QMat Scientific Day
17 June 2026

Search for new physics in $B \to K \pi \pi \gamma$ decays

- QMat thesis grant
- PhD student: Sahil Saha
- 15 Nov. 2024 - 14 Nov. 2027

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IPHC Strasbourg, CNRS/IN2P3

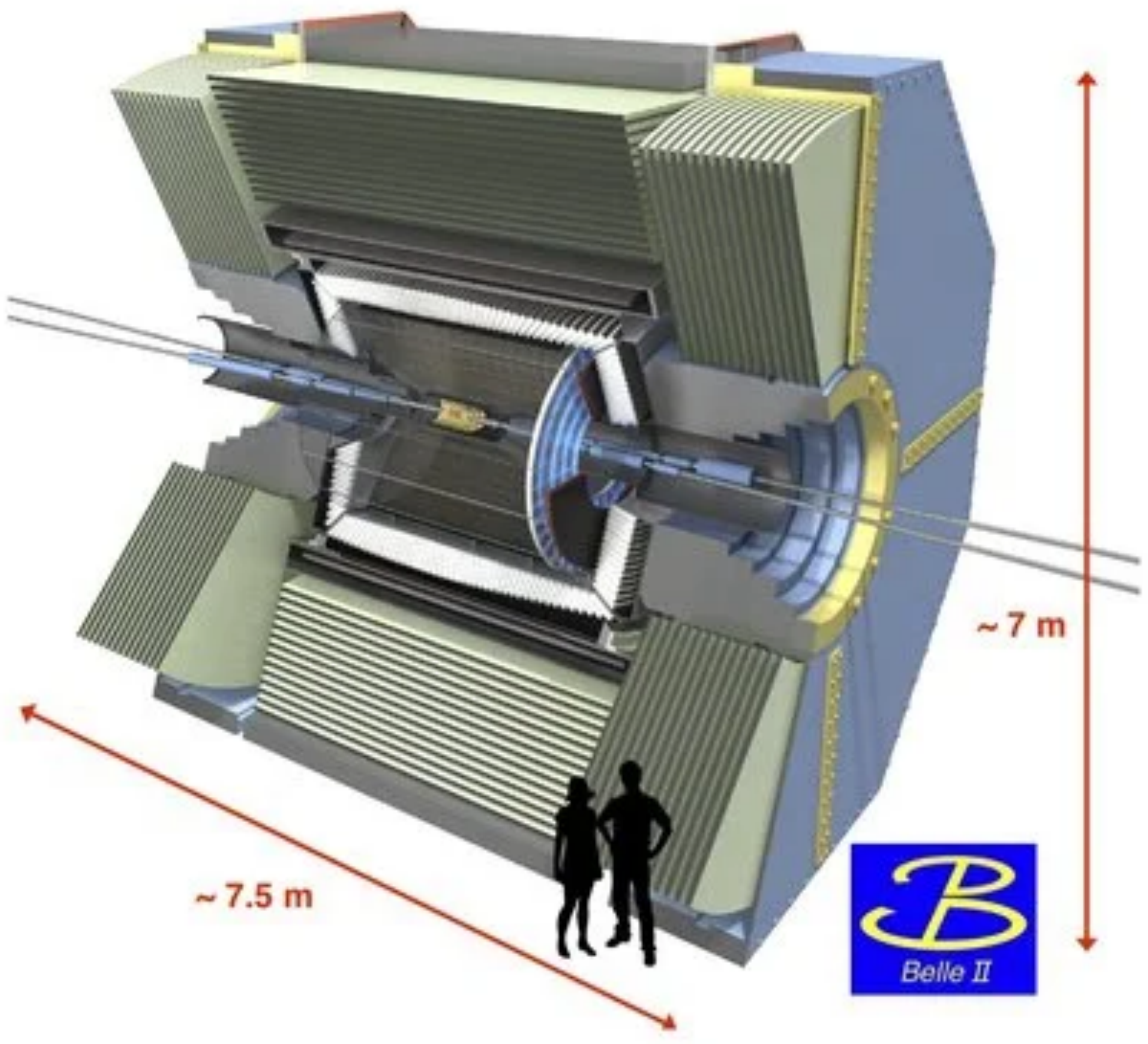
Scientific context

- The Standard Model of particle physics:
  - Quantum relativistic theory based on observation
  - Very precise description of elementary particles and their interactions

    ➛ Several observations show that the SM is only an effective theory valid up to an unknown energy scale above ~1 TeV

- Search for new physics beyond the SM:
  - Directly produce new unknown particles: with ultra-high energy at LHC hadronic collider
  - Be sensitive to the quantum manifestation of new, unknown particles: with ultra-high precision

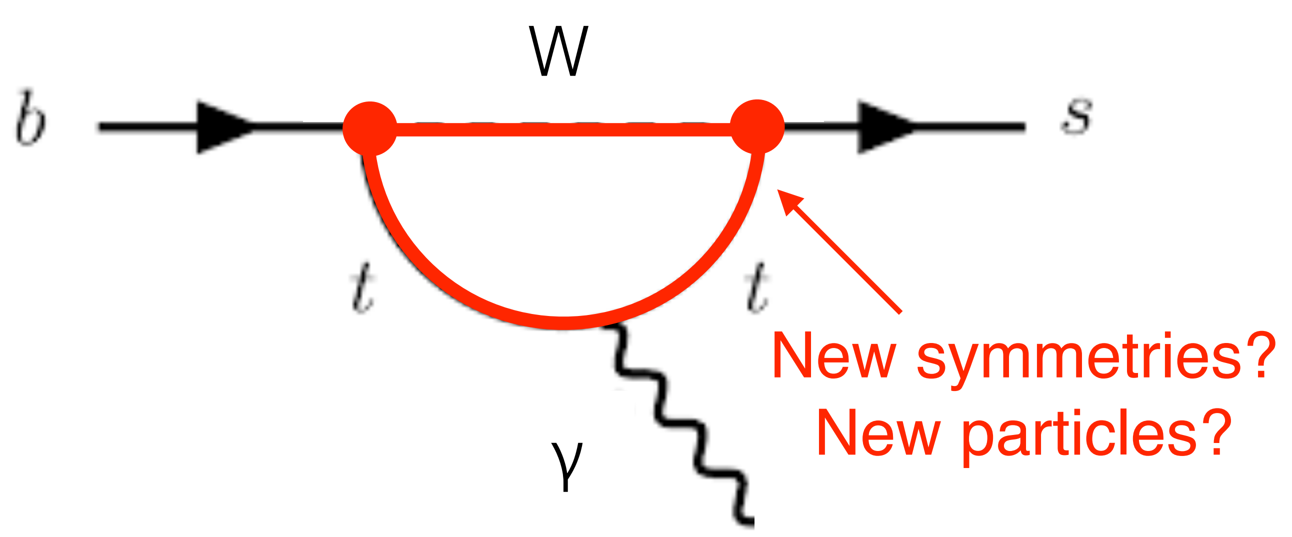
    ➛ Precision measurements in B-meson decays in the Belle II experiment at SuperKEKB delivering e^+e^- collision with world-record luminosity



Time-dependent CP asymmetry

- Photon polarisation in b → s γ quark transitions:
  - Photon nearly 100% polarised due to left-only coupling between $W^\pm$ and fermions
  - The time-dependent CP asymmetry of b → s γ processes is ~0
    due to the polarisation of the photon in the SM

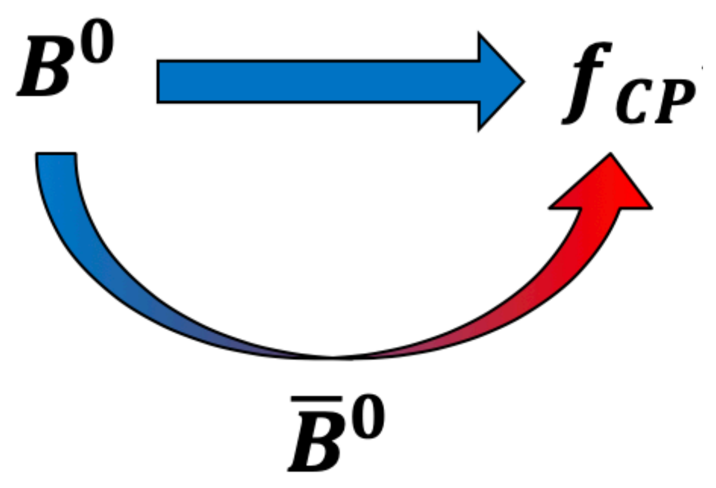
    ➛ Time-dependent CP asymmetry ≠ 0 means new physics beyond the SM



- CP violation in the interference between mixing and decay:

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

$$= S_{CP} \sin(\Delta m \Delta t) - C_{CP} \cos(\Delta m \Delta t)$$



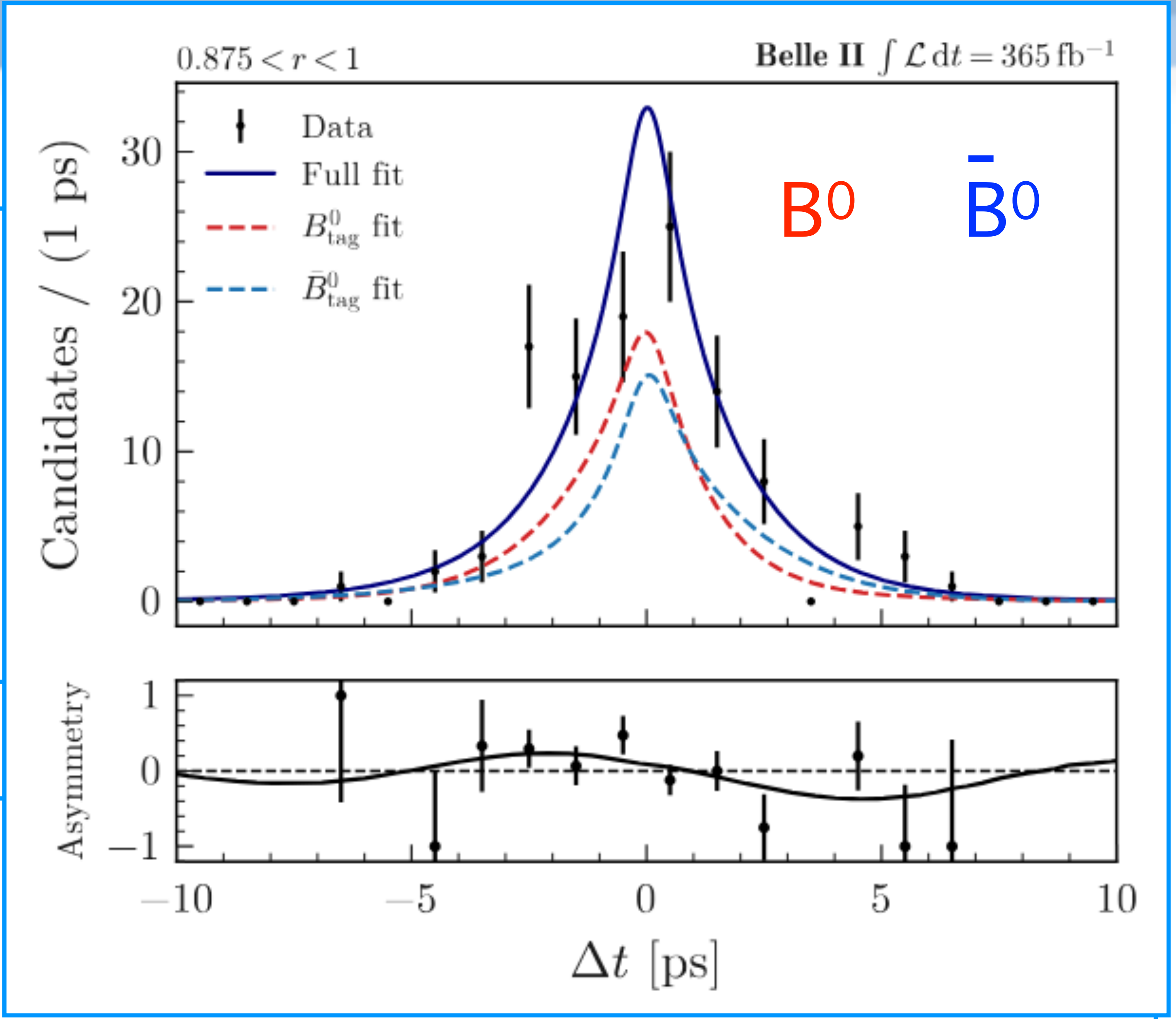
$B^0 = (\bar{b}\ d)$

The B → K π π γ decay

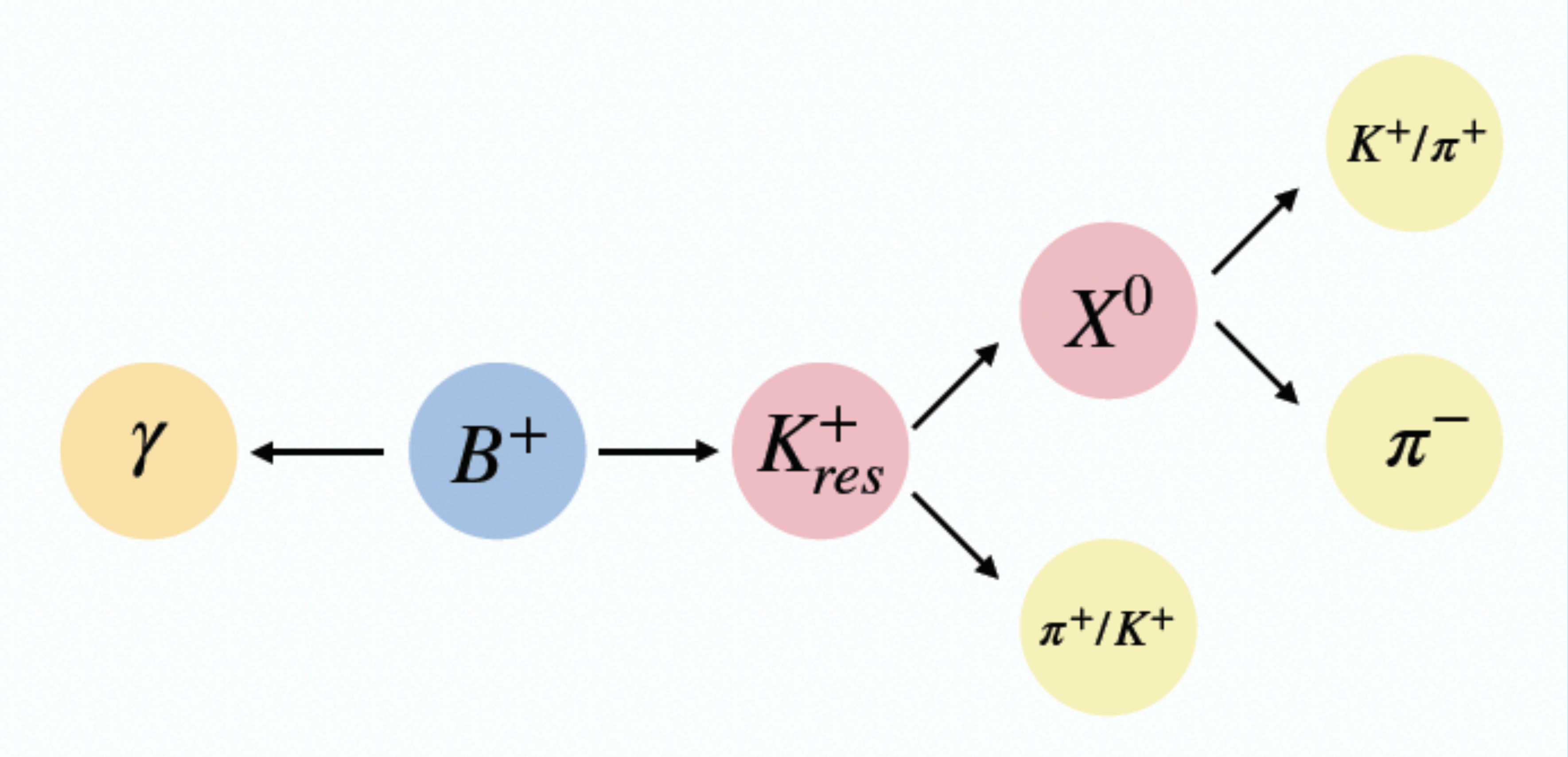
- Measurement of time-dependent CP asymmetry of $B^0 \to K^0_S \pi^+ \pi^- \gamma$
  - Published in [JHEP 01 (2026) 134]() by the Belle2-IPHC group
  - Effective $S_{CP} = -0.29 \pm 0.11 \pm 0.05$: world best precision
  - Null test of the standard model

$B^0 = (\bar{b}\ d)$

$K^0_S = (\bar{s}\ d)$



- Many possible paths: $B \to K_{res}\gamma \to K\pi\pi\gamma$ decay
  - Mix of CP and non-CP intermediate $K_{res}\gamma$ CP-states
  - Only contribution of pure intermediate $K_{res}\gamma$ CP-states must be used to constrain new physics
  - Quantum interference of all possible intermediate amplitudes



Dilution factor

- Non-CP intermediate modes dilute the CP-asymmetry:

$$\mathcal{S}_{B\to K\pi\pi\gamma} = \mathcal{D}\,\mathcal{S}_{CP}$$

measured — dilution factor — pure-CP parameter

with: $$\mathcal{D} = \frac{2\int \mathbb{A}^*(p_0,p_1,p_2)\,\mathbb{A}(p_1,p_0,p_2)\,d\Phi}{\int \left(|\mathbb{A}(p_0,p_1,p_2)|^2 + |\mathbb{A}(p_1,p_0,p_2)|^2\right) d\Phi}$$

and: $\mathbb{A}(p_0,p_1,p_2)$ is the complex amplitude of $B \to K^0_S(p_2)\,\pi^+(p_0)\,\pi^-(p_1)\,\gamma$

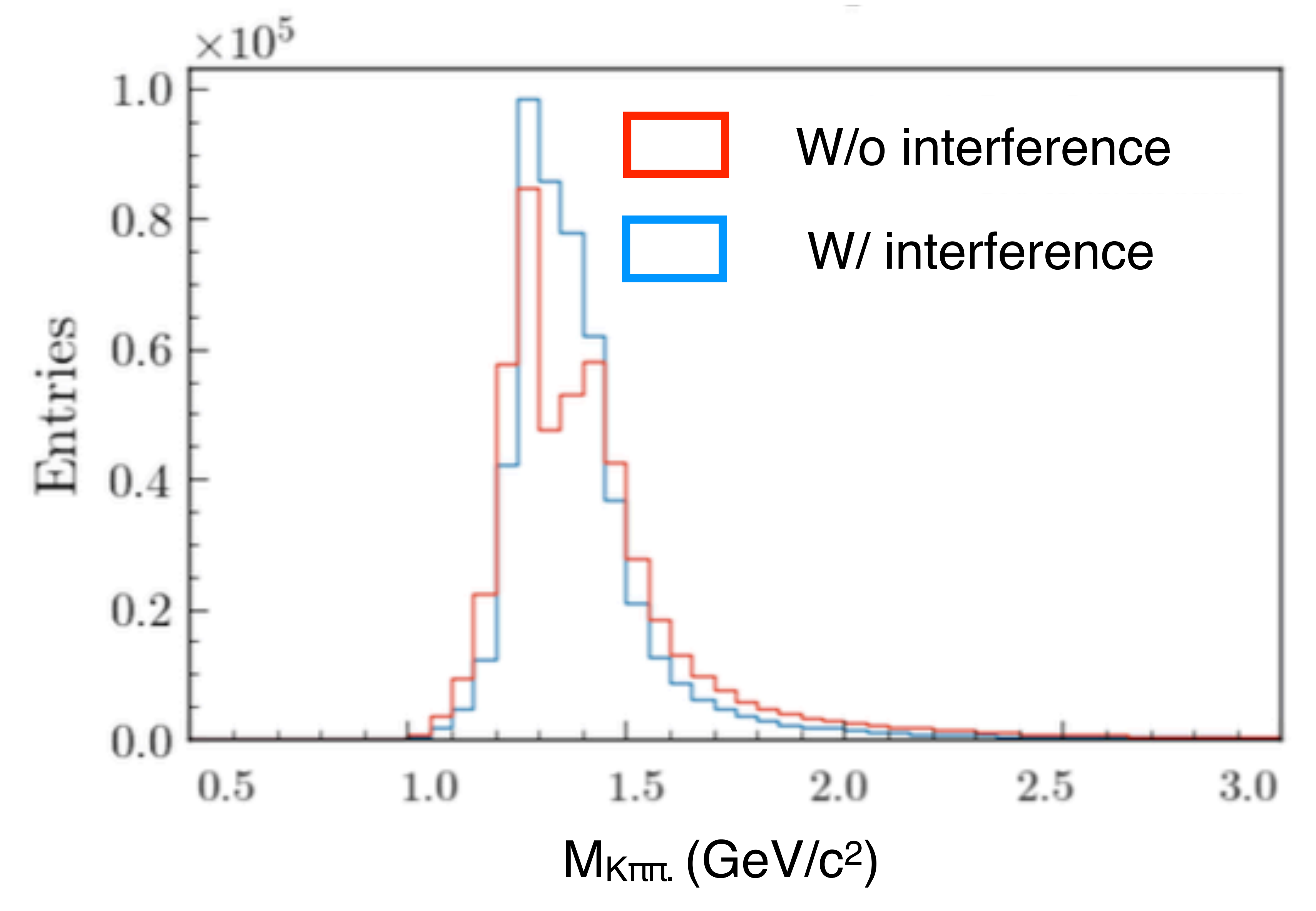
- Amplitude analysis needed to disentangle all K_{res} contributions
  - Because many states & quantum interference
  - Use isospin partner mode $B^+ \to K^+_{res}\,\gamma \to K^+\pi^+\pi^-\gamma$: more statistics

