New physics searches at e^+e^- collider experiments

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Outline

- Motivation
- e^+e^- colliders
- Some important results related to dark portals
  - Higgs portal
  - Axion portal
  - Vector portal
  - Neutrino portal
- Summary

Motivation

❖ Standard Model (SM) is incredibly successful, it is tested by experiments

❖ However, it is not a complete theory

facing some tensions:

Naturalness and stability, g-2, W mass, R_K, R_D, R_{D*}, ….

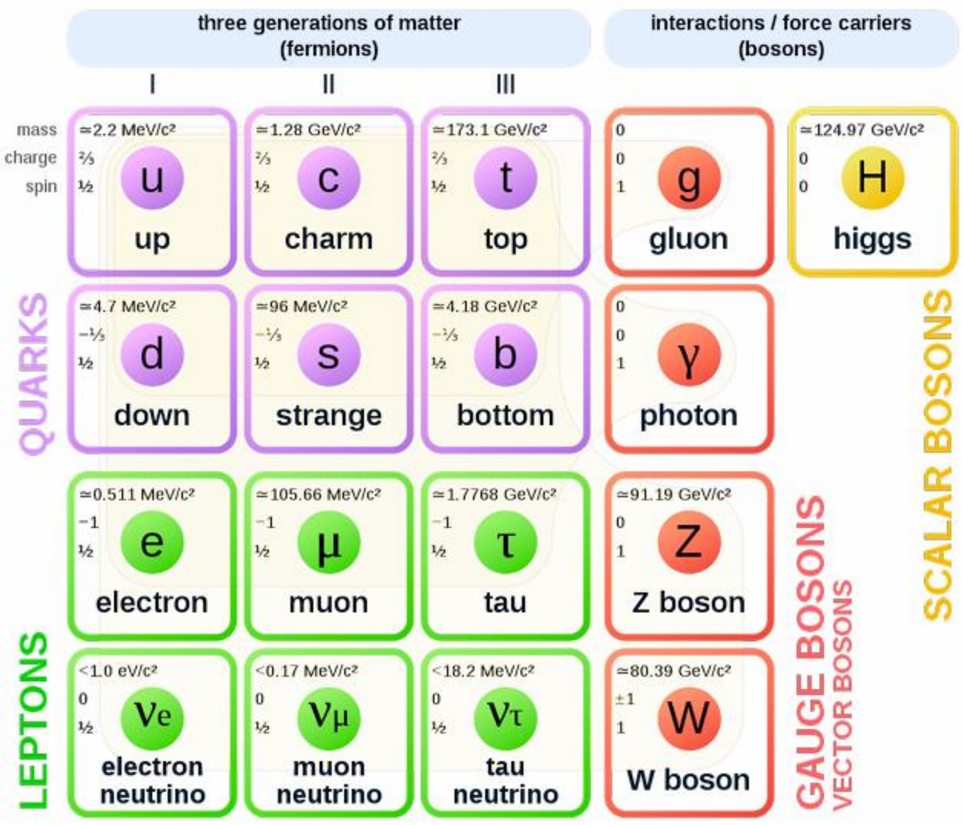
arXiv:2308.06230

Can not explain:

Existence & mechanism of dark matter and dark energy

Baryon asymmetry of the universe

Neutrino masses and oscillations, hierarchy

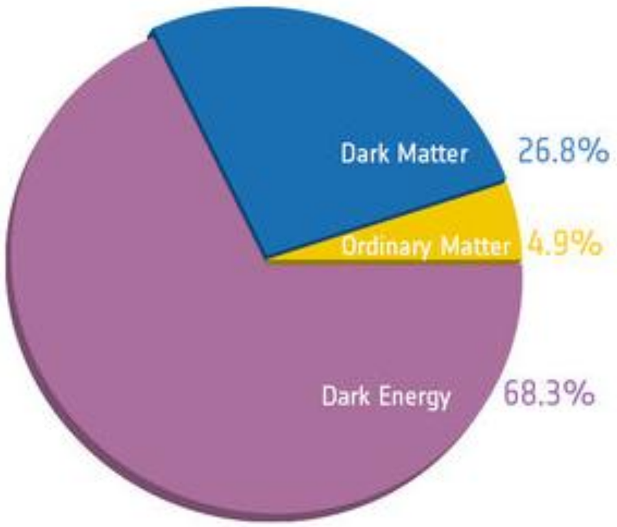


Real opportunity to search for new physics beyond the Standard Model

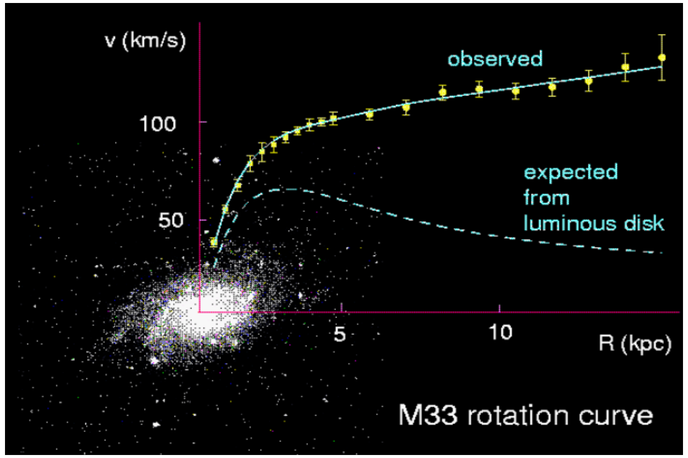
Motivation

❖ **Standard Model (SM) is incredibly successful but not complete!**

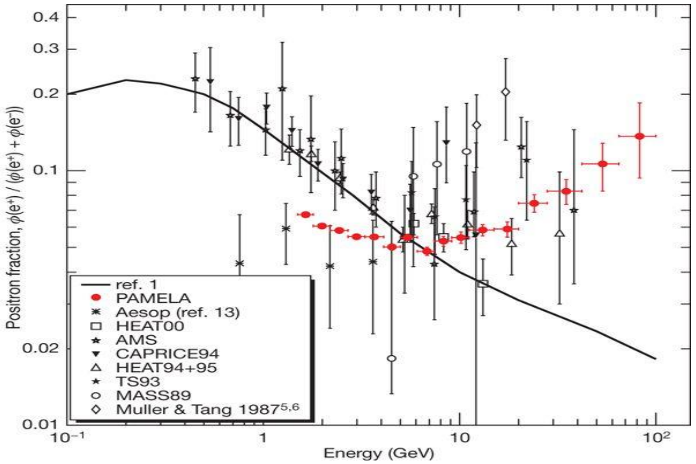
- ❑ Extensions of the SM needed to solve several outstanding issues, including the missing description of Dark Matter (DM)



- ❑ Why DM?
  - Amounts 27% of the total matter density of the universe
  - Not interact with strong and electromagnetic interactions, it presence so far can be inferred via the gravitational effects only.
  - Explain the features of recent astrophysical observations



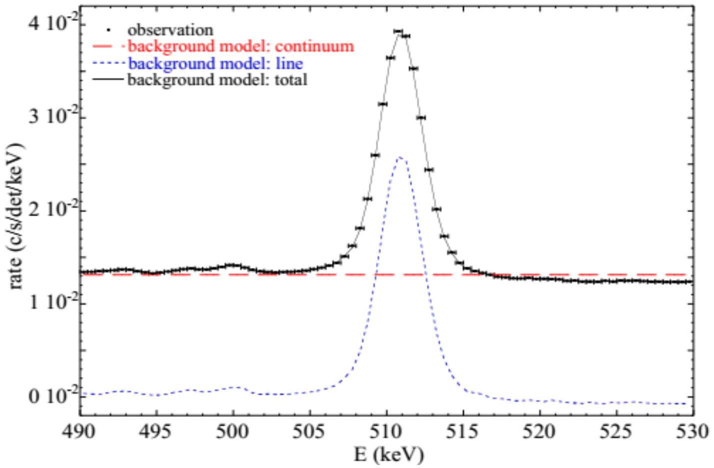
arXiv:astro-ph/0403324



PAMELA: Positron fraction

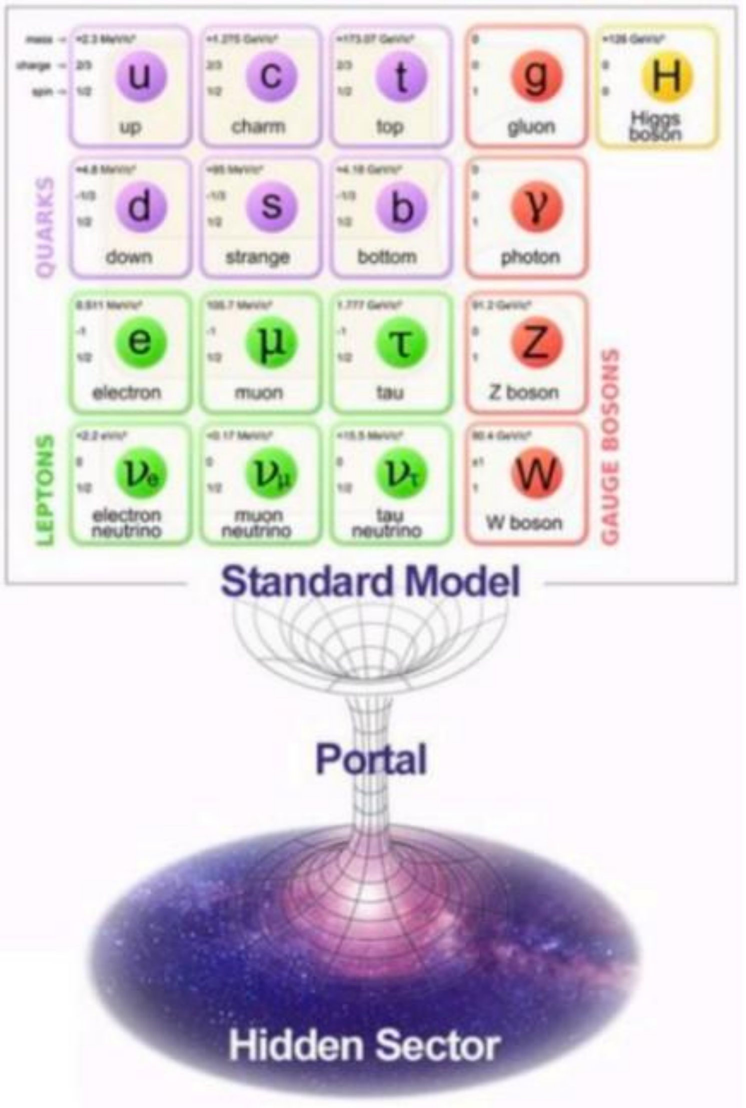
O Adriani et al., Nature **458** (2009) 607

SPI/Integral



P. Jean et al., A&A **407**, L-55-L58 (2003)

Coupling of DM with Standard Model



- Dark matter has not seen yet in particle physics experiments.
  - SM can't explain DM ⟹ Extend to the SM to include Dark matter
  - One of the simplest models is "DM hidden sector" that allows the coupling between DM and SM particles via the so called "portals"

$$\mathcal{L} \supset \begin{cases} -\dfrac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu} \,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H \,, & \text{Higgs portal} \\ y_n L H N, & \text{neutrino portal} \\ \dfrac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, & \text{axion portal} \end{cases}$$

