The Belle II experiment

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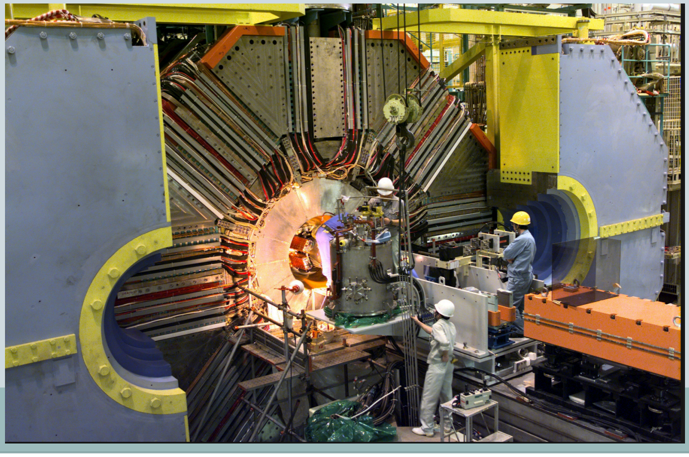
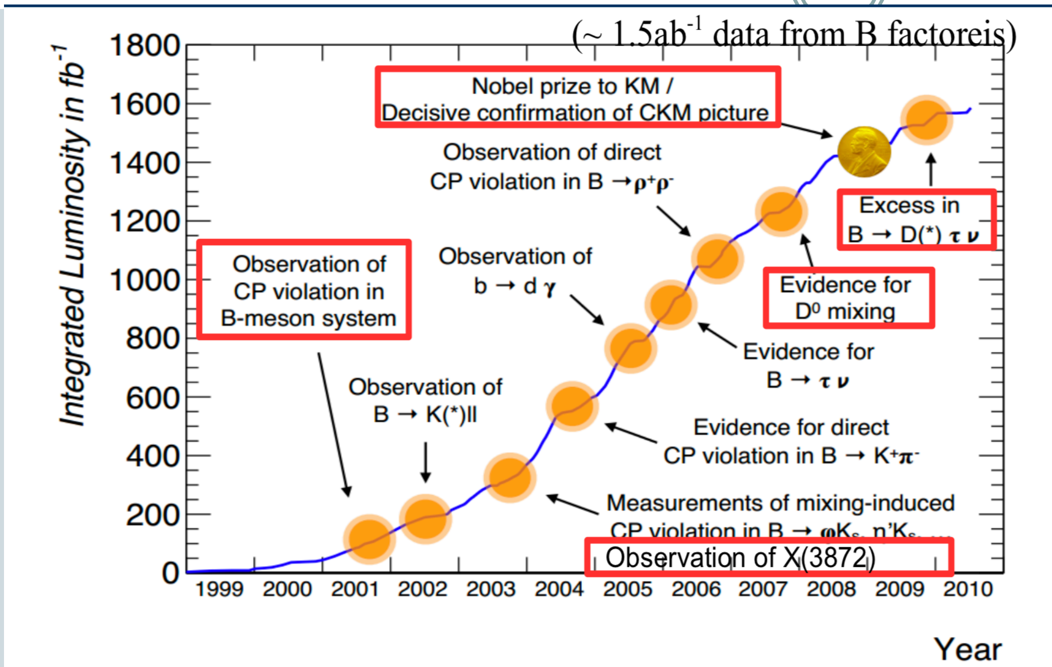
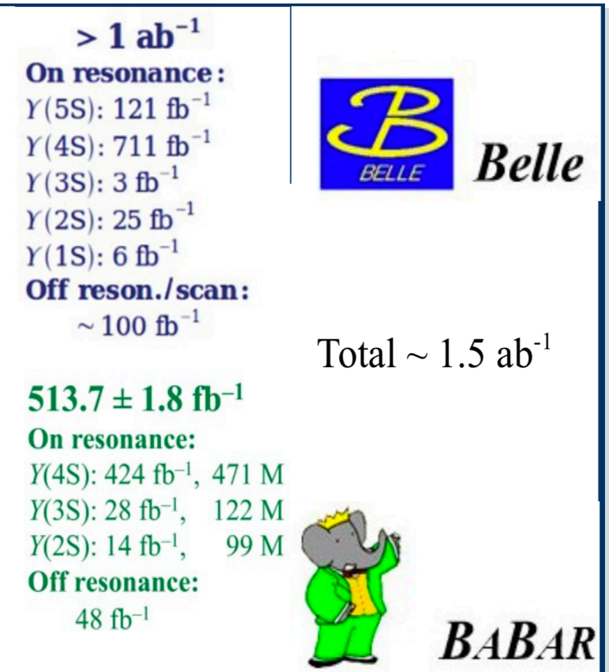
CAP CONGRESS

JUNE 5TH, 2019



Success of the B-factories



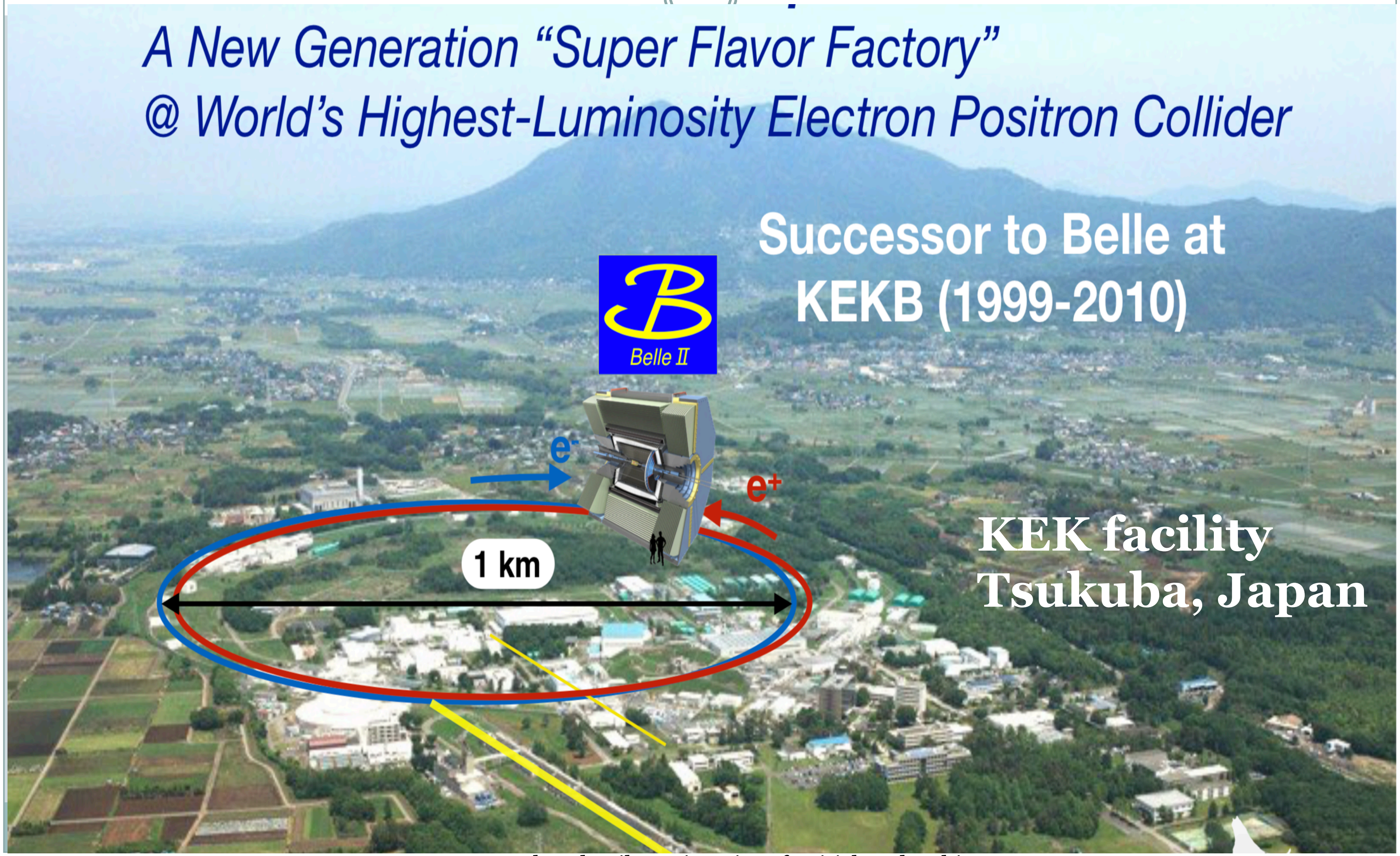


- The Nobel Prize:

Makoto Kobayashi,
KEK, Tsukuba, Japan

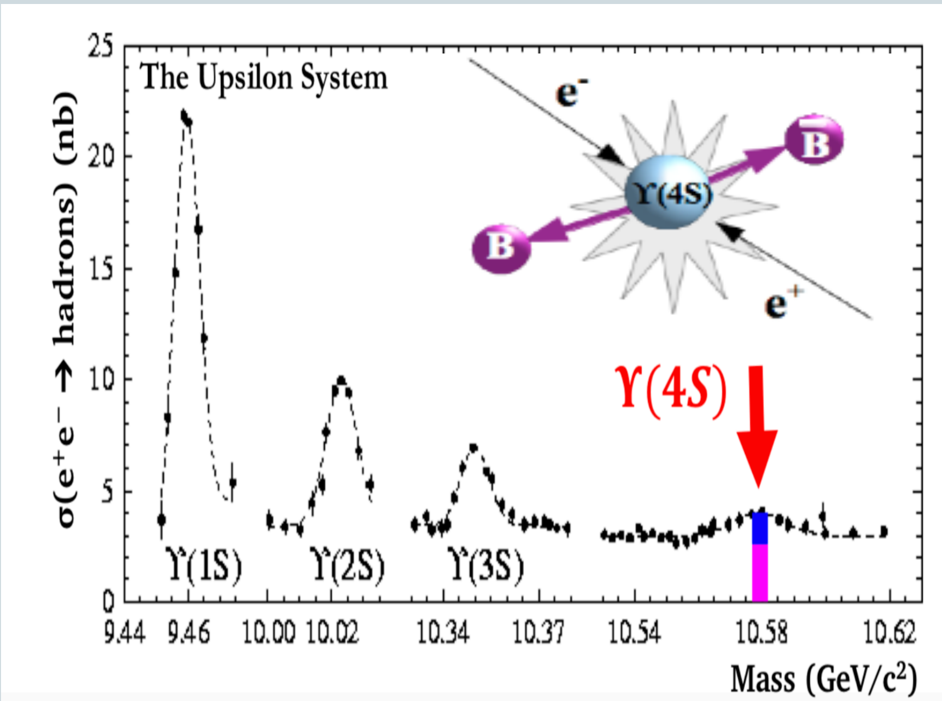
Toshihide Maskawa,
YITP, Kyoto University, and
Kyoto Sangyo University, Japan

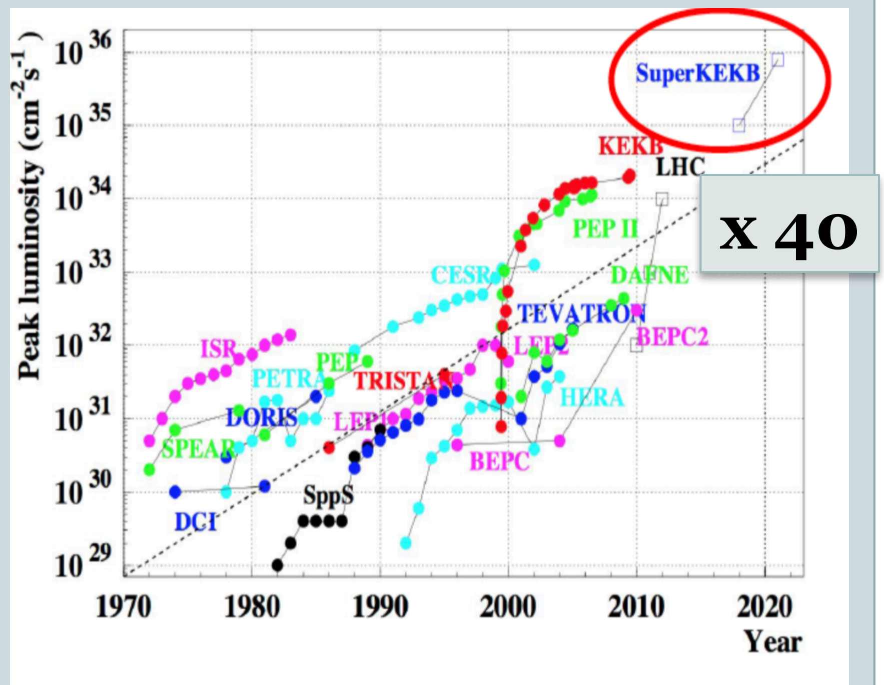
Belle II


A New Generation "Super Flavor Factory"
@ World's Highest-Luminosity Electron Positron Collider
Successor to Belle at KEKB (1999-2010)
Belle II
e-
e+
1 km
KEK facility
Tsukuba, Japan

Belle-II experiment

B factory with a target integrated luminosity of 50 ab^{-1}.



