Heavy Neutral Leptons as a Portal to the Dark Sector

Rare Processes and Precision Frontier Townhall Meeting

RF4
Baryon and Lepton Number Violating Processes:

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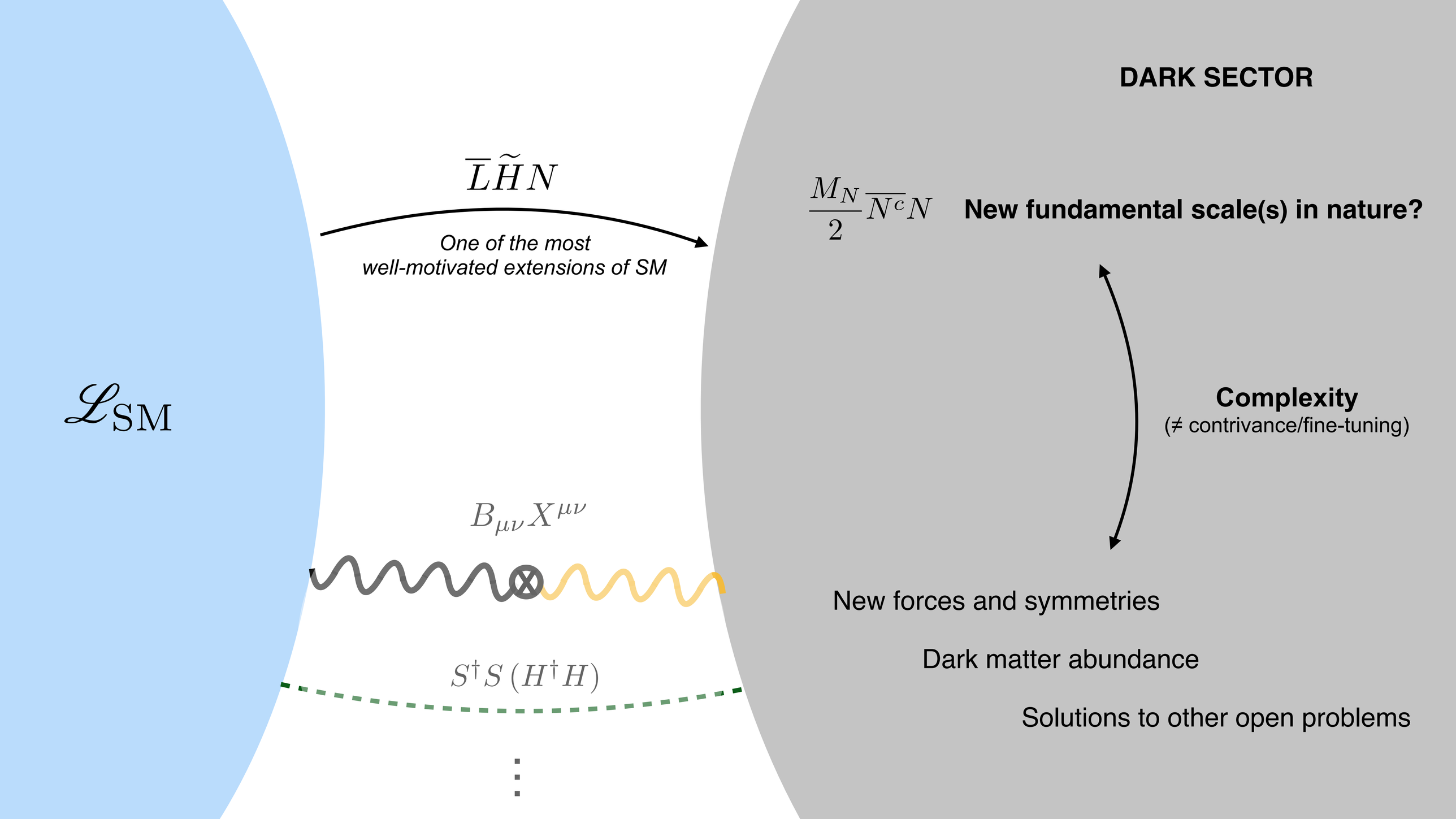