A' kinetic mixing with γ, Z

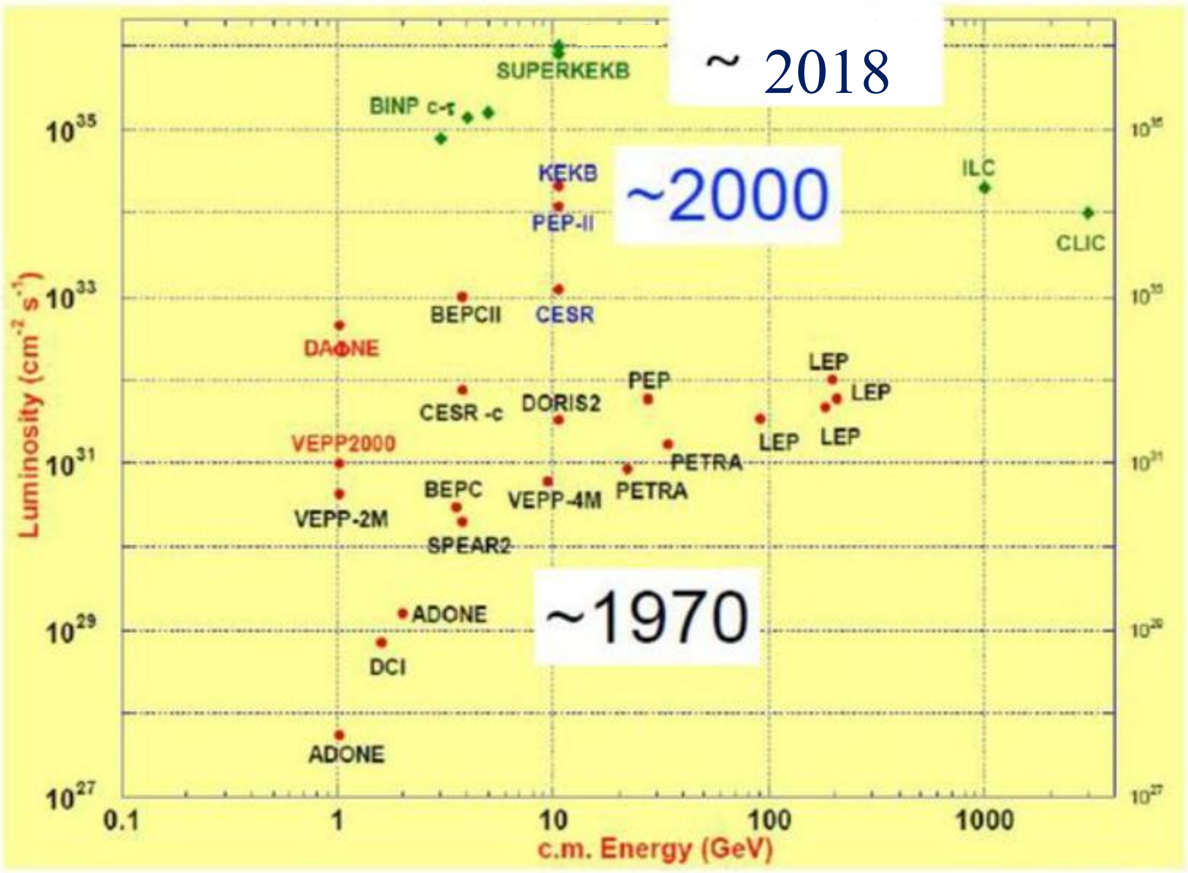
Dark Higgs (mixes with SM Higgs)

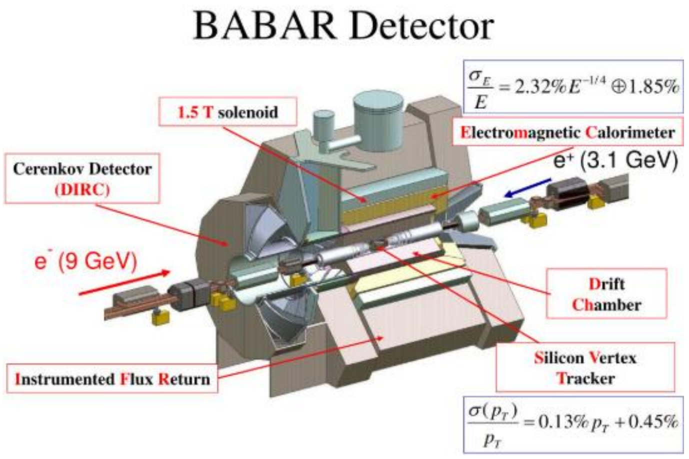
Sterile neutrino

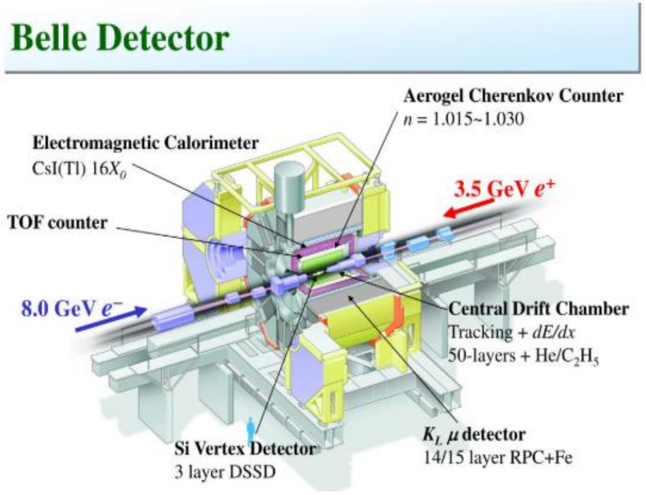
Axion, coupling to DM

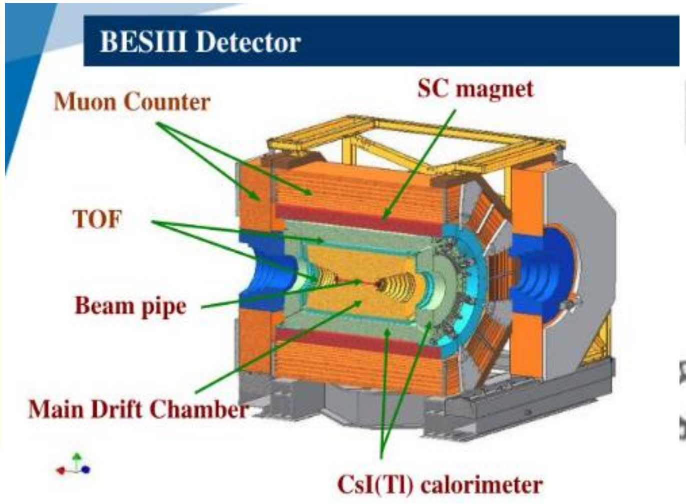
- Can be accessible by high intensity e^+e^- collider experiments, such as BESIII, BaBar and Belle/Belle II experiments, if their masses are a few GeV

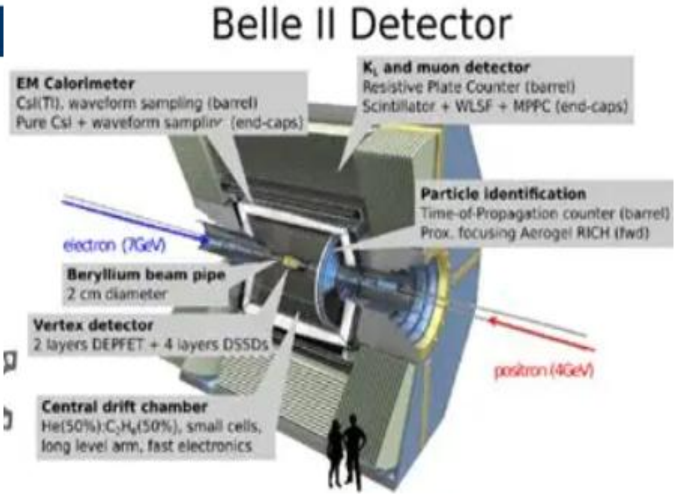
e^+e^- colliders











Proposed Chinese based e^+e^- collider experiments

- ✓ Circular electron-positron collider (CEPC) experiment
- ✓ Future Super-tau Charm Facility (STCF) experiment

Light Higgs boson A^0 search

PRD 105, 012008 (2022)

- A light Higgs boson is predicted by many extensions of Standard Model, such as Next-to-Minimal Supersymmetric Standard Model (NMSSM).

  - NMSSM contains a total of three CP-even, two CP-odd and two charged Higgs bosons.

    - **The lighter state of the A^0 is defined as:**

$$A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_s$$

$\cos\theta_A A_{MSSM}$ → Non-singlet; $\sin\theta_A A_s$ → Singlet

[PRD 76, 051105 (2007)]

  - Coupling of fermions and the CP-odd Higgs A^0

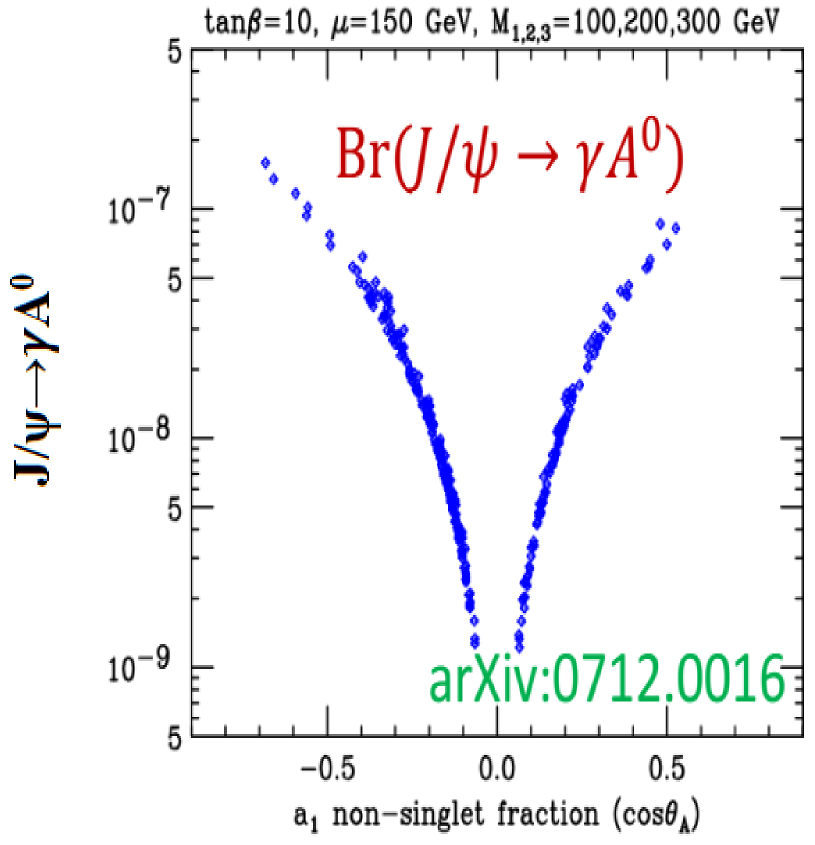
$$L_{int}^{f\bar{f}} = -\cos\theta_A \tan\beta \frac{m_f}{v} A^0 \bar{d}(i\gamma_5)d, \quad d = d,\ s,\ \mathbf{b},\ e,\ \mu,\ \tau$$

$$L_{int}^{f\bar{f}} = -\cos\theta_A \cot\beta \frac{m_f}{v} A^0 \bar{u}(i\gamma_5)u, \quad u = u,\ \mathbf{c},\ t,\ \nu_e,\ \nu_\mu,\ \nu_\tau$$

$$\tan\beta = \frac{v_u}{v_d}$$

Ratio of the VEVs of the up and down-types of Higgs doublets

E. Fullana et. al, Phys. Lett. B 653, 67 (2007)



Non singlet fraction $\cos\theta_A$

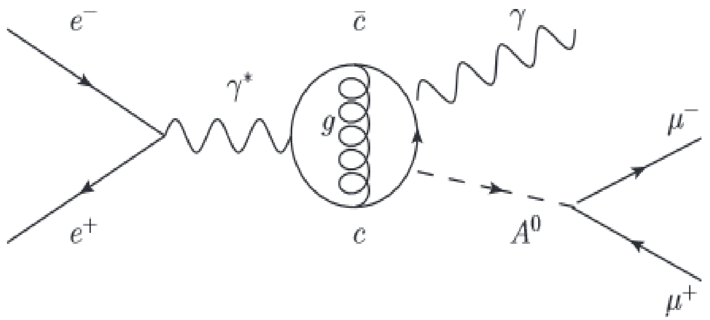
  - Can be detectable via radiative decays of J/ψ and ϒ(1S)

[Phys. Rev. Lett. **39**, 1304 (1977)]

