

Searches of light dark matter at e^+e^- accelerators

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On behalf of the Belle II collaboration

Exploring the Dark Universe

July 23-29, Quy Nhon, Vietnam

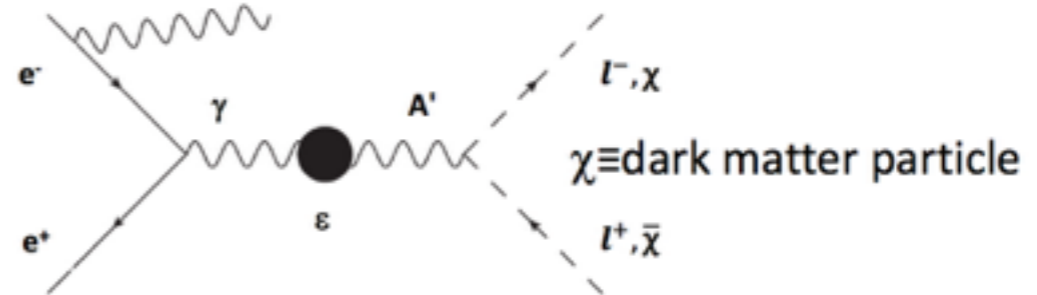


Outline:

- Introduction
- SuperKEKB&Belle II Detector
- Searches of light dark matter at Belle II
- Summary

Introduction

- Search for light dark matter at low-energy e^+e^- colliders (B-factories ~ 10 GeV)
 - High luminosity \Rightarrow large dataset
 - Coupling to SM particles \Rightarrow produce in experiment
 - Mass scale $\text{MeV}/c^2 \sim \text{GeV}/c^2 \Rightarrow$ within the collision energy region
- Production at e^+e^- colliders
 - Direct production from the e^+e^- annihilation e.g. $e^+e^- \rightarrow \gamma A'$
 - Light mediator A' (dark photon) coupling to SM photon via kinetic mixing with the mixing strength ϵ
 - $m_\chi < 1/2 m_{A'}$, invisible decay $A' \rightarrow \chi\bar{\chi}$
 - $m_\chi > 1/2 m_{A'}$, visible decay $A' \rightarrow l+l^-$
- Resonant production e.g. the tree level decay $Y(1S) \rightarrow$ invisible, the loop level rare decay e.g. $B \rightarrow K +$ invisible
- Other dark sectors searches at e^+e^- colliders e.g. Axion Like Particles (ALPs), dark Higgs



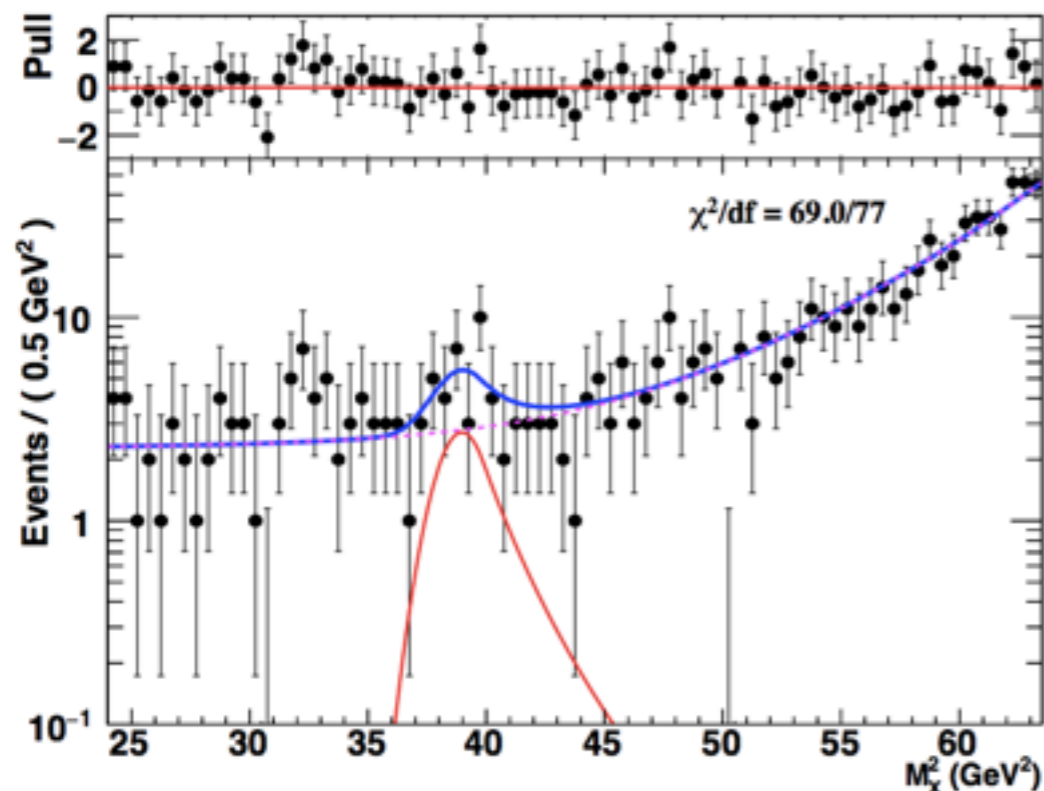
Introduction

$$e^+e^- \rightarrow \gamma A', A' \rightarrow \text{invisible}$$

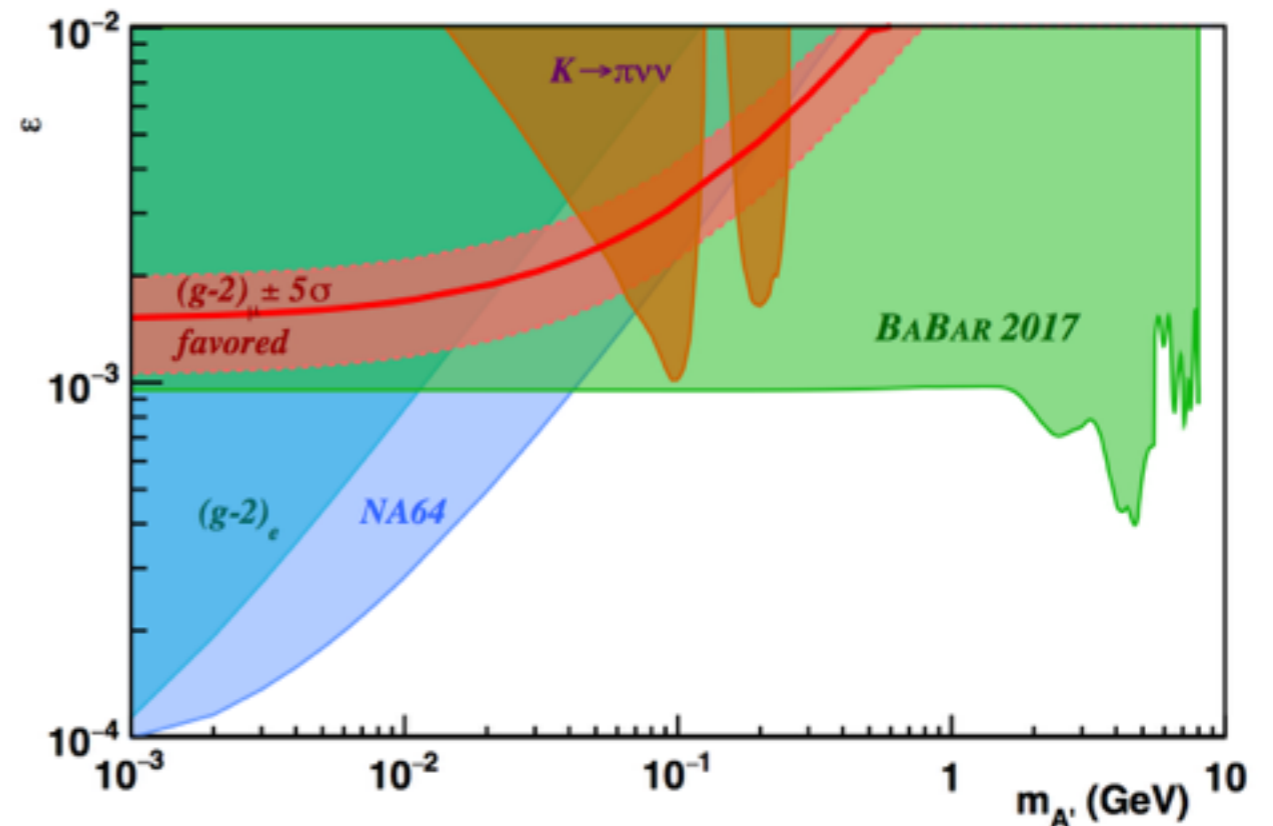
Search for a bump in the photon recoil mass

BaBar

- 53 fb⁻¹ data
- single photon trigger $E^* > 1$ or 2 GeV
- fit to the missing mass square of photon
- no evidence were found
- give the upper limit of the mixing strength at 90% C.L. in the mass region $m_{A'} \leq 8$ GeV
- arXiv: 1702.03327



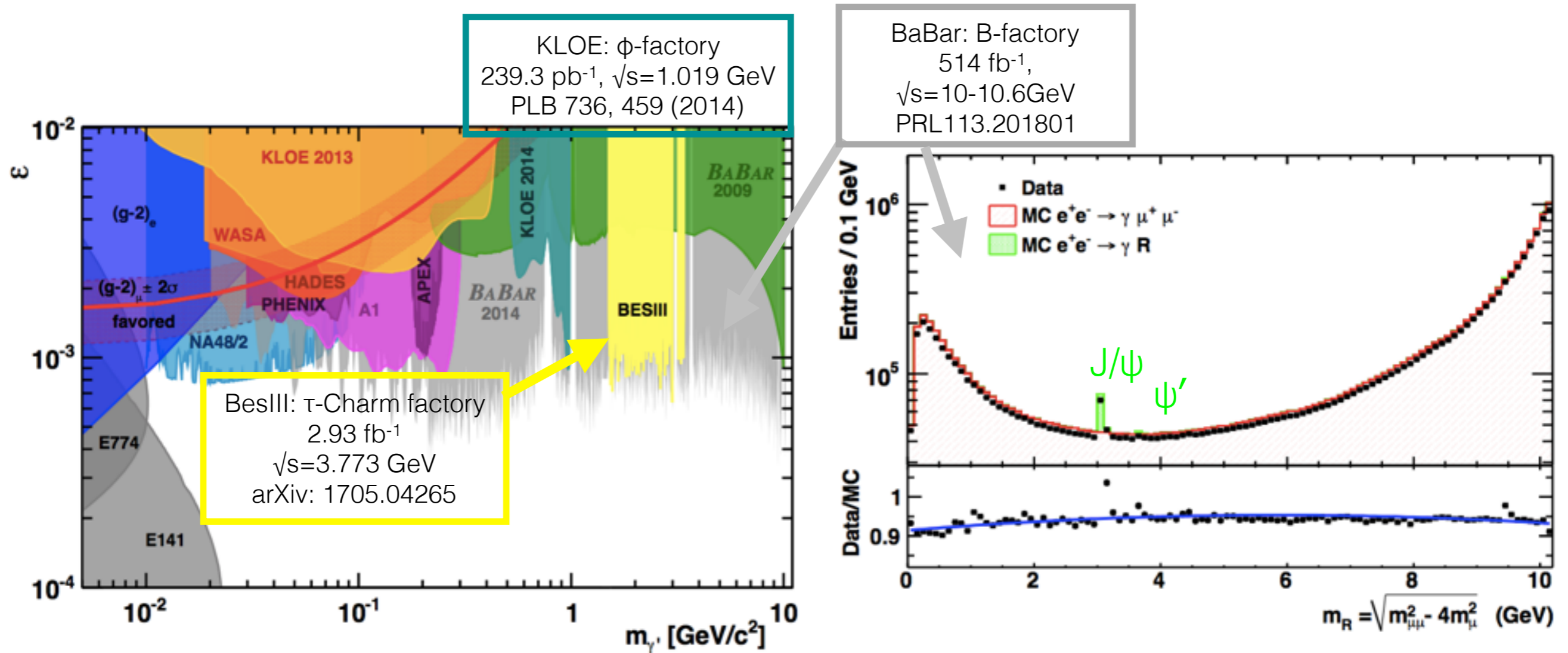
A representative fit $m_{A'} = 6.21$ GeV



