Belle II experiment: status and prospect

Doris Yangsoo Kim
Soongsil University

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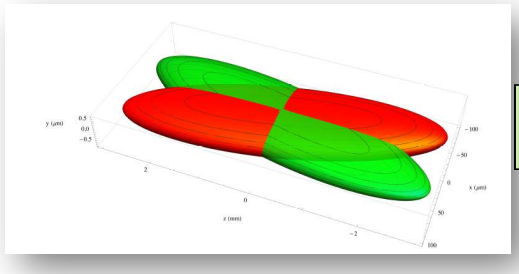
Contents

- The SuperKEKB Collider and the Belle II Experiment
- Luminosity Achievements
- Detector Performance
- The First Physics Results (Selected Topics)
- Run plan
- Summary

KEKB to SuperKEKB: Accomplished

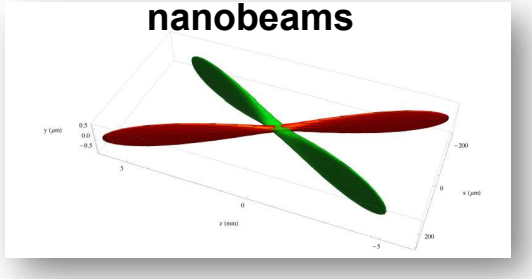
- Nano beam scheme + Crab waist optics
- Target: vertical beta function β_y^* 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction ξ_y

KEKB beams



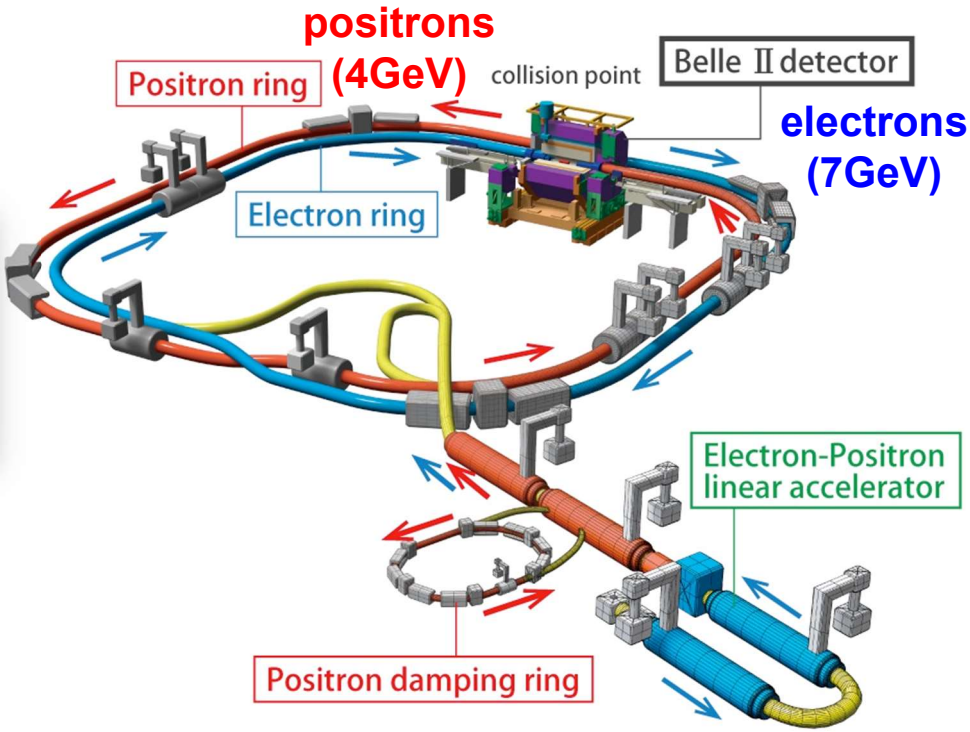
Beam crossing angle 22mrad

SuperKEKB nanobeams



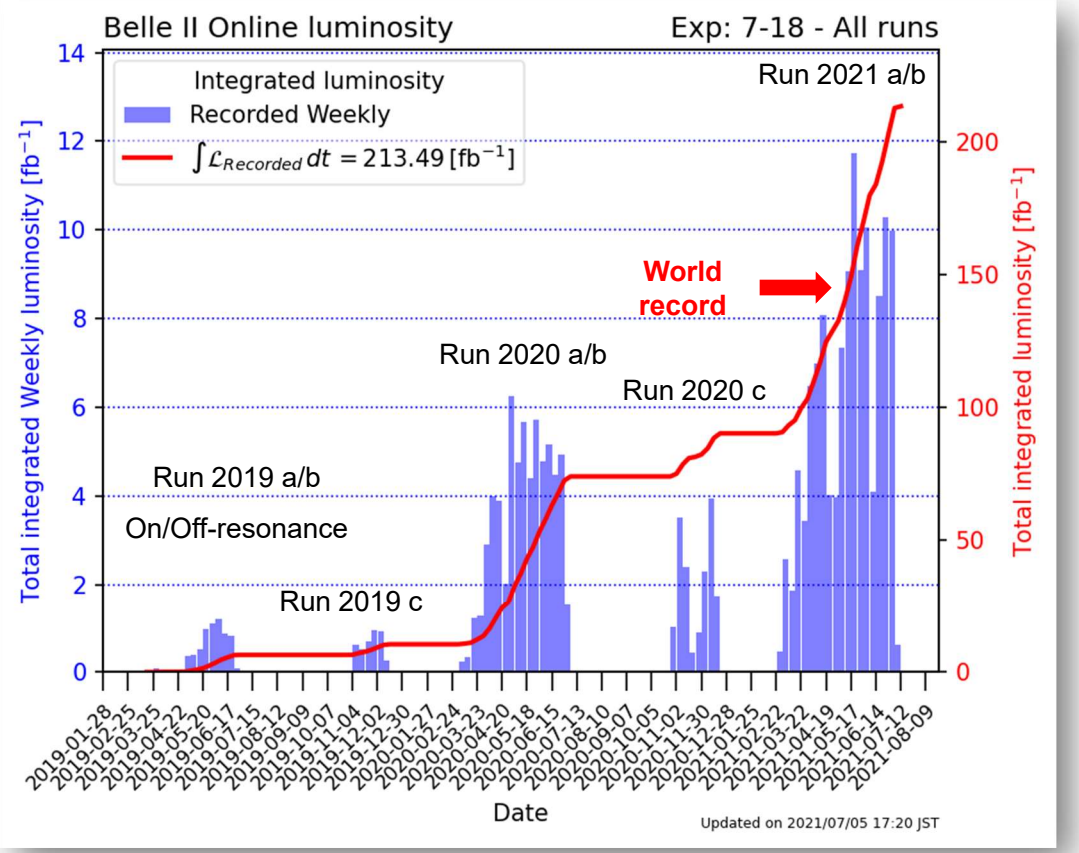
Beam crossing angle 83mrad

$$L = \frac{\gamma_{e\pm}}{2e\,r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\cdot\xi_{y,e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$



SuperKEKB Luminosity: Current Status

- After the commission phases, Phase III started spring 2019.
- Reclaimed the luminosity record on June 2020! (Previously held by LHC.)
- Spring/summer 2021 run ended on July 5th.
  - Another new luminosity record at $L_{peak} = 3.1 \times 10^{34} cm^{-2} s^{-1}$, the current world record on June 22nd.
  - Data taking efficiency is about 90%, continuously increased by improved detector operation.
  - The 2021 a/b run doubled the Belle II sample size to $\int L_{recorded} dt = 213.49\ fb^{-1}$.



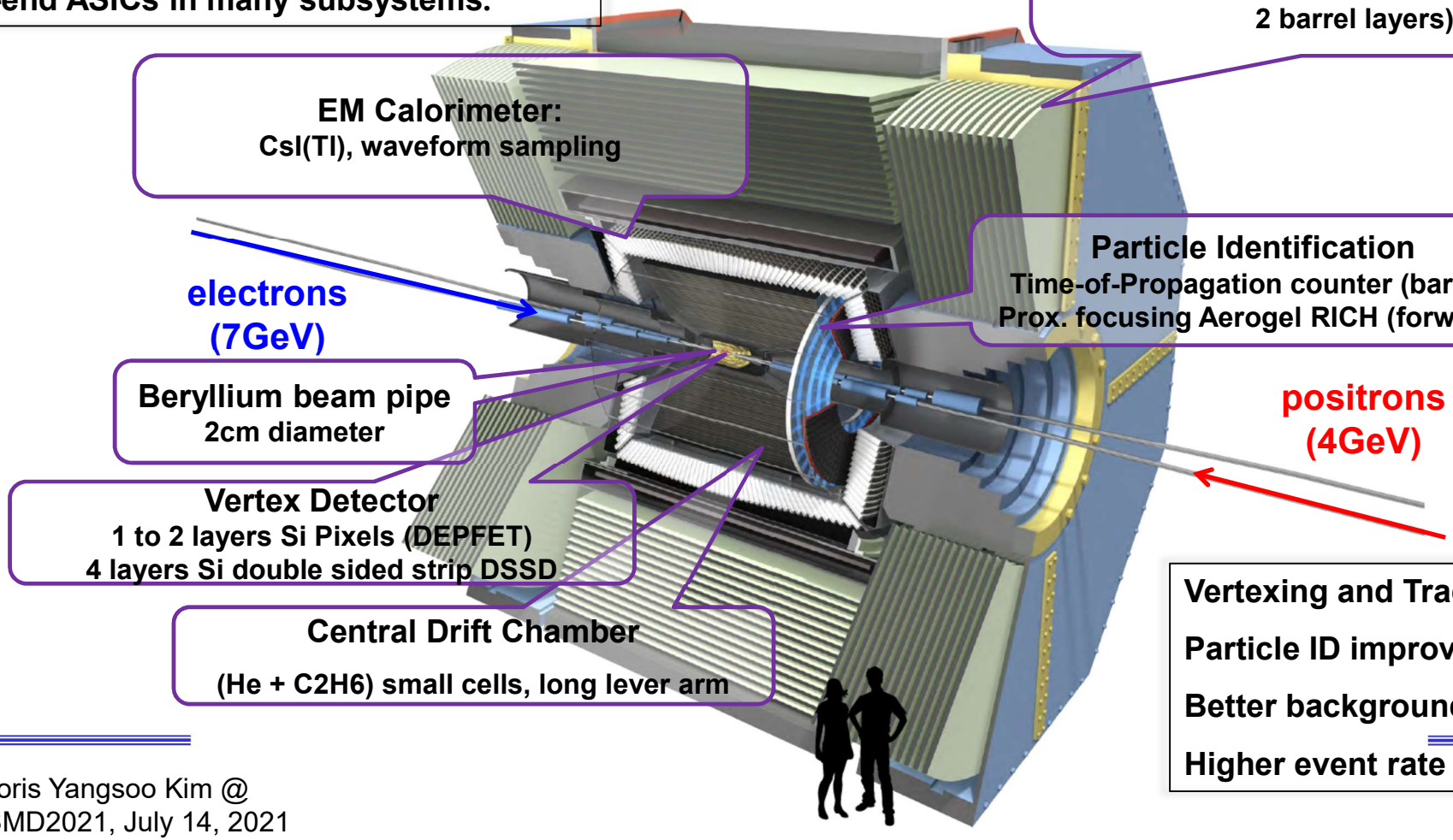
The Belle II Detector

7.4 m

Pixelated photo sensors in TOP/ARICH/KLM
Front-end ASICs in many subsystems.

KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling



Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

electrons (7GeV)

positrons (4GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector
1 to 2 layers Si Pixels (DEPFET)
4 layers Si double sided strip DSSD

Central Drift Chamber
(He + C2H6) small cells, long lever arm

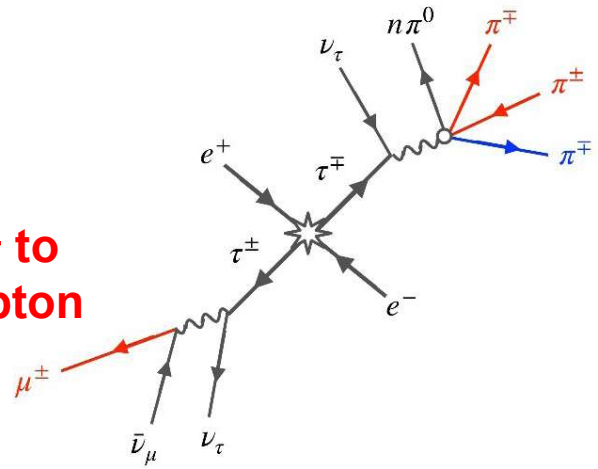
Vertexing and Tracking Improved
Particle ID improved
Better background insensitivity
Higher event rate

Belle II Experiment in a Nutshell

- Belle II Plan: collecting 50 ab^{-1} as $e^+ e^-$ collisions at Upsilon(4S) and nearby
  - About 50 times larger than its predecessor, Belle with 1.05 ab^{-1}
- Upsilon(4S) decays into $B\ \bar{B}$ meson pairs coherently with no additional fragments.
  - High tagging efficiency of B decays (Belle II ~30% vs LHCb ~5%)
  - Full event reconstruction tagging possible
- Direct detection of neutrals such as γ, π^0, K_L.
- A hermetic detector:
  - Detection of neutrinos or invisibles as missing energy/momentum.
- Large τ samples: Search for LFV τ decays at $O(10^{-9})$.
  - Detect both e and μ with similar performance.

DETECTOR PERFORMANCE

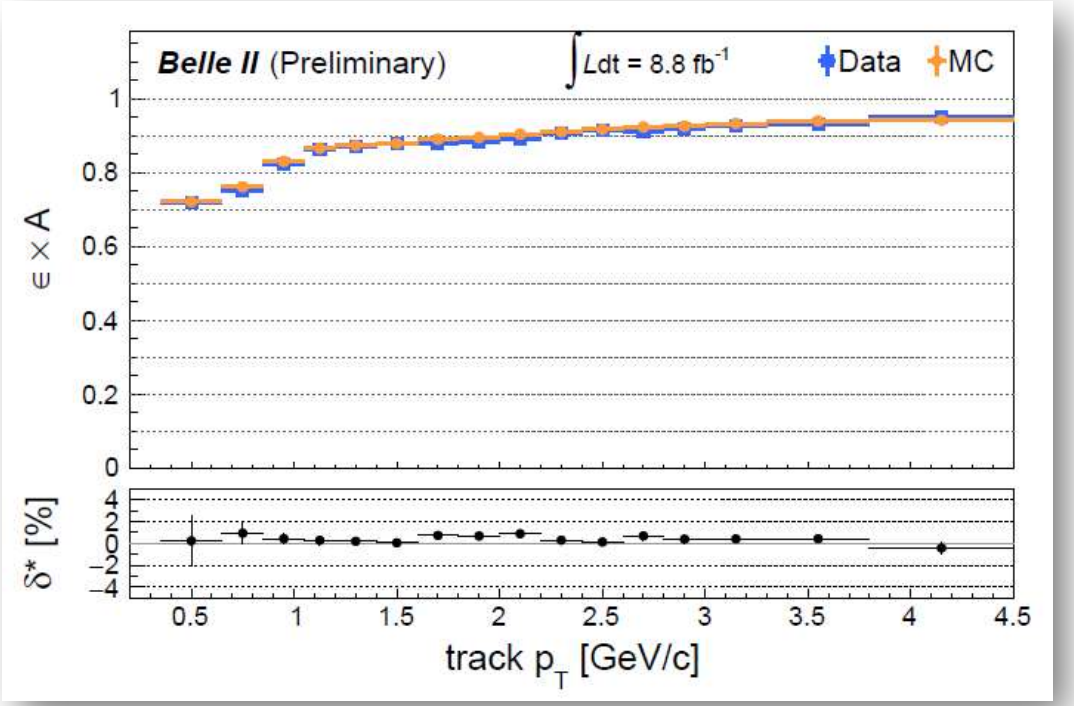
Tracking Efficiency



3-prong τ

prove

τ to lepton

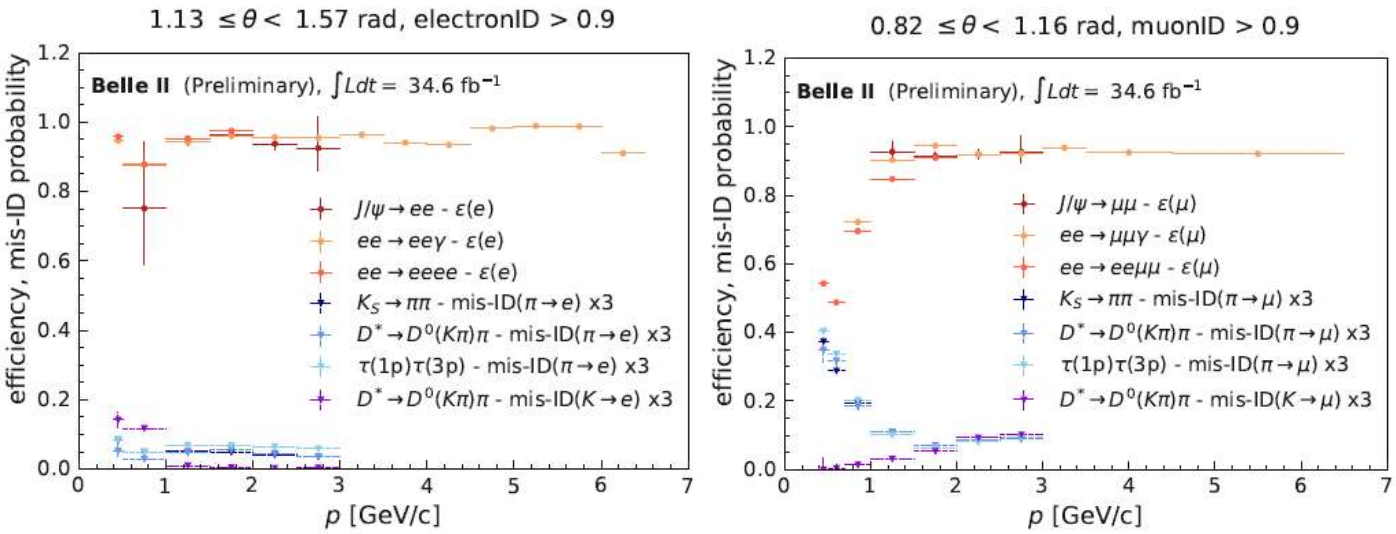


- Use $e^+e^- \to \tau^+\tau^-$ events.
- One side is a lepton.
- The other side has two charged tracks.
- Count the events where an additional prove track is found (N4) or not (N3).
- $\varepsilon \cdot A = N4/(N4 + N3)$
- A: detector acceptance, ε: track reconstruction efficiency

Particle ID: Charged

- The information from each PID detector defines a likelihood for each particle hypothesis, then merged to define a global PID likelihood.

$$l - ID = \frac{L_l}{L_e + L_\mu + L_\pi + L_K + L_p}$$



Mid-ID factor inflated by × 3 for illustrated purposes

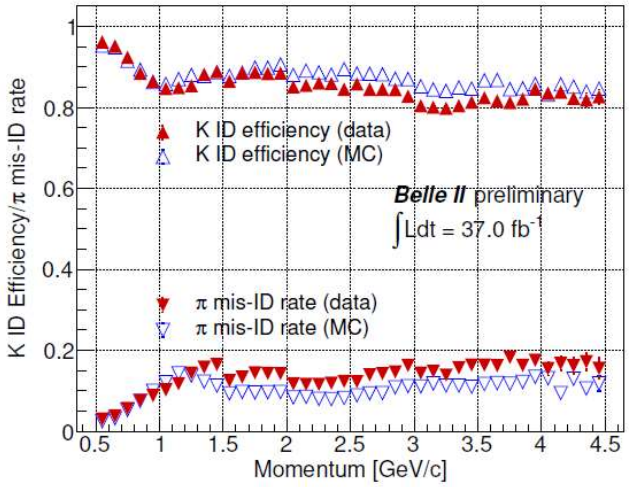
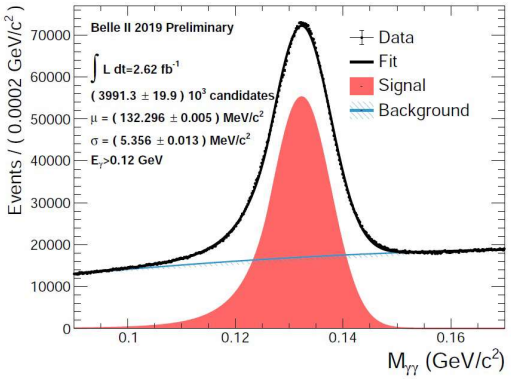


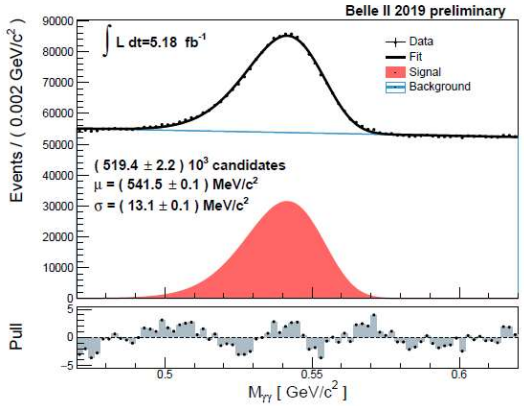
FIG. 4: Kaon efficiency and pion mis-ID rate for the PID criterion $\mathcal{R}_{K/\pi} > 0.5$ using the decay $D^{*+} \to D^0[K^-\pi^+]\pi^+$ in the bins of laboratory frame momentum of the tracks.

