Queen Mary
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A Light Dark Neutrino Sector

Matheus Hostert
(IPPP, Durham University)

based on:

1903.07589 / 1903.07590
Peter Ballett and Silvia Pascoli

1812.08768
Carlos Argüelles and Yu-Dai Tsai

Durham University

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

SCIENCE WITHOUT BORDERS

Outline

Dark neutrino models — what and why?

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Neutrino masses from our dark sector

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Phenomenology — MiniBooNE anomaly

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Dark neutrino models — what and why?

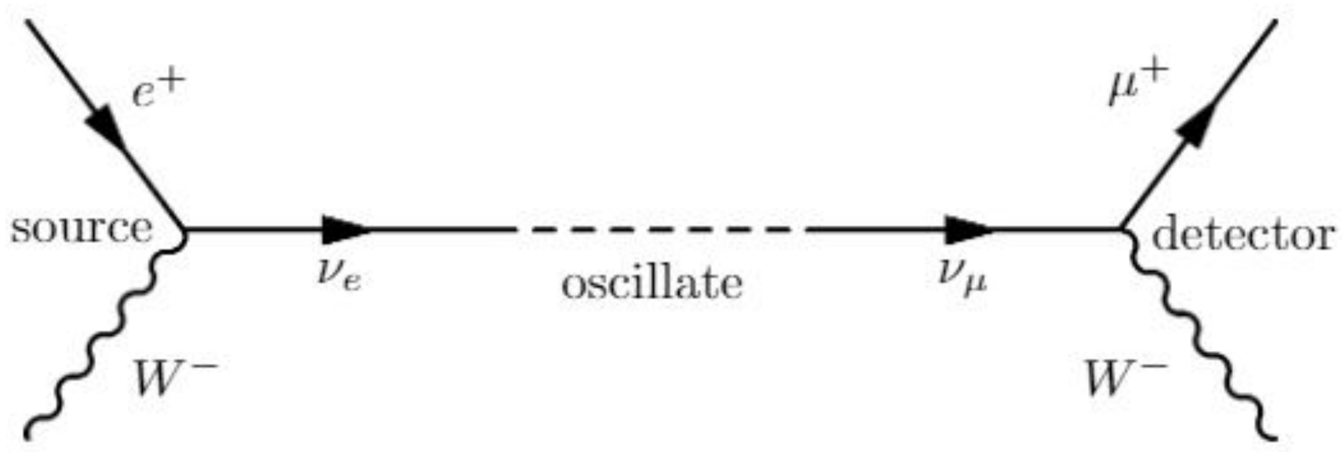
Neutrino masses from our dark sector

Phenomenology — MiniBooNE anomaly

MINERvA and CHARM-II

New physics is out there

At the electroweak scale, the Standard Model does too good a job, but…



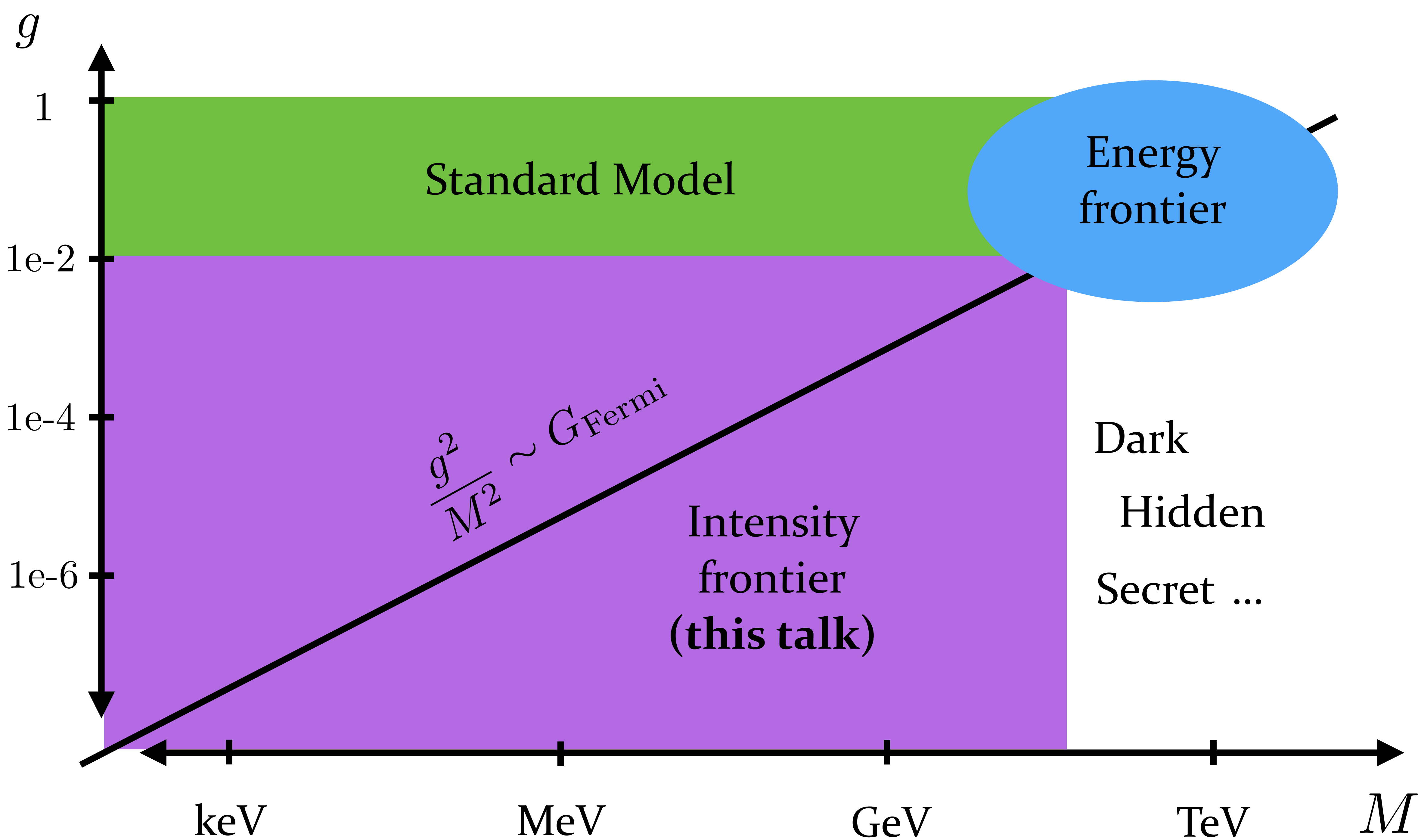
Neutrino mixing and masses

Dark Matter

heavy neutral leptons?

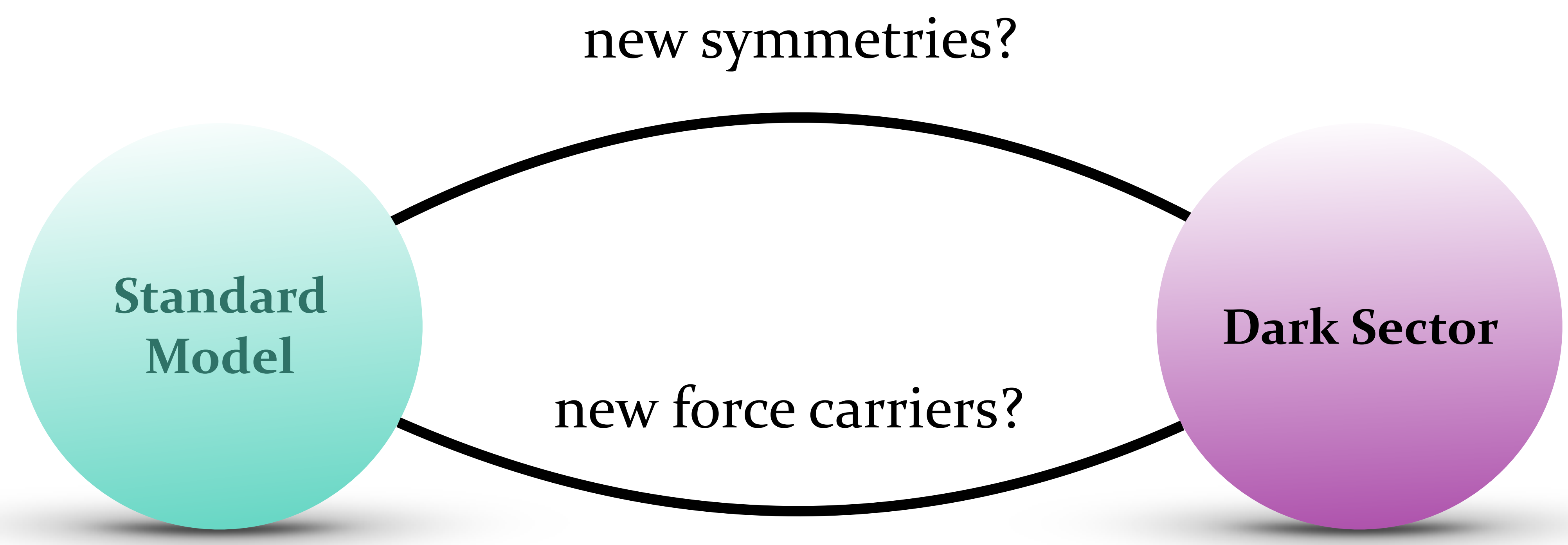
stable and neutral particles?

May be right under our noses?



Dark sector separate from the SM

Perhaps new degrees of freedom in a dark sector of their own?



DM, heavy neutrinos, ...

C. Boehm and P. Fayet, 2003

My dark sector wish list

1) Would like to have a **testable** neutrino mass model.

2) Dark sector: minimal, but consistent (e.g. dark photons need a mass mechanism).

3) Assume new interactions are confined to the dark sector (as opposed to B-L, etc).

Dark sector separate from the SM

A new gauge symmetry confined to the dark sector

$U(1)'$ with mediator X_μ

broken by the vev of a new complex scalar Φ

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A pair of heavy neutrino fields:

N

Completely sterile

ν_D

Charged under new dark force

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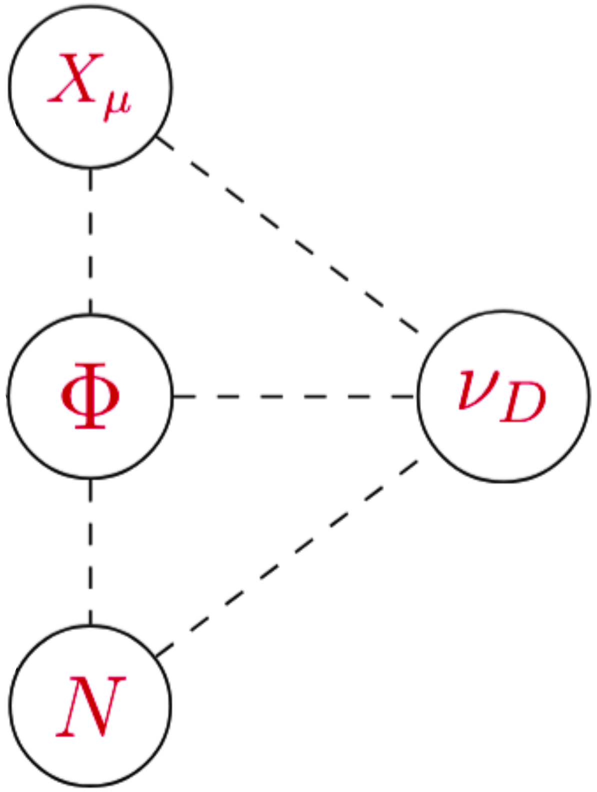

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
N	$\mathbf{1}$	$\mathbf{1}$	0	0
ν_D	$\mathbf{1}$	$\mathbf{1}$	0	Q
Φ	$\mathbf{1}$	$\mathbf{1}$	0	Q

Neutrino masses

Neutrino mass matrix with a single generation of active neutrinos

— Pair of heavy neutrinos resembles Inverse, Extended and Linear seesaw—

$$\mathcal{L}_{\text{mass}} \supset \frac{1}{2} \begin{pmatrix} \overline{\nu}_\alpha & \overline{N} & \overline{\nu_D} \end{pmatrix} \begin{pmatrix} 0 & m_D & \varepsilon' \\ m_D & \mu' & \Lambda \\ \varepsilon' & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_\alpha^c \\ N^c \\ \nu_D^c \end{pmatrix}$$

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symmetry protected

μ'

Lepton number violation

Neutrino masses

Neutrino mass matrix with a single generation of active neutrinos

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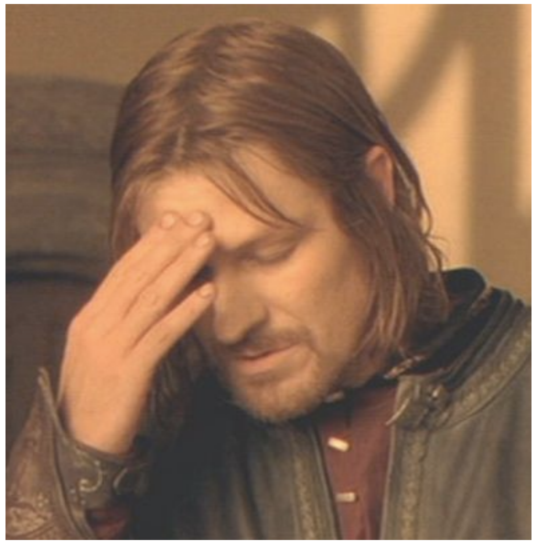
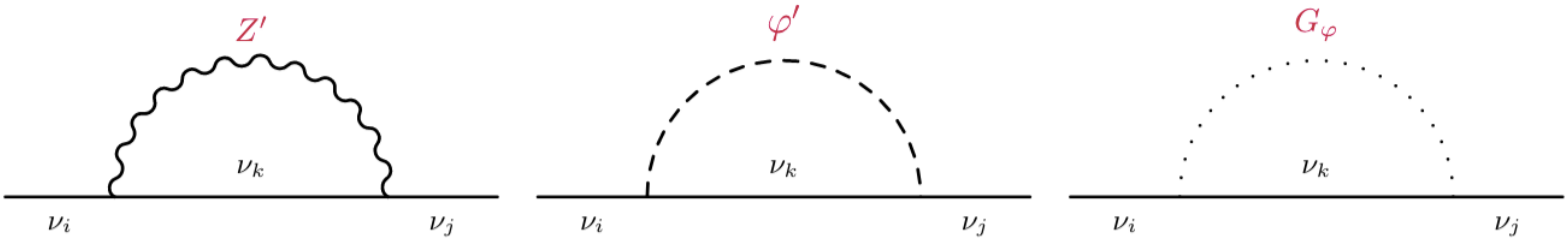


$$m_3 = 0$$

$$m_{4,5} = \frac{\mu' \mp \sqrt{\mu'^{\,2} + 4(\Lambda^2 + m_D^2)}}{2}$$

Neutrino masses at one-loop level

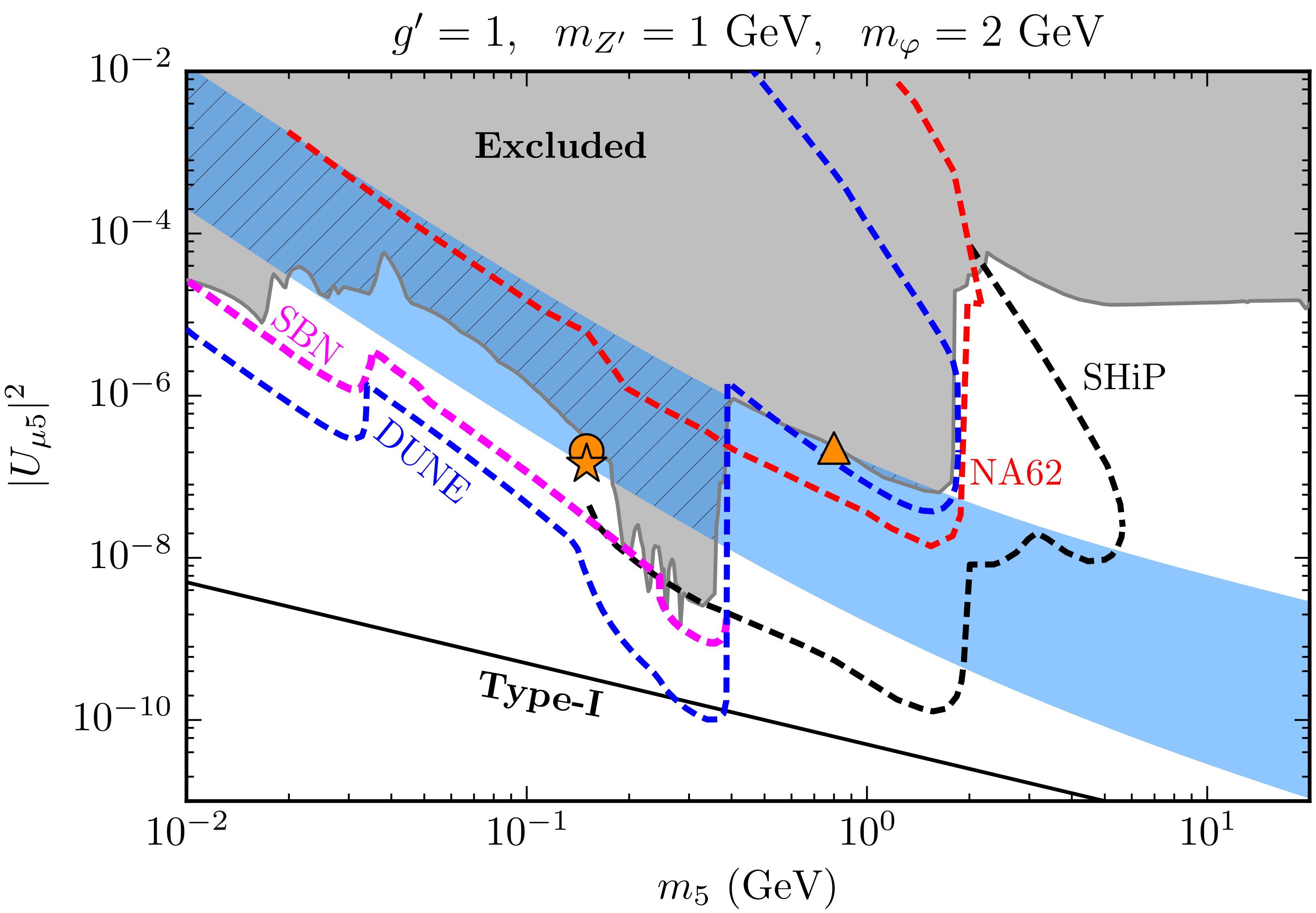


For instance, if in an Extended Seesaw scenario ($m_5 \gg m_4$) and $m_{Z'}, m_{\varphi'} \ll m_5$

$$m_3 \simeq \frac{g'^{\,2}}{16\pi^2} \frac{m_D^2}{\Lambda^2 + m_D^2} \frac{\Lambda^2}{m_{Z'}^2} \mu' \left(3 \ln \frac{m_{Z'}^2}{\mu'^2} + \ln \frac{m_{\varphi'}^2}{\mu'^2} \right)$$

New particles generate light neutrino masses radiatively!
Receive SM and BSM contributions.

