Milli-Charged Particles in ArgoNeuT and future LAr TPCs

POND^2

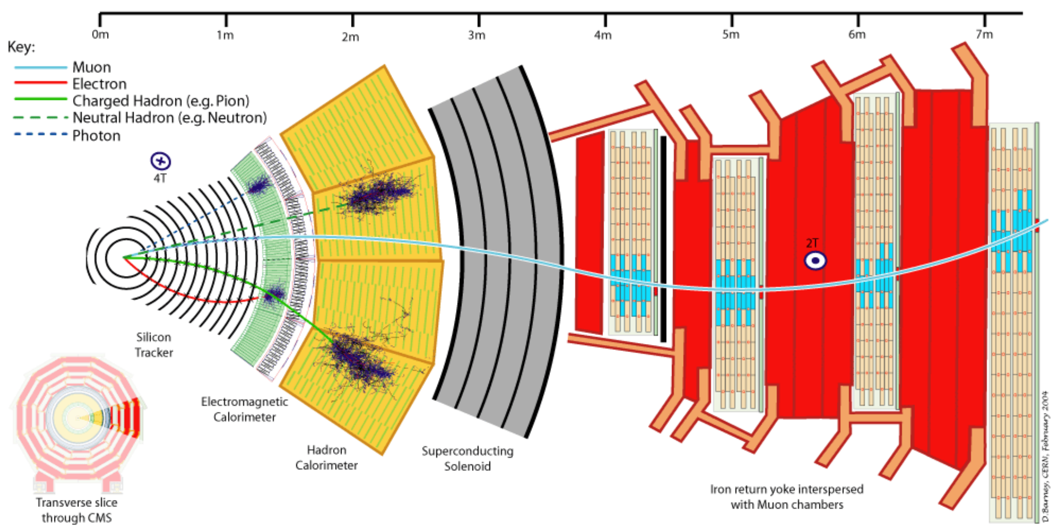
Roni Harnik

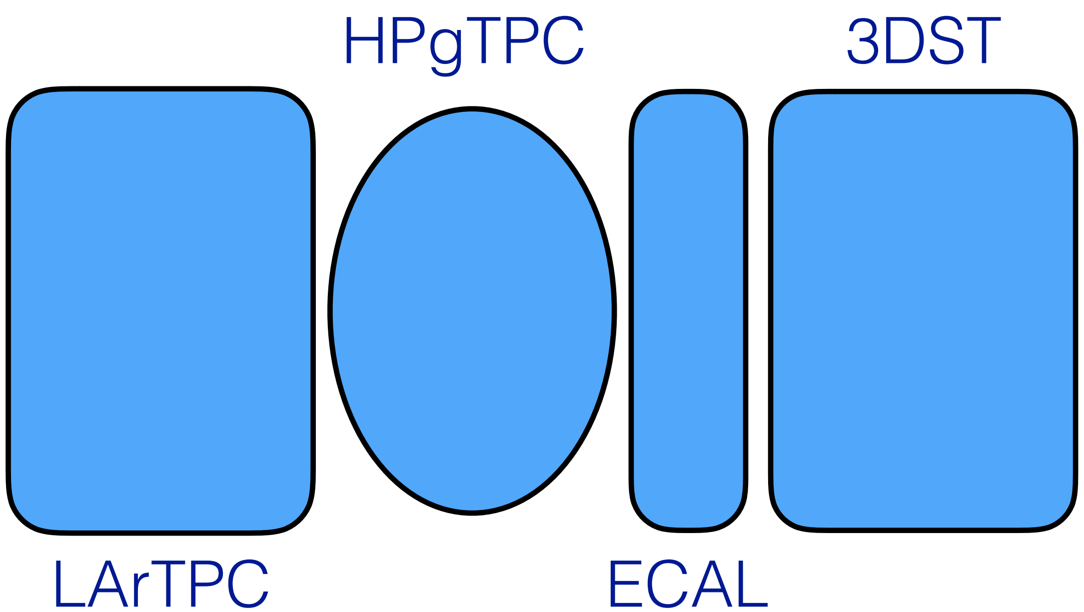
Work with Zhen Liu and Ornella Palamara

coming <u>very soon</u> to an arxiv near you.

see also - Yu-Dai's talk from yesterday and work with K. Kelly.

