Dark Matter Search with e^+ e^- collider: B05 Status Report

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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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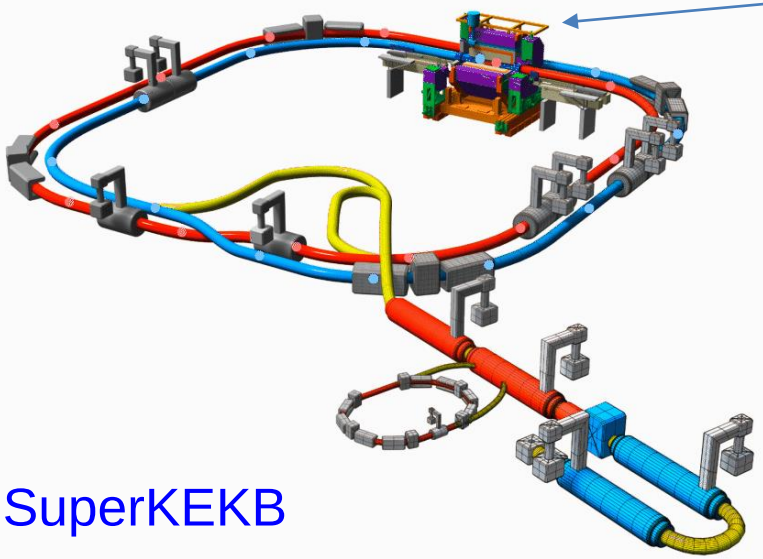
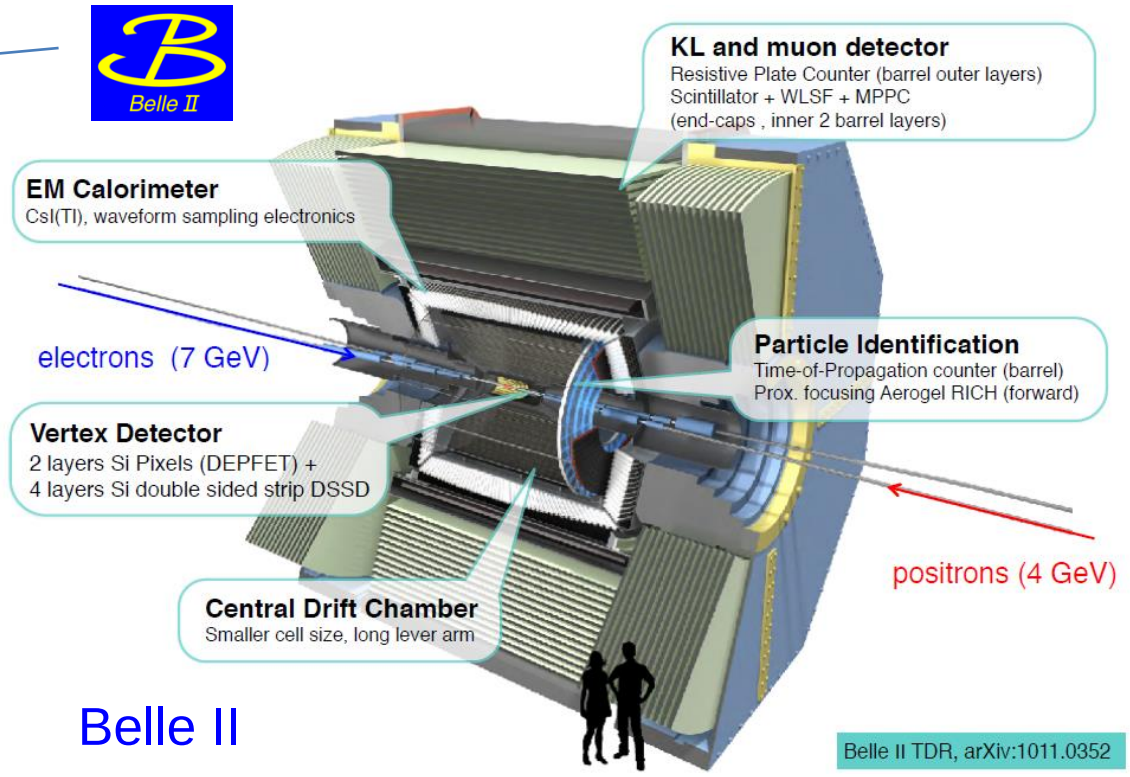
SuperKEKB and Belle II



SuperKEKB



$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

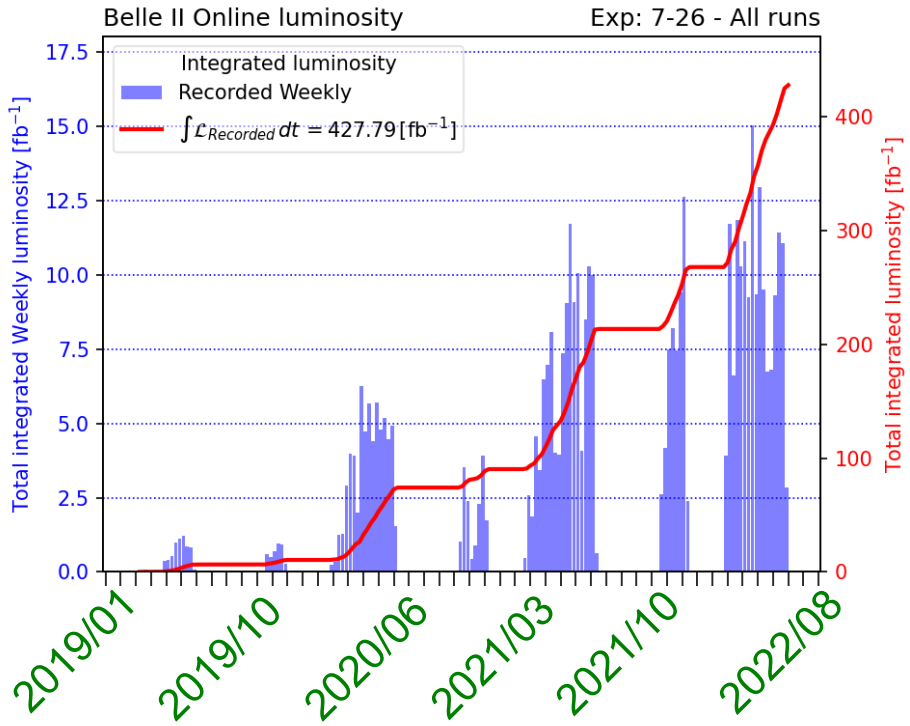
Belle II

- 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.
- General purpose Belle II detector.
  - ✓ Key components: vertex detector, particle identification.

SuperKEKB and Belle II

- Operation with full detector started in 2019.
- Luminosity $4.7 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ achieved (Jun 8, 2022).
  - ✓ World record (~ ×2 of KEKB)
  - ✓ Aiming one order higher.
- 424 $\mathrm{fb^{-1}}$ of data accumulated so far.
  - ✓ Belle: 1 $\mathrm{ab^{-1}}$ (= 1000 $\mathrm{fb^{-1}}$) in 11 years' operation.
  - ✓ Belle II target: O(10) of Belle.

