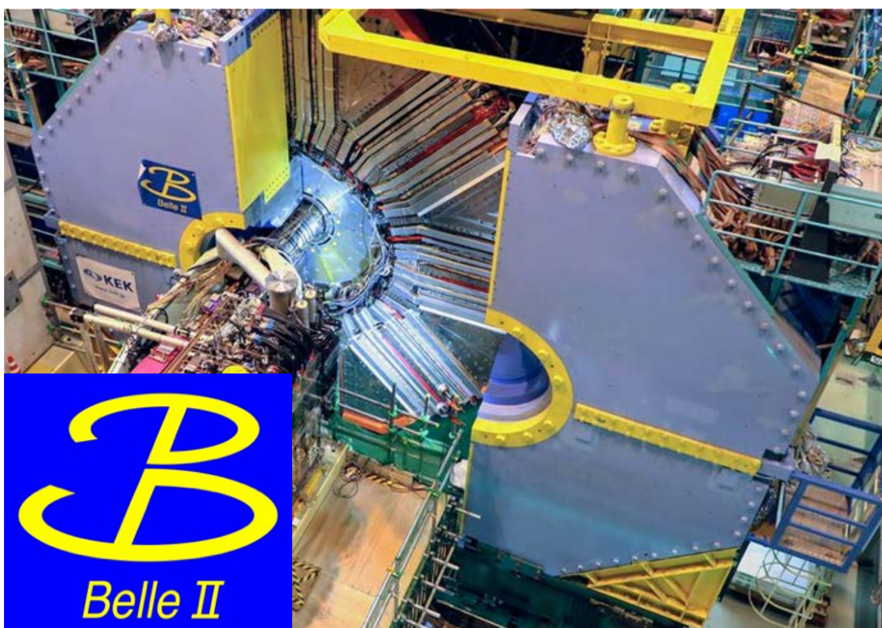
UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Department of Physics

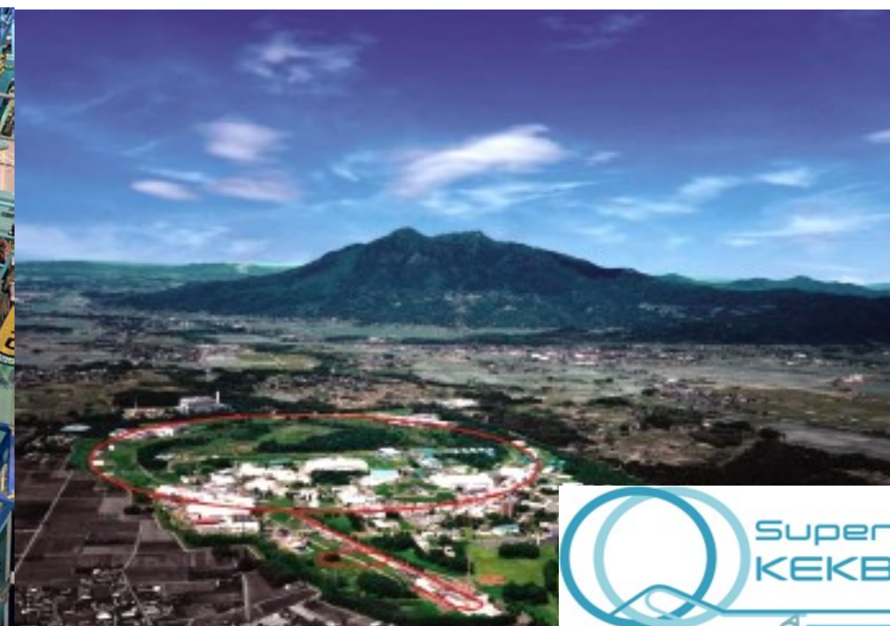
INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TRIESTE

Belle II experiment: status and prospects

Lorenzo Vitale – Univ. & INFN Trieste, Italy
On behalf of the Belle II Collaboration

8th ICNFC 2019, Crete, Greece, 2019.08.21-29





Talk outline

- Introduction:

  intensity frontier, flavor physics, B-factories
- Collider & Detector = Luminosity & Background challenge*
- Highlights from first physics run - spring 2019

  Detector performance

  First results**
- Prospects

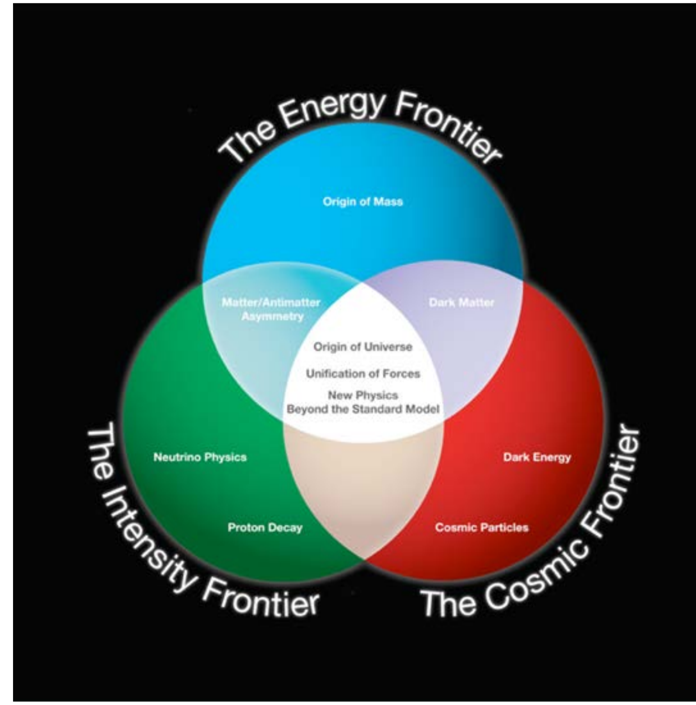
See also:

*P. Bambade “The SuperKEKB/BELLE II as a demonstrator of future colliders”

**P. Goldenzweig “First look at CKM parameters from early Belle II data”

**I. Komarov “Dark Sector Physics with Belle II: first results and prospects”

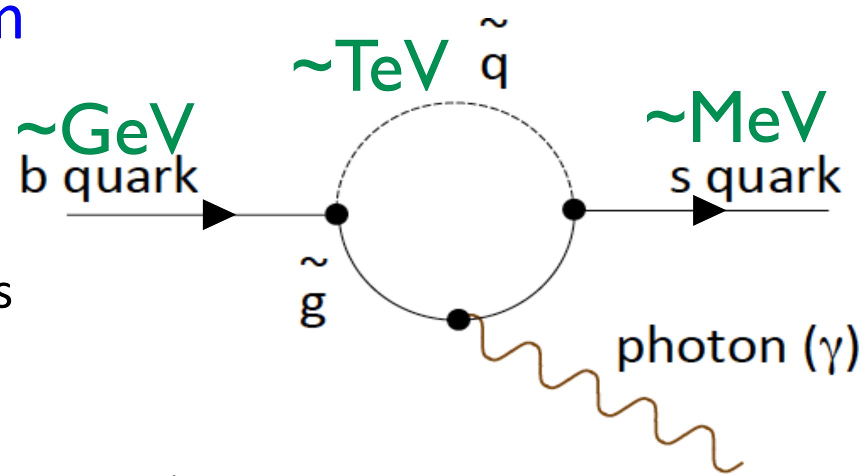
Intensity Frontier & Flavor Physics



Belle II is a leading **Flavor Physics** experiment at the **Intensity Frontier**

In **three fold approach** of near-mid term particle physics, Flavor Physics explores its goals with highest reachable intensity, being sensitive to New Physics - Beyond the Standard Model – up to the TeV scale in loop diagram

Typical example: a new particle that may appear in a loop diagram can deviate the related observables from the SM predictions

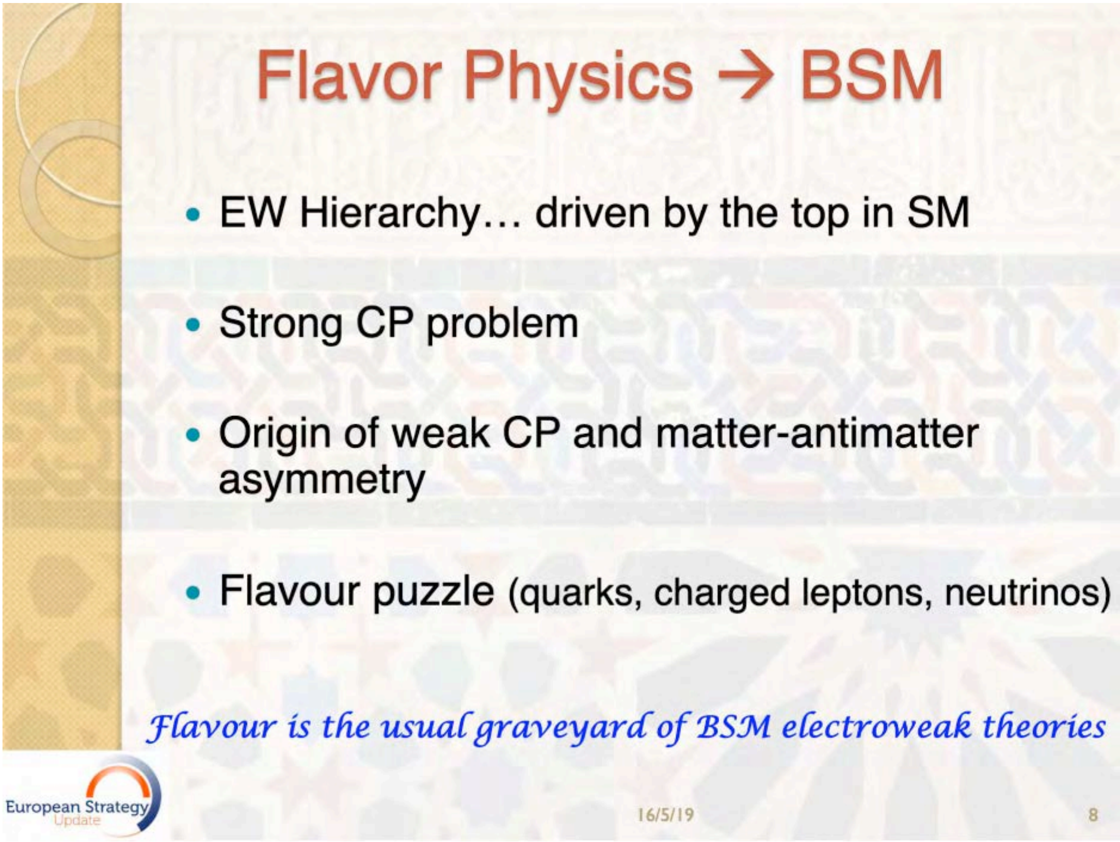


Flavor Physics to BSM

Widely endorsed approach

e.g. European Particle Physics Strategy Update 2018-2020

Summary talk from Zoccoli & Gavela Granada, 2019 May

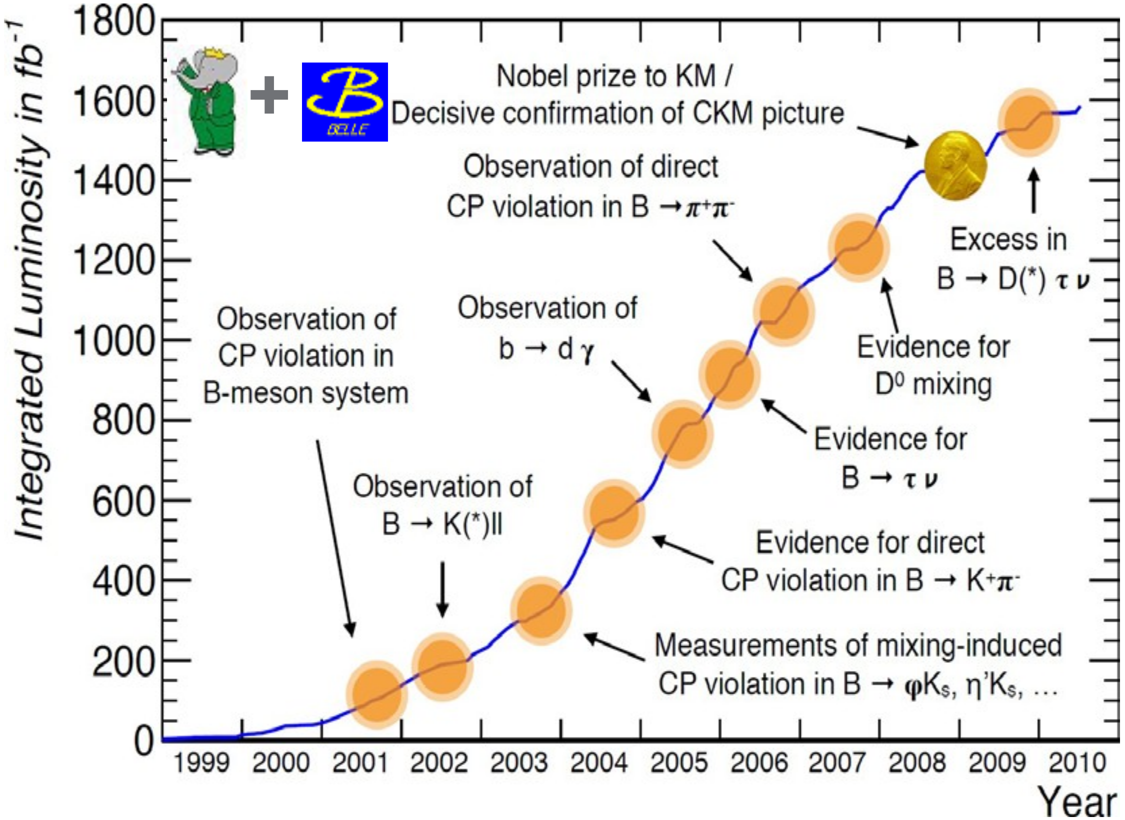


LHCb is the other leading **Flavor Physics** experiment

Belle II complements and competes with LHCb, similar goals, but different environment

