Belle IIでの軽い新粒子探索

～物理を中心に～

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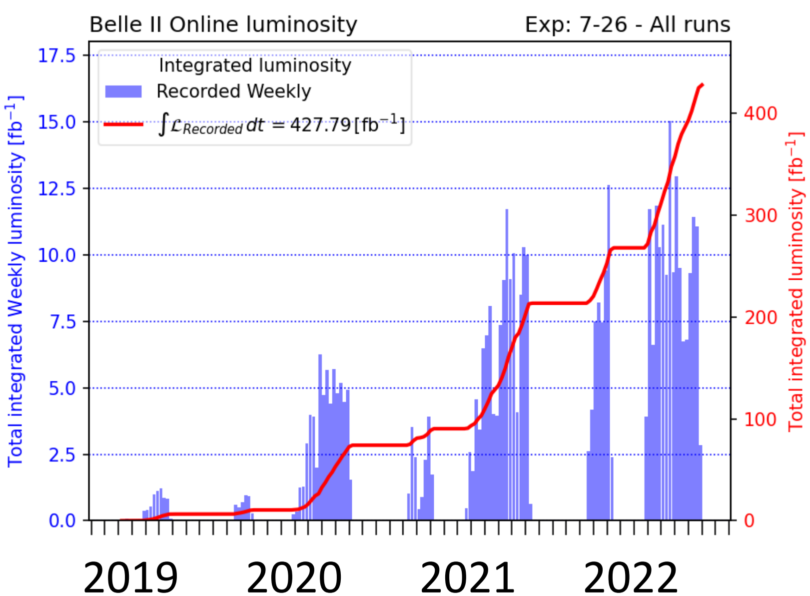
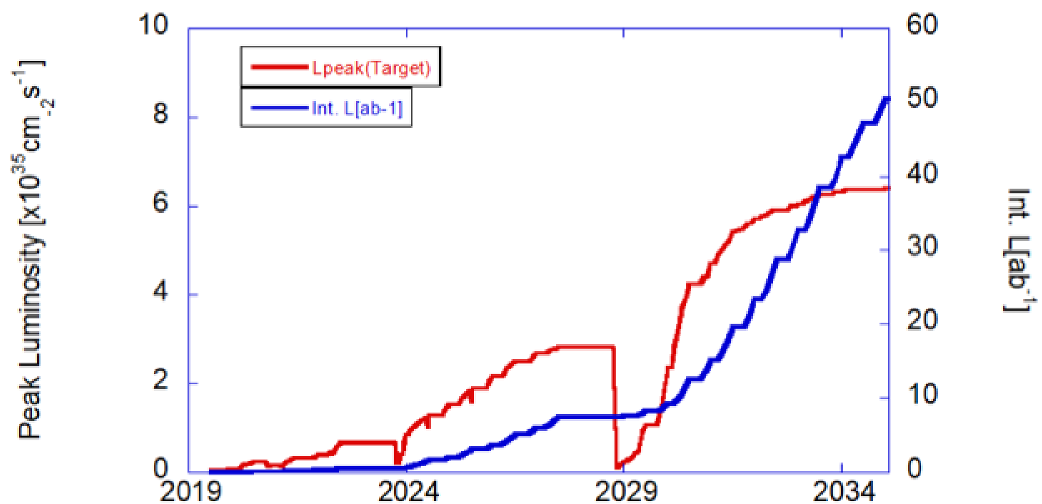
Luminosity Profile and Dataset

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





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_{μ}-L_{τ}
    - ATOMKI X17 (a variant of dark photon?)
    - Inelastic dark matter : χ_1 and χ_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。

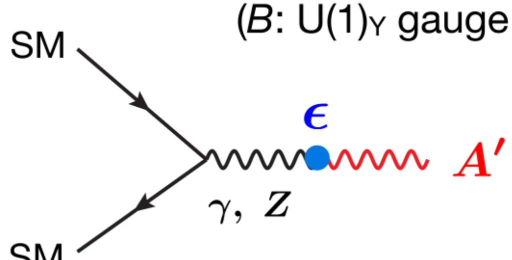
Dark Photon

- U(1) gauge boson の kinetic 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 α_D
  - Visible : SM 粒子に崩壊($m_{A'} < 2m_{DM}$), 結合定数 $\varepsilon^2\alpha_{EM}$

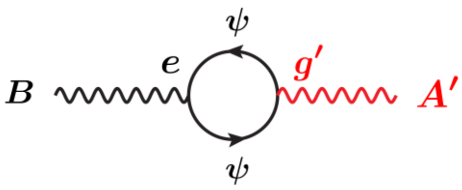
一般に$\alpha_D >> \varepsilon^2\alpha_{EM}$

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

(B: $U(1)_Y$ gauge boson)



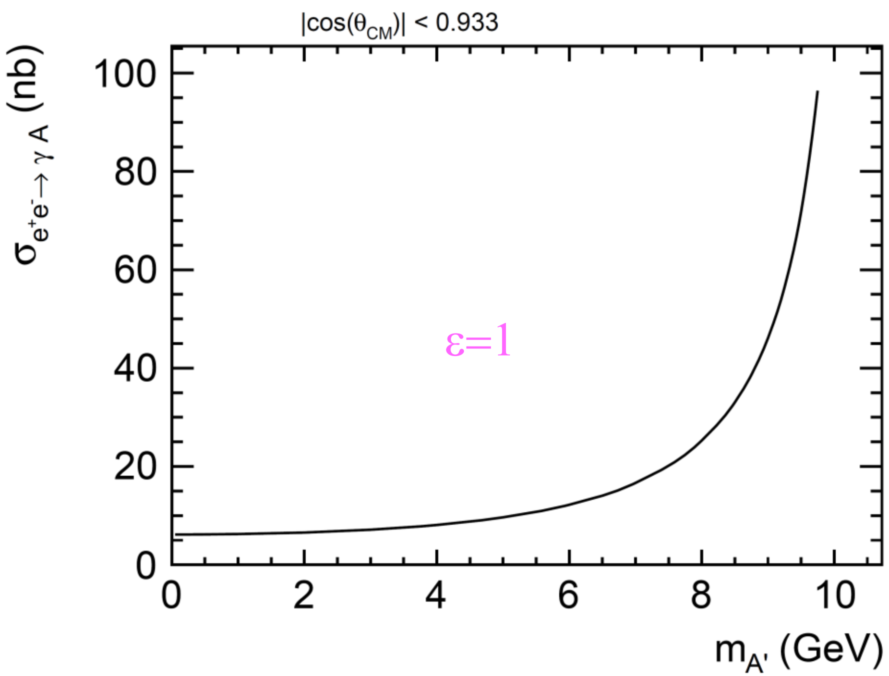
gauge kinetic mixing

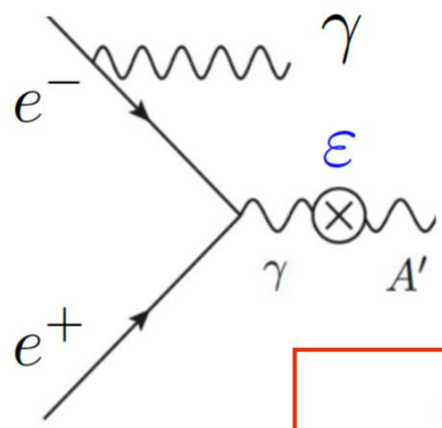


下村さん FPWS2019
他のスライドでも

Dark photon の生成

- $\varepsilon=10^{-3}$ とすると 1GeV A’ で $5fb^{-1}$

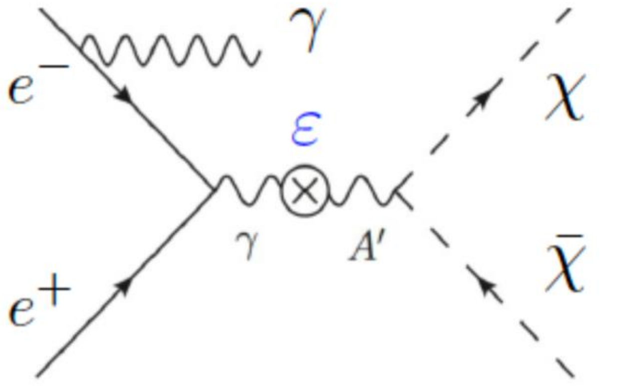




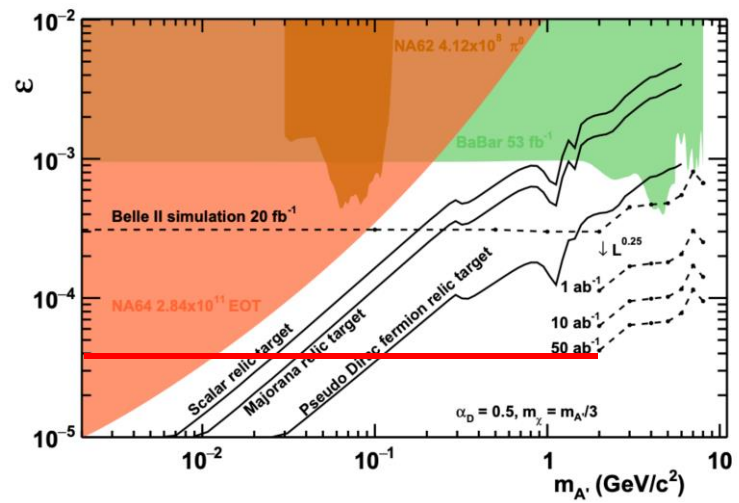
$$\sigma \propto \frac{\varepsilon^2 \alpha_{em}^2}{E^2}$$