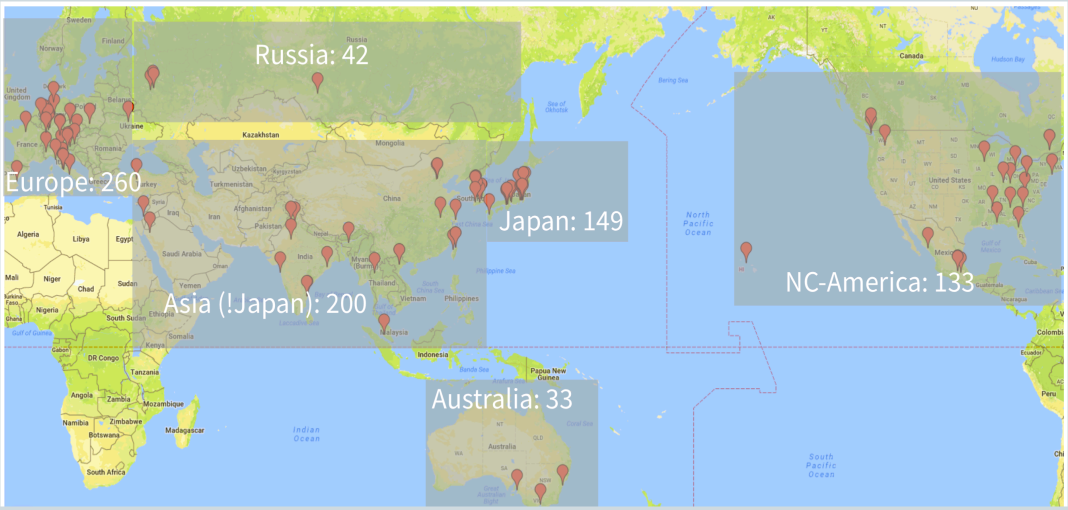


(Super) B-factory (~1.1 x 10^9 *BB* pairs/ab^{-1})
(Super) charm factory (~1.3 x 10^9 cc pairs/ab^{-1})
(Super) τ factory (~0.9 x 10^9 $\tau^+ \tau^-$ pairs/ab^{-1})

Analysis sensitivity in B, τ and charm to O(10^{-9}) branching fractions

The Belle II collaboration

101 institutions from 26 countries
~900 researchers ~270 graduate students

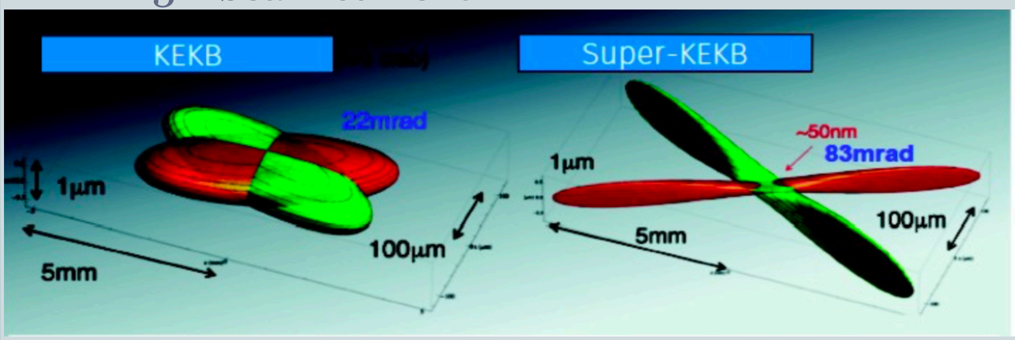


Current Canadian group:
7 faculty, 10 grad students, 3 postdocs/RA

UBC: C. Hearty, J. McKenna, R. Cheaib, E. Hill, A. Hershenhorn
Victoria: J. M. Roney, R. Kowalewski, R. Sobie, A. Sibidanov, S. Longo, C. Miller A. Beaulieu M. Ebert
McGill: S. Robertson, A. Warburton, A. Fodor, H. Wakeling, R. Seddon, R. MacGibbon, T. Shillington, K. Amirie

Super KEKB

- Increase luminosity by a factor of 40
  - 20 x smaller vertical beam size: "World's most complicated superconducting magnet system."
  - 2-3 x beam current



Twice the beam current

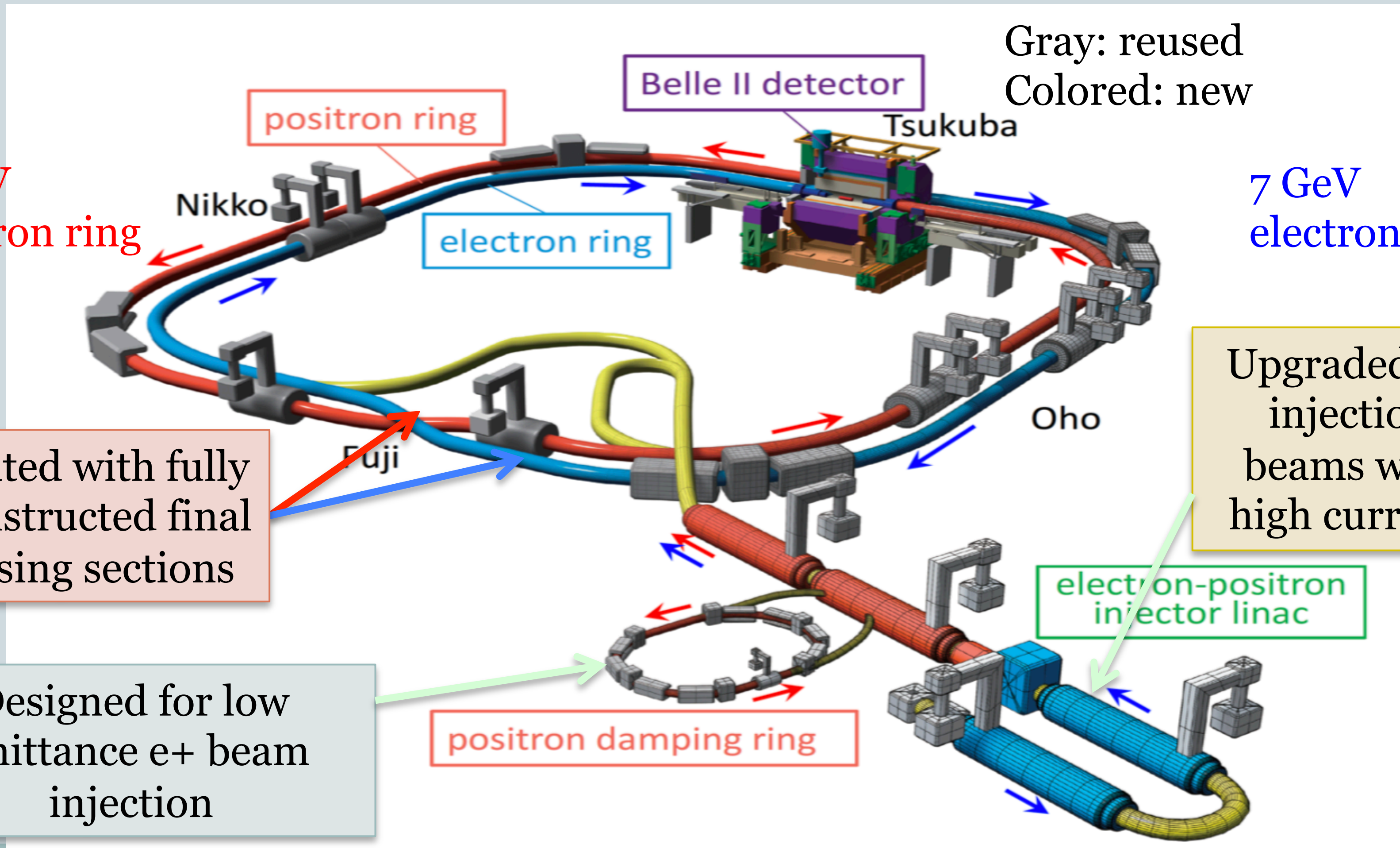
$$\mathcal{L} = \frac{\gamma_{e^\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{e^\pm}\xi_y^{e^\pm}}{\beta_y^{*e^\pm}}\left(\frac{R_L}{R_{\xi_y}}\right)$$

1/20 vertical beta function

Parameter	KEKB (LER/HER)	SuperKEKB (LER/HER)
Energy (GeV)	3.5/8.0	4.0/7.0
β_y (mm)	5.9/5.9	0.27/0.30
β_x (cm)	120/120	3.2/2.5
Current (A)	1.6/1.2	3.6/2.6
Luminosity($cm^{-2}s^{-1}$)	**2.1 x 10^{34}**	**80 x 10^{34}**

SuperKEKB

Significant upgrade of the KEKB $e^+ e^-$ collider.



Updated with fully reconstructed final focusing sections

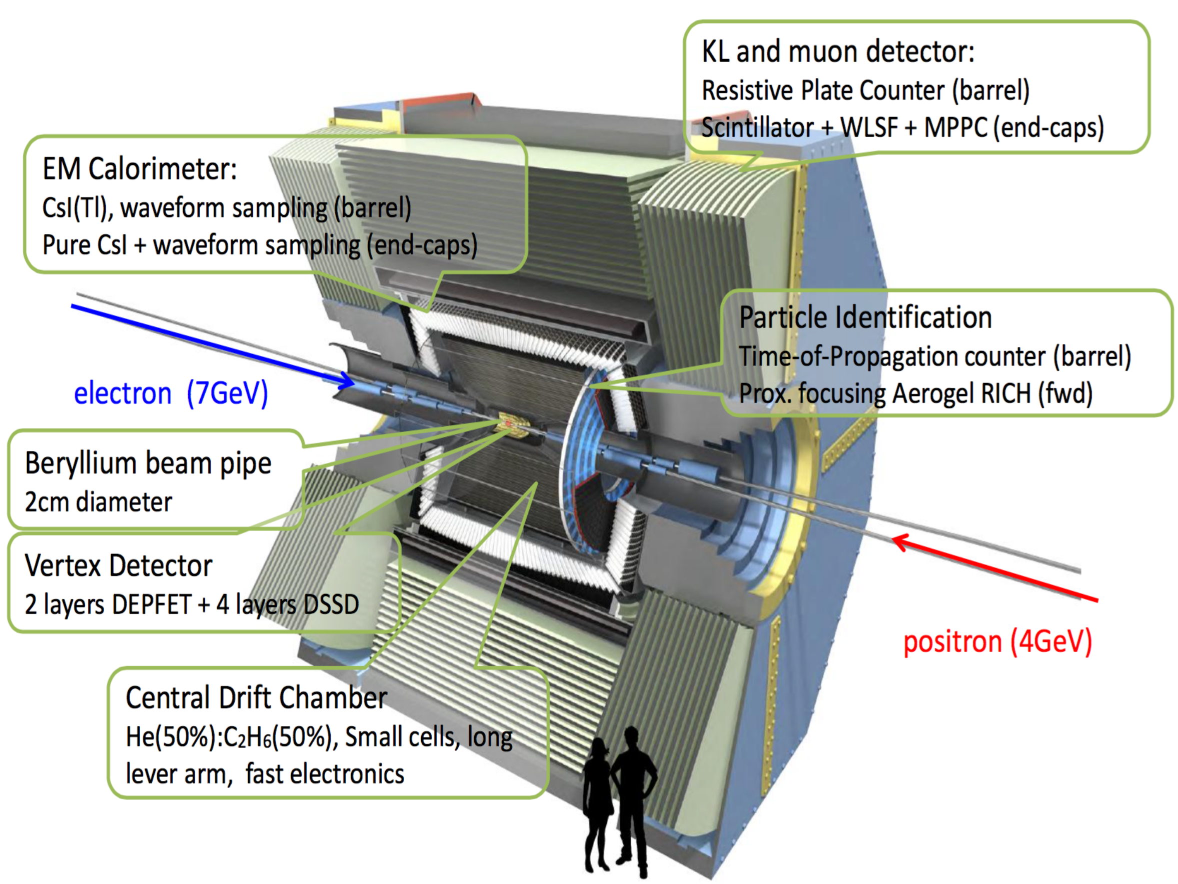
Upgraded for injection beams with high current.

Designed for low emittance e+ beam injection

Belle II detector

Significant upgrade of Belle II detector to handle higher event rate and higher background levels.

- **Extended vertex detector** region (added pixel detector)
- **Extended Drift Chamber** region
- **New calorimeter electronics** (waveform sampling and fitting)
- **New PID detector** in the barrel and forward region
- **High efficiency K_L and Muon** detector



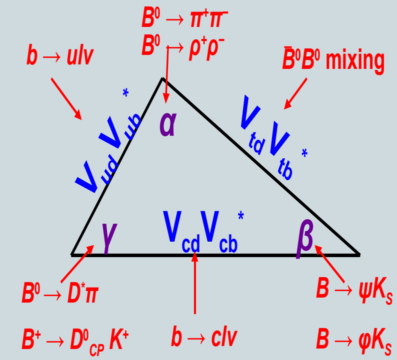
Rich Physics agenda

CKM matrix is unitary by design.

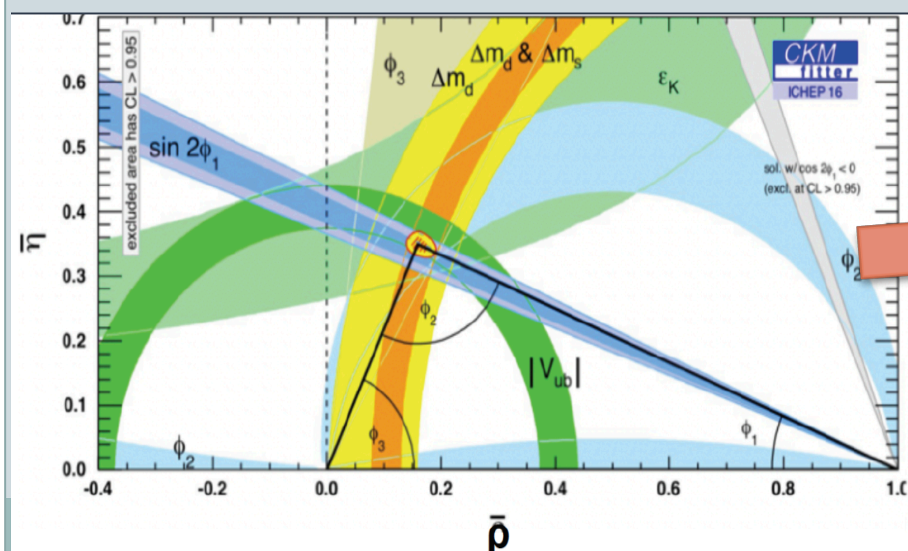
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates

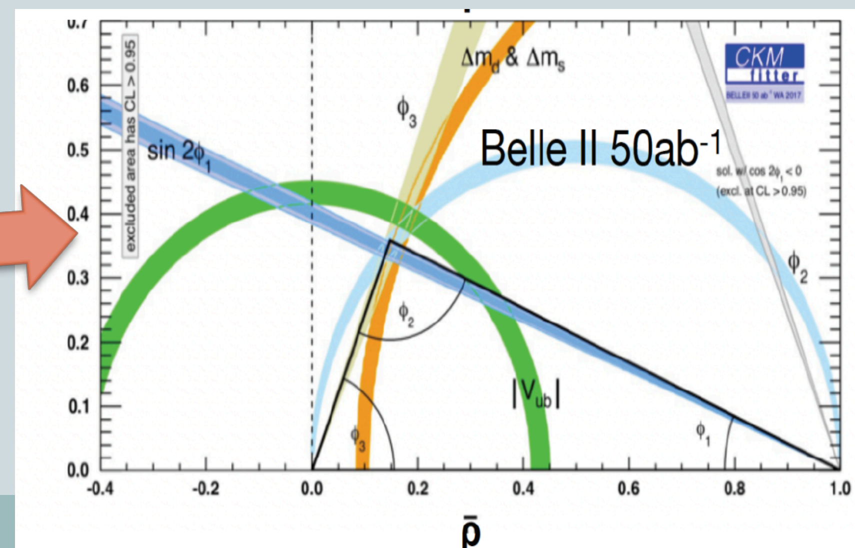
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Precision measurements with Belle II dataset



Deviations from Standard Model : New Physics



Rich Physics agenda

- B-physics:
  - CPV: B→ J/ψ K_s^o, ϕK^o
  - Rare B decays: B→Kνν, $K\tau^+\tau^-$
  - B anomalies
- Lepton flavour violation:
  - τ→μγ
- Charm Physics: D-mixing
  - CPV in charm sector
- Dark sector studies
  - A’, ALPs, Z’
- Bottomonium spectroscopy and exotic states

CP Violation				
$S(B \to \phi K^0)$	***	CPV	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				
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	(Semi) LEPTONIC	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				
$\mathcal{B}(B \to X_s\gamma)$	**	EWP	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***		0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***		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				
$\mathcal{B}(D_s \to \mu\nu)$	***	Charm	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***		2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**		0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***		0.03	Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ $[°]$	***		4	Belle II
Tau				
$\tau \to \mu\gamma$ $[10^{-10}]$	***	Tau	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***		< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***		< 3	Belle II/LHCb

Large data sample = wide range of possibilities.

