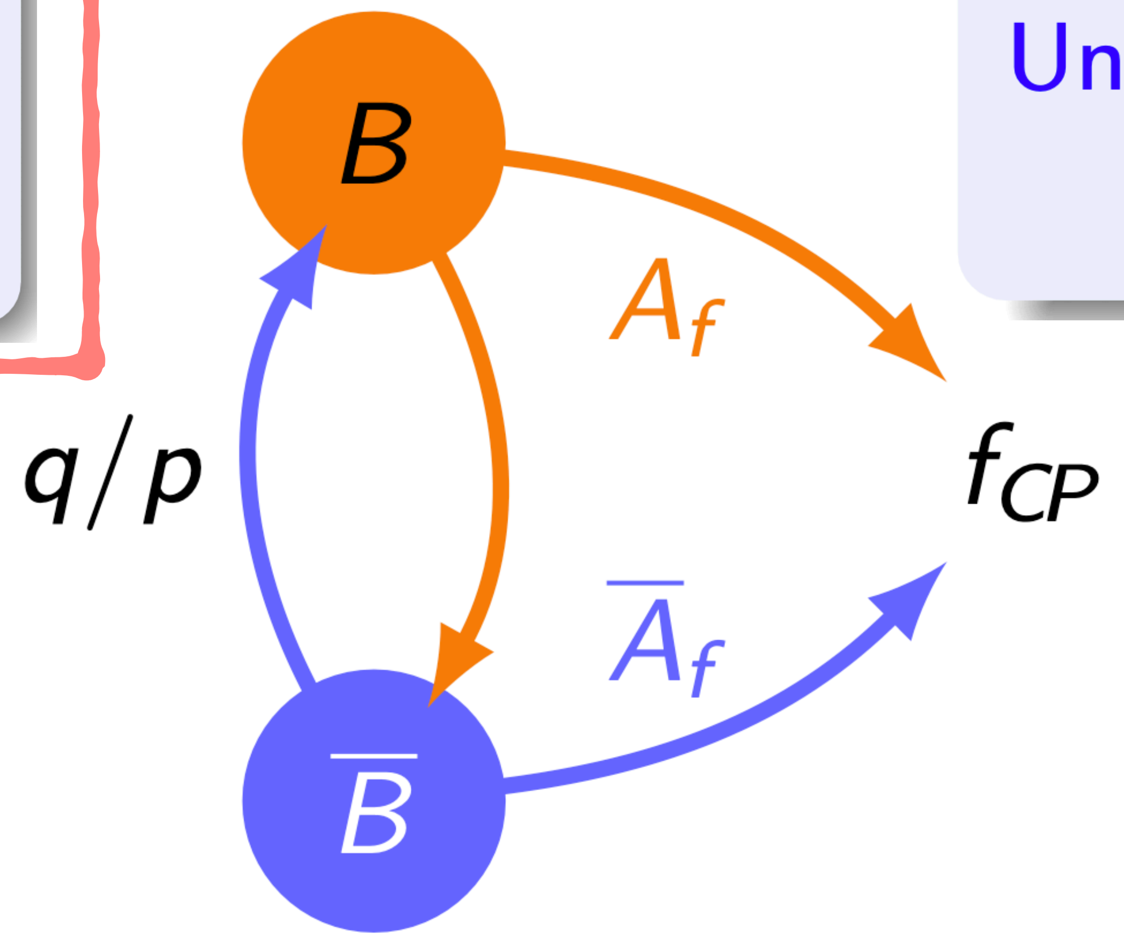

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time-dependent measurement!

CP violation in interference of decays with/without mixing

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$$\Gamma(B_{(\rightsquigarrow \overline{B})} \to f_{CP})(t) \neq \Gamma(\overline{B}_{(\rightsquigarrow B)} \to f_{CP})(t)$$

Time-dependent CP asymmetry

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

$$C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \qquad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2}, \qquad A_f^{\Delta\Gamma} \equiv -\frac{2\mathrm{Re}\lambda_f}{1 + |\lambda_f|^2} \qquad \lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

(direct CPV)

- CPV in decay or mixing if $|\lambda_f| \neq 1$
- For $b \to c\bar{c}q$ transition, $S_f \approx \sin 2\beta_{(s)}$

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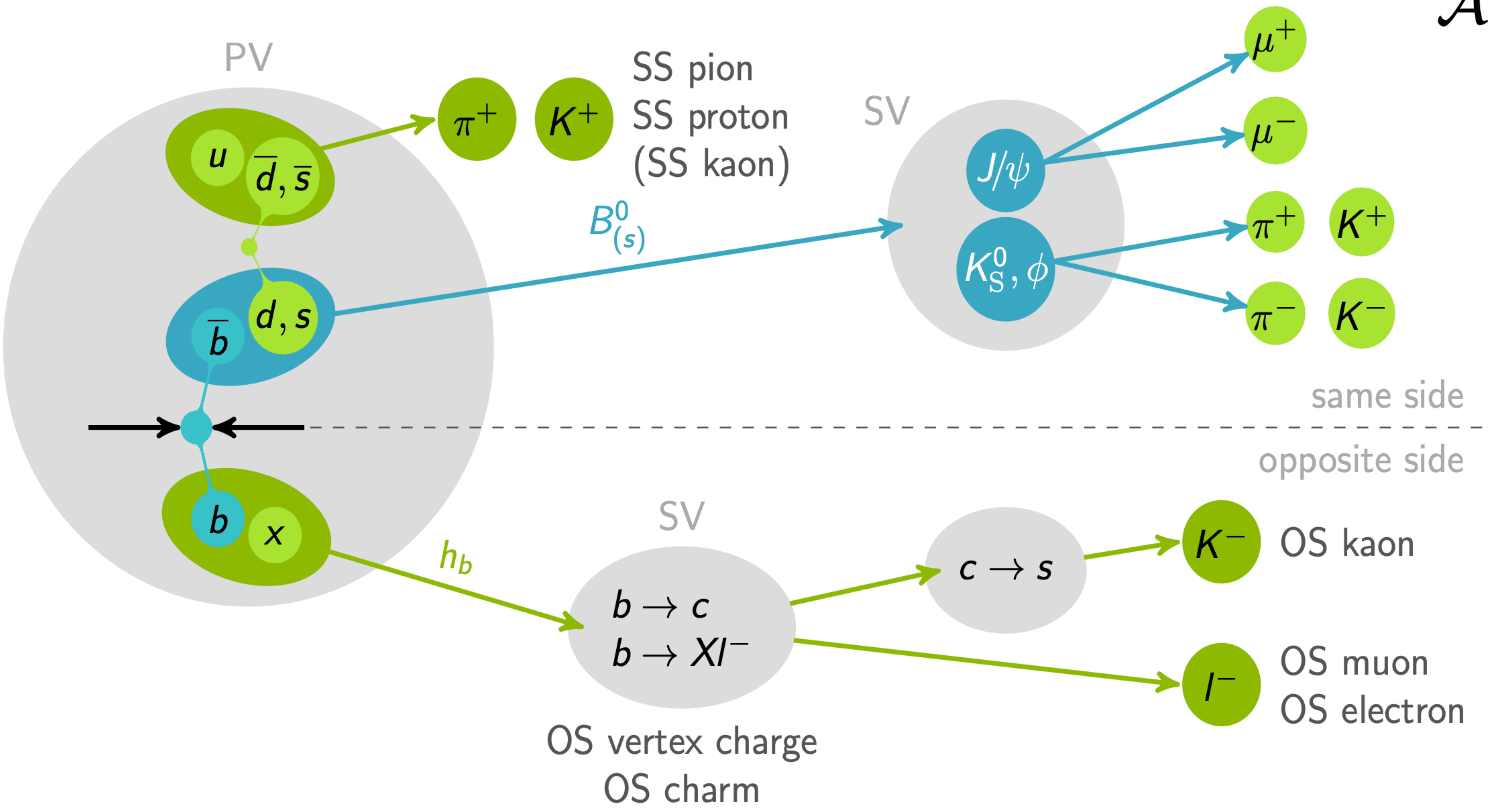
➡ Experimentally

$$A_{CP}(t) \propto e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \cdot (1 - 2\omega) \cdot (C_f \cos(\Delta m_{(s)} t) + \eta_f S_f \sin(\Delta m_{(s)} t))$$

- Flavour tagging of $B^0_{(s)}$ at production: probability of wrong tag ω
- Excellent decay-time resolution σ_t (vertex resolution)
- *CP* eigenvalue of the final state η_f

Flavour tagging

A ML-based statistical tool enables the identification of the B production flavour, allowing us to measure interference CP violation



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

- Same-side (SS) tagging: Use charge of K/π produced in the fragmentation

- Opposite-side (OS) tagging: charge of leptons or hadrons from the other *b* hadrons

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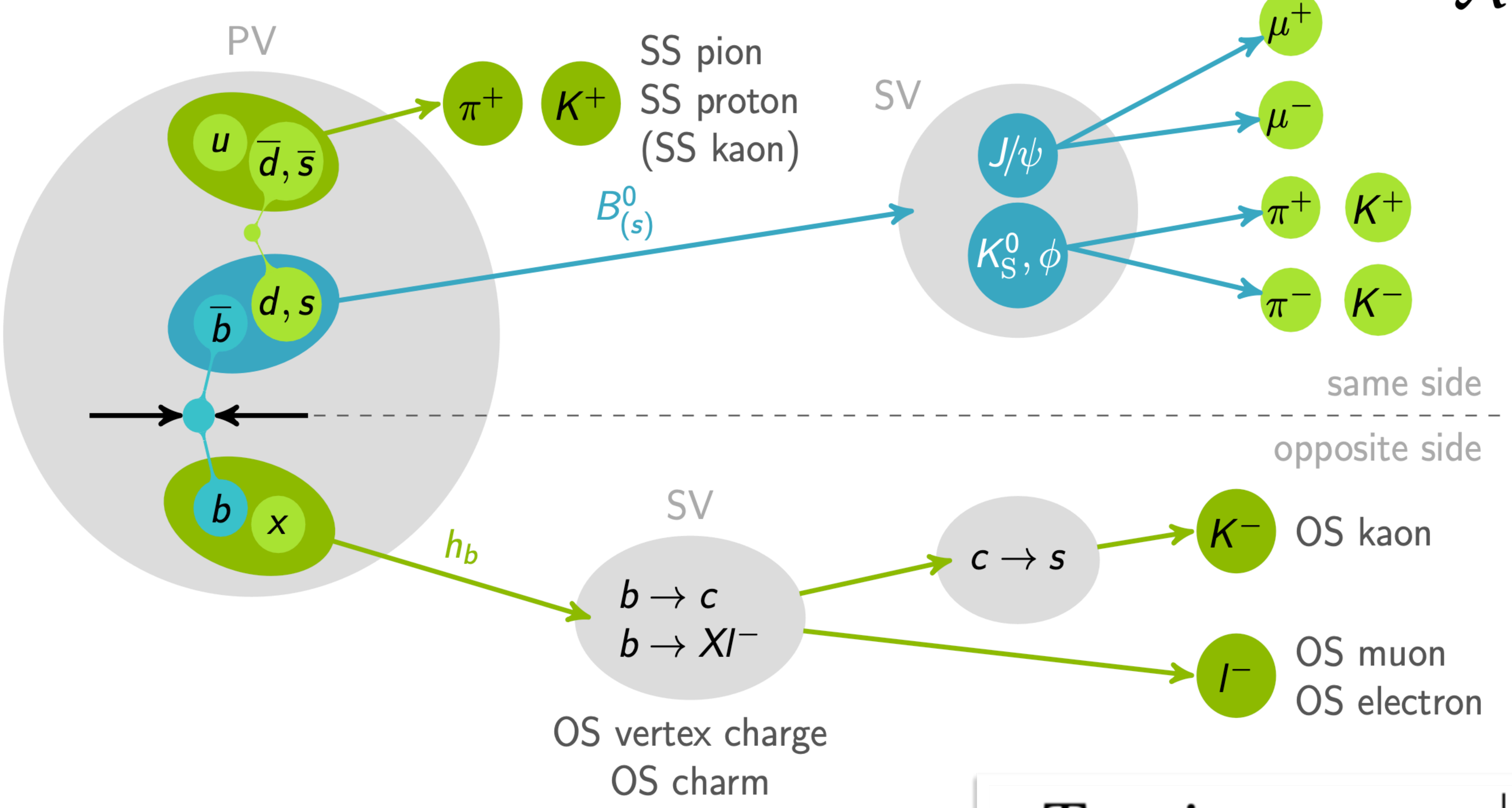

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- Same-side (SS) tagging: Use charge of K/π produced in the fragmentation
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Tagging power	$B^0 \to \psi K^0_S$	$B^0_s \to J/\psi KK$	$B^0_s \to \phi\phi$
$\epsilon_{\rm tag}(1-2\omega)^2$	(4-6)%	4.3%	6%

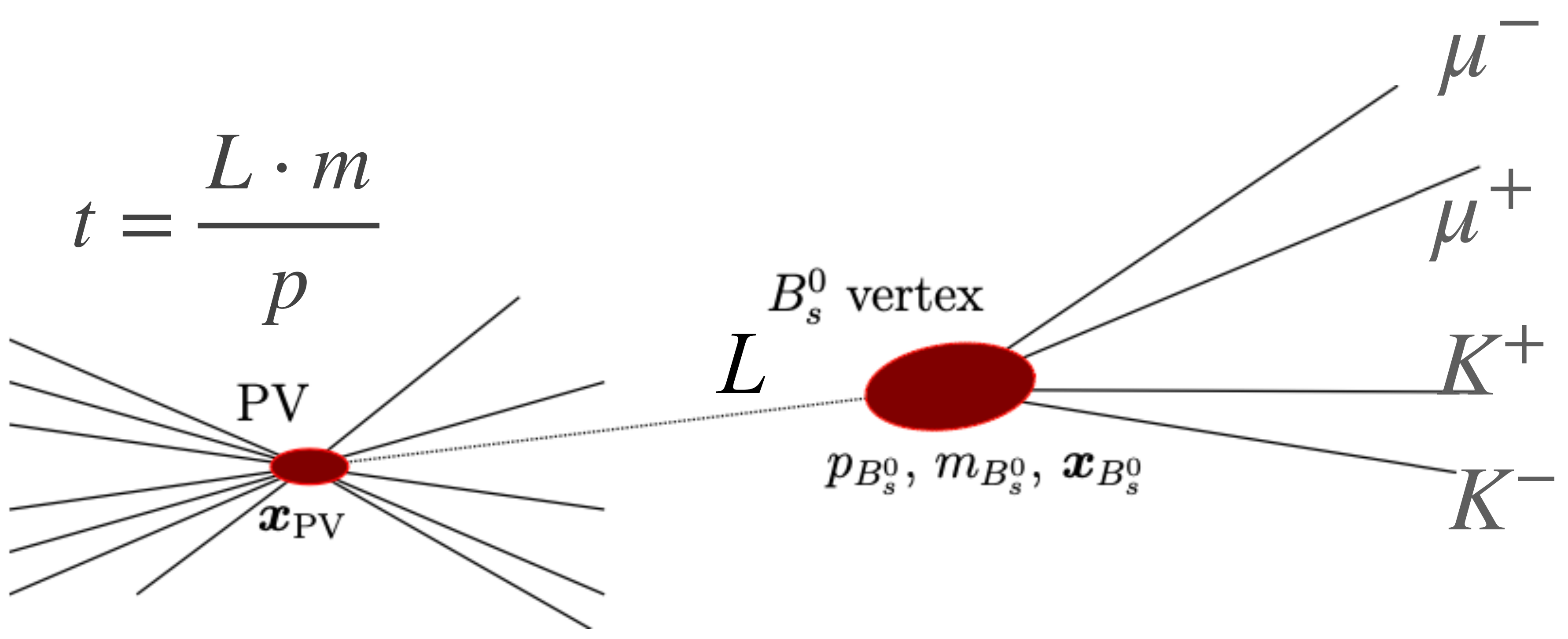
* tagging efficiency $\epsilon_{\rm tag}$, mistag rate ω

Decay-time resolution

- Decay time resolution dilutes oscillations, $\mathscr{D} = exp(-\frac{1}{2}\sigma_{\text{eff}}^2 \Delta m_s^2)$
- Significant for B_s^0 system, negligible for B^0

$$\delta_t^2 = (\frac{m}{p})^2 \sigma_L^2 + (\frac{t}{p})^2 \sigma_p^2$$

~ 200 μm $\quad \sigma_p/p \sim 0.4\,\%$



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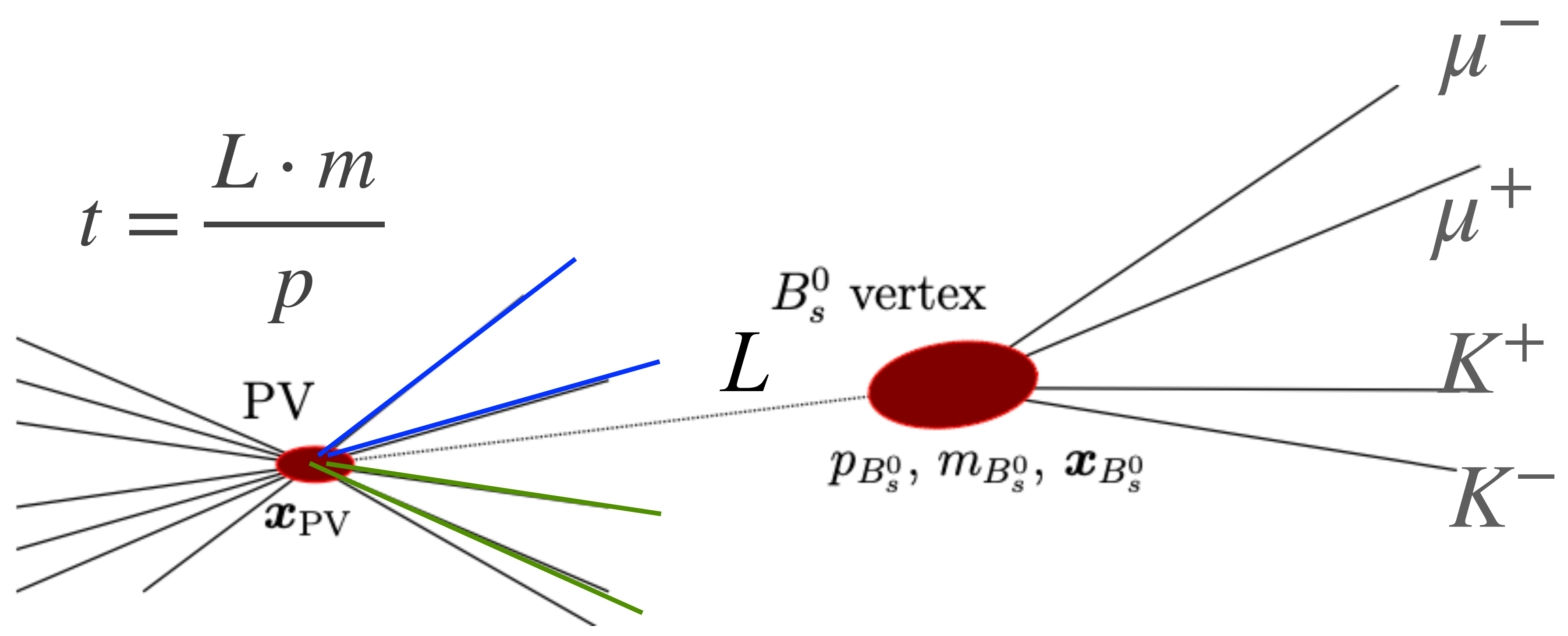
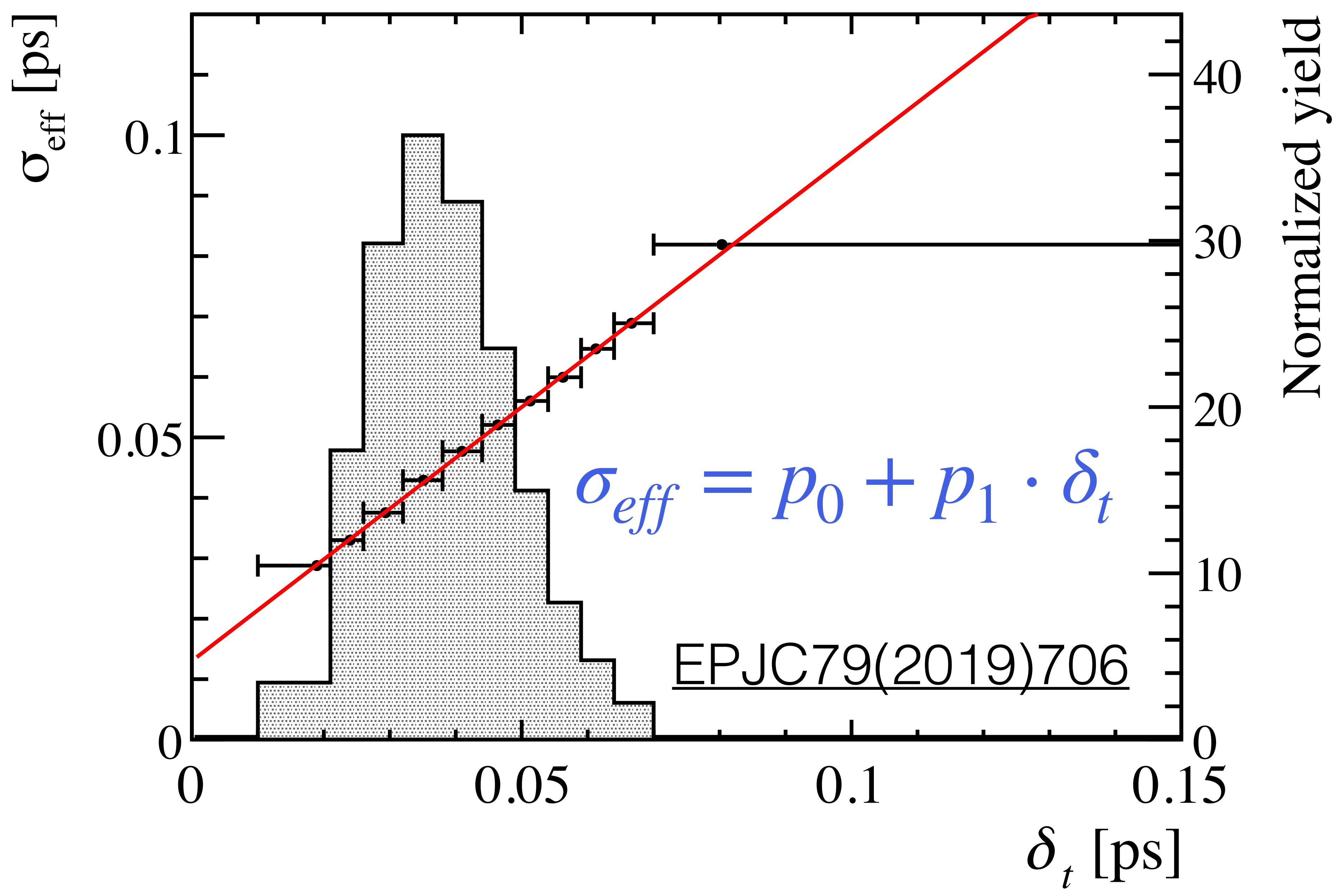


- Effective Gaussian resolution model:

  σ_{eff} as a function of δ_t (11 bins)

  $\sigma_{eff}(B_s^0) \sim 43$ fs $\rightarrow \mathscr{D} = 0.757$

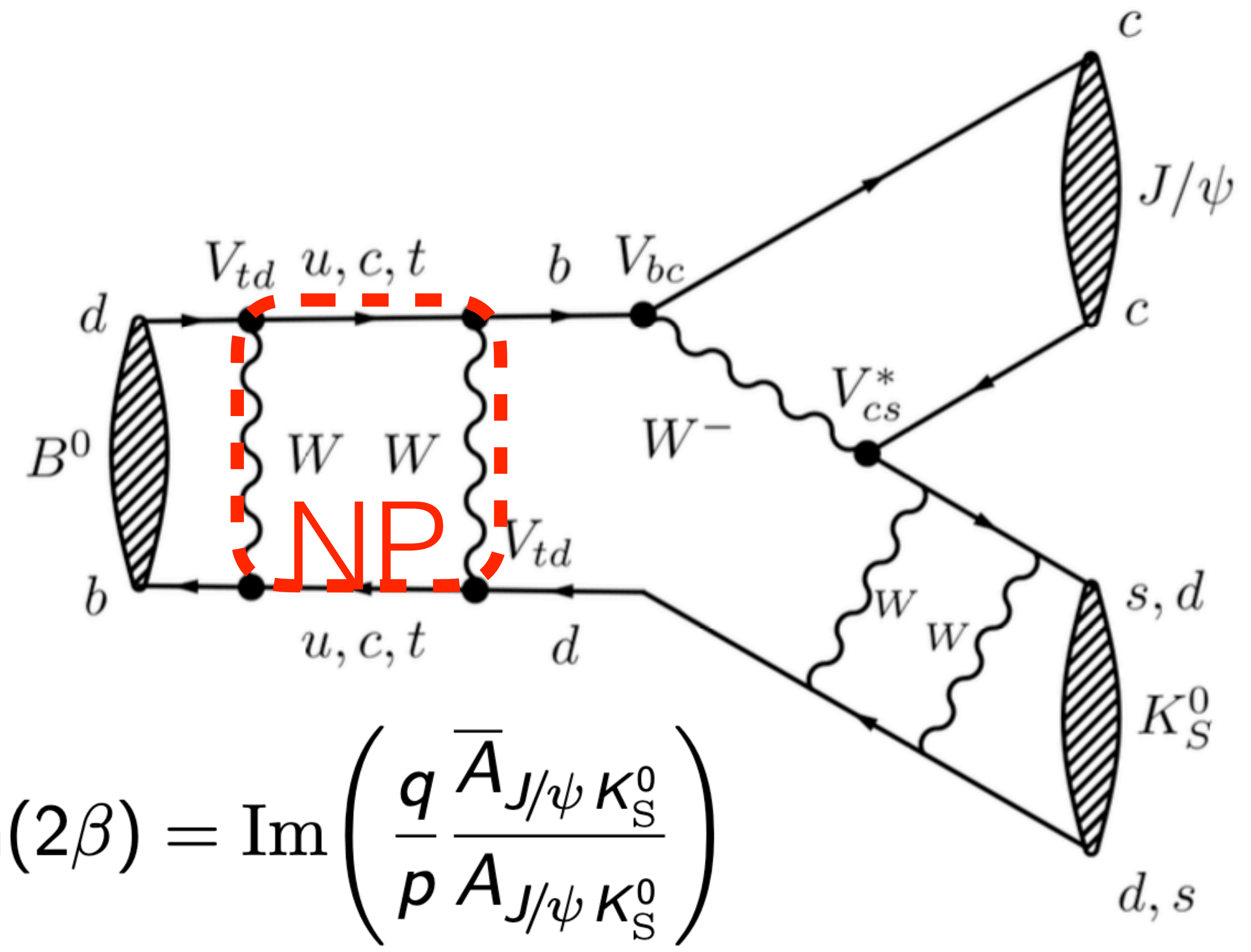
  $\sigma_{eff}(B^0) \sim 60$ fs $\rightarrow \mathscr{D} \sim 1$



