DARK NEUTRINO SECTORS
&
LOW ENERGY EXPERIMENTS

Brookhaven Neutrino Theory Virtual Seminars
BNTVS

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UNIVERSITY OF MINNESOTA

PERIMETER INSTITUTE

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PRD99, 091701(R)

Based on work with:

Silvia Pascoli & Peter Ballett
@ Durham University

1903.07590
***extended v2**
submitted to PRD

Outline

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- Heavy neutral leptons in seesaw extensions with dark U(1)’ symmetries

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- Heavy neutral leptons in seesaw extensions with dark U(1)' symmetries
- Overview of new signatures at neutrino, collider, and kaon experiments.

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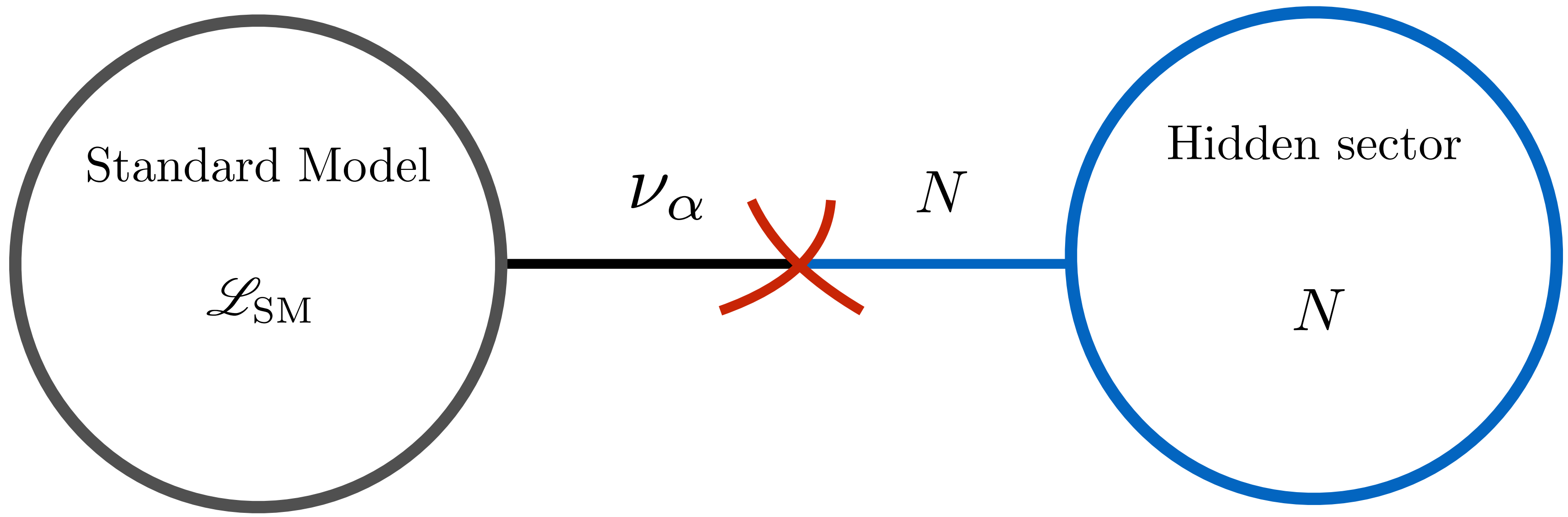
Outline

- Heavy neutral leptons in seesaw extensions with dark U(1)' symmetries
- Overview of new signatures at neutrino, collider, and kaon experiments.
- New ideas to search for dark neutrinos at NA62.

ordinary weak interactions, sterile, i.e. practically un-observable, since they have the "incorrect" helicity.

*B. Pontecorvo, Sov.Phys.JETP 26 (**1968**) 984-988.*

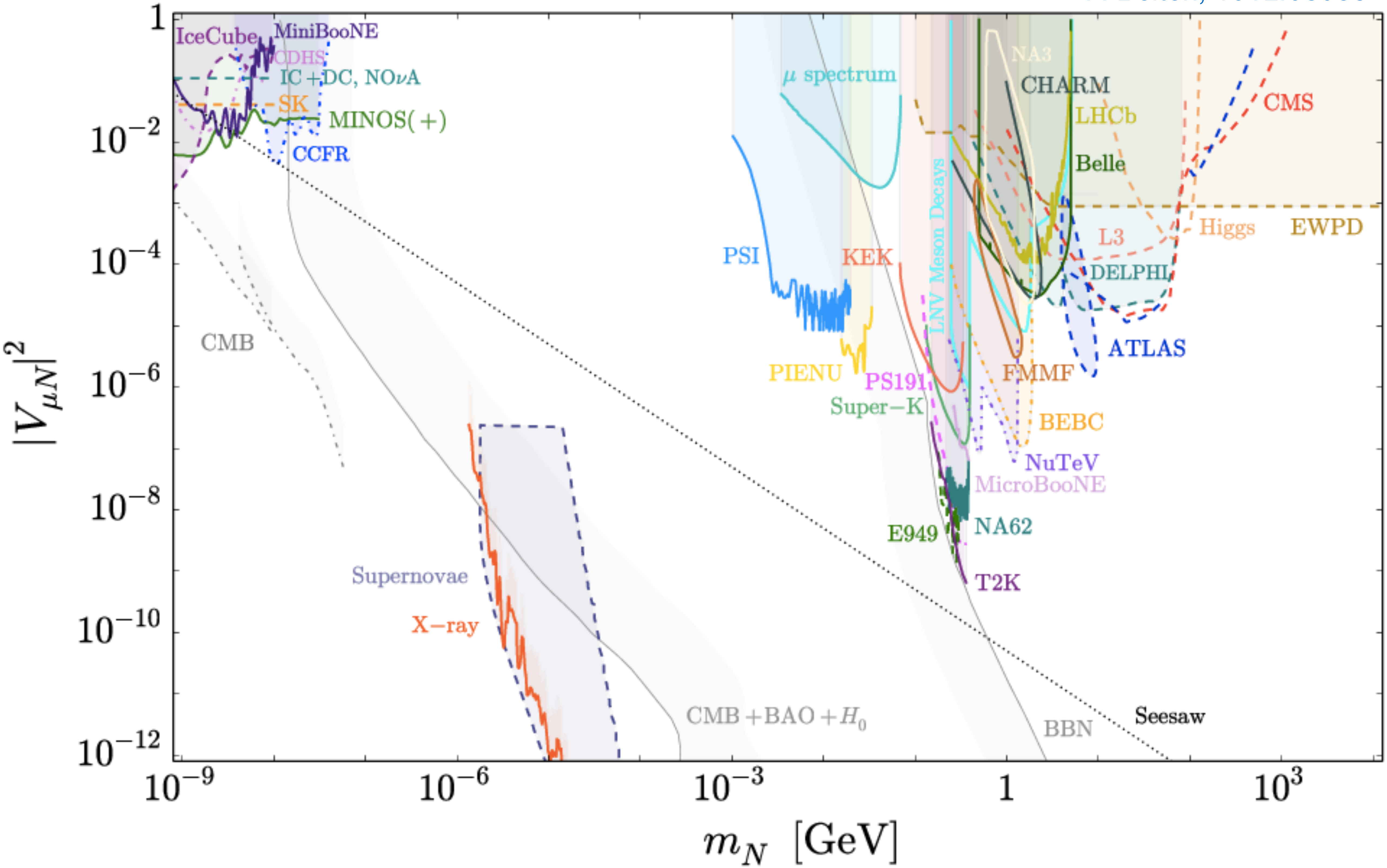


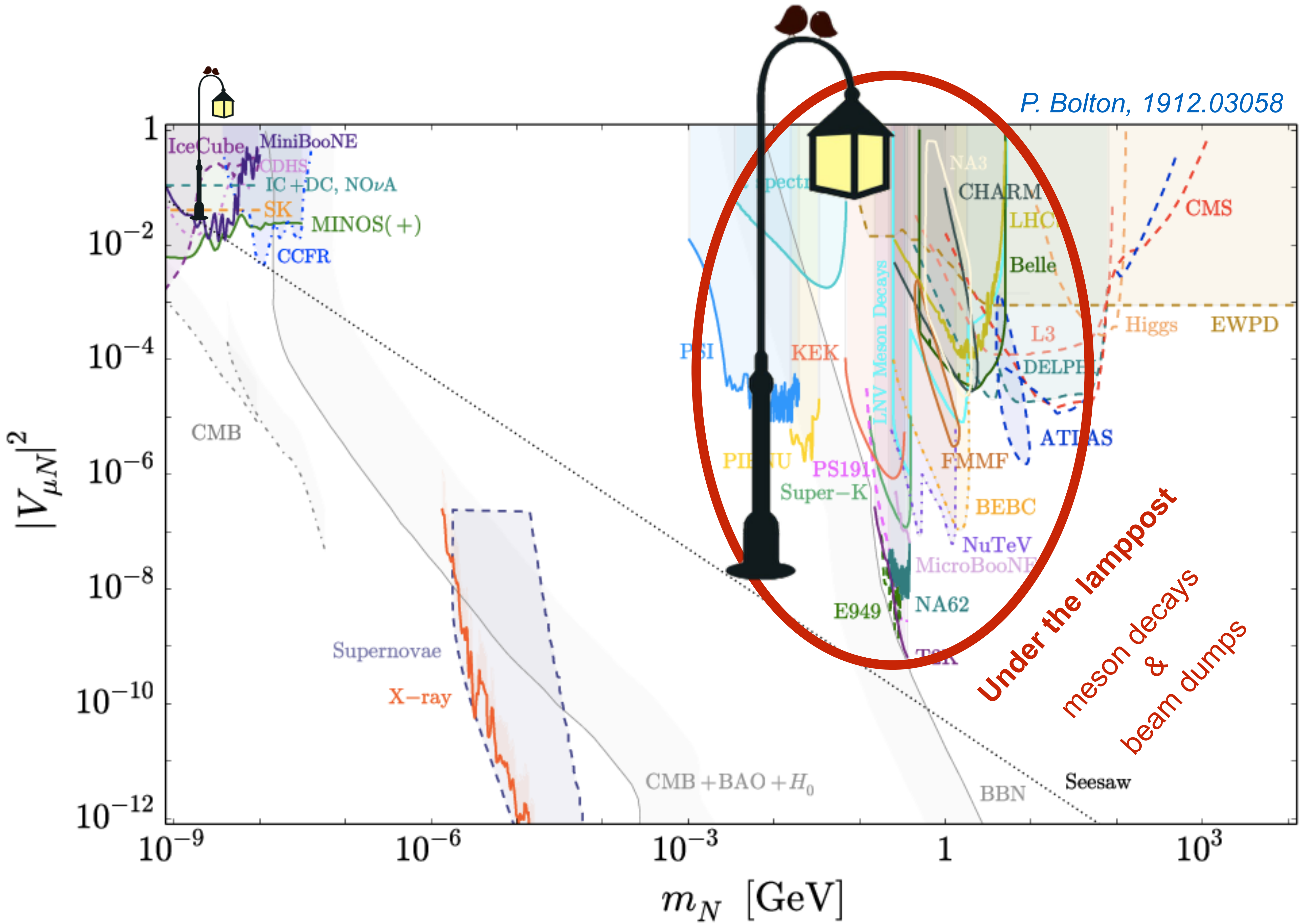
$$\mathscr{L} \supset -y^\nu \left(\overline{L}\tilde{H}\right) N - \frac{M_N}{2}\overline{N^c}N + \text{h.c.}$$

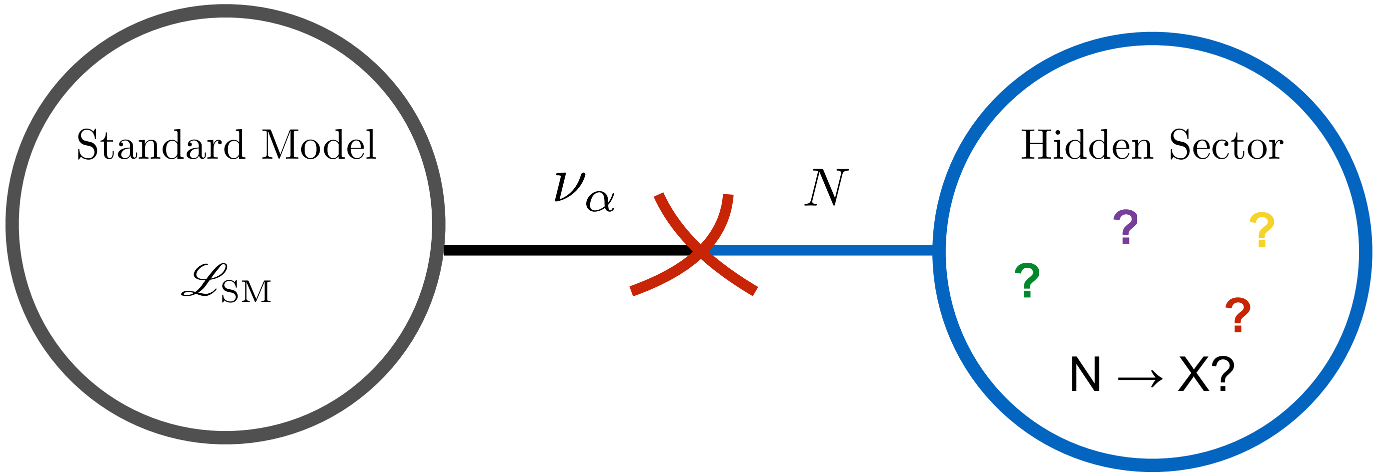
Well-motivated extension of the SM

- Type-I seesaw (and variants) for neutrino masses
- Generic renormalizable coupling to singlet fermions
- M_N need **not** be large. Nu masses may be small due to small Yukawas.