Introduction

$$e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-/\mu^+\mu^-$$

Search for a bump in the invariant mass spectrum of lepton pair



SuperKEKB

An asymmetric electron-positron collider at KEK, Japan
 $e^+ \sim 4\text{GeV}$ $e^- \sim 7\text{GeV}$

◎ Phase 1

- Done (2016)
- Beam commissioning

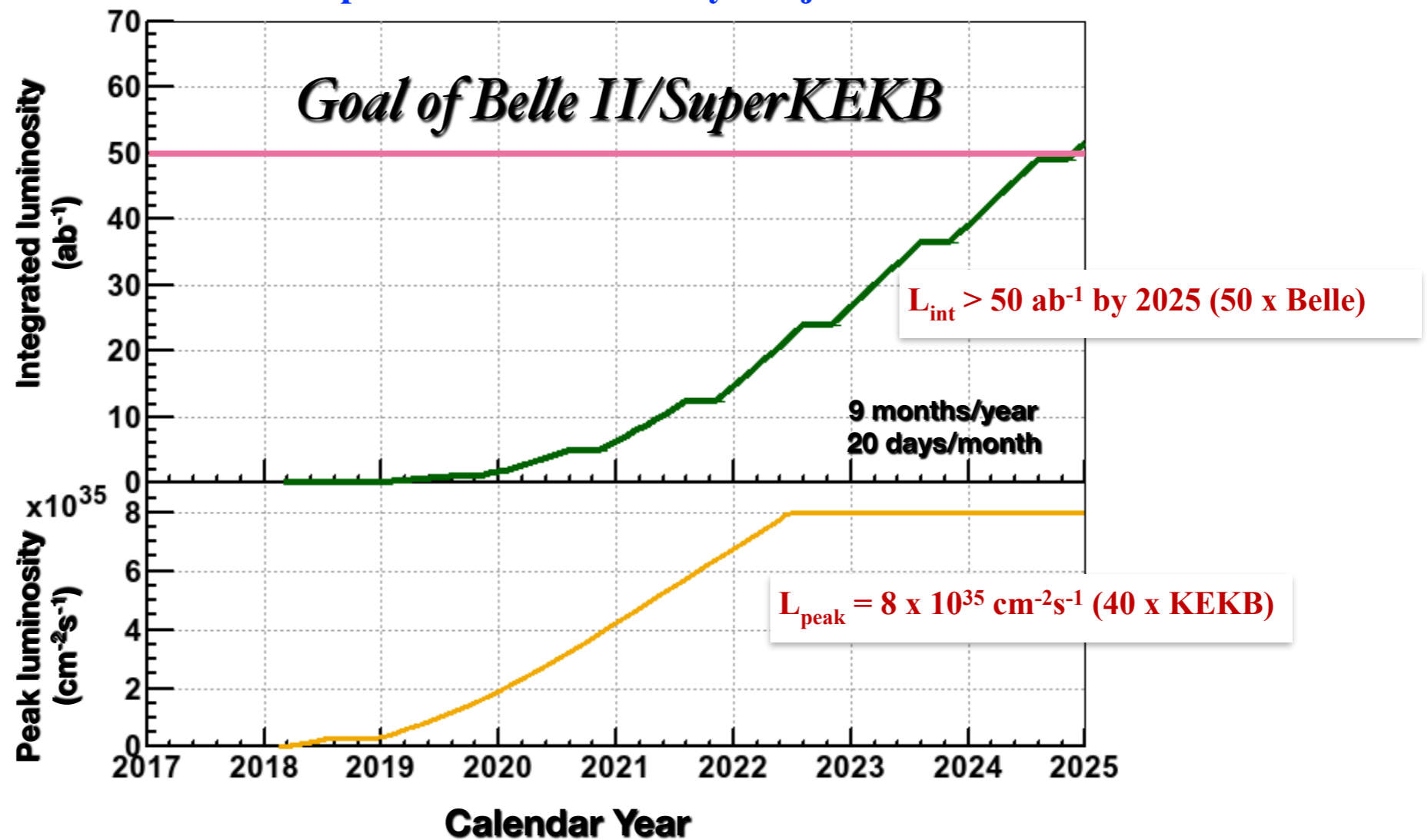
◎ Phase 2

- Feb. 2018
- w/o vertex detector
- Beam background measurement
- $20 \pm 20 \text{ fb}^{-1}$

◎ Phase 3

- End of 2018
- w/ all detectors
- Physics running

SuperKEKB Luminosity Projection



SuperKEKB

$$L = \frac{\gamma_{\pm}}{2e r_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{I_{\pm} \xi_{y\pm}}{\beta_{y\pm}^*} \left(\frac{R_L}{R_{\xi_y}} \right)$$

Lorentz factor γ_{\pm}
 Beam current I_{\pm}
 Beam-Beam parameter $\xi_{y\pm}$
 Geometrical reduction factors (crossing angle, hourglass effect) $\left(\frac{R_L}{R_{\xi_y}} \right)$
 Vertical beta function at IP $\beta_{y\pm}^*$
 Beam aspect ratio at IP $\frac{\sigma_y^*}{\sigma_x^*}$
 Minimum value is limited by hourglass effect

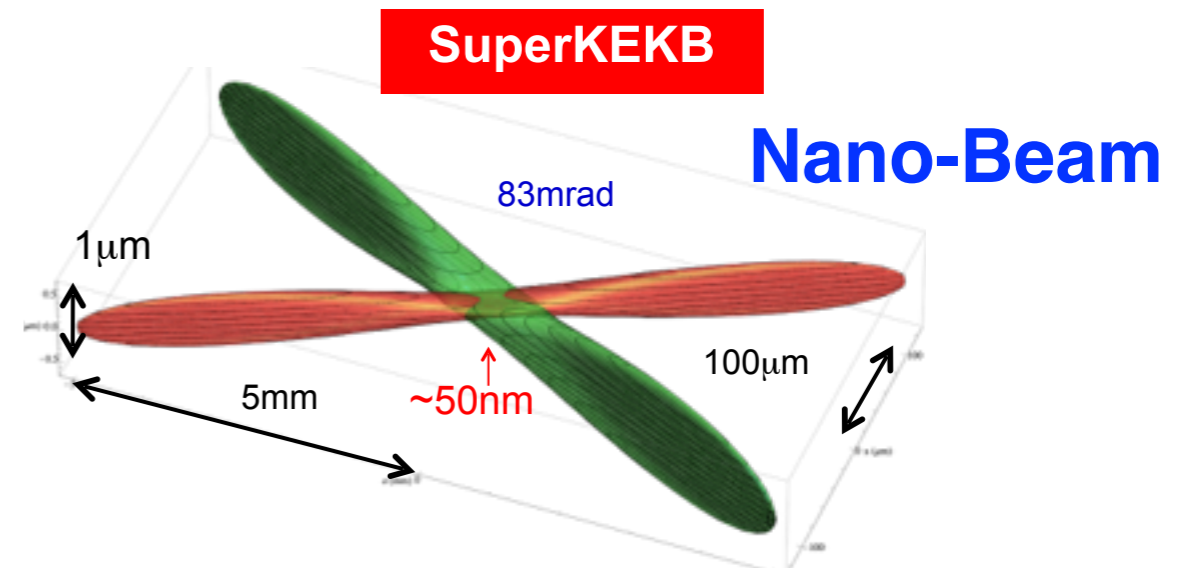
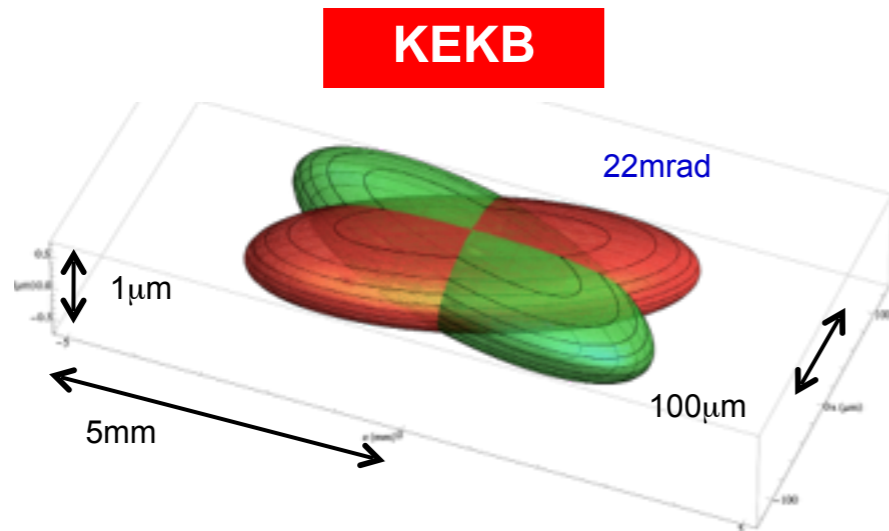
$$L_{peak} = 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \text{ (40 x KEKB)}$$

	E(GeV) LER/HER	β_y^* (mm) LER/HER	ξ_y LER/HER	I (A) LER/HER	L ($\text{cm}^{-2} \text{s}^{-1}$)
KEKB	3.5/8.0	5.9/5.9	0.129/0.090	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	0.0881/0.0807	3.6/2.6	80×10^{34}