$\sin 2\beta$

Phys. Rev. Lett. 132 (2024) 021801

- Decay mode $B^0 \to \psi K_S^0$ *(CP-odd only)* offers a theoretically clean access to the CKM angle β



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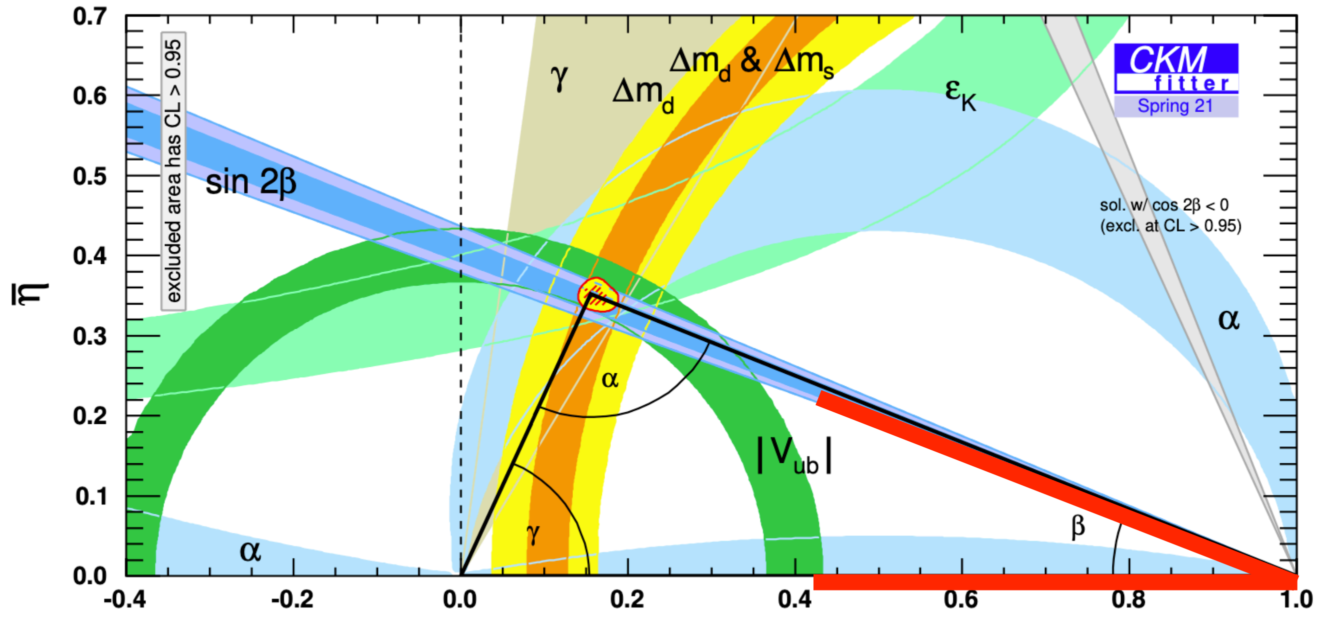
$$\sin(2\beta) = \mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}_{J/\psi K^0_S}}{A_{J/\psi K^0_S}}\right)$$

$$\beta = \arg\left(-\frac{V^*_{cb}V_{cd}}{V^*_{tb}V_{td}}\right)$$

$$S = \sin(2\beta + \Delta\phi_d + \Delta\phi_d^{\mathrm{NP}})$$

(penguin contributions $\Delta\phi_d \sim 0.5$ deg)



$\sin(2\beta) \neq 0 \Rightarrow$ *CP* violation

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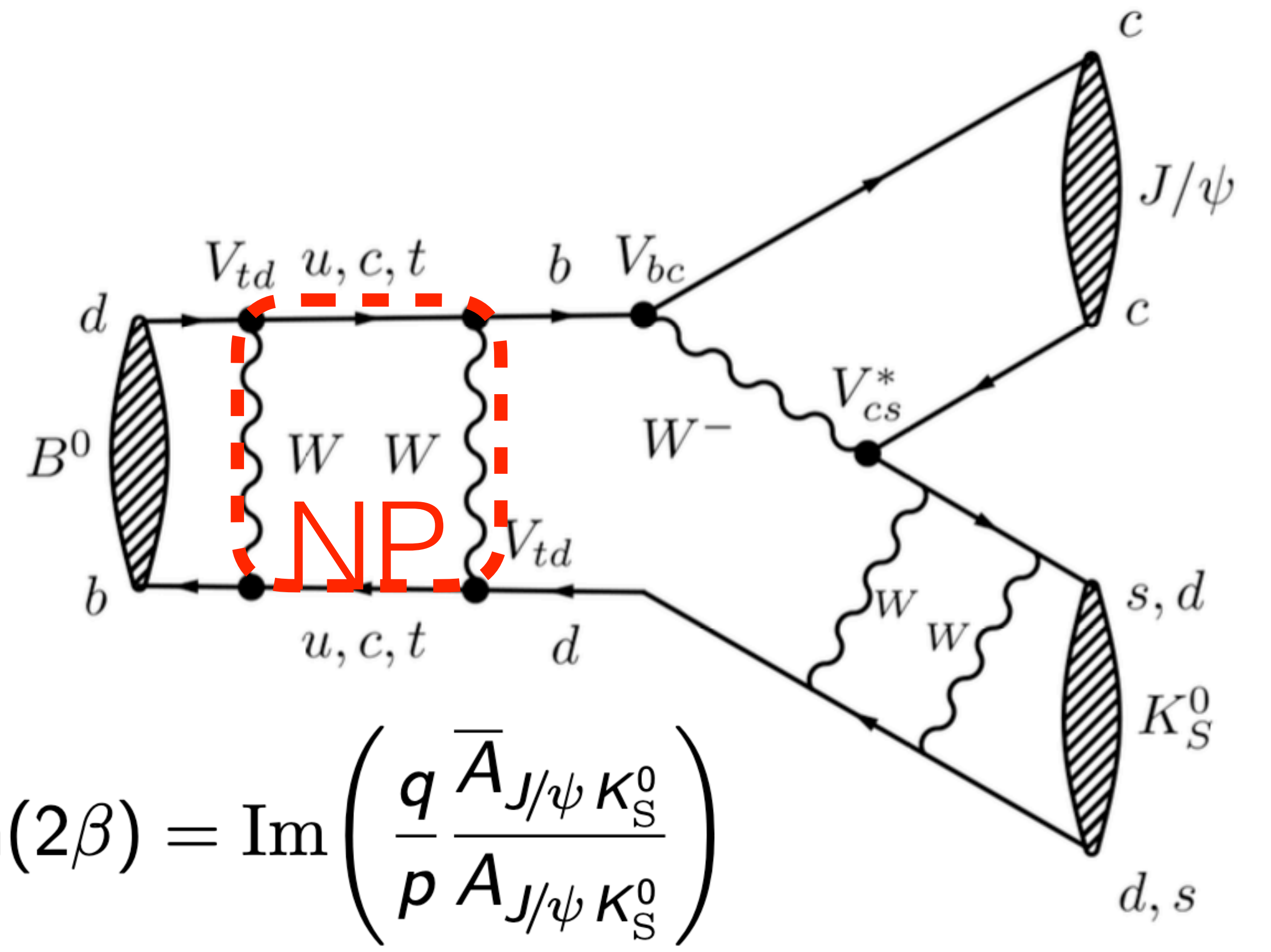

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- Consistent with other measurements, still statistical uncertainty limited
- LHCb results dominate the latest World Average

$$S^{\text{Run 2}}_{\psi K^0_S} = 0.716 \pm 0.013 \pm 0.008$$

$$C^{\text{Run 2}}_{\psi K^0_S} = 0.012 \pm 0.012 \pm 0.003$$

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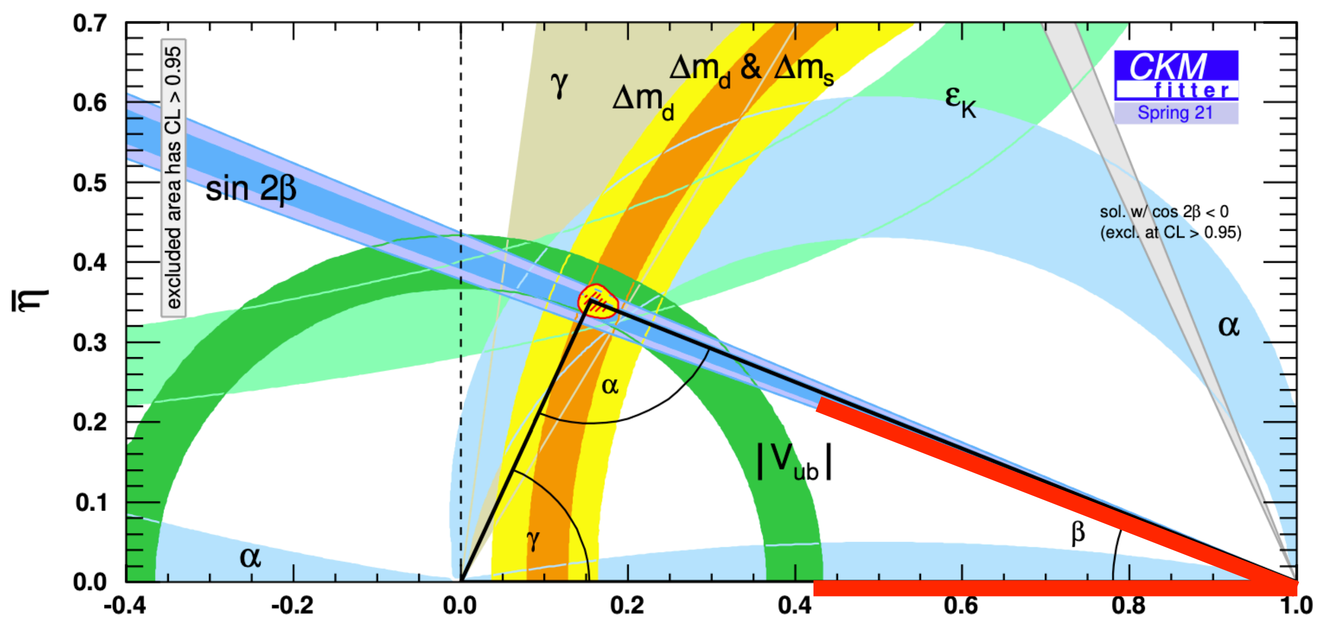
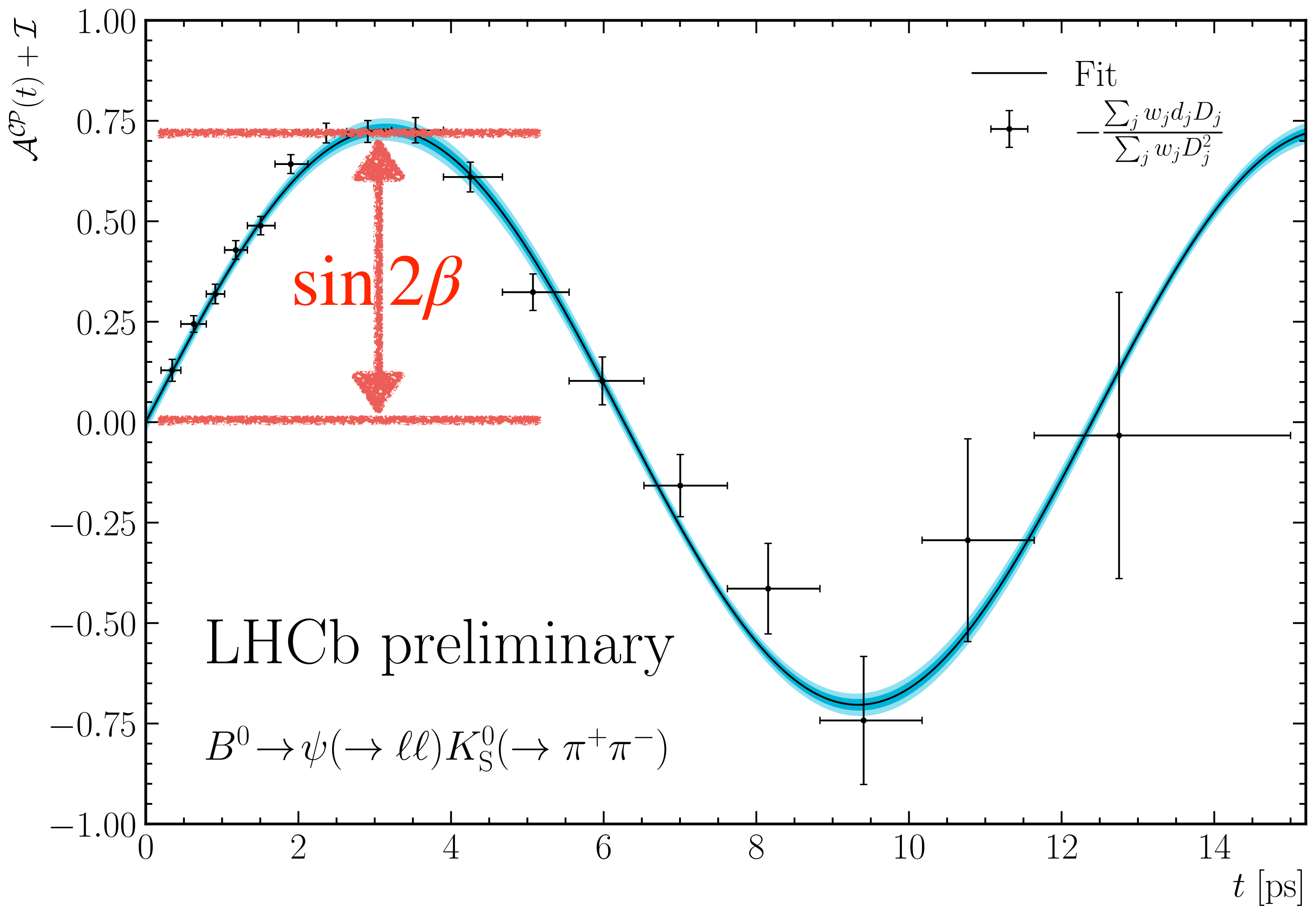
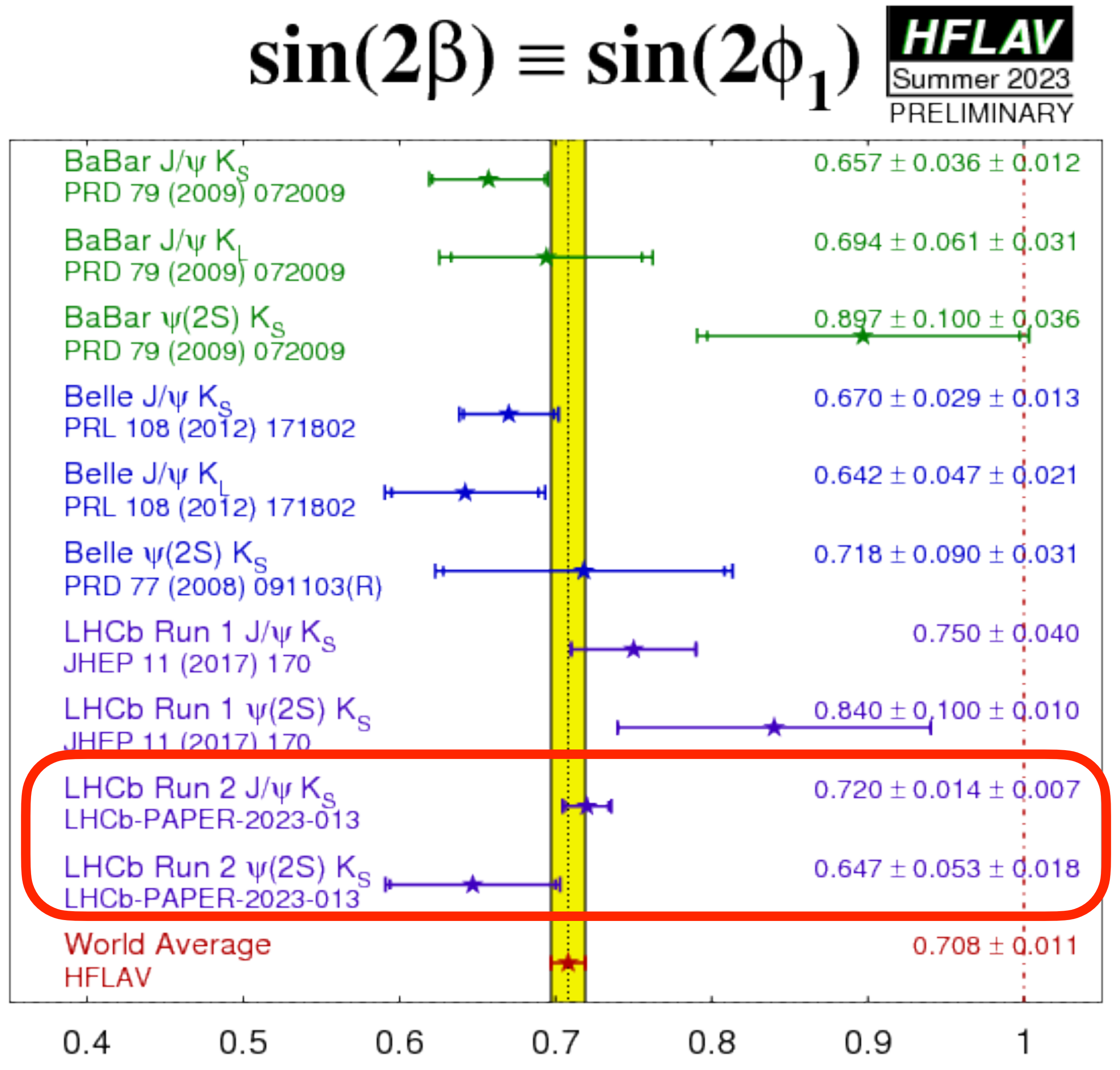


$\sin(2\beta) \neq 0 \Rightarrow$ ***CP* violation**



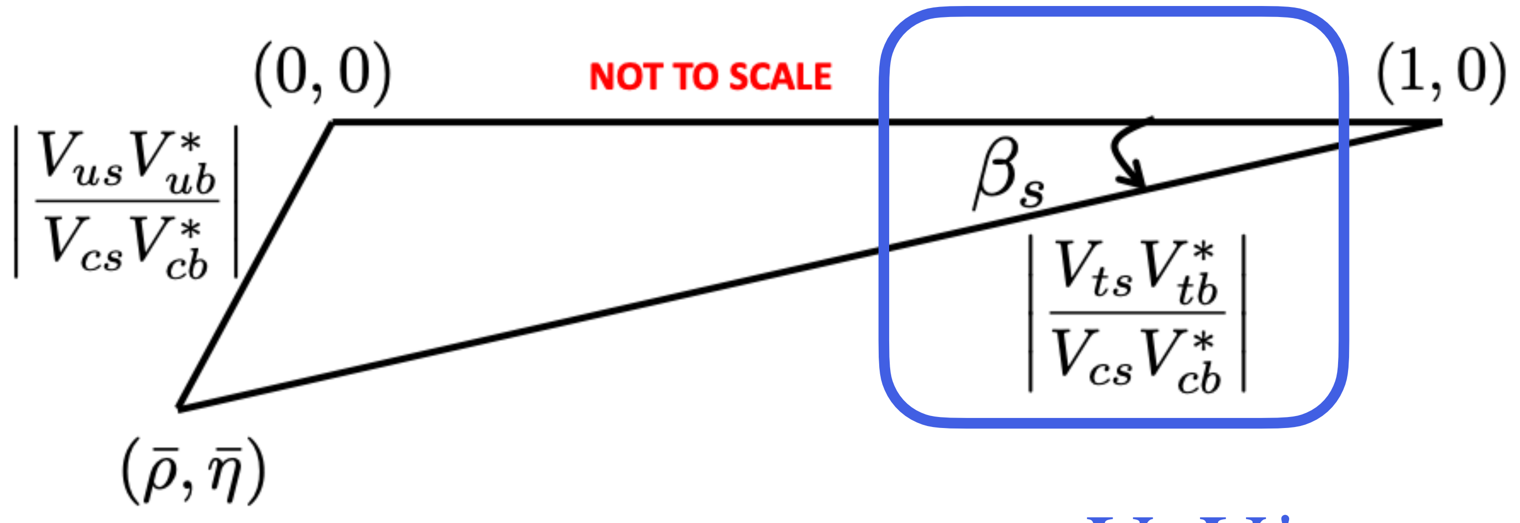


ϕ_s in $b \to c\bar{c}s$ transition

Phys. Rev. Lett. 132 (2024) 051802

- SM predicts: $\phi_s^{CKMFitter} \approx -2\beta_s = (-0.0368^{+0.0006}_{-0.0009})$ rad
  - Highly suppressed than in B^0 system (β ~22°)

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



$$\phi_s \approx -2\beta_s = 2arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$$

(ignoring penguin contribution)

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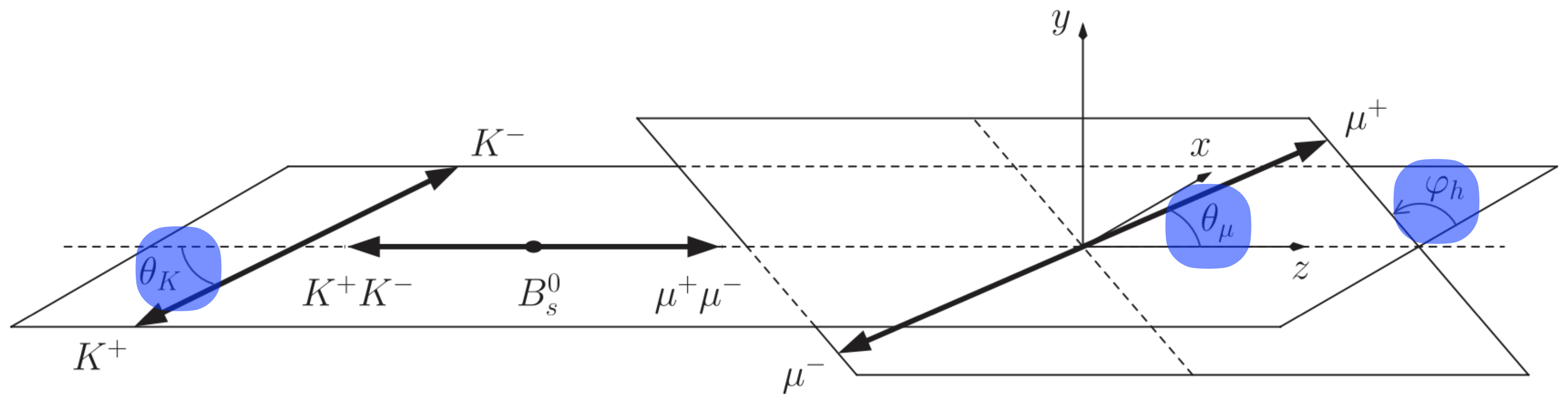
- Golden mode: $B_s^0 \to J/\psi\phi$

  (mix of CP-even & CP-odd)