Looking for the heavy neutrinos



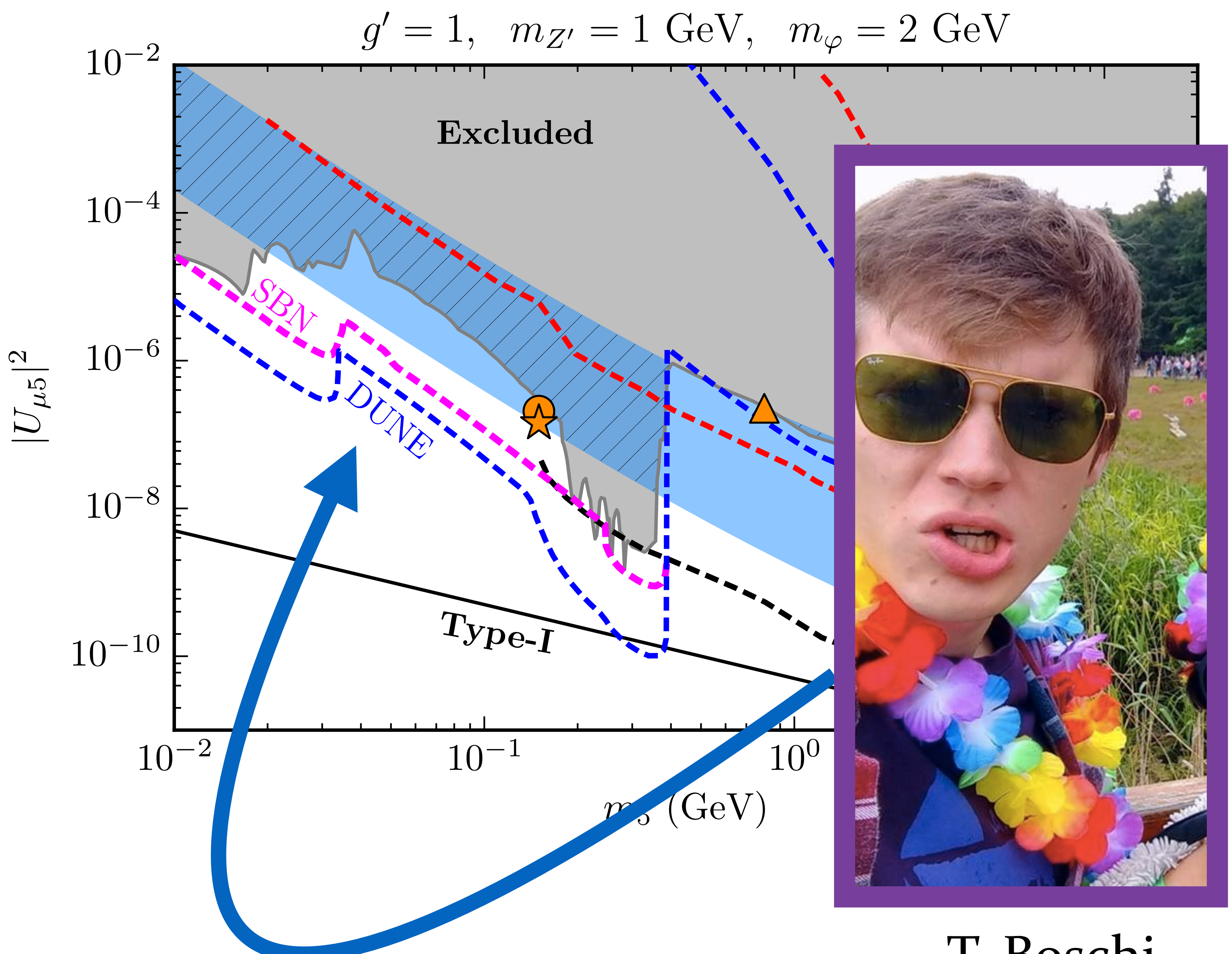
$$R = \frac{m_4}{m_5} = -\frac{U_{\alpha 5}^2}{U_{\alpha 4}^2}$$

Blue band is from:

$$m_3 = \sqrt{\Delta m^2_{\text{atm}}}$$

$$1\% < R < 99\%$$

Looking for the heavy neutrinos



T. Boschi

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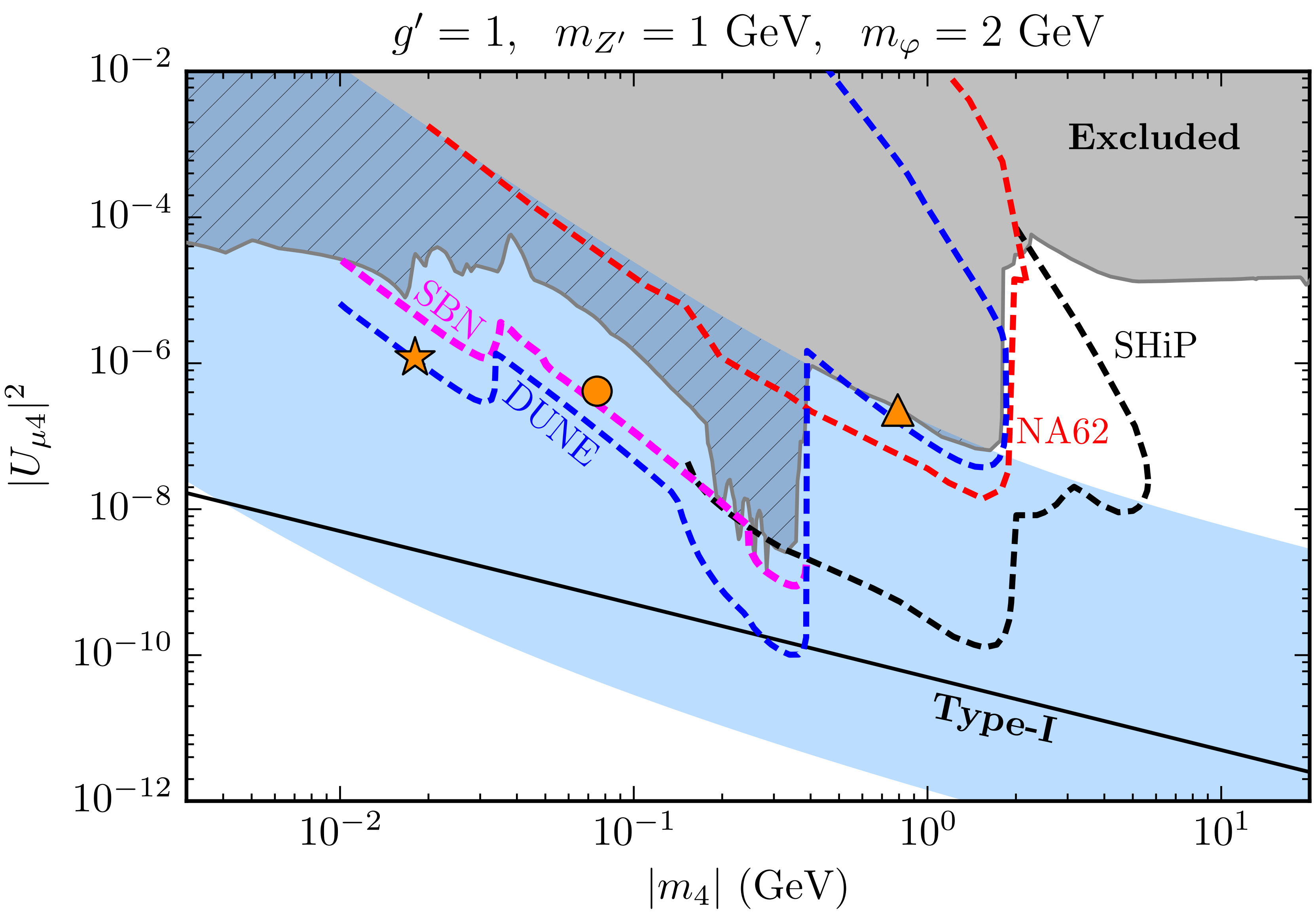

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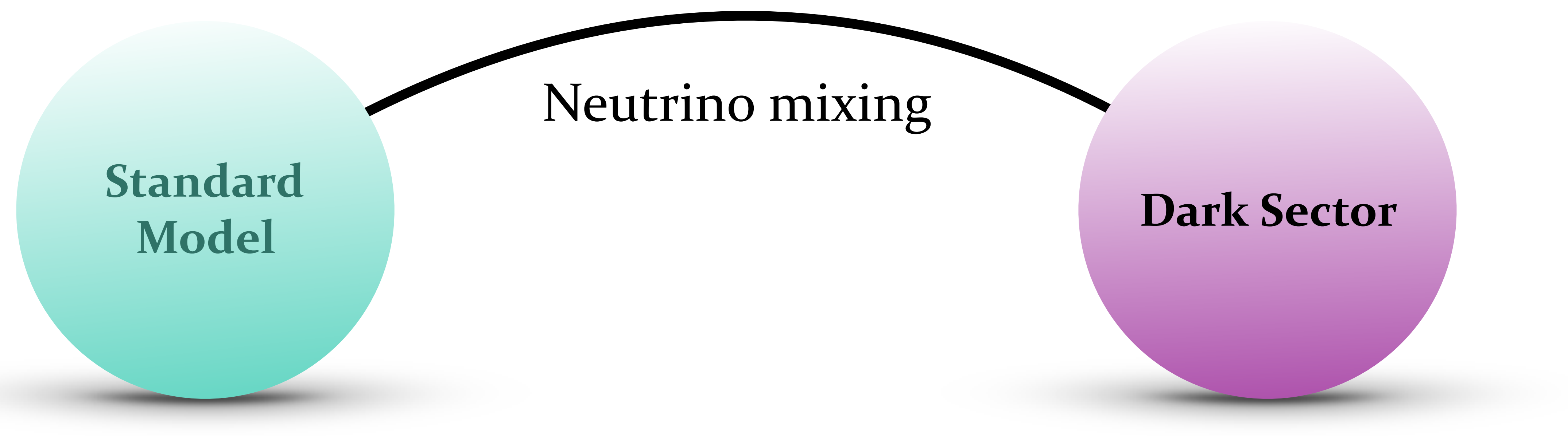
What we have so far

Heavy neutrinos interact strongly in a dark sector

Light neutrino masses arise radiatively



See also C. Diaz et al, 1712.05433, Bertuzzo et al, 1808.02500

Portals to the dark sector

Neutral BSM particle
+
SM singlet terms

$(\overline{L}\tilde{H})\ N^c$	—	Neutrino portal (neutrino mixing)
$B_{\mu\nu}\ X^{\mu\nu}$	—	Vector portal (kinetic mixing)
$H^\dagger H\ \|\Phi\|^2$	—	Higgs portal (scalar mixing)

} dim 4

Portals to the dark sector

Neutral BSM particle
+
SM singlet terms

$(\overline{L}\tilde{H})\ N^c$ — Neutrino portal (neutrino mixing)

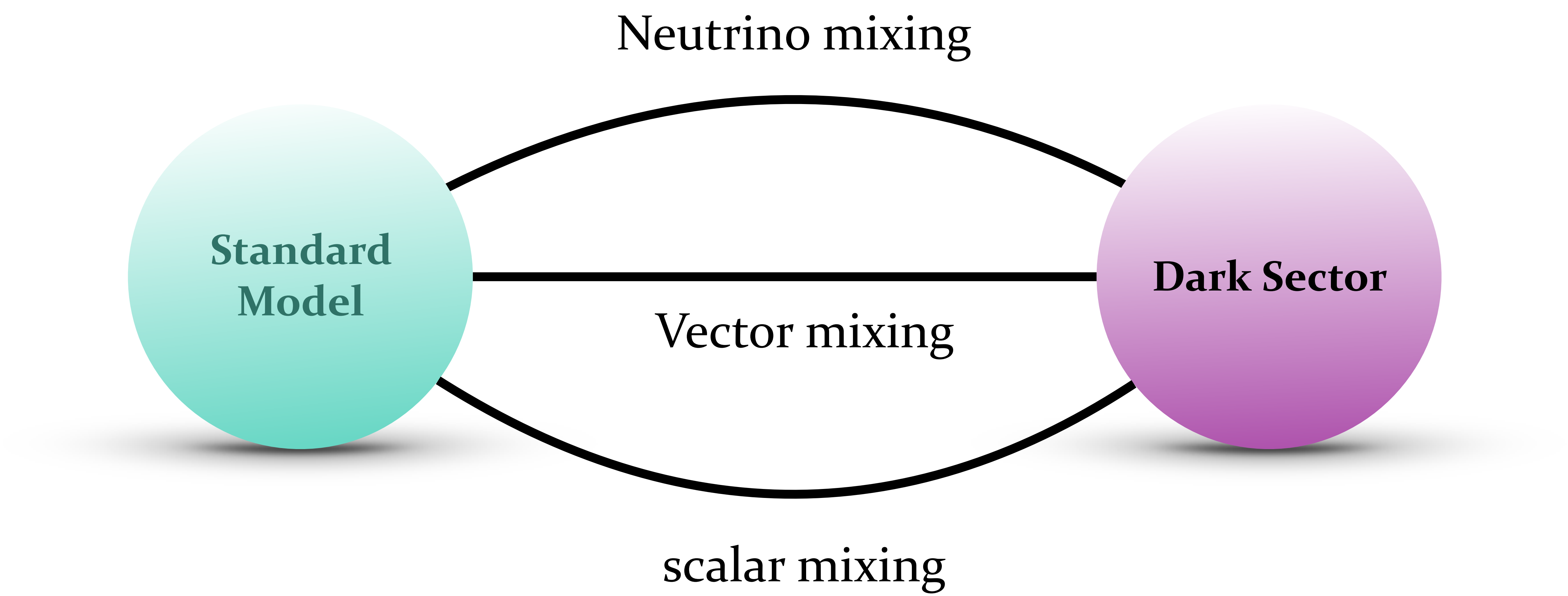
No reason why should not be there!

$B_{\mu\nu}\ X^{\mu\nu}$ — Vector portal (kinetic mixing)

$H^\dagger H\ |\Phi|^2$ — Higgs portal (scalar mixing)

} dim 4

Full picture



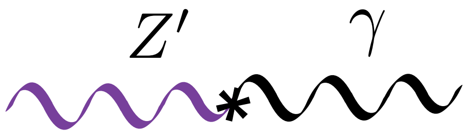
The dark sector interactions “leak” to the SM via the three portals.

Portal couplings are *theoretically* unconstrained and expected to be large!

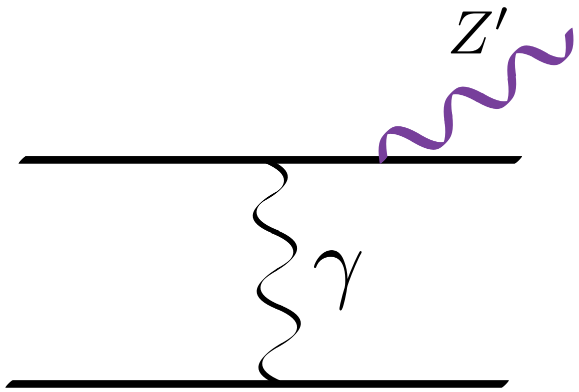
Vector portal

$$\frac{\sin\chi}{2} B_{\mu\nu} X^{\mu\nu}$$

For a light boson —> couples only to electric charge (dark photon).



At beam dumps and colliders:



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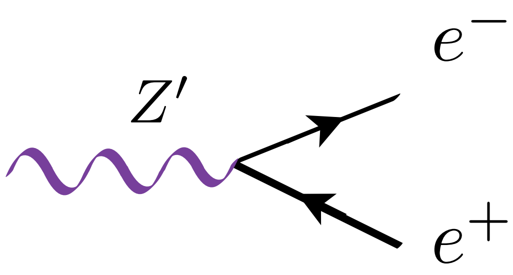

Dark photon

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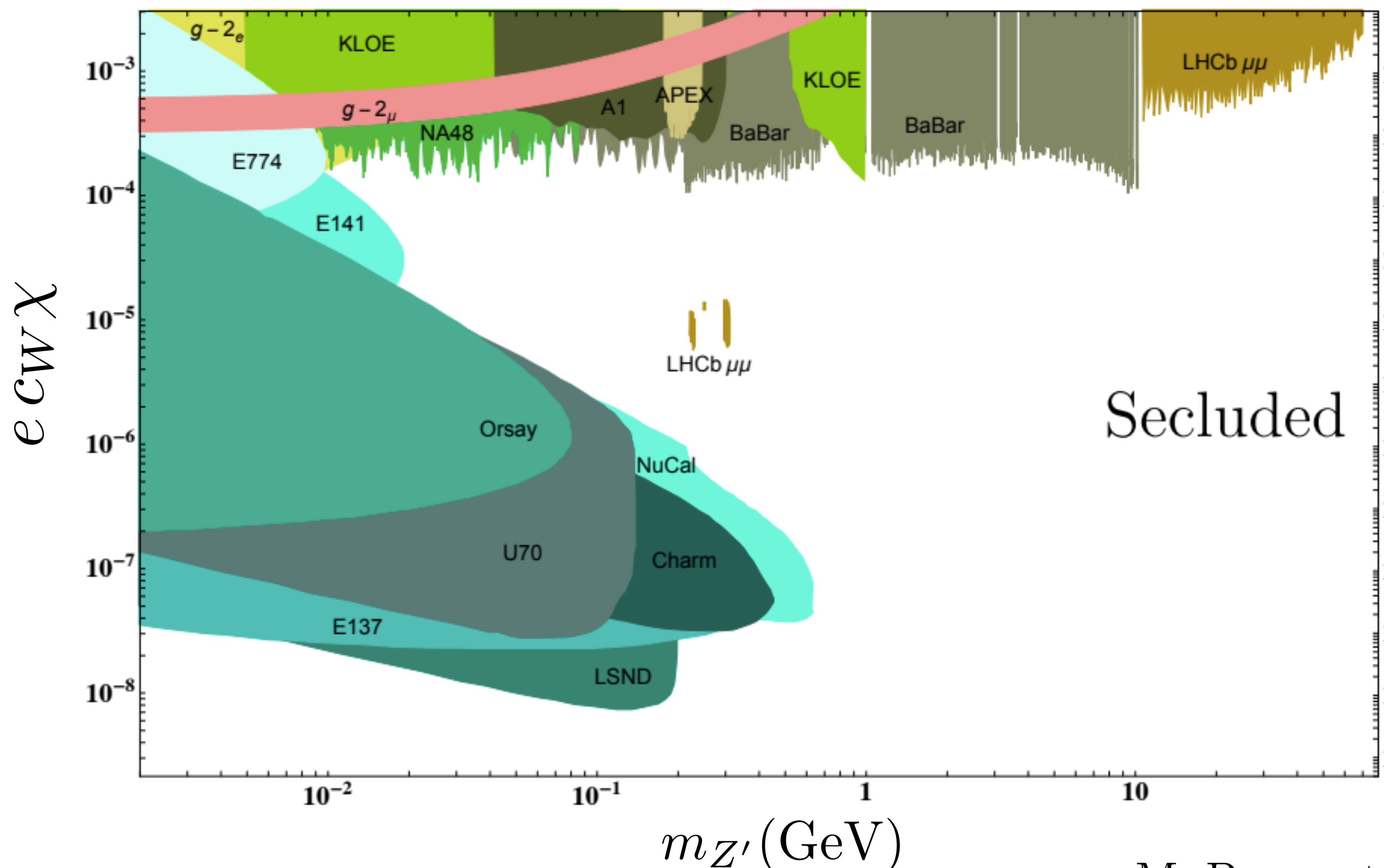


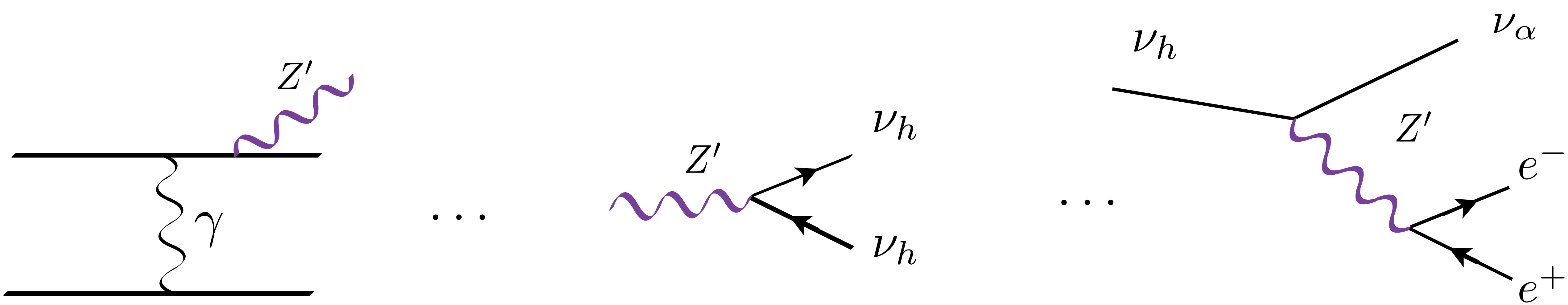
M. Bauer et al., 1803.05466

A *new* dark photon

$$\frac{\sin\chi}{2} B_{\mu\nu} X^{\mu\nu}$$

For a light boson —> couples only to electric charge (dark photon).

But in our full model, the dark photon mainly decays to heavy neutrinos!



Three-body kinematics, no longer reconstructs the invariant mass!

A *new* dark photon

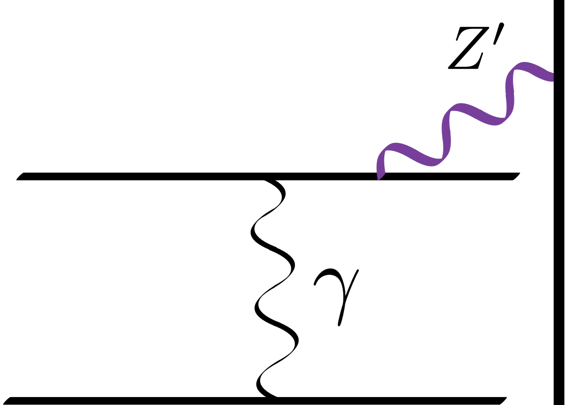
For a lig … hoton).