Multi-Purpose Detectors





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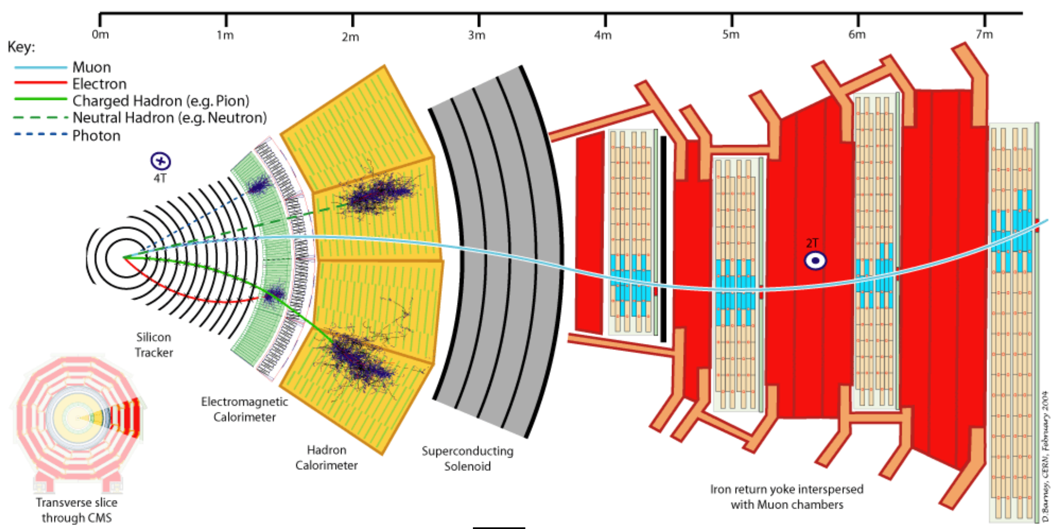

