SuperKEKB and Belle II

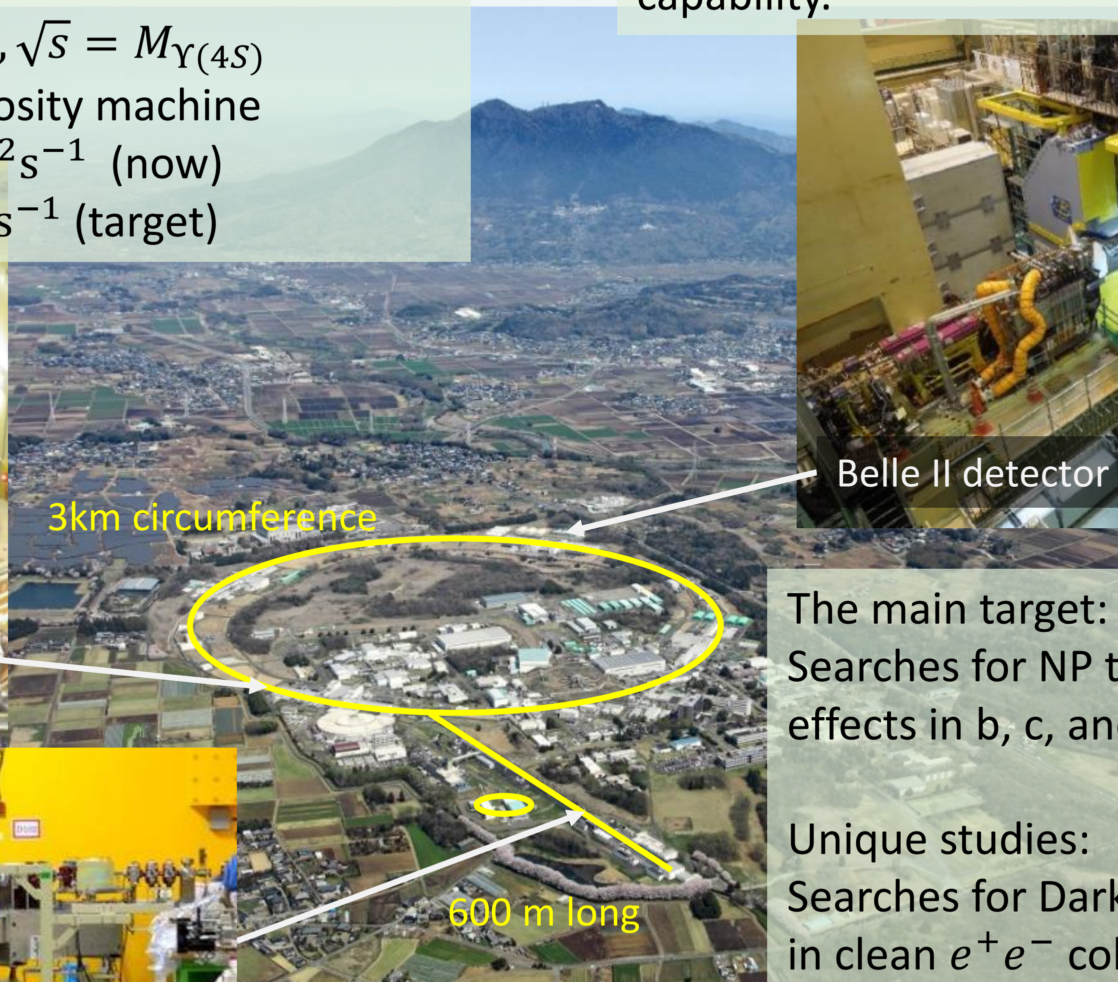
Yutaka Ushiroda (IPNS, KEK)
Belle II Project Manager

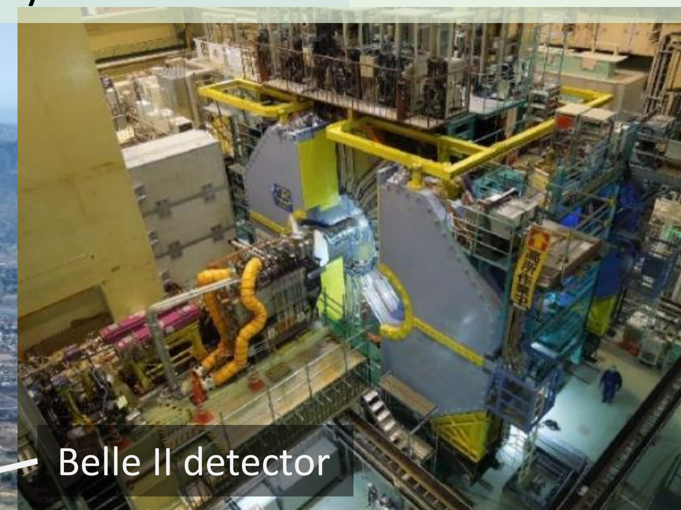
March 2023

Project Overview

SuperKEKB collider:
Largest scale e^+e^- collider in the world
$7\ \mathrm{GeV}e^- \times 4\ \mathrm{GeV}e^+, \sqrt{s} = M_{\Upsilon(4S)}$
World highest luminosity machine
$L \sim 4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (now)
$L \sim 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (target)

Belle II detector:
General purpose spectrometer for collider experiment with excellent vertex resolution and particle identification capability.





The main target:
Searches for NP through quantum effects in b, c, and τ decays.

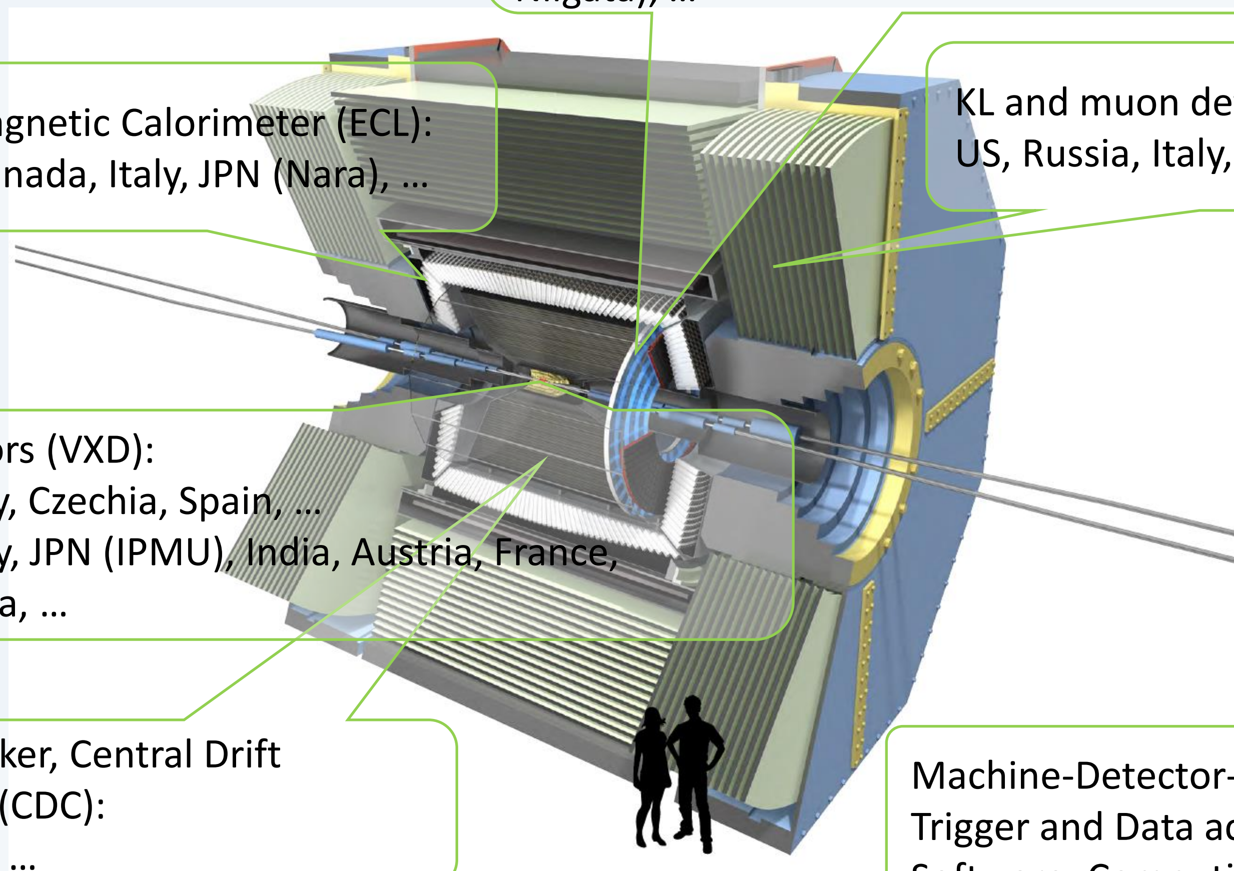
Unique studies:
Searches for Dark Sector particles in clean e^+e^- collisions
Studies of exotic hadrons

Belle II detector

Particle Identification (PID):
[TOP] JPN (Nagoya), US, Italy, Slovenia, …
[ARICH] KEK, Slovenia, JPN (Tokyo Metropolitan, Niigata), …

Electromagnetic Calorimeter (ECL):
Russia, Canada, Italy, JPN (Nara), …

KL and muon detector (KLM):
US, Russia, Italy, China, …

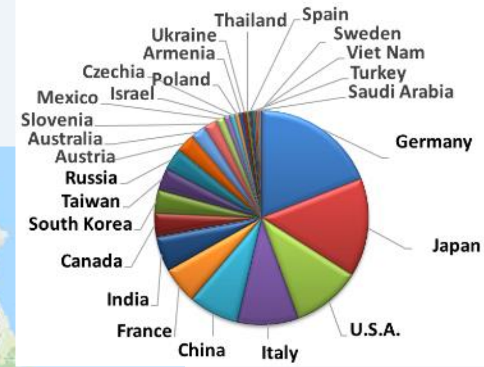


Vertex Detectors (VXD):
[PXD] Germany, Czechia, Spain, …
[SVD] KEK, Italy, JPN (IPMU), India, Austria, France, Australia, Korea, …