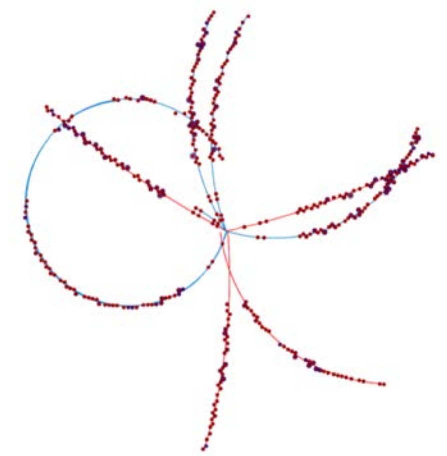
e^+e^- B-factory legacy

Belle II collects the inheritance of previous successful experiments at the e^+e^- B-factory: BaBar@PEPII and Belle@KEK, in total 1.6 ab^{-1}



The Physics of the B Factories

EPJ C74, 3026 (2014)



Success culminated in 2008

© The Nobel Foundation
Photo: U. Montan

Makoto Kobayashi

© The Nobel Foundation
Photo: U. Montan

Toshihide Maskawa

e^+e^- B-factory: keys of the success

- Colliders performance

  Endless order-of-magnitude improvements in luminosity

  But also long term steady operations and machine background control

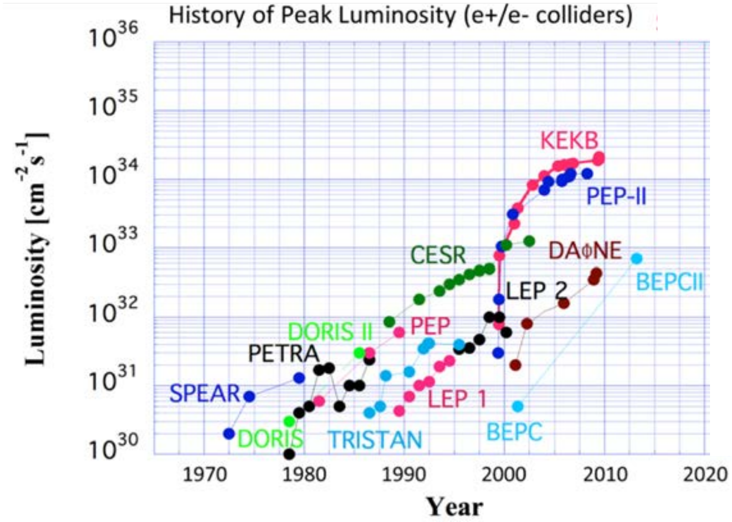
- e^+e^- clean initial state

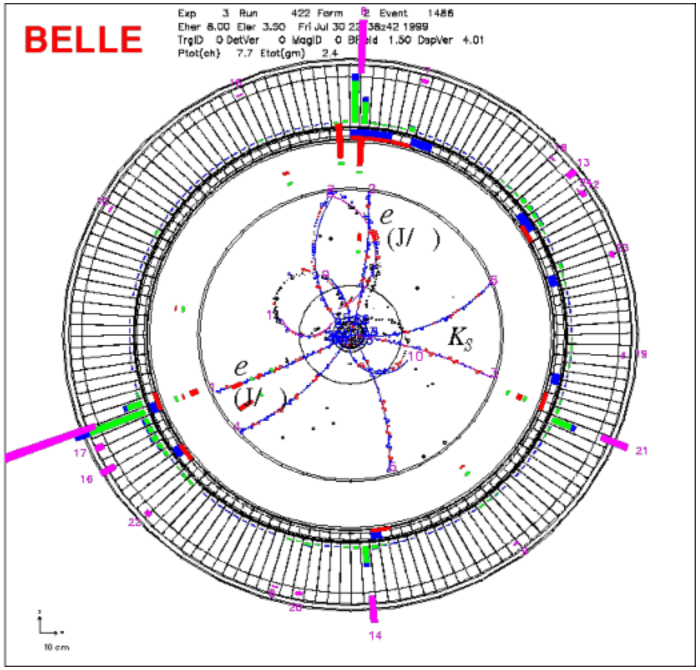
  Coherent, well defined, without additional interactions allowing low physics backgrounds, high trigger efficiency, kinematic constrains

- Detector performance

  Precise, efficient, fast, hermetic - as much as possible – in all aspects:

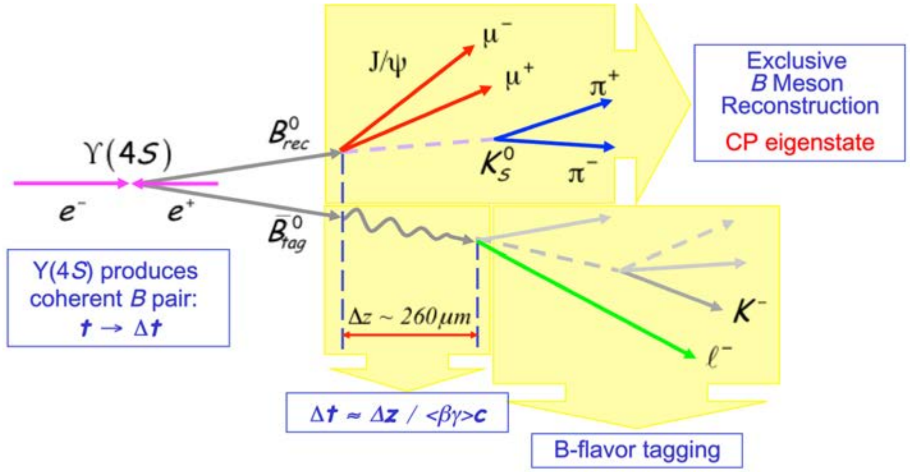
  Tracking, Vertexing, Particle ID, Neutral, DAQ





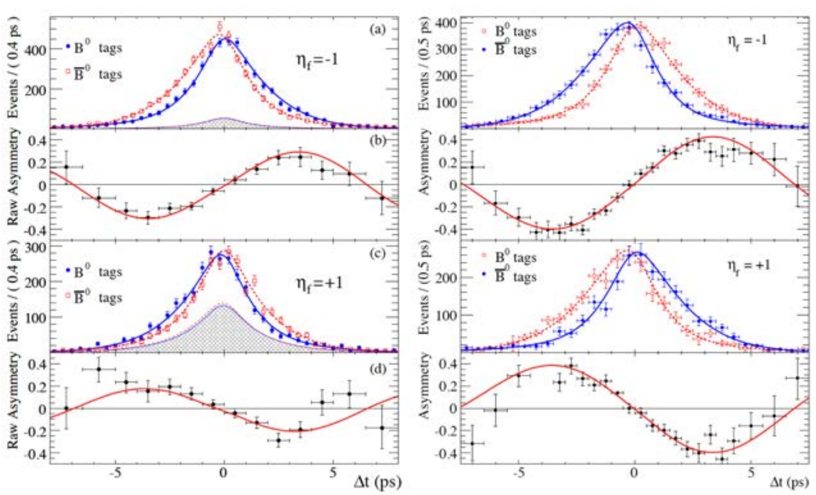
An example: Time Dependent CP Violation from discovery to precision measurements

Asymmetric beam energies allow measurement of vertex separation:
It allows to see time dependent CPV by interference between decay and mixing



$\Delta z \cong c\beta\gamma\tau$
BaBar Δz = 260 μm
Belle Δz = 200 μm
Belle II Δz = 130 μm

BaBar@PEPII   Belle@KEK

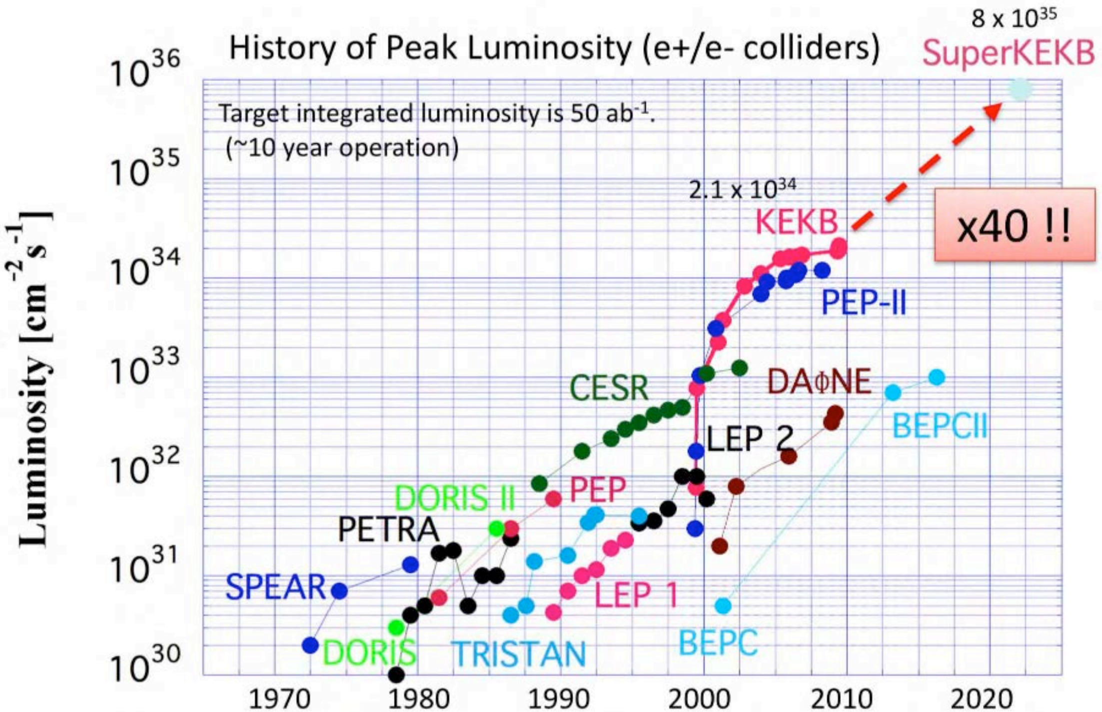


So why another e^+e^- B-factory?

Still several goals can be achieved, the among others:

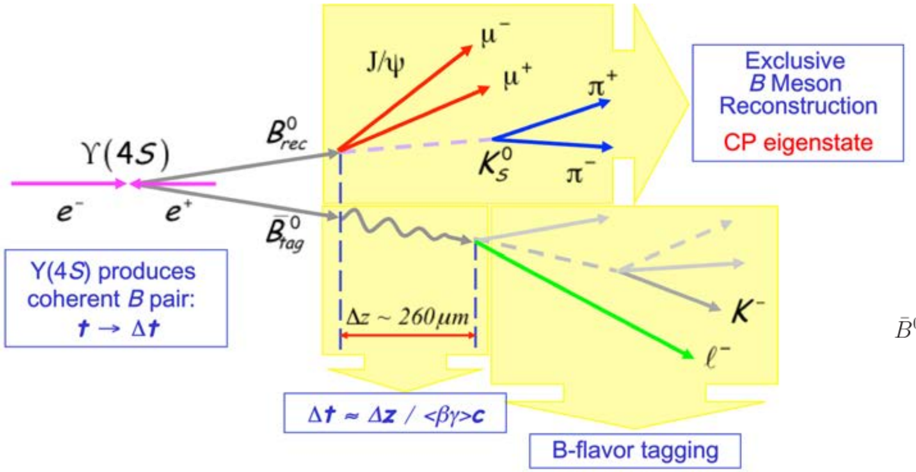
- Search/Limits of/on **New Physics -** Beyond Standard Model
- Precision measurements of CKM matrix elements
- CPV: TD in B decays, direct
- Rare or forbidden B,D, τ decays
- Dark sector searches

Belle II & SuperKEKB can raise the challenge with an increase of peak luminosity x40 !!