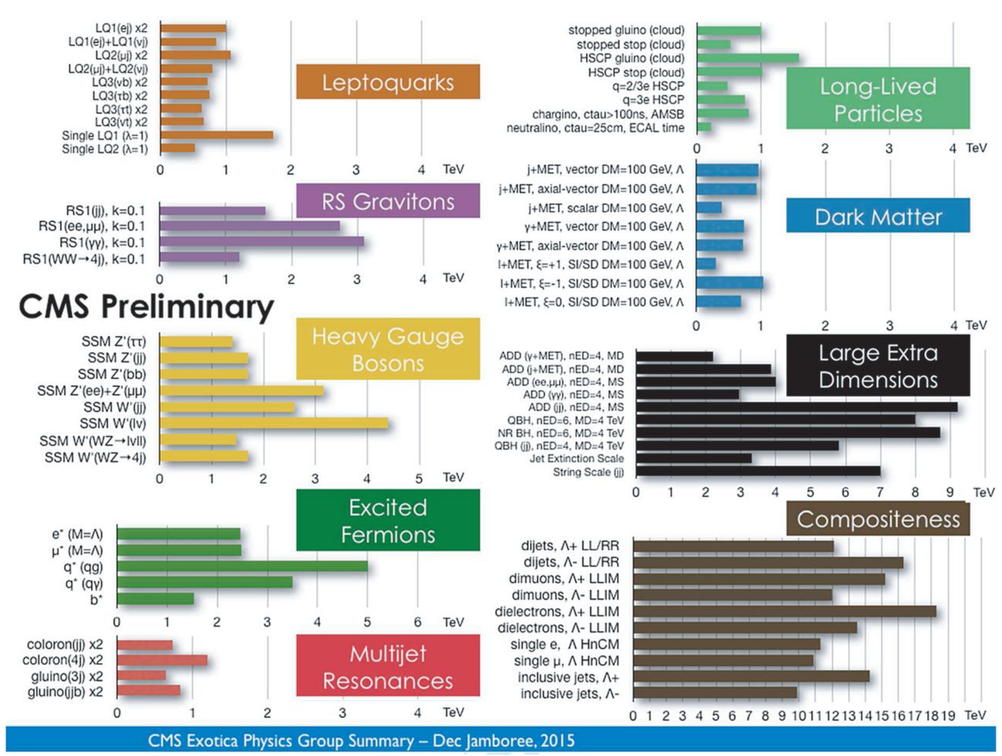

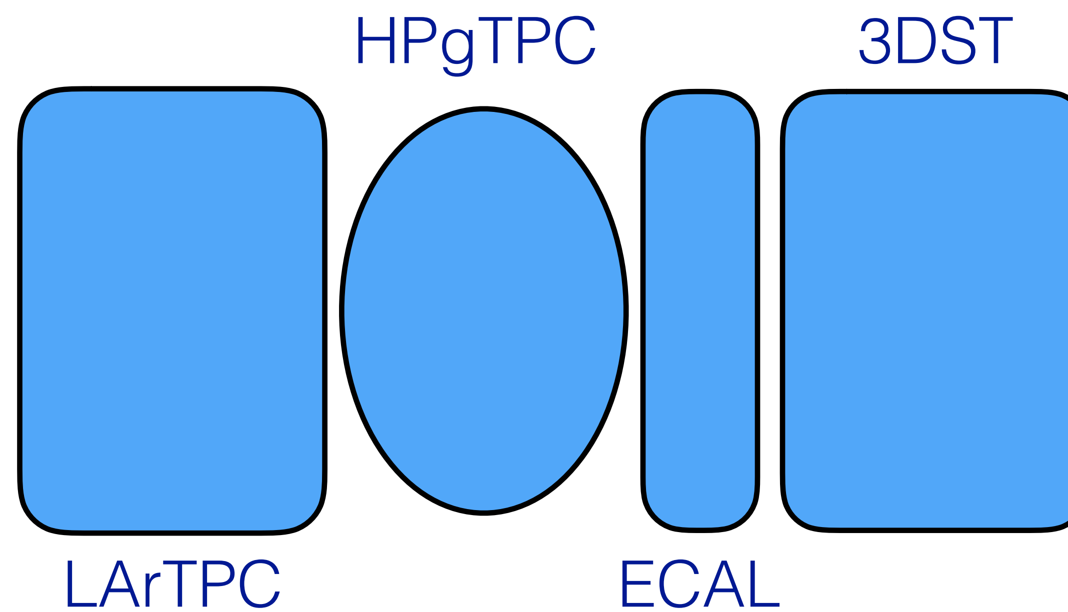

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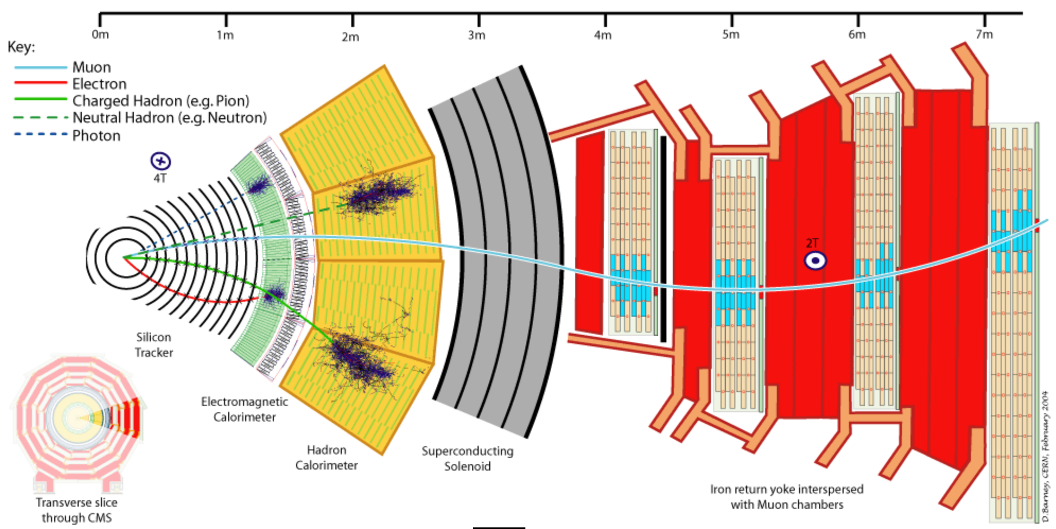