Belle II Physics book: arXiv:180810567

Belle II computing

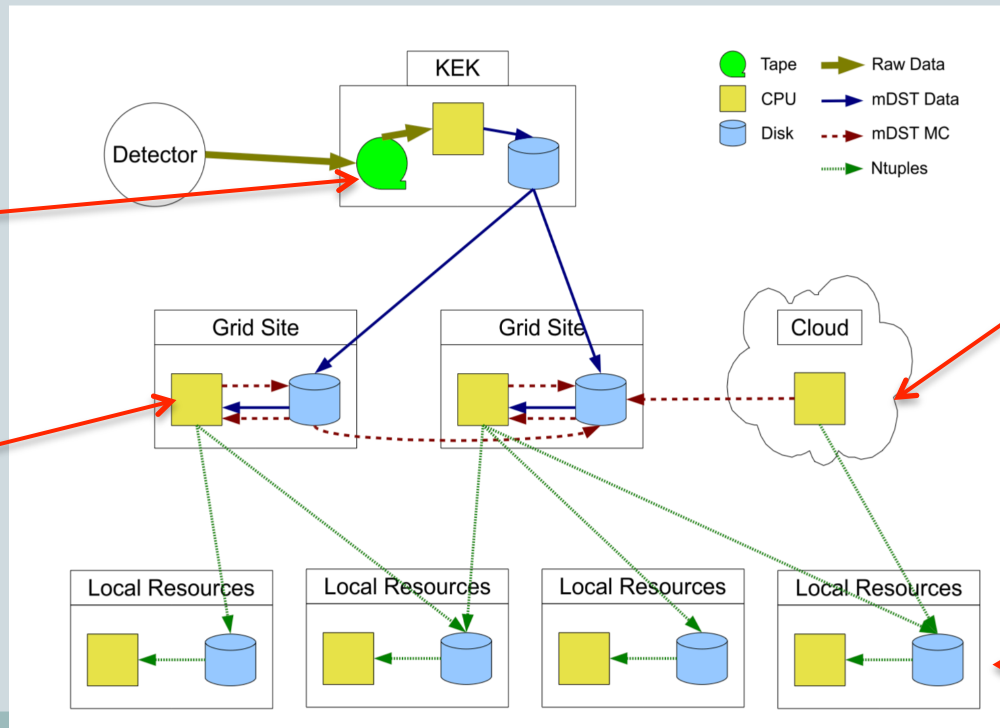
- Challenging computing system to handle high event rate

Experiment	Event Size [kB]	Event Rate [Hz]	Data Rate [MB/s]
Belle II (high rate scenario)	300	6,000	1,800
ALICE (HI)	12,500	100	1,250
ALICE (pp)	1,000	100	100
ATLAS	1,600	200	320
CMS	1,500	150	225
LHCb	25	2,000	50

- Distributed computing model with most of the Belle II institutions.

Raw data stored on tape at KEK.

Mini-DST format for data and Monte Carlo are replicated on grid sites.

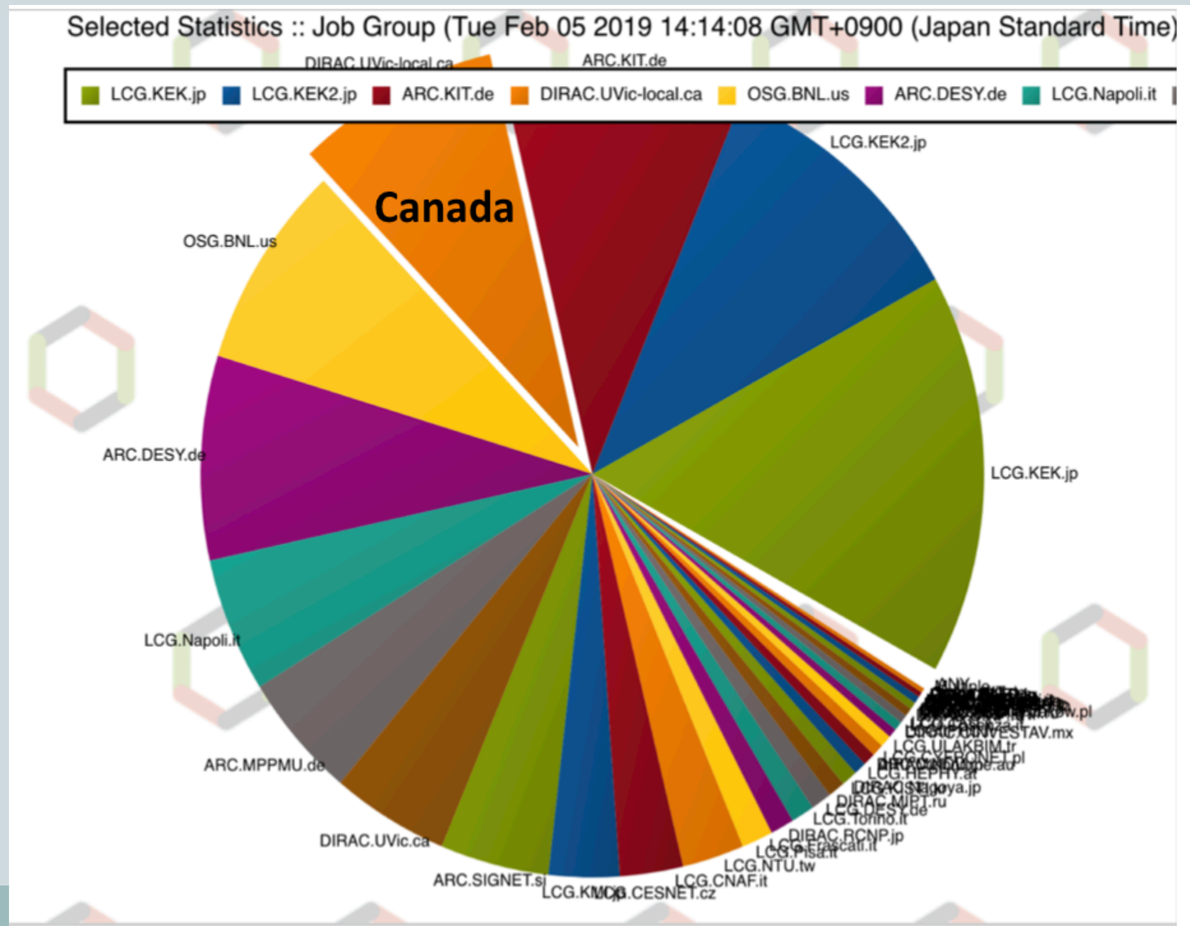


Cloud computing is used to address peaks on resource demand.

mDSTs copied to local resources.

Canadian Production in 2018

- Canada produced 13% of MC in 2018 entirely by cloud
- Canada will store 10% of raw data copy plus processing, starting 2021.

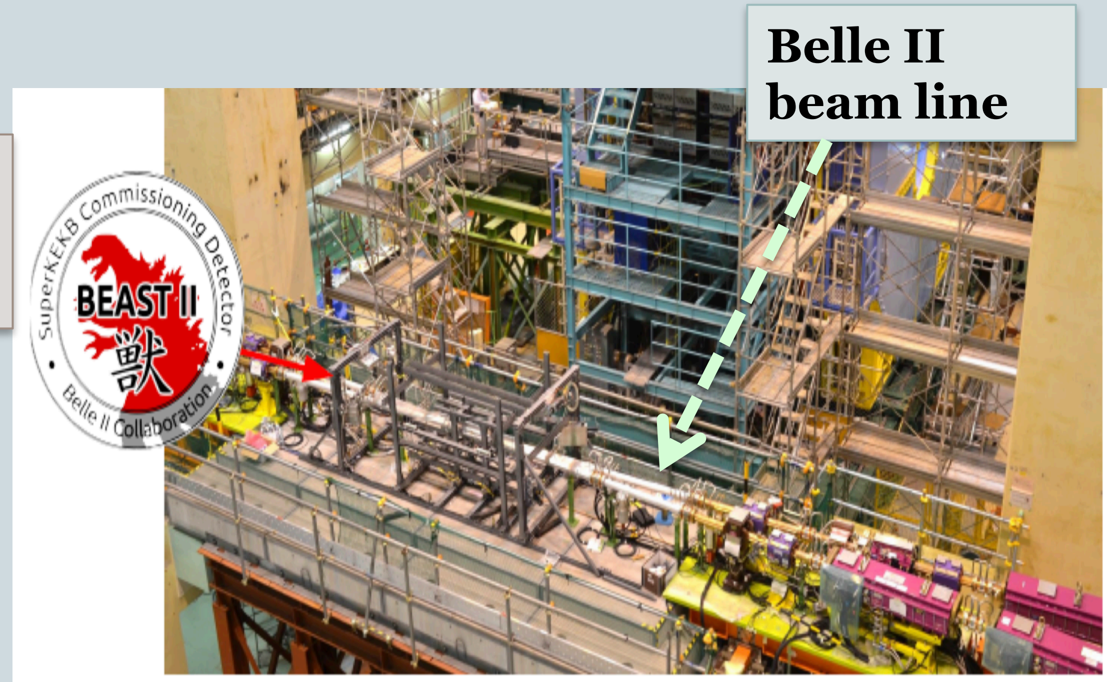


Belle II timeline :

2016	2017	2018	2019

Phase I

Beam on, no collisions.
Basic accelerator tuning.
Commissioning with BEAST ll



BEAST II to study the effect of beam backgrounds:

- Touschek scattering: Coulomb scattering between 2 particles in the same bunch
- Beam-gas: scattering off residual gas atoms in the beam pipe
- Synchotron radiation: photons emitted when electrons are bent by magnetic fields.

https://doi.org/10.1016/j.nima.2018.05.071

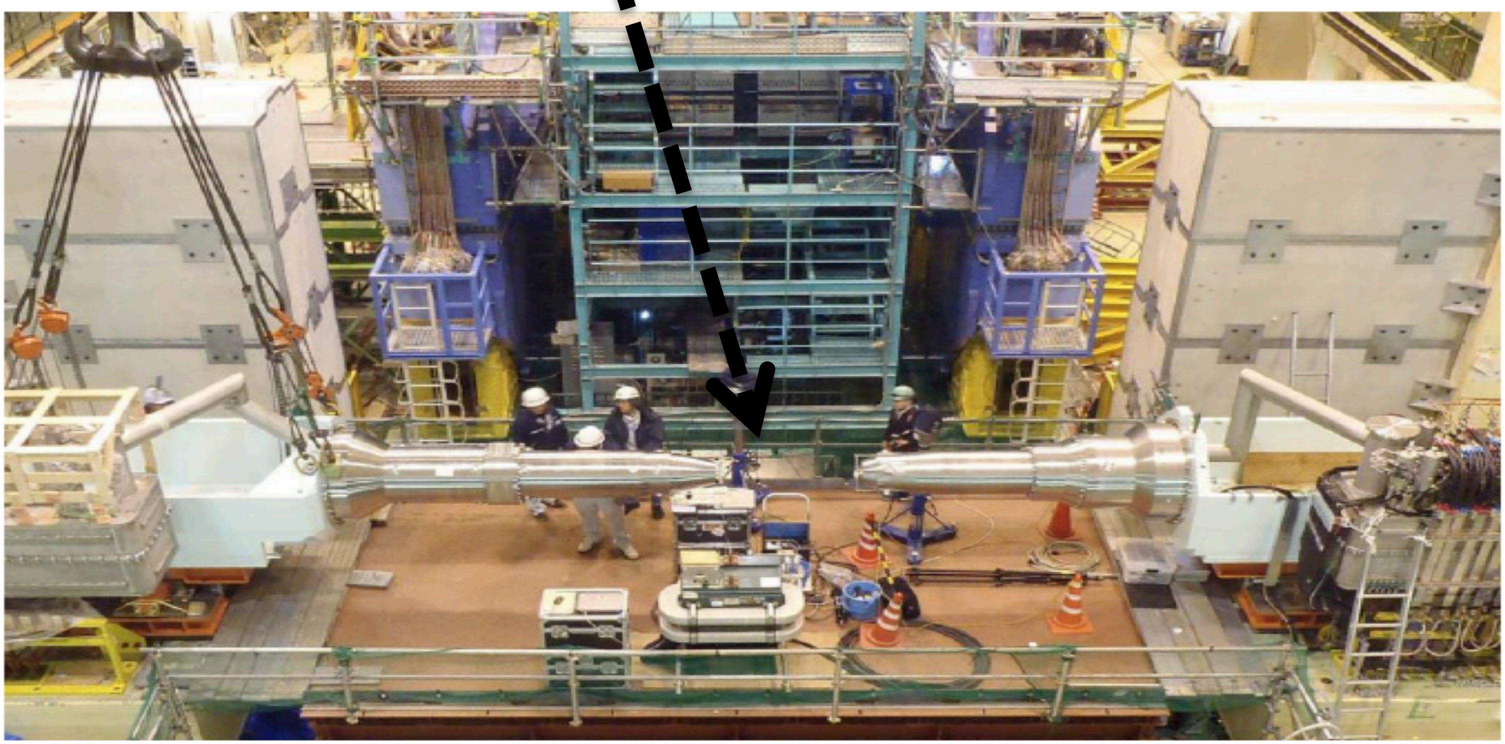
Belle II timleine:

2016	2017	2018	2019

Phase I

Install final focusing magnets

Precise and complex magnetic system to realize small βy*

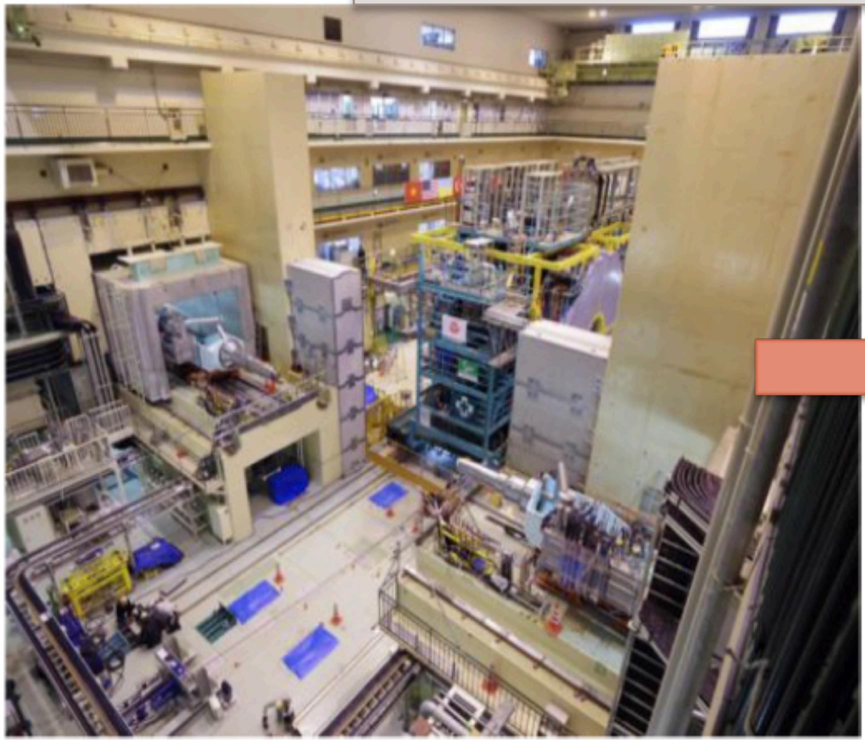


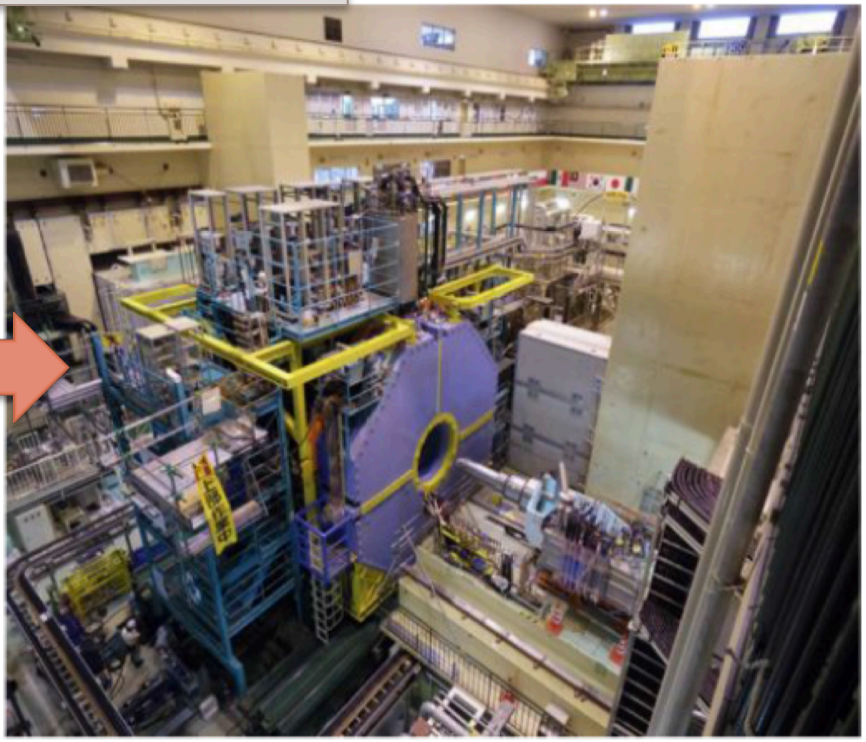
Belle II timeline:

2016	2017	2018	2019

Phase I

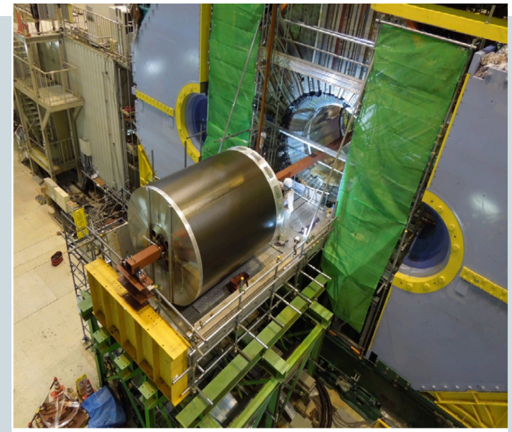
Belle II detector installation (TOP, CDC) and roll-in .





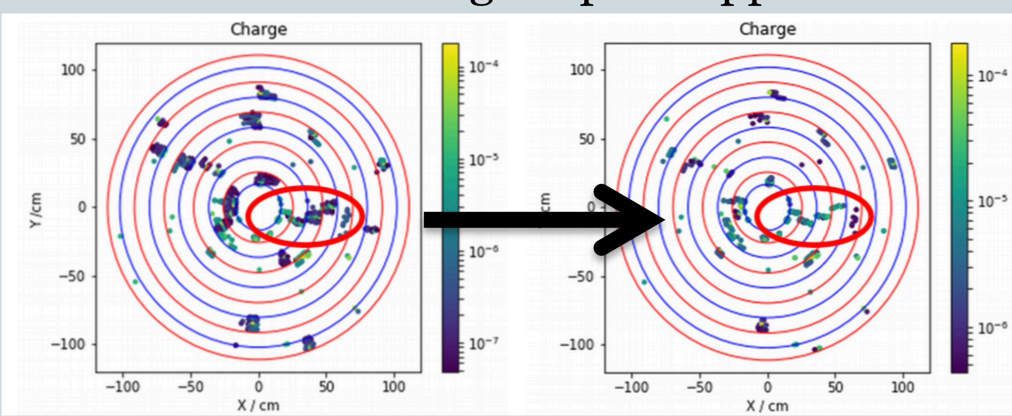
Central Drift Chamber

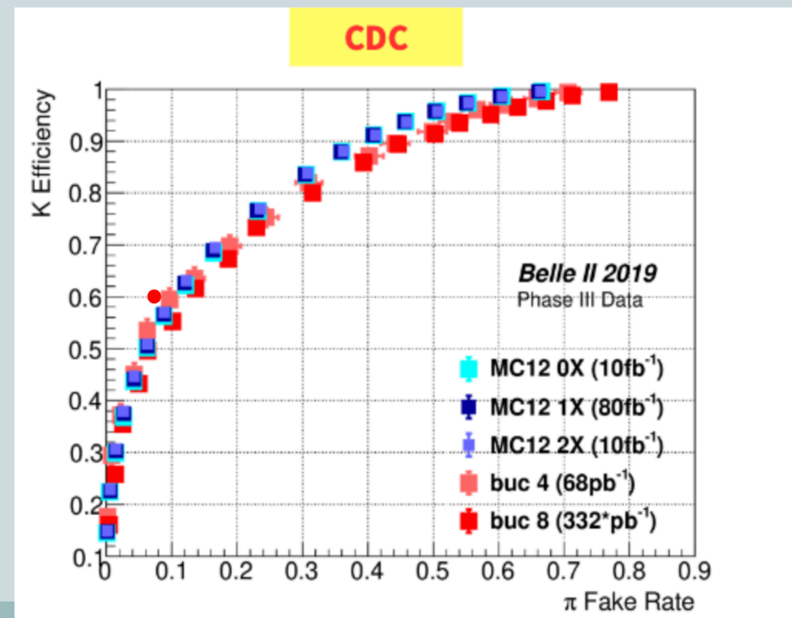
- CDC extends to a larger radius (1130 mm compared to 800 mm)
  - 14336 sense wires arranged in 56 layers
  - smaller drift cells, and thinner PID device.
- CDC tracking efficiency significantly influenced by cross-talk between cells.



Current Status (2019):

Cut on charge deposit applied



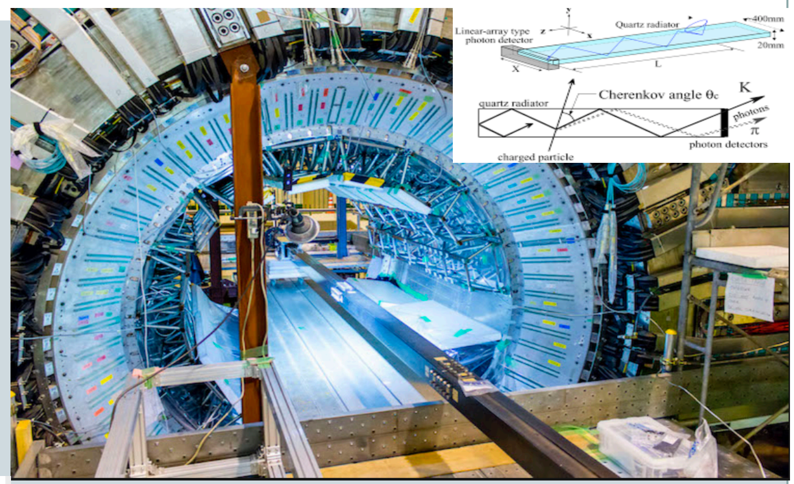


High current observed in outer CDC layers:

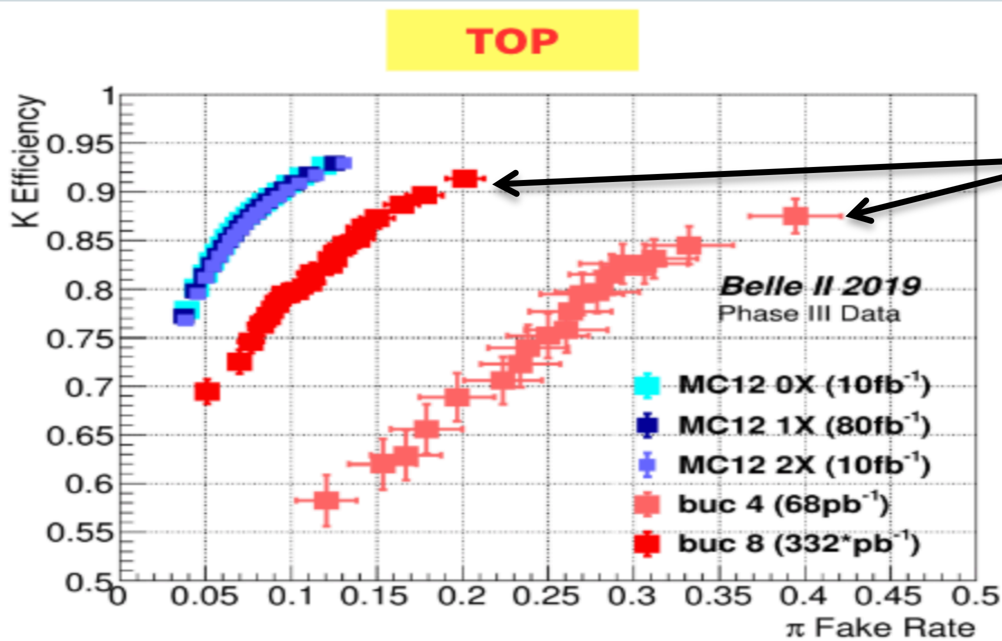
- add H2O, increase gas flow, low voltage operation.

Time Of Propagation Cherenkov Counter

- Consists of 2.6 m quartz radiator bar, micro-channel plate photomultipliers and a front-end readout.
- 2D information about a Cherenkov ring image: time of arrival and impact position.



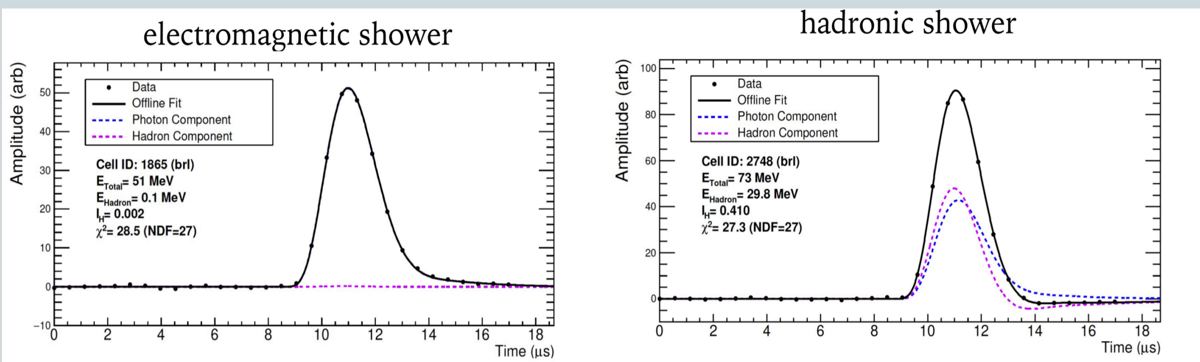
Current Status:



- Performance improving.
- Calibration and timing issues.
- 224 PMTs to be replaced by summer 2020

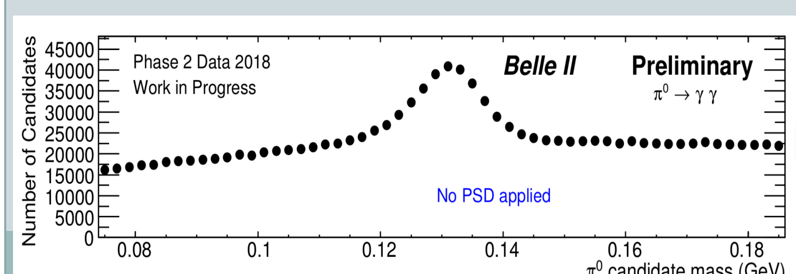
Electromagnetic CaLorimeter

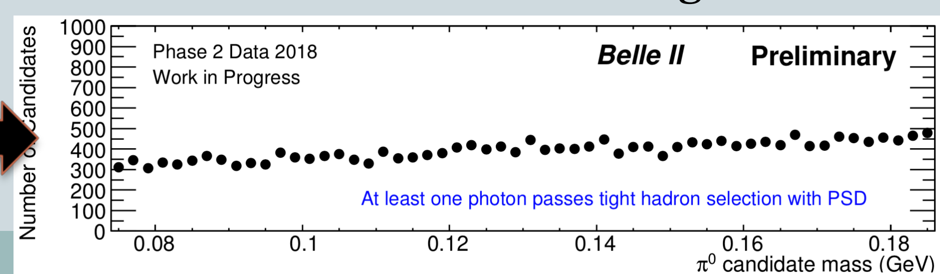
- Total of 8736 CsI crystals, covering about 90% of the solid angle, with **new readout** electronics.
- **Full cluster reconstruction code and ECL calibration developed by Canadian group**.
- Improve PID using Pulse Shape discrimination, by measuring fast scintillation emission (“hadron component”) produced by highly ionizing particles



Waveforms for crystals with energy above 30 MeV are saved offline.

