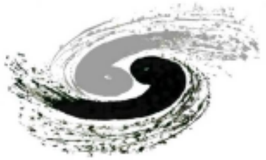
基于BESIII强相位输入的Belle II实验 γ角和D^0- $\bar{D}^0$mixing的测量

师晓东
高能所



中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

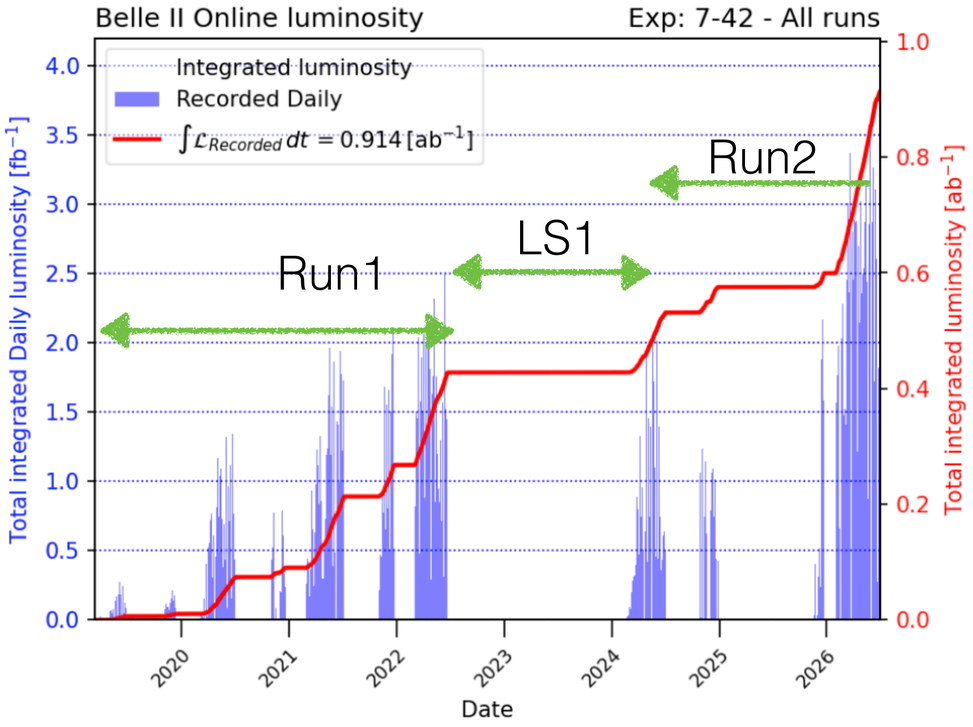
2026.10.16-10.20
2026年粲强子物理研讨会

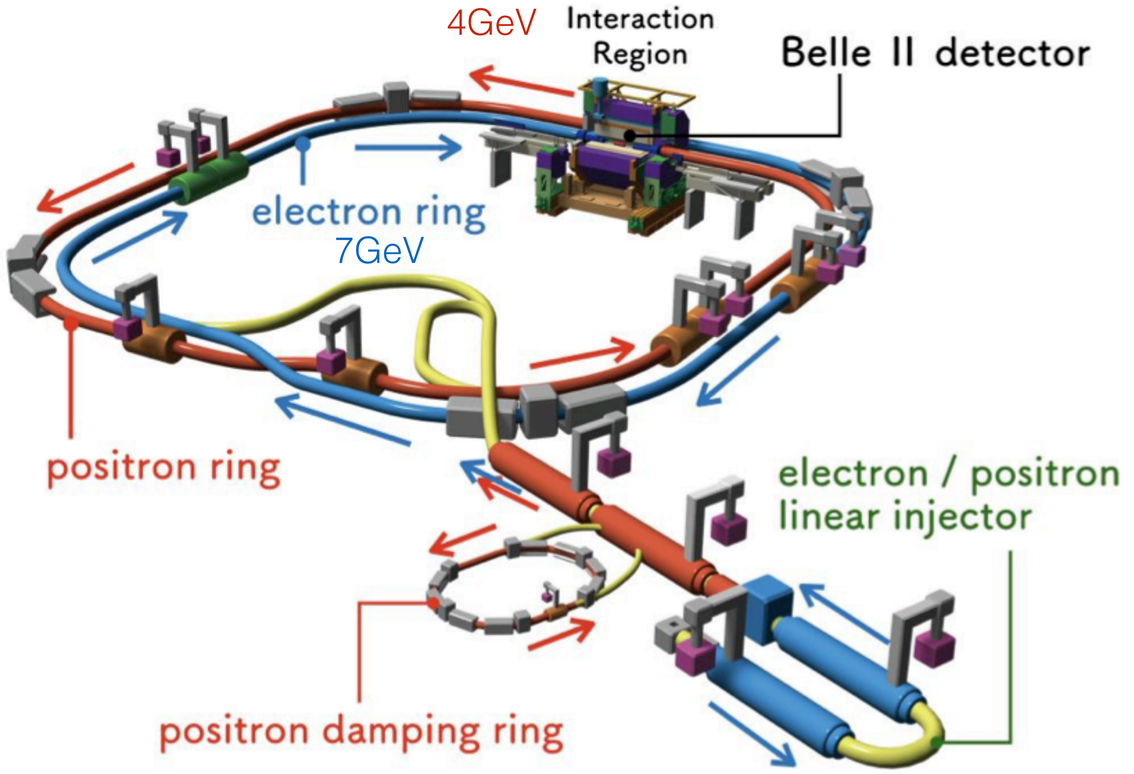




SuperKEKB

- Asymmetric e^+e^- collider, upgraded from KEKB
  - ✦ mainly running at Y(4S) energy point ($B\bar{B}$)
  - ✦ Nano-beam collision, crab waist scheme
  - ✦ Achieved **world's record** instantaneous luminosity of $5.32 \times 10^{34} cm^{-2} s^{-1}$ (x2.5 of KEKB's peak luminosity)