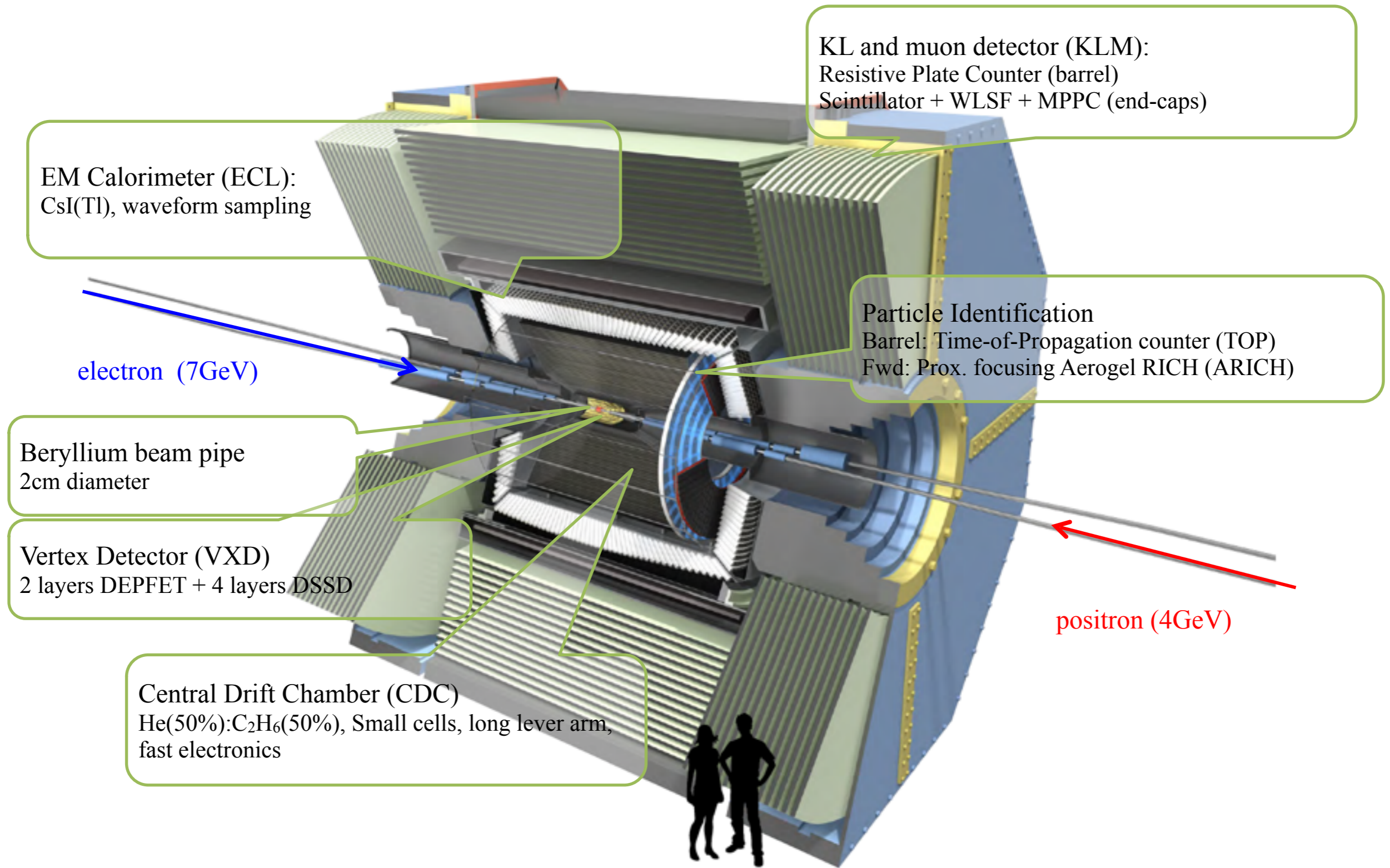
x 20

x 2

x 40



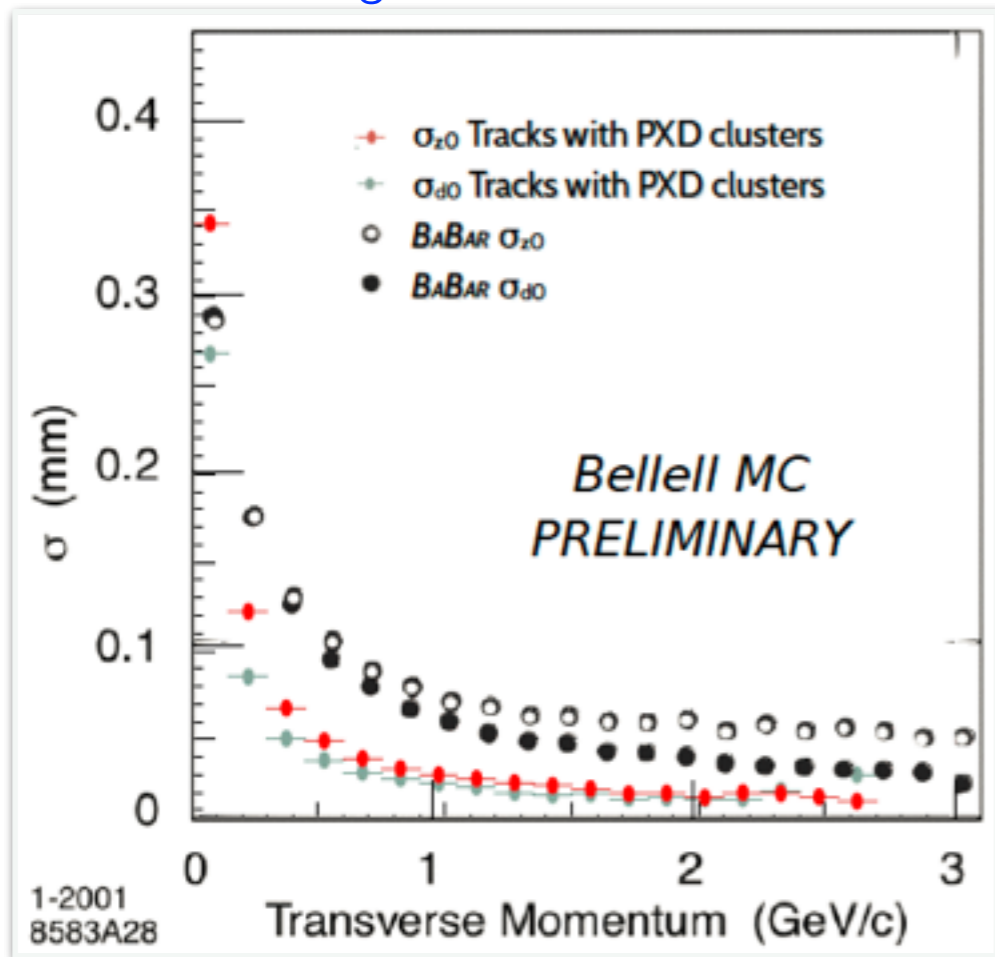
Belle II Detector



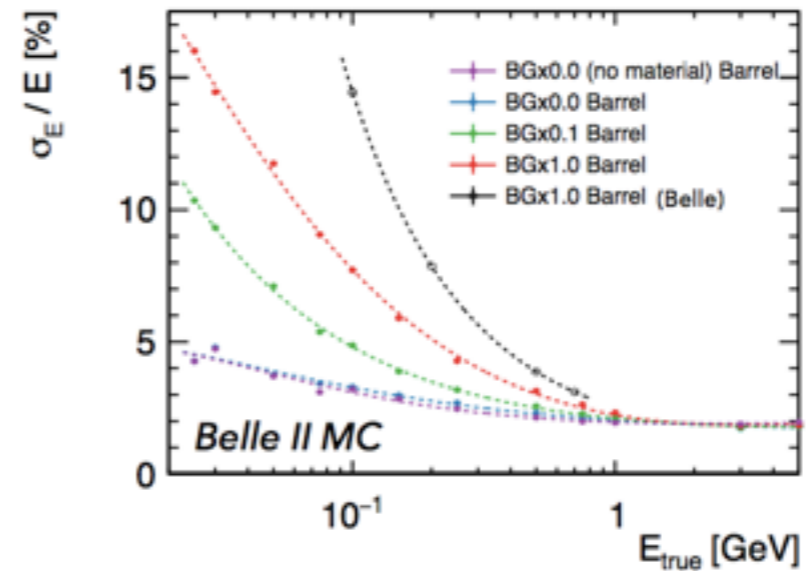
Belle II Detector

- a series of upgrades is implemented at Belle II to cope with high background and improve detector performance

