Hints and Tests of a Dark Seesaw

MiniBooNE, the Muon (g−2), and Meson Decays.

Neutrino Seminar
03/11

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The Outline

1. Low scale seesaws with a dark force.

2. Phenomenological applications of dark neutrinos

   - MiniBooNE
   - $(g\text{-}2)_\mu$ and tests at e+e- colliders,
   - Rare kaon decays.

IN COLLABORATION WITH:

Asli Abdullahi

Silvia Pascoli

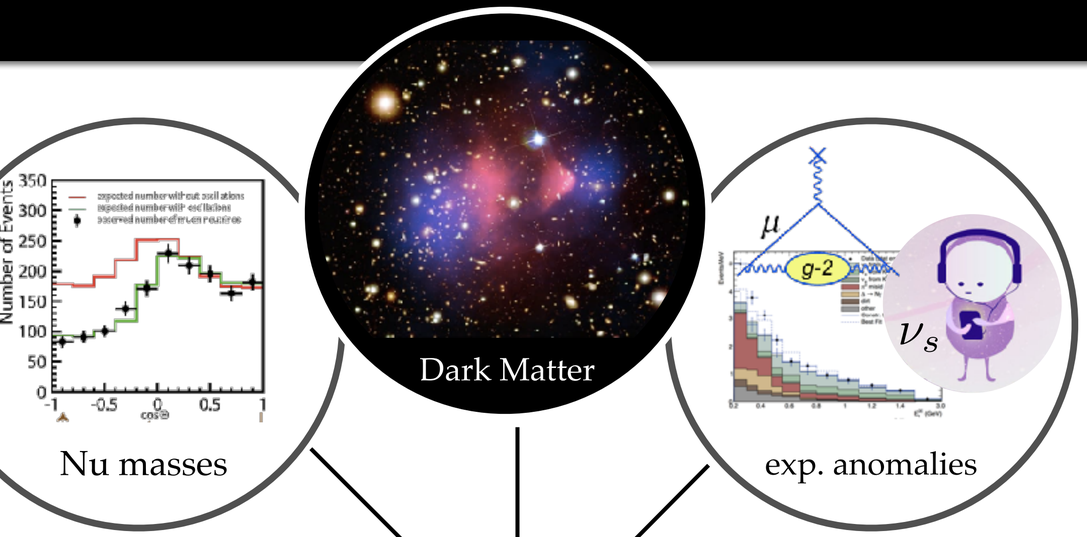
Based on

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

P. Ballett, MH, S. Pascoli, PRD 101 (2020) 11,115025

P.Ballett, MH, S. Pascoli, PRD 99, 091701 (2019)

New physics under the lamppost



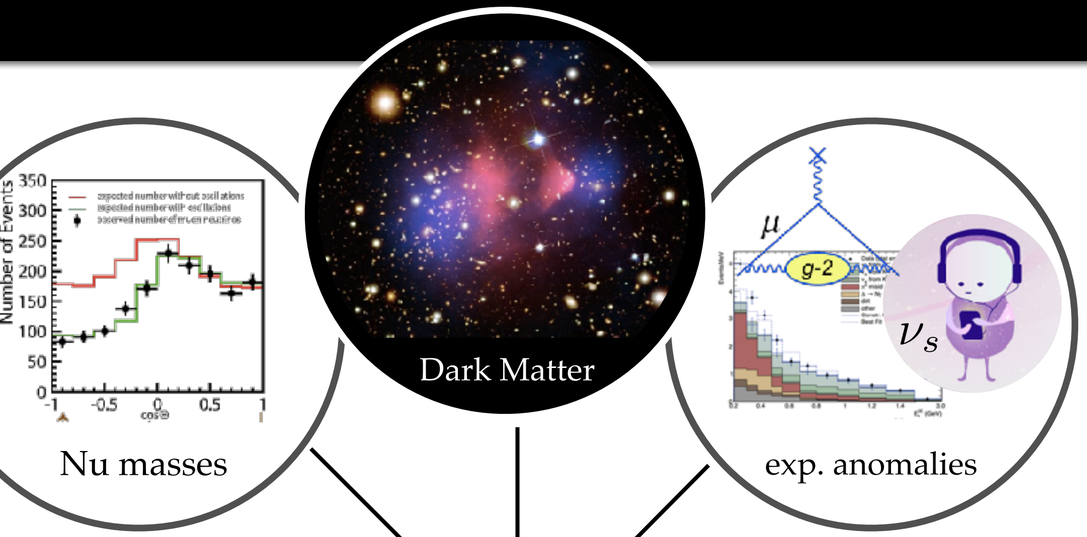
Many solutions to these problems invoke **new sectors of SM gauge singlets**

=

Dark Sector
(May or may not include a dark matter candidate)

New light states are naturally **feebly coupled to the SM.**

New physics under the lamppost



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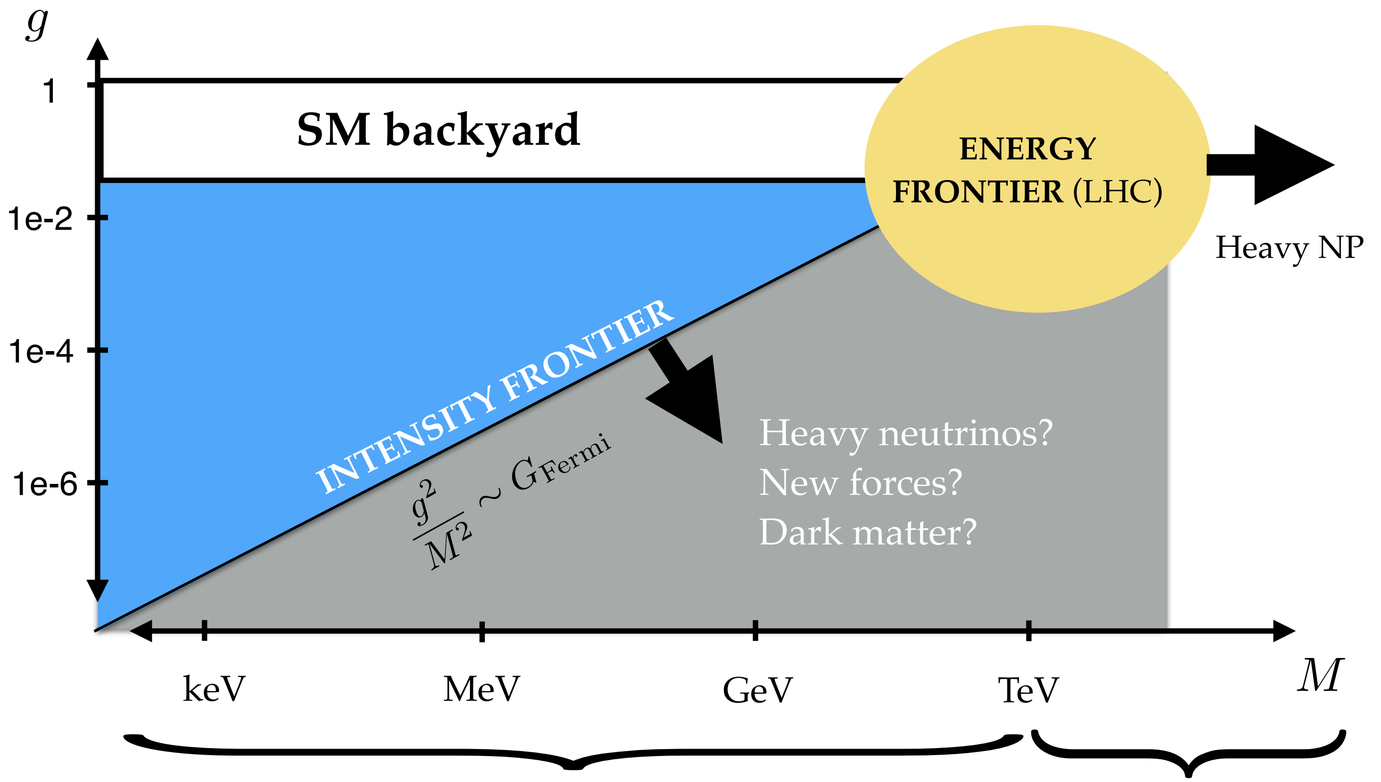


Accessible at current experimental program

Indirect tests only (EFTs)

Ruling out the SM in the laboratory

High Energies

Colliders (LHC)

UHE neutrinos (IceCube, ANITA)

Weak Decays

K factories

B decays

Quarkonium decays

Displaced Vertices

Beam dumps

FASER

Forward & ground LHC detectors

ν Sector

oscillations

Scattering

0nuBB

Missing Energy

NA64

Belle II

LDMX

Precision

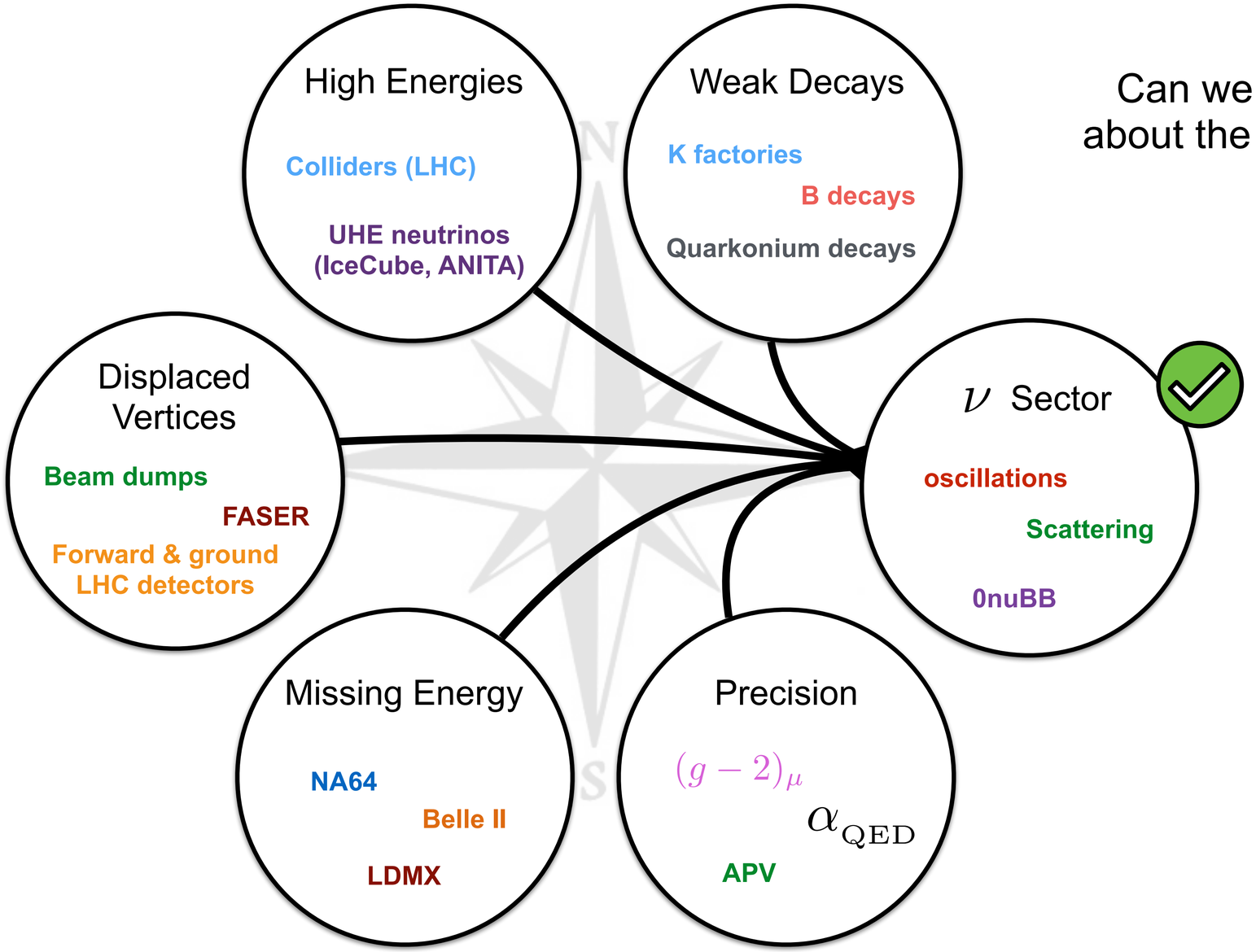
$(g-2)_\mu$

α_{QED}

APV

*Not an exhaustive list

Ruling out the SM in the laboratory



Can we learn anything about the neutrino sector?

*Not an exhaustive list

Heavy neutral leptons at low scales

Beyond the naive scaling in the Type-I seesaw

Type-I seesaw Lagrangian:

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

After EWSB, neutrinos get a mass:

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^\intercal & M_N \end{pmatrix} \quad \text{where} \quad M_D = \frac{y^\nu v_{\text{EW}}}{\sqrt{2}}$$

Single generation →

$$m_\nu \simeq \frac{M_D^2}{M_N}$$

$$|U_{\alpha 4}| \simeq \frac{M_D}{M_N}$$

$$\rightarrow \begin{cases} (y^\nu)^2 \approx 3 \times 10^{-15} \frac{M_N}{\text{GeV}} \\ |U_{\alpha 4}|^2 \approx 10^{-10} \frac{\text{GeV}}{M_N} \end{cases}$$

Multiple generations →

$$M_\nu \simeq M_D M_N^{-1} M_D^T$$

Matrix multiplication!

M_ν can be small even for small entries in M_N and large entries in M_D.

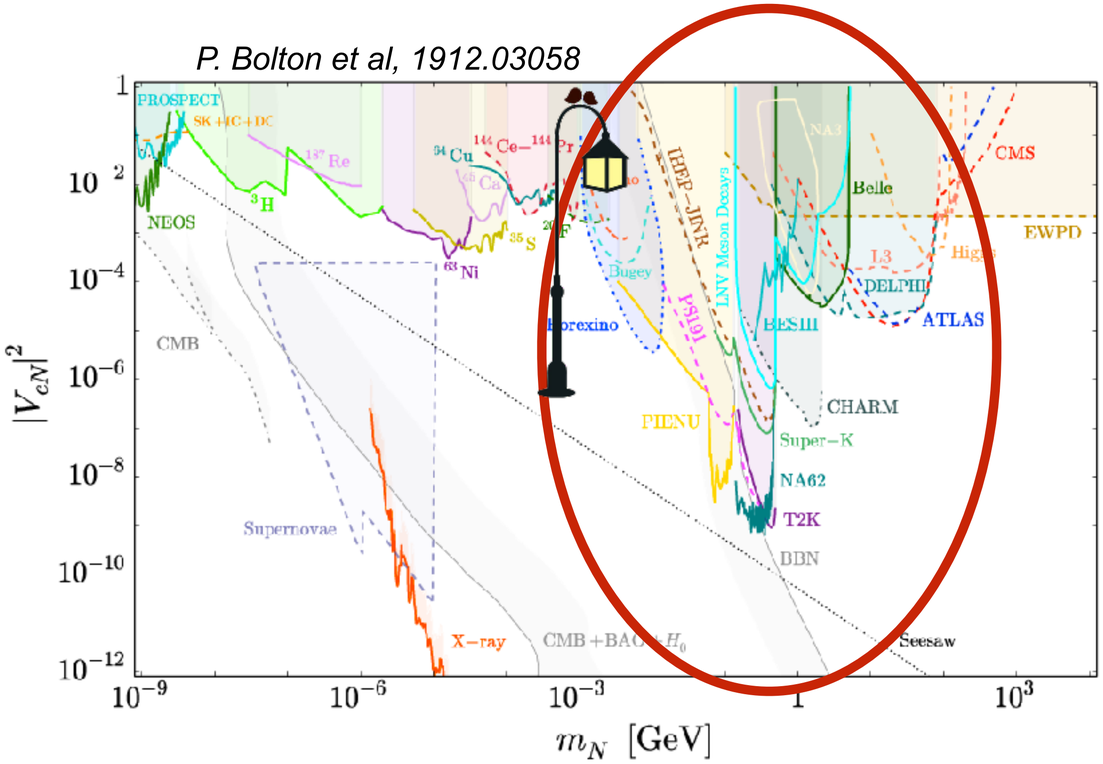
Why are neutrino masses small in a seesaw model?

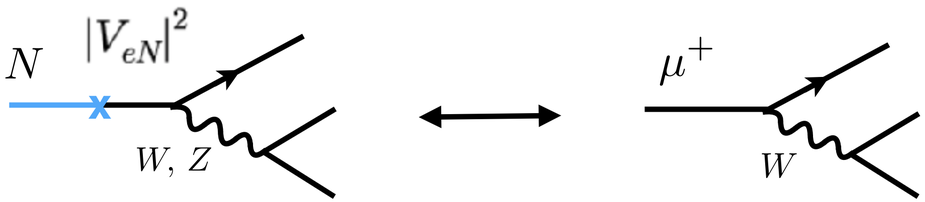
1) **Hierarchy of scales**
2) **Small couplings**
3) **New symmetries or cancellations**

?

Where are the HNLs?

P. Bolton et al, 1912.03058





HNLs are long-lived particles if they only interact via neutrino mixing.

<u>Under the MeV-GeV lamppost:</u>

1) Missing mass in pion or kaon decays

$$\pi/K \to \ell N$$

2) Decay-in-flight beam dumps/nu exps

$\pi/K \to \ell N$ ⟶ N propagates ⟶ N decays visibly

Most efforts have been dedicated to **invisible** or **long-lived HNLs**. Lifetime is bounded from above due to BBN constraints (t_N < 0.1 s).

What if N decays visibly and much faster?

Endowing N with new forces

Portal:
(SM SINGLET) X (DS SINGLET)

DARK SECTOR (DS)

$\mathscr{L}_{\rm SM}$

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

Neutrino portal

Heavy neutrinos

$\frac{M_N}{2}\overline{N^c}N$

Neutrino masses

$B_{\mu\nu}X^{\mu\nu}$

Vector portal

Dark photons

$G_{SM} \times U(1)_X$

Forces from Abelian gauge sym?

