A last chance for kinetic mixing: explaining $(g\text{-}2)_\mu$ with semi-visible dark photons

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Invisibles22 Workshop

20/06/2022

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UCLouvain

FNAL measurement

FNAL confirmed $(g\text{-}2)_\mu$ discrepancy with SM

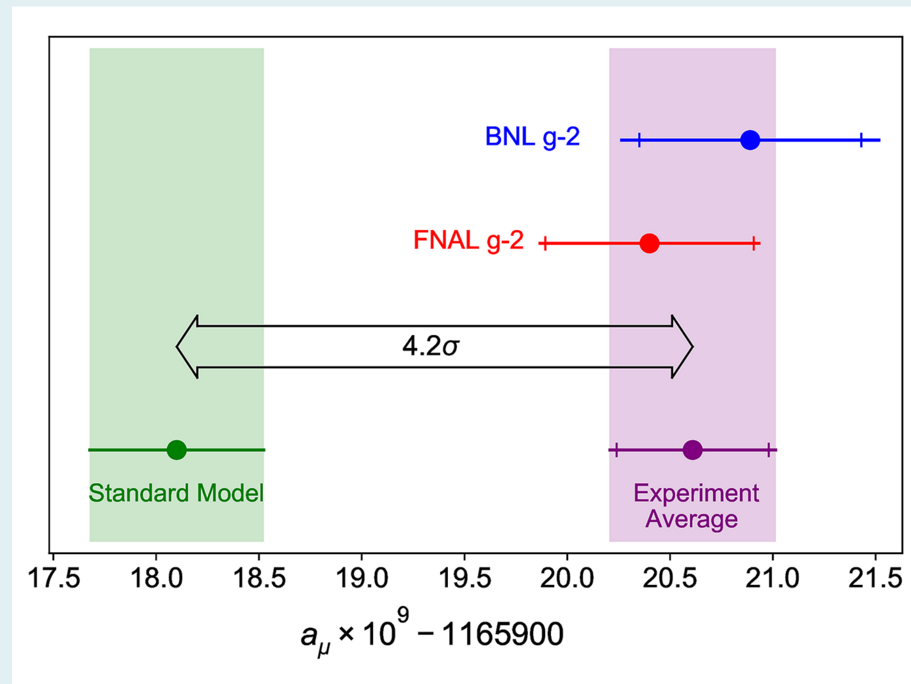
$$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (251 \pm 59) \times 10^{-11}$$

4.2 σ

Hints for new physics?

Not too far out of reach

$$\Delta a_\mu \propto \frac{g^2}{16\pi^2}\frac{m_\mu^2}{\Lambda^2} \Rightarrow \frac{\Lambda}{g} \approx \mathcal{O}(10^2)\ \mathrm{GeV}$$



[B. Abi et al. Phys. Rev. Lett. 126.14 (2021), p. 141801]

*Recent comparison of Lattice Results for Leading Order Hadron Vacuum Polarization would reduce the significance to 2.9 σ. [Cè et al. (2022), arXiv:2206.06582]

Semi-visible dark photon

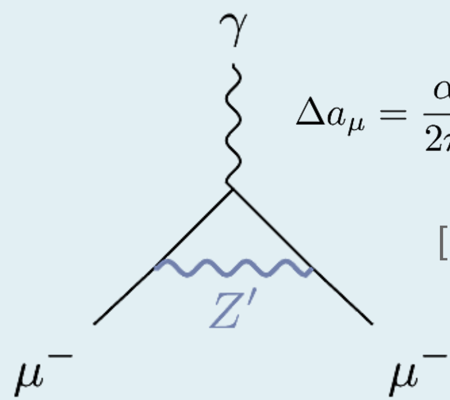
Dark U(1)' with **Z'** boson + dark Heavy Neutral Fermions ψ_i.

$$\mathcal{L} \supset \frac{\varepsilon}{2} B^{\mu\nu} X_{\mu\nu}$$

Kinetic mixing

Already constrained by <u>visible</u> and <u>invisible</u> Z' searches

Positive contribution to a_μ



$$\Delta a_\mu = \frac{\alpha}{2\pi}\varepsilon^2 \int_0^1 \mathrm{d}z \frac{2m_\mu^2 z(1-z)^2}{m_\mu^2(1-z)^2 + m_{Z'}^2 z}$$

[M. Pospelov. Phys. Rev. D 80 (2009), p. 095002]

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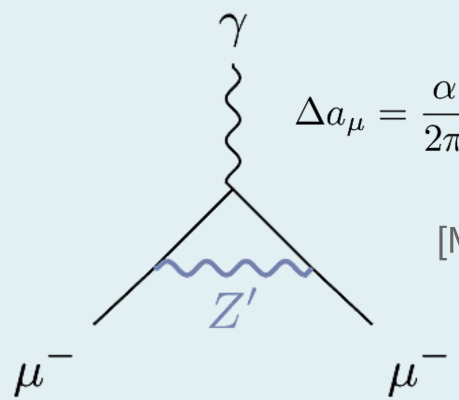