Neutral Particles

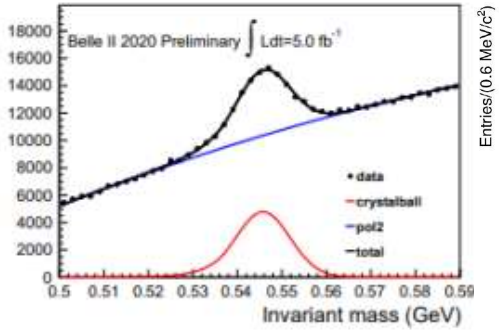
$\pi^0 \to \gamma\gamma$



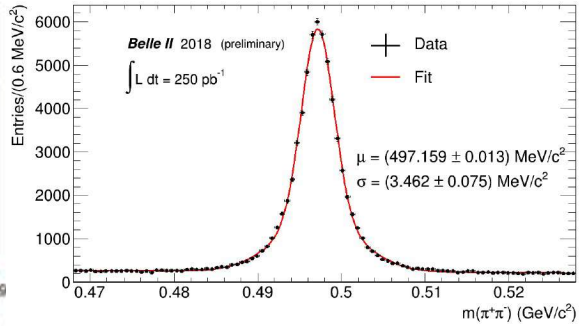
$\eta \to \gamma\gamma$



$\eta \to 3\pi^0$

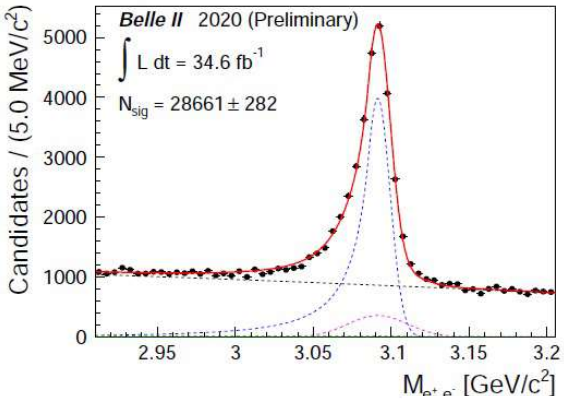


$K_S \to \pi^+\pi^-$

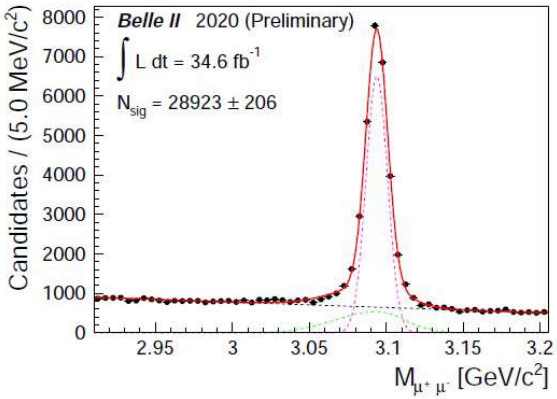


- Large hermeticity and uniform ID detectors allow good neutral reconstruction.
- Bremsstrahlung & isolated ISR/FSR photon reconstruction is also possible.

$J/\psi \to e^+e^-$



$J/\psi \to \mu^+\mu^-$

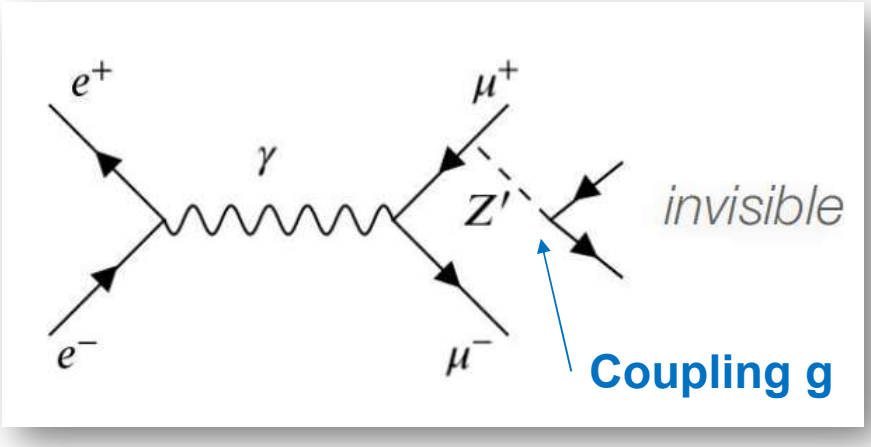


Bremsstrahlung recovered

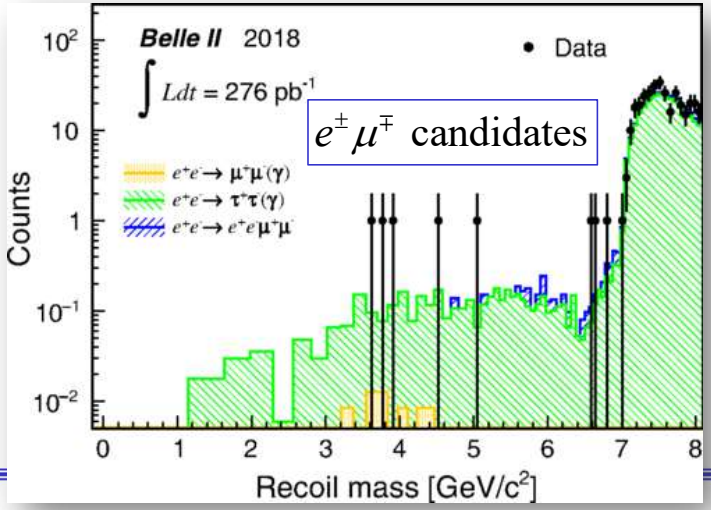
- Z' search
- Axion-like-particles search
- Charm lifetime
- Time dependent CPV
- Exclusive $\boldsymbol{B \to \pi\, l\nu}$ and $|V_{ub}|$
- $\boldsymbol{B^+ \to K^+ \nu\nu}$ with inclusive tagging

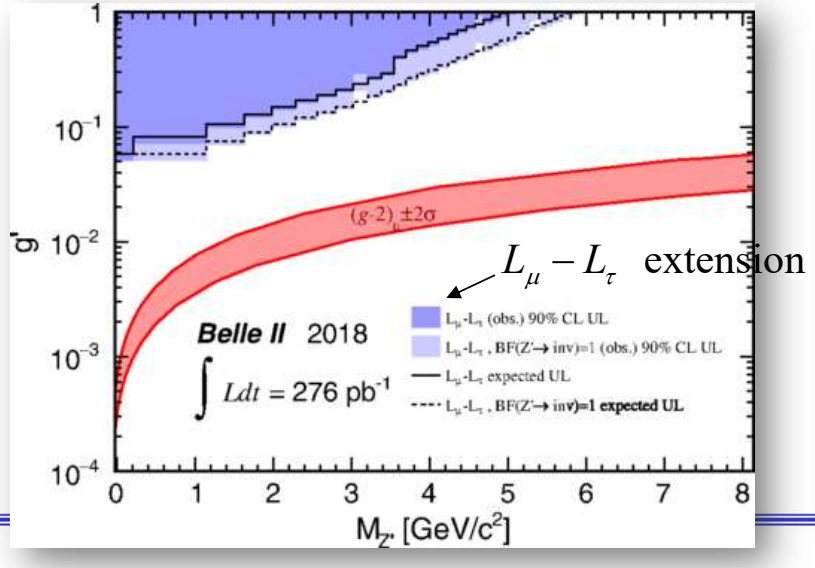
THE FIRST PHYSICS RESULTS

The First Physics Paper: Z′ Search

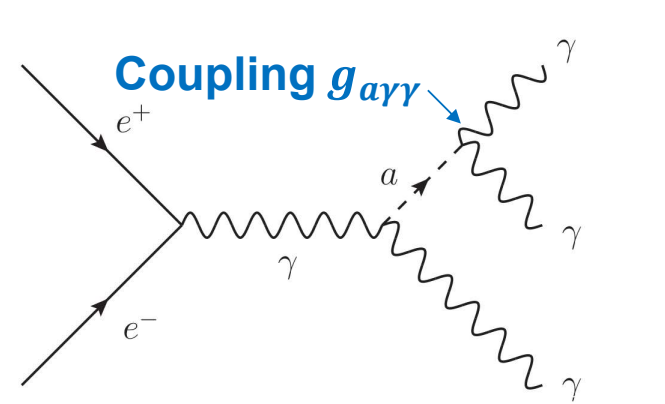


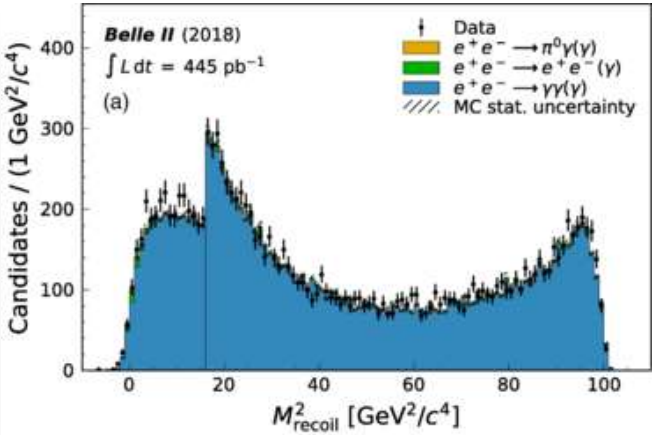
- A new result on the dark sector ($Z' \rightarrow$ nothing) recoiling against di-muons or electron-muon pair: Phys. Rev. Lett. 124, 141801 (2020).
- Both possibilities are poorly constrained at low Z' mass.
  - The di-muon case could explain the muon g-2 anomaly.

