DARK NEUTRINO SECTORS
&
LOW ENERGY EXPERIMENTS

Brookhaven Neutrino Theory Virtual Seminars
BNTVS

Matheus Hostert

University of Minnesota,
William I. Fine Institute
&
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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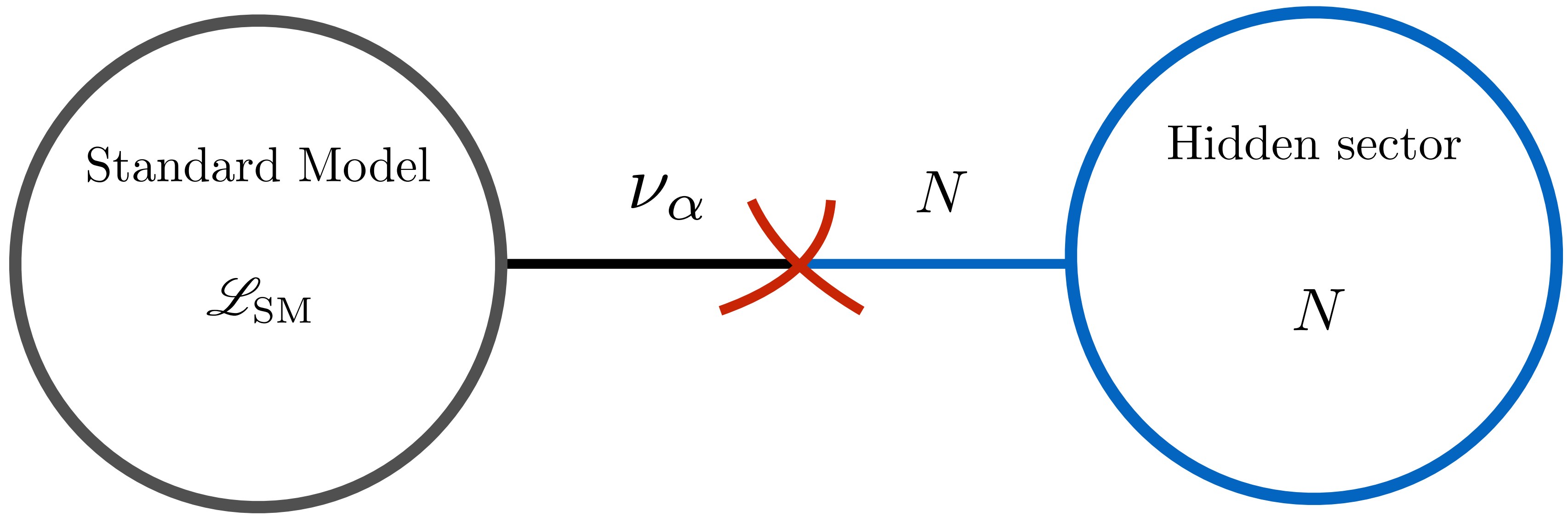
<u>Outline</u>

- 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.*

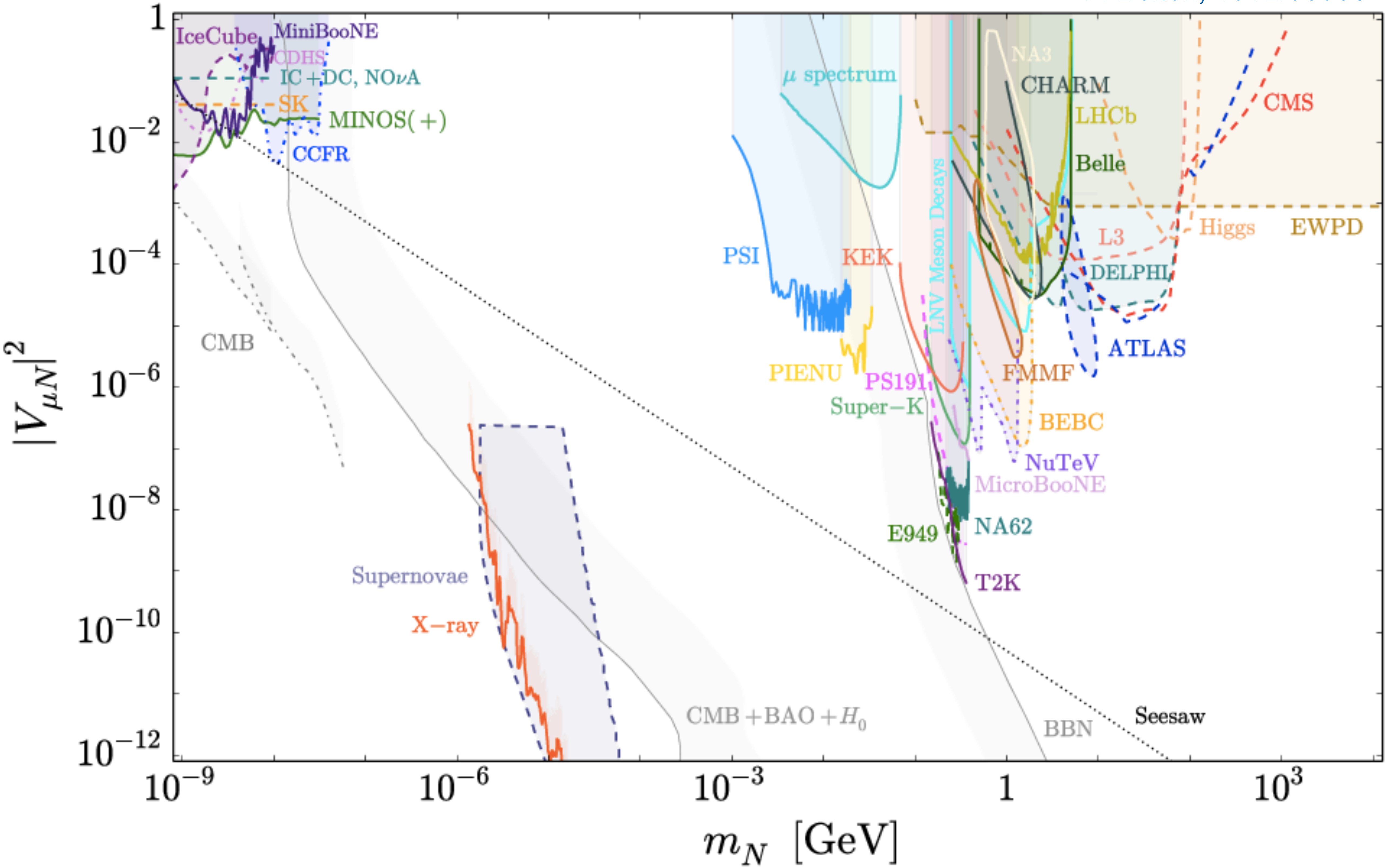


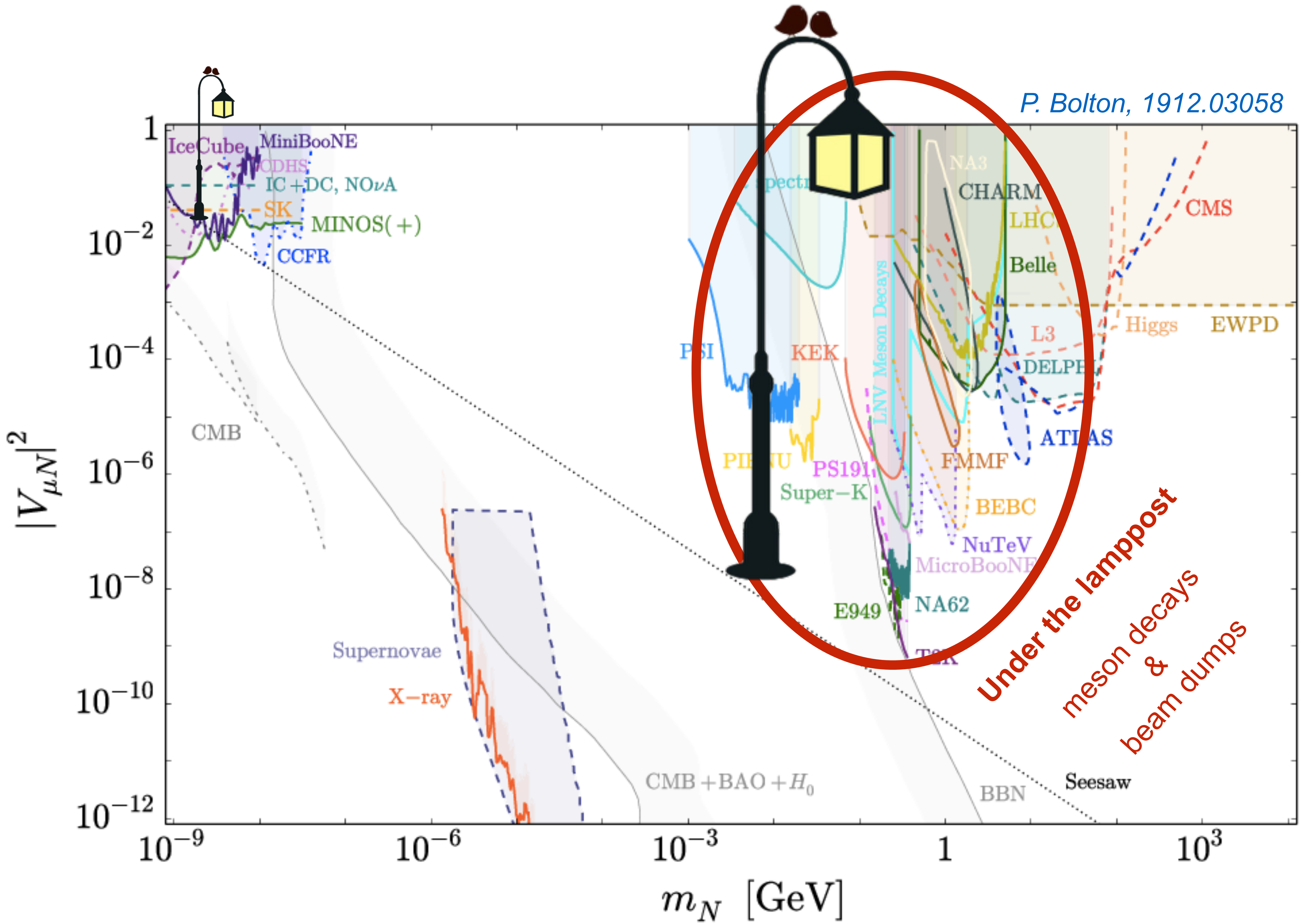
$$\mathscr{L} \supset -y^\nu \left(\overline{L}\tilde{H}\right) N - \frac{M_N}{2}\overline{N^c}N + \text{h.c.}$$

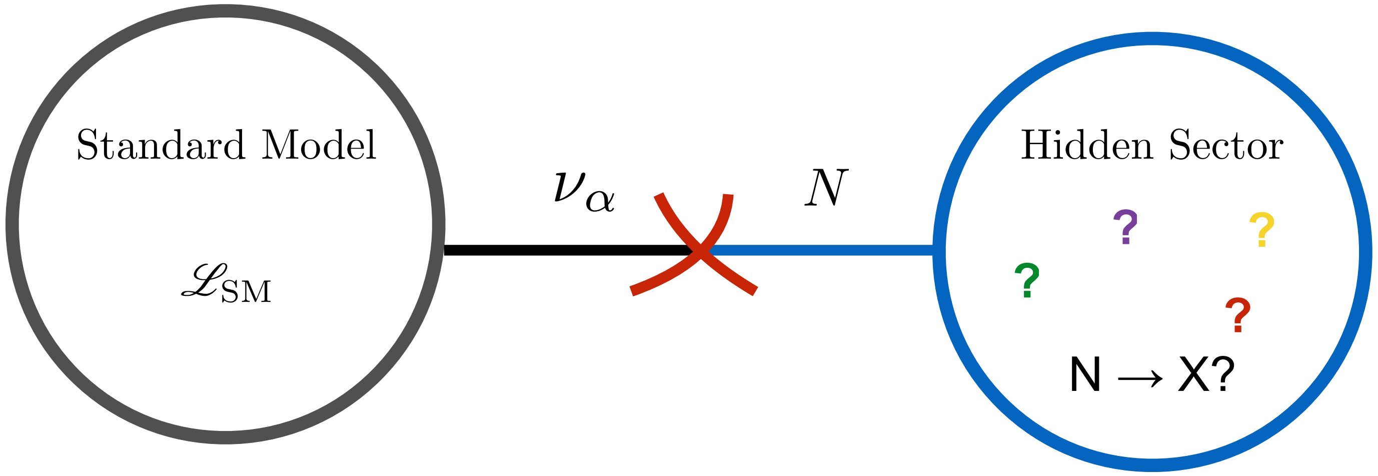
Well-motivated extension of the SM

- 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

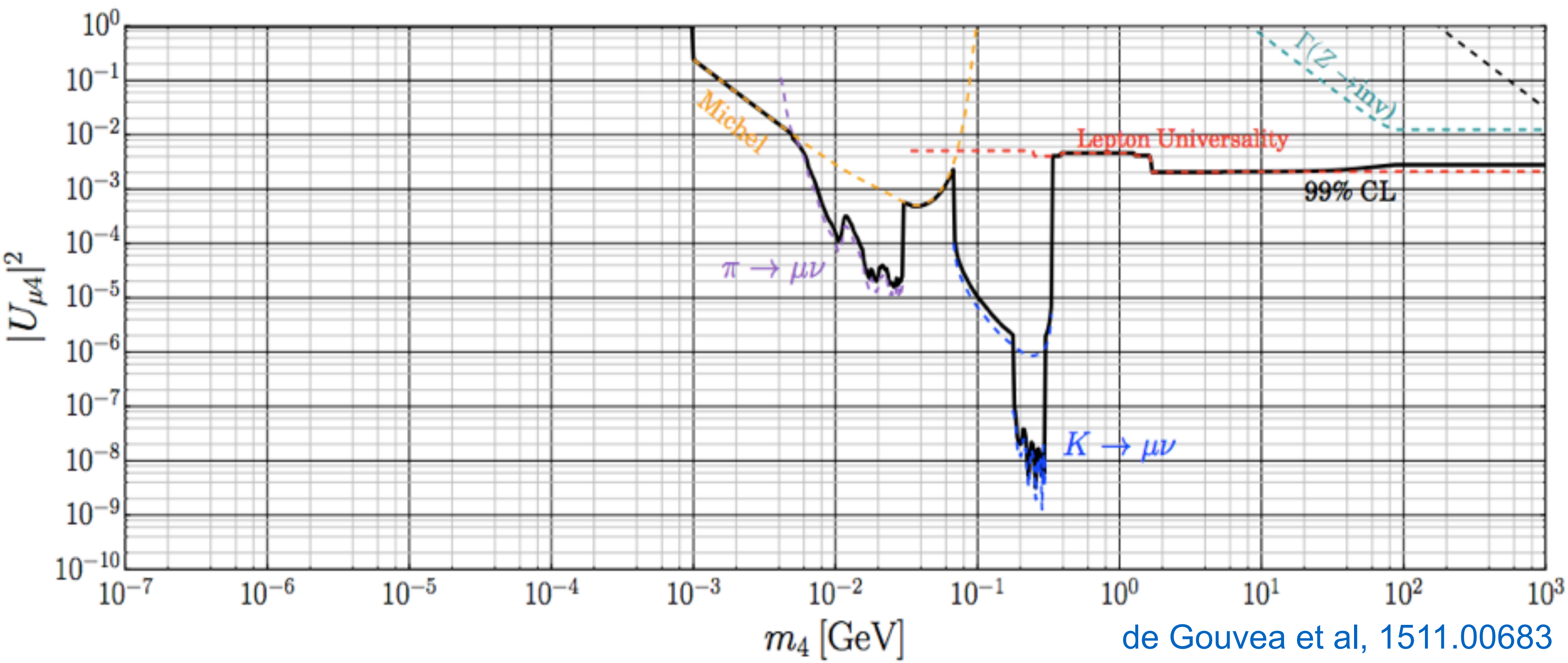



P. Bolton, 1912.03058
IceCube
MiniBooNE
CDHS
IC+DC, NOνA
SK
MINOS(+)
CCFR
PSI
KEK
LNV Meson Decays
NA3
CHARM
LHC
Belle
L3
DELPHI
ATLAS
CMS
Higgs
EWPD
PIENU
PS191
Super−K
FMMF
BEBC
NuTeV
MicroBooNE
NA62
E949
T2K
CMB
Supernovae
X−ray
CMB+BAO+H_0
BBN
Seesaw
$|V_{\mu N}|^2$
m_N [GeV]
Under the lamppost
meson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



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

$$\begin{aligned}\mathscr{L} =& \mathscr{L}_{\rm SM} + \left(D_\mu\Phi\right)^\dagger (D^\mu\Phi) - V(\Phi, H)\\ &- \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \overline{N}i\partial\!\!\!/N + \overline{\nu_D}i\not{D}\nu_D\\ &- \left[y_\nu^\alpha(\overline{L_\alpha}\cdot\widetilde{H})N^c + \frac{\mu'}{2}\overline{N}N^c + y_N\overline{N}\nu_D^c\Phi + \text{h.c.}\right],\end{aligned}$$

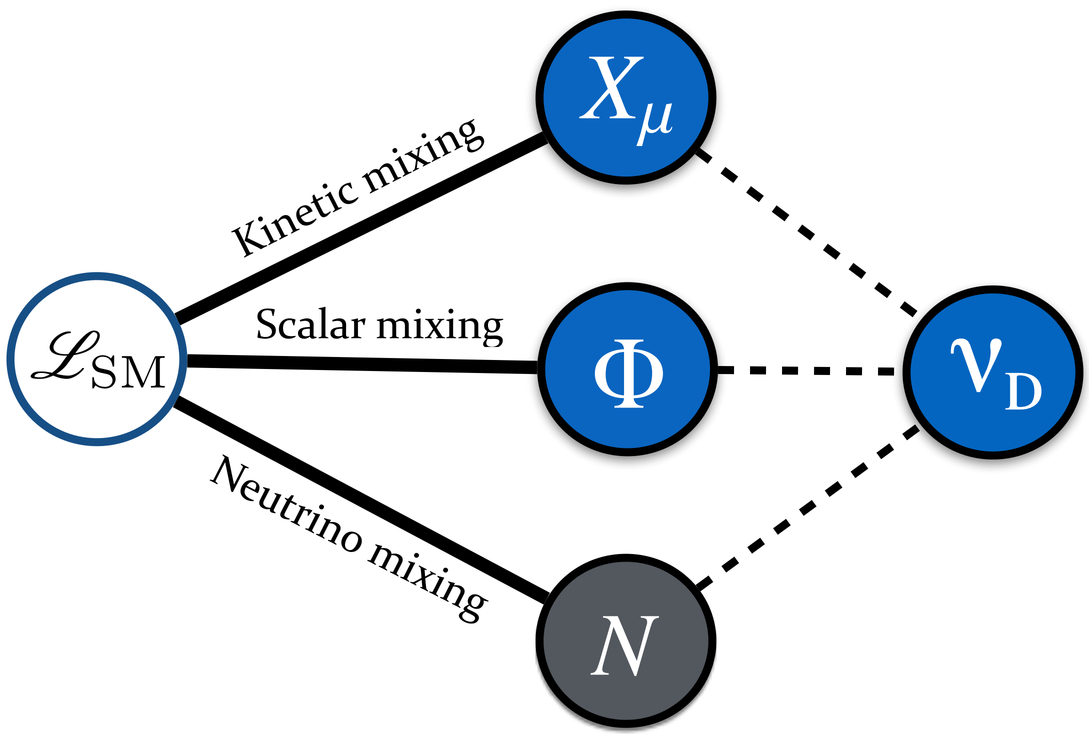
	$SU(2)_L$	$U(1)_Y$	$U(1)'$
N	$\mathbf{1}$	0	0
ν_D	$\mathbf{1}$	0	Q
Φ	$\mathbf{1}$	0	Q

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

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

	$SU(2)_L$	$U(1)_Y$	$U(1)'$
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

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

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

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 $\mu = \varepsilon = 0$

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

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

$$\frac{1}{2\mu'}\left(\overline{\nu_\alpha} \quad \overline{\nu_{\rm D}}\right)\begin{pmatrix} m^2 & m\,\Lambda \\ m\,\Lambda & \Lambda^2 \end{pmatrix}\begin{pmatrix} \nu_\alpha^c \\ \nu_{\rm D}^c \end{pmatrix}$$

rank-1

Massless SM-like neutrinos at tree-level

(holds provided #N = #S)

sterile-like

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

dark-like

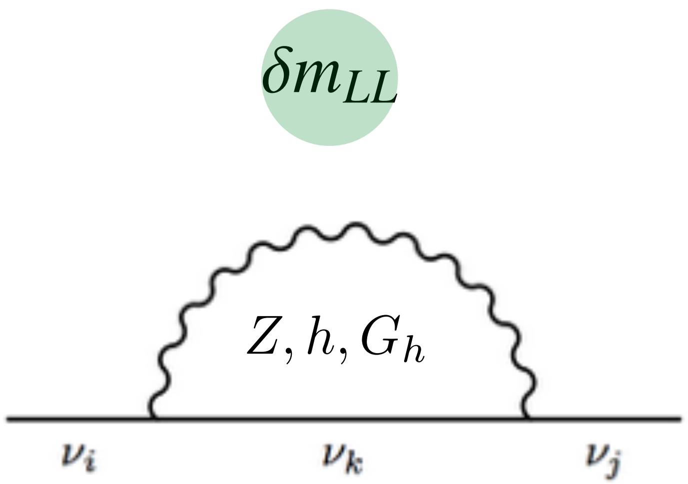
$$m_\nu = 0$$

SM-like

n.b.

