# *Other* New Physics and the MiniBooNE Excess?


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Prospects of Neutrino Physics, Kavli IPMU, April 12, 2019

# Overview

1) Review of the MiniBooNE Excess

2) Excluding Simple Models w/ Kinematic Distributions

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

# Overview

**1) Review of the MiniBooNE Excess**

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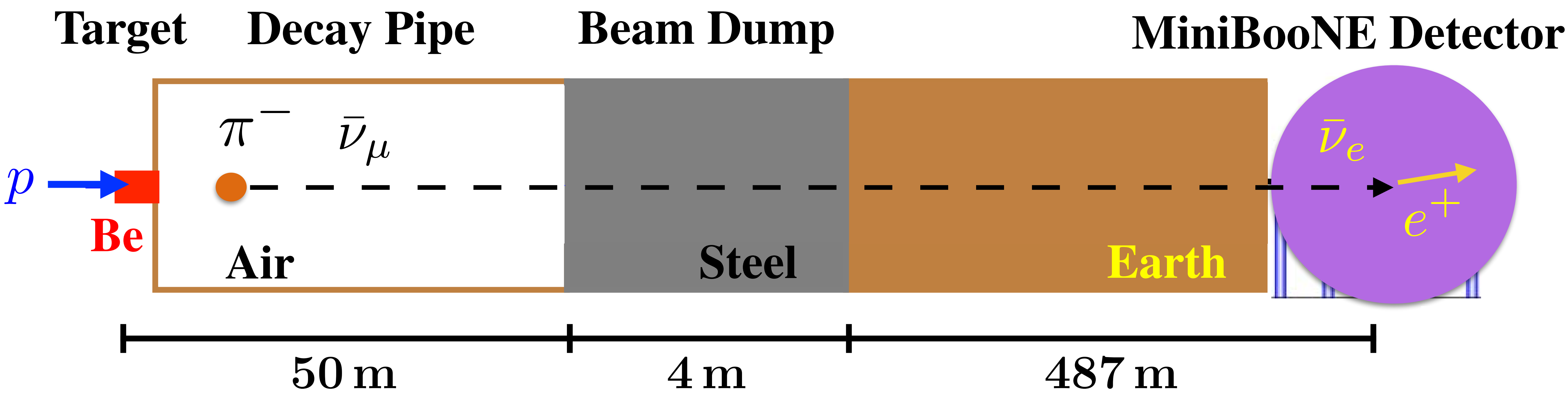
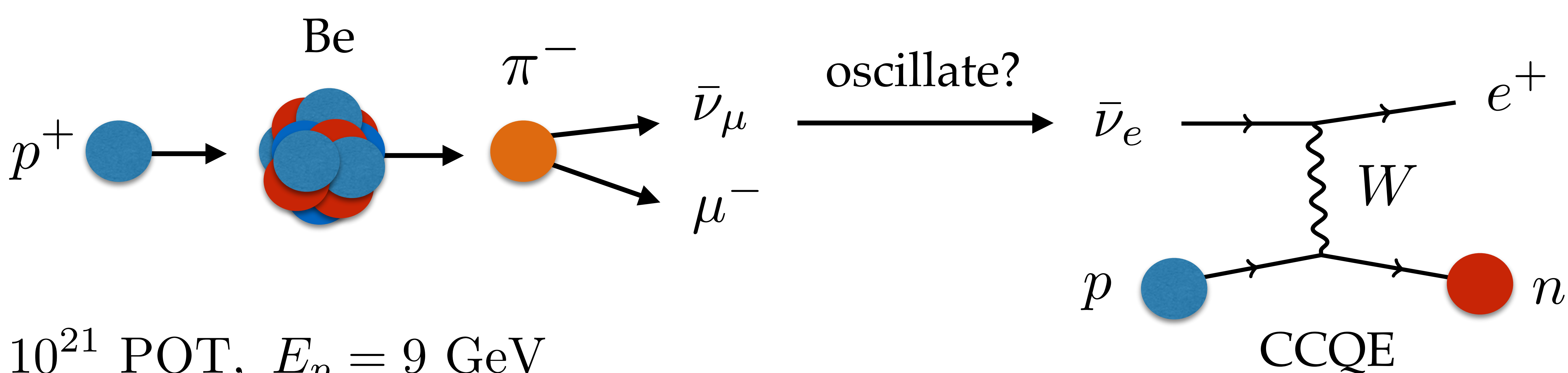
# MiniBooNE Experimental Setup




$10^{21}$ 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 | $12.84 \times 10^{20}$ POT | $11.27 \times 10^{20}$ POT |
| Reconstructed Neutrino Energy | $200 < E_\nu^{QE} < 1250$ MeV | |
| Excess events BG subtracted | $381.2 \pm 85.2$ | $79.3 \pm 28.6$ |

**Possibly Important Caveat**

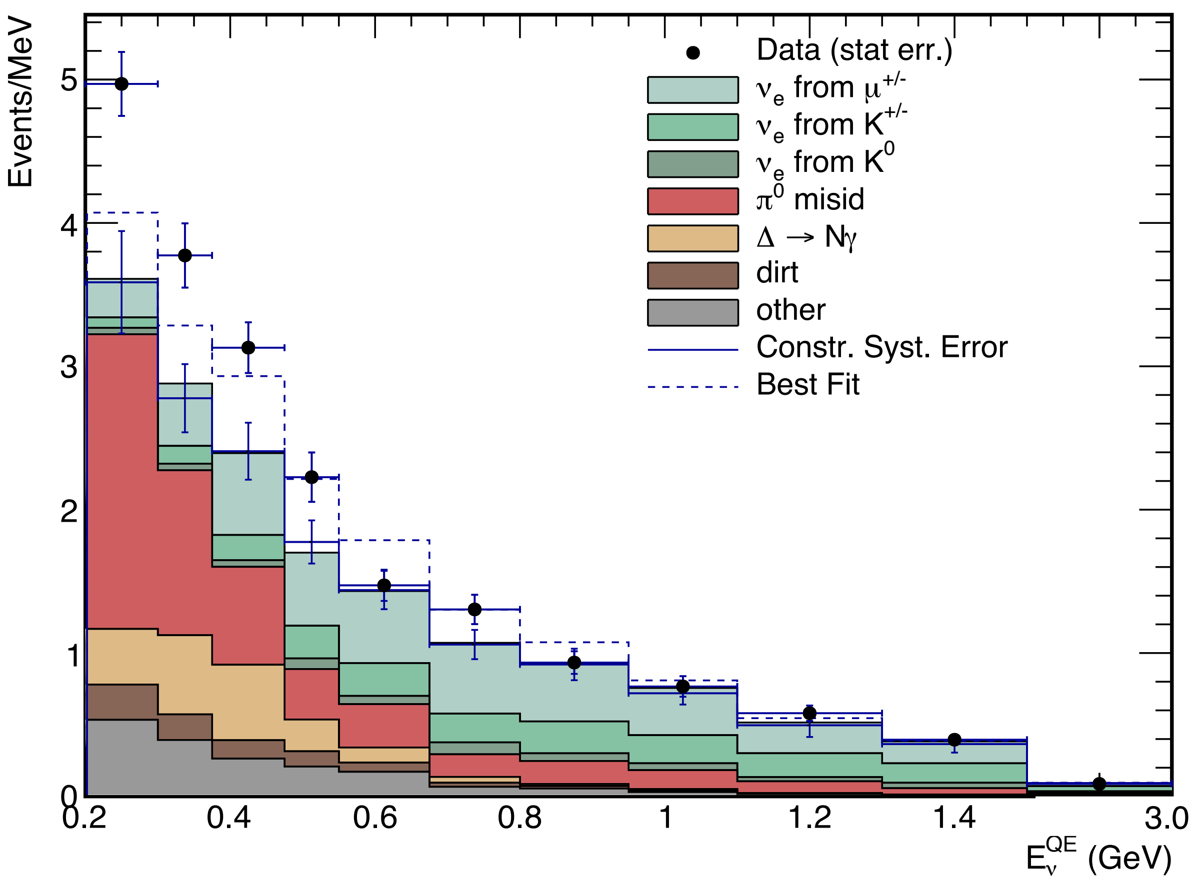
Mild tension ~ 2+ sigma between neutrino and antineutrino modes

Updated Neutrino Mode Analysis
MiniBooNE Collaboration1805.12028

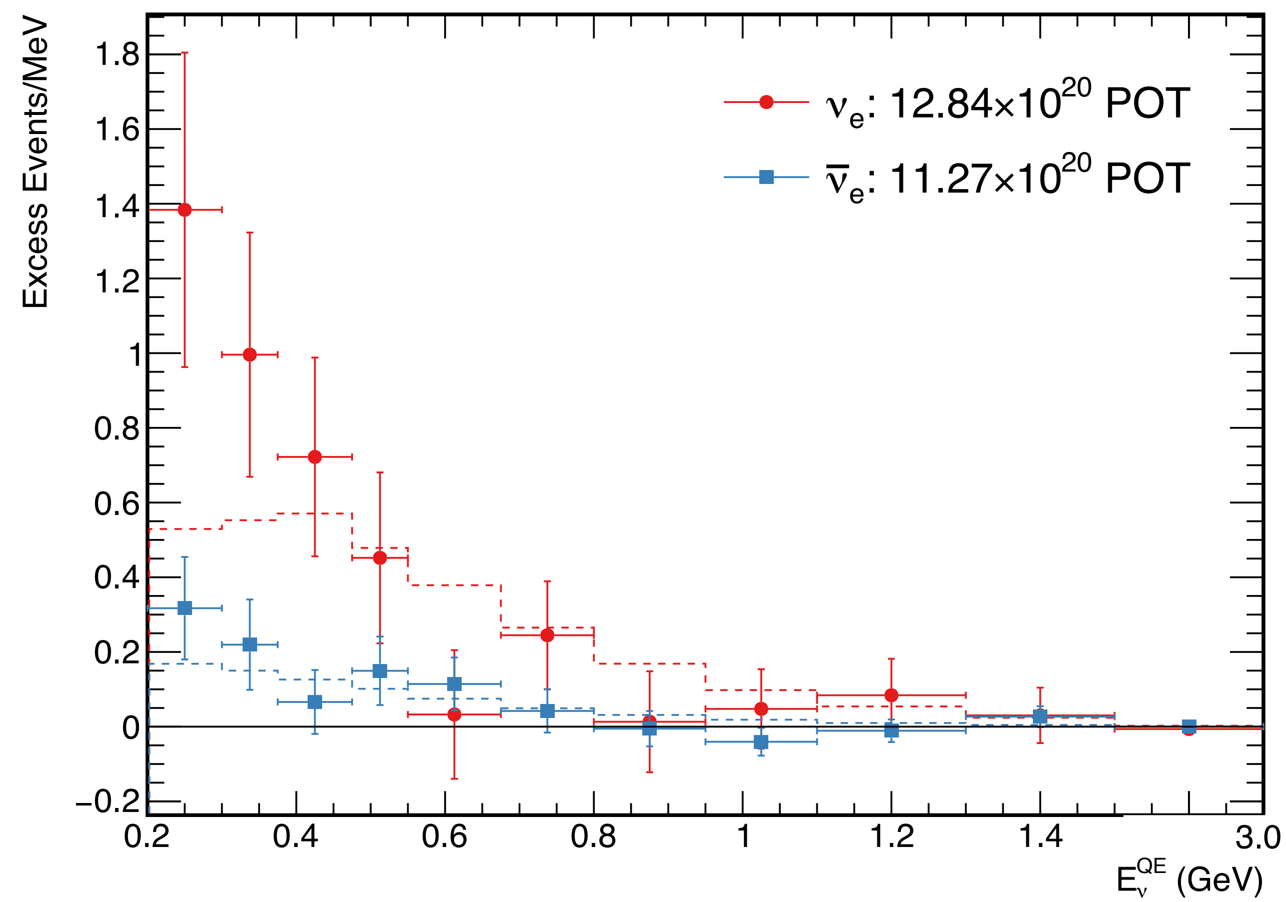
Complements earlier antineutrino results collected 2002-2010