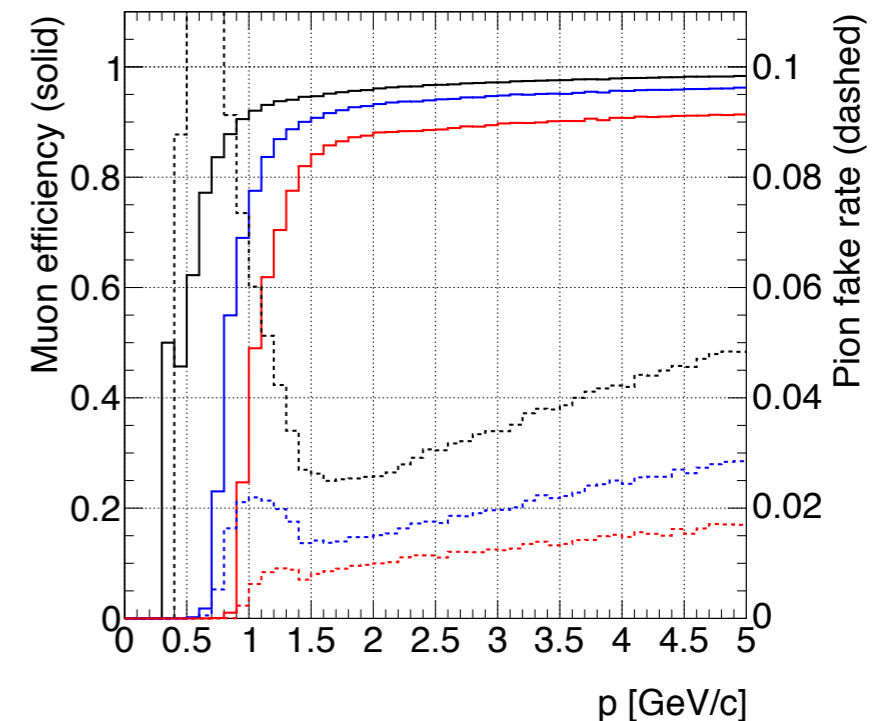
Tracking IP Resolution with VXD



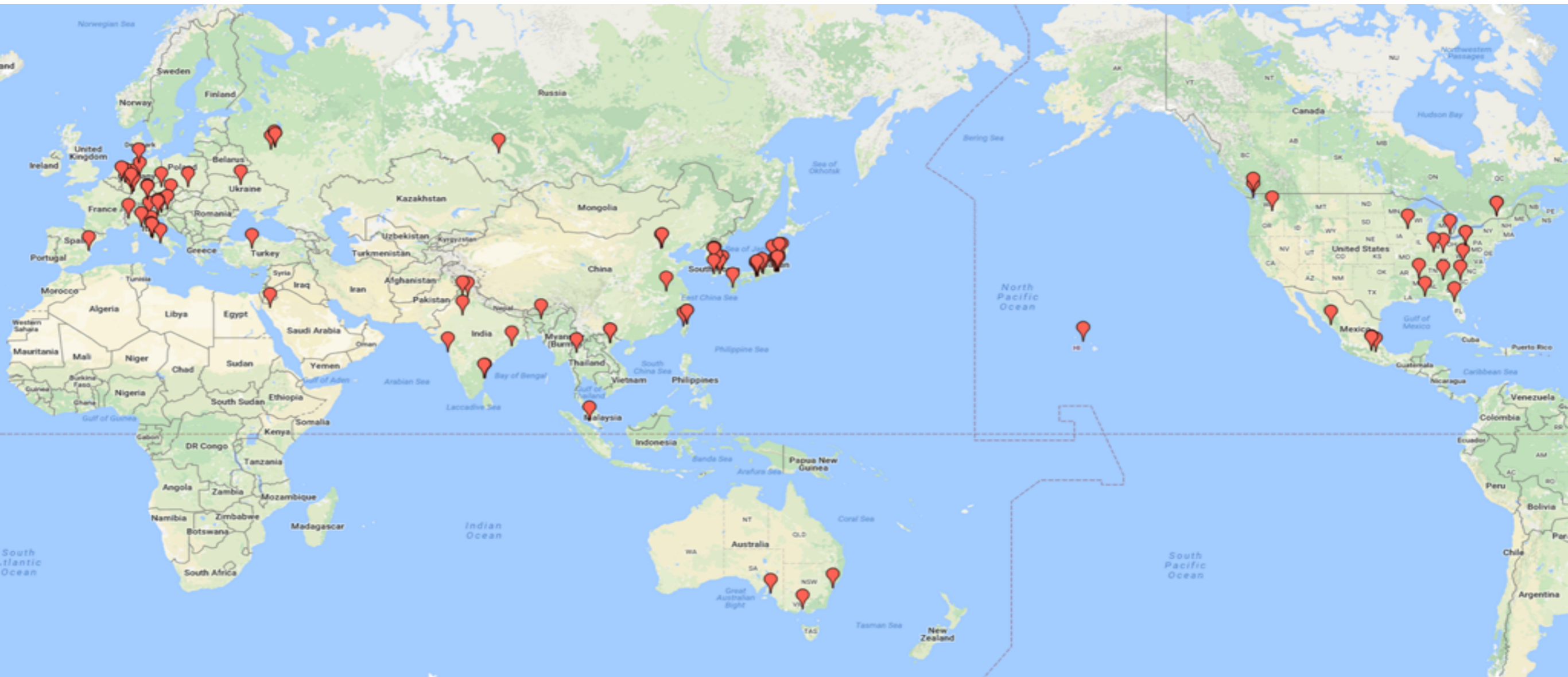
Resolution of ECL clusters



Muon ID



Belle II Collaboration

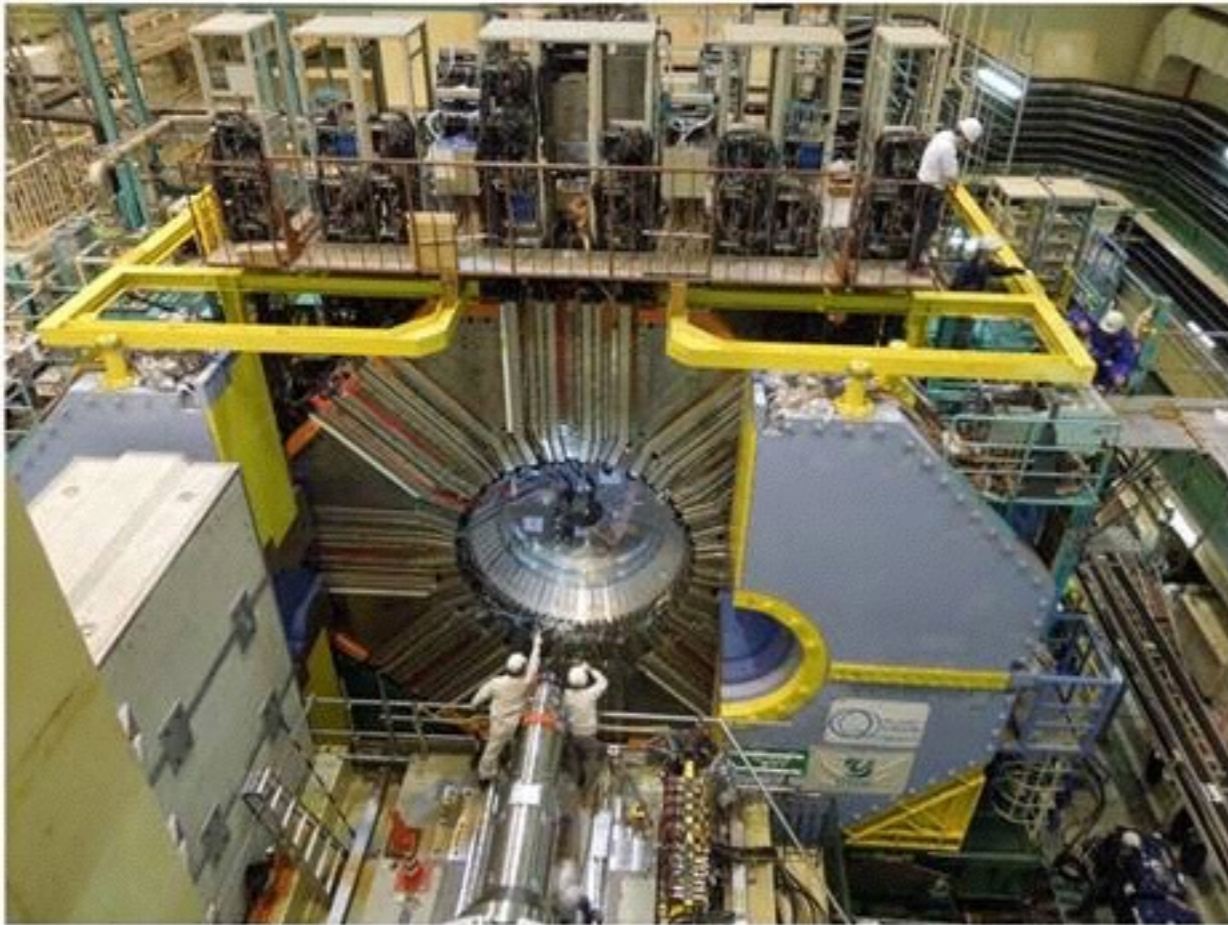


722 Colleagues
104 Institutions
24 Countries/regions



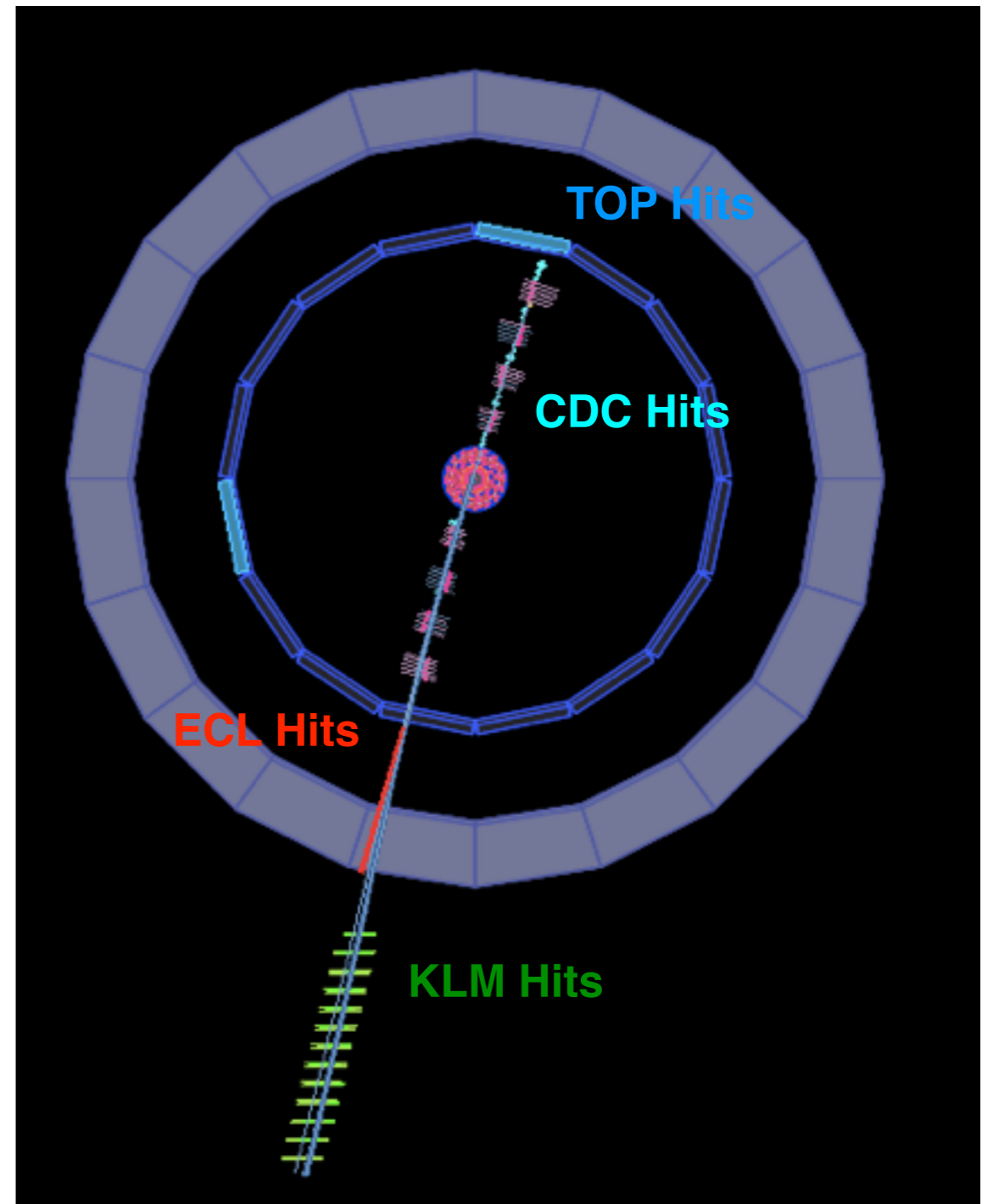
Belle II Roll-in

Belle II detector rolled in to the interaction region of SuperKEKB on April 11, 2017



Cosmic Ray Data Taking

- Integration of readout system of sub detectors is in progress
- Cosmic ray data taking is on going
 - Magnetic field: 1.5 T
 - Central draft chamber (CDC)
 - EM Calorimeter (ECL)
 - PID detectors (TOP, ARICH will join in soon)
 - KL and muon detector (KLM)
 - Trigger system



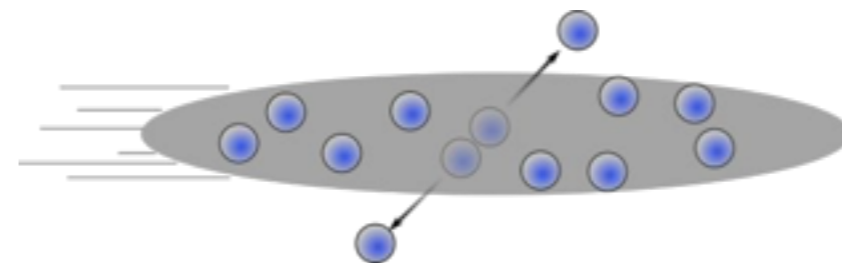
Belle II Beam Background

Due to the low final state particle multiplicity of dark matter processes, background from beams become a major challenge.

