SLAC - March 2016

Light dark matter and neutrino beams

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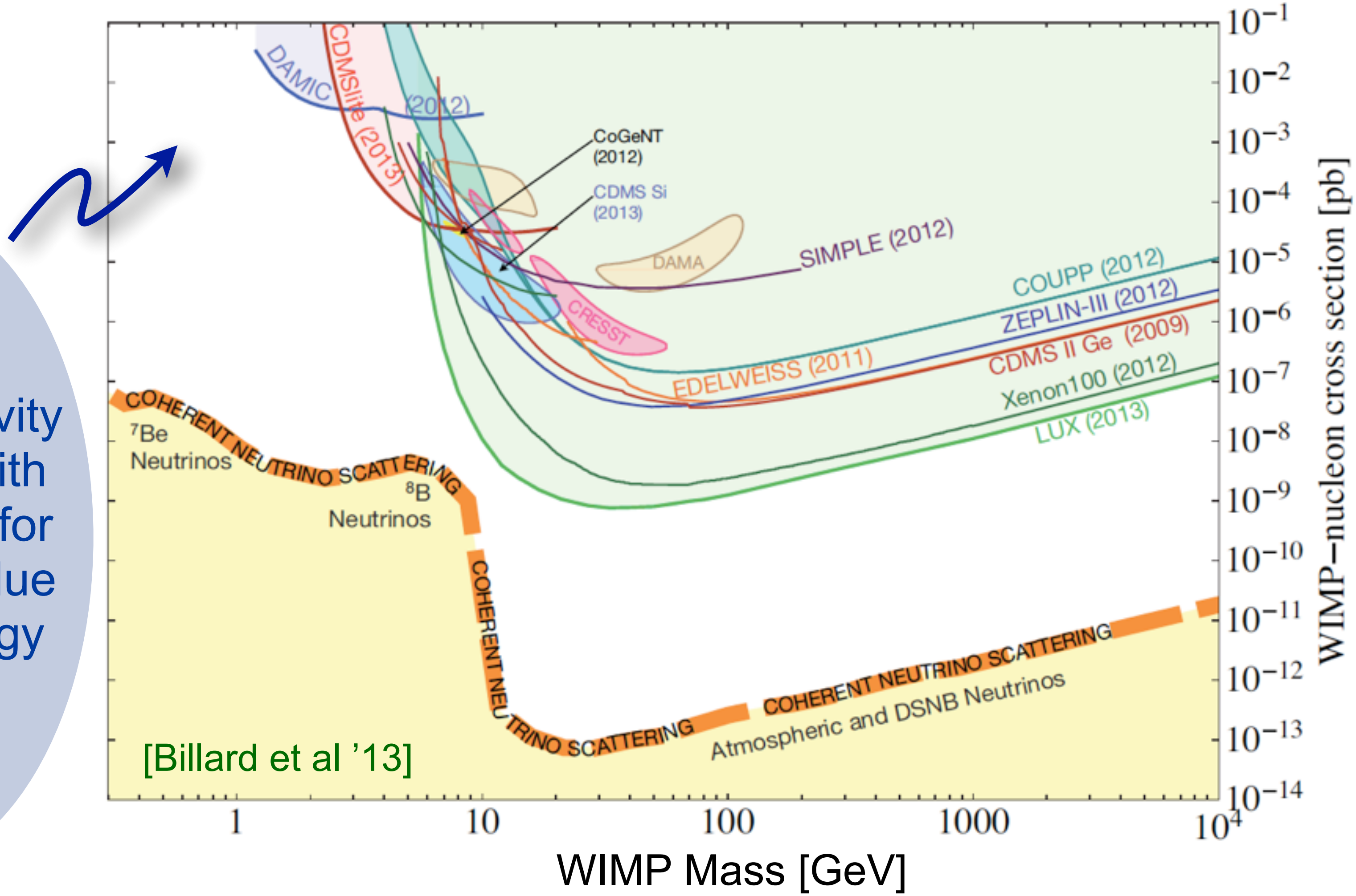
(with) B. Batell, P. deNiverville, D. McKeen, M. Pospelov
& MiniBooNE

WIMP (thermal relic) DM



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

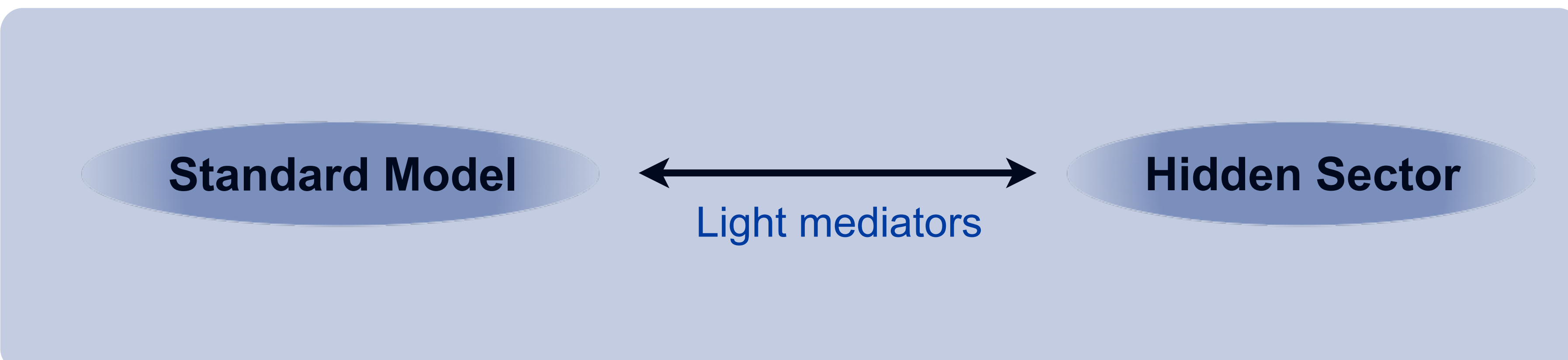
Impressive direct detection sensitivity to thermal relic (WIMP) dark matter in the halo with O(GeV - TeV) mass.

Light (thermal relic) DM

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

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

⇒ 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.



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⇒ 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.

➪ by inversion, light mediators allow direct production of DM at ***low energy!***

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

Br(mediator → DM) ~ 1

Philosophy - Neutrinos and Dark Matter…

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

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

"Minimal" Vector portal DM models

Standard Model ⟷ mediators ⟷ **Hidden Sector**

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

⇓

$$\mathcal{L}_{\mathrm{int}} = -\kappa e V_\mu J^\mu_{\mathrm{em}}$$

⇓ 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: $\kappa_q = e\kappa Q_q, \;\; \kappa_l = e\kappa Q_l$

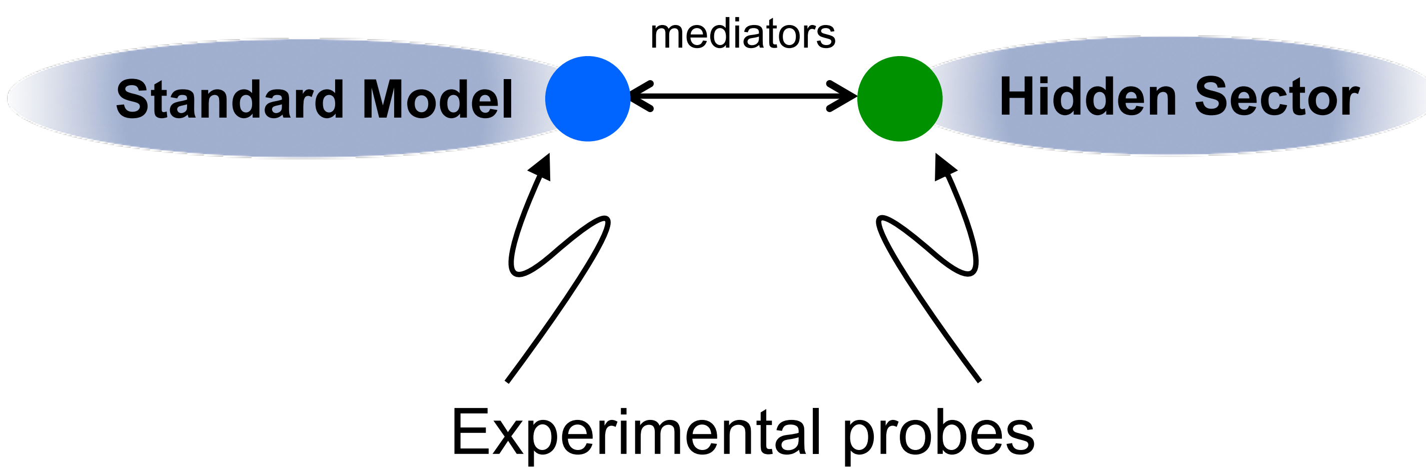
[Boehm et al '03; Fayet '04,'06; Pospelov, AR, Voloshin '07;...]

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

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

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

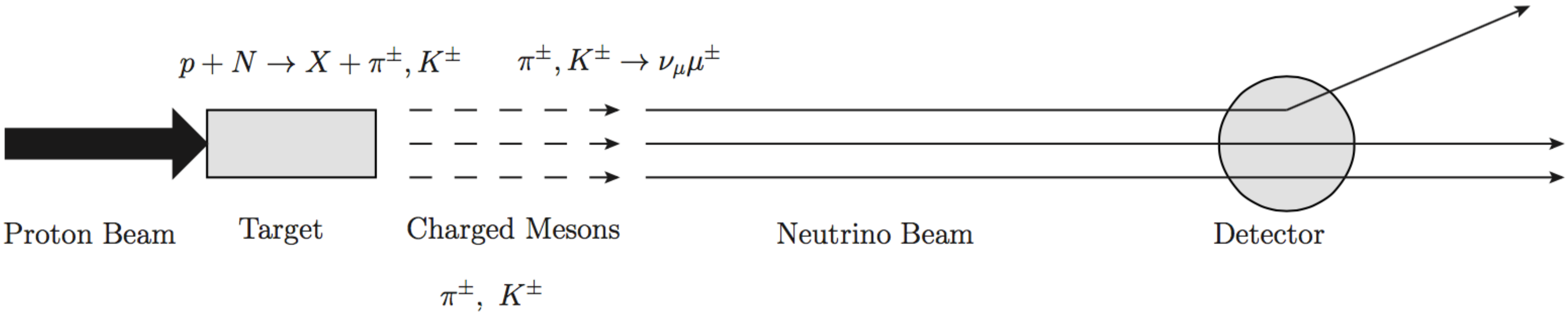
Probing the vector portal



- rare (invisible) decays
  - e.g. collider production plus missing energy in decays, $O(\kappa^2)$ x Br(Hid)
- precision corrections
  - e.g. lepton g-2
- rare (visible) decays
  - e.g. collider/fixed target production plus e.g. leptonic A' decays, $O(\kappa^2)$ x Br(SM)
- Anomalous NC-like scattering
  - e.g. FT production plus scattering, $O(\kappa^2 \text{ x } \kappa^2\alpha')$

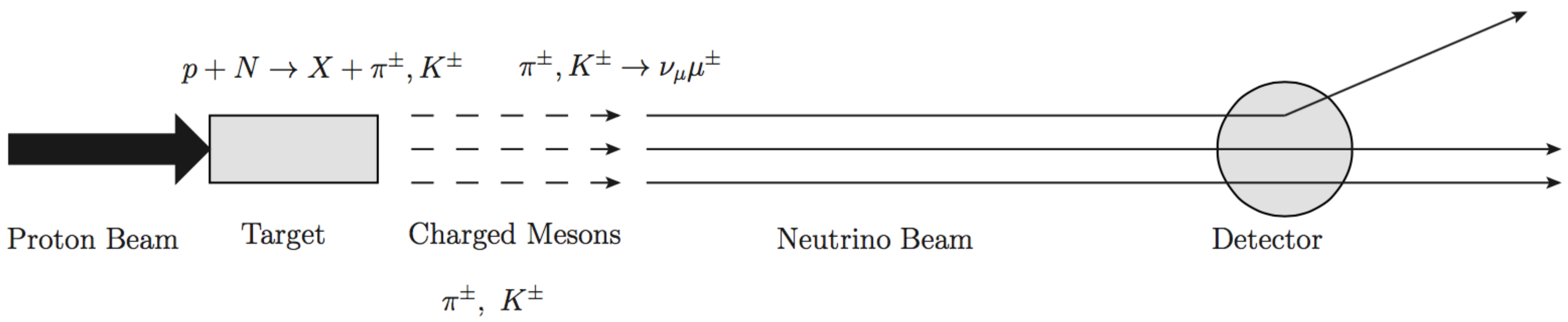
(also astrophysics & cosmology)

