# Semi-Visible Dark Photons and the Muon $g-2$

Asli Abdullahi*

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Instituto de Física Teórica UAM-CSIC

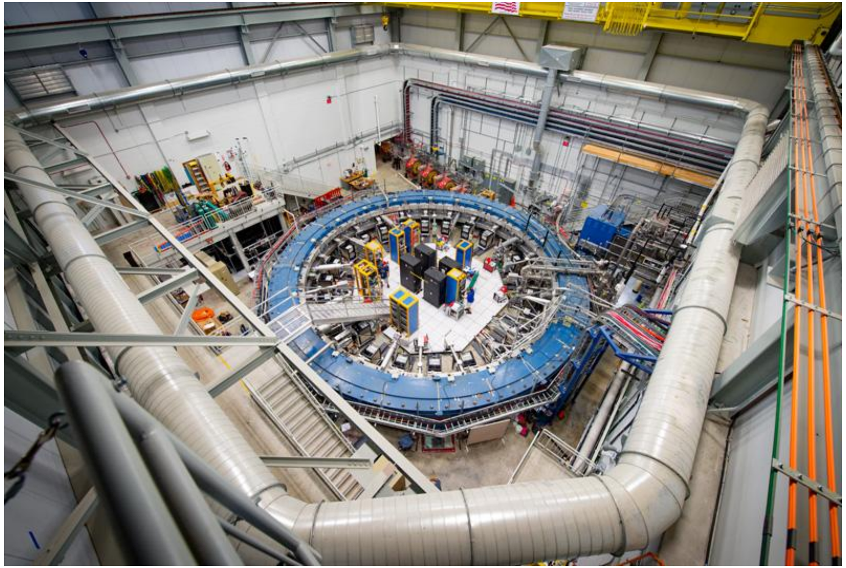
Fermilab

*in collaboration with

M. Hostert (UMN, PI), D. Massaro (UNIBO, UC Louvain) and S. Pascoli (UNIBO)

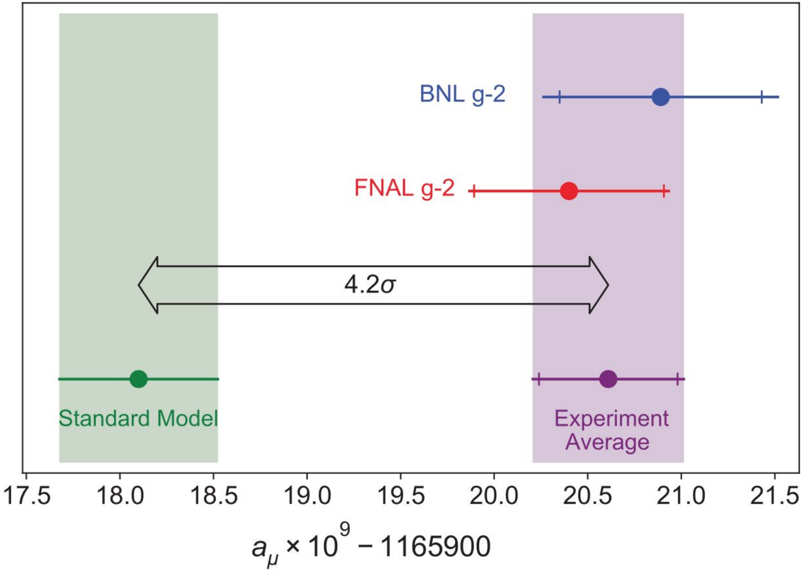
# Motivation

Muon g-2 experiment seems to confirm existing tension with SM



https://mod.fnal.gov/mod/stillphotos/2017/0100/17-0188-19

B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)




Combined BNL and FNAL result at **4.2σ** deviation from the SM theory prediction

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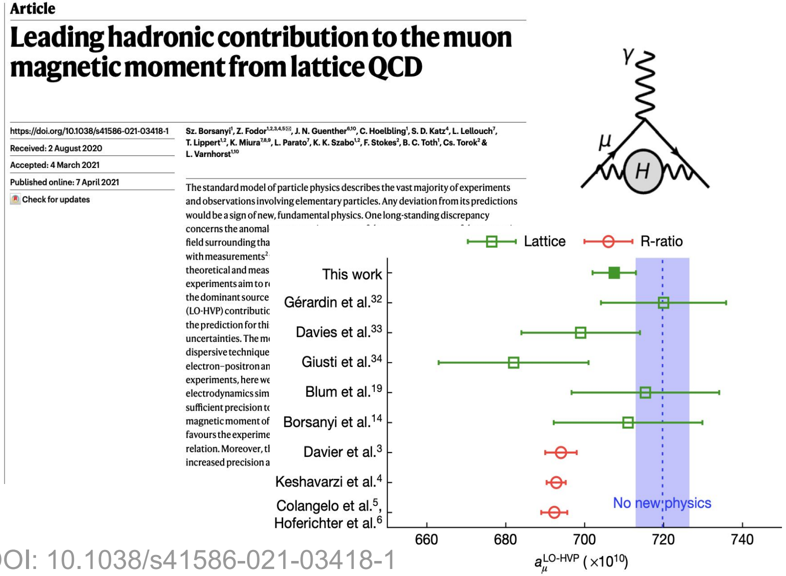


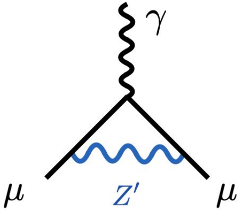

DOI: 10.1038/s41586-021-03418-1

Possible that the discrepancy is purely SM but exciting to consider otherwise!

Among the possibilities is the existence of a **dark photon (DP)**

$$\mathscr{L}_{\rm SM} - \frac{\varepsilon}{2c_{\rm W}} F_{\mu\nu}X^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu$$

DP provides a positive contribution to $\Delta a_\mu$

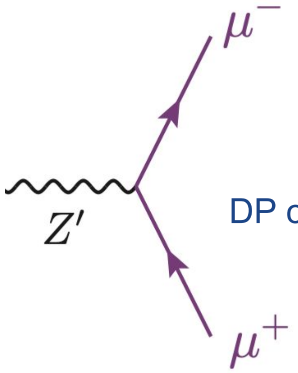



$$\Delta a_\mu \propto \int_0^1 dz \frac{2zm_\mu^2(1-z)^2}{m_\mu^2(1-z)^2 + zm_{Z'}^2}$$

M. Pospelov, Phys. Rev. D80, 095002

# Motivation

New interactions from gauging accidental U(1) symmetries of SM, e.g.




$$L_\mu, L_\mu - L_\tau \text{ etc.}$$

DP couples directly to muons

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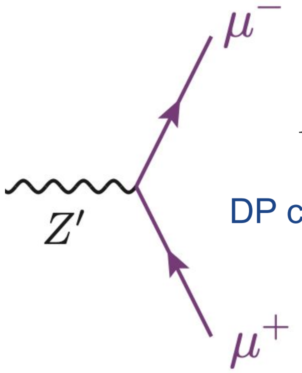


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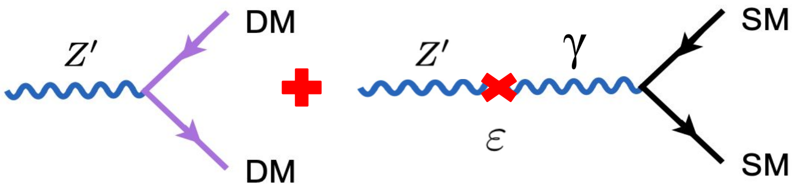
DP couples directly to muons

Or comprise a new and secluded dark sector, e.g. a U(1)_X

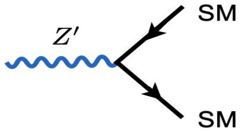
**This talk!**



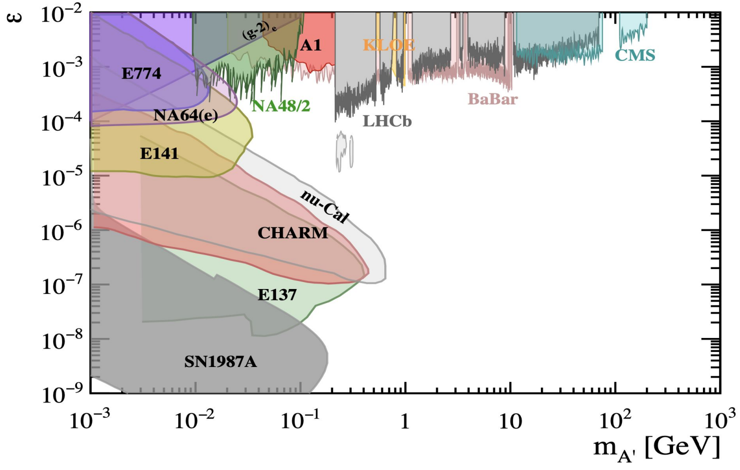

DP couples to muons via kinetic mixing

# Motivation

Minimal models of kinetically mixed DPs have already been studied by numerous experiments




**VISIBLE DP**




Fabbrichesi, et al. 10.1007/978-3-030-62519-1

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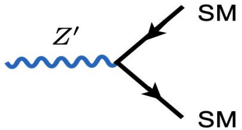


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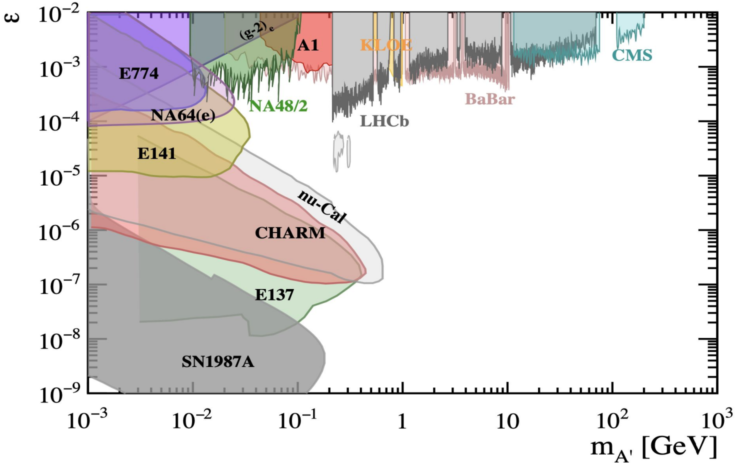