J^P	Decay Mode
1^+	$K_1(1270)^+ \to K^*(892)^0\pi^+$
	$K_1(1270)^+ \to K^+\rho(770)^0$
	$K_1(1270)^+ \to K^+\omega(782)^0$
	$K_1(1270)^+ \to K^*(1430)^0\pi^+$
	$K_1(1400)^+ \to K^*(892)^0\pi^+$
	$K_1(1400)^+ \to K^+\rho(770)^0$
1^-	$K^*(1410)^+ \to K^+\rho(770)^0$
	$K^*(1410)^+ \to K^*(892)^0\pi^+$
	$K^*(1680)^+ \to K^*(892)^0\pi^+$
	$K^*(1680)^+ \to K^+\rho(770)^0$
2^+	$K_2^*(1430)^+ \to K^*(892)^0\pi^+$
	$K_2^*(1430)^+ \to K^+\rho(770)^0$
	$K_2^*(1430)^+ \to K^+\omega(782)^0$
2^-	$K_2(1770)^+ \to K^*(892)^0\pi^+$
	$K_2(1770)^+ \to K^+\rho(770)^0$
	$K_2(1770)^+ \to K_2^*(1430)^0\pi^+$
	$K_2(1770)^+ \to K^+f_2(1270)^0$

(Pure-CP K^0_{res} modes in red)

Amplitude analysis strategy

- Development of an event generator
  - Only few K_{res} decays originally encoded in the usual EVTGEN event generator
  - Generate quantum interference between all states: based on AMPGEN



- Event simulation
  - Implementation in Belle II analysis framework, with detector simulation based on GEANT-4

- Selection and reconstruction of $B^+ \to K^+_{res}\,\gamma \to K^+\,\pi^+\,\pi^-\,\gamma$ decays
  - Part of another PhD thesis work, by Mattéo Maushart from IPHC Strasbourg

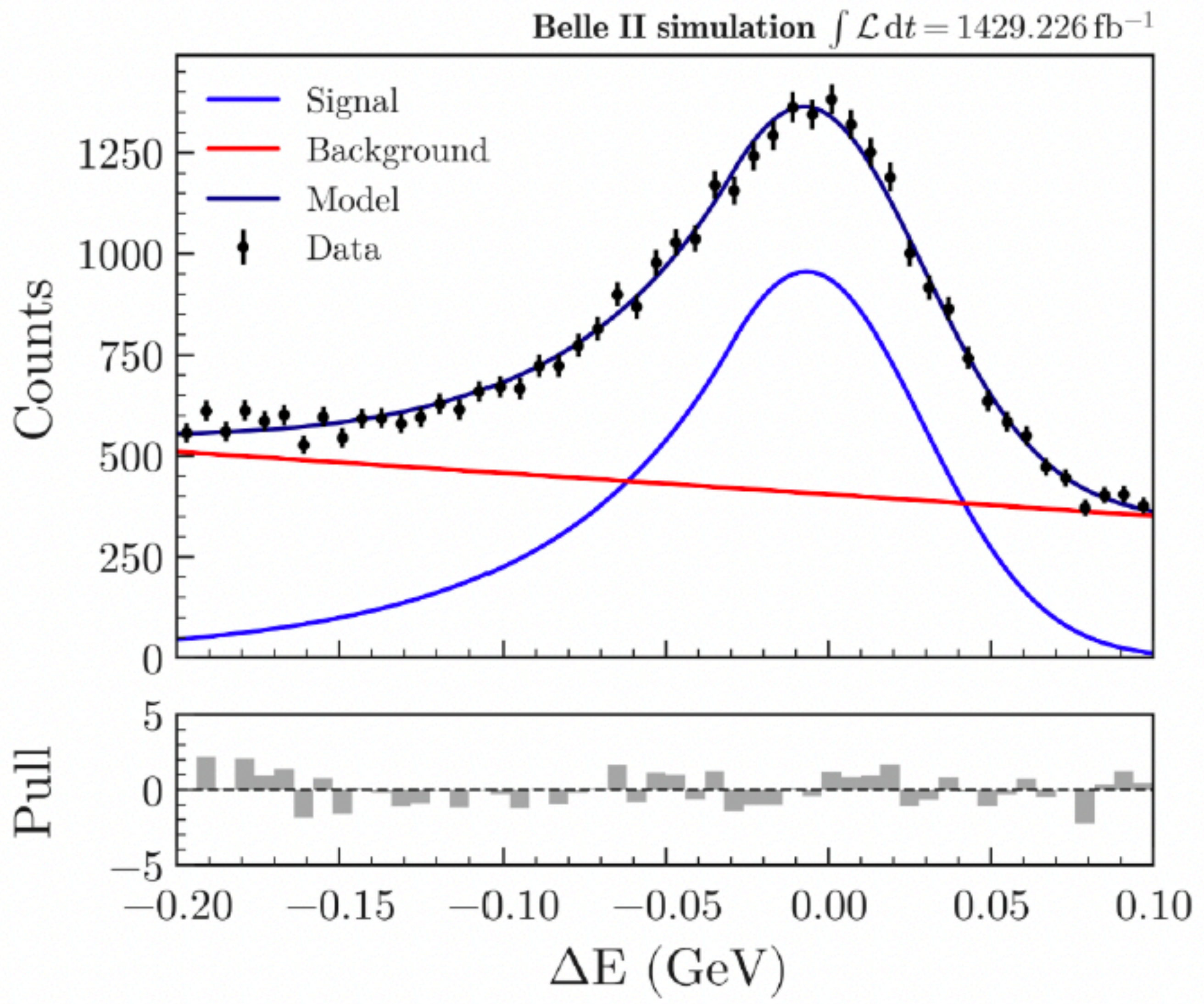
- Fit to Belle II data with an unbinned maximum-likelihood method
  - Develop the fit model
  - Blinded analysis strategy:
    - Statistical studies with Toy Monte-Carlo & bootstrap methods
    - Dilution factor in data not disclosed before analysis review by the collaboration

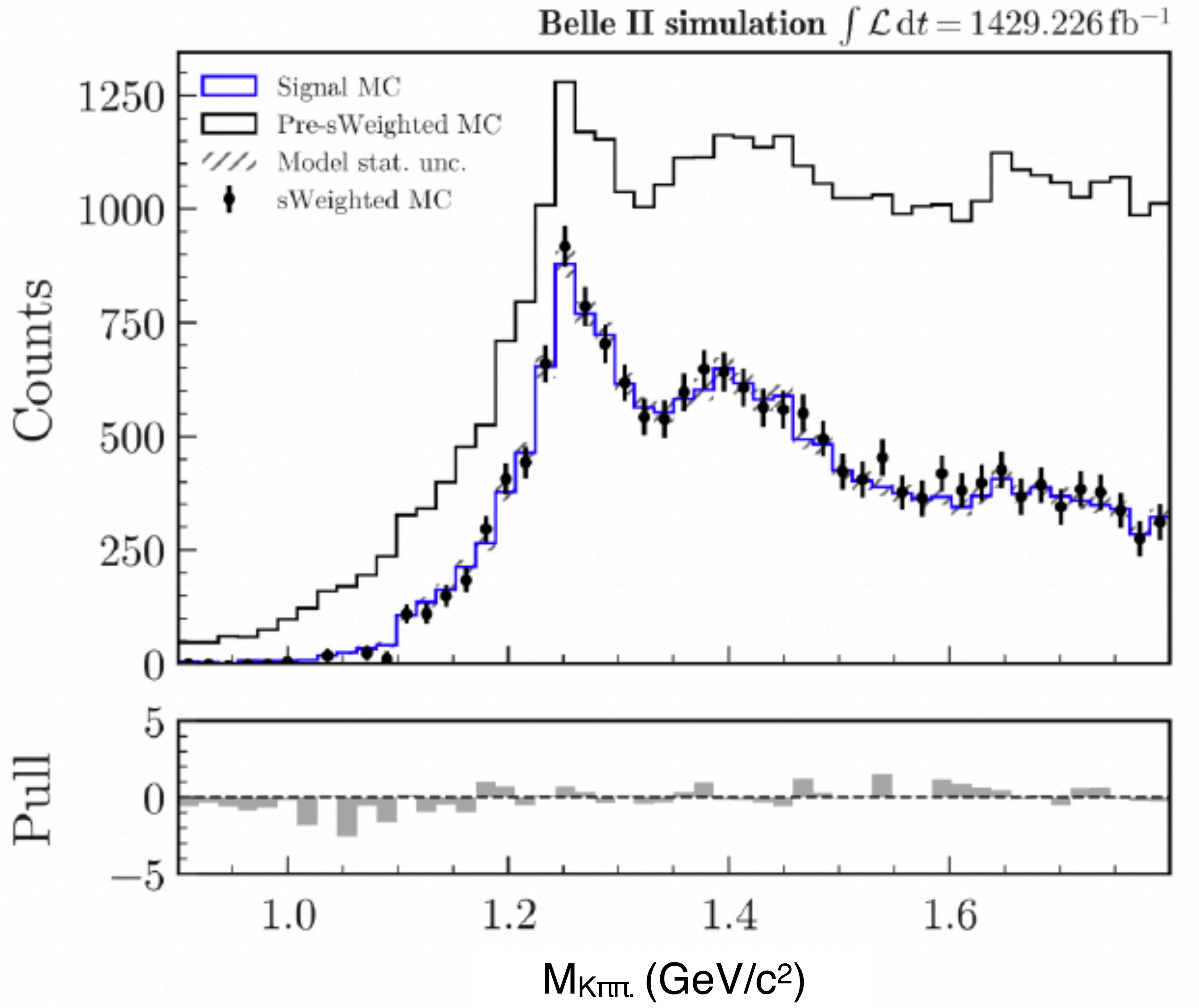
Event selection and reconstruction

- Reconstruction and selection of $B^+ \to K^+ \pi^+ \pi^- \gamma$ decays
  - Based on a series of sequential criteria and on neural networks
  - Bias control channel, bootstrap methods and toy Monte-Carlo