P. Bolton, 1912.03058

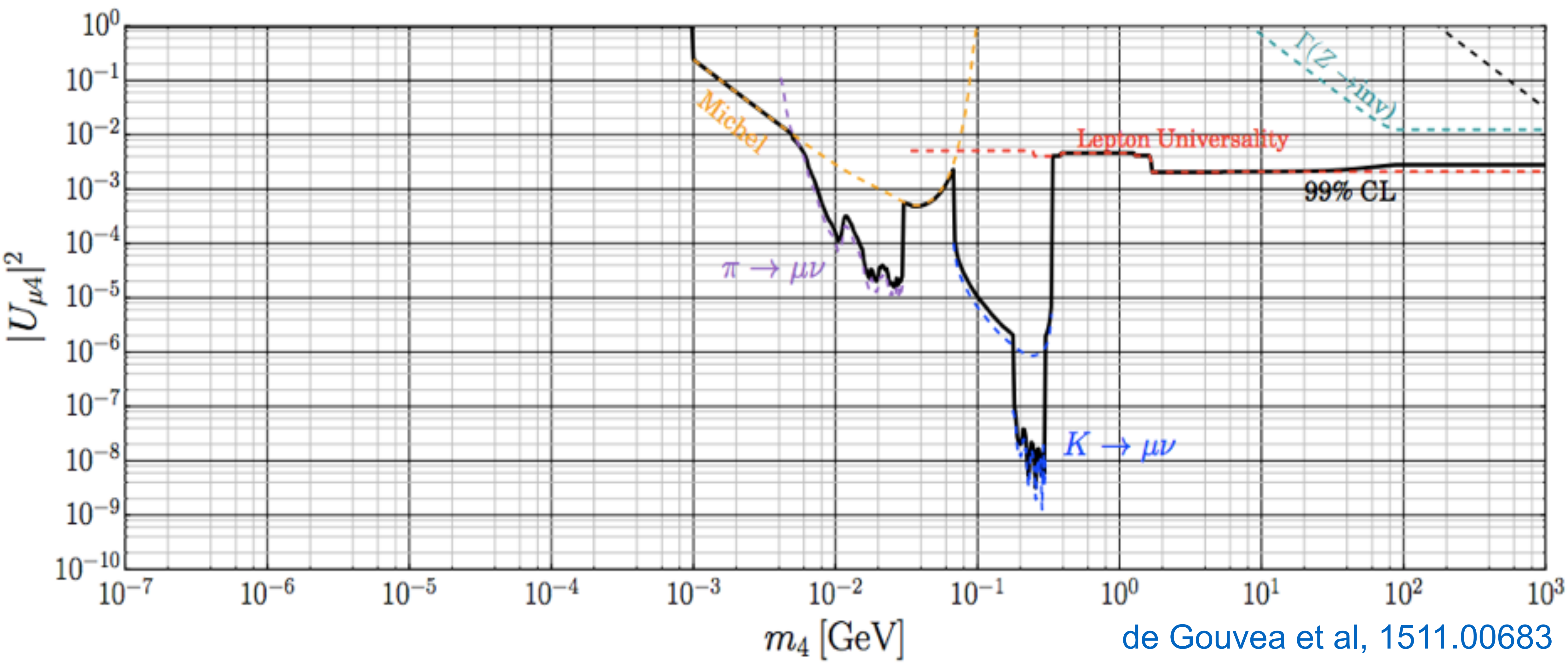



P. Bolton, 1912.03058
IceCube
MiniBooNE
CDHS
IC+DC, NOνA
SK
MINOS(+)
CCFR
PSI
KEK
LNV Meson Decays
NA3
CHARM
LHC
Belle
CMS
Higgs
EWPD
L3
DELPHI
ATLAS
PIENU
PS191
Super−K
FMMF
BEBC
NuTeV
MicroBooNE
E949
NA62
T2K
CMB
Supernovae
X−ray
CMB+BAO+H_0
BBN
Seesaw
Under the lamppost
meson decays
&
beam dumps
$|V_{\mu N}|^2$
m_N [GeV]



But how robust is this picture against enlarging the dark sector?

e.g., if open-minded about BRs and decays of N



de Gouvea et al, 1511.00683

New local U(1) gauge symmetry with Type-I-like HNL

Gauged (B - L)

W.Buchmüller, et al (1991), B. Batell et al, (2016), P. F. Perez (2017), many others.

Gauged (L_a-L_b)

J. Heeck and W. Rodejohann (2011), S. Baek et al (2015), J. Heeck and Y. Farzan (2016)
A. Biswas et al (2016), Takeshi Araki et al (2019), and others.

- -

this talk → Gauged (Q_X) — dark quantum number, not shared by SM

H. Okada and K. Yagyu (2014), J. Heeck and Y. Farzan (2016) , T. Nomura and H. Okada (2017, 2018),
C. Diaz *et al* (2017), M. D. Campos (2017), E.Bertuzzo *et al* (2017),
E. Bertuzzo *et al* (2018), C. Hagedorn et al, (2018), and others.

Dark fermion $\nu_{\rm D}$ no longer a complete singlet.

$(LH_{\rm D})\nu_{\rm D}$ in extended SM-charged scalar sectors (*e.g. 2HDM, richer scalar pheno*)

but can have much simpler model.

New dark U(1)’ symmetry spontaneously broken by SM-singlet scalar field

$$\begin{aligned}\mathscr{L} =&\mathscr{L}_{\rm SM} + \left(D_\mu\Phi\right)^\dagger (D^\mu\Phi) - V(\Phi, H)\\ &- \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \overline{N}i\partial\!\!\!/ N + \overline{\nu_D}iD\!\!\!\!/\,\nu_D\\ &- \left[y_\nu^\alpha(\overline{L_\alpha}\cdot\widetilde{H})N^c + \frac{\mu'}{2}\overline{N}N^c + y_N\overline{N}\nu_D^c\Phi + \text{h.c.}\right],\end{aligned}$$

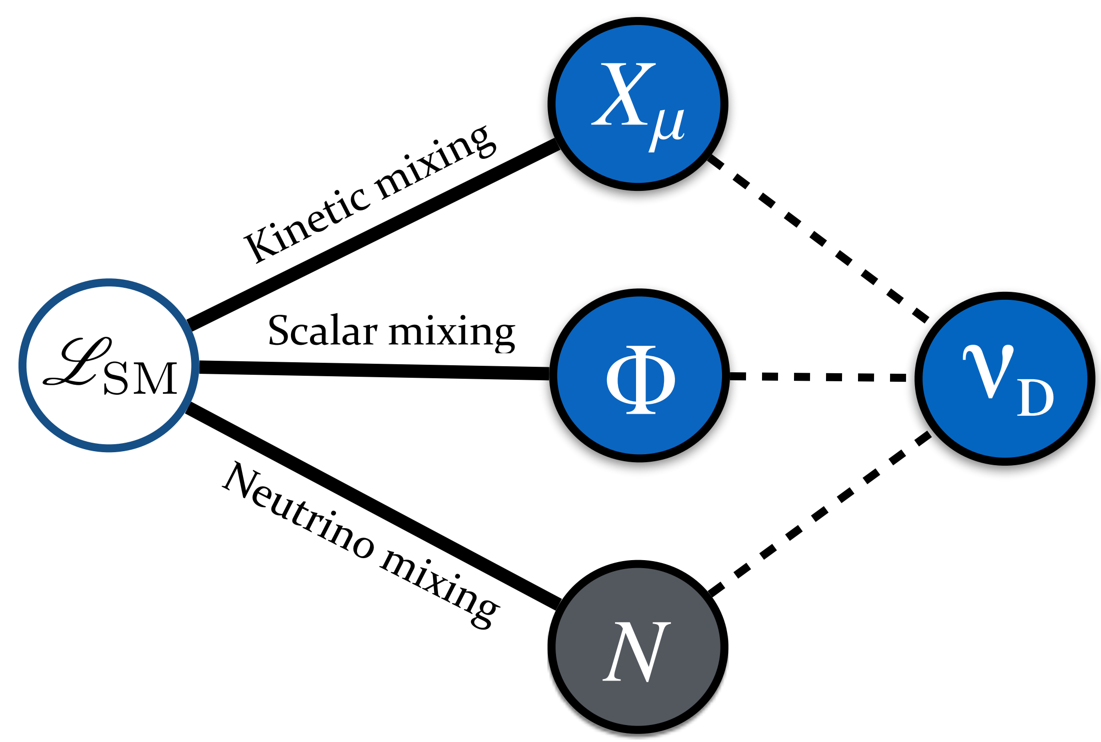
	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)'$
N	$\mathbf{1}$	0	0
ν_D	$\mathbf{1}$	0	Q
Φ	$\mathbf{1}$	0	Q

Two-step mixing with SM-like neutrinos.

kinetic mixing $\quad B_{\mu\nu}X^{\mu\nu}$

scalar mixing $\quad |\Phi|^2|H|^2$

neutrino mixing $\quad \left(\overline{L}\tilde{H}\right)N$



New dark U(1)’ symmetry spontaneously broken by SM-singlet scalar field

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	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)'$
N	$\mathbf{1}$	0	0
ν_D	$\mathbf{1}$	0	Q
Φ	$\mathbf{1}$	0	Q

<u>Anomaly freedom and extensions w/ fermionic DM candidates:</u>

- Option 1) Vector-like $\nu_{\rm D}$ and DM, where $\chi_{\rm L,R} \sim (\mathbf{1}, 0, Q/2)$ stable ✔

$$y_R\,\overline{\chi_R^c}\chi_R\Phi^* + y_L\,\overline{\chi_L^c}\chi_L\Phi^* + m_\chi\overline{\chi_L}\chi_R$$

- Option 2) Cancellation between $\nu_{\rm D}$ and dark matter $\chi_{\rm L} \sim (\mathbf{1}, 0, 0)$, $\chi_{\rm R} \sim (\mathbf{1}, 0, Q)$
  with residual dark parity (e.g., from lepton number).

stable ✔

$$\mu_L\,\overline{\chi_L^c}\chi_L + y\,\overline{\chi_L}\chi_R\Phi^*$$

see also:
J. Gherlein & M. Pierre
JHEP02 (2020) 068

Inverse, Extended and Linear seesaws — Pair of HNL with opposite L

$$-\mathscr{L}_{\nu-\text{mass}} \supset \frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{N} & \overline{\nu_{\text{D}}}\end{pmatrix}\begin{pmatrix}0 & m & \epsilon' \\ m & \mu' & \Lambda \\ \epsilon' & \Lambda & \mu\end{pmatrix}\begin{pmatrix}\nu_L^c \\ N^c \\ \nu_{\text{D}}^c\end{pmatrix} + \text{h.c.}$$

$$m_1 = \frac{\mu m^2 - 2\varepsilon' m\Lambda + \varepsilon'^2\mu'}{\Lambda^2 - \mu\mu'}.$$

Light neutrino masses proportional to **LNV** parameters.

Minimal Radiative Inverse Seesaw (MRISS)

P.S.B. Dev et al., 1209.4051
J. Lopez-Pavon et al, 1209.5342

When $\mu = \varepsilon = 0$

$$-\mathscr{L}_{\nu-\text{mass}} \supset \frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{N} & \overline{\nu_{\mathrm{D}}}\end{pmatrix}\begin{pmatrix}0 & m & 0\\ m & \mu' & \Lambda \\ 0 & \Lambda & 0\end{pmatrix}\begin{pmatrix}\nu_L^c \\ N^c \\ \nu_{\mathrm{D}}^c\end{pmatrix} + \text{h.c.}$$

Easy to see when integrating out N: $\mu' \to \infty$

$$\frac{1}{2\mu'}\begin{pmatrix}\overline{\nu_\alpha} & \overline{\nu_{\mathrm{D}}}\end{pmatrix}\begin{pmatrix}m^2 & m\,\Lambda \\ m\,\Lambda & \Lambda^2\end{pmatrix}\begin{pmatrix}\nu_\alpha^c \\ \nu_{\mathrm{D}}^c\end{pmatrix}$$

rank-1

Massless SM-like neutrinos at tree-level

(holds provided #N = #S)

sterile-like

$$m_{\text{dark}} = \frac{m^2 + \Lambda^2}{2\mu'}$$

dark-like

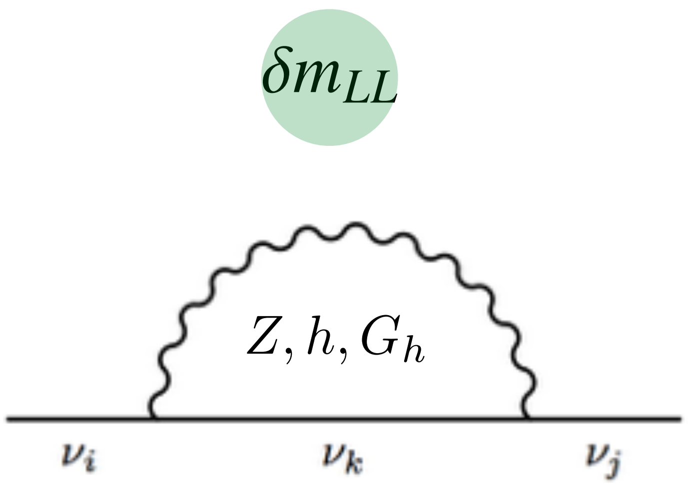
$$m_\nu = 0$$

SM-like

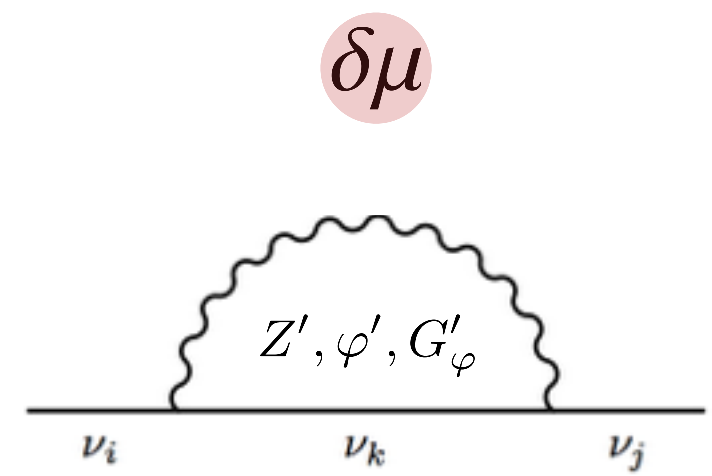
n.b.