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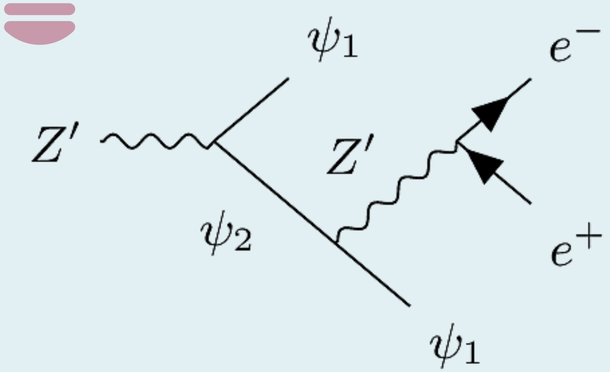
Semi-visible final states

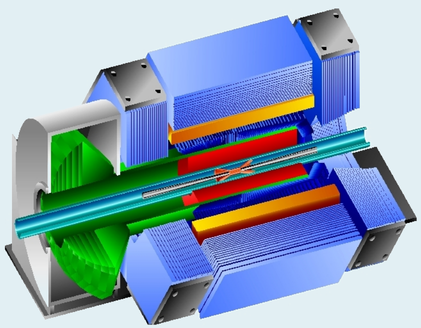


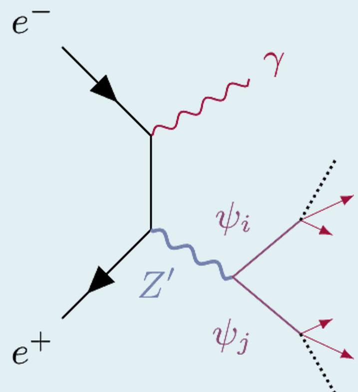
- **Missing energy**: evade visible constraints
- **Visible final states**: evade invisible constraints

[E. Izaguirre et al. Phys. Rev. D 96.5 (2017), p. 055007]
[G. Mohlabeng. Phys. Rev. D 99.11 (2019), p. 115001]

Main constraints

BaBar
monophoton

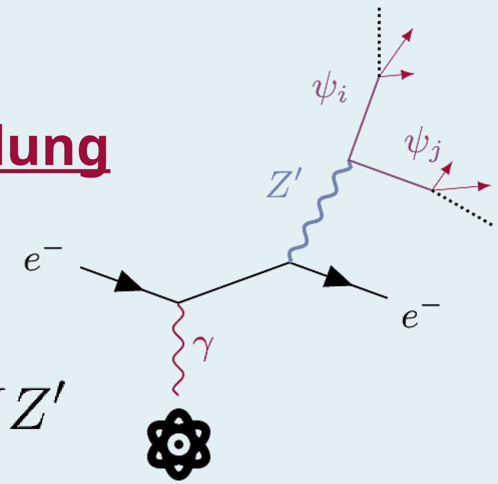




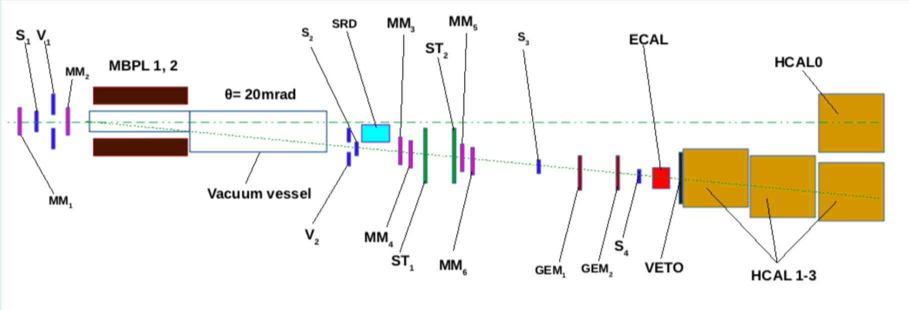
$$e^+e^- \to \gamma Z'$$

Monophoton + missing energy

NA64
Z' bremsstrahlung



$$e^-N \to e^-NZ'$$



Missing energy events with dark photon produced in electron bremsstrahlung

Are semi-visible Z' viable?

- ☑ Simulate production of semi-visible Z' in BaBar and NA64 detector
- ☑ Apply selection criteria
- ☑ Recast the bound

$$\varepsilon_{\text{bound}} = \varepsilon_{\text{new}} \sqrt{P^{\text{inv}}(\varepsilon_{\text{new}}, m_{Z'})}$$

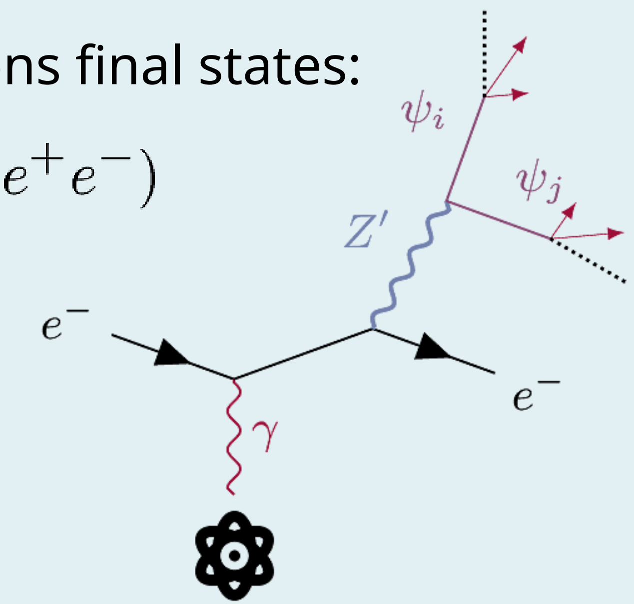
The NA64 simulation

Process: $e^- N \to e^- N Z'$

- ☑ Generate O(10^5) events for given $m_{Z'}$ and ε
- ☑ Apply **veto criteria** and compute new P^{inv}