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
  - ε~<3×10^{-4} with $20fb^{-1}$
  - ε~<4×10^{-5} with $50ab^{-1}$

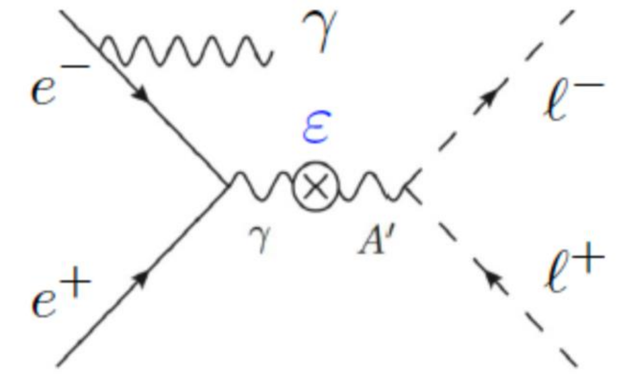


mono-photon + invisible

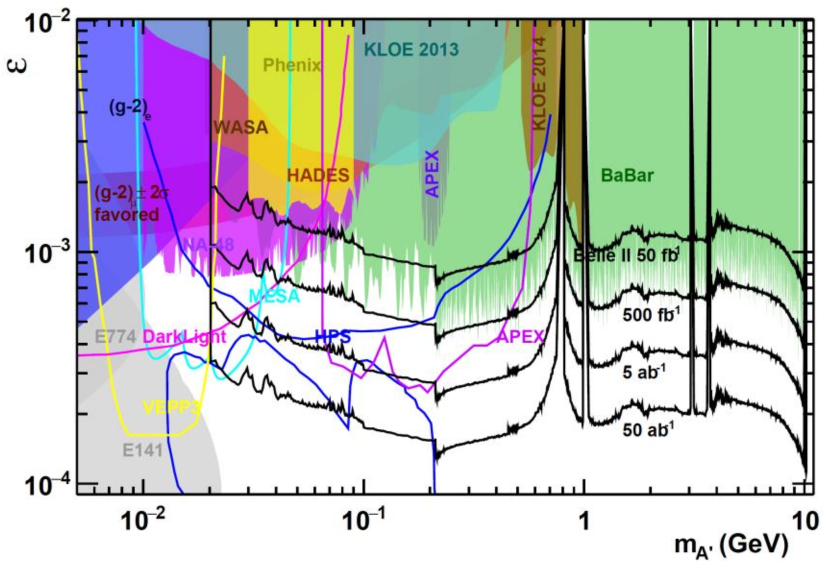


Visible Dark Photon

- 終状態は光子とdilepton
  - Trigger
    - hie or two track trigger
    - Special trigger for low mass A’
- 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
  - ε ~ a few x 10^{-4}



photon + di-lepton resonance



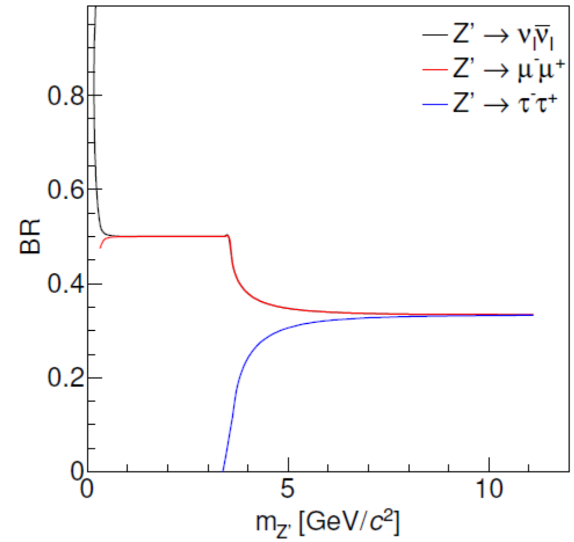
L_μ-L_τ 模型でのZ'

- 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_μ-L_τ 模型でのZ’



- L_μ-L_τ 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 : μ, τ, ν_μ, and ν_τ
  - 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% (fully invisible model)
  - DM に結合しない模型は Vanilla model

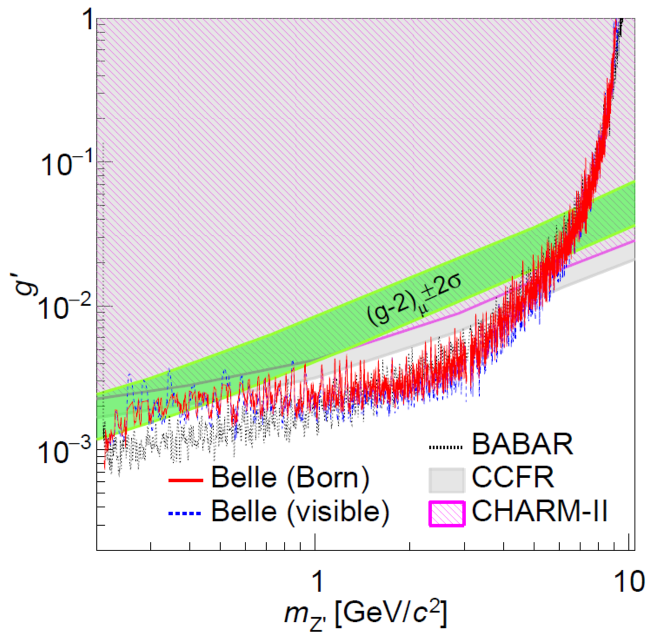
dark matter への崩壊分岐比を0%と仮定し muon モードで探索

- Muon g-2 anomalyを説明できる

Vanilla Model

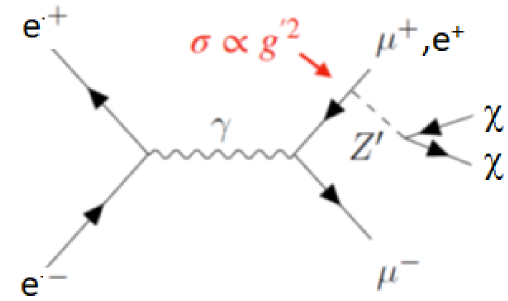
- Muon g-2 を説明する領域に対する制限
  - $m_{Z'}>2m_\mu$はほとんど排除されている
    - Belle and BaBar with muons
    - neutrino trident experiments CCFR and CHARM-II
  - < 10MeV (Not shown)
    - BOREXINOによる one loop での制限
  - 許されている領域は $10\text{Mev} < m_{Z'} < 2m_\mu$

