



# Belle IIでの軽い新粒子探索

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(KEK)



# 青木さんから

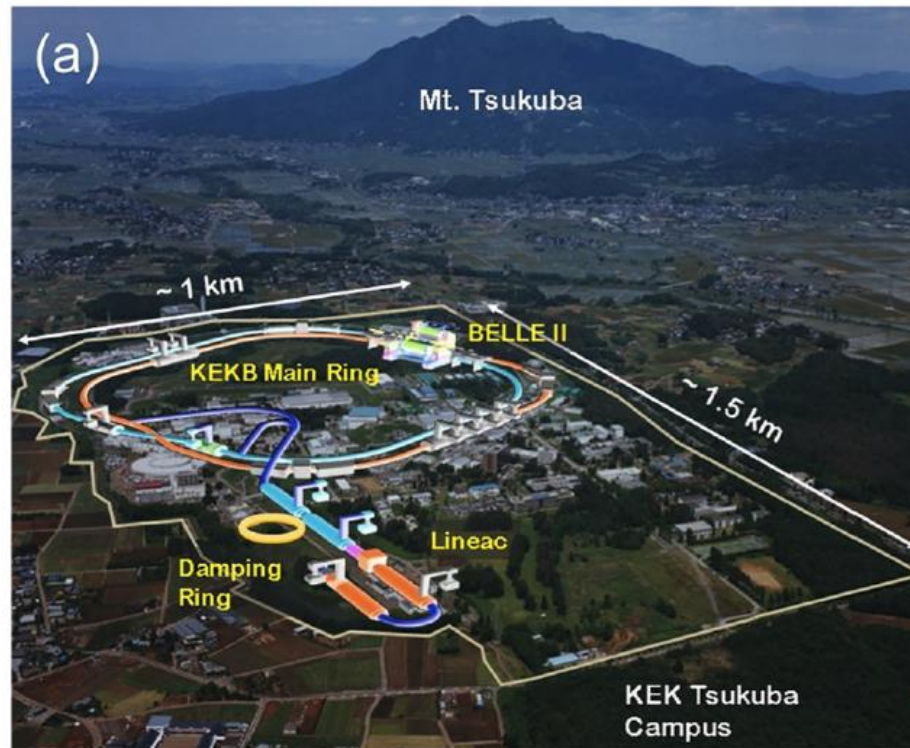
- ...
- 「今回、石川さんにも参加して頂いてBelle IIでの軽い粒子探索関連の講演をして頂き、研究会を盛り上げて頂けたらと思い、声をかけさせてもらいました。」
- ...
- というわけで軽い新粒子探索(Dark Sector)に focus した話をしたいと思います

# Contents

- Introduction
- Belle II での Trigger System
- Belle II での軽い新粒子探索

# Belle II Experiment

- KEK Tsukuba campus
  - SuperKEKB accelerator
  - Belle II detector



# SuperKEKB Accelerator

- Highest luminosity collider

- $L_{\text{target}} = 6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

- $E_{\text{CM}} = 10.58 \text{ GeV}$  on  $\Upsilon(4S)$

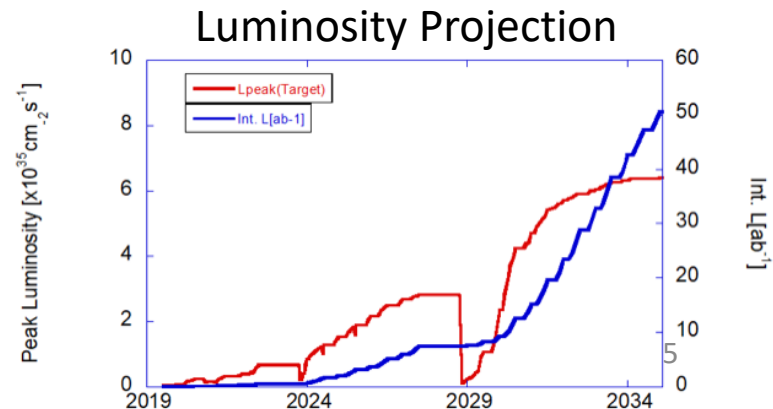
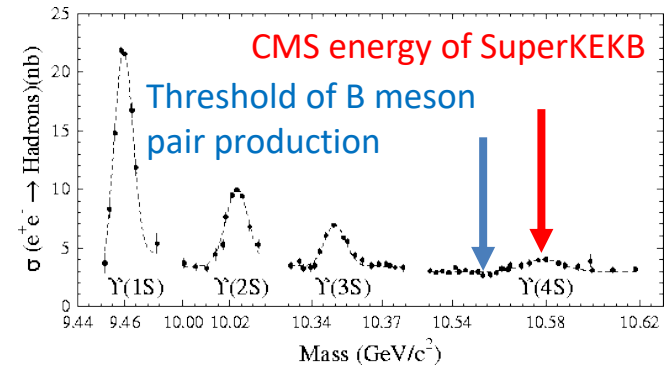
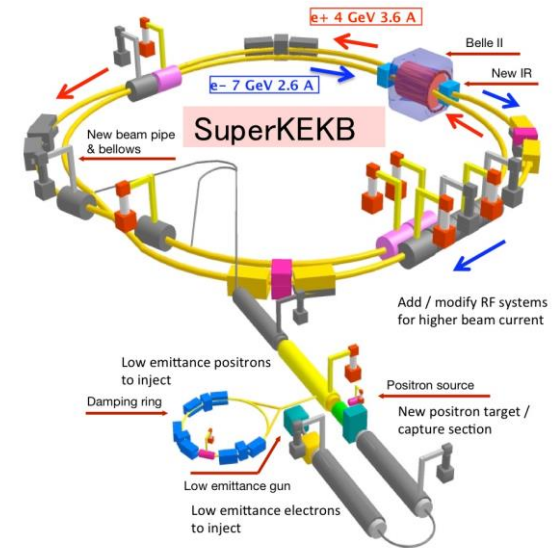
- Just above the BB threshold to produce B meson pairs efficiently
    - Can go higher,  $\Upsilon(5S)$  upto 11.24 GeV

- Energy-asymmetric collisions

- 7.0 GeV ( $e^-$ ) x 4.0 GeV ( $e^+$ )
    - To boost B mesons to measure time dependent CPV

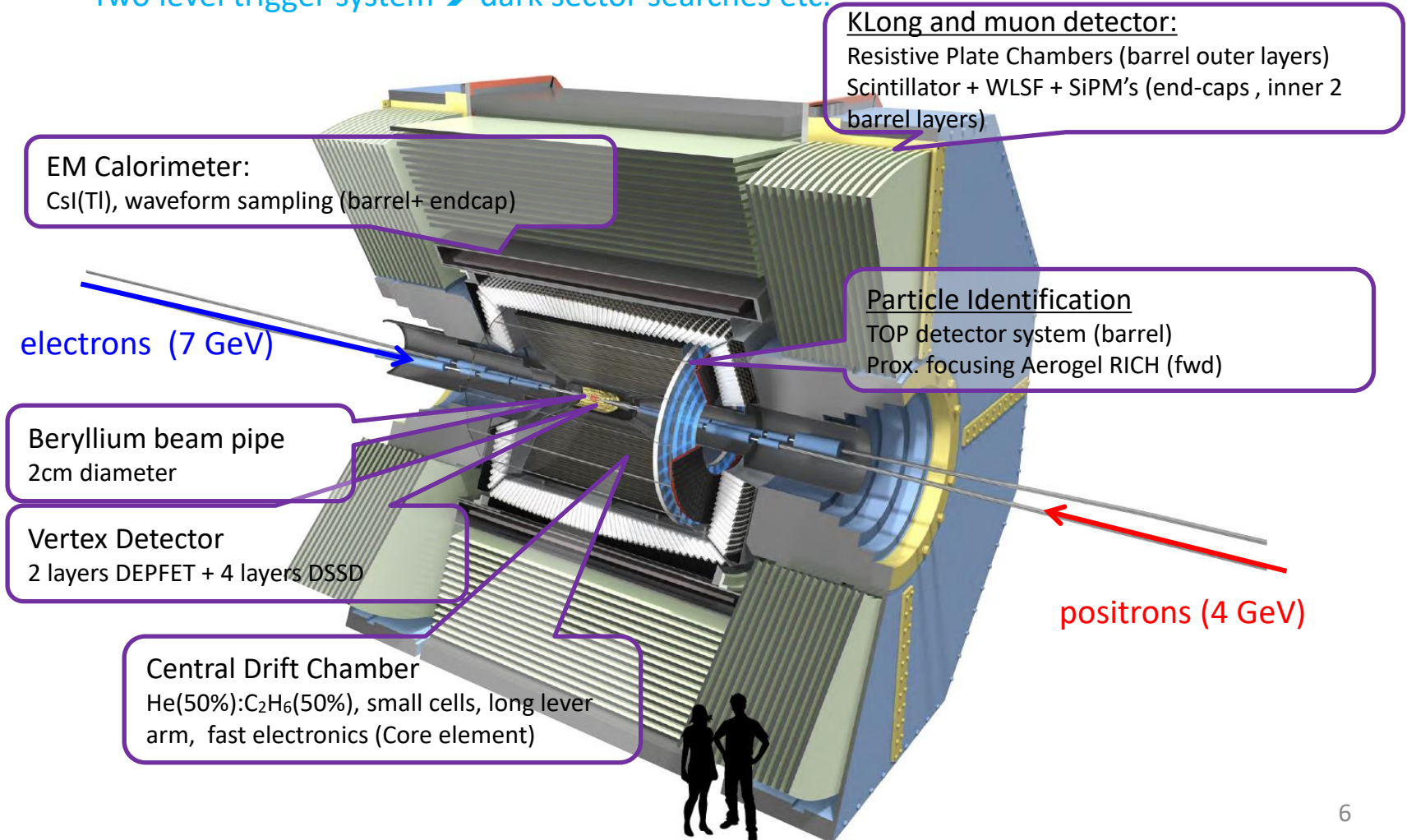
- $50 \text{ ab}^{-1}$  will be accumulated around 2035

- Containing  $1 \times 10^{11}$  B mesons,  $1.4 \times 10^{11}$  charm hadrons, and  $0.9 \times 10^{11}$   $\tau$
    - Processes with cross sections of  $O(1) \text{ ab}$  or less are reachable



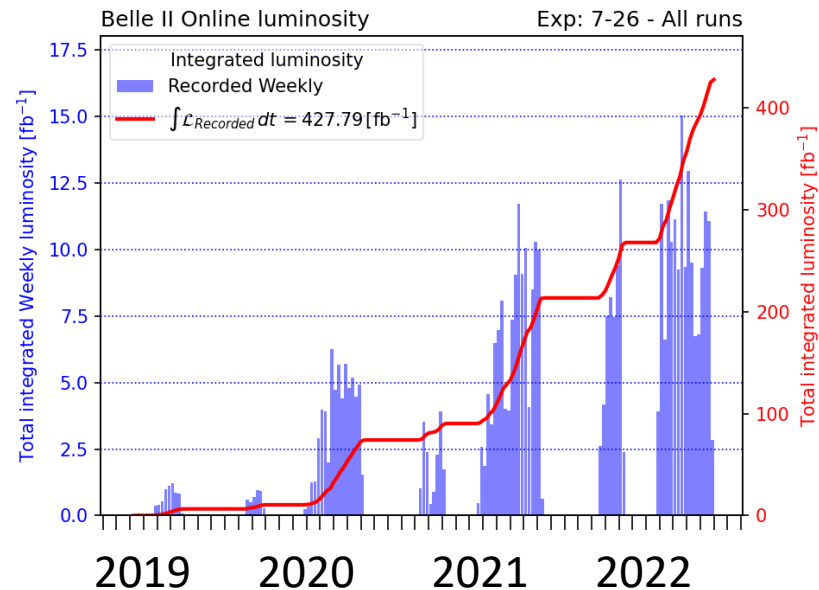
# Belle II Detector

- Significant detector improvements from Belle
  - Better and Larger Vertex Detector → Time dependent CPV, especially with long lived Ks.
  - Two level trigger system → dark sector searches etc.



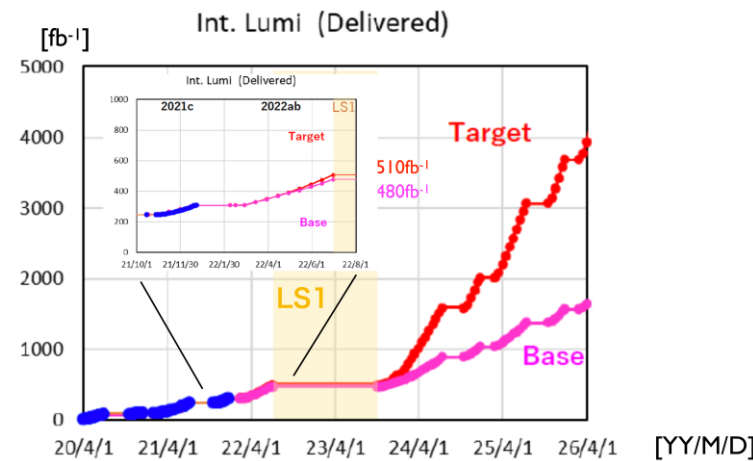
# Luminosity and Dataset

- June 2022 : Run1 operation stopped
  - World's highest luminosity of  $4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - $428 \text{ fb}^{-1}$  data were accumulated so far
    - $362 \text{ fb}^{-1}$  on resonance,  $42 \text{ fb}^{-1}$  off-resonance,  $19 \text{ fb}^{-1}$  energy scan
    - C.f. Belle collected  $1040 \text{ fb}^{-1}$