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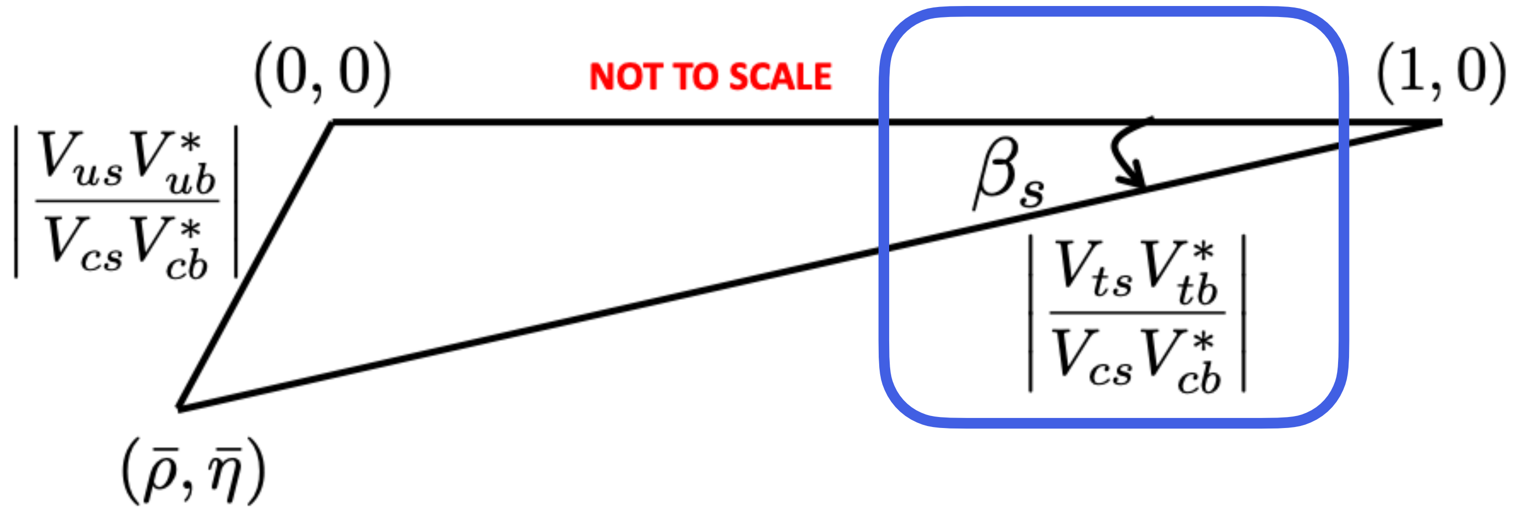

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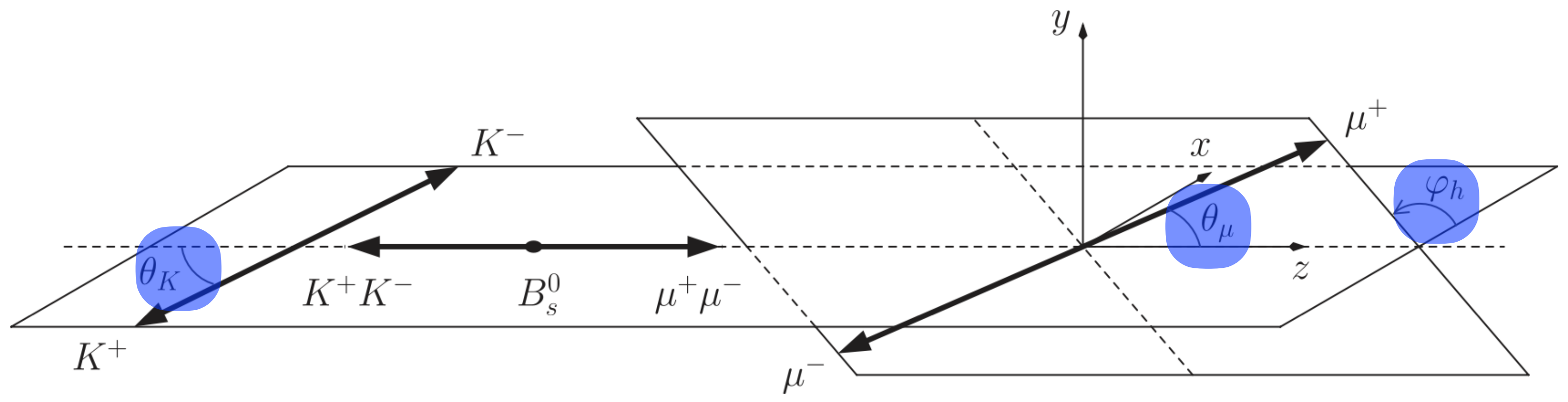

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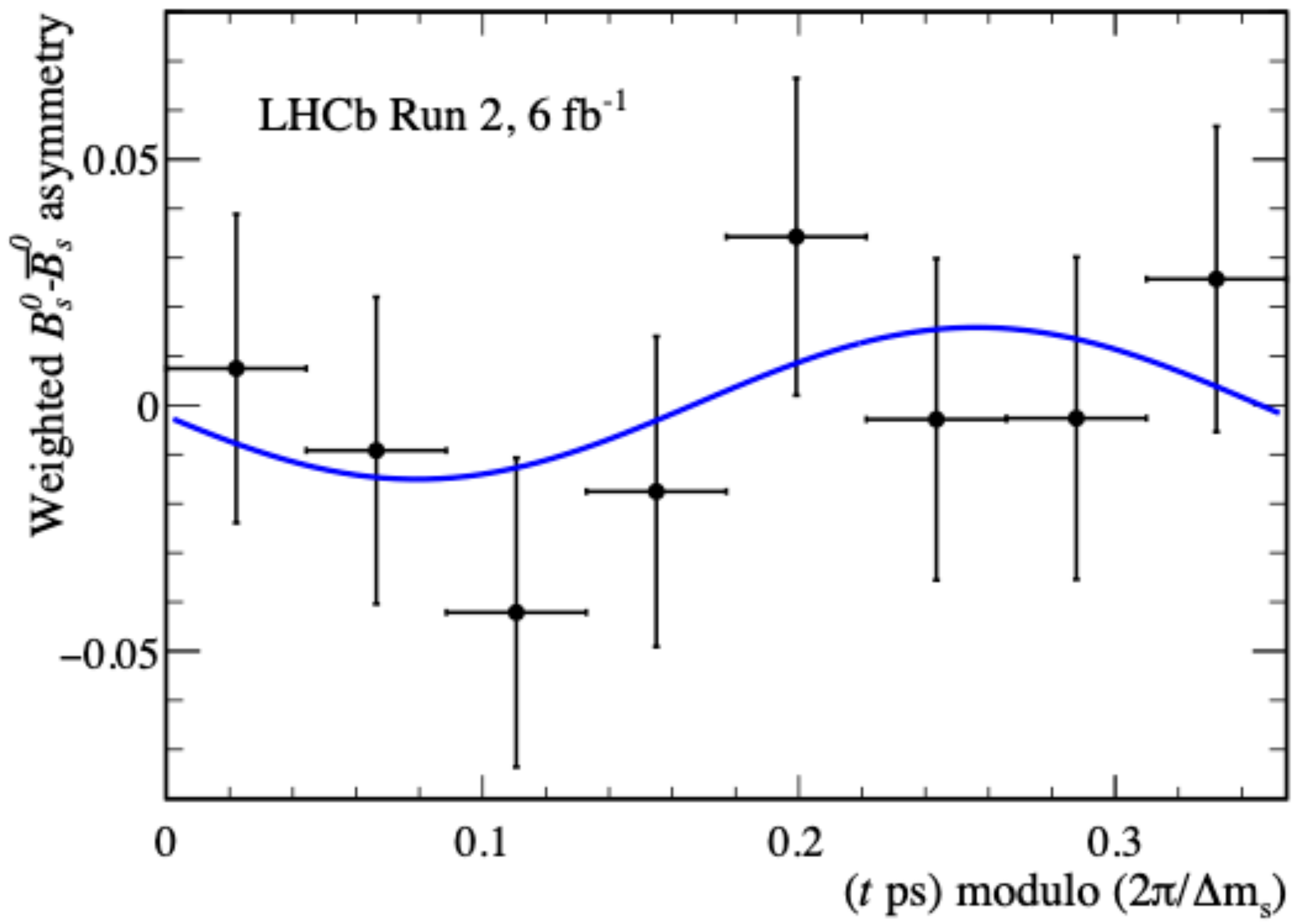
- World-best measurements, consistent with SM predictions
- Still statistical limited

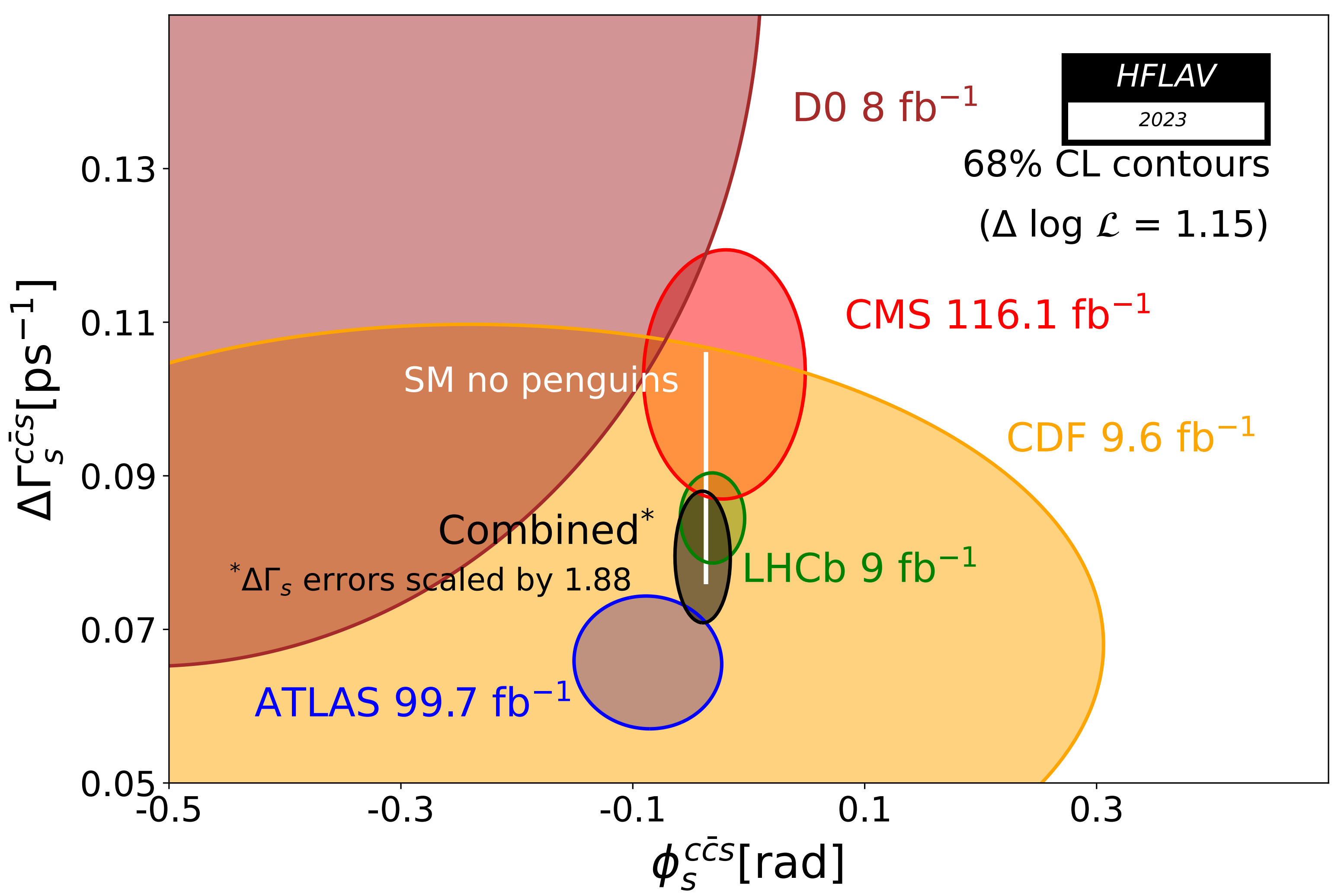
LHCb combination:

$\phi_s^{c\bar{c}s} = -0.031 \pm 0.018$ rad



New World Average: (↑ 16%)

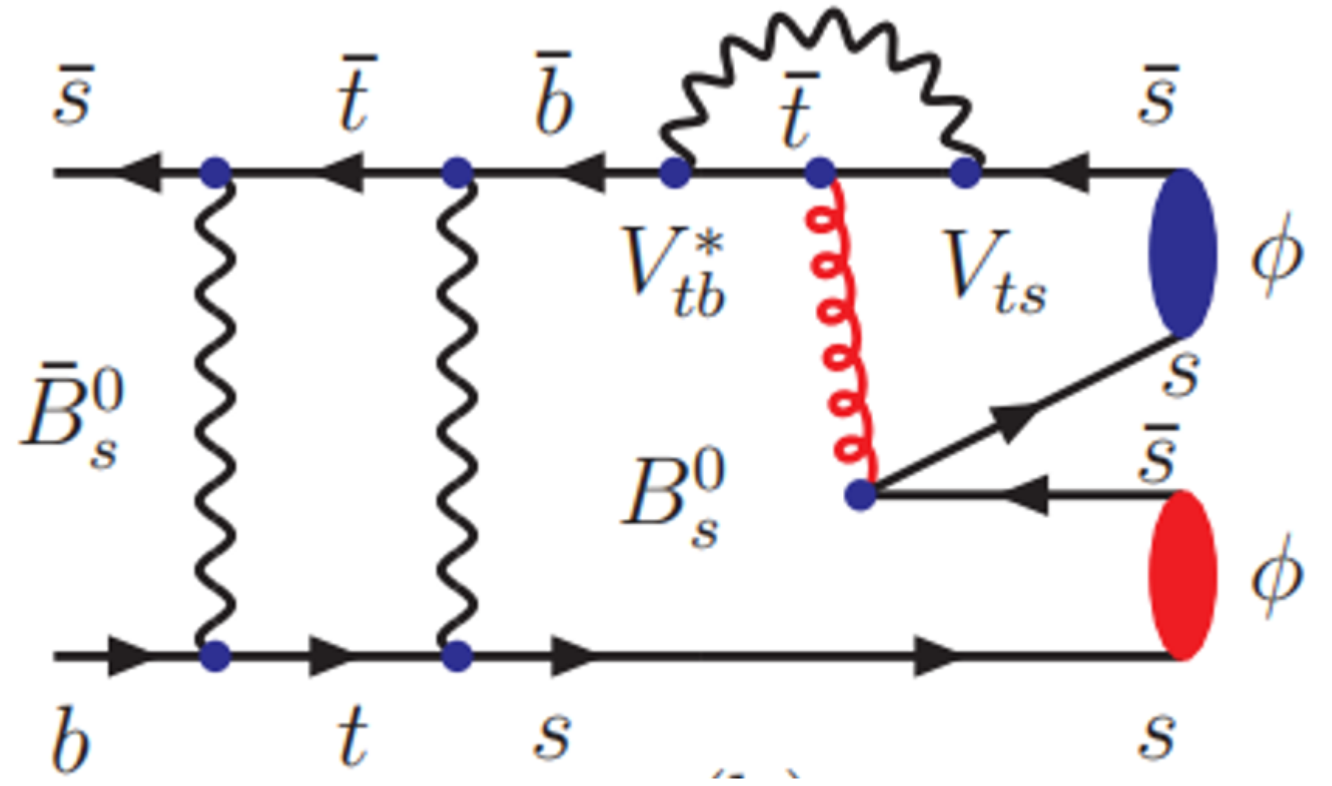
$\phi_s^{c\bar{c}s} = -0.050 \pm 0.016$ rad



ϕ_s in $b \to s\bar{s}s$ transition

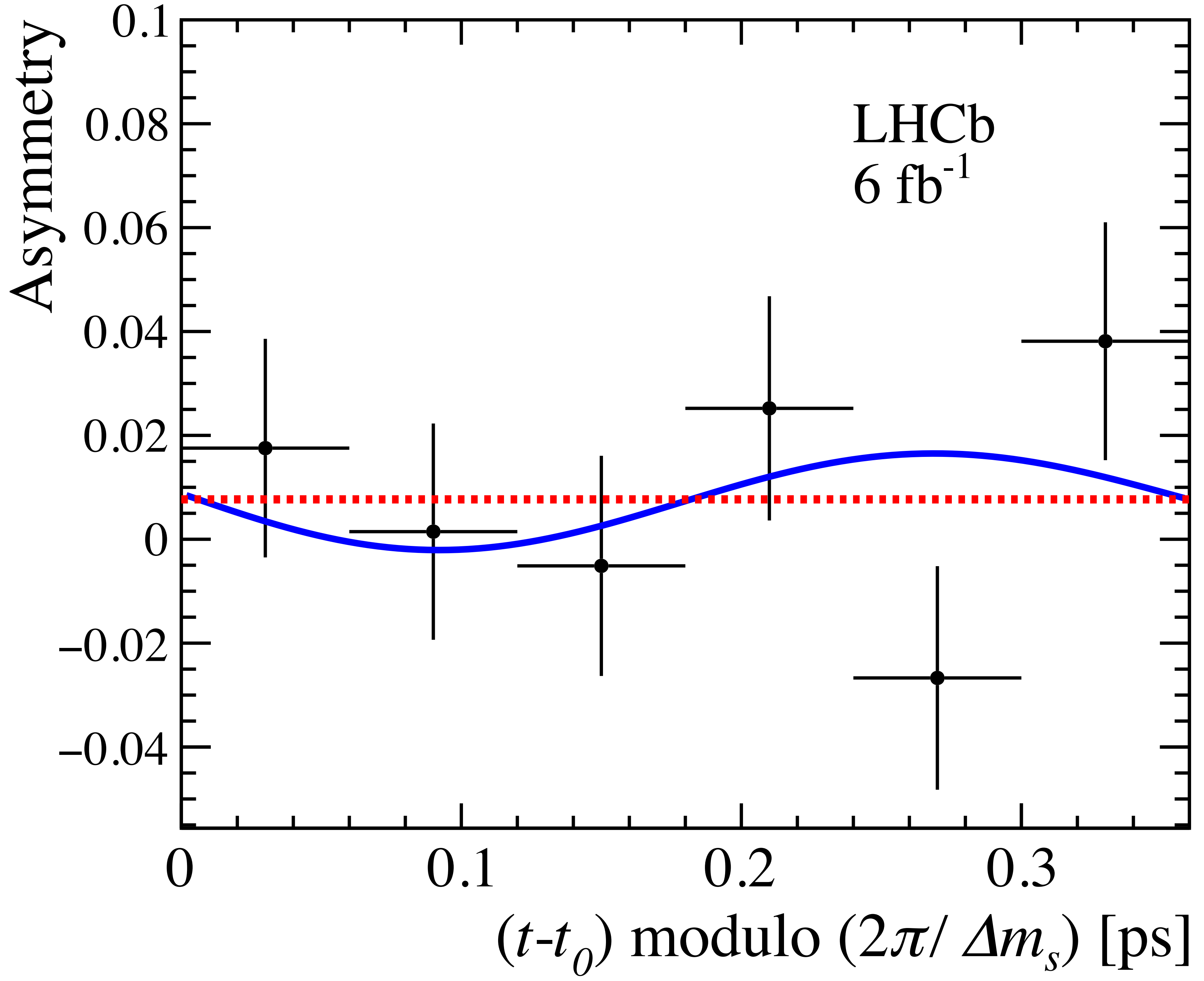
Phys. Rev. Lett.131 (2023) 171802

- Benchmark channel $B_s^0 \to \phi(KK)\phi(KK)$ proceeds via $b \to s\bar{s}s$ transition
  - Penguin dominated decay
  - NP contributes in penguin or mixing process



- Similar analysis strategy as $B_s^0 \to J/\psi\phi(KK)$

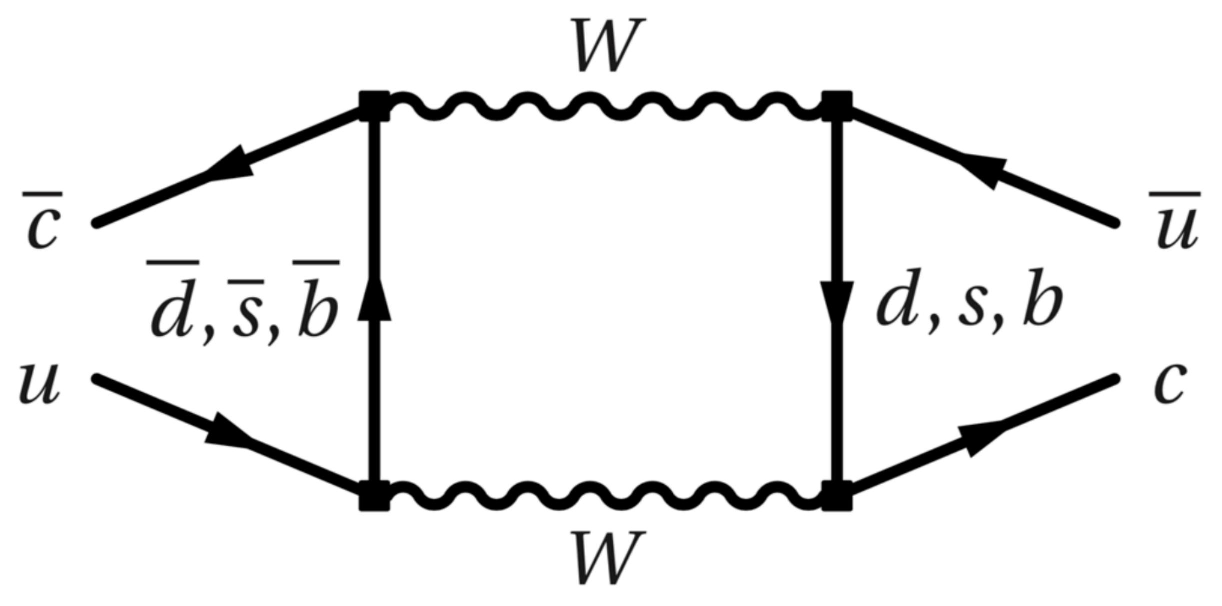
$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad},$$
$$|\lambda| = 1.004 \pm \pm 0.030 \pm 0.009$$

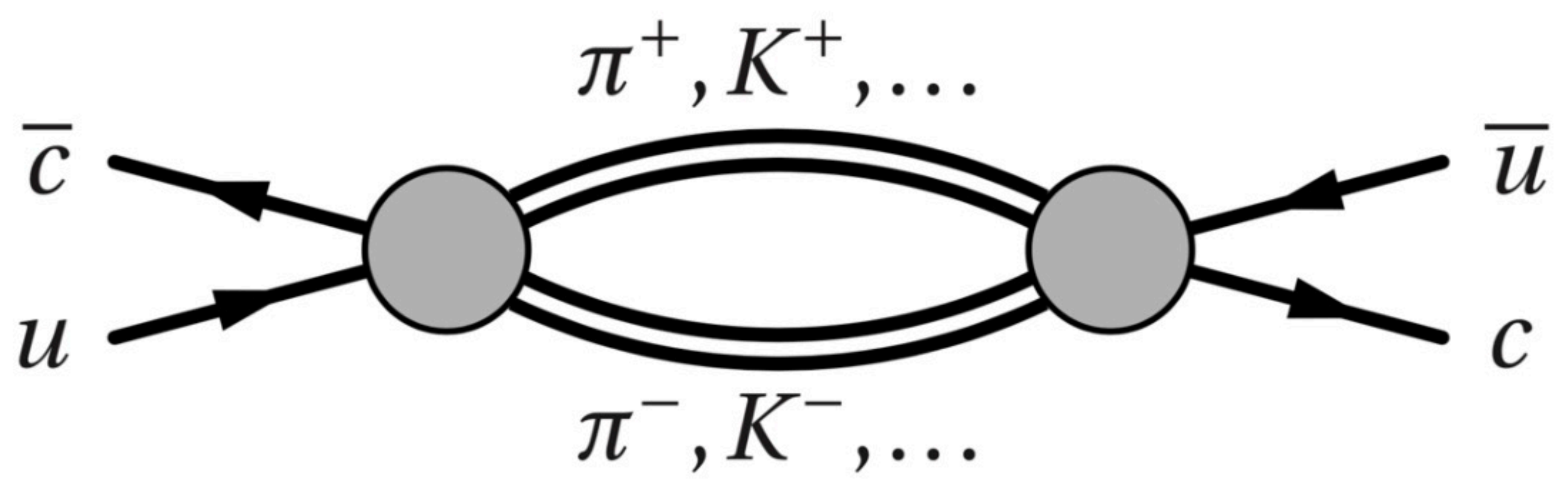


- The most precise measurement in any penguin dominated B decays
- No polarisation dependence is observed

