Severe Constraints on New Physics Interpretations of the MiniBooNE Excess

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arXiv:1810.07185

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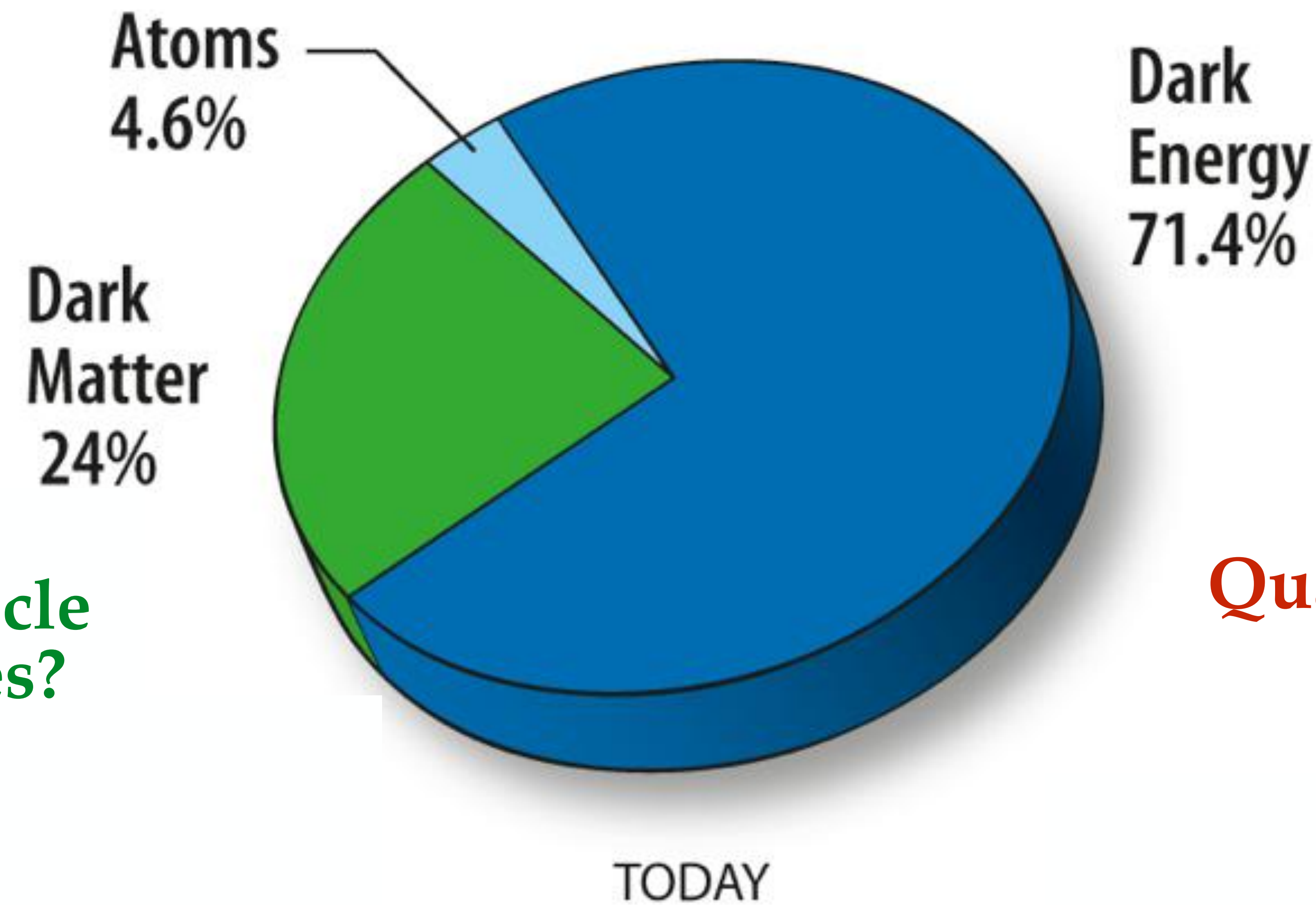
Theory Seminar — Nov 14, 2018

Zeroth Order Questions in Fundamental Physics

Neutrino Masses?
Matter Asymmetry
Inflation

Accelerated Cosmic Expansion



DM Particle Properties?

Quantum Gravity

Recent 2018 MiniBooNE results relevant for both DM and ν

Overview

1) History of the MiniBooNE Excess

2) Excluding Simple Models w/ Kinematic Distributions

3) Excluding (Nearly) All Other Models w/ Beam Dump Data

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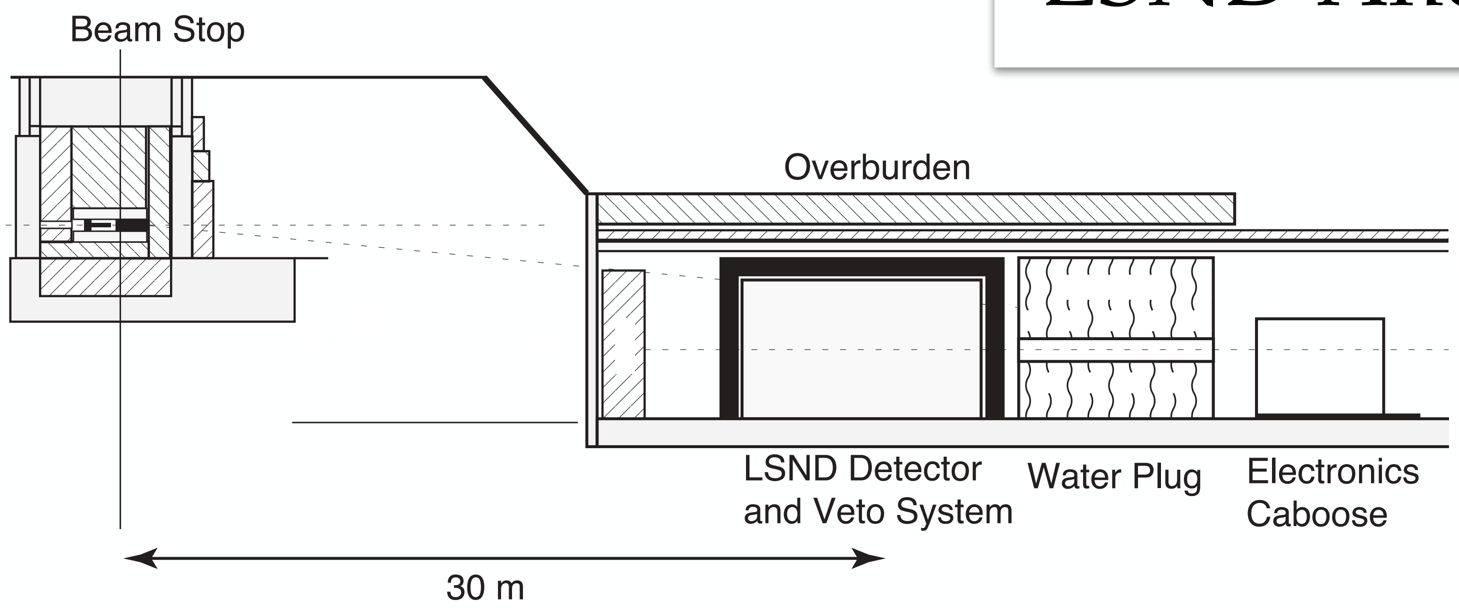
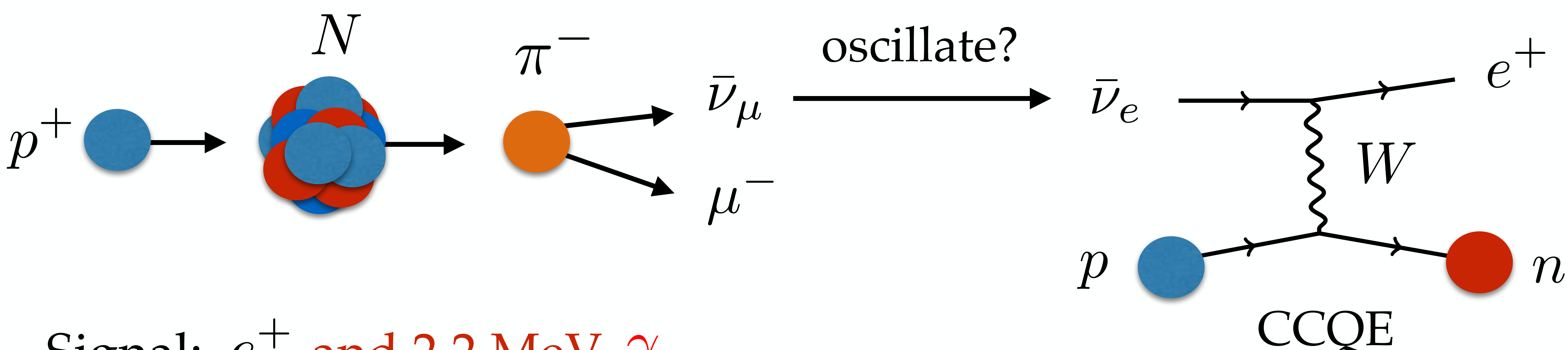
LSND Anomaly



10^{22} POT, $E_p = 800$ MeV



Signal: e^+ and 2.2 MeV γ

Scatter + neutron absorption

Observed 90 events

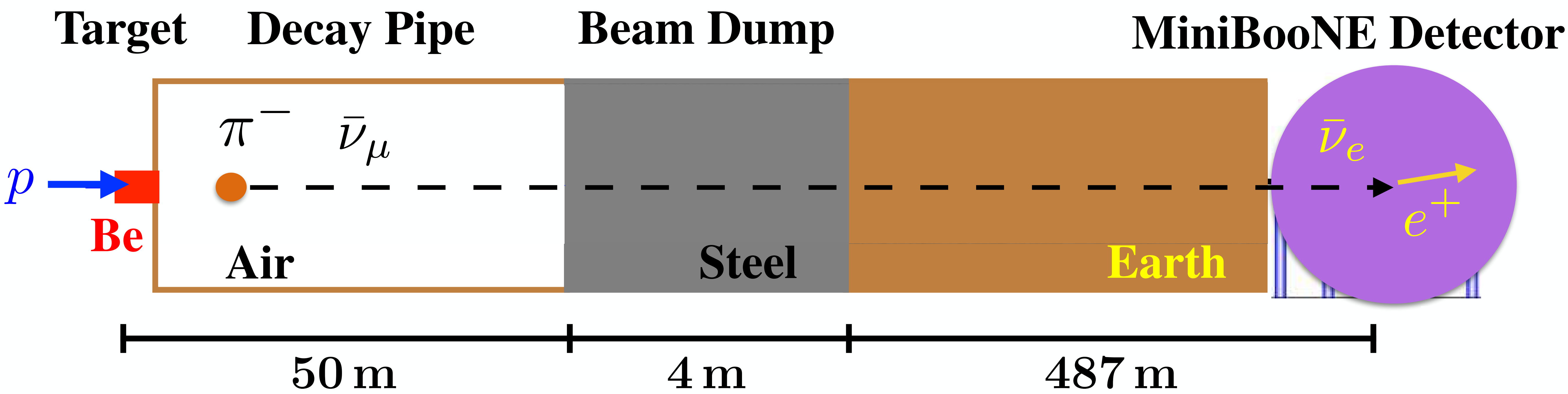
Expectation of 0 events

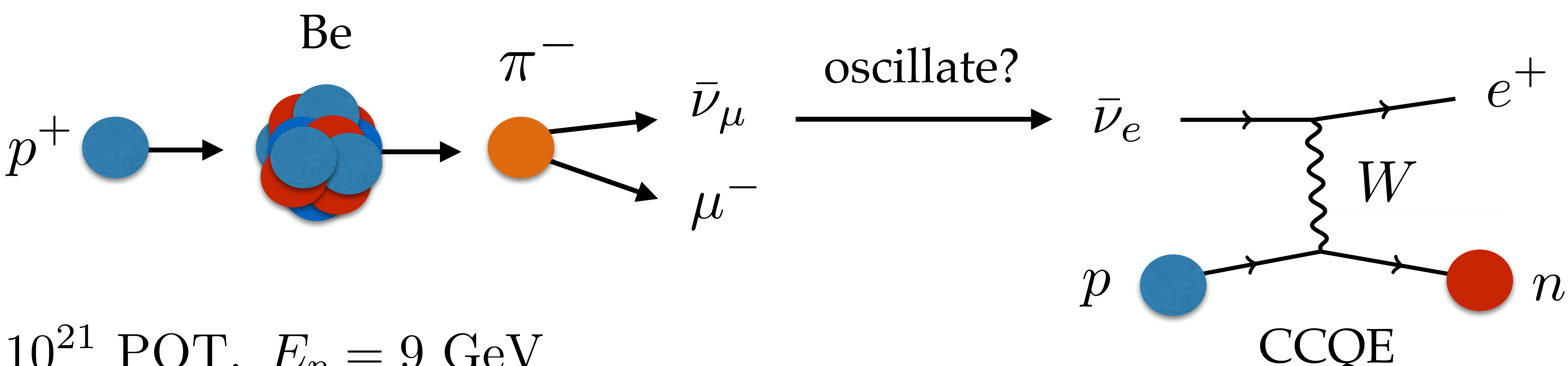
3.8σ significance

$$P_{\text{osc}} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

LSND Collaboration hep-ex/0104049

MiniBooNE Experimental Setup





10^{21} POT, $E_p = 9$ GeV

Energy and baseline chosen to test LSND

Comparable oscillation probabilities

MiniBooNE Collaboration 1805.12028

MiniBooNE Analysis Details

	neutrino mode	antineutrino mode
Luminosity	12.84×10^{20} POT	11.27×10^{20} POT
Reconstructed Neutrino Energy	$200 < E_\nu^{QE} < 1250$ MeV	
Excess events BG subtracted	381.2 ± 85.2	79.3 ± 28.6

Possibly Important Caveat

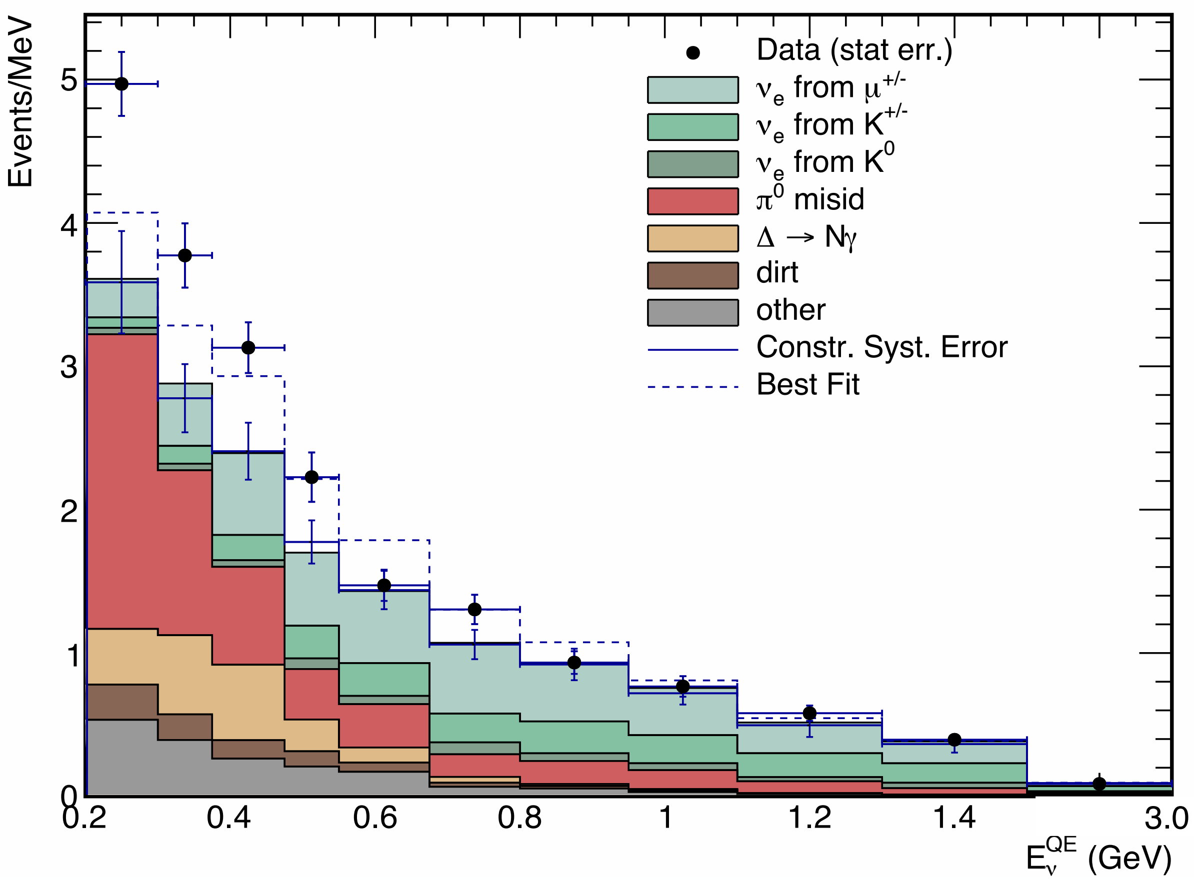
Mild tension ~ 2+ sigma between neutrino and antineutrino modes