- Production of background-free distributions:
  - Based on sPlot unfolding statistical method
  - Discriminating variable:

$$\Delta E = \frac{p_B \, p_{e^+e^-} - s}{2\sqrt{s}}$$





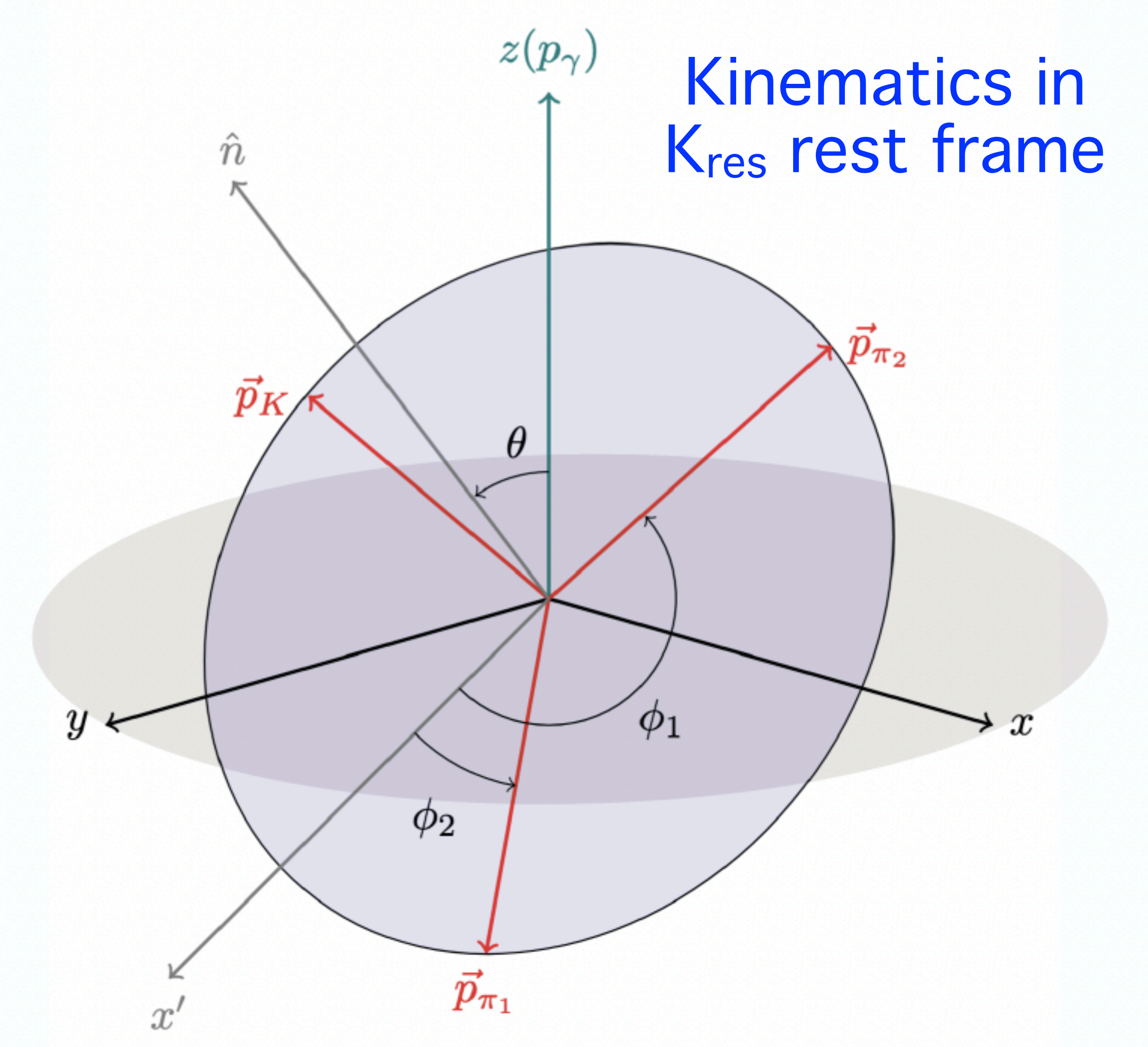
(© M. Maushart)

Amplitude model of $B^+ \to K^+ \pi^+ \pi^- \gamma$ decays

- Decay described with 5 kinematic variables in Kres rest frame:

$$d\Gamma = \frac{|\mathcal{A}|^2}{2m_B} d\Phi$$

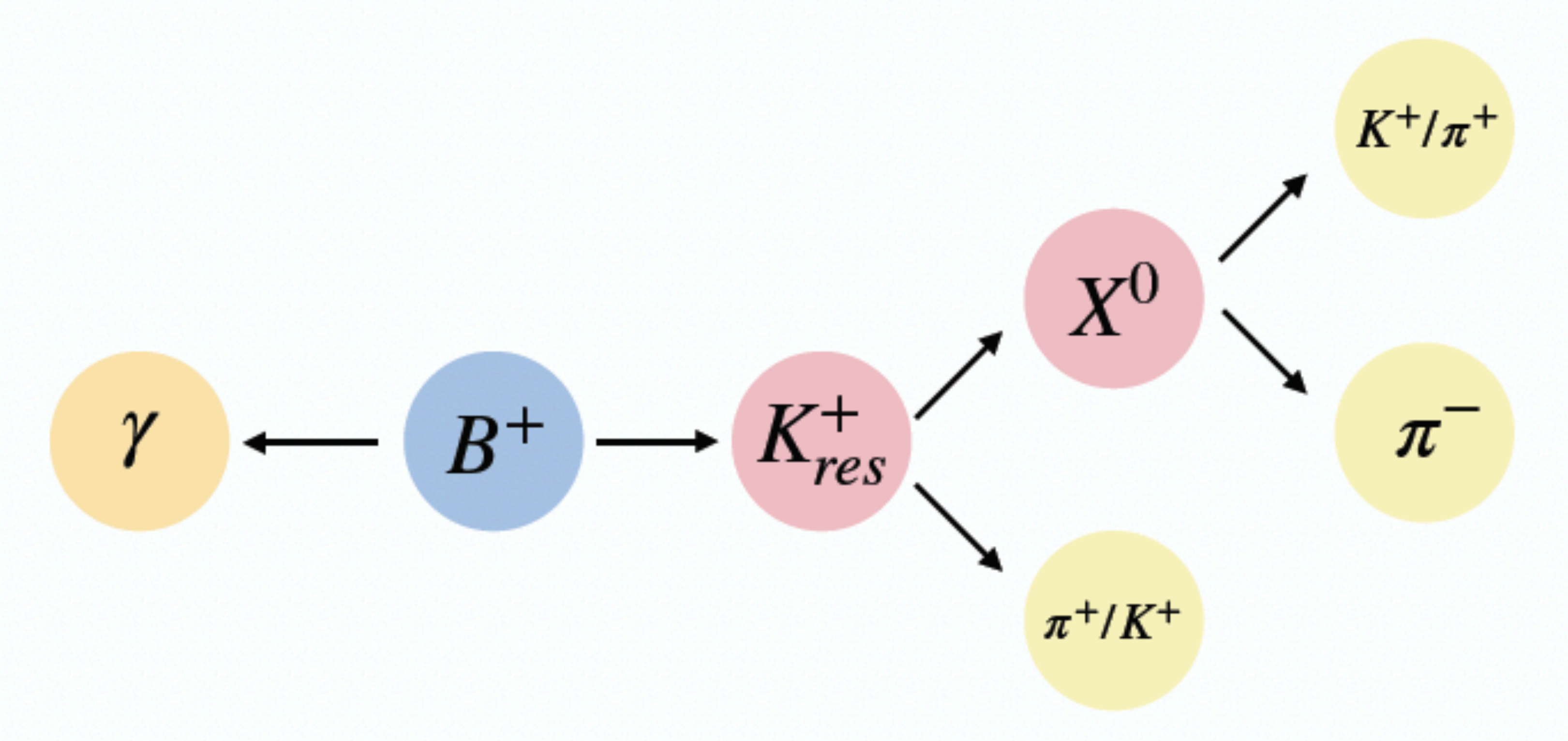
With Lorentz invariant phase space factor: $d\Phi = f(m_{K\pi\pi}, m_{K\pi}, m_{\pi\pi}, \cos\theta, \phi_1)$



- The total decay amplitude is a coherent sum of each individual amplitude i:

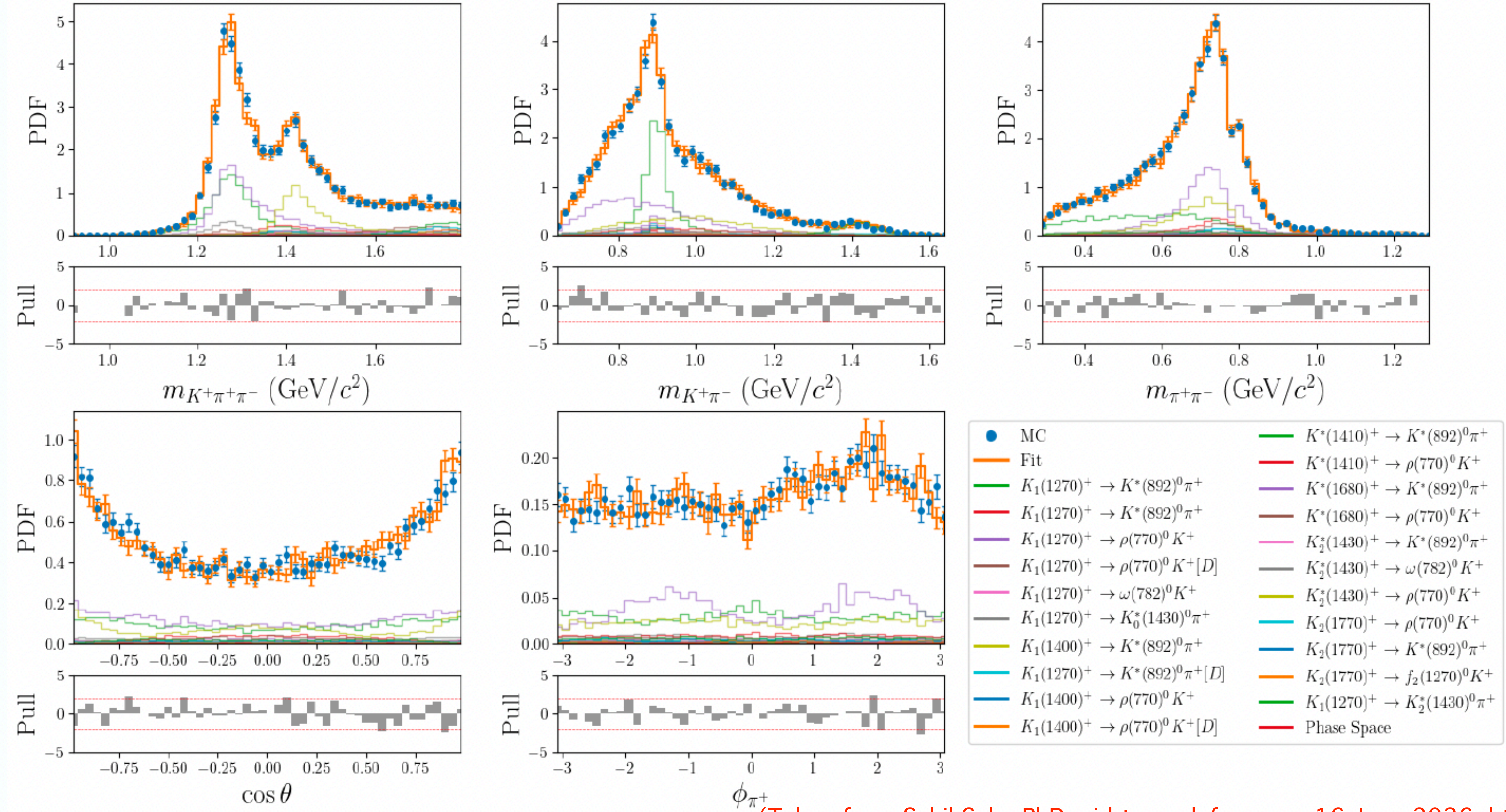
$$\mathcal{A}(P) = \sum_i (a_i + ib_i)\mathcal{A}_i(P)$$

