Belle II: status and prospects

Abi Soffer

Tel Aviv University

On behalf of the Belle II Collaboration

HEPMAD 2018, Antananarivo, Madagascar

Outline

- Belle II's B-factory predecessors: BABAR, Belle
- Physics motivation for Belle II
- The accelerator and detector
- Results from early data
- Summary

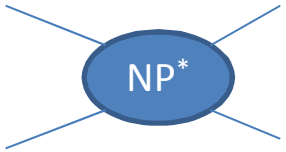
The first-generation B factories

- "B factory": High-luminosity, asymmetric-energy e^+e^- collider operating at $\sqrt{s} = 10.59$ GeV to produce $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

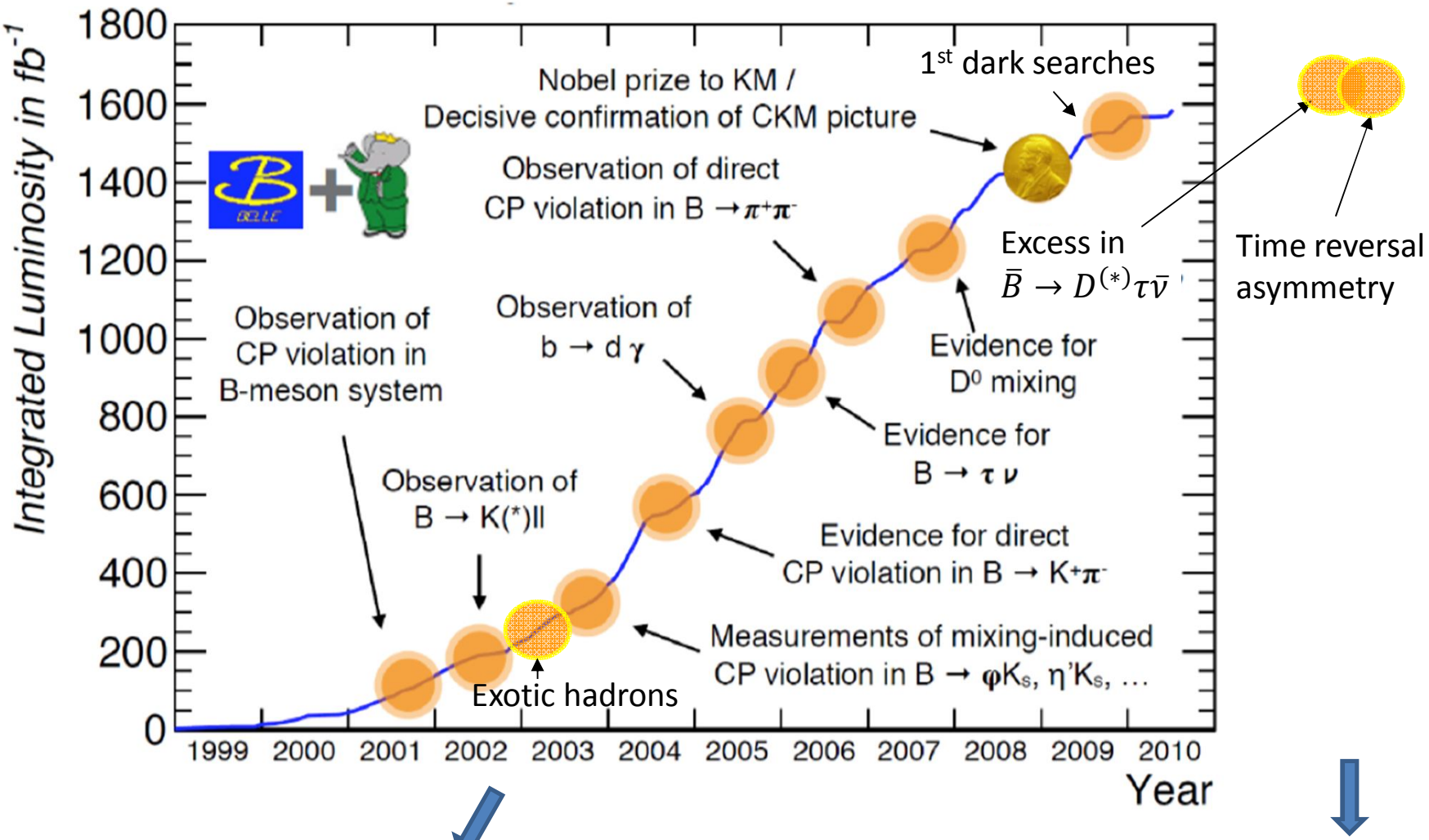
1999-2010
$\sim 1000\ \text{fb}^{-1} = 1\text{ab}^{-1}$

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

- Built on the success of $\Upsilon(4S)$ experiments ARGUS, CLEO, CUSB
- Initial goal: test the CP-violation mechanism of the SM,
  use virtual probes to study high-scale new physics



Some B-factory physics milestones



>100 unique CPV results

~350 papers published after shutdown, 21 in 2018

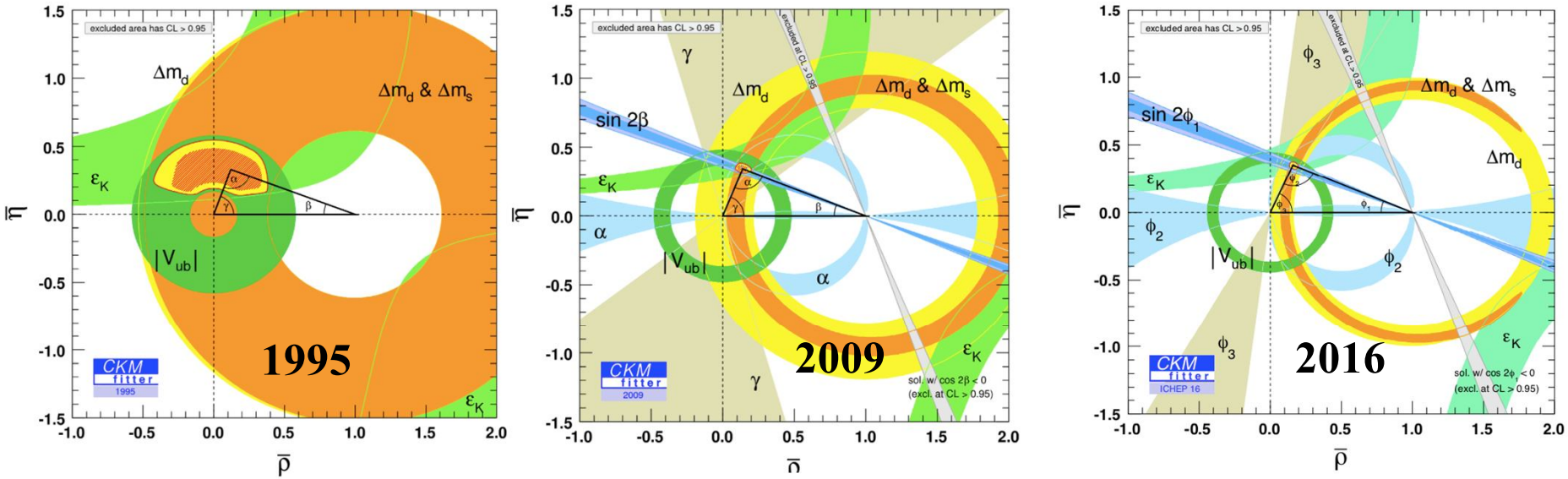
Motivation for $>\times$ 30 integrated luminosity

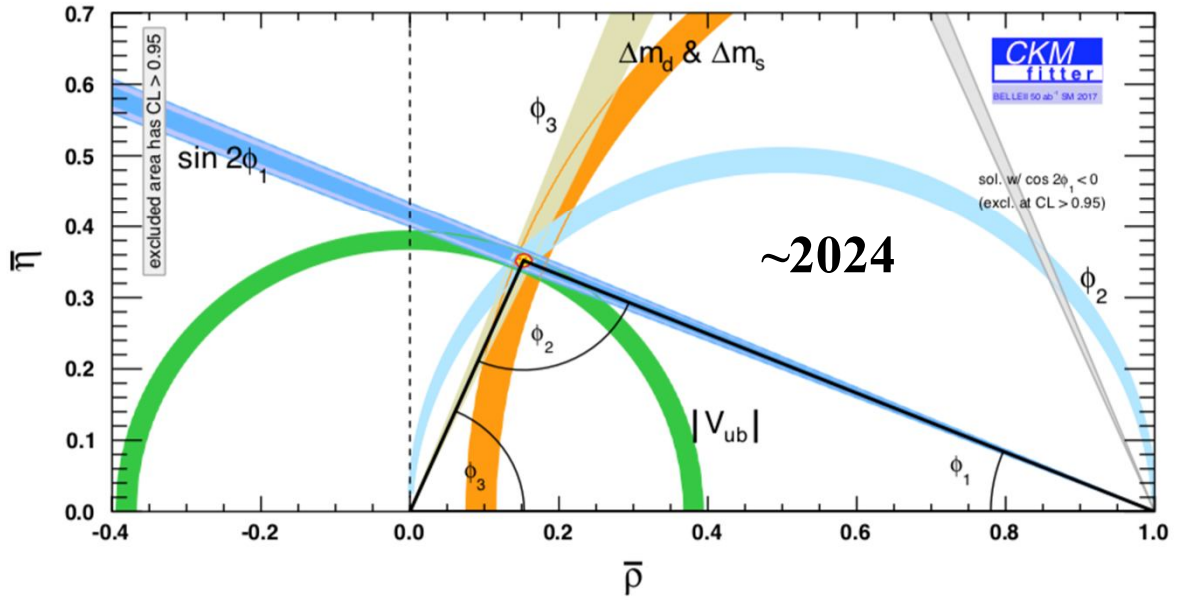
- BABAR and Belle:
  - Established SM flavor-physics picture, particularly the Kobayashi-Maskawa mechanism of CP violation
  - Constrained NP at scales >> direct searches at LHC
  - Discovered exotic (non-$q\bar{q}/qqq$) hadrons
  - Provided precision input for lattice, $(g-2)_\mu$ → $\sim 3.8\sigma$ tension
  - Conducted direct searches for light new physics
- This success sets the stage for the physics of Belle II:
  - Stress-testing the SM and sensitively probing new physics via, e.g.,
    - Precision flavor physics: CP violation, meson mixing, decay rates
    - Rare processes, e.g., flavor-changing neutral currents → Tension in $b \to s\ell^+\ell^-$
    - SM-forbidden processes, e.g., lepton-flavor non-universality, Lepton number/flavor violation → $\sim 3.8\sigma$ tension in $\bar{B} \to D^{(*)}\tau^-\bar{\nu}$
    - Direct searches for light new states

Checkout the Belle II Physics Book: https://arxiv.org/abs/1808.10567

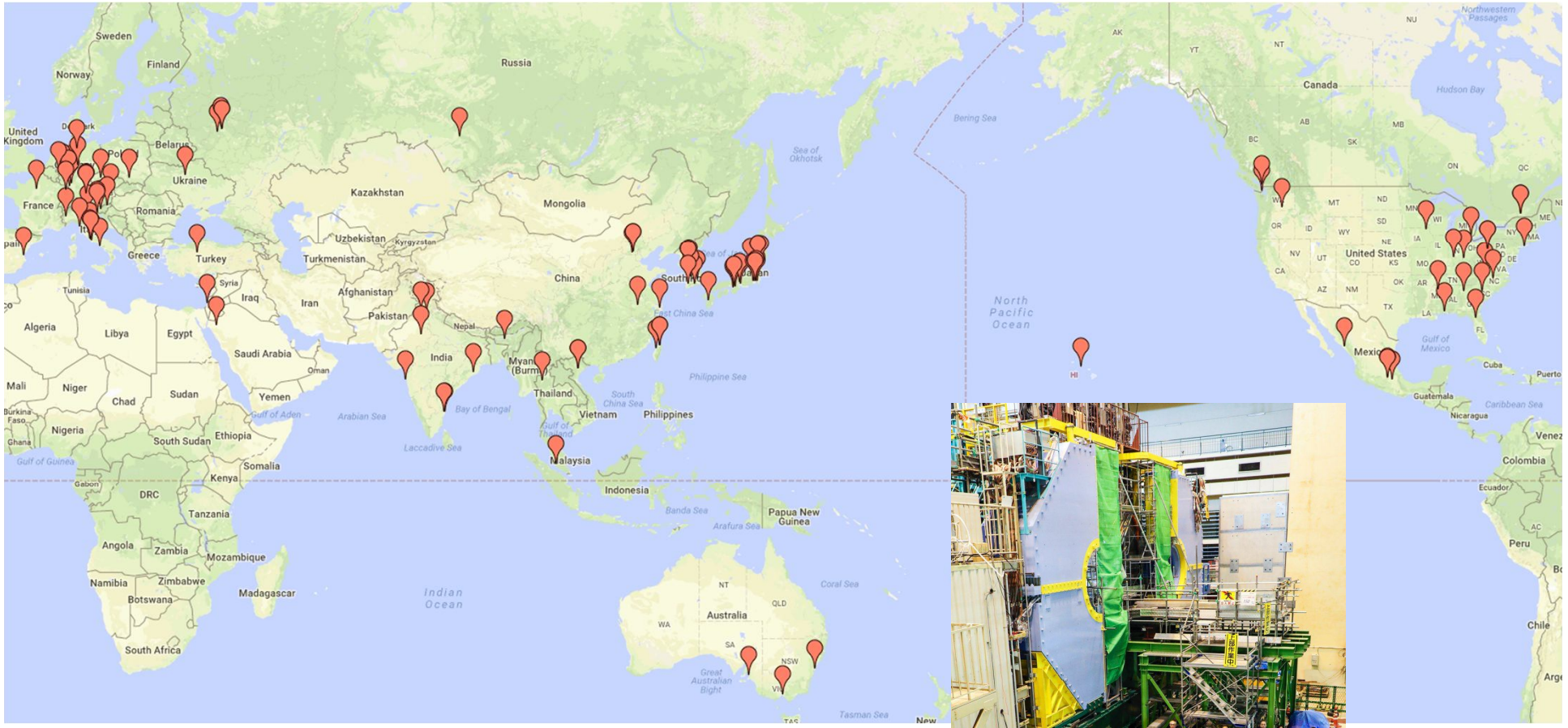
CKM unitarity triangle precision

http://ckmfitter.in2p3.fr/www/studies/plots_history/ckm_plots_history.html





Belle II collaboration



The physics prospects have brought together
~800 researchers from 25 countries
(some institutes not marked)

