Charm Physics at Belle II

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Belle II

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Annual Swedish Nuclear Physicists' meeting and SFAIR meeting 2025

Charlmers (Göteborg), 28-30 October 2025

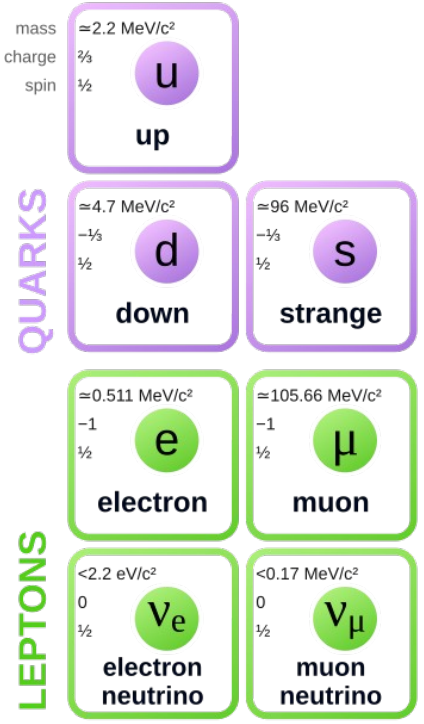
The November Revolution

The world of particle physics was revolutionised in November 1974

At the time, most of the elements of the Standard Model of particle physics had already been formulated

→ only a limited set of fundamental *fermions* were confidently believed to exist

→ the up, down and strange *quarks* were thought to make up the strongly interacting particles known at that time



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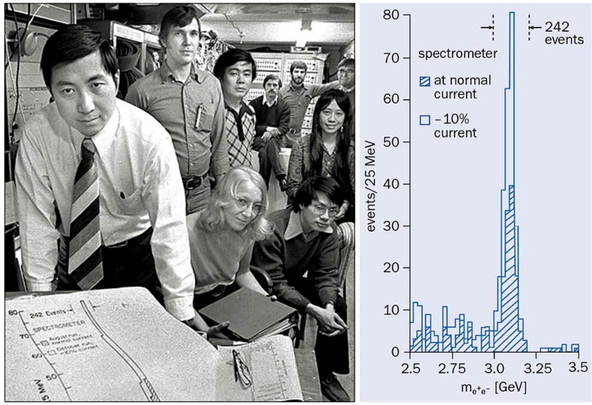
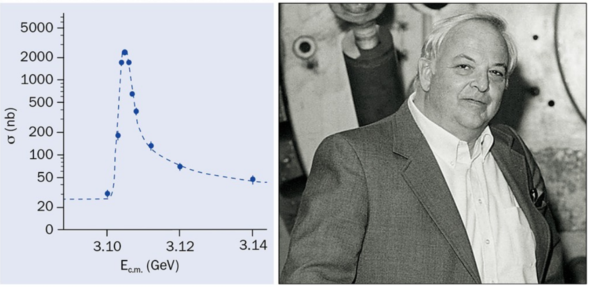
November 11, 1974:
two experimental groups discovered a narrow vector boson
→ 5 hypotheses were explored: *a hidden charm vector meson, a coloured vector meson, an intermediate vector boson, a Higgs meson, a narrow resonances in strong interactions.*

Samuel Ting (BNL), Phys. Rev. Lett. 33, 1404 (1974)





Burton Richter (SLAC), Phys. Rev. Lett. 33, 1406 (1974)

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A Charming Discovery

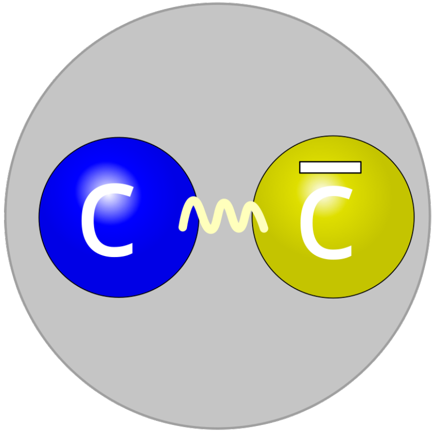
The J/ψ proved to be a charm-anticharm bound state

→ cemented by the subsequent discovery of related $c\bar{c}$-states and by the observation of charmed particles in 1976
→ vindicated the theory from Glashow and Bjorken
→ eliminated any doubts regarding the quark model of 1964
→ triggered the development of the Standard Model into its modern form

First example of quarkonium: a heavy quark bound to an anti-quark of the same flavour

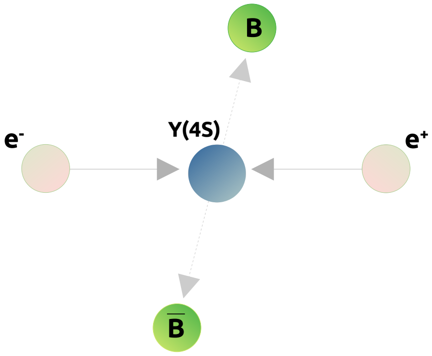
Composed of ***unstable quarks****, bound by gluons, decaying mainly via the annihilation of their constituent quarks, quarkonia have fascinated particle physicists ever since.*

The study of charm decays is characterized by many challenging and exiting peculiarities which make charm sector an ***ideal testing ground for Quantum Chromodynamics (QCD) based framework and very sensitive probe to New Physics (NP)***



B-factories

B-factories are dedicated for the production of a **$B\bar{B}$ pairs**



Y(4S): $b\bar{b}$ meson, $J^{PC} = 1^{--}$
Γ : 20.5 MeV
$m_{Y(4S)}$: 10.58 GeV
→ right above the $B\bar{B}$ production threshold (10.56 GeV)

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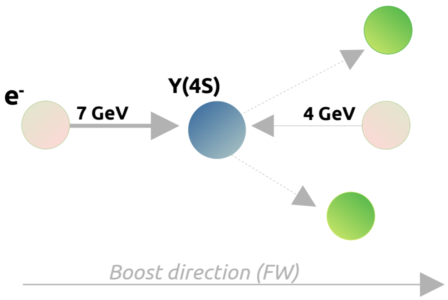
B-factories

B-factories are dedicated for the production of a $B\bar{B}$ pairs at e^+e^- **asymmetric-energy** colliders



Υ(4S): $b\bar{b}$ meson, $J^{PC} = 1^{--}$
Γ : 20.5 MeV
$m_{\Upsilon(4S)}$: 10.58 GeV
→ right above the $B\bar{B}$ production threshold (10.56 GeV)

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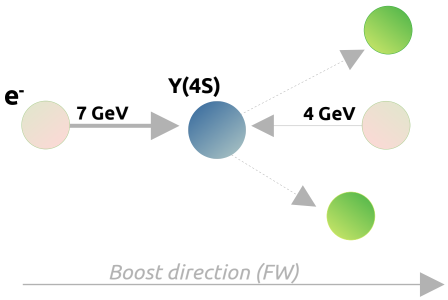

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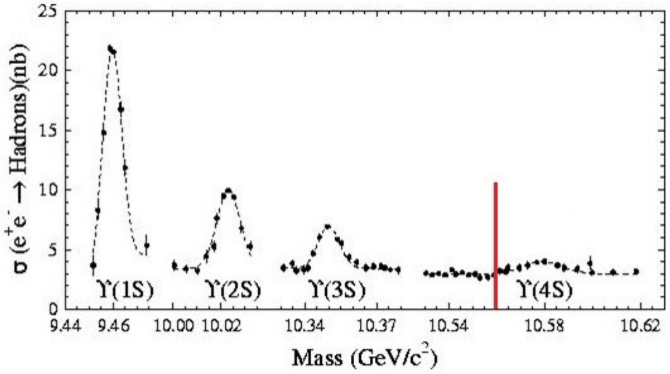

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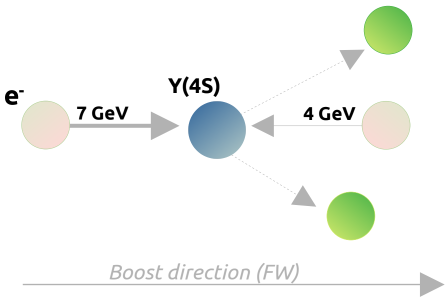