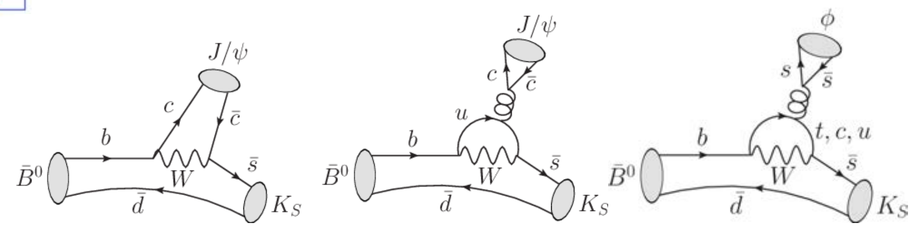


Time Dependent CP Violation at 50 ab^{-1} $J/\psi K_S$ vs $\eta' K_S$

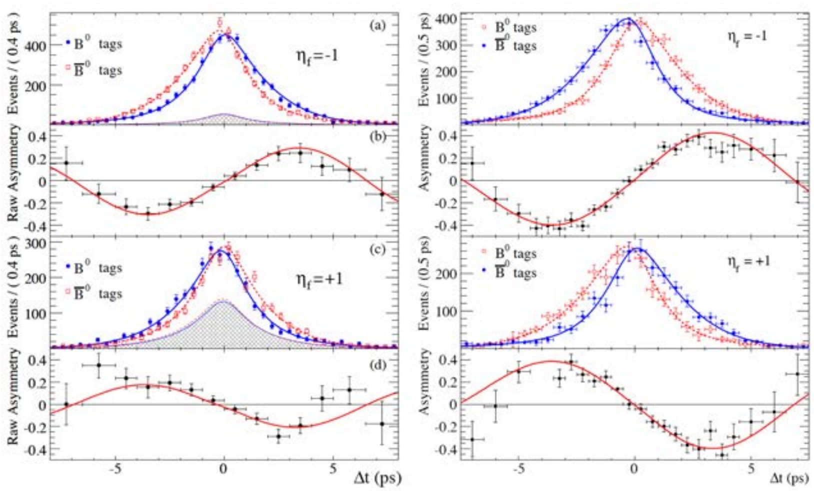
Asymmetric beam energies allow measurement of vertex separation:
It allows to see time dependent CPV by interference between decay and mixing

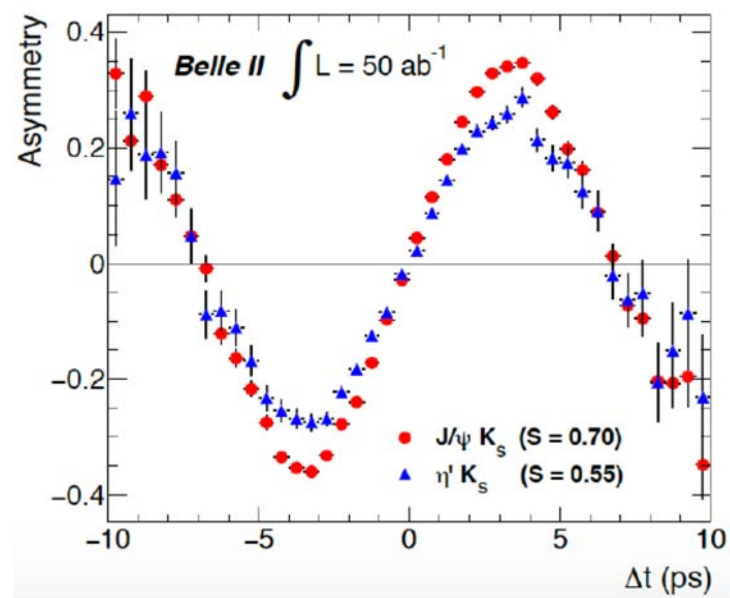


Golden mode vs gluonic penguin dominated b → s (sensitive to NP in loop)



BaBar@PEPII Belle@KEK



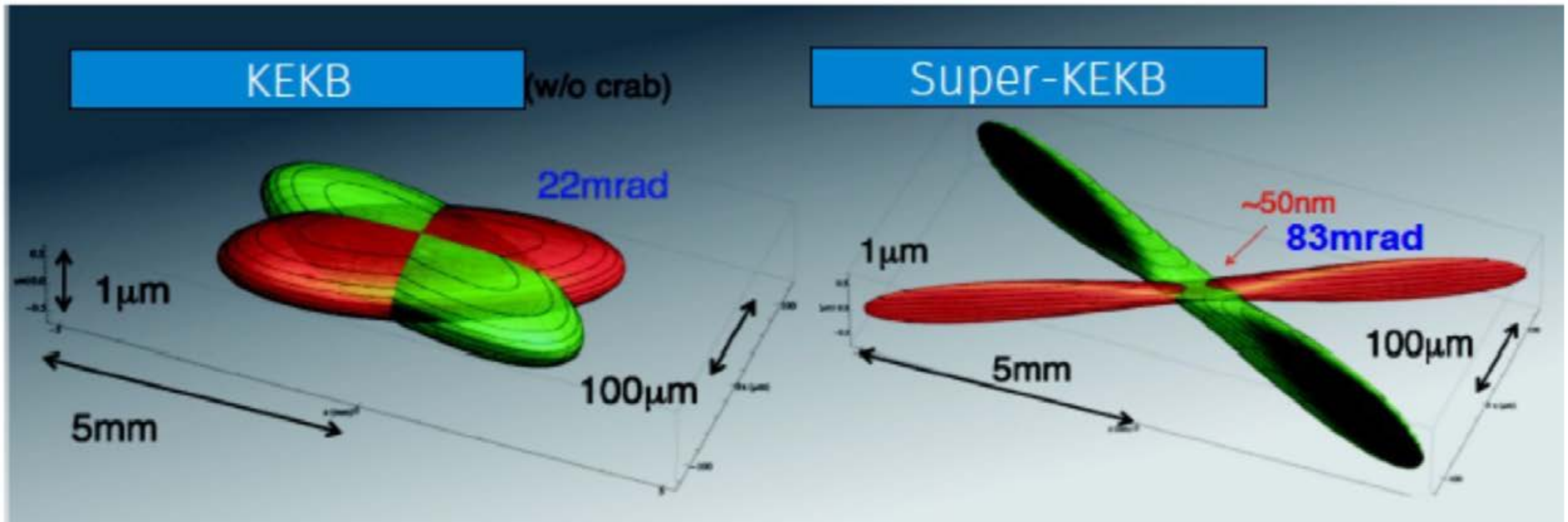


SuperKEKB: how to gain x40?

A x20 gain from “nano beam” scheme, proposed by P. Raimondi for SuperB:

- Beam size at interaction from (100x2) μm^2 KEKB to (10,000x50) **nm^2** SuperKEKB
- Lower emittance & beta*, higher crossing angle, large Piwinski angle

Another x2 gain by increasing beam currents



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20 factor 2-3

SuperKEKB: major upgrade

Major upgrades towards KEKB × 40

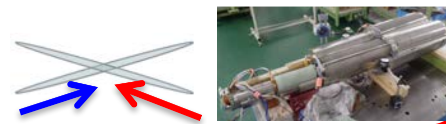
$$L = 8\times 10^{35}\left[cm^{-2}s^{-1}\right] \propto \frac{I_{e\pm}\xi_{\pm y}}{\beta_y^*}.$$

Taking advantage of existing items

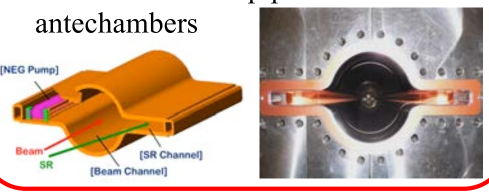
- **the KEKB tunnel,**
- **the KEKB components as much as possible!**

Belle detector is upgraded to Belle II

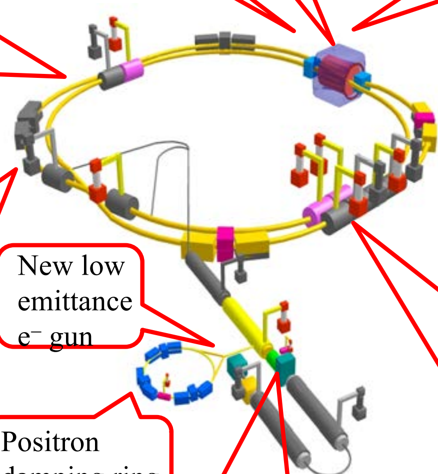
New QCS magnet for Nano-beam scheme
New superconducting final focusing quads



New beam pipe& bellows
TiN-coated beam pipe with antechambers



New design for IR

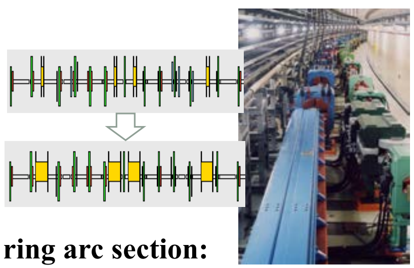


Add / modify RF systems for higher beam current

Main ring arc and straight section:
Redesign the lattices of both rings to reduce the emittance

KEKB

Super KEKB



Main ring arc section:
LER: Replace all main dipoles
HER: Preserve the present cells

New low emittance e⁻ gun

Positron damping ring

New e⁺ source

New and re-use wiggler magnets are mixed:
Oho section (LER&HER)
Nikko section (LER)

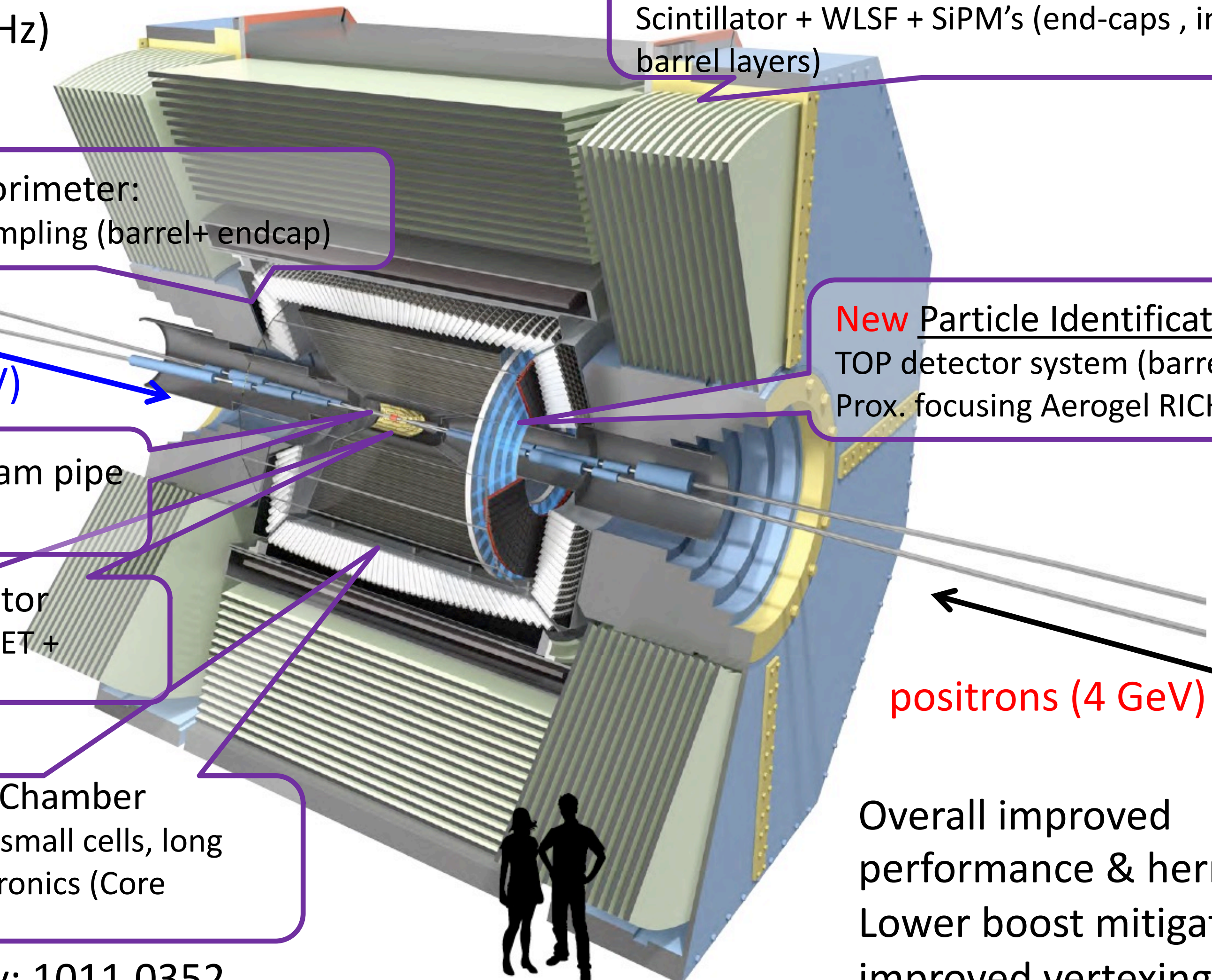
10

Change beam energies to solve the problem of short LER lifetime

From Y. Funakoshi, IAS2017

Belle II Detector

Deal with higher background (x10-20), Radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)



Upgraded KLong and Muon detector:
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's (end-caps , inner 2 barrel layers)

