B05: Electron-Positron Accelerator

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KEK

Dark Matter Symposium

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B05 Members

B05「電子陽電子加速器によるダークマター探索」
B05 “Dark Matter Search with Electron-Positron Collider”

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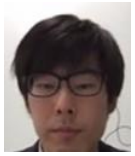
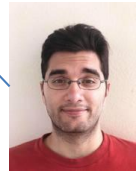
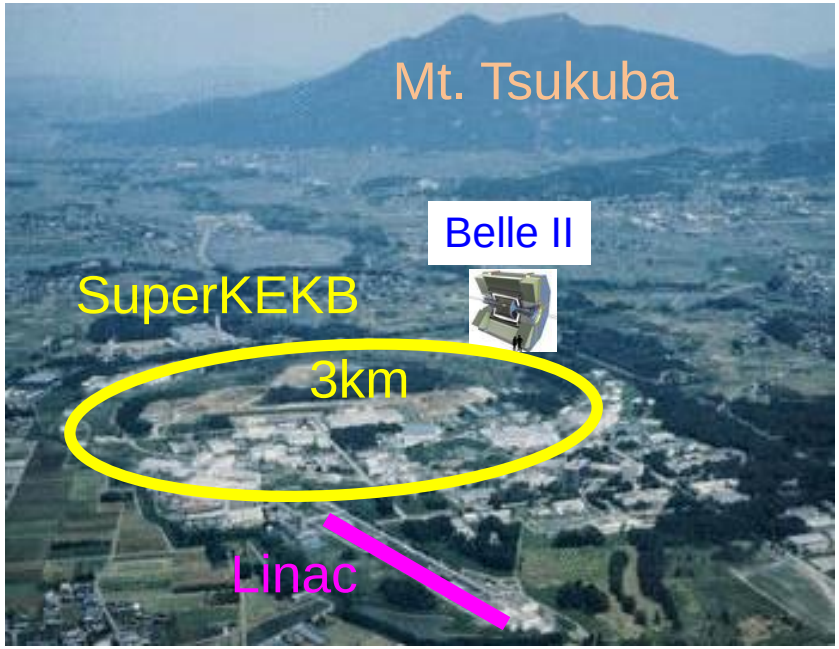


Belle and Belle II



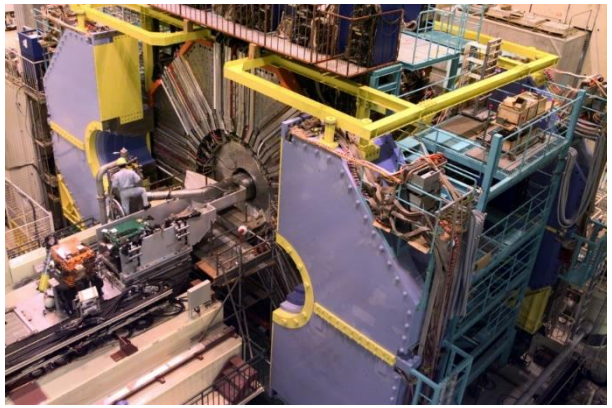
Belle and Belle II experiment:

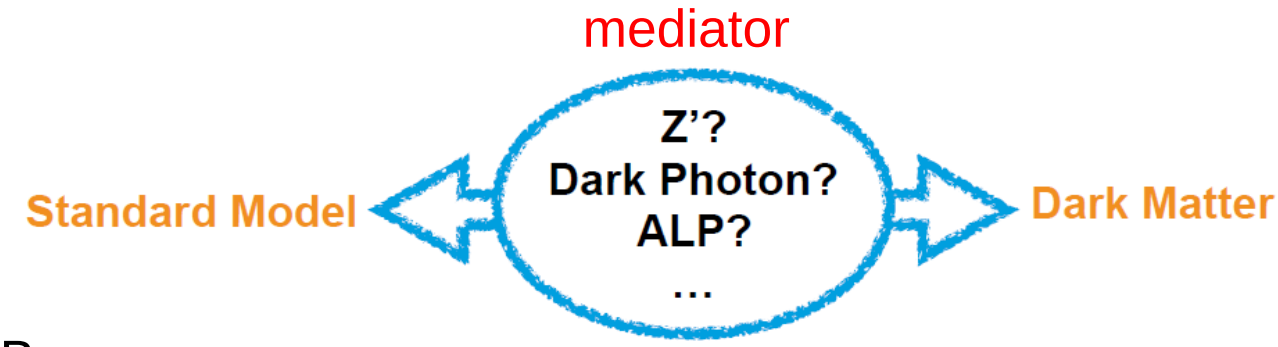
- KEK (High Energy Accelerator Research Organization) in Tsukuba, Japan.
- Accelerator: KEKB / SuperKEKB
  - ✓ Linac + 3km ring
  - ✓ Asymmetric e^+-e^- collider
- "B factory experiments" (produce large amount of B mesons).

Accelerator	KEKB	SuperKEKB
Experiment (Detector)	Belle	Belle II
Operation (Year)	1999-2010	2019-
Beam Energy	3.5 GeV e^+ + 8 GeV e^-	4 GeV e^+ + 7 GeV e^-
Luminosity [$cm^{-2}\ s^{-1}$]	2.1×10^{34}	3.8×10^{34} / 6×10^{35} (target)

Dark Matter Search at Belle (II)

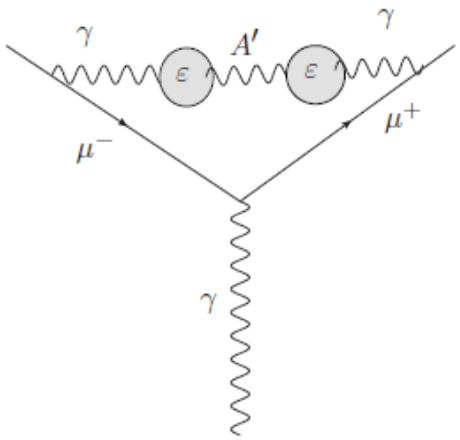
- Search for Dark Matter (DM) at Belle, Belle II.
  - ✓ CM energy is ~10GeV
    → mass region up to O(1) GeV (“light DM”)





Bonus

- ➢ A’, Z’ may explain the discrepancy of $(g-2)_\mu$ between theory and experiment.

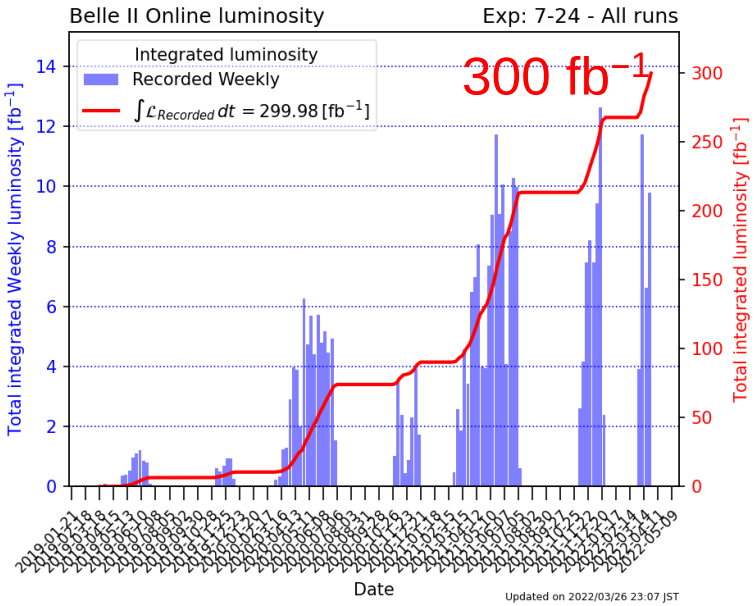


- Typical process
  - ✓ $e^+ + e^- \rightarrow$ SM-particles + Mediator
  - ✓ B (or other hadron) $\rightarrow$ SM-particles + Mediator
- Some of these processes have not been searched in BaBar or Belle experiment (due to trigger setting etc.), and may be searched with initial Belle II data.

Luminosity

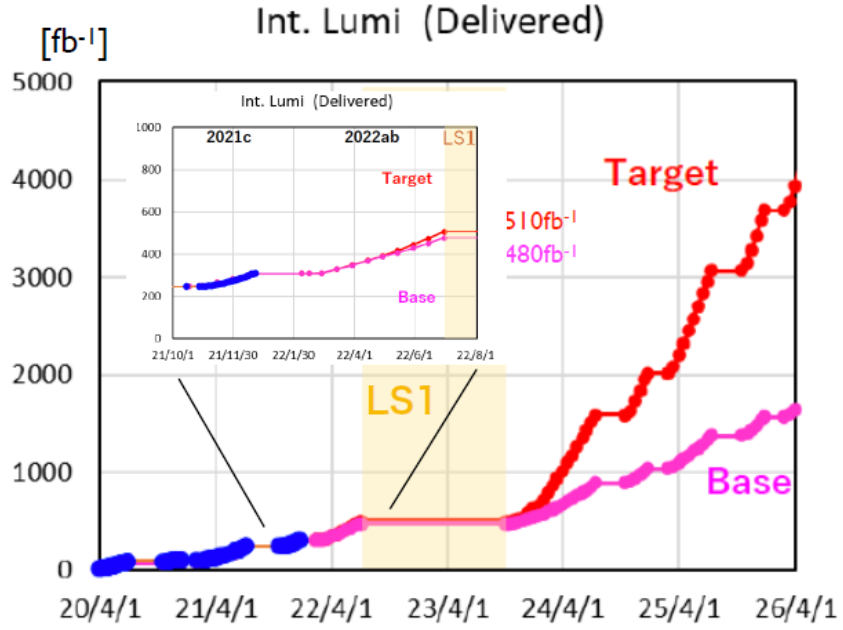
- Luminosity [$cm^{-2}\,s^{-1}$] = (event rate [s^{-1}]) / (cross-section [cm^{-2}])
  - ✓ performance of accelerator (~ ability of collision). $10^{34}\ cm^{-2}\,s^{-1} = 10\ nb^{-1}s^{-1}$
- Integrated luminosity = Luminosity × (operation time) = Data Size
  - ✓ $1\ ab^{-1} = 1000\ fb^{-1}$: total amount of Belle data in 10 year's operation.

Belle : 1999-2010 1040 fb^{-1}



Belle II 2019-2022

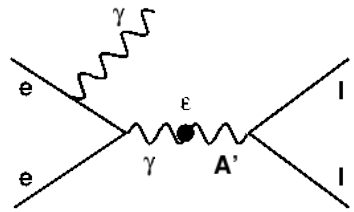
Belle II near term plan



(delayed from the original plan…)

Trigger

- "Trigger" initiates the data acquisition: only triggered events will be recorded.
- The main purpose of Belle II is the study of B meson decays.
  - ✓ $e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \rightarrow$ many (~10) particles
- Hadronic events ($B\bar{B}$ or $q\bar{q}$) are triggered with highest property, high efficiency.
  - ✓ e.g. events with many charged tracks, large energy deposit.
- Other events are triggered as far as the bandwidth is allowed.
  - ✓ Typical Dark Matter events are low multiplicity events.



Requirement of Belle II Trigger

- Maximum trigger rate 30 kHz
- ~100% efficiency for hadronic events.