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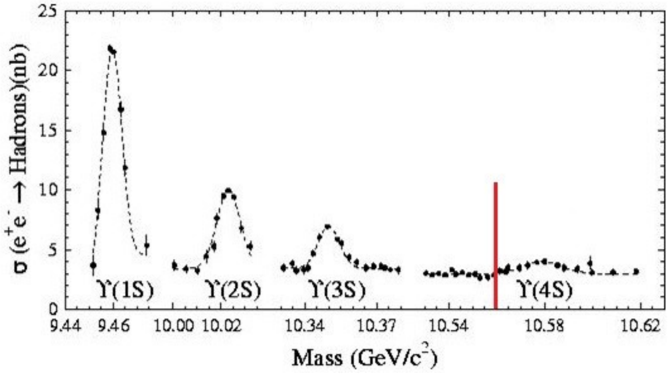


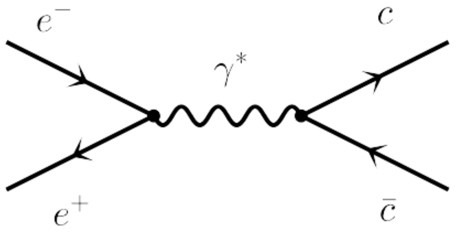
$\sigma(e^+e^- \to b\bar{b}) = 1.1$ nb
$\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb
$\sigma(e^+e^- \to \tau^+\tau^-) = 0.9$ nb
$\sigma(e^+e^- \to uds) = 2.1$ nb

rich charm, tau and low-multiplicity program!

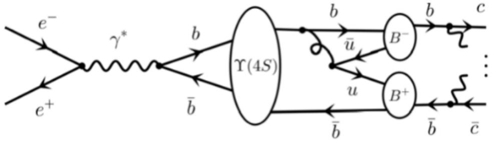
Charm at B-factories

B-factories are dedicated for the production of a $B\bar{B}$ pairs at e^+e^- **asymmetric-energy** colliders
Charm particles can be produced as

1. **Prompt production**
   charmed hadrons are produced as a direct result of the beam collision



2. **Secondary production**
   result of the decay of another heavier particle produced in the collision



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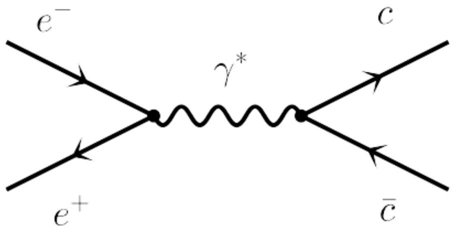
Charm particles can be produced as

1. **Prompt production**
   charmed hadrons are produced as a direct result of the beam collision
   *more dominant at B-factories



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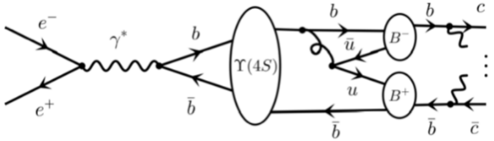

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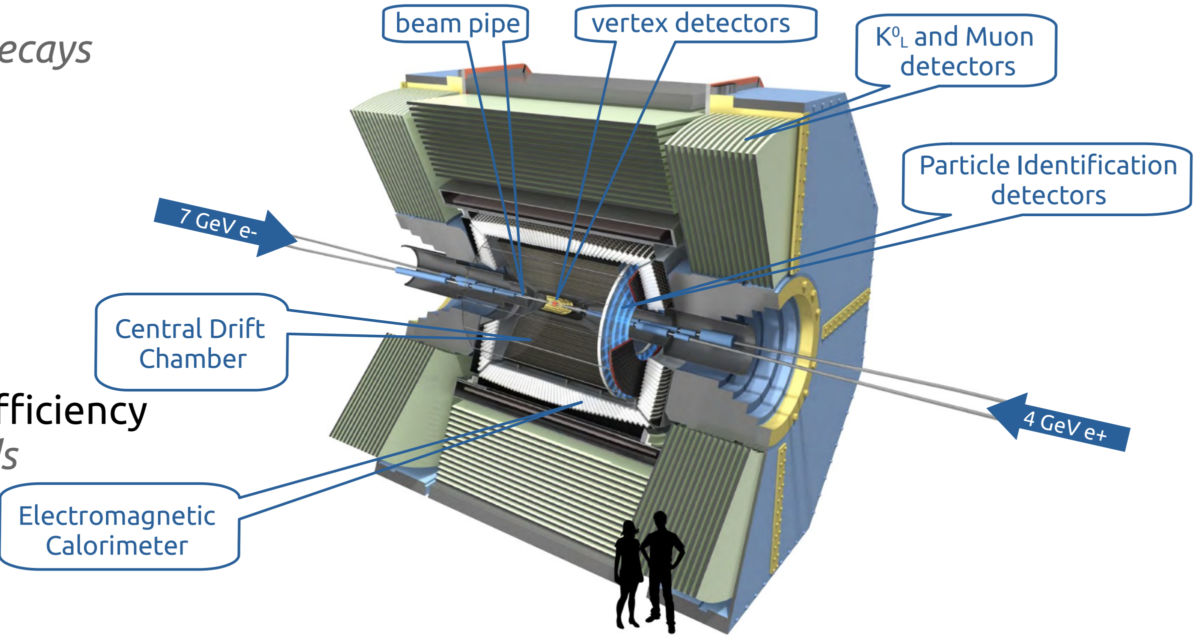
Charm at Belle II

1. excellent vertex reconstruction
   → *allow identification of prompt decays*
2. excellent momentum resolution
   → *translate into mass resolution*
3. excellent particle identification
   → *suppress background level*
4. high trigger and reconstruction efficiency
   → *maximize number of signal yields*
5. particle boost & time resolution
   → *for time-dependent studies*
6. reconstruction of neutrals
   → *for final states with neutral particles*



CP Violation in Charm

[1] PRL122(2019)211803

- CP symmetry combines *Charge conjugation* (C) — swapping particles with antiparticles — and *Parity* (P) — mirroring spatial coordinates

- If CP were an exact symmetry, matter and antimatter would behave identically, ***instead almost no anti-matter is left***

- CP violation is one of the necessary ingredients to explain why our universe is made of matter

- Theory takes into account some CP violation
  → not right amount to account for the *missing* anti-matter

- **The first and only observation of CPV in charm from LHCb [1]**
  → ***It is essential to continue searching for CPV in charm hadrons to understand its origin and further constrain the SM***

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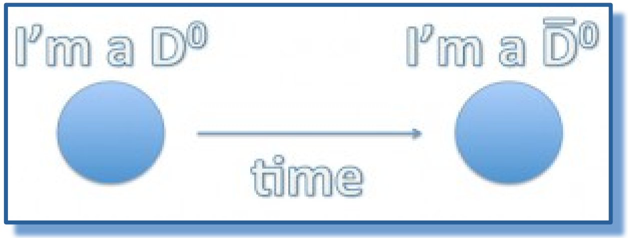
Mixing in Charm

Some neutral mesons (like K^0, B^0, D^0) can *oscillate* into their antiparticle
→ their ***flavor eigenstates*** (D^0, $\bar{D}^0$) are not the same as their ***mass eigenstates***

The oscillation rate depends on:

- the **mass difference** (Δm) between the two eigenstates
- the **lifetime difference** ($\Delta\Gamma$)



and it is a **rare and subtle** effect in weak interactions

Belle II can measure:

- mixing parameters ($x = \Delta m/\Gamma$, $y = \Delta\Gamma/2\Gamma$) with **high precision**
- time-dependent decay rates in channels like $D^0 \to K^+\pi^-$ or $D^0 \to K^+K^-$

→ The **clean e^+e^- environment** and **excellent vertex resolution** are ideal for resolving the tiny decay-time differences

→ ***Combining mixing and CPV measurements helps disentangle Standard Model vs. New Physics effects***

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Charmed Baryons

[2] Nature volume 643, pages 1223–1228 (2025)

- Baryon physics is a rich field, offering insights complementary to those from meson studies

- The observation of *CP violation in b-baryon decays by LHCb* [2] marks a major milestone in flavour physics — *but what about charm baryons?*

- There's still plenty of room to improve our knowledge of charm baryons: **branching ratios**, **Dalitz structures of multi-body decays**, **hadronic form factors**

- A deeper understanding is crucial to:
  → **probe CP violation**
  → **search for New Physics**
  → **explore rare or forbidden processes**