# 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 $\sim 400$ events, PMNS predicts 0

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

MiniBooNE Collaboration 1805.12028

# Important Caveats

**1) Could be an experimental artifact**

Unknown systematic or mismeasured BG

**2) LSND/MiniBooNE connection is *assumes* steriles**

Disfavored by disappearance & cosmolgy

See Marztinez-Soler and Marfatia's talks

**3) I will ignore both LSND and sterile neutrinos**

Can MiniBooNE anomaly be any ***other*** new physics?

# Overview

1) Review 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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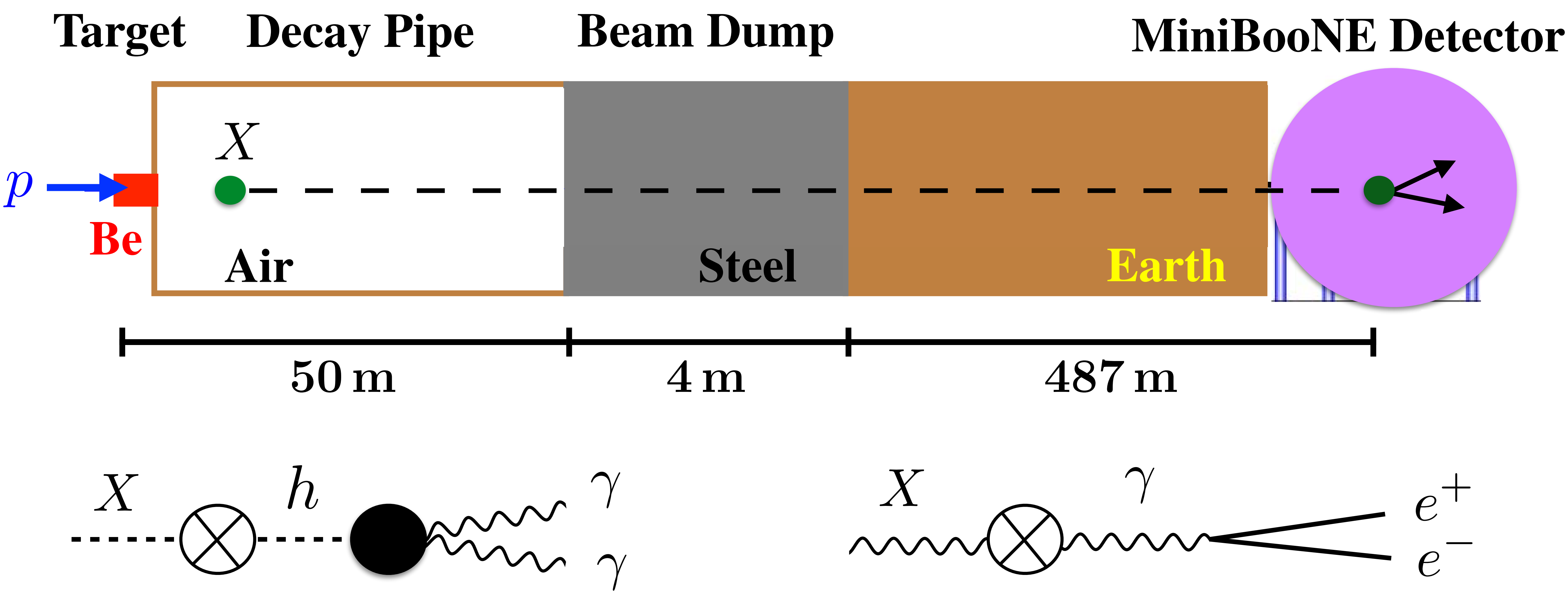
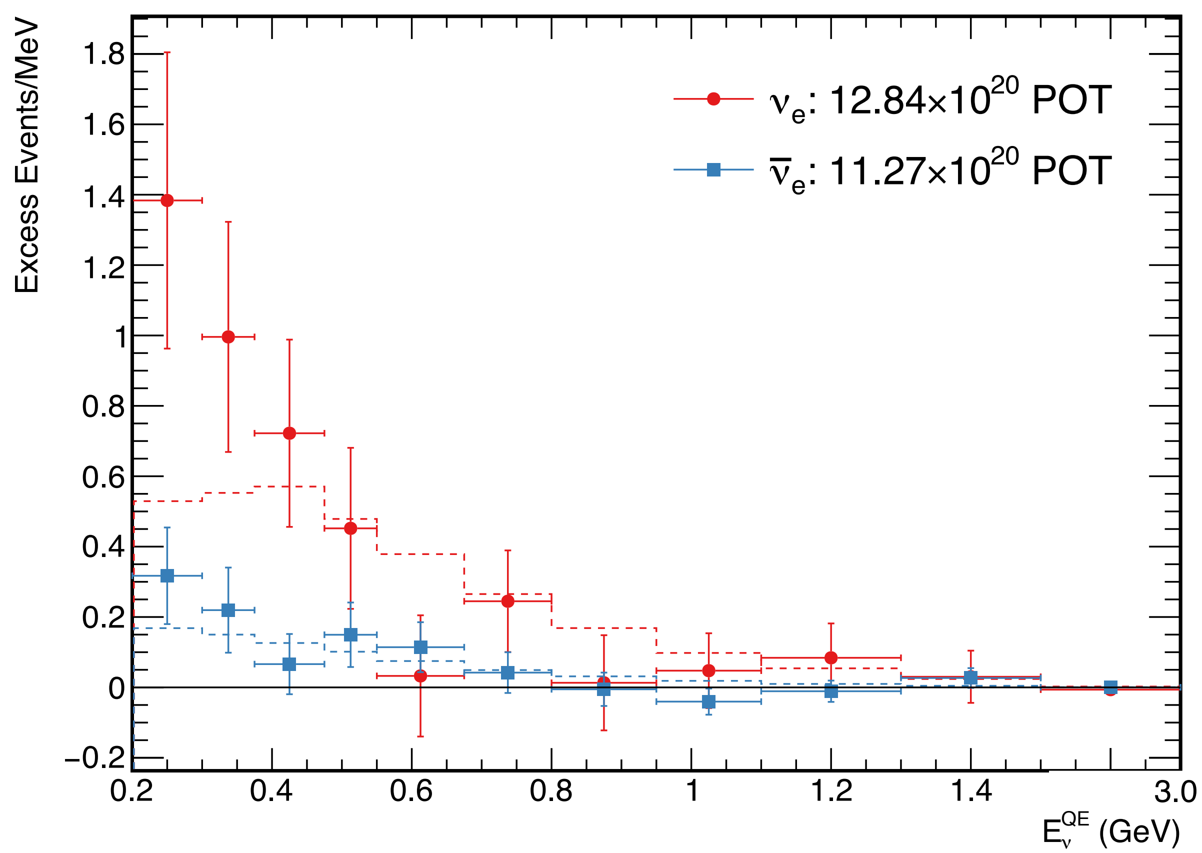
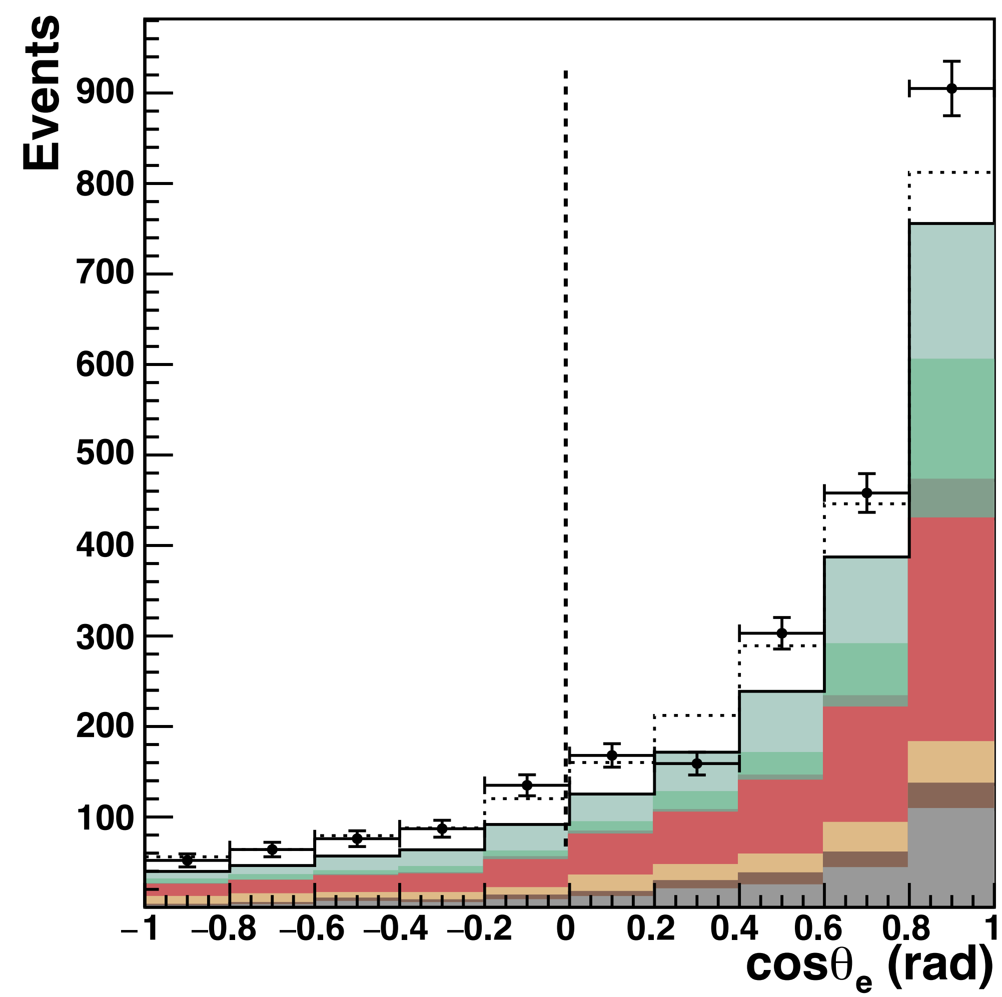



