The flavor intensity frontier: Belle II and LHCb and some of their recent results

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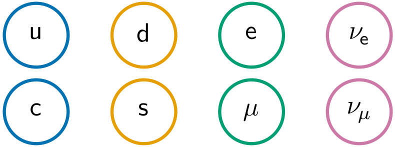

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- **Grand scheme:** find origin of mass and interaction hierarchies
- **Nearer goals:** measure standard-model parameters and search for new forces and particles

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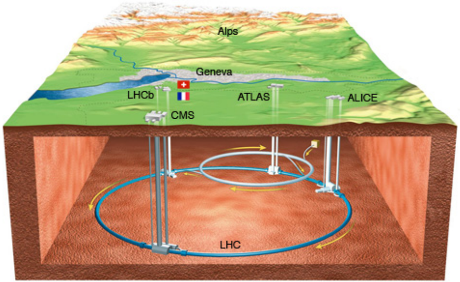

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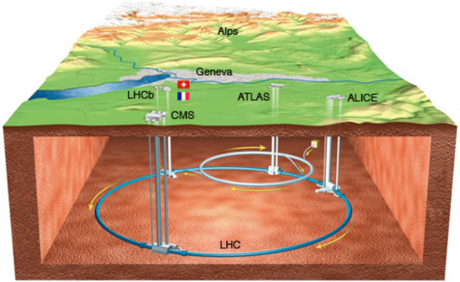

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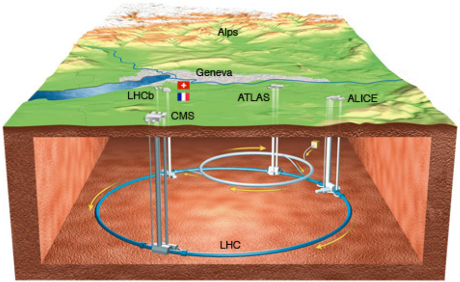

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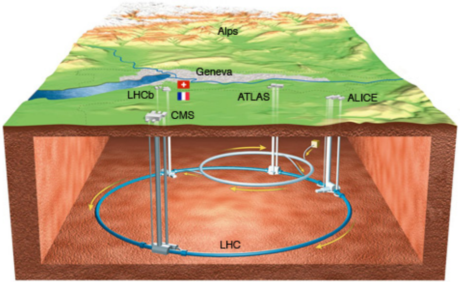

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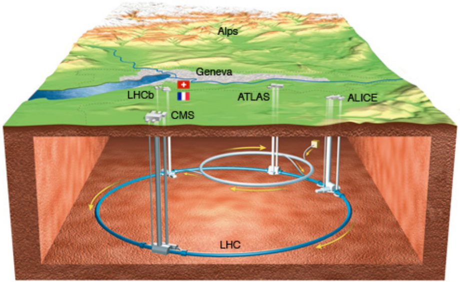

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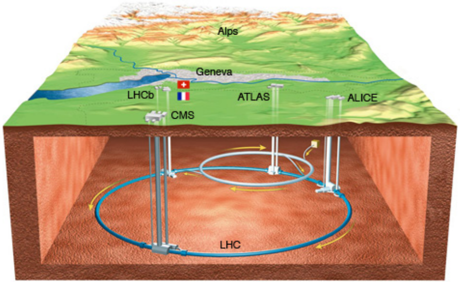

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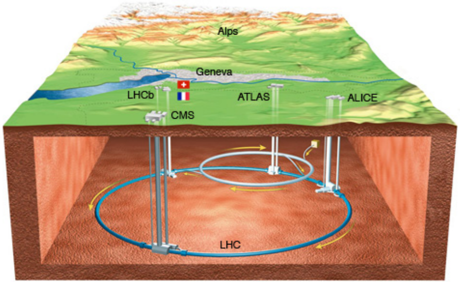

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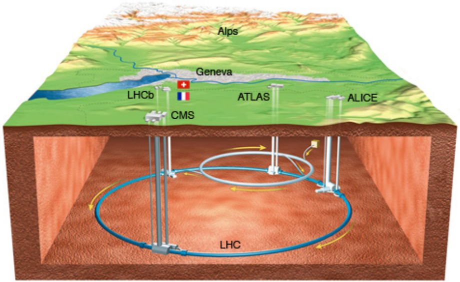

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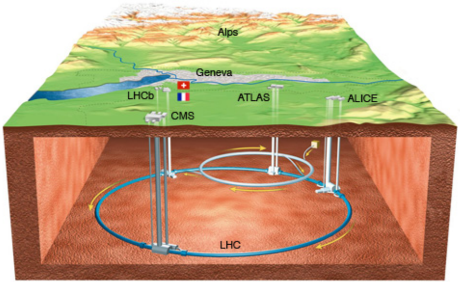

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Particles of interest have high momenta in the beam directions.

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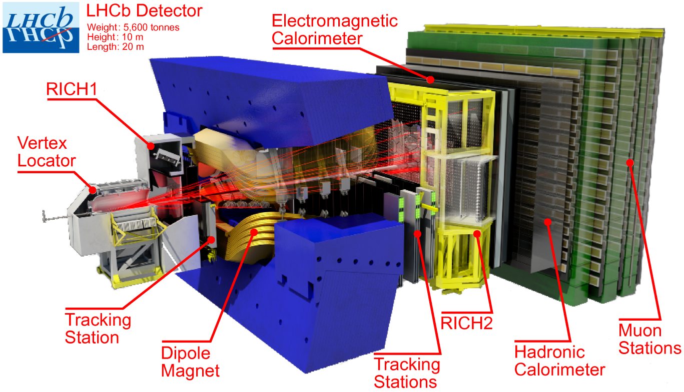

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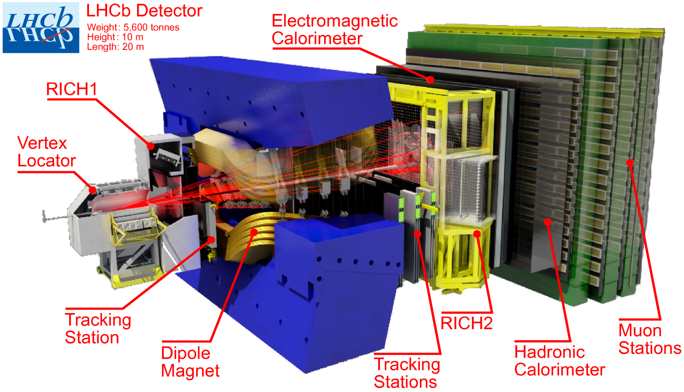

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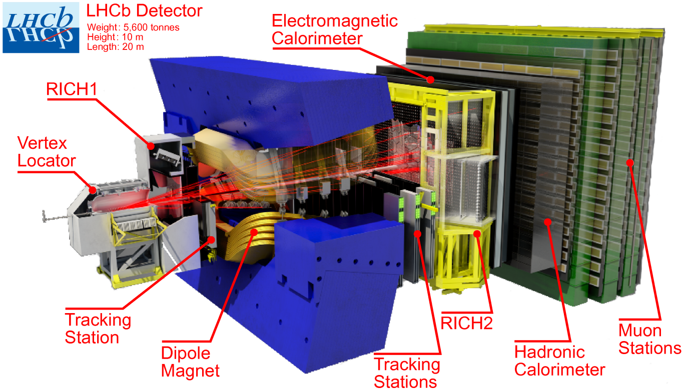

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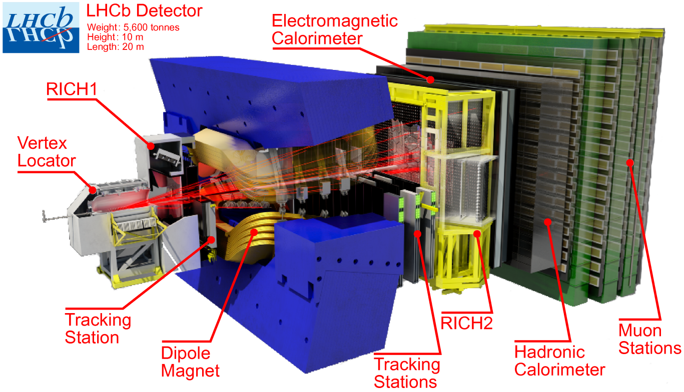

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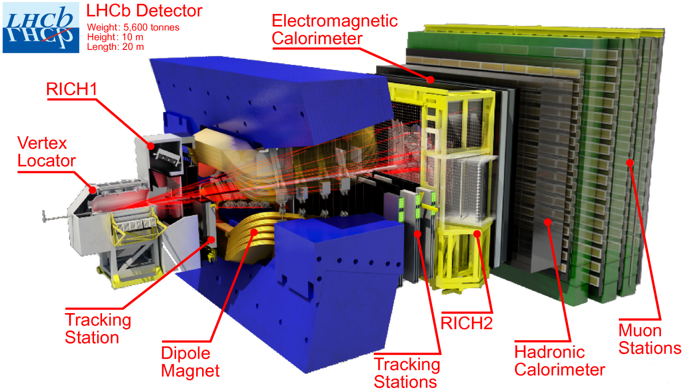

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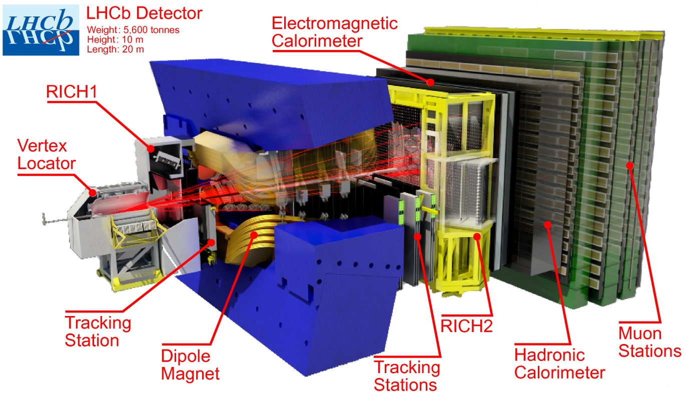

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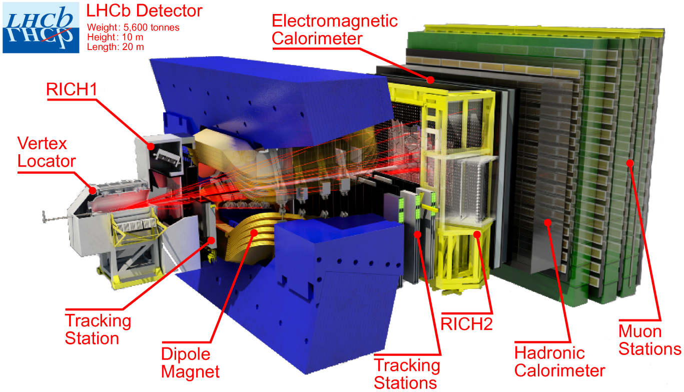

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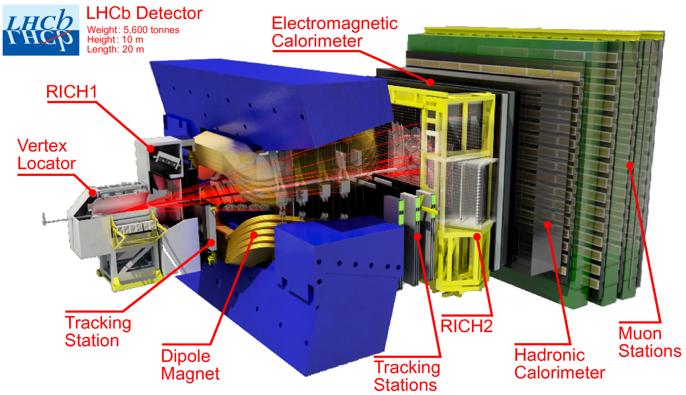

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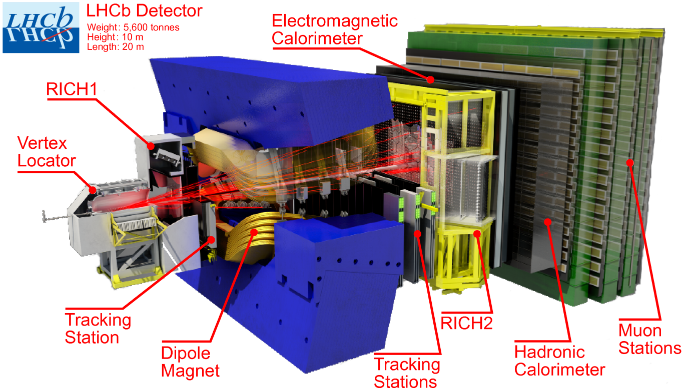

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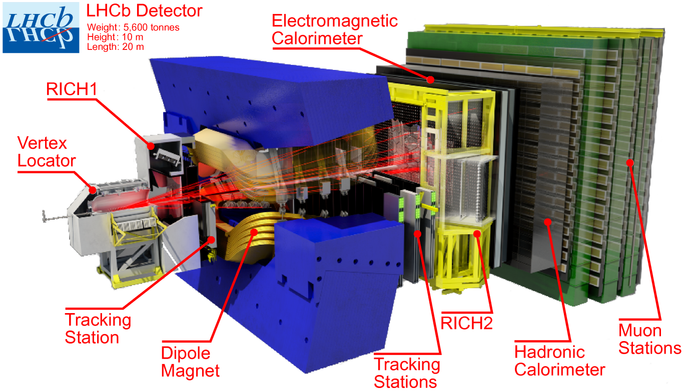

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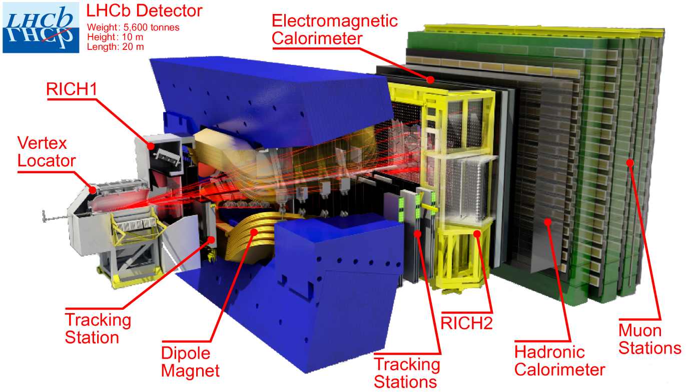

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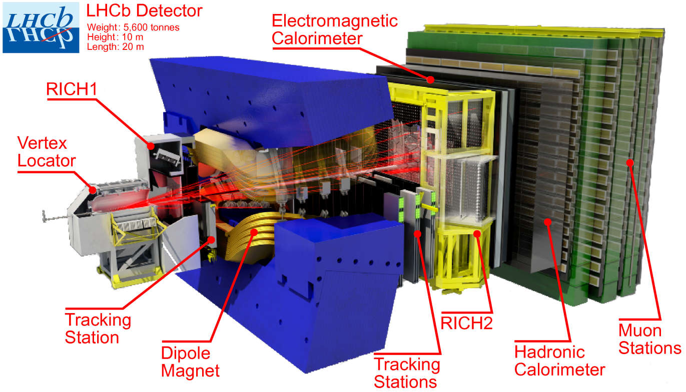