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Highlights from Belle II

CP Asymmetry in Charm Meson Decays

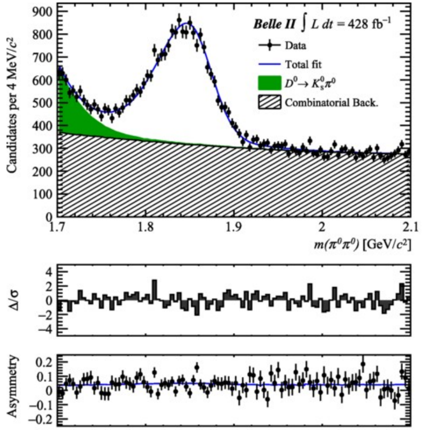
Phys. Rev. D 112, 012006 (2025)

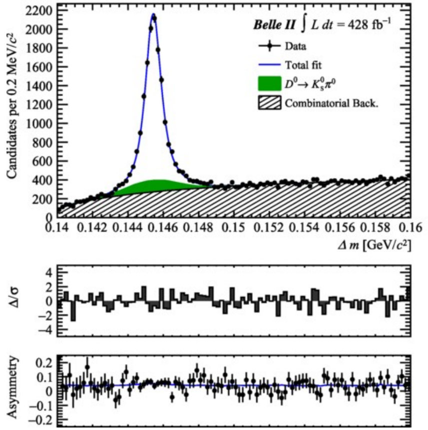
- Reconstruct $D^{*+} \to \pi^+ D^0(\to\pi^0\pi^0)$
  → Large backgrounds because of *4γ final state*
  → BDT to suppress background using information on photons kinematics and on the reconstructed calorimeter clusters

$$A^{\pi^0\pi^0} = \frac{N[D^{*+}\to(D^0\to\pi^0\pi^0)\pi^+] - N[D^{*-}\to(\bar{D}^0\to\pi^0\pi^0)\pi^-]}{N[D^{*+}\to(D^0\to\pi^0\pi^0)\pi^+] + N[D^{*-}\to(\bar{D}^0\to\pi^0\pi^0)\pi^-]} = A_{CP}(D^0\to\pi^0\pi^0) + A_P^{D^{*+}} + A_\epsilon^{\pi_s}$$

- Asymmetry extracted from a fit to the D^0 invariant mass and the D^{*+} - D^0 mass difference
  - ***production asymmetry*** (odd in $\cos\theta_{CM}$) removed by averaging A_{raw} of forward ($\cos\theta_{CM} > 0$) and backward ($\cos\theta_{CM} < 0$) decays
  - ***tag-pion detection asymmetry*** measured with tagged & untagged $D^0 \to K^-\pi^+$ decays and corrected

- A_{CP} = (0.30 ± 0.72 ± 0.20) %
  ~15% less precise than BELLE but with half of the statistics





unique for Belle II!

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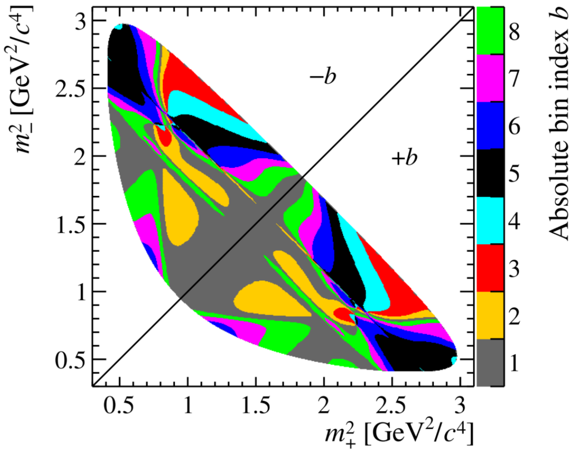
Mixing in Charm Mesons Decays

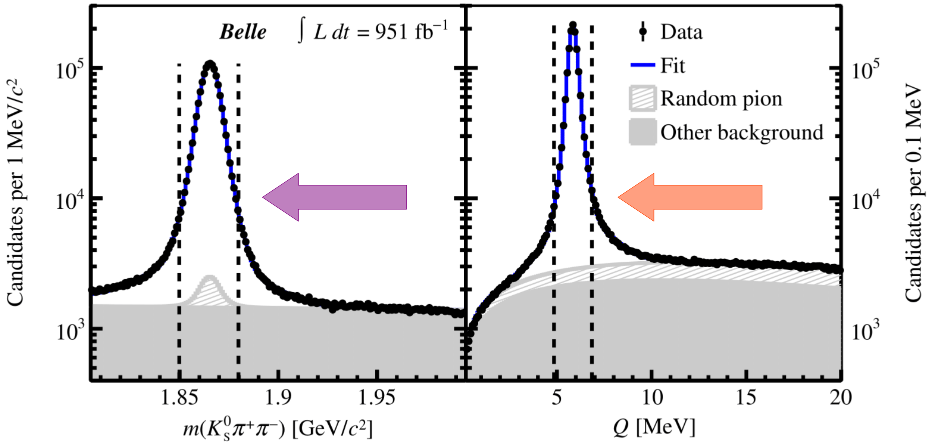
Phys. Rev. D 111, 112011 (2025)

Mixing parameters: $|D_{1,2}\rangle = p\,|D^0\rangle + q\,|\overline{D}^0\rangle$ from masses and widths of the $D_{1/2}$ states:

$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

- Reconstruct **$D^{*+} \to \pi^+ D^0 (\to K_S^0 \pi^+ \pi^-)$**
- Split Dalitz plot in bins to be independent from any explicit model [$m_\pm = m(K_S^0 \pi^\pm)$]
- Separate signal and backgrounds using the **$K_S^0\pi^+\pi^-$ invariant mass** and the **energy released in the D^{*+} decay**
- Restrict to the 2D peak signal region for the rest of the analysis





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Mixing in Charm Mesons Decays

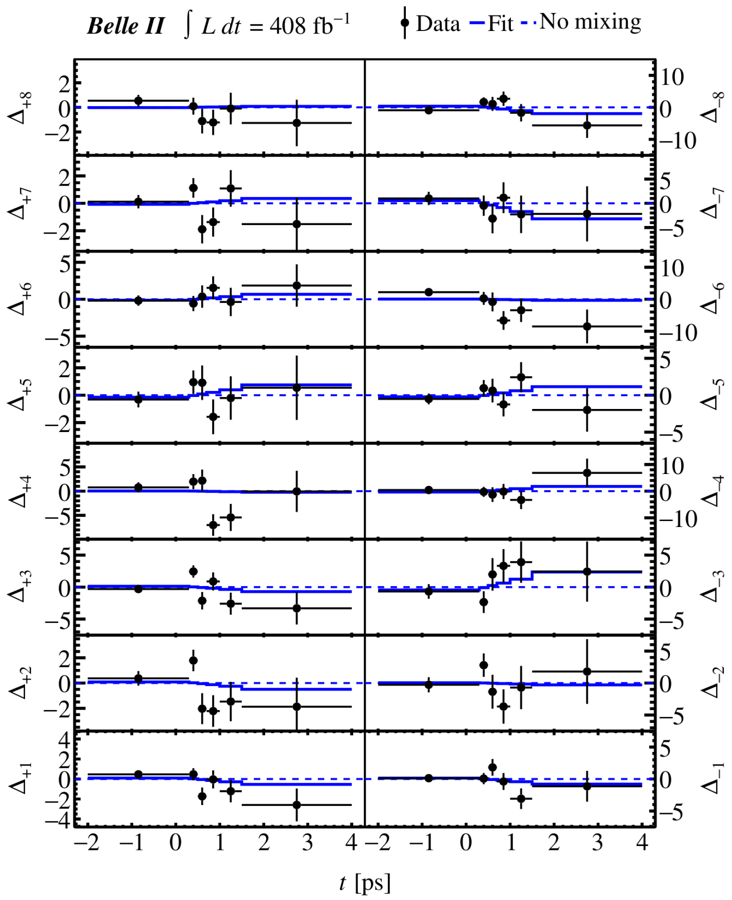
Phys. Rev. D 111, 112011 (2025)

- Fit decay time ***t*** and per-candidate **uncertainty σ(t)** *simultaneously* in Dalitz bins

- Shapes: directly determined from the ***t*** or data templates from the $m(K_S^0 \pi^+\pi^-)$ sideband