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

electrons (7 GeV)

New Particle Identification
TOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd)

New beryllium beam pipe
20mm diameter

New VerteX Detector
~2 layers pixels DEPFET +
4 layers strips DSSD

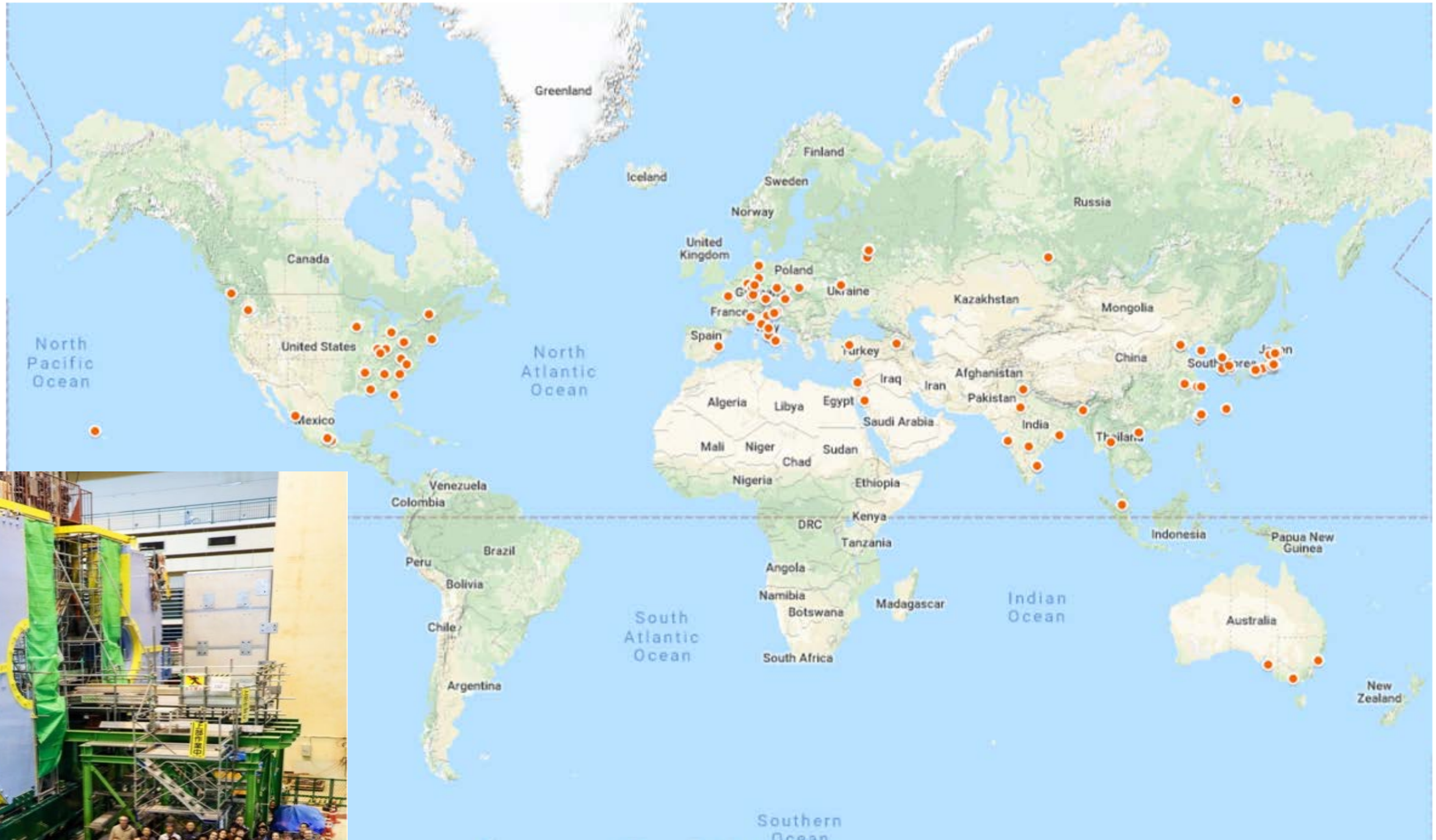
positrons (4 GeV)

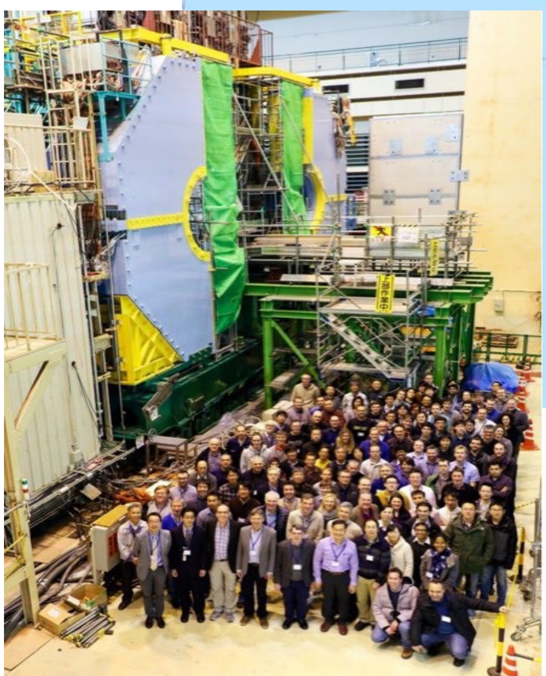
New Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics (Core element)

Overall improved performance & hermeticity
Lower boost mitigated by improved vertexing

Belle II TDR, arXiv: 1011.0352

Belle II international collaboration

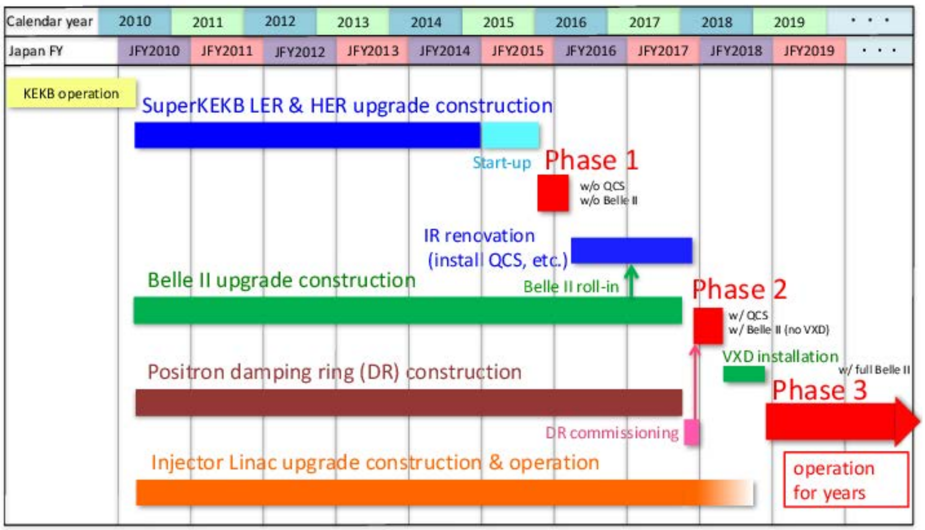


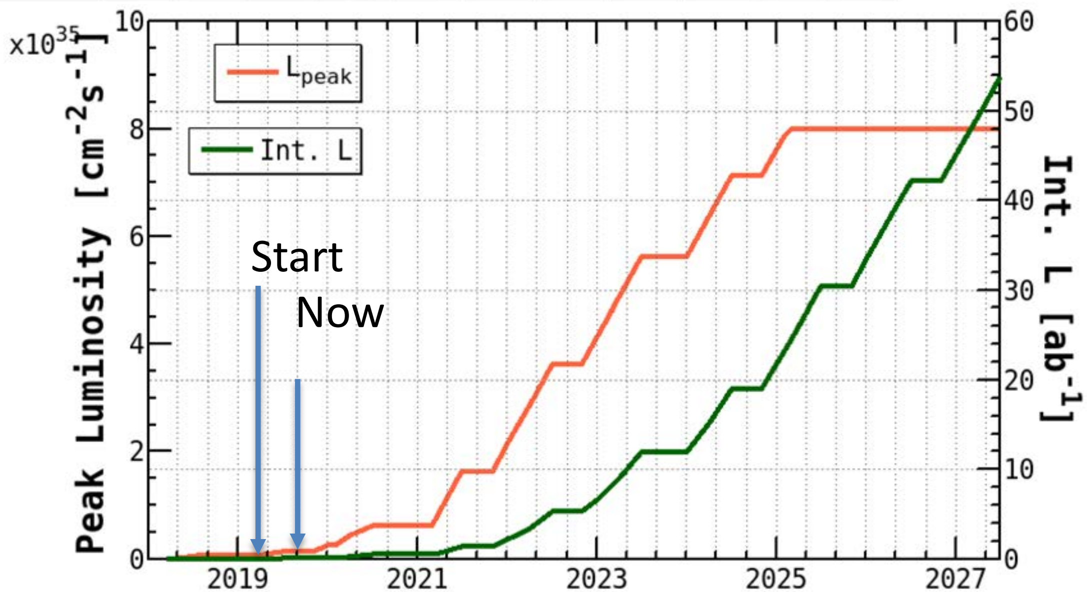


Belle II now has ~947 researchers from 112 institutions in 26 countries

After construction & commissioning runs: Physics run (started in Spring 2019)

SuperKEKB/Belle II schedule





Phase 1: Optics Commissioning
Dedicated detectors for background studies
No collisions, no Belle II
Brand new 3 km positron ring.
Feb-June 2016

Phase 2: Pilot run
First Collisions (0.5 fb^{-1}).
Belle II w/o VXD (just a sector)
Superconducting Final Focus,
add positron damping ring,
April 27-July 17, 2018

Phase 3: → Physics run with Full Belle II Detector
Just started
1st run March 27-July 1st, 2019

Belle II/SuperKEKB Phase 3 Goals

Early aims: Resolve the problems uncovered in the Phase 2 pilot run. Demonstrate SuperKEKB Physics running with acceptable backgrounds, and all the detector, readout , DAQ and trigger capabilities of Belle II including tracking, electron/muon id, high momentum PID, and especially the *ability to do time-dependent measurements needed for CP violation.*

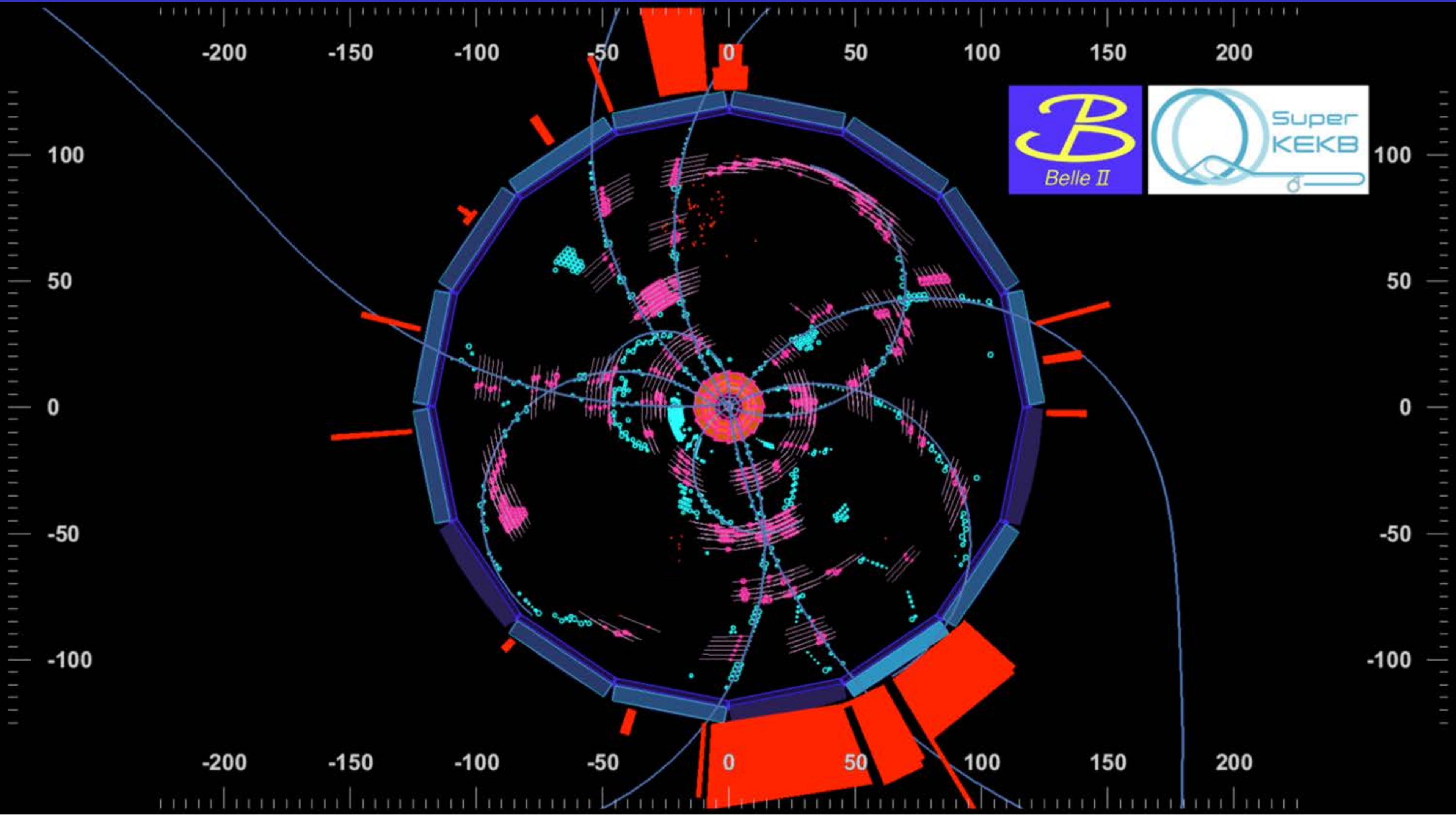
Belle II VXD ~6 layers installed on Nov 21, 2018
PXD L1 & two ladders of L2
SVD (4 layers)

Carry out dark sector searches/measurements as well.

