

Recontre de Blois - June 2016

Light dark matter and neutrino beams

Adam Ritz

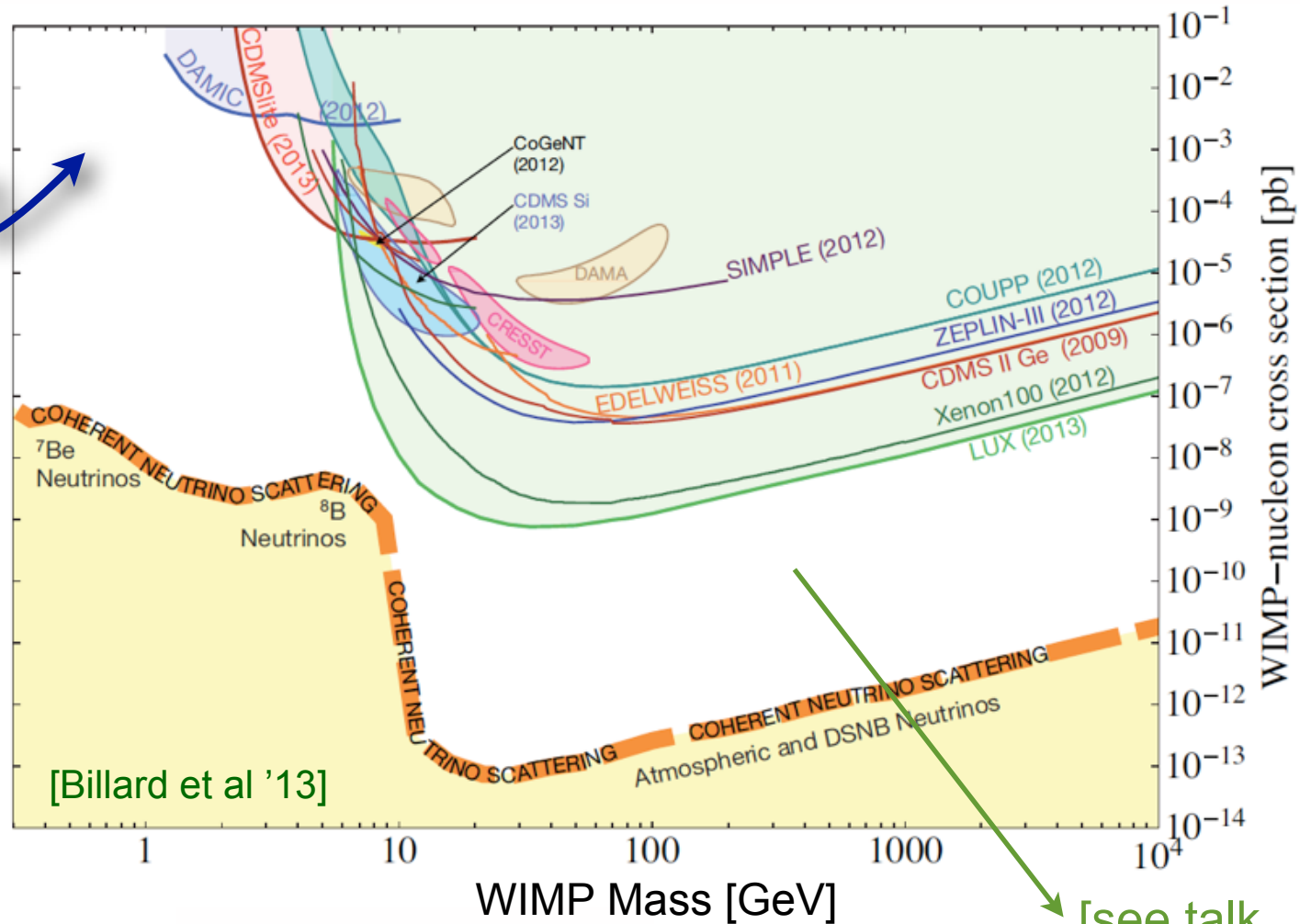
University of Victoria



(with) B. Batell, P. deNiverville, D. McKeen, M. Pospelov
& members of MiniBooNE, T2K & SHiP

WIMP (thermal relic) DM

Conventional direct sensitivity to halo DM with $v \sim 10^{-3}$ drops for $m < O(\text{GeV})$, due to recoil energy thresholds.



[Billard et al '13]

[see talk by L. Hsu]

For sub-GeV DM: $m_e < m_{\text{DM}} < m_{\text{had}}$, a (high intensity) relativistic beam can be used to detect scattering.

Light (thermal relic) DM

The Lee-Weinberg bound (WIMP mass \geq few GeV) applies if annihilation in the early universe is via SM forces.

$$\sigma_{\text{ann}} \propto \frac{m_{\text{DM}}^2}{M_{\text{mediator}}^4}$$

⇒ viable thermal relic density for a sub-GeV WIMP requires new annihilation channels through light states, i.e. light DM as part of a hidden sector.

Standard Model



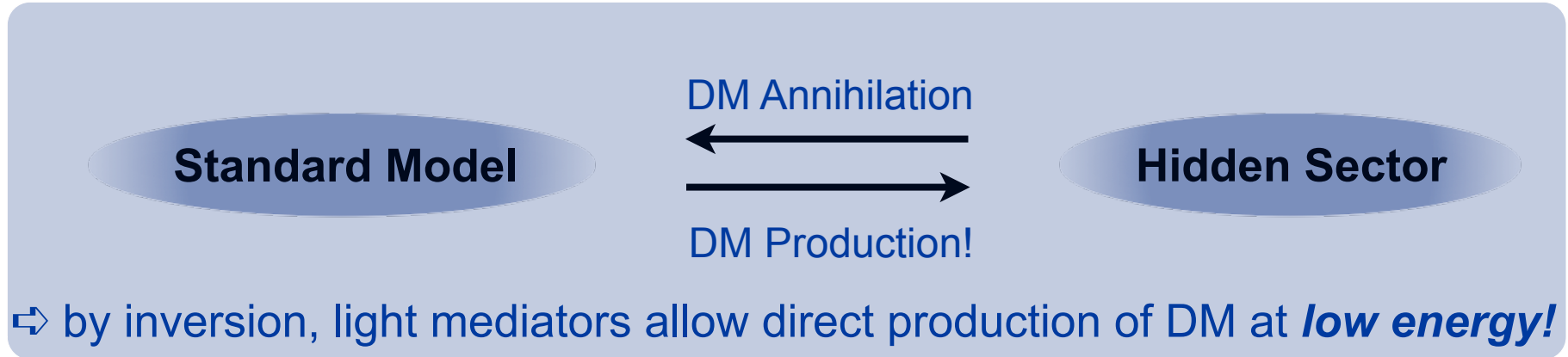
Hidden Sector

Light (thermal relic) DM

The Lee-Weinberg bound (WIMP mass \geq few GeV) applies if annihilation in the early universe is via SM forces.

$$\sigma_{\text{ann}} \propto \frac{m_{\text{DM}}^2}{M_{\text{mediator}}^4}$$

⇒ viable thermal relic density for a sub-GeV WIMP requires new annihilation channels through light states, i.e. light DM as part of a hidden sector.



(particularly if $m_{\text{mediator}} > 2 m_{\text{DM}}$)

$\text{Br}(\text{mediator} \rightarrow \text{DM}) \sim 1$

Philosophy - Neutrinos and Dark Matter...

⇒ maybe dark matter is more like the CvB...

- neutrinos are a (small) component of dark matter
- very abundant $\sim O(100/\text{cm}^3)$
- very hard to see via direct detection, since $KE \sim 10^{-4} \text{ eV}$

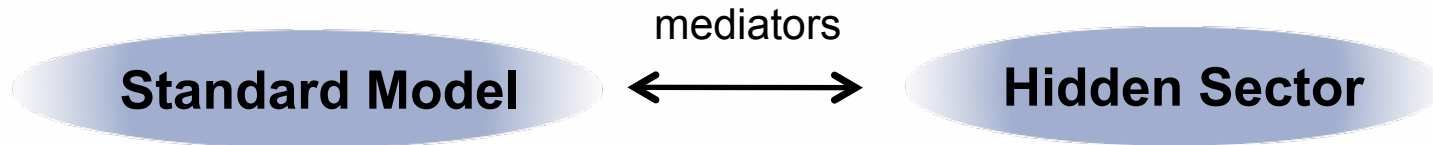
⇒ BUT muon neutrinos were discovered via hadronic production in meson decays (large rate!), and observing the (weak) scattering of the relativistic neutrino beam

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE
OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry,
M. Schwartz,[†] and J. Steinberger[†]

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

EFT for a (neutral) hidden sector



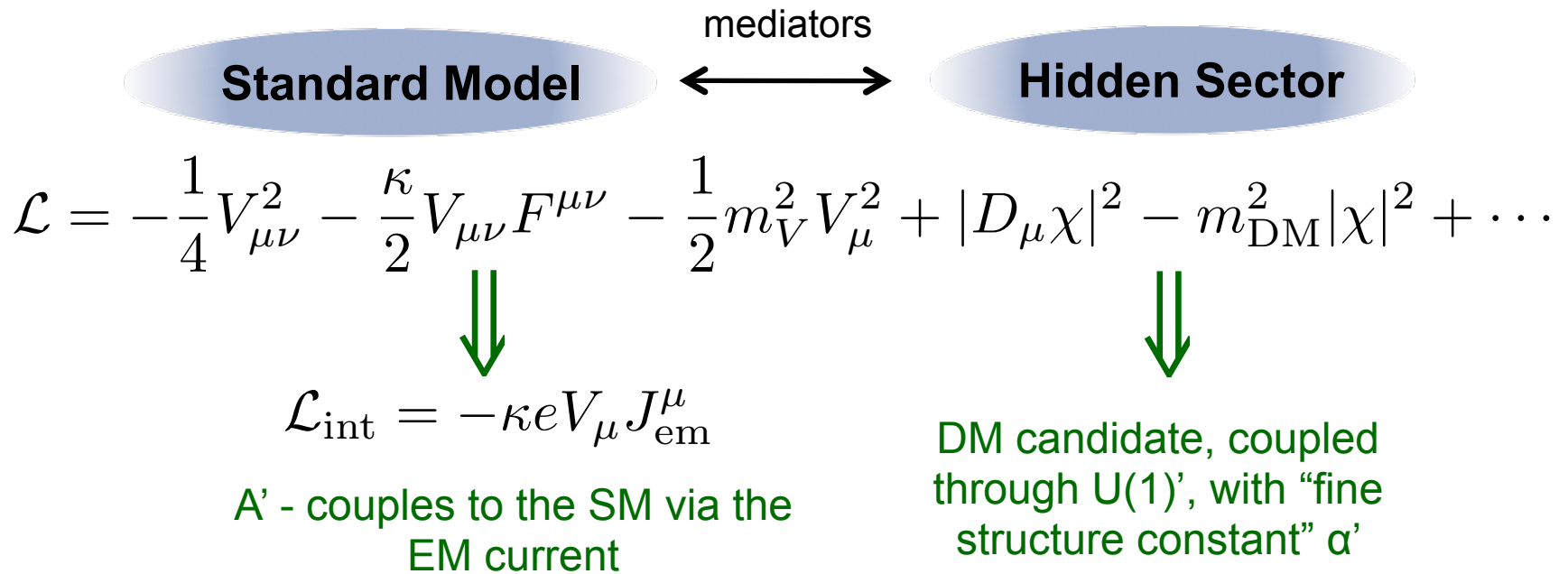
$$\mathcal{L} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(SM)} \mathcal{O}_l^{(med)}}{\Lambda^n} \sim \mathcal{O}_{portals} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Generic interactions are irrelevant (dimension > 4), but there are three UV-complete relevant or marginal “portals” to a neutral hidden sector

- Vector portal: $\mathcal{L} = -\frac{\kappa}{2} B^{\mu\nu} V_{\mu\nu}$ [Okun; Holdom; Foot et al]
 - Higgs portal: $\mathcal{L} = -H^\dagger H (AS + \lambda S^2)$ [Patt & Wilczek]
 - Neutrino portal: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j$ ← sterile neutrinos
- Mediator for simplest benchmark light WIMP DM models

Many more UV-sensitive interactions at dim ≥ 5 (e.g. axions) 6

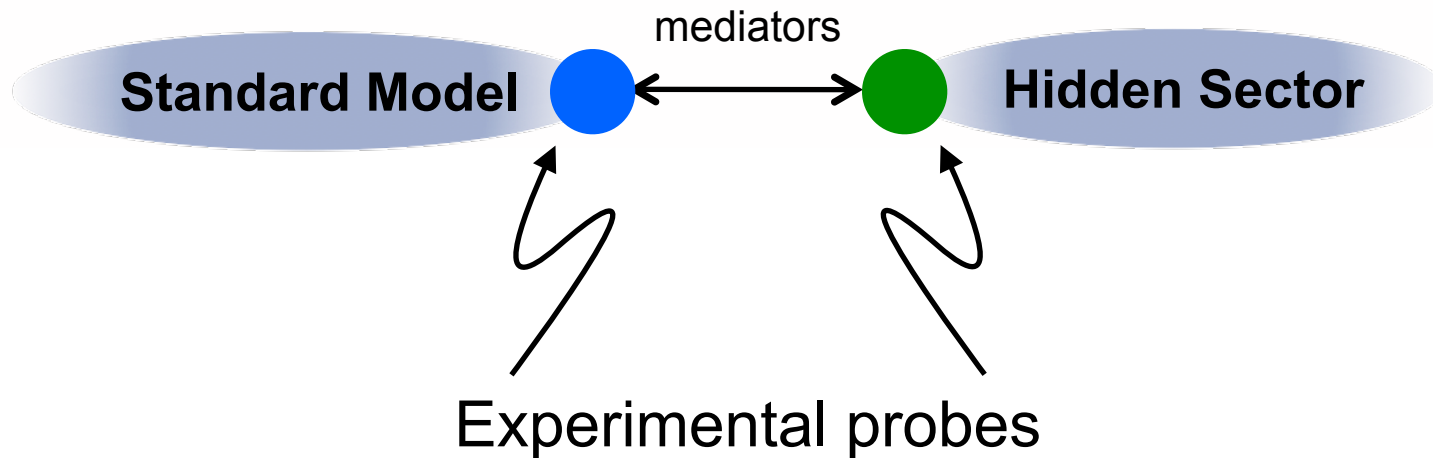
(Minimal) Vector portal DM model



- Allows viable sub-GeV thermal relic DM candidates [Boehm et al '03, Fayet '04,'06; Pospelov, AR, Voloshin '07; Hooper & Zurek '08].
- For $m_{\text{DM}} < m_V$, the correct relic density fixes a specific relation between $\{\kappa, \alpha', m_V, m_{\text{DM}}\}$ [Pospelov, AR & Voloshin '07]