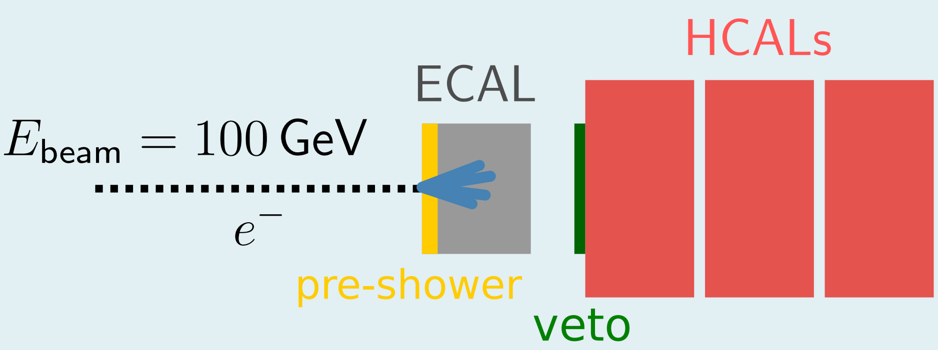
Z' decays instantly to HNL, producing pairs of leptons final states:

$$Z' \to (\psi_i \to \psi_k e^+ e^-)\,(\psi_j \to \psi_l e^+ e^-)$$



Recast: solve $\varepsilon_{\mathrm{NA64}} = \varepsilon\sqrt{P^{\mathrm{inv}}(\varepsilon, m_{Z'})}$

where $P^{\mathrm{inv}}(\varepsilon, m_{Z'}) = 1 - \dfrac{N_{\mathrm{veto}}(\varepsilon, m_{Z'})}{N(\varepsilon, m_{Z'})}$



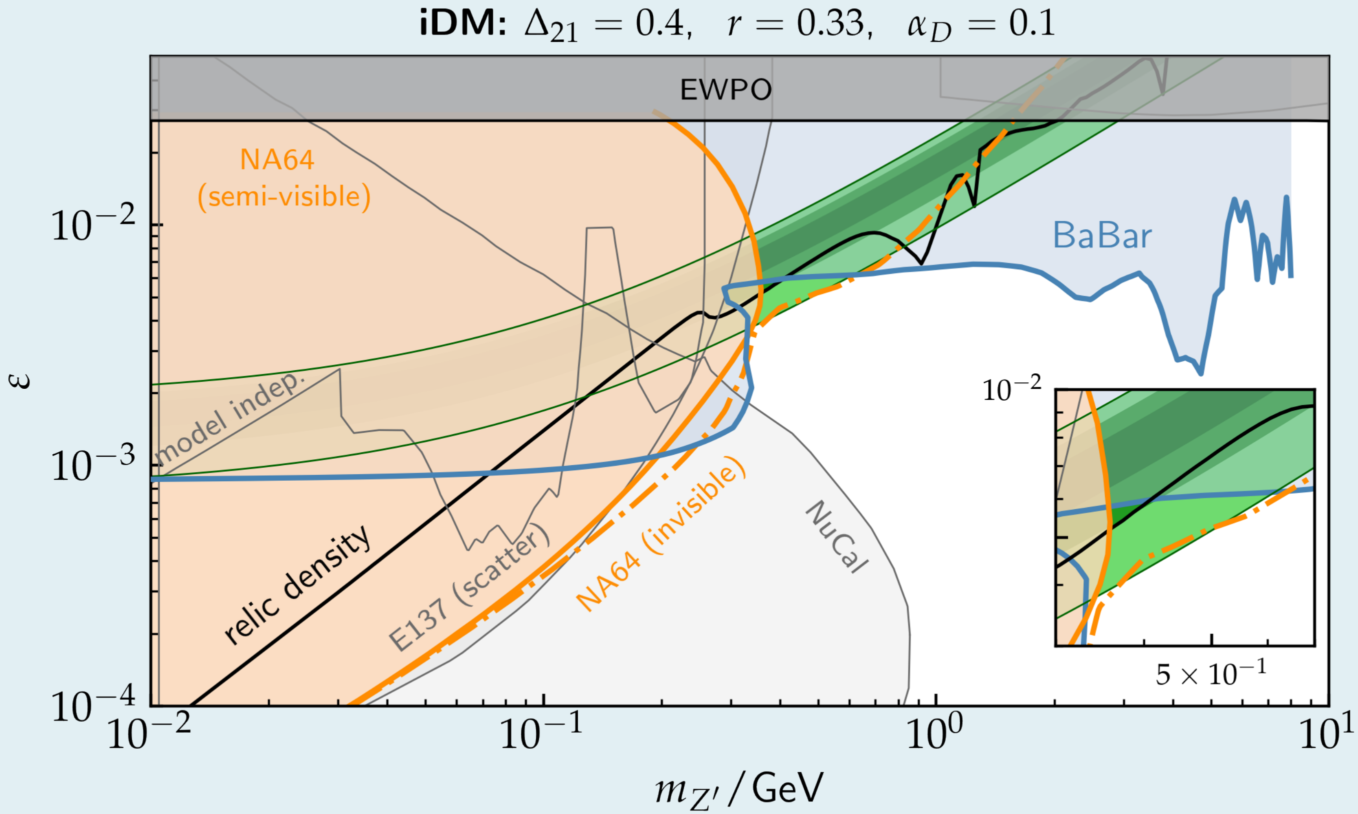
e^+e^- pairs deposit energy in the calorimeters or in the veto, so new events are vetoed according cut conditions.

