Belle II status and prospects

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(On behalf of the Belle II Collaboration)

LHC Days 2018, Split, Croatia

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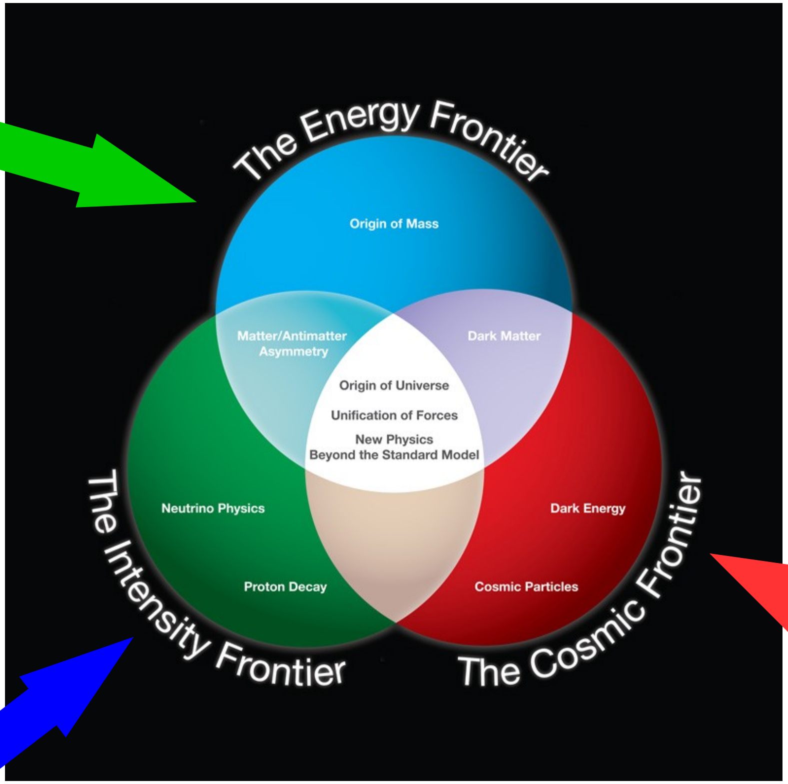
Outline

- Introduction, history
- Physics motivation
- The SuperKEKB accelerator and Belle II detector
- Results from early data
- Prospects
- Summary and conclusions

Three Frontiers of Particle Physics

- **LHC experiments**



- **Astroparticle experiments**

- **Neutrino experiments**
- **Particle factories, such as Belle (II), and tau-charm factories**

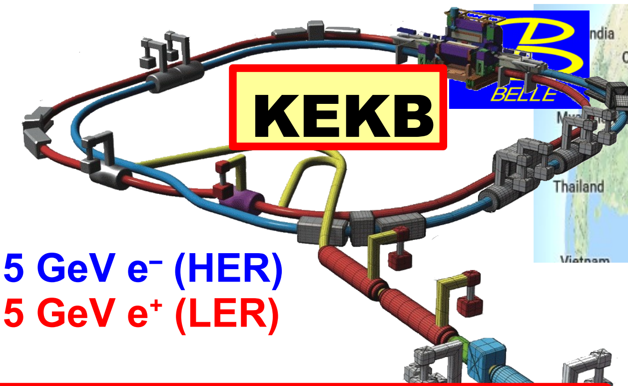
Intensity Frontier researchers use a combination of intense particle beams and highly sensitive detectors to make extremely precise measurements of particle properties, study some of the rarest particle interactions predicted by the Standard Model of particle physics, and search for new physics.

https://science.energy.gov/hep/research/

Legacy of B-Factories

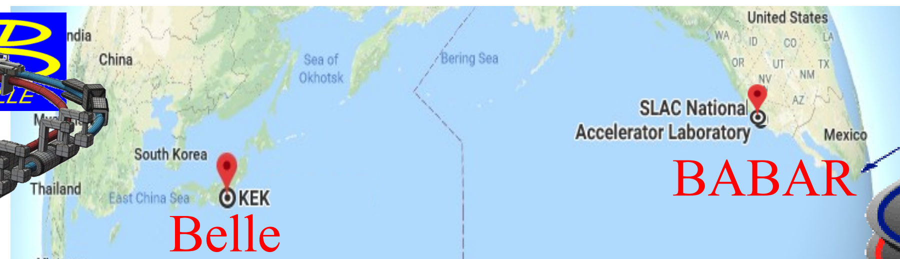
- **B-Factories**: High luminosity asymmetric-energy e^+e^- colliders (PEP-II/BABAR, KEKB/Belle),

operating at $E_{CMS} \sim m_{\Upsilon(4S)} c^2 = 10.58\ GeV$ to produce $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$



8.5 GeV e⁻ (HER)
3.5 GeV e⁺ (LER)

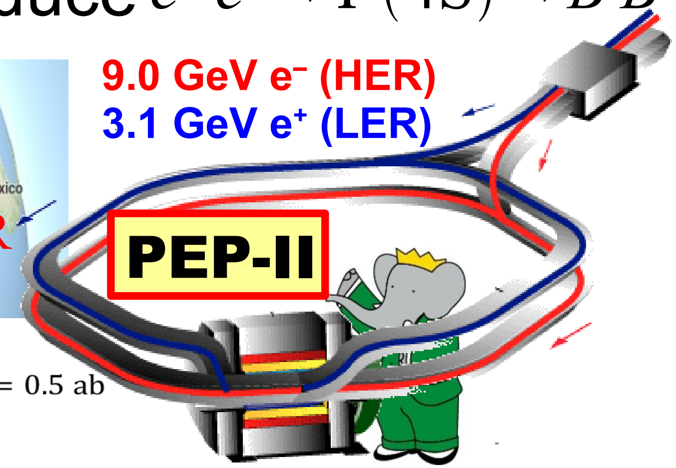
2.11x10^{34} cm^{-2}s^{-1}(WR!)



1999-2010
$\sim 1000\ fb^{-1} = 1 ab^{-1}$

1999-2008
$\sim 500\ fb^{-1} = 0.5\ ab$

9.0 GeV e⁻ (HER)
3.1 GeV e⁺ (LER)



1.21x10^{34} cm^{-2}s^{-1}

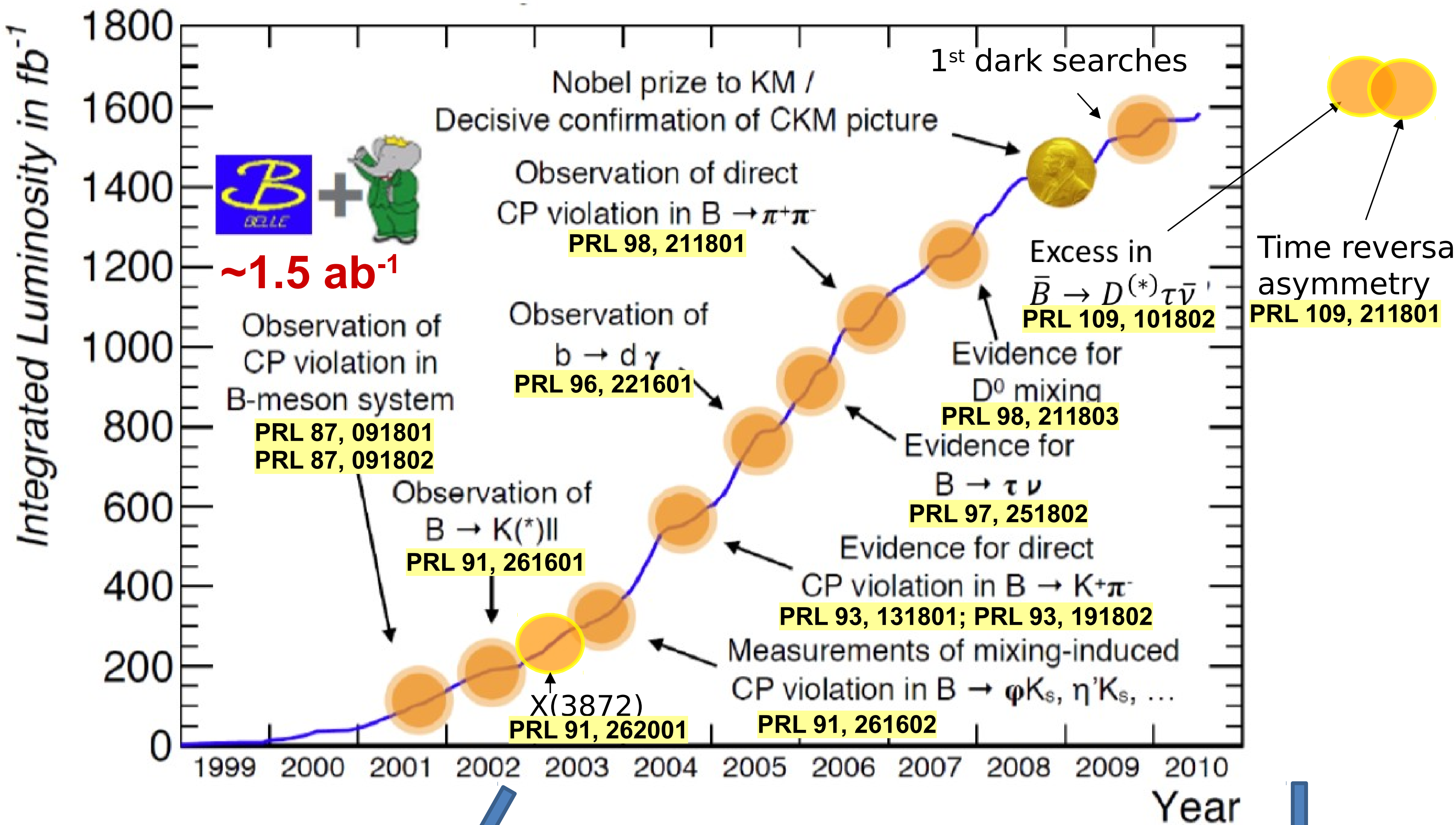
Step1
Discovery of CPV in B decay

Step2
Precise test of KM(CPV) and SM

Step3
Search/Evidence for New Physics

B decays → QCD/Lattice, New Resonances
Also, excellent τ/charm factory

B-Factories physics milestones



>100 unique CPV results

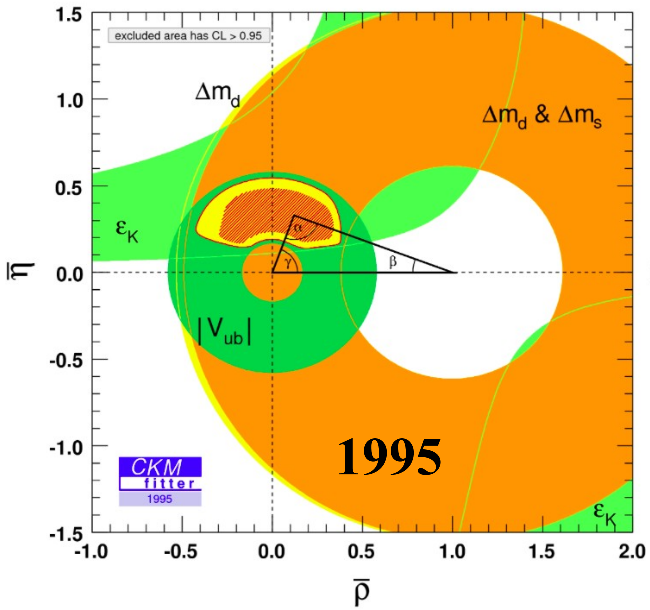
~350 papers published after shutdown, 21 in 2018

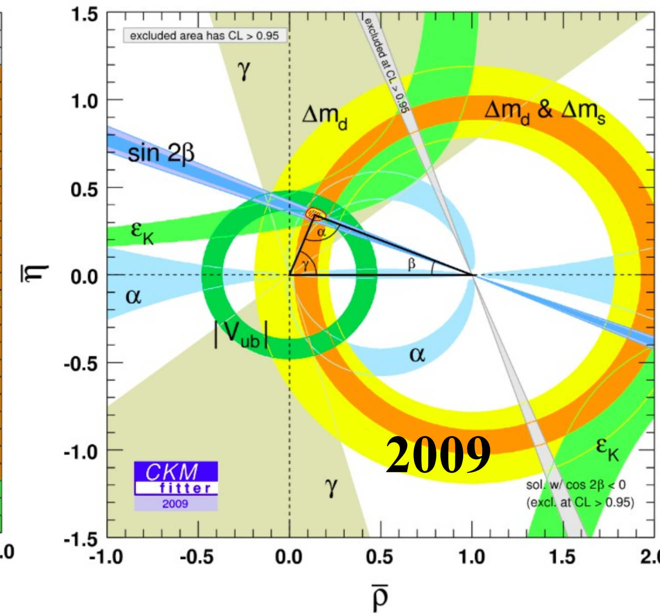
Physics motivation for increased luminosity

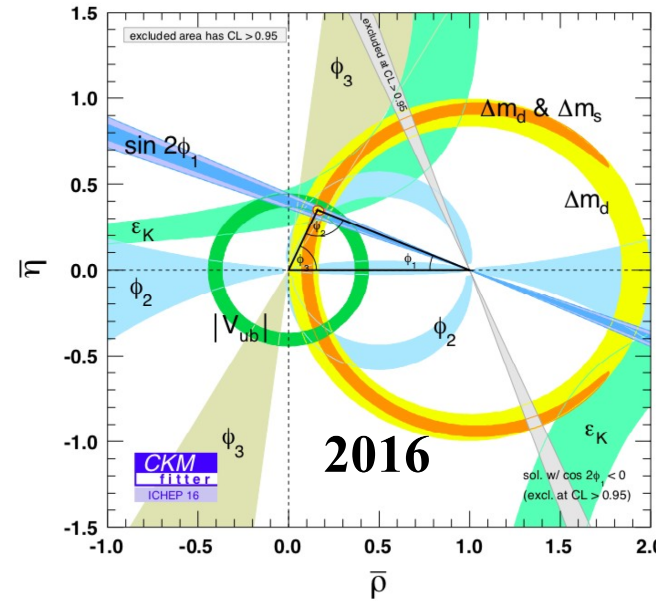
- BABAR and Belle:
  - Established SM flavour-physics picture, particularly the Kobayashi-Maskawa (KM) mechanism of CP violation
  - Discovered exotic (non-)hadrons
  - Provided precision input for lattice,
  - Conducted direct searches for light new physics,
  - ...
- This sets the stage for the physics of Belle II:
  - Stress-testing the SM and sensitively probing new physics via, e.g.,
    - Precision CKM measurements: CP violation, meson mixing, decay rates;
    - Rare processes, e.g., flavour-changing neutral currents; → Tension in $b \to s\ell^+\ell^-$
    - SM-forbidden processes, e.g., lepton-flavour non-universality, Lepton number/flavour violation;
    - Direct searches for light new states.

