A Dark Seesaw at Low Energy Experiments

HIDDeν

Webinar 02/02/21

Matheus Hostert

mhostert@umn.edu

University of Minnesota and Perimeter Institute

University of Minnesota

Perimeter Institute

The Outline

1. The type-I seesaw at the MeV/GeV scale and a hidden gauge symmetry.

2. Phenomenological applications

    - MiniBooNE excess,
    - $(g-2)_\mu$ anomaly and e+e- colliders,
    - Kaon decays.

IN COLLABORATION WITH:

Asli Abdullahi

Silvia Pascoli

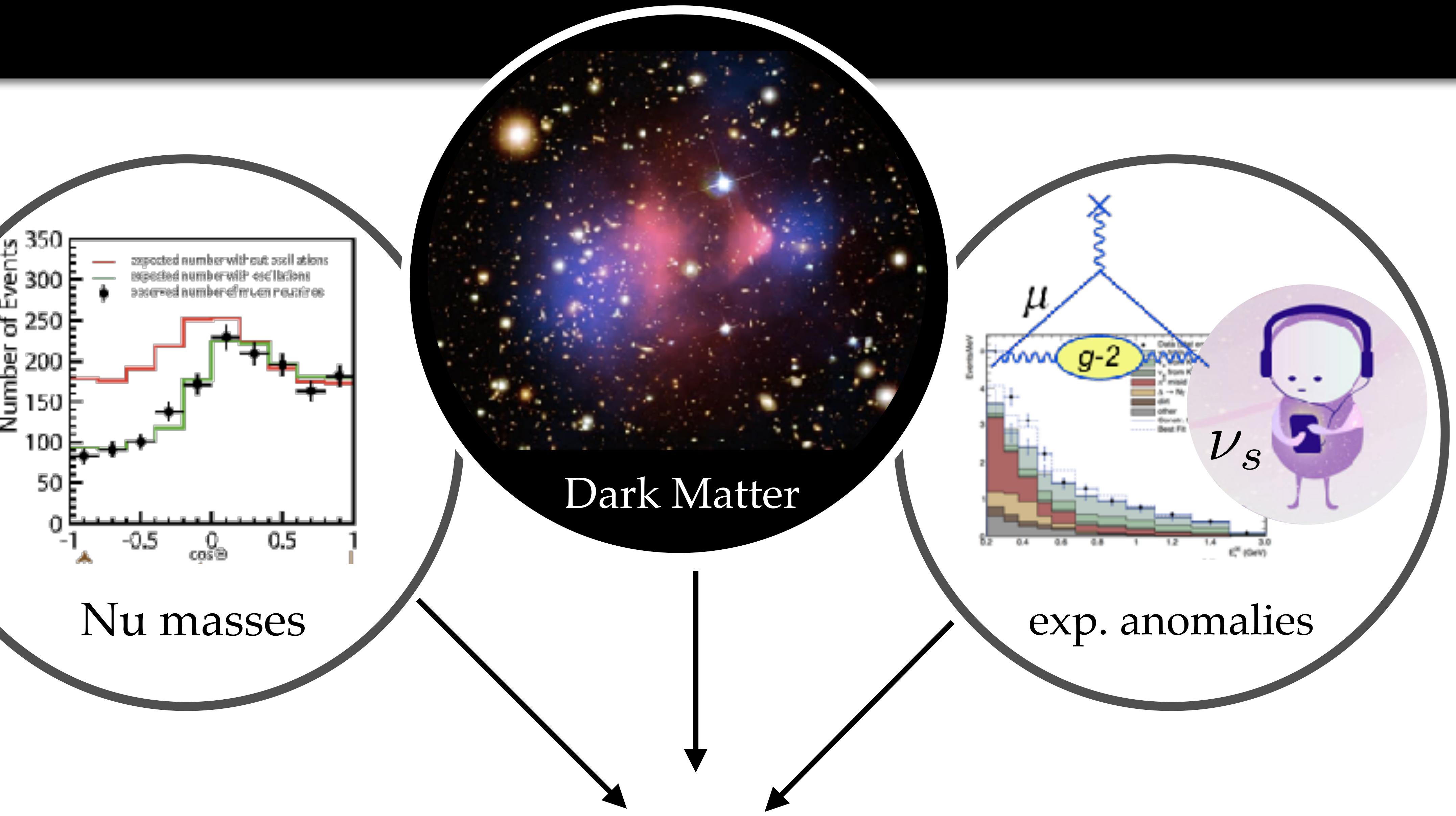
ARTCLES

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 gauge singlets**

=

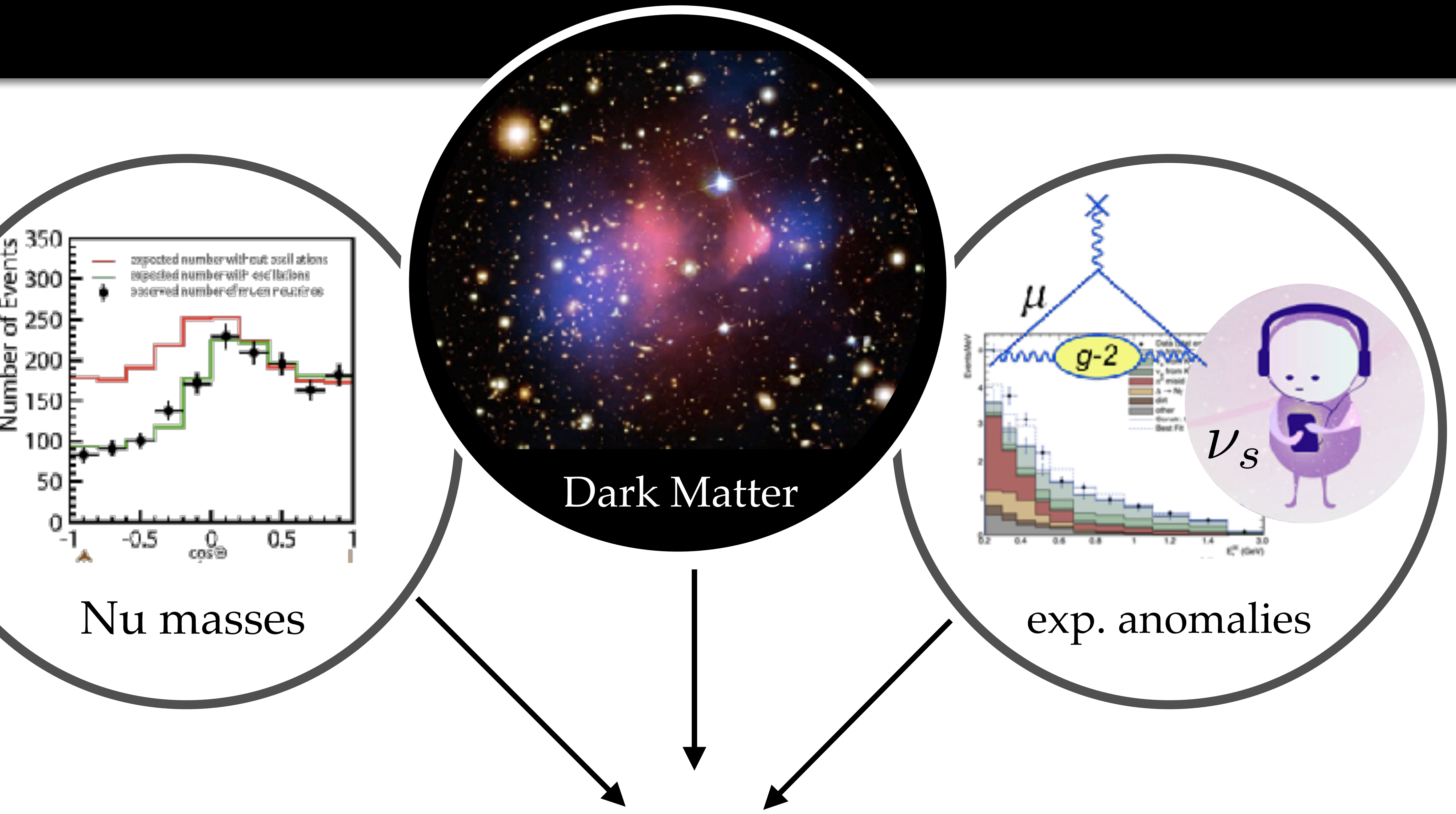
Dark Sector
(May or may not include a dark matter candidate)

1. New light states are naturally **feebly coupled to the SM** so as to have escaped detection.

2. Preserves anomaly cancellation in SM.

3. May not be related to the weak scale.

New physics under the lamppost



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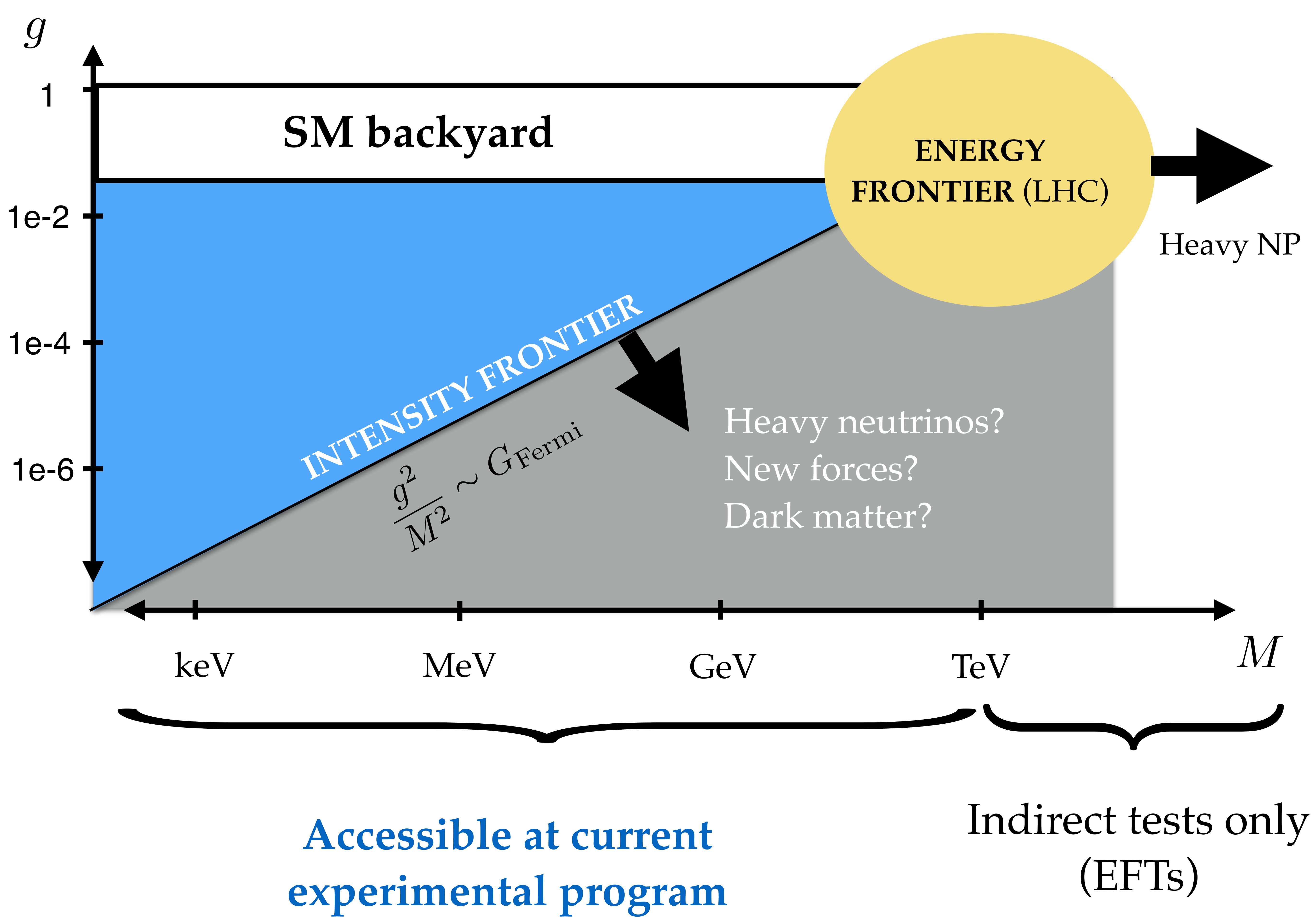

Ruling out the SM in the laboratory

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

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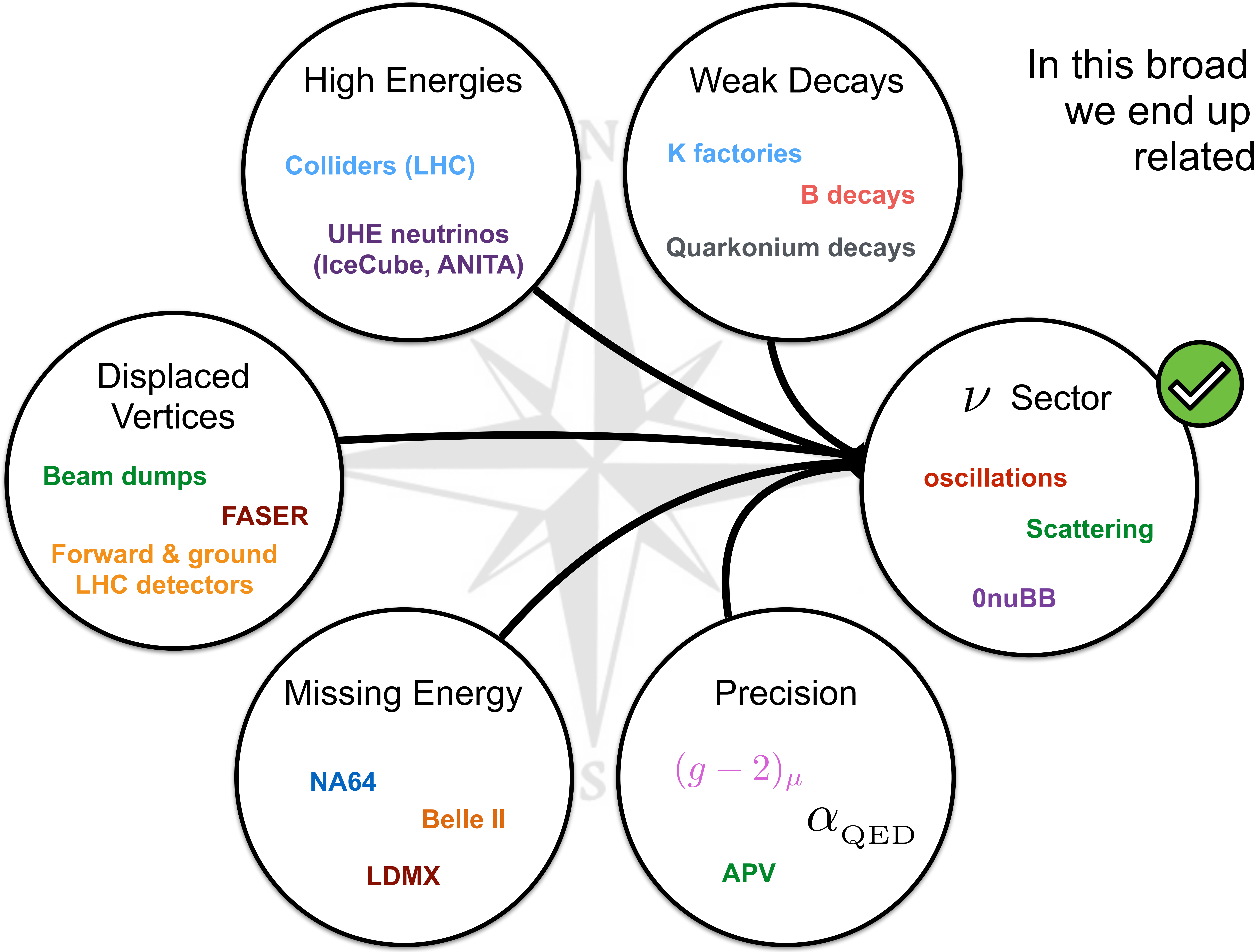

In this broad exp landscape, can we end up learning anything related to neutrinos?

*Not an exhaustive list


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 and
(new fundamental scale?)
$B_{\mu\nu}X^{\mu\nu}$
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
(new fundamental scale?)


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

Type I seesaw — why are neutrino masses so small?

Type-I seesaw Lagrangian:

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

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^{\mathsf{T}} & M_R \end{pmatrix}$$

$$M_{\nu_L} \simeq -M_D M_R^{-1} M_D^{\mathsf{T}} .$$

Single generation →

$$(y^{\nu})^2 \approx 3 \times 10^{-15} \frac{M_N}{\text{GeV}}$$

$$|U_{\alpha 4}|^2 \approx 10^{-10} \frac{\text{GeV}}{M_N}$$

Multiple generations →

$$M_D M_R^{-1} M_D^{\mathsf{T}}$$

M_R may lead to strong cancellations, e.g. respecting new symmetries such as Lepton number

Large hierarchy of scales? Small couplings? New symmetries?

In this talk, we will remain agnostic and invoke a combination of all these.

Low Scale Seesaws

Inverse, Extended and Linear seesaws — Adding complexity to M_R

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

= violating lepton number

(L= -1)

(L= +1)

Light neutrino masses proportional to LNV parameters

Seesaw limit →

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

Small LNV parameters are technically natural (protected by L symmetry)

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

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"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** ($\mu \to \infty$)

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

Intermediate state: $m_4 \simeq \frac{\Lambda^2}{\mu}$

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

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** ($\mu' \to \infty$)

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

Intermediate state: $m_4 \simeq \frac{\Lambda^2}{\mu}$

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)

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

+ freedom

“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** ($\mu' \to \infty$)

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

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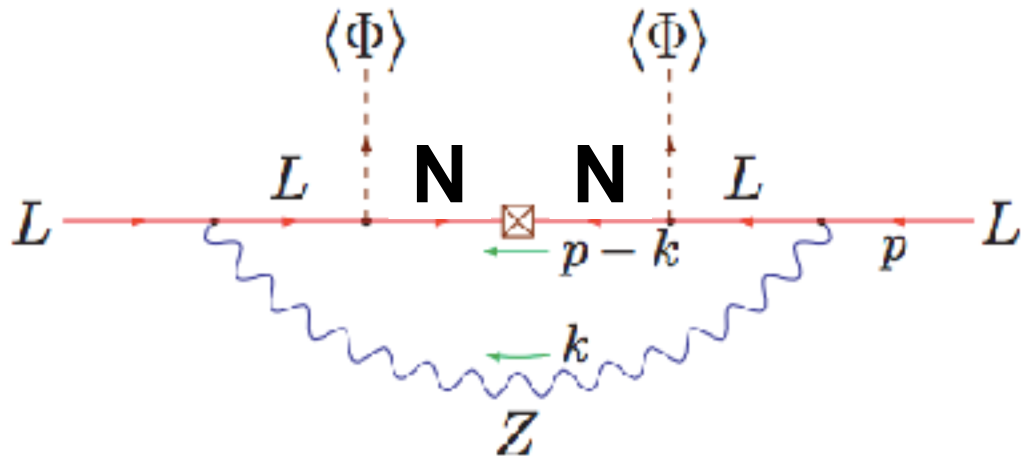
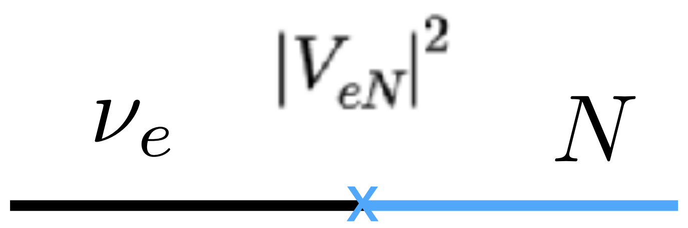
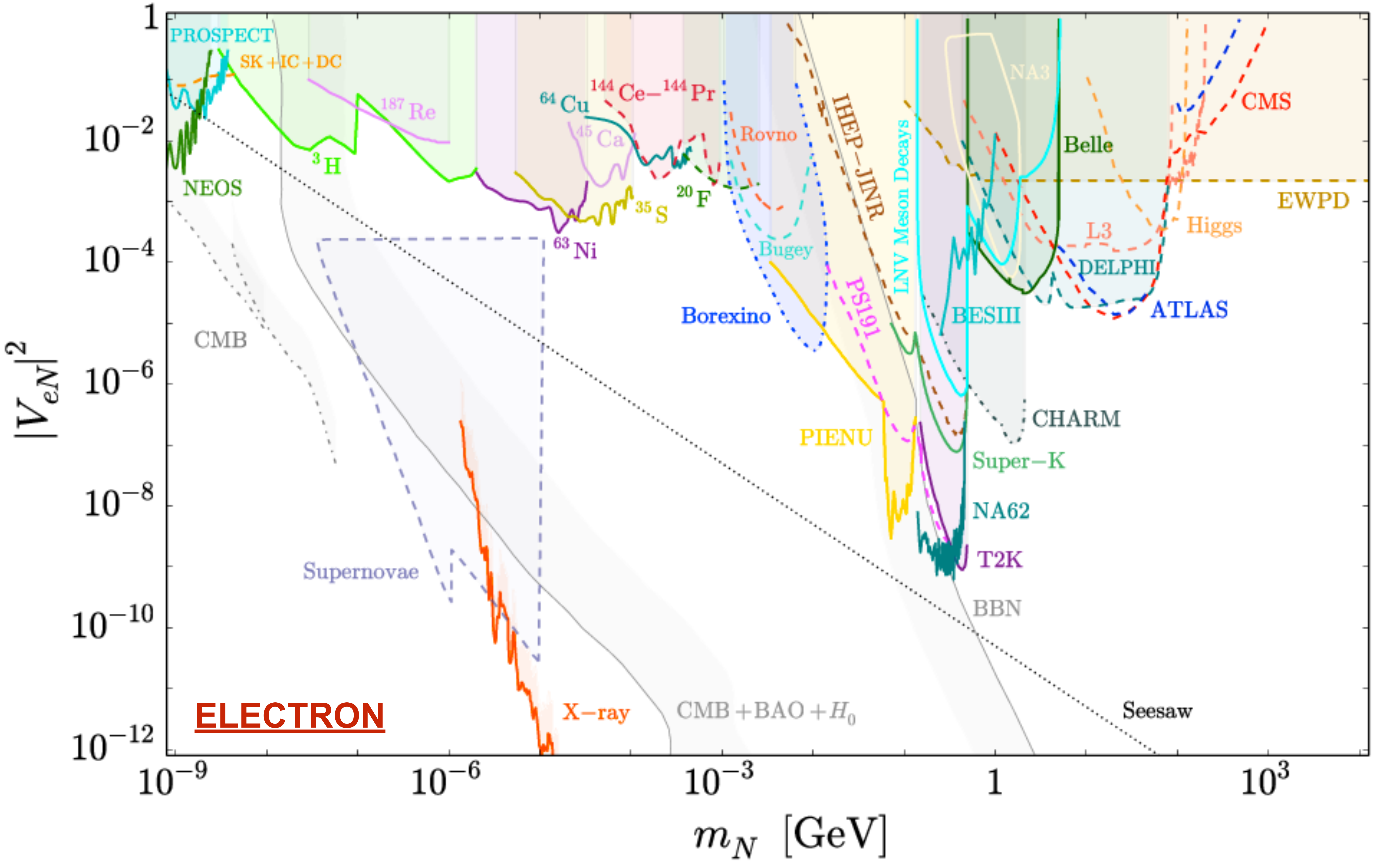


Light state: $m_\nu^{\text{loop}} \simeq \frac{\alpha_W}{16\pi}\frac{m_D^2}{\mu'} f(m_Z, m_h, \mu')$

Where are the HNLs?



P. Bolton et al, 1912.03058



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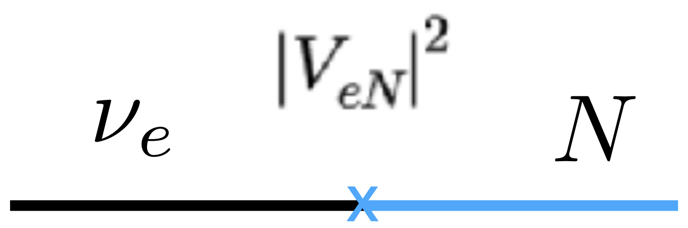

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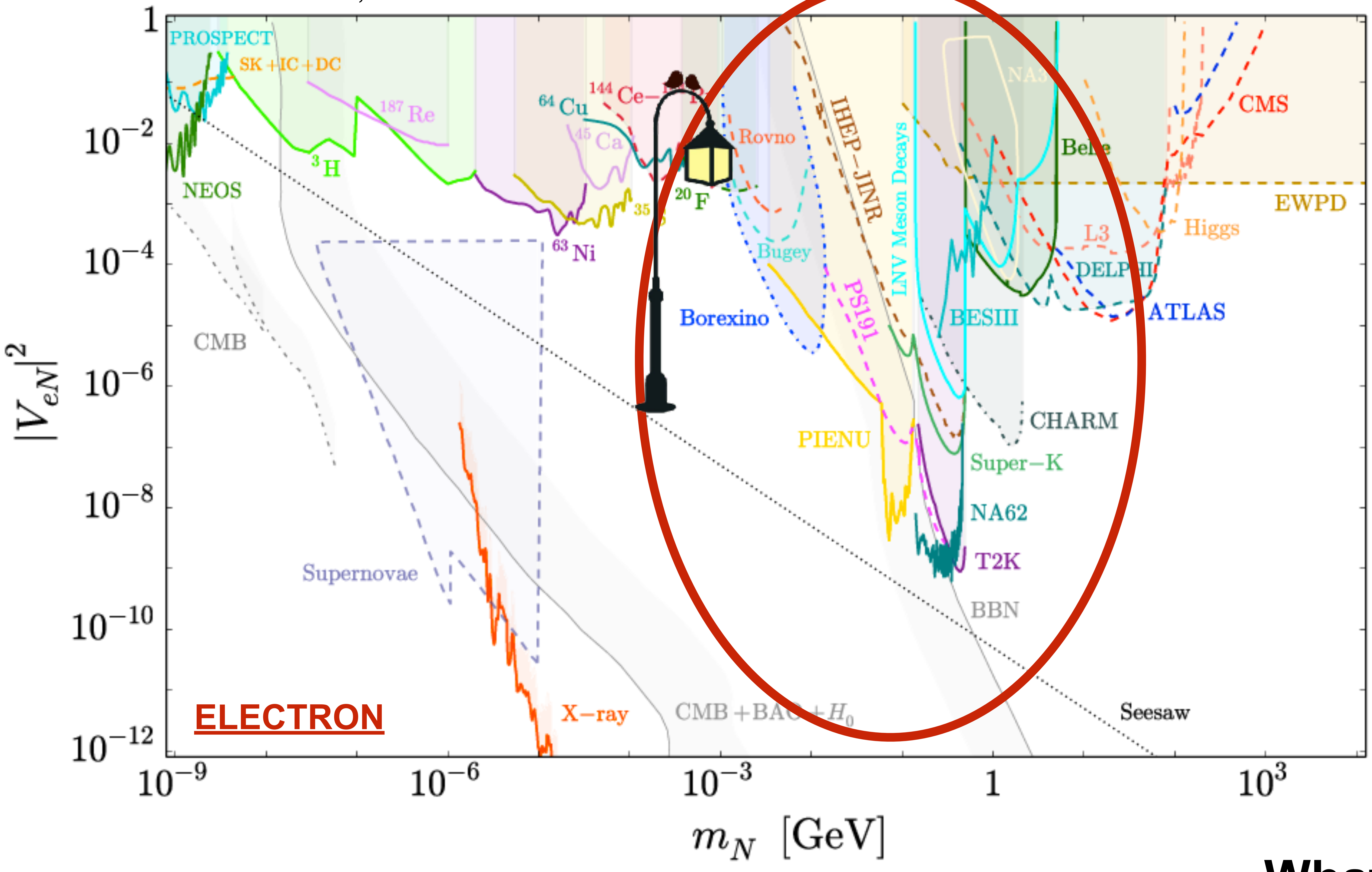


Under the MeV/GeV lamppost:

1) Missing mass in pion or kaon decays.\

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

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

$$\pi/K \to \ell N \quad (\dots) \quad N \to \mathrm{SM}$$

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?

A dark sector model

w/ short-lived HNLs

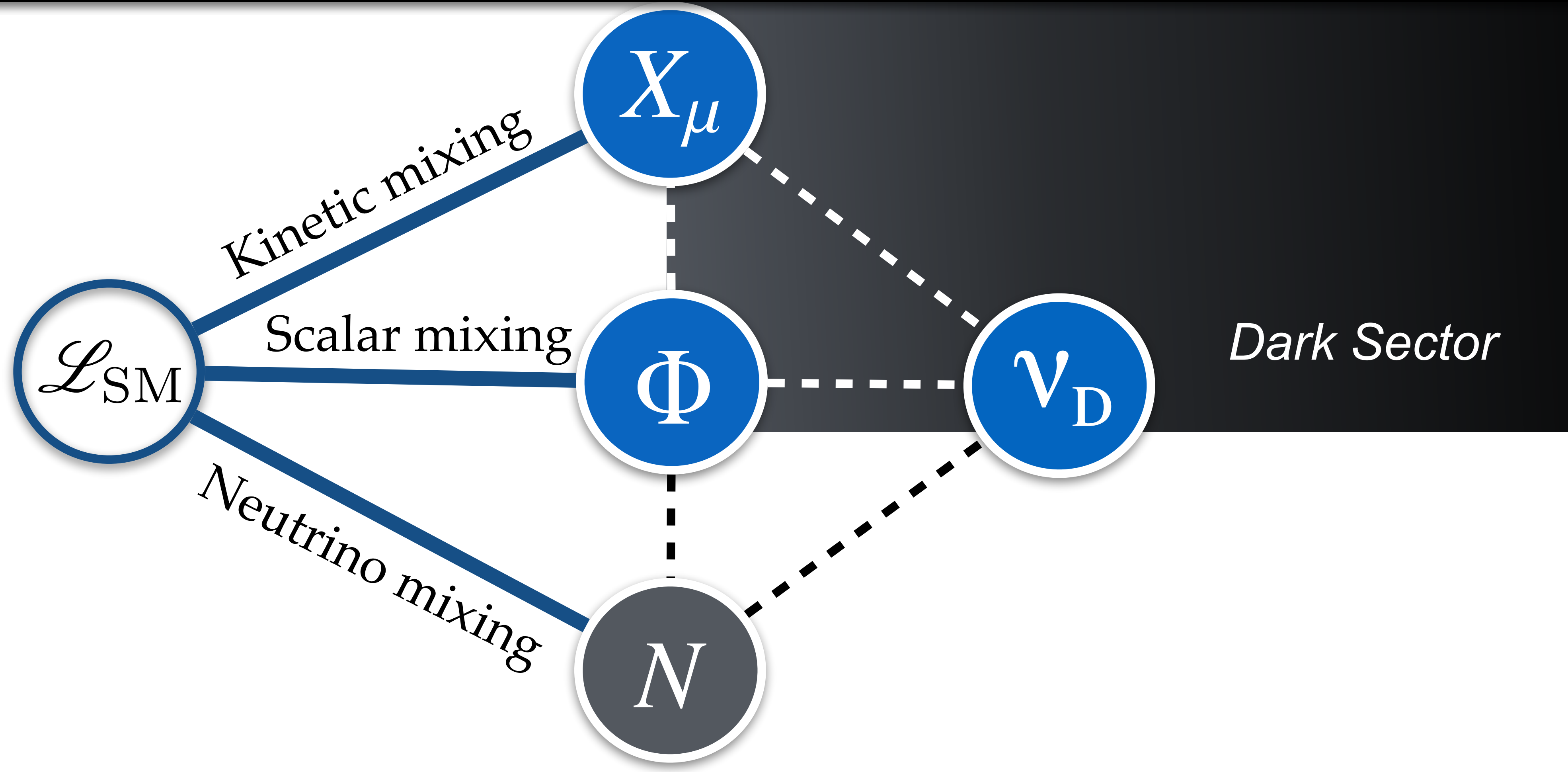
A renormalizable model for a dark neutrino sector

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

1) A minimal **renormalizable model:**

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

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



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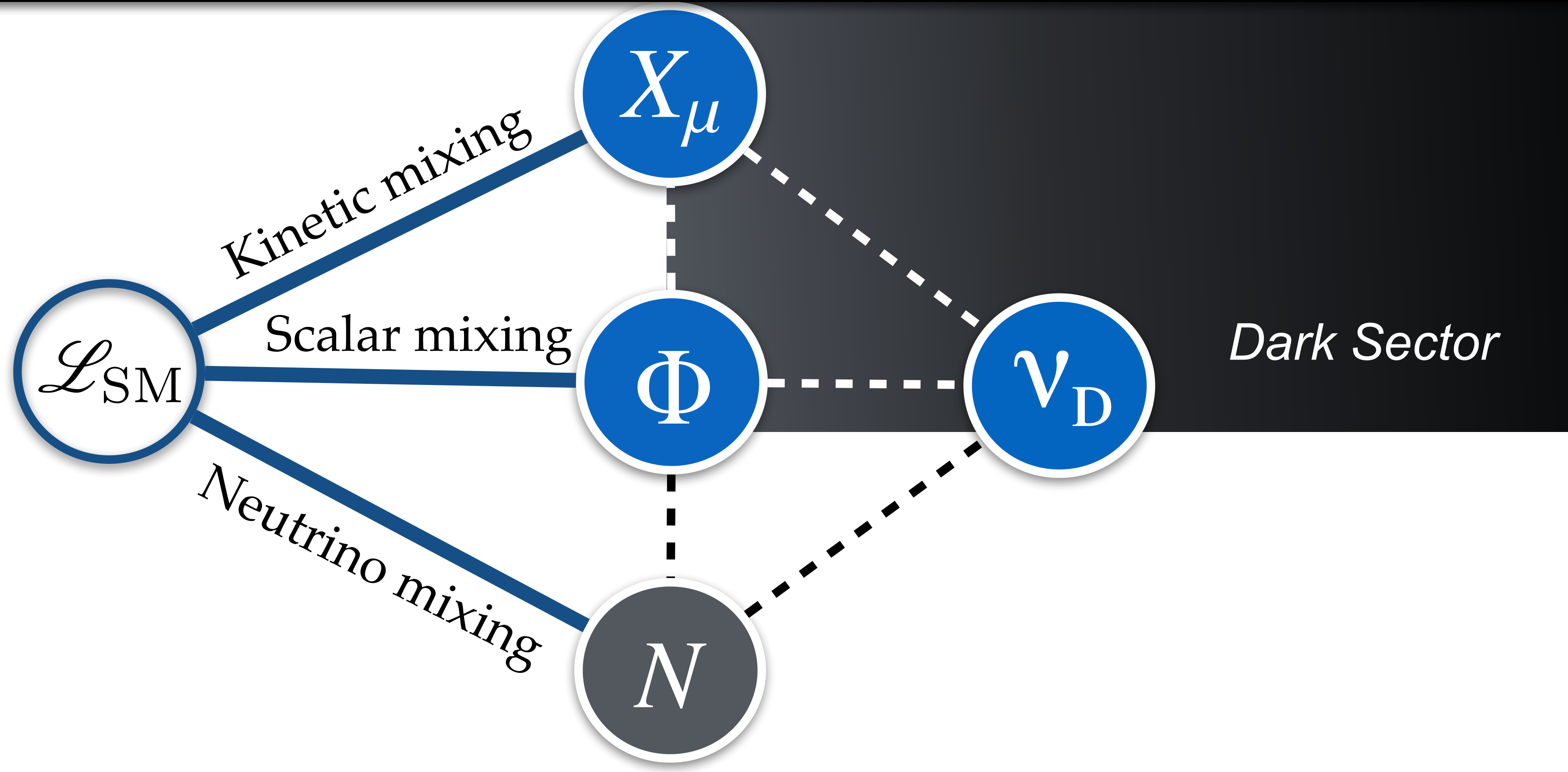
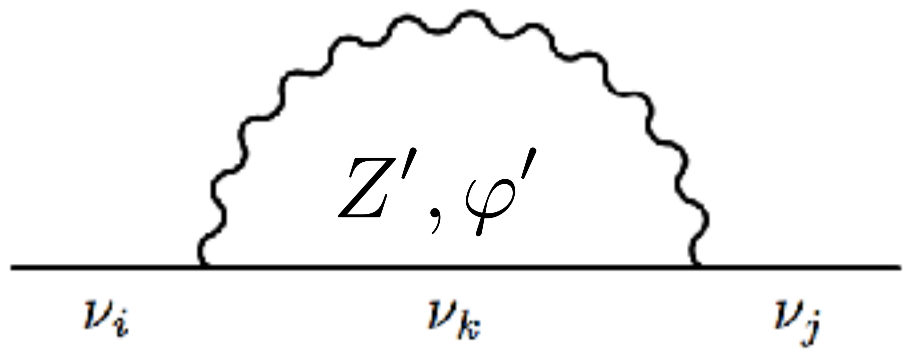


2) Neutrinos masses from LNV & dark sector scale:

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

Simplifying notation:

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



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

May come w/ opposite signs

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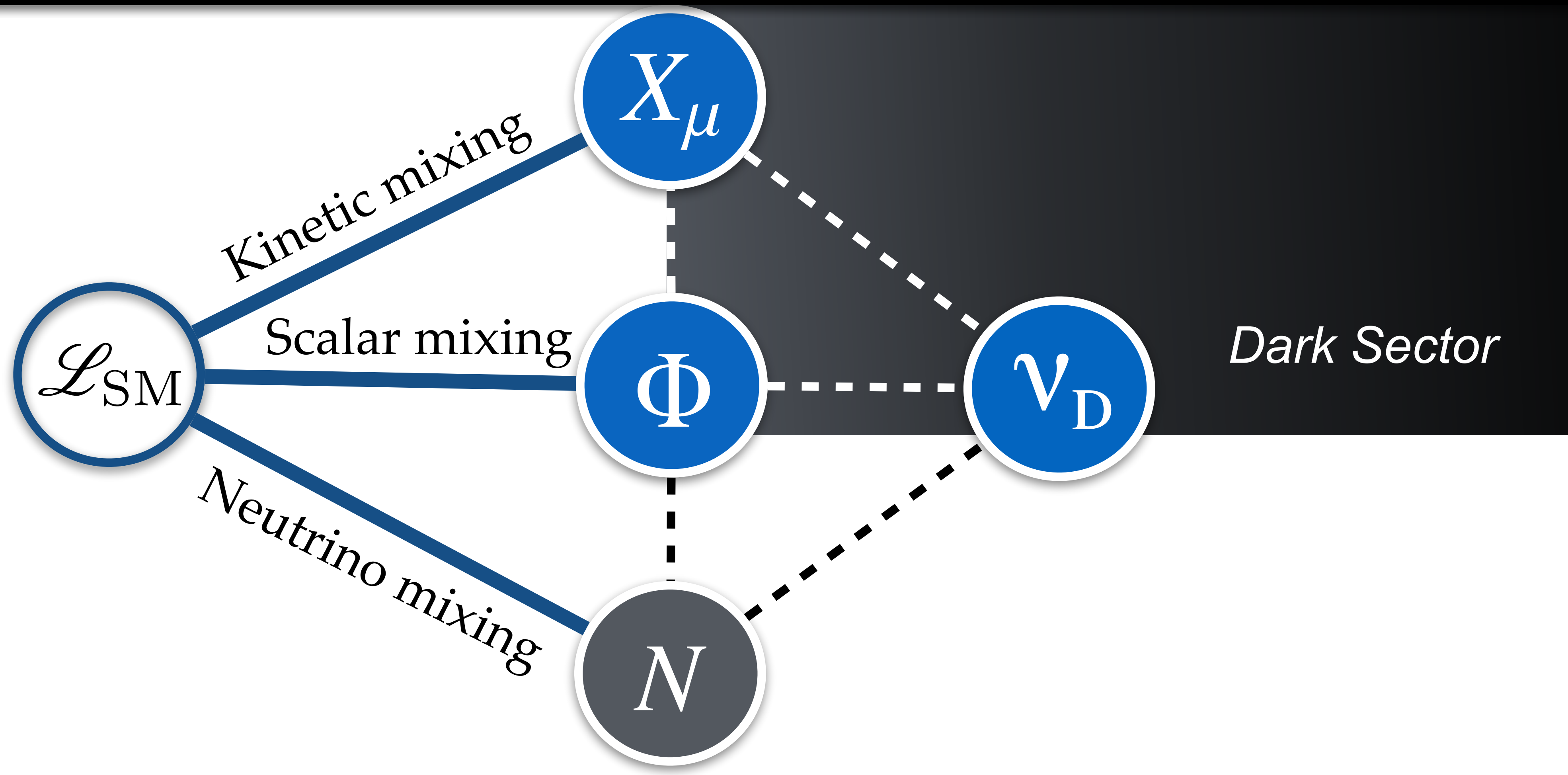

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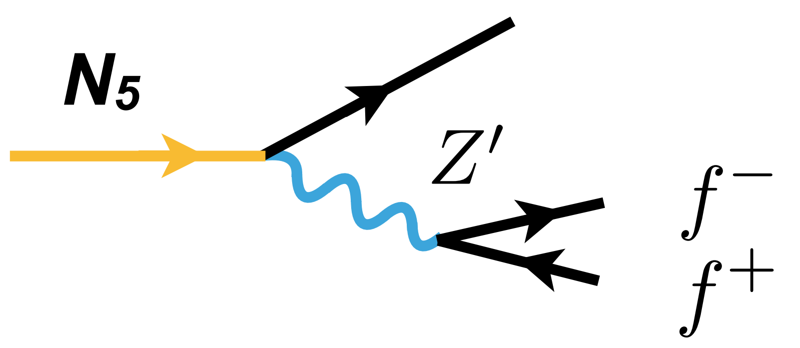
3) Modified experimental landscape



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

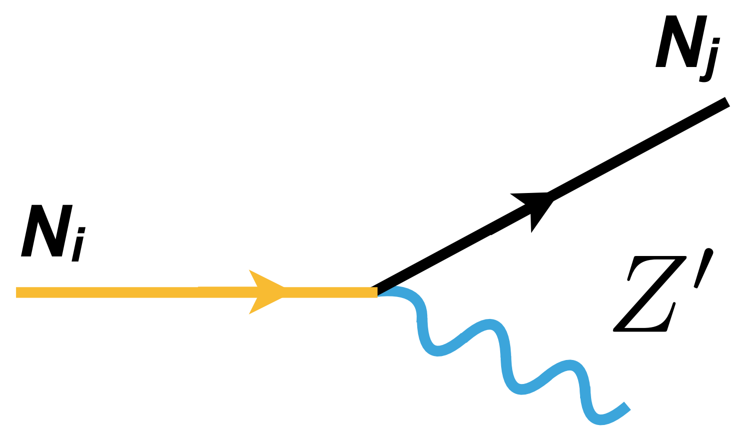
Novel production and decay channels important when vector and scalar portals are considered.