CP violation in charm sector

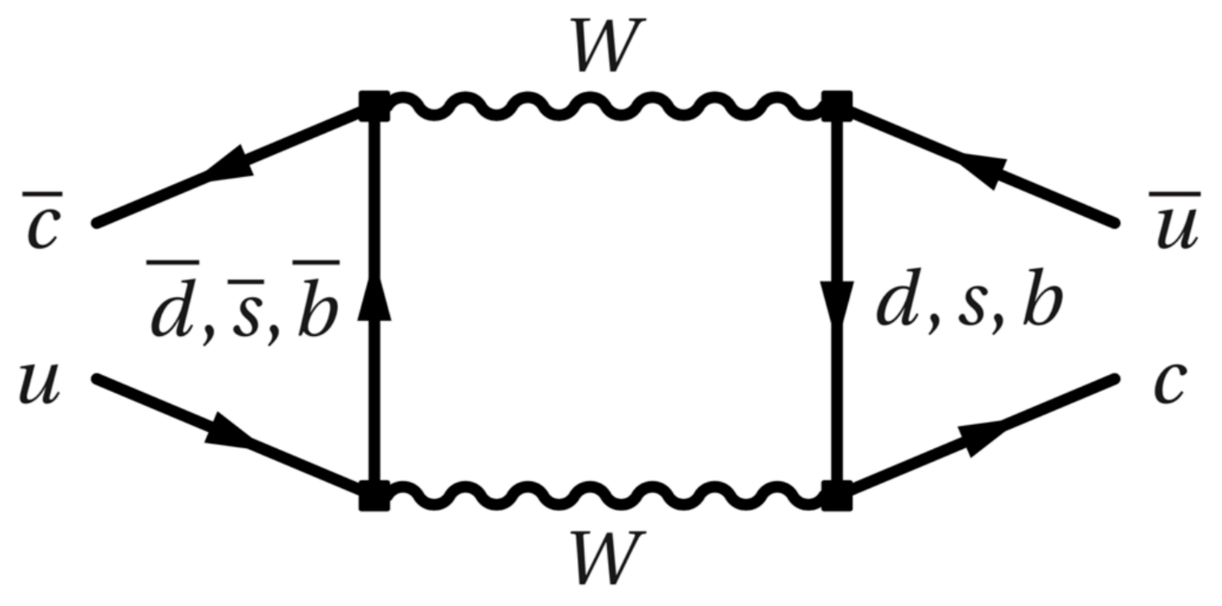
- GIM mechanism very effective for charm decays, SM loops highly suppressed
- Tiny weak phases in first two generations of CKM matrix (< λb~ 0.1%)
- Oscillation and CPV ($\leq 10^{-3}$)
- Long distance contribution comparable/larger than short distance

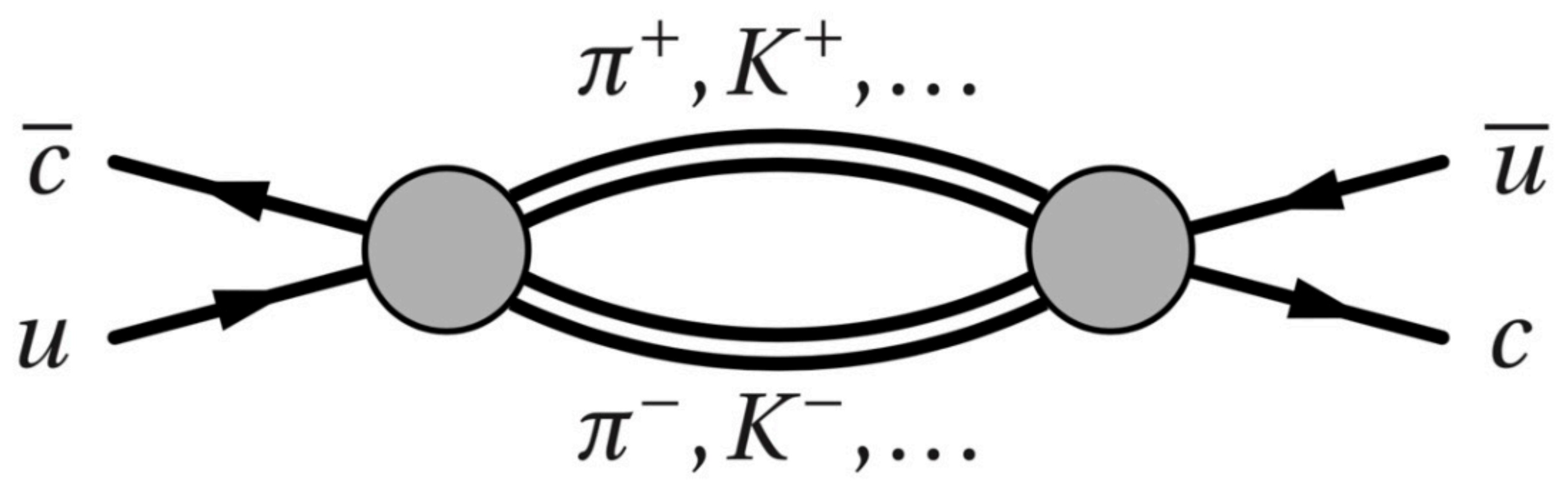




CP violation in charm sector

- GIM mechanism very effective for charm decays, SM loops highly suppressed
- Tiny weak phases in first two generations of CKM matrix (< λb~ 0.1%)
- Oscillation and CPV ($\leq 10^{-3}$)
- Long distance contribution comparable/larger than short distance





Breakthroughs by LHCb thanks to huge statistics:

First observation of CPV in $D^0 \to h^+h^-$ decays

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$ [PRL(2019)211803]

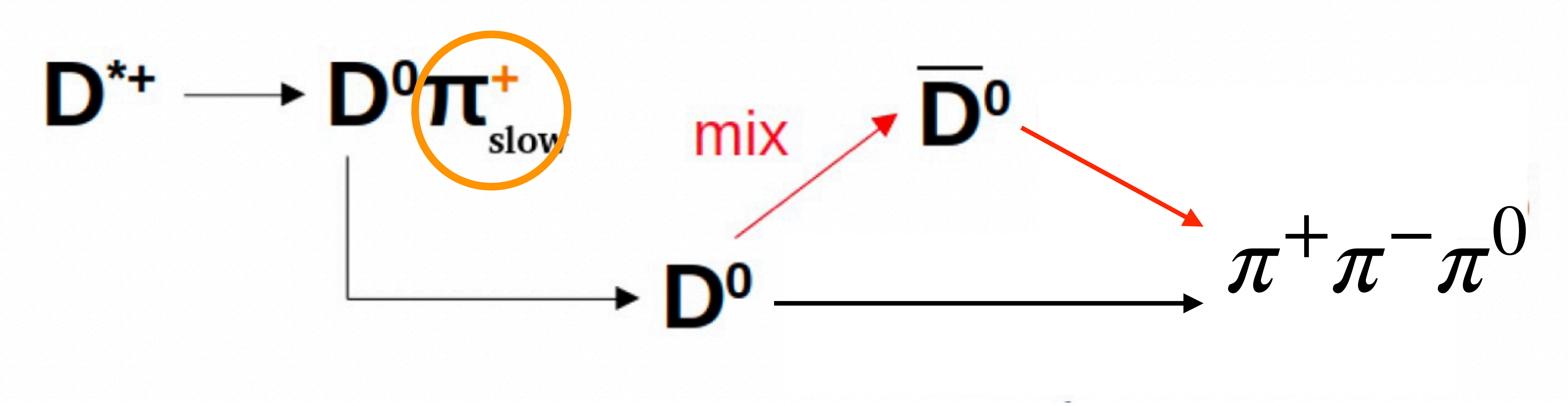
Evidence of CPV in $D^0 \to \pi^+\pi^-$ decay

$A_{CP}(\pi^+\pi^-) = (23.2 \pm 6.1)\times 10^{-4}\ (3.8\sigma)$ [PRL(2023)211803]

Time-dependent CP violation in $D^0 \to \pi^+\pi^-\pi^0$

arXiv:2405.06556

- First measurement of time-dependent CP violation in SCS mode



$$A_{CP}(f_{CP}, t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)}$$

$$\approx a^{\mathrm{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}}.$$

$$A_{\mathrm{meas}}(\langle t/\tau_{D^0}\rangle_i) \equiv \frac{N^i_{D^0} - N^i_{\bar{D}^0}}{N^i_{D^0} + N^i_{\bar{D}^0}}$$

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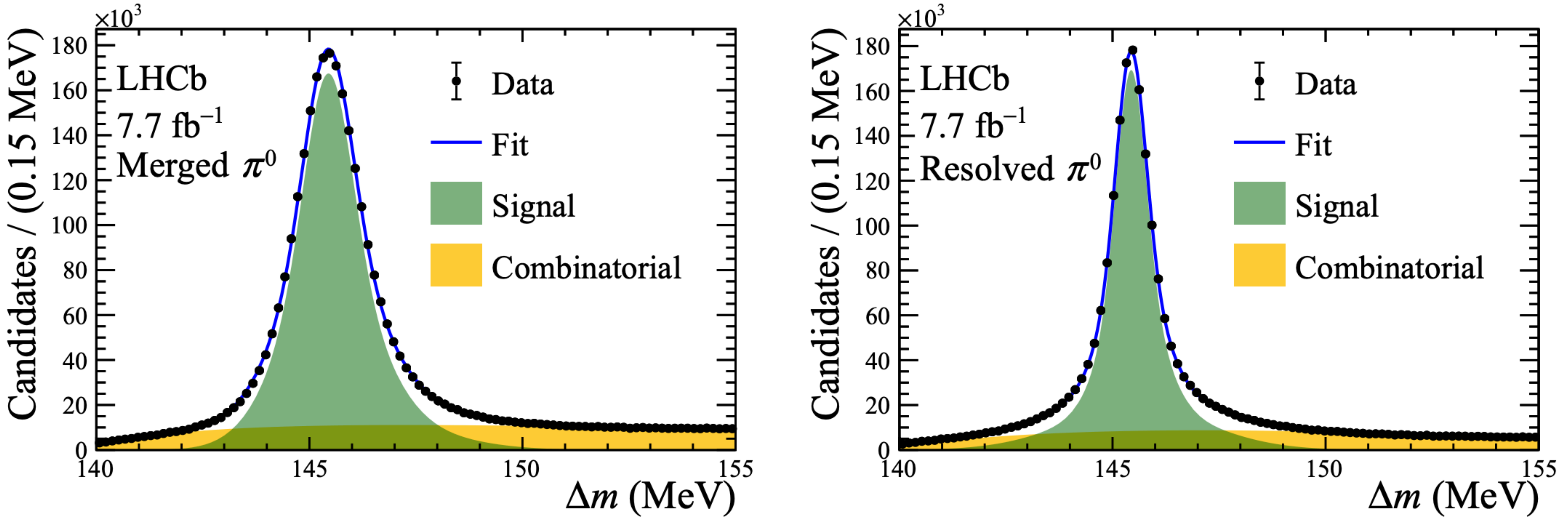

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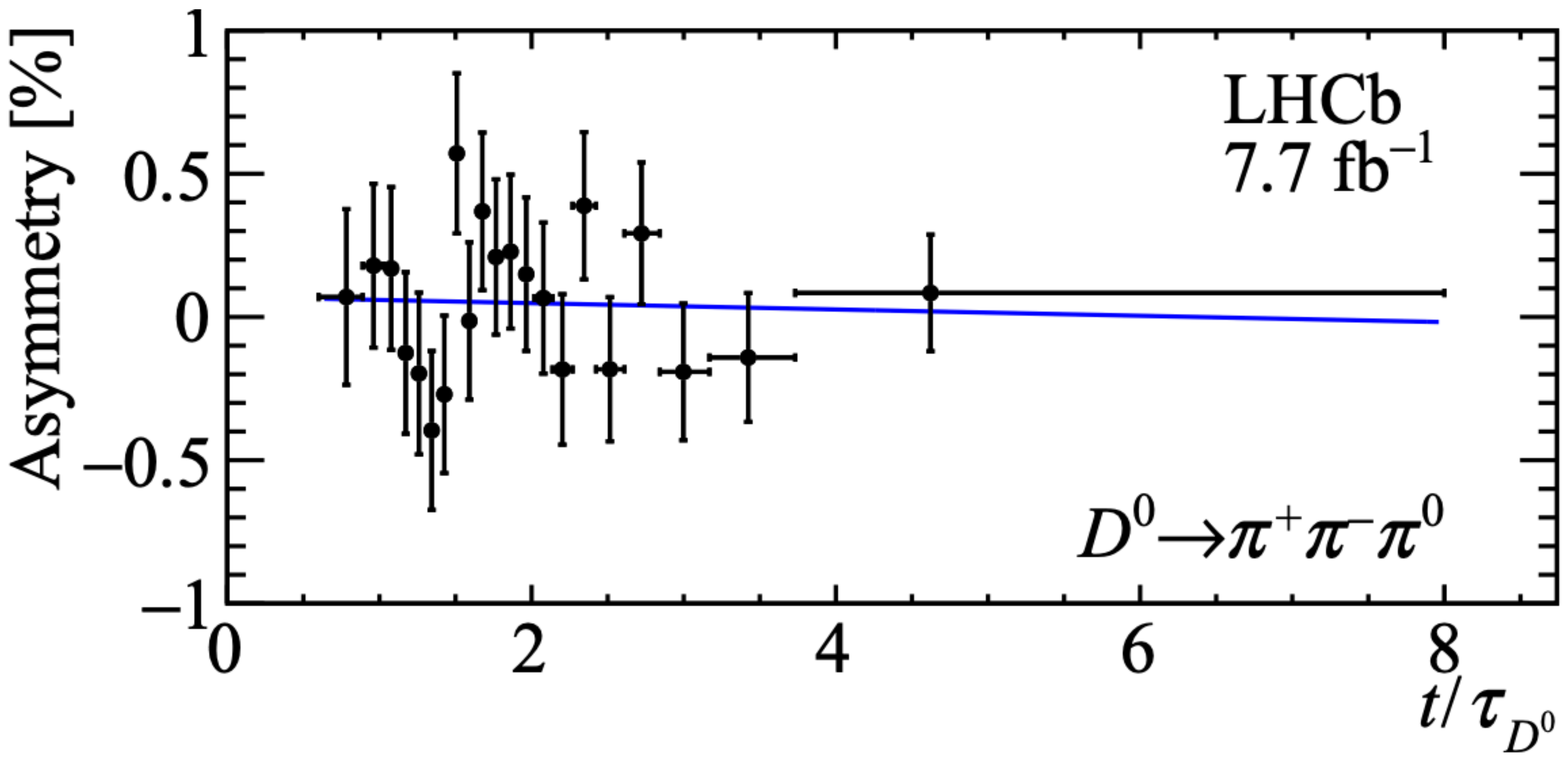


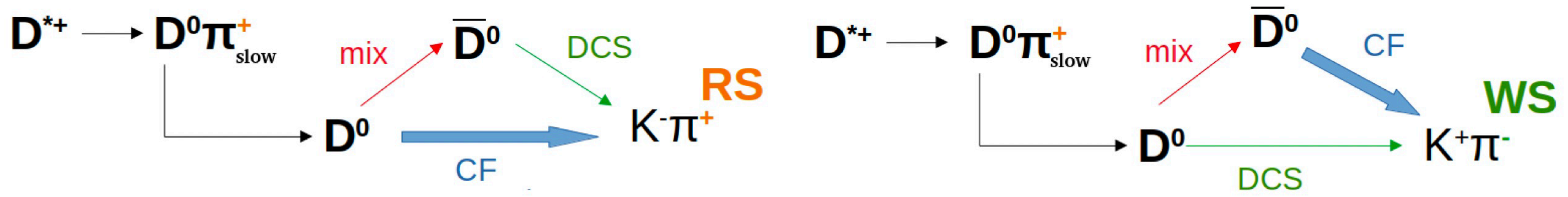
$$\Delta Y_{f_{CP}} \approx \frac{\eta_{f_{CP}}}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi\right]$$

- No evidence for time-dependent CP violation, constant with world average

$$\Delta Y \equiv \eta_{CP}\Delta Y_{f_{CP}} = (-1.3 \pm 6.3 \pm 2.4)\times 10^{-4}$$

Time-dependent CP violation in $D^0 \to K\pi$

- Interference between mixing and decay for favoured RS and suppressed WS decays



$$R^{+}_{K\pi} = \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D^0} \to K^-\pi^+)}; \quad R^{-}_{K\pi} = \frac{\Gamma(\overline{D^0}(t) \to K^-\pi^+)}{\Gamma(D^0 \to K^+\pi^-)};$$

DCS over CF amplitude

$$R^{\pm}_{K\pi}(t) \approx \boxed{R_{K\pi}}(1 \pm A_{K\pi}) + R_{K\pi}(1 \pm A_{K\pi})(c_{K\pi} \pm \Delta c_{K\pi})\left(\frac{t}{\tau_{D^0}}\right) + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

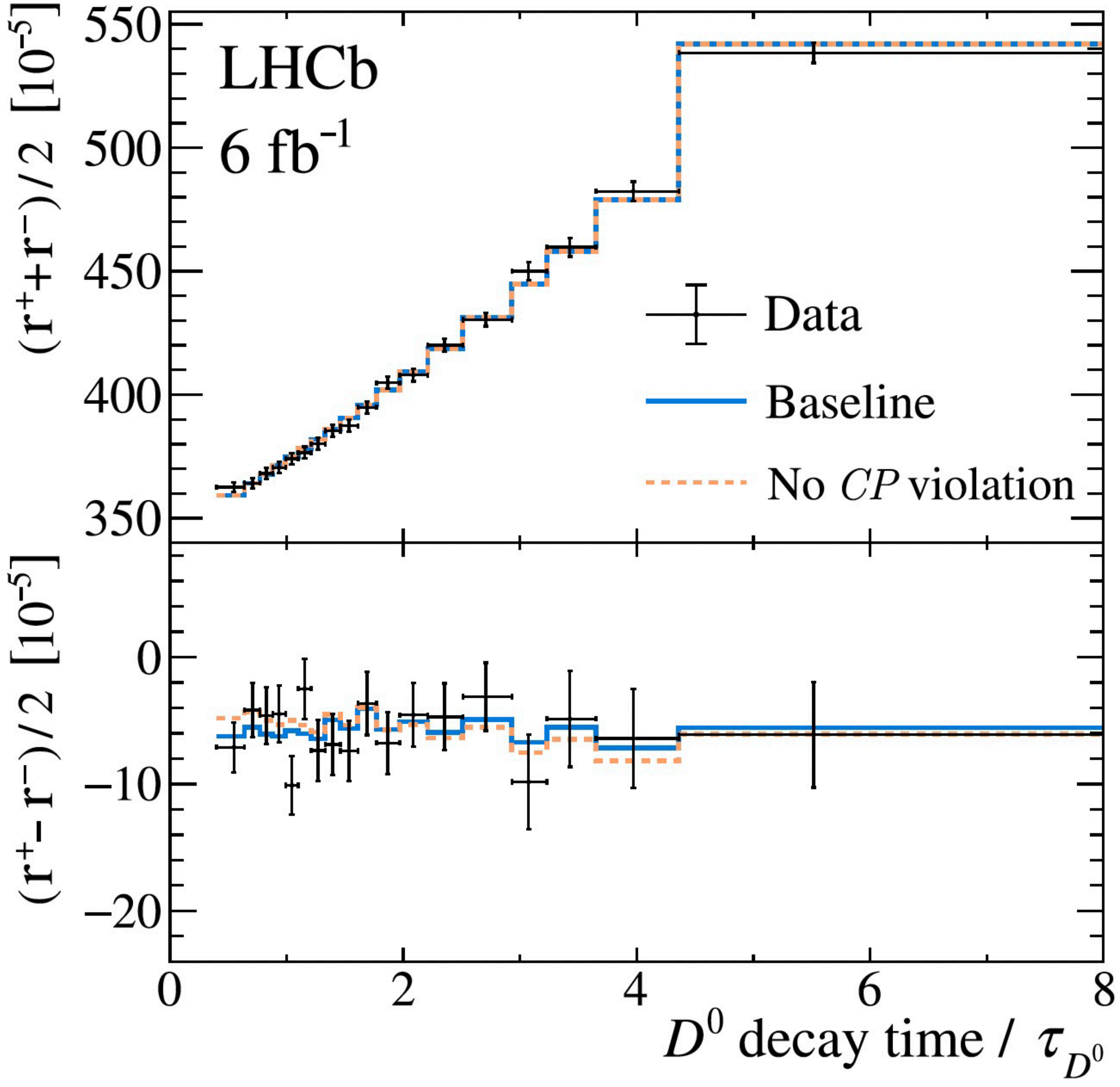
CPV observables: $A_{K\pi}$ (in decays), $\Delta c_{K\pi}$ (in interference), $\Delta c'_{K\pi}$ (in mixing).

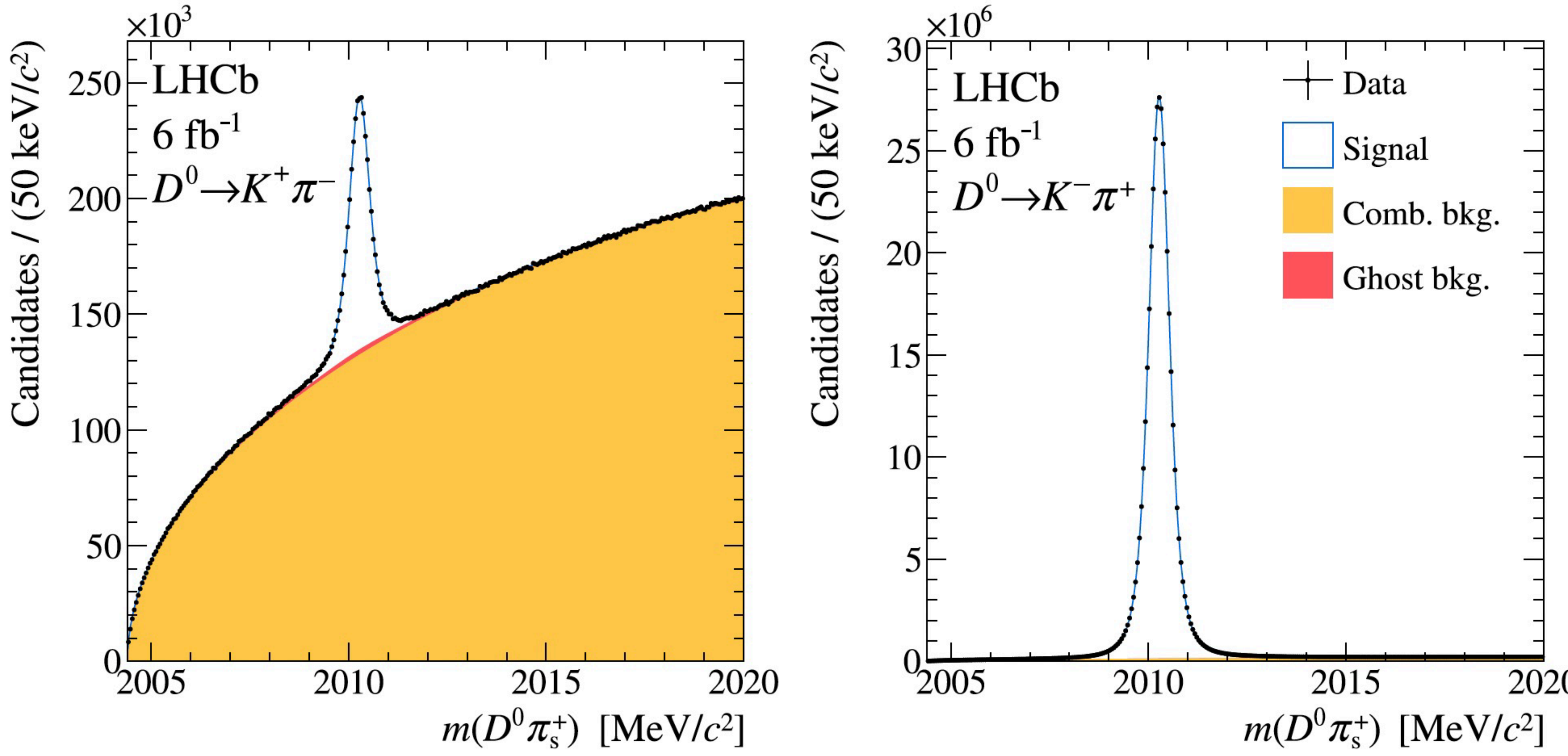
Mixing observables: $c_{K\pi}$, $c'_{K\pi}$

Time-dependent CP violation in $D^0 \to K\pi$

arXiv:2407.18001

- Measured with yields: RS ~400 M, WS ~1.6 M





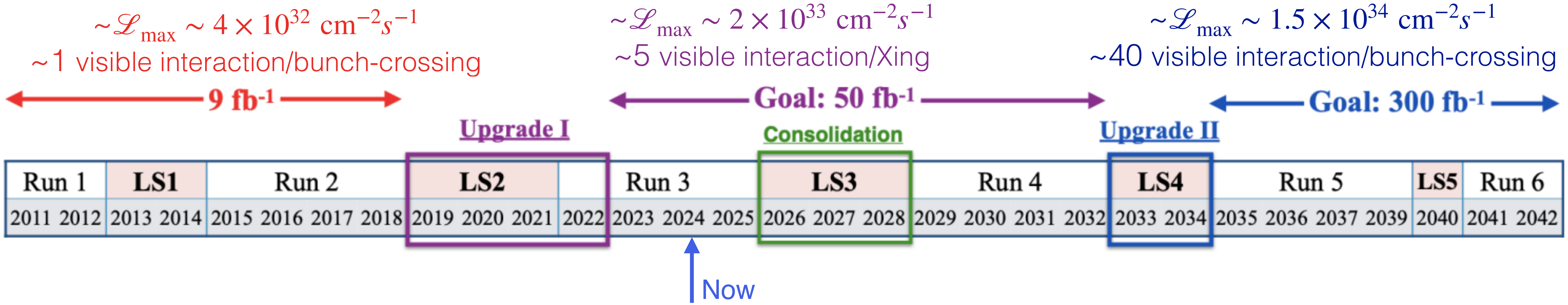
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