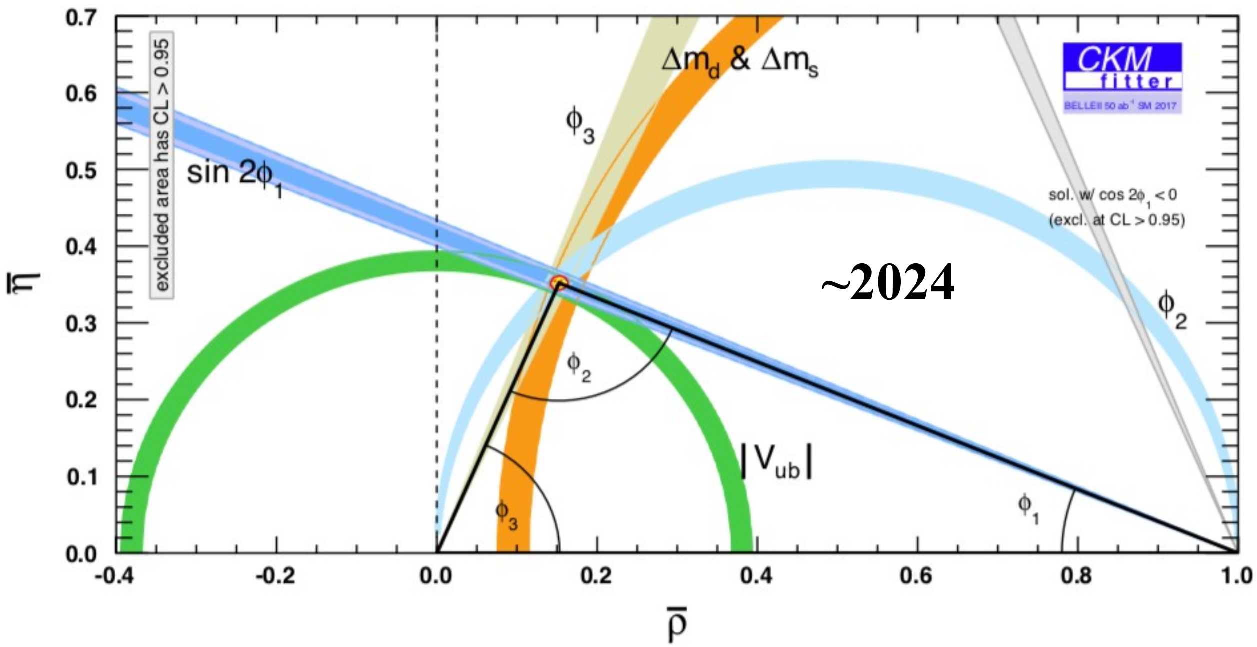
→ $\sim 3.8\sigma$ tension in $\bar{B} \to D^{(*)}\tau^-\bar{\nu}$

Precision of CKM unitarity triangle







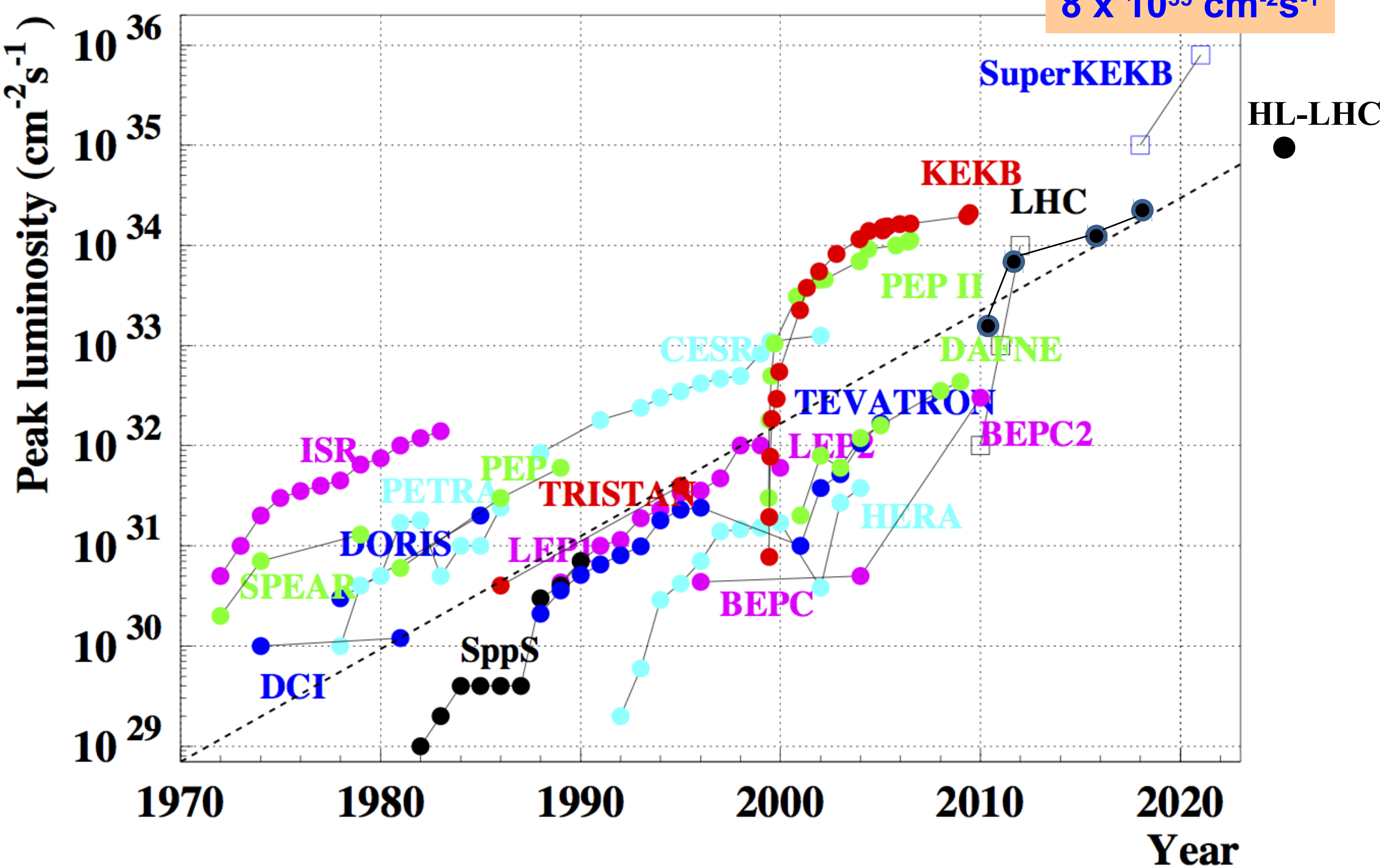


Belle II 50 ab^{-1} projection, all constraints

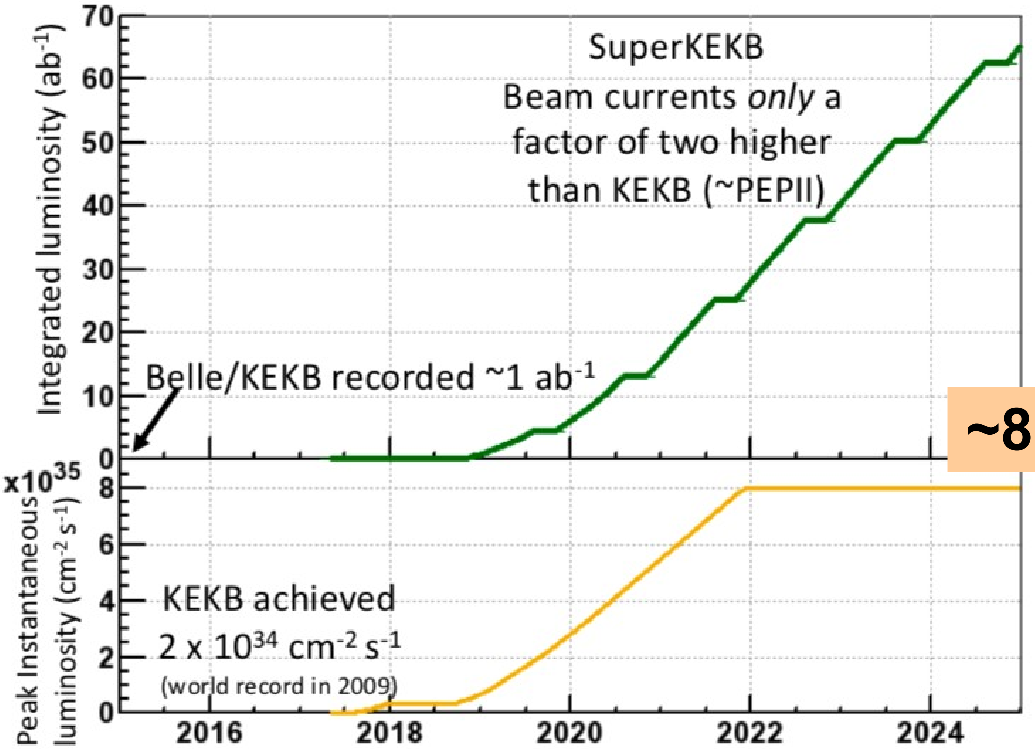
Intensity Frontier: new luminosity record

<u>Increased sensitivity</u>: Belle II data sample will be **50-times** larger than Belle's, by collecting data from the SuperKEKB collider with **40-times** higher luminosity

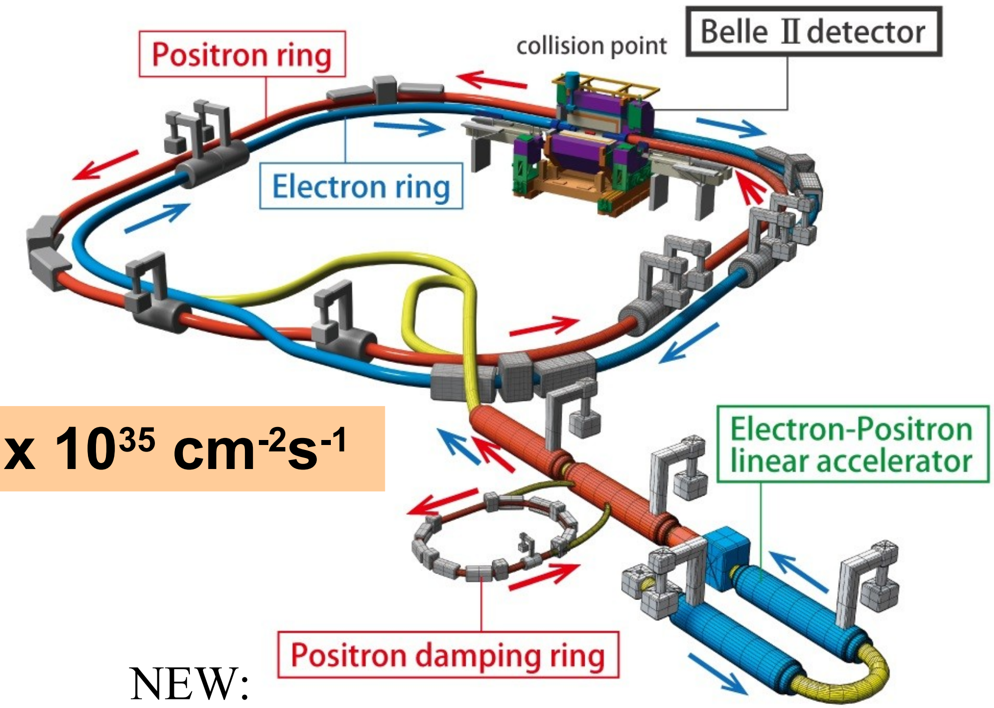
8×10^{35} cm^{-2}s^{-1}



SuperKEKB Collider



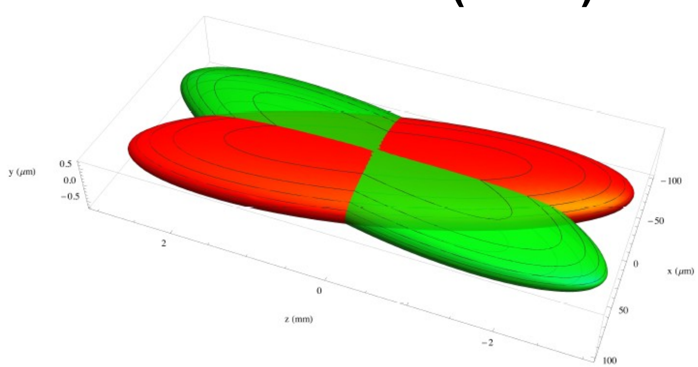
~8 x 10^{35} cm^{-2}s^{-1}



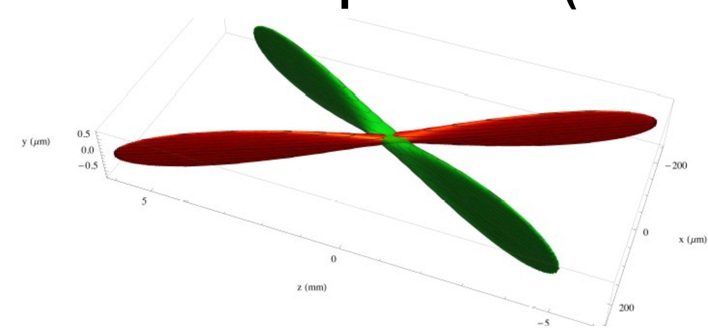
NEW:

- 3-km-long positron ring vacuum chamber.
- Positron damping ring.
- Complex superconducting final focusing.