ESS-like scenario relevant for:

- light steriles w/ secret interactions,
- neutrino self-interactions



$$\begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_\alpha^c \\ N^c \\ \nu_D^c \end{pmatrix}$$

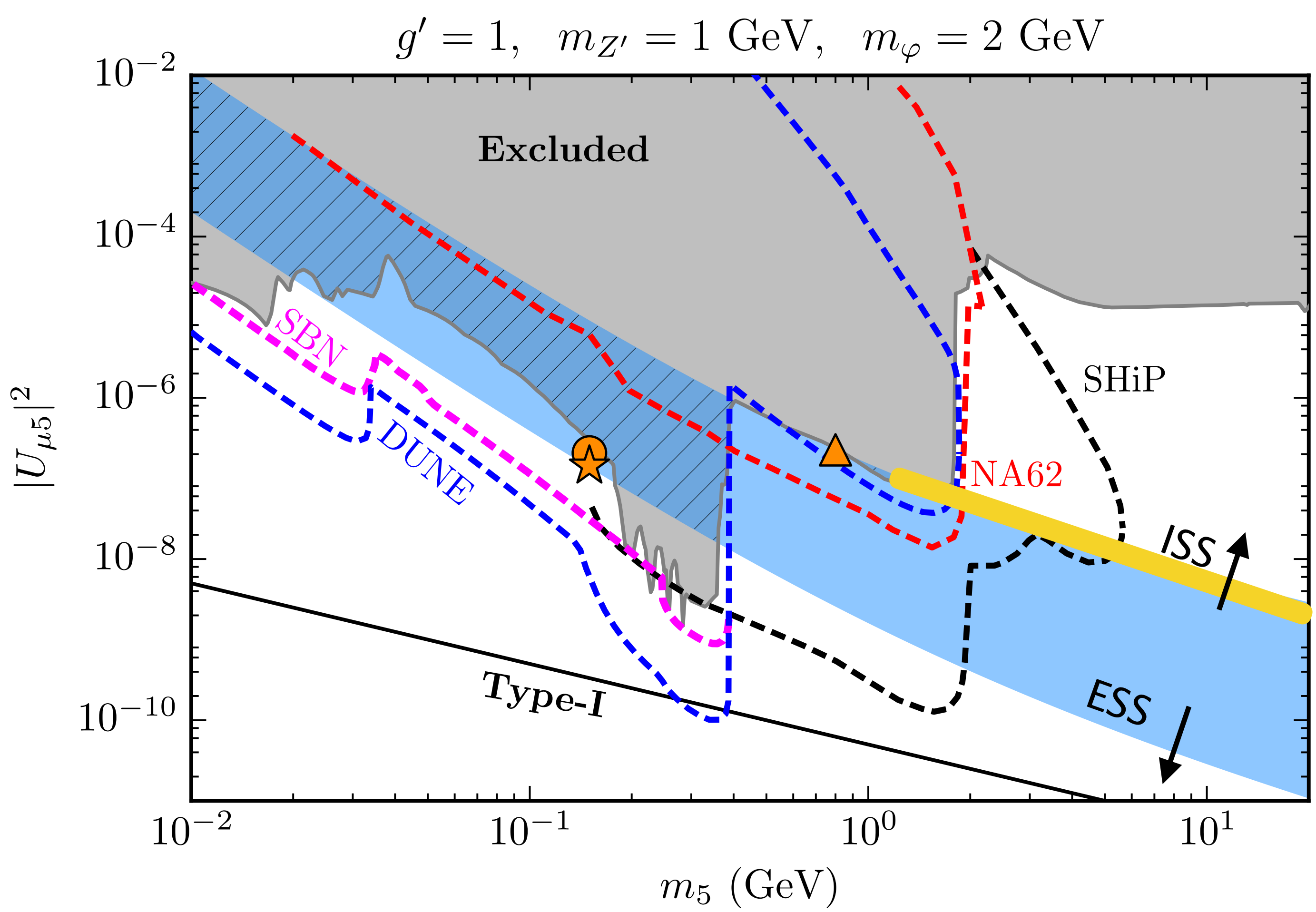


After U(1)' and EW group are broken,
no longer protected.

With light new particles, NP loops dominate: neutrino masses are small because m_D is small.

ISS-like: $\mu' \ll \Lambda$	ESS-like: $\mu' \gg \Lambda$
$m_\nu \sim \frac{g'^2}{8\pi^2}\frac{m_D^2}{m_{Z'}^2}\mu'\left(3\ln\frac{m_{Z'}^2}{\Lambda^2} + \ln\frac{m_{\varphi'}^2}{\Lambda^2} - 4\right)$	$m_\nu \sim \frac{g'^2}{8\pi^2}\frac{m_D^2}{\mu'}\left(3\ln\frac{m_{Z'}^2}{\Lambda^2} + \ln\frac{m_{\varphi'}^2}{\Lambda^2} - 4\right)$
where $m_{Z'}, m_{\varphi'} \ll \Lambda$	where $m_{Z'}, m_{\varphi'} \gg \mu'$

Ignoring kinetic and scalar mixing



Provided neutrino mixing is small:

ISS-limit: both steriles behave "standard"HNL

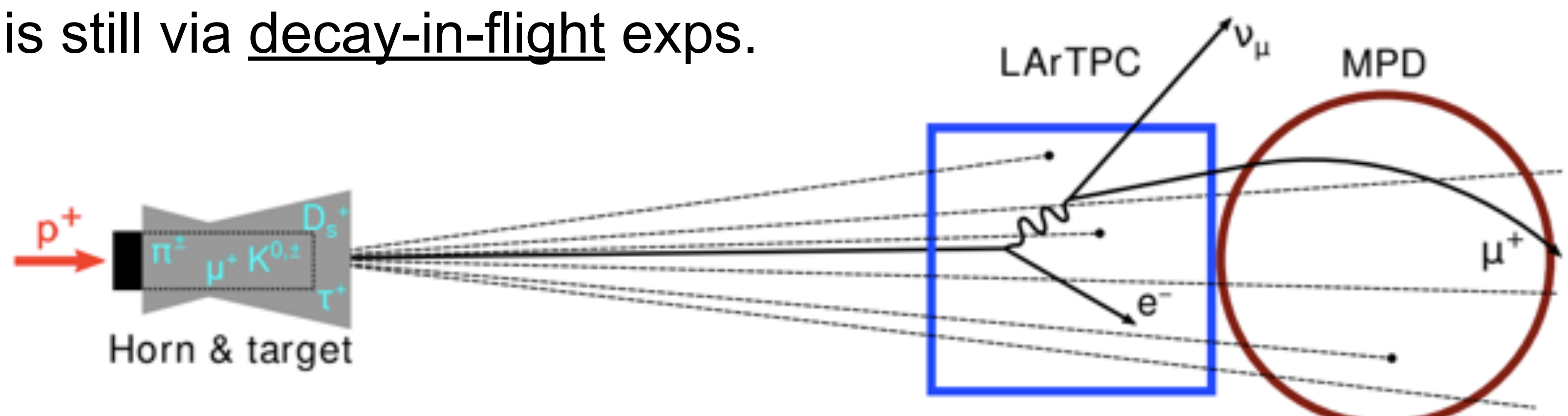
$$\Gamma(\nu_5 \to \nu_4 + \dots) \propto (\mu')^{3(5)}$$

ESS-limit: Heavy steriles cascade to nu4, which in turn behaves as "standard" HNL.

$$\nu_5 \to \nu_4 Z' \to \nu_4 \nu_4 \nu_4$$

$m'_Z, m'_\phi < m_4$: HNL decay invisibly.

Best way to search for such HNL is still via decay-in-flight exps.



P. Ballett et al, 1905.00284
J. M. Berryman et al, 1912.07622

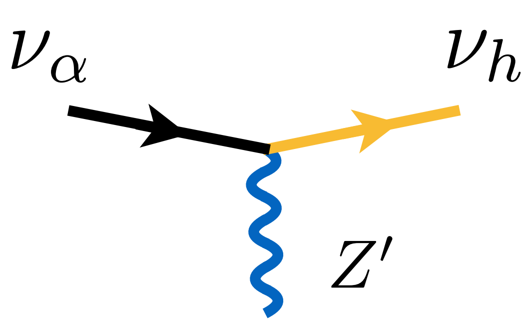
UV completion for “neutrino-philic” interactions & explains the zero in the MRISS mass matrix…

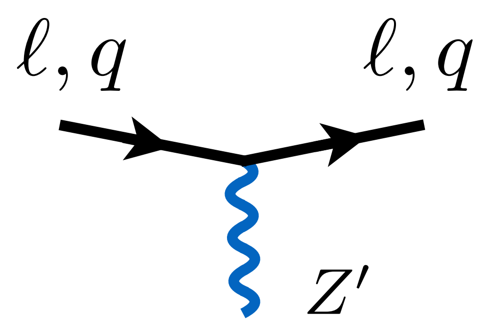
…but phenomenology is somewhat “boring”.

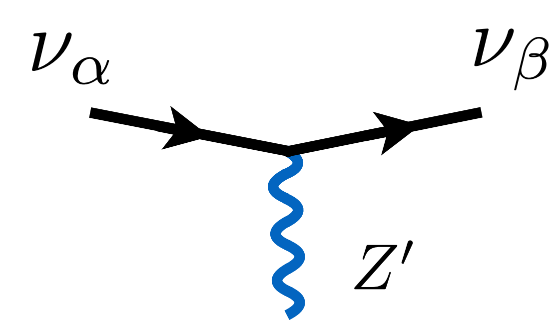
This changes when we turn on additional portal couplings.

Focus on dark photon + HNL case, and neglect the dark scalar for now.

New “*stronger-than-weak*” neutrino-charged matter interactions!







$U^*_{\alpha h} g'$	$e\,\chi\,q_f$	$U^*_{\alpha h} U_{\beta h}\, g'$
<u>SM + heavy neutrino</u>	<u>Quarks and charged leptons</u>	<u>SM neutrinos only</u>
Mixing x O(1) coupling	Kinetic mixing	Doubly suppressed