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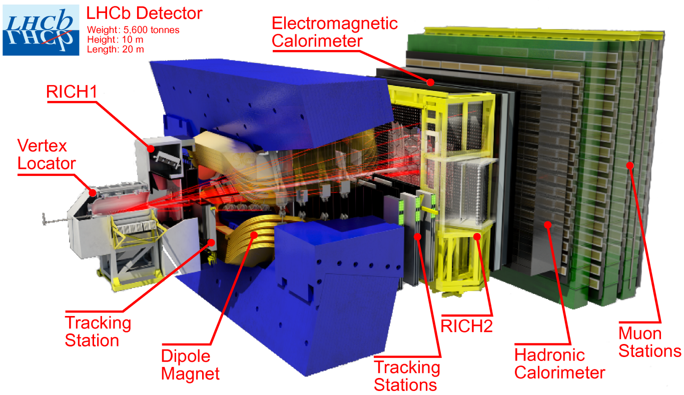

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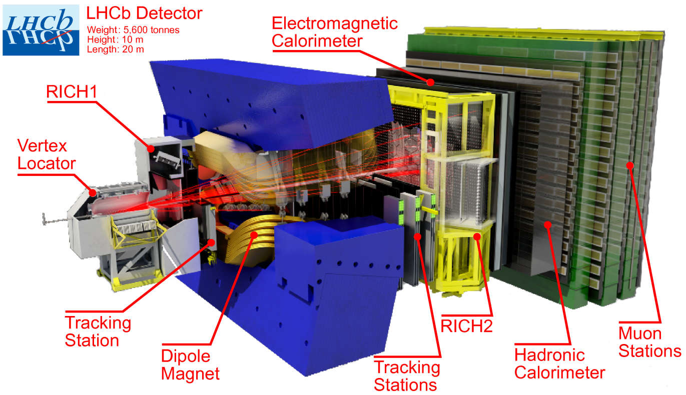

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Reconstructs $\mathrm{K}^0_\mathrm{S} \to \pi^+\pi^-$, $\Lambda^0 \to \mathrm{p}\,\pi^-$, $\pi^0 \to \gamma\gamma$, ...

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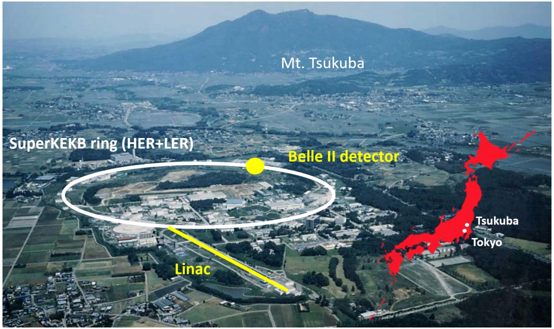

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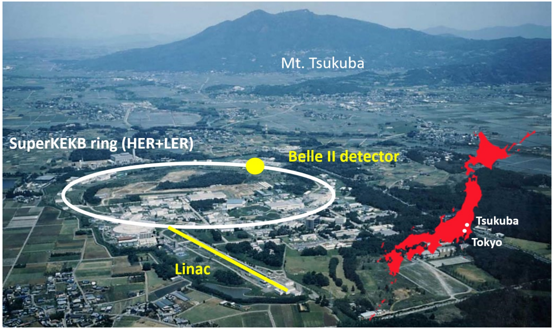

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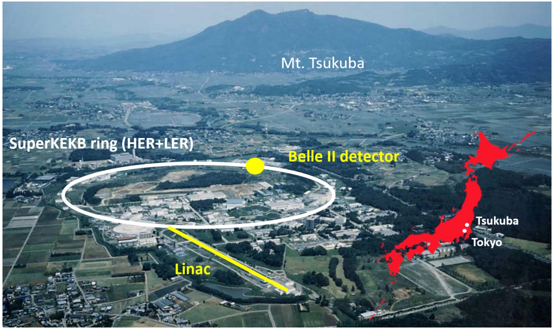

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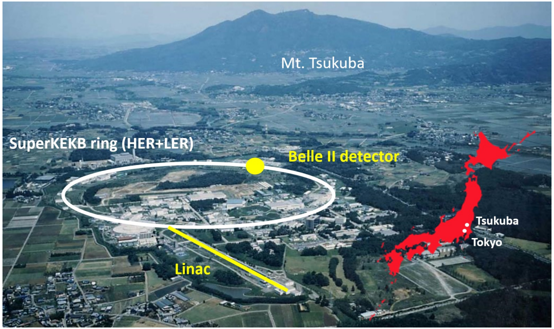

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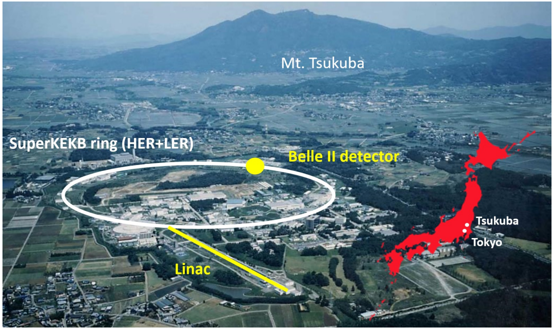

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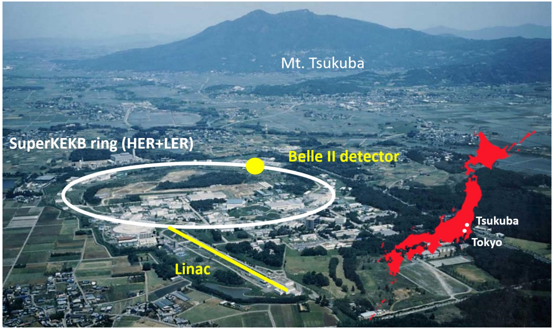

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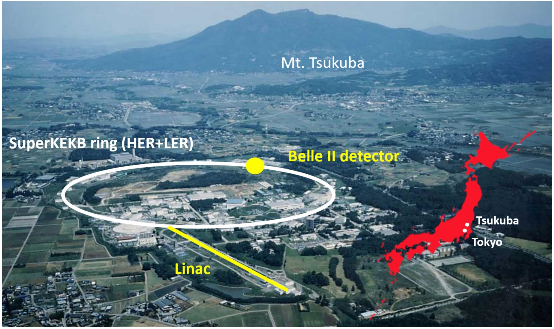

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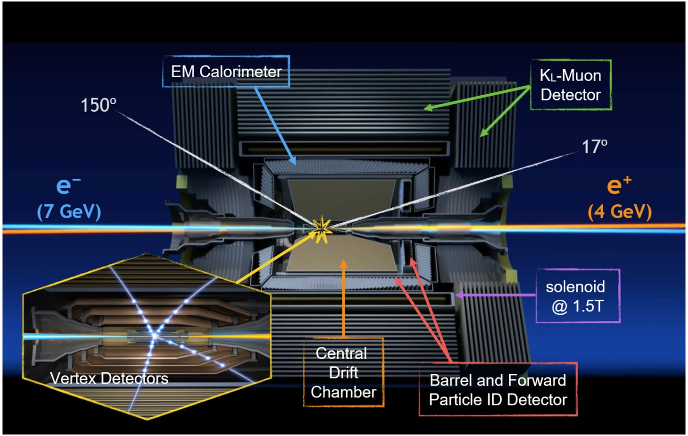

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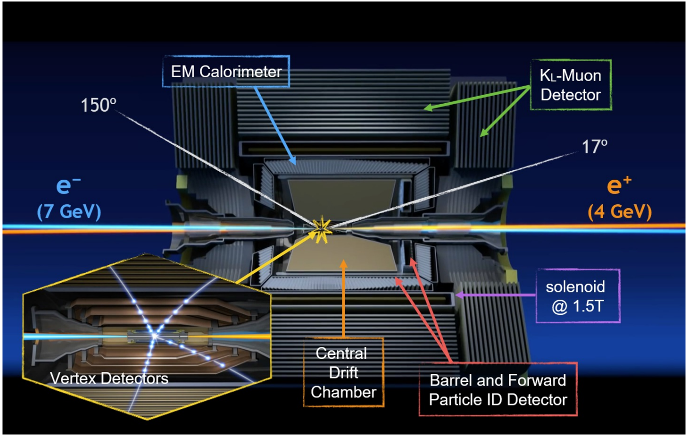

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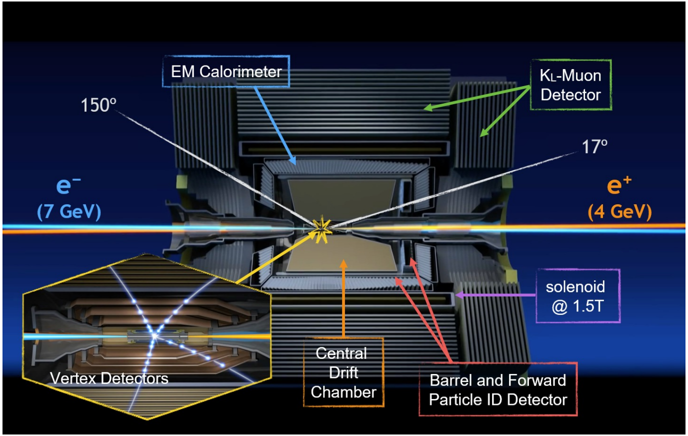

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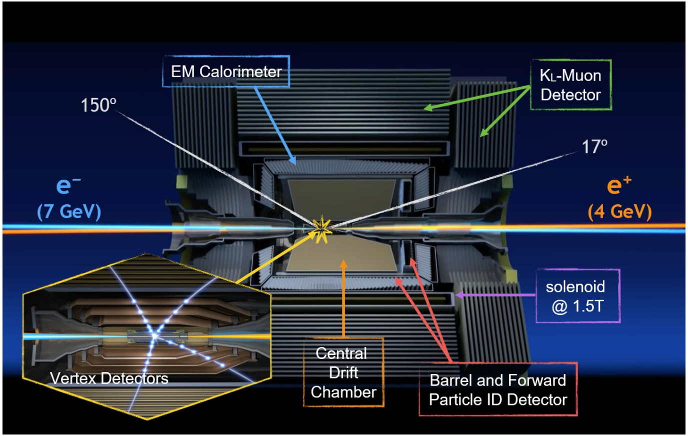

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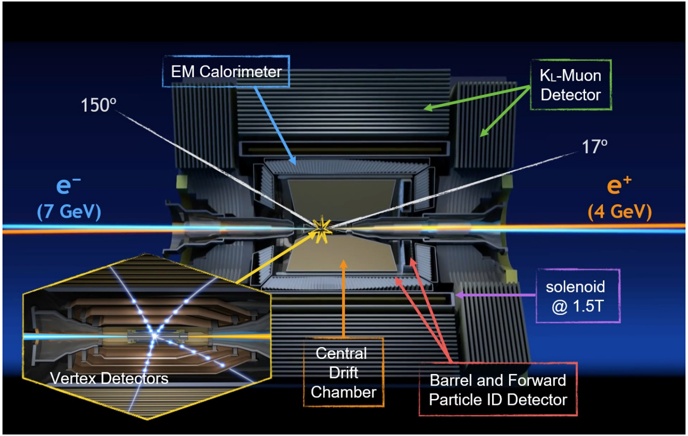

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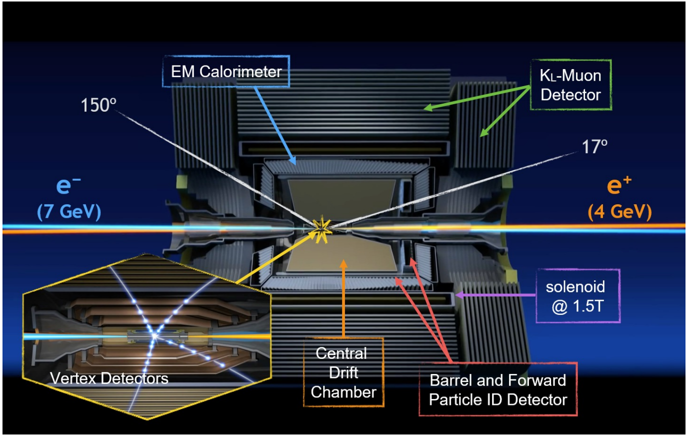

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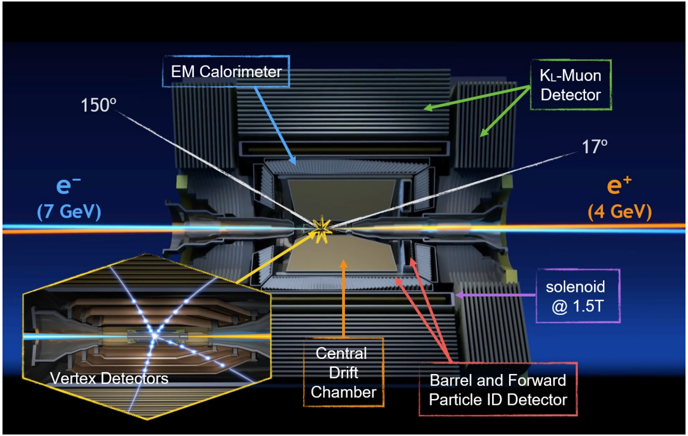

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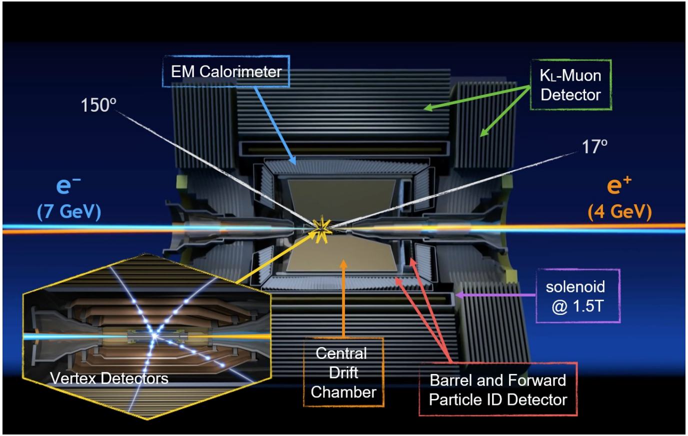

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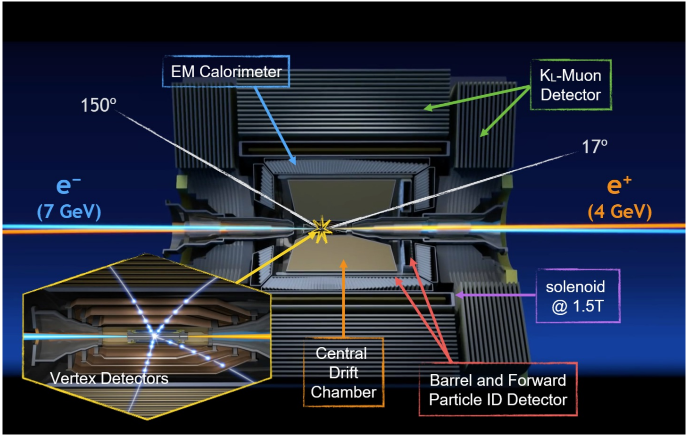