Phase2 Lum. Record

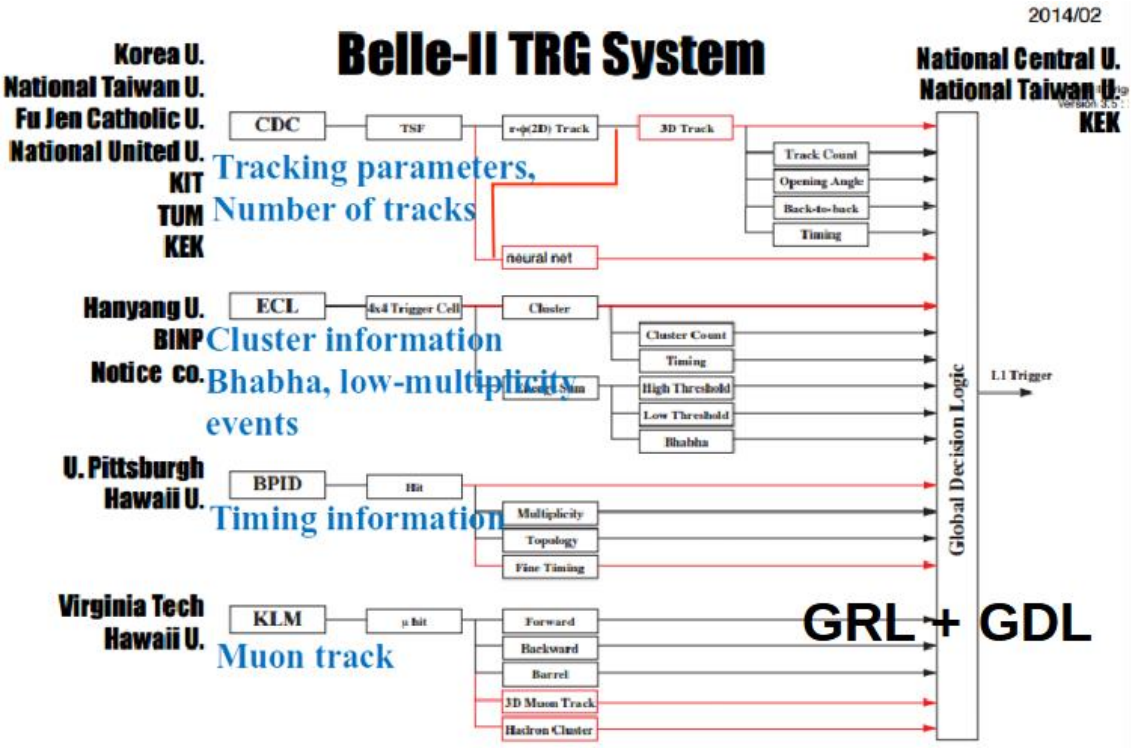
Process	C.S. (nb)	R@L=5.5x10^{33} (Hz)	R@L=8x10^{35} (Hz)	TRG logic
Upsilon(4S)	1.2	6.6	960	CDC 3trk(fff) ECL high energy(hie) ECL 4 clusters(c4)
Continuum	2.8	15.4	2200	
μμ	0.8	4.4	640	CDC 2trk(ffo) etc
ττ	0.8	4.4	640	
Bhabha	44	242	350 *	ECL Bhabha(bhabha, 3D bhabha)
γ-γ	2.4	13.2	19 *	
Two photon	13	71.5	10000	CDC 2trk(ffo) etc
Total	67	357.5	~15000	

Key Issue

- Suppress triggers from beam background, keeping efficiency for low-multiplicity (~dark) events.

Trigger

- Sub-trigger systems: CDC (tracking), ECL (calorimeter), TOP, KLM (muon).
- Global trigger systems: Global Reconstruction Logic (GRL), Global Decision Logic (GDL)



CDC trigger

- 2D: pt and ϕ (Hough transformation)
- 3D: cotθ and z0 (Fitting with Track Segment in stereo Super Layer).
- Neuro-3D: cotθ and z0 (with pre-trained neuros)

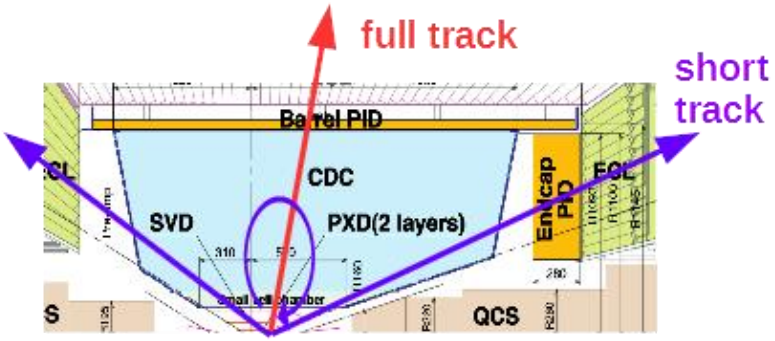
ECL trigger

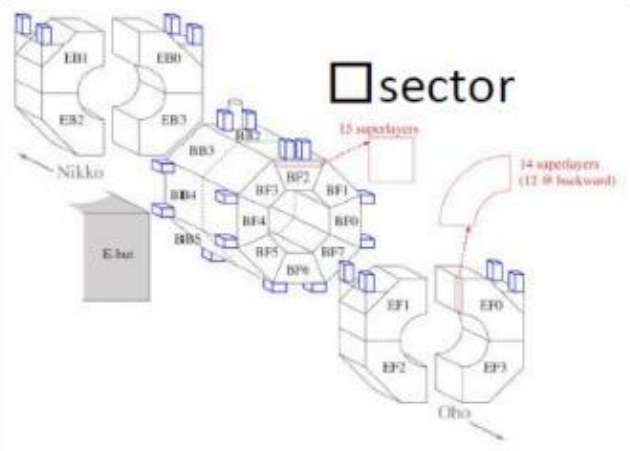
- Clustering output: to GRL. For matching purpose.
- Bhabha.
- Low-multiplicity (lml).
- Energy sum: e_high, e_low (hie, lowe).

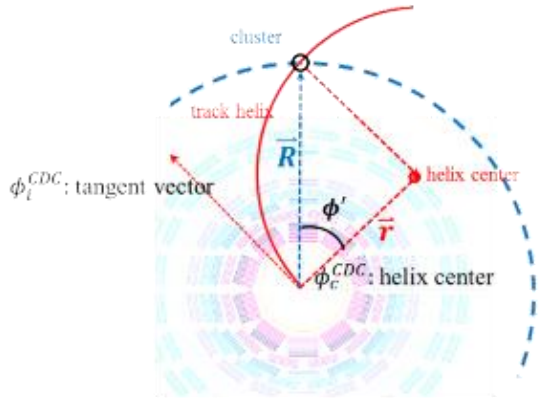
Trigger (GRL)

[Slides by Y.T.Lai]

- Short tracking: Pattern recognition with 5 SL.
  - Compensation to the full tracking from CDCTRG.
  - Extend the angular acceptance to endcap region.
- Matching:
  - CDC-ECL
  - CDC-KLM
  - ECL-EKLM







Trigger Menu for Dark Sector

[Slides by Y.T.Lai]

- ECLTRG Low-multilpicity (*lml*):
  - *lml0,12* for tau
  - *lml2* for ISR, ALP, (+..?) with wide θid
  - *lml6,7,13* for single photon (dark matter and dark photon etc.)
  - *lml8,9,10* for ALP and any back to back photon

- KLM bits,
  CDC-KLM (*cdcklm*),
  inner track - KLM (*ieklm*),
  ECL-EKLM matching (*eclekIm*):
  for muon related tau/dark e.g. $Z' \rightarrow \mu\mu$.

- Three-track (*fff*), two-track with opening angle > 90° (*ffo*),
  two-track with opening angle > 90° (*ff30*, prescaled) for Z'.

- Single-track-trigger (*stt*) with Neuro-3D requirement: Any charged track.
  For various tau/dark

Trigger

- Trigger logic is implemented in general-purpose Universal Trigger (UT) board.
- Upgrade from UT3 to UT4 to implement new tracking algorithm with more complicated logic (partially purchased with this budget).

~50% of UT3 boards in CDCTRG and global triggers have been upgraded.

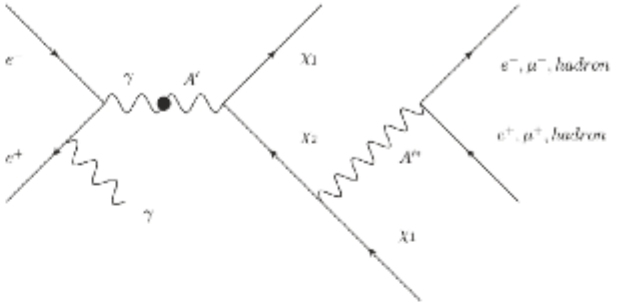
	Board	#	Status of using UT4	note	
Track-Segment-Finder	TSF	9	**Upgraded**		Used in present TRG for Belle II run
	2D	4	**Upgraded**		
	3D	4			
	NN	4	Preparing		
Event-Timing-Finder	ETF	1	**Upgraded**		
	GRL	1	Preparing		
	GDL	1	Installed. Preparing		
	New 2D	4	Installed. Preparing		Future plan: Not used for data taking yet
	3D Hough	4	Installed. Preparing		
	Displaced vertex	2	Preparing.		

UT3
Xilinx Virtex-6

UT4
Xilinx UltraScale

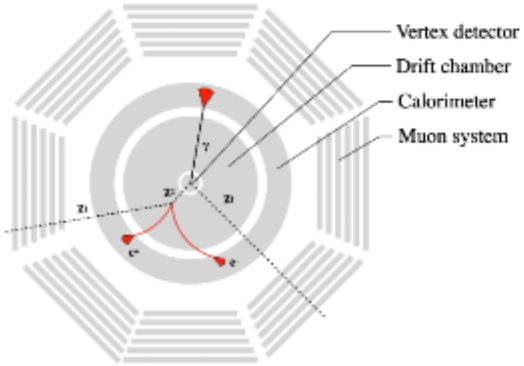
Plan: Displaced Vertex Tracking

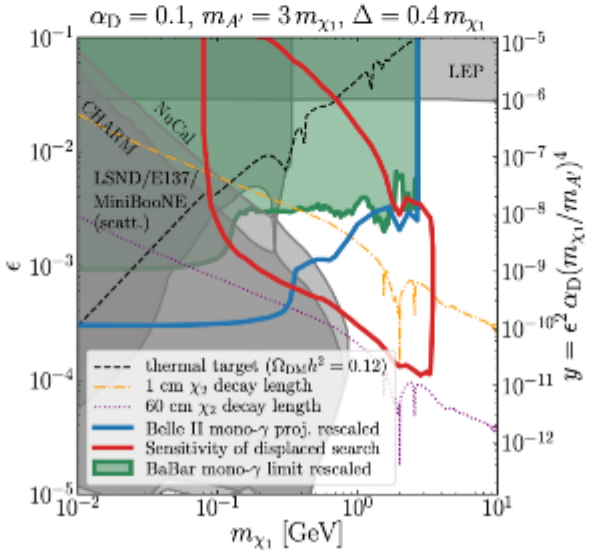
- For now, all the CDCTRG tracking is for IP-originated tracks.
- Inelastic dark matter models: pair of leptons from displaced vertices (+ photons)

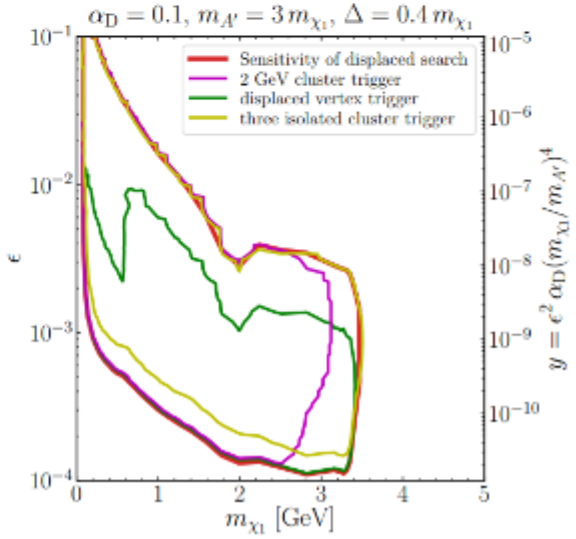


- Sensitivity from L1 TRG:
  - Mainly from gamma trigger. Displaced vertex trigger can enhance higher mass region.