See poster by Savino Longo!





KLM (K_L and μ detector)

- Detect K_L mesons or muons above 0.6 GeV/c
- Use the Belle-era glass-electrode RPCs in the outer 13 layers
- Install scintillators in the 2 innermost barrel layers, due to the higher background levels.

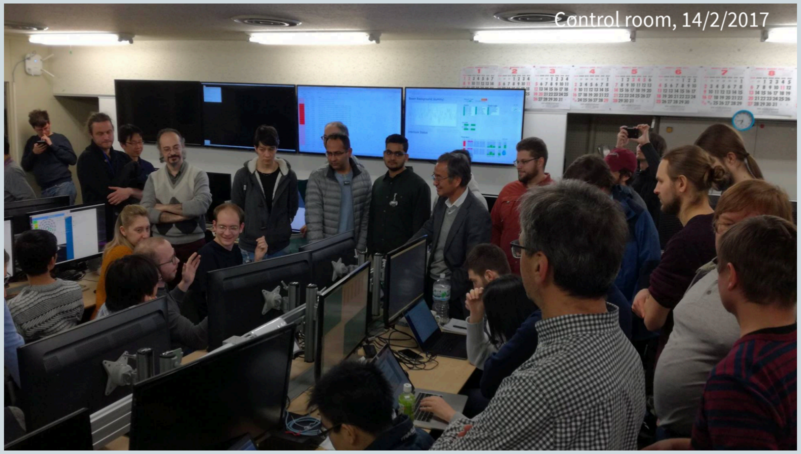
Belle II timeline:

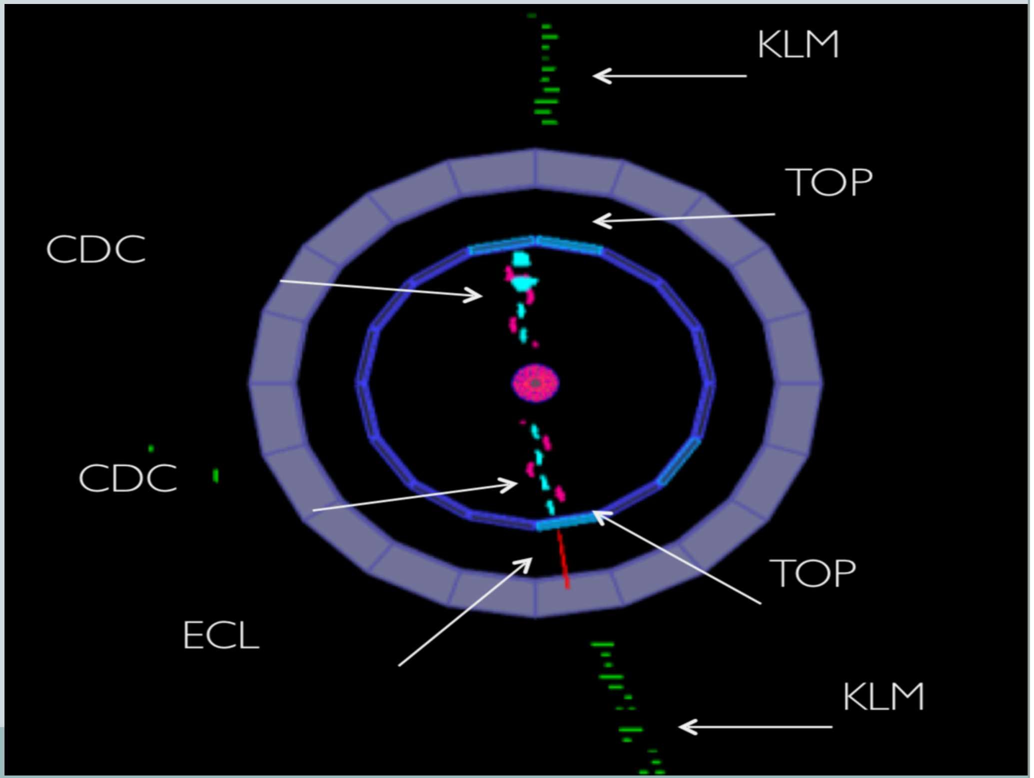
2016	2017	2018	2019

Phase I

Belle II global cosmics run (July-August)

- Established 1.5 T magnetic field
- Readout integration of installed sub-detectors central DAQ in progress.





First collisions at Belle II

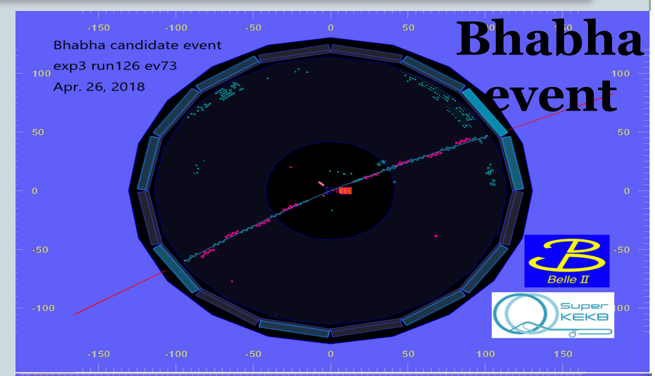
2016	2017	2018	2019

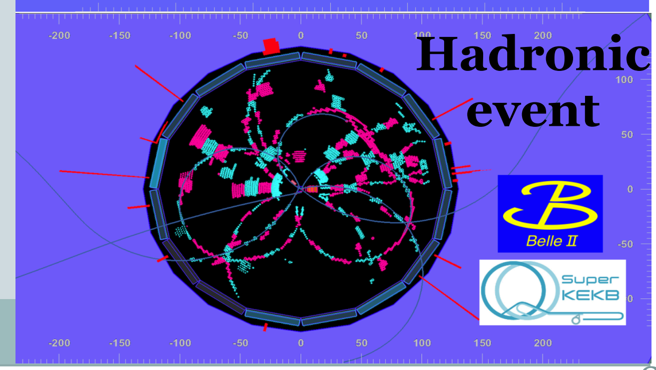
Phase I

Phase II

Phase III

April 2018: Beam collisions with QCS.
VXD not yet installed
Luminosity: ~500 pb^{-1}

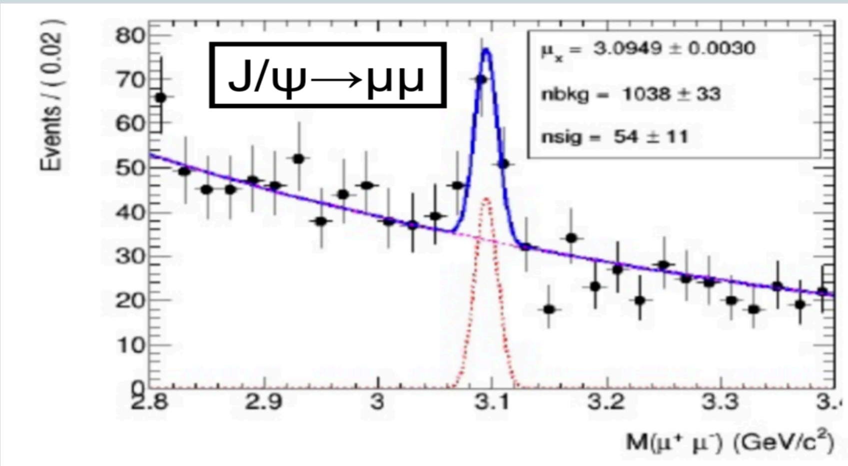


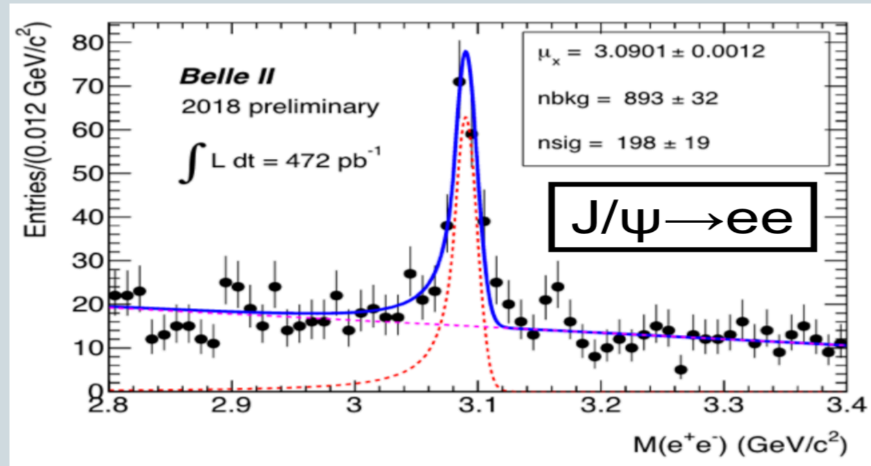


Reduced β_y^* to 3 mm, σ_y^* ~400nm
(Final target β_y^*=0.3mm, σ_y^*~50nm)

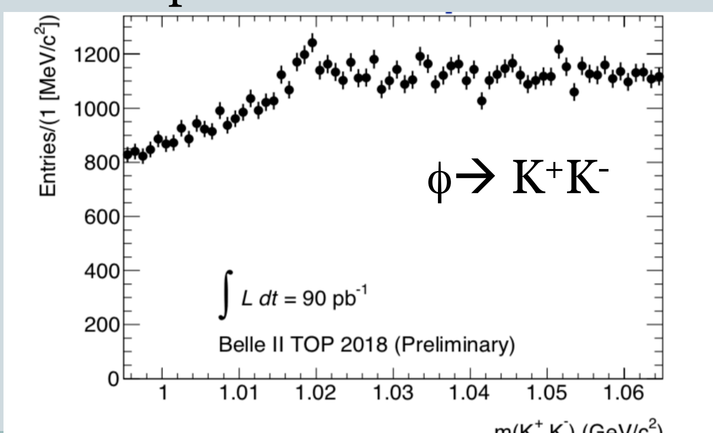
Belle II Tracking in Phase II

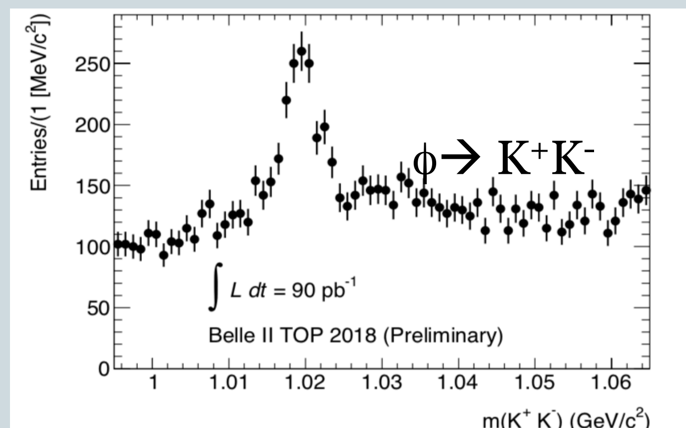
- Tracks reconstructed with CDC and partially installed VXD.