$1\ \mathrm{ab^{-1}} \sim 10^9\ B\bar{B}$

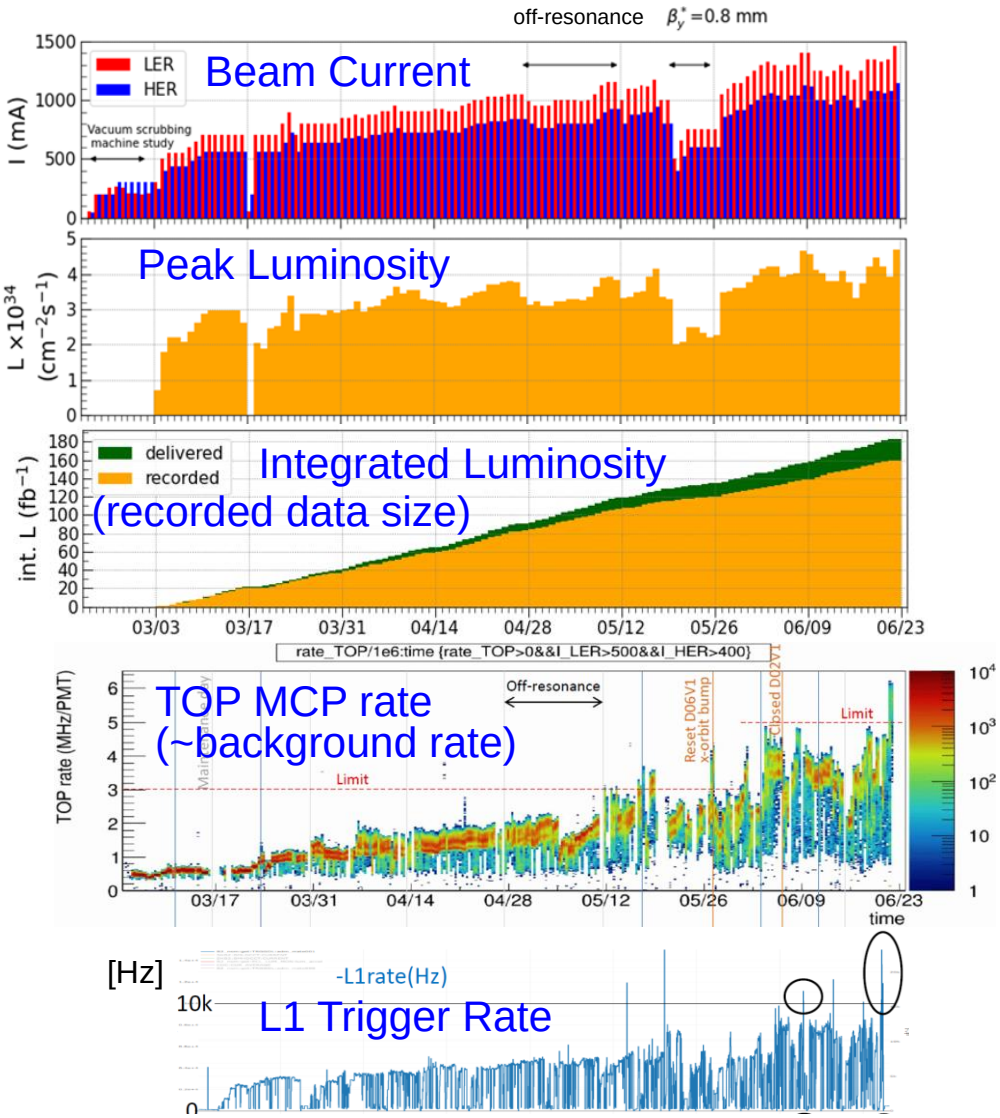


- Long shutdown (LS) 1 starts from summer 2022 to fully install VXD (PXD).
  - ✓ PXD is still in preparation (due to some trouble).
- Operation will be resumed in the end of 2023 or beginning of 2024.

Belle II Operation

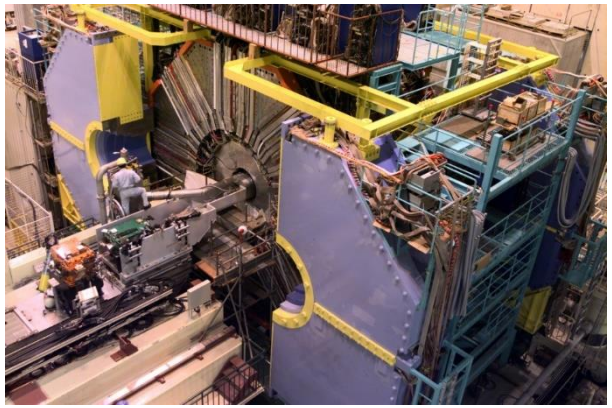
Year 2022 Operation

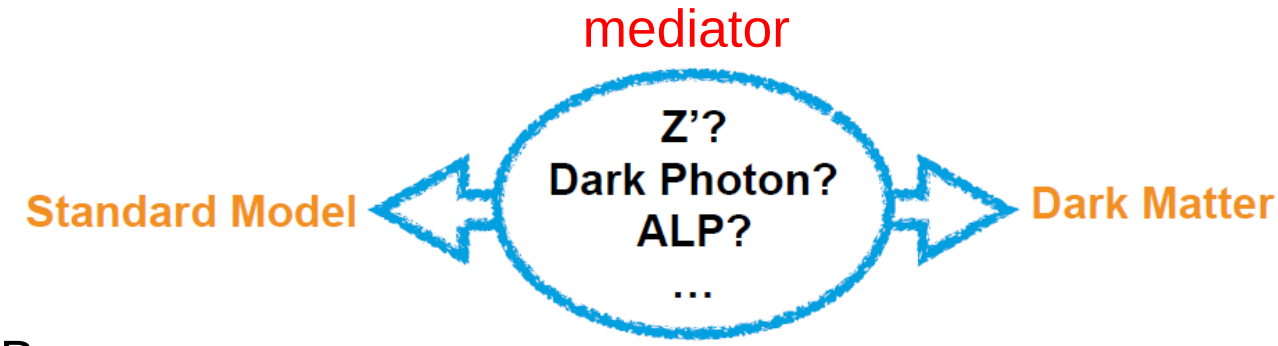
- Still affected by COVID (operated by local members, partially remote; foreign people could come only in June).
- Increasing electricity prices is a big problem (autumn run canceled → last week of June run is also canceled).
- Large beam background is an issue.
  - ✓ Background rate and trigger rate increases as the beam current increases (trigger rate reached to ~13 kHz, the current limit).
- Sudden beam loss needs to be understood for safe operation.
  - ✓ This prevents the beam increase.



Dark Matter Search at Belle (II)

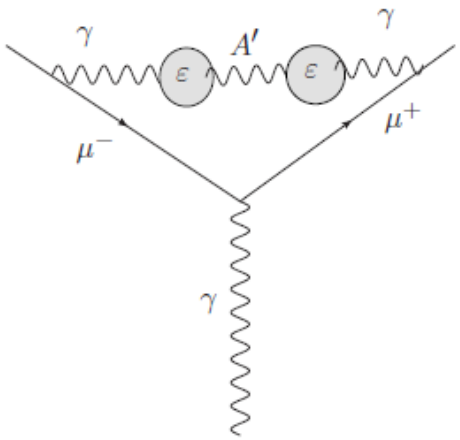
- Search for Dark Matter (DM) at Belle, Belle II.
  - ✓ CM energy is ~10GeV
    → mass region up to O(1) GeV (“light DM”)





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.

