Highlights from the Belle and Belle II experi ments

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SM: successes and failures

Standard Model is a strange theory: It is simultaneously is
very good and very bad

The SM successes is due to confirmation from experiment:

- All particles have been observed
- All symmetries have been confirmed and the mechanism of symmetry breaking is established
- All parameters have been measured
- Essentially all experimental measurements are consistent with the SM predictions

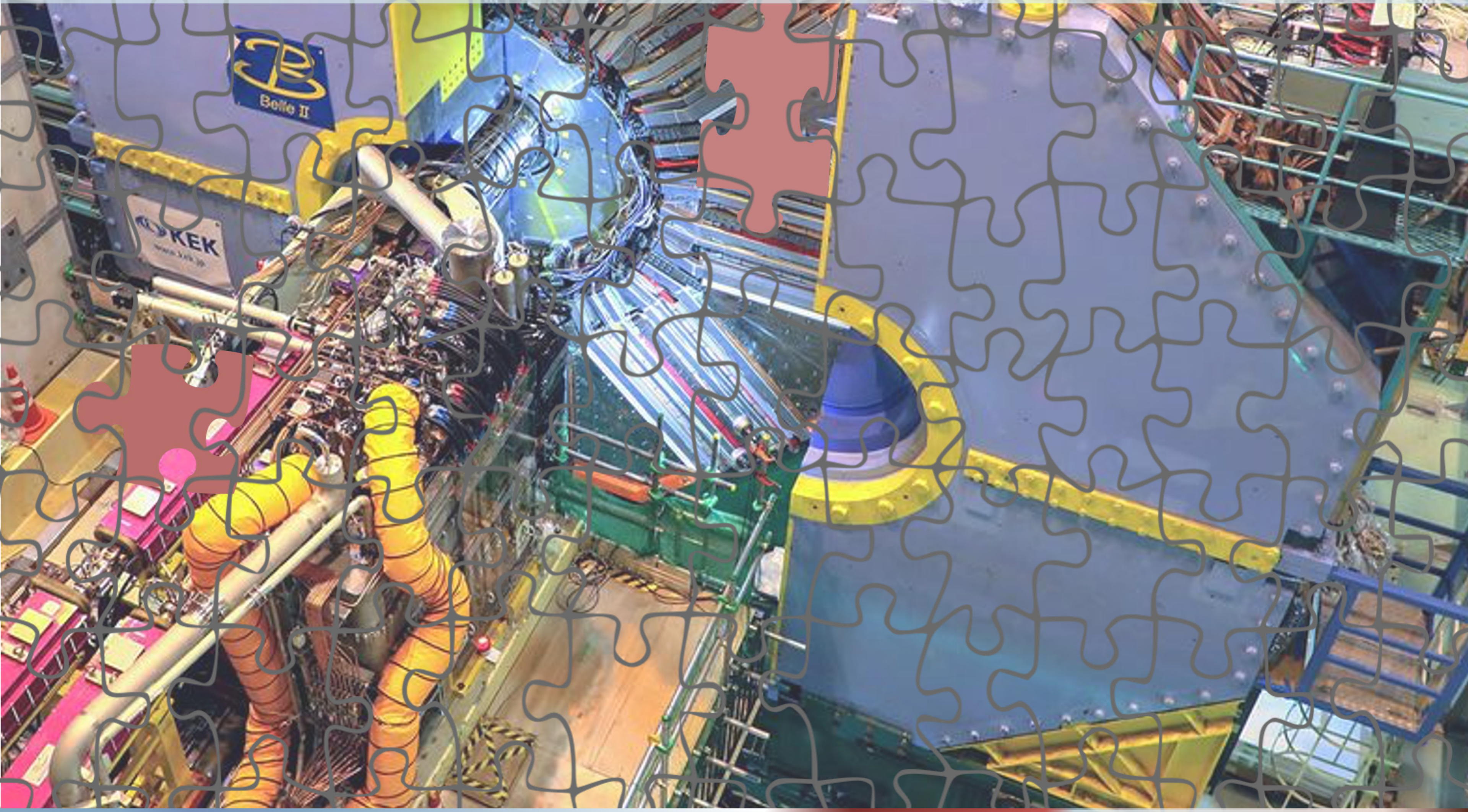
BUT in the same time a lot of intrinsic problems:

- Inconsistencies at high energies (rad. corrections, UV divergences, Landau pole)
- Still no unification of strong and electroweak interactions
- Large number of free parameters
- CP-violation & flavor mixing are not completely understood
- The origin of the mass spectrum is unclear

The goal of all modern experiments is further precise tests of SM (to exclude some NP scenario) and search for something beyond SM

BELLE II EXPERIMENT

is aimed at precision tests of flavour sector, search for NP in loop diagrams, search for medium energy new hardly visible particles



KEKB upgrade → SuperKEKB(nano-beam)

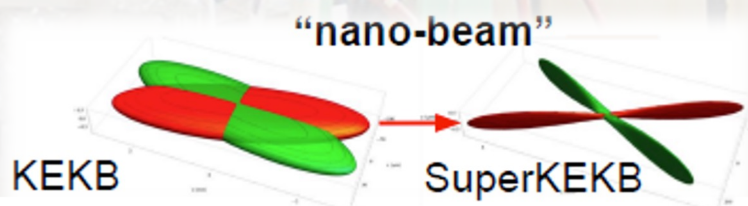
2009 → 2018

Parameter	KEKB Design	KEKB Achieved	SuperKEKB Design
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
β_y^* (mm)	10/10	5.9/5.9	0.27/0.30
β_x^* (mm)	330/330	1200/1200	32/25
ε_x (nm)	18/18	18/24	3.2/5.3
$\frac{\varepsilon_y}{\varepsilon_x}$ (%)	1	0.85/0.64	0.27/0.24
σ_y (μm)	1.9	0.94 $\xrightarrow{1/20}$	0.048/0.062
ξ_y	0.052	0.129/0.090	0.09/0.081
σ_z (mm)	4	6/7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19 $\xrightarrow{x2}$	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity ($10^{34} cm^{-2} s^{-1}$)	1.0	2.11 $\xrightarrow{x40}$	80

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

SuperKEKB is built in tunnel of KEKB but is almost entirely new machine:

- **× 20 smaller beam focus at interaction region**
- **Twice higher beam current**
- **First beam in 2016 → first collision in April 2018**