- Observed improvement in Particle Identification with the TOP detector

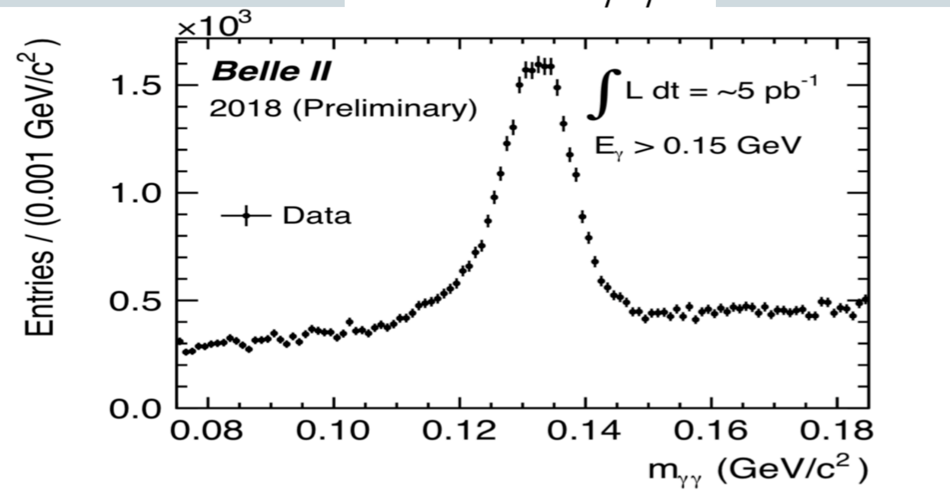




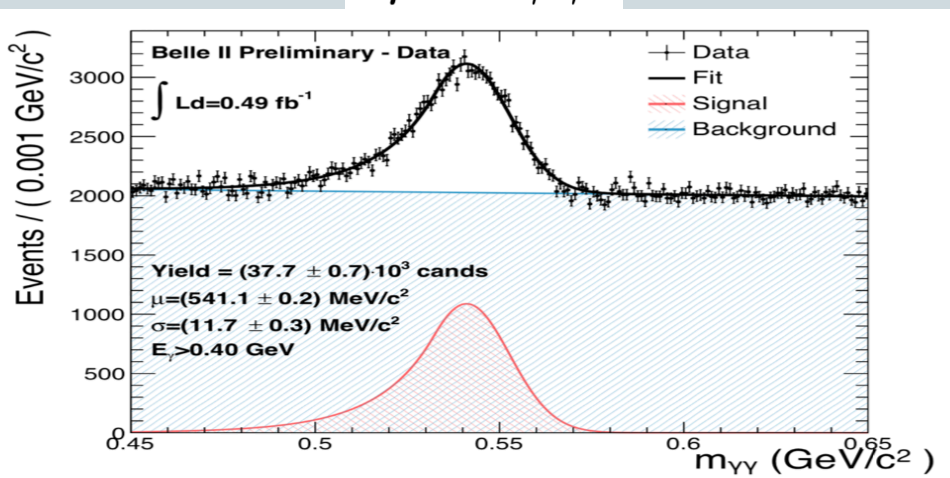
Without PID With PID

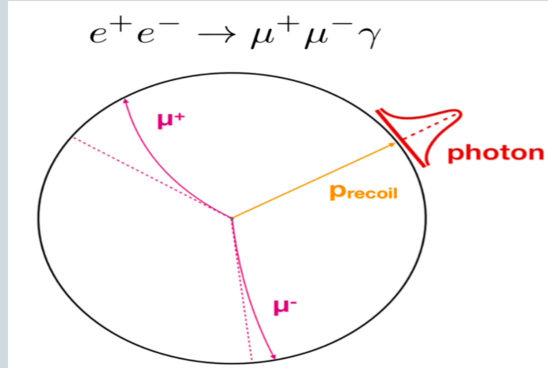
Belle II Neutrals in Phase II

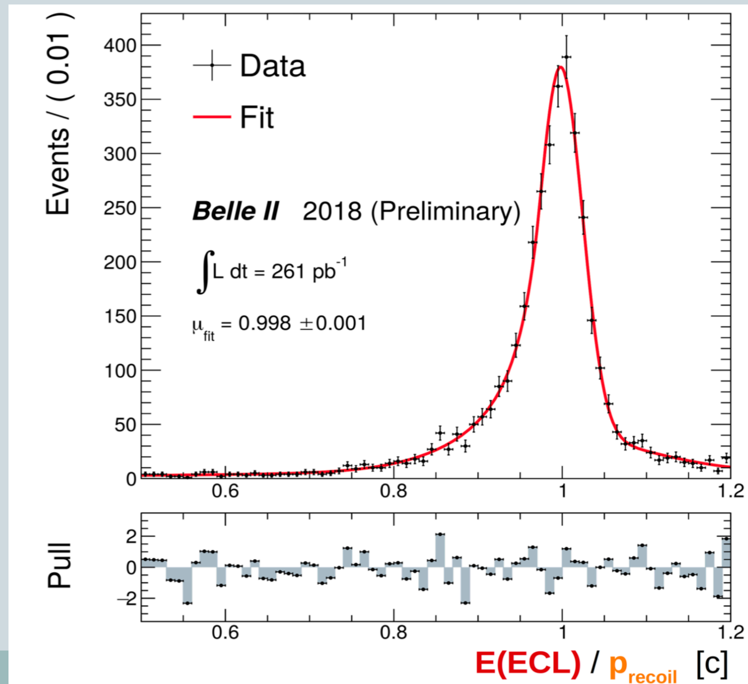
$\pi^0 \to \gamma\gamma$



$\eta \to \gamma\gamma$

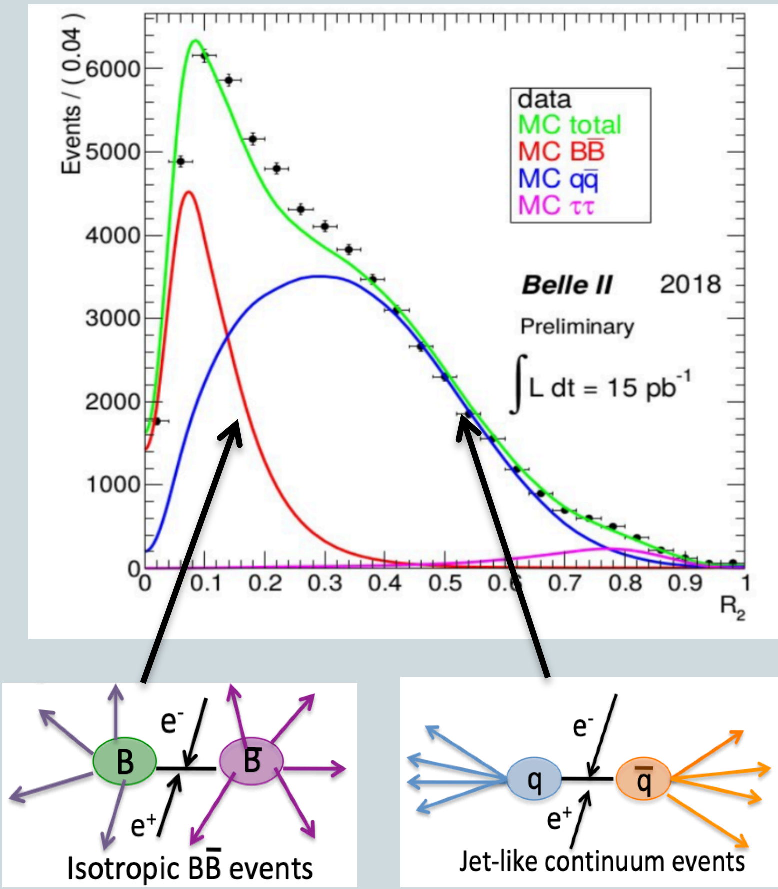


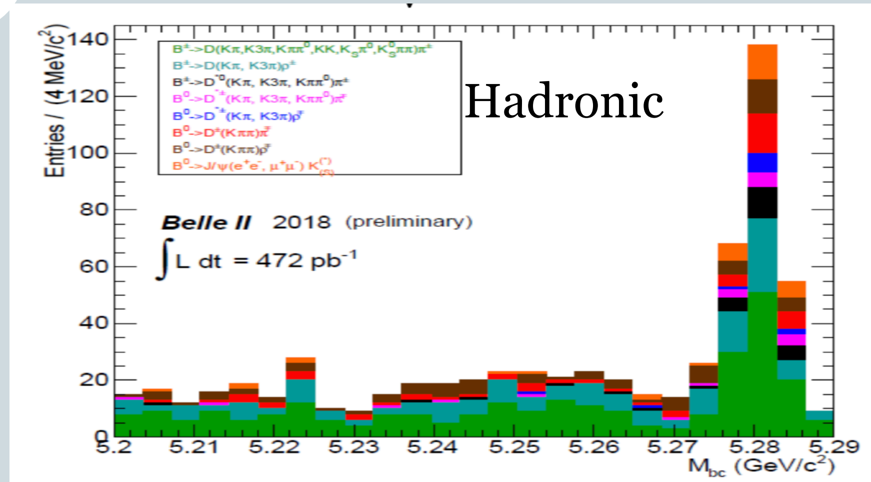


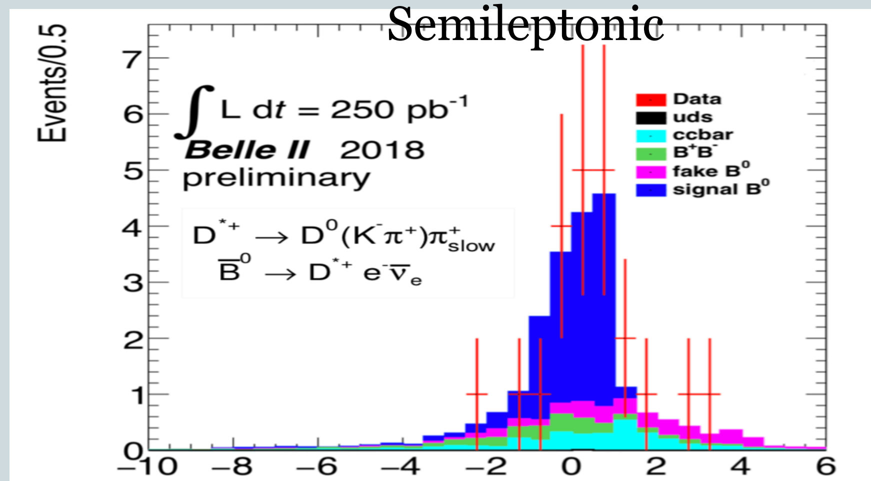


B mesons

Ratio of 2^{nd} to first Fox-Wolfram moments:



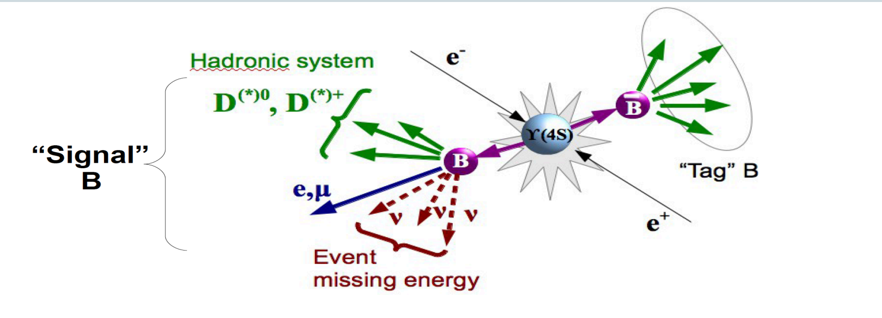




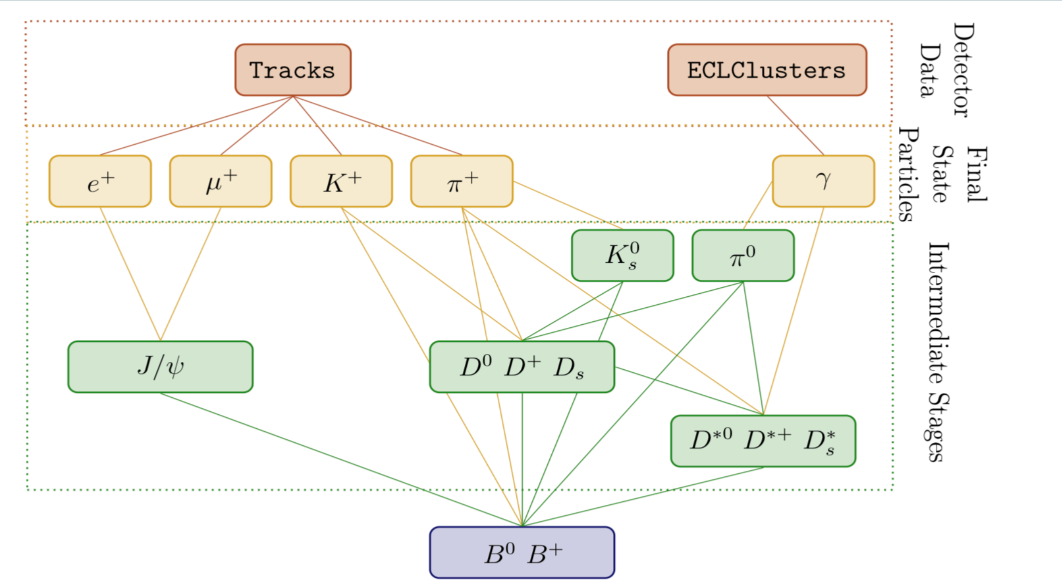
$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - M_Y^2}{2p_B^* p_Y^*}$$

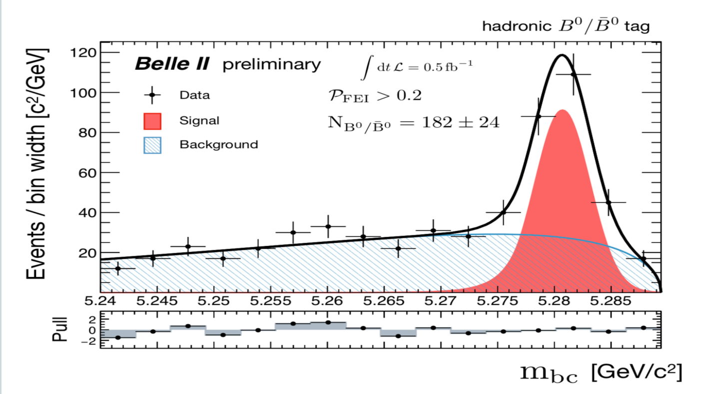
Exclusive B-tagging algorithm

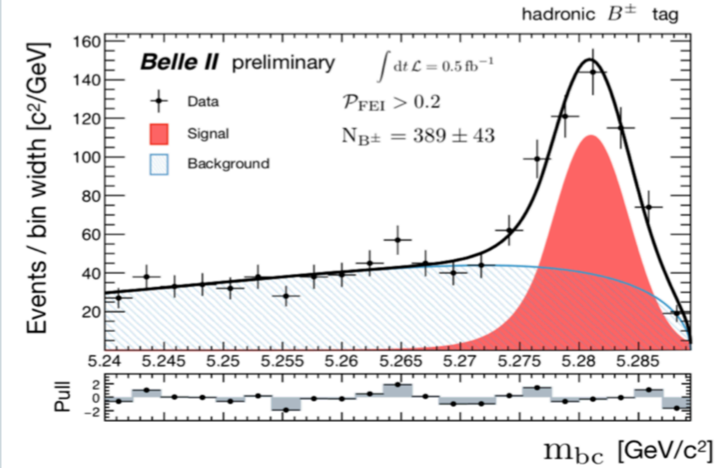
Multivariate hadronic and semileptonic B-tagging algorithm



Hierarchical approach with O(10000) modes







2-3 x more efficient than previous algorithms.