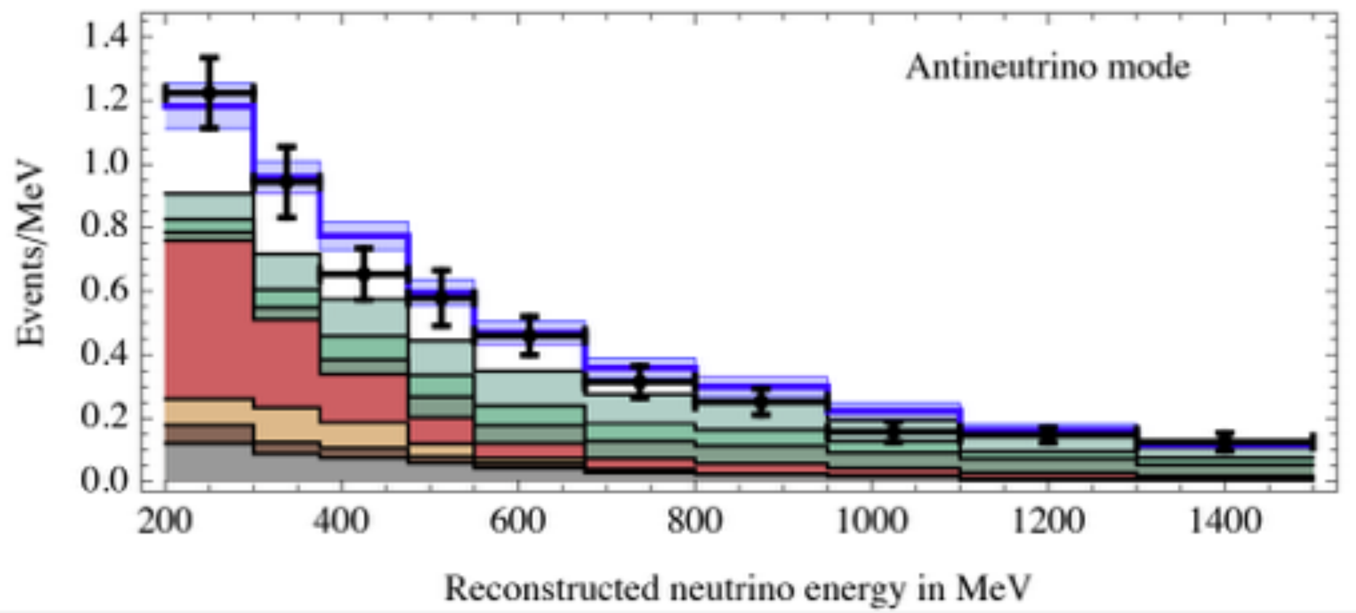
Explaining MiniBooNE

MiniBooNE Coll., PRL.121.221801

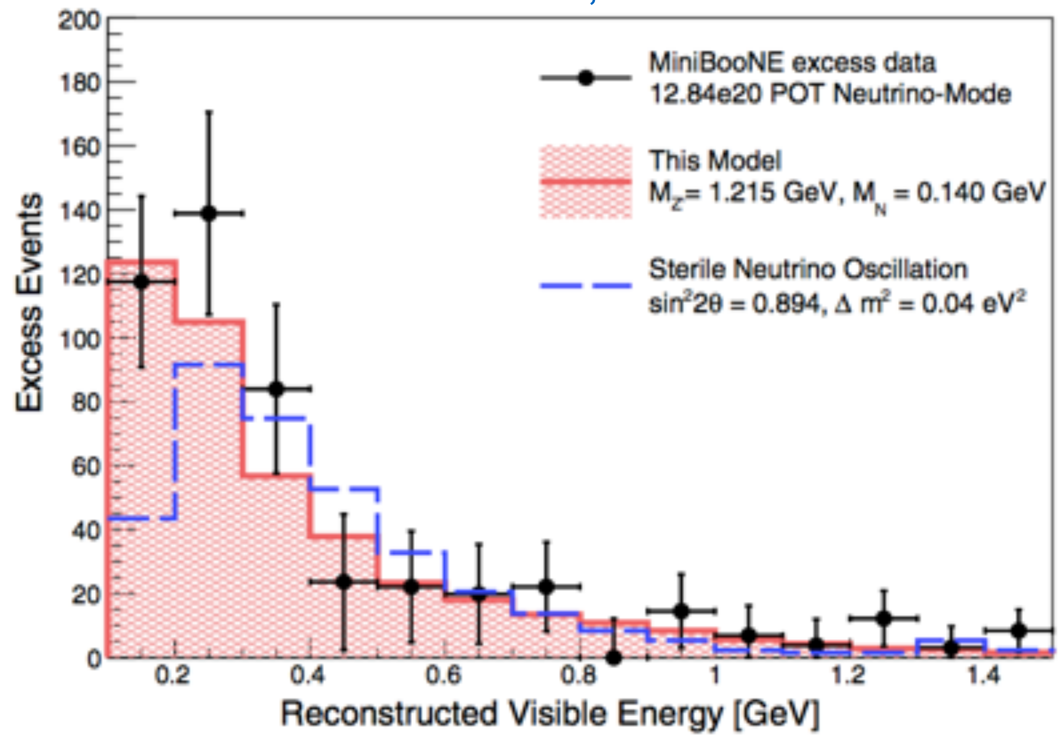
4.7σ excess observed in nu + nubar mode

— data/MC disagreement beyond statistical doubt —

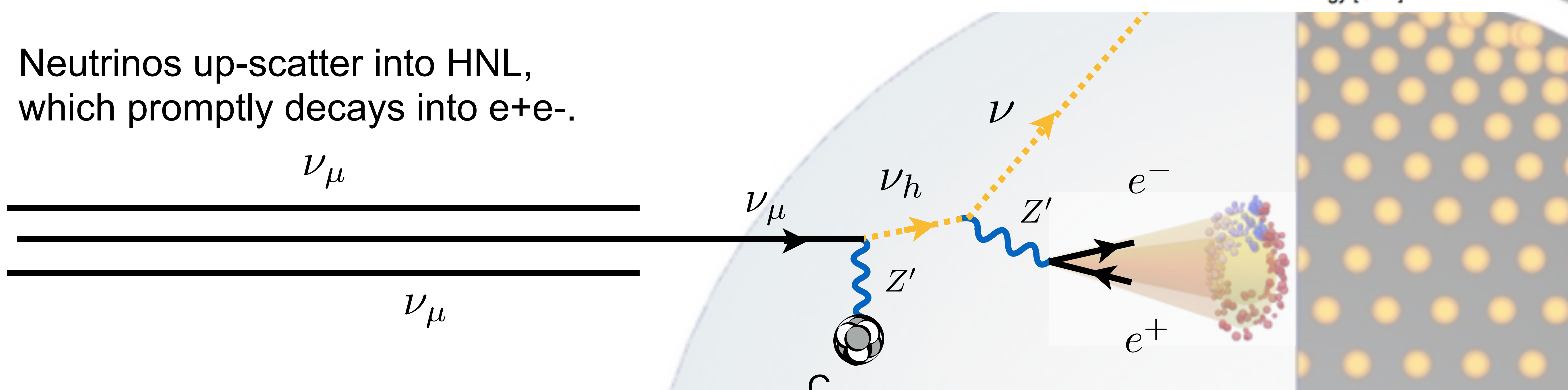
E. Bertuzzo et al., 1807.09877



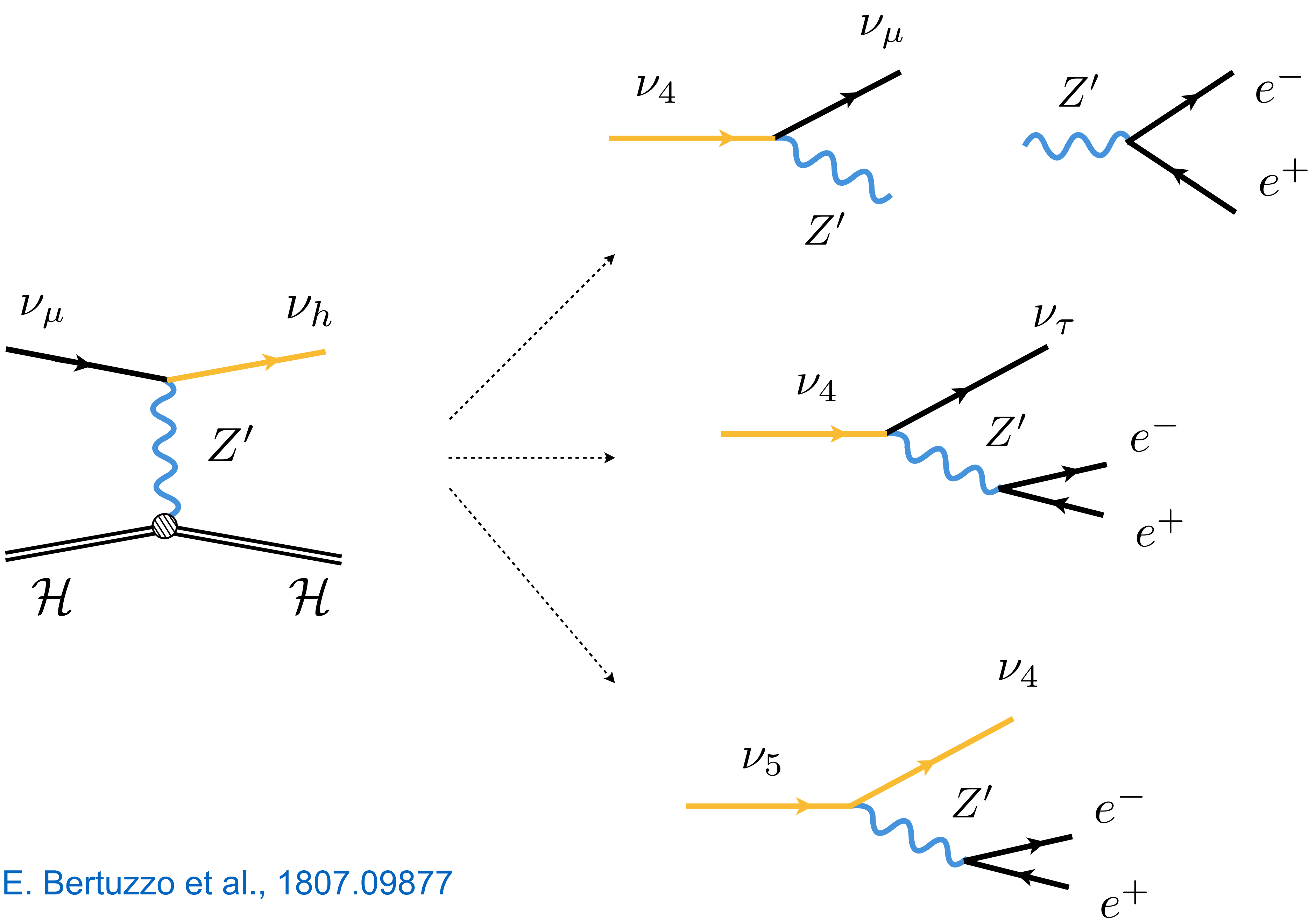
P. Ballett et al., 1808.02915



Neutrinos up-scatter into HNL, which promptly decays into e+e-.



Several scenarios discussed so far



Coherent scattering,
fast decays,
forward signal

Less forward,
but too large scattering
cross section for nutaus.

nu5 much shorter-lived,
(m5-m4) max inv masses,
nu4 fine tuned to be long lived
to avoid PS-191 bounds.

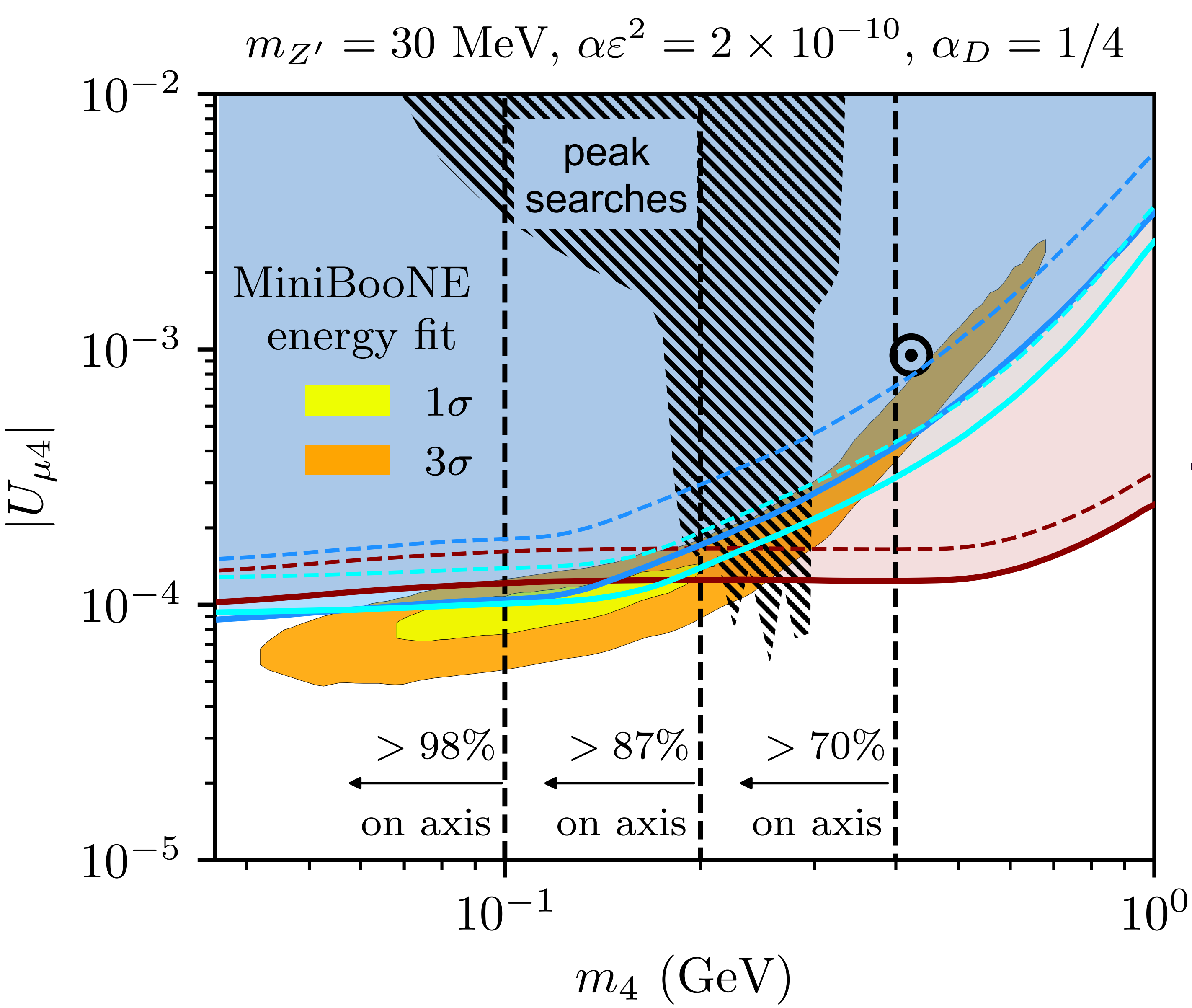
E. Bertuzzo et al., 1807.09877

P. Ballett et al., 1808.02915

P. Ballett, **MH**, S. Pascoli, 1903.07589

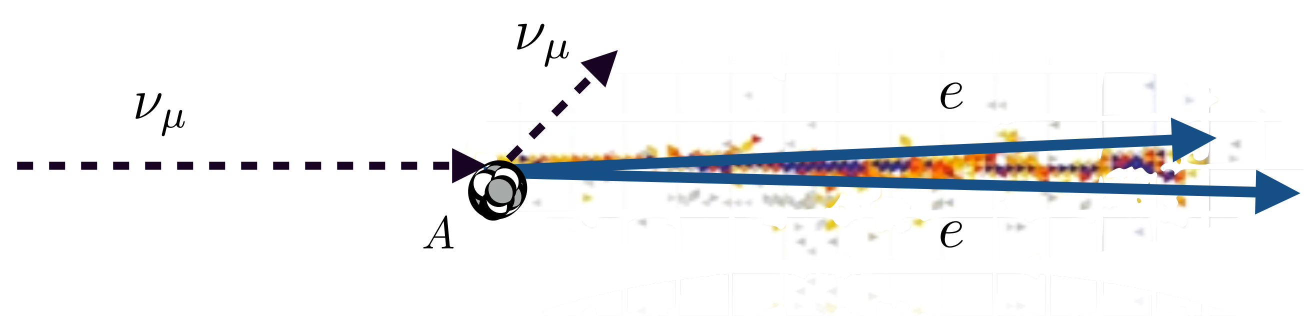
Light Dark Photon case

C. Argüelles, **MH**, Y. Tsai, PRL123, 261801 (2019)



on axis = events in forward bin at MiniBooNE

New bounds from single-photon sample in nu-e scattering analyses.