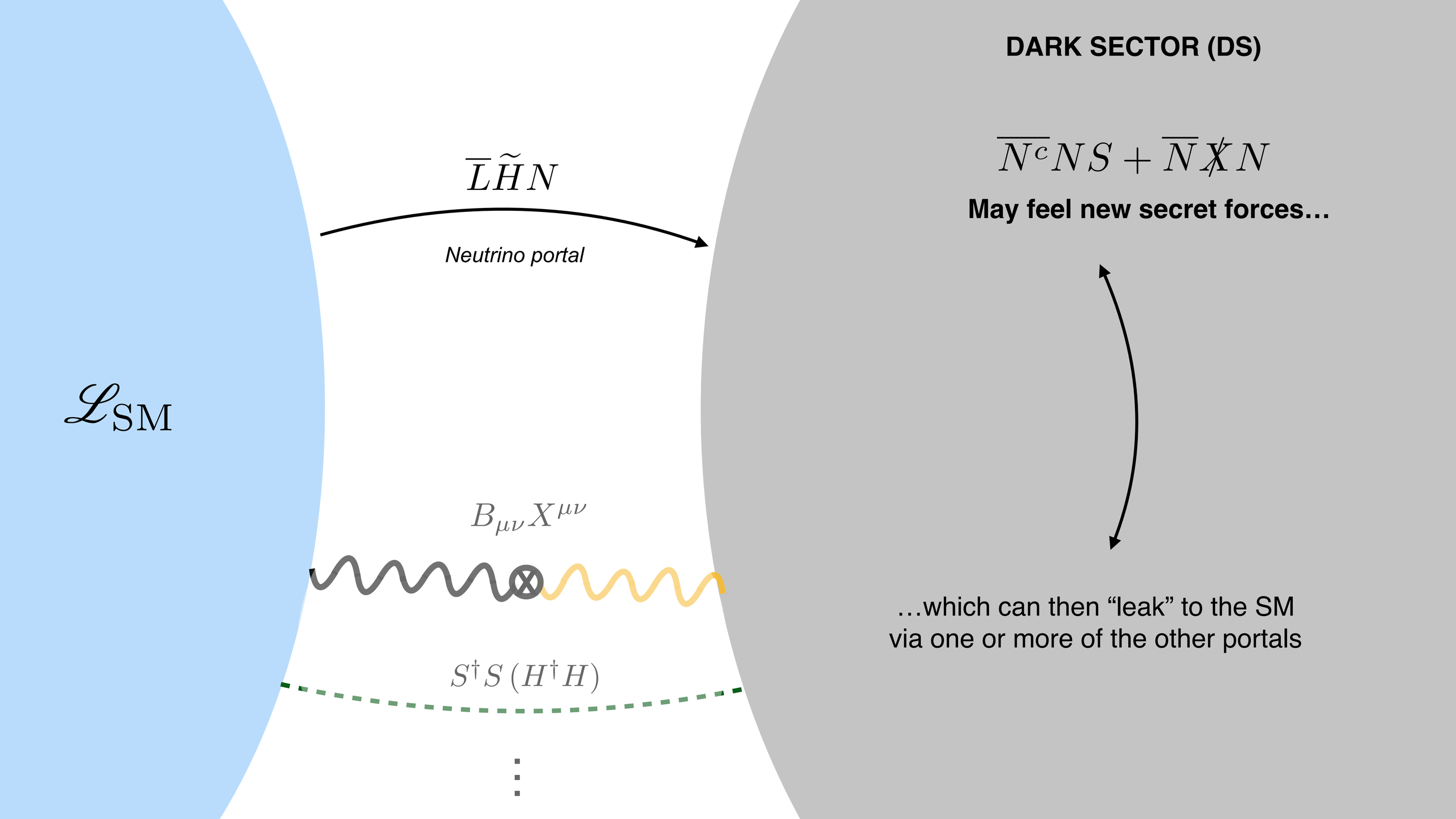
$S^\dagger S\,(H^\dagger H)$

Scalar portal

Real or complex scalars

$V(H,S)$

New scalar potential


DARK SECTOR (DS)
$\overline{N^c} N S + \overline{N} \not{X} N$
May feel new secret forces…
$\overline{L} \widetilde{H} N$
Neutrino portal
$\mathscr{L}_{\rm SM}$
$B_{\mu\nu} X^{\mu\nu}$
$S^\dagger S \, (H^\dagger H)$
…which can then "leak" to the SM
via one or more of the other portals

A “Dark Seesaw” Model

A renormalizable model for a dark neutrino sector

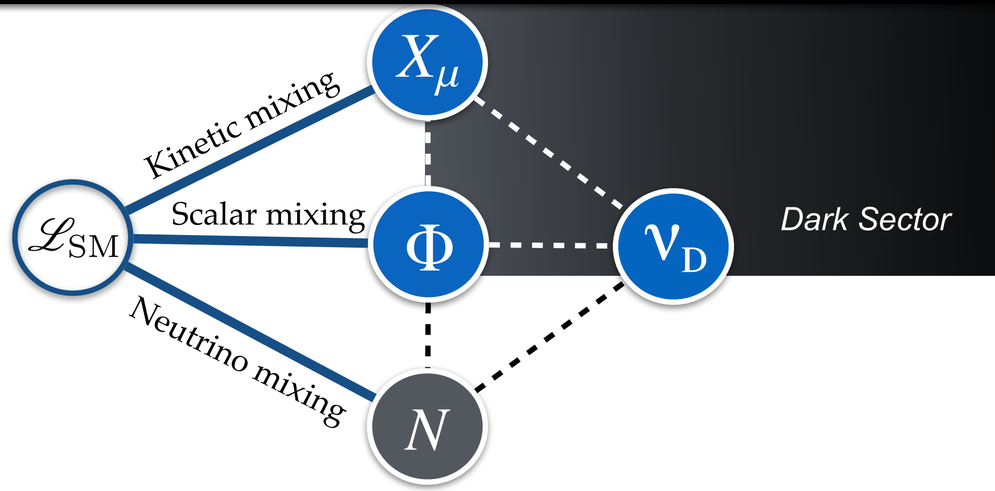
A. Abdullahi, MH, S. Pascoli
arXiv:2007.11813

See also B. Batell et al, JHEP 1608 (2016) 052
Bertuzzo et al, PLB 791 (2019) 210-214 + others w/ 2HDM models

1) A minimal **renormalizable model:**

	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
ν_N	**1**	0	0
ν_{D_L}	**1**	0	Q
ν_{D_R}	**1**	0	Q
Φ	**1**	0	Q

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



$$y^\nu (LH)N + M_N NN + y_N N\nu_D\Phi + M_X \nu_{D_L}\nu_{D_R}$$

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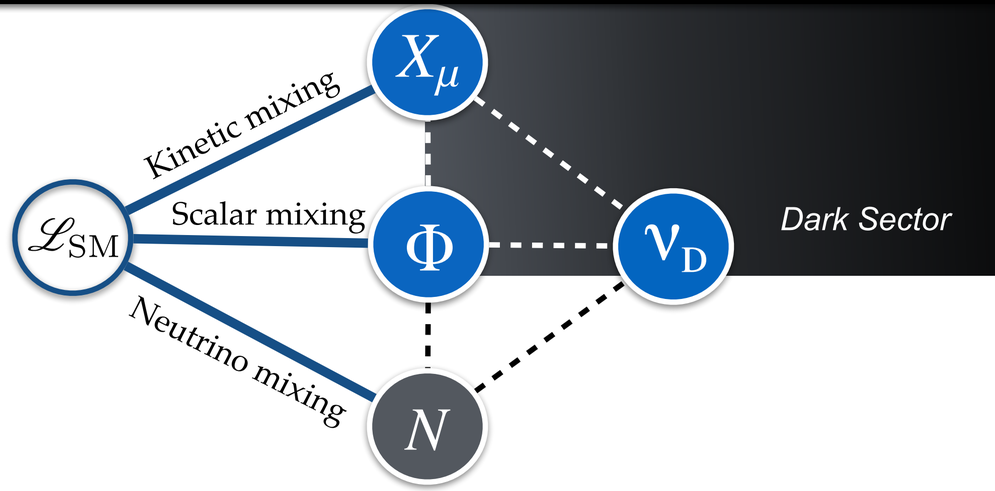
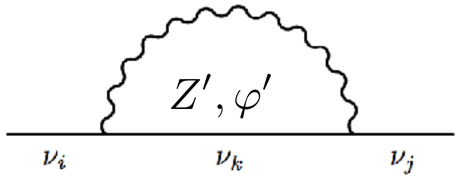


2) Neutrinos masses:

$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & M_N & \Lambda \\ 0 & \Lambda^T & \mathcal{M}_X \end{pmatrix} \begin{pmatrix} \nu_\alpha^c \\ \nu_N^c \\ \nu_D^c \end{pmatrix} \Rightarrow$$

$$m_\nu \simeq \underbrace{M_D^T(\Lambda^T)^{-1}\mathcal{M}_X\Lambda^{-1}M_D}_{\text{Tree-level}} + \underbrace{\delta M_{1-\text{loop}}(M_N, M_Z, M_{Z'})}_{\text{Loop-level}}$$



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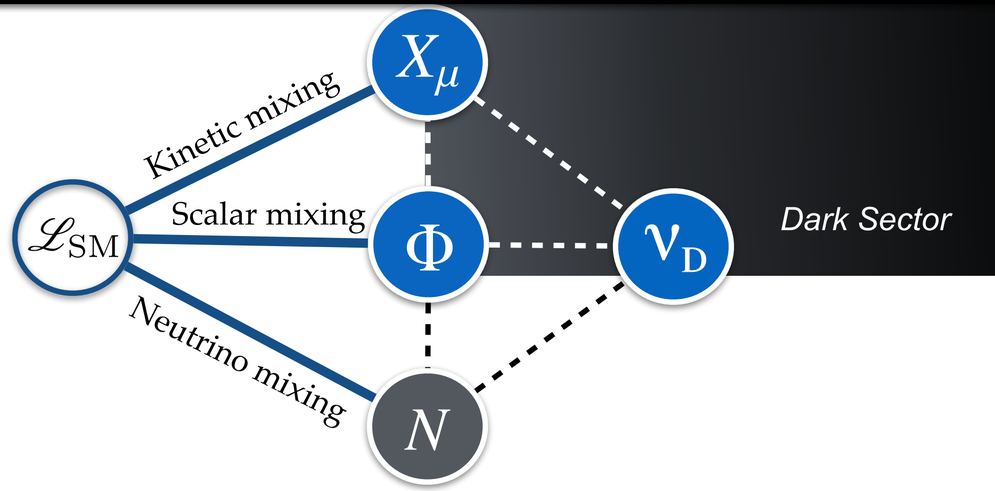

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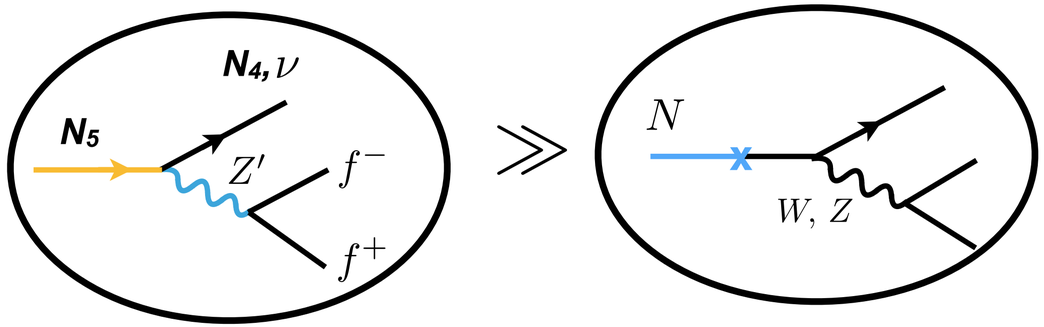
3) Modified decays:



1) Faster decays
2) CC decays are negligible
3) Always accompanied by missing energy

MiniBooNE

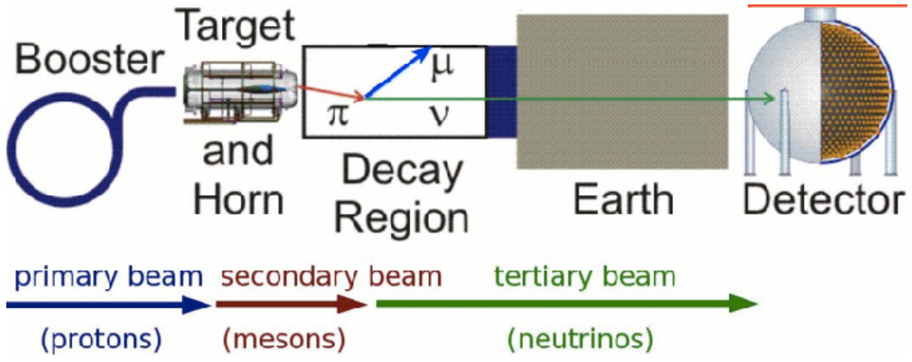
The MiniBooNE excess

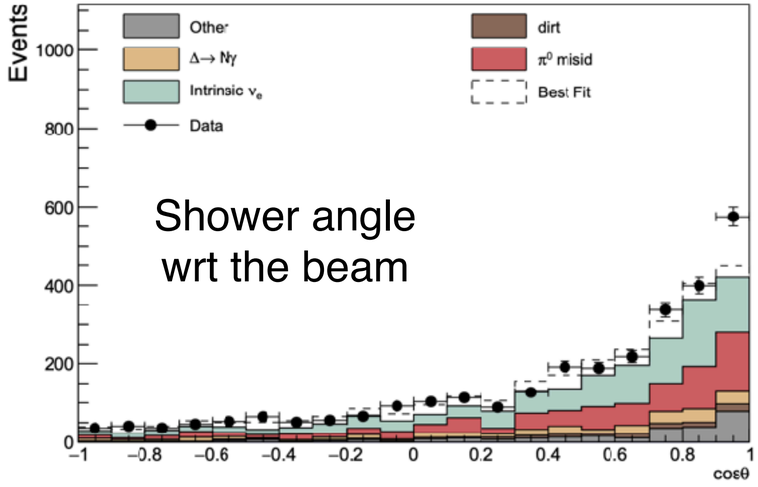
2020 MiniBooNE results:

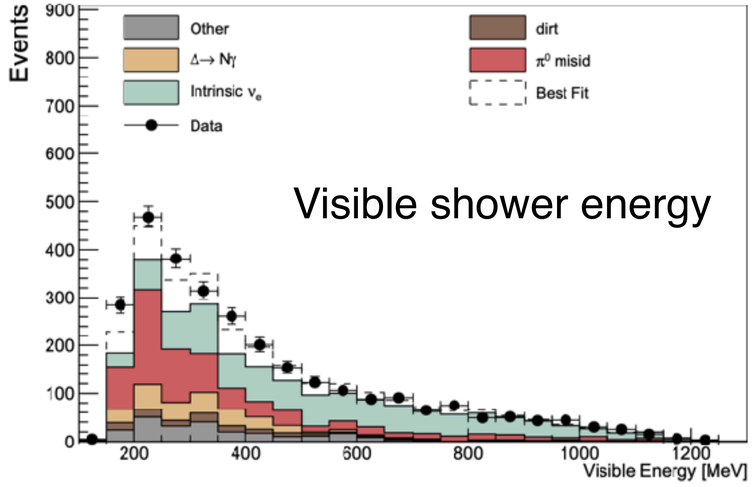
arXiv:2006.16883

1) Significance increases when restricting to smaller fiducial volume
2) Excess overlaps w/ the beam time
3) New 2-D distributions in E vs angle.

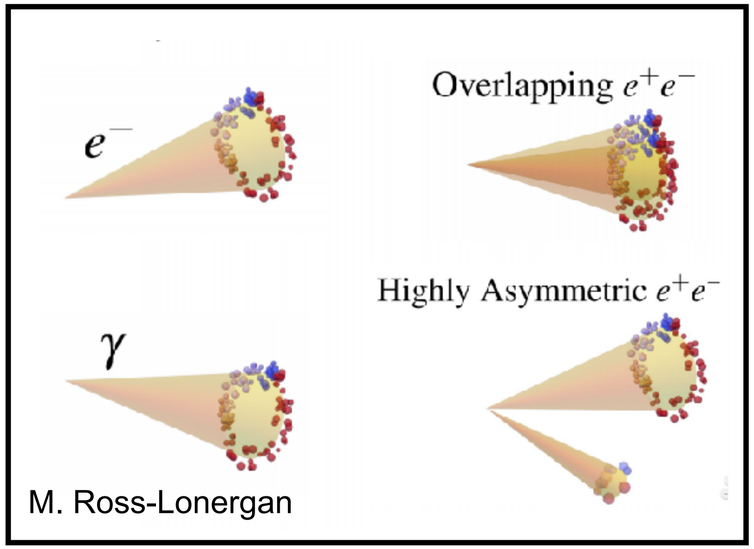
638.0±132.86 excess events
4.8σ significance







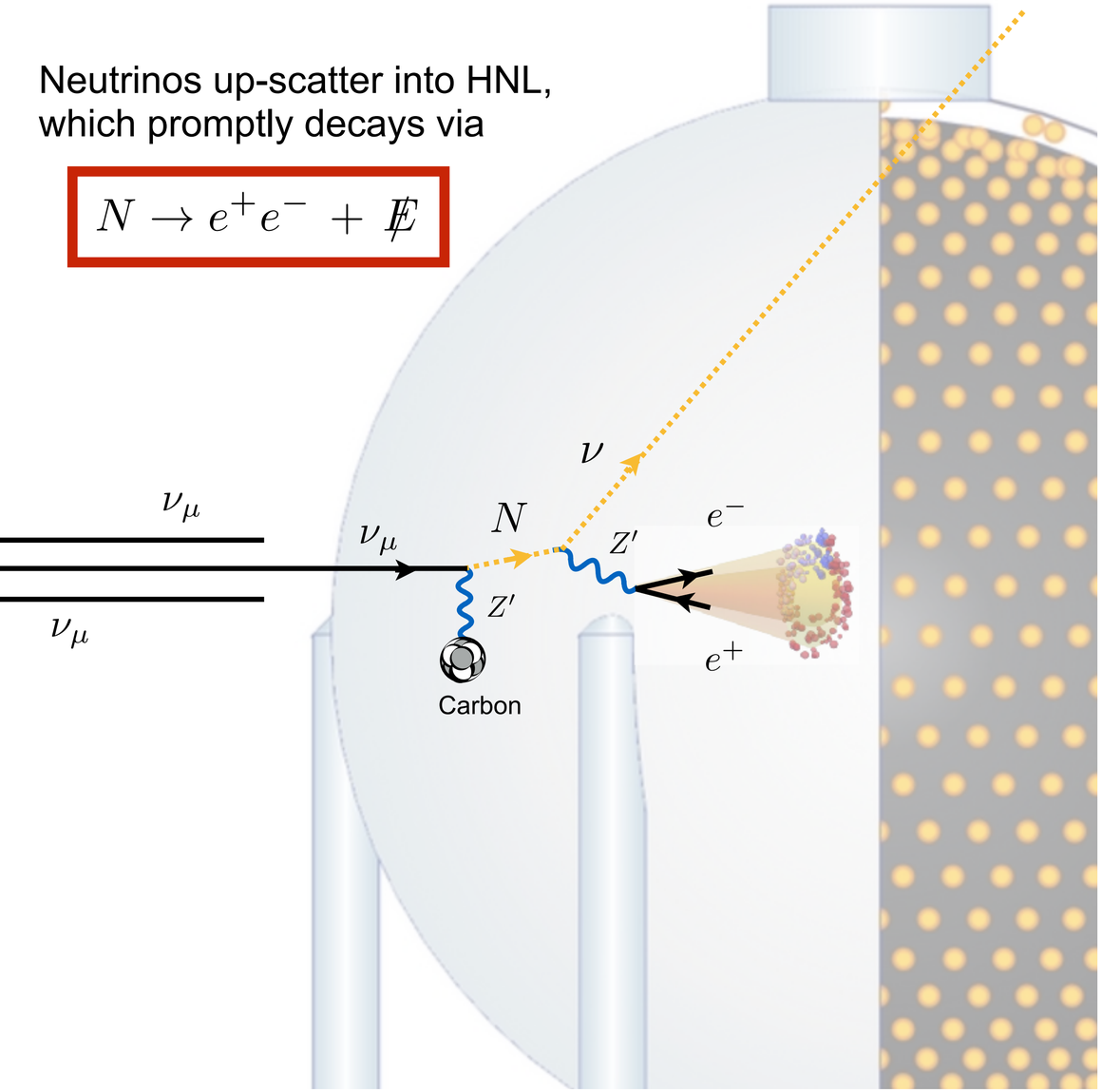
MiniBooNE is a very "inclusive" experiment:



Heavy neutrinos + dark forces to accommodate MiniBooNE

Neutrinos up-scatter into HNL, which promptly decays via

$$N \to e^+e^- + \not{E}$$



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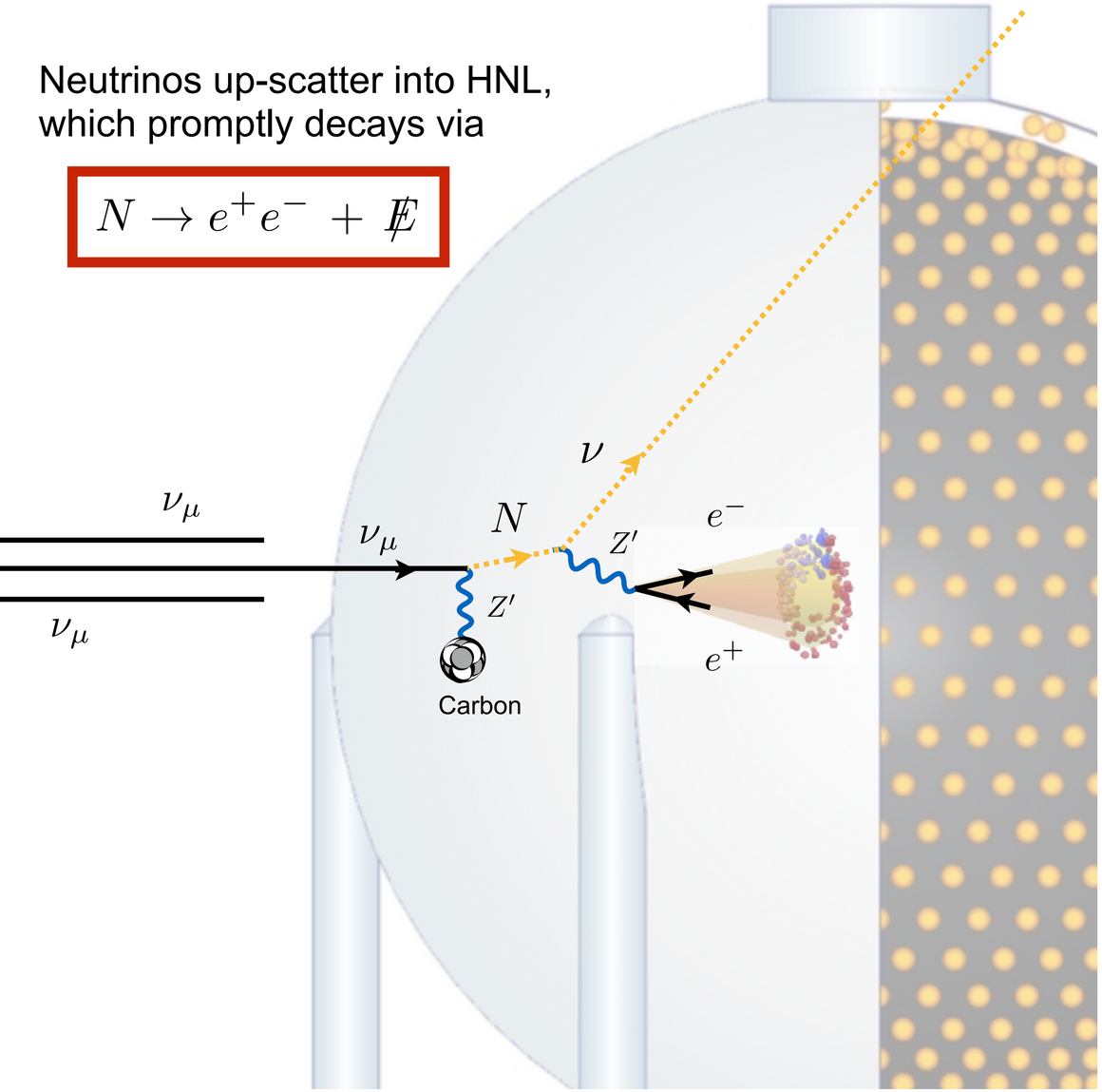
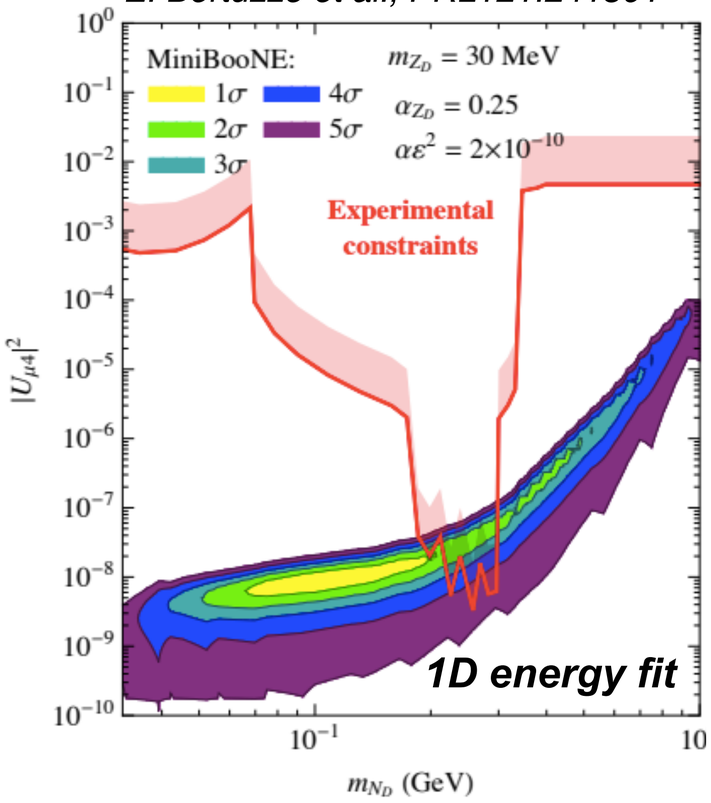


Neutrino portal + kinetic mixing.

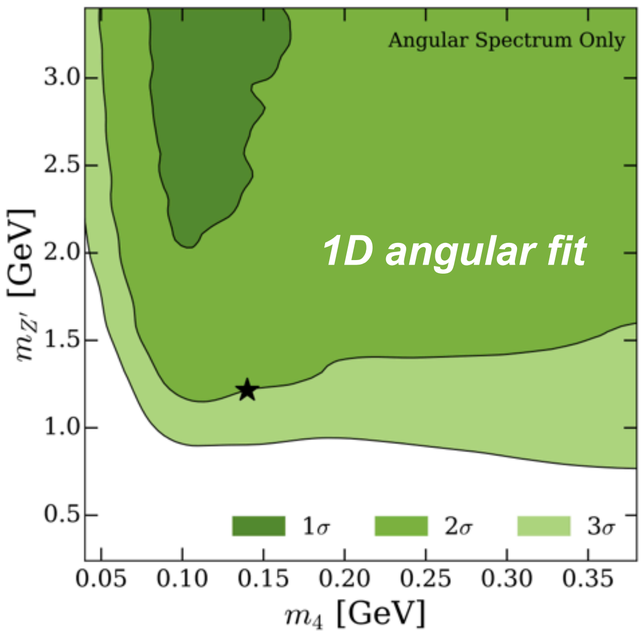
Light mediator (10 - 100s of MeV)

E. Bertuzzo et al., PRL121.241801



Heavy mediator (~ GeV scale)

P. Ballett et al, PRD 99.071701



Explaining MiniBooNE with our full model

HNLs produced in neutrino scattering

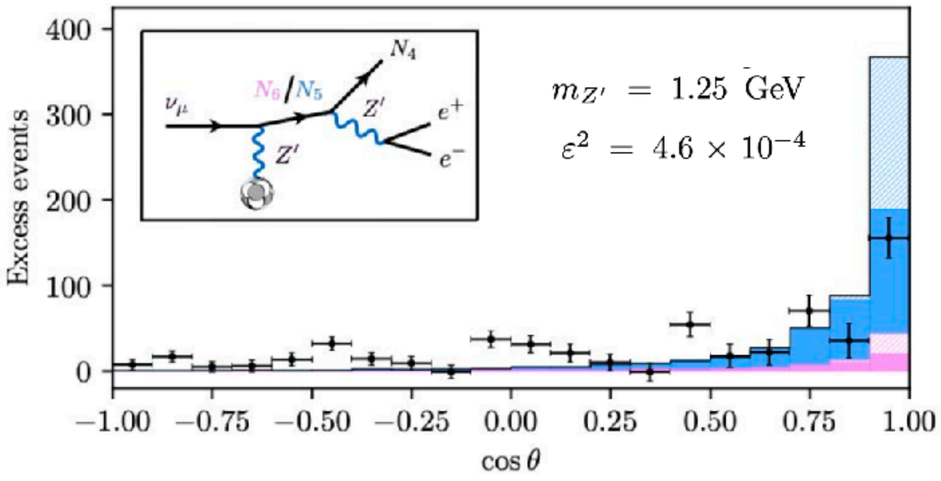
Using our benchmark point

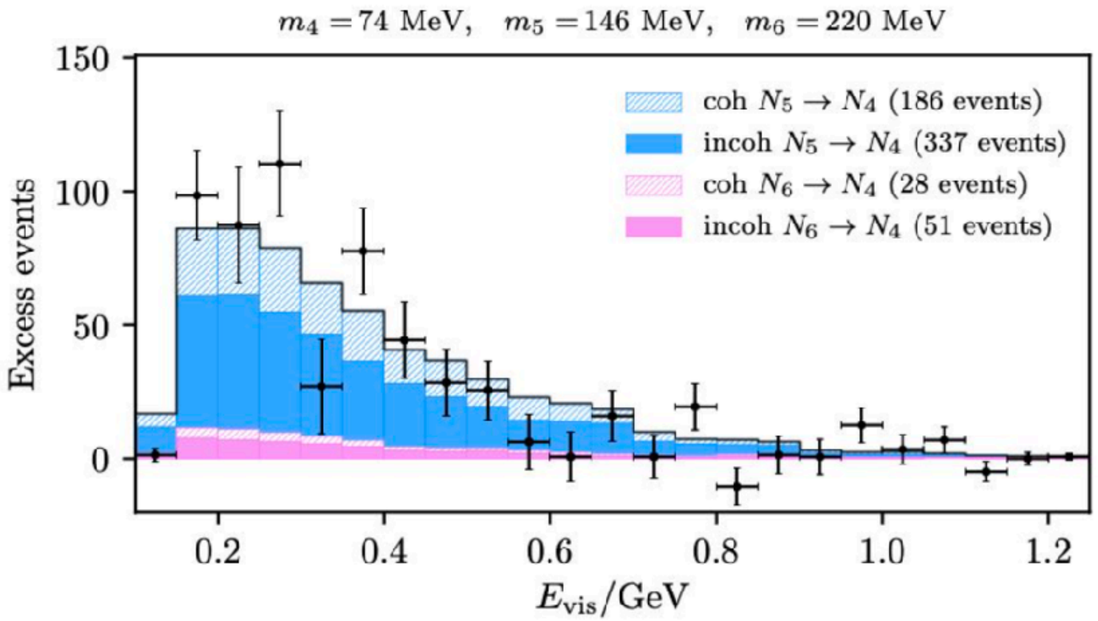
$m_{Z'} \sim 1.25$ GeV $\quad \epsilon^2 \sim 4.6 \times 10^{-4}$

Dark coupling | *HNL masses* | *HNL lifetimes*

α_D	m_3 /eV	m_4	m_5	m_6 /MeV
0.32	0.05	74	146	220

$c\tau^0$/cm N_4	N_5	N_6
1.1×10^7	2.2	0.14





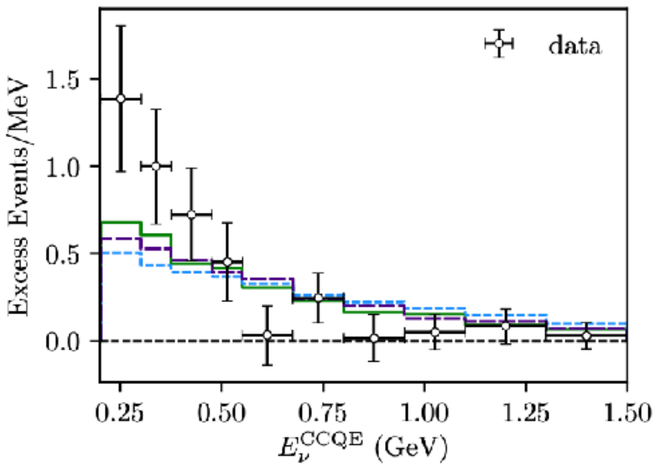
Angular distribution forward due to vectorial nature of **Z'-proton-proton** interaction.

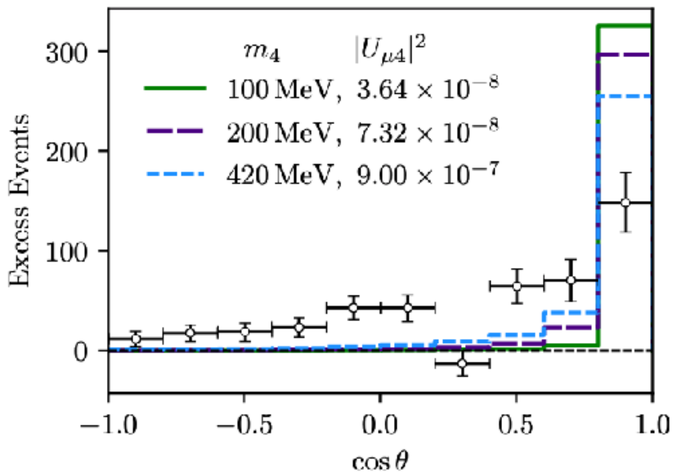
Higher-Q2 and nuclear effects not included (important for GeV Z').

All Distributions

On-shell light Z'

E. Bertuzzo et al., PRL121.241801
C. Arguelles, MH, Y. Tsai, PRL123.261801

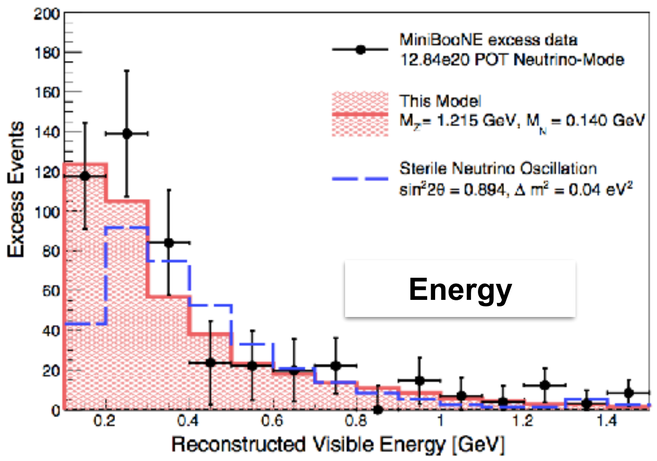


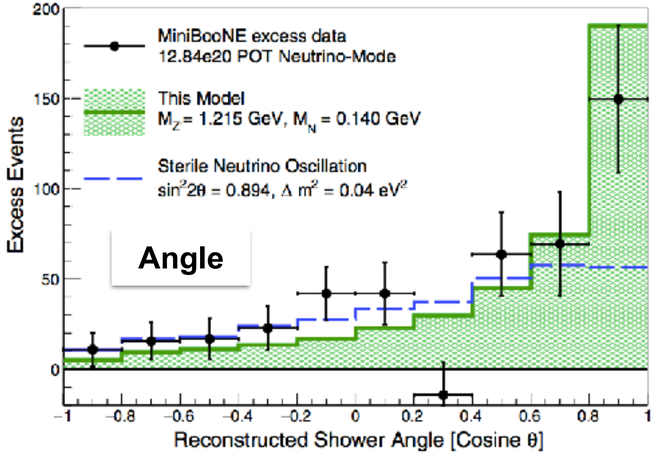


MiniBooNE 2018

Off-shell Z' (Z-Z' interference)

P. Ballett et al, PRD 99.071701

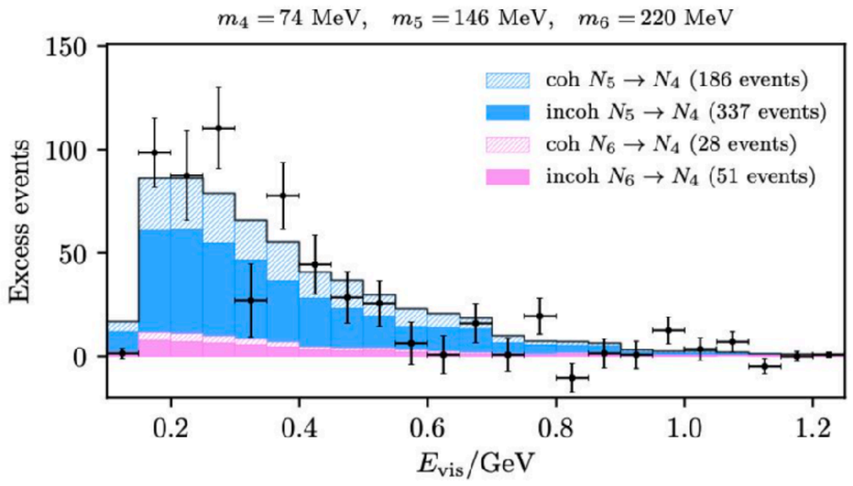


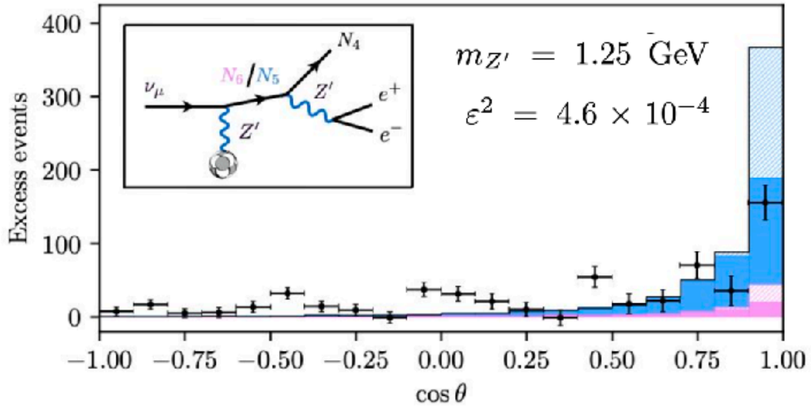


MiniBooNE 2018

Off-shell Z' (no Z-Z' interference)

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





MiniBooNE 2020

Surely we would have seen this elsewhere…

Pseudo-photons at ν detectors

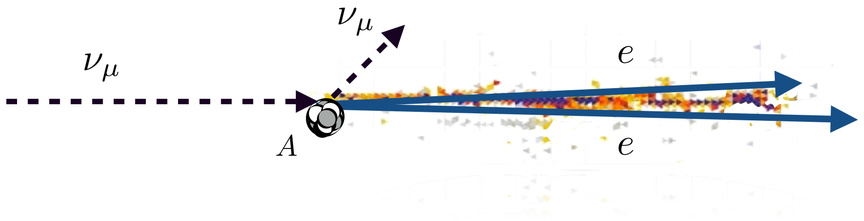
Neutrino-electron scattering datasets

Carlos Argüelles

Yu-Dai Tsai

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

Currently, neutrino experiments can search for photon-like showers inside their detectors.