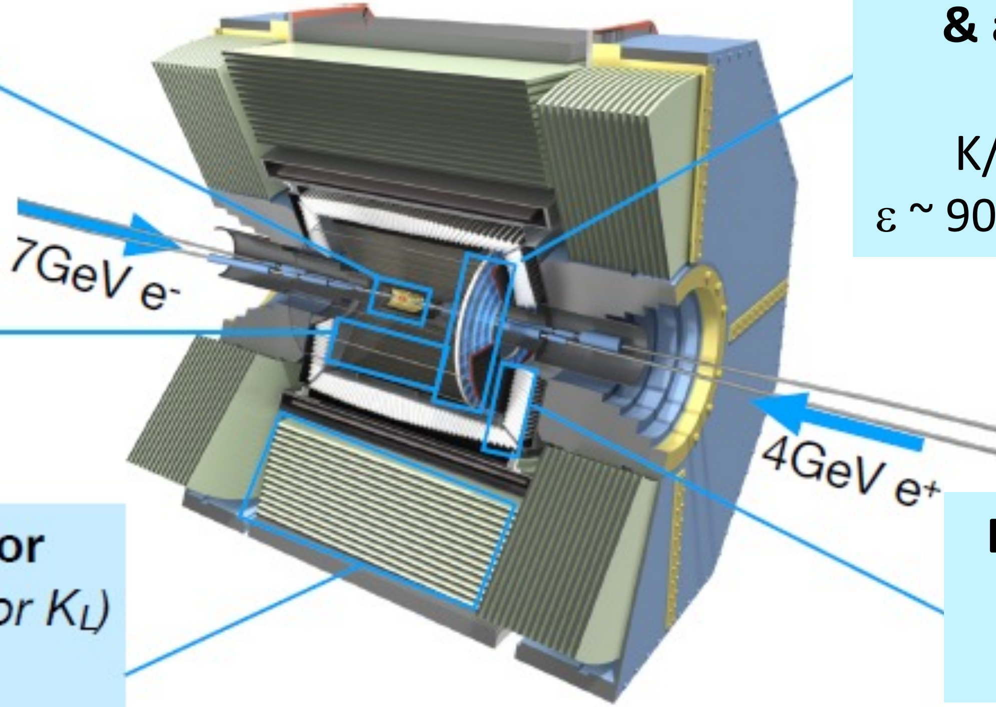


The Belle II detector

Vertex detector
Tracking
$\sigma_{z0} \sim 15\ \mu m$
(2x better than Belle)

Drift chamber
Tracking
$\sigma_{r\phi} \sim 100\ \mu m$
$\sigma_{dE/dx} \sim 5\%$

K_L and Muon detector
$\Delta\phi = \Delta\theta \sim 10\text{-}20\ mrad$ *(for K_L)*
μ/π separation:
$\varepsilon \sim 90\%$ @ 1.5% fake

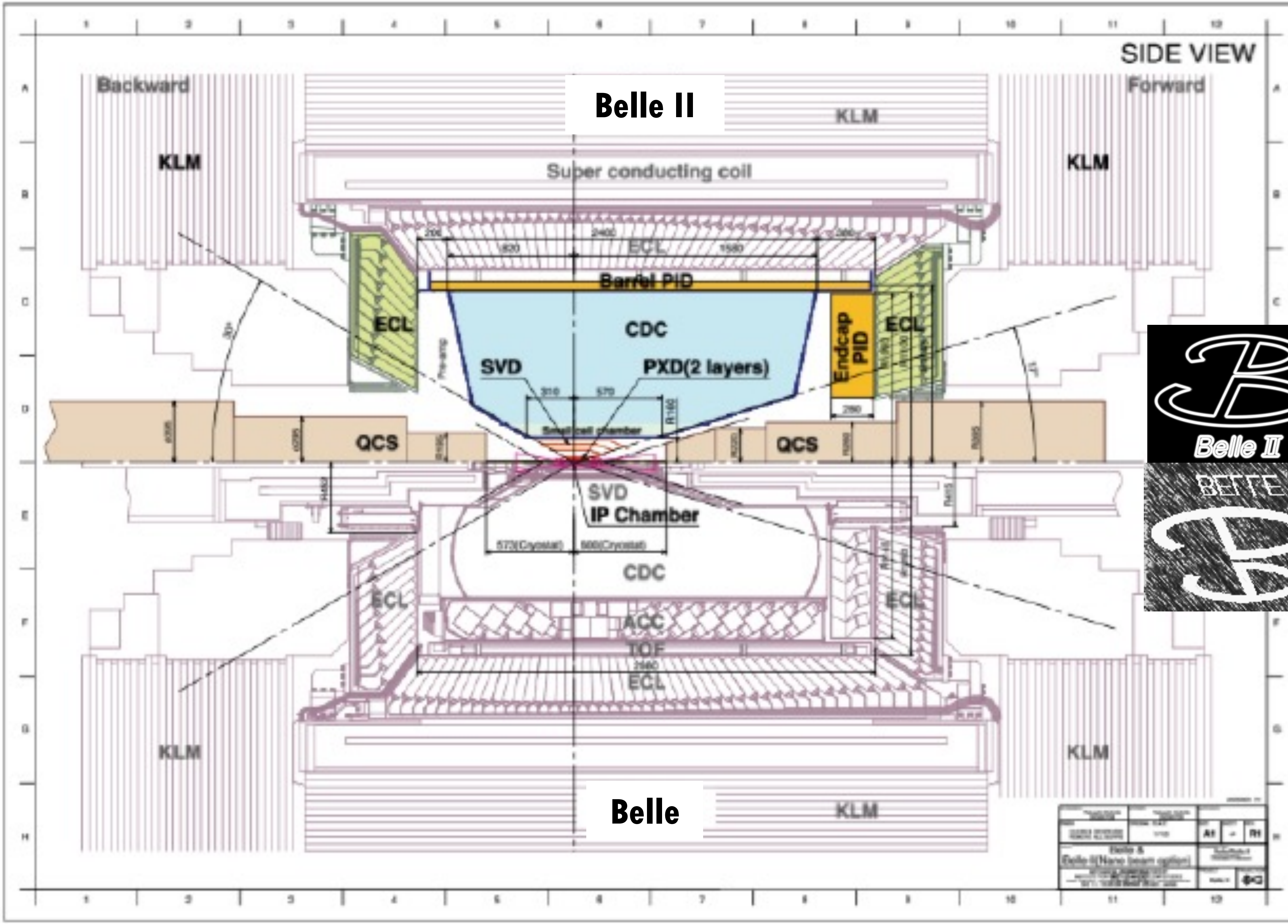


Time of propagation & aerogel RICH detectors
K/π separation
$\varepsilon \sim 90\%$ @ 5% fake rate

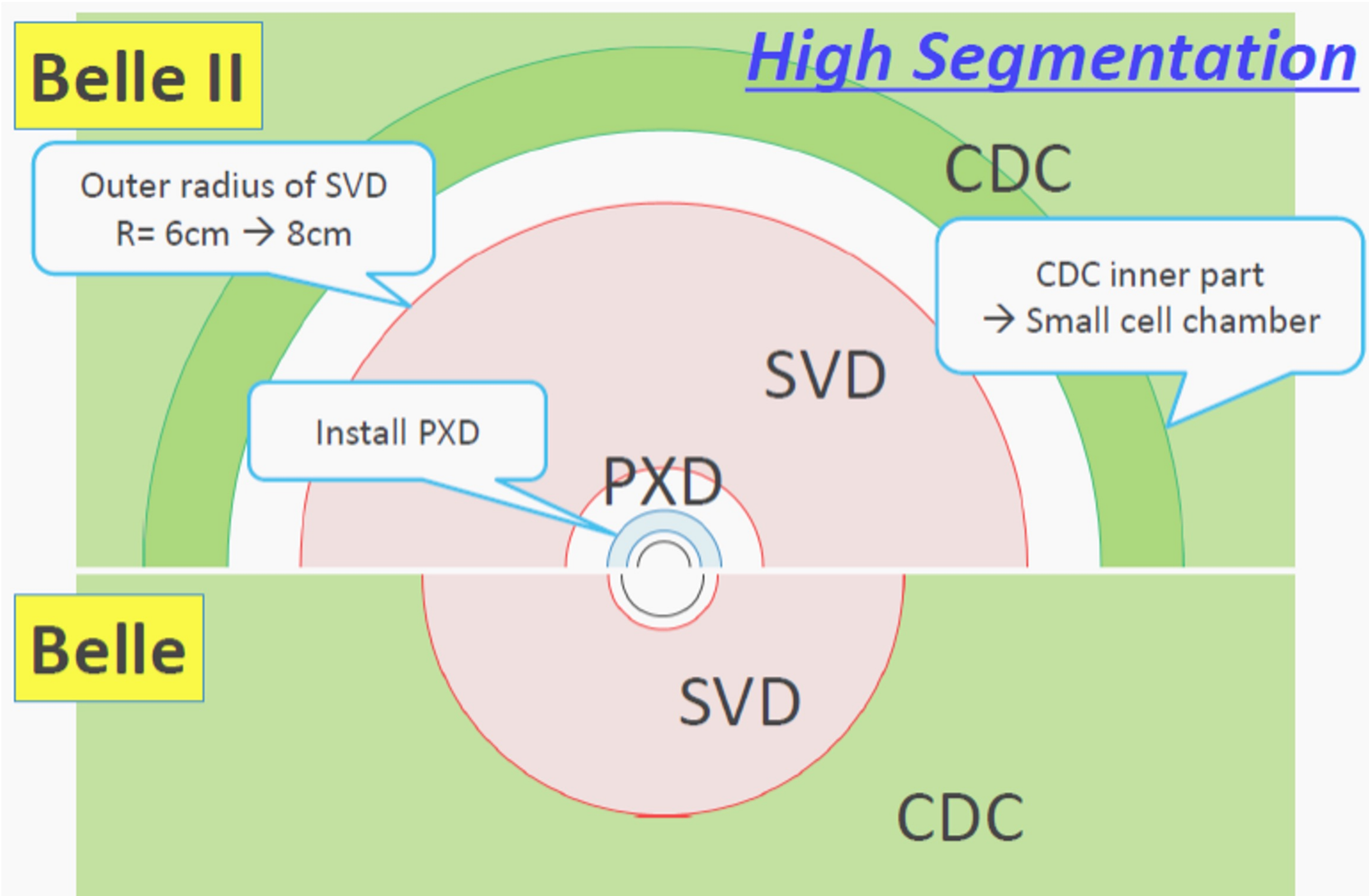
EM Calorimeter
$\sigma E/E \sim 2\%$ @
E =1 GeV