[Slides by Y.T.Lai]

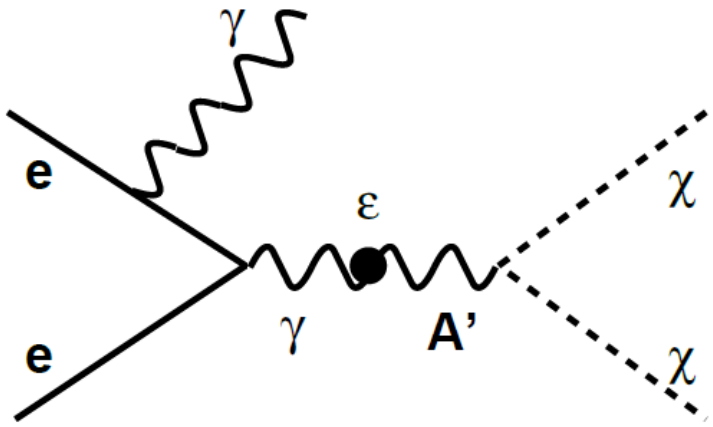






Invisible Mode

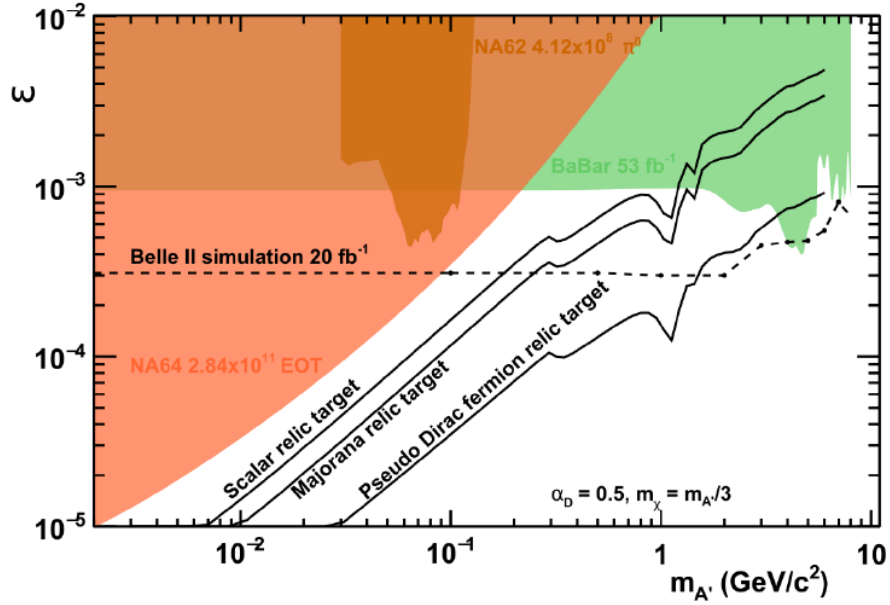
$e^+e^- \to \gamma$ + invisible



- Final state: a single photon only.
- Bump in a recoil mass or photon energy.
- Need special "single photon trigger" to collect such events.
  - ✓ Belle didn't have this trigger.
  - ✓ BaBar had it (for some period).
- Main background $e^+e^- \to \gamma\gamma(\gamma)$
  - ✓ Need understanding the detector.

On-going analysis at Belle II

Dark Photon A', SIMP (Strongly Interacting Massive Particle)…



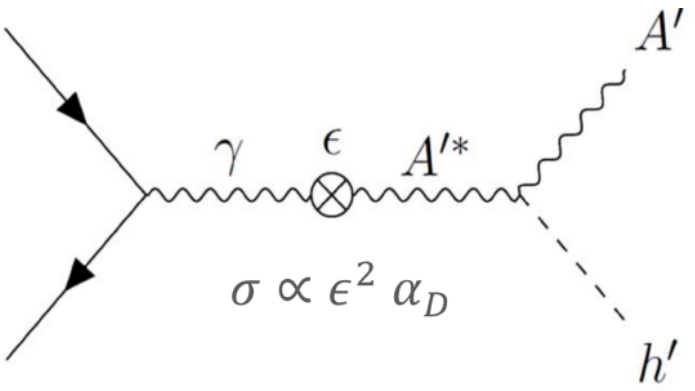
Still need more time to study.

Dark Higgsstrahlung

New result from Belle II using 8.34 fb^{-1}

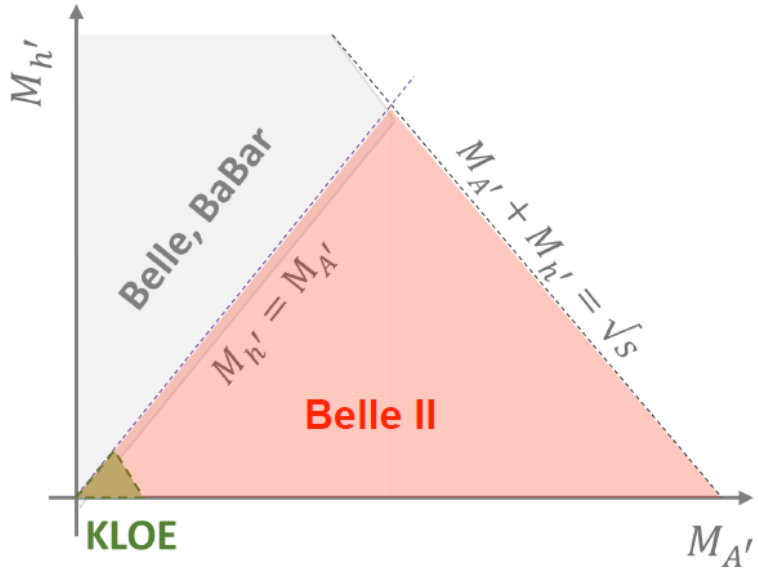
Next to minimal dark photon model

- Dark photon (A') couples to SM photon via kinetic mixing parameter ϵ
- A' mass can be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson (h') to the theory.
  Phys. Rev. D 79, 115008 (2009)
- No dark Higgs mixing with SM Higgs.
- Both particles can be produced via **dark Higgsstrahlung process**.



Mass hierarchy scenarios

- $m_{h'} > m_{A'}$: $h' \to A'A' \to 4\ell$, 4had, 2ℓ + 2had ⇒ 6 charged tracks
  Investigated by BaBar (2012) and Belle (2015).
- $m_{h'} < m_{A'}$: h' is long-lived and thus invisible ⇒ 2 charged tracks
  Partially constrained by KLOE (2015).

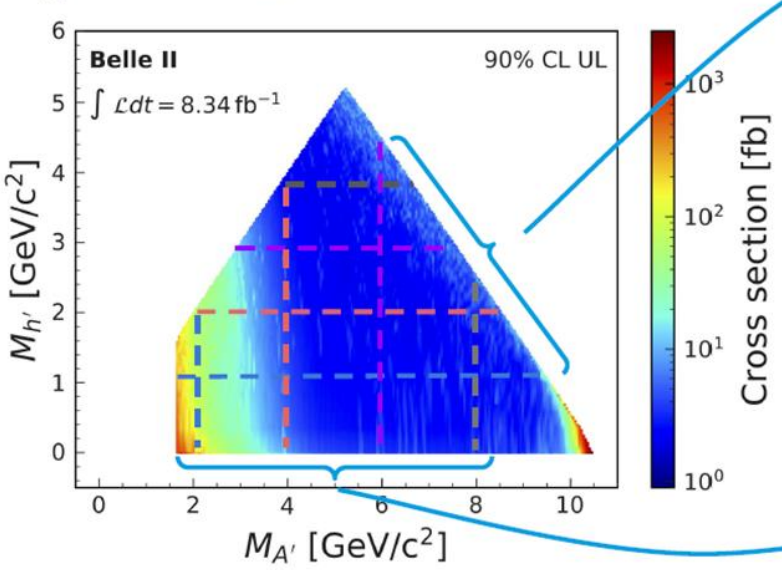


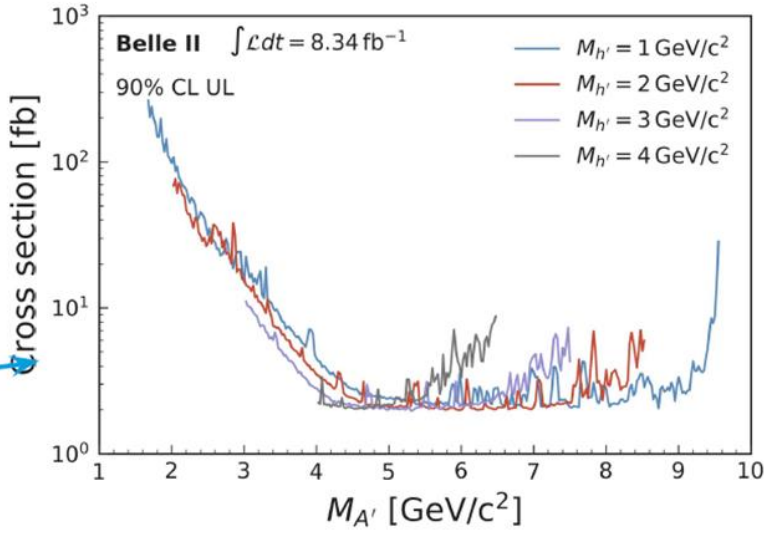
Exploring unconstrained territories at BelleII !