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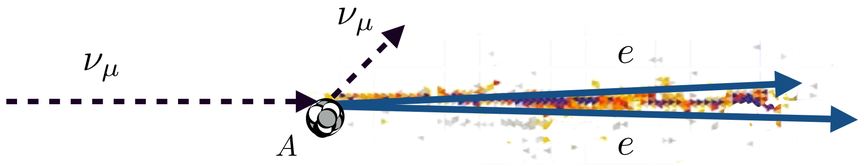

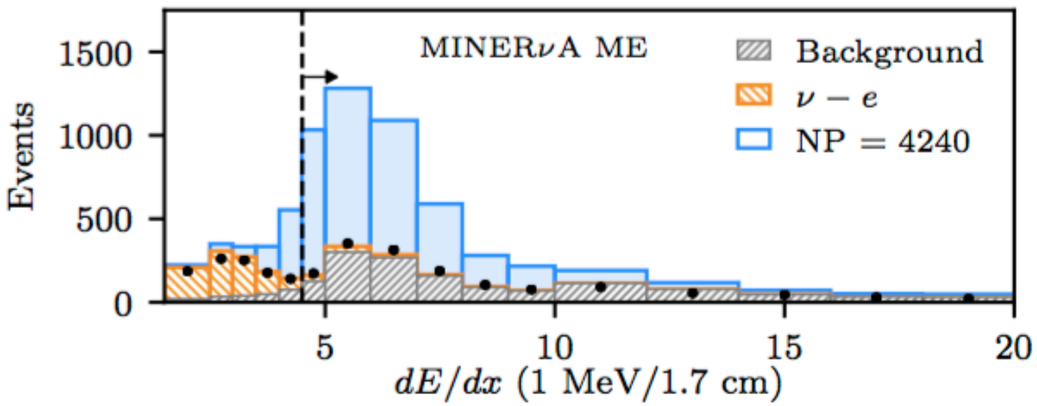

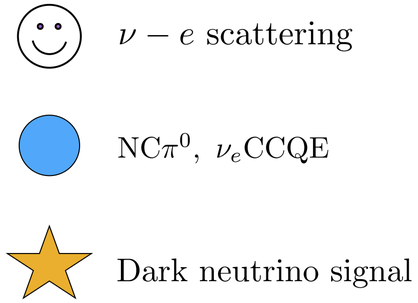

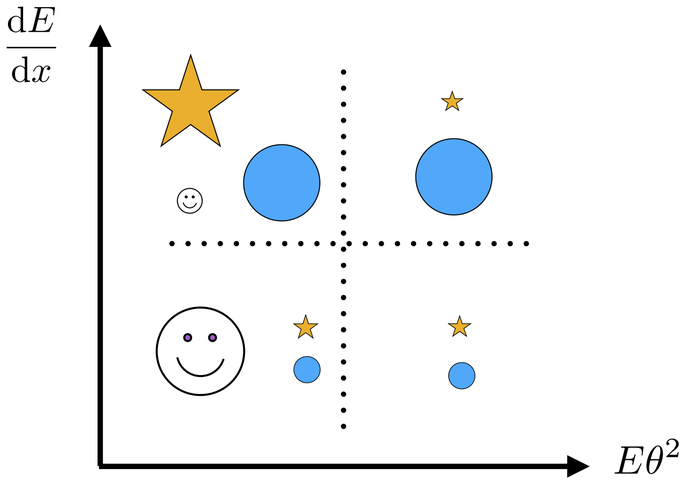

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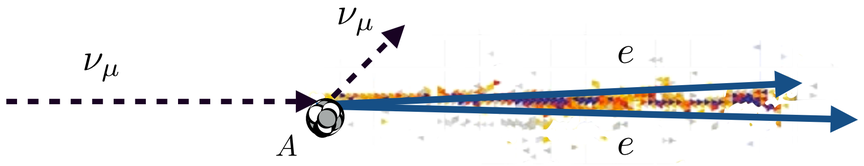
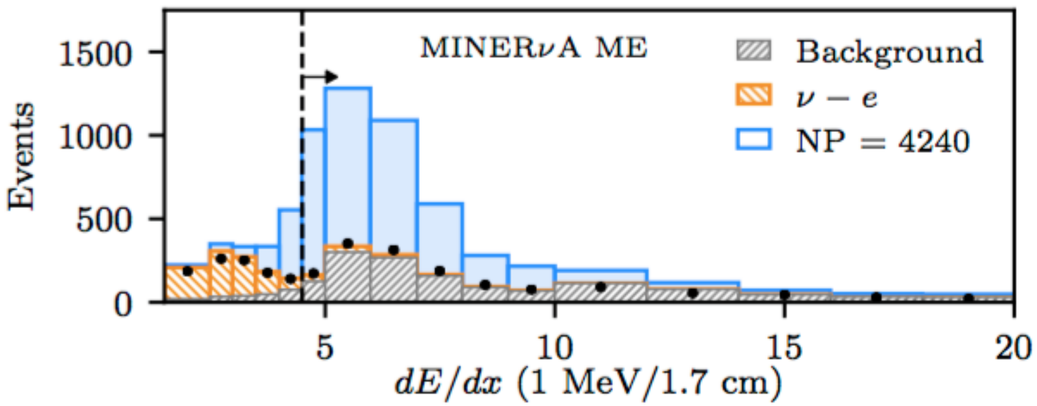
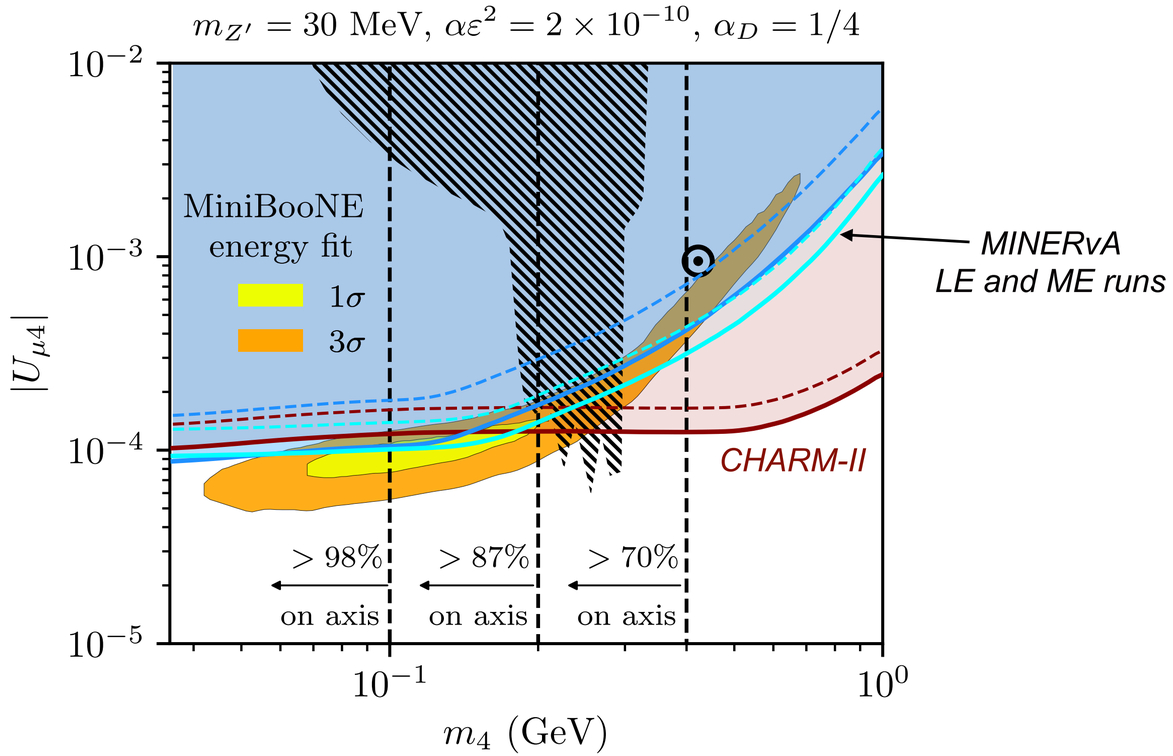






Some tension with light dark photon scenarios (coherent scattering) but **ineffective for heavy mediator scenarios** (higher Q2 scattering).

Datasets to keep an eye on:
NOvA and **MINERvA** (anti-)nu-e scattering.

Re-adapting decay-in-flight HNL searches
@ T2K near detector (ND280)

Carlos Argüelles Nicolo Foppiani

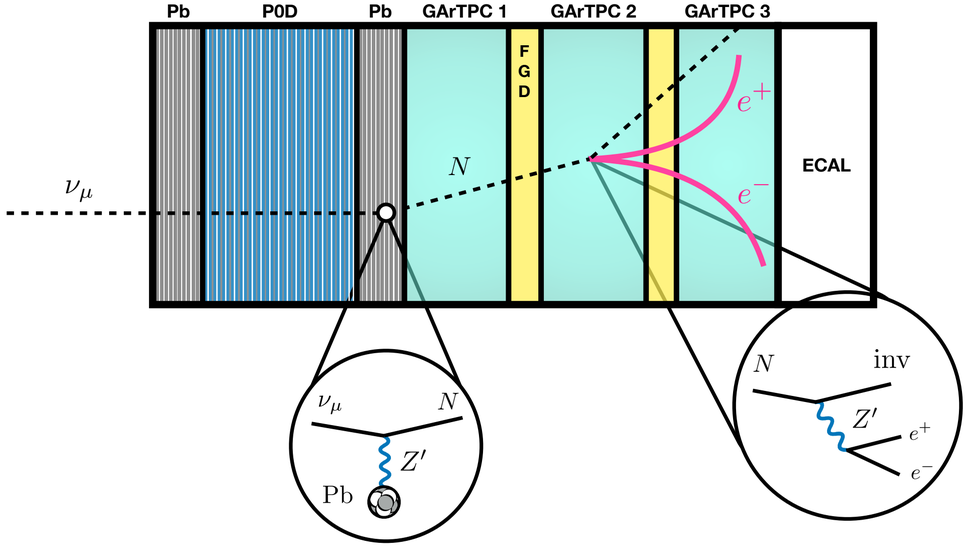
C. Arguelles, MH, N. Foppiani, in preparation.

T2K provides leading constraints on standard HNLs above the pion mass.

T2K Collaboration, Phys. Rev. D 100, 052006 (2019)

See also, Vedran Brdar et al, arXiv:2007.14411

Large target mass
Gaseous Argon modules
+ Magnetic field to separate e+e-



Constrains events with no hadronic activity at vertex and HNLs w/ finite lifetimes.

Re-adapting decay-in-flight HNL searches
@ T2K near detector (ND280)

Carlos Argüelles Nicolo Foppiani

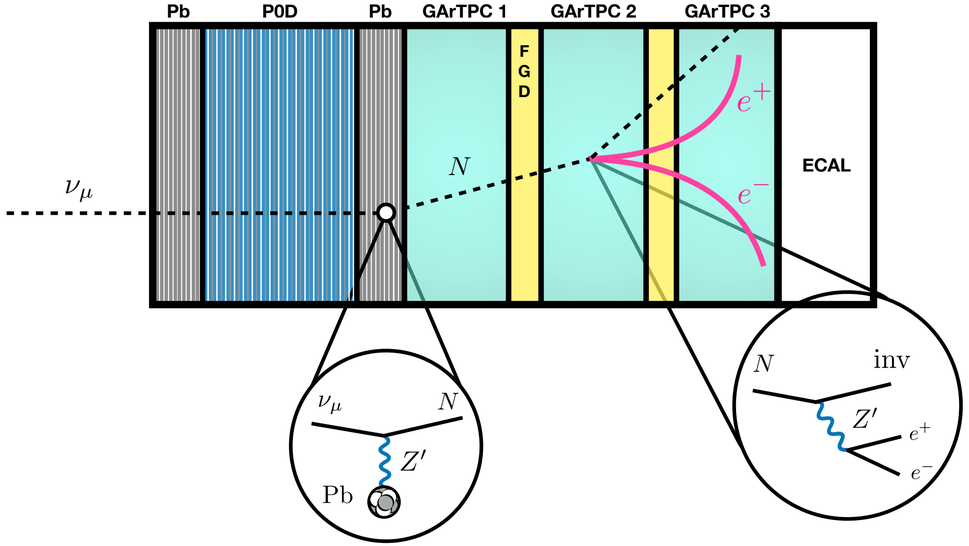
C. Arguelles, MH, N. Foppiani, in preparation.

T2K provides leading constraints on standard HNLs above the pion mass.

T2K Collaboration, Phys. Rev. D 100, 052006 (2019)

See also, Vedran Brdar et al, arXiv:2007.14411

Large target mass
Gaseous Argon modules
+ Magnetic field to separate e+e-

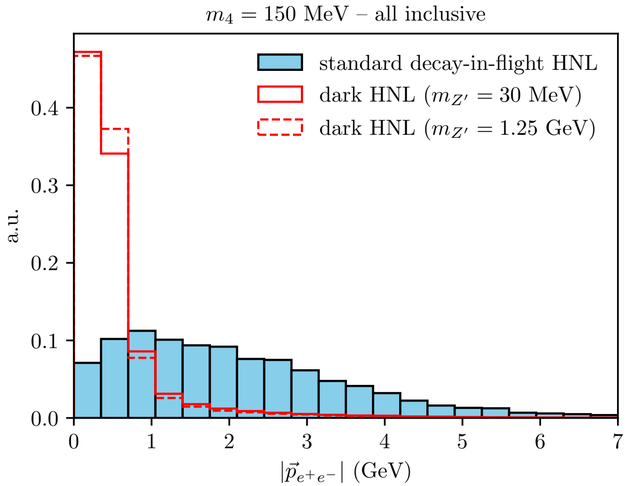


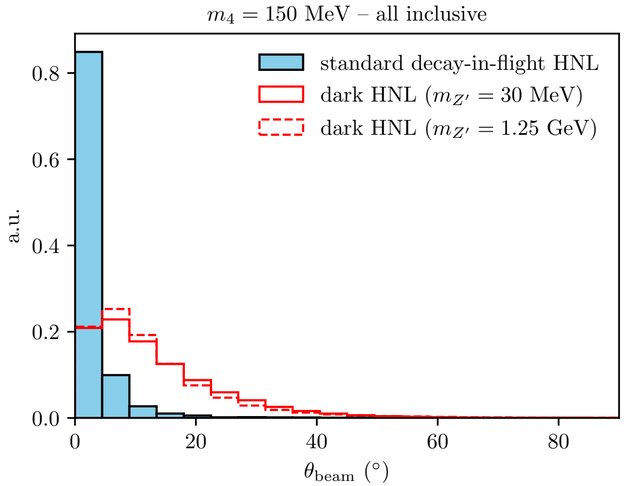
Constrains events with no hadronic activity at vertex and HNLs w/ finite lifetimes.

Multi-component detector — active target followed by Gaseous Ar modules.

Can use heavy target for upscattering and GAr modules for decay.

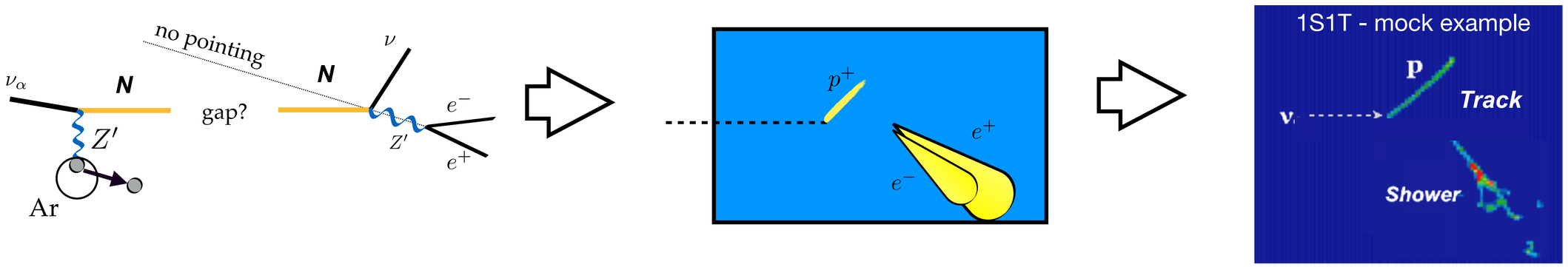
Dark neutrino signal is softer and more off-axis than standard DIF signal.





Dark neutrinos @ MicroBooNE

New generation of Liquid Argon detectors at Fermilab can search for (e+e-) events and will test MiniBooNE results.



