Recent dark sector results from accelerator experiments

~Belle II and LHCb~

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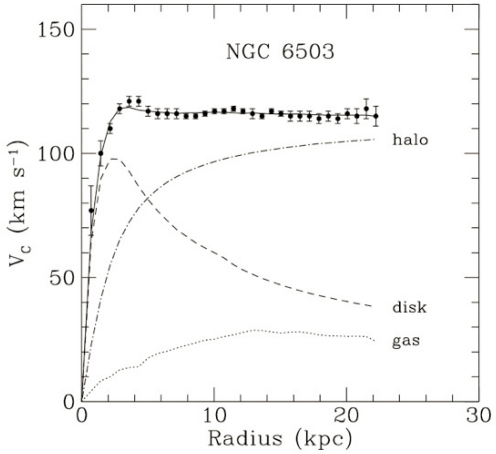
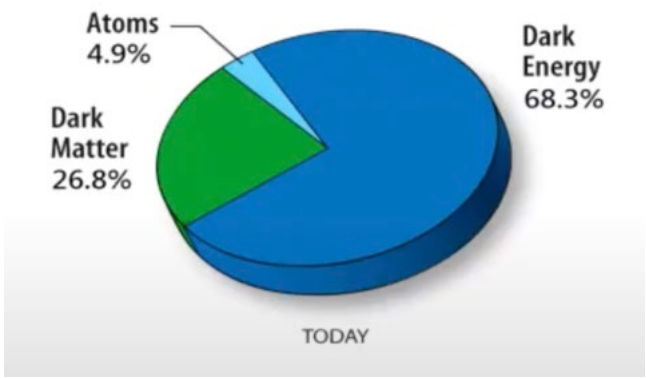
FPCP2022 @University of Mississippi

Dark Matter

- Existence of dark matter (DM) had been established in astrophysics.
  - Rotation curve of a disk galaxy
  - Spatial distributions of luminous baryonic matter (with X-ray) and total matter (with gravitational lens) in a collision of galaxy clusters
  - And more
- We know the DM density in the Universe
  - $\Omega h^2 = 0.1188 \pm 0.0010$
  - 27% of total energy
- However there is no DM candidate in the SM
- Search for DM is a central issue in elementary particle physics



NASA

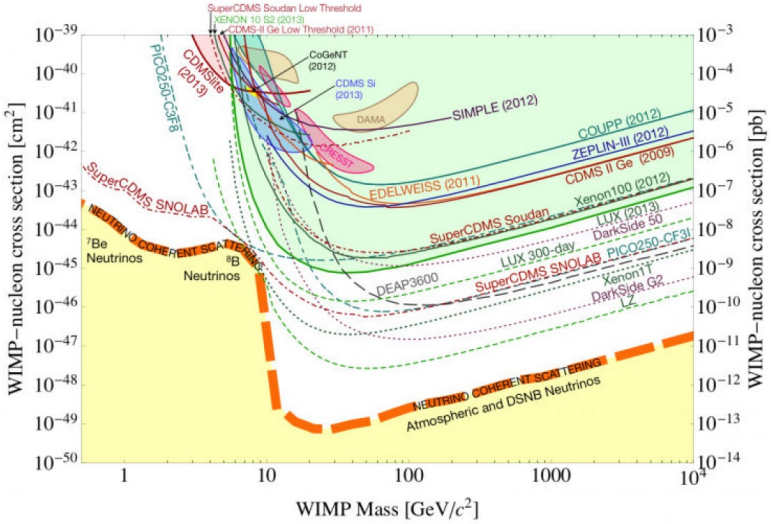


WIMP Miracle and…

- Assuming the thermal relic, WIMP with mass around O(100) GeV can explain the relic density.
- WIMP miracle !!

$$\Omega h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \mathrm{cm}^3/\mathrm{s}} \right)^{-1}$$

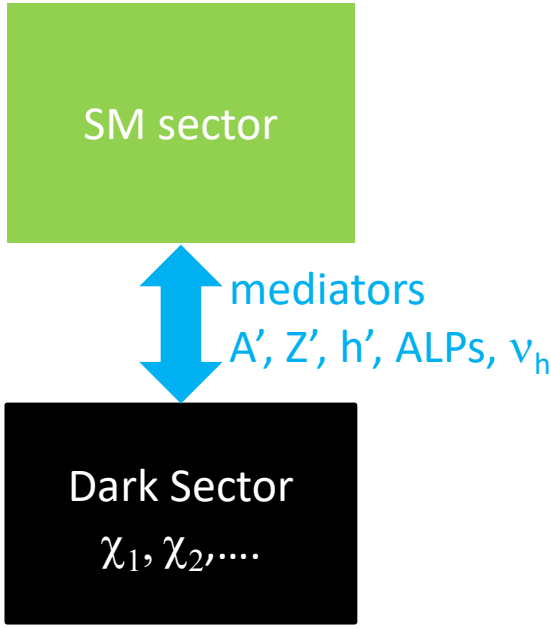
$$10^{-26}\ \mathrm{cm}^3/\mathrm{s} \simeq 10^{-9}\ \mathrm{GeV}^{-2} \sim \frac{g_2^4}{4\pi} \frac{1}{m_{\mathrm{DM}}^2}$$



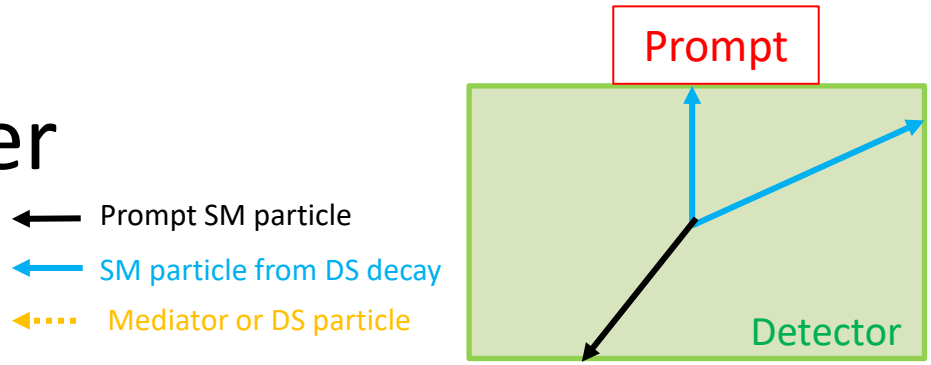
- However, WIMP has not been observed yet at the energy frontier collider, direct and indirect experiments.
- So wide variety of DM scenarios got attention recently.
- Dark sector (DS) is one of the important scenarios.

Dark Sector Models

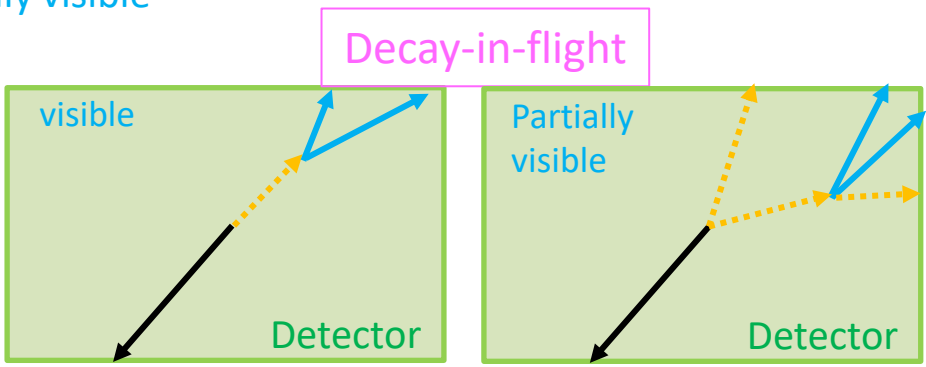
- Particles in the dark sector are SM gauge singlet
- Dark sector and SM sector weakly couple with mediators (portal particles)
- (At least)four types of mediators
  - Scalar portal
    - Dark Higgs h'
  - Pseudo scalar portal
    - Axion like particles (ALPs) a
  - Vector portal
    - Dark photon A', Z' in L_μ-L_τ model
  - Fermion portal
    - Sterile neutrinos ν_H
  - (Tensor portal??)
- The mediators could have mass around MeV-GeV
- Parameter space which can explain thermal relic
  - heavy sterile neutrinos could also explain leptogenesis

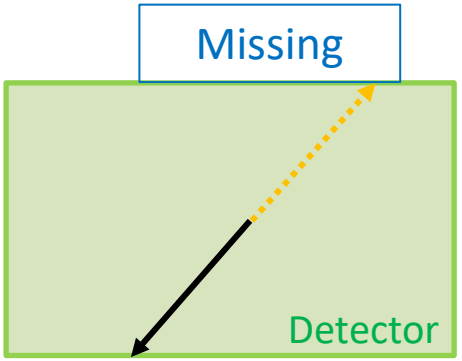


Signatures at Collider



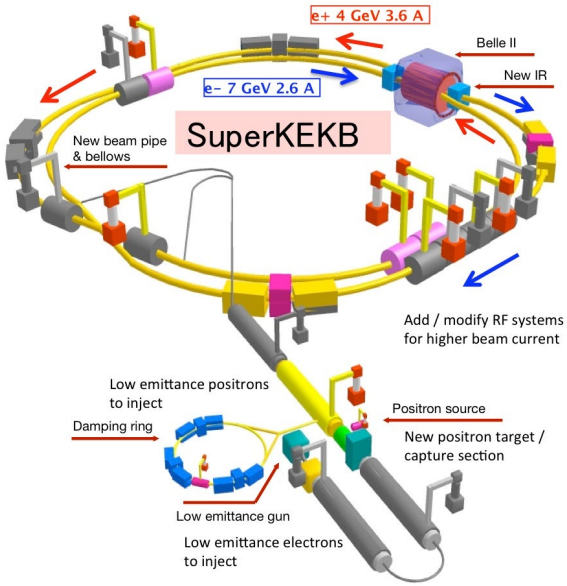
- Mediator can decays to
  - SM particles : visible
  - DS particles (or no decays) : invisible
  - DS particles → SM+DS final states : partially visible
    - Ex. Inelastic DM
- Decay length
  - Prompt ($c\tau\beta\gamma << 1mm$)
    - Same as SM physics
    - Bump hunting (visible)
    - Recoil or endpoint (partially visible)
  - Long lived (Decay-in-flight) ($O(1)mm < c\tau\beta\gamma < O(1)m$)
    - BG is smaller with vertex reconstruction
      - except for photon conversions, Ks and Λ
    - Pointing to IP (visible)
    - No pointing to IP (partially visible)
  - Very Long lived (Missing) ($c\tau\beta\gamma >> O(1)m$)
    - Or invisible decays
    - Missing mass from 4-momentum conservation
    - ν and misreconstructed events (inefficiency) are the BG sources