Model 1: inelastic dark matter (iDM) with one pseudo-Dirac pair

$$\mathcal{L} \supset g_{\rm D} \overline{\psi}_1 \not{Z}' \psi_2$$

- After diagonalisation, lightest state ψ_1 is DM, with ψ_2 decaying semi-visibly
- DM relic abundance from co-annihilations

Minimal iDM is almost excluded



Model 2: iDM with several pseudo-Dirac pair

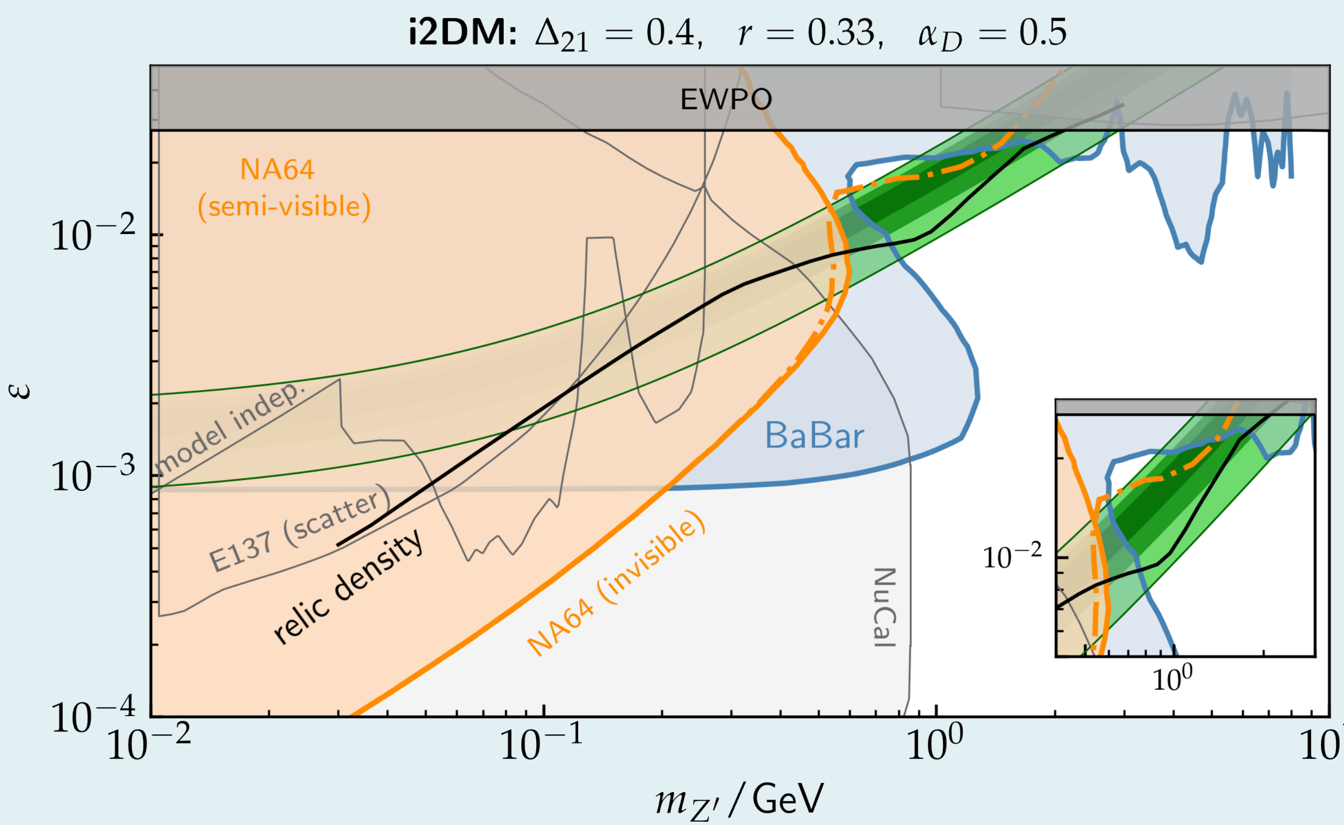
$$\mathcal{L} \supset g_{\mathrm{D}}\theta^2\,\overline{\psi_1}\not{Z}'\psi_1 + g_{\mathrm{D}}\theta\,\overline{\psi_2}\not{Z}'\psi_1 + g_{\mathrm{D}}\overline{\psi_2}\not{Z}'\psi_2$$

- After diagonalisation: light neutral state ψ_1 and heavier state ψ_2 more strongly coupled to dark force with small mixing ϑ