Full Event Interpretation T. Keck et al., Comp. Softw. Big Sci. 3:6 (2019)

Current Status :

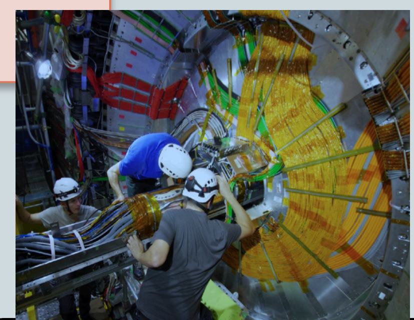
2016	2017	2018	2019

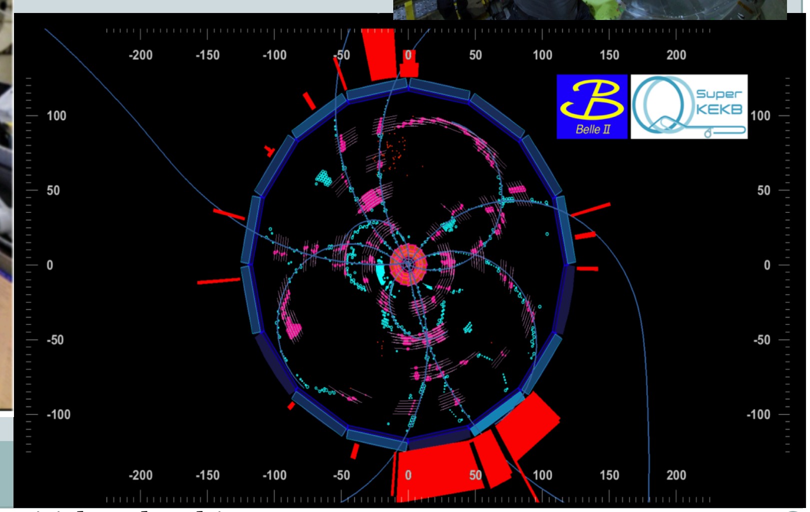
Phase I

Phase II

Phase III

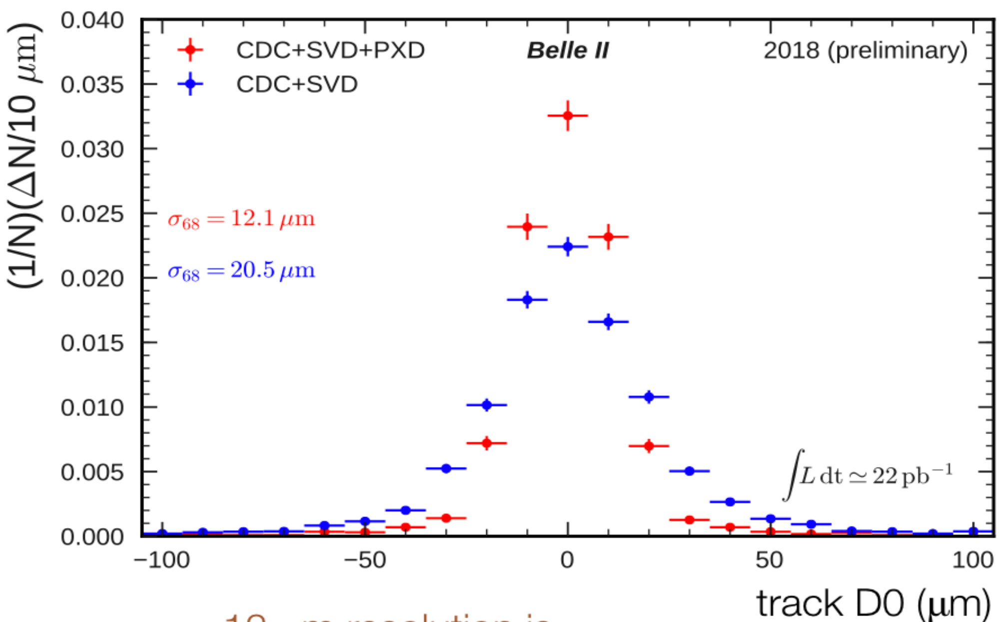
VXD installed.
PXD first layer fully equipped.
Full physics run: March 2019



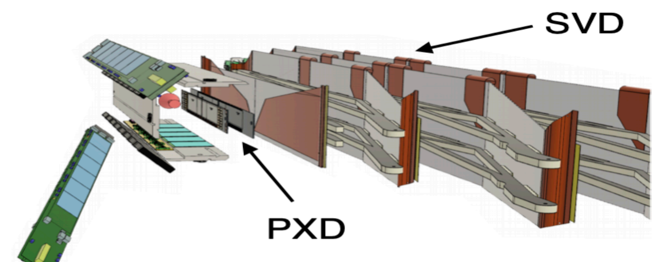


Vertex Detector

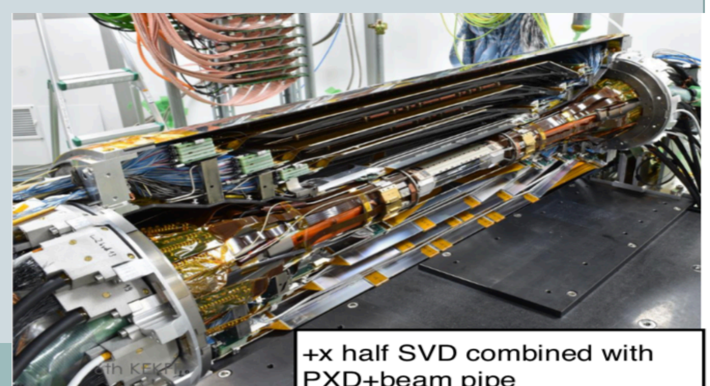
- PiXel Detector: 2 layers of DEPFET (DEPleted Field Effect Transistor) at r = 14 mm and r = 22 mm. Closer to interaction region than Belle.
- Silicon Vertex Detector (SVD):4 layers of double-sided silicon sensors on 6” wafers.
- Larger outer SVD radius 30% efficiency increase $K_S \rightarrow \pi^+\pi^-$ decays inside the SVD.
- **Current Status:**



12 μm resolution is 2x better than Belle



VXD slice in horizontal plane

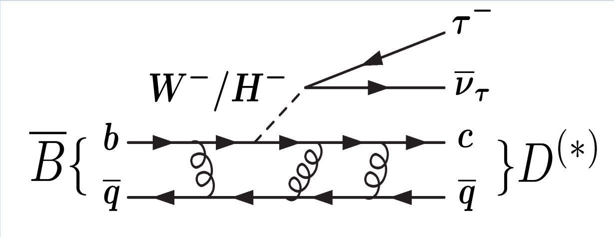


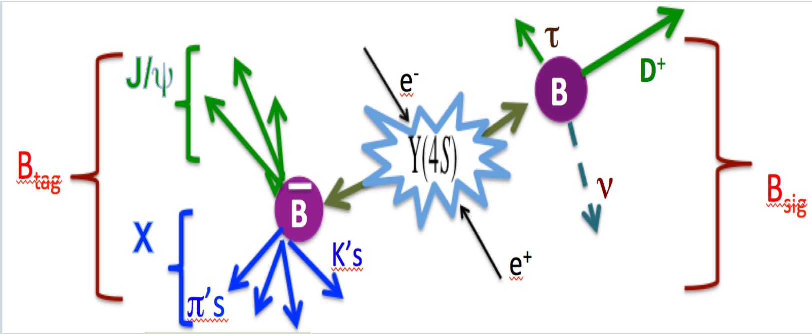
+x half SVD combined with PXD+beam pipe

CHEF'S CHOICE

R(D) and R(D*)

Tree level decay in the Standard Model

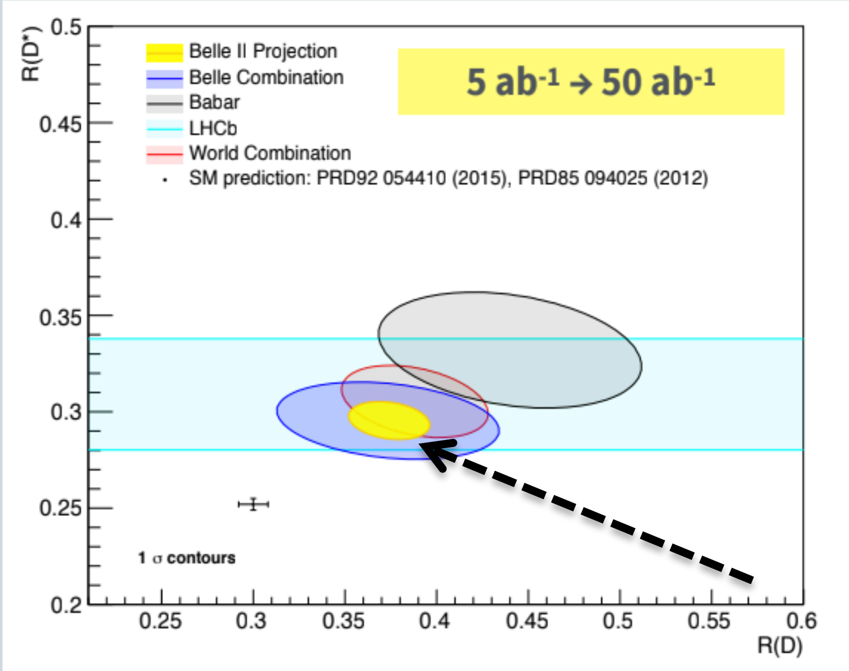




Measurements of R(D) and R(D*) show > 3σ deviation from the SM

$$R(D) \equiv \frac{\mathcal{B}(\bar{B}\to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^+\ell^-\bar{\nu}_\ell)} \qquad R(D^*) \equiv \frac{\mathcal{B}(\bar{B}\to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{*+}\ell^-\bar{\nu}_\ell)} \qquad \ell = e,\mu$$

Belle II measurement with FEI hadronic tagging.



Substantial Canadian effort (4+ members) leading this analysis

Canadian convenors of the Semileptonic Working Group at Belle II.

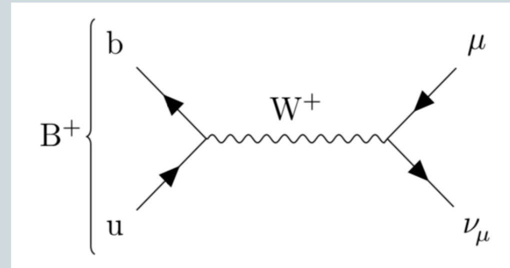
See talk by Hannah Wakeling!

CHEF'S CHOICE

Rare decays

$B \rightarrow \mu\nu$

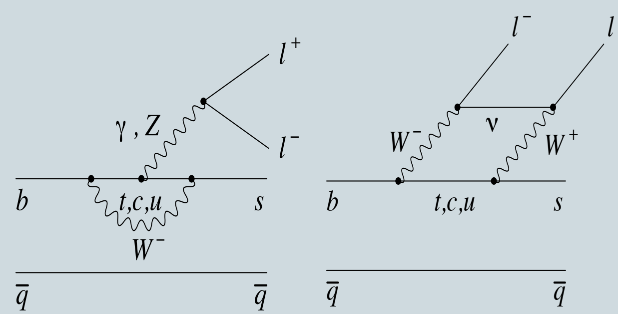
- Rare decay with $O(10^{-7})$ branching fraction.
- Probe for new physics
- Clean mode, untagged analysis with one signal side track

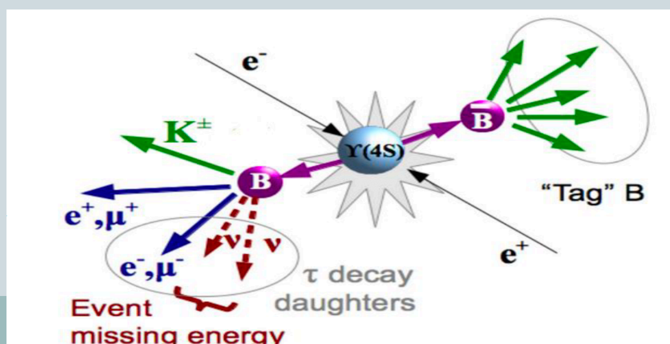


See Andrea Fodor's talk!

$B \rightarrow K^+ \tau^- l^+$

- Loop level process, forbidden in the SM.
- Test of lepton flavour violation
- Hadronic tagged analysis using FEI algorithm





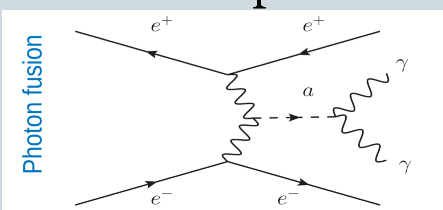
Truly Canadian!

Dark sector studies

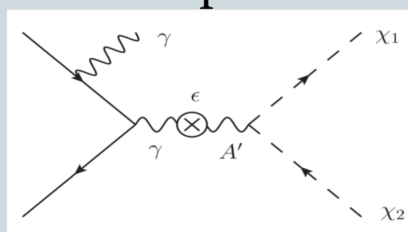
CHEF'S CHOICE

- Rich trigger menu allows for a wide range of dark sector and low multiplicity studies.

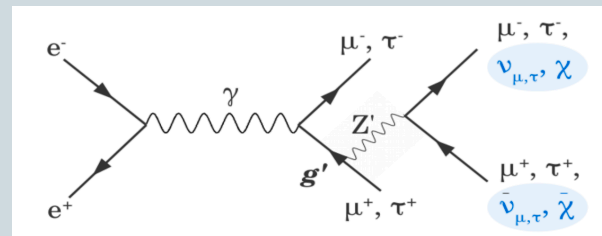
Axion-like particles



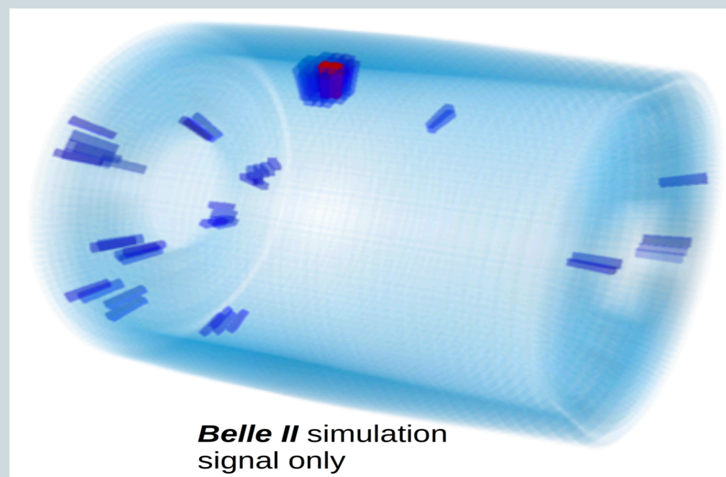
Dark photon



Z'