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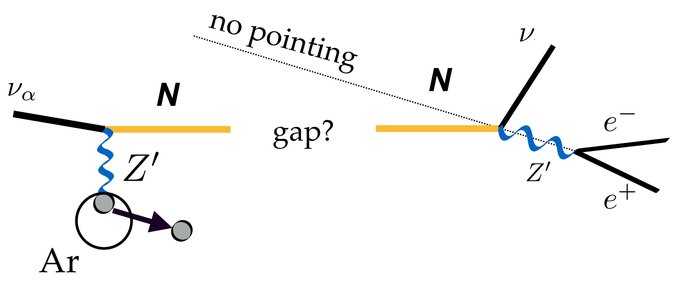
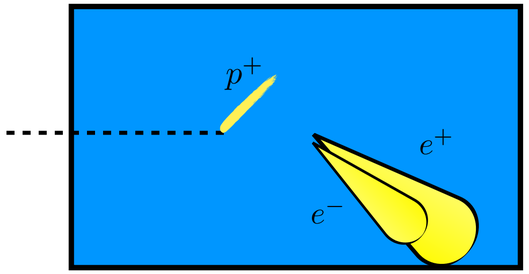
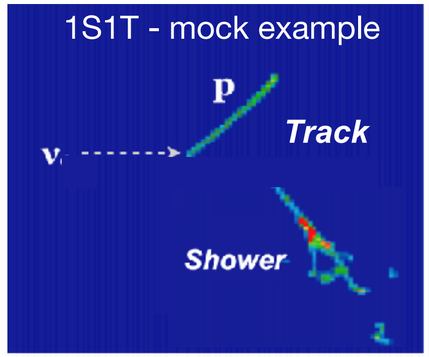
Currently investigating these signatures in LAr together with microBooNE single-photon group.







1S0T	2S0T
1S1T	2S1T

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.*

In our benchmark, before efficiencies, we expect

~800 events of $\nu_\mu \longrightarrow N_5 \longrightarrow \nu\, e^+e^-$

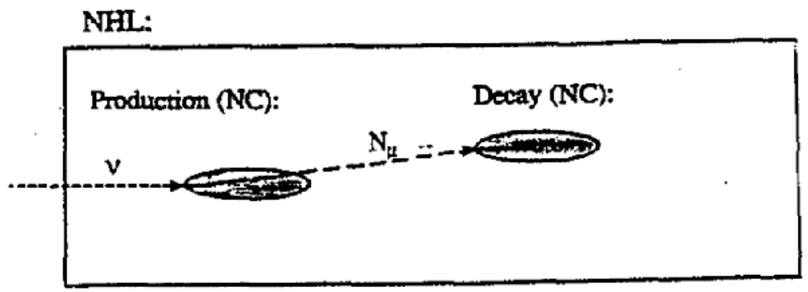
~3000 events of $\nu_\mu \longrightarrow N_6 \longrightarrow \nu\, e^+e^-$

Looking further back

“Double-bang” events

Experimental anomalies in the 80/90’s — not ruled w/ newer hypotheses

Double-bangs @ CCFR



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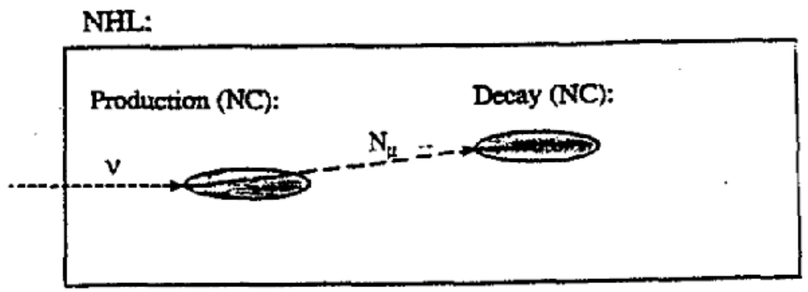


9 NC/NC observed on a background of $3 \pm 0.2\,(\mathrm{stat.}) \pm 0.4\,(\mathrm{syst.})$

To the best of our knowledge, this is not explained to this date.
P. de Barbaro, doi.org/10.1063/1.43269

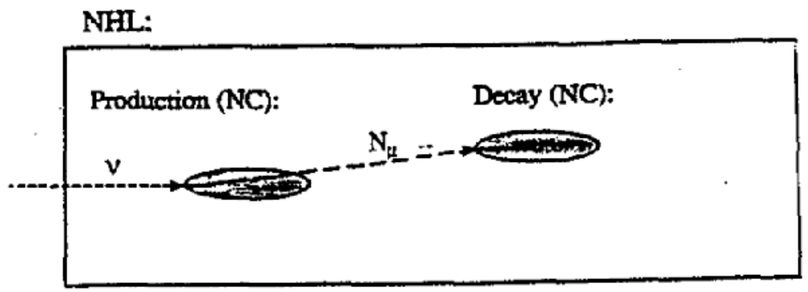
Result was not pursued further as standard HNLs would also lead to NC/CC events (N —› μ π).

But our dark HNLs only decay via NC channels, compatible few events at $E_\nu \sim 100$ GeV (DIS **cross section is small via Z’).**

“Double-bang” events & old accelerator excesses

Experimental anomalies in the 80/90’s — not ruled w/ newer hypotheses

Double-bangs @ CCFR



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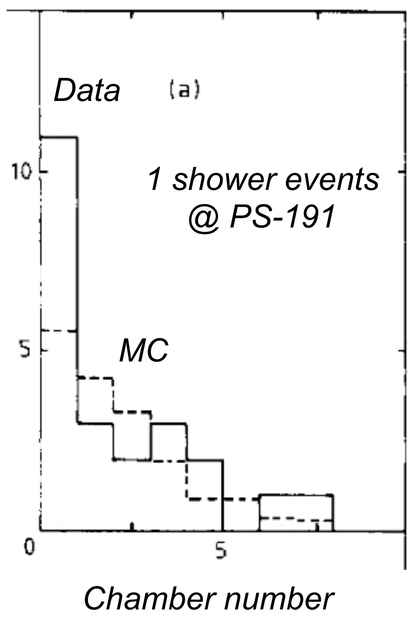
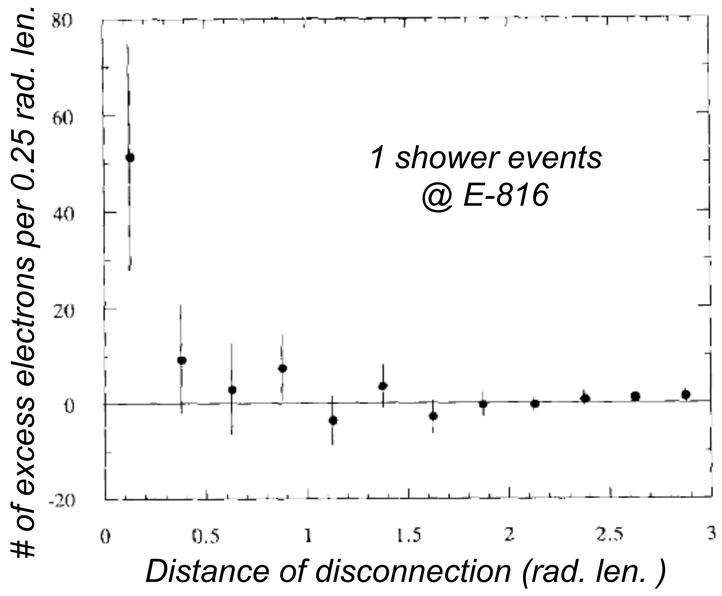
Accelerator anomalies





PS-191 (’86 @ CERN): 3σ deviation from expectation.

E-816 (’90 @ BNL): built to address PS-191, found a ~2σ excess.

Oscillation interpretation only ruled out by high-energy exps.

Compatible w/ ν_μ —› N_6 —› ν (e^+e^-) decays, which are fast.

Anomalous Magnetic Moment of the Muon

$(g-2)_\mu$

Dark forces contributing to (g-2)$_\mu$

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HVP,\,LO} + a_\mu^{\rm HVP,\,NLO} + a_\mu^{\rm HVP,\,NNLO} + a_\mu^{\rm HLbL} + a_\mu^{\rm HLbL,\,NLO}$$
$$= 116\,591\,810(43) \times 10^{-11}\,.$$

Phys. Rept. 887 (2020) 1–166

$$a_\mu^{\rm exp} = 116\,592\,089(63) \times 10^{-11}$$

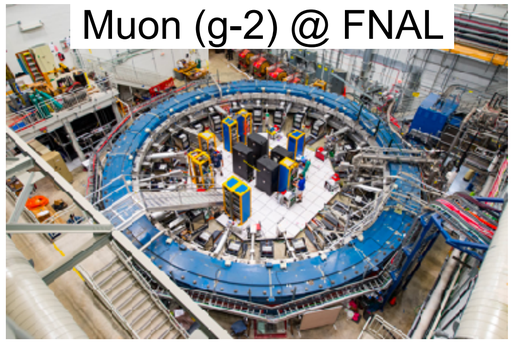
Muon (g–2) Collab., PRD73:072003,2006

$$\Delta a_\mu := a_\mu^{\rm exp} - a_\mu^{\rm SM} = 279(76) \times 10^{-11}$$

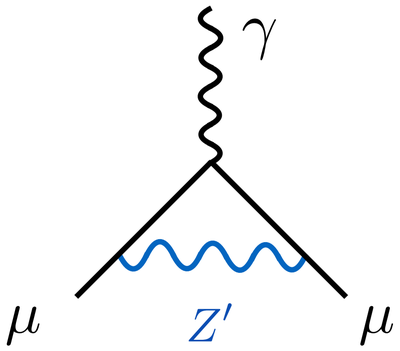
3.7σ discrepancy with SM

Not conclusive yet, but expect updates from FNAL Muon (g-2) very soon.

In full run, expect 4x better precision.



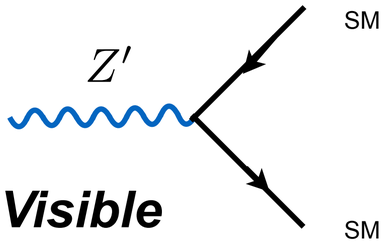
Need not come from high scale physics, but also from light new scalars or vectors:

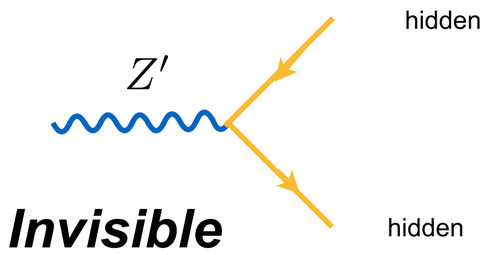


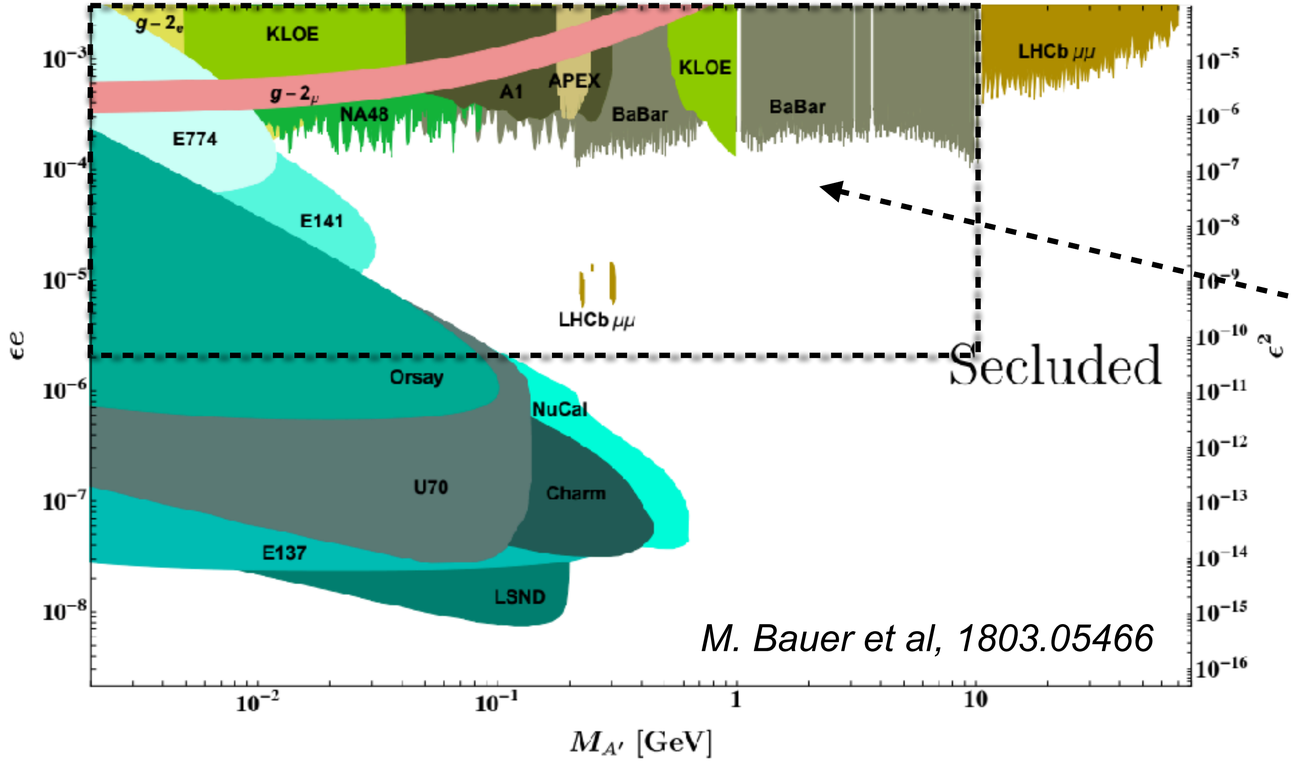
$$a_\mu^{Z'} \simeq \frac{\epsilon^2 \alpha}{\pi} \frac{m_\mu^2}{3 m_{Z'}^2} \quad \text{for} \quad m_\mu \ll m_{Z'}$$

Pospelov, PRD80:095002,2009

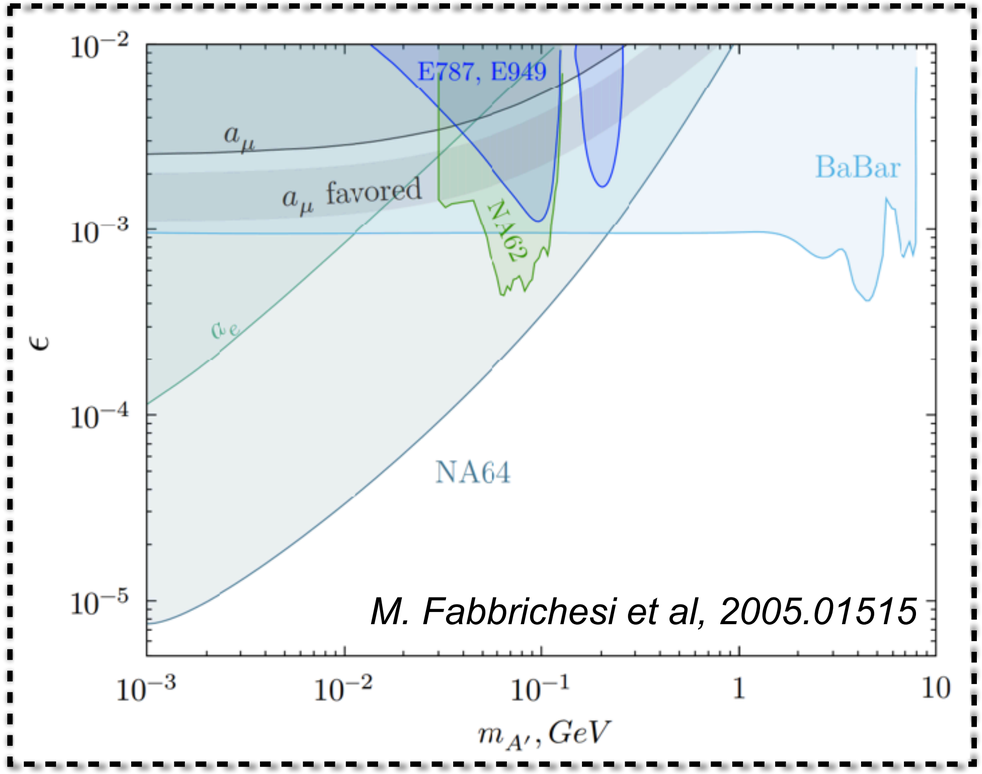
Minimal Dark Photon models







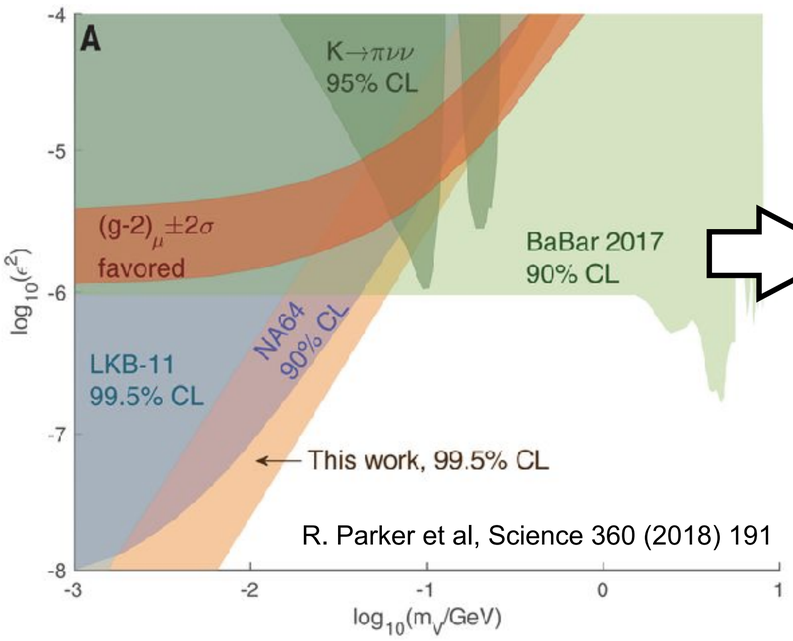
M. Bauer et al, 1803.05466



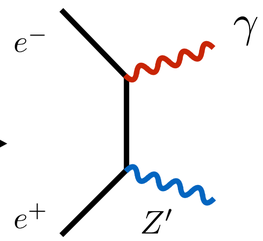
M. Fabbrichesi et al, 2005.01515

Revisiting the muon (g-2) with semi-visible dark photons

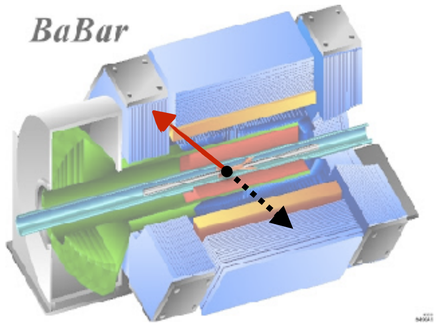
Similar to Inelastic DM models,
G. Mohlabeng, Phys. Rev. D 99, 115001 (2019)



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



Invisible dark photon



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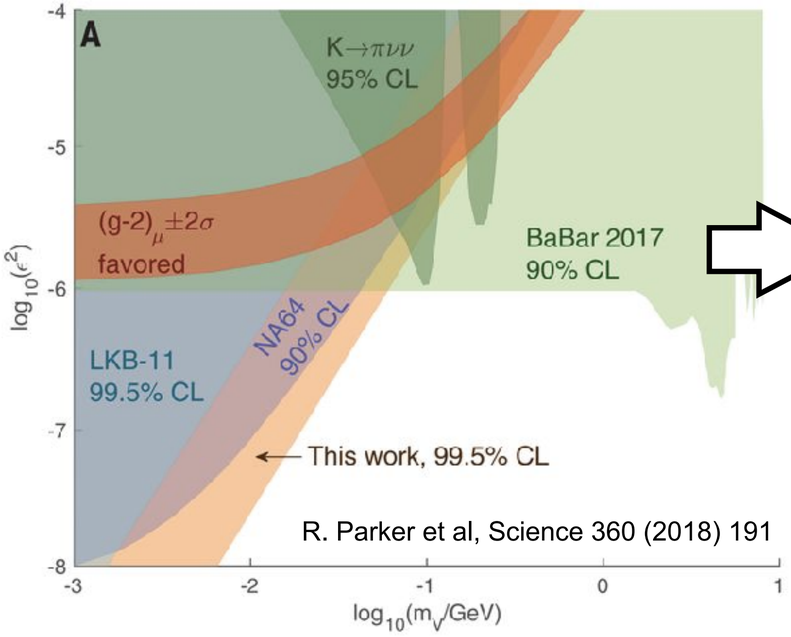

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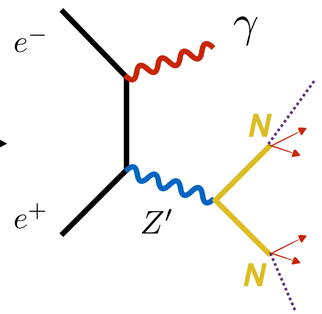

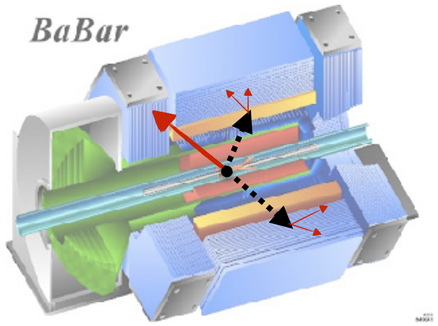

Invisible dark photon bounds relaxed.