Updated Neutrino Mode Analysis
MiniBooNE Collaboration1805.12028

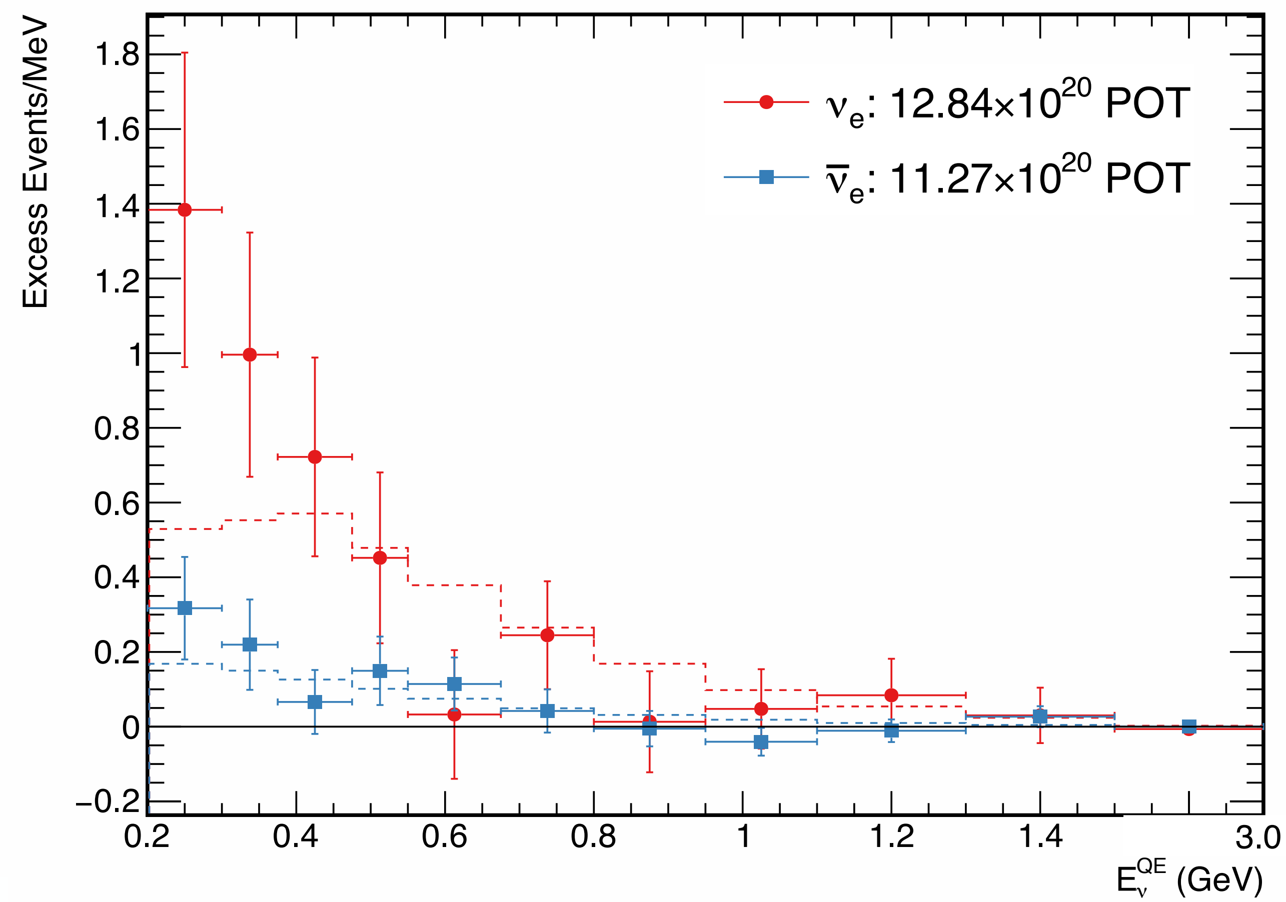
Complements earlier antineutrino
results collected 2002-2010

MiniBooNE Anomaly

Neutrino mode only



Both excesses, BG subtracted



$$E_\nu^{(\text{reconst.})} = \frac{2m_n E_e + m_p^2 - m_n^2 - m_e^2}{2(m_n - E_e + \cos\theta_e \sqrt{E_e^2 - m_e^2})}$$

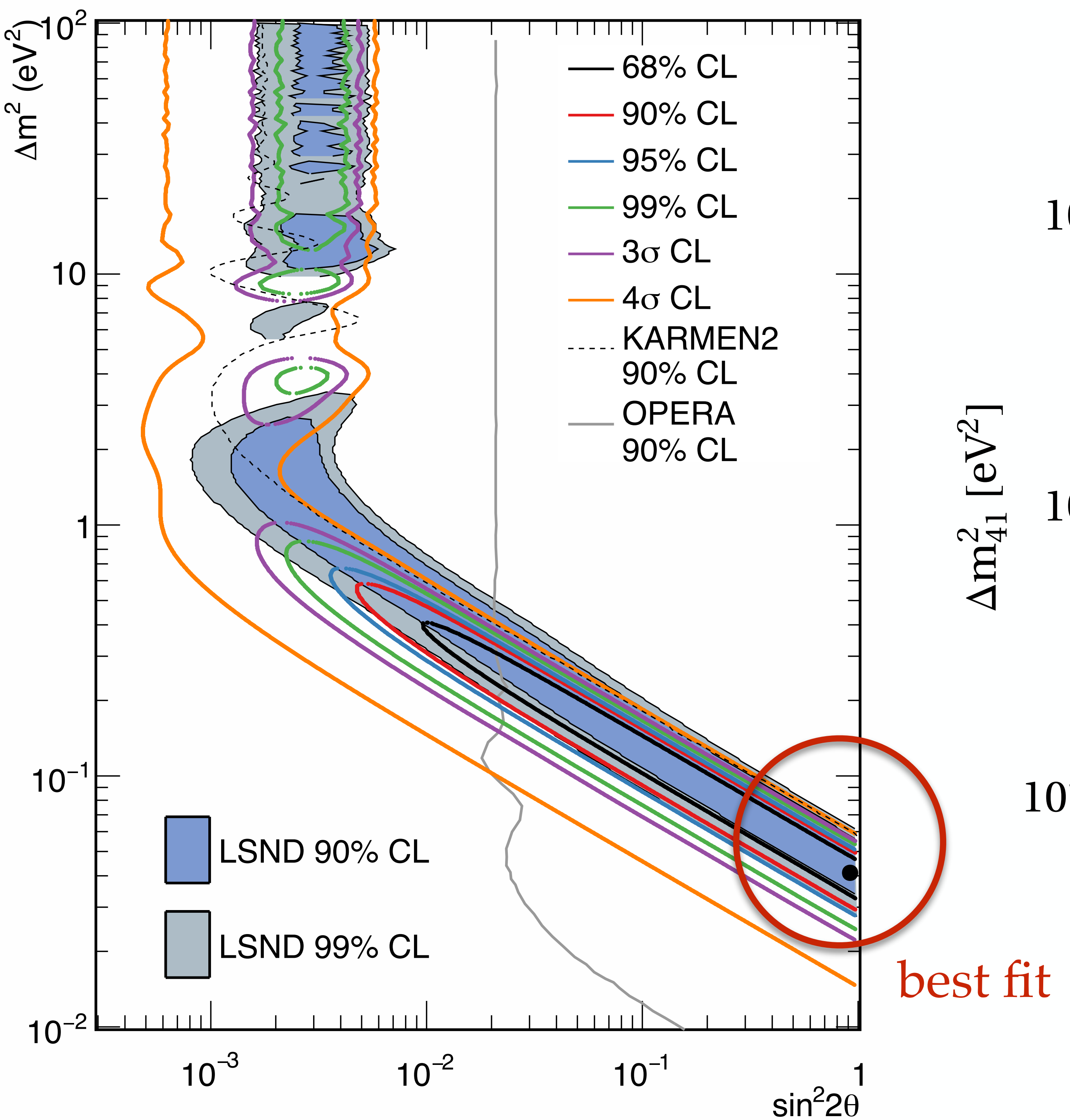
Measure charged lepton energy/angle

Observed ~ 400 events, PMNS predicts 0

Combined $\nu/\bar{\nu}$ modes : 4.8σ excess

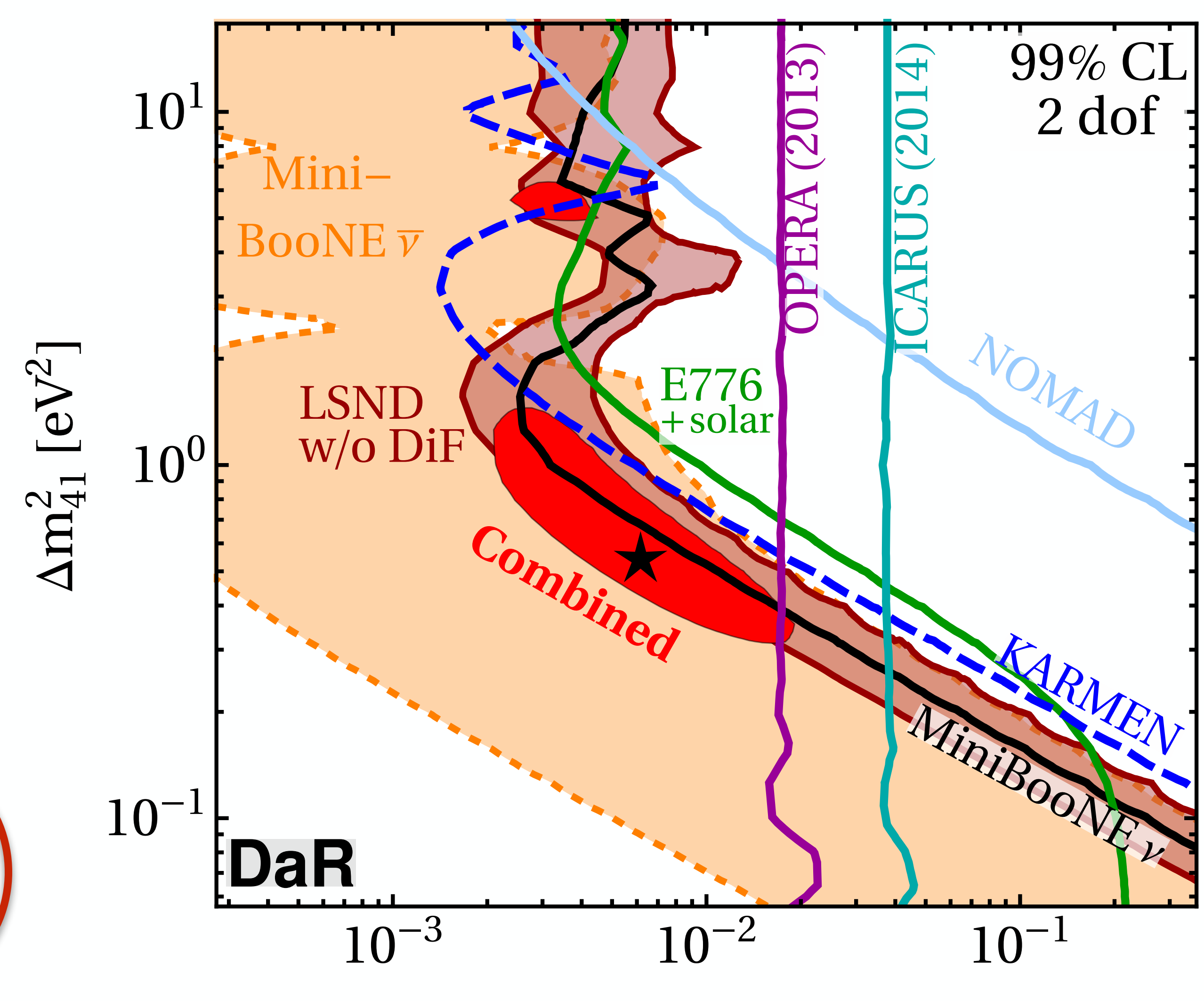
MiniBooNE Collaboration 1805.12028

Explaining LSND + MiniBooNE: **eV Sterile Neutrino?**



MiniBooNE Collaboration 1805.12028

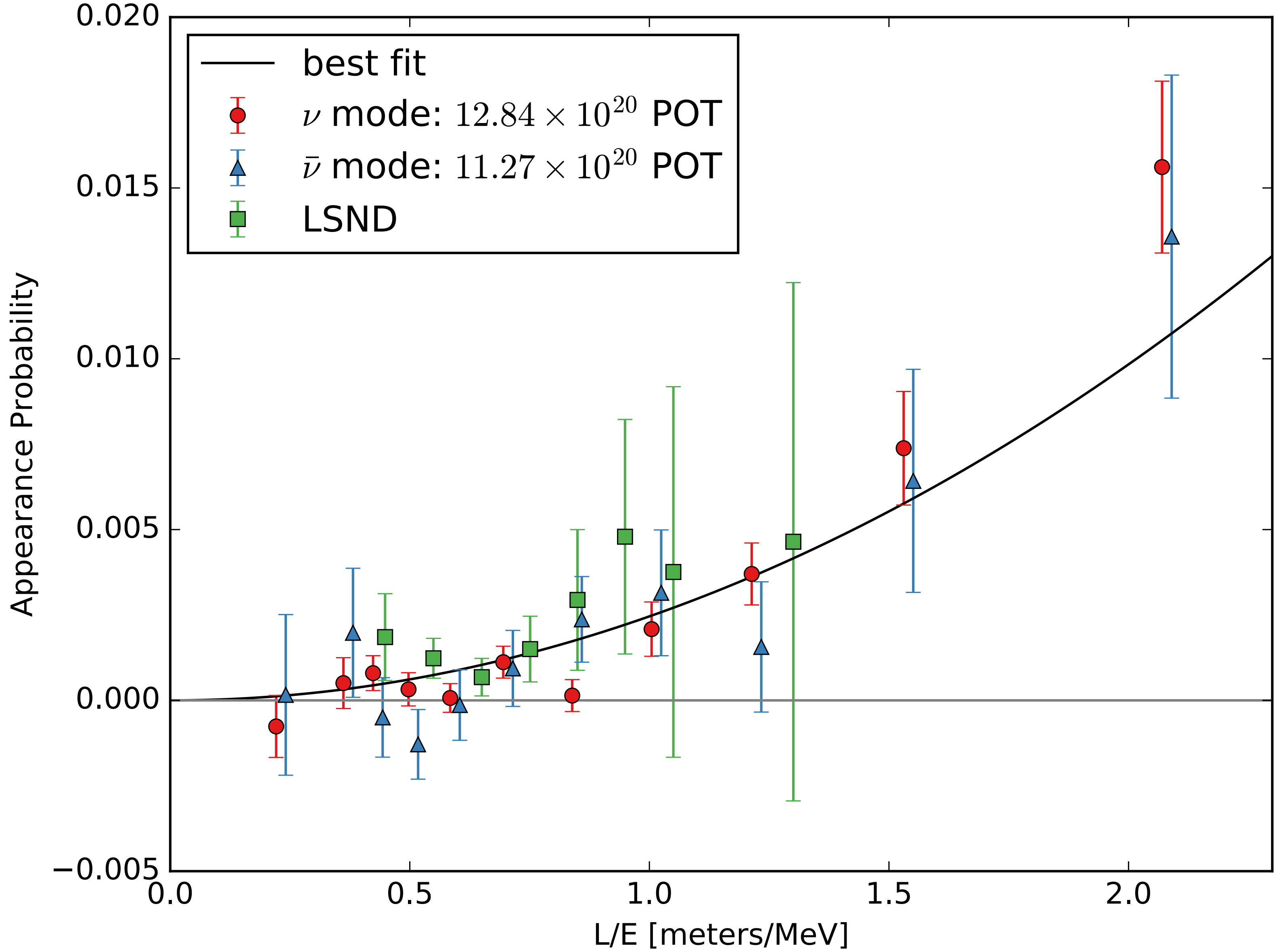
Best fits [appearance only]



Combined 6.1 sigma excess!