Mixing parameter
Evidence of non 0

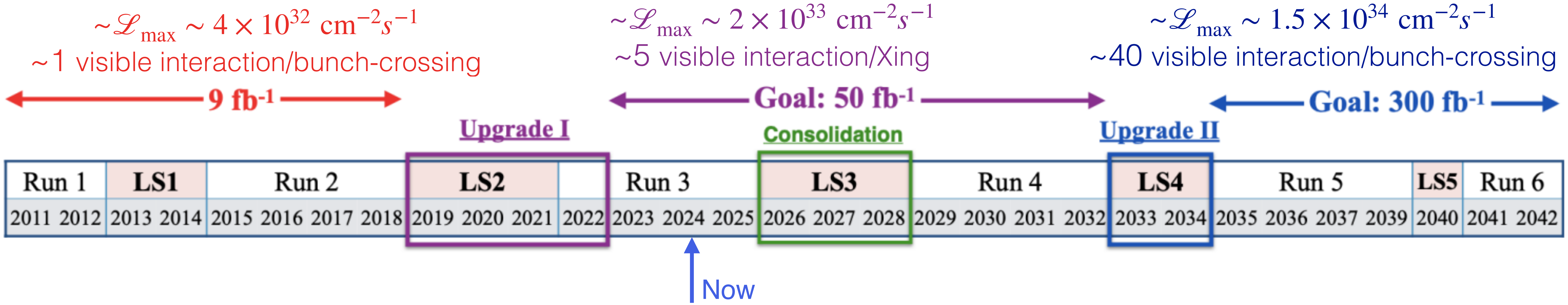
No CPV

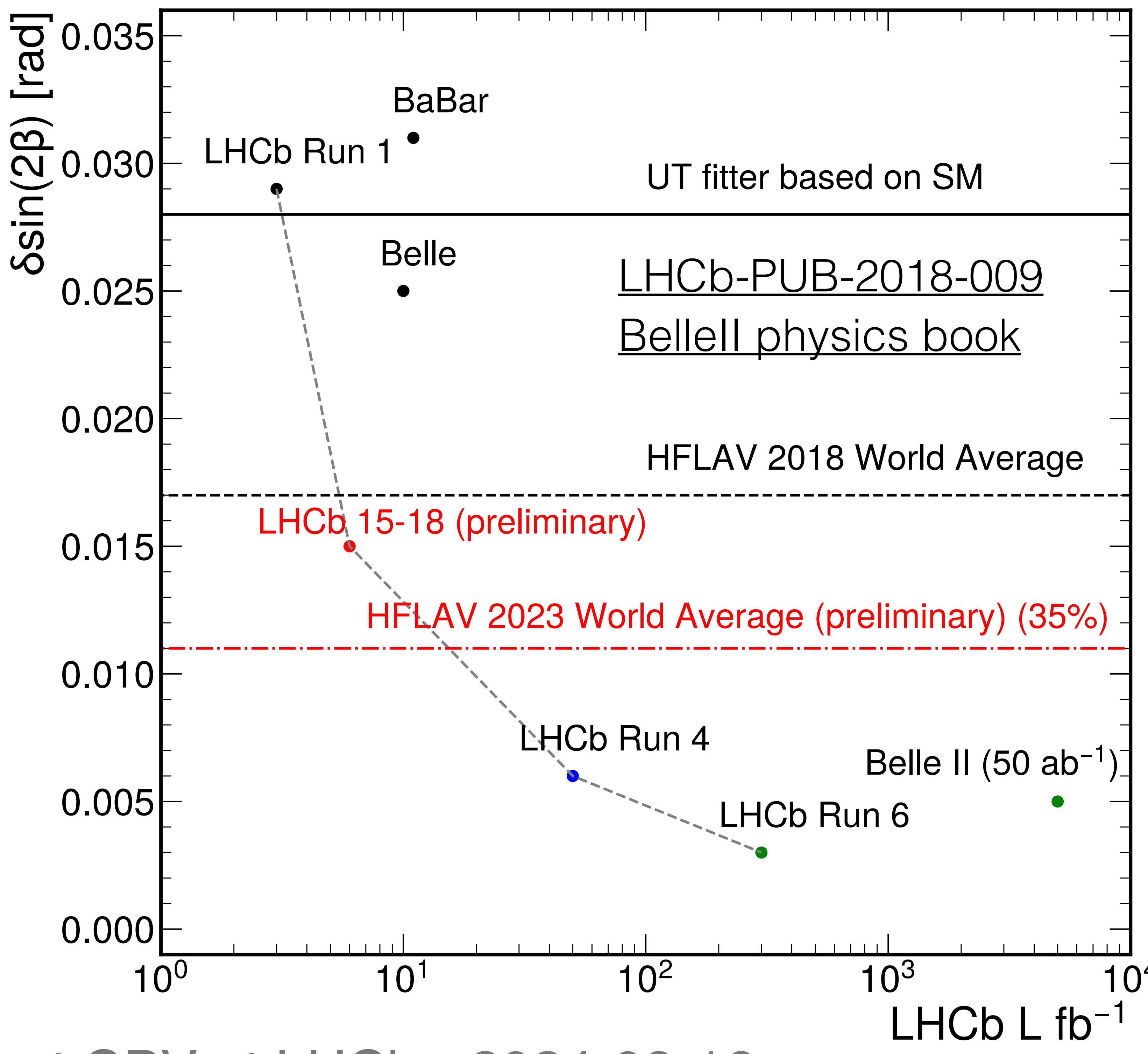
$$c_{K\pi} \approx y_{12} \cos \phi_f^\Gamma \cos \Delta_f + x_{12} \cos \phi_f^M \sin \Delta_f$$

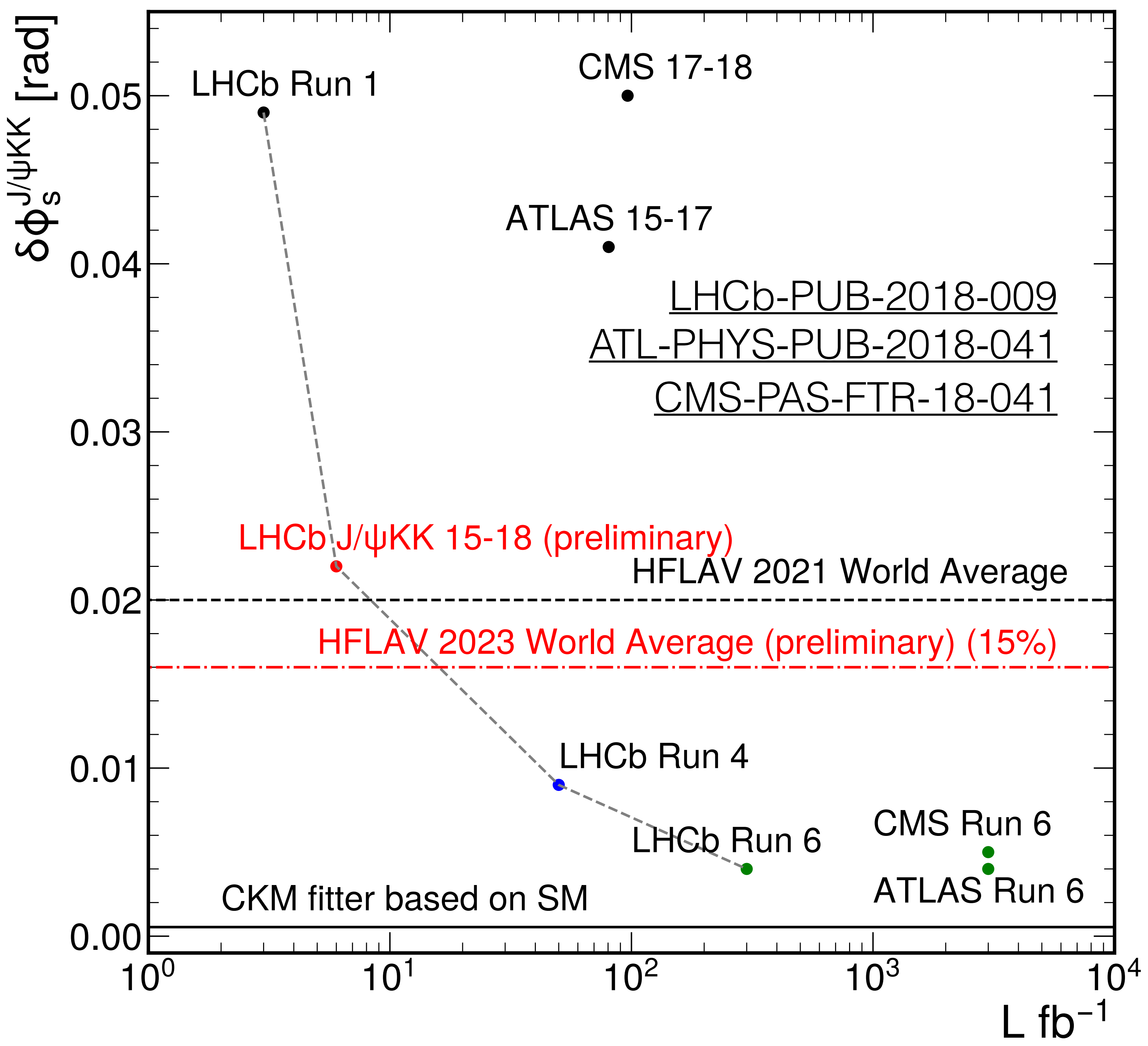
Looking at Run 3 and beyond



Looking at Run 3 and beyond

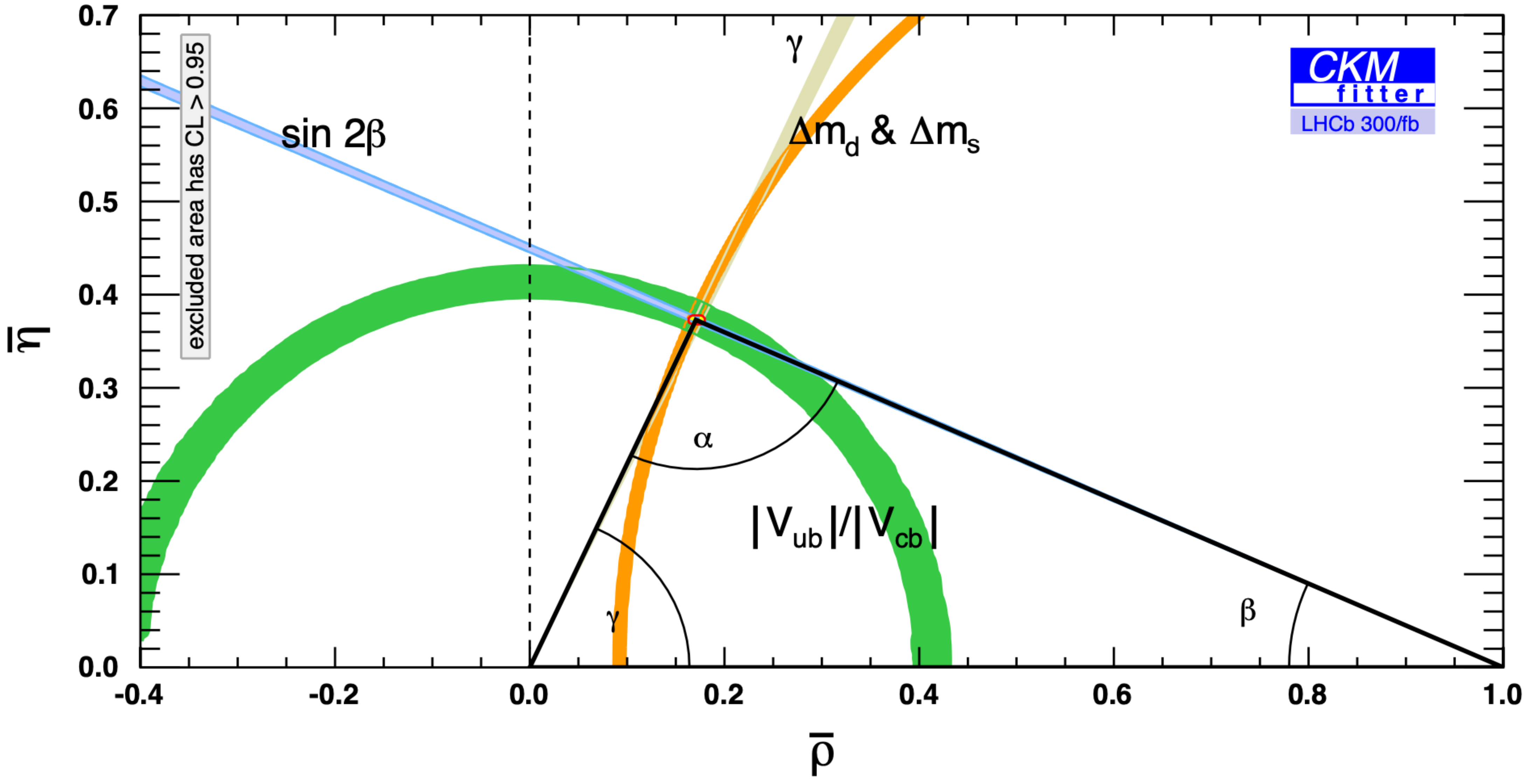


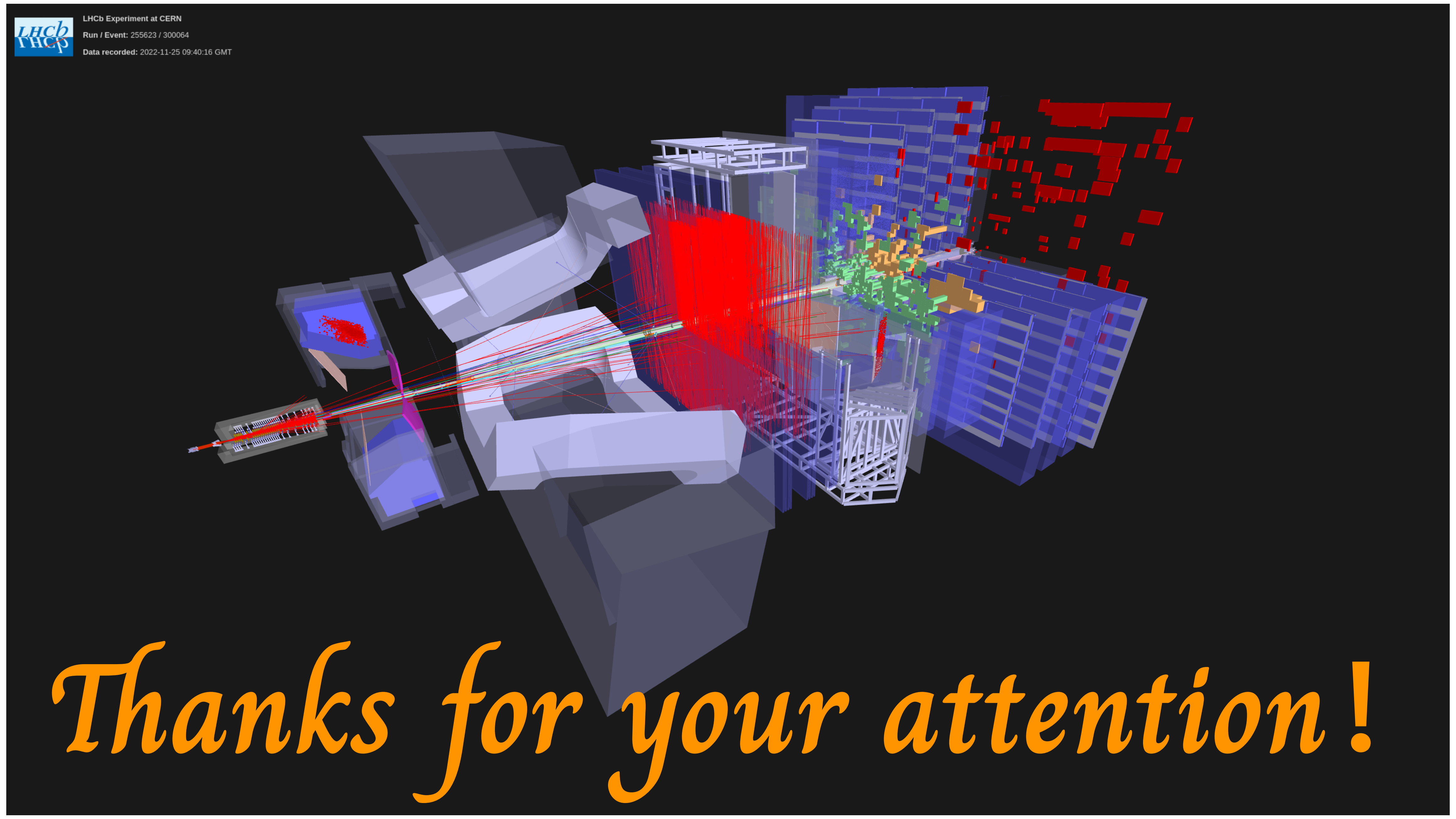




Summary

- ✓ LHCb dominates the world average of many measurements in CKM and CPV
- ✓ Flag-ship time-dependent measurement of CP violation in $B^0_{(s)}$ and D^0 decays with full LHCb data sample, providing the most precise results
- ✓ Run 3 is running, looking forward to further test of the SM and search for new physics



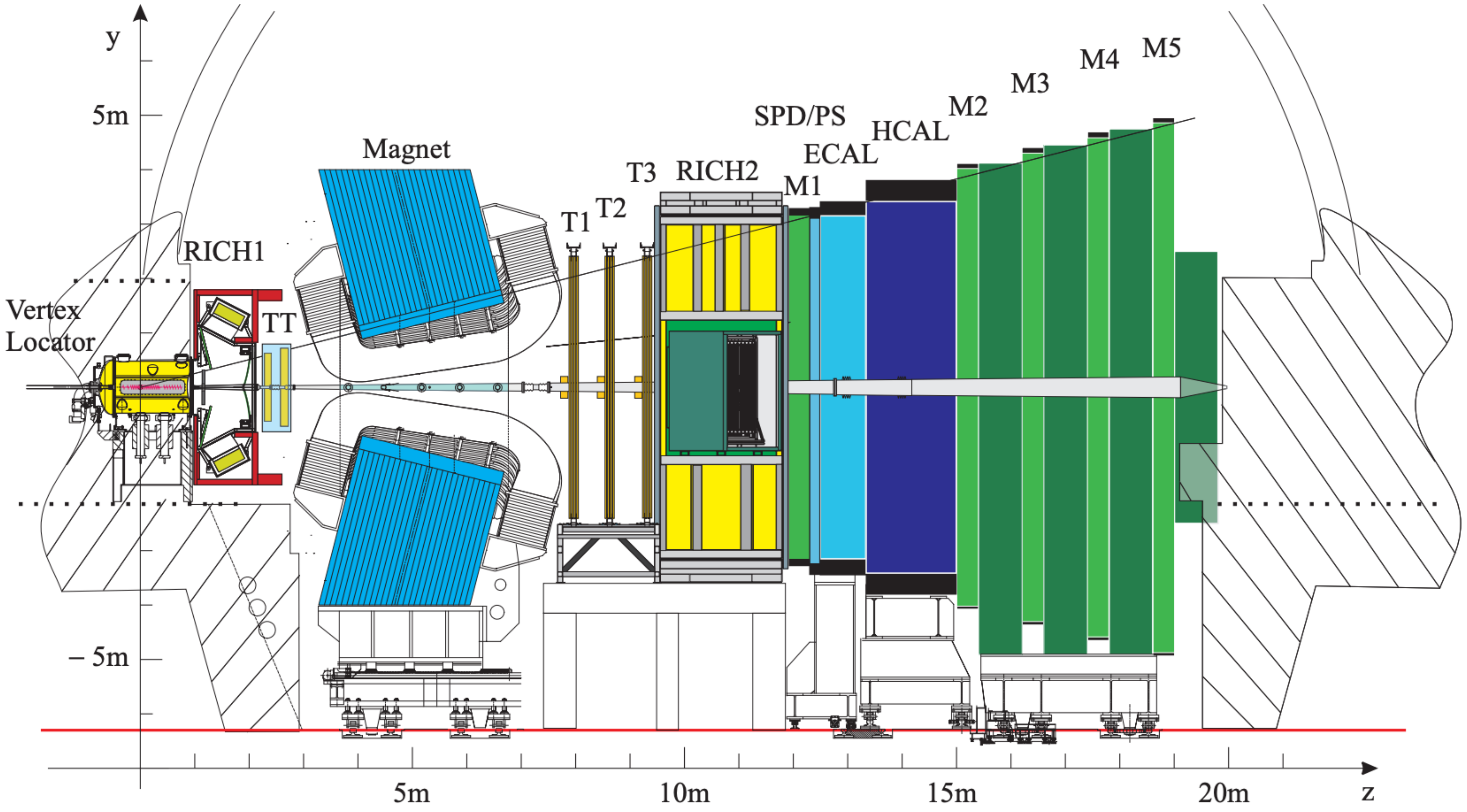


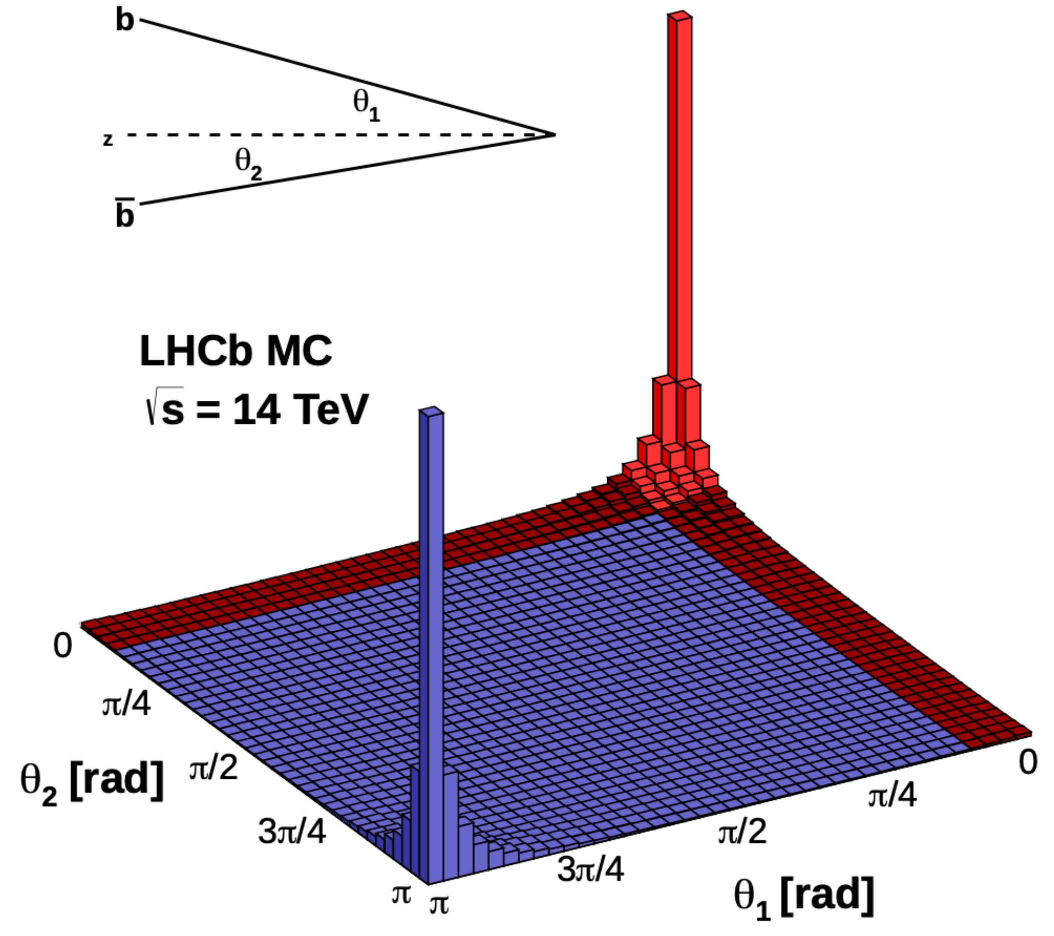
Back up slides

LHCb detector

General purpose detector specialised in beauty and charm hadrons

proton beam





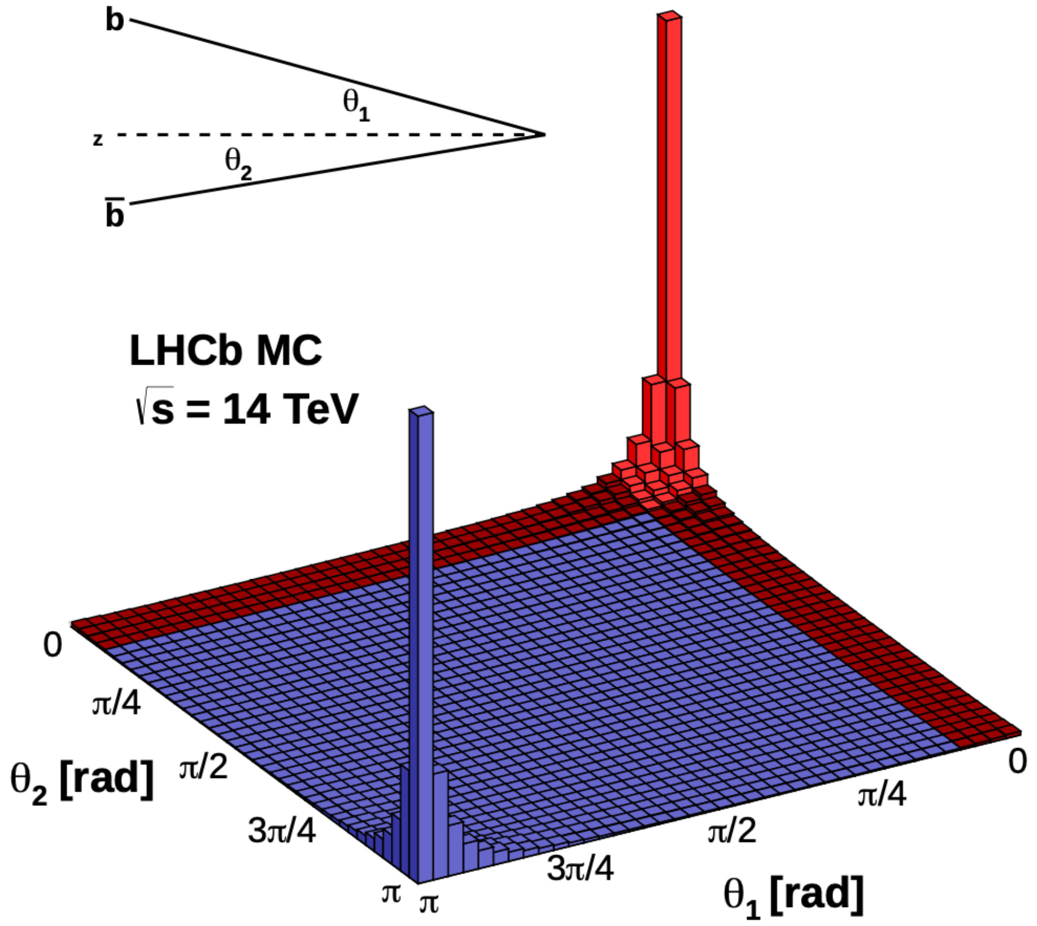
$2 < \eta < 5$

LHCb performance:
JINST 14 (2019) P04013

LHCb detector

General purpose detector specialised in beauty and charm hadrons

- Daughters of b & c hadron decays: $p_T \sim \mathcal{O}(1\ \mathrm{GeV}/c)$, flight distance L~1mm