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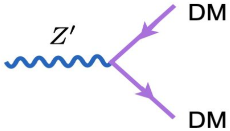
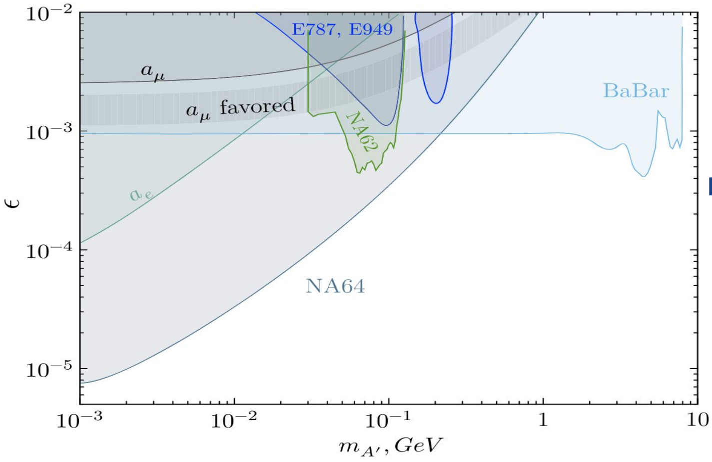



**INVISIBLE DP**

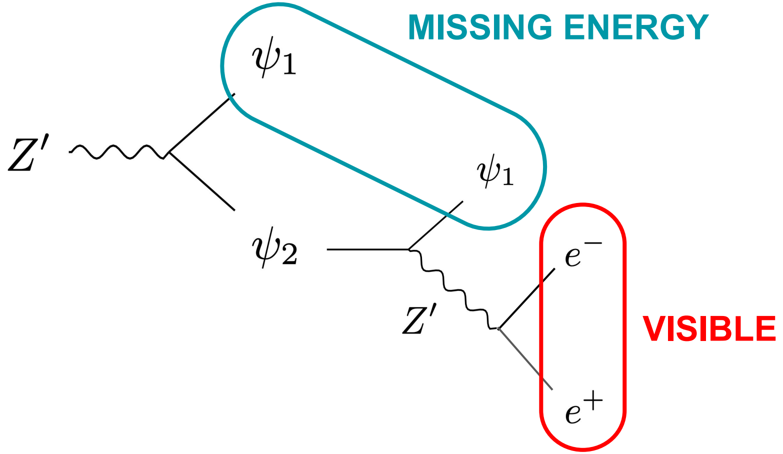



D. Banerjee et al, PRL 123, 121801 (2019)

**A g-2 solution is excluded in the minimal scenarios**

# Motivation

Recently, **SEMI-VISIBLE DPs** have been invoked as a potential solution




G.Mohlabeng, *10.1103/PhysRevD.99.115001*

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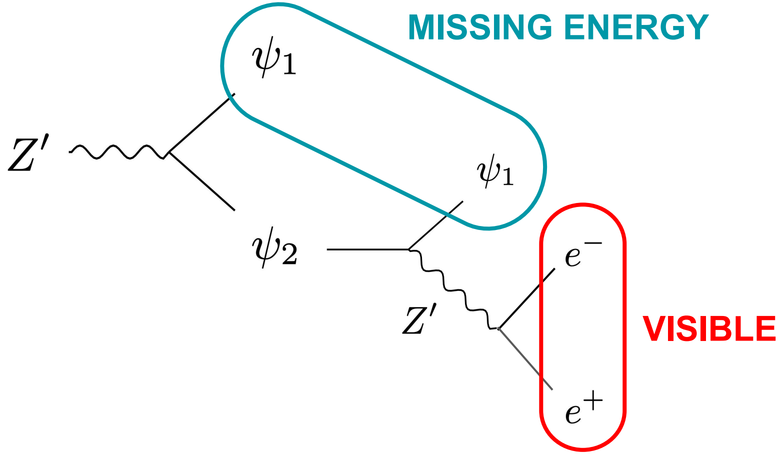


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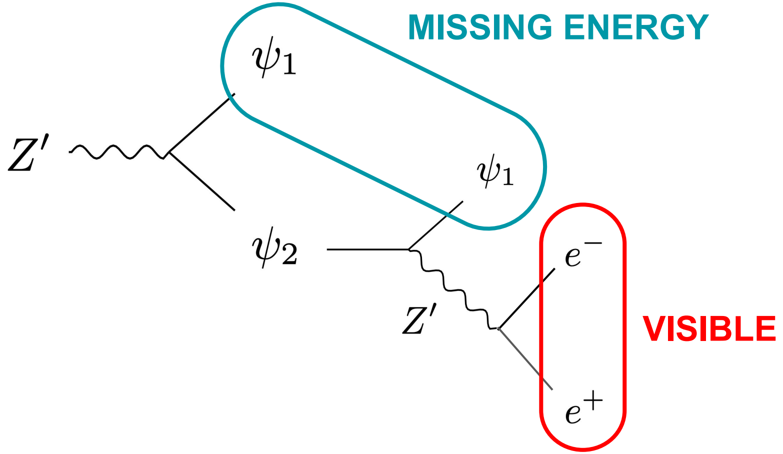


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- ✓ Evades visible DP searches with **missing energy**
- ✓ Evades invisible DP searches with **visible final states**

# Rest of this talk

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1) Does the kinetically-mixed semi-visible DP remain a viable solution to g-2?

2) Which models does it point us toward?

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  - Inelastic DM (iDM)
  - Dirac iDM (i2DM)
  - Heavy Neutral Leptons

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  - Heavy Neutral Leptons
- **Constraints and recasts**
  - BaBar and NA64
- **Future searches + Conclusions**

# Vector Portal Inelastic Dark Matter

# Inelastic Dark Matter (iDM)

- Introduced as a solution to DAMA anomaly *D.Smith, N. Wiener, Phys. Rev. D 64, 043502*

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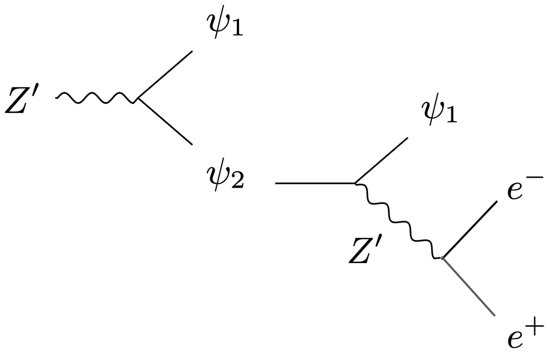

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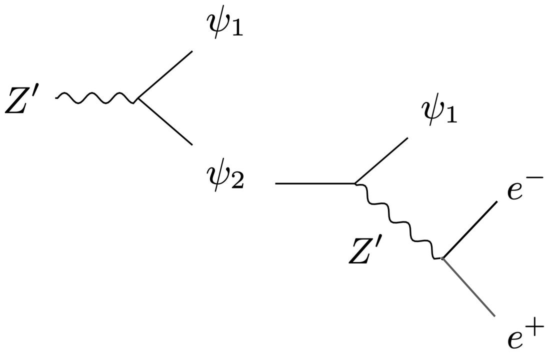


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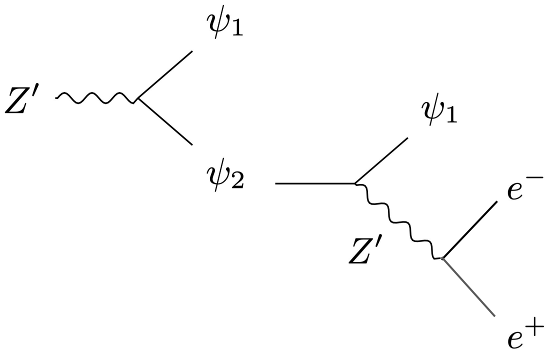


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*E. Izaguirre et al. Phys. Rev. D 93, 063523*
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*G. Giudice et al. Phys. Lett. B780, 543–552*
*A. Berlin, F. Kling, Phys. Rev. D99, 015021*
*G. Mohlabeng, Phys. Rev. D99, 115001*
*J. Eby et al. J. High Energ. Phys. 2019, 115*
*Y.D. Tsai et. al Phys. Rev. Lett. 126 (2021) 181801*
*M. Duerr et al. JHEP 02 (2020) 039*

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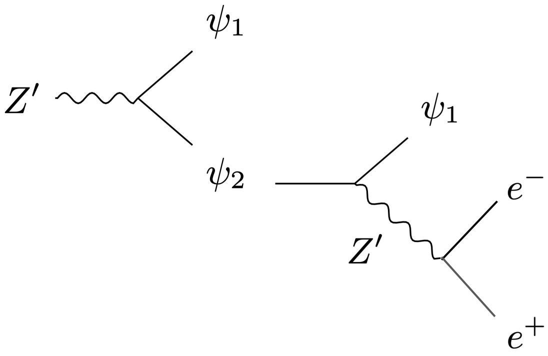


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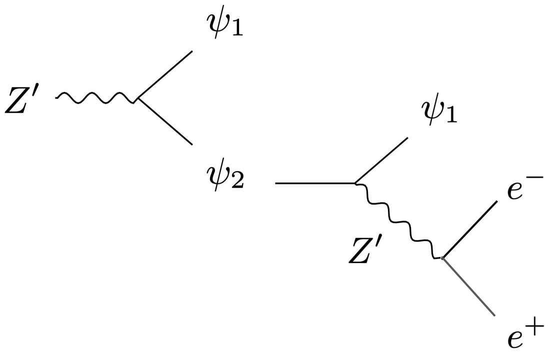
… and many many more

# Inelastic Dark Matter (iDM)

In addition to DP Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{\varepsilon}{2c_{\rm W}} F_{\mu\nu}X^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_X X_\mu \mathcal{J}^\mu_{\rm X} + \frac{m^2_{\rm X}}{2} X_\mu X^\mu$$

introduce a pair of Weyl fermions,



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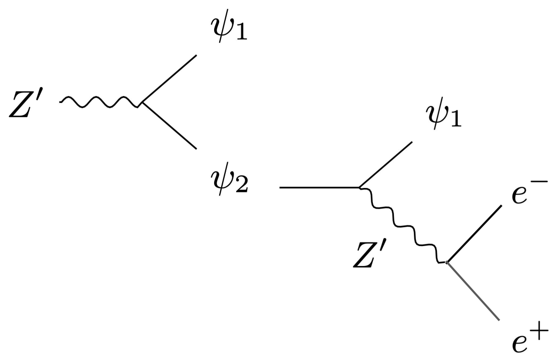