Fixed target probes - Neutrino Beams



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

Fixed target probes - Neutrino Beams



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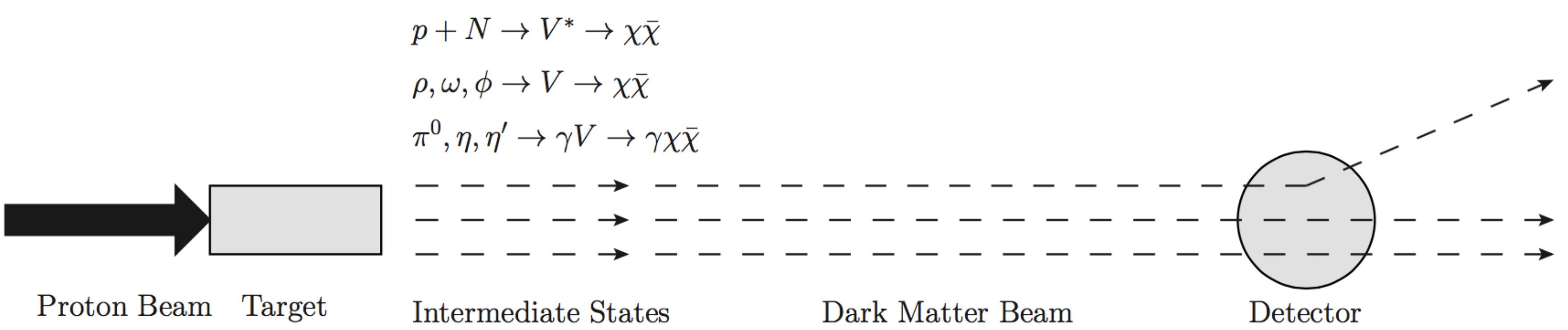
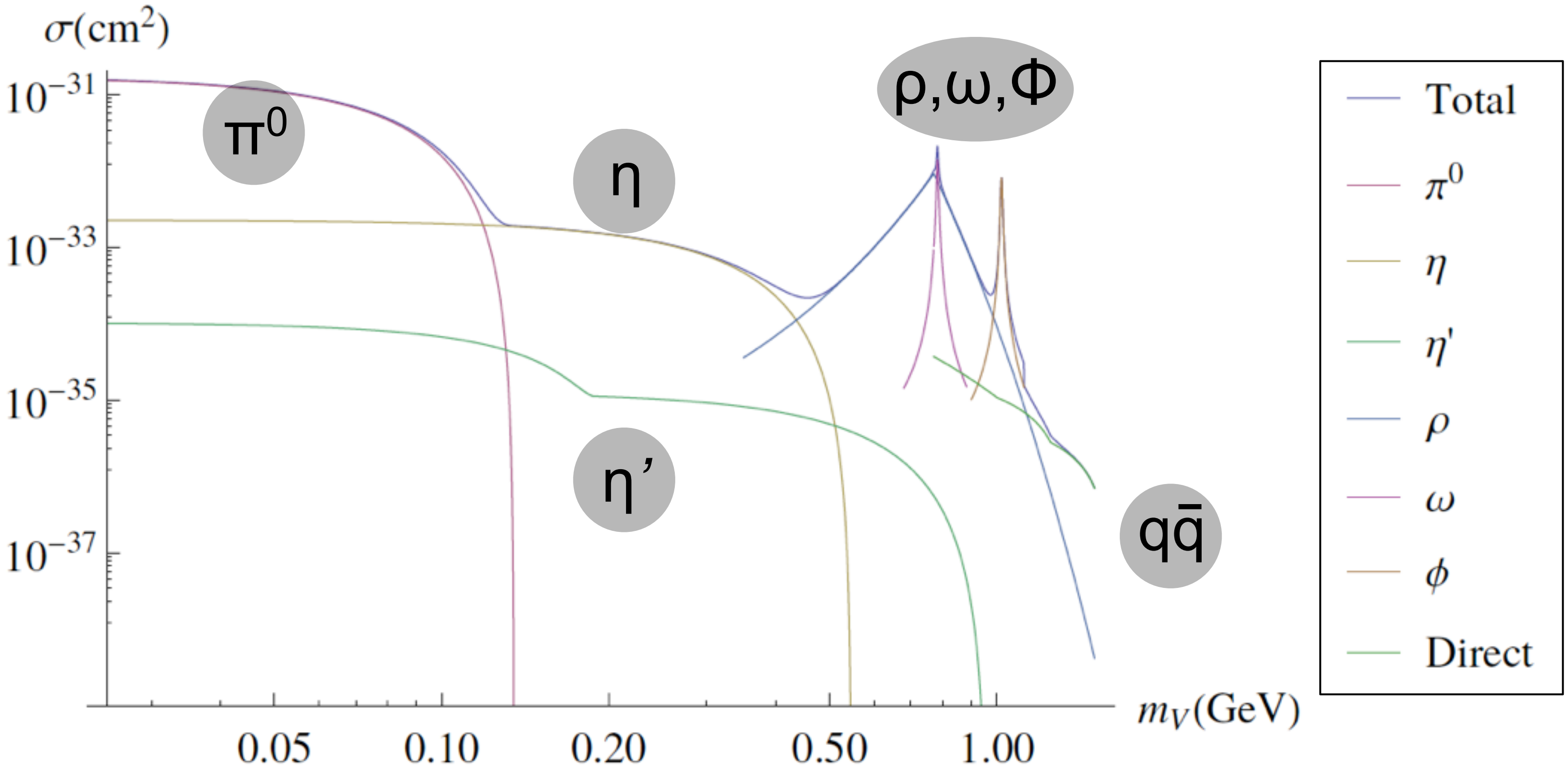


Fixed target probes - Neutrino Beams

- Experimental Facilities
  - LSND
    - 800 MeV, 10^{23} POT, off-axis detector at 30m
  - MiniBooNE (absorber)
    - 9 GeV, 2×10^{20} POT, 650 ton on-axis detector at 450m
  - T2K
    - 30 GeV beam, 10^{21} POT, 2^{o} off-axis detectors,
      - near (~2ton, 280m), far (~50 kton, Super-K)
  - also CHARM, MINOS, NOvA,…
  - Future
    - COHERENT @ SNS (1 GeV, 10^{23} POT/yr, 90^{o} off-axis at 20m)
    - SHiP (400 GeV, 10^{20} POT, ~10 ton LArTPC on-axis at ~100m)
    - MicroBooNE, DUNE,…

DM Production Channels

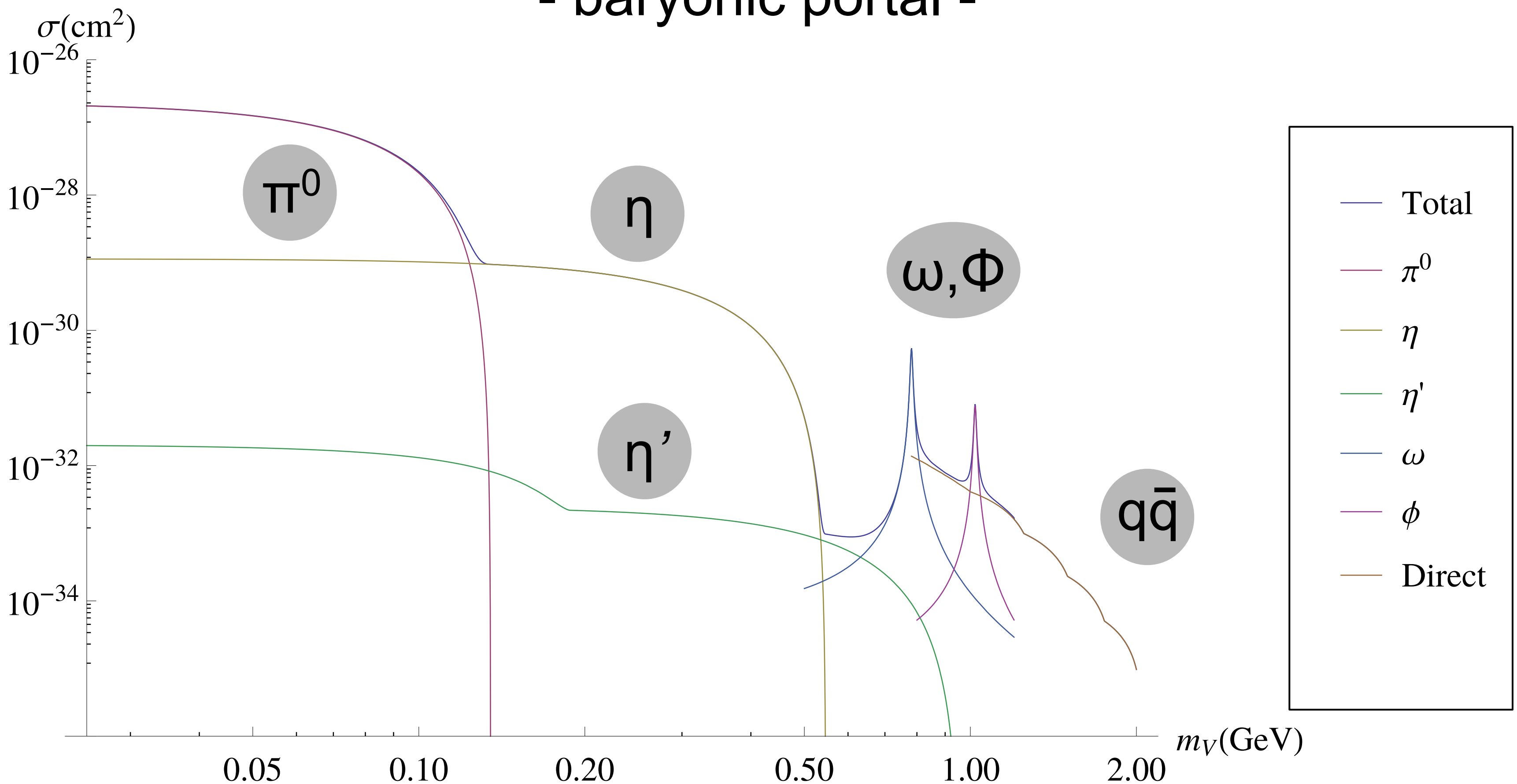
Production in proton fixed targets (e.g. MiniBooNE)
- vector portal -



[9 GeV beam, Ge target]

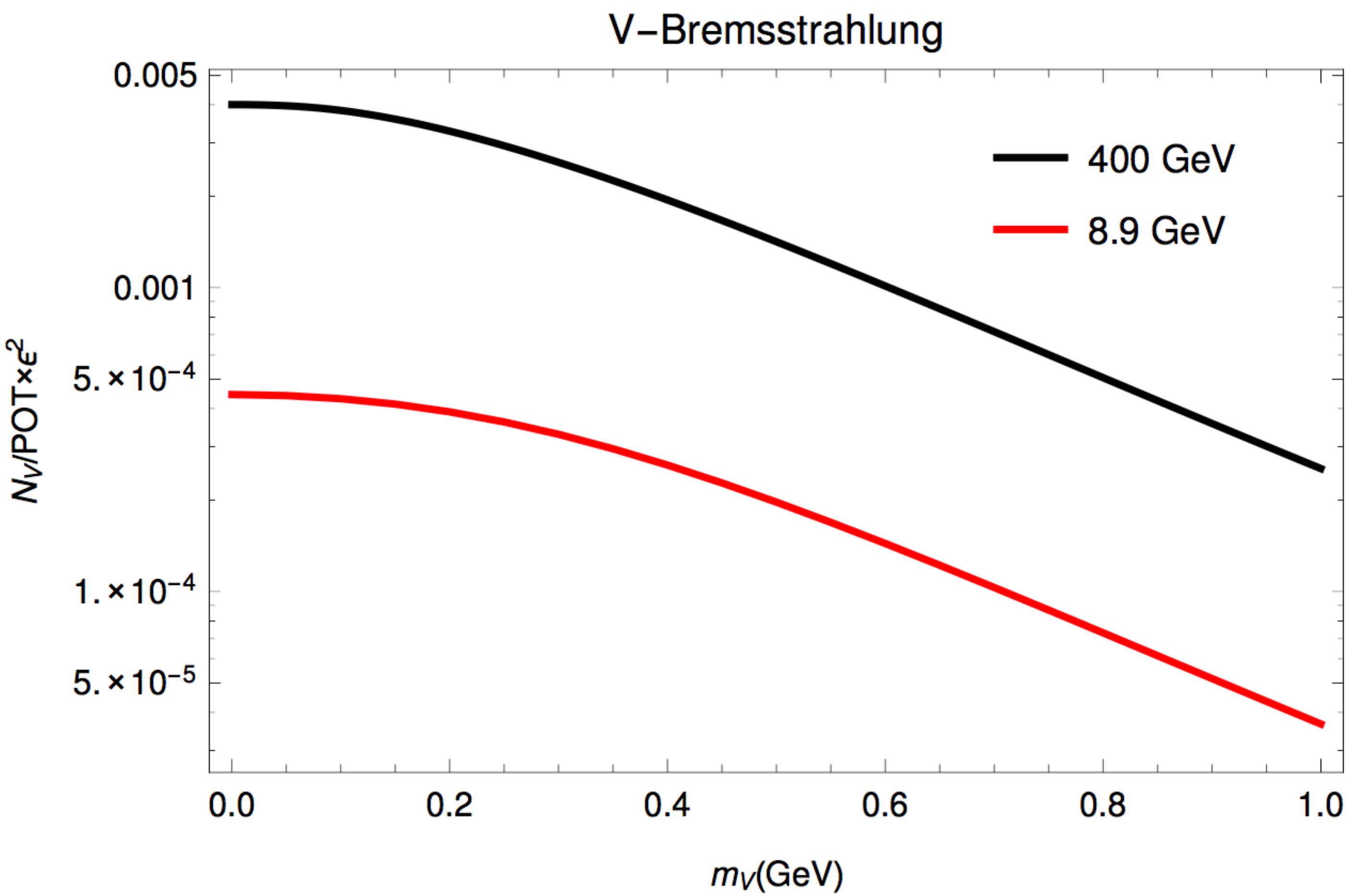
DM Production Channels

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



[9 GeV beam, Ge target]