Belle II is an upgrade of the Belle detector: capable to work at much higher background environment

Highlights. <u>*Vertex:*</u> 2 layers of pixels, 4 layers of DS Si strips with extended coverage, <u>*Drift chamber:*</u> smaller cell size + longer lever arm, <u>*PID:*</u> new TOP + ARICH


SIDE VIEW
Backward
Forward
Belle II
KLM
KLM
KLM
Super conducting coil
ECL
Barrel PID
ECL
CDC
Endcap PID
ECL
SVD
PXD(2 layers)
QCS
QCS
SVD
IP Chamber
CDC
ECL
ACC
TOF
ECL
ECL
KLM
KLM
Belle
KLM

Belle II vs Belle



Belle: total dataset 998 fb^{-1} at $\Upsilon(1{,}2{,}3{,}4{,}5S)$ and continuum + energy scan from $\Upsilon(4S)$ till 11.02 GeV

Belle II: total dataset to-date is 424 fb^{-1} mostly at $\Upsilon(4S)$

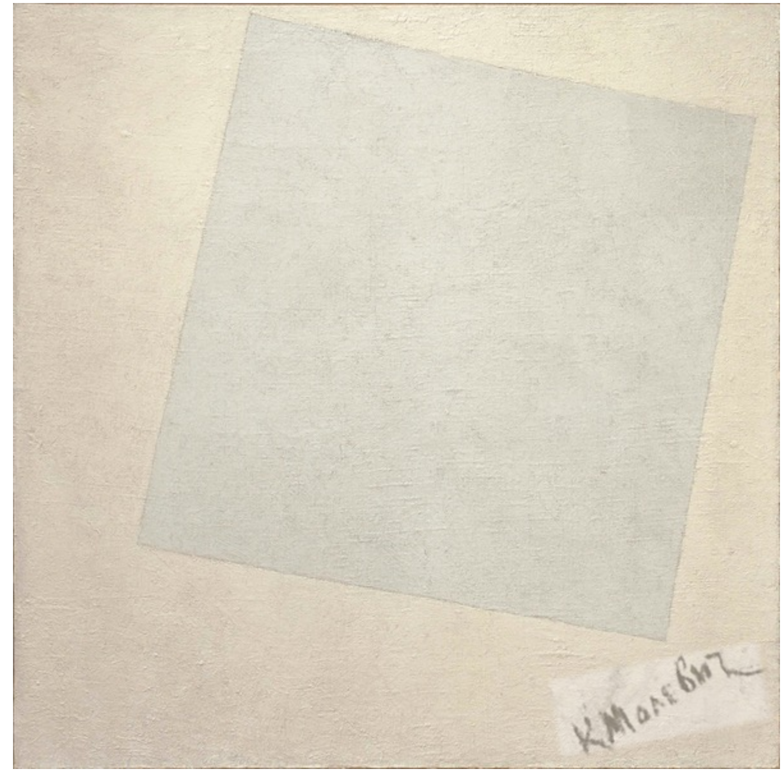
Belle II talks at XXI Lomonosov's conference:

- Semileptonic decays and tests of lepton flavour universality at Belle II: R. Cheaib
- Hadronic B decays at Belle II: F. Meier
- Exotic quarkonium and hadron spectroscopy at Belle II: P. Krokovny
- Searches for invisible new particles at Belle II: L. Corona

This talk is to

- demonstrate breadth of Belle II program
- show that Belle data analysis is ongoing
- do not overlap with the talks of my colleagues, but advertise them

DARK AND INVISIBLE



Specialized **Dark Sector Triggers at Belle II** enabled:

- **Single muon trigger**;
- **3D track reconstruction at L1** using neural networks;
- **Single photon trigger** operational for entire dataset;
- **Displaced vertex trigger** is under development.

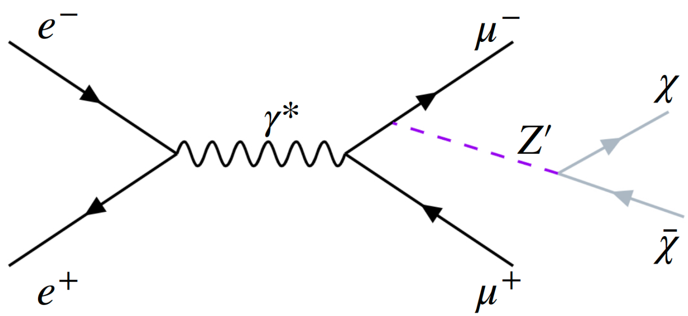
Search for invisible Z’

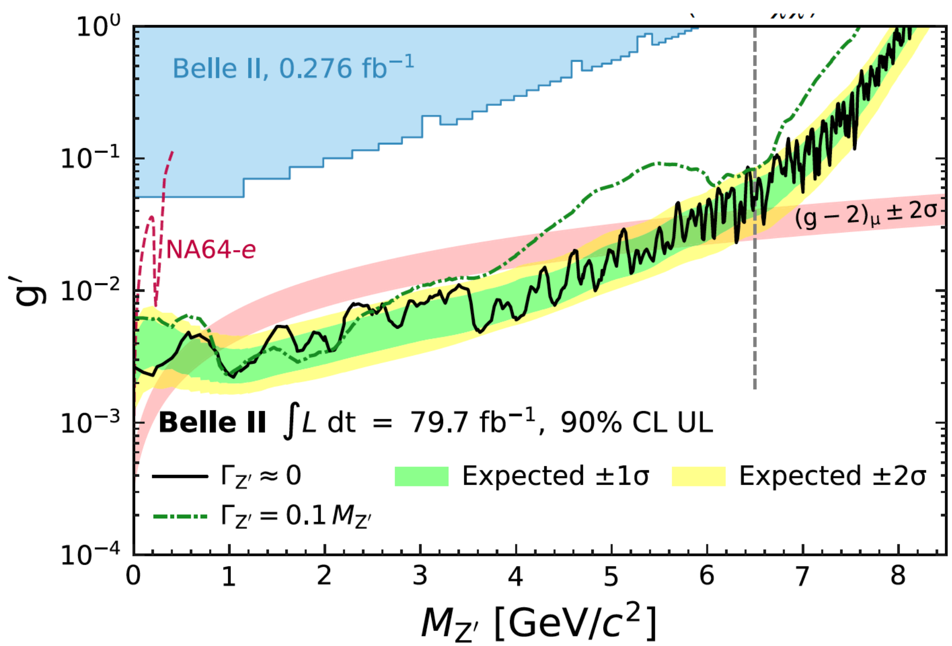
PRL 130, 231801 (2023)

Search for nonSM massive vector boson with coupling to only particles having muon (and tau lepton) number.