(NB: notation $\kappa = \varepsilon$ for some later plots)

Probing the vector portal



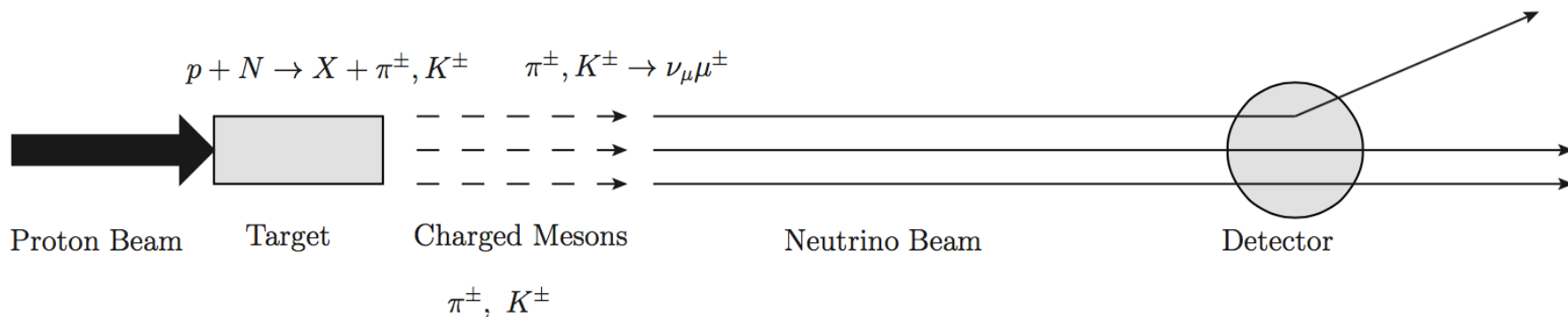
- precision corrections
 - e.g. lepton $g-2$
- rare (visible) decays
 - e.g. collider/fixed target production plus e.g. leptonic A' decays, $O(\kappa^2) \times \text{Br}(\text{SM})$

- rare (invisible) decays
 - e.g. collider production plus missing energy in decays, $O(\kappa^2) \times \text{Br}(\text{Hid})$

- Anomalous NC-like scattering
 - e.g. FT production plus scattering, $O(\kappa^2 \times \kappa^2 \alpha')$

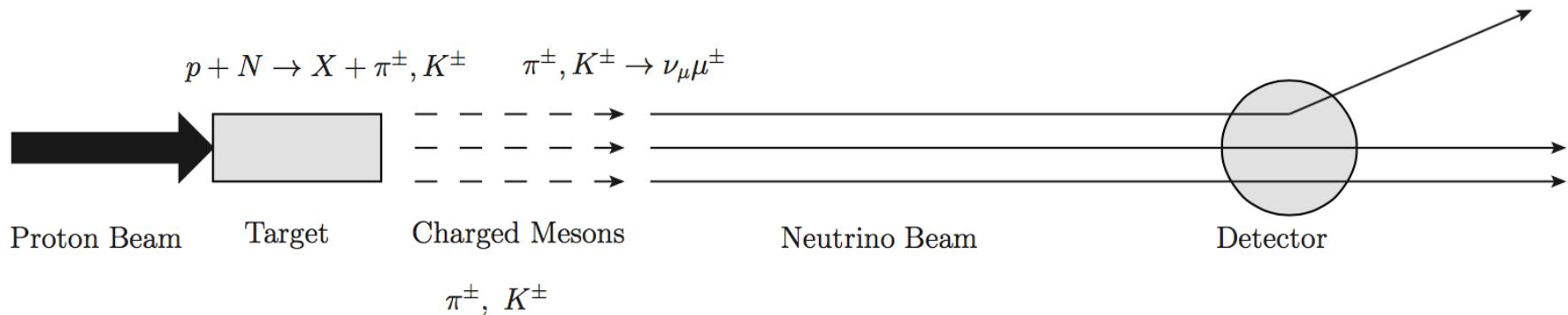
(also astrophysics & cosmology)

Fixed target probes - Neutrino Beams

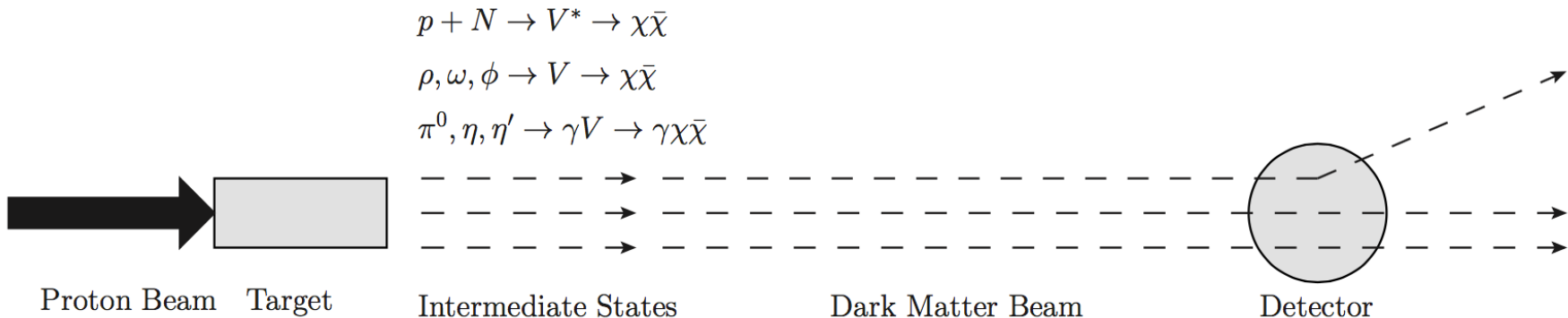


Basic idea: use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam.

Fixed target probes - Neutrino Beams



Basic idea: use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam.

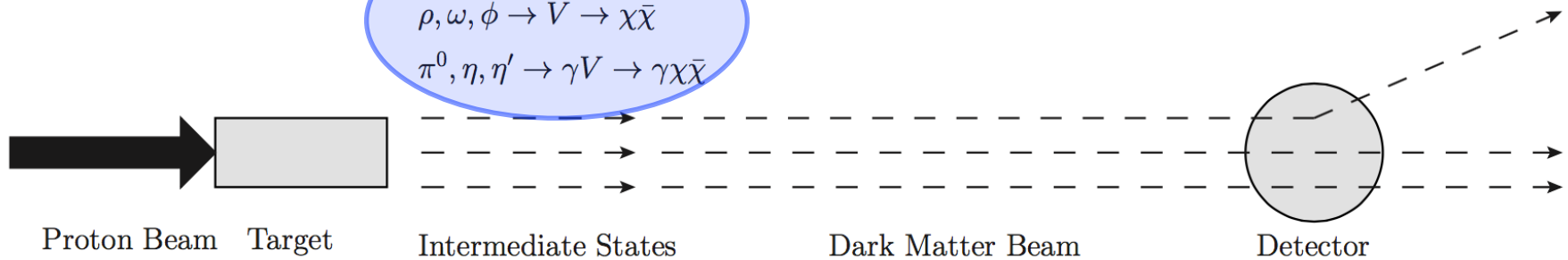
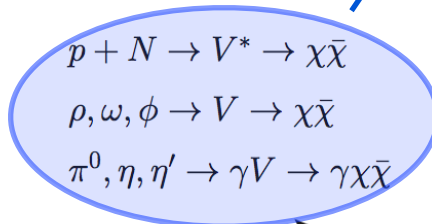
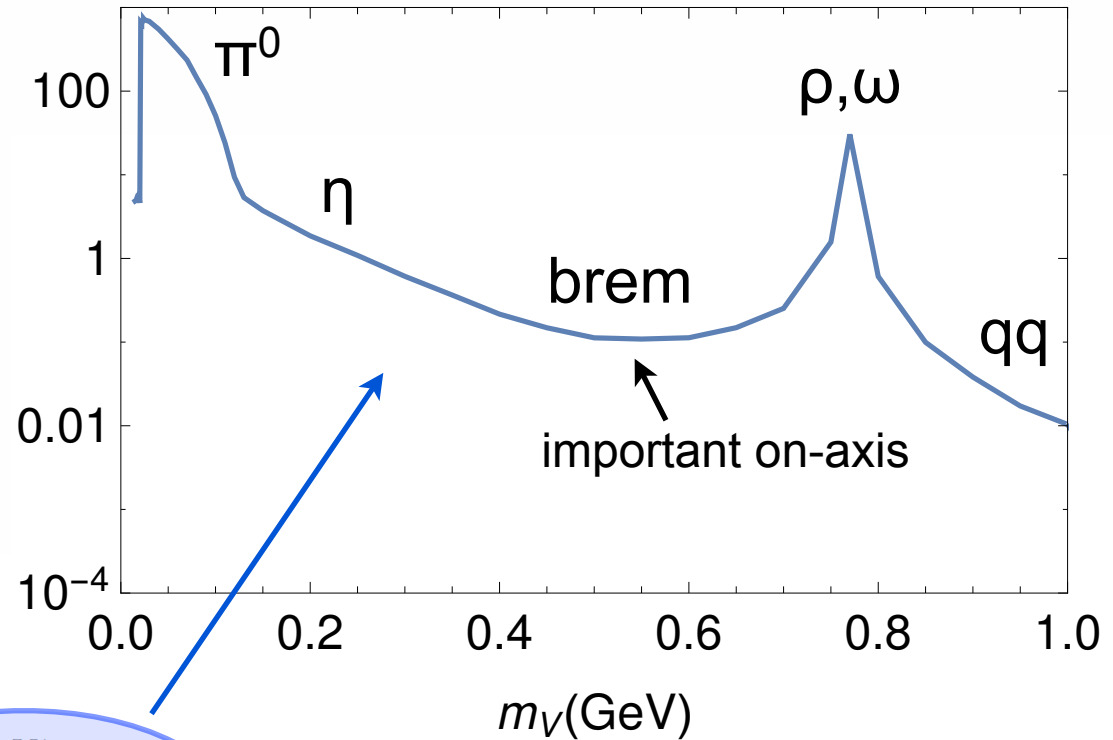


Fixed target - DM production

[deNiverville et al, to appear]

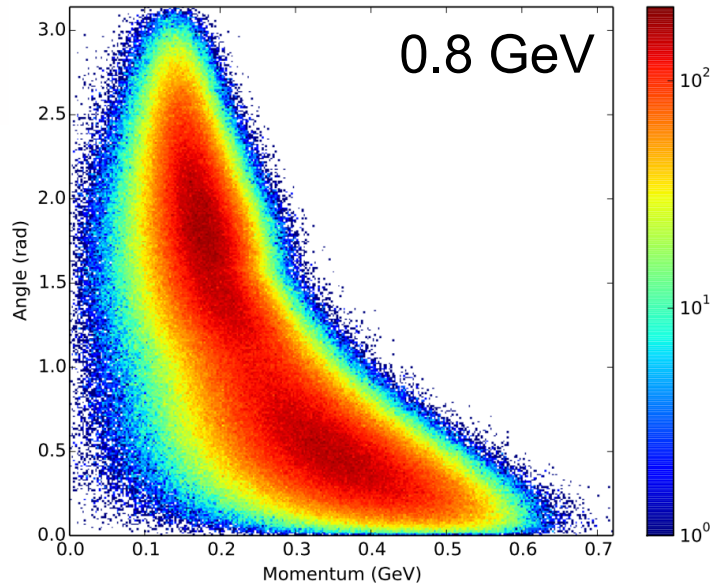
Unnormalized production rate at e.g. MiniBooNE (vector mediator)

- NB: some components of production model can be validated with data, but not all...