Belle II and LHCb: competition and complementarity

Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1}) by ~2024	~25	~50,000
Background level	Very high	Low
Typical efficiency	Low	High
π^0, K_S reconstruction	Inefficient	Efficient
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Very good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	36%

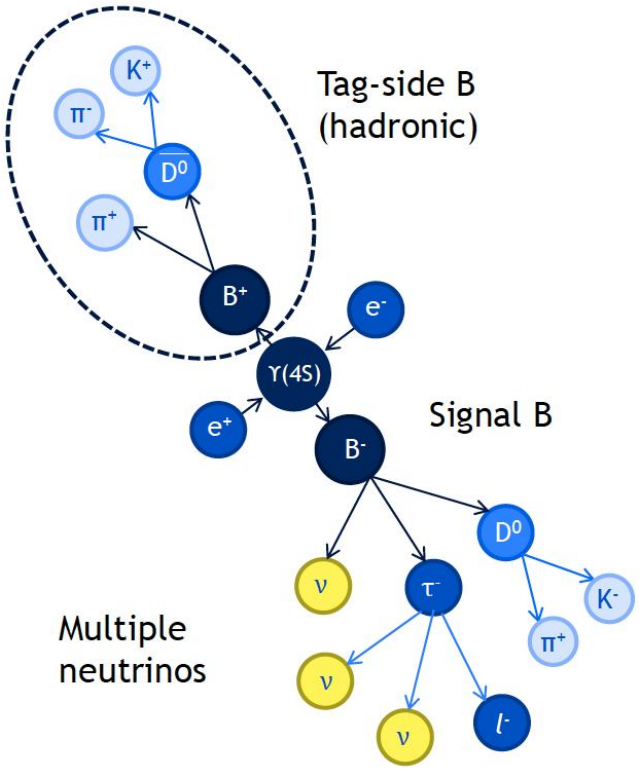
$e^+e^- \to B\bar{B}$ full-event reconstruction

Important B-factory technique:

- Reconstruct one of the B mesons using >1000 hadronic modes (semileptonic decays also used)
- Then look for a signal decay of interest in the other B

Efficiency < 1%, but, this

- Greatly reduces background
- Provides signal-B momentum vector
- Regularly used for (rare) decays with (multiple) neutrinos:
  - $\bar{B} \to D^{(*)}\tau^-\bar{\nu}$, $B^- \to \tau^-\bar{\nu}$, $\bar{B} \to \pi\ell^-\bar{\nu}$, $\bar{B} \to K\nu\bar{\nu}$, $\bar{B} \to K\tau^+\tau^-$, etc.
- Inclusive studies
  - $\bar{B} \to KX_{c\bar{c}}$, $B \to \gamma X_s$



- Factor of 2 wrt. Belle, e.g., faster algorithms enable analysis-specific training

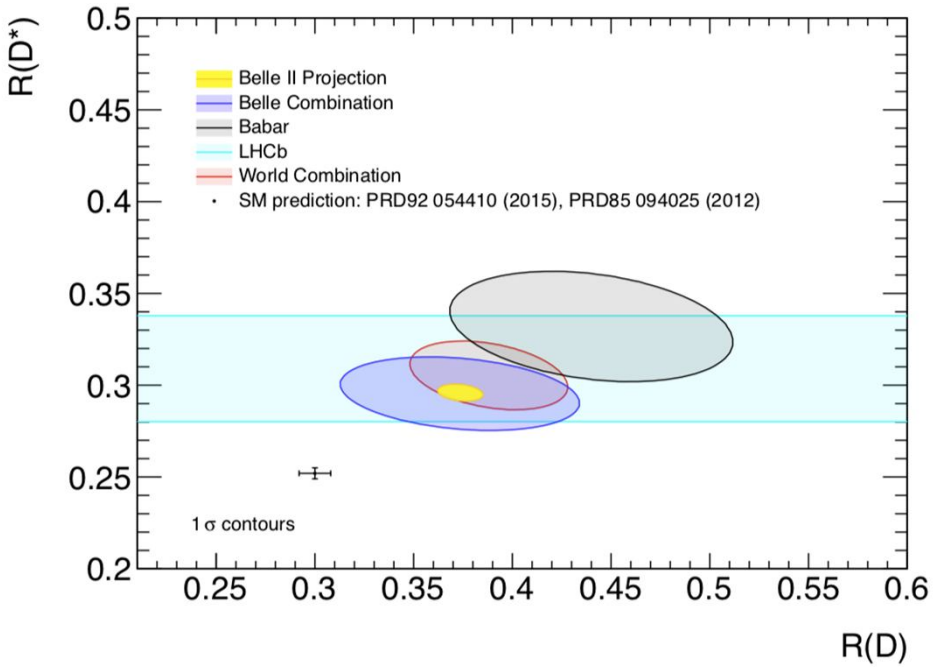
Example case study: $\bar{B} \to D^{(*)}\tau^{-}\bar{\nu}$

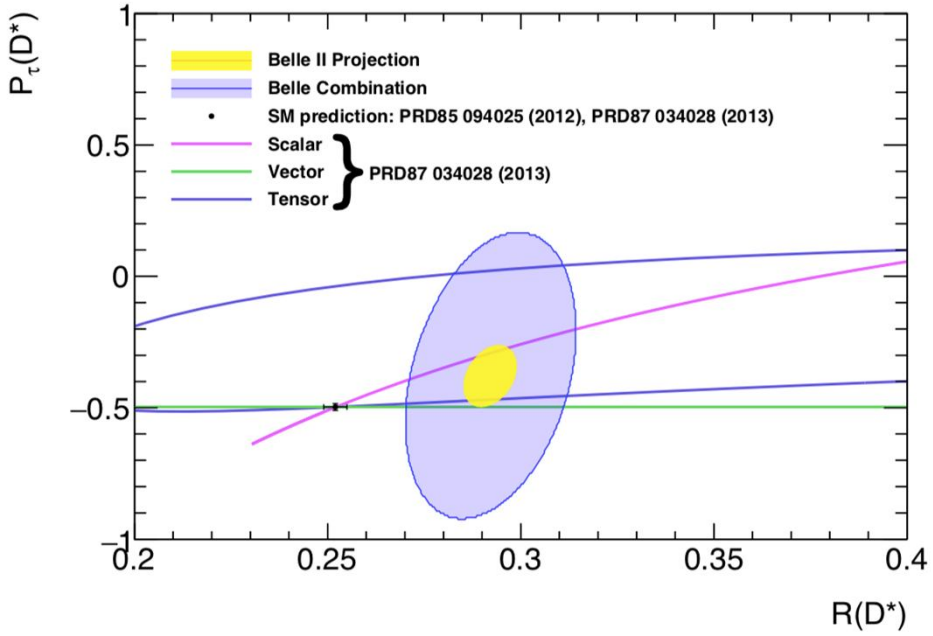
Quantities measured so far:

$$R\left(D^{(*)}\right) \equiv \frac{Br\left(\bar{B} \to D^{(*)}\tau^{-}\bar{\nu}\right)}{Br\left(\bar{B} \to D^{(*)}\ell^{-}\bar{\nu}\right)} \quad , \qquad P_{\tau}(D^{*}) \equiv \tau \text{ polarization in } \bar{B} \to D^{*}\tau^{-}\bar{\nu}$$

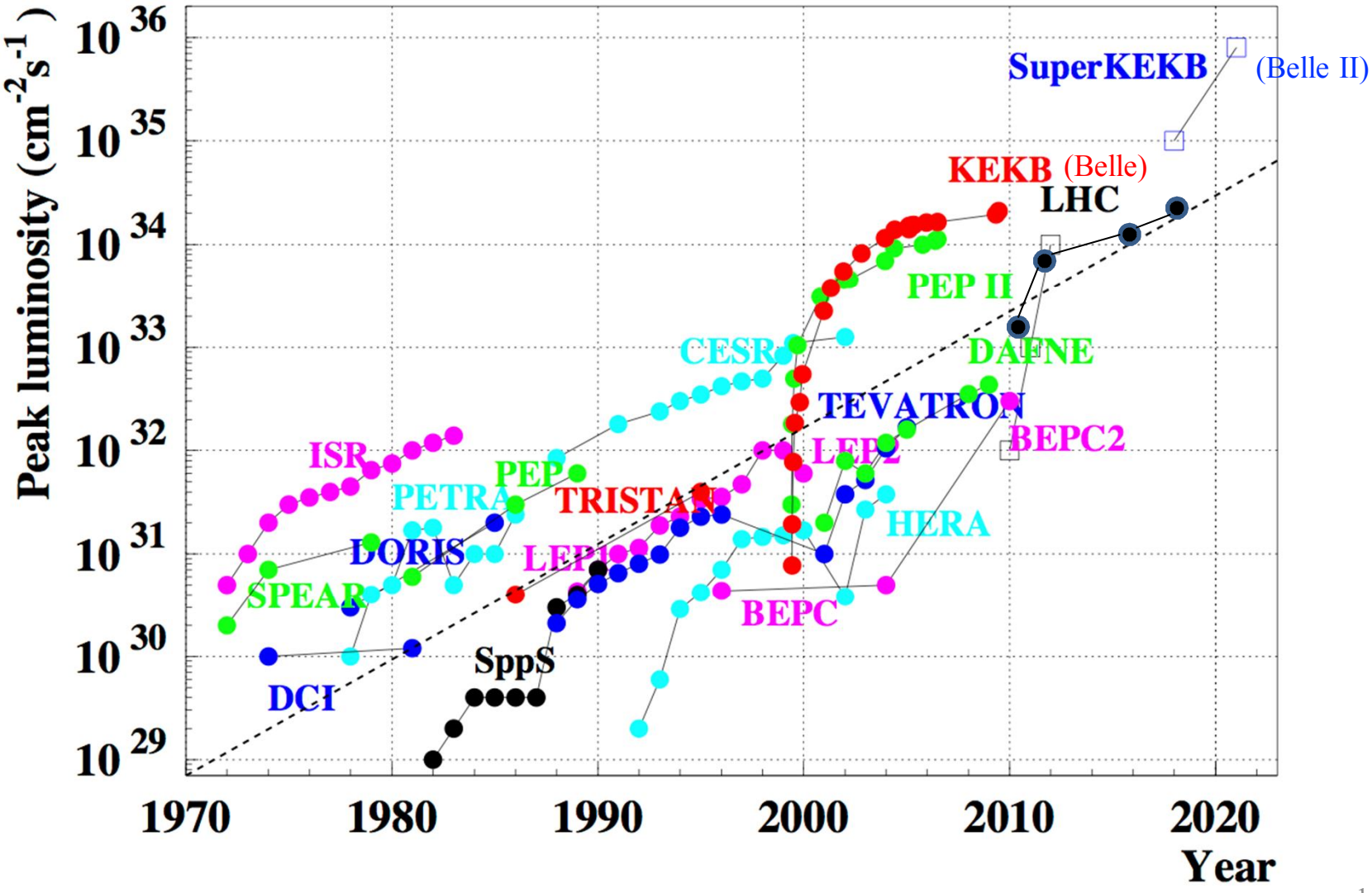
3.8 σ tension wrt. the SM.