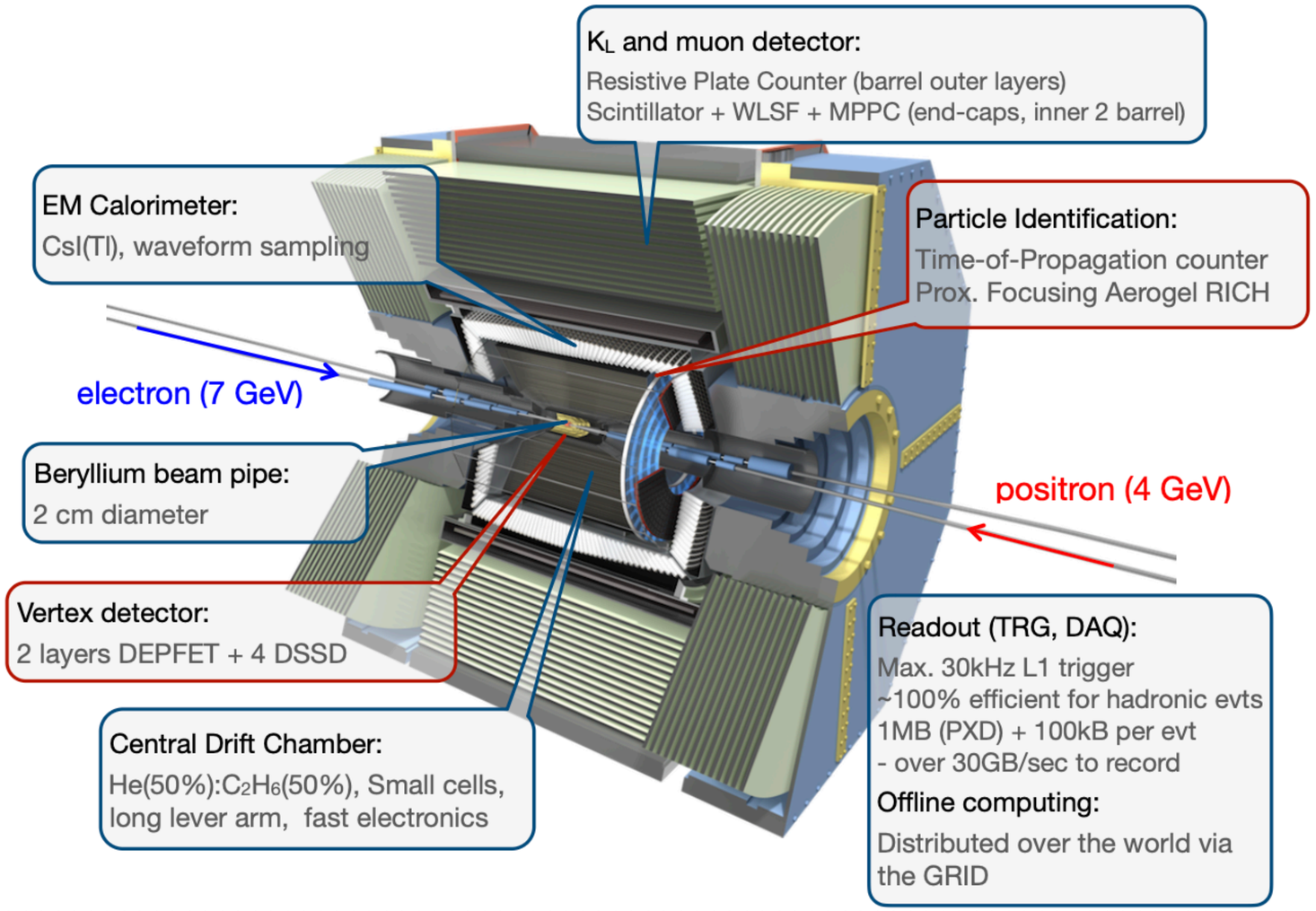




Per ab^{-1} (events $\times 10^9$): 1.1 $B\bar{B}$, 1.3 $c\bar{c}$, 2.1 $q\bar{q}$, 0.9 $\tau^+\tau^-$

Also a charm factory!