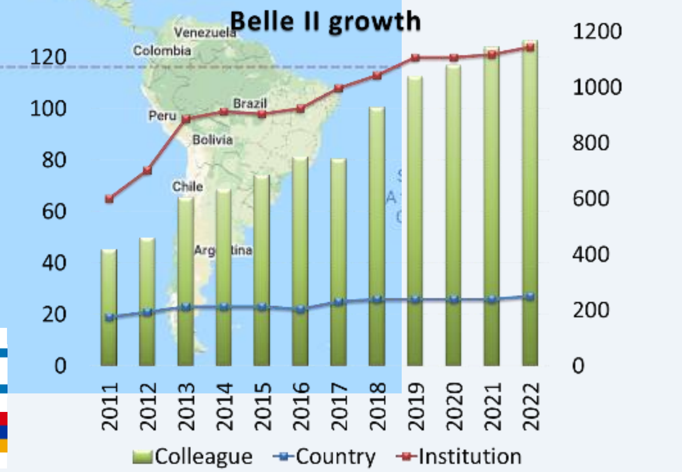
Main Tracker, Central Drift Chamber (CDC):
KEK, NPC, …

Machine-Detector-Interface,
Trigger and Data acquisition,
Software, Computing,
Detector Structure and services

Belle II collaboration



27 countries/regions
124 institutions
>1100 researchers



Brookhaven National Laboratory	Univ. of Mississippi(UM)
Carnegie Mellon Univ.(CMU)	Univ. of Pittsburgh
Duke University	Univ. of South Alabama
Indiana Univ.	Univ. of South Carolina
Iowa State University	University of Cincinnati
Kennesaw State University	University of Louisville
Luther College	Virginia Polytechnic Institute and State Univ.(Virginia Tech)
Pacific Northwest National Laboratory	Wayne State Univ.
Univ. of Florida	
Univ. of Hawaii	

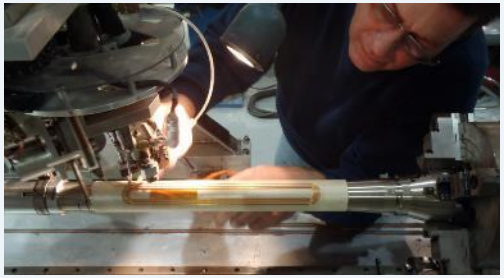
122 researchers from 18 institutions in US

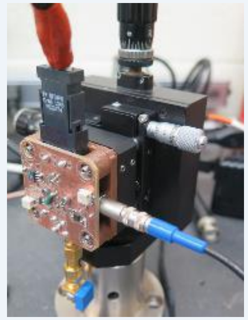
US contributions

non-exhaustive

Constructed

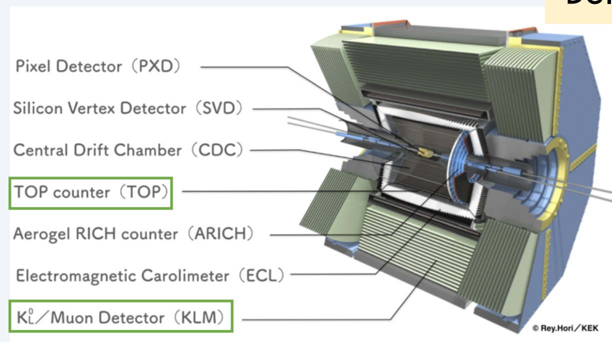
SuperKEKB

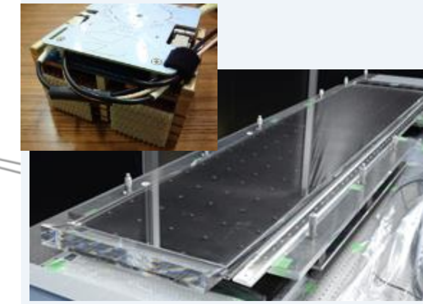




- QCS corrector magnets by BNL
- X-ray beam size monitor with SLAC and Hawaii
- Single stretched wire system to measure the field center and angle of Q magnets by FNAL
- Quadrupole field vibration measurement system with BNL
- Dithering feedback systems with SLAC
- Large angle beamstrahlung monitor with Wayne

Belle II





- TOP counter quartz bar from US
- TOP front-end electronics by Hawaii

- Barrel KLM scintillator module by Virginia Tech (Scintillator by FNAL)
- KLM readout by Hawaii

- Beam background study and mitigation

On-going

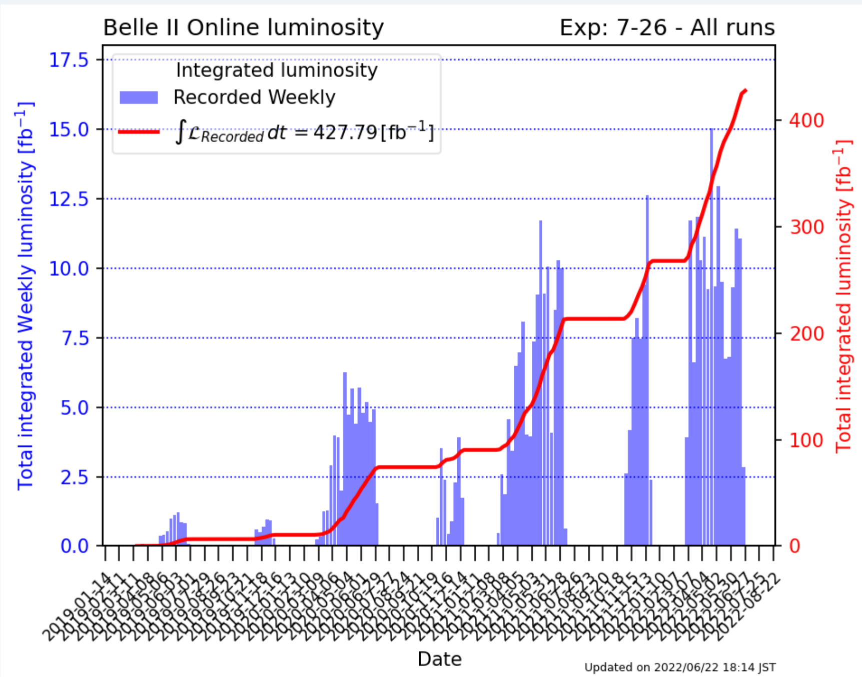
- Digital IP feedback system with SLAC
- Polarized electron source with BNL, JLab
- Spin rotator for polarized beam with BNL

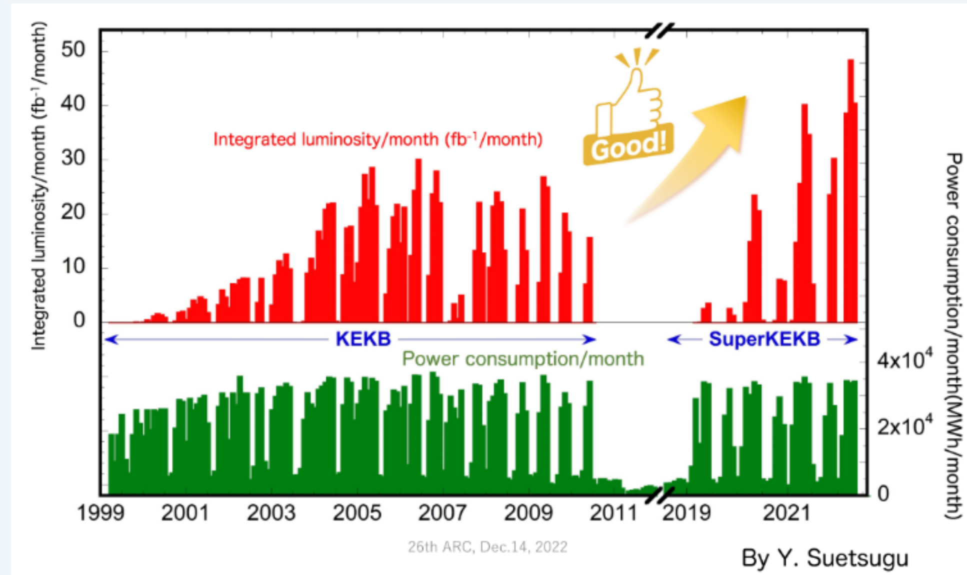
- Raw data center at BNL
- TOP/KLM operation
- TOP L1 trigger with Pittsburgh, Hawaii
- New readout ASIC for detector upgrade by Hawaii

Operation Status

$L \sim 4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (w.r.)

Integrated luminosity reached ~430/fb
much quicker than KEKB/Belle





Twice better luminosity than KEKB
with similar power consumption.

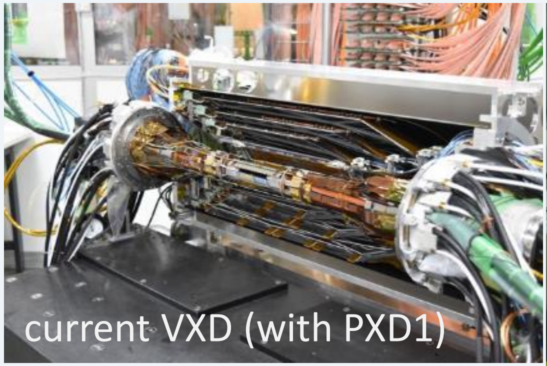
Exploring uncharted territory
… and we want more!