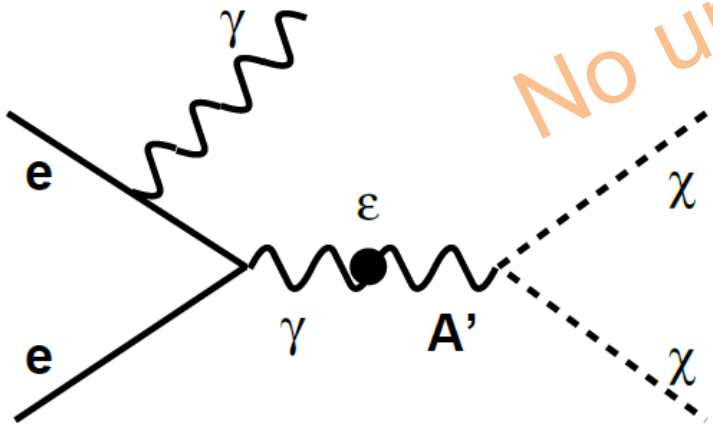
Searches at Belle (II)

Recent or on-going searches at Belle (II)

- $e^+e^- \to \gamma A'(\to \text{invisible})$ [on-going at Belle II]
- $Z' \to$ invisible [PRL124 (2020), 141801]
- $Z' \to \mu^+\mu^-$ [PRD 106, 012003 (Belle), arXiv:2212.03066 (Belle II)] → T. Czank's talk
- ALP (Axion Like Particle) $e^+e^- \to a(\to\gamma\gamma)\ \gamma$ [PRL125 (2020), 161806]
- Dark Higgsstrauhlung $e^+e^- \to A'(\to\mu^+\mu^-)\ h'(\to$invisible$)$ [PRL 130, 071804 (2023)]
- Dark Matter etc. from B (Υ, τ, ….) decays.
  - ✓ $B^0 \to A'\,A'$: dark photon [JHEP 04 (2021) 191]
  - ✓ $B \to \Lambda\psi_{DS}$ [PRD 105 (2022) L051101 (Belle)]
  - ✓ $B \to K\,S\,(\to$ leptons$)$: dark scalar
  - ✓ $B \to K\,S$ (long-lived) : long-lived dark scalar → Coming soon
  - ✓ $B \to K\,a\,(\to\gamma\gamma)$: ALP search
  - ✓ $B \to K\,a\,(\to$ hadrons$)$: heavy QCD axion (S.Ito, E.Waheed)
  - ✓ $\Upsilon(1S) \to \gamma$ + invisible : light Higgs [PRL 128, 081804 (2022) (Belle)]
  - ✓ $\tau \to l\,\alpha$ (invisible boson) [arXiv:2212.03634]
  - ✓ $D^{*0} \to D^0A'\,(\to e^+e^-)$ (H.Kindo)

Invisible Mode

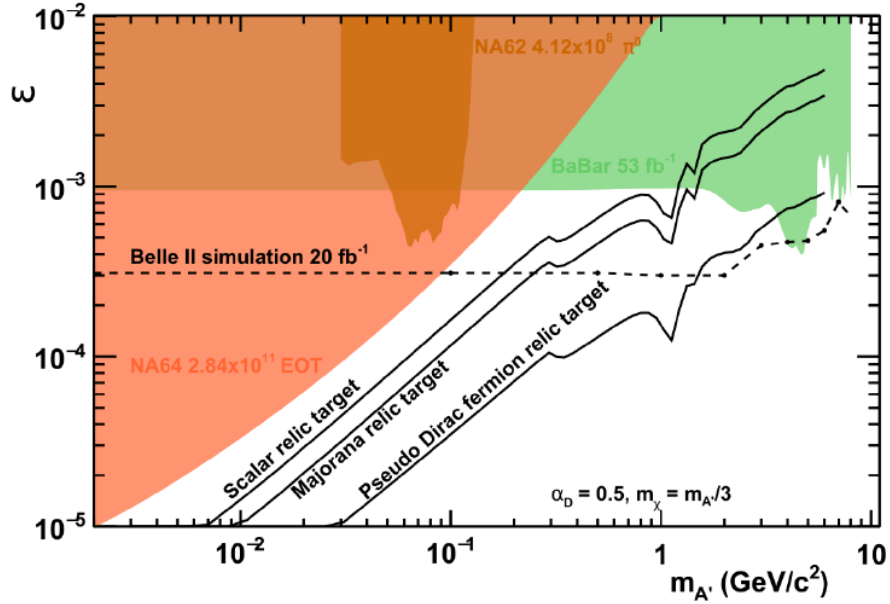
$e^+e^- \to \gamma$ + invisible



No update

On-going analysis at Belle II

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



- 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.

Still need more time to study.
Waiting the update of the analysis library + process…

Search for Heavy QCD Axion

[S. Ito]

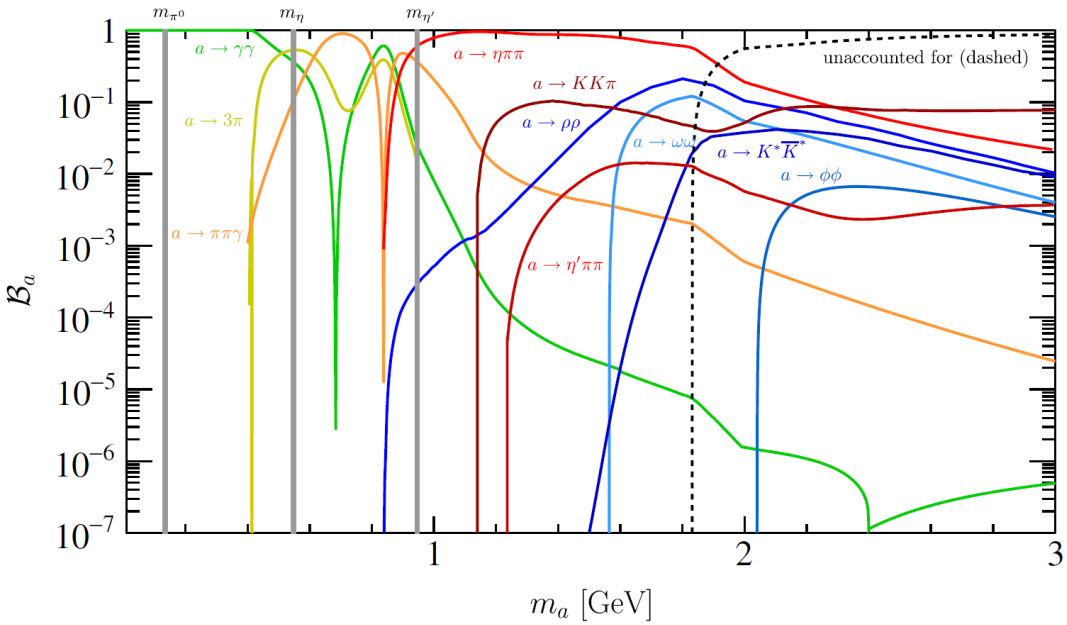
- Peccei-Quinn symmetry to solve strong CP problem
  → QCD axion (pseudo Nambu-Goldstone boson in PQ violation)

  QCD axion mass m_a and decay constant f_a: $m_a f_a \simeq m_\pi f_\pi$

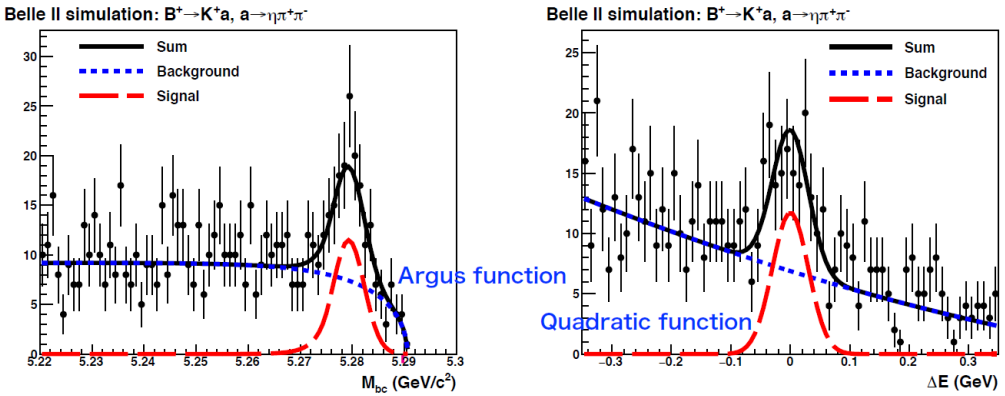
  If axion is dark matter, the mass range is $10^{-6} \lesssim m_a \lesssim 10^{-3}$ eV