Total background is significantly higher than Belle

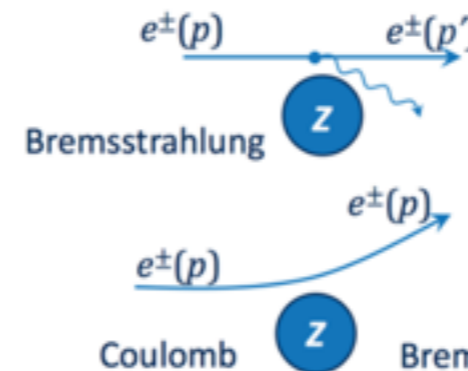
Touschek effect

- Intra bunch scattering
- Rate \propto the inverse beam size, number of bunches et.al
- Suppressed with movable collimators



Beam gas

- Coulomb and bremsstrahlung scattering by the residual gas atoms
- Rate \propto the vacuum level and the beam current

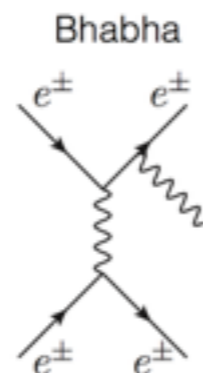


Synchrotron radiation

- Rate \propto the beam energy squared and magnetic field squared

Physical backgrounds

- Bhabha $ee \rightarrow (\gamma)ee$
- Two photon: $ee \rightarrow eeee$
- Rate \propto luminosity



Dominant when luminosity is high

Belle II Trigger System

- A well-designed trigger system is essential for the search of dark matters

Scheme: Hardware trigger + Software trigger

- Level 1 (L1): hardware based, readout rate: 30 kHz
- High Level Trigger (HLT): software based, readout rate: 10 kHz

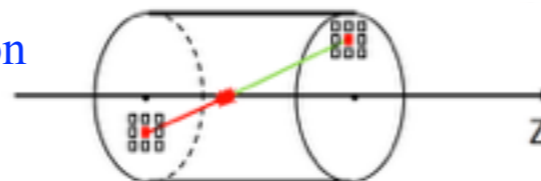
- The trigger system is entirely new with a vastly expanded search scope

L1 CDC Trigger

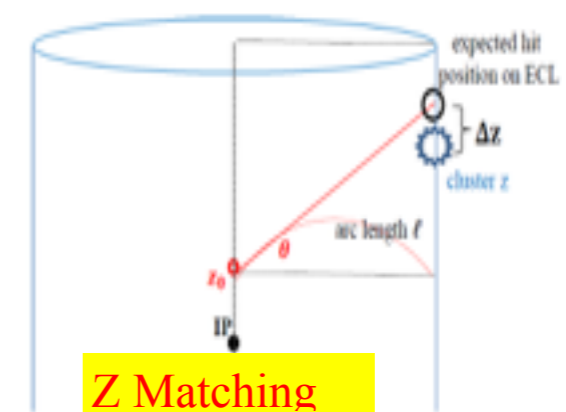
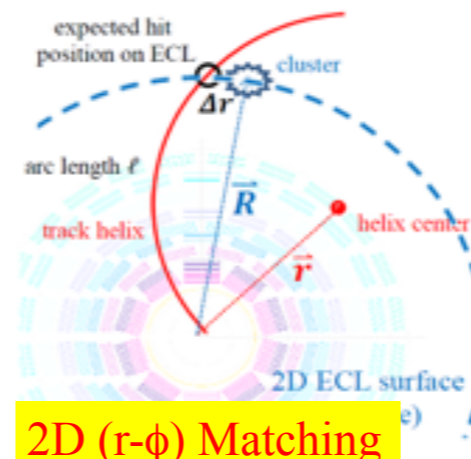
- 3D Tracking
 - Suppress background
 - 3D Tracking direction and momentum

L1 ECL Trigger

- 3D Bhabha-veto logic
 - 3D cluster position information
 - Cluster energy requirements



L1 Track-Cluster Match



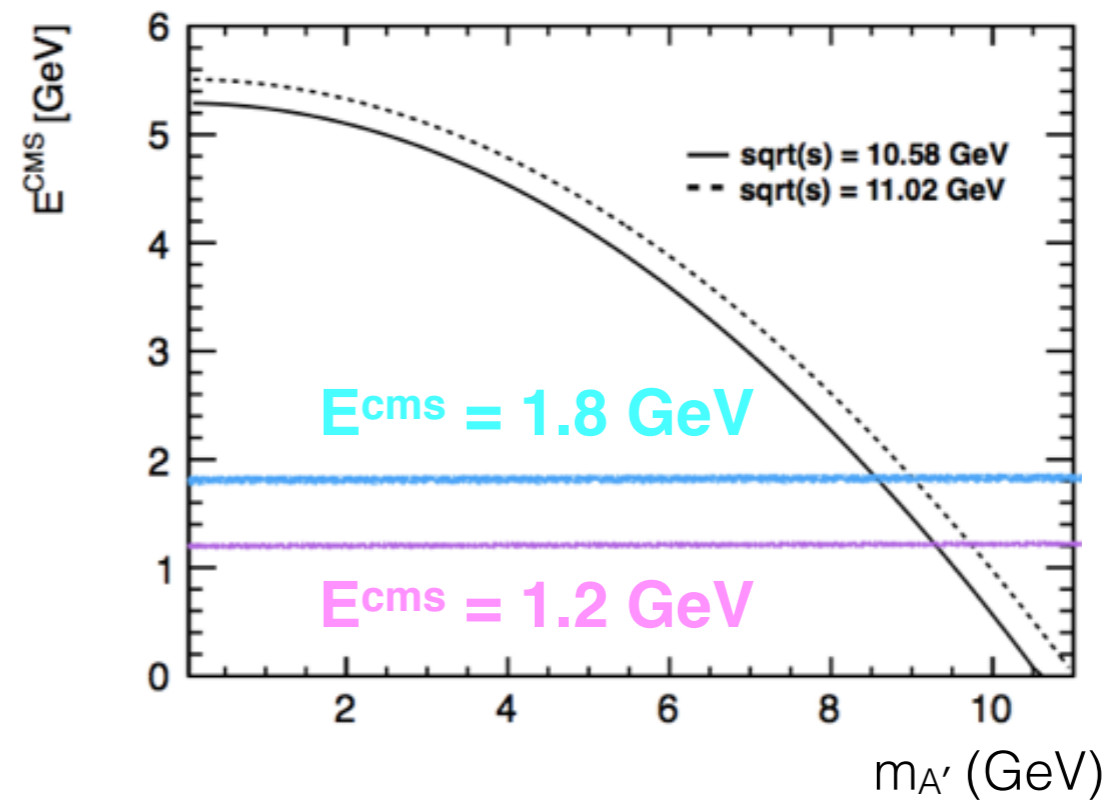
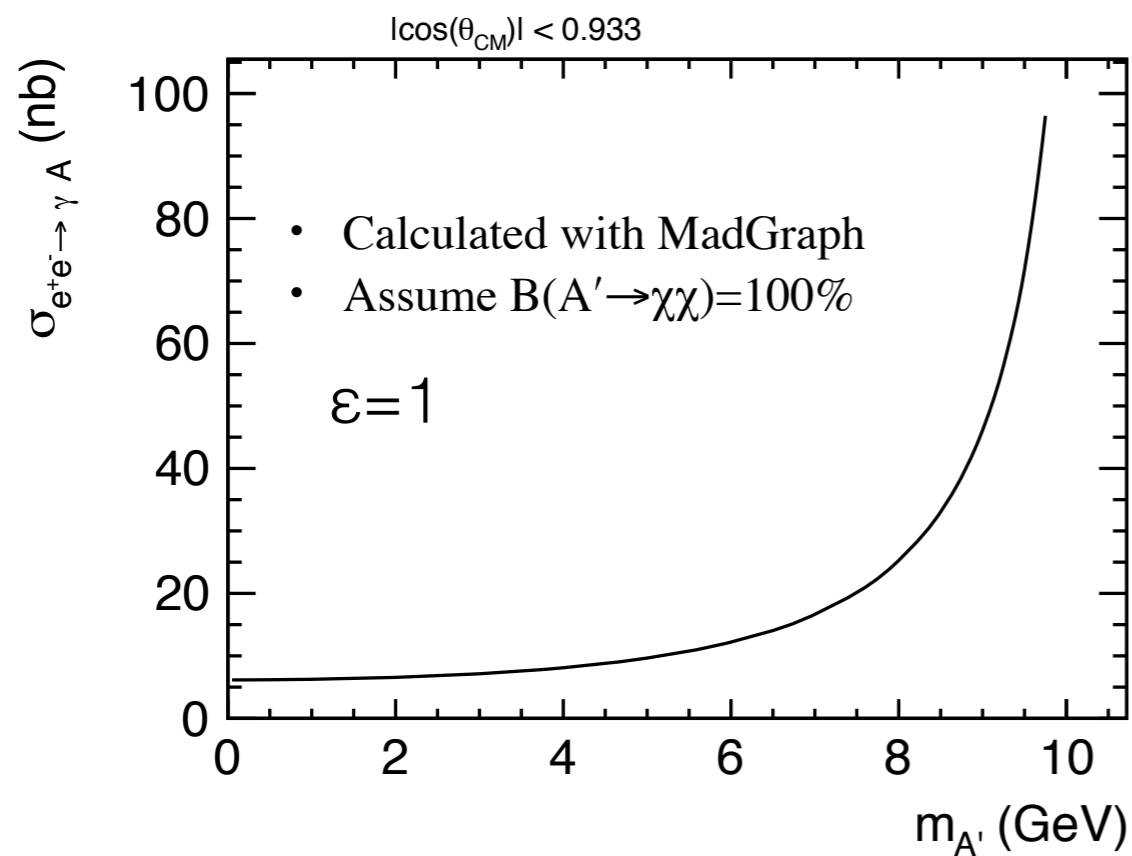
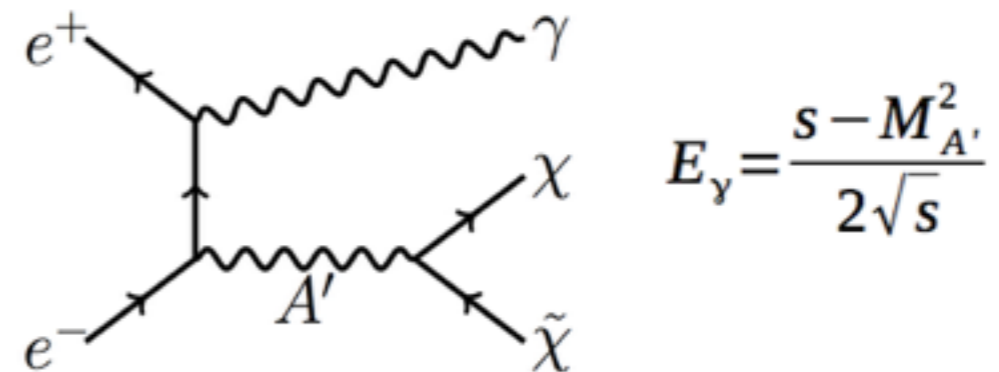
Belle II Trigger System

- High Level Trigger
 - Operating offline reconstruction algorithms as a component of DAQ
 - Suppress event rate to 10 kHz for the offline storage
 - Strong computing power to cope with high event rate
 - 1500 cpu at Phase 2, and 6000 cpu at Phase 3 with target luminosity

- Trigger menus at L1 and HLT
 - High Multiplicity
 - BB
 - continuum: u, d, s, c
 - Low Multiplicity
 - τ physics
 - dark matter searches
 - ISR processes for precision measurement
 - Pre-scaled samples for luminosity and performance study

Search for dark matter in A' invisible decay

- Single photon in detector
- Search for a bump in the photon recoil mass spectrum



Search for dark matter in A' invisible decay

- Dominant backgrounds are QED process with only one photon is detected
- Large cross section in detector acceptance
 - $\sigma(ee \rightarrow ee(\gamma)) \sim 74 \text{ nb}$
 - $\sigma(ee \rightarrow \gamma\gamma(\gamma)) \sim 3 \text{ nb}$
- Dedicated single photon trigger with threshold 1 GeV and 2 GeV
 - exclude the ECL crystals close to beam pipe to suppress the background
 - further tuning is necessary at high luminosity due to the increasing background

	YY	Bhabha		Total
		both e have $\theta^* > 1^\circ$	one e has $\theta^* < 1^\circ$	
1 GeV* E* > 1 GeV and second cluster E* < 0.2 GeV	0.2 nb	0.4 nb	1.6 nb	2.2 nb rate@1/40 lumi: 0.05 kHz rate@final lumi.: 1.76 kHz
2 GeV* E* > 2 GeV and eclbhabhaveto and bhabhveto	0.5 nb	2.9 nb	0.1 nb	3.5 nb rate@1/40 lumi: 0.08 kHz rate@final lumi.: 2.80 kHz