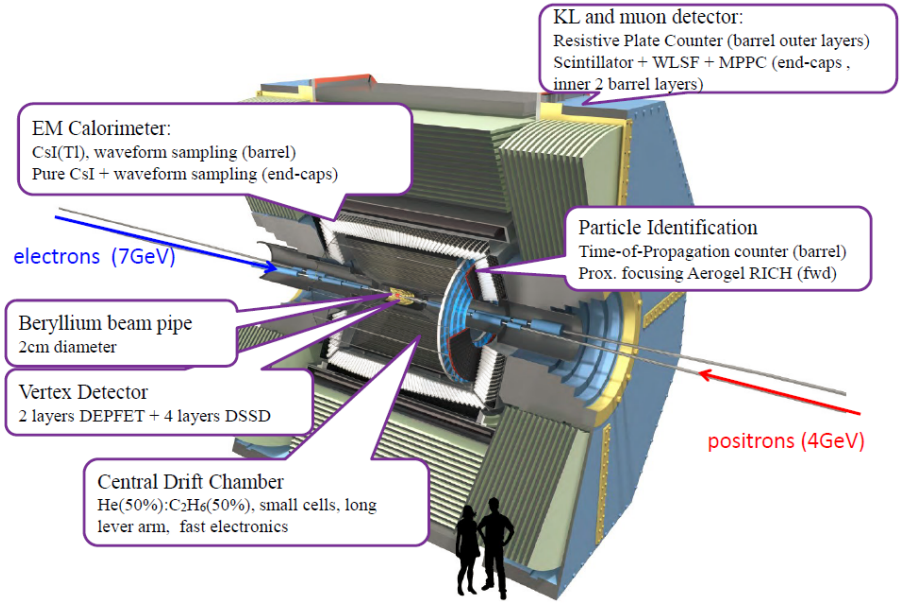




SuperKEK and Belle II

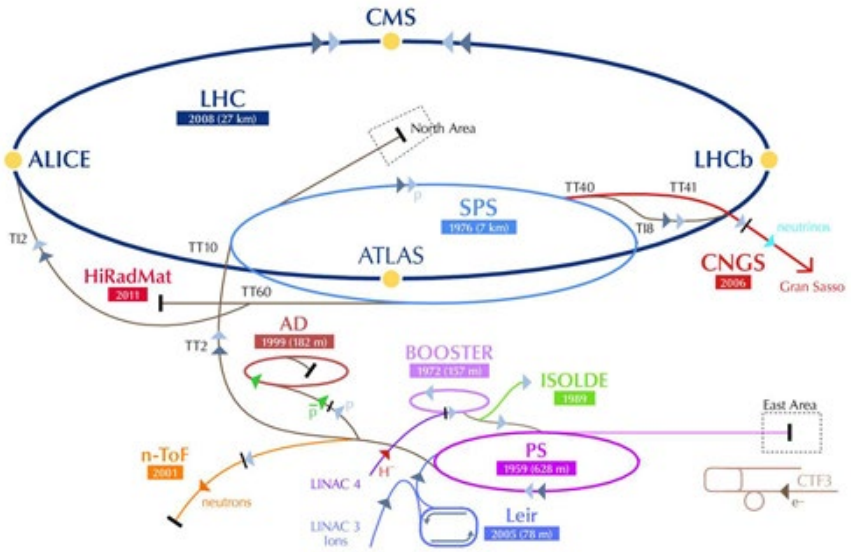
- Belle II@SuperKEKB is a good playground to search for these mediators and DM around MeV-GeV scale
  - E_{CM}~10GeV
  - Highest luminosity in the world 4.1x10^{34} /cm^2/s
  - 4π x 94% detector → 4momentum conservation usable
  - Dark sector searches with heavy flavor b, τ and c decays
  - Single photon/track trigger enable us to search for dark sector with missing energy

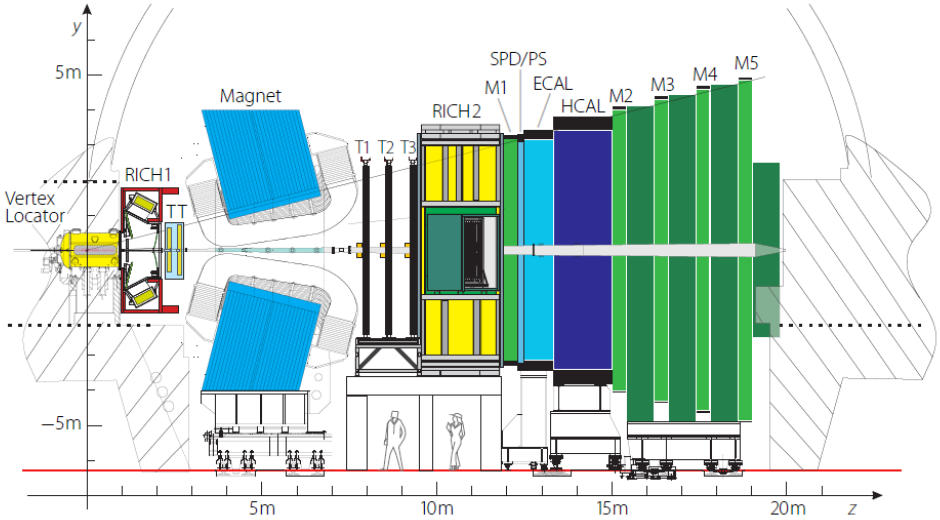




LHC and LHCb

- LHCb@LHC is also good for dark sector searches with final states having muons and long lived particles.
  - Forward experiments with long liver arm
  - Good performance on trigger for muons
  - Mediator mass >10GeV is also accessible

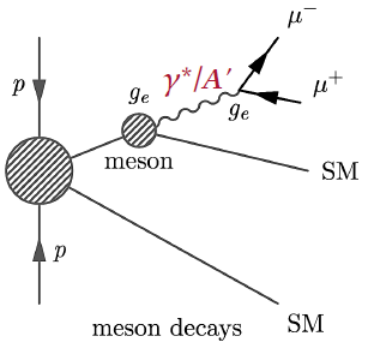


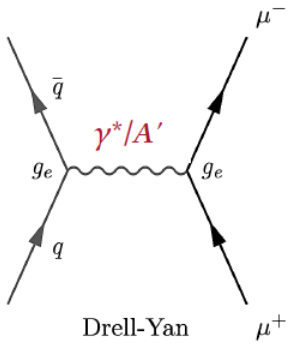


Dark Photon A'

- Extra U(1) gauge boson
- Kinetic mixing ε with photon

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$





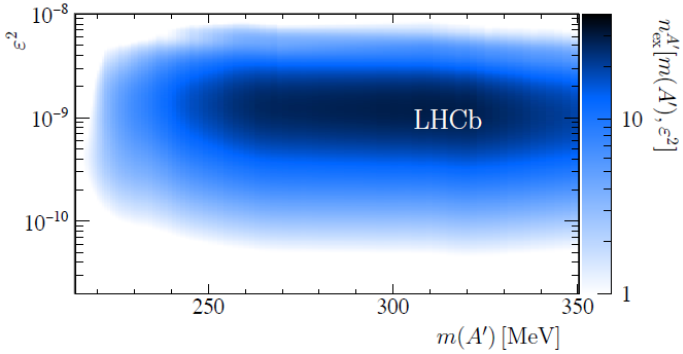
- Two parameters
  - $m_{A'}$ and ε
- Produced from meson decays or Drell-Yan
- decays to charged particles via kinetic mixing
  - A'→μμ is searched
- Trigger on dimuon
- If kinetic mixing is very small and decaying into dark matter is suppressed, A' is long lived
  - long lived using vertex detector also searched (d<20cm)

Dark Photon A'→μμ

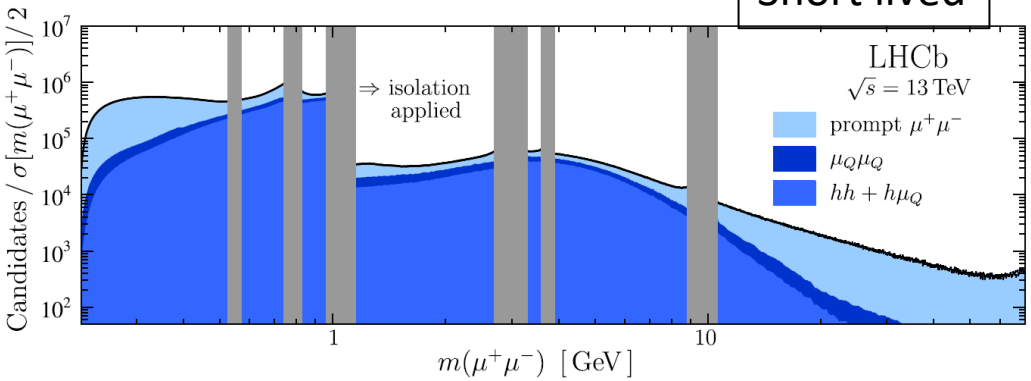
- Data
  - 5.5fb^{-1} for long lived
  - 1.6fb^{-1} for short lived
- Both short lived and long lived A' are searched
- Backgrounds
  - Short lived : Prompt dimuon
  - Lonv lived : photon conversion
- No significant excess is observed

Long lived

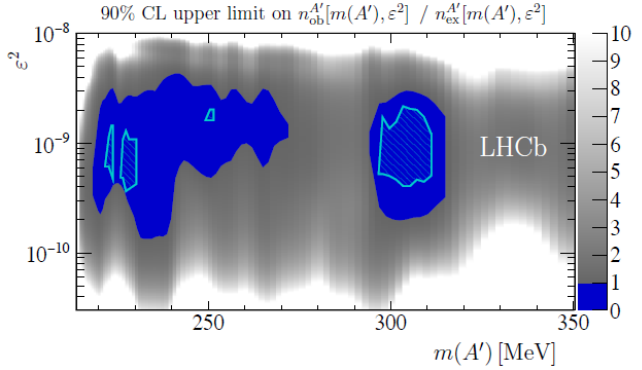
Expected events



Short lived



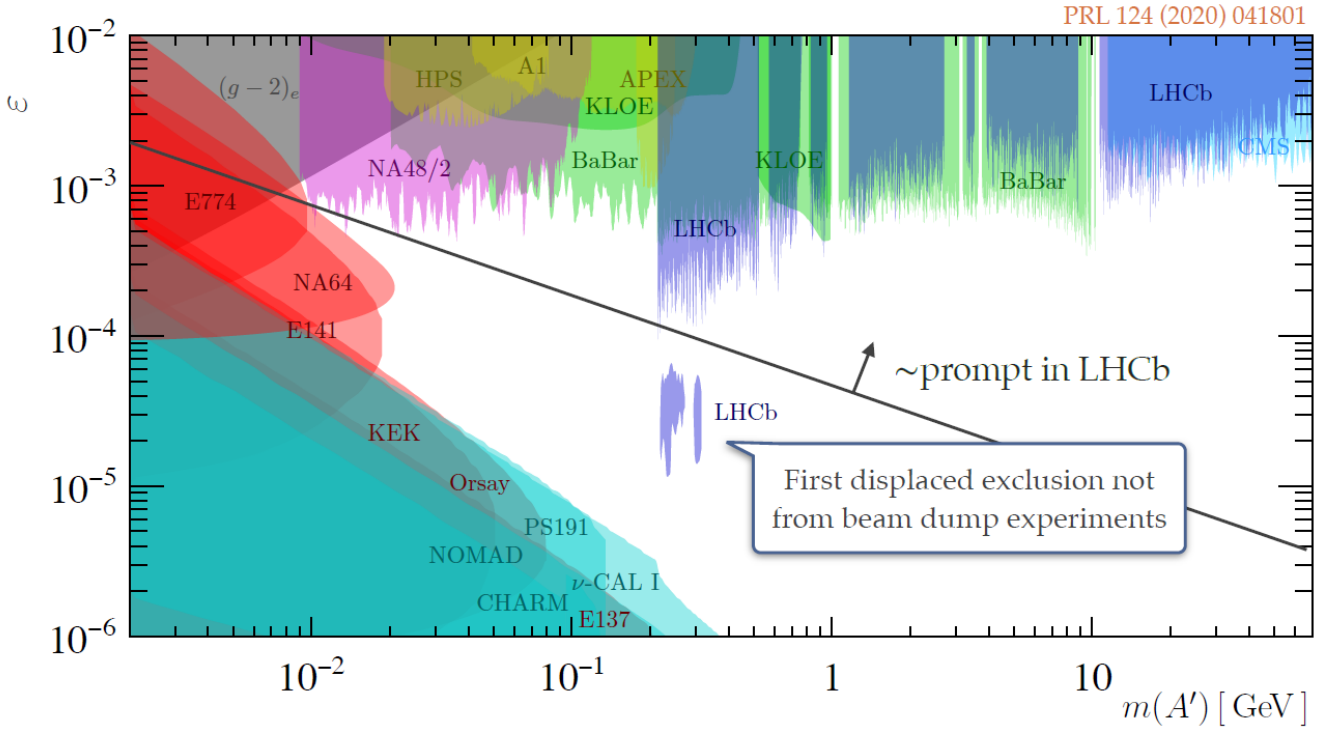
Observed dimuon mass



Limit on signal events

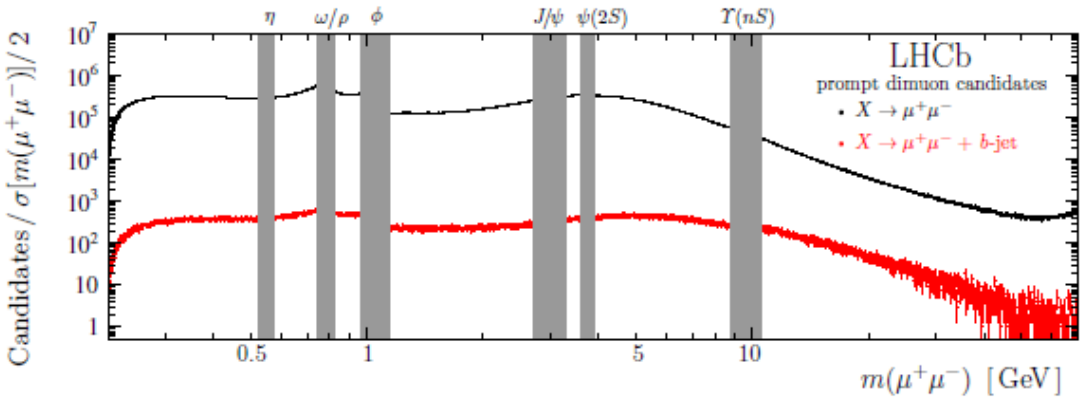
Limit on Kinetic Mixing

- Best limits on kinetic mixing for
  - $217 < m_{A'} < 740$MeV
  - $10.6 < m_{A'} < 30$ GeV
  - $214 < m_{A'} < 740$MeV for long lived