Detector can't distinguish electrons / photons
Collimated particles reconstruct as one "CCQE" track

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




Energy threshold = 200 MeV

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

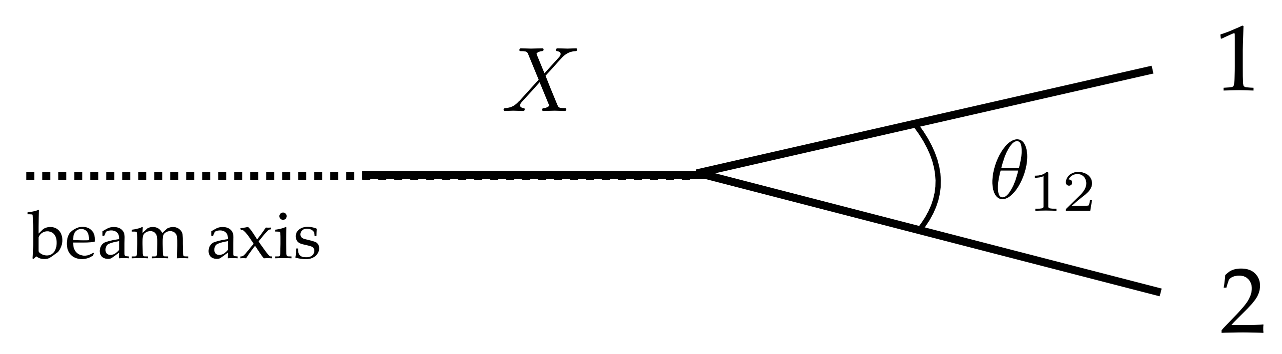
Many wide angle events for reconstructed "electron"

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** $m_{\text{track}} < 30\text{ MeV}$

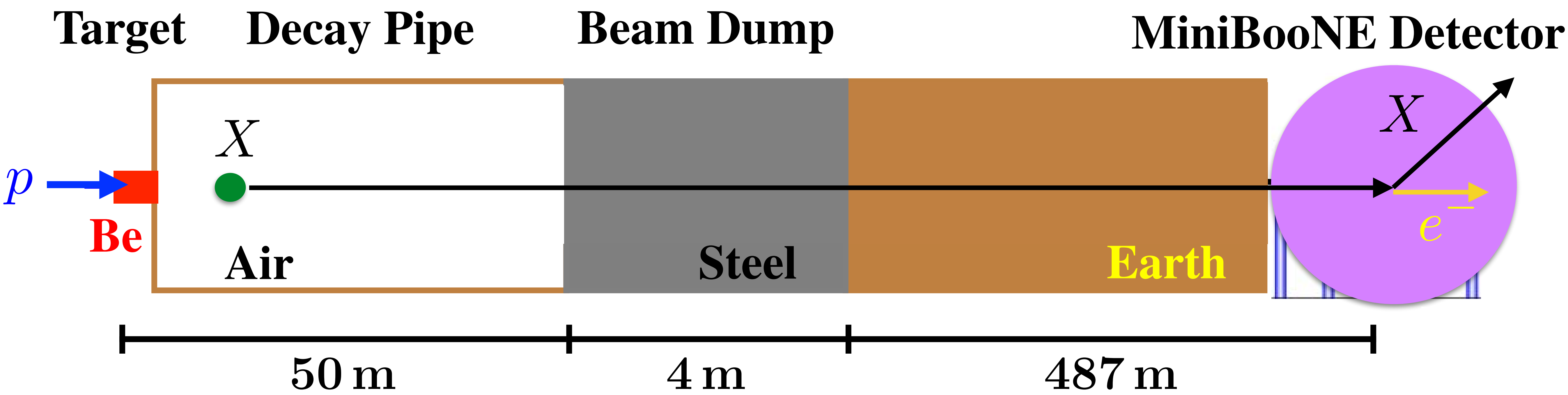
$$m_{\text{track}} \equiv \sqrt{2E_1E_2(1-\cos\theta_{12})} \longrightarrow \cos\theta_{12} > 1 - \frac{(30\text{ MeV})^2}{2E_1E_2}$$

***E* > 200 MeV required by cuts, easy to fake a single track**

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

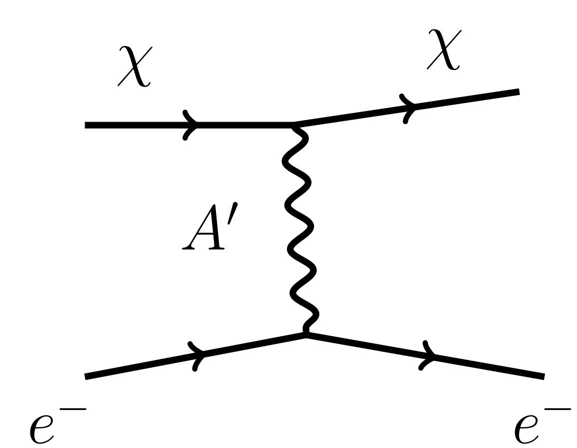
**Model independent exclusion of visible decays**

**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** $E_X \gtrsim m_X$

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

Fails selection cuts

**Elastic scatter ruled out model independently**

# Generalizing our assumptions

## Model Independent Arguments (Kinematic Features Only)

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

Allow decays with both visible and invisible final states

---

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

Allow scattering with

1) Nuclear targets for angular distribution

2) Inelastic coupling to produce visible EM energy

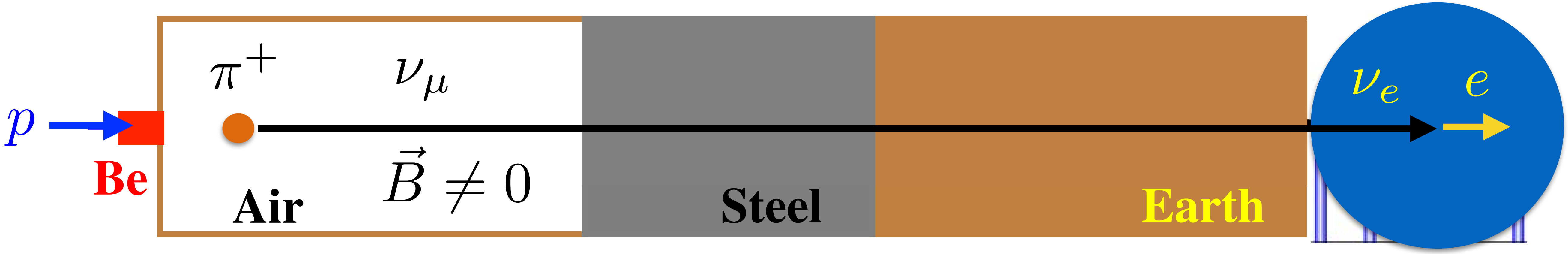
# Overview

1) Review of the MiniBooNE Excess

2) Excluding Simple Models w/  Kinematic Distributions

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

# Neutrino Mode vs. Beam Dump Mode




**Neutrino mode uses Be target and magnet focusing**

**Charged** particles collimated

**Neutral** particles diffuse

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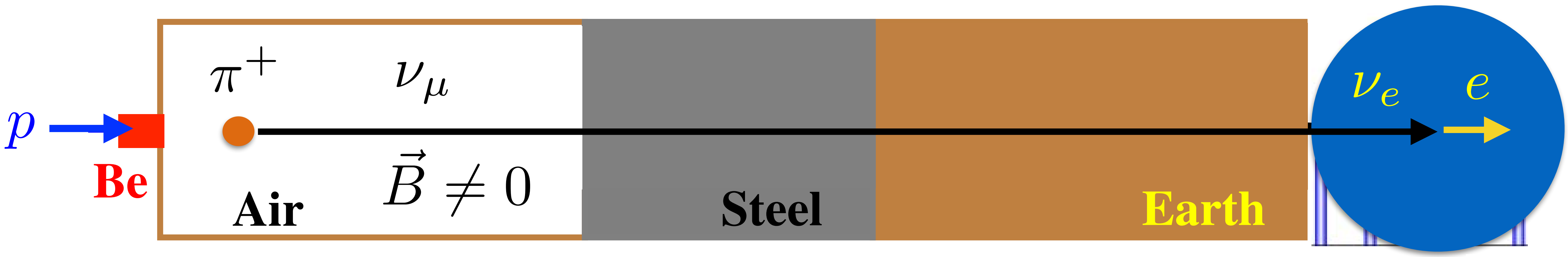