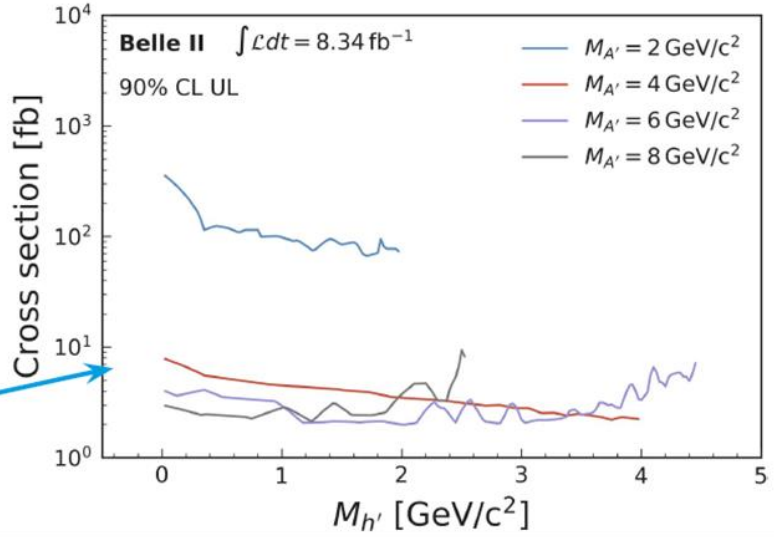
Dark Higgsstrahlung

[paper in preparation]

- Upper limits are set on σ and $\epsilon^2 \alpha_D$:
  - covered region: $1.65 < M_{A'} < 10.51$ GeV and $M_{h'} < M_{A'}$
  - **90% CL UL on σ ranges from 1.7 to 5 fb**
    - in the most sensitive regions ($4 < M_{A'} < 9.7$ GeV)
  - for $M_{A'} < 4$ GeV: low sensitivity due to trigger efficiency
  - for $M_{A'} > 9$ GeV: large dimuon background







⇒ World-leading results, in previously unexplored regions!

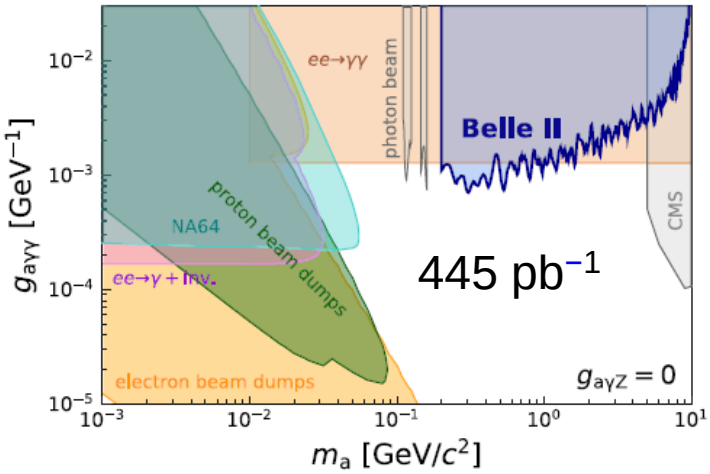
Searches at Belle (II)

Recent or on-going searches at Belle (II)

1st Belle II paper

2nd Belle II paper

- $e^+e^- \to \gamma A'(\to \text{invisible})$ [on-going at Belle II]
- $Z' \to$ invisible [PRL124 (2020), 141801]
- $Z' \to \mu^+\mu^-$ [arXiv:2109.08596 (Belle)] ◆
- ALP (Axion Like Particle) $e^+e^- \to a(\to\gamma\gamma)\,\gamma$ [PRL125 (2020), 161806]
- Dark Higgsstrauhlung $e^+e^- \to A'(\to\mu^+\mu^-)\,h'(\to\text{invisible})$
- Dark Matter etc. from B (or Υ) decays.
  - ✓ $B^0 \to A'\,A'$: dark photon [JHEP 04 (2021) 191]
  - ✓ $B \to \Lambda\psi_{DS}$ [PRD 105 (2022) L051101 (Belle)]
  - ✓ $B \to K\,S\,(\to \text{leptons})$: dark scalar
  - ✓ $B \to K\,a\,(\to\gamma\gamma)$: ALP search
  - ✓ $B \to K\,a\,(\to \text{hadrons})$: heavy QCD axion ◆
  - ✓ $\Upsilon(1S) \to \gamma$ + invisible : light Higgs [PRL 128, 081804 (2022) (Belle)]
- Search for long-lived particles (dark Higgs).

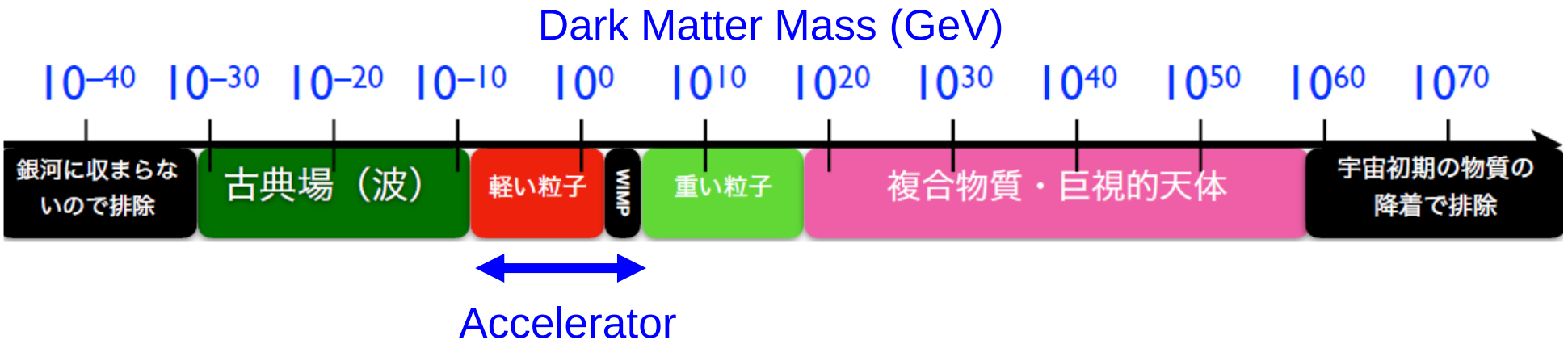


◆ = later talks.

E. Waheed is also working for it

Backup

Dark Matter Search @Accelerator



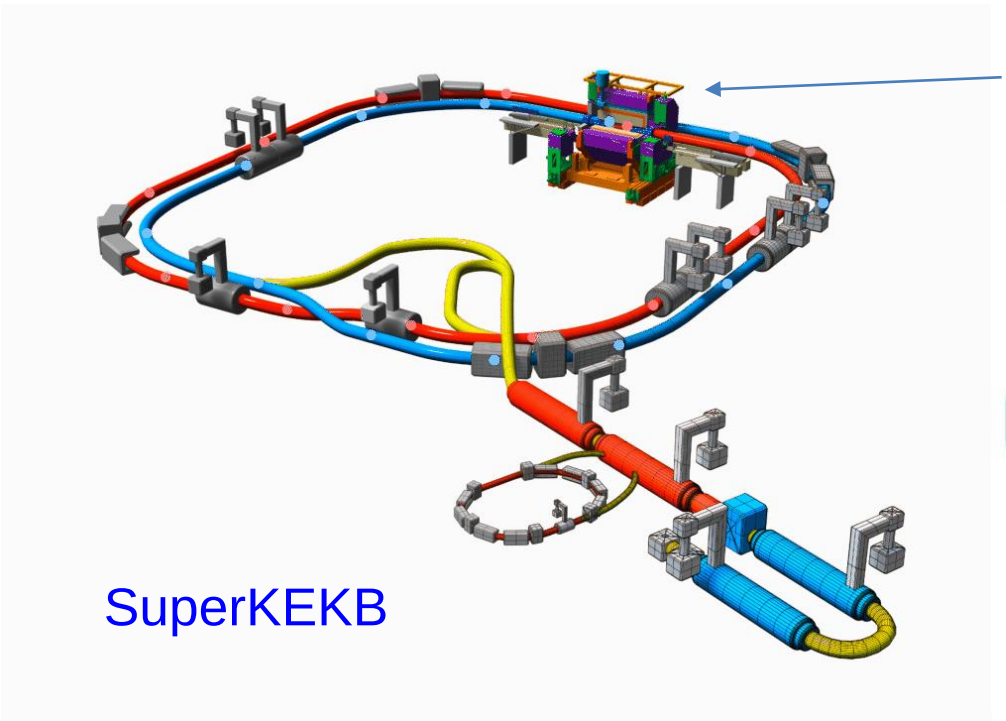
e^+e^- collider

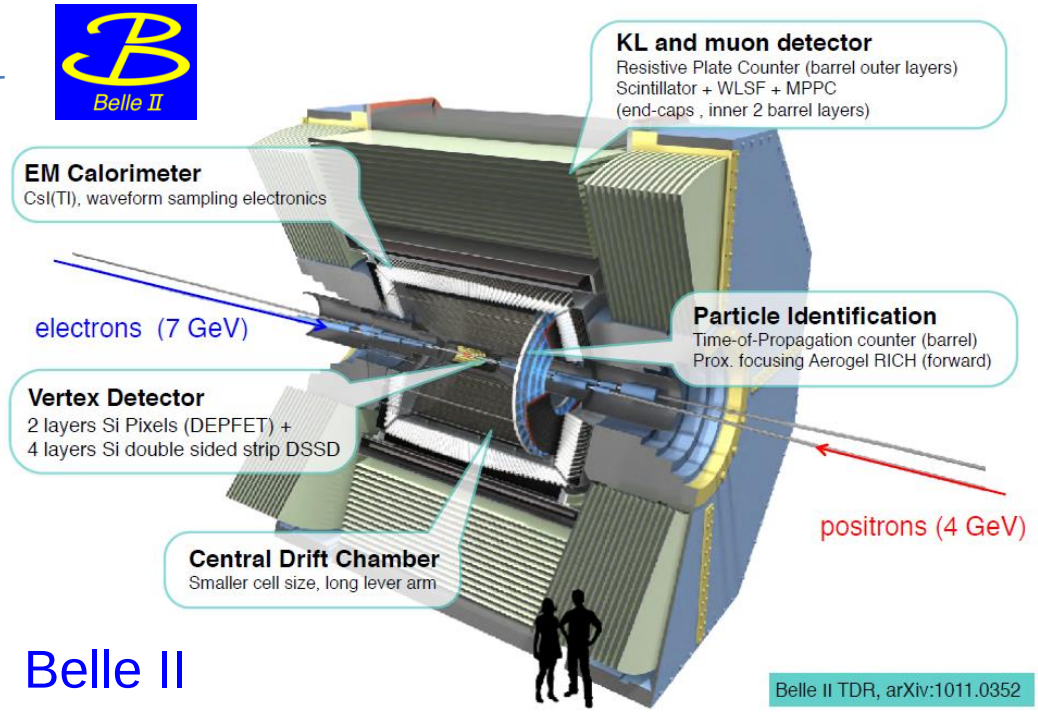
- KLOE, BaBar, Belle, Belle II
- ~ 10 GeV : sub GeV region
- Clean environment
  - ✓ missing energy → invisible channels.
- (ILC 250 GeV … future)

hadron collider

- LHC (ATLAS, CMS, LHCb)
- ~ 10 TeV : WIMP search
- Also search to sub GeV region (competitive)
  - ✓ large cross section.