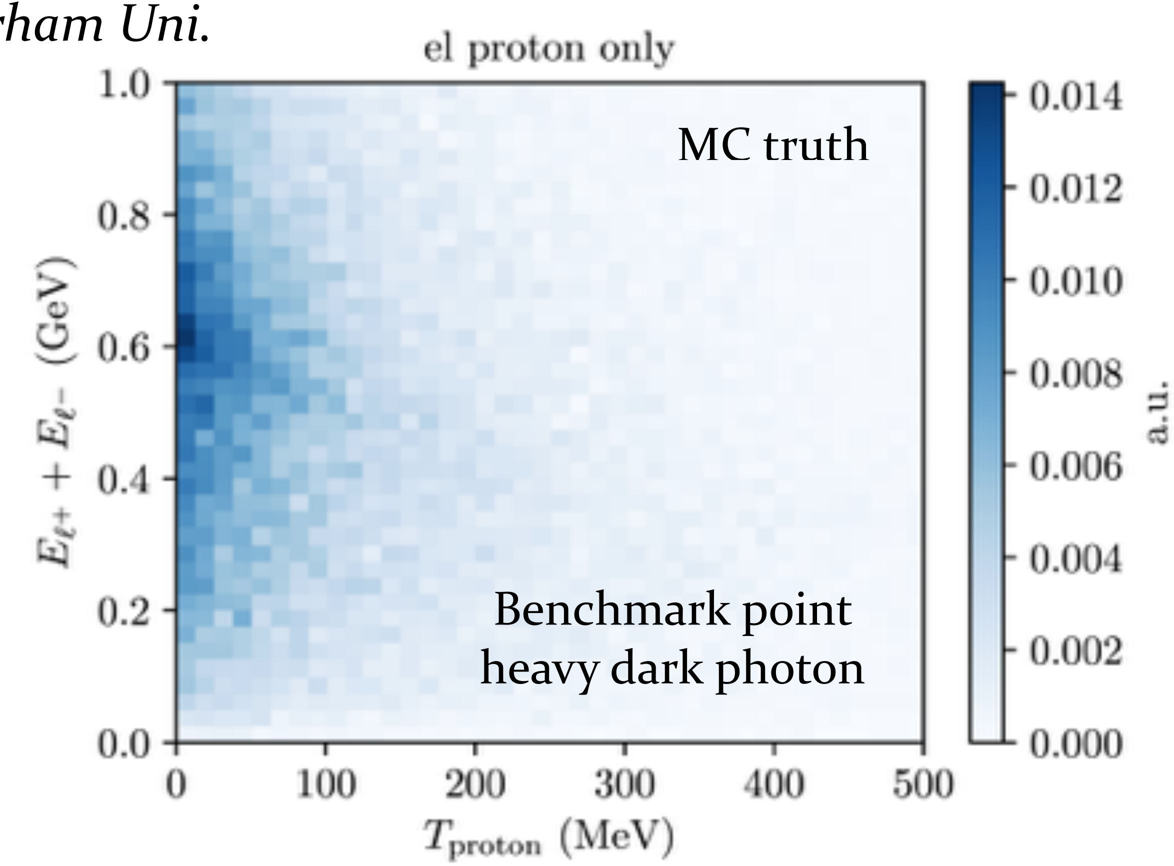


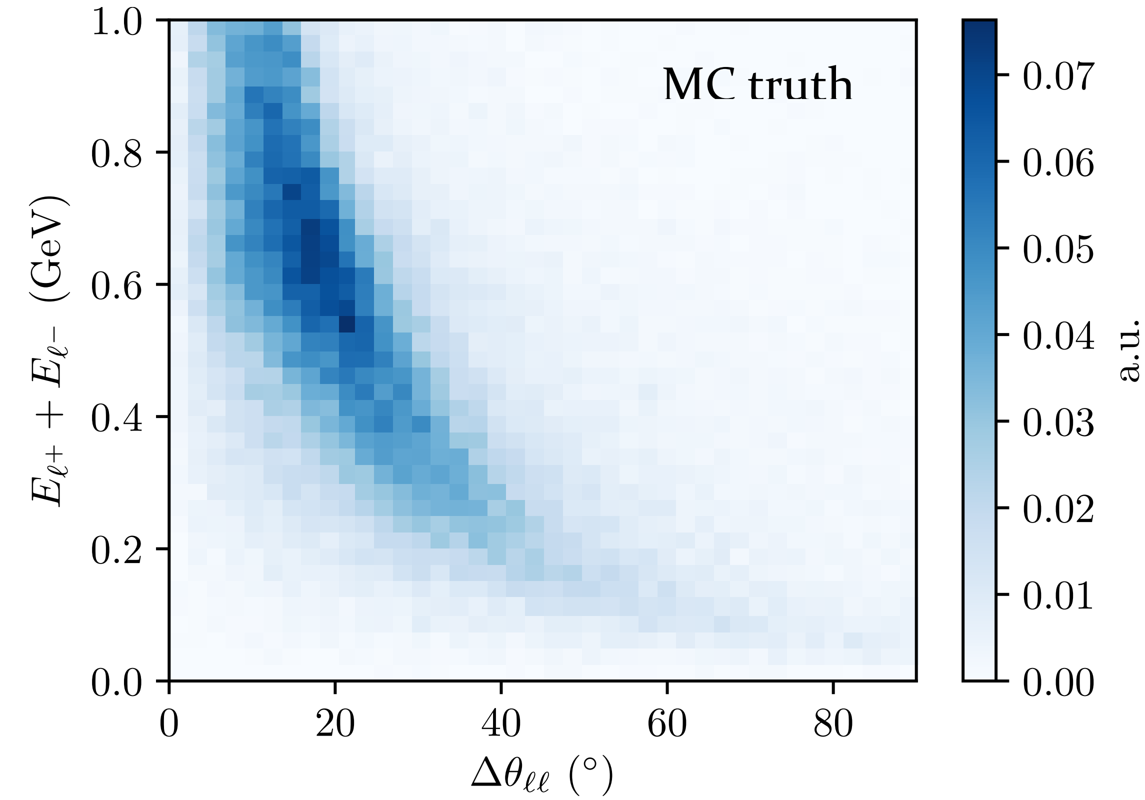
Conclusion:
HNL mass cannot be too large,
MiniBooNE signal typically very forward.

Asli Abdullahi
Durham Uni.

Currently studying all such cases in
LAr together with microBooNE single-photon group
@ Nevis Labs, Columbia University.

µBooNE





4 topologies currently under consideration:

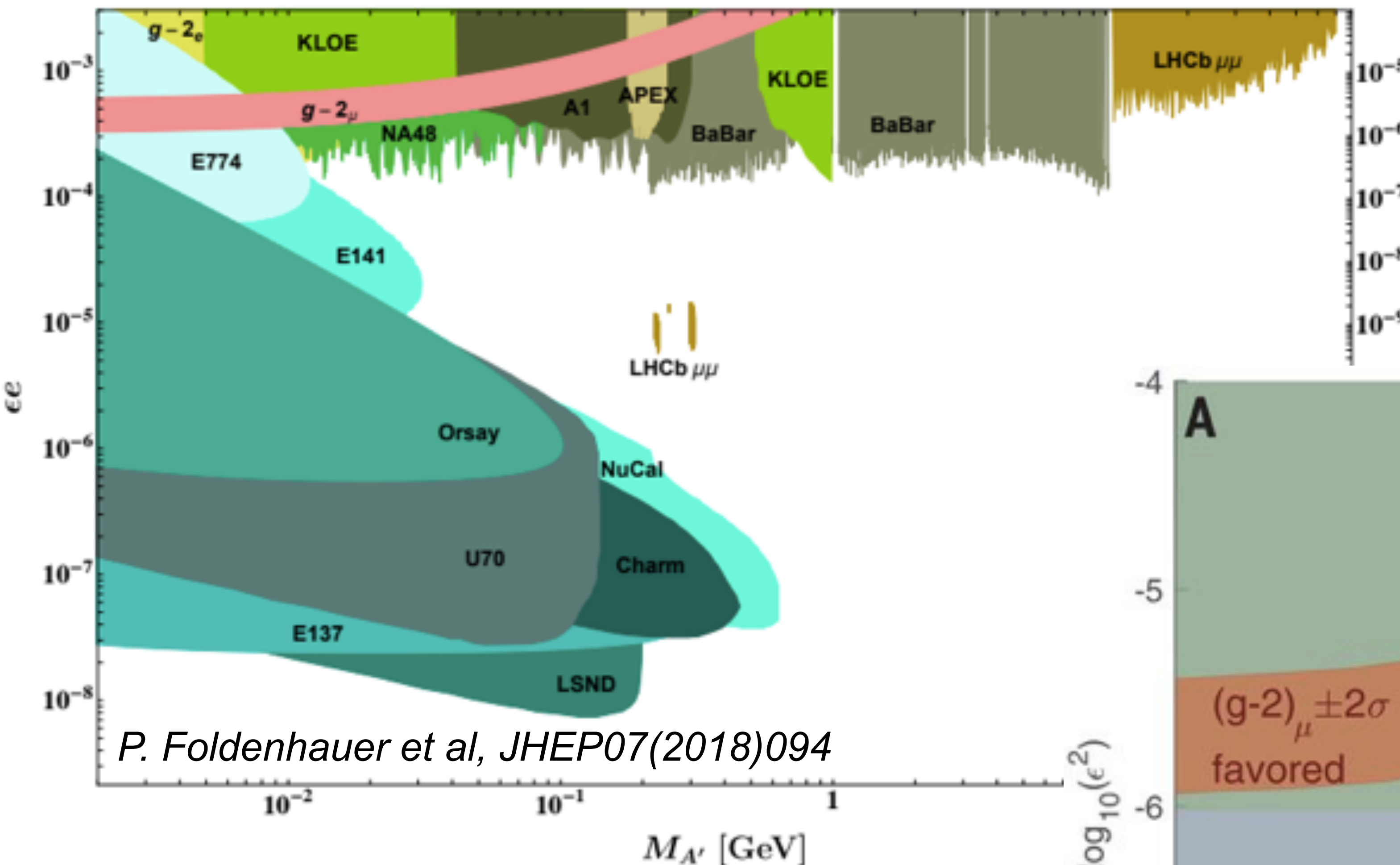
$0p^+ 1\gamma$ $0p^+ 2e$
$1p^+ 1\gamma$ $1p^+ 2e$

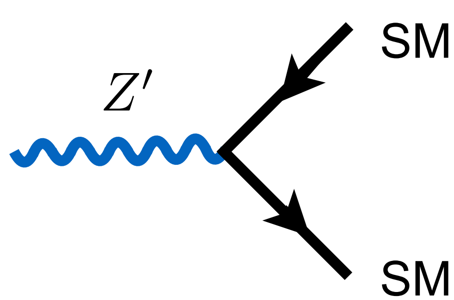
Pioneering study of genuine dielectron pairs in LAr.

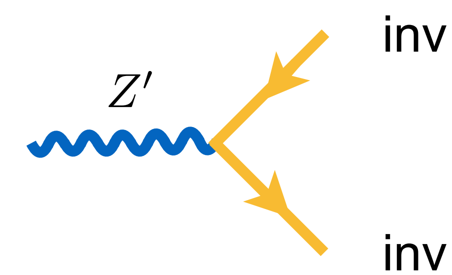
Light Dark Photon: no proton so smaller efficiencies, but enhanced in LAr (A^2 coherent.)