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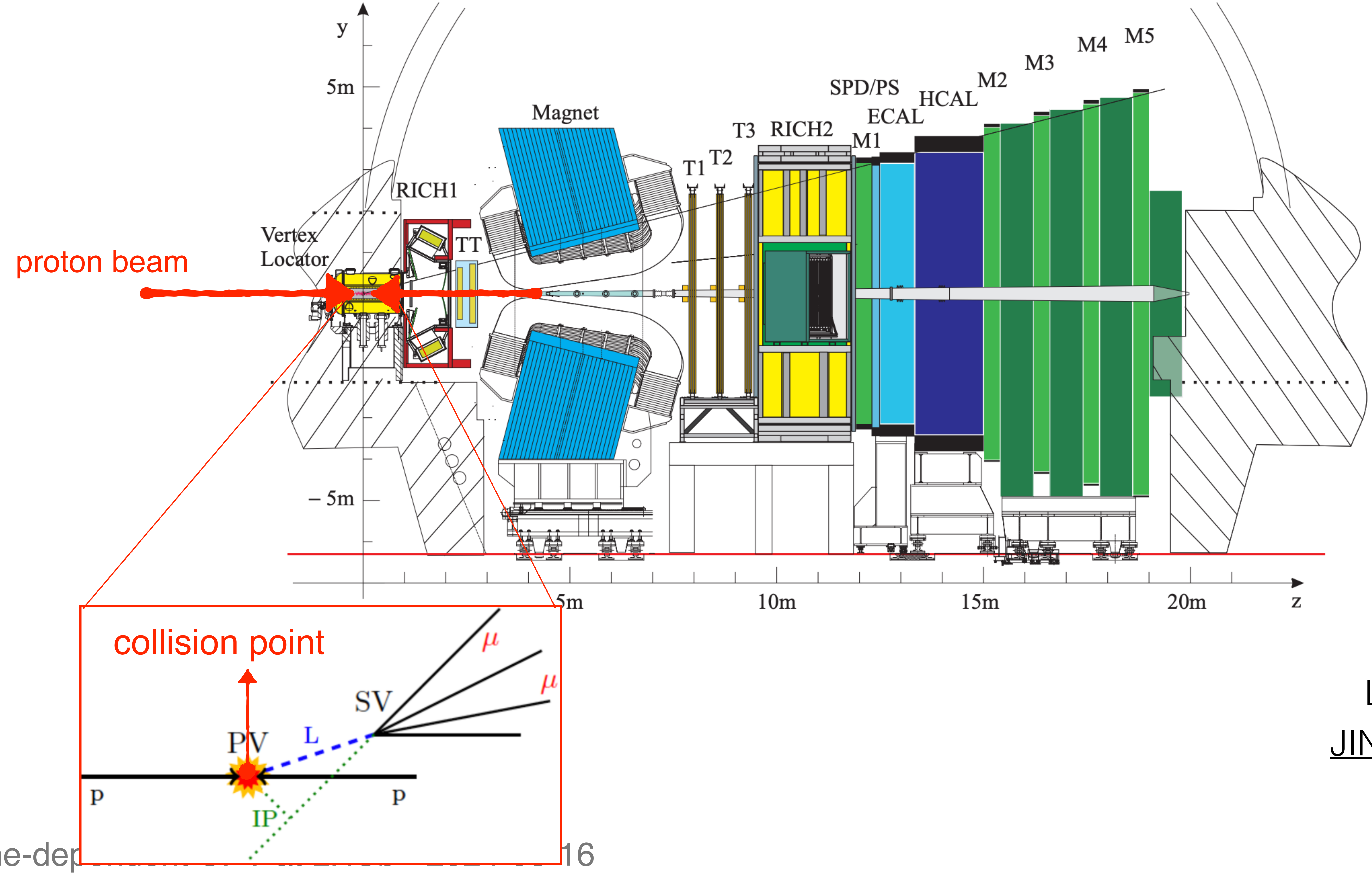

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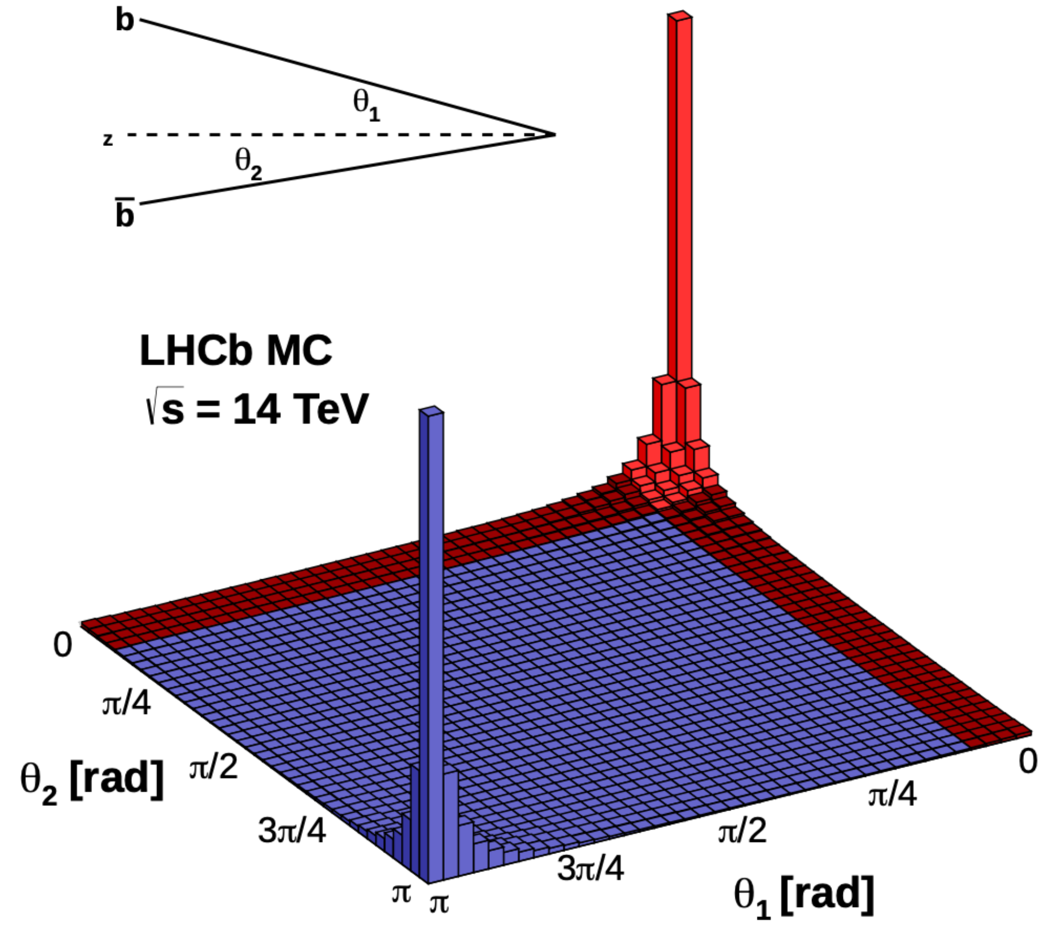

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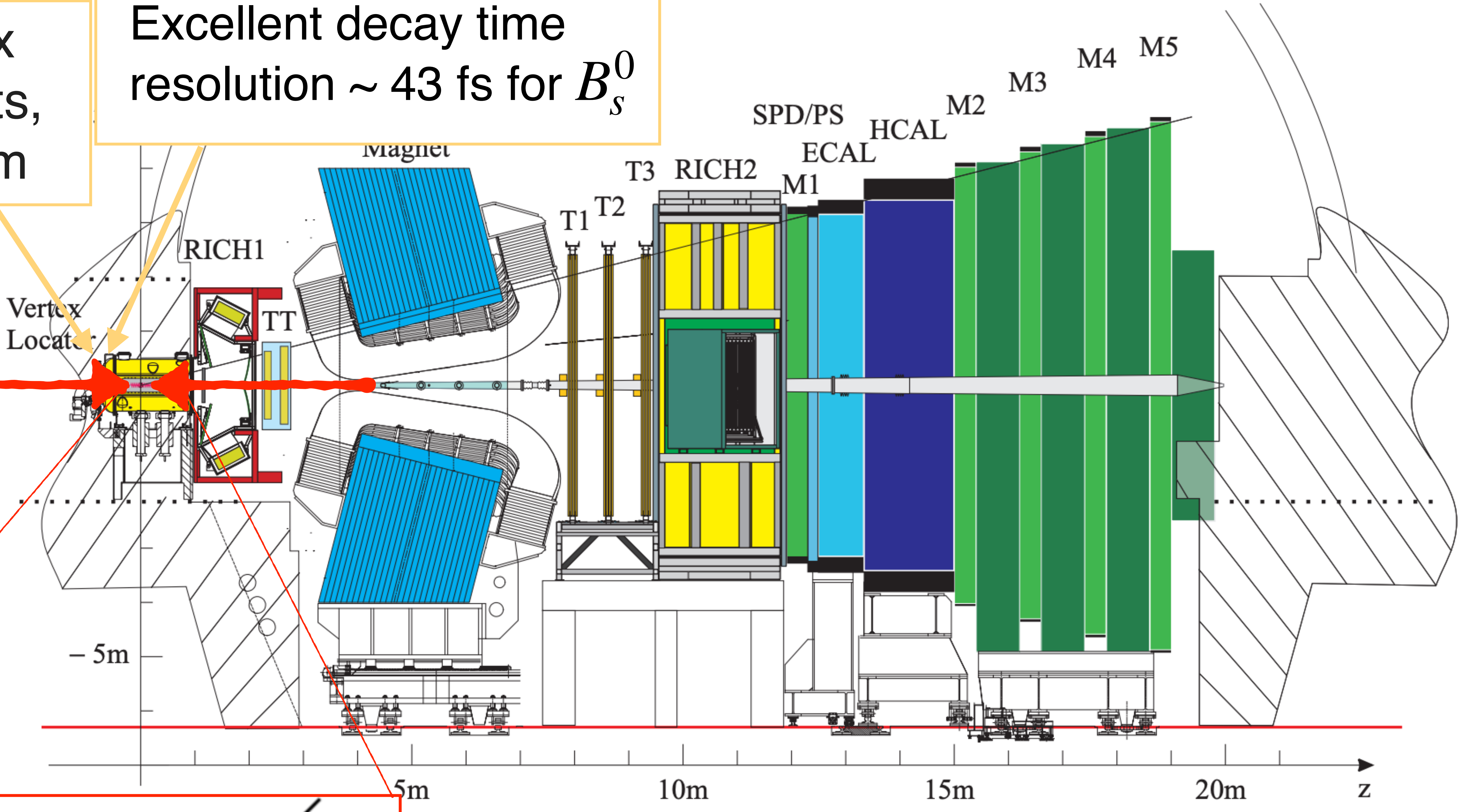
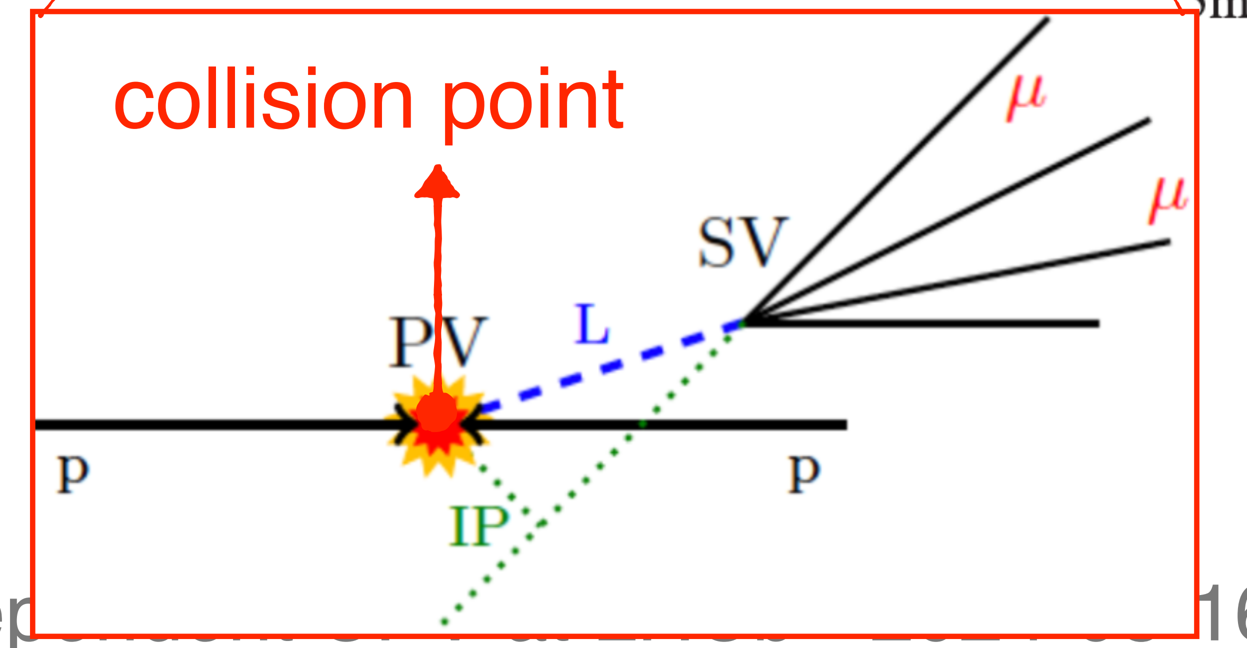
Precise vertex measurements, $\sigma(IP_x)$~ 35 μm

Excellent decay time resolution ~ 43 fs for B_s^0

proton beam





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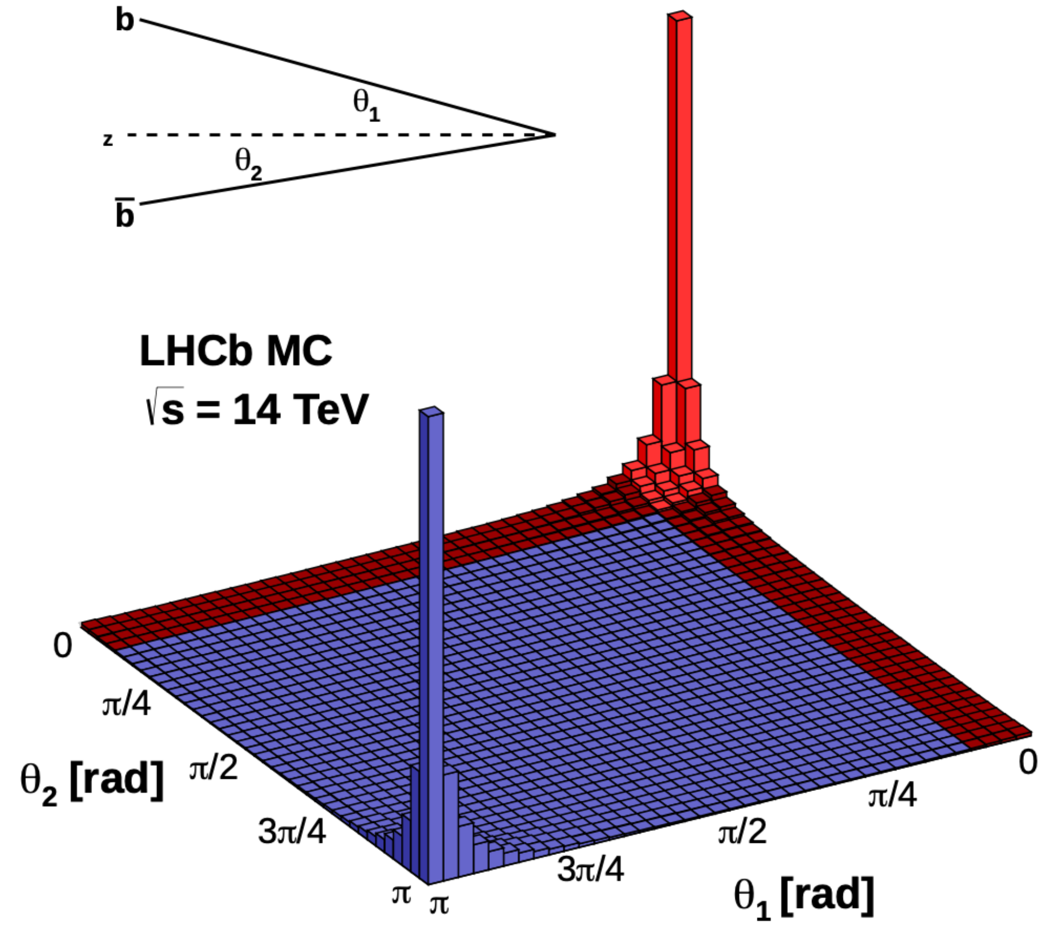

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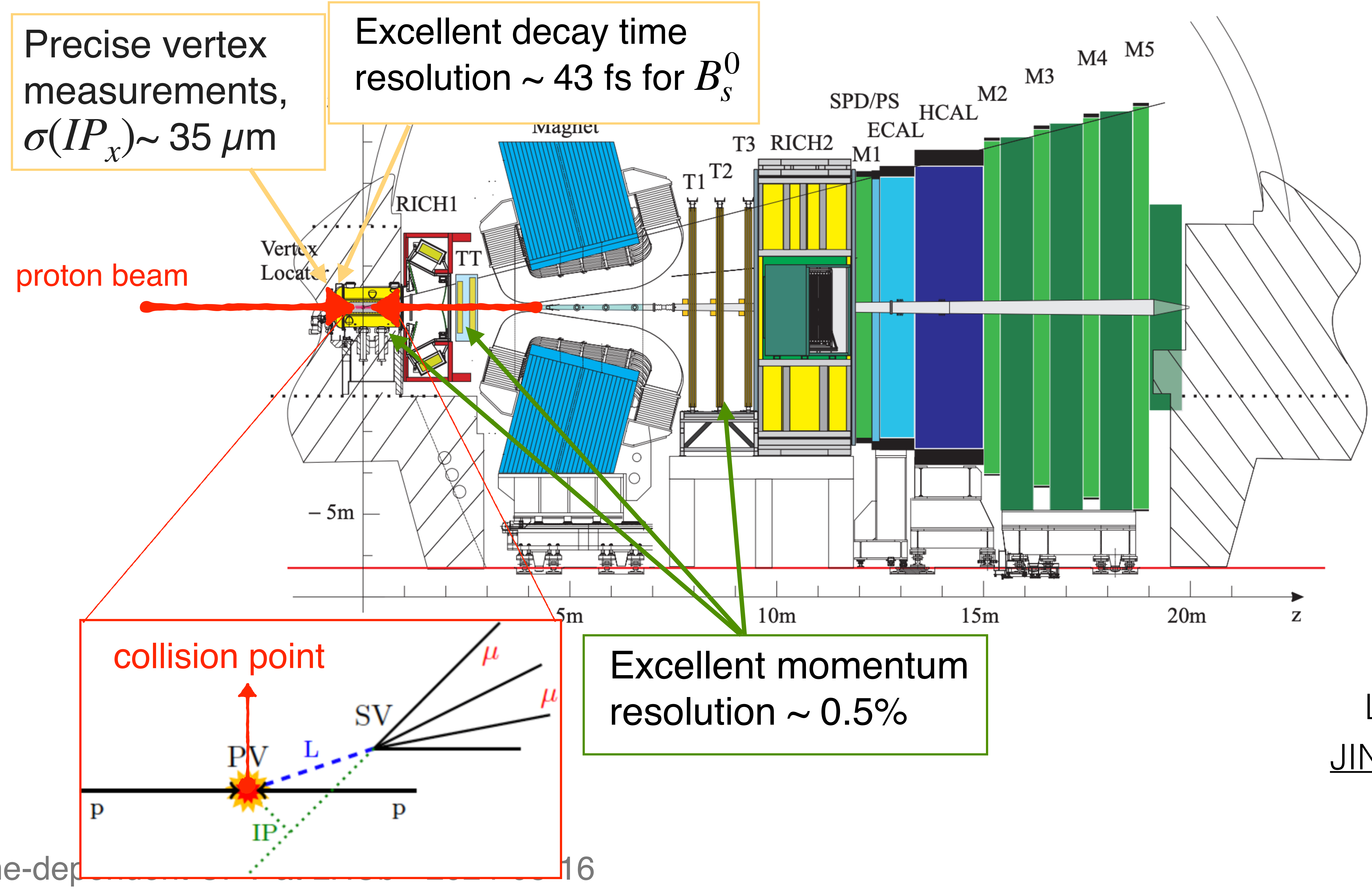

LHCb performance:
JINST 14 (2019) P04013

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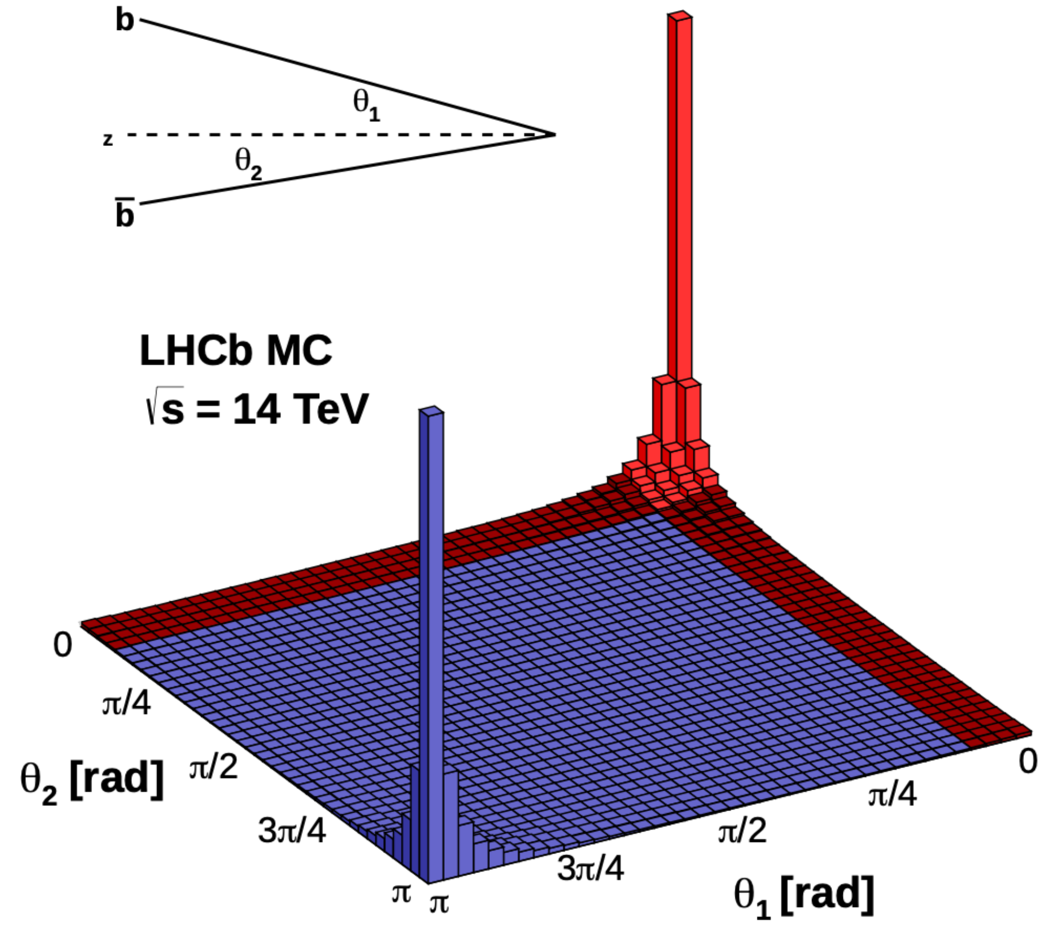