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$$\mathscr{L} \supset \overline{\chi_L}(i\partial\!\!\!/ - g_X Q_L X\!\!\!/)\chi_L + \overline{\chi_R}(i\partial\!\!\!/ - g_X Q_R X\!\!\!/)\chi_R + \mathscr{L}_{\text{mass}}$$

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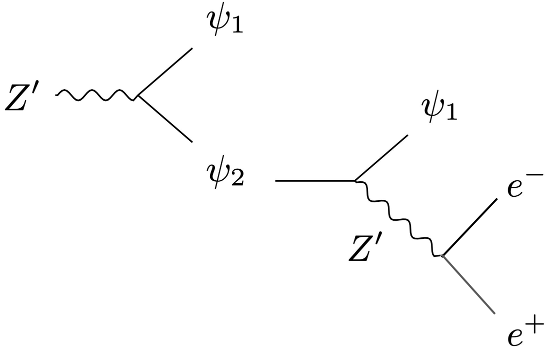


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After SSB of U(1)', generate Majorana masses

$$\mathscr{L}_{\mathrm{mass}} = -\frac{1}{2} \begin{pmatrix} \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} \mu_L & m_D \\ m_D & \mu_R \end{pmatrix} \begin{pmatrix} \chi_L^c \\ \chi_R \end{pmatrix} + \mathrm{h.c.}$$

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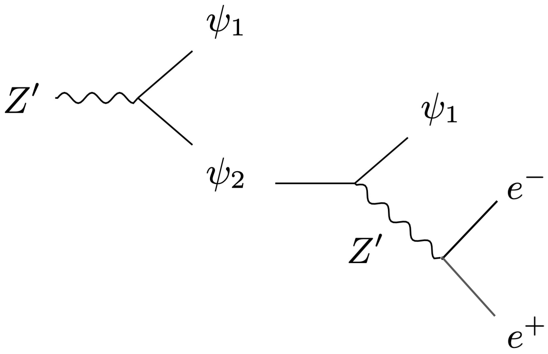


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In the mass basis,

$$\mathscr{L}_{\rm mass} = \frac{m_1}{2}\overline{\psi_1}\psi_1 + \frac{m_2}{2}\overline{\psi_2}\psi_2 + \text{h.c.}$$

$$m_{1,2} = \frac{\mu_L + \mu_R}{2} \pm \sqrt{M_D^2 + \left(\frac{\mu_R - \mu_L}{2}\right)^2}$$ and $$\Delta = \frac{m_2 - m_1}{m_1}$$

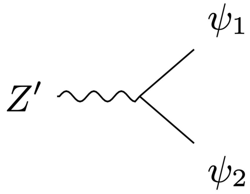
# Inelastic Dark Matter (iDM)

Dark sector current reads

$$\mathcal{J}_X^\mu = \frac{Q_L c_\theta^2 - Q_R s_\theta^2}{2}\overline{\psi_2}\gamma^\mu\gamma^5\psi_2 + \frac{Q_L s_\theta^2 - Q_R c_\theta^2}{2}\overline{\psi_1}\gamma^\mu\gamma^5\psi_1$$
$$+ i\frac{Q_L + Q_R}{2}\sin 2\theta\cos\delta\,\overline{\psi_2}\gamma^\mu\psi_1 + \frac{Q_L + Q_R}{2}\sin 2\theta\sin\delta\,\overline{\psi_2}\gamma^\mu\gamma^5\psi_1,$$

with $\tan 2\theta = m_D/(\mu_L - \mu_R)$.

In the vector-like limit, $Q_L = Q_R$, and for pseudo-Dirac states




Dark photon couples **purely off-diagonally**,
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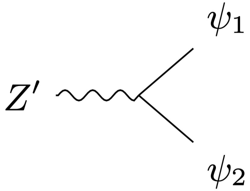


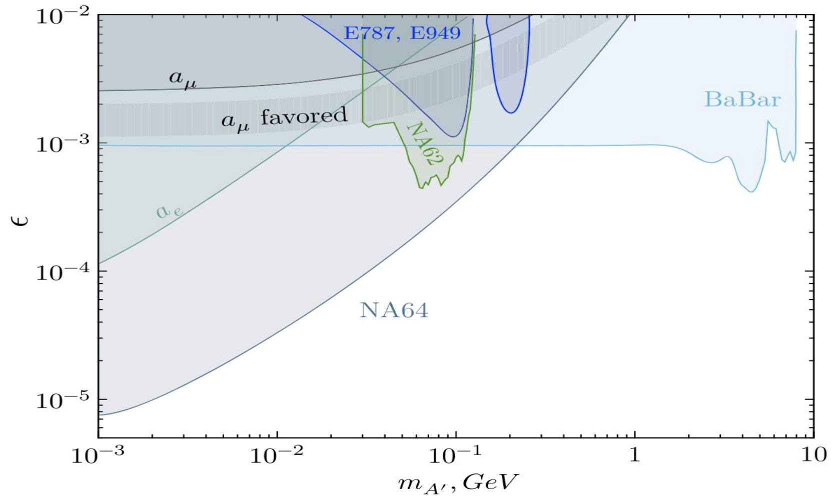

Dark photon couples **purely off-diagonally**, with diagonal couplings suppressed by a factor $\mu_L - \mu_R$

- Light state constitute the DM → **relic abundance sourced by co-annihilations**
- Heavy state decays to DM and light SM fermions

## Main constraints
## +
## Selections for recast

# Constraints on iDM

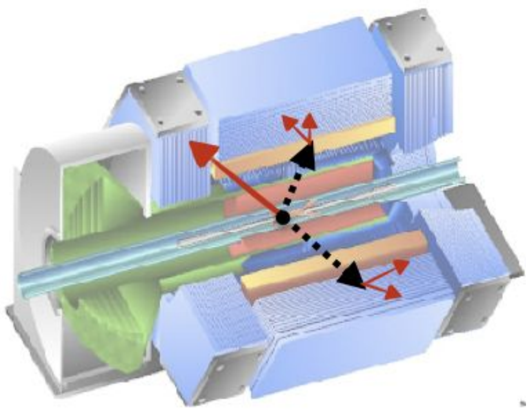
In the g-2 preferred region, strongest constraints come from NA64 and BaBar searches for invisible dark photon decays

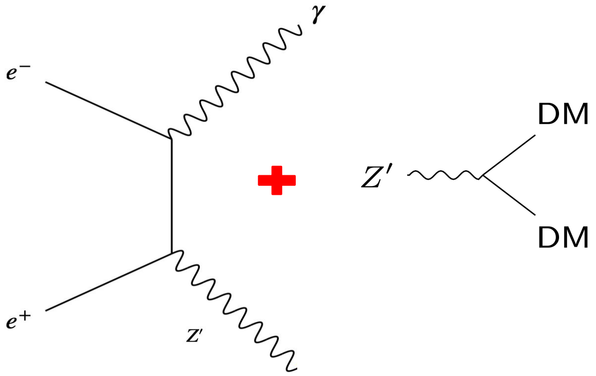



D. Banerjee et al, PRL 123, 121801 (2019)

# BaBar monophoton search

BaBar search for initial state radiation (ISR) in the process $e^+e^- \to \gamma Z'$, accompanied by missing energy





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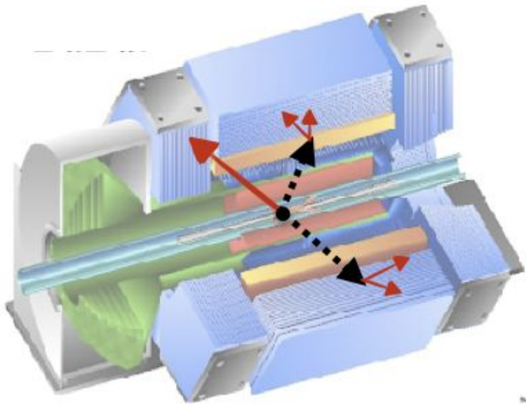

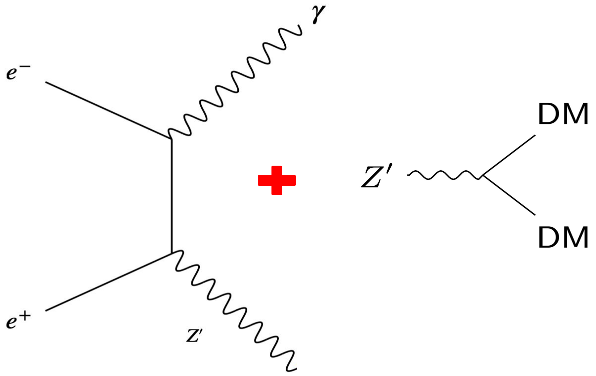


DP assumed to have 100% invisible branching ratio

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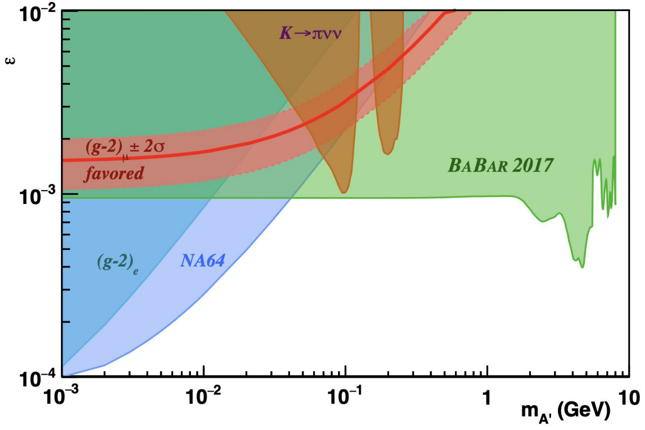