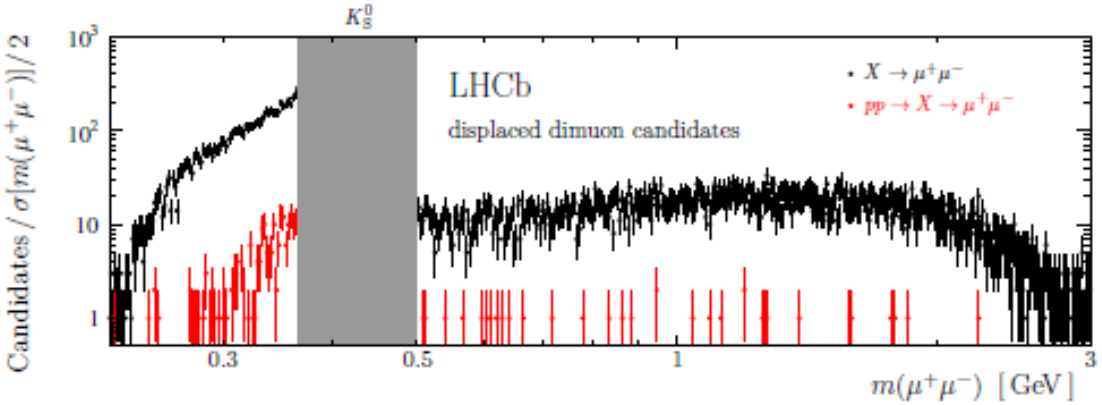


Inclusive Dimuon Resonance X Search

- Similar search as A' but with minimum assumption
- Data
  - 5.1fb^{-1}
- No significant excess observed



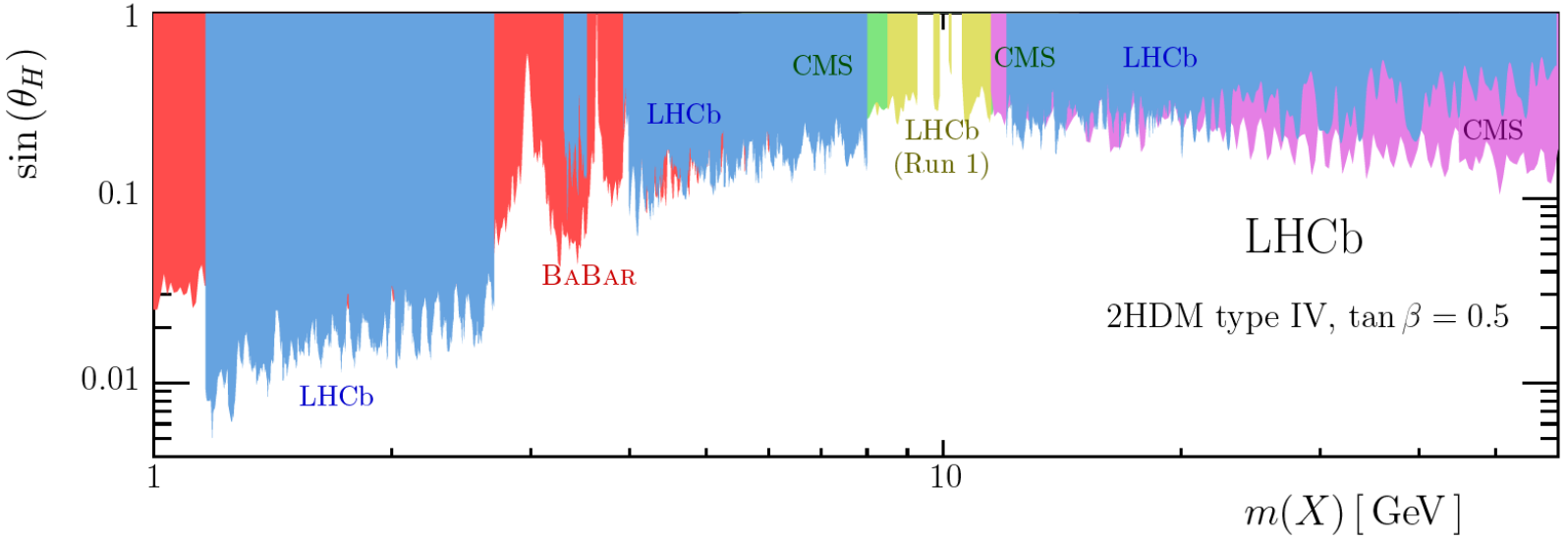
Prompt



Displaced for $M_X < 3$GeV

Interpretation of X Boson

- Interpretation of prompt search
  - hidden valley scalar particle mixing (θ_H) with Higgs in 2HDM
- World's leading limits given

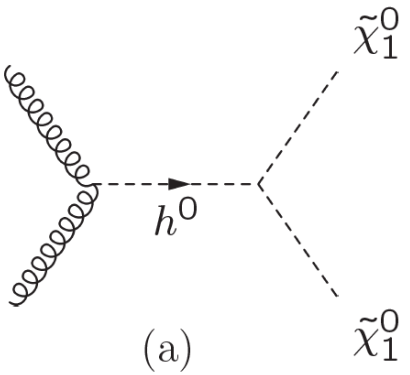


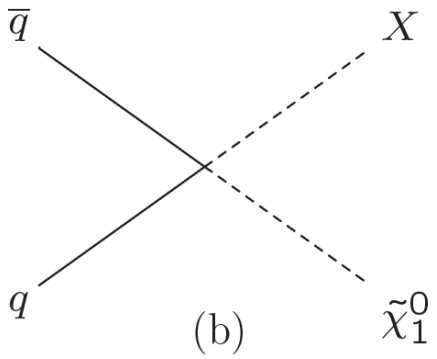
Search for Long Lived Particles (LLP)

- Inspired by SUGRA with R-parity violation
- Production and search region
  - Decay from Higgs like particle via gluon fusion
    - $30 < m_h < 200$GeV
    - $10 < m_\chi < m_h/2$ GeV
  - Non resonant contact interaction
    - $10 < m_\chi < 90$ GeV
- Decay
  - One muon + two jets

$$\tilde{\chi}_1^0 \to \mu^+ q_i q_j (\mu^- \bar{q}_i \bar{q}_j)$$

- Data
  - 5.4fb^{-1}





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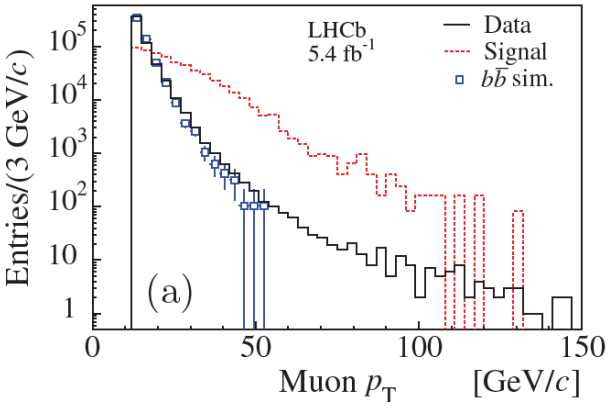
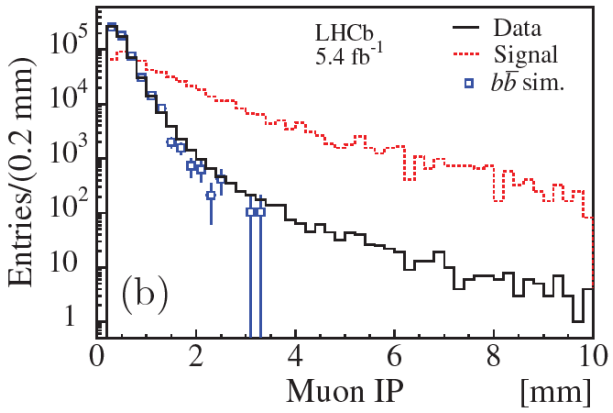
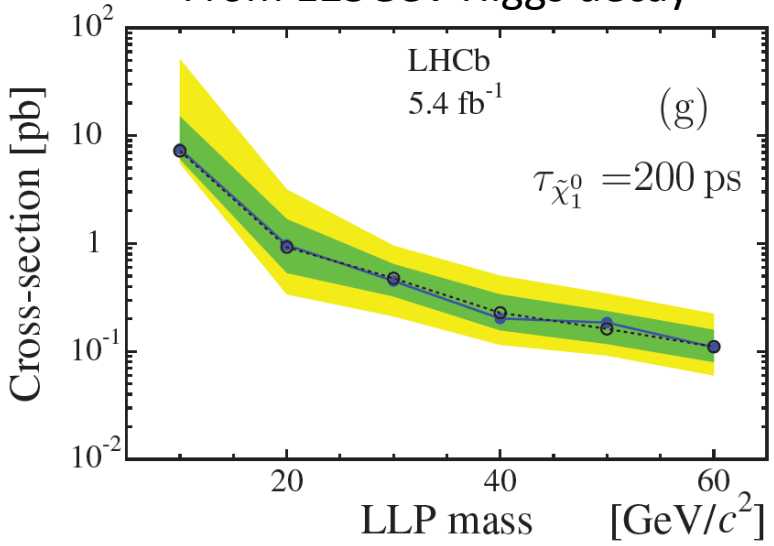
Limit on σ*BF

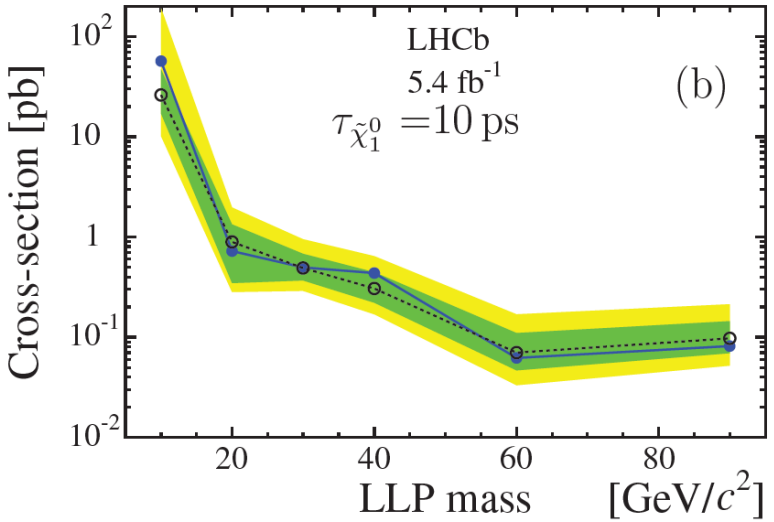
- Selection
  - High pT muon
  - displacement from primary vertex required.
  - At least three tracks attached to muon
  - Vertex fit quality cut.
- Using long lever arm, LLP with lifetime of 200ps can be searched