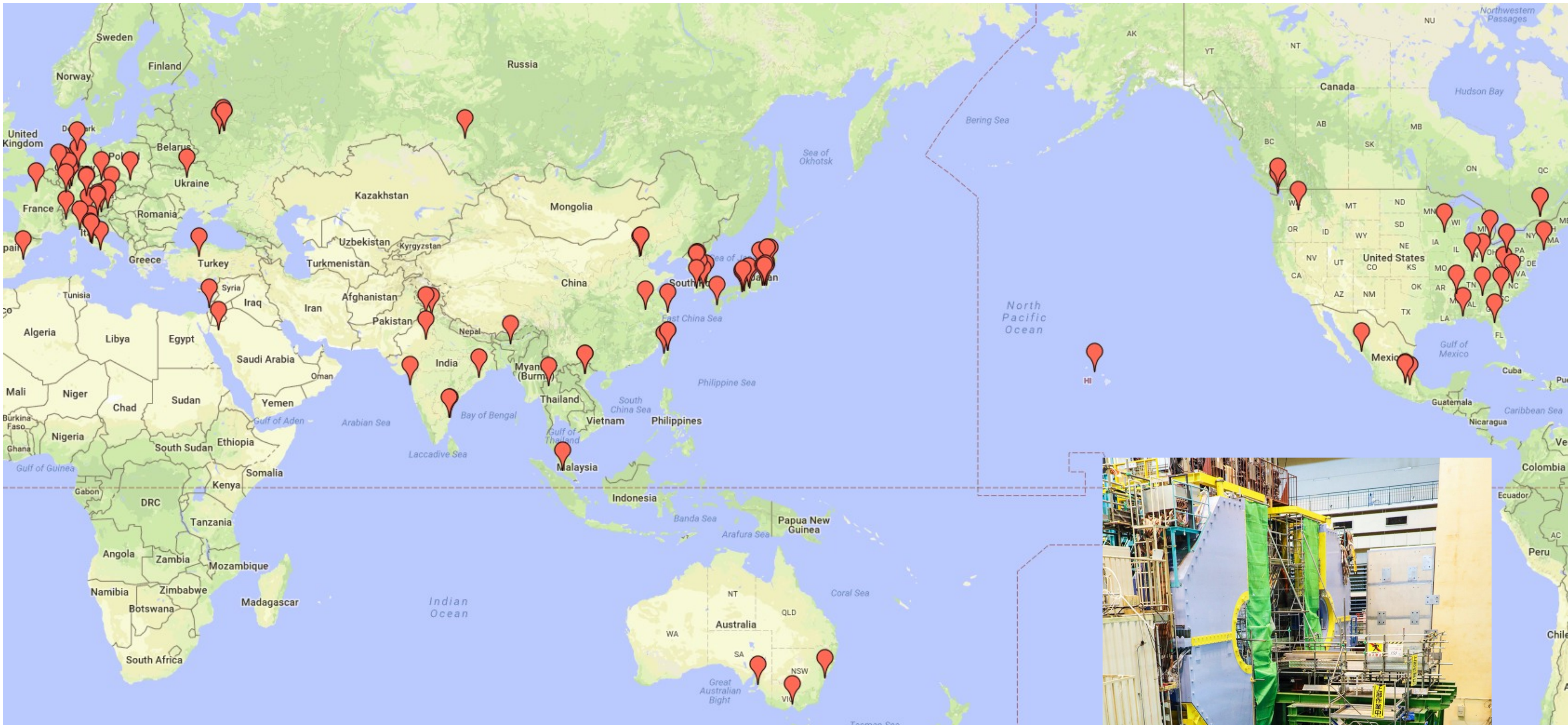
Beams at KEKB (Belle)



Nanobeams at SuperKEKB (Belle II)

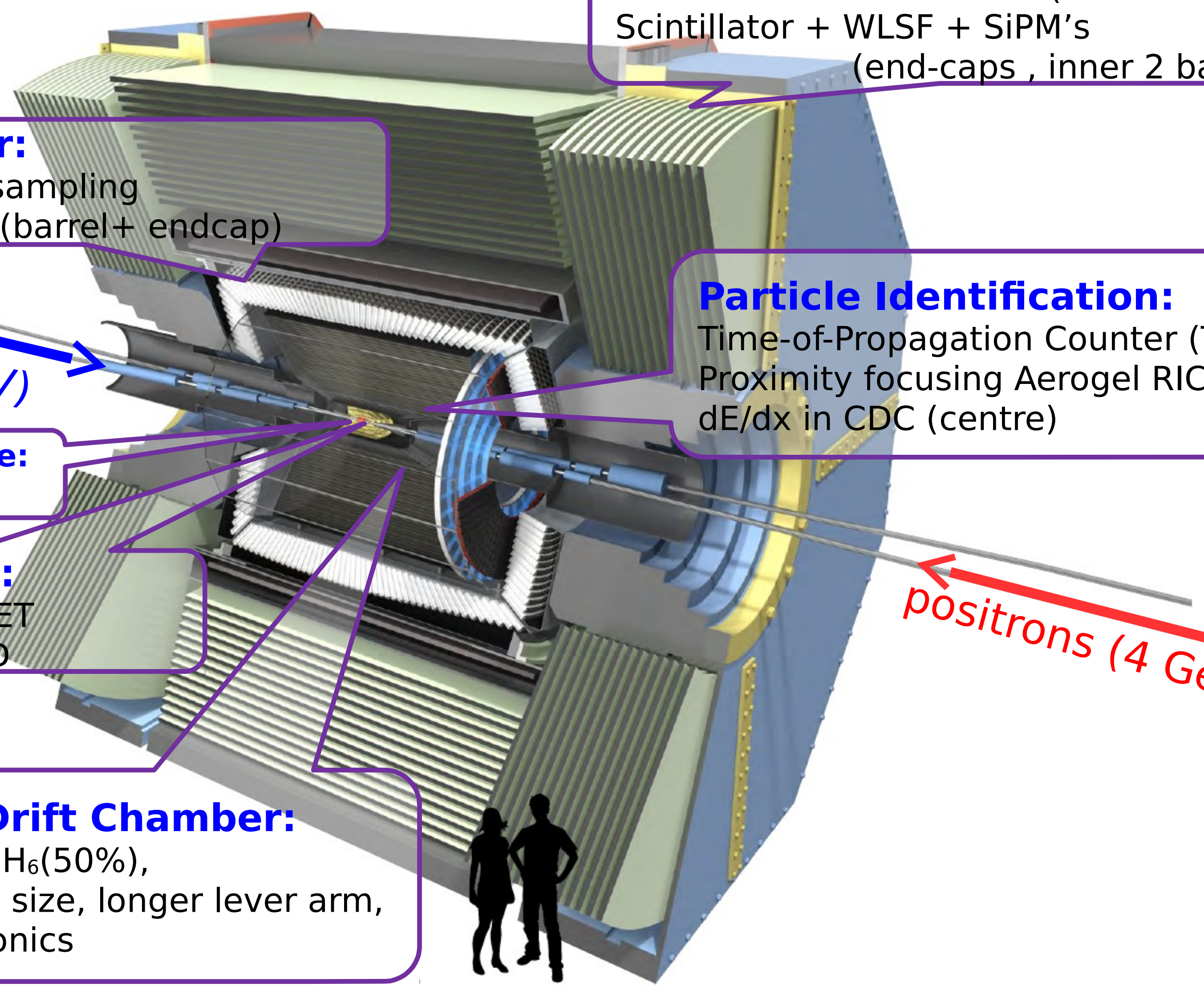


Belle II Collaboration



The Belle II collaboration:
~800 researchers from **25 countries** (**>100 institutions**)
have joined efforts to built and operate the detector,
and explore the physics potential of collected data

Belle II detector



K_L and μ Detector:
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's
(end-caps , inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling
(barrel+ endcap)

Particle Identification:
Time-of-Propagation Counter (TOP) (barrel)
Proximity focusing Aerogel RICH (ARICH) (fwd)
dE/dx in CDC (centre)

Beryllium beam pipe:
2cm diameter

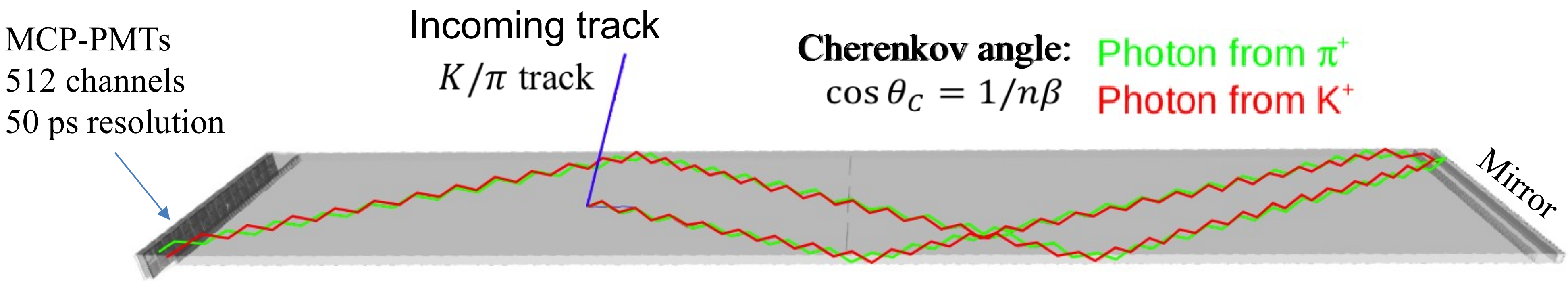
Vertex Detector:
PXD: 2 layers DEPFET
SVD: 4 layers DSSD

Central Drift Chamber:
He(50%):C_2H_6(50%),
smaller cell size, longer lever arm,
fast electronics

Belle II detector highlights

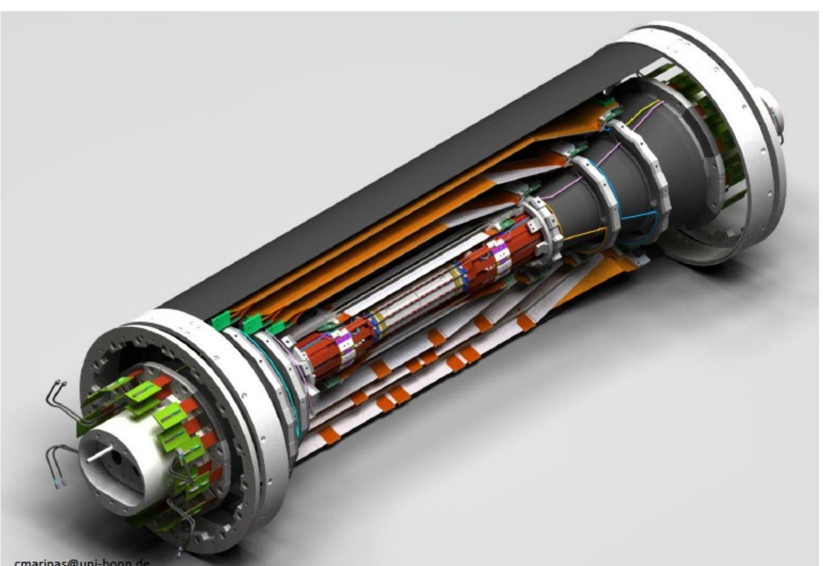
TOP: Barrel Particle Identification (uses Cherenkov radiation)

The paths of Cherenkov photons from a 2 GeV pion and kaon interacting in a TOP quartz bar.