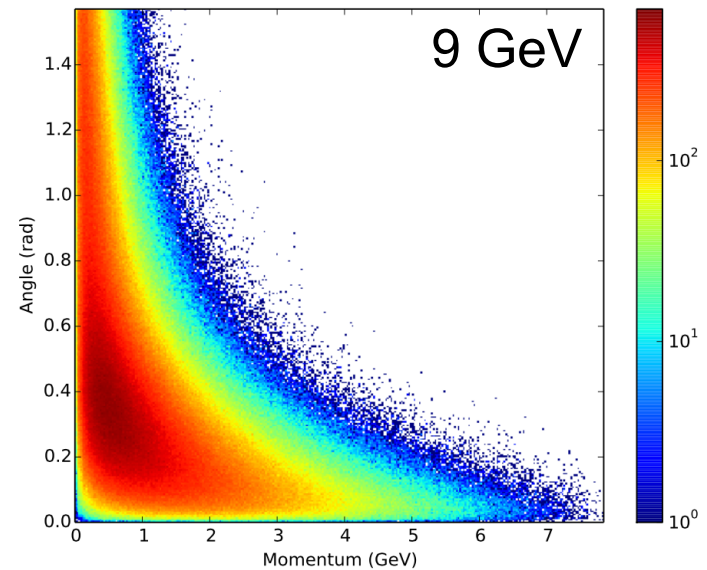


DM Production - π , η distributions

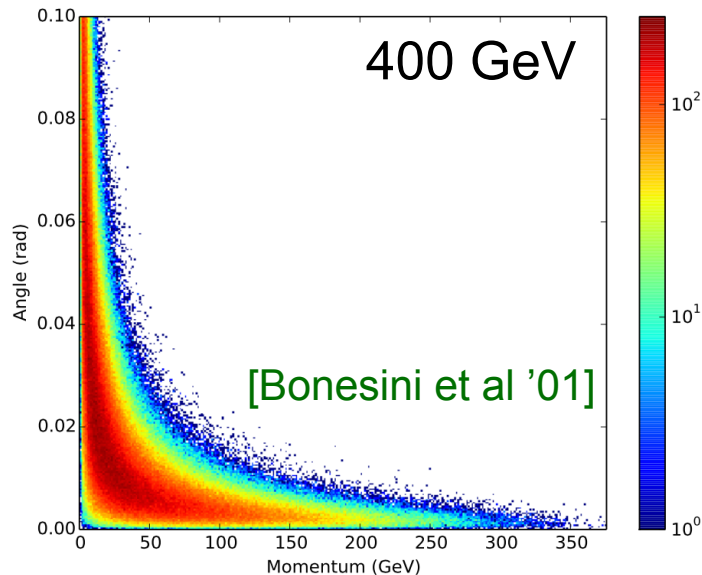
Burman-Smith (800 MeV) Distribution



Sanford Wang Distribution



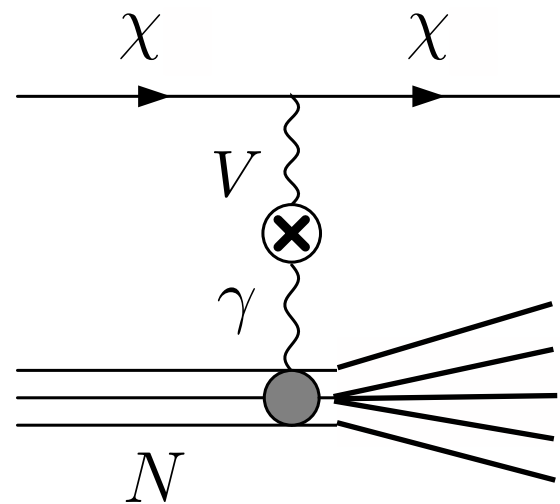
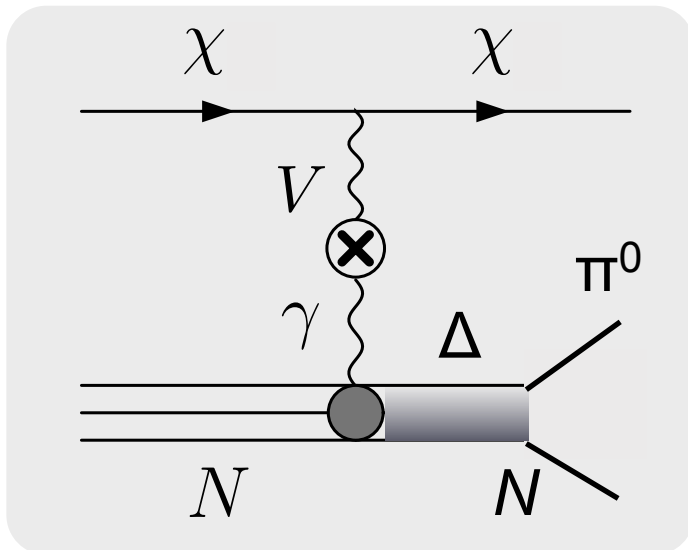
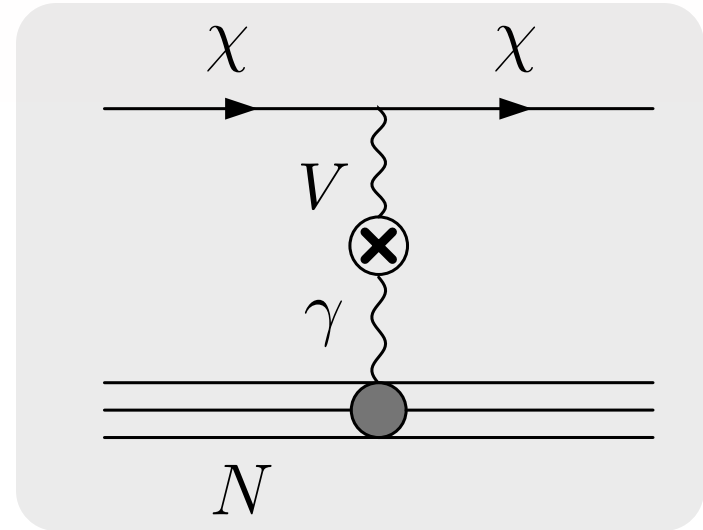
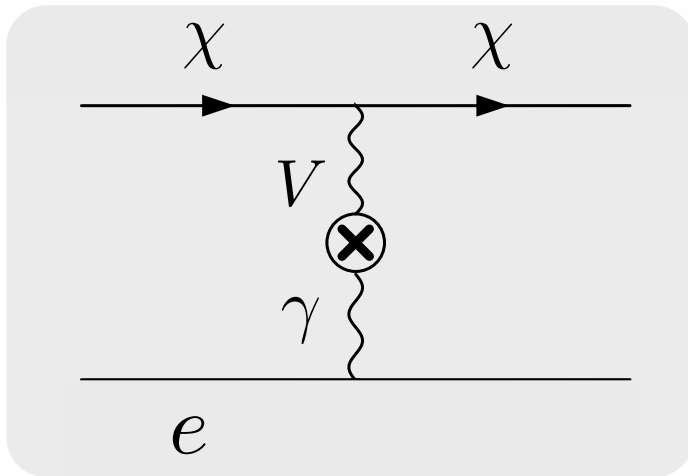
BMPT (400 GeV) Distribution on Tungsten



- Rate for π^0, η given by averaging rates for π^+, π^-
- calibrated for thin targets, so will broaden for an absorber
- *charged mesons are magnetically focused, and neutrino energy spectrum has a lower peak*

Signatures

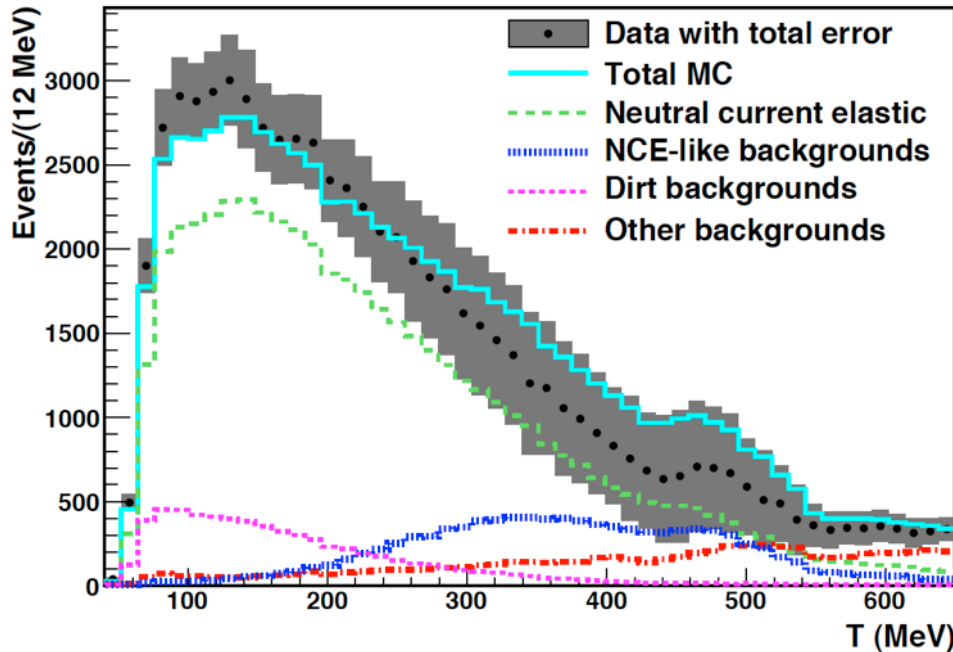
Characteristic DM (in)elastic scattering signatures



Mimics scattering of neutrinos, which provide dominant background₁₃

Neutrino backgrounds...

Neutrino elastic scattering provides a large background at all ν -beam facilities with a decay volume after the target, e.g. at MiniBooNE



$\sim 10^5 - 10^6$ scattering events, with neutral current cross-sections measured to $O(18\%)$
[MiniBooNE '10]

⇒ Counting experiments are not enough...

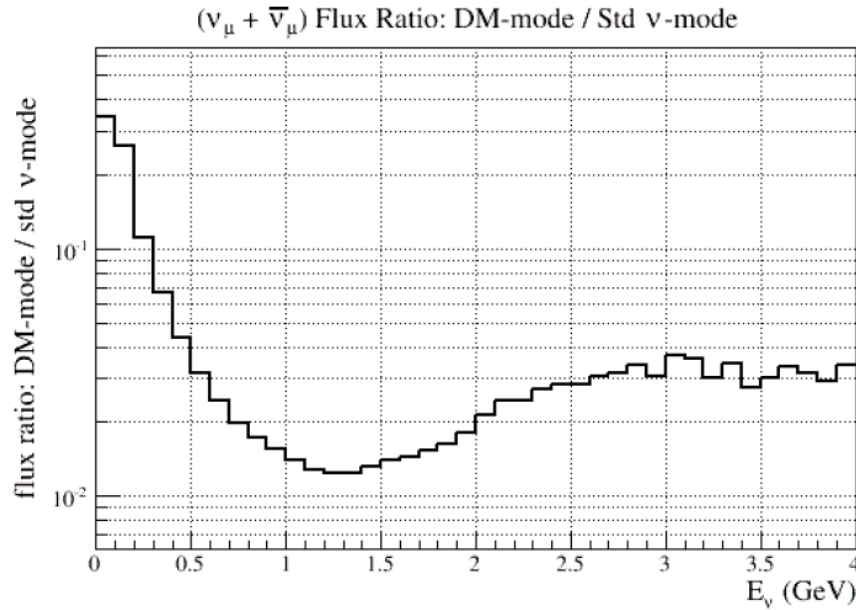
Neutrino backgrounds...

However, there are ways to enhance S/B

- Run as a “beam dump”
 - steer beam past target and into absorber. This removes decay volume, cuts down neutrino background by a large factor (but cannot run in “parasitic” mode, unless well off axis)
- Timing
 - time delay ($\gamma=10$) = $O(10\text{ns})$, effective for higher mass
 - possible at MiniBooNE, also very effective at a far detector (e.g. T2K \rightarrow SuperK)
- Energy cuts (especially if detector is off-axis)
 - neutrino beam peaks at lower energy
 - different scattering kinematics
- Scattering angle cuts
 - forward angle cut ($\cos\theta > 0.99$) very effective for e-scattering

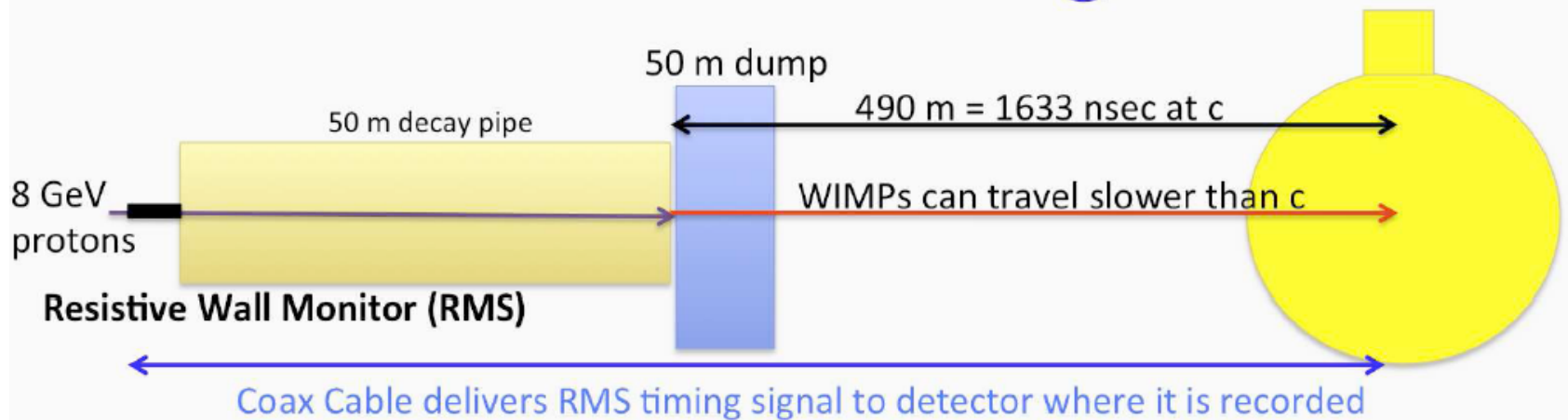
Multiple techniques are being tested in the current MiniBooNE analysis

MiniBooNE beam dump




- removal of decay volume for charged mesons reduces neutrino background by factor of ~ 70



WIMP Time of Flight



Experimental Facilities

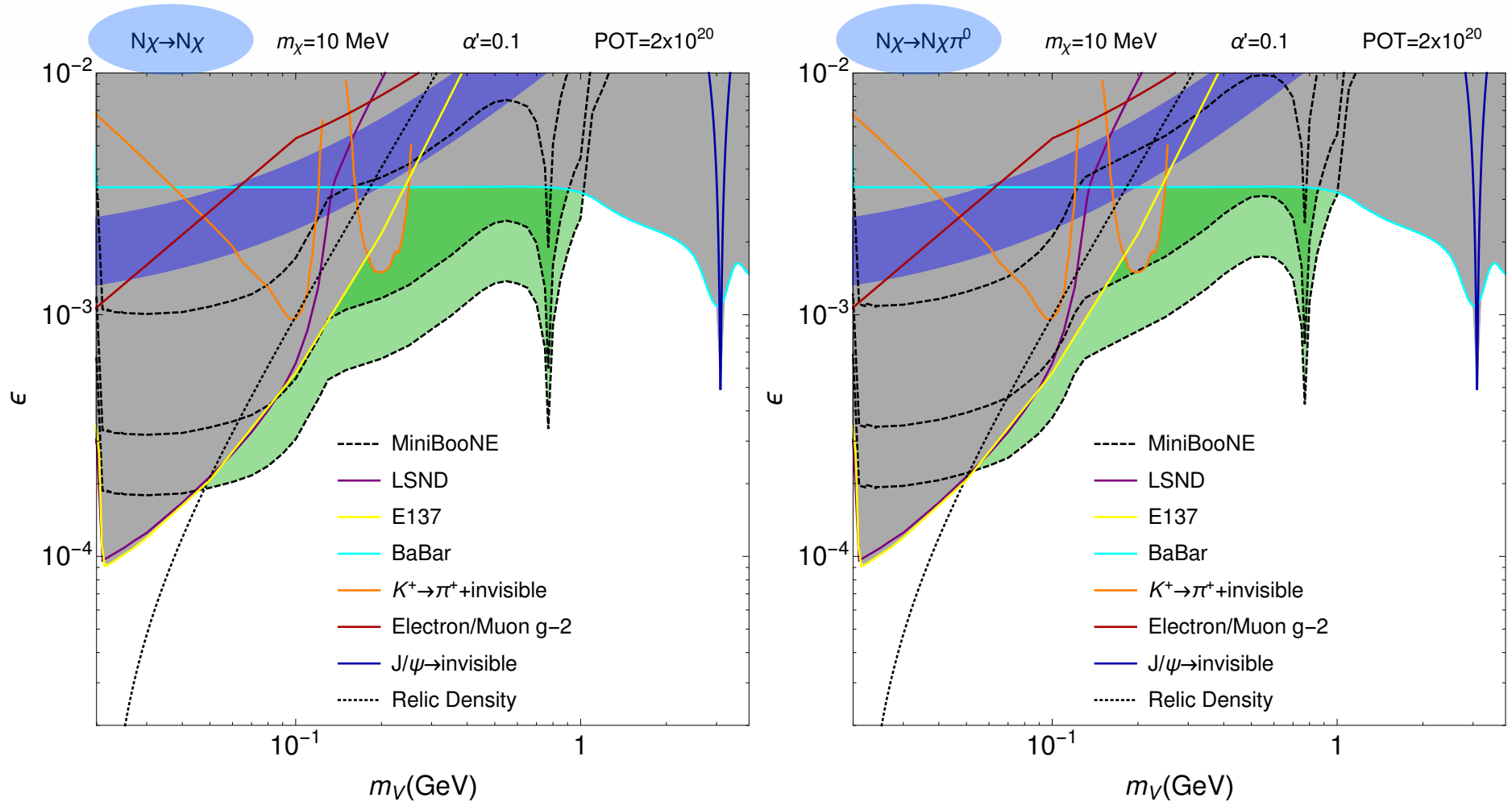
- **LSND**
 - 800 MeV, 10^{23} POT, off-axis detector at 30m (no decay volume, so effectively a beam dump)
- **MiniBooNE (absorber)**
 - 9 GeV, 2×10^{20} POT, 650 ton on-axis detector at 450m
- **T2K**  [talk by A. Missert]
 - 30 GeV beam, 10^{21} POT, 2° off-axis detectors,
 - near (~2ton, 280m), far (~50 kton, Super-K)
- **(also CHARM, MINOS,...)**