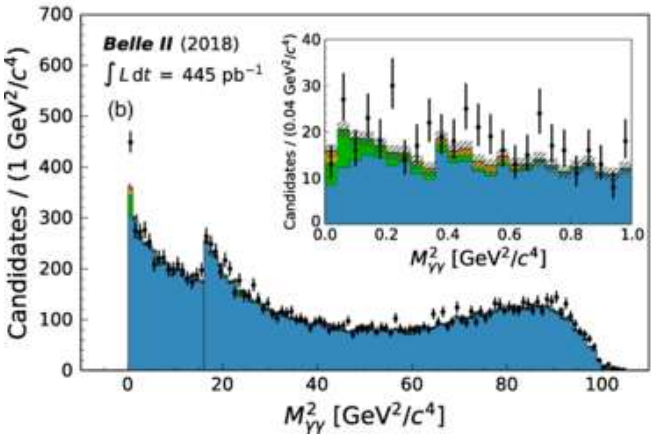




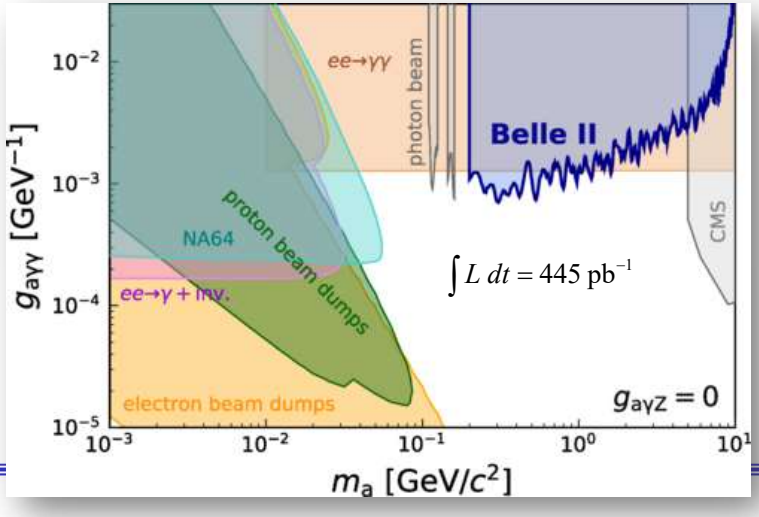
Search for Axion Like Particles







- Axion like particles at low mass are cold dark mater candidates: Phys. Rev. Let. 125, 161806 (2020)
- They couple naturally to photons.
- Look for 3-photon final states via ALP-strahlung in
  - Recoil invariant mass for high m_a.
  - Di-photon mass for low m_a.
- Also studies 1-photon final states.



Charm Lifetime

The new pixel detector improved the lifetime resolution of the charm particles by a factor of 2 with respect to the previous Belle detector.

One example is the $D^0 \to K^-\pi^+$ lifetime study.

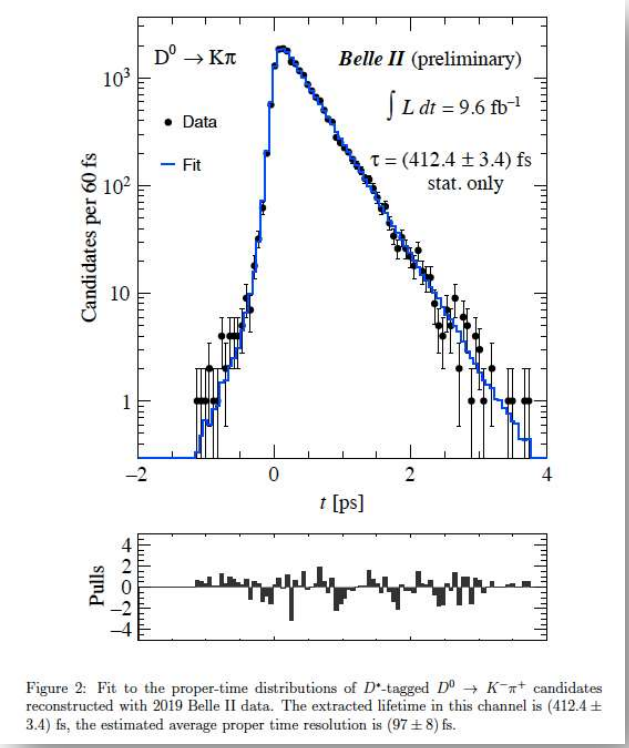
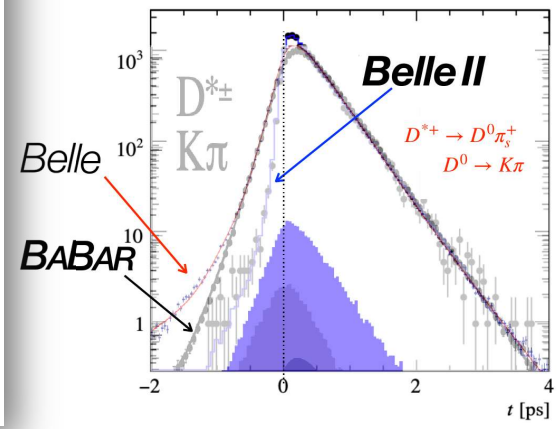
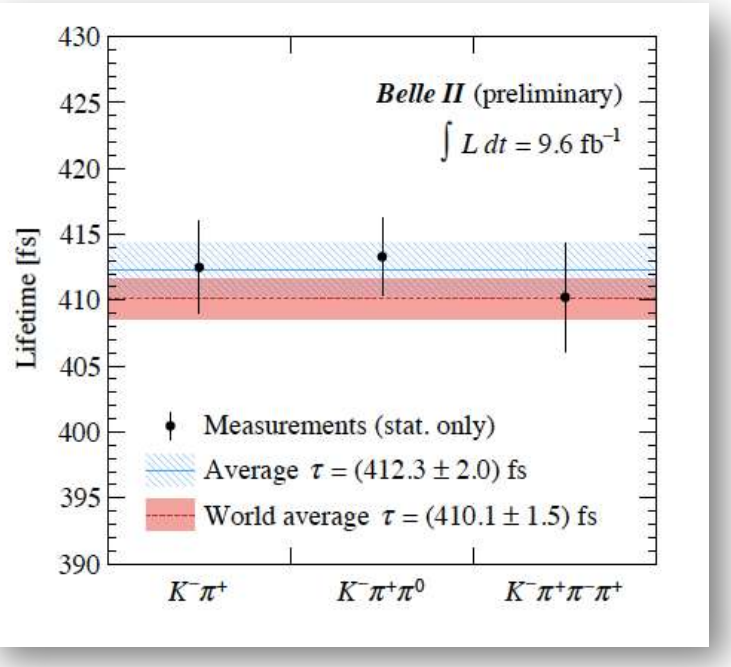
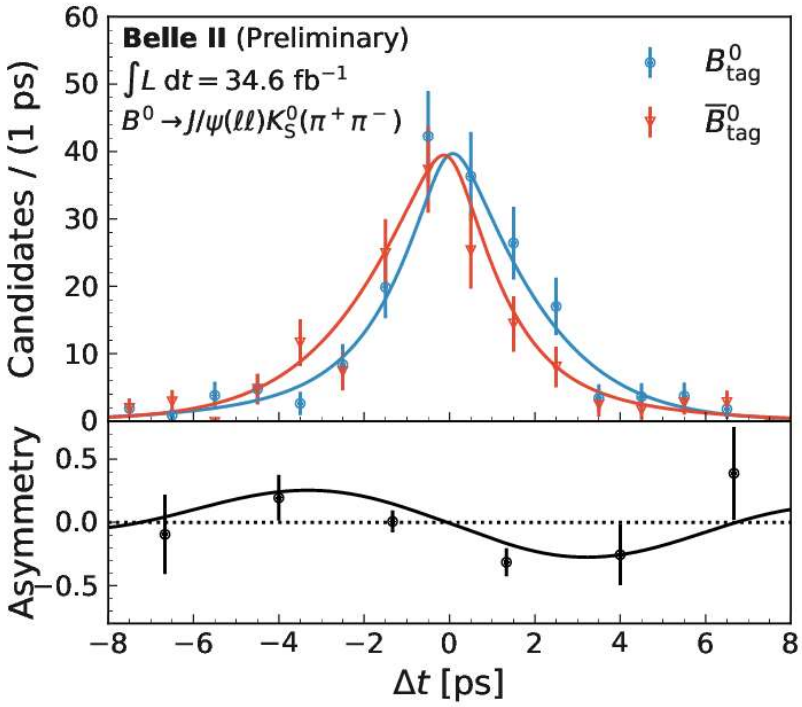


Figure 2: Fit to the proper-time distributions of D^*-tagged $D^0 \to K^-\pi^+$ candidates reconstructed with 2019 Belle II data. The extracted lifetime in this channel is (412.4 ± 3.4) fs, the estimated average proper time resolution is (97 ± 8) fs.