- Heavy QCD axion $m_a \gg m_\pi f_\pi / f_a$
  - ✓ Solve strong CP problem.
  - ✓ May provide some hints in dark matter search.
- Can be searched through $B^+ \to K^+ a$, $a \to$ hadrons
  - ✓ B.F. of $a \to$ hadrons can be predicted assuming axion-gluon coupling is dominant over axion-SM coupling

PRL 123 031803 (2019)

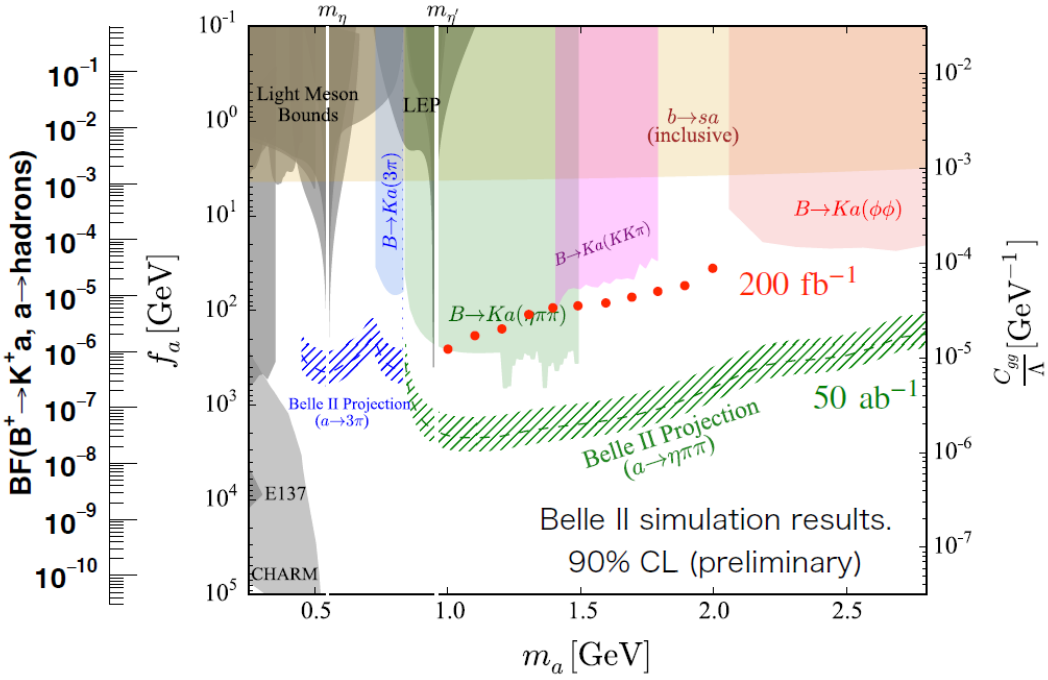


Search for Heavy QCD Axion



$m_a = 1.5\ \mathrm{GeV}/c^2,\ BF(B^+ \to K^+ a) = 5 \times 10^{-5},\ 200\ \mathrm{fb}^{-1}$

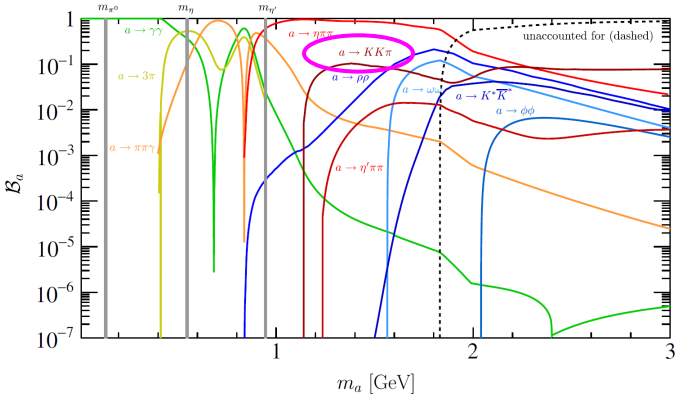
- Increased the search region up to ~3 GeV (not shown in the plot)
- Selection criteria is optimized.
- Start looking at the real data (first from the sideband).
- Planned to get the result this winter. But need a little more time.

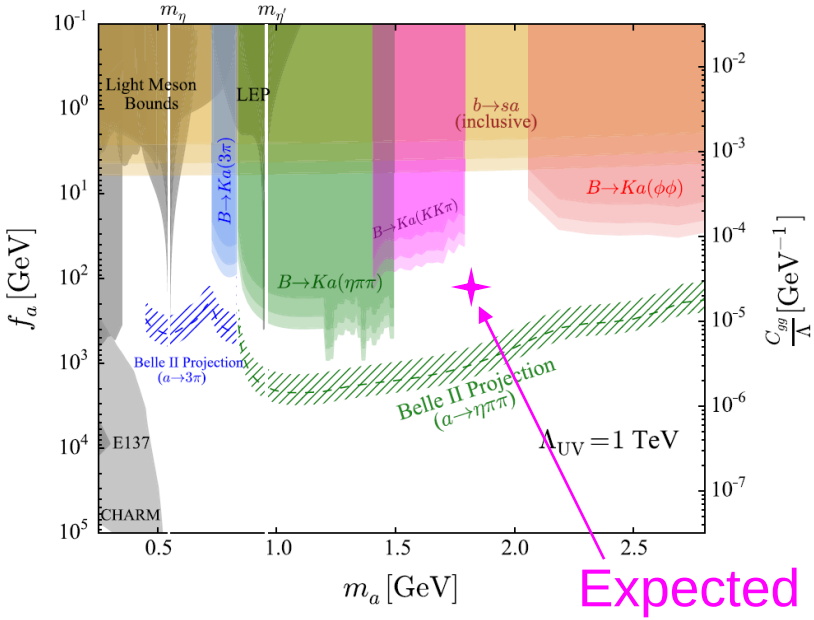


Search for Heavy QCD Axion

$B^+ \to K^+ a$, $a \to K_S K^+ \pi^-$

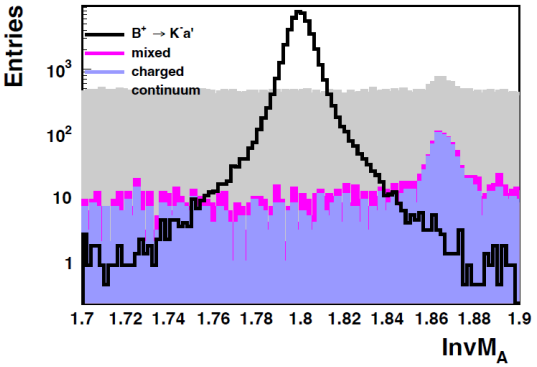
[E.Waheed]