Belle II detector



- Multipurpose detector designed to reconstruct all visible particles
- Excellent vertexing - silicon pixels improve track impact parameter and vertex resolution by about a factor of two over Belle/BaBar
- High-efficiency detection of neutrals (γ, π^0, η, η', ...)
- High trigger efficiency, including for low multiplicity events
- Reconstruction performance at least as good as B-factories

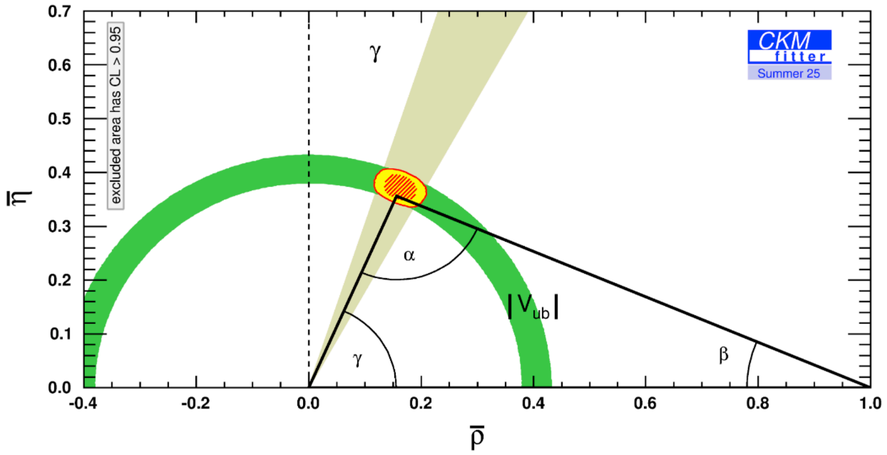
CKM matrix & γ angle

- CKM matrix connects *u*- and *d*-type quarks via weak force
- In SM, 3 generation of quarks, and CKM matrix is unitary: **four free parameters**, including one **phase**, the **only one source of CPV** in SM!

$$V_{\mathrm{CKM}} \propto \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\, e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\, e^{-i\beta} & -|V_{ts}|\, e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$

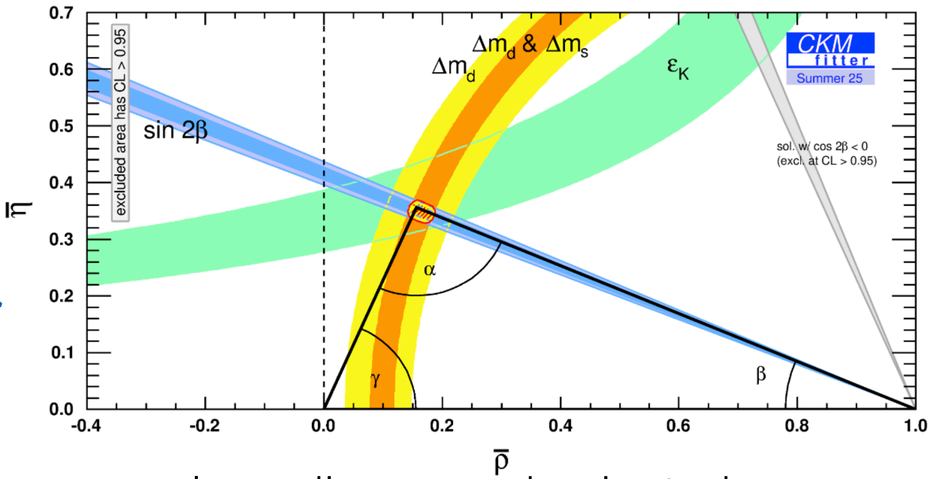
*special for γ, it's the **phase**!

- Unitary of CKM provides $\Sigma_i V_{ik} V_{il}^* = \Sigma_i V_{ki} V_{li}^* = \delta_{kl}$
  - One related to b quark is the famous CKM triangle



tree diagrams dominated (only 3)

Possible difference indicates new physics!