Belle II full data set compared to current measurements:

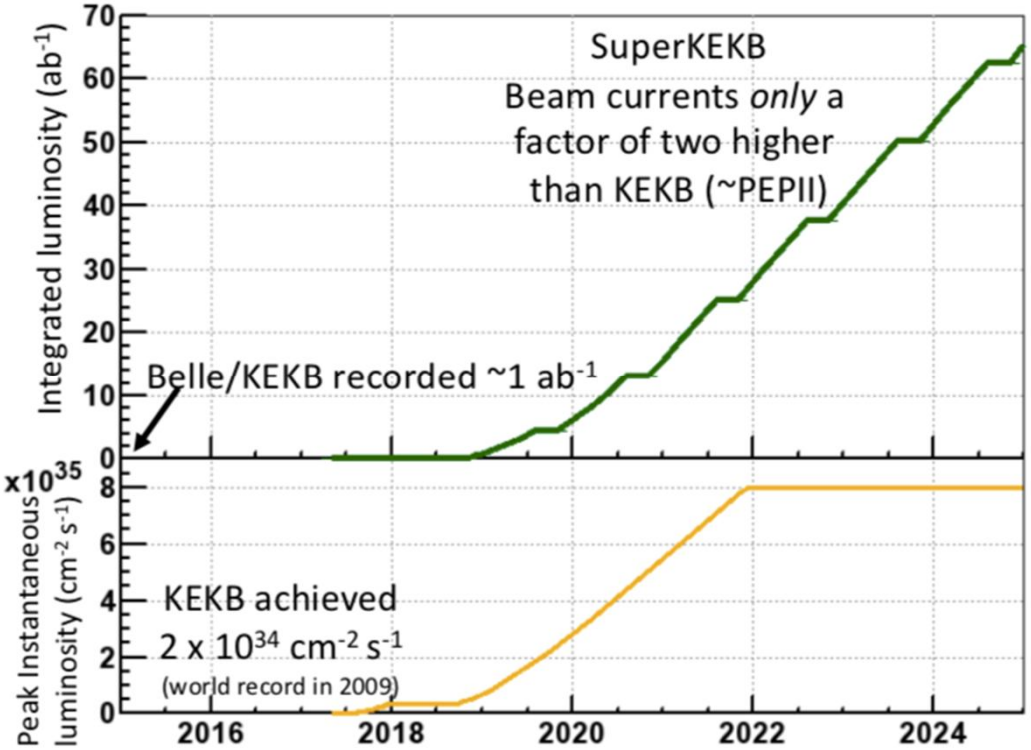




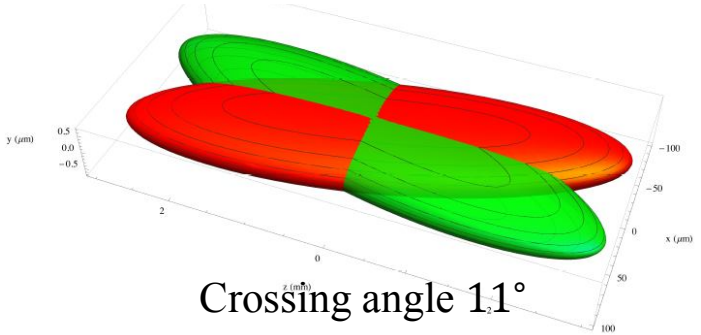
Moore's law of collider luminosity



40-fold increase in luminosity wrt. Belle

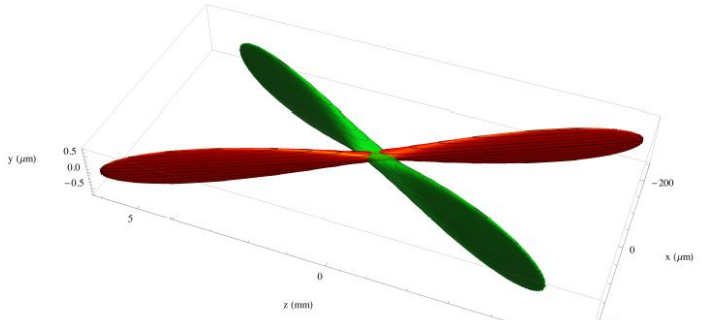


Beams at KEKB (Belle)



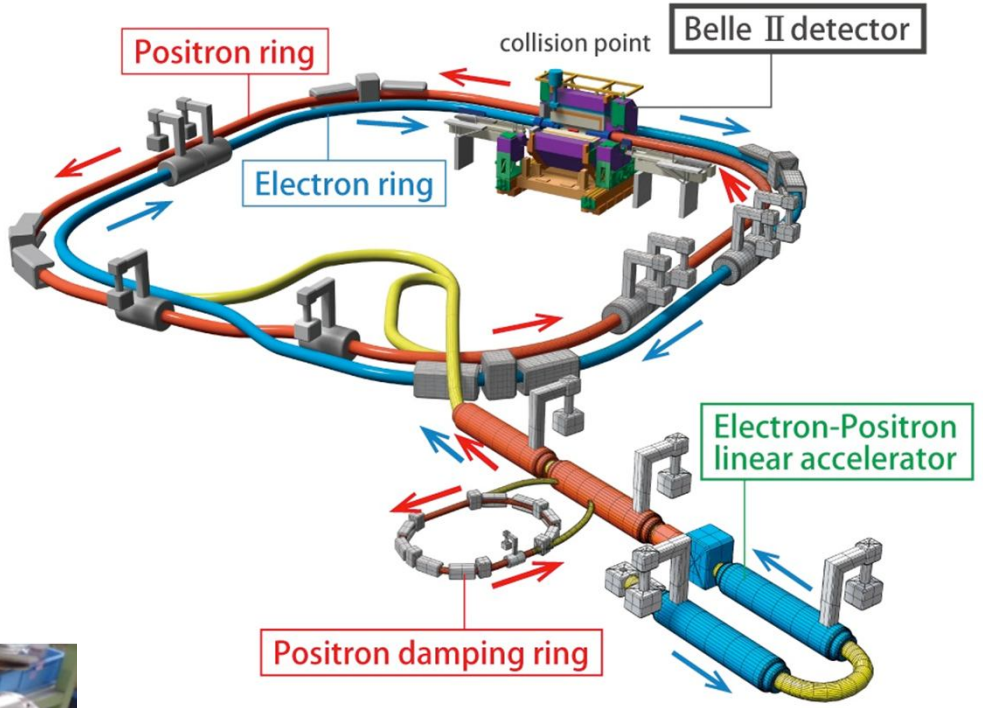
Crossing angle 11°

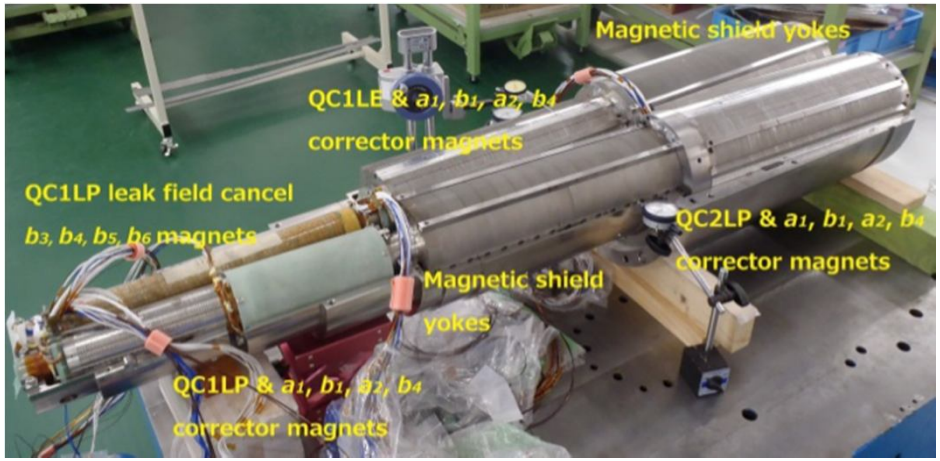
Nanobeams at SuperKEKB (Belle II)



Crossing angle 41°

SuperKEKB collider



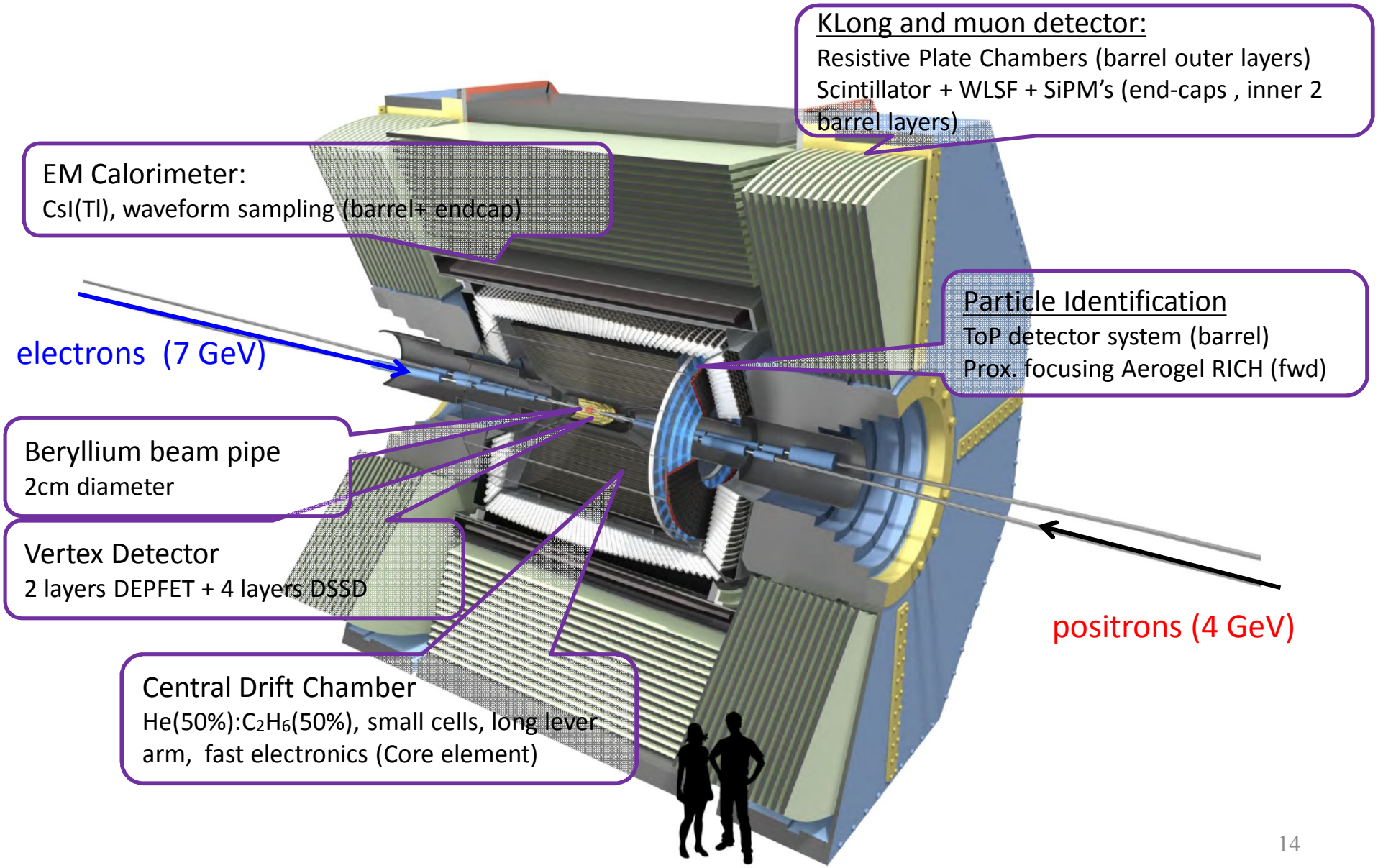


http://ipac2018.vrws.de/papers/tuzgbe2.pdf

New:

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

Belle II detector



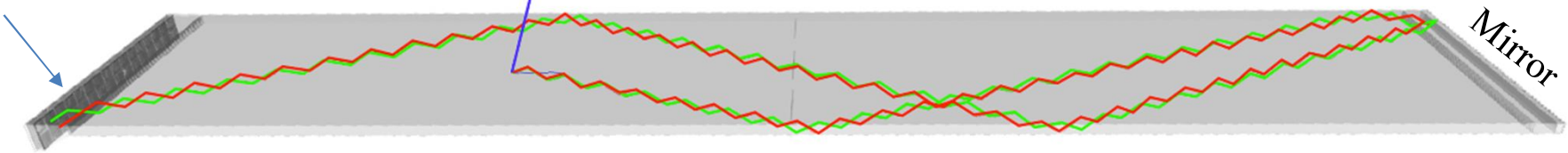
Barrel hadron ID: Time of Propagation (ToP)