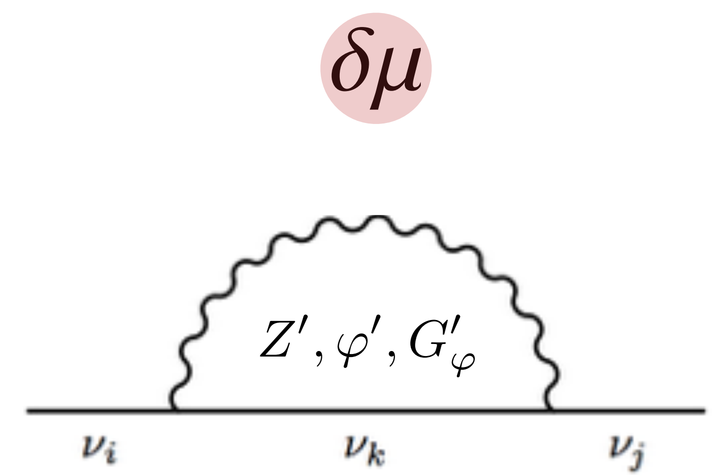
ESS-like scenario relevant for:

- 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: <u>neutrino masses are small because m_D is small.</u>

<u>ISS-like:</u> $\mu' \ll \Lambda$

$$m_\nu \sim \frac{g'^2}{8\pi^2}\frac{m_D^2}{m_{Z'}^2}\mu'\left(3\ln\frac{m_{Z'}^2}{\Lambda^2} + \ln\frac{m_{\varphi'}^2}{\Lambda^2} - 4\right)$$

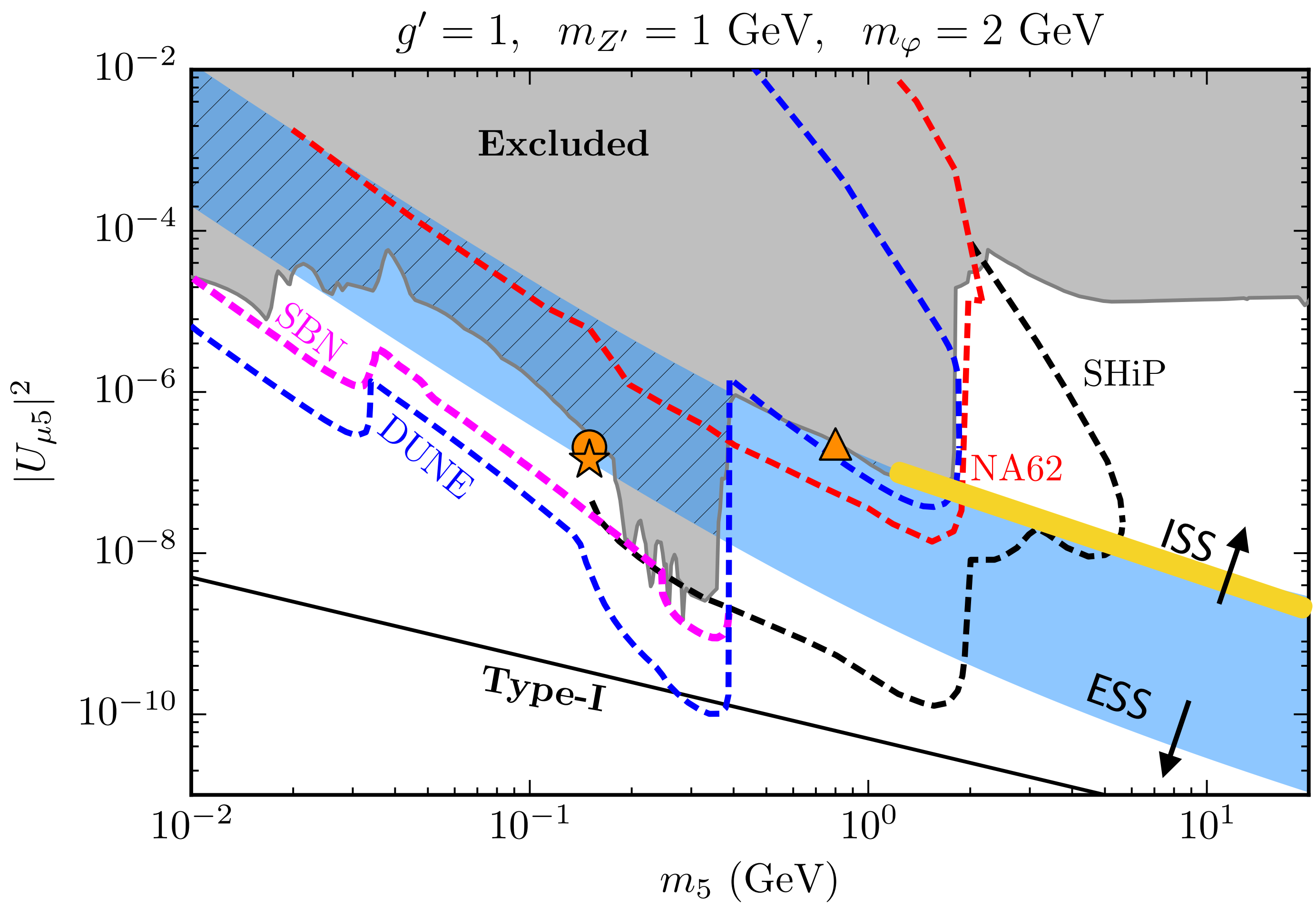
where $m_{Z'}, m_{\varphi'} \ll \Lambda$

<u>ESS-like:</u> $\mu' \gg \Lambda$

$$m_\nu \sim \frac{g'^2}{8\pi^2}\frac{m_D^2}{\mu'}\left(3\ln\frac{m_{Z'}^2}{\Lambda^2} + \ln\frac{m_{\varphi'}^2}{\Lambda^2} - 4\right)$$

where $m_{Z'}, m_{\varphi'} \gg \mu'$

Ignoring kinetic and scalar mixing



Provided neutrino mixing is small:

ISS-limit: both steriles behave “standard”HNL

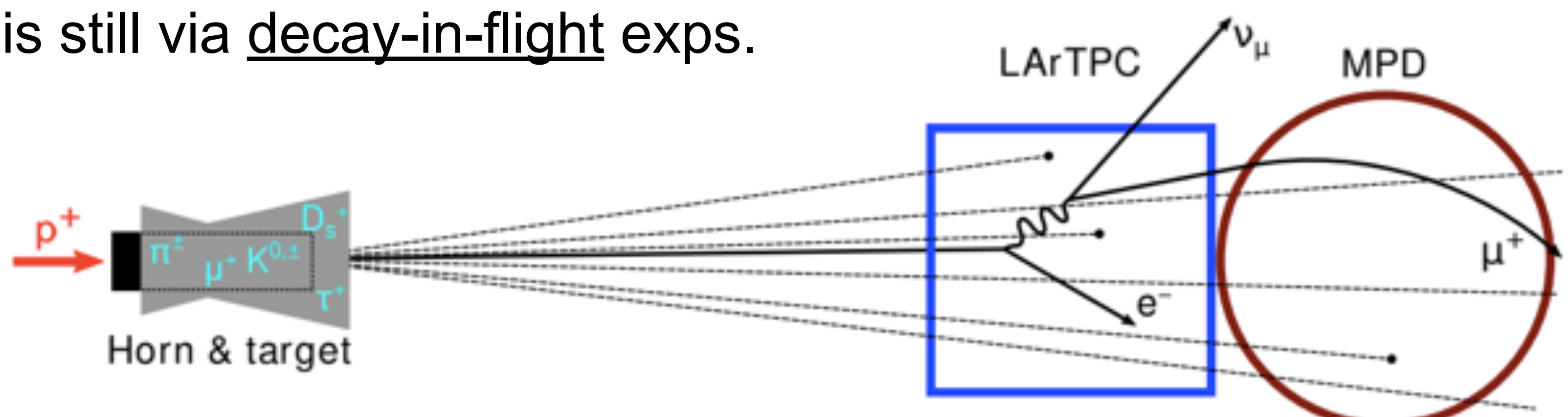
$$\Gamma(\nu_5 \to \nu_4 + \dots) \propto (\mu')^{3(5)}$$

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

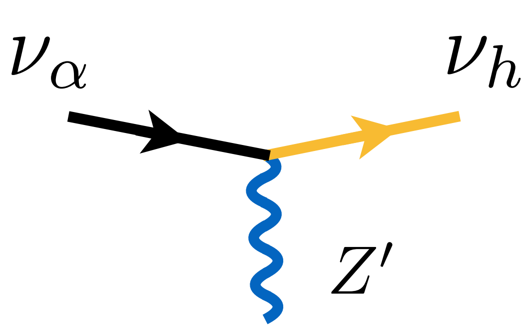
UV completion for “neutrino-philic” interactions & explains the zero in the MRISS mass matrix…

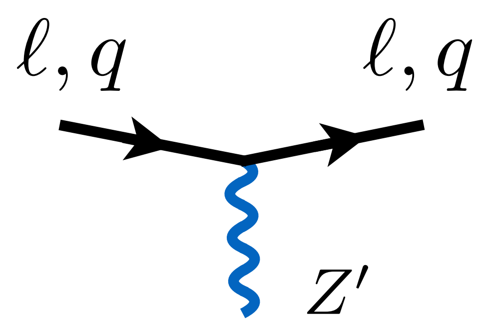
…but phenomenology is somewhat “boring”.

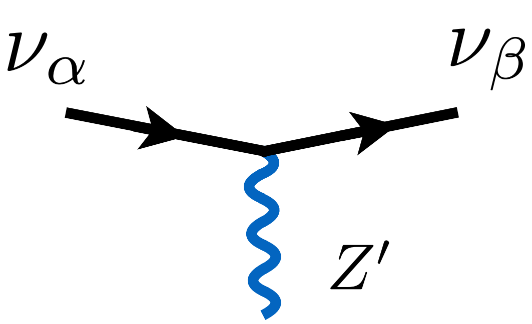
This changes when we turn on additional portal couplings.

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>

Mixing x O(1) coupling

<u>Quarks and charged leptons</u>

Kinetic mixing

<u>SM neutrinos only</u>

Doubly suppressed

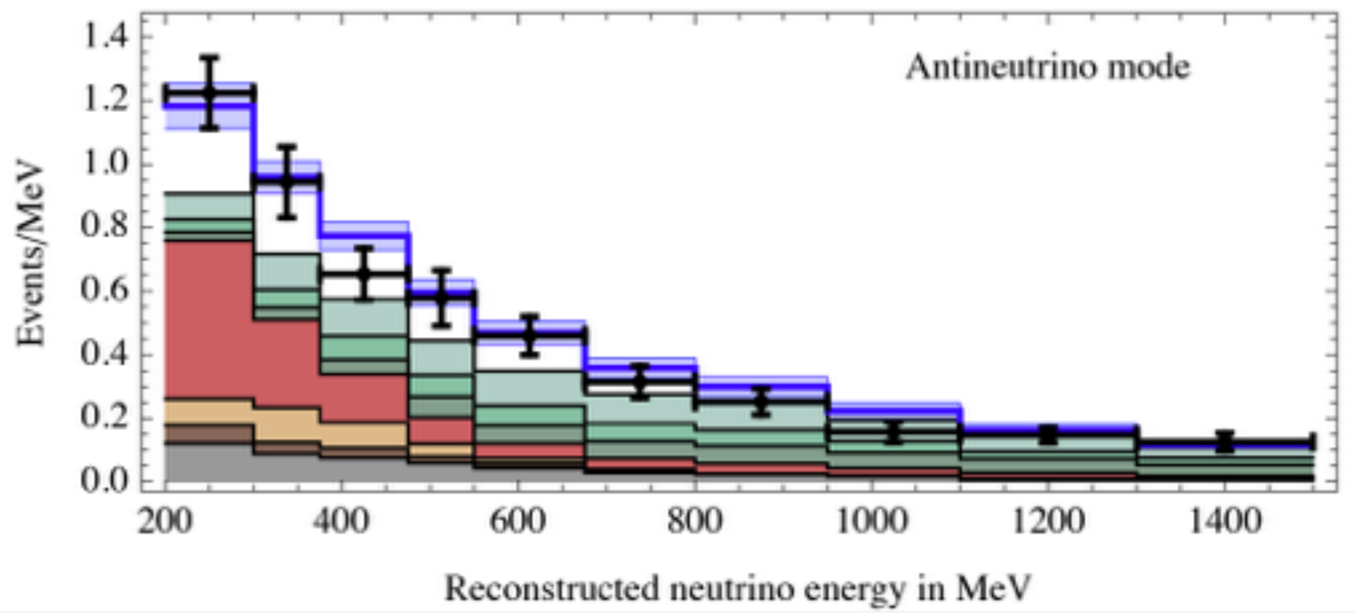
Explaining MiniBooNE

MiniBooNE Coll., PRL.121.221801

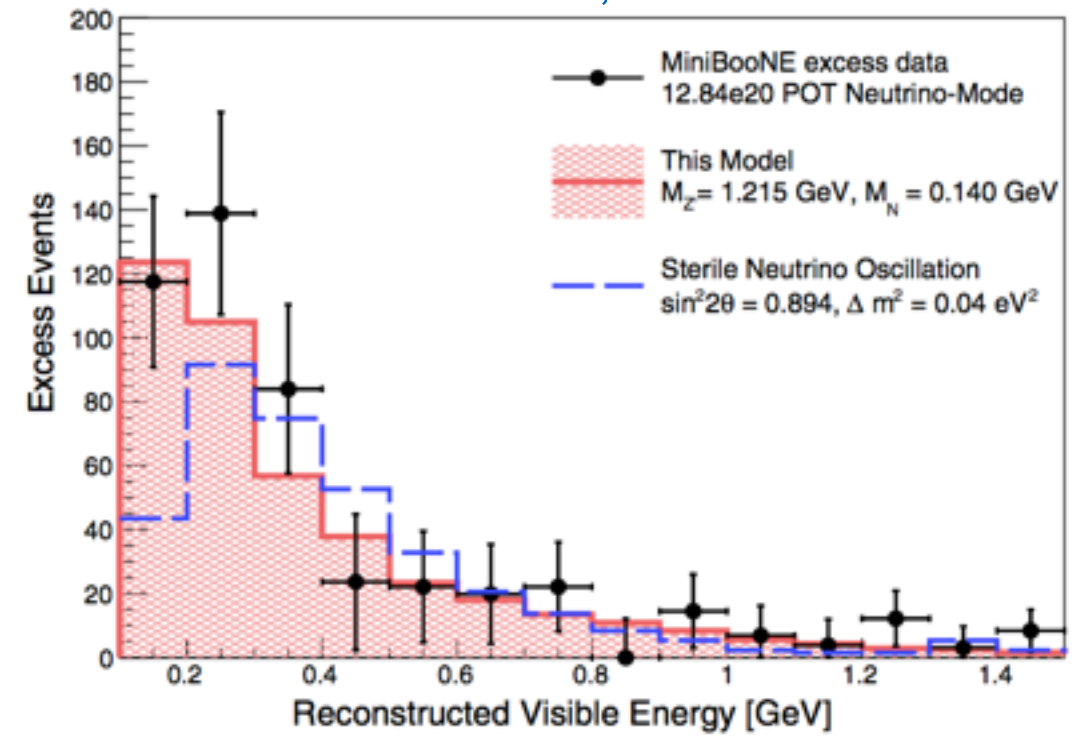
4.7σ excess observed in nu + nubar mode

— data/MC disagreement beyond statistical doubt —

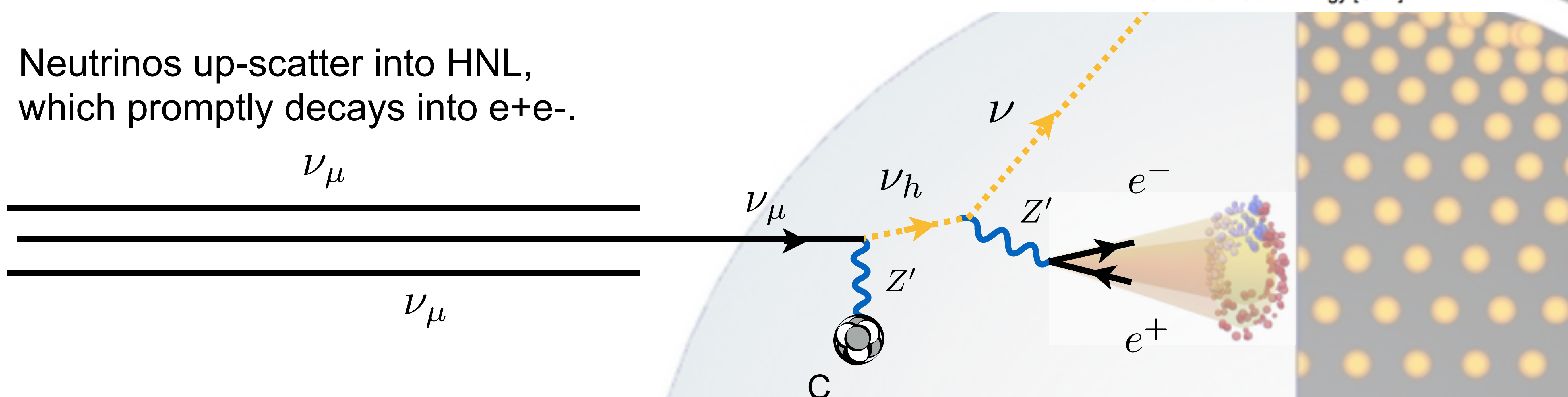
E. Bertuzzo et al., 1807.09877



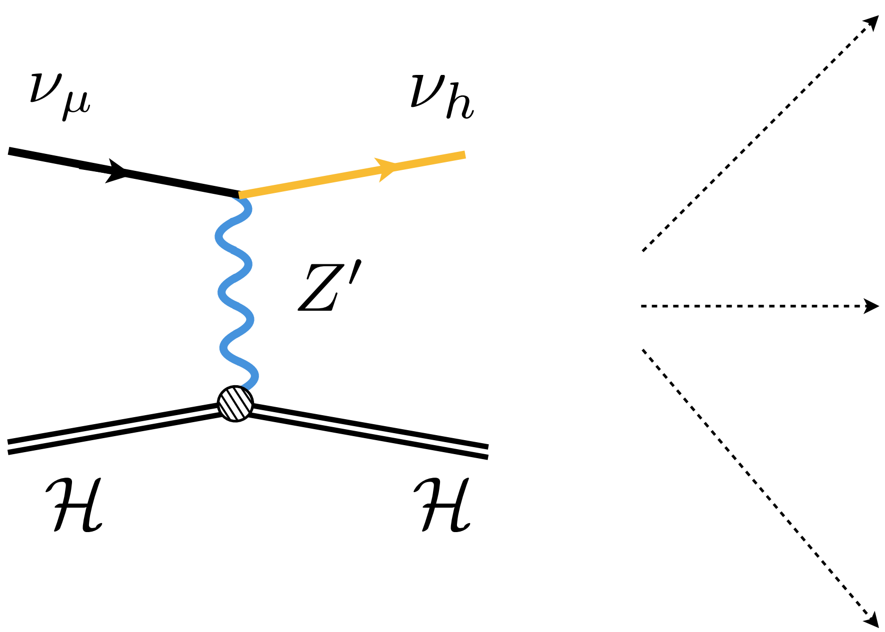
P. Ballett et al., 1808.02915

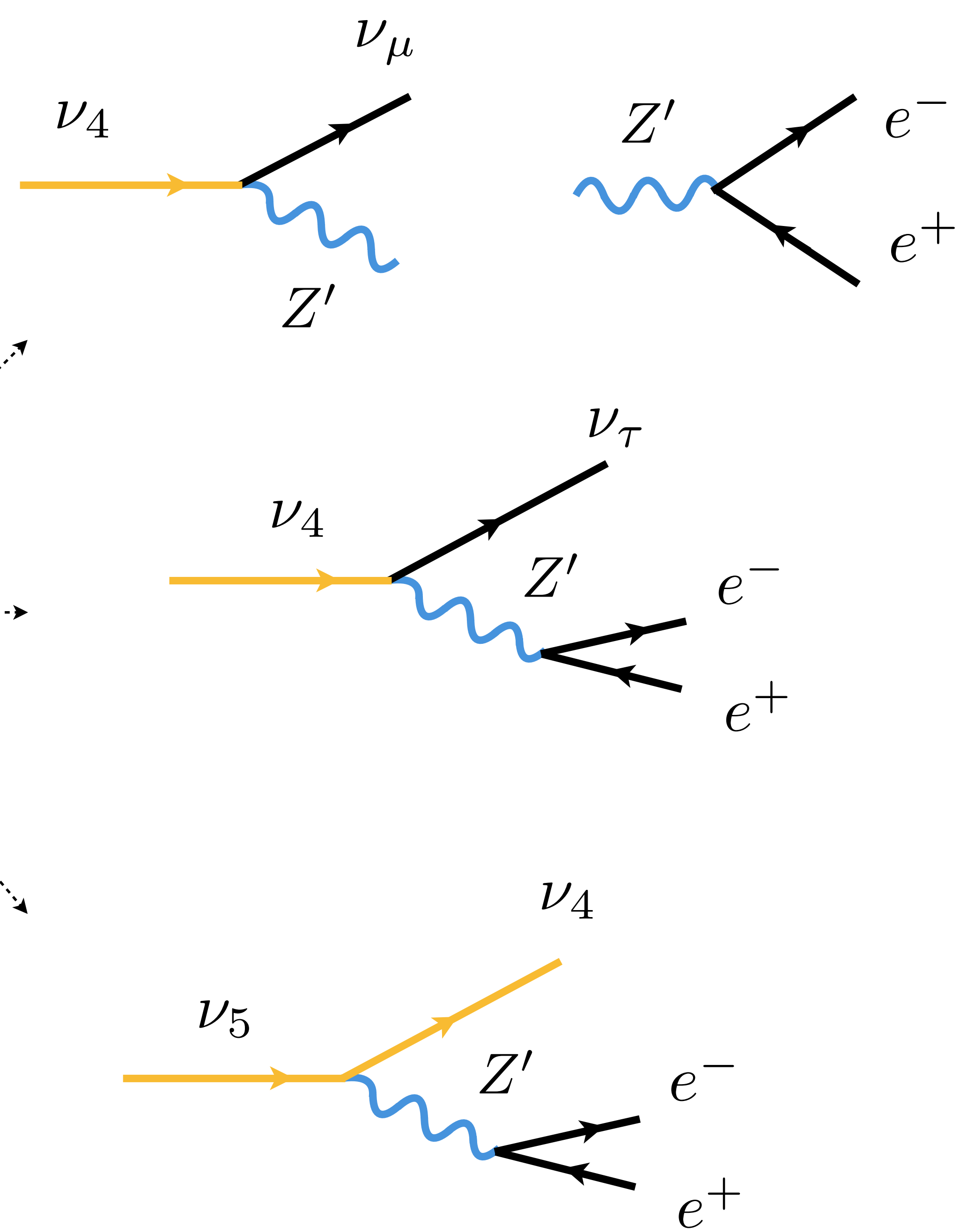


Neutrinos up-scatter into HNL, which promptly decays into e+e-.



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.

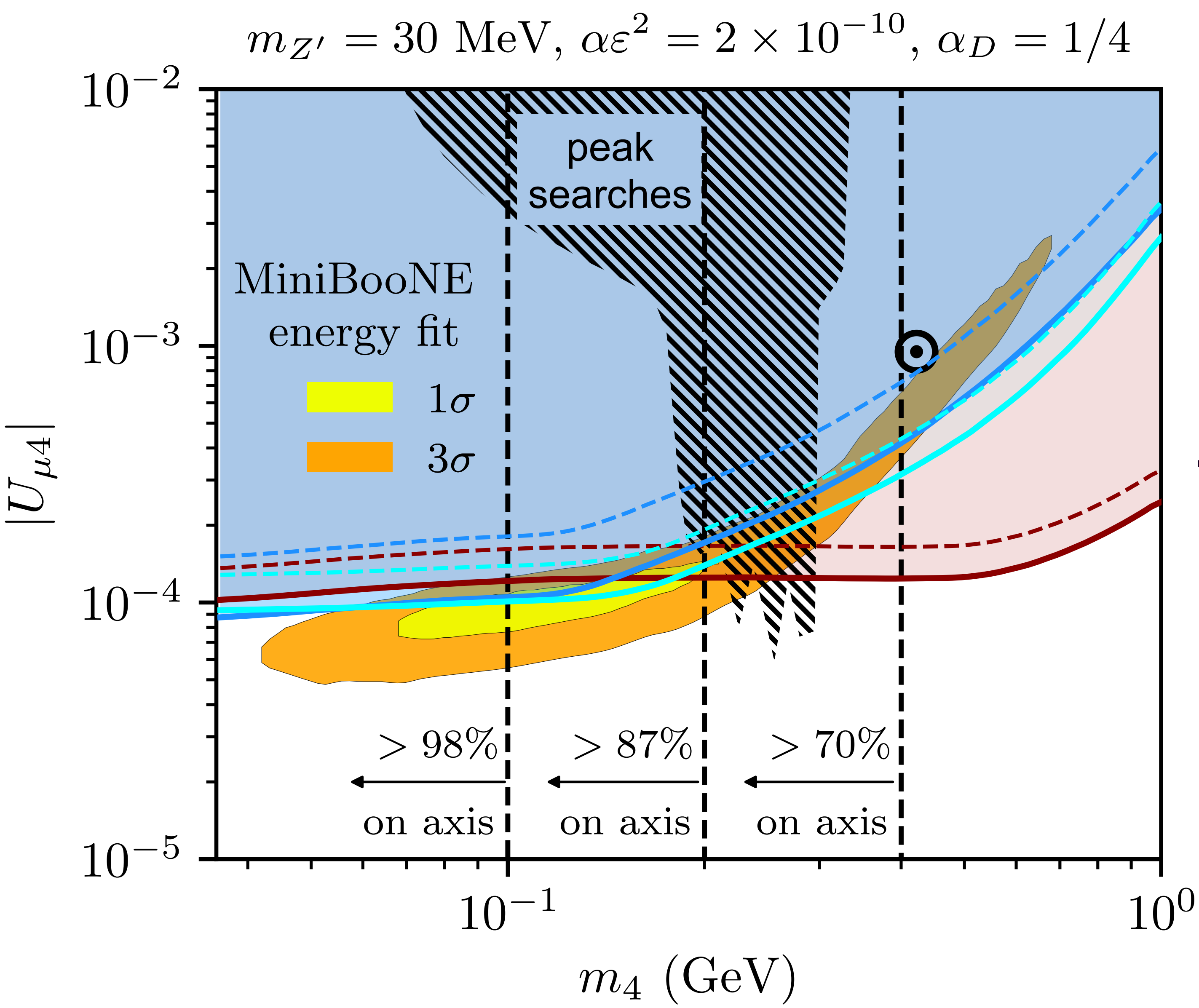
E. Bertuzzo et al., 1807.09877

P. Ballett et al., 1808.02915

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

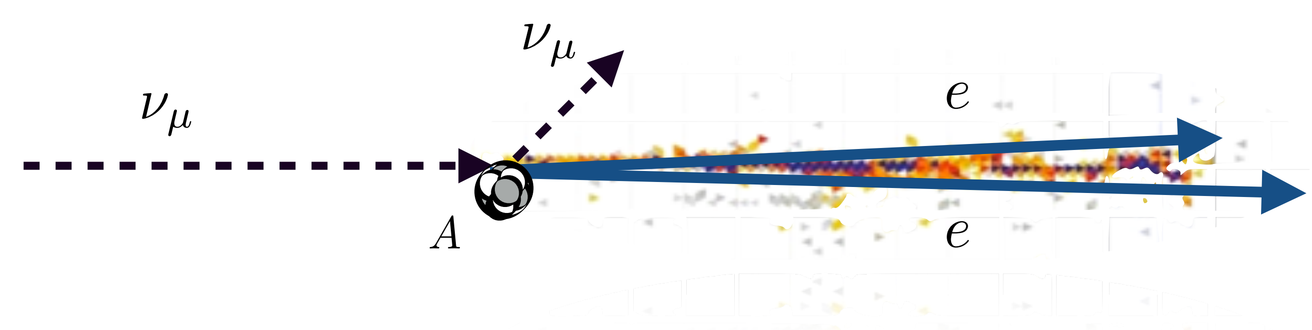
Light Dark Photon case

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



on axis = events in forward bin at MiniBooNE

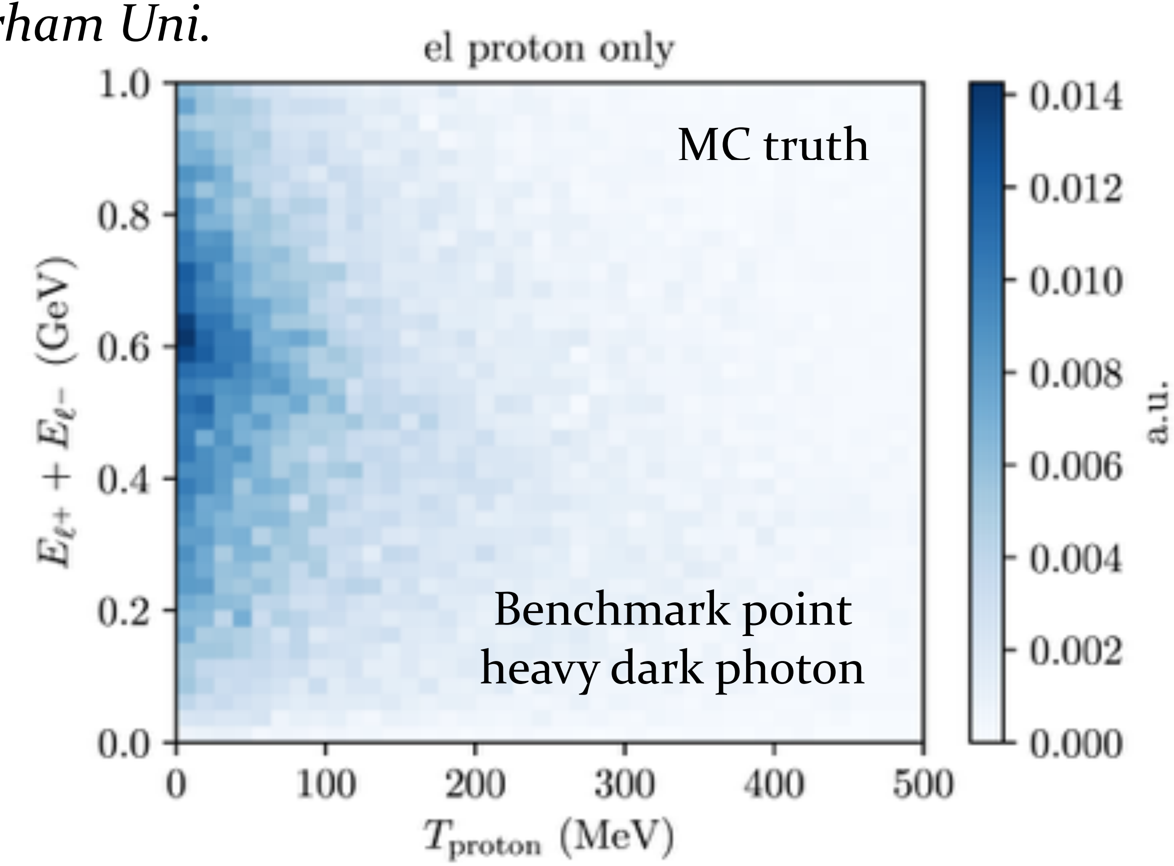
New bounds from single-photon sample in nu-e scattering analyses.

