Searching for New Physics with Belle II

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On Behalf of the Belle II Collaboration

High Energy Physics in the LHC Era
Valparaiso, Chile
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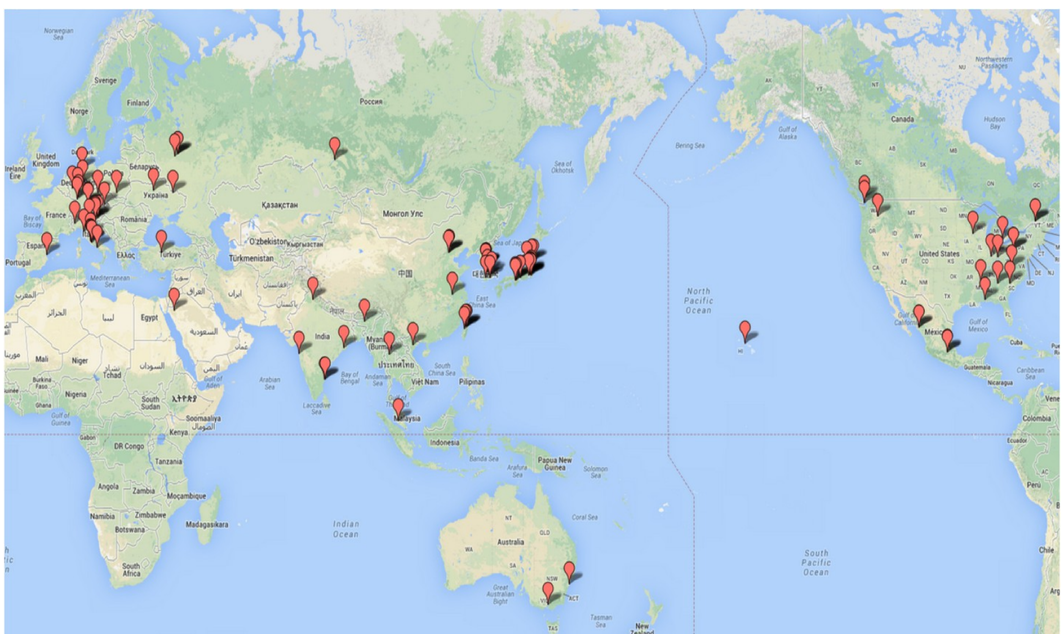
INSTITUTE OF PARTICLE PHYSICS

McGill

Belle II

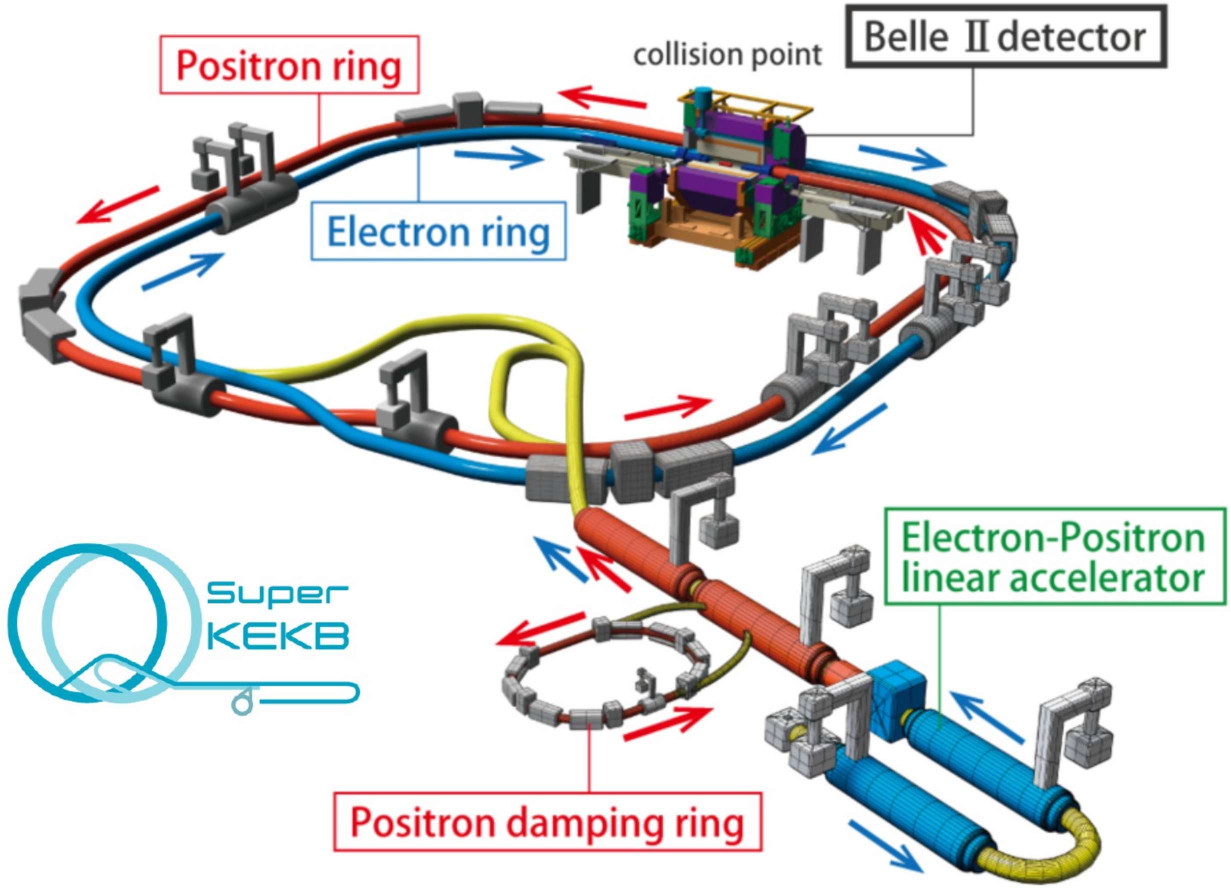
The Belle II experiment is a upgrade of Belle at the KEK laboratory

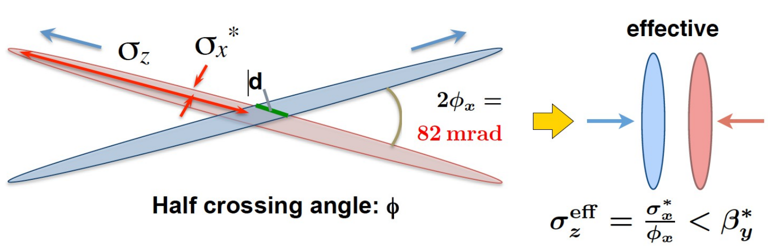
- Target data set of ~30x the combined integrated luminosity of BABAR + Belle
- 750 collaborators, including over 260 graduate students



First physics collisions to begin in 2018

SuperKEKB





SuperKEKB is a very substantial upgrade of KEKB collider to provide 4 GeV on 7 GeV e^+e^- collisions at $8\times10^{35}cm^{-2}s^{-1}$ luminosity for Belle II

- Low-emittance "nanobeam" scheme exploiting ILC and light-source technologies
- Crossing angle at IP
- Very small (vertical) beta function at IP

What's so “Super”?

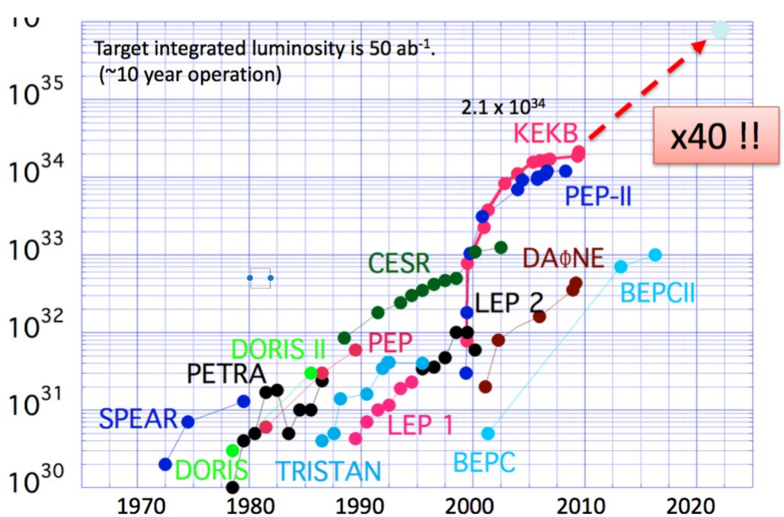
How to get to $8 \times 10^{35}\ cm^{-2}s^{-1}$:

- Very high charge density bunches
- Bunch crossings every 6ns (~1.2m spacing)
- Low emittance beams
- Tiny beam spot at IP

$$L = \frac{\gamma_{\pm}}{2 e r_e}(1+a)\frac{R_L}{R_{\xi}}\left(\frac{I_{\pm}\xi_{y\pm}}{\beta^*_{y\pm}}\right)$$

beam current **x2**   beam-beam param. **x1**

vertical beta function **x20**



	KEKB Achieved LER	KEKB Achieved HER	SuperKEKB LER	SuperKEKB HER
RF frequency f [MHz]	508.9			
# of Bunches N	1584		2500	
Horizontal emittance εx [nm]	18	24	3.2	4.6
Beta at IP $\beta x^*/\beta y^*$ [mm]	1200/5.9		32/0.27	25/0.30
beam-beam param. ξy	0.129	0.090	0.088	0.081
Bunch Length Sz [mm]	6.0	6.0	6.0	5.0
Horizontal Beam Size sx^* [μm]	150	150	10	11
Vertical Beam Size sy^* [nm]	0.94		48	62
Half crossing angle φ [mrad]	11		41.5	
Beam energy Eb [GeV]	3.5	8	4	7.007
Beam currents Ib [A]	1.64	1.19	3.6	2.6
Lifetime t [min]	133	200	6	6
Luminosity L [$cm^{-2}s^{-1}$]	**2.1 x 10^{34}**		**8 x 10^{35}**	

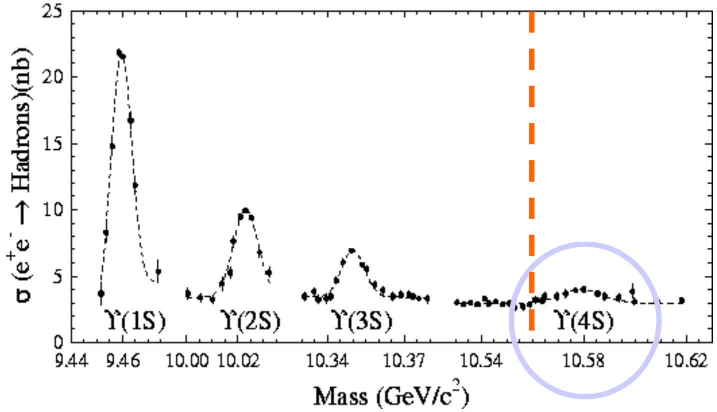
Short beam lifetime requires continuous (“trickle”) injection during live data taking

What's so "Super"?

e^+e^- collisions provide a very rich data set and a clean analysis environment

"Inclusive" hadronic and low multiplicity datasets are key features:

- Target data sample has a cross section of ~ 5 – 10 nb



8 x10^{35} $cm^{-2}s^{-1}$ luminosity yields O(5 kHz) of "interesting" physics events

- O(1 kHz) of $B\bar{B}$ events
- ~30 kHz Bhabhas within detector acceptance
  - Level 1 trigger rejection essential!
  - Probability of multiple collisions per bunch crossing (aka "pileup"): ~0.02%

Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

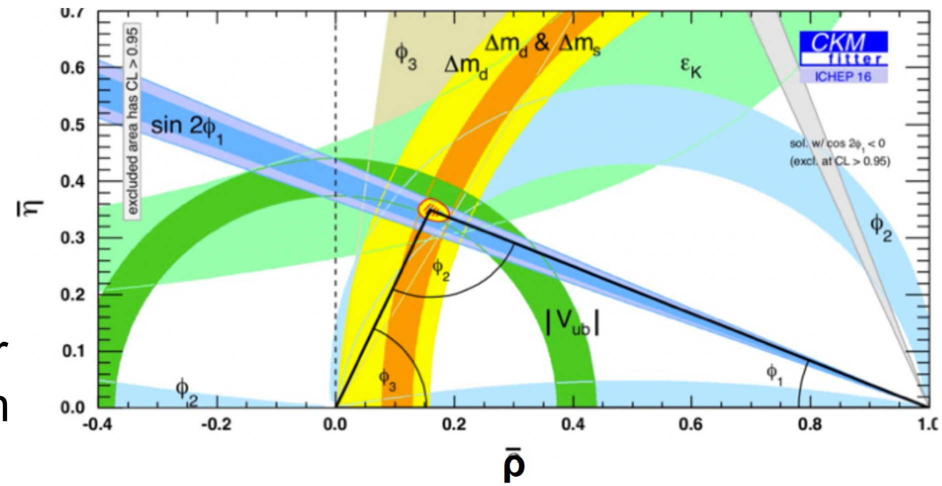
50 ab^{-1} integrated luminosity implies ~55 billion $B\bar{B}$ pairs in target data sample