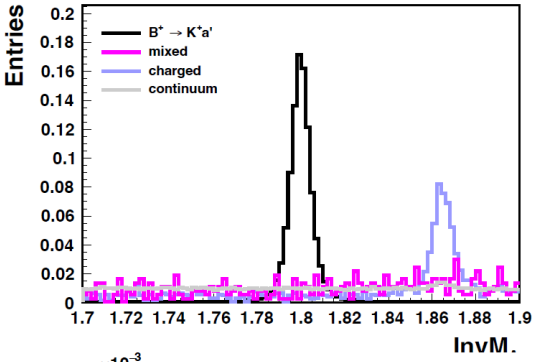


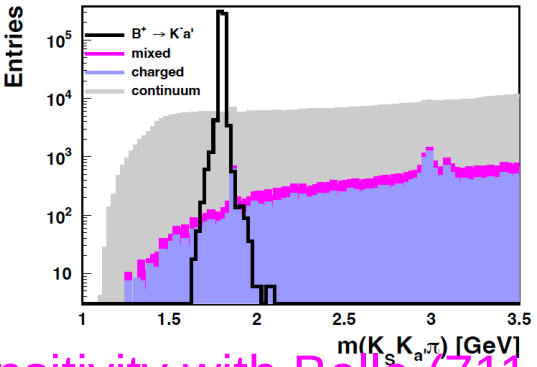


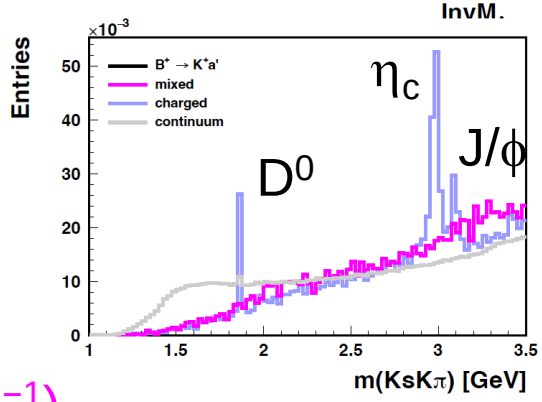
- large B.F. at $1.2 < m_a < 1.7$ GeV
  - ✓ Benchmark study at 1.8 GeV

without background suppression









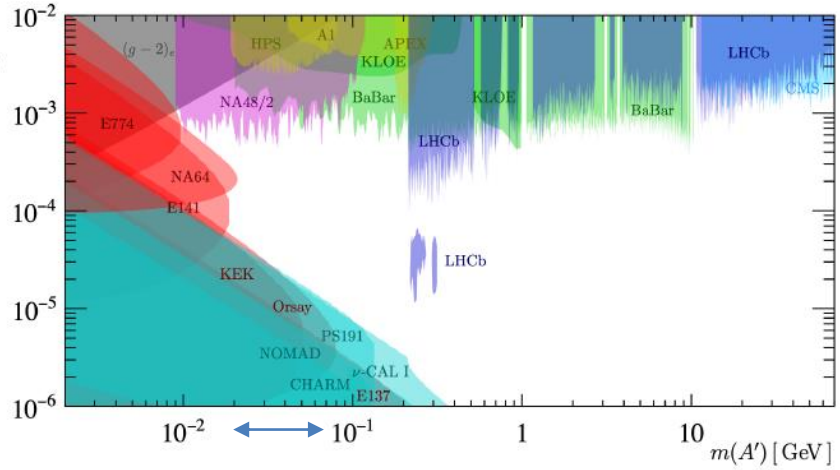
Expected sensitivity with Belle (711 fb^{-1})

$D^{*0} \rightarrow D^0 A'$

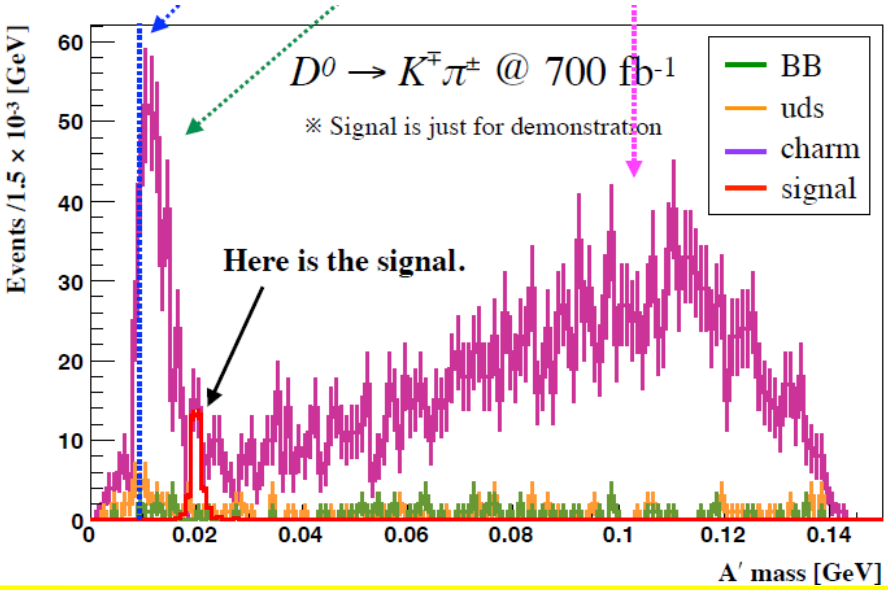
$D^{*0} \rightarrow D^0 A' (\rightarrow e^+e^-)$

[H.Kindo]

- Kinetic mixing of γ from $D^{*0} \rightarrow D^0\gamma$ to dark photon A'.
- Sensitive to $10<M_{A'}<140$ MeV.
  - ✓ cf) X(17) by Atomski (internal pair creation of $^8Be^*$) : $\varepsilon \sim 10^{-3}$
- Proposal for LHCb or Belle II [P. Ilten et. al. PRD92, 115017].



MC for Belle



- The sensitivity of Belle experiment is estimated to be $\varepsilon \sim 10^{-2}$ to 10^{-3}.
- Probably not enough to explore new region, but first result with coupling to charm.
- Analysis is going on (hope to get result soon).

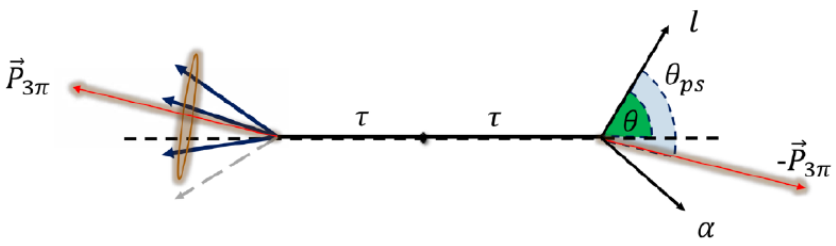
Invisible Scaler in LFV τ Decays

$\tau \to l\,\alpha$ (l = e, μ) 62.8 fb^{-1} [arXiv:2212.3634]

[JHEP09 (2021) 173]

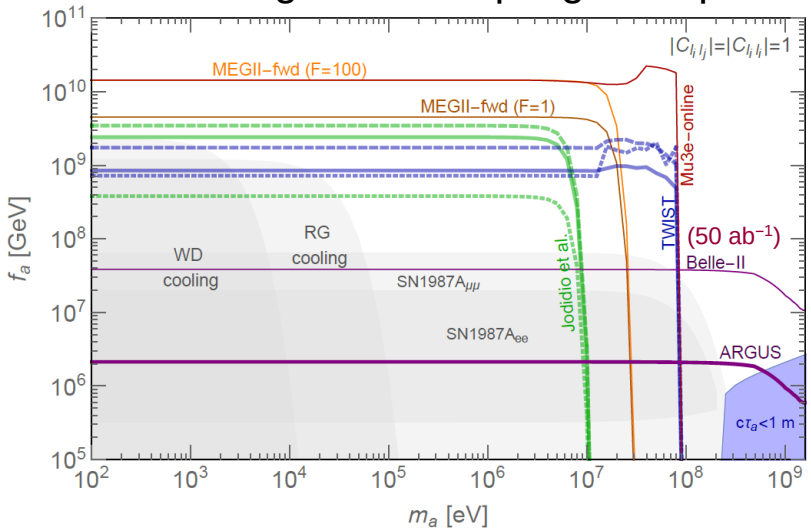
- τ decays with invisible scalar α : predicted in models with ALP etc.
- Sharp peak in the lepton momentum in τ rest frame (← not accessible).
- Pseudo τ rest frame, calculated from 3h in $\tau \to 3h\,\nu$ (h = K, π).