Heavy Dark Photon: shower displaced from proton. *Mostly photon-like showers.*

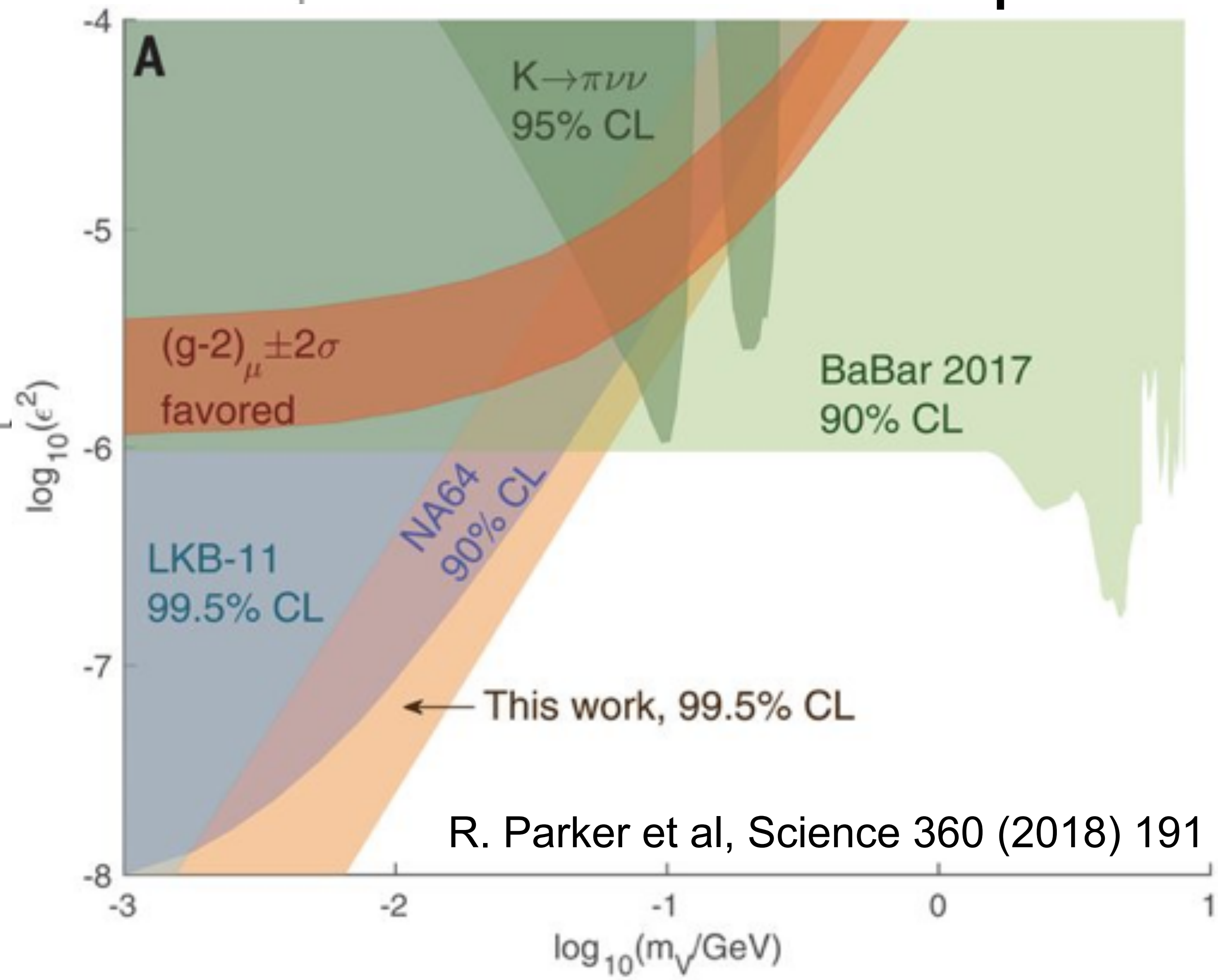
Minimal dark photon model

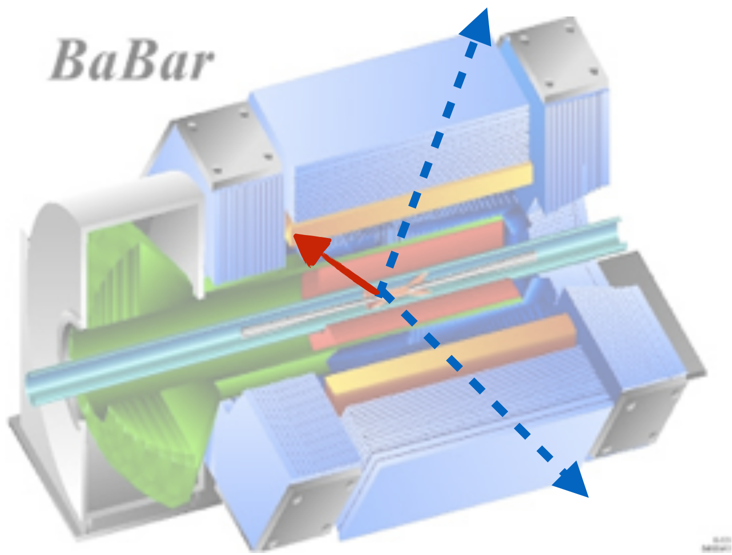






Invisible dark photon

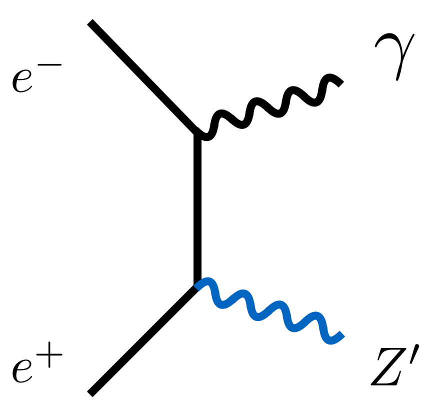




J.P. Lees, PRL.119.131804

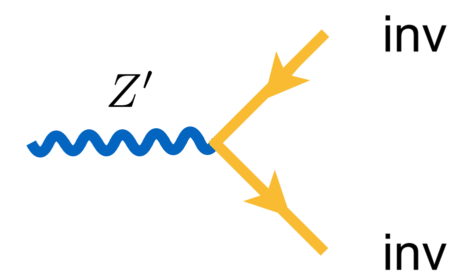
Signal: mono-photon + $\not{E}$

Muon (g-2) is excluded, but only by mono-photon searches at **BaBar**

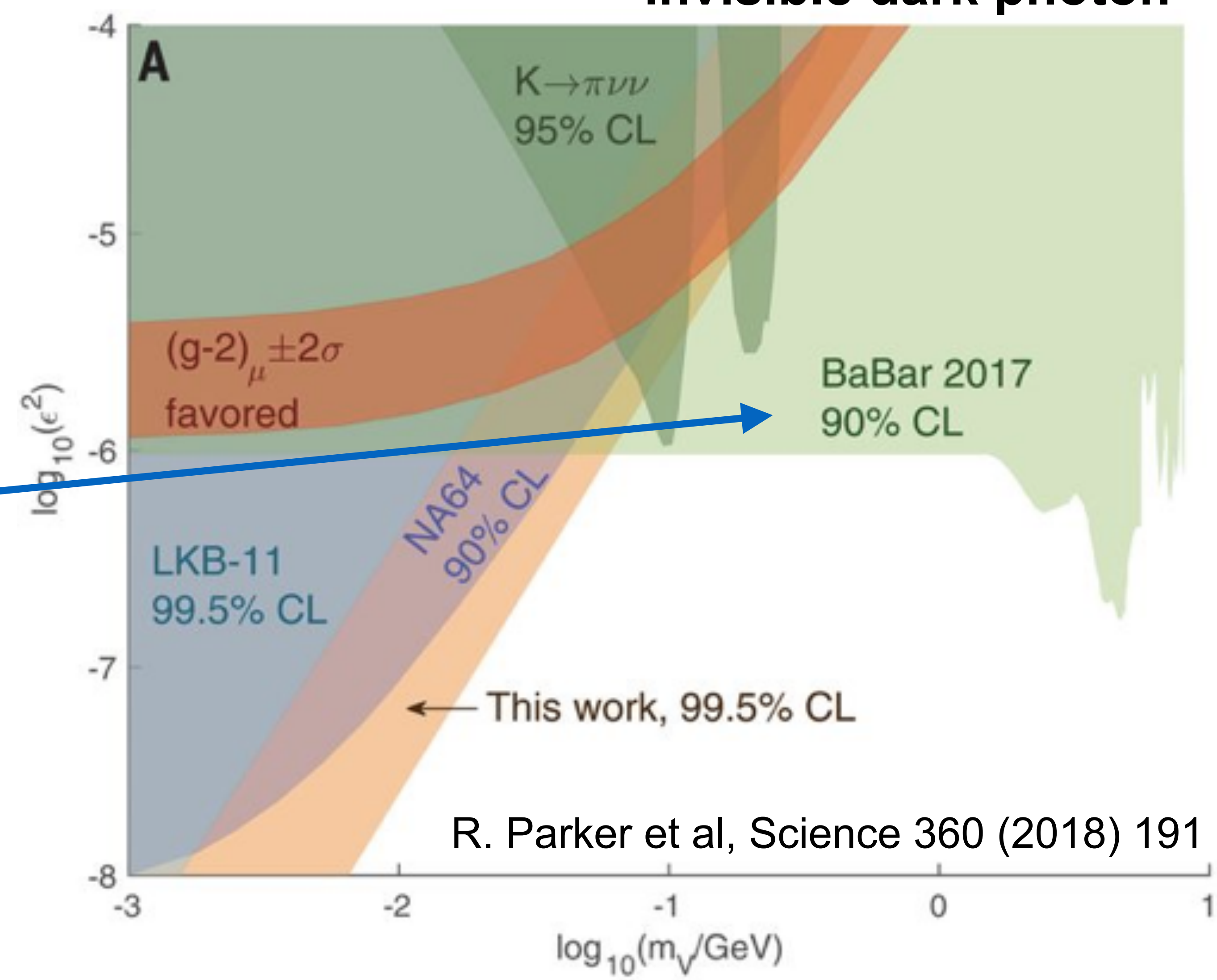


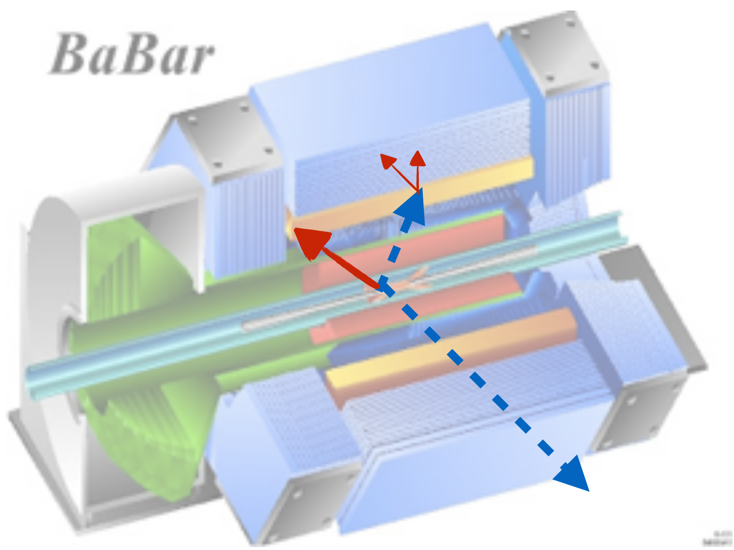
bump hunt

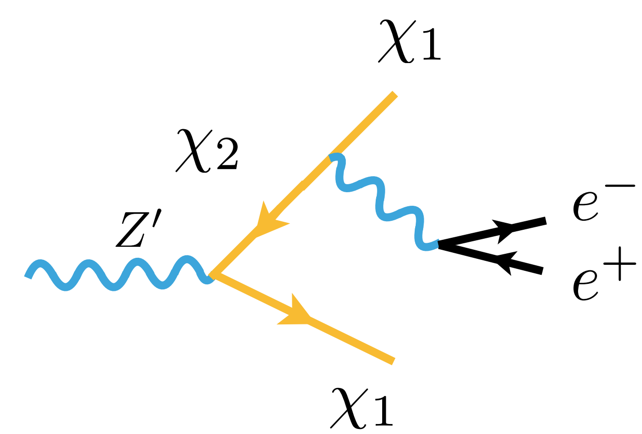
$$M_{Z'}^2 = s - 2E_\gamma \sqrt{s}$$



Invisible dark photon

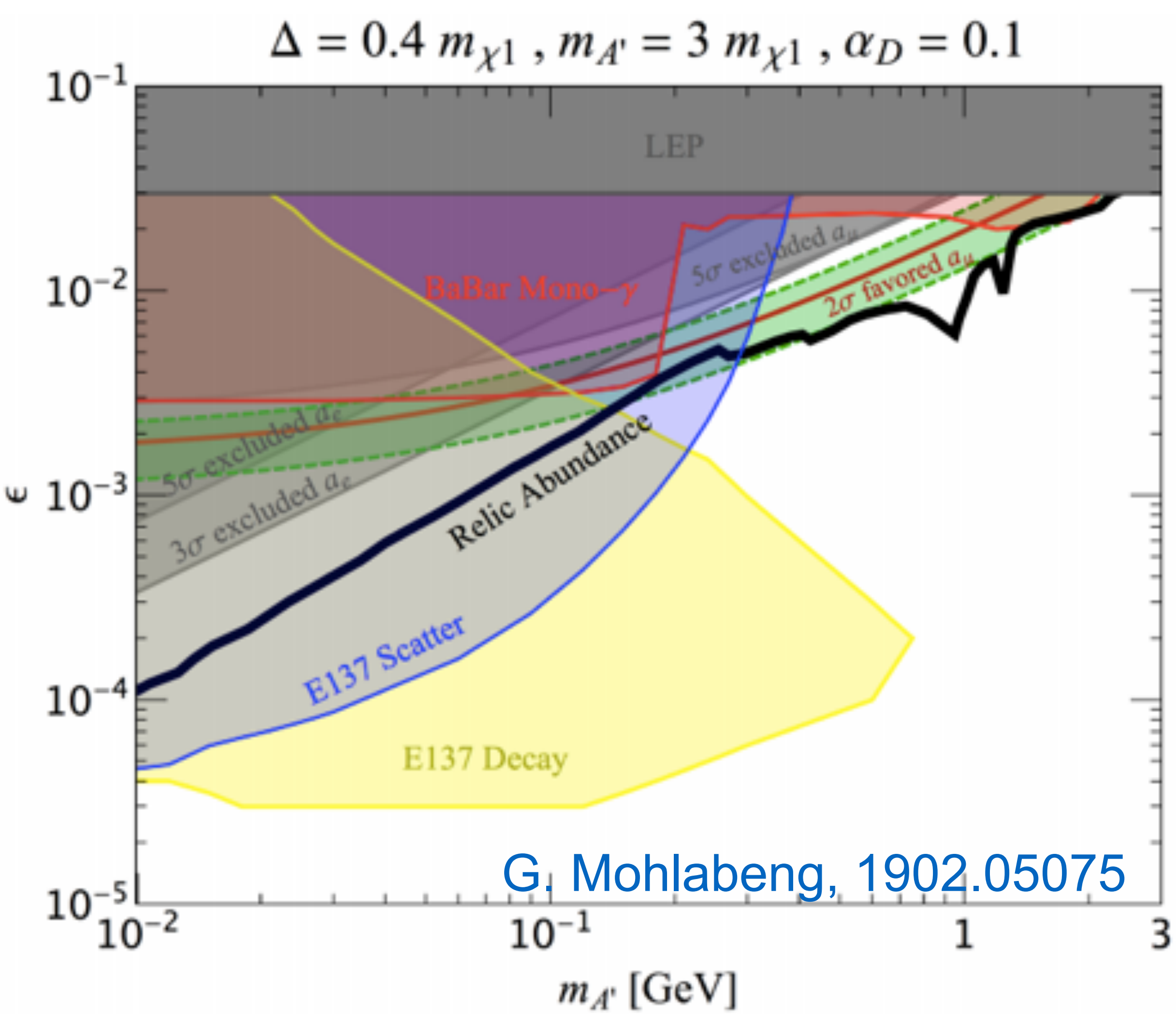


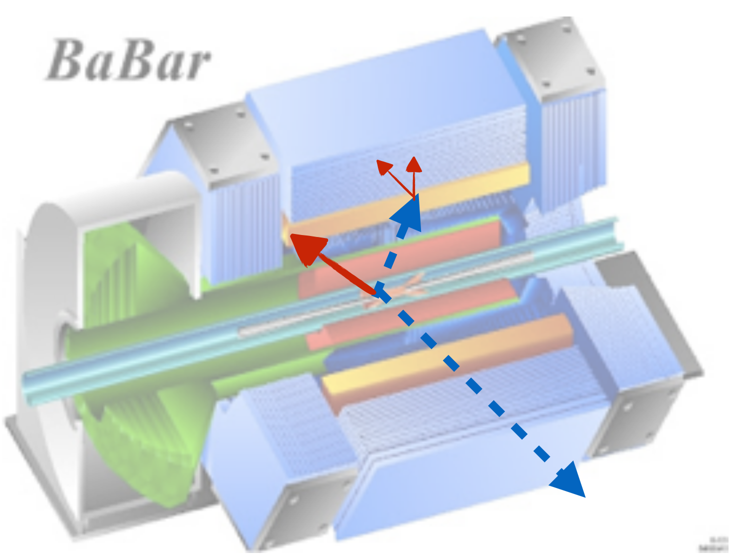




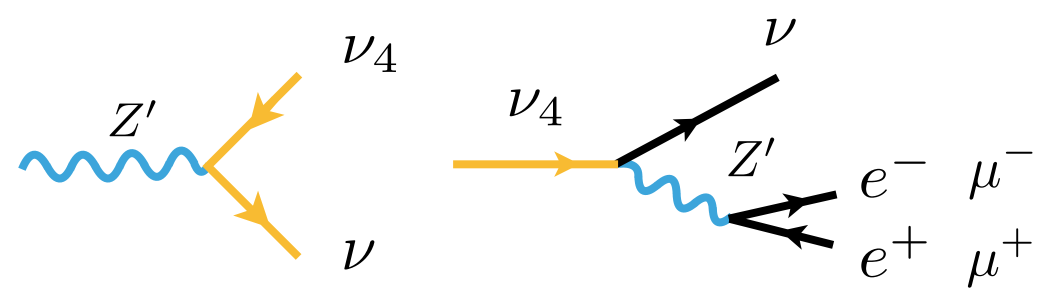
In a 2-fermion dark sector, one may relax such bounds if the heaviest fermion decays visibly.

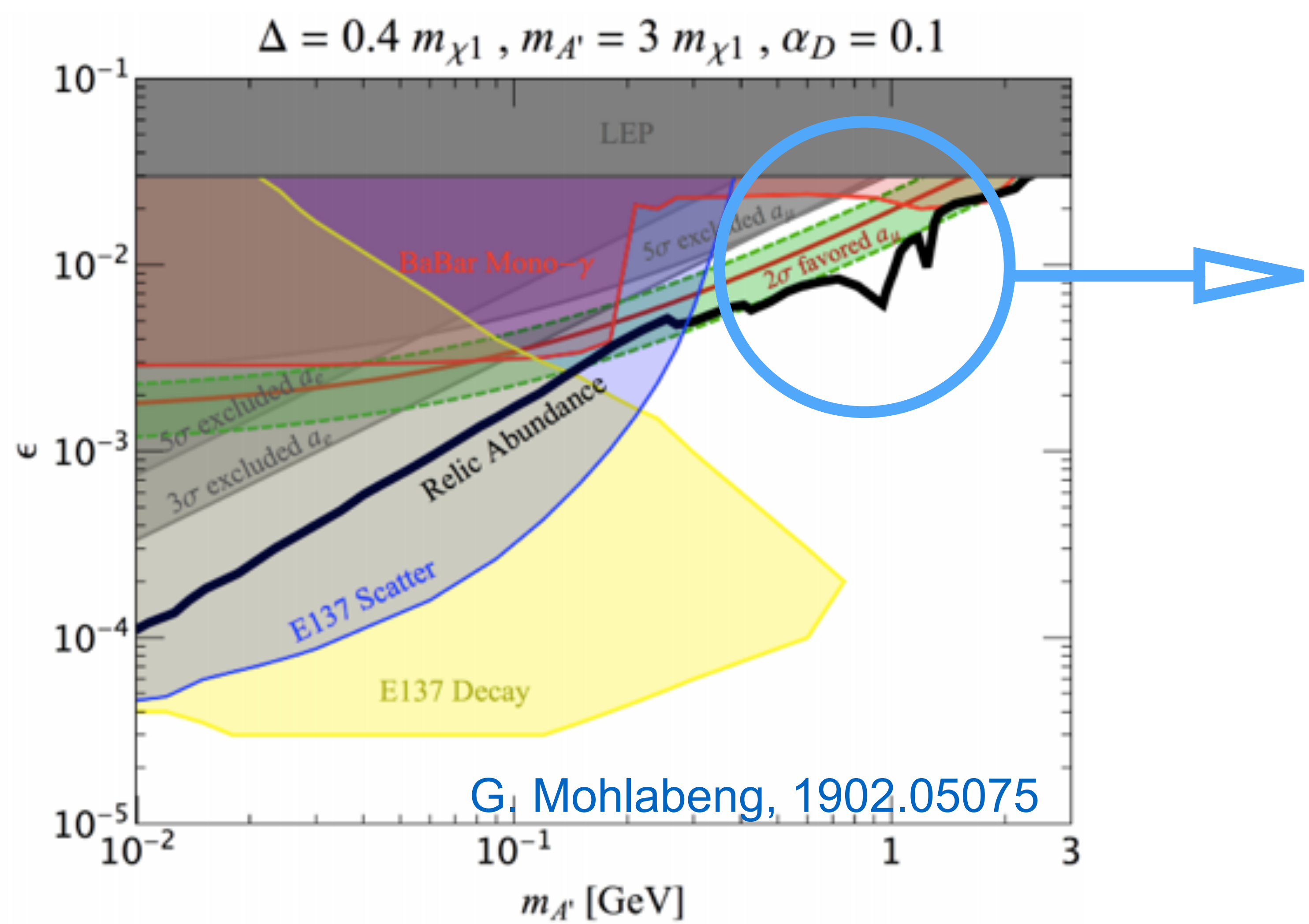
Proven for an <u>inelastic DM model.</u>