- 今後の探索
  - Z'→νν を使う
  - BF(Z '→νν) ~ 100%
  - つまり invisible mode である。

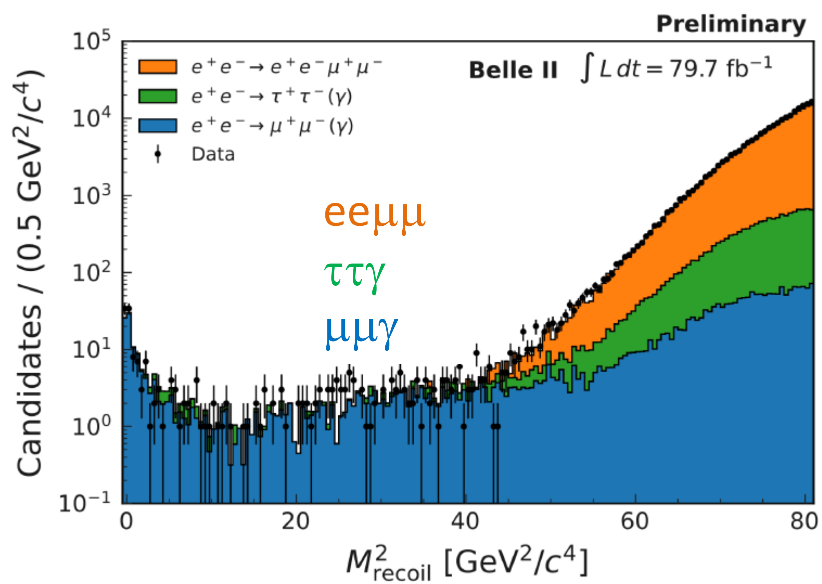


79.7fb^{-1} data

Invisible Z' in L_μ-L_τ model

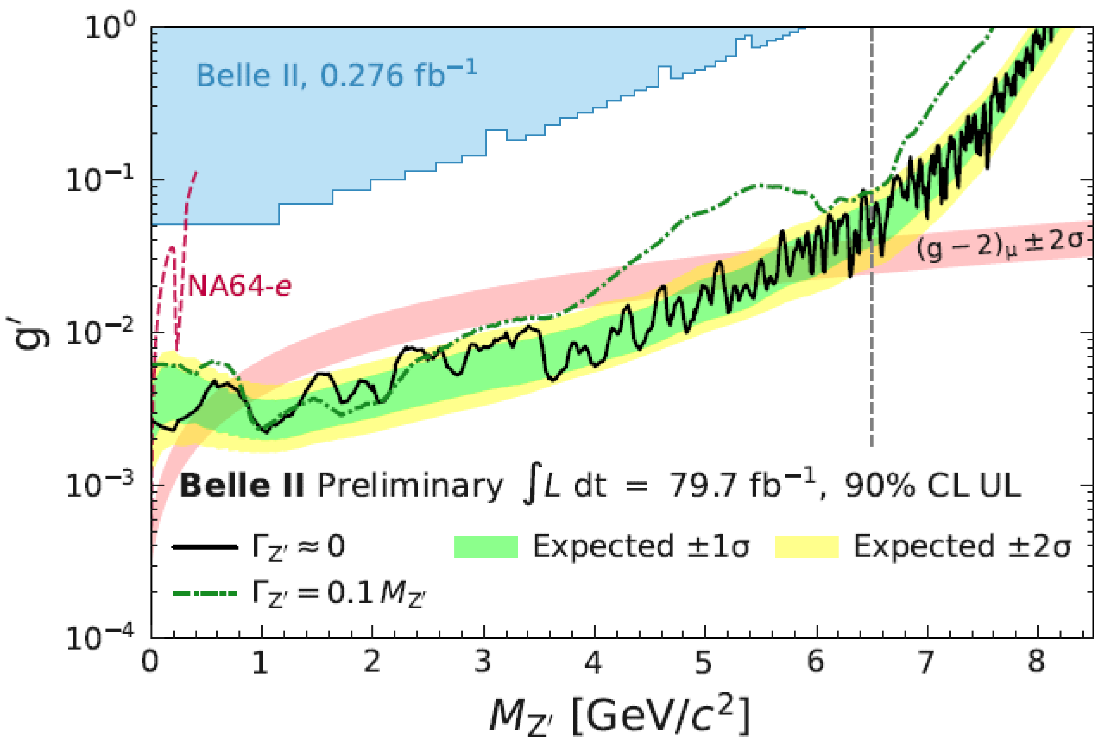


- Typical cross section
  - ~10fb with g'=0.01 and $M_{Z'}$ = 1GeV
- Signature
  - $e^+e^- \rightarrow \mu^+\mu^- Z' \rightarrow \mu^+\mu^-\chi\chi$
- Trigger
  - 2 track with opening angle
- Search
  - Dominant backgrounds
    - ee→eeμμ, ττγ, μμγ
  - Recoil mass and θ_{Recoil} to identify the signal



Limit on invisible Z’

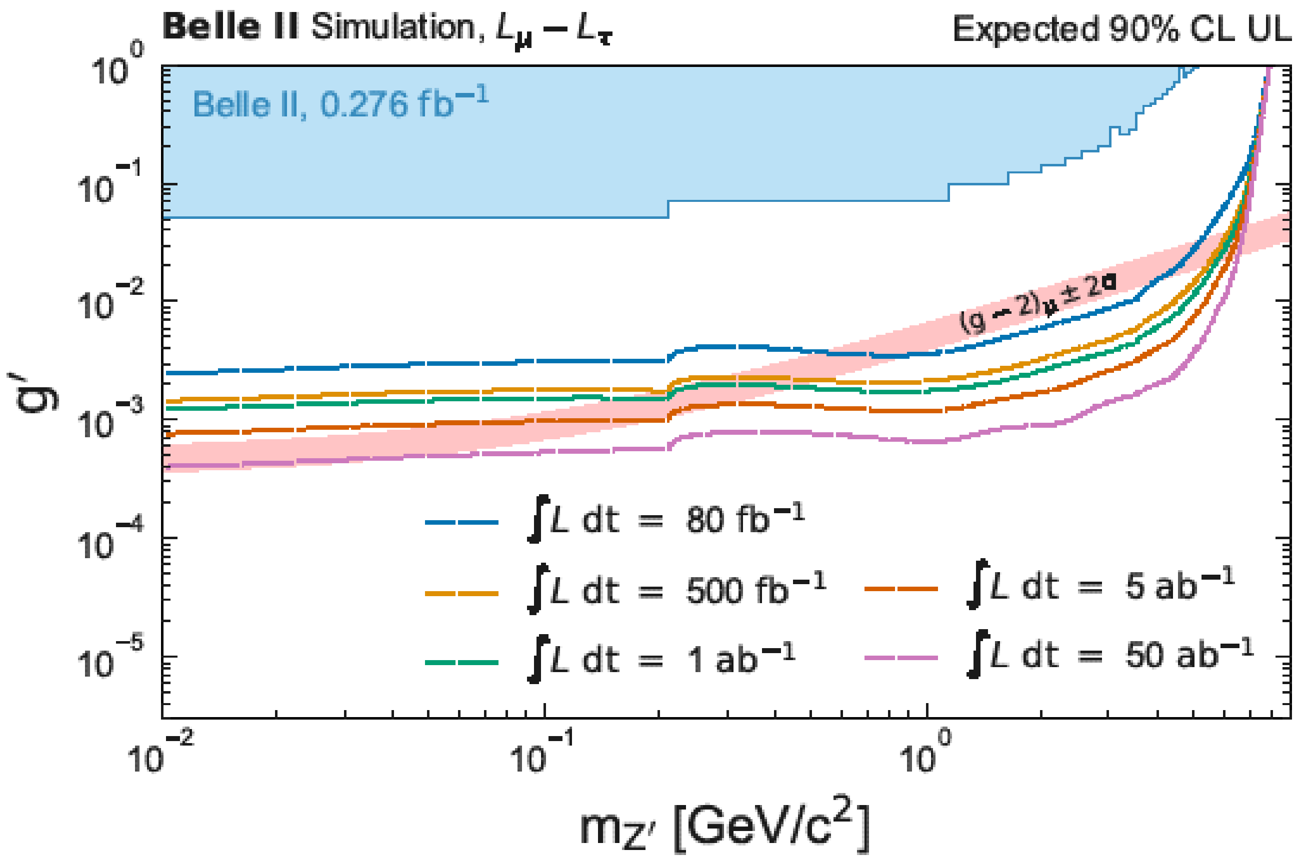
- Invisible 崩壊で世界で初めて muon g-2 anomaly を説明する領域を排除
  - $0.8 < M_{Z'} < 4.5$GeV



arxiv: 2212:03066 submitted to PRL

Invisible Z’ : 将来の展望

- 50ab^{-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)

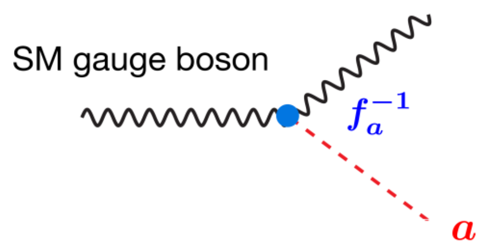
- Axion like particles (ALPs) 以下の
  - Global 対称性の自発的破れ
  - 超弦理論の String compactification
    - SM gauge group を作れる最大の群を選ぶと 181820 種類のALPs が存在
- QCD Axion は質量と崩壊定数に関係があるが ($m_\pi f_\pi \sim m_a f_a$) ALPs には無い
  - 探索可能な parameter space が広い
- 単純のために ALP が光子としか結合しないと 2 parameters
  - $g_{a\gamma\gamma}$: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

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

  - Decay width (lifetime)

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

- Axion Portal : $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$



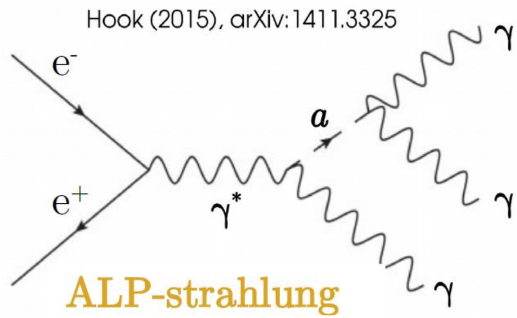
Signature

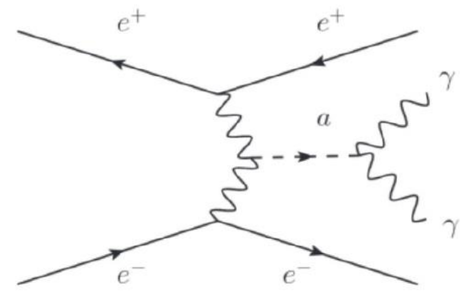
- ALP can be generated from
  - ALP-strahlung
  - Photon fusion
    - under study
- Cross section
  - ~1fb for $g_{a\gamma\gamma}=10^{-4}\ \mathrm{GeV}^{-1}$

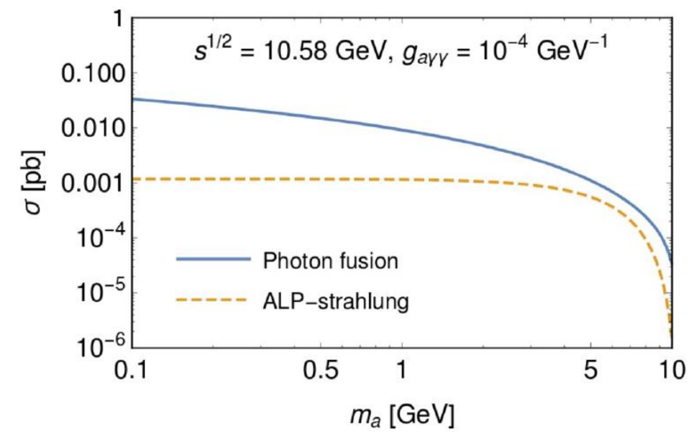
$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\mathrm{QED}}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$