- Could explain current $g-2$ muon tension and mediate interactions between SM and dark matter.

Search performed via $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to$ *Invisible*, $M(Z') \equiv M_{recoil}(\mu^+\mu^-)$





More Belle II results

on search for:

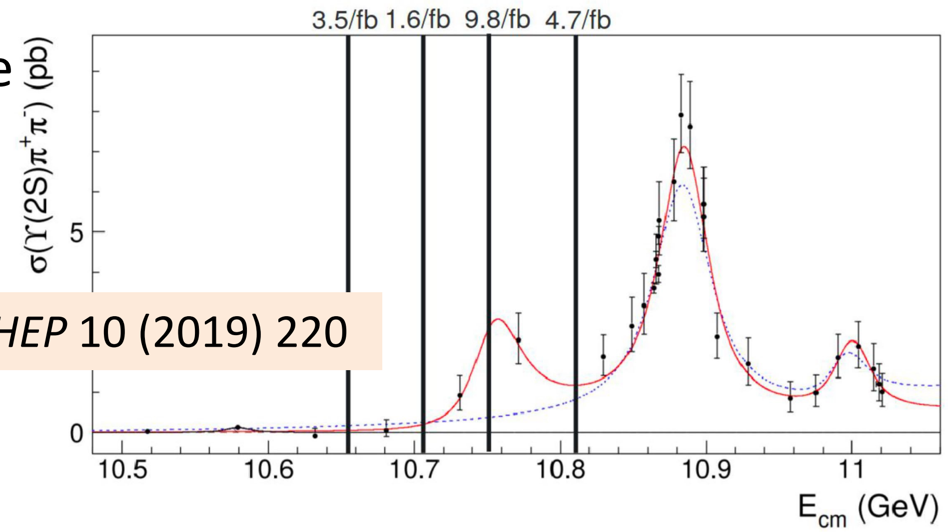
- Z’, scalar of axion(-like) particle decaying into tau-pair;
- Muophilic particles in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$;
- Long-lived spin-0 boson in $b \to s$ transitions;
- Invisible axion in $\tau^\pm \to \ell^\pm\alpha$

is on talk by Luigi Corona tomorrow at “Dark matter and g-2” session

BOTTOMONIUM(-LIKE)

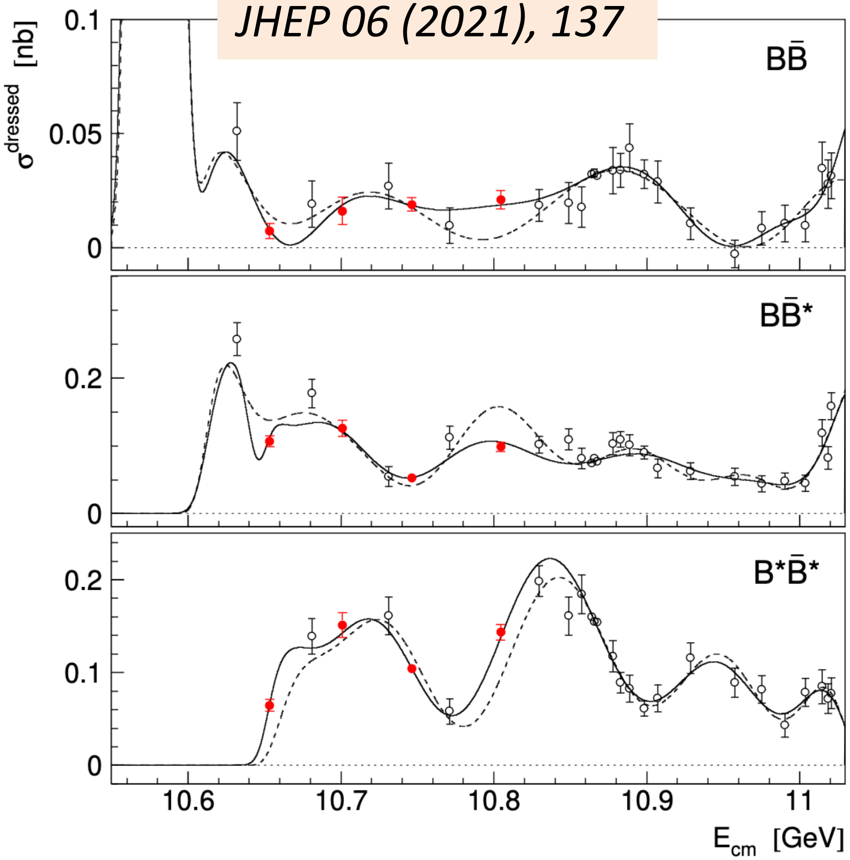
Bottomonium (prehistory)

Belle observed $\Upsilon(10753)$ – a structure in $e^+e^- \to \Upsilon(nS)\pi\pi$ cross using energy scan data above $\Upsilon(4S)$



JHEP 10 (2019) 220

JHEP 06 (2021), 137

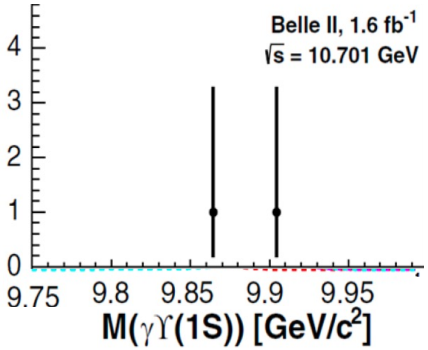


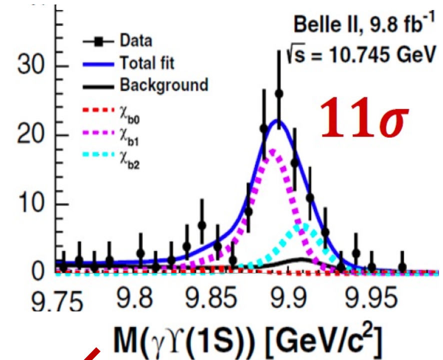
To study the nature of the $\Upsilon(10753)$, Belle II collected $19 fb^{-1}$ of scan data at four energy points near $10.75\ GeV$.