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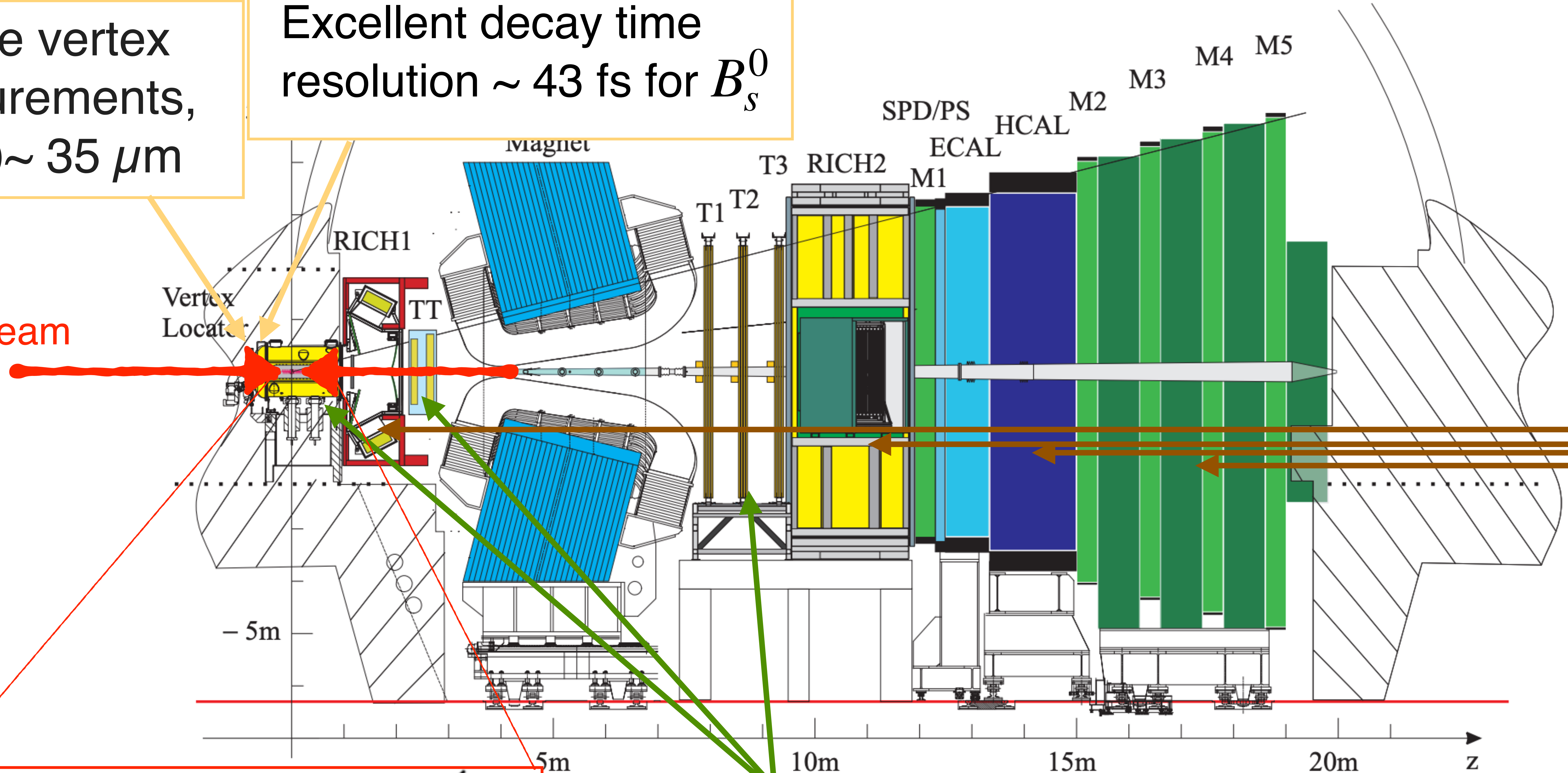
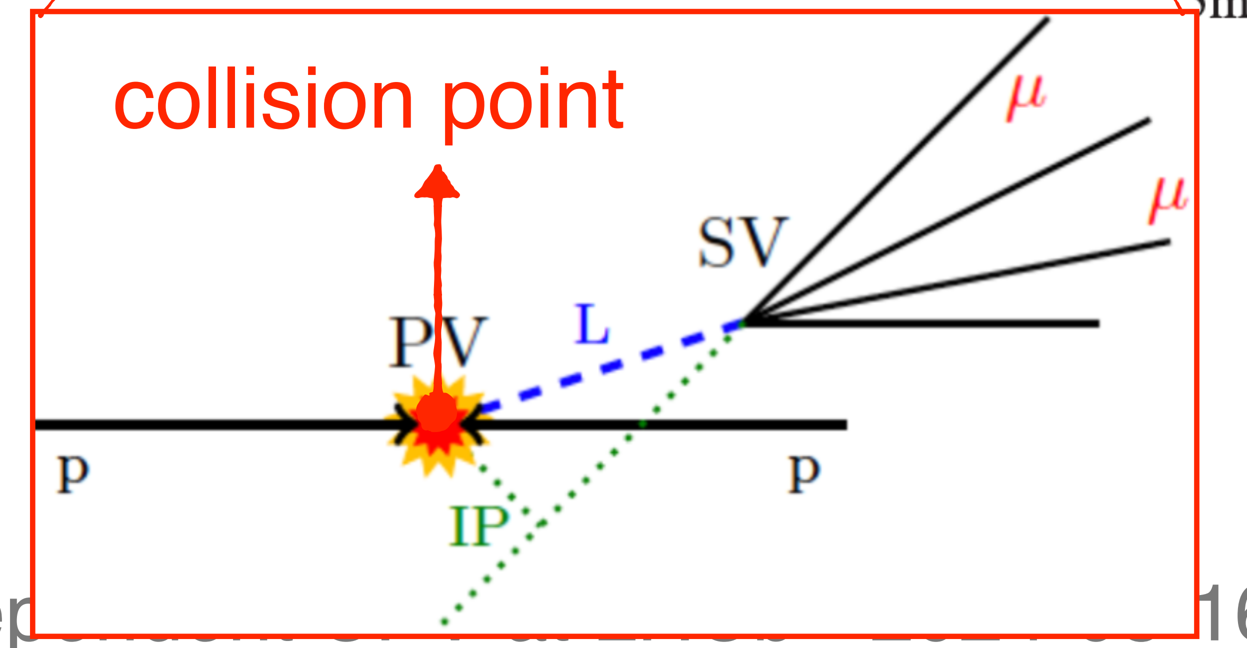


Excellent particle identification
$\epsilon(K) \approx 95\,\%$
misID $p(\pi \to K) \approx 5\,\%$
$\epsilon(\mu) \approx 97\,\%$



Excellent momentum resolution ~ 0.5%

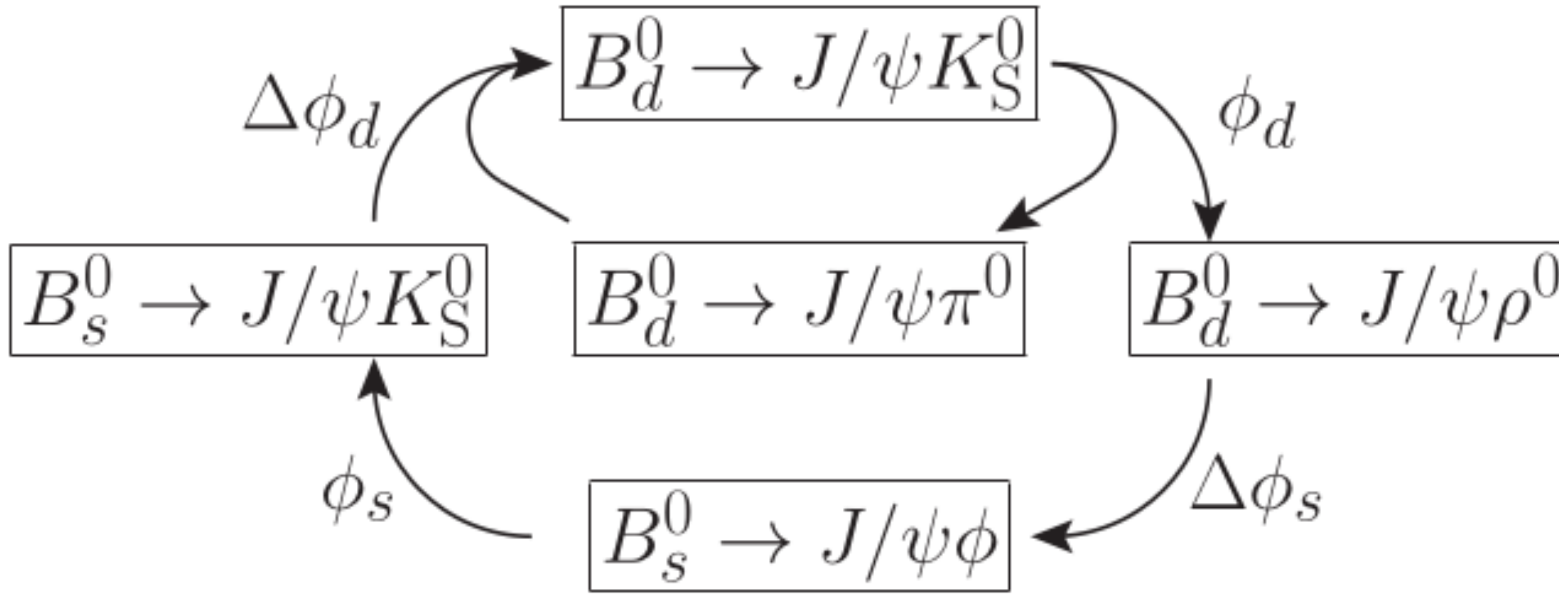
LHCb performance: JINST 14 (2019) P04013

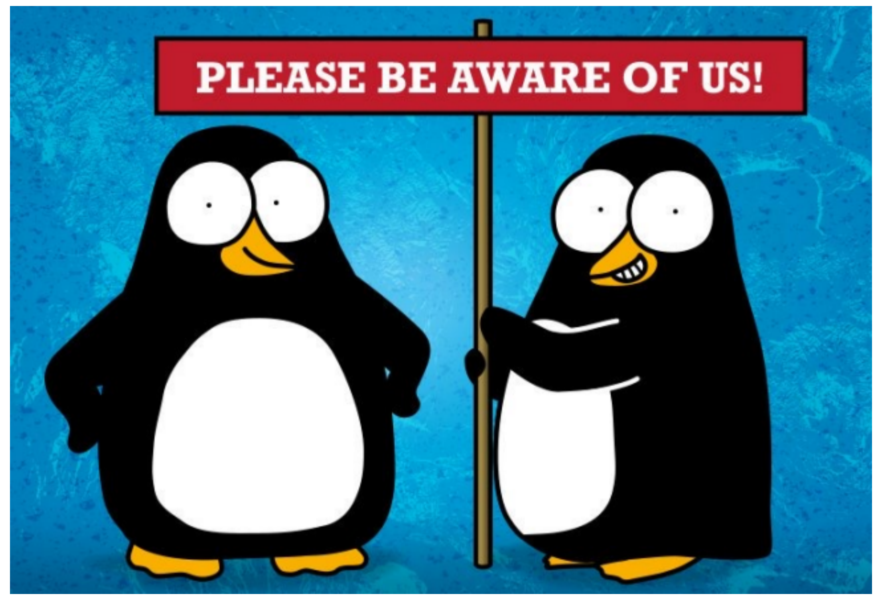
Control of penguin contribution

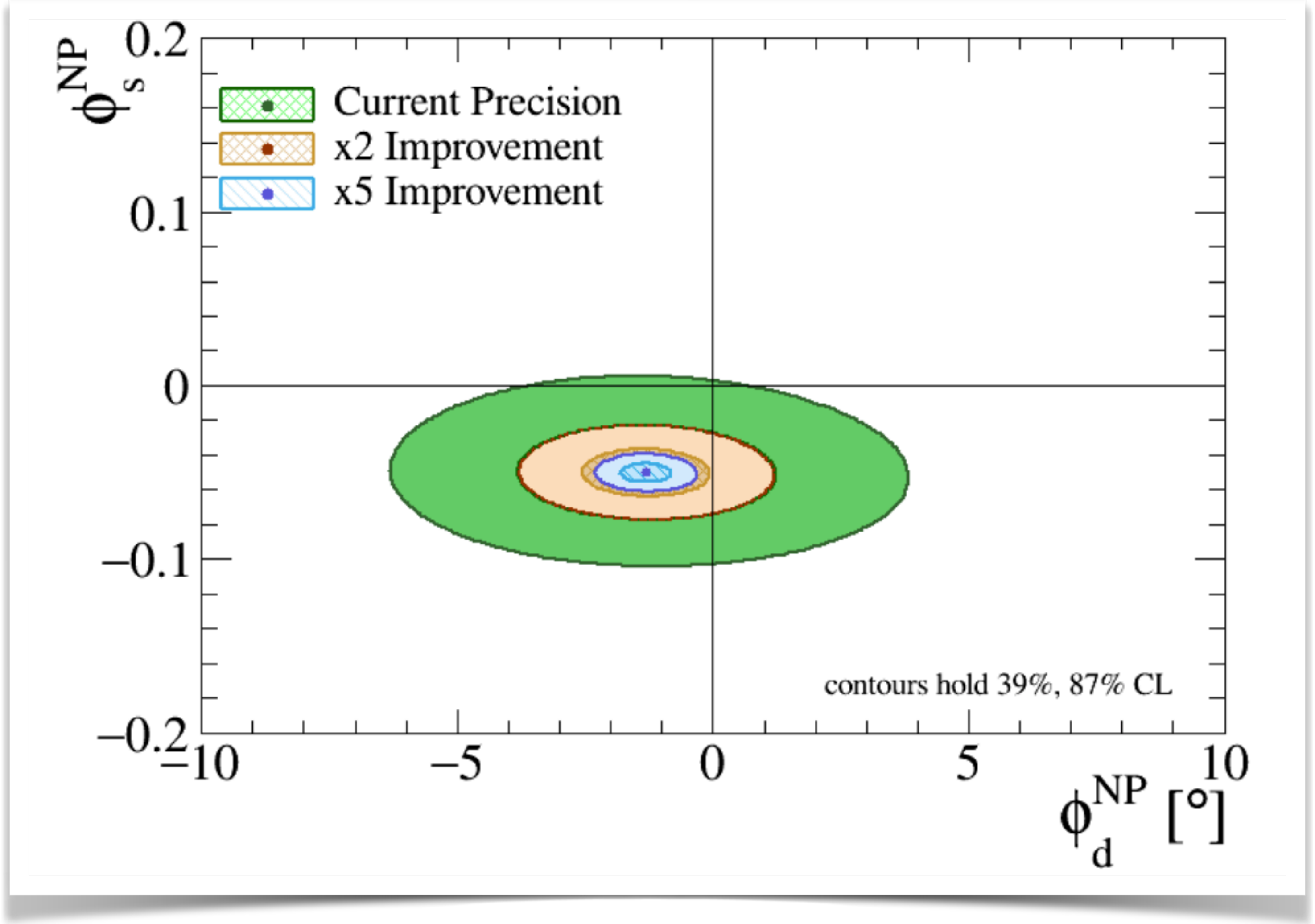
- $\sigma(\phi_s) \sim 0.016$ comparable with the theoretical estimation of $\Delta\phi_s^{penguin} \sim 1^\circ \approx 0.017$, better control of penguin effect necessary
- Combined analysis of penguin contributions in ϕ_s and ϕ_d $(\sin 2\beta)$, using SU(3) flavour symmetry

$$\phi_d = \sin(2\beta^{\text{tree}}) + \Delta\phi_d{}^{\text{penguin}} + \phi_d{}^{\text{NP}}$$

$$\phi_s = \phi_s^{\text{tree}} + \Delta\phi_s^{\text{penguin}} + \phi_s^{NP}$$





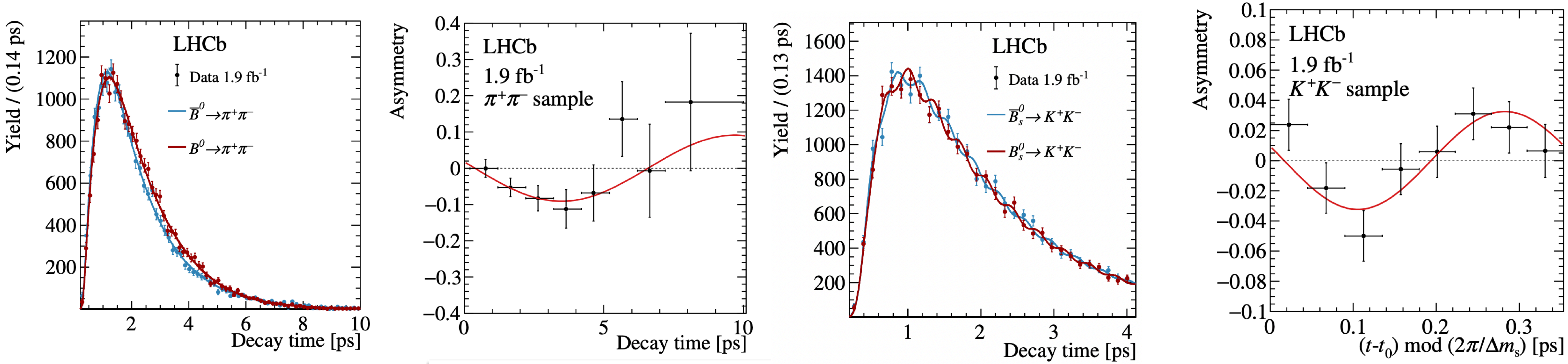


J.Phys.G 48 (2021) 6, 065002

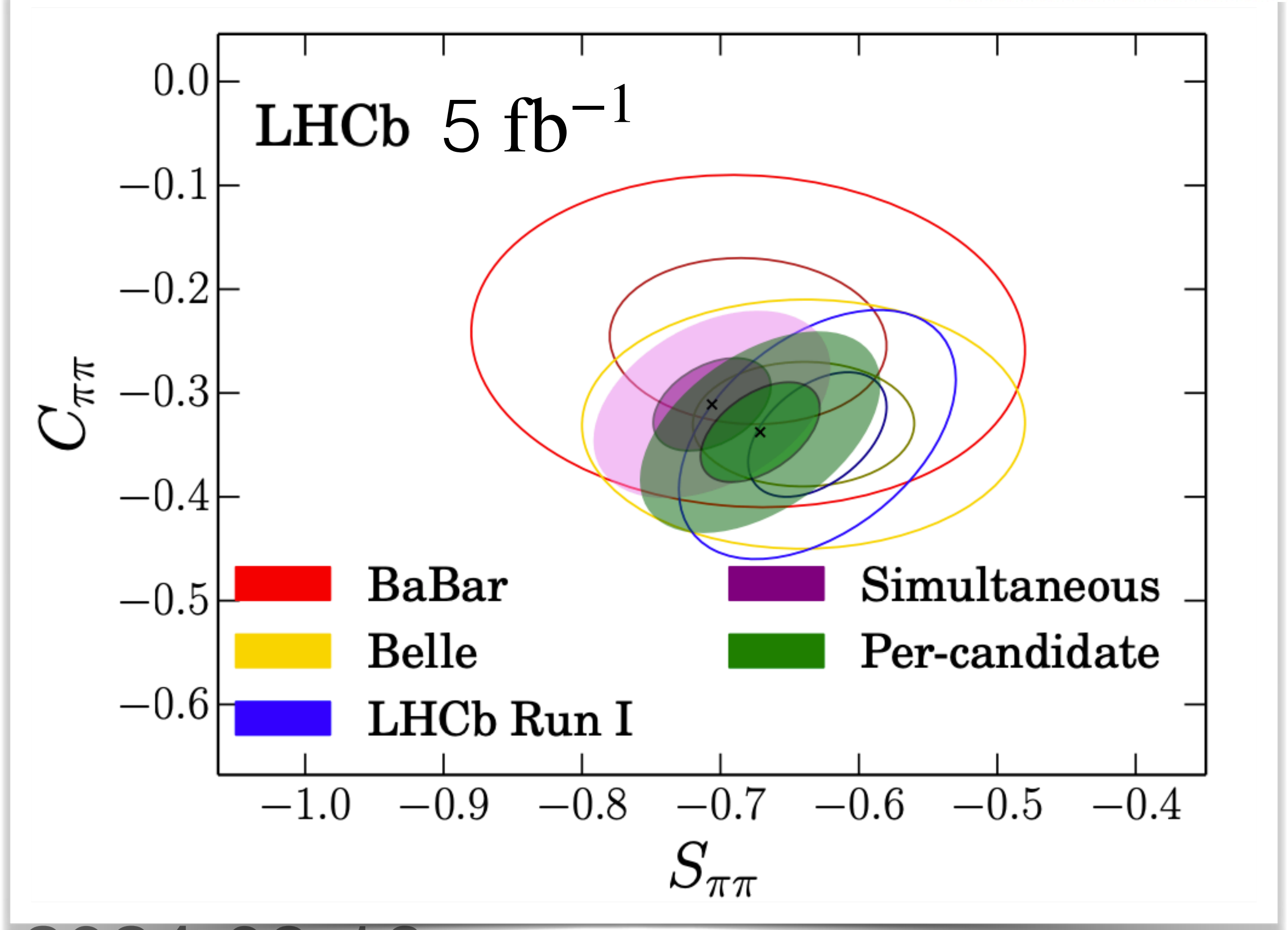
CP asymmetry in $B^0_{(s)} \to h^+h^-$

JHEP03(2021)075

- Simultaneous fit to the invariant mass, $B^0_{(s)}$ decay time and tagging decision for $B^0 \to \pi^+\pi^-$, $B^0_s \to K^+K^-$, $B^0_{(s)} \to K\pi$, providing constraints to α, γ, $\sin 2\beta_s$
- The first observation of time-dependent *CP* violation in B^0_s decay



Analysis of full Run 2 data in progress



$$
\begin{aligned}
C_{\pi\pi} &= -0.311 \pm 0.045 \pm 0.015,\\
S_{\pi\pi} &= -0.706 \pm 0.042 \pm 0.013,\\
A_{CP}^{B^0} &= -0.0824 \pm 0.0033 \pm 0.0033,\\
A_{CP}^{B^0_s} &= 0.236 \pm 0.013 \pm 0.011,\\
C_{KK} &= 0.164 \pm 0.034 \pm 0.014,\\
S_{KK} &= 0.123 \pm 0.034 \pm 0.015,\\
\mathcal{A}_{KK}^{\Delta\Gamma} &= -0.83 \pm 0.05 \pm 0.09,
\end{aligned}
$$

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JHEP03(2021)075

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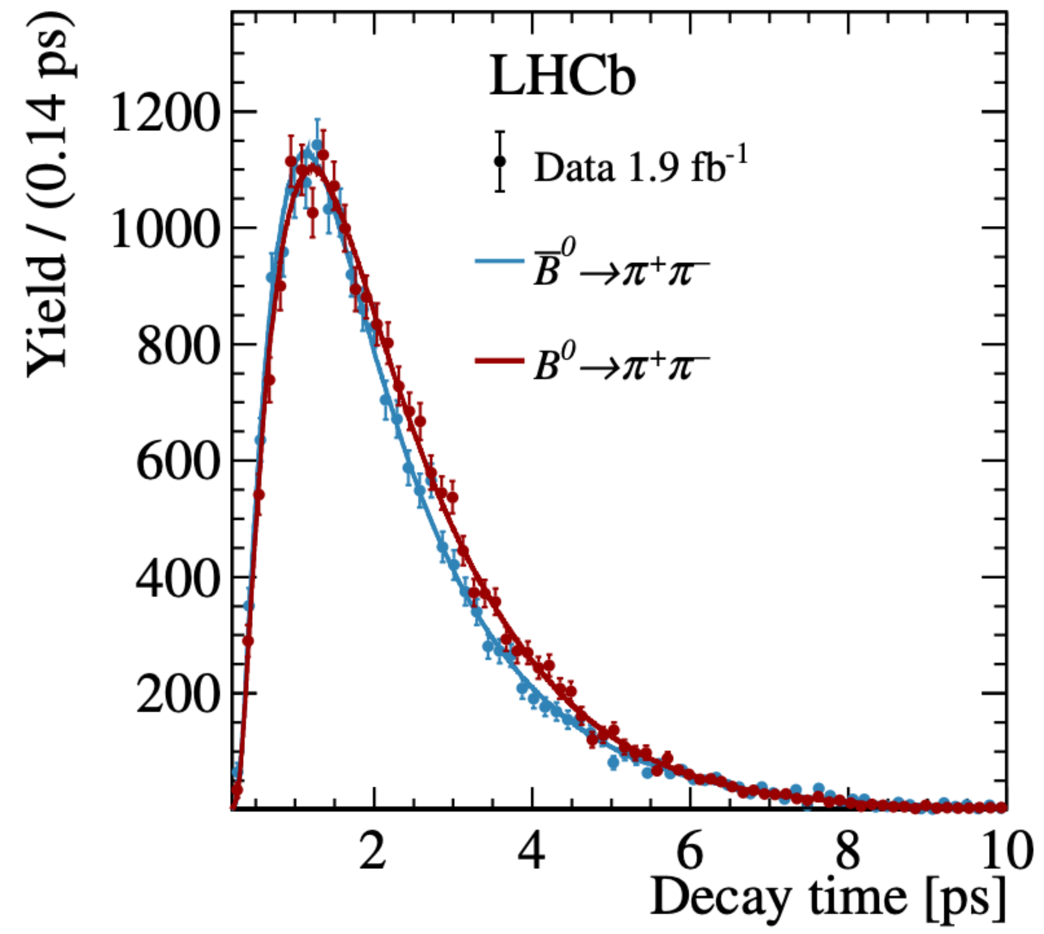