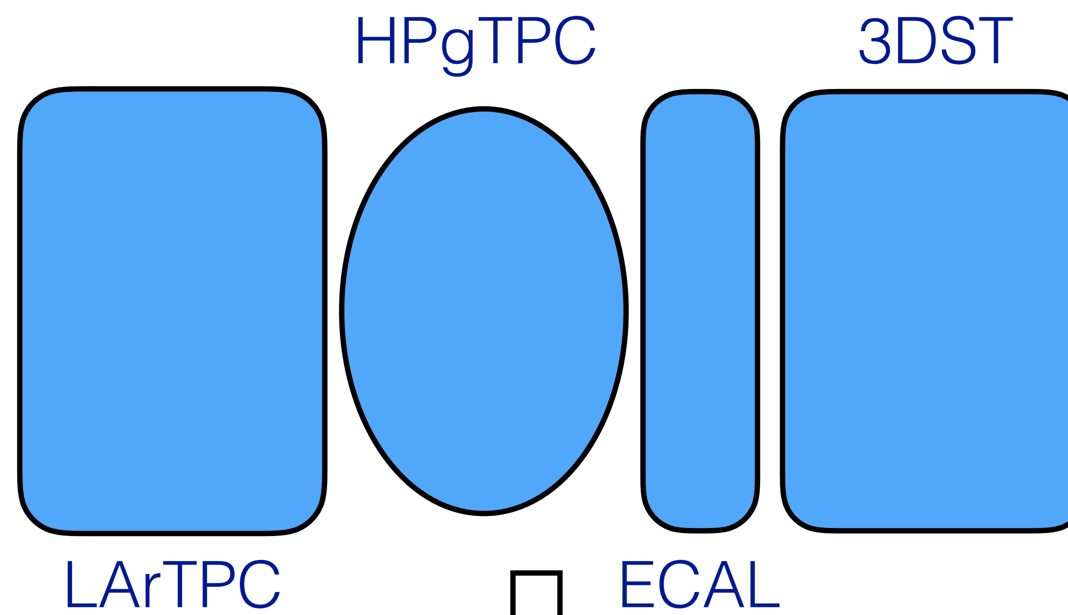

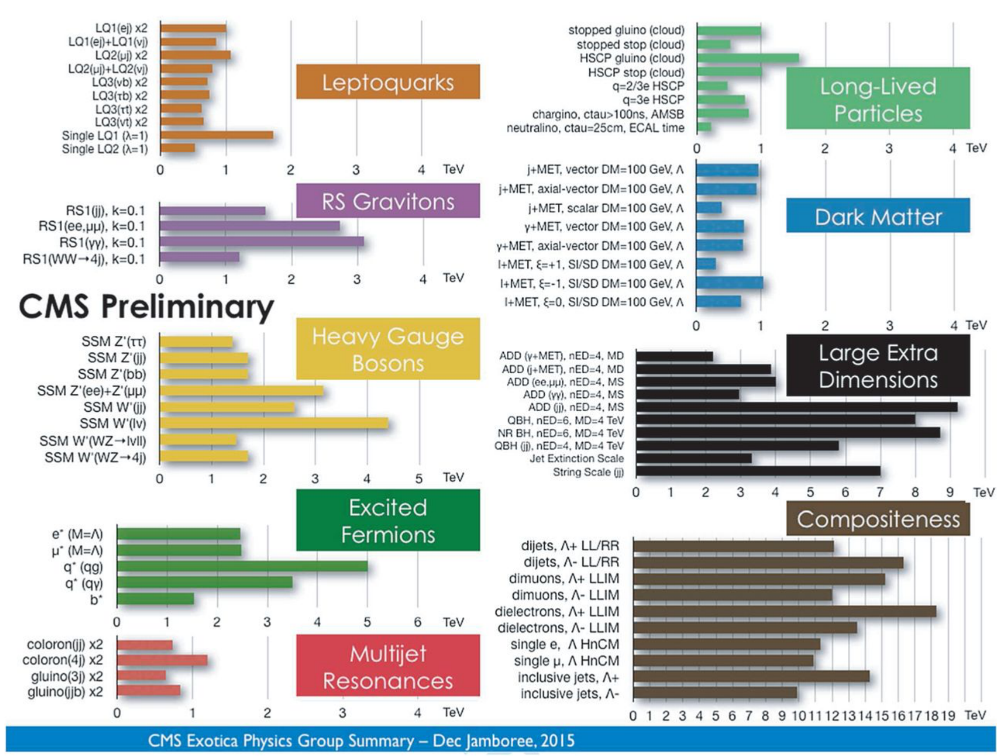

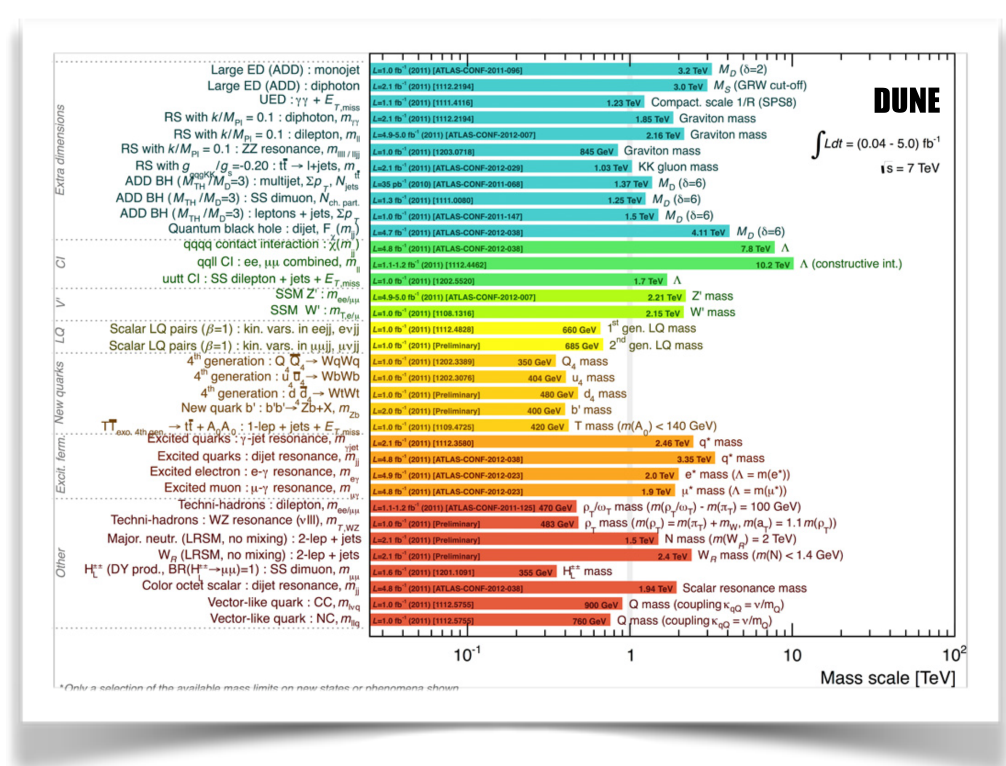

Multi-Purpose Detectors

- A broad menu of searches is being developed for LAr near (and far) detectors. Many covered in this workshop.
  - di-lepton resonances.
  - displaced decays
  - mono potons
  - millicharged particles
  - ....

Milli-Charged Particles

- A very simple model:

  $\mathcal{L} =$ a particle with charge ε.