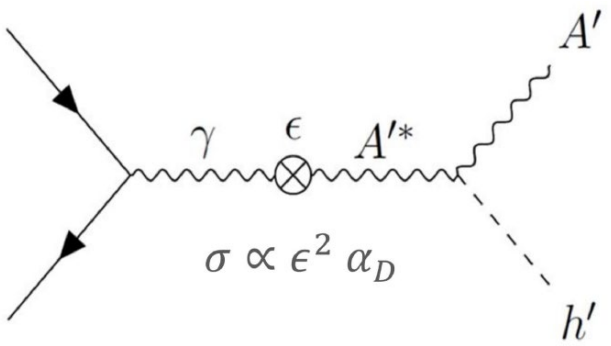
From 125GeV Higgs decay

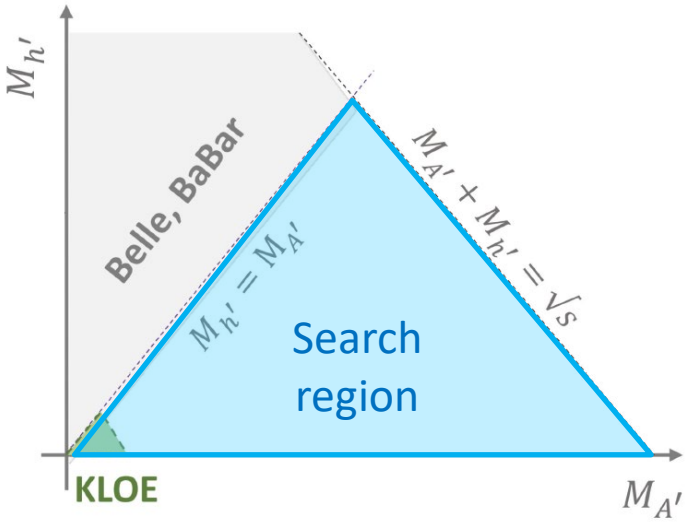




Dark Higgs

- Dark photon A’ may acquire mass from the spontaneous symmetry breaking of dark Higgs field → physical dark Higgs h’ emerges.
  - No mixing with SM Higgs is assumed in the analysis
- Dark Higgs can be generated from dark higgsstrahlung process : e^+e^- → A’h’
- 4 parameters
  - $M_{A'}$, $M_{h'}$
  - ε : kinetic mixing
  - α_D: coupling constant of dark sector
- $M_{h'} > M_{A'}$
  - Dark Higgs is visible
  - already covered by Belle and Babar
- $M_{h'} < M_{A'}$
  - Dark Higgs is invisible
  - Only done by KLOE.
  - There is a wide room for search

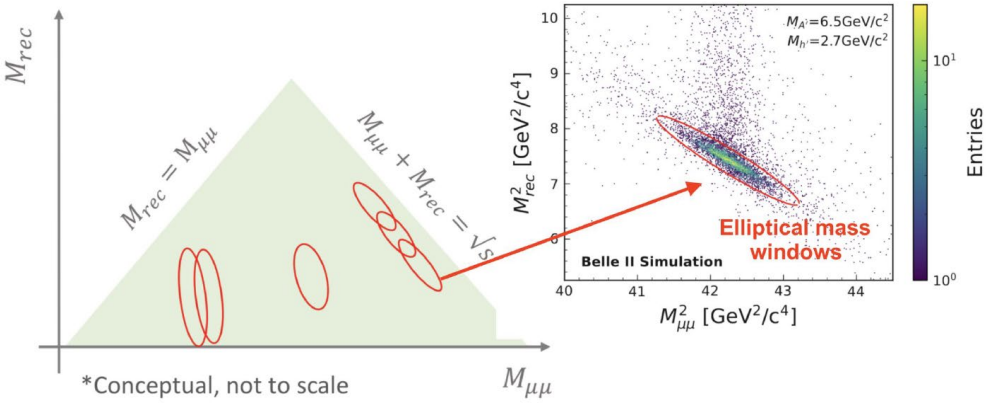


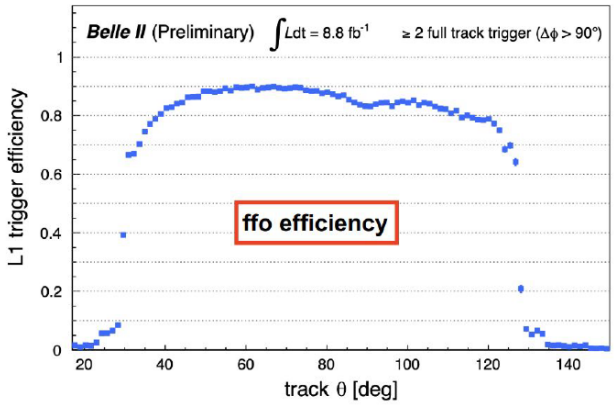


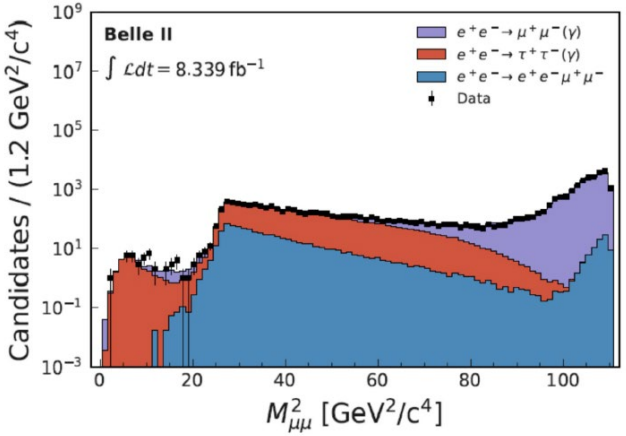
Preliminary

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

- Data
  - 8.34fb^{-1} in 2019
- 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 $\Delta\phi$>90deg
  - 90% efficiency
- Search in two dimensional plain
  - $M_{\mu\mu}$ VS M_{rec}
    - Correlated
  - Ellipse signal windows
- Dominant backgrounds
  - $e^+e^- \rightarrow \mu\mu\gamma$
  - $e^+e^- \rightarrow \tau\tau$
  - $e^+e^- \rightarrow ee\mu\mu$