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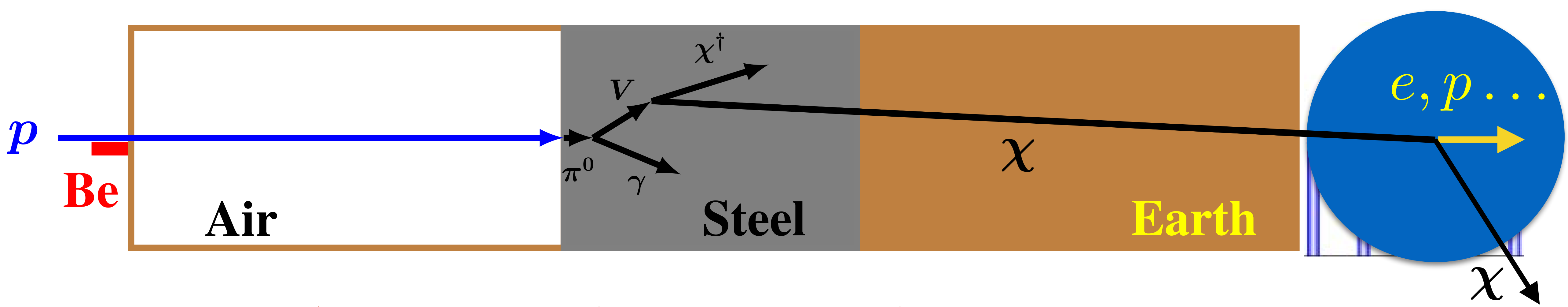
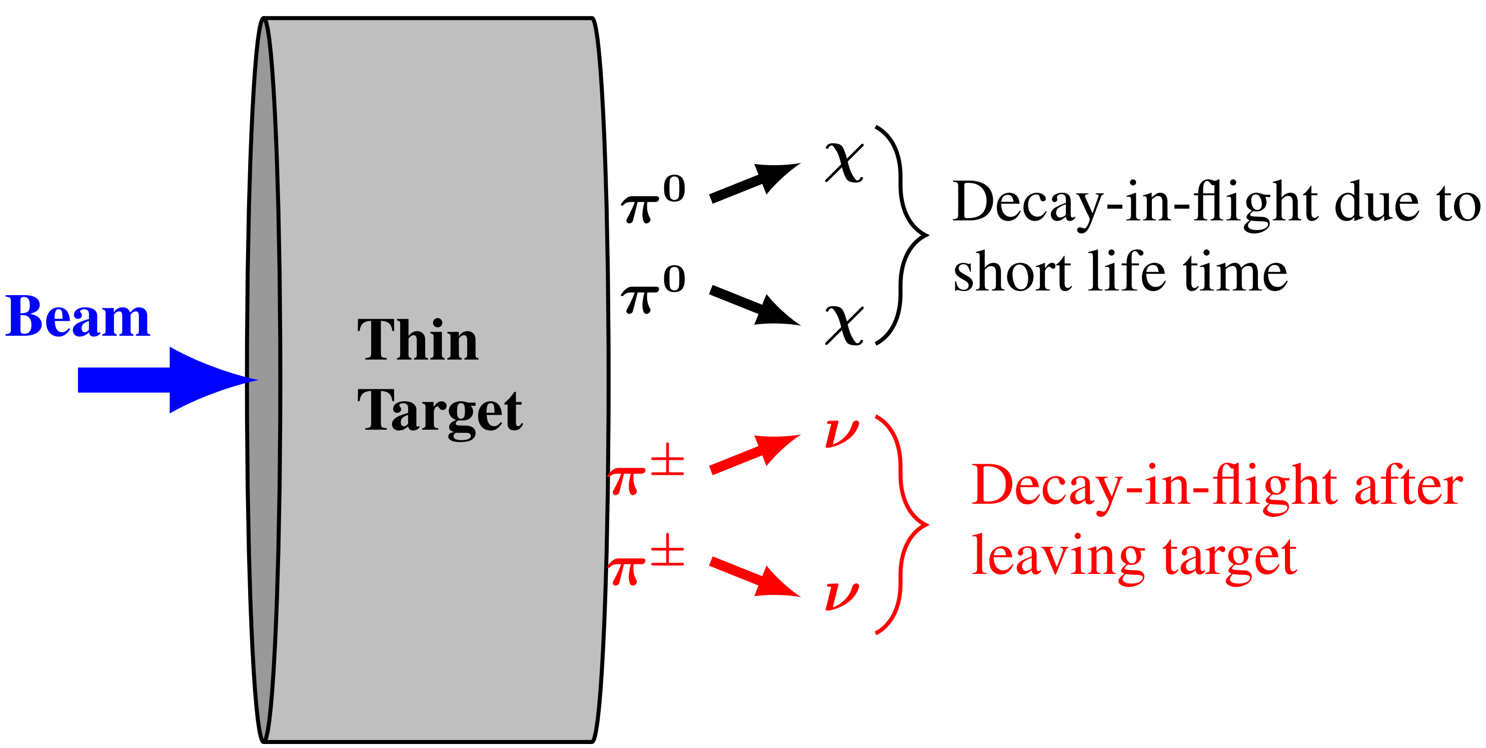