Benchmarking our model

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

HNL masses — *HNL vertices with the dark photon* — *HNL lifetimes*

α_D	m_3 /eV	m_4 m_5 m_6 /MeV			$\vert V_{43}\vert^2$ $\vert V_{53}\vert^2$ $\vert V_{63}\vert^2$ $/10^{-8}$			$c\tau^0$/cm N_4 N_5 N_6		
0.32	0.05	74	146	220	13.6	26.5	123	1.1×10^7	2.2	0.14



Dark photon mass — *Kinetic mixing*

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

No Higgs-Phi mixing (2 portal assumption)

$$m_{\varphi'} = 1.6 \text{ GeV}$$

Working under a single active-flavor approximation and noting that $\nu_3 \sim \nu_\mu$

Note: we reproduce the correct scale for nu-masses w/ some fine tuning between tree and loop level.

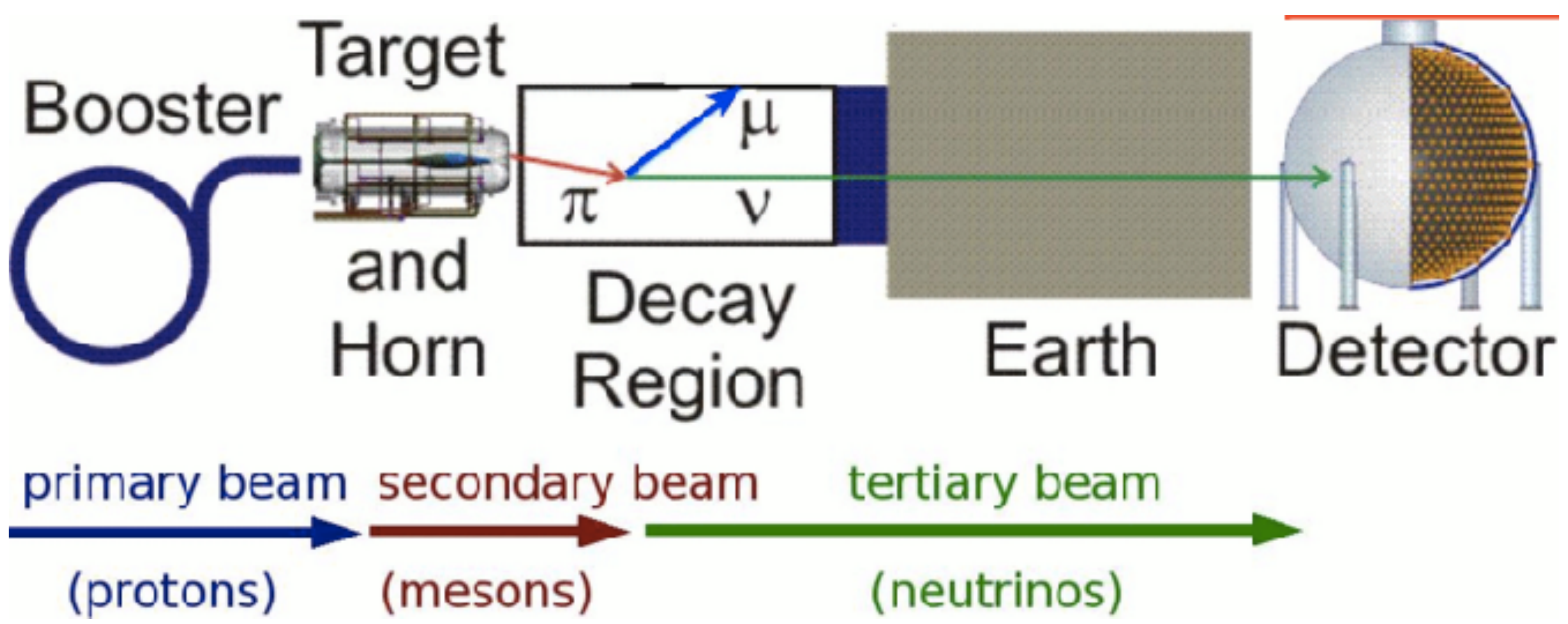
The MiniBooNE Excess

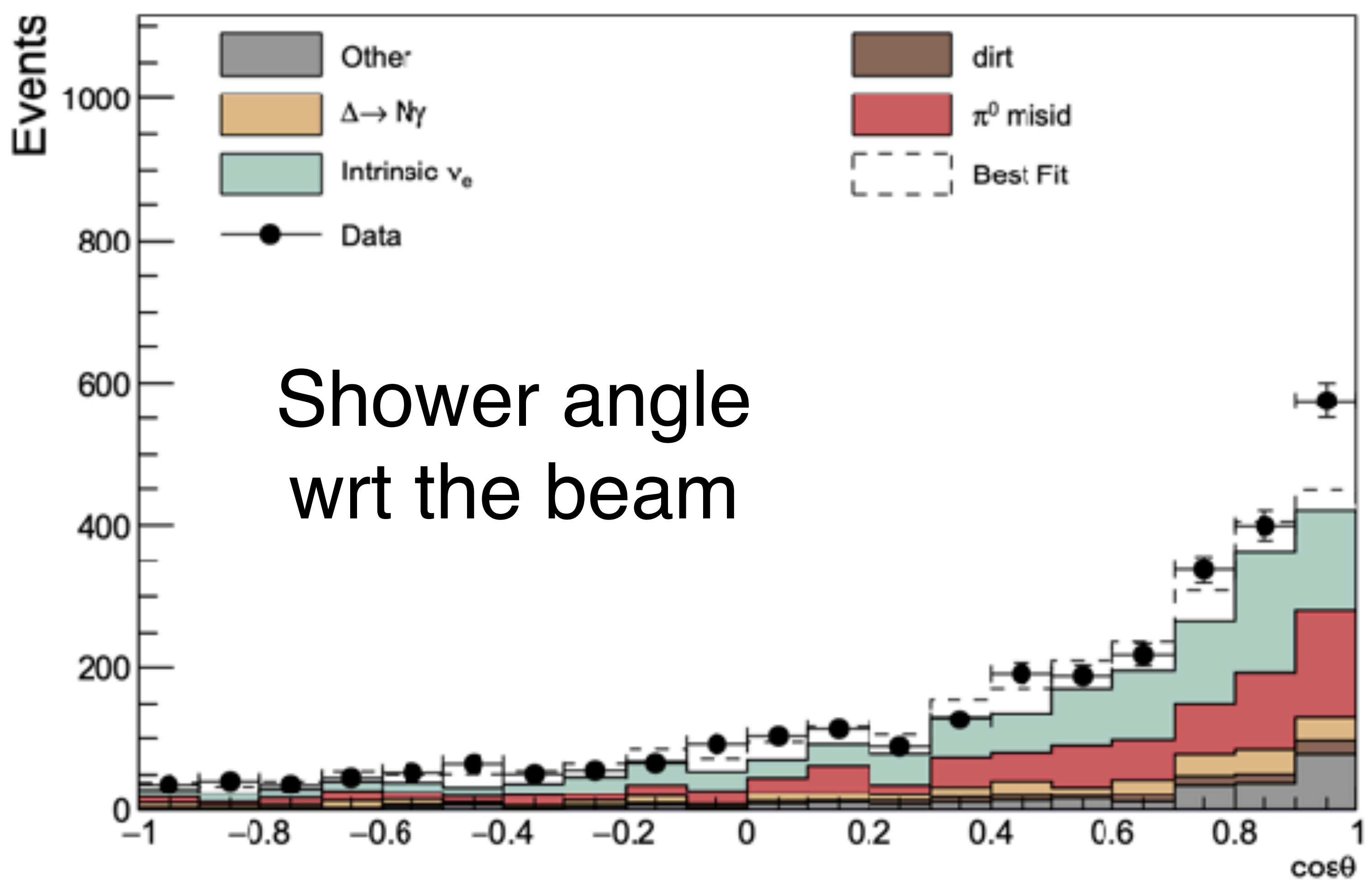
<u>2020 MiniBooNE results:</u>

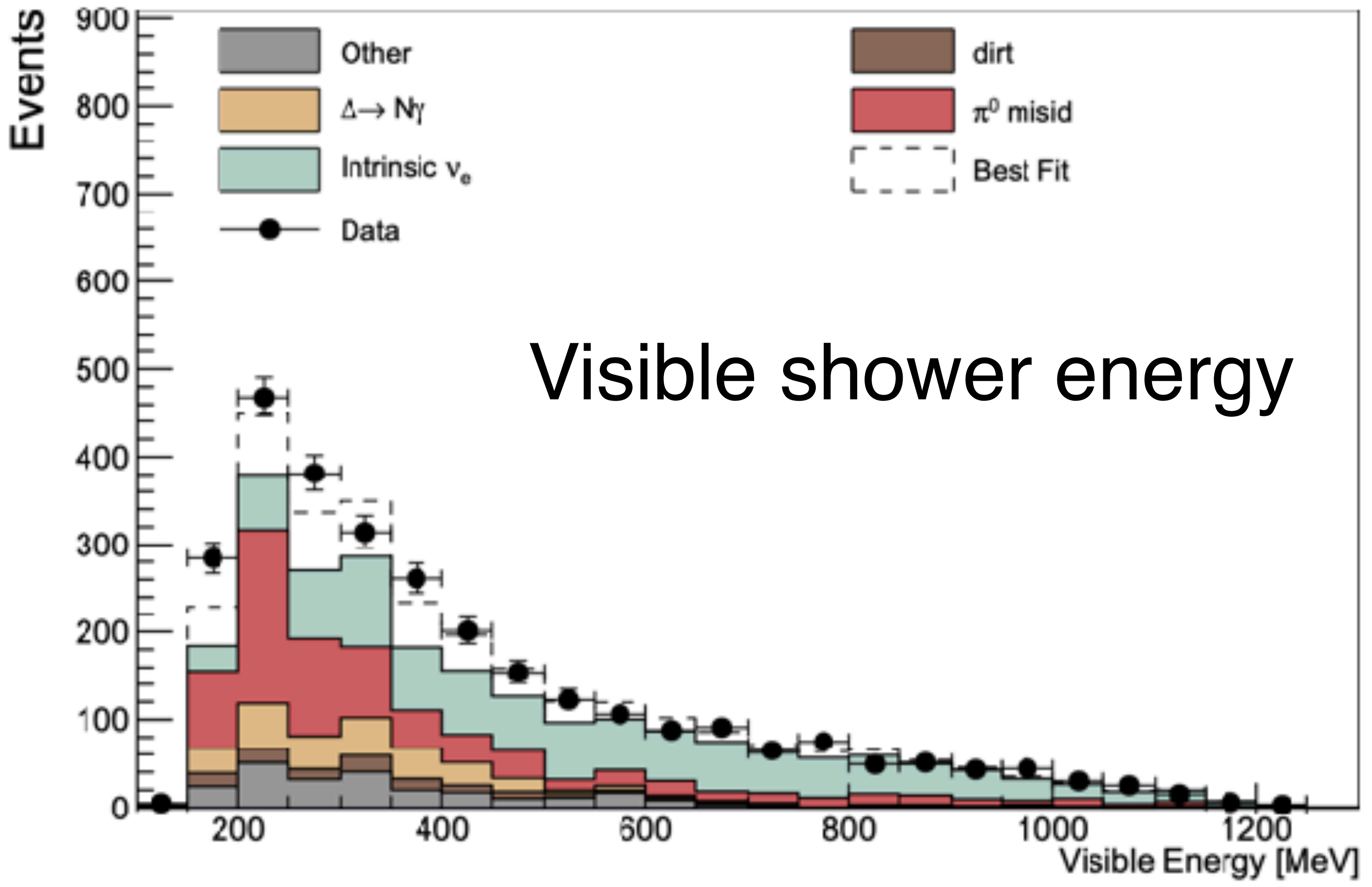
arXiv:2006.16883

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.

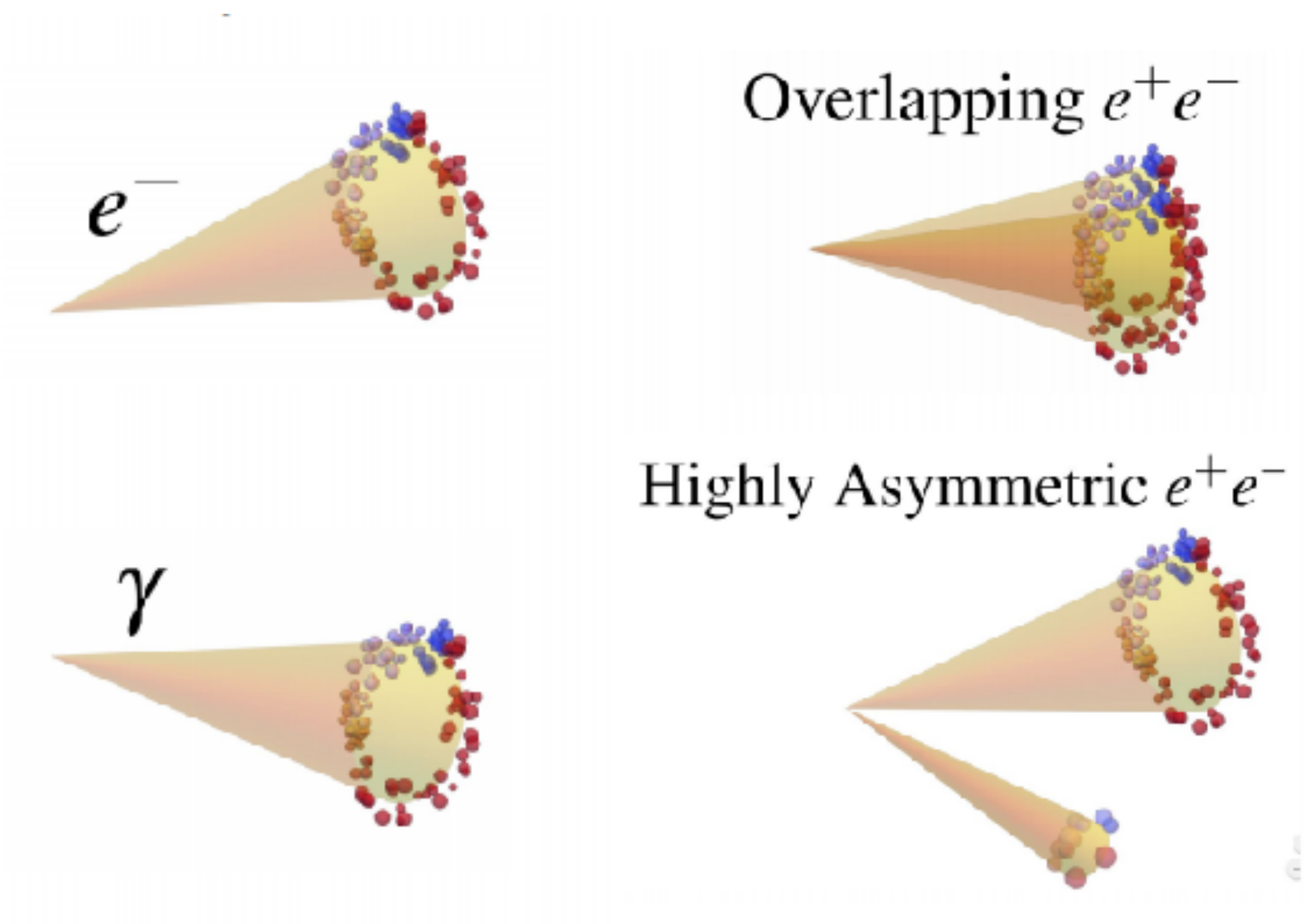
638.0±132.86 excess events
4.8σ significance







MiniBooNE is an “inclusive” experiment:
All final states below could contribute

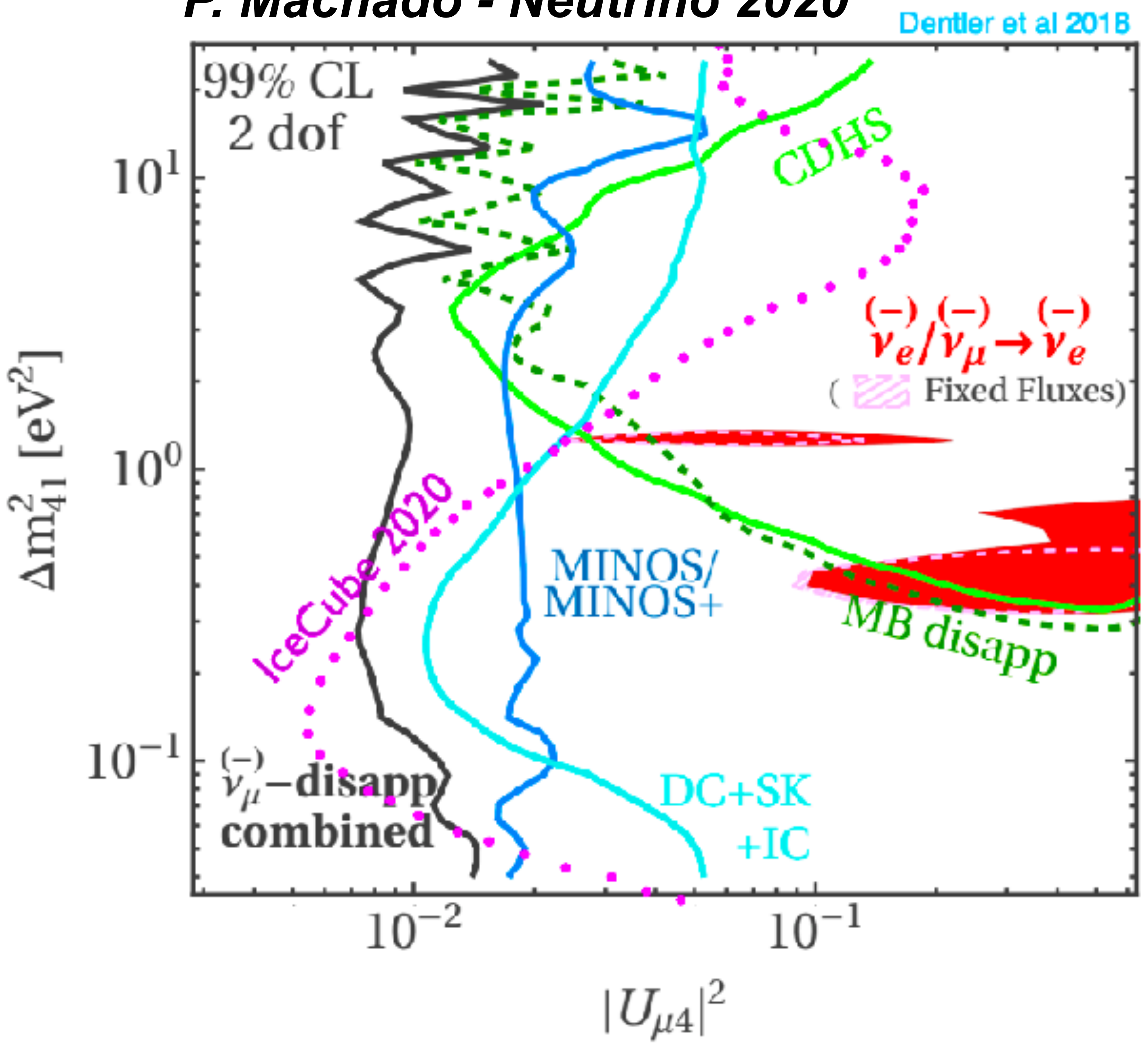


by M. Ross-Lonergan

Minimal eV sterile oscillations.

ν_μ disappearance + cosmology excludes this model.

P. Machado - Neutrino 2020

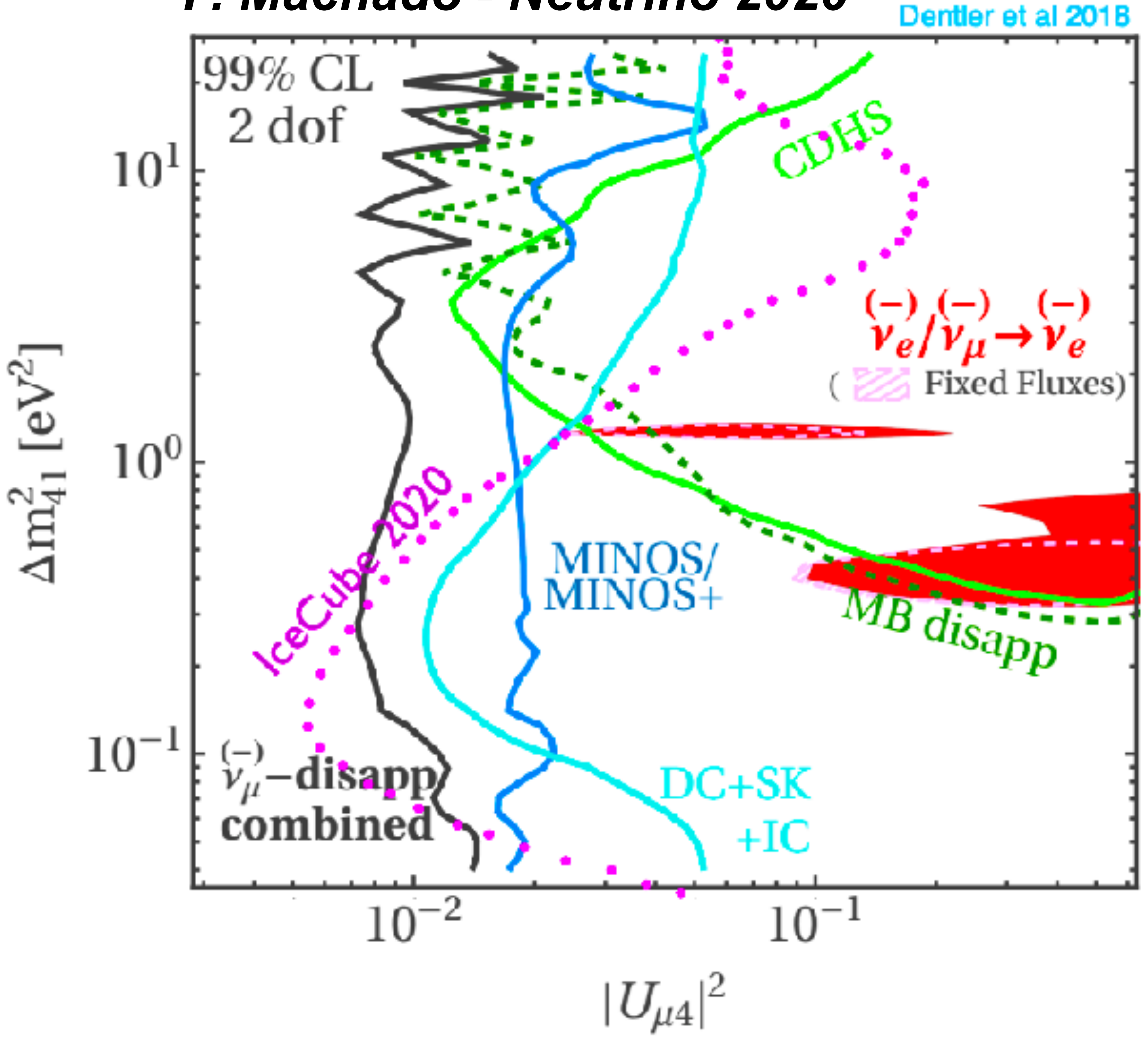


New exotic hypothesis to explain MiniBooNE

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 ~~No LSND~~

W. Abdallah et al 2010.06159

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:

O. Fischer et al 1909.09561 *Delayed signal?*

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..*

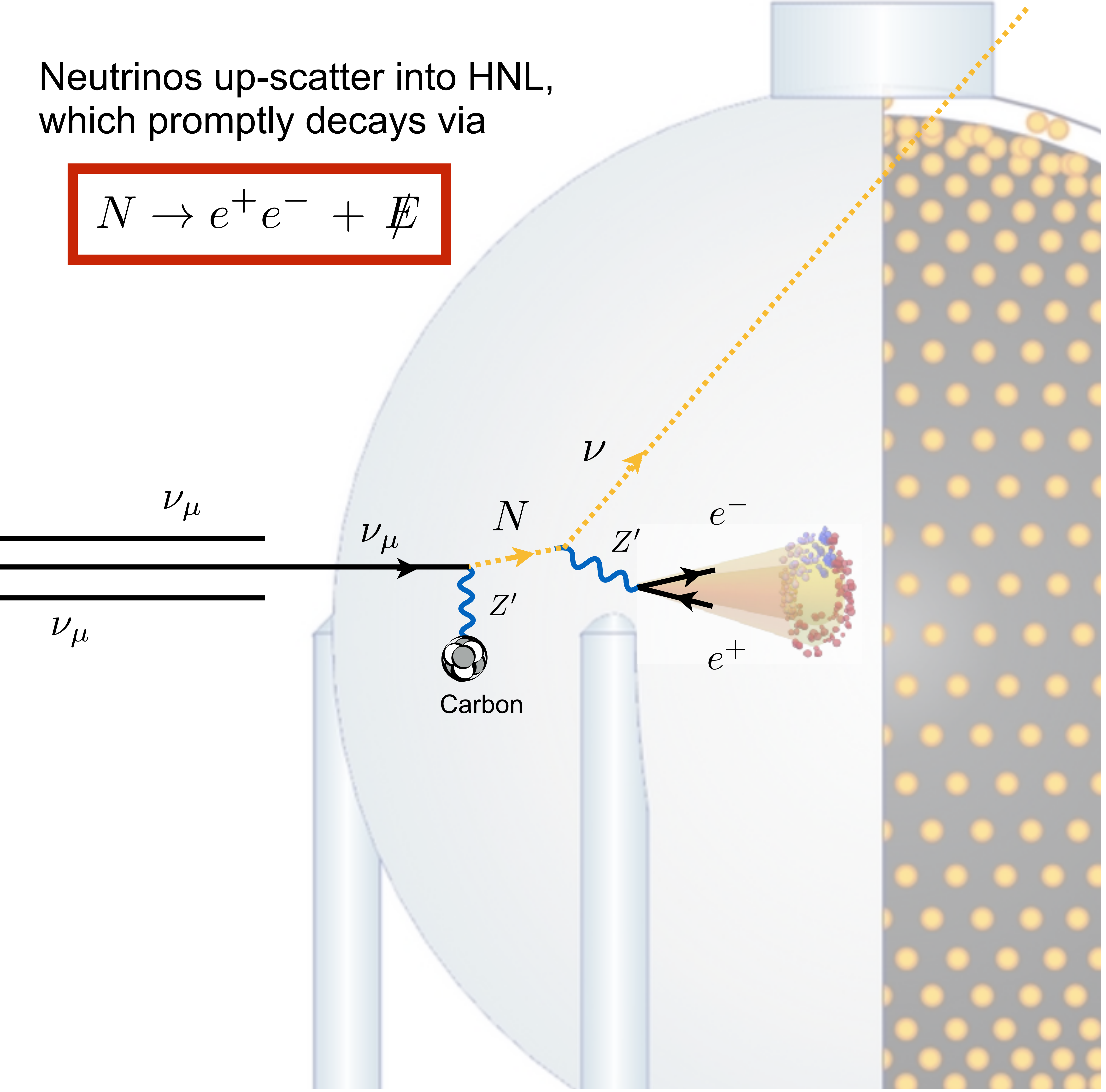
New physics In scattering

New physics In propagation

New "visible" states in the beam

Neutrinos up-scatter into HNL, which promptly decays via

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



Heavy neutrinos + dark forces to accommodate MiniBooNE

Neutrinos up-scatter into HNL, which promptly decays via

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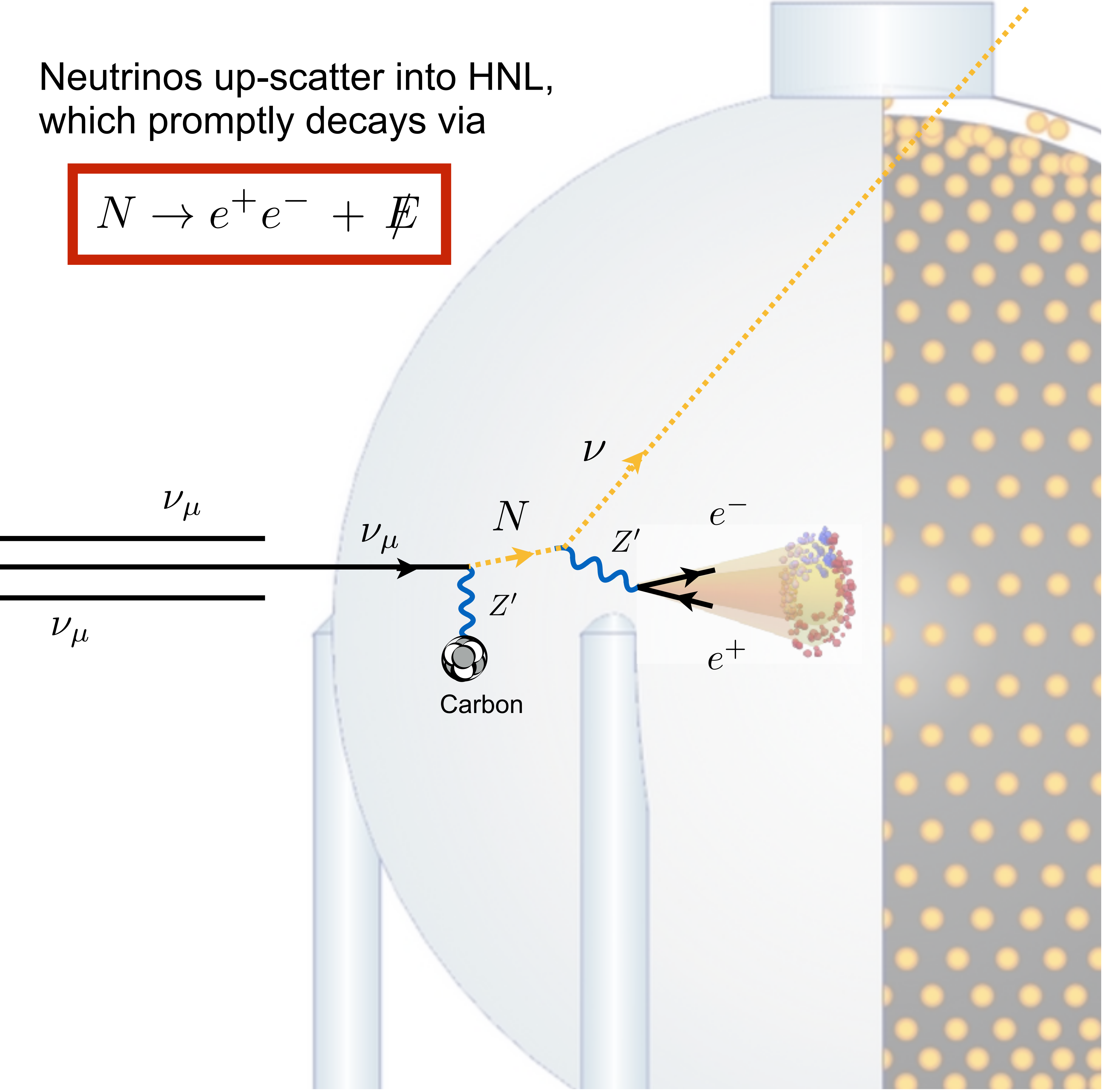
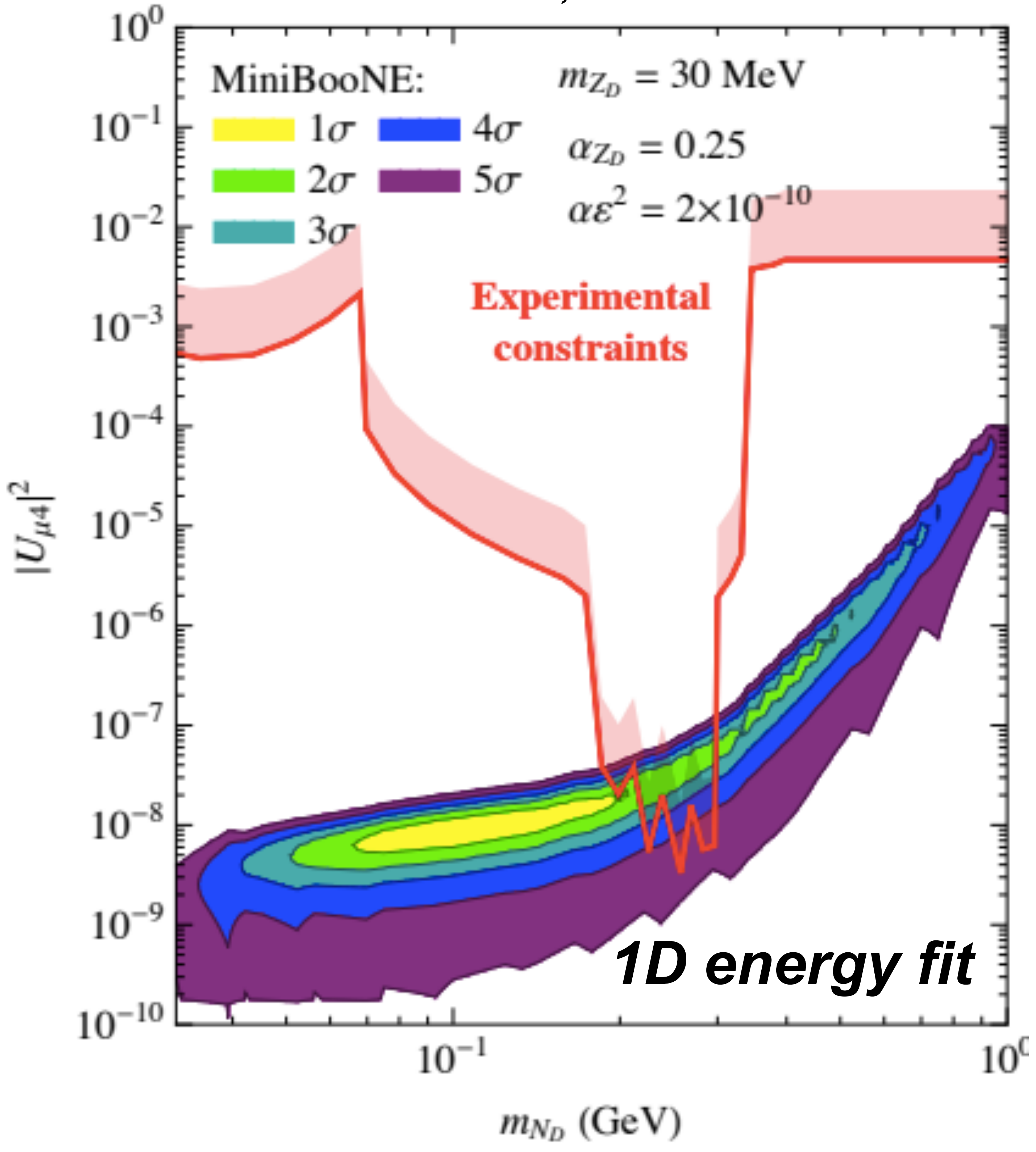


Neutrino portal + kinetic mixing.