Bar length = 2600 mm, width = 450 mm, thickness = 20 mm

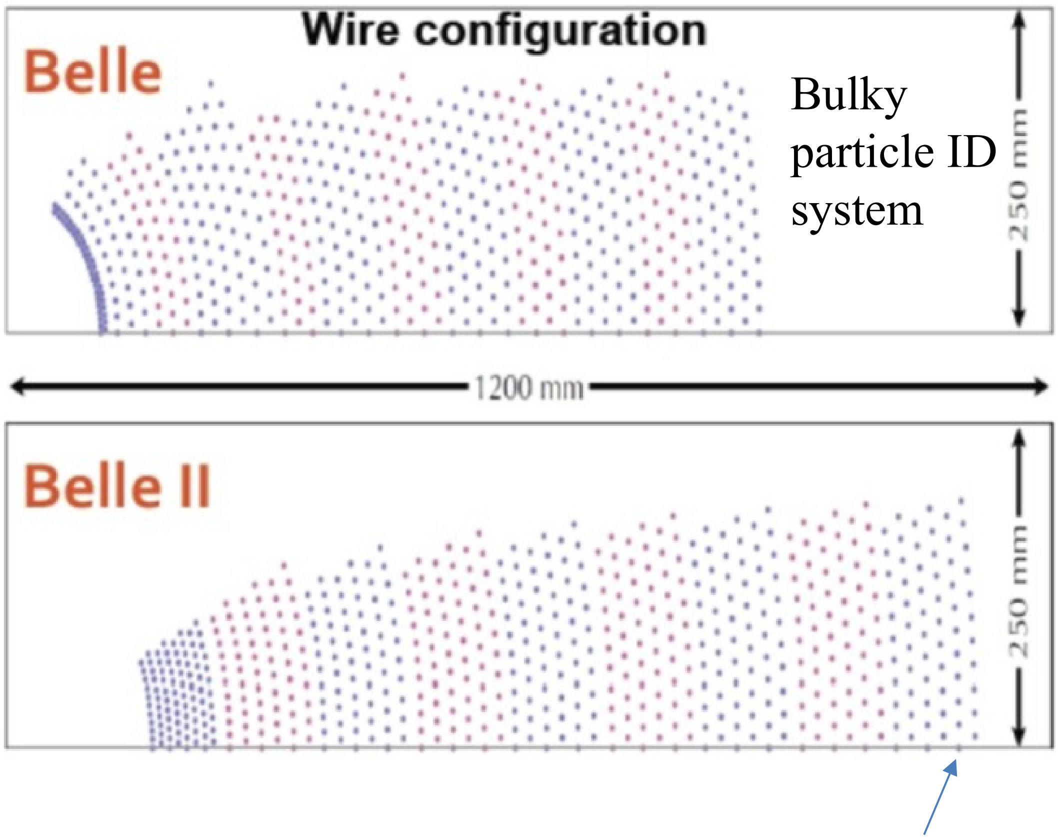
Vertexing/Inner Tracking



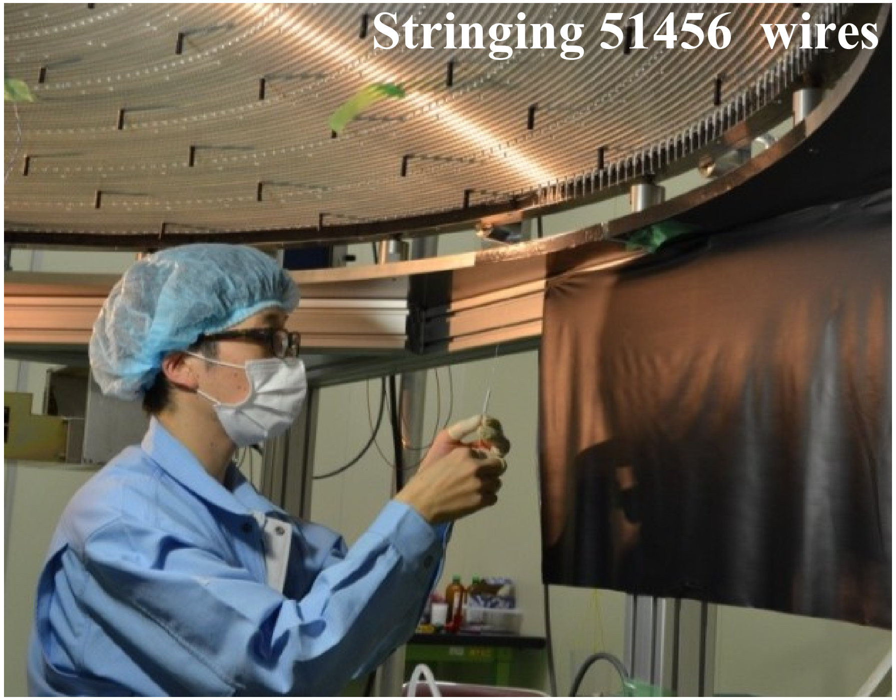
Beampipe r= 10 mm
DEPFET pixels
- Layer 1 r=14 mm
- Layer 2 r= 22 mm

DSSD (double sided silicon detectors)
- Layer 3 r=38 mm
- Layer 4 r=80 mm
- Layer 5 r=115 mm
- Layer 6 r=140 mm

Belle II detector highlights



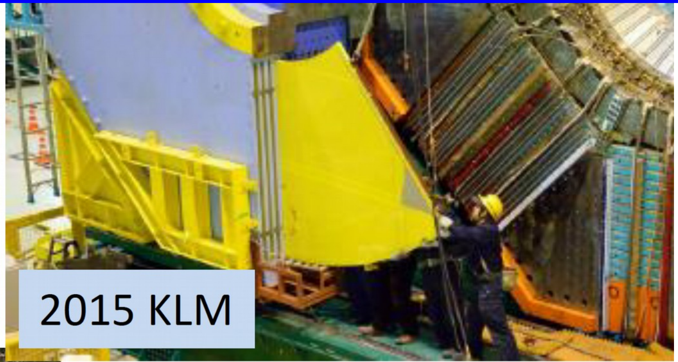
Note:
Outer radius almost ~20% larger than at BABAR/Belle:
Improved momentum resolution



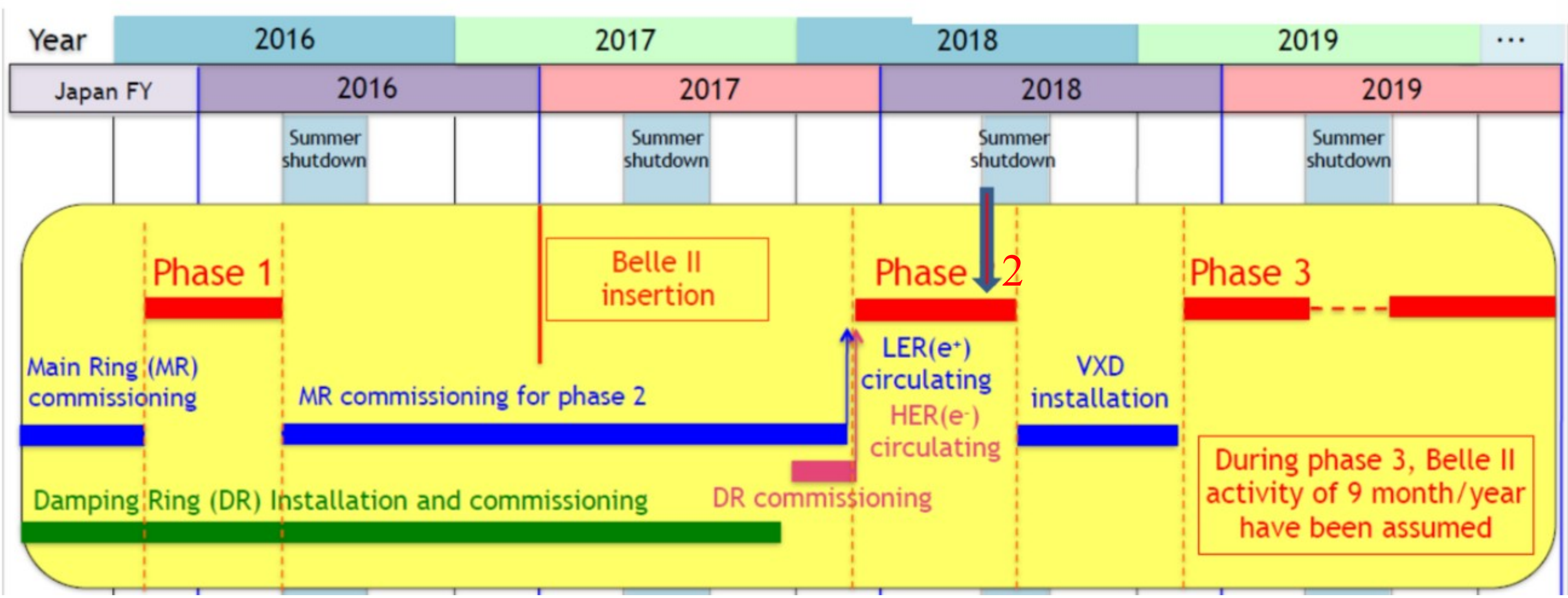
	Belle	Belle II
Innermost sense wire	r=88mm	r=168mm
Outermost sense wire	r=863mm	r=1111.4mm
Number of layers	50	56
Total sense wires	8400	14336
Gas	He:C_2H_6	He:C_2H_6
Sense wire	W(Φ30μm)	W(Φ30μm)
Field wire	Al(Φ120μm)	Al(Φ120μm)

Belle II sub-detector installation

2015 → now (2018)



Startup of SuperKEKB/Belle II



First collisions, 26 April, 2018

Phase 2 goals:

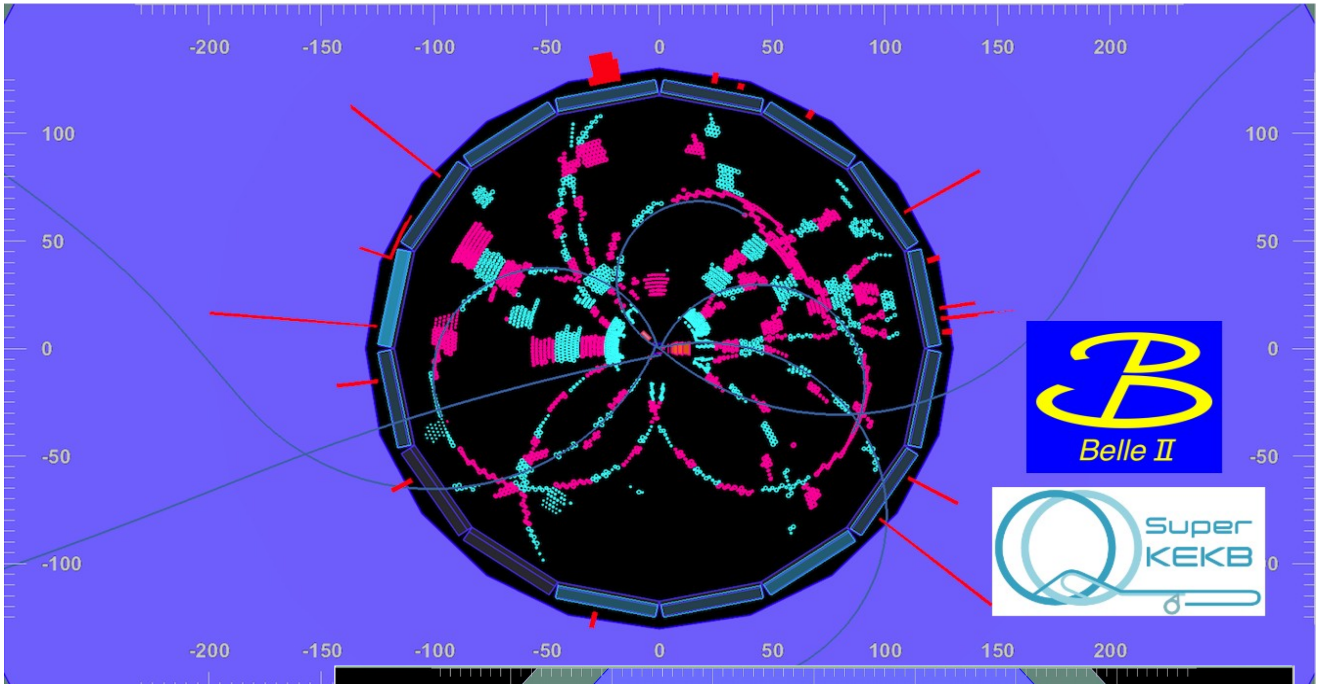
- Progress toward high luminosity
- Progress toward stable operation

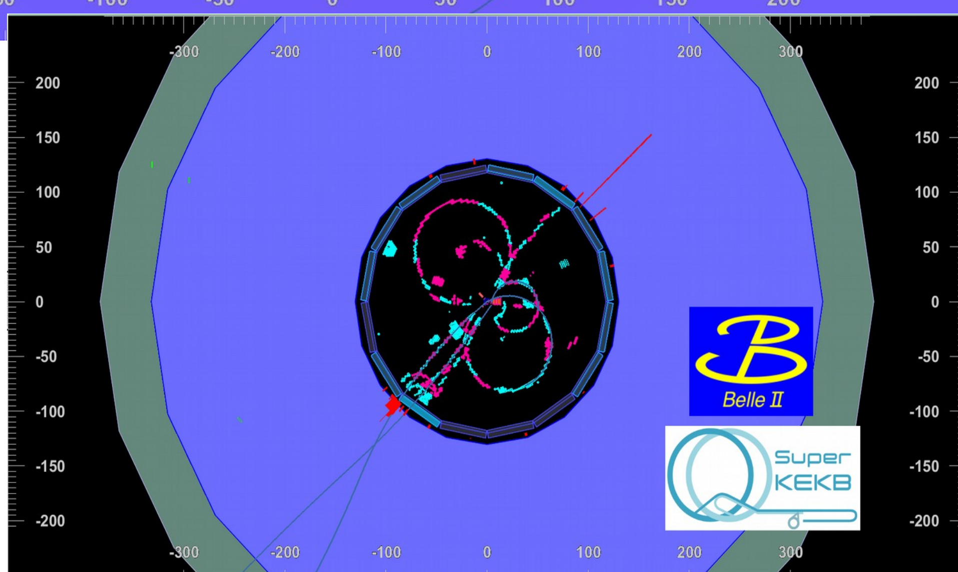
Achievements:

- $L = 5.5{\times}10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Collected $\sim 0.5\ \mathrm{fb}^{-1}$ for commissioning & calibration