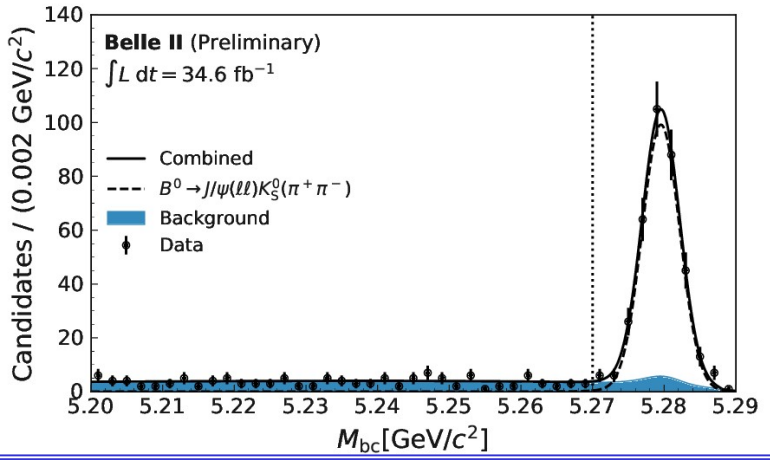
Time Dependent CPV and Mixing



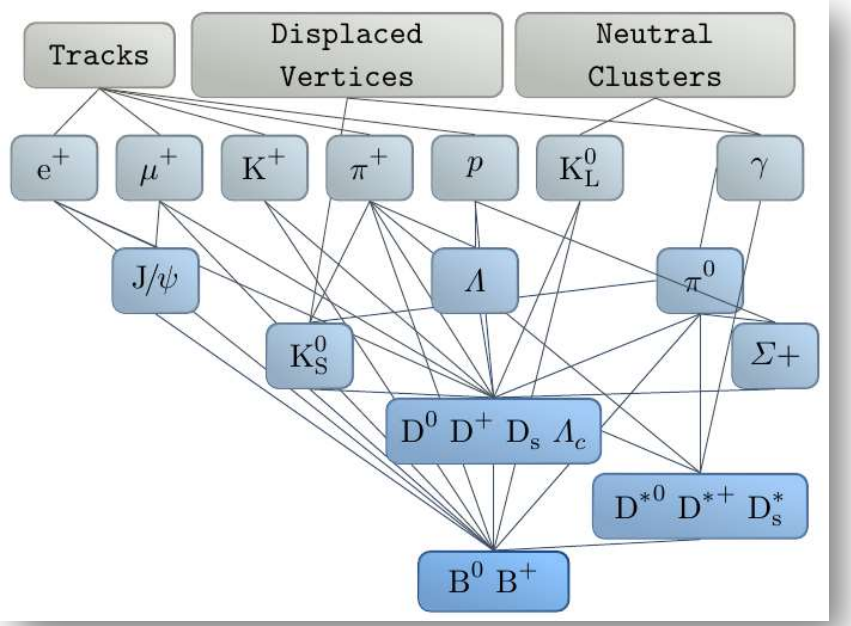
Belle II: $S_f \approx \sin 2\phi_1 = 0.55 \pm 0.21 \pm 0.04.$

W. A.: $S_f \approx 0.691 \pm 0.017.$

- The golden channel $B^0 \to J/\psi(ll)K^0_S(\pi^+\pi^-)$ is studied and the time dependent CPV parameter $\sin 2\phi_1$ is extracted.
- CPV is assumed only from the B^0 mixing ($A_{CP} = 0$).
- The wrong sign tag ratio $w = (20.9 \pm 2.1)\%$ is obtained from the $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ sample where $\Delta m_d = (0.531 \pm 0.046 \pm 0.013)\ \mathrm{ps}^{-1}$.

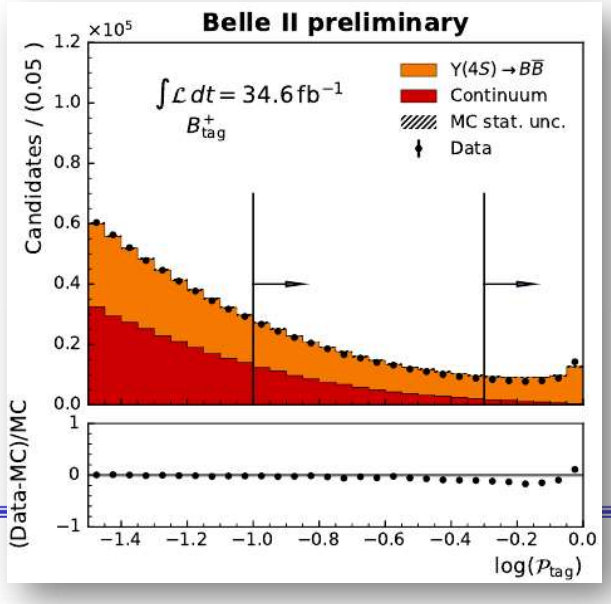


Full Event Interpretation

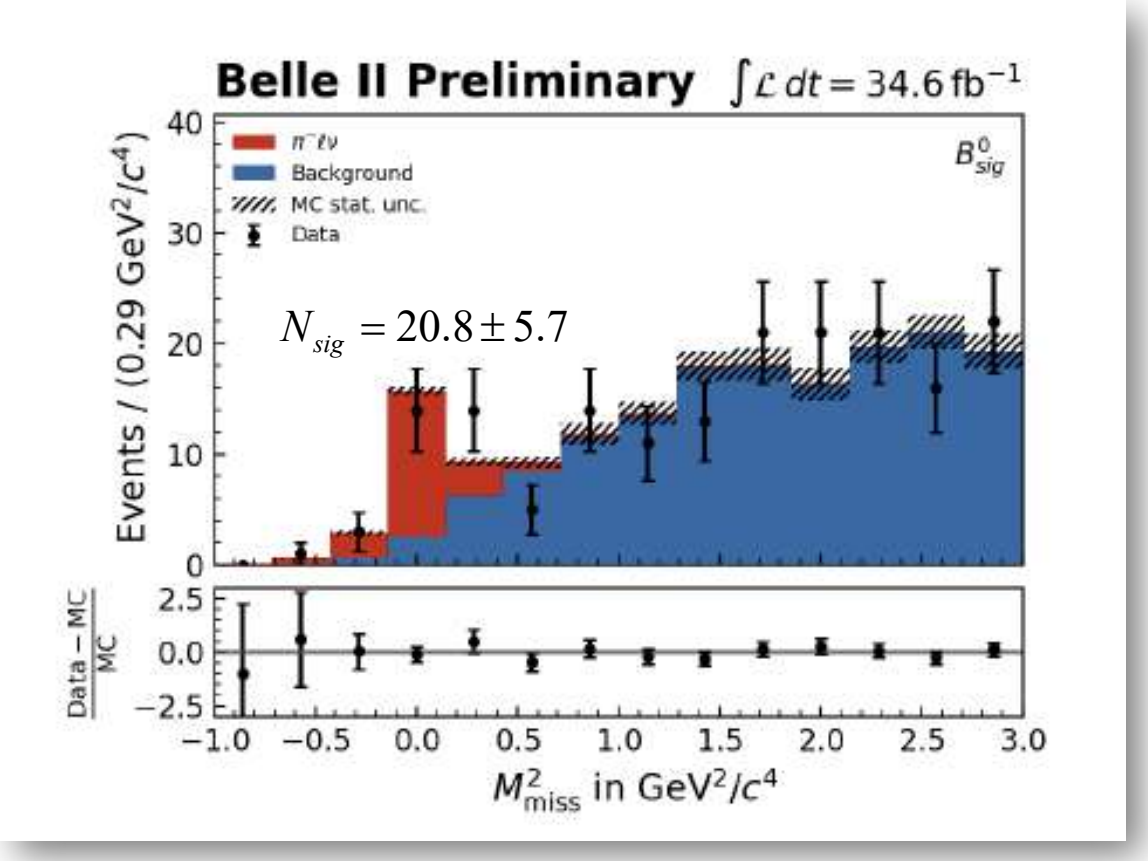


Hierachial reconstruction is performed to obtain B (tag) mesons exclusively.

- Traditionally, at Upsilon(4s), one B (tag) is reconstructed first. The rest of the event is considered as a signal B.
  https://arxiv.org/abs/2008.02707
- An improved tool (FEI) is developed based on Boosted Decision Tree.
  T. Keck et al., Comput. Softw. Big Sci. 3, 6 (2019)



$|V_{ub}|$: Exclusive $B \to \pi\, l\nu$



- Here is an example of FEI applied to a semileptonic decay of B meson.

  PDG $|V_{ub}|$

  inclusive : $(4.25 \pm 0.12^{+0.15}_{-0.14} \pm 0.23) \times 10^{-3}$

  exclusive : $(3.70 \pm 0.10 \pm 0.12) \times 10^{-3}$

- Measurement of branching fraction and Lattice QCD calculation result can extract $|V_{ub}|$ at q^2(max).

  $BF(B^0 \to \pi^- l^+ \nu)$

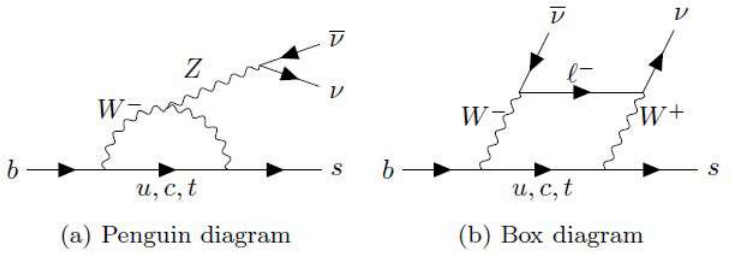
  Belle II: $[1.58 \pm 0.43(\text{stat}) \pm 0.07(\text{sys})] \times 10^{-4}$

  W.A.: $[1.50 \pm 0.06] \times 10^{-4}$

https://arxiv.org/abs/2008.08819

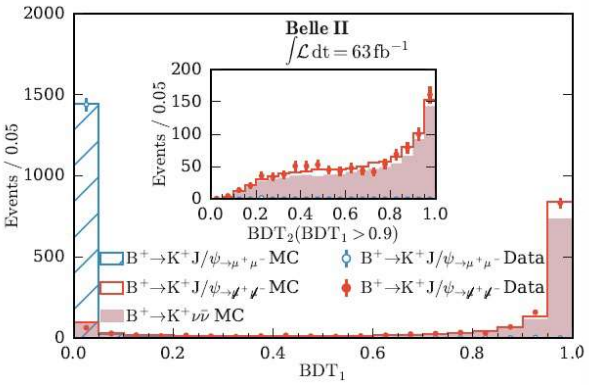
For other SL decays, see https://indico.belle2.org/event/4615/contributions/22862/