MCP-PMTs
512 channels
50 ps resolution

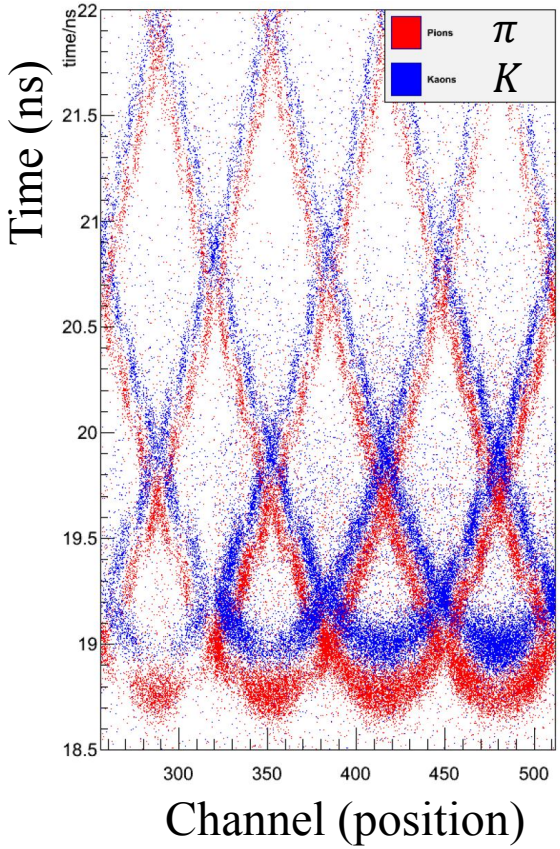
K/π track

Cherenkov angle: $\cos\theta_C = 1/n\beta$

Photon from π^+
Photon from K^+



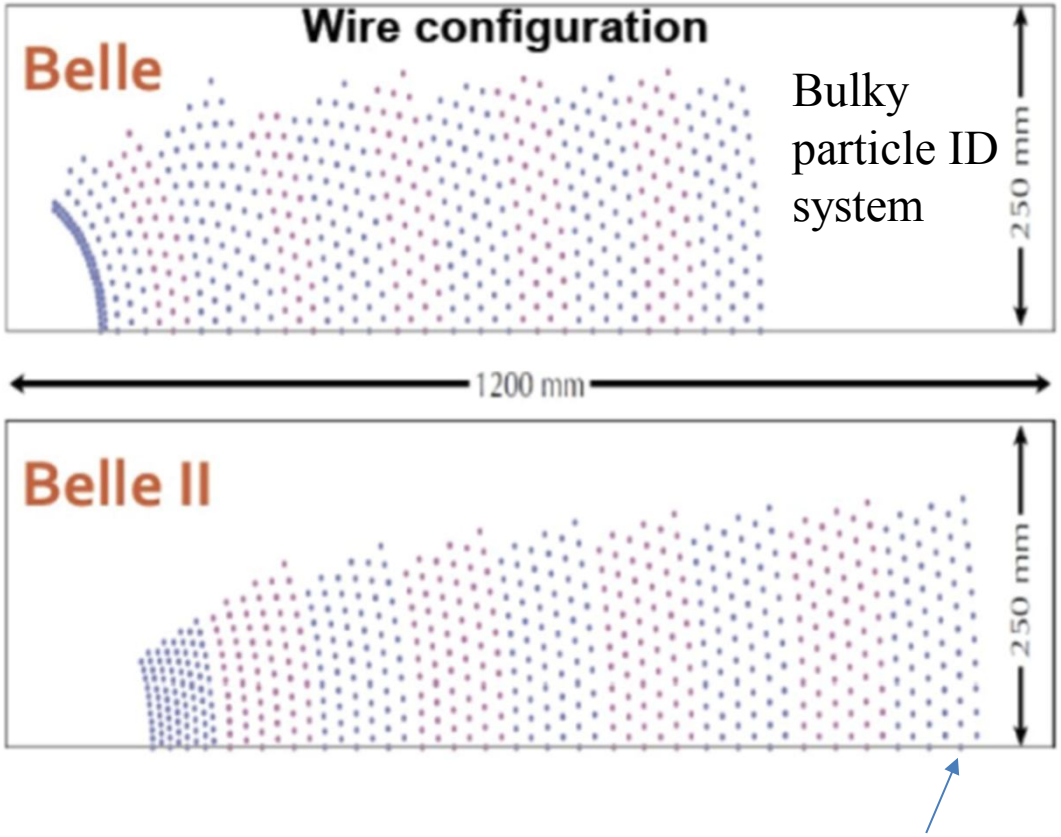
Bar length = 2600 mm, width = 450 mm, thickness = 20 mm



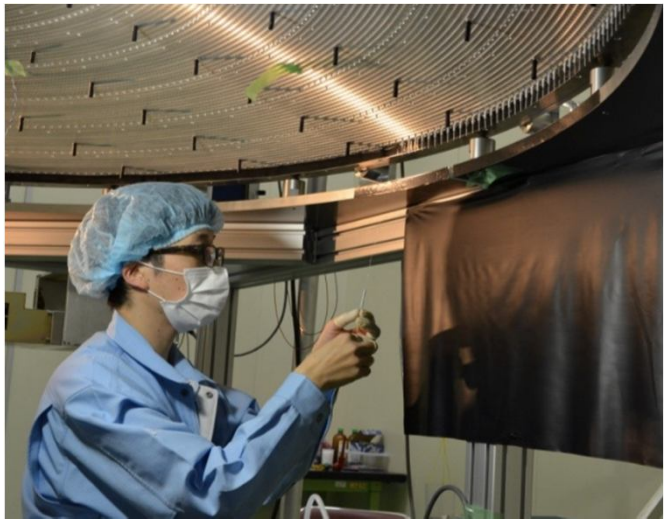
32 quartz bars:

Quartz Property	Requirement
Flatness	<6.3µm
Perpendicularity	<20 arcsec
Parallelism	<4 arcsec
Roughness	< 0.5nm (RMS)
Bulk transmittance	> 98%/m
Surface reflectance	>99.9%/reflection

Detector highlights: drift chamber



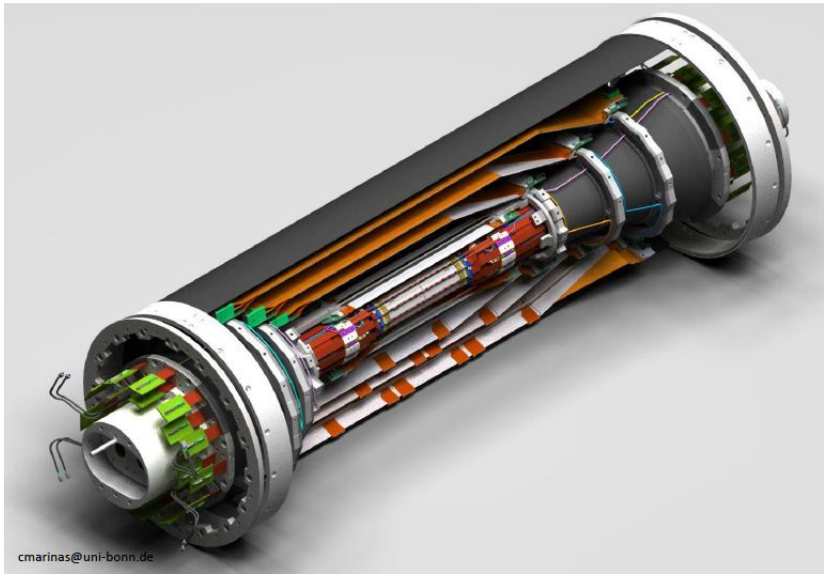
Outer radius almost ~20% larger than at BABAR/Belle:
Improved momentum resolution

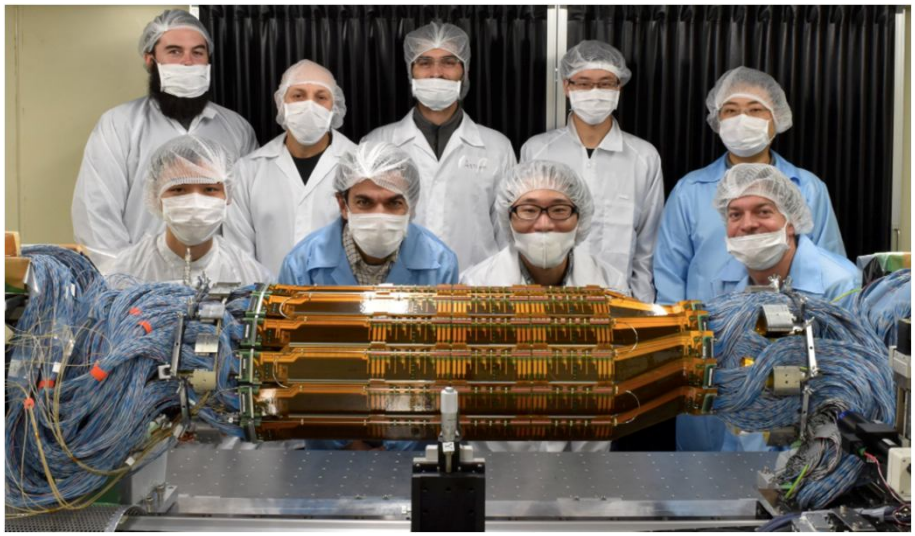


Stringing 51456 wires

	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)

Detector highlights: vertex detector



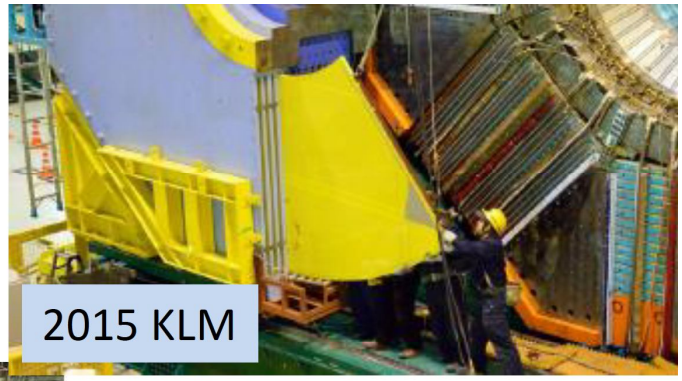


		(@ Belle)
Beampipe	r= 10 mm	(14 mm)
DEPFET pixels		
Layer 1	r=14 mm	
Layer 2	r= 22 mm	
DSSD (double sided silicon detectors)		
Layer 3	r=38 mm	(20 mm)
Layer 4	r=80 mm	
Layer 5	r=115 mm	
Layer 6	r=140 mm	

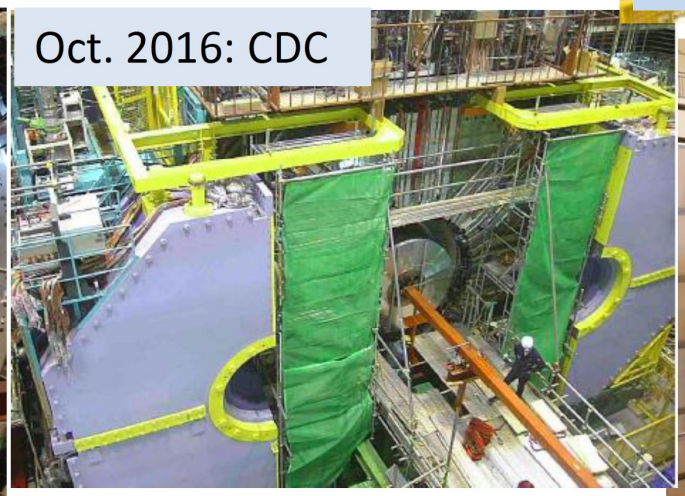
Improvement relative to Belle:

- ~ × 2 better resolution
- Tolerance of ~ × 20 background rate

Sub-detector installation


2015 KLM


May 2016: TOP


Oct. 2016: CDC

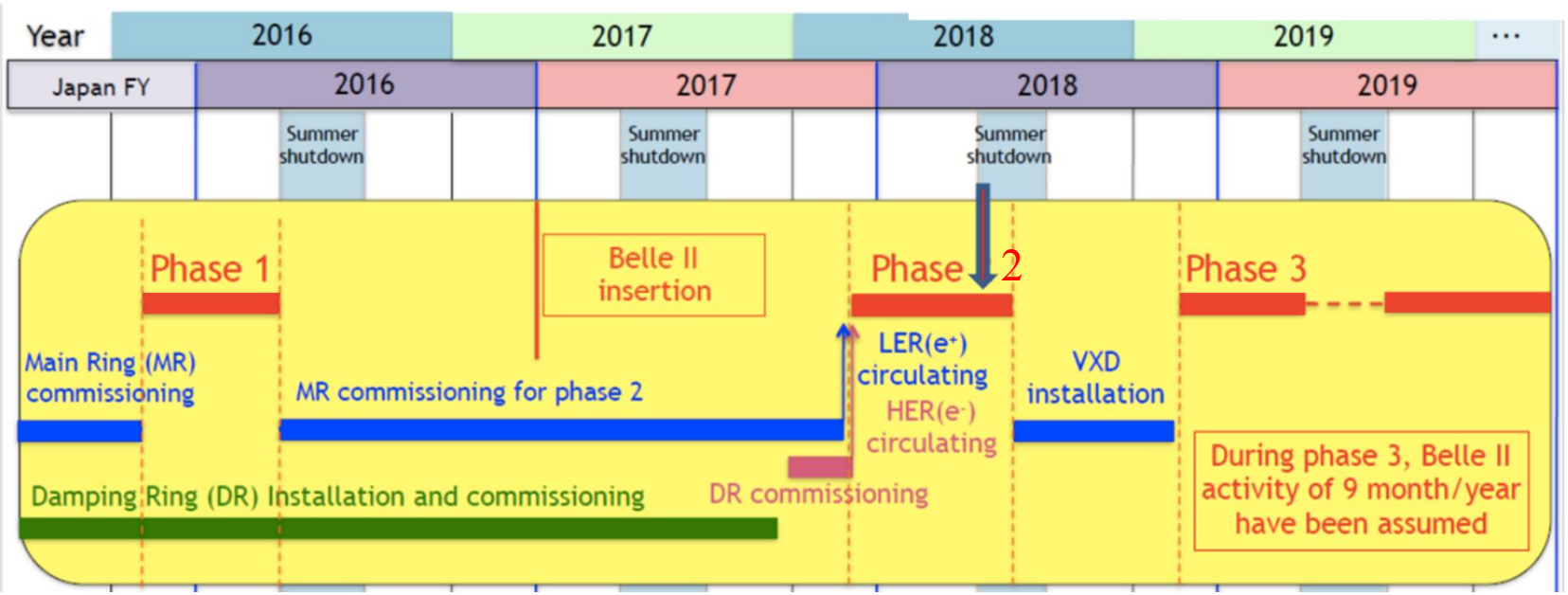

Jan. 2017 BWD ECL


Apr 2017
Belle II roll-in


Aug.2017:ARICH


VXD: ongoing

Startup schedule



First collisions, 26 April, 2018

Phase 2 goals:

- Progress toward high luminosity
- Progress toward stable operation

Achievements:

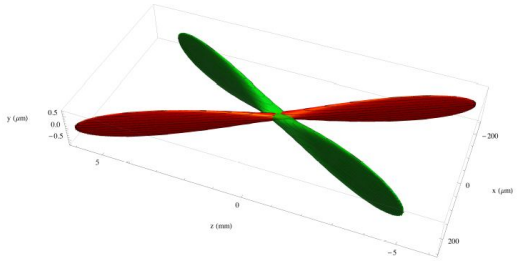
- $L = 5.5 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$
- Collected ~0.5 $\mathrm{fb^{-1}}$ for commissioning & calibration

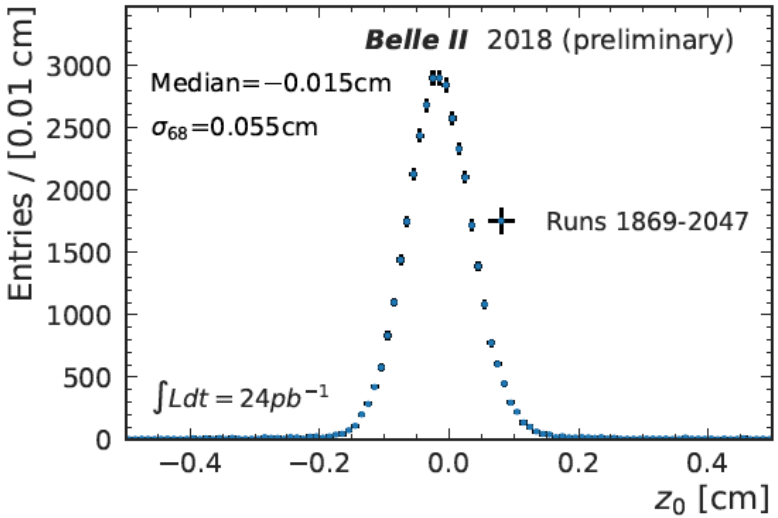
Some phase-2 results

- SuperKEKB performance
- Belle II performance:
  - Basic physics signals with early calibration and alignment

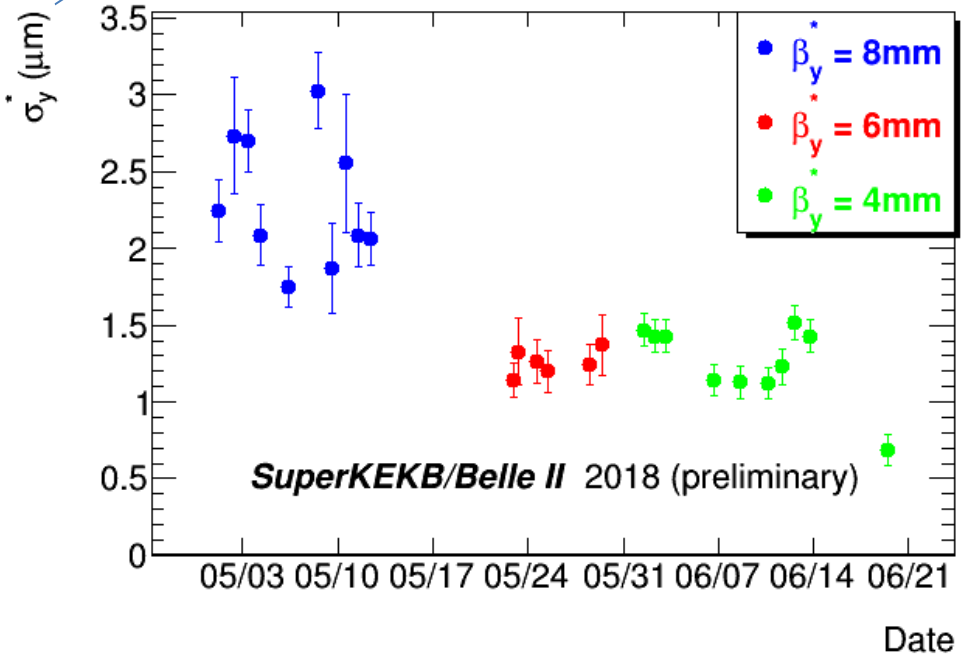
Progressing toward × 40 luminosity

As expected, vertical beamspot size $\sigma_z^* = 0.55$ mm (O(cm) at Belle), from $e^+e^- \to \mu^+\mu^-$ events





From lumi measurement w. diamond detectors



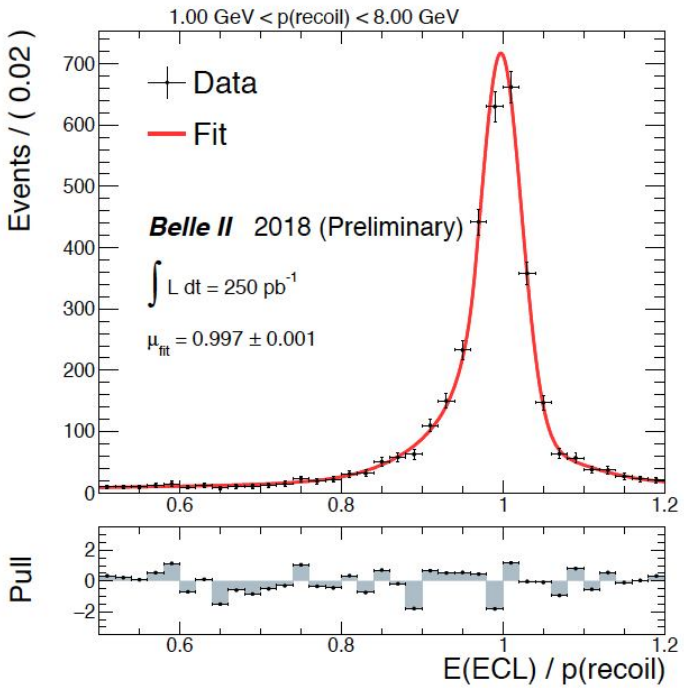
At design luminosity,
vertical beam size $\sigma_y^* = 50$ nm.
So far achieved $\sigma_y^* = 700$ nm.

Luminosity stalls as β_y^* is reduced,
due to beam blowup @ high current.

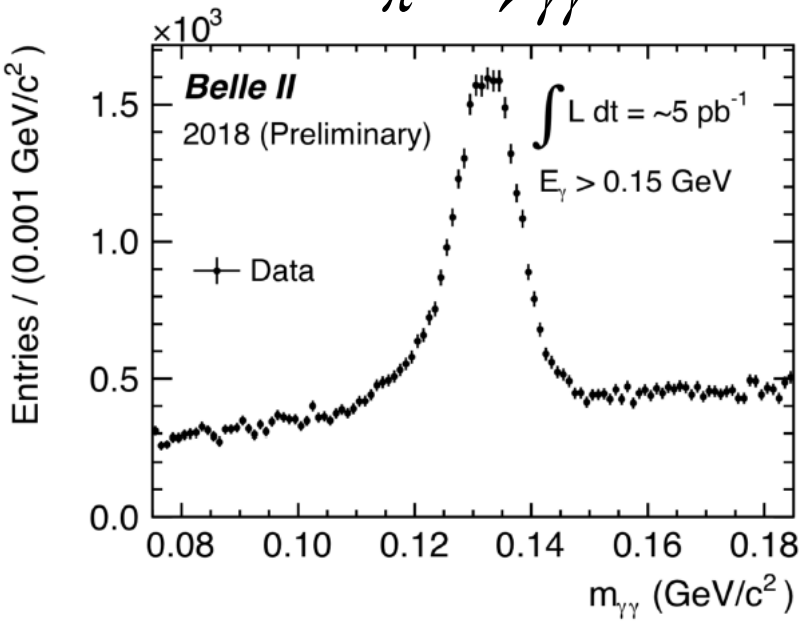
Usual growing pains of a new machine.
Design luminosity expected in 2022.