With: $\mathcal{A}(P) = \underbrace{S_B \cdot B_{L_B}}_{B^0\text{ decay}} \cdot \underbrace{T_{K_{Res}} \cdot S_{K_{Res}} \cdot B_{L_{K_{Res}}}}_{K_{res}\text{ decay}} \cdot \underbrace{T_X \cdot S_X \cdot B_{L_X}}_{X\text{ decay}}$



- Angular momentum factors S_i
- Barrier factors B_i
- Lineshapes T_i

Preliminary fit results on simulation



Fit on signal with fit PDF including all possible decays

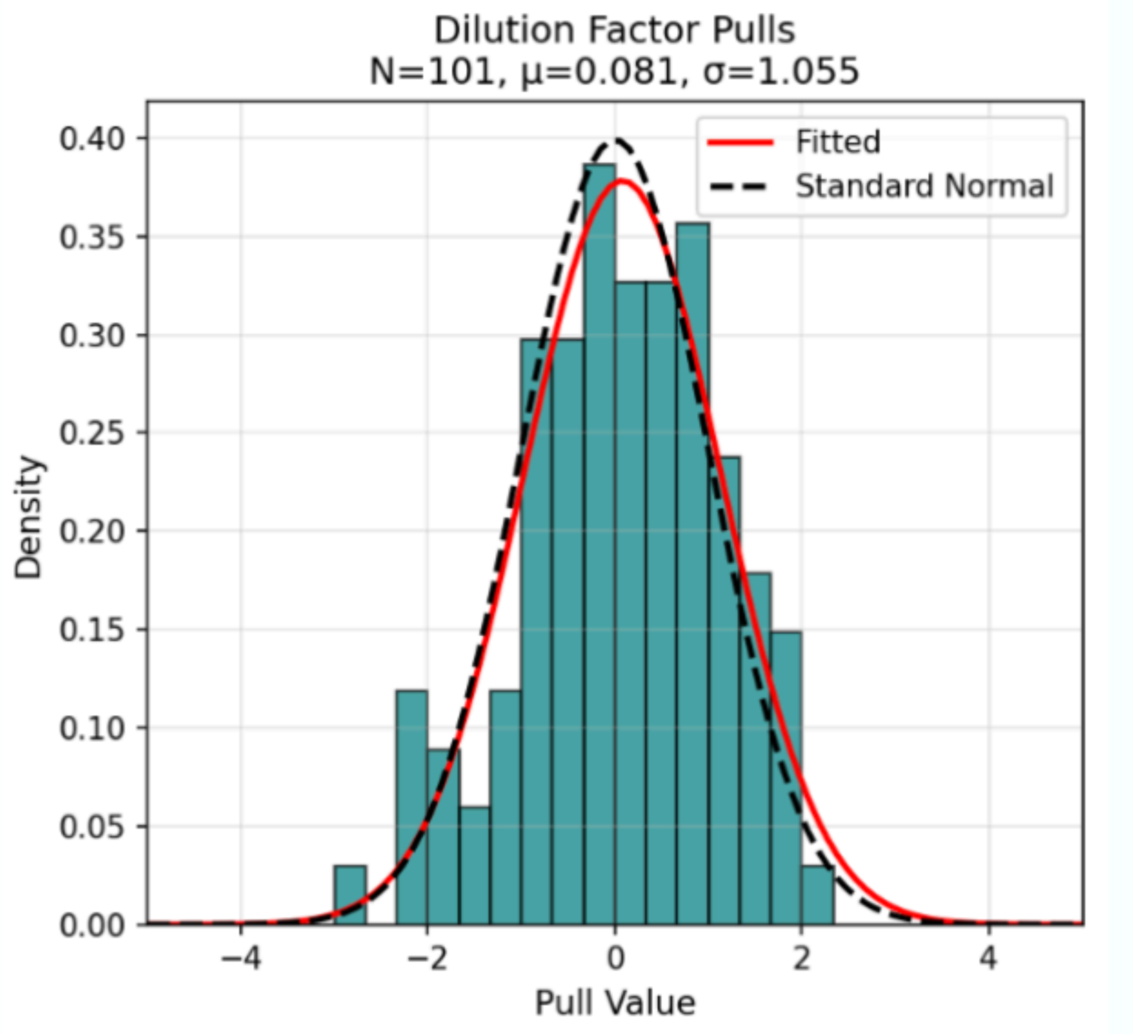
- $n_{\textbf{free parameters}} = 40$
- $n_{\textbf{events}} = 8000$
- $\chi^2/dof\,(\text{mass, 3D}) = 0.965$
- $\chi^2/dof\,(\cos\theta) = 0.982$
- $\chi^2/dof\,(\phi_{\pi^+}) = 0.779$

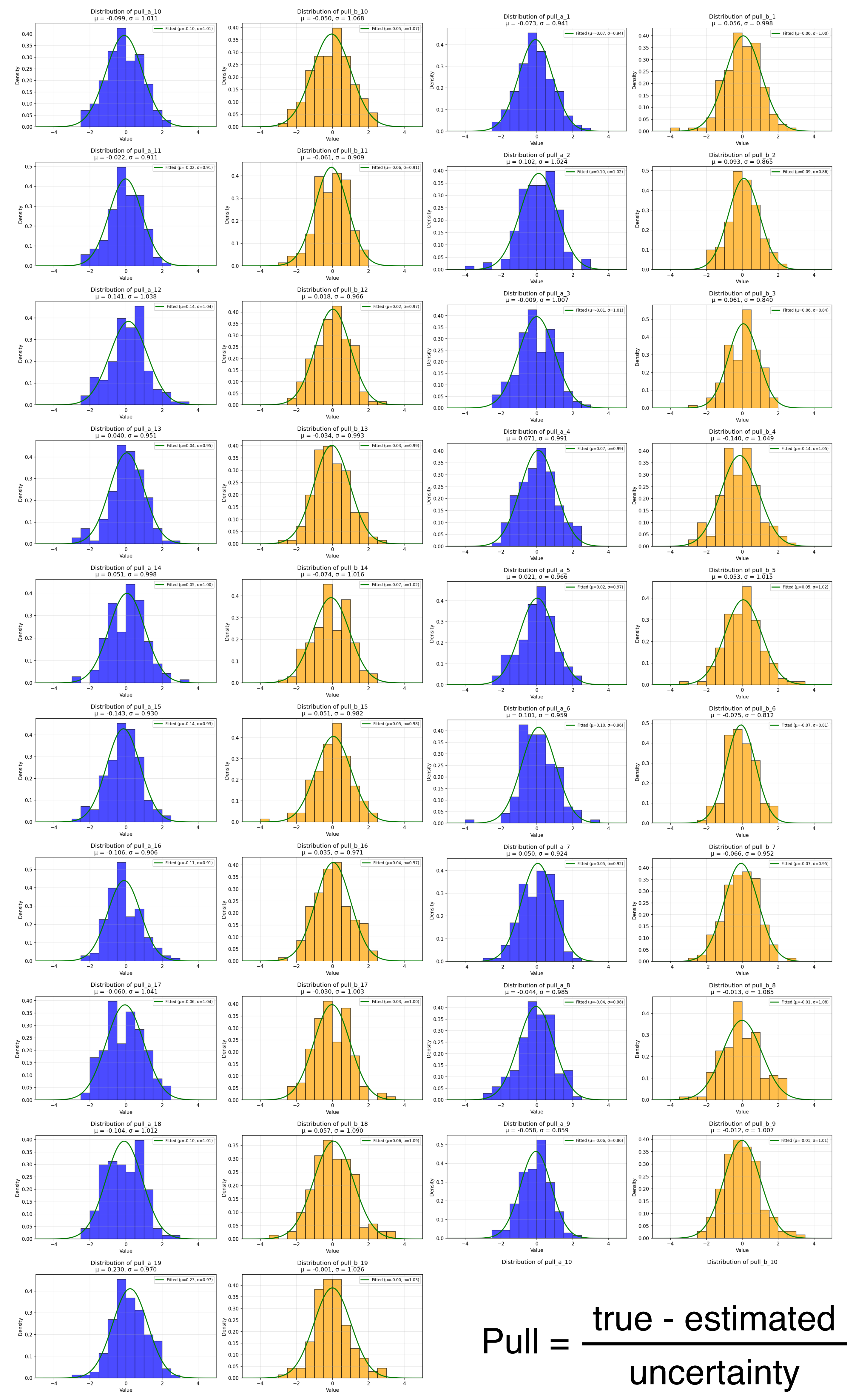
(Taken from Sahil Saha PhD mid-term defence on 16 June 2026: https://indico.in2p3.fr/event/40141/)

Fit robustness checks

- Statistical studies with Toy Monte-Carlo & bootstrap methods
  - Test fit biases, fit stability, and fit statistical sensitivity

- Set the strategy to choose the best fit model on data
  - Dilution factor and branching ratios kept blinded
  - Start the fit on data with the largest amplitude model
  - If the fit is not satisfactory: switch to simpler model (less channels)
  - Based on different quality figures of merit (work ongoing): fit χ^2, Akaike or Bayesian Information Criterion, Kolmogorov-Smirnov test





$$\text{Pull} = \frac{\text{true - estimated}}{\text{uncertainty}}$$

Status & prospects

- First full amplitude analysis of $B \to K \pi \pi \gamma$ decays
  - QMat PhD thesis grant enabled Sahil Saha to develop the full amplitude model
  - Had been tried for a long time by concurrent experiment at CERN, LHCb
  - Several outputs expected: first measurements of kaonic branching ratios, $B \to K \pi \pi \gamma$ CP dilution factor enabling to constrain new physics beyond the SM

- Presentation by Sahil Saha at the international conference Les Rencontres de Moriond Electroweak. Proceeding will be published shortly: arXiv: 2604.26315 [hep-ex] (2026).