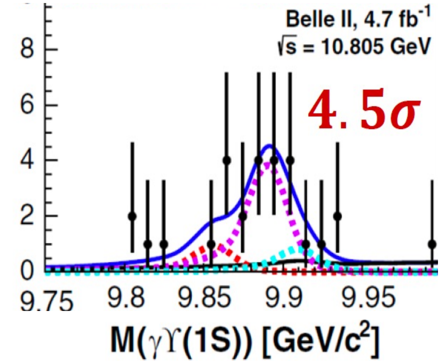
Belle (II) decomposed $\sigma_{b\bar{b}}$ into $B\bar{B}$, $B^*\bar{B}$ and $B^*\bar{B}^*$ (using Belle and new Belle II energy scan data) – important input for couple channel model.

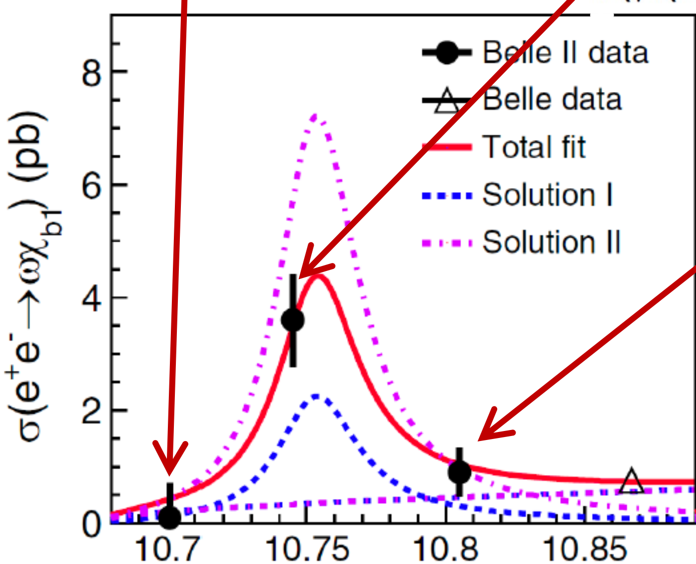
Observation of $\Upsilon(10753) \to \chi_{bJ}(1P)\omega$

PRL 130 091902 (2023)









Fit combined Belle+Belle II data with coherent P.S.+B-W:
Two solutions (with destructive and constrictive interference).

Ratio of cross sections $e^+e^- \to \chi_{bJ}(1P)\omega$ to $e^+e^- \to \Upsilon(nS)\pi\pi$ at $\Upsilon(10753)$ is 10 times larger than at $\Upsilon(5S)$.

Details and more results in Pavel Krokovny talk tomorrow (sect. 25.08. A)

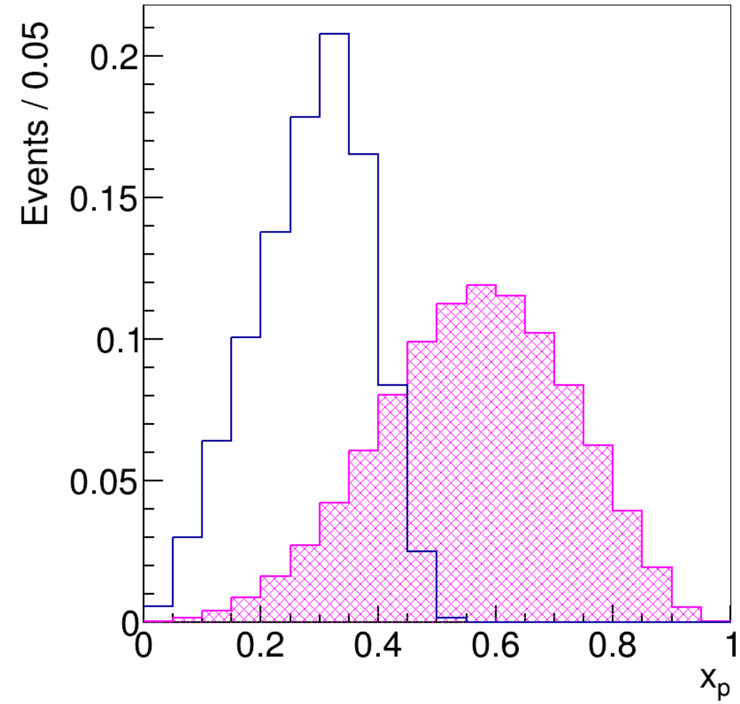
Study of the $e^+e^- \to B_s\bar{B}_sX$ cross section

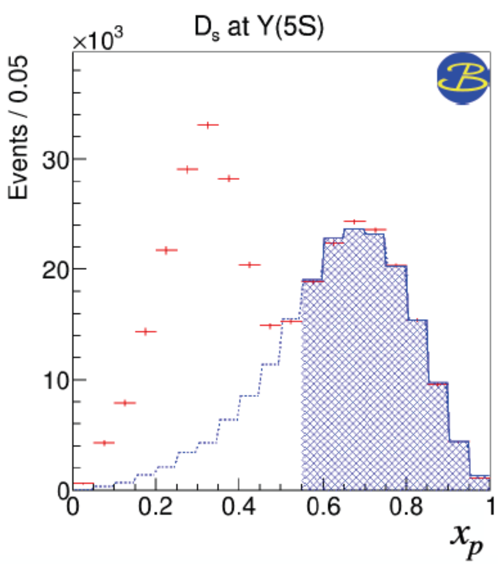
arXiv:2305.10098

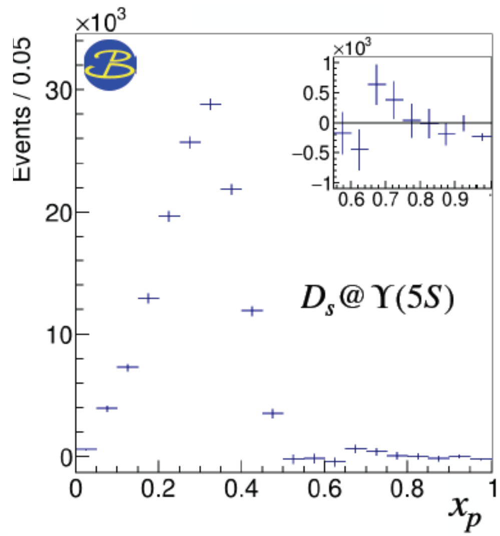
For coupled channel model one needs to decompose $e^+e^- \to b\bar{b}$ into different components…

Reconstruct inclusive D^0 and D_s^+ at each energy scan point;

Use $x_p = \frac{p}{p_{max}}$ to separate continuum and $b\bar{b}$-events (subtract continuum data and count excess of D^0 and D_s^+ with x_p<0.5);







continuum data fully subtracts charm contribution with x_p >0.5 as seen at $\Upsilon(5S)$ data; all the excess is $b\bar{b}$ contribution