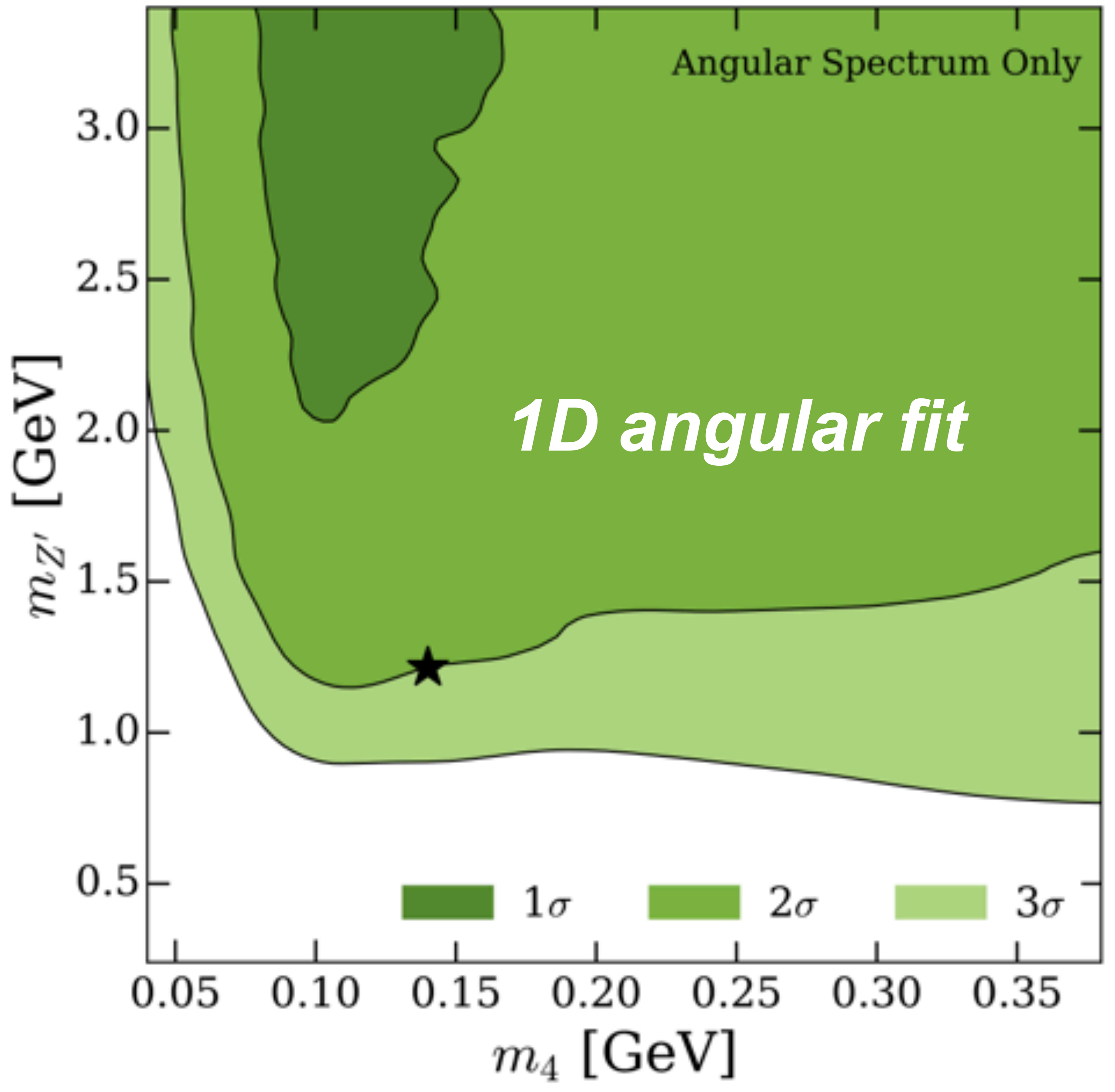
On-shell mediator

E. Bertuzzo et al., PRL121.241801



Off-shell mediator

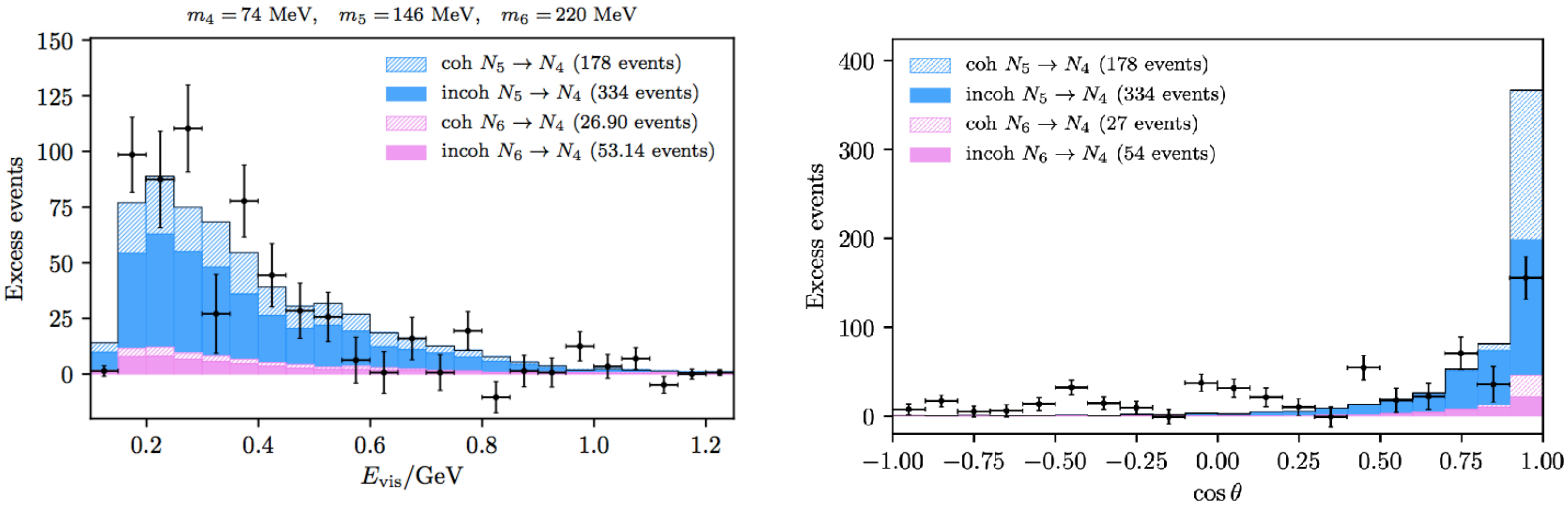
P. Ballett et al, PRD 99.071701



Explaining MiniBooNE with our benchmark

HNLs produced in neutrino scattering

N5 and N6 states decay promptly to long-lived N4 states.



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

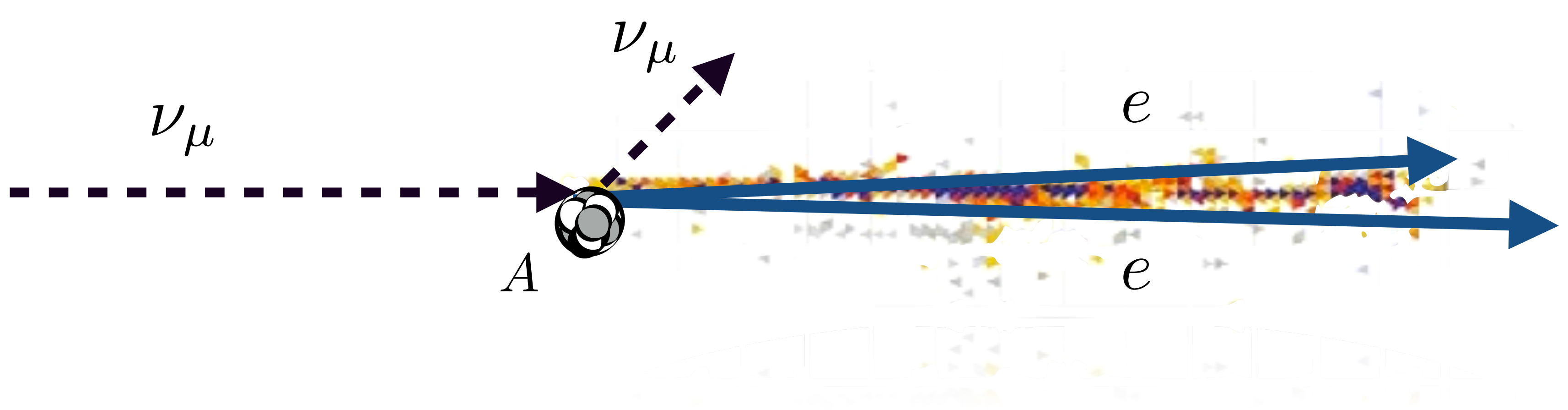
Higher-Q2 and nuclear effects not included (important for GeV Z').

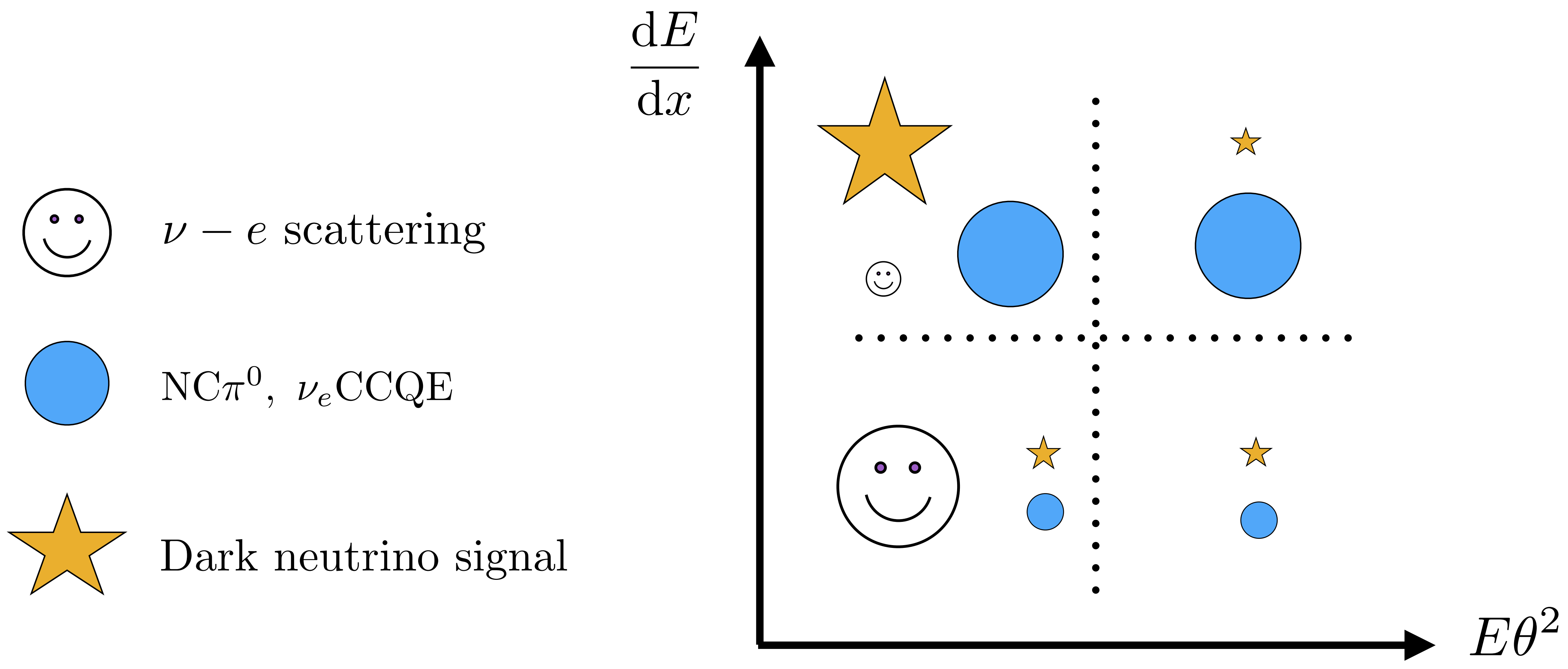
Pseudo single photons at ν detectors

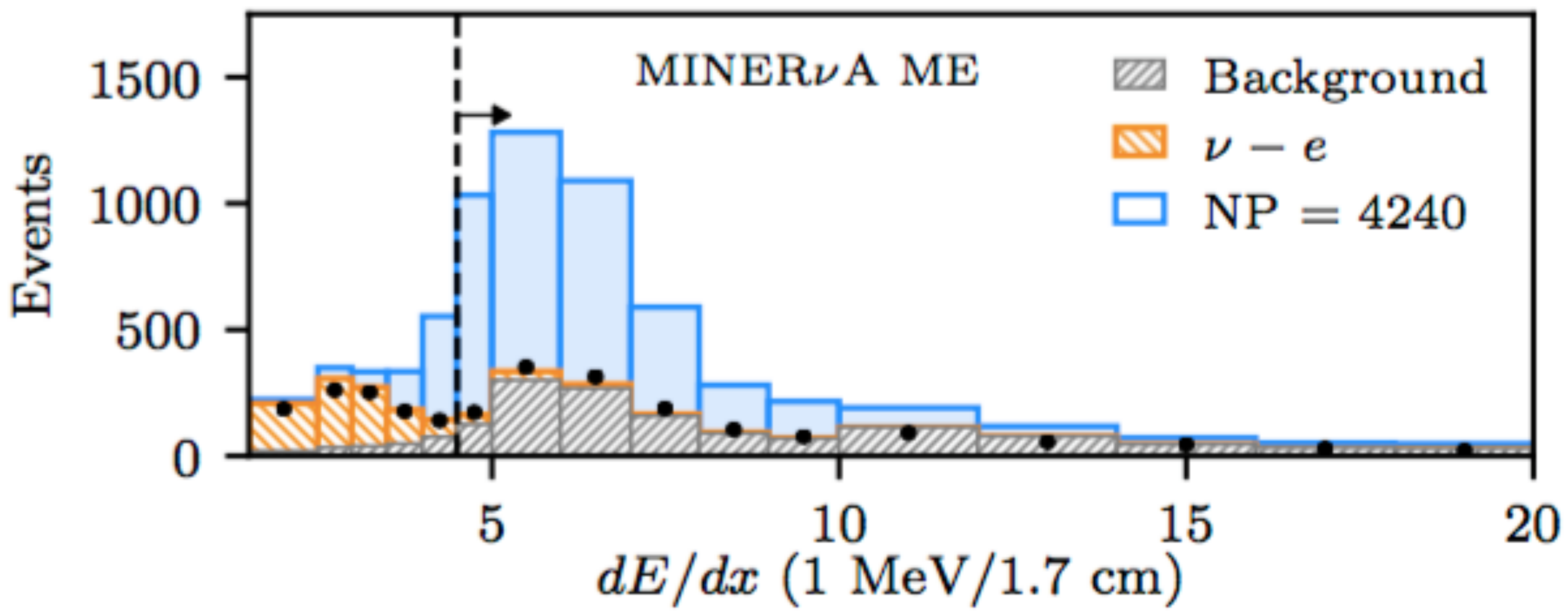
Neutrino-electron scattering datasets

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

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







Some tension with light dark photon scenarios (coherent scattering) but become less effective with larger mediator masses (higher Q2 scattering).

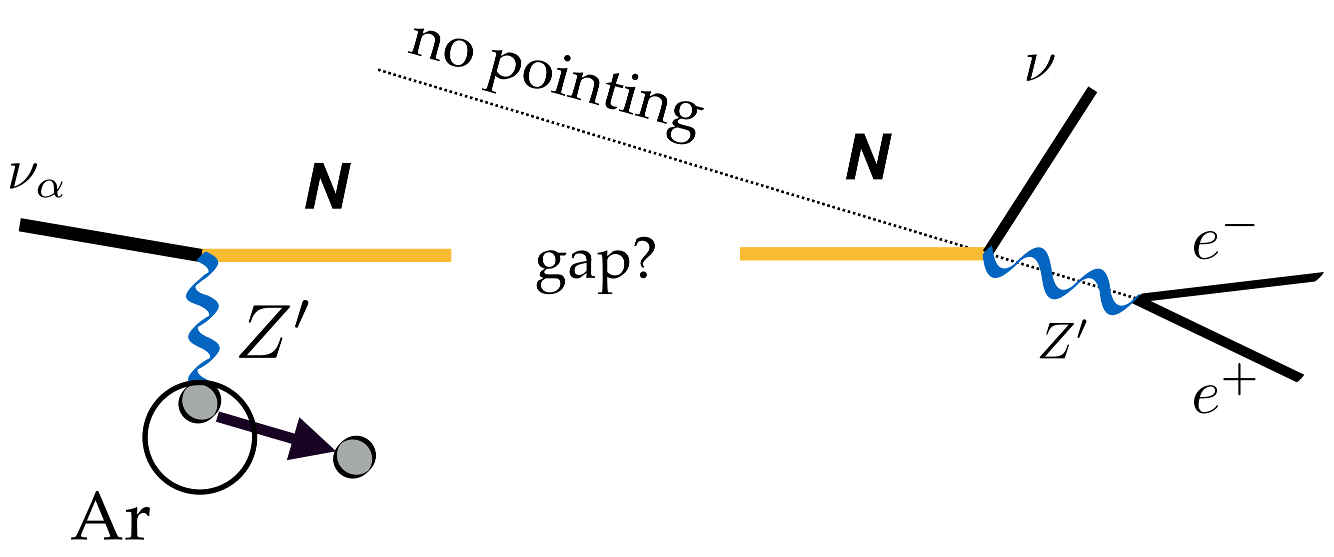
Datasets to keep an eye on:
NOvA and **MINERvA** (anti-)nu-e scattering.

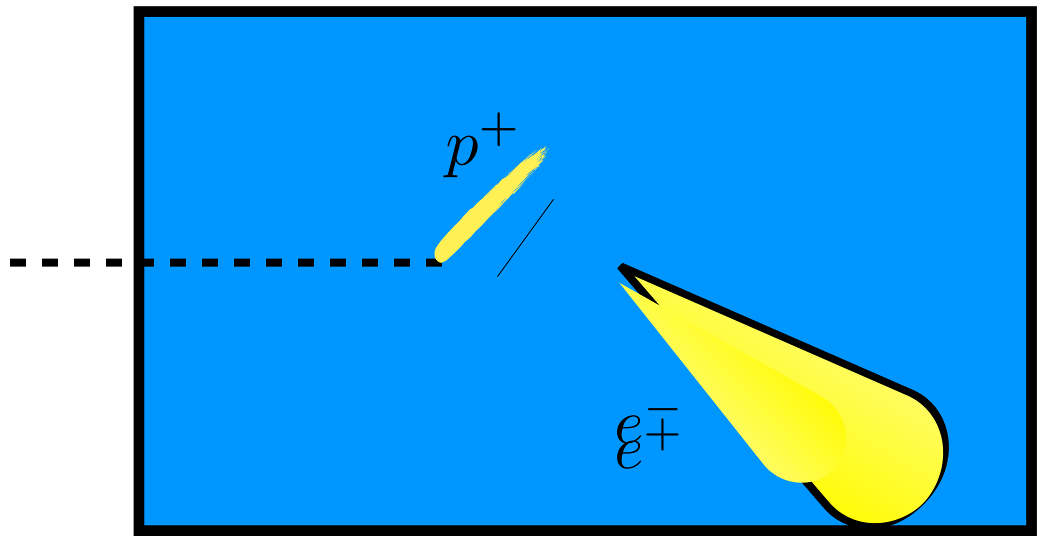
Dark neutrinos @ MicroBooNE

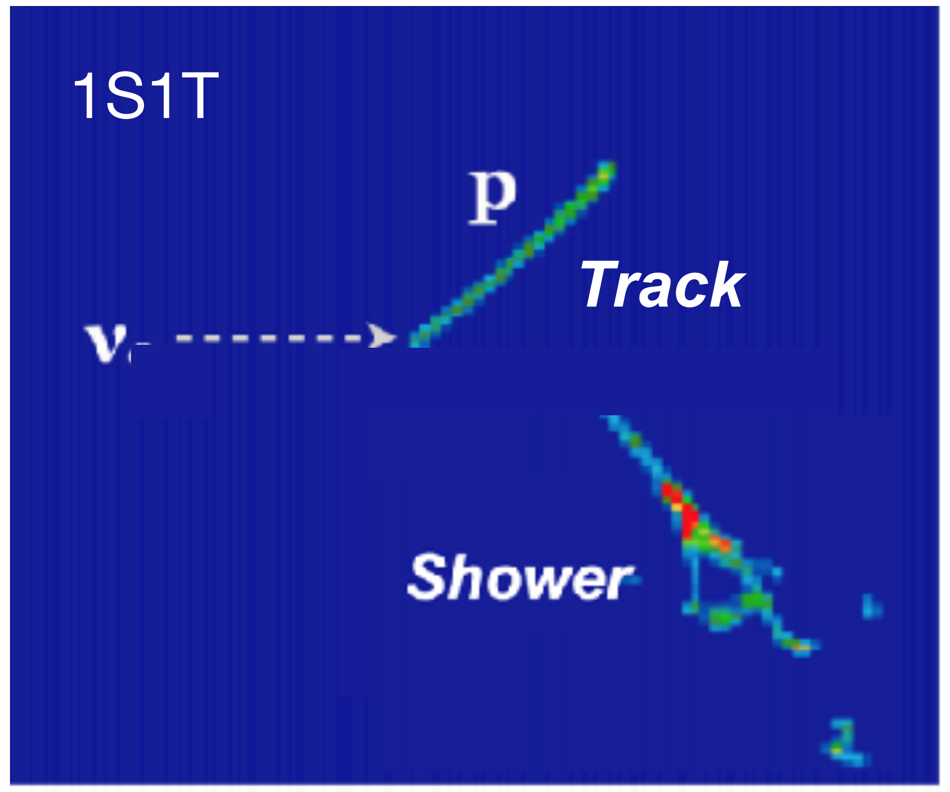
Asli Abdullahi
Durham Uni.

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

Currently studying 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 BP:

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

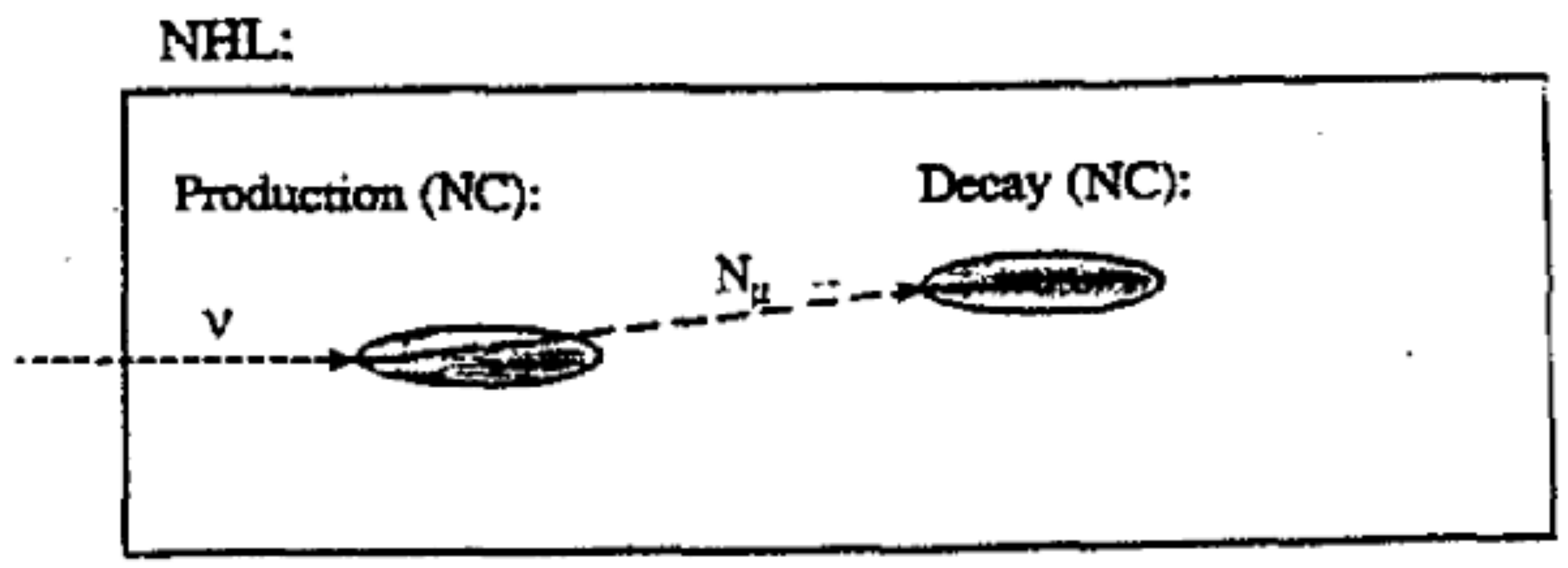
~3000 events of $\nu_\mu \longrightarrow N_6 \longrightarrow \nu e^+e^-$

A new hypothesis for other anomalies?

"Double-bang" events & old accelerator anomalies

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

Double-bangs @ CCFR



NC/NC excess observed at CCFR (1990s), but no excess of NC/CC events.

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

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 minimal HNLs would also lead to CC decays (N -> μπ).

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').

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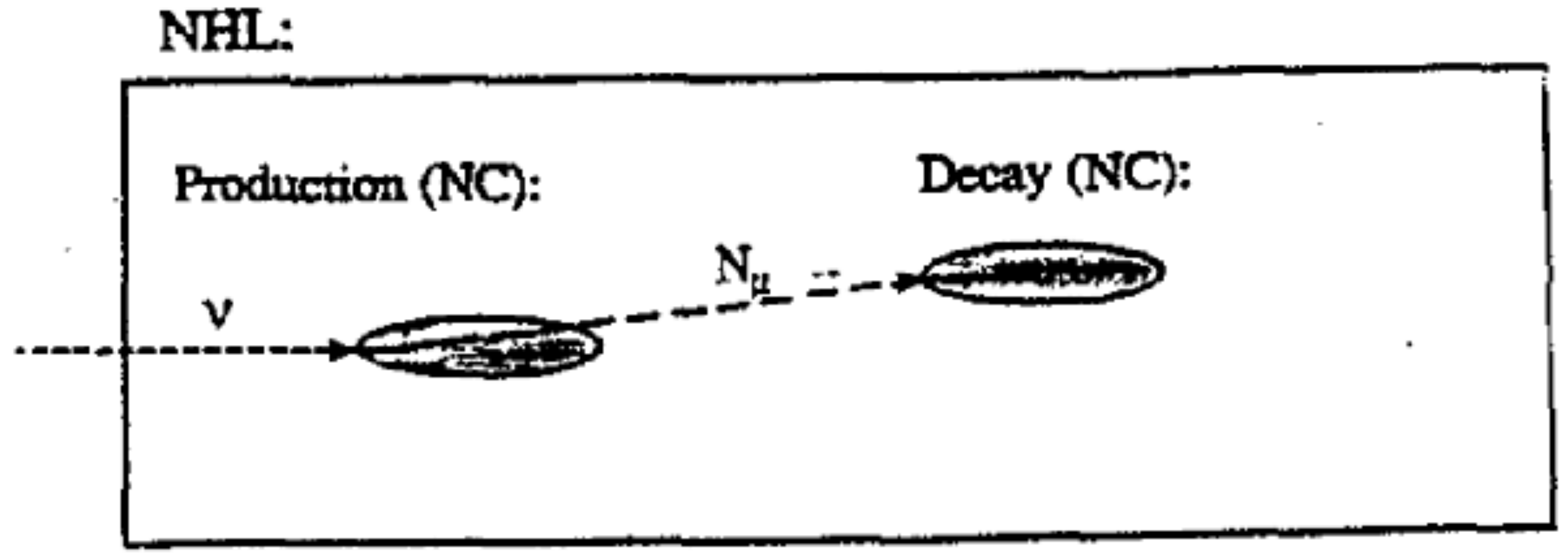

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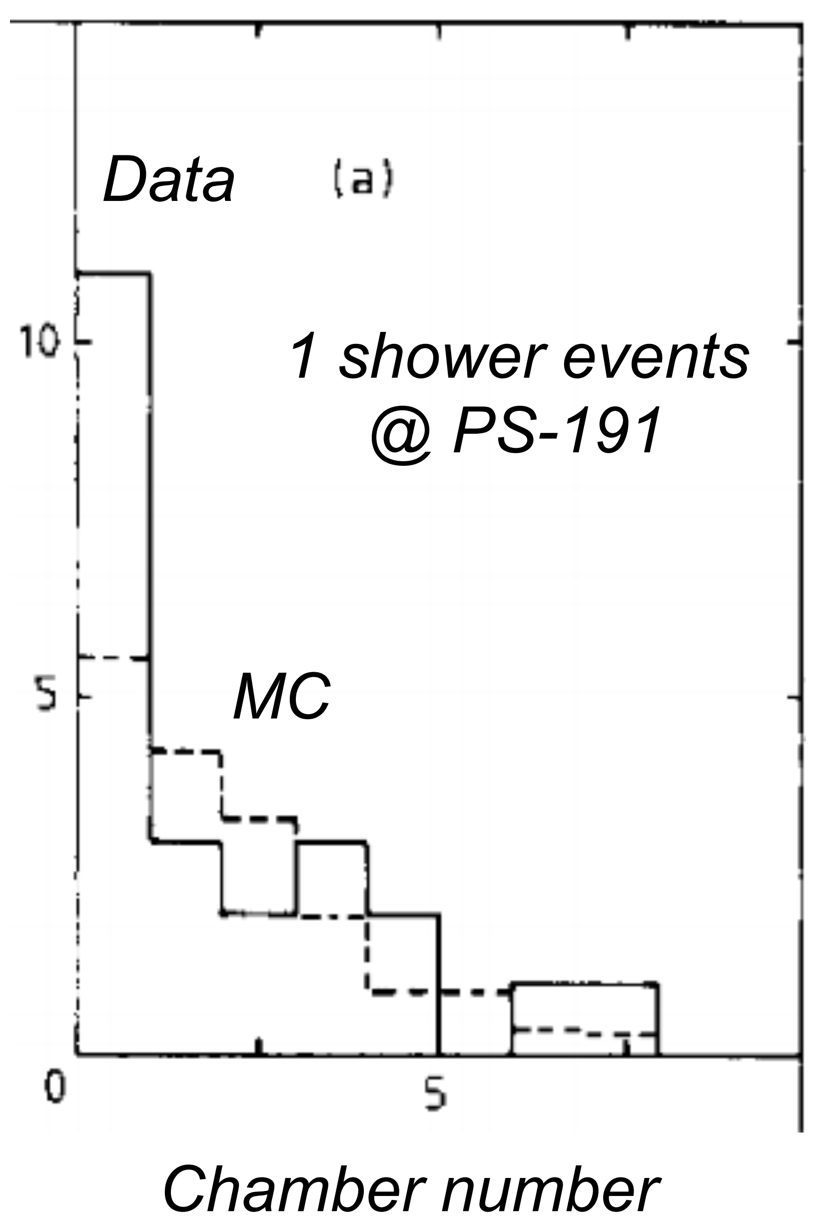
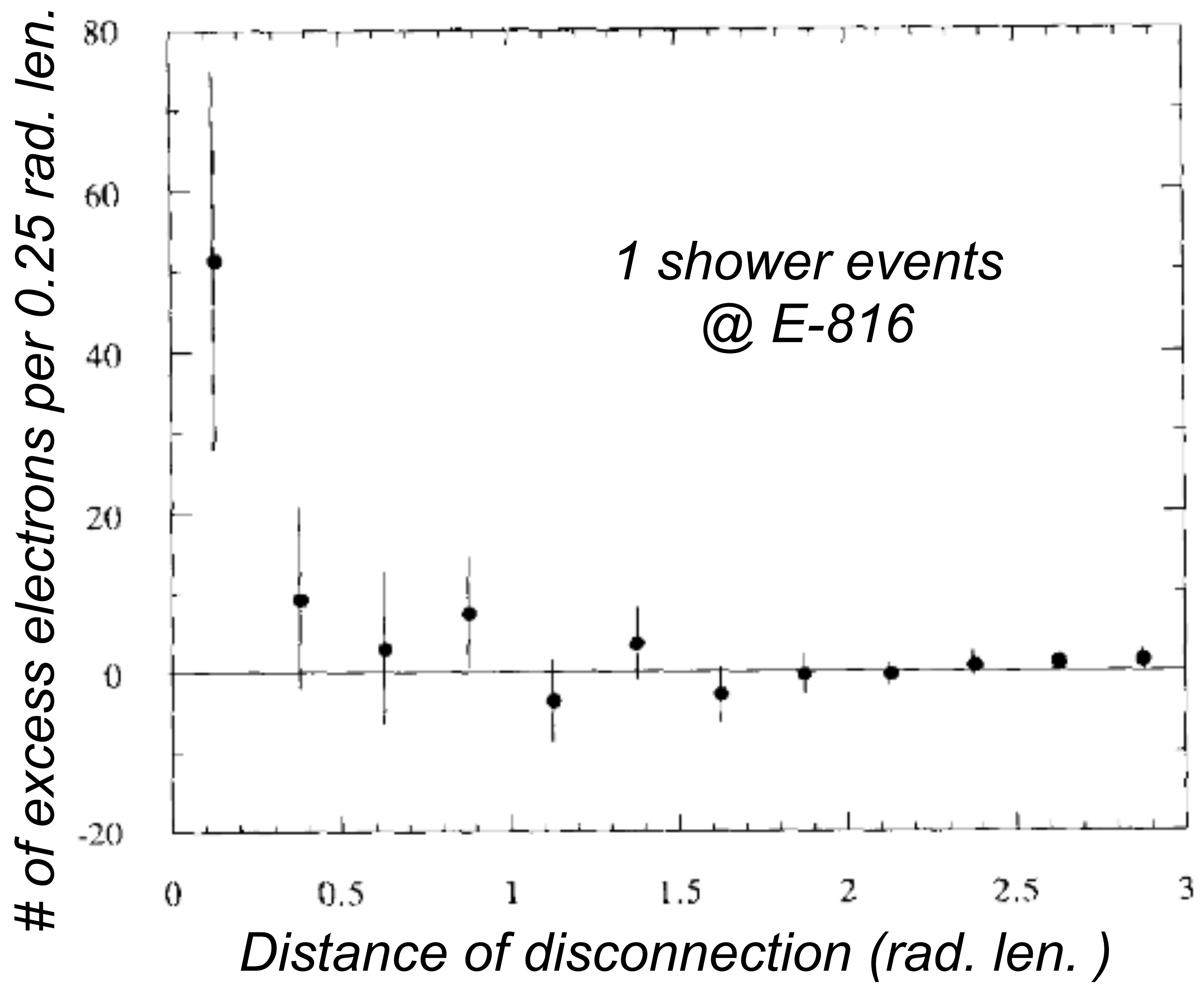
Accelerator anomalies





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

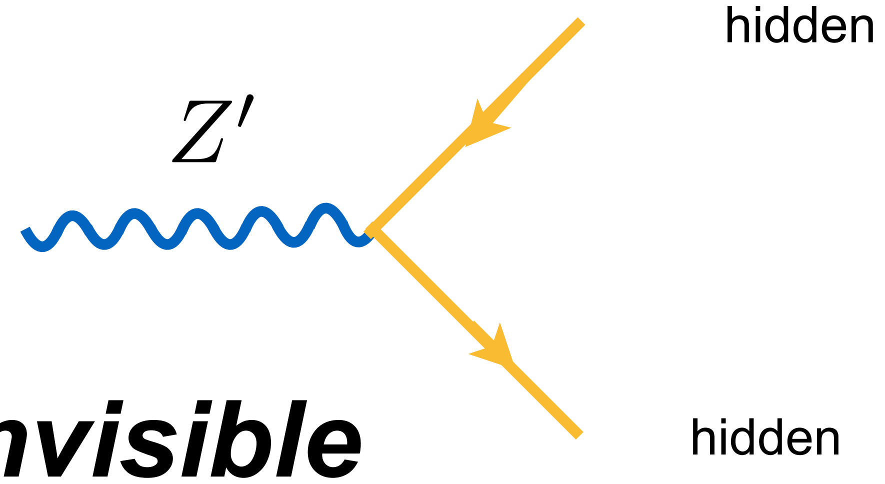
E-816 (’90 @ BNL): built to address PS-191, found a ~2σ excess.

Oscillation interpretation only ruled out by high-energy exps.

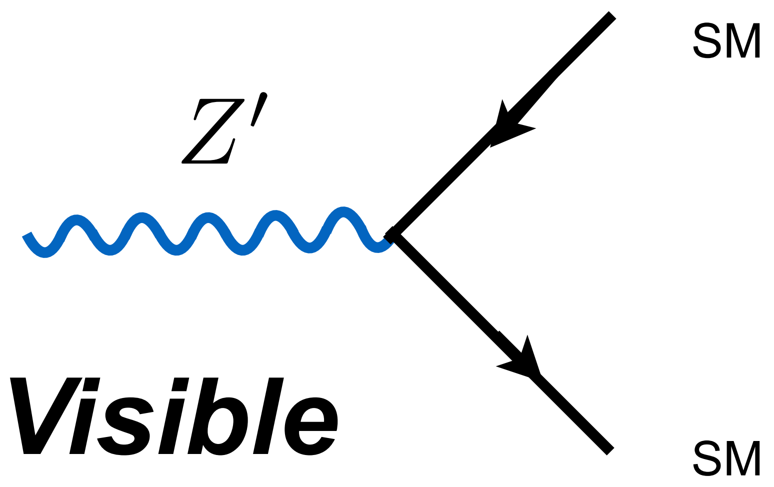
Compatible w/ ν_μ —› N_6 —› ν (e^+e^-) decays, which are fast.