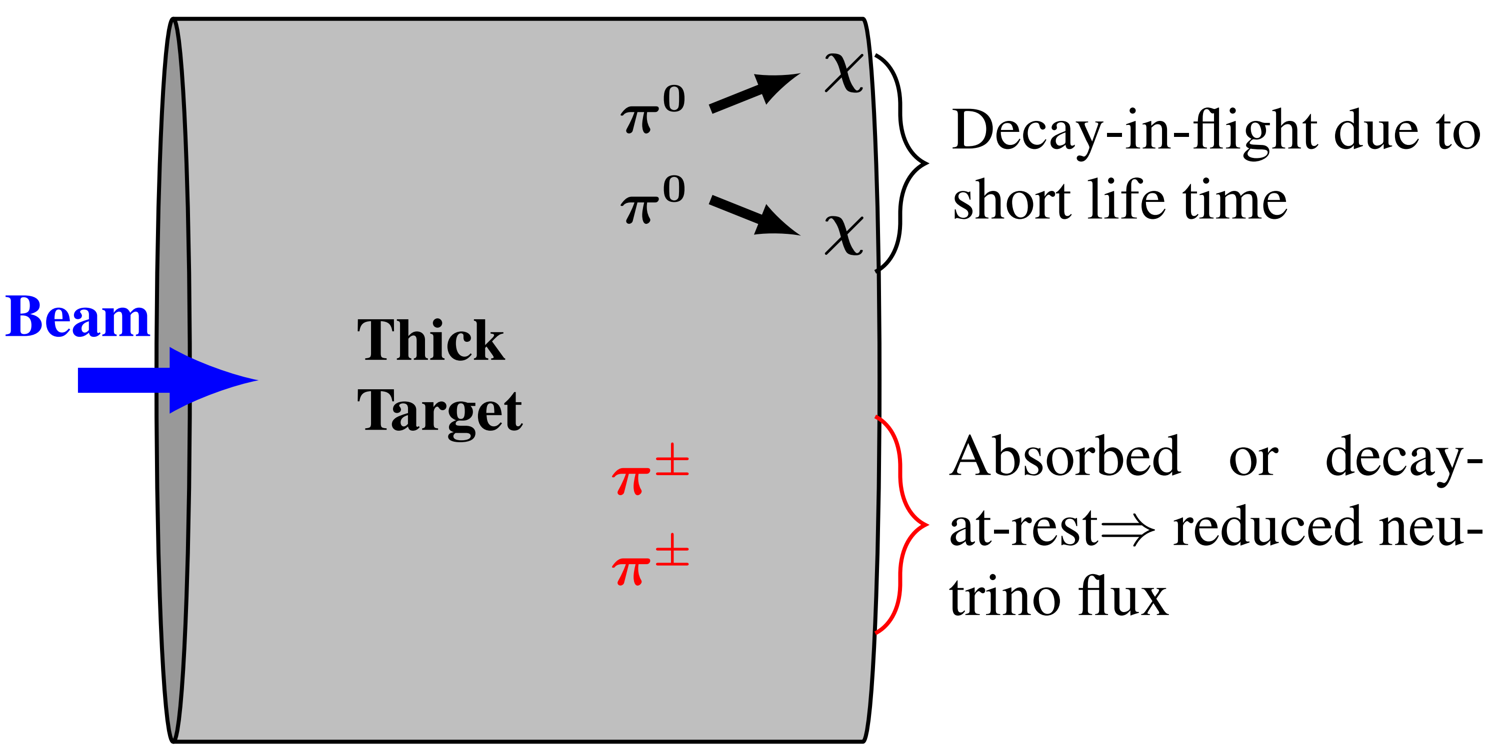

**Beam dump avoids target and magnet**

Optimized for dark matter production

**All** particles diffuse

# Neutrino Mode vs. Beam Dump Mode

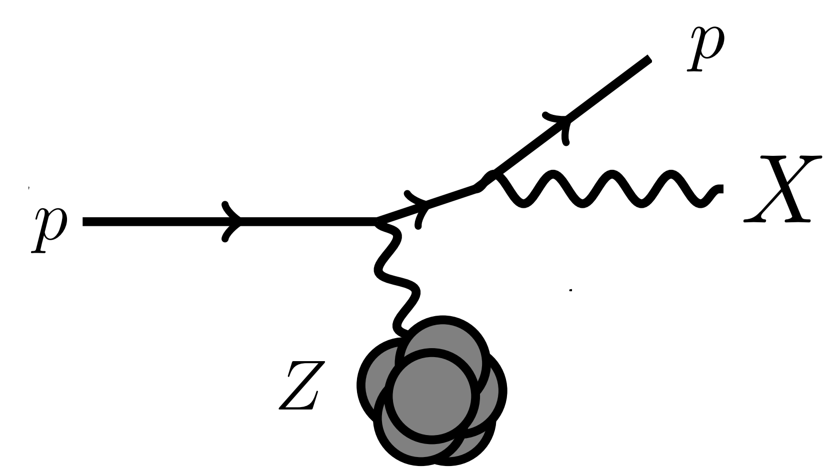



MiniBooNE Collaboration arXiv1807.06137

Continuum production

Similar in both modes




Uses full beam energy

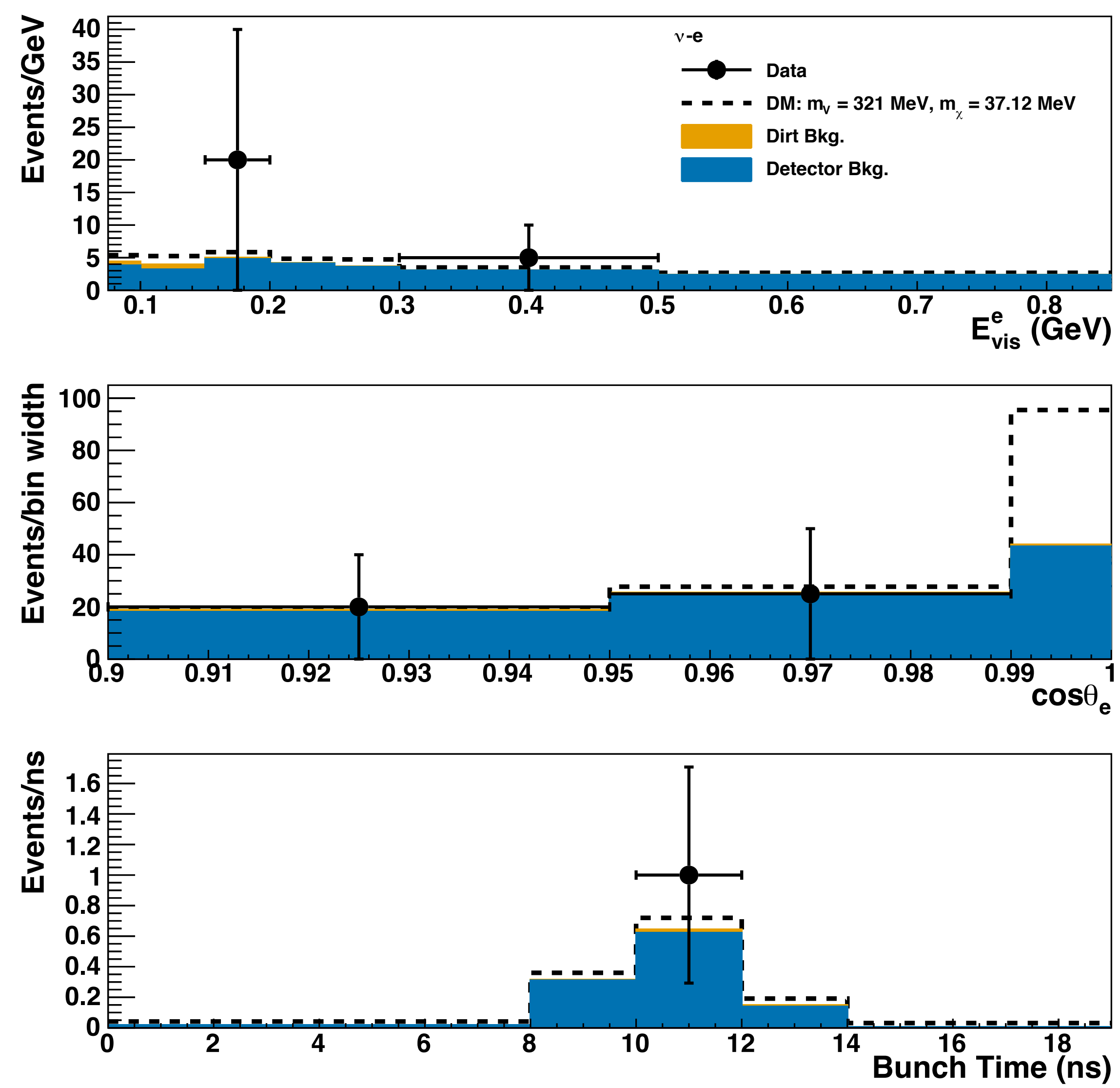
Important for heavy X

Thickness irrelevant

if greater than rad. length

# Null Beam Dump Mode Search: Strong BSM Bounds

No signal events observed above BG




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

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

MiniBooNE Collaboration arXiv1807.06137

## 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 **nucleons**

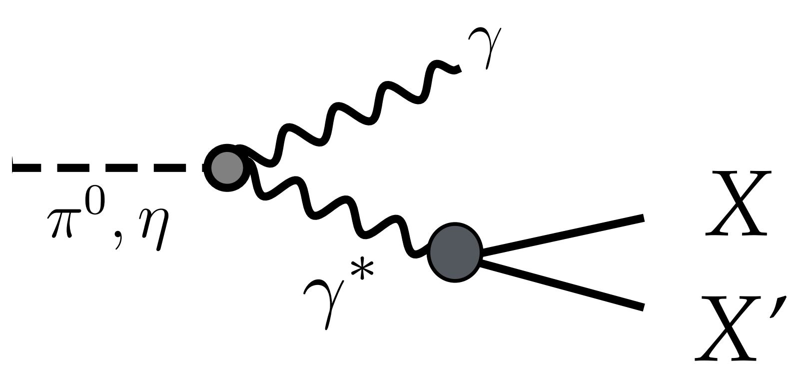
**Scenario A′**

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

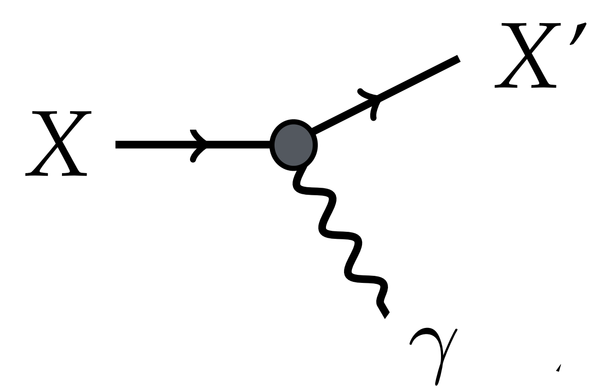
$X \to X' + \mathrm{EM}$ $\qquad$ $X'$ is invisible

Example: dipole interaction for a Pseudo-Dirac fermion

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




Production (target)

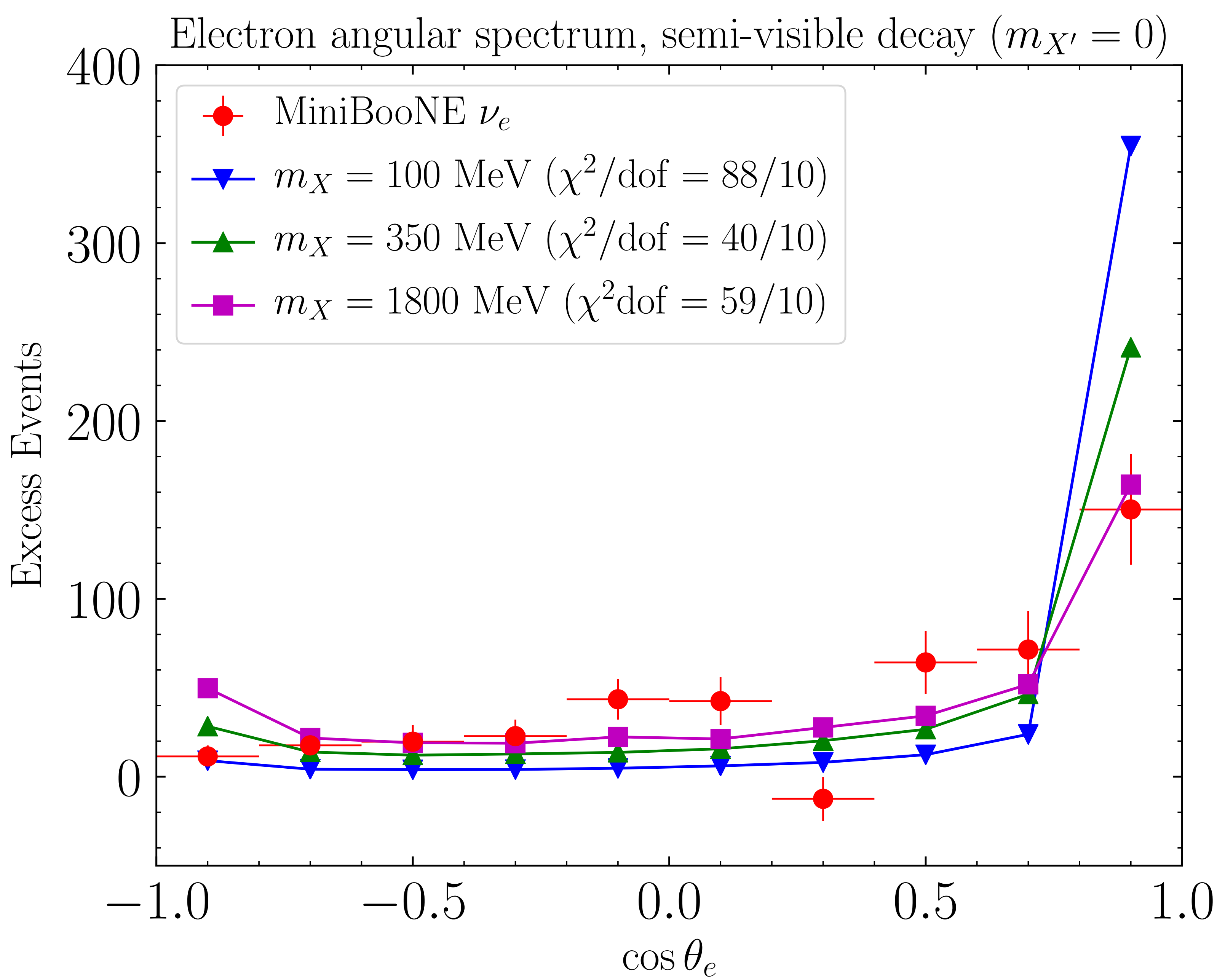



Decay (detector)

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




Scenario **Disfavored** by angular distribution, unless $m_X >$ GeV

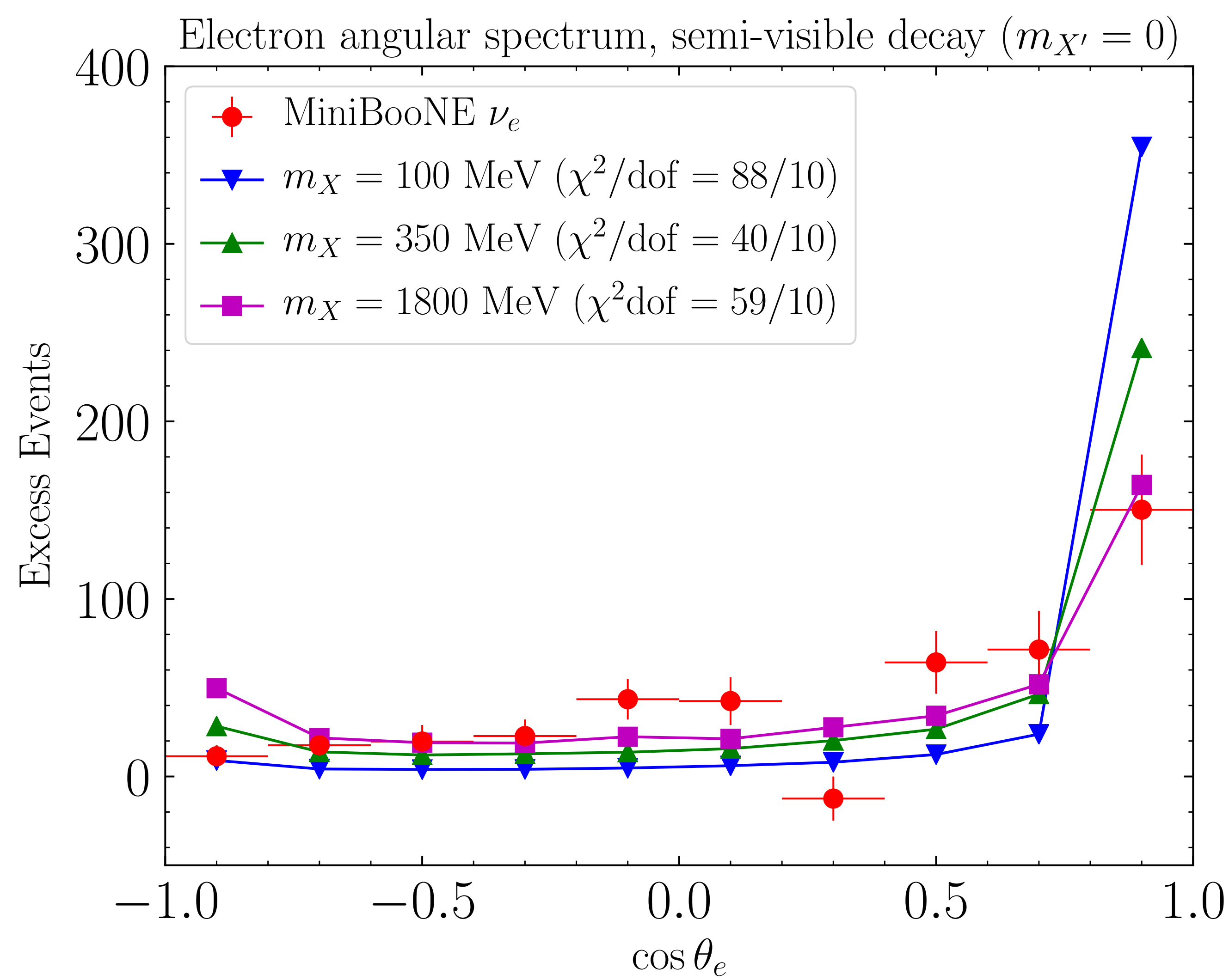
**Scenario A′** **Unstable** particle produced in target
Each decay has **visible & invisible** daughters