# Near Future Prospects

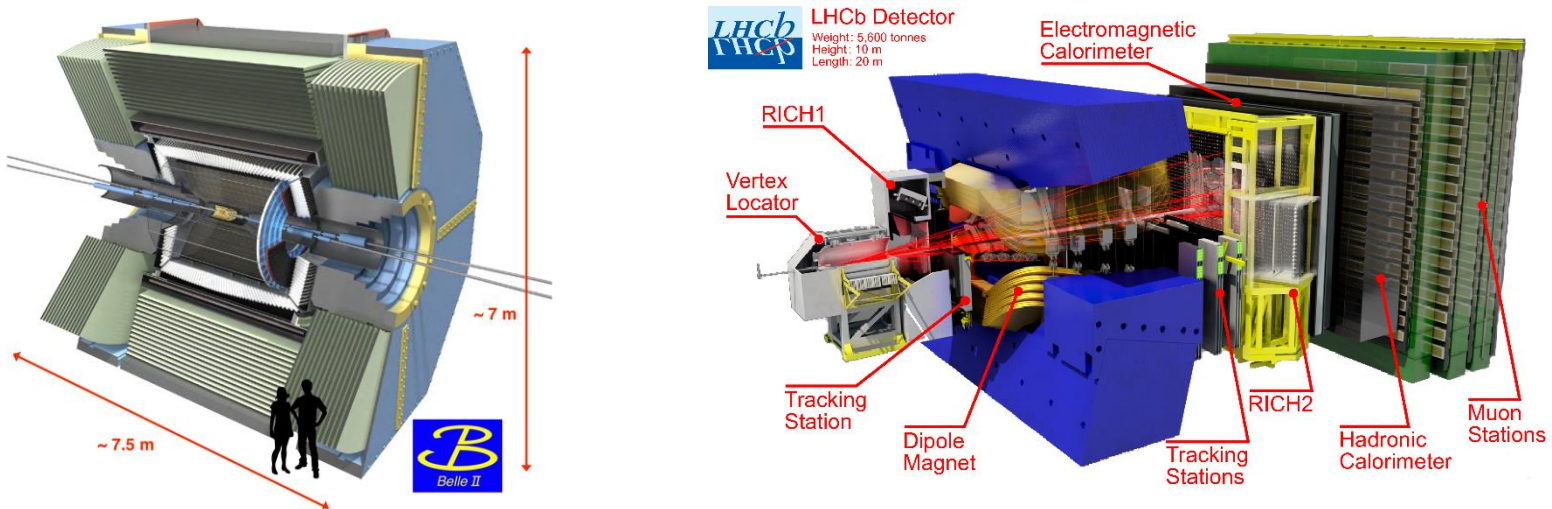
- June 2022 – Jan 2024: Long Shutdown 1 for SuperKEKB and Belle II upgrades
  - New collimators to reduce beam induced backgrounds which limit beam current
    - → can go **higher luminosity**
  - Two-layer pixel detector was installed
    - → **better vertex resolution** under higher beam induced background
  - TOP PMT replacement → **better Kaon ID**
- **Jan 2024 : SuperKEKB operation resumed**
  - Plan to accumulate more data than Belle in run2





# Belle II Cons and Pros (vs. LHCb)

- Cons.
  - Statistics of **b hadrons!!** (cross section  $1\text{nb}$  vs.  $144\mu\text{b}$ )
    - We will only have  $10^{11}$  B mesons with  $50\text{ab}^{-1}$  on Y(4S) and  $5 \times 10^8$   $B_s$  with  $5\text{ab}^{-1}$  on Y(5S)
  - No large samples of **b baryons** and  $B_c$ 
    - Production of these hadrons are not yet established at  $e^+e^-$  collisions around Y(nS).
  - **Proper time resolution** is **worse** and B meson is not so boosted.
    - Background suppression with B vertex displacement is not so easy
    - **$B_s$  mixing ( $\Delta m_s$ ) can not be measured** (while  $\Delta\Gamma_s$  can be measured).



# Belle II Cons and Pros (vs. LHCb)

- Pros.
  - Smaller background cross section ( $O(1)\text{nb}$  vs.  $O(10)\text{mb}$ )
    - $\sim 3.4\text{nb}$  for  $ee \rightarrow qq$ ,  $\sim 1.08\text{nb}$  for  $ee \rightarrow \Upsilon(4S) \rightarrow BB$
  - Almost 100% trigger efficiency for BB events
  - Two level trigger system for low multiplicity events
    - Many dark sectors signature (X+missing) can be triggered
  - High hermeticity  $4\pi \times 94\%$ 
    - High reconstruction efficiency of  $O(1) \sim O(10)\%$ .
    - Full reconstruction of B meson possible (tagging of the other B meson)
      - More than one missing neutrino modes  $\rightarrow B \rightarrow D(*)\tau\nu$ ,  $B \rightarrow \tau\nu$ ,  $B \rightarrow K(*)\nu\nu$ ,  $B \rightarrow K\tau\tau$ ,  $B \rightarrow \nu\nu$
    - 4 momentum conservation usable  $\rightarrow$  dark sector searches
  - Detection of electron
    - Detection efficiency of electron is almost the same as that of muon  $\rightarrow$  test of LFU
    - Easy to recover bremsstrahlung photon
  - Detection of neutrals
    - reconstruction of  $\gamma$ ,  $\pi^0$  and  $K_s$  efficiently  $\rightarrow$  sum-of-exclusive method for  $B \rightarrow Xsl^+l^-$ ,  $B \rightarrow \pi^0\pi^0$ ,  $B_{(s)} \rightarrow \gamma\gamma$
    - Better energy resolution of hard  $\gamma$   $\rightarrow B \rightarrow K^*\gamma$  background to  $B \rightarrow \rho\gamma$  can be suppressed

# Rich Physics Program

- Flavor physics
  - B
    - CKM Unitarity Triangle
    - Rare decays
    - Lepton Flavor Universality
    - etc
  - Charm
    - CPV
    - mixing
    - Lifetime
    - etc
  - $\tau$ 
    - Mass
    - Lifetime
    - CPV
    - EDM
    - etc
- QCD
  - Bottomonia, charmonia and exotic hadrons containing heavy quark
  - HVP with radiative return for muon g-2
  - fragmentation
  - etc
- EW
  - Weak mixing angle
  - etc
- Light new particle searches
  - Dark sector (DS) mediators
  - etc
- And more

# Belle II での Trigger System

- 自分の模型の事象が trigger にかからなければ、データとして残ることは無いので、実験屋がその探索をする事は不可能

# Trigger は物理の選択

- Trigger : 事象の特徴をオンラインで見積もり**興味ある事象を選別**する
  - Trigger された物理事象・背景事象はストレージに保存される
    - ストレージに書ける**データ量は予算による限界**がある
    - 10回 trigger されたうちの1回だけストレージに保存のような自由度はある (prescale)
  - Trigger されなかったら物理事象・背景事象は捨てる

## • 物理事象

- SM : **BB, qq,  $\tau\tau$** ,  $\mu\mu$ ,  $\gamma\gamma$ ,  $\pi\pi\gamma$ , two photon...
- NP : dark sector etc.

## • 背景事象

- Beam 起因の背景事象
- **(radiative) Bhabha**
- Two photon

Physics process	Cross section [nb]	Selection Criteria
$\Upsilon(4S)$	$1.110 \pm 0.008$	-
$u\bar{u}(\gamma)$	1.61	-
$d\bar{d}(\gamma)$	0.40	-
$s\bar{s}(\gamma)$	0.38	-
$c\bar{c}(\gamma)$	1.30	-
$e^+e^-(\gamma)$	$300 \pm 3$ (MC stat.)	$10^\circ < \theta_e^* < 170^\circ$ , $E_e^* > 0.15$ GeV
$e^+e^-(\gamma)$	74.4	$p_e > 0.5$ GeV/c and e in ECL
$\gamma\gamma(\gamma)$	$4.99 \pm 0.05$ (MC stat.)	$10^\circ < \theta_\gamma^* < 170^\circ$ , $E_\gamma^* > 0.15$ GeV
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5$ GeV in ECL
$\mu^+\mu^-(\gamma)$	1.148	-
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5$ GeV/c in CDC
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5$ GeV in CDC, $\geq 1 \gamma$ ( $E_\gamma > 0.5$ GeV) in
$\tau^+\tau^-(\gamma)$	0.919	-
$\nu\bar{\nu}(\gamma)$	$0.25 \times 10^{-3}$	-
$e^+e^-e^+e^-$	$39.7 \pm 0.1$ (MC stat.)	$W_{\ell\ell} > 0.5$ GeV/c <sup>2</sup>
$e^+e^-\mu^+\mu^-$	$18.9 \pm 0.1$ (MC stat.)	$W_{\ell\ell} > 0.5$ GeV/c <sup>2</sup>

5nb

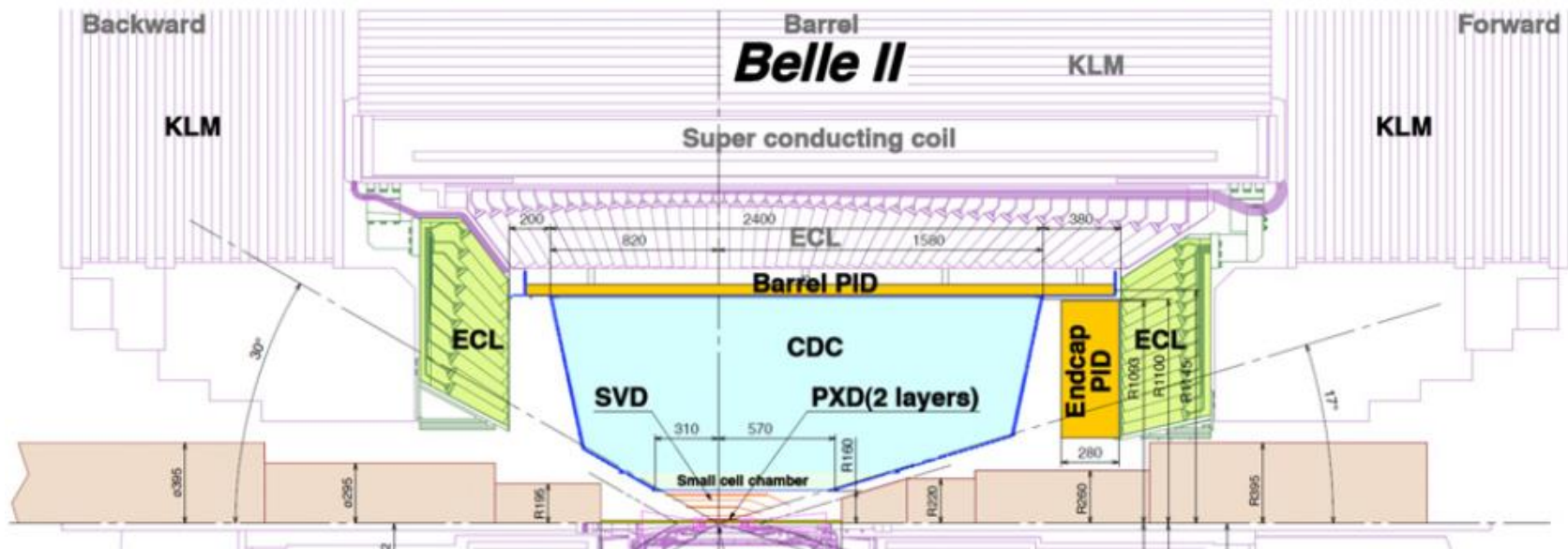
1nb

# 2 Level の Trigger

- Hardware L1 trigger (L1)
  - 短時間に大雑把な情報を用いて事象を選別する
  - Belle 1 では L1 のみしか無かった
  - Belle II では最大30kHz( $L_{\max}=6 \times 10^{35}/\text{cm}^2/\text{s}=600/\text{nb}/\text{s} \rightarrow \sigma_{L1}^{\max}=50\text{nb}$ )
- Software Higher Level trigger (HLT)
  - L1 でTriggerされた事象をさらに選別
  - PC server 上で比較的長い時間を使って物理解析に近い運動量・エネルギー精度の情報を用いて事象を選別する
  - Belle II で導入された
  - これにより L1 でより多くの(特に背景事象に近い)事象を取得する事が可能に
    - Dark sector 事象にとっては重要
  - Belle II では最大10kHz(になる予定)
- L1 が最も重要なのでその説明をします

# Belle II での L1 Trigger 情報

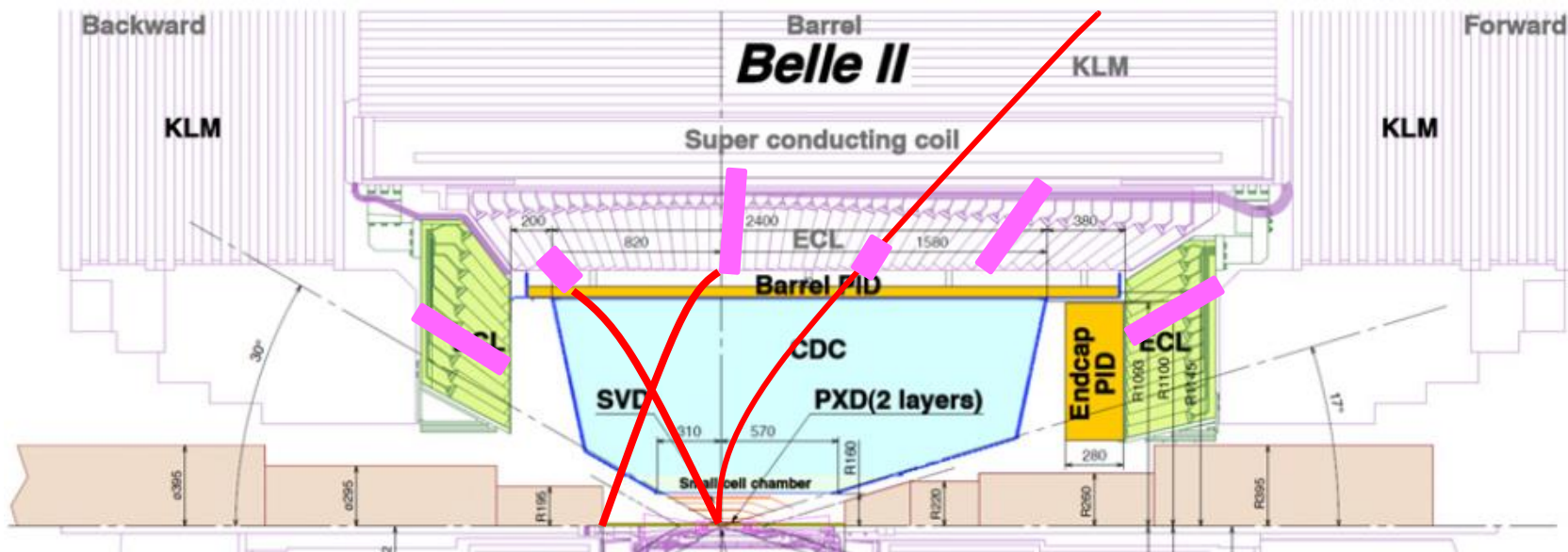
- CDC (Central Drift Chamber)
  - 荷電粒子の飛跡と運動量測定
    - 2次元の飛跡の数
    - 3次元の飛跡の数
    - 2次元での飛跡対の opening angle
- ECL (Electromagnetic CaLorimeter)
  - エネルギー測定 (電子・光子、荷電粒子の通過)
    - Energy sum
    - Cluster の数
    - cluster 対の opening angle
- KLM (KL and Muon system)
  - KLM を貫通した飛跡(muon)の測定
    - Muon の数
    - Muon 対の Opening angle