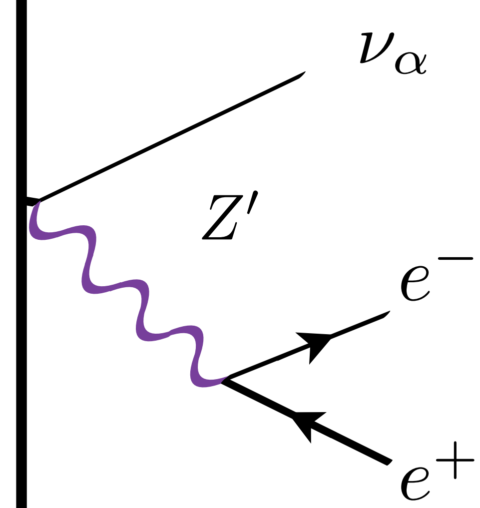
But in our … neutrinos!

A **neutrinophilic dark photon**
hiding in plain sight…

Weakened bounds
— final states do not pass the current vetoes —

Similar considerations apply for dark scalar.





Three-b … riant mass!

New signatures at neutrino experiments

For simplicity, let us take a phenomenological approach and consider a single **dark** neutrino.

This can be achieved in a extended seesaw limit of the model discussed before.

New signatures at neutrino experiments

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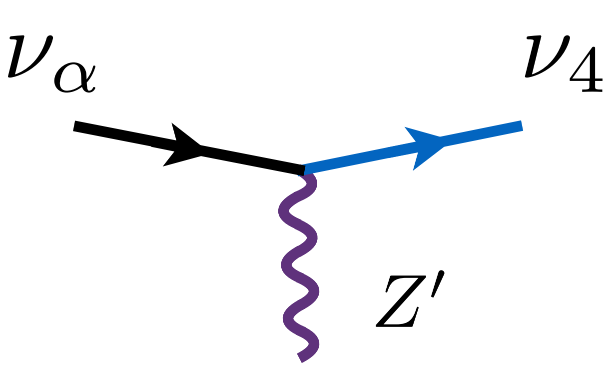
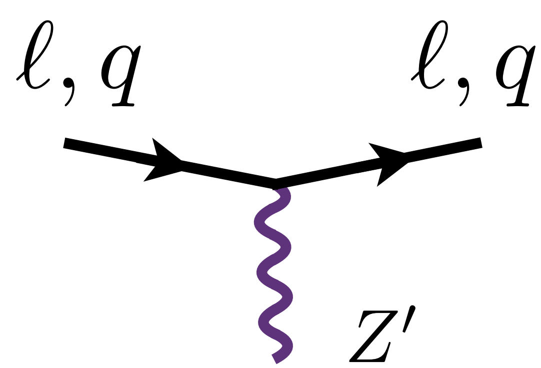
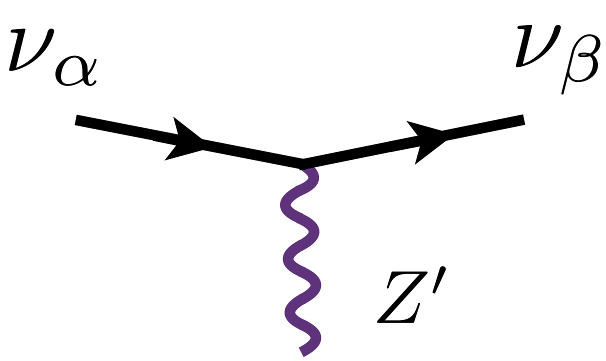






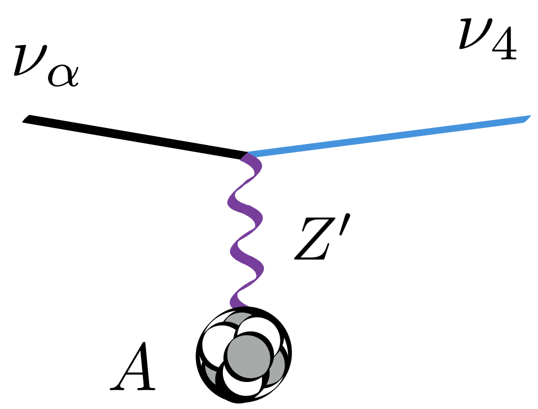
$U_{\alpha 4}^{*}\, g'$	$e\, \chi\, q_f$	$U_{\alpha 4}^{*}\, U_{\beta 4}\, g'$
<u>SM + heavy neutrino</u>	<u>Quarks and charged leptons</u>	<u>SM neutrinos only</u>
Mixing + O(1) coupling	Kinetic mixing	Two mixings needed

Neutrino scattering

Interest from the point of view of neutrino scattering and experimental anomalies

Neutrino NC cross sections are enhanced due to the light mediator:

"Upscattering"



$$\propto \; g'^{\,2}\chi^2|U_{\alpha 4}|^2\frac{1}{m_{Z'}^4}$$

E. Bertuzzo et al, PhysRevLett.121.241801

P. Ballett et al, 1808.02915

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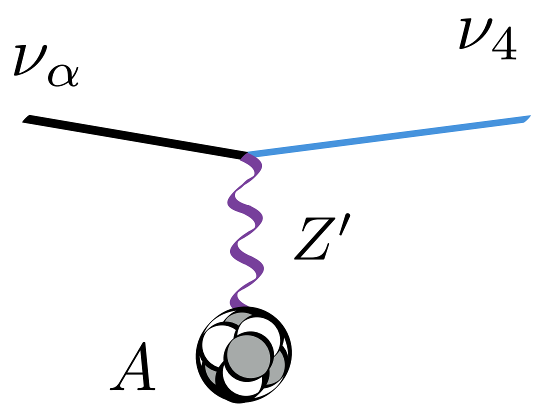
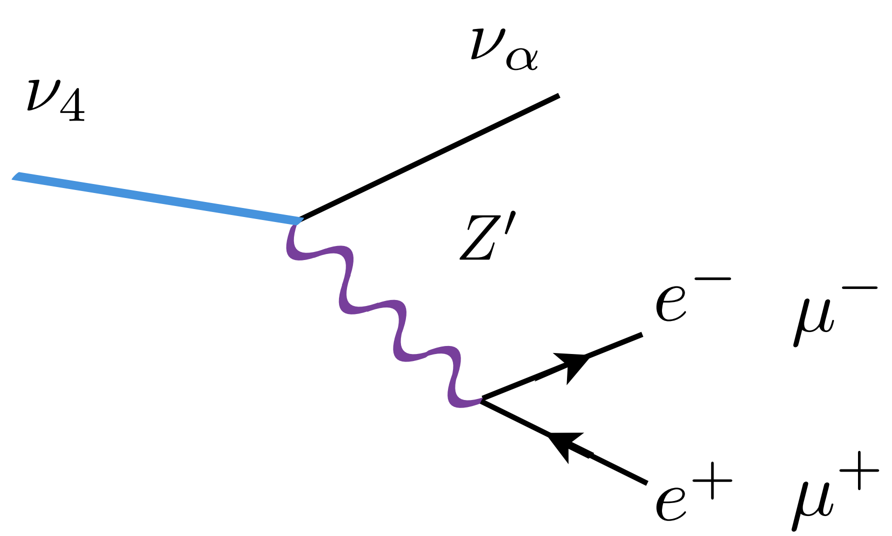
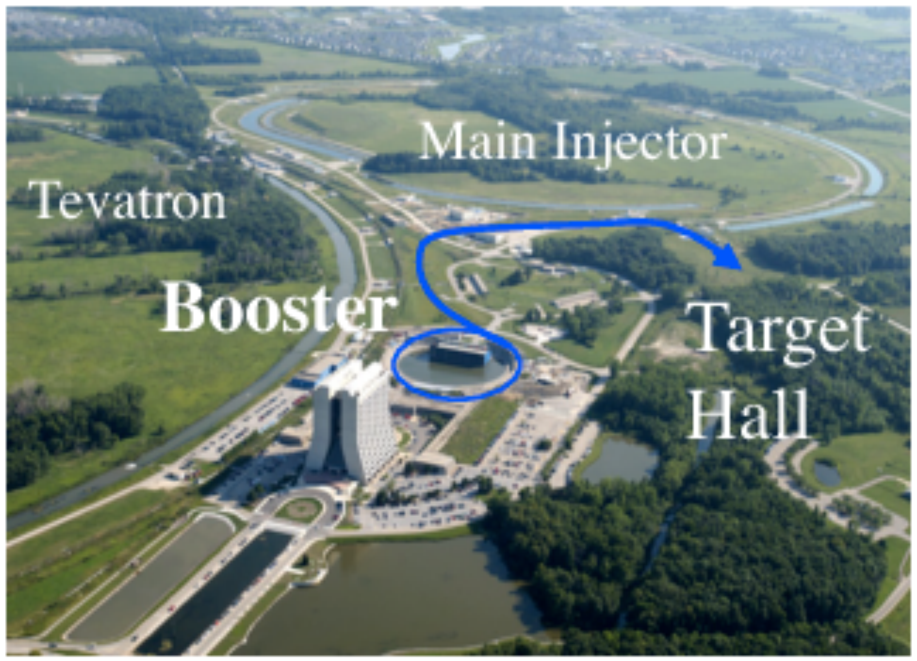


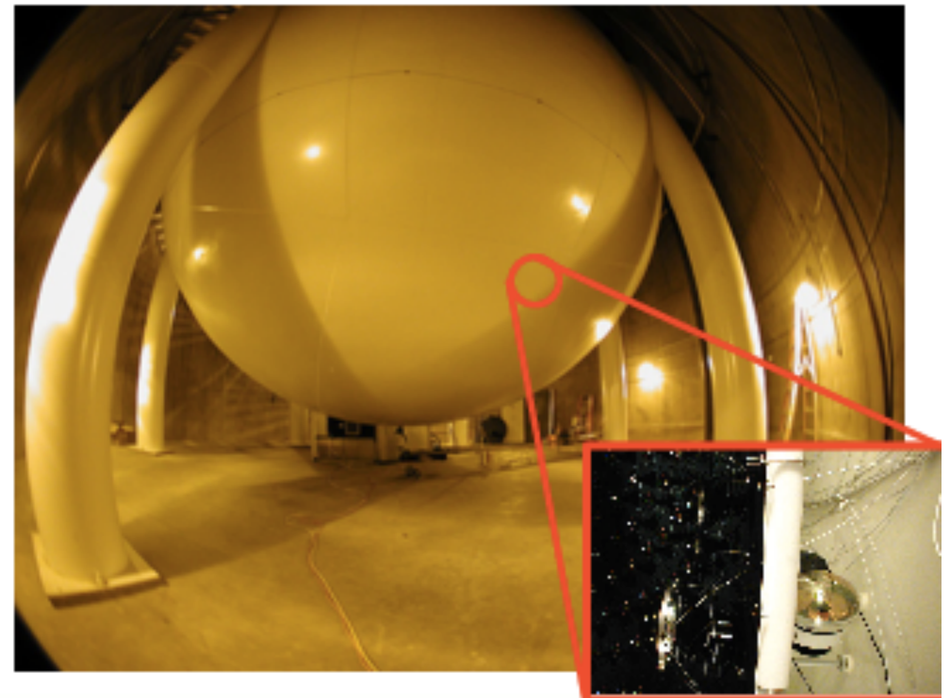


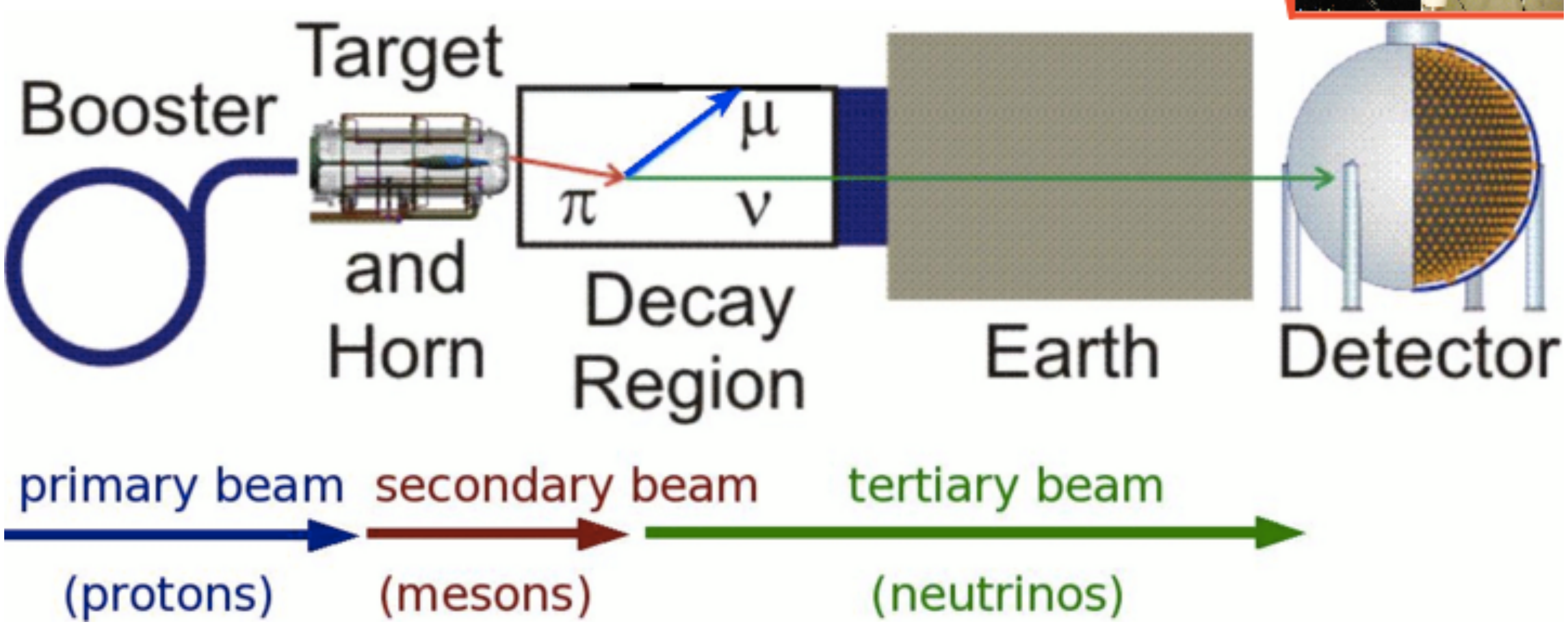
E. Bertuzzo et al, PhysRevLett.121.241801