Preliminary simulation

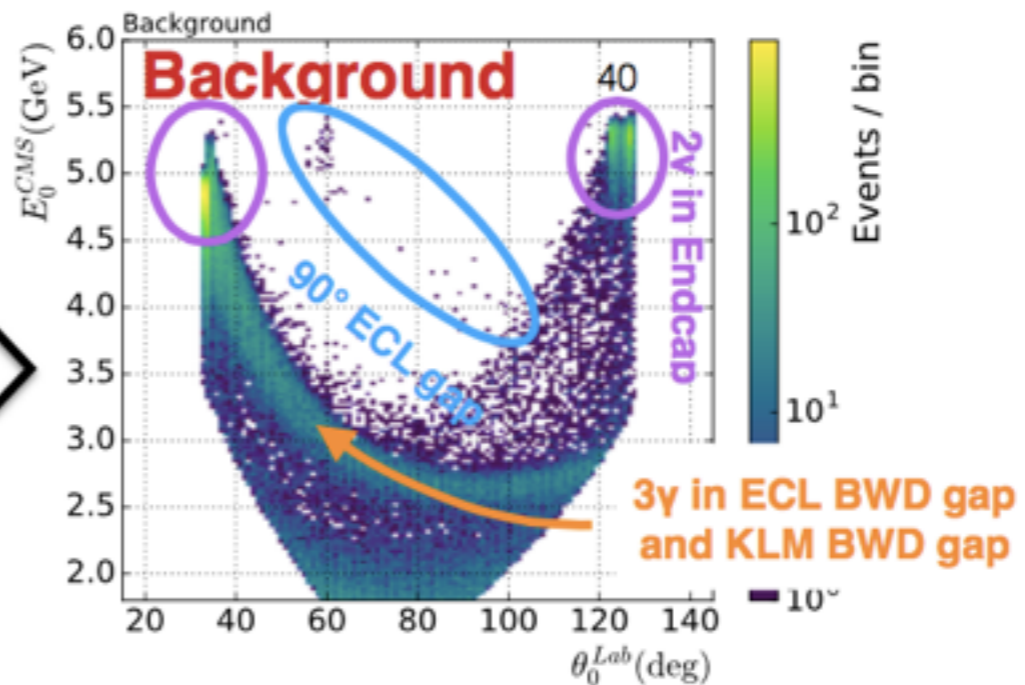
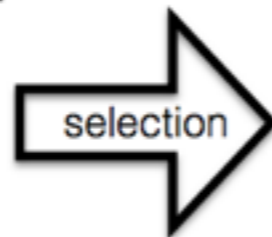
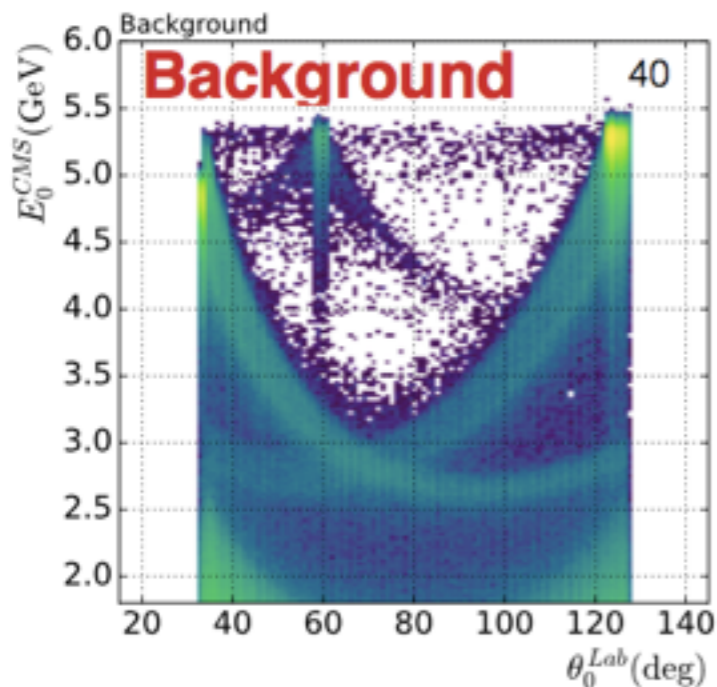
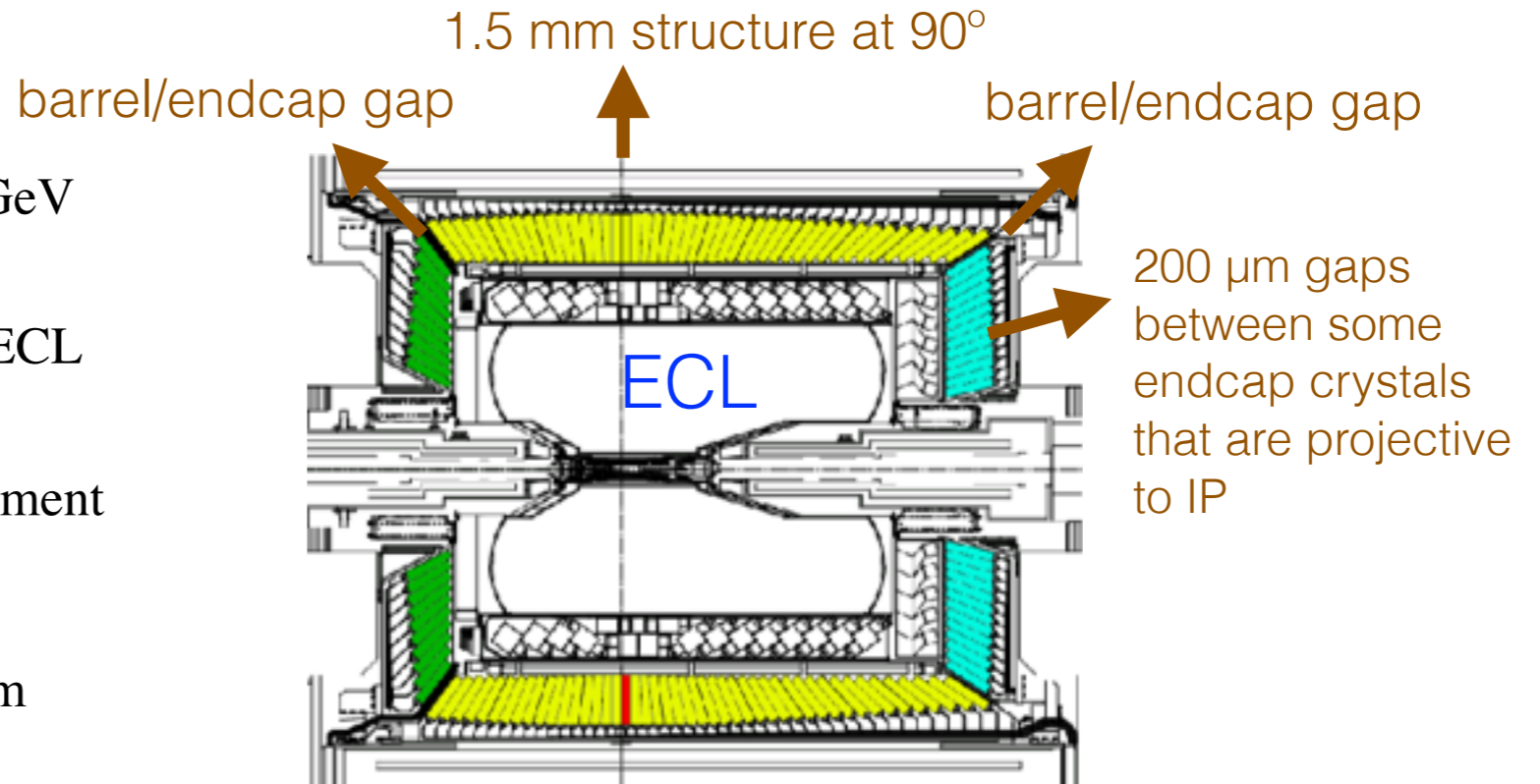
Search for dark matter in A' invisible decay

◎ Basic event selection

- $E^* > 1.8$ GeV
- No extra ECL clusters with $E^* > 0.1$ GeV
- No tracks with $P_t > 0.2$ GeV/c
- No KLM clusters out of 25° cone of ECL Cluster
- Energy dependent polar angle requirement

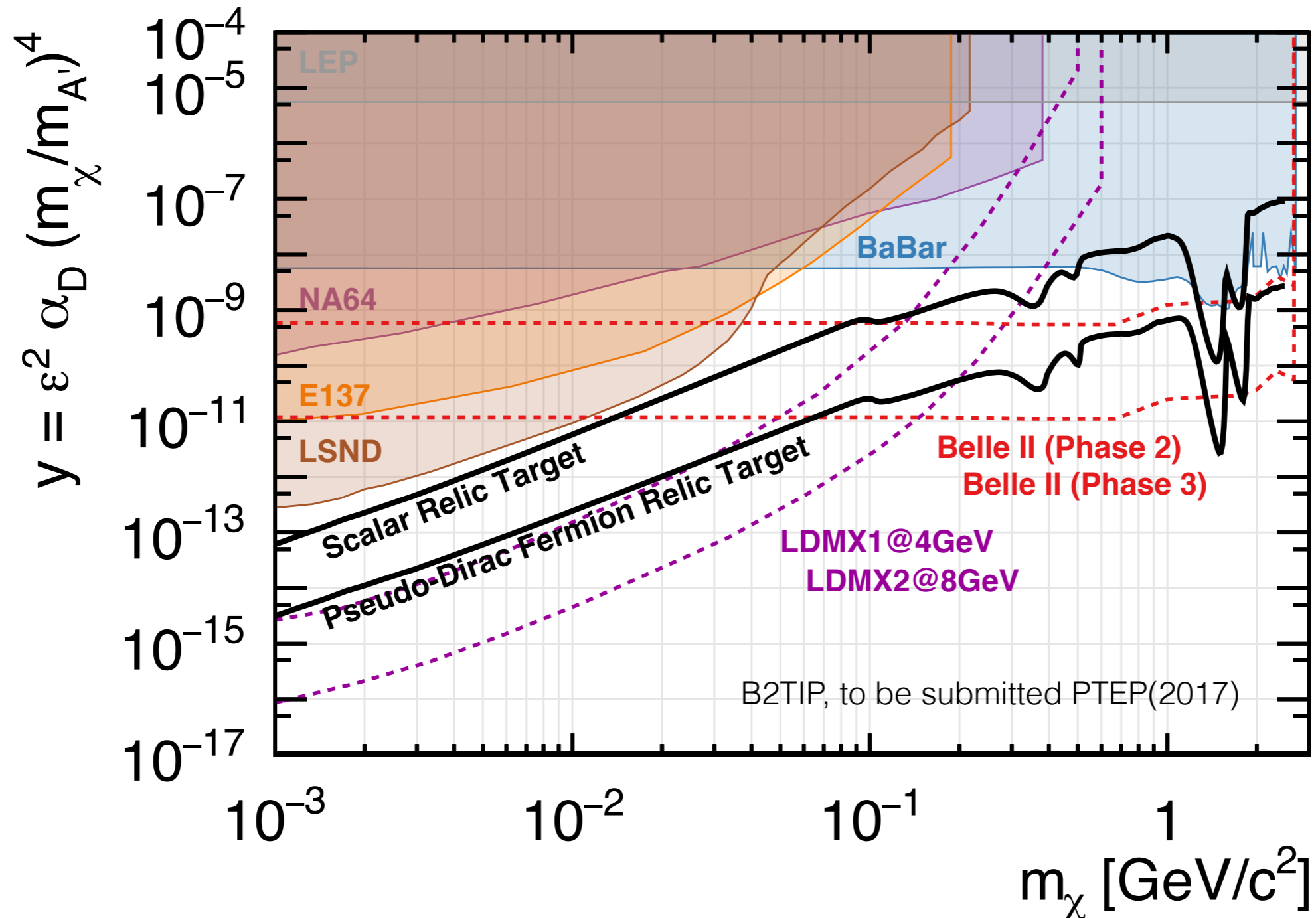
◎ Dominant background

- $ee(\gamma), \gamma\gamma(\gamma)$ with particles escape from the inefficient ECL regions