Light Higgs boson A^0 search in radiative J/ψ decay

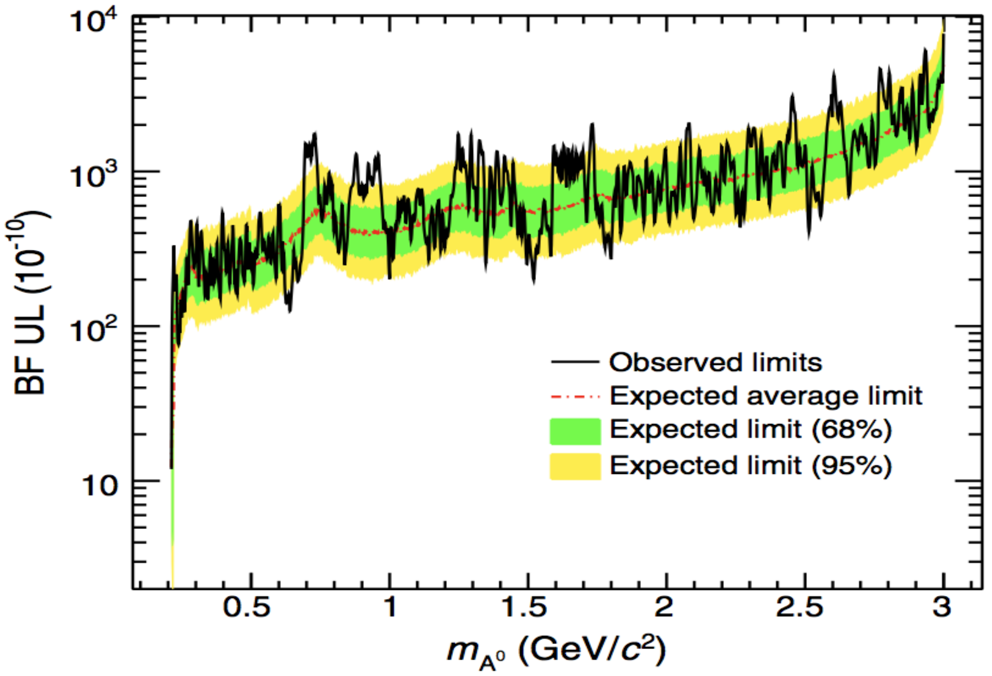
PRD 105, 012008 (2022)

Expected $B(J/\psi \to \gamma A^0) \sim 10^{-9} - 10^{-7}$ [PRD 76, 051105 (2007)]



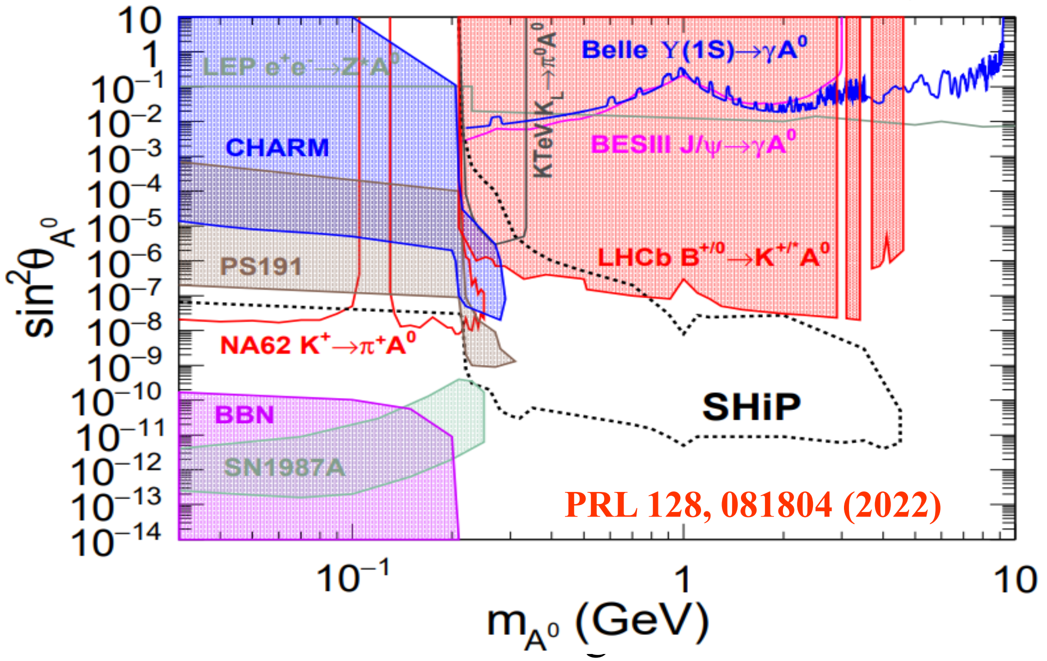
- Use 9 billion J/ψ events collected by BESIII experiment to perform this study.

- No evidence of A^0 production is found and set 90% confidence level upper limits on product BFs .



Mixing angle ($sin\theta_{A^0}$)

$$\frac{\mathcal{B}(\Upsilon(1S) \to \gamma A^0)\mathcal{B}(A^0 \to \text{hadrons})}{\mathcal{B}(\Upsilon(1S) \to \ell^+\ell^-)} = \sin^2\theta_{A^0} \frac{G_F m_b^2}{\sqrt{2}\pi\alpha} \sqrt{(1 - \frac{m_{A^0}^2}{m_{\Upsilon(1S)}^2})},$$



Our result in the low-mass region is better than recent BELLE measurement

Search for an Axion-like particle

An Axion-like particle (ALP), a

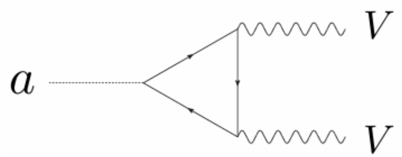
- is a pseudo-scalar particle
- introduced by the spontaneous breaking of Peccei-Quinn symmetry to solve the strong CP problem of the QCD

Phys. Rev. Lett. **40**, 223 (1978); Phys. Rev. Lett. **40**, 279 (1978) Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977)

- Predicted by many models beyond the SM and proposed to be a cold DM candidate.

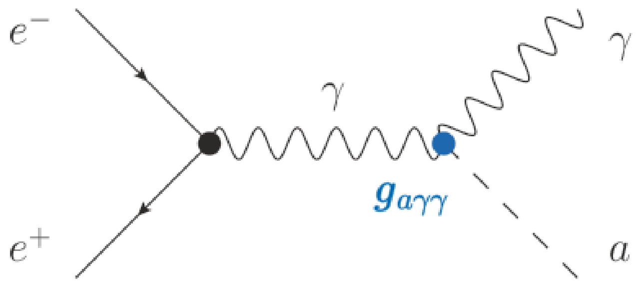
Phys. Lett. B 753, 482 (2016)

$$\mathcal{L} = -\frac{g_{aV}}{4} a V_{\mu\nu} \tilde{V}^{\mu\nu}$$

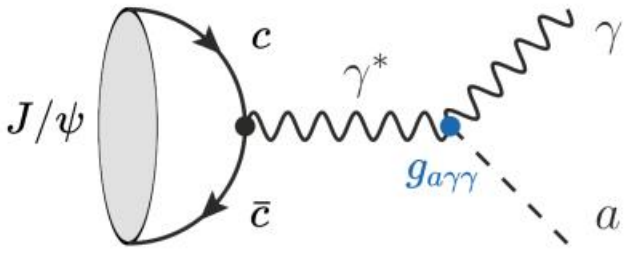


- ALP production at e^+e^- colliders
  - **ALP-Strahlung process**
  - **Radiative decay process**
  - **Via B meson decays**

Phys. Rev. D **52**, 1755 (1995)

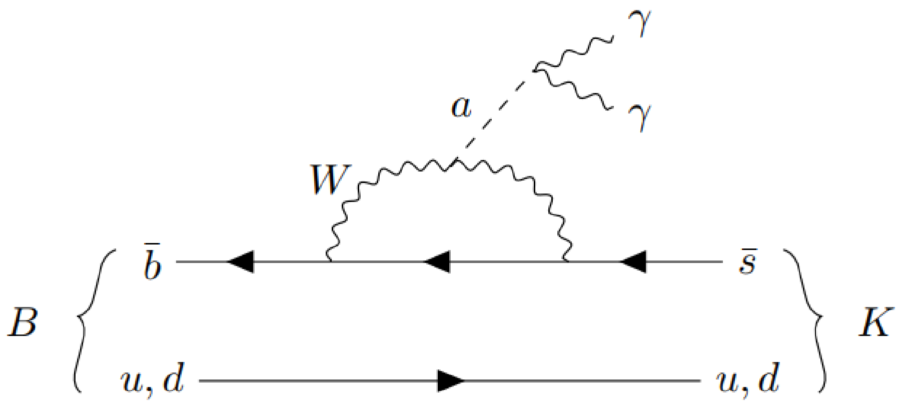


$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha.(\hbar.c)^2}{24}\left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^3$$



JHEP **06**, 091 385 (2019)

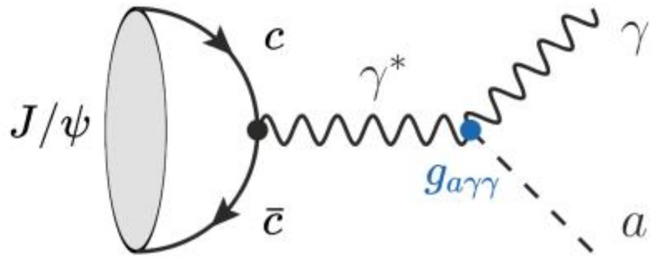
$$\mathcal{B}(J/\psi \to \gamma a) = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 \left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^3 \mathcal{B}(J/\psi \to e^+e^-)$$



Phys. Rev. Lett. **118**, 111802 (2017)

Search for ALP via radiative J/ψ decays at BESIII

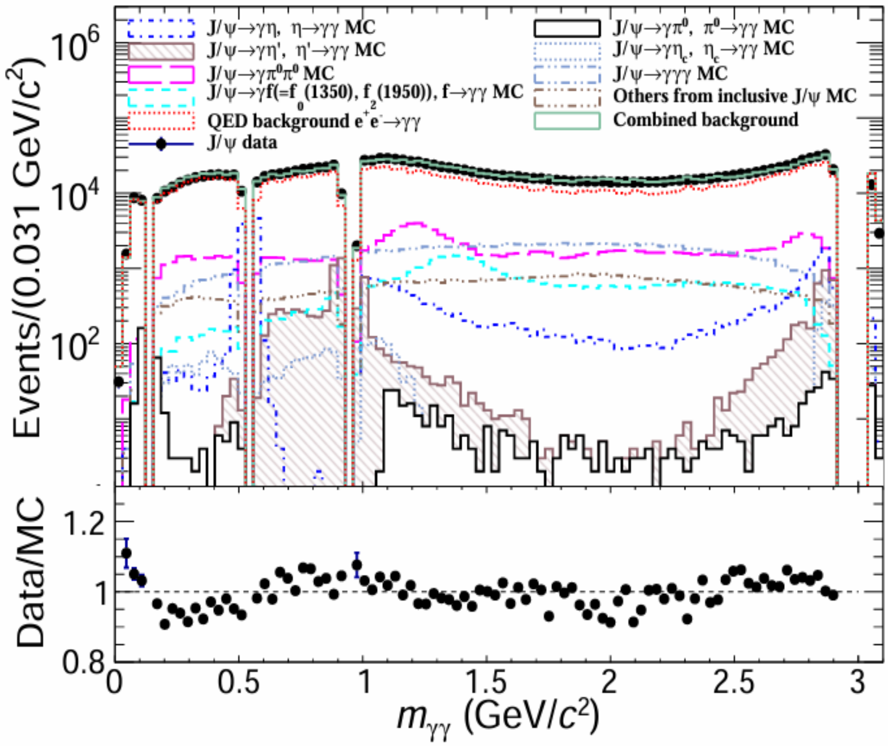
Phys. Rev. D **110**, L031101 (2024)