Milli-Charged Particles

- Even if you don't like such fractional charges, its easy to start with integer charges and get milli-charges. Start with 2 sectors:

Our $U(1)_{EM}$

+ our matter

another massless $U(1)'$

+ matter'

Milli-Charged Particles

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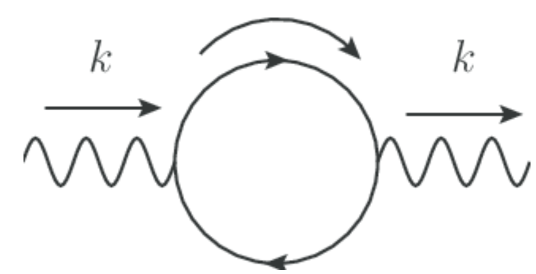
heavy particles charged under both.



$$\boxed{\varepsilon\, F_{\mu\nu} F'^{\,\mu\nu}}$$

Our $U(1)_{EM}$ + our matter

another massless $U(1)'$ + matter'

Milli-Charged Particles

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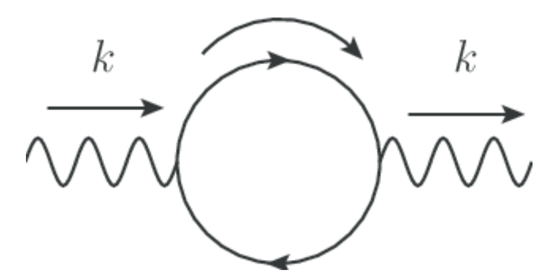


$$\boxed{\varepsilon F_{\mu\nu} F'^{\mu\nu}}$$

Our $U(1)_{EM}$

+ our matter

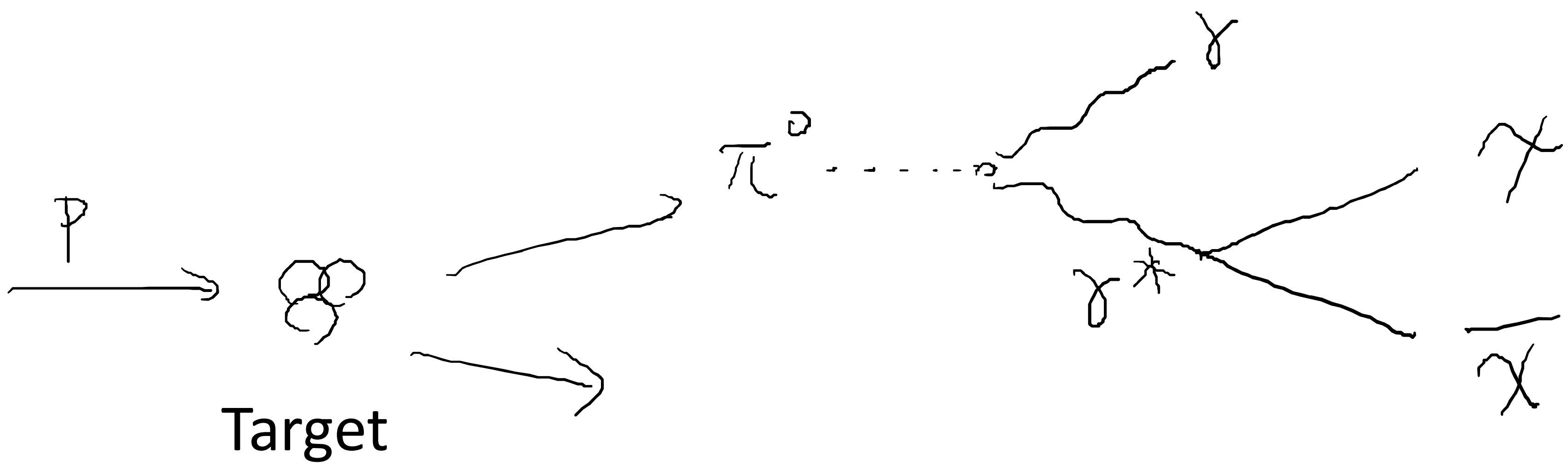
After we diagonalized everything, matter′ picks up a charge of ε under our EM.

Outline

- mCP production
- mCP Interaction
  - mCP propagation through matter
  - mCP Detection
- An mCP search in ArgoNeuT
- Implications for the DUNE ND

Production

- mCP are produced in abundance in proton interactions: meson decay and DY.