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

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

Need neutral mesons or continuum production

Similar production rate in beam dump mode

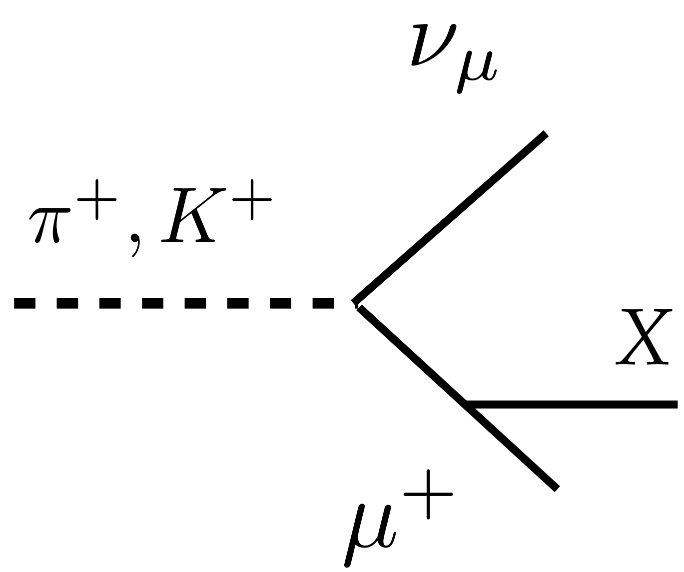


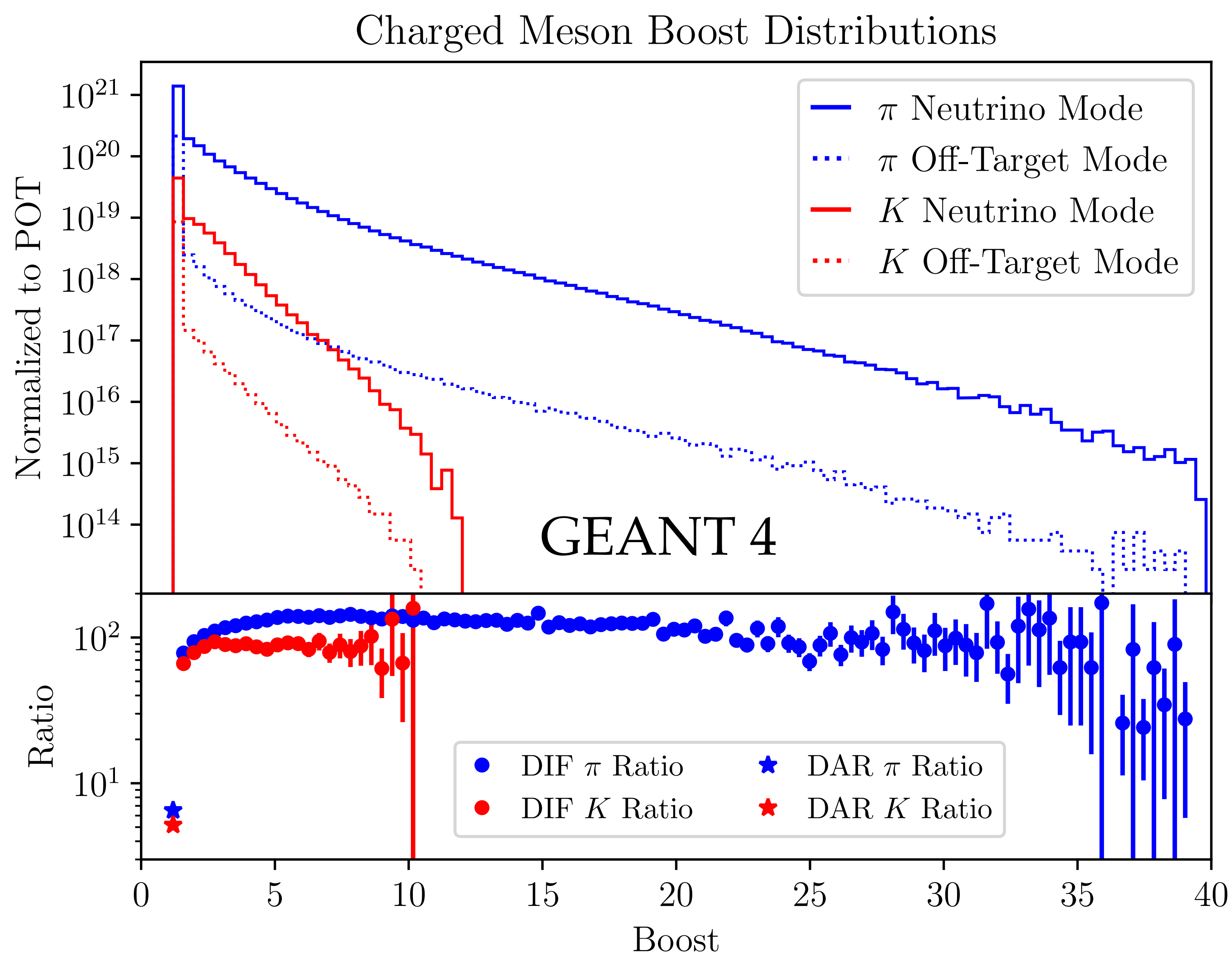

**Scenario A′ ruled out** ~ 60 events in beam dump mode (obs ~2)

**Scenario B′**

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

**Step 1)** produce $X$ from charged meson decays



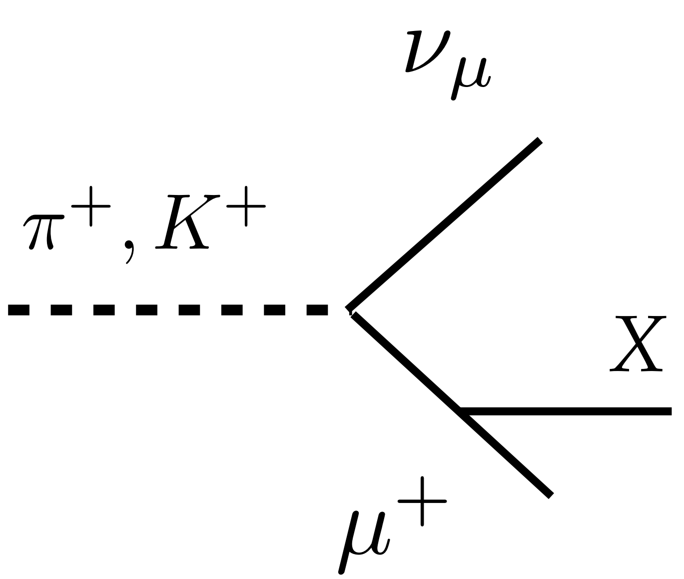

Production in target
charged meson decays

100x reduction in beam dump mode for all boosts $\Longrightarrow$ $\mathcal{O}(\text{few})$ events

**Scenario B′**

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

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




Production in target
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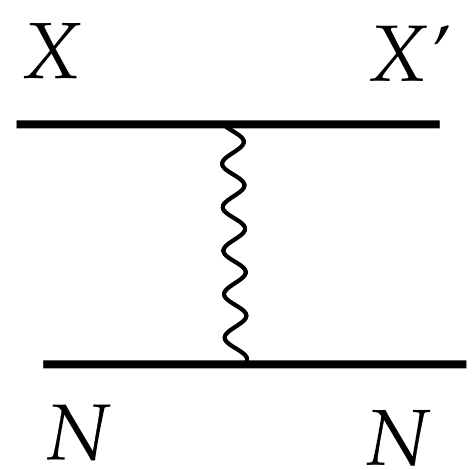


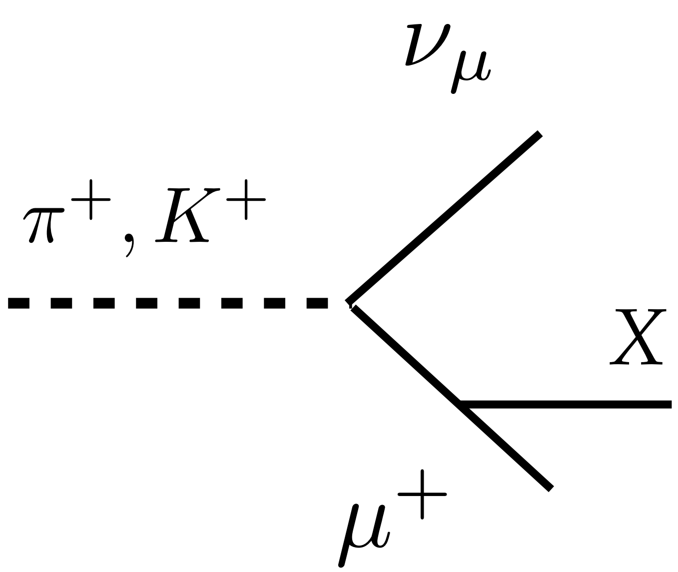

Scattering in detector
produces new state X′

Can’t scatter off detector electrons (always recoils w/ cos > 0.99)