- Next steps:
  - Study systematic uncertainties
  - Write the Belle II internal note and undergo the Belle II internal analysis review
  - Perform the analysis on data

    ➛ Target to publish by the end of 2027

Additional material

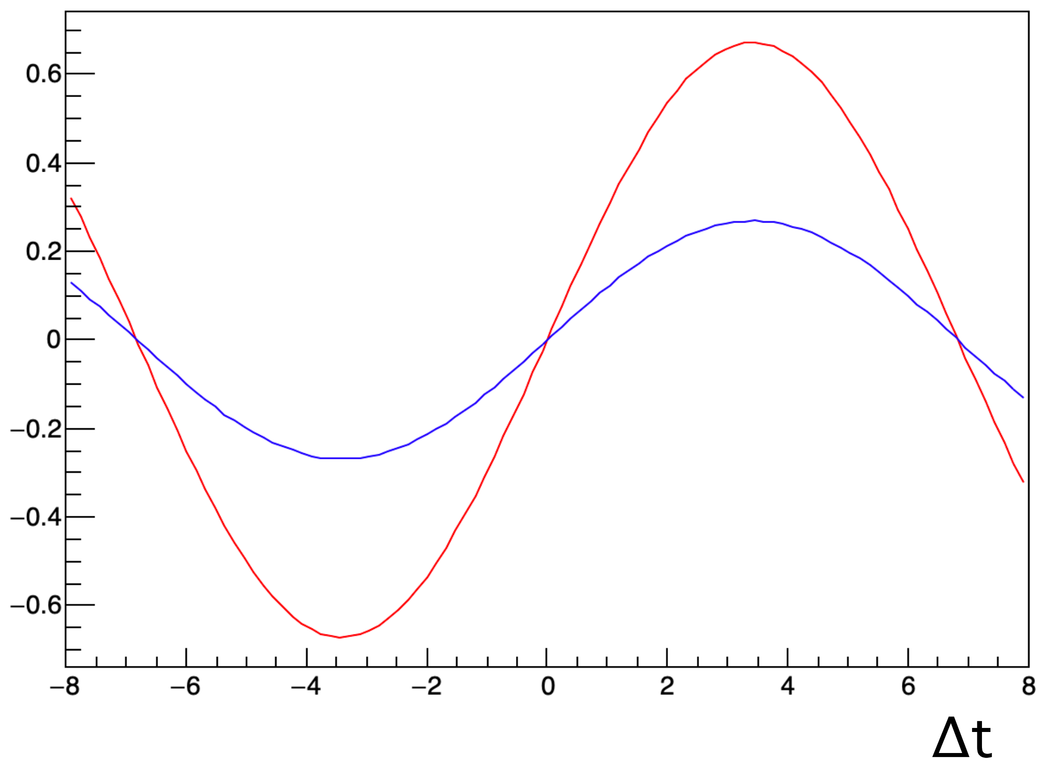
Performance drivers

- Statistics:
  - Integrated luminosity
  - Production cross-section
  - Detector acceptance
  - Trigger efficiency
  - Reconstruction efficiency

- Hadron species:
  also B_s^0, baryons

- Flavour tagging:
  Hadron or anti-hadron

$$\mathcal{A}_{CP}(t) = \frac{N(B^0(t) \to f_{CP}) - N(\bar{B}^0(t) \to f_{CP})}{N(B^0(t) \to f_{CP}) + N(\bar{B}^0(t) \to f_{CP})}$$



$\mathcal{A}_{CP}$ Perfect reconstruction

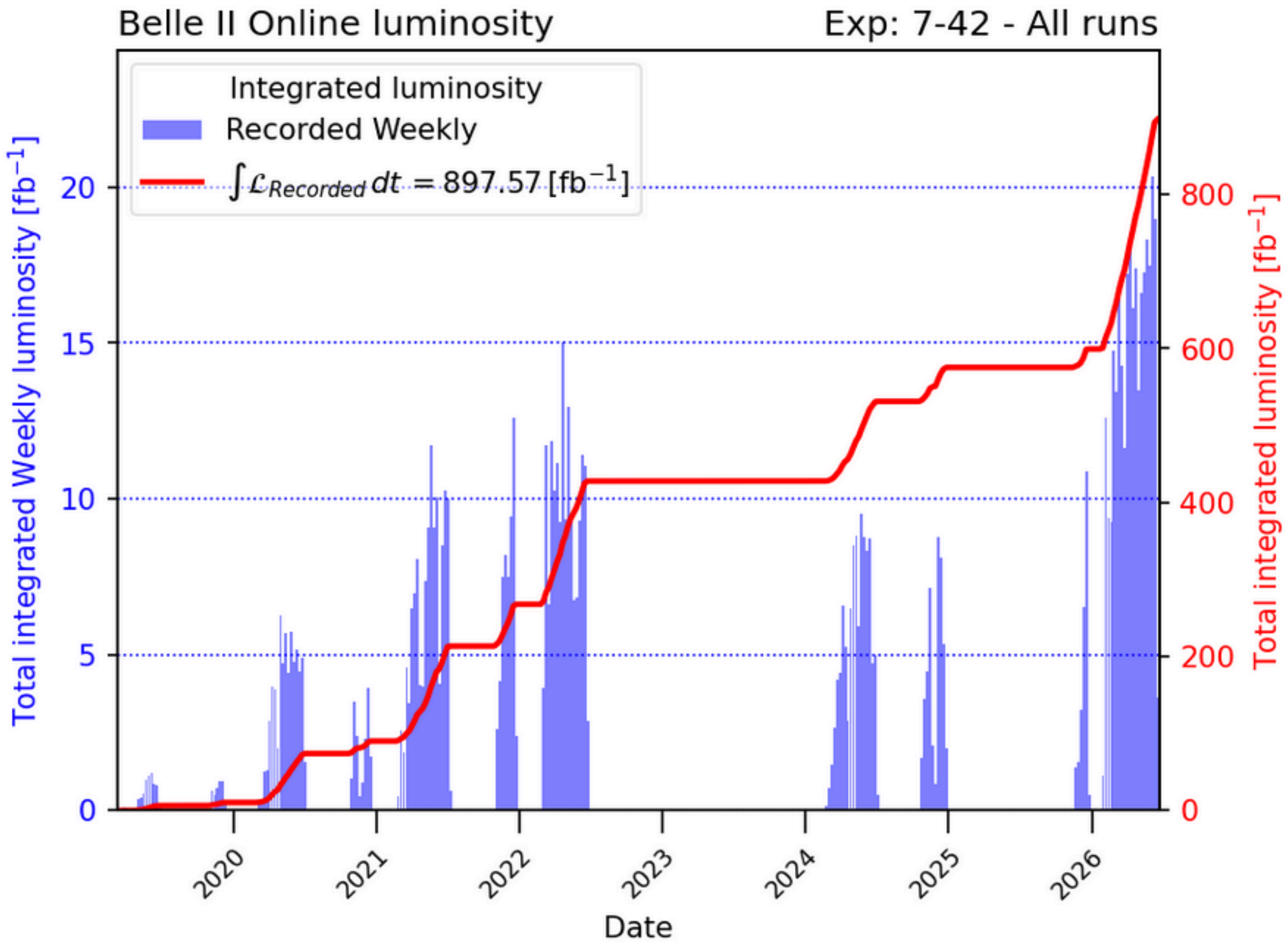
$\mathcal{A}_{CP}$ Impact of wrong tagging or of finite spatial resolution

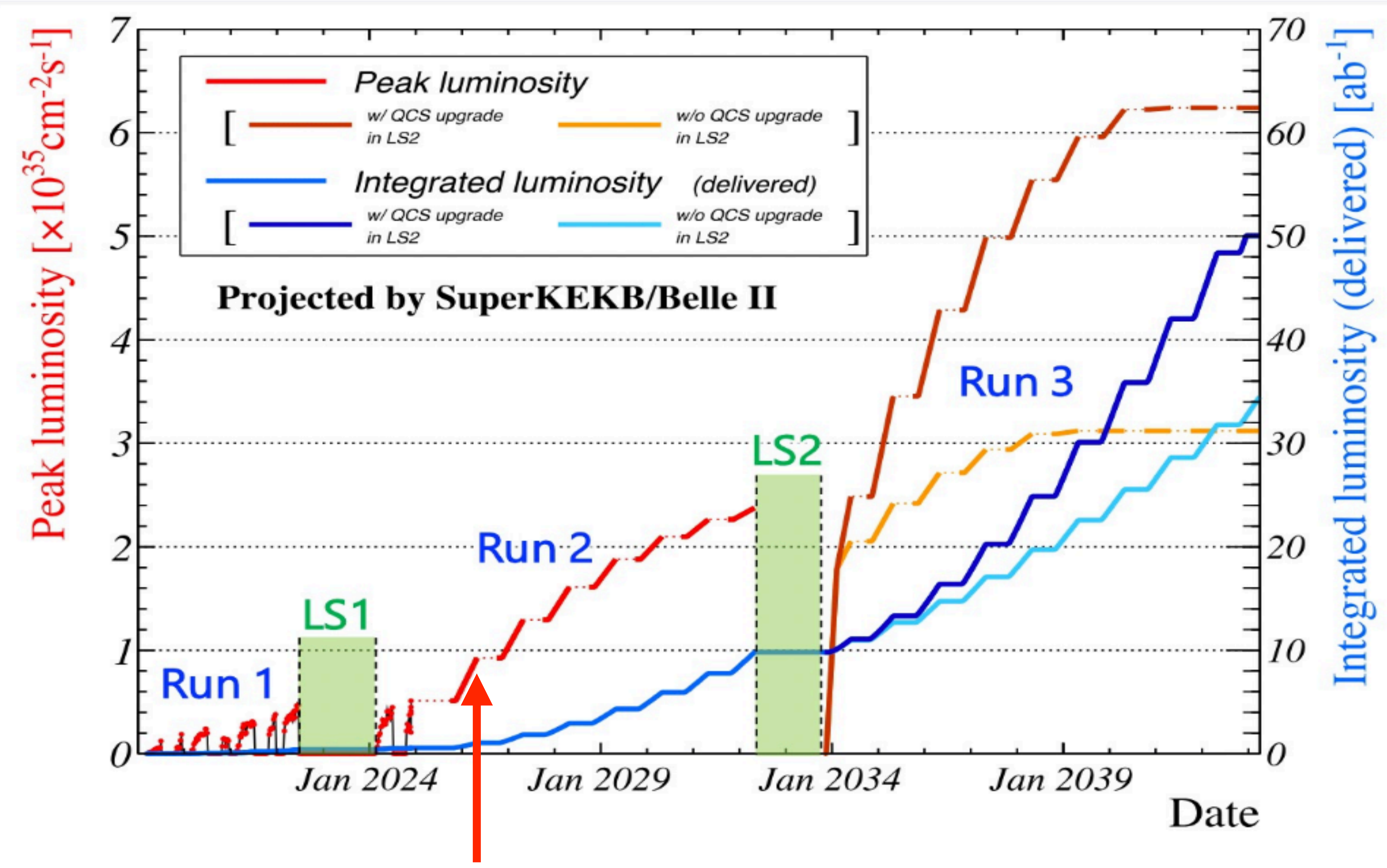
- B, D and τ reconstruction:
  - Particle identification, K/π separation
  - Neutrals: γ, π^0, η, V^0, ...
  - Hermiticity for ν
  - S/N (physics, combinatorial, pile-up, beam background)