Tip: inject more visible final states

- $Z' \to \psi_1\psi_1$
- $Z' \to \psi_1\psi_2$
- $Z' \to \psi_2\psi_2$

Modified iDM allowed

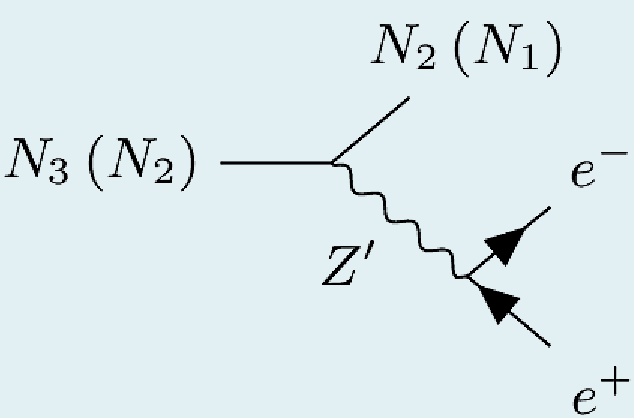


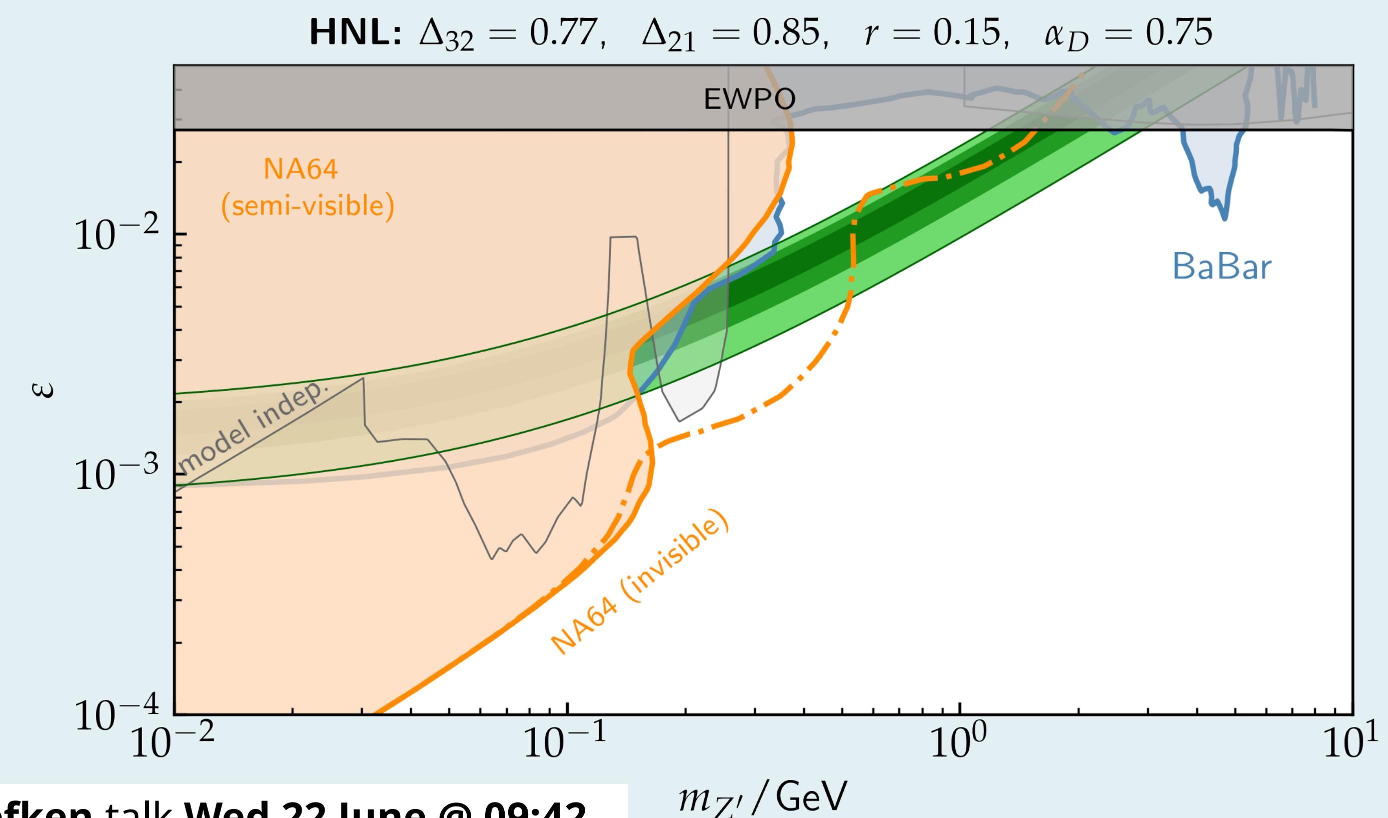
*Relic density courtesy of authors of [A. Filimonova et al. JHEP 06 (2022), p. 048].