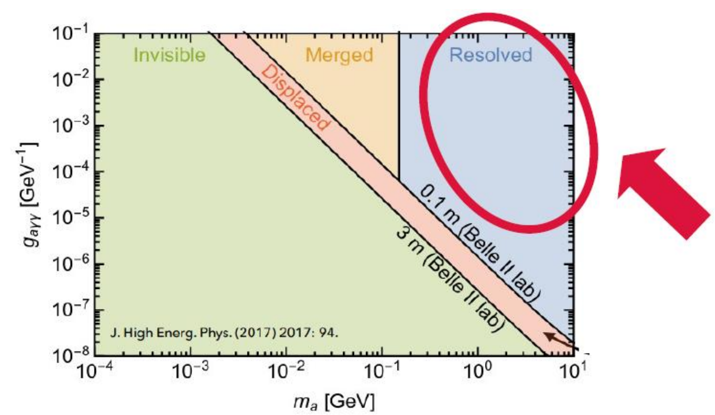
- Sequential two-body decays
  - $e^+e^- \rightarrow \gamma a$, $a \rightarrow \gamma\gamma$
  - Only three photons in a final states
- Belle II search for shorter lifetime region
  - Large coupling and large mass
    - beam dump experiments → longer lifetime
  - two photons are resolved in EM calorimeters

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





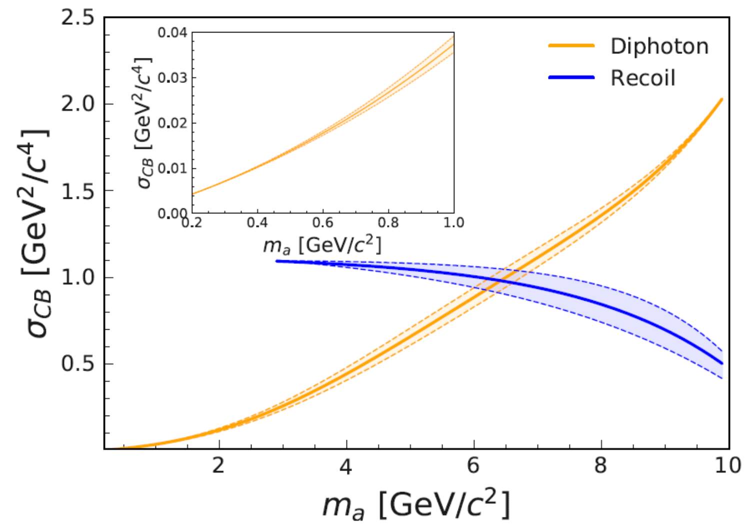




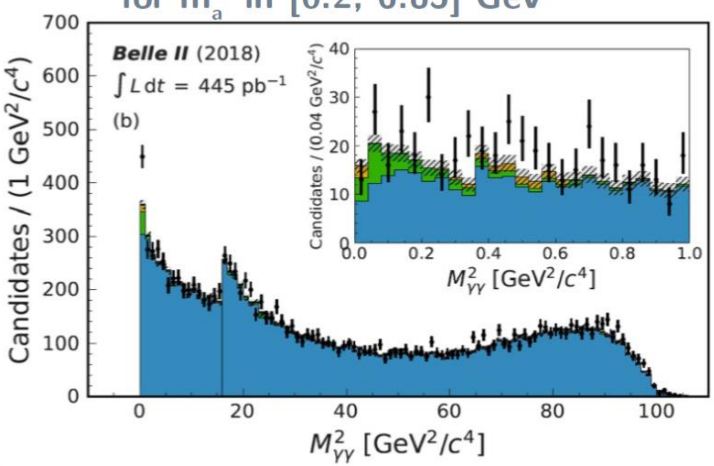
$445 pb^{-1}$

Search for ALPs at Belle II

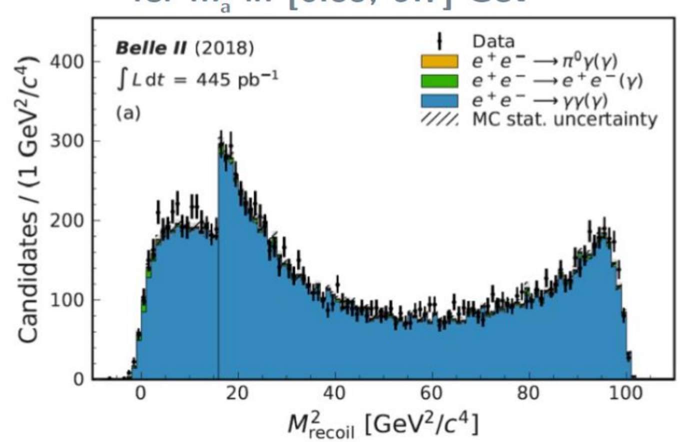
- Trigger
  - hie : E_{sum}>1GeV
- Two Reconstruction technique
  - Invariant mass for low mass [0.2, 6.85]GeV
  - Recoil mass for high mass [6.85, 9.7]GeV
- Dominant background is SM $e^+e^- \rightarrow \gamma\gamma\gamma$



Diphoton invariant mass for m_a in [0.2, 6.85] GeV

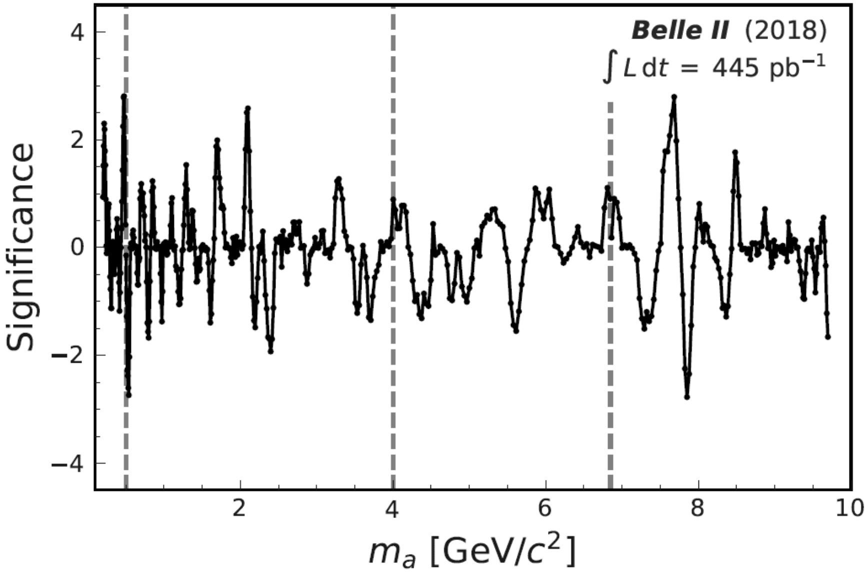


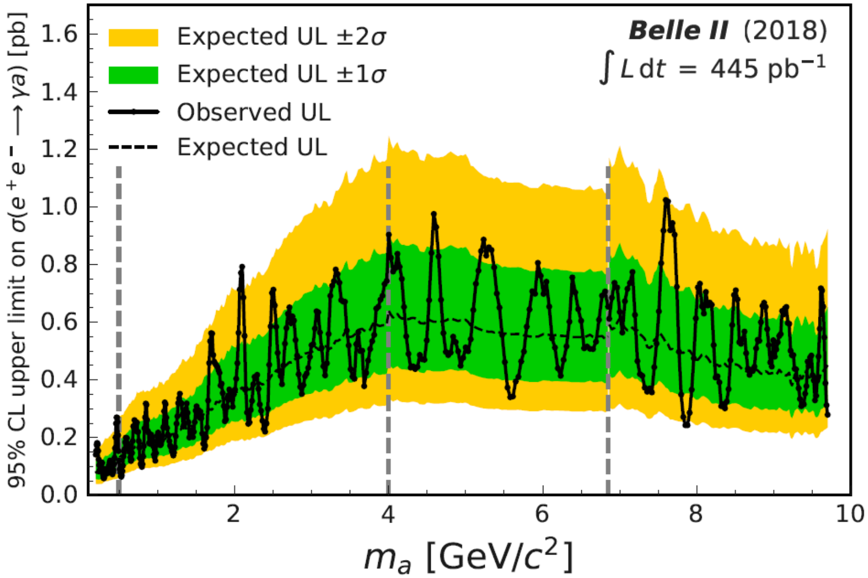
Recoil invariant mass for m_a in [6.85, 9.7] GeV



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

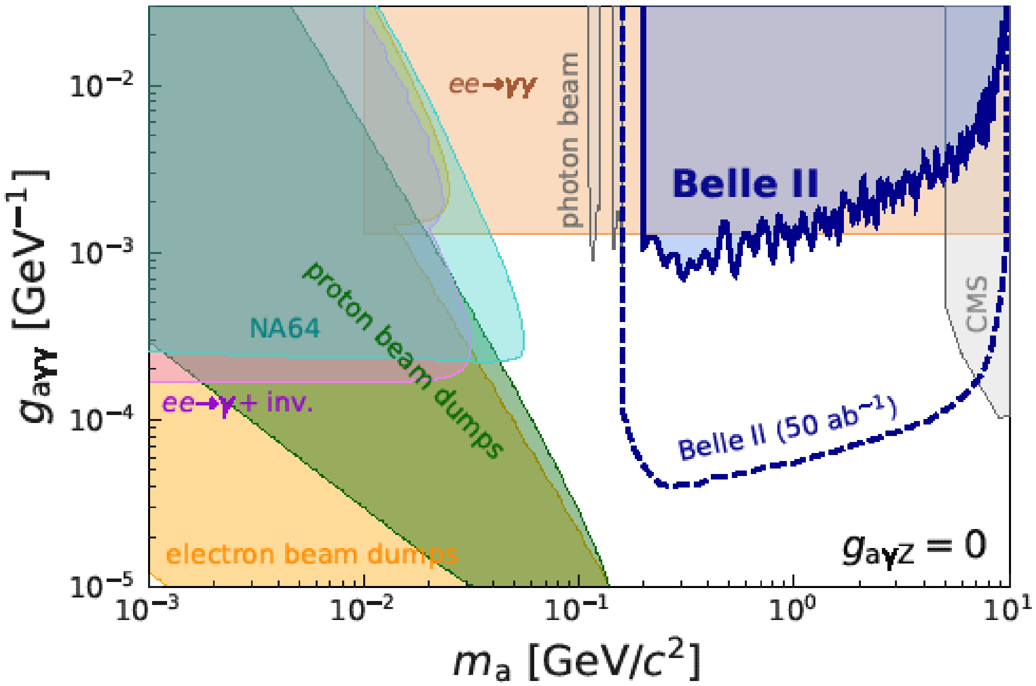
- No significant excess is observed
  - Largest local significance of 2.8σ at m_a=0.447GeV
- Set a limit on σ.
  - $\sigma < 1$pb