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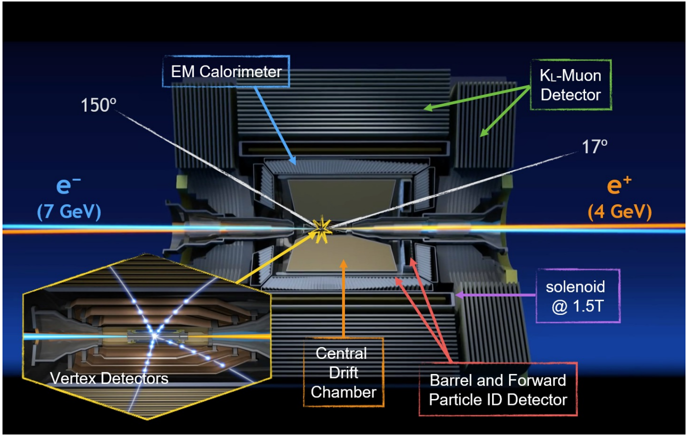

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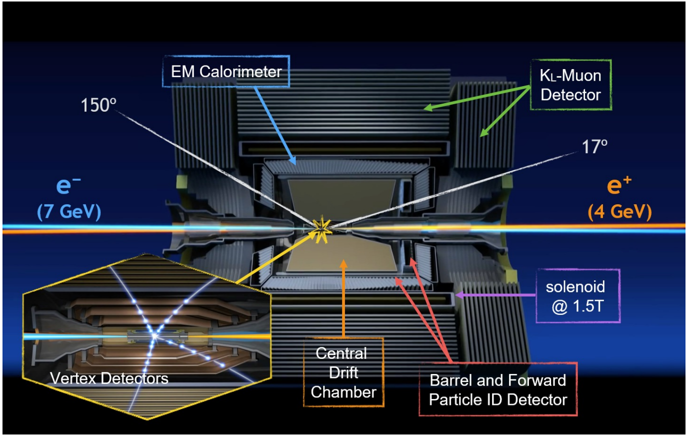

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- **$\mathrm{K_L}$ & muon detector**

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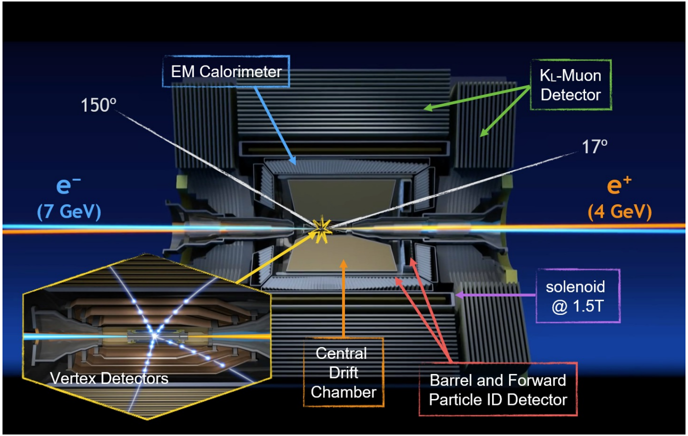

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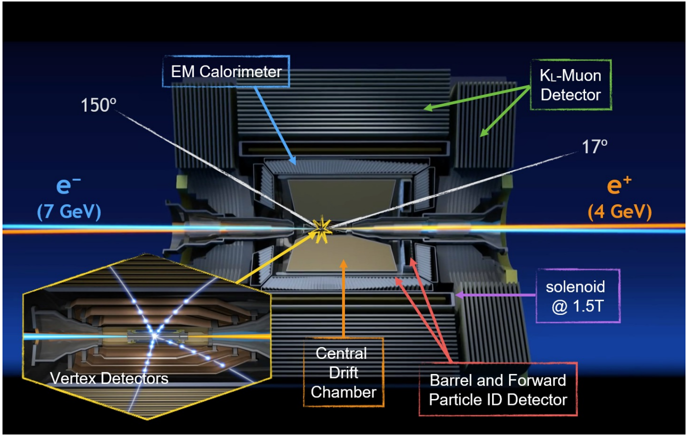

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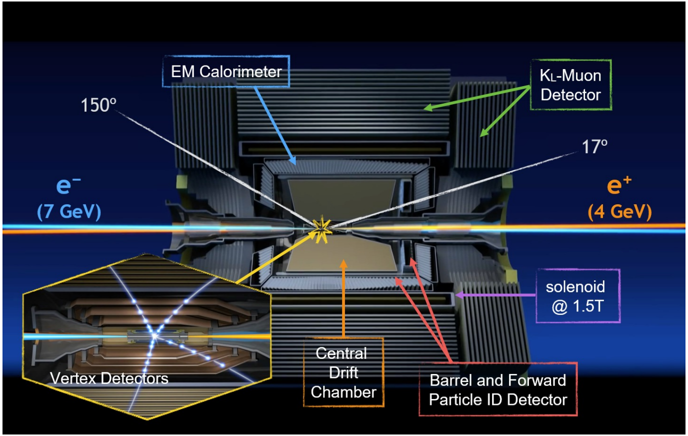

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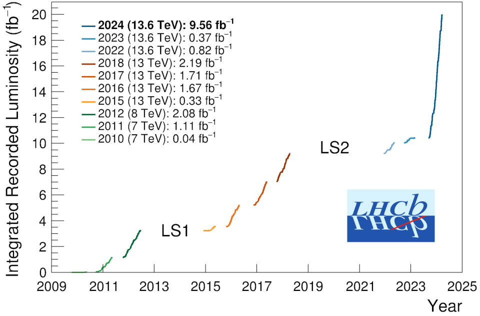

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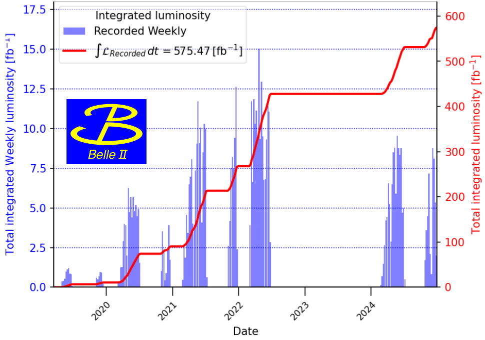

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German Contributions

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LHCb: search for CP violation in baryon decay

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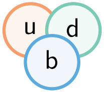

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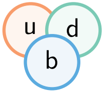

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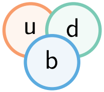

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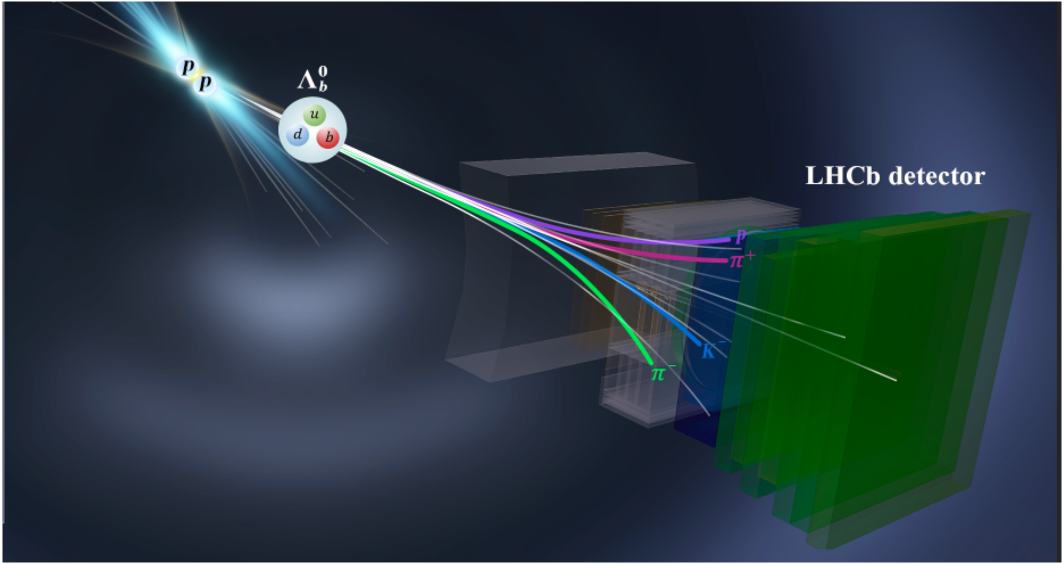

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LHCb: Λ_b^0 decay-rate CP asymmetries

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$$p\,\pi^-\pi^+K^-, \quad \Lambda^0\pi^+\pi^-, \quad \Lambda^0K^+\pi^-, \quad \Lambda^0\pi^+K^-, \qquad\qquad (\Lambda^0 \to p\pi^-)$$

- Require
  - they come from common point far from pp collision since Λ_b^0 flies before decaying.
  - their momentum sum point back to pp collision since Λ_b^0 comes from pp interaction.
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- Use machine-learning algorithm to remove random background

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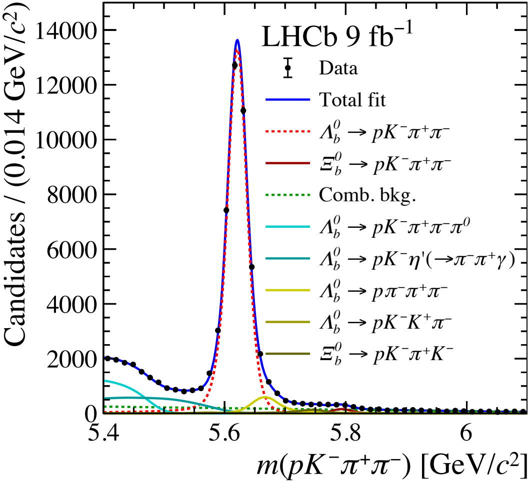

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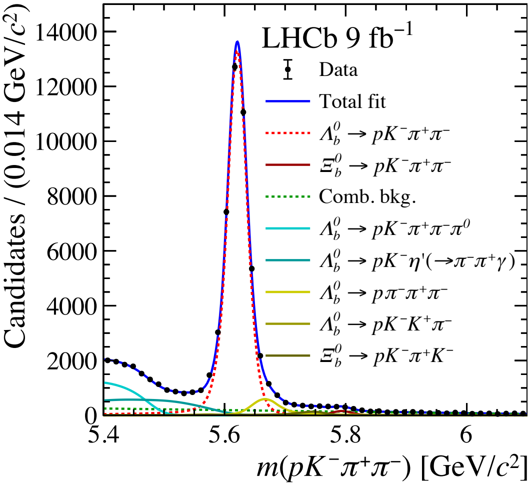

Fit to the mass spectrum to get signal yield, $N(\Lambda_b^0 \to \cdots)$

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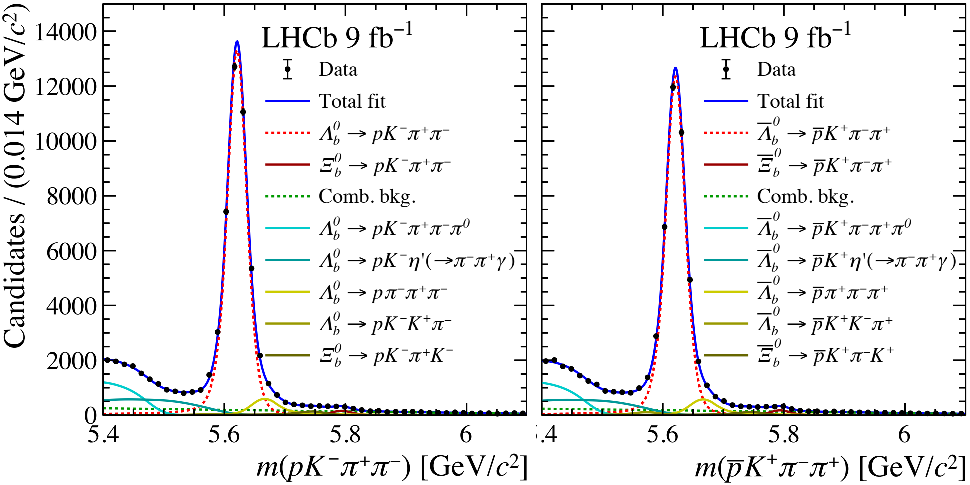

Fit to the mass spectra to get signal yields, $N(\Lambda_b^0 \to \cdots)$ and $N(\overline{\Lambda}_b^0 \to \overline{\cdots})$.