- Time-dependent analysis:
  - Boost
  - Vertex resolution

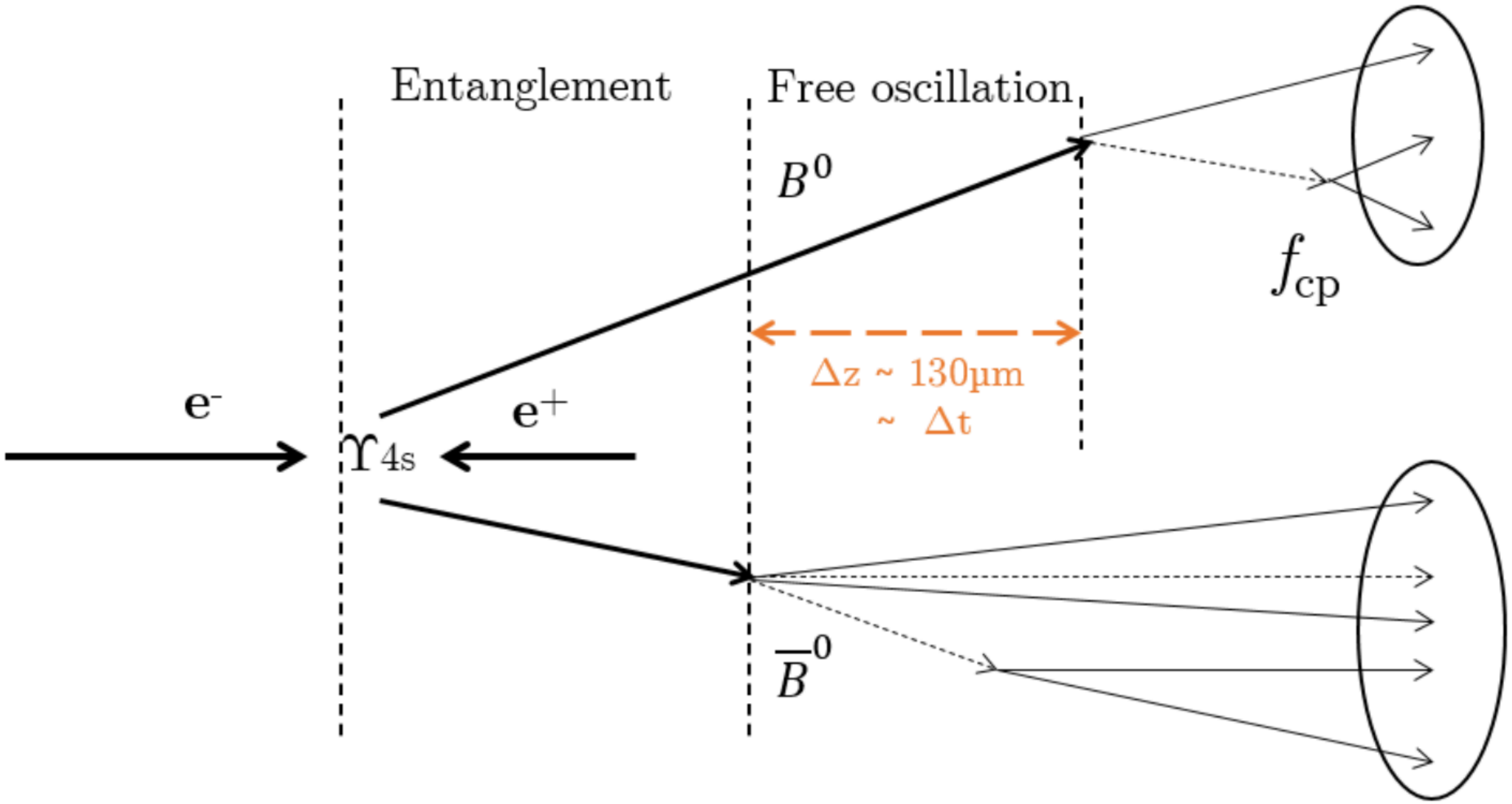
➛ **Current main actors are Belle II and LHCb**