Model 3: HNLs

$$\mathcal{L} \supset g_{\rm D} V_{ij} \overline{N_i} \not{Z}' N_j + \text{h.c.}$$

- After diagonalisation: we obtain 3 HNLs, interacting by V_{ij}
- BPs and model: [A. Abdullahi et al. Phys. Lett. B 820 (2021), p. 136531]



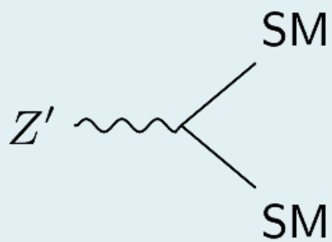


HNLs model allowed

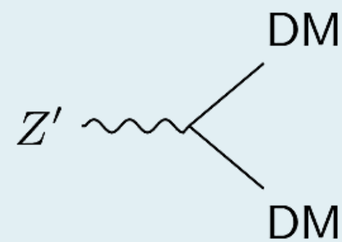
More on this model in **Jaime Hoefken** talk **Wed 22 June @ 09:42**

Backup slides

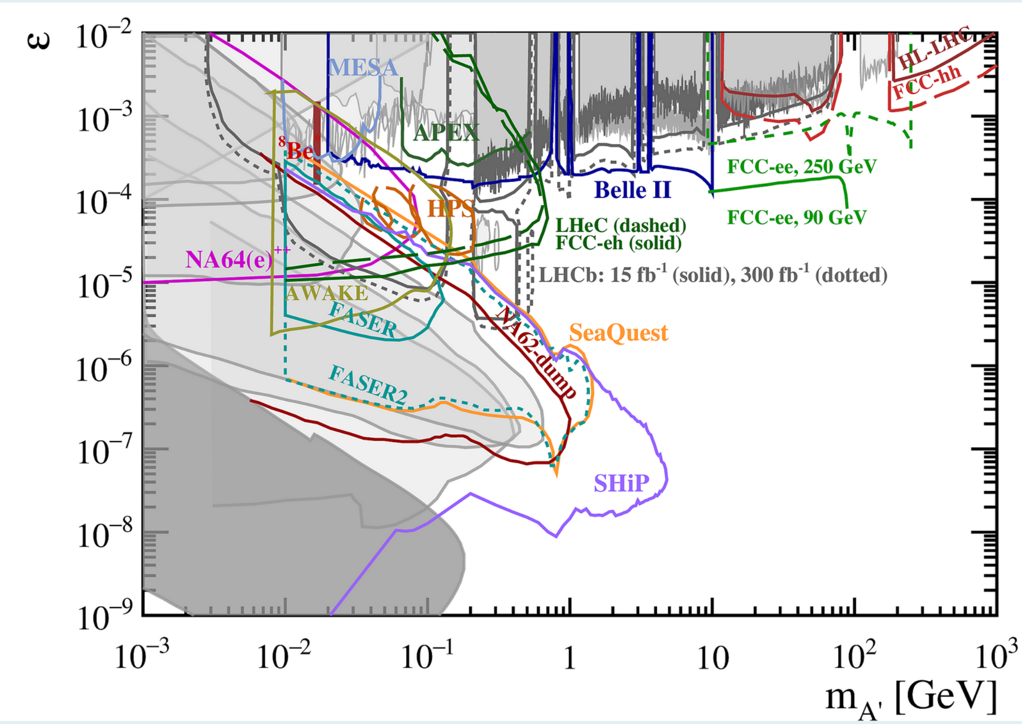
Dark photon decay modes

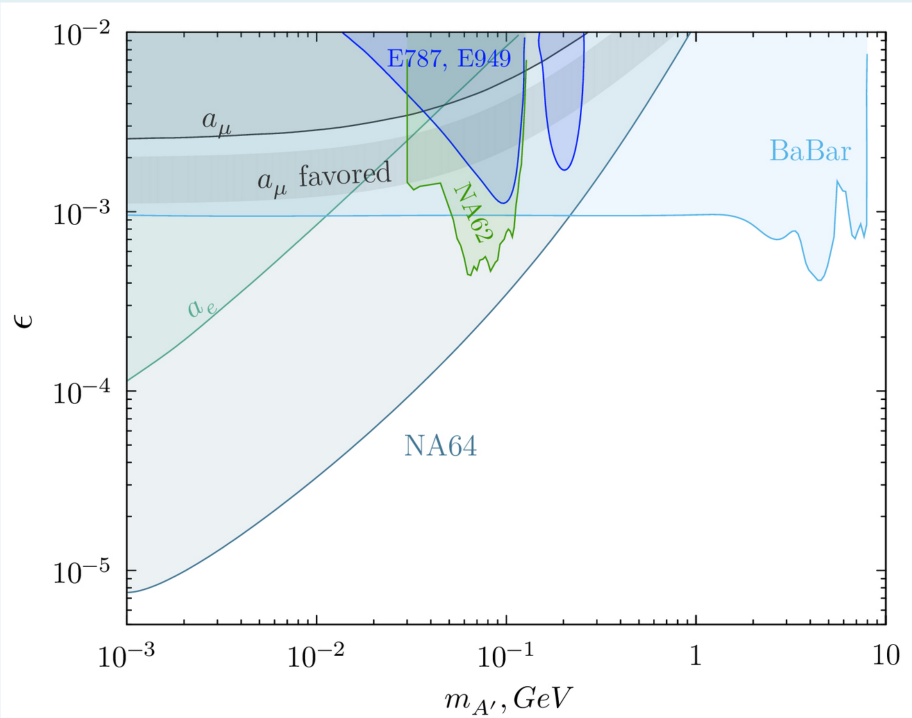


Visible



Invisible





[M. Fabbrichesi et al. (2020). arXiv: 2005.01515]

[D. Banerjee et al. Phys. Rev. Lett. 123.12 (2019), p. 121801]

Visible decays in SM final states are **excluded** by colliders in resonance searches