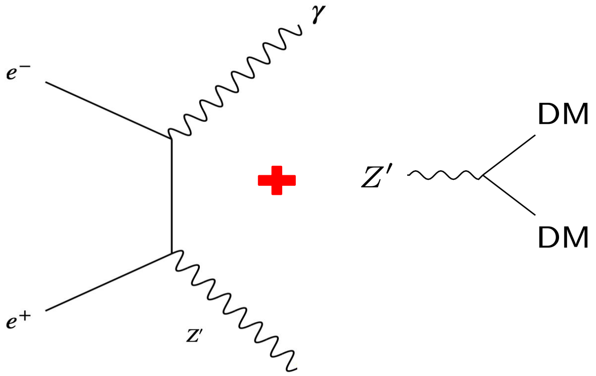


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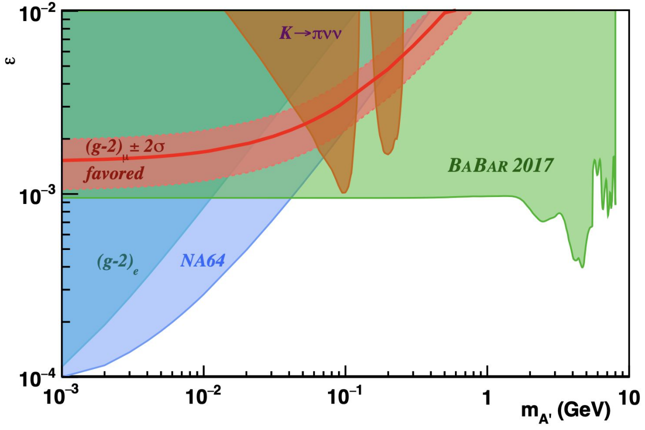
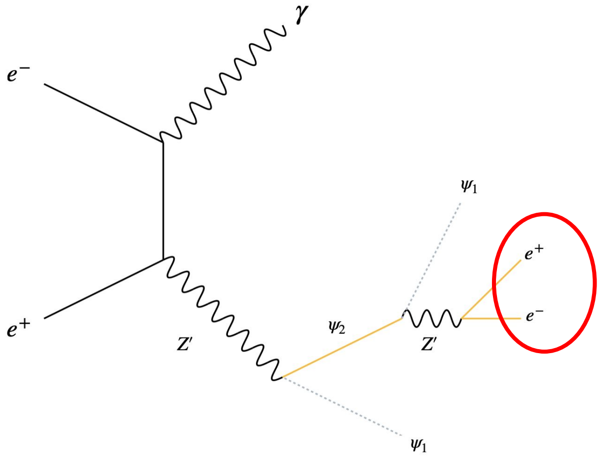
In the case of a semi-visible DP (e.g. in iDM), photon accompanied by **displaced, visible lepton tracks**



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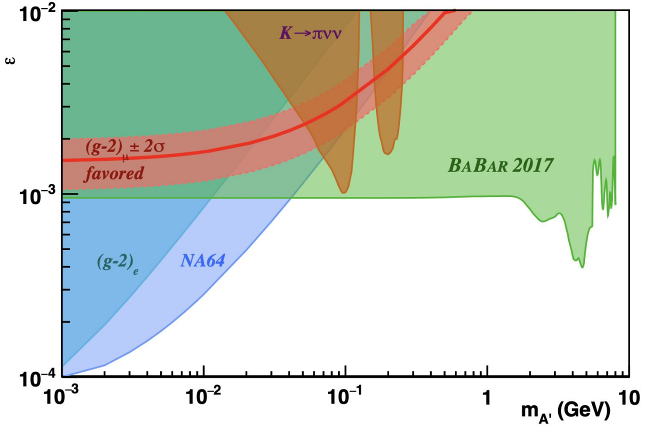


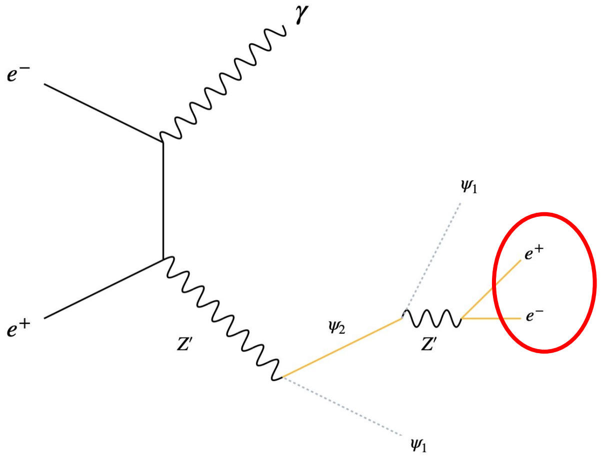


If leptons sufficiently energetic, events are **vetoed** leading to **significant relaxation** of the bound

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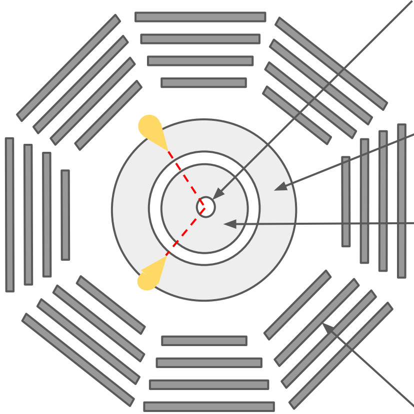



<u>Dedicated monophoton trigger lines:</u>

Low-mass DP (high-energy monophoton):

- One cluster in ECAL with E ≥ 2 GeV
- **NO** e+e- tracks in DCH

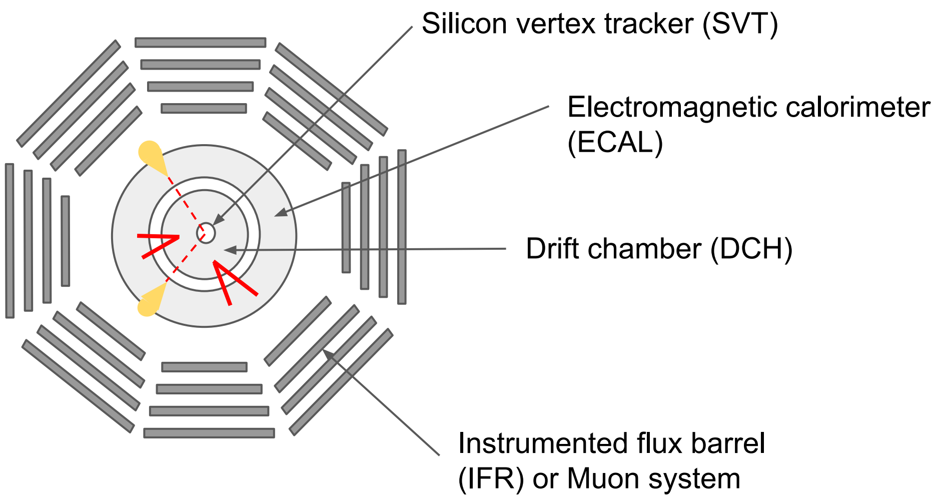
High-mass DP (low-energy monophoton):

- One cluster in ECAL with E ≥ 1 GeV
- **NO** e+e- tracks in DCH

Photons accepted in polar angle range, $|\cos\theta^*_\gamma| < 0.6$

# BaBar monophoton search

Veto criteria: For decays that occur in instrumented regions of the detector (SVT, DCH, ECAL, IFR)



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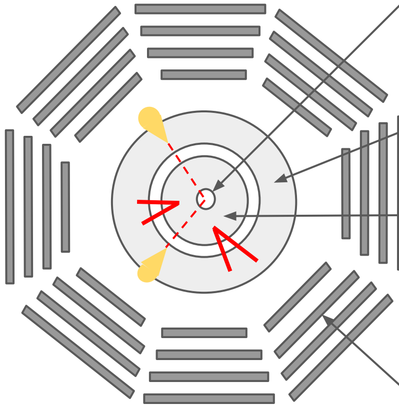



**Require**

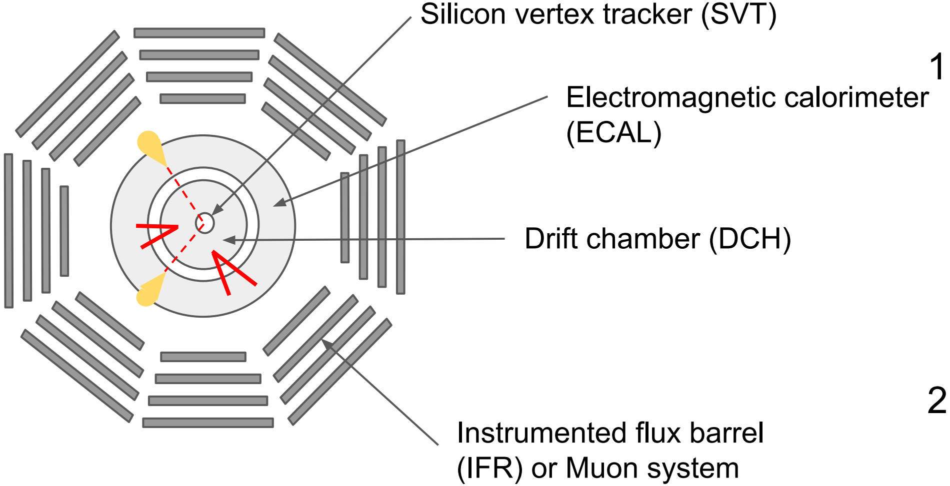
1. Energy of lepton tracks must exceed BaBar detection threshold for charged lepton tracks

If $\theta_{\text{sep}} > 10^\circ$, then cut: $E_\pm > 100\ \text{MeV}$

If $\theta_{\text{sep}} < 10^\circ$, then cut: $E_+ + E_- > 100\ \text{MeV}$

# BaBar monophoton search

Veto criteria: For decays that occur in instrumented regions of the detector (SVT, DCH, ECAL, IFR)