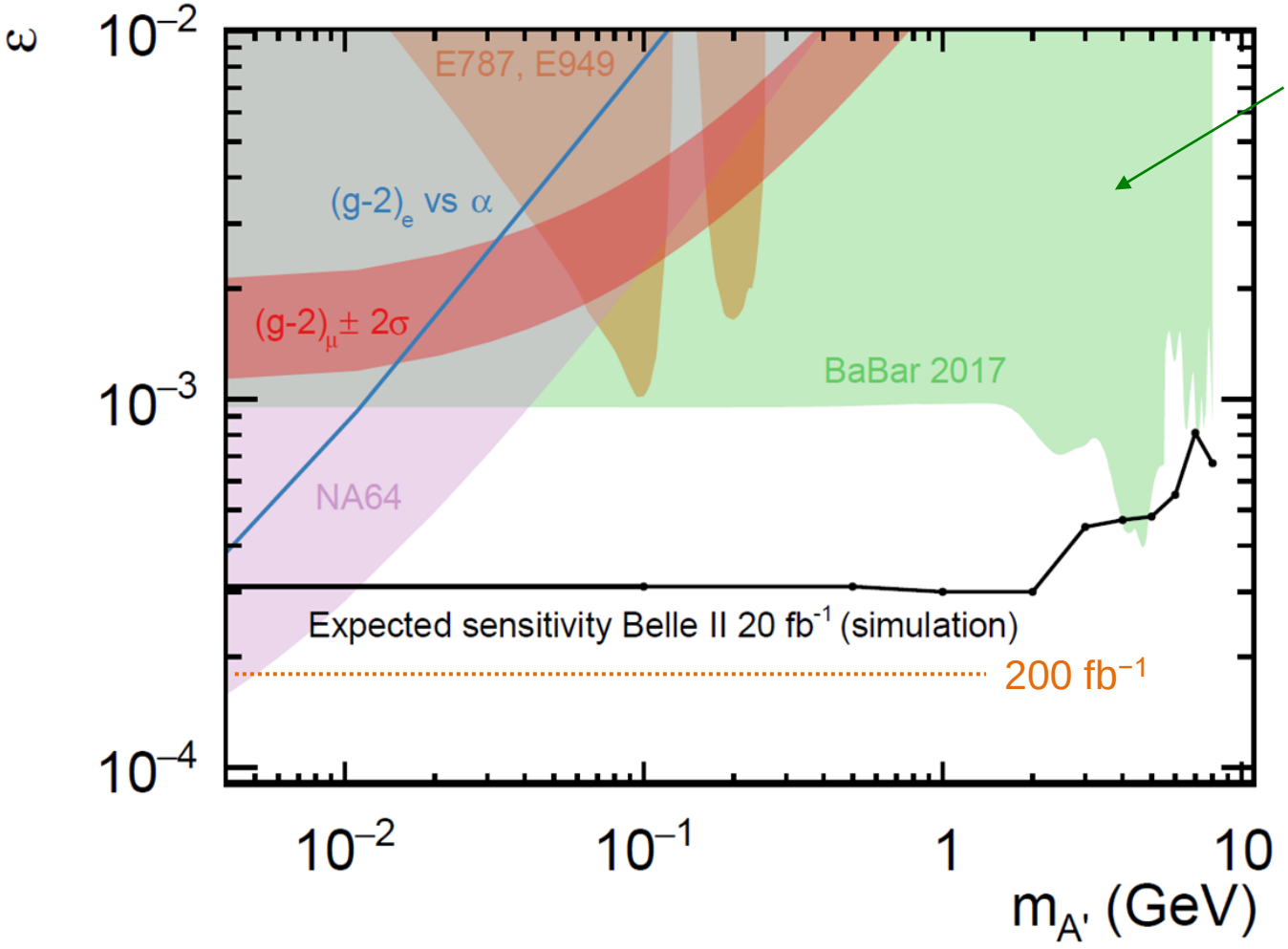
Belle II @ SuperKEKB





- Belle II experiment at KEK: flavor physics experiment, successor of Belle.
- SuperKEKB Asymmetric electron-positron collider: 4 GeV e^+ + 7 GeV e^-.
- Nano beam scheme to achieve high luminosity.
- Operation with full detector started in 2019.
- Luminosity $3.8 \times 10^{34}\ cm^{-2}\ s^{-1}$ achieved so far (aiming one order higher).
- Plan to accumulate 50 ab^{-1} in ~10 years (50 times of Belle).

Invisible Mode



BaBar experiment (53 fb^{-1}) [PRL 119 131804 (2017)]

- ✓ Single photon trigger is available for 53 out of 550 fb^{-1}

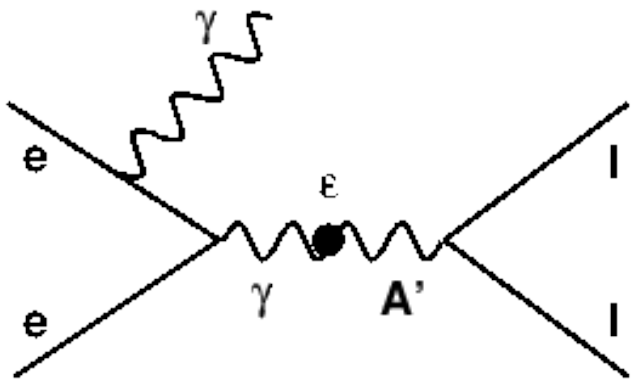
- Belle didn't have a single photon trigger.

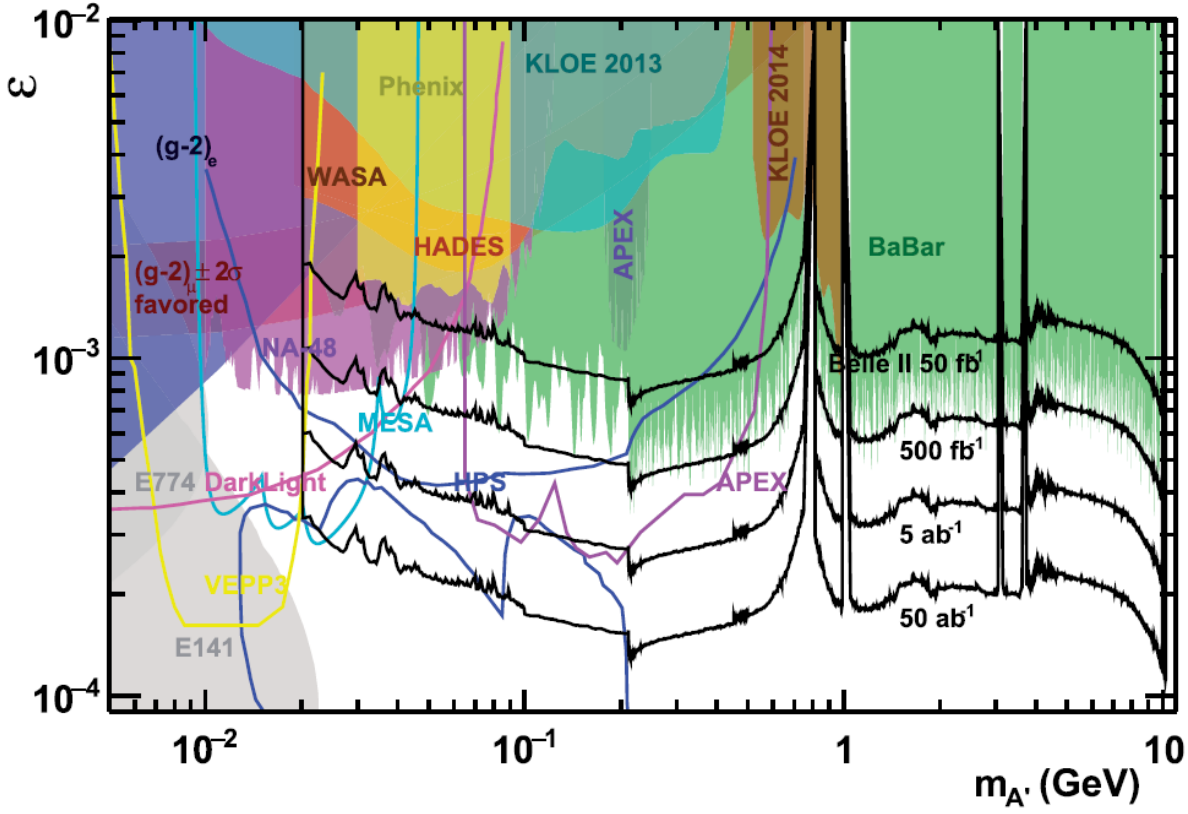
- Better limit is expected at Belle II with 20 fb^{-1} (due to detector configuration).
- Need good understanding of the detector.

Leptonic Mode

If m(A') < 2m(χ), A' decays to SM particles.

- e.g. $e^+e^- \to \gamma A'$, $A' \to l^+l^-$ ($l = e, \mu, \tau$)





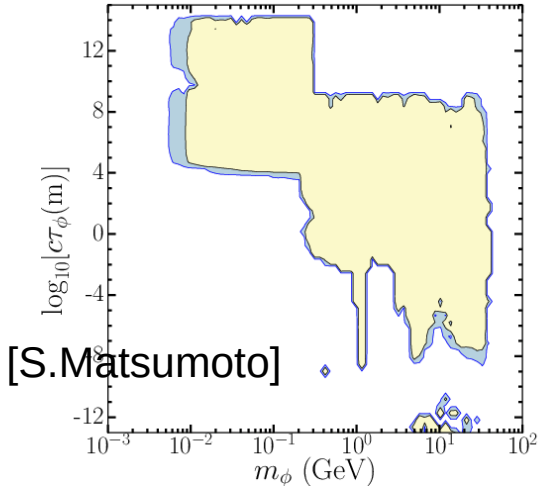
- Best limit in 0.1 – 10 GeV by BaBar [PRL 113, 201801 (2014)]
- Some analyses are going on at Belle II, but need more data.
  - ✓ Best sensitivity by Belle II within a few years.
- Competition with LHCb.

Dark Matter Search at Belle II

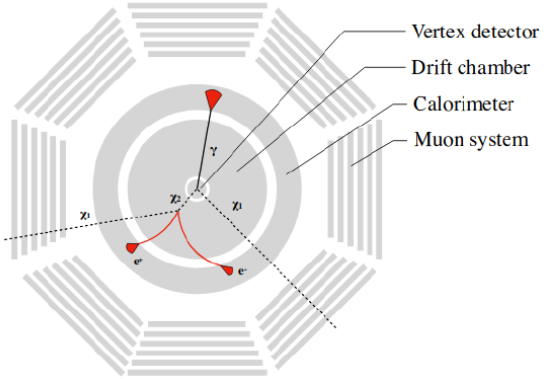
Target	Process	Mass Range (GeV)
SIMP / Dark Photon (A')	$e^+e^- \to A'\gamma,\ A' \to$ invisible	$m_{A'} < 10$
SIMP / Dark Photon (A')	$e^+e^- \to A'\gamma,\ A' \to \ell^+\ell^-, h^+h^-$	$0.1 < m_{A'} < 10$
Dark gauge boson (Z')	$e^+e^- \to Z'\mu^+\mu^-,\ Z' \to \mu^+\mu^-$	$0.2 < m_{Z'} < 10$
Dark gauge boson (Z')	$e^+e^- \to Z'\mu^+\mu^-,\ Z' \to$ invisible	$m_{Z'} < 10$
Axion (a)	$e^+e^- \to \gamma a,\ a \to \gamma\gamma$	$m_a < 10$
A' and Dark Higgs (h')	$e^+e^- \to A'h',\ A' \to \ell\ell,\ h' \to$ invisible	$m_{A'} + m_{h'} < 10$
Dark Scaler (S)	$B \to KS,\ S \to \gamma\gamma$	$m_a < 10$
Light WIMP (ϕ)	$B \to K\phi$ (ϕ は long-lived)	$m_a < 3$
Dark Photon (A')	$D^{*0} \to D^0 A',\ A' \to e^+e^-$	$0.01 < m_{A'} < 0.1$
Dark Photon (A')	$\Upsilon(2S,3S) \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(1S) \to A'\gamma,\ A' \to$ invisible	$m_{A'} < 10$

- Production at e^+e^- collision.
- Decay of B, D*, Υ mesons, which are largely produced at Belle II.
- Displaced vertex (long lived particles)

- Many search processes.
- Close discussion with theorists.