$B^+ \to K^+ \nu\nu$ with Inclusive Tagging

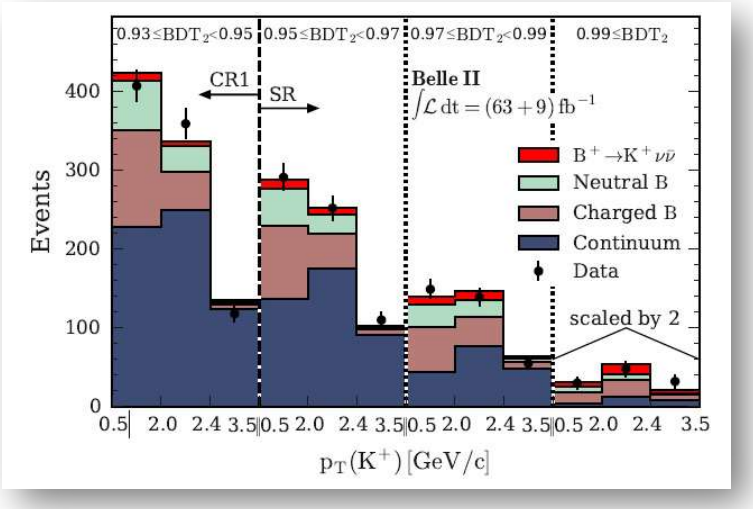


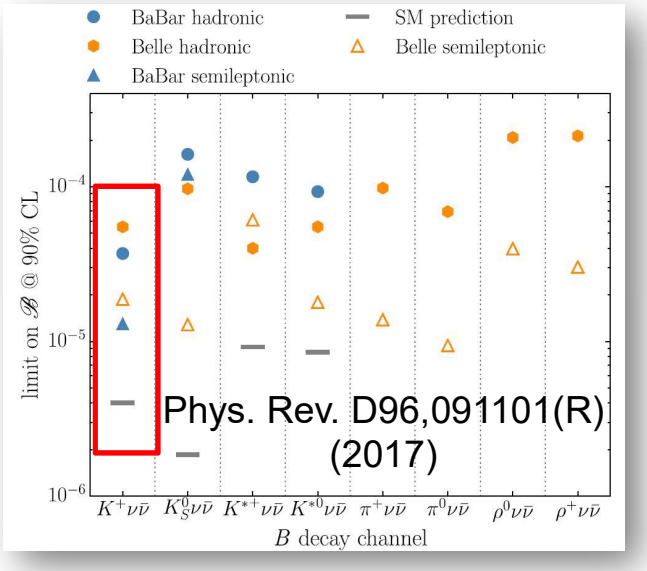
(a) Penguin diagram (b) Box diagram

FIG. 1: Lowest-order quark-level diagrams for the $b \to s\nu\bar{\nu}$ transition in the SM.



Boosted Decision Tree Outputs



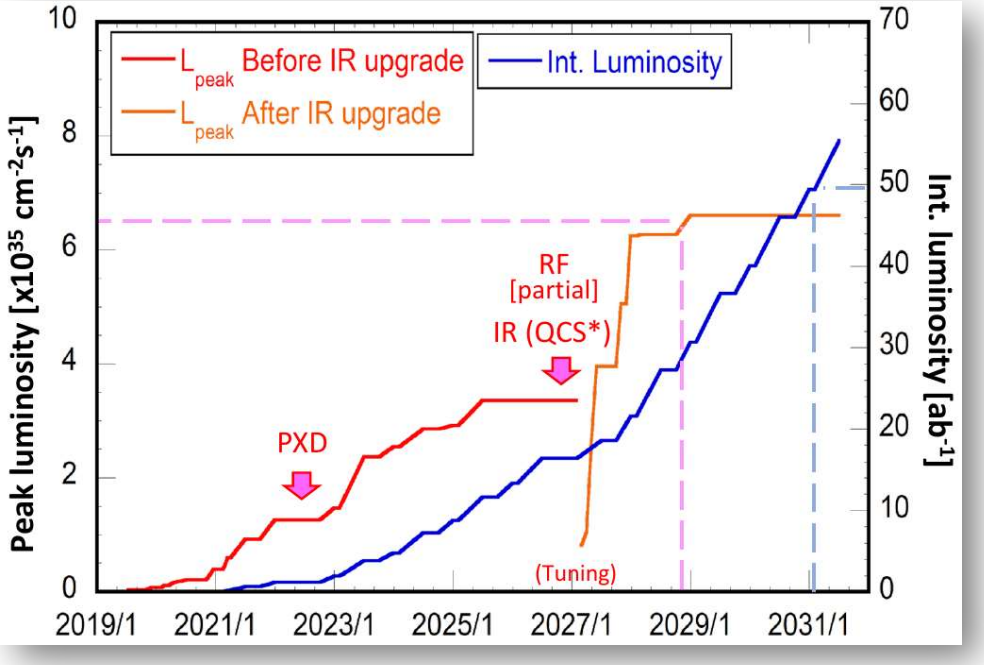


- The Belle II measurement at $63\ fb^{-1}$ is comparable to the previous Babar/Belle measurements.

Babar	$< 1.6 \times 10^{-5}$ (90% C.L.)	Phys. Rev. D87,112005 (2013)
Belle	$< 1.9 \times 10^{-5}$ (90% C.L.)	Phys. Rev. D96,091101(R) (2017)
Belle II	$< 4.1 \times 10^{-5}$ (90% C.L.)	https://arxiv.org/abs/2105.05754

SUMMARY

Near Term Prospects and Run Plan



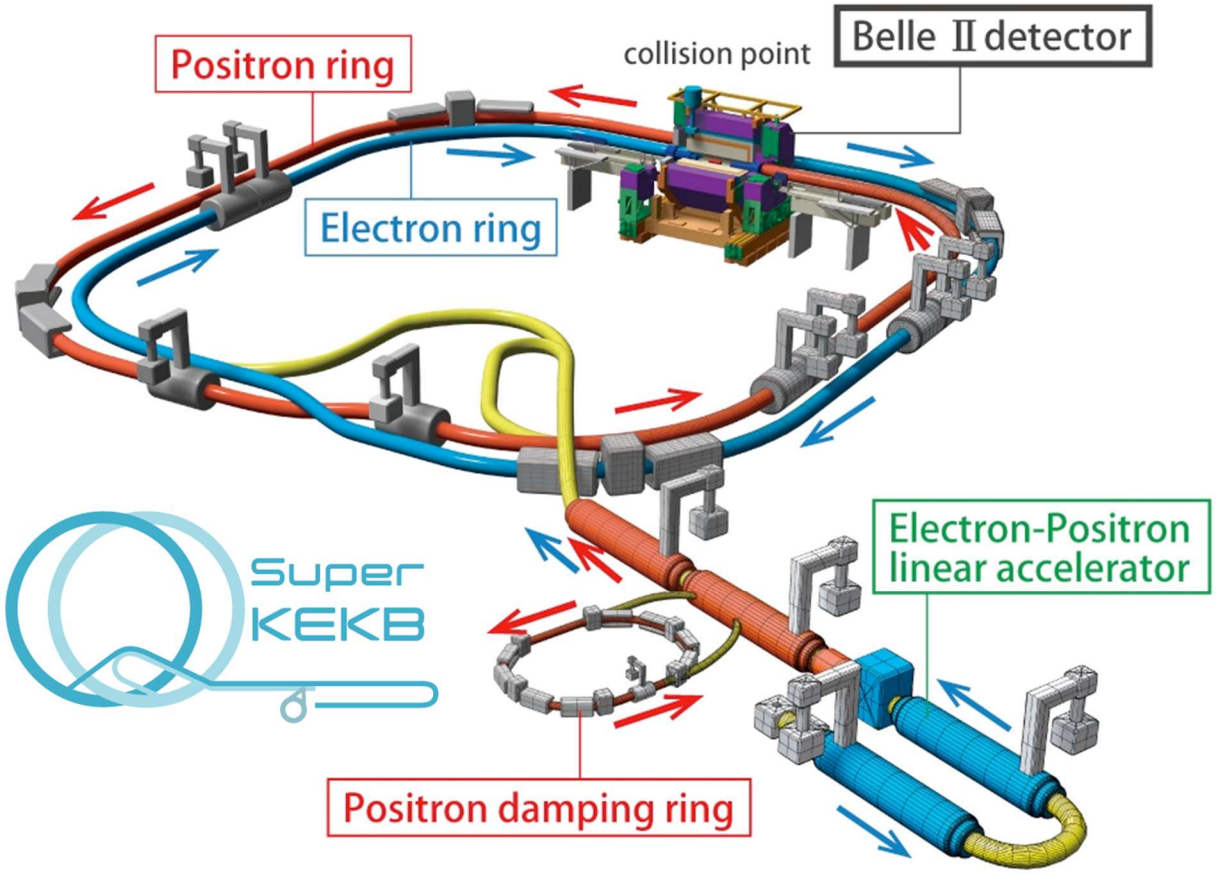
- In general, SuperKEKB will run 8 months per year.
- 2021 autumn
  - Upsilon(4S) $\sim 400\ fb^{-1}$ (Babar)
  - 10.75 GeV scan for $10\ fb^{-1}$
- 2022 summer $\sim 700\ fb^{-1}$ (Belle)
- 2022 Long shutdown 1
  - PXD exchange. TOP PMT replacement
- 2026 $\sim 15\ ab^{-1}$
- 2026 Long shutdown 2
  - Partial RF-power upgrade. IR upgrade.
- 2031 $\sim 50\ ab^{-1}$

Summary

- SuperKEKB has achieved $L_{peak} = 3.1 \times 10^{34} cm^{-2} s^{-1}$, the world record on June 22nd.
  - It is a super B factory now.
- Belle II has started producing new results, including a world leading results in dark sector with limited Phase II data: Z′ and ALP papers
  - More updates are coming with Phase III data
- Belle II rediscovered many flavor physics signatures based on the early Phase III data: 12+8 conference papers at arXiv/Belle II docs
  - Reports at ICHEP 2020, Moriond 2021.
- Belle II is planning to collect 50 ab^{-1} by 2031. This is a very exciting time to do flavor physics, looking for physics beyond the Standard Model.