Future

- COHERENT @ SNS (1 GeV, 10^{23} POT/yr, 90° off-axis at 20m)
 - SHiP (400 GeV, 10^{20} POT, ~10 ton LArTPC on-axis at ~100m)
 - MicroBooNE & NOvA
 - LBNF/DUNE,...
- 
- 
- [talk by K. Scholberg]
- [talk by E. Graverini]

Sample event rates - MiniBooNE

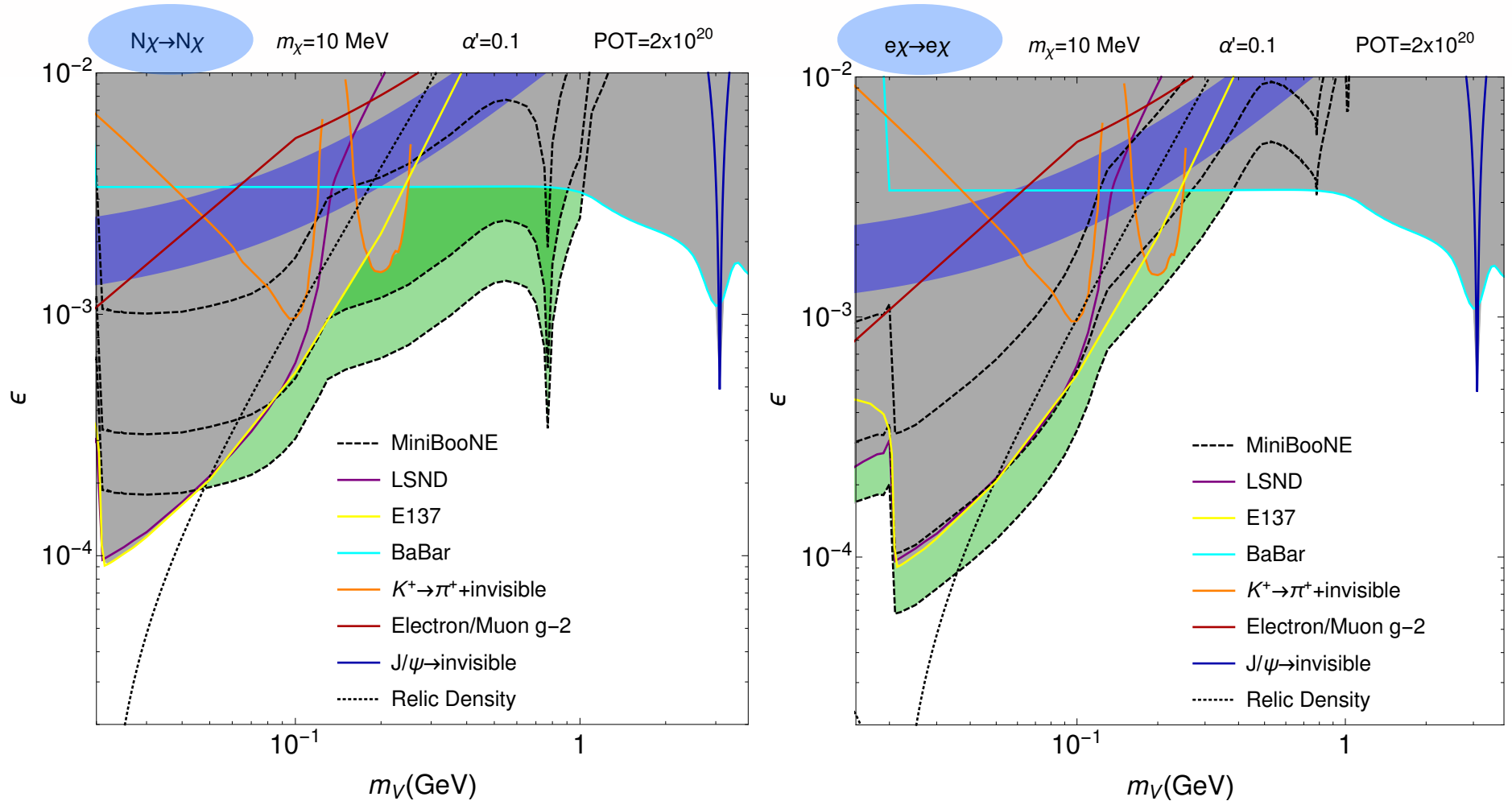
[Batell et al '14, deNiverville et al, to appear]



Green contours show 1, 10, 1000 events

Sample event rates - MiniBooNE

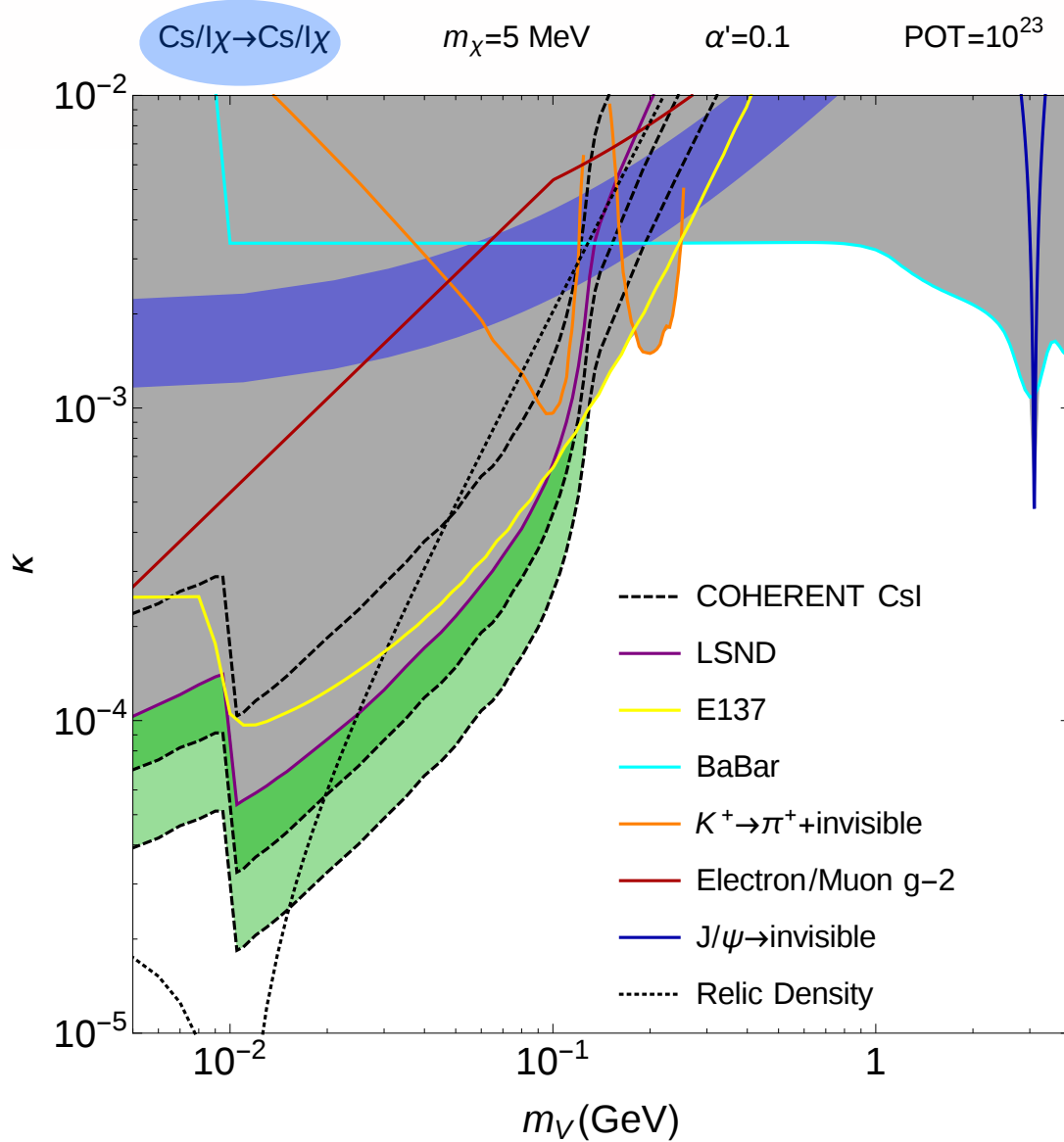
[Batell et al '14, deNiverville et al, to appear]



Green contours show 1, 10, 1000 events

Sample event rates - COHERENT (SNS)

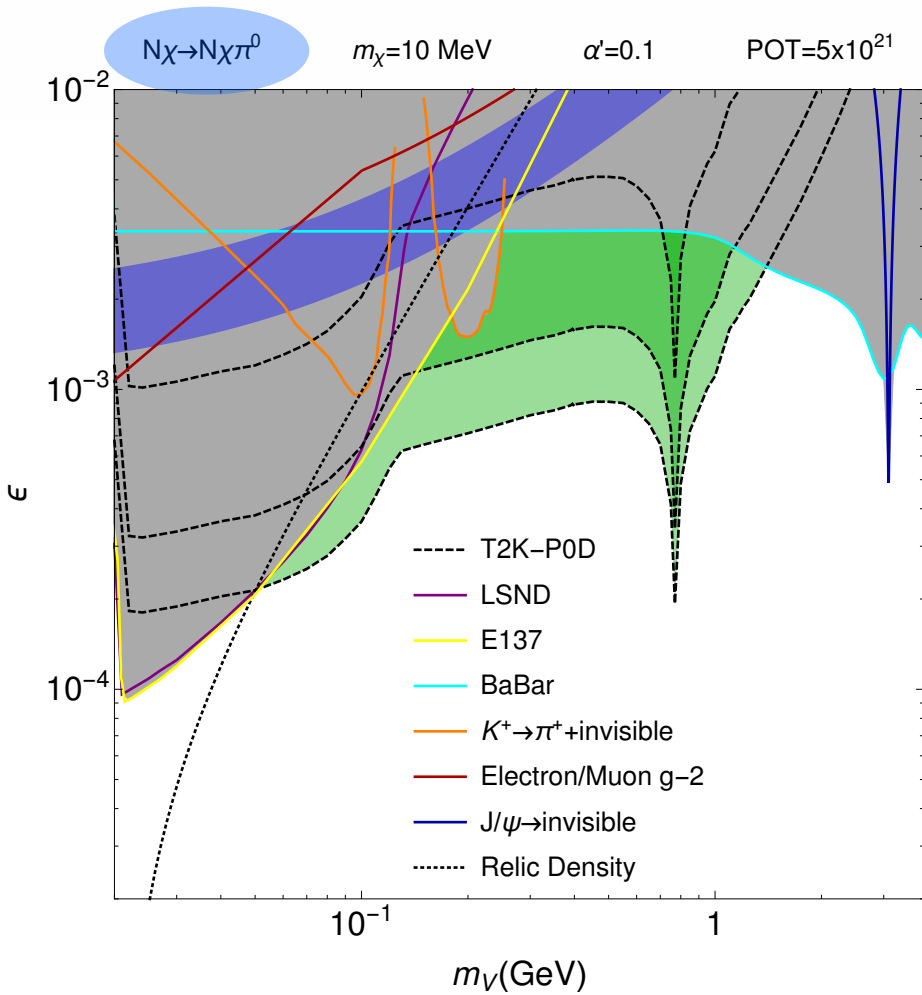
[deNiverville et al '15]