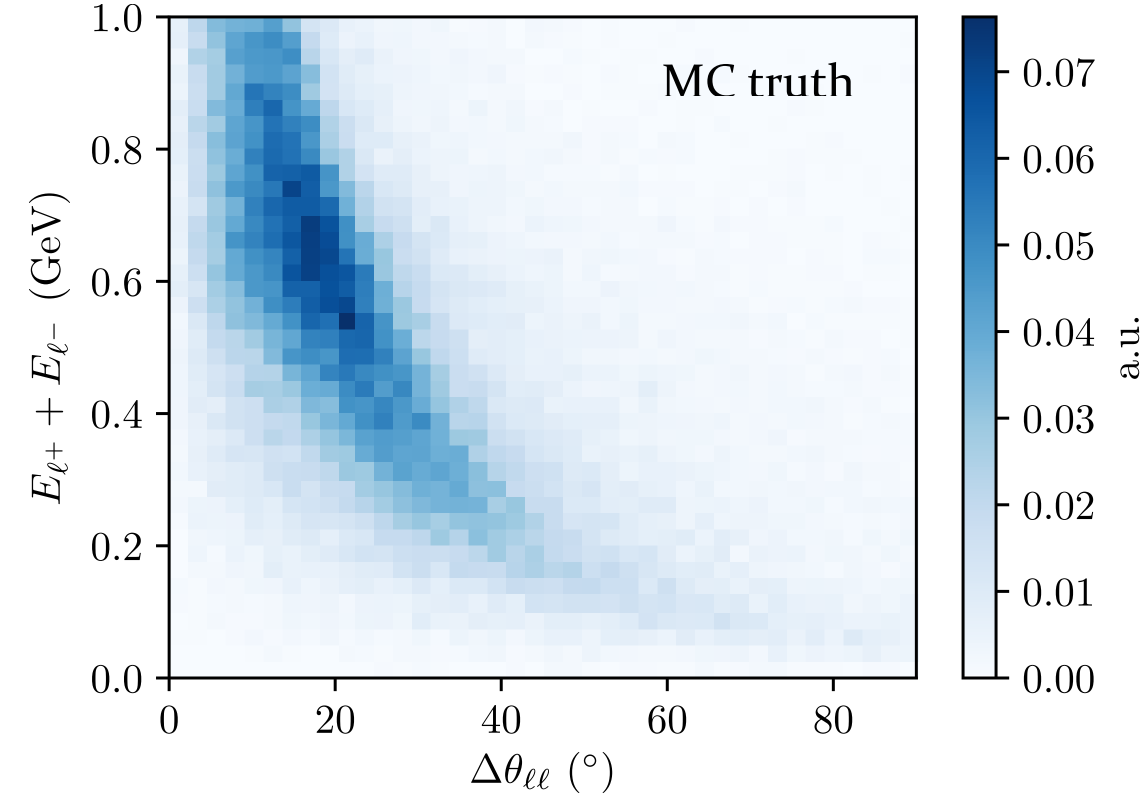


Conclusion:
HNL mass cannot be too large,
MiniBooNE signal typically very forward.

Asli Abdullahi
Durham Uni.

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





4 topologies currently under consideration:

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

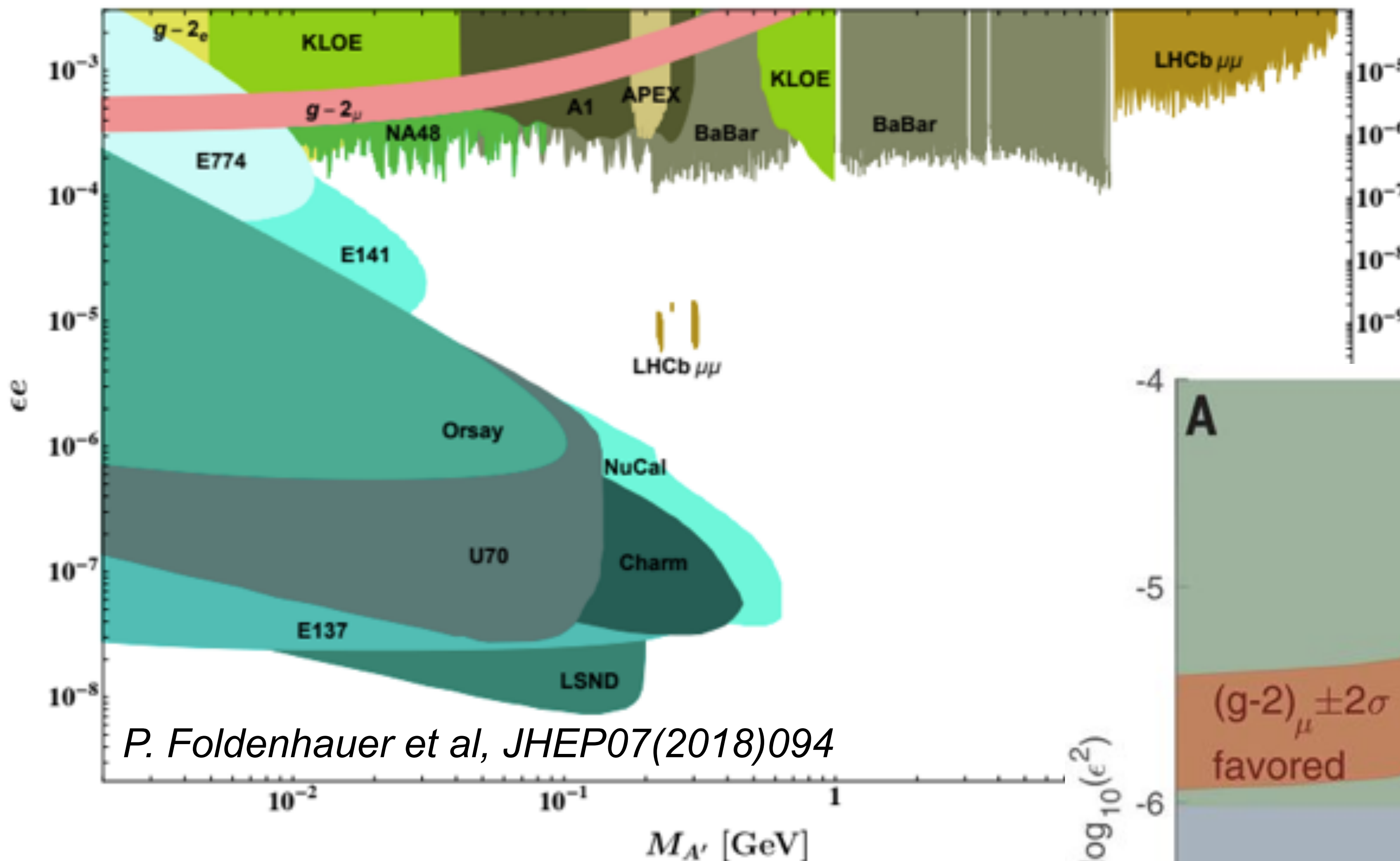
$1p^+ 1\gamma$ $1p^+ 2e$

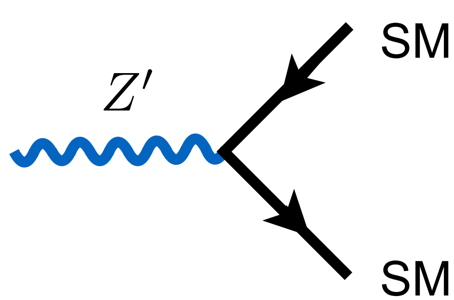
Pioneering study of genuine dielectron pairs in LAr.

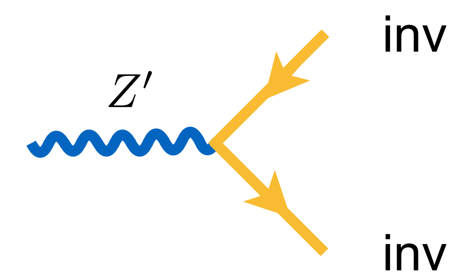
Light Dark Photon: no proton so smaller efficiencies, but enhanced in LAr (A^2 coherent.)