Even more relevant for dark neutrinos





$$\Gamma(Z' \to \nu_h \nu) \approx |U_{\alpha h}|^2 \frac{g'^2 m_{Z'}}{12\pi}$$

$$m_{Z'} \sim 1 \text{ GeV}$$

$$m_4 \sim 800 \text{ MeV}$$

$$\chi \sim 2.2 \times 10^{-2}$$

Now final states are even harder to miss:

pair of electrons, muons or pions!

$$\Gamma(\nu_4 \to \nu_\alpha e^+ e^-) \approx |U_{\alpha 4}|^2 \frac{(e\, c_W \chi g')^2}{384\pi^3} \frac{m_4^5}{m_{Z'}^4}$$

A smoking gun signature at NA62

Searches for HNL at NA62 @ CERN

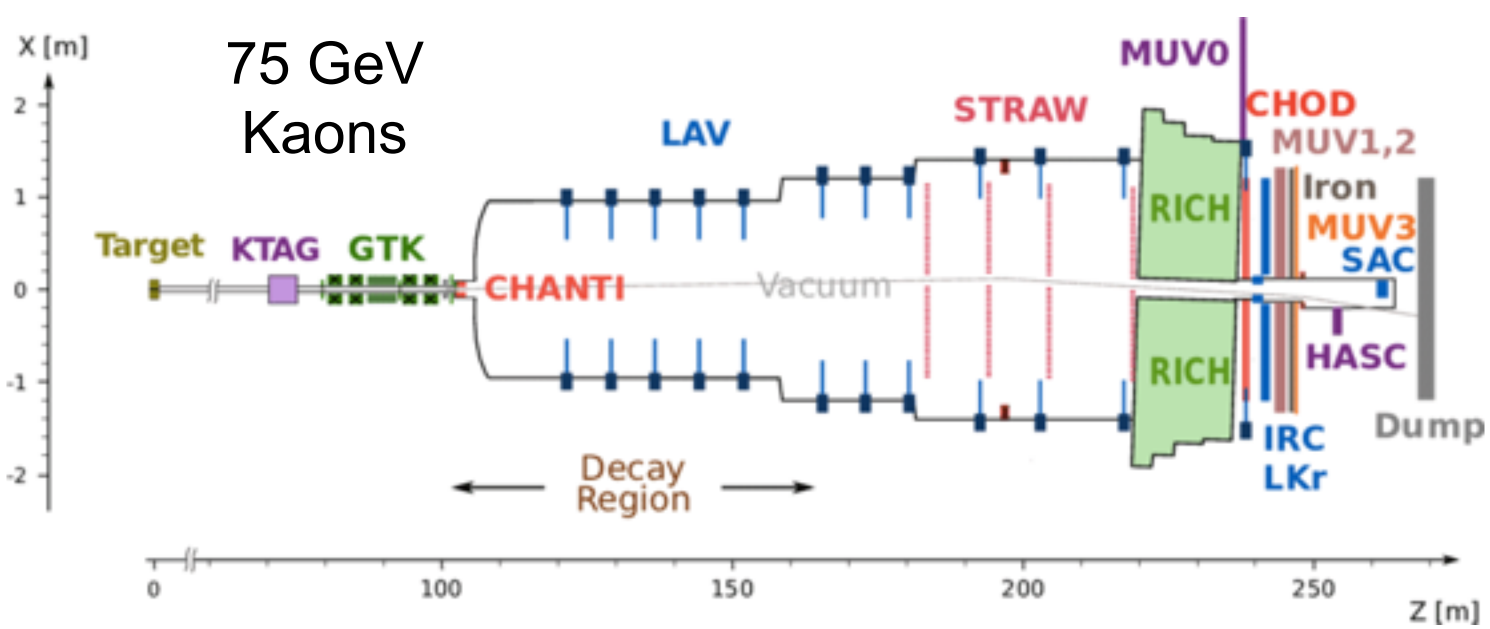
Usual peak searches based on kinematical argument:

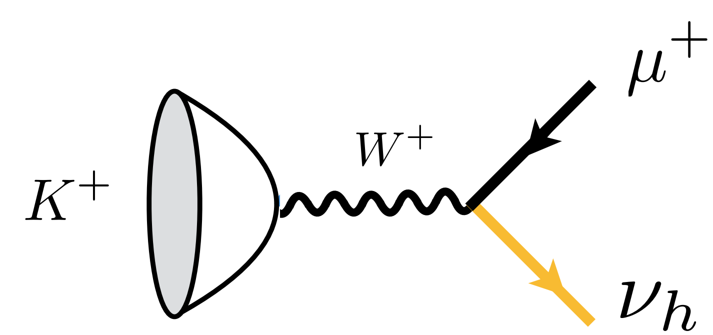
$$m^2_{p_K - p_\alpha} \equiv (p_K - p_\alpha)^2 = m^2_{\nu_h},$$

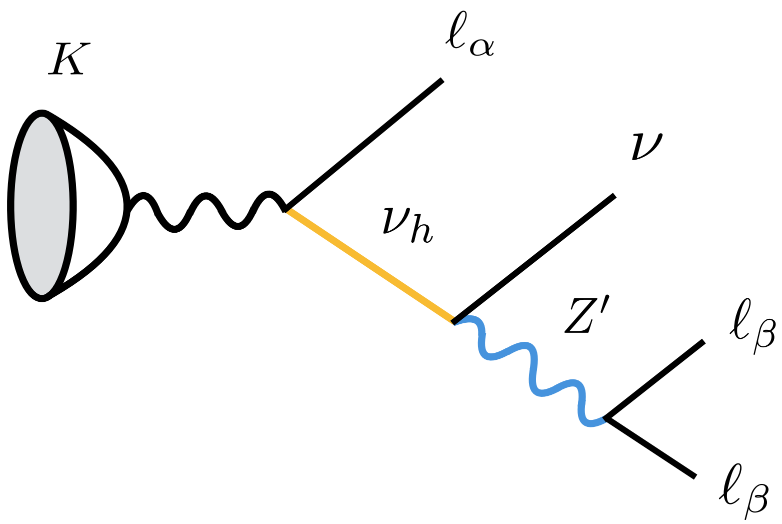
Stringent vetoes on additional photons or charged particles to avoid backgrounds such as $K^+ \to \mu^+ \nu \gamma$.

Provided the detection *inefficiency* to additional particles is not too small, can be relaxed significantly!

HNL + light dark photon ⟶ $K^+ \to \mu^+ \nu_h \to \mu^+ \nu Z' \to \mu^+ \nu e^+ e^-$ is vetoed from sample.







But this is in itself is quite a striking prediction:

$$K^+ \to \ell_\alpha^+ \nu_h \to \ell_\alpha^+ \nu Z' \to \ell_\alpha^+ \nu \ell_\beta^+ \ell_\beta^-$$

Production is still controlled:

$$\mathrm{BR}(M^+ \to \ell_\alpha^+ \nu_h) = |U_{\alpha h}|^2 \rho_\alpha(m_{\nu_h})\, \mathrm{BR}(M^+ \to \ell_\alpha^+ \nu_\alpha)$$

“Multi-dimensional bumps” from 2-body kin:

Directly measure dark state masses

$$m^2_{\beta\beta} \equiv (p_{\beta^+} + p_{\beta^-})^2 = m^2_{Z'},$$

$$m^2_{p_K - p_\alpha} \equiv (p_K - p_\alpha)^2 = m^2_{\nu_h},$$

$$m^2_{\rm miss} \equiv (p_K - p_\alpha - p_{\beta^+} - p_{\beta^-})^2 = 0$$

$$m^2_{\alpha\beta\beta} + m^2_{\alpha\nu} + m^2_{p_K - p_\alpha} = m^2_K + m^2_\alpha + m^2_{\rm miss} + m^2_{\beta\beta},$$

With perfect resolution this constitutes a zero-background search!

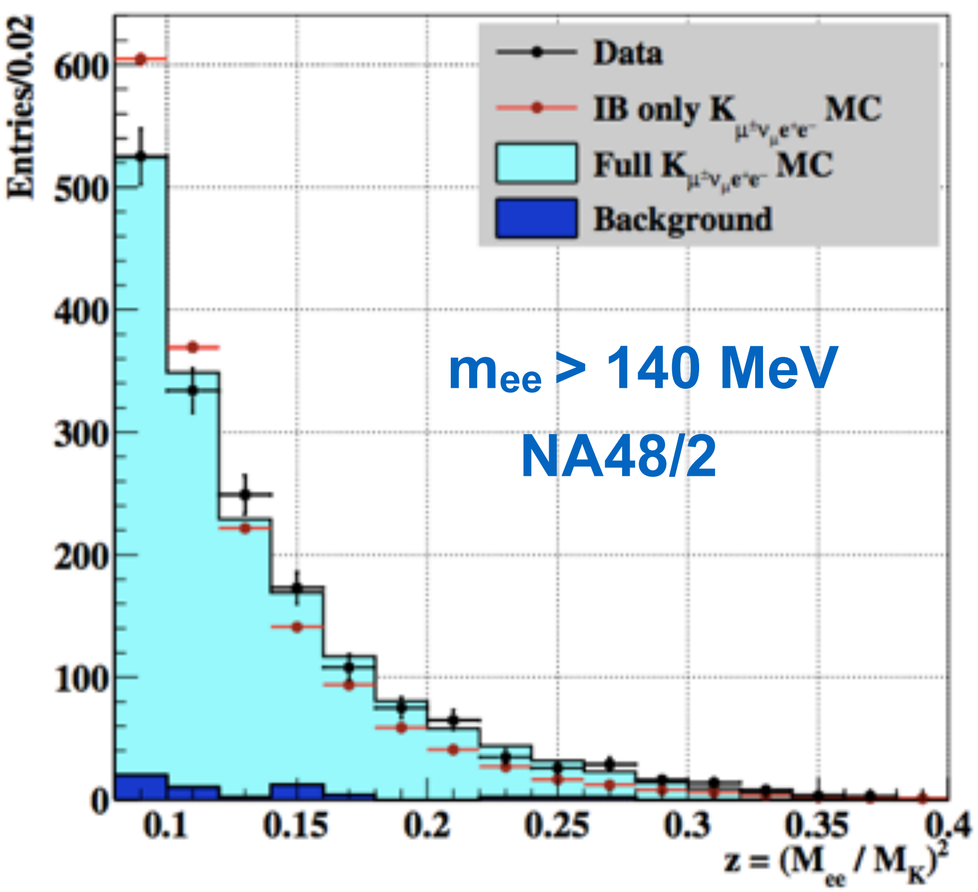
e.g. Main challenge comes from pion Dalitz decays at m_{ee} < 140 MeV

missed soft photon from $K^+ \to \mu^+ \nu_\mu (\pi^0 \to \gamma e^+ e^-)$

Bkgs such as $K^+ \to (\pi^+ \to \mu^+ \nu) e^+ e^-$ can be reduced from additional cuts:

$$m_{\mu\nu} > 150 \text{ MeV}$$

M. S. Atiya *et al.*, PRL.63, 2177 (1989)



Ultimately, depends on resolution, but at very small mixing, NA62 can also reduced bkgs by searching for displaced vertices when

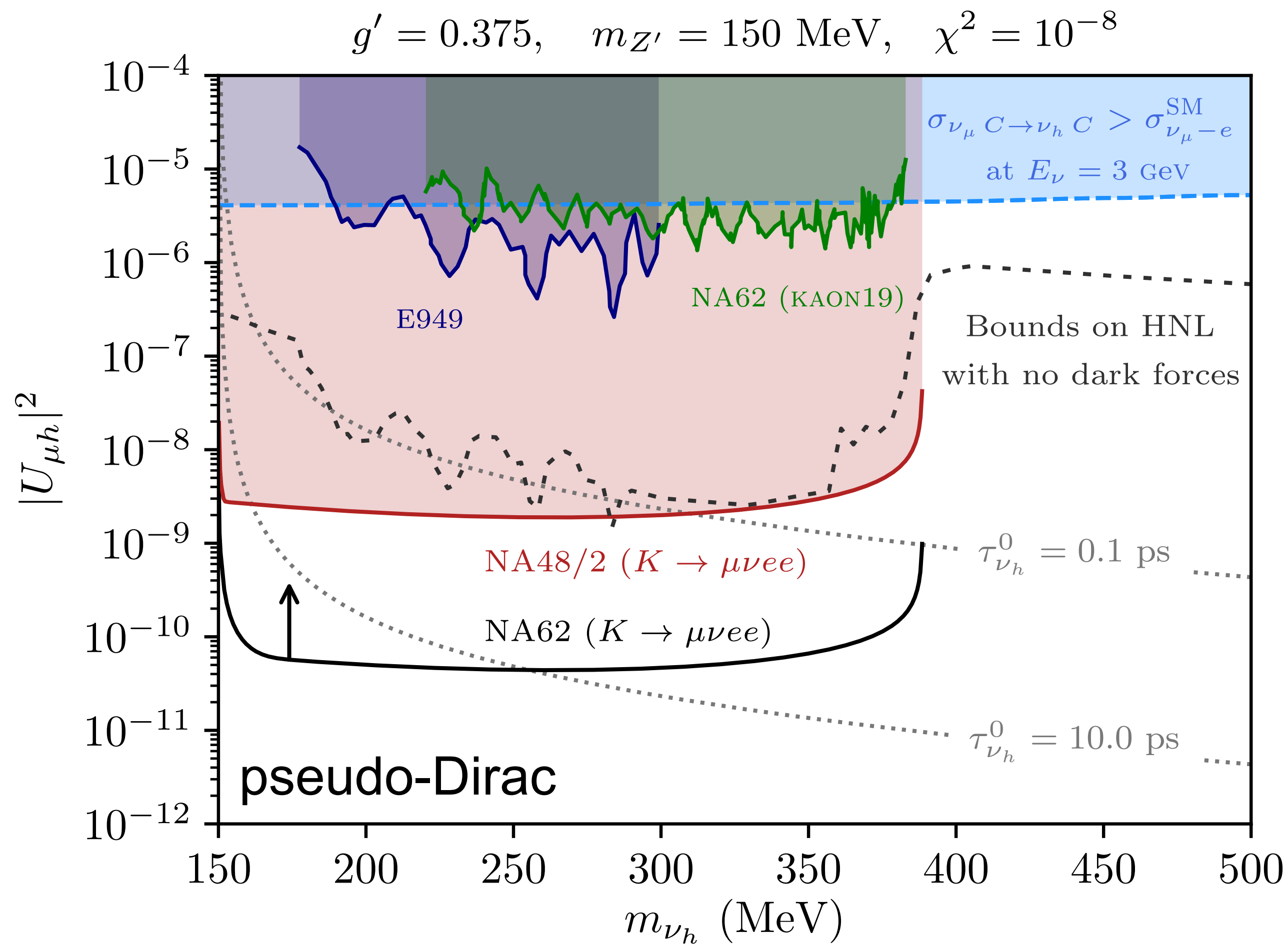
$c\tau$ > 10 ps

Existing measurements

$$\text{BR}(K^+ \to \mu^+ \nu e^+ e^-) = (7.81 \pm 0.21 \text{ stat.}) \times 10^{-8}$$ @ NA48/2

$$\text{BR}(K^+ \to \mu^+ \nu \mu^+ \mu^-) < 4.7 \times 10^{-7}$$ @ E787

Both SM process will be measured by NA62.