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

Precision measurements

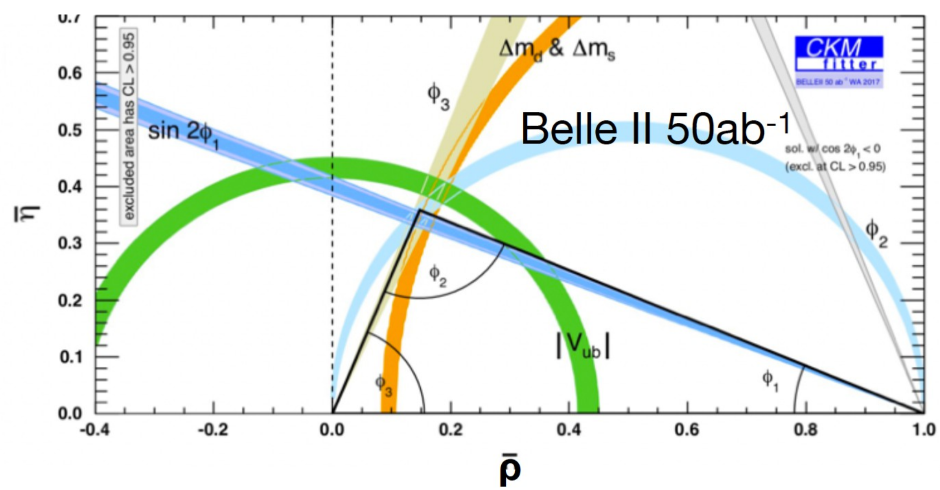
Previous generation of B factory experiments sought to validate the KM mechanism for CP violation within the SM

- i.e. demonstrated that a large number of measurements were consistent with CKM "Unitarity Triangle" expectations



In contrast, Belle II will look for **deviations** from this picture that would provide evidence of non-SM contributions to these processes

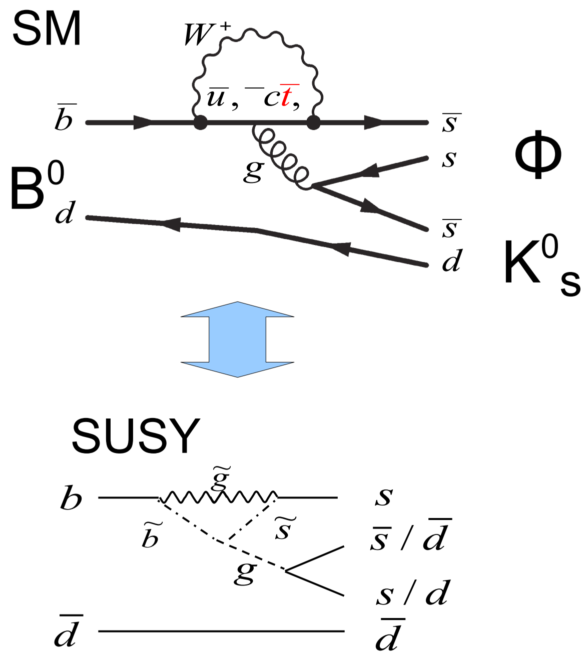
- Compare precise measurements with (equally precise) SM expectations



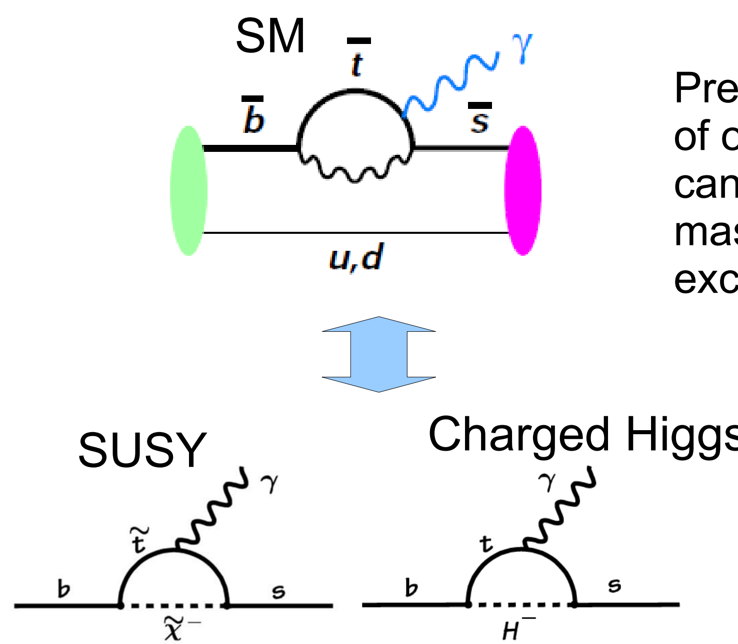
FCNC decays

Many decay modes with potential sensitivity to new physics contributions:

Hadronic decays:



Electroweak FCNCs:



Precision measurements of one-loop processes can probe new physics mass scales which far exceed direct searches

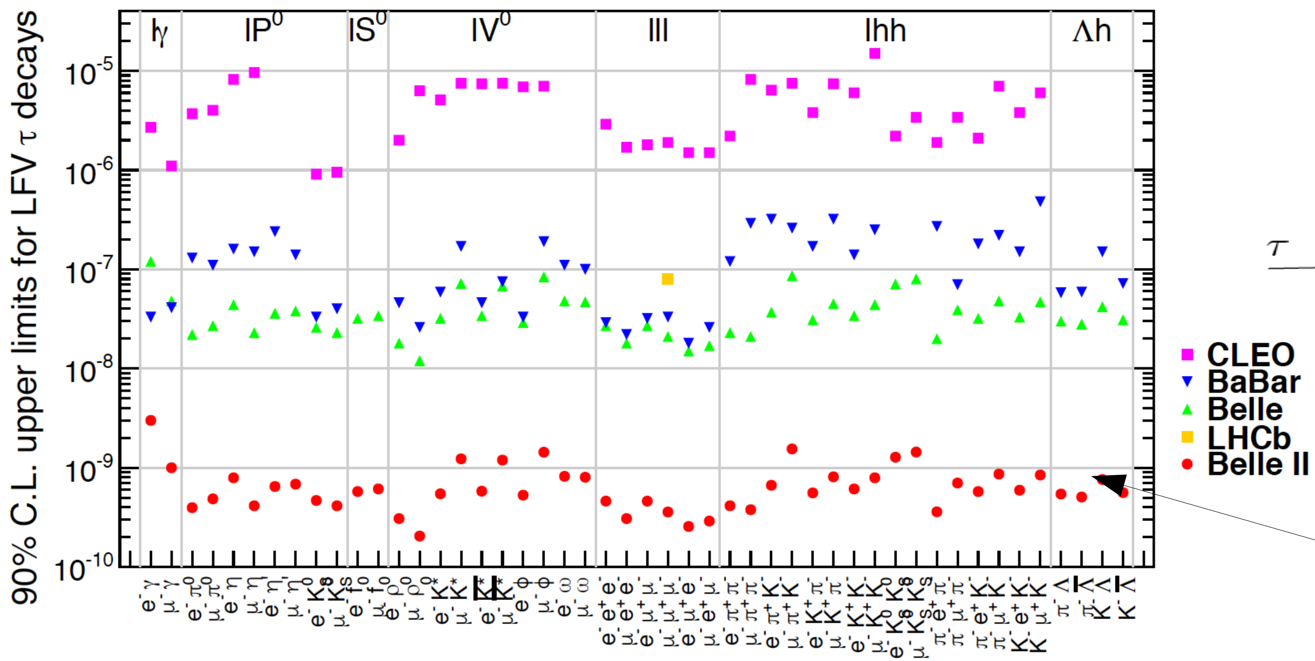
Many observables:

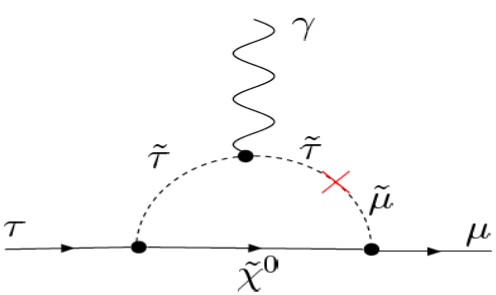
- Branching fractions, CP asymmetries, kinematic distributions, angular observables and asymmetries

Rare and forbidden decays

Processes that are suppressed or forbidden within the SM can potentially be dramatically enhanced by new physics contributions

- e.g. Lepton flavour violation in τ decays:
  - "forbidden" in SM, but many new physics models saturate existing limits





Estimated Belle II sensitivity with full data sample

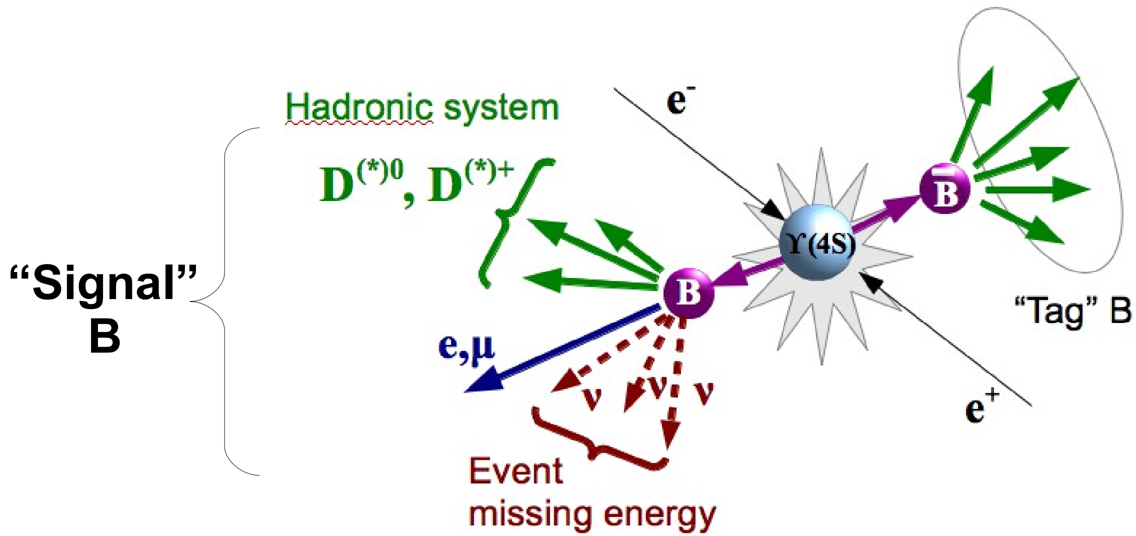
Very clean searches at B factories and unambiguous signal of new physics

Missing energy decays

Unique capability to study B decay modes with missing energy:

- Semileptonic B decays such as $B \rightarrow D^{(*)}\tau^+\nu$, $B^+ \rightarrow \mu^+\nu$, and $B^+ \rightarrow \tau^+\nu$
- FCNC modes such as $B \rightarrow K^{(*)}\nu\bar{\nu}$, $B^0 \rightarrow \nu\bar{\nu}$ etc.

Precisely known CM energy, combined with exclusive hadronic reconstruction of the accompanying B, permit the decay daughters of missing energy decays to be uniquely identified:



$$m_{ES} \equiv \sqrt{E^{*2}_{\rm beam} - p^{*2}_B}$$
$$\Delta E^* \equiv E^*_B - E^*_{\rm beam}$$

"Full event interpretation" or "hadronic tag reconstruction"

Other topics

Many potential analysis topics beyond the usual “flavour” of B factories:

- Quarkonium and new states
- QED and continuum production cross sections
- Direct searches for light new particles
  - dark matter candidates, “dark sector”, light Higgs, ALP searches etc.