- ***Results***:
  $x = (4.0 \pm 1.7 \pm 0.4) \times 10^{-3}$
  $y = (2.9 \pm 1.4 \pm 0.3) \times 10^{-3}$

  → ***20% and 14% improvement*** compared to previous model-dependent determinations



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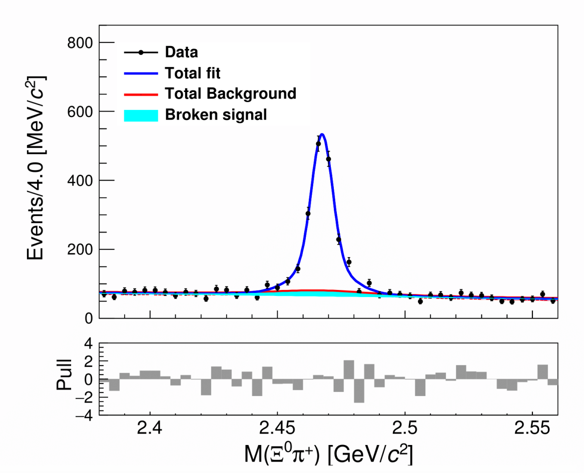
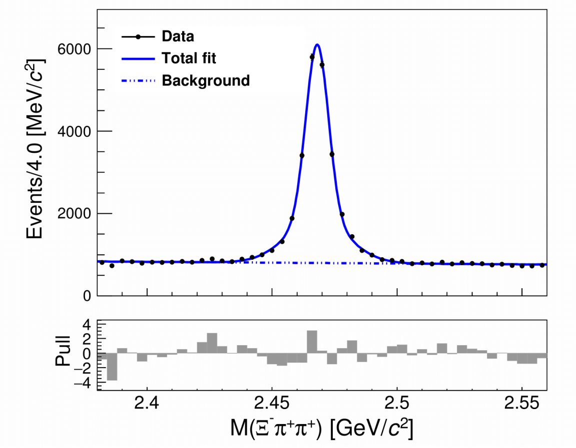
Charmed Baryons Branching Fractions

JHEP 08 (2025) 195

Measure the BR of Ξ_c^+ decays in a **BELLE + Belle II combined analysis:**

- reconstruct $\Sigma^+ K_S^0$, $\Xi^0 \pi^+$ and $\Xi^0 K^+$ decays
- currently many predictions
  → ***need measurement to rule out some of them***
- from π, K and p reconstruct intermediate baryons Λ, Σ, Ξ, then optimize selection ranges on each invariant mass
- **measure signal yields with invariant mass fit, extract branching fractions using $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$ as normalization mode**





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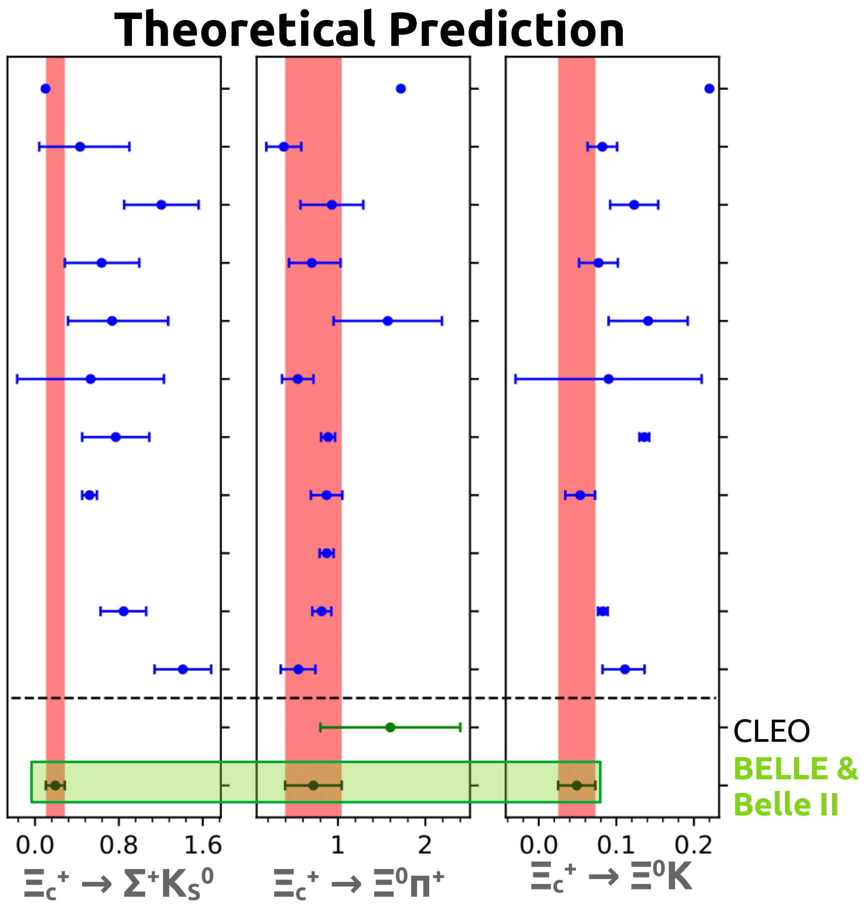
first

$B(\Xi_c^+ \to \Sigma^+ K_S^0) = (0.194 \pm 0.021 \pm 0.009 \pm 0.087)$ %
$B(\Xi_c^+ \to \Xi^0 \pi^+) = (0.719 \pm 0.014 \pm 0.024 \pm 0.322)$ %
$B(\Xi_c^+ \to \Xi^0 K^+) = (0.049 \pm 0.007 \pm 0.002 \pm 0.022)$ %

most precise



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CP Asymmetry in Charmed Baryons Decays

arXiv:2509.25765

U-spin rule that connects the Single-Cabibbo-Suppressed (SCS) $\Lambda_c^+ \to p h^+ h^-$ and and $\Xi_c^+ \to \Sigma^+ h^+ h^-$ (h = K, π) direct CP asymmetries:

$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) + A_{CP}(\Lambda_c^+ \to p K^+ K^-) = 0,$$
$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) + A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) = 0.$$

$$A_N(X_c^+ \to f^+) = A_{CP}(X_c^+ \to f^+) + A_{\mathrm{p}}(X_c^+) + A_{\mathrm{d}}(f^+)$$

- **Raw asymmetry** extracted from a fit to the baryon invariant mass
- **Production asymmetry** (odd in $\cos\theta_{CM}$) is removed by averaging it on forward and backward decays
- **Detection asymmetry** removed using CF control channels that provide high yields and negligible CPV

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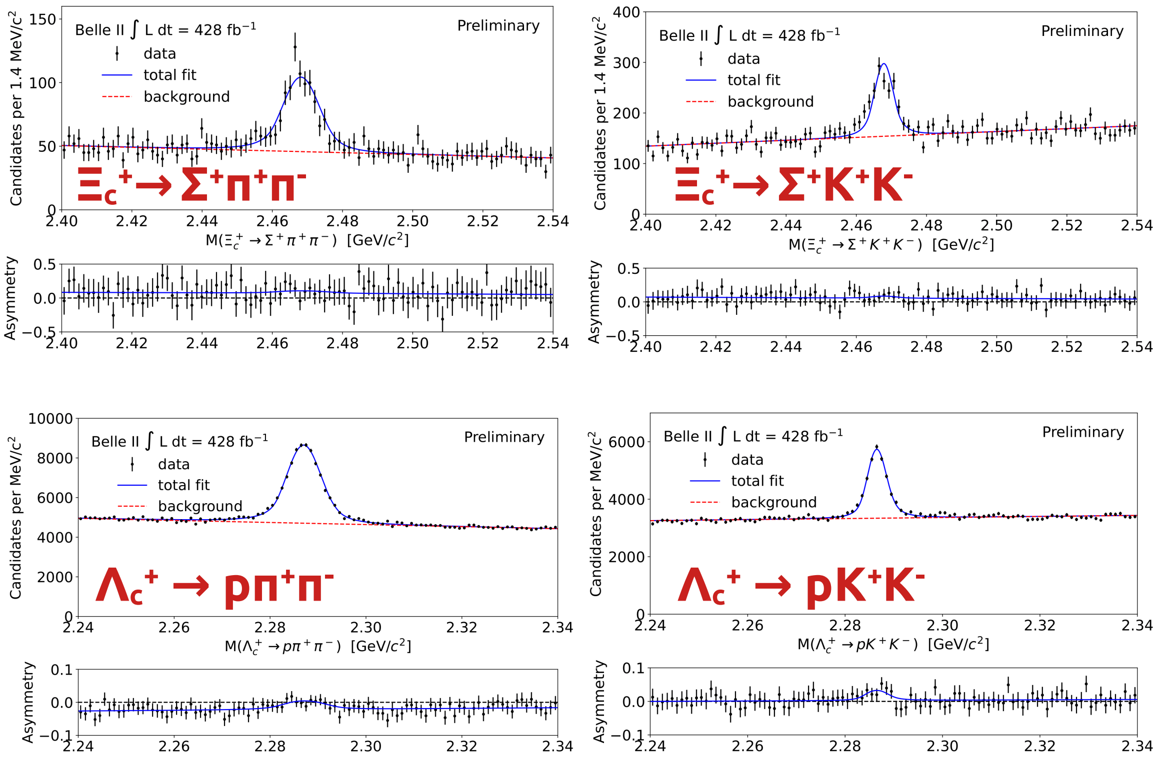
CP Asymmetry in Charmed Baryons Decays