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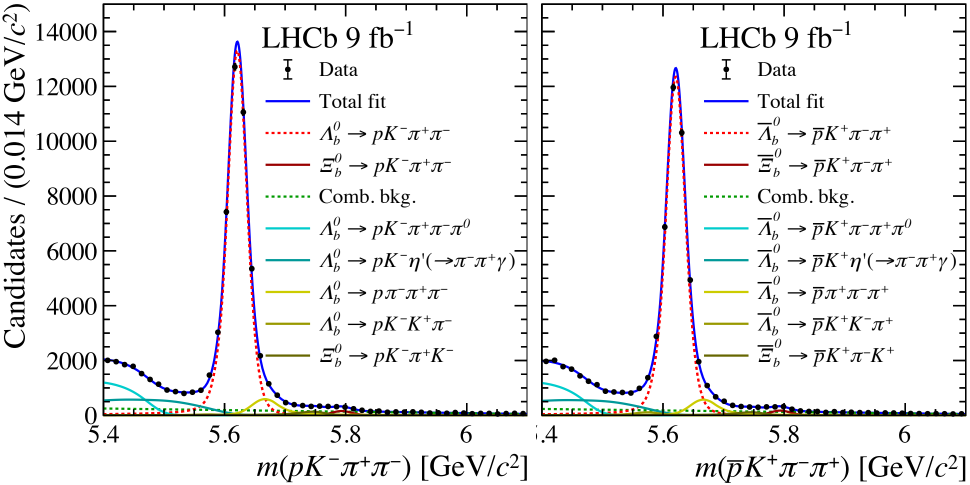

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$$A_{\rm CP}(\Lambda_b^0 \to \Lambda^0 K^+ K^-) = (8.3 \pm 2.3 \pm 1.6)\%$$

[LHCb: PRL134.101802 2025]

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$A_{\rm CP}(\Lambda_b^0 \to p\,K^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$ [LHCb: Moriond EW, 2025]

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$A_{\rm CP}(\Lambda_b^0 \to \Lambda^0 K^+ K^-) = (8.3 \pm 2.3 \pm 1.6)\% \quad \to \quad 3.1\sigma$ [LHCb: PRL134.101802 2025]

$A_{\rm CP}(\Lambda_b^0 \to p\, K^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\% \quad \to \quad 5.2\sigma$ [LHCb: Moriond EW, 2025]

LHCb: Λ_b^0 decay-rate CP asymmetries

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2019	CP violation in D decay	charm meson

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2025	CP violation in Λ_b^0 decay	bottom **baryon**

Belle II & LHCb: D $\to \pi\pi$ decay-rate CP asymmetries

Let's look at charm

Belle II & LHCb: D $\rightarrow \pi\pi$ decay-rate CP asymmetries

Let's look at charm—at decays of D mesons

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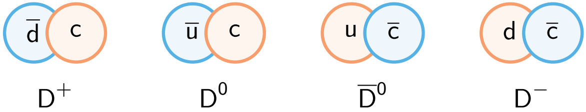

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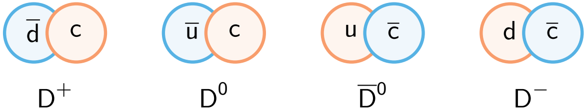

to pion pairs

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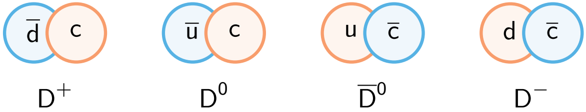

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isospin superpositions: $0{+}1{+}2$, $0{+}2$, 2

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Belle II & LHCb: D $\to \pi\pi$ decay-rate CP asymmetries

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$\boxed{\text{isospin } \frac{1}{2}}$

to pion pairs

$\pi^+\pi^0$ $\pi^+\pi^-$ $\pi^0\pi^0$

$\boxed{\text{isospin superpositions: } 0{+}1{+}2,\ 0{+}2,\ 2}$

Standard model:

$$A_{\mathrm{CP}}^{\mathrm{SM}}(|\Delta I|{=}\tfrac{3}{2}\ \mathrm{D} \to \pi\pi) = 0 \quad \text{and} \quad A_{\mathrm{CP}}^{\mathrm{SM}}(|\Delta I|{=}\tfrac{1}{2}\ \mathrm{D} \to \pi\pi) \ll 1$$

- $D^+ \to \pi^+\pi^0$ only has $|\Delta I| = \frac{3}{2}$,

Belle II & LHCb: D $\to \pi\pi$ decay-rate CP asymmetries

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- $\mathrm{D}^+ \to \pi^+\pi^0$ only has $|\Delta I| = \frac{3}{2}$, so $A_{\mathrm{CP}}^{\mathrm{SM}}(\mathrm{D}^+ \to \pi^+\pi^-) = 0$
- $\mathrm{D}^0 \to \pi\pi$ has both $|\Delta I| = \frac{1}{2}$ and $\frac{3}{2}$, but nonzero $A_{\mathrm{CP}}^{\mathrm{SM}}$ only from $|\Delta I|{=}\frac{1}{2}$ part.

Belle II & LHCb: D $\to \pi\pi$ decay-rate CP asymmetries

- $A_{\mathrm{CP}}^{\mathrm{SM}}(\mathsf{D}^+ \to \pi^+\pi^0) = 0$
- $A_{\mathrm{CP}}^{\mathrm{SM}}(\mathsf{D}^0 \to \pi\pi)$ only from $A_{\mathrm{CP}}^{\mathrm{SM}}(|\Delta I|=\frac{1}{2}\ \mathsf{D} \to \pi\pi)$ and small

Belle II & LHCb: $\mathsf{D} \to \pi\pi$ decay-rate CP asymmetries

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Asymmetries are limiting inputs,

Belle II & LHCb: D $\to \pi\pi$ decay-rate CP asymmetries

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Asymmetries are limiting inputs, $A_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^0\pi^0)$ most limiting.

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

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$$A_{\mathrm{CP}}(D^0 \to \pi^0\pi^0) = \frac{\Gamma(D^0 \to \pi^0\pi^0) - \Gamma(\overline{D}^0 \to \pi^0\pi^0)}{\Gamma(D^0 \to \pi^0\pi^0) + \Gamma(\overline{D}^0 \to \pi^0\pi^0)}$$

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Distinguish $D^0 \to \pi^0\pi^0$ and $\overline{D}^0 \to \pi^0\pi^0$

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Distinguish $D^0 \to \pi^0\pi^0$ and $\overline{D}^0 \to \pi^0\pi^0$ by requiring they come from $D^{*\pm}$ decay:

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$$\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+ \qquad \mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-$$

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- Find final state particles: $\pi^\pm\pi^0\pi^0$

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- Require

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- Require
  - $\pi^0\pi^0$ mass be consistent with D^0 mass
  - $\pi^\pm\pi^0\pi^0$ mass consistent with $D^{*\pm}$-D^0 mass difference

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- Find final state particles: $\pi^\pm\pi^0\pi^0$
- Require
  - $\pi^0\pi^0$ mass be consistent with D^0 mass
  - $\pi^\pm\pi^0\pi^0$ mass consistent with $D^{*\pm}$-D^0 mass difference
  - $D^{*\pm}$ have enough momentum to not come from B decay

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

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  - $\pi^\pm\pi^0\pi^0$ mass consistent with $D^{*\pm}$-D^0 mass difference
  - $D^{*\pm}$ have enough momentum to not come from B decay $\longrightarrow$ don't inherit A_{CP} from B decay

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  - $\pi^\pm\pi^0\pi^0$ mass consistent with $D^{*\pm}$-D^0 mass difference
  - $D^{*\pm}$ have enough momentum to not come from B decay $\longrightarrow$ don't inherit A_{CP} from B decay
- Use machine-learning algorithm to remove background.

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

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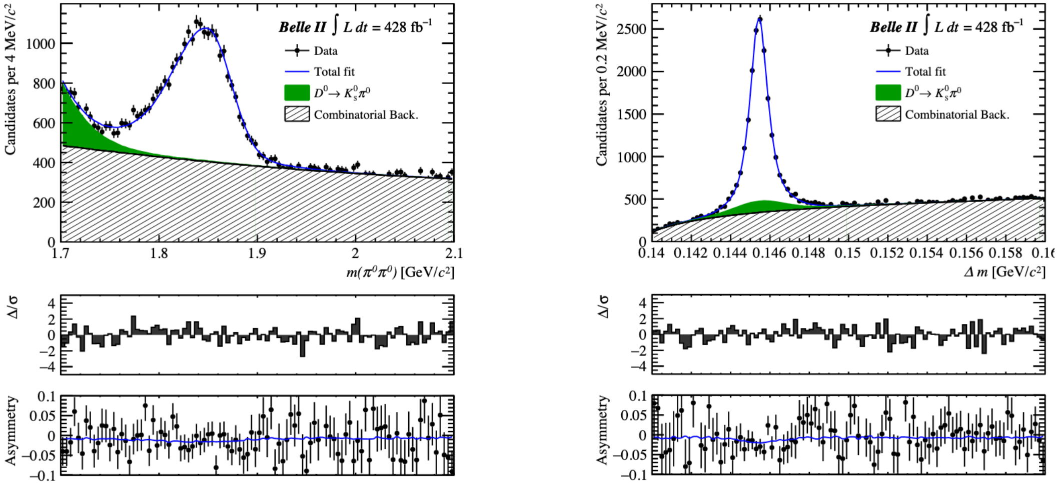
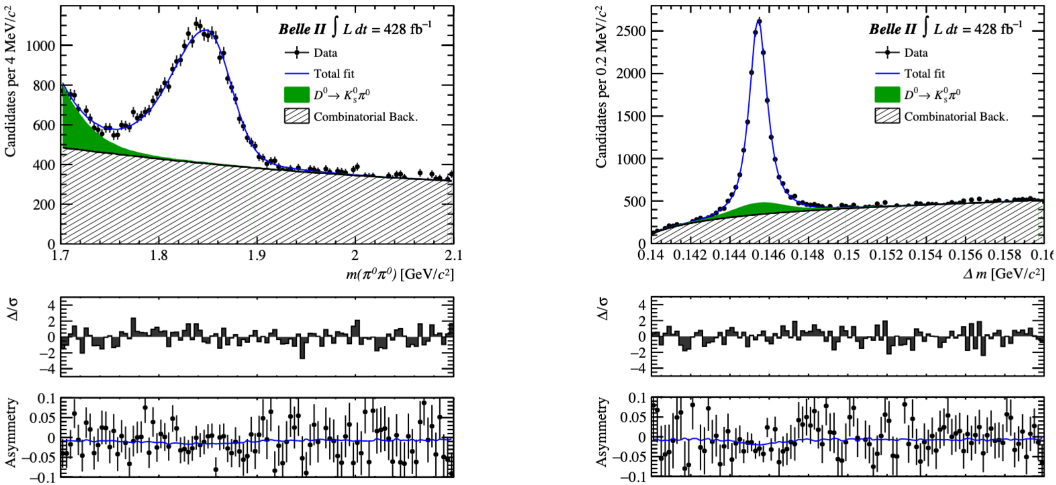


Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry



Fit to the mass and Δm spectra to get signal yields, $N(D^0 \to \pi^0\pi^0)$ and $N(\overline{D}^0 \to \pi^0\pi^0)$.

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

Again this the **raw** asymmetry is not the CP one

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$$A_N(D^{*+} \to D^0\pi^+, D^0 \to \pi^0\pi^0) = A_{\mathrm{CP}}(D^0 \to \pi^0\pi^0) + A_{\mathrm{prod}}(D^{*+}) + A_{\mathrm{det}}(\pi^+)$$

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- $A_{\rm prod}(D^0) \equiv$ from $e^+e^- \to c\bar{c}$ forward-backward asymmetry

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  cancel by averaging over forward and backward D^*

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$$\overline{A}_N \equiv \tfrac{1}{2}\left[A_N^{\mathrm{F}} + A_N^{\mathrm{B}}\right]$$

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Again this the **raw** asymmetry is not the CP one

$$A_N(D^{*+} \to D^0\pi^+, D^0 \to \pi^0\pi^0) = A_{\mathrm{CP}}(D^0 \to \pi^0\pi^0) + A_{\mathrm{prod}}(D^{*+}) + A_{\mathrm{det}}(\pi^+)$$

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$$\overline{A}_N \equiv \frac{1}{2}\left[A_N^{\mathrm{F}} + A_N^{\mathrm{B}}\right] = A_{\mathrm{CP}}(D^0 \to \pi^0\pi^0) + A_{\mathrm{det}}(\pi^+)$$

Belle II: $\mathrm{D}^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

Again this the **raw** asymmetry is not the CP one

$$A_N(\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+, \mathrm{D}^0 \to \pi^0\pi^0) = A_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^0\pi^0) + A_{\mathrm{prod}}(\mathrm{D}^{*+}) + A_{\mathrm{det}}(\pi^+)$$

- $A_{\mathrm{prod}}(\mathrm{D}^0) \equiv$ from $\mathrm{e}^+\mathrm{e}^- \to \mathrm{c}\bar{\mathrm{c}}$ forward-backward asymmetry
  cancel by averaging over forward and backward D^*

$$\overline{A}_N \equiv \frac{1}{2}\left[A_N^{\mathrm{F}} + A_N^{\mathrm{B}}\right] = A_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^0\pi^0) + A_{\mathrm{det}}(\pi^+)$$

- calculate $A_{\mathrm{det}}(\pi^+)$ from $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+, \mathrm{D}^0 \to \mathrm{K}^-\pi^+$

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

Again this the **raw** asymmetry is not the CP one

$$A_N(D^{*+} \to D^0\pi^+, D^0 \to \pi^0\pi^0) = A_{\rm CP}(D^0 \to \pi^0\pi^0) + A_{\rm prod}(D^{*+}) + A_{\rm det}(\pi^+)$$

- $A_{\rm prod}(D^0) \equiv$ from $e^+e^- \to c\bar{c}$ forward-backward asymmetry
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- calculate $A_{\rm det}(\pi^+)$ from $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$

$$\overline{A}_N(D^0 \to K^-\pi^+, \textbf{w/}\ D^* \text{ req.}) = A_{\rm CP}(D^0 \to K^-\pi^+) + A_{\rm det}(\pi^+) + A_{\rm det}(K^-\pi^+)$$

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

Again this the **raw** asymmetry is not the CP one

$$A_N(D^{*+} \to D^0\pi^+, D^0 \to \pi^0\pi^0) = A_{\rm CP}(D^0 \to \pi^0\pi^0) + A_{\rm prod}(D^{*+}) + A_{\rm det}(\pi^+)$$

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$$\overline{A}_N(D^0 \to K^-\pi^+, \textbf{w/o } D^* \text{ req.}) = A_{\rm CP}(D^0 \to K^-\pi^+) + A_{\rm det}(K^-\pi^+)$$

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

Again this the **raw** asymmetry is not the CP one

$$A_N(D^{*+} \to D^0\pi^+, D^0 \to \pi^0\pi^0) = A_{CP}(D^0 \to \pi^0\pi^0) + A_{prod}(D^{*+}) + A_{det}(\pi^+)$$

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$$\overline{A}_N(D^0 \to K^-\pi^+, \textbf{w/ } D^* \text{ req.}) = A_{CP}(D^0 \to K^-\pi^+) + A_{det}(\pi^+) + A_{det}(K^-\pi^+)$$
$$\overline{A}_N(D^0 \to K^-\pi^+, \textbf{w/o } D^* \text{ req.}) = A_{CP}(D^0 \to K^-\pi^+) + A_{det}(K^-\pi^+)$$

So

$$A_{det}(\pi^+) = \overline{A}_N(D^0 \to K^-\pi^+, \textbf{w/ } D^* \text{ req.}) - \overline{A}_N(D^0 \to K^-\pi^+, \textbf{w/o } D^* \text{ req.})$$

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

$$\boxed{A_{\rm CP}(D^0 \to \pi^0\pi^0) = (3.0 \pm 7.2 \pm 2.0) \times 10^{-3}}$$

[Belle & Belle II: Moriond EW, 2025]

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Let's calculate $A_{\mathrm{CP}}(|\Delta I| = \frac{1}{2}\ D \to \pi\pi)$.