# Belle II での L1 Trigger 情報

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    - 2次元での飛跡対の opening angle
    - Forward/backward 方向は eff が低い
    - 2次元はビーム起因背景事象を拾いやすい
- ECL (Electromagnetic CaLorimeter)
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Topology 情報を使える

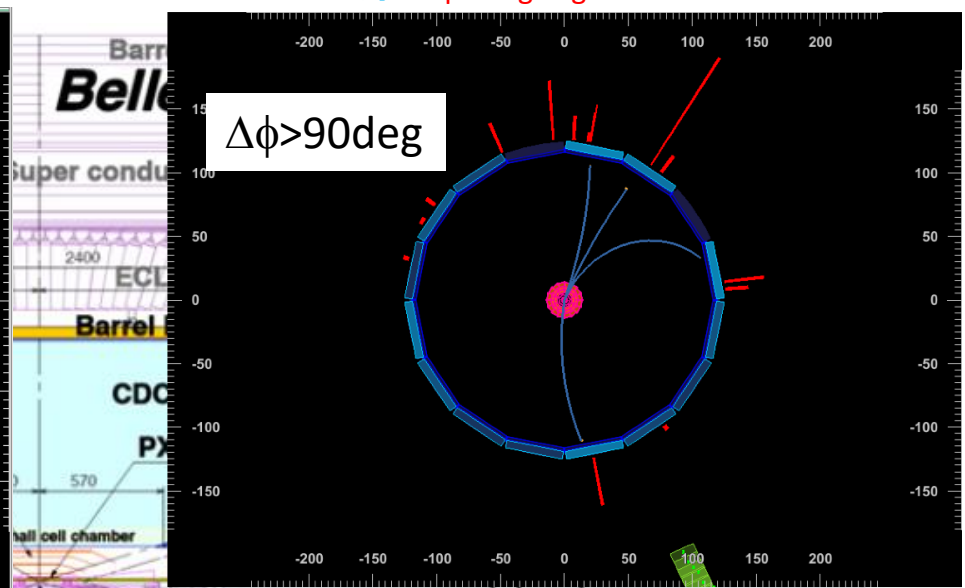
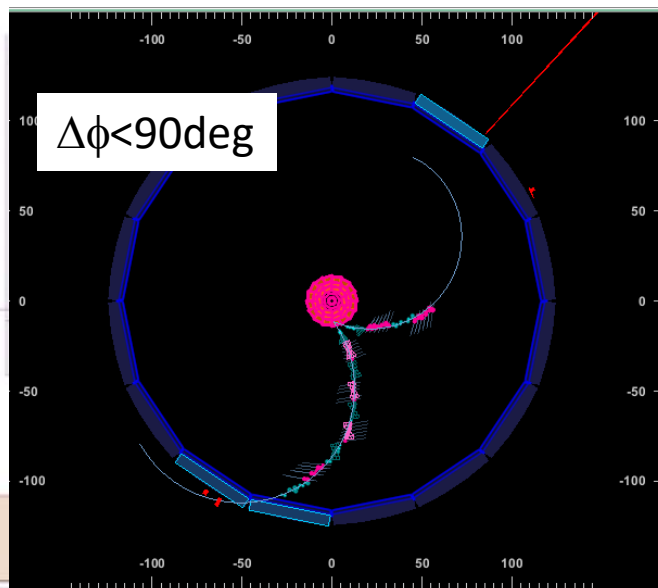




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Topology 情報を使える



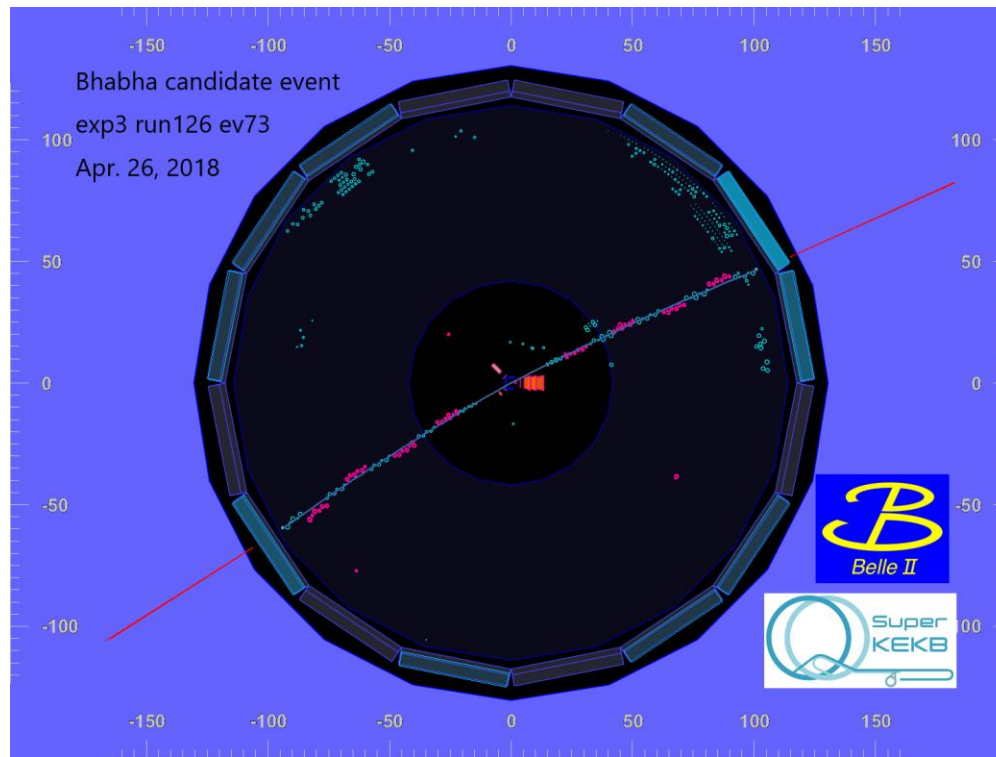
# Standard Trigger

- BBbar 事象は最優先 (1nb)
  - ほぼ100%の trigger efficiency が要求される
  - $L_{\max}=6 \times 10^{35}/\text{cm}^2/\text{s} = 600 \text{ nb/s}$  だと 600Hz
- BBbar 事象での粒子数
  - 平均11本の荷電粒子
  - 平均5個の光子
  - 最も multiplicity が高い
- Trigger 条件は以下の OR
  - 3 track (2 2D-track + 1 3D-track)
  - 2 track (1 2D-track + 1 3D-track) with opening angle  $\Delta\phi > 90\text{deg}$  with Bhabha veto
  - hie =  $E_{\text{sum}} > 1\text{GeV}$  with Bhabha veto
  - nCluster  $\geq 4$
- 非常に緩い条件かつ背景事象を取ることがそれほど多くない
  - ee $\rightarrow$ qq もこれでほとんど取れる
  - ただし、これだけだと low multiplicity な event はとれない場合もある

Physics process	Cross section [nb]	Selection Criteria
$\Upsilon(4S)$	$1.110 \pm 0.008$	} 5nb
$u\bar{u}(\gamma)$	1.61	
$d\bar{d}(\gamma)$	0.40	
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$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5 \text{ GeV}$ in CDC, $\geq 1 \gamma$ ( $E_\gamma > 0.5 \text{ GeV}$ ) in
$\tau^+\tau^-(\gamma)$	0.919	← 1nb
$\nu\bar{\nu}(\gamma)$	$0.25 \times 10^{-3}$	-
$e^+e^-e^+e^-$	$39.7 \pm 0.1$ (MC stat.)	$W_{\ell\ell} > 0.5 \text{ GeV}/c^2$
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# Esum > 1GeV with Bhabha veto

- Bhabha は  $\sigma$  が大きいので veto しないと trigger rate があふれてしまう
- CM系で  $E > 4.5\text{GeV}$  と  $E > 3.0\text{GeV}$  の3次元の back-to-back cluster がある event を veto
  - Bhabha に似ている dark sector 事象は veto されてしまう
  - 次の run からは single photon が Forward に行く radiative Bhabha も veto される



# DS と Standard Trigger

- **hie** =  $E_{\text{sum}} > 1\text{GeV}$  with Bhabha veto
  - High energy photon がある event はだいたいこれでいける
    - Dark photon :  $e^+e^- \rightarrow \gamma A', A' \rightarrow \mu\mu$ 
      - low mass  $A' \rightarrow ee$  は Bhabha veto されるので専用の trigger が必要
    - Invisible Dark Higgs :  $e^+e^- \rightarrow A'H', A' \rightarrow \mu\mu$
    - ALP :  $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma\gamma$
- 2 track with opening angle  $\Delta\phi > 90\text{deg}$  with Bhabha veto
  - Track と Invisible な final state。ただ、invisible が重いと eff が悪くなるので  $\phi > 30\text{deg}$ 
    - Invisible  $Z'$  in  $L_\mu-L_\tau$  :  $e^+e^- \rightarrow \mu\mu Z', Z' \rightarrow \chi\chi$

# Low Multiplicity Trigger ( $\tau$ , DS, HVP, etc)

- Single track trigger : 3D-track with  $p > 0.7 \text{ GeV}$ 
  - Track が multiplicity が低い event はほとんど
    - Invisible  $Z'$  in  $L_\mu$ - $L_\tau$  :  $e^+e^- \rightarrow \mu\mu Z'$ ,  $Z' \rightarrow \chi\chi$
- Single Barrel Cluster trigger  $E > 1 \text{ GeV}$  with no other cluster with  $E > 300 \text{ MeV}$ 
  - Single photon
    - Invisible Dark photon :  $e^+e^- \rightarrow \gamma A'$ ,
- Low mass Dark photon  $ee$  : 3D Bhabha in barrel, one cluster-track matching, track opening angle  $\phi < 90 \text{ deg}$ 
  - 2つの近接電子陽電子 が 1つの cluster に見えるので Bhabha と認識される
    - Dark photon :  $e^+e^- \rightarrow \gamma A'$ ,  $A' \rightarrow ee$

# Belle II での軽い新粒子探索

# Belle II での軽い新粒子探索

- Dark Sector Mediators (and dark matter)
  - Pseudo Scalar : ALPs
  - Scalar : Dark Higgs
  - Vector : Dark Photon,  $Z'$  in  $L_\mu-L_\tau$ 
    - ATOMKI X17 (a variant of dark photon?)
    - Inelastic dark matter :  $\chi_1$  and  $\chi_2$
    - SIMP
  - Fermion : sterile neutrinos
- Heavy QCD Axion
- Dark matter in B-Mesogenesis (Dark Matter has baryon number)
- CP odd scalar  $A^0$
- SUSY singlino
- Magnetic monopole/dyon
  
- And new particles in your models

# Dark Photon

- Belle II での探索結果はまだ出ていない
  - Belle, Babar の制限が強いので。

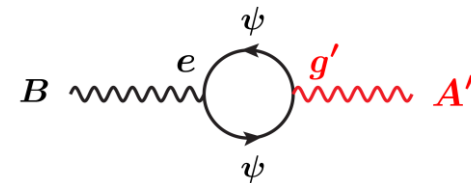
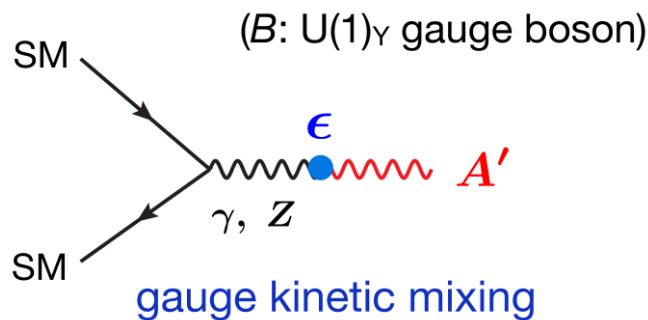


# Dark Photon

- U(1) gauge boson の mixing は禁止されていない。
- 光子が dark photon  $A'$  に転換することが可能である。
- Dark photon は
  - Invisible : dark matter に崩壊 ( $m_{A'} > 2m_{DM}$ ), 結合定数  $\alpha_D$
  - Visible : SM 粒子に崩壊 ( $m_{A'} < 2m_{DM}$ ), 結合定数  $\varepsilon^2 \alpha_{EM}$

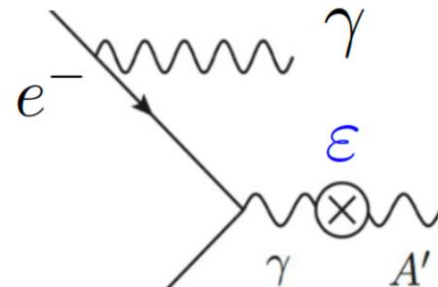
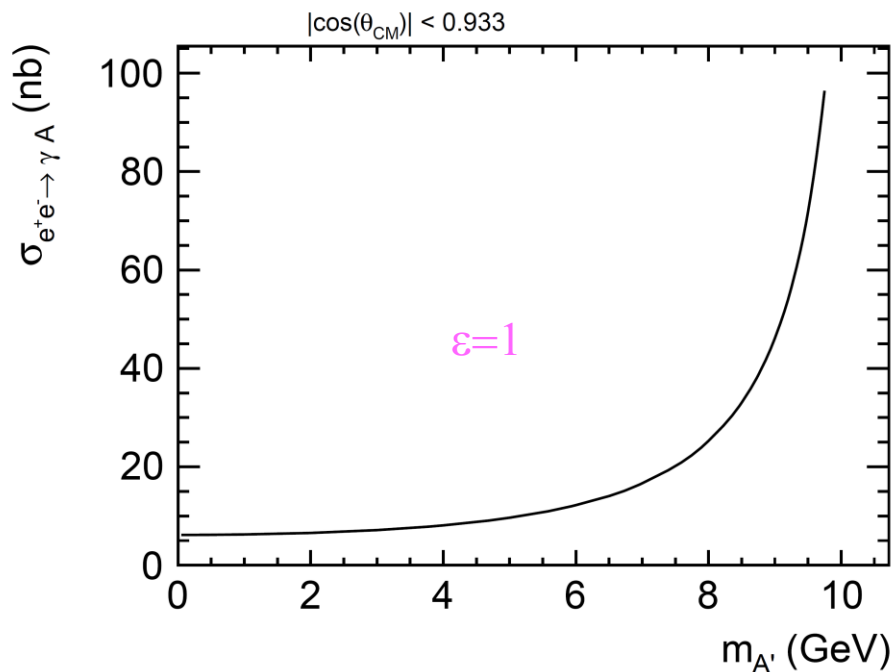
一般に  $\alpha_D \gg \varepsilon^2 \alpha_{EM}$