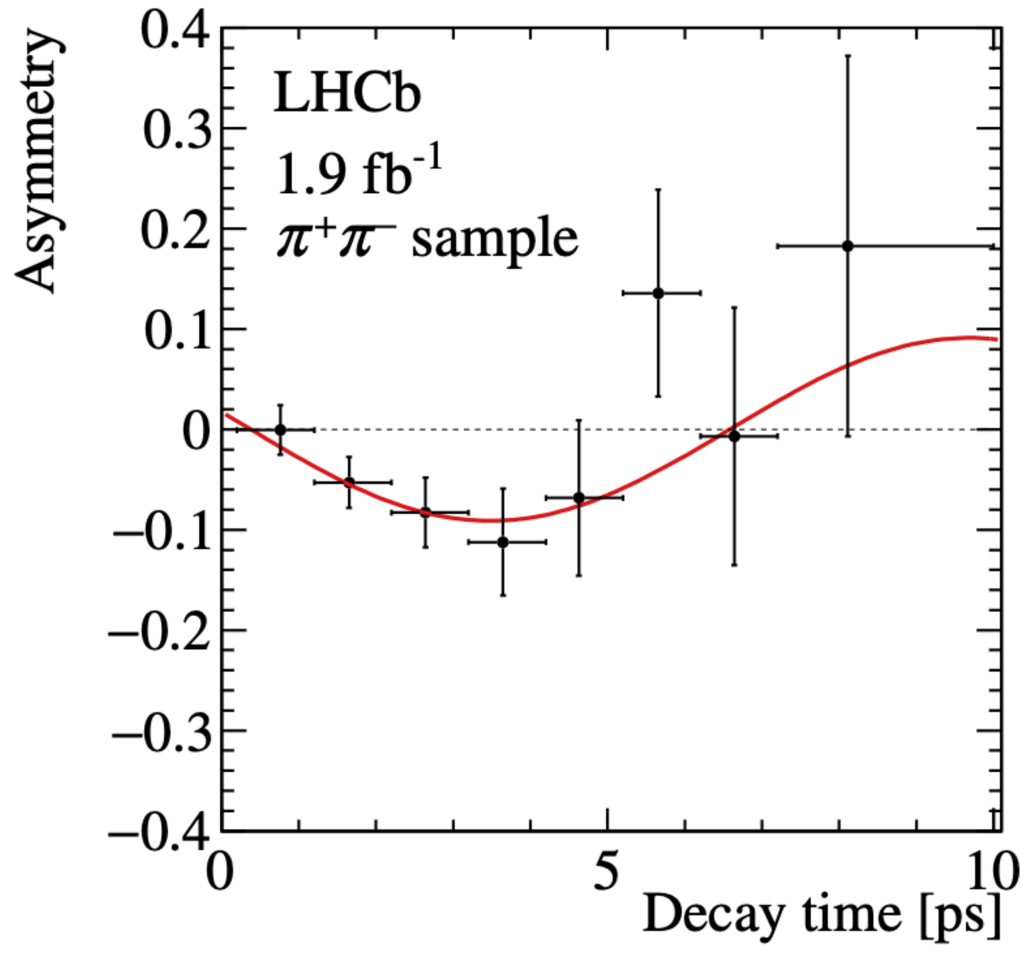

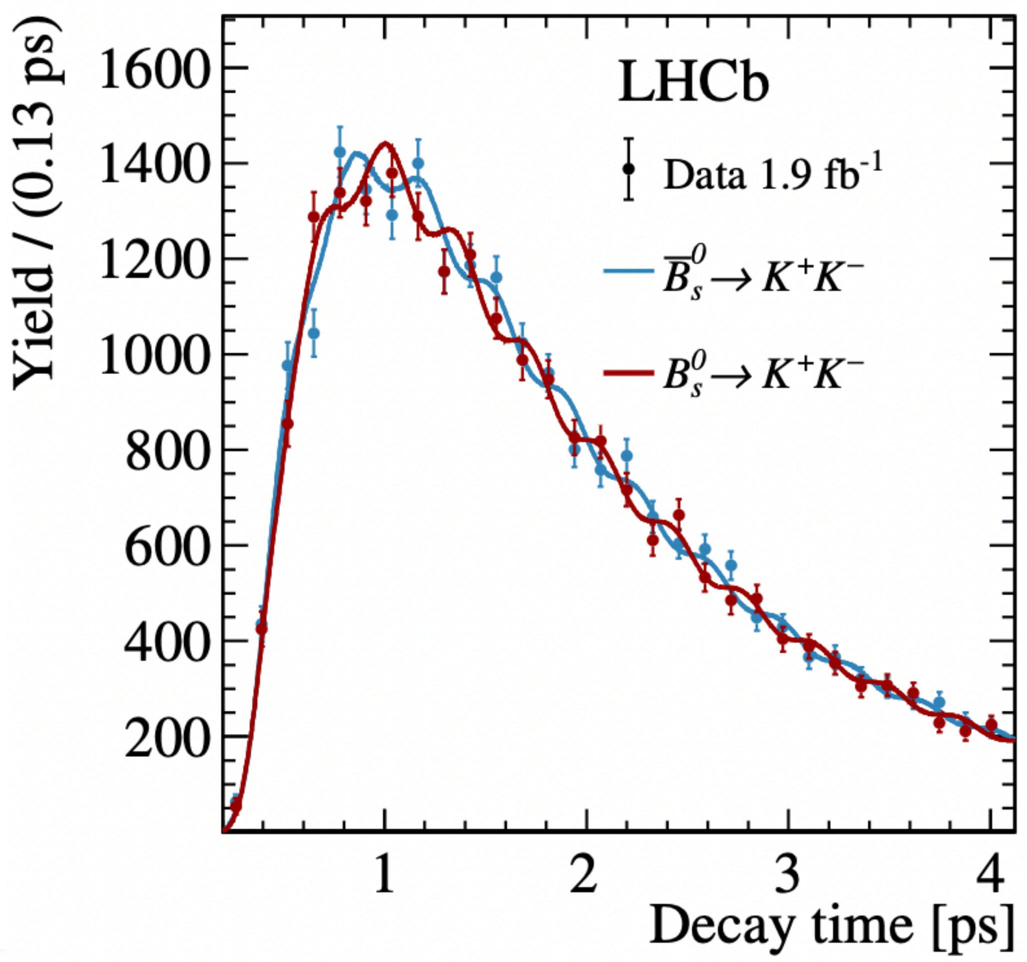

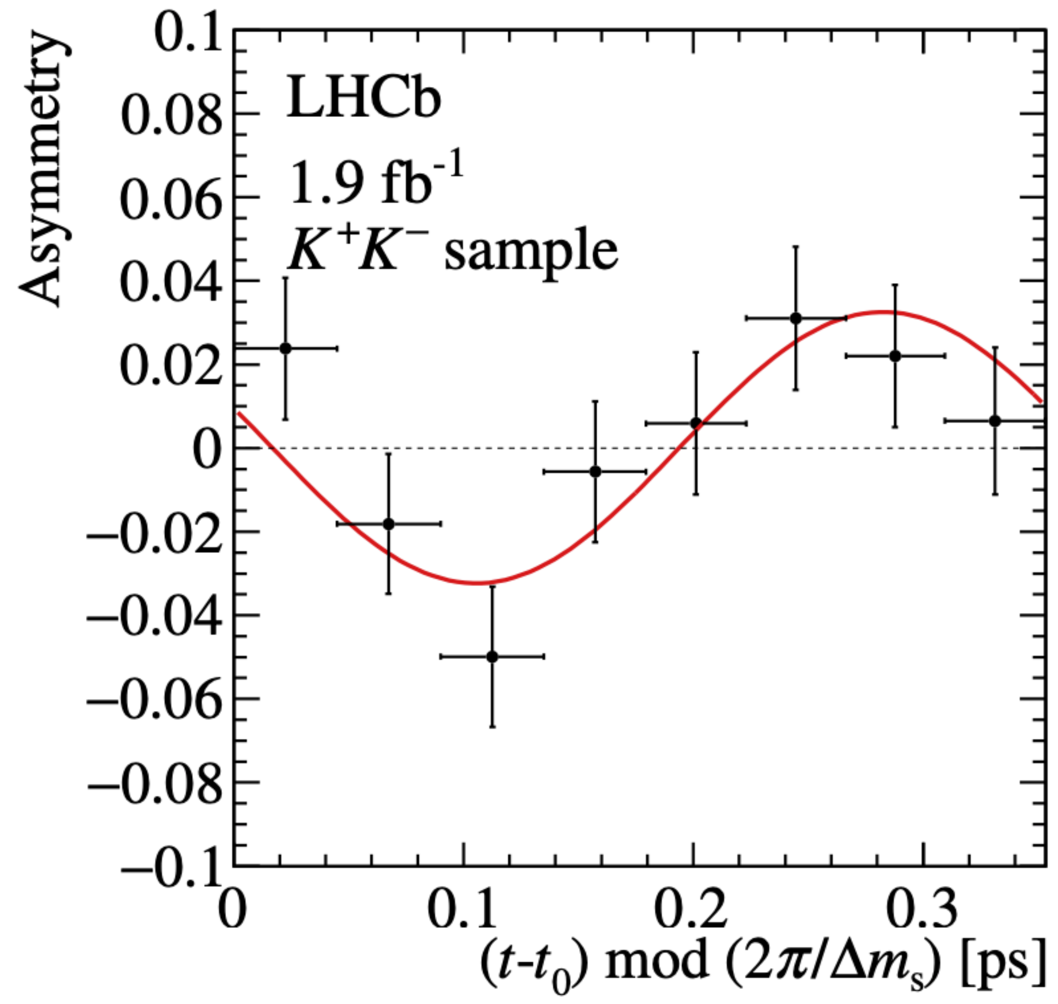

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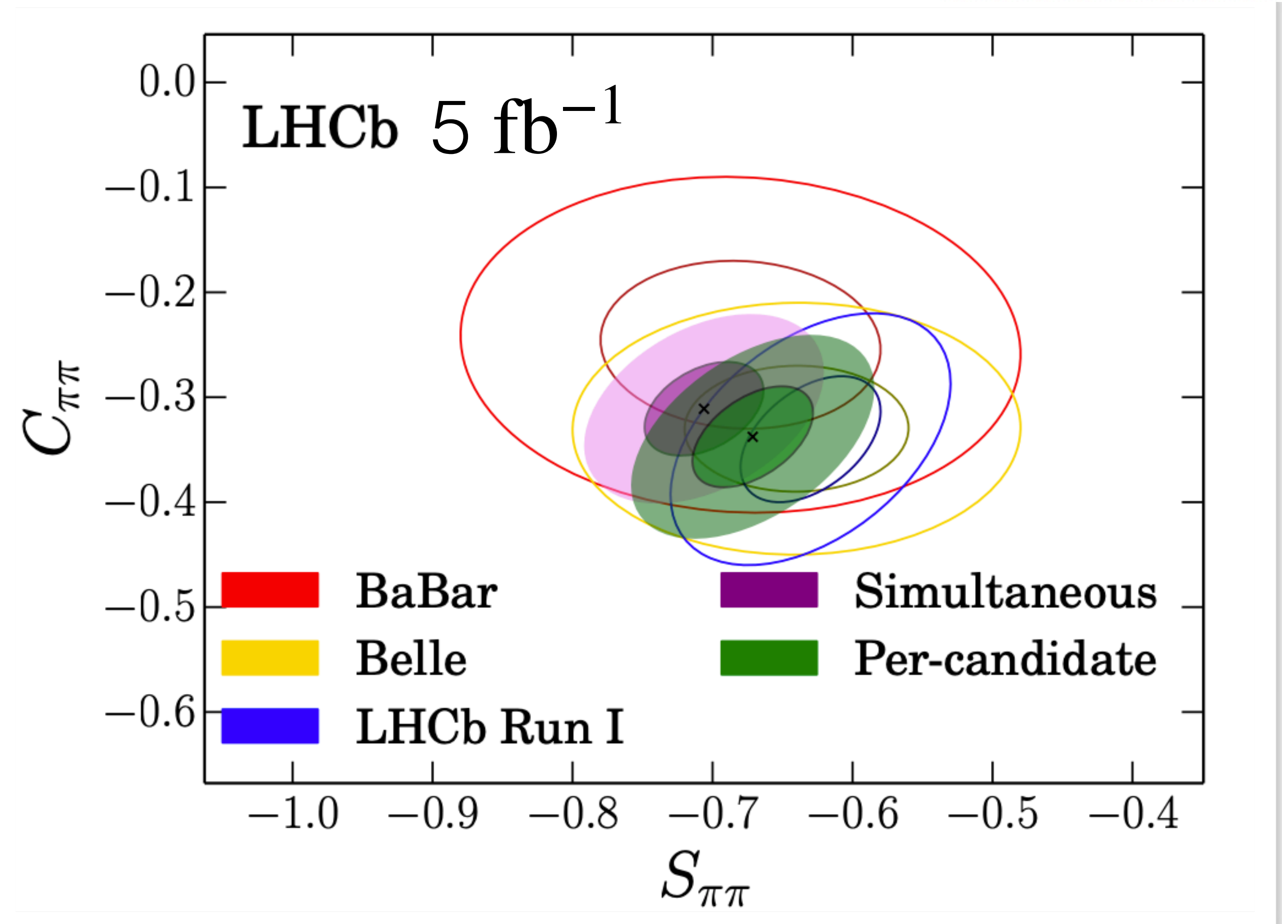

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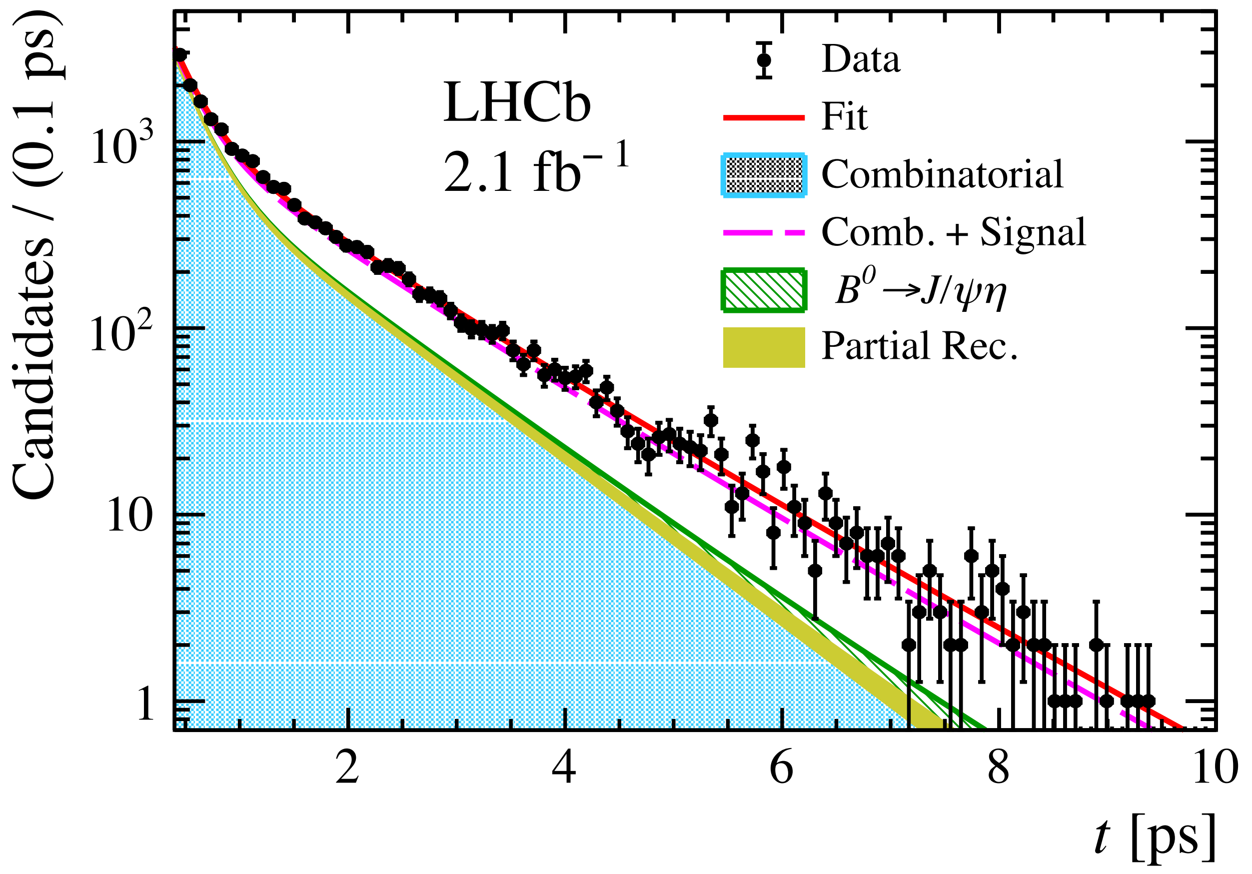
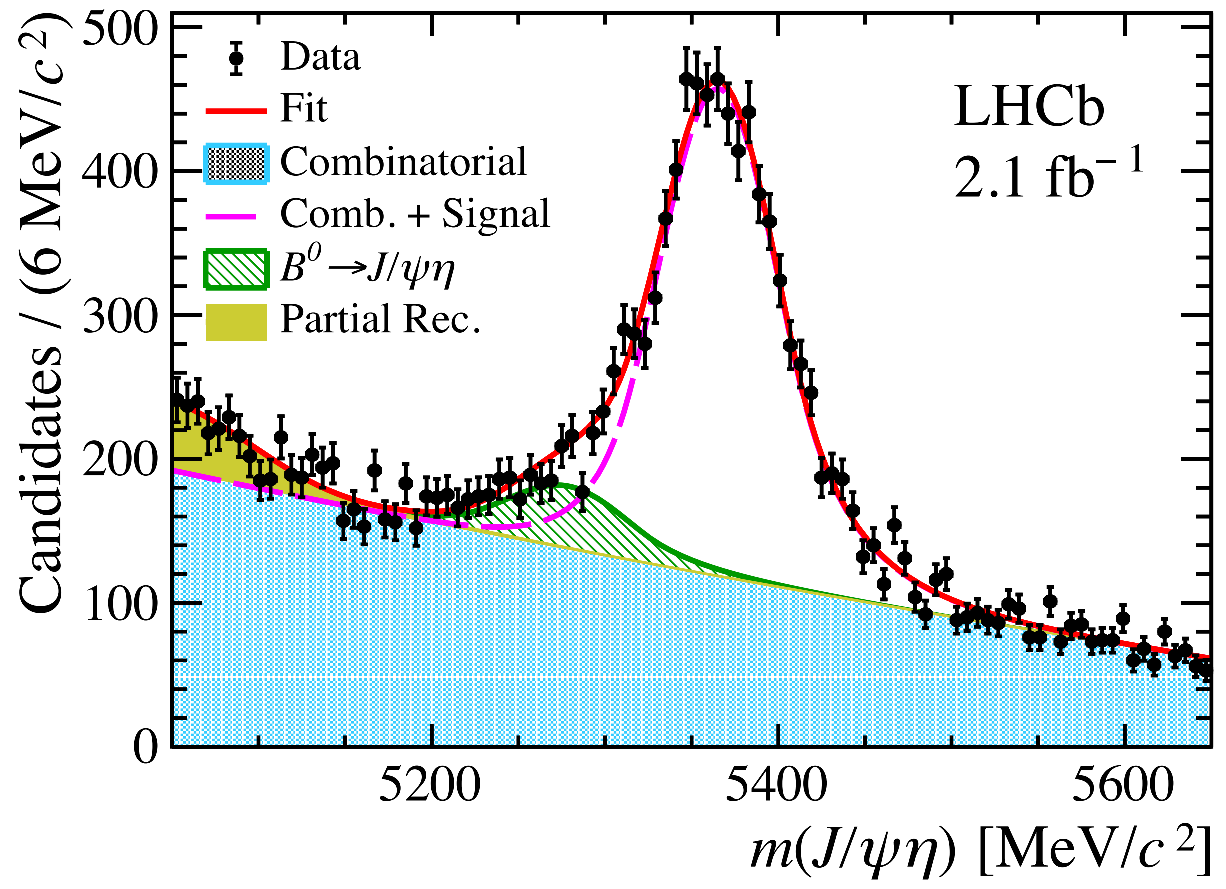
\end{aligned}
$$

Effective lifetime measurements in $B_s^0 \to J/\psi\eta$

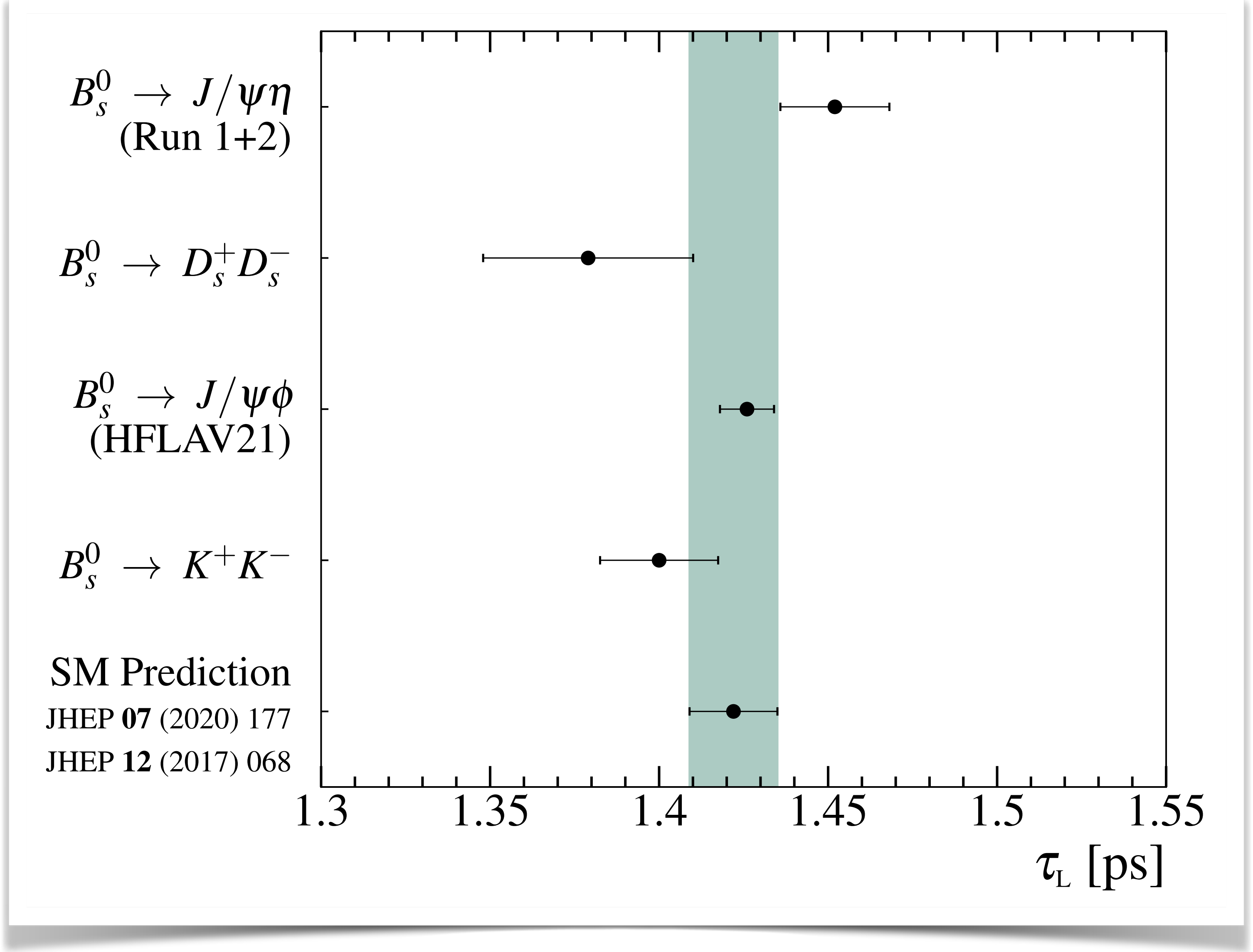
EPJC83 (2023) 629

- CP-even decay $B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$ allows to determine $\tau_L = 1/\Gamma_L$
- Simultaneous fit to invariant mass and decay time





$$\tau_L = 1.452 \pm 0.014 \pm 0.007 \pm 0.002\,\text{ps}$$



Agree with the SM prediction and other measurements