Limit on ALP parameter space

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

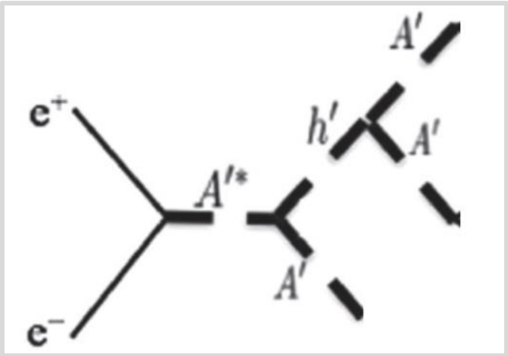


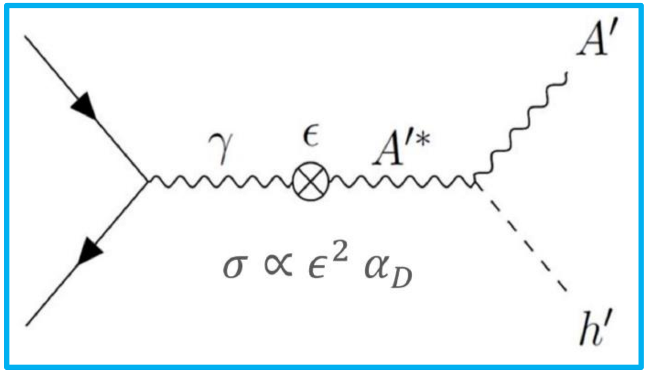
Dark Scalar

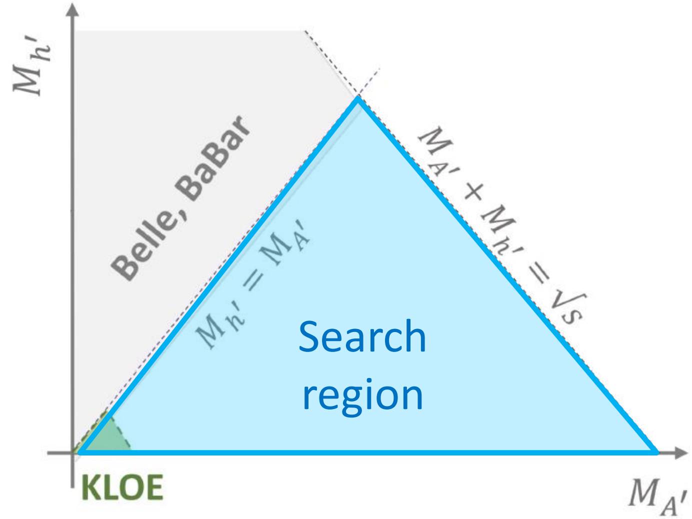
- Dark Photon からの輻射
- B中間子ループ崩壊での top quark からの輻射

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→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
  - $M_{A'}$, $M_{h'}$
  - ε : kinetic mixing
  - α_D: coupling constant of dark sector
- $M_{h'} > M_{A'}$
  - Dark Higgs は visible h’→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