P. Ballett et al, 1808.02915

MiniBooNE





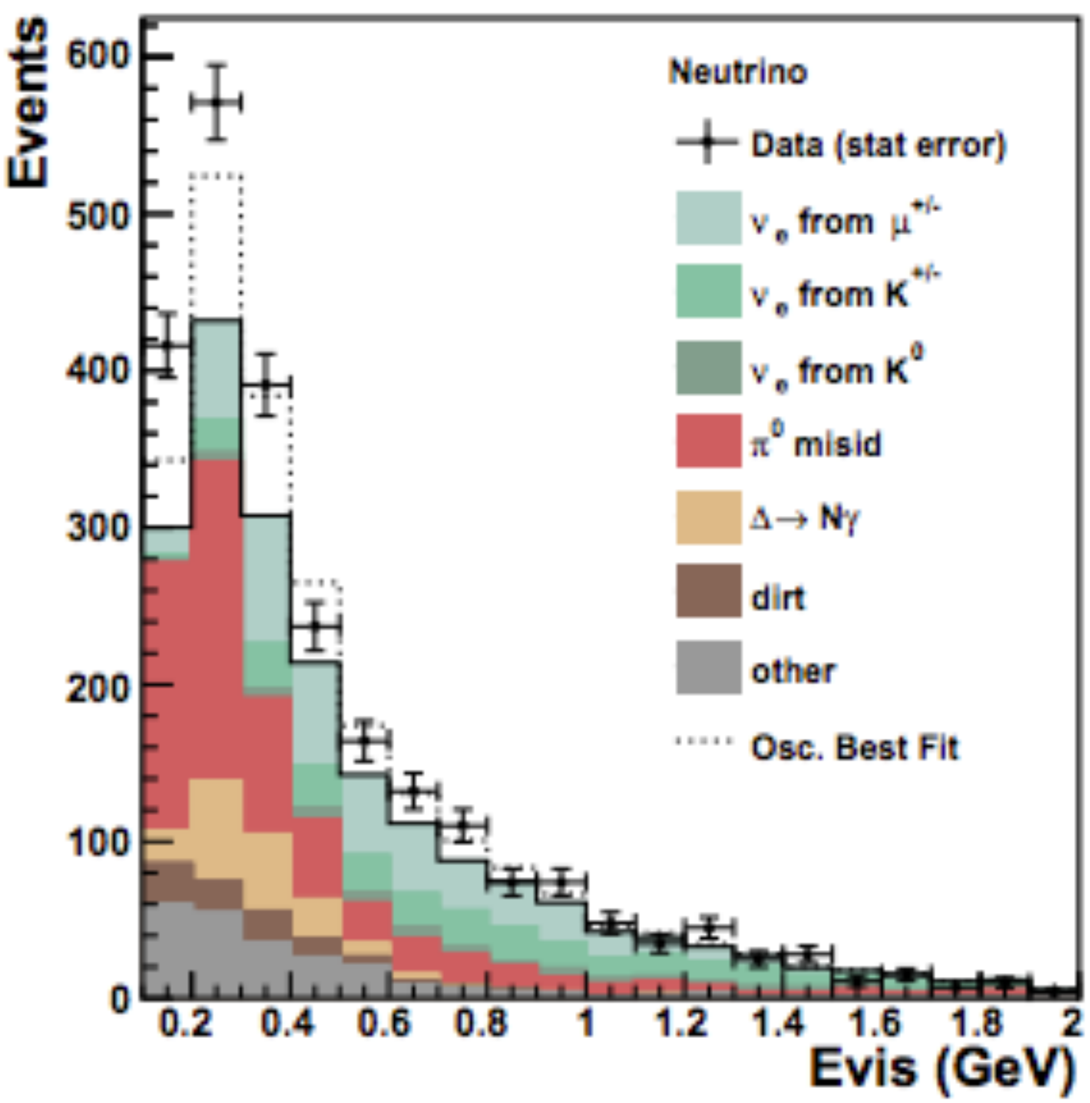


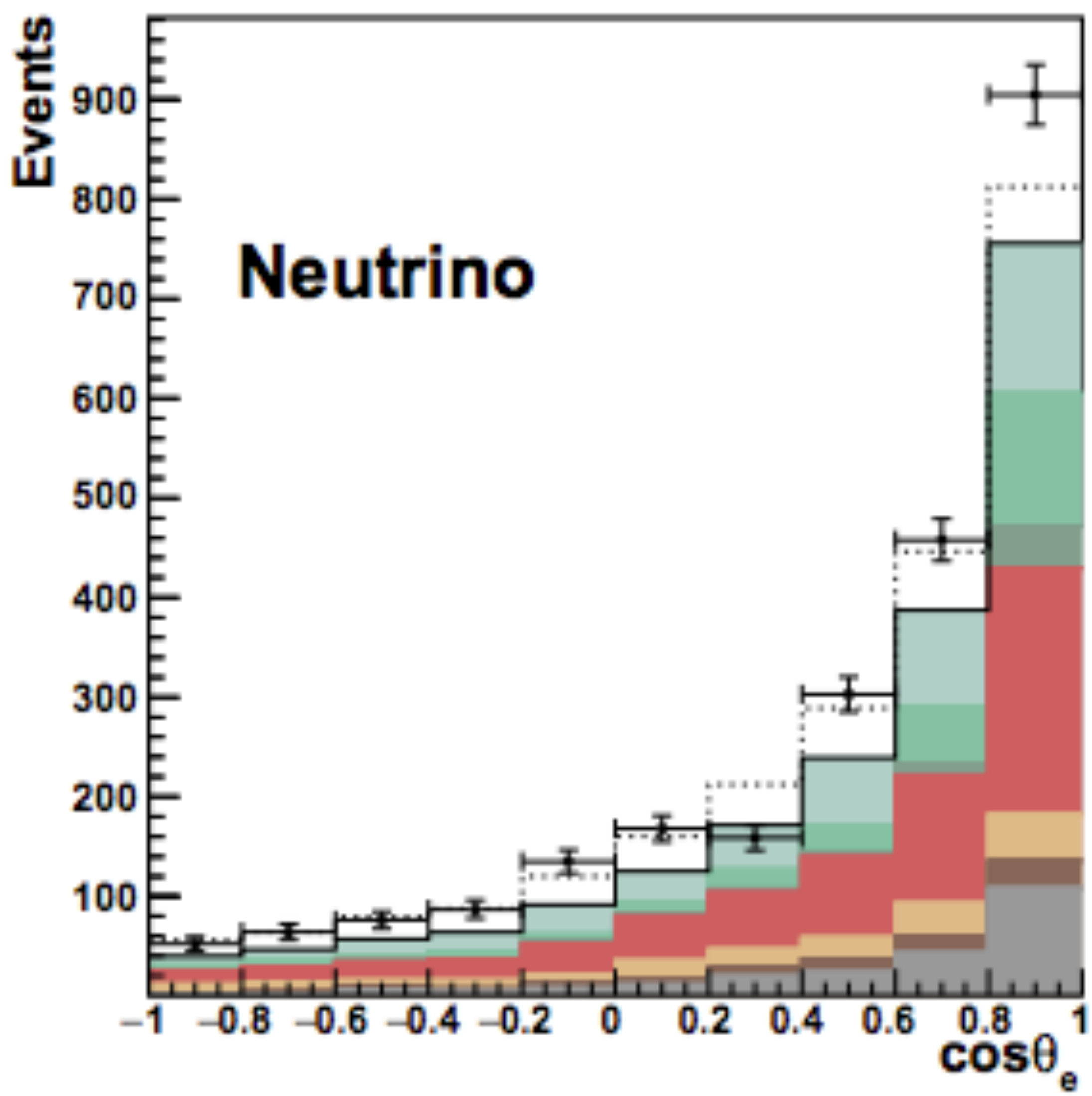
818 t

MiniBooNE

4.7σ excess observed in neutrino + antineutrino modes

— data/MC disagreement beyond statistical doubt —





MiniBooNE

4.7σ excess observed in neutrino + antineutrino modes

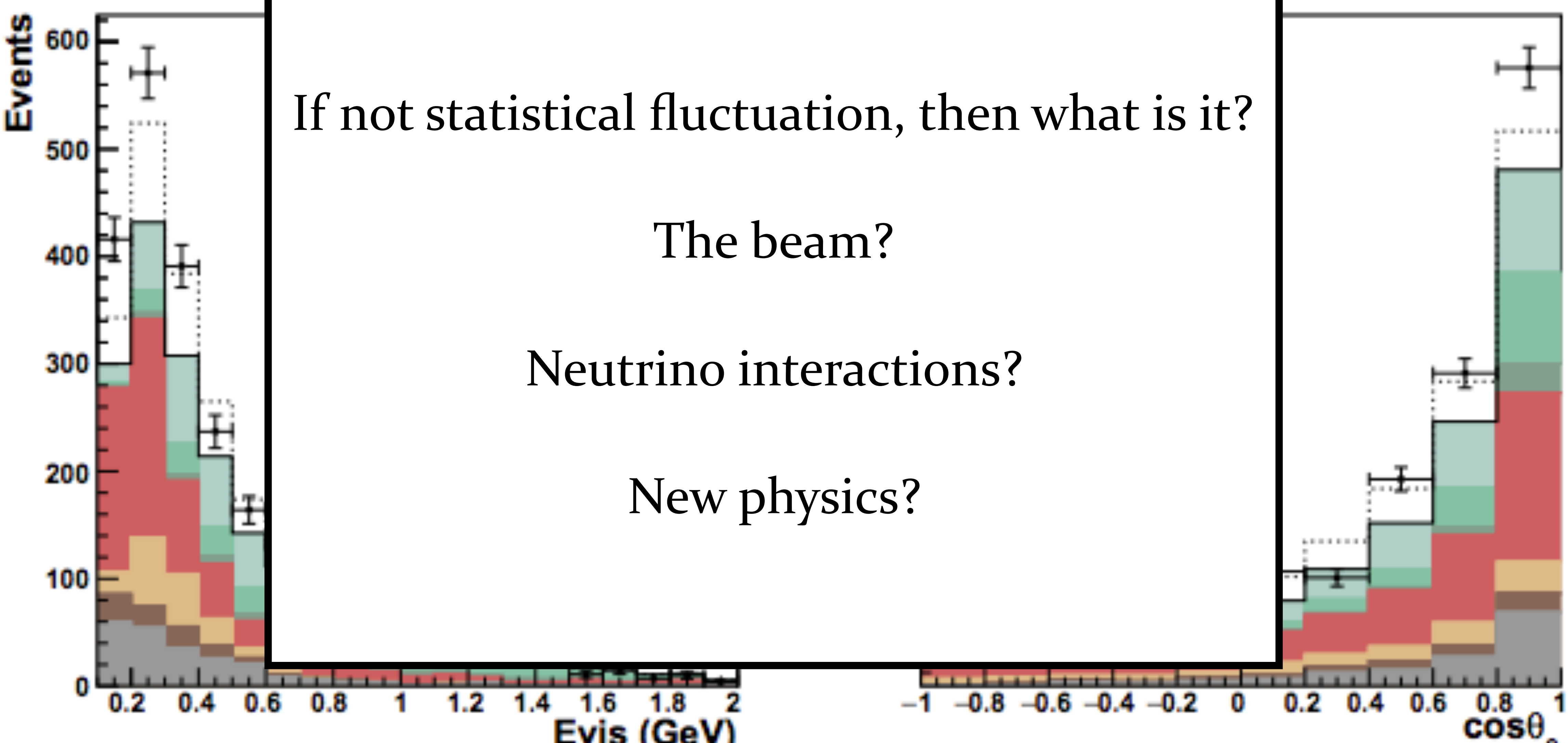
— data/MC disagreement beyond statistical doubt —

If not statistical fluctuation, then what is it?

The beam?

Neutrino interactions?

New physics?



We need something new

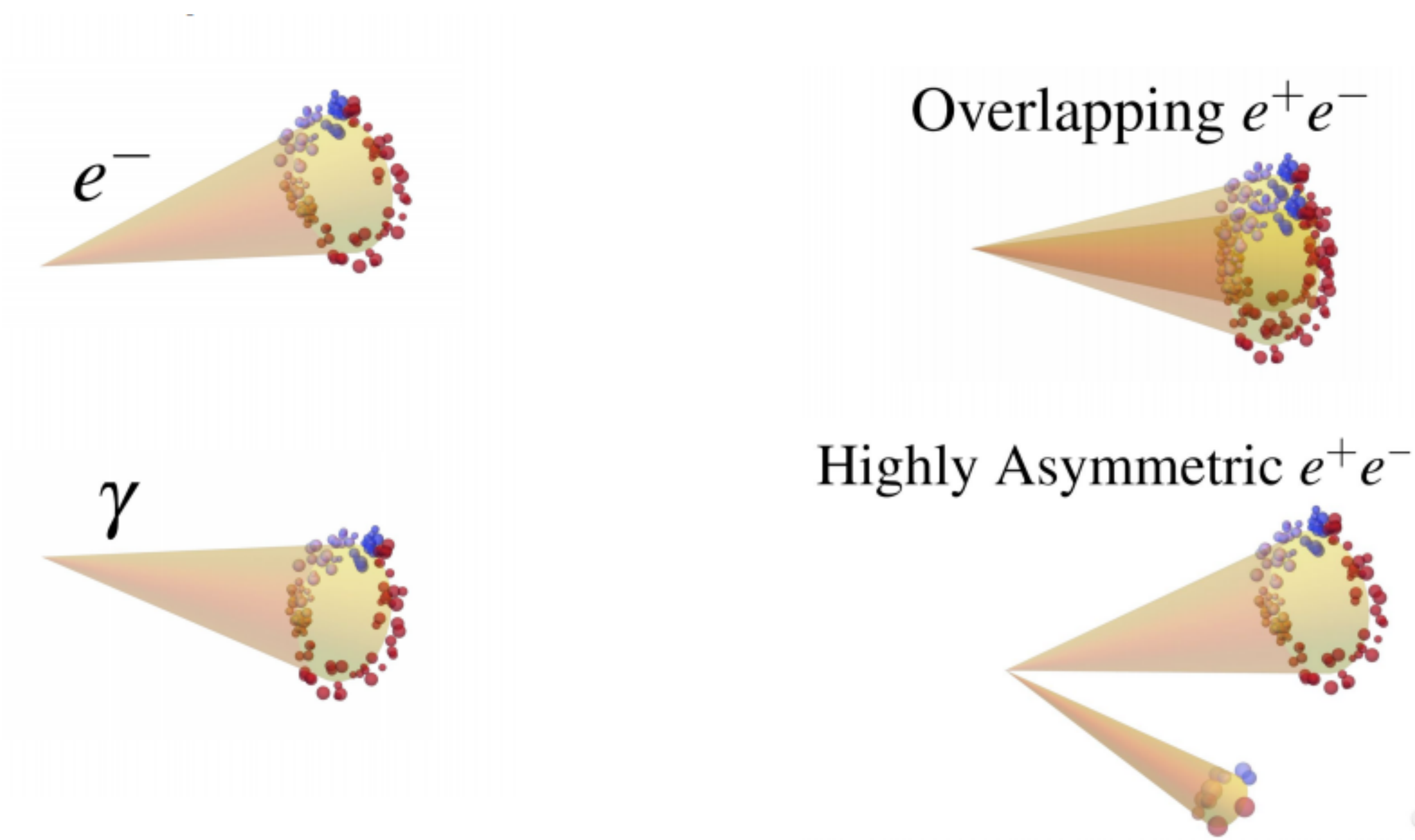
"If the data doesn't agree with the null hypothesis or the alternative hypothesis, some say you need more data, while some say you need <u>more hypotheses</u>."

Maury Goodman, arXiv:1901.07068

At this point the anomaly requires **<u>non-minimal scenarios.</u>**

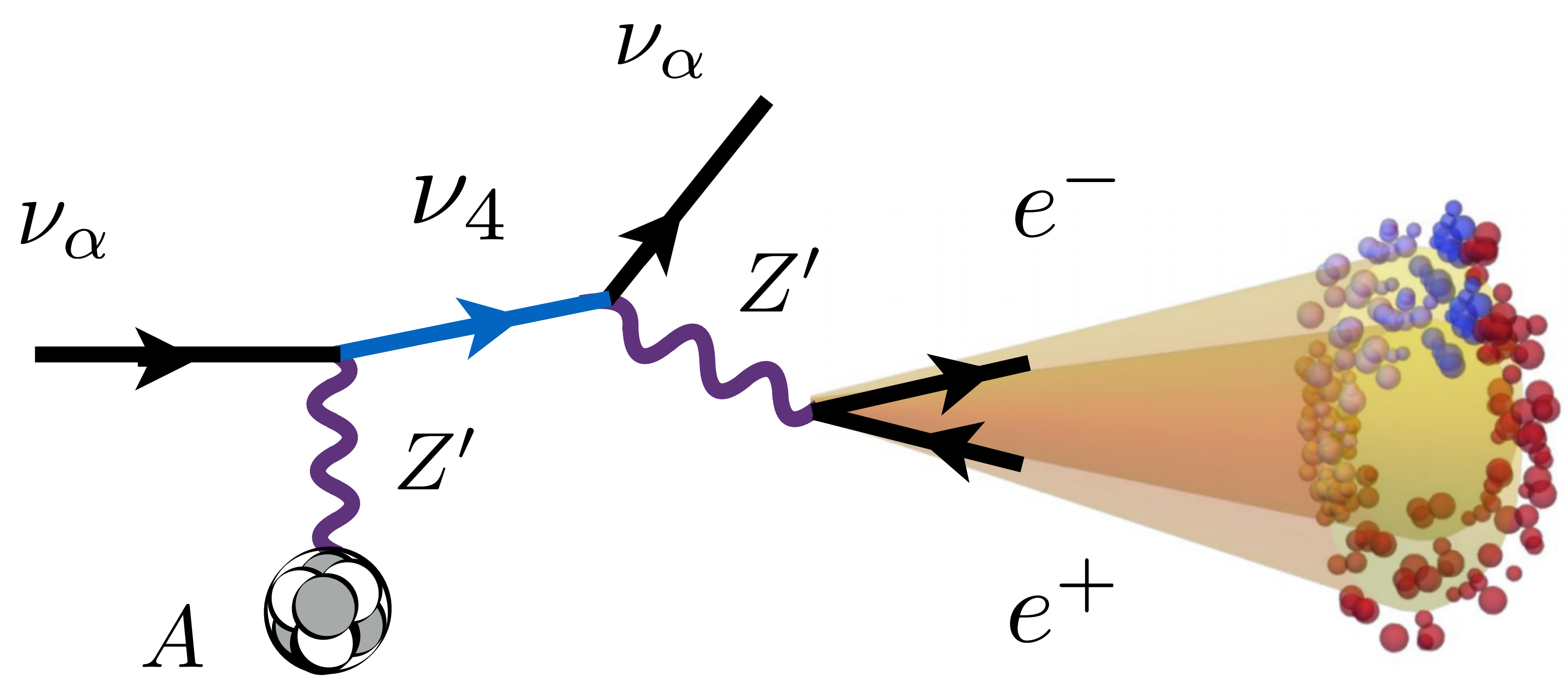
MiniBooNE

What kind of events contribute to the excess:



The Signal at MiniBooNE

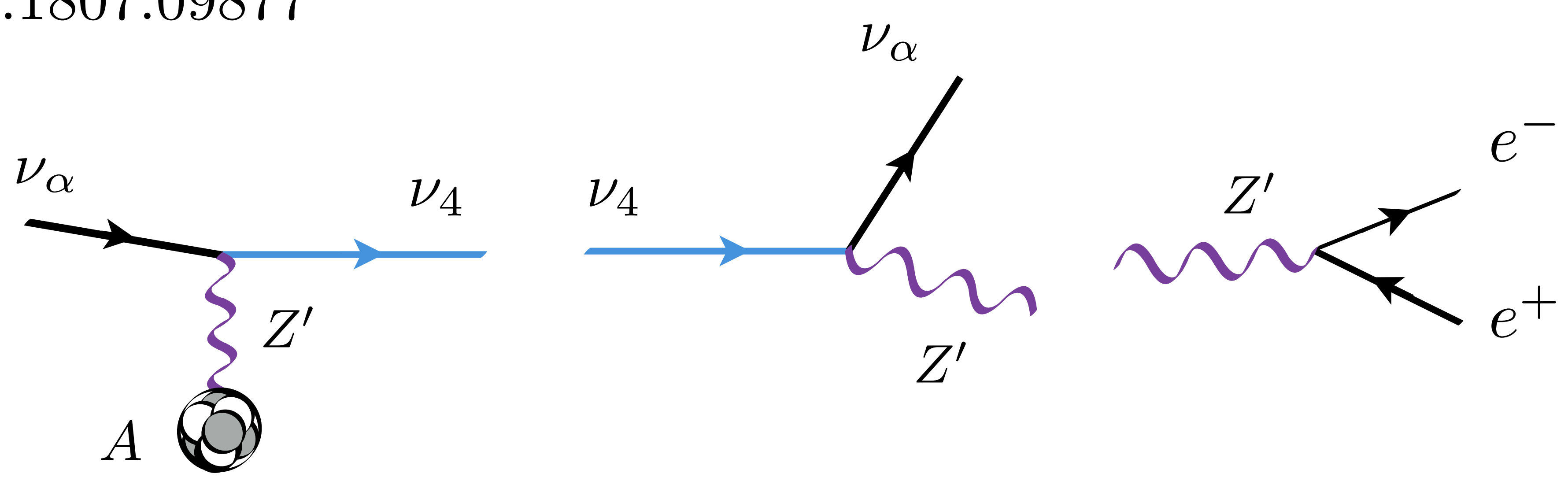
Neutrinos upscatter into heavy state, which immediately decays into an overlapping pair of electrons.