Invisible decays **fully excluded** by BaBar and NA64

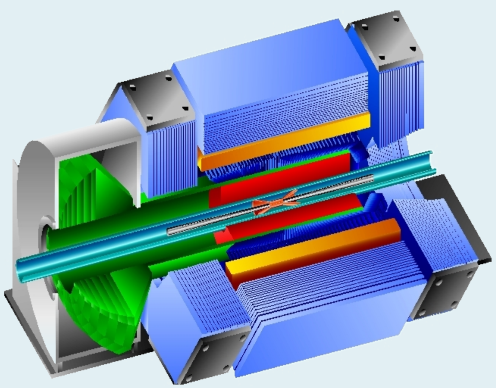
The BaBar simulation: generation

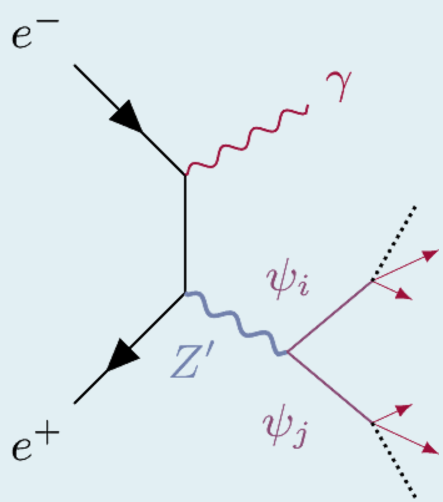
Process: $e^+e^- \rightarrow \gamma Z'$

- ☑ Generate O(10^6) events for given $m_{Z'}$ and ε
- ☑ Apply primary selection cut on monophoton CM angle
- ☑ Apply veto criteria and compute new P^{inv}

Z' decays instantly to HNL, producing pairs of leptons final states:

$$Z' \rightarrow (\psi_i \rightarrow (\psi_k \rightarrow \ldots)e^+e^-)\,(\psi_j \rightarrow (\psi_l \rightarrow \ldots)e^+e^-)$$





Events containing visible final states are vetoed

The BaBar simulation: veto criteria

Veto criteria: if decays happen in instrumented region of detector then veto event if both

(1) Energy of lepton tracks exceeds BaBar detection threshold

(1) $\theta_{\text{sep}} > 10^\circ : \ E_\pm > 100\,\text{MeV}$ well separated pairs

(2) $\theta_{\text{sep}} < 10^\circ : \ E_+ + E_- > 100\,\text{MeV}$ overlapping pairs

(2) Wide polar angle to avoid electrons escaping along the beam pipeline

$$17^\circ < \theta_{\text{pol}} < 142^\circ$$

Recast: solve $\varepsilon_{\text{BaBar}} = \varepsilon \sqrt{P^{\text{inv}}(\varepsilon, m_{Z'})}$

where $P^{\text{inv}}(\varepsilon, m_{Z'}) = 1 - \dfrac{N_{\text{veto}}(\varepsilon, m_{Z'})}{N(\varepsilon, m_{Z'})}$

The NA64 simulation: veto criteria

Analysis 1: "invisible"
[Phys. Rev. Lett. 123.12 (2019), p. 121801]
HNLs decays can be prompt, thus depositing energy in the ECAL. Produced pairs can also be intercepted by the veto.

1. Pre-shower cut $E_{\rm tot} \notin [0.5,\ 10]$ GeV
2. ECAL cut: $E_{\rm tot} > 50\,\mathrm{GeV}$
   $E_{\rm tot}$ is the sum of the main electron energy + the deposited energy by any other e^+e^- pair produced in the ECAL.
3. Check for pairs leaking out of the ECAL. Veto cut: $E_{\pm}(x_{\rm veto}) > 10\,\mathrm{MeV}$
4. HCAL cut: $E_{\pm} > 1\,\mathrm{GeV}$

Analysis 2: "semi-visible"
[Eur. Phy. J. C 81.10 (2021), p. 959]
Same analysis cuts applied also to other models in addition to the inelastic dark matter model:

1. Any e^+e^- pair triggering an activity before HCAL 2 is vetoed.
2. Max 1 e^+e^- pair in HCAL.

Assumptions:

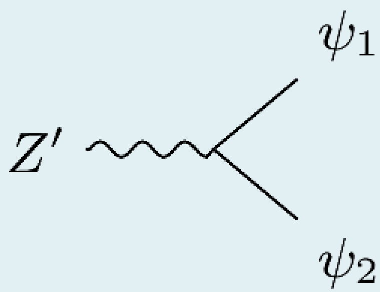
- e^+e^- sufficiently overlapped: sum energies
- Neglect *leakage* of particles from transversal dimension of detector: everything is sufficiently *forward*

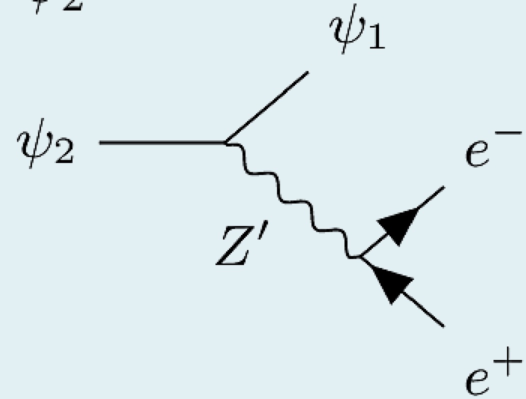
Model 1: inelastic dark matter (iDM) with one pseudo-Dirac pair