Dark Forces:

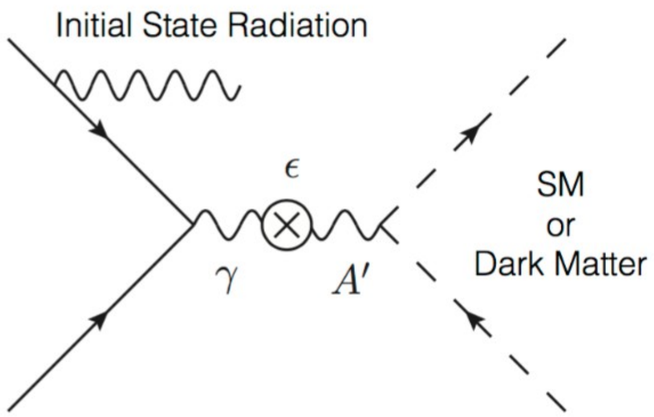
Various models exist in which dark matter arises as part of a “dark sector” containing its own gauge interactions and particles

- Simplest scenario is to add a new U(1) gauge symmetry, with associated charge carried by dark-sector fermions
  - Spin-1 gauge boson “dark photon” A' can mix with SM photon, providing a “portal” to the dark sector. Mixing strength characterized by ε

Dark Forces

- Search for decay of $e^+e^- \to \gamma A'$ via $A' \to \chi\bar{\chi}$ or into SM particles
  - "visible" $A' \to l^+l^-$, or
  - "Invisible" A' decays, with A' mass determined from photon energy

$$E_\gamma^* = \frac{s - M_X^2}{2\sqrt{s}}$$



.... however, dark sector could be much more extensive, with one or more Abelian or non-Abelian interactions, fermions and Higgs bosons

Can potentially be detected via one of a number of "portals" coupling the Dark Sector to the SM

Vector Portal → *Dark Photon*
Scalar Portal → *Higgs/Dark Scalars*
Pseudoscalar Portal → *Axion-like Particles*
Neutrino Portal → *Sterile Neutrinos*

- Sensitivity studies performed in the context of "Belle II physics book" (B2TiP), to be published in near future
- ALP sensitivity studies: arxiv: 1709.00009

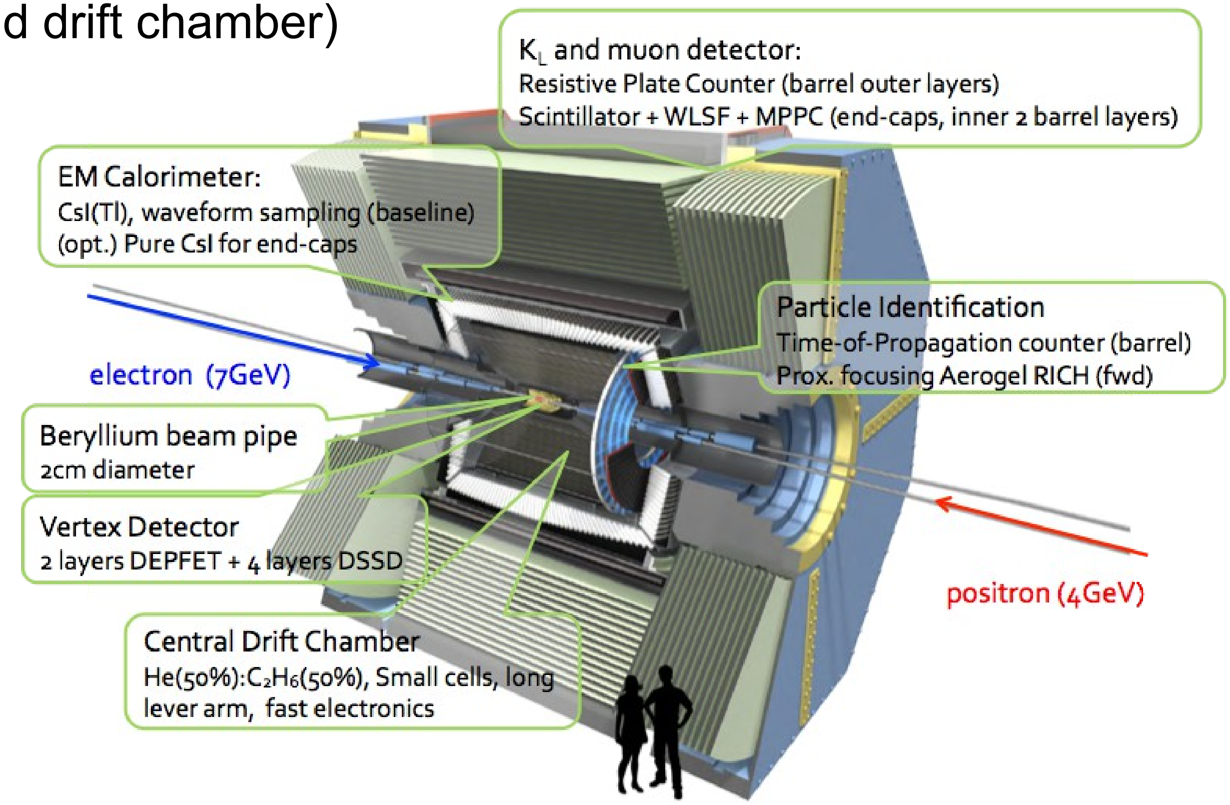
Typically, these are narrow resonance ("bump hunt") searches in low multiplicity data samples

Belle II Detector

Anticipate ~40x increased instantaneous luminosity, and greatly increased background rates

Very substantial “upgrades” to the original Belle detector:

- Replacement of beam pipe and redesign of entire inner detector (including vertex detectors and drift chamber)
- New quartz-bar Time-of-Propagation PID in barrel region
- Retain existing CsI(Tl) calorimeter crystals, but front-end electronics, feature extraction and reconstruction software entirely new
- Entirely new software framework and distributed computing environment

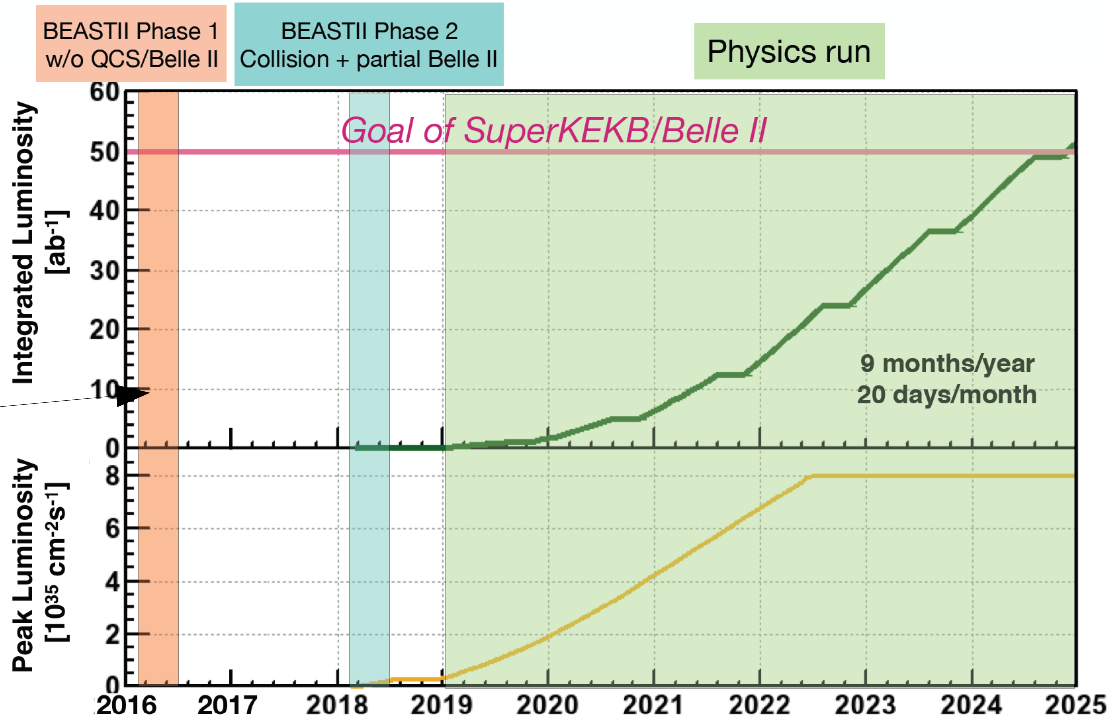


Schedule

Belle II target data sample of 50 ab^{-1} by 2025 with physics data taking beginning in 2018

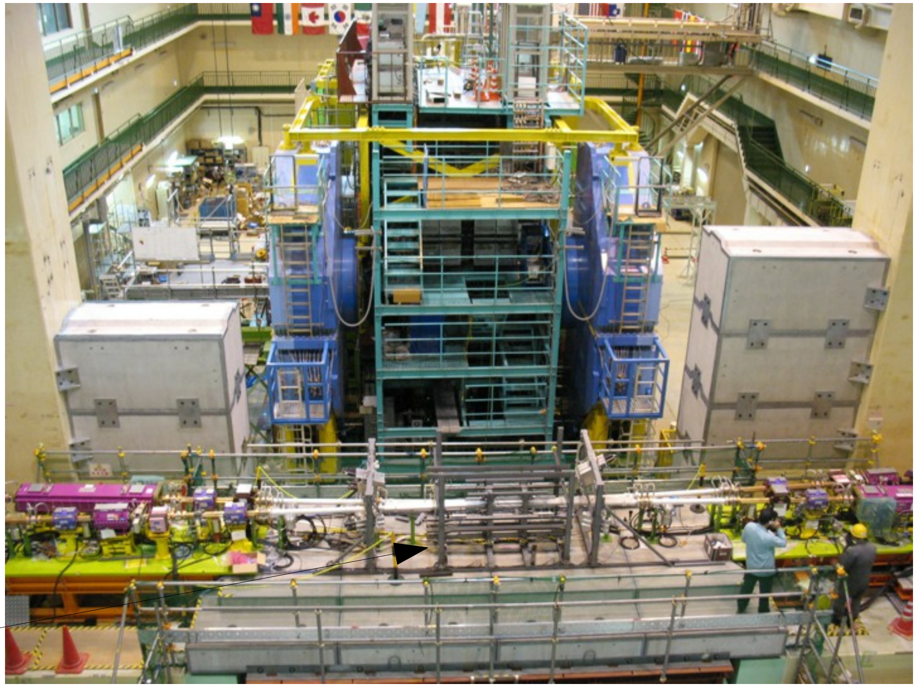
Three-phase commissioning plan beginning in 2016

- Phase 1: accelerator (non-colliding) beam commissioning with dedicated BEAST background detector at IP



Phase 1 commissioning

Beam-related backgrounds have potential to produce detector occupancy and dead time, to cause radiation damage, and to negatively impact physics performance



Background Sources (single beam):

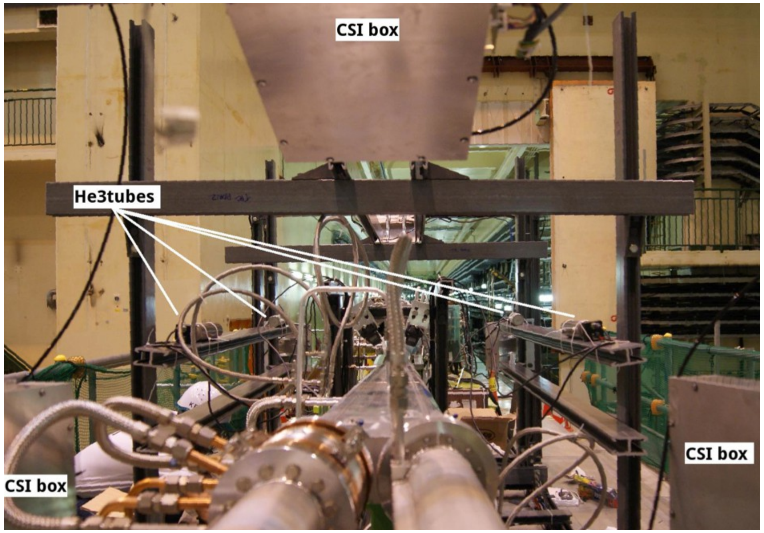
- Touschek scattering
- Beam-gas: Coulomb scattering and bremsstrahlung
- Injection backgrounds
- Beam "dust"

Dedicated "BEAST2" detector constructed to provide background commissioning measurements prior to installation of Belle II detector

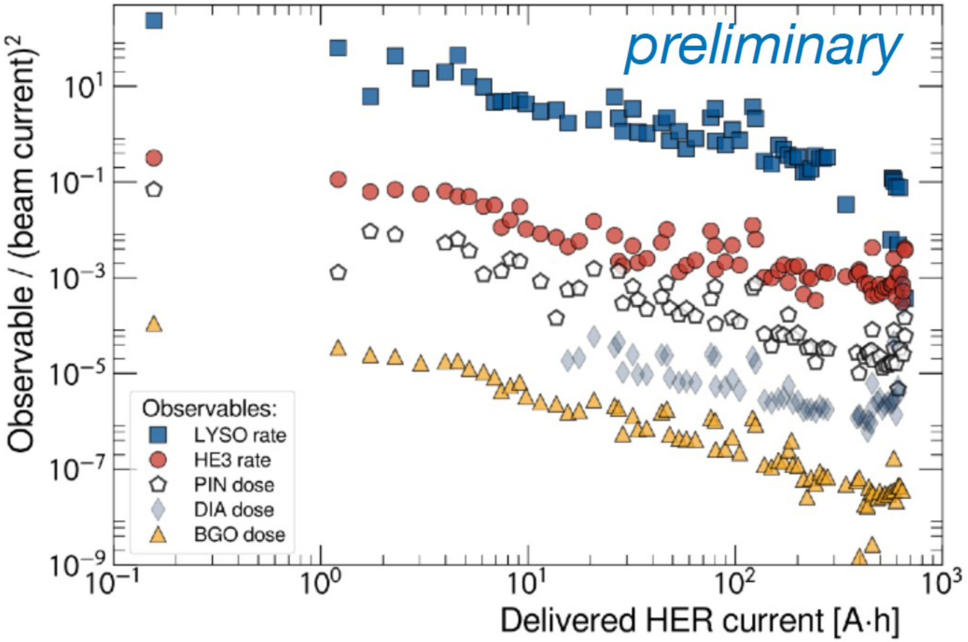
- PIN diodes, diamond detectors,
- "CLAWS" silicon detectors
- Micro-TPCs,
- ^{3}He tubes
- BGO
- Scintillating crystals (CsI, CsI(Tl) and LYSO)