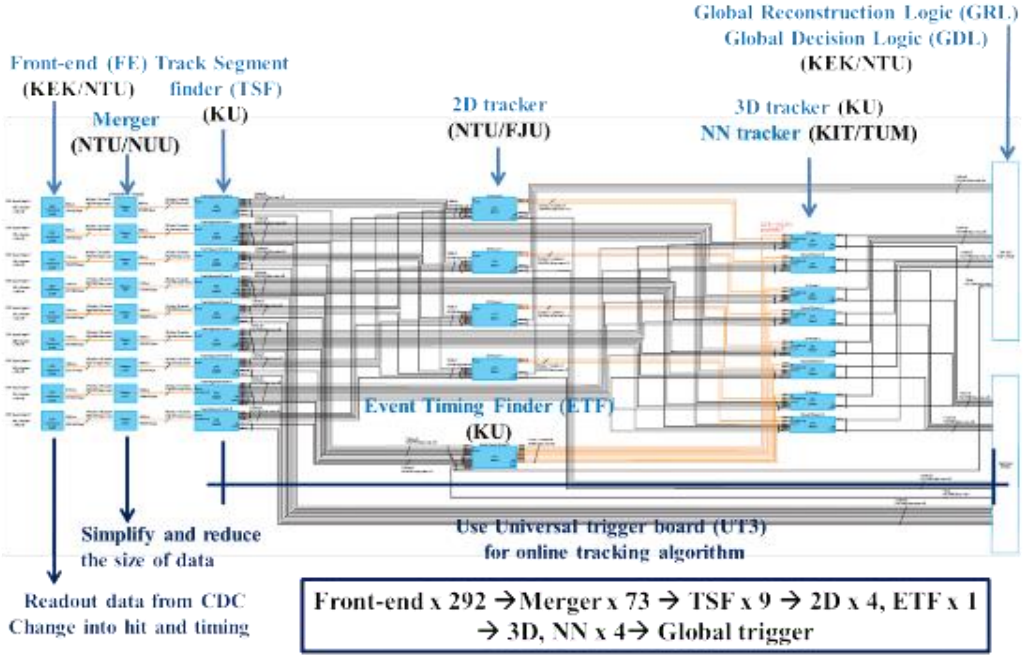
[S.Matsumoto]

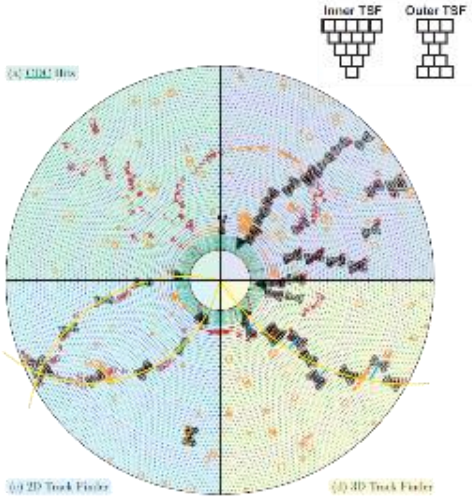


CDC Trigger

- TSF in each SL: Basic element of tracking in L1.
  - 2D: Hough transformation. pt and ϕ.
  - 3D: Fitting with TS in stereo SL. cotθ and z0.
  - Neuro-3D: with pre-trained neuros. cotθ and z0.
- GRL: Master of CDCTRG, making summary to GDL.

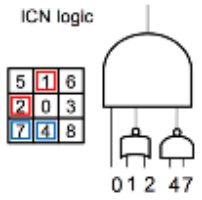
[Slides by Y.T.Lai]



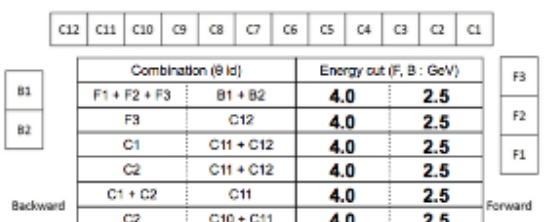


ECL Trigger

- ECLTRG information:
  - Clustering output: to GRL. For matching purpose.
  - Bhabha.
  - Low-multiplicity (lml).
  - Energy sum: e_high, e_low (hie, lowe).

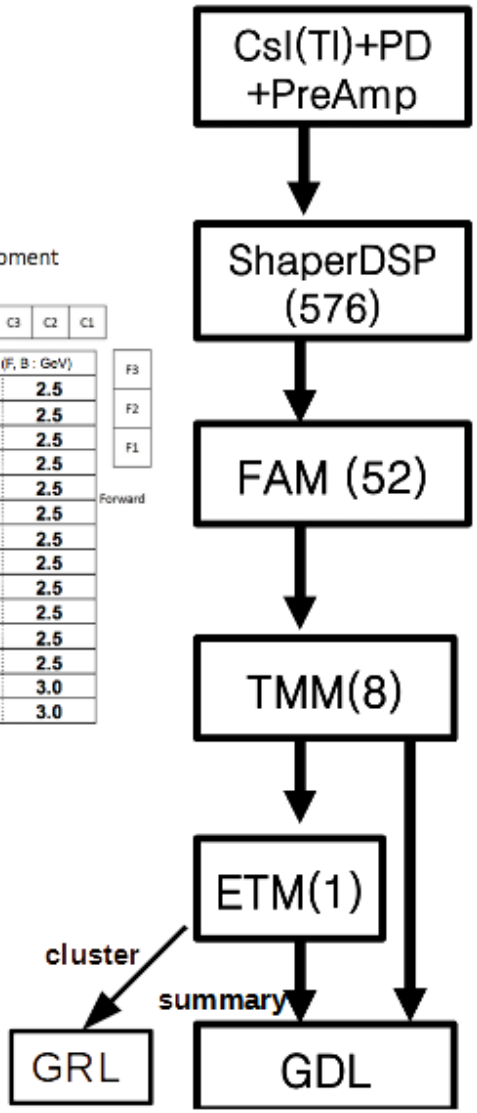


ϕ-ring combinations in Belle II enviroment



Combination (θ id)		Energy cut (F, B : GeV)	
F1 + F2 + F3	B1 + B2	4.0	2.5
F3	C12	4.0	2.5
C1	C11 + C12	4.0	2.5
C2	C11 + C12	4.0	2.5
C1 + C2	C11	4.0	2.5
C2	C10 + C11	4.0	2.5
C2	C9 + C10	4.0	2.5
C2 + C3	C10	4.0	2.5
C2 + C3	C9	4.0	2.5
C3 + C4	C9	4.0	2.5
C3 + C4	C8	4.0	2.5
C4 + C5	C8	4.0	2.5
C5	C7 + C8	3.0	3.0
C5 + C6	C6 + C7	3.5	3.0

(lmlδ in GDL)	meaning
0	(NCL $\geq$ 3, at least 1 CL $\geq$ 300 MeV(Lab)) (with θ_{id} = 1 ~ 17), not an ECL 3D Bhabha
1	one CL $\geq$ 2 GeV(CM) with θ_{id} = 4 ~ 14
2	one CL $\geq$ 2 GeV(CM) with θ_{id} = 2, 3, 15 or 16 and not an ECL 3D Bhabha
3	one CL $\geq$ 2 GeV(CM) with θ_{id} = 2, 3, 15 or 16 and an ECL 3D Bhabha
4	one CL $\geq$ 2 GeV(CM) with θ_{id} = 1 or 17 and not an ECL 3D Bhabha
5	one CL $\geq$ 2 GeV(CM) with θ_{id} = 1 or 17 and an ECL 3D Bhabha
6	only one CL $\geq$ 1 GeV(CM) with θ_{id} = 4 ~ 15 and no other CL $\geq$ 300 MeV(Lab) anywhere
7	only one CL $\geq$ 1 GeV(CM) with θ_{id} = 2, 3, or 16 and no other CL $\geq$ 300 MeV(Lab) anywhere
8	170° < $\Delta\phi_{CM}$ < 190°, both CL > 250 MeV(Lab), no 2GeV(CM) CL in an event
9	170° < $\Delta\phi_{CM}$ < 190°, one CL < 250 MeV(Lab), the other CL > 250 MeV(Lab), no 2GeV(CM) CL in an event
10	160° < $\Delta\phi_{CM}$ < 200°, 160° < $\Sigma\theta_{CM}$ < 200°, no 2GeV(CM) CL in an event
11	No 2GeV(CM) CL in an event
12	(NCL $\geq$ 3, at least 1 CL $\geq$ 500 MeV(Lab)) (with θ_{id} = 2 ~ 16), not an ECL 3D Bhabha
13	only one CL $\geq$ 0.5 GeV(CM) with θ_{id} = 6 ~ 11 and no other CL $\geq$ 300 MeV(Lab) anywhere

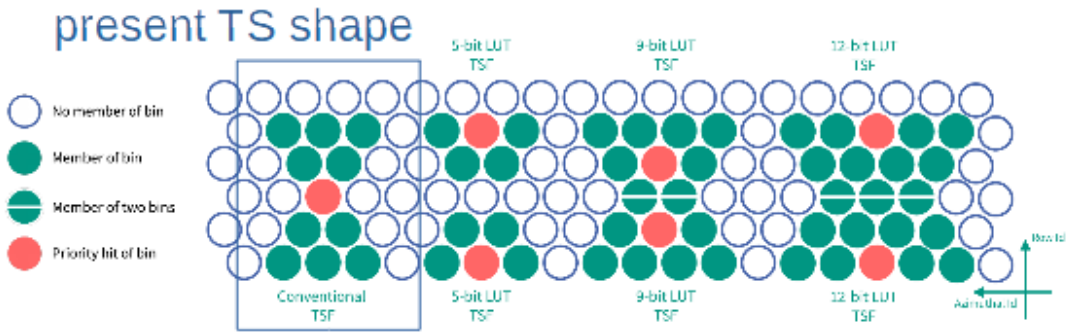


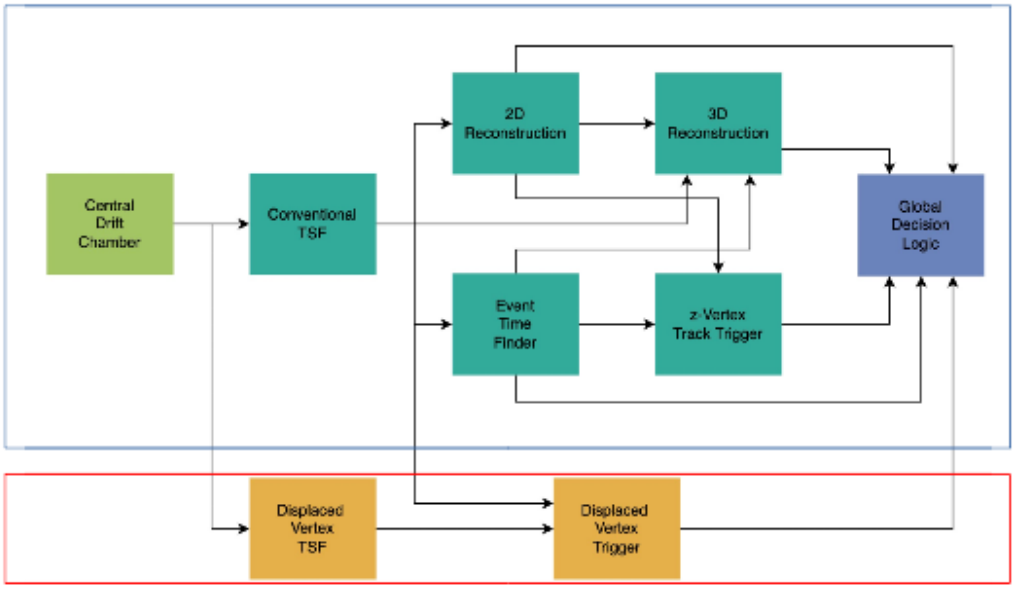
[Slides by Y.T.Lai]