$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\psi_\mathrm{L}} & \overline{\psi^\mathsf{c}_\mathrm{R}} \end{pmatrix} \begin{pmatrix} \mu_\mathrm{L} & m_\mathrm{D} \\ m_\mathrm{D} & \mu_\mathrm{R} \end{pmatrix} \begin{pmatrix} \psi^\mathsf{c}_\mathrm{L} \\ \psi_\mathrm{R} \end{pmatrix} + \text{h.c.}$$

- $\mu_\mathrm{L} \approx \mu_\mathrm{R} \ll m_\mathrm{D}$: on-diagonal couplings suppressed
- After diagonalisation, lightest state ψ_1 is DM, with ψ_2 decaying visibly
- DM relic abundance from co-annihilations

$$\mathcal{L} \supset g_\mathrm{D} \overline{\psi}_1 \not{Z}' \psi_2$$





- Proposed in [G. Mohlabeng. Phys. Rev. D 99.11 (2019), p. 115001], where the study assumed BaBar energy threshold of 60 MeV (optimistic, we used 100 MeV, which is the same used in BaBar selection criteria)

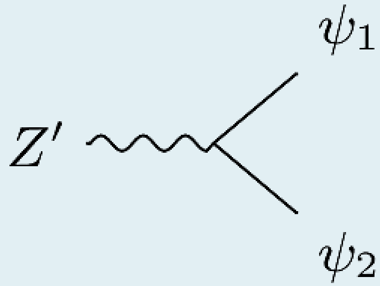
Model 2: iDM with several pseudo-Dirac pair

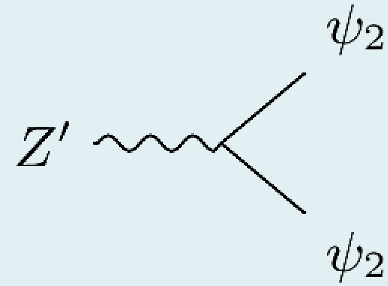
$$\mathcal{L} \supset \begin{pmatrix} \eta_{\mathrm{L}} & \chi_{\mathrm{L}} \end{pmatrix} \begin{pmatrix} M_1 & M_{\mathrm{L}} \\ M_{\mathrm{R}} & M_2 \end{pmatrix} \begin{pmatrix} \eta_{\mathrm{R}} \\ \chi_{\mathrm{R}} \end{pmatrix} + \text{h.c.}$$

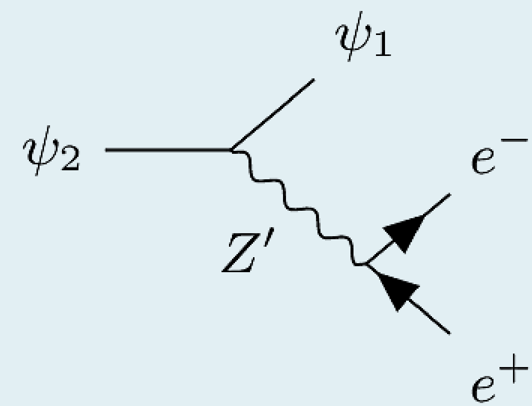
- neutral (η) and U(1)' charged (χ) pseudo-Dirac pairs
- After diagonalisation: light neutral state ψ_1 and heavier state ψ_2 more strongly coupled to dark force with small mixing ϑ

$$\mathcal{L} \supset g_{\mathrm{D}} \theta^2\, \overline{\psi_1} \not{Z}' \psi_1 + g_{\mathrm{D}} \theta\, \overline{\psi_2} \not{Z}' \psi_1 + g_{\mathrm{D}} \overline{\psi_2} \not{Z}' \psi_2$$

- $Z' \to \psi_1 \psi_1$
- $Z' \to \psi_1 \psi_2$
- $Z' \to \psi_2 \psi_2$







- ψ_1 can not be dark matter, unless secluded annihilations
- If not DM, then must decay (e.g. mixing w/ SM ν).

Model 3: HNLs

[A. Abdullahi et al. Phys. Lett. B 820 (2021), p. 136531]

$$\mathcal{L} \supset \left(\overline{N} \quad \overline{\psi}_{\mathrm{L}} \quad \overline{\psi}^{\mathsf{c}}_{\mathrm{R}}\right) \begin{pmatrix} M_N & \Lambda_{\mathrm{L}} & \Lambda_{\mathrm{R}} \\ \Lambda_{\mathrm{L}}^{\mathsf{T}} & 0 & M_X \\ \Lambda_{\mathrm{R}}^{\mathsf{T}} & M_X^{\mathsf{T}} & 0 \end{pmatrix} \begin{pmatrix} N^{\mathsf{c}} \\ \psi_{\mathrm{L}}^{\mathsf{c}} \\ \psi_{\mathrm{R}} \end{pmatrix} + \text{h.c.}$$

- With neutral state N and U(1)'-charged fermions
- After diagonalisation we obtain 3 HNLs, interacting by V_{ij} (in principle they can mix also with SM ν).

$$\mathcal{L} \supset g_{\mathrm{D}} V_{ij} \overline{N_i} \not{Z}' N_j + \text{h.c.}$$