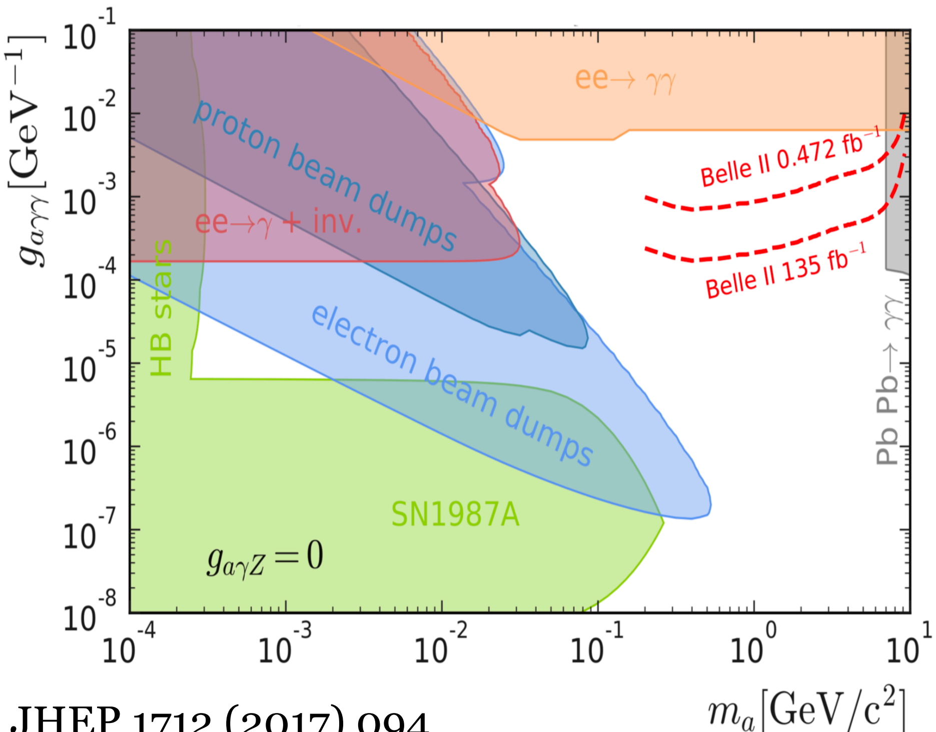
- Requires single photon trigger
- Bump hunt in the recoil mass system
- Backgrounds:
  - Cosmics
  - Beam backgrounds
  - ee $\rightarrow$ ee$\gamma(\gamma)$
  - ee $\rightarrow$ $\gamma\gamma(\gamma)$



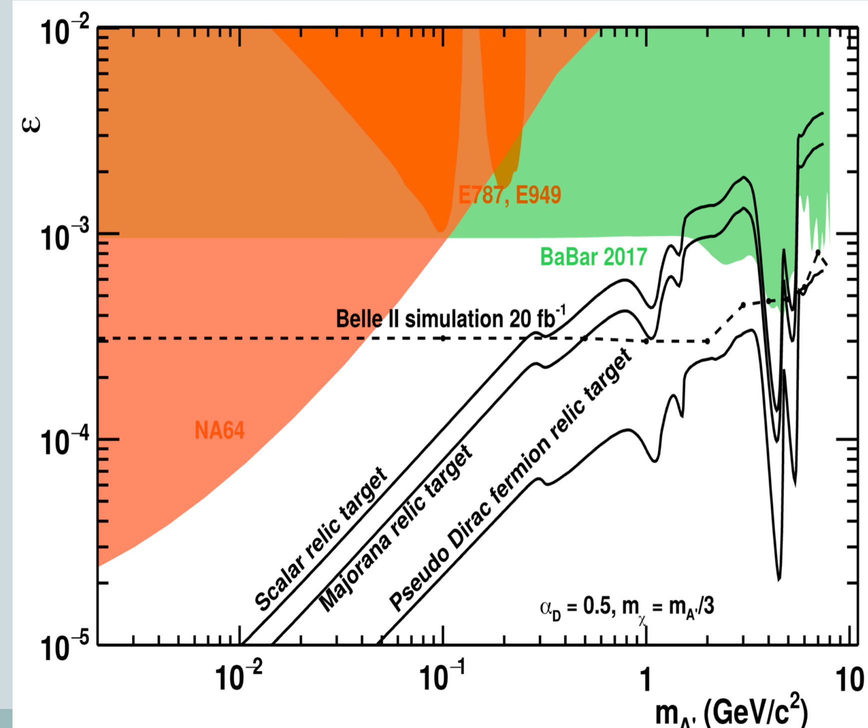
Dark Photon Search

- Canadian group leading effort in dark photon search
  - Study of backgrounds from cosmics and γ detection efficiency in the muon system

Belle II has world-leading sensitivity with only 20fb^{-1}



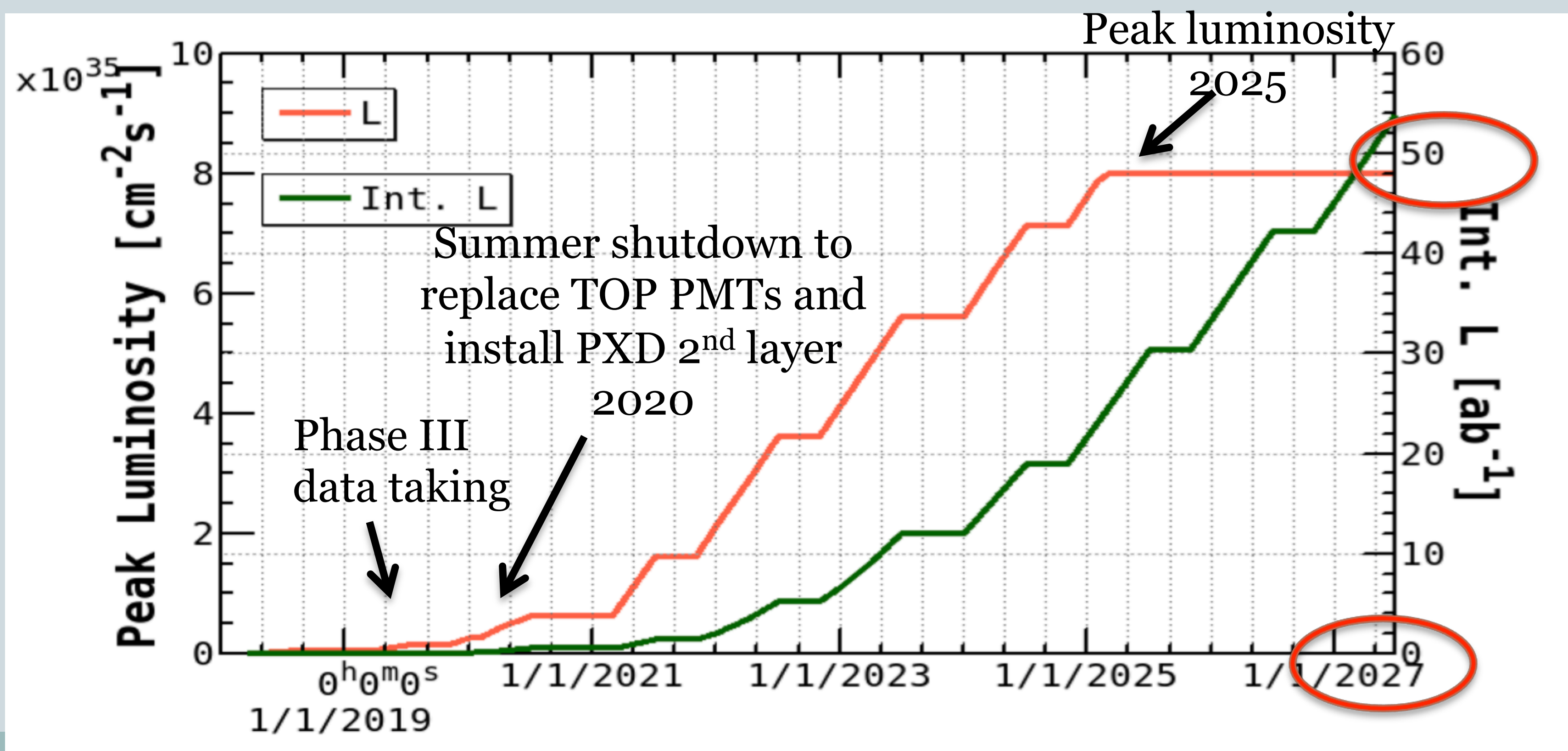
JHEP 1712 (2017) 094



Phase III timeline

Belle II aims:

- ~5 fb-1 by July 2019
- 100 fb-1 by December 2019
- >500 fb-1 by 2020
- 1 ab-1 by 2021



Proposed Polarized Electron Beam at SuperKEKB

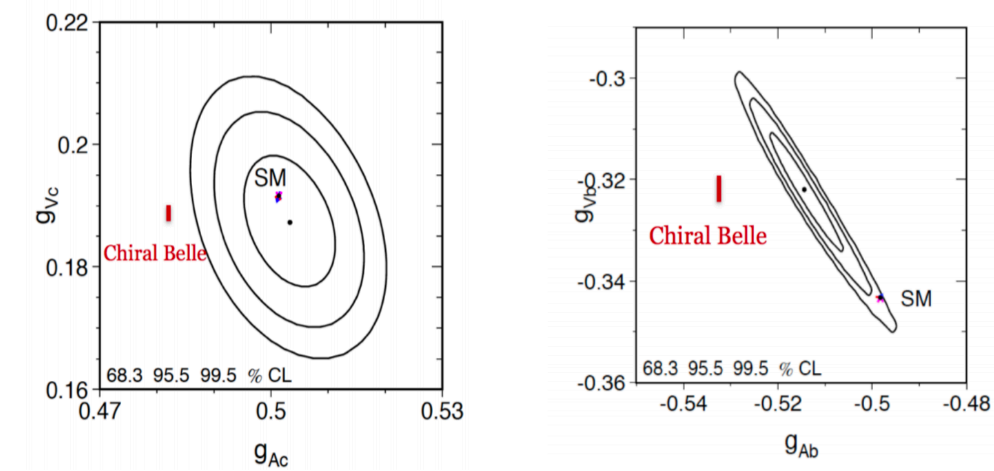
- Canadian-led effort.
- A measurement of the asymmetry in the cross-section for producing left and right handed particles(ALR) gives access to the neutral current couplings and $\sin^2\theta_W$
- At Belle II this can be done for e,μ,τ,b,c

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle Pol \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

c-quark: Chiral Belle ~7 times more precise

with 20 ab⁻¹

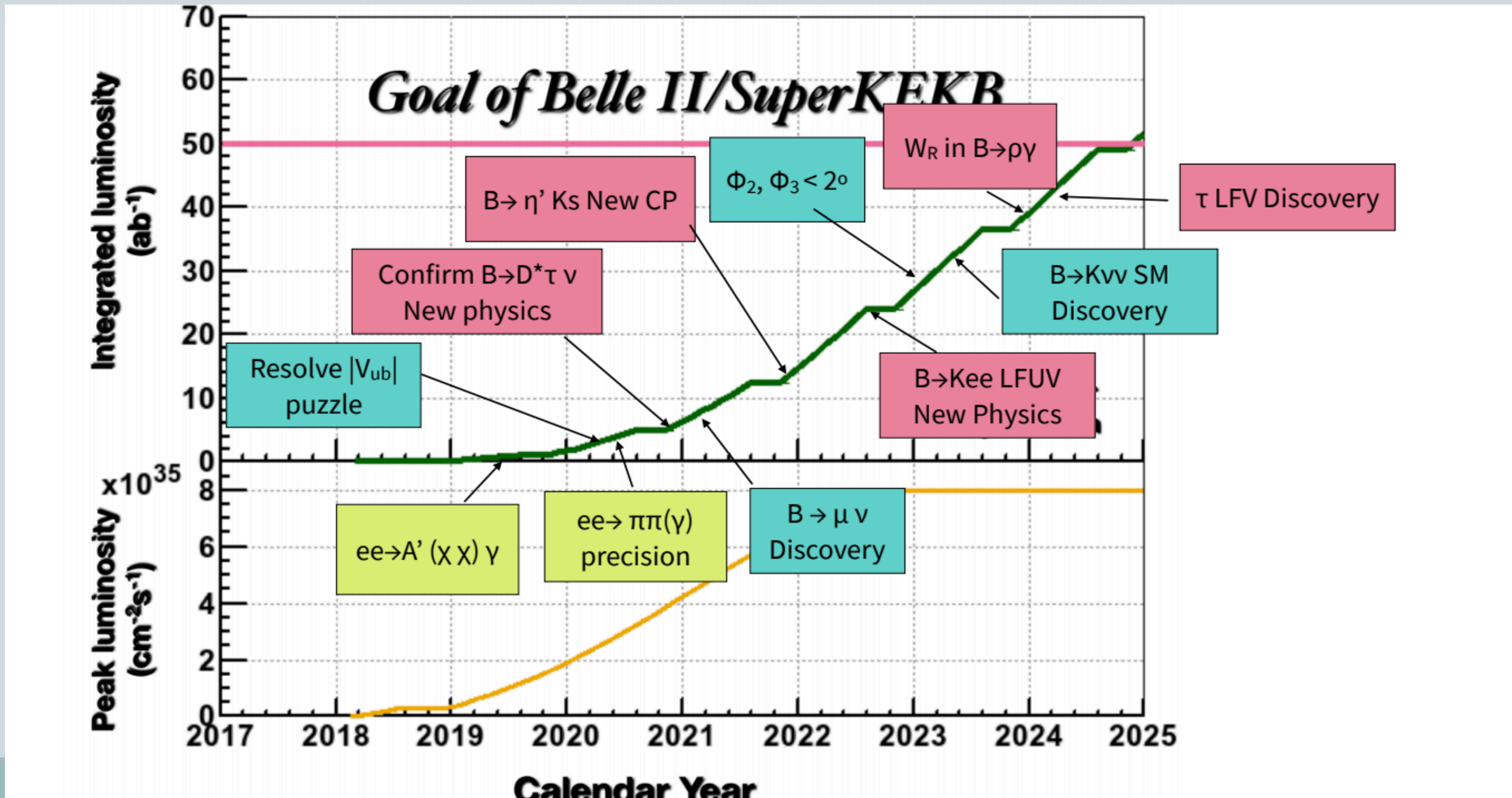
b-quark: Chiral Belle ~4 times more precise



See talk and poster by Caleb Miller!

Summary

- Belle II physics run has started in March 2019.
- Upcoming data set is promising, panorama of results to come.
- STAY TUNED!



Back up slides

Beam backgrounds in Phase III

Time Of Propagation Cherenkov Counter

Current Status:

- 224 PMTs to be replaced by summer 2020

Year		2019				2020		
Month	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9
Global schedule			Physics run		Physics run			
PMT production			Mass production					
(for spares)								
PMT test								
(in B-field)	~80 PMTs				~180 PMTs			
PMT installation						Assembly		Install

Should be ready for the replacement by the end of June 2020.

Net time for PMT replacement only is 2 weeks.