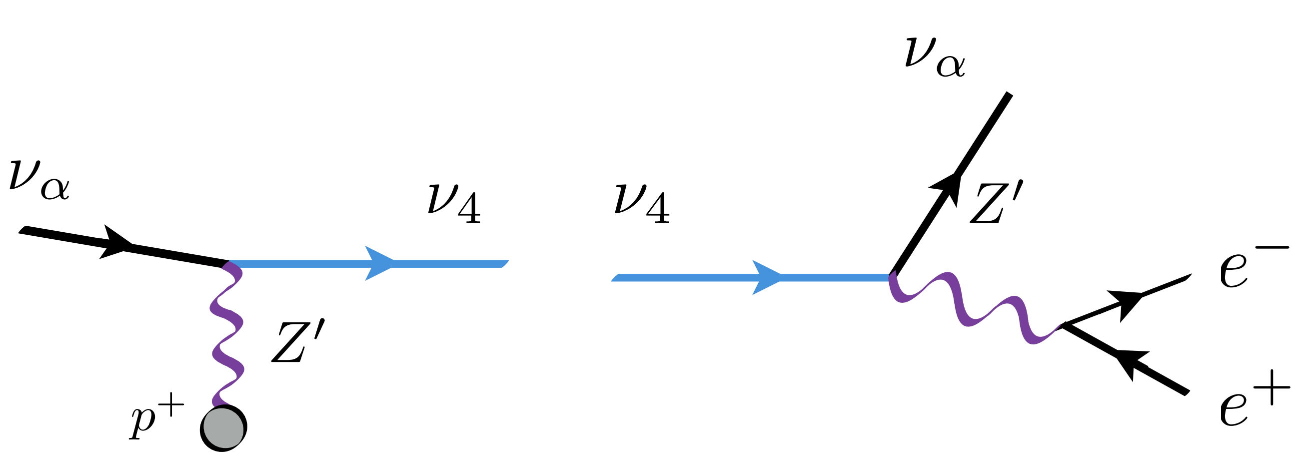


Two realisations

E. Bertuzzo et al. arXiv:1807.09877

$m_{Z'} < m_4$





P. Ballett et al. arXiv:1808.02915

$m_{Z'} > m_4$

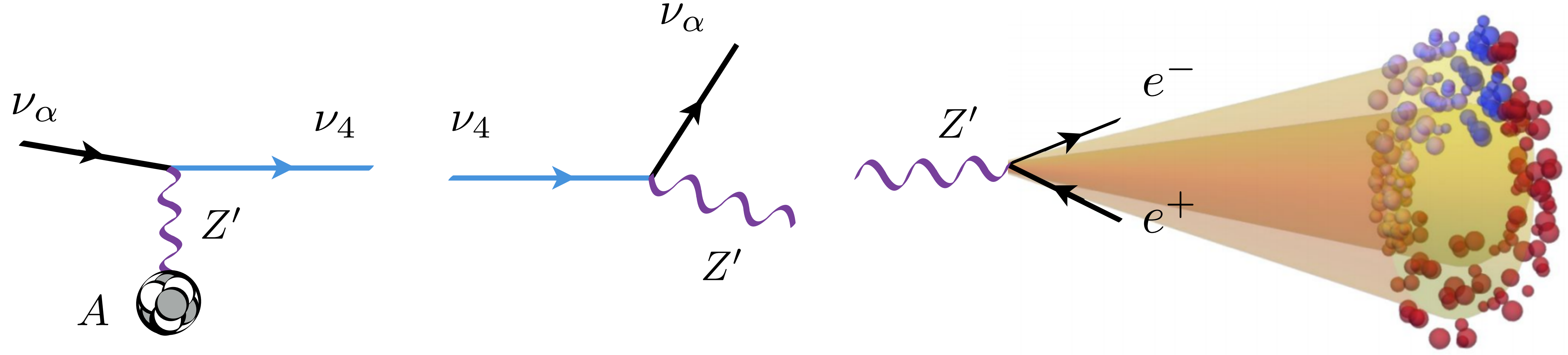
Light dark photon case

E. Bertuzzo et al. arXiv:1807.09877

$m_{Z'} < m_4$

Coherent signal

— single <u>boosted</u> EM shower —



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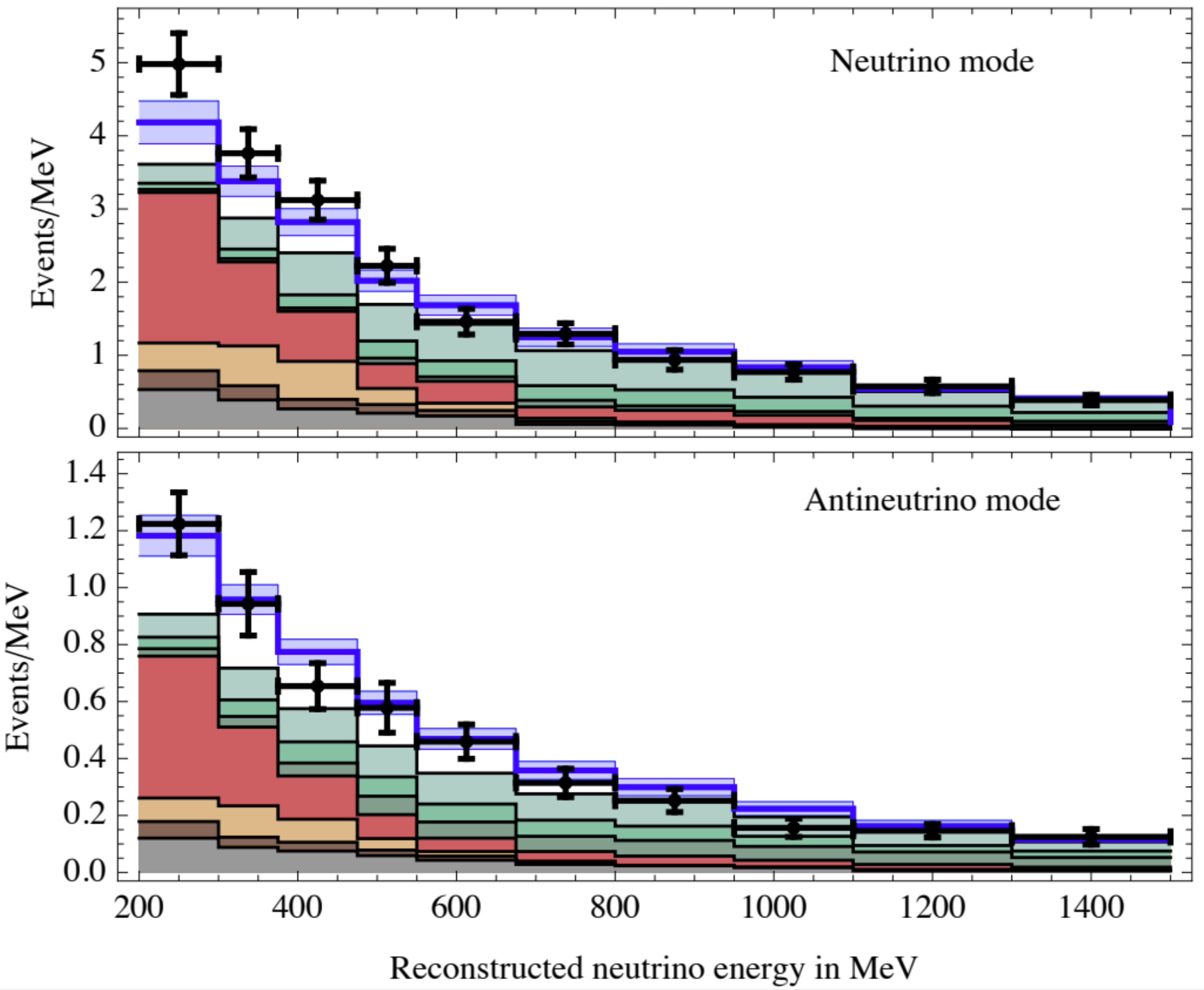
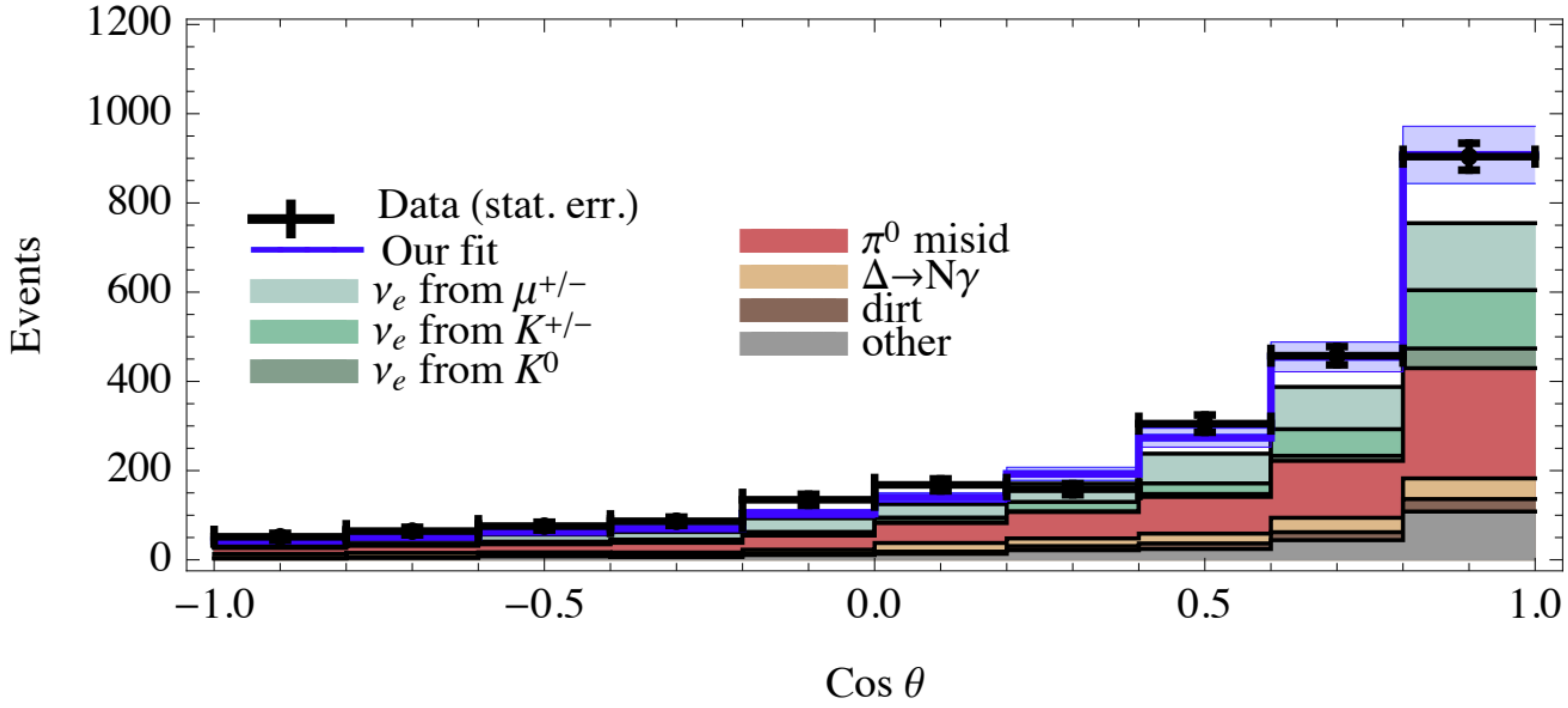


$m_{Z'} < m_4$

The predictions of our benchmark point $m_{N_\mathcal{D}} = 420$ MeV, $m_{Z_\mathcal{D}} = 30$ MeV, $|U_{\mu 4}|^2 = 9 \times 10^{-7}$, $\alpha_\mathcal{D} = 0.25$ and $\alpha\,\epsilon^2 = 2 \times 10^{-10}$ are also shown as the blue lines.

Light dark photon case

$m_{Z'} < m_4$



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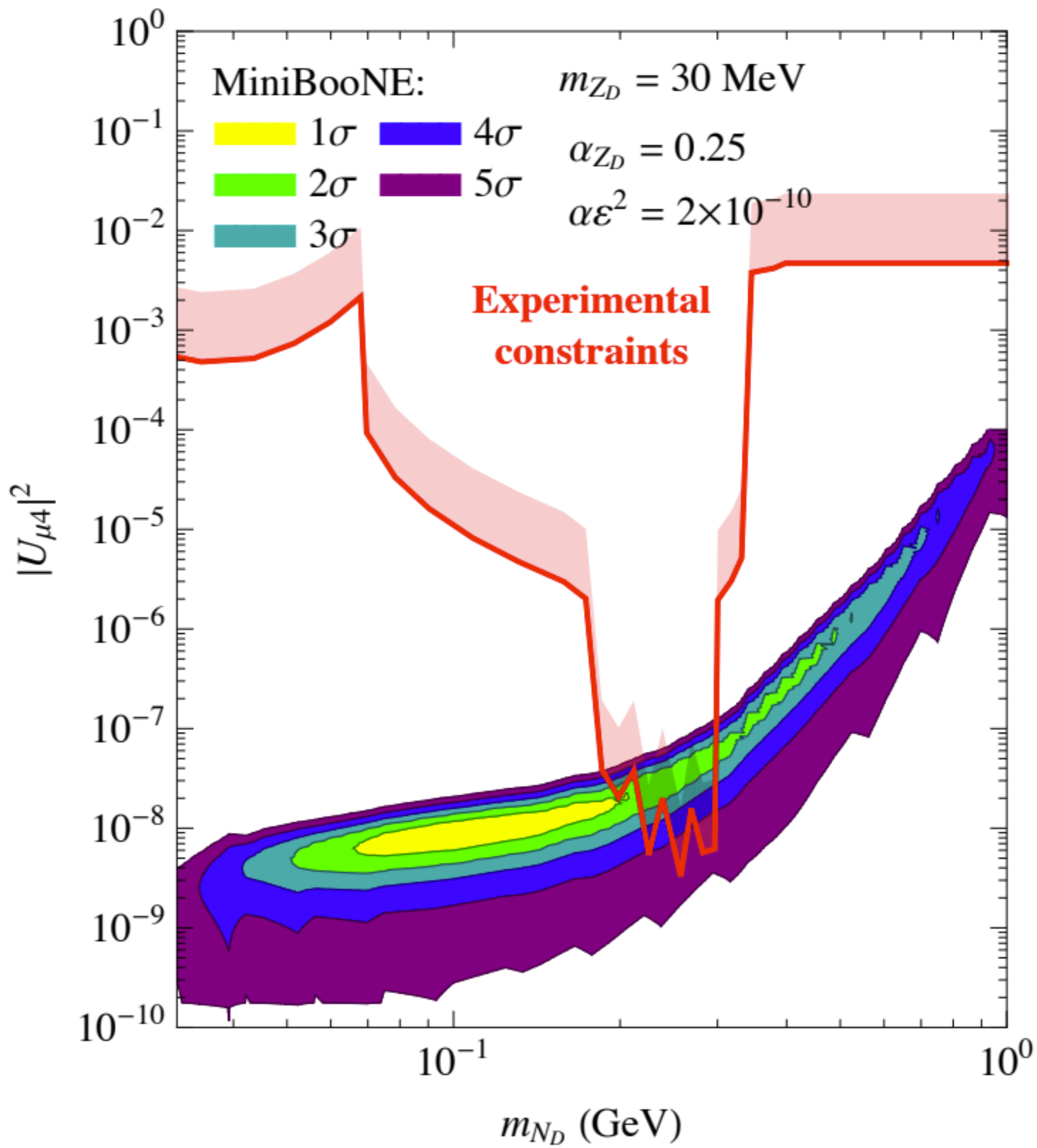


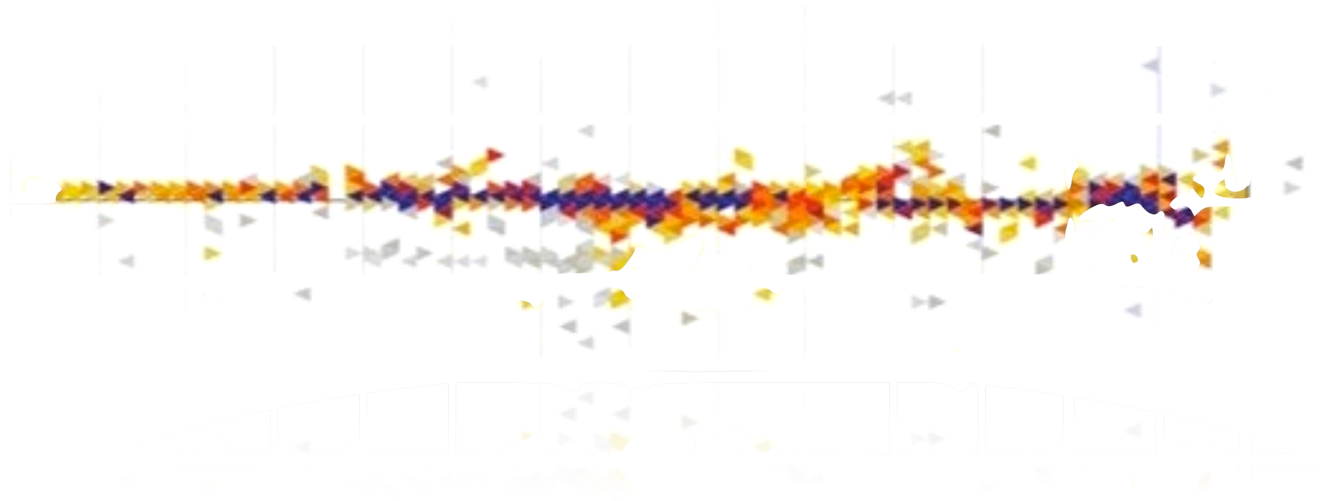
$m_{Z'} < m_4$

Testing light dark photon case

Coherent signal

$m_{Z'} < m_4$

— single <u>boosted</u> EM shower —



See pi0 and coherent gammas. Also recent search for coherent gammas in T2K.

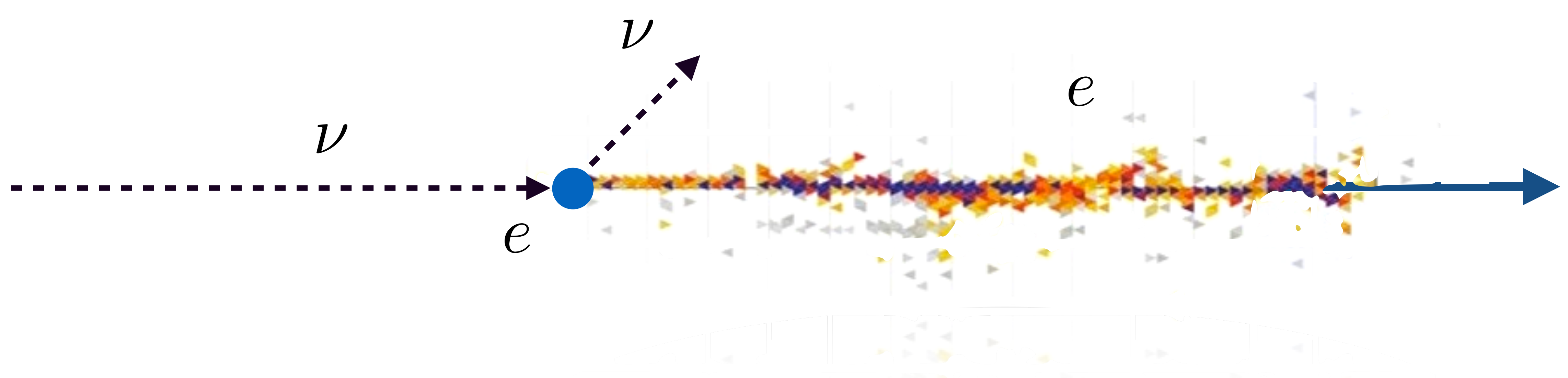
Testing light dark photon case

Coherent signal

$m_{Z'} < m_4$

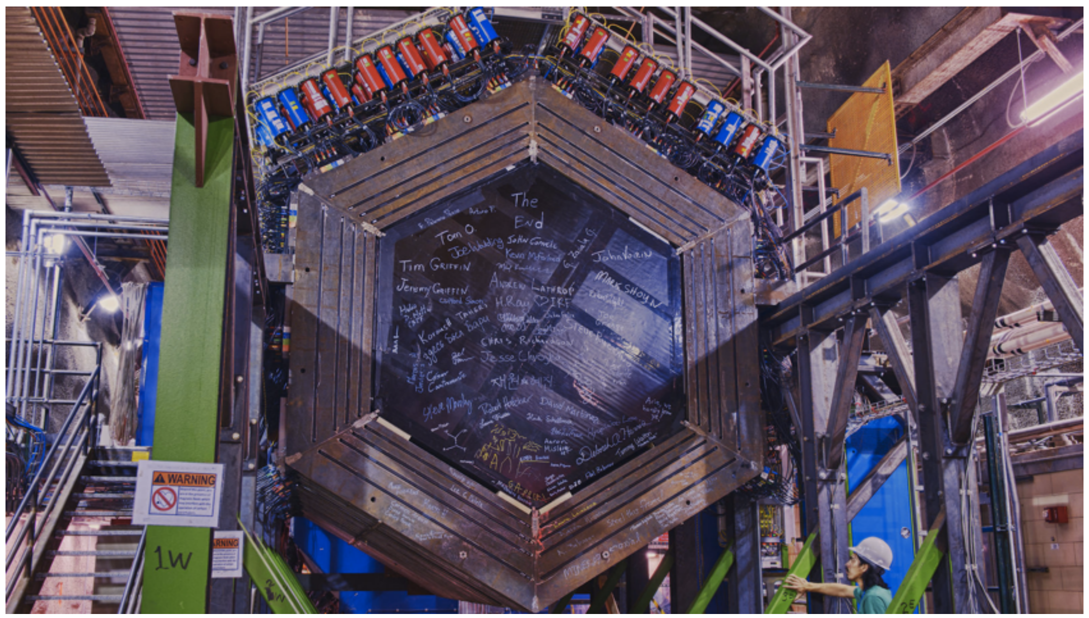
— single <u>boosted</u> EM shower —

neutrino-electron scattering.



Rare SM process with similar signature.

Neutrino-electron scattering



MINERvA
NuMI beam FNAL
Low-Energy data on nu-e scattering
8 t

CHARM-II
WANF beam at CERN back in the 90s
692 t

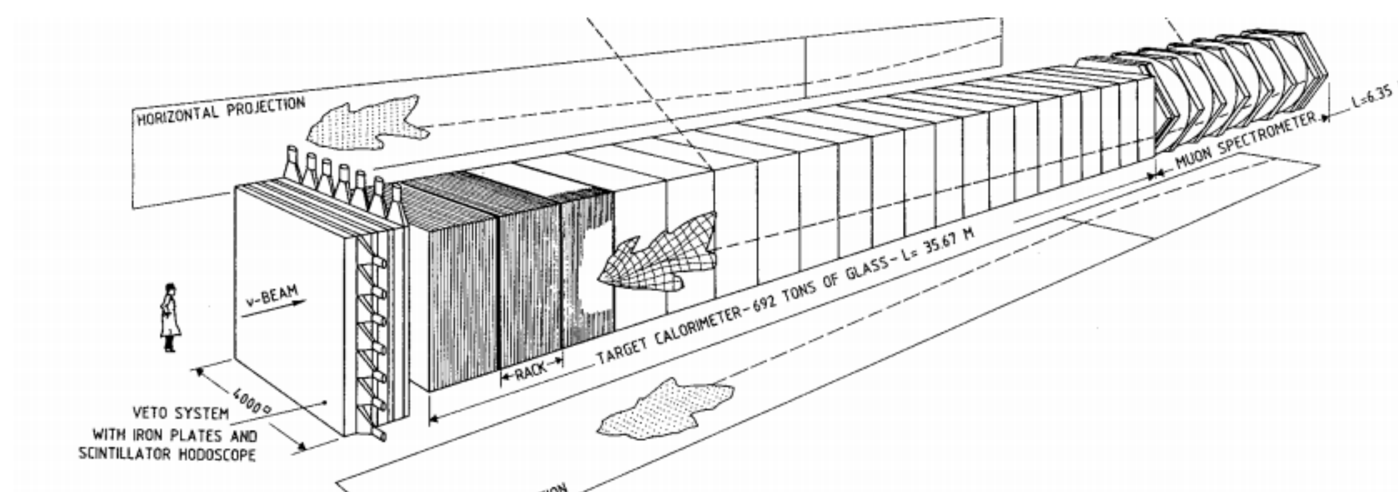
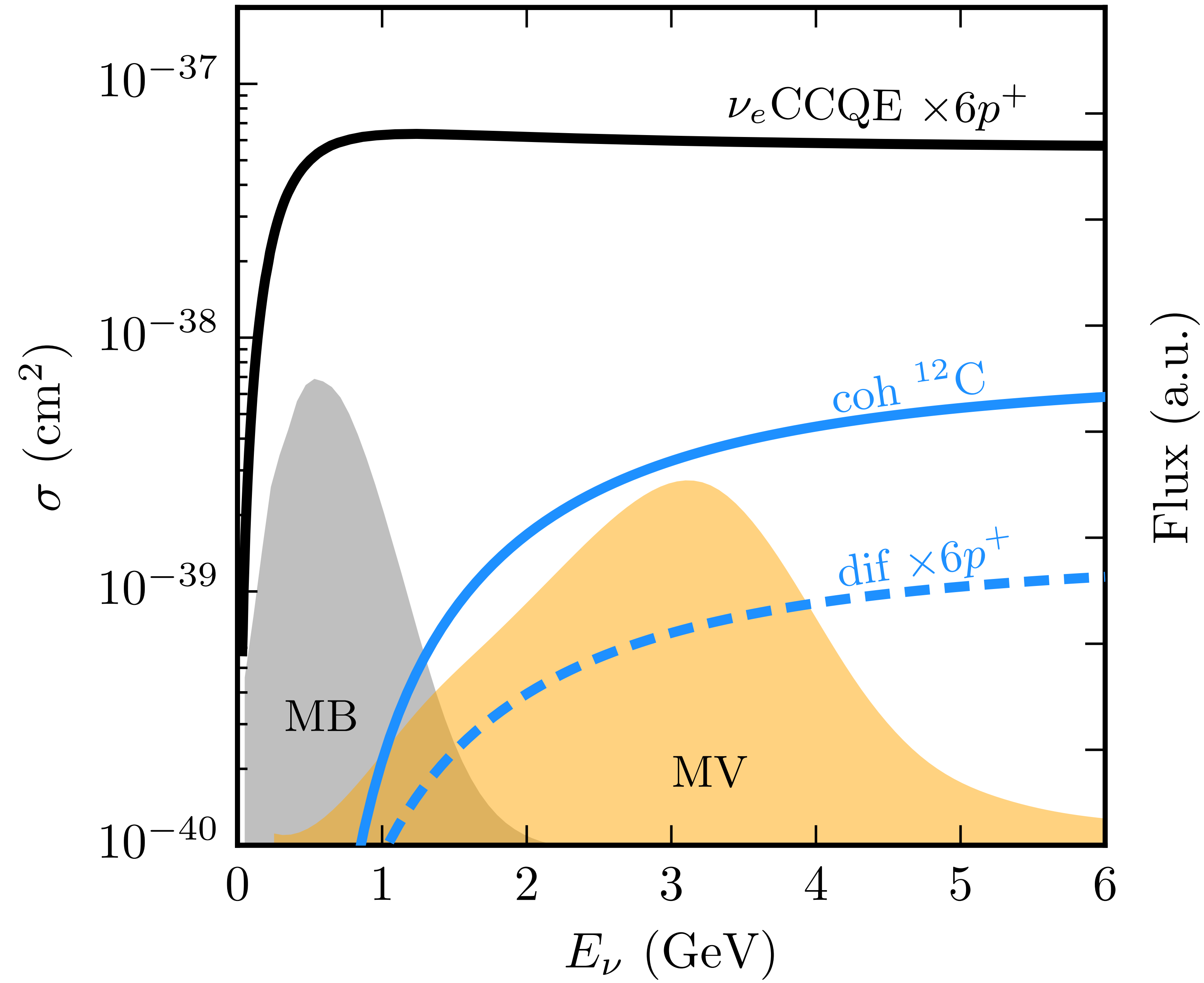
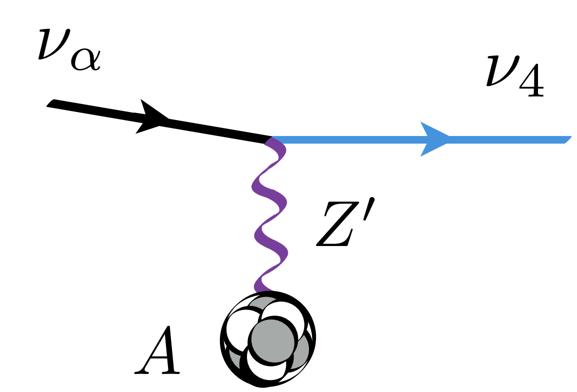