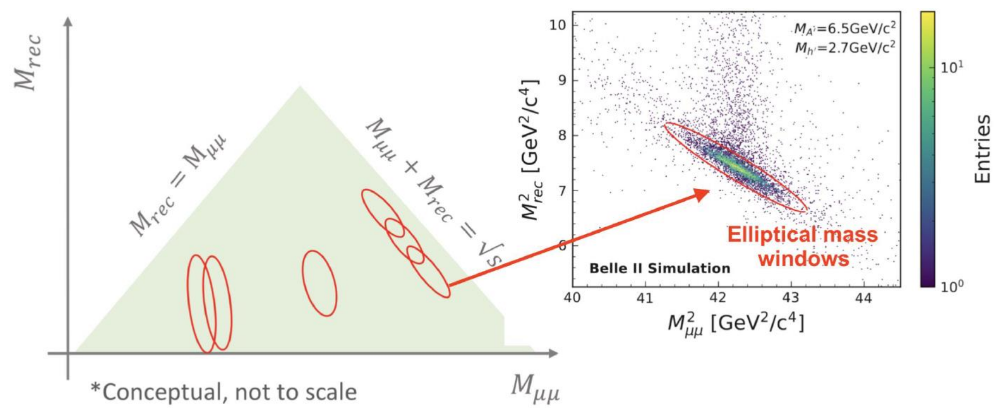


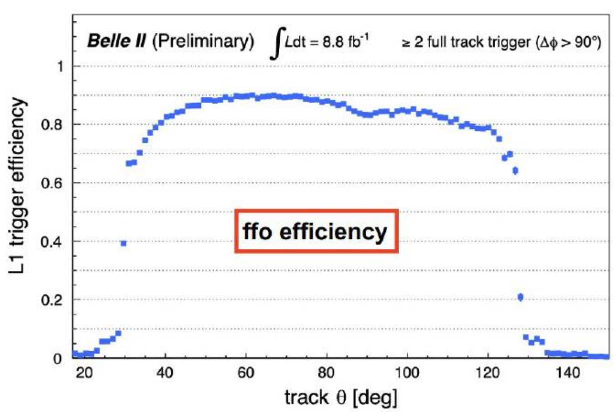


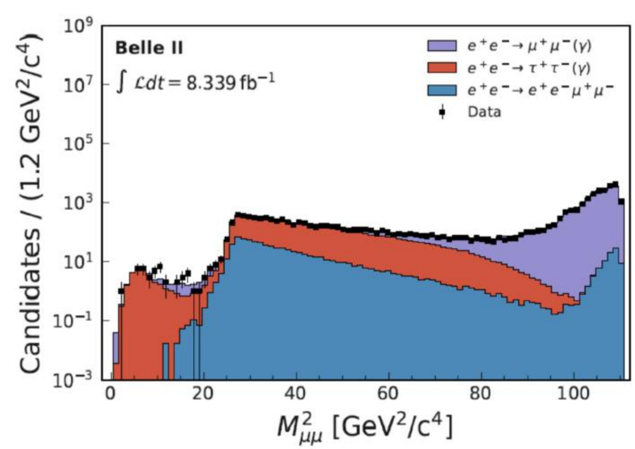


Search for Dark Higgs in $e^+e^- \rightarrow A'h'$

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

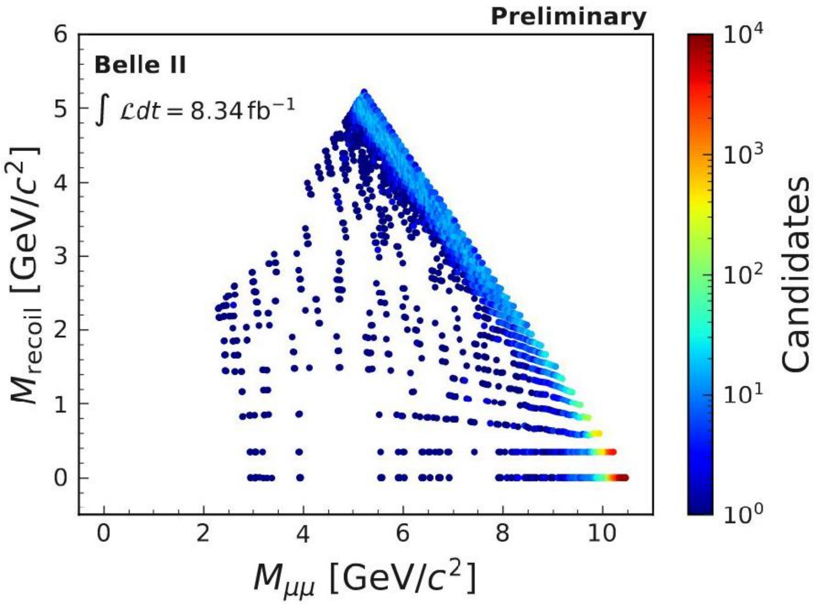




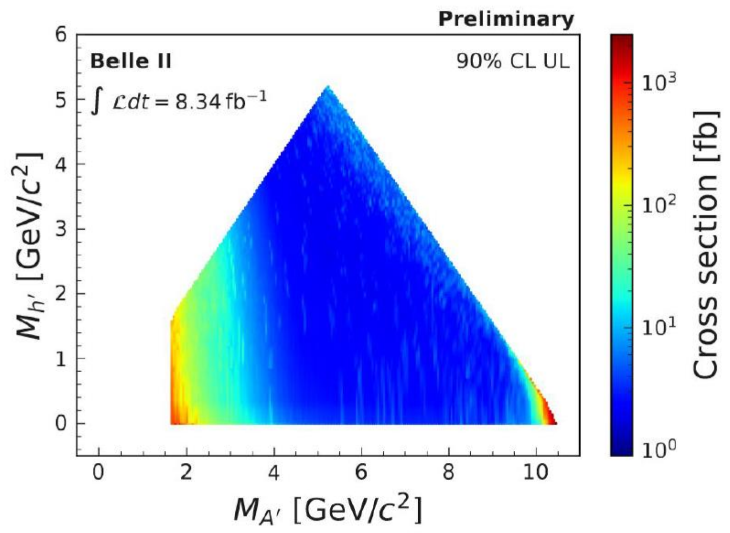


Limits on $\sigma(e^+e^- \rightarrow A'h')$

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

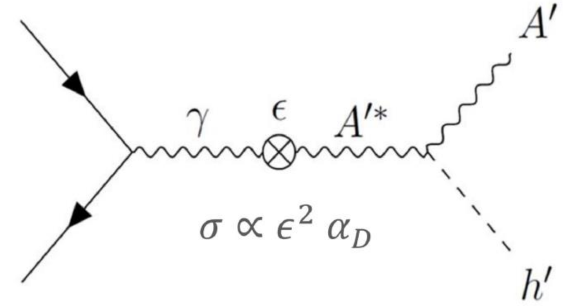


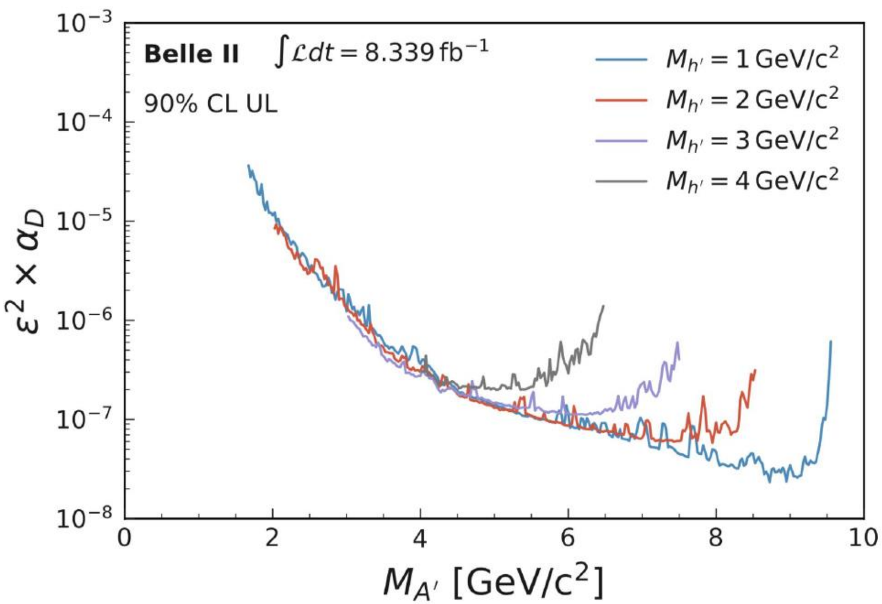
Discreteness is due to binning effect

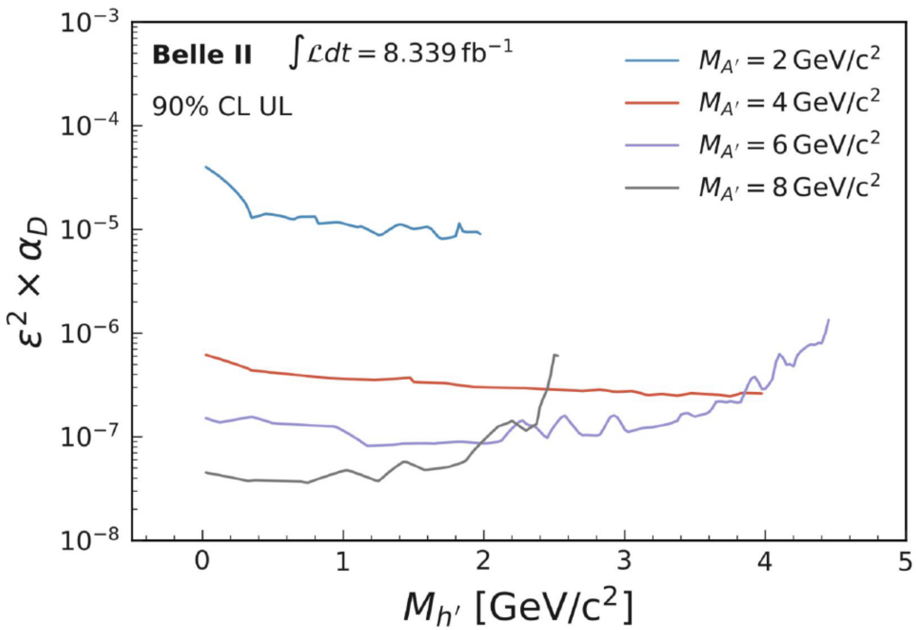


Limits on Physics Parameters

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

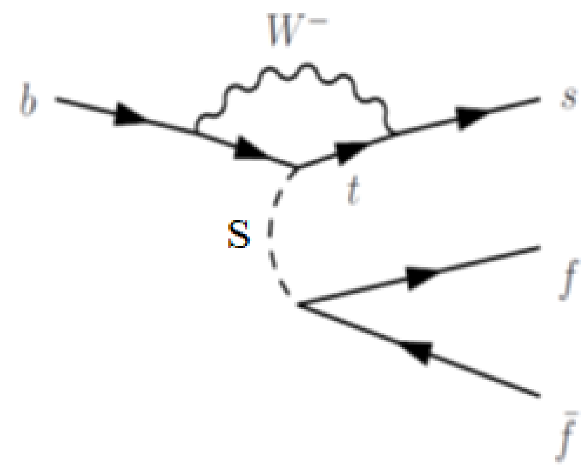


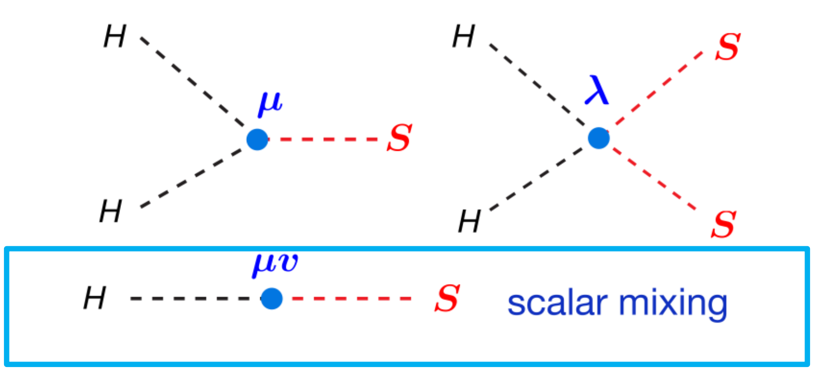




B中間子崩壊でのDark Scalar

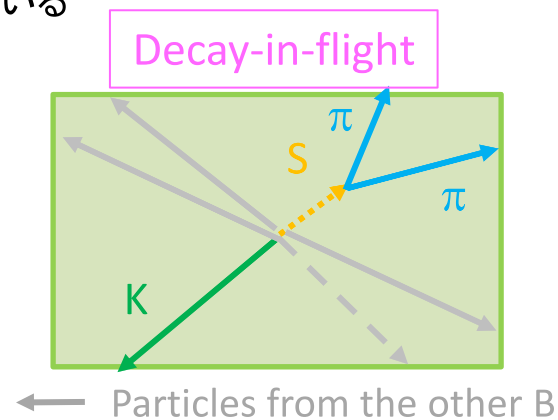
- B中間子の b→s Penguin 崩壊は loop の中に top quark を含む
  - 湯川結合がデカい
- SM Higgs との mixing があれば dark scalar を作ることが可能である
  - Mixing angle θ

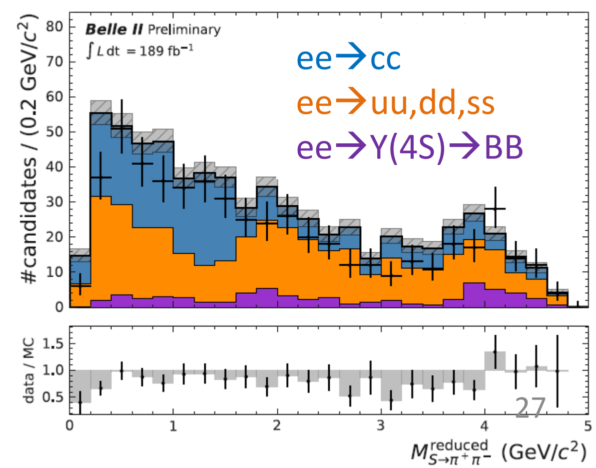




Long-lived Dark Scalar in B Decays

- Dark scalar particles S
  - $M_s < 2M_\chi$
    - S→χχ 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 θ
    - 湯川結合は重い fermion でデカい
  - long-lived if θ is small
- B→K^+ S and B→K^{*0} S decays
  - S is radiated off from internal top quark in b→s decays
  - S→ee, μμ, ππ, 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→cc, ee→uu,dd,ss , ee→Y(4S)→BB
  - Long-lived K_S^0 is a good control sample