Revisiting the dark photon explanation to (g-2) of the muon

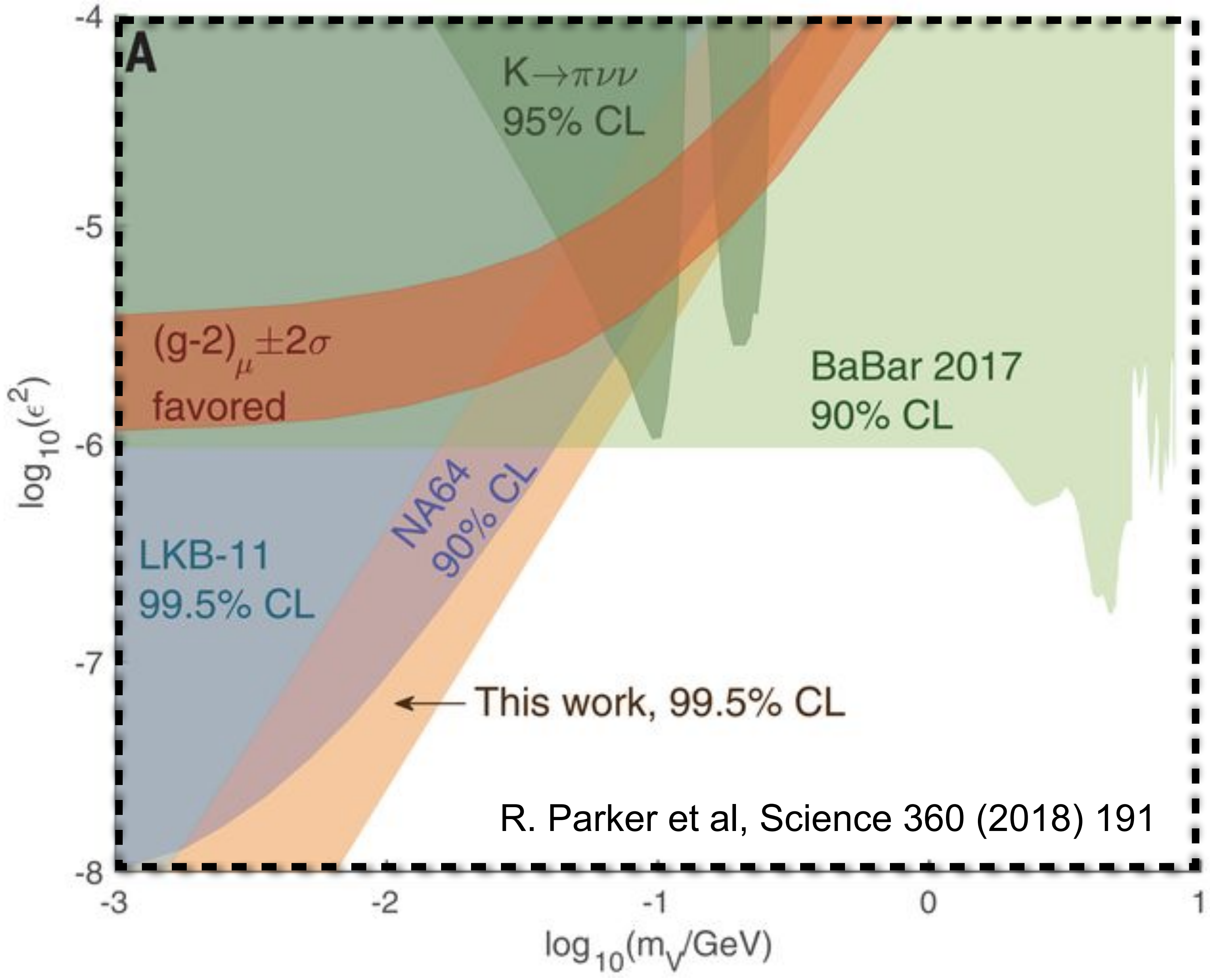
Looking at the dark photon

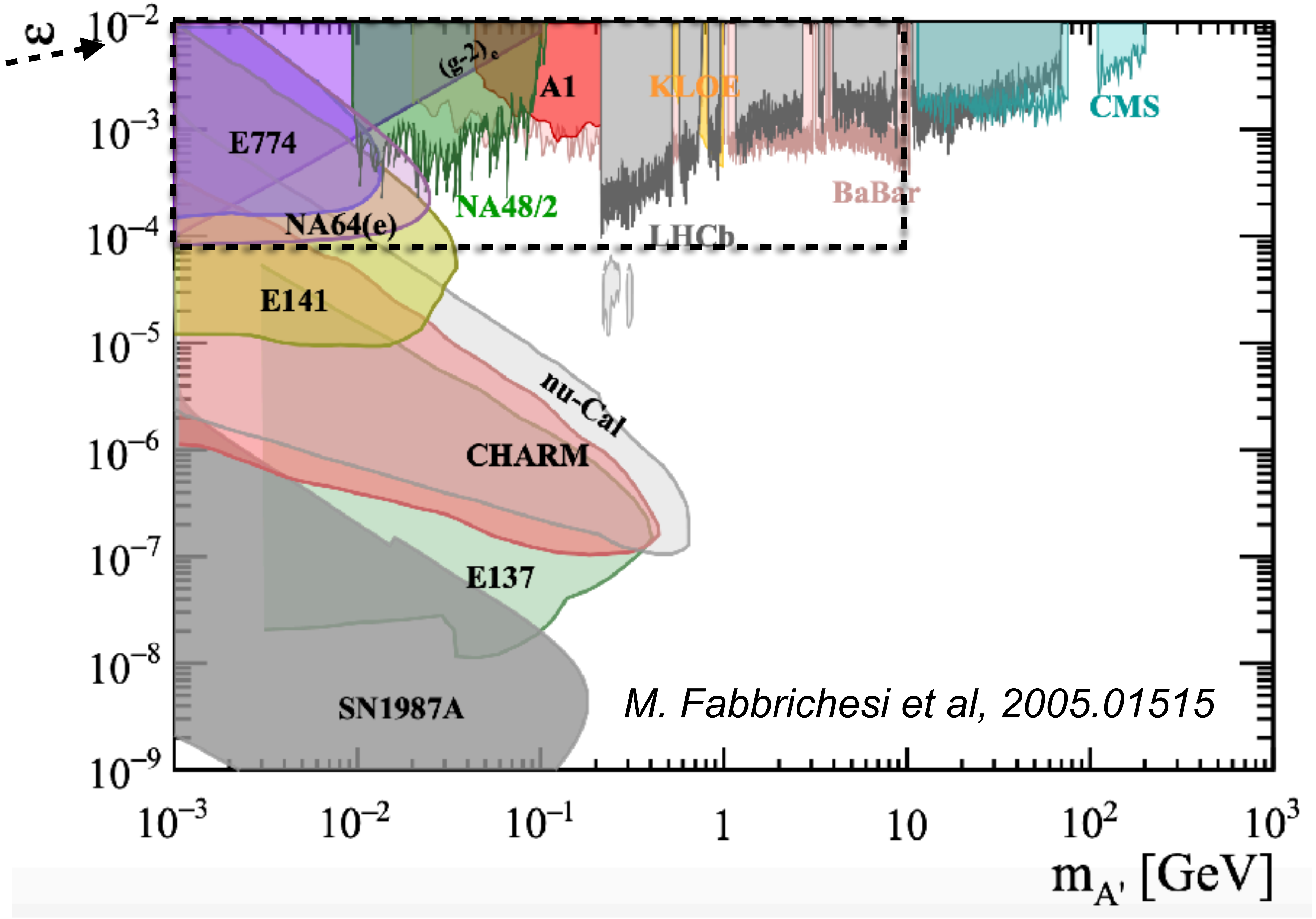


Invisible



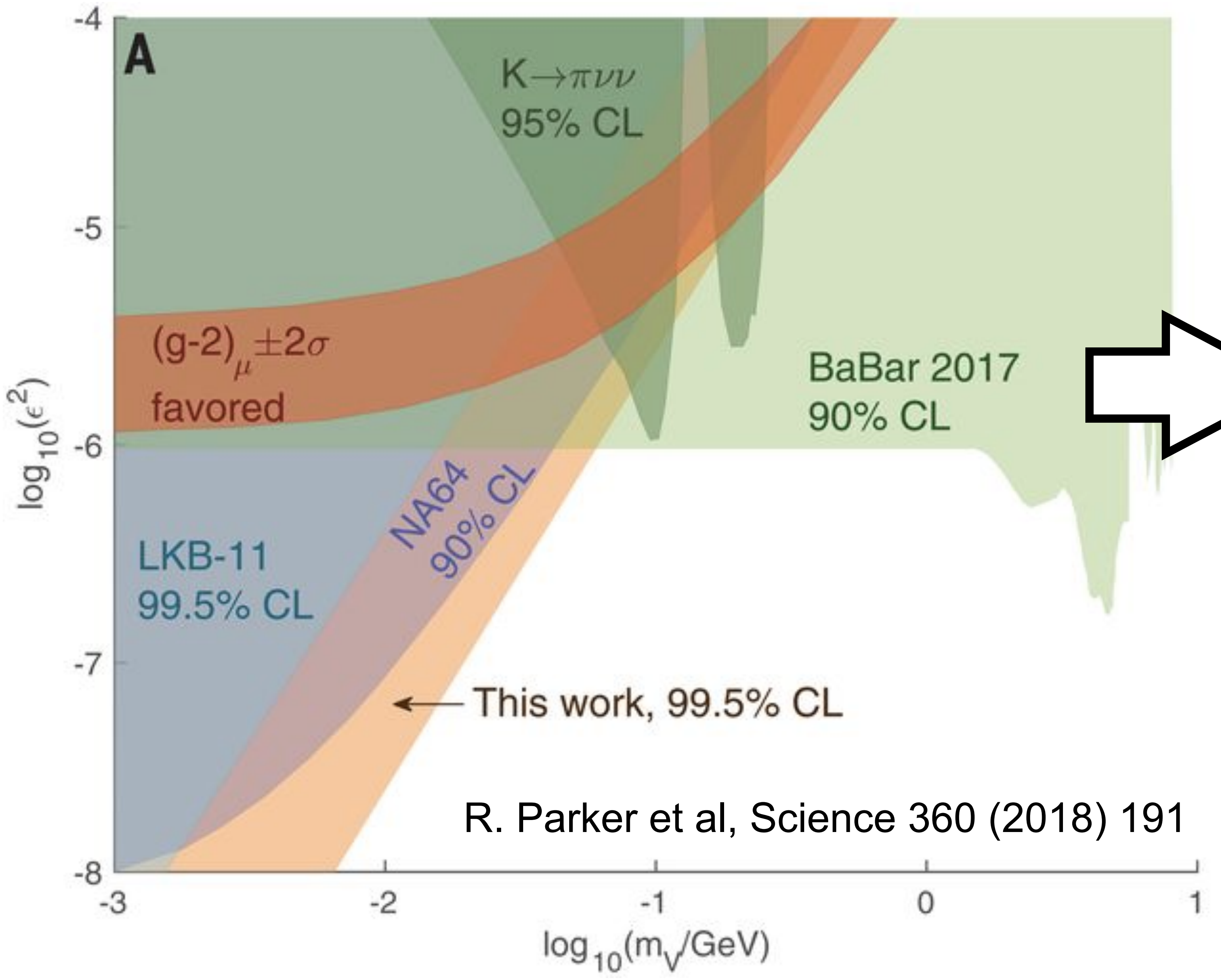
Visible



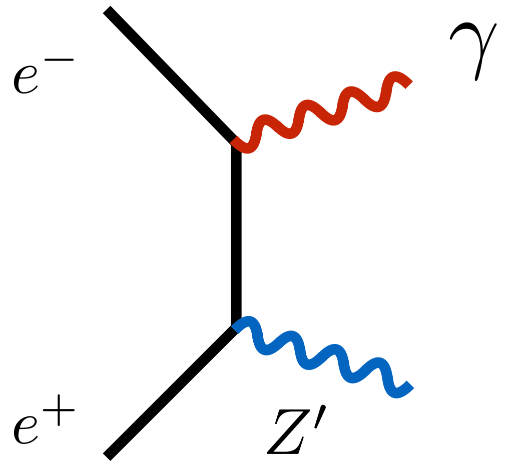


Bonus: revisiting the muon (g-2)

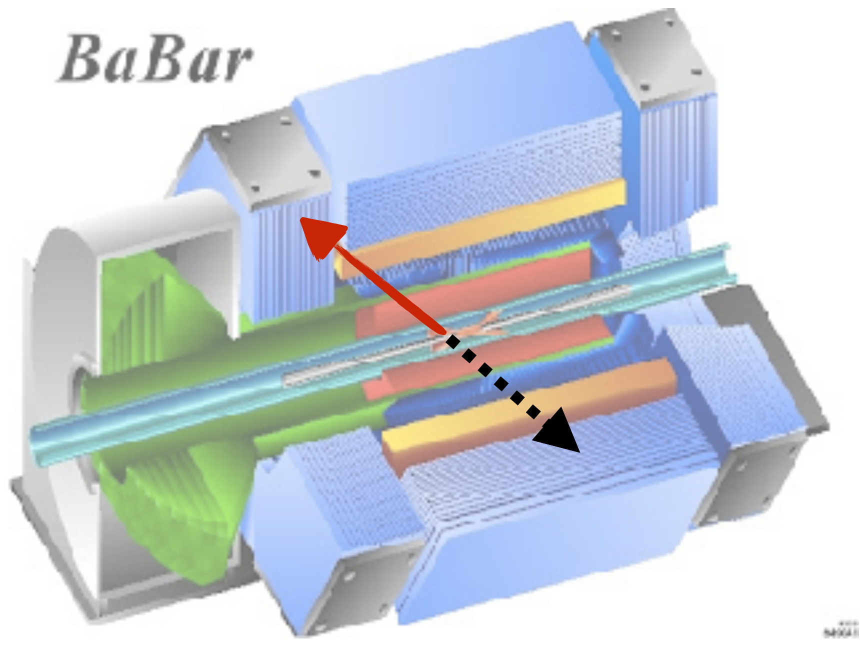
and re-interpreting the BaBar monophoton search



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



Invisible dark photon



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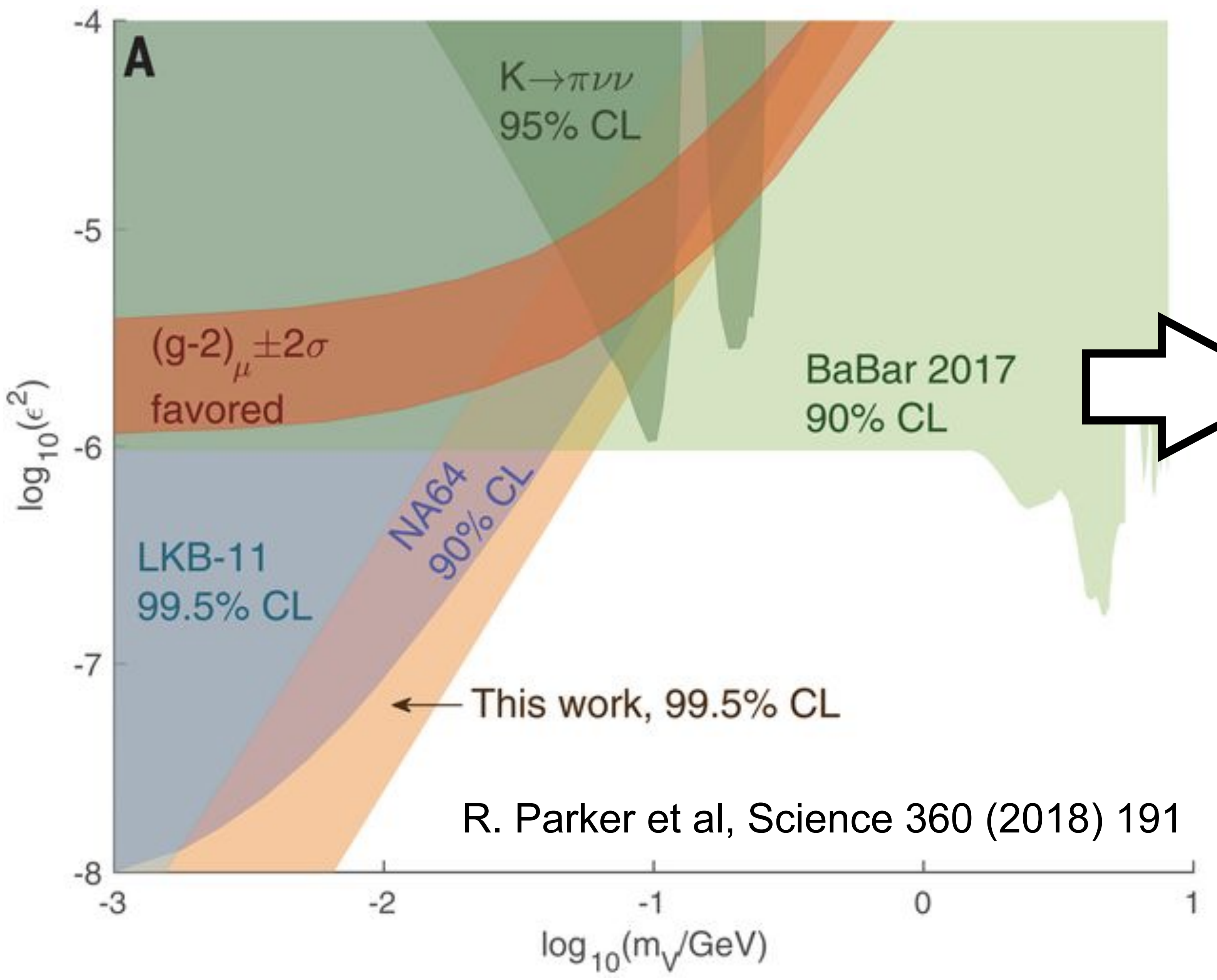
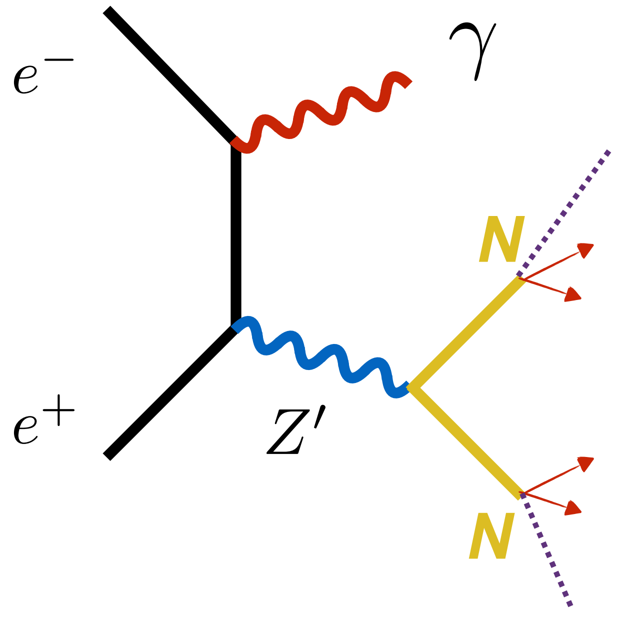
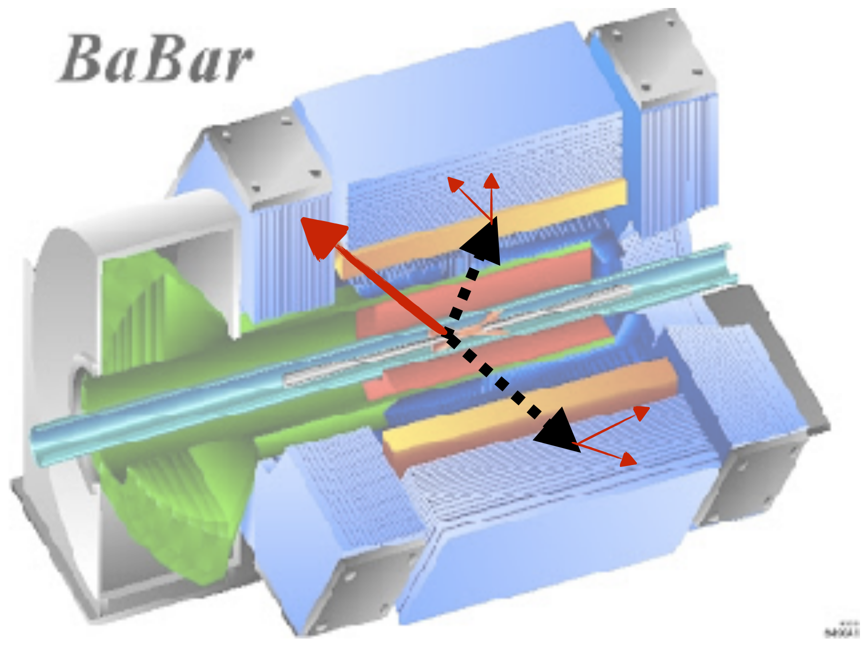
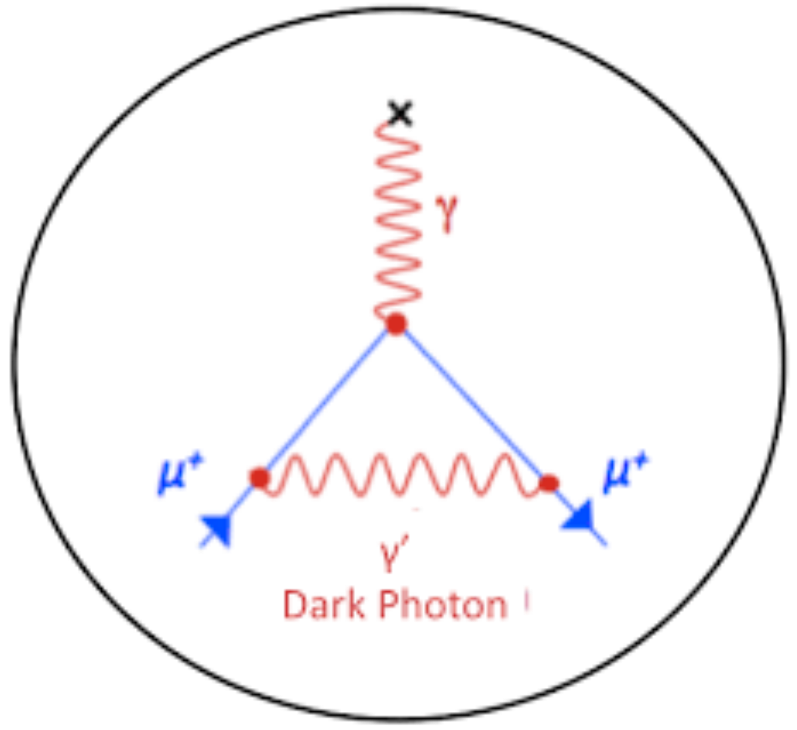


Semi-visible dark photon





Invisible dark photon bounds relaxed.



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

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

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

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

Bonus: revisiting the muon (g-2)

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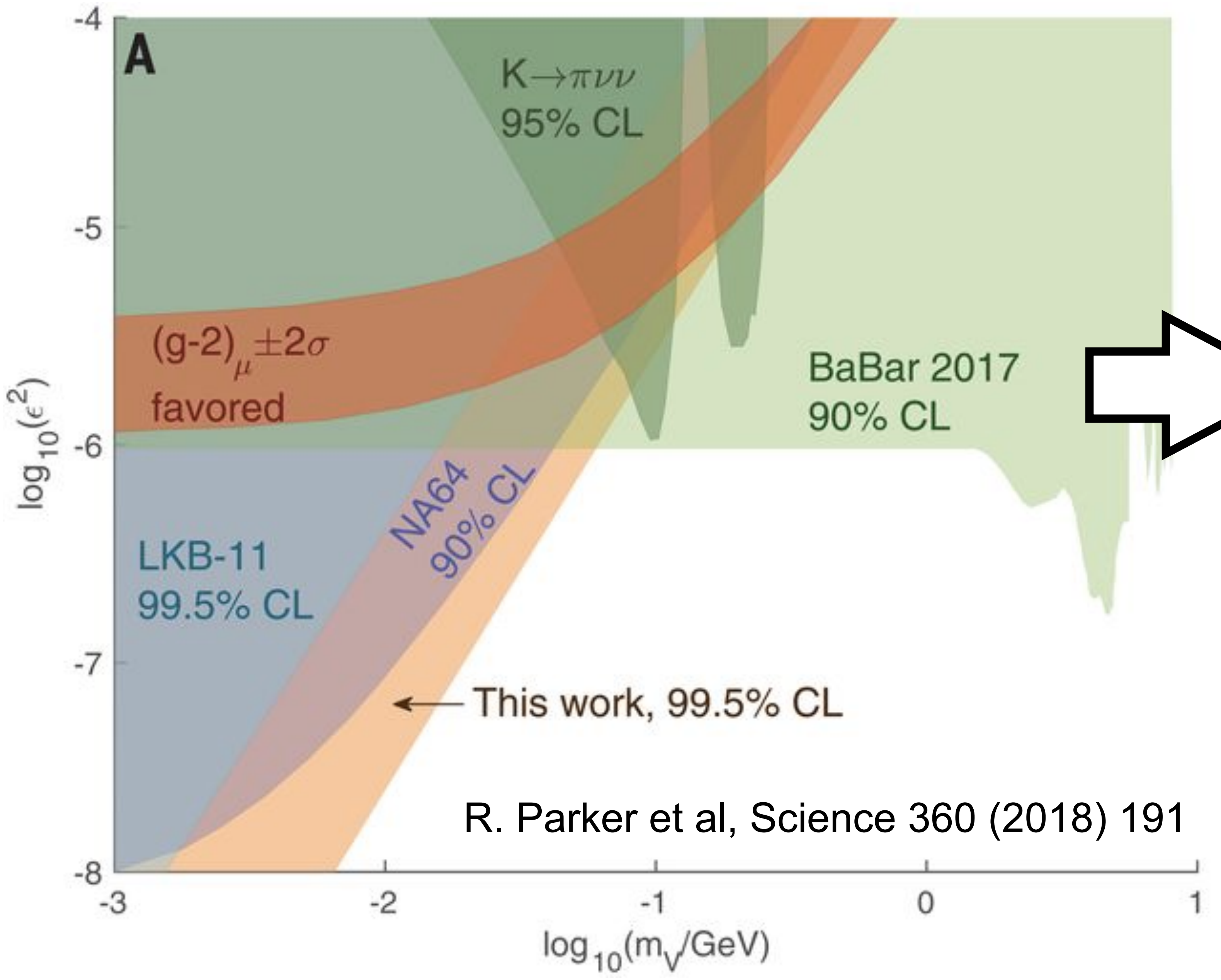

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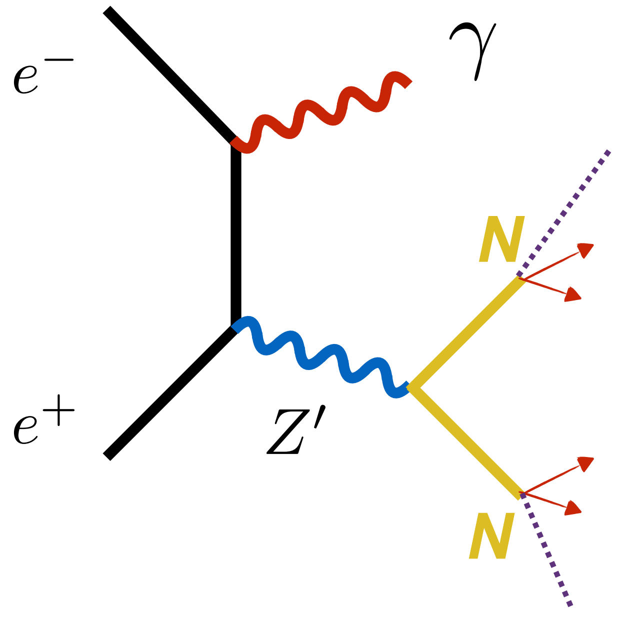

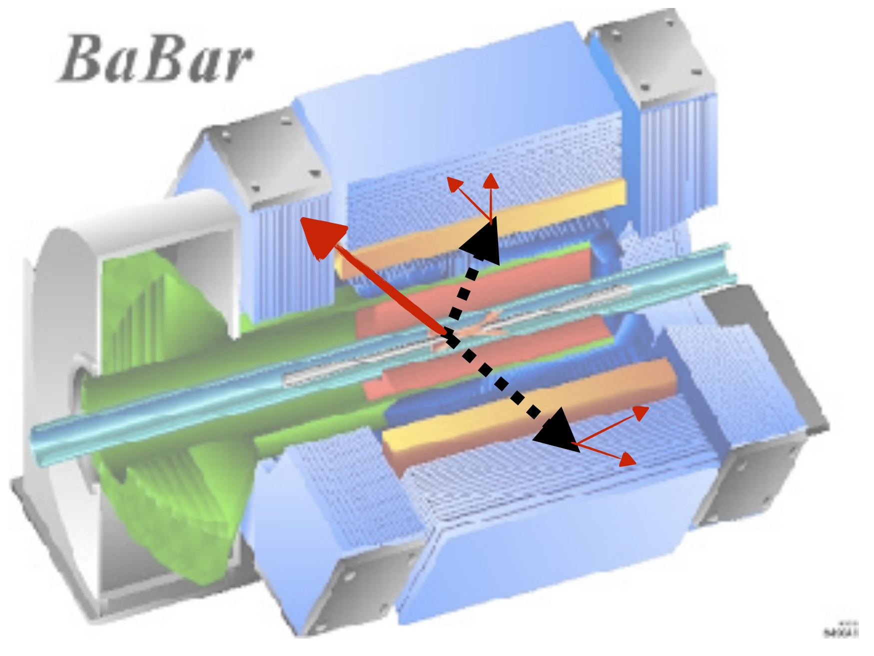

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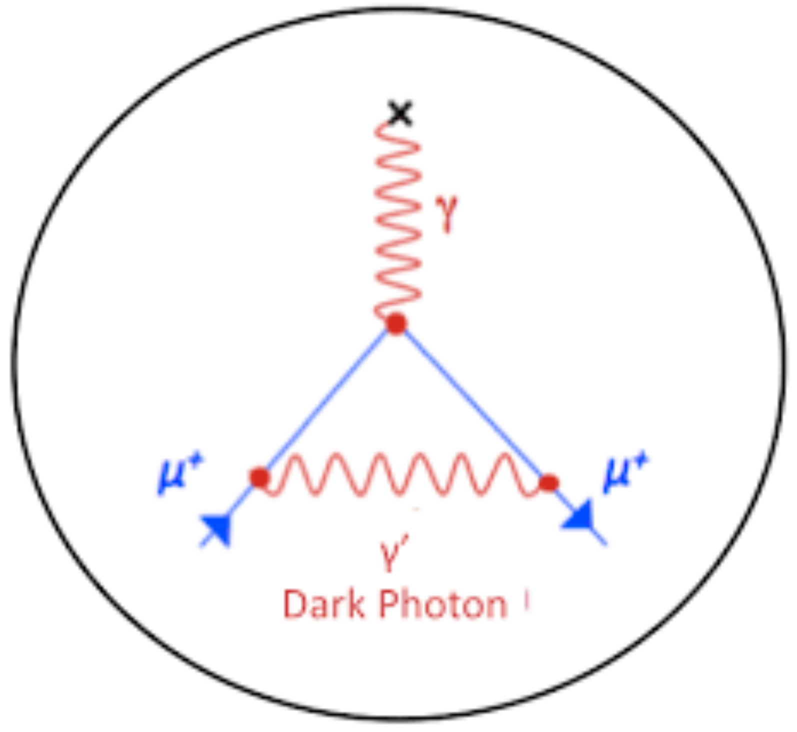

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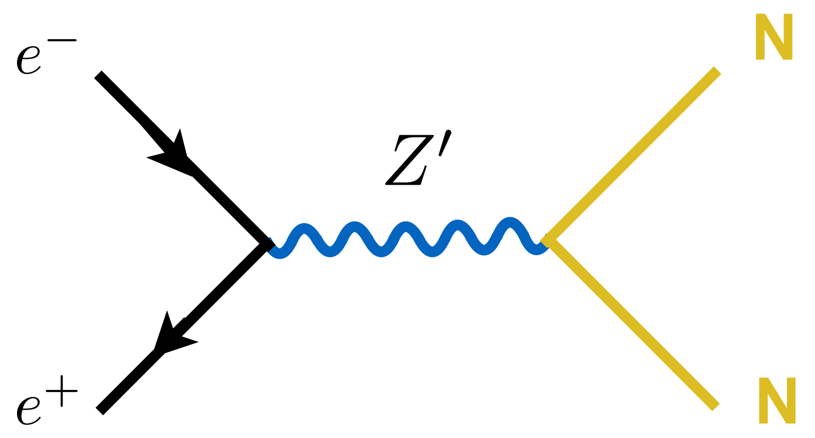
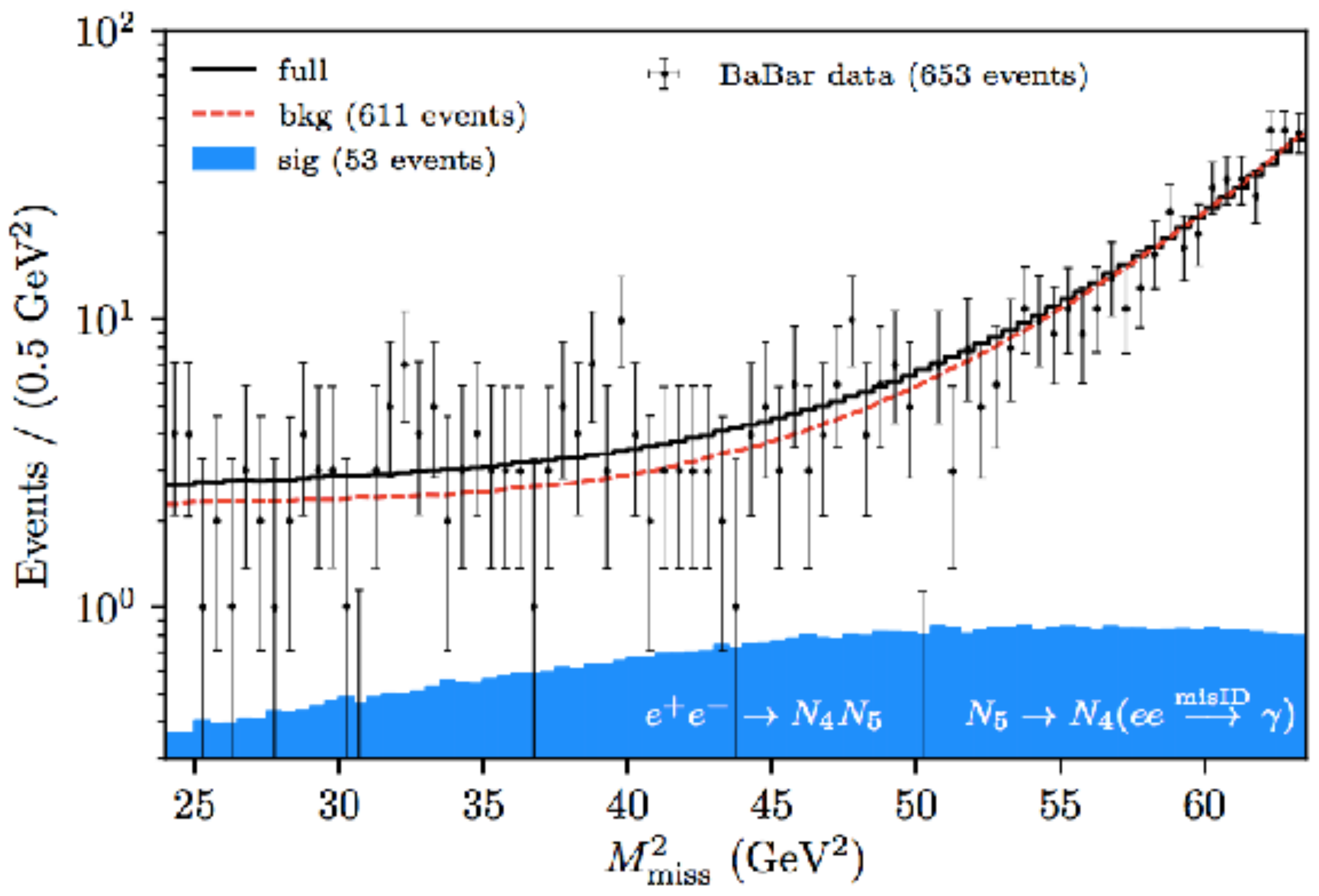


*Predicts a huge rate of s-channel $e^+e^- \to NN$ production @ **BaBar** and **Belle-II** ($\mathcal{O}(10^4)$ events).*

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

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



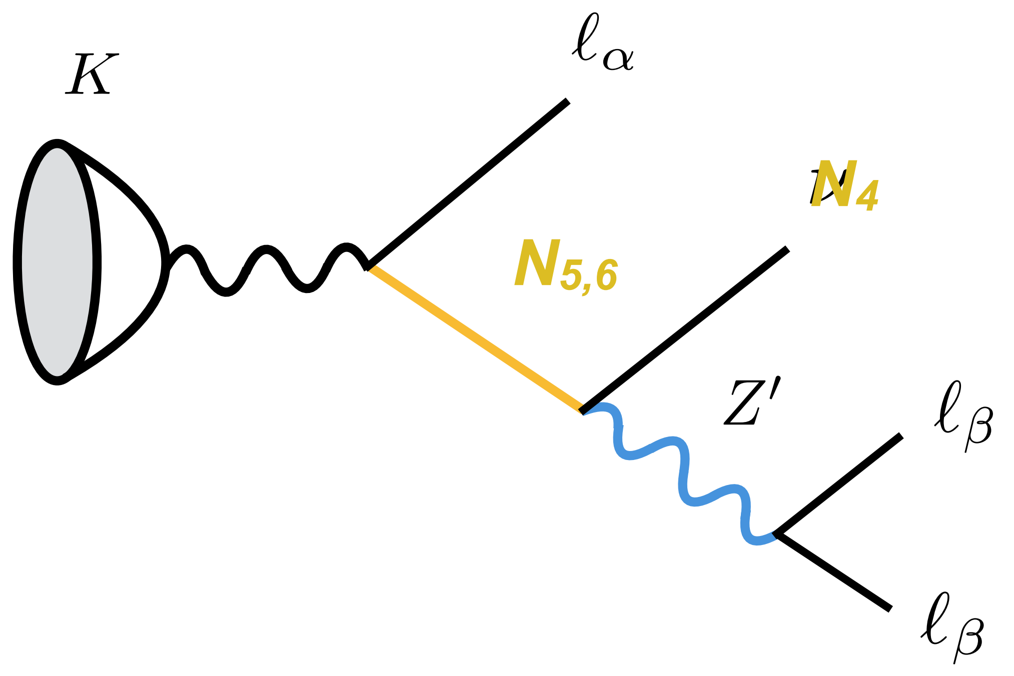
Smoking gun at Kaon decays

Looking for the dark HNLs elsewhere

Smoking gun signature at kaon experiments

Rare leptonic kaon decays

Peak search + (displaced) e+e- vertex



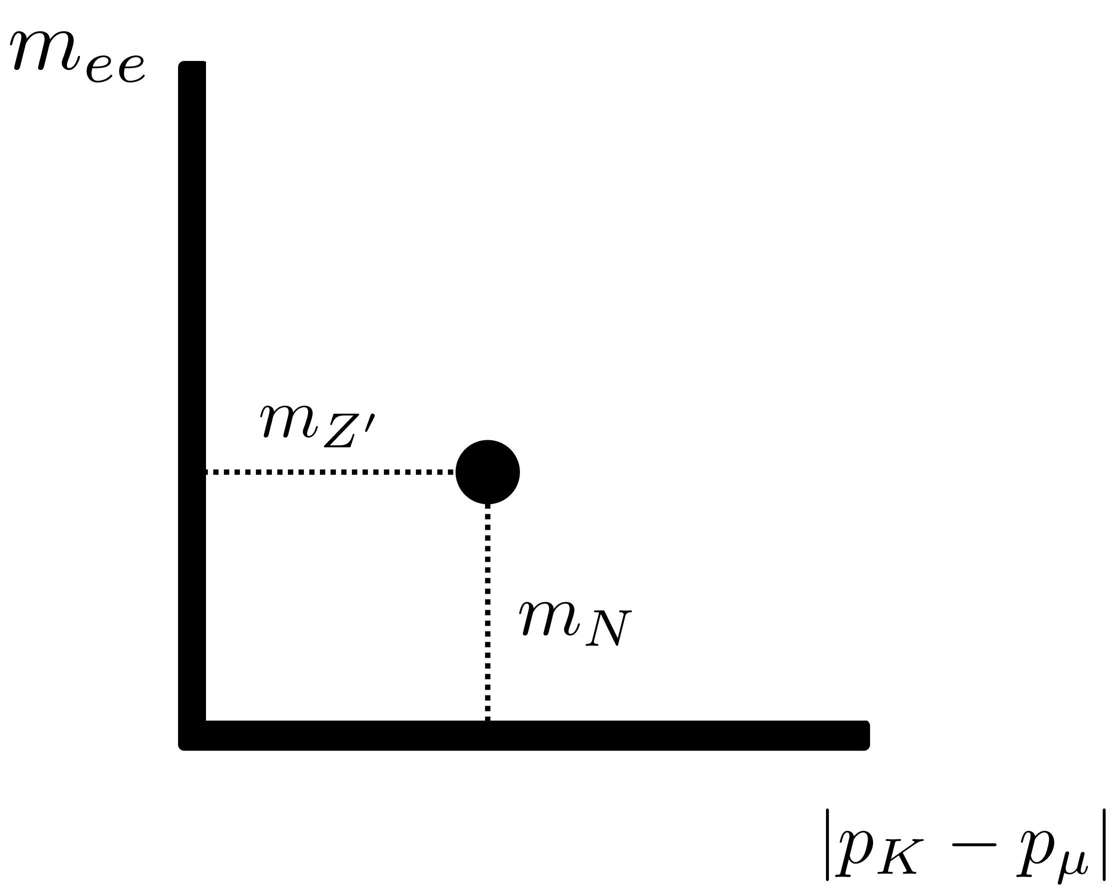
At **NA62**, would expect ~3000 events in existing data for our *BP*.