**Require**

1. Energy of lepton tracks must exceed BaBar detection threshold for charged lepton tracks

   If $\theta_{\text{sep}} > 10^\circ$, then cut: $E_\pm > 100\ \text{MeV}$

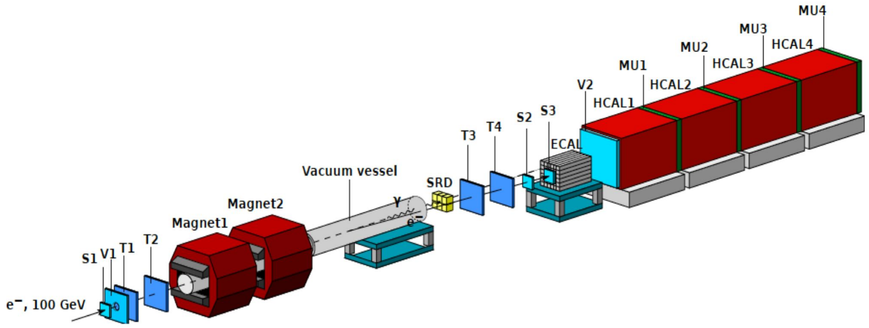
   If $\theta_{\text{sep}} < 10^\circ$, then cut: $E_+ + E_- > 100\ \text{MeV}$

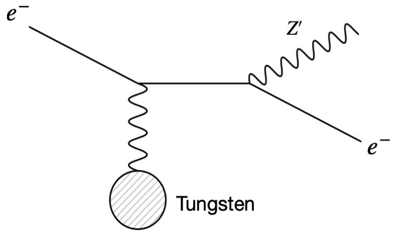
2. The polar angles are sufficiently wide that the electrons do not escape along the beam pipeline

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

# NA64 dark photon searches

NA64 performed a missing energy search with DP production in **dark bremsstrahlung,** $e^- N \to e^- N Z'$

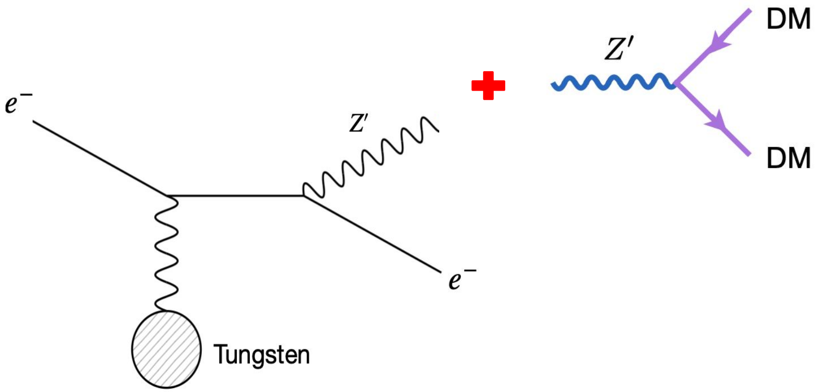


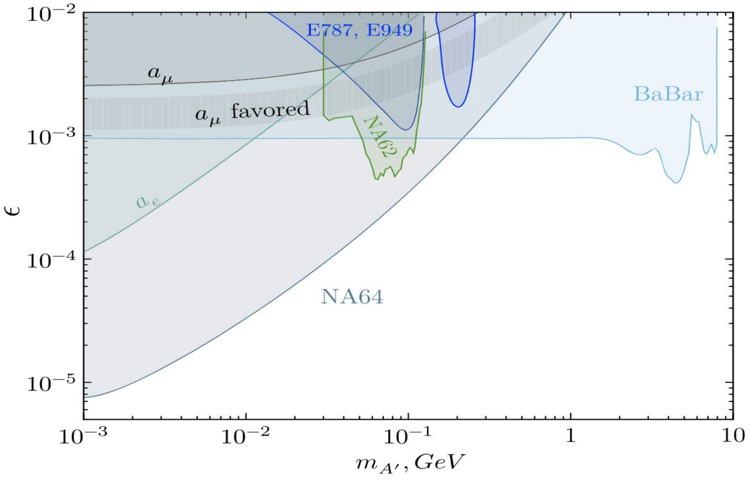




…performing two distinct analyses for the DP model

# NA64 dark photon searches

1) Invisible DP



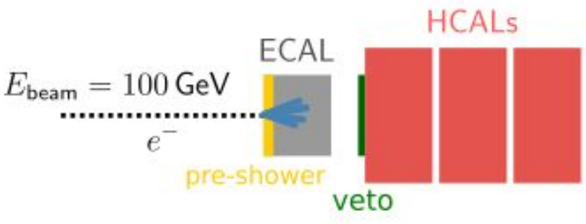




D. Banerjee et al, PRL 123, 121801 (2019)

# NA64 dark photon searches

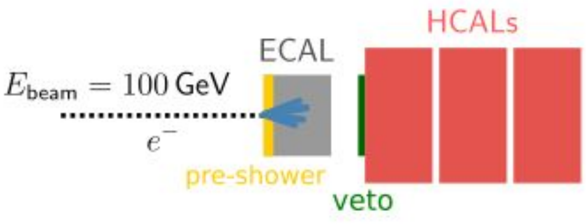
1) invisible search

➔ Apply *trigger* conditions on energy deposited in pre-shower ECAL: $E_{\text{tot}} \in [0.2,\, 80]\ \text{GeV}$



# NA64 dark photon searches

1) invisible search




➔ Apply *trigger* conditions on energy deposited in pre-shower ECAL: $E_{\text{tot}} \in [0.2,\, 80]$ GeV

**Selection criteria**

1. ECAL: Total energy deposited < 50 GeV, i.e. total missing energy > 50 GeV

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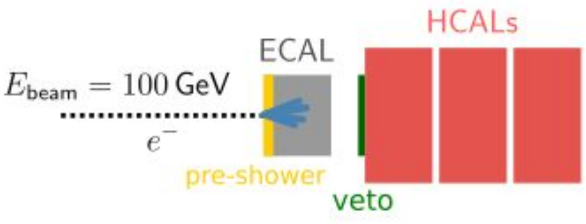


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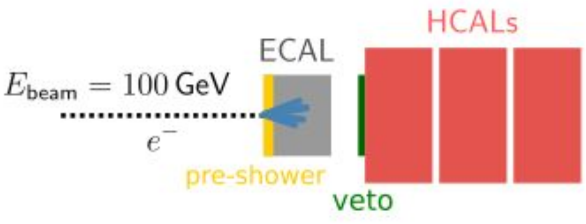


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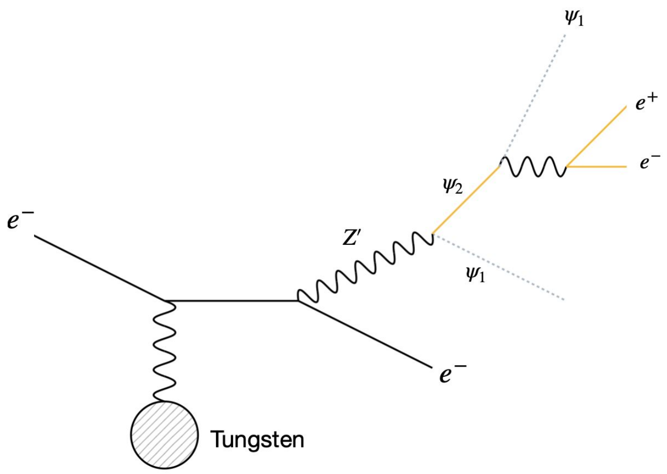
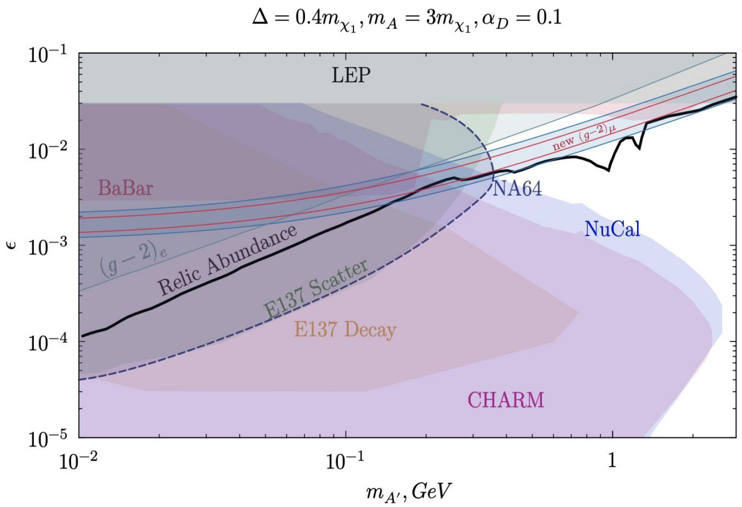
2. Veto counter: < 10 MeV deposited in veto
3. HCAL: < 1 GeV deposited in HCALs

# NA64 dark photon searches

2) semi-visible DP in iDM

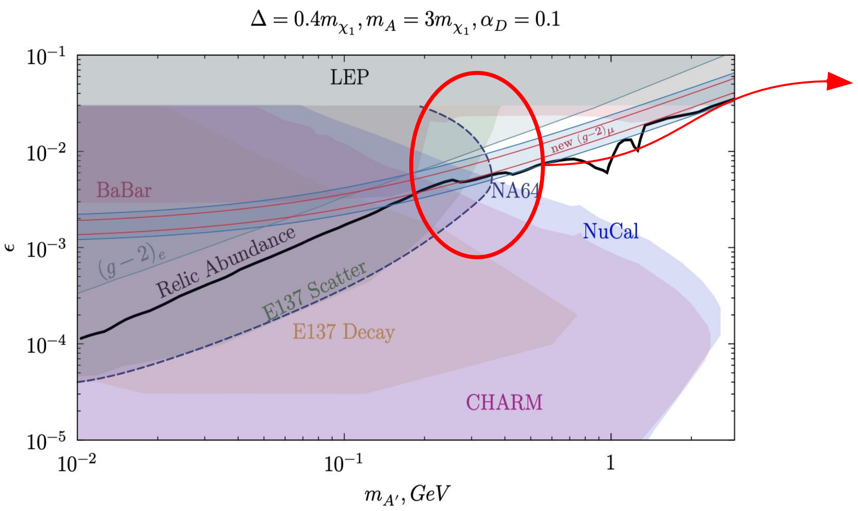



Cazzaniga, C. et al, *Eur. Phys. J. C* 81 (2021) 10, 959

# NA64 dark photon searches

2) semi-visible DP in iDM



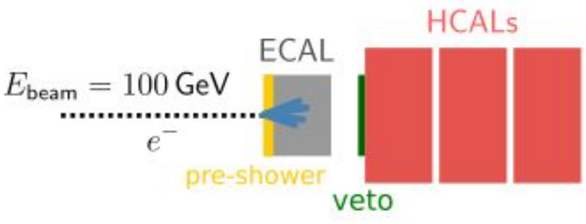

Cazzaniga, C. et al, *Eur. Phys. J. C* 81 (2021) 10, 959

Constraint from semi-visible search **not sensitive to prompt decays**

- Efficiency to distinguish collimated e+e- showers from primary electron beam in ECAL is challenging