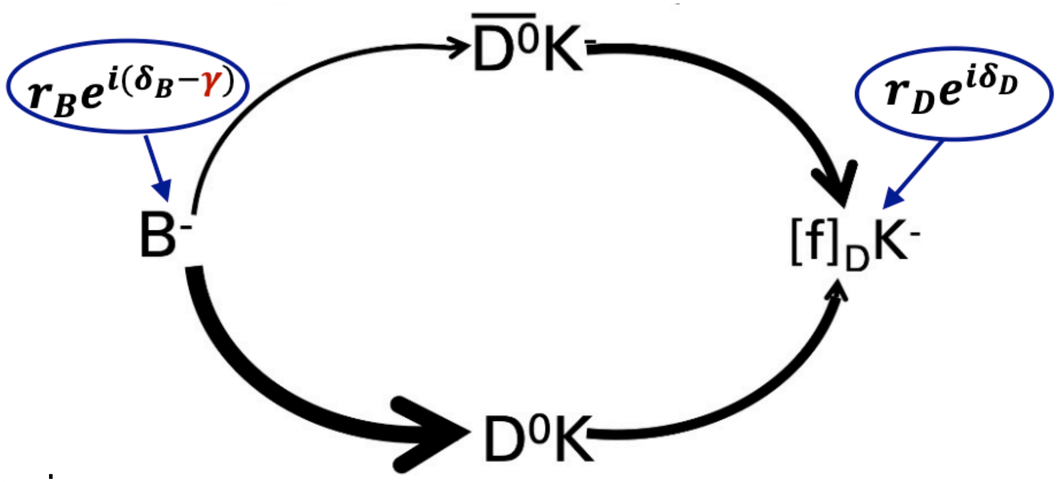


loop diagrams dominated

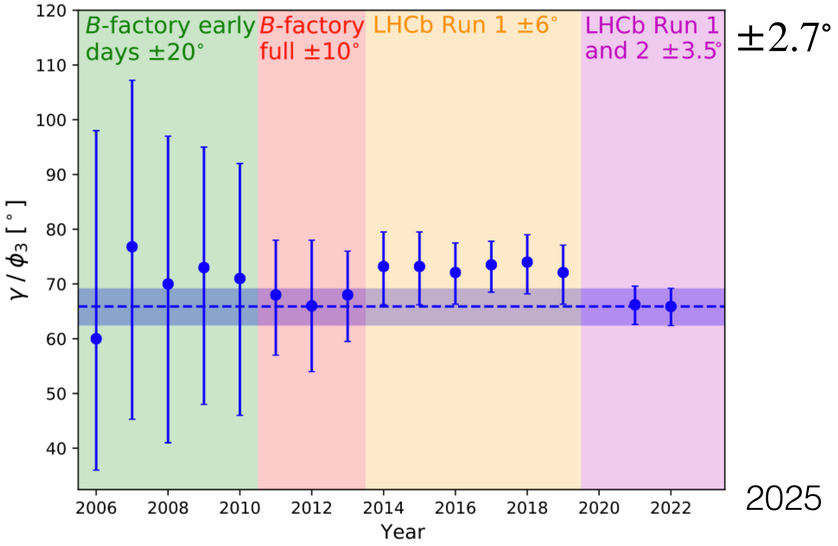
Measurement of γ and strong-phase difference δ_D

$$\gamma(\equiv \phi_3) = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$$

- Golden channels to measure γ: $B^{\pm} \to D^0(\bar{D}^0)K^{\pm}$
- Needs δ_D, the model-independent δ_D can only be measured @ CLEO-c, BESIII
  - For BESIII's measurements, check talks by Yang & Yunyi.



- Precision of γ has been improved dramatically:
  - $\sim 23^\circ$ (2009) to $\sim 2.7^\circ$ (2025)
- BESIII's δ_D results are **crucial** inputs
  - otherwise the precision will be limited at $\sim 4^\circ$ (due to $\sigma(\delta_D)$)



±2.7°

2025

Belle and Belle II's γ results using BESIII's input

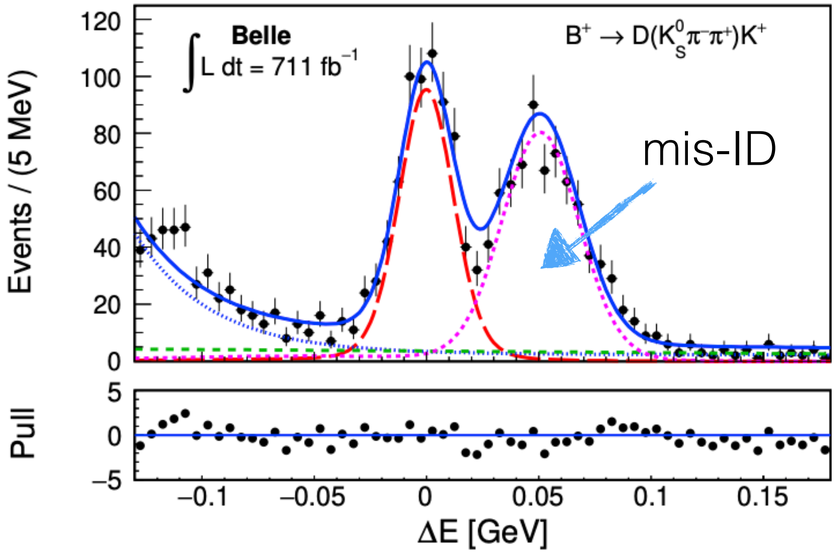
- Belle and Belle II's measurements til now.

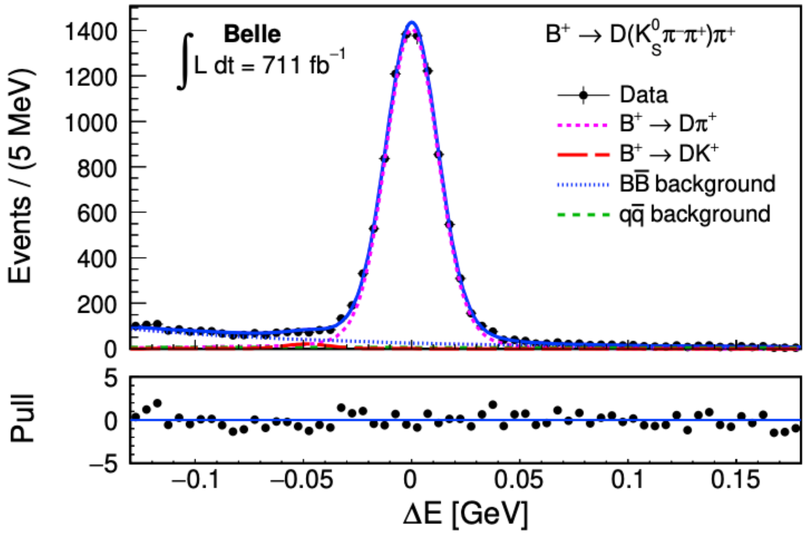
B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]	
$B^+ \to Dh^+$	$D \to K^0_S\pi^0, K^-K^+$	GLW	$711 + 189$	[JHEP 05 212 (2024)]
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	$711 + 0$	[PRL 106 231803 (2011), PRD 88 091104(2013)]
$B^+ \to Dh^+$	$D \to K^0_S K^-\pi^+$	GLS	$711 + 362$	[JHEP 09 146 (2023)]
$B^+ \to Dh^+$	$D \to K^0_S h^-h^+$	BPGGSZ (m.i.)	$711 + 128$	[JHEP 02 063 (2022)]
$B^+ \to Dh^+$	$D \to K^0_S\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	$711 + 0$	[JHEP 10 178 (2019)]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D \to K^0_S\pi^0, K^0_S\phi, K^0_S\omega,$ $K^-K^+, \pi^-\pi^+$	GLW	210+0	[PRD 73 051106 (2006)]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D\gamma, D \to K^0_S\pi^-\pi^+$	BPGGSZ (m.d.)	$605 + 0$	[PRD 81 112002 (2010)]