Signals involving photons

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

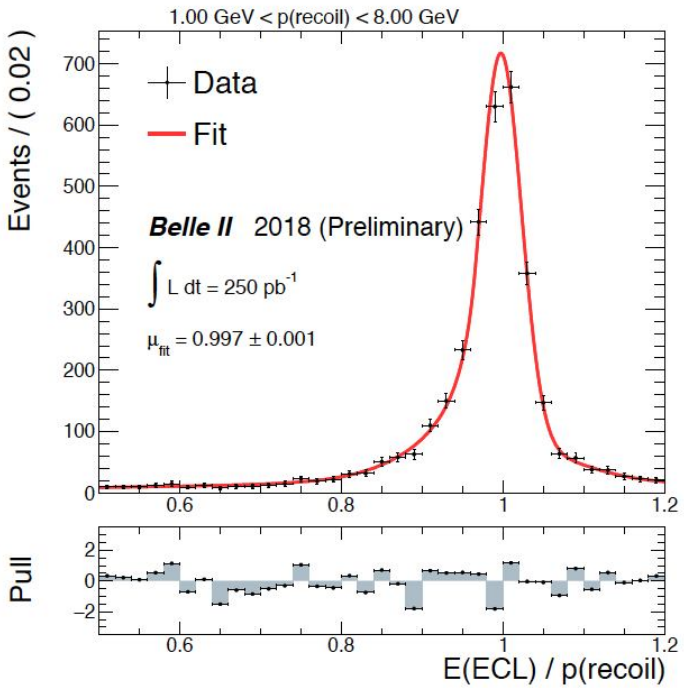


$\pi^0 \to \gamma\gamma$



Signals involving photons

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



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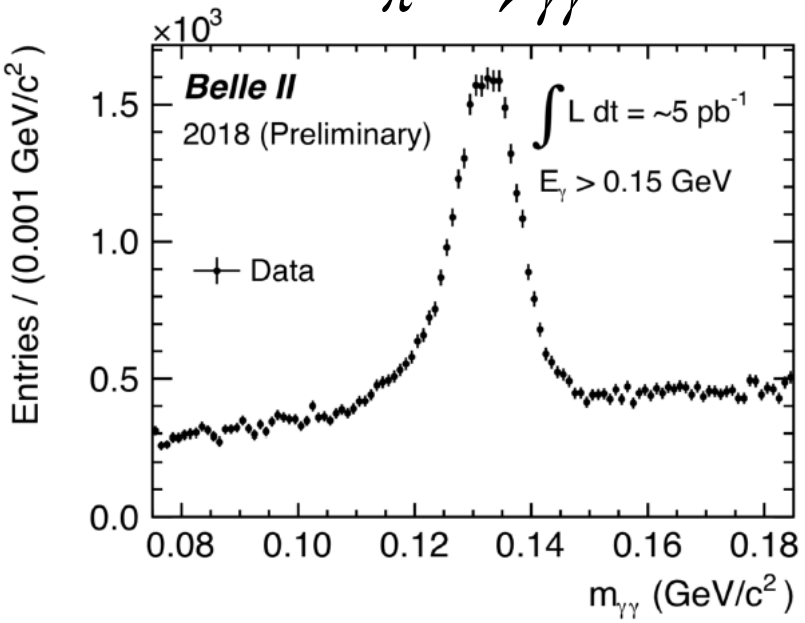
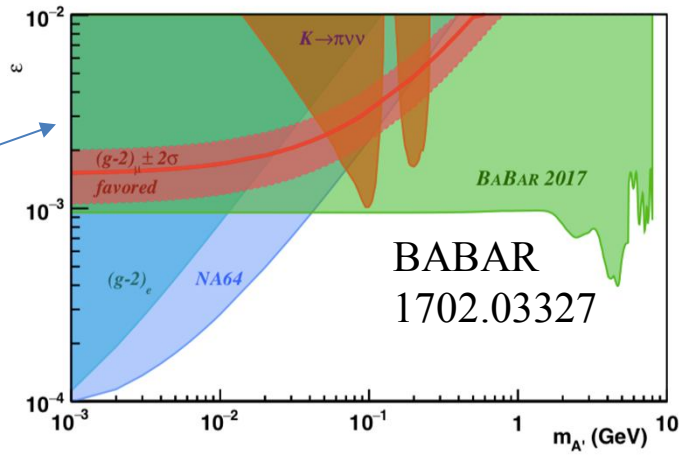
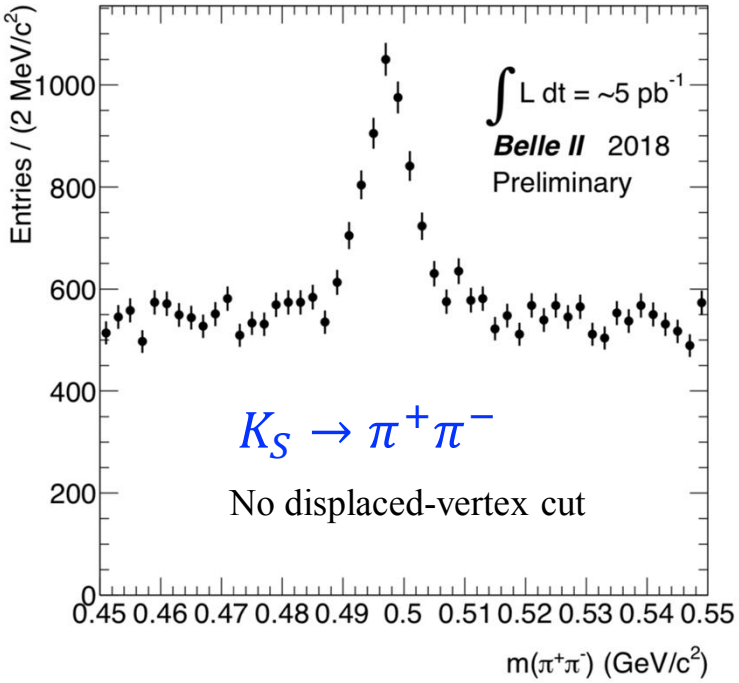


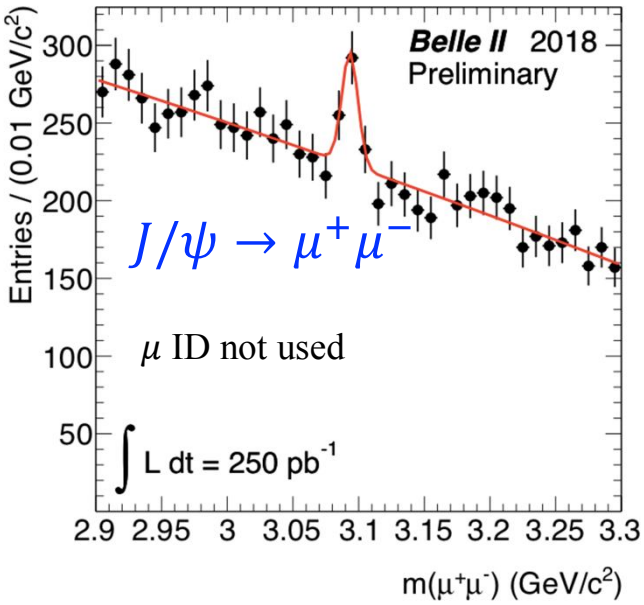
Single-photon triggers are ready for dark-sector searches, e.g., $e^+e^- \to \gamma +$ invisible (BABAR limits):

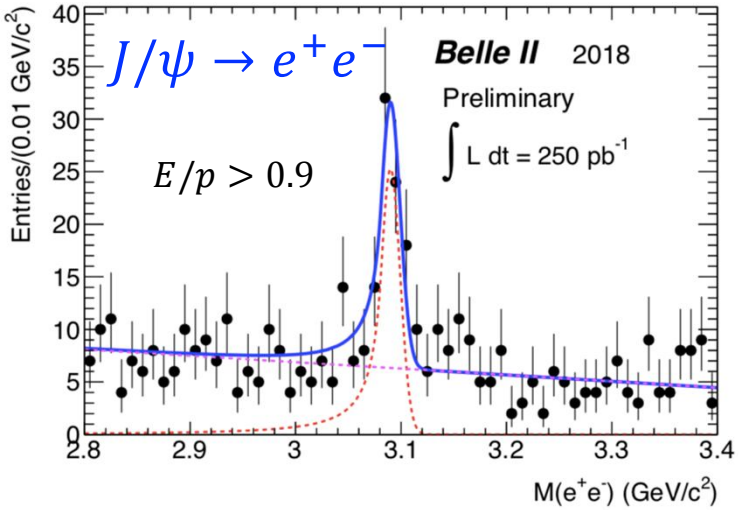


Belle II: 1000 ×more lumi, better calorimeter

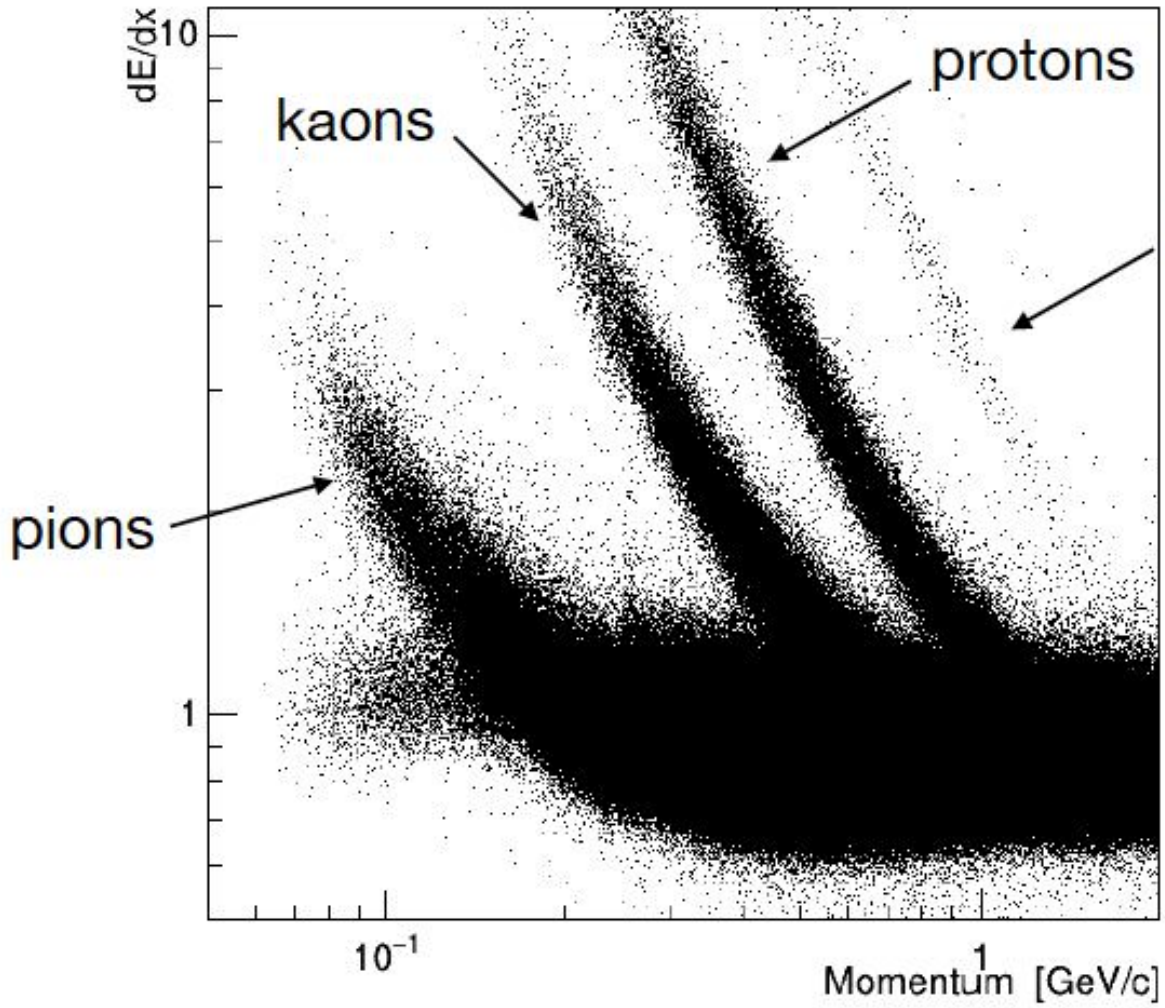
Some 2-track signals







dE/dx in drift chamber



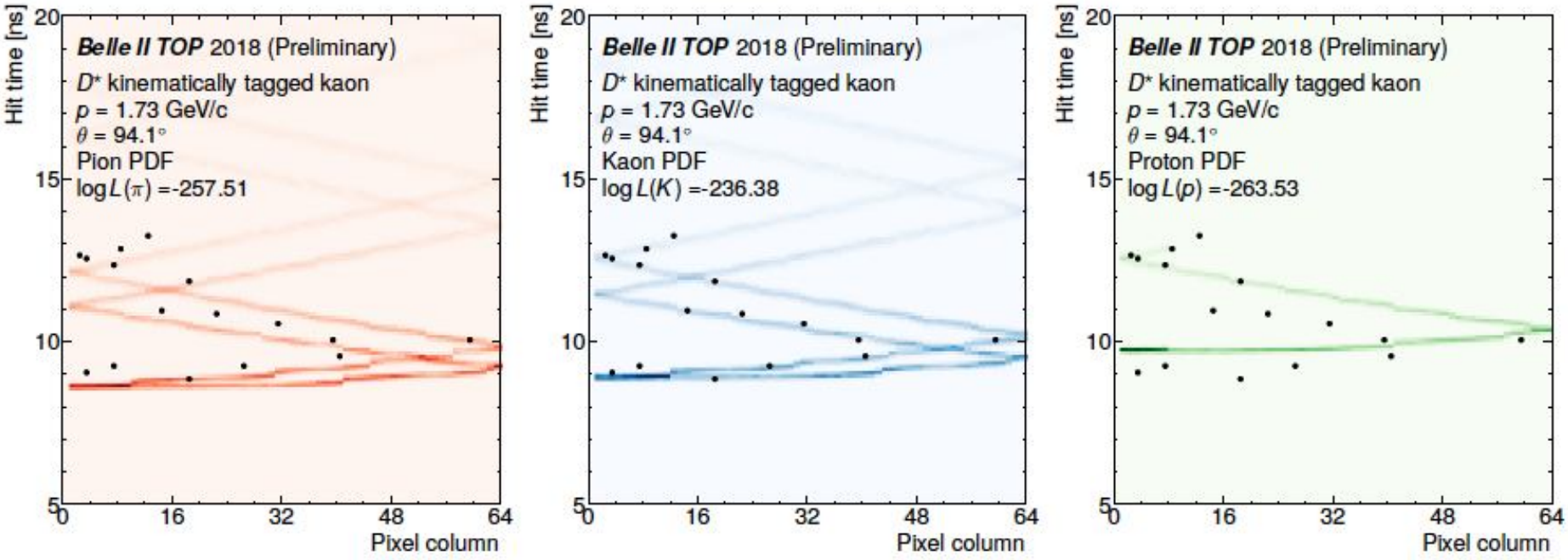
Level indicates high beam-wall and beam-gas background