# NA64 dark photon searches

2) semi-visible DP in iDM




**Selection criteria**

1. HCAL: < 1 GeV deposited in HCALs
2. All decays beyond HCALs selected (long-lived fermions)

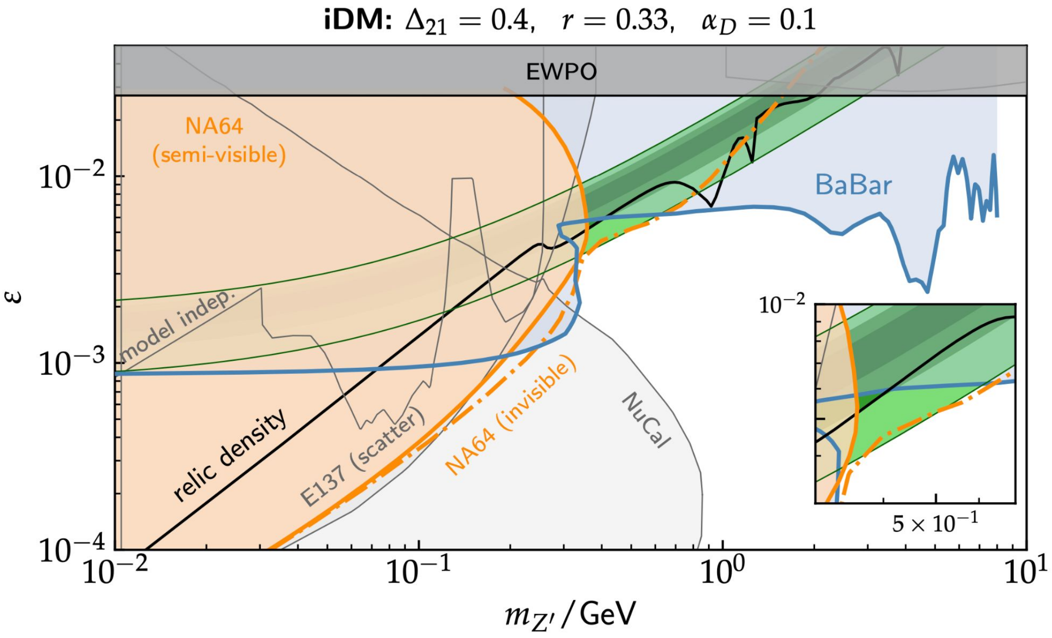
**Note:** In the semi-visible search, all decays that occur prior to HCAL are vetoed regardless of energy

*"The largest limitation to probe the missing region comes from the increasingly short decay time of $\chi_2$, which makes the chance of detection vanishingly small."* - *Eur. Phys. J. C* 81 (2021) 10, 959

**Treat invisible search as "sensitivity" rather than a constraint**

# iDM Recast

We consider a benchmark model of iDM inspired by recent work on this topic in relation to g-2



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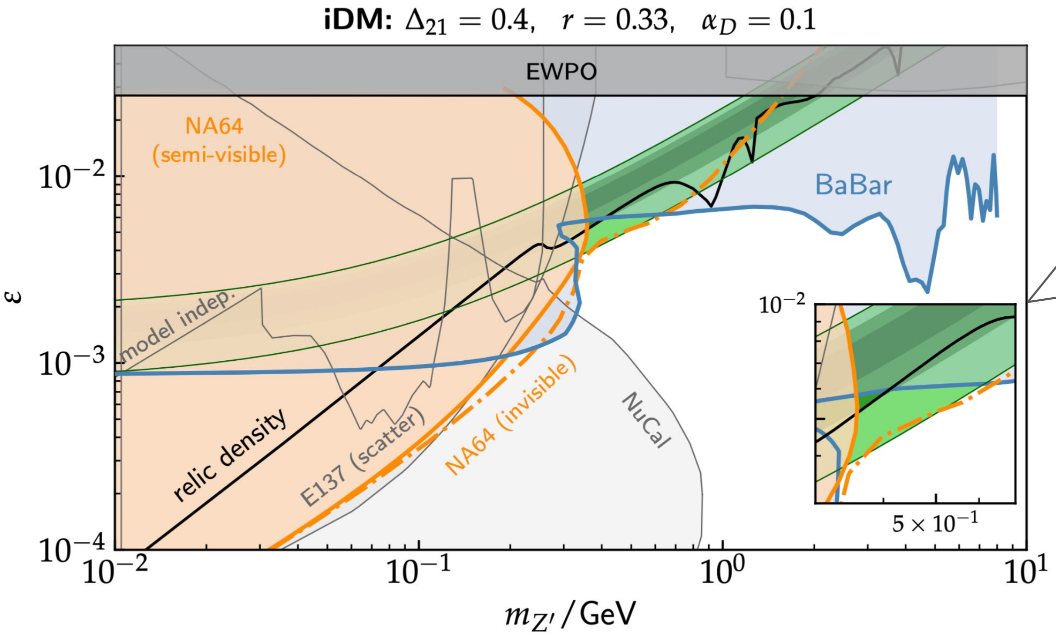
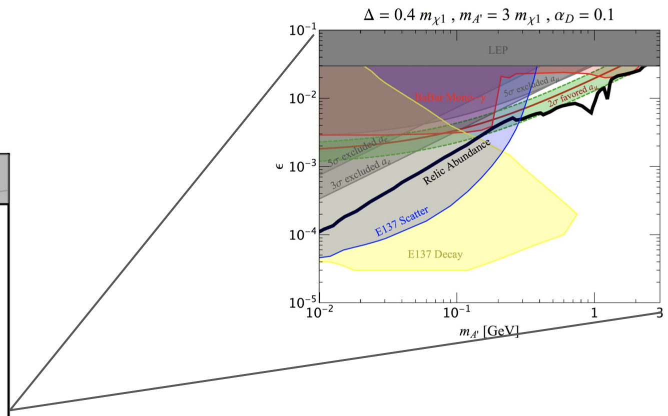



G. Mohlabeng, Phys. Rev. D99, 115001




iDM model for (g-2) is **disfavoured** at **2σ**

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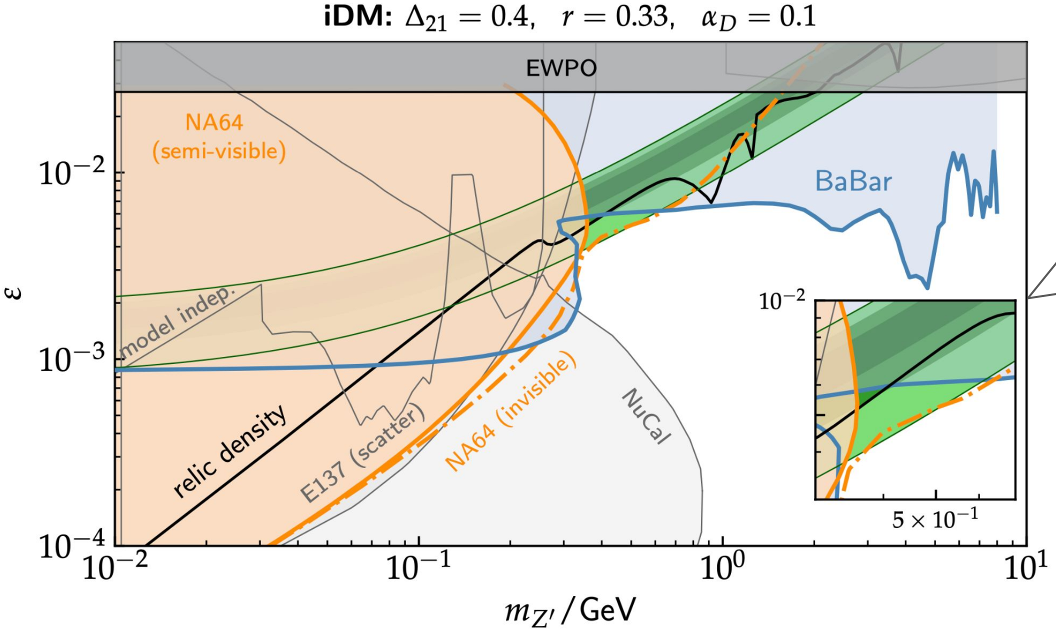


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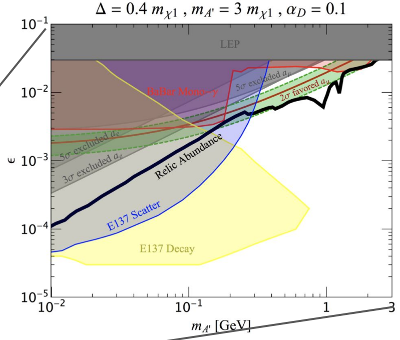
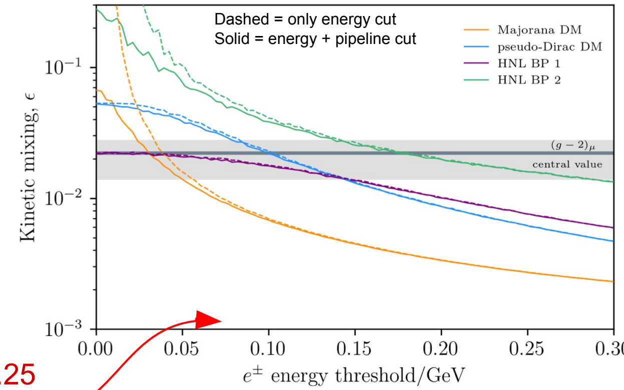


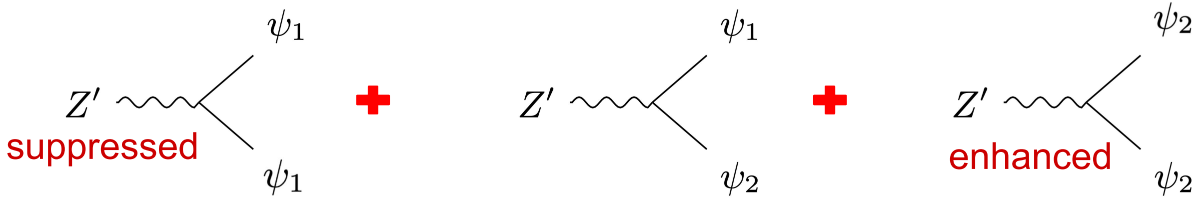




BaBar constraint on kinetic mixing for Mz' = 1.25 GeV as function of e+e- energy threshold cut

# Vector Portal *Dirac* Inelastic Dark Matter

# i2DM

- We would like to consider a model in which we couple diagonally to the heavy fermion state, while suppressing the diagonal coupling to the DM, e.g.