Using

- $A_{\mathrm{CP}}(D^0 \to \pi^0\pi^0) = (1.1 \pm 4.9) \times 10^{-3}$ from Belle II (2025) and Belle (2014)

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$$\boxed{A_{\mathrm{CP}}(|\Delta I| = \tfrac{1}{2}\ \mathrm{D} \to \pi\pi) = (1.5 \pm 0.4 \pm 2.1 \pm 1.4) \times 10^{-3} = (1.5 \pm 2.5) \times 10^{-3}}$$

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

$$\boxed{A_{CP}(D^0 \to \pi^0\pi^0) = (3.0 \pm 7.2 \pm 2.0) \times 10^{-3}}$$

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uncertainty from $D^0 \to \pi^0\pi^0$ drops by 25%,

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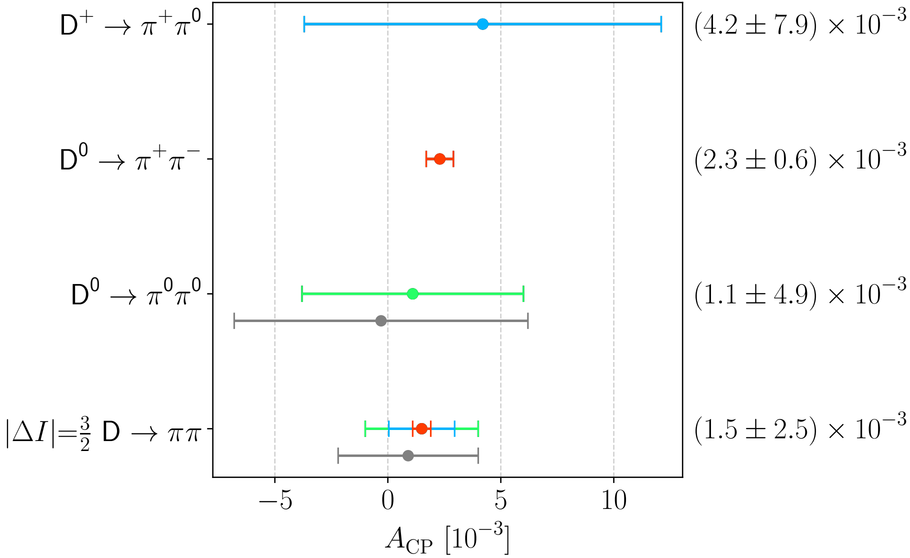
uncertainty from $D^0 \to \pi^0\pi^0$ drops by 25%, total uncertainty drops by 19%.

Status in D $\to \pi\pi$



Belle II: new measurements of $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$

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In standard model $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ could be as large as %.

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- **charm flavor tagger**

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  new algorithm that looks at rest of event,

$$\mathrm{e}^+\mathrm{e}^- \to \mathrm{c}\bar{\mathrm{c}} \to \mathrm{D}^0 + X_{\bar{\mathrm{c}}}$$

[Belle II: PRD107.112010, 2023]

Belle II: new measurements of $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}_\mathrm{S}^0\mathrm{K}_\mathrm{S}^0)$

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  $$A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-1.4 \pm 1.3 \pm 0.1)\%$$

  [Belle II: PRD111.012015, 2025]

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[Belle II: PRD107.112010, 2023]

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$$A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (1.3 \pm 2.0 \pm 0.3)\%$$

[Belle II: Moriond EW, 2025]

Belle II: new measurements of $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$

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[Belle II: Moriond EW, 2025]

- combined:

$$A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-0.6 \pm 1.1 \pm 0.1)\%$$

[Belle II: Moriond EW, 2025]

Belle II: new measurements of $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$

In standard model $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ could be as large as %.

Belle II measured it (using Belle data, too), learning D^0 flavor from

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[Belle II: Moriond EW, 2025]

- and with LHCb (2021, 2015) & Belle (2017)

$$\boxed{A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-1.3 \pm 0.8)\%}$$

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Nearing CP-violation discovery.

LHCb: new search for CP violation in $D^0 \to K^{\pm}\pi^{\mp}$

LHCb: new search for CP violation in $D^0 \to K^\pm \pi^\mp$

LHCb recently measured decay-time dependence of decay-rate ratios

$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(\overline{D}^0 \to K^+\pi^-)}$$

LHCb: new search for CP violation in $D^0 \to K^\pm \pi^\mp$

LHCb recently measured decay-time dependence of decay-rate ratios

$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(\overline{D}^0 \to K^+\pi^-)} \quad \text{and} \quad \frac{\Gamma(\overline{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+)}$$

LHCb: new search for CP violation in $D^0 \to K^{\pm}\pi^{\mp}$

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where D^0 and $\overline{D}^0$ are the produced states—they oscillate before decaying.

LHCb: new search for CP violation in $D^0 \to K^\pm \pi^\mp$

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From this, we learn about D^0-$\overline{D}^0$ mixing

LHCb: new search for CP violation in $\mathrm{D}^0 \to \mathrm{K}^\pm \pi^\mp$

LHCb recently measured decay-time dependence of decay-rate ratios

$$\frac{\Gamma(\mathrm{D}^0 \to \mathrm{K}^+\pi^-)}{\Gamma(\overline{\mathrm{D}}^0 \to \mathrm{K}^+\pi^-)} \quad \text{and} \quad \frac{\Gamma(\overline{\mathrm{D}}^0 \to \mathrm{K}^-\pi^+)}{\Gamma(\mathrm{D}^0 \to \mathrm{K}^-\pi^+)}$$

where D^0 and $\overline{\mathrm{D}}^0$ are the produced states—they oscillate before decaying.

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and $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^+\pi^-)$,

LHCb: new search for CP violation in $\mathsf{D}^0 \to \mathsf{K}^\pm\pi^\mp$

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From this, we learn about D^0-$\overline{\mathsf{D}}^0$ mixing

and $A_{\mathrm{CP}}(\mathsf{D}^0 \to \mathsf{K}^+\pi^-)$, which the standard-model expects to be zero (less than 10^{-5}).

LHCb: new search for CP violation in $D^0 \to K^\pm \pi^\mp$

LHCb recently measured decay-time dependence of decay-rate ratios

$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(\overline{D}^0 \to K^+\pi^-)} \quad \text{and} \quad \frac{\Gamma(\overline{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+)}$$

where D^0 and $\overline{D}^0$ are the produced states—they oscillate before decaying.

From this, we learn about D^0-$\overline{D}^0$ mixing

and $A_{CP}(D^0 \to K^+\pi^-)$, which the standard-model expects to be zero (less than 10^{-5}).

$$\boxed{A_{CP}(D^0 \to K^+\pi^-) = (-6.6 \pm 5.7) \times 10^{-3}}$$

[LHCb: PRD111.012001, 2025]

Inching towards testing the standard model.

Belle II: Testing lepton universality with leptonic τ decay

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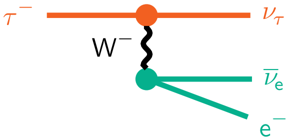

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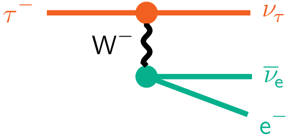

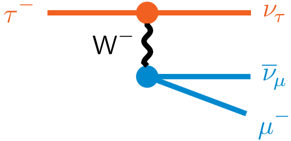

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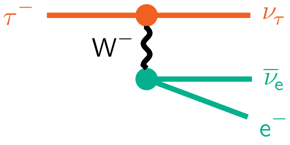

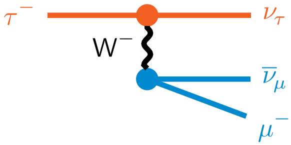

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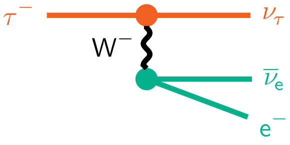

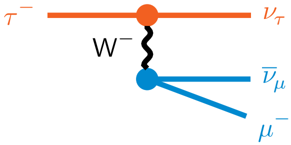

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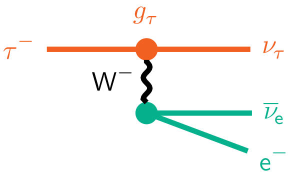

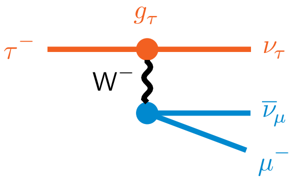

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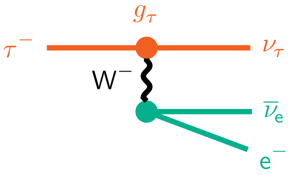

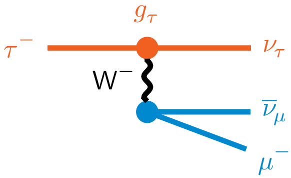

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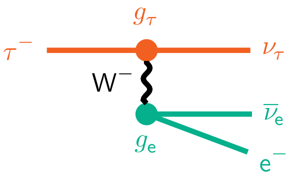

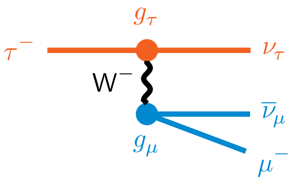

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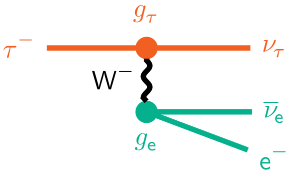

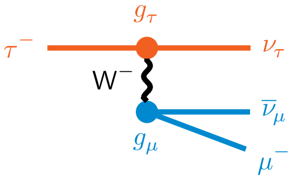

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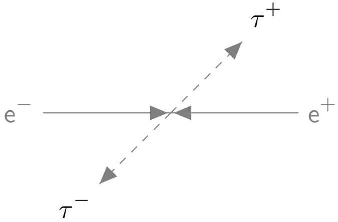

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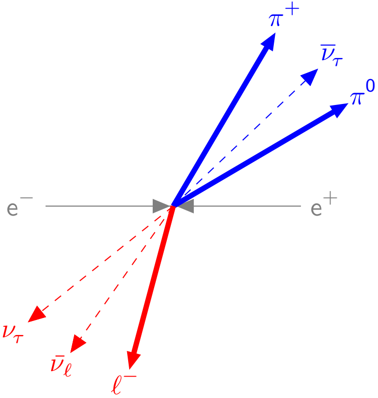

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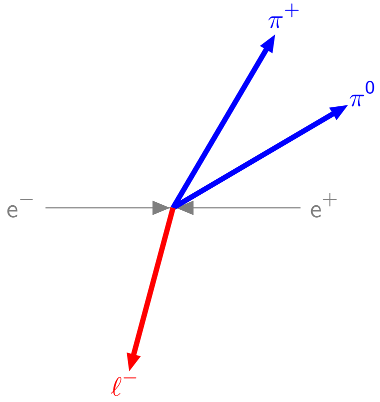

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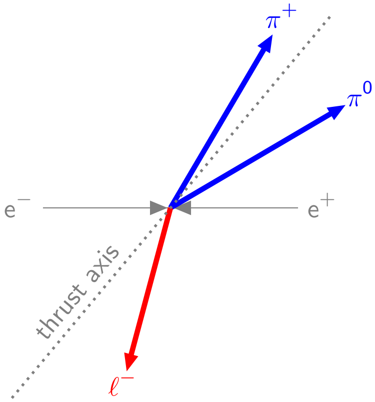

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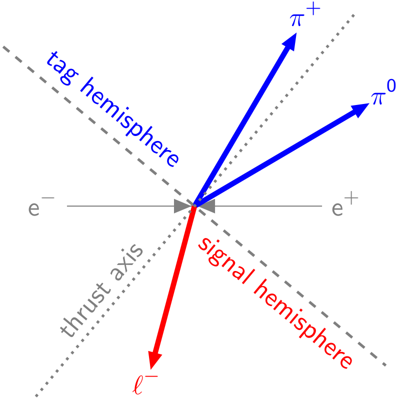

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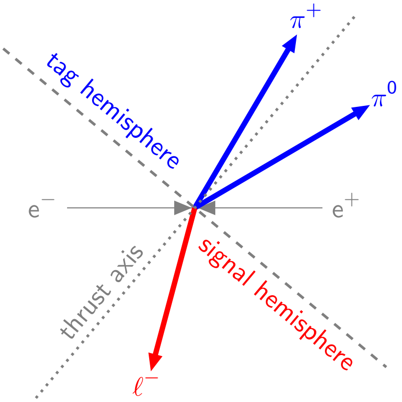

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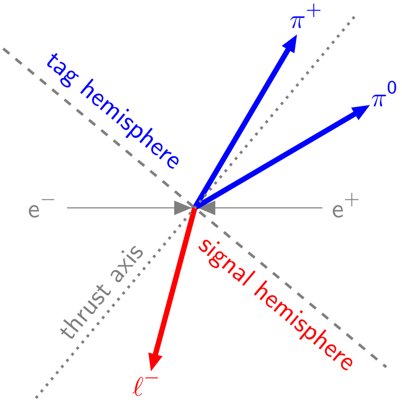

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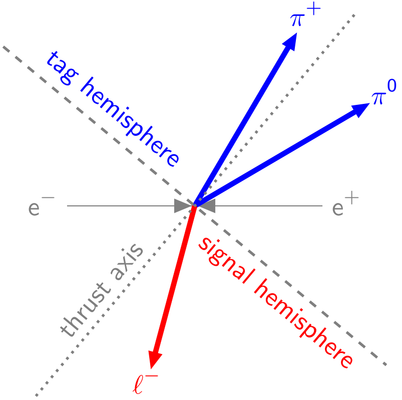

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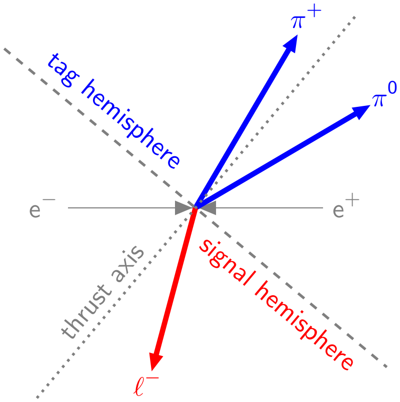

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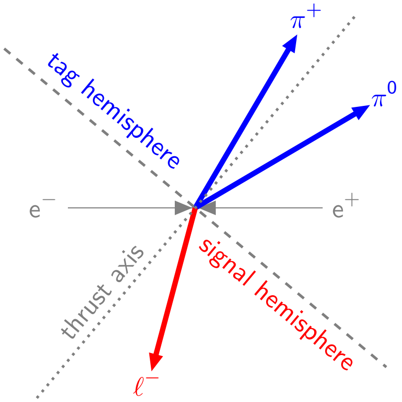

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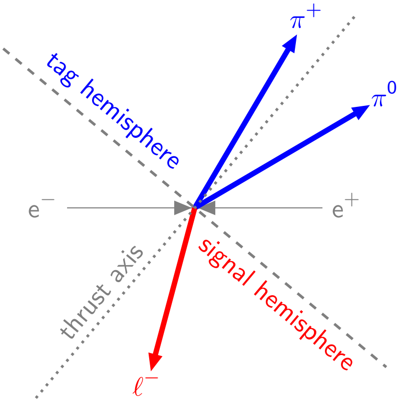

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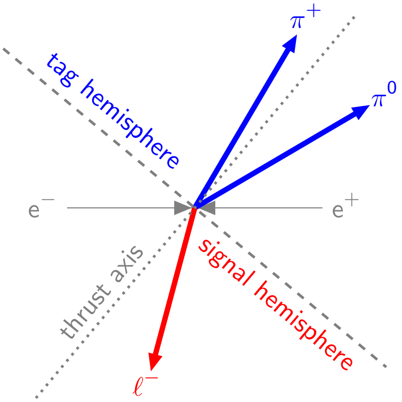