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

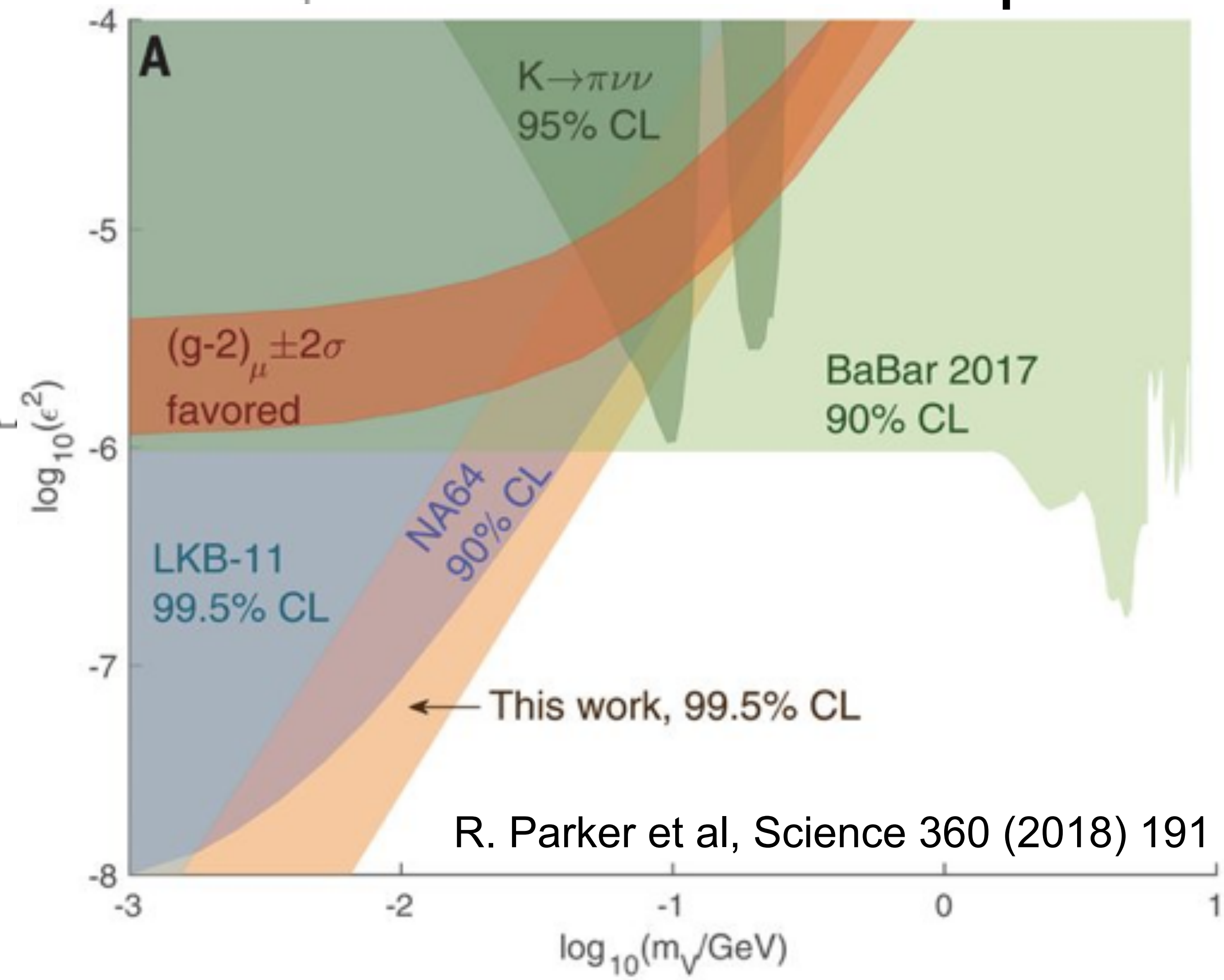
Minimal dark photon model

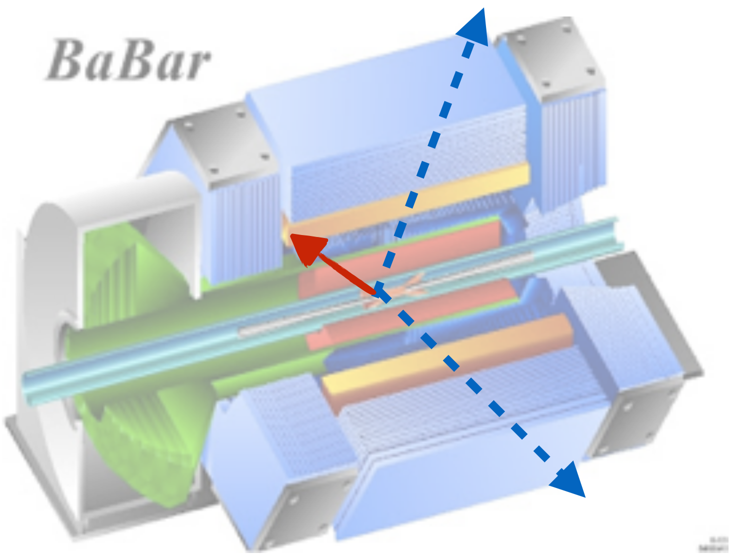






Invisible dark photon

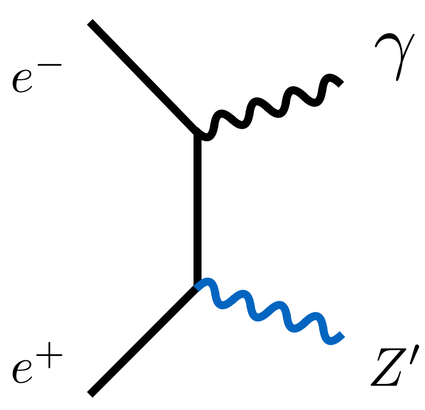




J.P. Lees, PRL.119.131804

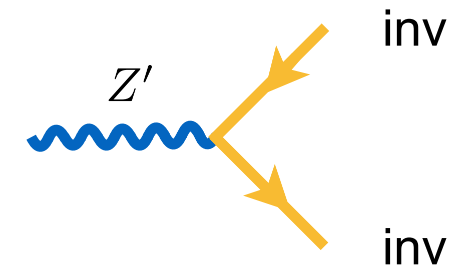
Signal: mono-photon + $\not{E}$

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

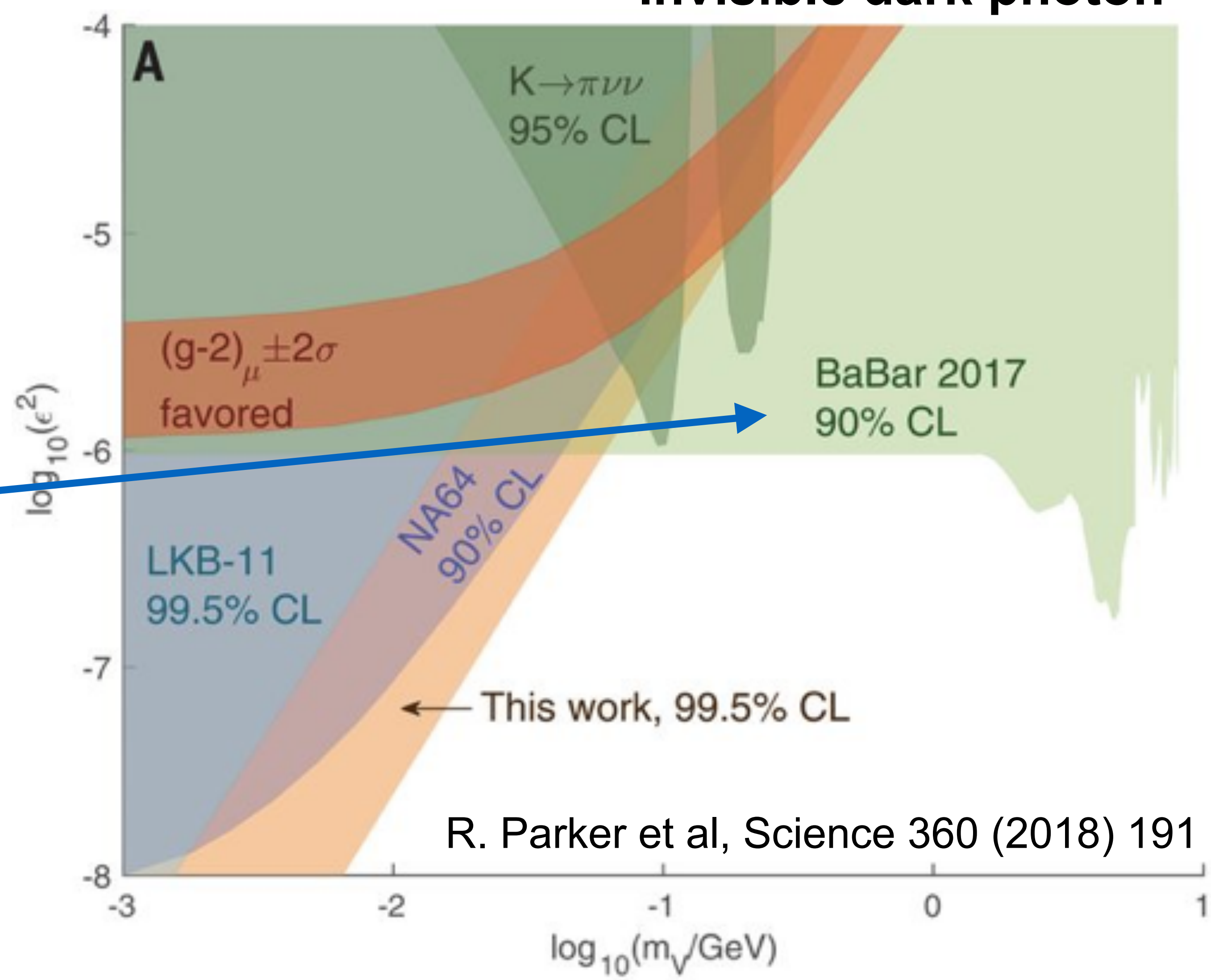


bump hunt

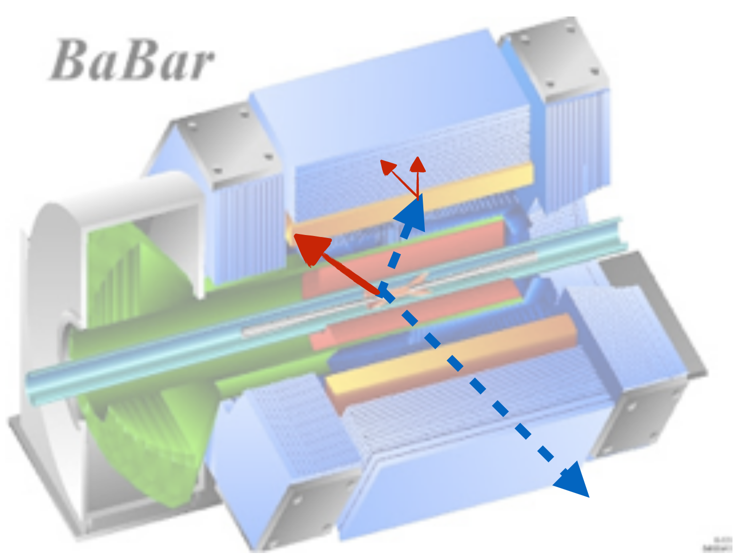
$$M_{Z'}^2 = s - 2E_\gamma \sqrt{s}$$

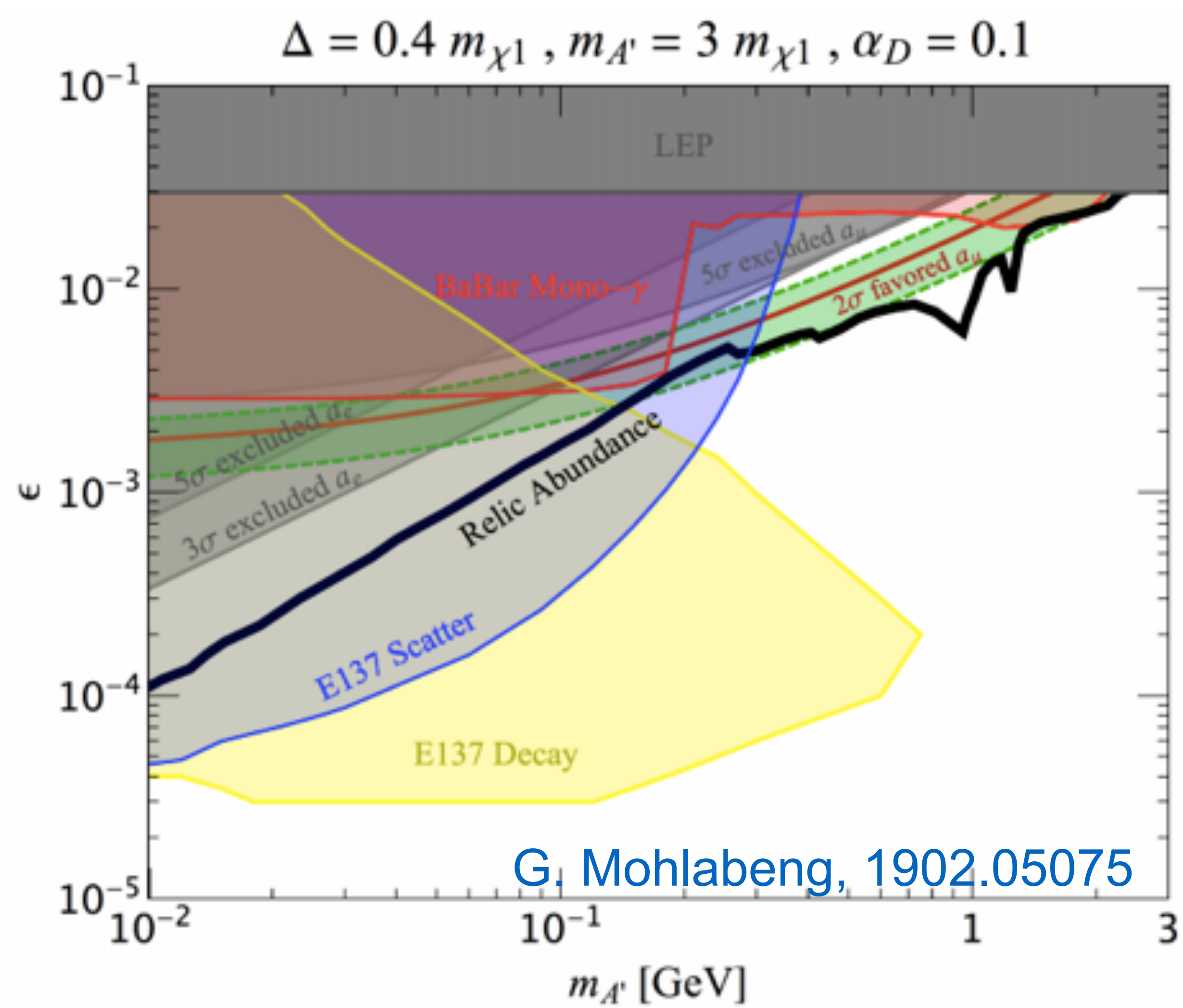


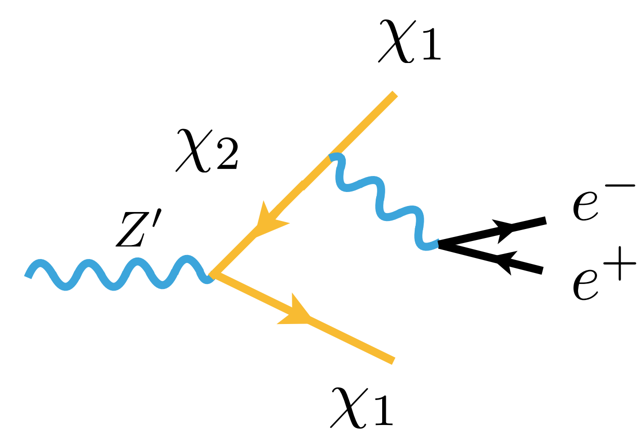
Invisible dark photon



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

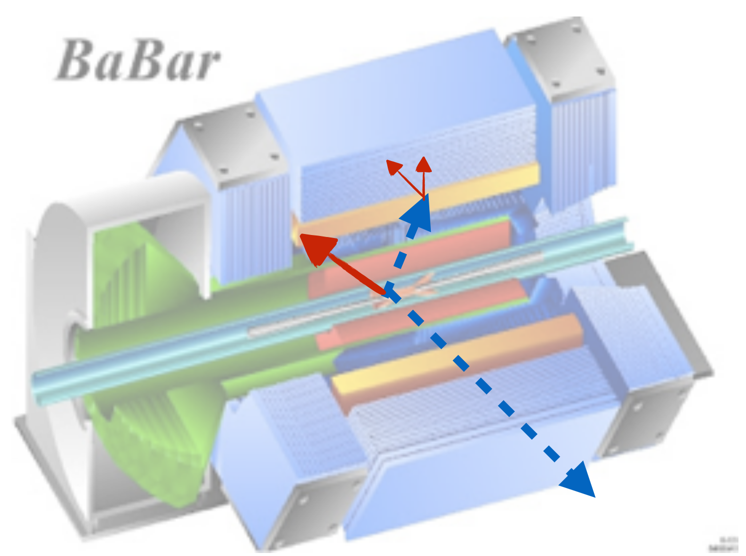




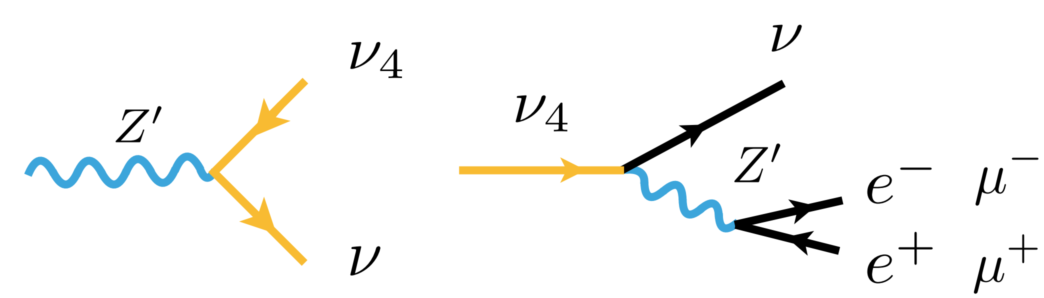


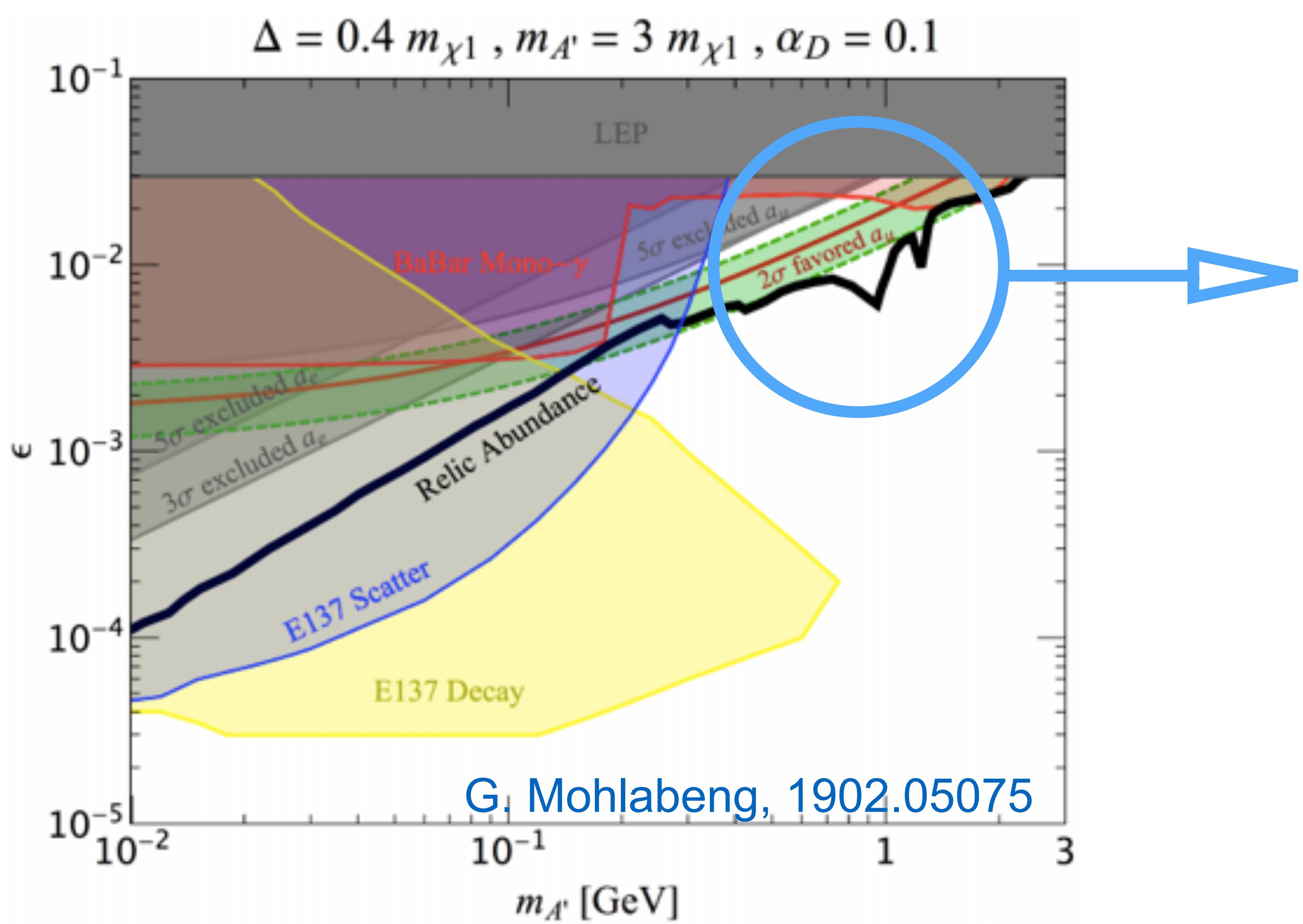
In a 2-fermion dark sector, one may relax
such bounds if the heaviest fermion decays visibly.

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



<u>Even more relevant for dark neutrinos</u>





G. Mohlabeng, 1902.05075

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

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

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

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

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

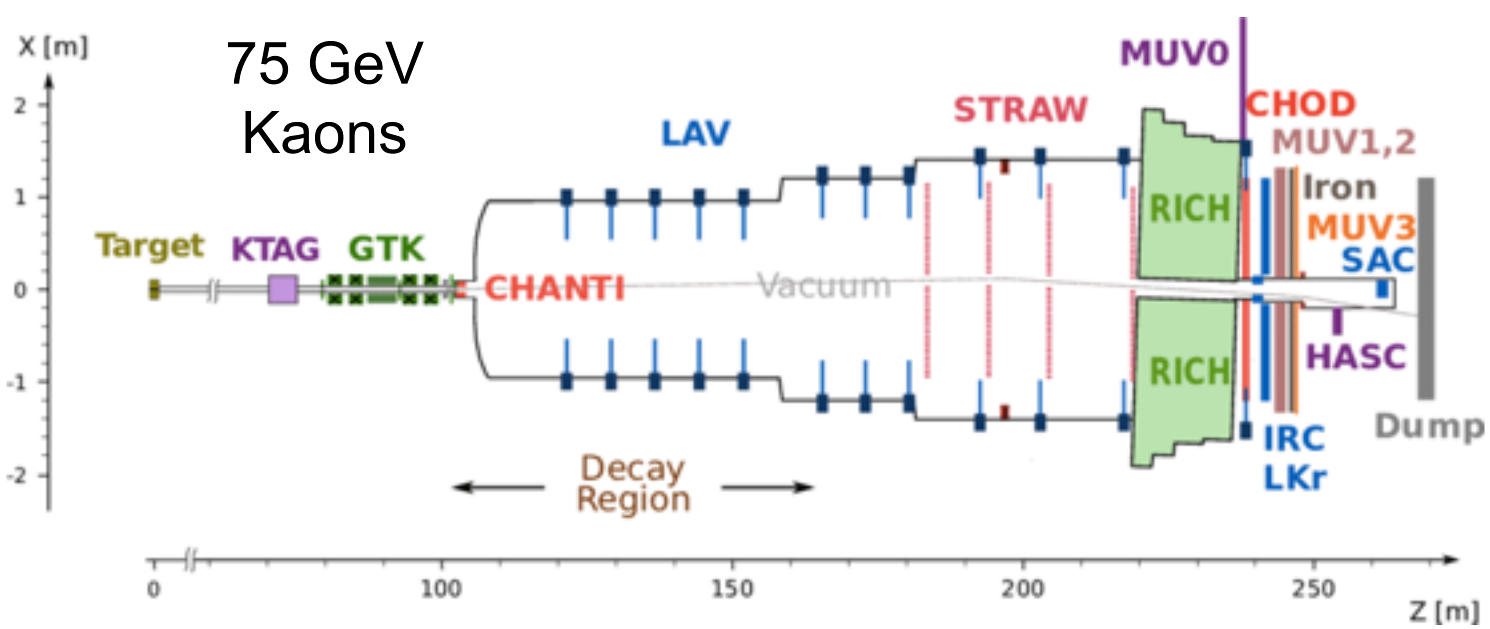
Usual peak searches based on kinematical argument:

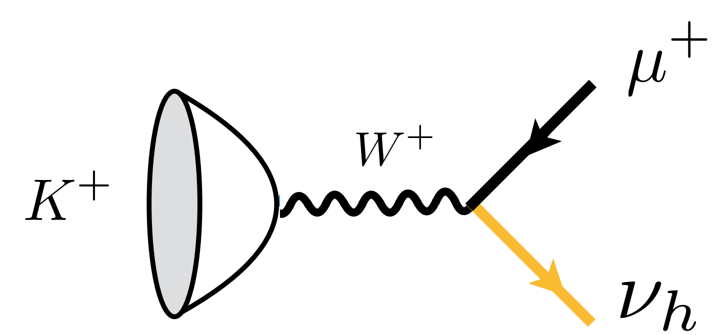
$$m^2_{p_K - p_\alpha} \equiv (p_K - p_\alpha)^2 = m^2_{\nu_h},$$

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

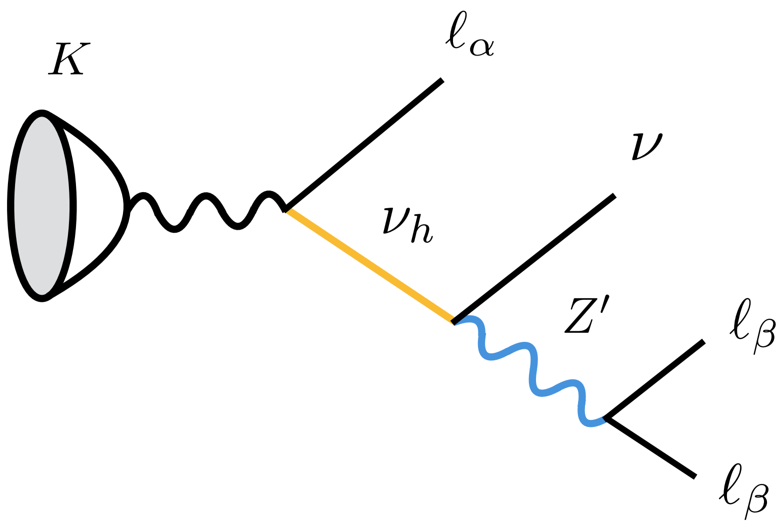
Provided the detection *inefficiency* to additional particles is not too small, can be relaxed significantly!

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





 *special thanks to Evgueni Goudzovski for discussion on NA62



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:

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

<u>“Multi-dimensional bumps” from 2-body kin:</u>

Directly measure dark state masses

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

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

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

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

With perfect resolution this constitutes a zero-background search!

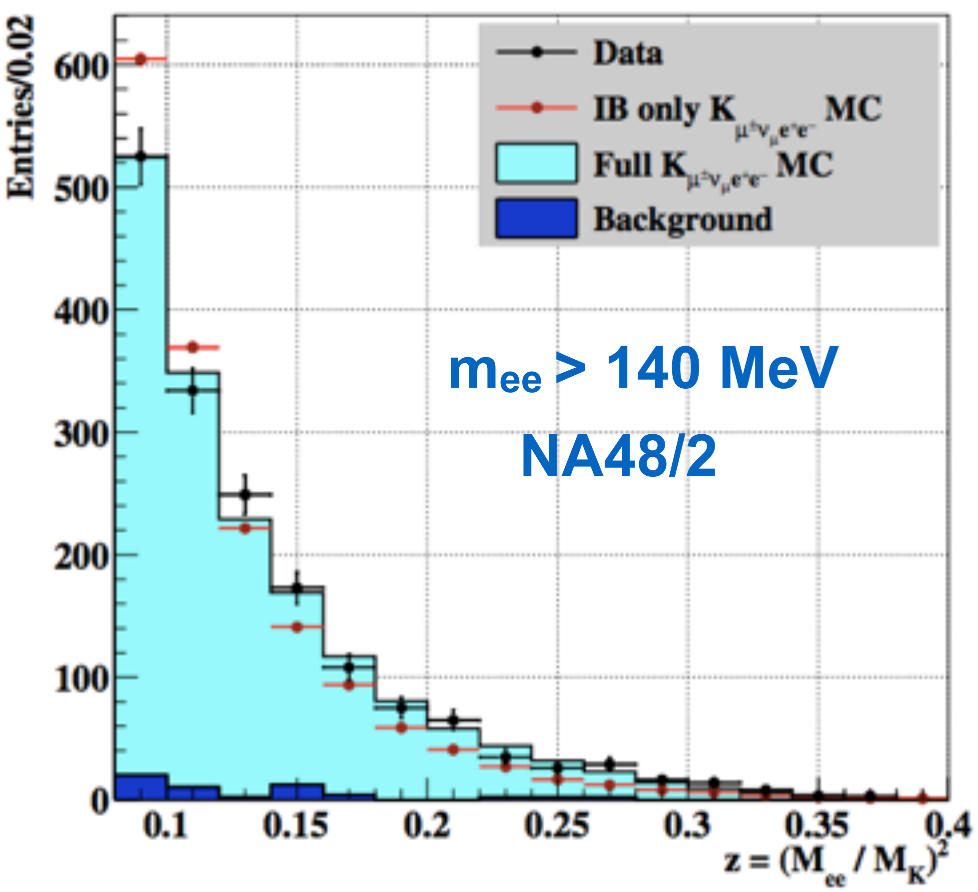
e.g.

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

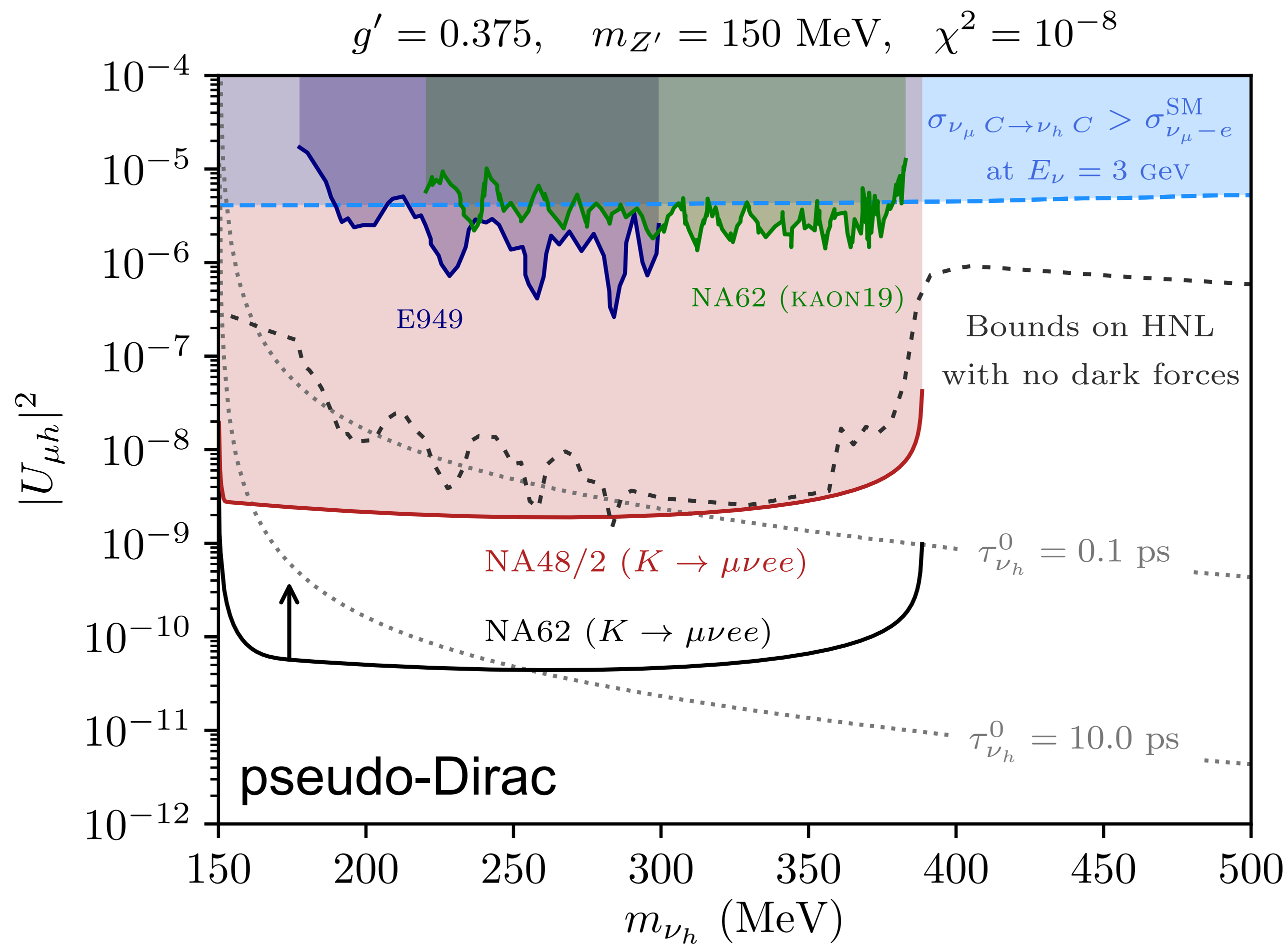
$c\tau$ > 10 ps

Existing measurements

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

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

Both SM process will be measured by NA62.



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.

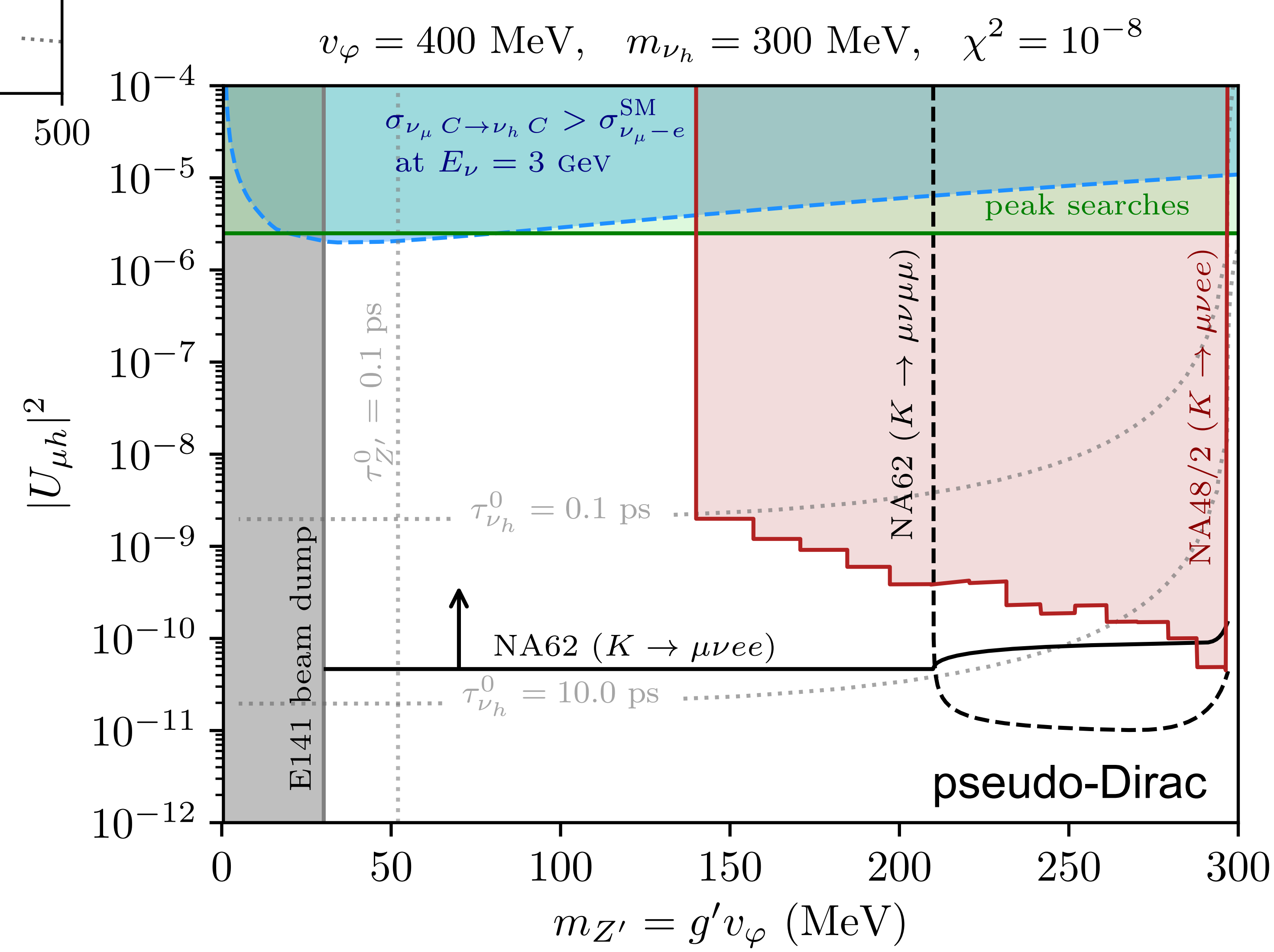
NA62 S.E.S. assuming background-free search.