Fig. 2

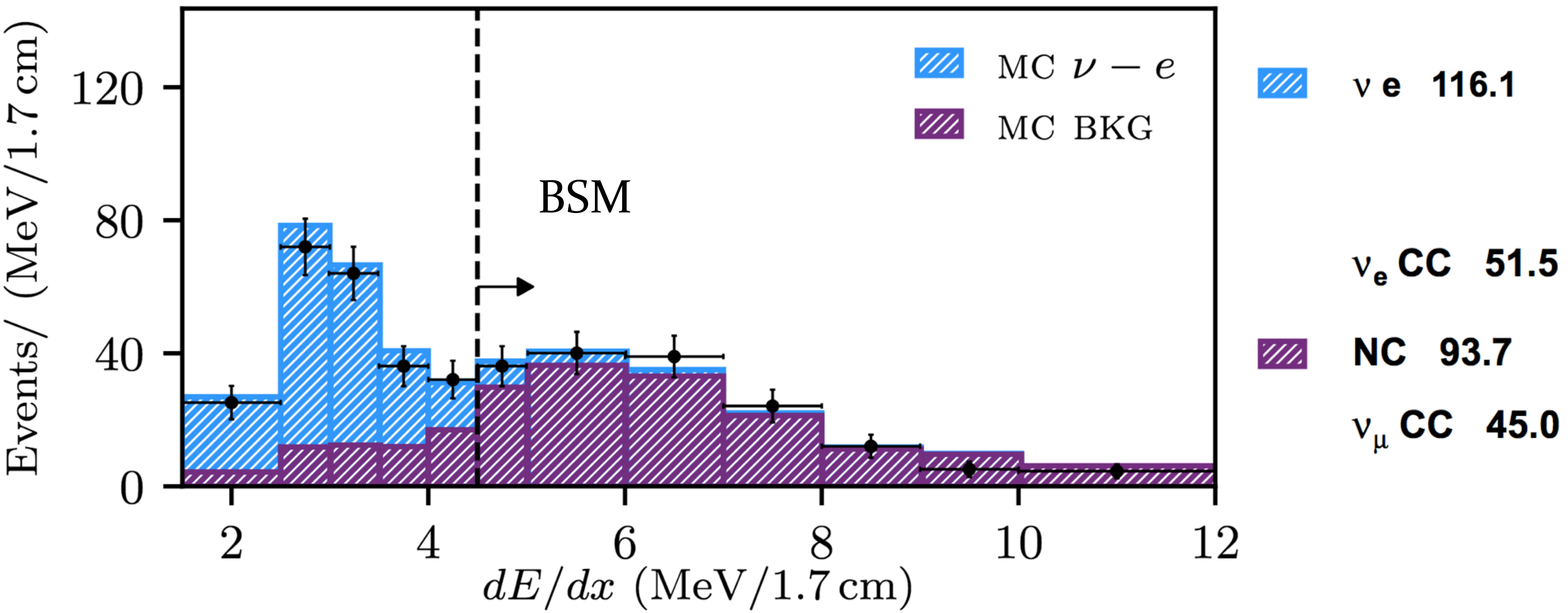
BSM cross sections



New physics is large at larger energies!



MINERvA



Backgrounds are small but are tuned! Based on tuning, assign a 30% uncertainty.

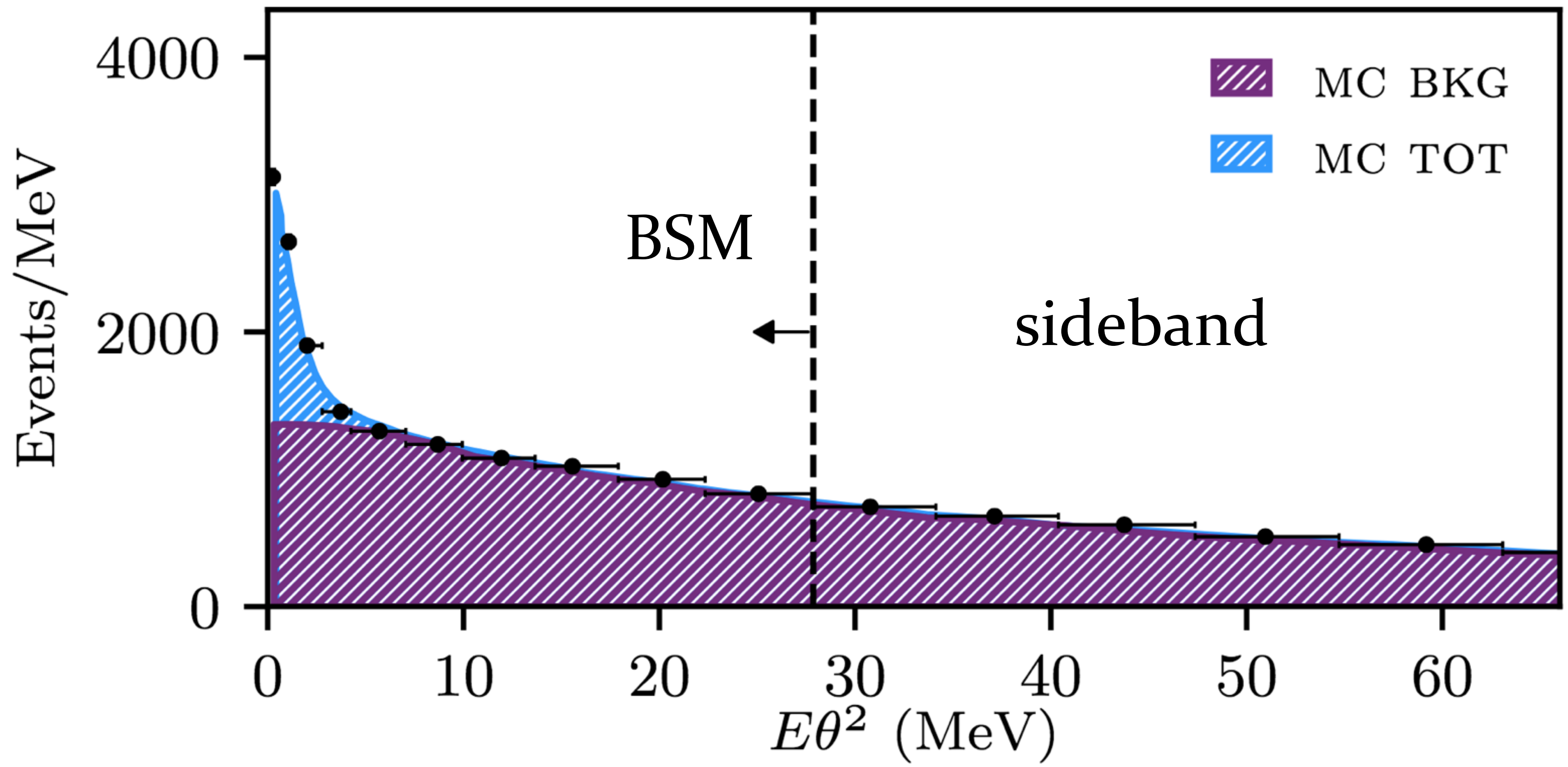
BSM signal typically overshoots bkg:
232 BSM events!

CHARM-II

$\nu - e$

2677 ± 82 events in the ν beam and

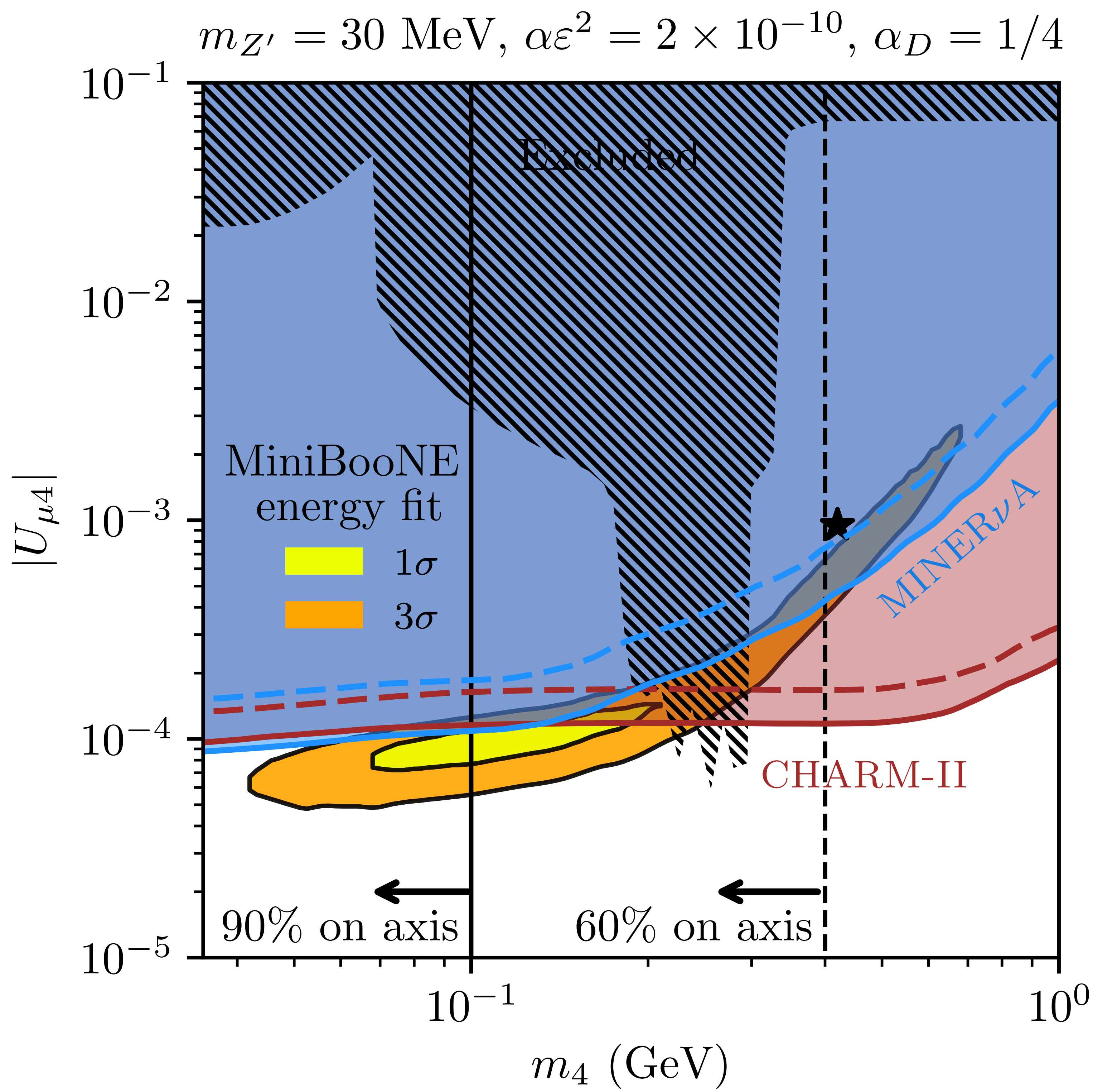
2752 ± 88 events in the $\bar{\nu}$ beam



Measure backgrounds at large angles (3% uncertainties).

1.43×10^5 BSM events in signal region!

Constraints on light boson case



$m_{Z'} < m_4$

Vary background systematics:

from 30% — 100% for MINERvA

from 3 — 10% for CHARM-II

Small mass region:
disagreement with angular data!

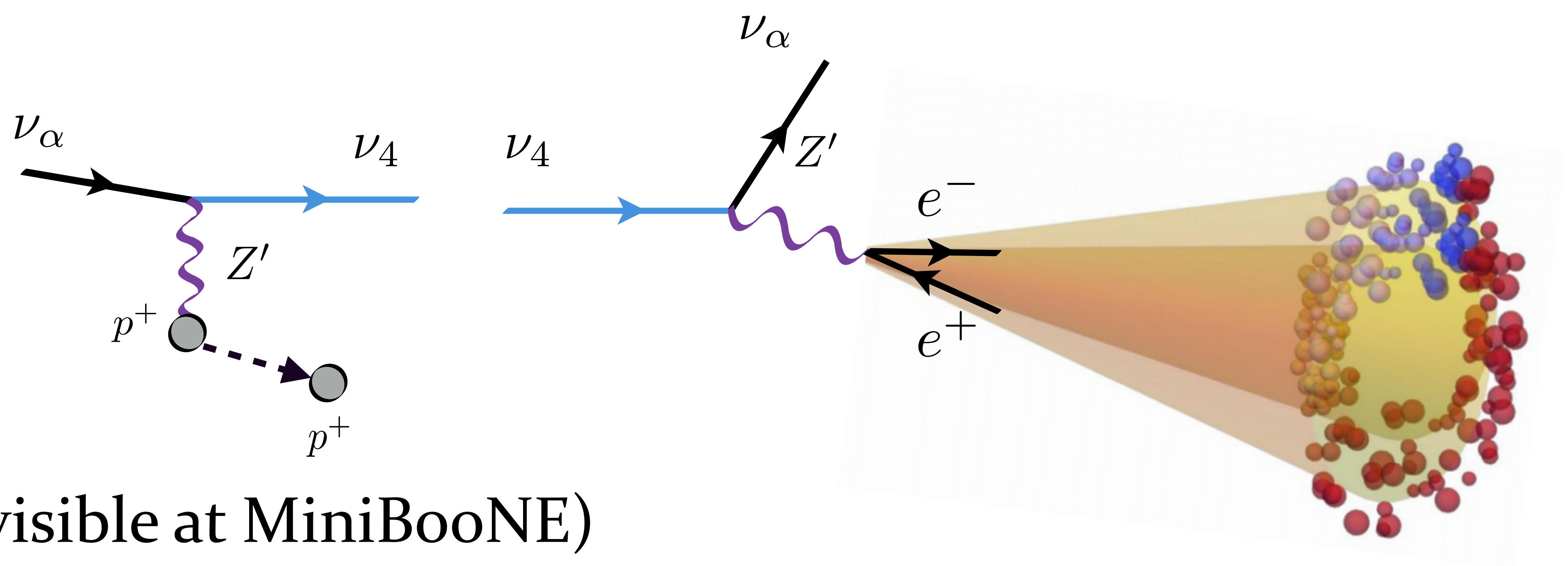
Heavy dark photon case

P. Ballett et al. arXiv:1808.02915

$m_{Z'} > m_4$

Incoherent signal

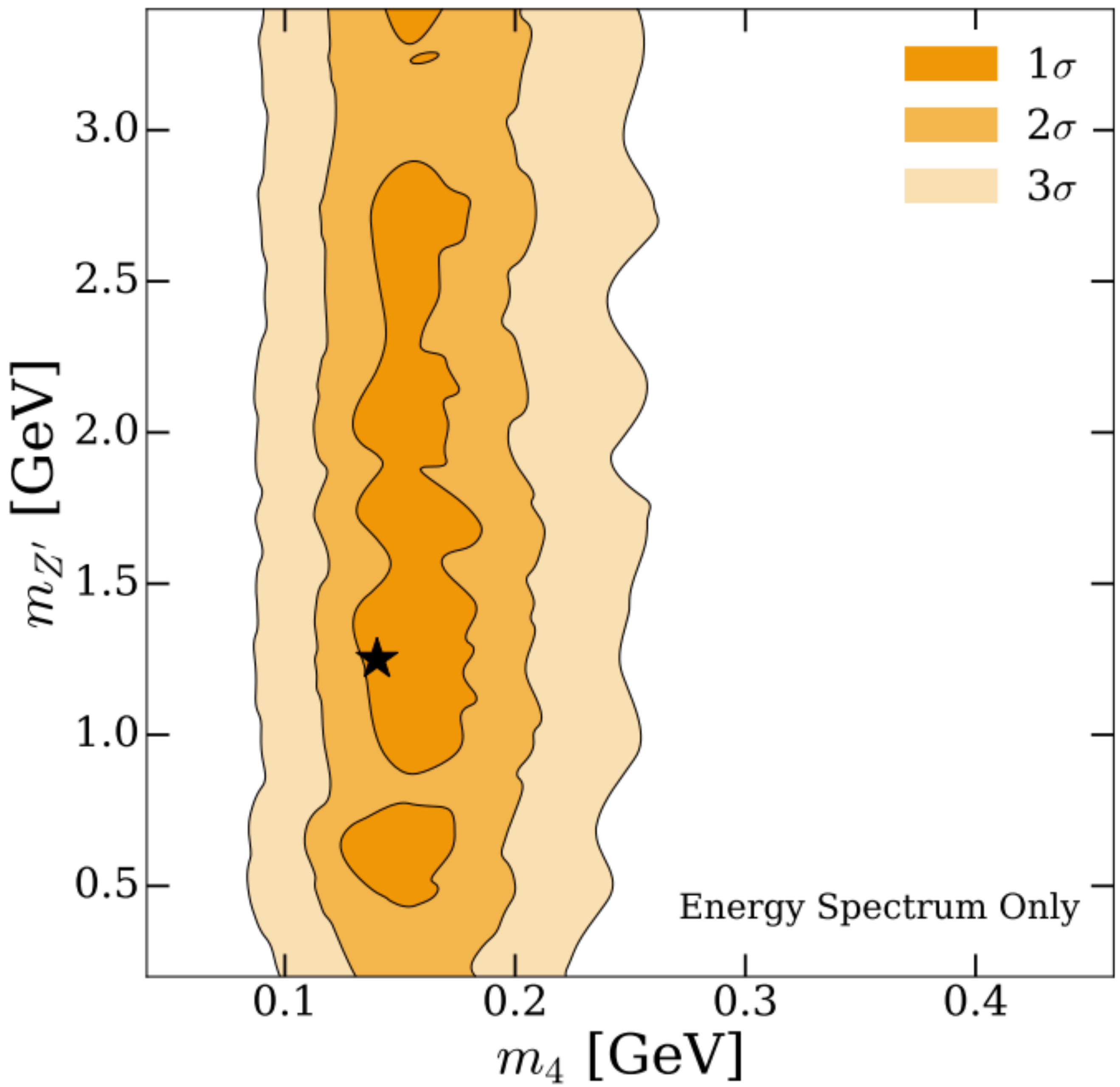
— single EM shower + some hadronic activity —