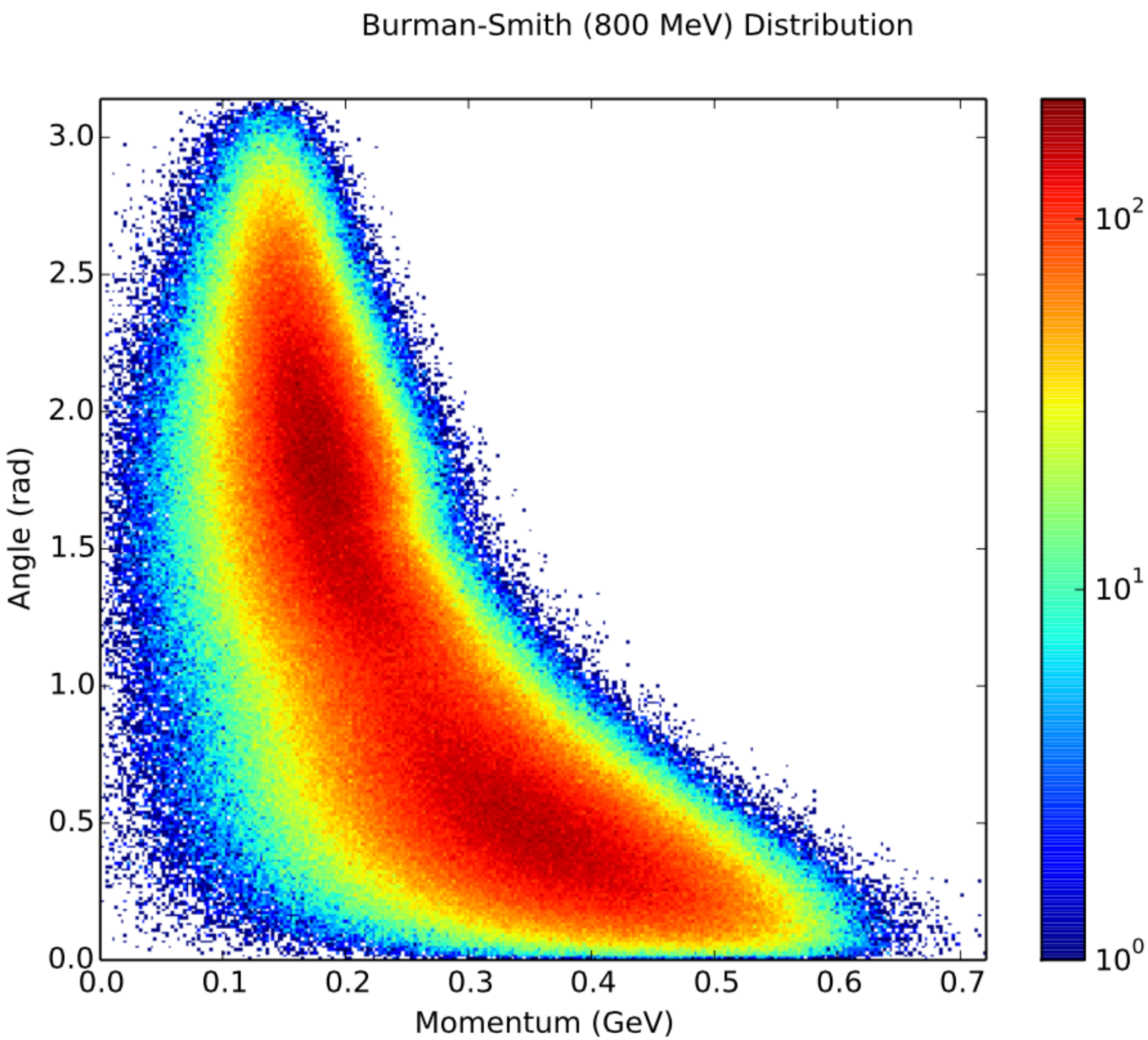
DM Production channels



Overall rate is quite low, but still important for on-axis detectors as highly forward focused

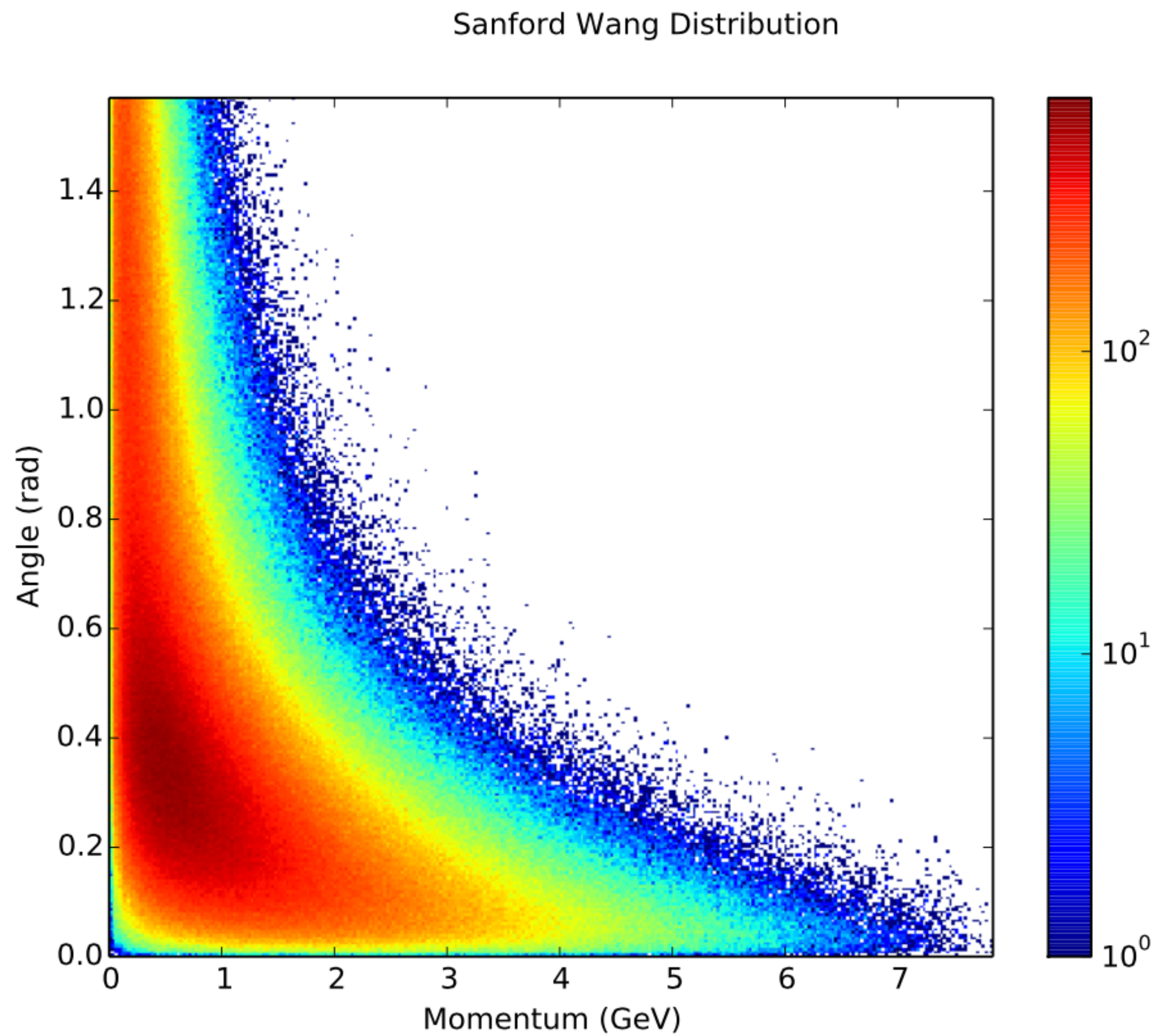
[following Blümlein & Brunner ’13]

DM Production - Pion distributions (low E)



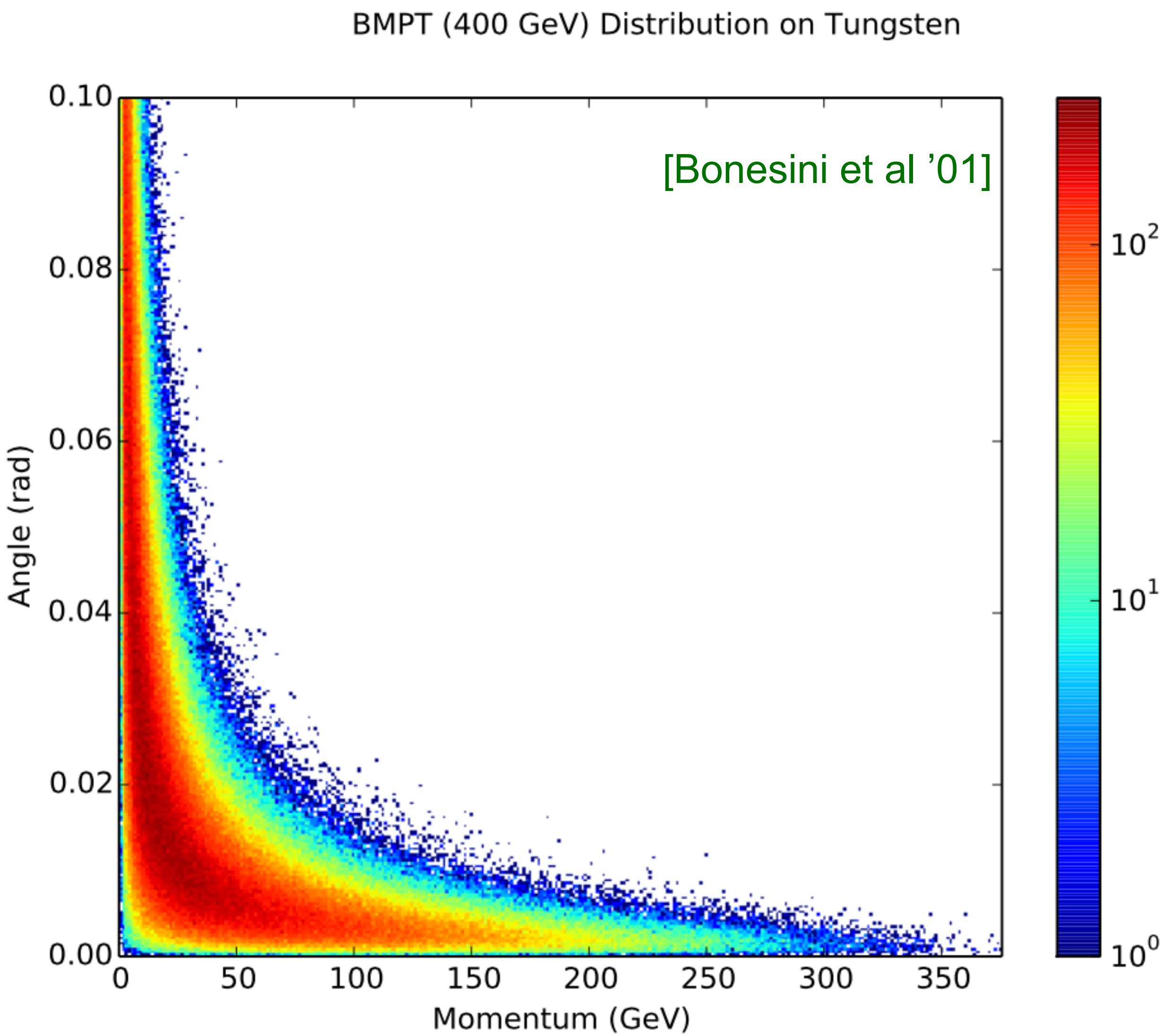
Overall rate for e.g. π^0 given by averaging rates for π^+, π^-

DM Production - Pion distributions (medium E)