arXiv:2509.25765

$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) = (3.7 \pm 6.6 \pm 0.6)\%$$
$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) = (9.5 \pm 6.8 \pm 0.5)\%$$
$$A_{CP}(\Lambda_c^+ \to p K^+ K^-) = (3.9 \pm 1.7 \pm 0.7)\%$$
$$A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) = (0.3 \pm 1.0 \pm 0.2)\%$$

- First measurement of A_{CP} in SCS three-body charm baryon decays
- Statistical uncertainty that reach 1% in the $\Lambda_c^+ \to p\pi^+\pi^-$ channel much smaller systematics
- ***Results consistent with CP symmetry and the U-spin rule***



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Charmed Baryons Polarization

[3] S. Pacetti, et al. Phys. Rep. 550–551, 1 (2015)

Very few measurements exist

→ often assuming charm baryon unpolarized

→ apply simplified spin formalism

Can be studied from two points of view:

1. **Fragmentation Functions**
2. Form Factors [3]

Spontaneous hadron polarization observed in hadron-hadron collisions

→ **Polarizing Fragmentation Functions (FF):**

- describe the production of a transversely polarized hadrons in the fragmentation of an unpolarized quark
- are needed as non-perturbative inputs for the calculation of all the cross sections

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Progress in the study of light baryons, including a first attempt to calculate the charge radius of the Λ based on the measured time-like form factors

How would the heavier charm quark affect the quark dynamics and the inner structure?

→ time-like complex form factors G_E and G_M accessible in the annihilation process through the joint angular distribution of production and decay

→ **the relative phase manifests through a polarized final state!**

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Charmed Baryons Polarization

Very few measurements exist

→ often assuming charm baryon unpolarized

→ apply simplified spin formalism

Can be studied from two points of view:

1. Fragmentation Functions
2. Form Factors [3]

Belle II is currently investigating the inclusive process $e^+e^- \to \Lambda^+_c + X$ to ***evaluate the transverse polarization of the Λ^+_c hyperon***

→ **the better we know the production process, the better precision we can reach in future decay studies and CP tests with charm baryons**

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Conclusion

- **Charm physics provides a powerful probe of flavor dynamics, CP violation, and possible new physics beyond the Standard Model**

- Belle II offers a clean environment and exceptional sensitivity for precision SM tests and new physics searches

  → Recent results include ***first observations and world-leading measurements*** in charm meson and baryon decays

  → Charmed baryon polarization studies are ongoing — demonstrating strong future potential

  → With more data and improved techniques, Belle II will lead the field in the coming years

Run 2 ongoing – stay tuned!

Thank you!

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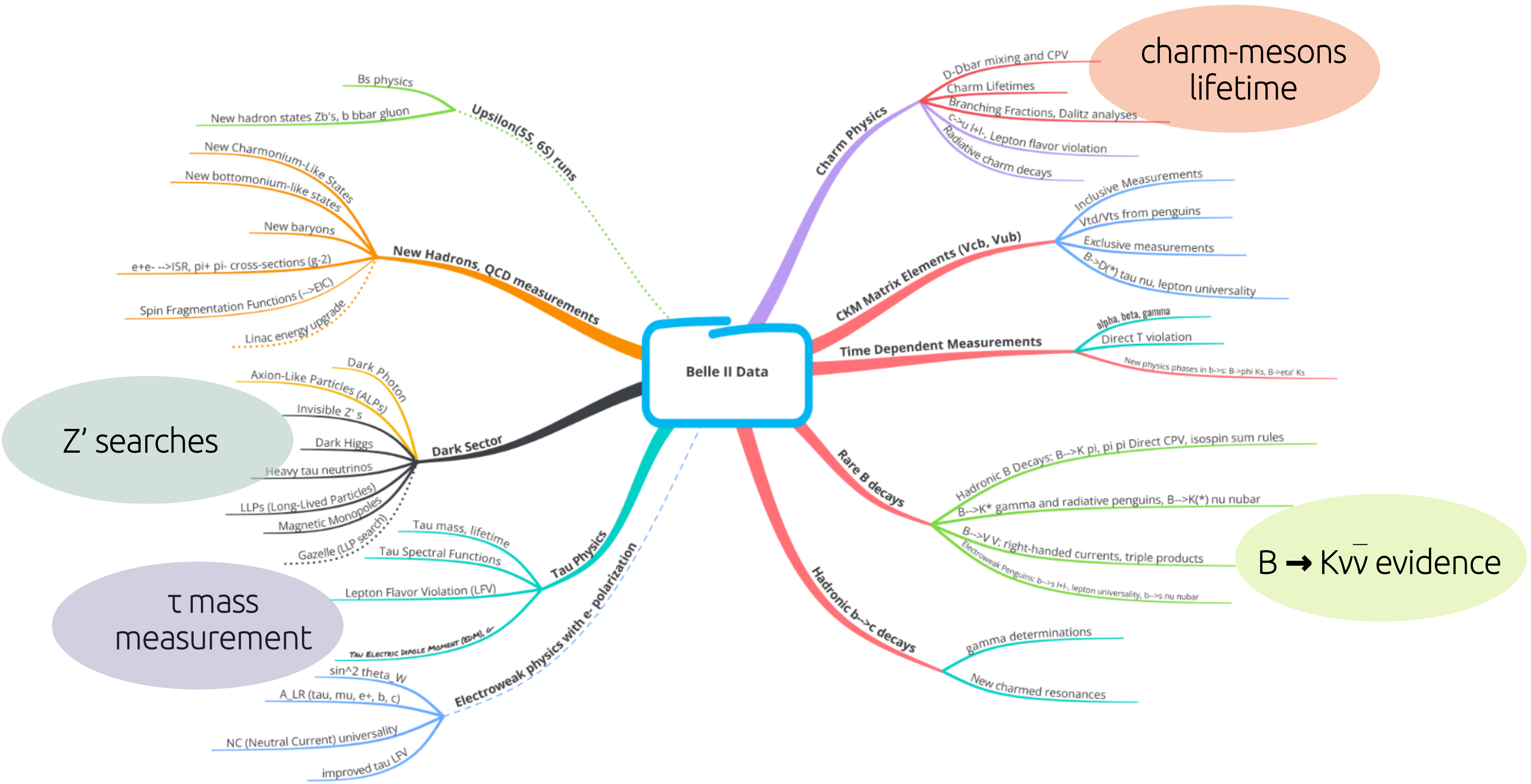
Backup

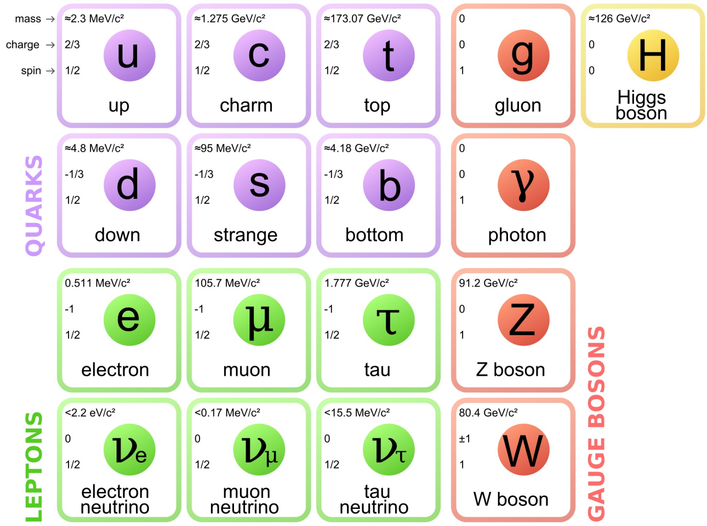
Belle II: the physics program in this talk