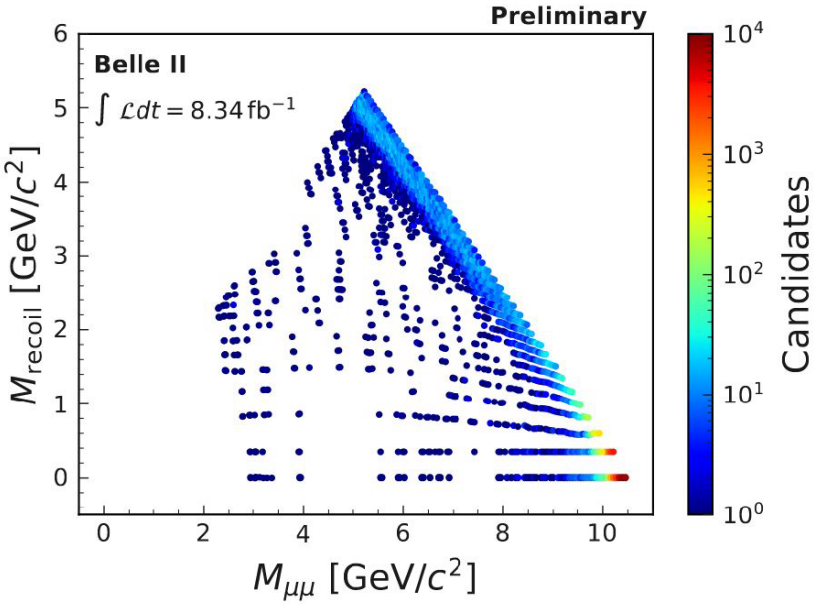


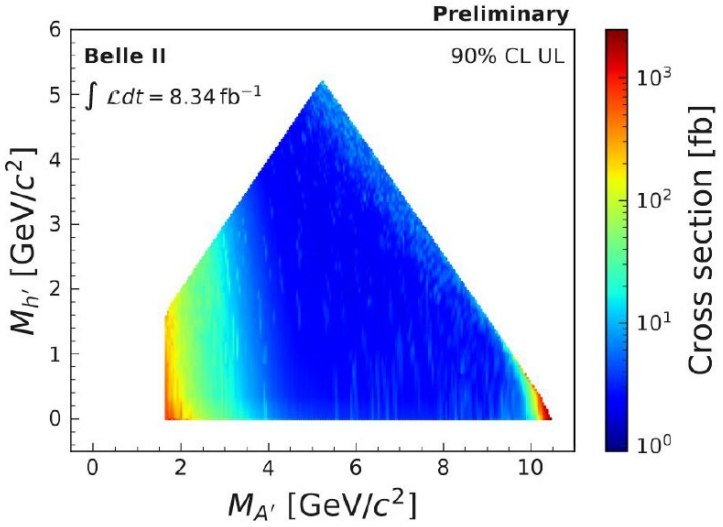


Preliminary

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

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



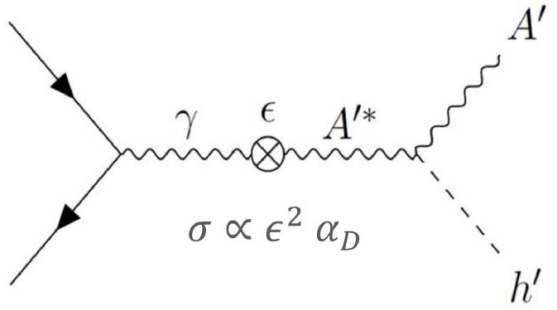


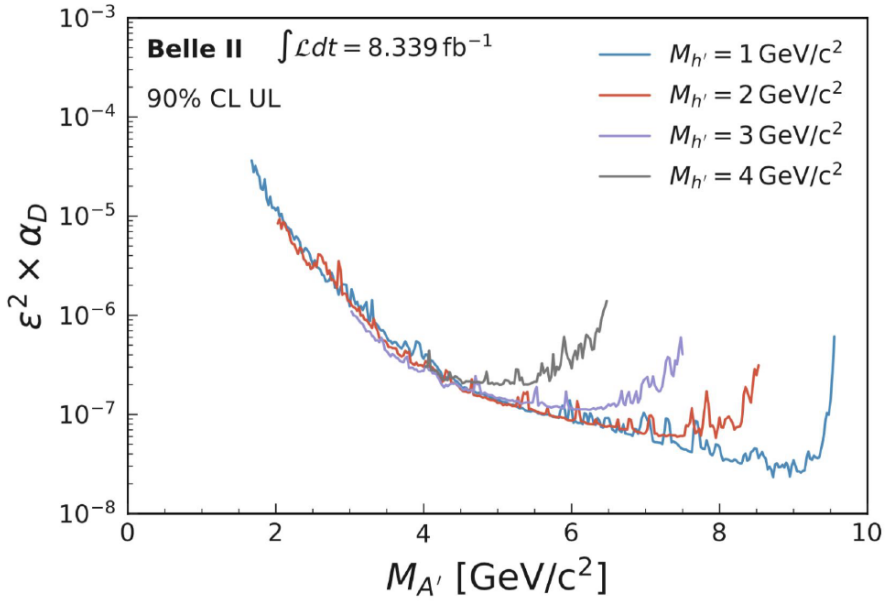
Discreteness is due to binning effect

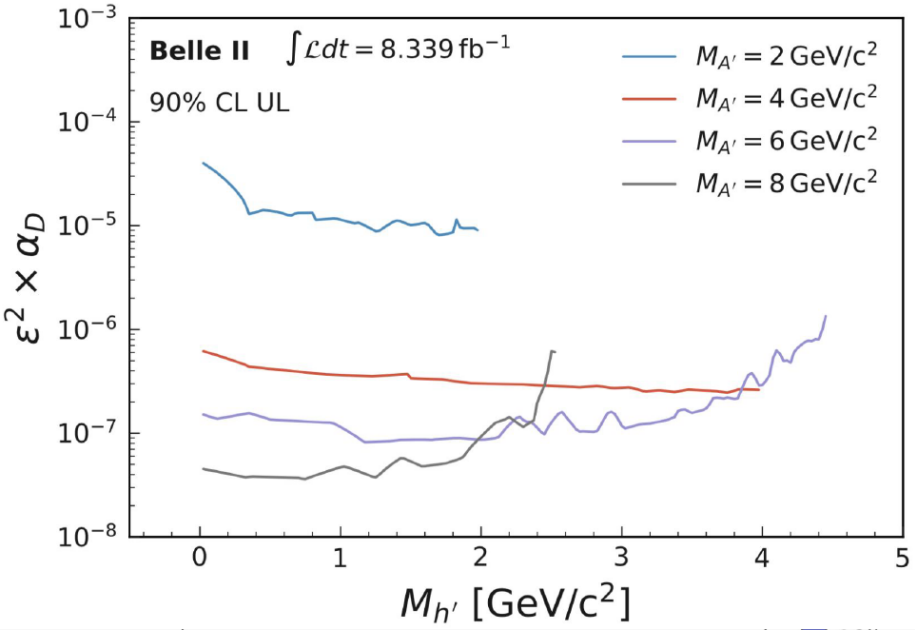
Preliminary

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





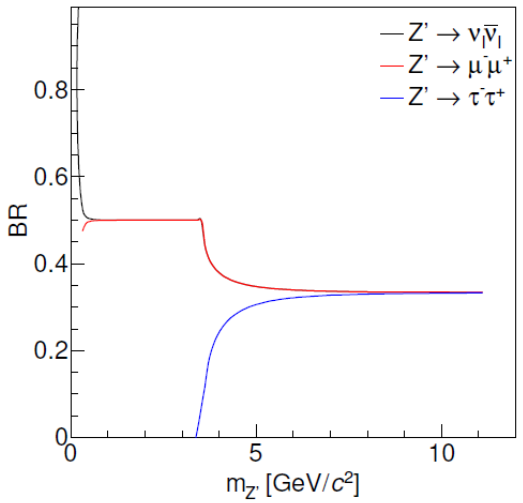


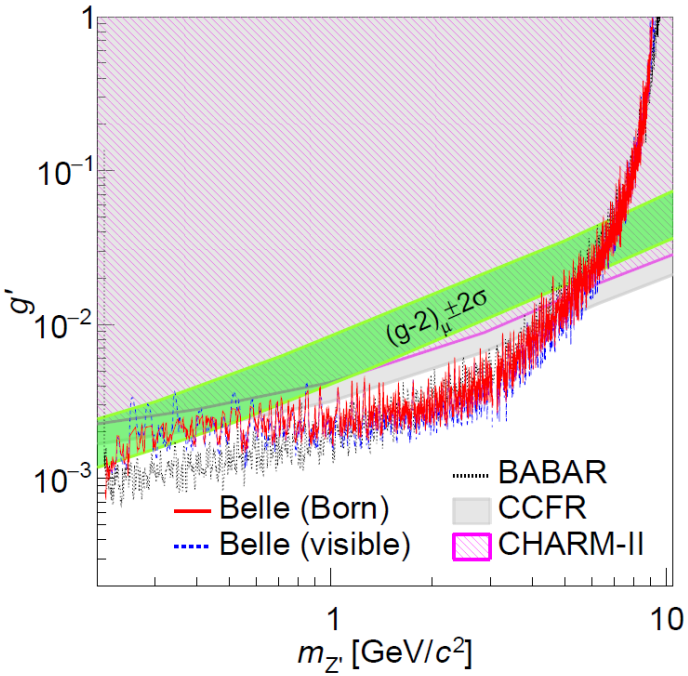
Invisible Z' in L_μ-L_τ model

- In the L_μ-L_τ model, Z' only couples to particles with second and third lepton family numbers : μ, τ, ν_μ, and ν_τ
  - Two parameters : $m_{Z'}$ and g'

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

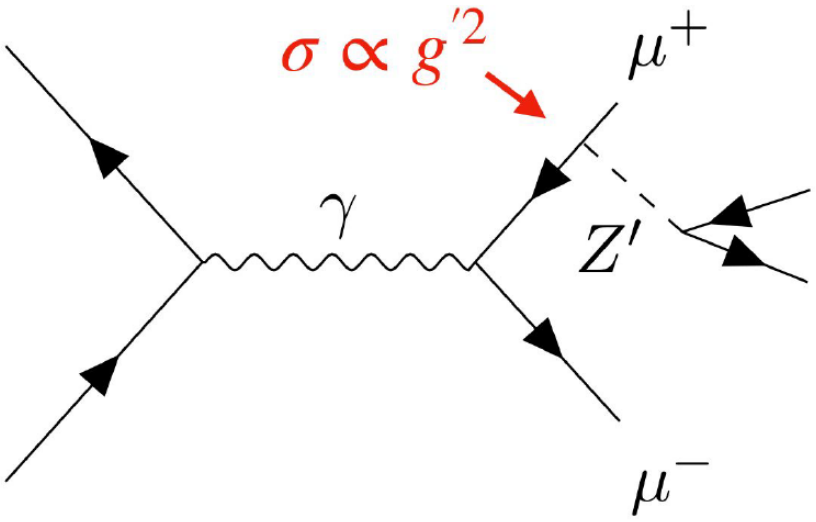
  - If dark matter carries the lepton family numbers, invisible BF can be larger if kinematically allowed.
  - Can access to $m_{Z'} < 2m_\mu$
- This model can explain the muon g-2 anomaly
- Searches performed by Belle and BaBar, with muons
- interpretations with neutrino trident experiments CCFR and CHARM-II
- And BOREXINO limit > 10MeV
  - Not shown in the figure





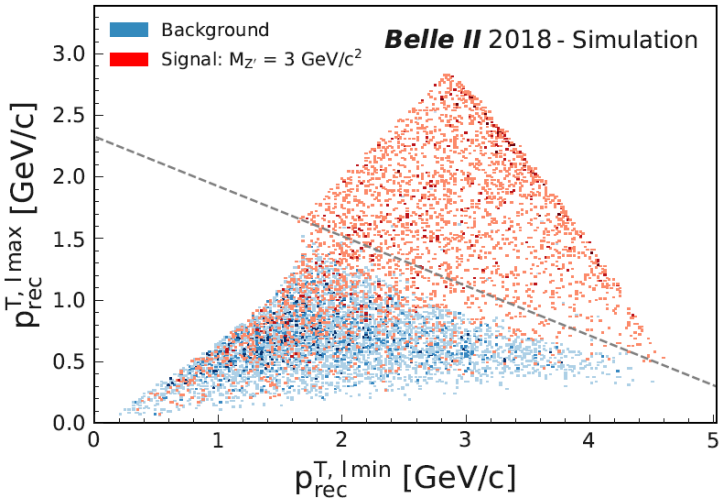
Signature of invisible Z’

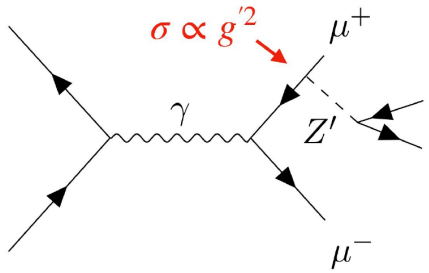
- Z’ can be radiated off from muons
- Decays to either of ν_μ, and ν_τ (and DM) pairs.
  - $e^+e^- \rightarrow \mu^+\mu^- Z' \rightarrow \mu^+\mu^-\nu\nu$
  - Two muons and missing energy
- Typical cross section
  - ~10fb with g’=0.01 and $M_{Z'}$ = 1GeV

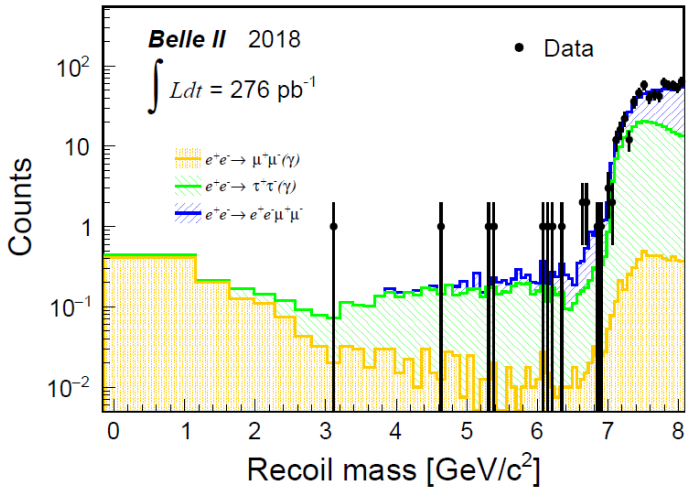


Search for Z' in L_μ-L_τ model

- Data
  - 276pb^{-1} in 2018 pilot run
- Trigger
  - two track with opening angle $\Delta\phi$>90deg
- Recoil mass to reconstruct Z'
- Dominant backgrounds
  - $e^+e^- \rightarrow \mu\mu(\gamma)$
  - $e^+e^- \rightarrow \tau\tau(\gamma)$
  - $e^+e^- \rightarrow ee\mu\mu$
  - Suppressed by lepton p_T against Z' direction



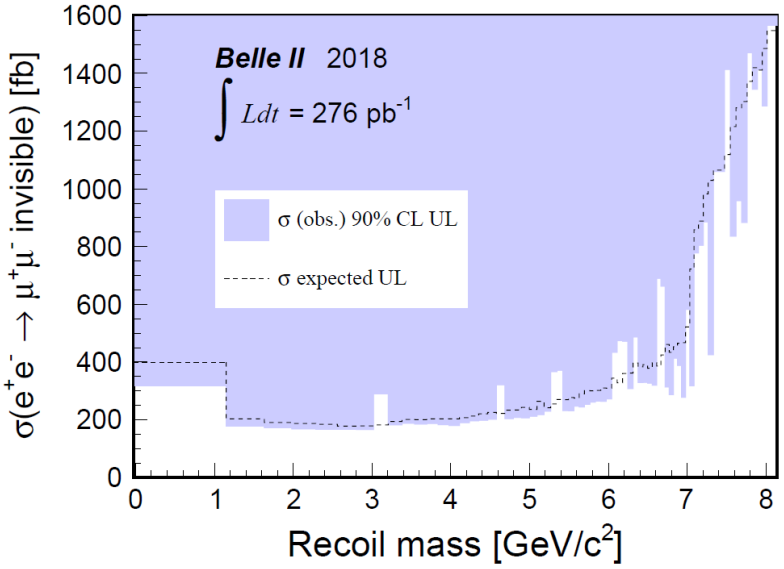


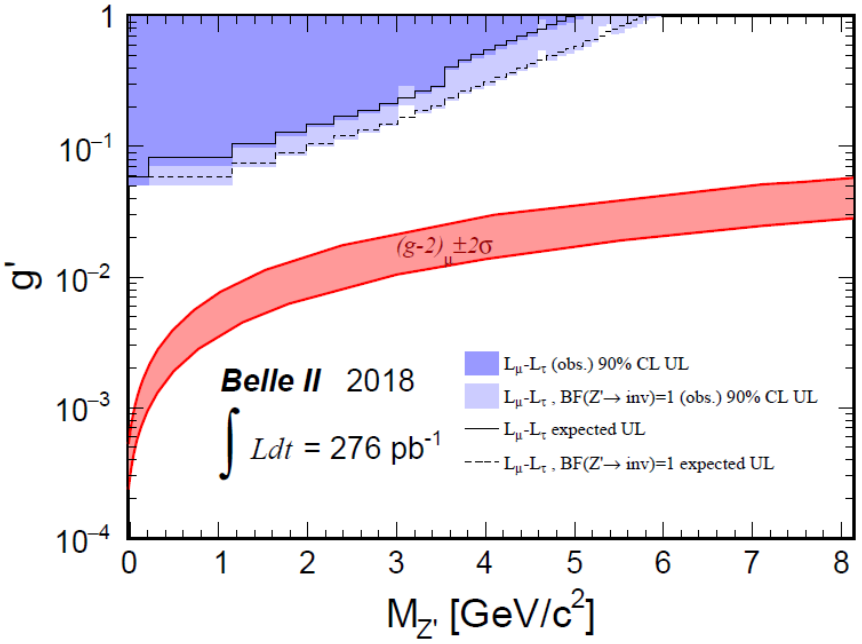


Phys. Rev. Lett. 124, 141801 (2020)

Limits for in L_μ-L_τ model

- First limit with invisible Z' decays.
- Can search for $m_{Z'} < 2m_\mu$
  - Impossible with $Z' \rightarrow \mu\mu$
- We already have 1000 time more data than this analysis