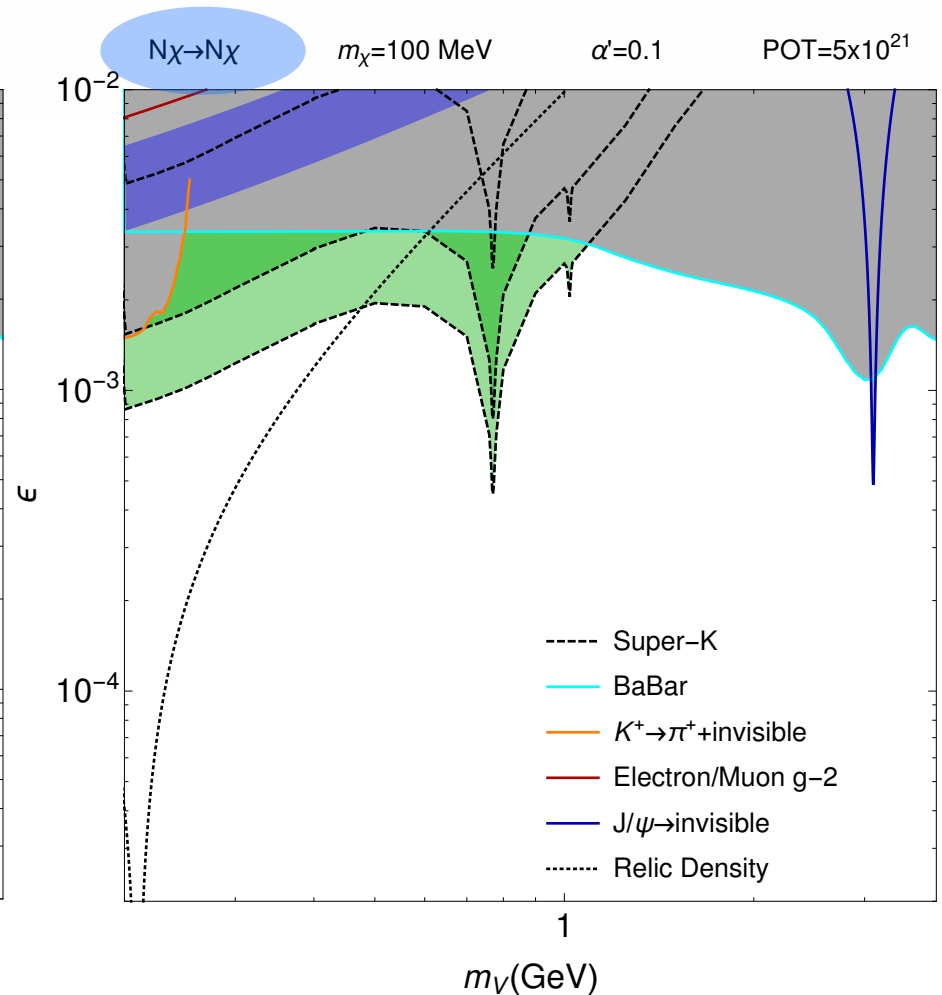
Includes production
via pion capture:
 $\pi^- + p \rightarrow n + V$

Sample event rates - T2K

[deNiverville et al, to appear]



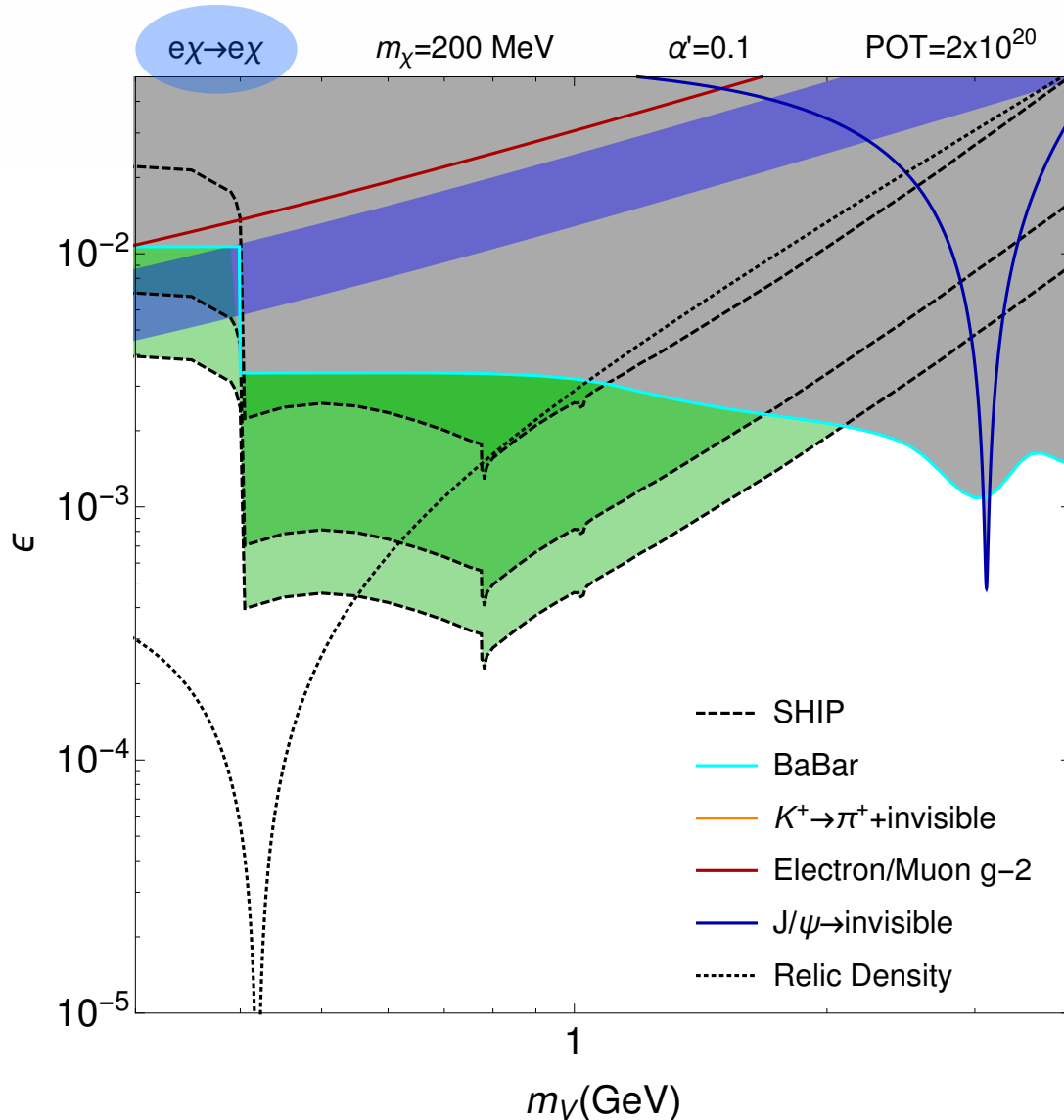
ND280 - P0D



SuperK

Sample event rates - SHiP

[deNiverville et al, to appear]

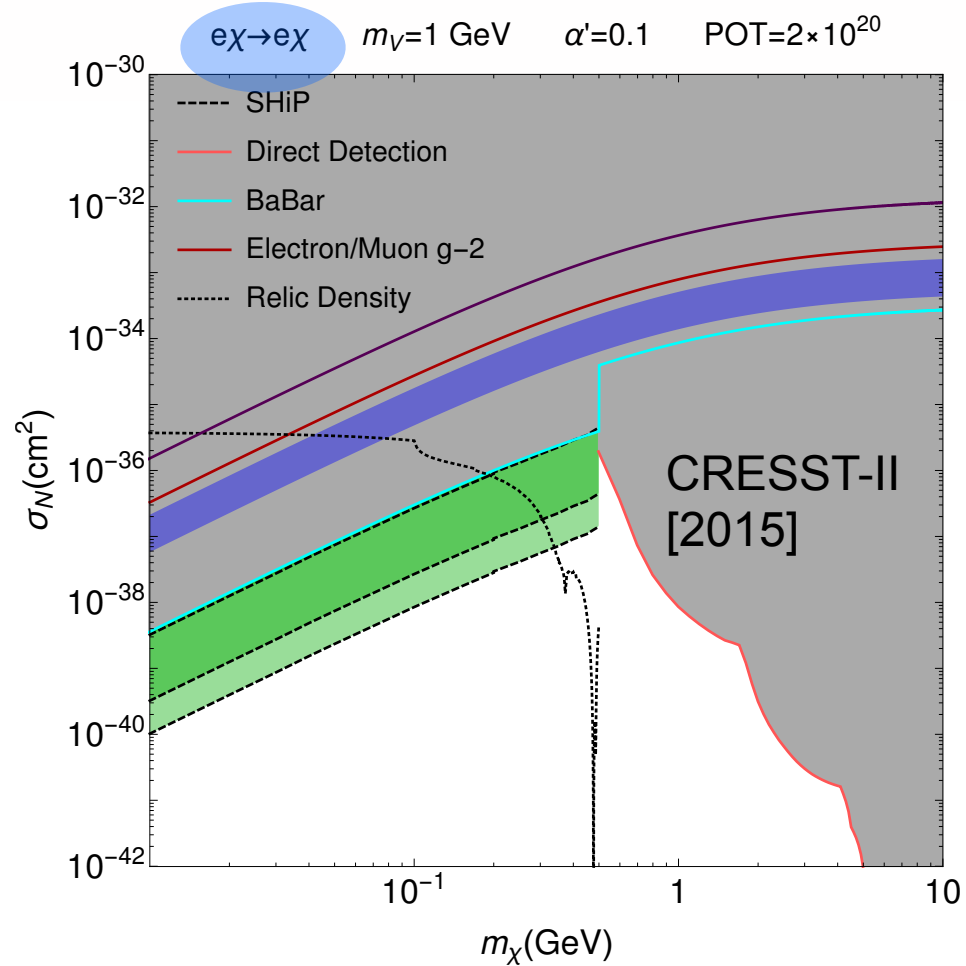
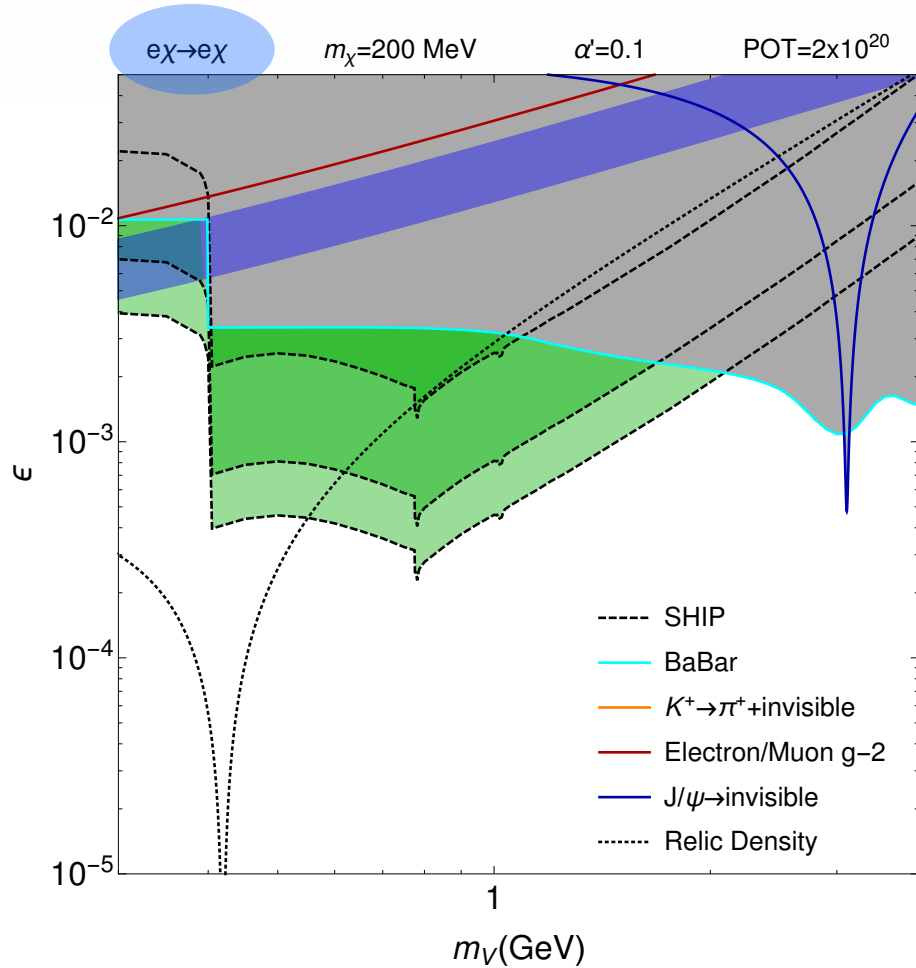


LArTPC at 100m (rates assume only 2.5tons)

- ▶ Electron Energy $\in [2, 20]$ GeV.
- ▶ Electron Scattering Angle $\in [10, 20]$ mrad.
- ▶ ~ 300 background events expected in this energy and angular range. [W. Bonivento]

Sample event rates - SHiP

[deNiverville et al, to appear]



Concluding Remarks

Light DM at the Luminosity frontier

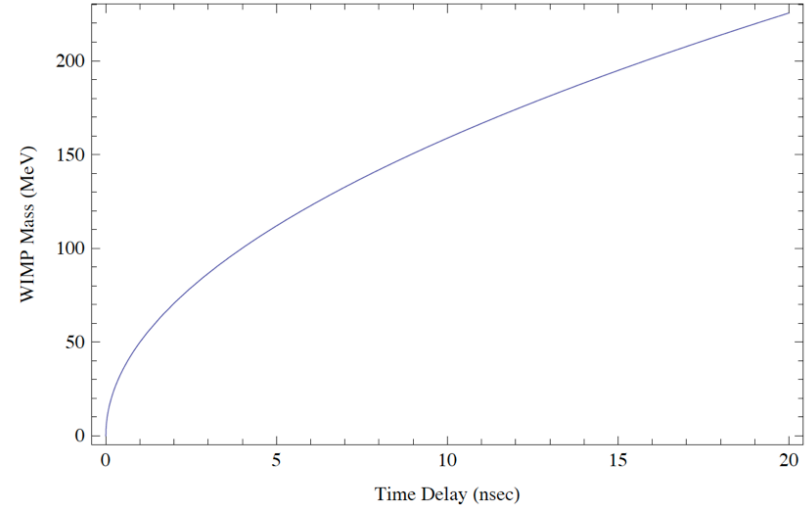
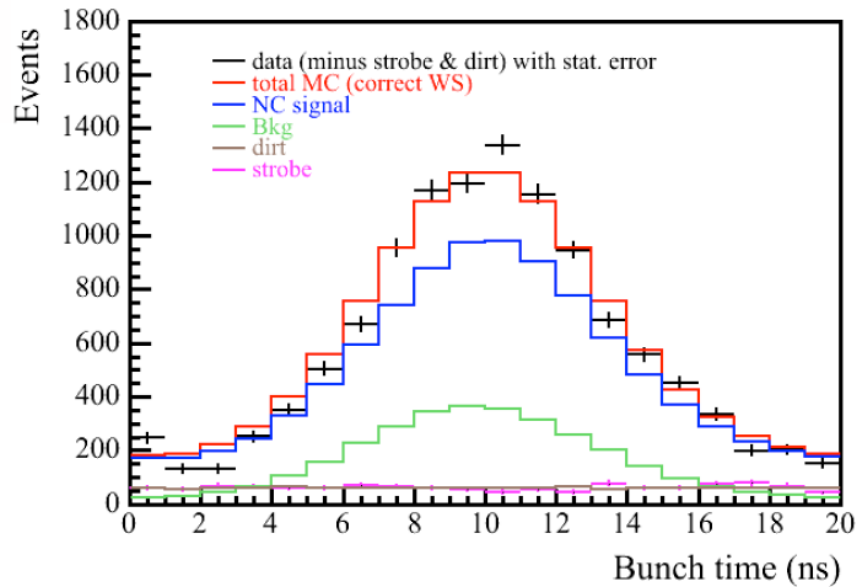
- Light sub-GeV thermal relic DM is difficult to probe using conventional direct detection.
 - provides benchmark models to test within a broader exploration of the relevant/marginal “portal” operators (hidden sector)

$$B_{\mu\nu}V^{\mu\nu}, \quad (AS + \lambda S^2)H^\dagger H, \quad Y_N LHN, \quad \dots$$