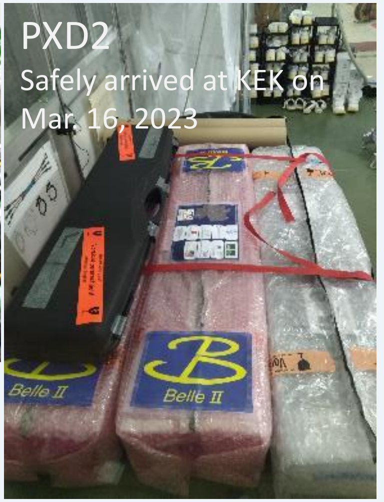
Works during LS1

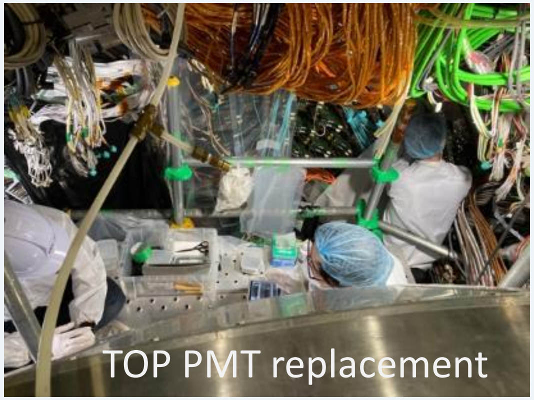
Operation stopped in summer 2022 for a long shutdown

- [main purpose] Install a 2-layered pixel vertex detector (PXD) with a new IP beam pipe
- Other improvements in detector
    - Replace aged photomultipliers for barrel PID (TOP)
    - Complete transition to the new DAQ system (PCIe40), improved data-quality monitoring and alarm system.
    - Improvement in central drift chamber, KL and muon detector
    - Additional shielding, …
- Improvements in accelerator
    - Non-Linear Collimator
    - Cu-coated collimator head
    - Aperture-widened injection section
    - More monitors

Plan to resume operation from the next winter





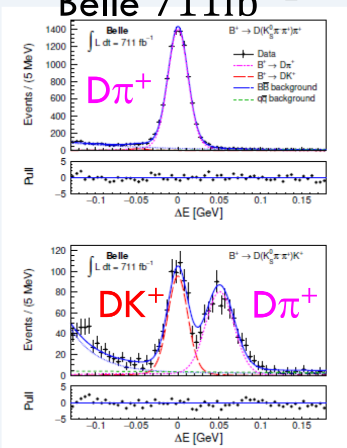


Physics data analyses

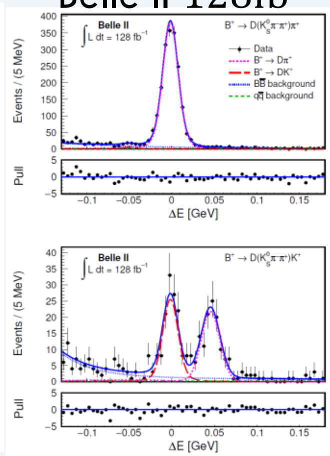
Belle II data is not a tiny addition to Belle. Good detector and good analysis method give a significant improvement

Visit Moriond EW for the latest results. Papers are coming out overcoming the "author list crisis".

Belle $711 fb^{-1}$

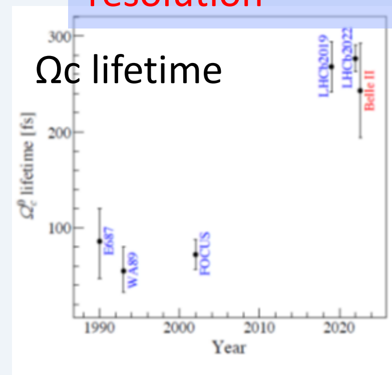


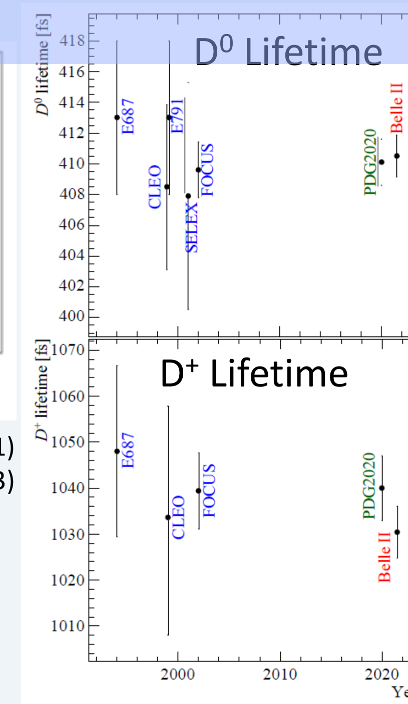
Belle II $128 fb^{-1}$



$$\phi_3 = (78.3 \pm 11.4 \pm 0.5 \pm 1.0)^\circ \quad \text{(was } \pm 15^\circ\text{)}$$

World leading charm lifetime measurement with excellent vertex resolution



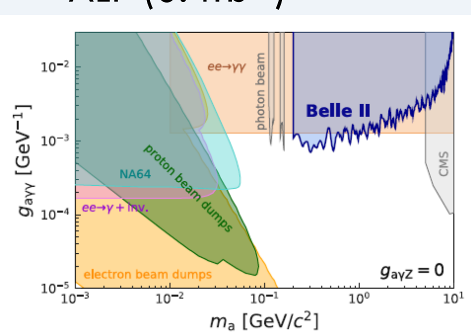


Phys. Rev. Lett. 127, 211801 (2021)
Phys. Rev. Lett. 130, 071802 (2023)
Phys. Rev. D 107, L031103 (2023)

A. Ishikawa @KEK RPC

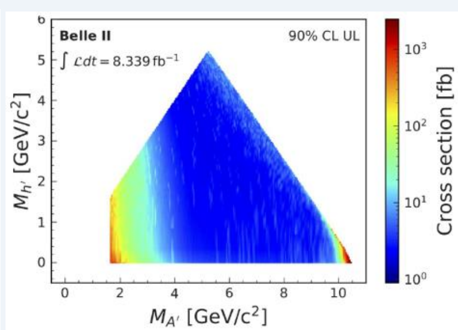
L1 trigger compatible with Dark sector searches.
Setting new exclusion regions

ALP ($0.4 fb^{-1}$)



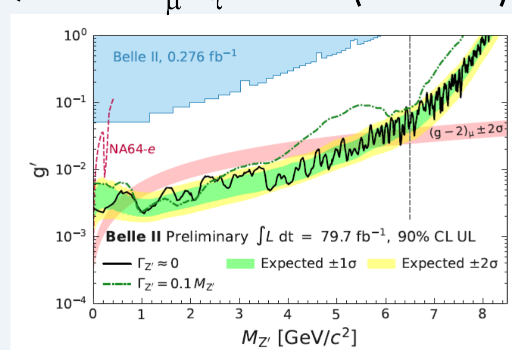
Phys. Rev. Lett. 125, 161806 (2020)

Darkhiggsstrahlung ($8.34 fb^{-1}$)



Phys. Rev. Lett. 130, 071804 (2023)

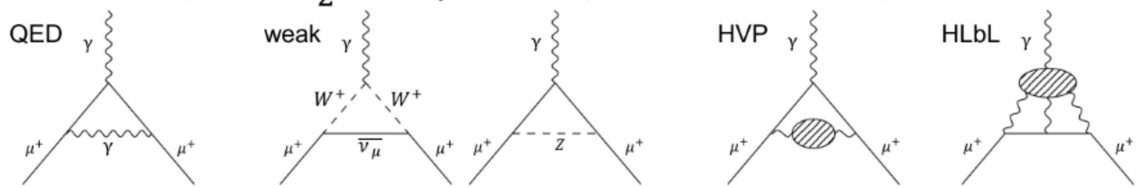
Z' in L_μ-L_τ model ($79.7 fb^{-1}$)



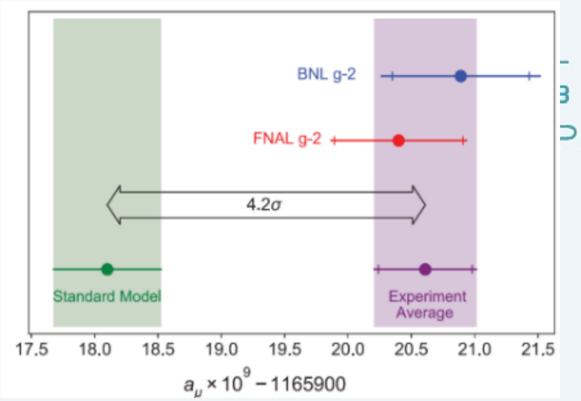
submitted to PRL in 2022

Muon g-2 puzzle

$$a_\mu^{\rm SM} = \frac{g-2}{2} = a_\mu^{\rm QED} + a_\mu^{\rm weak} + a_\mu^{\rm HVP} + a_\mu^{\rm HLbL}$$