Plan: Displaced Vertex Tracking

- Track Segment (TS) shape: wider → larger memory in FPGA for LUT→ UT4

[Slides by Y.T.Lai]

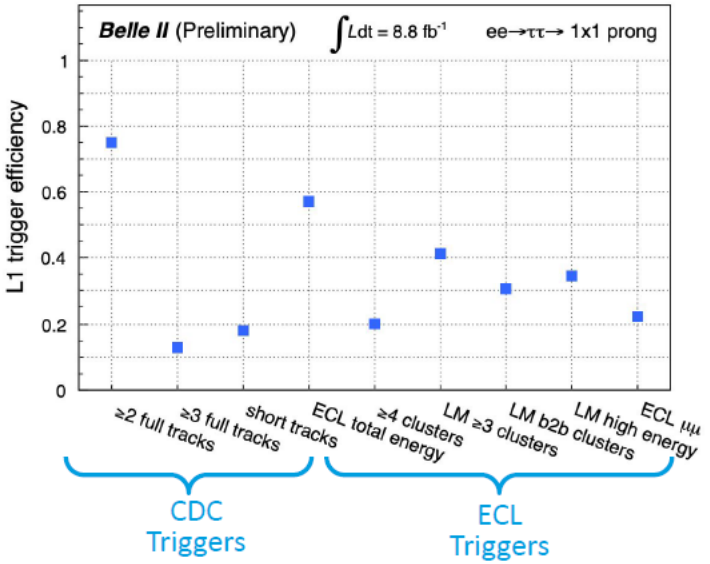


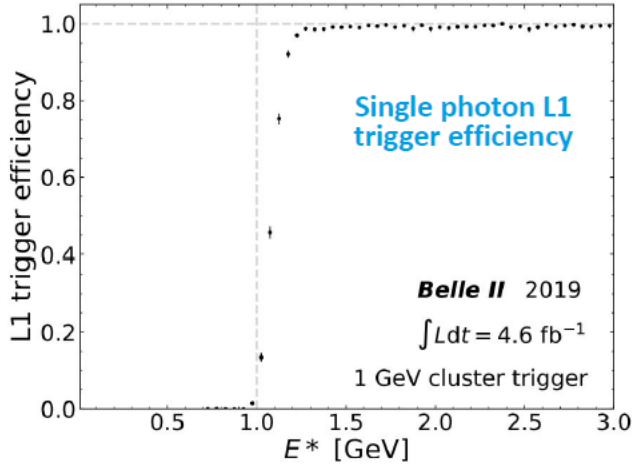


Trigger Performance

Trigger performance

- essential for dark-sector and tau physics
  - typical signatures include low-multiplicity of tracks, and ECL clusters…
  - large background from radiative Bhabha and $e^+e^- \to \gamma\gamma$
- some of the dedicated low-multiplicity triggers:
  - single muon
    - combine CDC and KLM information
  - single track:
    - neural-net based hardware trigger
  - single photon:
    - high efficiency for E(γ) > 1 GeV

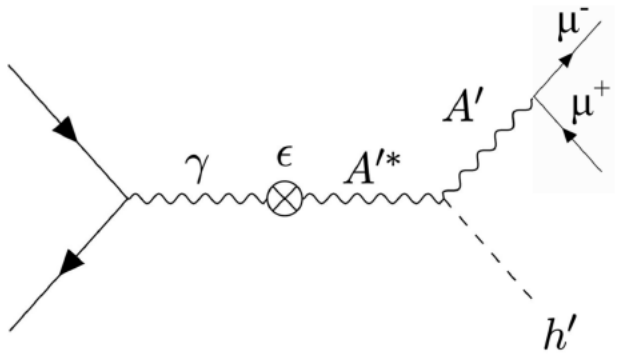




Dark Higgsstrahlung

Analysis Strategy

Data sample: 2019 dataset ⇒ 8.34 fb-1

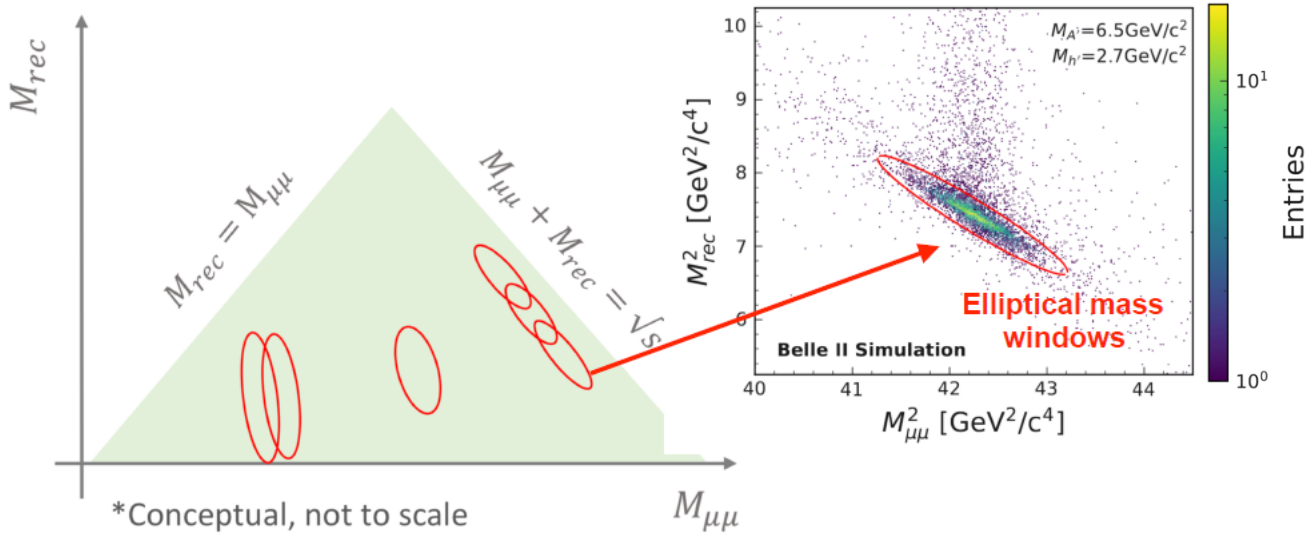


Detector signature

- Looking for invisible h' with $A' \rightarrow \mu^+\mu^- \Rightarrow$ μμ + missing energy
- 2D peak in in $M_{\mu\mu}$ vs M_{rec}
  M_{rec} = invariant mass of the system recoiled against μμ.

Search strategy:

- $M_{\mu\mu}$ & M_{rec} are correlated ⇒ search in tilted elliptical mass windows
- Spacing α M^2 resolution in the two directions
- ~9000 overlapping windows (large look-elsewhere effect)
- Bayesian counting technique (on average, 1 event in ~3 windows)

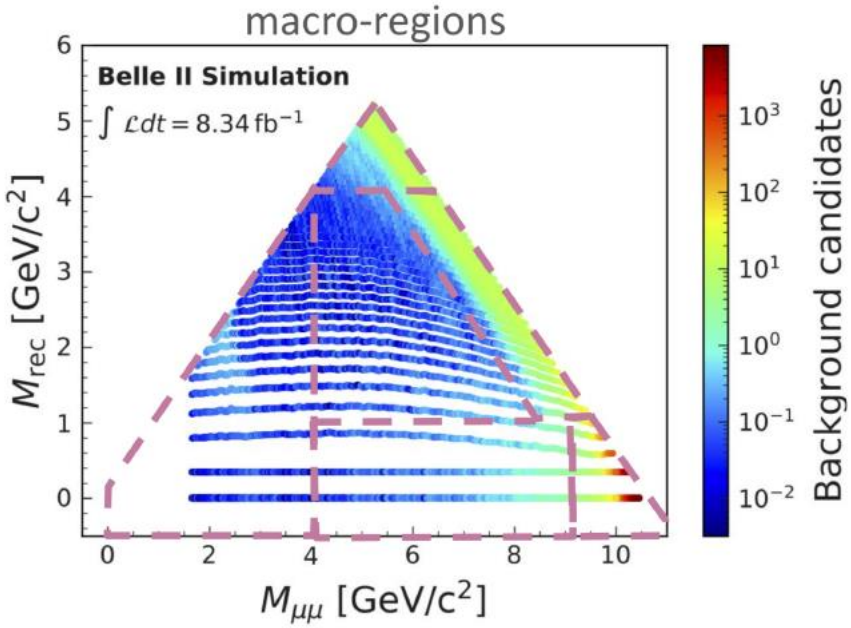


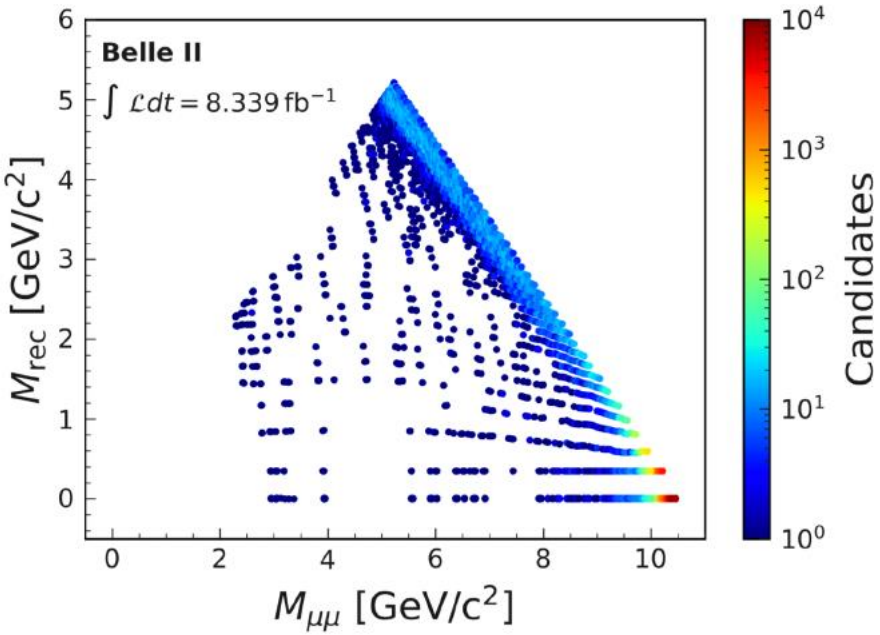
Dark Higgsstrahlung

- Event counts in a single window interpreted as:

$$N = \epsilon_{sig} \times L \times \sigma_{DH} + B$$

with systematic uncertainties taken into account.