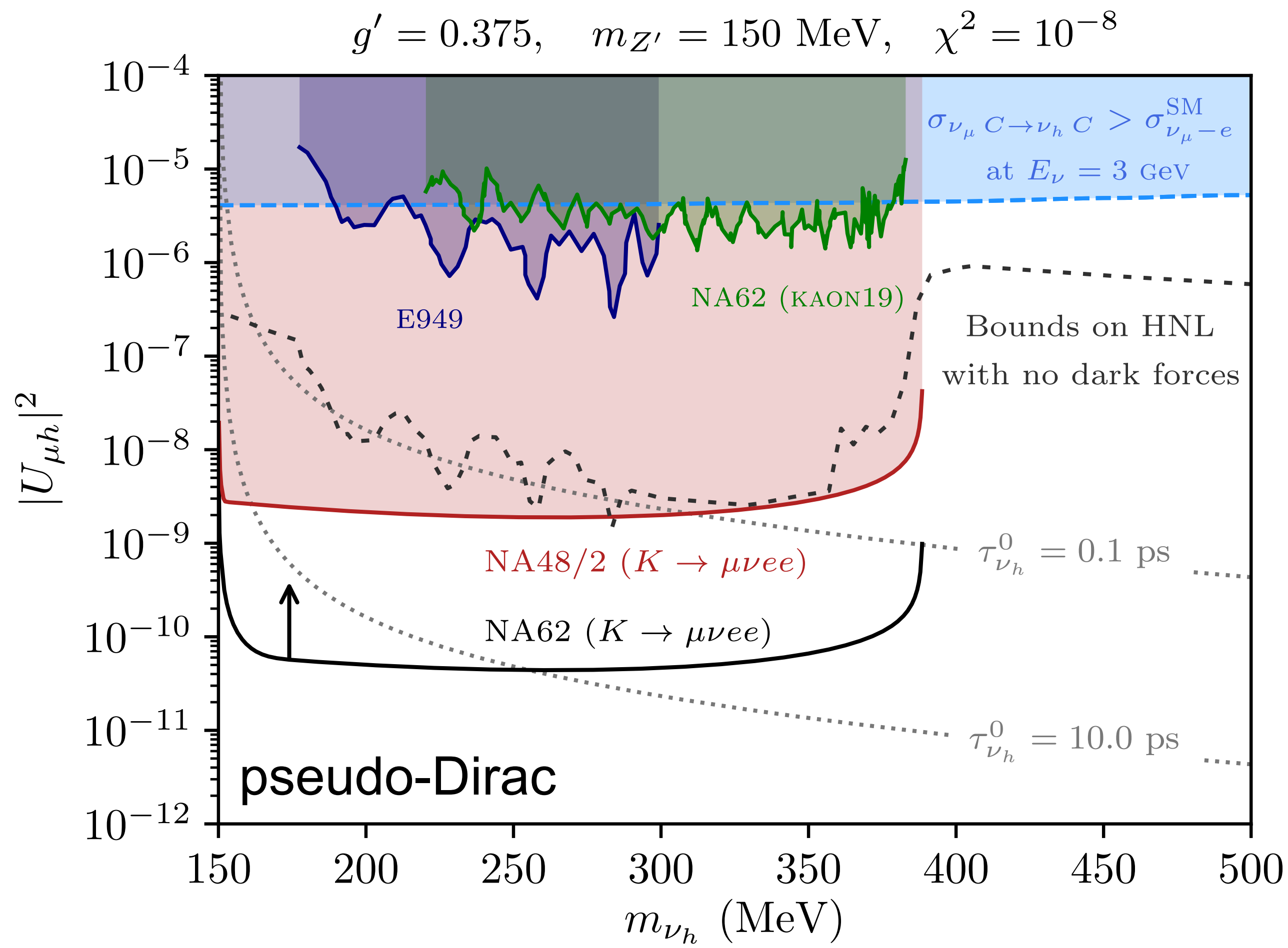
Assumptions matched to LNV search in K+→π−e+e+ and K+→π−μ+μ+

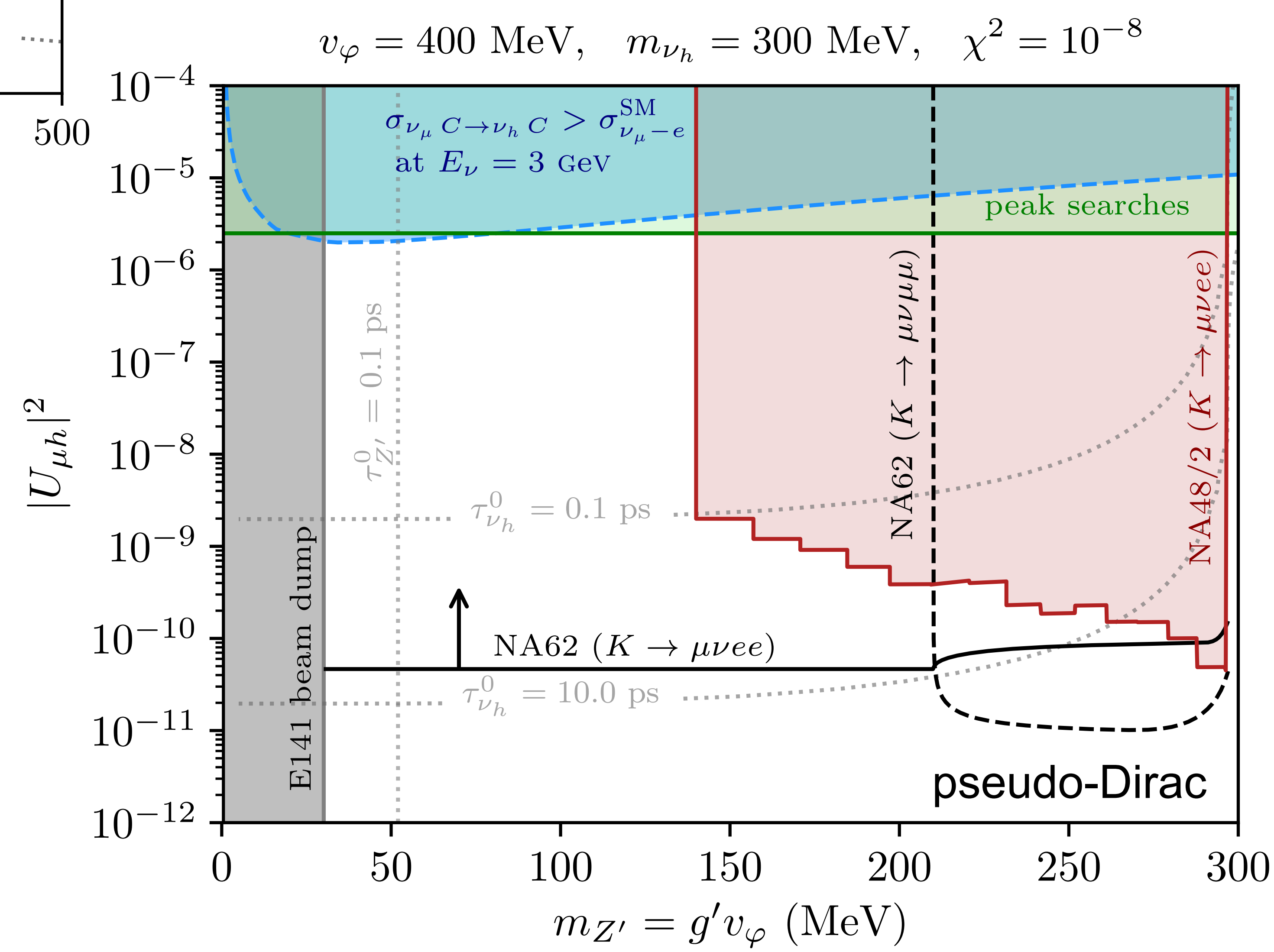
Total of 1.6e12 useful Kaon decays
(only 30% of NA62 dataset!)

4% acceptance of ee
8% acceptance for μμ

NA62 Coll., *j.physletb*.2019.07.041







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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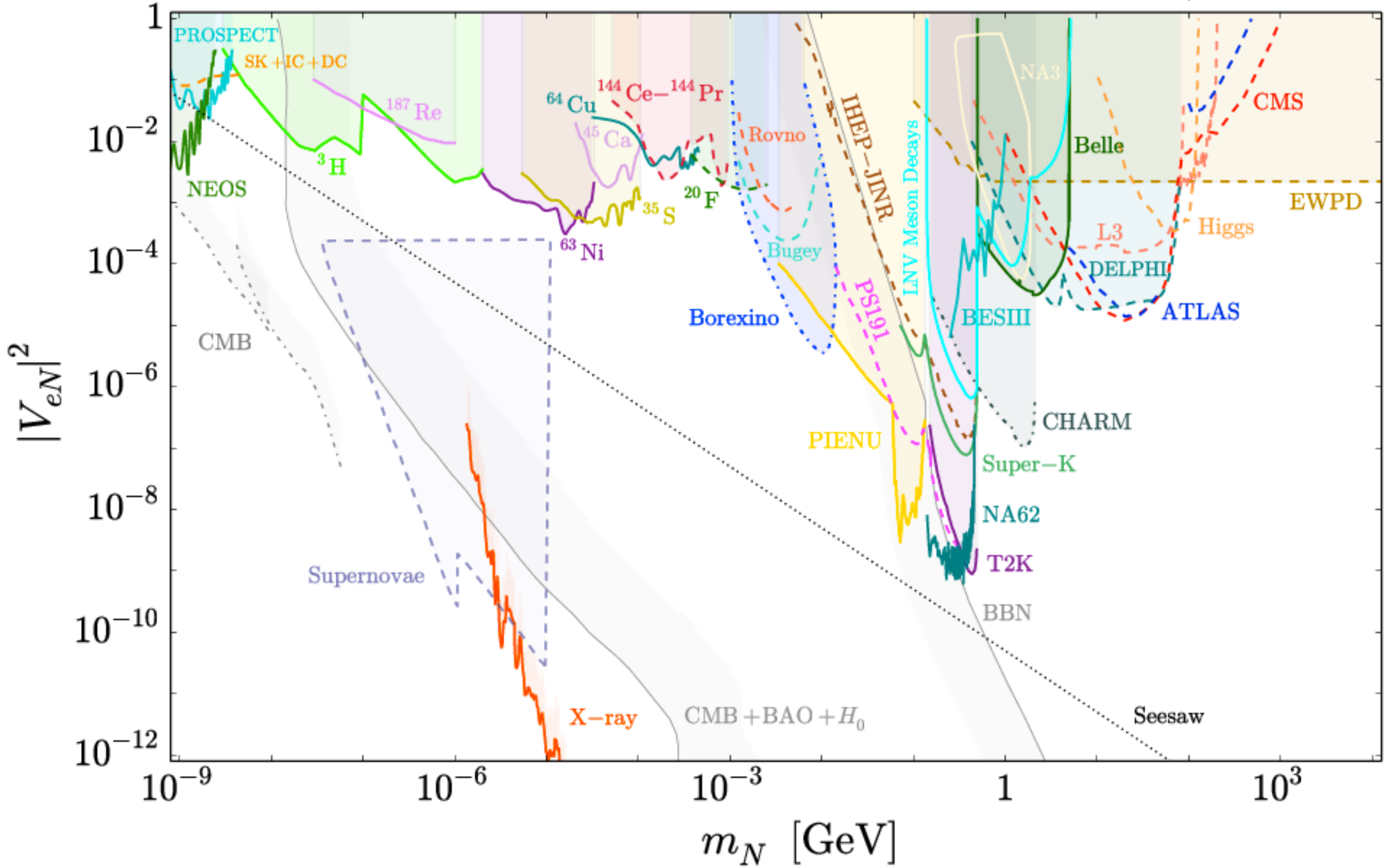
New searches for such dark neutrino sectors at NA62. "Smoking-gun" signature in

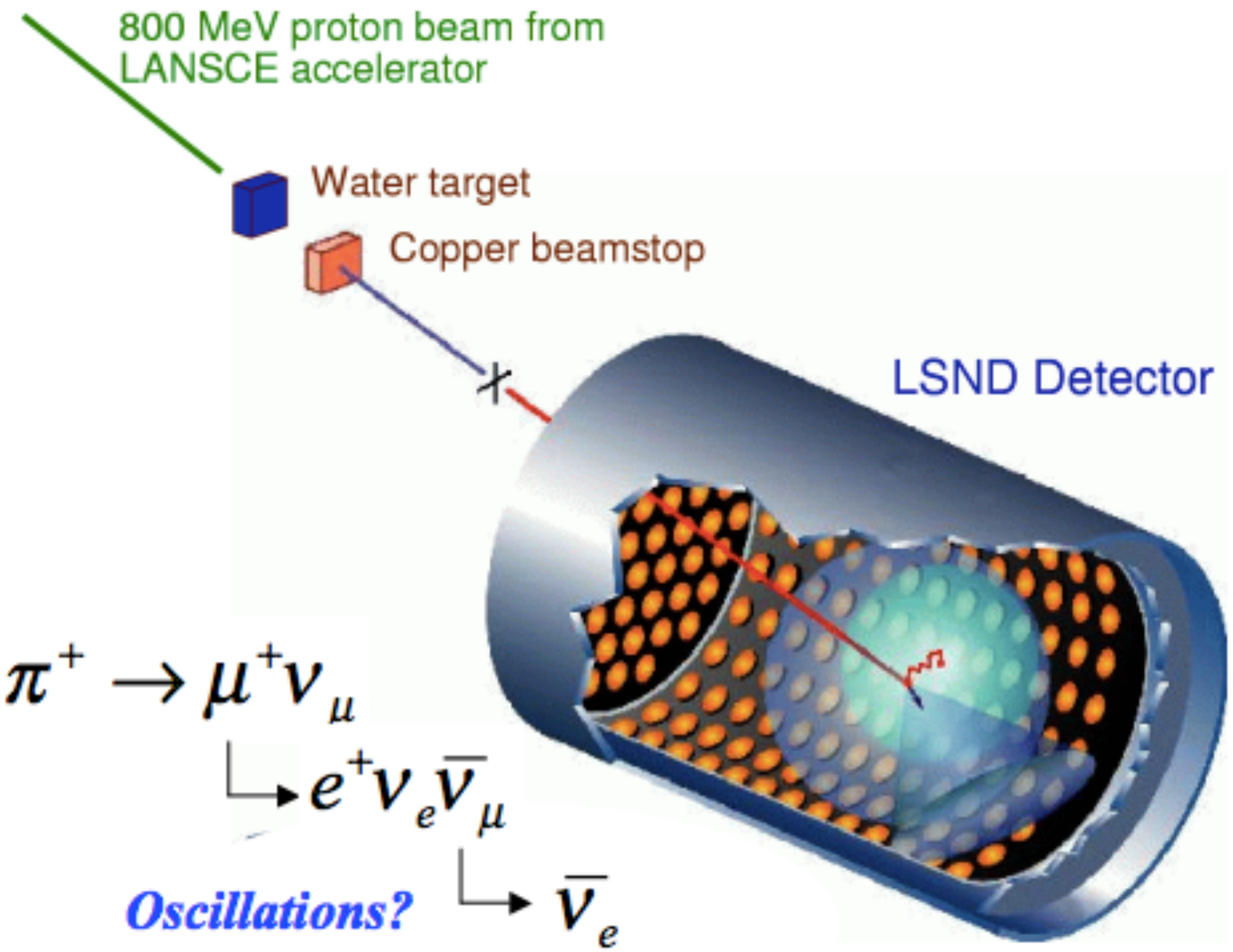
$$K^+ \to \ell^+ \nu e^+ e^-$$

APPENDIX

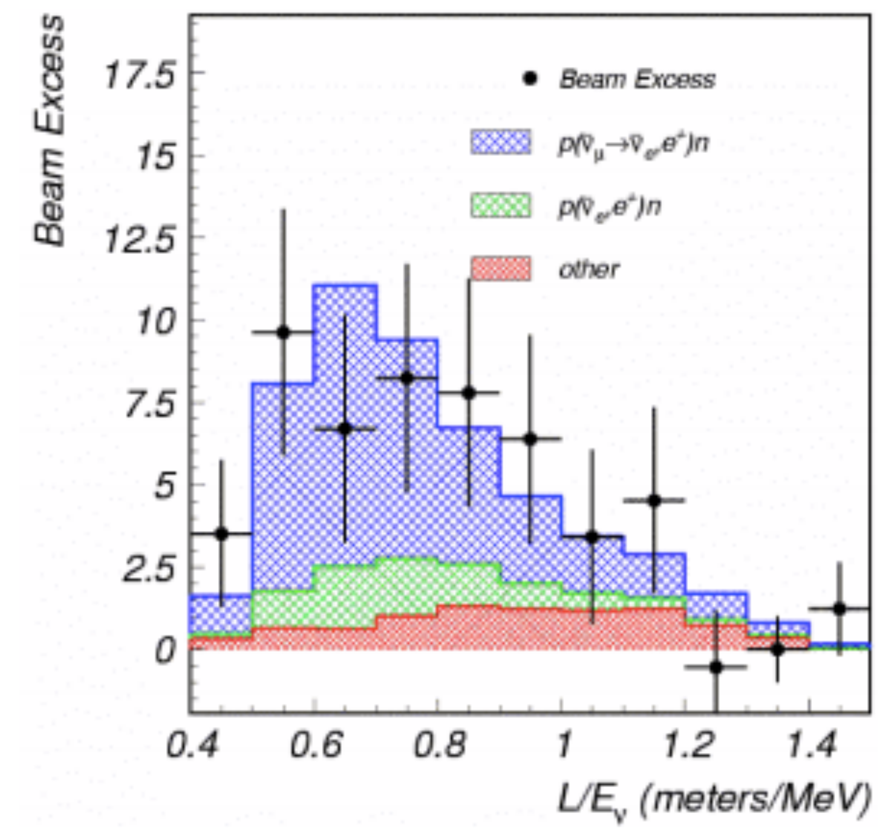
P. Bolton, 1912.03058



Liquid Scintillator Neutrino Detector: 1993 - 1998



Inverse Beta Decay events



Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

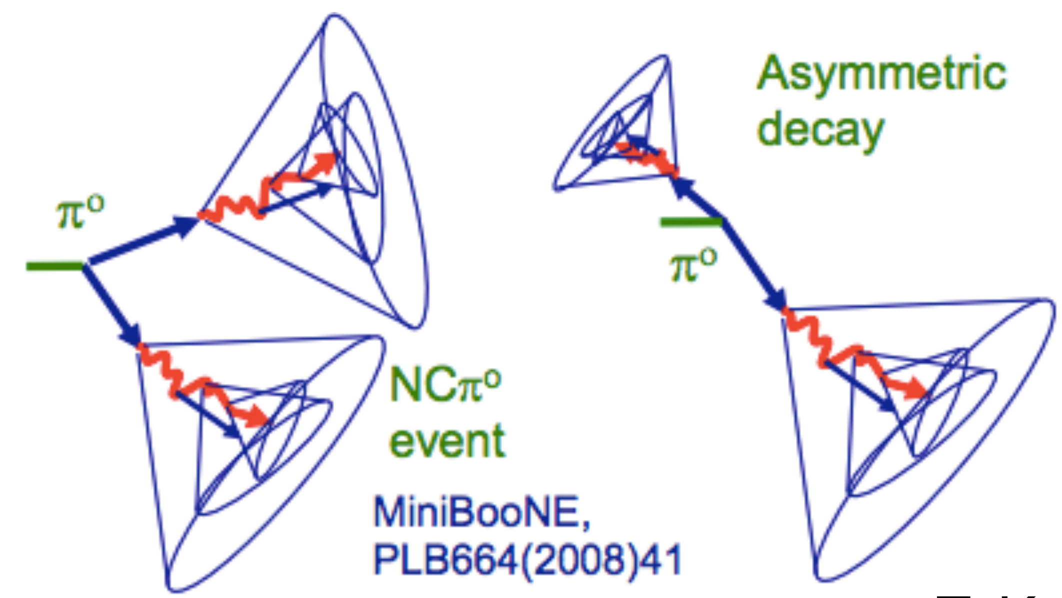
3.8 σ evidence for oscillation.

*Another similar experiment, KARMEN, did not see an effect — but could not rule out all parameter space either.

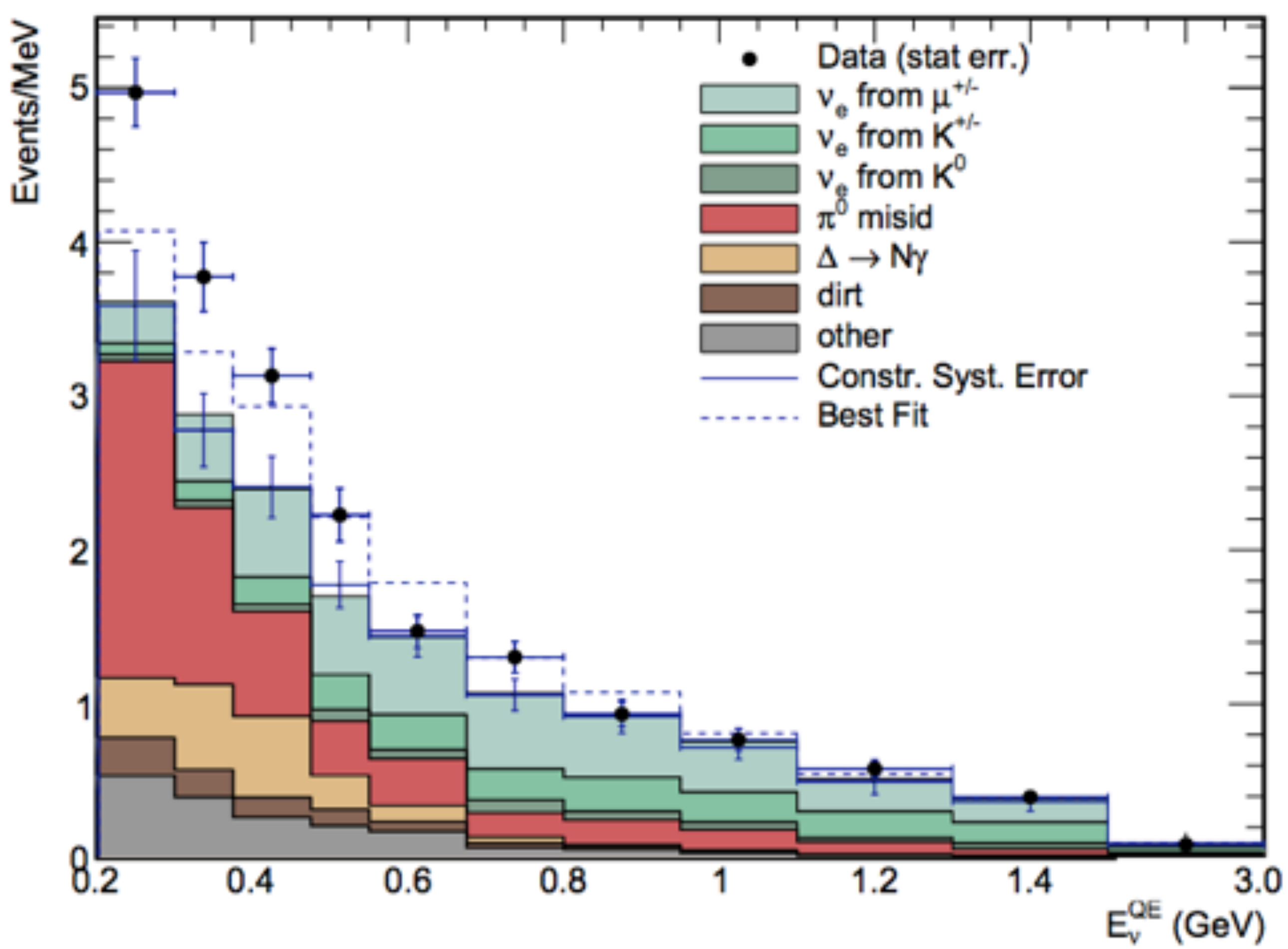
Endpoint 52 MeV — detector 30 m away.