Axion Like Particles

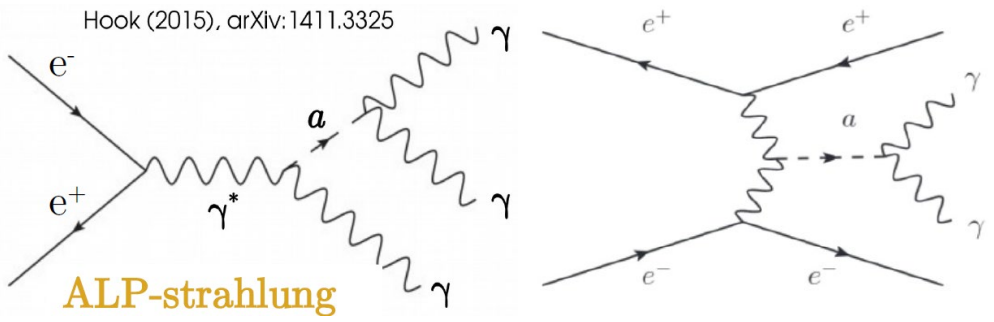
- Axion like particles (ALPs) emerge from
  - Spontaneous breaking of global symmetry
  - String compactification
    - 181820 species of ALPs in a model
- QCD Axion has a relation between mass and decay constant ($m_\pi f_\pi = m_a f_a$) while ALPs do not.
  - Large parameter space to explore
- For simplicity, ALP coupling to photon only→ 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)

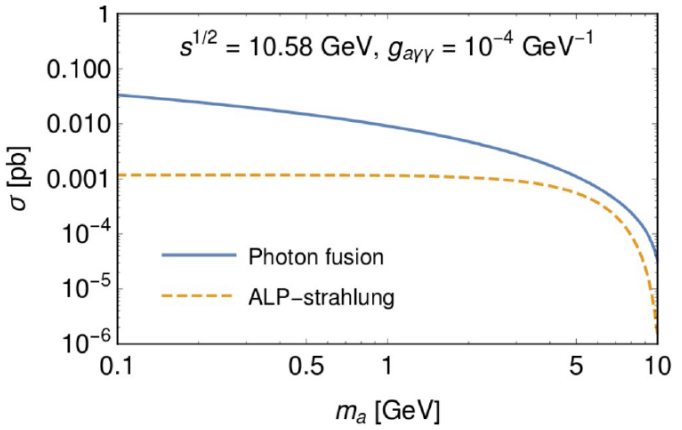
$$\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

Signature



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

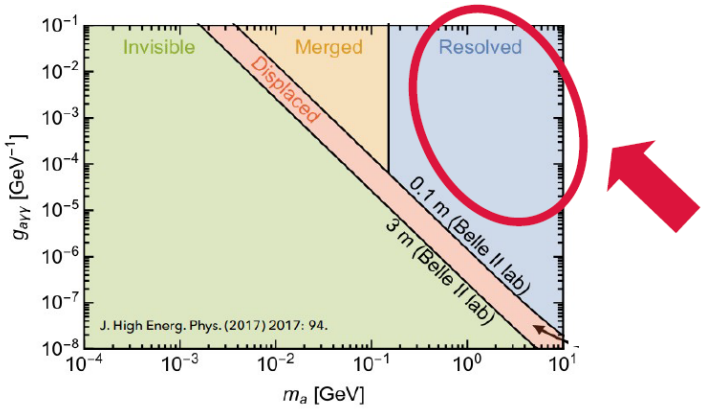
$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\rm QED}}{24}\left(1-\frac{m_a^2}{s}\right)^3$$



- 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

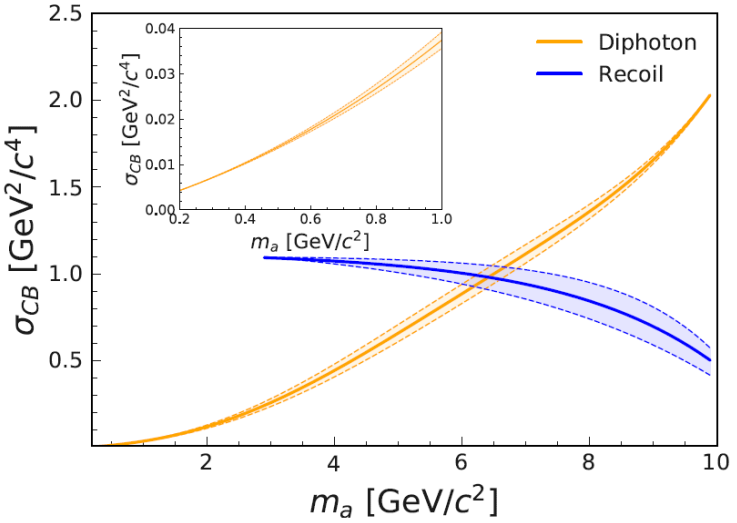
$$\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

  - two photons are resolved in EM calorimeters

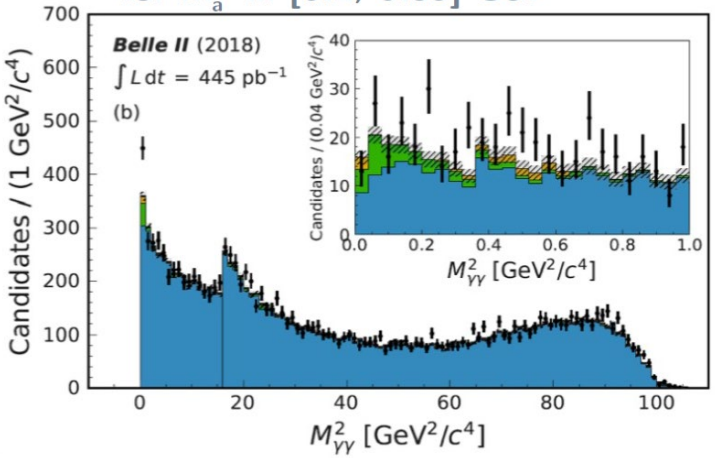


Search for ALPs at Belle II

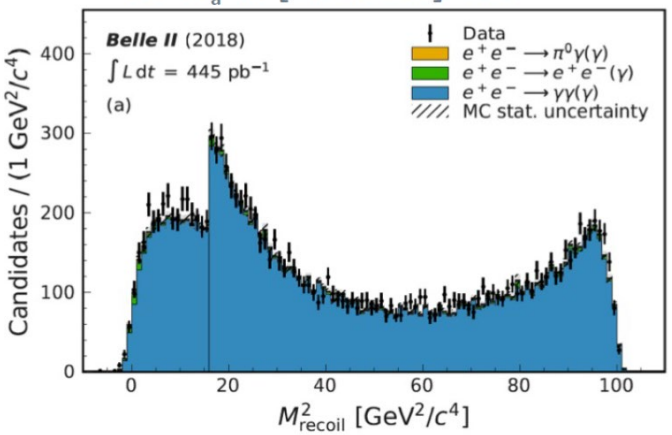
- Data
  - 445pb^{-1} in 2018 pilot run
- Trigger
  - Energy sum in barrel calorimeter >1GeV
  - almost 100% efficiency
- Two Reconstruction technique
  - Invariant mass for low mass [0.2, 6.85]GeV
  - Recoil mass for high mass [6.85, 9.7]GeV
- Dominant background is SM $e^+e^- \rightarrow \gamma\gamma\gamma$



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

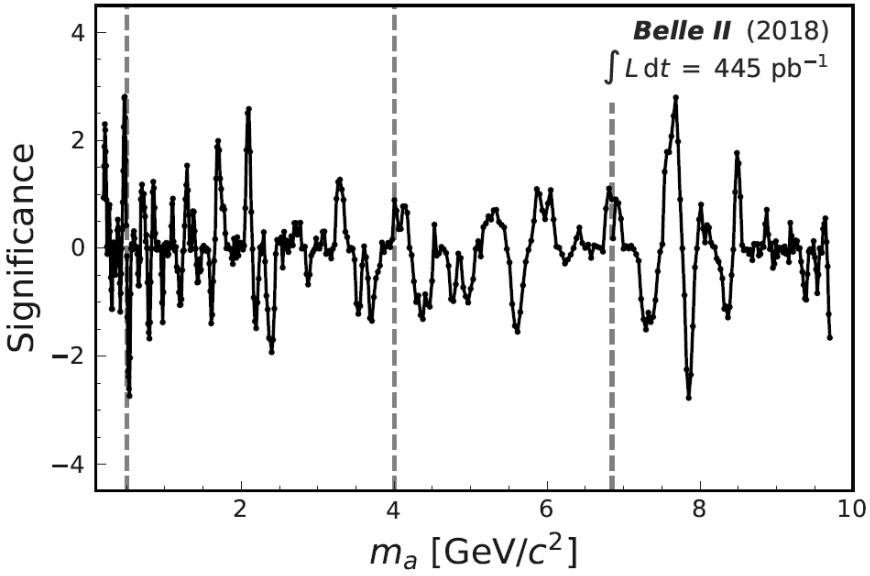


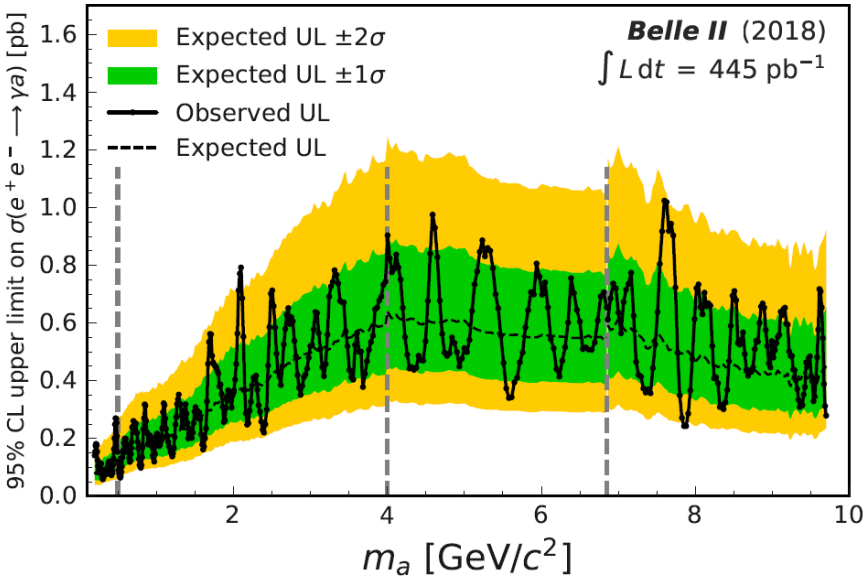
Recoil invariant mass for m_a in [6.85, 9.7] GeV



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

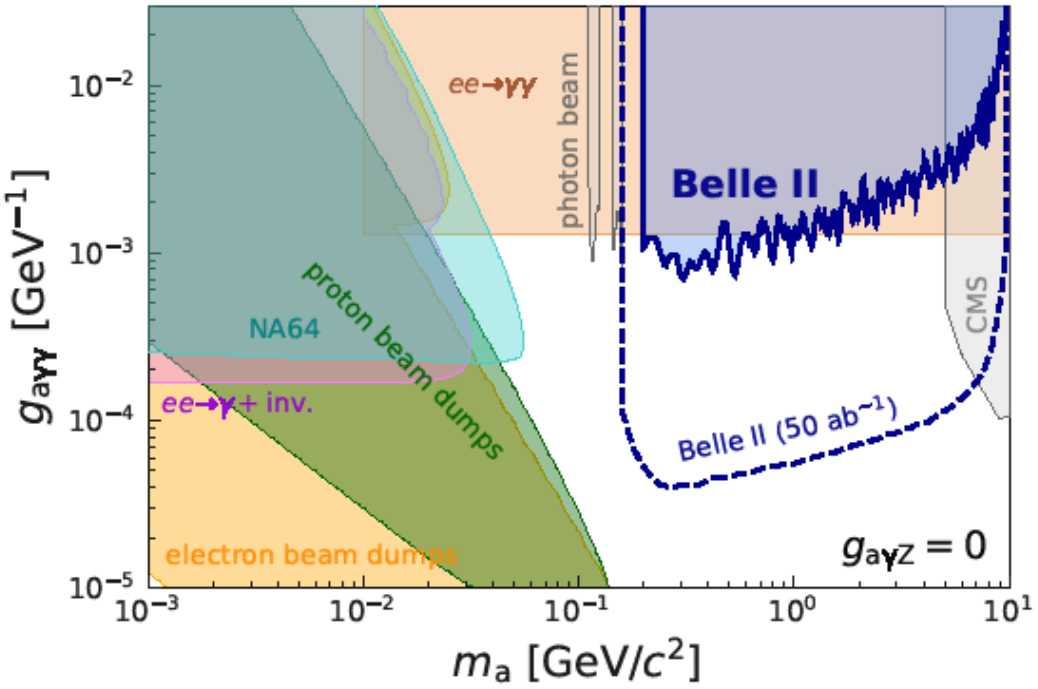
- No significant excess is observed
  - Largest local significance of 2.8σ at m_a=0.447GeV
- Set a limit on σ.
  - $\sigma < 1$pb