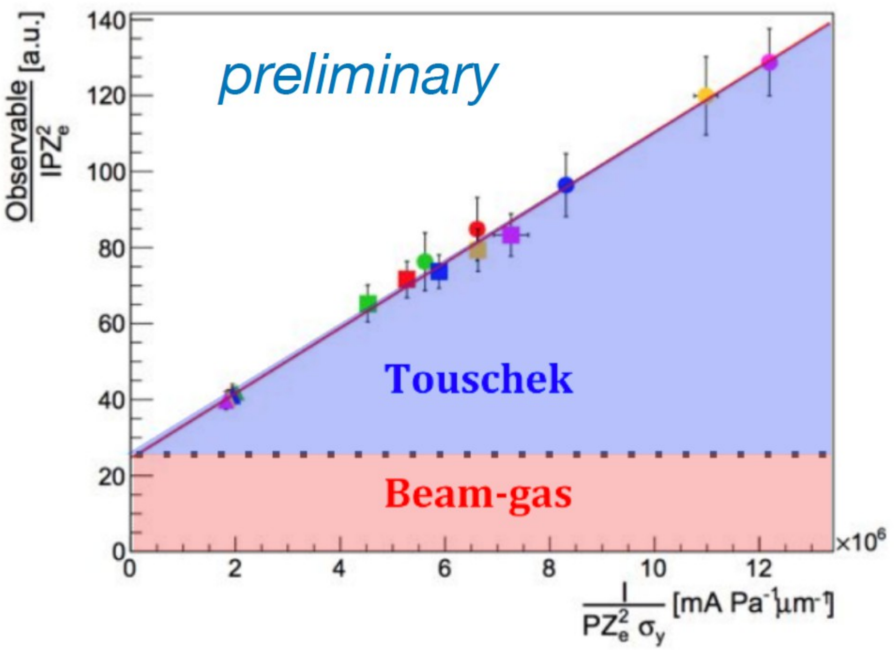
Phase 1 commissioning took place Feb – June 2016

- First turns of SuperKEKB beams achieved in March 2016



Paper (long!) describing BEAST background measurements currently undergoing internal review; to be submitted to NIM A





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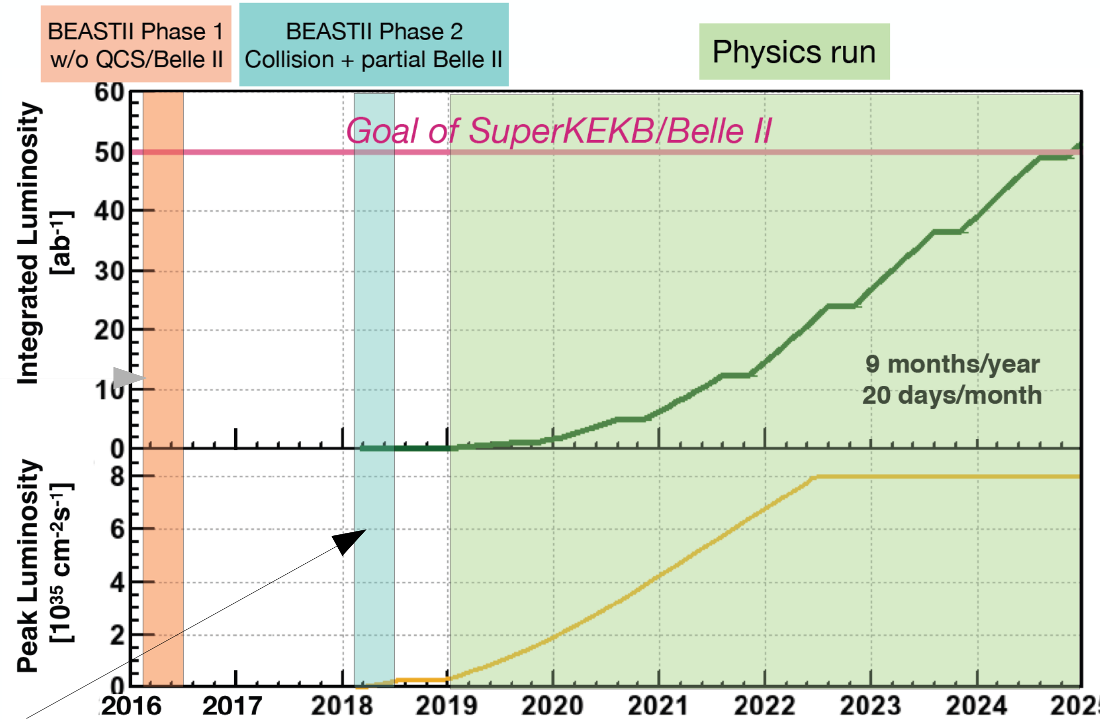


Phase 2 commissioning

Objectives:

- Machine commissioning
  - Final focus magnets in place; colliding beams!
- Study radiation safety of Belle II detectors
  - Continued study of single-beam backgrounds
  - Synchrotron radiation
  - Significant "beam background" contribution from "luminosity" sources, e.g. small angle radiative Bhabha ($e^+e^- \rightarrow e^+e^-\gamma$) in which outgoing particles strike QCS magnet region

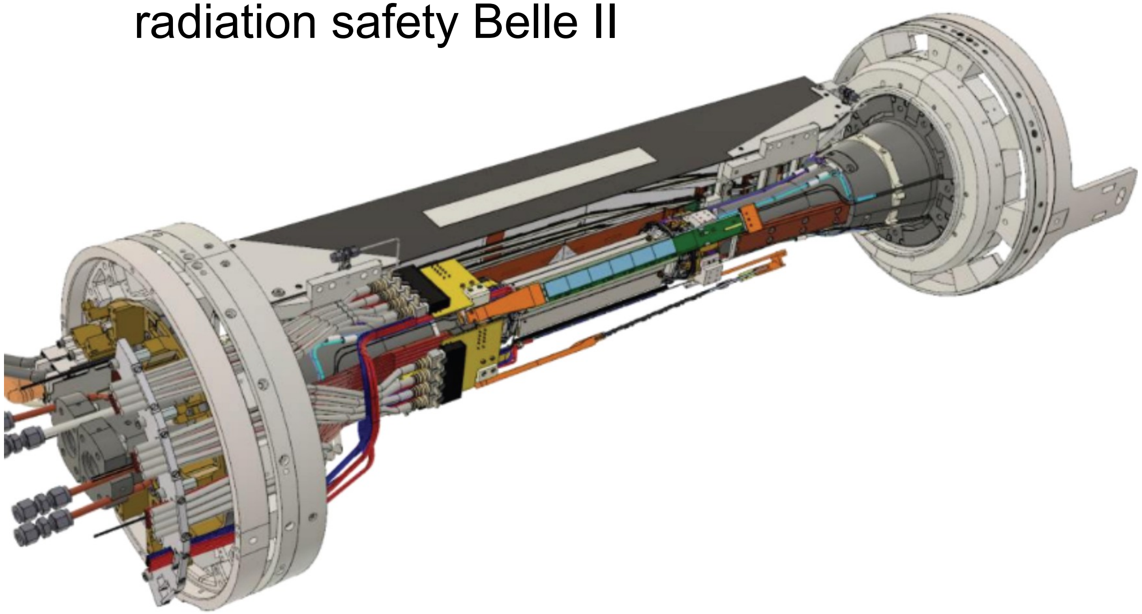
Target instantaneous luminosity of 1 x 10^{34} $cm^{-2}s^{-1}$

- Comparable to BABAR/Belle
- Expected data set of (20 +/- 20) fb^{-1} ; potential for "physics", but with limited data and without silicon tracking

BEAST – phase 2

Belle II detector in position at IP, but without vertex detectors

- Dedicated background monitoring detectors positioned close to the IP to ensure radiation safety Belle II



2 PXD and 4 SVD layers in sector where the highest backgrounds are expected.

FANGS - FE-I4 based hybrid pixel to study Synchrotron Radiation background

CLAWS - scintillators with SiPM to study trickle injection background

PLUME - double-sided high granularity MIMOSA pixels

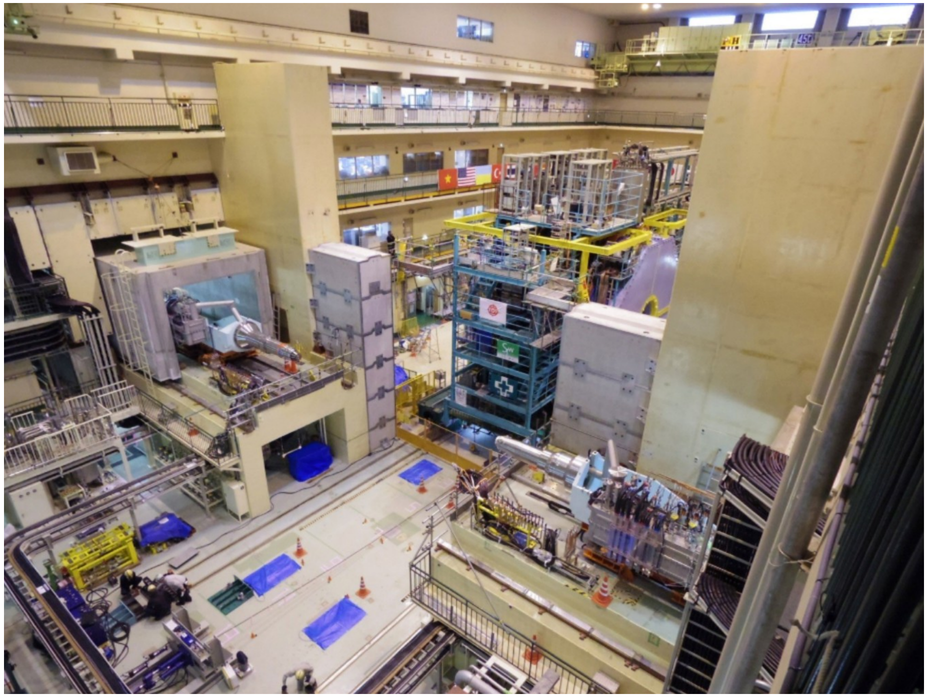
Also “permanent” background monitors installed along beam line outside of nominal Belle II angular acceptance:

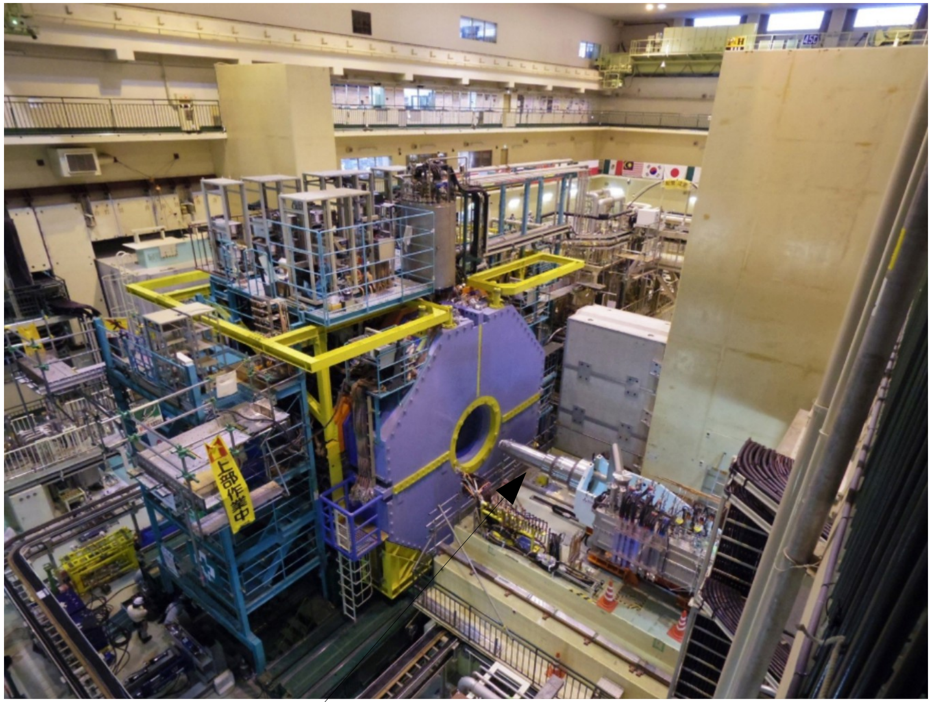
- PIN diodes
- Scintillator/MPPC (trickle injection backgrounds)
- He3 tubes (neutrons)

Signals relayed to Belle II and SuperKEKB control rooms for beam tuning

Belle II roll-in

In preparation for phase 2, Belle II detector was moved onto the SuperKEKB beam line in April 2017:

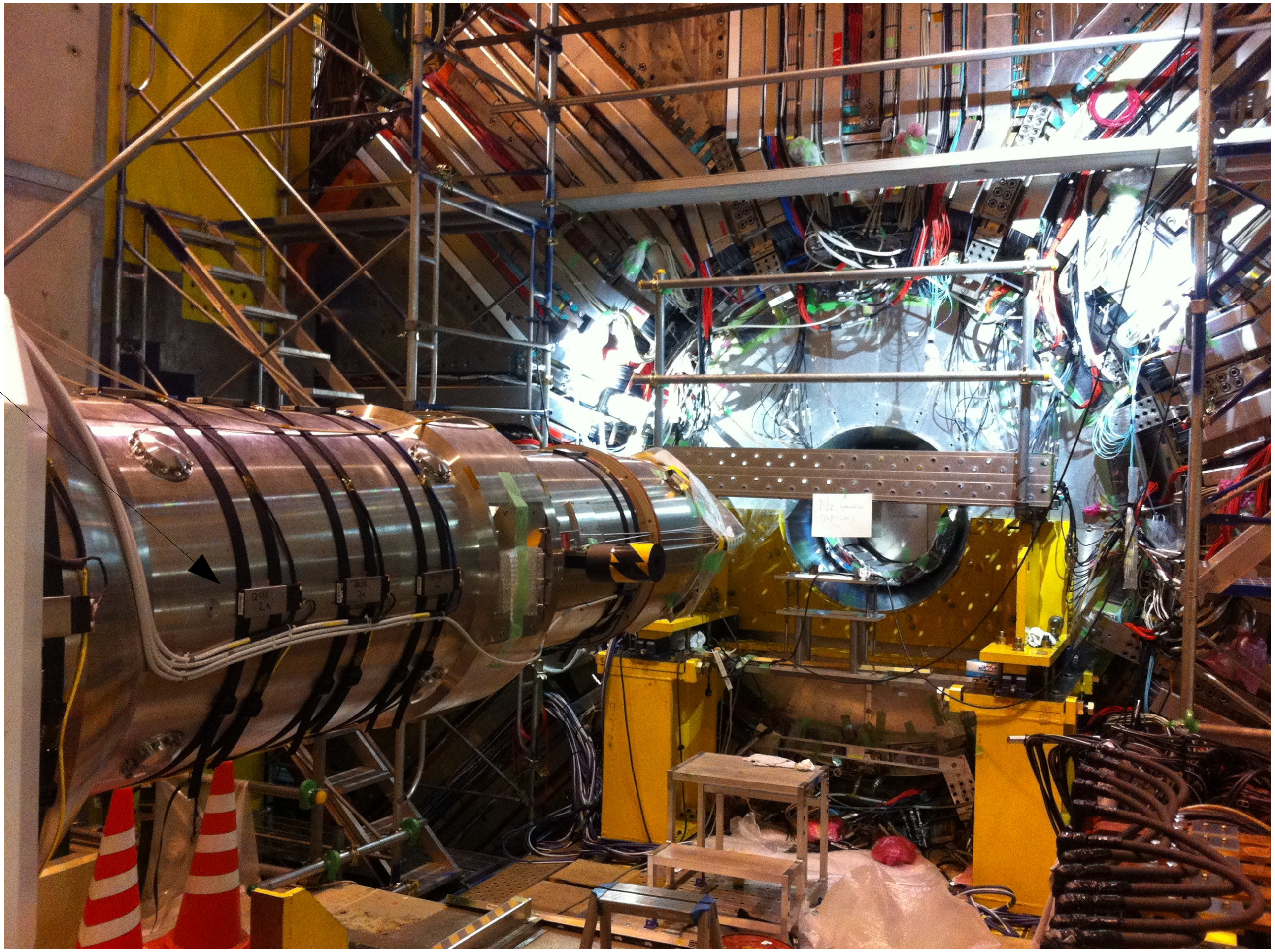




- Final focus magnets installed after completion of phase 1

QCS insertion

Scintillator/MPPC and PIN diode Background detectors



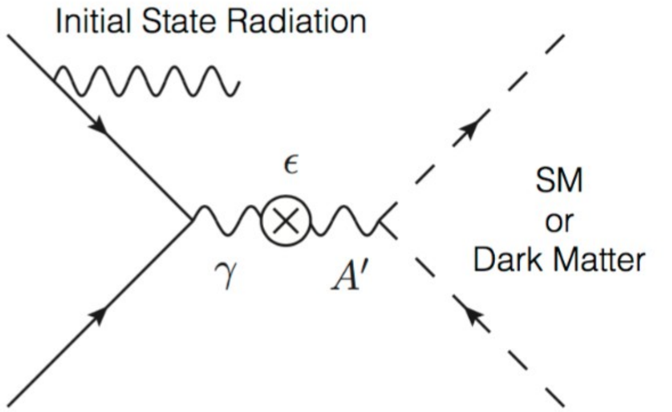
Dec 21, 2017

QCS final focus magnets inserted this week!

- Endcaps to be pushed in at end of January

Phase 2 physics?

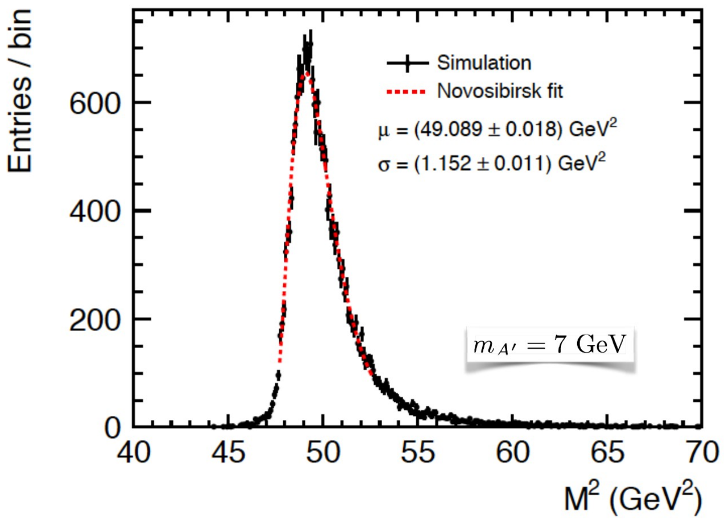
What can be studied with a small data set and no vertexing?



- "Dark photon search, based on invisibly decaying A' $\rightarrow \chi\bar{\chi}$
  - Requires low energy single-photon trigger
  - Tracking only needed to veto background (i.e. No vertexing)
  - BABAR study (see Thurs 5:00PM talk) based on small data sample due to trigger limitations; Belle did not do this analysis

Simulation studies to understand potential Belle II performance:

- Mass resolution of dark photon A' from ISR photon energy



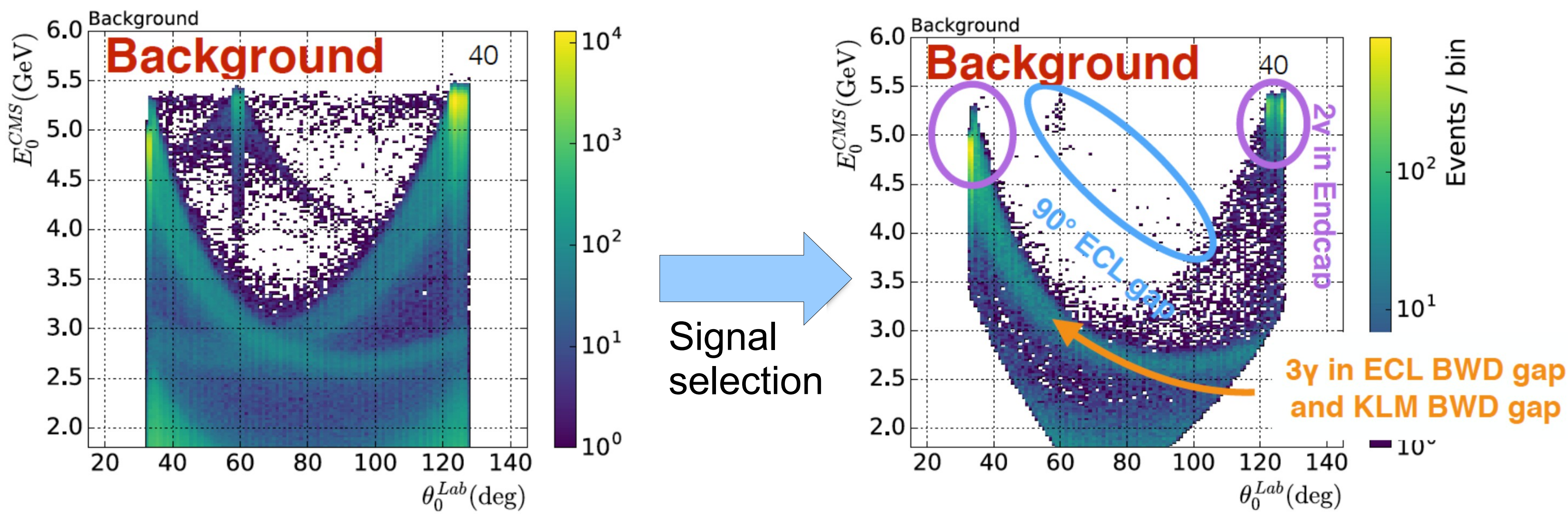
Invisible dark photon decays

Belle II calorimeter is more hermetic than BABAR

- Forward and backward endcaps (and smaller beam energy asymmetry)
- Cracks between crystals do not point to IP

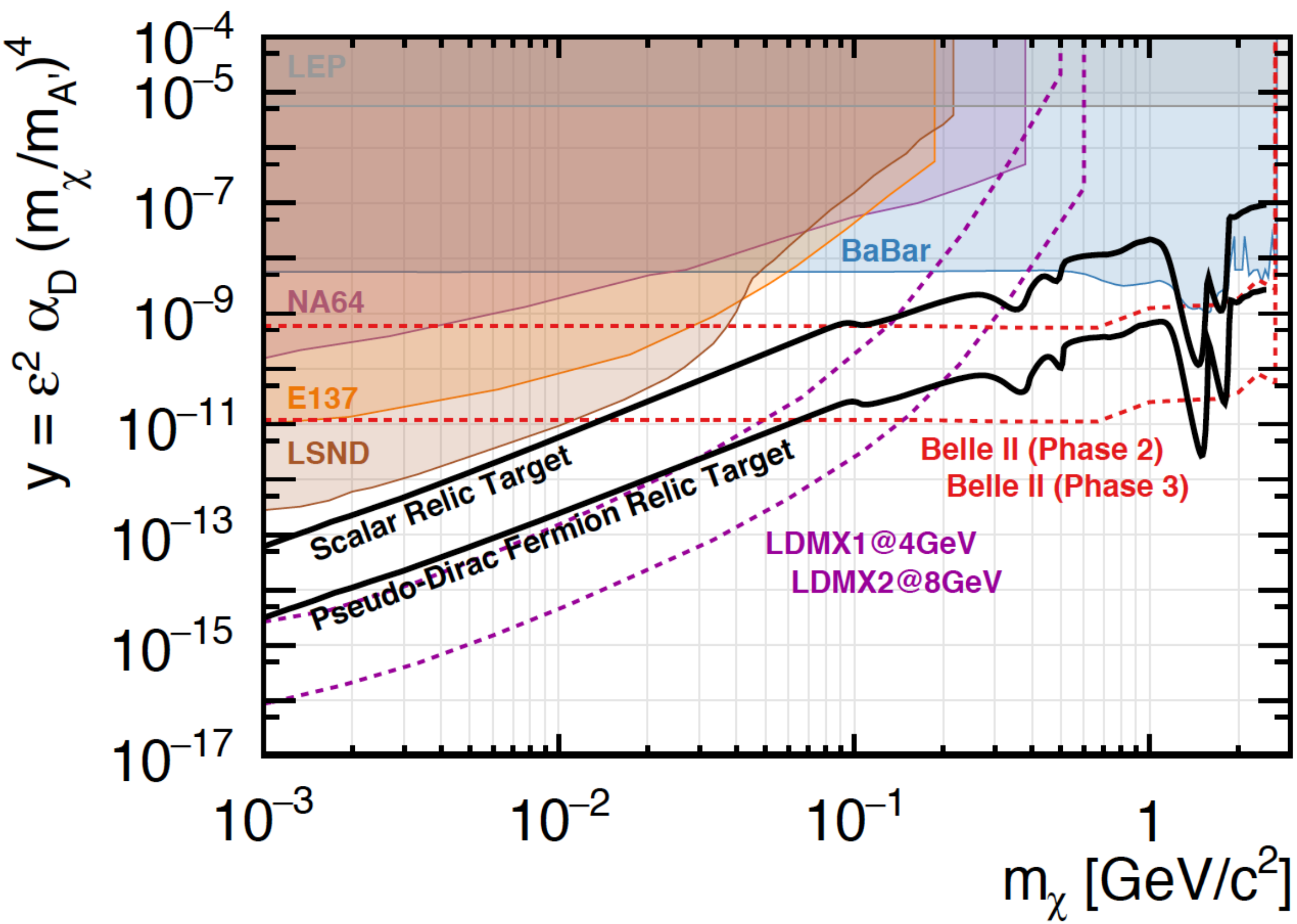
Dominant backgrounds from (radiative) Bhabha and $e^+e^-\rightarrow\gamma\gamma(\gamma)$

- How do these processes mimic single-photon signatures?