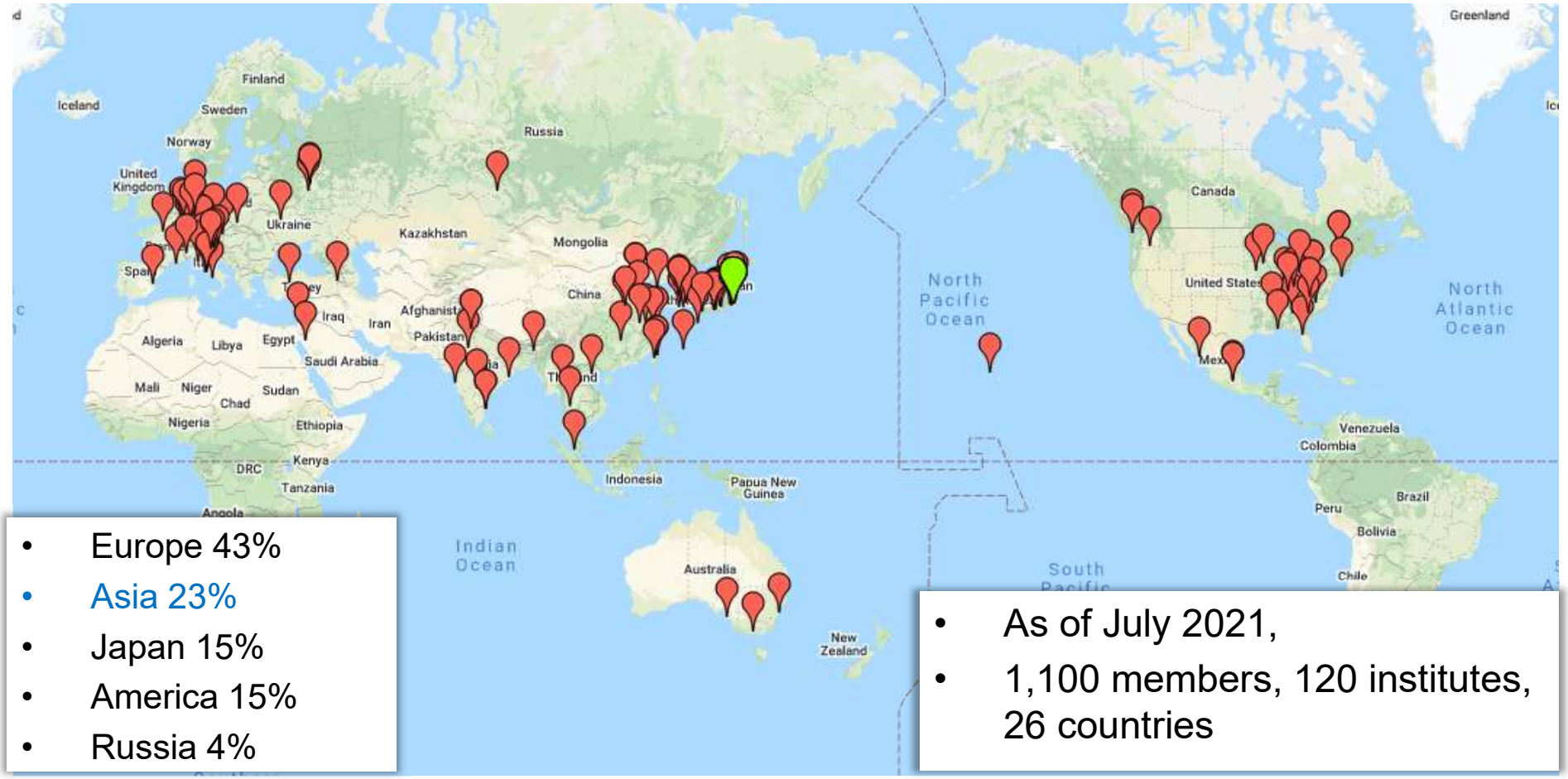
EXTRA

KEKB to SuperKEKB: Commission Timeline



- New 3km positron ring ready for Phase I (2016)
  - Single beam with simple background detector.
- Positron damping ring added for Phase II (2018)
  - Beast II + outer Belle II with beam colliding.
- Phase III started February 2019 with the full Belle II detector.
- The nominal energy for run is at Upsilon(4s) with 7 GeV electron and 4 GeV positron beams.
  - Other energies also included.

The Belle II Collaboration

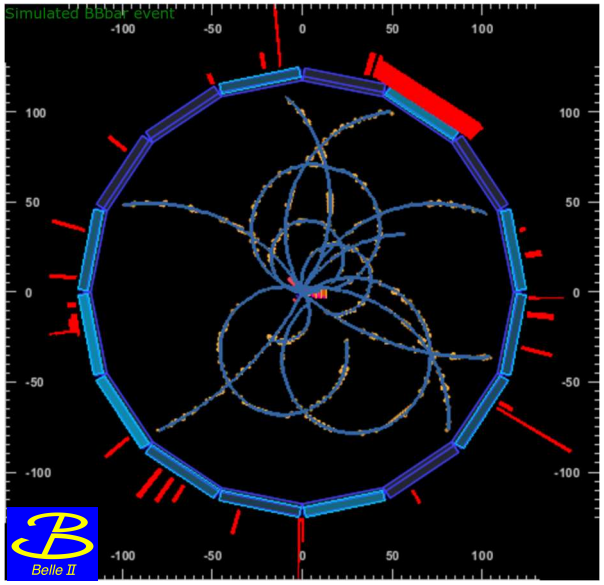


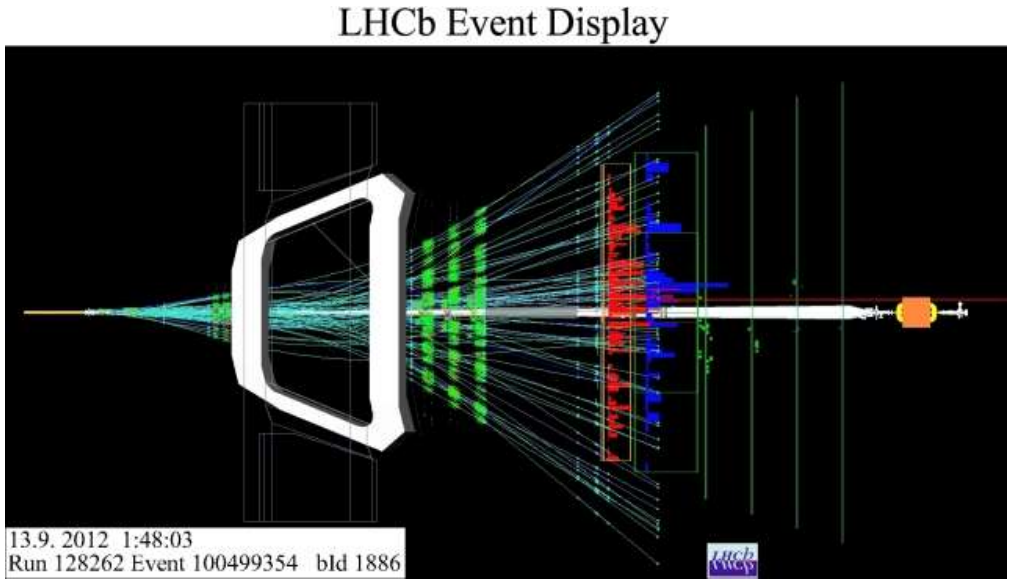
- Europe 43%
- Asia 23%
- Japan 15%
- America 15%
- Russia 4%

- As of July 2021,
- 1,100 members, 120 institutes, 26 countries

Belle II and LHCb

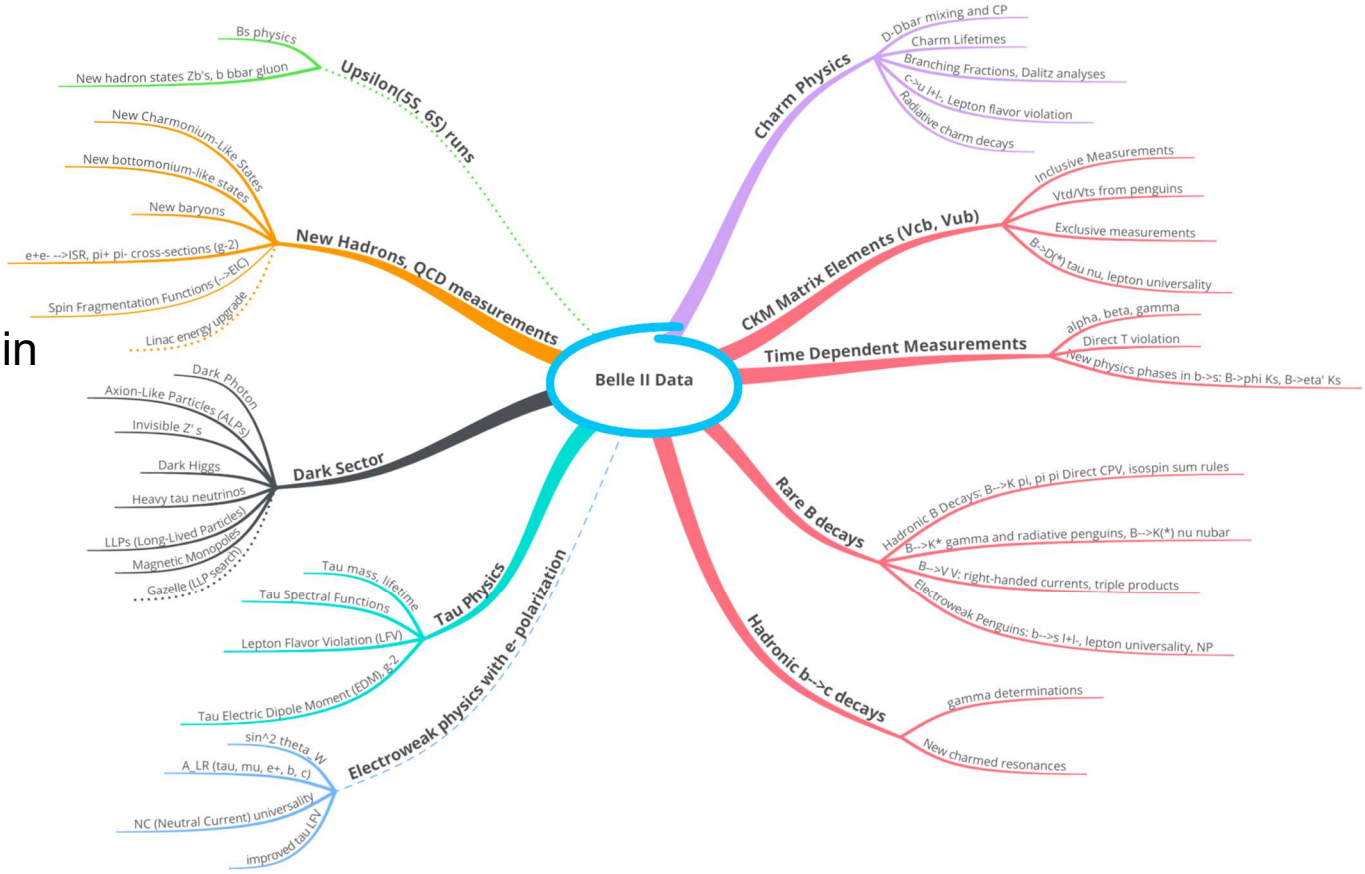
- Belle II and LHCb have different systematics
  - Two experiments are required to establish NP.
  - LHCb: large $b\bar{b}$ cross-section (LHCb 1 fb^{-1} ~ Belle II 1 ab^{-1}). Good sensitivity and S/N with di-muon modes and charged tracks with a vertex.