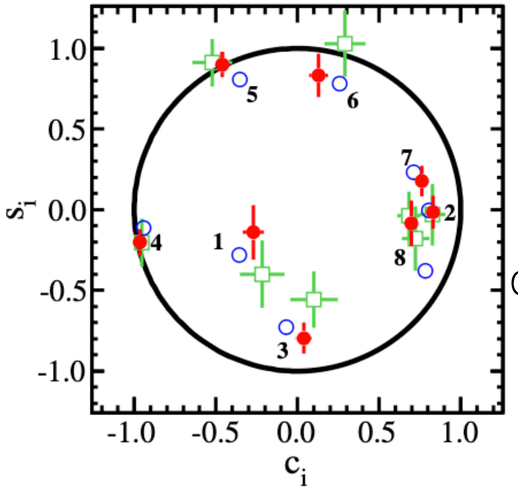
- All results except GLW method use inputs from CLEO-c and BESIII.
  - for $D \to K^-\pi^+(\pi^0), K^0_S K^\pm\pi^\mp$ the δ_D, κ_D, r_D are used in the combination.
  - for $D \to K_S\pi^+\pi^-, K_S K^+K^-$, the c_i, s_i are used in the measurement.

$B^+ \to Dh^+, D \to K^0_S h^+ h^-$ from Belle and Belle II

- Pair production of B meson, using $\Delta E, M_{\rm bc}$. (Same trick in D study at BESIII)







Blue:model
Red:BESIII
Green:CLEO

Inputs are BESIII's 2.9 fb^{-1} results

- Low background level.
- Mis-ID can be constrained via $D\pi$ data.

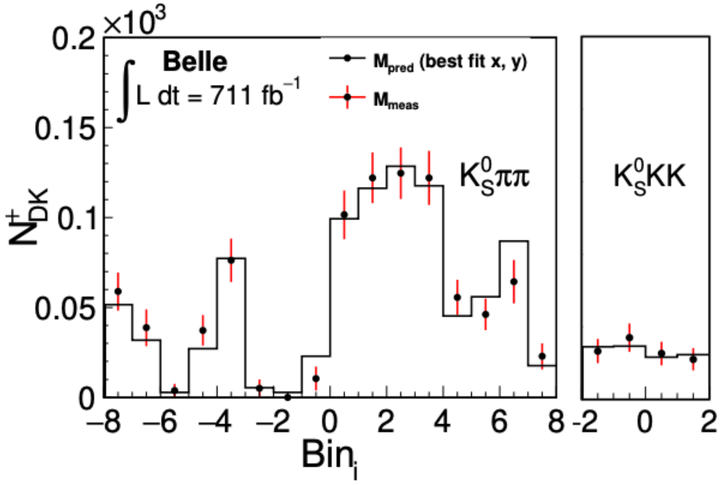
$B^+ \to Dh^+, D \to K^0_S h^+ h^-$ from Belle and Belle II

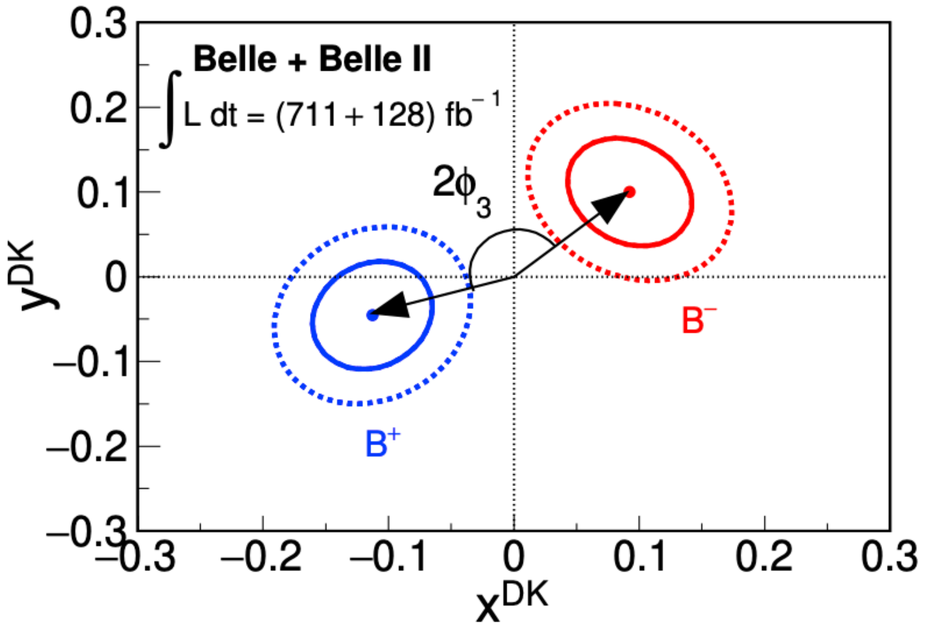
- Simultaneous fit to data in 80 bins, bin schemes are same ones in BESIII measurements.