Invisible dark photon decays

Simulation studies suggest competitive sensitivity even with only phase 2 data:



B2TIP report, to be published

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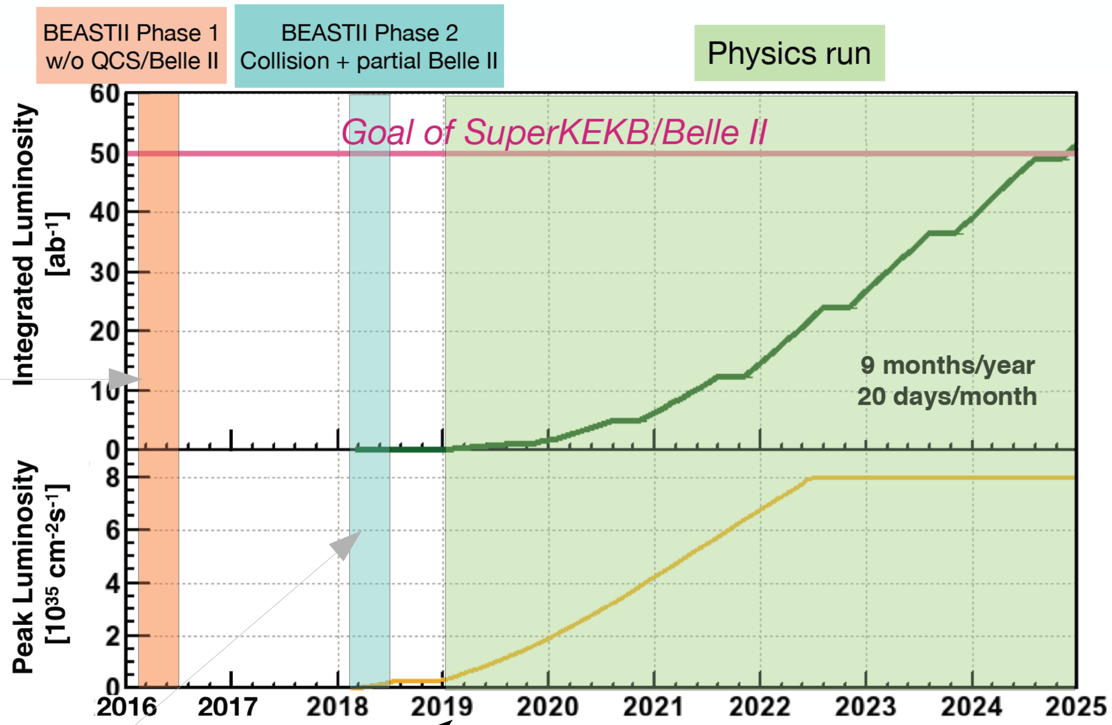
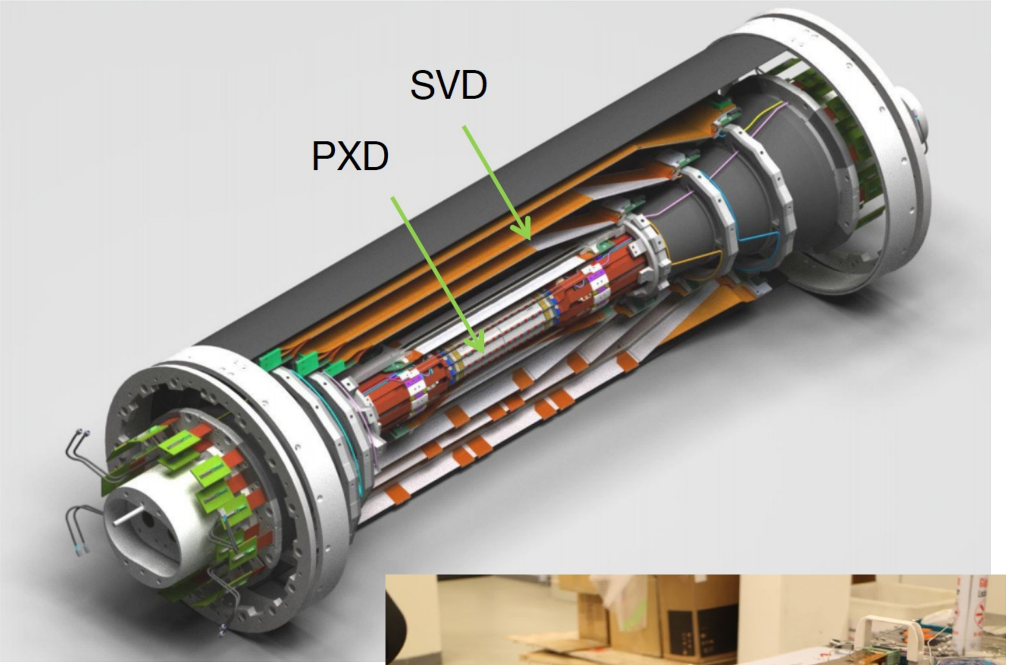


- Phase 3: Belle II physics commissioning with full detector

Vertex detectors

Once it is determined that operating conditions in SuperKEKB are safe for Belle II, the vertex detector will be installed

- Actually, two distinct detectors:

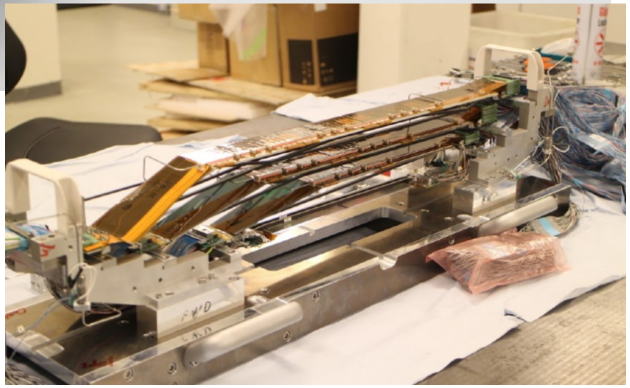


Pixel Detector (PXD)

- 2 layers DEPFET modules
- Pixel size: 50 x 55-85 μm.
- Thickness: 75 μm, 0.21% X_0 per layer

Silicon Vertex Detector(SVD)

- 4 layers of double-sided silicon strip detectors
- Slant in FWD region.
- material budget: 0.7% X_0 per layer



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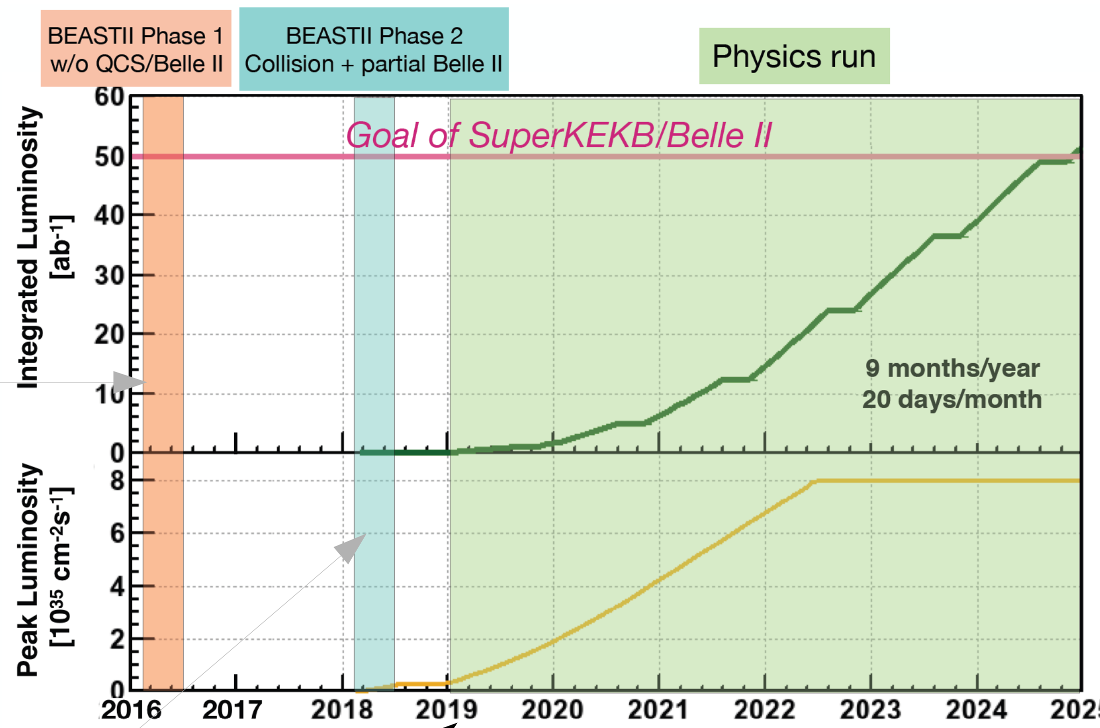

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- Phase 3: Belle II physics commissioning with full detector

Rapid integration of luminosity to exceed BABAR/Belle datasets by 2020

Summary

Very exciting time for Belle II right now

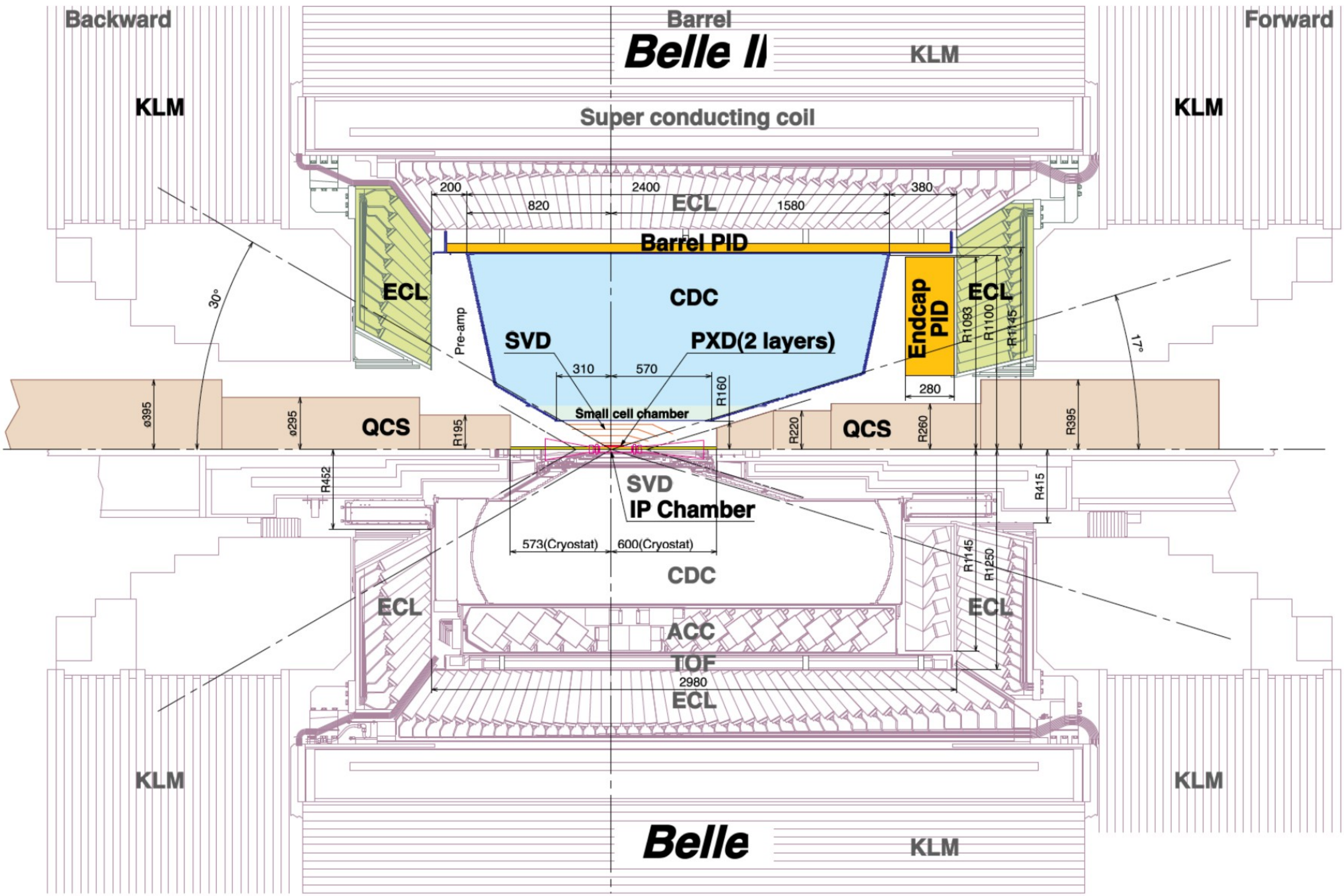
- Phase 1 commissioning completed; preparations for "Phase 2", colliding beams with Belle II detector in beamline, beginning shortly
- High luminosity data taking with fully commissioned Belle II detector to begin by end of 2018
- Diverse and interesting physics program beginning this year!