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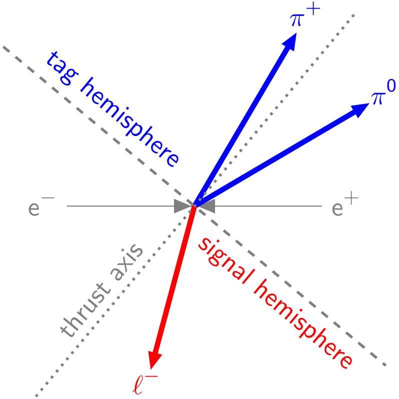

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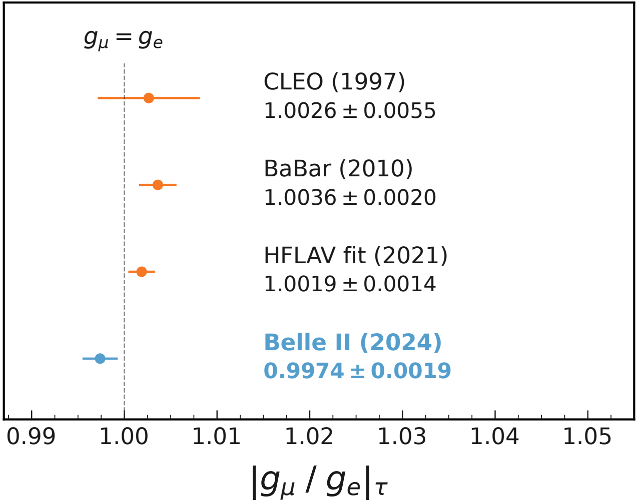

[Belle II: JHEP08.205, 2024]

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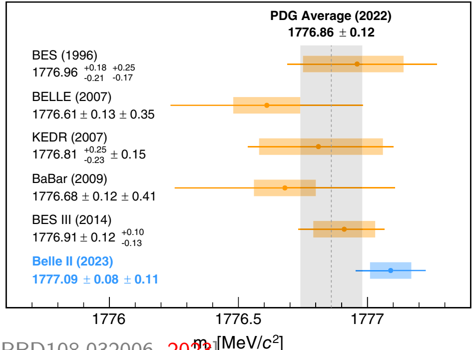

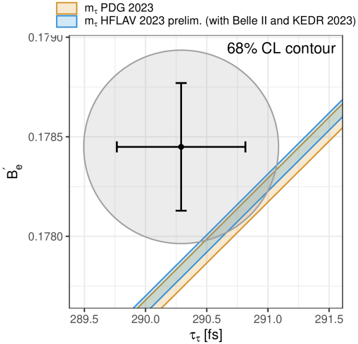

[Belle II: PRD108.032006, 2023]

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Both experiments are active in many other areas, including

- study of quarkonia, tetraquarks, pentaquarks
- dark-matter searches
- measuring quark-mixing-matrix parameters
- hadron spectroscopy
- measuring electroweak parameters
- study of B mesons

Some event counts

- $A_{\mathrm{CP}}(\Lambda_b^0 \to \cdots)$ @ LHCb

$\Lambda_b^0\pi^+\pi^-$	636 ± 42
$\Lambda_b^0 K^+\pi^-$	618 ± 32
$\Lambda_b^0 K^+K^-$	1920 ± 50
$p\,K^+\pi^+\pi^-$	$80\,690 \pm 340$

- $A_{\mathrm{CP}}(D^0 \to \cdots)$ @ Belle II

$\pi^0\pi^0$	$\mathcal{O}\left(10^4\right)$	
$K_S^0K_S^0$	2214 ± 51	Belle II
	4864 ± 78	Belle

- $D^0 \to K^\pm\pi^\mp$ @ LHCb

$K^+\pi^-$	412×10^6
$K^-\pi^+$	1.6×10^6

- $\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$ @ Belle II

e	4.4×10^6
μ	4.4×10^6

thrust

$$|\vec{t}| \equiv \frac{\sum_i \vec{p}_i \cdot \hat{t}}{\sum_i |\vec{p}_i|}$$

The flavor intensity frontier: Belle II and LHCb and some of their recent results

Daniel Greenwald

Institute for Hadronic Structure & Fundamental Symmetries
Technische Universität München

DPG Frühjahrstagung 2025
Göttingen, April 4, 2025

What is flavor physics?

We know of the following elementary fermions

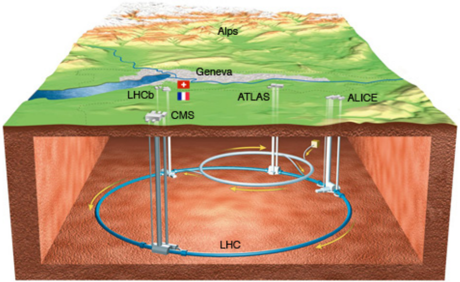
u	d	e	ν_e
c	s	μ	ν_μ
t	b	τ	ν_τ

these **flavors** are distinguishable only by their masses and couplings to the $W^\pm$ (for the quarks)

$$\boxed{\text{flavor physics} \equiv \text{study of differences and dynamics between flavors}}$$

- **Grand scheme:** find origin of mass and interaction hierarchies
- **Nearer goals:** measure standard-model parameters and search for new forces and particles

The LHCb experiment at CERN's Large Hadron Collider



The LHC symmetrically collides **protons with protons** at center-of-mass energies of **7–14 TeV**

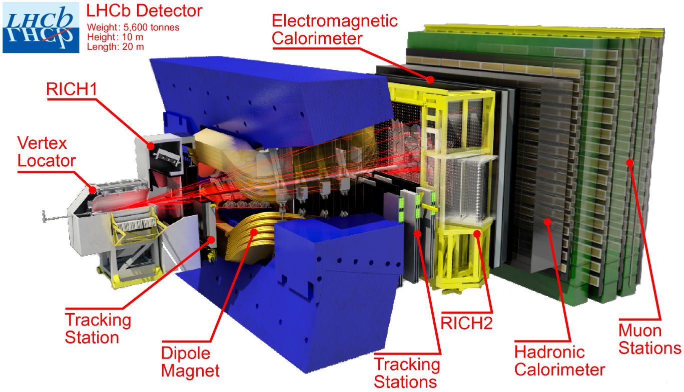
$$\mathrm{pp} \to q\bar{q} + X, \qquad \mathrm{pp} \to \mathrm{W} + X, \qquad \mathrm{pp} \to \mathrm{Z} + X$$

$q = \mathrm{u},\ \mathrm{d},\ \mathrm{s},\ \mathbf{c},\ \mathbf{b},\ \mathrm{t}$ $\qquad$ $X =$ hadrons, charged leptons, neutrinos

Only parts of protons interact with each other, at an energy much less than collision energy.

Particles of interest have high momenta in the beam directions.

The LHCb detector



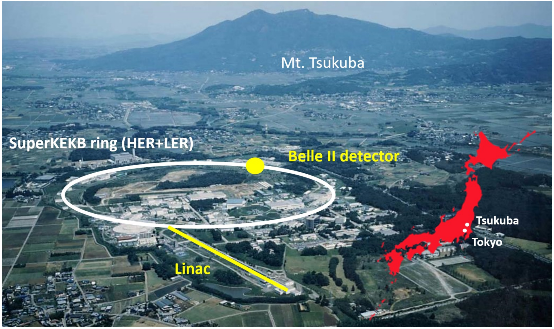
It's a **forward detector** consisting of

- **vertex & tracking detectors**
  measure charged-particle trajectories, determine p from bending in B field
- **ring-imaging Cherenkov det's**
  identify charged-particle types ($\pi^{\pm}$, $\mathrm{K}^{\pm}$, ...)
- **calorimeters**
  measure particle energies
- **muon detectors**
  detect muons

Detects and identifies $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $\mathrm{K}^{\pm}$, $p^{\pm}$; γ

Reconstructs $\mathrm{K}^0_\mathrm{S} \to \pi^+\pi^-$, $\Lambda^0 \to \mathrm{p}\,\pi^-$, $\pi^0 \to \gamma\gamma$, ...

The Belle II experiment at KEK's SuperKEKB collider



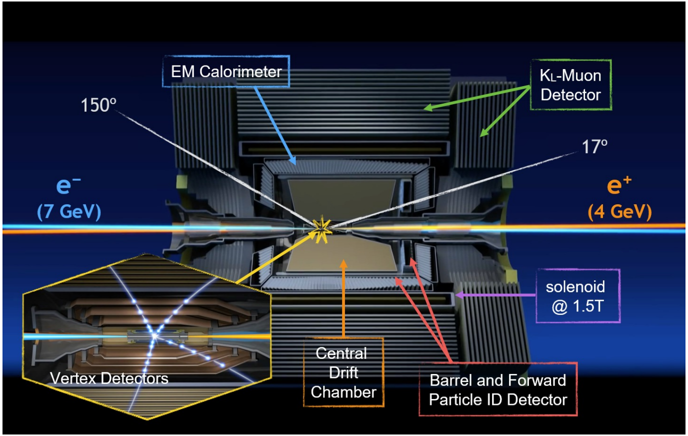
SuperKEKB asymmetrically collides **electrons with positrons** at c.m. energies near $\mathbf{10.6}$ **GeV**

$$e^+e^- \to f\bar{f}$$

$$f = e, \mu, \boldsymbol{\tau}, u, d, s, \mathbf{c}, \mathbf{b}$$

incoming $E(e^-) > E(e^+) \longrightarrow$ **outgoing system moves in electron direction** in lab frame

The Belle II detector

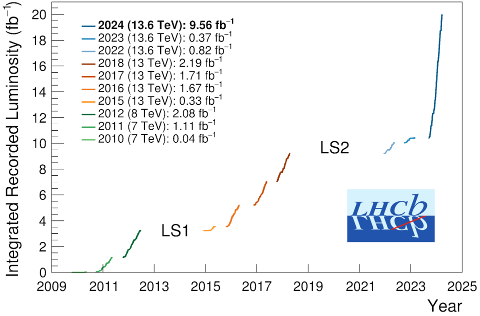


It's a 4π **detector** consisting of

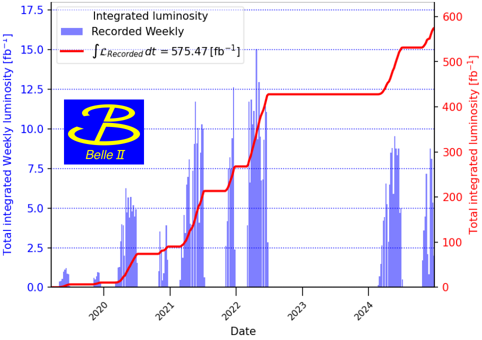
- **vertex det's & drift chamber** measure charged-particle trajectories, determine p from bending in B field
- **Particle ID (Cherenkov) det's** identify charged-particle types $(\pi^{\pm}, \mathrm{K}^{\pm}, \ldots)$
- **calorimeter** measure particle energies
- **$\mathrm{K_L}$ & muon detector** detect $\mathrm{K_L}$ & muons

Detects and identifies $\mathrm{e}^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $\mathrm{K}^{\pm}$, $p^{\pm}$; γ, $\mathrm{K_L}$
Reconstructs $\mathrm{K_S^0} \to \pi^+\pi^-$, $\Lambda^0 \to \mathrm{p}\,\pi^-$, $\pi^0 \to \gamma\gamma$, $\ldots$

- Taking data since 2010.



- Taking data since 2019.



- Taking data since 2010.
- Collected several fb^{-1} of data.
- **Millibarn cross sections** for $\mathrm{pp} \to q\bar{q} + X$.
- **trillions of events**
- **high cross sections**

- Taking data since 2019.
- **collected 100s of fb^{-1} of data**
- nanobarn cross sections for $\mathrm{e}^{+}\mathrm{e}^{-} \to f\bar{f}$.
- **100s of millions of events**
- **high luminosity** (world's highest)

$$\boxed{\textbf{lots of data} = \textbf{high intensity} \to \textbf{precise measurements}}$$

- can study particles heavier than B, 5.3 GeV
- larger lab-frame momenta
- more data

- can (better) detect γ's and reconstruct π^0's
- can study decays to invisible particles
- can study τ decay

Bundesministerium
für Bildung
und Forschung

Belle II

- 1700 members
- 100 institutes
- 22 countries

- 1200 members
- 124 institutes
- 28 countries

German Contributions

- Aachen
- Bonn
- Bochum
- Freiburg
- Dortmund
- Heidelberg
  Uni, MPK

- Bonn
- Giessen
- Göttingen
- DESY
- Heidelberg
- Karlsruhe
- Mainz
- München
  LMU, MPP, TUM

Let's look at some of the most recent measurements.

Focusing on

- **what** we measure,
  limited to my personal selection,
  given the time constraints,
- **why** we measure it, and
- **how** we measure it.

Let's start with CP violation

CP $\equiv$ swaps left-handed particles and right-handed antiparticles
CP violation $\equiv$ CP conjugated states behaving differently

Why do we care?

- Universe is CP asymmetric—made of matter, not antimatter.
  $\Rightarrow$ better understand where and how CP is violated.
- Standard model predicts particular processes are CP symmetric.
  $\Rightarrow$ search for new forces and particles beyond the standard model.