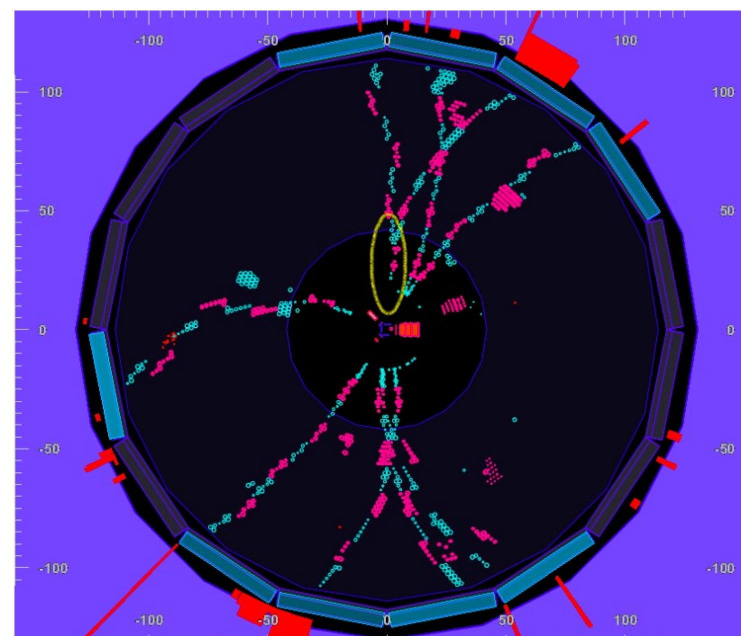
Startup: First collision events

A $B\bar{B}$-like event





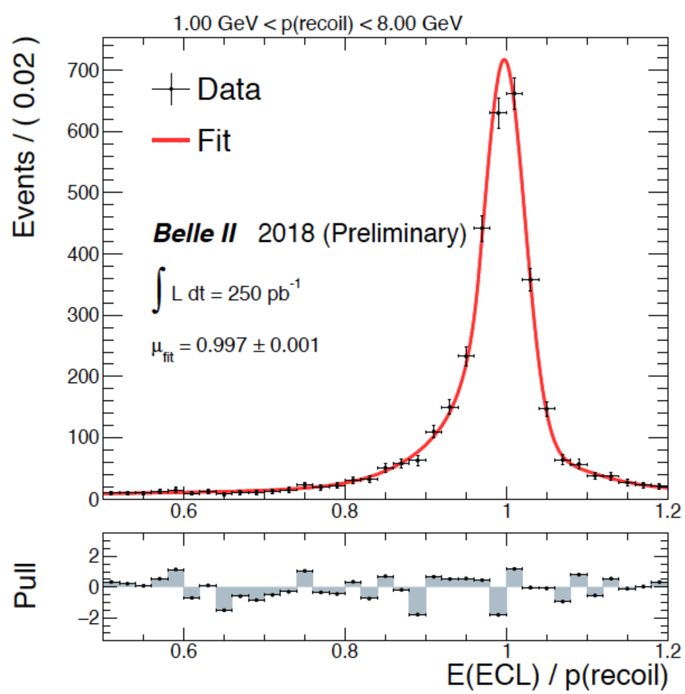
A light-quark $q\bar{q}$-like events



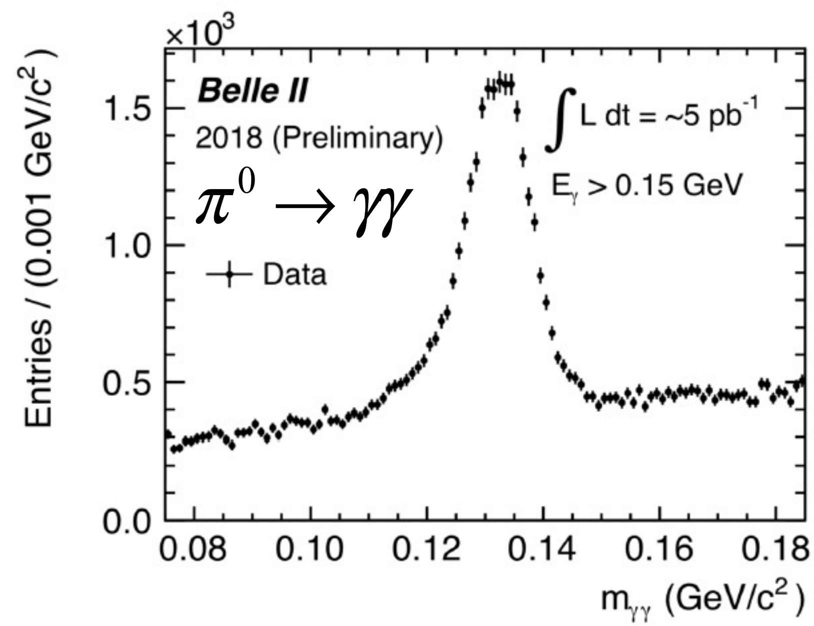
Proof of principle: signals with photons

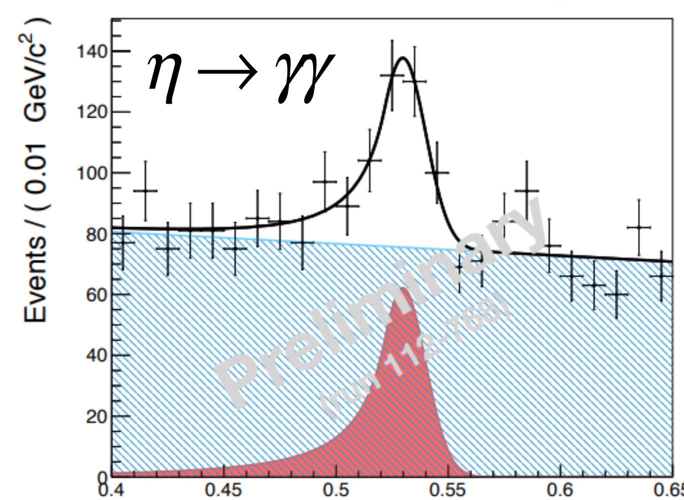
Most of the detector sub-systems are working well.

$e^+e^- \to \mu^+\mu^-\gamma$



Single Photon Lines





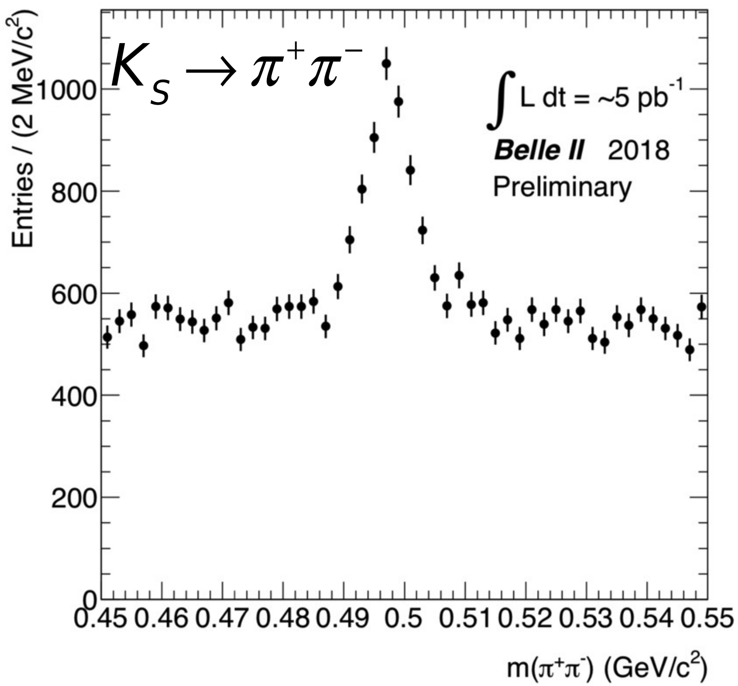
Ready for the dark sector:

$e^+e^- \to \gamma X$

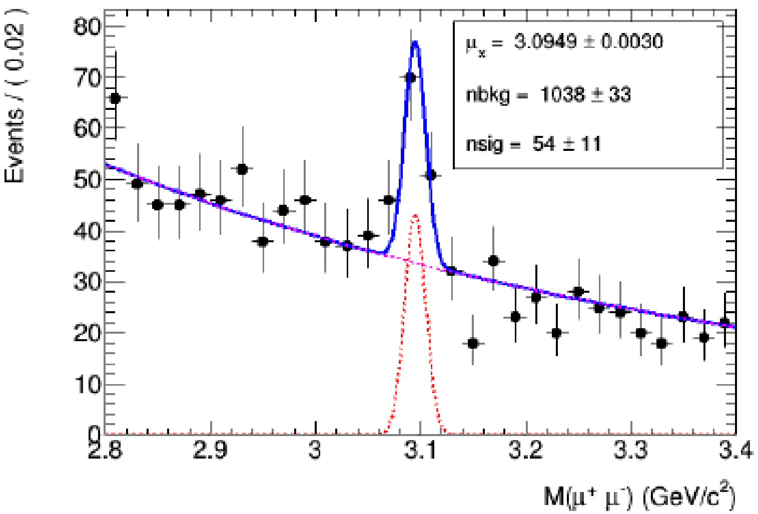
$e^+e^- \to \gamma ALPS \to \gamma(\gamma\gamma)$

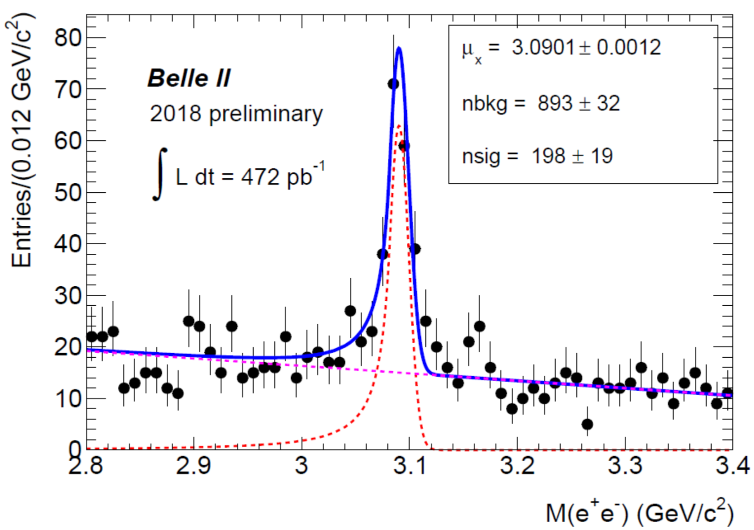
Proof of principle: signals with charged tracks

Most of the detector sub-systems are working well.



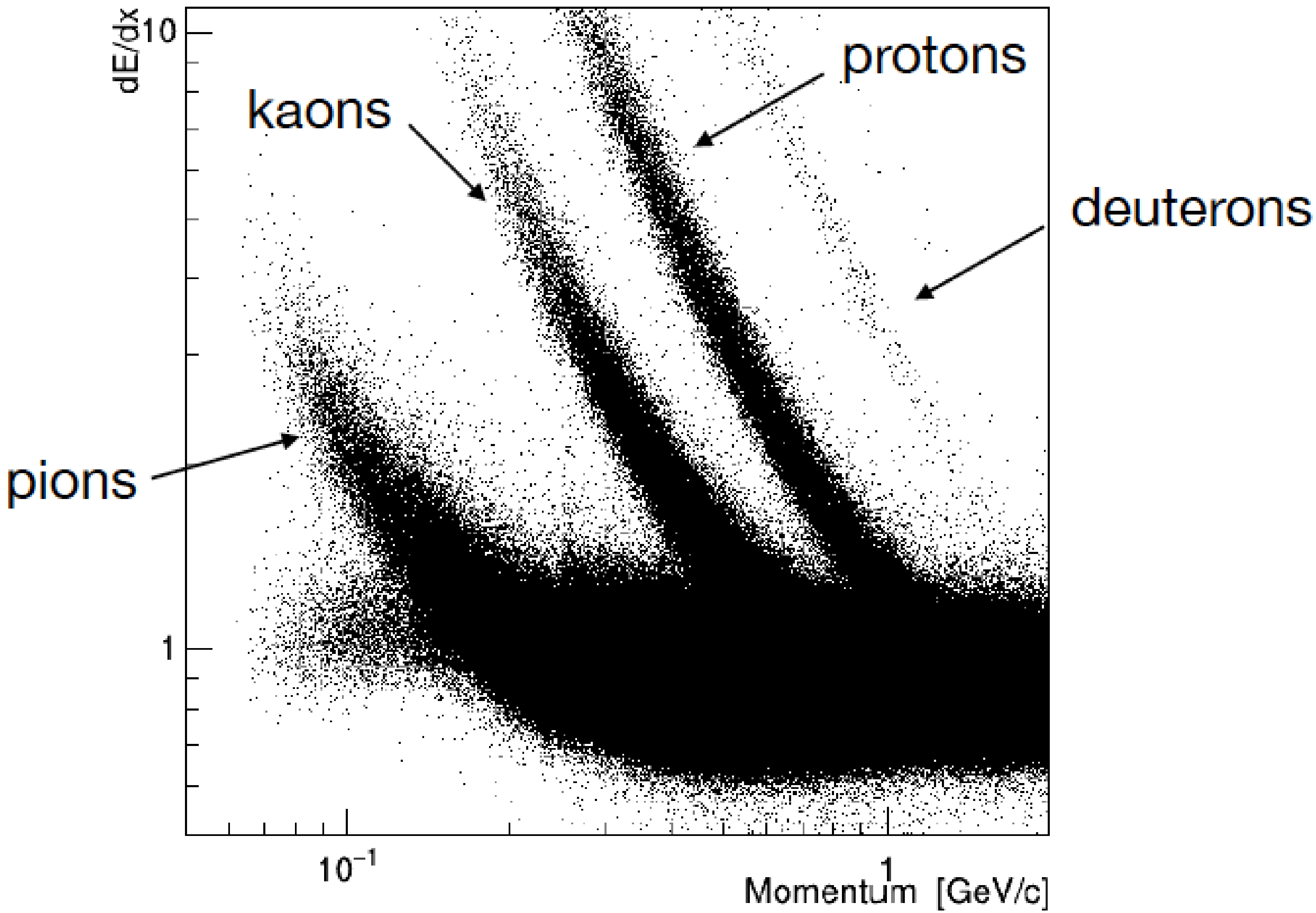
$J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$





Proof of principle: dE/dx in CDC

Performance of CDC **dE/dx particle identification** with early calibrations in the hadronic event sample.