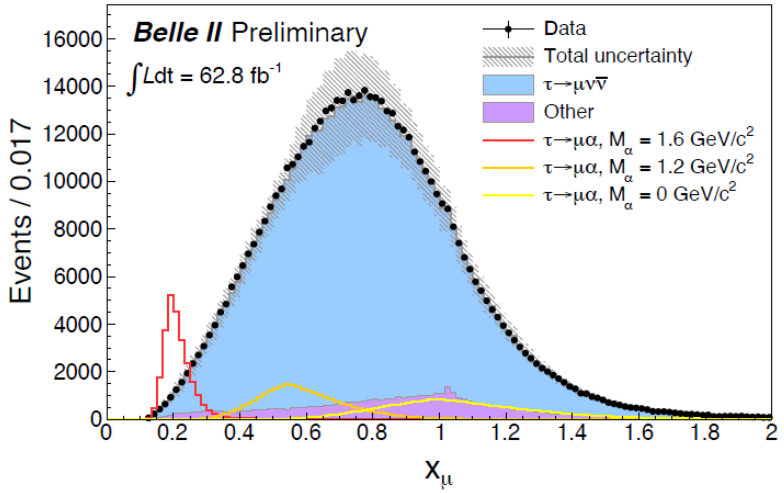
$$E_\tau = E_{\rm cms}/2, \quad \hat{p}_\tau \approx \vec{p}_{\rm tag}/|\vec{p}_{\rm tag}|$$



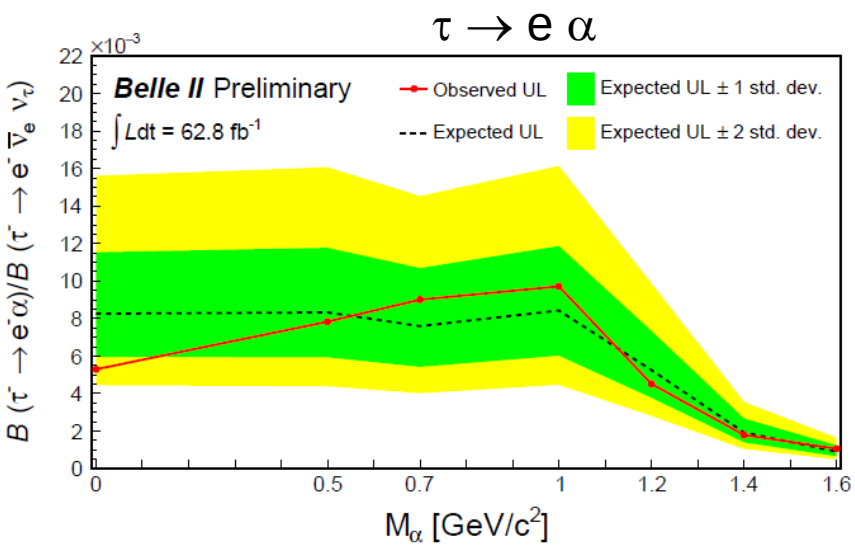
- Fit the spectrum with the SM expectation (mainly $\tau \to l\,\nu\,\nu$) + Signal ($\tau \to l\,\alpha$)
- Smearing due to missing ν in the tag side.

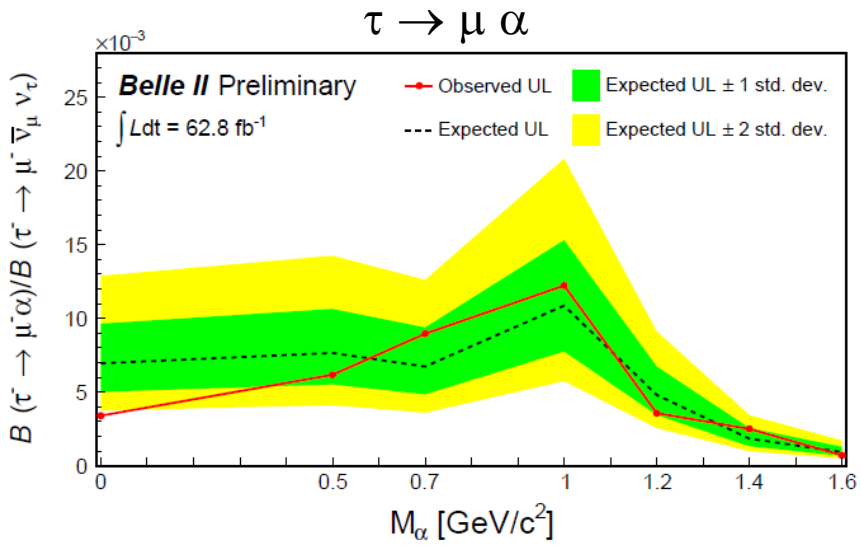
ALP with generic couplings to leptons



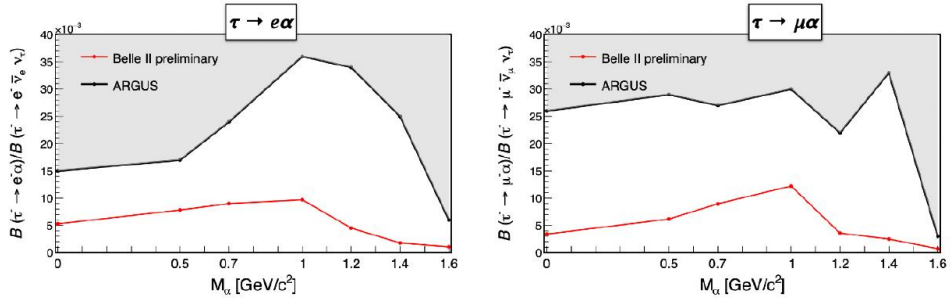


Invisible Scaler in LFV τ Decays



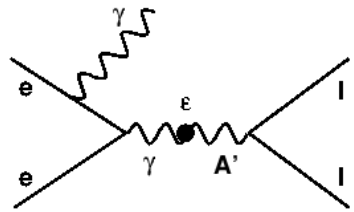


- Upper limits at 95% C.L. are obtained with partial data of Belle II
- 2.2-14 times stringent than previous result by ARGUS [Z. Phys. C68, 25 (1995)].
- A new analysis is going on using Belle data (×10 more data).



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 (now ~13 kHz)
- ~100% efficiency for hadronic events.

Key Issue

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

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).

Most of the modules have been upgraded to UT4.