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \to N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
Unconstrained Bkgd.	1590.6 ± 176.9	398.2 ± 49.7
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6

This channel relies on pion decay being highly asymmetric

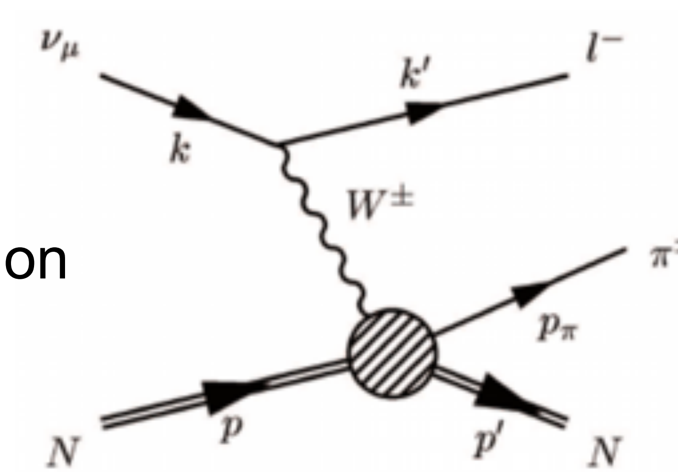


T. Katori



Effectively constrained by measuring other channels and extrapolating (somewhat model dependent):

CC/NC pion production



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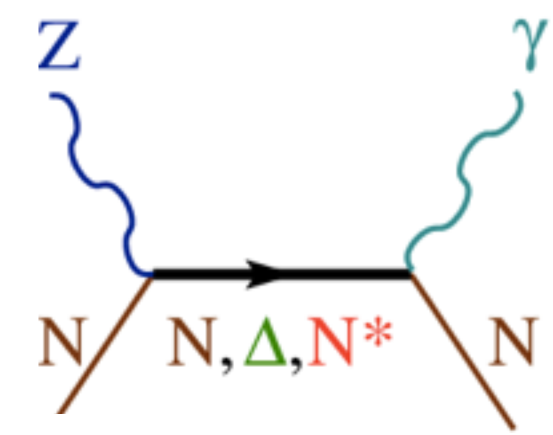
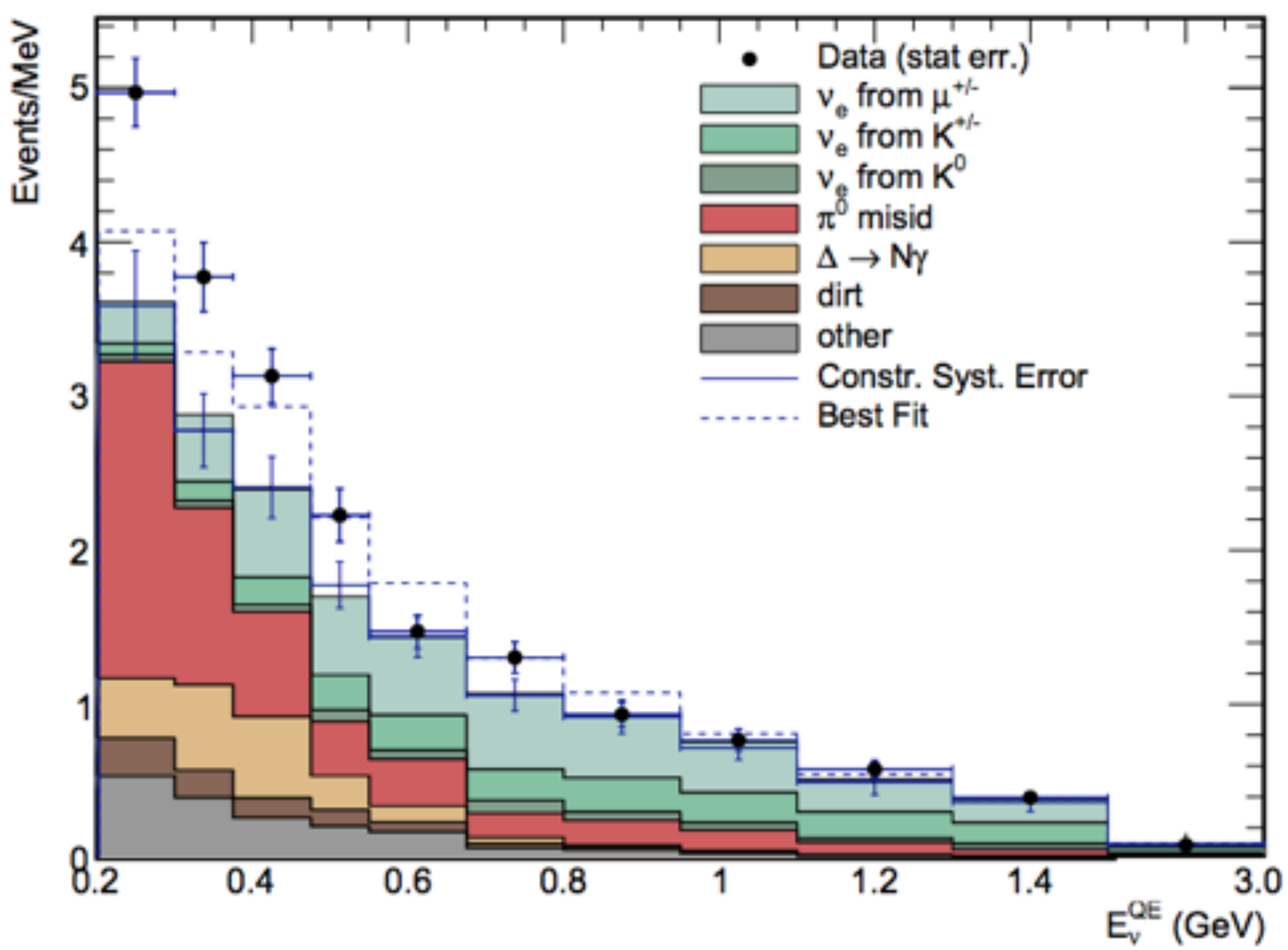
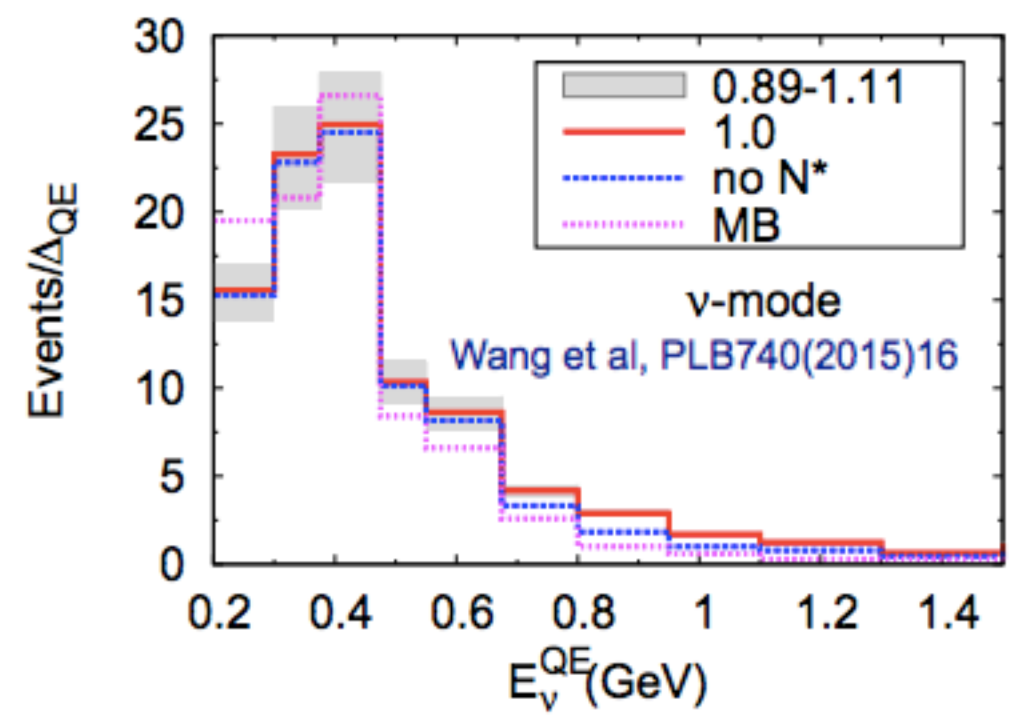
Mostly NC resonant through Delta(1232)

Constrained by pion events





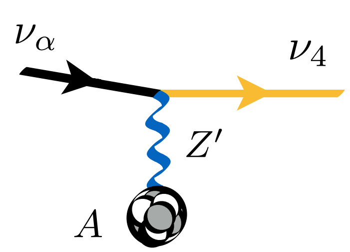


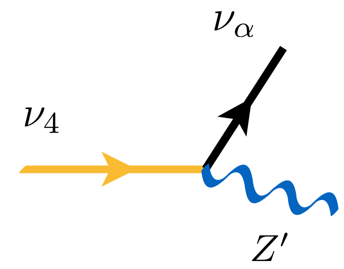
Coherent contribution shown to be small in “theory”

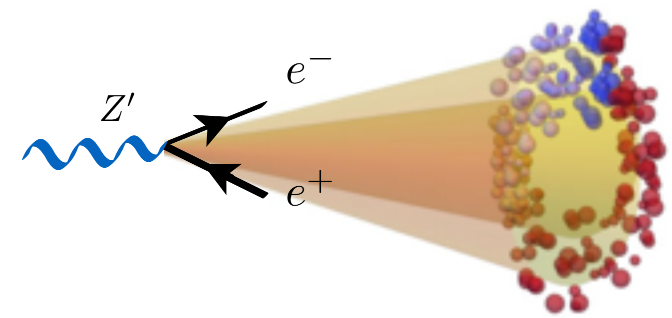
Hill, PRD84(2011)017501
Zhang and Serot, PLB719(2013)409
Wang et al, PLB740(2015)16

E. Bertuzzo et al., PRL121.241801

$$m_{Z'} < m_4$$

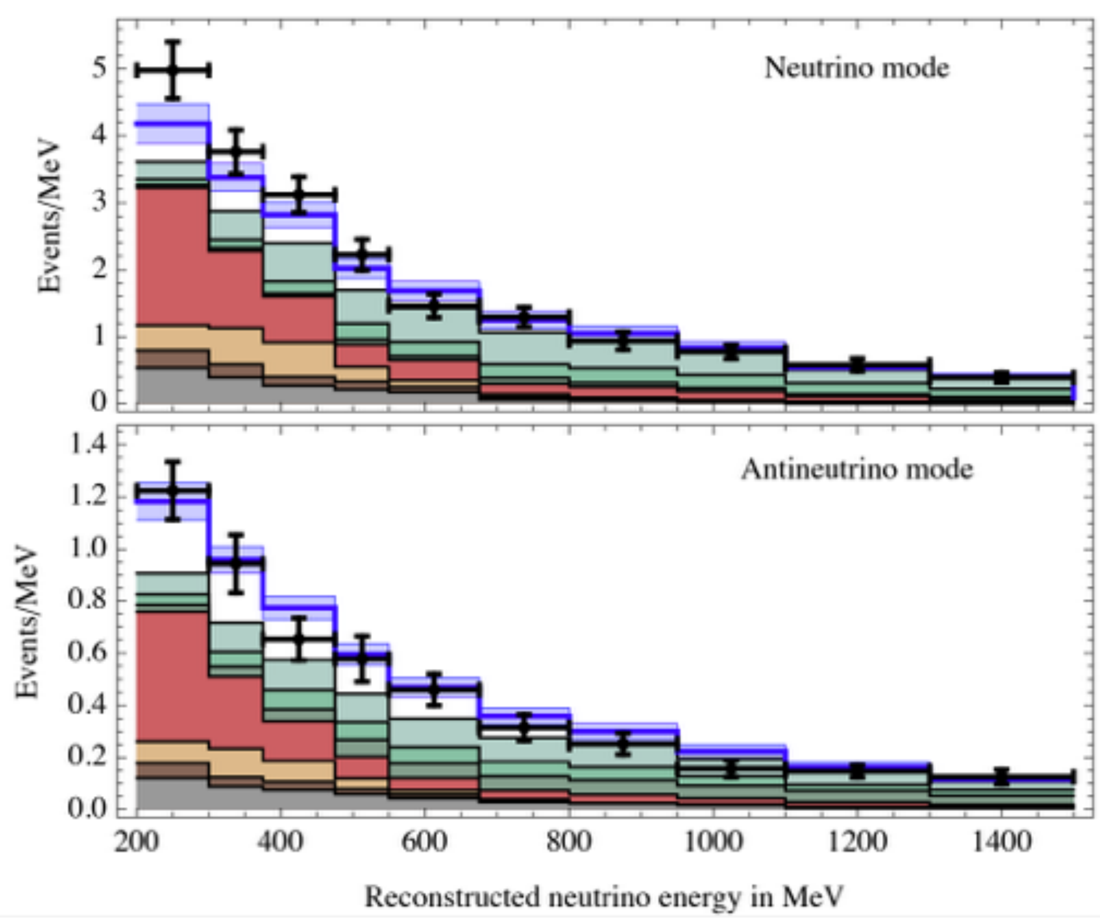


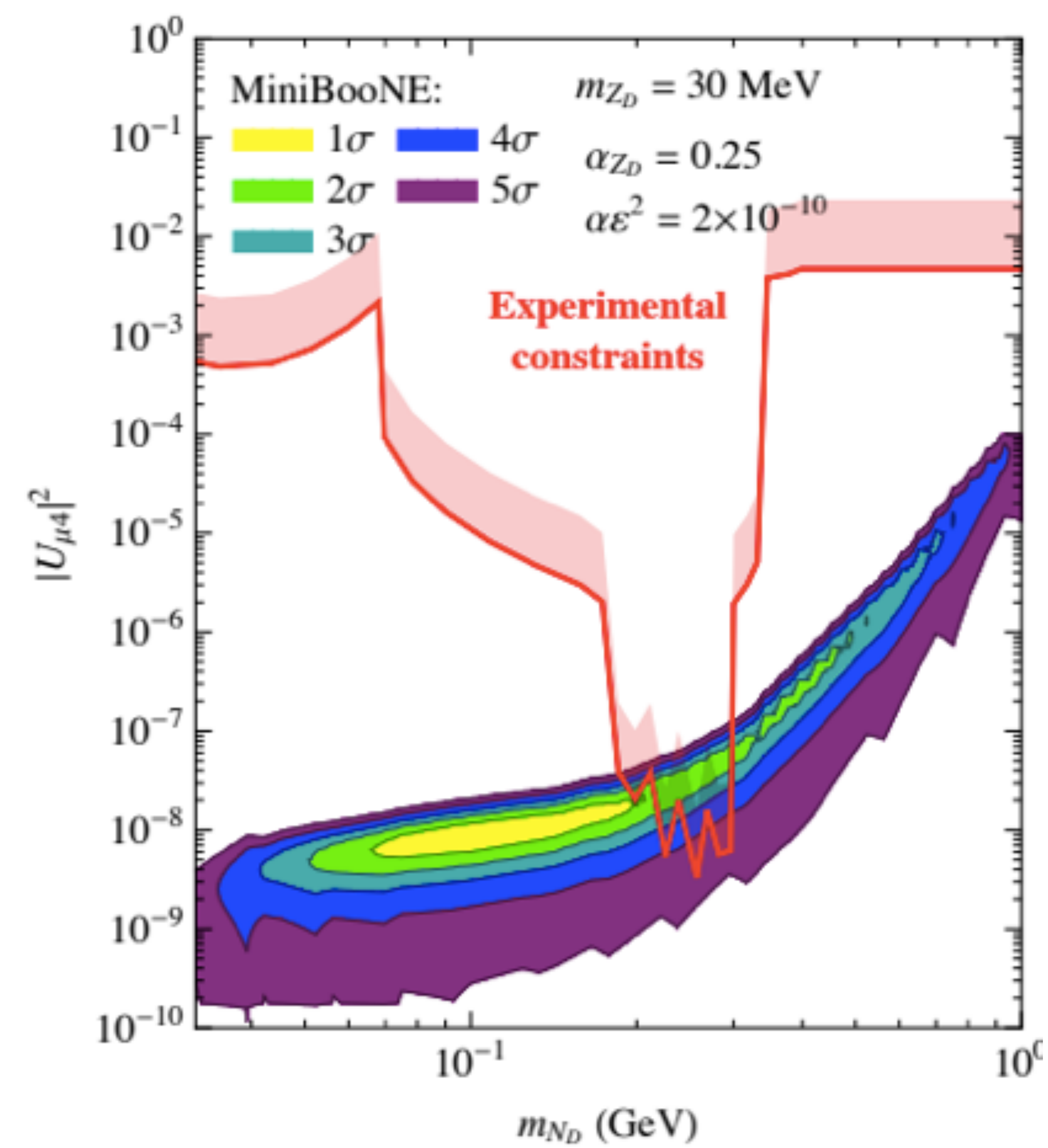




Coherent signal

single <u>boosted</u> EM shower

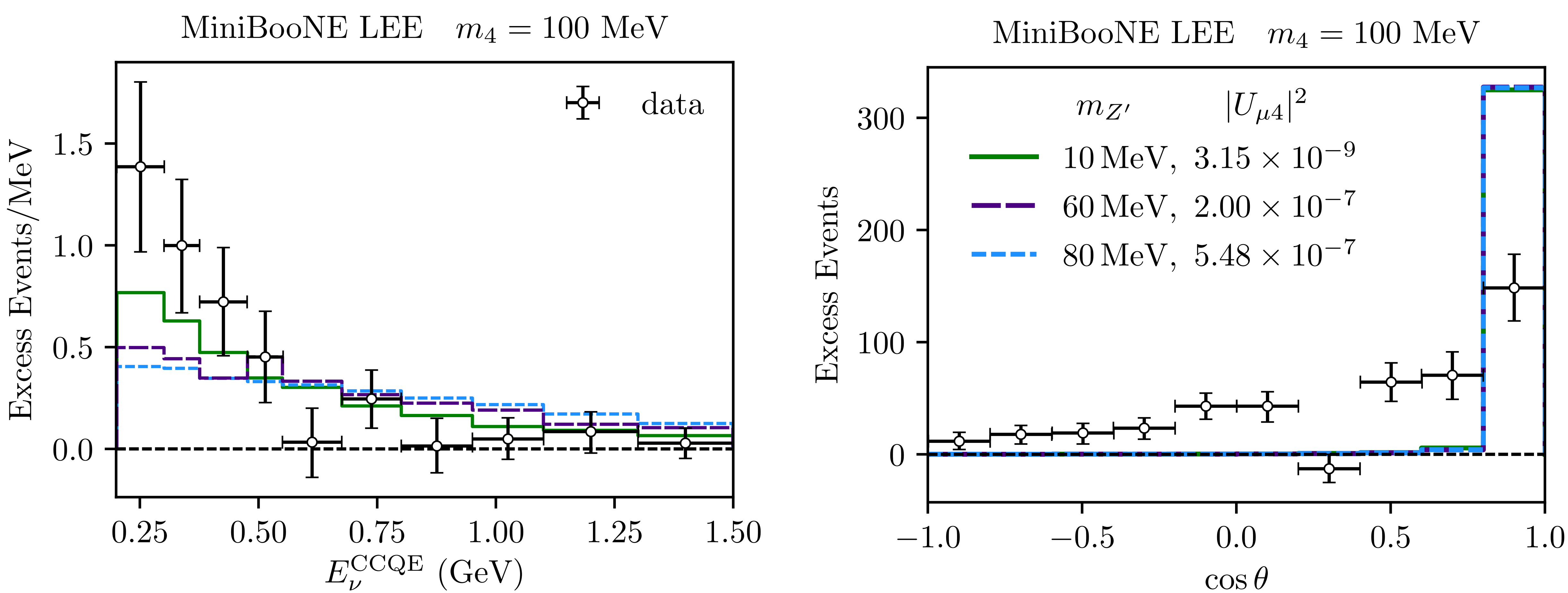




C. Argüelles, MH, *Y. Tsai, PRL123, 261801 (2019)*

We revisit this MiniBooNE explanation using a better signal definition:

only *overlapping* + *asymmetric* ee pairs used to define $E_\nu^{\rm CCQE}$ and $\cos\theta$



$m_{Z'} = 30$ MeV, $\alpha\varepsilon^2 = 2 \times 10^{-10}$, $\alpha_D = 1/4$

MiniBooNE — Light dark photon — revisited

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

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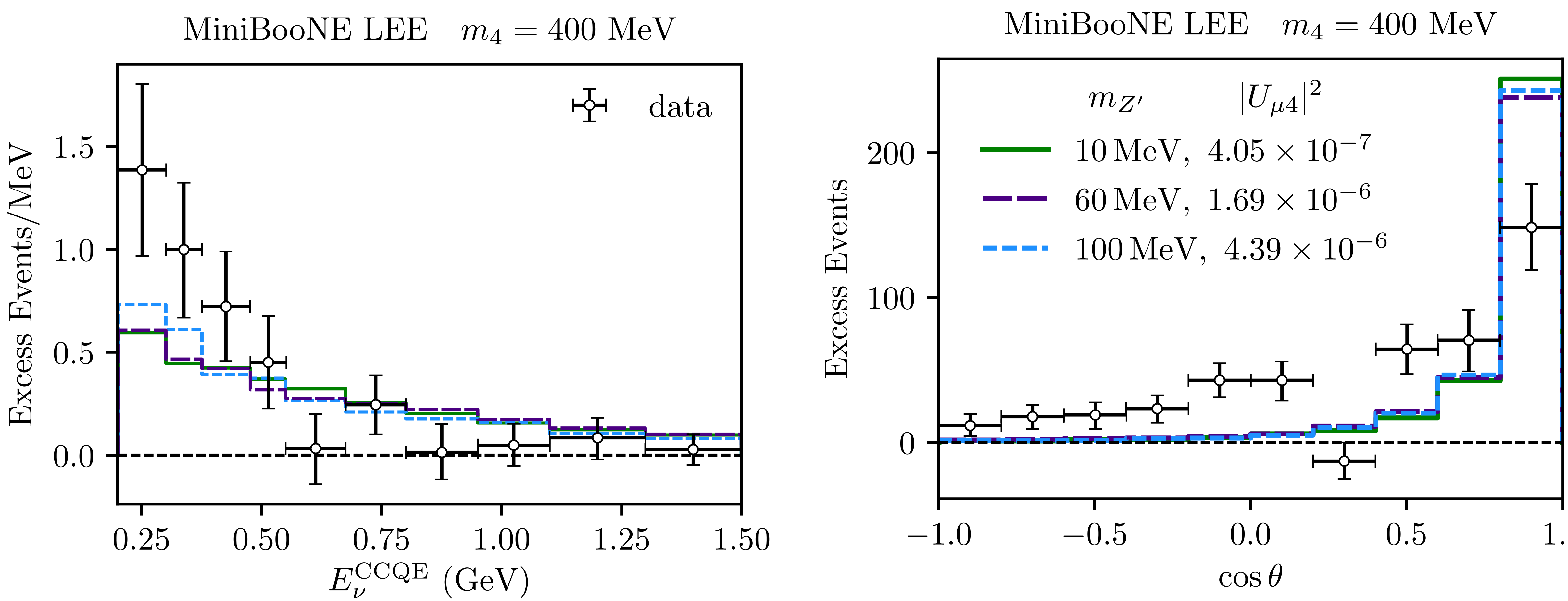

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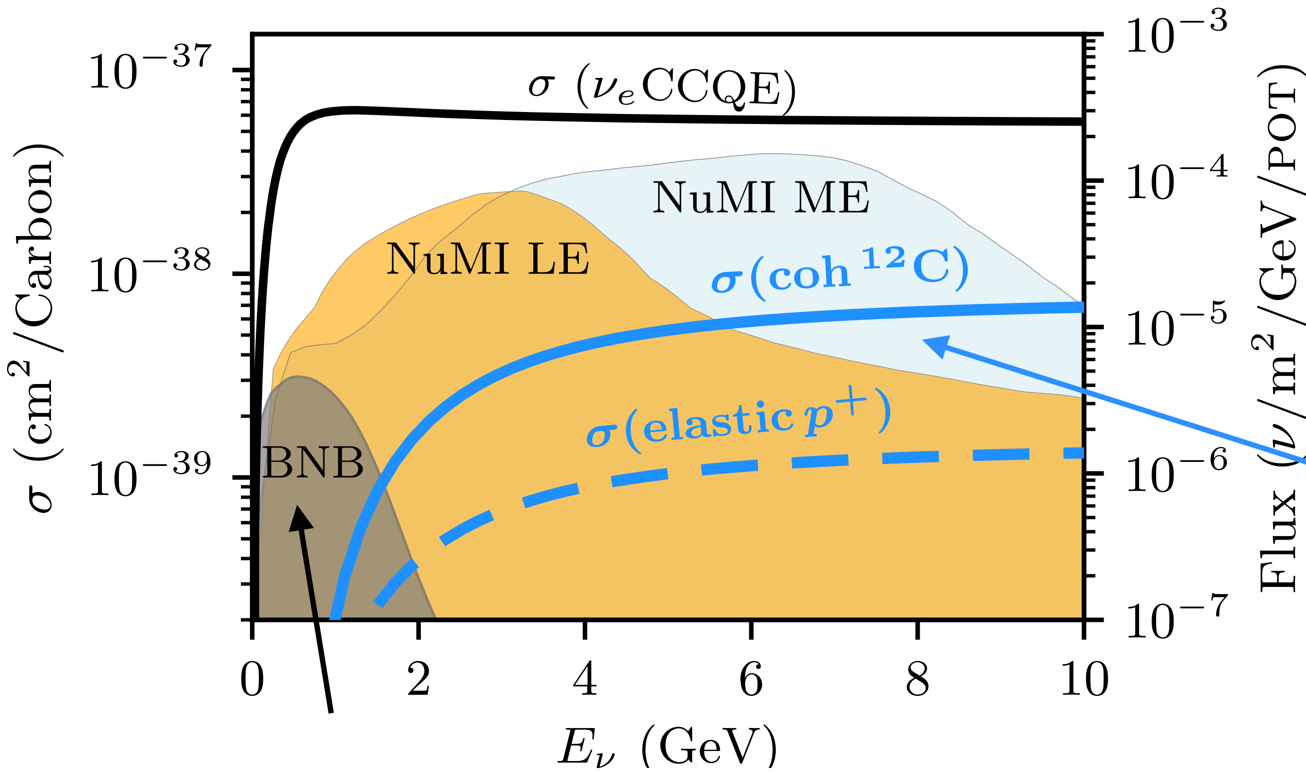
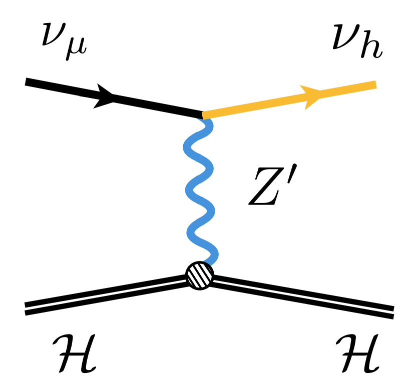


MiniBooNE flux

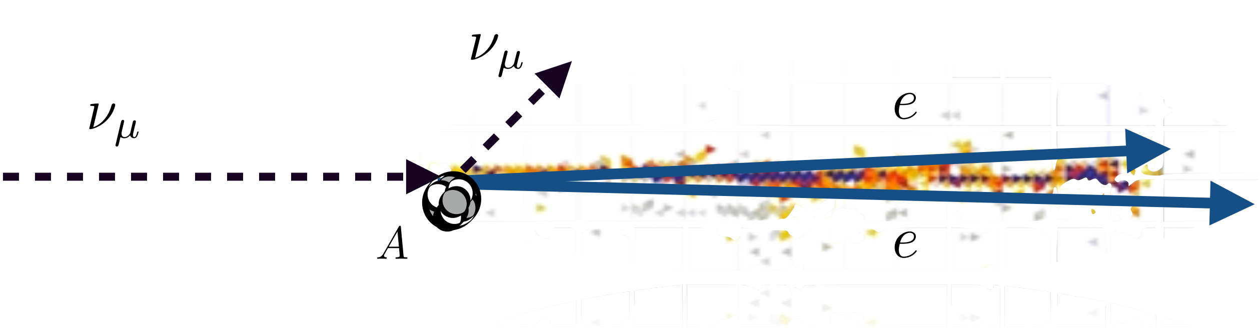
Large mass for MB angular spectrum
=> strong prediction for **HE exps.**