Extra cuts:

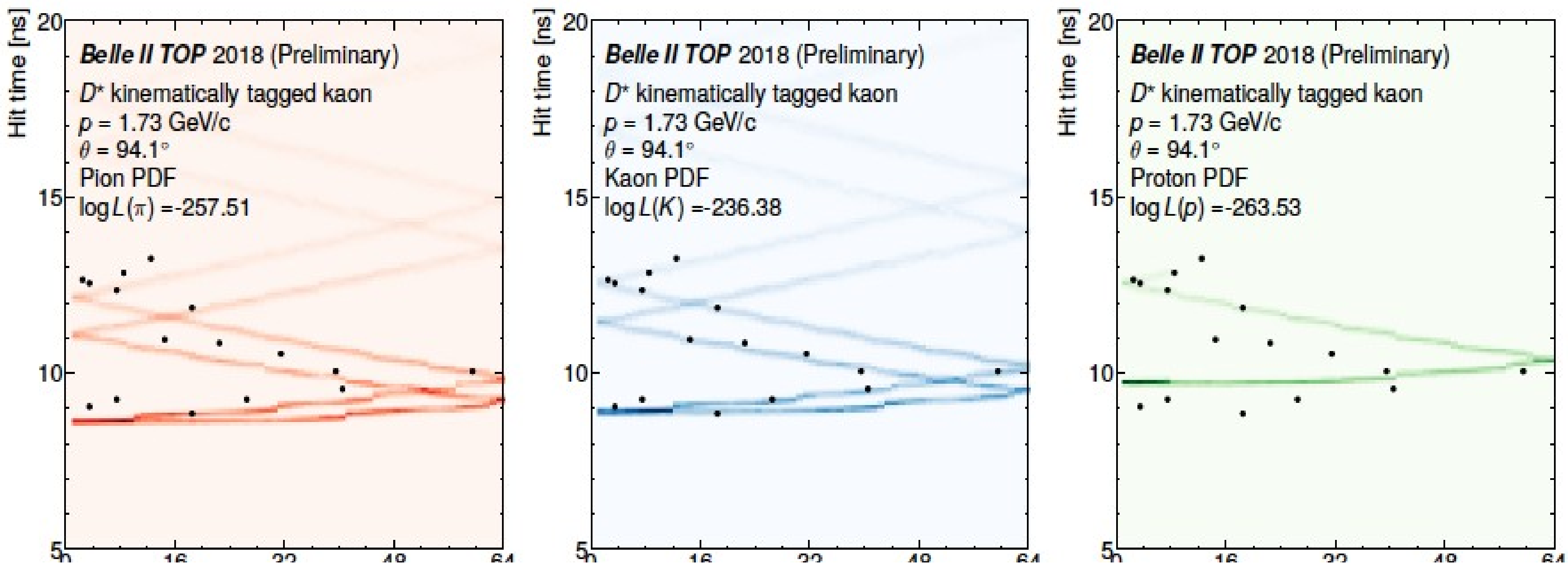
- |d0| < 1
- |dz| < 3
- # layers hit > 20

Proof of principle: TOP Particle Identification

$$D^{*+} \rightarrow D^0 \pi_s^+ ; D^0 \rightarrow K^- \pi^+$$

Kaon (pion) track is identified based on the the charge correlation with the slow pion.

Kinematically identified kaon from a D^{*+} in the TOP;
Cherenkov x vs t pattern (mapping of the Cherenkov ring)

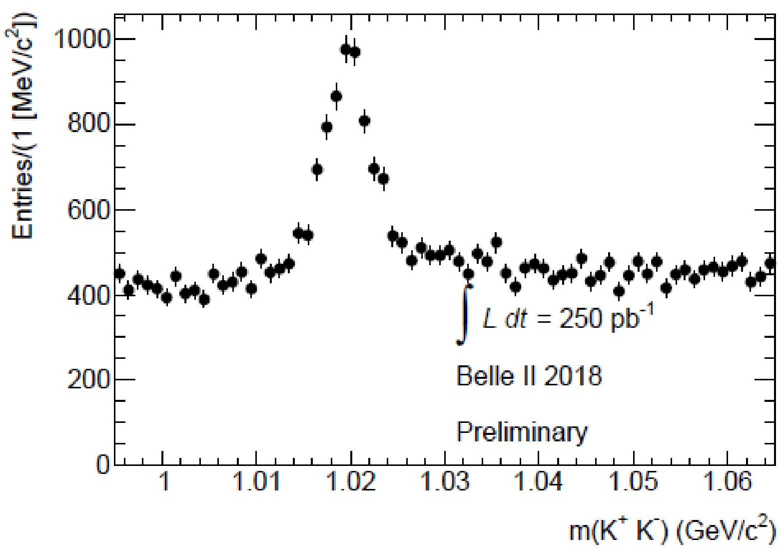


Clearly track is more consistent with a hypothesis for being a kaon than a pion or proton.

Proof of principle: TOP Particle Identification

$\phi \to K^- K^+$ inclusive

An example of TOP PID effect on $\varphi \to K^+ K^-$ reconstruction (with early calibration and alignment).



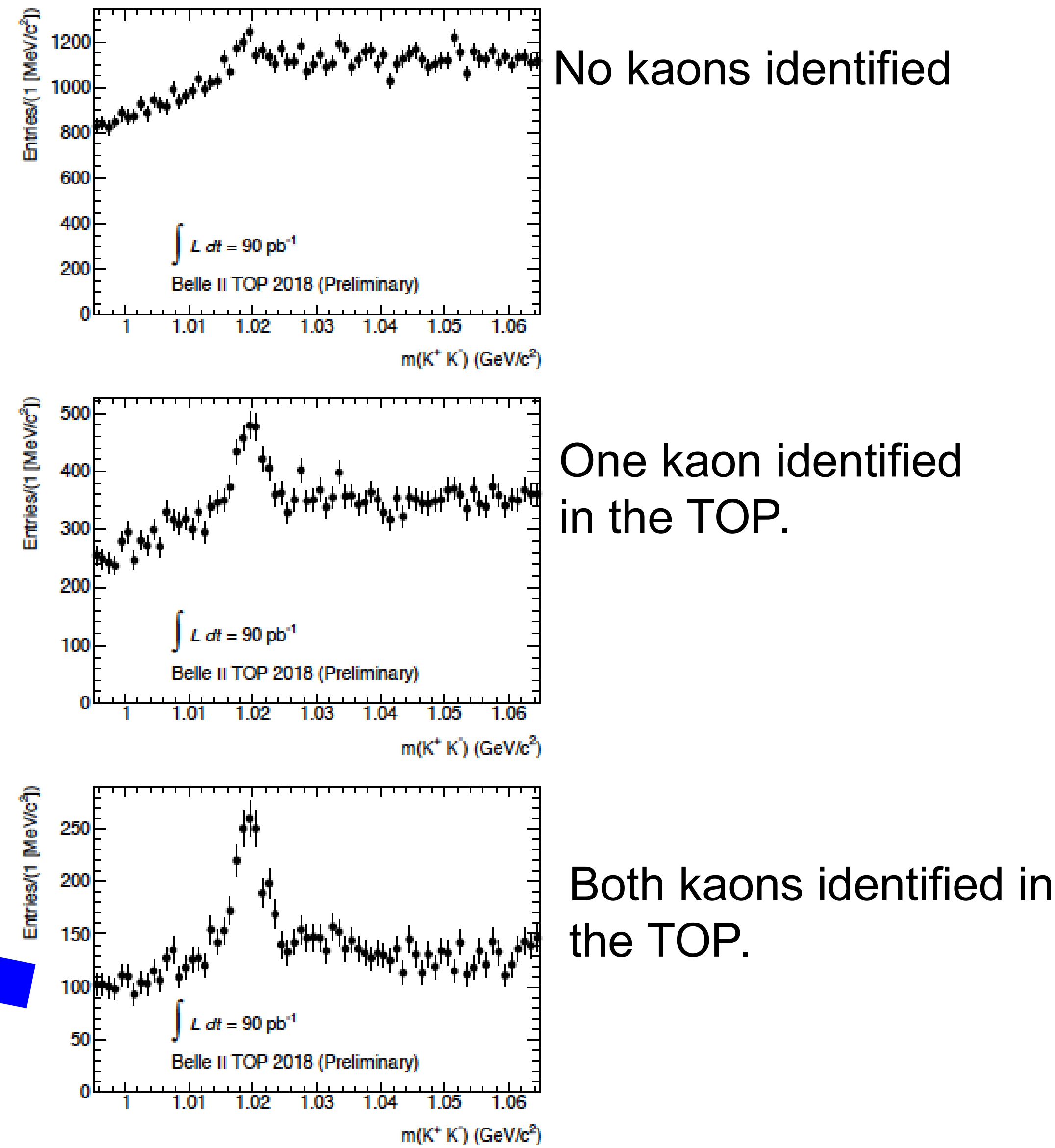


FIG. 7: $m(K^+K^-)$ distributions for runs with TOP calibration (run number up to 2531). Tracks are required to be in the TOP acceptance. Top: No PID requirement. Middle: $LL(K)^{TOP} > LL(\pi)^{TOP}$ for one of the tracks. Bottom: $LL(K)^{TOP} > LL(\pi)^{TOP}$ for both tracks.

Proof of principle: TOP Particle Identification

Rediscovery of $D_s^+ \rightarrow \varphi\pi^+$, with $\varphi \rightarrow K^+ K^-$

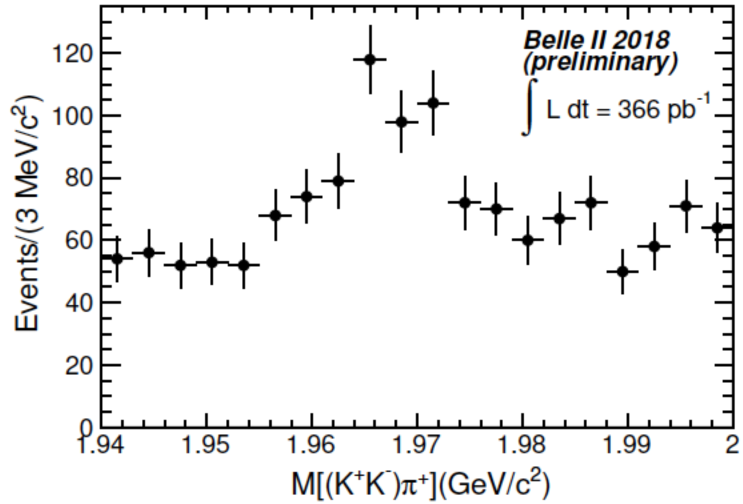


FIG. 1: This figure shows $M[(K^+K^-)\pi^+]$ distribution, which was produced using phase-II 366 pb^{-1} hadron skim data. No PID criteria are applied to any of the charged tracks ($K^\pm\pi^+$). Selection criteria and further details are described in the internal note BELLE2-NOTE-PH-2018-026.

No PID

An example of TOP PID effect on D_s decay reconstruction (with early calibration and alignment).

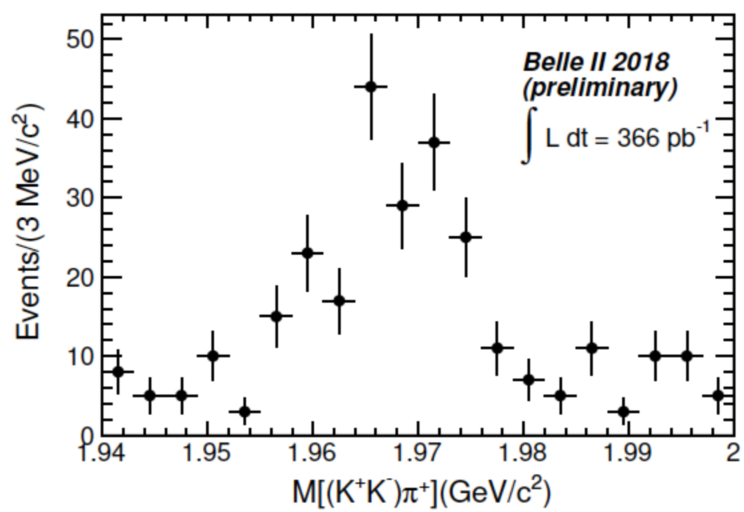
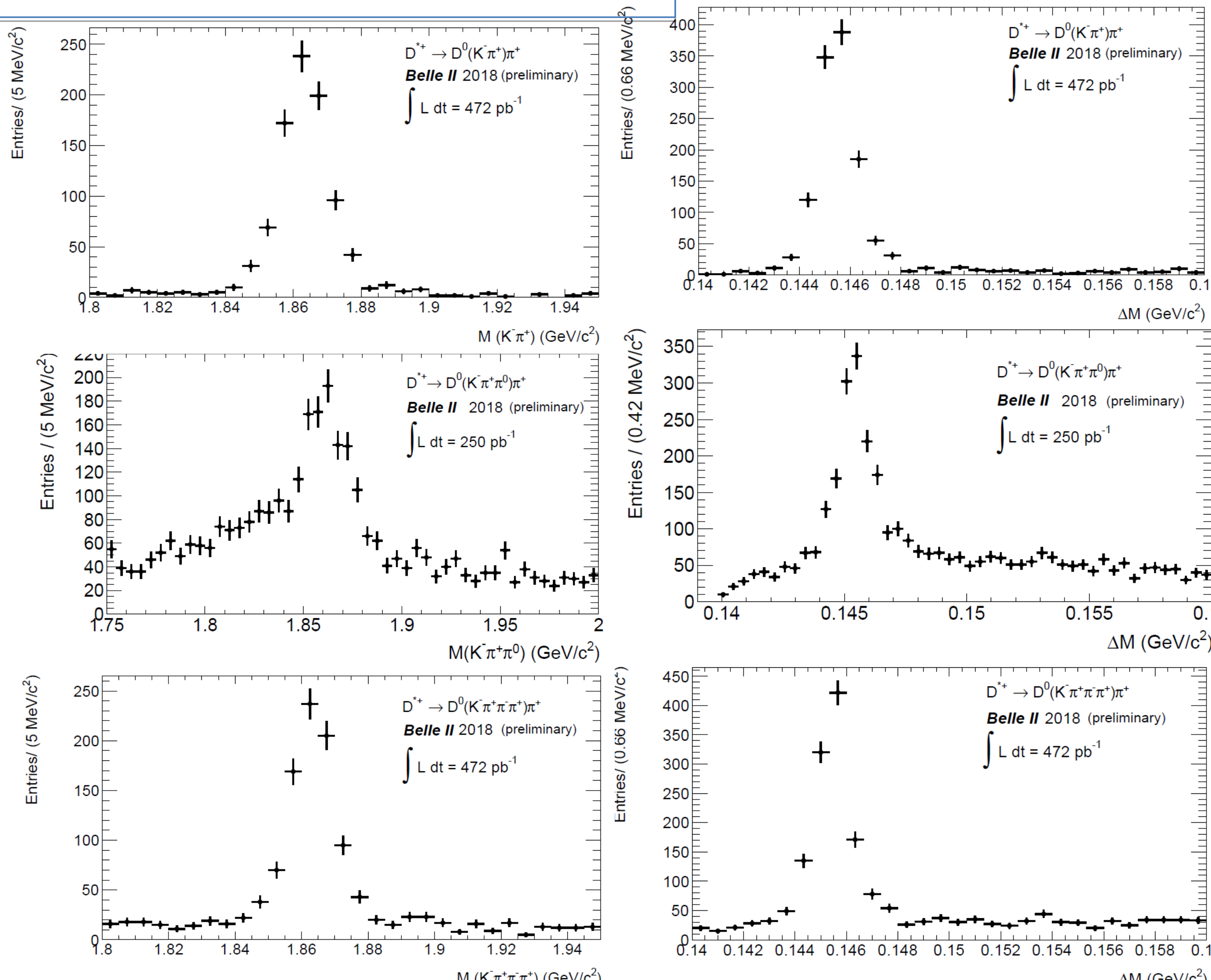


FIG. 2: This figure shows $M[(K^+K^-)\pi^+]$ distribution, which was produced using phase-II 366 pb^{-1} hadron skim data. Combined PID criteria, Prob(K:π) >0.5 for $K^\pm$ tracks and Prob(π:K) >0.5 for π^+ tracks are applied. Selection criteria and further details are described in the internal note BELLE2-NOTE-PH-2018-026.