[Belle II Physics Book](#) [Snowmass White Paper](#)

Standard Model: a successful theory

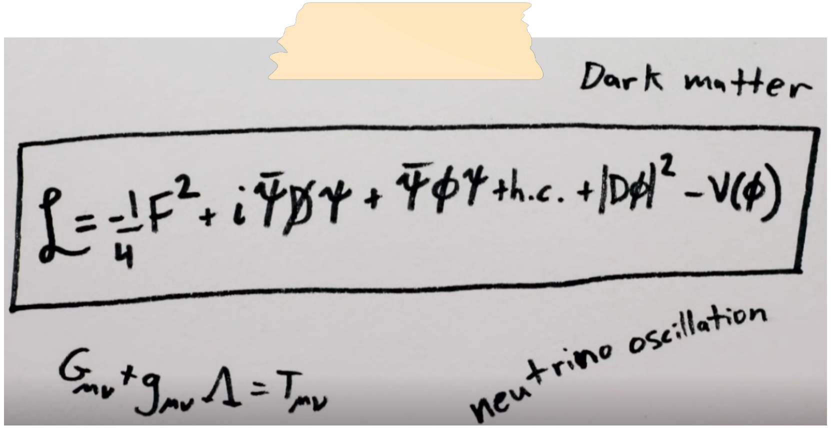
- the Standard Model (SM) is the best tested theory of nature at fundamental level describing particles ad their interactions:
  - the elementary **fermions and bosons** have been observed and their properties measured
  - the **quark model** predicts the vast majority of observed bound states, mesons and baryons



  - **interactions** between mesons, baryons and lepton are predicted with a precision of $\mathcal{O}(1\%)$
  - hundreds of **observables** (branching ratios, CP violation parameters, asymmetries, …) are measured to be consistent with the theory predictions

Standard Model: open questions

- there are still open questions coming from **observations unexplained by the SM**
  - no explanation of the observed **matter-antimatter asymmetry**
  - no **dark matter** candidate or **dark energy** explanation
  - no explanation of **masses hierarchy**, …
- and **tensions between measurements and SM predictions** that need to be interpreted (**see $(g\text{-}2)_\mu$** for example)



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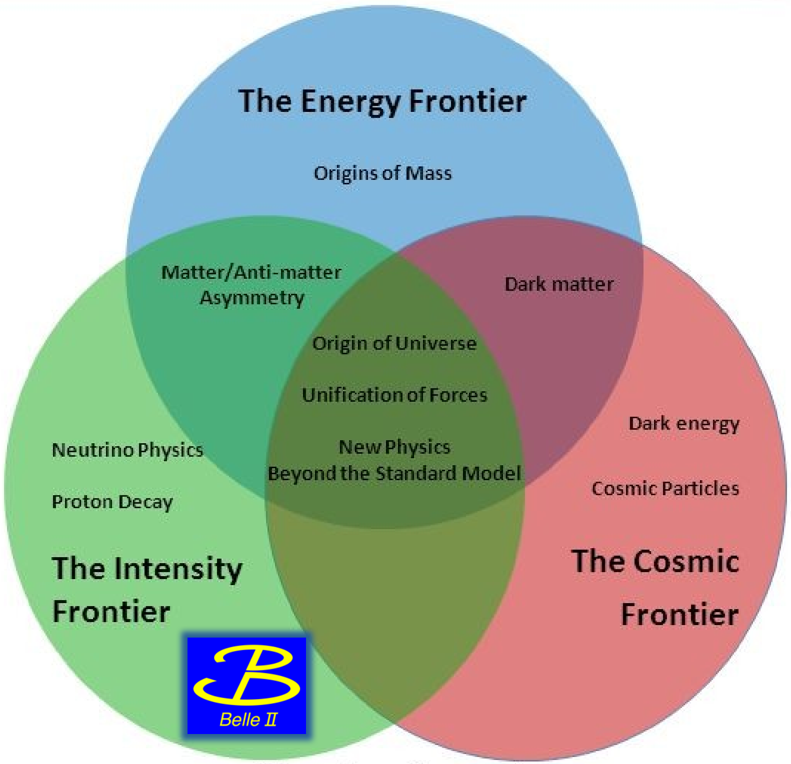
Moving beyond the Standard Model

- at energy frontier experiments are able to discover new particles
  → mass reach for new particle $O(1\ \text{TeV}/c^2)$

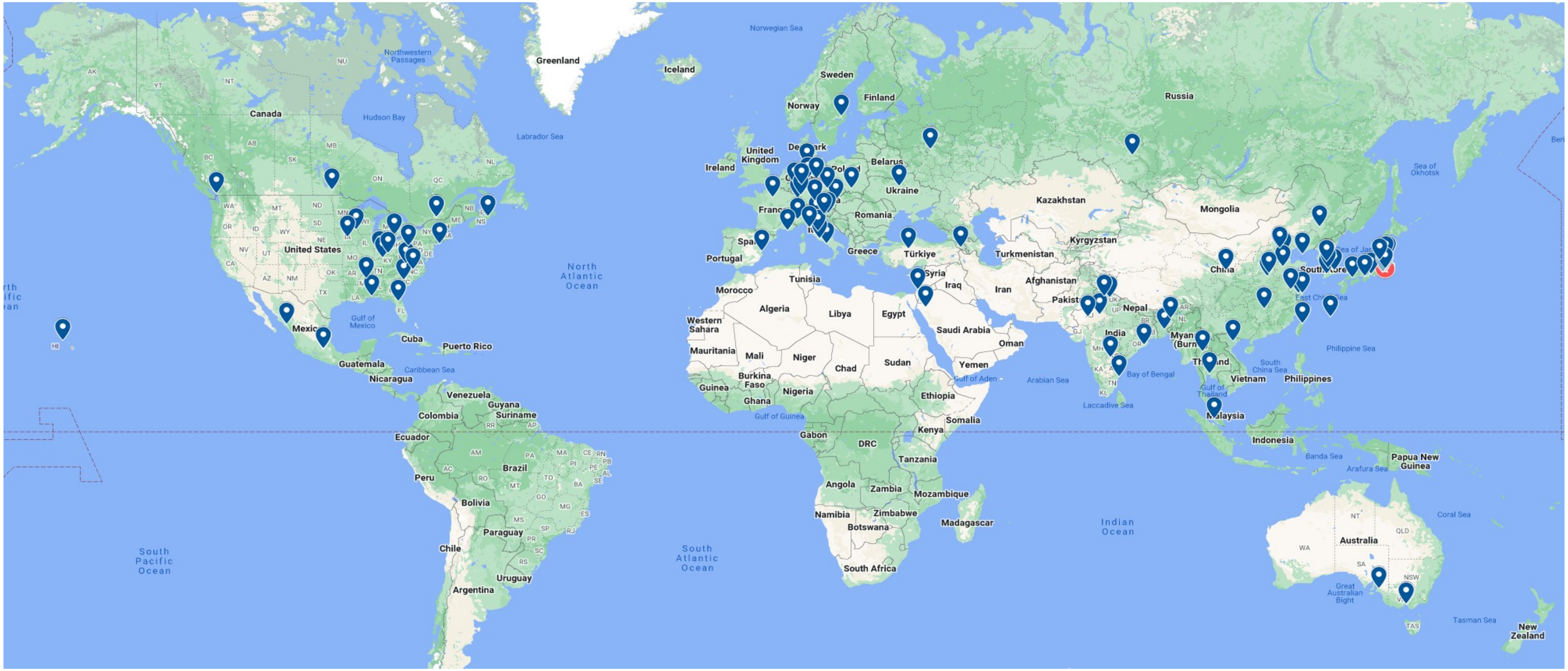
- at rare/precision frontier, observable signatures of new particles or processes can be obtained through measurements of flavor physics reactions at lower energies
  → an observed discrepancy can be interpreted in terms of (New Physics) NP models
  - unprecedented sensitivity to the effect of NP
  - probes NP mass scale higher than the one accessed at the energy frontier