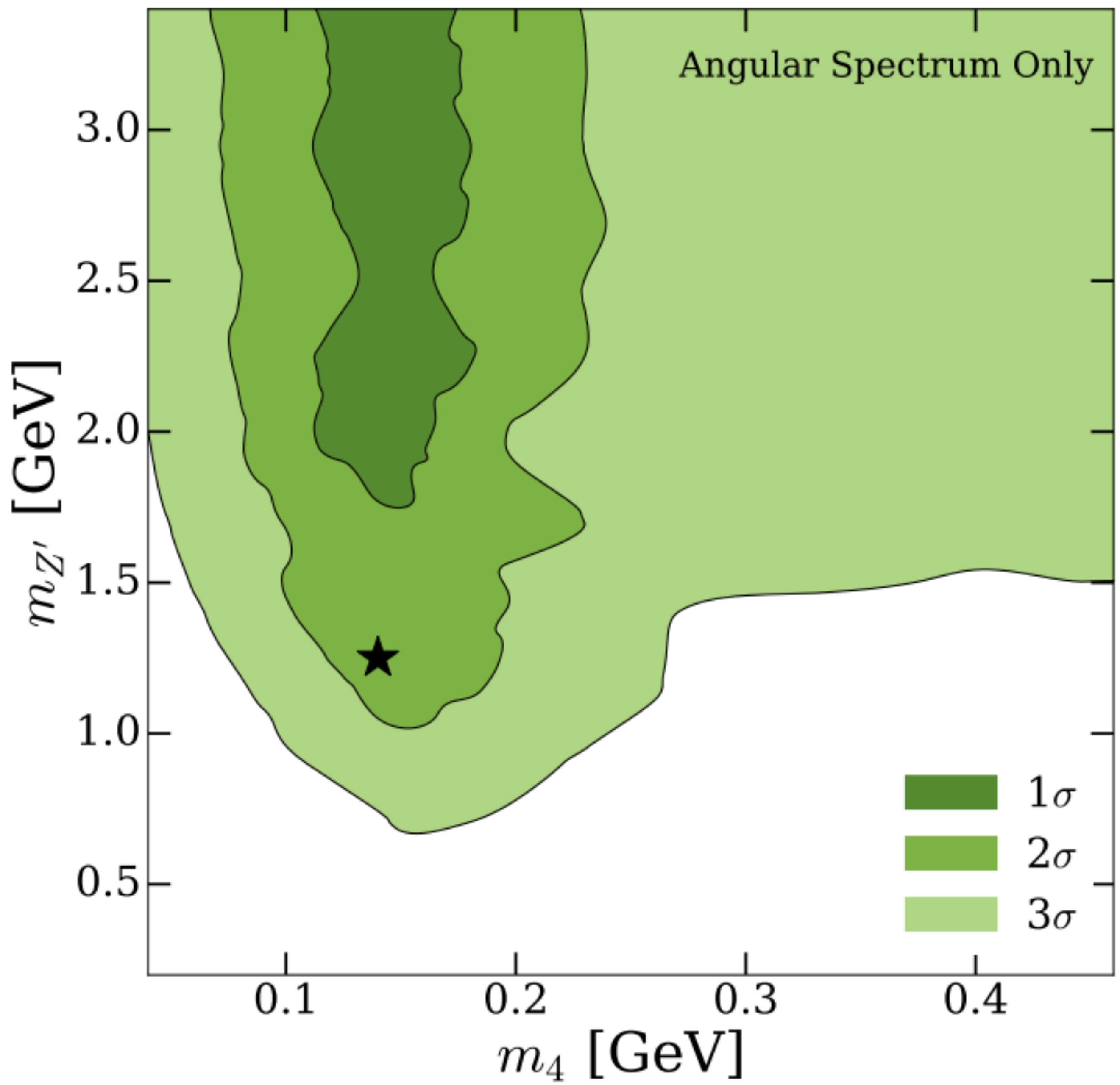


(invisible at MiniBooNE)

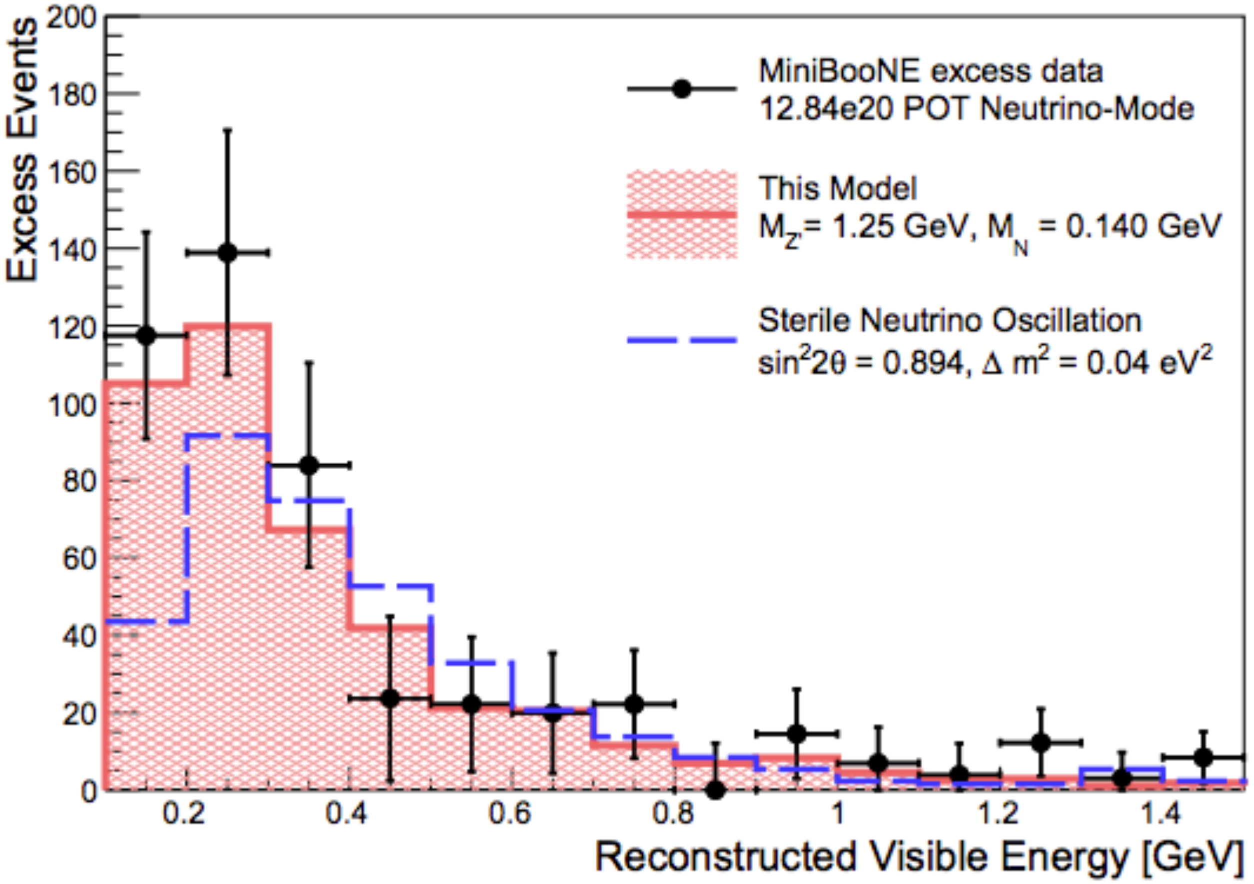
Heavy dark photon case

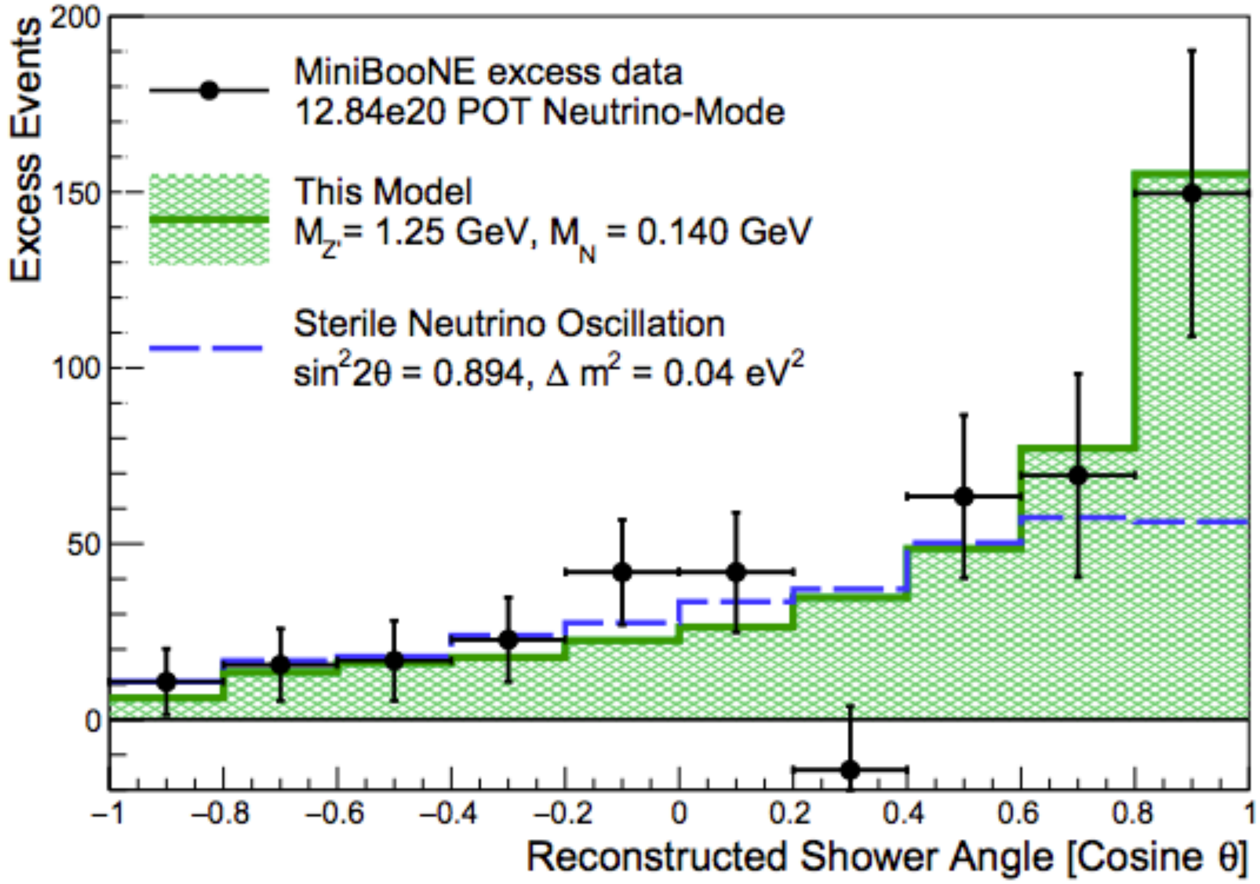
Shape-only fit





Heavy dark photon case





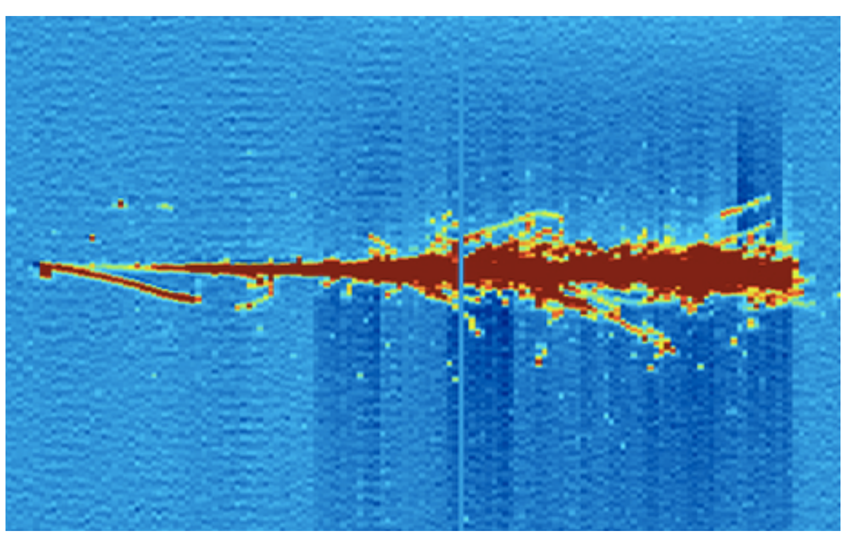
Much better angular fit to MiniBooNE data throughout parameter space.

Prospects for this case?

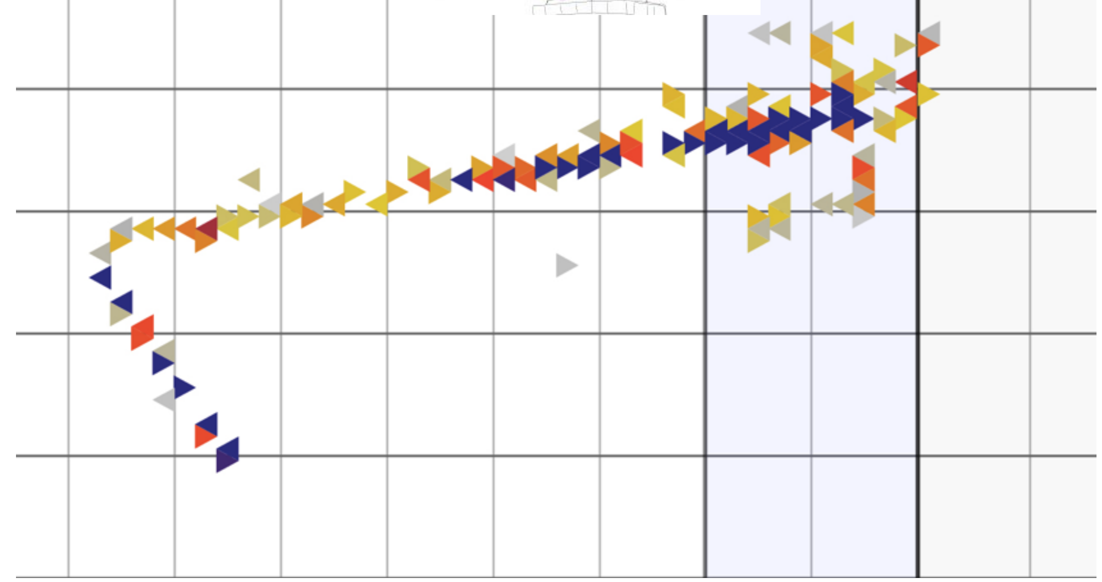
Harder to constrain at neutrino experiments, but could try!

proton + EM shower (+ gap?)

μBooNE



MINERvA



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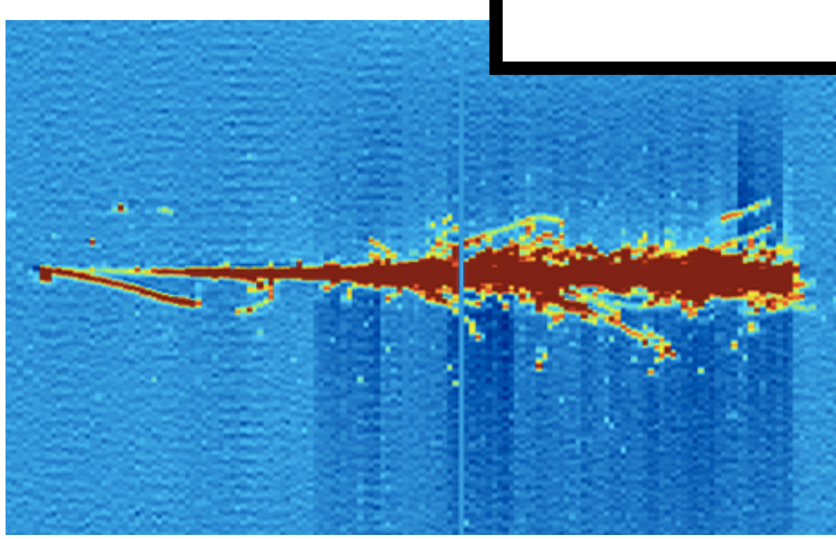
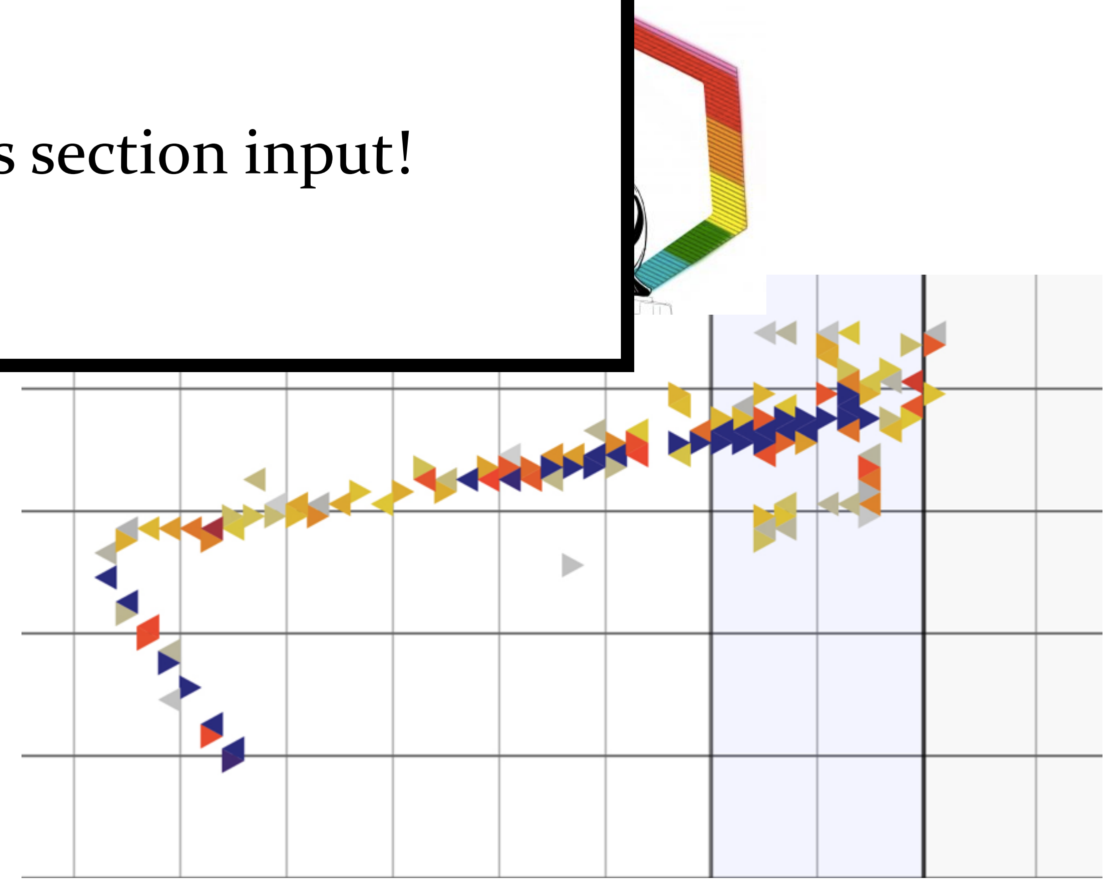


Need neutrino cross section input!



Conclusions

Dark neutrinos are a class of models with
novel interactions connected to the neutrino sector.

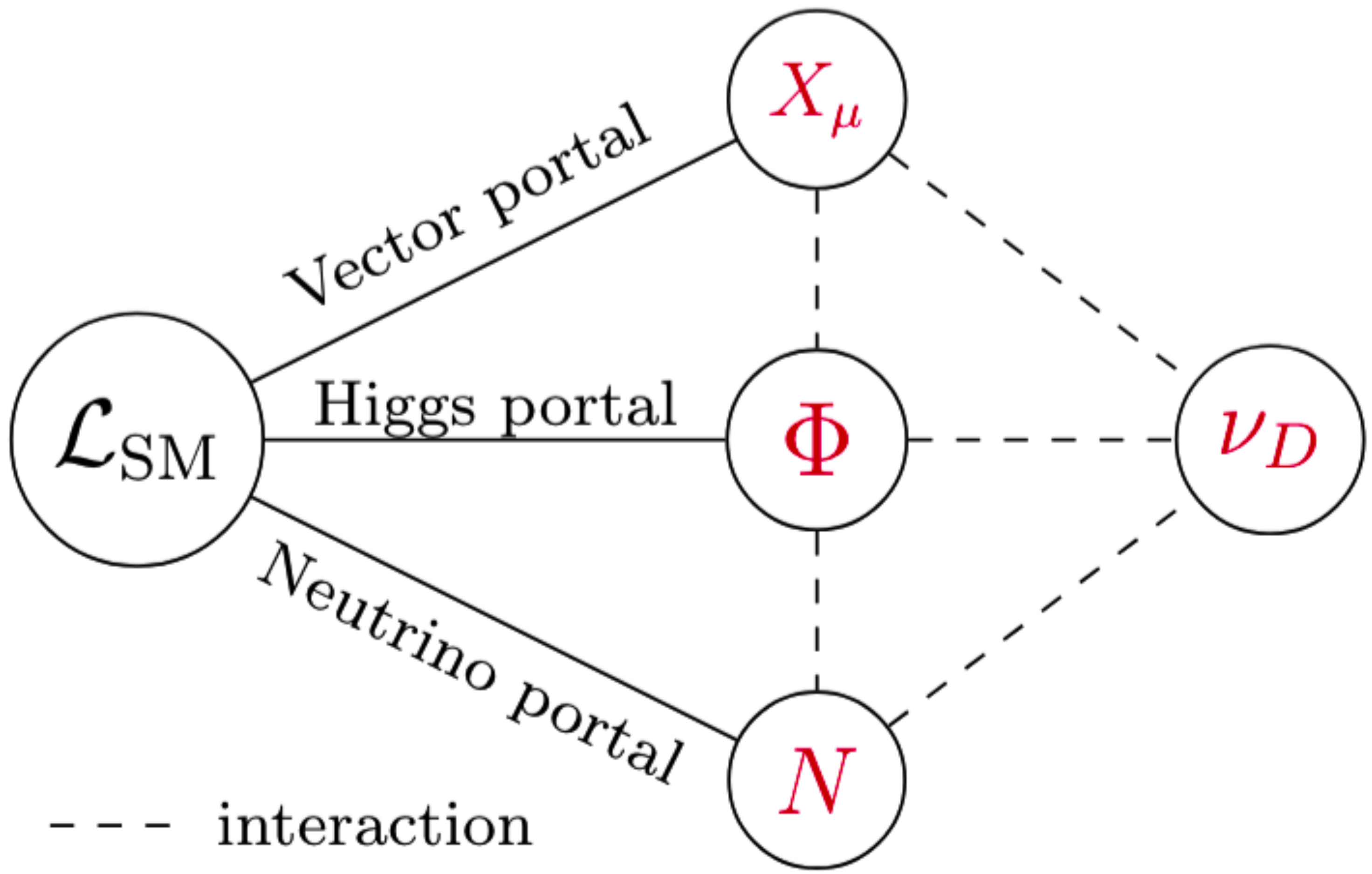
Can also generate neutrino masses at one-loop level — novel mechanism

Dark photon and scalar searches do not apply at face value
— more work needed to understand how open the parameter space is—

Predicts the MiniBooNE result in two different realisations.