- Vector Portal :  $\varepsilon B_{\mu\nu} A'^{\mu\nu}$



# Dark photon の生成

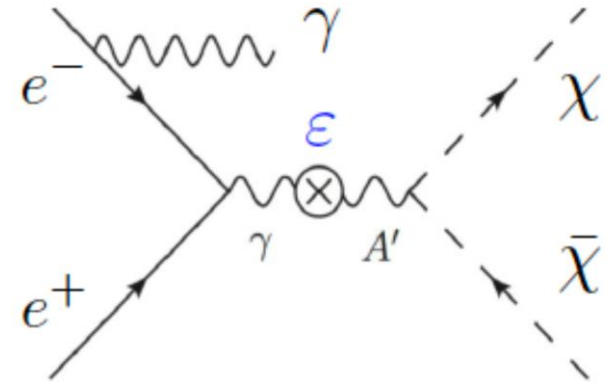
- $\epsilon=10^{-3}$  とすると 1GeV  $A'$  で  $5\text{fb}^{-1}$



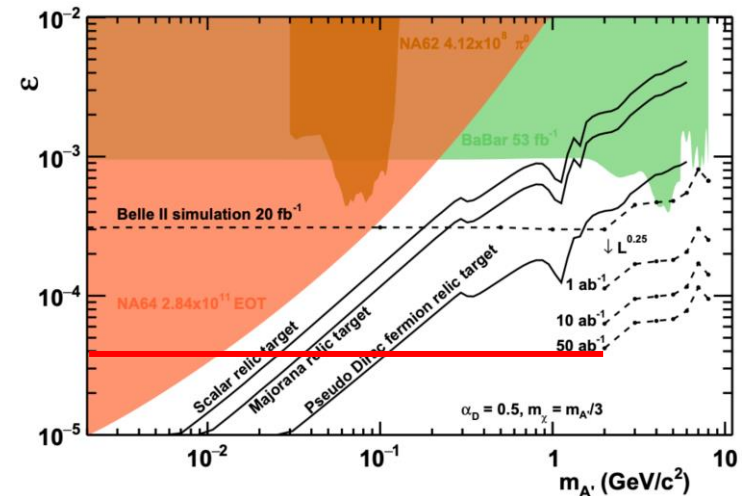
$$\sigma \propto \frac{\epsilon^2 \alpha_{\text{em}}^2}{E^2}$$

# Invisible Dark Photon

- 終状態は光子1つ
  - Trigger : ECL total energy >1GeV
- 背景事象
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$
  - Cosmic
  - Single beam background
- 制限
  - $\epsilon \sim < 3 \times 10^{-4}$  with  $20 \text{ fb}^{-1}$
  - $\epsilon \sim < 4 \times 10^{-4}$  with  $50 \text{ ab}^{-1}$

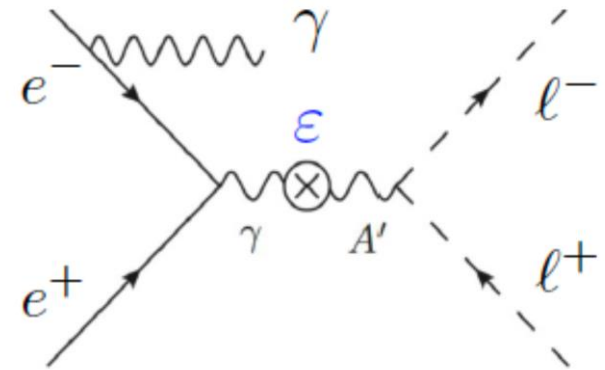


mono-photon + invisible

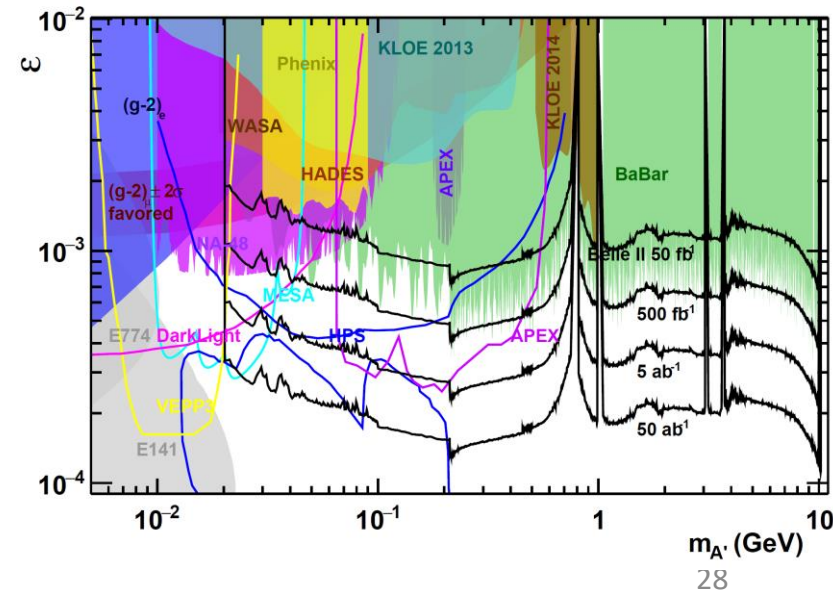


# Visible Dark Photon

- 終状態は光子と dilepton
  - Trigger : hie or two track trigger
- Signature
  - $e^+e^- \rightarrow A' \gamma, A' \rightarrow e^+e^-$  or  $\mu^+\mu^-$
- 背景事象
  - $e^+e^- \rightarrow e^+e^- \gamma$
  - $e^+e^- \rightarrow \mu^+\mu^- \gamma$
- 感度
  - $\varepsilon \sim$  a few  $\times 10^{-4}$



photon + di-lepton resonance



# $L_\mu - L_\tau$ 模型での $Z'$

- 特殊な dark photon
- むしろ dark sector というより anomaly free に motivate された模型という印象
- 最近だと muon  $g-2$  に motivate された模型

# $L_\mu$ - $L_\tau$ 模型での $Z'$

- $L_\mu$ - $L_\tau$  模型では  $Z'$  は第二第三世代のレプトンにしか結合しない:  $\mu, \tau, \nu_\mu$ , and  $\nu_\tau$

- Two parameters :  $m_{Z'}$  and  $g'$

$$\mathcal{L} = -g' \bar{\mu} \gamma^\mu Z'_\mu \mu + g' \bar{\tau} \gamma^\mu Z'_\mu \tau - g' \bar{\nu}_{\mu,L} \gamma^\mu Z'_\mu \nu_{\mu,L} + g' \bar{\nu}_{\tau,L} \gamma^\mu Z'_\mu \nu_{\tau,L}$$

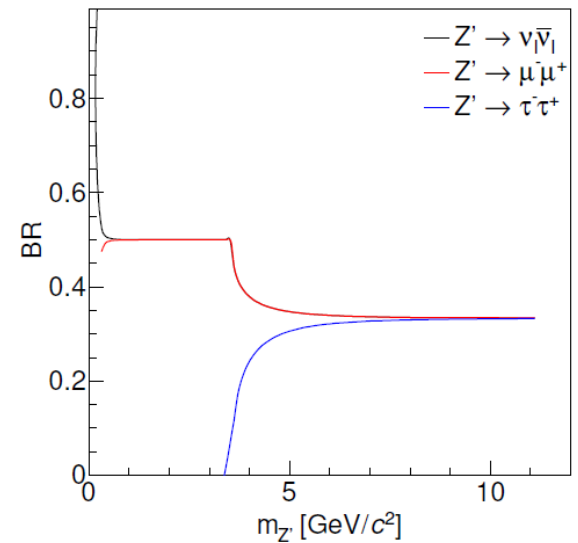
- もし dark matter と結合可能で  $m_{Z'} > 2m_\chi$  なら dark matter への崩壊分岐比がほぼ100%

- muon  $g-2$  anomalyを説明できる

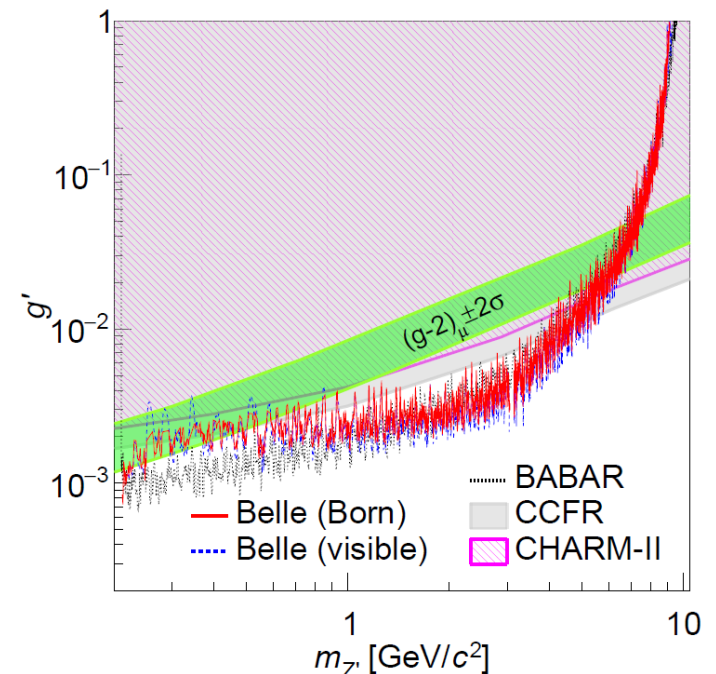
- $m_{Z'} > 2m_\mu$  は排除されている

- Belle and BaBar, with muons
- neutrino trident experiments CCFR and CHARM-II
- BOREXINO limit  $> 10\text{MeV}$  (Not shown)

- Invisible decay で探索する

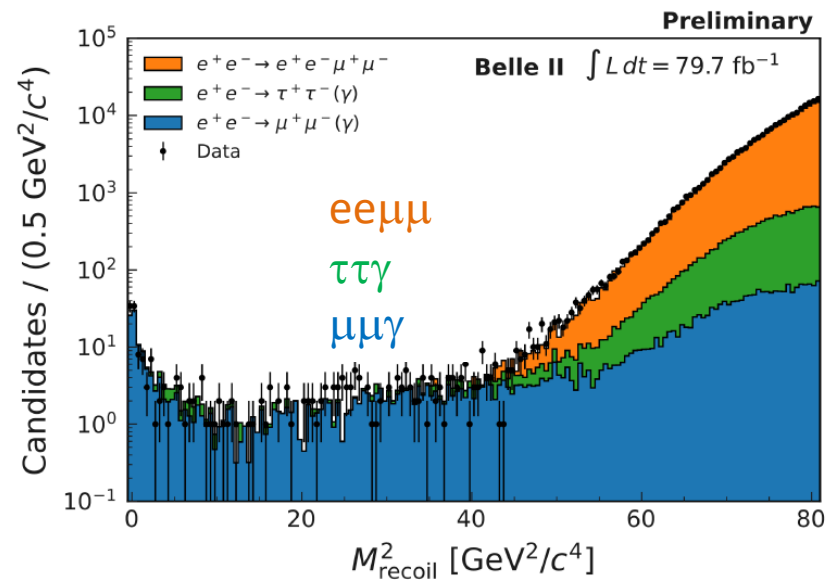
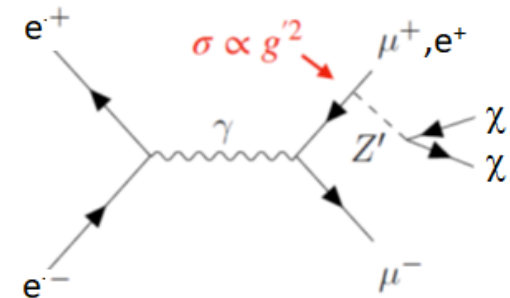


dark matter への崩壊分岐比を0%と仮定し muon モードで探索



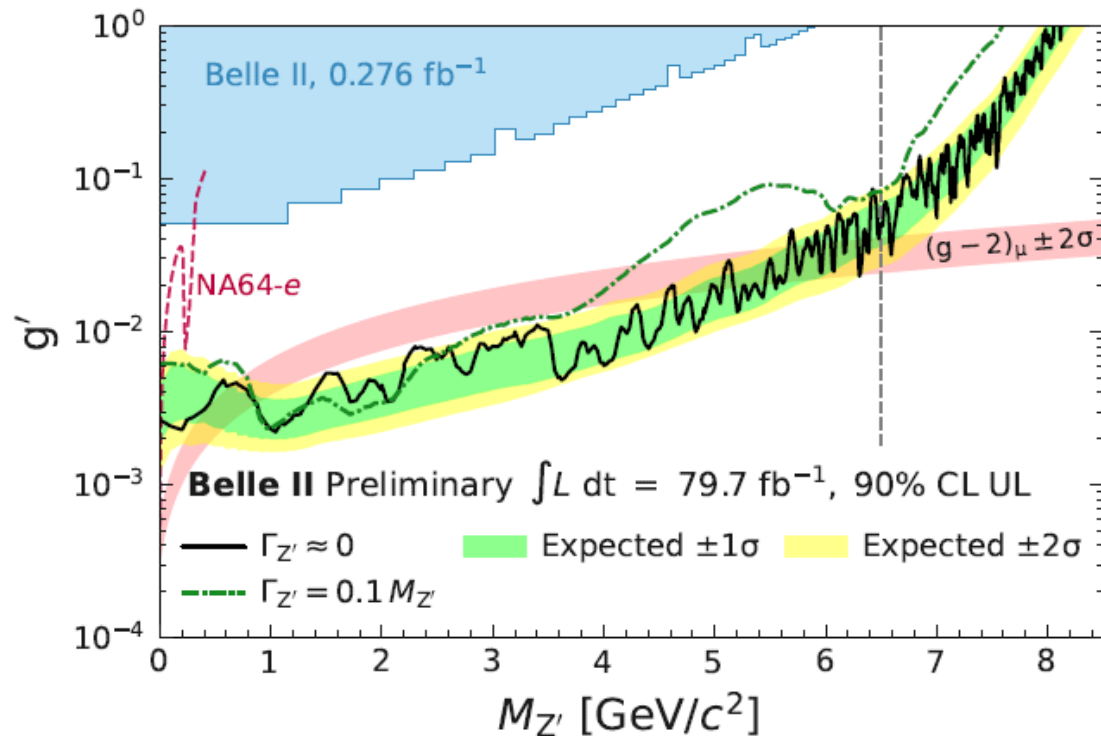
# Invisible Z' in L<sub>μ</sub>-L<sub>τ</sub> model