$$
\begin{aligned}
N_i^+ &= h_{B^+}\left[F_{-i} + \left\{\left(x_+^{DK}\right)^2 + \left(y_+^{DK}\right)^2\right\} F_i \;\; + 2\sqrt{F_i F_{-i}}\left(x_+^{DK} c_i - y_+^{DK} s_i\right)\right] \\
N_{-i}^+ &= h_{B^+}\left[F_i \;\; + \left\{\left(x_+^{DK}\right)^2 + \left(y_+^{DK}\right)^2\right\} F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_+^{DK} c_i + y_+^{DK} s_i\right)\right] \\
N_i^- &= h_{B^-}\left[F_i \;\; + \left\{\left(x_-^{DK}\right)^2 + \left(y_-^{DK}\right)^2\right\} F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_-^{DK} c_i + y_-^{DK} s_i\right)\right] \\
N_{-i}^- &= h_{B^-}\left[F_{-i} + \left\{\left(x_-^{DK}\right)^2 + \left(y_-^{DK}\right)^2\right\} F_i \;\; + 2\sqrt{F_i F_{-i}}\left(x_-^{DK} c_i - y_-^{DK} s_i\right)\right]
\end{aligned}
$$

Fit from B data

from BESIII





$$
\begin{aligned}
\phi_3 &= (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ, \\
r_B^{DK} &= 0.129 \pm 0.024 \pm 0.001 \pm 0.002, \\
\delta_B^{DK} &= (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ,
\end{aligned}
$$

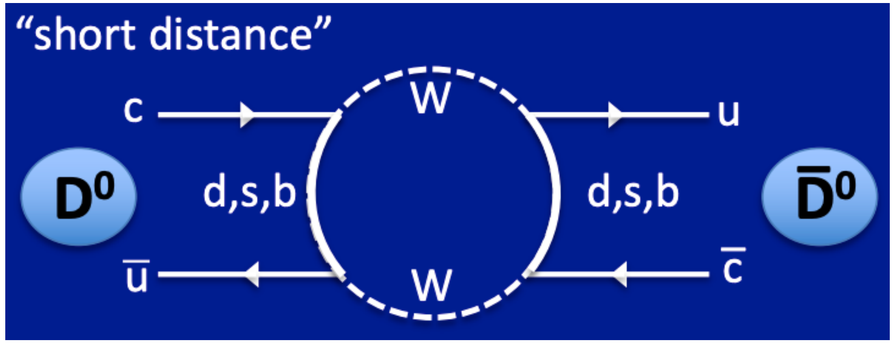
Stat Syst ci/si

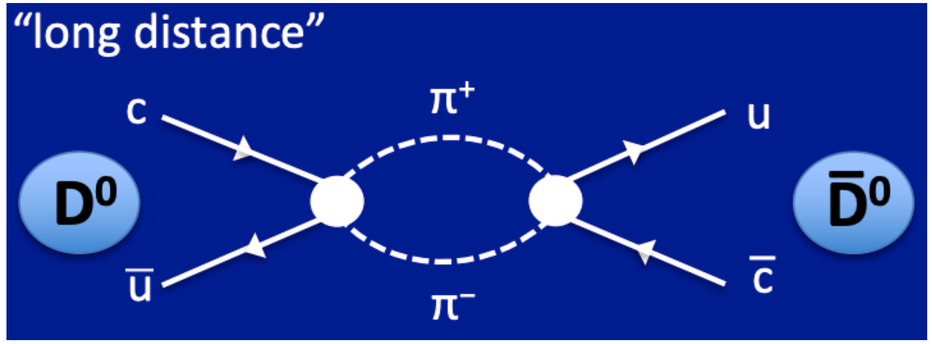
γ from Belle II in near future

- Now there are only two ongoing analyses @ Belle II.
  - $B^+ \to D^* h^+, D \to K^0_S h^+ h^-$, will use BESIII's published 8 fb^{-1} results
  - $B^+ \to D h^+, D \to K^0_S \pi^+ \pi^- \pi^0$, will use BESIII's 20.3 fb^{-1} results (ongoing)

- Belle II also measured $B^+ \to D h^+, D \to K^0_S K^\pm \pi^\mp$, once BESIII published the δ_D, κ_D, r_D, will be used in the next combination.
- In next 5 years, Belle II may measure $B^+ \to D h^+, D \to \pi^+ \pi^- \pi^0, K^- \pi^+ \pi^0 \pi^0, K^0_S h^+ h^-$
  - BESIII's measurements would be the key to these results.