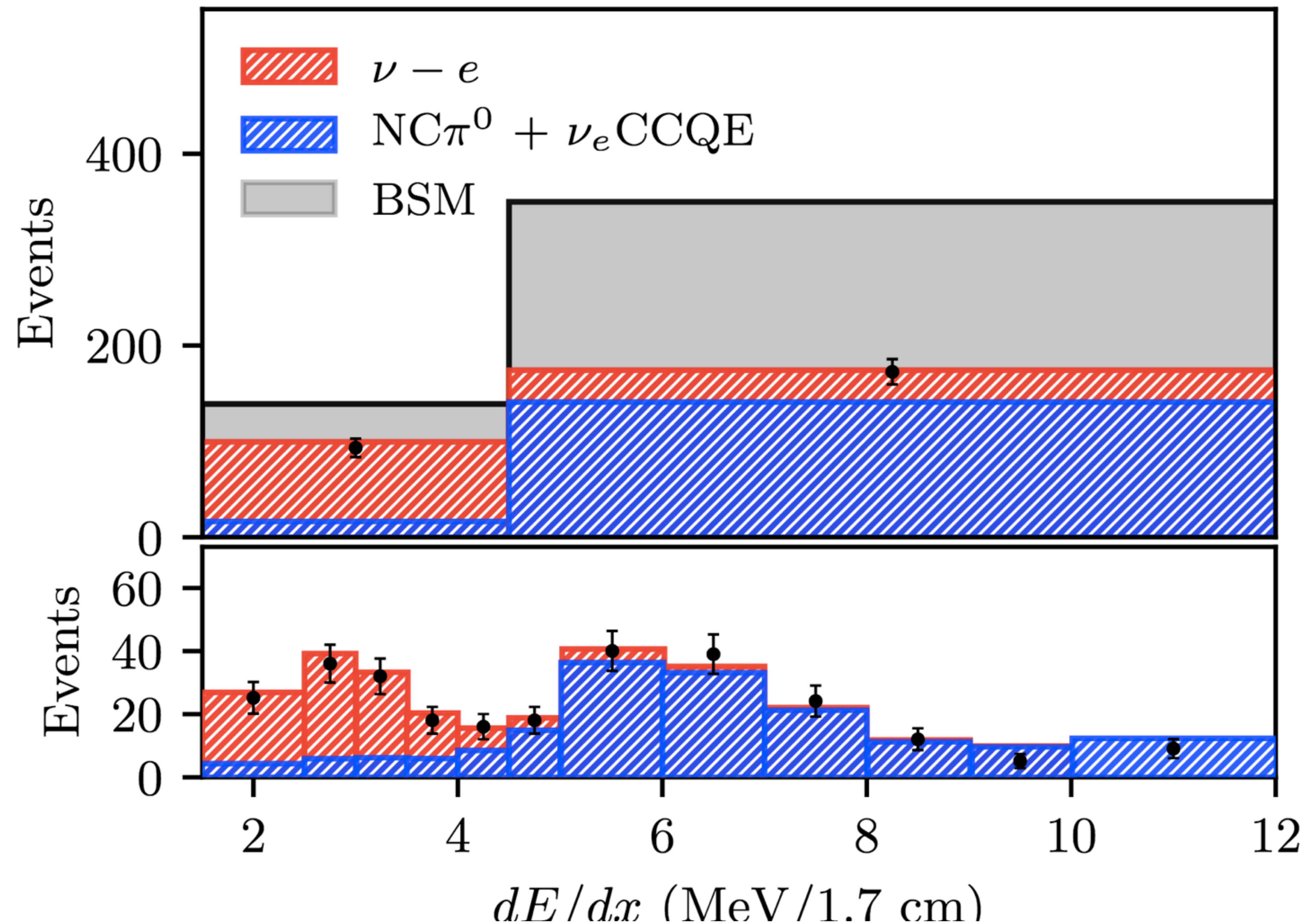
Angular information and nu-e scattering data points us
to heavy dark photon masses (~1 GeV) boson mass.

THANK YOU



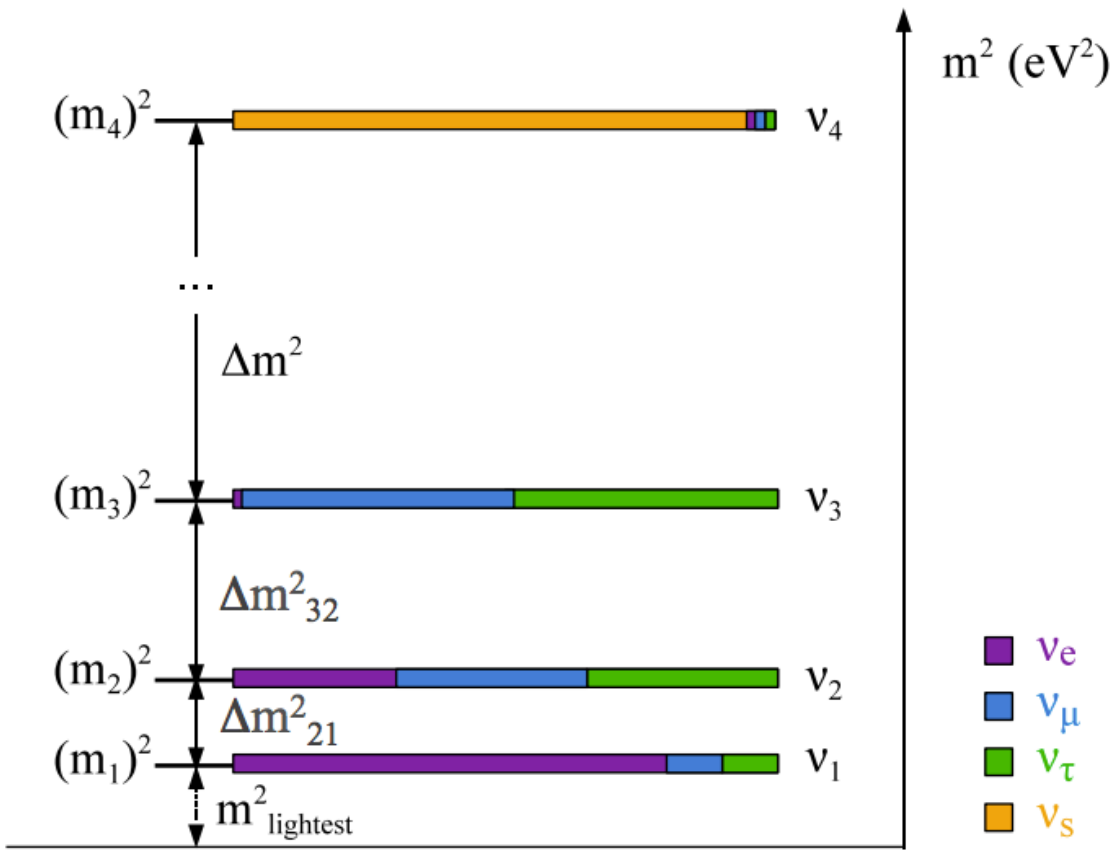
X_μ
Vector portal
$\mathcal{L}_{\rm SM}$
Higgs portal
Φ
ν_D
Neutrino portal
N
interaction

APPENDIX



$\nu - e$
$\mathrm{NC}\pi^0 + \nu_e\mathrm{CCQE}$
BSM
Events
400
200
0
Events
60
40
20
0
2
4
6
8
10
12
dE/dx (MeV/1.7 cm)

eV sterile neutrinos



Sterile neutrino with eV mass

$$P^{3+1}_{\nu_e\to\nu_\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2}{4E}\right)$$

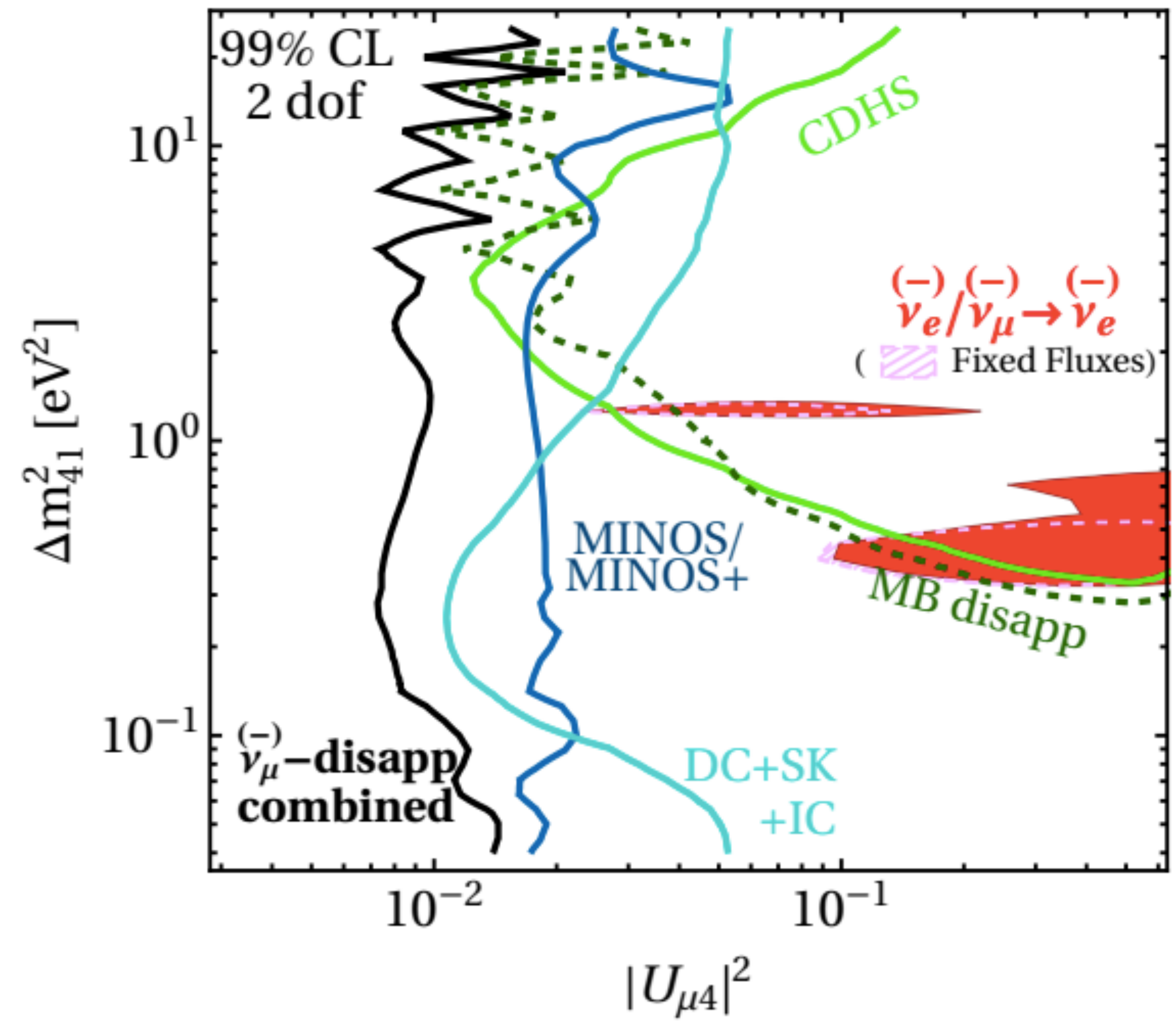
$$P^{3+1}_{\nu_\mu\to\nu_\mu} = 1 - 4\,|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m^2}{4E}\right)$$

Need electron and muon disappearance

for an appearance signal.

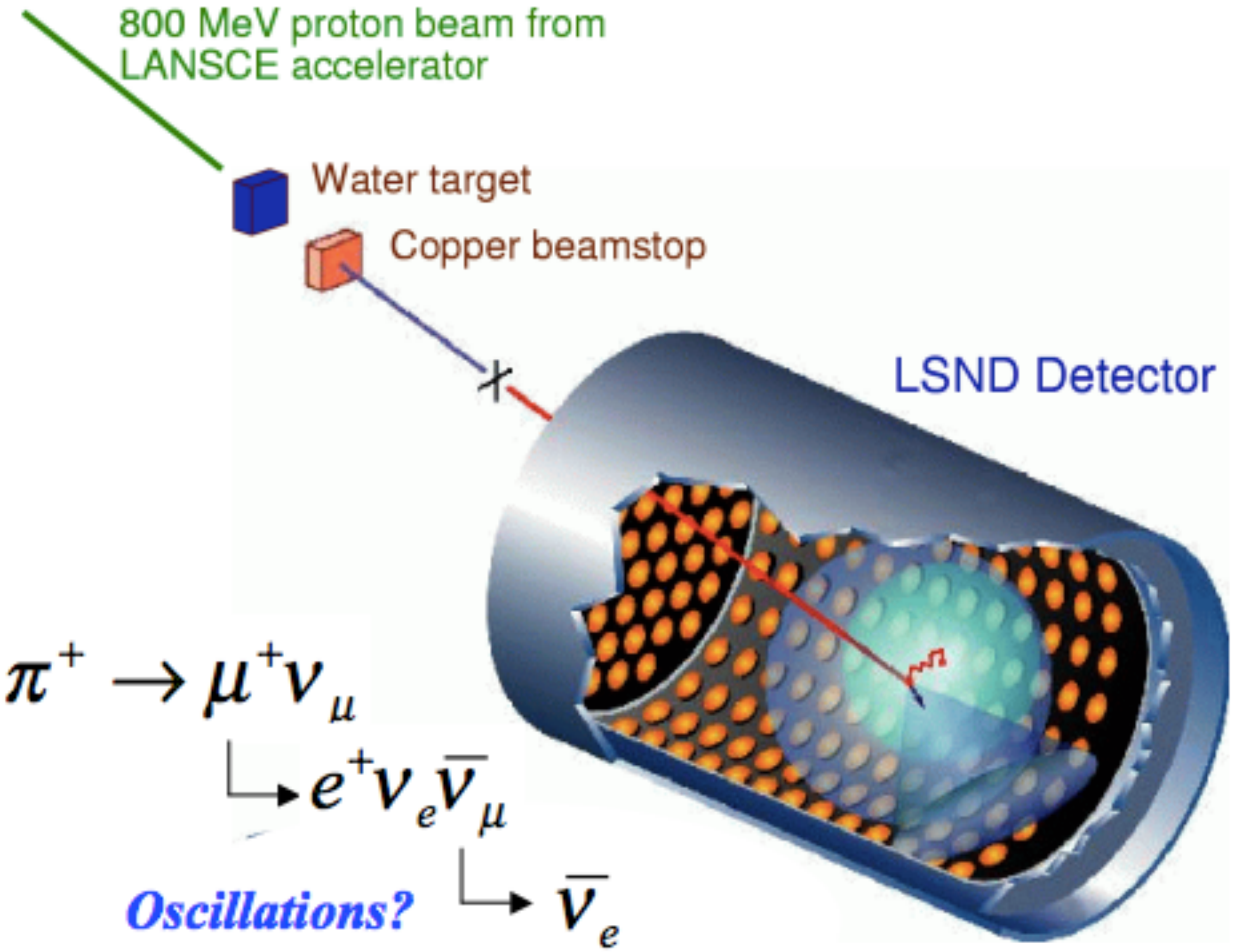
eV sterile neutrinos

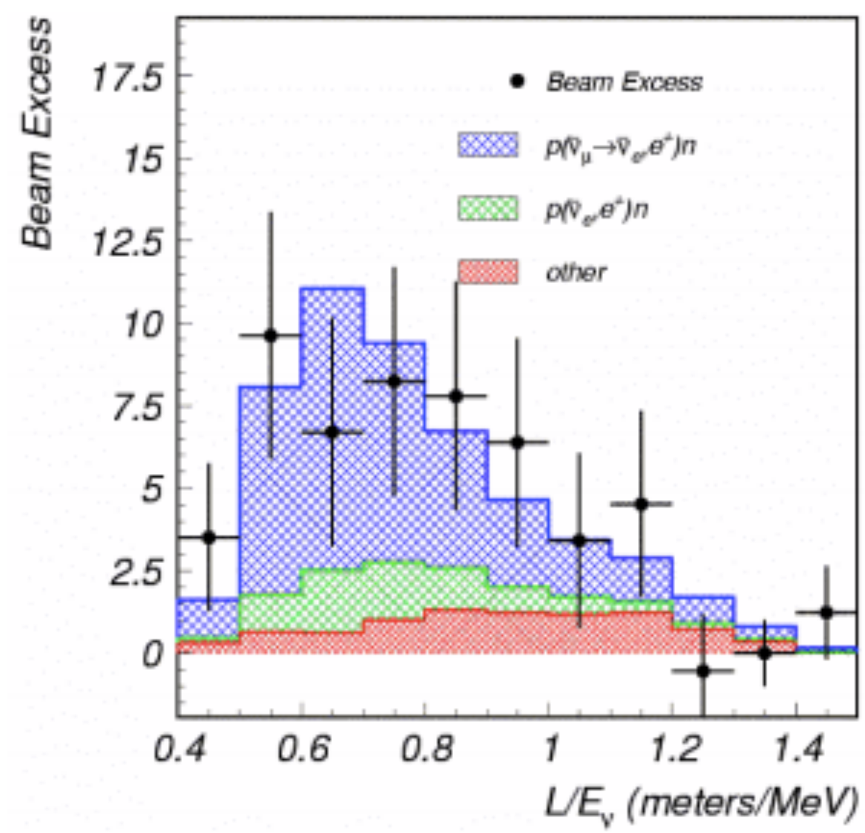
Standard eV sterile explanation in large tension with disappearance experiments.



See Dentler at al, 1803.10661

LSND





LSND in conjunction with the atmospheric and solar oscillation results needs more than 3 ν's

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.

M. Shaevits, BLV2011

A closer look

Series of published papers by HARP-CDP collaboration.

Anomaly goes from 3.8σ to 2.3σ.

Revisiting the 'LSND anomaly' I: impact of new data

The HARP-CDP Group: A. Bolshakova, I. Boyko, G. Chelkov, D. Dedovitch, A.

Revisiting the 'LSND anomaly' II: critique of the data analysis

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Corrections to the HARP-CDP Analysis of the LSND Neutrino Oscillation Backgrounds

G. T. Garvey, W. C. Louis, G. B. Mills, D. H. White

Unpublished 1 page paper as reply.

Conclusion claimed to hold, but discussions end here because…

Reply to 'Corrections to the HARP-CDP Analysis of the LSND Neutrino Oscillation Backgrounds'

A. Bolshakova, I. Boyko, G. Chelkov, D. Dedovitch, A. Elagin, D. Emelyanov, M. Gostkin, A. Guskov, Z. Kroumchtein, Y. Nefedov, K. Nikolaev, A. Zhemchugov, F. Dydak, J. Wotschack, A. De Min, V. Ammosov, V. Gapienko, V. Koreshev, A. Semak, Y. Sviridov, E. Usenko, V. Zaets

(Submitted on 16 Dec 2011)