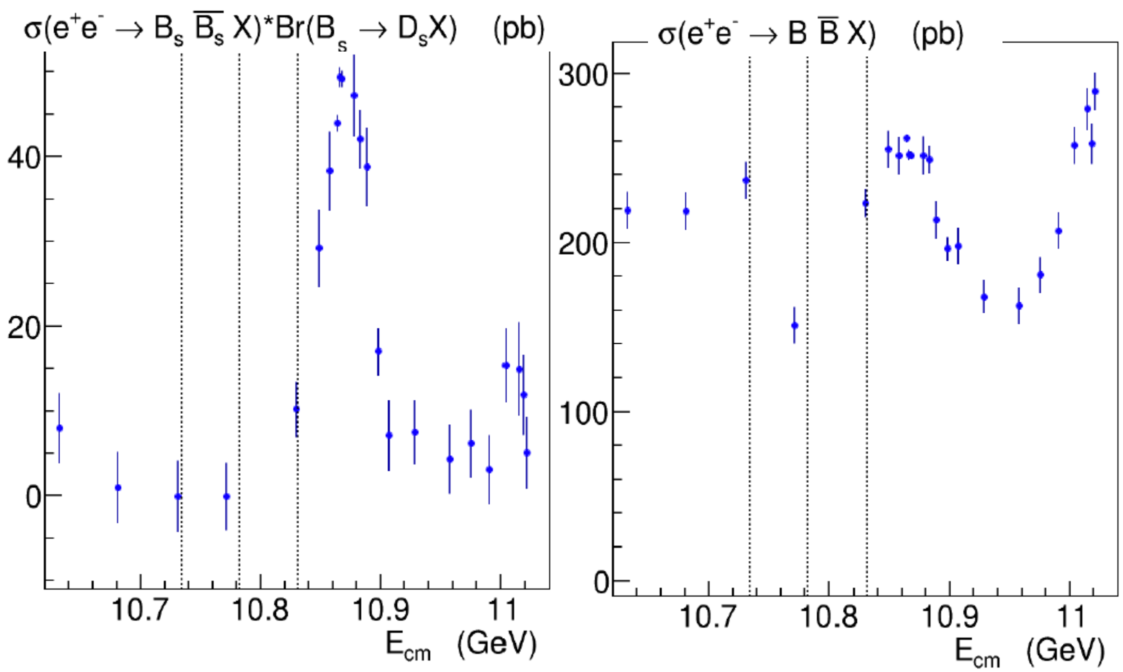
Solve the system of equations to decompose $B_s\bar{B}_s$ and non-$B_s\bar{B}_s$ events:

unknowns

$$\begin{cases} \sigma(D_s^+X) = \mathcal{B}(B_s \to D_s^+X)\sigma(B_s\bar{B}_sX) + \mathcal{B}(B \to D_s^+X)\sigma(B\bar{B}X) \\ \sigma(D^0X) = \mathcal{B}(B_s \to D^0X)\sigma(B_s\bar{B}_sX) + \mathcal{B}(B \to D^0X)\sigma(B\bar{B}X) \end{cases}$$

Two extra inputs to resolve:
Use $\Upsilon(4S)$ data (no $B_s\bar{B}_s$) to measure $\mathcal{B}(B \to D_s^+X)$ and $\mathcal{B}(B \to D^0X)$;
Use $\Upsilon(5S)$ data measurements of $\sigma(B\bar{B}X)|_{\Upsilon(5S)}$

Result

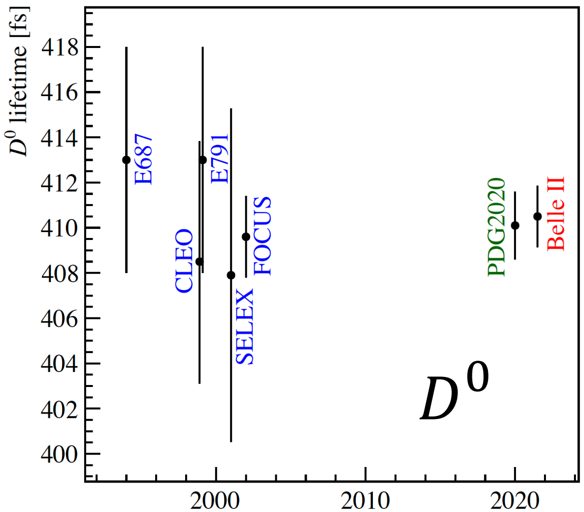


$B_s\bar{B}_s$:
- no signal below $B_s^*\bar{B}_s^*$
- clear $\Upsilon(5S)$ peak
- small non-resonant
- hint for $\Upsilon(6S)$

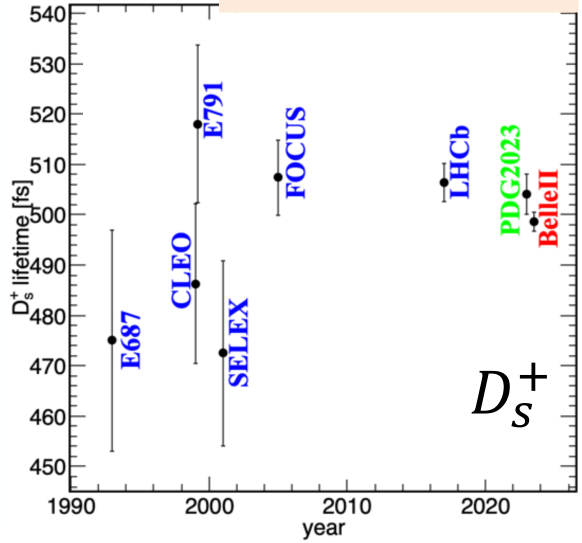
$B\bar{B}$:
- similar to $\sigma(b\bar{b})$

CHARM & TAU LEPTONS

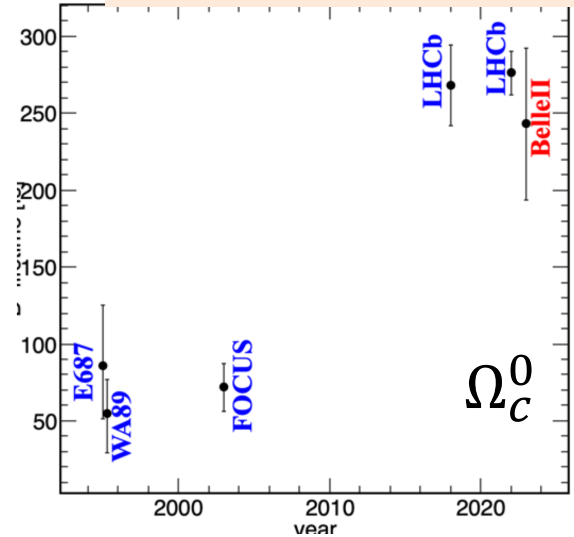
New charm hadrons lifetimes at Belle II

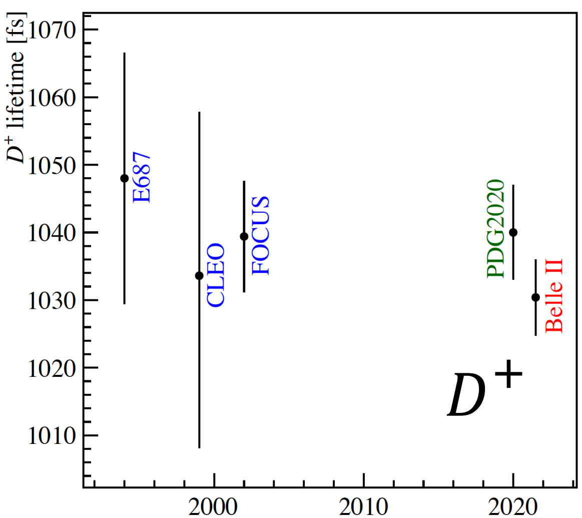


arXiv:2306.00365



PRD107, L031103 (2023)





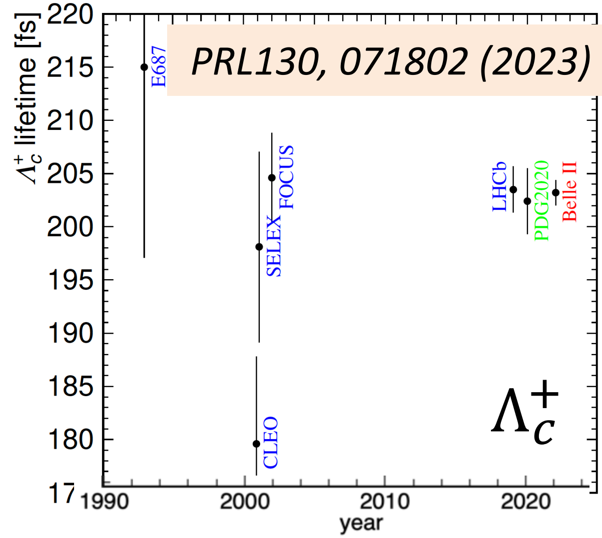
- D-mesons and Λ_c^+:

Belle II improves precision of WA measurement

- Ω_c^0:

confirms the longer lifetime observed by LHCb

PRL130, 071802 (2023)



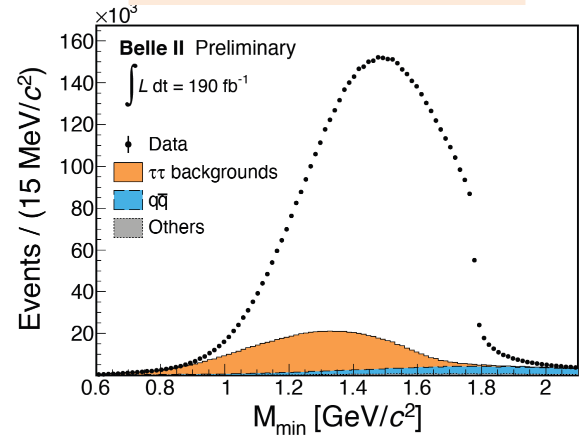
Tau mass

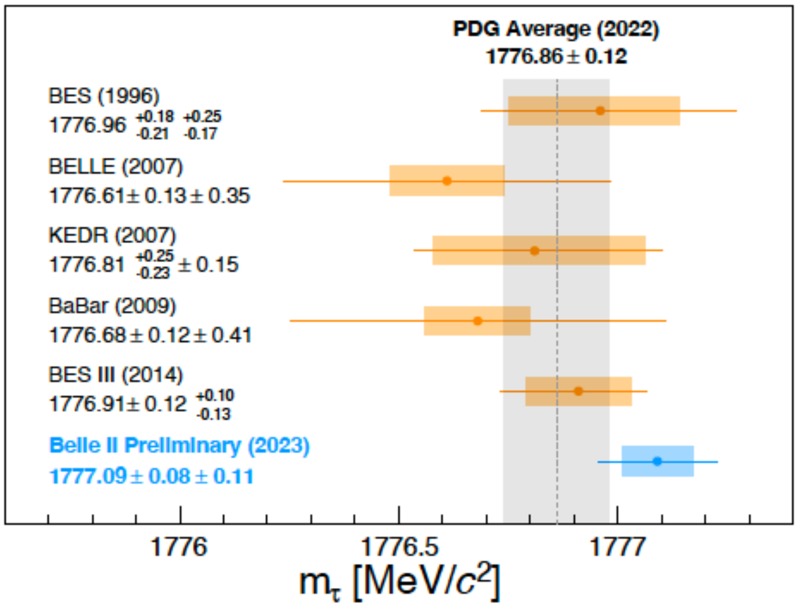
arXiv:2305.19116

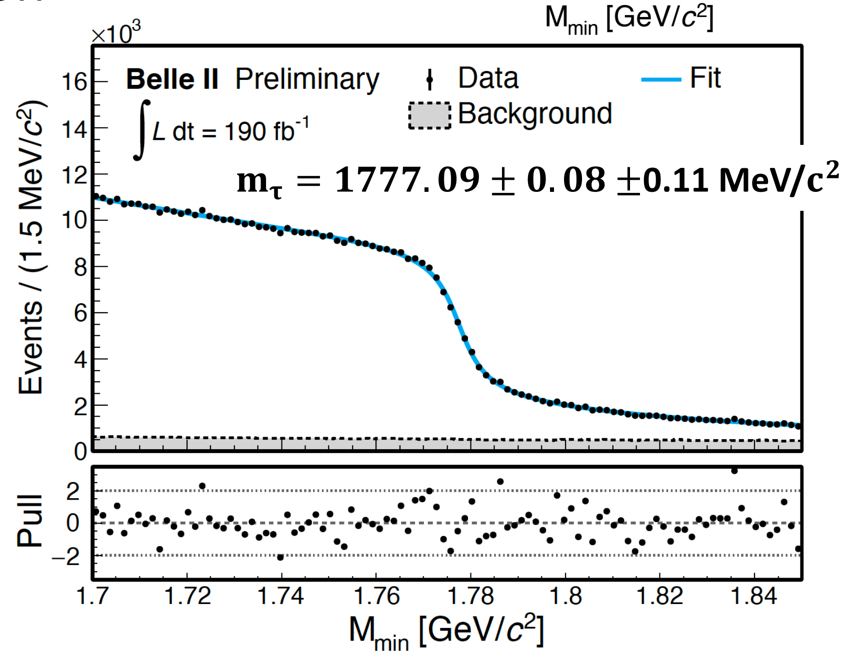
use pseudomass endpoint method in $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$
calculate the minimum mass

$$M_{min} = \sqrt{M_{3\pi}^2 + (E_{cms} - 2E_{3\pi})(E_{3\pi} - p_{3\pi})}$$

– sharp edge smeared by ISR, FSR, resolution







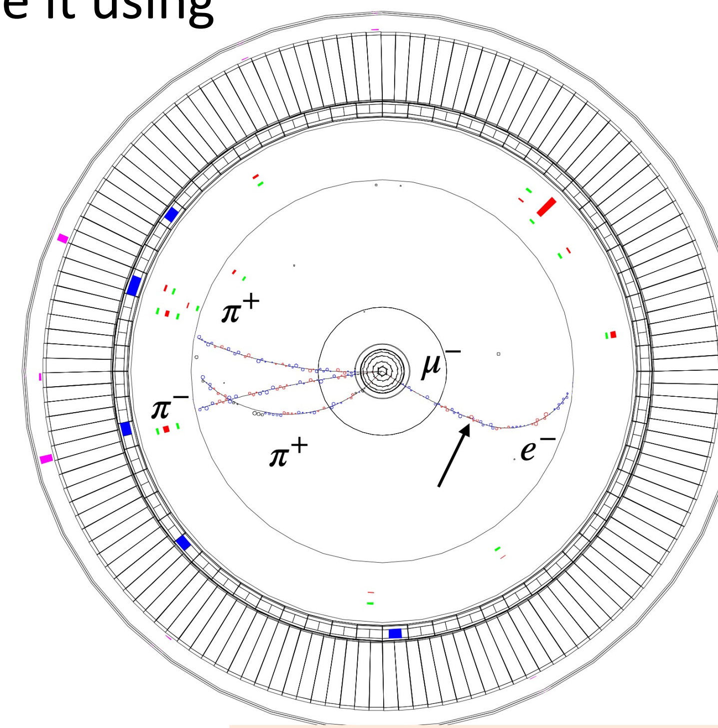
Charm lifetime and τ mass measurements demonstrates that not only detector (and accelerator) performance, but the systematics effects (alignment, calibration) are improved

First measurement of the Michel parameter ξ' in $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$ decay

- ξ' ($= 1$ in SM) is a parameter related to polarization of daughter lepton. Belle has already attempted to measure it using τ radiative decays, but precision was too poor: $\xi' = -2.2 \pm 2.4$

- The new method is based on the muon decay-in-flight reconstruction in the tracker as a kink. Very rare because of large muon lifetime, but huge Belle statistics allows to see few hundreds such events