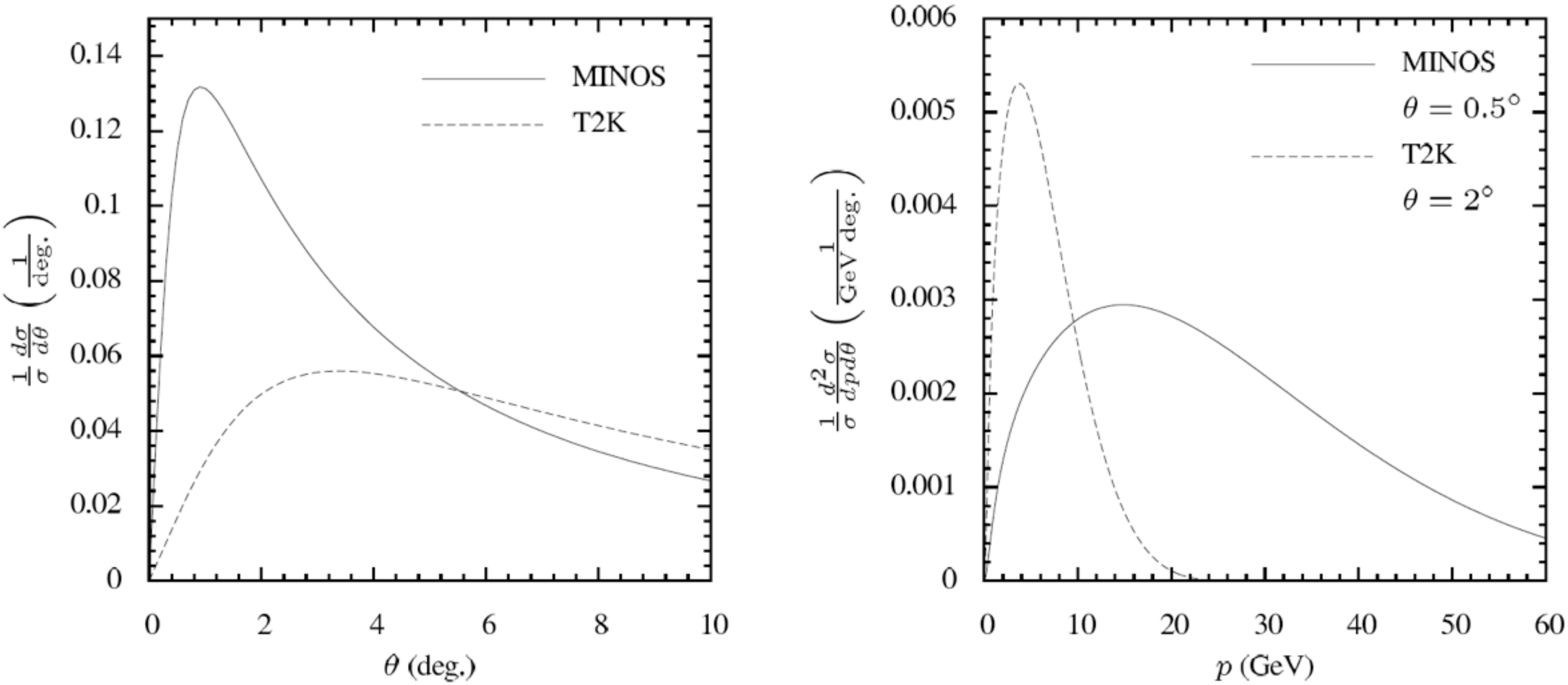
NB: calibrated for thin targets (1-2 interaction lengths), so will change for an absorber

DM Production - Pion distributions (higher E)



(Scalar) DM production - parton level (higher m_V)

[deNiverville, McKeen, AR '12]

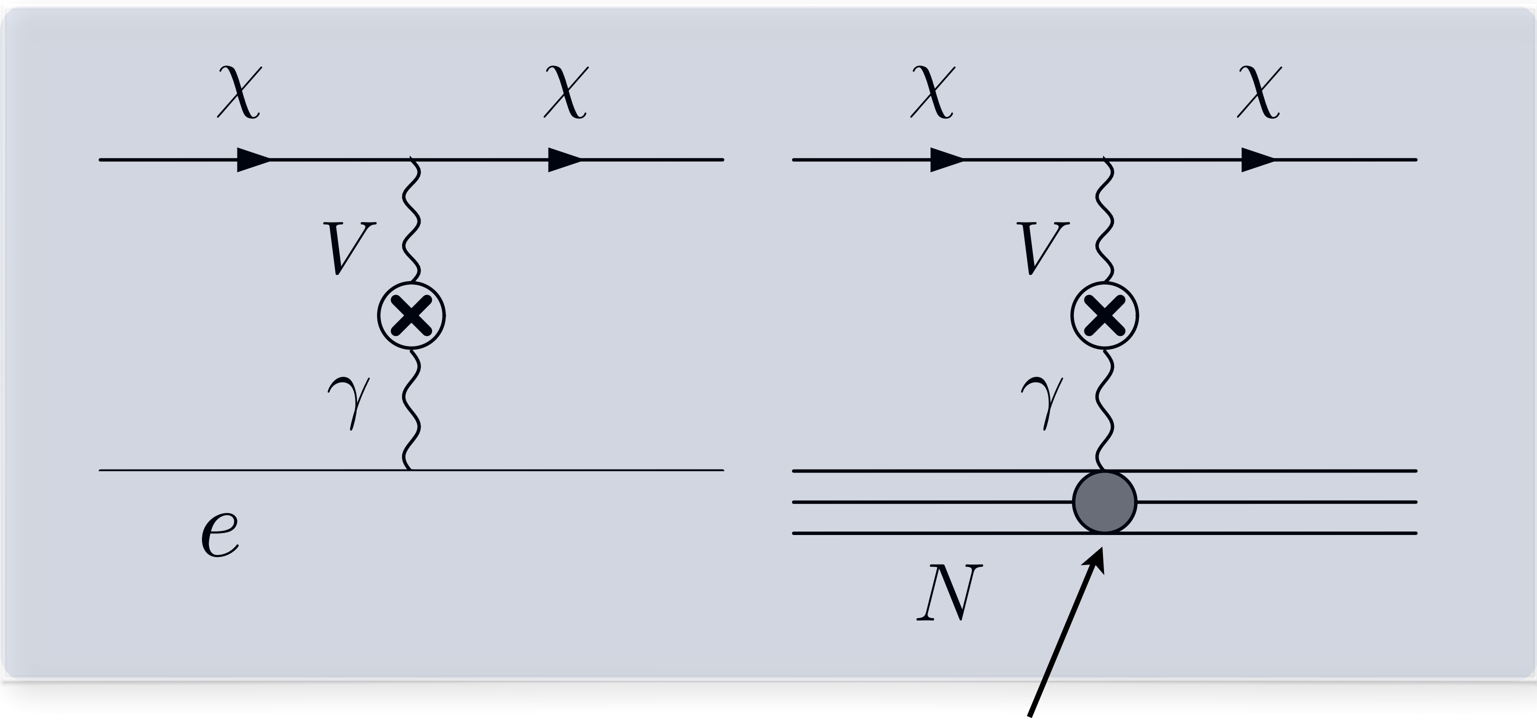


NB: Charged mesons are magnetically focussed, and the neutrino energy spectrum has a lower peak

T2K (2^o) ~ 0.7 GeV
MINOS ~ 3 GeV

Signatures

Characteristic DM elastic scattering signatures

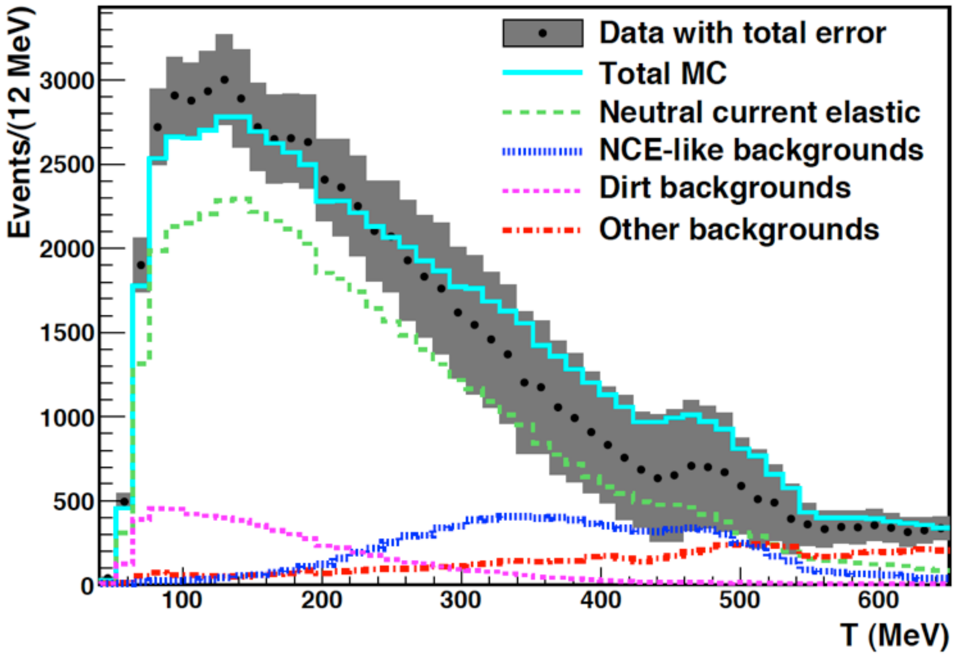


NB: Utilize full nucleon form factors

These processes mimic neutral current elastic scattering of neutrinos, and can lead to an observable excess.

Neutrino backgrounds...

Neutrino elastic scattering provides a large background at all superbeam facilities with a decay volume, e.g. at MiniBooNE



~10^5 -10^6 scattering events, with neutral current cross-sections measured to O(18%)
[MiniBooNE ’10]

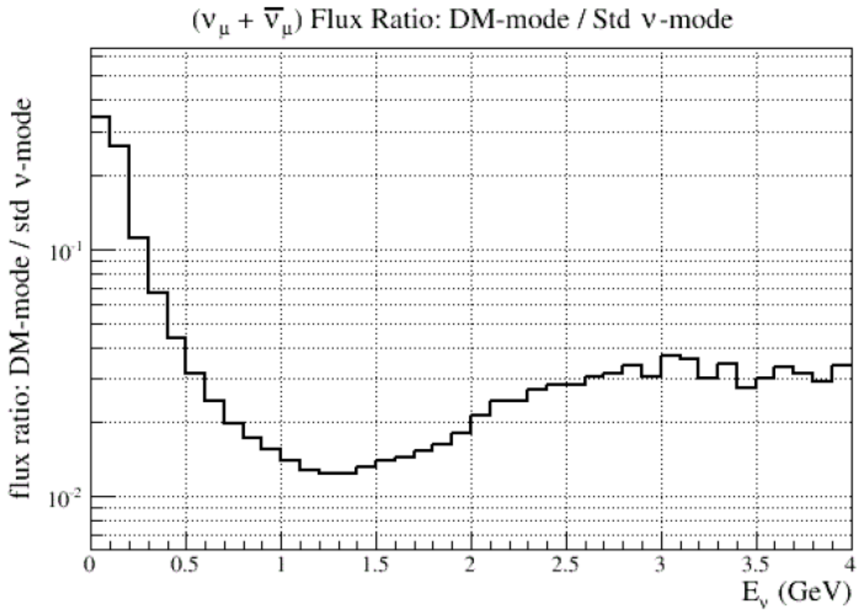
➠ Counting experiments are not enough…

Neutrino backgrounds...