Dentler et. al. 1803.10661

Explaining LSND + MiniBooNE: **eV Sterile Neutrino?**

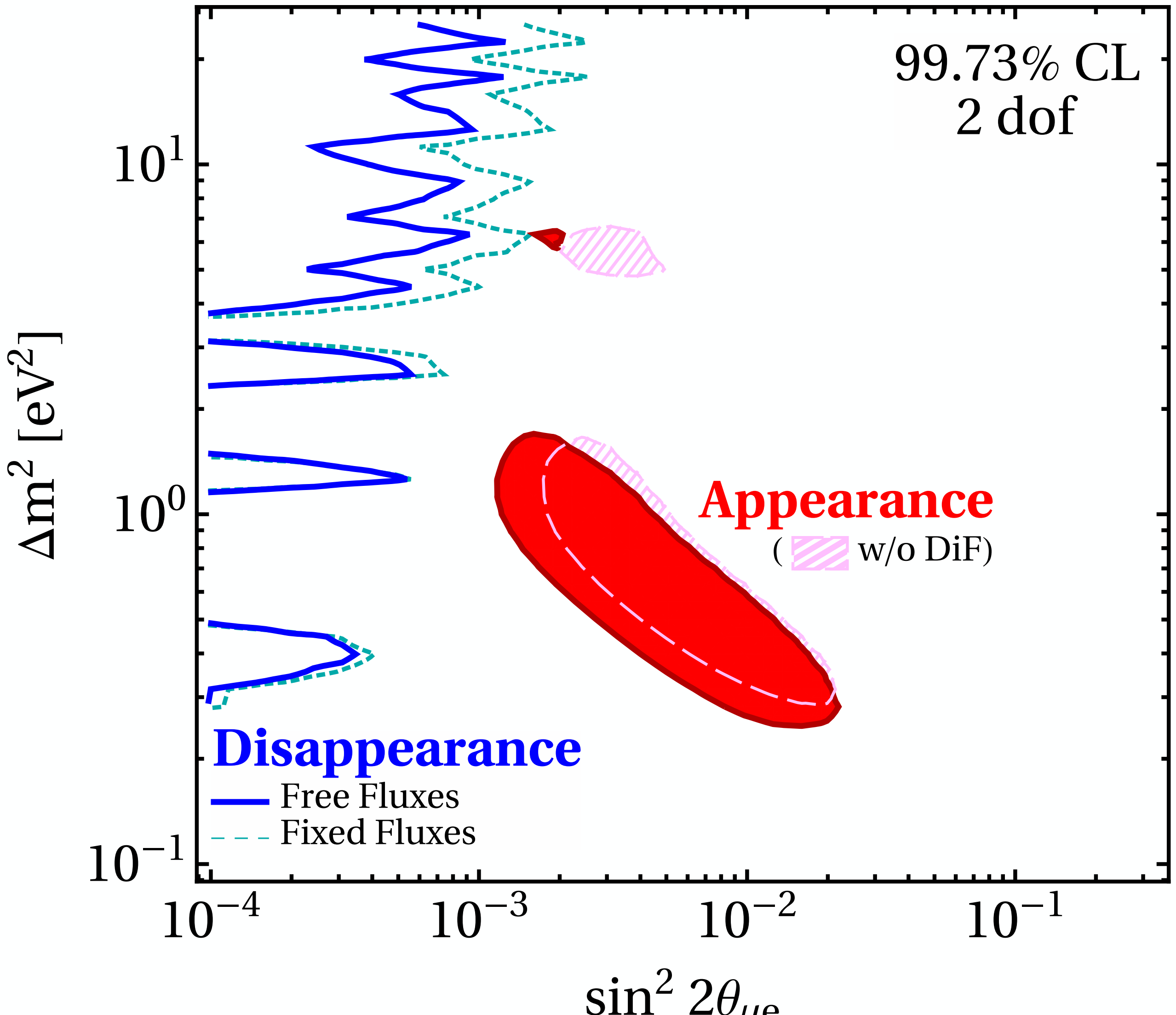


@ face value the scaling seems to support LSND / MB compatibility

MiniBooNE Collaboration 1805.12028

Explaining LSND + MiniBooNE: **eV Sterile Neutrino?**

Including disappearance



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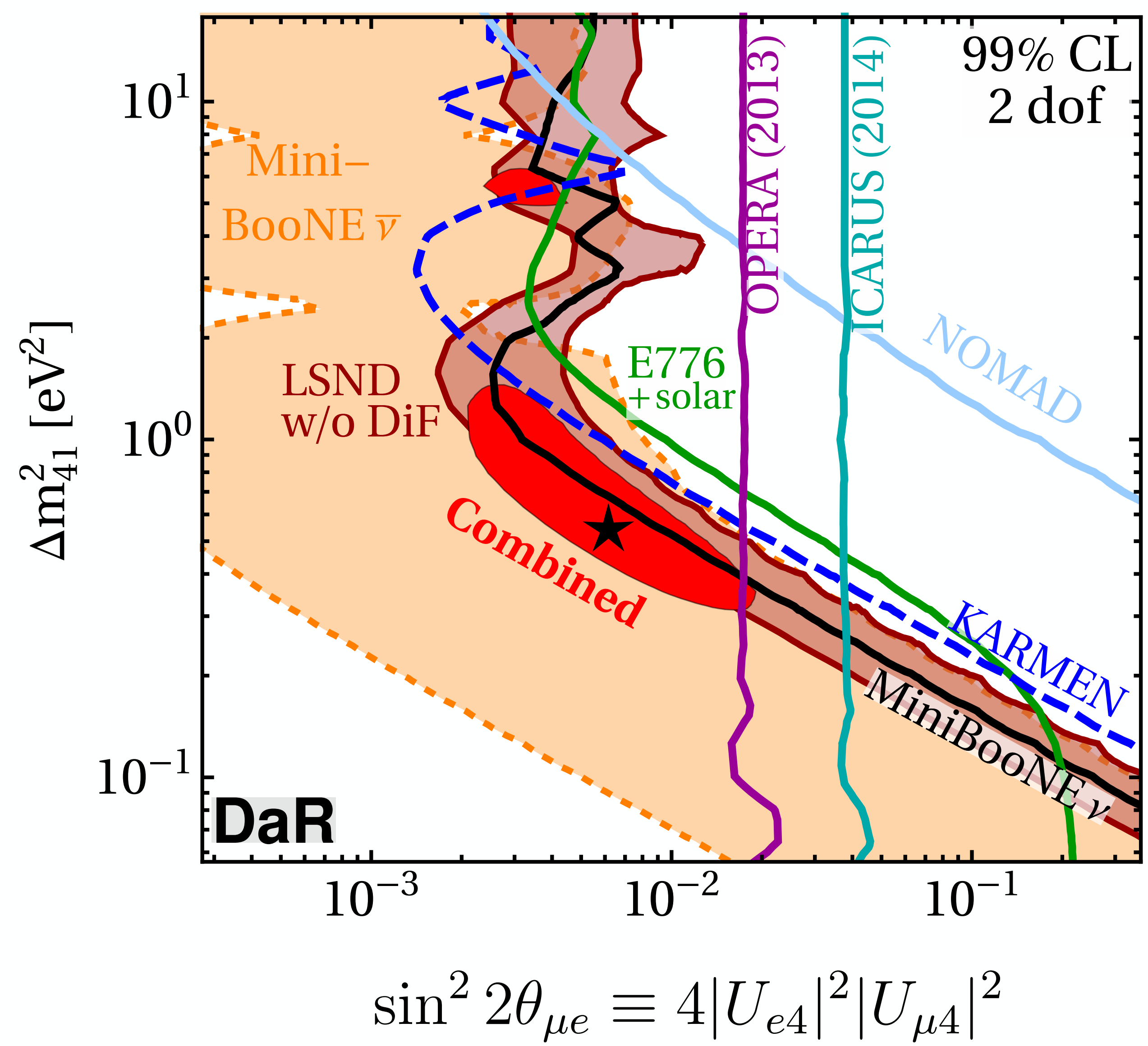

Significant tension with multiple null disappearance results

Dentler et. al. 1803.10661

Cosmological Problems for Light Sterile Neutrinos

Sterile neutrinos require $\sin^2 2\theta_{\mu e} > 10^{-3}\ ,\ m_4 < \text{few eV}$

Generic early universe thermalization

$$\Gamma > H \implies \sin^2 2\theta_{\mu e} G_F^2 T^5 > \sqrt{g_*}\frac{T^2}{m_{\rm Pl}} \implies n_4 \sim n_\nu$$

Excluded by BBN/CMB $N_{\rm eff} = 2.99 \pm 0.17$ Planck 1807.06209

Unless max temperature satisfies $T_{\rm max} \lesssim 15\ \text{MeV} \left(\frac{10^{-3}}{\sin^2 2\theta_{\mu e}}\right)^{1/3}$

What else could this be?

LSND / MiniBooNE connection **assumes** sterile neutrinos

Otherwise completely unrelated in principle

I will ignore LSND from now on

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I will ignore LSND from now on

Strong motivation for alternative explanations to MB excess

Could be a systematic: { Excess peaks in IR near threshold; Same basic shape as the BG }

Also could be a different kind of new physics unrelated to neutrino oscillations

Just need new particles to deposit EM energy in the detector

Overview

1) History of the MiniBooNE Excess

2) Excluding Simple Models w/ Kinematic Distributions

3) Excluding (Nearly) All Other Models w/ Beam Dump Data

What's a "Simple Model"?

New particle unrelated to neutrino oscillation or production

Scenario A: **Unstable** particle produced in target
Decays **visibly** inside the detector

Scenario B: **Stable*** particle produced in target
Scatters **elastically** inside the detector

Scenario A: **Unstable** particle produced in target
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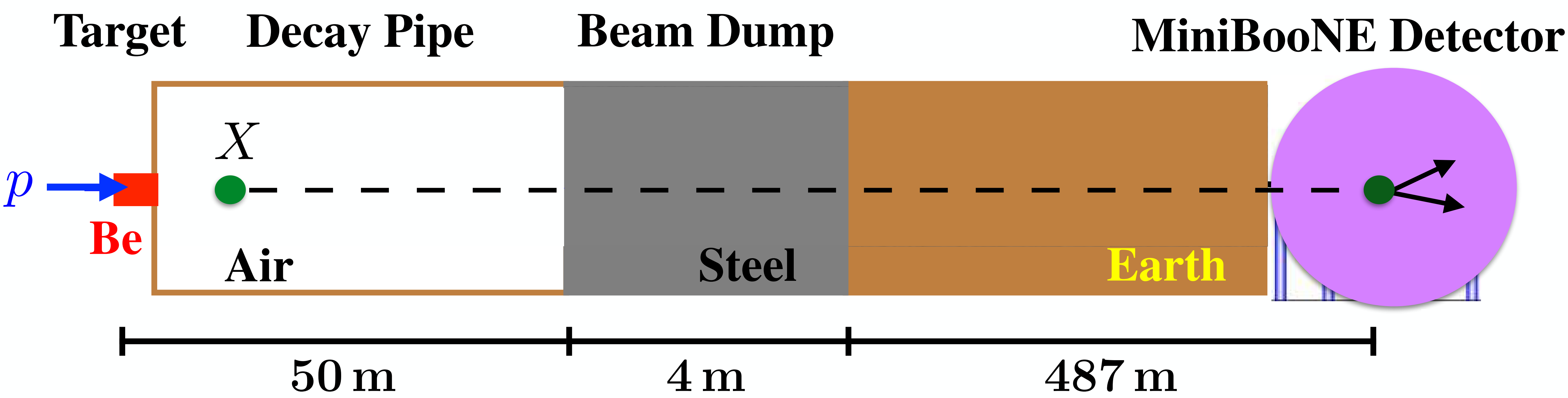
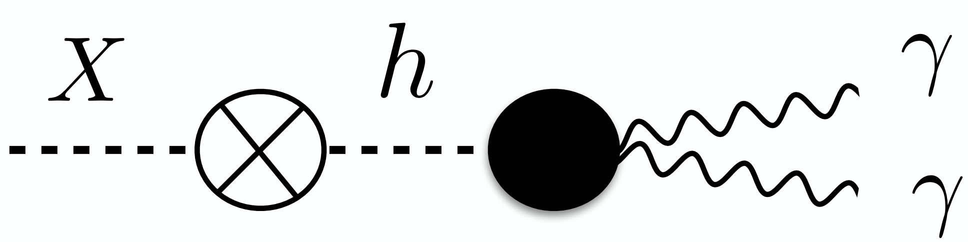
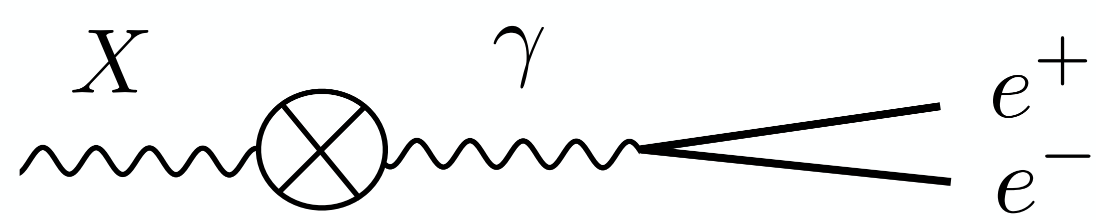
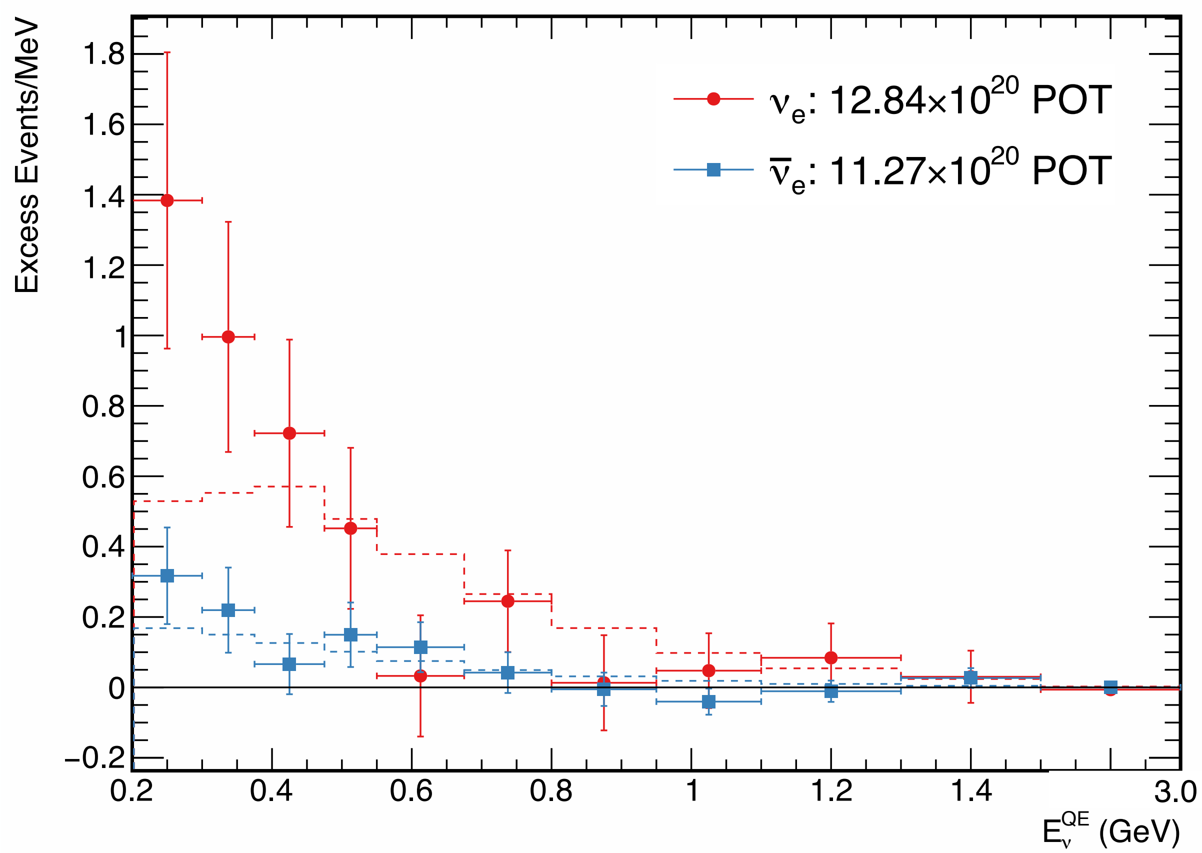