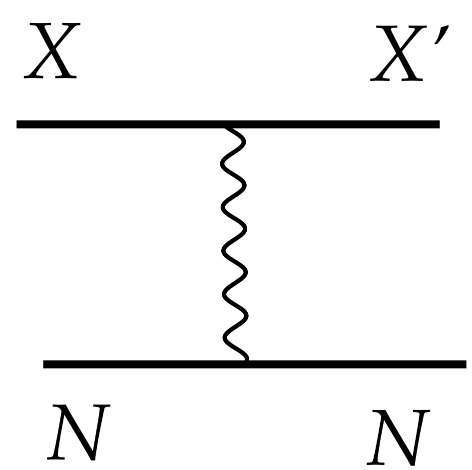
**Scenario B′**

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

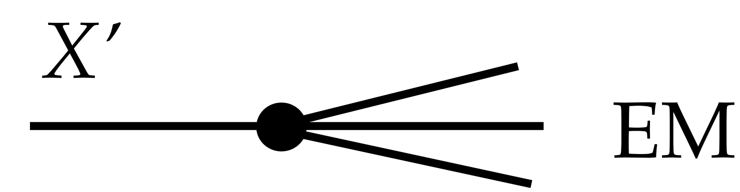
**Step 3)** X′ injects EM Energy inside detector to mimic CCQE signal




Production in target charged meson decays




Scattering in detector produces new state X′




New state decays EM final states

EM energy must be collimated to fake single track for CCQE signal

**Scenario B′**

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

**Step 1**

$$\pi^+ \text{ or } K^+ \to X \cdots$$

**Step 2**

$$XN \to X'N \cdots$$

**Step 3**

$$X' \to \text{EM}$$

**Model building challenges:**

Couple to nucleons for detector upscatter
satisfy angular distribution

Avoid neutral meson+continuum production
ruled out by beam dump

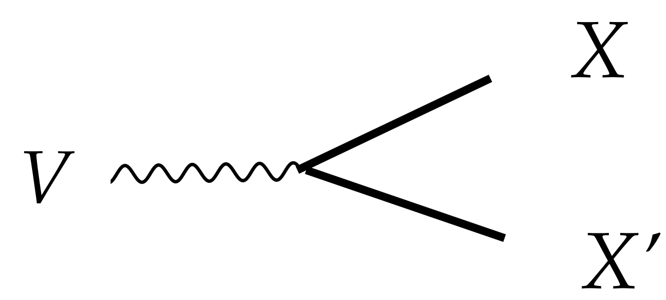
Avoid electron scattering
otherwise always forward electrons

**Scenario B′**

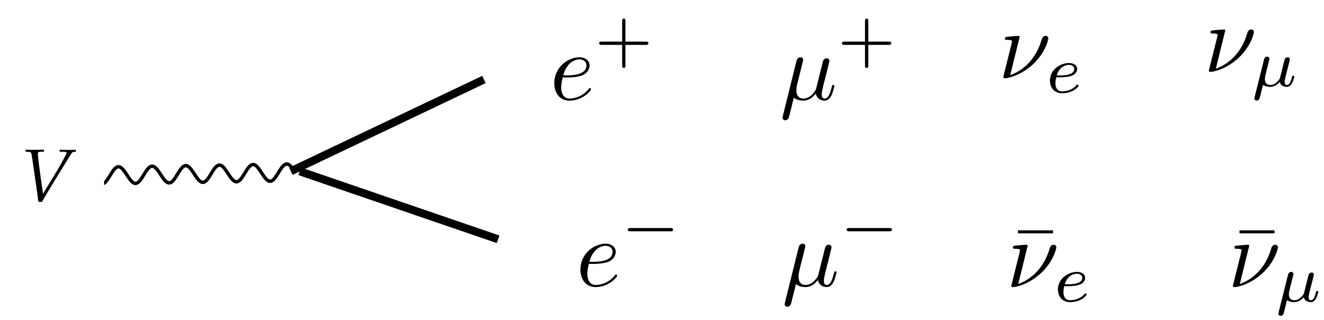
**Stable** particle produced in target
**Inelastically** scatters of **nucleon/nucleus**

**Example:** pseudo-dirac X & X′ coupled to new force $U(1)_{L_e - L_\mu}$

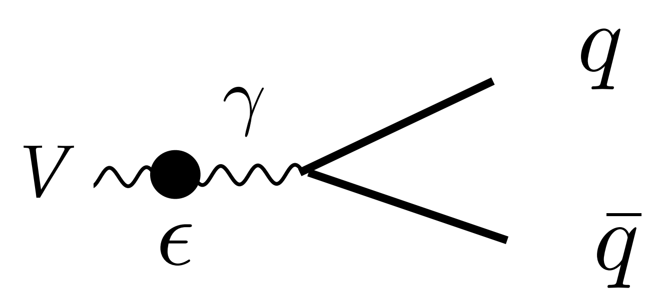
V couples dominantly to
X X′ off-diagonally




V couples weakly to
electron and muon flavors




V couples feebly to all charged
particles via kinetic mixing



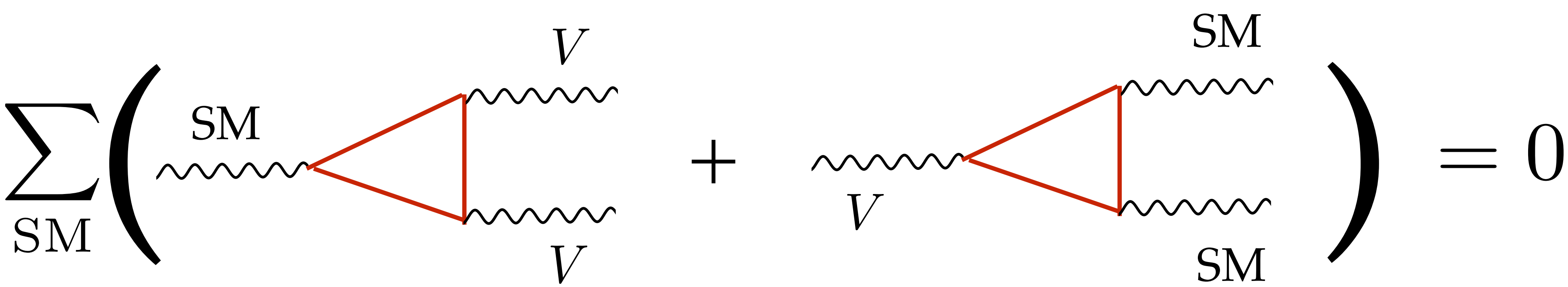

$\propto \epsilon \ll 1$

**Scenario B′**

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

**Example:** pseudo-dirac X & X′ coupled to new force $U(1)_{L_e - L_\mu}$

**This model is UV consistent and anomaly free**



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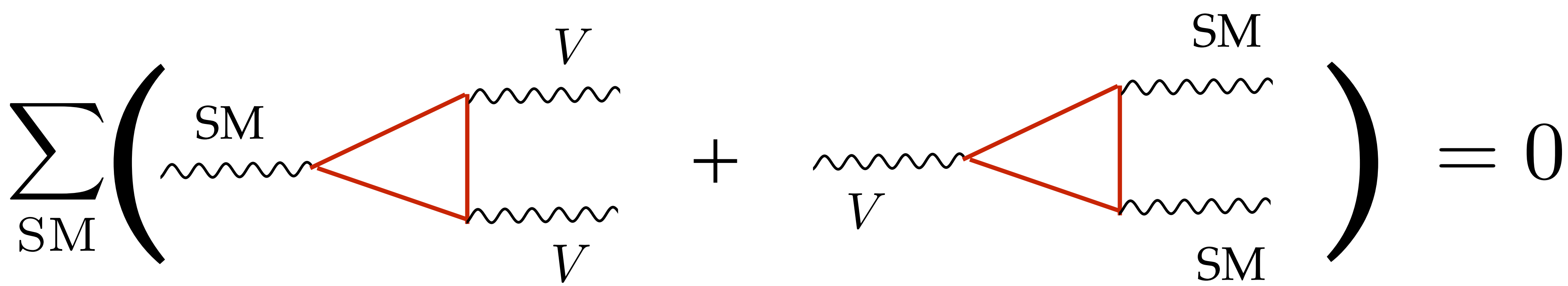
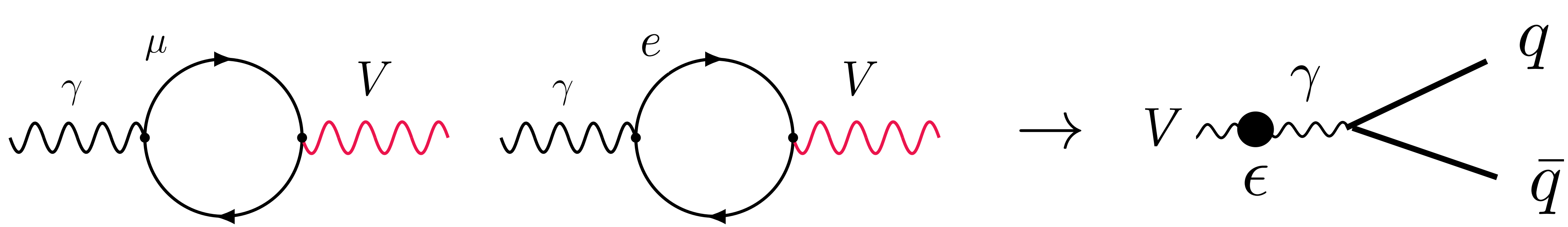



### Kinetic mixing arises for "free" from loops



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

**Example:** pseudo-dirac X & X′ coupled to new force $U(1)_{L_e - L_\mu}$

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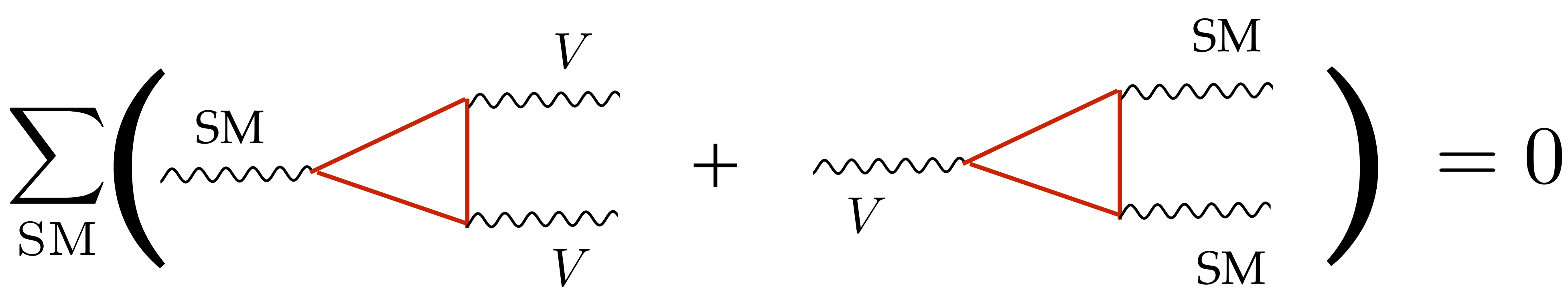