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

for $\varepsilon^2 = 4.6 \times 10^{-4}$

$m_{Z'} = 1.25$ GeV

this requires

$$P_{\text{missing all } N} < 2.2 \times 10^{-3}$$

$\mathcal{B}(Z' \to N_j N_k)/\%$					
44	45	46	55	56	66
0.15	11	0.48	1.6	86	0.59

Revisiting the muon (g-2) with semi-visible dark photons

Pseudo-monophotons from HNLs

Similar to Inelastic DM models,
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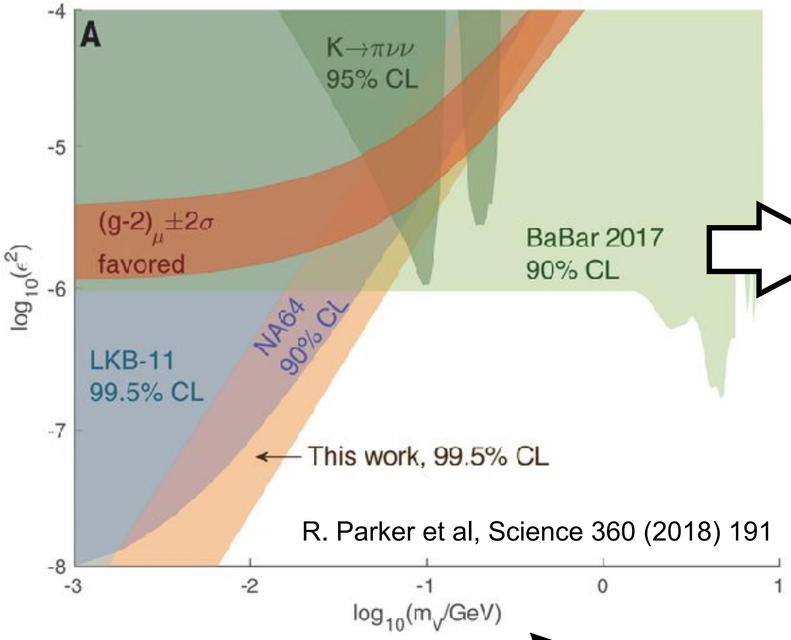

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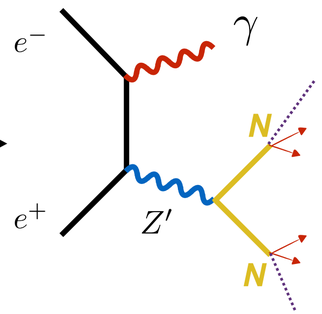

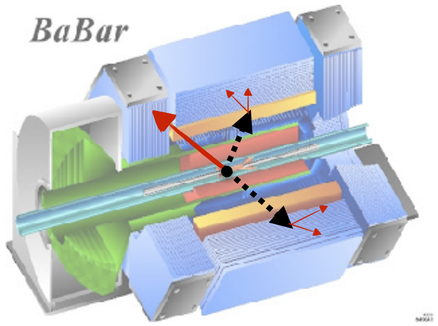

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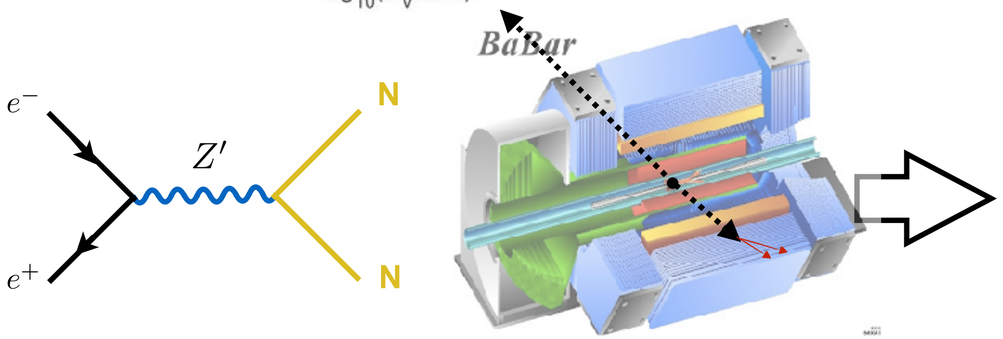
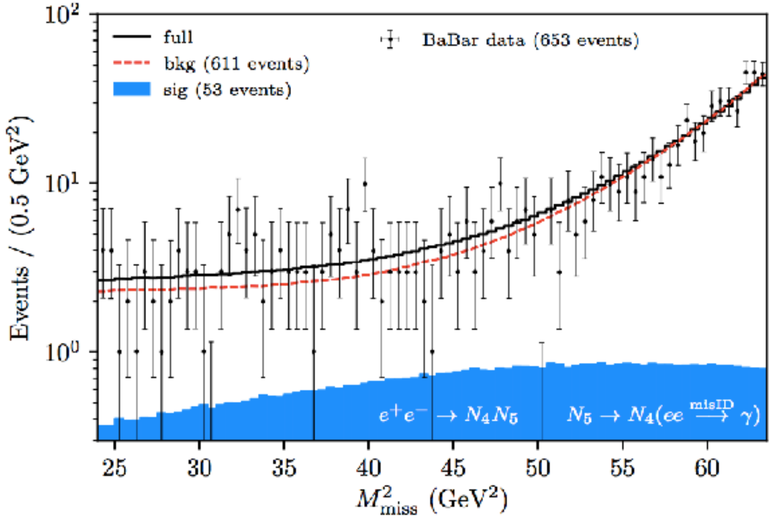


*Predicts a huge rate of s-channel $e^+e^- \to NN$ production @ **BaBar** and **Belle-II** ($\mathcal{O}(10^4)$ events).*

When only one N decays inside the ECAL, it can fake a monophoton event.

Signal is compatible with mild excess at low missing masses.

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



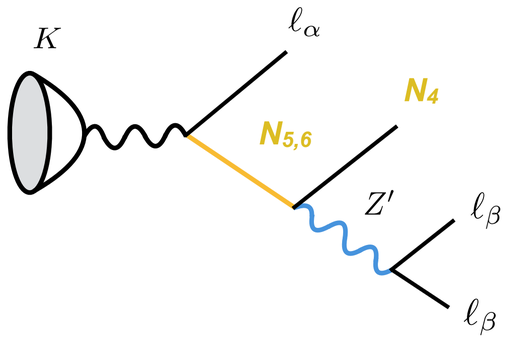
Direct tests with kaon decays

Looking for the dark HNLs elsewhere

Smoking gun signature at kaon experiments

Rare leptonic kaon decays

Peak search + (displaced) e+e- vertex



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

$$|p_K - p_\ell| = m_{5,6}$$

$$m_{\text{miss}} = |p_K - p_\ell - p_{ee}| = m_4$$

$$m_{ee} < m_{5,6} - m_4$$

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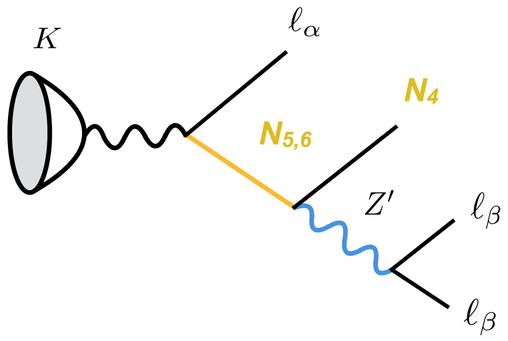

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Existing measurements:

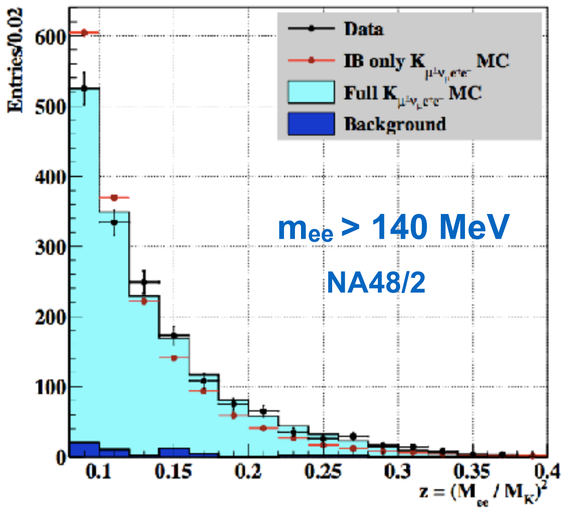
$$\text{BR}(K^+ \to \mu^+ \nu e^+ e^-) = (7.81 \pm 0.21\ \text{stat.}) \times 10^{-8} \quad \text{@ NA48/2}$$

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

Both SM process will be measured by NA62.

New physics challenges:

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



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

$$K^+ \to \mu^+ \nu_\mu (\pi^0 \to \gamma e^+ e^-)$$

Additional cuts can reduce pi+ decay backgrounds:

$$K^+ \to (\pi^+ \to \mu^+ \nu) e^+ e^- \qquad m_{\mu\nu} > 150\ \text{MeV}$$

Ultimately, depends on exp resolution, but BKGs can also be reduced with displaced vertices. At NA62, this is feasible for

$c\tau$ > 10 ps

Looking for the dark HNLs elsewhere

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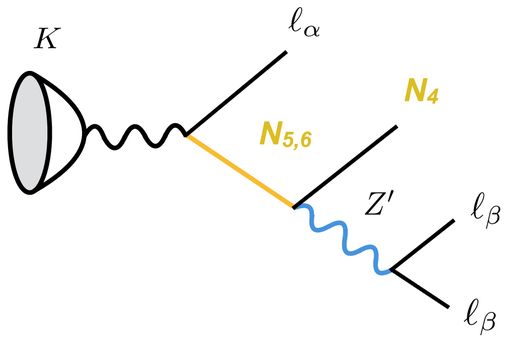

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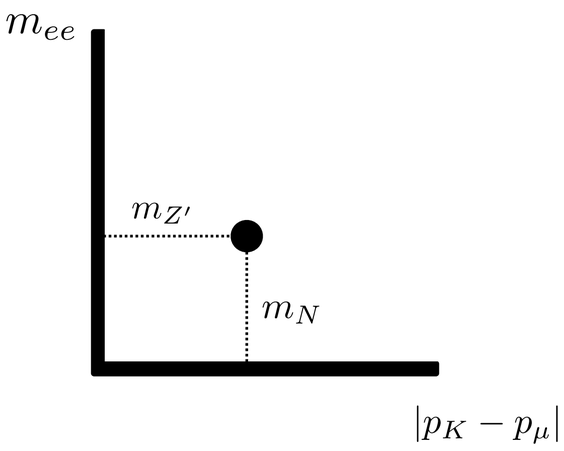
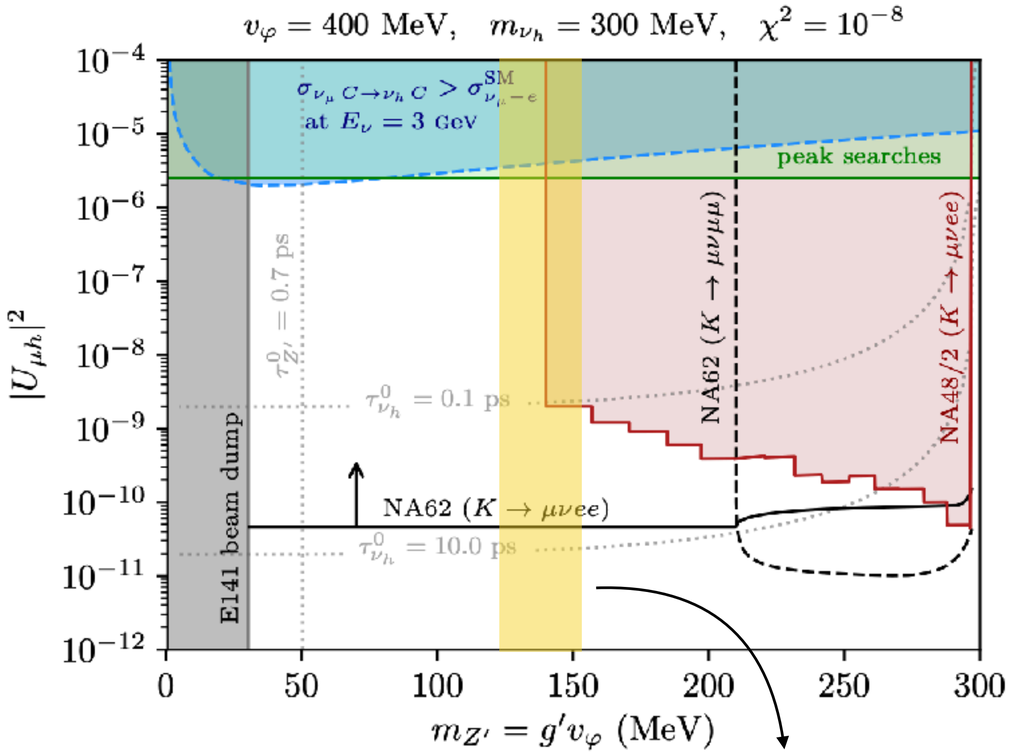
Light dark photon case

Smoking gun peak at light dark photon and HNL mass





Competing with pion Dalitz decays.

Provides a direct and robust test of MiniBooNE explanations

More exotic signatures in kaon decays

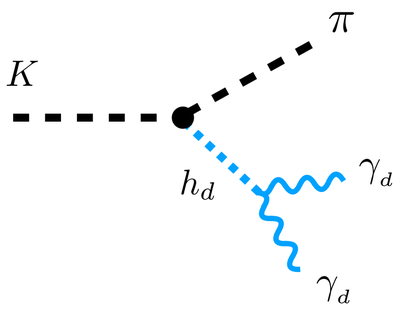
Dark higgs decays to dark photon

M. Hostert, M. Pospelov, arXiv:2012.02142

If the dark higgs is light but heavier than 2 dark photons, we also expect kaon decays with 4-leptons via a cascade in the dark sector. **Large (e+e-) multiplicities "for free".**

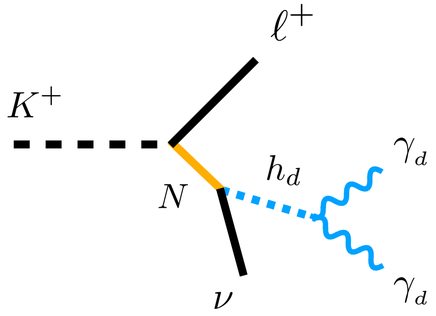
Several channels never even searched for, which can exceed **Br ~ O(10^{-8} - 10^{-6}).**

$$K \to \pi 2(e^+e^-)$$



$$m_{ee} \stackrel{!}{=} m_{\gamma_d}$$
$$m'_{ee} \stackrel{!}{=} m_{\gamma_d}$$
$$m_{4e} \stackrel{!}{=} m_{h_d}$$

$$K^+ \to \ell^+_\alpha \nu 2(e^+e^-)$$



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$$m_{\nu 4e} = |p_K - p_{\ell_\alpha}| \stackrel{!}{=} m_N;$$

CONCLUSIONS

Renormalizable and testable neutrino mass generation model with a U(1)' dark sector that incorporates the Radiative Inverse Seesaw

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Renormalizable and testable neutrino mass generation model with a U(1)' dark sector that incorporates the Radiative Inverse Seesaw

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<u>Also compatible with:</u>

- **PS-191 and E949 results — EM shower signals "ruled out" in other explanations**
- **CCFR — double neutral vertices at a high energy experiment**

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Testable at:

- **μBooNE (+SBN program)**
- **NA62** $K^+ \to \ell^+ \nu e^+ e^-$

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Also compatible with:

- **PS-191 and E949 results — EM shower signals "ruled out" in other explanations**
- **CCFR — double neutral vertices at a high energy experiment**

Testable at:

- **μBooNE (+SBN program)**
- **NA62** $K^+ \to \ell^+ \nu e^+ e^-$

Thank you!

Weak Interactions and Neutrinos (WIN 2021)

Online Workshop

Takes place every 2 years, alternating with Neutrino conference series.

win2021.umn.edu

Indico page

The 28th International Workshop on Weak Interactions and Neutrinos (WIN2021)

7-12 June 2021
US/Central time zone

- Overview
- Scientific Programme
- Call for Abstracts
- Timetable
- Contribution List
- Registration
- Participant List
- Conference Webpage
- Conveners
- Committees

WIN2021 Contact
win2021-loc@umn.edu

The International Workshops on Weak Interactions and Neutrinos have been organized regularly for the past 40 years at many venues in Africa, Asia, Europe, Latin America, and the United States.