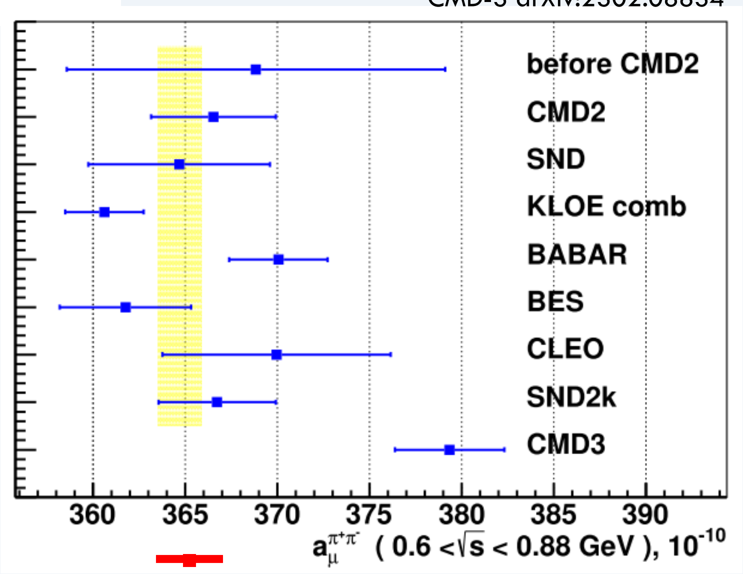


B. Abi *et al*,, PRL126, 141801 (2021)
T. Aoyama *et al*., Phys. Rept. 887 (2020).

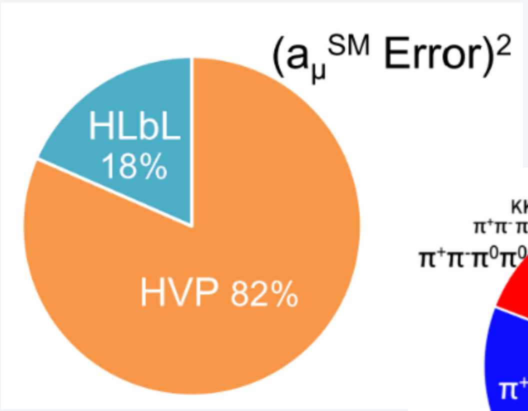


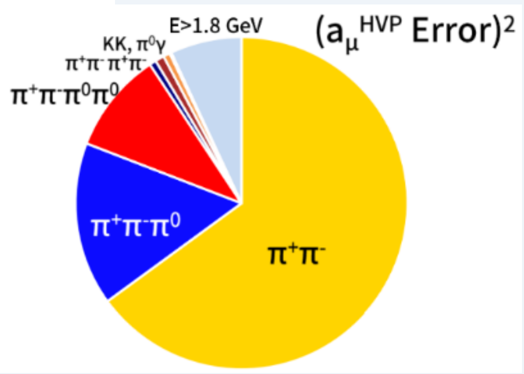
Important to understand the SM corrections by Lattice QCD and by data-driven way

CMD-3 arXiv:2302.08834



Belle II target (0.5%)

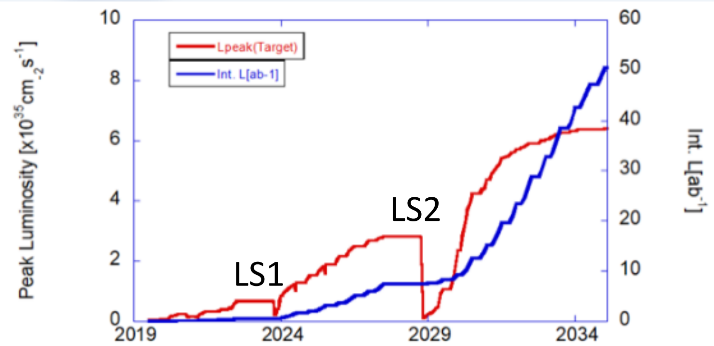




Y. Sue (Nagoya) @KEK-FF 2023

Belle wasn't in the game, but Belle II will.
$e^+e^- \rightarrow \pi^+\pi^-(\gamma), \pi^+\pi^-\pi^0(\gamma)$ for HVP and $\gamma\gamma^* \rightarrow \pi^0$ for HLbL

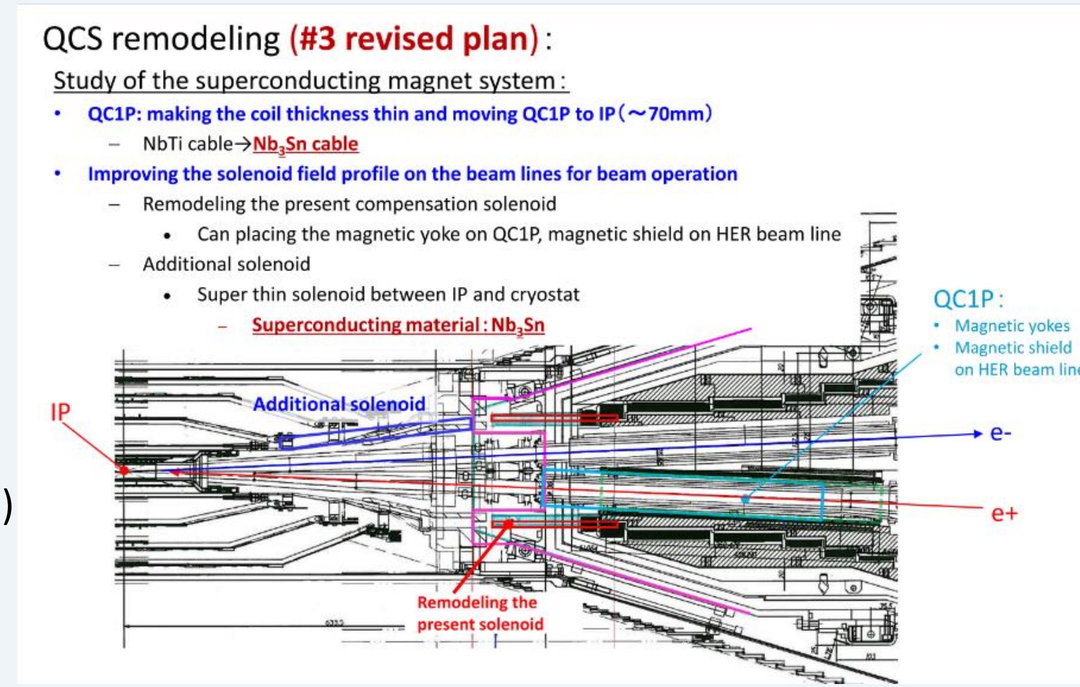
Longer-term



Need one more upgrade to bring up the luminosity to ~6e35
Ideas, R&Ds welcome
-> International Task Force (contact me or the chair: Y. Ohnishi)

Most likely there will be an upgrade of interaction region (QCS, VXD, …)

- Thin superconducting magnets (anti-solenoid, Quadrupole) to be placed very close to the interaction point -> Nb_3Sn
- Compact Vertex Detector (including service)
- A new Remote Vacuum Connection system



N. Ohuchi

Other Upgrade Item:

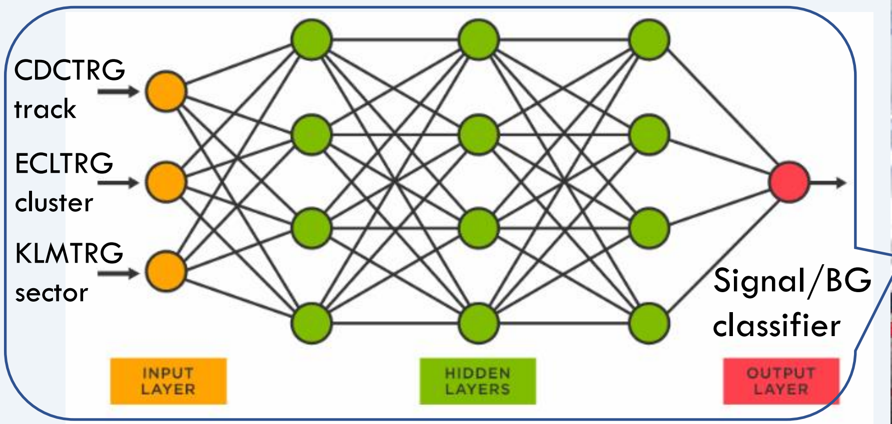
- Polarized electron beam (polarized source, spin rotator)

Challenges in L1 trigger

Keep high efficiency even for low multiplicity events (originally not in the design), while keeping the latency (5us) and the allowed rate (30kHz@max.)

➡ Put all the sub-trigger info into NN

Neural network



~200ns latency

	Current	Upgrade
Tau 1-1 prong signal	50%	97%
Background rejection	60%	60%

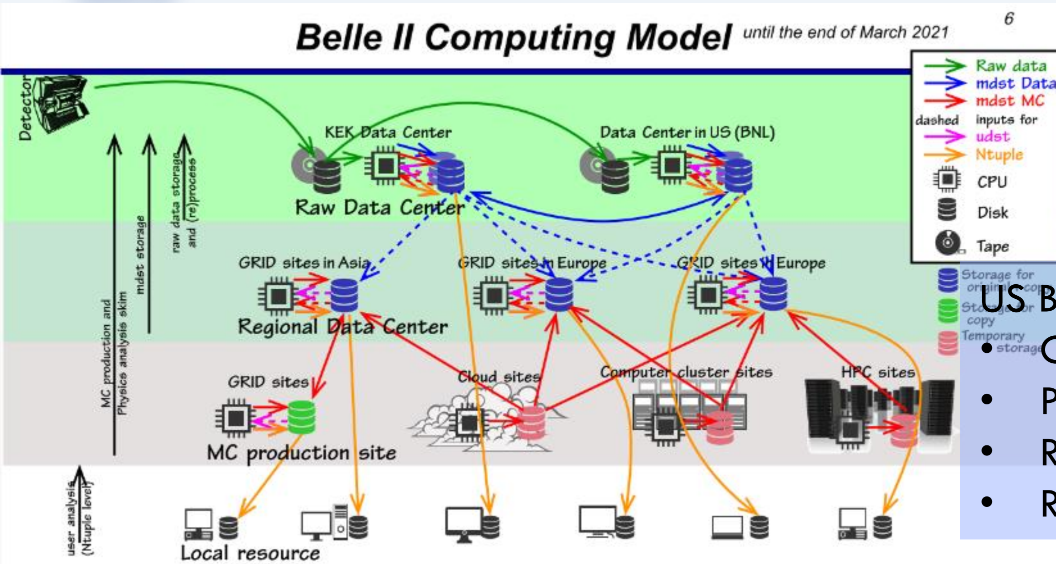
preliminary

Need more R&Ds

This upgrade keeps the window open for:

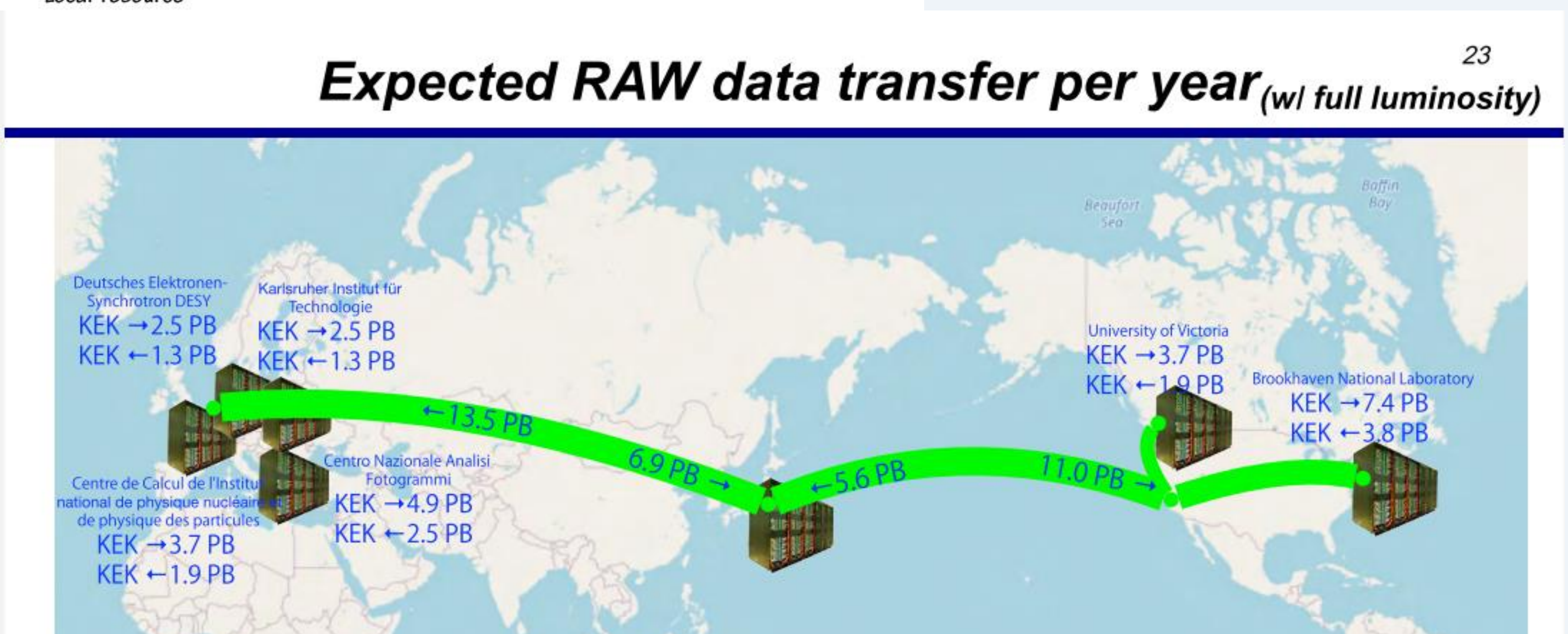
- tau LFV, LFU, EDM with 1-prong decays
- Search for dark photon($e^+e^-\to\gamma X$), ALP ($e^+e^-\to\gamma a$, $a\to\gamma\gamma$), long lived particles, ...
- hadronic vacuum polarization ($e^+e^-\to\pi^+\pi^-\gamma$) to understand muon g-2 puzzle

and in computing



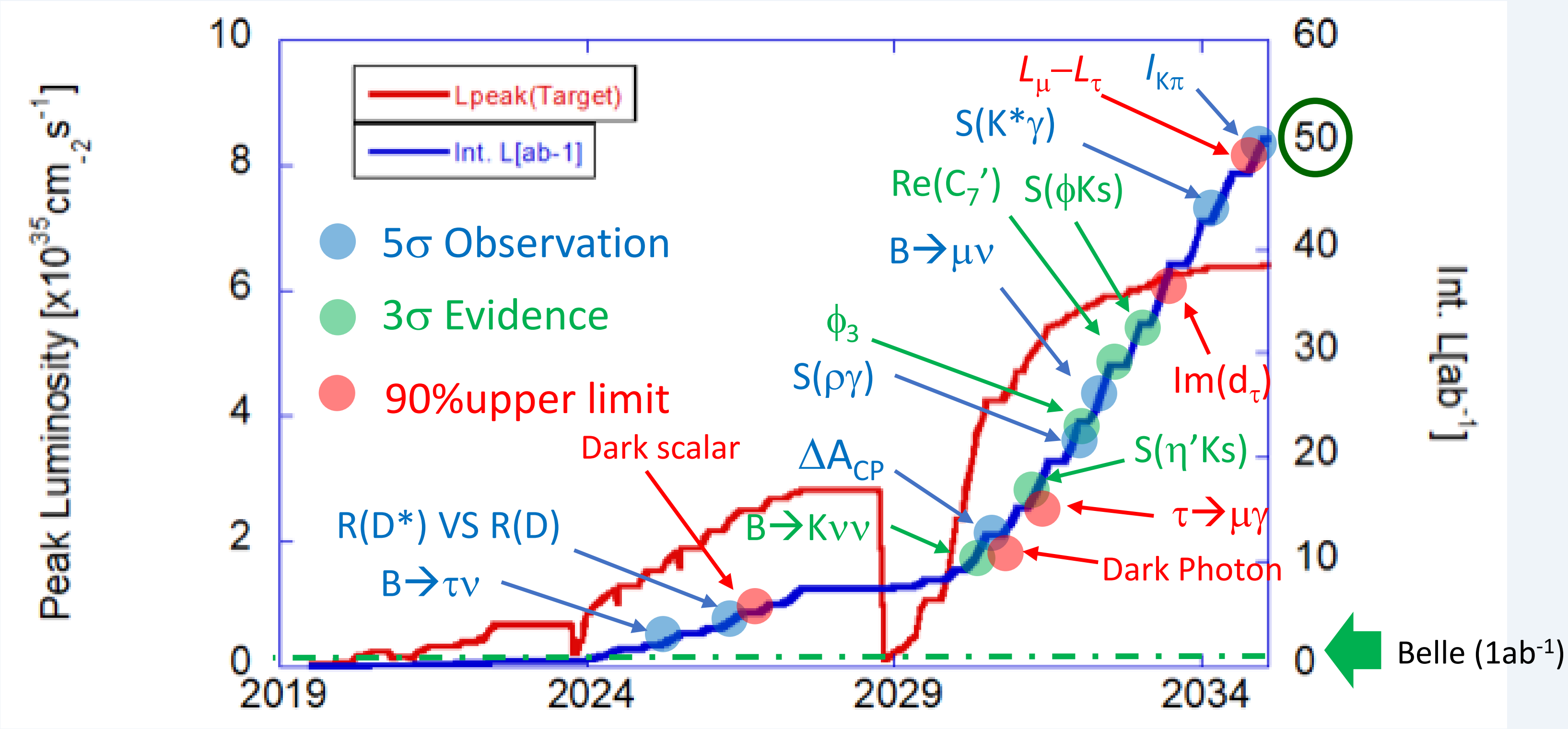
US Belle II in computing:

- One of raw data centers
- Prompt calibration center
- Rucio, distributed data management system
- Resources for production, processing and analysis



T. Hara@ATCF6 Belle II prospect is compatible with the network upgrade plans

Possible evidences and observations



There may be new findings even with small amount of data

Summary

- SuperKEKB and Belle II have started operation, regularly updating the world record luminosity. Although the integrated luminosity is still smaller than Belle, physics sensitivities are already competitive with Belle and other experiments.
- Currently in LS1 to upgrade BP, PXD, collimators, … Plan to resume from the next winter.
- Upgrade foreseen in the accelerator (especially in the final focusing system) and in the detector. Collaboration in R&D very welcome.
- Looking forward to reporting new findings.

Tsukuba hall is good to visit especially in this season.

backup

Policy statement:
https://confluence.desy.de/display/BI/Messages+from+Management?preview=/246222204/280861236/Belle%20II%20Response%20to%20the%20Ongoing%20Russian%20Invasion%20of%20Ukraine-Revised13Oct2022-endorsed20Oct2022.pdf

Summary –Belle II Measures

Considering the above points, the Belle II Collaboration adopts the following measures:

- Belle II members from Russian institutes continue to contribute to the experiment as collaboration members.

As for publications,

- We list the names of all individuals who signed the authorship confirmation.
- Author affiliations and country names are not listed. Instead, individual authors are uniquely identified using their ORCID.
- Papers will include the following acknowledgements that accurately recognize historical contributions pre-dating the Russian invasion of Ukraine:

"This work, based on data collected using the Belle II detector, which was built and commissioned prior to March 2019, was supported by ...(list of funding sources).

These acknowledgements are not to be interpreted as an endorsement of any statement made by any of our institutes, funding agencies, governments, or their representatives.

We thank the SuperKEKB team for delivering high-luminosity collisions; the KEK cryogenics group for the efficient operation of the detector solenoid magnet; the KEK computer group and the NII for on-site computing support and SINET6 network support; and the raw-data centers at BNL, DESY, GridKa, IN2P3, INFN, and the University of Victoria for offsite computing support."

These measures will be reviewed regularly at every Belle II General Meeting until these extraordinary measures are no longer required.