- Typical cross section
  - ~10fb with  $g'=0.01$  and  $M_{Z'} = 1\text{GeV}$
- Signature
  - $e^+e^- \rightarrow \mu^+\mu^- Z' \rightarrow \mu^+\mu^- \chi\chi$
- Trigger
  - 2 track with opening angle
- Search
  - Dominant backgrounds
    - $ee \rightarrow ee\mu\mu$ ,  $\tau\tau\gamma$ ,  $\mu\mu\gamma$
  - Recoil mass and  $\theta_{\text{Recoil}}$  to identify the signal



# Limit on invisible Z'

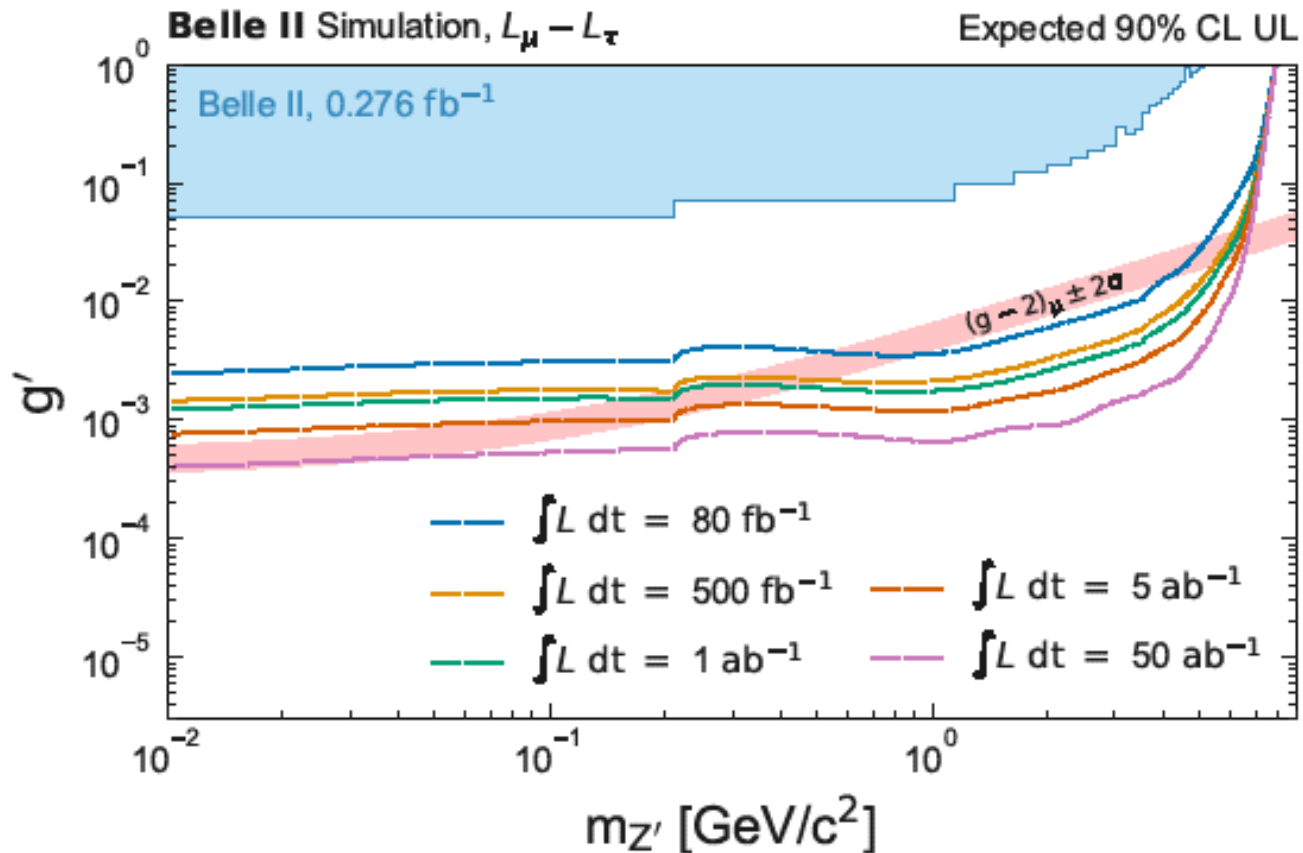
- Invisible 崩壊で世界で初めて **muon g-2 anomaly** を説明する領域を排除
  - $0.8 < M_{Z'} < 4.5\text{GeV}$





# Invisible $Z'$ : 将来の展望

- $50\text{ab}^{-1}$  あれば muon  $g-2$  を説明できる領域での発見もしくは排除が可能



# Axion Like Particles (ALPs)

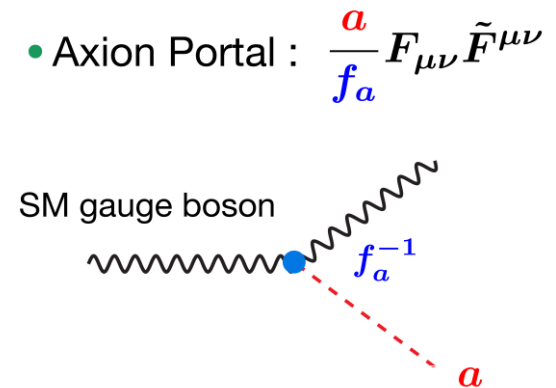
# Axion Like Particles (ALPs)

- Axion like particles (ALPs) 以下の
  - Global 対称性の自発的破れ
  - 超弦理論の String compactification
    - SM gauge group を作る最大の群を選ぶと 181820 種類の ALPs が存在
- QCD Axion は質量と崩壊定数に関係があるが ( $m_\pi f_\pi \sim m_a f_a$ ) ALPs には無い
  - 探索可能な parameter space が広い
- 単純のために ALP が光子としか結合しないと 2 parameters
  - $g_{a\gamma\gamma}$  : coupling constant
  - $m_a$  : mass of ALP

$$\delta\mathcal{L} = -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2$$

- Decay width (lifetime)

$$\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$



# Signature

- ALP can be generated from

- ALP-strahlung
- Photon fusion
  - under study

- Cross section

- $\sim 1\text{fb}$  for  $g_{a\gamma\gamma} = 10^{-4} \text{ GeV}^{-1}$

$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\text{QED}}}{24} \left(1 - \frac{m_a^2}{s}\right)^3$$

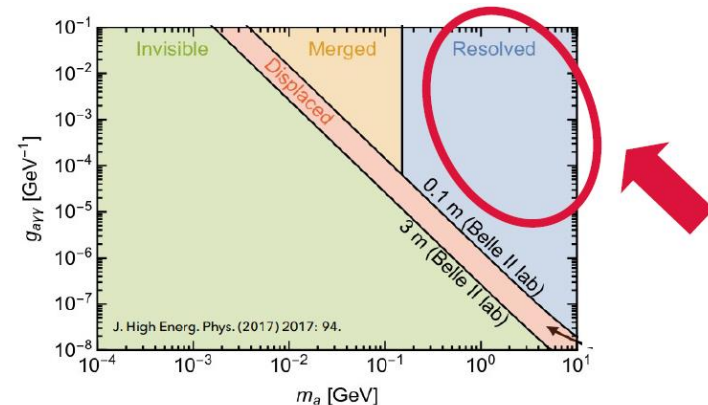
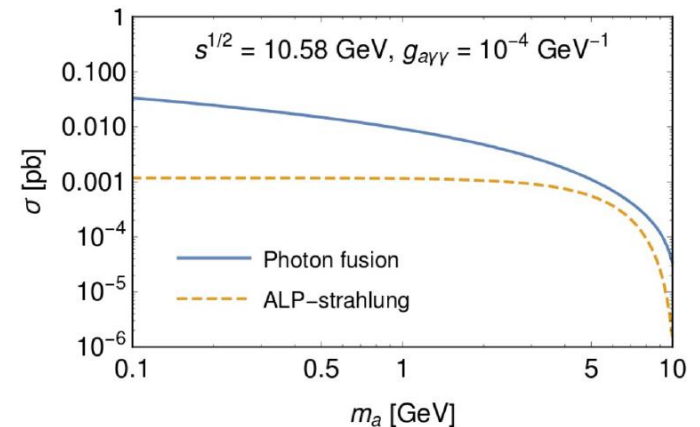
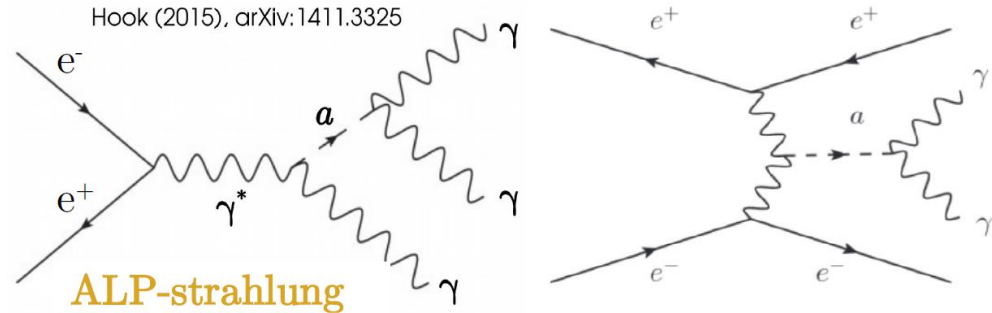
- Sequential two-body decays

- $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma\gamma$
- Only three photons in a final states

- Belle II search for **shorter lifetime region**

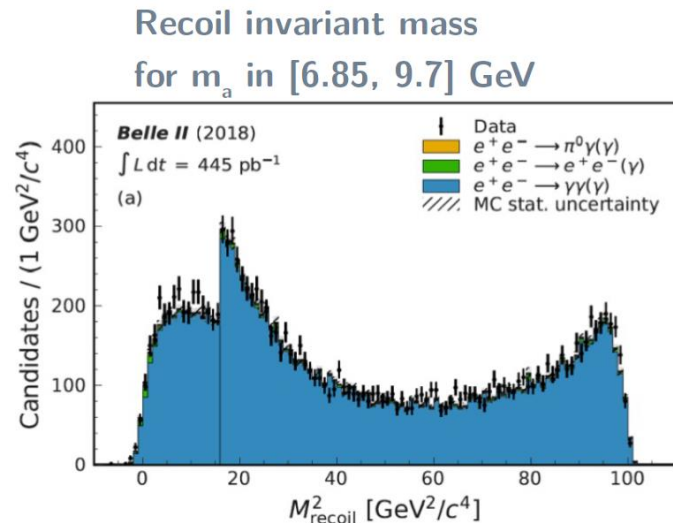
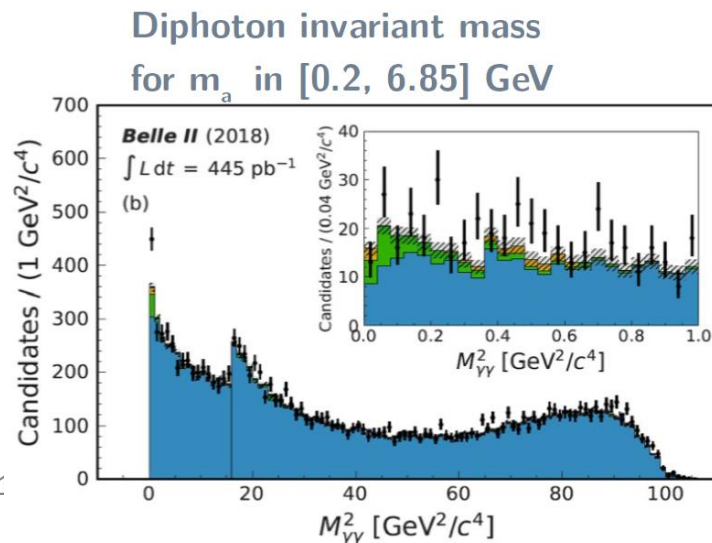
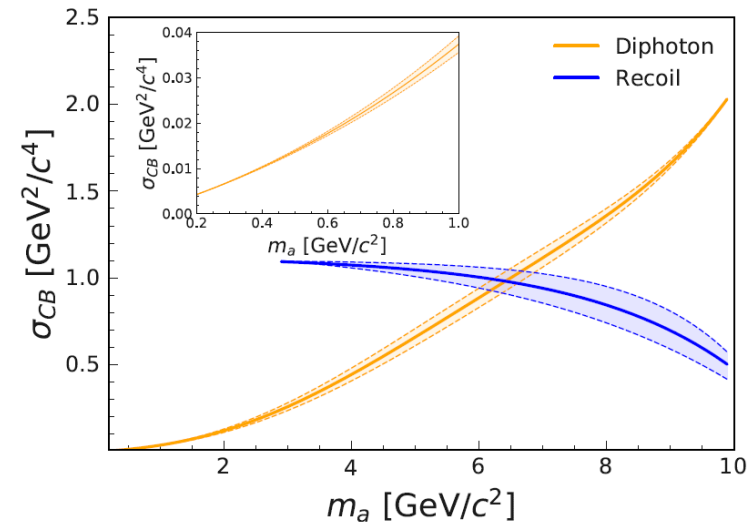
- Large coupling and large mass
  - beam dump experiments  $\rightarrow$  longer lifetime
- two photons are resolved in EM calorimeters