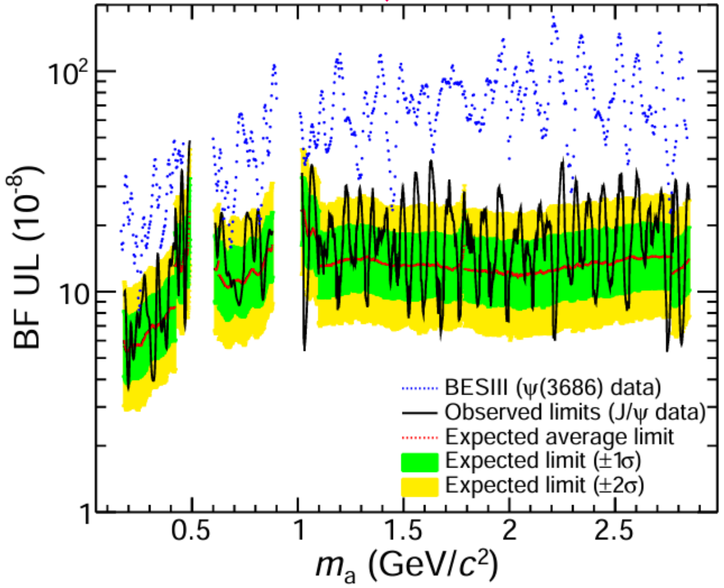


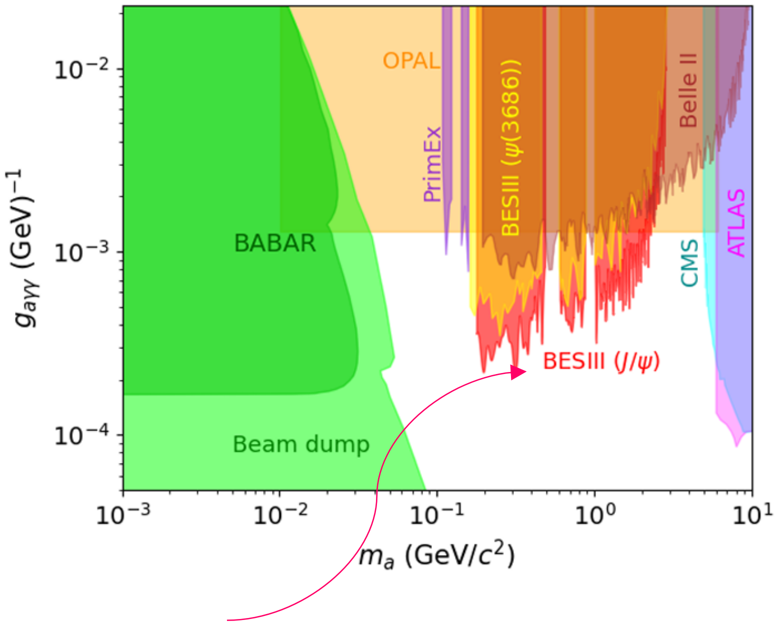
JHEP **06**, 091 385 (2019)

- 10^{10} J/ψ events
- Extract signal from $M_{\gamma\gamma}$ distribution
- Maximum signal significance: $< 3\sigma$

- UL on the BF of $\mathcal{B}(J/\psi \to \gamma a) \times \mathcal{B}(a \to \gamma\gamma)$
  $(3.6 \sim 53.1) \times 10^{-8}$@ 95% CL.

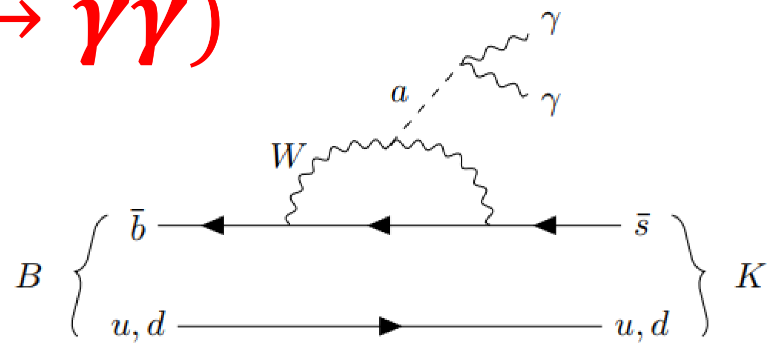






- New stringent constraints on ALP-photon coupling for $0.18 \le m_a \le 2.85$ GeV

Search for ALP in $B \to K^{(*)} a(\to \gamma\gamma)$

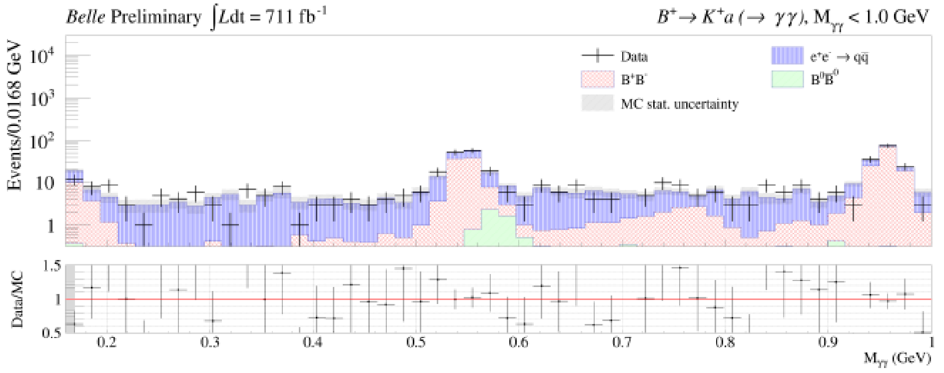


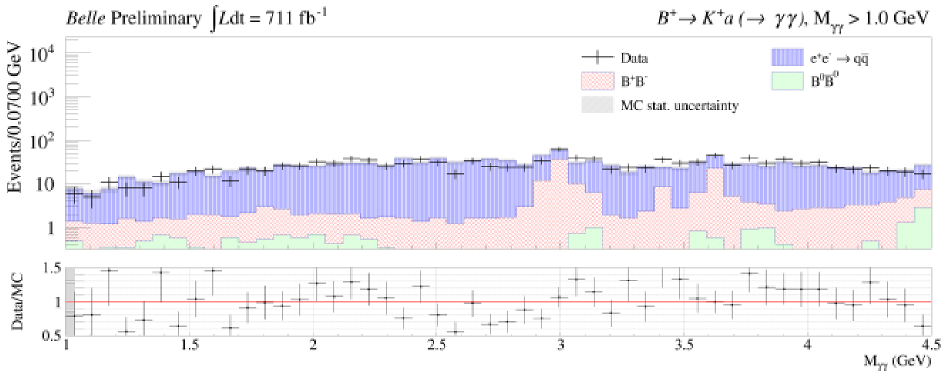
- Search is based on a 711 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance by Belle detector

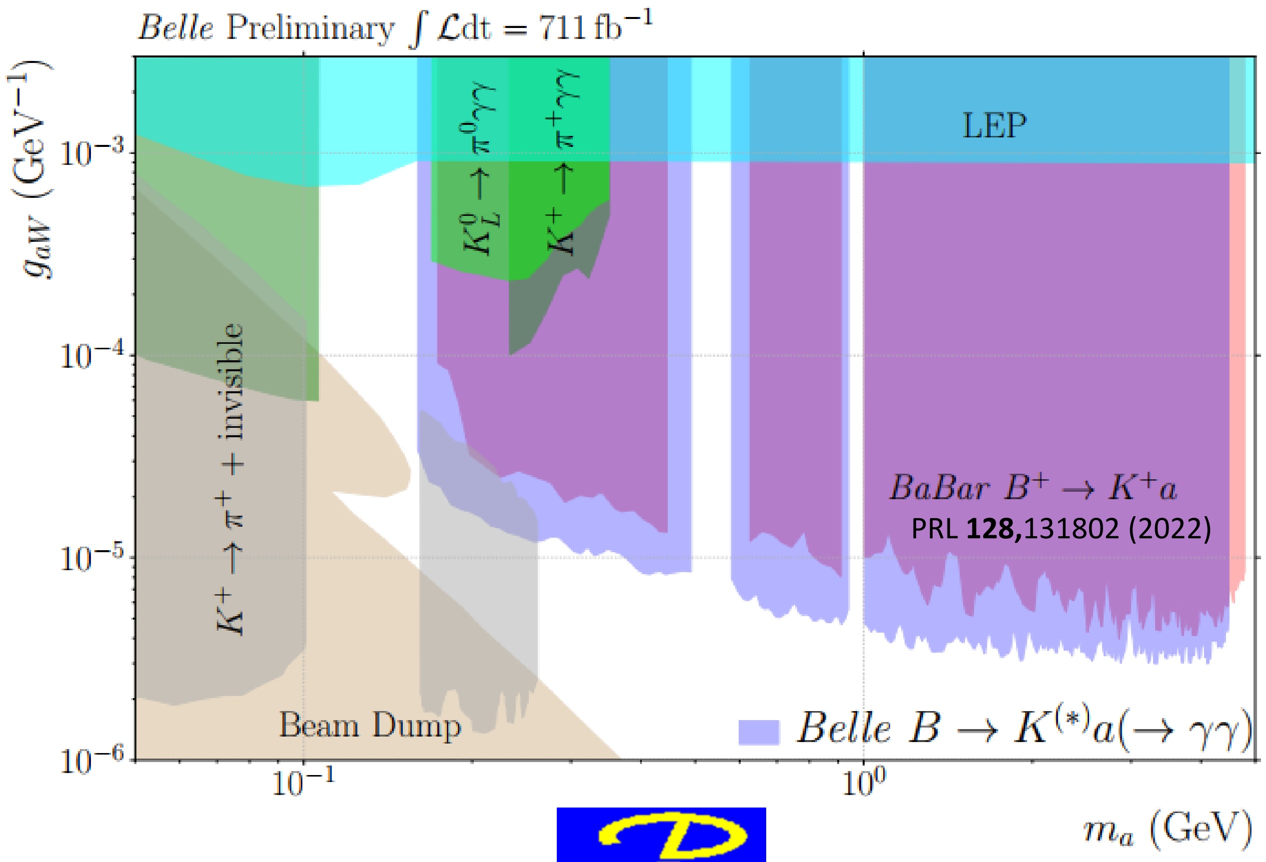
arXiv:2507.01249 (2025)

- Four kaon modes: K_S^0, K^+, K^{*0} and K^{*+}

- Excluded the π^0, η, η' mass regions for ALP search





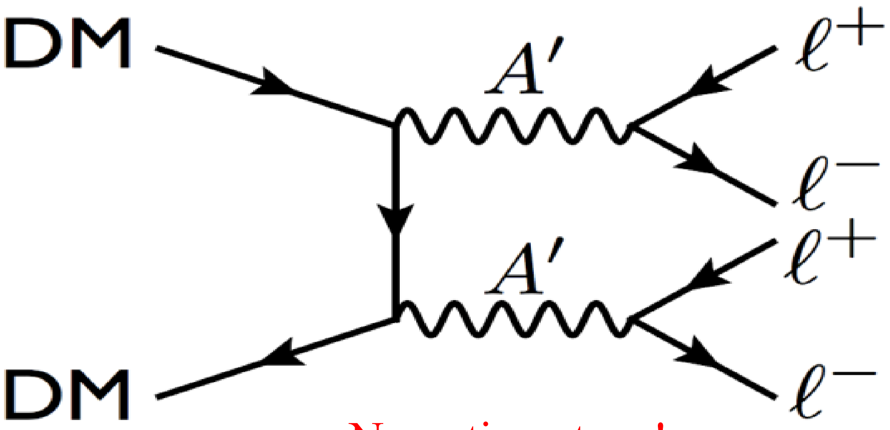


BELLE

Dark photon

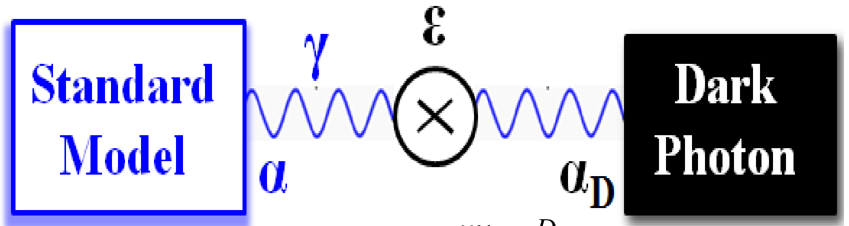
- DM hidden sector introduces a new U(1) interaction or dark force carrier (e.g. dark-photon A′, U or γ′).

N. Arkani-Hamad et al, PRD 79, 015014 (2009)



No anti-protons!