(Adopted by the Institutional Board, 20 October 2022)

Example from Belle

20 Dec 2022

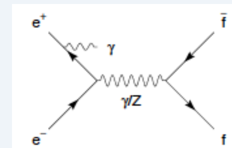
Search for a heavy neutrino in

D. Liventsev, I. Adachi, H. Aihara, S. Al Said
R. Ayad, V. Babu, Sw. Banerjee, M. Bauer
J. Bennett, M. Bessner, T. Bilka, D. Biswas
J. Borah, A. Bozek, M. Bračko, P. Branchini,
M. Campajola, D. Červenkov, M.-C. Chang,
H. E. Cho, K. Cho, S.-J. Cho, S.-K. Choi,
D. Cinabro, S. Das, G. De Nardo, G. De Pietro
Z. Doležal, T. V. Dong, D. Dossett, D. Epifanov
B. G. Fulsom, R. Garg, V. Gaur, A. Giri, P.
T. Gu, K. Gudkova, C. Hadjivasiliou, X. Han

Future programs (2) -- Chiral Belle

Y. Ushiroda @KEK SAC 2021

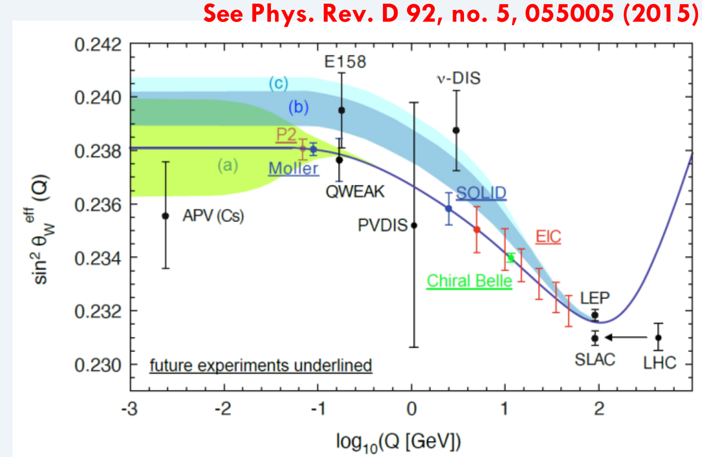
- Upgrade of SuperKEKB with polarized electron beams (70±0.5%@IP)
  - for precision Neutral Current EW physics.
    - World's most precise $\sin^2\theta_W$ (σ~0.02% w/ 20/ab) and probe its running
    - Unprecedented clean NC universality studies for e, μ, τ, c and b.
    - NP searches: Sensitive to >TeV Z' and dark sector P-violating Z'_D below M_Z
  - and other programs:
    - Tau physics (tau EDM, $(g-2)_\tau$, τ-LFV)
    - Dynamical mass generation in QCD via polarized Λ or a hadron pair



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

$$\propto T_3^f - 2Q_f \sin^2\theta_W$$

See Phys. Rev. D 92, no. 5, 055005 (2015)



Scenarios with dark Z bosons for m_{Zd} of (a) 50 MeV, (b,c) 15 GeV (where area (c) is in tension with existing constraints)

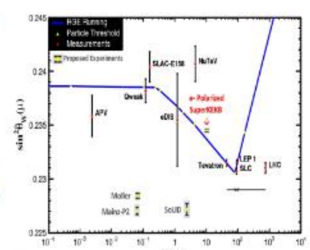
Polarized electron beam

Physics case: precision $\sin^2\theta_W$ measurements from b, c, e, μ & τ, probing its running and universality.

Planning 70% polarization with 80% polarized source.

NEW HARDWARE FOR POLARIZATION UPGRADE:

- Low emittance polarized Source: electron helicity can be flipped bunch-to-bunch by controlling circular polarization of source laser illuminating a GaAs photocathode (à la SLC). Inject vertically polarized electrons into the 7 GeV e- Ring, needs low enough emittance source to be able to inject.
- Spin rotators: Rotate spin to longitudinal before Interaction Point (IP) in Belle II, and then back to vertical after IP using solenoidal and dipole fields
- Compton polarimeter: monitors longitudinal polarization with <1% absolute precision, provides real time polarimetry. Use tau decays from $e^+e^- \to \tau^+\tau^-$ measured in Belle II to provide high precision absolute average polarization at IP.



e- spin vector around ring

Project under active development

F. Forti @BPAC 2023

Belle II observables and models

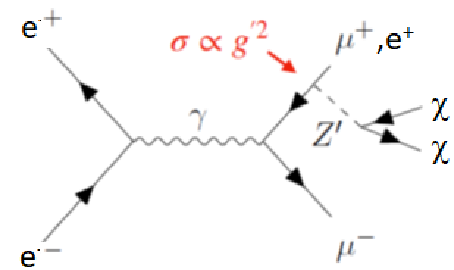
Combination of different observables helps discriminating the NP models.

Observables	Charged Higgs	SUSY	Minimal Flavor Violation	Z'	Gauged Flavor	3-3-1	LR symmetric model	Leptoquark	Compositeness	Dark Sector
$S_{CP}(B\to\eta' K^0)$	★	★	★	★	★	★	★★	×	?	×
$S_{CP}(B\to K^{*0}\gamma)$	★★★	★★★	★★★	★	★	★	★★	★	★★★	×
$S_{CP}(B\to\rho\rho)$	×	×	×	★★★	★	★★★	?	?	?	×
$I_{K\pi}$	×	★	×	★★★	★	★★★	?	×	?	×
$R(D^{(*)}\tau\nu)$	★★	×	×	×	×	×	★	★★★	★	★
$R_{K(*)}$	×	×	×	★★	×	★★	×	★★★	★★	×
$B(B\to X_s l^+ l^-)$	×	×	★★★	★★	×	★★	×	★★★	★★	×
$B(B\to X_s\gamma)$	★★★	★★★	★★★	★	★★	×	★	★	★★★	×
$\Delta A_{CP}(B\to X_s\gamma)$	★★★	★★★	×	★	★	★	★★	★	★	×
$B(\tau\to\mu\gamma)$	★	★★★	★	★	★	★	×	★	★★★	?
$B(\tau\to\mu\mu\mu)$	★	×	×	★★★	★★★	★★★	×	×	★★★	?
Dark photon	★	×	?	★	×	★	×	×	×	★★★

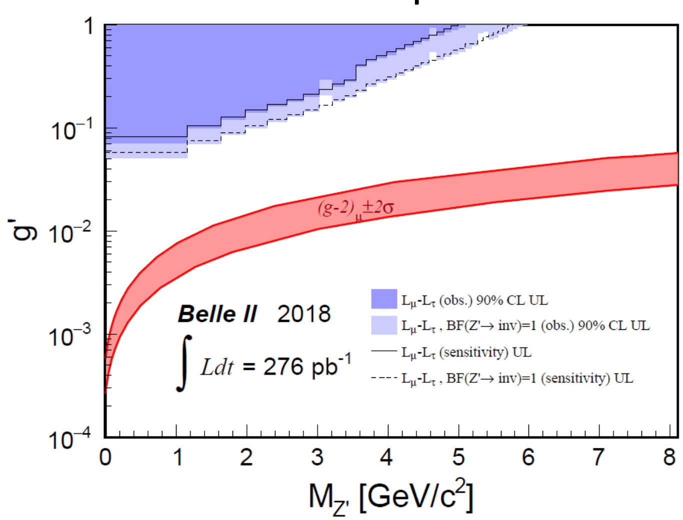
★ World leading

Dark Sector : Z' in L_μ-L_τ model

- At Belle, this analysis was not easy due to limited trigger acceptance
- First search for invisible decays of Z' in L_μ-L_τ model with Phase 2 data of 276pb^{-1} in 2020
  - The first physics paper from Belle II
- Update in 2022 with 300 times larger data of 79.7fb^{-1}
  - Parameter space explaining muon g-2 can be excluded.



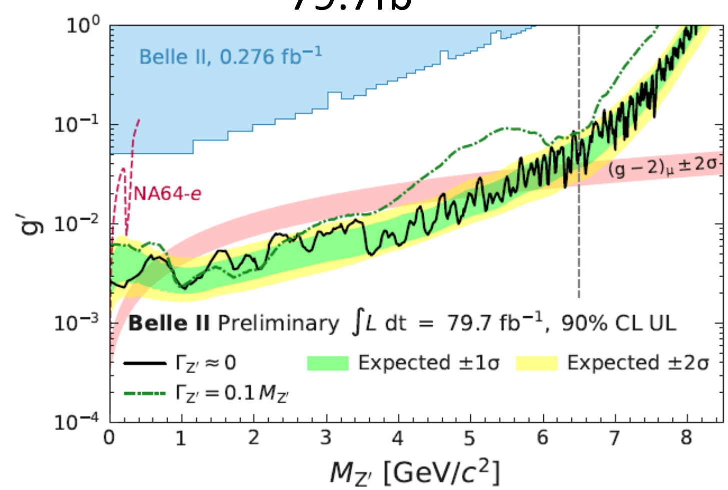
276pb^{-1}



Phys. Rev. Lett. 124, 141801 (2020)

x300

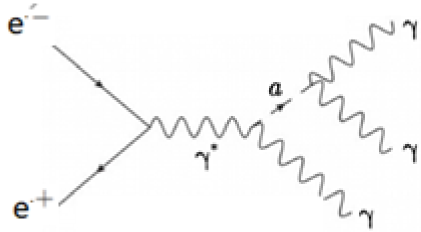
79.7fb^{-1}



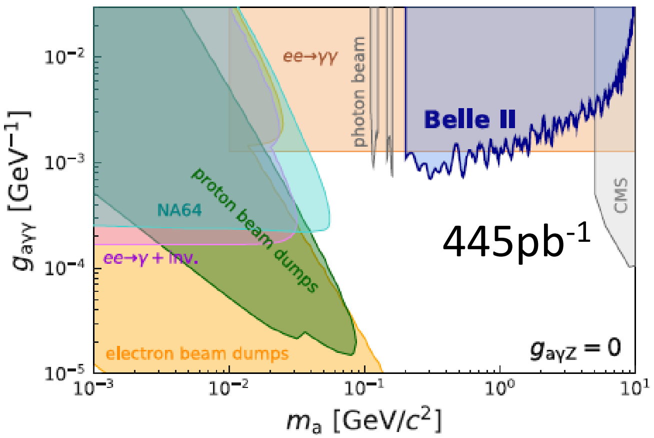
submitted to PRL in 2022

★ World leading

Dark Sector : Axion Like Particles



- Axion Like Particles
  - Emerge from
    - New global symmetry breaking
    - String compactification
  - Unlike the QCD axion, there is no relation between mass and decay constant → could exist anywhere!
- Search for ALPs with photon coupling with phase 2 data of 445pb^{-1}
  - The second physics paper
  - $e^+e^- \rightarrow a\gamma$, $a \rightarrow \gamma\gamma$
  - New limit can be set around m_a=500MeV