Belle II "Physics Book" to be submitted for publication soon

https://confluence.desy.de/display/BI/B2TiP+ReportStatus

Backup Slides

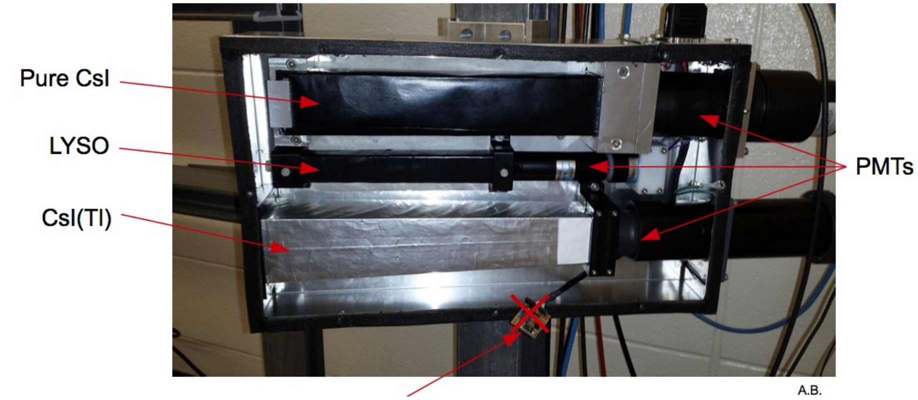
Belle II vs Belle



Phase 1 detectors

- ^{3}**He detectors** to characterize (difficult to simulate) thermal neutrons, which cause aging of ECL photodiodes and other detector components
- **Scintillating crystals** used to measure background photon energy spectrum and injection backgrounds

S. de Jong

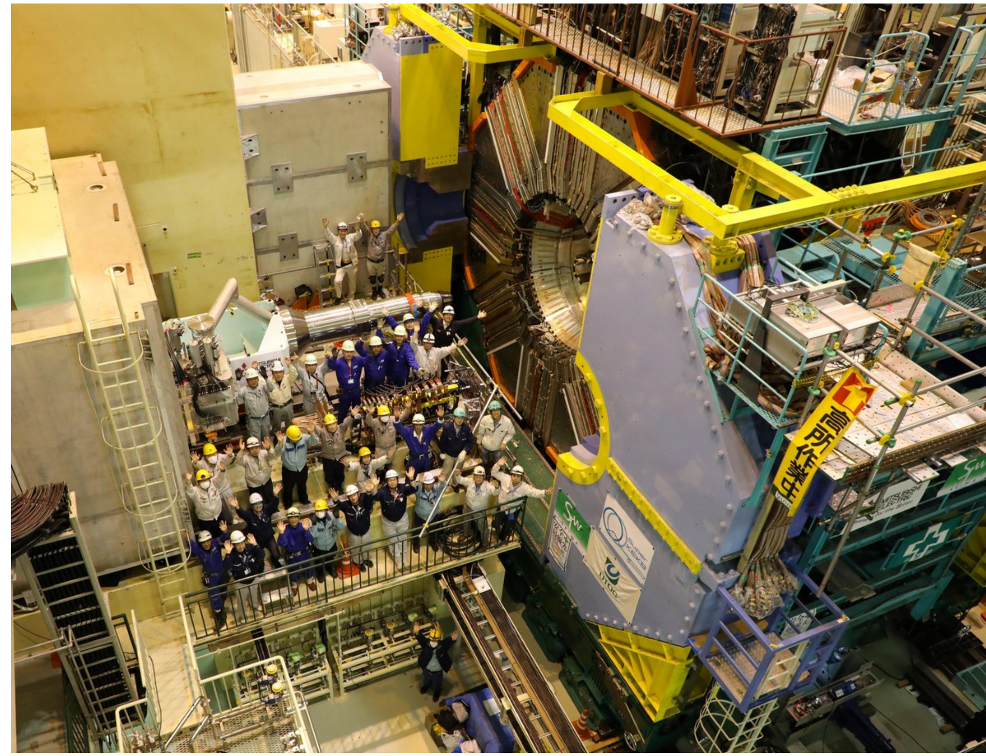


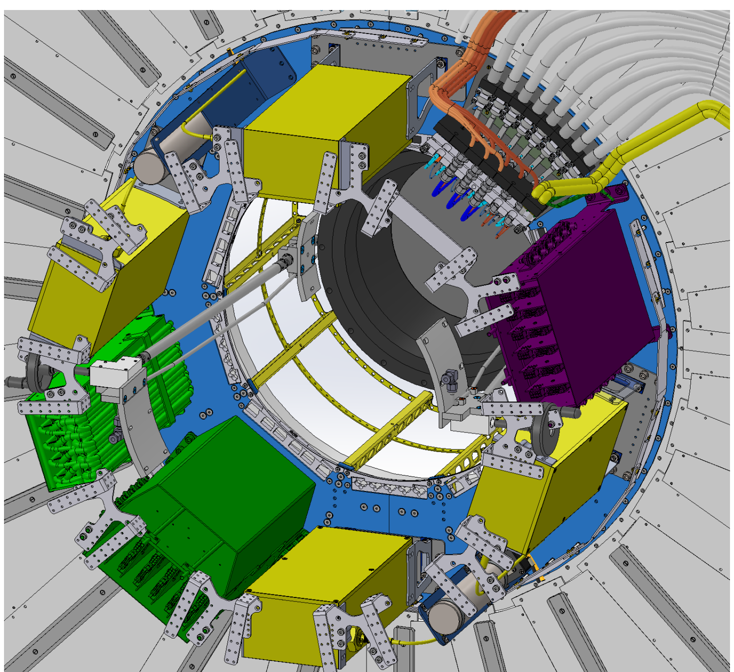
NIMA paper describing phase 1 results in preparation

Phase 2 commissioning

Belle II detector, (minus silicon vertex detector), rolled into SuperKEKB beam line April 11, 2017

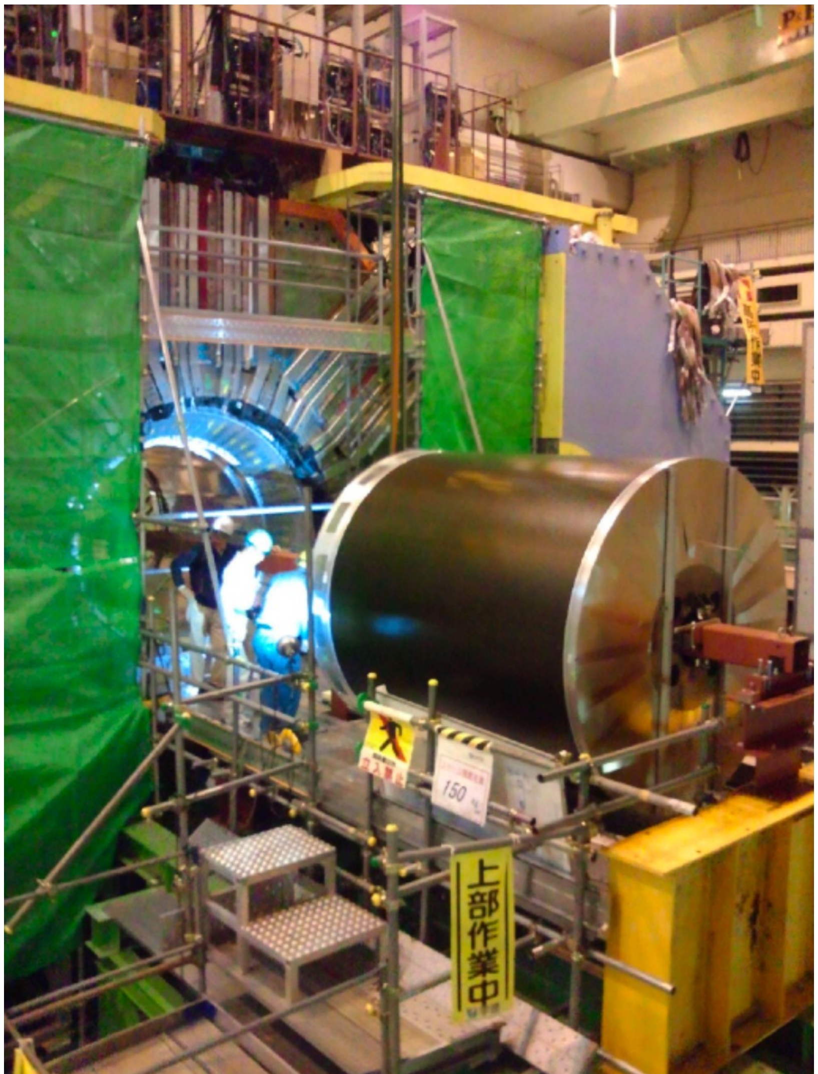
- 2-beam commissioning with collisions beginning in early 2018





Additional BEAST instrumentation arrayed in central detector region, including Canadian He3 tubes

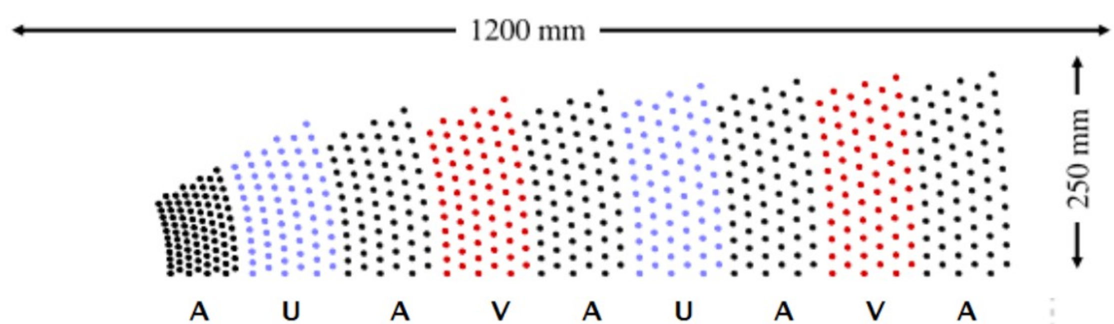
CDC



56 layer large-volume drift chamber

$He:C_2H_6$ 1:1 gas mixture
Total of 14336 sense wires

Smaller azimuthal cell sizes relative to Belle CDC

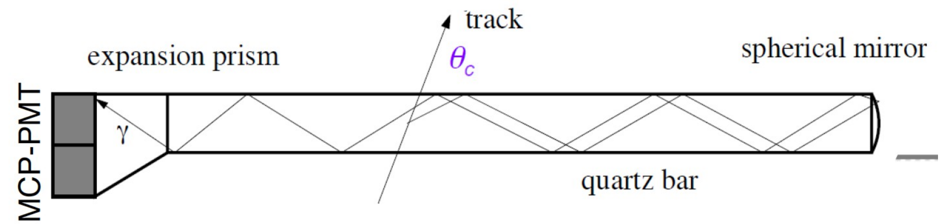


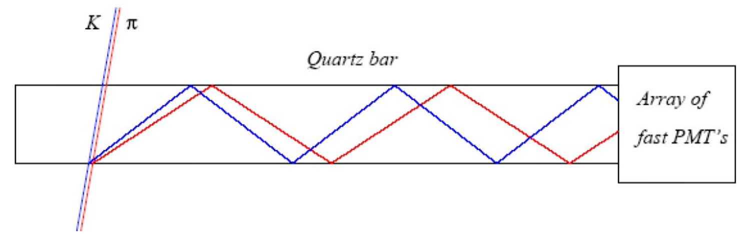
A: Axial layer
U: stereo layer, stereo angle > 0
V: stereo layer, stereo angle < 0

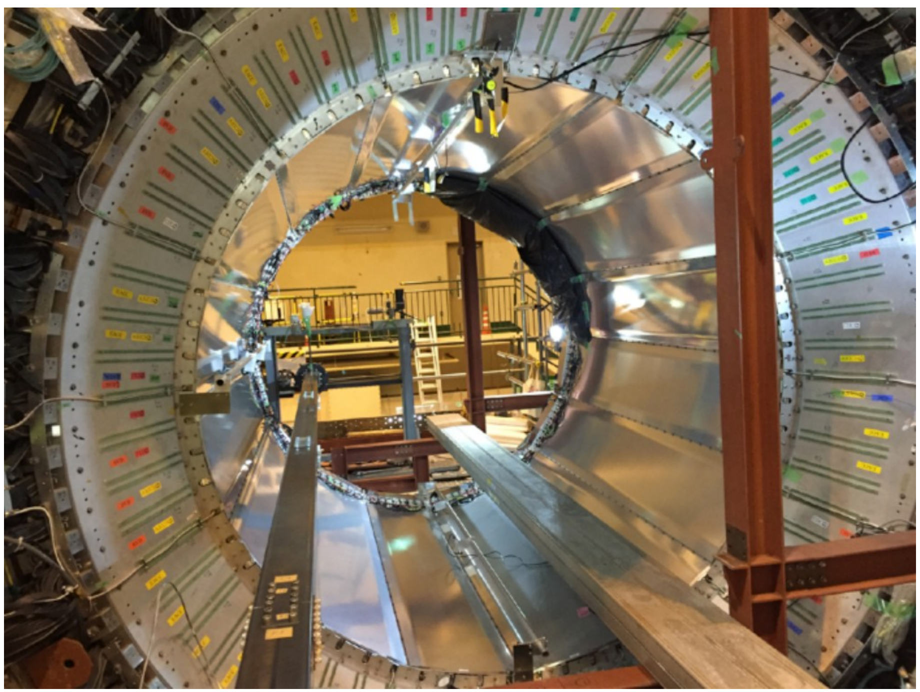
iTOP

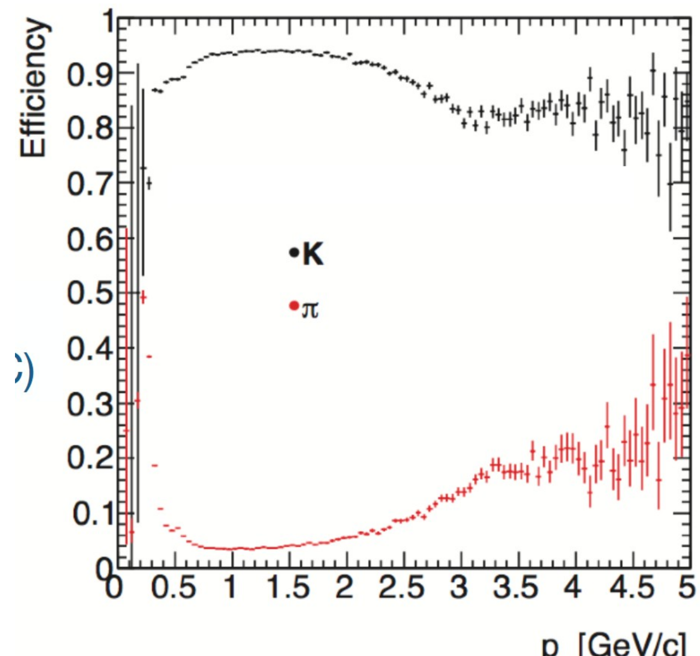
Barrel particle identification based on Cherenkov radiation in quartz bars