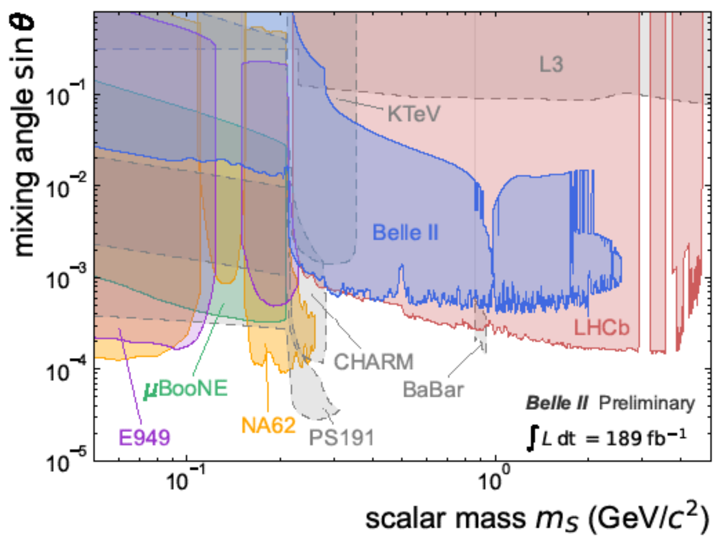
189fb^{-1} data

Limit on B→K$^{(*)}$ S

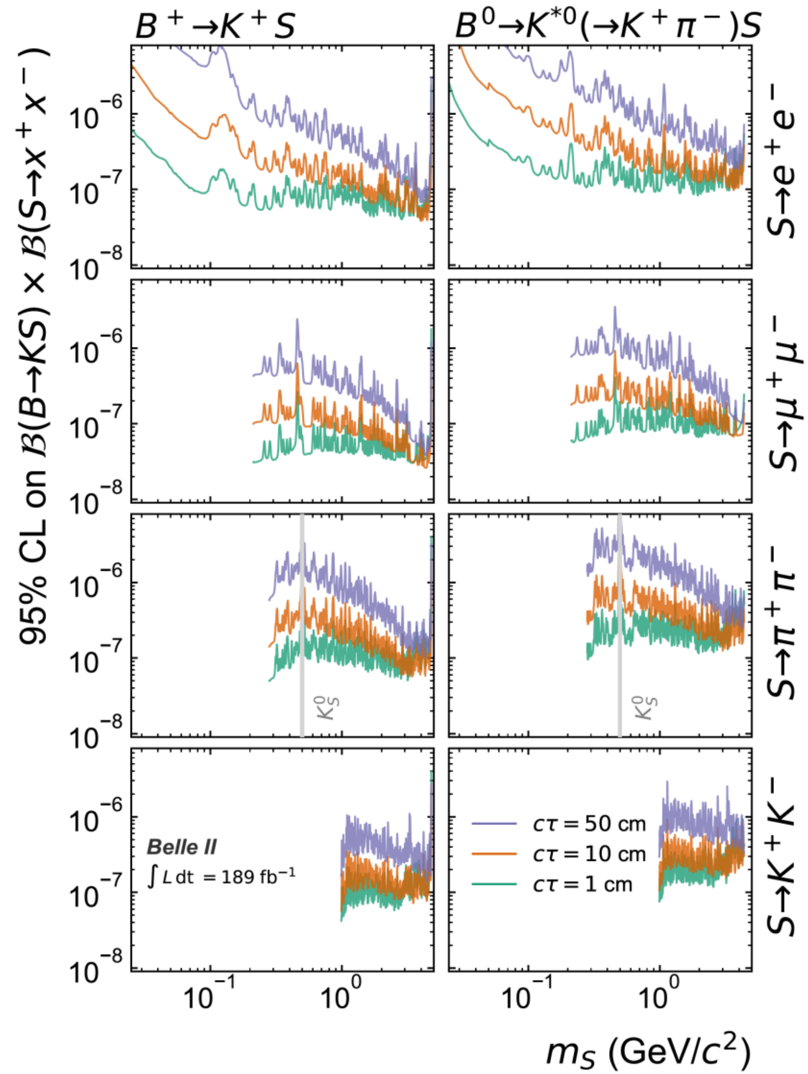
- BFに対するモデル非依存の制限
  - As functions of cτ and mass.
  - For 8 decay modes
  - First limit on S decaying to hadrons
- モデル依存の制限 on m_S vs. sinθ
  - Dark Higgs mixing with the SM Higgs

Filimonova, Schäfer, Westhoff, Phys. Rev. D 101, 095006

Model dependent



Model independent cτ=1cm, 10cm, 50cm



20231218

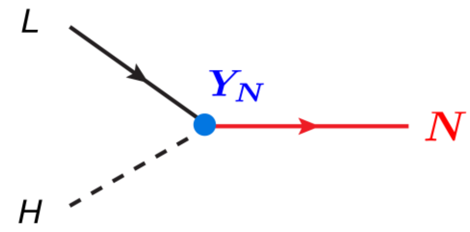
publication in preparation

Sterile Neutrino

- Belle II で最近始めました
  - Belle の制限が強い

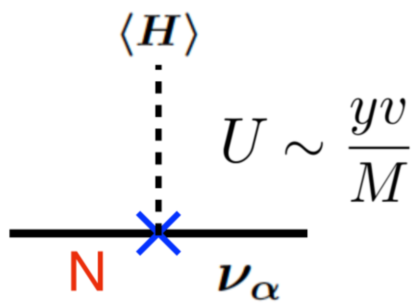
Sterile Neutrino

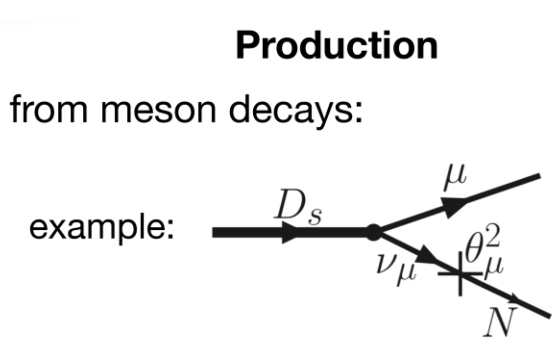
- Fermion Portal : $Y_N \overline{L} H N$

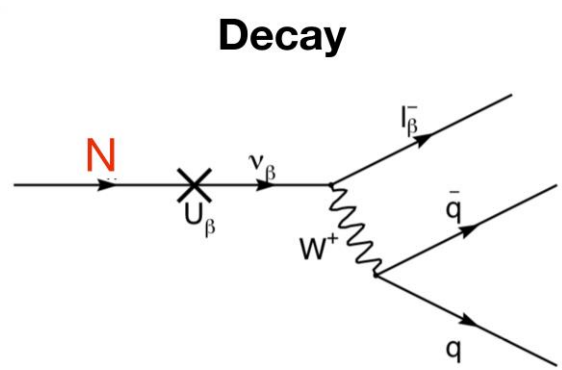


right-handed neutrino

- 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
    - $B \to D^{(*)} l\nu$, $B^+ \to \mu^+\nu$
  - τ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