Separation to improve with further alignment and calibration

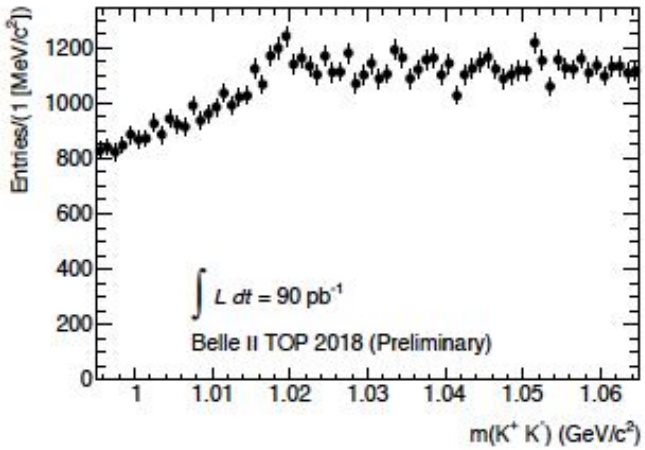
Performance of Cherenkov ToP detector

ToP signature of kaon identified kinematically via $D^{*+} \to D^0 \pi_s^+; D^0 \to K^- \pi^+$

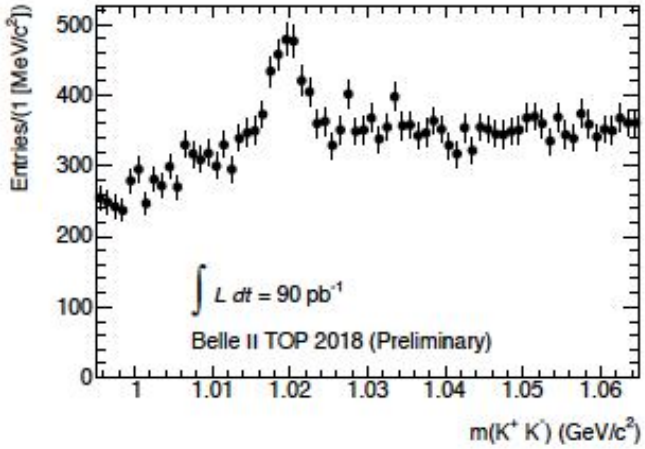
is visibly more consistent with being a kaon than a pion or proton



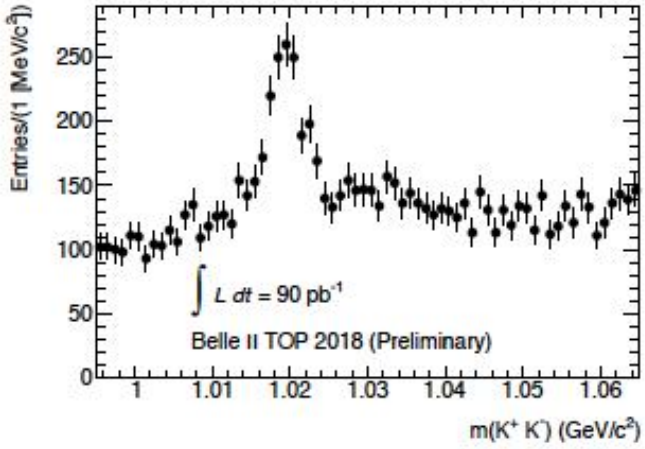
ToP impact on $\phi \to K^+K^-$ reconstruction



No kaon ID required



One kaon identified in ToP

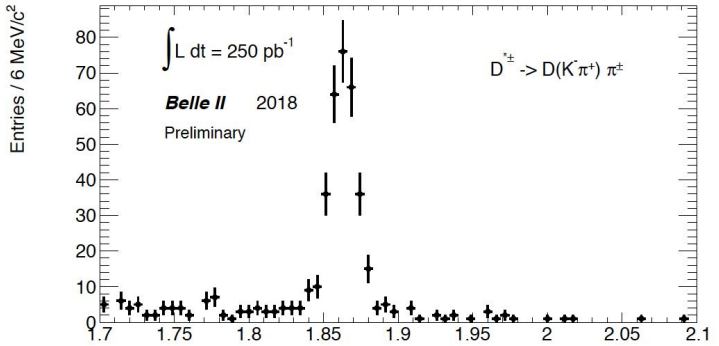


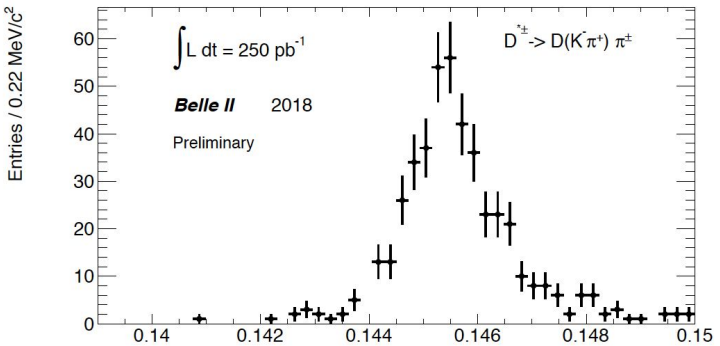
Both kaons identified in ToP

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

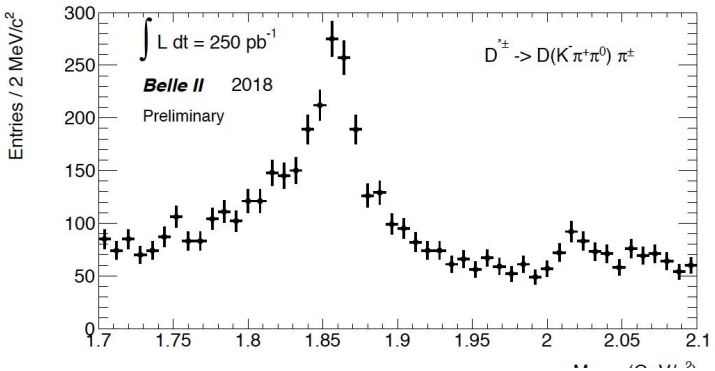
$$D^{*+} \to D^0\pi^+,$$

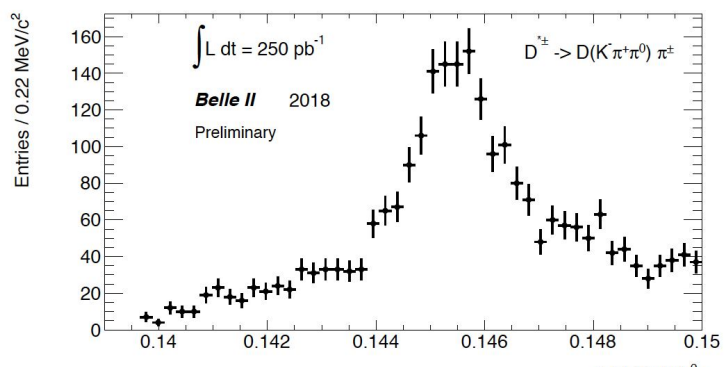
$$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$$



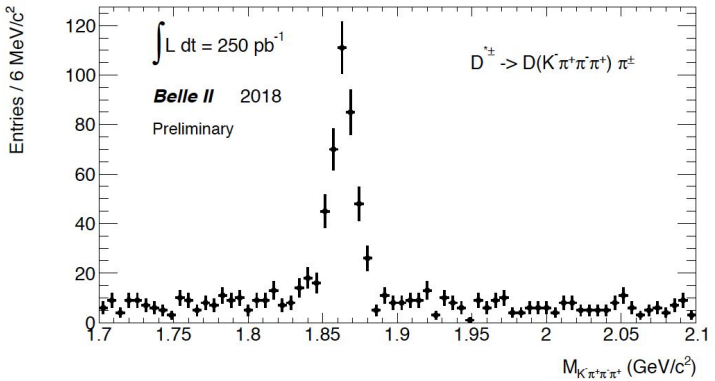


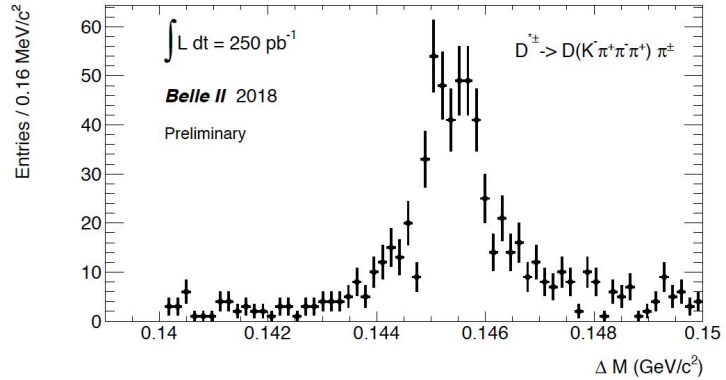
With hadron ID cuts





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

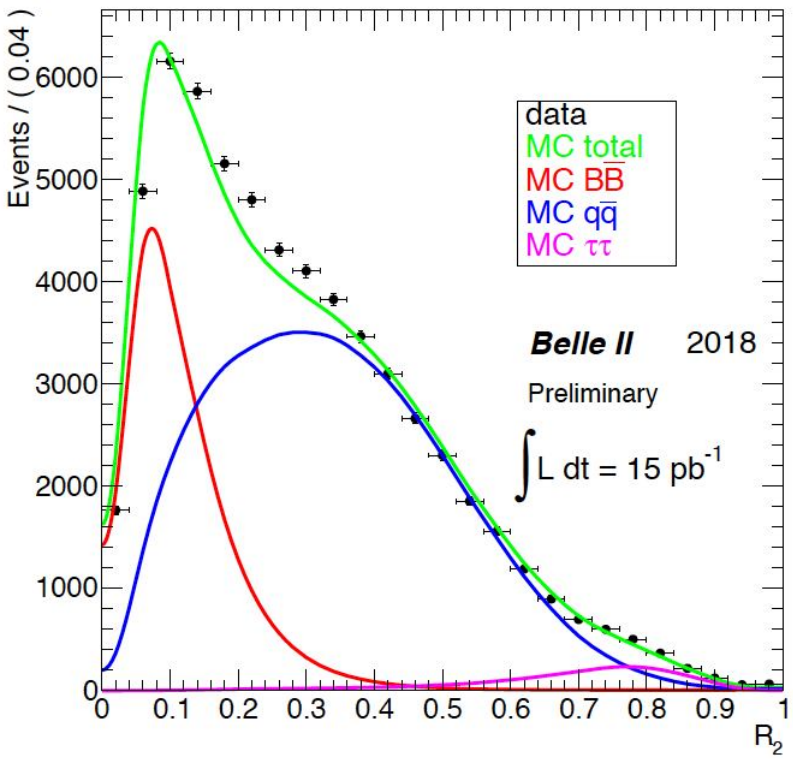




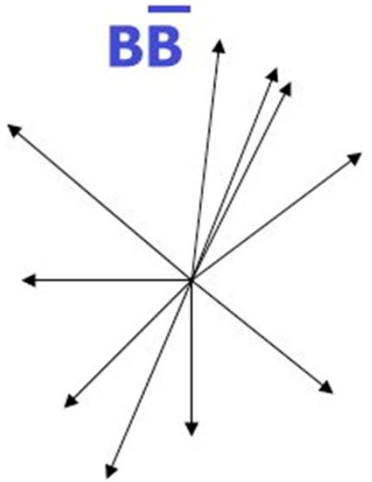
$M(D^0 \text{ candidate})$

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

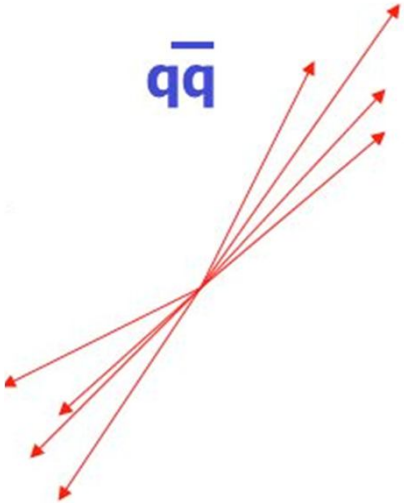
Event Topology tells us we are producing B's