- Exploit propagation time of Cherenkov photons to infer Cherenkov angle



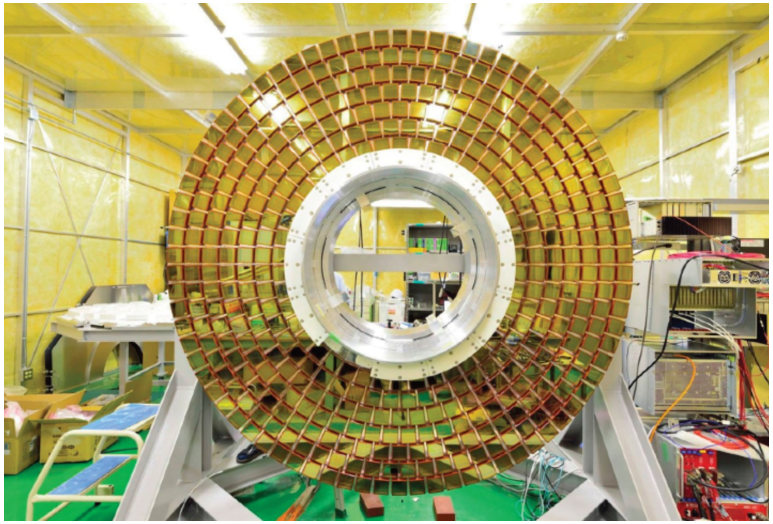




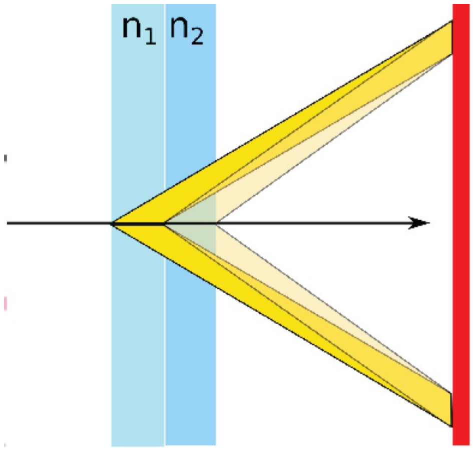


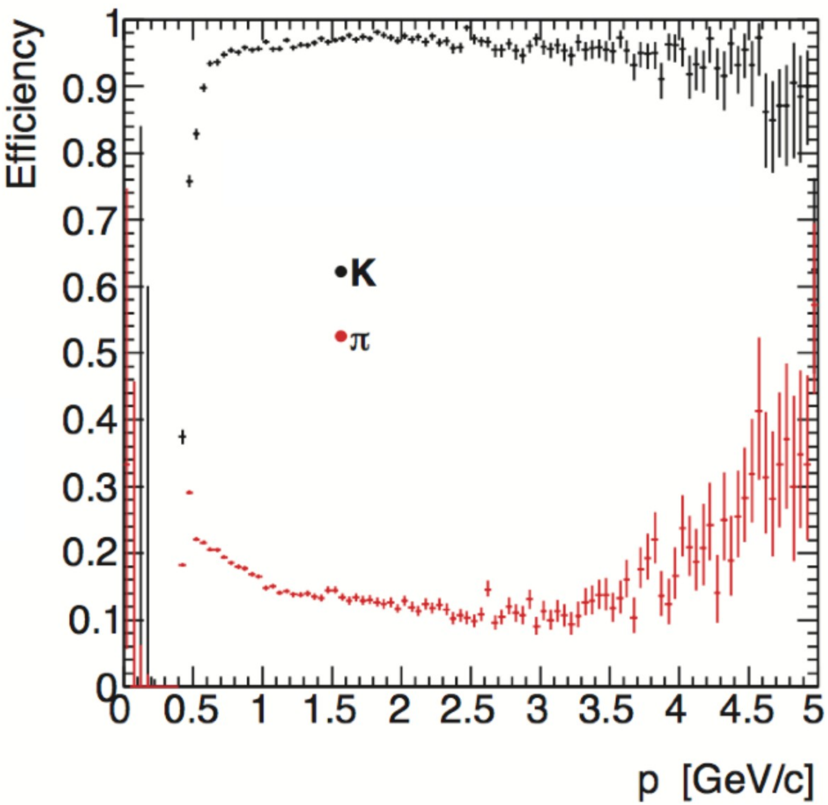
- 16 quartz bars: 2x1.25 m x 0.45 m x 2 cm
- 32 Micro-channel plate PMTs Hamamatsu SL-10 MCP PMT

ARICH



Proximity focusing aerogel RICH
n = 1.045-1.055





- Hybrid Avalanche Photo Detectors
- 420 units, 144 channels each

Flavour and New Physics

Effective flavour-violating couplings

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{k=1} \left(\sum_i C_i^k \, Q_i^{(k+4)}\right) / \Lambda^k$$

New Physics scale

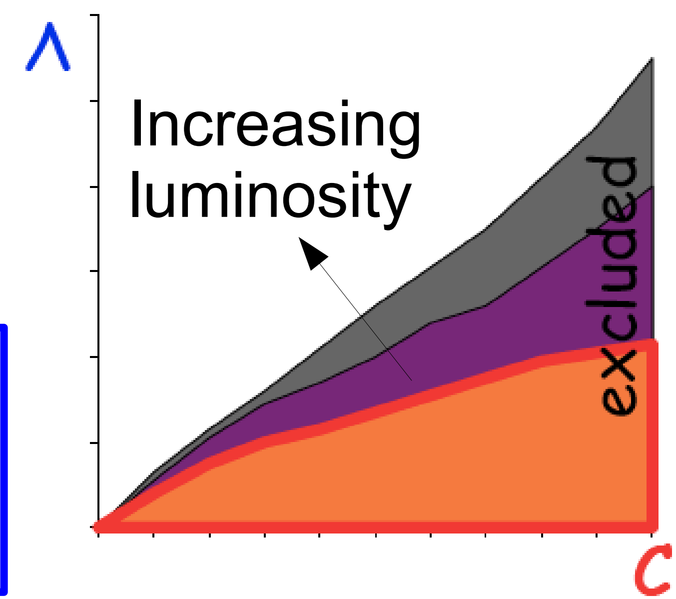
In explicit models:

- Λ ~ mass of virtual particles

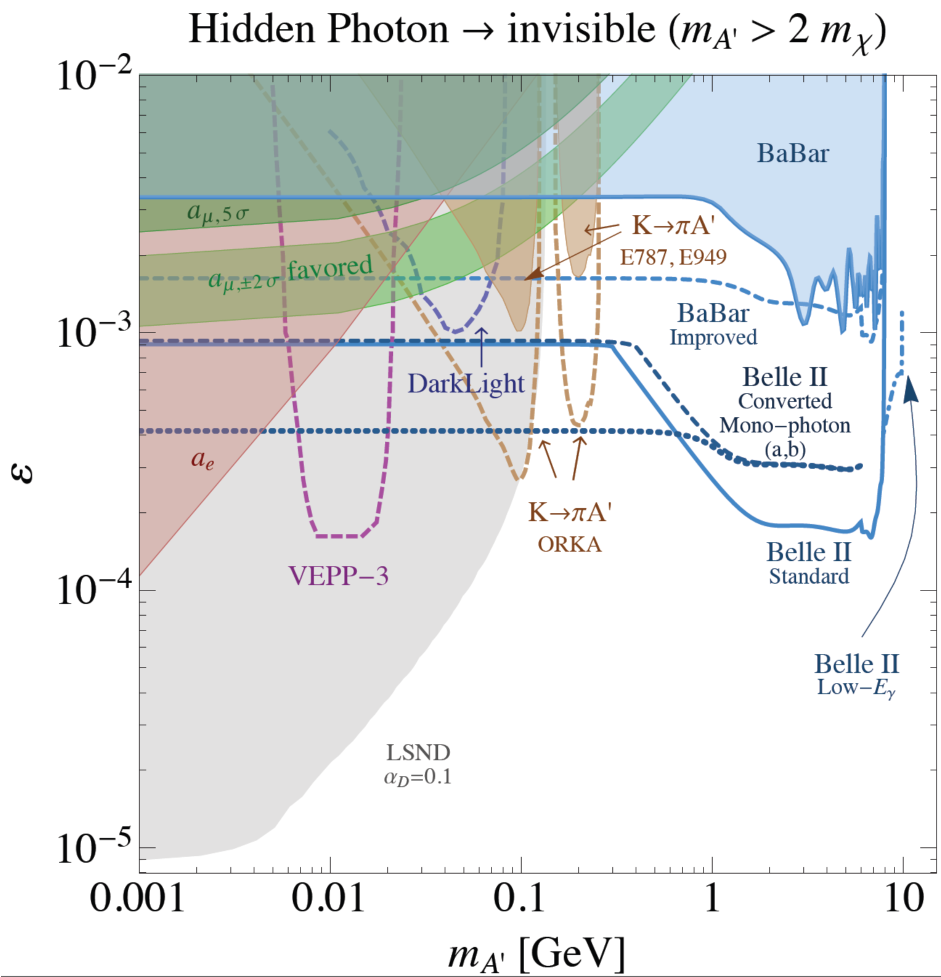
  (e.g. Fermi theory: m_W)

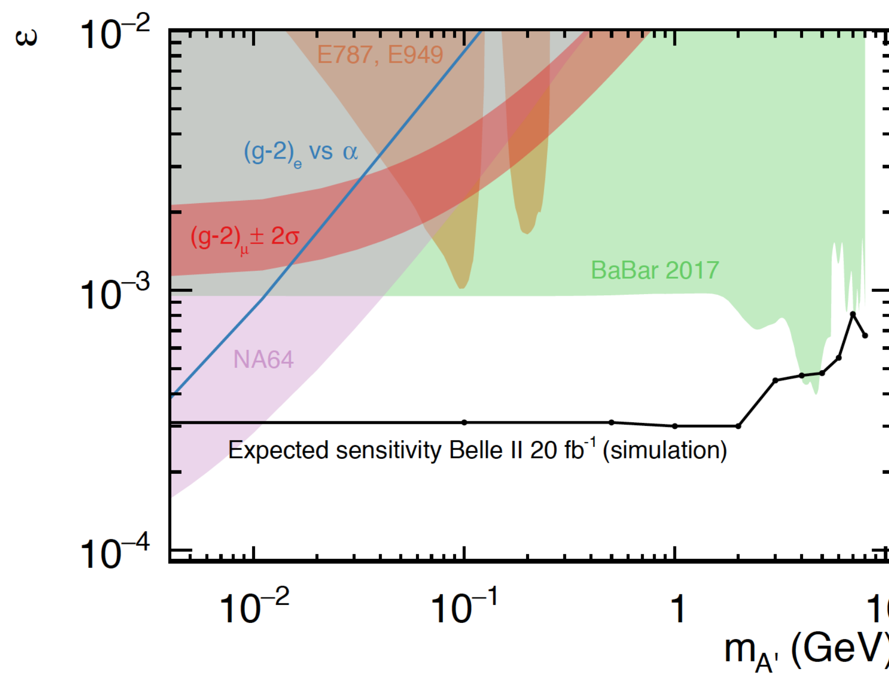
- C ~ (loop coupling) x (flavour coupling)

  (e.g. SM/MFV: α_w x CKM)



Precision flavour measurements provide bounds on ratio C / Λ i.e. constrain coupling strengths at any given mass scale


Hidden Photon → invisible ($m_{A'} > 2\, m_\chi$)
BaBar
$a_{\mu,5\sigma}$
$a_{\mu,\pm2\sigma}$ favored
K→πA'
E787, E949
BaBar
Improved
DarkLight
Belle II
Converted
Mono−photon
(a,b)
a_e
K→πA'
ORKA
Belle II
Standard
VEPP−3
Belle II
Low−E_γ
LSND
α_D=0.1
ε
$m_{A'}$ [GeV]


ε
E787, E949
$(g\text{-}2)_e$ vs α
$(g\text{-}2)_\mu \pm 2\sigma$
BaBar 2017
NA64
Expected sensitivity Belle II 20 fb^{-1} (simulation)
$m_{A'}$ (GeV)