DARK SECTOR
$\mathscr{L}_{\rm SM}$
$\overline{L}\widetilde{H}N$
One of the most
well-motivated extensions of SM
$\frac{M_N}{2}\overline{N^c}N$
New fundamental scale(s) in nature?
Complexity
(≠ contrivance/fine-tuning)
$B_{\mu\nu}X^{\mu\nu}$
$S^\dagger S\,(H^\dagger H)$
New forces and symmetries
Dark matter abundance
Solutions to other open problems

See also RF06/NF02/NF03 talks

Neutrino masses

Type-I seesaw, low-scale variants, and more exotic.

Baryon asymmetry of the Universe

Leptogenesis, nu-assisted EW baryogenesis.

Dark matter

Warm DM or portal to dark sector.

Experimental anomalies

Short-baselines, Hubble, XENON1T, + others.

$\overline{L}\widetilde{H}N$

Extended EW sector

LH_XN

Higgs decays (H -> inv)

APV

Z decays

Light scalars

Majorons

SBL anomalies

nu decay

Solar $\overline{\nu}$

Dark matter

FIMPs

"Portalinos"

monochromatic nu fluxes

Gauge extensions

secluded symmetries

B - L

Li - Lj

SBL anomalies

Cosmology

Neff

Neutrino decay

secret interaction mechanism

Effective operators

Magnetic moments

NSI

H^2N^2 (H -> N N)

… and others.

A diverse and vibrant community spanning a wide range of energy scales and expertise.

Beyond Minimality

HNLs as a bridge to exotic sectors

Approach I

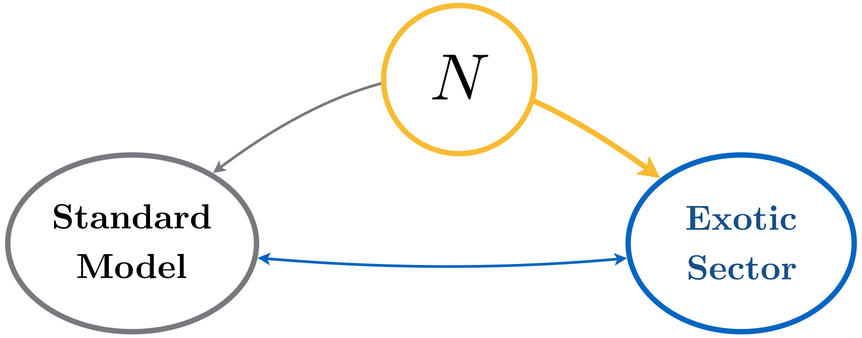
Multiple scales and new symmetries in the neutrino mass matrix.

nuMSM, inverse/linear/extended seesaws, …

Approach II

HNLs as part of/portal to some exotic sector

new gauge symmetries,
scalar sectors,
effective operators,
dark sectors, ….



Opportunities and signatures of non-minimal Heavy Neutral Leptons

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Cross listed frontiers NF1-6, 9, 10, TF8 &10, RF 4 & 6, EF9.

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[View LoI]