$D^0 - \bar{D}^0$ mixing



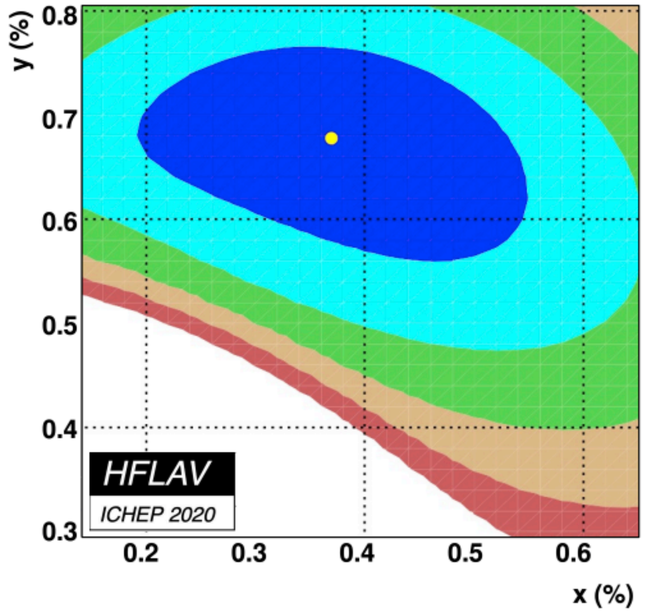


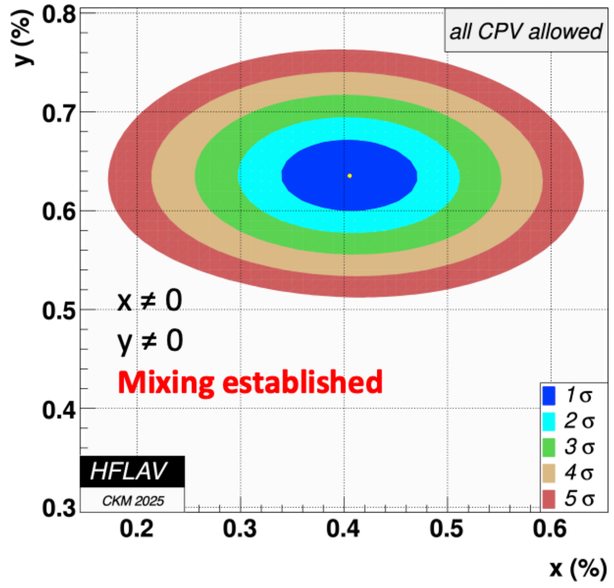
Long distance contribution is ~100x than short distance

mass eigenstates **flavor eigenstates**

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$x = (m_1 - m_2)/\Gamma$
$y = (\Gamma_1 - \Gamma_2)/2\Gamma$
} **meson mixing**





- Huge progress in precision in last 6 years.
- Measurements are mainly from BaBar, Belle (II), LHCb.

$D^0 - \bar{D}^0$ mixing measurement method

$$e^+e^- \to \gamma^* \to c\bar{c} \to D^{*+} + X$$
$$D^{*+} \to D^0\pi^+, D^0 \to K_S^0\pi^+\pi^-$$

charge tells us the flavor at t=0

$$g_\pm(t) = \theta(t)e^{-im\Gamma t}e^{-\Gamma t/2}\begin{matrix}\cosh\\ \sinh\end{matrix}(z\Gamma t/2)$$
$$z = -(y + ix)$$

Mixing Parameters

$x = \frac{m_1 - m_2}{\Gamma}$ and $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$, $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

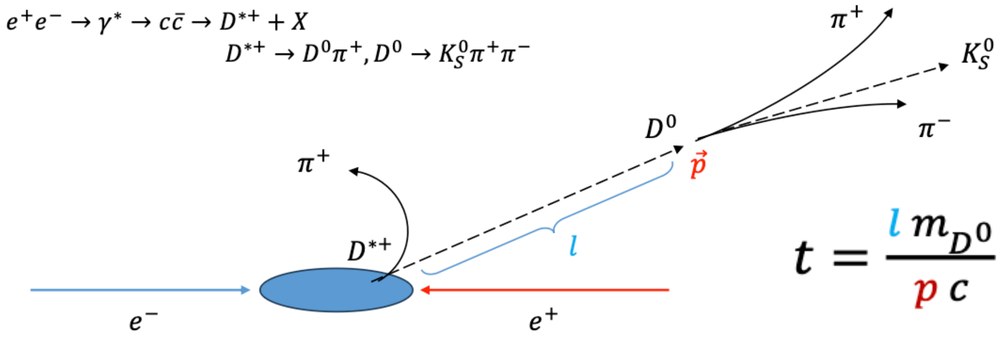
$$|\langle f|D^0(t)\rangle|^2 = \left|T_f(m_+^2, m_-^2; t)\right|^2 = \left|A_f(m_+^2, m_-^2)\, g_+(t) + \bar{A}_f(m_-^2, m_+^2)\,\frac{q}{p}\, g_-(t)\right|^2$$