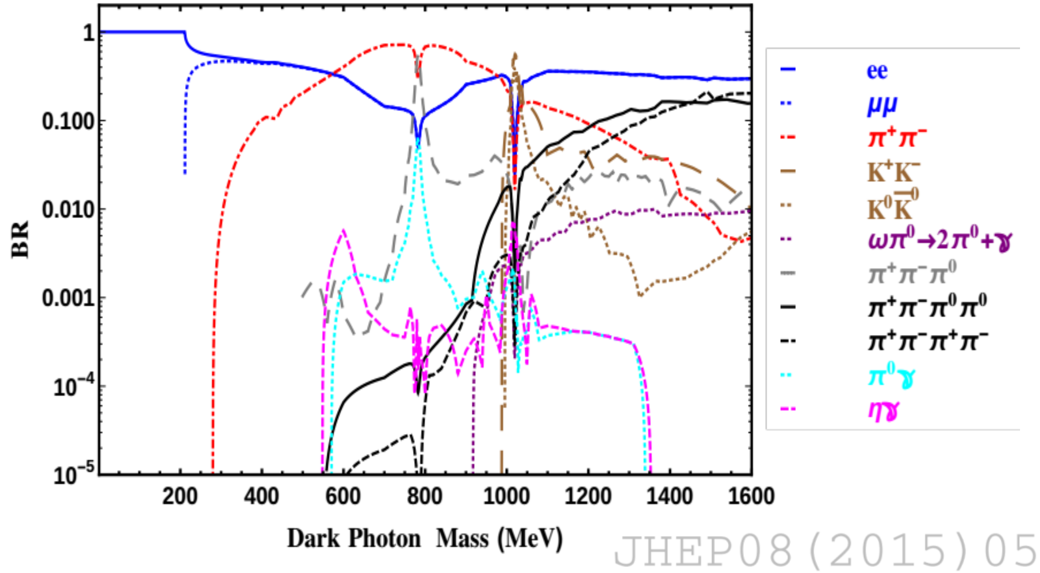
$m_{DM} \sim$ TeV   MeV $\lesssim m_{A'} \lesssim$ GeV



$$\Delta L = \varepsilon F^{\mu\nu} F^{D}_{\mu\nu}$$

ε = Kinetic mixing strength.
$\alpha_D = \alpha\varepsilon$
α = fine structure constant

B. Batell, et al, PRD79, 115008 (2009);
R. Essig, et al, PRD80, 015003 (2009)



JHEP08(2015)050

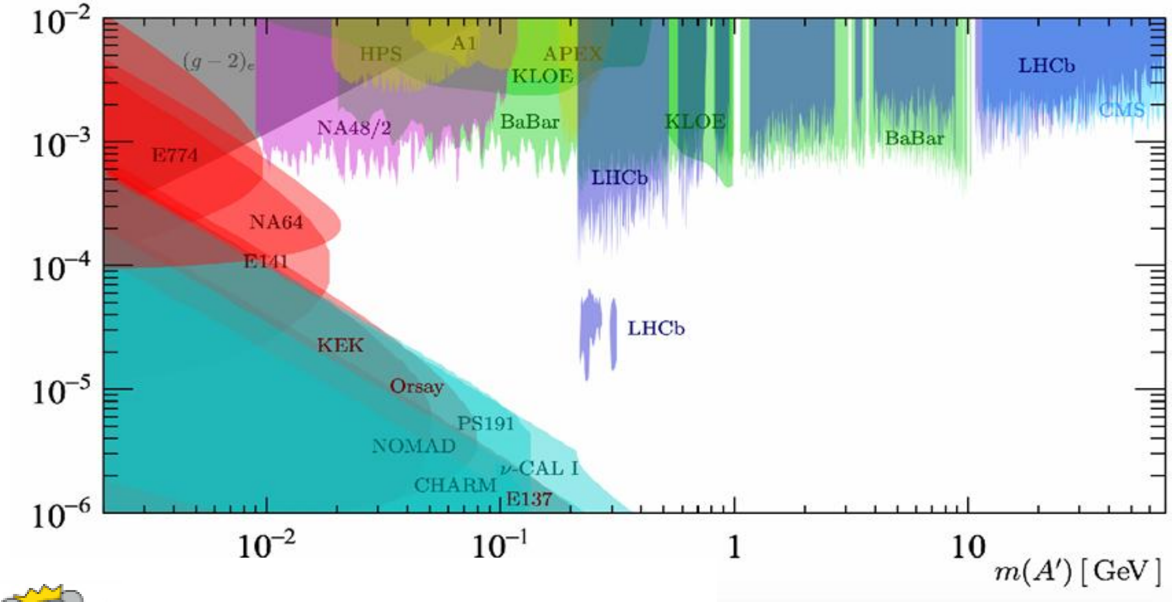
- Could explain the features of astrophysical observations (such PAMELA, AMS etc.).

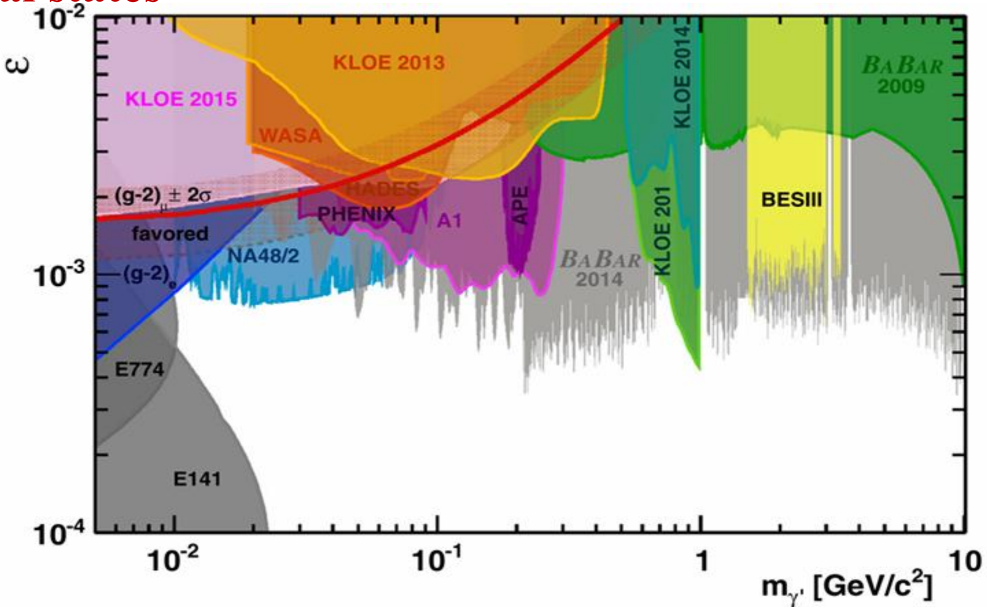
- The dark U(1) symmetry could be spontaneously broken, by a Higgs mechanism, adding a dark Higgs boson (h′) to the theory.

PRD79, 115008 (2009)

Current status of dark photon searches

Visible final states



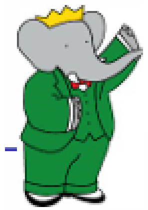


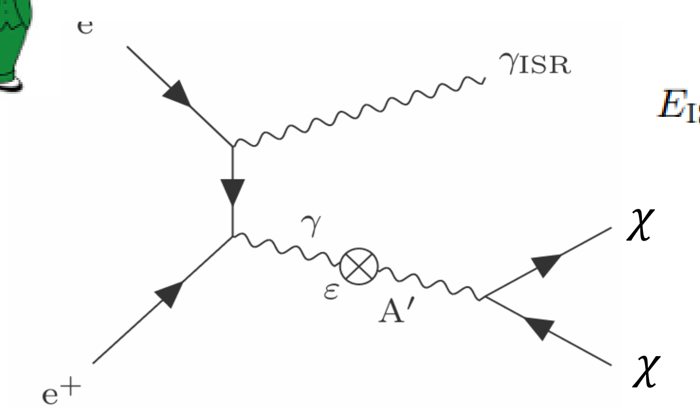
BESIII: arXiv:1705.04265

Babar: arXiv:1406.2980

LHCb: PRL (2020) 124 041801

Invisible final state

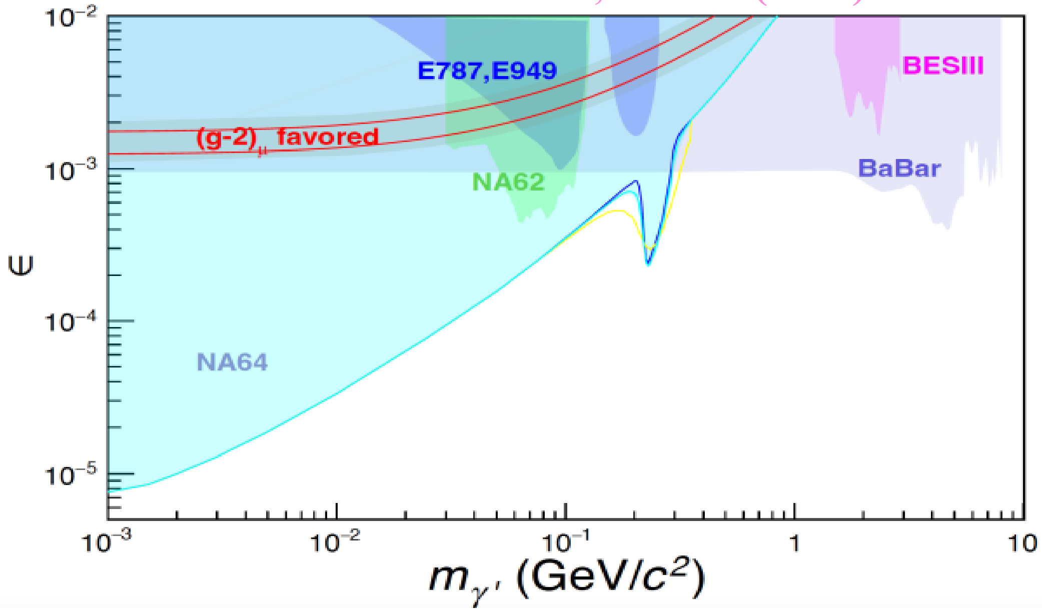




$$E_{\rm ISR} = \frac{s - m_{\gamma'}^2 c^4}{2\sqrt{s}},$$

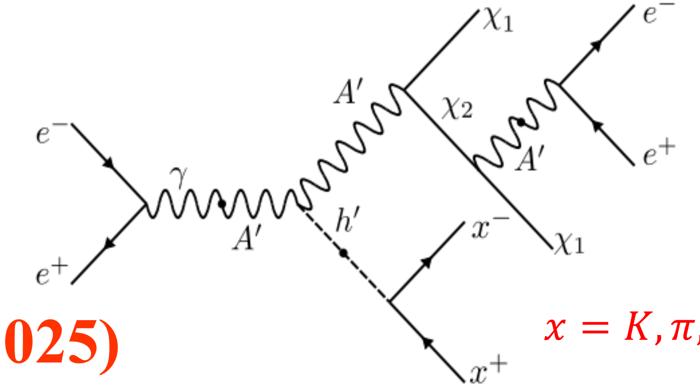
BaBar: Phys. Rev. Lett. **119**, 131804 (2017)

BESIII: PLB 839, 137785 (2023)



Dark Higgs boson produced in association with inelastic dark matter

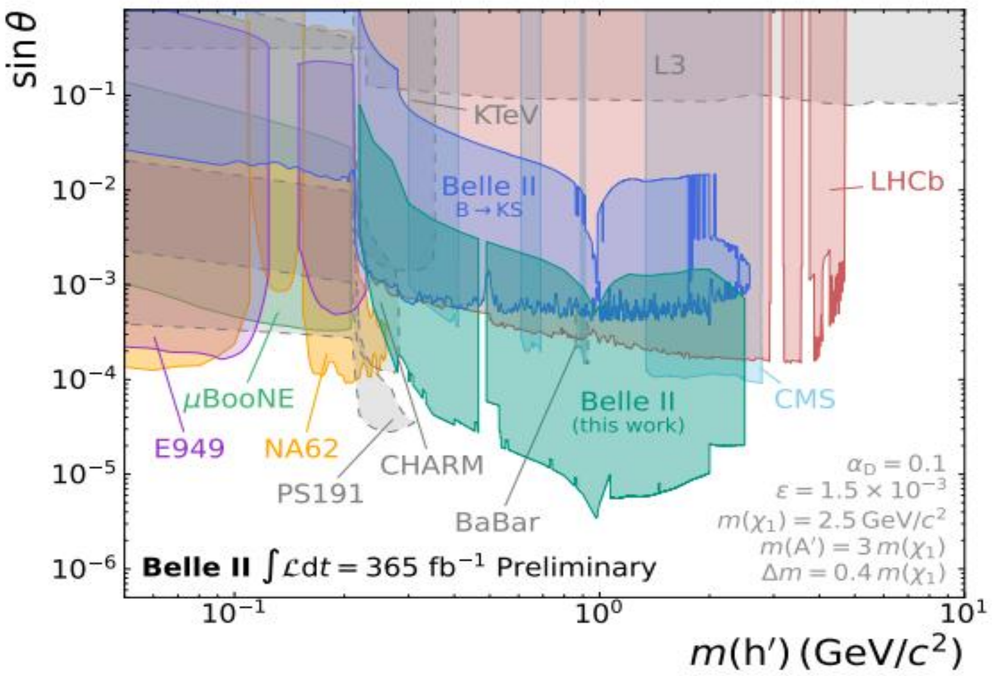
- Inelastic dark matter models that have two dark matter particles and a massive dark photon can reproduce the observed relic dark matter density without violating cosmological limits.
- The mass splitting between the two dark matter particles is induced by a dark Higgs field and a corresponding dark Higgs boson *h'*
- Search is based on 365 fb^{-1} data sample collected at Belle II
- Remaining events in data after selection: 0, 8 and 1 for $\mu^+\mu^-$, $\pi^+\pi^-$ and K^+K^- final states.