One example in the context of

neutrino masses + low energy anomalies

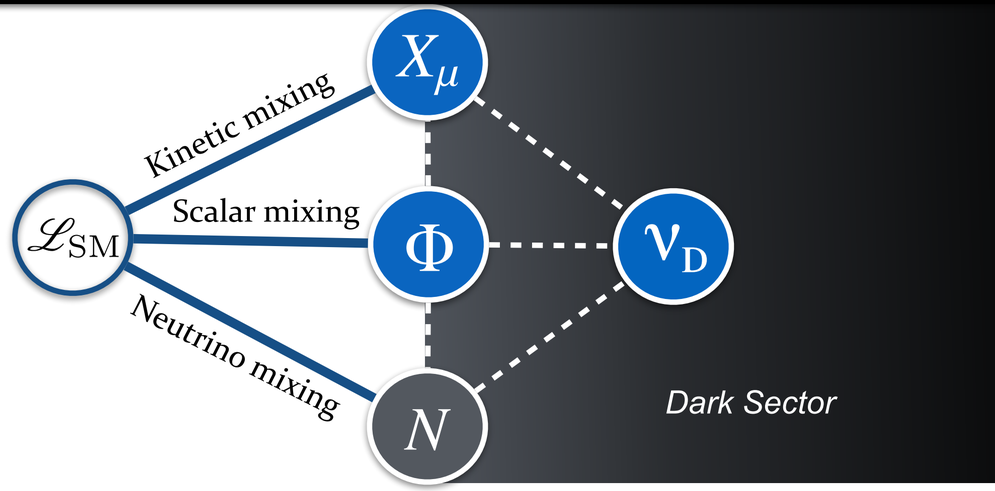
A dark seesaw solution to low energy anomalies

A. Abdullahi, MH, S. Pascoli
arXiv:2007.11813

1) A minimal renormalizable model:

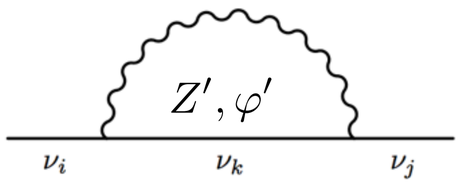
	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
N	$\mathbf{1}$	0	0
ν_{D_L}	$\mathbf{1}$	0	Q
ν_{D_R}	$\mathbf{1}$	0	Q
Φ	$\mathbf{1}$	0	Q

Dark neutrinos charged under a dark U(1)' symmetry, broken at the GeV scale by $\langle\Phi\rangle$.



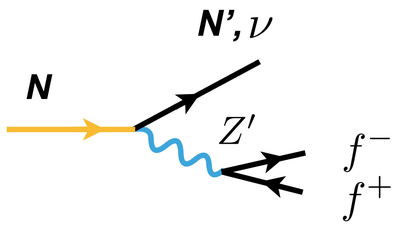
2) Neutrinos masses from LNV & dark sector scale:

$$\begin{pmatrix} 0 & M_D & 0 & 0 \\ M_D^T & M_N & \Lambda_L & \Lambda_R \\ 0 & \Lambda_L^T & 0 & M_X \\ 0 & \Lambda_R^T & M_X^T & 0 \end{pmatrix} \begin{pmatrix} \nu_\alpha^c \\ N^c \\ \nu_{D_L}^c \\ \nu_{D_R} \end{pmatrix}$$



Extended seesaw w/ radiative corrections from dark bosons.

3) Modified experimental landscape



$$\propto \alpha_D (e\varepsilon)^2 |U|^2$$

Novel production and decay channels important when vector and scalar portals are considered.

For a similar point with B-L gauge see also B. Batell et al, JHEP 1608 (2016) 052.