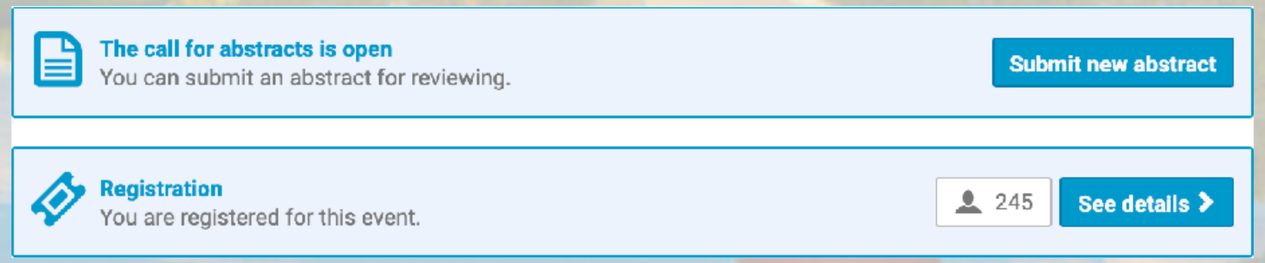
The 28th edition (WIN2021) will be held entirely online and will be hosted by the University of Minnesota, from June 7 – 11, 2021.

The goal of these Workshops is to offer the physics community a significant opportunity to assess the status of major topics within the field and initiate collaborative efforts to address current challenges. The Workshops attract leading experimentalists and theorists, from all over the world, allowing them to exchange ideas and to develop new strategies. In many cases, the efforts initiated at these Workshops result in completed projects that are published in international journals. These projects have sometimes proven to be major breakthroughs such as the MSW effect, which was first discussed at the WIN85 meeting in Finland.

As customary in this workshop series, the program will be structured to allow ample time for formal and informal discussions in the four working groups:

1. Neutrino Physics
2. Electroweak Interactions
3. Flavor and Precision Physics
4. Astro-particle Physics and Cosmology

Registration and abstract submission open.



The call for abstracts is open
You can submit an abstract for reviewing.
Submit new abstract

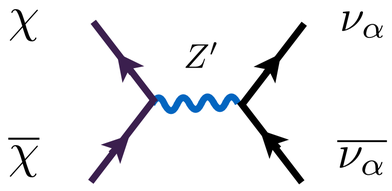
Registration
You are registered for this event.
245
See details

Back-up slides

A renormalizable model for a dark neutrino sector

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

Fermionic DM extensions parentheses



- Option 1) Accidental symmetries

$$\chi_{\mathrm{L,R}} \sim (\mathbf{1}, 0, Q/2) \qquad y_R\, \overline{\chi_R^c}\chi_R\Phi^* + y_L\, \overline{\chi_L^c}\chi_L\Phi^* + m_\chi \overline{\chi_L}\chi_R$$

- Option 2) Imposed dark parity (e.g., from residual lepton number symmetry).

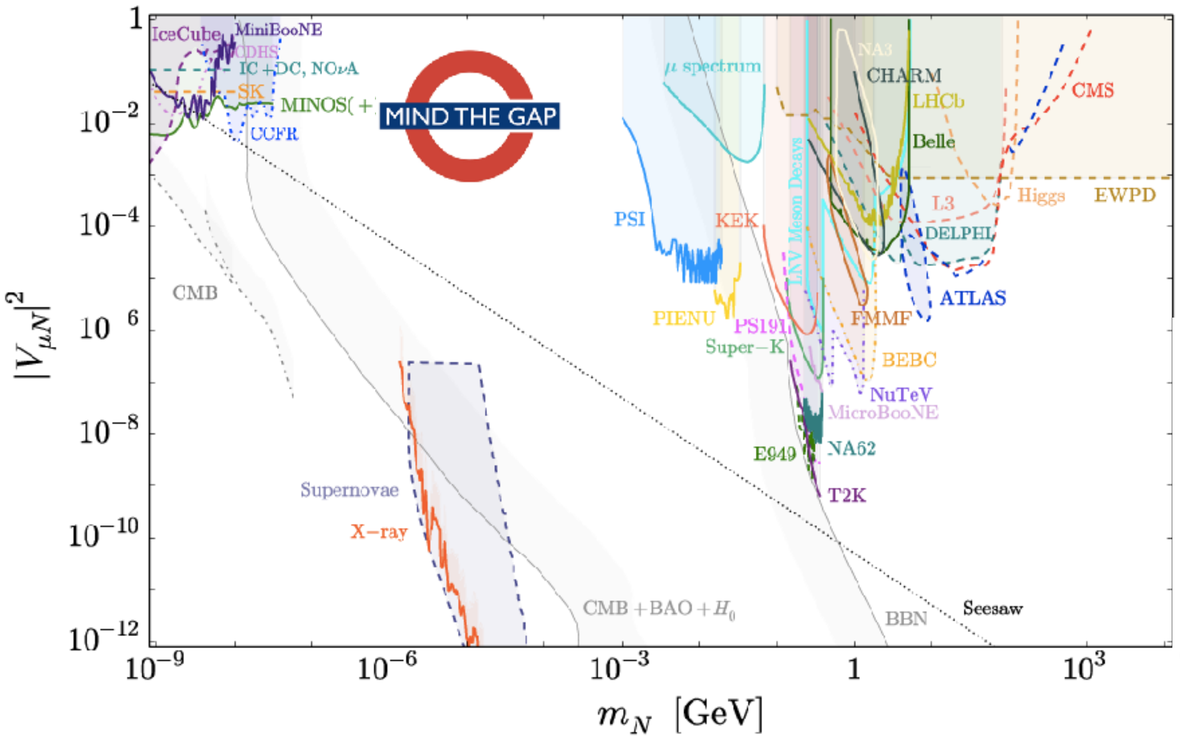
$$\chi_{\mathrm{R}} \sim (\mathbf{1}, 0, Q) \quad \chi_{\mathrm{L}} \sim (\mathbf{1}, 0, 0) \qquad \mu_L\, \overline{\chi_L^c}\chi_L + y\, \overline{\chi_L}\chi_R\Phi^*$$

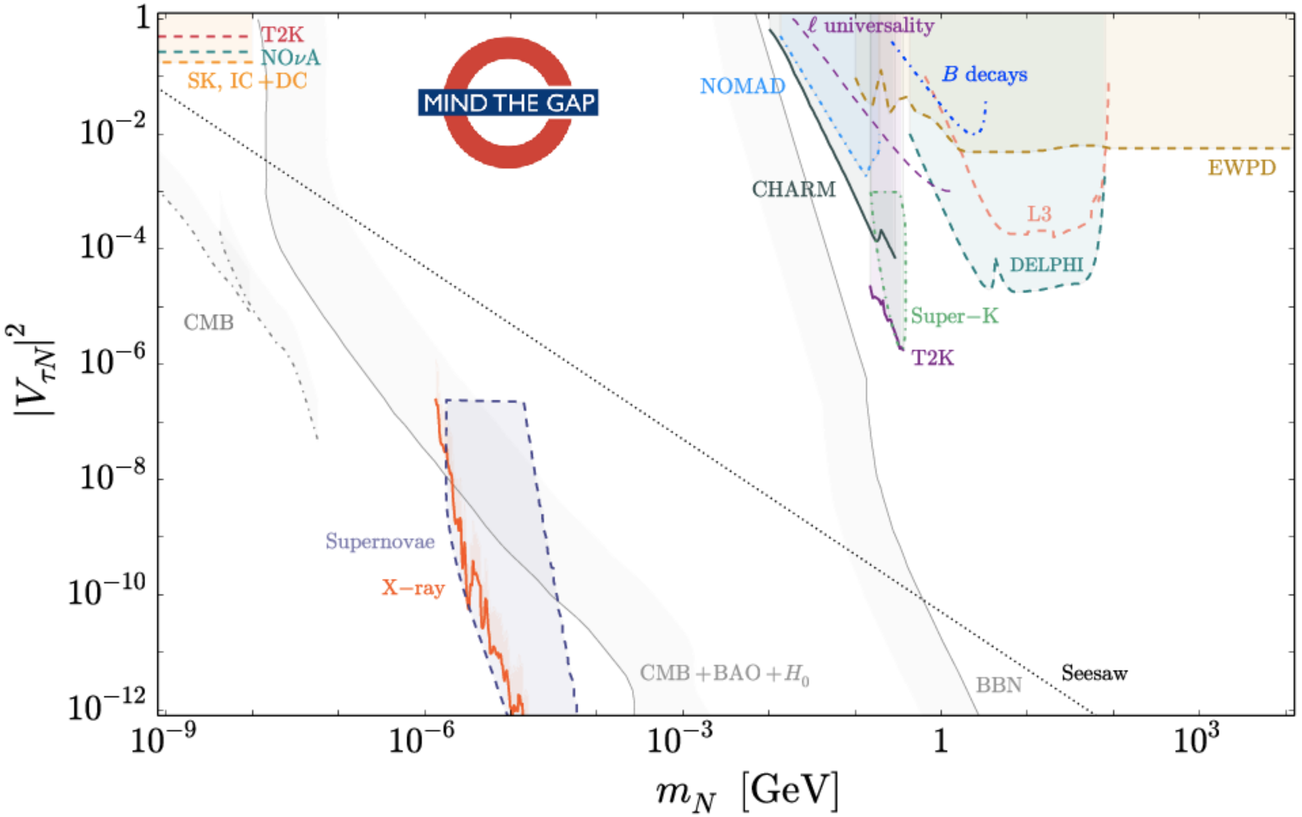
When vector and scalar portals are turned off the model is promising avenue for MeV/GeV scale thermal nu-philic DM.

B. Bertoni et al, 1412.3113
B. Batell et al, 1709.07001
M. Blennow et al, 1903.00006
J. Gherlein & M. Pierre 1912.06661

Minimal HNL Phenomenology

P. Bolton et al, 1912.03058





Low Scale Seesaws

LNV = lepton number violating

3 families of neutral leptons — new symmetries in M_N

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

(L= -1)

(L= +1)

$$\begin{cases} M_D = (m \;\; \epsilon') \\ M_N = \begin{pmatrix}\mu' & \Lambda \\ \Lambda & \mu\end{pmatrix} \end{cases}$$

Light neutrino masses proportional to **LNV** parameters

$$m_\nu \simeq \frac{\mu m^2 - 2\varepsilon' m\Lambda + \varepsilon'^2\mu'}{\Lambda^2 - \mu\mu'}.$$

Approximate conservation of **Lepton number** ⟶ Small neutrino masses.

Low Scale Seesaws — two kinds of contributions

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

"Inverse Seesaw" (ISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & 0 & \Lambda \\ 0 & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

"Minimal Radiative Inverse Seesaw" (MRISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Low Scale Seesaws — two kinds of contributions

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

"Inverse Seesaw" (ISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & 0 & \Lambda \\ 0 & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **S** ($\mu \to \infty$)

$$\begin{pmatrix} 0 & m_D \\ m_D & \frac{\Lambda^2}{\mu} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \end{pmatrix}$$

Active-heavy mixing: $|U_{\alpha 4}|^2 \simeq \frac{m_D \mu'}{\Lambda^2}$

Light state: $m_\nu \simeq \frac{m_D^2}{\Lambda^2}\mu$

"Minimal Radiative Inverse Seesaw" (MRISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **N** ($\mu' \to \infty$)

$$\begin{pmatrix} \frac{m_D^2}{\mu'} & \frac{\Lambda m_D}{\mu'} \\ \frac{\Lambda m_D}{\mu'} & \frac{\Lambda^2}{\mu'} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ S^c \end{pmatrix}$$

Active-heavy mixing: $|U_{\alpha 4}|^2 \simeq \frac{m_D^2}{\Lambda^2}$

Light state: $m_\nu^{\text{tree}} = 0$

(Holds provided #S = #N)

Low Scale Seesaws — two kinds of contributions

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

"Inverse Seesaw" (ISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & 0 & \Lambda \\ 0 & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **S** ($\mu \to \infty$)

$$\begin{pmatrix} 0 & m_D \\ m_D & \frac{\Lambda^2}{\mu} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \end{pmatrix}$$

Active-heavy mixing: $|U_{\alpha 4}|^2 \simeq \frac{m_D \mu'}{\Lambda^2}$

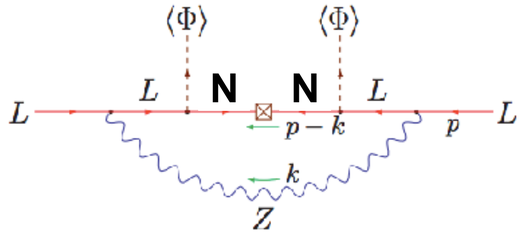
Light state: $m_\nu \simeq \frac{m_D^2}{\Lambda^2} \mu$

"Minimal Radiative Inverse Seesaw" (MRISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **N** ($\mu' \to \infty$)

$$\begin{pmatrix} \frac{m_D^2}{\mu'} & \frac{\Lambda m_D}{\mu'} \\ \frac{\Lambda m_D}{\mu'} & \frac{\Lambda^2}{\mu'} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ S^c \end{pmatrix}$$



Active-heavy mixing: $|U_{\alpha 4}|^2 \simeq \frac{m_D^2}{\Lambda^2}$

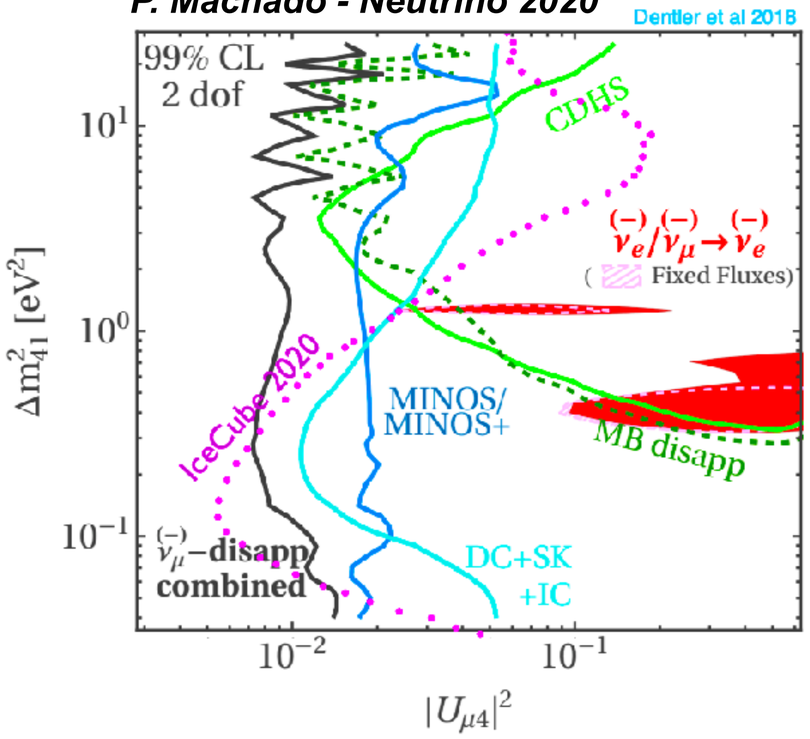
Light state: $m_\nu^{\text{loop}} \simeq \frac{\alpha_W}{16\pi} \frac{m_D^2}{\mu'} f(m_Z, m_h, \mu')$

New exotic hypothesis to explain MiniBooNE

Minimal eV sterile oscillations.

ν_μ disappearance + cosmology excludes this model.

P. Machado - Neutrino 2020



Open the floodgates to *exotica*

New signatures:
Gninenko 1107.0279 No LSND
Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916,
Arguelles et al 1812.08768
Heavy neutrino O(1-100MeV), light Z', decay
W. Abdallah et al 2010.06159 ~~No LSND~~

Oscillations+:
Asaadi et al 1712.08019
Resonant matter effect UV challenge

Doring et al 1808.07460, Barenboim et al 1911.02329
eV steriles and extra dimensional shortcuts
not clear

Liao et al 1810.01000
Steriles + NCNSI + CCNSI Baroque

Decay:
Delayed signal?
O. Fischer et al 1909.09561
Long lived HNL O(MeV) mag moment

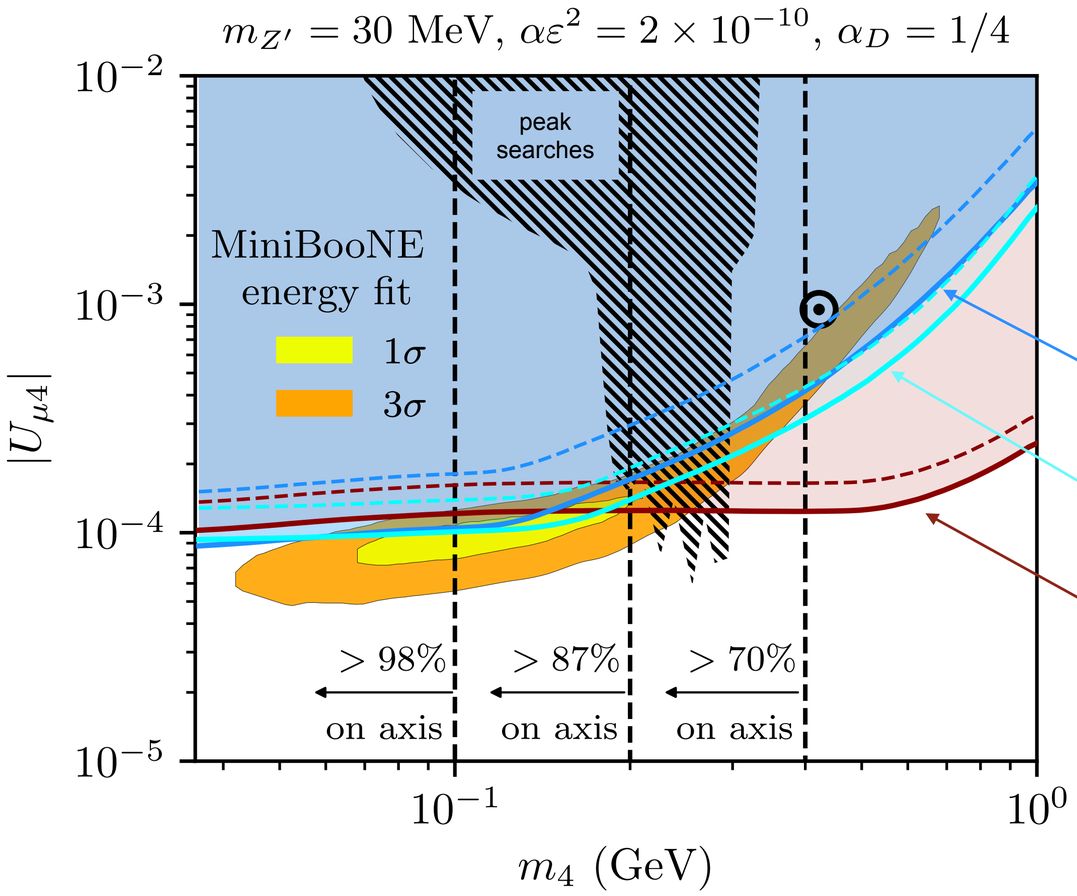
Bai et al 1512.05357, Dentler et al 1911.01427, de Gouvêa et al 1911.01447
Heavy sterile O(keV-MeV) decay to ν_e May work..