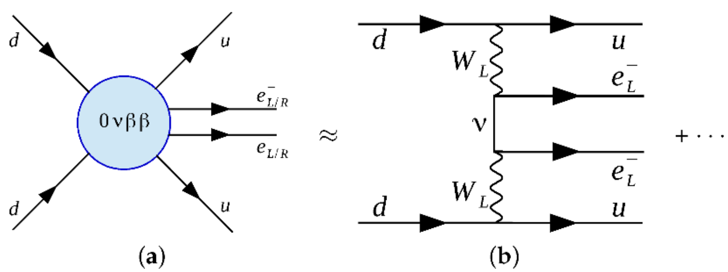




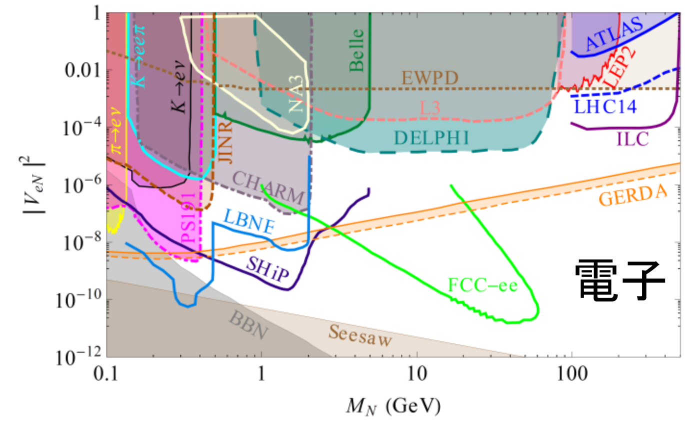


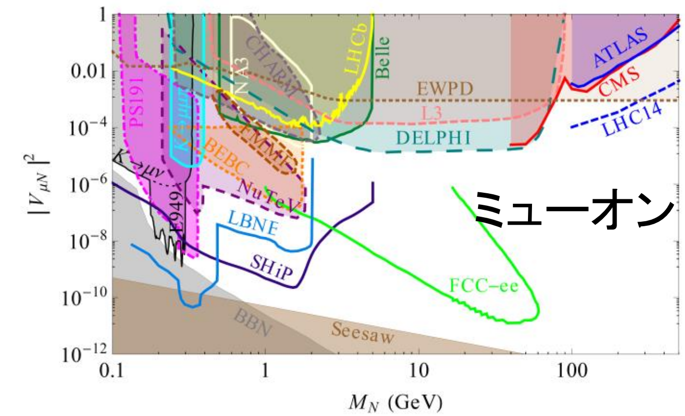
Sterile Neutrinoの制限

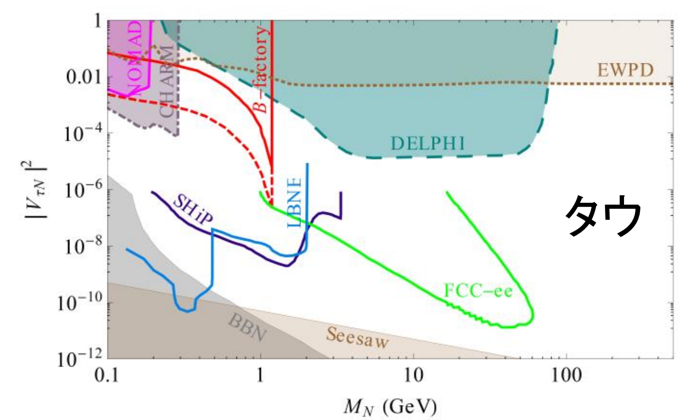
- Collider
  - LEP, LHC, Belle
- Fixed target
  - CHARM
- 0νββ
  - 電子モードはこれで強い制限がついている
    - 標準模型では 2νββ だが majorana neutrino であれば 0νββが可能
  - $^{76}Ge \rightarrow {}^{76}Se\ e^- e^-$ (GERDA)
  - $^{136}Xe \rightarrow {}^{136}Ba\ e^- e^-$ (KAMLand-Zen)



- 重要なのはミューオンとタウ

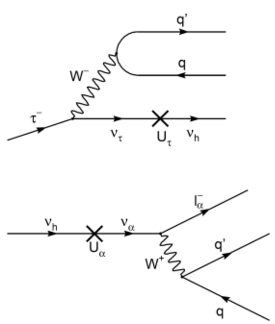






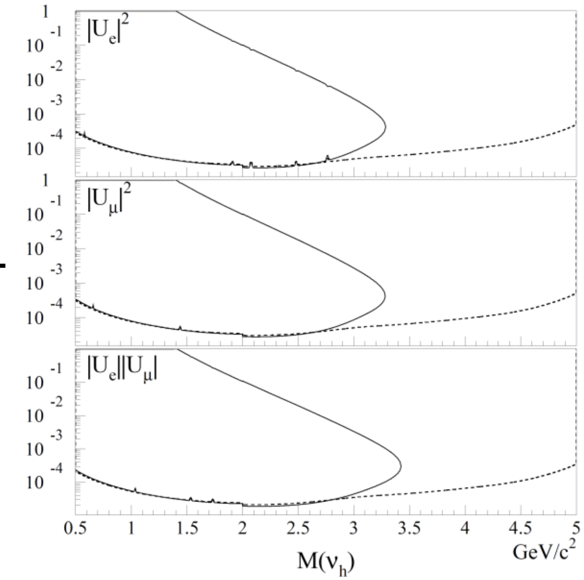
Belle での Sterile Neutrino 探索

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

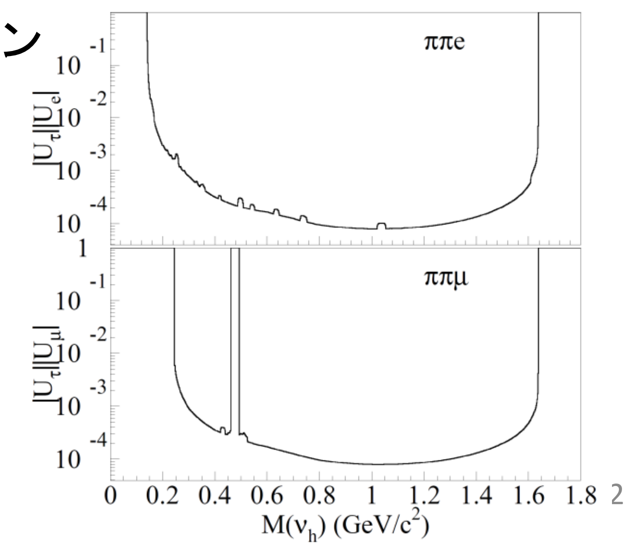


- 生成と崩壊を見るので mixing matrix element の4乗 $|U|^4$ に制限

B中間子

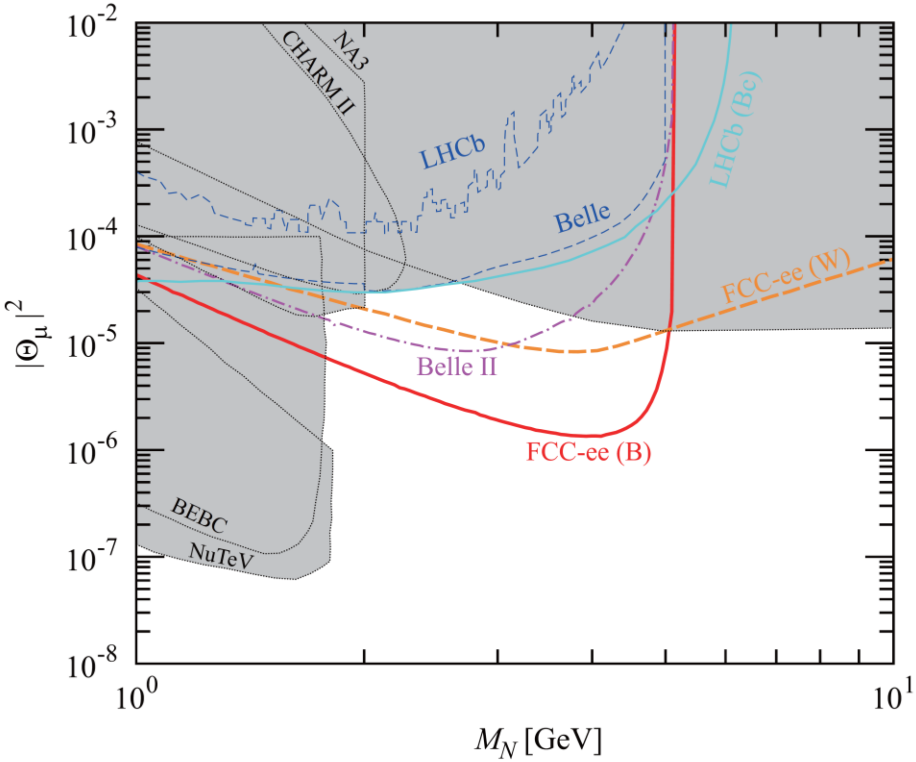


τレプトン



$B^+ \rightarrow \mu^+ N$ 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→D(*) l N
  - $B^+ \to \mu^+ N$
- 逆側のBを tag して Recoil mass を測定
  - FEIの efficiency (~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 なども探しています
- 新しい模型がありましたら教えてください。

backup

P5 HEPAP

- アメリカは Belle II を強力にサポート（将来の Higgs factoryも）

Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: Operation Construction R&D, Research P: Primary S: Secondary
§ Possible acceleration/expansion for more favorable budget situations

Science Experiments	Timeline 2024–2034	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
LHC			P	P		P	P	
LZ, XENONnT				P				
NOvA/T2K		P				S		
SBN		P				S		
DESI/DESI-II		S		S	P			P
Belle II				S		S	P	
SuperCDMS				P				
Rubin/LSST & DESC		S		S	P			P
Mu2e							P	
DarkSide-20k				P				
HL-LHC			P	P		P	P	
DUNE Phase I		P				S	S	S
CMB-S4		S		S	P			P
CTA				S				P
G3 Dark Matter §		S		P				
IceCube-Gen2		P		S				P
DUNE FD3		P				S	S	S
DUNE MCND		P				S	S	
Higgs factory §			P	S		P	P	
DUNE FD4 §		P				S	S	S
Spec-S5 §		S		S	P			P
Mu2e-II							P	
Multi-TeV §	DEMONSTRATOR		P	P		P	S	
LIM		S		P	P			P
Advancing Science and Technology through Agile Experiments								
ASTAE §		P	P	P	P	P	P	
Science Enablers								
LBNF/PIP-II								
ACE-MIRT								
SURF Expansion								
ACE-BR §, AMF								
Increase in Research and Development								
GARD §	TEST FACILITIES							
Theory								
Instrumentation								
Computing								

Approximate timeline of the recommended program within the baseline scenario. Projects in each category are in chronological order. For IceCube-Gen2 and CTA, we do not have information on budgetary constraints and hence timelines are only technically limited. The primary/secondary driver designation reflects the panel's understanding of a project's focus, not the relative strength of the science cases. Projects that share a driver, whether primary or secondary, generally address that driver in different and complementary ways.

Figure 2 – Construction in Various Budget Scenarios

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary
Delayed: Recommend construction but delayed to the next decade
\# Can be considered as part of ASTAE with reduced scope

Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
US Construction Cost >$3B										
on-shore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
off-shore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N						P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

Medium and large-scale US investments in new construction projects for possible budget scenarios. The projects are ordered in three budget brackets according to the number of "N" entries and then by approximate budget sizes. For the off-shore Higgs factory, test facilities & demonstrators, see Recommendation 6. See the caption of Figure 1 concerning the science drivers, and Section 8 for the rationale behind these choices.