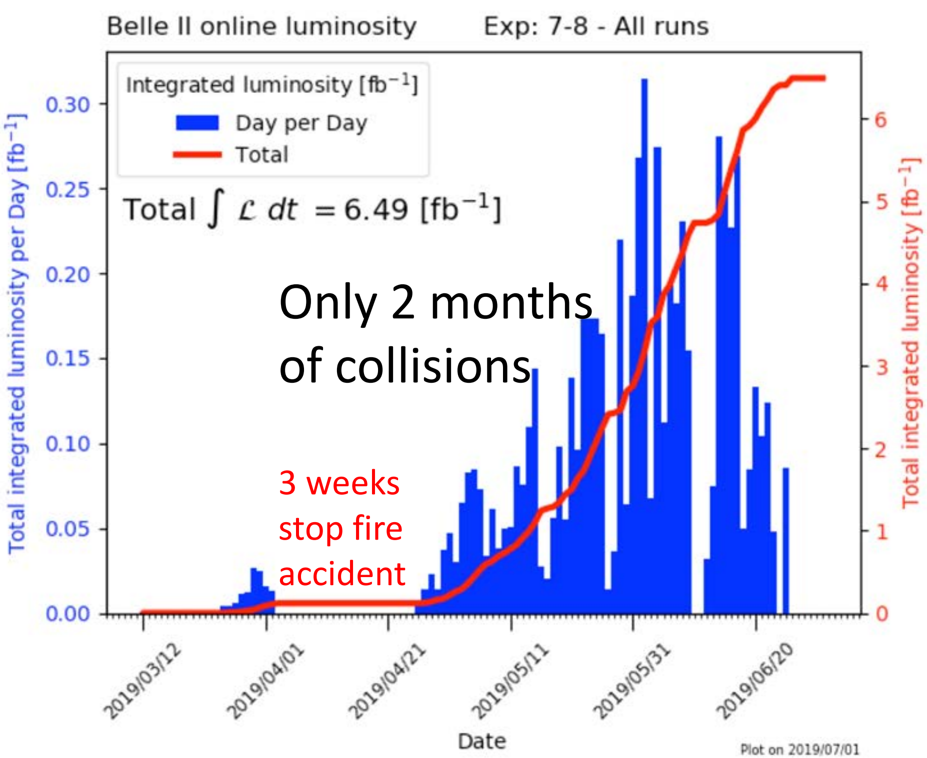
Long term: Integrate the world's largest e^+e^- data samples and observe or constrain New Physics.

From T. Browder, LP 2019

1st physic run - 1st B-B like event



First run, Spring 2019, ~~3~~ 2 months



Some issues solved

e.g. continuous injection works well

Challenge: keeping bkg under control → Beam abort crucial

Results shown are based on a smaller data set

Progressively squeezing β_y^* to increase L

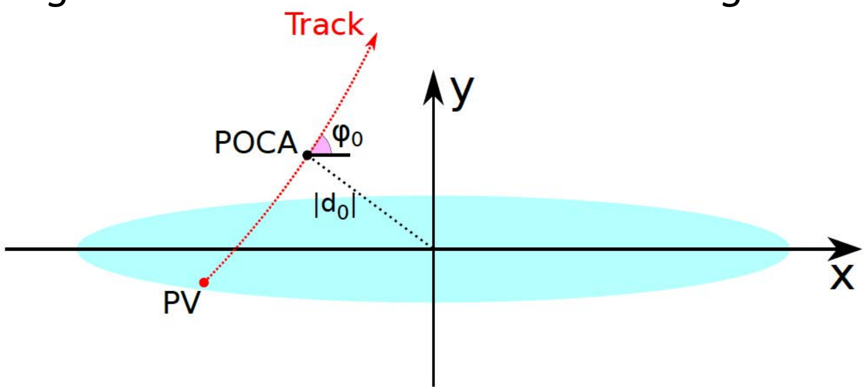
L_{peak}(in physics) ~6 x 10^{33}/cm^2/s β_y^*=3mm

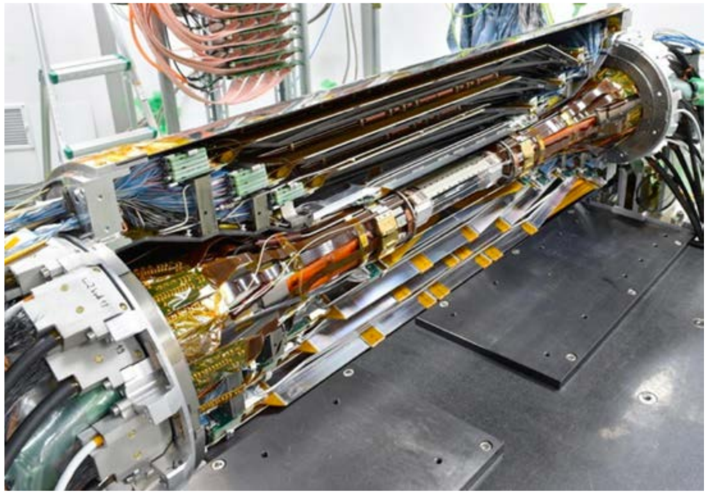
L_{peak}(det OFF) ~1.2 x 10^{34}/cm^2/s β_y^*=2mm
Close to PEP-II best, but bkgs X3 too large to turn on Belle II

Parameter	Achieved	Target
I_{LER}(max)(A)	0.880	2.6
I_{HER}(max)(A)	0.940	3.6
β_y^* (mm)	2	0.3
# bunches	1576	2364
L_{peak}(cm^{-2} s^{-1})	6.1 x 10^{33}	8 x 10^{35}
L(det OFF)	12 x 10^{33}	

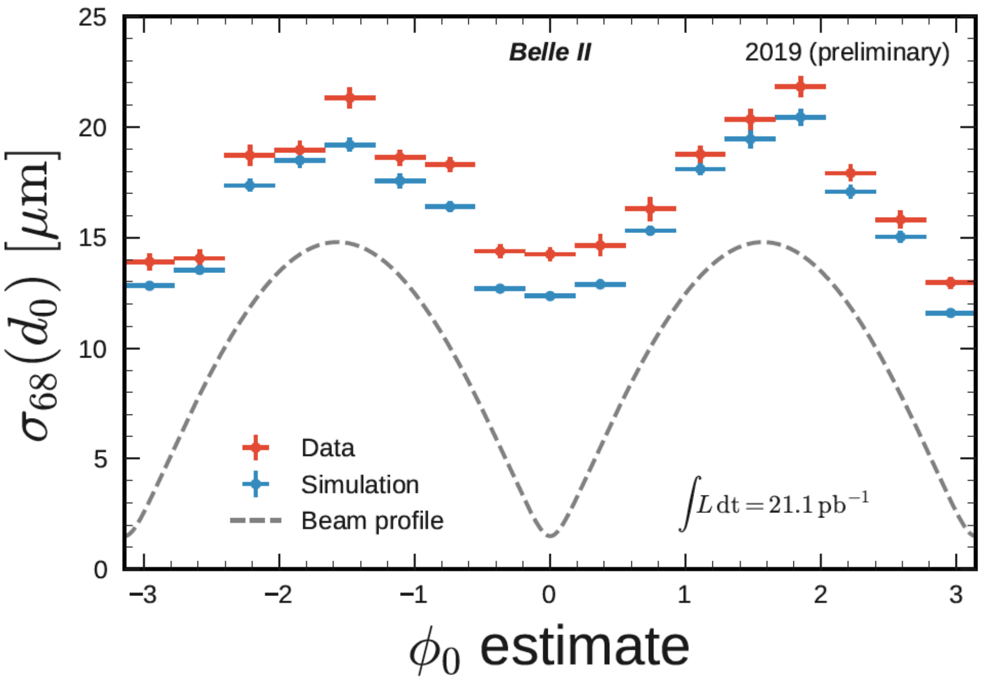
VXD resolution in impact parameter distributions in two-track events

Alignment and calibration are working well





Width of impact parameter resolution distribution

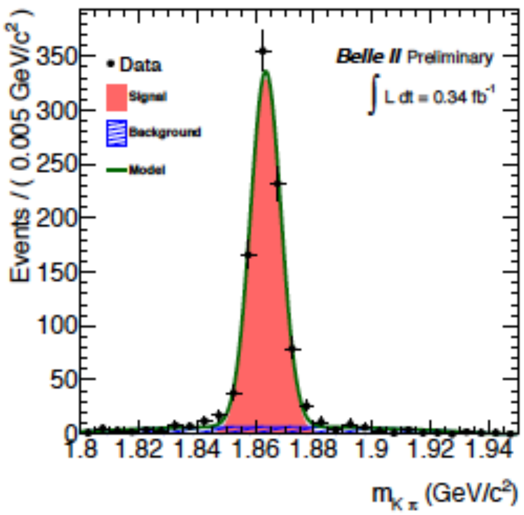


VXD resolution in impact parameter ~14 μm

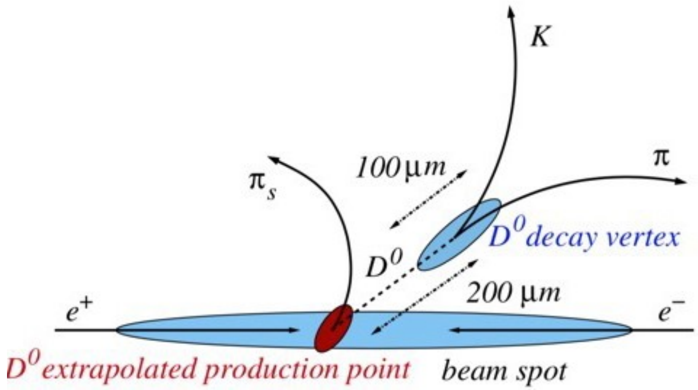
x2 better than Belle

PXD 1st layer R=14mm

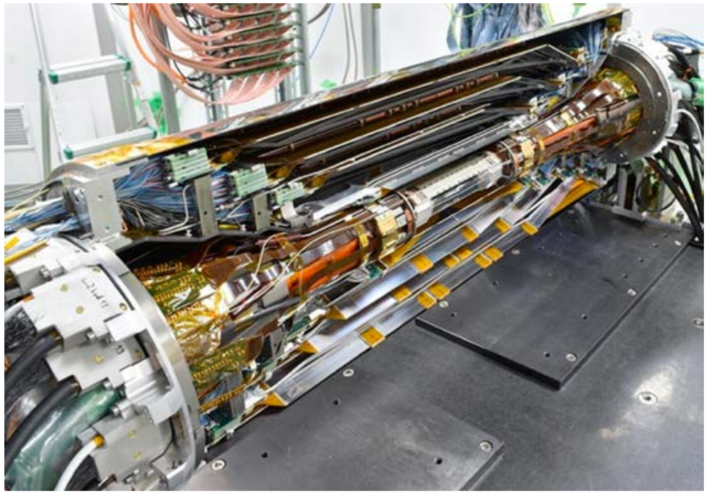
D^0 lifetime: demonstration of VXD performance