Two identified charged kaons.

Proof of principle: Charm reconstruction

Charm in $e^+e^- \to c\bar{c}$



$D^{*+} \to D^0\pi^+,\quad D^0 \to K^-\pi^+$

$D^{*+} \to D^0\pi^+,\quad D^0 \to K^-\pi^+\pi^0$

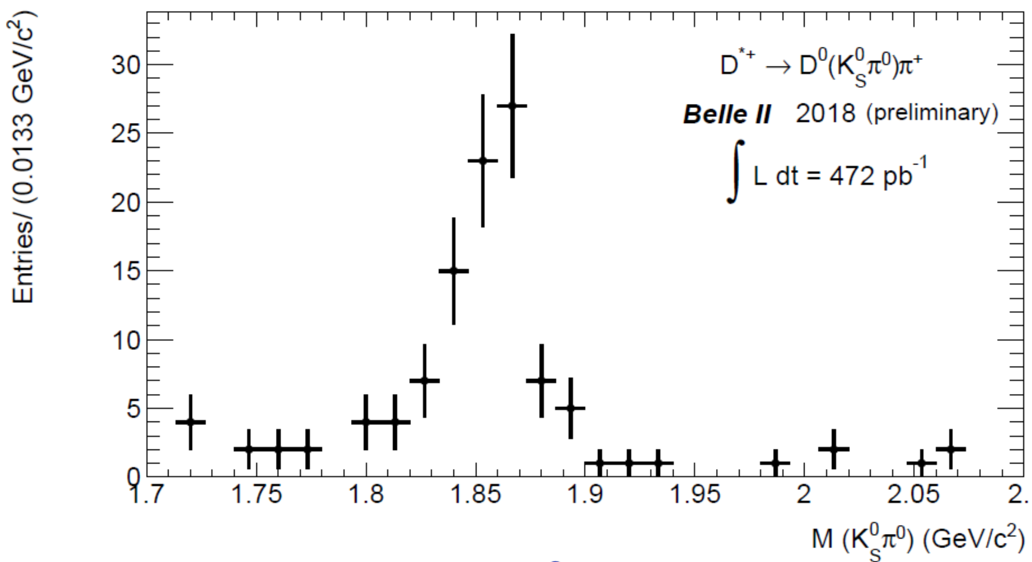
$D^{*+} \to D^0\pi^+,\quad D^0 \to K^-\pi^+\pi^-\pi^+$

Belle II is ready for charm physics and for charm as a building block of B physics

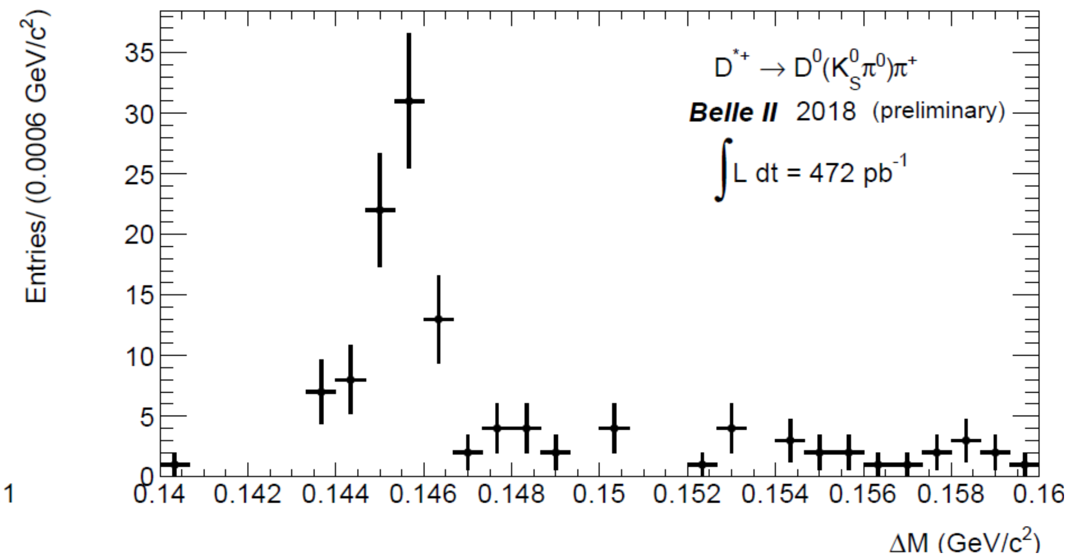
$M(D^0 \text{ candidate})$ $\qquad \Delta M = M(D^0 \text{ candidate}) - M(D^0 \text{ candidate})$

Finding CP Eigenstates

CP Eigenstate: $D^0 \rightarrow K_S\pi^0$



$M(D^0 \text{ candidate})$

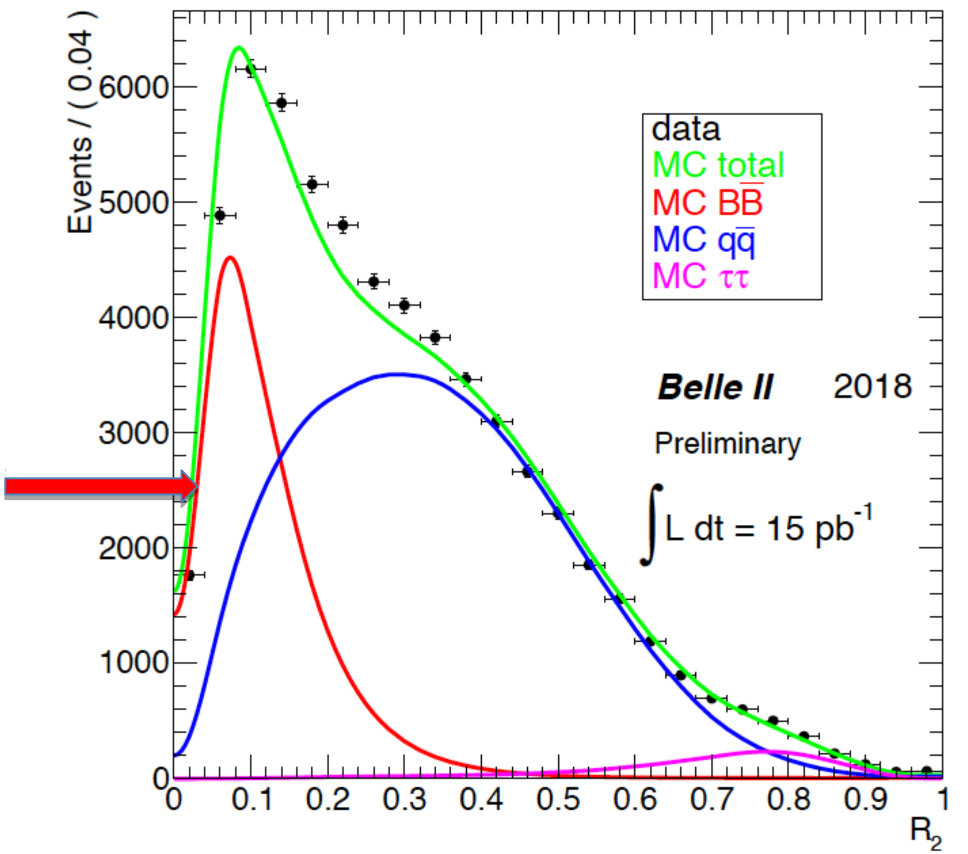


$\Delta M = M(D^0 \text{ candidate}) - M(D^0 \text{ candidate})$

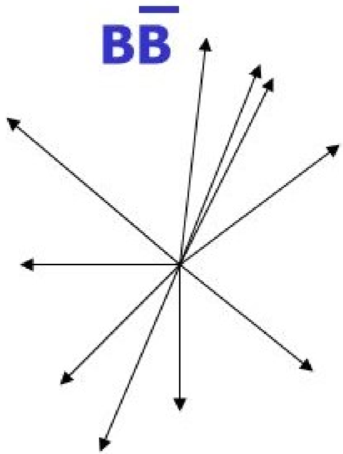
This is a proof of a very important capability of the Belle II detector.

Finding $B\bar{B}$ pairs

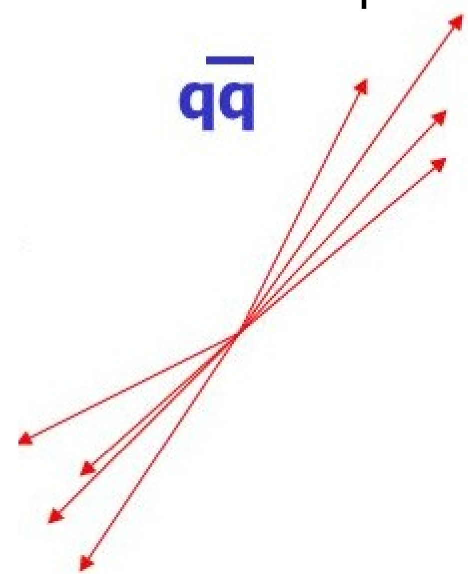
The **Event Topology** indicates, if we are seeing B's or not:



Spherical R_2 Jet-like



B pairs are produced at rest in the CMS with no extra particles

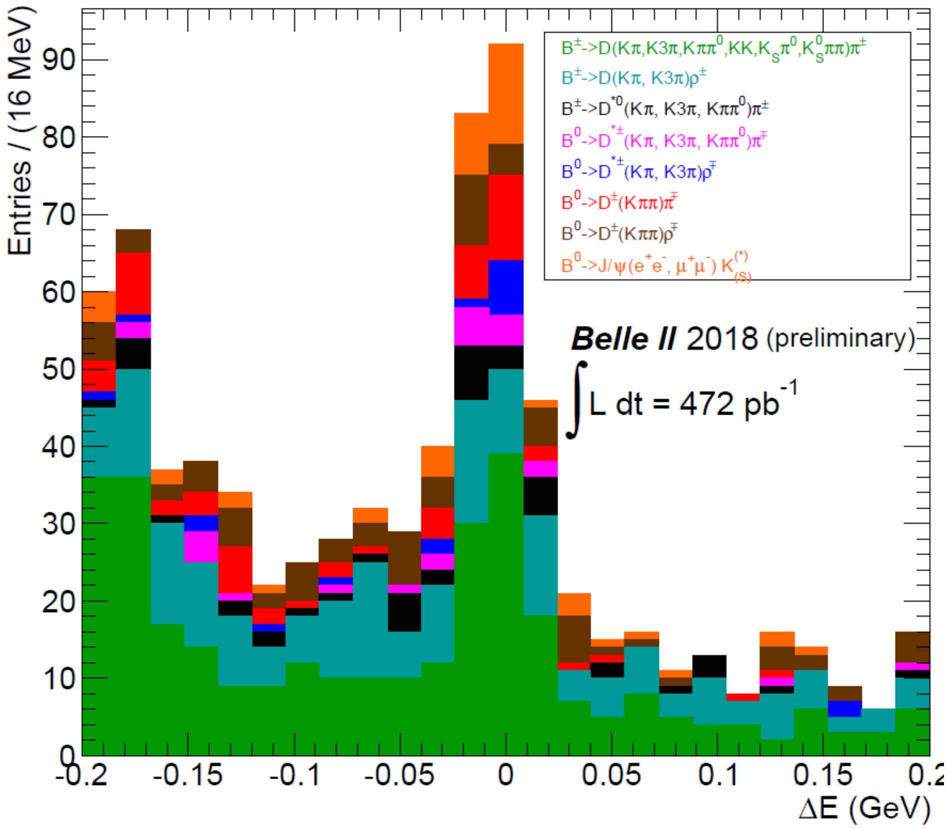


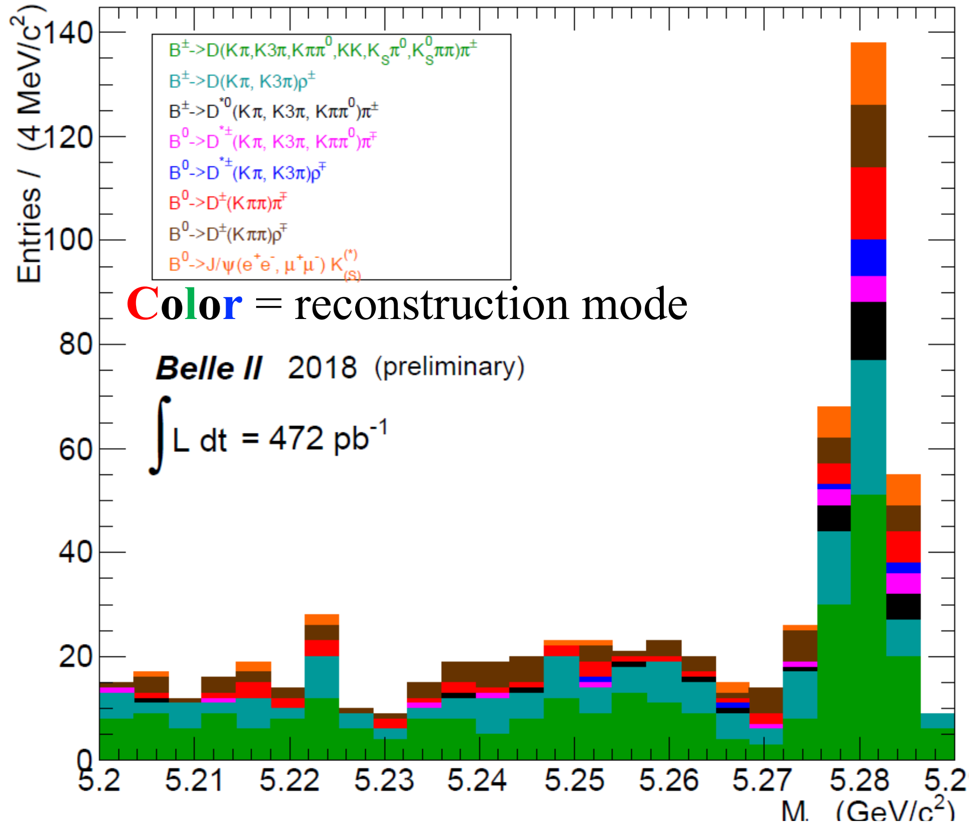
Running on the Y(4S) resonance and recording B anti-B pairs with ~99% efficiency.