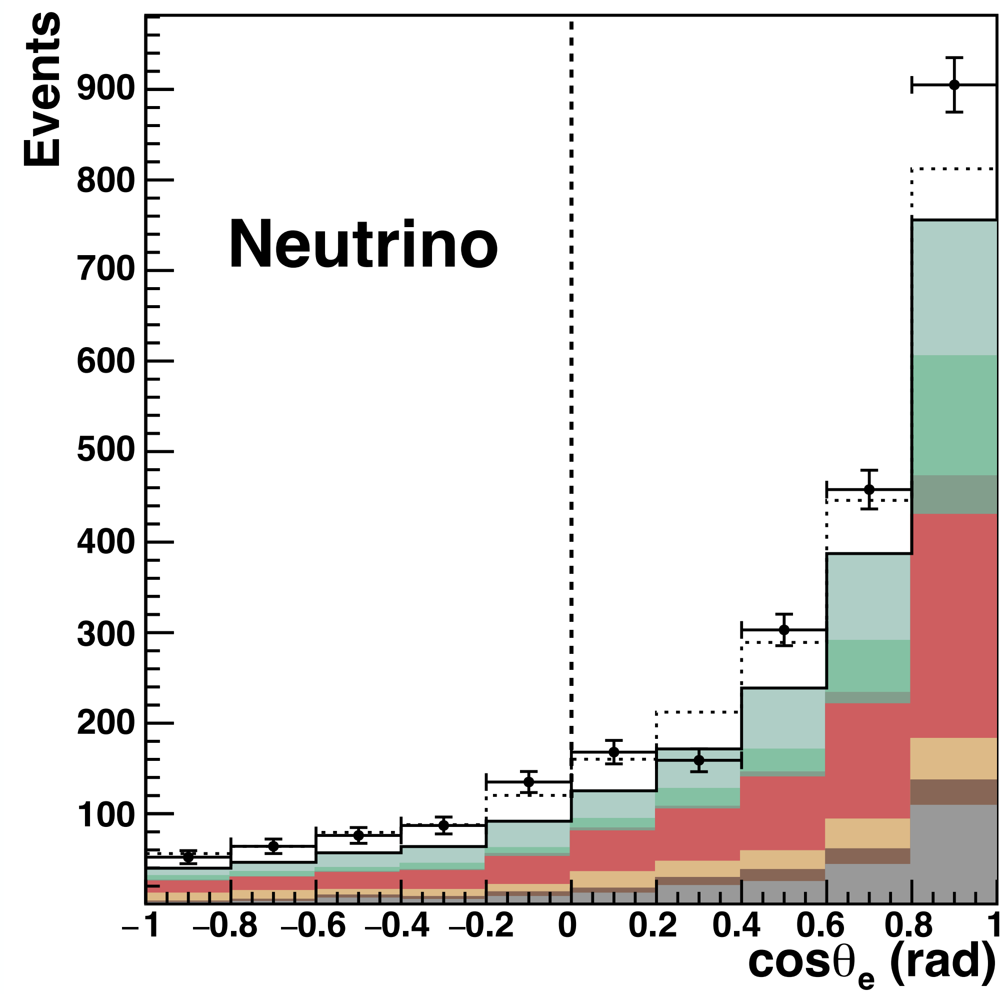




Detector can’t distinguish electrons/photons
Collimated particles reconstruct as one ”CCQE” track

Scenario A: **Unstable** particle produced in target
Decays **visibly** inside the detector





Energy threshold = 200 MeV

$$E_\nu^{(\mathrm{reconst.})} = \frac{2m_n E_e + m_p^2 - m_n^2 - m_e^2}{2(m_n - E_e + \cos\theta_e \sqrt{E_e^2 - m_e^2})}$$

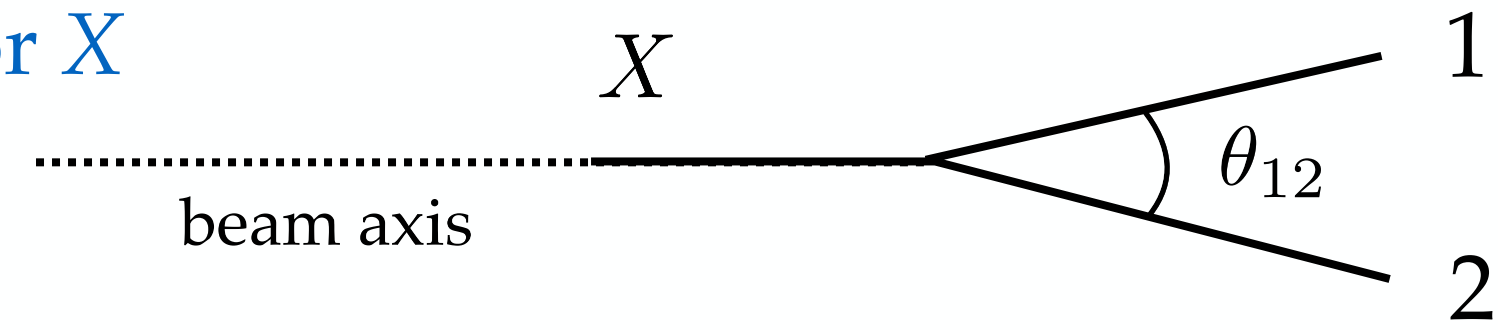
Many wide angle events
for reconstructed "electron"

MiniBooNE 1805.12028

Scenario A: **Unstable** particle produced in target
Decays **visibly** inside the detector

Geometric acceptance for X

$$\cos\theta_X > 0.999$$



Reconstruct as single particle if $m_{\text{track}} < 30 \text{ MeV}$

$$m_{\text{track}} \equiv \sqrt{2E_1E_2(1-\cos\theta_{12})} \longrightarrow \cos\theta_{12} > 1 - \frac{(30 \text{ MeV})^2}{2E_1E_2}$$

$E > 200$ MeV, easy to be collimated

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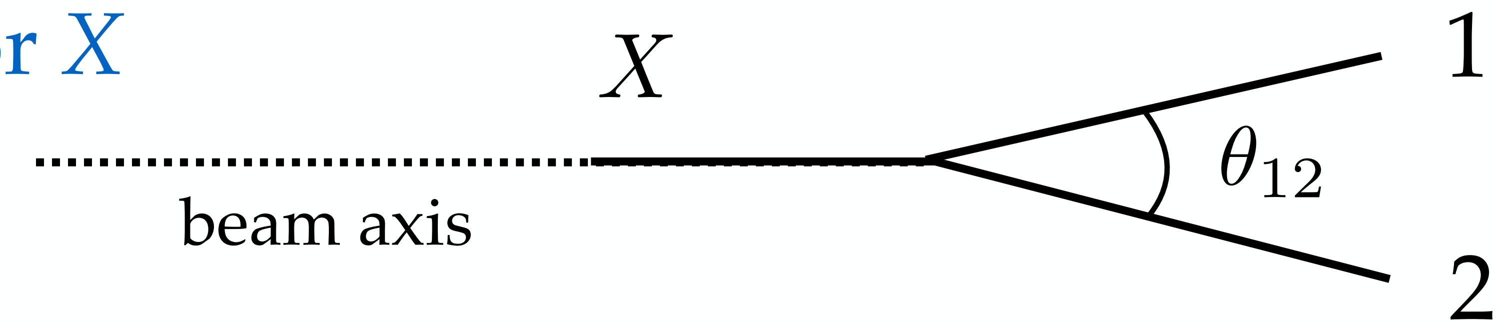

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$E > 200$ MeV, easy to be collimated

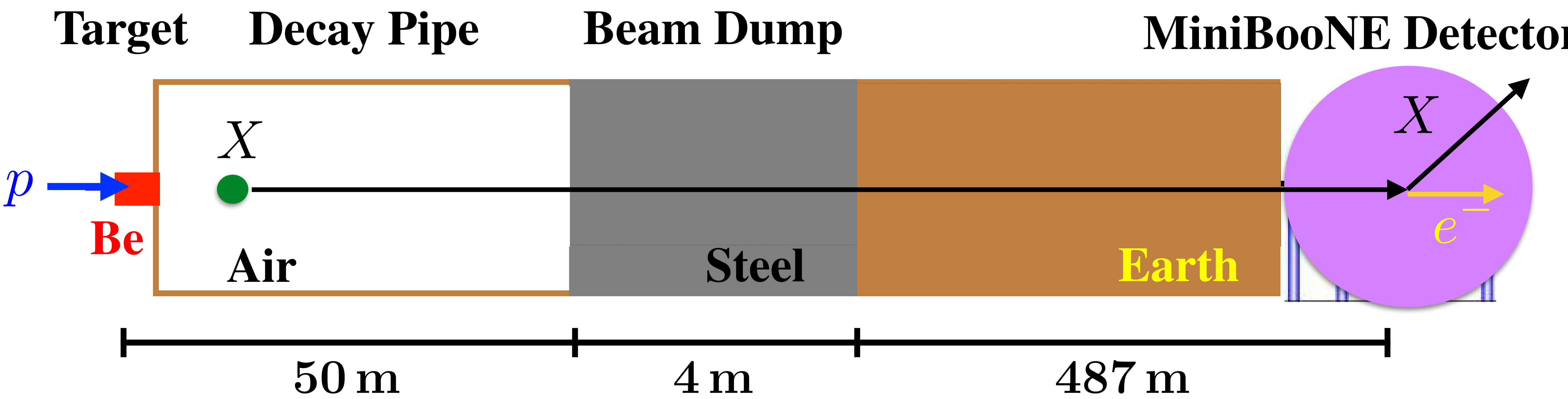
Angular reconstruction: direction of total daughter momentum

$$\cos\theta_{12} \approx \cos\theta_X > 0.999$$

Fully visible decays ruled out — only populate last bin

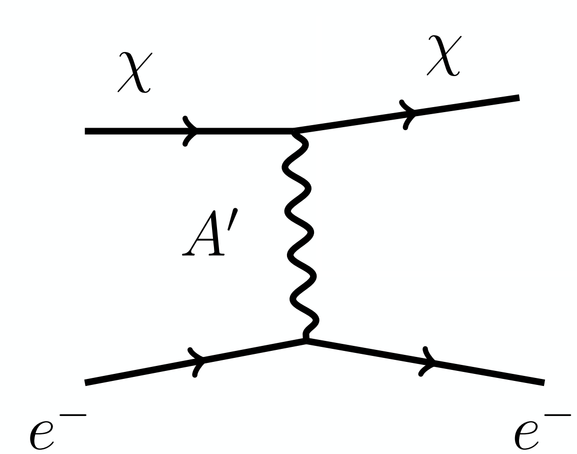
Model independent exclusion

Scenario B: **Stable*** particle produced in target
Scatters **elastically** inside the detector



Elastic scatter must use detector electrons as targets to fake CCQE

$$\cos\theta_e = \frac{E_X E_e - m_e(E_X + m_e - E_e)}{\sqrt{(E_X^2 - m_X^2)(E_e^2 - m_e^2)}}$$



e.g. dark matter induced

Scenario B: **Stable*** particle produced in target
Scatters **elastically** inside the detector

If X is relativistically produced $E_X \gg m_X$

$$\cos\theta_e = 1 - m_e\left(\frac{E_X - E_e}{E_X E_e}\right) + \mathcal{O}\left(\frac{m_e^2}{E_e^2}\right) \quad > 0.99$$

Same problem: all events in last bin after $E_e > 200$ MeV cut

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Same problem: all events in last bin after $E_e > 200$ MeV cut

If X is quasi-relativistic $E_X \gtrsim m_X$

$$\cos\theta_e = \frac{E_X E_e - m_e(E_X + m_e - E_e)}{\sqrt{(E_X^2 - m_X^2)(E_e^2 - m_e^2)}} \implies E_e \sim m_e \quad \text{for} \cos\theta_{\rm e} \sim 0$$

Which fails selection cuts

Elastic scatter ruled out model independently

What have we learned?