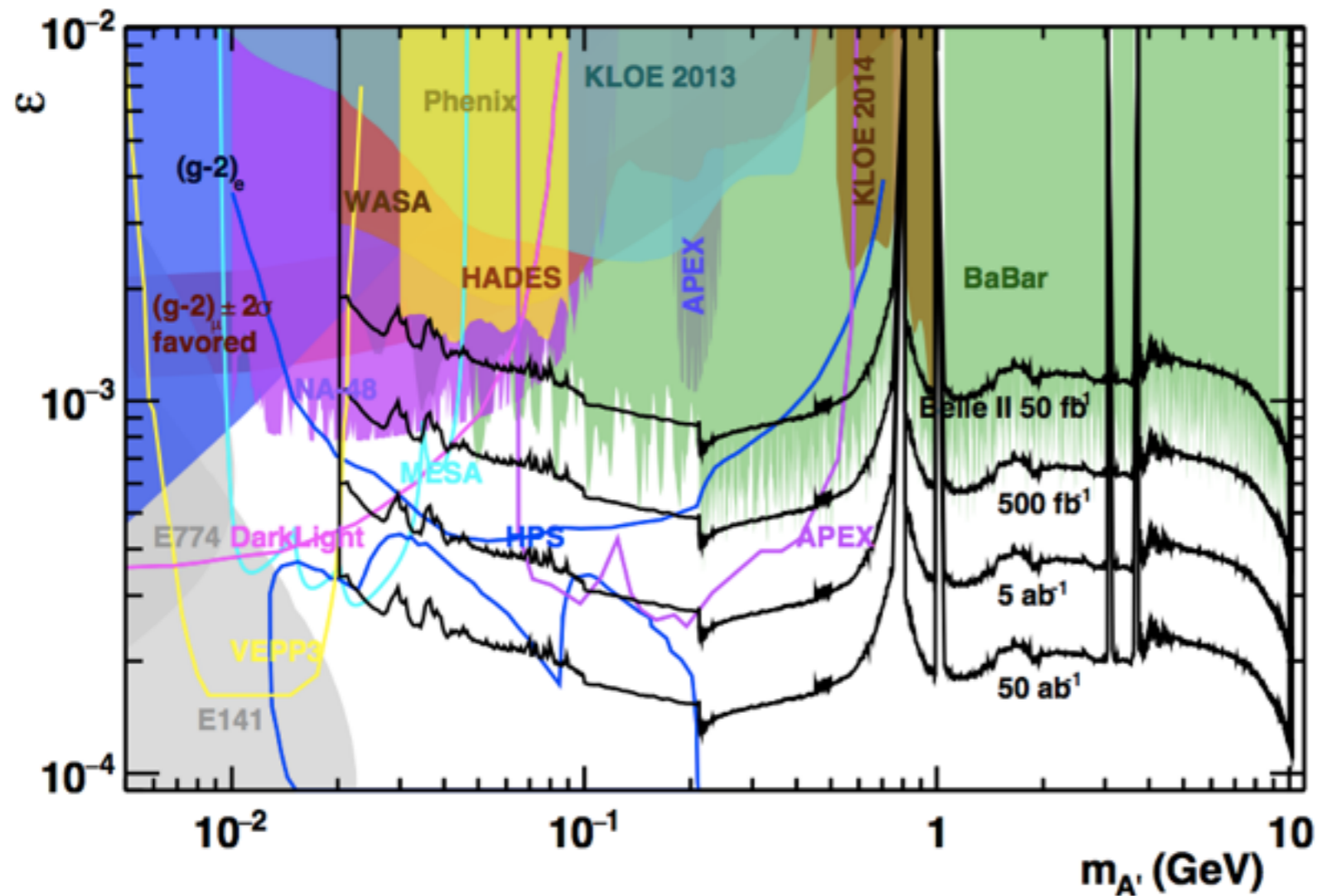
Search for dark matter in A' invisible decay

Projection of Belle II at Phase 2 & 3



Search for A' decaying to leptons

- ⊙ $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow e^+e^-/\mu^+\mu^-$
- ⊙ Main backgrounds: QED processes $e^+e^- \rightarrow \gamma e^+e^-/\mu^+\mu^-$



projections made based on BaBar's measurement

Search for dark matter in $Y(1S)$ invisible decays

◎ $Y(1S)$ invisible decay

- In SM, $B(Y(1S) \rightarrow \nu\nu) \approx 10^{-5}$ (PLB 441(1998) 419-424)
- If low mass dark matter less than b quark mass exist, $Y(1S) \rightarrow$ invisible is enhanced
- $B < 3 \times 10^{-4}$ at 90% C.L. by Babar: PRL 103(2009) 251801, other measurements by Belle: PRL 98(2007) 132001, CLEO: (PRD 75(2007) 031104)

◎ Production at Belle II

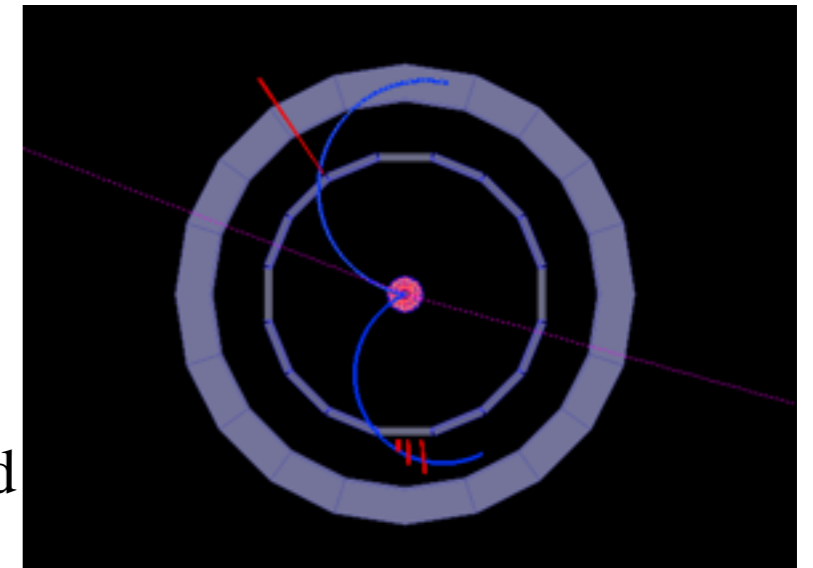
- $e^+e^- \rightarrow Y(2,3S) \rightarrow \pi^+\pi^- Y(1S), Y(1S) \rightarrow$ invisible
- Two slow charged π in the final state

◎ Dedicated trigger

- Trigger with low threshold of transverse momentum is needed
- Study is in progress

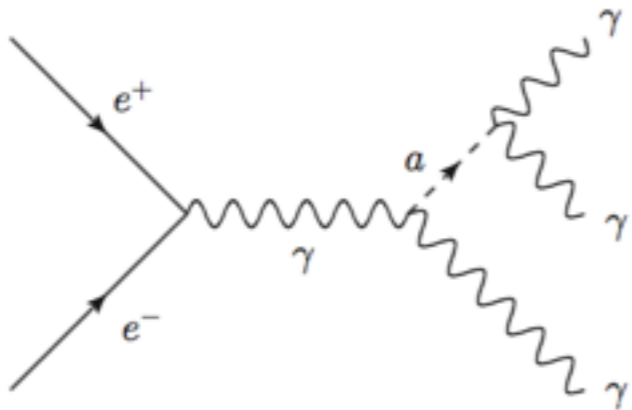
◎ Main backgrounds

- Two photon process $e^+e^- \rightarrow e^+e^- X$, where e^+e^- are out of detector, and $X = \pi^+\pi^-/\mu^+\mu^-$,



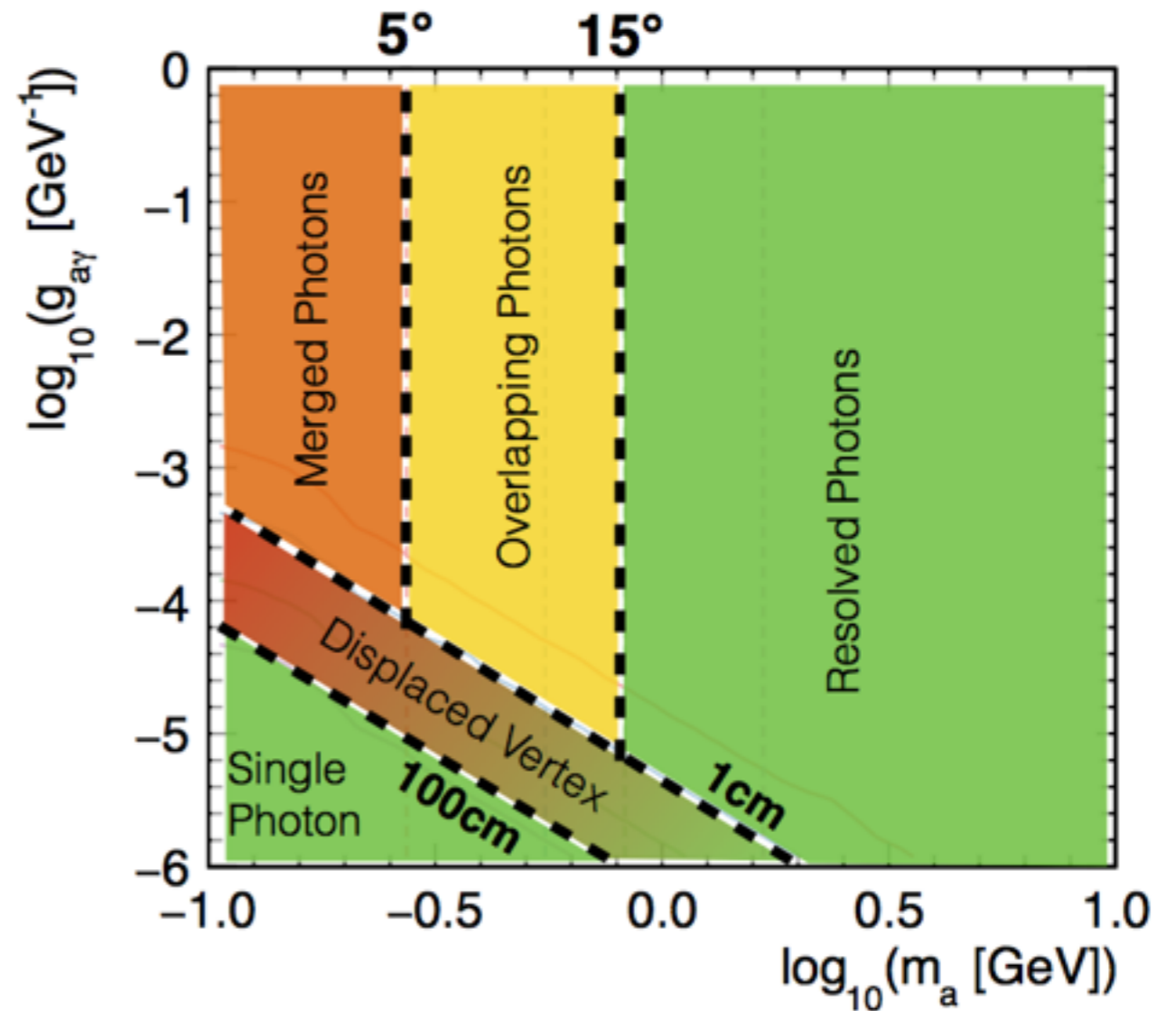
Search for Axion Like Particle (ALP)