- Discussed a detection strategy by searching for deviations in NC (or NCQE) scattering at fixed-target neutrino facilities.
 - *MiniBooNE analysis nearly complete (results expected spring 2016), utilizing various techniques to improve S/B (removal of decay volume, kinematic cuts)*
- More model-independently, these searches are for anomalous NC/CC ratios in scattering, distinct from NSI that impact oscillations.
 - *Discovery potential* (beyond setting limits) provides further motivation for improving calculational precision in production modes, and neutrino scattering (particularly if carried out parasitically)

Extra slides

MiniBooNE beam dump - timing

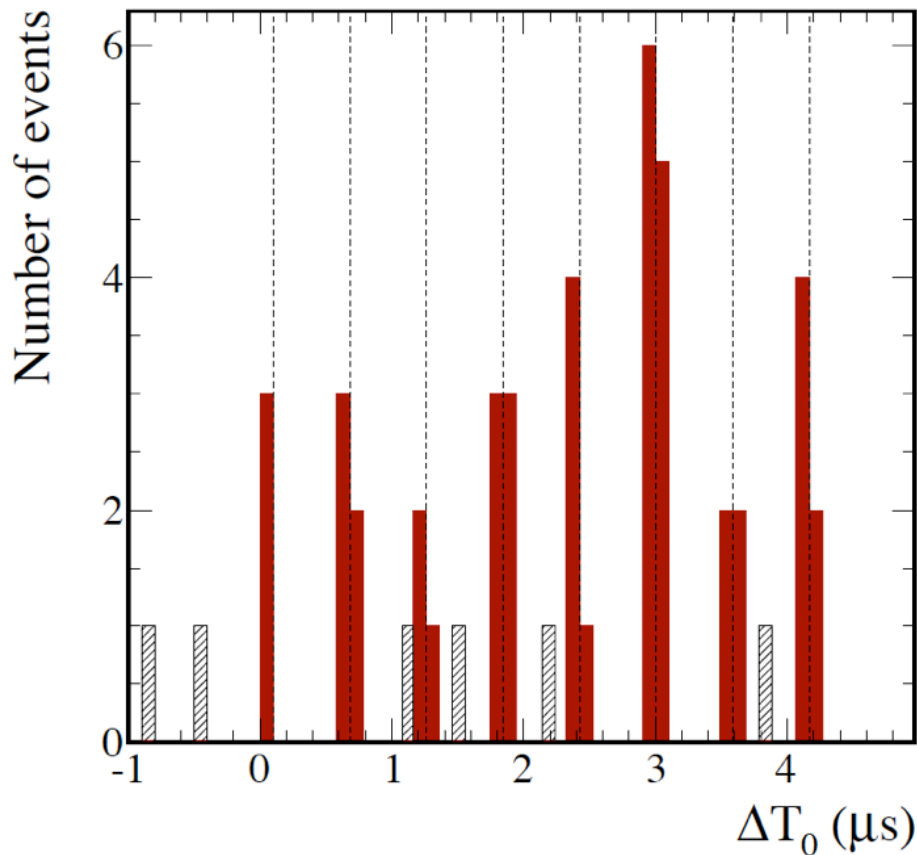


- Travel time from 50m absorber to detector is 1633ns at $v=c$.
- Absolute beam-detector event timing known to ~ 1.8 ns
- For higher mass WIMPs, with $v < c$, a timing cut can be used to further reduce the neutrino background

Timing cut (nsec)	Background Reduction (%)	WIMP Velocity β	WIMP Mass (MeV)
3.0	90	0.9984	85
4.6	99	0.9974	108
5.9	99.9	0.9967	122

DM @ T2K/SK using timing

[T2K '14, analysis of NCQE events]

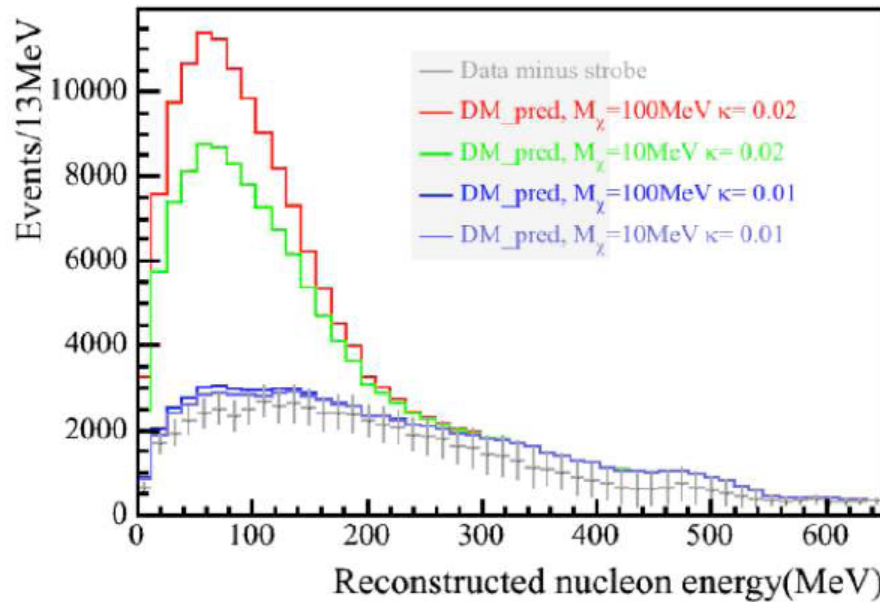


Alternative - use timing in combination with a sufficiently large far-detector, possible at T2K due to the size of Super-K

- Signal rate is down by $O(10^2)$. But, using the beam timing structure + long travel distance, the search for out-of-time events has almost zero background!

[T2K, in progress]

MiniBooNE beam dump - N_χ scattering

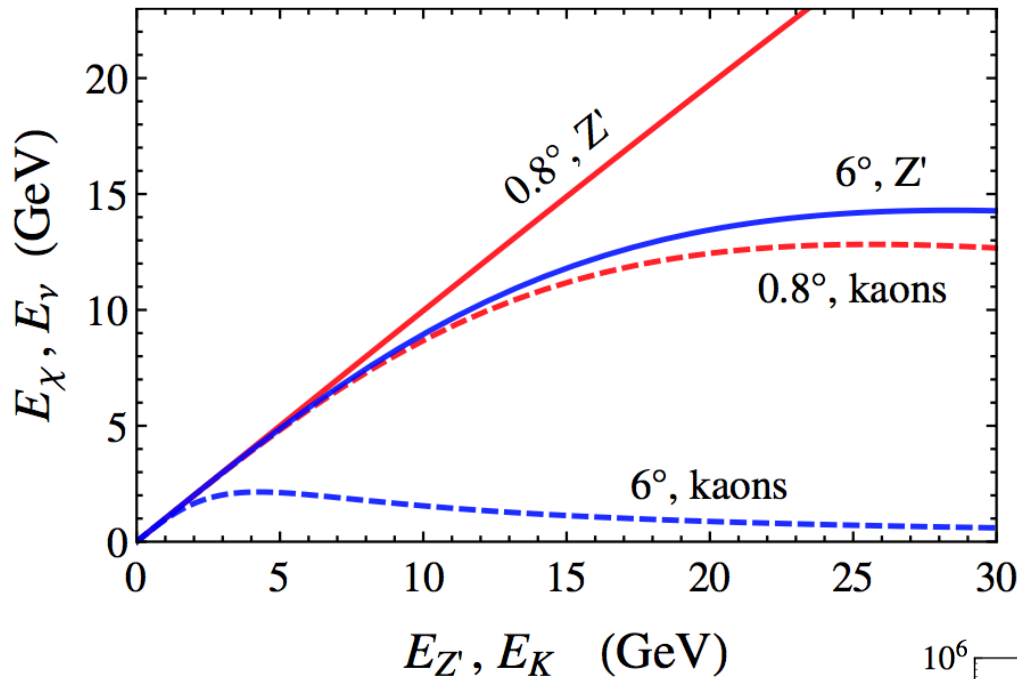


- background reduction using scattering kinematics

Neutrino backgrounds and signal significance in g-2 band

	0.35×10^{20} POT	0.35×10^{20} POT	1.75×10^{20} POT	1.75×10^{20} POT
Event Type	In-Time	Out-Time	In-Time	Out-Time
Data	-	-	-	-
NCE	54.9	10.9	274.6	54.7
Dirt	7.1	4.7	35.9	23.9
Cosmic	43.3	28.8	216.6	143.9
Total Background	$105.5 \pm 10.3 \pm 6.7$	$44.4 \pm 6.7 \pm 1.5$	$527.1 \pm 23.0 \pm 25.3$	$222.5 \pm 14.9 \pm 6.2$
Dark Matter Signal	67	45	275	221
Signal Significance	5.4σ	6.5σ	8.0σ	13.7σ

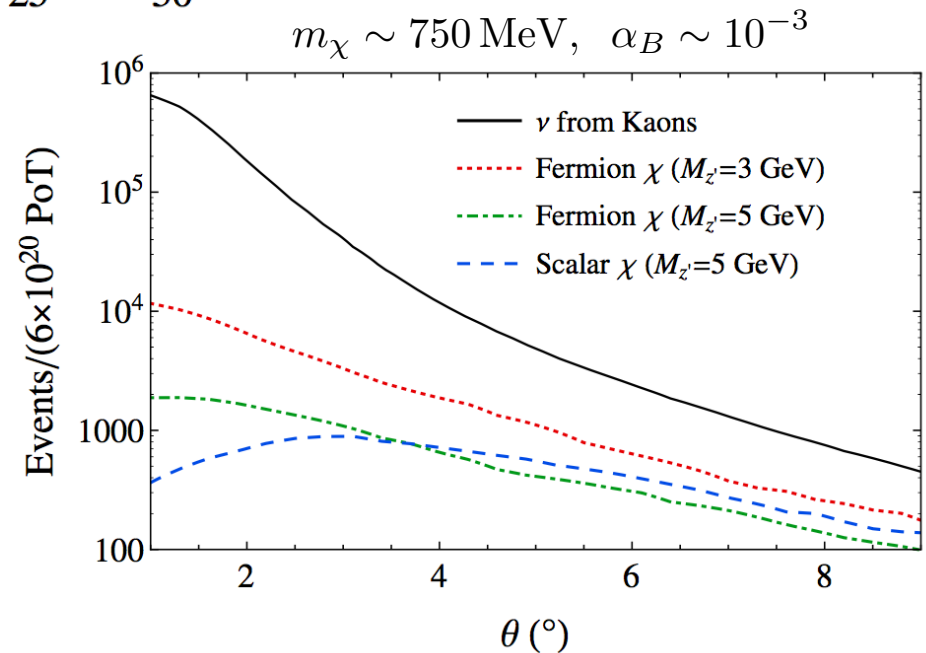
NuMI/LBNF off-axis kinematics



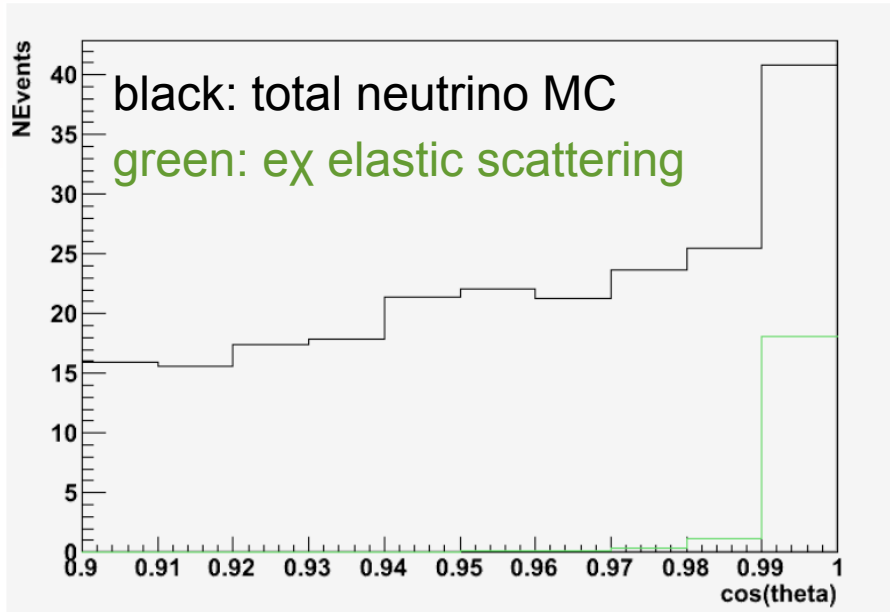
Recent study for ~ 100 GeV beam, using parton-level DM production via baryonic vector mediator [Coloma et al '15]

[Coloma et al '15]

NB: MiniBooNE/MicroBooNE are $\sim 6^\circ$ off-axis wrt NuMI target



MiniBooNE beam dump - $e\bar{\nu}$ scattering



- Use of electron scattering allows the neutrino background to be further reduced (98%) with a forward angle cut

estimated neutrino backgrounds and 90% CL upper limits

POT ($\times 10^{20}$)	Beam Configuration	25m Absorber ν -Background	25m Absorber 90% U.L.	50m Absorber ν -Background	50m Absorber 90% U.L.
10.1	$\bar{\nu}$ beam on target			31	8.6
6.5	ν beam on target			41	10.3
6.5	beam off target	0.45	2.75	0.90	3.20
4.0	beam off target	0.30	2.60	0.60	2.90
2.0	beam off target	0.15	2.45	0.30	2.60
1.0	beam off target	0.08	2.38	0.15	2.45

Constraints on (minimal) sub-GeV thermal relic DM

Classes of sub-GeV (thermal relic) DM models ($m_{\text{med}} > 2m_{\text{DM}}$)

$$\frac{\Omega_{\text{DM}}}{\Omega_{\text{m}}} \sim \frac{1 \text{ pb}}{\langle \sigma v \rangle_{\text{fo}}}$$

[Boehm et al '03;
Fayet '04,'06;
Pospelov, AR,
Voloshin '07;...]