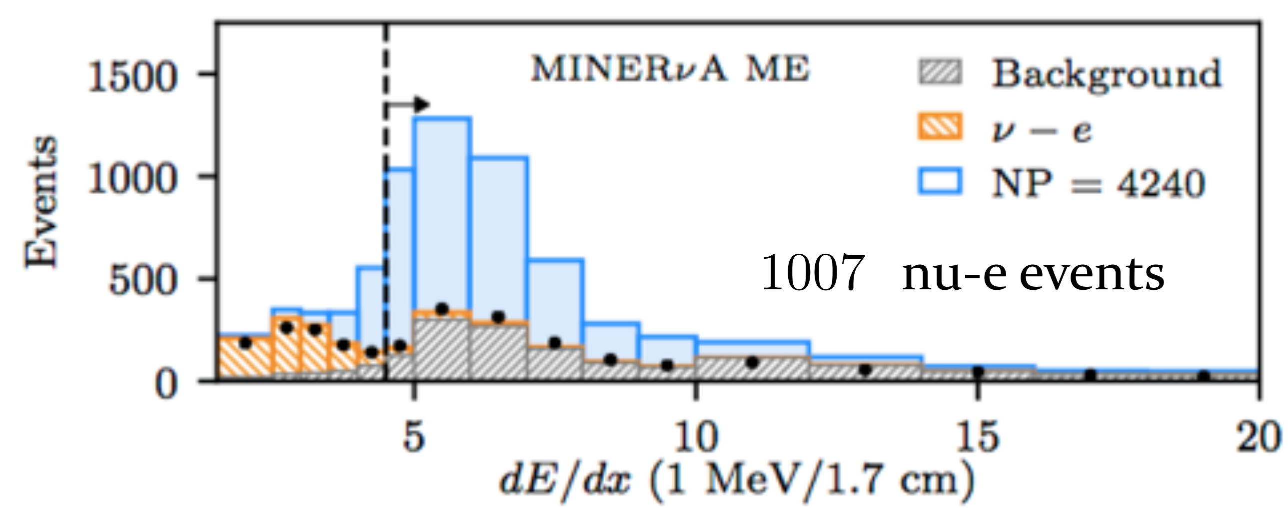


Upscattering cross section for mh = 420 MeV

nu-e scattering

Photon-like shower + no hadronic activity





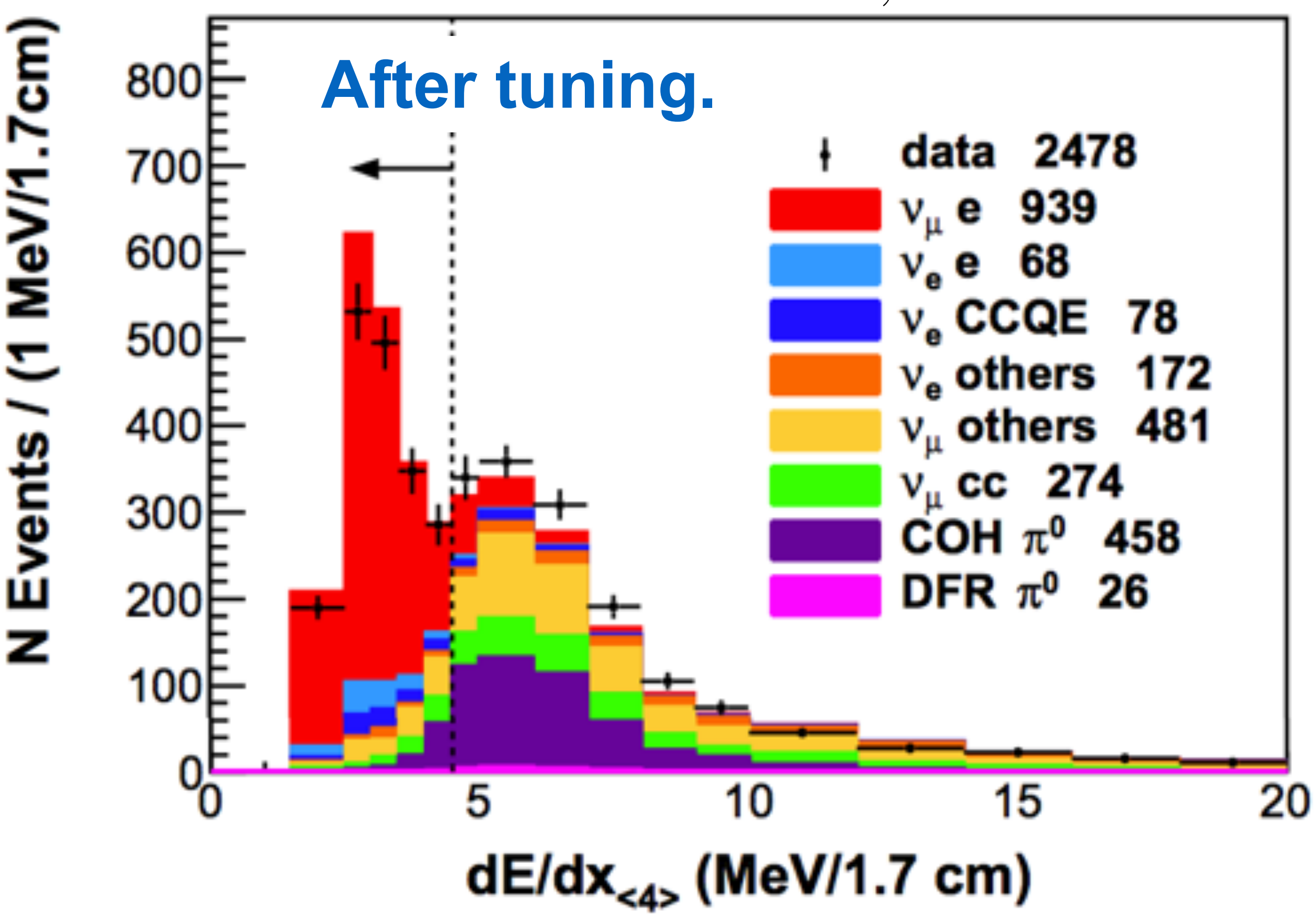
MINERvA Collaboration, 1906.00111

MiniBooNE — Light dark photon — revisited

BUT! MINERvA actually sees an excess at large dE/dx!

… and tunes it away to measure the neutrino flux.

MINERvA Collaboration, 1906.00111



MINERvA Collaboration, 1906.00111

Process	Normalization
ν_e	0.87 ± 0.03
ν_μ CC	1.08 ± 0.04
ν_μ NC	0.86 ± 0.04
NC COH $0.8 < E_e < 2.0$ GeV	0.9 ± 0.2
NC COH $2.0 < E_e < 3.0$ GeV	1.0 ± 0.3
NC COH $3.0 < E_e < 5.0$ GeV	1.3 ± 0.2
NC COH $5.0 < E_e < 7.0$ GeV	1.5 ± 0.3
NC COH $7.0 < E_e < 9.0$ GeV	1.7 ± 0.8
NC COH $9.0 < E_e$	3.0 ± 0.9

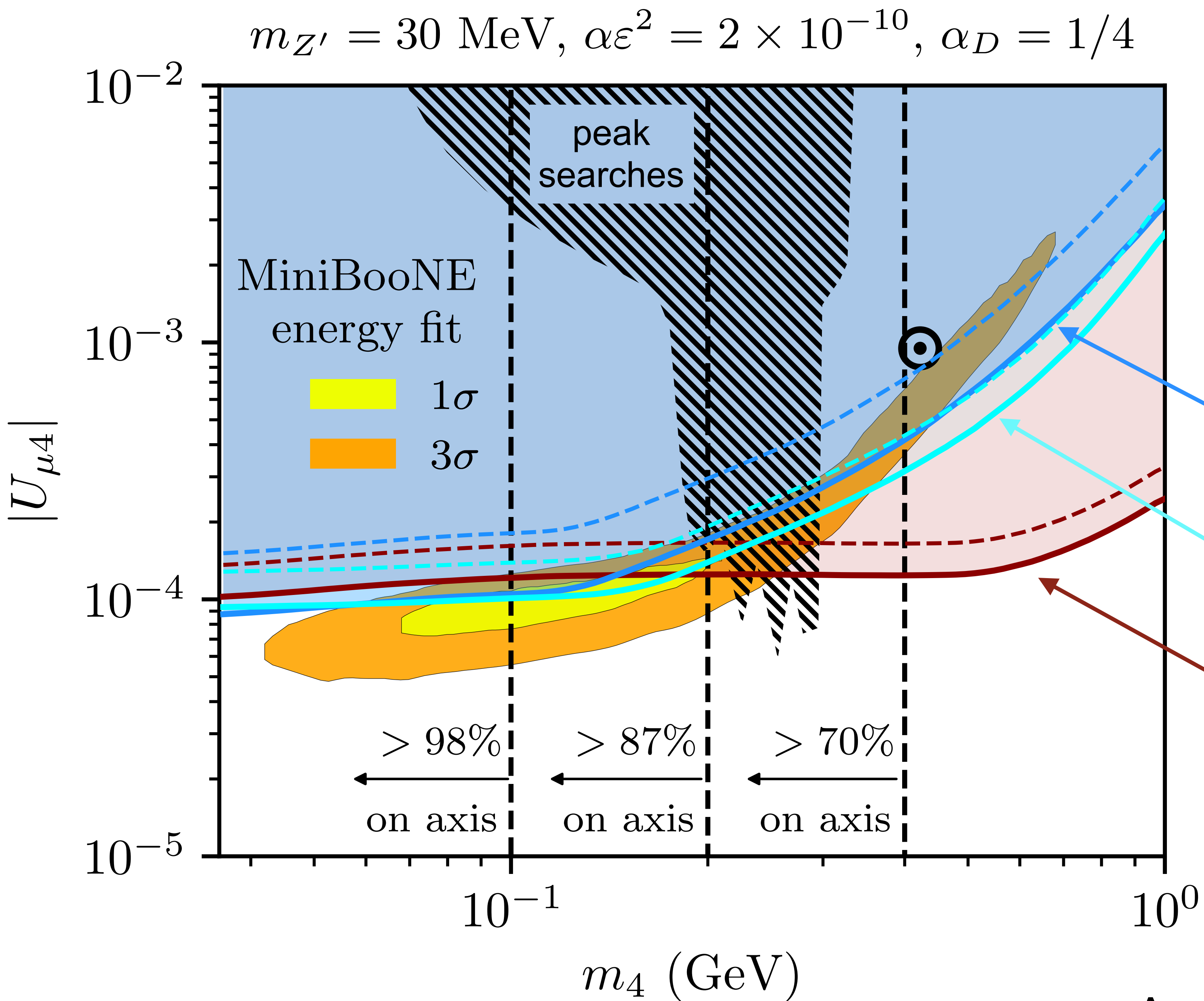
TABLE I. Background normalization scale factors extracted from the fits to kinematic sidebands, with statistical uncertainties.

Excess attributed to coherent π0 events — grows with energy.

— disagreement with GENIE prediction claimed both in **NC and CC channels** —

MiniBooNE — Light dark photon — revisited

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



Vary uncertainty on backgrounds:

30% — 100% for MINERvA LE

40% — 100% for MINERvA ME

3 — 10% for CHARM-II

on axis = events in forward bin at MiniBooNE

Analysis can be improved with future data:

- *MINERvA* ME nubar-e data
- *NOvA* nu-e data

MiniBooNE — Light dark photon — revisited

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

$|U_{\mu 4}|$

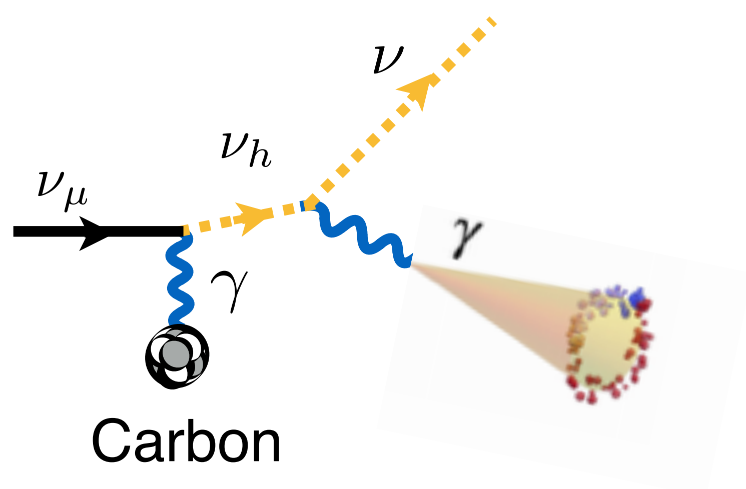
nu-e scattering data

key for ANY explanation that relies on:

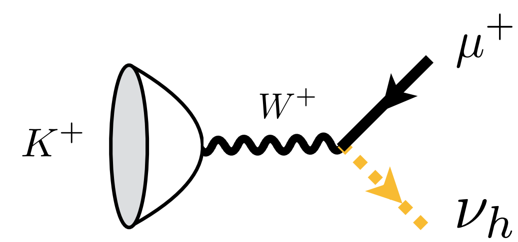
e/γ or e/ee mis-ID.

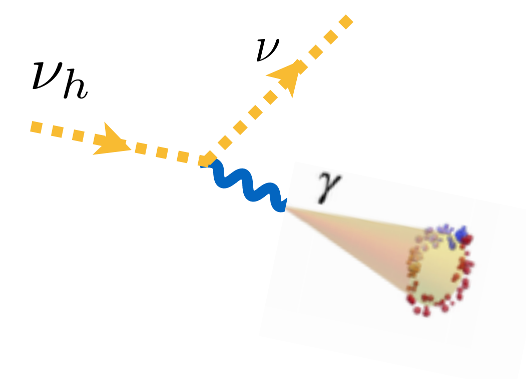
see, e.g.,

N. Gninenko, 1009.5536,



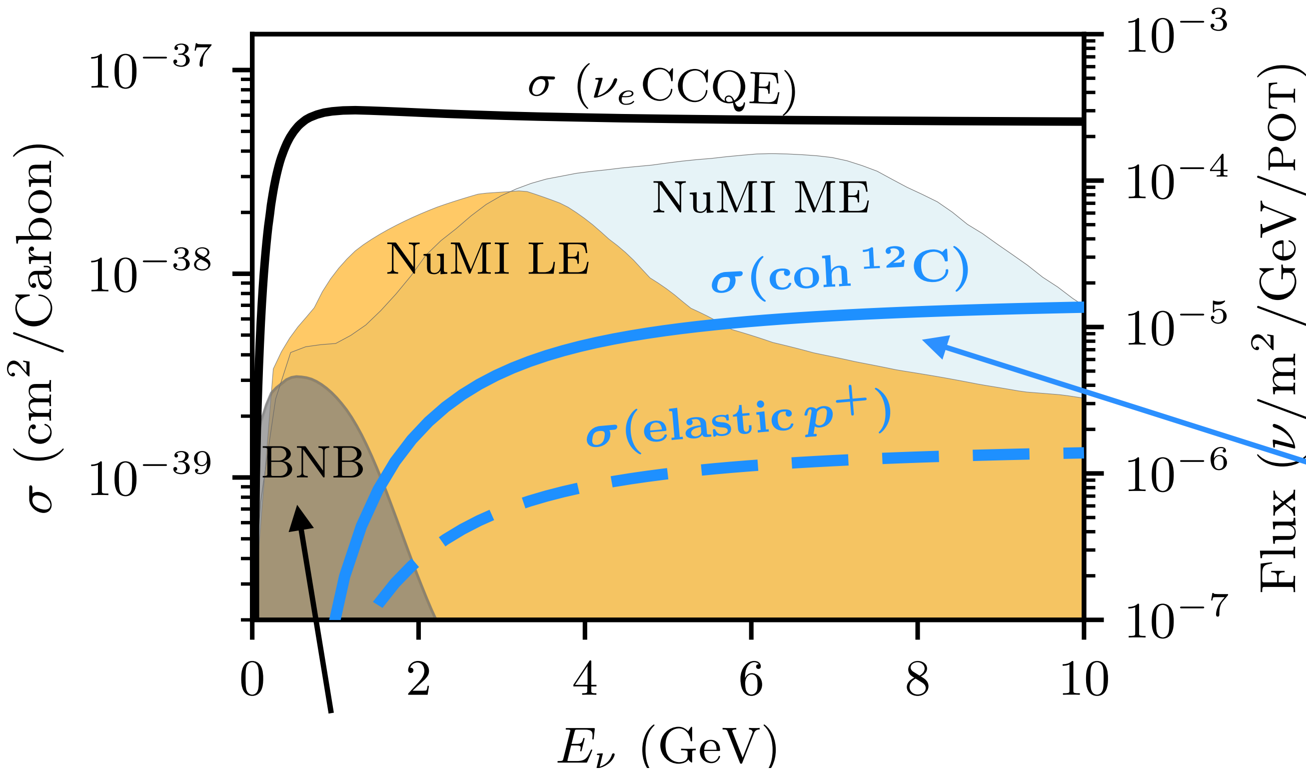
O. Fischer et al., 1909.09561.





on axis = events in forward bin at MiniBooNE

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



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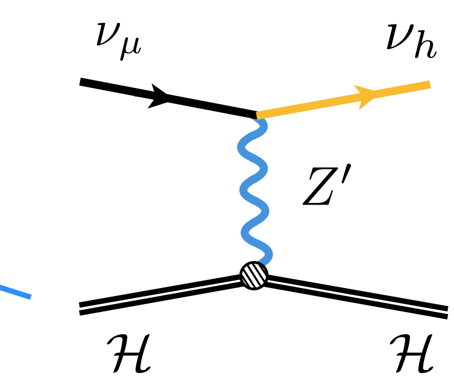

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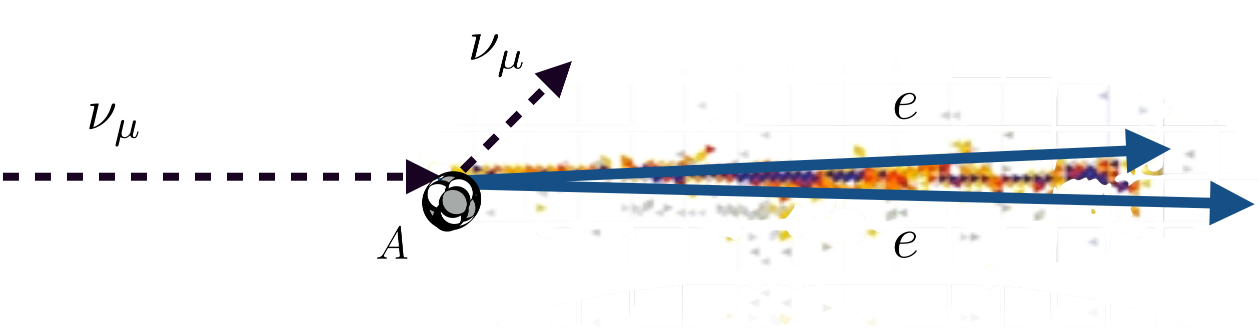
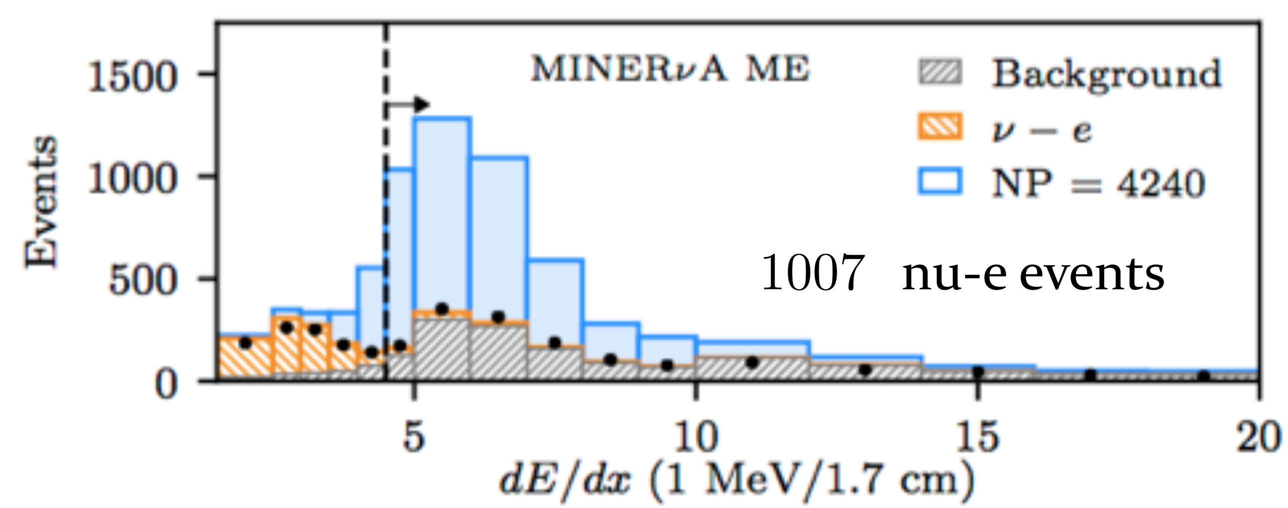
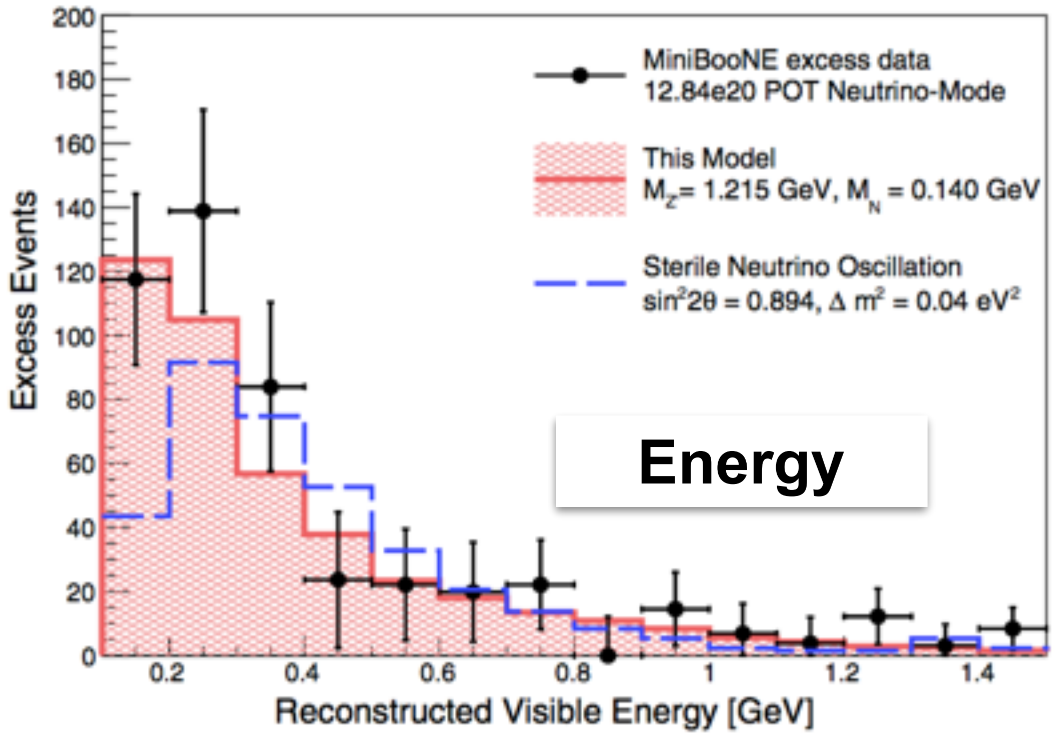
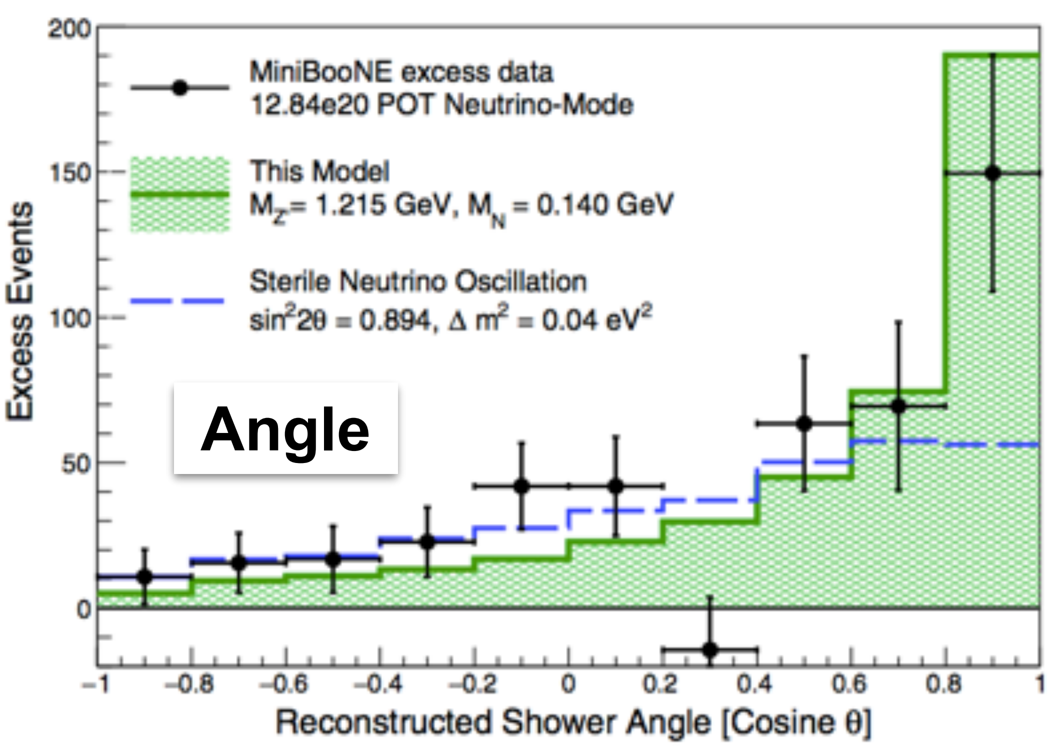