	Board	#	Status of using UT4	note	
Track-Segment-Finder	TSF	9	**Upgraded**		CDCTRG
	2D	4	**Upgraded**		
	3D	4	Preparing		
	NN	4	Preparing		
Event-Timing-Finder	ETF	1	**Upgraded**		
	New 2D	4	Installed. Preparing		
	3D Hough	4	Installed. Preparing		
	Displaced vertex	2	Preparing.		
	ETM	1	**Upgraded**		Other Trigger systems
	TOP	1	Installed. Preparing		
	GRL	1	**Upgraded**		
	GDL	1	**Upgraded**		

UT3
Xilinx Virtex-6

UT4
Xilinx UltraScale

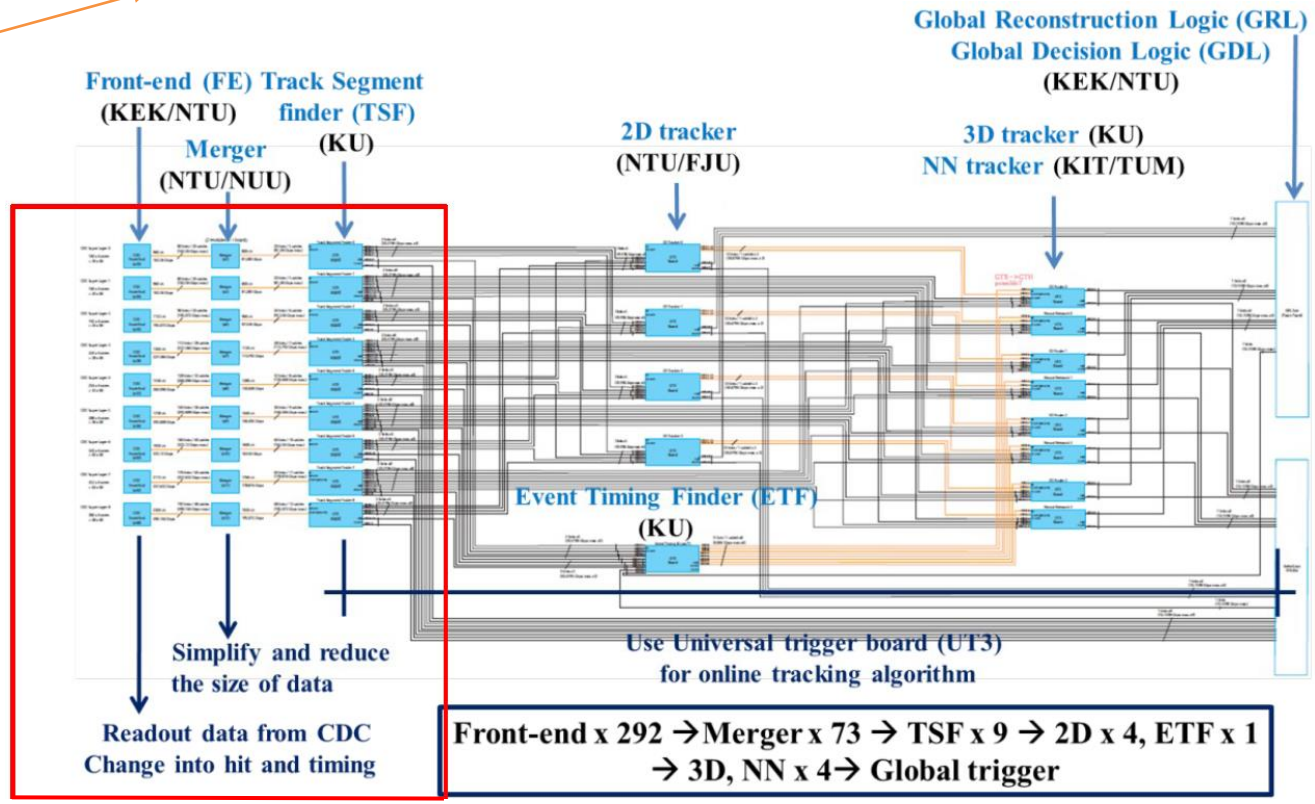
Larger Bandwidth in CDCTRG

[Y.Lai]

- CDCFE x 292 → Merger x 73 → TSF x 9: Larger bandwidth with UT4
  - ✓ CDCFE → Merger: **2.54 Gbps** x 4 lanes → **3.175 Gbps** x 4 lanes
  - ✓ Merger → TSF: **5.08 Gbps** x 2 lanes. → **6.35 Gbps** x 2 lanes.
- Have been tested and ready in LS1.
  - ✓ Benefit: Include ADC info in L1 tracking. (Now only TDC info is used.)

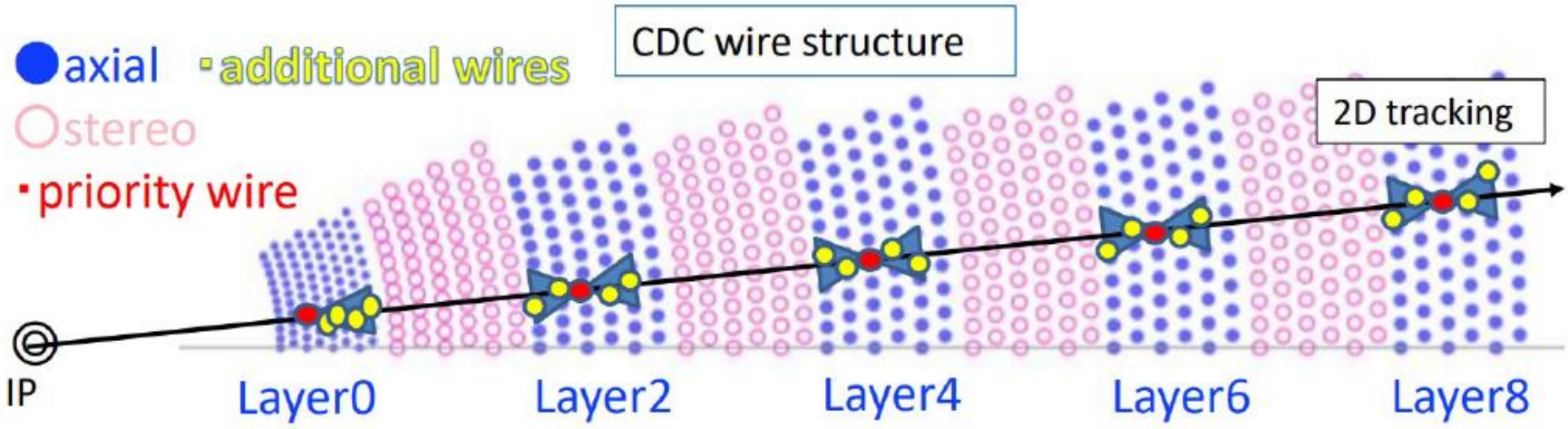
timing

pulse height



New Tracking using ADC

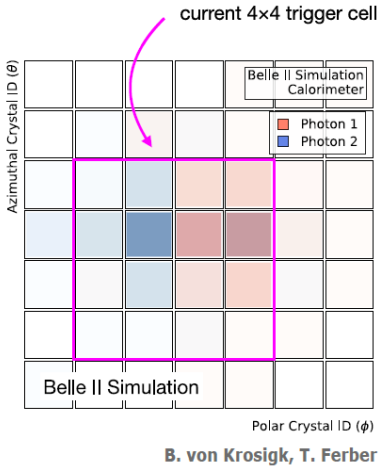
- The upgrade (in bandwidth) in the previous page is needed to send ADC info in data.
- Upgrade in tracking:
  - ✓ In the Hough transformation, use all wires' info instead of only Track Segment from Axial Stereo Layer.
  - ✓ ADC info: apply proper threshold to reduce background.
- Purpose: Reduce the fake tracking rate from cross-talk in CDC.
  - ✓ This will reduce the trigger rate from background, which helps keeping triggers for low-multiplicity events.
- Will be ready in LS1.
  - ✓ Expected to reduce track trigger rate by 30% (simulation)