Physics Frontiers

Belle II: the collaboration

27 countries, 123 institutions, >1000 members



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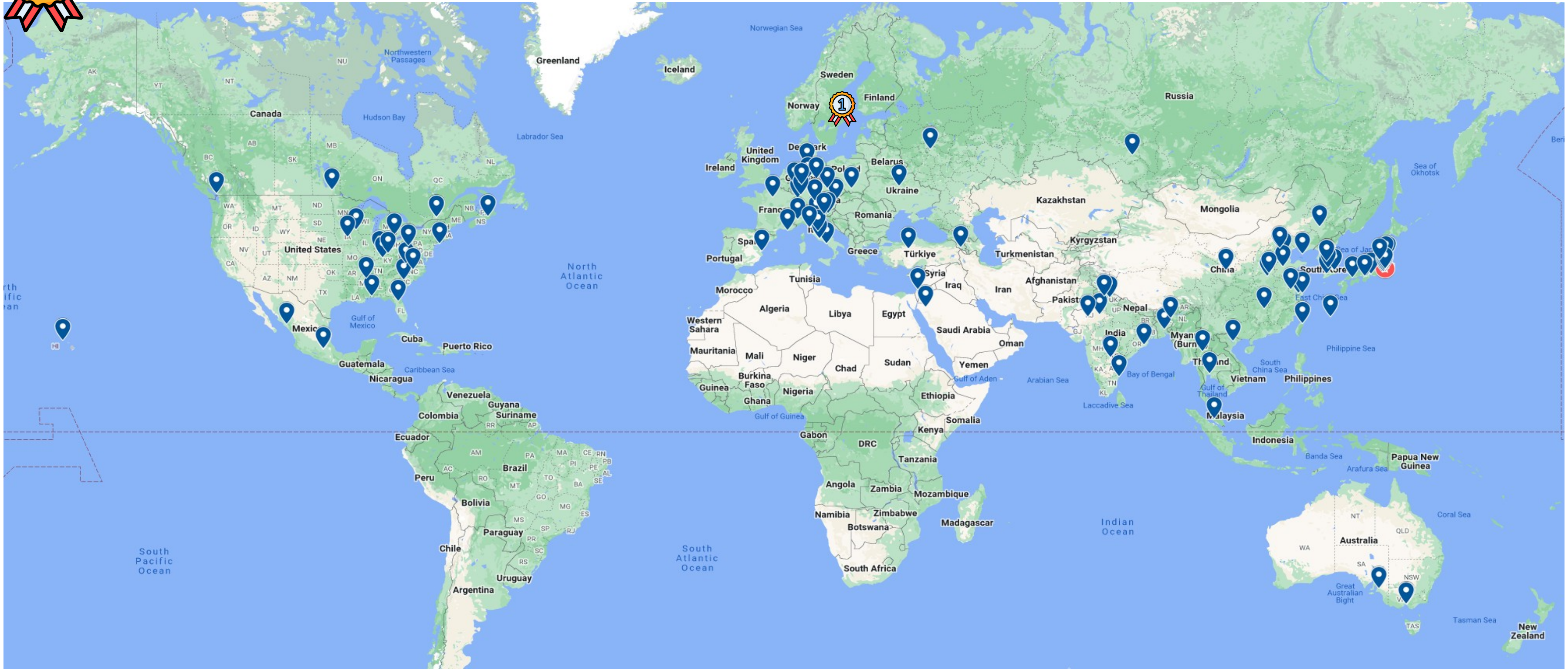
Belle II: the collaboration

Uppsala is first institution from a nordic country



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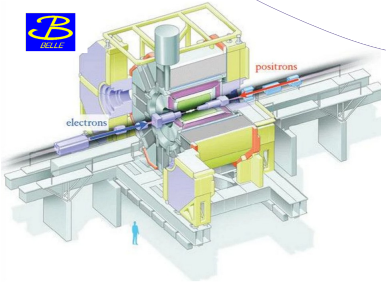
B-factories: first generation

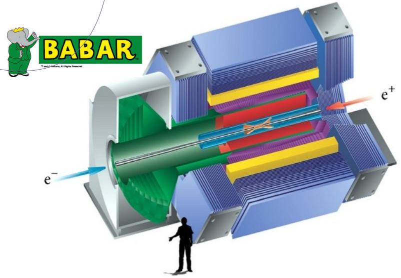
Dedicated experiment at e^+e^- asymmetric-energy colliders for the production of a $B\bar{B}$ pairs:
→ main process:

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

b quark and b anti-quark bound state
$M \sim 10.58\ GeV/c^2$



@KEKB collider (KEK, Japan)

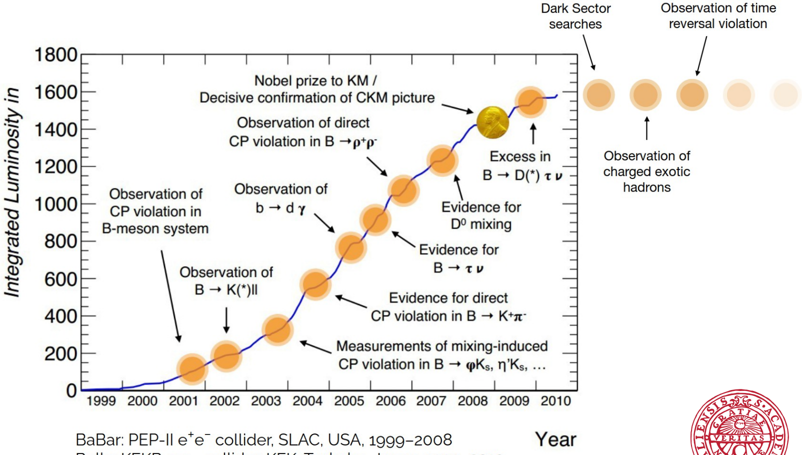


@PEP II collider (SLAC, California)

→ **Belle** and **BaBar** have collected together 1.5 ab^{-1}
→ the majority of existing measurements are limited by statistical uncertainties

not only $B\bar{B}$ are produced:

$\sigma(e^+e^- \rightarrow b\bar{b}) = 1.1$ nb
$\sigma(e^+e^- \rightarrow c\bar{c}) = 1.3$ nb
$\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.9$ nb
$\sigma(e^+e^- \rightarrow uds) = 2.1$ nb
→ rich charm, τ, quarkonium and low-multiplicity program



BaBar: PEP-II e^+e^- collider, SLAC, USA, 1999–2008
Belle: KEKB e+e– collider, KEK, Tsukuba, Japan, 1999–2010

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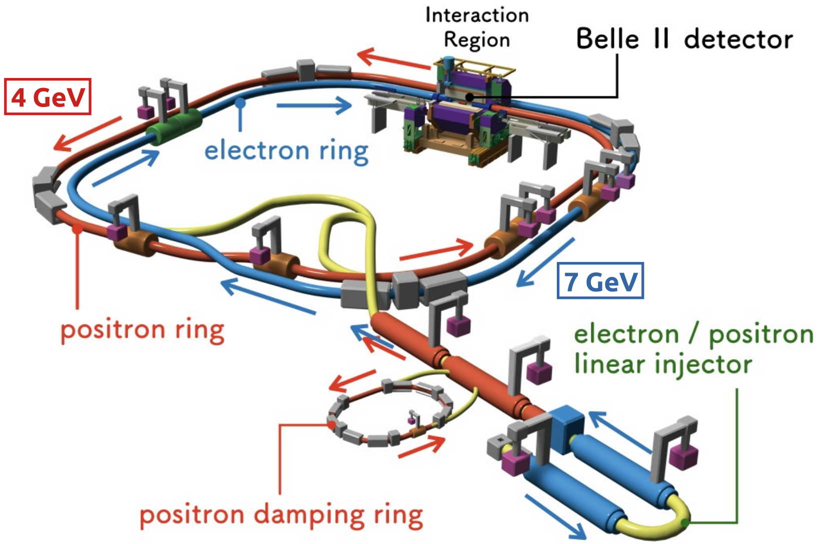
SuperKEKB: a second generation B-factory

- SuperKEKB is a 2nd generation asymmetric e^+e^- collider at the $\Upsilon(4S)$ energy located at **Tsukuba, Japan**
- target instantaneous luminosity is 6×10^{35} $cm^{-2}s^{-1}$ (x30 KEKB/Belle)