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

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

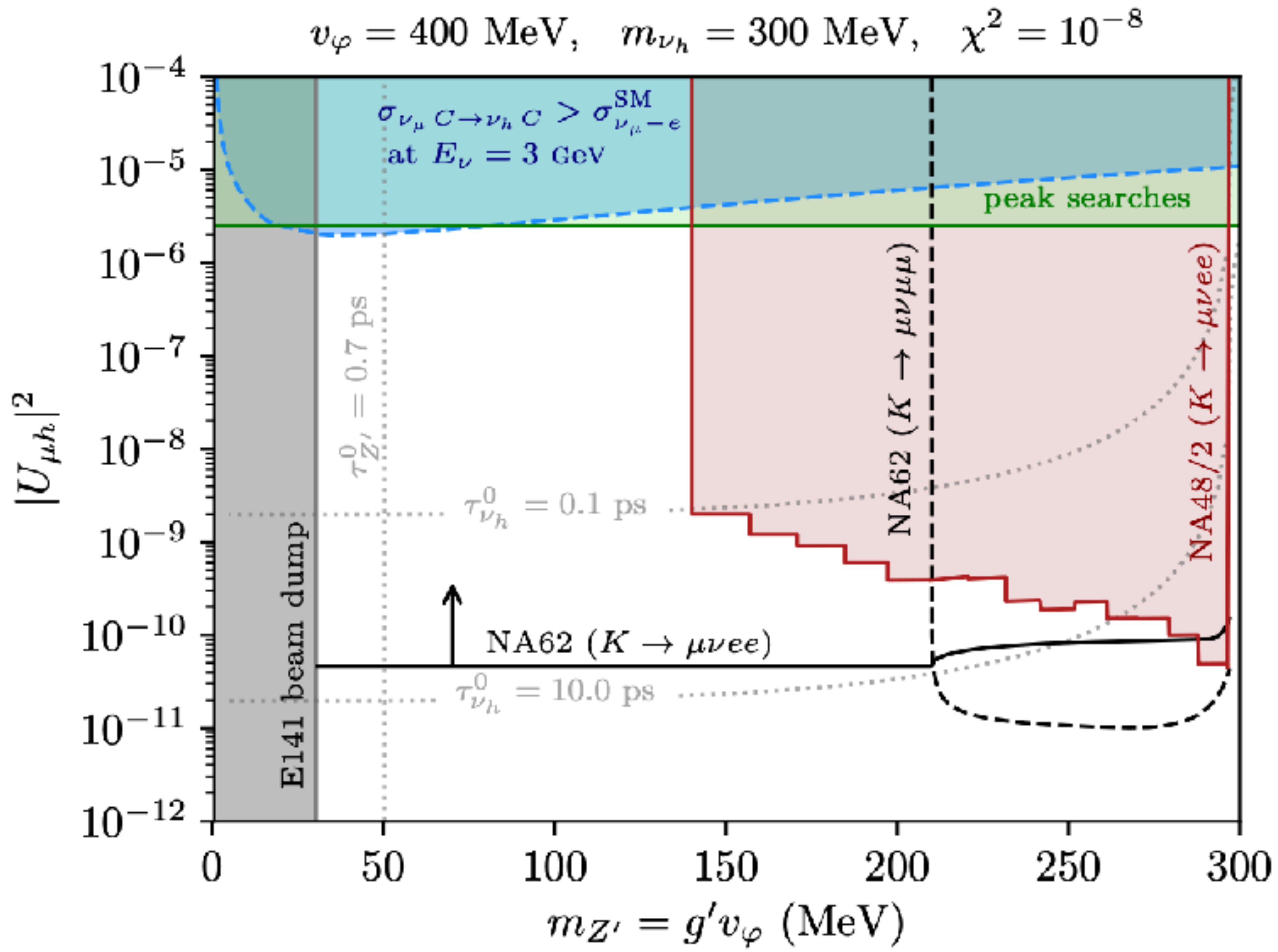
$$m_{ee} < m_{5,6} - m_4$$

Light dark photon case



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

Smoking gun peak at light dark photon and HNL mass



More exotic signatures in kaon decays

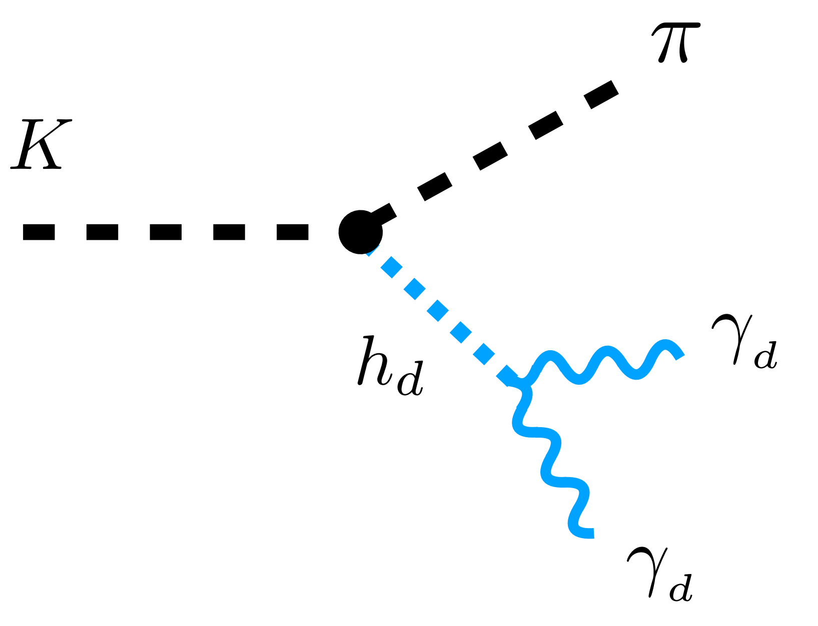
Dark higgs decays to dark photon

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".**

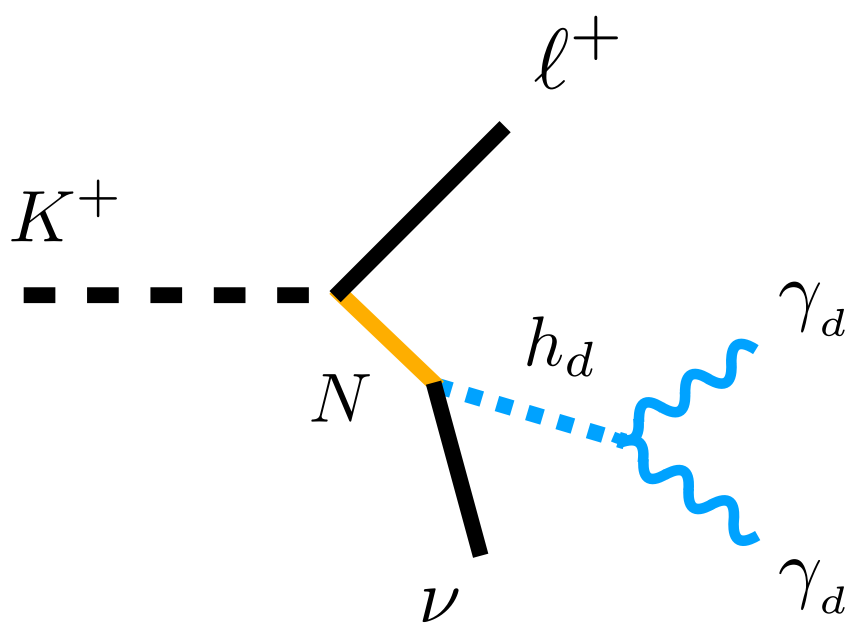
Several channels never even searched for, which can exceed **Br ~ O(10^{-8} - 10^{-6}).**

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



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

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



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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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Also compatible with:

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Testable at:

- μBooNE (+SBN program)
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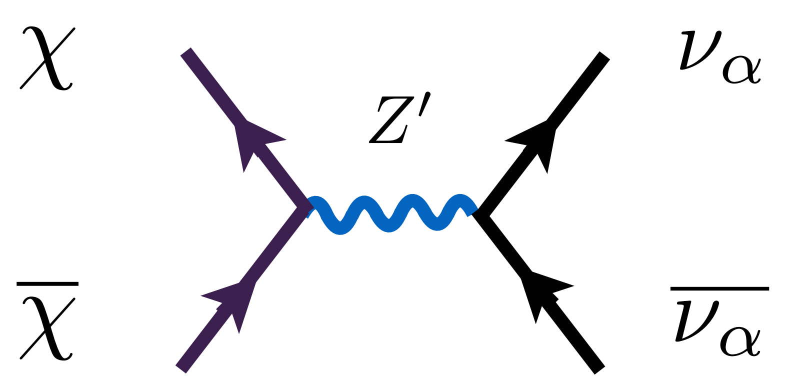
Thank you!

Back-up slides

A renormalizable model for a dark neutrino sector

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



Dark Sector

Fermionic DM extensions parentheses

- Option 1) Accidental symmetries

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

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

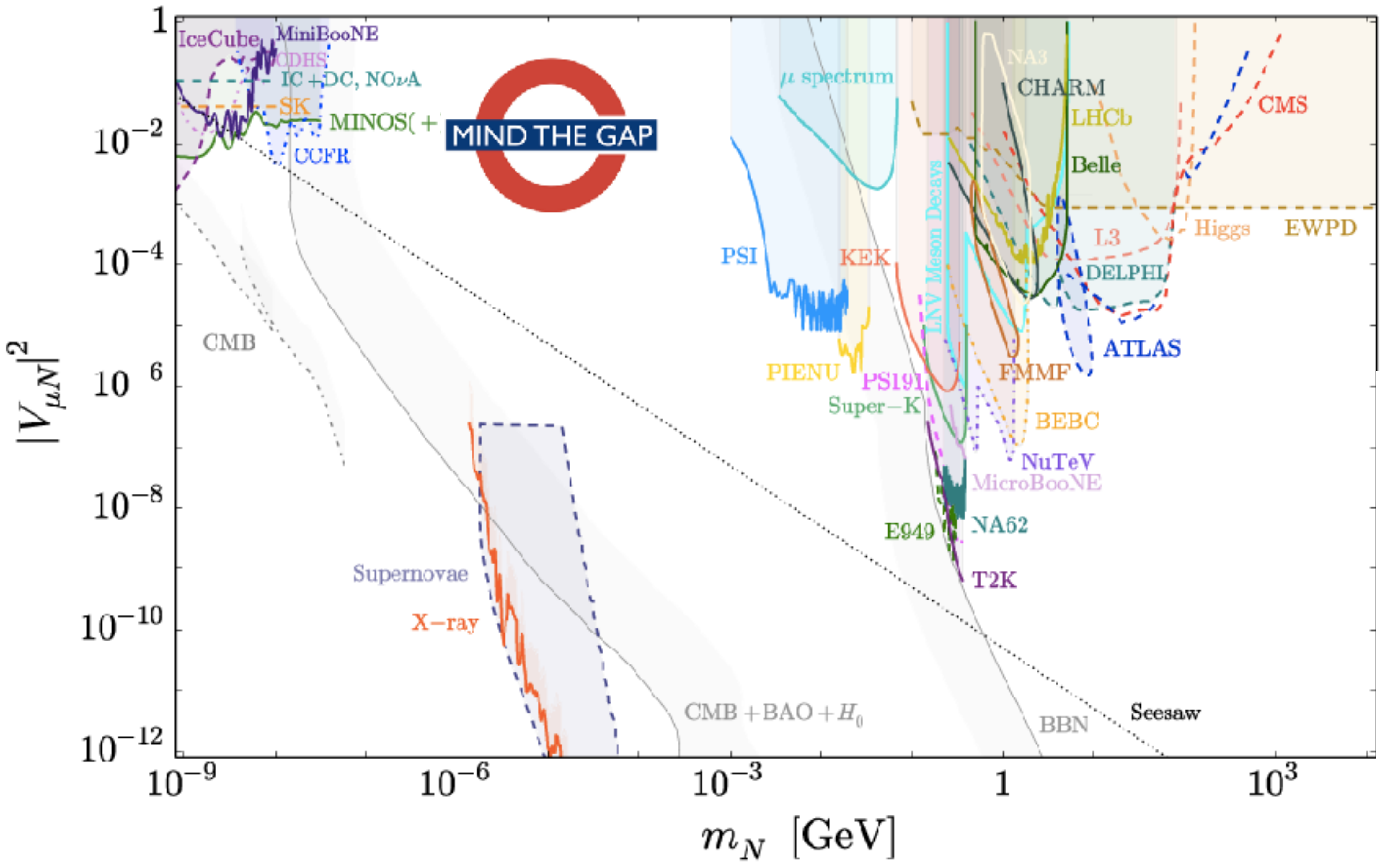
$$\chi_{\rm R} \sim (\mathbf{1}, 0, Q) \quad \chi_{\rm L} \sim (\mathbf{1}, 0, 0) \qquad \mu_L\,\overline{\chi_L^c}\chi_L + y\,\overline{\chi_L}\chi_R\Phi^*$$

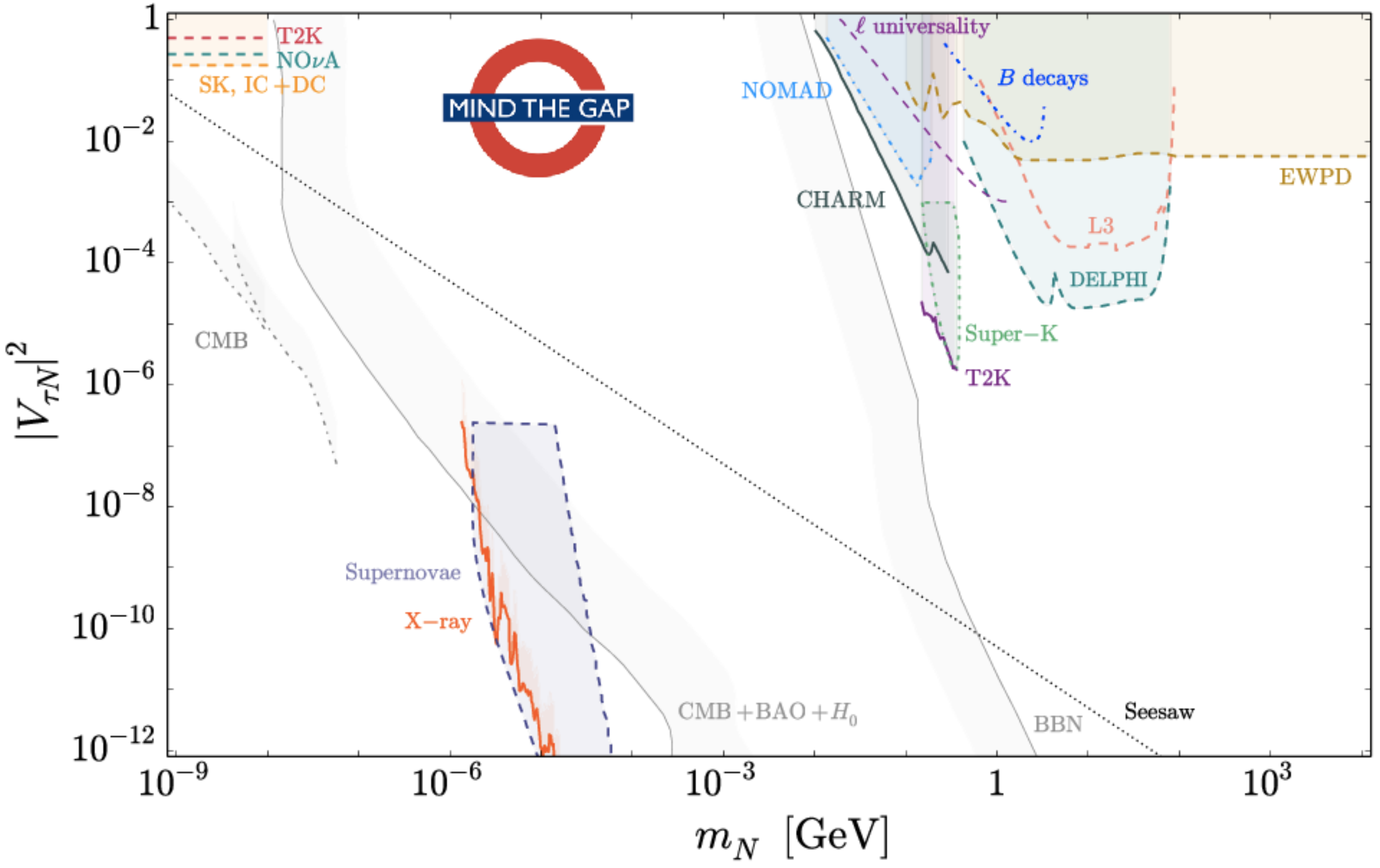
When vector and scalar portals are turned off the model is promising avenue for MeV/GeV scale thermal nu-philic DM.

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

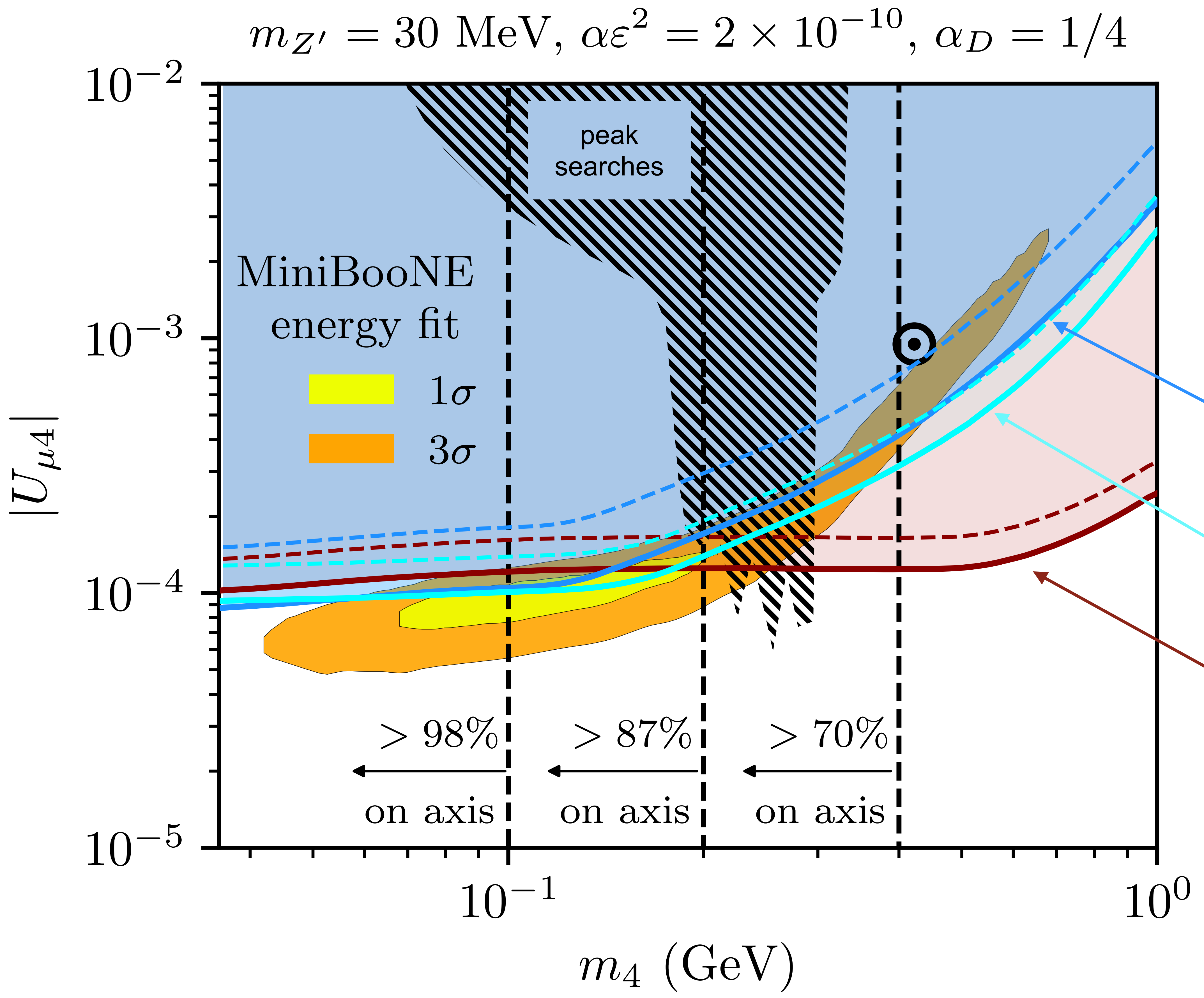
Minimal HNL Phenomenology

P. Bolton et al, 1912.03058





Neutrino-electron scattering constraints

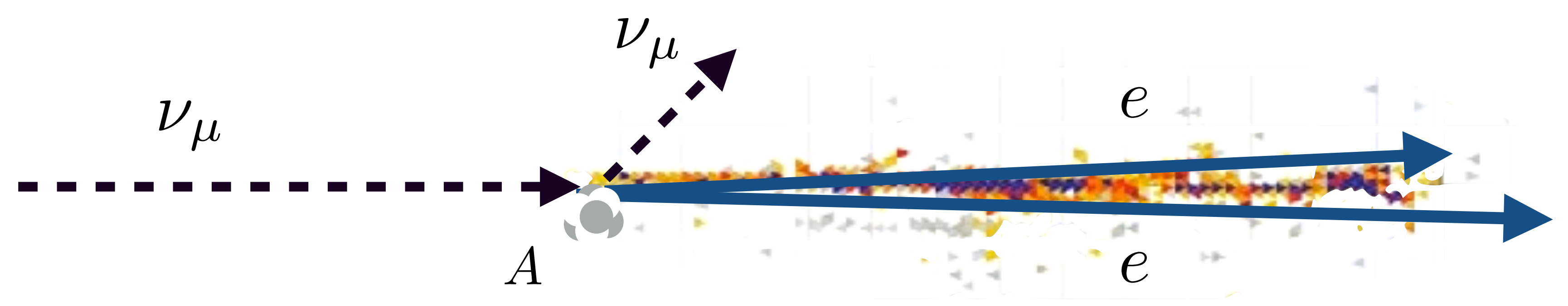


Vary uncertainty on backgrounds:

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

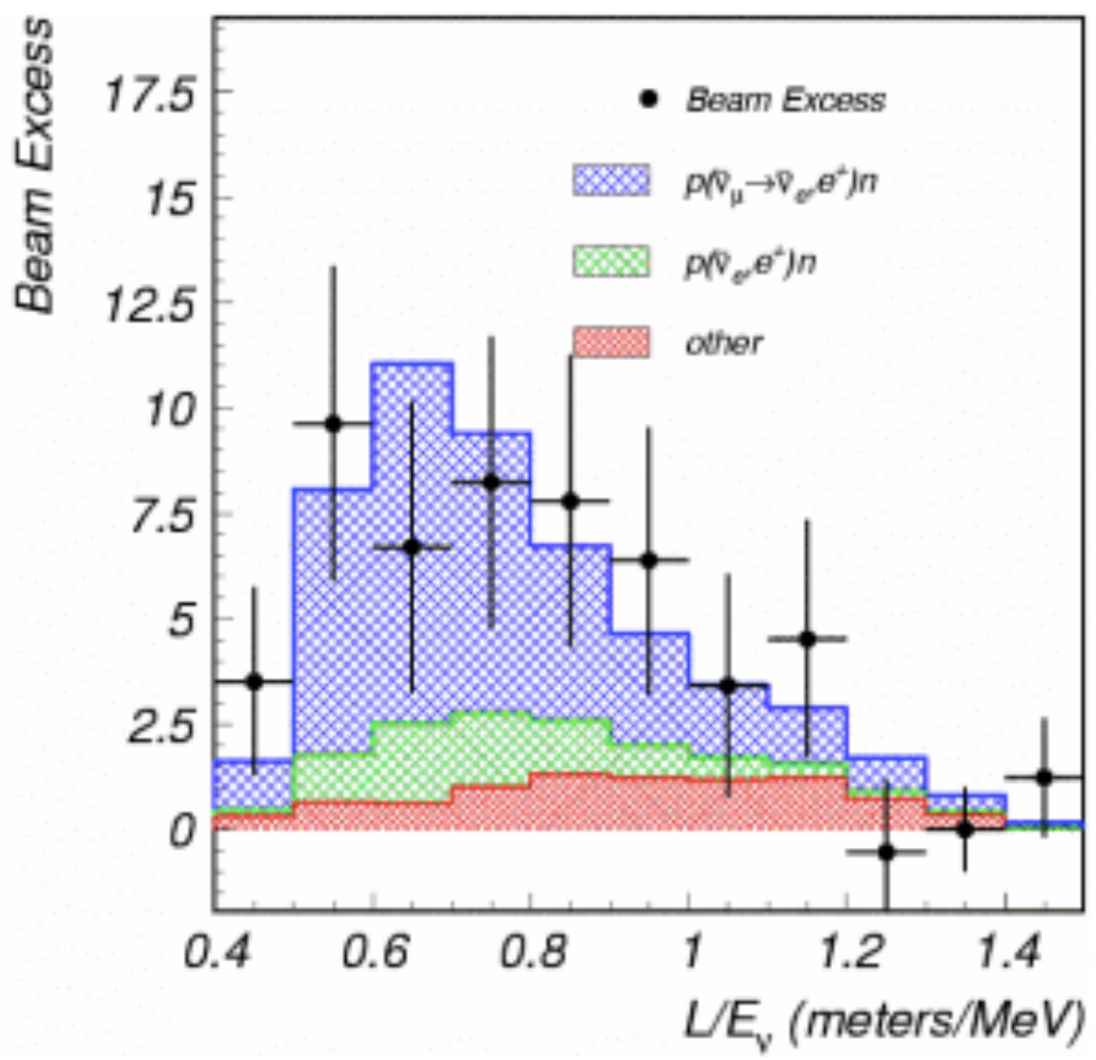
Analysis can be improved with future data:

- *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.

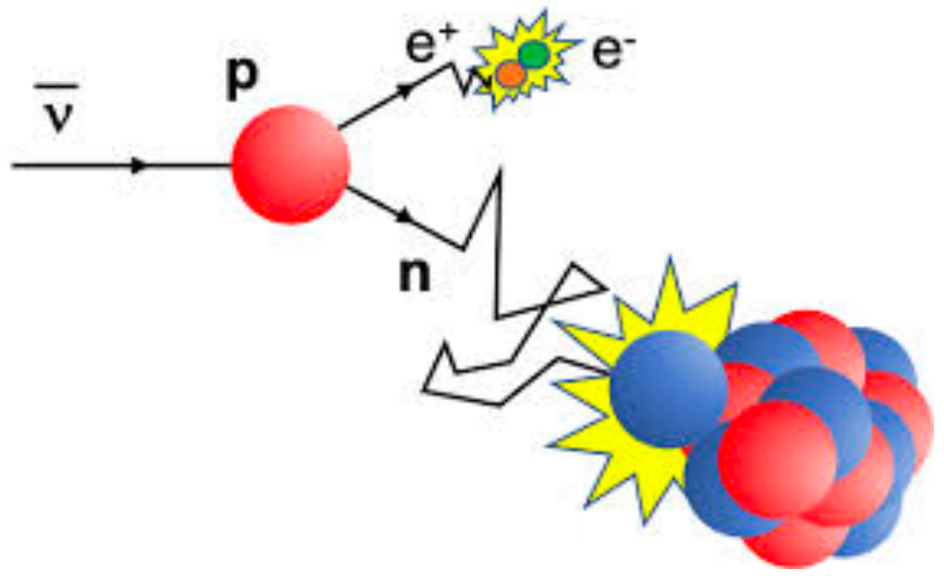


EXCESS: 87.9 ± 22.4 ± 6 EVENTS
3.8 sigma

General idea:

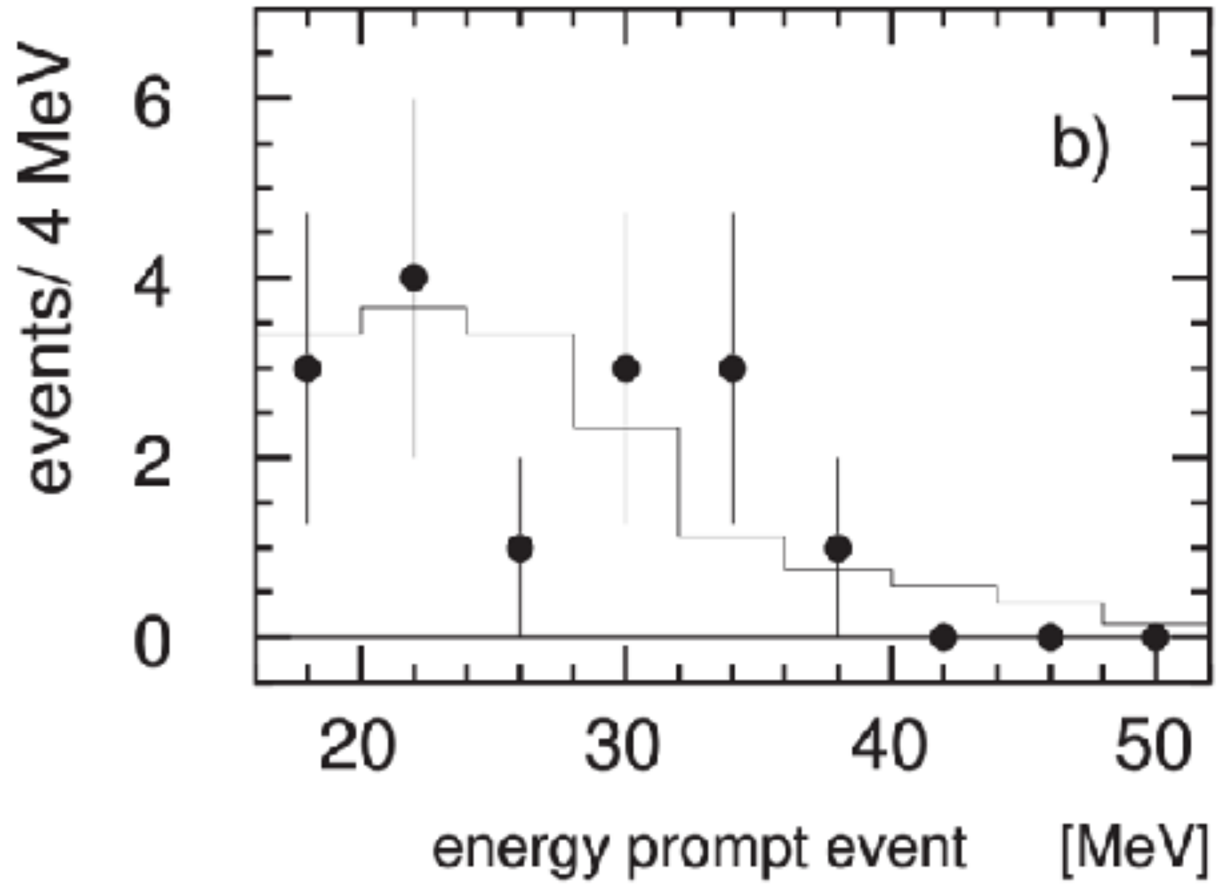
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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



KARMEN: 1990 - 2001 arXiv:020302

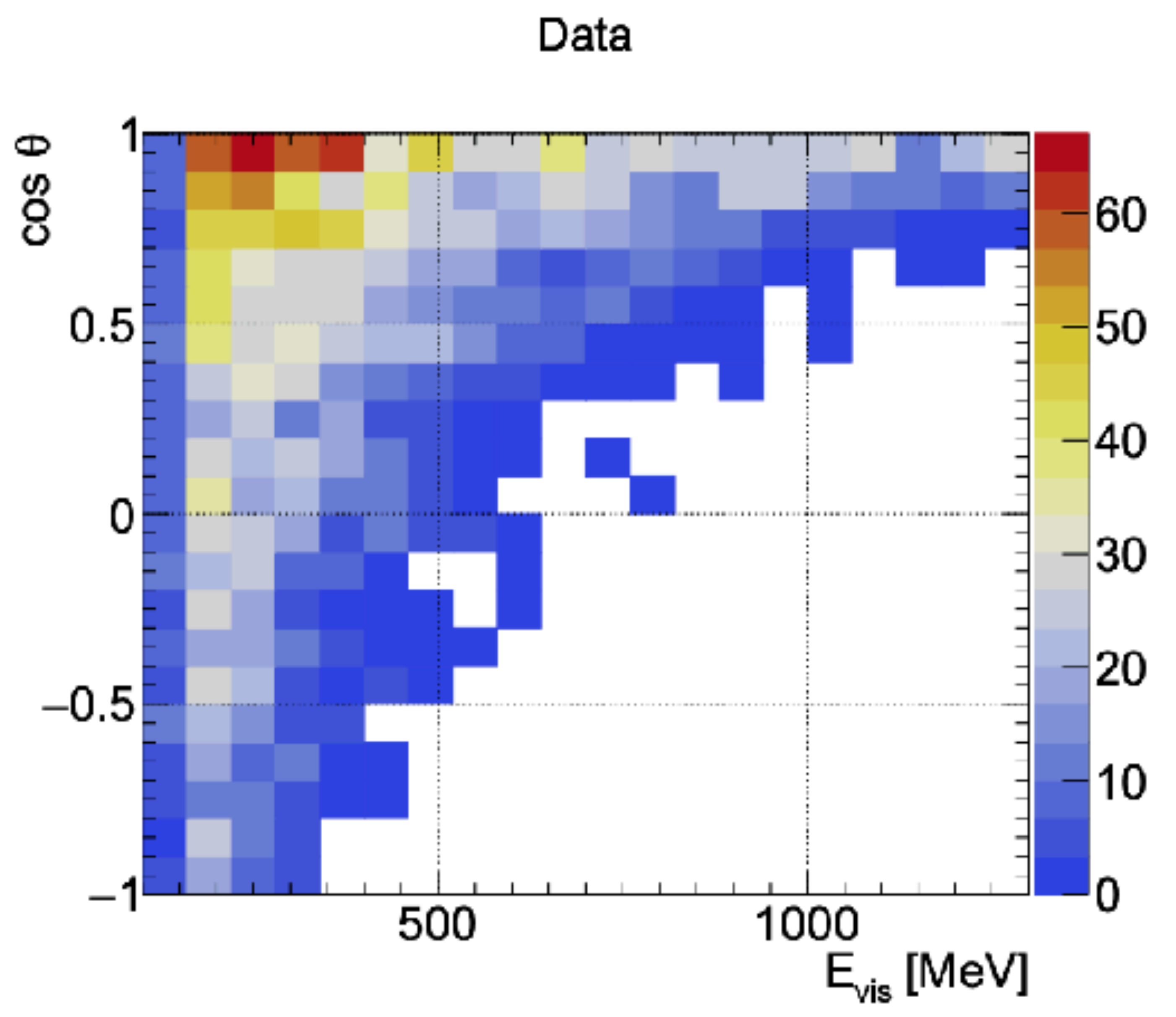
1) 800 MeV proton beam, 6e22 POT!
2) π decay at rest mostly. Detector 90º from p beam.
3) π- contamination: $\bar{\nu}_e/\bar{\nu}_\mu = 6.4 \cdot 10^{-4}$
4) Baseline of 17.7 m
5) ~57 tonnes of liquid scintillator
6) 3.5 m long det along nu beam.