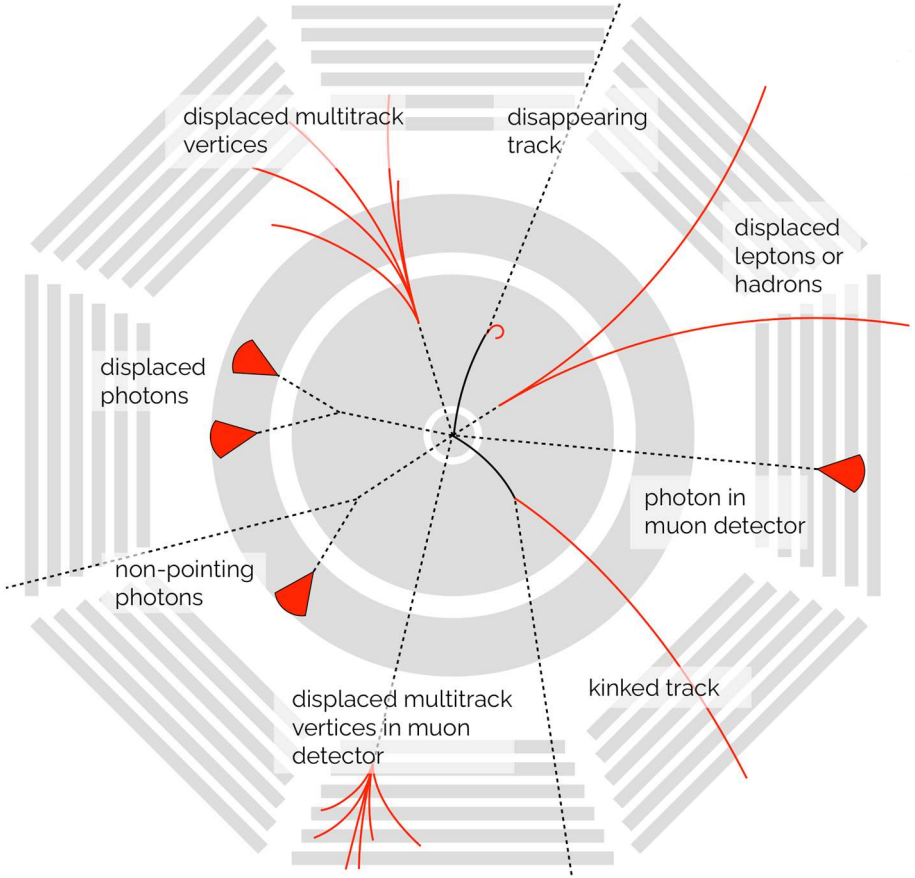
Belle II Physics Prospects

- Dark sector
- Long lived particles
- Next precision CKM measurements
- CP violation in $b \to s$ penguin decays
- Lepton flavor violation in τ decays
- FCNC
- Charm decays
- τ physics
- Hadron spectroscopy



https://confluence.desy.de/display/BI/Snowmass+2021

Long Lived Particles



- December 2020, FSP Workshop focusing on feasibility studies

  https://indico.belle2.org/event/2920/
- Additional displacement vertex trigger is needed to enhance the LLP sensitivities.
- A Snowmass White Paper including a proposal of the Gazelle detector

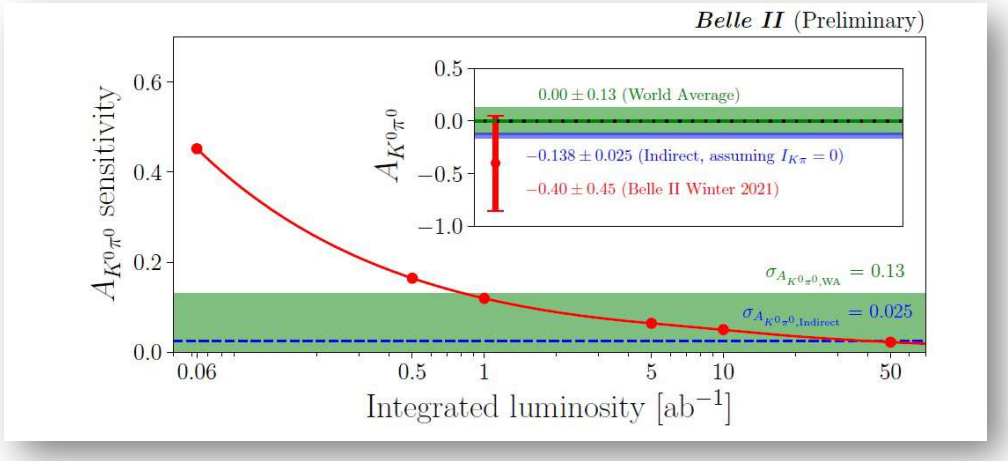
  https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0_Torben_Ferber-020.pdf

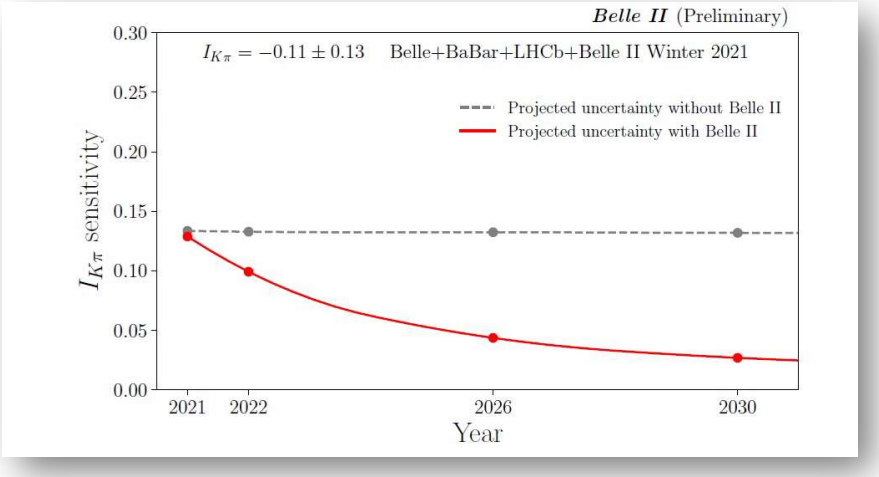
Direct CPV in $B^0 \to K^0\pi^0$ Decays

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- Isospin rule was proposed to test SM: 0 or not. Currently, $I_{K\pi} = -0.11 \pm 0.13$
- Belle II measurements on the neutral decay mode: (2021 preliminary)

$$A_{K^0\pi^0} = -0.40^{+0.46}_{-0.44} \pm 0.04, \quad B(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6} \pm 1.2] \times 10^{-6}$$

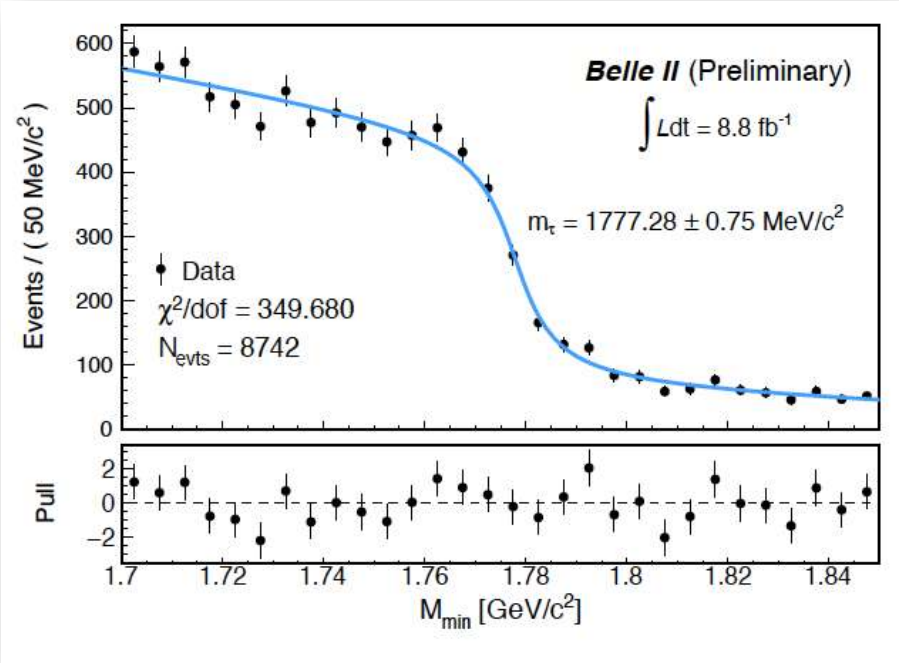




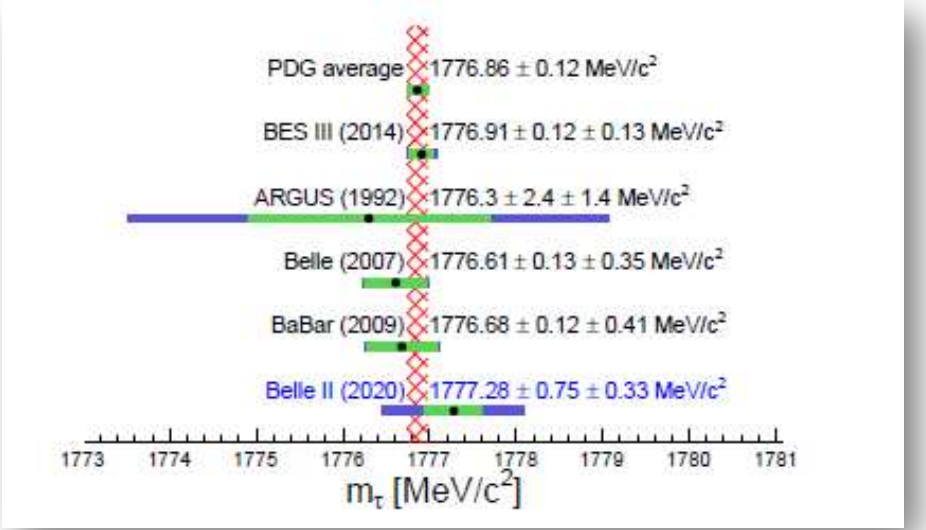
https://arxiv.org/abs/2104.14871

τ Mass Measurement

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



- Select one-prong τ and 3-prong τ pair events.
- The mass is measured from the threshold of the pseudomass variable.



https://arxiv.org/abs/2008.04665