Introduce the four-component fields $\eta = \eta_L + \eta_R$ (sterile), $\chi = \chi_L + \chi_R$ (charged)

in addition to standard DP Lagrangian, we have

$$
\begin{aligned}
\mathscr{L} \supset\ & \overline{\chi_L}(i\partial\!\!\!/ - g_X Q_L X\!\!\!/)\chi_L + \overline{\chi_R}(i\partial\!\!\!/ - g_X Q_R X\!\!\!/)\chi_R + \overline{\eta} i\partial\!\!\!/ \eta \\
& - \left\{ M_1 \overline{\eta}\eta + \frac{1}{2}\mu_L \overline{\eta_L}\eta_L^c + \frac{1}{2}\mu_R \overline{\eta_R}\eta_R^c + M_2 \overline{\chi}\chi + y_L \Phi \overline{\chi_L}\eta_R + y_R \Phi \overline{\chi_R}\eta_L + \text{h.c.} \right\}
\end{aligned}
$$

# i2DM

Introduce the four-component fields $\eta = \eta_L + \eta_R$ (sterile), $\chi = \chi_L + \chi_R$ (charged)

in addition to standard DP Lagrangian, we have

$$\mathscr{L} \supset \overline{\chi_L}(i\partial\!\!\!/ - g_X Q_L X\!\!\!/)\chi_L + \overline{\chi_R}(i\partial\!\!\!/ - g_X Q_R X\!\!\!/)\chi_R + \overline{\eta} i\partial\!\!\!/ \eta$$
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If we assume Majorana masses of sterile state are small, we have

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2} \begin{pmatrix} \overline{\eta_L} & \overline{\chi_L} \end{pmatrix} \begin{pmatrix} M_1 & M \\ M & M_2 \end{pmatrix} \begin{pmatrix} \eta_R \\ \chi_R \end{pmatrix} + \text{h.c.}$$

# i2DM

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2}\begin{pmatrix}\overline{\eta_L} & \overline{\chi_L}\end{pmatrix}\begin{pmatrix}M_1 & M \\ M & M_2\end{pmatrix}\begin{pmatrix}\eta_R \\ \chi_R\end{pmatrix} + \text{h.c.}$$

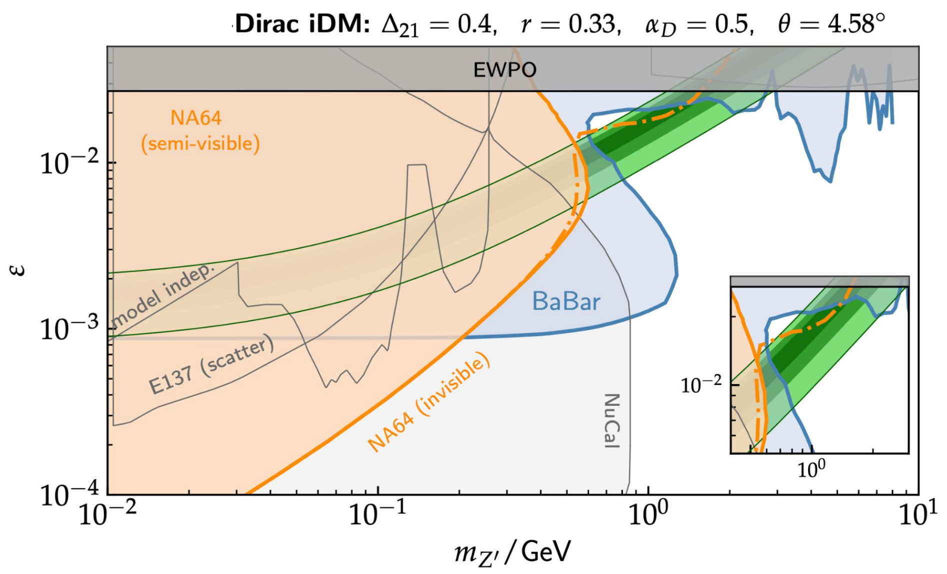
If we also also take $M \ll M_{1,2}$, the mass basis is very **nearly aligned** with the flavour basis

Perform a nearly diagonal rotation by $\theta \approx M/(M_2 - M_1)$ to find the mass states

$$\mathcal{J}_X^\mu = Q(s_\theta^2 \overline{\psi_1}\gamma^\mu\psi_1 - s_\theta c_\theta \overline{\psi_2}\gamma^\mu\psi_1 + c_\theta^2 \overline{\psi_2}\psi_2)$$

# i2DM RECAST

For comparison, keep most parameters the same as iDM benchmark model



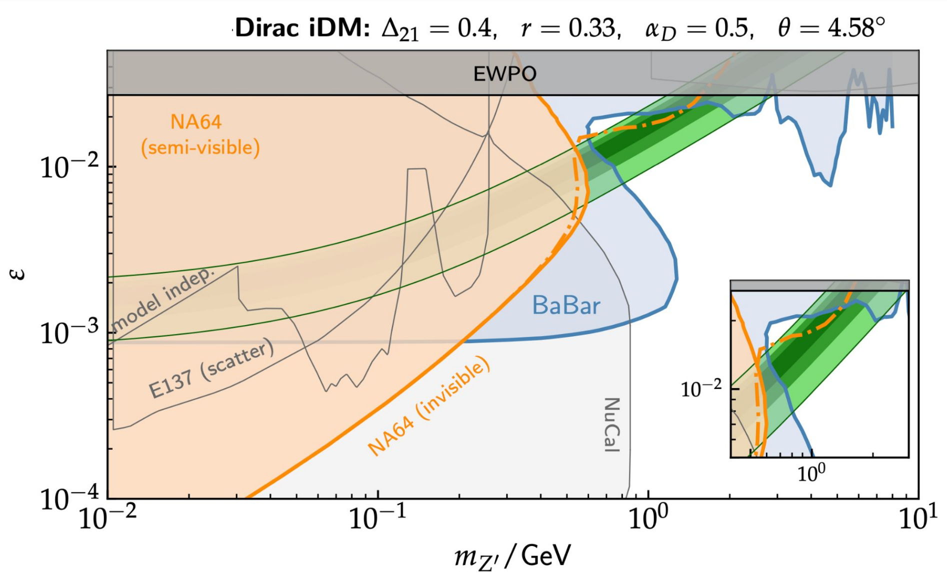

Full 3σ g-2 preferred region opens up for DP masses between **600 MeV - 2 GeV**

Main features:

- Relaxation occurs at larger DP masses
- NA64 semi-visible constraint stronger

# Dirac iDM RECAST

For comparison, keep most parameters the same as iDM benchmark model

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Main features:

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- NA64 semi-visible constraint stronger

**Important caveat!**

- Benchmark model *may not* give the dark matter relic abundance

(see arXiv:2201.08409 for more detail about Dirac iDM story)

# Heavy Neutral Leptons

# Heavy Neutral Leptons

**AA**, M.Hostert, S.Pascoli, j.physletb.2021.136531

- Similar to i2DM scenario, with the sterile state now coupling to SM neutrinos as in the Type 1 seesaw

$$\mathscr{L} \supset \overline{\chi_L}(i\partial\!\!\!/ - g_X Q X\!\!\!/)\chi_L + \overline{\chi_R}(i\partial\!\!\!/ - g_X Q X\!\!\!/)\chi_R + \overline{\eta} i\partial\!\!\!/ \eta$$
$$-\{y_\nu \overline{L}\tilde{H}\eta^c + y_R \overline{\eta}\chi_R \Phi^* + y_L \overline{\eta}\chi_L^c \Phi + \frac{1}{2} M_N \overline{\eta}\eta^c + M_X \overline{\chi}\chi + \text{ h.c.}\}$$

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$$-\{y_\nu \overline{L}\tilde{H}\eta^c + y_R \overline{\eta}\chi_R \Phi^* + y_L \overline{\eta}\chi_L^c \Phi + \frac{1}{2} M_N \overline{\eta}\eta^c + M_X \overline{\chi}\chi + \text{ h.c.}\}$$

Dark sector Yukawa allows for mass mixing between the dark fermions and SM neutrinos

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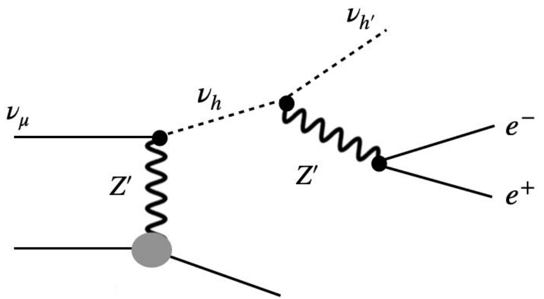
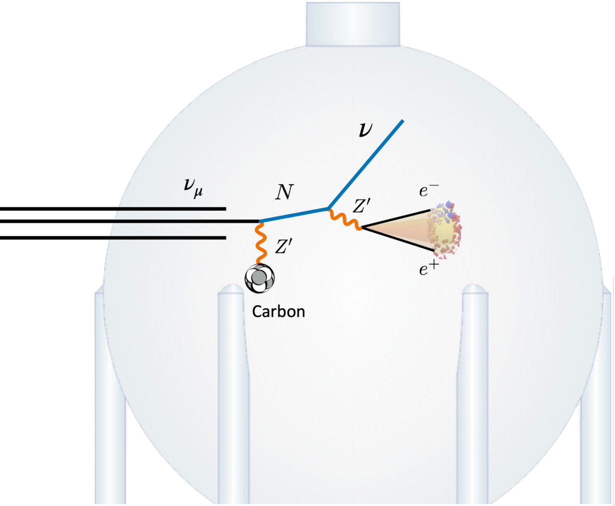