• U(1) mediator $\mathcal{O}_4 = -\frac{\kappa}{2} V^{\mu\nu} B_{\mu\nu}$

- fermionic DM: s-wave annihilation, constrained by CMB

[Padmanabhan & Finkbeiner et al '05; Slatyer et al '08]

- scalar DM: p-wave annihilation, viable for small mixing κ .

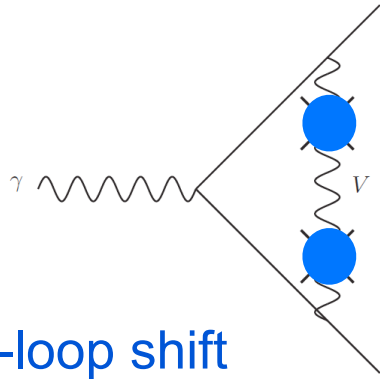
• Scalar mediator $\mathcal{O}_3 = ASH^\dagger H$

- fermionic DM: p-wave annihilation, so needs large mixing, in tension with limits from $B \rightarrow K + E_{\text{miss}}$. [Bird, Kowalewski & Pospelov '06]

- scalar DM: s-wave annihilation, also needs large mixing, in tension with rare B-decays and the CMB.

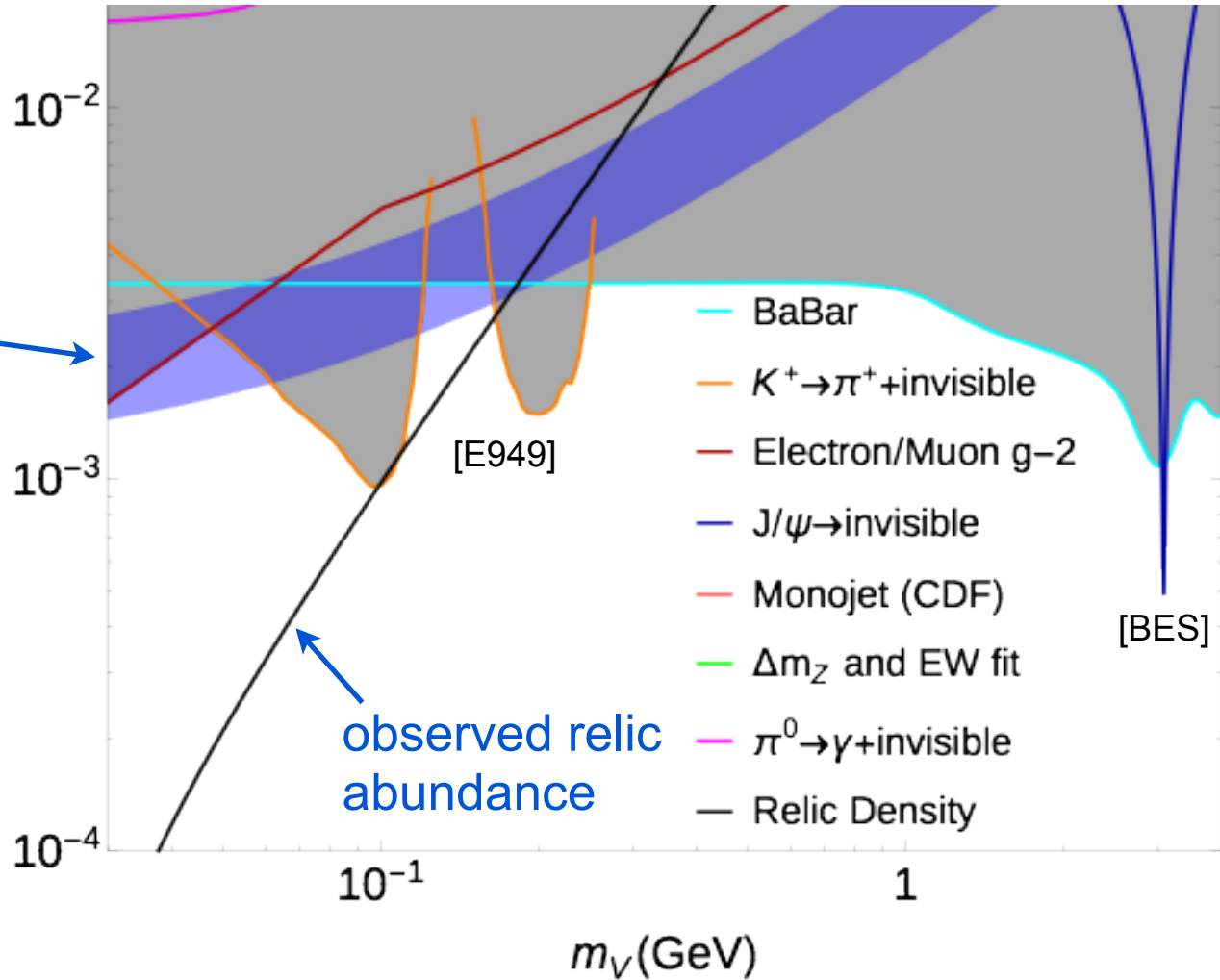
Parameter space - vector portal DM

$\text{Br}(V \rightarrow \text{invisible}) \sim 1$



V-loop shift helps resolve muon $g-2$ discrepancy [Pospelov '08]

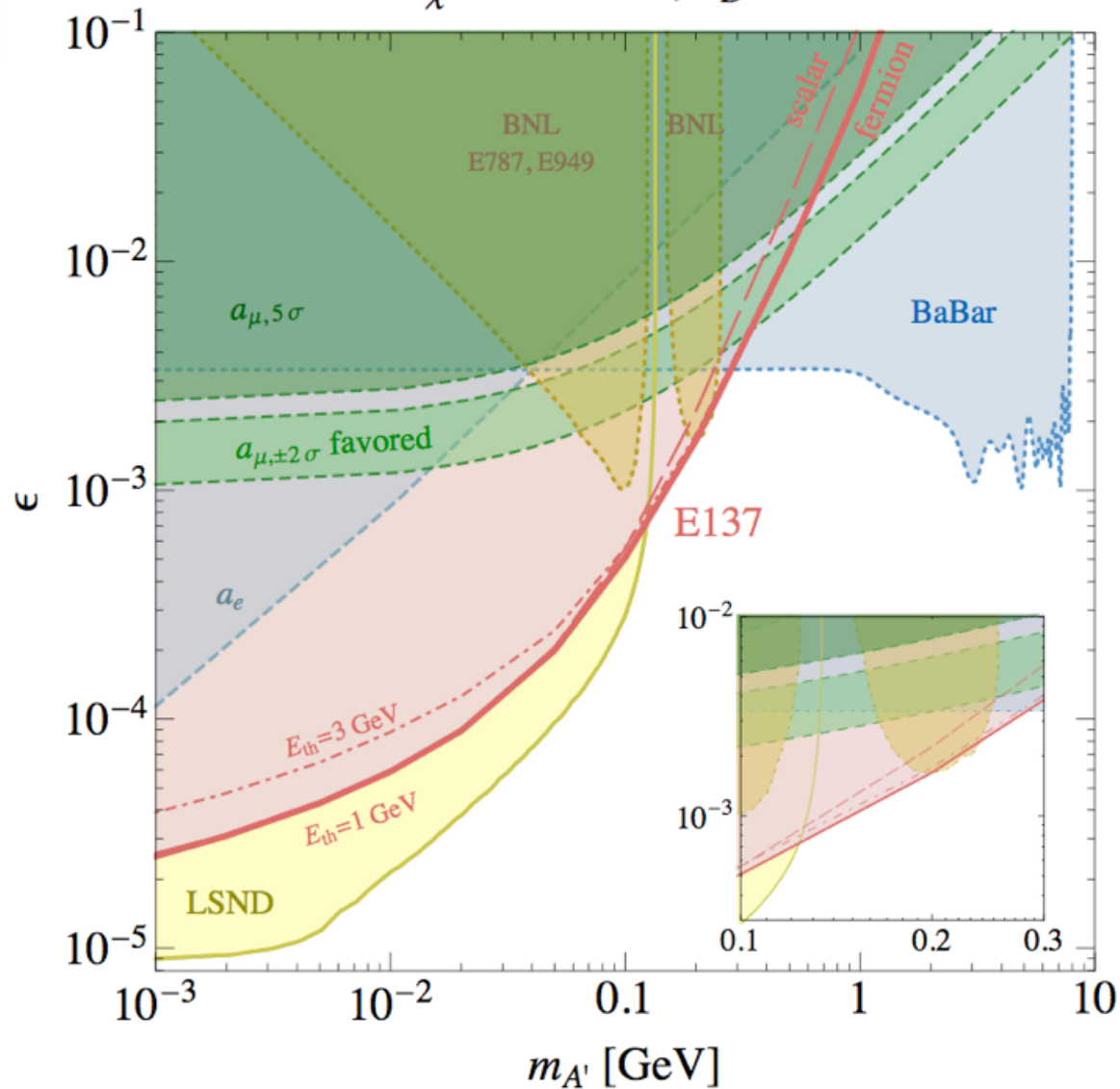
NB: many of these limits rely on V coupling to the *leptonic* vector current...



Current Sensitivity - Br(Hid)~O(1)

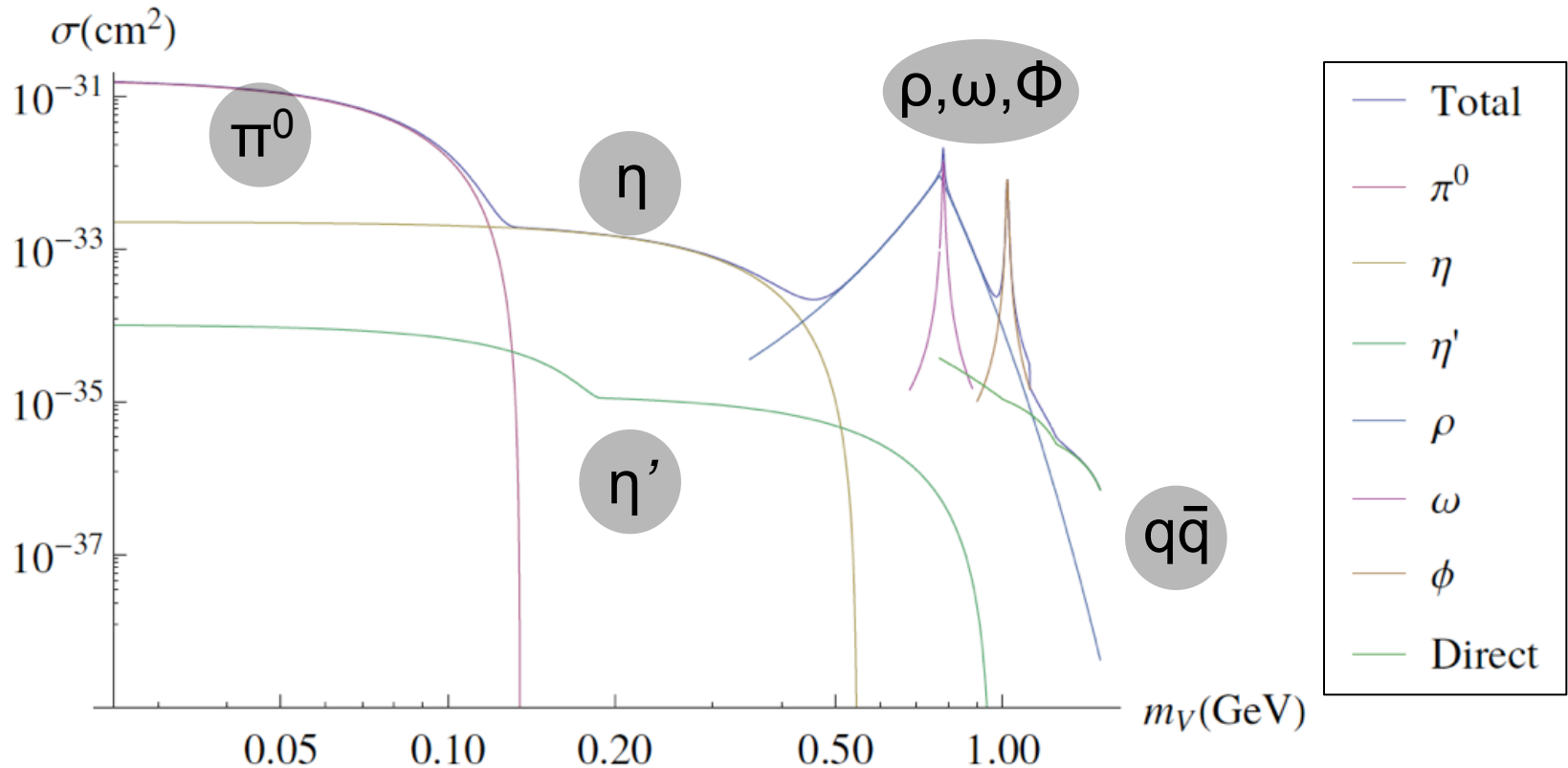
[Batell, Essig, Surujon '14]

$m_\chi < 0.5 \text{ MeV}, \alpha_D = 0.1$



DM Production Channels

Production in proton fixed targets (e.g. MiniBooNE)
- vector portal -



[9 GeV beam, Ge target]

“Minimal” sub-GeV DM models

Standard Model

mediators



Hidden Sector

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_V^2V_\mu^2 + |D_\mu\chi|^2 - m_{\text{DM}}^2|\chi|^2 + \dots$$



$$\mathcal{L}_{\text{int}} = -\kappa e V_\mu J_{\text{em}}^\mu$$



DM candidate, coupled through U(1)'



Simple UV-incomplete generalization, to isolate hadronic couplings

$$V_\mu \sum_{q,l} (\kappa_q \bar{q} \gamma^\mu q + \kappa_l \bar{l} \gamma^\mu l)$$

Vector current: $\kappa_q = e\kappa Q_q, \kappa_l = e\kappa Q_l$

[Boehm et al '03;
Fayet '04,'06;
Pospelov, AR,
Voloshin '07;...]