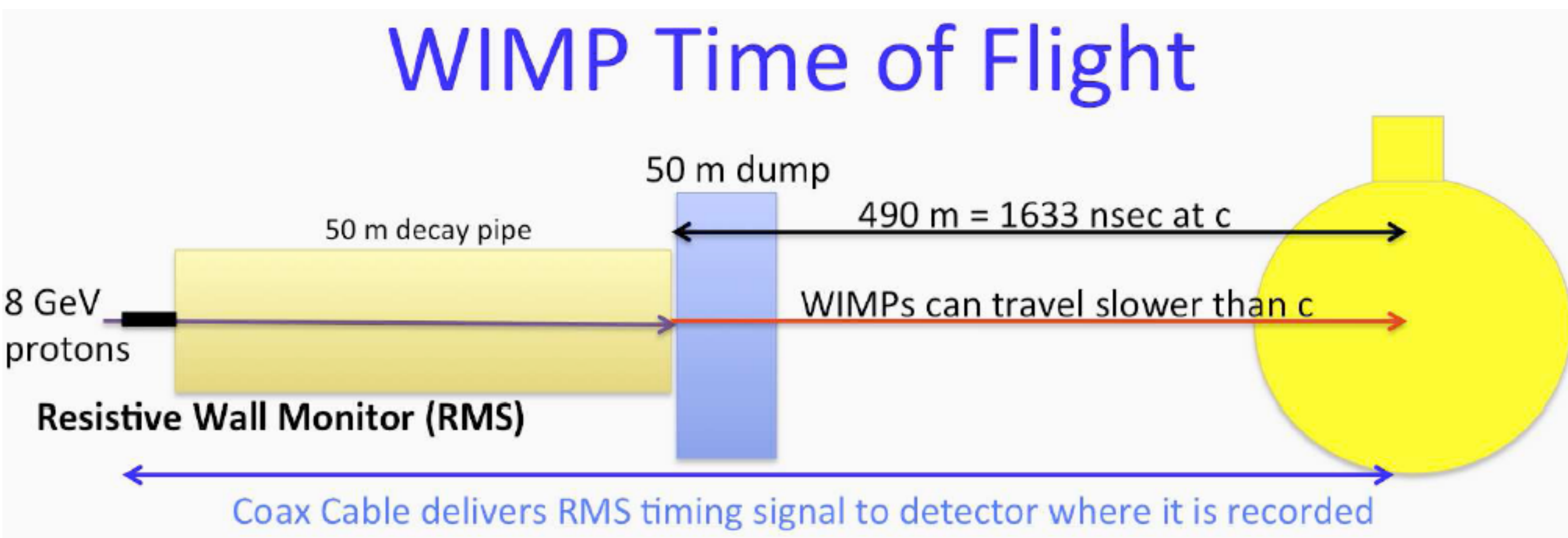
However, there are ways to enhance S/B

- Run as a “beam dump”
  - steer beam past target and into absorber (removes decay volume)
- Timing (3ns resolution at MiniBooNE, along with pulsed beams)
  - time delay (Υ=10) = O(10ns)
- Energy cuts (especially if detector is off-axis)
  - neutrino beam peaks at lower energy
  - different scattering kinematics

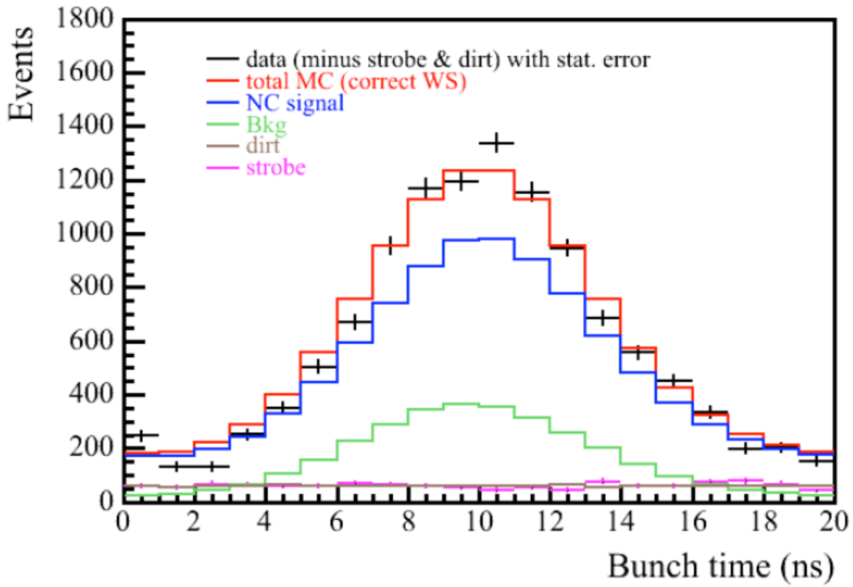
MiniBooNE beam dump

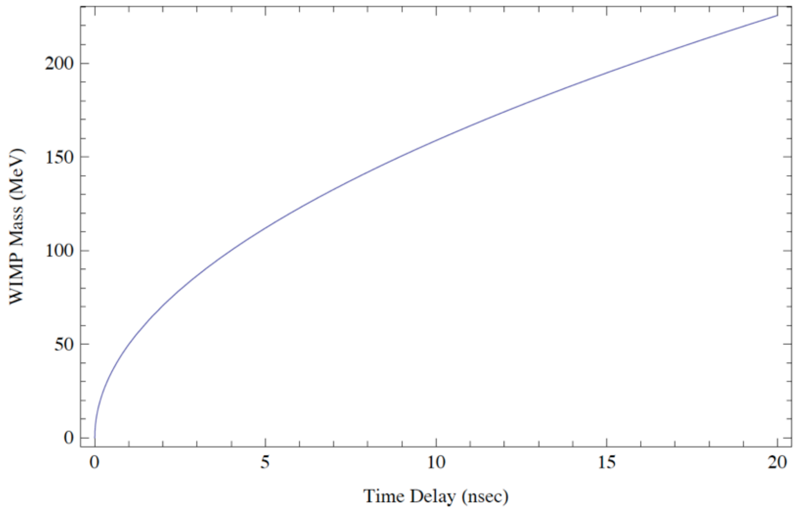


- removal of decay volume for charged mesons reduces neutrino background by factor of ~70



MiniBooNE beam dump - timing



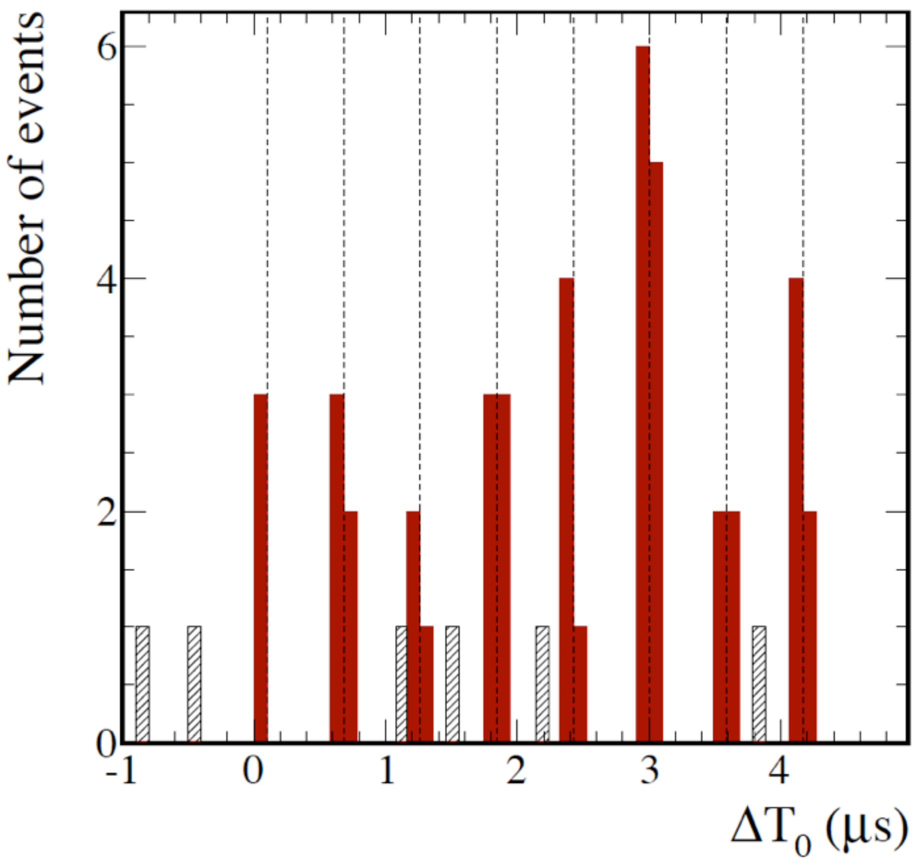


- Travel time from 50m absorber to detector is 1633ns at v=c.
- Absolute beam-detector event timing known to ~ 1.8ns
- For higher mass WIMPs, with v<c, a timing cut can be used to further reduce the neutrino background

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]

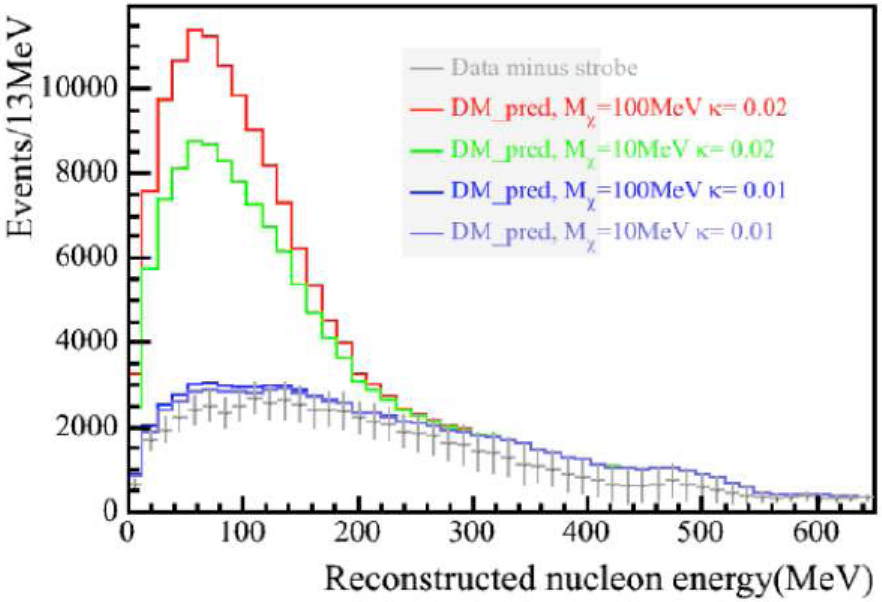


Alternative - use timing in combination with a sufficiently large far-detector, possible at T2K due to the size of Super-K

- 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 - Nχ scattering

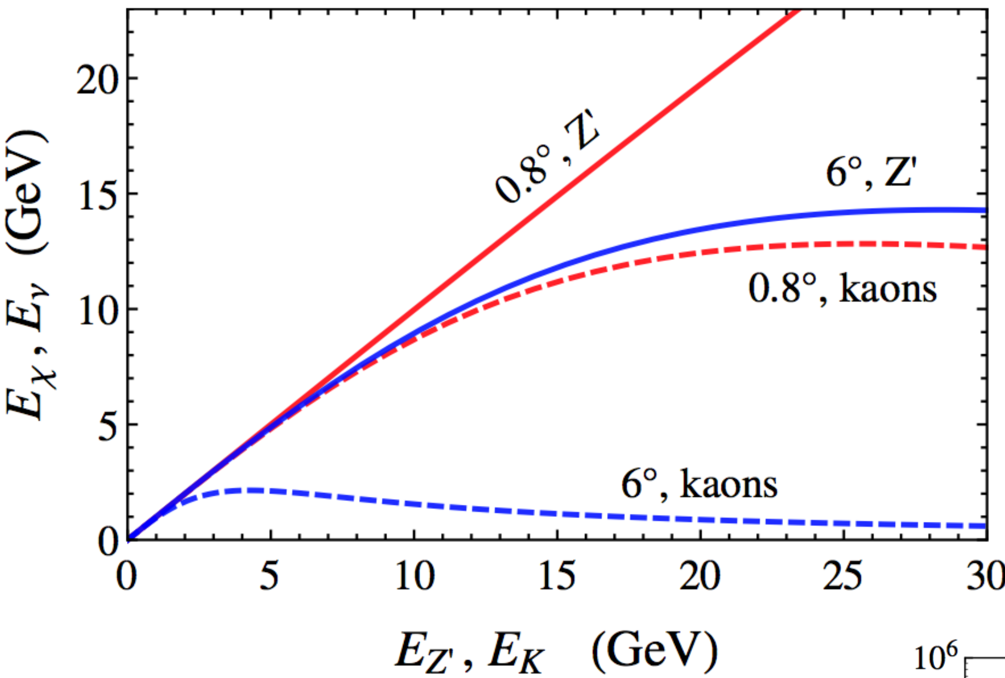


- background reduction using scattering kinematics

Neutrino backgrounds and signal significance in g-2 band

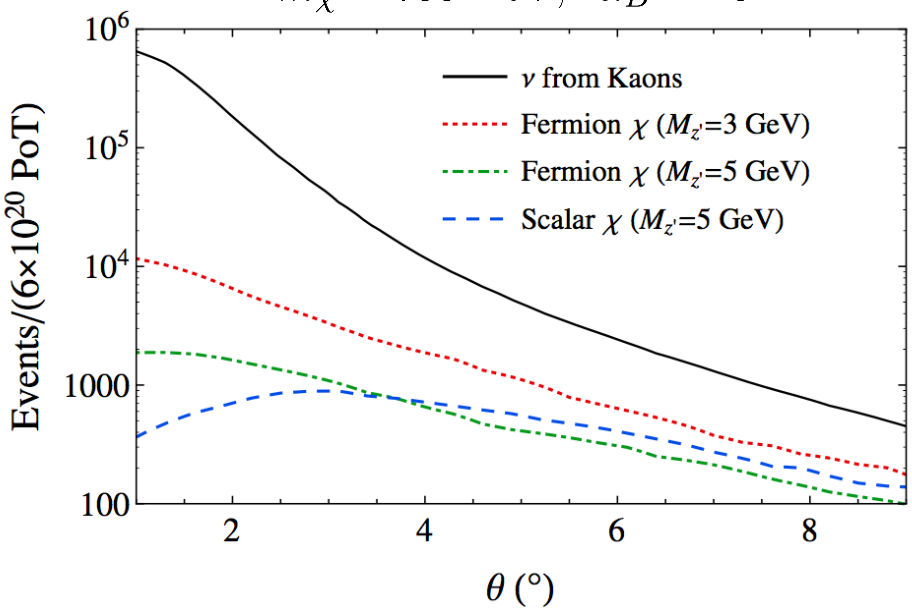
Event Type	0.35×10^{20}POT In-Time	0.35×10^{20}POT Out-Time	1.75×10^{20}POT In-Time	1.75×10^{20}POT Out-Time
Data	-	-	-	-
NCE	54.9	10.9	274.6	54.7
Dirt	7.1	4.7	35.9	23.9
Cosmic	43.3	28.8	216.6	143.9
Total Background	$105.5 \pm 10.3 \pm 6.7$	$44.4 \pm 6.7 \pm 1.5$	$527.1 \pm 23.0 \pm 25.3$	$222.5 \pm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