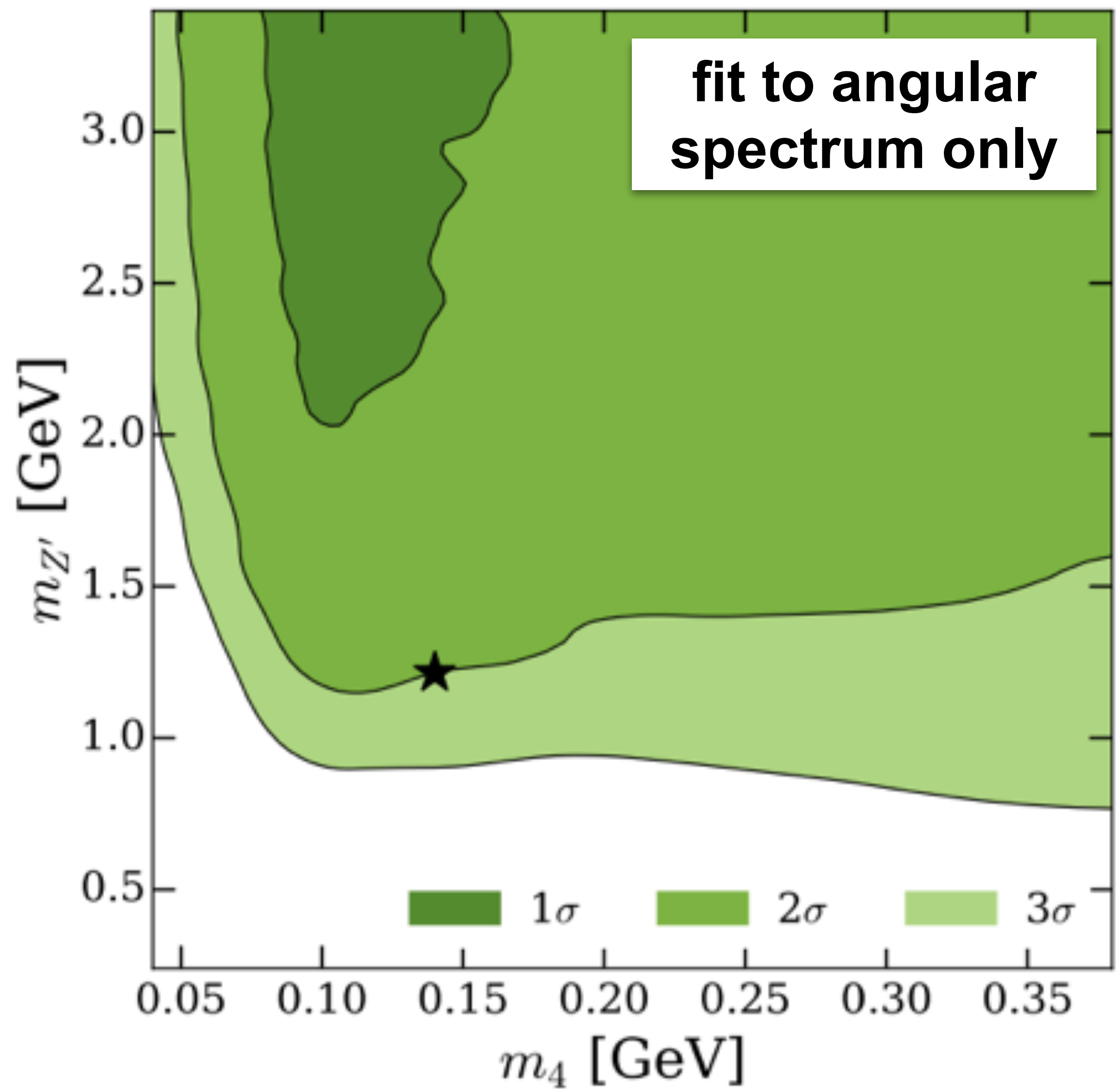


MINERvA Collaboration, 1906.00111

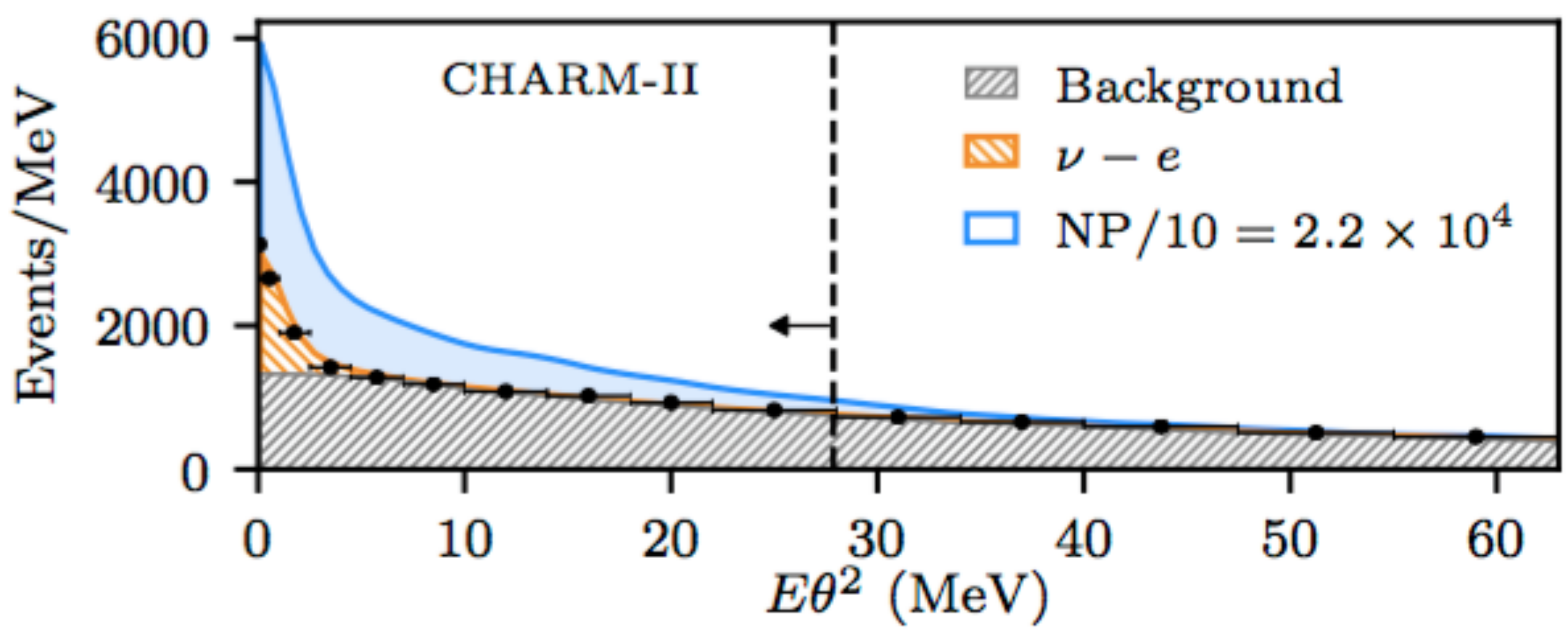
P. Ballett et al, 1808.02915



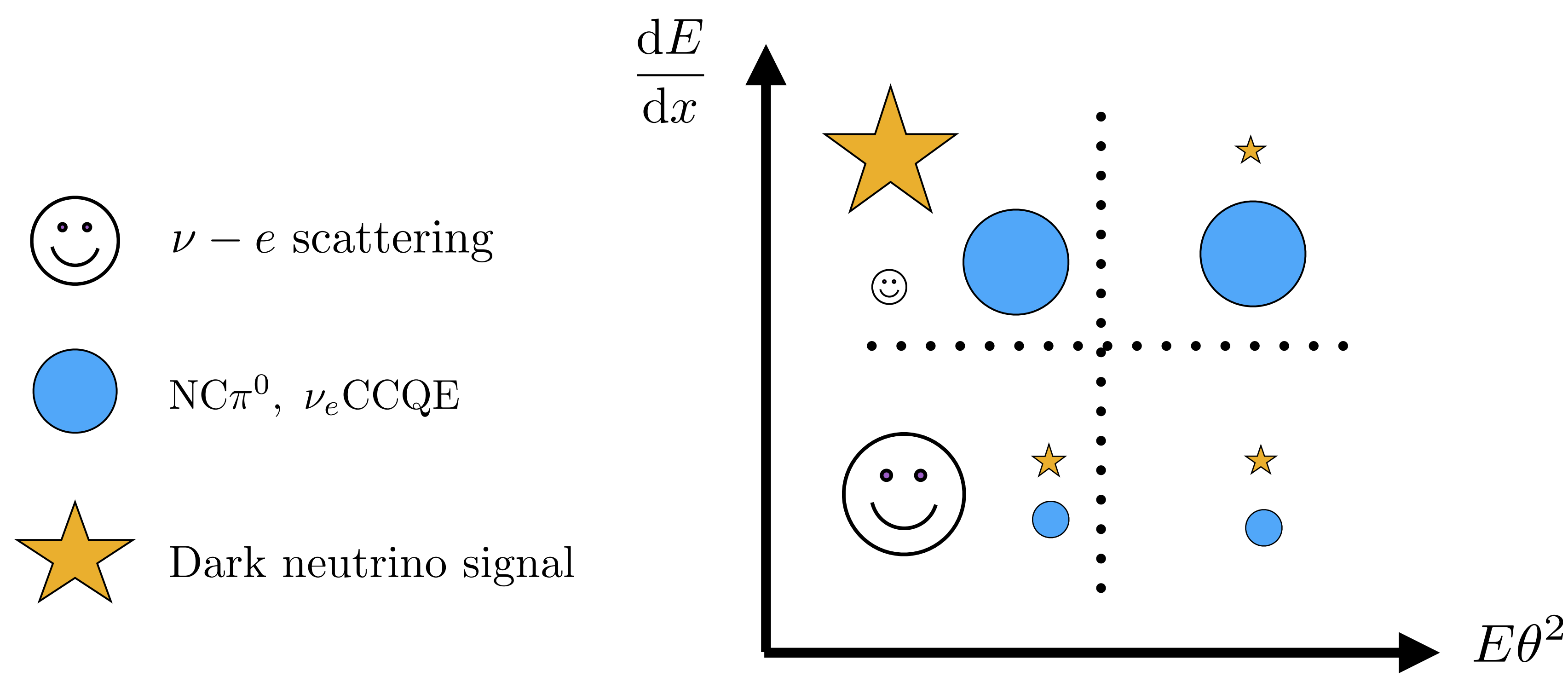




CHARM-II ν



2677 nu-e events in neutrino mode.

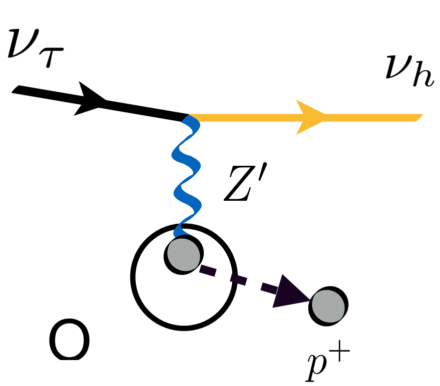


Heavy dark photon case

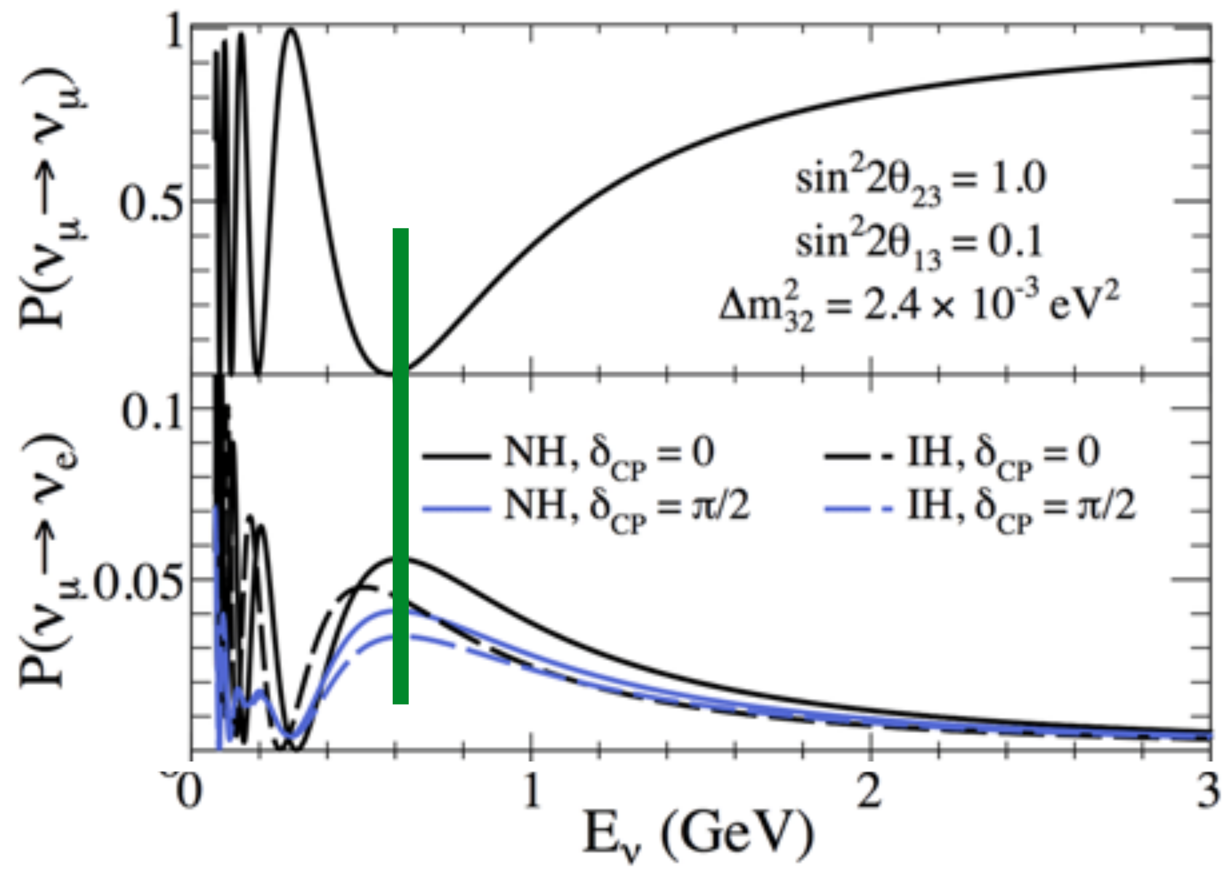
P. Ballett et al, 1808.02915

ν_τ appearance at T2K

$$|U_{\tau 4}| \approx 22 \times |U_{\mu 4}|$$



SuperK is a Cherenkov detector so ee pairs look like <u>nueCCQE</u>.

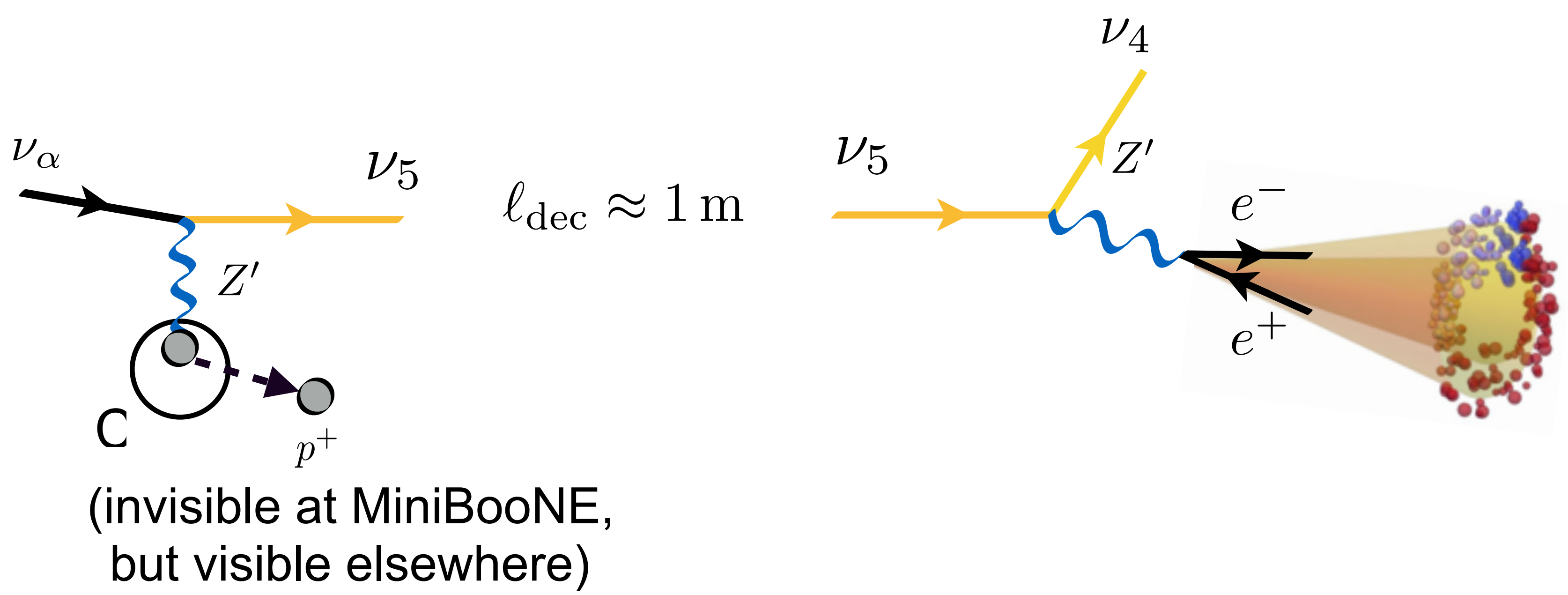


Most of the flux is made of **tau-neutrinos.**

This model predicts:
nu-e like events ~ *O*(# NC events).

Heavy dark photon case

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

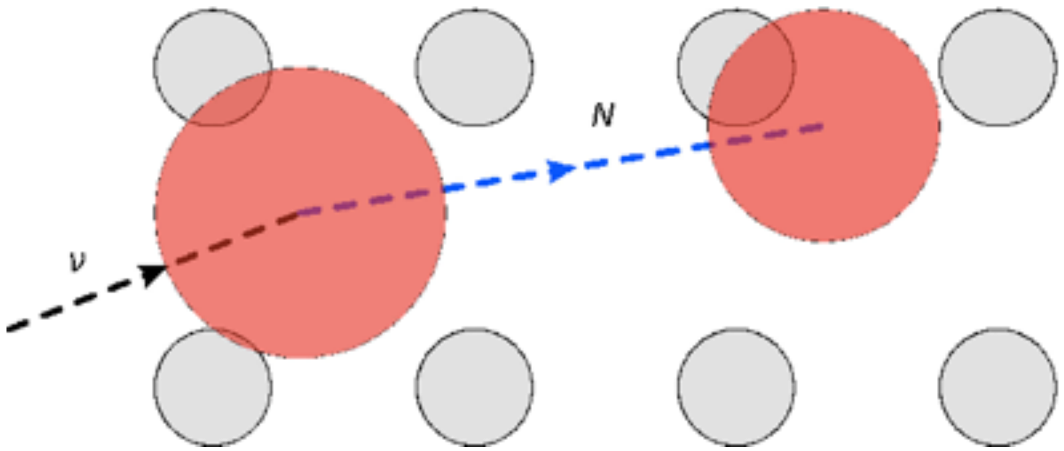


- Decay length of nu5 is much smaller than in 3+1 model.
- nu4 is much more long lived.

- Identical to a 3+1 case, but now efficiencies of $m_{ee} < m_{\pi^0}$ cuts are smaller since $m_{ee} < (m_5 - m_4)$.

Dedicated analysis *in-progress* aiming to distribute a public MC generator for all cases of interest.

https://github.com/mhostert/DarkNews — currently, contains only light dark photon HEPEVT files.

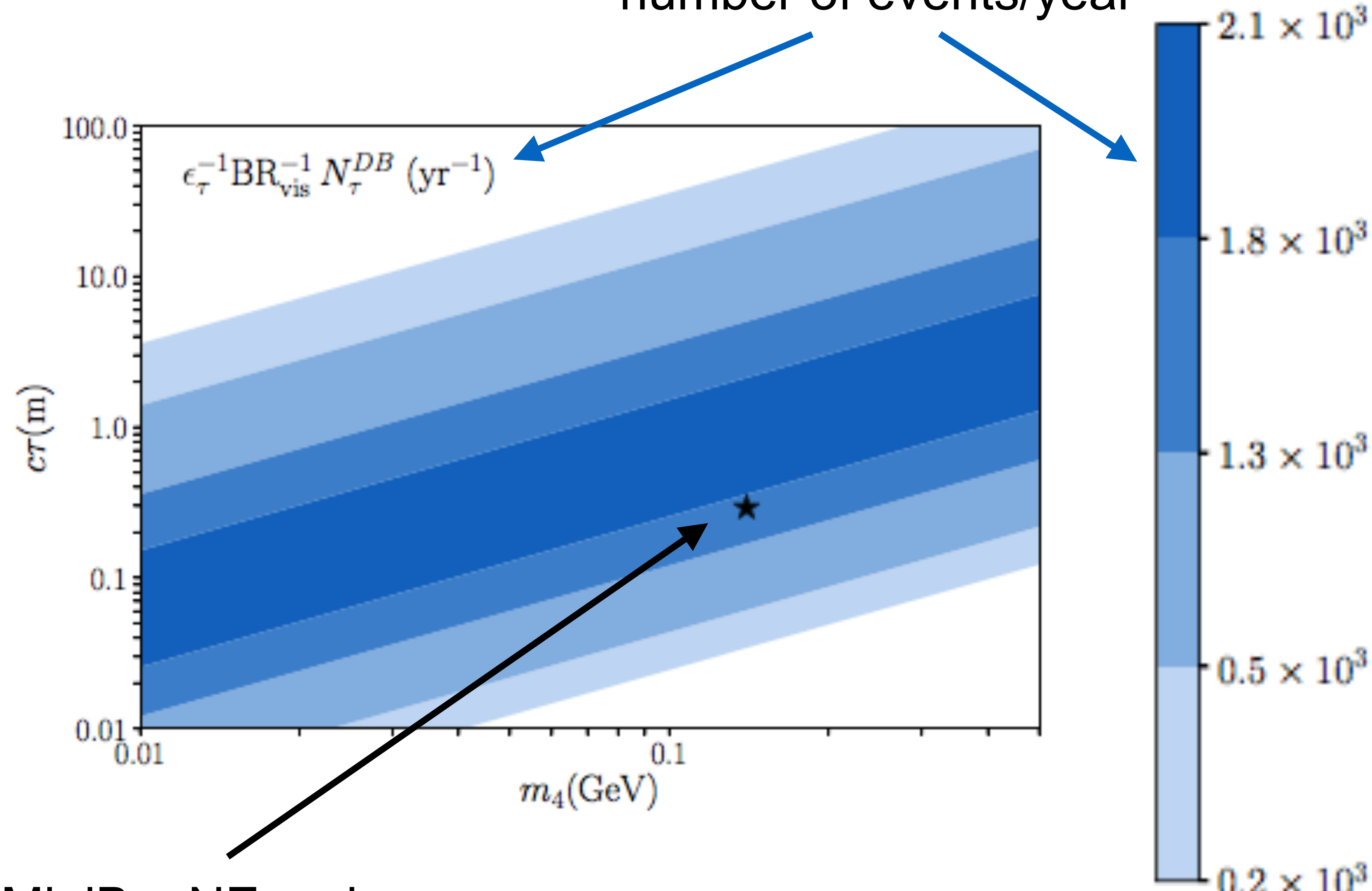


Prediction: **Double-bang events at IceCube**.

Large rate for large tau mixing (3+1),
but smaller rate for muon mixing only (3+2).

~ number of events/year

P. Coloma, 1906.02106



MiniBooNE r.o.i.