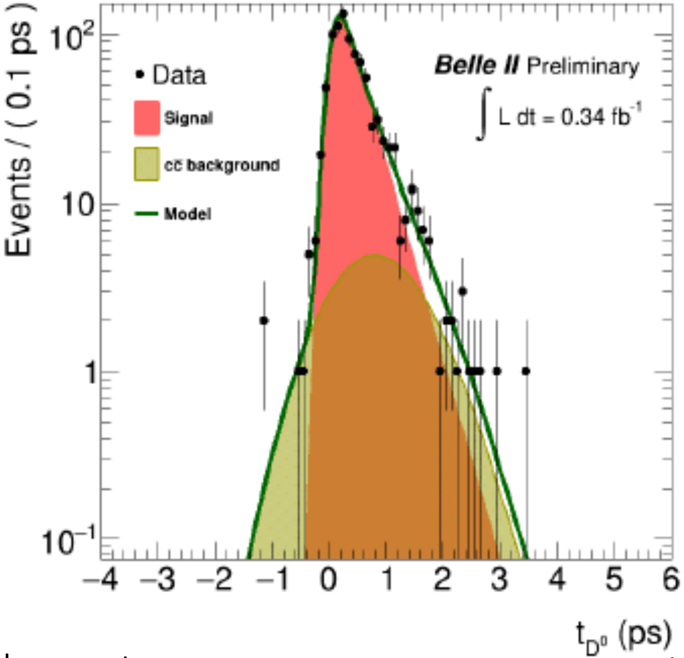


Uses a small data set
~1/15

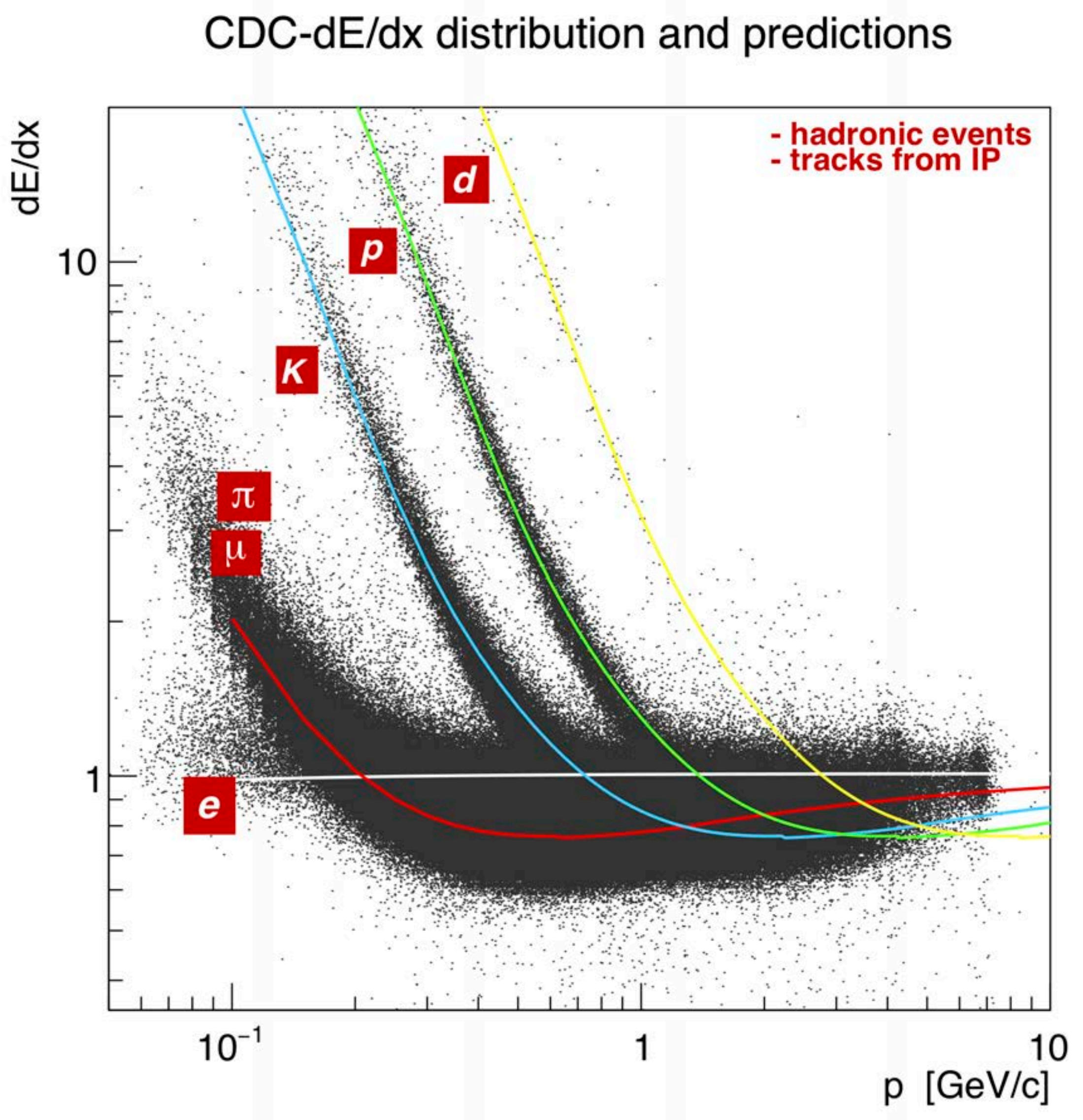


$$\tau_{D^0} = 370 \pm 40(stat)\ \text{fs}$$





dE/dx in CDC


CDC-dE/dx distribution and predictions
dE/dx
10
1
10^{-1}
1
10
p [GeV/c]
- hadronic events
- tracks from IP
d
p
K
π
μ
e

PID performance

Particle IDentification (π, K, e, μ, ...) is crucial:

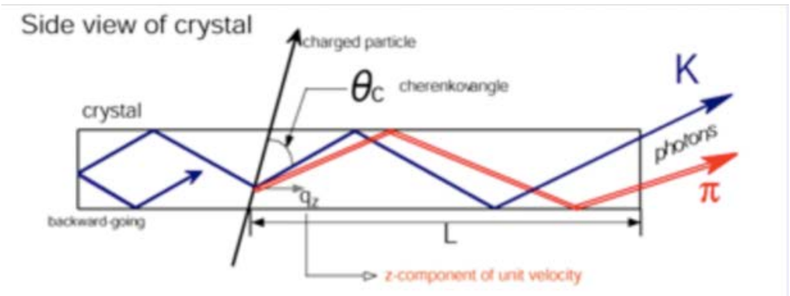
- particle reconstruction
- B-flavour tagging

Contributions from sub-detectors: here an example of K efficiency & mis-ID, from TOP (barrel) only and combined with CDC dE/dx, ARICH (forward endcap)

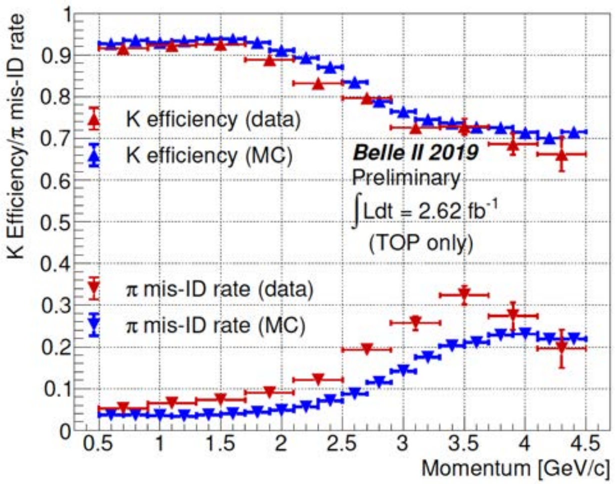
Measured on a control sample:

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

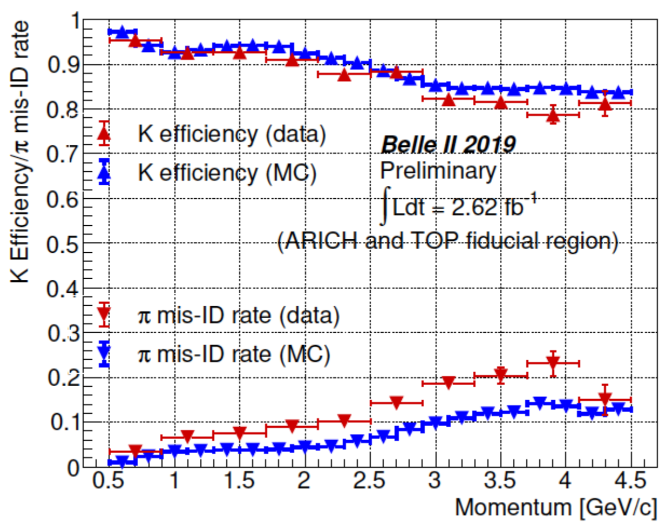
compared with MC expectations



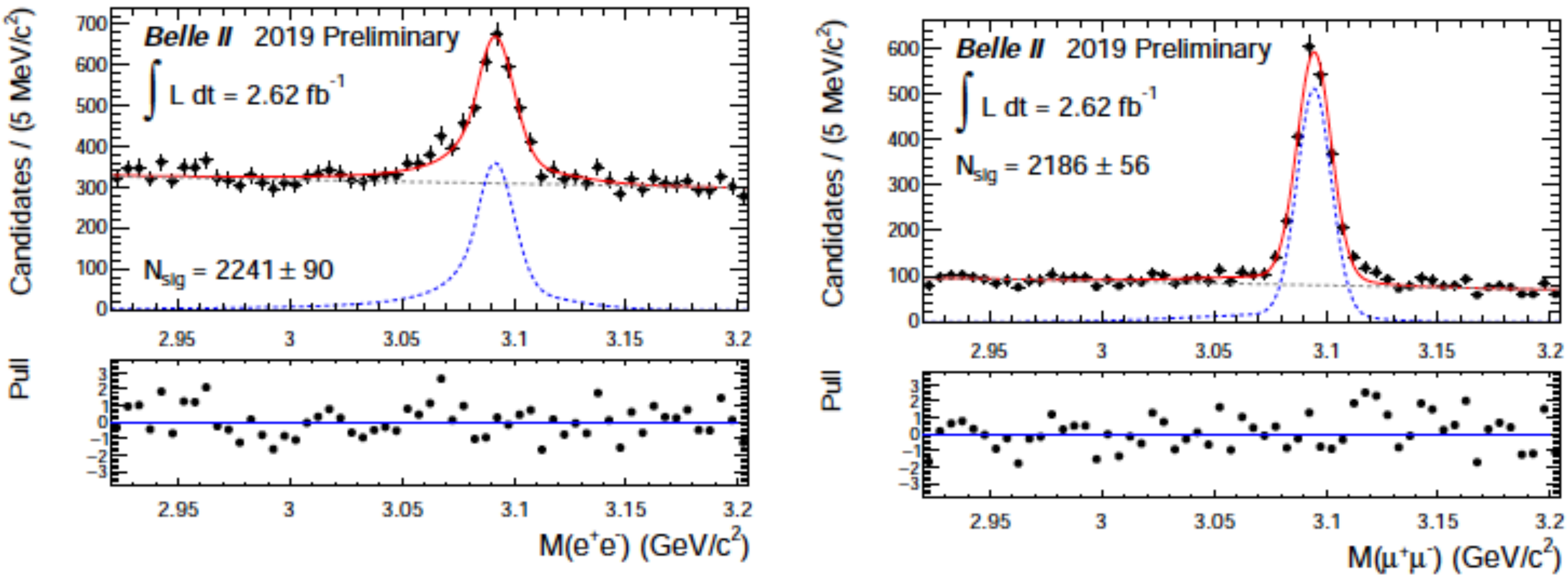
K ID from TOP only



K ID from CDC, TOP, ARICH

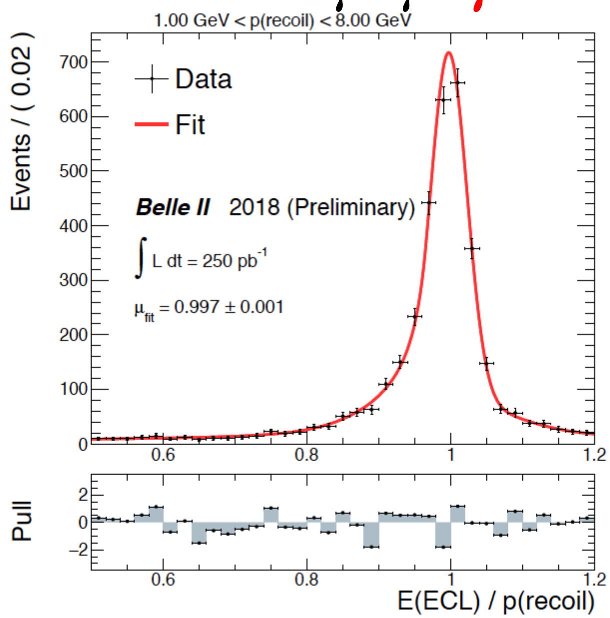


$J/\psi \rightarrow e^+e^-, \mu^+\mu^-$: equally good

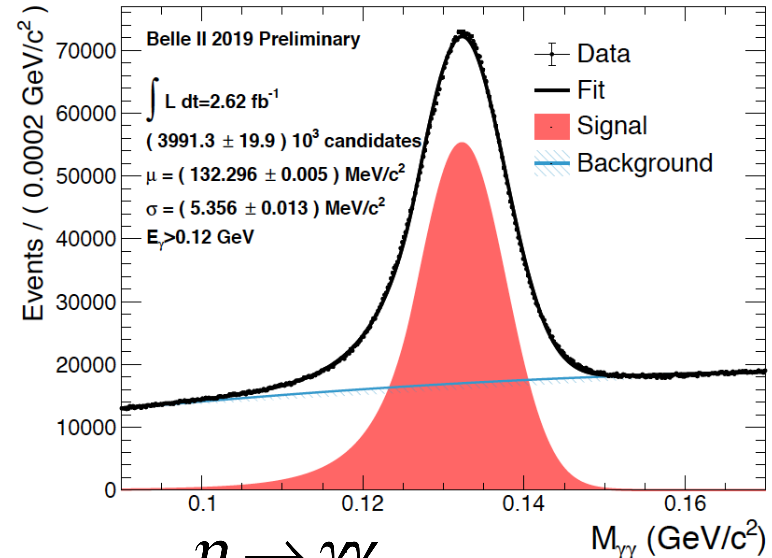


Photons

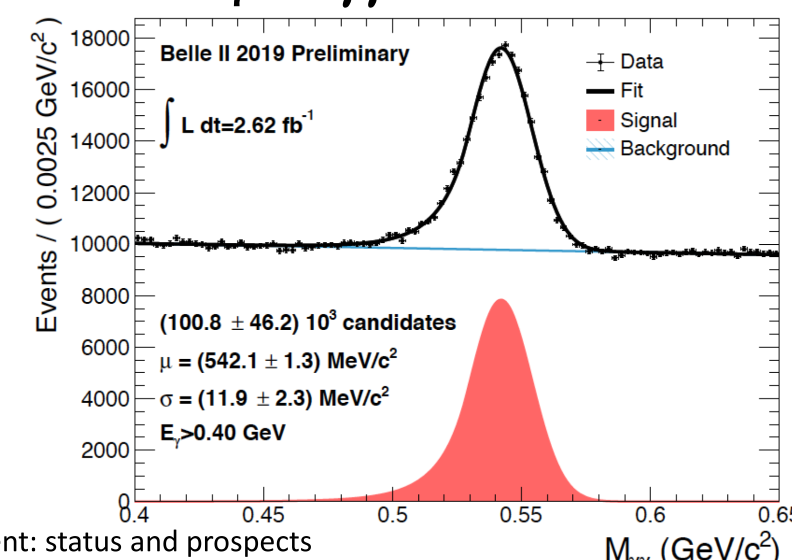
$e^+e^- \to \mu^+\mu^-\gamma$



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



$\eta \to \gamma\gamma$



Single Photon Lines → ISR γ for Dark sector

More on Dark in I.Komarov talk

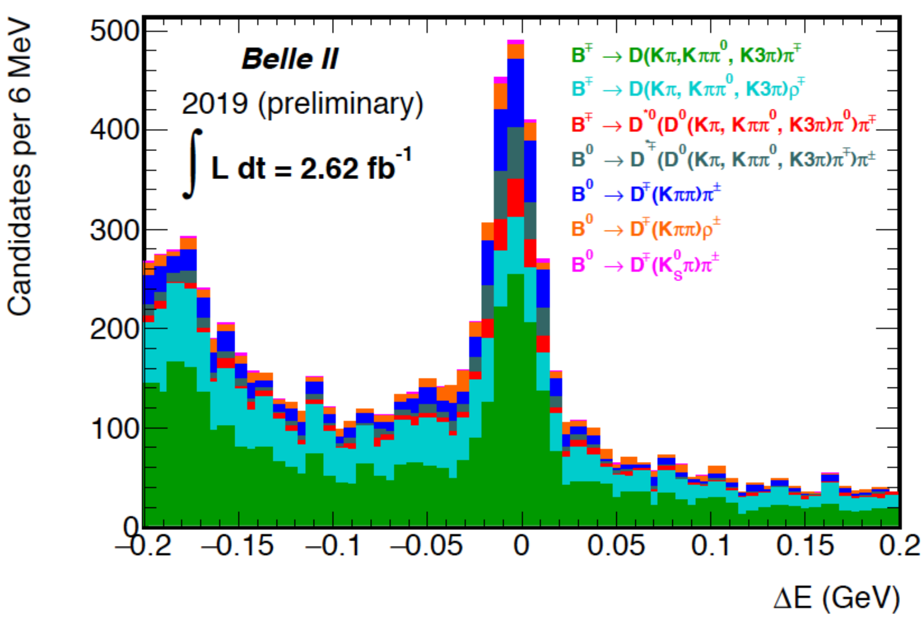
$B \to D^{(*)}h$ exclusive reconstruction

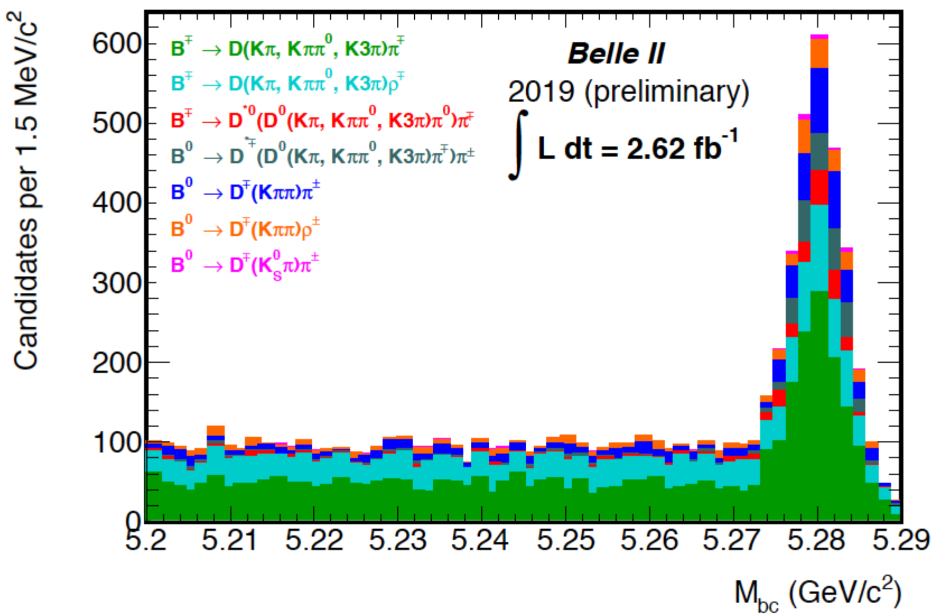
Usual two the kinematical variables

$$\Delta E = E_{cm} / 2 - E_{recon}$$

beam-constrained invariant mass

$$M_{bc} = \sqrt{(E_{cm} / 2)^2 - p^2_{recon}}$$

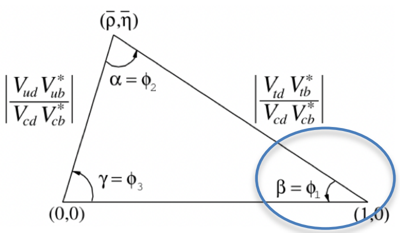


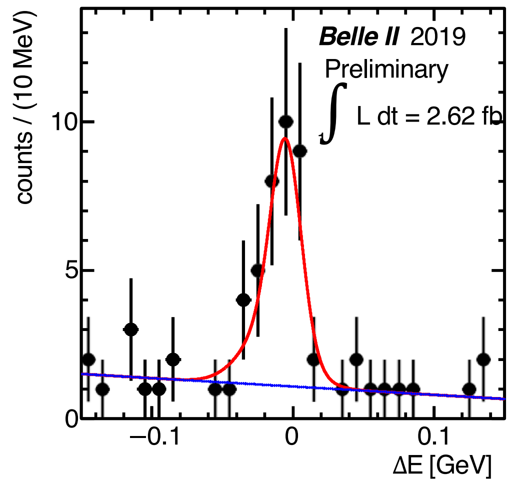


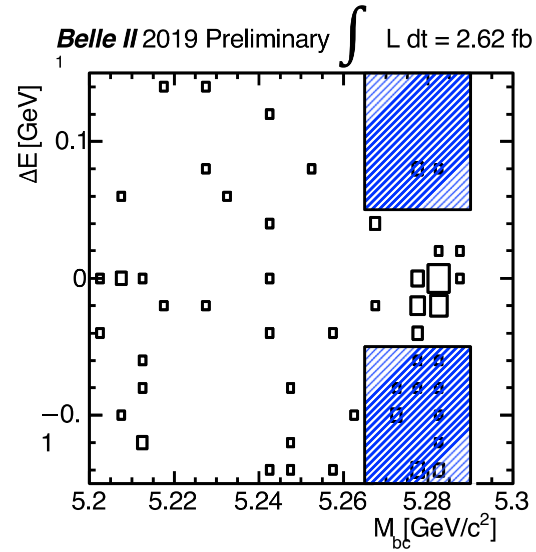
2200 Fully reconstructed hadronic B decays in $2.6 fb^{-1}$

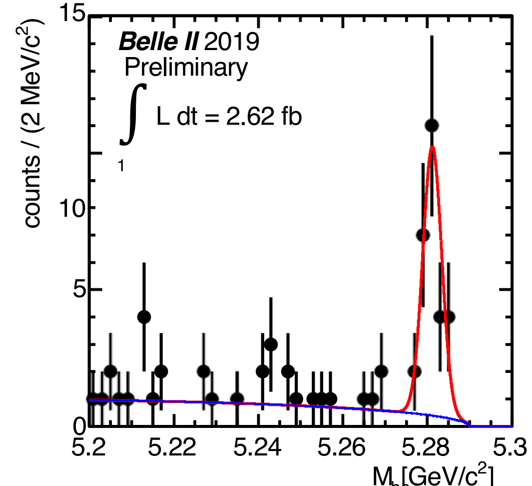
$B^0 \to J/\psi Ks$

Golden CP eigenstate mode for CPV, CKM angle sin2β ($\sin 2\phi_1$)









Signal yield:

$N(B^0 \to J/\psi K_S) = 26.9 \pm 5.2$

More in P. Goldenzweig "First look at CKM parameters from early Belle II data"

Prospects: Physics

https://arxiv.org/abs/1808.10567

Outcome of the B2TIP (Belle II Theory Interface) Workshops
Emphasis is on New Physics (NP) reach.

Strong participation from theory community,
lattice QCD community and Belle II experimenters.
689 pages, submitted to PTEP, Oxford Academic

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

E. Kou[74,¶,†], P. Urquijo[143,§,†], W. Altmannshofer[133,¶], F. Beaujean[78,¶], G. Bell[120,¶], M. Beneke[112,¶], I. I. Bigi[146,¶], F. Bishara[148,16,¶], M. Blanke[49,50,¶], C. Bobeth[111,112,¶], M. Bona[150,¶], N. Brambilla[112,¶], V. M. Braun[43,¶], J. Brod[110,133,¶], A. J. Buras[113,¶], H. Y. Cheng[44,¶], C. W. Chiang[91,¶], M. Ciuchini[58,¶], G. Colangelo[126,¶], H. Czyz[154,29,¶], A. Datta[144,¶], F. De Fazio[52,¶], T. Deppisch[50,¶], M. J. Dolan[143,¶], J. Evans[133,¶], S. Fajfer[107,139,¶], T. Feldmann[120,¶], S. Godfrey[7,¶], M. Gronau[61,¶], Y. Grossman[15,¶], F. K. Guo[41,132,¶], U. Haisch[148,11,¶], C. Hanhart[21,¶], S. Hashimoto[30,26,¶], S. Hirose[88,¶], J. Hisano[88,89,¶], L. Hofer[125,¶], M. Hoferichter[166,¶], W. S. Hou[91,¶], T. Huber[120,¶], S. Jaeger[157,¶], S. Jahn[82,¶], M. Jamin[124,¶], J. Jones[102,¶], M. Jung[111,¶], A. L. Kagan[133,¶], F. Kahlhoefer[1,¶], J. F. Kamenik[107,139,¶], T. Kaneko[30,26,¶], Y. Kiyo[63,¶], A. Kokulu[112,138,¶], N. Kosnik[107,139,¶], A. S. Kronfeld[20,¶], Z. Ligeti[19,¶], H. Logan[7,¶], C. D. Lu[41,¶], V. Lubicz[151,¶], F. Mahmoudi[140,¶], K. Maltman[171,¶], S. Mishima[30,¶], M. Misiak[164,¶],

Physics program with $50ab^{-1}$

1808.10567

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K^0_S\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K^0_S\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K^0_S\pi^+\pi^-)$	***	0.03	Belle II
$\phi(D^0 \to K^0_S\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