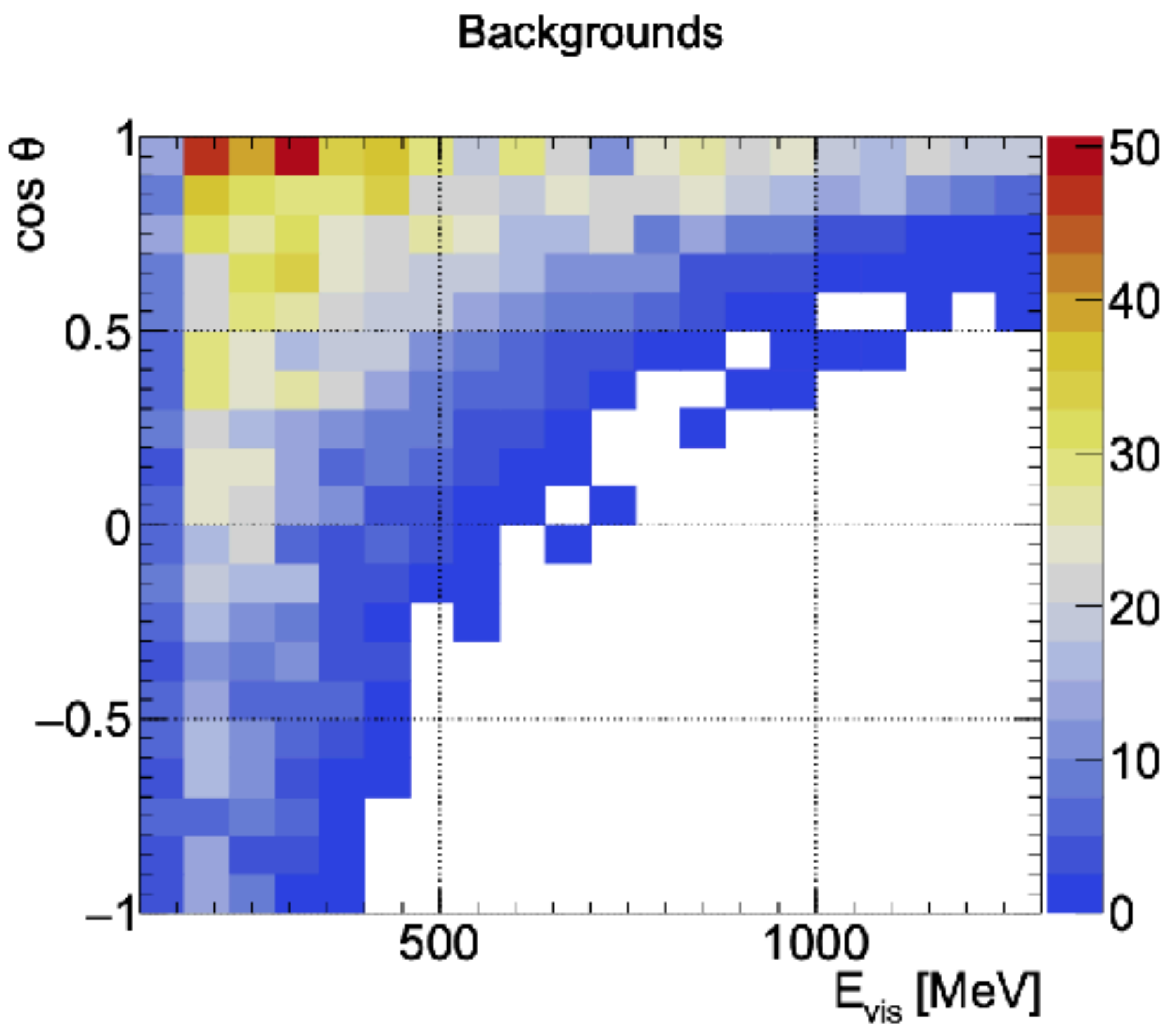


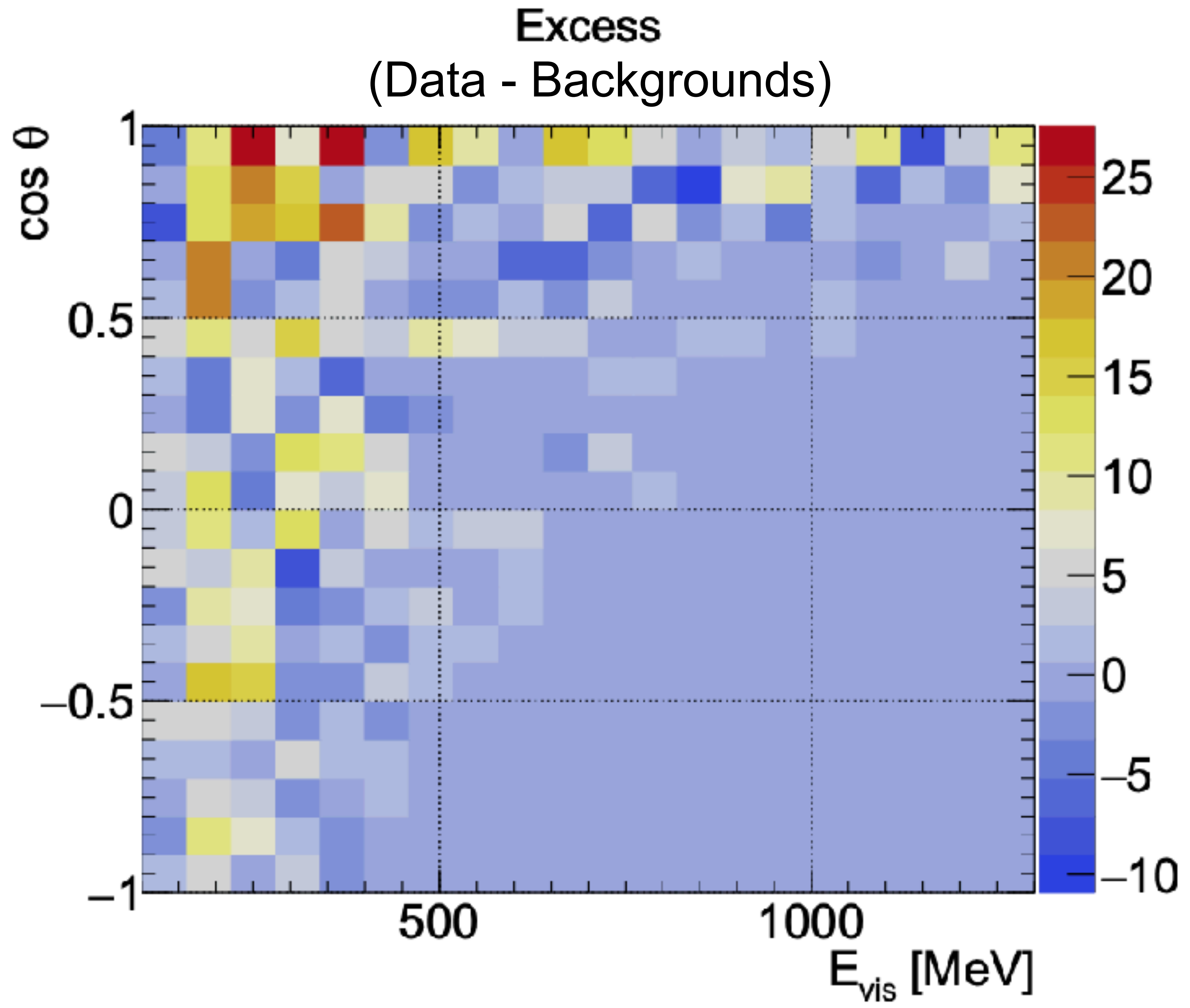
NO EXCESS

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

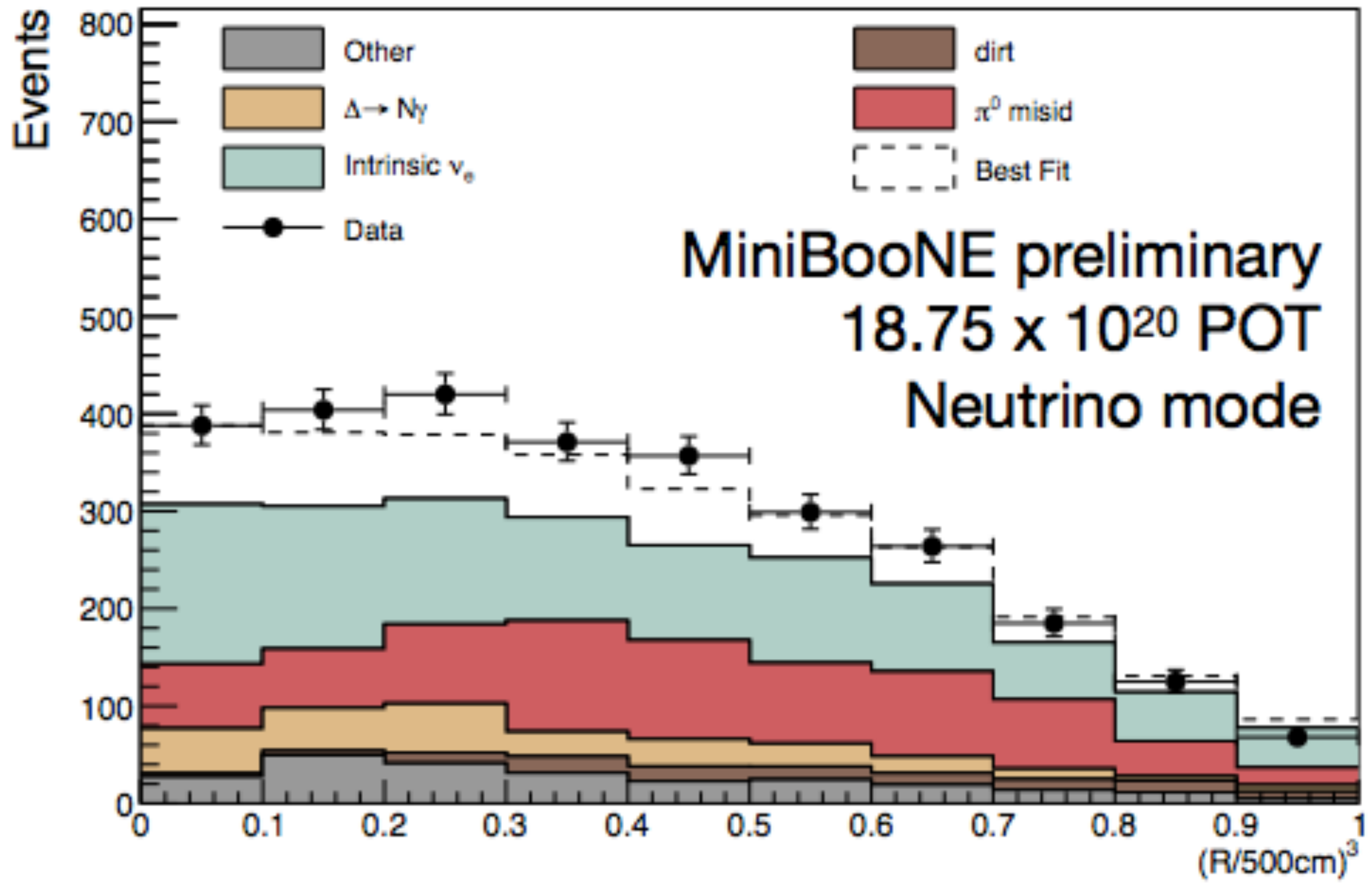
MiniBooNE data
2-D distributions



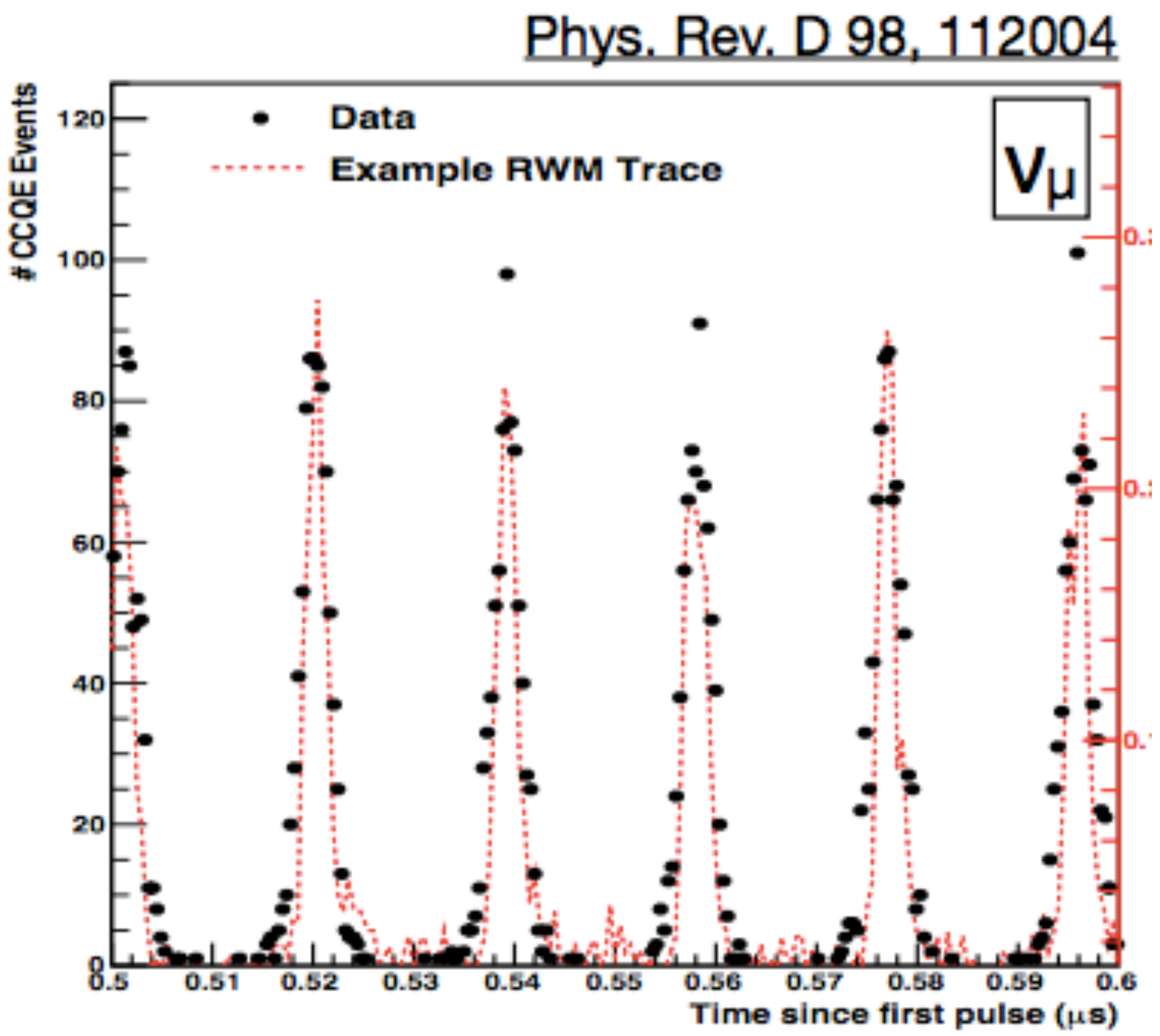


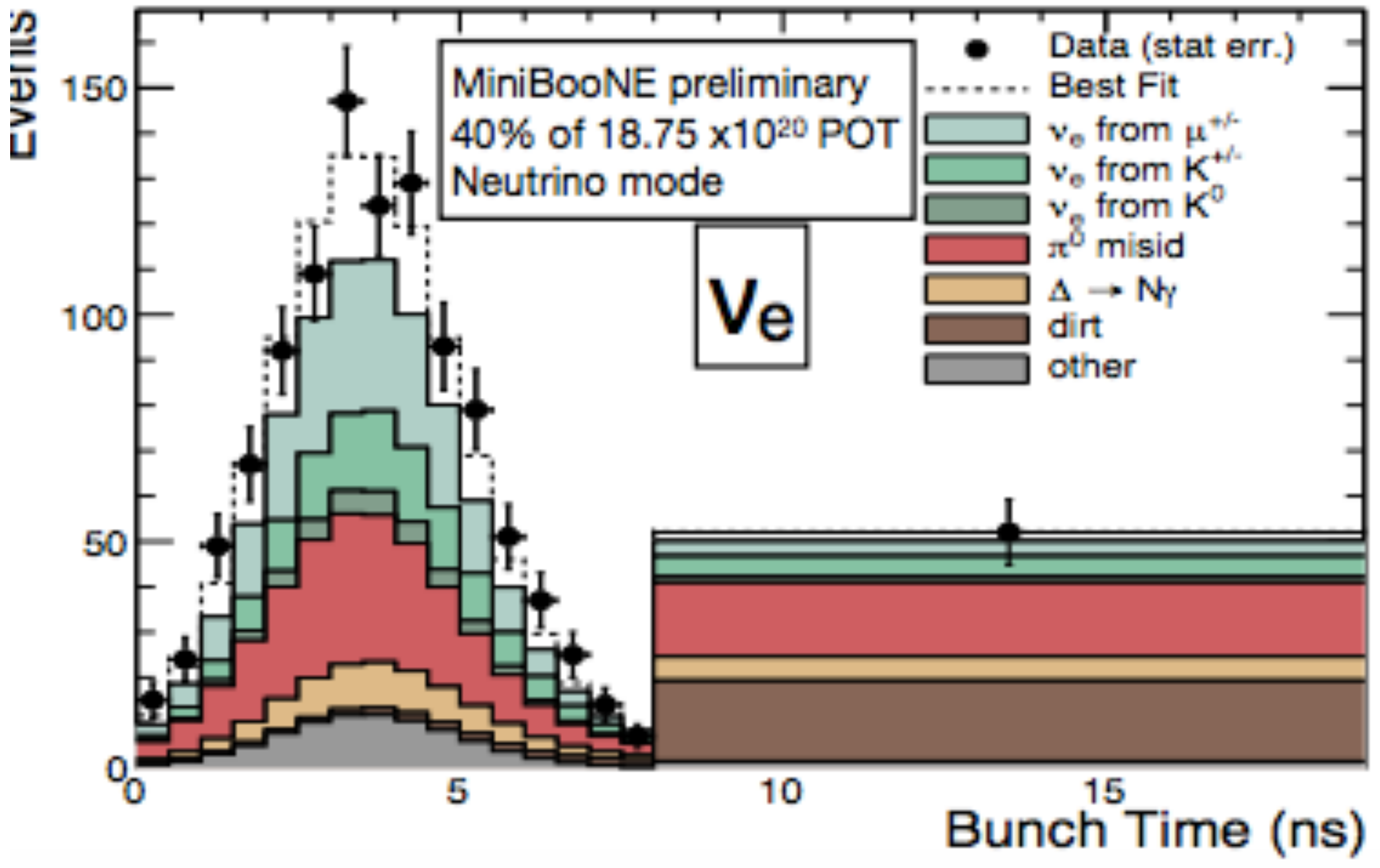


New distributions — Radius and Event Timing



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	$5.2\ \sigma$





Excess in Invariant Mass, assuming 2 showers

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

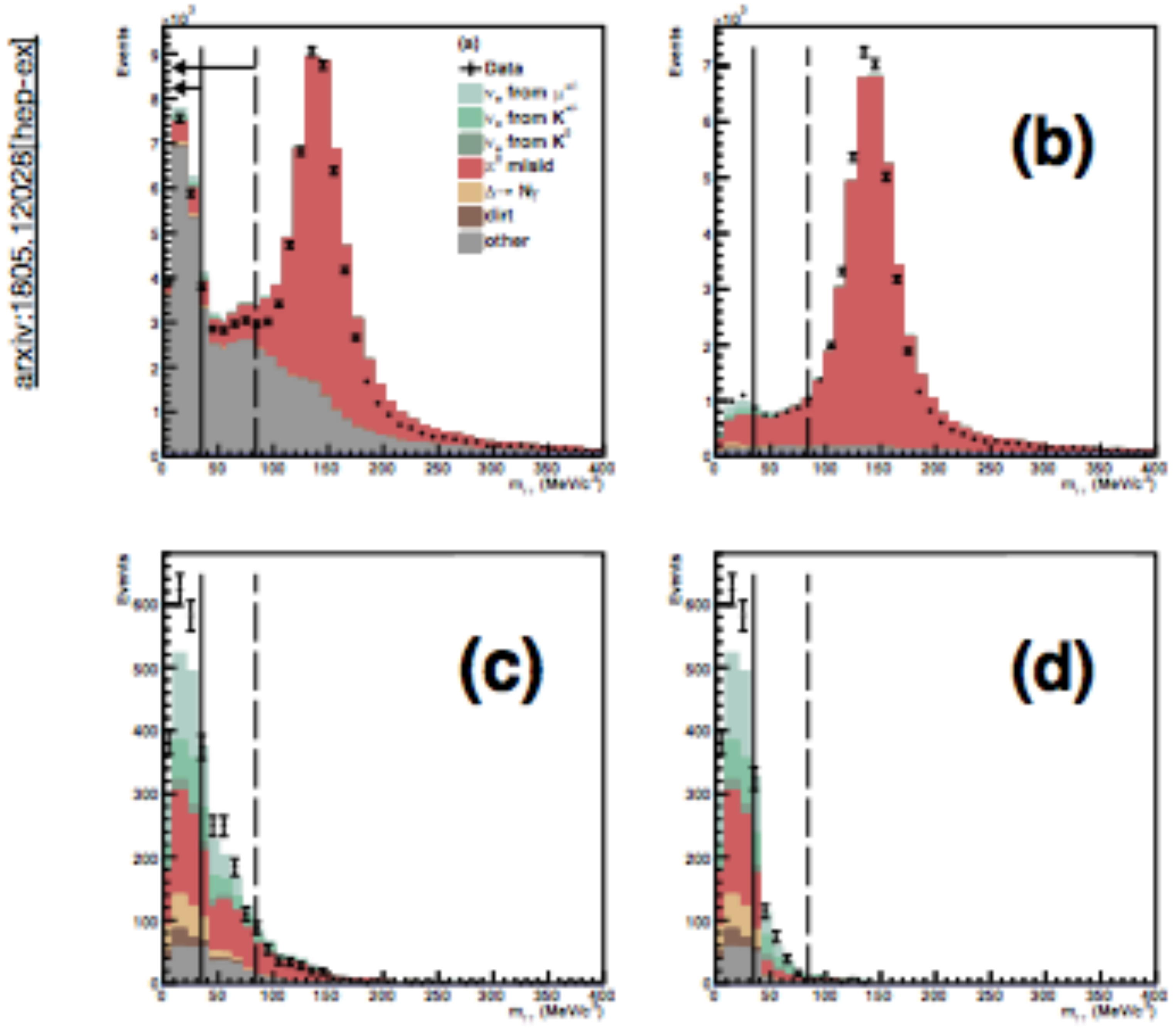
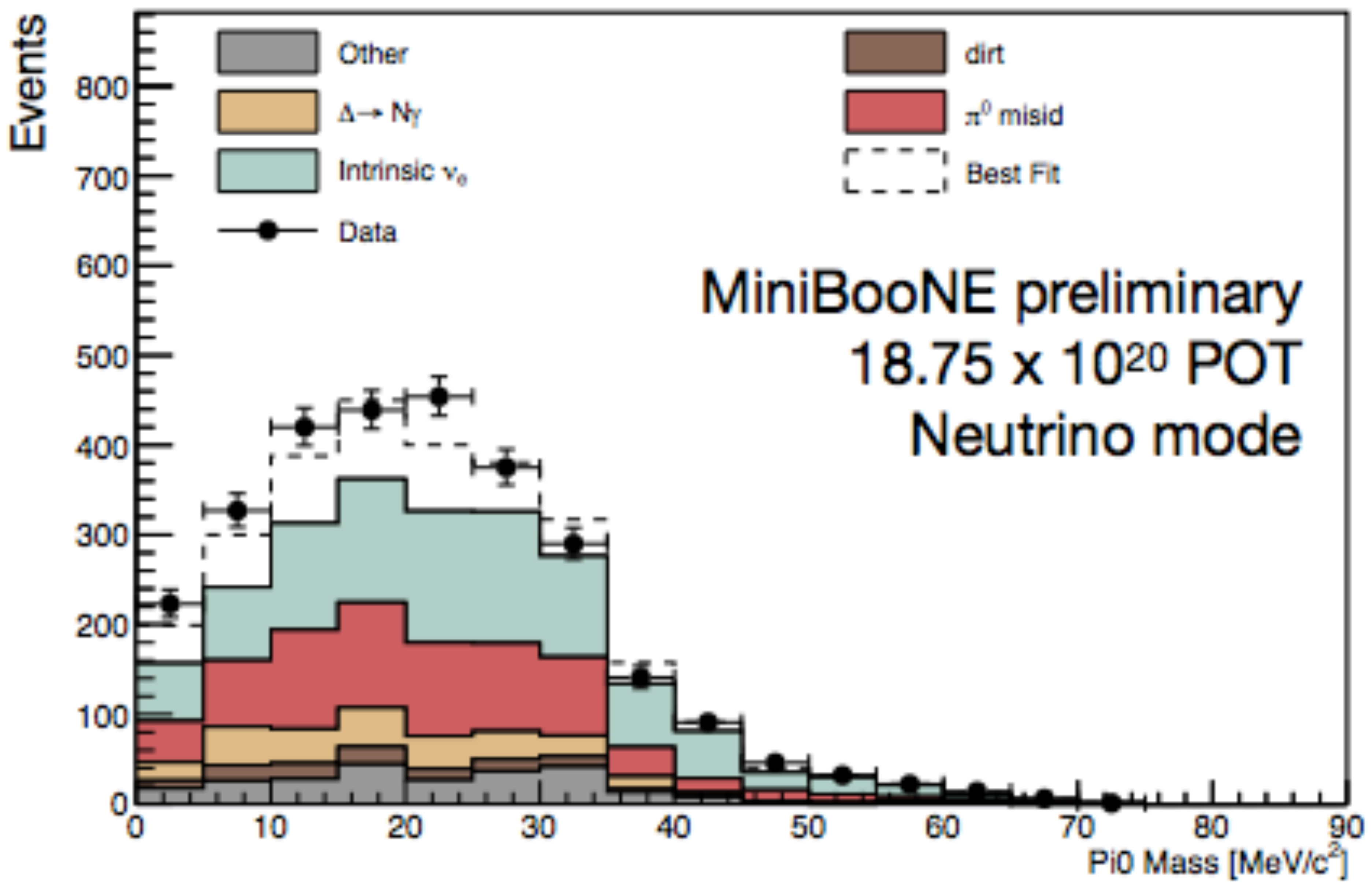
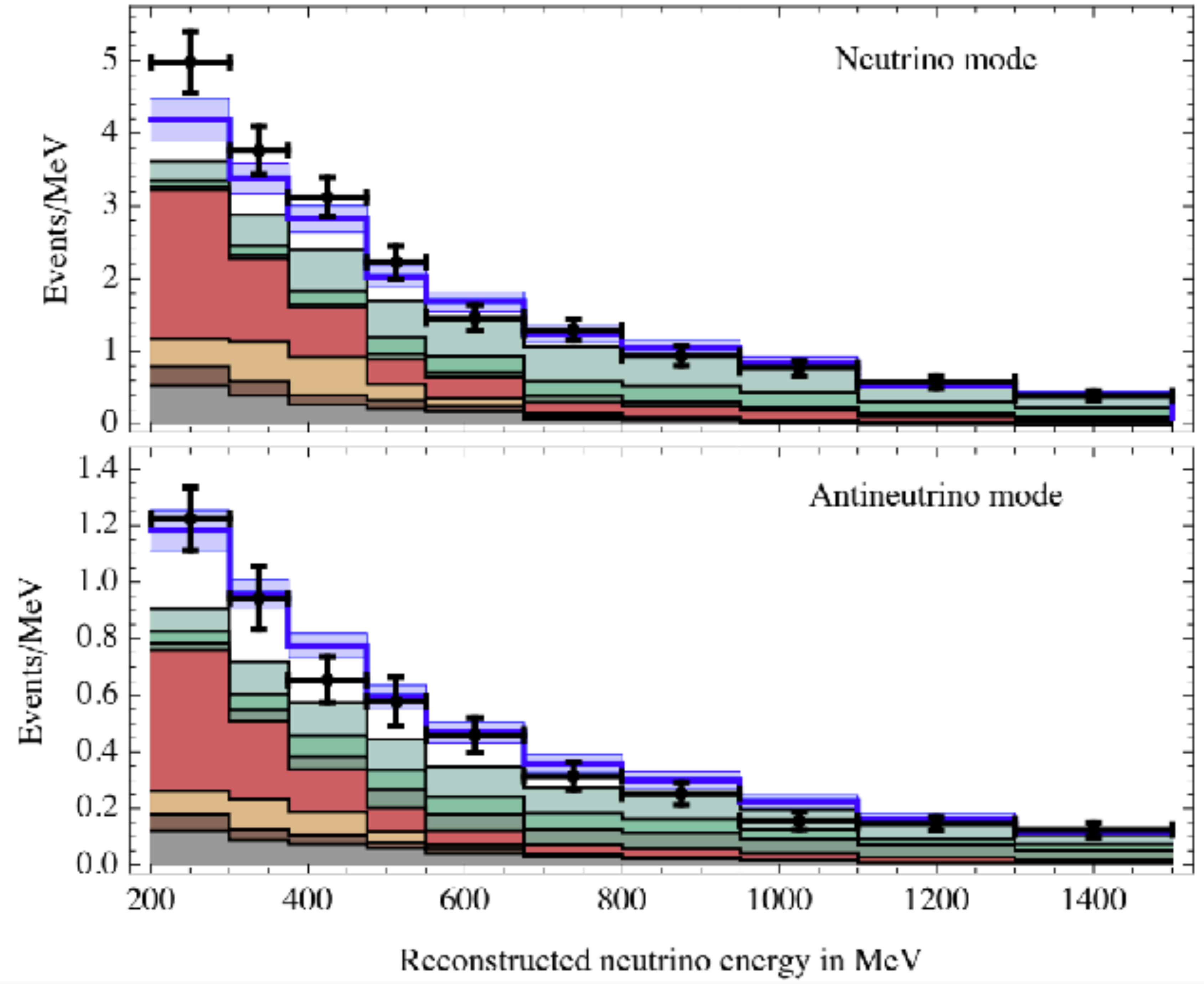


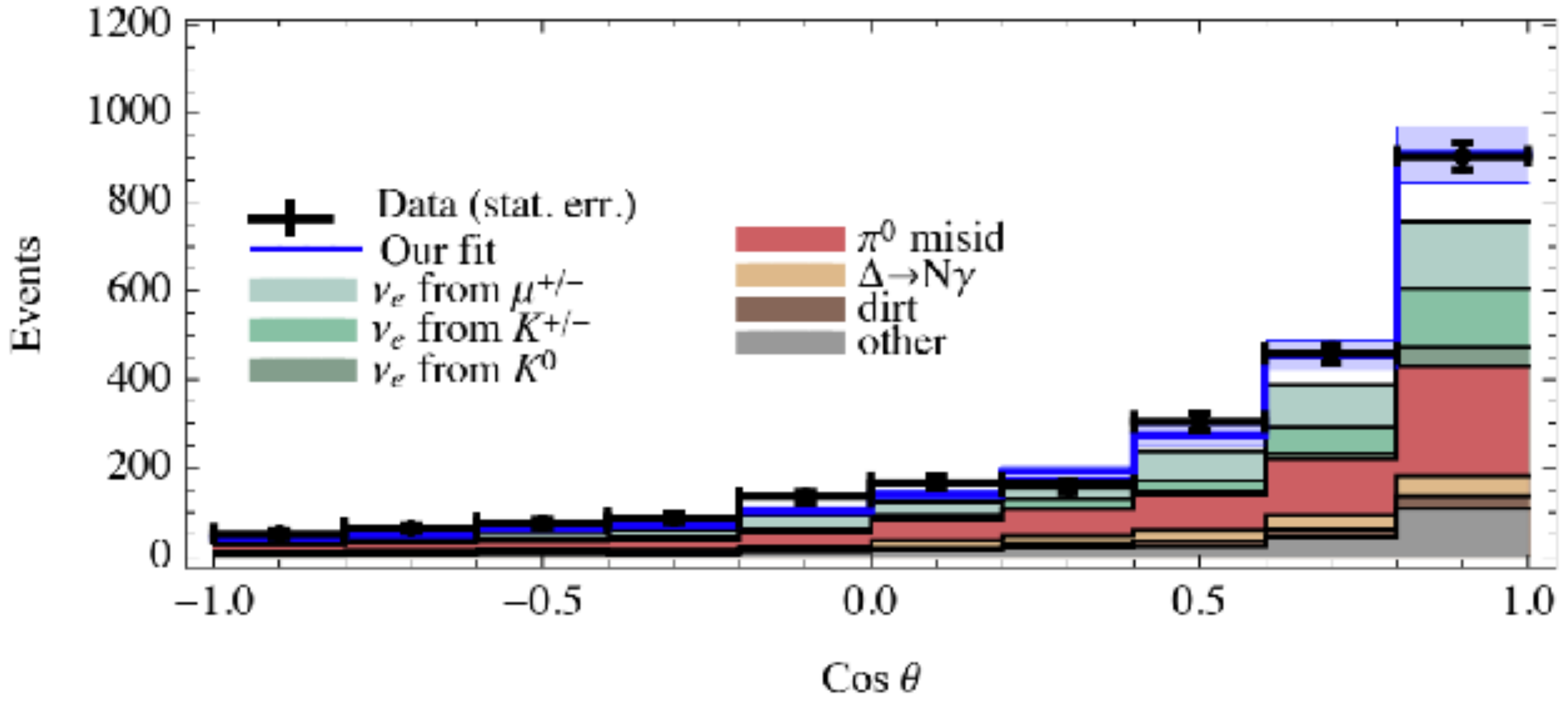
FIG. 11: Comparisons between the data and simulation for the gamma-gamma mass distribution after successive cuts are applied: (a) no PID cut, (b) electron-muon likelihood cut, (c) electron-muon plus electron-pion likelihood cuts, and (d) electron-muon plus electron pion likelihood cuts plus a gamma-gamma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