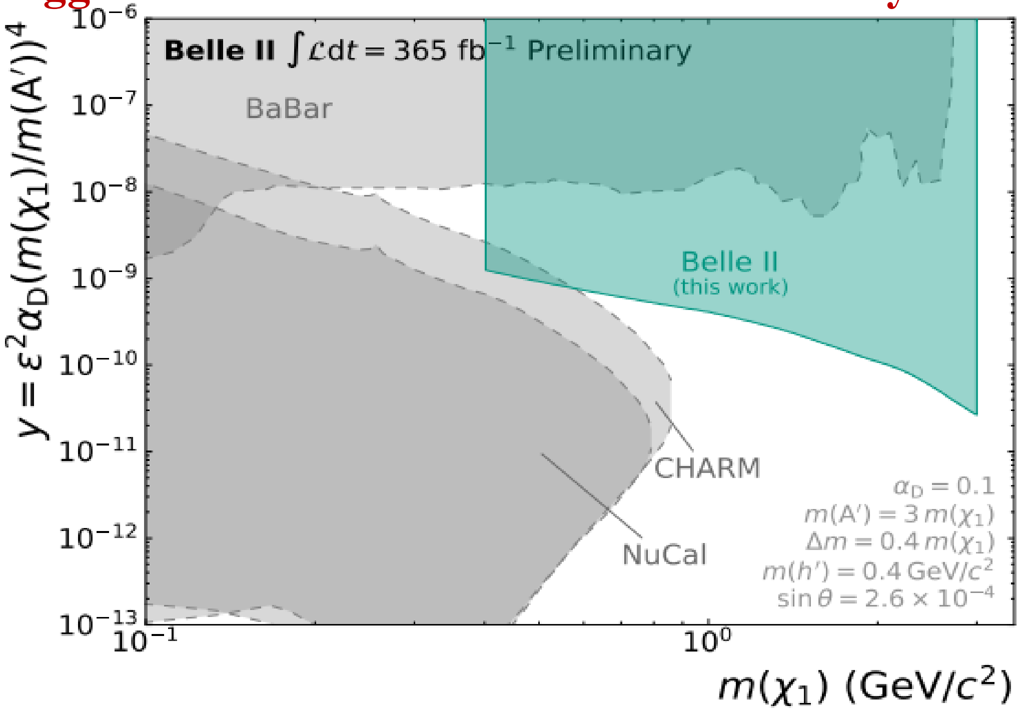


$x = K, \pi, \mu$

arXiv:2505.09705 (2025)

95% CL upper limits on mixing angle between SM Higgs and *h'* as well dimensionless variable y.





Baryogenesis

Baryon Asymmetry of the Universe (BAU) implies baryogenesis

Canetti *et al.*, NJOP **14** (2012) 095012

$$\eta = \frac{N_B}{N_\gamma} \approx \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}$$

Sakharov, A D, JETP 5 (1967) 24

Baryogenesis requires Sakharov conditions:

1. **Baryon number violation**
2. **C and CP violation**
3. **Deviation from thermal equilibrium**

Conditions are all compatible with the Standard Model (SM), but current measurements don't allow necessary level of baryogenesis to explain BAU. Several New Physics models could introduce necessary ingredients to explain observed level of baryogenesis.

Recently, the B mesogenesis mechanism has been proposed to simultaneously generate the DM abundance and BAU

Phys. Rev. D **99**, 035031 (2019)

Phys. Rev. D **104**, 035028 (2021)

Baryogenesis

Elor, Escudero, Nelson, PRD 99 (2019) 035031

Consider the following possibility:

- **There exist non-SM dark baryons and anti-baryons**
- **The concept of baryon number conservation counts dark baryons and anti-baryons equivalently to SM baryons and anti-baryons**

Propose a new dark sector anti-baryon, ψ_{D}, and search for:

$$B^{+} \to \psi_{\mathrm{D}} + p$$

Will have a distinct experimental signature

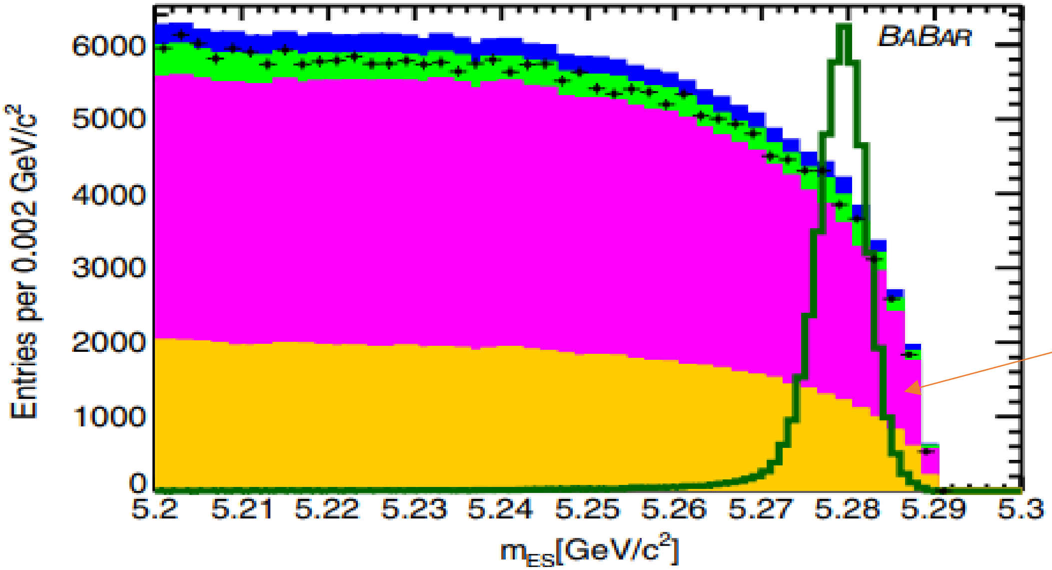
Note that the dark baryons must be charge neutral

Charge conjugation implied throughout

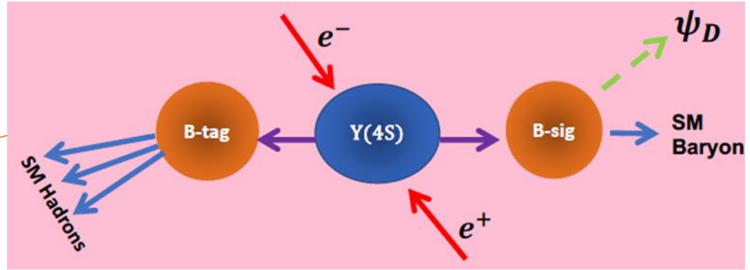
- The $B^0 - \bar{B}^0$ meson can undergo CP-violating oscillations before decaying into a SM baryon, such as proton, and ψ_D, and any number of additional light mesons.
- These CP-violating oscillations can originate from the SM or beyond the SM process

Search for evidence of Baryogenesis and dark matter in $B^+ \to \psi_D + p$

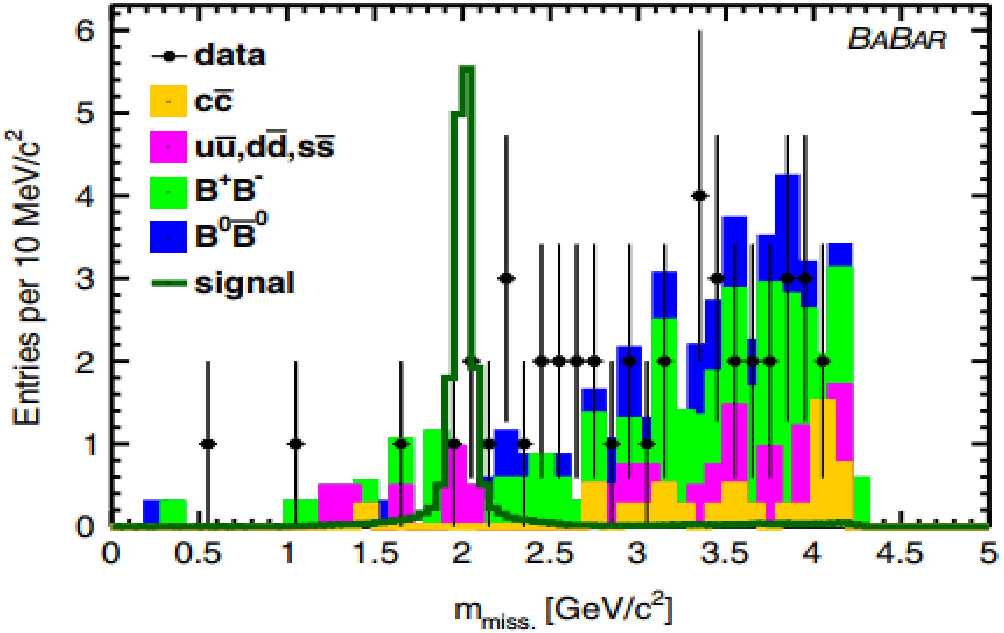
Phys. Rev. Lett. 131, 201801 (2023)

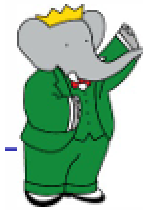


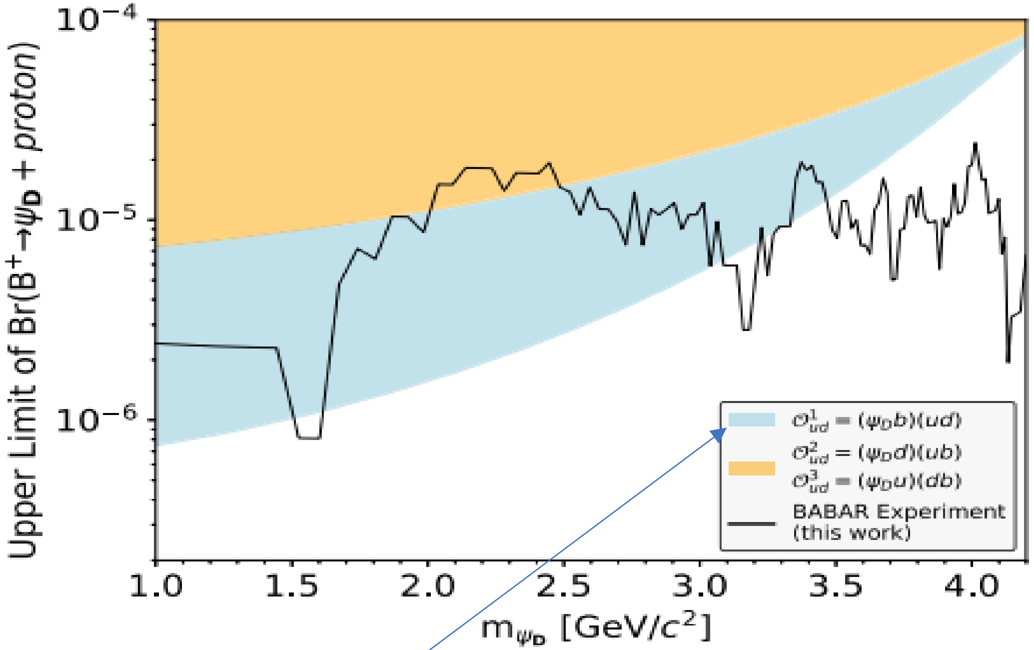
$$m_{\rm ES}c^2 = \sqrt{E^{*2}_{\rm beam} - \vec{p}^{\,*2}_{B_{\rm tag}} c^2}$$