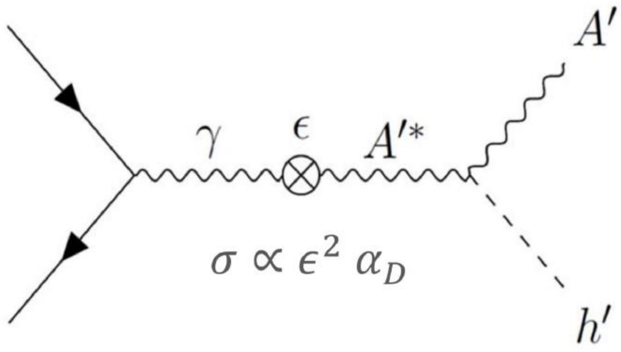


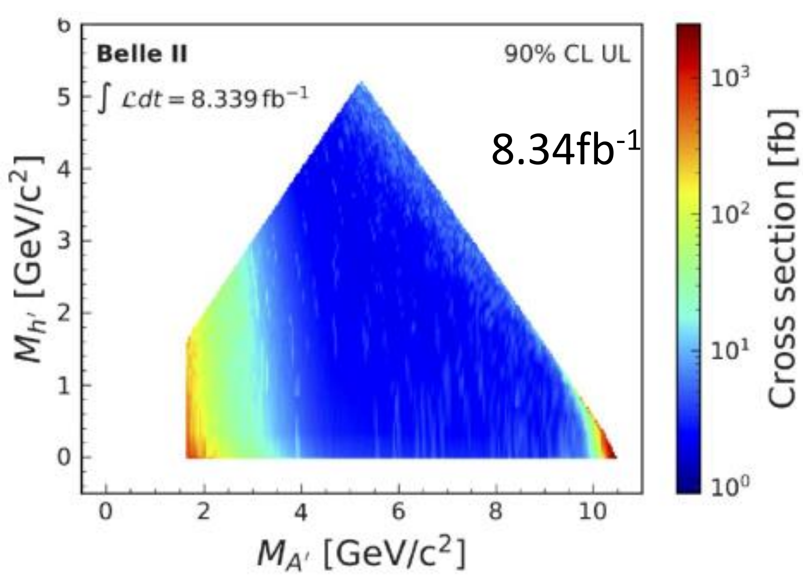
Phys. Rev. Lett. 125, 161806 (2020)

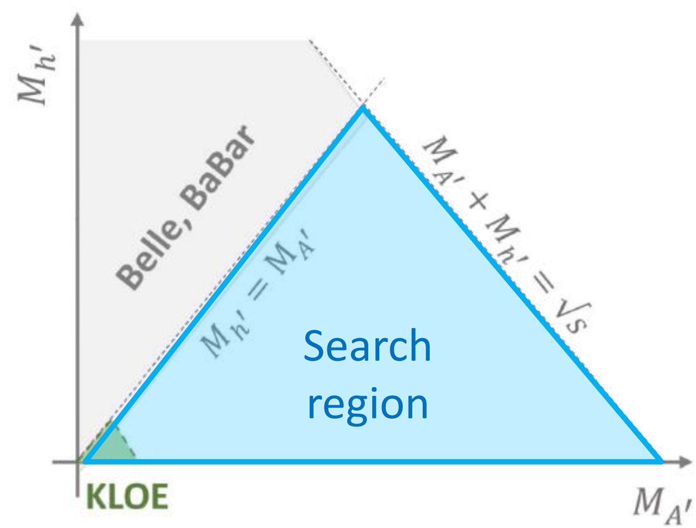
★ World leading

Dark Sector : Dark Higgsstralung

- Dark photon might acquire mass from dark Higgs
  - If h' is lighter than A', h' is long-lived (invisible)
- KLOE did the search but only low mass region
- First search for higher mass h'
  - Ee→A'h', A'→μμ
  - Invariant and recoil mass
  - Strong limit on the cross section







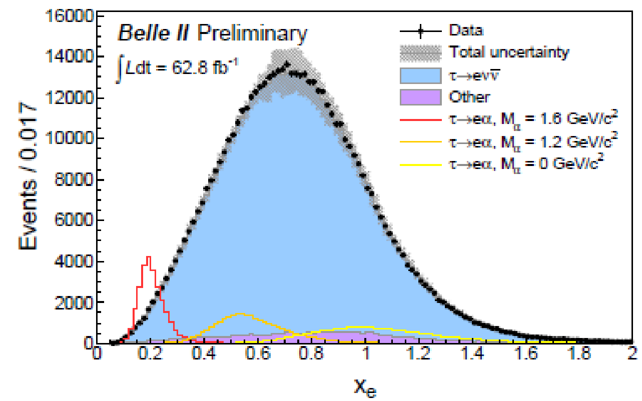
[Phys. Rev. Lett. 130, 071804 (2023)]

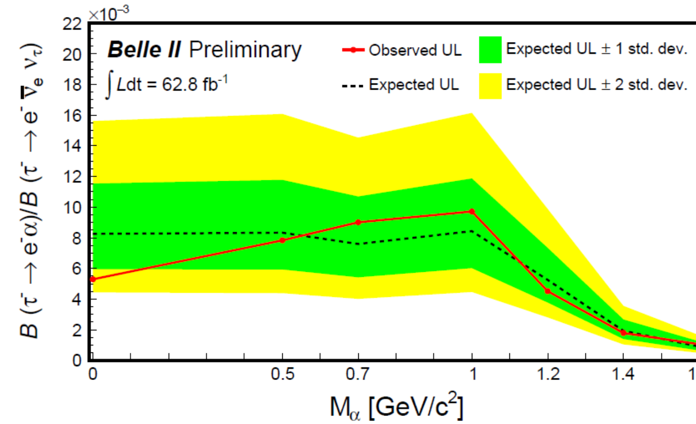
★ World leading

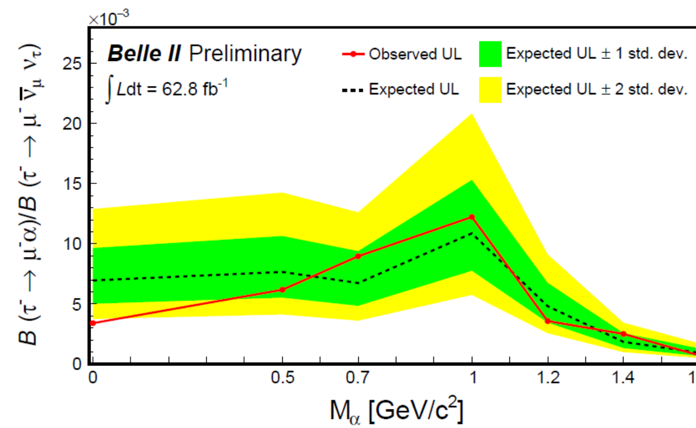
Dark Sector in τ decays

- Search for τ lepton decaying to lepton and invisible particles a with 62.8fb^{-1}
  - $t^+ \rightarrow e^+a, \mu^+a$
- Long lived ALPs, etc contribute the decays.

- The analysis was not done in Belle nor BaBar.
- New since ARGUS results in 1995.
- The improvement is from 2-fold to 14-fold dependent on the mass of a