Limit on ALP parameter space

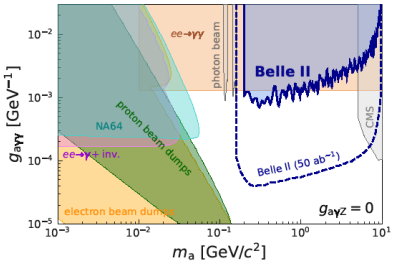
- Coupling around 10^{-3}GeV^{-1} level
- World's best limit around 500MeV
- We can improve the sensitivity more than one order of magnitude in coupling with 50ab^{-1} data
- Adding photon fusion process gives better limit



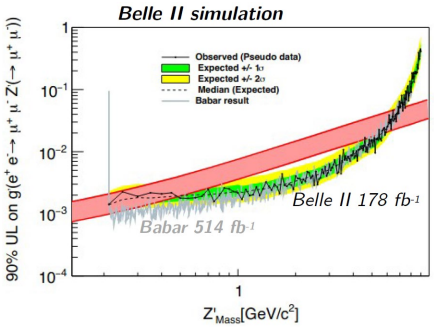
Other Dark Sector Searches

- Many searches are possible at Belle II and LHCb, and are in pipeline with more data

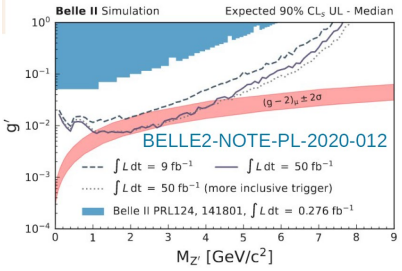
ALPs → diphoton



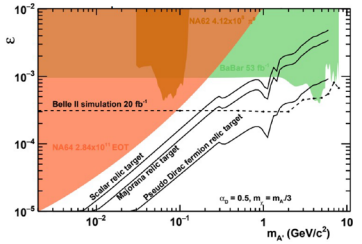
Visible Z' in L_μ-L_τ



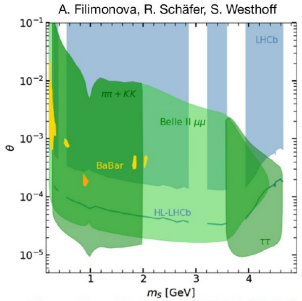
Invisible Z' in L_μ-L_τ



Invisible dark photon

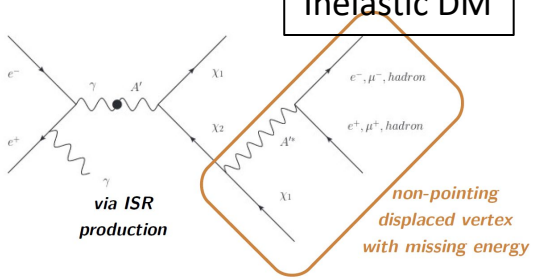


ALPs or dark scalar in B→Ka, a→ff

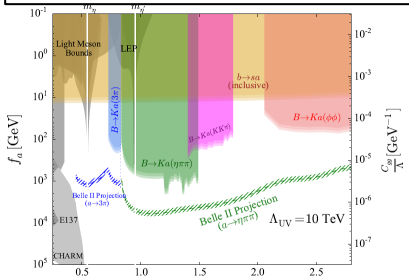


Phys. Rev. D 101, 095006 (2020)

Inelastic DM

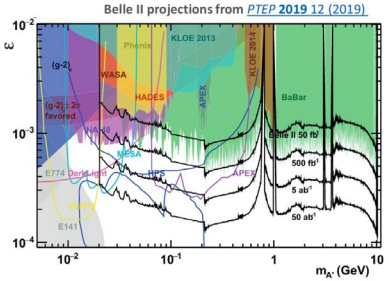


Heavy QCD axion in B→Ka, hadronic a decays



Phys. Rev. D 104, 055036 (2021)

Visible dark photon



ALPs in B→Ka, a→γγ

Sterile neutrino in B decays

Singlino in Y(1S) decays

Sterile neutrino in τ decays

Dark Higgs in Y(1S) decays

Dark shower

Displaced jets

Summary

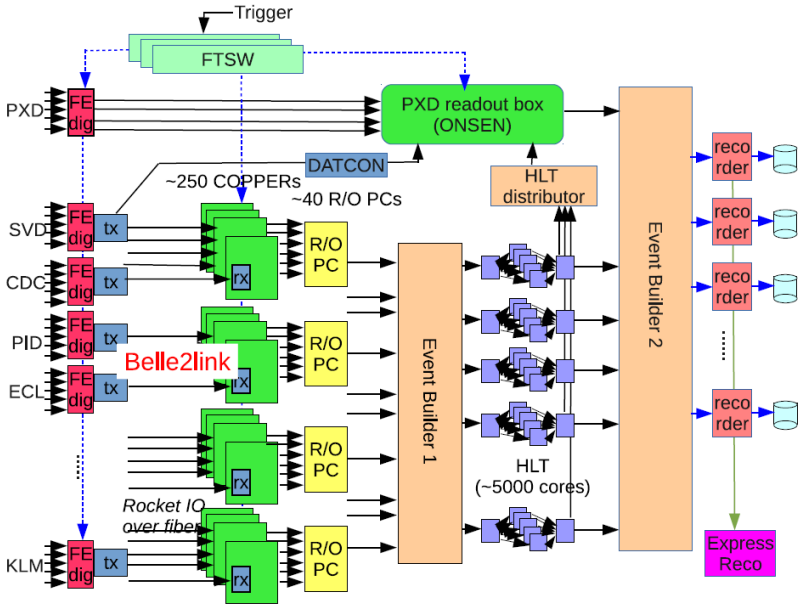
- Dark sector scenarios are very interesting
- Belle II and LHCb are good playgrounds for dark sector searches
- Several searches has been performed with limited statistics
  - Dark Photon
  - Dark Higgsstrahlung
  - Invisible Z’
  - Axion like particles
- World best limits has been obtained.

- Many searches are possible at Belle II and LHCb, and are in pipeline with more data
- Stay tuned

backup

Trigger and DAQ at Belle II

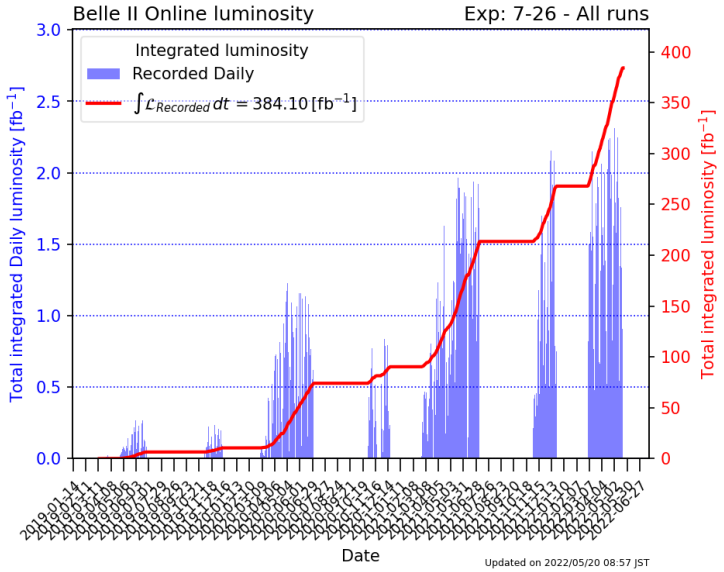
- Trigger
  - Adopted two-level trigger system
  - Level1 Hardware trigger
    - Maximum output rate 30kHz
  - Higher level software trigger
    - Maximum output rate 10kHz
- DAQ
  - Pipelined readout system

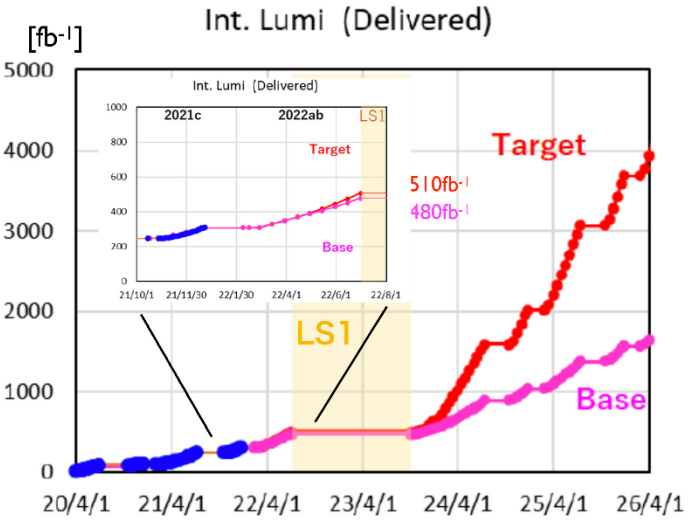


- This trigger and DAQ system allows triggering on dark sector signatures which was difficult at Belle
  - Single photon trigger
  - Single track trigger for missing energy events
  - Two-track trigger with missing energy events

SuperKEKB and Belle II

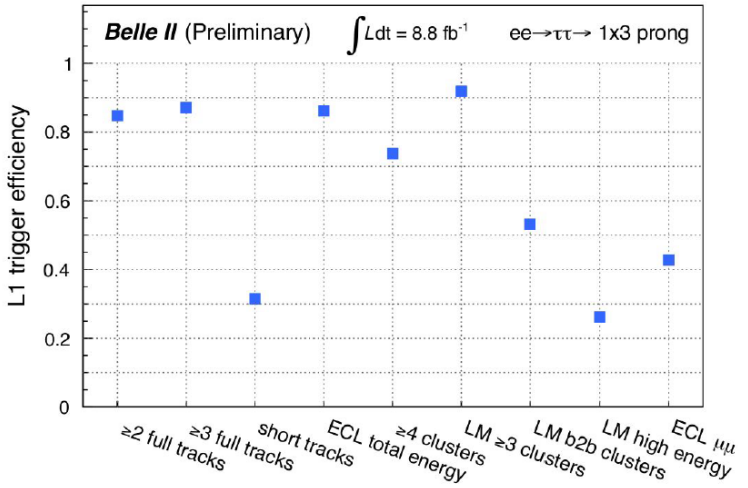
- Status and Plan
  - Pilot run in 2018
    - Without pixel detector
    - ~500pb^{-1} data
  - Started experiment in 2019
  - Accumulated ~0.4ab^{-1} so far
    - 40% of Belle
  - LS1 from July 2022
    - To install second layer of pixel detector
  - Resume the operation in 2023
  - ~4ab^{-1} by 2025
  - LS2 around 2026
    - to upgrade SuperKEKB and Belle II to achieve 6x10^{35} /cm^2/s
  - 50ab^{-1} will be accumulated around 2031