Spherical R_2 Jet-like

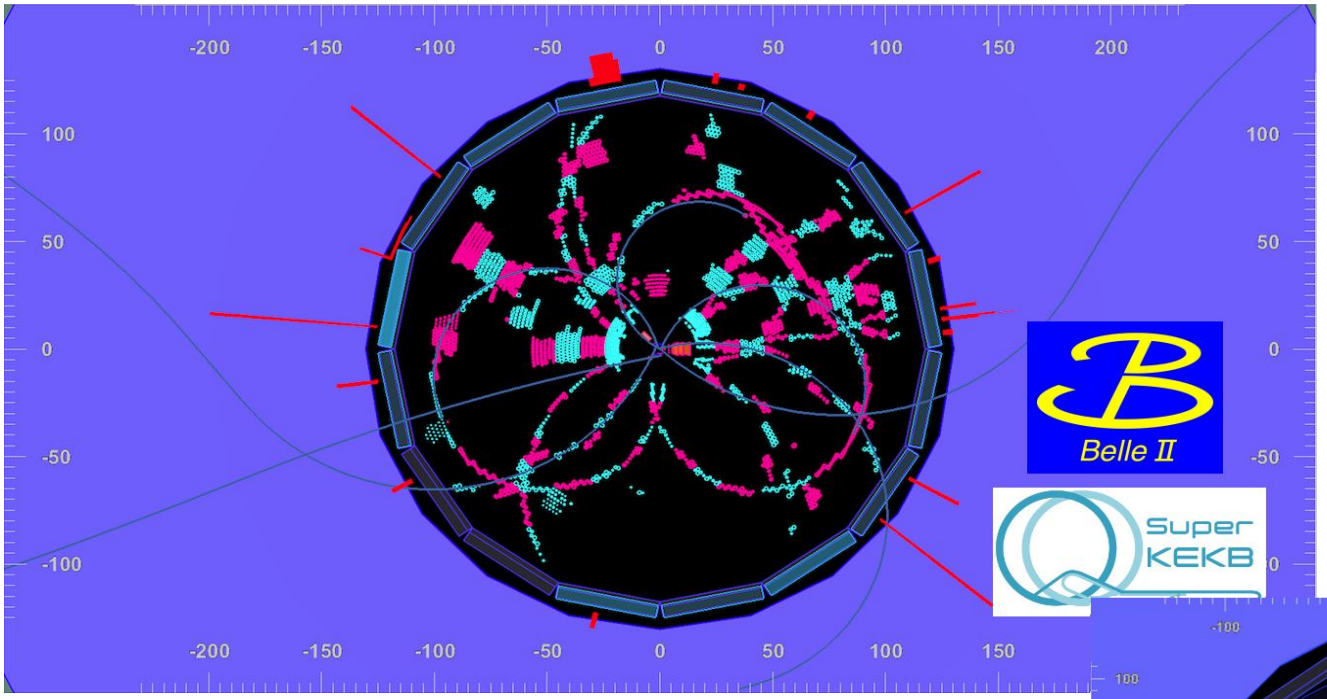


B pairs produced at rest in the CM with no extra particles

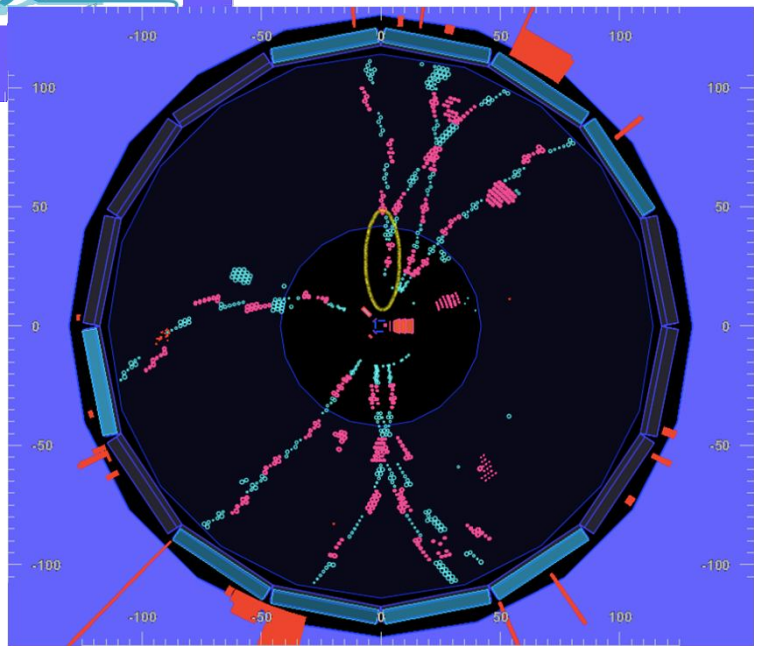


We are on the $\Upsilon(4S)$ resonance and recording $B\bar{B}$ pairs with ~99% efficiency.

First-data event displays

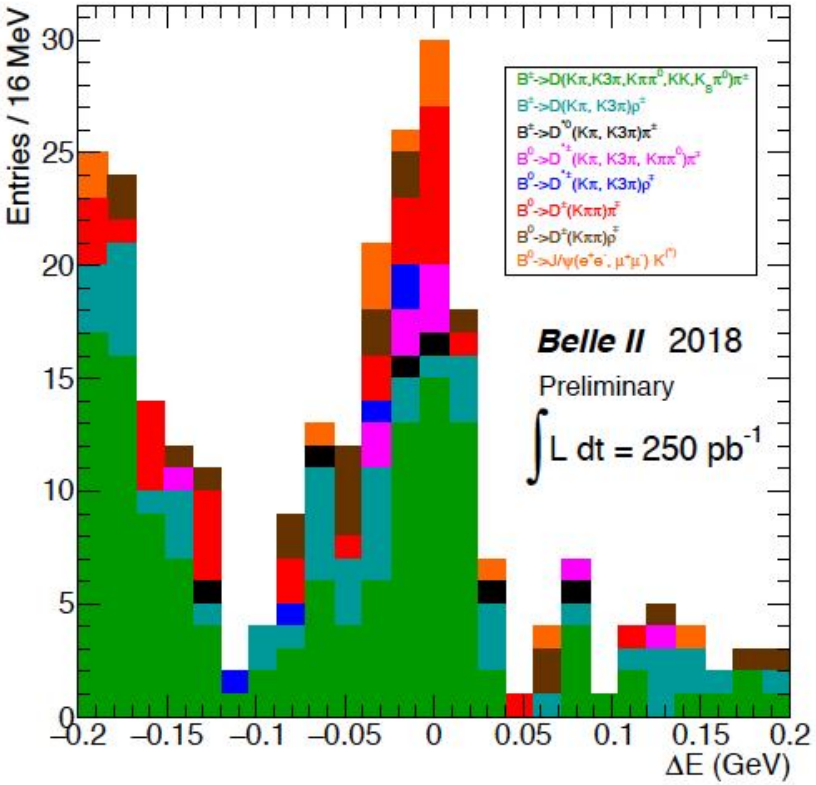


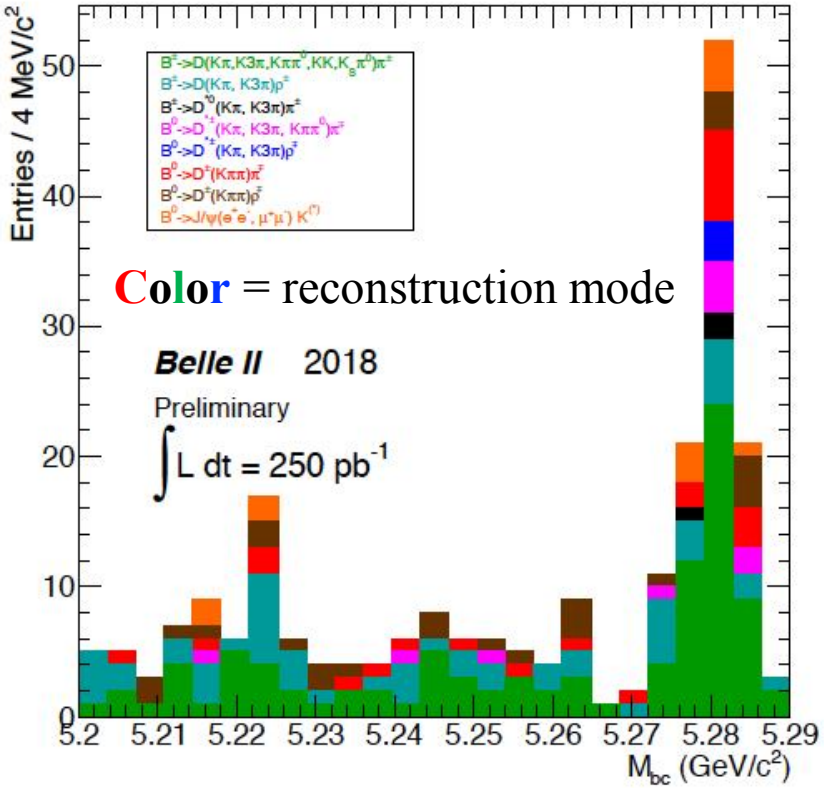
A $B\bar{B}$-like event



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

Full reconstruction of hadronic B decays





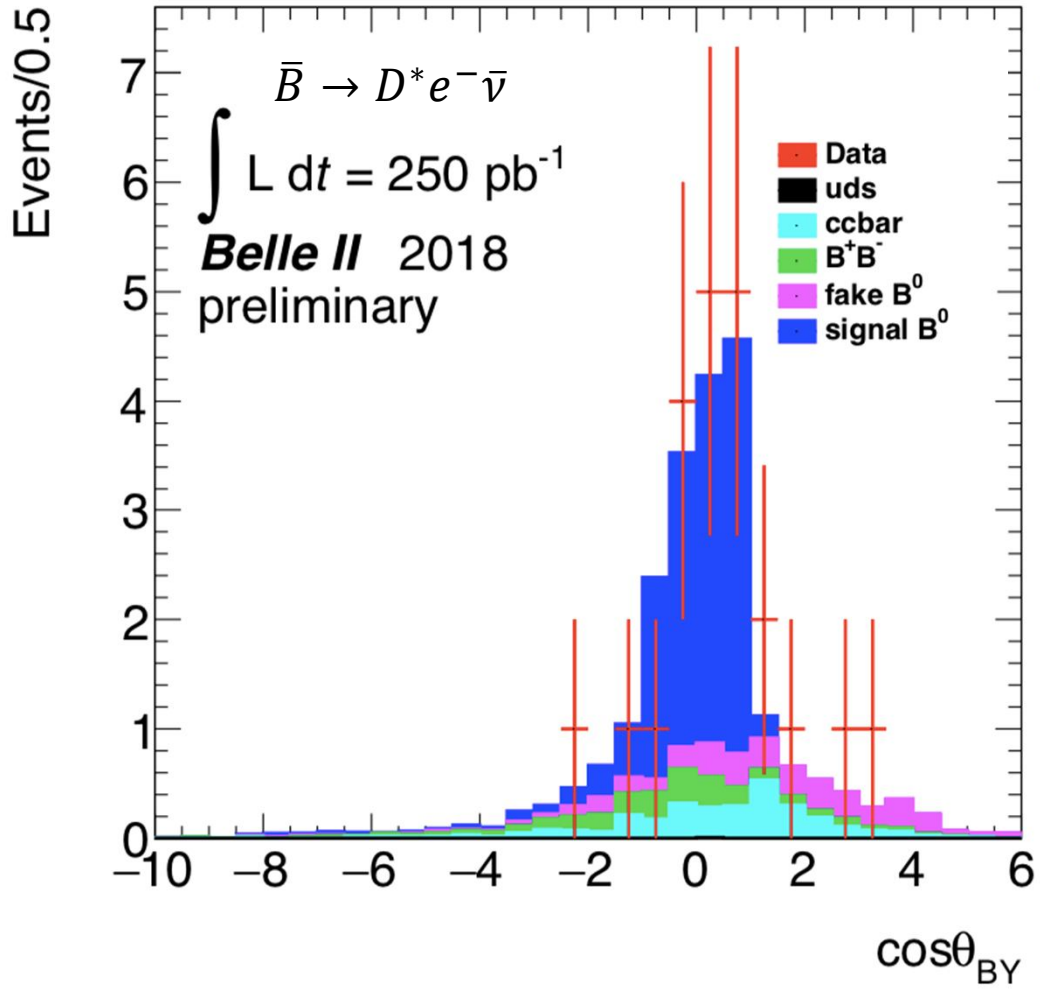
1983:
CLEO expt.

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 $\bar{B} \to D^{(*)} \tau^- \bar{\nu}$

Summary

- Highly successful program of $e^+e^- \to B\bar{B}$ machines of growing luminosity since the 1980s
- The Belle II experiment and the SuperKEKB collider take performance to a new level:
  - 40-fold increase in luminosity wrt. previous record
  - 21st-century detector technology
  - Probing new physics with unprecedented precision
- Phase-2 data: the collider and detector are performing well
- Look forward to starting the phase-3 physics run with the full detector in 2019.