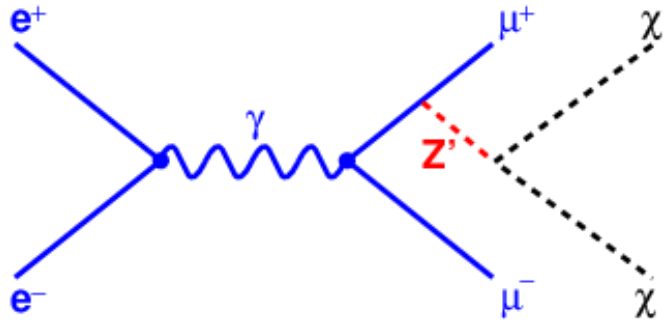


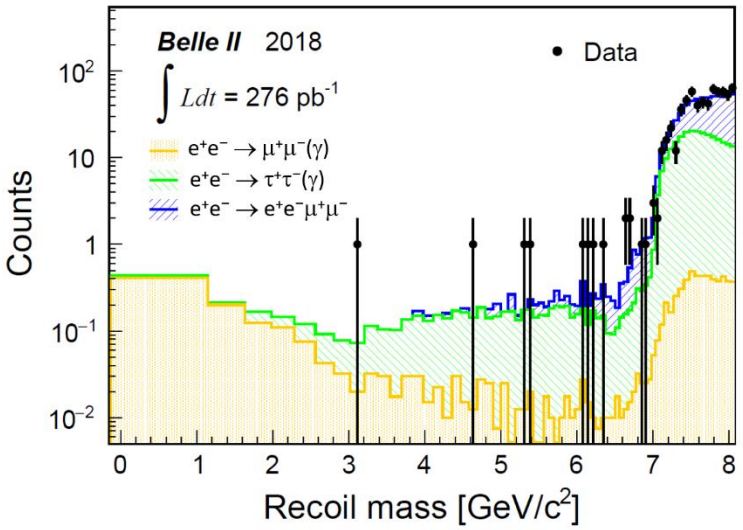


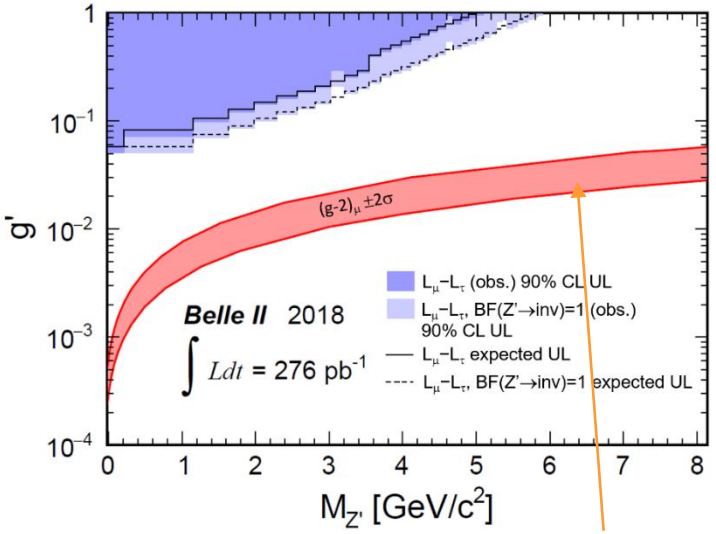
Search for Z' at Belle II

First Belle II result: Search for Z' → invisible [PRL124 (2020), 141801]

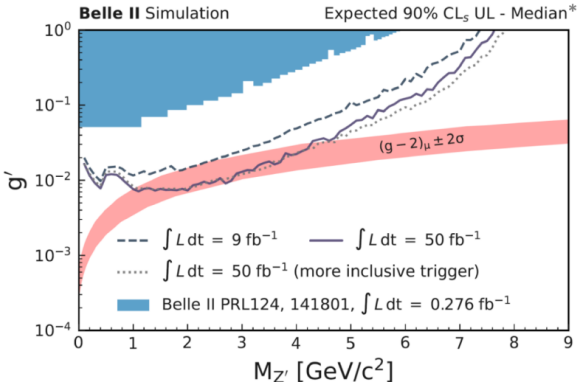
- New light neutral gauge Z' boson which couples to μ and τ lepton ($L_\mu - L_\tau$ model) [PRD 89, 113004]
- Can solve the deviation of $(g-2)_\mu$, and other anomalies seen in flavor physics ($B \to K^{(*)}\mu\mu$).







Simulation



Limits on the coupling g' even with small amount of data from commissioning run.

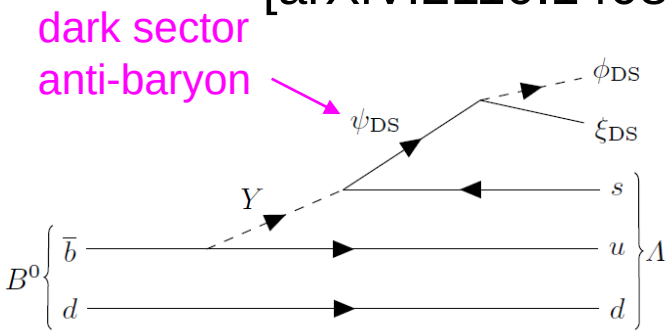
not updated with the latest $(g-2)_\mu$ result (but the change is small)

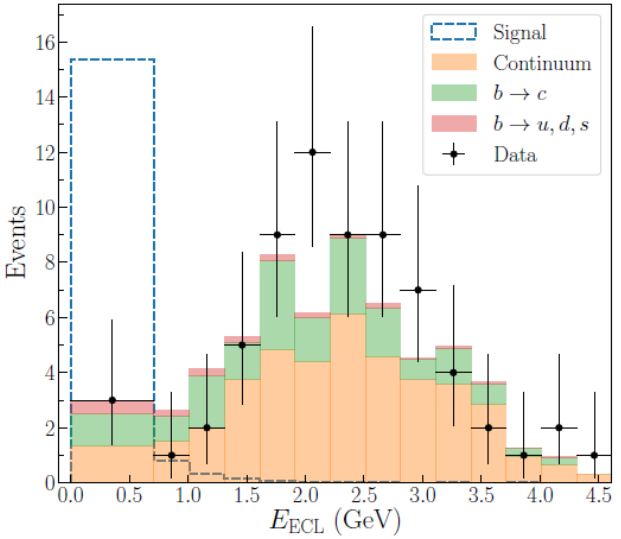
Analysis with ~100 /fb data is going on. Will reach to $(g-2)_\mu$ band.

$B^0 \to \Lambda \psi_{DS}$ at Belle

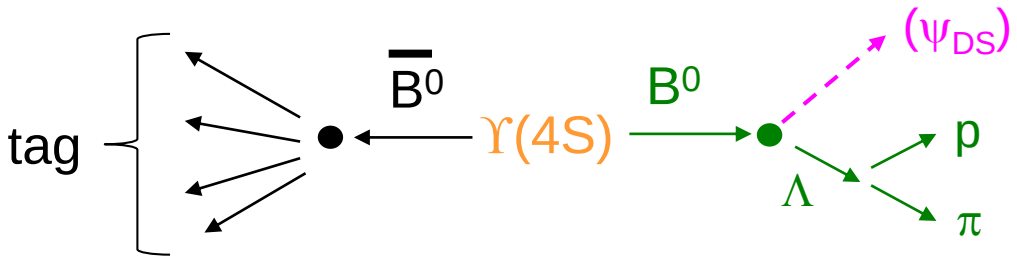
- B-Mesogenesis: explain Baryogenesis and DM with B decay [Elor,Escudero,Nelson PRD99,035031 (2019)]
- Robust prediction $B(B^0 \to \Lambda\ \psi_{DS}$ +meson) > 10^{-4}
- Experimental limit
  - ✓ $B(B^0 \to \Lambda\psi_{DS}) < 2\times10^{-4}$ by ALEPH [EPJC19,213 (2001)]
  - ✓ $m(\psi_{DS})$<3.5 GeV from CMS [JHEP 1910, 244] and ATLAS [JHEP 2102, 143].
- Search $B^0 \to \Lambda\ \psi_{DS}$ at Belle with 711 fb^{-1} data.
  - ✓ Reconstruct one B with hadronic mode.
  - ✓ Reconstruct Λ in the signal side and look at E_{ECL} (remaining energy in the event)

[arXiV:2110.14086]





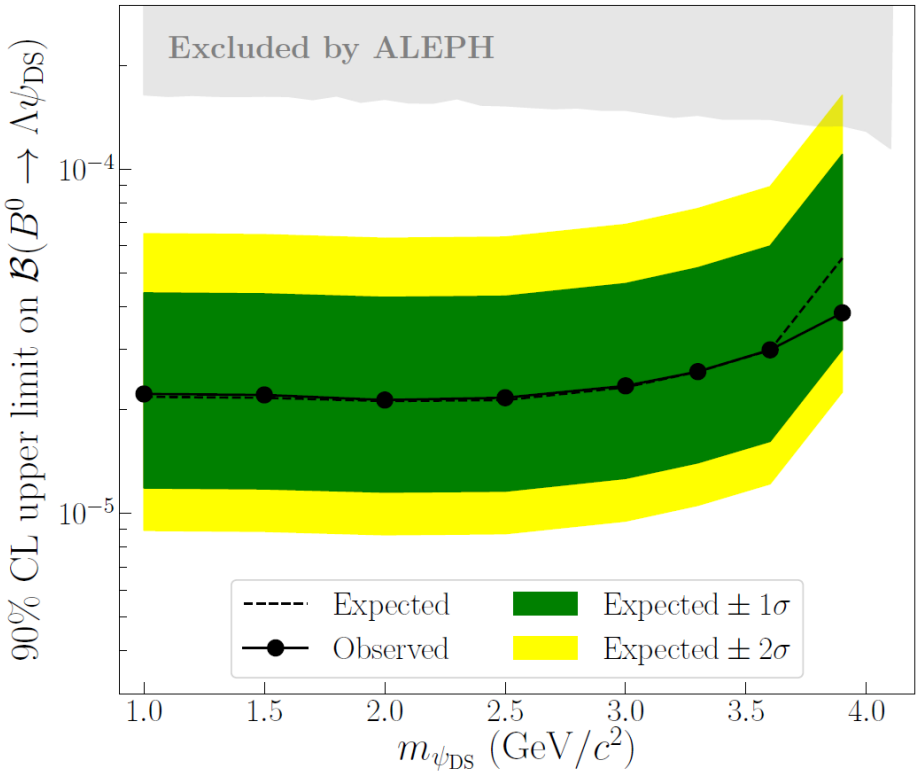
Signal assumes $m(\psi_{DS})$=2.5 GeV and $B(B^0 \to \Lambda\psi_{DS}) = 8\times10^{-5}$



$B^0 \to \Lambda\psi_{DS}$ at Belle

- No signal. Upper limit of $B(B^0 \to \Lambda\psi_{DS}) < (2\text{-}4) \sim 10^{-5}$ is set. [arXiV:2110.14086]
  - ✓ Prediction of B-Mesogenesis: $B(B^0 \to \Lambda + \psi_{DS} + \text{meson}) > 10^{-4}$

90% upper limit of $B(B^0 \to \Lambda\psi_{DS})$



Lower bounds on $B(B^0 \to \Lambda\psi_{DS})$
(prediction from PRD104, 035028)