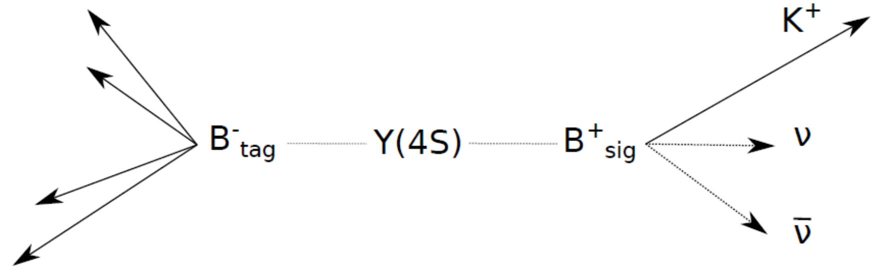




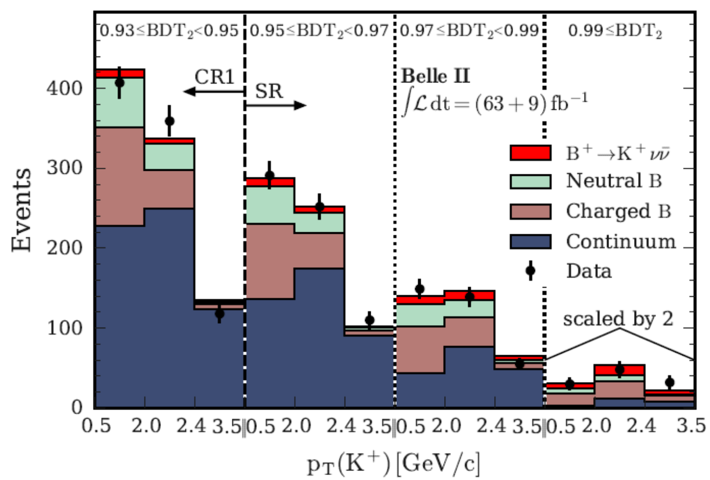


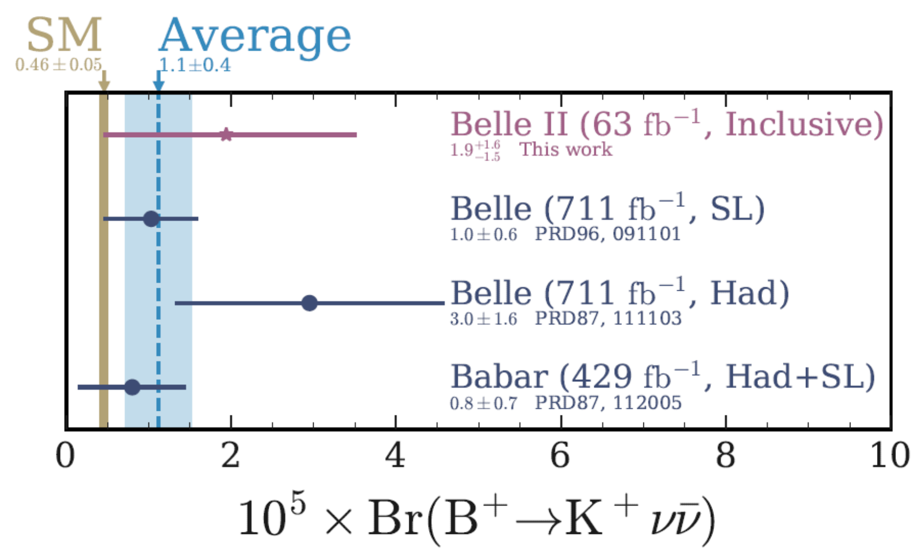
Submitted to Physical Review Letters
arXiv:2212.03634

$B^+ \rightarrow K^+\nu\nu$



- Deficits of BF of b→sl+l- decays were observed.
- Important to check weak isospin counter decays $B^+ \rightarrow K^+\nu\nu$
  - Tagging of the other B is required due to multiple neutrinos in the final state
- With improved vertex resolution and new inclusive tagging method, $B^+ \rightarrow K^+\nu\nu$ is searched for with 63fb^{-1} data
- Only with 9% data of Belle II, the result is comparable with Belle hadronic analysis





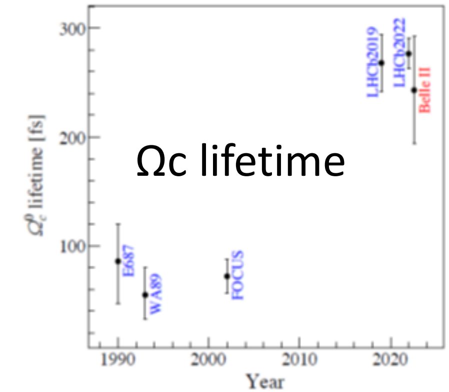
Phys. Rev. Lett. 127, 181802 (2021)

A. Ishikawa @KEK RPC

★ World leading

Phys. Rev. Lett. 127, 211801 (2021)
Phys. Rev. Lett. 130, 071802 (2023)
Phys. Rev. D 107, L031103 (2023)

Charmed Hadron Lifetime



- Hard to perform at Belle due to limited knowledge of vertex detector alignment
- Last measurements for D^0 and D^+ were by FOCUS
- World's best charmed hadron lifetime
  - D^0, D^+, Λc, Ωc
  - Confirmed Ωc lifetime is not the shortest lifetime

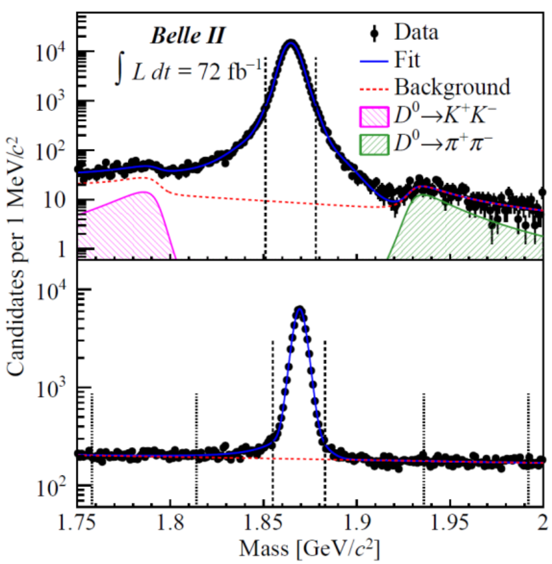
$$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) \Rightarrow \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

- Belle II results are better than PDF averages

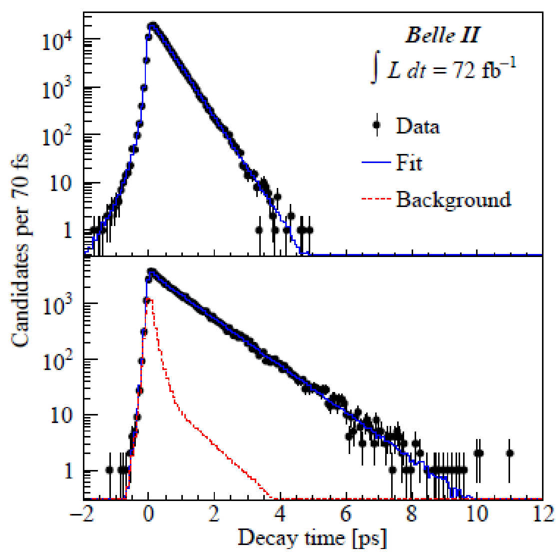
Mass

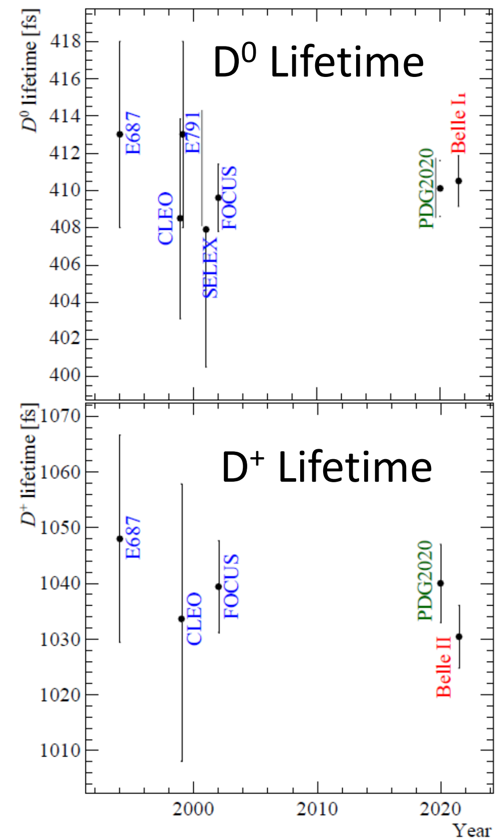
D0

D+



Propertime distribution



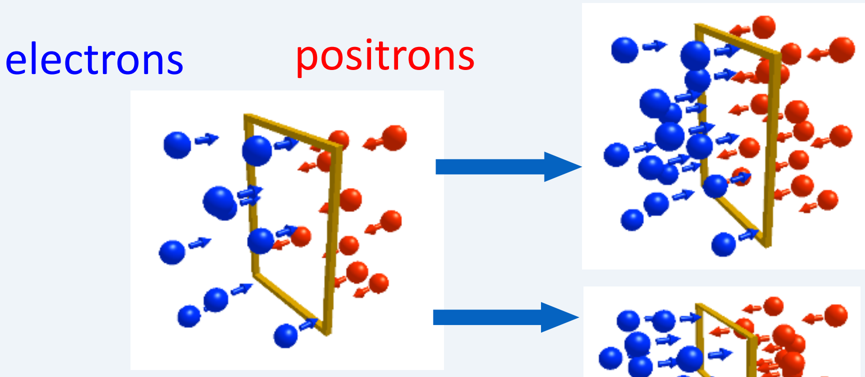


SuperKEKB “nano-beam” scheme

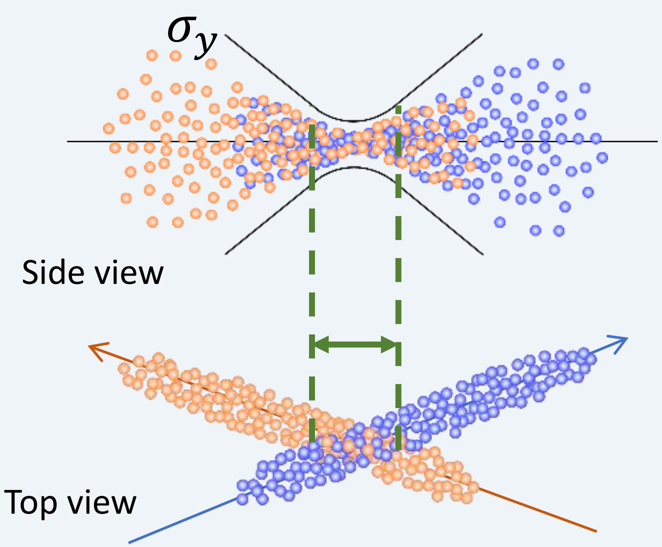
Idea by Dr. P. Raimondi for INFN SuperB

To get high luminosity:

Larger number =
Higher current



Higher density =
smaller size at IP



- Low emittance
- Squeeze vertical beam size to the size of virus ($\sigma \sim 50$ nm) @IP.
- Large crossing angle to avoid unwanted overlap of beams. Beams will collide only at the most squeezed part.

Principle verified, practically functioning well.

Project Development

1994	…	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

KEKB/Belle (1994-2010)

Construction 1994-1999

Experiment 1999-2010

Proof of KM theory

Still active

SuperKEKB/Belle II

Planning, Design

Construction

Phase 1 "Test" Operation

Phase 2 Operation for collision Tuning

Phase 3 Physics Runs

LS1

Inauguration of Belle II collaboration (2008)