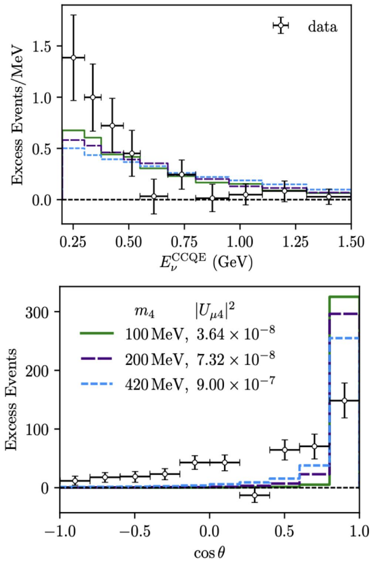

**Can have light neutrino upscattering to heavy states**

# Heavy Neutral Leptons

This phenomenological signature has been extensively studied for MiniBooNE

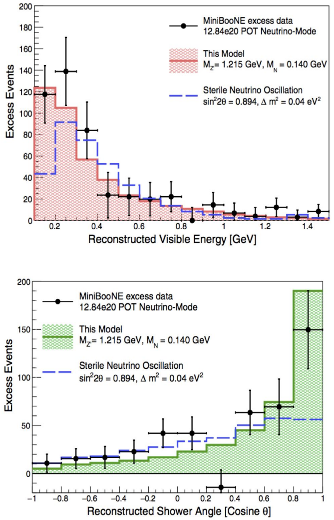



**Light mediators (10 - 100s of MeV Z')**



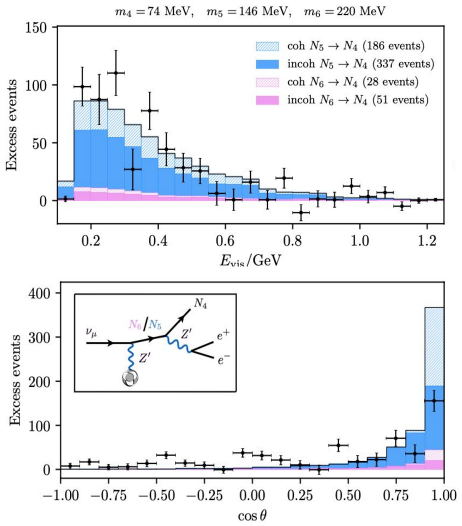

E. Bertuzzo et al., [arXiv:1807.09877]
C. Argüelles et al, [arXiv:1812.08768]

**Heavy mediators (~GeV scale Z') interference Z-Z'**




P. Ballett et al. [arxiv:1808.02915]

**Inter-generational decays (~GeV scale Z')**



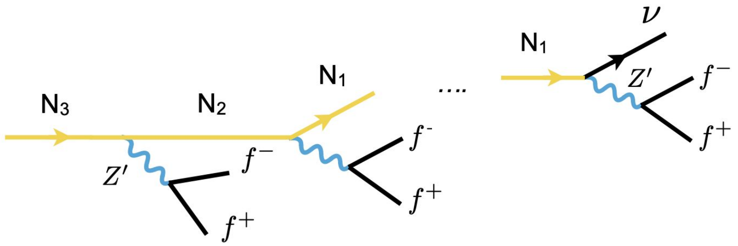

P. Ballett et al. [arxiv:1903.07589]
A. Abdullahi et al., [arXiv:2007.11813]

# Heavy Neutral Leptons

- Increased particle content allows for rapid, cascade decays in the detector

- multi-lepton final states can vastly increase the visibility of the dark photon decays

$$\mathcal{J}_X^\mu \approx V_{ij}\overline{\psi_i}\gamma^\mu P_L\psi_j \text{ with } V_{ij} \equiv U^\dagger_{\chi_L i}U_{\chi_L j} - U^\dagger_{\chi_R i}U_{\chi_R j}$$



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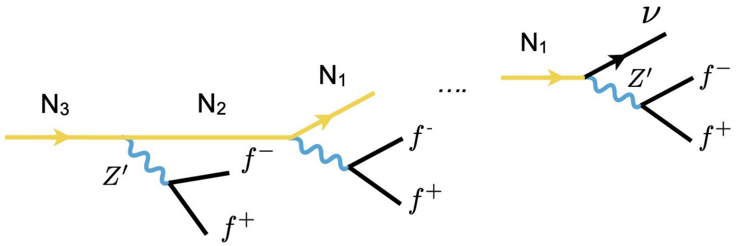


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Parameter space relevant for MiniBooNE predicts semi-visible dark photon states!

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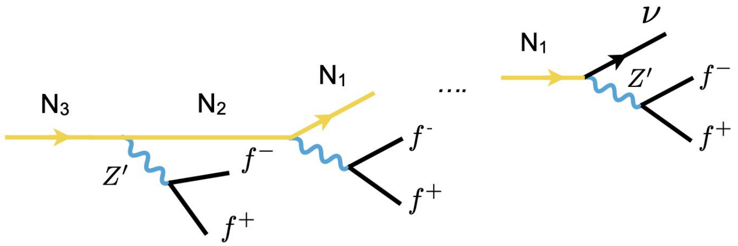


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**Benchmark models:**

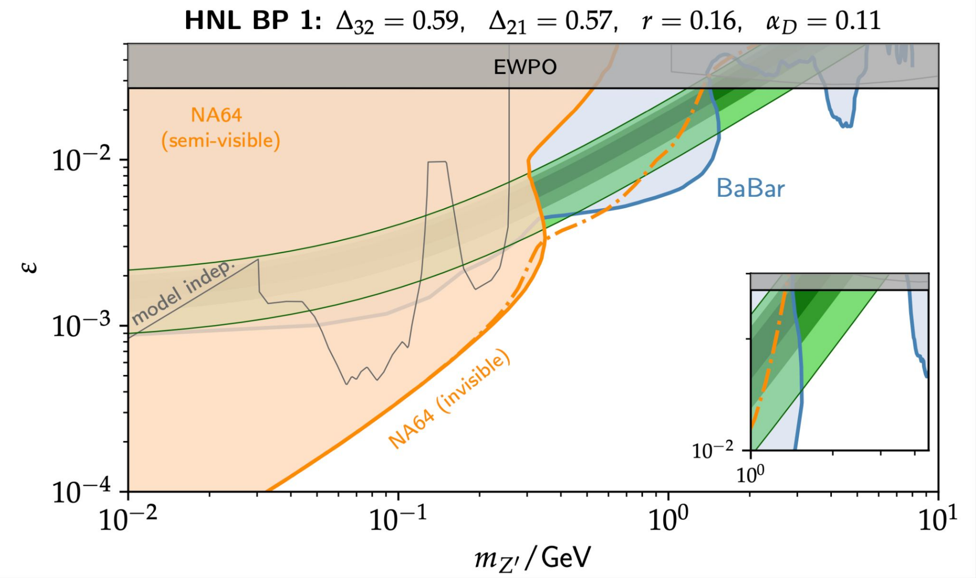
1) theory parameters consistent with a MB explanation

2) generic parameters for g-2 → designed to maximise visibility of decay signal

# Heavy Neutral Leptons

AA, M.Hostert, S.Pascoli, j.physletb.2021.136531

1) MiniBooNE benchmark model




Small opening between **1.2 - 2.8 GeV**

Main features:

- Double bump feature due to two unstable fermions, **BR(Z' → 32) ~ 96%**

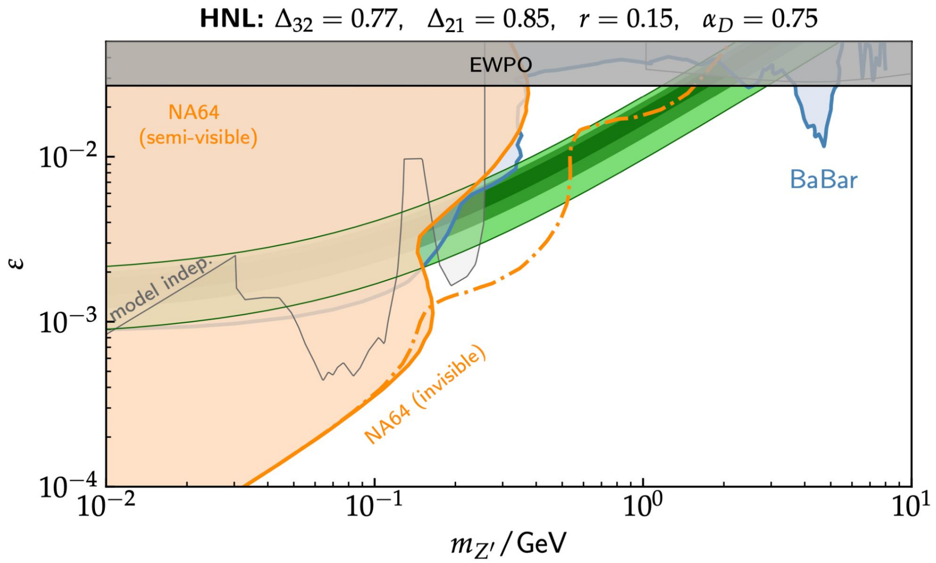
**Important!**

- Benchmark consistent with constraints on the **light neutrino masses** and the MiniBooNE excess → highly constrained parameter space

- Compatibility of g-2 and MiniBooNE requires further study

# Heavy Neutral Leptons

2) g-2 benchmark model




Significant relaxation between **150 MeV - 3 GeV**

Main features:

- Double bump feature due to two unstable fermions, **BR(Z' → 32) ~ 99%**
- A prompt decay search from NA64 may exclude part of this region

# Future searches

Testing the allowed parameter space of the models presented will be an important task for currently running and upcoming experiments

- NA64 prompt regime for semi-visible dark photon search
  - **Work-in-progress** - understanding NA64 sensitivity to multiple showers in the ECAL
- Monophoton searches at Belle II and BES III will provide stronger constraints on the invisible DP and, consequently, the semi-visible DP
- Displaced vertex search at Belle II

# Conclusions

- Minimal iDM scenario is **disfavoured at 2σ**. Lepton pairs from decay are too soft and do not pass BaBar's energy threshold

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  - Potential connection to DM

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**Thanks for listening!**