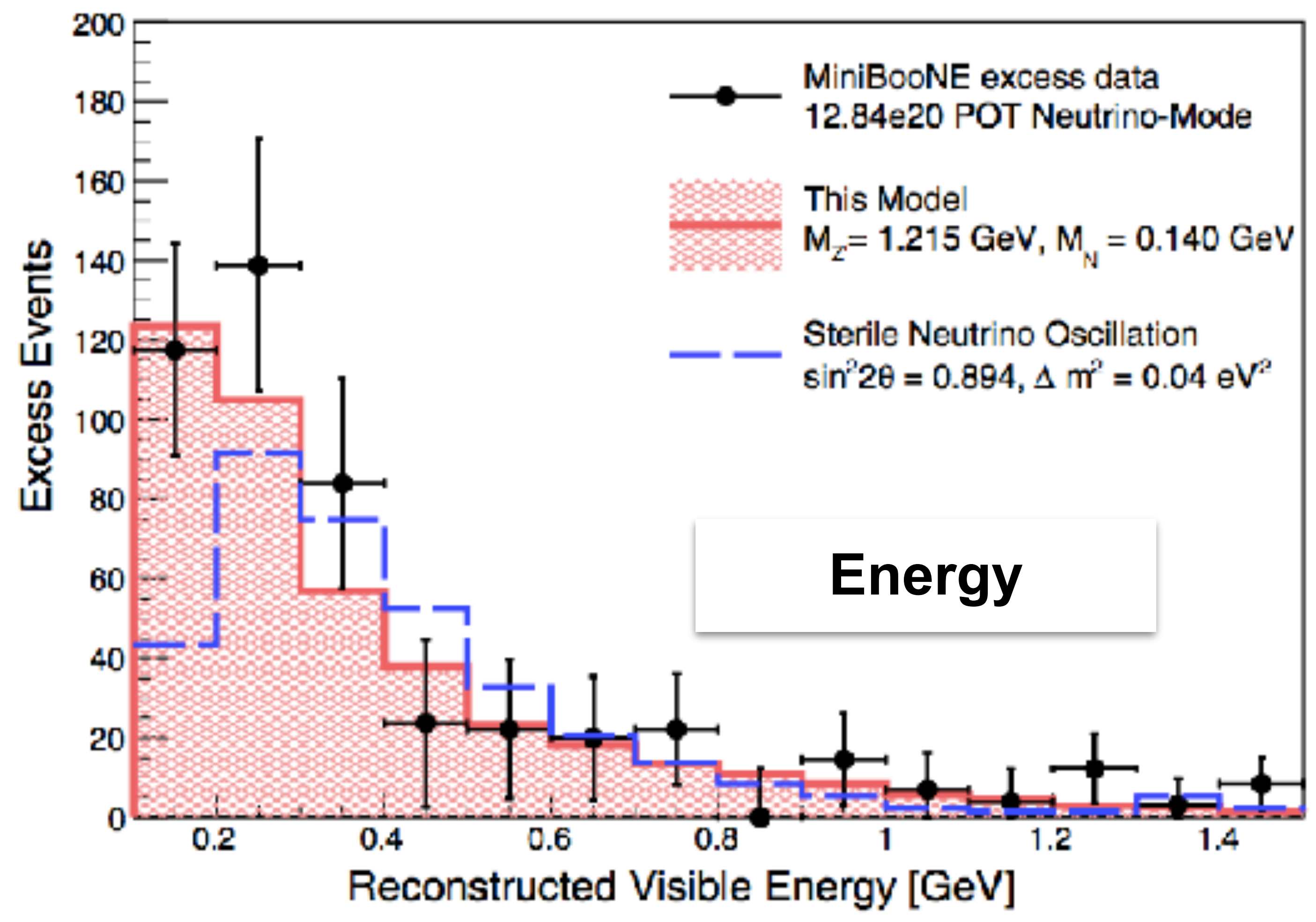


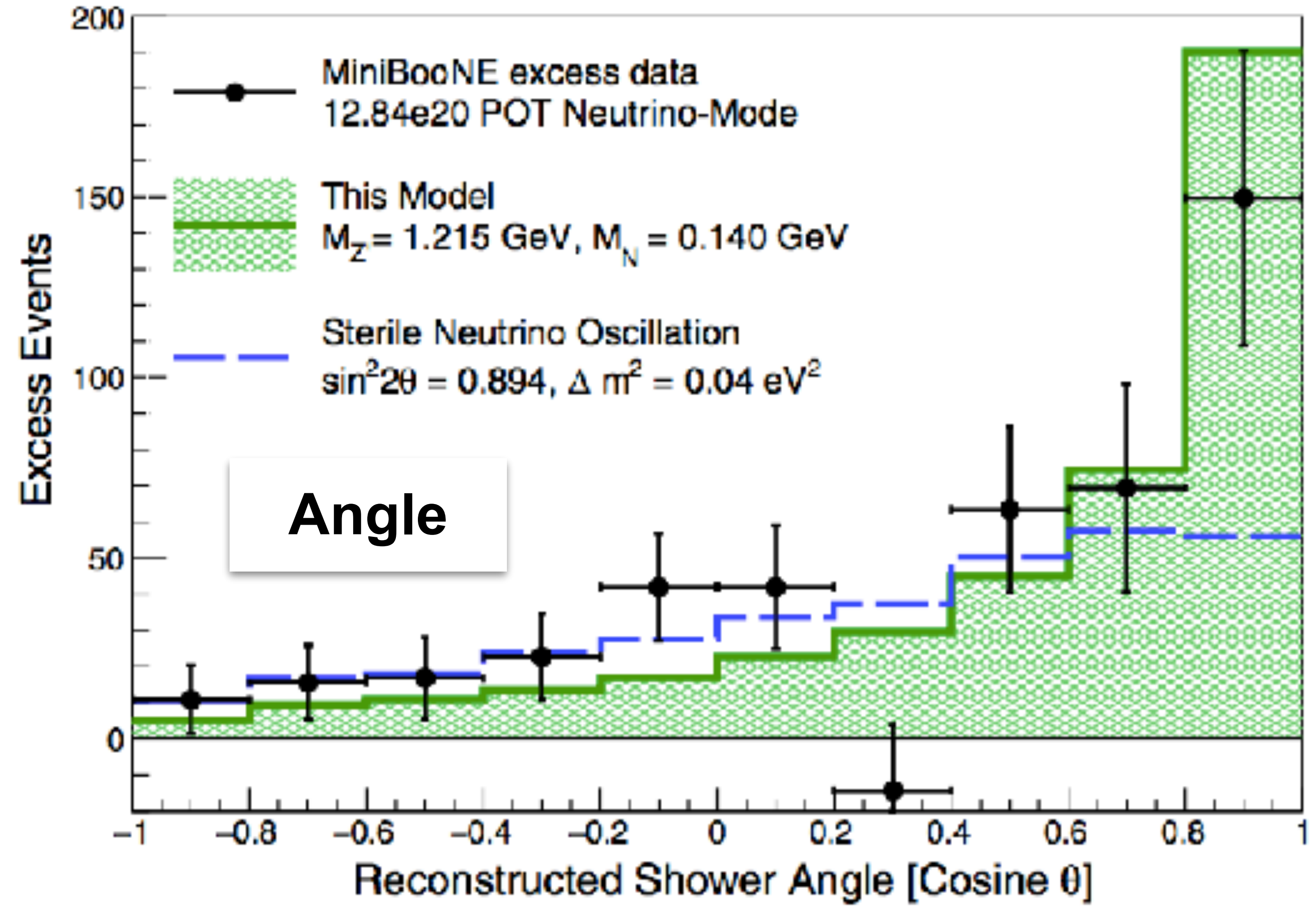
All Distributions

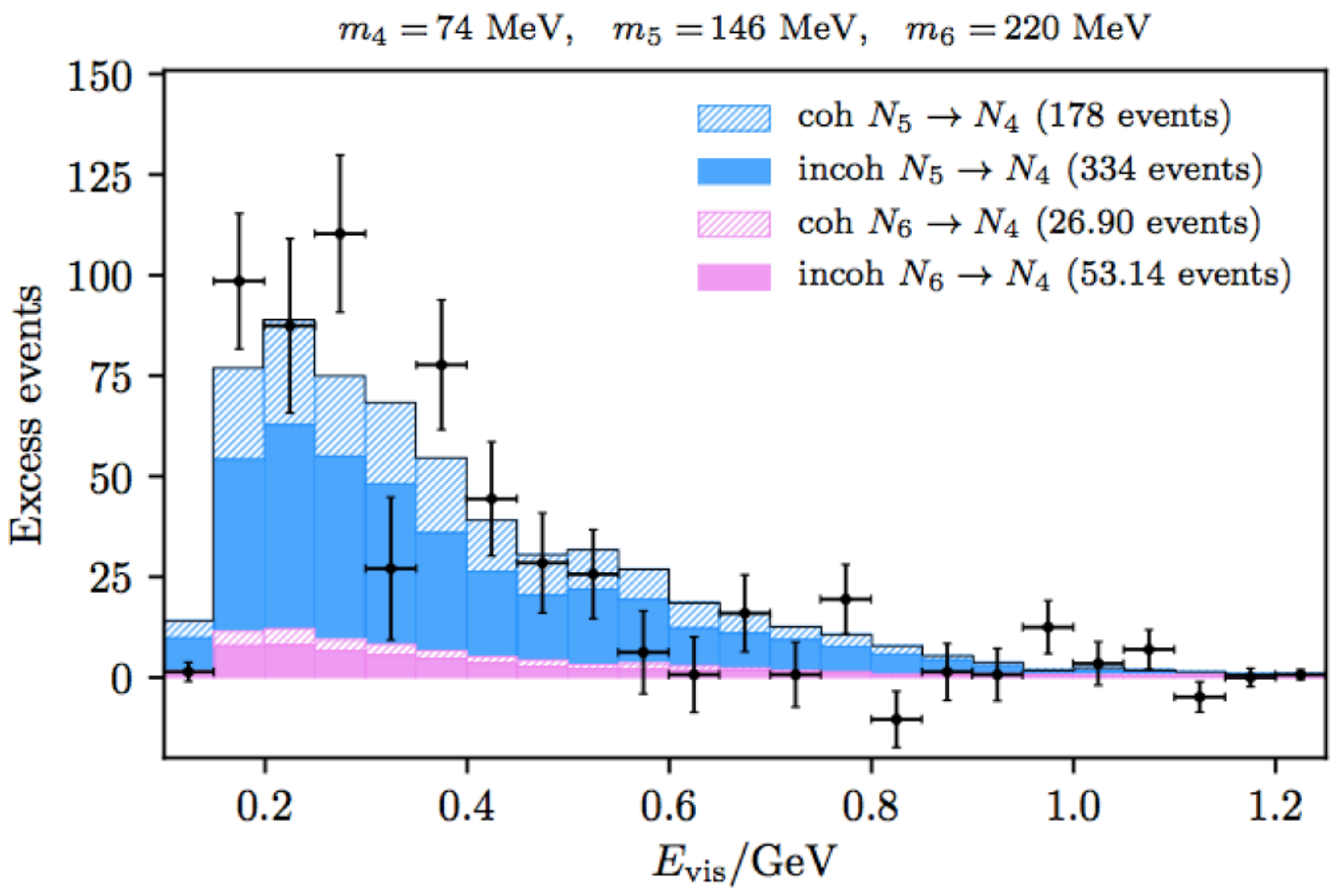
No nuclear effects. :(

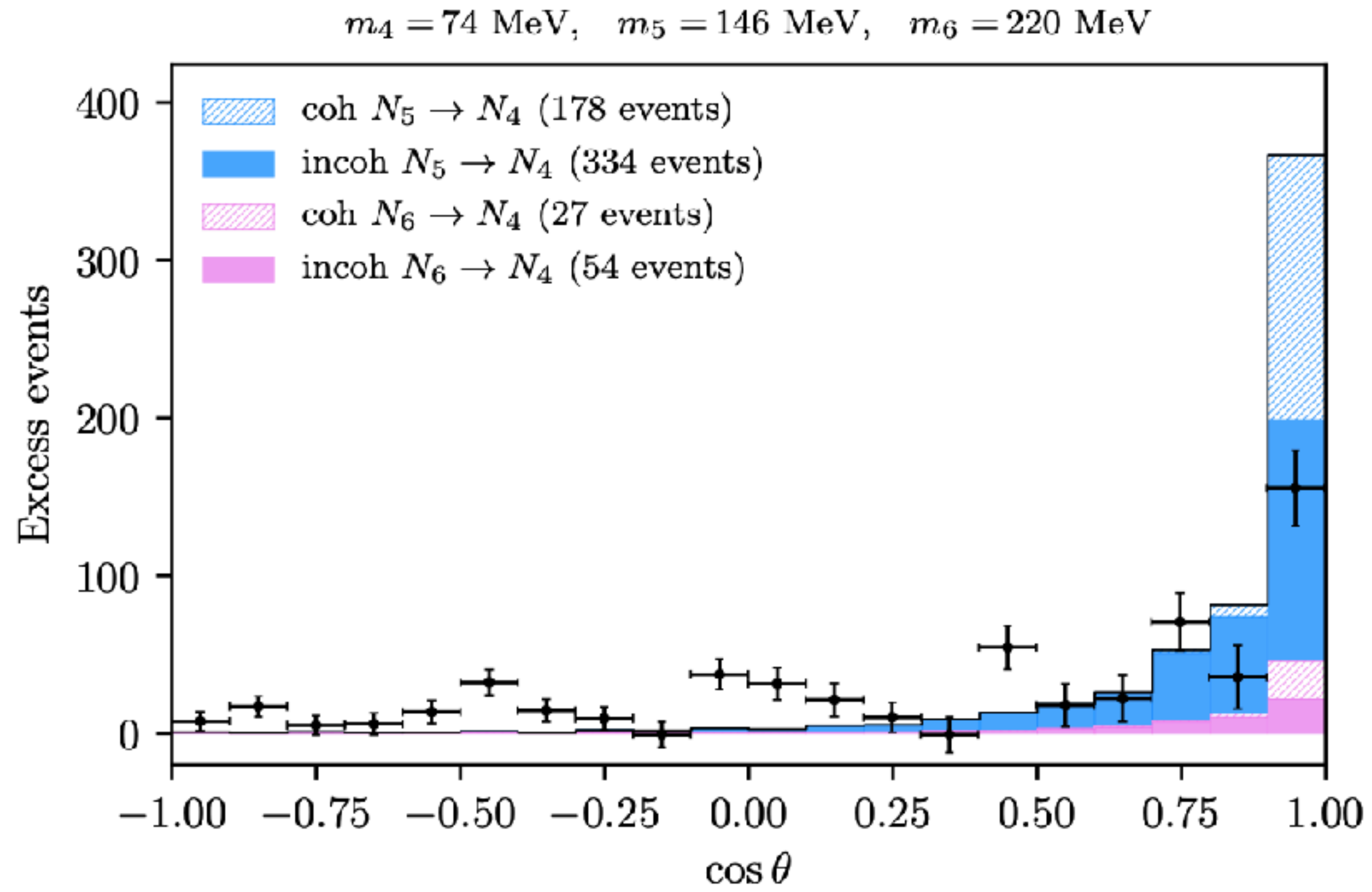












On-shell Z'

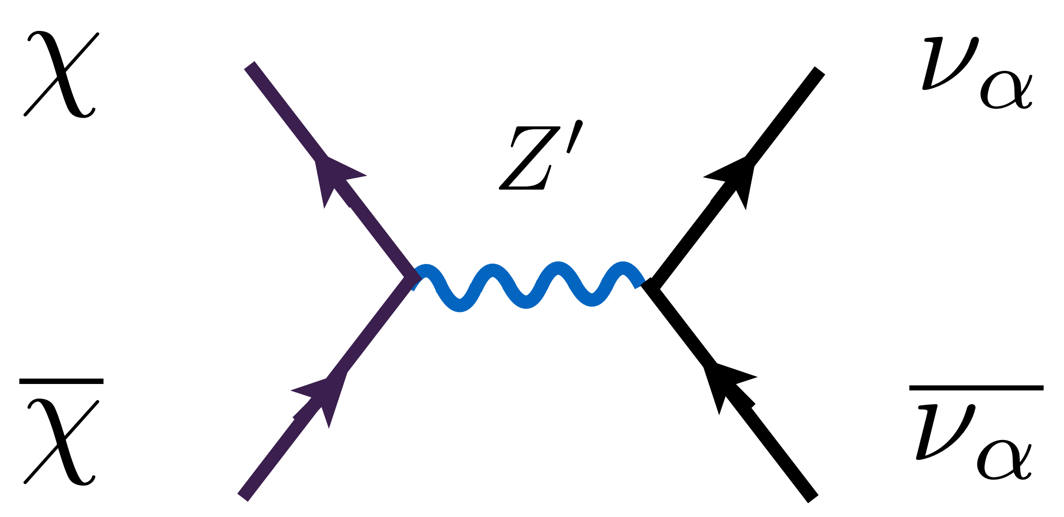
Off-shell Z' (Z-Z' interference)

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

Neutrino portal DM — growing literature, see, *e.g.*,

B. Bertoni et al, 1412.3113
B. Batell et al, 1709.07001
M. Blennow et al, 1903.00006

$$\langle \sigma v_r \rangle \approx \frac{g'}{8\pi} |U_{\alpha 4}|^4 \frac{m_\chi^2}{\left(4m_\chi^2 - m_{Z'}^2\right)^2}$$



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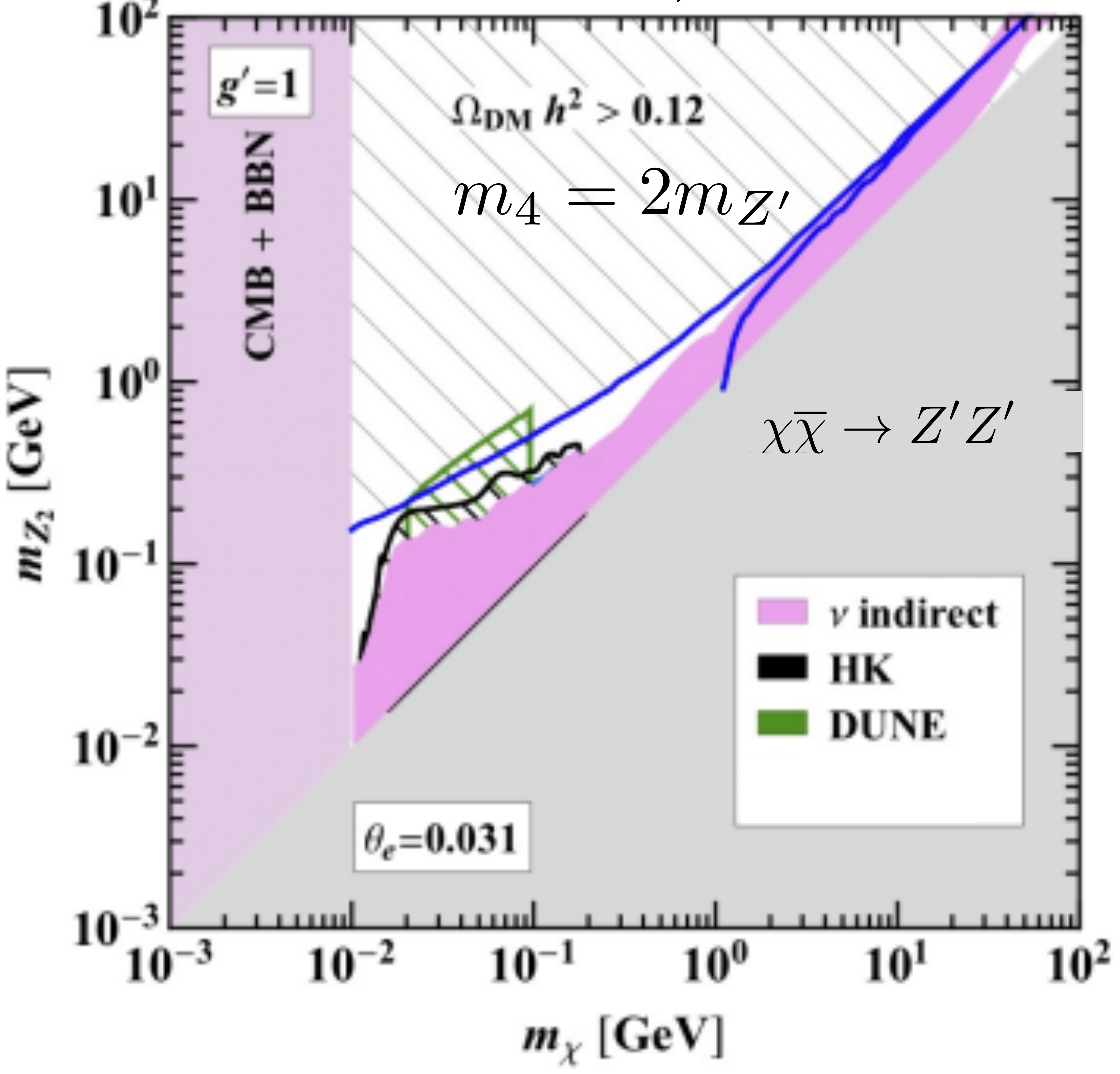
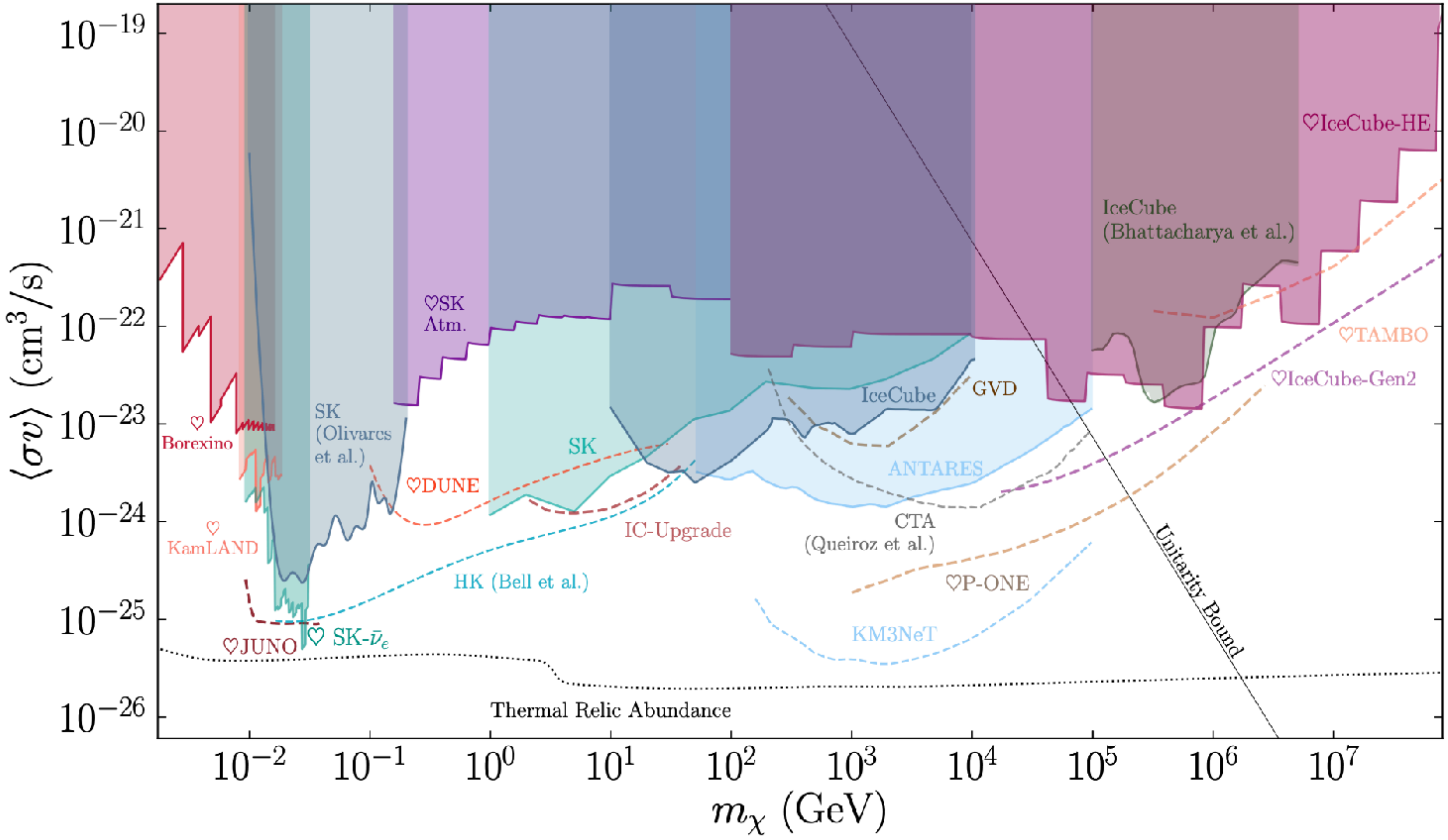


Monochromatic neutrinos from the Galaxy!

Can be searched for in large volume detectors.

Arguelles et al, 1912.09486

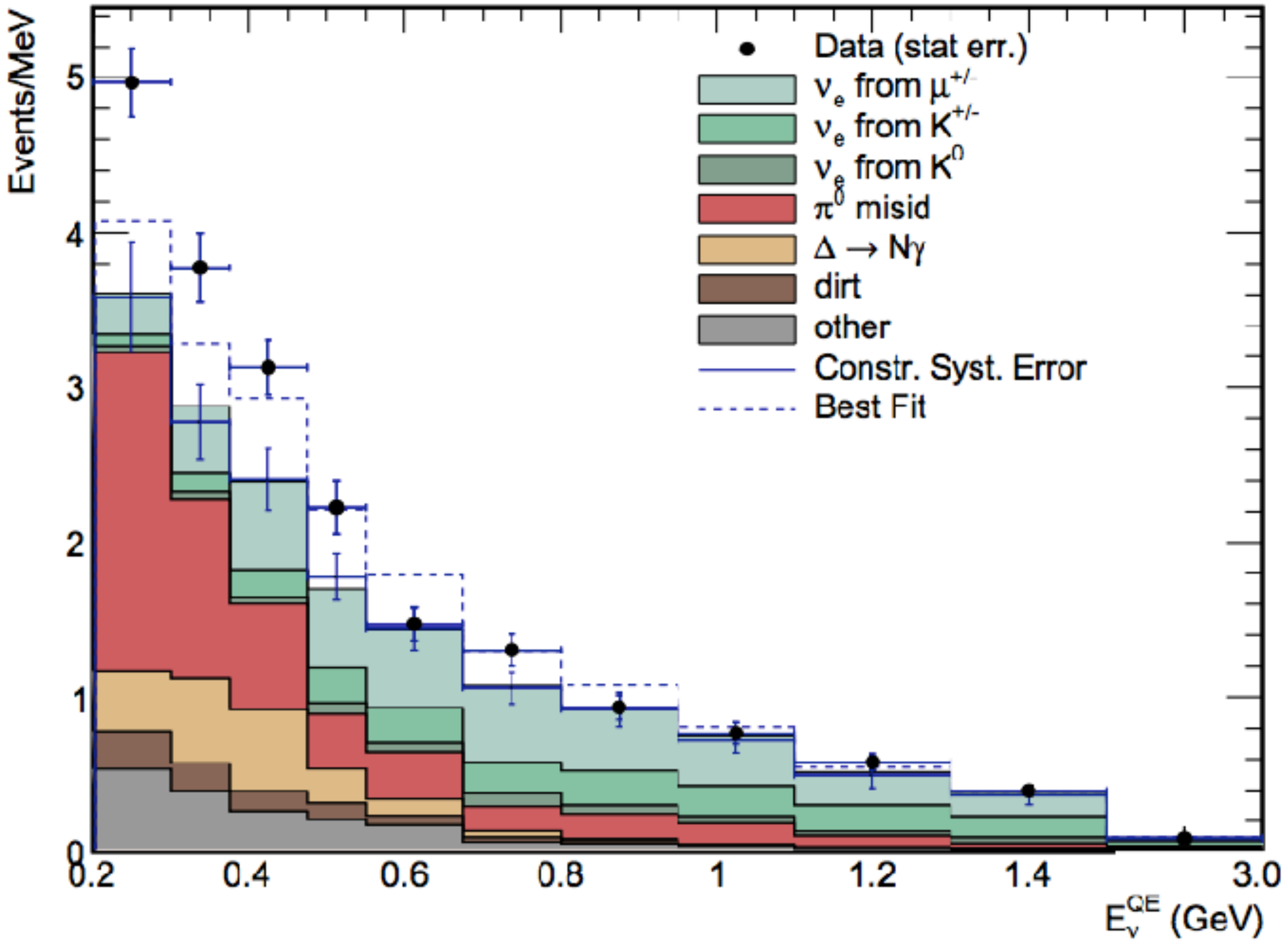


SM Backgrounds at MiniBooNE

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 $\Delta \rightarrow N\gamma$	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

misID backgrounds

intrinsic background



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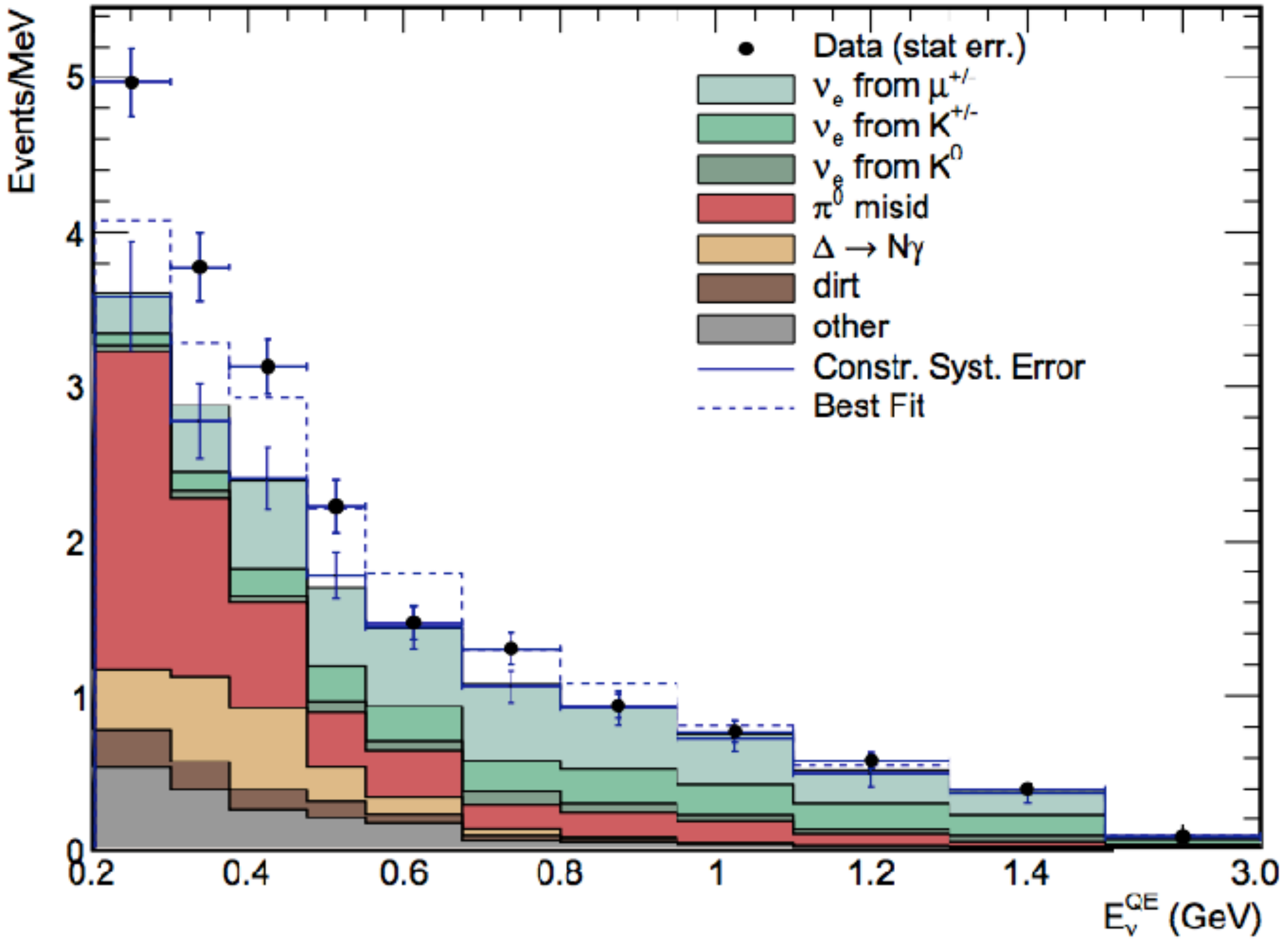

Can populate lower energies, but always get

$$\mu^+ \rightarrow e^+ \overline{\nu_\mu} \nu_e$$

So can constrain by measuring ν_μ

Very large statistics!
Can effectively constrains parent particle spectrum
(essentially a neutrino flux measurement)

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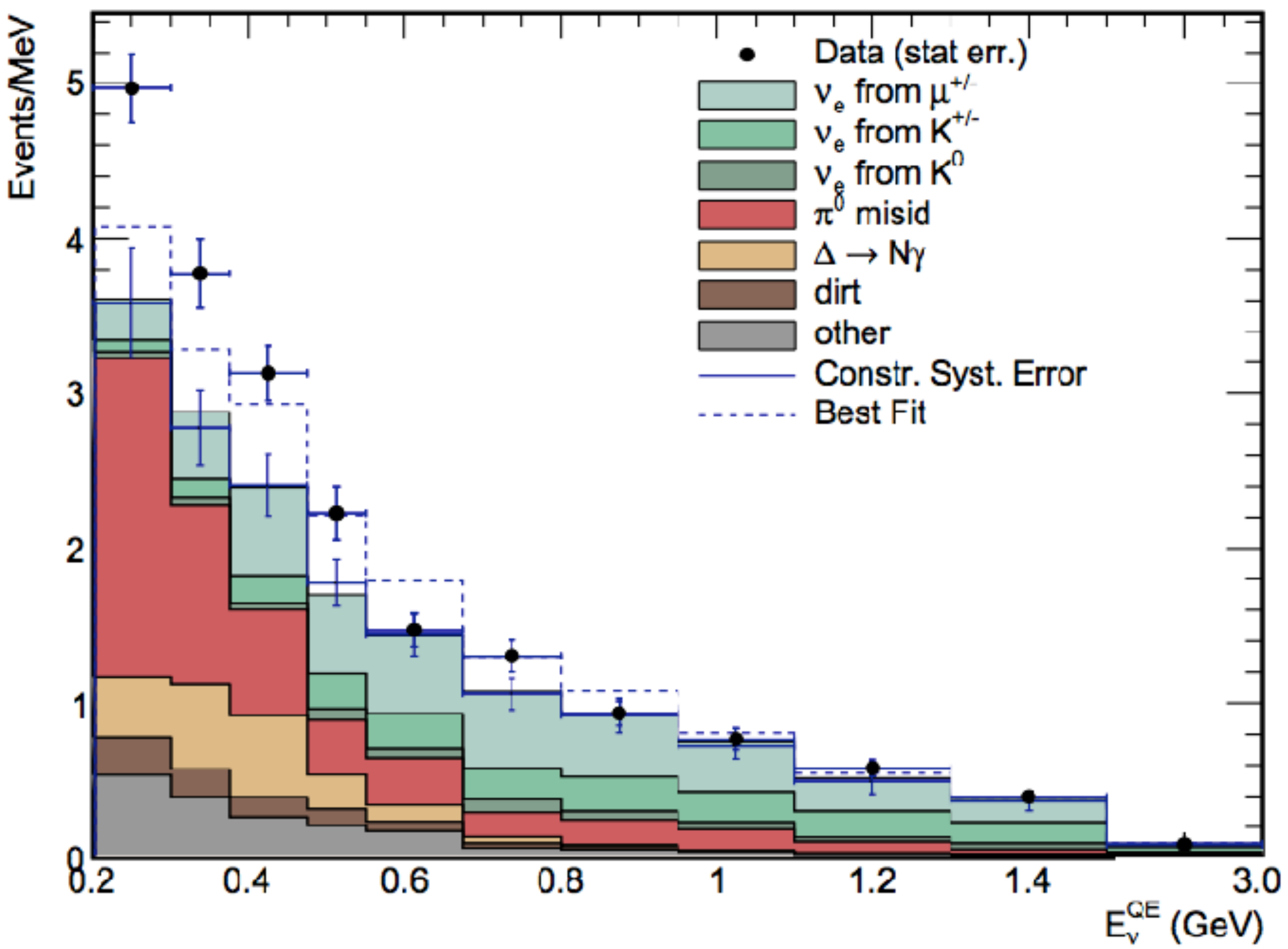
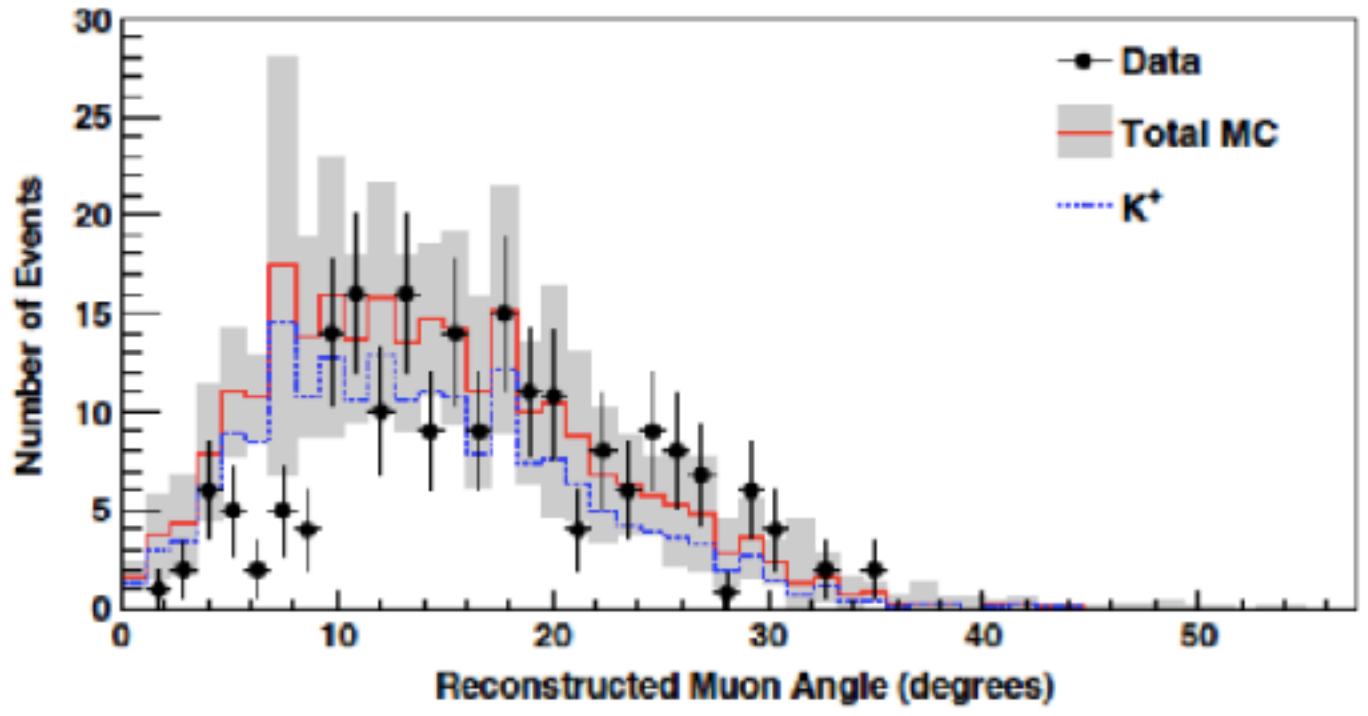
Dominant flux component above 2 GeV
&
constrained by a *SciBooNE*
("near detector" of MiniBooNE @ 100 m)





(c) 3-Track Sample

Analysis benefits from 3 track events (~CC1pi) that are more common at higher E.