One method: measure **decay-rate CP asymmetries**

$$A_{\mathrm{CP}} \equiv \frac{\Gamma(X \to abc) - \overline{\Gamma(X \to abc)}}{\Gamma(X \to abc) + \overline{\Gamma(X \to abc)}} \in [-1, 1] = \begin{cases} \text{zero} & \to \text{ CP conserving} \\ \textbf{nonzero} & \to \textbf{ CP violating} \end{cases}$$

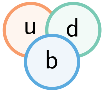
LHCb: search for CP violation in baryon decay

Why? CP violation is not a widely-scene phenomenon:

1964	**CP violation in K^0** mixing	**strange meson**
1999	CP violation in K^0 decay	strange meson
2001	**CP violation in B^0** mixing & decay	**bottom meson**
2004	CP violation in B^0 decay	bottom meson
2012	CP violation in B^+ decay	bottom meson
2013	CP violation in B_s^0 decay	bottom-strange meson
2019	**CP violation in D^0** decay	**charm meson**

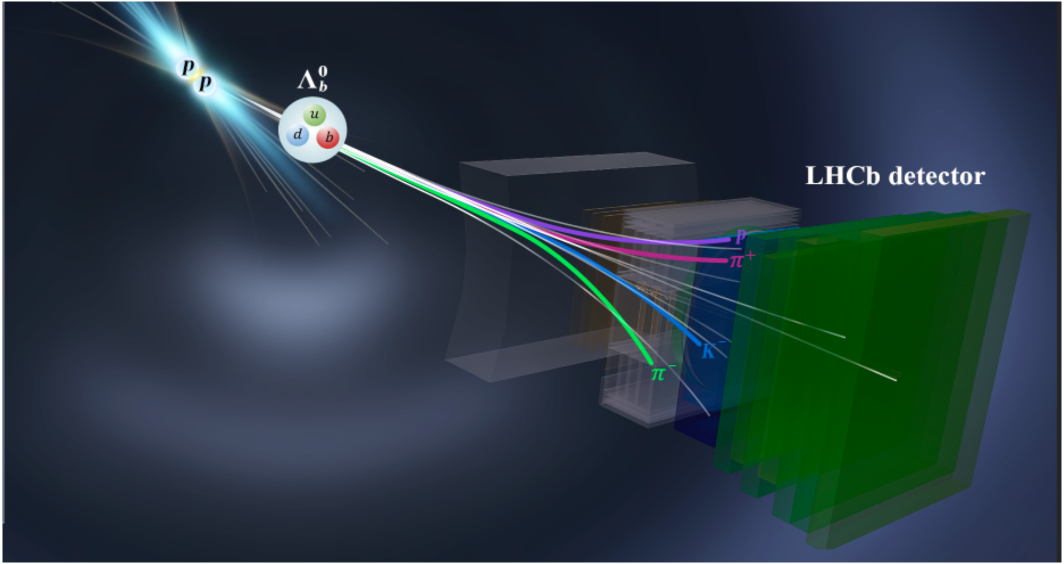
CP violation was not seen in process involving baryons.
Yet the CP asymmetry of the universe is a **baryon-antibaryon asymmetry**

LHCb measured the decay-rate CP asymmetries of some decays of the Λ_b^0 baryon



- for $\Lambda_b^0 \to \Lambda^0\pi^+\pi^-$, $\Lambda^0K^+\pi^-$, $\Lambda^0\pi^+K^-$, [LHCb: PRL134.101802, 2025]
- for $\Lambda_b^0 \to p\,K^-\pi^+\pi^-$ [LHCb: Moriond EW, 2025]

LHCb: Λ_b^0 decay-rate CP asymmetries



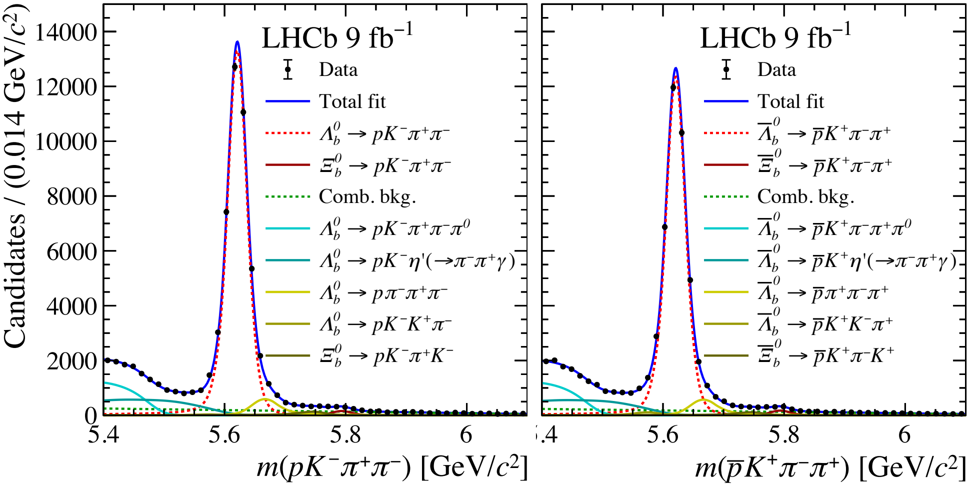
LHCb: Λ_b^0 decay-rate CP asymmetries

- Find final-state particles

$$p\,\pi^-\pi^+K^-, \quad \Lambda^0\pi^+\pi^-, \quad \Lambda^0K^+\pi^-, \quad \Lambda^0\pi^+K^-, \qquad\qquad (\Lambda^0 \to p\pi^-)$$

- Require
  - they come from common point far from pp collision since Λ_b^0 flies before decaying.
  - their momentum sum point back to pp collision since Λ_b^0 comes from pp interaction.
- Veto weakly-decaying intermediate states: when final-state subset has mass near such a state.
- Use machine-learning algorithm to remove random background

Selected candidates are predominantly correct Λ_b^0, but also incorrect ones.



Fit to the mass spectra to get signal yields, $N(\Lambda_b^0 \to \cdots)$ and $N(\overline{\Lambda}_b^0 \to \overline{\cdots})$.

likewise for $\Lambda^0\pi^+\pi^-$, ...

From fit results, calculate **raw** asymmetry

$$A_{\text{raw}}(\Lambda_b^0 \to \text{fsp's}) \equiv \frac{N(\Lambda_b^0 \to \cdots) - N(\overline{\Lambda}_b^0 \to \overline{\text{fsp's}})}{N(\Lambda_b^0 \to \cdots) + N(\overline{\Lambda}_b^0 \to \overline{\text{fsp's}})}$$

$$= A_{\text{CP}}(\Lambda_b^0 \to \text{fsp's}) + A_{\text{prod}}(\Lambda_b^0) + A_{\text{det}}(\text{fsp's})$$

$A_{\text{prod}}(\Lambda_b^0) \equiv$ asymmetry of **production of Λ_b^0 and $\overline{\Lambda}_b^0$ from pp collision**

$A_{\text{det}}(\text{fsp's}) \equiv$ asymmetry of **detection of Λ_b^0 and $\overline{\Lambda}_b^0$ decay products**

Use raw asymmetry in $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ to remove these:

$$A_{\text{CP}}(\Lambda_b^0 \to \text{fsp's}) = A_{\text{raw}}(\Lambda_b^0 \to \text{fsp's}) - A_{\text{prod}}(\Lambda_b^0) - A_{\text{det}}(\text{fsp's})$$

$$0 = A_{\text{CP}}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = A_{\text{raw}}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) - A_{\text{prod}}(\Lambda_b^0) - A_{\text{det}}(\Lambda_c^+ \pi^-)$$

Λ_c^+ final state chosen to match Λ_b^0's.

LHCb reported two significant asymmetries

$A_{\text{CP}}(\Lambda_b^0 \to \Lambda^0 K^+ K^-) = (8.3 \pm 2.3 \pm 1.6)\% \quad \to \quad 3.1\sigma$ [LHCb: PRL134.101802 2025]

$A_{\text{CP}}(\Lambda_b^0 \to p\, K^- \pi^+ \pi^-) = (2.45 \pm 0.46 \pm 0.10)\% \quad \to \quad 5.2\sigma$ [LHCb: Moriond EW, 2025]

LHCb: Λ_b^0 decay-rate CP asymmetries

$$\boxed{A_{\mathrm{CP}}(\Lambda_b^0 \to p\,K^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\% \quad \to \quad 5.2\sigma}$$

[LHCb: Moriond EW, 2025]

LHCb observed CP violation in baryon decay.

1964	CP violation in K^0 mixing	strange meson
1999	CP violation in K^0 decay	strange meson
2001	CP violation in B^0 mixing & decay	bottom meson
2004	CP violation in B^0 decay	bottom meson
2012	CP violation in B^+ decay	bottom meson
2013	CP violation in B_s^0 decay	bottom-strange meson
2019	CP violation in D decay	charm meson
2025	CP violation in Λ_b^0 decay	bottom **baryon**

Belle II & LHCb: D $\to \pi\pi$ decay-rate CP asymmetries

Let's look at charm—at decays of D mesons

D^+ D^0 $\overline{D}^0$ D^-

$\boxed{\text{isospin } \tfrac{1}{2}}$

to pion pairs

$\pi^+\pi^0$ $\pi^+\pi^-$ $\pi^0\pi^0$

$\boxed{\text{isospin superpositions: } 0{+}1{+}2,\ 0{+}2,\ 2}$

Standard model:

$$A_{\mathrm{CP}}^{\mathrm{SM}}(|\Delta I|{=}\tfrac{3}{2}\ \mathrm{D} \to \pi\pi) = 0 \quad \text{and} \quad A_{\mathrm{CP}}^{\mathrm{SM}}(|\Delta I|{=}\tfrac{1}{2}\ \mathrm{D} \to \pi\pi) \ll 1$$

- $D^+ \to \pi^+\pi^0$ only has $|\Delta I| = \frac{3}{2}$, so $A_{\mathrm{CP}}^{\mathrm{SM}}(D^+ \to \pi^+\pi^-) = 0$
- $D^0 \to \pi\pi$ has both $|\Delta I| = \frac{1}{2}$ and $\frac{3}{2}$, but nonzero $A_{\mathrm{CP}}^{\mathrm{SM}}$ only from $|\Delta I|{=}\frac{1}{2}$ part.

Belle II & LHCb: $\mathrm{D} \to \pi\pi$ decay-rate CP asymmetries

- $A_{\mathrm{CP}}^{\mathrm{SM}}(\mathrm{D}^+ \to \pi^+\pi^0) = 0$
- $A_{\mathrm{CP}}^{\mathrm{SM}}(\mathrm{D}^0 \to \pi\pi)$ only from $A_{\mathrm{CP}}^{\mathrm{SM}}(|\Delta I|{=}\frac{1}{2}\ \mathrm{D} \to \pi\pi)$ and small

So, if we measure

- $A_{\mathrm{CP}}(\mathrm{D}^+ \to \pi^+\pi^0) \neq 0$
  $\longrightarrow$ something beyond the standard model
- $A_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^+\pi^-)$ and $A_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^0\pi^0)$ inconsistent with $A_{\mathrm{CP}}(|\Delta I|{=}\frac{1}{2}\ \mathrm{D} \to \pi\pi)$
  $\longrightarrow$ something beyond the standard model

Can't directly measure $A_{\mathrm{CP}}(|\Delta I|{=}\frac{1}{2}\ \mathrm{D} \to \pi\pi)$,
but can calculate it from asymmetries, branching fractions, and D^0-D^+ lifetime ratio

$$A_{\mathrm{CP}}(|\Delta I|{=}\tfrac{1}{2}\ \mathrm{D} \to \pi\pi) = \frac{B_{+-}A_{+-} \ + \ B_{00}A_{00} \ - \ \frac{2}{3}\frac{\tau_0}{\tau_+}B_{+0}A_{+0}}{B_{+-} \ + \ B_{00} \ - \ \frac{2}{3}\frac{\tau_0}{\tau_+}B_{+0}}$$

Asymmetries are limiting inputs, $A_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^0\pi^0)$ most limiting.

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

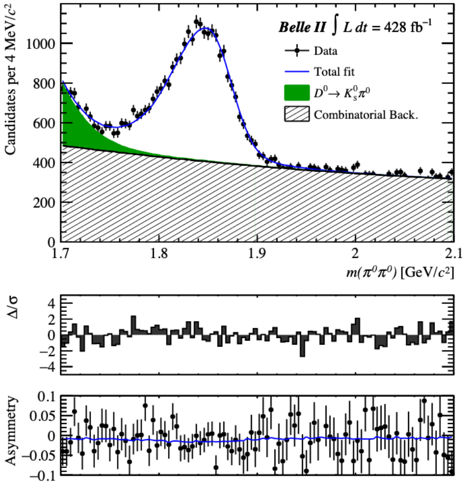
$$A_{\mathrm{CP}}(D^0 \to \pi^0\pi^0) = \frac{\Gamma(D^0 \to \pi^0\pi^0) - \Gamma(\overline{D}^0 \to \pi^0\pi^0)}{\Gamma(D^0 \to \pi^0\pi^0) + \Gamma(\overline{D}^0 \to \pi^0\pi^0)}$$

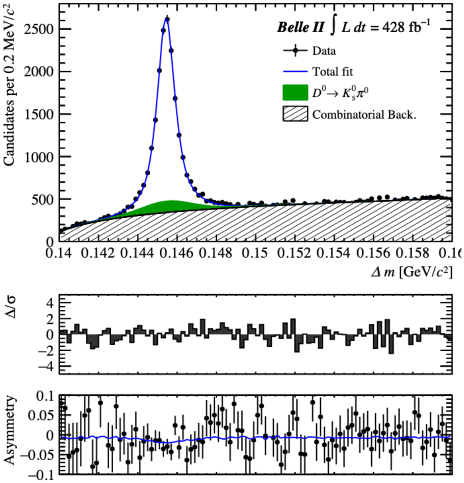
Distinguish $D^0 \to \pi^0\pi^0$ and $\overline{D}^0 \to \pi^0\pi^0$ by requiring they come from $D^{*\pm}$ decay:

$$D^{*+} \to D^0\pi^+ \qquad D^{*-} \to \overline{D}^0\pi^-$$

- Find final state particles: $\pi^\pm\pi^0\pi^0$
- Require
  - $\pi^0\pi^0$ mass be consistent with D^0 mass
  - $\pi^\pm\pi^0\pi^0$ mass consistent with $D^{*\pm}$-D^0 mass difference
  - $D^{*\pm}$ have enough momentum to not come from B decay $\longrightarrow$ don't inherit A_{CP} from B decay
- Use machine-learning algorithm to remove background.

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry





Fit to the mass and Δm spectra to get signal yields, $N(D^0 \to \pi^0\pi^0)$ and $N(\overline{D}^0 \to \pi^0\pi^0)$.

Belle II: $\mathrm{D}^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

Again this the **raw** asymmetry is not the CP one

$$A_N(\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+, \mathrm{D}^0 \to \pi^0\pi^0) = A_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^0\pi^0) + A_{\mathrm{prod}}(\mathrm{D}^{*+}) + A_{\mathrm{det}}(\pi^+)$$

- $A_{\mathrm{prod}}(\mathrm{D}^0) \equiv$ from $\mathrm{e}^+\mathrm{e}^- \to \mathrm{c}\bar{\mathrm{c}}$ forward-backward asymmetry
  cancel by averaging over forward and backward D^*

$$\overline{A}_N \equiv \frac{1}{2}\left[A_N^{\mathrm{F}} + A_N^{\mathrm{B}}\right] = A_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^0\pi^0) + A_{\mathrm{det}}(\pi^+)$$

- calculate $A_{\mathrm{det}}(\pi^+)$ from $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+, \mathrm{D}^0 \to \mathrm{K}^-\pi^+$

$$\overline{A}_N(\mathrm{D}^0 \to \mathrm{K}^-\pi^+, \textbf{w/ } \mathrm{D}^* \text{ req.}) = A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^-\pi^+) + A_{\mathrm{det}}(\pi^+) + A_{\mathrm{det}}(\mathrm{K}^-\pi^+)$$
$$\overline{A}_N(\mathrm{D}^0 \to \mathrm{K}^-\pi^+, \textbf{w/o } \mathrm{D}^* \text{ req.}) = A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^-\pi^+) + A_{\mathrm{det}}(\mathrm{K}^-\pi^+)$$

So

$$A_{\mathrm{det}}(\pi^+) = \overline{A}_N(\mathrm{D}^0 \to \mathrm{K}^-\pi^+, \textbf{w/ } \mathrm{D}^* \text{ req.}) - \overline{A}_N(\mathrm{D}^0 \to \mathrm{K}^-\pi^+, \textbf{w/o } \mathrm{D}^* \text{ req.})$$

Belle II: $D^0 \to \pi^0\pi^0$ decay-rate CP asymmetry

$$\boxed{A_{\rm CP}(D^0 \to \pi^0\pi^0) = (3.0 \pm 7.2 \pm 2.0) \times 10^{-3}}$$

[Belle & Belle II: Moriond EW, 2025]

Let's calculate $A_{\rm CP}(|\Delta I| = \frac{1}{2}\ D \to \pi\pi)$.