Model Independent Arguments (Kinematic Features Only)

~~**Scenario A:** **Unstable** particle produced in target~~
~~Decays **visibly** inside the detector~~

Decays require both visible and invisible daughters

~~**Scenario B:** **Stable*** particle produced in target~~
~~Scatters **elastically** inside the detector~~

Scattering requires nuclear/nucleon targets for angular spread
& inleasticity to yield final state EM energy

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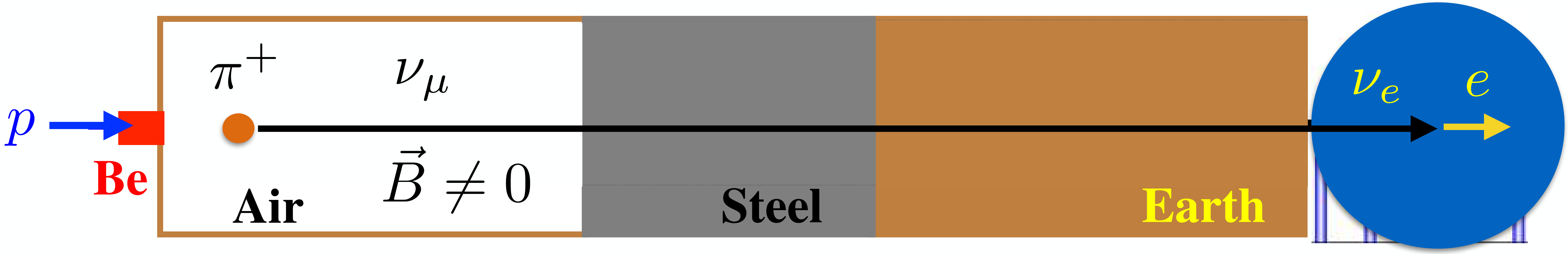
Neutrino Mode vs. Beam Dump Mode



Neutrino mode uses Be target and magnet focusing

Collimated flux of **charged** mesons and daughters

Diffuse spread of **neutral** particles

Neutrino Mode vs. Beam Dump Mode

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Collimated flux of **charged** mesons and daughters

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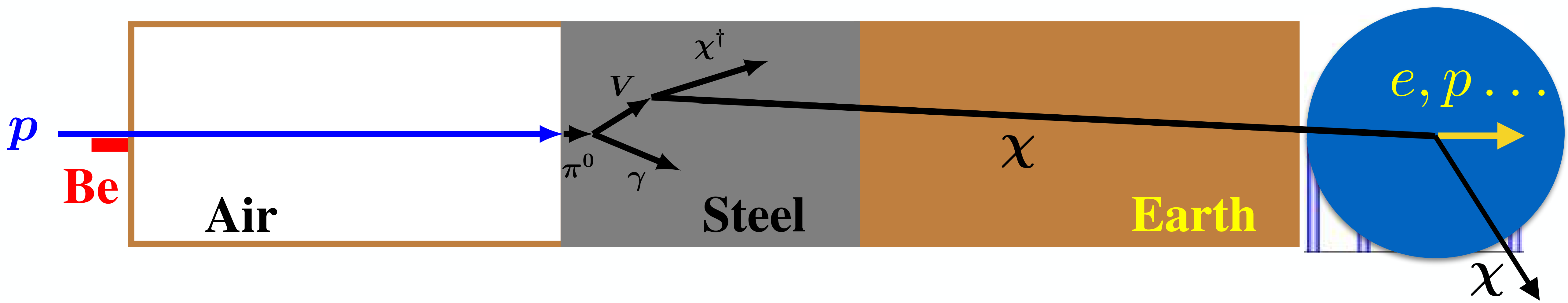
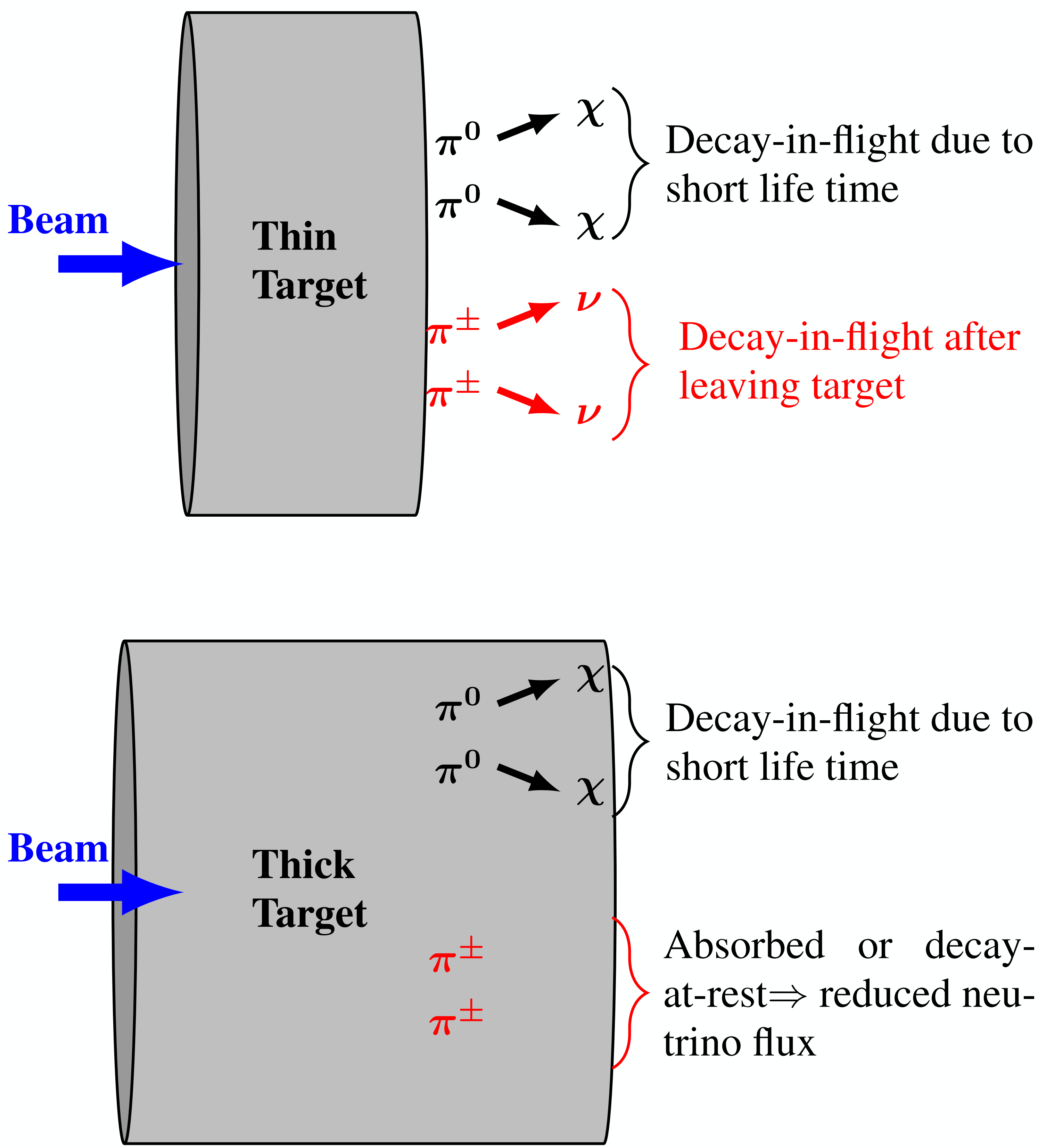


Beam dump avoids target and magnet

Diffuse spread of **all** secondary particles

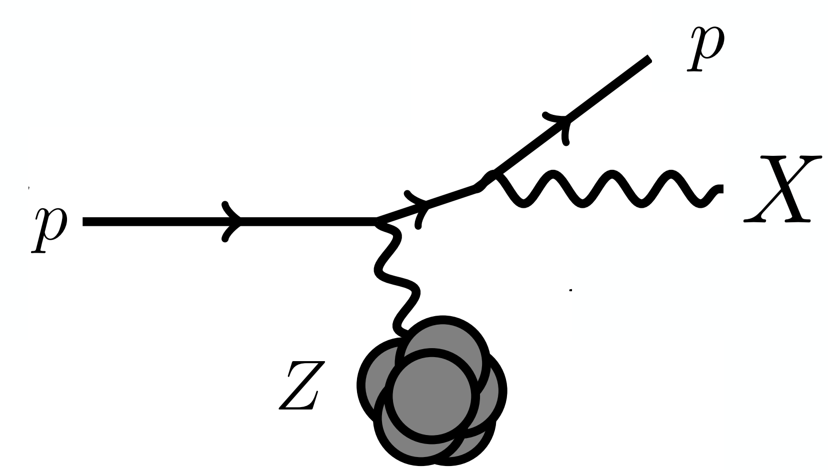
Reduces neutrino BG for exotic searches

Neutrino Mode vs. Beam Dump Mode



MiniBooNE Collaboration arXiv1807.06137

Continuum production
Similar in both modes

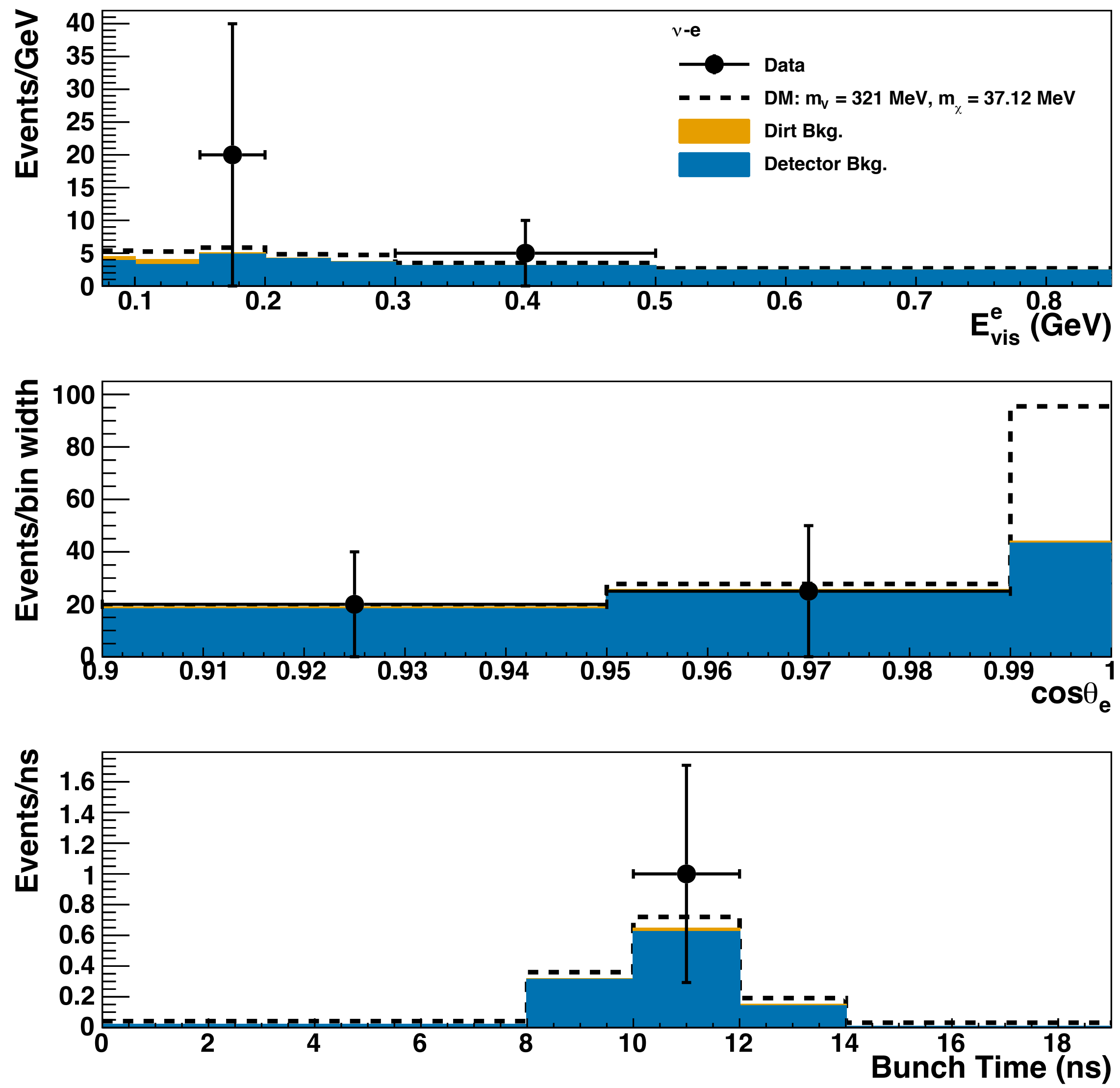


Uses full beam energy
Important for heavy X

Thickness irrelevant
if greater than rad. length

Null Result Imposes Nontrivial BSM Bounds

No signal events observed above BG



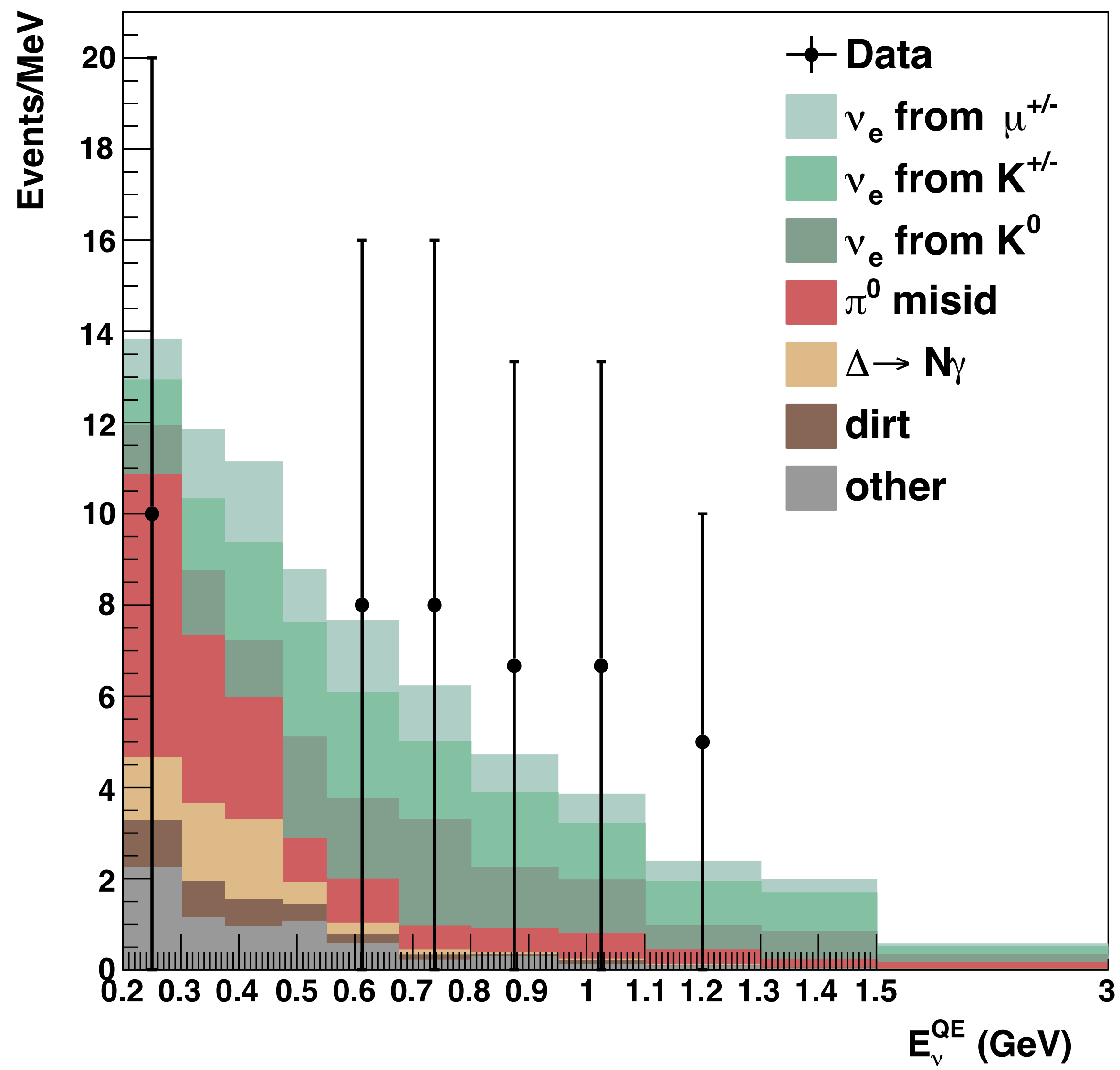
$\sim 10^{20}\mathrm{POT}$ $\quad \cos\theta_e > 0.9 \quad 75 \leq E^e_{\mathrm{vis}}\,(\mathrm{MeV}) \leq 850$