Search is performed using an integrated luminosity of 398 fb^{-1} data at $\Upsilon(4S)$ resonance collected by BaBar experiment



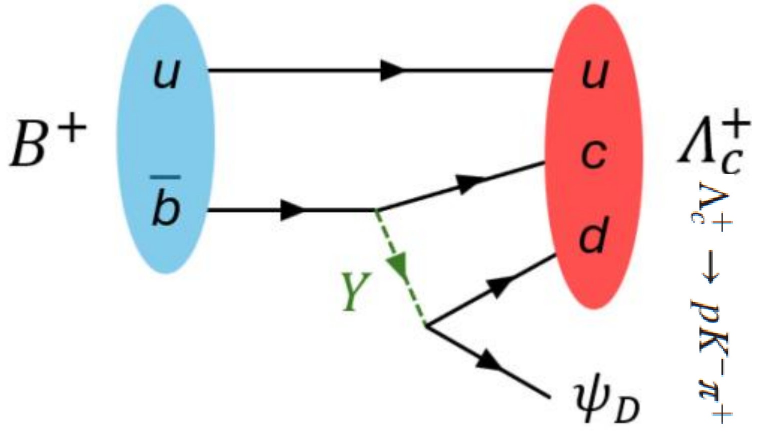




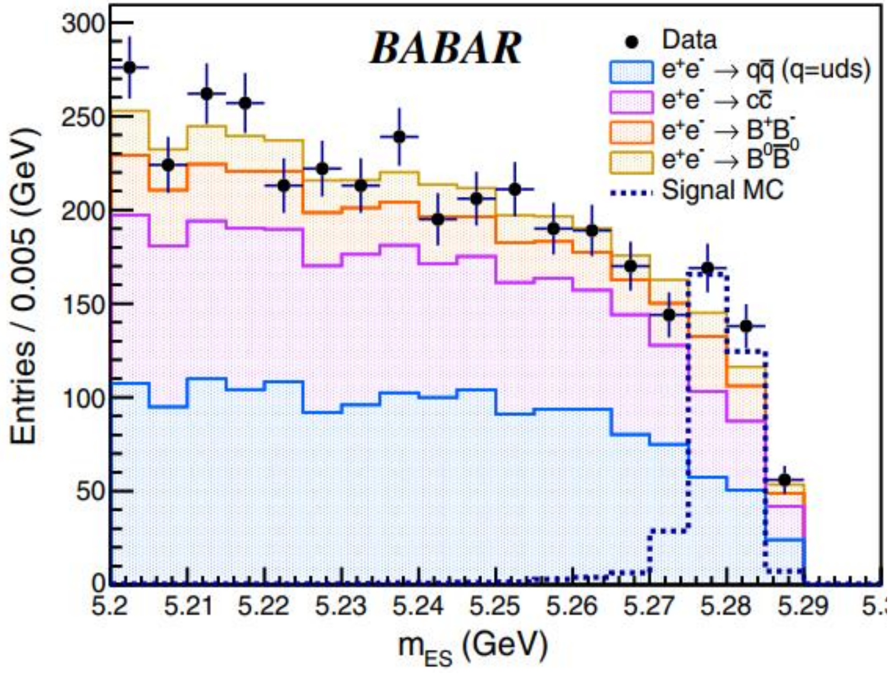
effective operators $\mathcal{O}_{i,j} = (\psi_{\rm D} b)(q_i q_j)$

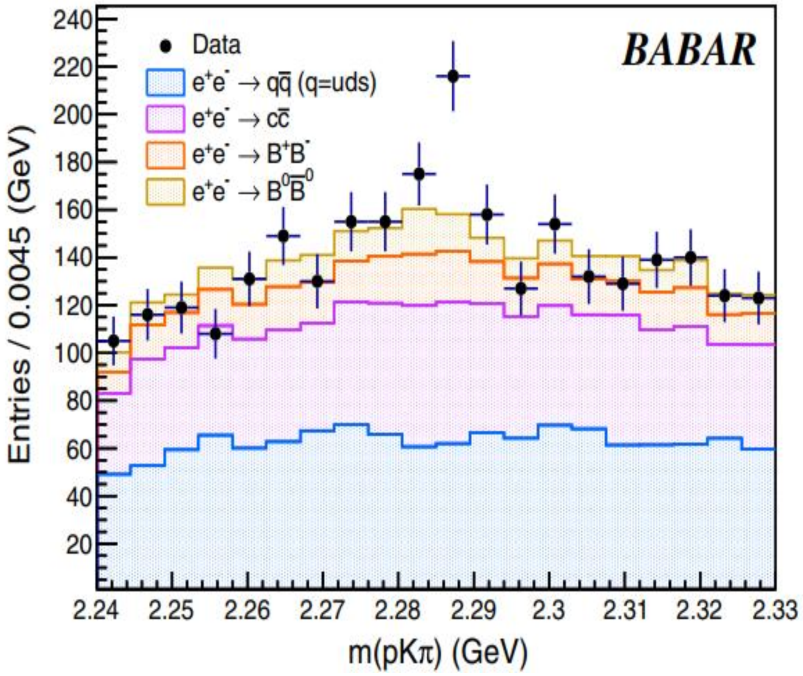
Search for Baryogenesis and dark matter in $B^+ \to \Lambda_c^+ + \text{invisible}$

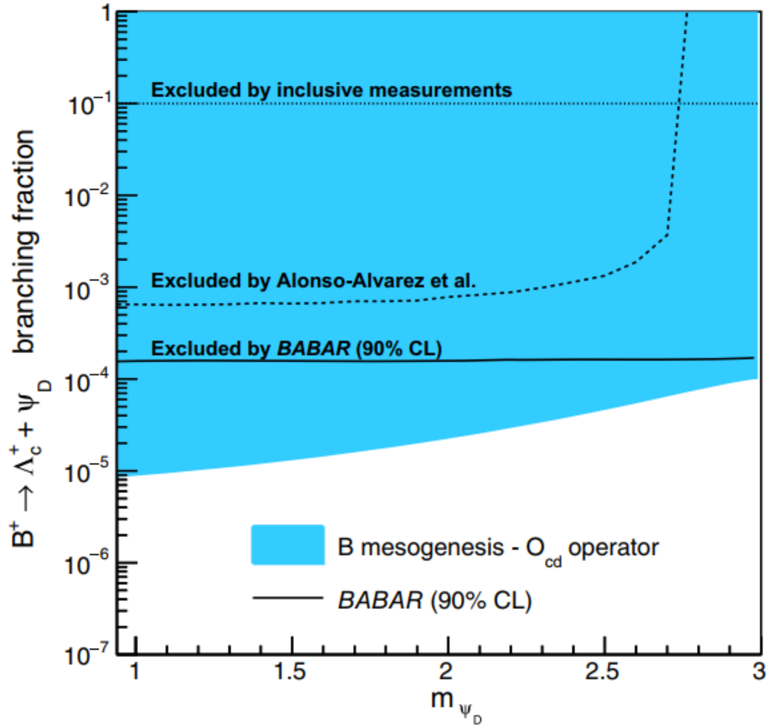
- Search is performed using an integrated luminosity of 398 fb^{-1} data at $\Upsilon(4S)$ resonance collected by BaBar experiment
- No obvious peaking structure is visible at the B mass, but a clear Λ_c^+peak is evident in data for the sideband region $m_{ES} < 5.27$ GeV, which is not properly modelled in the background MC.

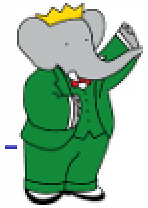


Phys. Rev. D 111, L031101 (2025)









Neutrino Oscillations

Phys. Rev. D **107**, 052009 (2023)

Neutrino oscillation firmly established:

neutrinos have mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix parametrization:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P$$

Experiments at accelerators, reactors and underground facilities are providing more and more precise determinations of

PMNS matrix elements and Δm^2_{21} and Δm^2_{32}

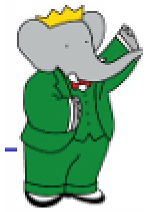
but a number of questions unanswered

- Neutrino mass is small: what are the origins of this mass?
- Why is neutrino mixing so different from quark mixing?
- CP violation?
- Nature of neutrinos?

Heavy neutral leptons

Phys. Rev. D **107**, 052009 (2023)

- Heavy Neutral Leptons (HNLs) are additional neutrino states.



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_L \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{L1} & U_{L2} & U_{L3} & U_{L4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Different models may introduce HNL in a broad mass range:

- $m_4 \approx \mathcal{O}(\mathrm{eV}/c^2)$ address the so-called "oscillation anomalies"
- $m_4 \approx \mathcal{O}(\mathrm{keV}/c^2)$ provide warm dark matter candidate.
- $m_4 \approx \mathcal{O}(\mathrm{GeV}/c^2)$ explain deviations in SM decays.
- $m_4 \approx \mathcal{O}(\mathrm{TeV}/c^2)$ explain Baryonic Asymmetry via low-scale scenarios of leptogenesis without conflict with other cosmological observations.

- **Searching for HNLs at BABAR**

$\sigma(e^+e^- \to \tau^+\tau^-) = 0.919 \pm 0.003$ nb $\quad \mathcal{L}_{int} = 424$ fb^{-1} → $N_{\tau^+\tau^-} = 4.6 \times 10^8$ collected

Exploit the peculiar topology provided by the boost in E_{CM} to select τ pairs charged daughters from each τ in one hemisphere

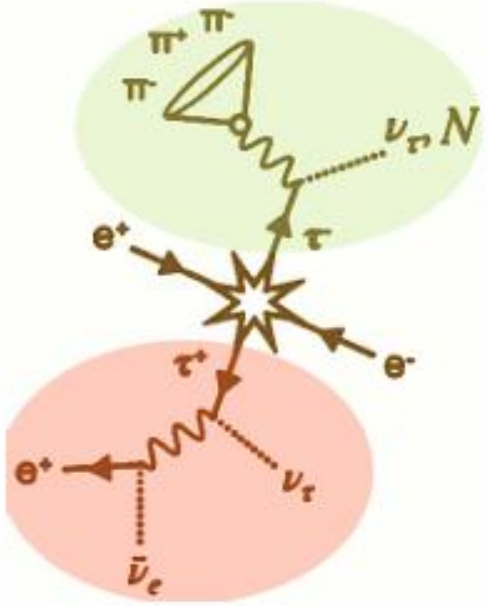
Method proposed in PRD 91, 053006 (2015), inspired by ALEPH, EPJ 1137C 2, 395 (1998)

The study of $\tau^- \to \pi^-\pi^-\pi^+\nu$ decay allows to access $100 < m_4 < 1360$ MeV$/c^2$

model independent: rely only on kinematics

3h dynamics $\Longleftrightarrow$ neutrino mass

Select clean samples with $\tau^+ \to e^+\nu\overline{\nu}$ (tag) and $\tau^- \to \pi^-\pi^-\pi^+\nu$ (3h)



Experimental method

Phys. Rev. D **107**, 052009 (2023)

$\tau^- \to \pi^-\pi^-\pi^+\nu_x$

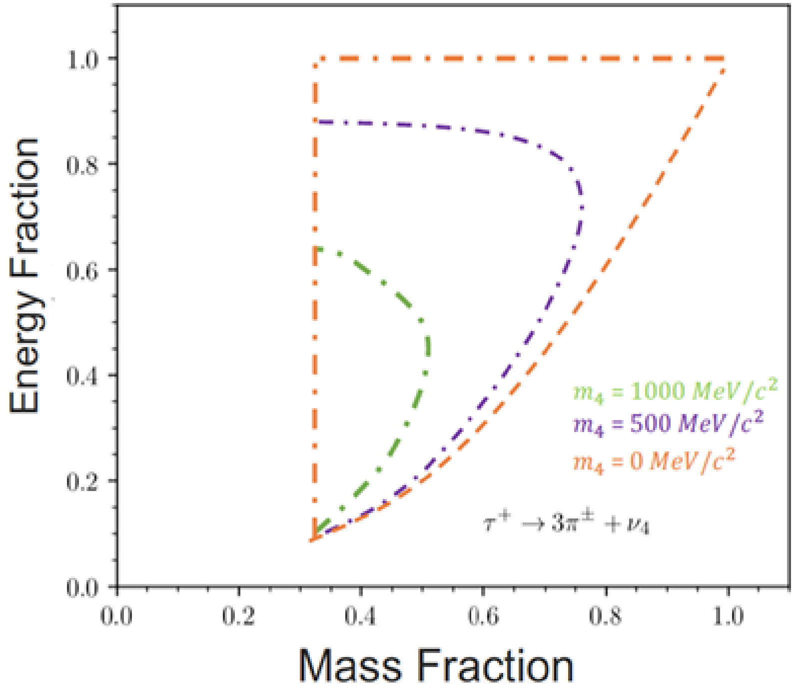
Mass of the missing neutrino (m_4) determines the 2D distribution of hadronic energy E_h vs invariant mass m_h