Belle II luminosity prospects

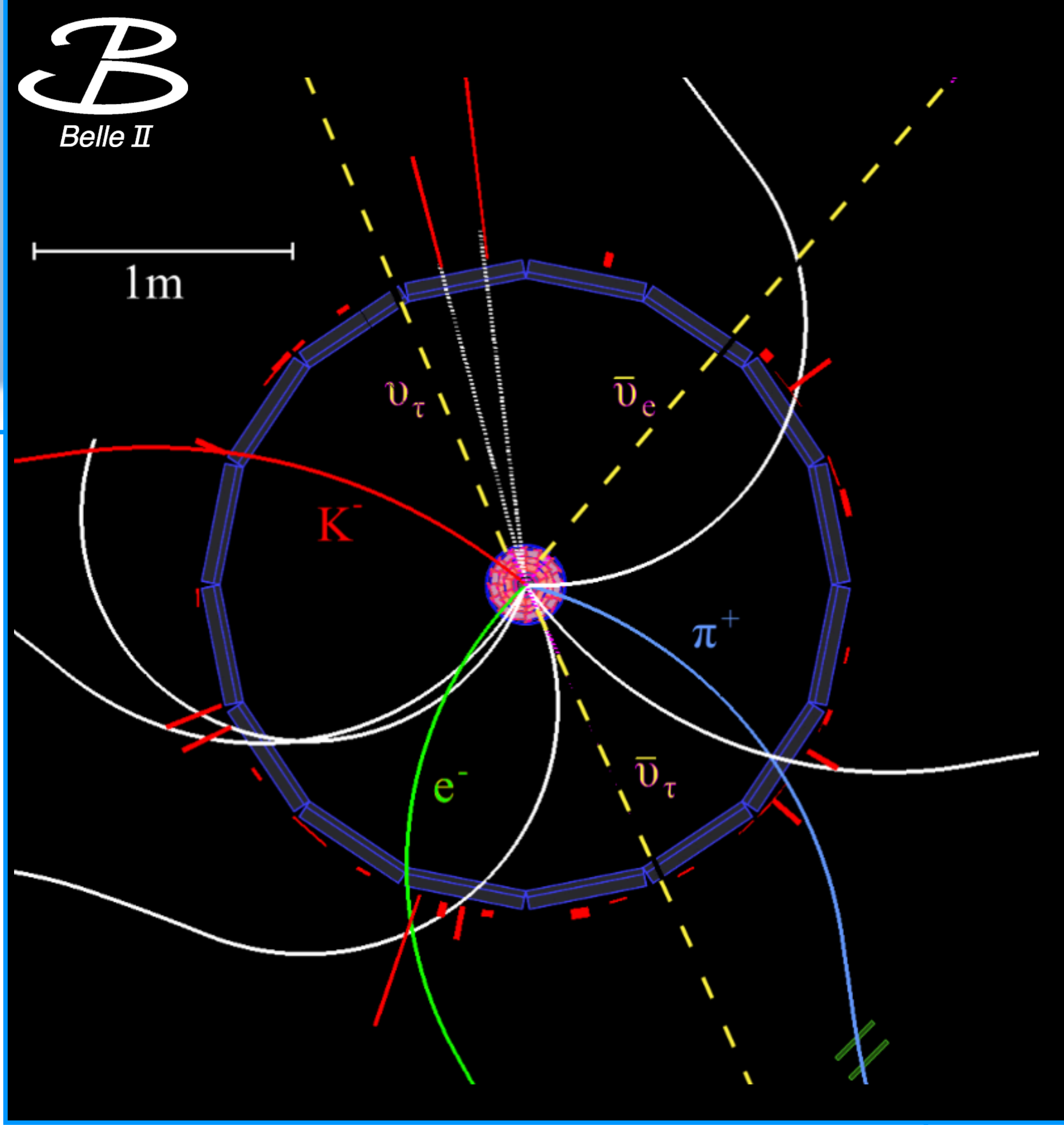




A Belle II event

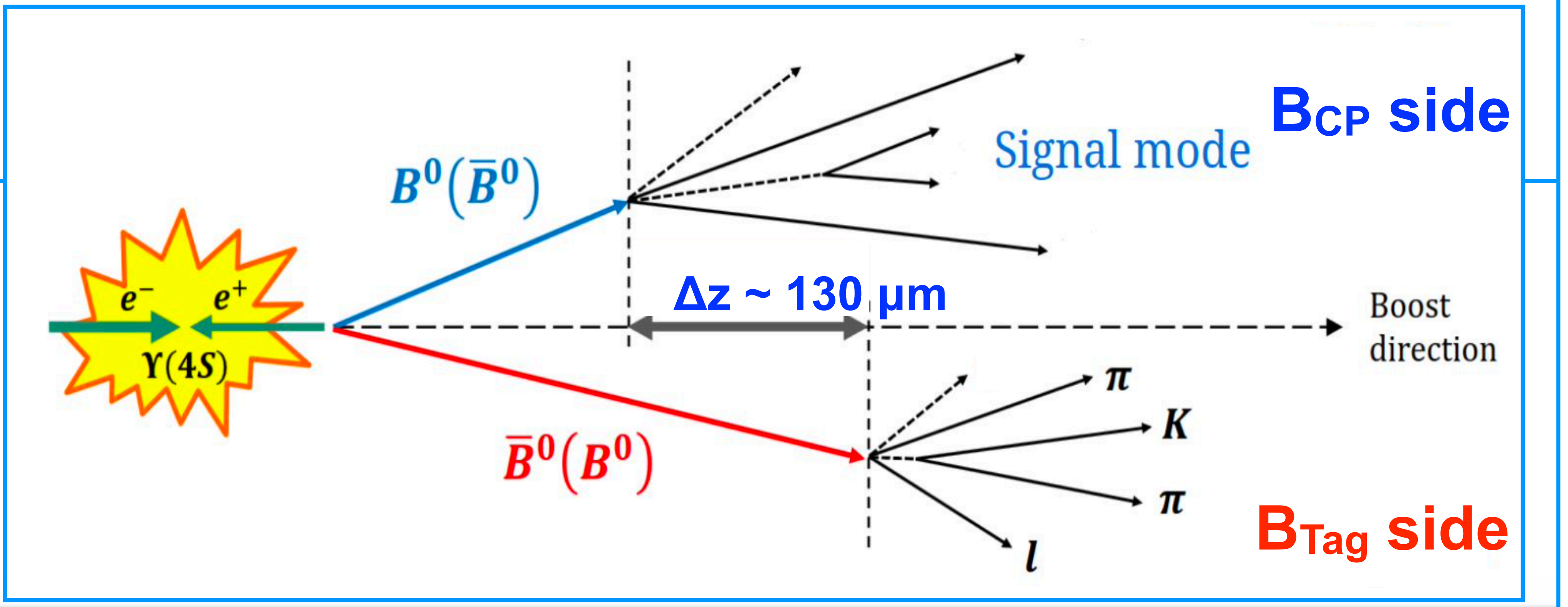


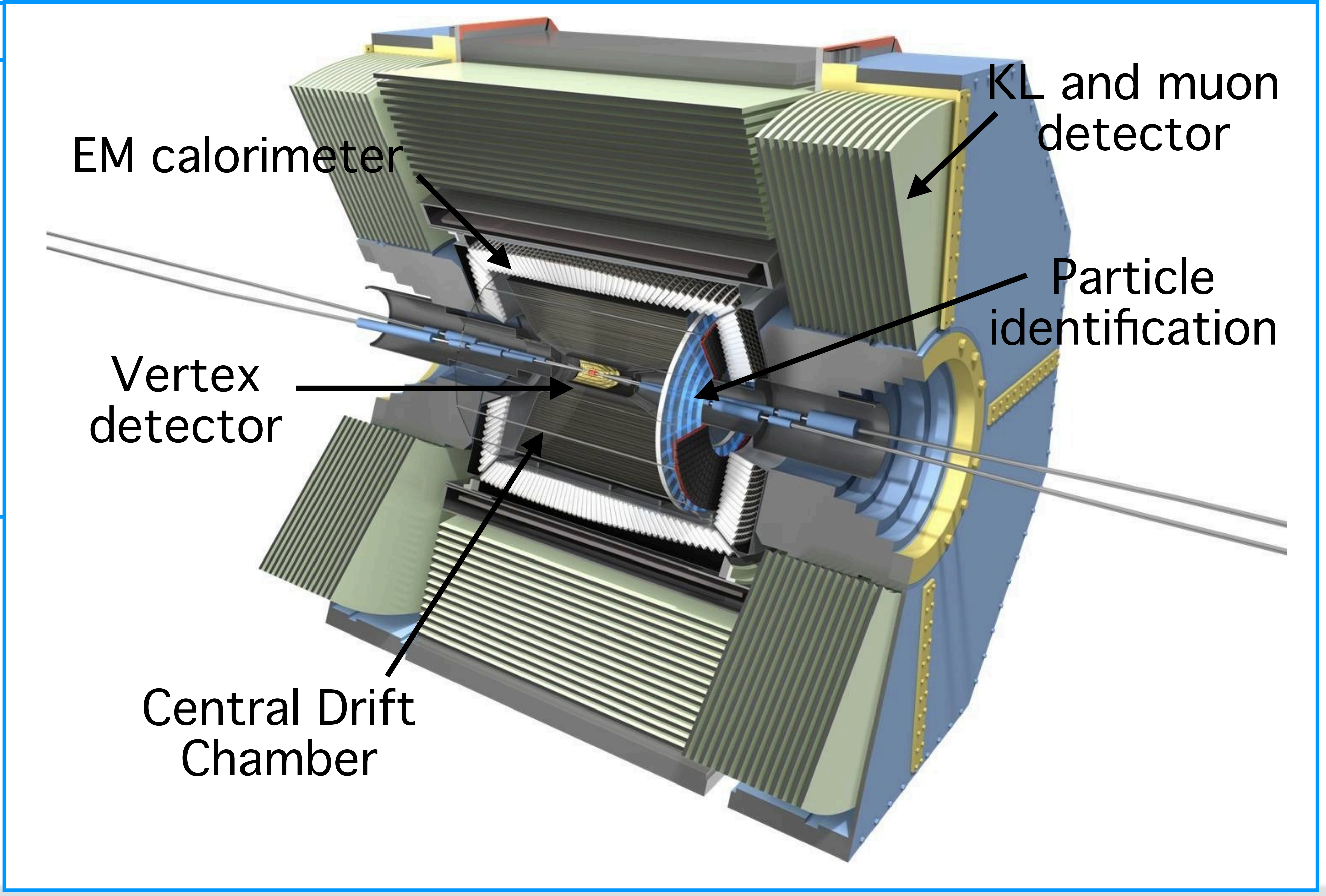
Belle II at SuperKEKB



- SuperKEKB collider:
  - e^+e^- collisions mainly at $\Upsilon(4S)$ with $\sqrt{s} = 10.58$ GeV:
    - Production of $c\bar{c}$, $\tau^+\tau^-$, B^+B^-, $B^0\bar{B}^0$, $\sigma_{cc} \sim \sigma_{\tau\tau} \sim \sigma_{bb} \sim 1$ nb
  - World record instantaneous luminosity: 5.2×10^{34} cm^{-2} s^{-1}
  - Asymmetric collisions: B flight distance ~130 μm
  - Nano beam transverse size

- Belle II detector:
  - Good reconstruction of K^0_S, γ, π^0, missing energy
  - $B\bar{B}$ entanglement: flavour tagging efficiency ~ 38%
  - 803 fb^{-1} collected
    (on May 11th, 2026)





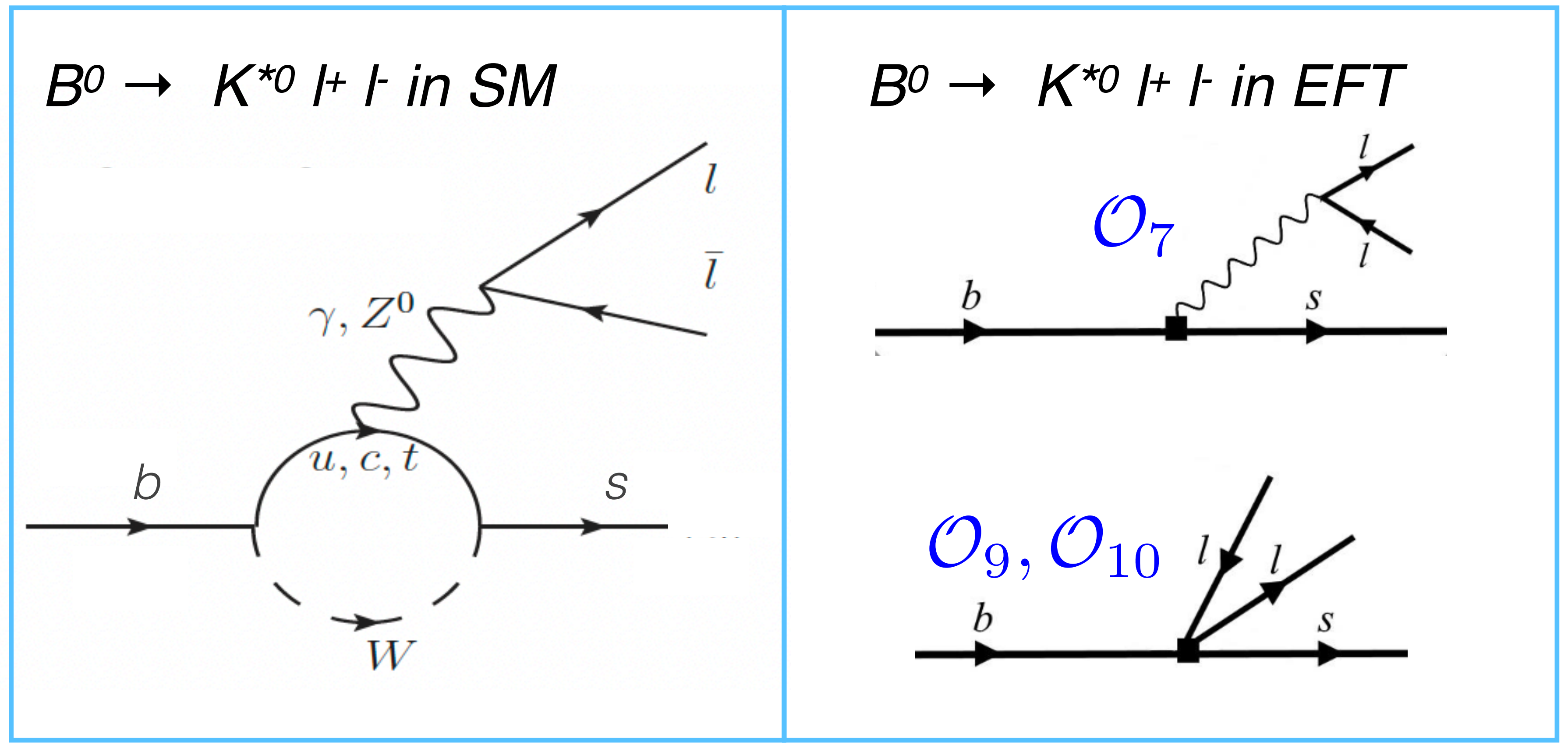
Beyond the SM

- Model-independent approach: Effective Field Theory.
  - Operator Product Expansion.
  - Unknown field content of NP, but invariance and symmetry principles.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum \frac{C_n}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

NP scale

- B-physics: decouple heavy particles >> m_b.
  - Multi-scale: $m_{NP} >> m_{H,W,Z,top} >> m_b$.
  - OPE restricted to dim-6.



- $$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} V_{qb} V^*_{qq'} \sum_{i=1}^{10} \left(\underbrace{C_i(\mu)\mathcal{O}_i(\mu)}_{\text{left currents}} + \underbrace{C'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right currents}} \right) \quad (\mu = m_b)$$

  - Long distance operators $\mathcal{O}_i^{(\prime)}$.
    Hadronic matrix elements still needed: main uncertainty.
  - Short distance Wilson coefficients $C_i^{(\prime)}$. $C_i = \underbrace{C_i^{SM}}_{\text{known}} + \underbrace{C_i^{NP}}_{\text{what we want to determine}}$