Finally: Hadronic B decays reconstructed ...

Belle II

Re-discovery of B mesons!





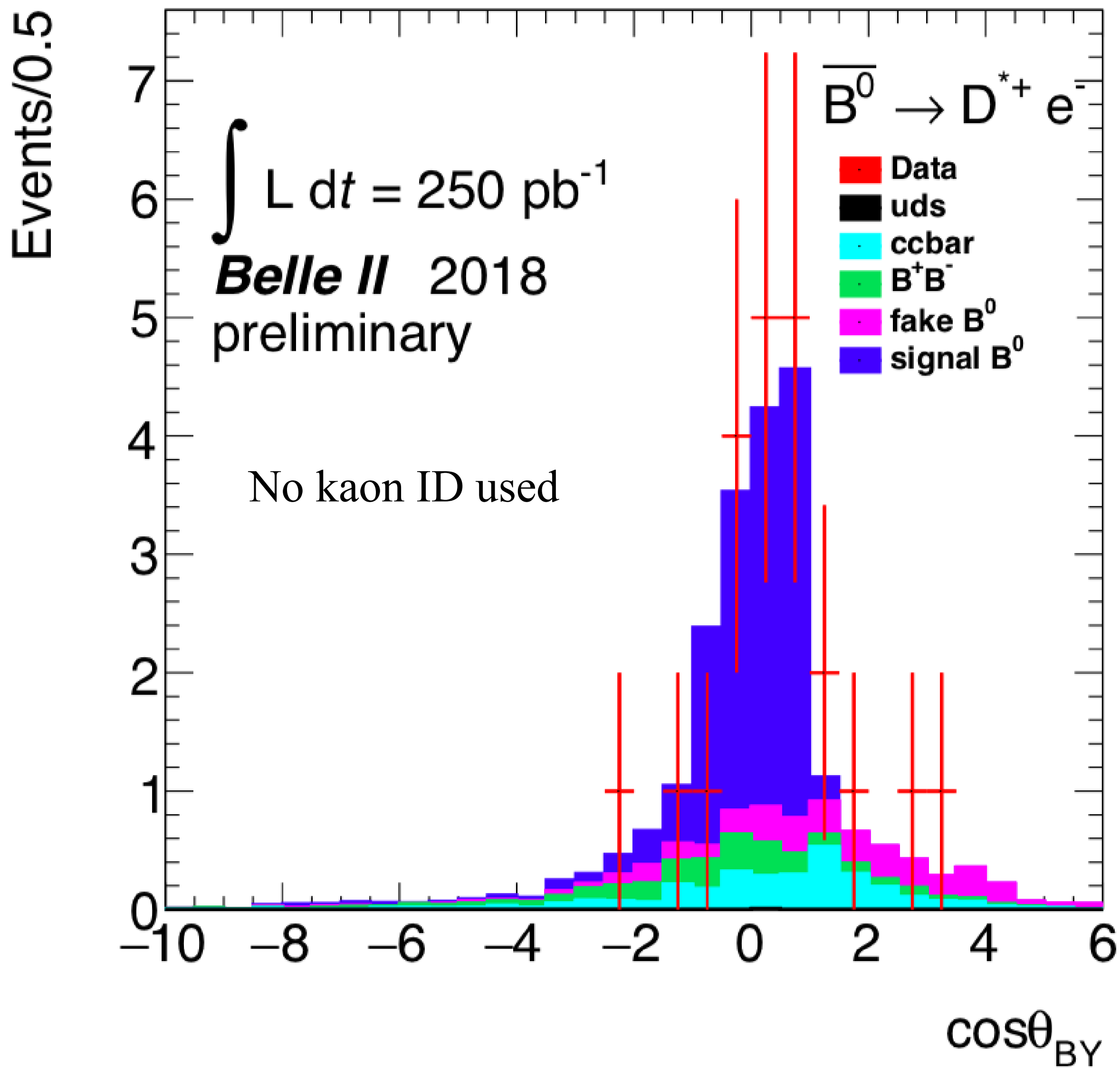
1983:
CLEO expt.

VOLUME 50, NUMBER 12 — PHYSICAL REVIEW LETTERS — 21 MARCH 1983

Observation of Exclusive Decay Modes of *b*-Flavored Mesons $40.7\ pb^{-1}$

B-meson decays to final states consisting of a D^0 or $D^{*\pm}$ and one or two charged pions have been observed. The charged-B mass is $5270.8 \pm 2.3 \pm 2.0$ MeV and the neutral-B mass is $5274.2 \pm 1.9 \pm 2.0$ MeV.

… and semileptonic B decays



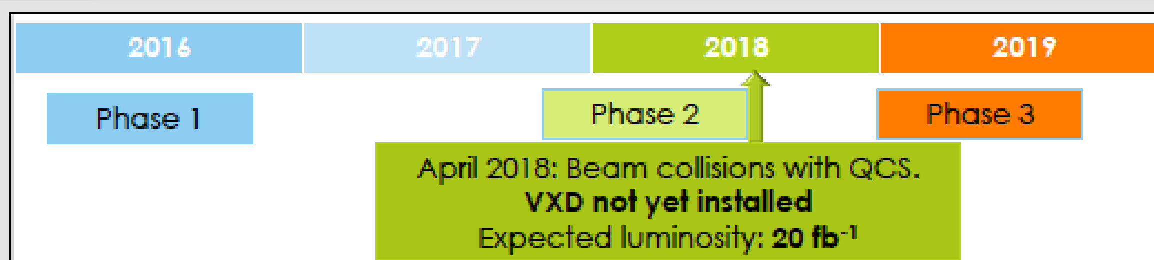
A background and control sample for $\bar{B} \to D^{(*)}\tau^-\bar{\nu}$

Comparison with other experiments

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
		Run III						Run IV					Run V	
LS2						LS3					LS4			
LHCb 40 MHz UPGRADE I		$L = 2 \times 10^{33}$			**LHCb** Consolidate: Upgr Ib			$L = 2 \times 10^{33}$ $50\ fb^{-1}$			**LHCb** UPGRADE II		$L = 1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$	
ATLAS Phase I Upgr		$L = 2 \times 10^{34}$			**ATLAS** Phase II UPGRADE			**HL-LHC** $L = 5 \times 10^{34}$			**ATLAS**		**HL-LHC** $L = 5 \times 10^{34}$	
CMS Phase I Upgr		$300\ fb^{-1}$			**CMS** Phase II UPGRADE						**CMS**		$3000\ fb^{-1}$	
Belle II	$5\ ab^{-1}$		$L = 8 \times 10^{35}$		$50\ ab^{-1}$									

LHC schedule: Frederick Bordry, Jun 2015

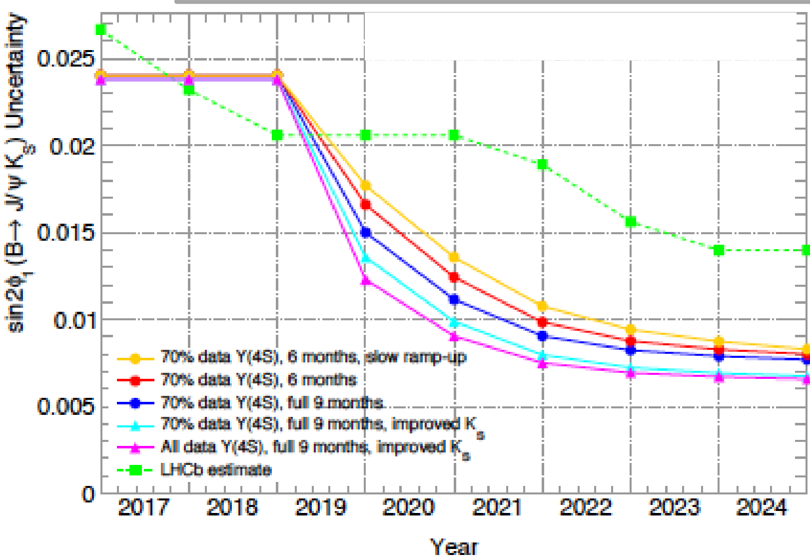
- Belle II
  - $L = 5 \times 10^{33}\ cm^{-2}s^{-1}$ achieved!
  - Physics with VXD in 2019

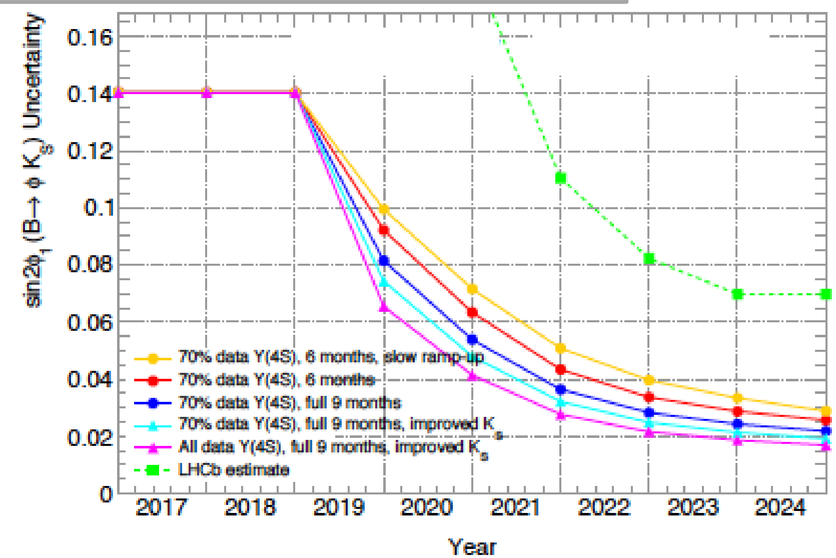


R. Cheaib, Moriond, 12 Mar 2018, arXiv:1802.01366

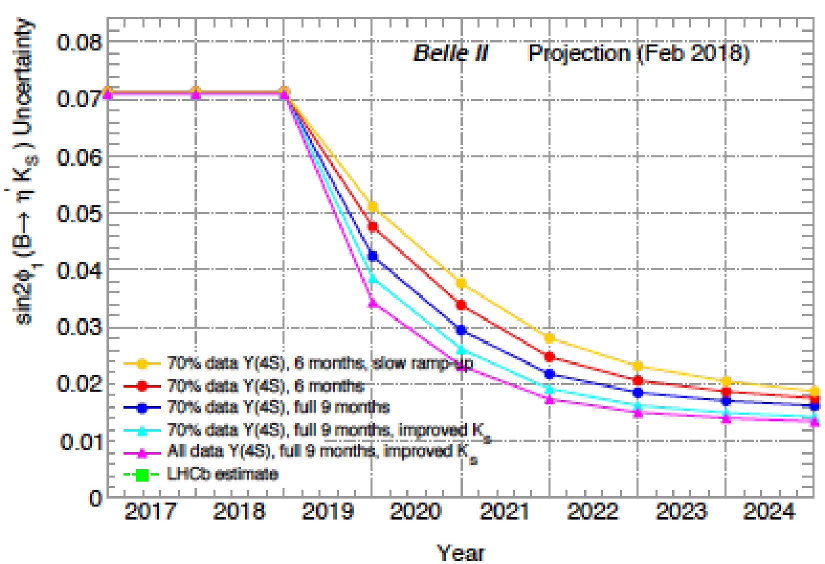
Physics complementarity and competition

Few examples of comparisons with the LHCb





Belle II Projections (February 2018)



Comparison is based on publicly available LHCb projections.

Summary and Conclusions

- There has been highly successful program of machines with increased luminosity since the 1980s.
- The SuperKEKB colider and Belle II experiment will continue the tradition with performance at a new level:
  - 40-times higher luminosity with respect to the previous record,
  - the most advanced, 21^{st}-century detector technology.

- This will enable Belle II to explore New Physics on the Luminosity/Intensity Frontier, which is different and complementary to the LHC high p_T experiments, operating on the Energy Frontier.
- Competition and complementarity with the LHCb experiment.

- Phase-2 data-taking just finished: The data show that both the collider and detector are performing well.
- We are ready to start a long physics run (Phase 3) in 2019, operating in the Super Factory mode:
  - extensive running of SuperKEKB with world's highest luminosity,
  - high-efficiency data-taking with the complete Belle II detector.

Our results are eagerly awaited by the HEP community.