NuMI/LBNF off-axis kinematics



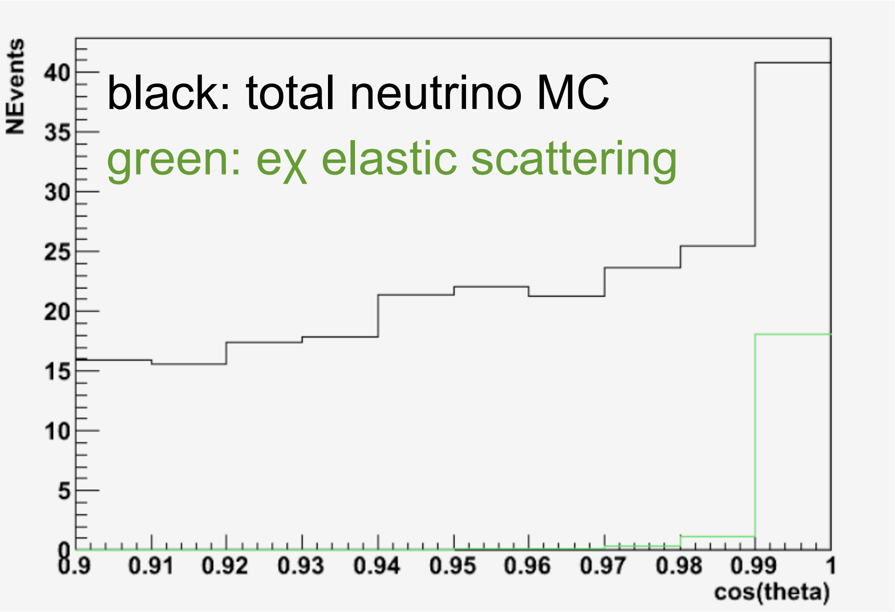
Recent study for ~100 GeV beam, using parton-level DM production via baryonic vector mediator [Coloma et al '15]

$m_\chi \sim 750\,\text{MeV}, \quad \alpha_B \sim 10^{-3}$



NB: MiniBooNE/MicroBooNE are ~6° off-axis wrt NuMI target

MiniBooNE beam dump - eχ scattering



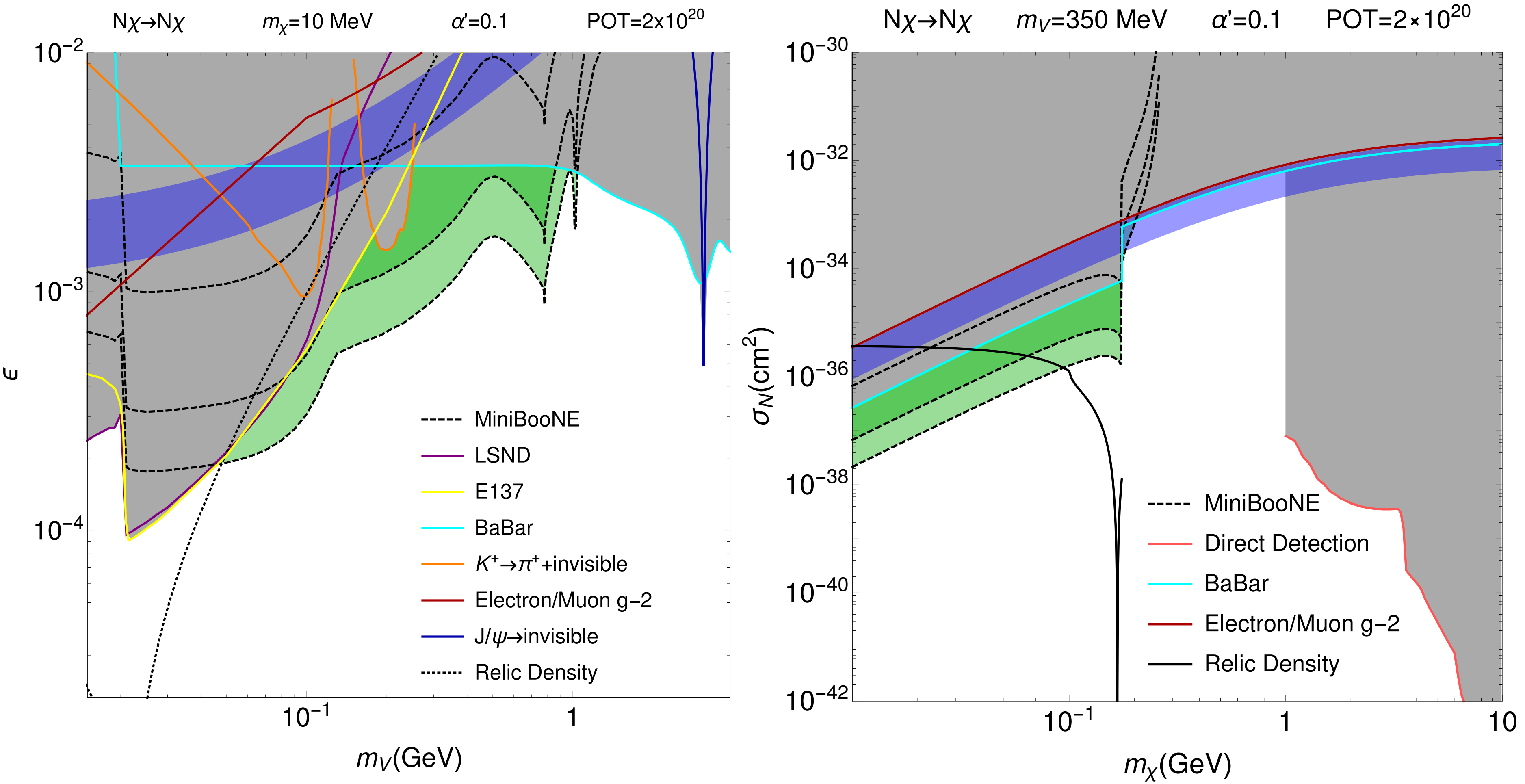
- Use of electron scattering allows the neutrino background to be further reduced (98%) with a forward angle cut

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

Sample event rates - MiniBooNE

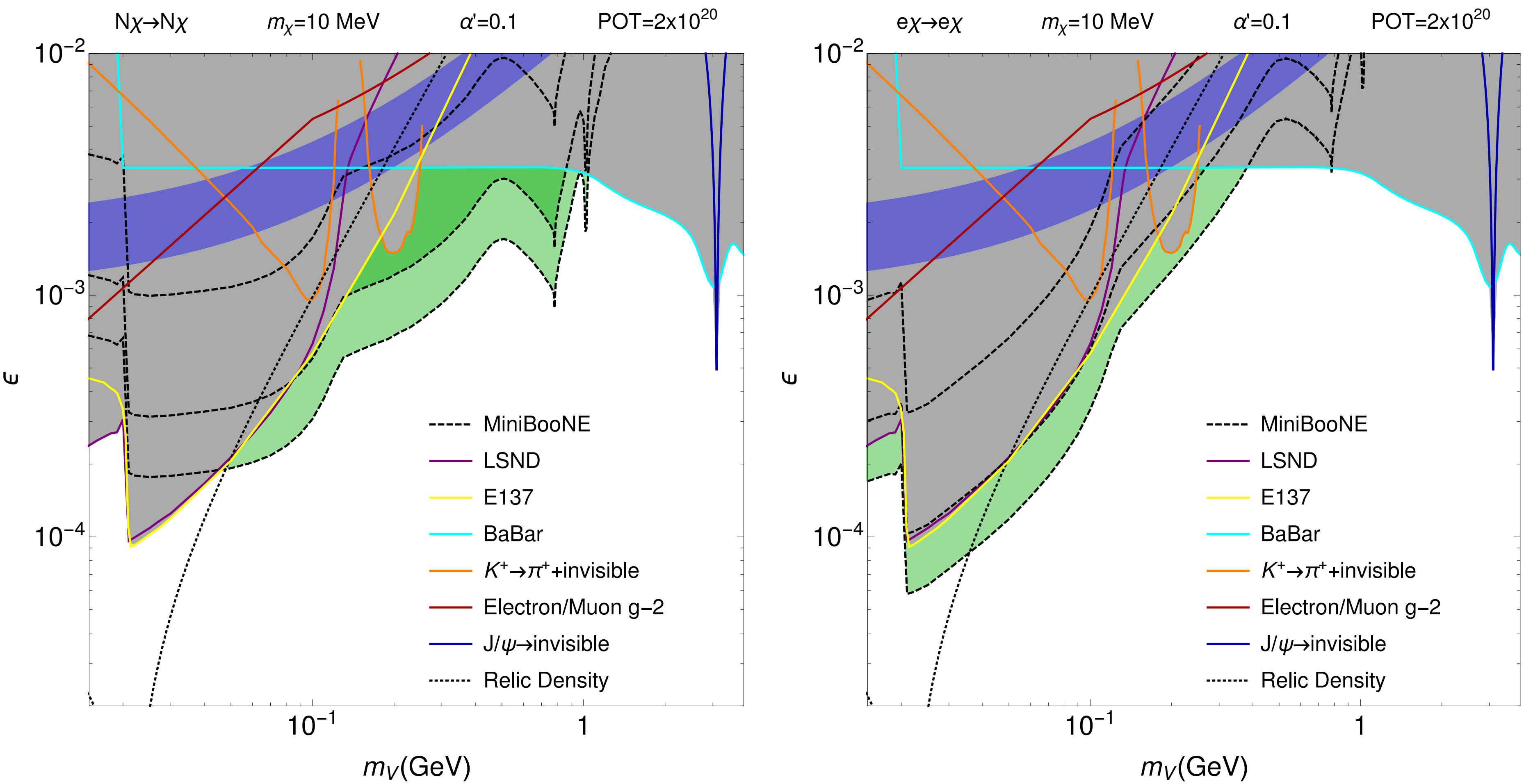
[Batell et al '14]