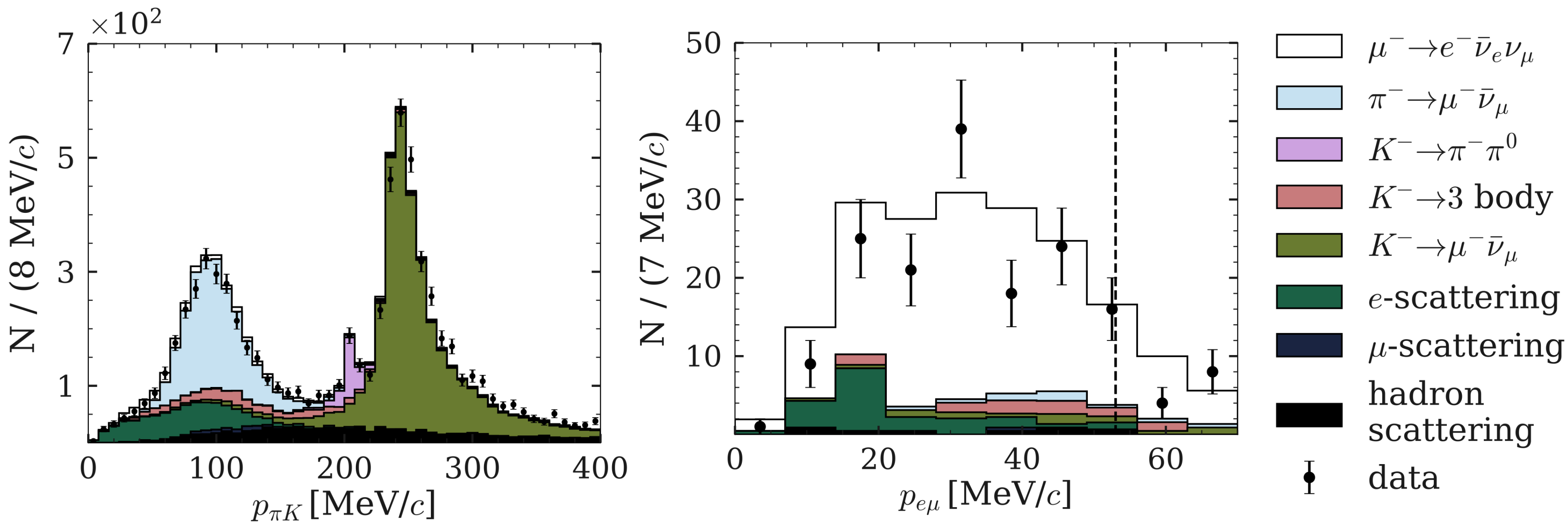
- The information about muon spin can be inferred from the daughter electron direction in the muon rest frame due to *P*-violation in the decay



PRL 131, 021801 (2023); PRD 108, 012003 (2023)

Use the full Belle data sample of $988 fb^{-1}$

Kink candidates

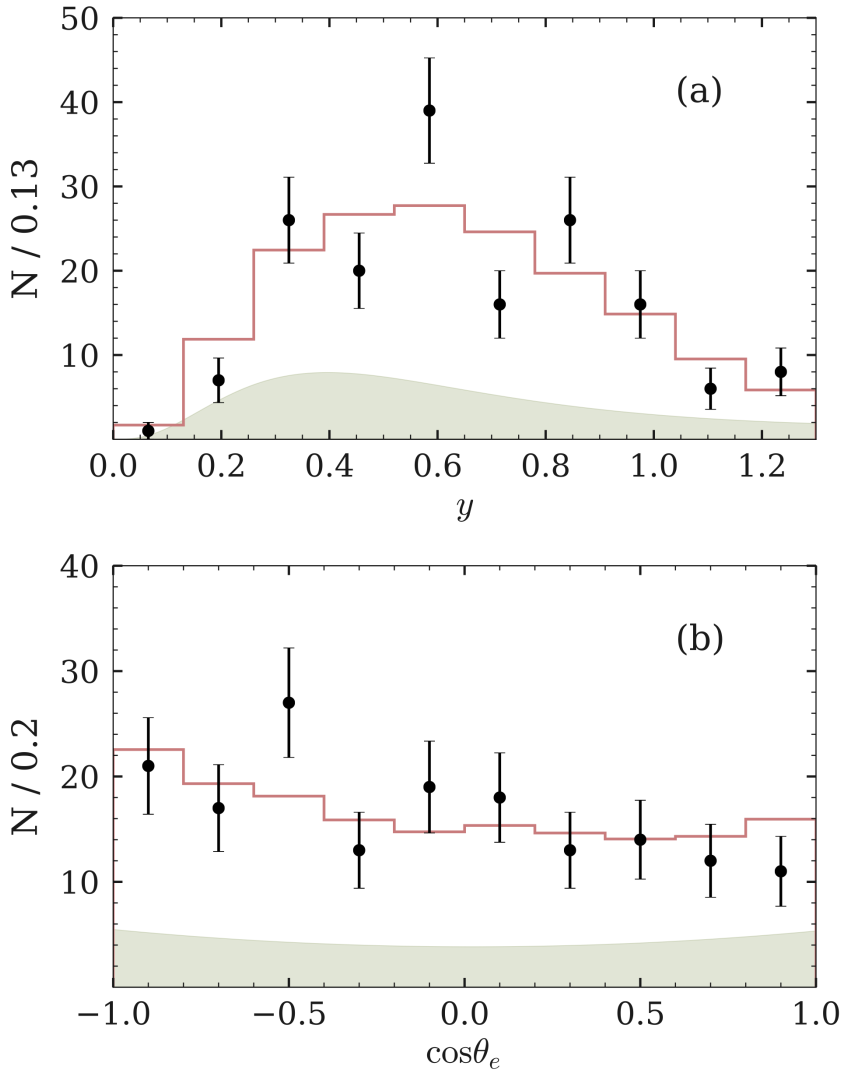


The main background sources are two body decays of $\pi^\pm$ and $K^\pm$.
The daughter particle momenta in the rest frame of the mother particle with correct mass hypotheses are peaked.

BDT is used to suppress background by 50 times with the signal efficiency $\varepsilon_{\text{sig}} \approx 80\%$

use huge control samples with tagged kinks of different types ($\pi^\pm$, $K^\pm$, and hadron scattering) selected from the $D^{*+} \to D^0(K^-\pi^+)\pi^+$ decays, and electron scattering from the γ-conversion.

Result



- The result of the first direct measurement of the Michel parameter ξ' in the $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$ decay at Belle is $\xi' = 0.22 \pm 0.94(\text{stat}) \pm 0.42(\text{syst})$
- The result with the combined uncertainty is $\xi' = 0.22 \pm 1.03$
- Statistical uncertainty dominates in this study, another limiting factor is kinematic resolution, while systematic uncertainty is well under control.
- Belle II can do a real precise measurement (larger arm drift chamber, mother track recontraction from vertex detectors, proper kink reconstruction and much larger statistics in future)

Summary

- Belle II + SuperKEKB has successfully launched and collected data already comparable to those by Belle (10 years). SuperKEKB has achieved $L_{peak} = 4.7\times10^{34}/cm^2/s$, the world record on June, 2022
- Luminosity and physics output expected to continue to ramp up with next data-taking period planned to start in fall 2023
- Belle II started producing results on many interesting physics from B and other sectors
- (old) Belle data is still interesting: unique data sample around and above $\Upsilon(5S)$; well known detector; elaborate new methods to anticipate future Belle II precise measurements