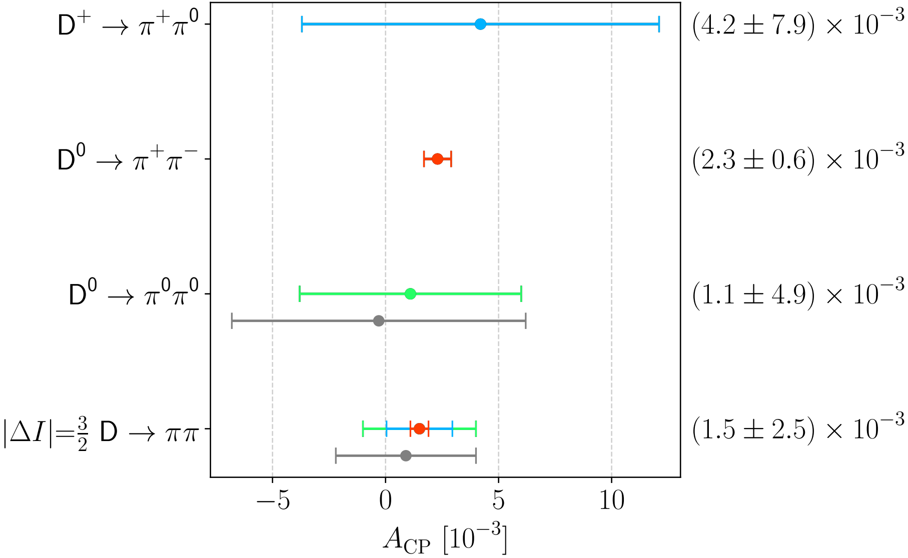
Using

- $A_{\rm CP}(D^0 \to \pi^0\pi^0) = (1.1 \pm 4.9) \times 10^{-3}$ from Belle II (2025) and Belle (2014)
- $A_{\rm CP}(D^0 \to \pi^+\pi^-) = (2.3 \pm 0.6) \times 10^{-3}$ from LHCb (2022)
- $A_{\rm CP}(D^+ \to \pi^+\pi^0) = (4.2 \pm 7.9) \times 10^{-3}$ from LHCb (2021), Belle (2018), and CLEO (2010)

$$\boxed{A_{\rm CP}(|\Delta I| = \tfrac{1}{2}\ D \to \pi\pi) = (1.5 \pm 0.4 \pm 2.1 \pm 1.4) \times 10^{-3} = (1.5 \pm 2.5) \times 10^{-3}}$$

uncertainty from $D^0 \to \pi^0\pi^0$ drops by 25%, total uncertainty drops by 19%.

Status in D $\to \pi\pi$



Belle II: new measurements of $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$

In standard model $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ could be as large as %.

Belle II measured it (using Belle data, too), learning D^0 flavor from

- $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$

$$A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-1.4 \pm 1.3 \pm 0.1)\%$$

[Belle II: PRD111.012015, 2025]

- **charm flavor tagger**
  new algorithm that looks at rest of event,

$$\mathrm{e}^+\mathrm{e}^- \to \mathrm{c}\bar{\mathrm{c}} \to \mathrm{D}^0 + X_{\bar{\mathrm{c}}}$$

[Belle II: PRD107.112010, 2023]

first used for this analysis.

$$A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (1.3 \pm 2.0 \pm 0.3)\%$$

[Belle II: Moriond EW, 2025]

- combined:

$$A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-0.6 \pm 1.1 \pm 0.1)\%$$

[Belle II: Moriond EW, 2025]

- and with LHCb (2021, 2015) & Belle (2017)

$$\boxed{A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-1.3 \pm 0.8)\%}$$

Nearing CP-violation discovery.

LHCb: new search for CP violation in $\mathrm{D}^0 \to \mathrm{K}^{\pm}\pi^{\mp}$

LHCb recently measured decay-time dependence of decay-rate ratios

$$\frac{\Gamma(\mathrm{D}^0 \to \mathrm{K}^+\pi^-)}{\Gamma(\overline{\mathrm{D}}^0 \to \mathrm{K}^+\pi^-)} \quad \text{and} \quad \frac{\Gamma(\overline{\mathrm{D}}^0 \to \mathrm{K}^-\pi^+)}{\Gamma(\mathrm{D}^0 \to \mathrm{K}^-\pi^+)}$$

where D^0 and $\overline{\mathrm{D}}^0$ are the produced states—they oscillate before decaying.

From this, we learn about D^0-$\overline{\mathrm{D}}^0$ mixing

and $A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^+\pi^-)$, which the standard-model expects to be zero (less than 10^{-5}).

$$\boxed{A_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^+\pi^-) = (-6.6 \pm 5.7) \times 10^{-3}}$$

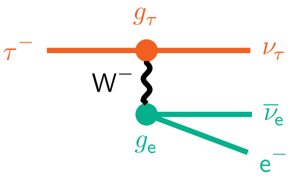
[LHCb: PRD111.012001, 2025]

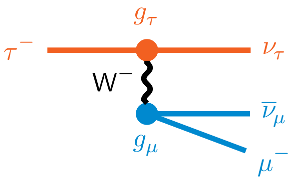
Inching towards testing the standard model.

Belle II: Testing lepton universality with leptonic τ decay

$$\boxed{\text{Lepton-flavor universality} \equiv \text{e}, \mu, \text{and } \tau \text{ have the same electroweak couplings.}}$$

We can test that with leptonic τ decay:





$\Gamma(\tau^- \to e^- \nu_\tau \overline{\nu}_e) \propto |g_\tau|^2 \, |g_e|^2$

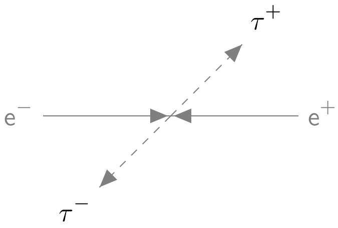
$\Gamma(\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu) \propto |g_\tau|^2 \, |g_\mu|^2$

$$\boxed{\left|\frac{g_\mu}{g_e}\right| \propto \sqrt{\frac{B(\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu)}{B(\tau^- \to e^- \nu_\tau \overline{\nu}_e)}}}$$

Belle II: Testing lepton universality with leptonic τ decay

clean data set from $e^+e^- \to \tau^+\tau^-$.

require one τ decay leptonically and the other decay hadronically (to $\pi^+\pi^0$).



- Find only two charged particles, opp'ly charged, and one or more π^0 (in one hemisphere)
- Require
  - large thrust, high missing mass, low missing p_{t}, to isolate $e^+e^- \to \tau^+\tau^-$.
  - charged particle in π^0 hemisph. not look like $e^\pm$, to veto $e^+e^- \to e^+e^-$.
  - other charged particle look like $e^\pm$ or $\mu^\pm$.
- Use neural network to remove background.
- Fit to p_ℓ spectra to get branching-fraction ratio.
- **Study lepton-ID efficiencies and correlations.**

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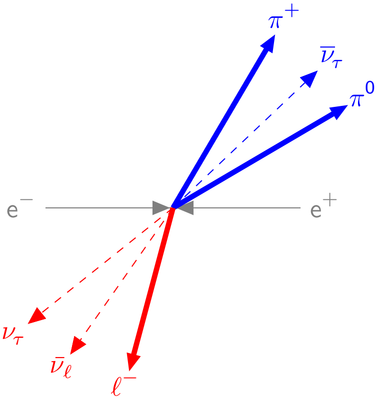

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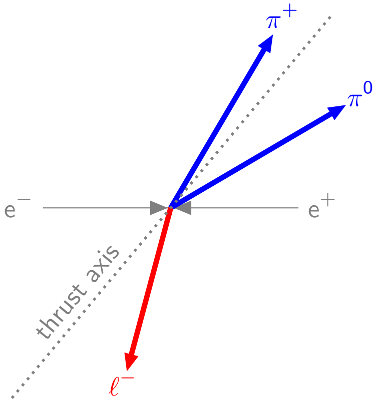

thrust axis $\equiv$ axis most along momenta

- Find only two charged particles, opp'ly charged, and one or more π^0 (in one hemisphere)
- Require
  - large thrust, high missing mass, low missing p_t, to isolate $e^+e^- \to \tau^+\tau^-$.
  - charged particle in π^0 hemisph. not look like $e^\pm$, to veto $e^+e^- \to e^+e^-$.
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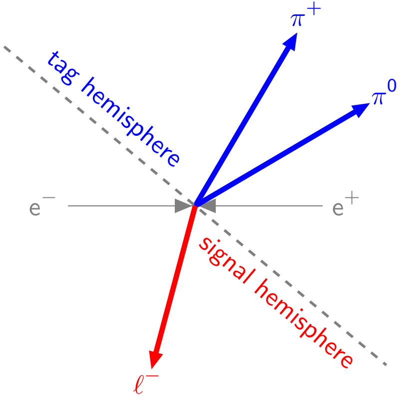
Belle II: Testing lepton universality with leptonic τ decay

clean data set from $e^+e^- \to \tau^+\tau^-$.

require one τ decay leptonically and the other decay hadronically (to $\pi^+\pi^0$).



thrust axis $\equiv$ axis most along momenta

- Find only two charged particles, opp'ly charged, and one or more π^0 (in one hemisphere)
- Require
  - large thrust, high missing mass, low missing p_t, to isolate $e^+e^- \to \tau^+\tau^-$.
  - charged particle in π^0 hemisph. not look like $e^\pm$, to veto $e^+e^- \to e^+e^-$.
  - other charged particle look like $e^\pm$ or $\mu^\pm$.
- Use neural network to remove background.
- Fit to p_ℓ spectra to get branching-fraction ratio.
- **Study lepton-ID efficiencies and correlations.**

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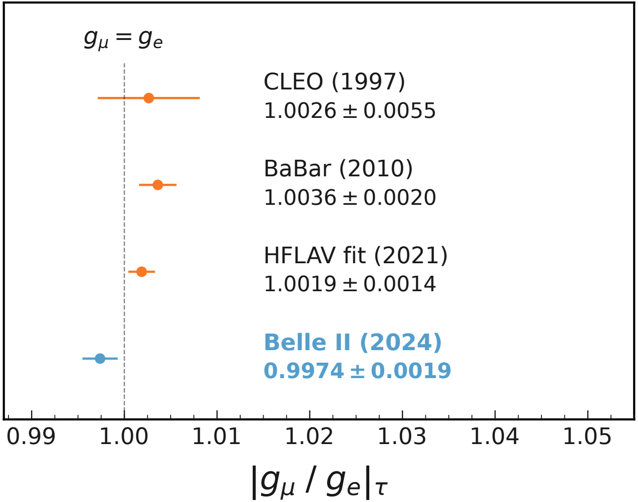


[Belle II: JHEP08.205, 2024]

Belle II: Other recent τ measurements

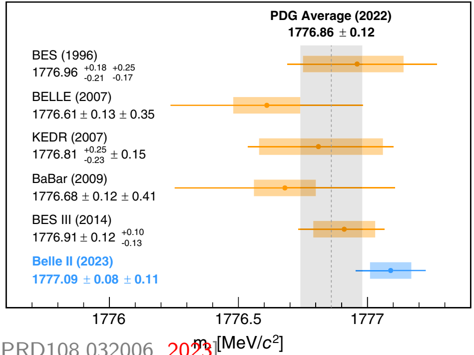
- Limits on lepton-flavor violation:

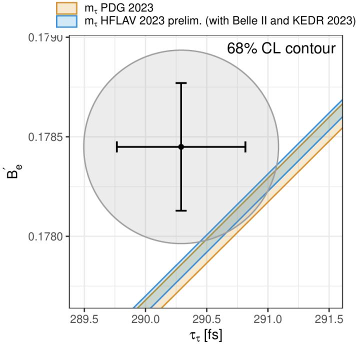
$$B(\tau^- \to \Lambda^0\pi^-) < 4.7 \times 10^{-8} \text{ @ } 90\% \text{ credibility}$$ [Belle II: PRD110.112003, 2024]

$$B(\tau^- \to \overline{\Lambda}^0\pi^-) < 4.3 \times 10^{-8} \text{ @ } 90\% \text{ credibility}$$ [Belle II: PRD110.112003, 2024]

$$B(\tau^- \to \mu^-\mu^+\mu^-) < 1.9 \times 10^{-8} \text{ @ } 90\% \text{ credibility}$$ [Belle II: JHEP09.062, 2024]

- Measurement of τ mass:





[Belle II: PRD108.032006, 2023]

Summary

Belle II & LHCb are very active.
I have highlighted only a few recent results.
Give me another 25 minutes and I'm happy to talk about more.

- **Discovery of CP violation in baryons:**

$$\Lambda_b^0 \to p\,K^-\pi^+\pi^-,\ \Lambda^0 K^+ K^-$$

- **Search for physics beyond standard model via A_{CP}(D decay)**:

$$D^0 \to \pi^0\pi^0,\ K_S^0 K_S^0,\ K^\pm K^\mp$$

- **Testing testing lepton universality in τ decay:**

$$\tau^- \to e^-\nu_\tau\,\overline{\nu}_e,\ \mu^-\nu_\tau\,\overline{\nu}_\mu$$

Both experiments are active in many other areas, including

- study of quarkonia, tetraquarks, pentaquarks
- dark-matter searches
- measuring quark-mixing-matrix parameters
- hadron spectroscopy
- measuring electroweak parameters
- study of B mesons

Some event counts

- $A_{\mathrm{CP}}(\Lambda_b^0 \to \cdots)$ @ LHCb

$\Lambda_b^0 \pi^+ \pi^-$	636 ± 42
$\Lambda_b^0 K^+ \pi^-$	618 ± 32
$\Lambda_b^0 K^+ K^-$	1920 ± 50
$p\, K^+ \pi^+ \pi^-$	$80\,690 \pm 340$

- $A_{\mathrm{CP}}(D^0 \to \cdots)$ @ Belle II

$\pi^0 \pi^0$	$\mathcal{O}\left(10^4\right)$	
$K_S^0 K_S^0$	2214 ± 51	Belle II
	4864 ± 78	Belle

- $D^0 \to K^\pm \pi^\mp$ @ LHCb

$K^+ \pi^-$	412×10^6
$K^- \pi^+$	1.6×10^6

- $\tau^- \to \ell^- \nu_\tau \bar{\nu}_\ell$ @ Belle II

e	4.4×10^6
μ	4.4×10^6

thrust

$$|\vec{t}| \equiv \frac{\sum_i \vec{p}_i \cdot \hat{t}}{\sum_i |\vec{p}_i|}$$