Green contours show 1, 10, 1000 events

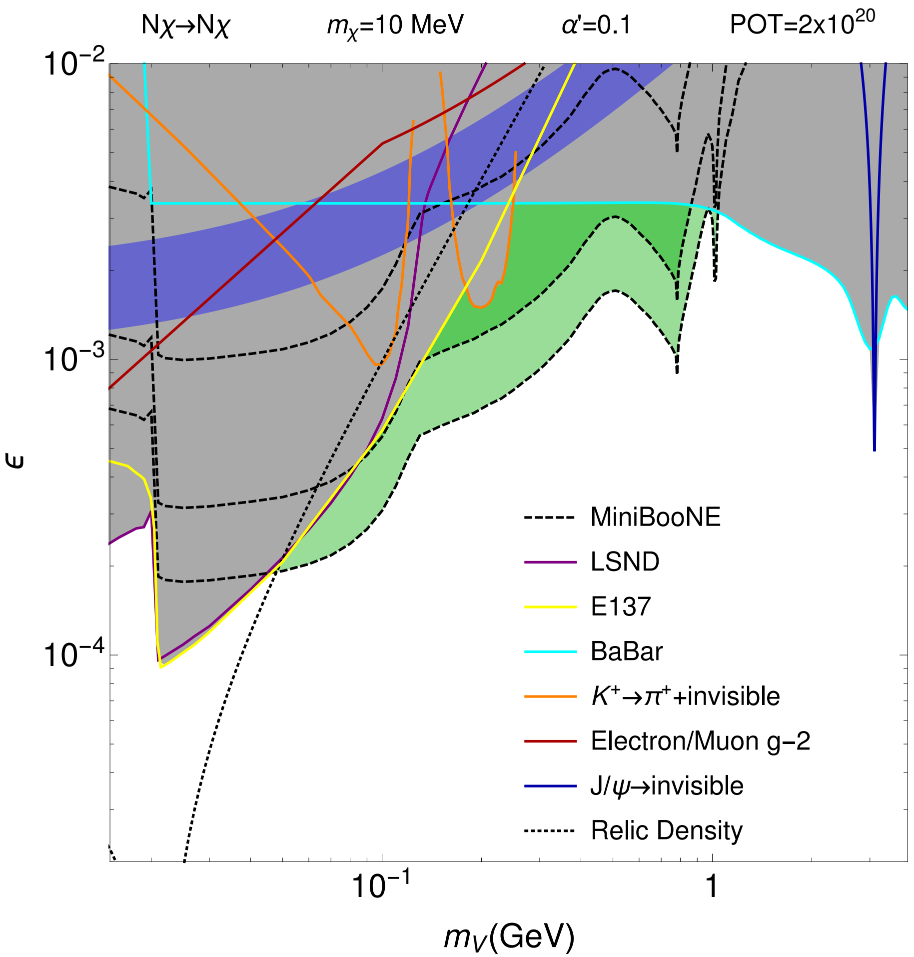
Sample event rates - MiniBooNE

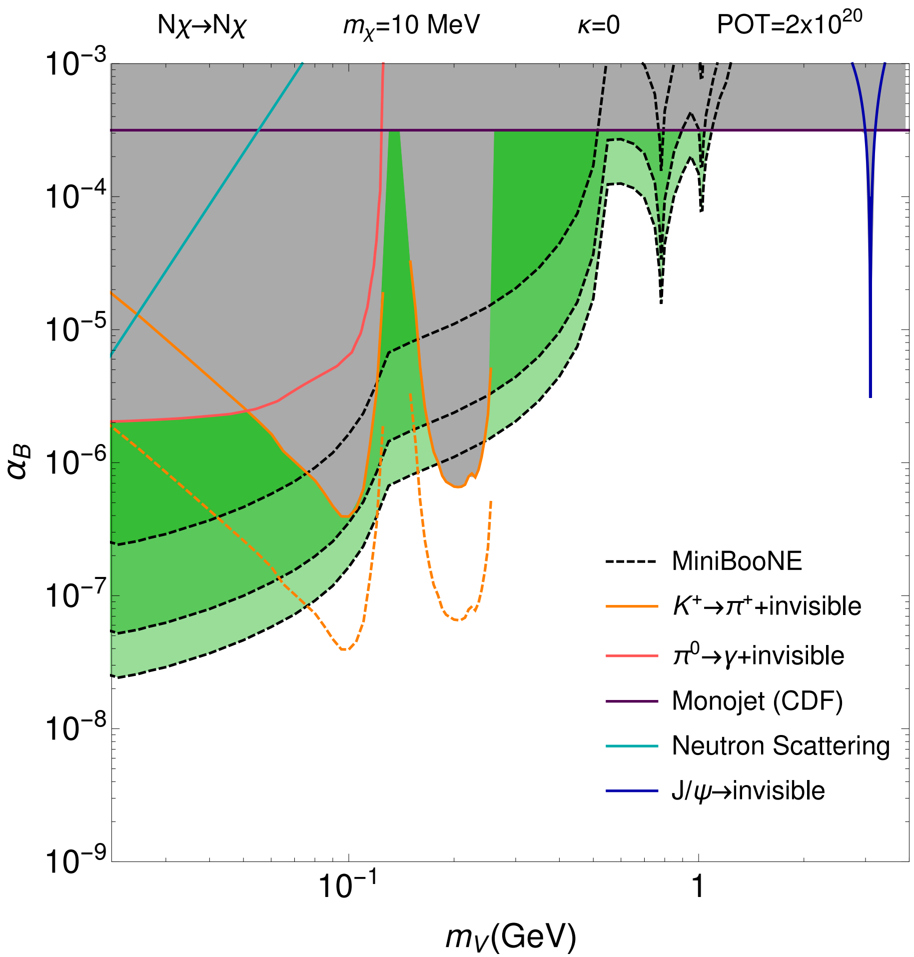
[Batell et al '14]



Sample event rates - MiniBooNE

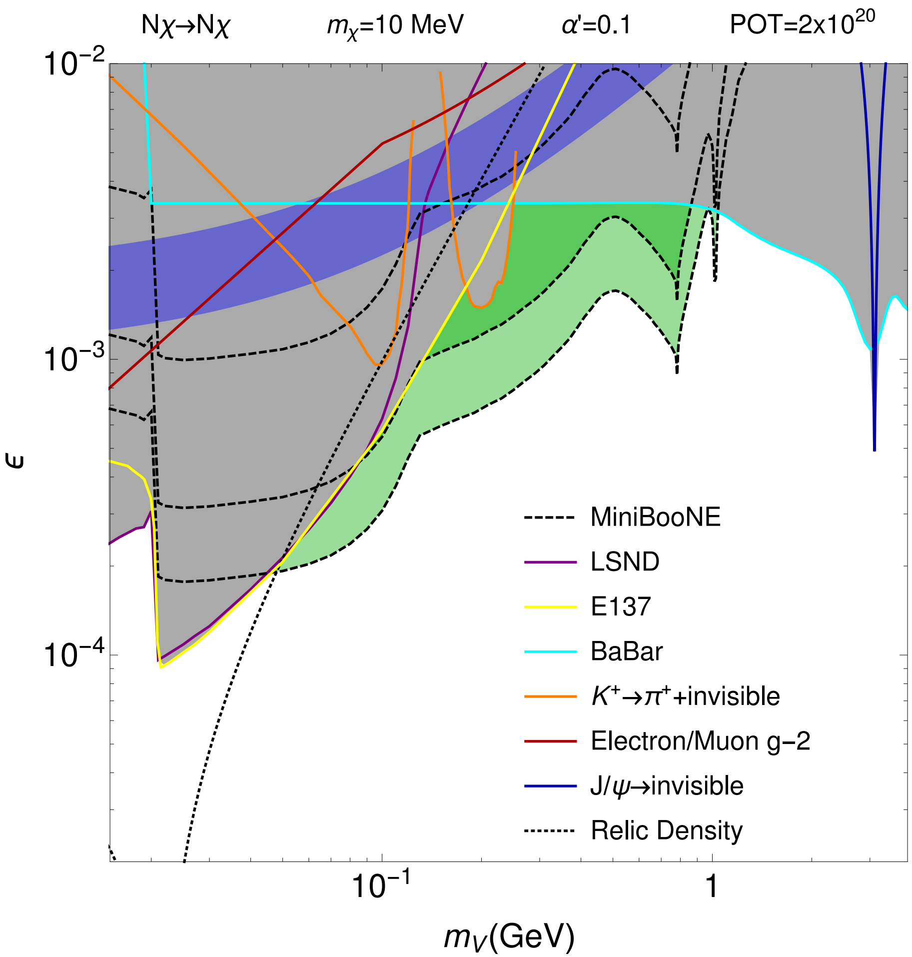
[Batell et al '14]

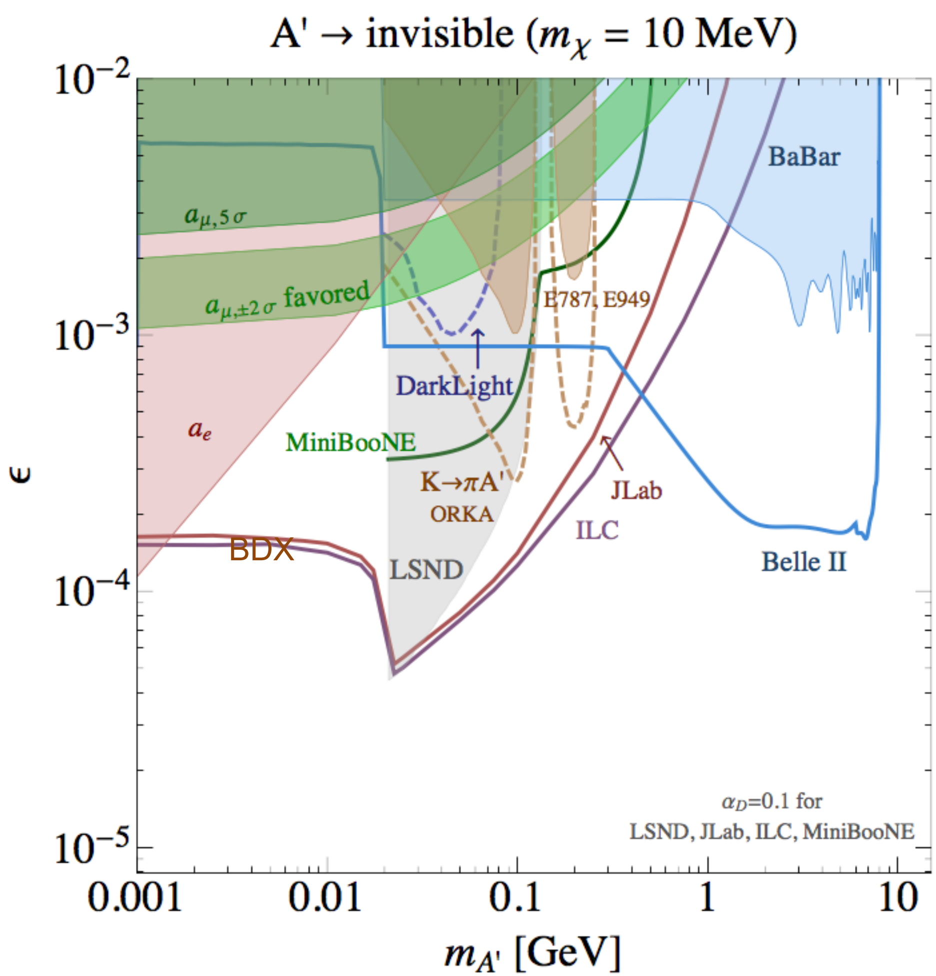




Sample event rates - MiniBooNE

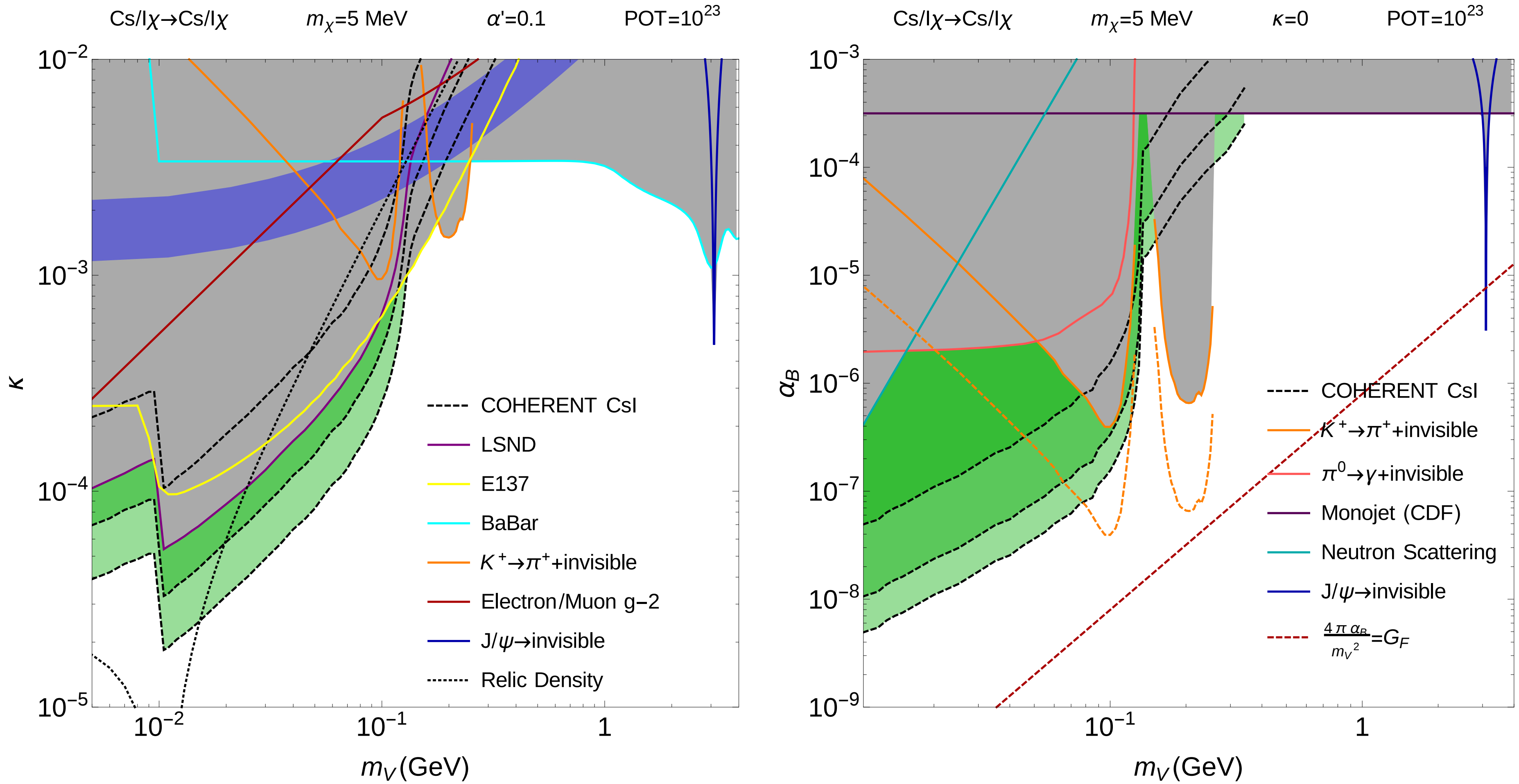
[Essig et al, Snowmass IF5 '13]