$$\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$



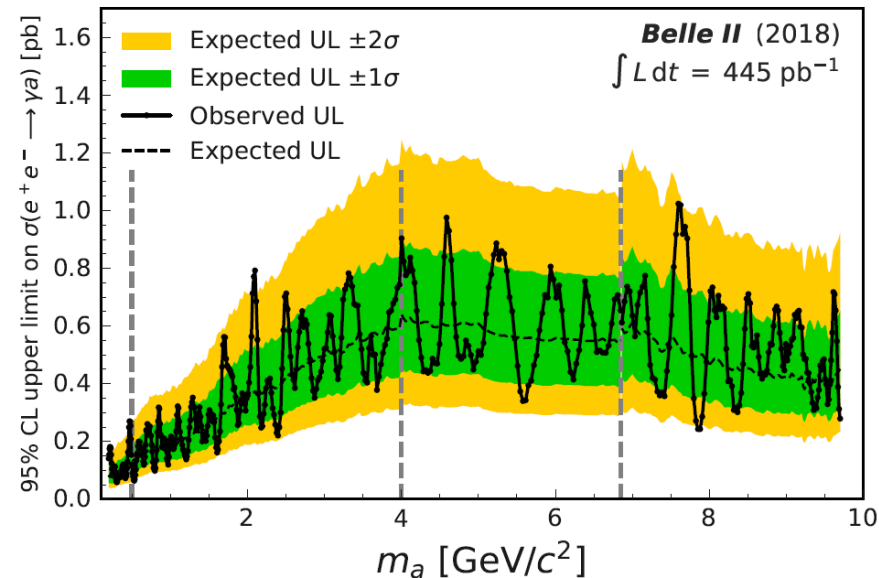
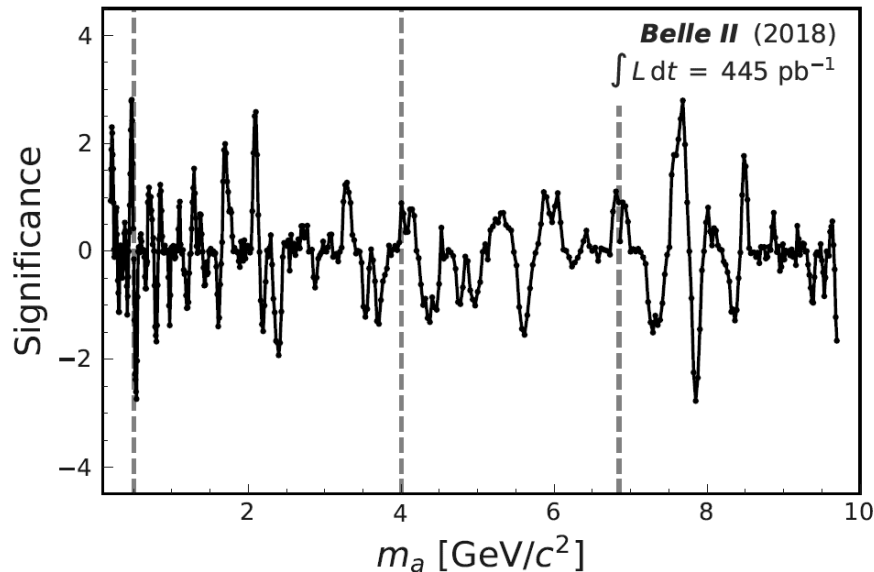
# Search for ALPs at Belle II

- Trigger
  - hie
- Two Reconstruction technique
  - Invariant mass for low mass [0.2, 6.85]GeV
  - Recoil mass for high mass [6.85, 9.7]GeV
- Dominant background is SM  $e^+e^- \rightarrow \gamma\gamma\gamma$



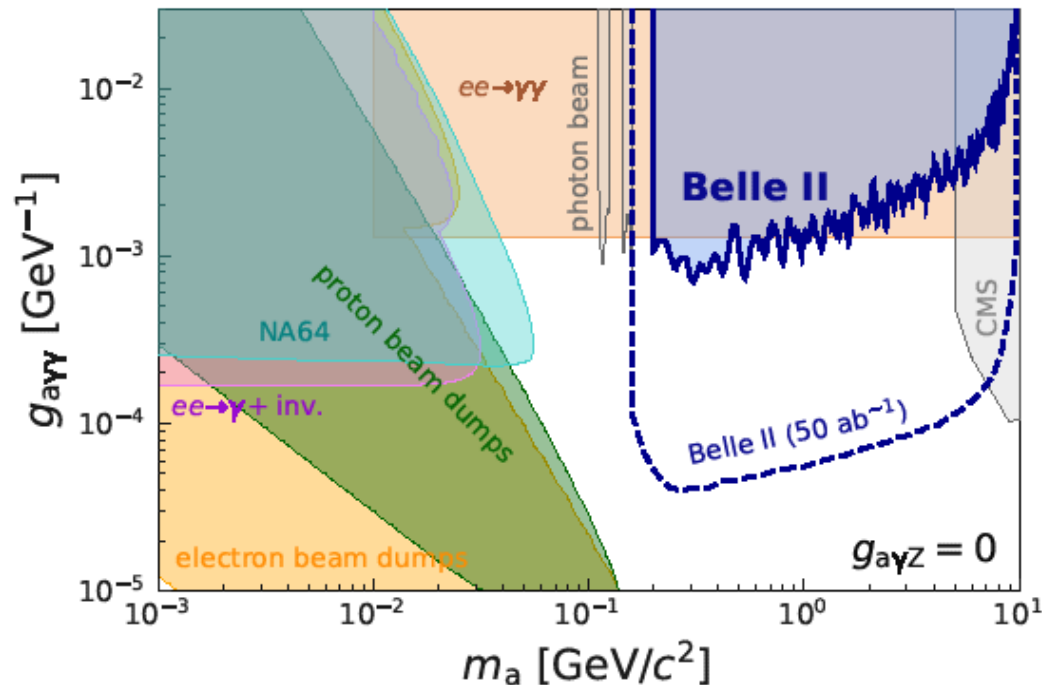
# Limit on $\sigma(e^+e^- \rightarrow a\gamma)$

- No significant excess is observed
  - Largest local significance of  $2.8\sigma$  at  $m_a=0.447\text{GeV}$
- Set a limit on  $\sigma$ .
  - $\sigma < 1\text{pb}$



# Limit on ALP parameter space

- Coupling around  $10^{-3}\text{GeV}^{-1}$  level
- World's best limit around 500MeV
- We can improve the sensitivity more than one order of magnitude in coupling with  $50\text{ab}^{-1}$  data
- Adding **photon fusion process** gives better limit



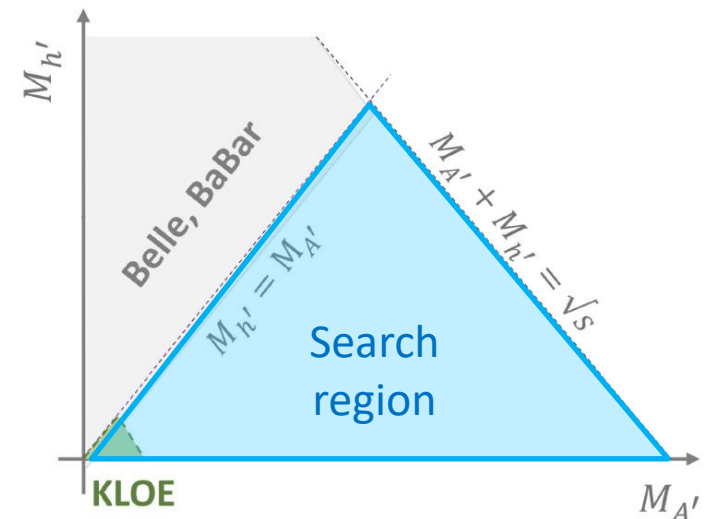
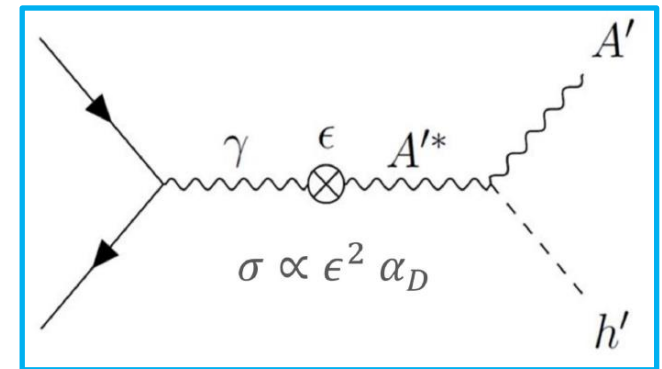
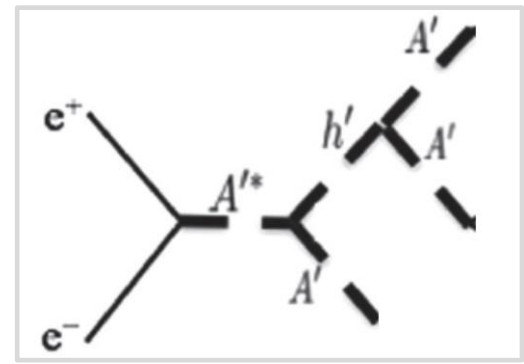
# Dark Scalar

- Dark Photon からの輻射
- B中間子ループ崩壊での top quark からの輻射



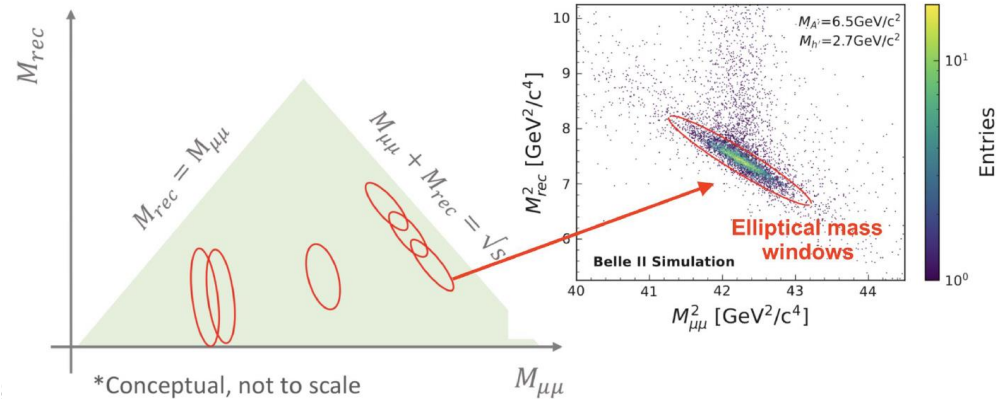
# Dark Higgs

- Dark photon  $A'$  は dark Higgs field の自発的対称性の破れで質量を獲得したかもしれない  $\rightarrow$  physical dark Higgs  $h'$  が存在
  - 今回は SM Higgs との mixing は仮定しない
  - Portal 粒子では無い
- Dark Higgs は dark higgsstrahlung process で生成可能 :  $e^+e^- \rightarrow A'h'$
- 4 parameters
  - $M_{A'}, M_{h'}$
  - $\epsilon$  : kinetic mixing
  - $\alpha_D$  : coupling constant of dark sector
- $M_{h'} > M_{A'}$ 
  - Dark Higgs は visible  $h' \rightarrow A'A'$
  - already covered by Belle and Babar
- $M_{h'} < M_{A'}$ 
  - Dark Higgs は invisible
  - KLOE. でのみしか探索されていない
  - 広い探索領域が残っている

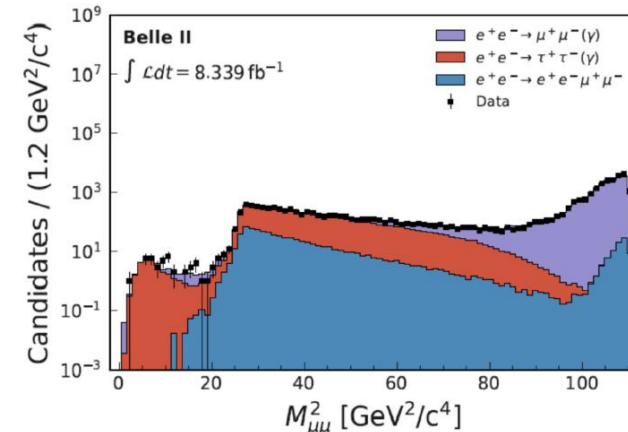
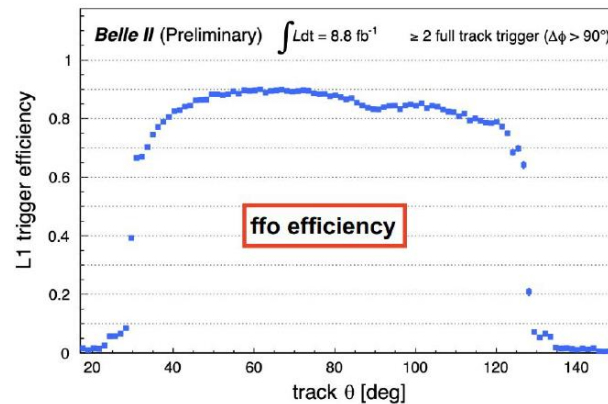


# Search for Dark Higgs in $e^+e^- \rightarrow A'h'$

- Dark photon decay
  - $A' \rightarrow \mu\mu$
  - $M_{\mu\mu} > 1.65\text{GeV}$  for trigger limitation
- Dark Higgs
  - invisible
  - Recoil mass against dimuon system
- Trigger on dimuon
  - two track with opening angle  $\Delta\phi > 90^\circ$
  - 90% efficiency
- Search in two dimensional plain
  - $M_{\mu\mu}$  VS  $M_{\text{rec}}$ 
    - Correlated
  - Ellipse signal windows

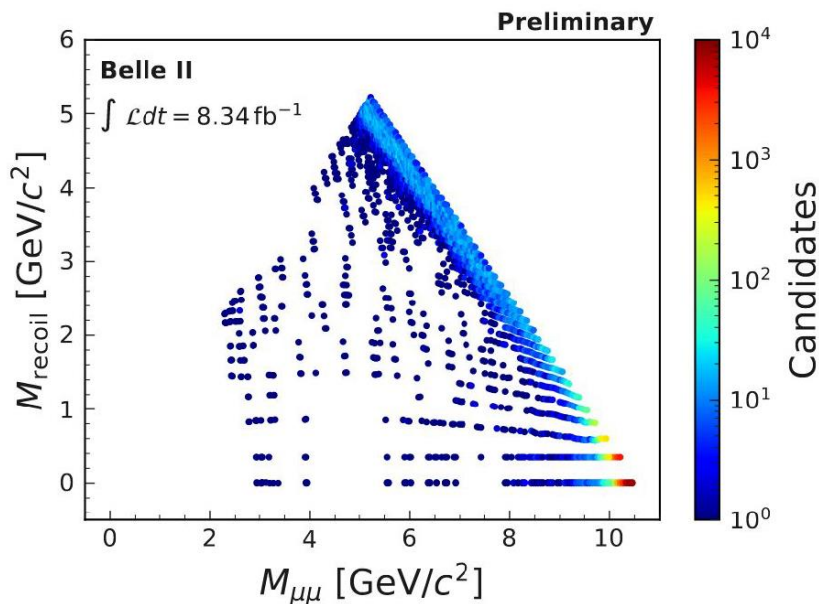


- Dominant background
  - $e^+e^- \rightarrow \mu\mu\gamma$
  - $e^+e^- \rightarrow \tau\tau$
  - $e^+e^- \rightarrow ee\mu\mu$