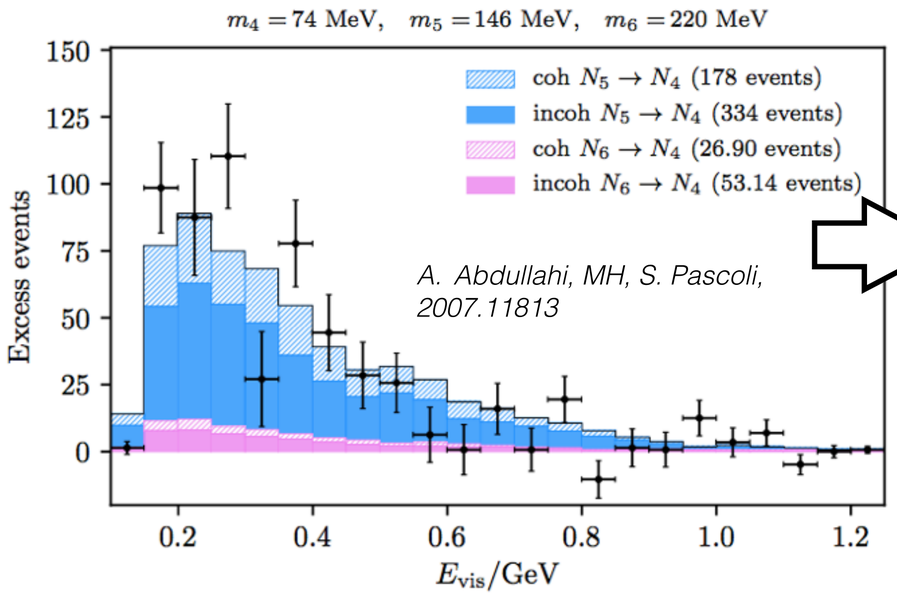
Connection to the MiniBooNE excess

HNLs produced in neutrino scattering

see also E. Bertuzzo et al, PRL121.241801, P. Ballett et al, PRD 99.071701, + others

Recent updates strenghten the MiniBooNE anomaly:
4.8 sigma excess of e-like events

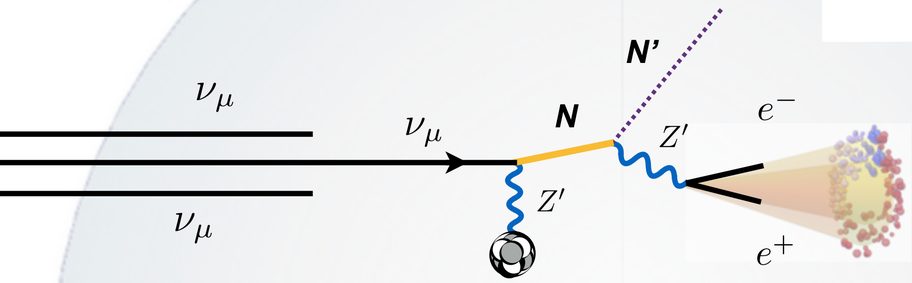
MiniBooNE (2020), arXiv:2006.16883



A. Abdullahi, MH, S. Pascoli, 2007.11813

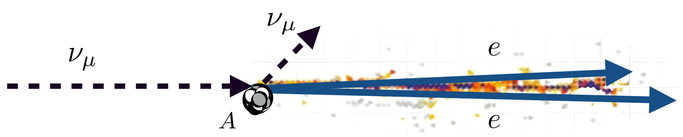
New ideas to explain it:

Neutrinos up-scatter into HNLs, which rapidly decay into e+e-.



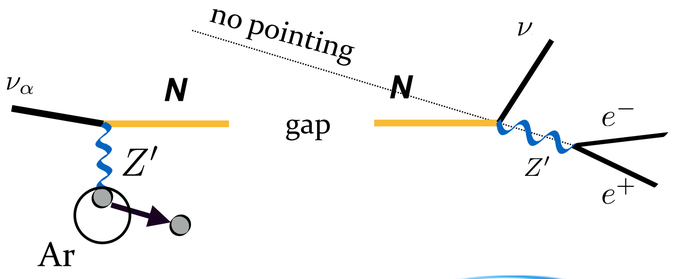
Direct Predictions

Pseudo single photons at ν detectors:



C. Arguelles, MH, Y. Tsai, PRL123.261801

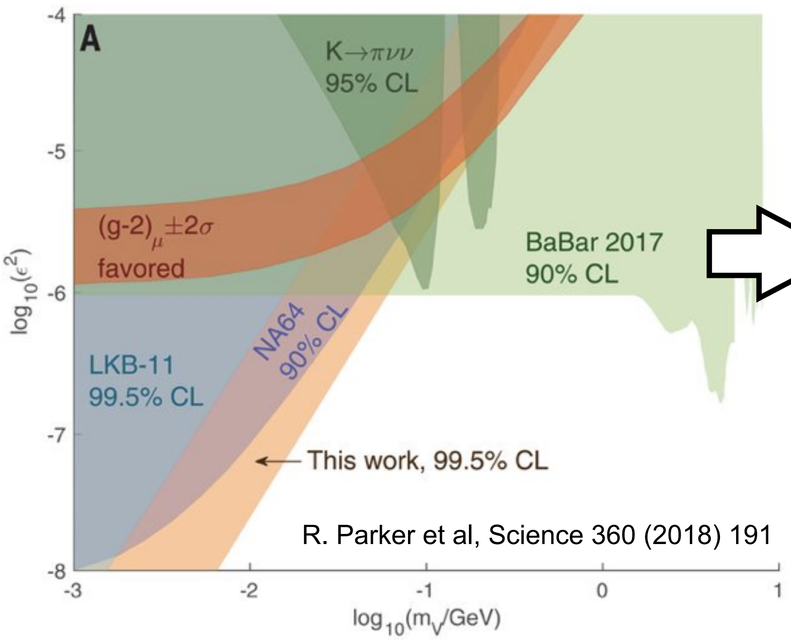
With better PID of LAr detectors, search for trident-like (e+e-) events.



µBooNE

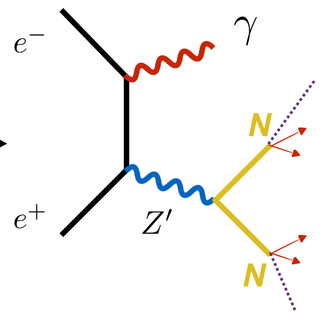
Revisiting the muon (g-2)

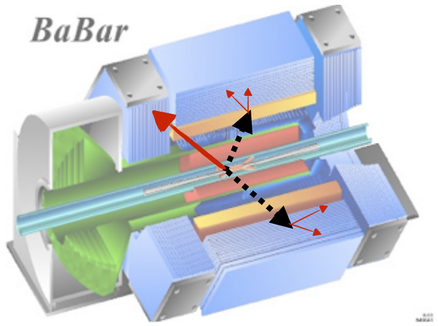
and re-interpreting the BaBar monophoton search

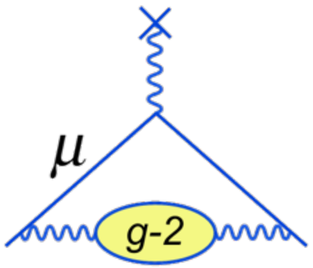


R. Parker et al, Science 360 (2018) 191

Semi-visible dark photon



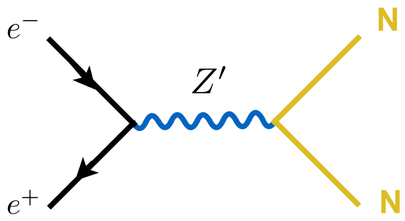




$m_{Z'} = 1.25$ GeV and $\varepsilon^2 = 4.6 \times 10^{-4}$

Explanation of the muon (g-2) anomaly via a dark photon now viable?

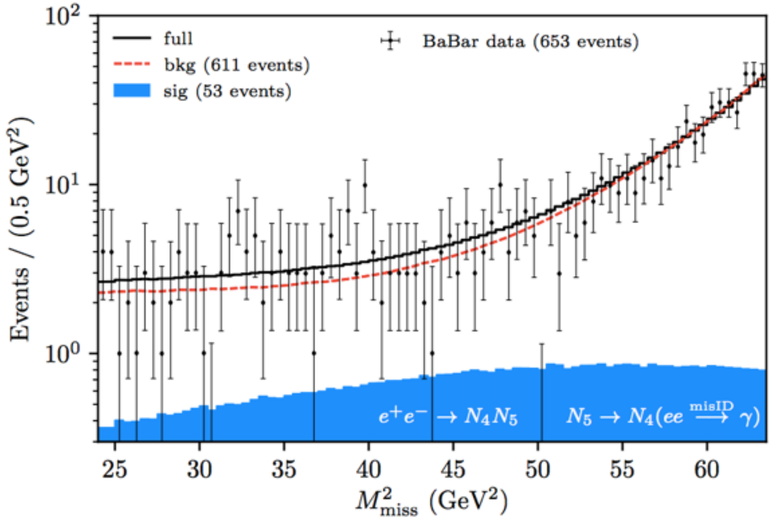
Invisible dark photon bounds relaxed.