New physics
In scattering

New physics
In propagation

New "visible" states
in the beam

Neutrino-electron scattering constraints

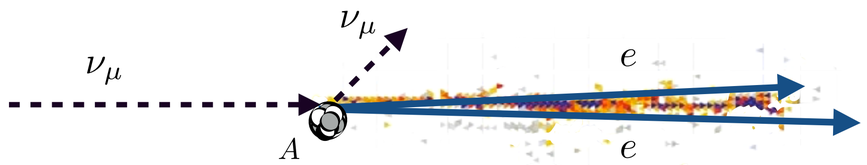


Vary uncertainty on backgrounds:

30% — 100% for MINERvA LE

40% — 100% for MINERvA ME

3 — 10% for CHARM-II



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

on axis = events in forward bin at MiniBooNE

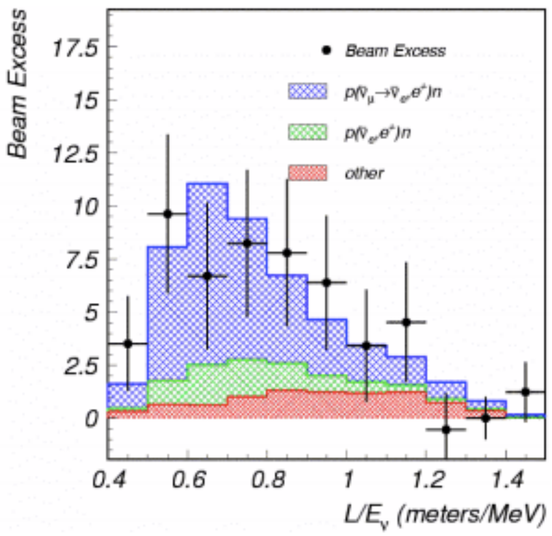
Analysis can be improved with future data:

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

LSND & KARMEN

LSND: 1993 - 1998 arXiv:0104049

1) 800 MeV proton beam, 1.8e23 POT!
2) π decay at rest and in flight:12º nu/p beam angle.
3) π- contamination: $\bar{\nu}_e/\bar{\nu}_\mu \sim 8 \times 10^{-4}$
4) Baseline of 30 m
5) ~167 tonnes of liquid scintillator
6) 8.3 m long det along nu beam.

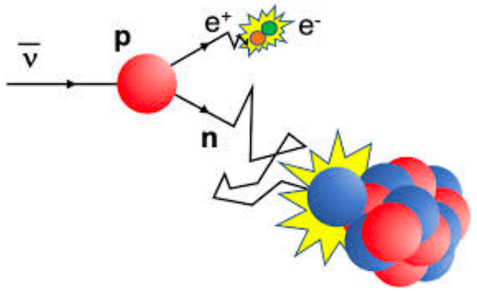


EXCESS: 87.9 ± 22.4 ± 6 EVENTS
3.8 sigma

General idea:

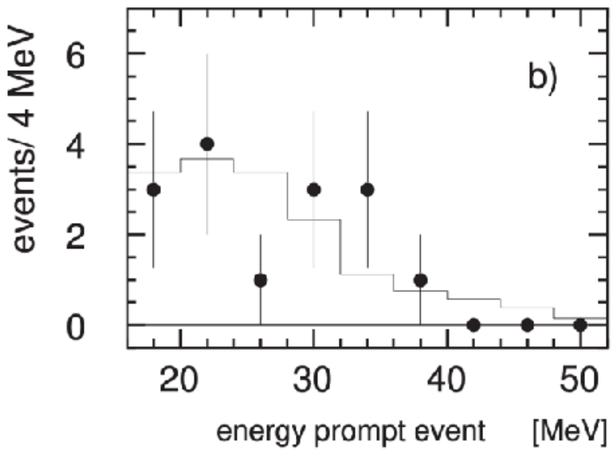
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$



KARMEN: 1990 - 2001 arXiv:020302

1) 800 MeV proton beam, 6e22 POT!
2) π decay at rest mostly. Detector 90º from p beam.
3) π- contamination: $\bar{\nu}_e/\bar{\nu}_\mu = 6.4 \cdot 10^{-4}$
4) Baseline of 17.7 m
5) ~57 tonnes of liquid scintillator
6) 3.5 m long det along nu beam.

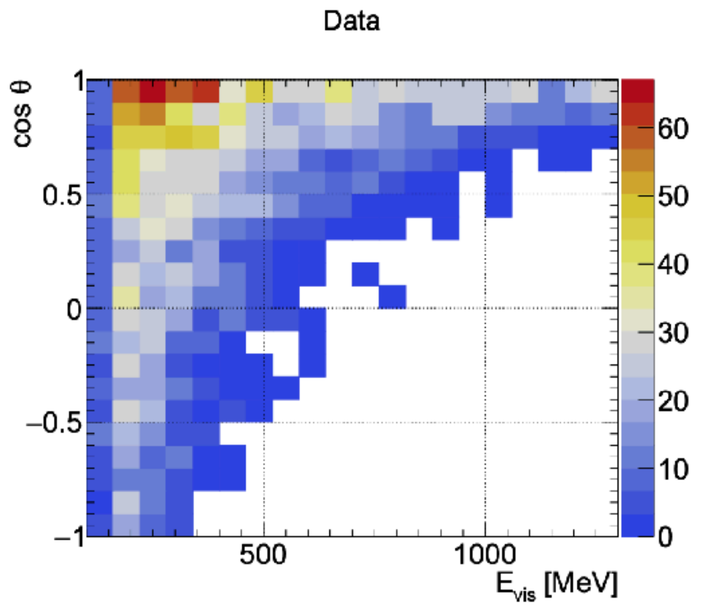


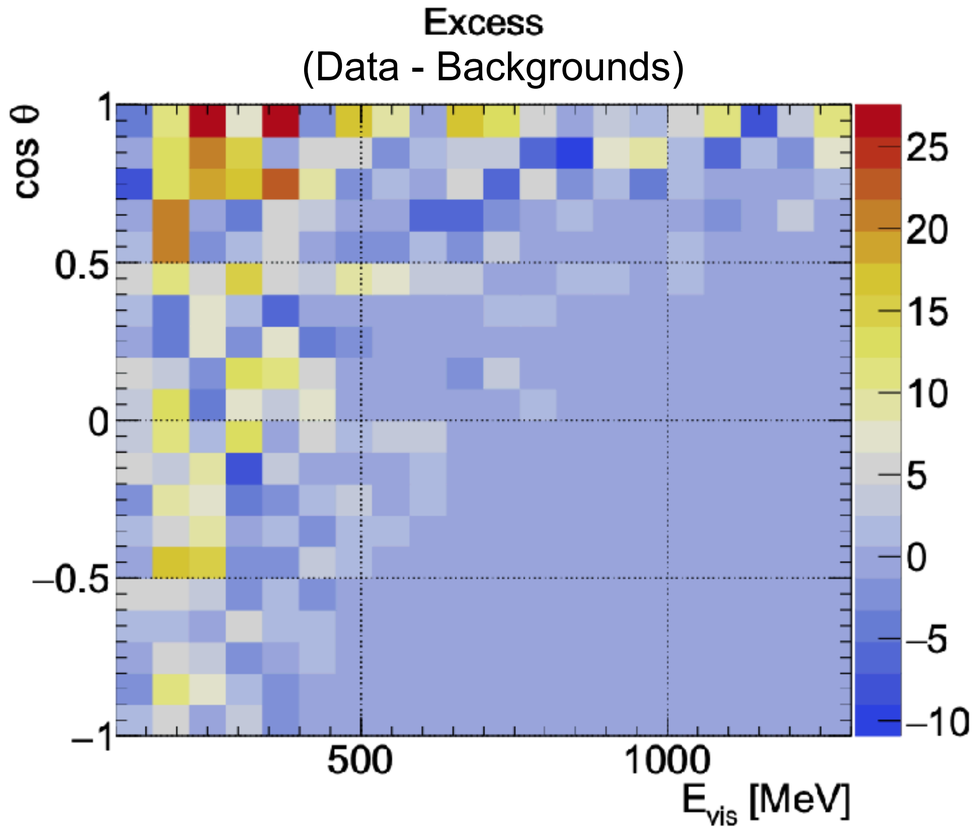
NO EXCESS

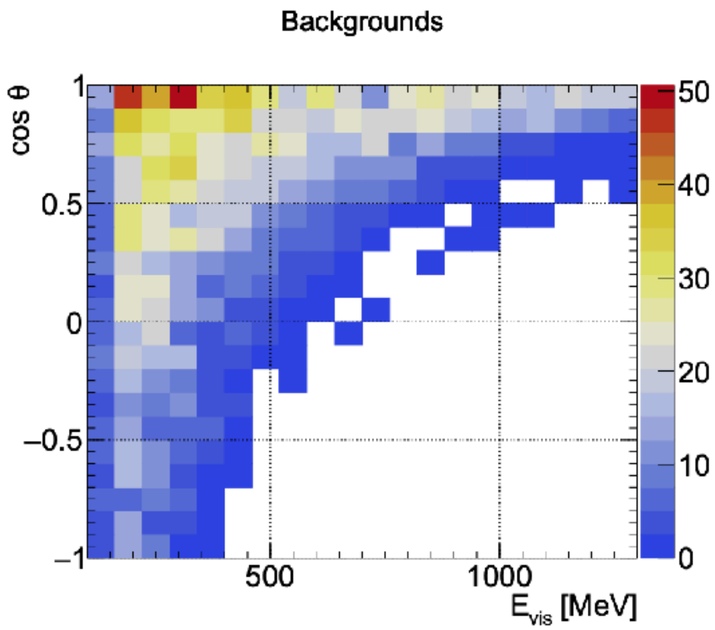
To this day, the most sensitive SBL $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance experiments.

MiniBooNE data

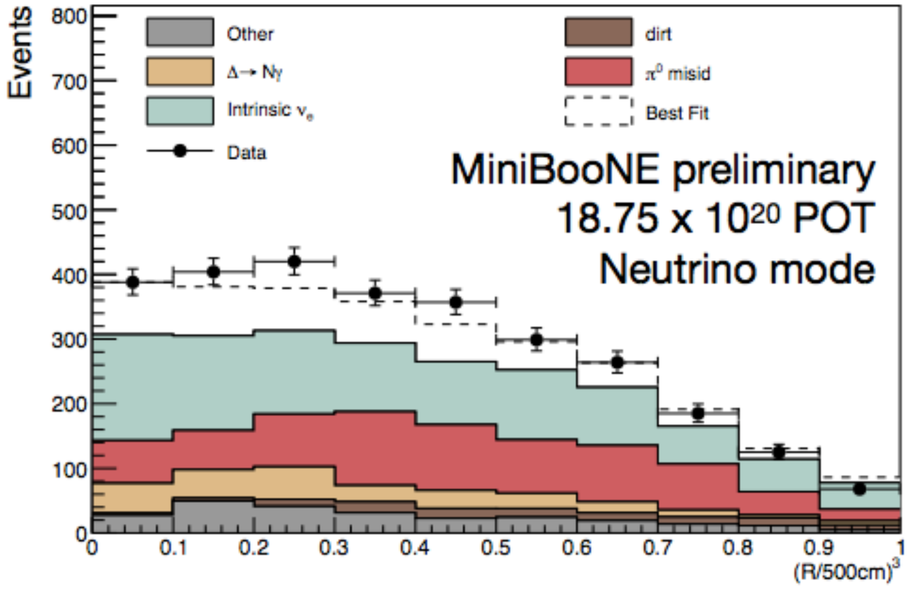
2-D distributions





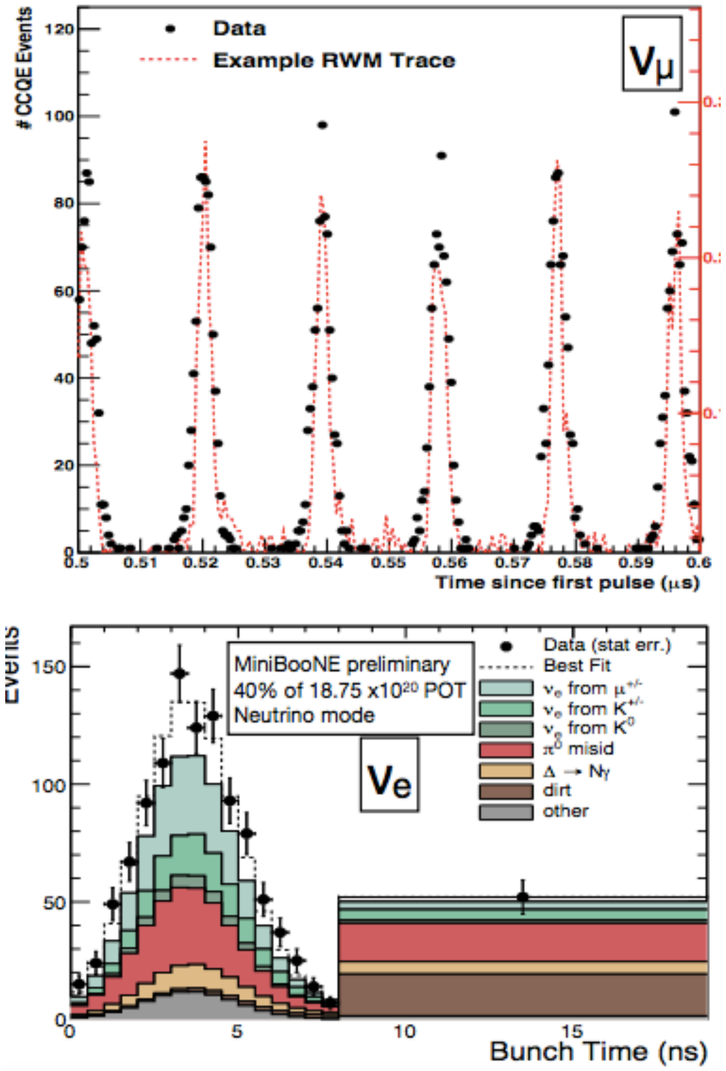


New distributions — Radius and Event Timing



Fiducial cut	Excess	significance
$R < 500$ cm	560.6 ± 119.6	$4.7\ \sigma$
$R < 400$ cm	472.6 ± 81.7	$5.8\ \sigma$
$R < 300$ cm	208.8 ± 40.3	$5.2\ \sigma$

Phys. Rev. D 98, 112004



Excess in Invariant Mass, assuming 2 showers

PID variables : $m_{\gamma\gamma}$ distribution

arxiv:1805.12028[hep-ex]

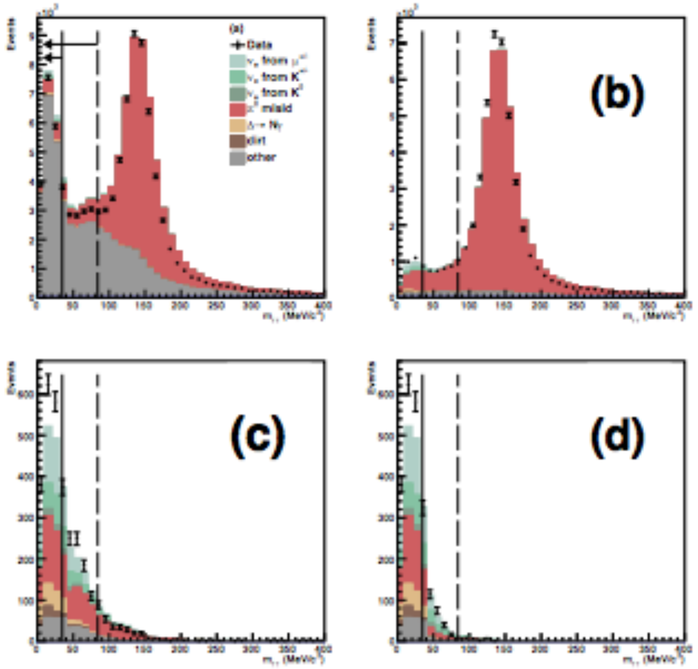
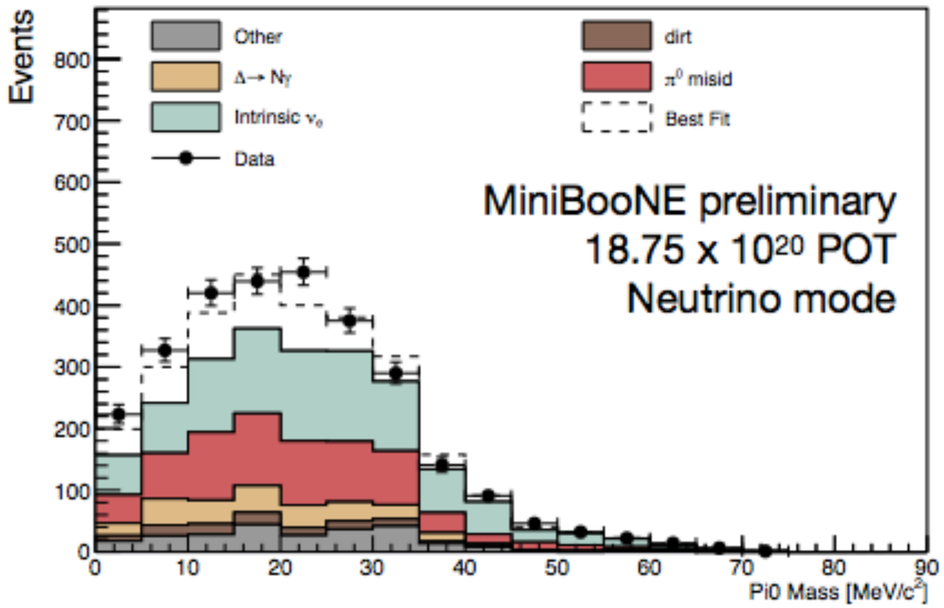


FIG. 11: Comparisons between the data and simulation for the gamma-gamma mass distribution after successive cuts are applied: (a) no PID cut, (b) electron-muon likelihood cut, (c) electron-muon plus electron-pion likelihood cuts, and (d) electron-muon plus electron pion likelihood cuts plus a gamma-gamma mass cut. The vertical lines in the figures show the range of energy-dependent cut values.



Adrien Hourlier — The XXIX International Conference on Neutrino Physics and Astrophysics — July 2nd 2020 31