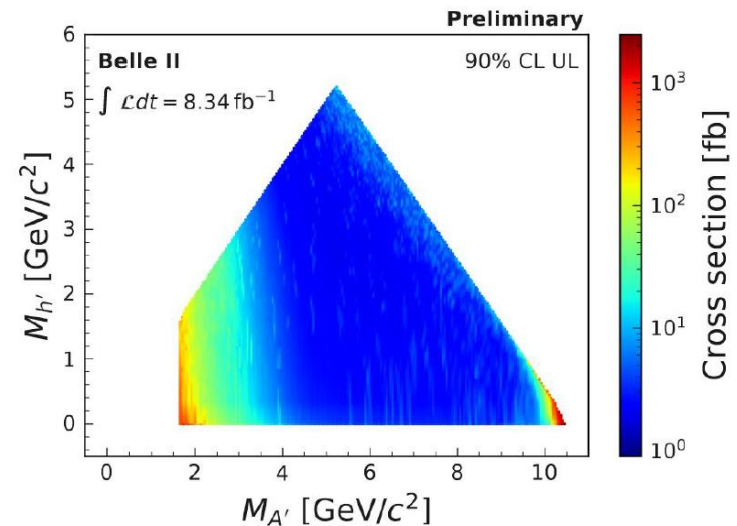


# Limits on $\sigma(e^+e^- \rightarrow A'h')$

- No significant signal is observed
- Counting method to set the cross section limits in each bin
  - $\sigma(e^+e^- \rightarrow A'h') < 10\text{fb}$  for wide region
- World's leading limit for  $1.65 < M_{A'} < 10.51\text{GeV}$

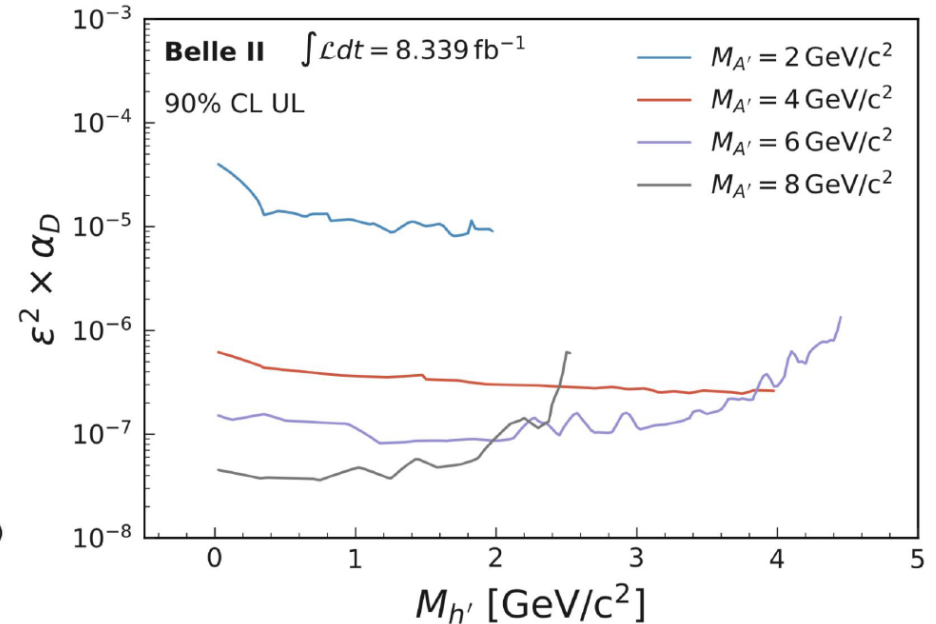
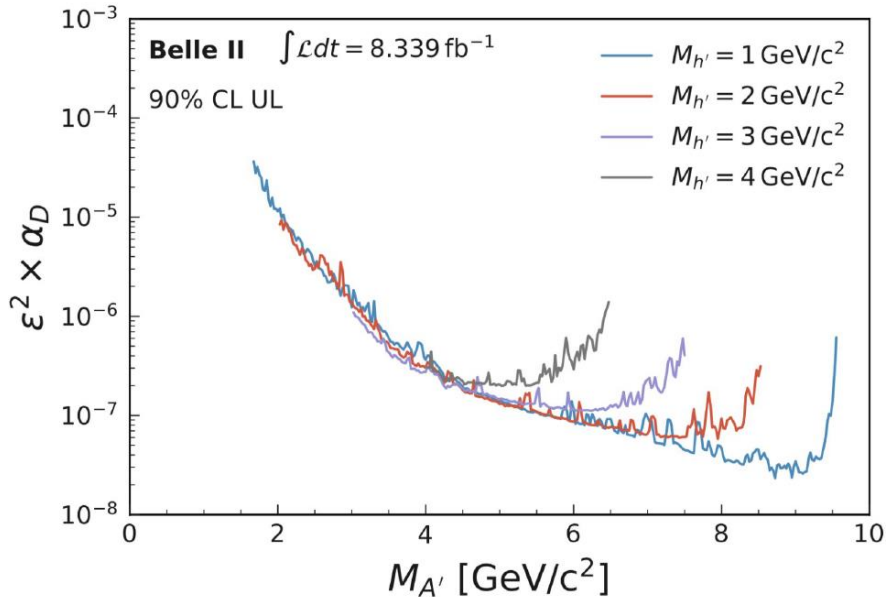
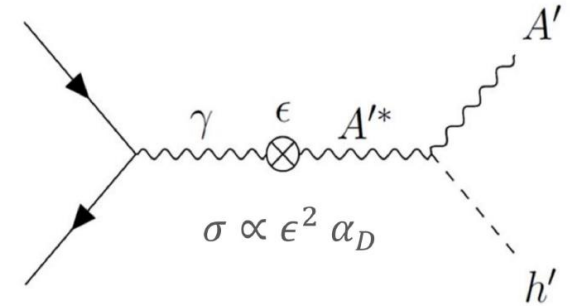


Discreteness is due to binning effect



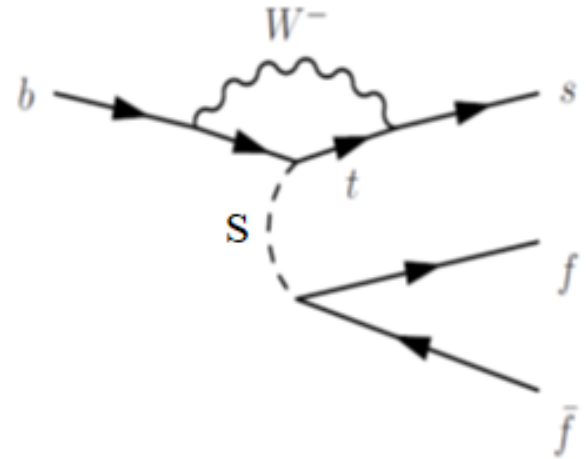
# Limits on Physics Parameters

- 4 parameters :  $M_{A'}$ ,  $M_{h'}$ ,  $\epsilon$  and  $\alpha_D$
- Limit on  $\epsilon^2 \alpha_D$ 
  - Kinetic mixing  $\epsilon$  and coupling constant  $\alpha_D$  cannot be separately constrained in this process.
- First limits in this mass region

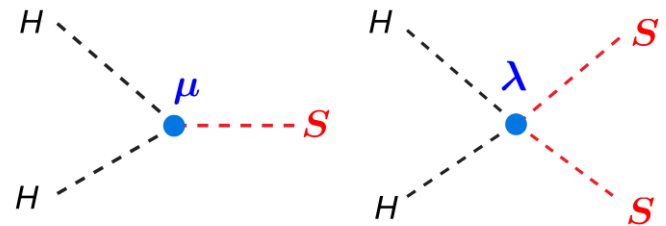


# B中間子崩壊でのDark Scalar

- B中間子の  $b \rightarrow s$  Penguin 崩壊は loop の中に top quark を含む
  - 湯川結合がデカい
- SM Higgs との mixing があれば dark scalar を作ることが可能である
  - Mixing angle  $\theta$



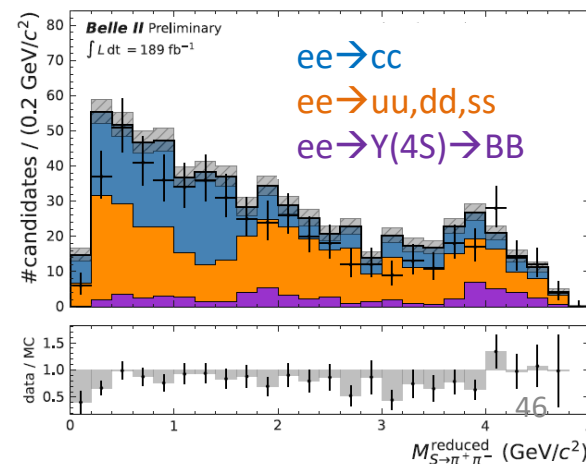
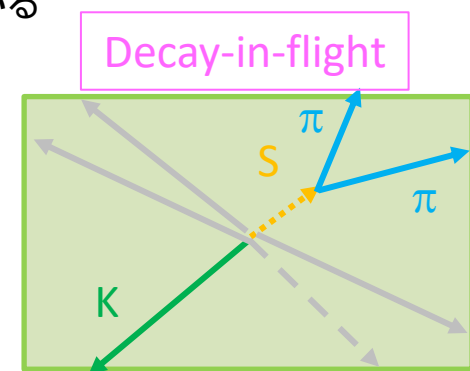
• Scalar Portal :  $(\mu S + \lambda' S^2)|H|^2$



$H$  ---  $\mu v$  ---  $S$  scalar mixing

# Long-lived Dark Scalar in B Decays

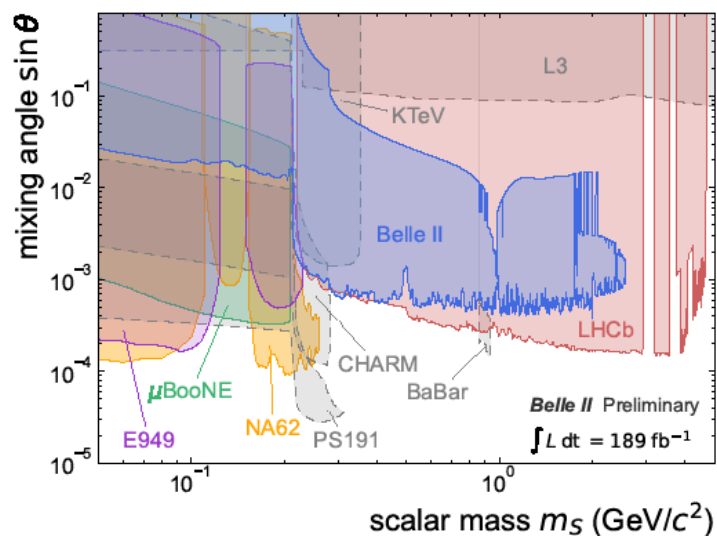
- Dark scalar particles  $S$ 
  - $M_S < 2M_\chi$ 
    - $S \rightarrow \chi\chi$  は relic density を説明出来る領域はすでに排除されている
  - SM Higgs と混ざることが出来る with the mixing angle  $\theta$ 
    - 湯川結合は重い fermion でデカイ
  - long-lived if  $\theta$  is small
- $B \rightarrow K^+ S$  and  $B \rightarrow K^{*0} S$  decays
  - $S$  is radiated off from internal top quark in  $b \rightarrow s$  decays
  - $S \rightarrow ee, \mu\mu, \pi\pi, KK$
  - In total, 8 decay modes
- $B$ が長寿命粒子に崩壊
  - Trigger を気にしなくて良い
  - Clean displaced vertex signature
  - Dominant backgrounds are combinatorial
    - $ee \rightarrow cc, ee \rightarrow uu, dd, ss, ee \rightarrow Y(4S) \rightarrow BB$
  - Long-lived  $K_S^0$  is a good control sample



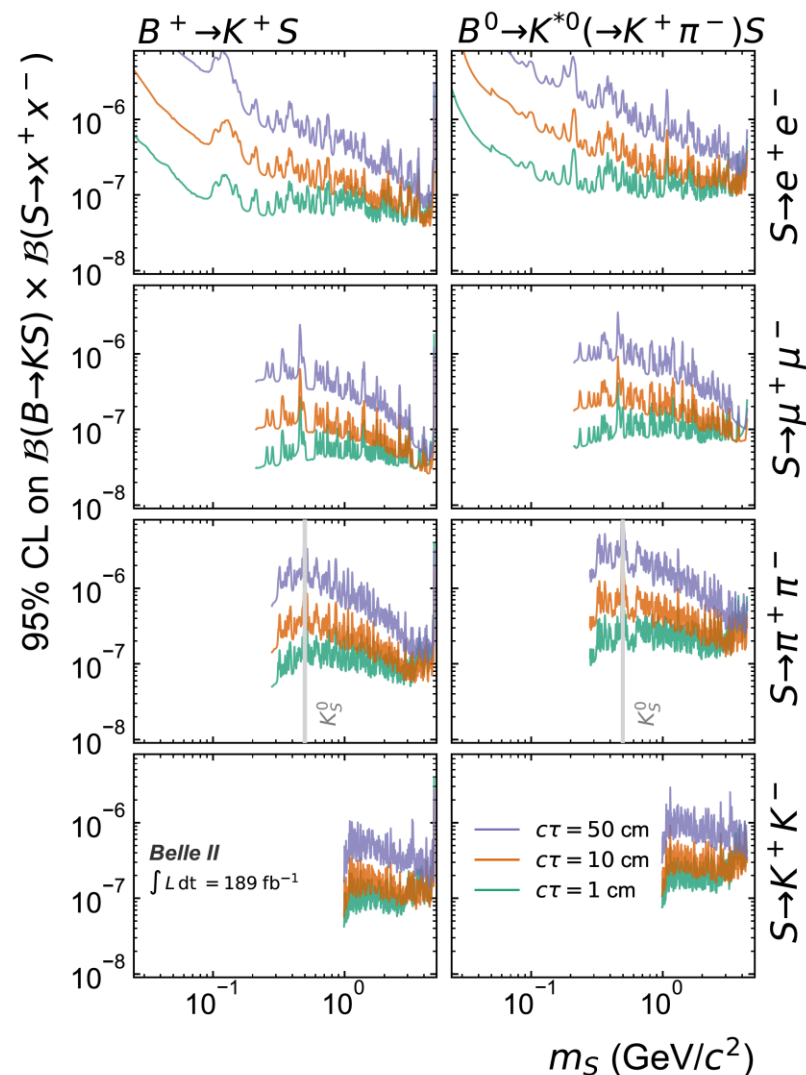
# Limit on $B \rightarrow K^{(*)} S$

- BFに対するモデル非依存の制限
  - As functions of  $c\tau$  and mass.
  - For **8 decay modes**
  - **First limit on S decaying to hadrons**
- モデル依存の制限 on  $m_S$  vs.  $\sin\theta$ 
  - Dark Higgs mixing with the SM Higgs  
Filimonova, Schäfer, Westhoff, Phys. Rev. D 101, 095006