10% of luminosity in neutrino mode which saw ~460 events

MiniBooNE Collaboration arXiv1807.06137

Null Result Imposes Nontrivial BSM Bounds

No signal even with neutrino mode cuts in beam dump mode

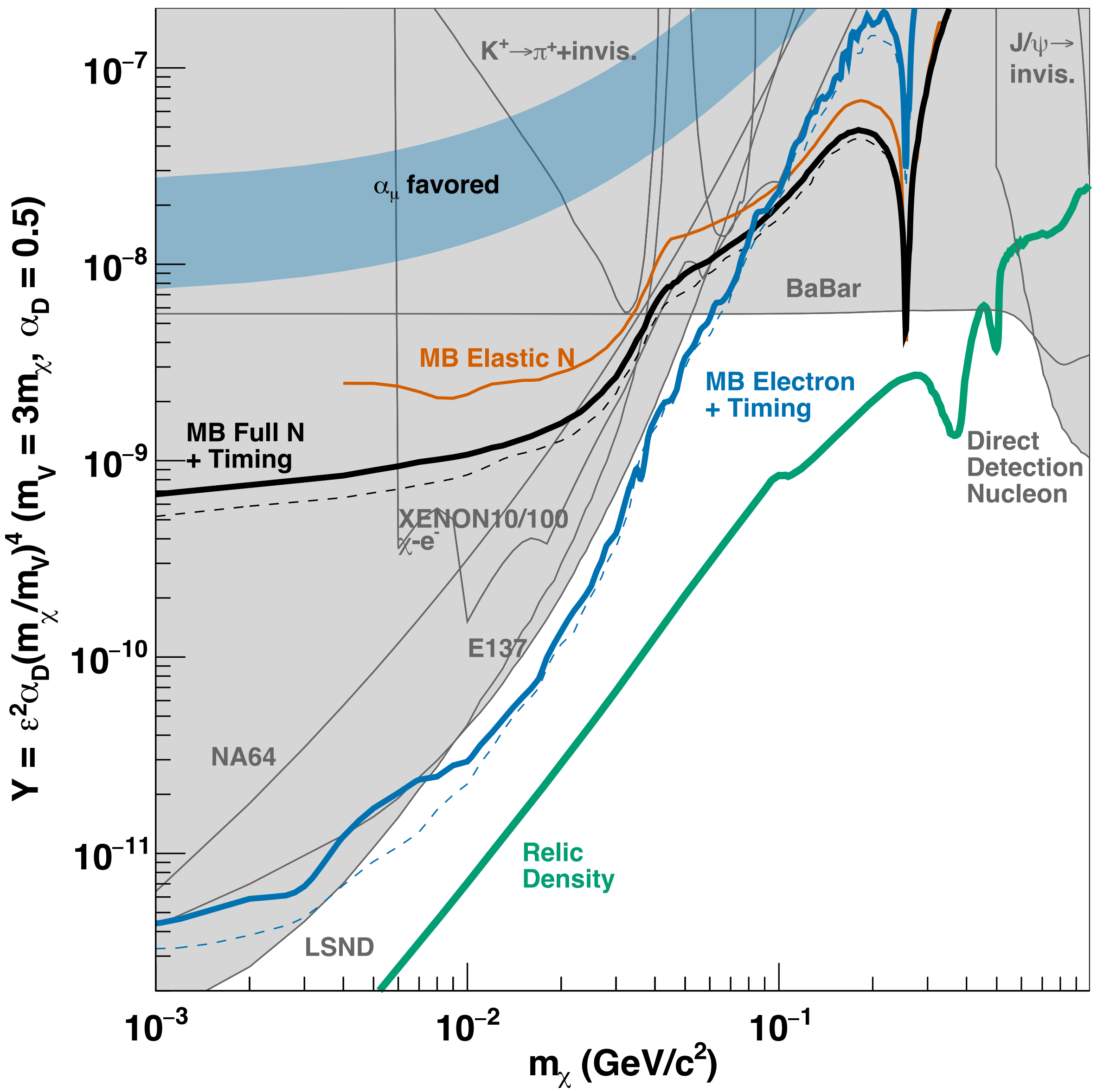


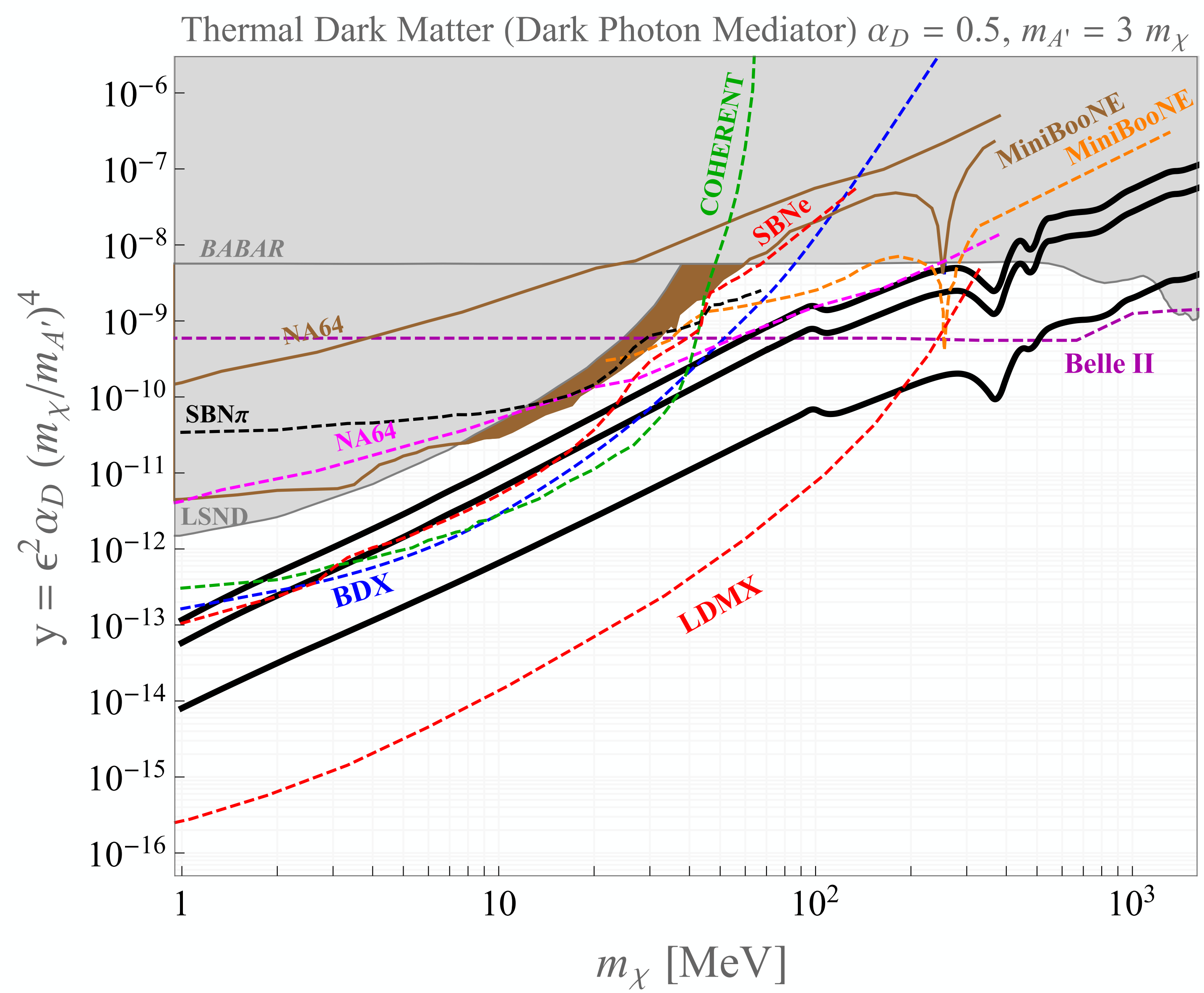
$E_p \sim 9$ GeV $\quad \sim 10^{20}$POT $\quad 200 < E_\nu^{QE} < 1250$ MeV

10% of luminosity in neutrino mode which saw ~460 events

MiniBooNE Collaboration arXiv1807.06137

First **ever** dedicated < GeV DM search





First shot in a new program of accelerator DM searches

Already has consequences for MiniBooNE anomaly BSM

MiniBooNE Collaboration arXiv1807.06137

Izaguirre, GK, Schuster, Toro 1505.00011

Cosmic Visions Report 1707.04591

What have we learned?

~~**Scenario A:**~~ ~~**Unstable** particle produced in target~~
~~Decays **visibly** inside the detector~~

Scenario A′ **Unstable** particle produced in target
Each decay has **visible & invisible** daughters

~~**Scenario B:**~~ ~~**Stable*** particle produced in target~~
~~Scatters **elastically** inside the detector~~

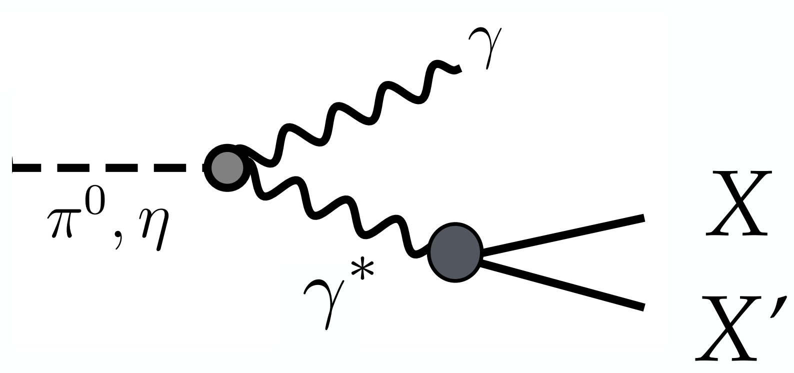
Scenario B′ **Stable*** particle produced in target
Inelastically scatters of **nucleon/nucleus**

Scenario A′ **Unstable** particle produced in target
Each decay has **visible & invisible** daughters

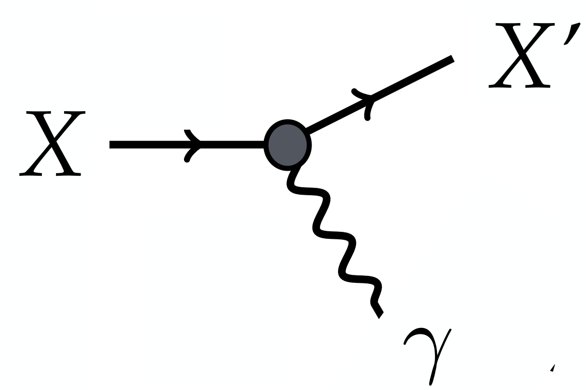
$X \to X' + \mathrm{EM}$ X' is invisible

Example: dipole interaction for a Pseudo-Dirac fermion

$$\mathcal{L} \supset d_X \, \overline{X} \sigma^{\mu\nu} X' F_{\mu\nu} + \mathrm{h.c.}$$



Production (target)



Decay (detector)

Invisible, lighter X′ to carries forward momentum
Wide angle visible energy to fake CCQE electron

Scenario A′ **Unstable** particle produced in target
Each decay has **visible & invisible** daughters

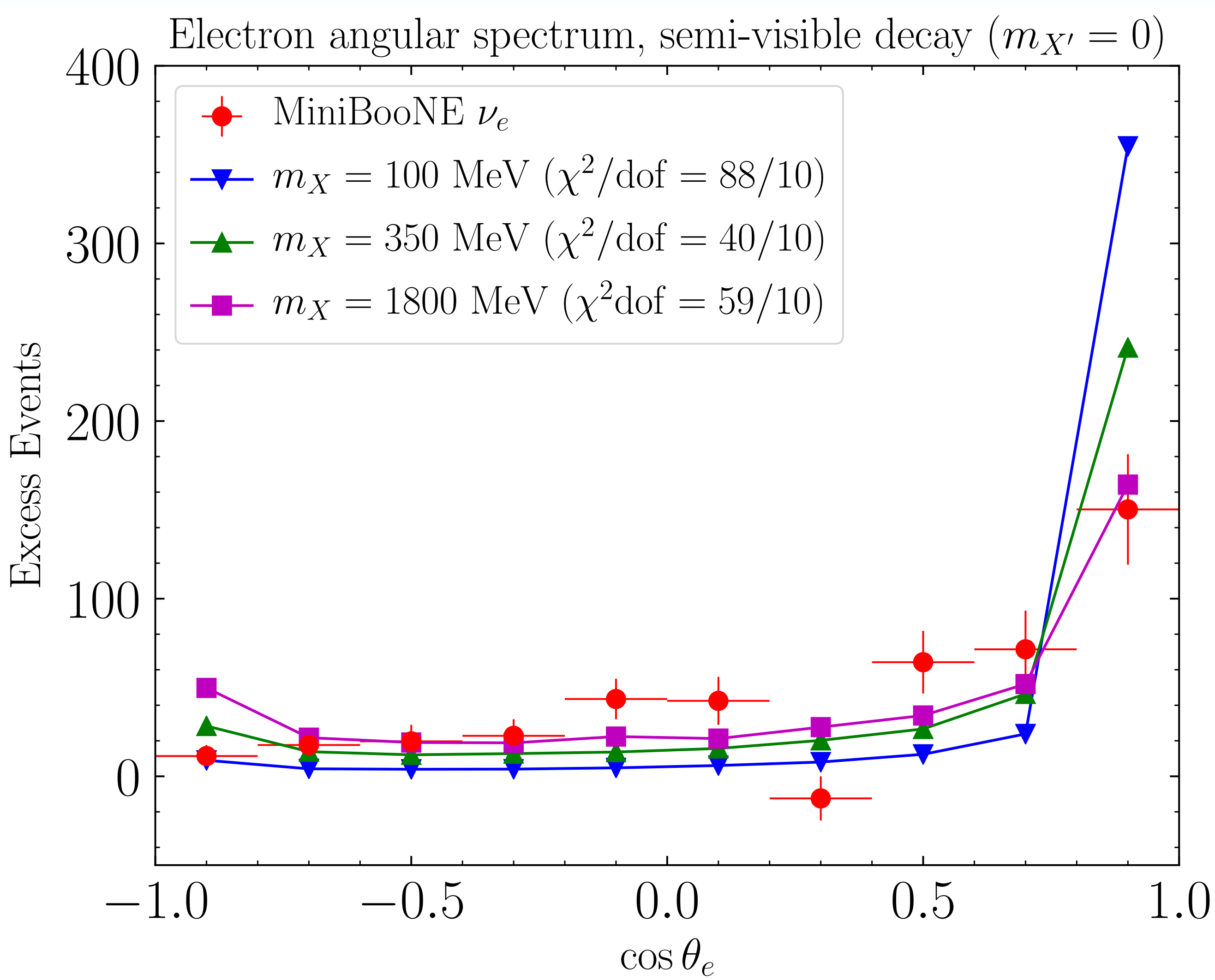
Note this is already **disfavored** by angular distribution

Conservative Strategy

1) assume visible particle(s) fit the excess E spectrum

2) this predicts X boost distribution & angular spread for visibles

3) generalizes to N body decay with massive X'



Verdict: can partially explain angular distribution w/ heavy X

Scenario A′ **Unstable** particle produced in target
Each decay has **visible & invisible** daughters