Precision CKM Unitarity Triangle

CP Violation in b ⟶ s penguin decays

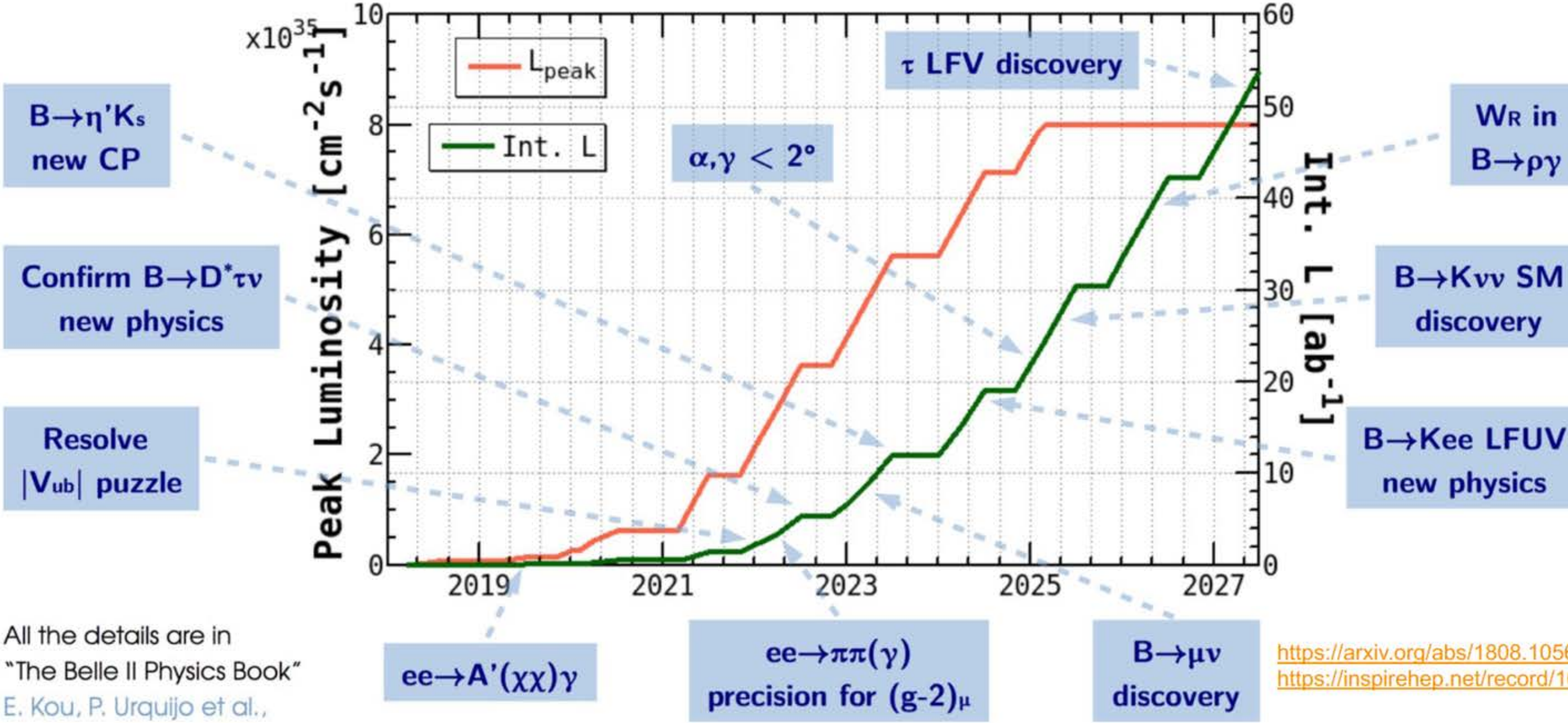
(Semi-)leptonic B decays

Radiative & EW Penguins

Charm

Lepton flavor violating τ decays
+ Dark sector & much more…

Prospects: an (optimistic) future roadmap



All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/

From F. Forti, EPS-HEP 2019

Prospects: beam backgrounds

e+e- colliders are “clean”, but…
at high luminosity, beam-induced backgrounds become a challenge

at the highest luminosities,
QED backgrounds will dominate:

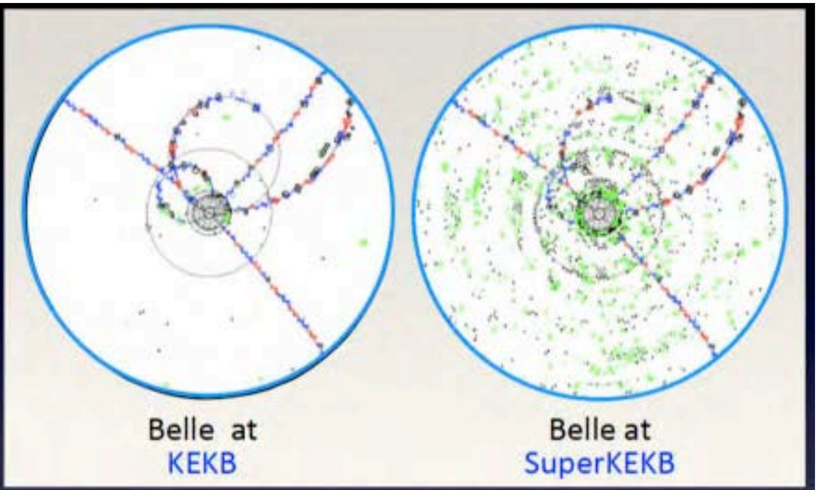
$e^+e^- \rightarrow e^+e^-\gamma$

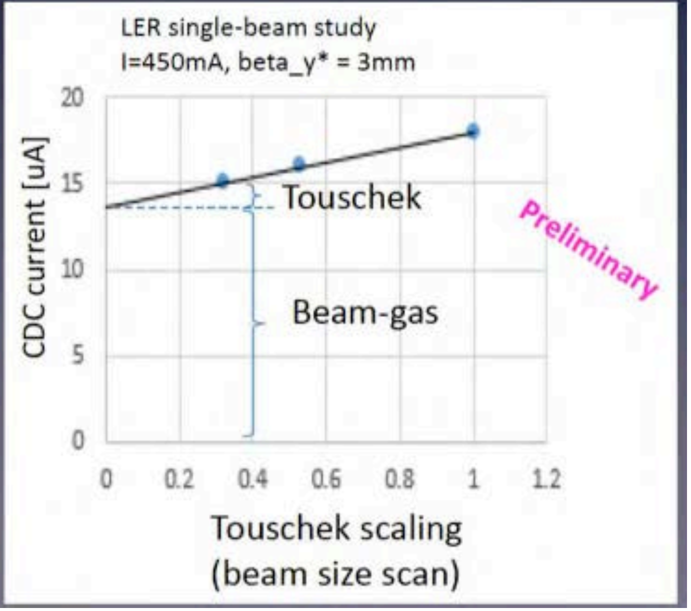
$e^+e^- \rightarrow e^+e^-e^+e^-$

at present, single beam backgrounds are predominant, higher in LER:

- beam-gas (residual gas in beam pipe)
- Touschek (intra-bunch scattering)
- injection-induced
- “dust events”, occasional large losses

CDC HV trips with large bkgd
beam abort protection against radiation spikes
simulations & collimator studies





From L. Lanceri, SSI 2019

Prospects: Detector improvement program

- Short term:
  - Replacement of TOP PMTs with ALD PMTs
  - Replacement of the PXD with complete detector
  - DAQ upgrade
- Medium term:
  - Looking at options to make the detector more robust against background and radiation bursts
- Longer term:
  - Started looking at luminosity upgrade possibilities

  e.g. Belle II VXD open Workshop https://indico.cern.ch/event/810687/

From F. Forti, EPS-HEP 2019

Conclusions

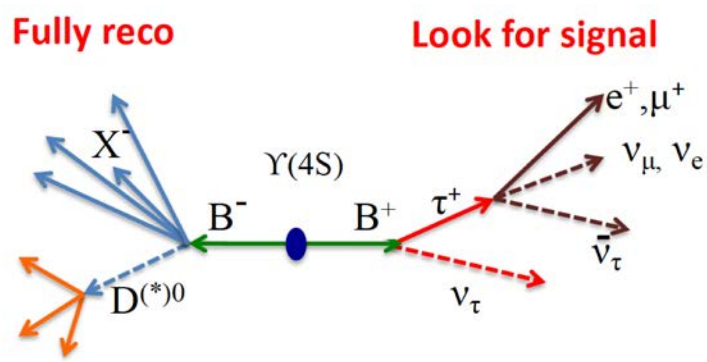
- Flavor physics at high luminosity e^+e^- B-factory offers a very inviting and challenging menu
- The first physics run of Belle II at SuperKEKB in Spring 2019 has just completed with 6.5 fb^{-1}
- Detector and accelerator initial performances are good, but the road is still very long to achieve the goals
- Luminosity and beam backgrounds are the main challenges
- Looking forward for more data

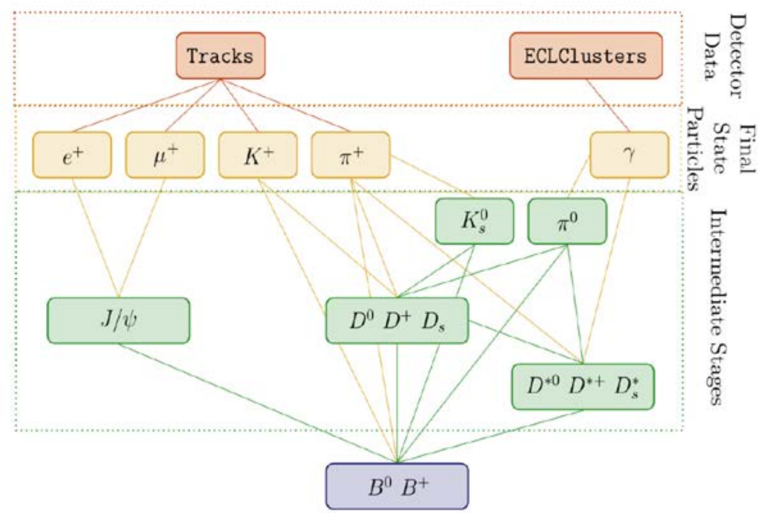
BACK-UP SLIDES

FEI Full Event Interpretation technique

based on boosted decision trees (BDTs, a machine learning technique)

- Fully reconstruct B decays in many many modes to reduce backgrounds and provide tagging
- Useful for channels with weak exp. signature
  - Missing momentum (many neutrinos in the final state)
  - Inclusive analyses
- Tag with semileptonic decays
  - PRO: Higher efficiency εtag ~ 1.5%
  - CON: more background, B momentum unmeasured
- Tag with hadronic decays
  - PRO: cleaner events, B momentum reconstructed
  - CON: smaller efficiency εtag ~ 0.3%





T.Keck, et al. Comput Softw Big Sci (2019) 3: 6.

Belle II vs LHCb

From J. Libby – Anomalies 2019

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%

Phase 3 Highlights

SUPERKEKB goals achieved:

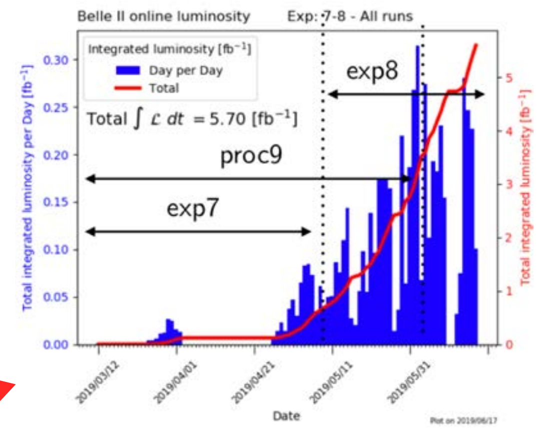
✓ "nano beam scheme" demonstrated in phase 2, now progressing squeezing β_x^* / β_y^* to 80/2mm

✓ Peak luminosity 1.24 x 10^{34} cm^{-2} s^{-1} (0.56 in Phase 2, goal 80 x 10^{34})

Luminosity in physics run 0.5 x 10^{34} cm^{-2} s^{-1}, limited by background

✓ Specific luminosity 2.9 x 10^{31} $cm^{-2}s^{-1}/mA^2$, but beam blow up effect

✓ Continuous injection for May & June



Belle II: Integrated luminosity 6.4 fb^{-1} (target 11 fb^{-1})

✓ Very good detector performance

✓ Excellent SVD cluster efficiency (99.5%) and position resolution

efficiency	u/P	v/N
layer3	(99.75 ± 0.02)%	(98.46 ± 0.05)%
layer4	(99.66 ± 0.04)%	(99.37 ± 0.06)%
layer5	(99.62 ± 0.06)%	(99.43 ± 0.08)%
layer6	(99.3 ± 0.1)%	(99.3 ± 0.1)%

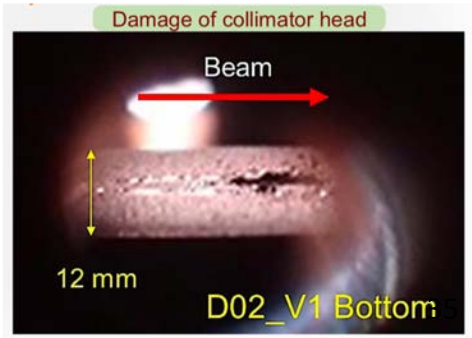
ISSUES

Fire accident, 3 weeks stop

Beam background → in progress, diamonds taken as reference

QCS quenches → diamonds drastically reduce their rate

Background accidents → in one instance diamonds promptly (10 us) issued abort, but huge beam losses, collimator and VXD damages



Other Belle II/SKB talks in this conference

- Aug. 22 15.30 - Pablo Goldenzweig: First look at CKM parameters from early Belle II data
- Aug. 23 8.30 - Philippe Bambade: The SuperKEKB/BELLE II as a demonstrator of future colliders
- Aug. 26 15.20 - Ilya Komarov: Dark Sector Physics with Belle II: first results and prospects