## Model dependent



Model independent  $c\tau = 1\text{cm}, 10\text{cm}, 50\text{cm}$



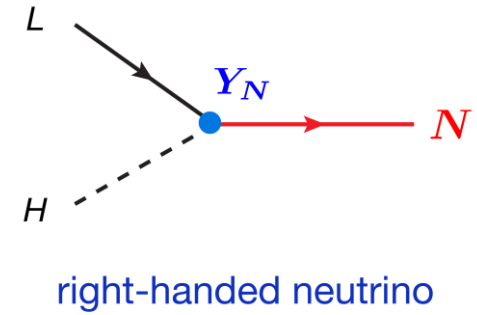
# Sterile Neutrino

- Belle II で最近始めました
  - Belle の制限が強い

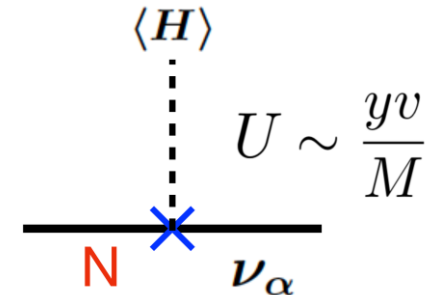


# Sterile Neutrino

• Fermion Portal :  $Y_N \bar{L} H N$

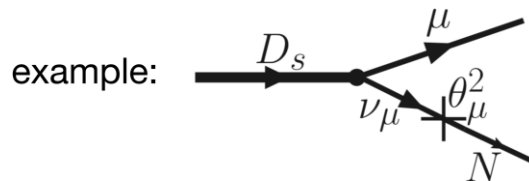


- EW scaleより下であればNeutrino の生成は
  - B,D中間子の(セミ)レプトニック崩壊
    - $B \rightarrow D^{(*)} l \nu, B^+ \rightarrow \mu^+ \nu$
  - $\tau$ レプトンの崩壊
- Active neutrino が Sterile neutrino と mixing
  - $U_{e4}, U_{\mu 4}, U_{\tau 4}$
- 崩壊の時も active neutrino への mixing で
- 基本的に長寿命
  - Weak interaction で崩壊
  - さらに mixing の効果

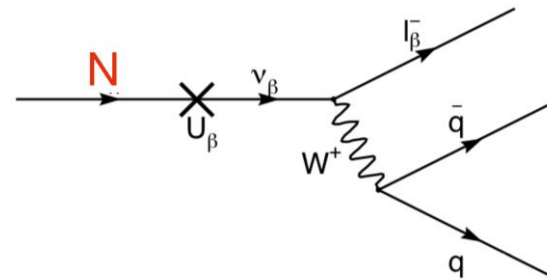


## Production

from meson decays:

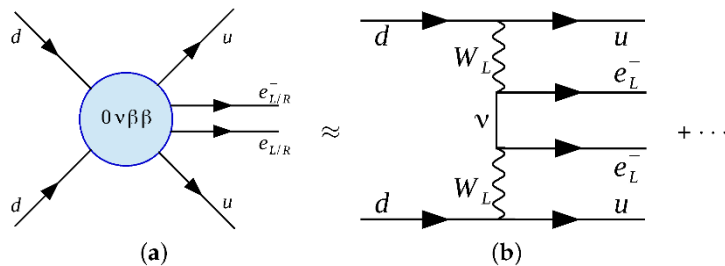


## Decay

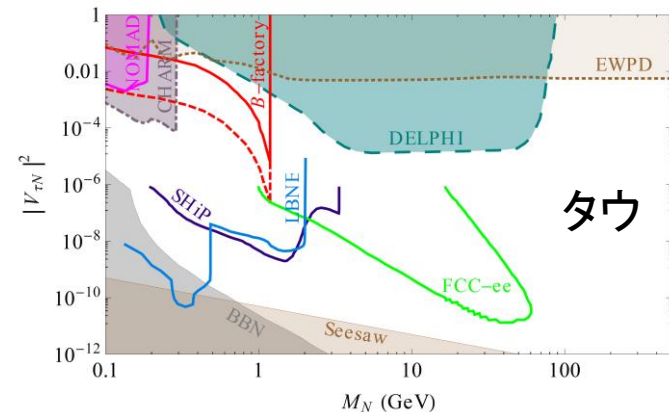
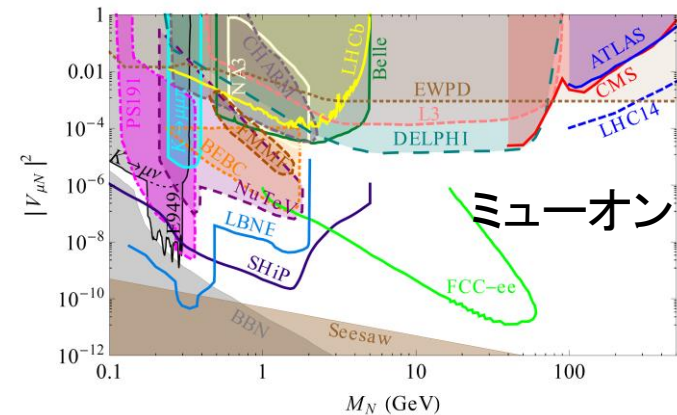
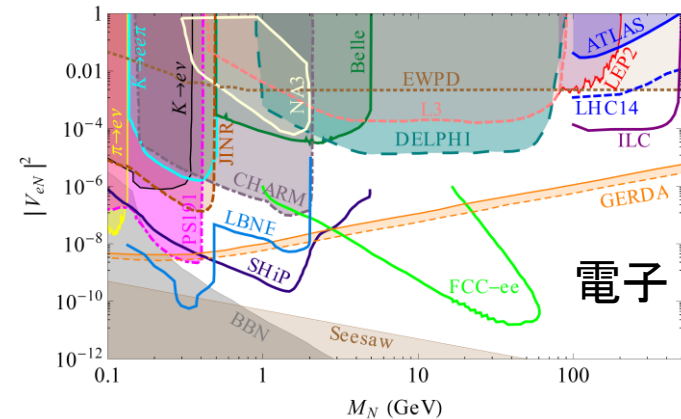


# Sterile Neutrinoの制限

- Collider
  - LEP, LHC, Belle
- Fixed target
  - CHARM
- $0\nu\beta\beta$ 
  - 電子モードはこれで強い制限がついている
    - 標準模型では  $2\nu\beta\beta$  だが majorana neutrino であれば  $0\nu\beta\beta$  が可能
  - $^{76}\text{Ge} \rightarrow ^{76}\text{Se} e^- e^-$  (GERDA)
  - $^{136}\text{Xe} \rightarrow ^{136}\text{Ba} e^- e^-$  (KAMLAND-Zen)

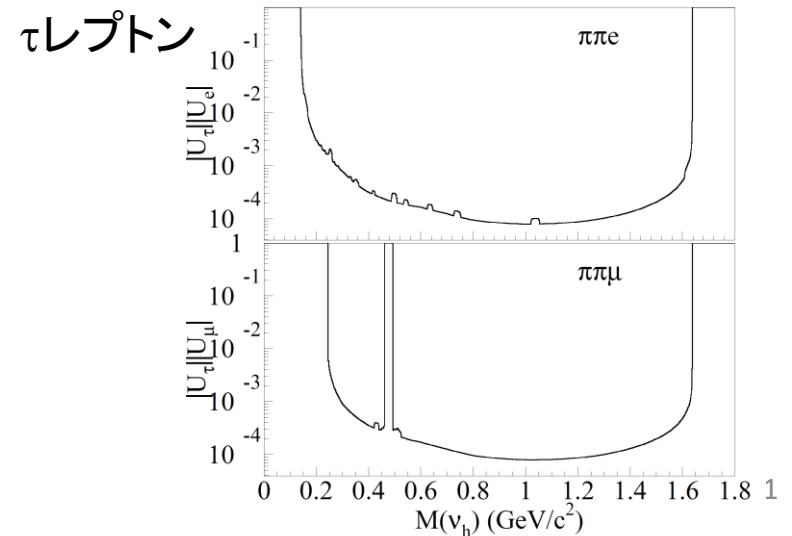
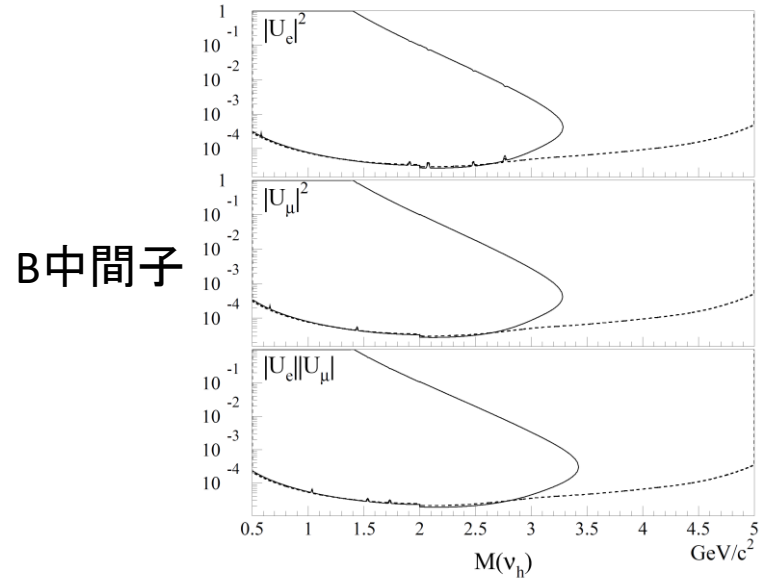
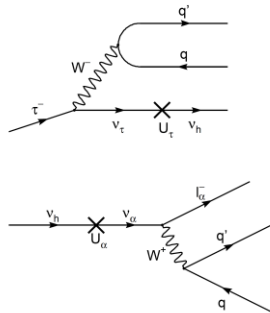


- 重要なのは**ミュオン**と**タウ**



# Belle での Sterile Neutrino 探索

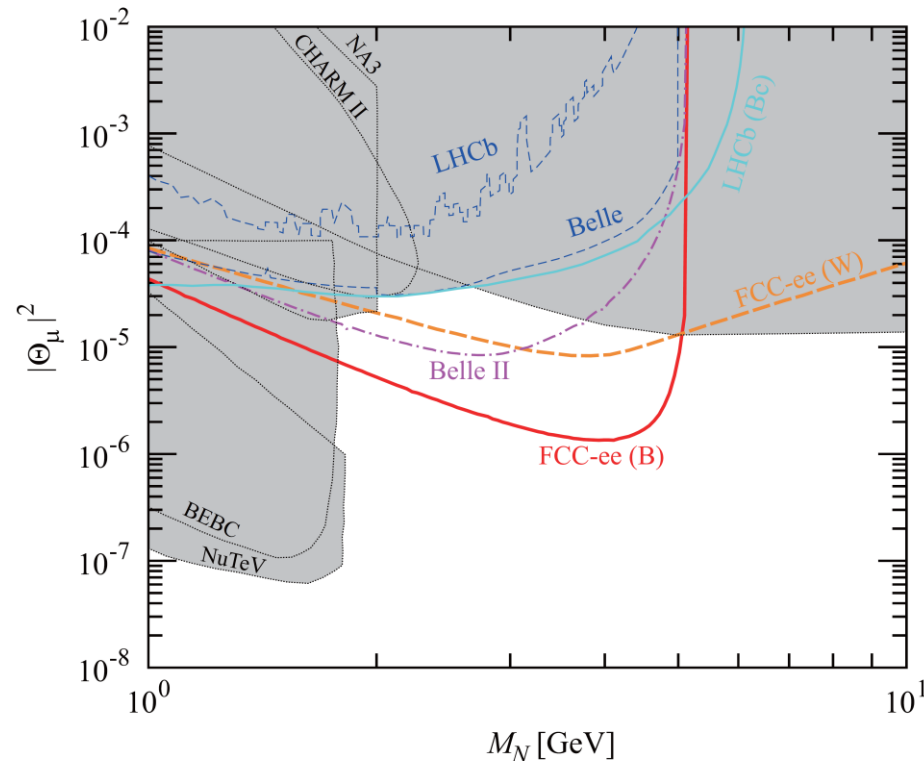
- B中間子崩壊 1301.1105
  - $B \rightarrow D^{(*)} | N, N \rightarrow | \pi$  ( $l=e, \mu$ )
  - $|U_e|^2, |U_\mu|^2, |U_e||U_\mu|$  に制限
- $\tau$ レプトン崩壊 2212.10095
  - $\tau \rightarrow N \pi, N \rightarrow | \pi$  ( $l=e, \mu$ )
  - $|U_e||U_\tau|, |U_\mu||U_\tau|$  に制限



- 生成と崩壊を見るので mixing matrix element の4乗  $|U|^4$  に制限

# $B^+ \rightarrow \mu^+ N$ at Belle II

- $B^+ \rightarrow \mu^+ N, N \rightarrow \mu^+ \pi^-$
- $N$  は重いので Helicity suppression が緩和される



Asaka, Ishida 15

# Invisible Sterile Neutrino

- 崩壊しない場合  $N$  は観測できない
  - $B \rightarrow D(*) \ell N$
  - $B^+ \rightarrow \mu^+ N$
- 逆側の  $B$  を tag して Recoil mass を測定
  - FEI の efficiency ( $\sim 0.3\%$ ) がかかる
  - 背景事象が多い
- 生成しか見ないので mixing matrix element の2乗  $|U|^2$  に制限

# Summary

- Belle II ではフレーバーの物理以外にも、軽い新粒子探索が可能である。
- Dark sector mediator 探索では暗黒物質に崩壊する場合も探索出来る。
- 今回説明できませんでしたが、inelastic dark matter や ATOMKI X17 など探しています
- 新しい模型がありましたら教えてください。

# backup