- ALPs are pseudo-scalars and couple to bosons
- Search for ALP at Belle II via its coupling to $\gamma\gamma$

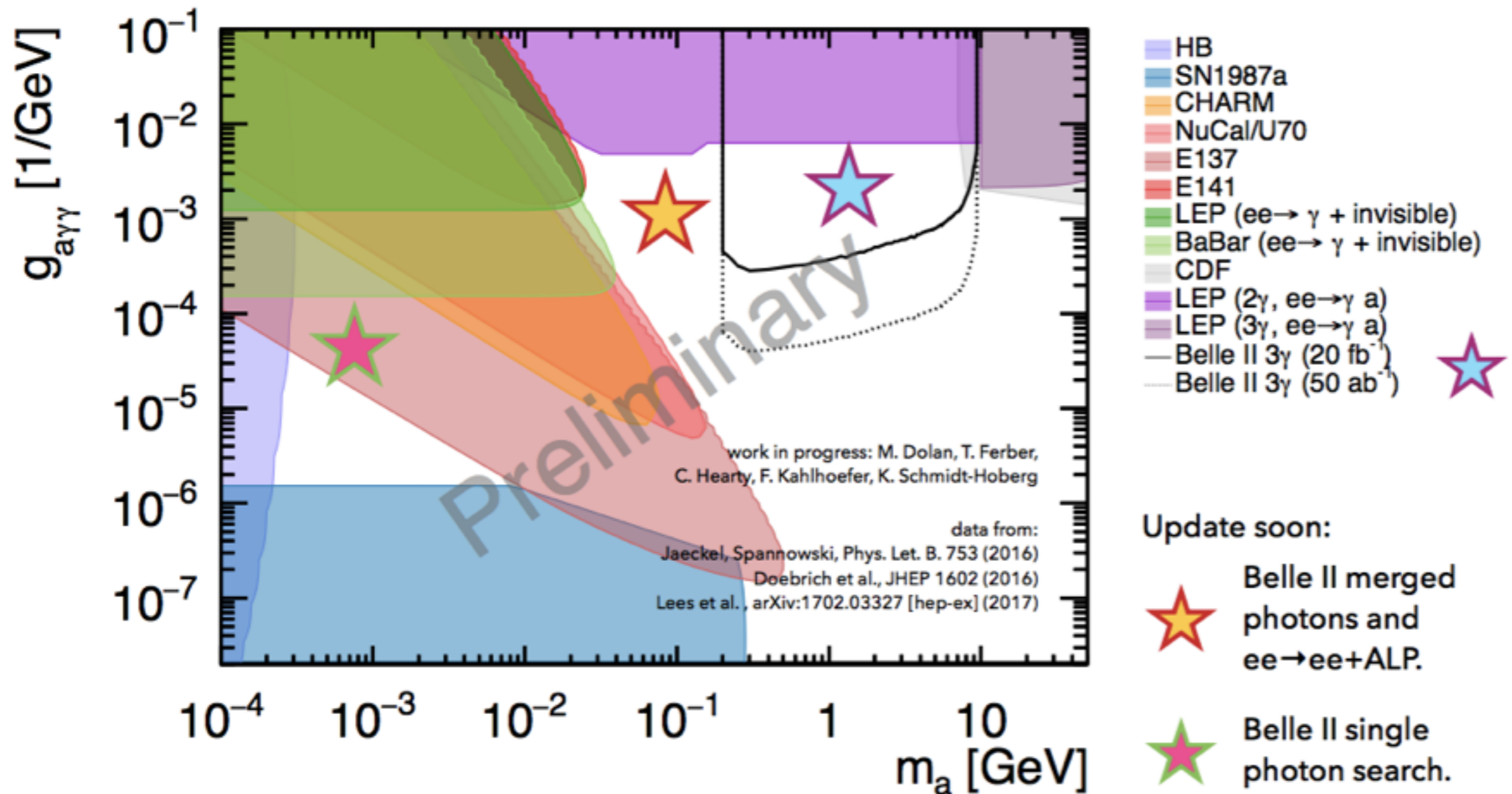


Signature in detector

- $m_a > 500 \text{ MeV}/c^2$
 - three photons are well separated
 - detect 3γ
- Low mass region
 - two decay photons overlap or merge
 - detect 2γ
- ALPs fly out of detector
 - detect 1γ



Search for Axion Like Particle (ALP)

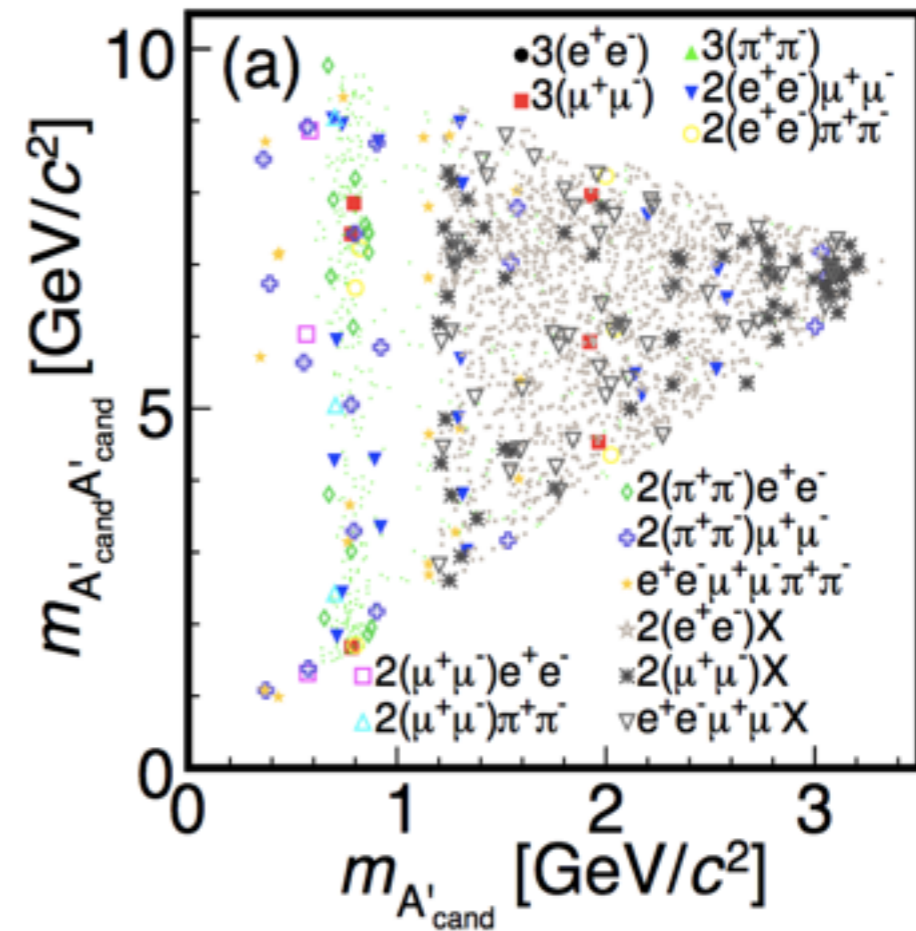
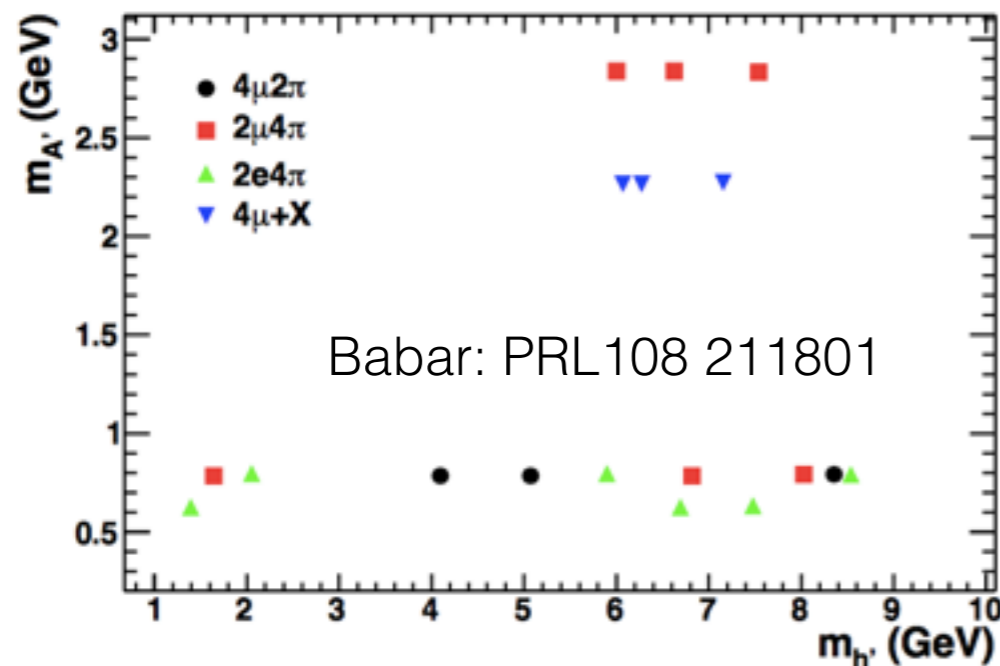
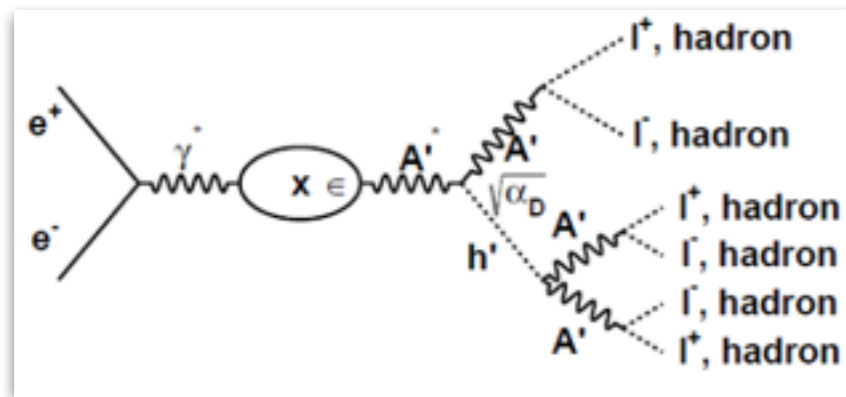


ALP coupling to two photons only.

T. Ferber, EPS-HEP, Venice: "Dark Sector Searches at Belle II" (July 2017)

Search for dark higgs

- Dark photon could arise from Higgs-strahlung process $e^+e^- \rightarrow A'h'$, $h' \rightarrow A'A'$
 - Six leptons or hadrons in the final state
 - Clear process with few background



Belle: PRL 114. 211801(2015)

Summary

- Belle II is a good place for the searching of light dark sectors.
 - High luminosity $\sim 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ at Phase 3, $\sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at Phase 2
 - Upgrade detectors e.g. better tracking vertex resolution, better energy resolution, improved trigger schemes
 - Improved reconstruction software
- Start commissioning w/o VXD on Feb. 2017 (Phase 2)
 - $20 \pm 20 \text{ fb}^{-1}$ physics data
 - Belle II will provide the strong constraint on dark photons in the GeV mass and ALPs searching even with phase 2 data
- Physics running with all detectors (Phase 3) start at the end of 2018, aim to collect 50 ab^{-1} data by 2025