*Predicts a huge rate of s-channel $e^+e^- \to NN$ production @ **BaBar** and **Belle-II** ($O(10^4)$ events).*

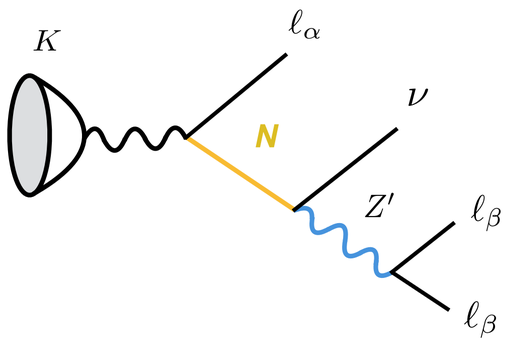
Can lead to "fake" monophoton events if N decays inside the ECAL

$\gtrsim 2\sigma$ **preference for ~50 signal events**



Other important searches for dark neutrino sectors

Rare leptonic kaon decays



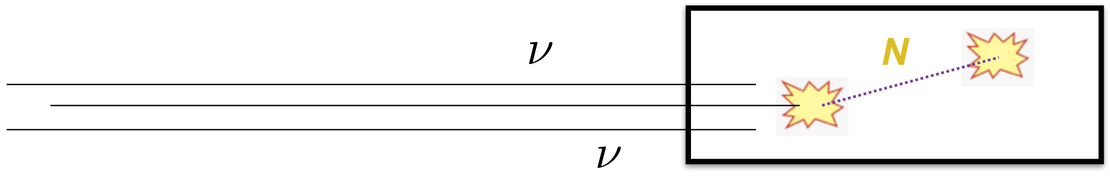
At **NA62**, would expect ~3000 events in existing data.

Peak search + displaced vertex

For light dark photons:
Inv. mass peaks in $m_{Z'}$ and m_N

$$|U_{\mu 4}|^2 \gtrsim \mathcal{O}(10^{-10})$$

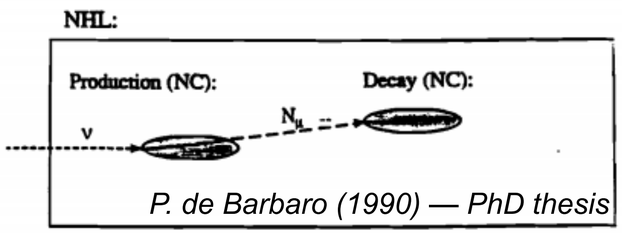
"Double bang" events*



Upscattering followed by a NC-like decay.

1000s of events/year at **IceCube** *"Double-Bangs", P. Coloma et al, PRL119.201804*

9 NC/NC observed on a background of
$3 \pm 0.2\,(\text{stat.}) \pm 0.4\,(\text{syst.})$



NC/NC excess observed at CCFR, but no excess of NC/CC events.
Not explained to this date to the best of our knowledge
P. de Barbaro, doi.org/10.1063/1.43269

Conclusions

- **Early days of experimental searches for HNLs in more exotic settings**
  - Dark neutrino sectors are one example
  - first works mainly focused on exp anomalies but plenty of unexplored parameter space.

- **New ideas to explain existing discrepancies in the data**
  - MiniBooNE
  - Muon (g-2)
  - Double NC vertices at CCFR

- **Interplay of several intensity frontier experiments**
  - Neutrino detectors — dileptons and double vertices
  - Kaon factories $K^+ \to \ell^+ \nu e^+ e^-$
  - e+e- colliders $e^+ e^- \to N N$

from G. Raffelt, 9712538

"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."