- With model-independent result from BESIII, the decay rate:

$$p_b(t; D^0) \propto F_b g_+^2(t) + \bar{F}_{-b}|\frac{q}{p}|^2 g_-^2(t) + 2\sqrt{F_b\bar{F}_{-b}}Re[X_b\frac{q}{p}g_+^*(t)g_-(t)]$$

$$X_b = c_b - is_b$$

BESIII's input based on 2.9 fb^{-1}



$$t = \frac{l\, m_{D^0}}{p\, c}$$

- Decay time is determined by decay length
  - vertex detector & boost effect

$D^0 - \bar{D}^0$ mixing using Belle and Belle II data

Signal PDF = D^0 decay rate ⊗ time resolution

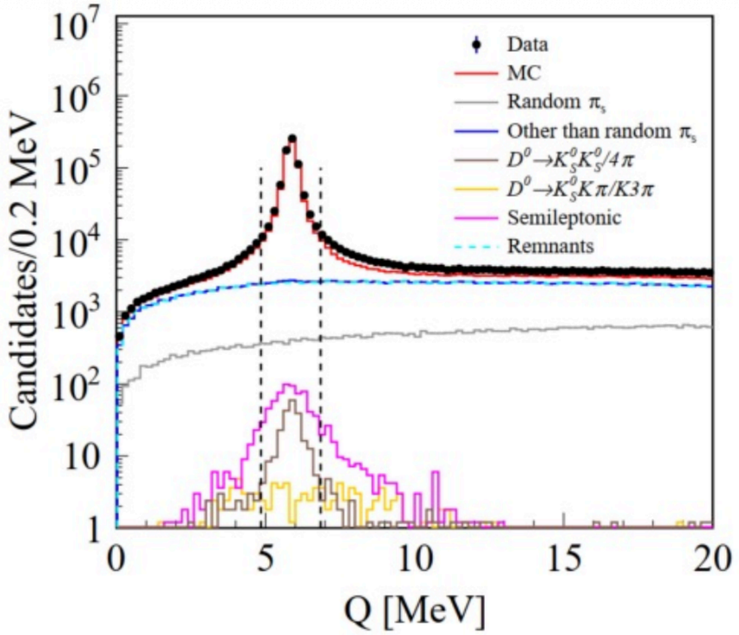
$$\mathrm{pdf}_0(t, \sigma_t; D^0, b) = f_{\mathrm{sig}}(D^0, b)\mathrm{pdf}_{\mathrm{sig}}(t, \sigma_t; D^0, b) + f_{\mathrm{rnd}}(D^0, b)\mathrm{pdf}_{\mathrm{rnd}}(t, \sigma_t; D^0, b) + (1 - f_{\mathrm{sig}}(D^0, b) - f_{\mathrm{rnd}}(D^0, b))\mathrm{pdf}_{\mathrm{oth}}(t, \sigma_t; b)$$

$D^{*+} \to D^0\pi^+$, $D^0 \to K^0_S\pi^+\pi^-$

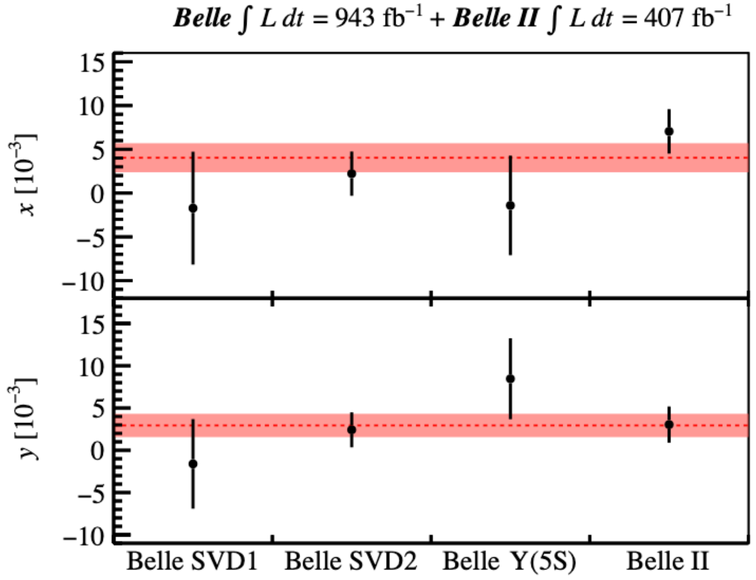
PDF for Random soft pions background is defined by the signal PDF and mis-tag rate (measured with Q sideband)

Fractions are from the MQ fit (unbinned fit to 2D distribution of $M(D^0)$ and release energy of D^* decay)

PDF for other background is decided by the sideband



Clean D sample



- Most precise result from e^+e^- collider.
- Consistent with LHCb's result.

$$x = (4.0 \pm 1.7 \pm 0.4) \times 10^{-3}$$

$$y = (2.9 \pm 1.4 \pm 0.3) \times 10^{-3}$$

[PRD 111, 112011 (2025)]

Summary

- High precision of CKM γ and $D^0 - \bar{D}^0$ mixing requires both measurements from B factories (LHCb, Belle II) and charm factories (BESIII). Equal important!
- Belle II already uses many strong-phase difference results from BESIII:
  - $D \to K^-\pi^+(\pi^0)$, $D \to K_S\pi^+\pi^-, K_SK^+K^-$

- Our wish list: [My personal viewpoint, not official from Belle II :)]
  - $D \to K^0_S\pi^+\pi^-\pi^0$
  - $D \to \pi^+\pi^-\pi^0$
  - $D \to K^-\pi^+\pi^0\pi^0$

Thanks!

$$V_{CKM} = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$V_{\text{CKM}} \propto \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\, e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\, e^{-i\beta} & -|V_{ts}|\, e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$