In the center of mass: $E_\tau = \frac{1}{2}E_{cm}$

$3m_{\pi^\pm} < m_h < m_\tau - m_4$

$E_\tau - \sqrt{m_4^2 + q_+^2} < E_h < E_\tau - \sqrt{m_4^2 + q_-^2}$

$$q_\pm = \frac{m_\tau}{2}\left(\frac{m_h^2 - m_\tau^2 - m_4^2}{m_\tau^2}\right)\sqrt{\frac{E_\tau^2}{m_\tau^2} - 1} \pm \frac{E_\tau}{2}\sqrt{\left(1 - \frac{(m_h+m_4)^2}{m_\tau^2}\right)\left(1 - \frac{(m_h-m_4)^2}{m_\tau^2}\right)}$$



2D distribution as sum of ν_τ (SM,m=0) component and a HNL component

$$\left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{\text{Total}} = |U_{\tau 4}|^2 \left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{\text{HNL}} + (1 - |U_{\tau 4}|^2)\left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{\text{SM}}$$

Limits on $|U_{\tau 4}|^2$ versus HNL mass

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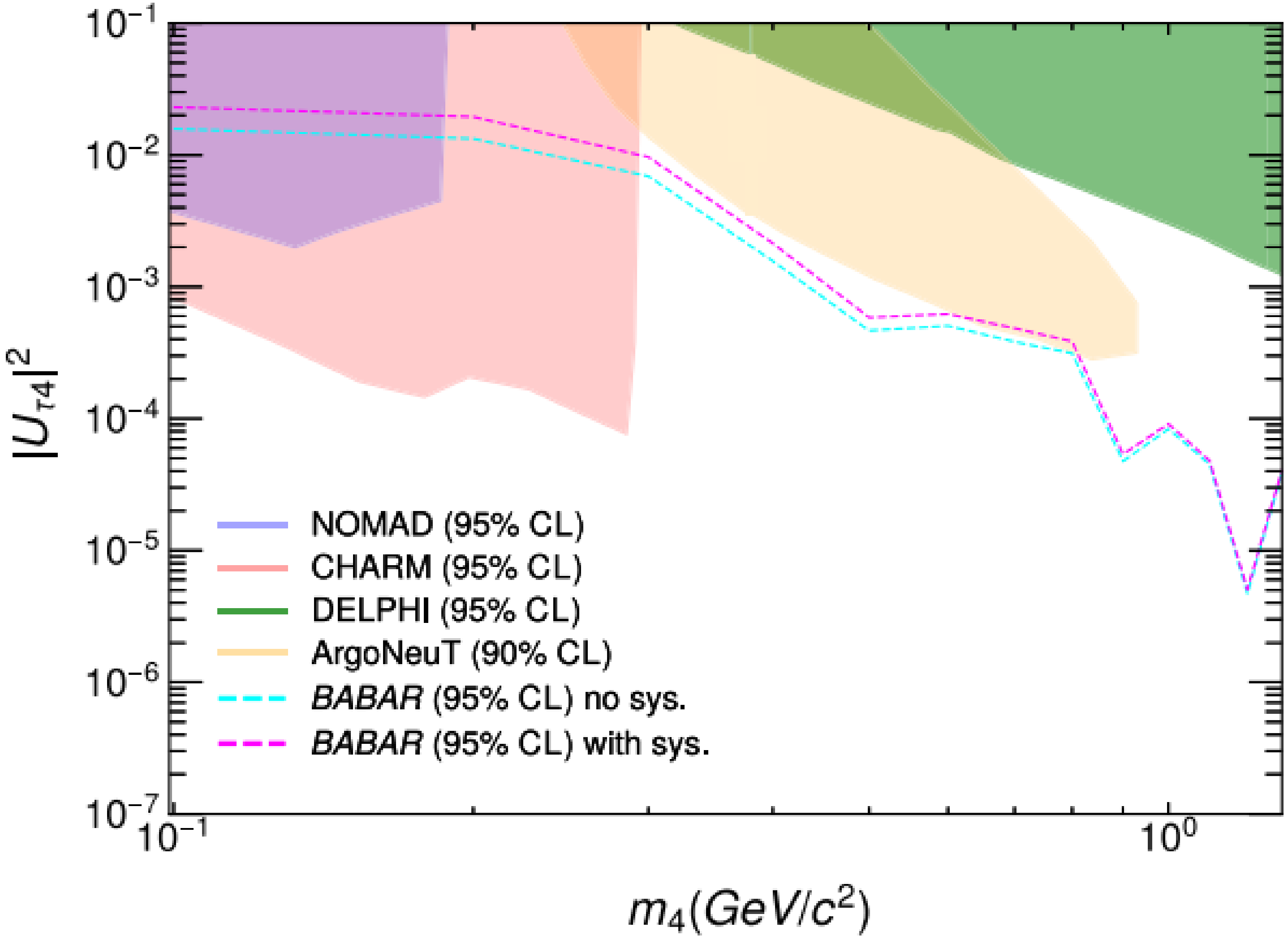


- Binned profile likelihood approach used to find 95% C.L. on $|U_{\tau 4}|^2$.
- Considers both lepton tags and + and – signal tau channels.
- Provides upper limits for HNLs mixing with taus in range 100 < $|U_{\tau 4}|^2$ < 1300 MeV/c²

Mass [MeV/c^2]	No sys.	With sys.
100	1.58×10^{-2}	2.31×10^{-2}
200	1.33×10^{-2}	1.95×10^{-2}
300	6.91×10^{-3}	9.67×10^{-3}
400	1.57×10^{-3}	2.14×10^{-3}
500	4.65×10^{-4}	5.85×10^{-4}
600	5.06×10^{-4}	6.22×10^{-4}
700	3.82×10^{-4}	4.85×10^{-4}
800	3.12×10^{-4}	3.85×10^{-4}
900	4.70×10^{-5}	5.38×10^{-5}
1000	8.34×10^{-5}	9.11×10^{-5}
1100	4.49×10^{-5}	4.78×10^{-5}
1200	4.70×10^{-6}	5.04×10^{-6}
1300	3.85×10^{-5}	4.09×10^{-5}

Summary

- Searching for possible extensions of the Standard Model (SM) is a top priority of current experimental investigations.
- Dark matter (DM) hidden-sector models often predict couplings to SM particles via portal interactions.
- These portal scenarios have been explored by several electron–positron collider experiments.
- So far, no conclusive signals have been observed.
- Existing experimental limits have excluded a significant portion of the parameter space of many beyond-SM models.
- Further results are expected in the near future, particularly from the BESIII and Belle II experiments.

Thanks!

Back up slide

Heavy neutral leptons

- Heavy Neutral Leptons (HNLs) are additional neutrino states. Have mass, but no weak hyper-charge, electric charge, weak isospin and color charge. Could be produced in experiments only via mixing with active neutrinos.

- HNLs are proposed by several beyond Standard Model (BSM) theories to explain three major observational phenomena:
  - Neutrino oscillations and origins of their mass via seesaw models etc. (Phys. Rev. D **23**, 165)
  - Baryonic asymmetry of Universe (Phys. Rev. Lett. **81**, 1359);
  - Dark matter candidate (Phys. Lett. B **631**, 151–156).

- If neutrinos get their mass from Higgs, Yukawa couplings must be exceedingly small. Not so in seesaw models with 5 dim operator and additional Majorana neutrinos.

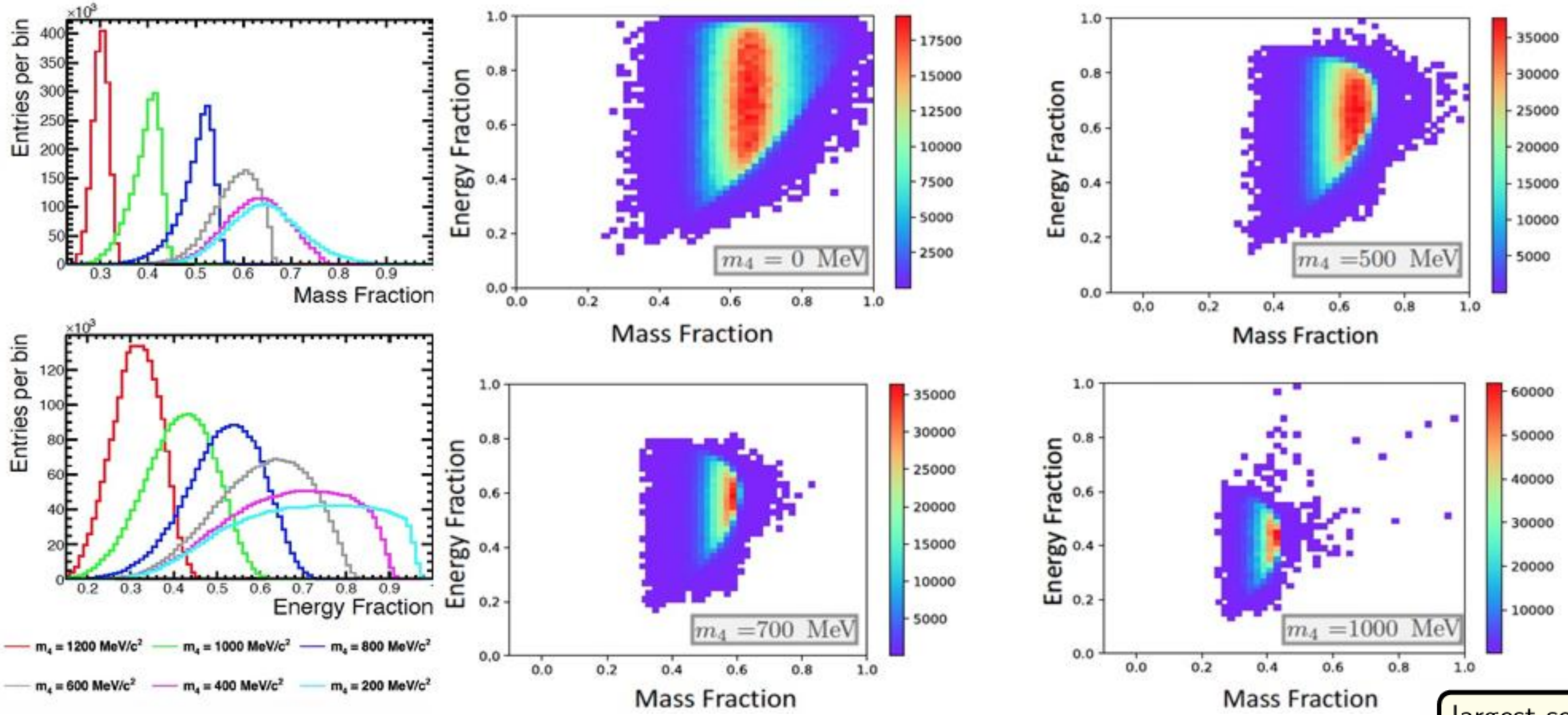
- Lighter sterile (eV-scale) neutrinos can also help explain various experimental observations:
  - "Reactor Anti-neutrino anomaly:" (Phys. Rev. D **83**, 07300).
  - "Gallium anomaly:" (Phys. Rev. C **80**, 015807).
  - "Accelerator anomaly:" LSND (Phys. Rev. D **64**, 112007) MiniBooNE (Phys. Rev. Lett. **110**, 161801)

- Heavy neutrinos can interact with the tau via charged-current weak interactions.

Heavy neutral leptons (signal MC)

1D and 2D projections for signal HNL 3-prong decays $\tau^- \to \pi^+\pi^-\pi^-\nu_X$

visible change in the expected 2D template as a function of m_4



largest sensitivity for large m_4

Heavy neutral leptons (data and MC)

electron-tag τ^+ and τ^- samples studied separately for consistency

(similarly for muon-tag)