SciBooNE collaboration, 1105.2871

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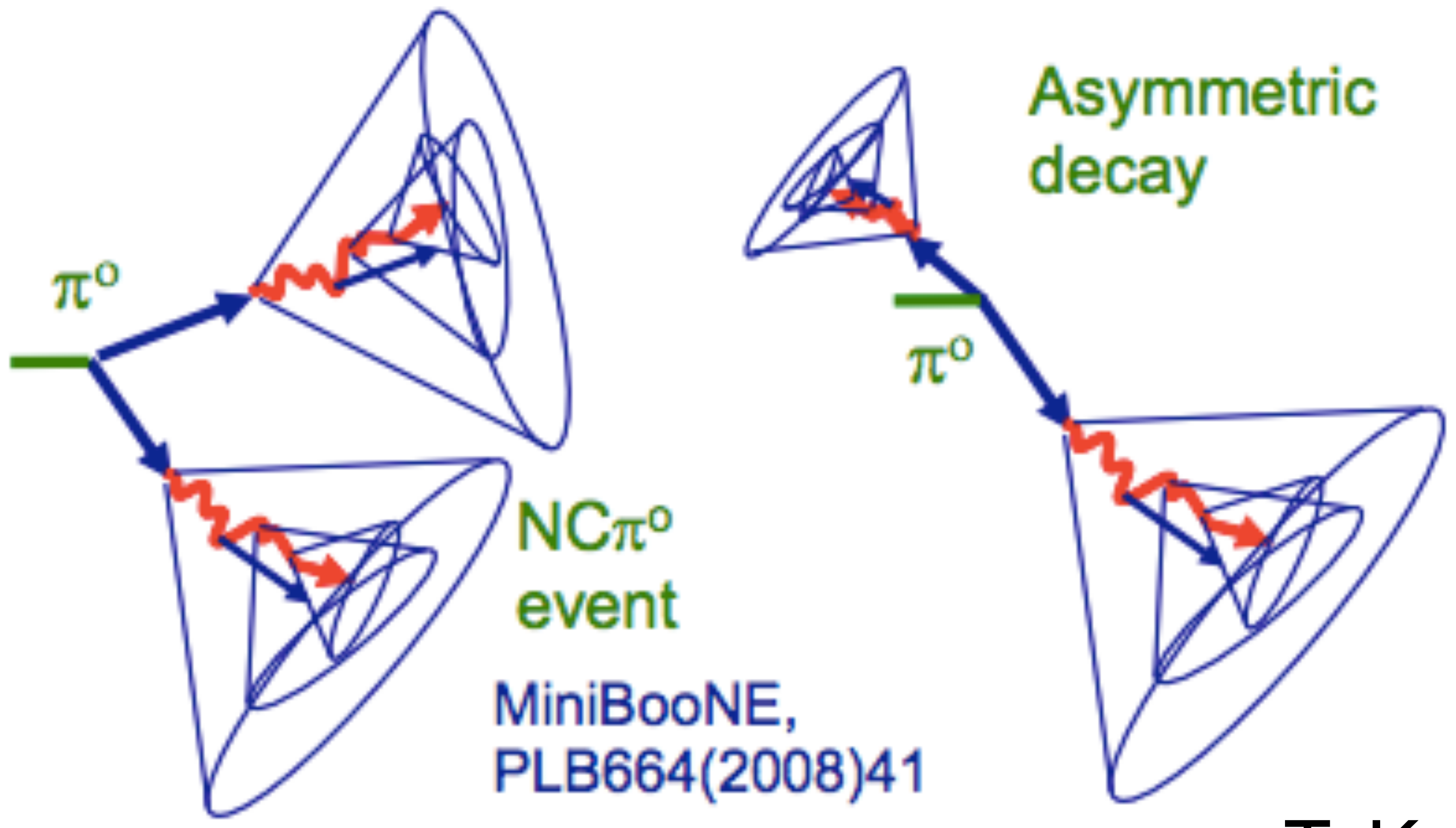
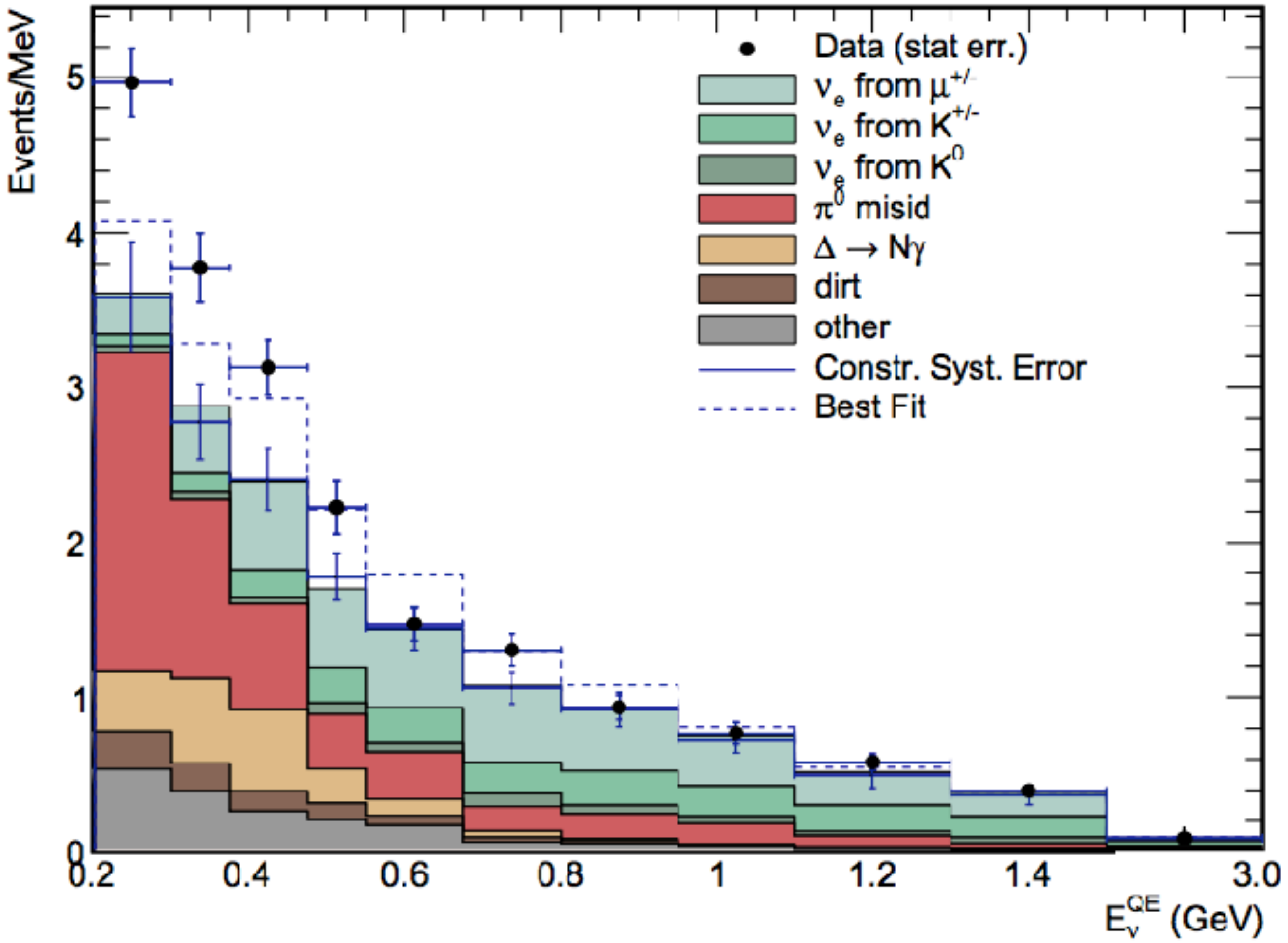
This channel relies on pion decay being highly asymmetric

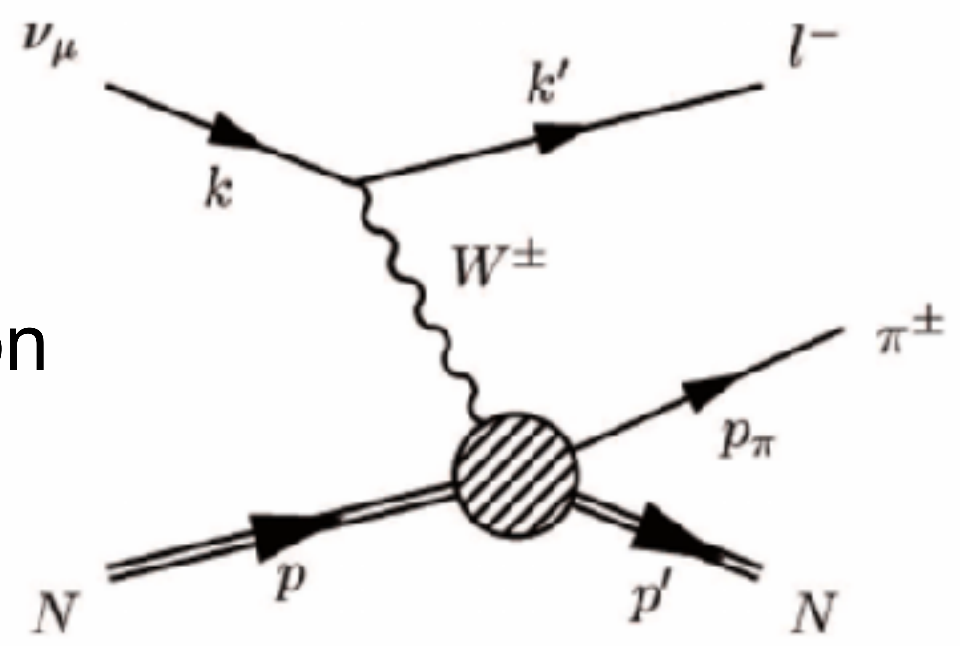


T. Katori



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

CC/NC pion production



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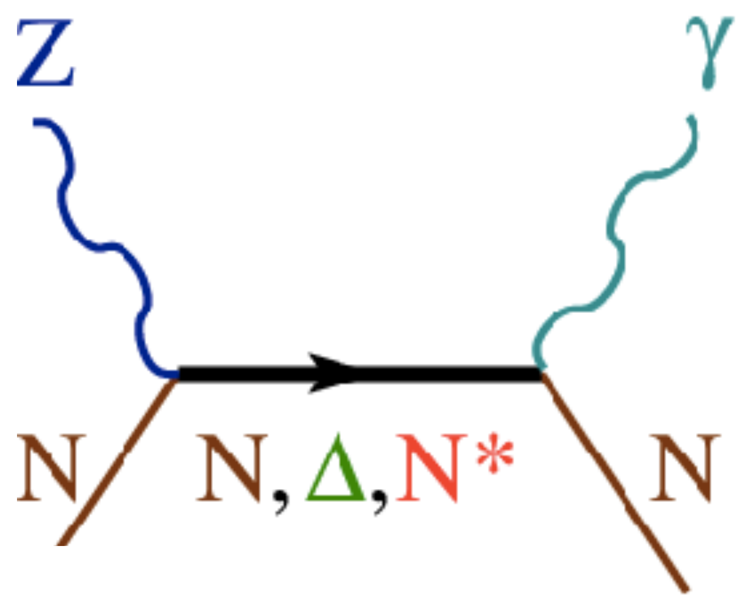
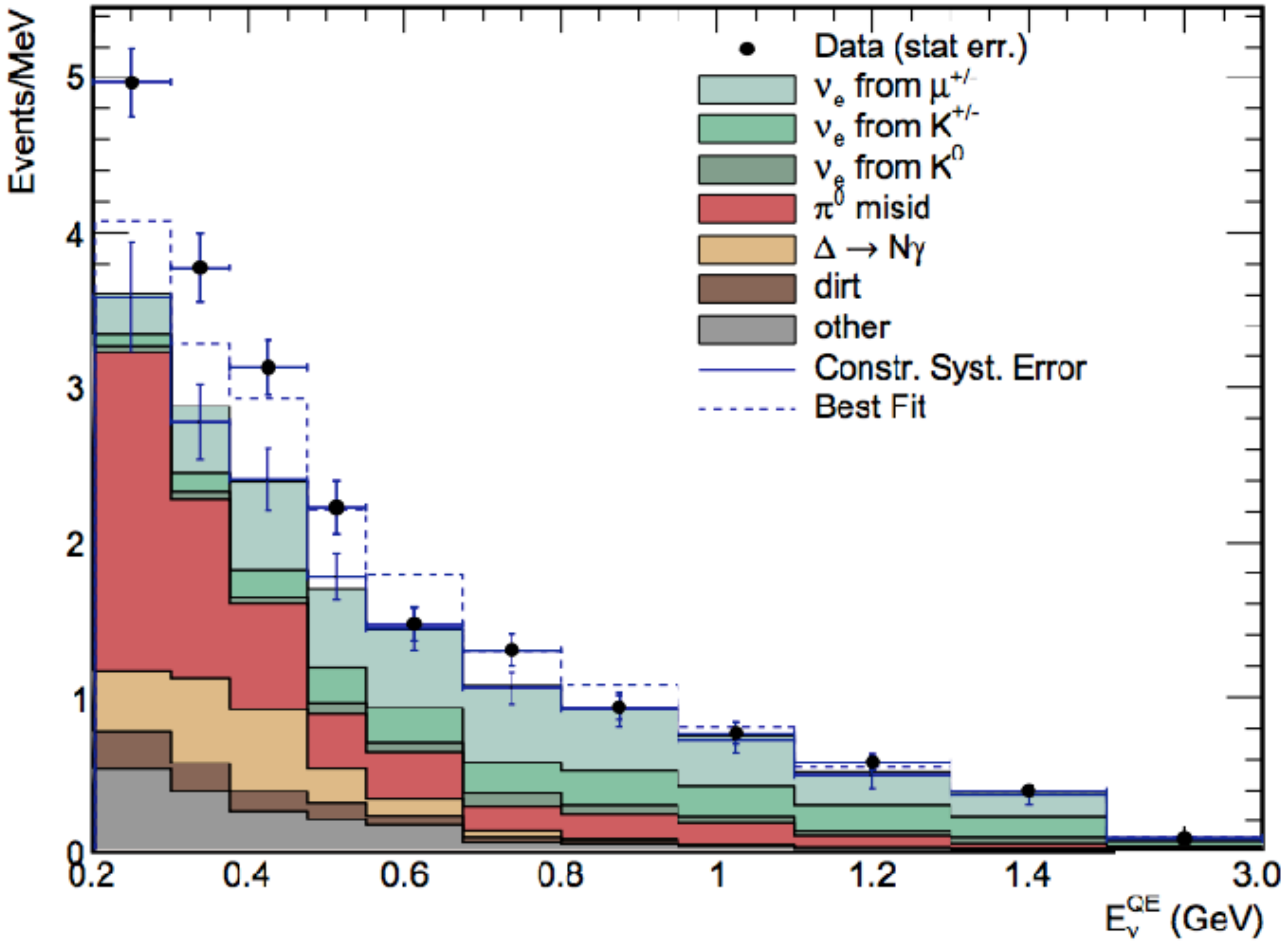
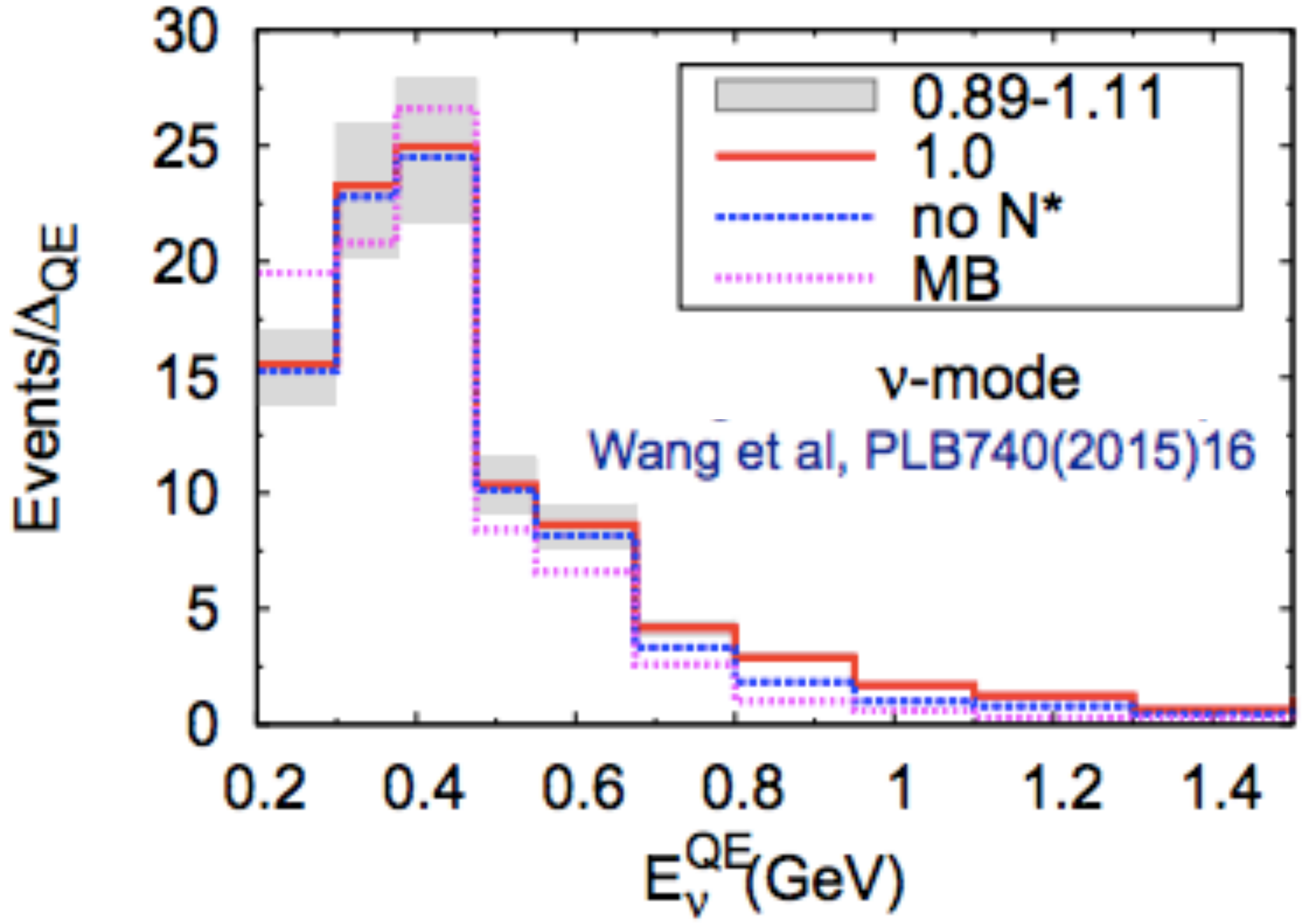
Mostly NC resonant through Delta(1232)

Constrained by pi events



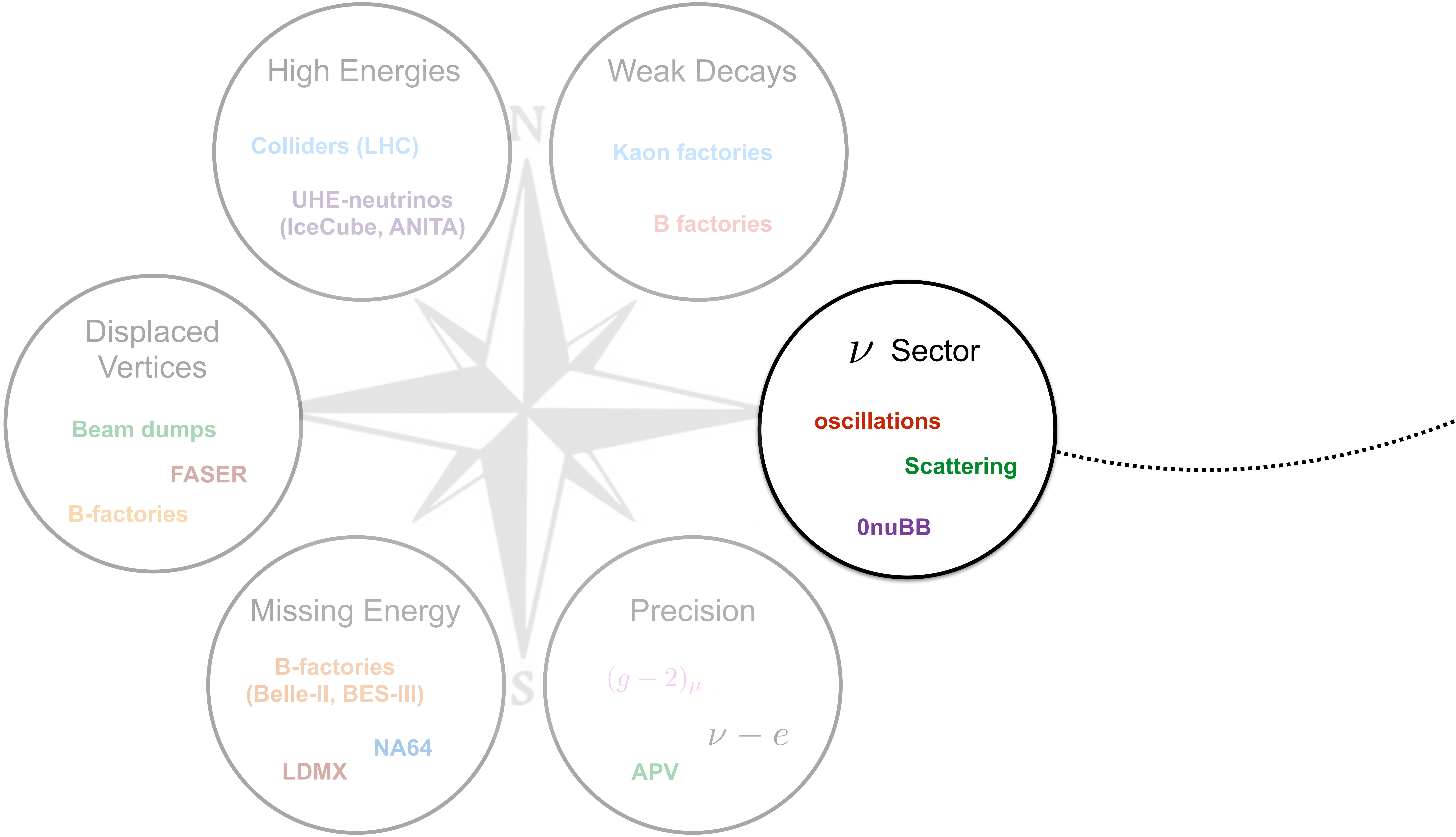




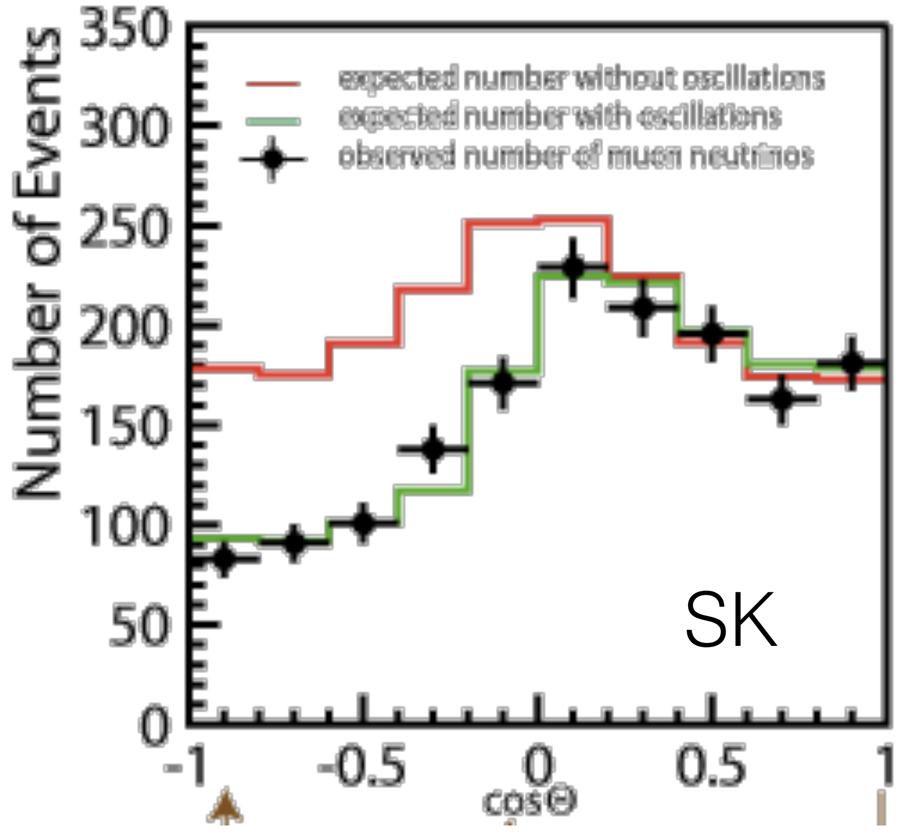
Coherent contribution shown to be small

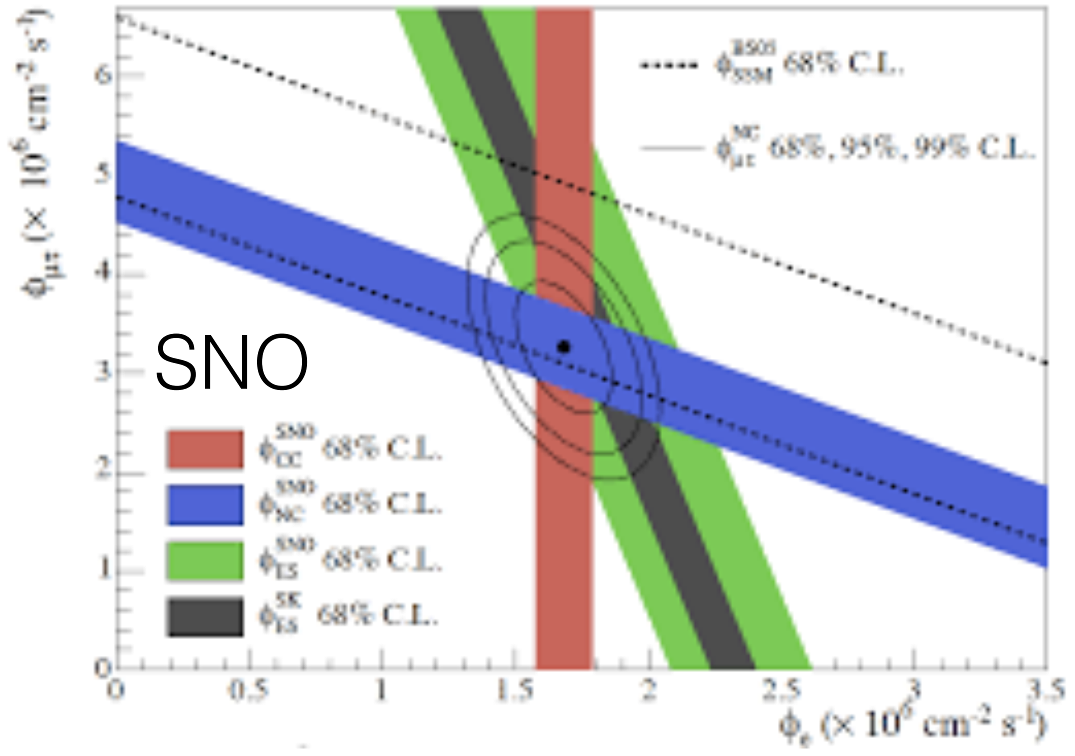
Hill, PRD84(2011)017501
Zhang and Serot, PLB719(2013)409
Wang et al, PLB740(2015)16

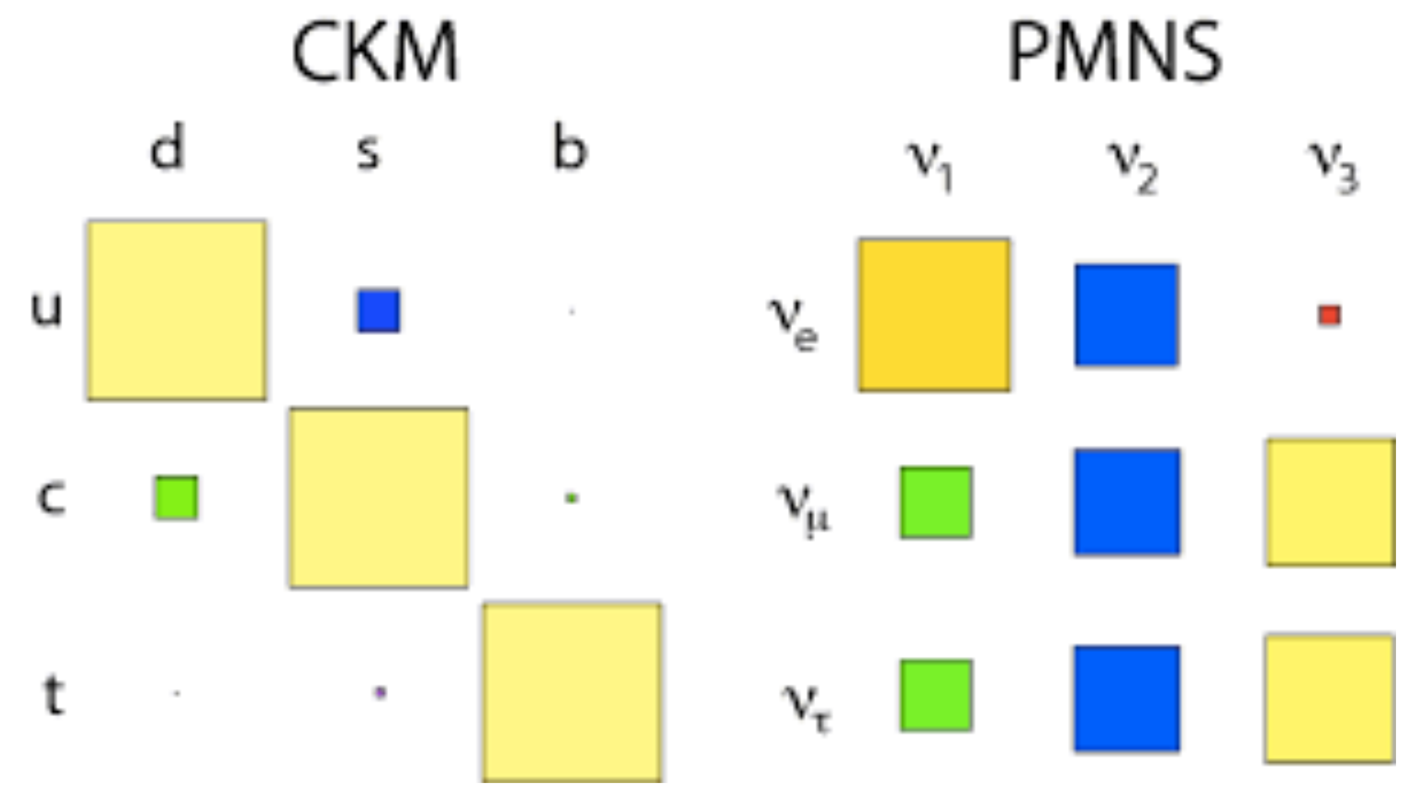
Ruling out the SM in the laboratory



*Not an exhaustive list







S. King

Theory prejudice	Exp
Neutrinos are massless	**No.**
Mixing is small	**No.**
Theta13 is zero (TBM)	**No.**
Neutrinos are Majorana	?
Seesaw at 10^14 GeV	?
…	…

Neutrinos held several surprises in the past.

We ought to at least continue to be suspicious…

THE NEUTRINO PORTAL

Motivations

Neutrino masses

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

Baryon asymmetry of the Universe

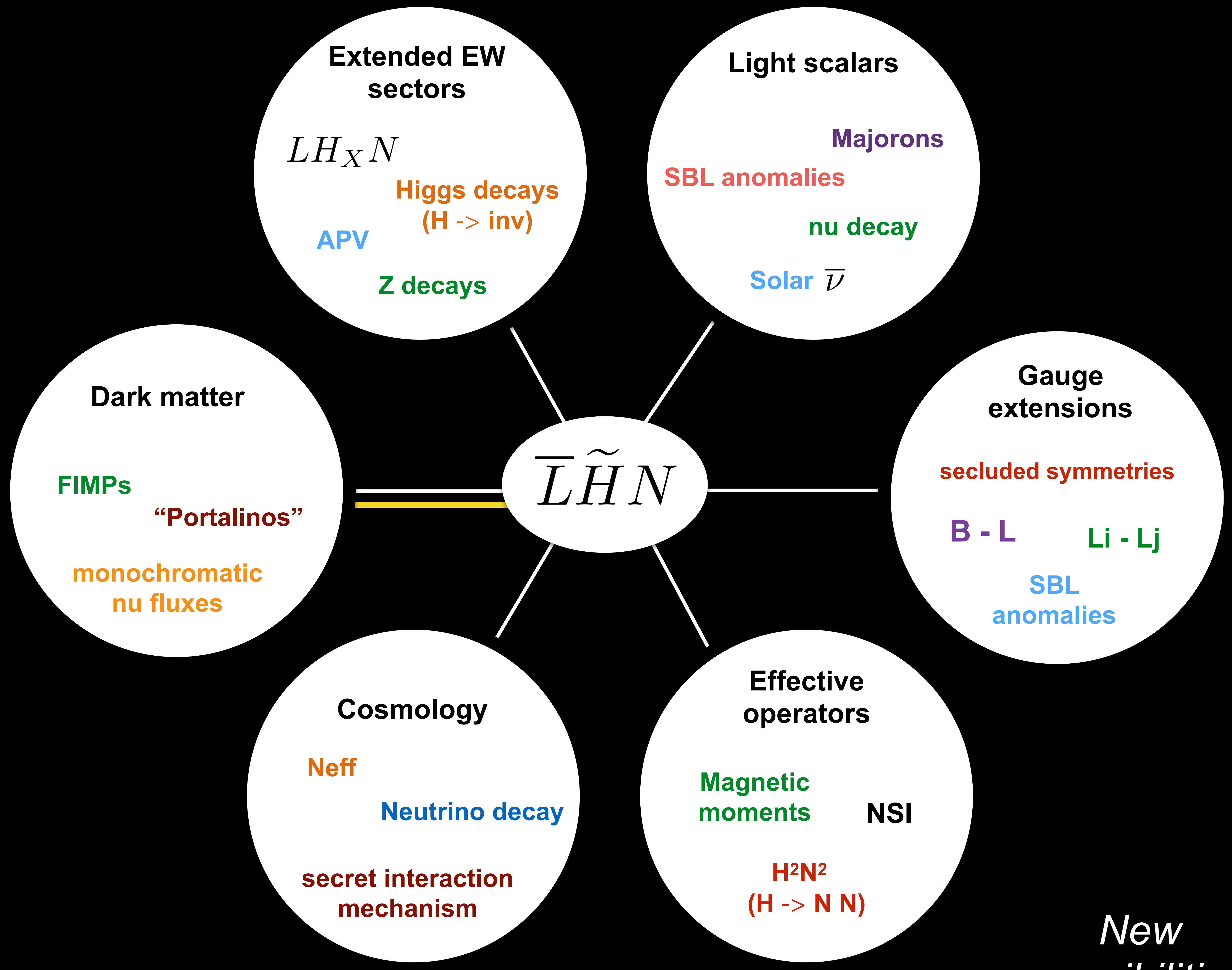
Leptogenesis, nu-assisted EW baryogenesis.

Dark matter

Warm DM or DM annihilation partner.

Experimental anomalies

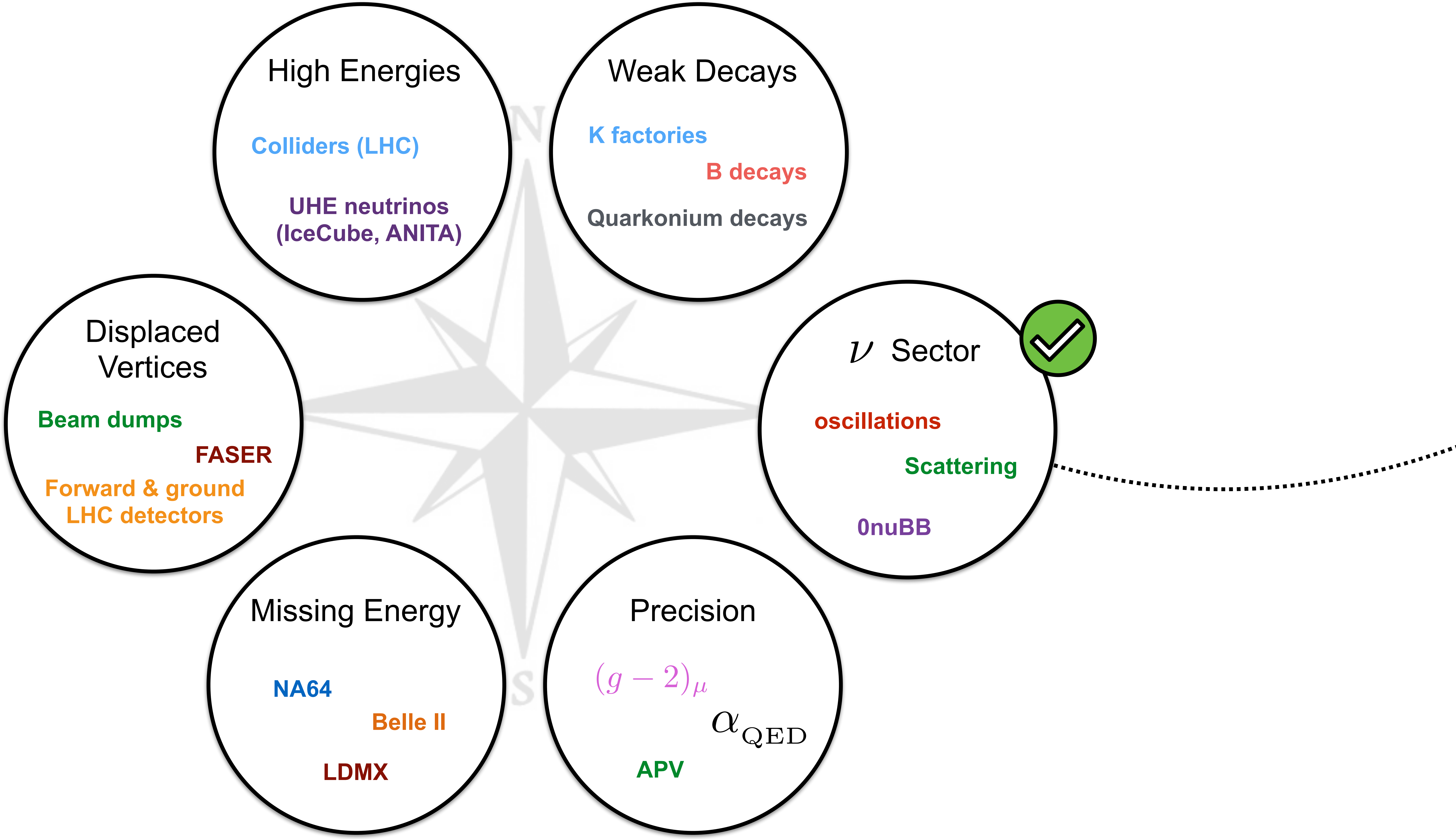
Short-baselines, Hubble, XENON1T, + others.



New possibilities

One of the most well-motivated portals also admits a variety of non-minimal realizations.

Ruling out the SM in the laboratory



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