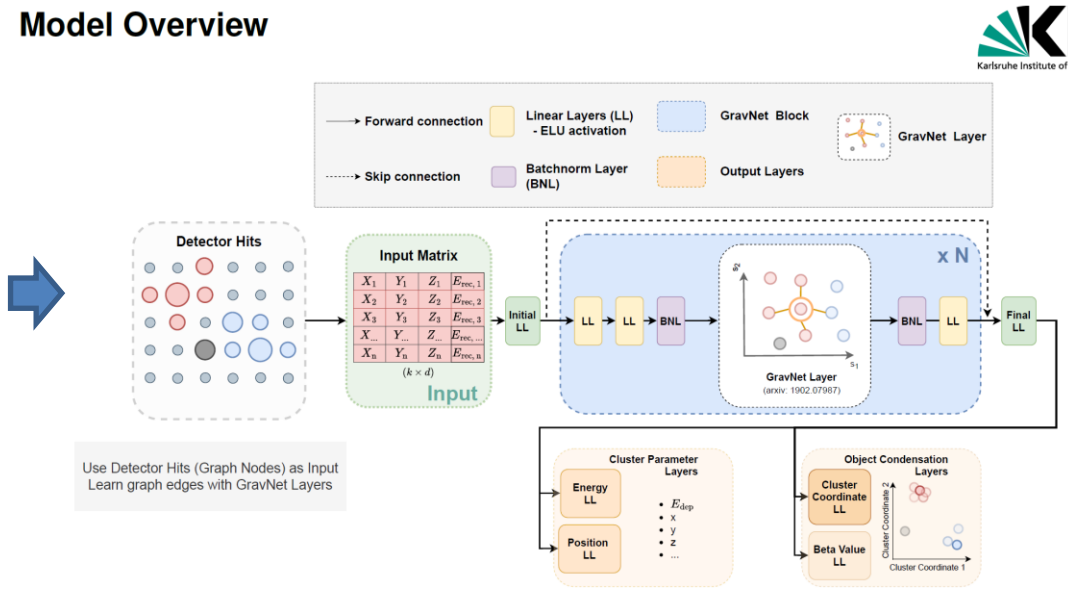


Development for Future Trigger

- When the luminosity is increased, the trigger rate will also increase.
  - ✓ Need to improve the trigger performance (i.e., reject background events, pick up events with special signal-like topology).
  - ✓ Otherwise, trigger conditions will be tightened to discard events with low-multiplicity tracks (=less particles) → bad for dark sector analysis (and τ physics etc.)
- Enhance the performance of low-multiplicity (dark sector) is a major concern.
- For most of the new plan, using machine-learning becomes a trend.
  - ✓ New ideas rely on stronger FPGA, such UT4, or even future one.

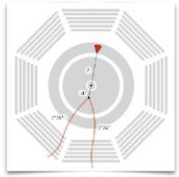
Example: Usage of Graph Neural Networks (GNNs) for ECL Trigger



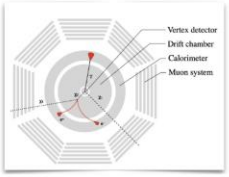


Development for Future Trigger

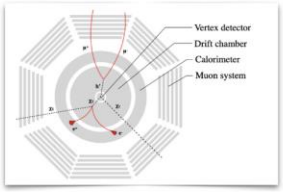
- Long-lived Dark Photon A'



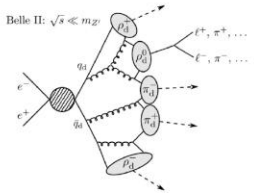
- Inelastic Dark Matter (iDM)



- Inelastic Dark Matter with a Dark Higgs (iDMDH)

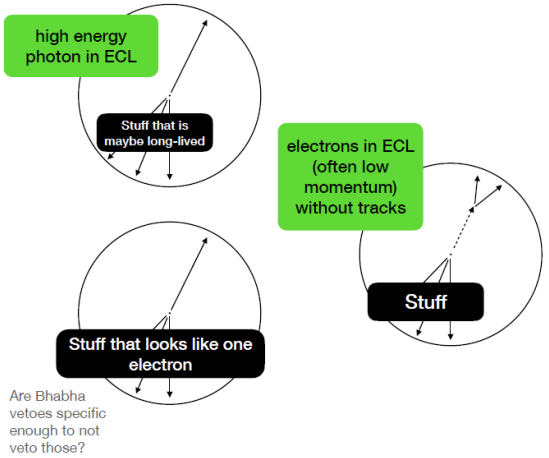


- Dark Showers



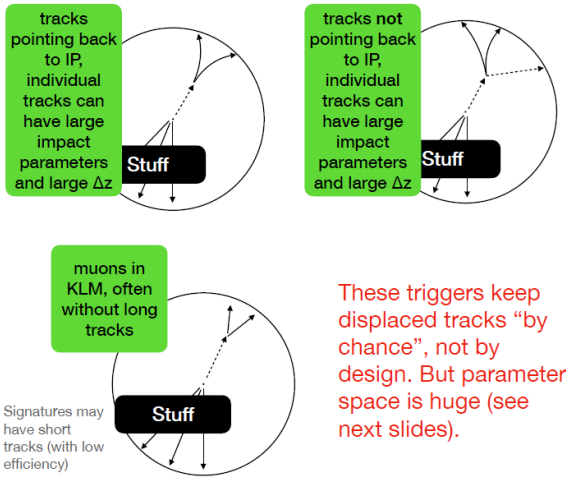
Triggers for long-lived particles

ECL based triggers



Are Bhabha vetoes specific enough to not veto those?

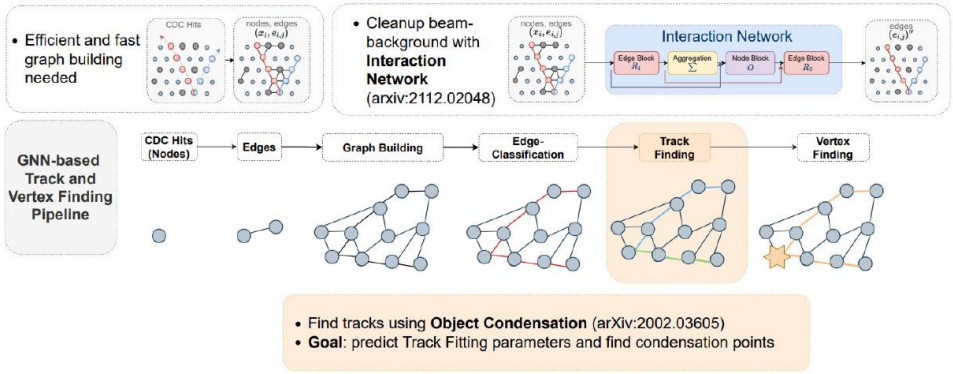
Track based triggers



Signatures may have short tracks (with low efficiency)

These triggers keep displaced tracks “by chance”, not by design. But parameter space is huge (see next slides).

- Use GNN for tracking
  - Displaced vertex is considered: Dark Sector physics.



Summary and Plan

- SuperKEKB and Belle II were operated till 2022 summer and are now in Long Shutdown1 (LS1). Operation will be resumed in the end of JFY2023.
  - ✓ No additional data for analyses in ~2024.
- Some results on the dark sector, and more analyses follow.
  - ✓ $e^+e^- \to \gamma A'(\to \text{invisible})$ takes time.
- Large background is an issue. Some efforts to improve triggers for the coming run.