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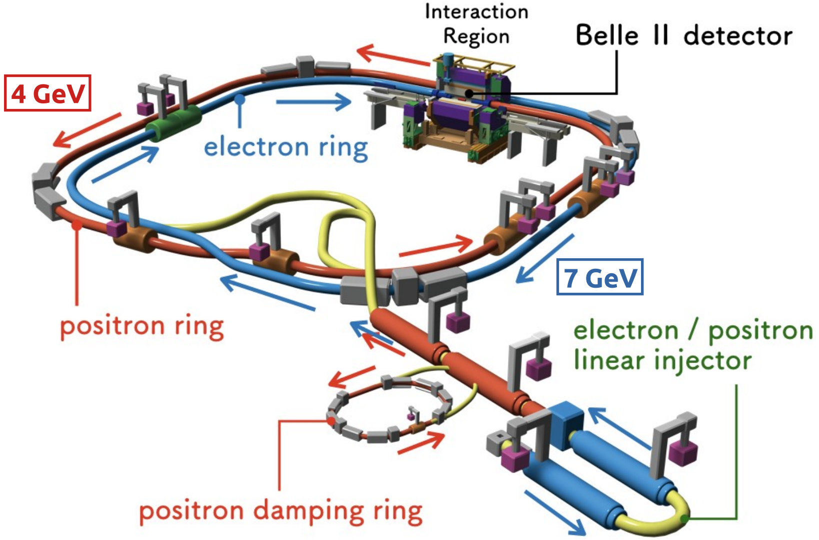
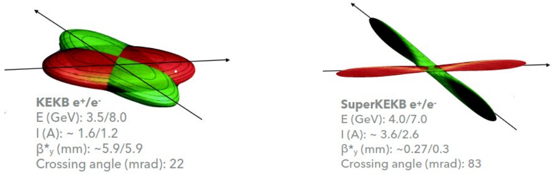


nano-beam scheme



$$L=\frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{y\pm}}{\beta_{y\pm}^*}\right)\left(\frac{R_L}{R_{\xi y}}\right)$$

- Lorentz factor
- beam current (2xBelle)
- beam-beam parameter
- Geometrical reduction factors
- Beam aspect ratio at the IP
- Vertical beta function at the IP (1/20xBelle)

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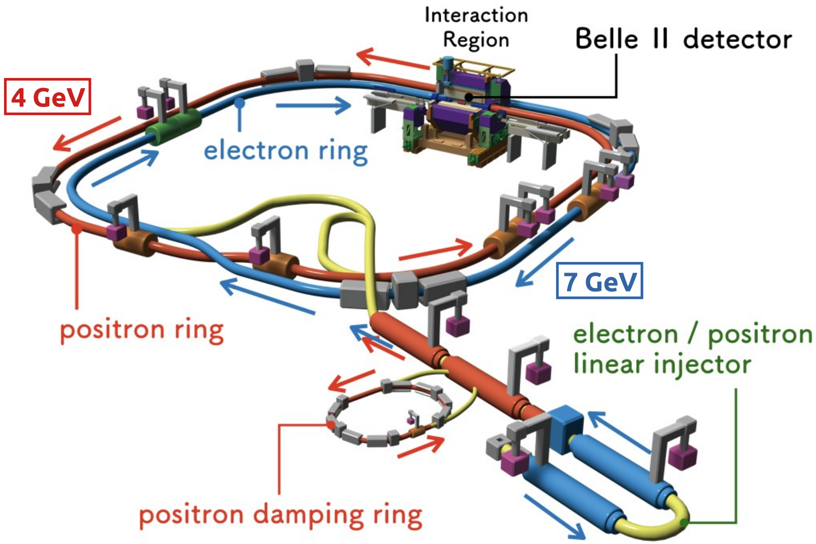

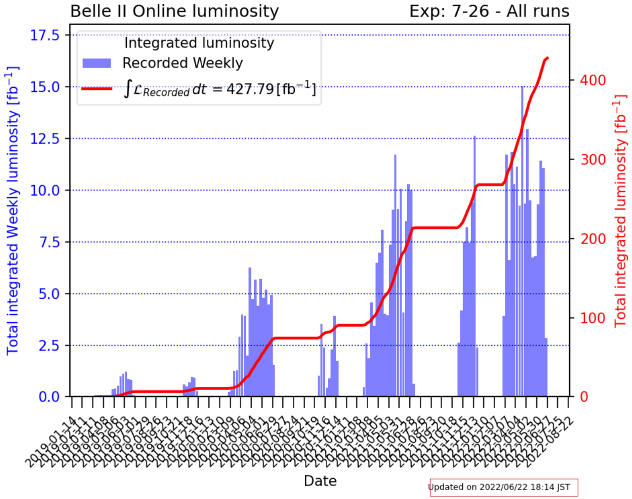

unprecedented instantaneous luminosity:
4.7 x 10^{34} cm^{-2} s^{-1}

currently in long shutdown
➜ data taking will be resumed by the end of 2023

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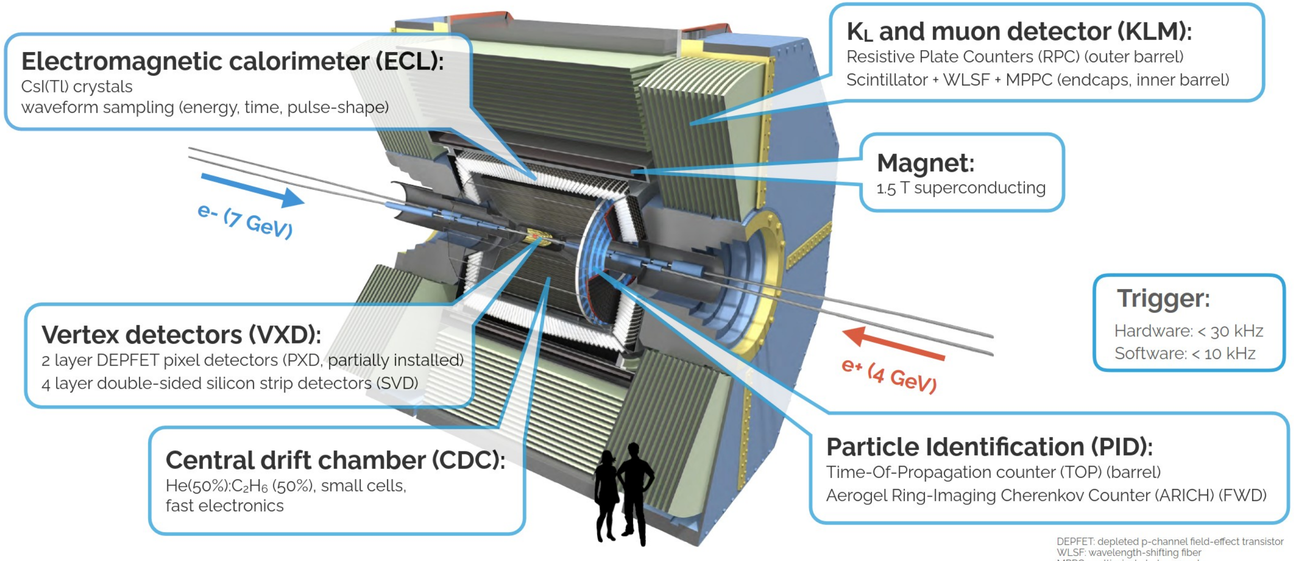
Belle II: the detector

- efficient reconstruction of neutrals (γ, π^0, η, η’…)
- high trigger efficiency
  (including some specific trigger for low-multiplicity events)
- excellent particle identification capabilities
- very good vertexing



DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

The Belle II TDR

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Direct CP asymmetry measurement in $D^0 \rightarrow \pi^+\pi^0$

- self-tagging decay but $D^{*+} \rightarrow D^+\pi^0$ decays are also reconstructed
- raw asymmetry extracted from a fit to the D^+ invariant mass

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

→ split in *D*-tagged* and *non-tagged* candidates improves precision given the different backgrounds and purities

- compatible with CP conservation
  - 30% improvement in statistical precision wrt BELLE thanks to much higher purities at Belle II; systematics also reduced by a factor 2
  - more precise than LHCb (9/fb)

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