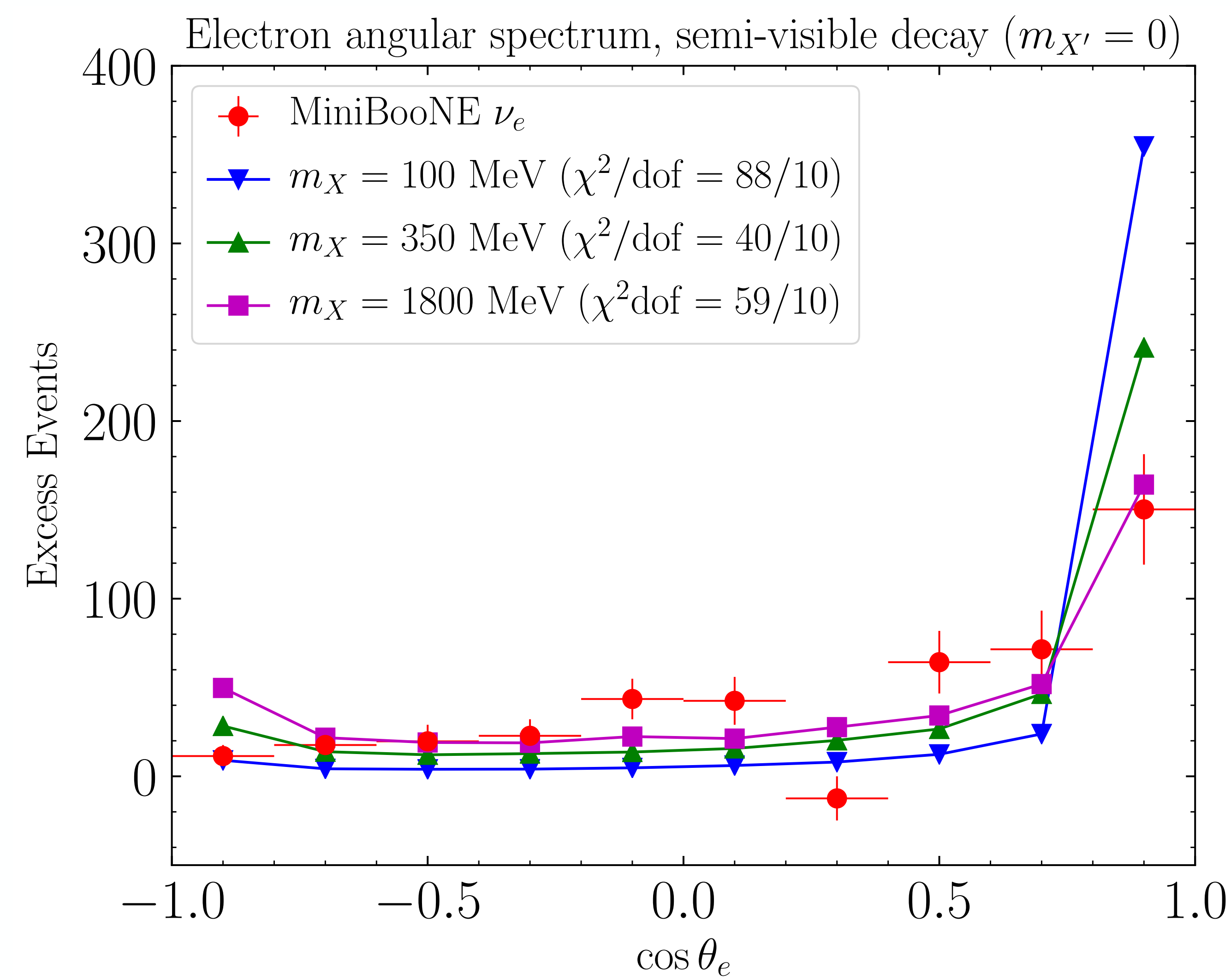
Bigger Problem: can't make heavy ~ GeV *X* in charged meson decays

No available progenitors

$$m_{\pi^+} = 139.54 \text{ MeV}$$
$$m_{K^+} = 493.67 \text{ MeV}$$

Need neutral meson decays or continuum production

Comparable production rate in beam dump mode (per POT)

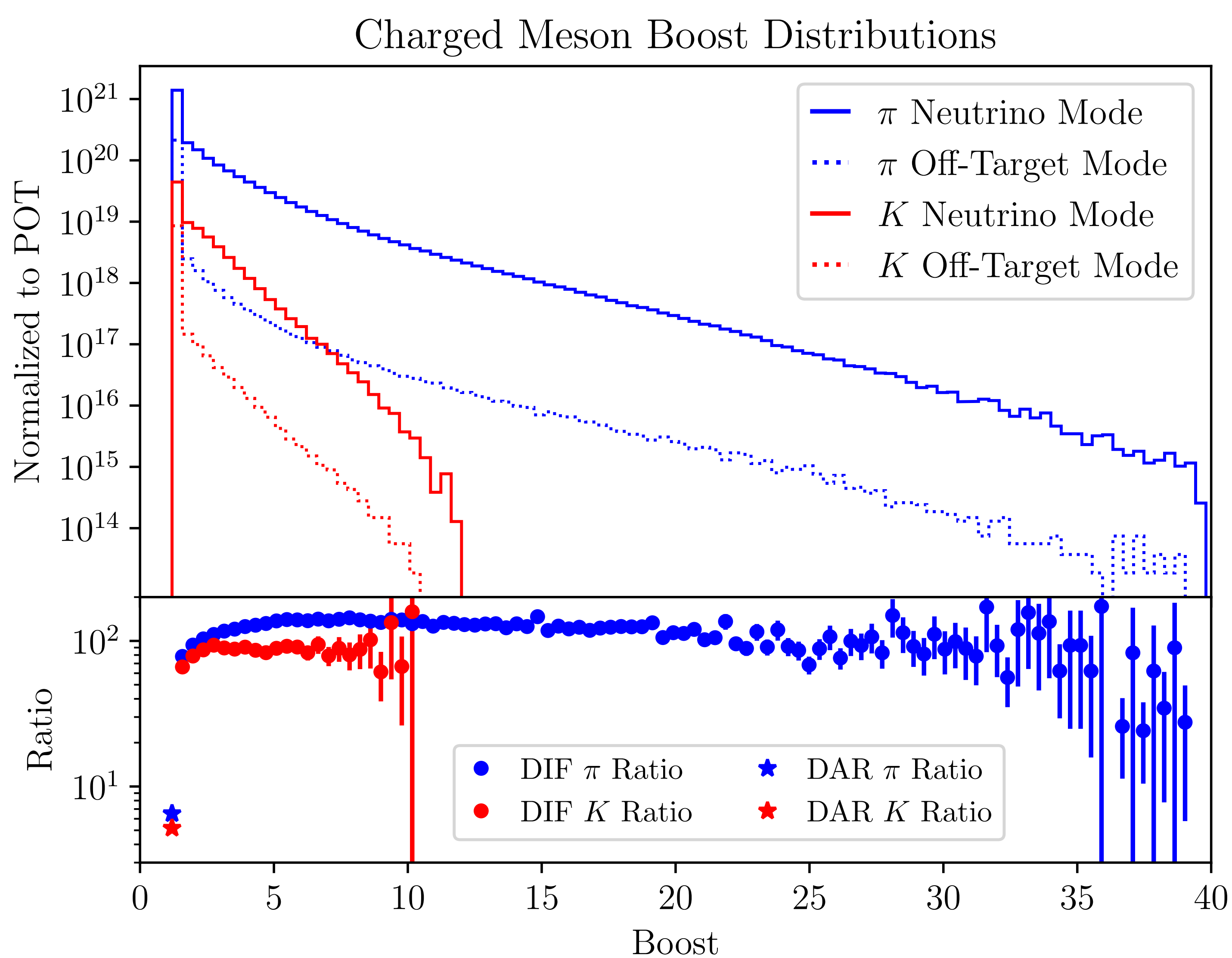


Predicts ~ 60 events in beam dump mode: ruled out!

Scenario B′

Stable* particle produced in target
Inelastically scatters of **nucleon/nucleus**

Step 1) produce X in charged meson decays



GEANT 4 simulation

100x reduction relative to neutrino mode for all boosts $\implies \mathcal{O}(\text{few})$ events

now sensitive to cos > 0.9 cut (model dependent, but close!)

Scenario B′

Stable* particle produced in target
Inelastically scatters of **nucleon/nucleus**

Step 2) scatter X inelastically off detector hadrons for wide angle recoils

$$XN \to X'N \ , \ X' \to \ \mathrm{EM}+\cdots$$

Model building challenge:

Couple to nucleons for detector upscatter
(satisfy angular distribution)

…. while avoiding neutral meson+continuum production
(ruled out by beam dump)

…. and avoiding detector electron scattering
(otherwise always forward electrons)

Scenario B′

Stable* particle produced in target
Inelastically scatters of **nucleon/nucleus**

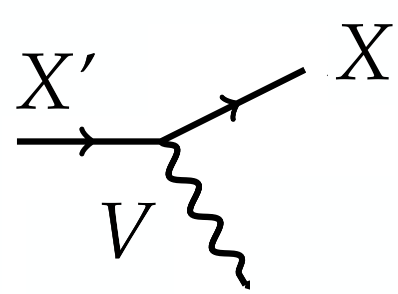
Example: Pseudo-Dirac DM charged under broken, gauged $U(1)_{L_e - L_\mu}$

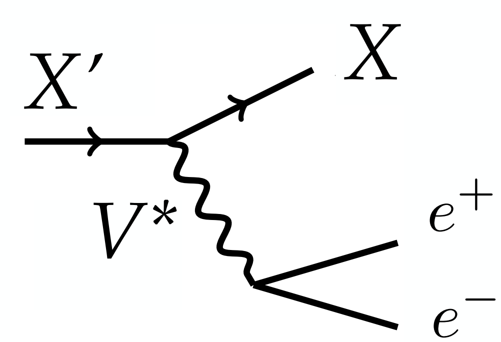
$$\mathcal{L} \supset g\left(\overline{X}'\gamma^\sigma X + J^\sigma_{L_e - L_\mu}\right)V_\sigma + e\epsilon J^\sigma_{\text{EM}} V_\sigma$$ add kinetic mixing

Suppress beam dump production from neutral+ continuum $g \gg e\epsilon$

a) X′ must decay **promptly**

otherwise semi-visible decay inside detector





b) Need to inject EM energy after scatter $m_V, m_X - m_{X'} > 2m_e$

c) Large inelasticity to forbid upscattering off electrons

Scenario B′

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Inelastically scatters of **nucleon/nucleus**

Example: Pseudo-Dirac DM charged under broken, gauged $U(1)_{L_e - L_\mu}$

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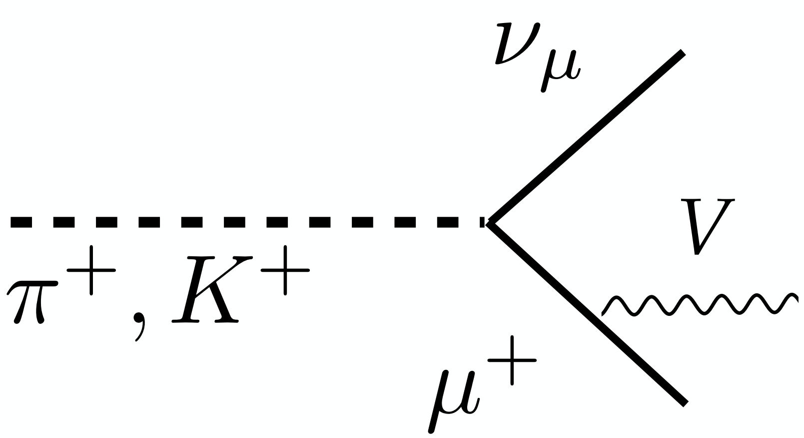
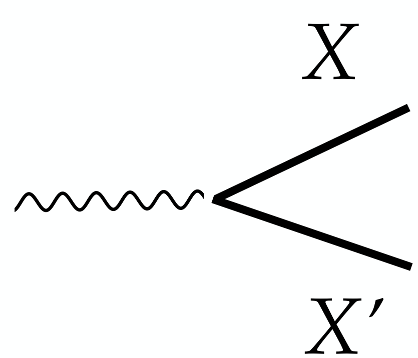
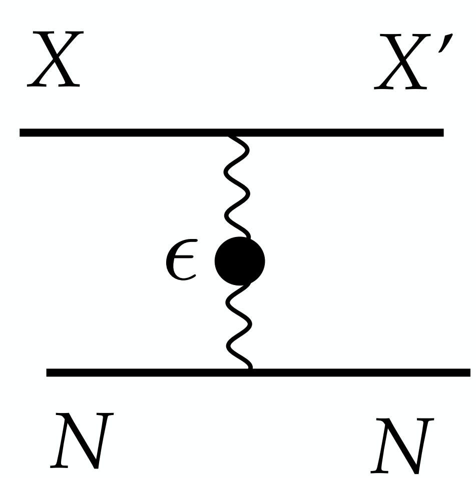
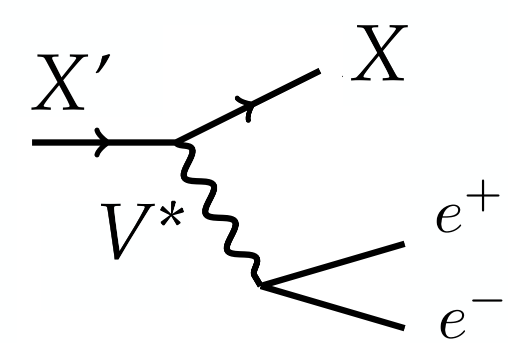




target production

prompt V, X′ decay



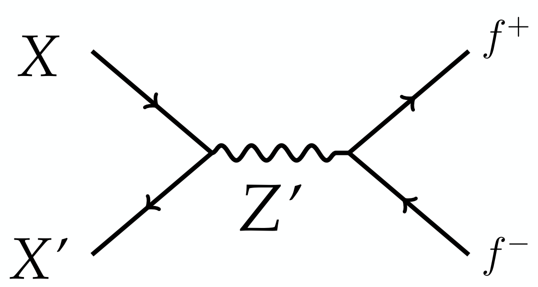


two-step detector signal

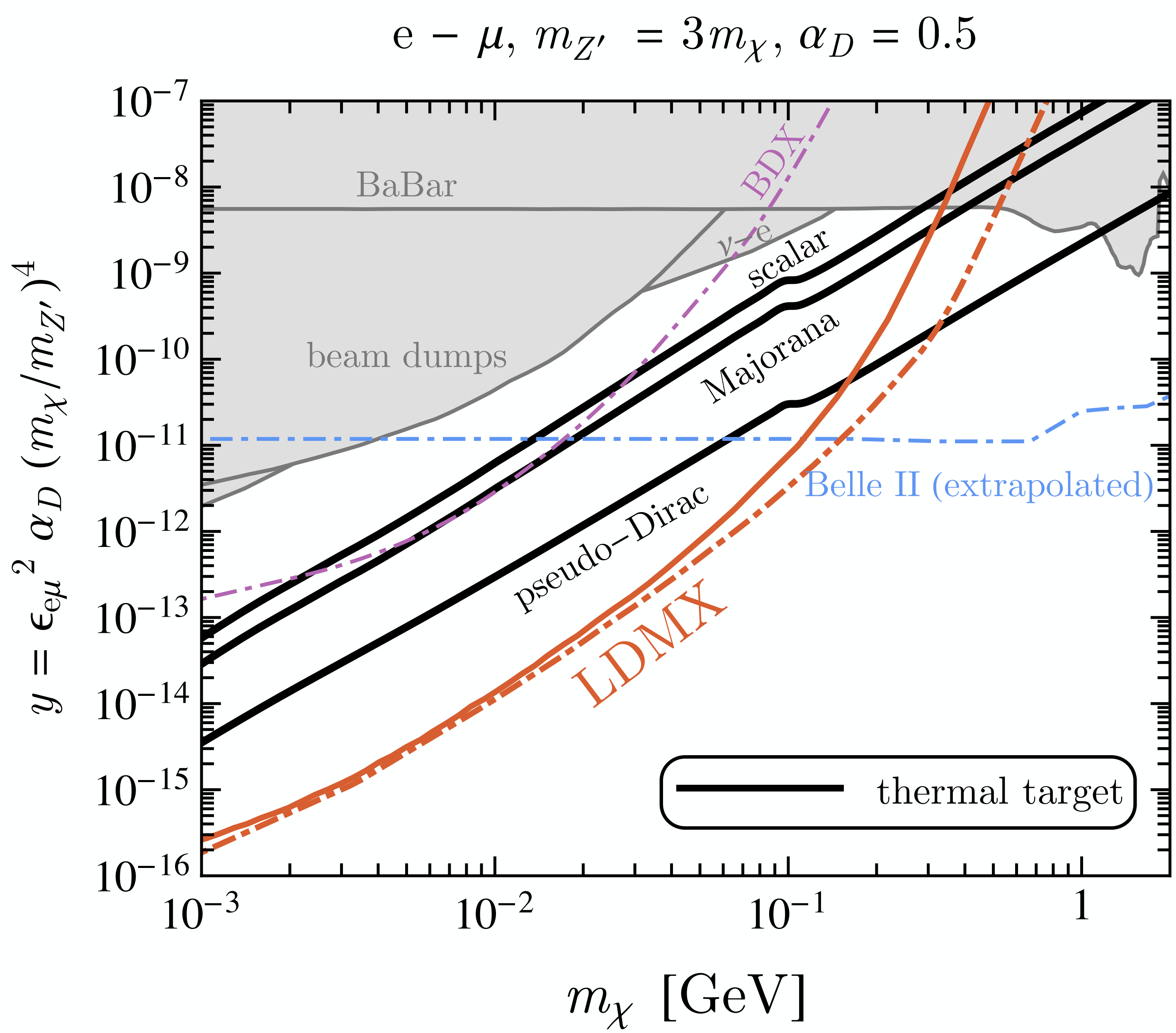
Scenario B′

Stable* particle produced in target
Inelastically scatters of **nucleon/nucleus**

Step 3) Interpret X as dark matter w/ coannihilation?