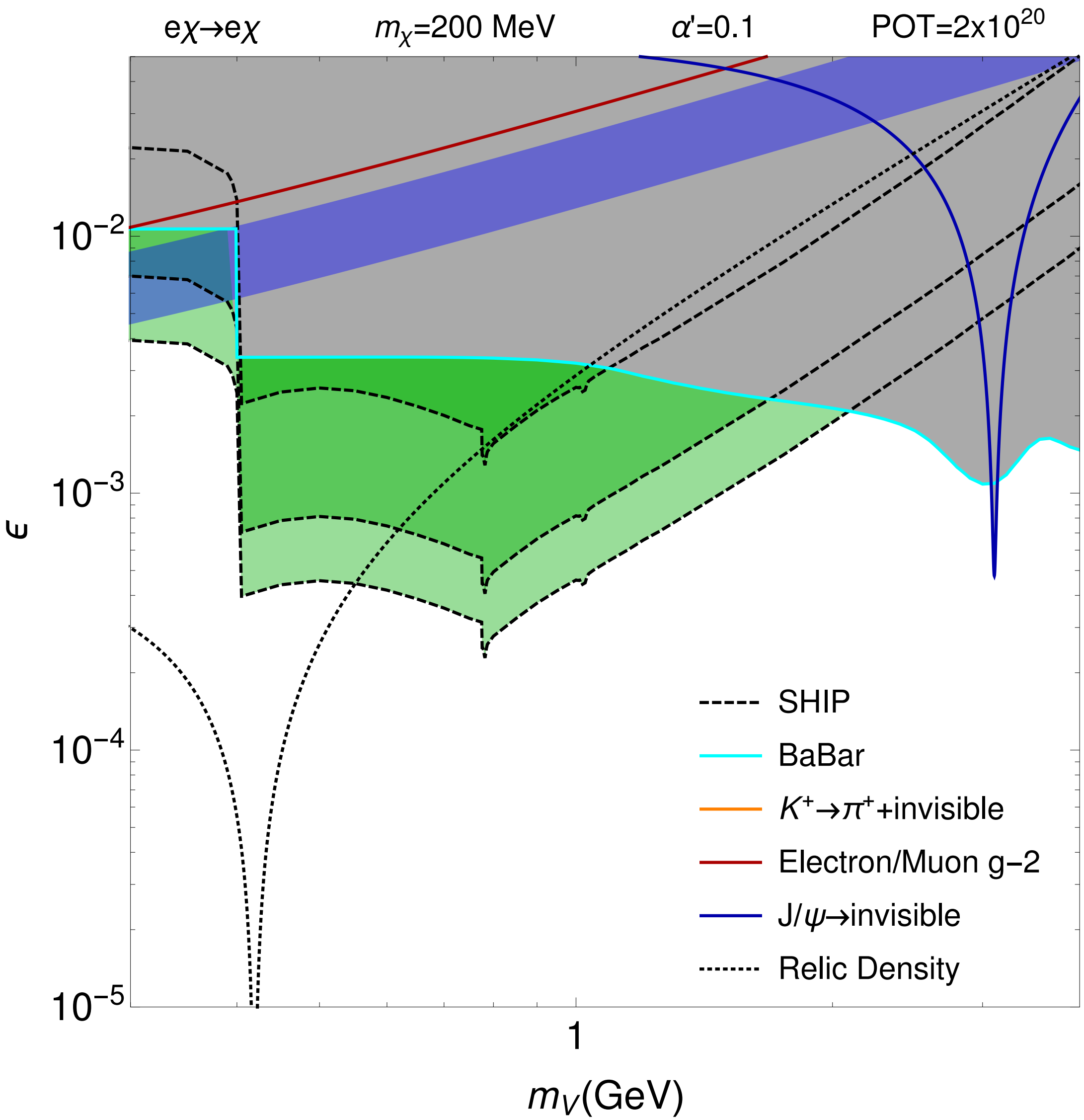
Sample event rates - COHERENT (SNS)

[deNiverville et al ’15]



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

Sample event rates - SHiP



- 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]

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)

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

- 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)*

- NB: Possibility for searches for light DM or other light hidden sectors to be carried out ("parasitically") in conjunction with SM measurements, e.g. for neutrinos.

Extra slides

EFT for a (neutral) hidden sector

Standard Model ⟷ (mediators) ⟷ **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: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j$

Mediator for simplest benchmark light DM models

Many more UV-sensitive interactions at dim ≥ 5

Constraints on (minimal) sub-GeV thermal relic DM

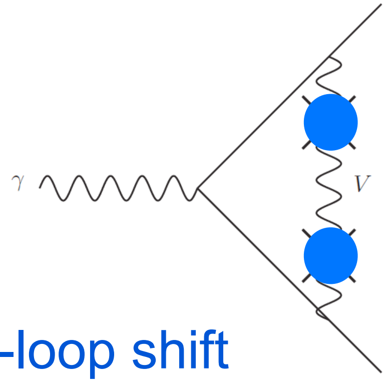
Classes of sub-GeV (thermal relic) DM models ($m_{med} > 2m_{DM}$)

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

[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 → K + E_{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

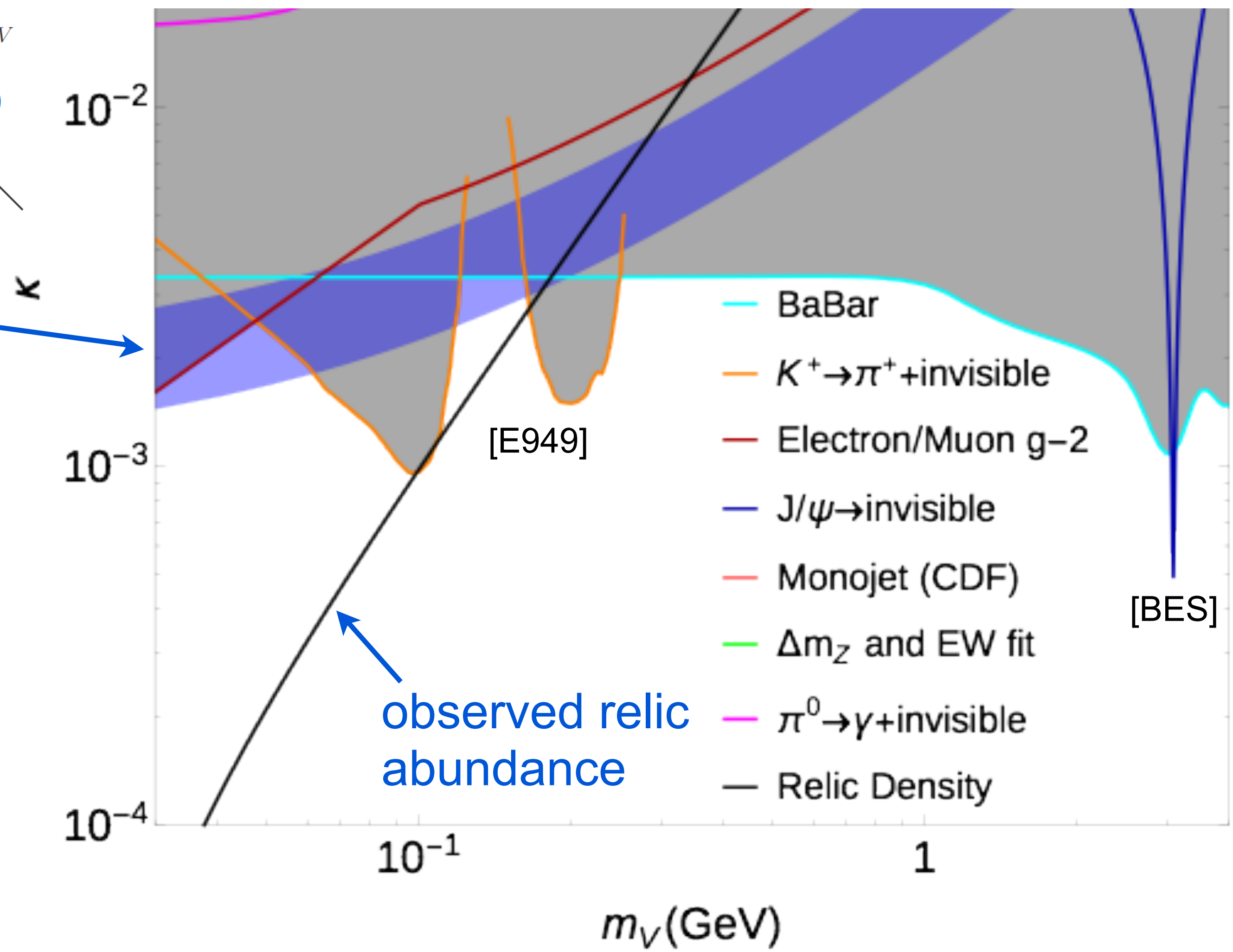


V-loop shift helps resolve muon g-2 discrepancy

[Pospelov '08]

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

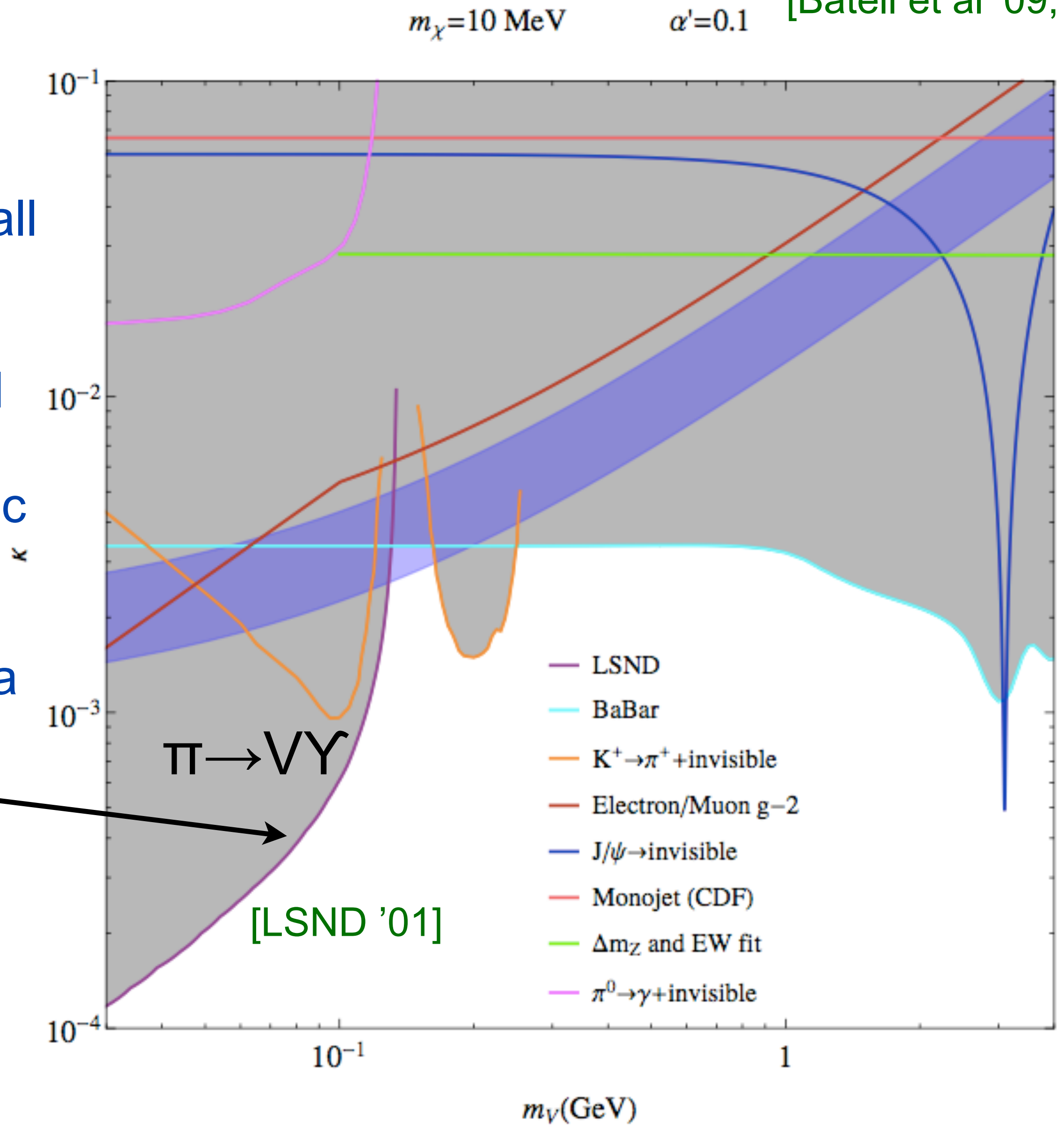
Br(V → invisible)~1



Limit from LSND (eχ → eχ)

[Batell et al ’09; deNiverville et al ’11]

Relatively small neutrino background, and dedicated electron-neutrino elastic scattering analysis by LSND allows a 90% CL limit



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

[Batell, Essig, Surujon '14]