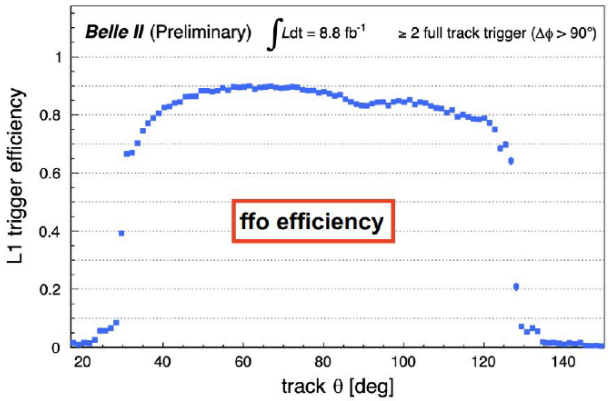




Trigger for dark Higgs

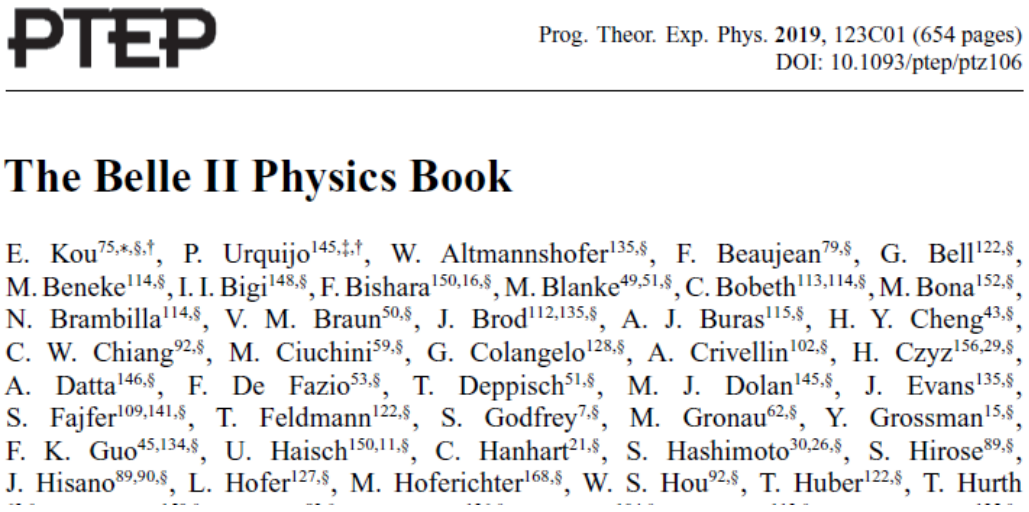
- Two-tier trigger system:
  - Hardware based low level trigger (L1)
  - Software based high level trigger (HLT)
- Reduce effects from beam backgrounds (Touschek effect, beam-gas scattering, radiative Bhabha, …)
- L1 trigger
  - Max trigger rate 30KHz
  - Combines 4 sub-detector triggers; **CDC**, **TOP**, **KLM**, **ECL**
- Dedicated trigger lines for dark sector and low-multiplicity physics (not available in Belle):
  - Single photon / track (muon)
  - Multi-track triggers
    - **ffo - ≥2 full tracks with opening angle > 90°**
    - **ff30 - ≥2 full tracks with opening angle > 30°**
  - 3D neural trigger





Belle II Physics Book

- Published in Dec 2019
  - https://arxiv.org/abs/1808.10567
  - https://doi.org/10.1093/ptep/ptz106



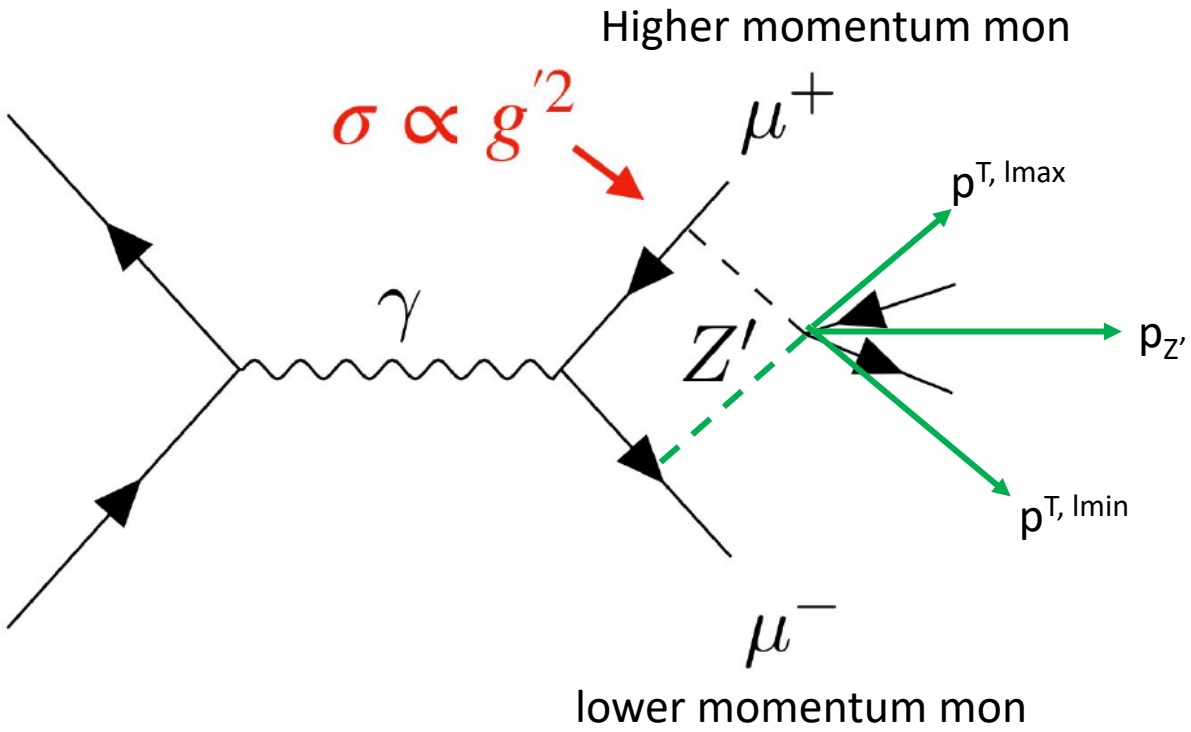
PTEP

Prog. Theor. Exp. Phys. **2019**, 123C01 (654 pages)
DOI: 10.1093/ptep/ptz106

The Belle II Physics Book

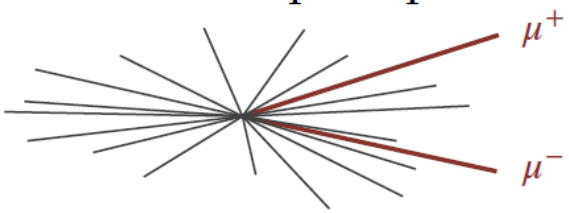
E. Kou[75,*,§,†], P. Urquijo[145,‡,†], W. Altmannshofer[135,§], F. Beaujean[79,§], G. Bell[122,§], M. Beneke[114,§], I. I. Bigi[148,§], F. Bishara[150,16,§], M. Blanke[49,51,§], C. Bobeth[113,114,§], M. Bona[152,§], N. Brambilla[114,§], V. M. Braun[50,§], J. Brod[112,135,§], A. J. Buras[115,§], H. Y. Cheng[43,§], C. W. Chiang[92,§], M. Ciuchini[59,§], G. Colangelo[128,§], A. Crivellin[102,§], H. Czyz[156,29,§], A. Datta[146,§], F. De Fazio[53,§], T. Deppisch[51,§], M. J. Dolan[145,§], J. Evans[135,§], S. Fajfer[109,141,§], T. Feldmann[122,§], S. Godfrey[7,§], M. Gronau[62,§], Y. Grossman[15,§], F. K. Guo[45,134,§], U. Haisch[150,11,§], C. Hanhart[21,§], S. Hashimoto[30,26,§], S. Hirose[89,§], J. Hisano[89,90,§], L. Hofer[127,§], M. Hoferichter[168,§], W. S. Hou[92,§], T. Huber[122,§], T. Hurth

Joint effort of theorists and experimentalists.
Some of you contributed to the book. Thank you!


Higher momentum mon
$\sigma \propto g'^2$
μ^+
$p^{T,\,lmax}$
γ
Z'
$p_{Z'}$
$p^{T,\,lmin}$
μ^-
lower momentum mon

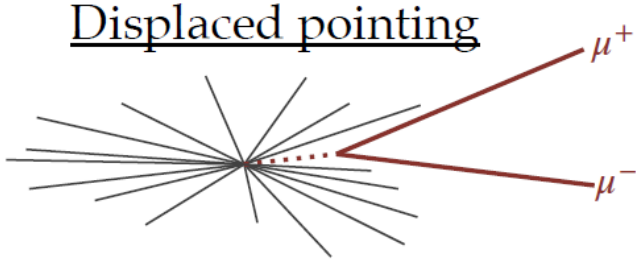
Inclusive Dimuon

Inclusive prompt

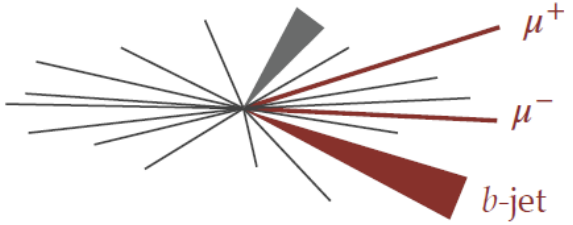


- No isolation requirements
- Non-zero width considered

Displaced pointing

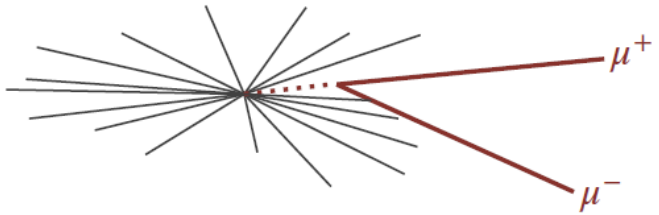


Prompt + *b*-jet



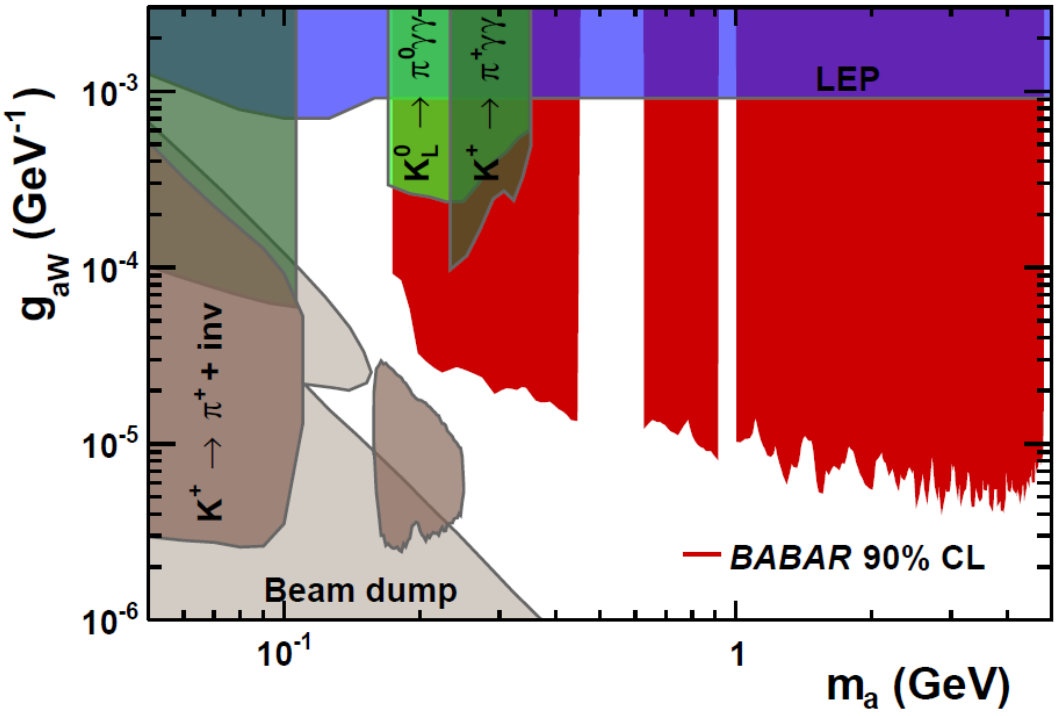
- Non-zero width considered

Displaced non-pointing



Search for B→Ka, a→γγ at BaBar

- Maybe next speaker Brian Shuve covers this?
  - Done by Brian



Search for visible Z' to μμ at Belle

- ISR effect is included in generator for the first time in this signature
- Comparable with BaBar for >1GeV