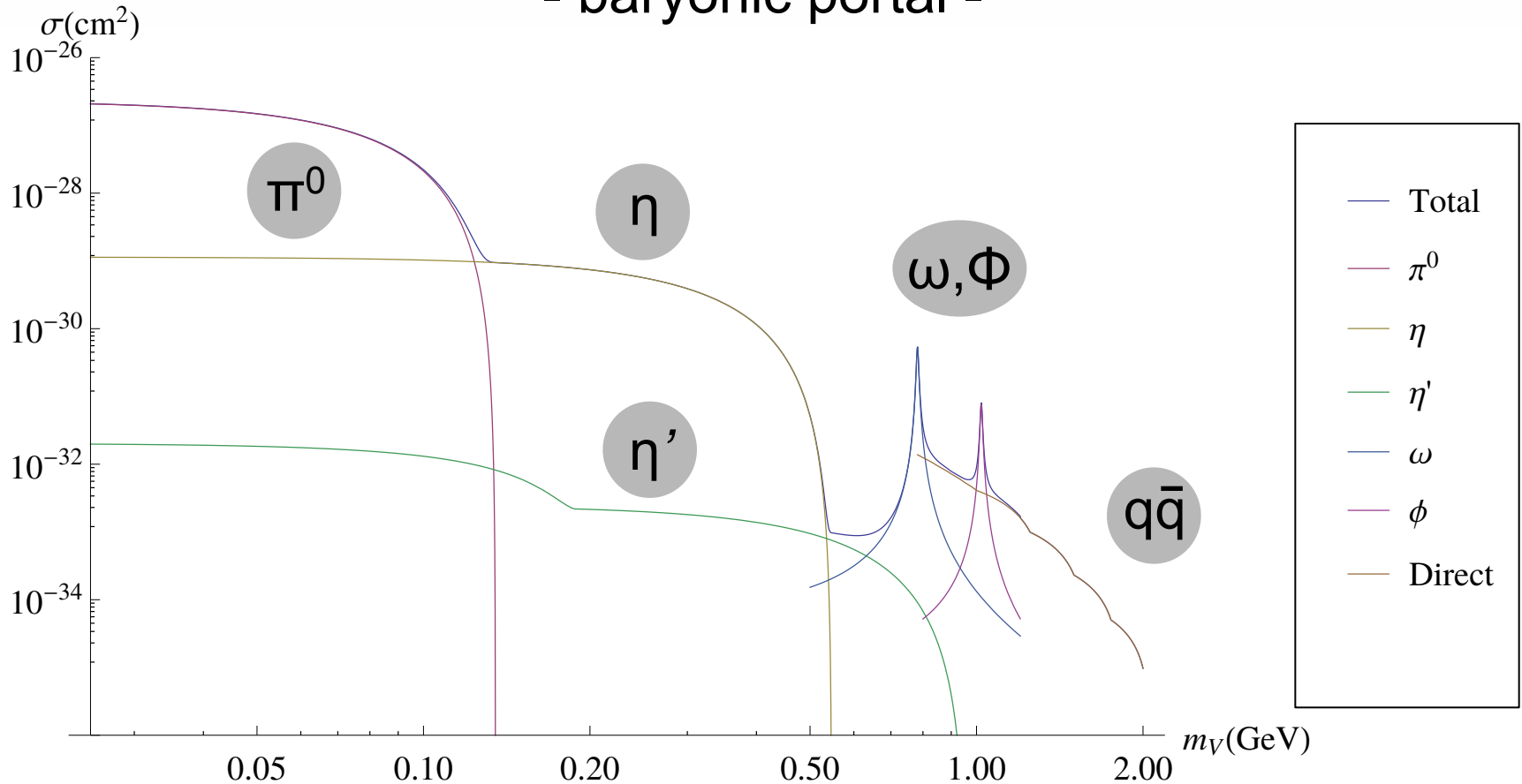
Baryonic current*: $\kappa_q = \frac{g_B}{3}, \kappa_l = 0$

[Recent analyses: Tulin '14;
Dobrescu & Frugiuiele '14]

(*)Anomalous, and requires additional heavy B-charged states

DM Production Channels

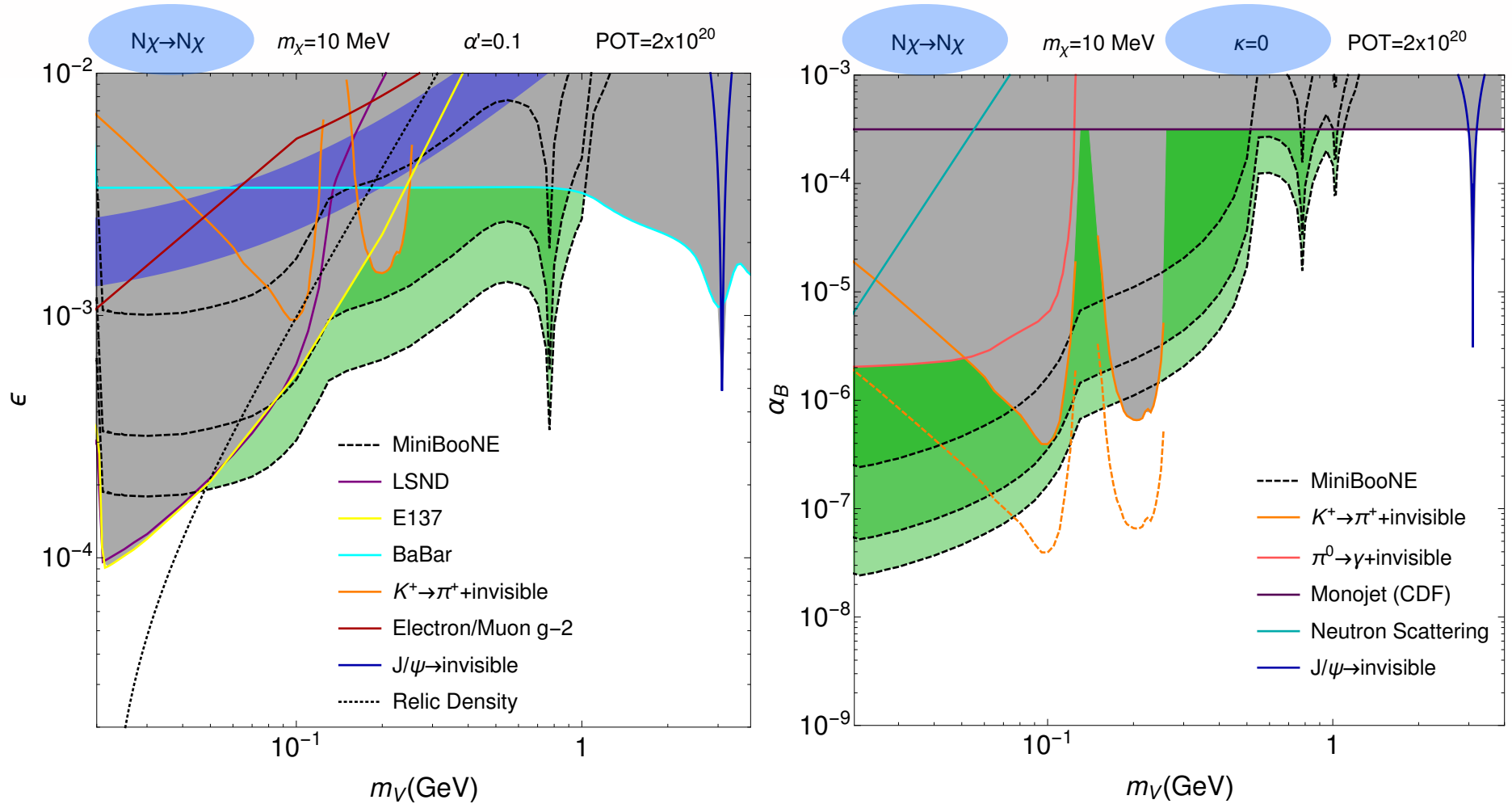
Production in proton fixed targets (e.g. MiniBooNE)
- baryonic portal -



[9 GeV beam, Ge target]

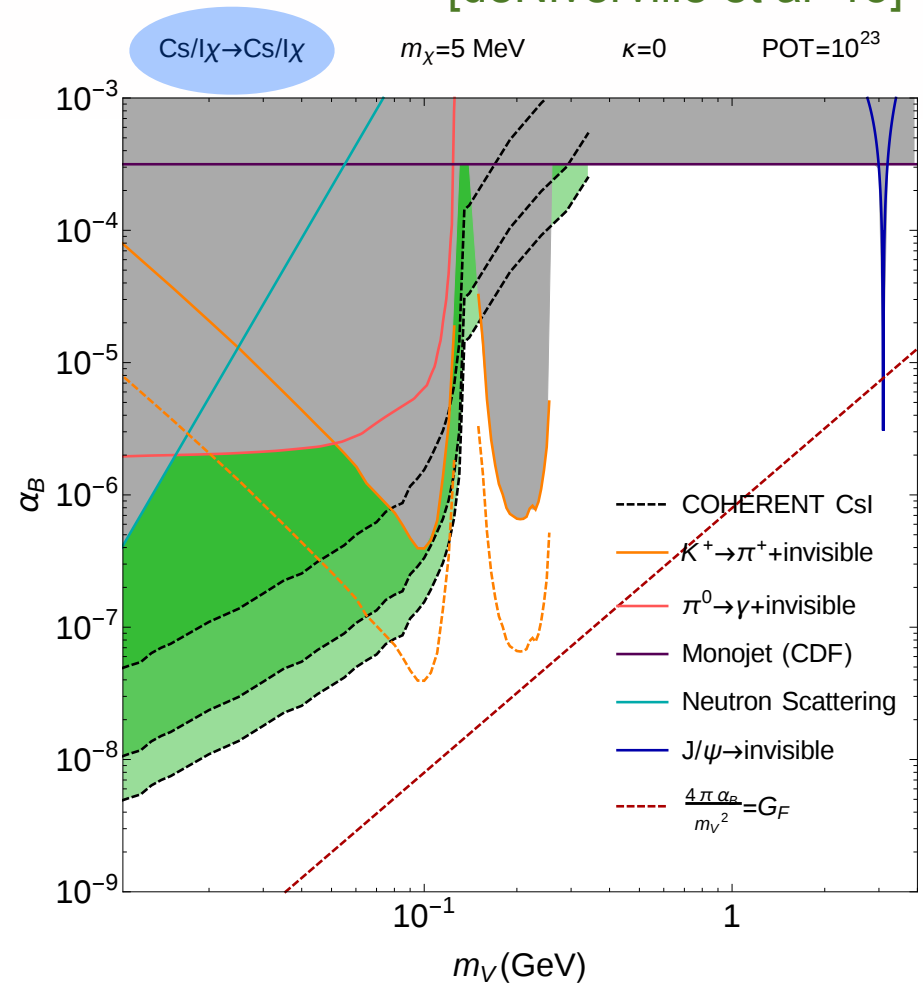
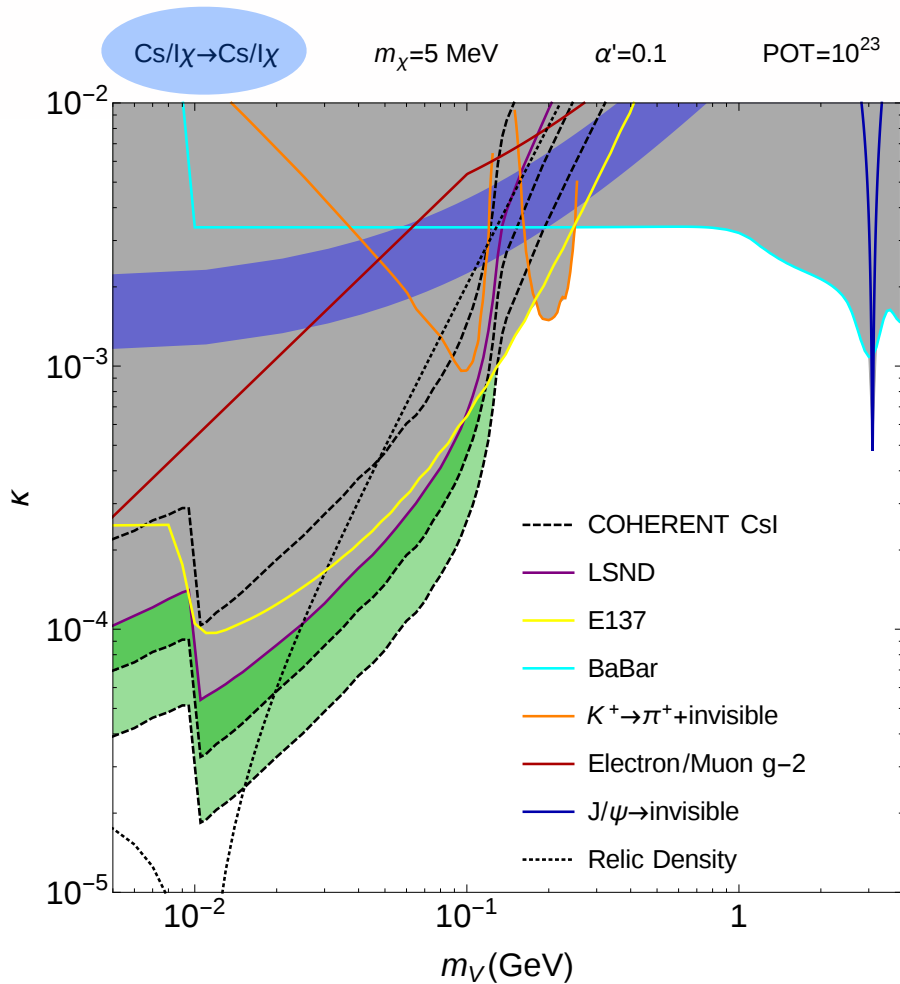
Sample event rates - MiniBooNE

[Batell et al '14, deNiverville et al, to appear]



Sample event rates - COHERENT (SNS)

[deNiverville et al '15]



Includes production via pion capture: $\pi^- + p \rightarrow n + V$