NA62 S.E.S. assuming background-free search.

Assumptions matched to LNV search in K+→π−e+e+ and K+→π−μ+μ+

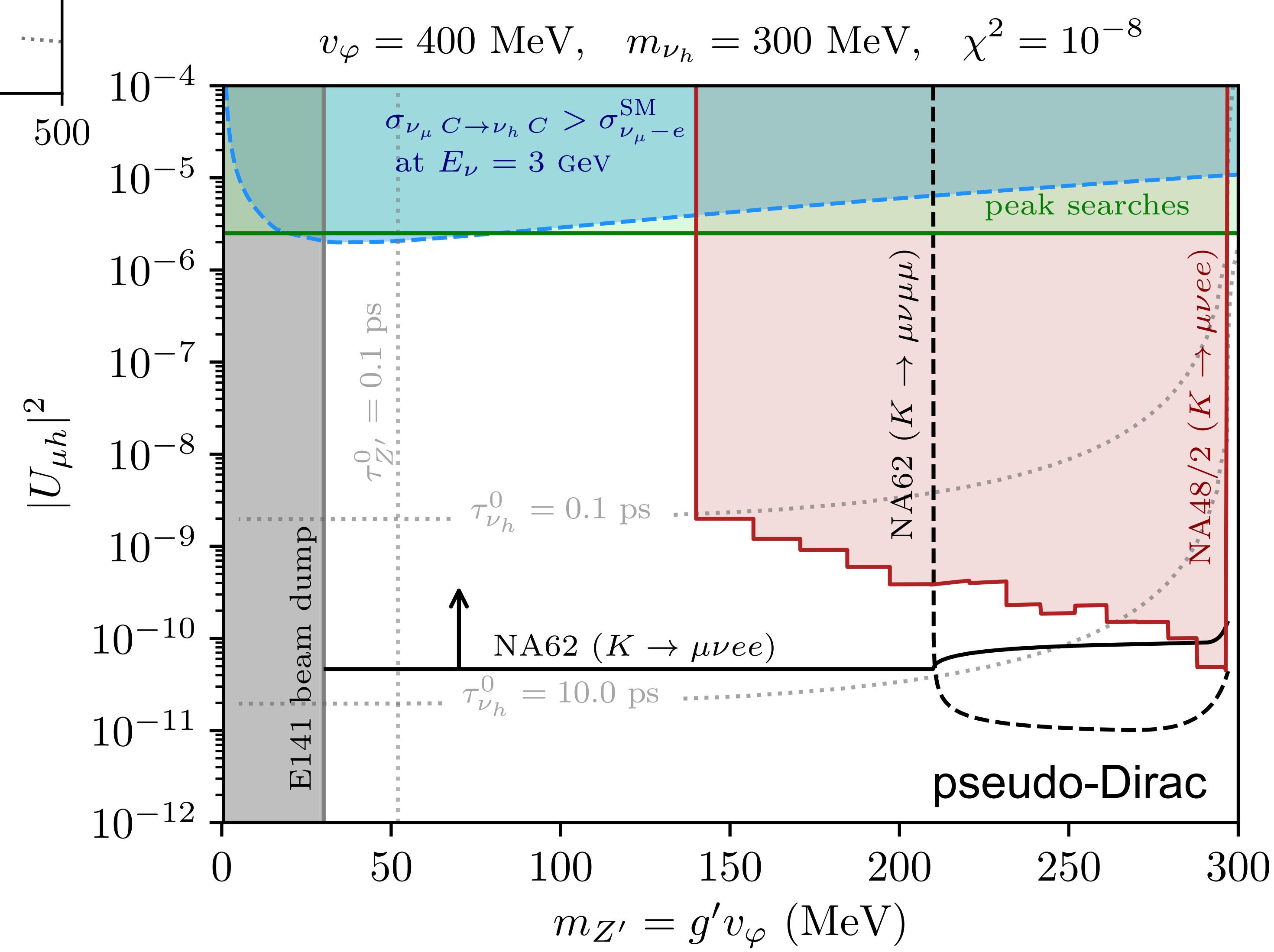
Total of 1.6e12 useful Kaon decays *(only 30% of NA62 dataset!)*

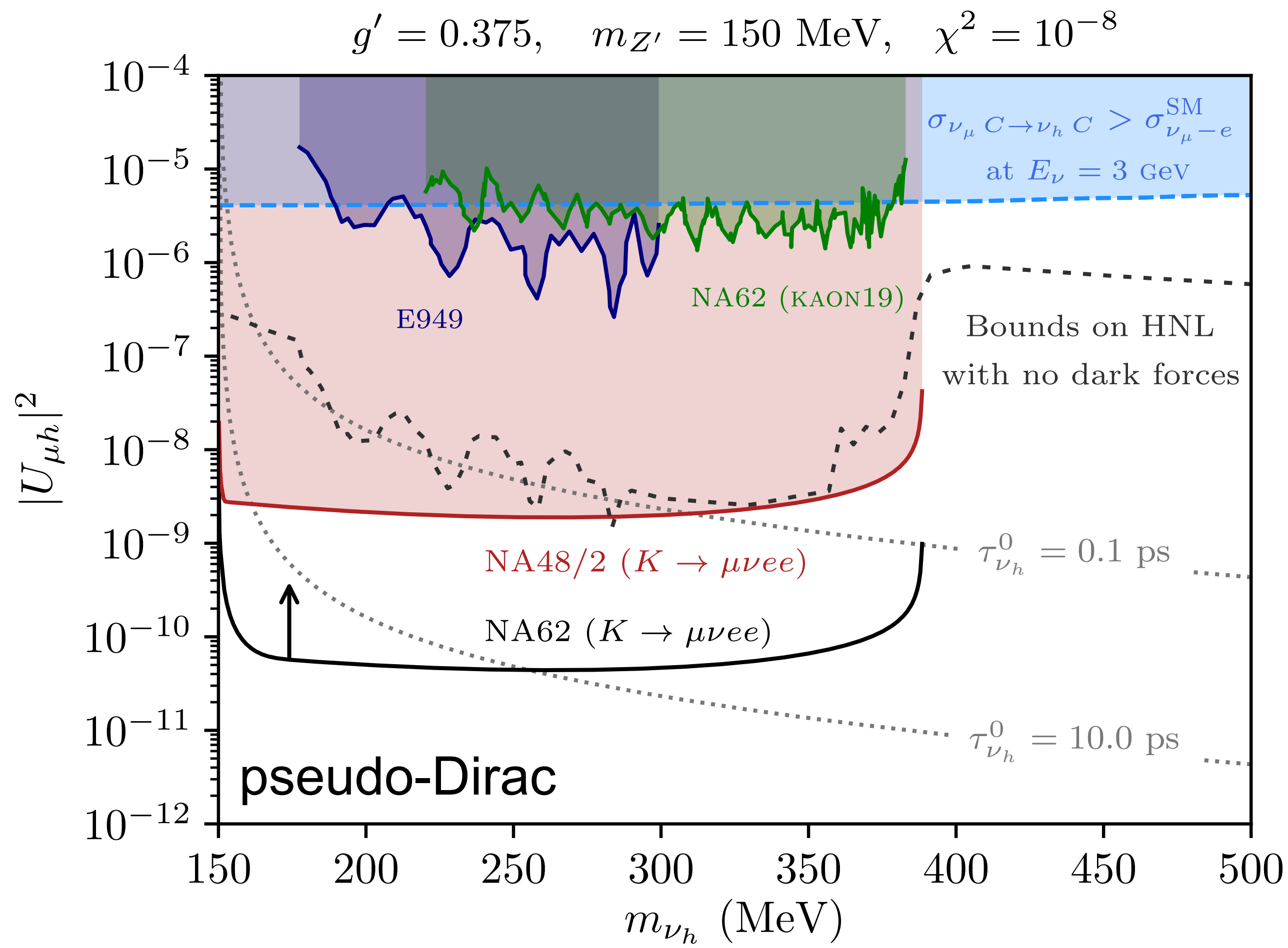
4% acceptance of ee
8% acceptance for μμ

NA62 Coll., *j.physletb*.2019.07.041

Other bounds:

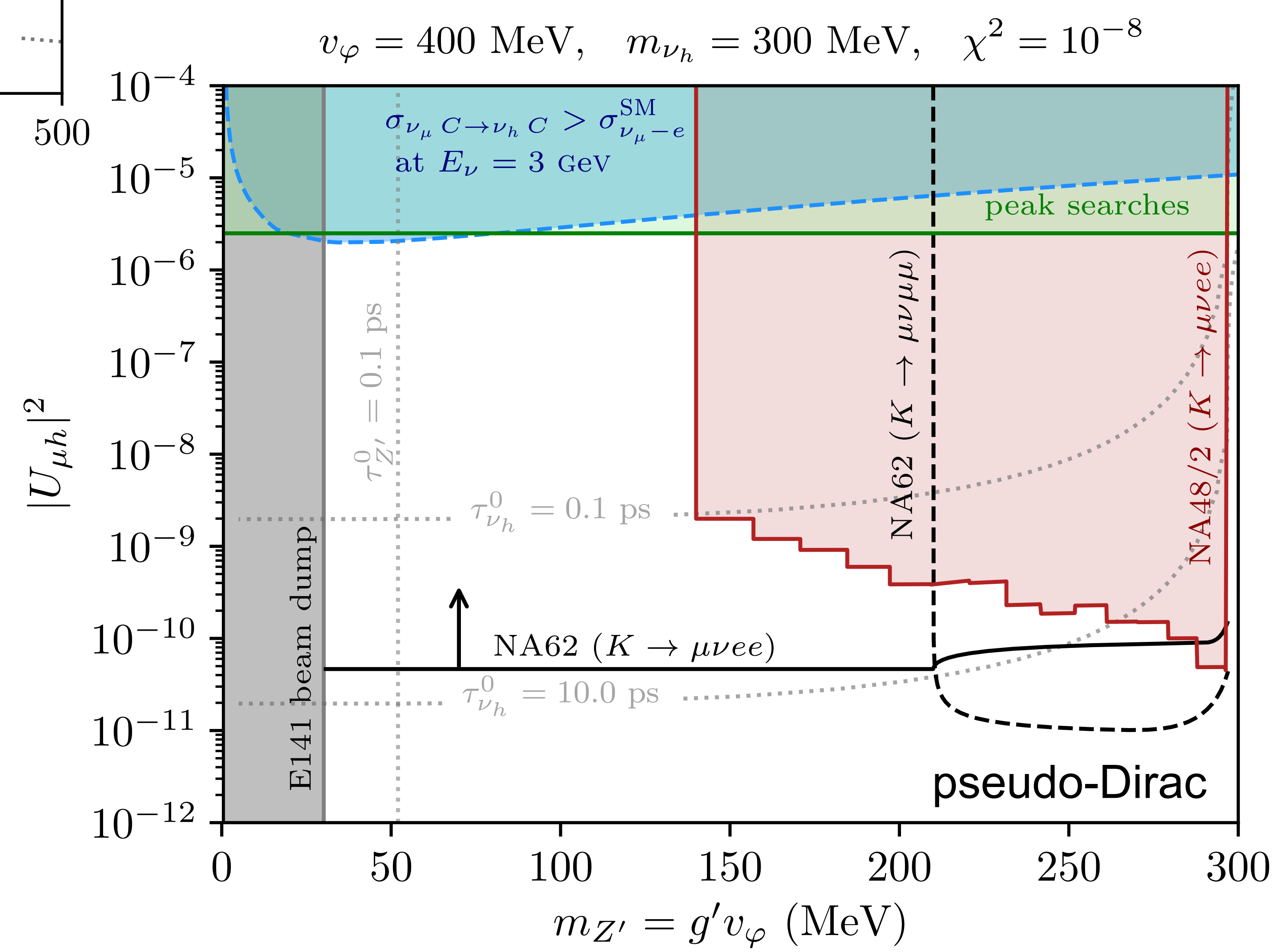
- Peak searches relaxed due to visible events (very conservative 0.5% inneff.)
- Upscattering cannot be much larger than nu-e scattering in the SM
- Existing bound based on NA48/2 measurement.





If zero-bkg assumption correct, provides direct test of MiniBooNE explanation with light dark photons

E. Bertuzzo et al.,1807.09877



CONCLUSIONS

Presented a “harmless” and minimal UV completion for neutrino-phillic interactions.

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- MiniBooNE explanations from upscattering and decay.
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New searches for such dark neutrino sectors at NA62. “Smoking-gun” signature in

$$K^+ \to \ell^+ \nu e^+ e^-$$