$\langle \sigma v \rangle \propto y$



Overlap with thermal target?
Beam dump coverage close …

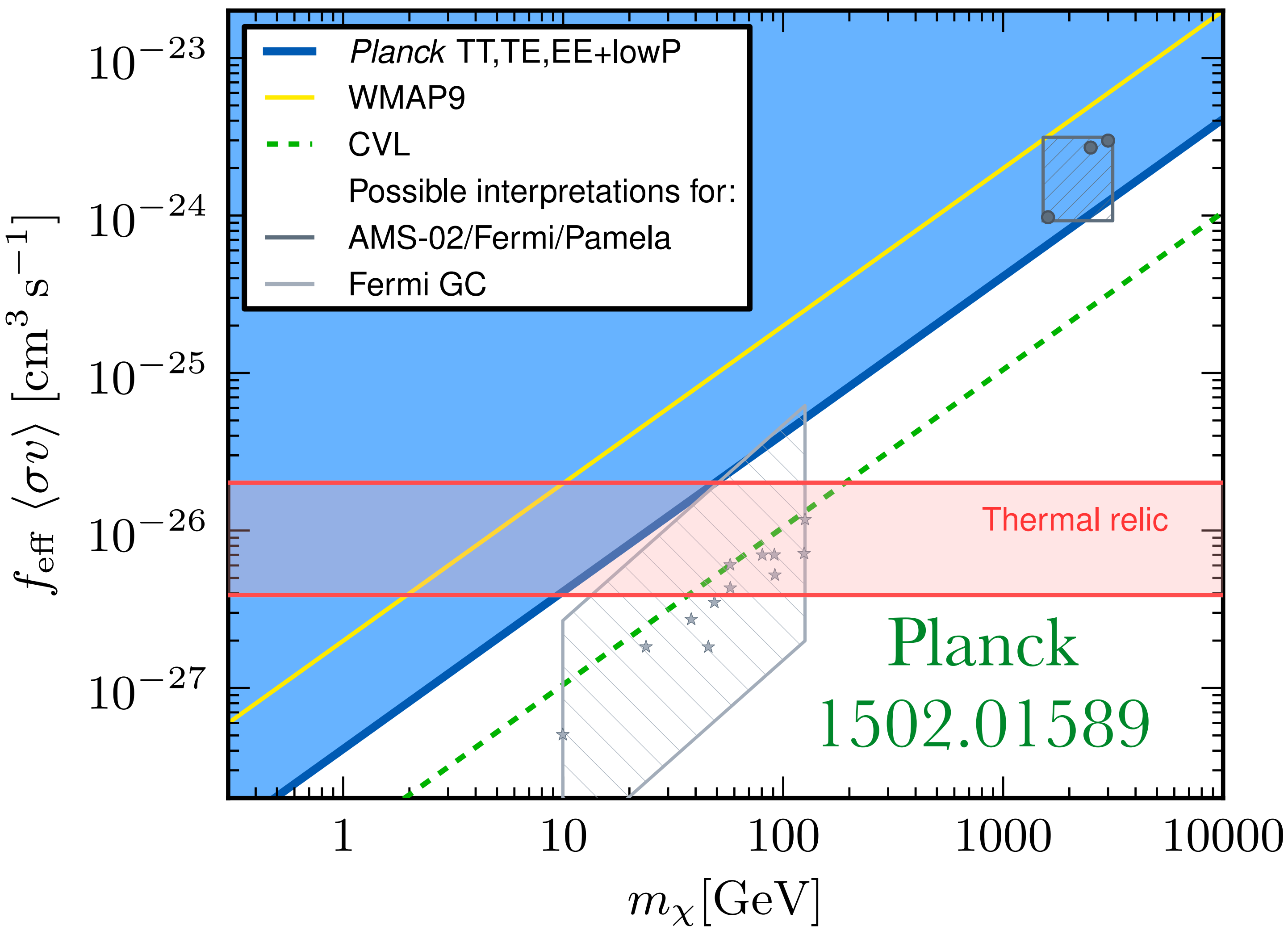
[Preliminary speculation]

Berlin, Blinov GK, Schuster, Toro arXiv: 1807.01730

Scenario B′

Stable* particle produced in target
Inelastically scatters of **nucleon/nucleus**

Note CMB naively rules out *s*-wave annihilation < 10 GeV



Viable models require either

1) p-wave annihilation

OR

2) annihilation shuts off before CMB epoch

Coannihilation naturally realizes option (2)

Dark Neutrino Portal

$$\mathcal{L}_{\mathcal{D}} \supset \frac{m_{Z_{\mathcal{D}}}^2}{2} Z_{\mathcal{D}\mu} Z_{\mathcal{D}}^{\mu} + g_{\mathcal{D}} Z_{\mathcal{D}}^{\mu} \overline{\nu}_{\mathcal{D}} \gamma_\mu \nu_{\mathcal{D}} + e\epsilon\, Z_{\mathcal{D}}^{\mu} J_\mu^{\rm em} + \frac{g}{c_W} \epsilon'\, Z_{\mathcal{D}}^{\mu} J_\mu^{\rm Z}$$

broken U(1) | dark heavy neutrino | kinetic mixing

Also add mixing between active and (unstable) dark neutrinos

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i + U_{\alpha 4}\, N_{\mathcal{D}}\,, \quad \alpha = e, \mu, \tau, \mathcal{D},$$

Bertuzzo, Jana, Machado, Funchal 1807.09877

Dark Neutrino Portal

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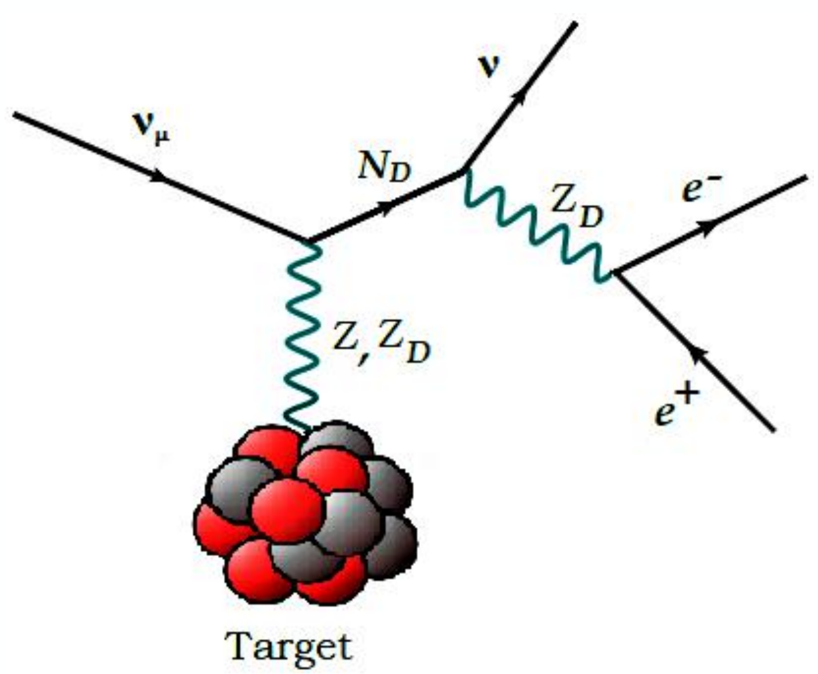
Beam neutrinos mix (not oscillate) to "dark"

Scatter nuclei through kinetic mixing

Make dark neutrino

Decays emitting Z′



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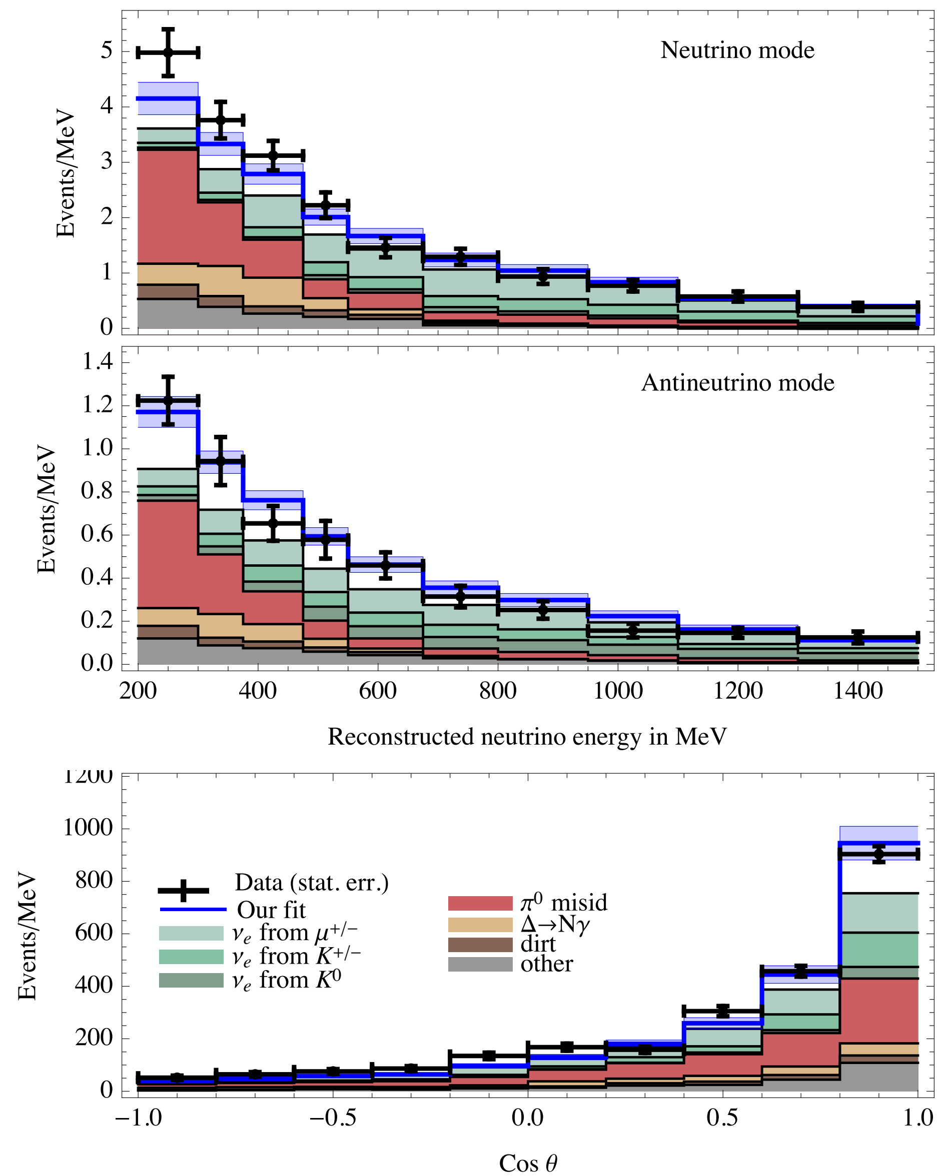
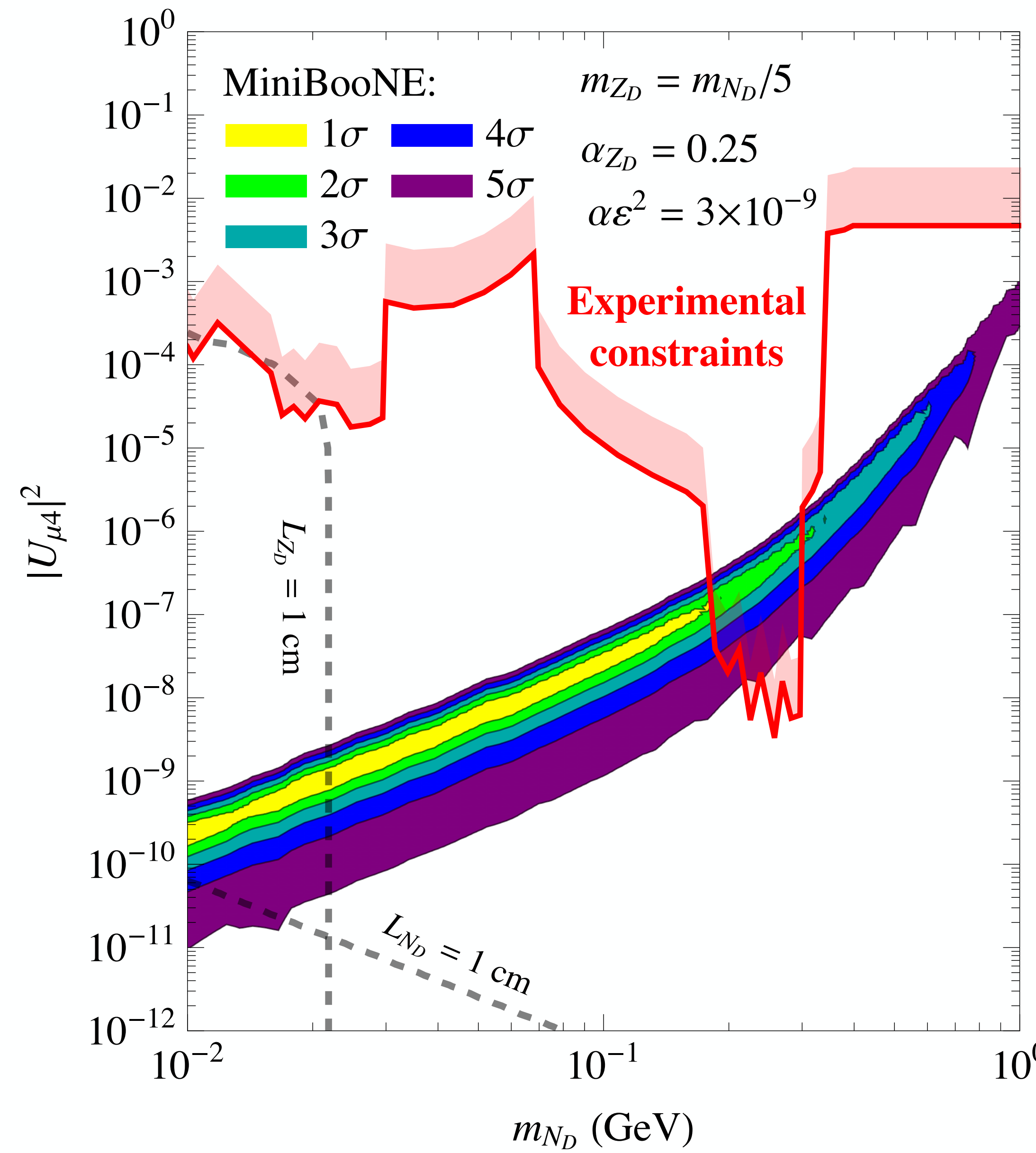
Dark Neutrino Portal





Pretty good fit! Beam dump search (published after) imposes borderline constraint. Model predicts ~ few events

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Conclusions

4.8 sigma MB excess, oscillations interpretation disfavored

Tension w disappearance & cosmology

Simple non-neutrino models ruled out (model independent)

angular distribution { X decays all-visibly; X scatters elastically }

New Beam Dump DM search is powerful constraint

Kills all neutral meson + continuum production models

Surviving models need both

1) production from charged mesons (target)
2) inelastic scatter off nuclei (detector)

All will be tested with ~ 10x existing beam dump data

Thanks!