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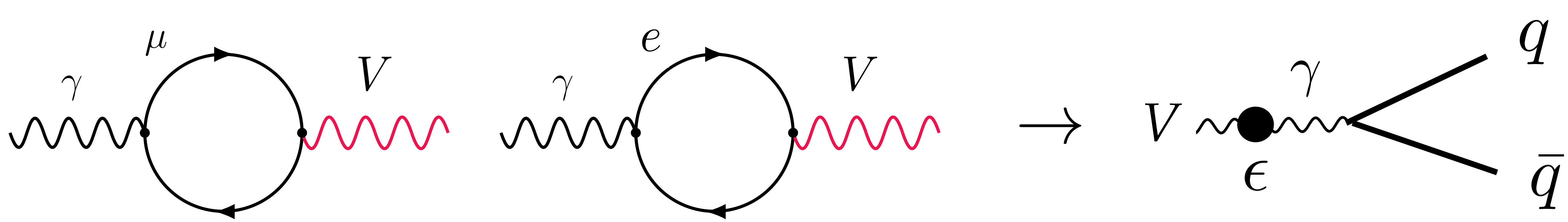


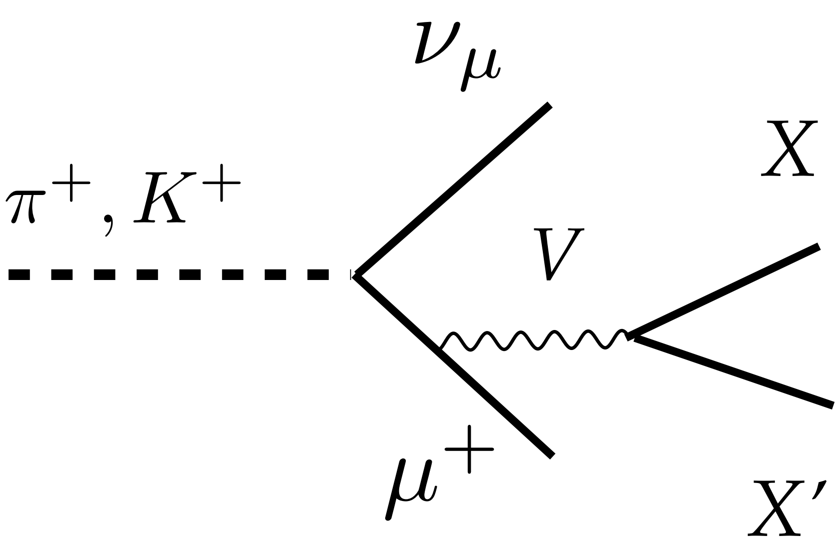

## Inelastic X X′ coupling easy

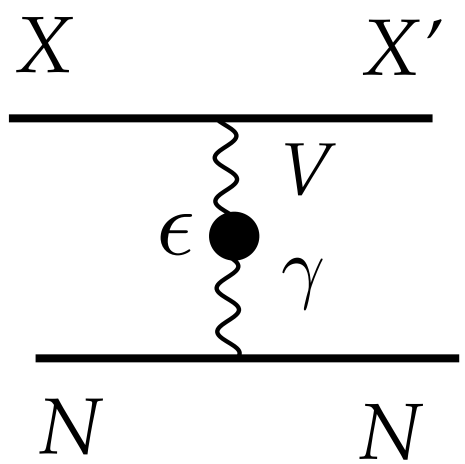
2 Weyl fermions w/ large Dirac mass & small Majorana mass

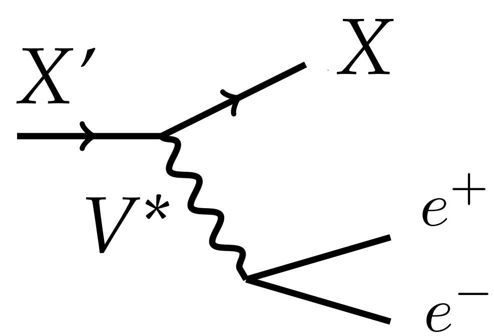
**Scenario B′**

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

**Example:** pseudo-dirac X & X′ coupled to new force $U(1)_{L_e - L_\mu}$




Charged meson decay
V decays makes X & X′
X′decays promptly

X scatters inelastically
via kinetic mixing
produces X′

X′ 3-body decay
EM final states

# Conclusions

**4.8 sigma MB excess, simple sterile interpretations disfavored**

**Disappearance + Cosmology**

**Simple other BSM (non-neutrino) models ruled out**

**Angular distribution** {
- X decays all-visibly
- X scatters elastically

**New beam dump DM search is powerful constraint**

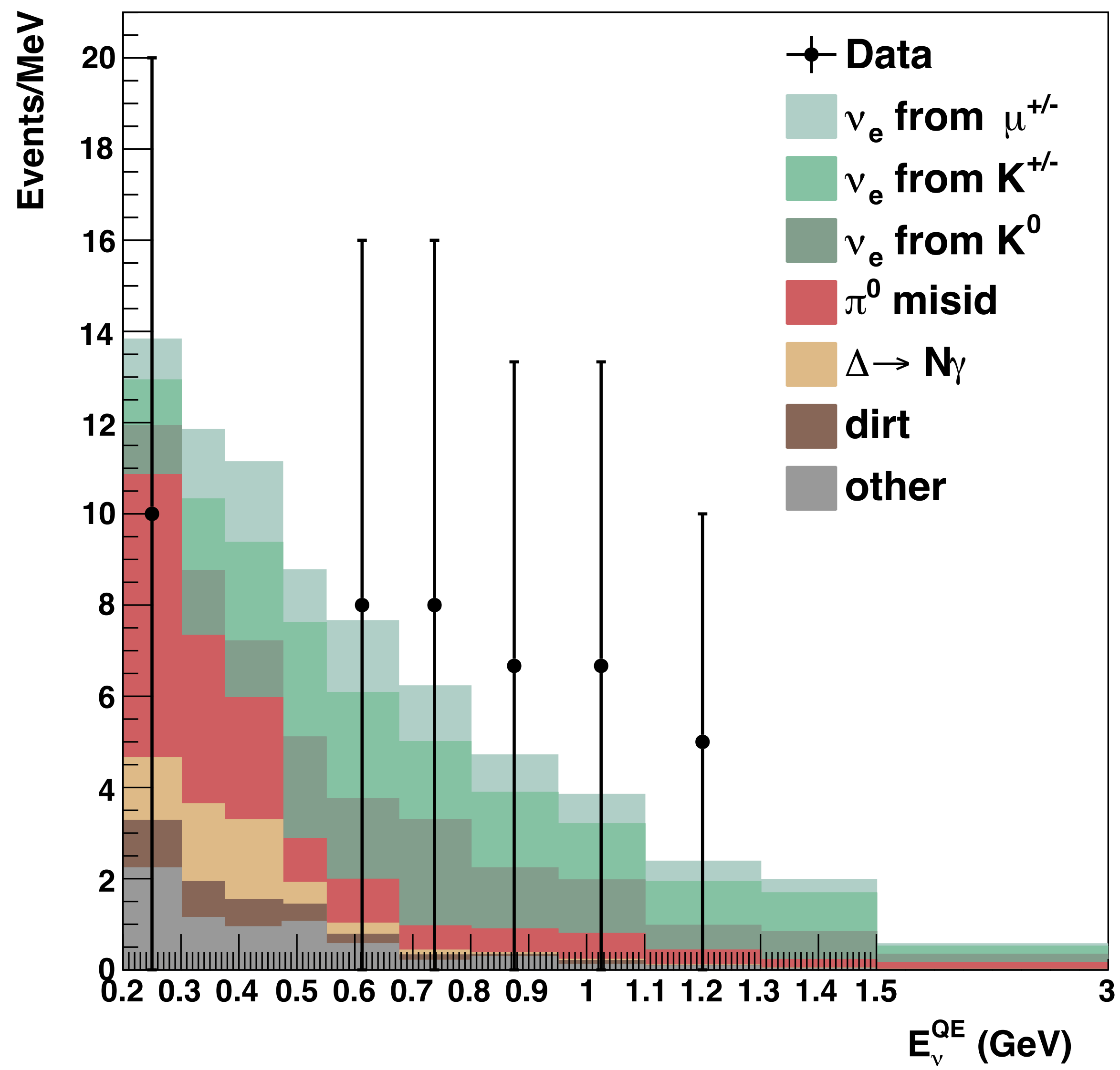
**Requires** {
1) production from charged mesons
2) inelastic scatter off nuclei
3) produce new, visibly decaying particle

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

Thanks!

# Null Result Imposes Nontrivial BSM Bounds

## No signal even with neutrino mode cuts in beam dump mode




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

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

MiniBooNE Collaboration arXiv1807.06137

# 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

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

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# Dark Neutrino Portal

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

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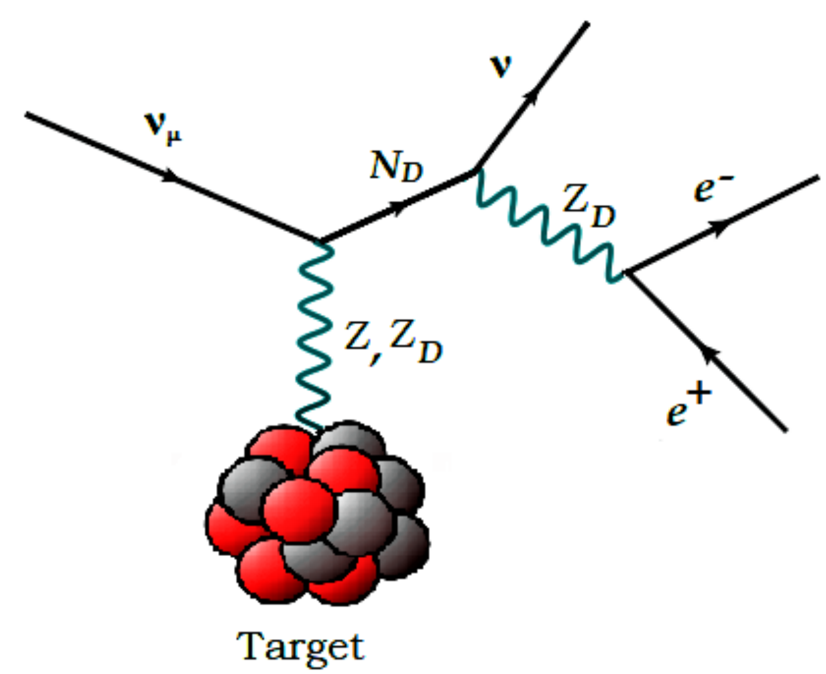
Beam neutrinos mix (not oscillate) to “dark”

Scatter nuclei through kinetic mixing

Make dark neutrino

Decays emitting Z′

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