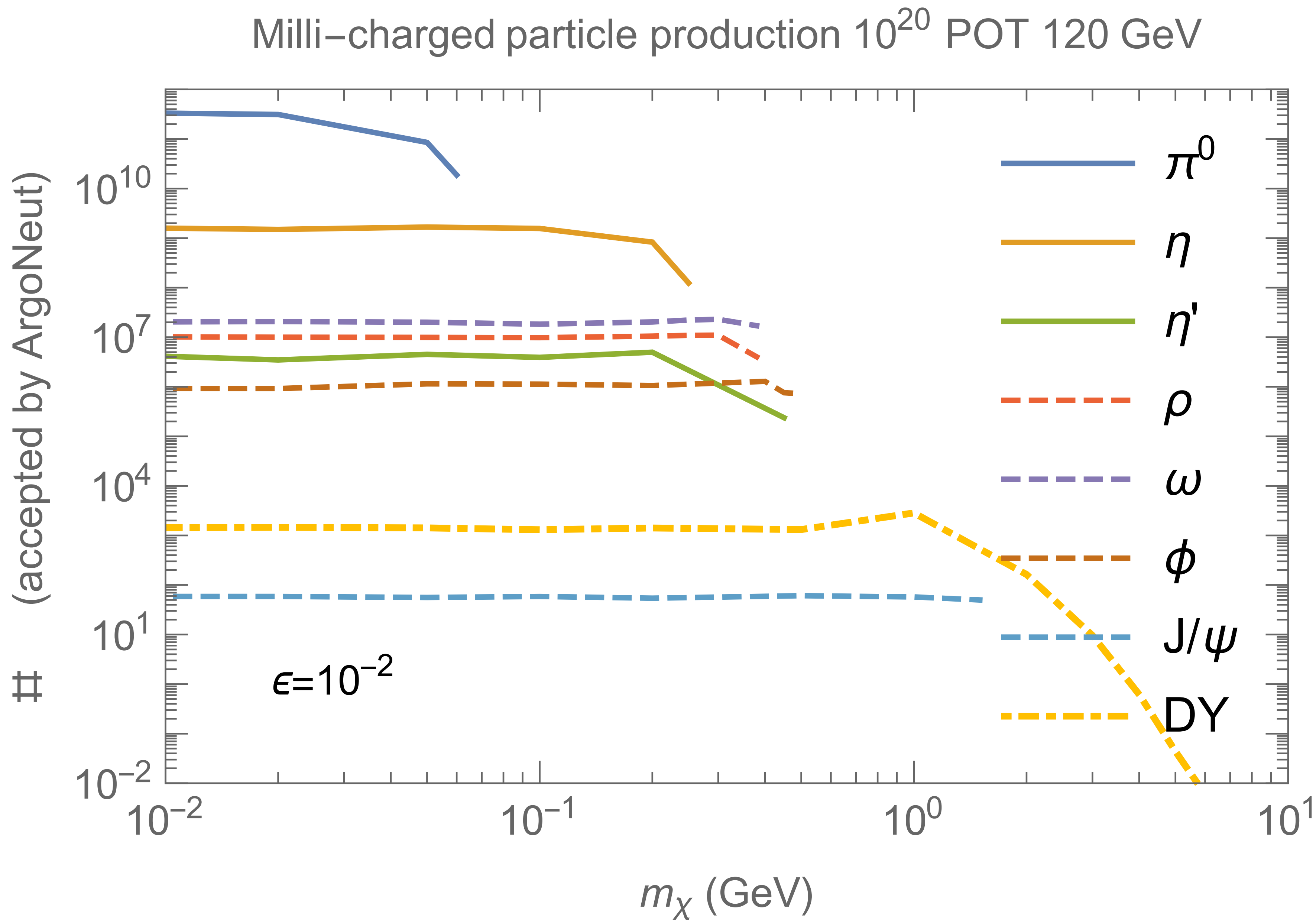


sketch by Yu-Dai

- Consider **ArgoNeuT**: A Small LAr TPC in NuMI.

~ 0.5 m × 0.5 m × 1 m, 10^{20} POT

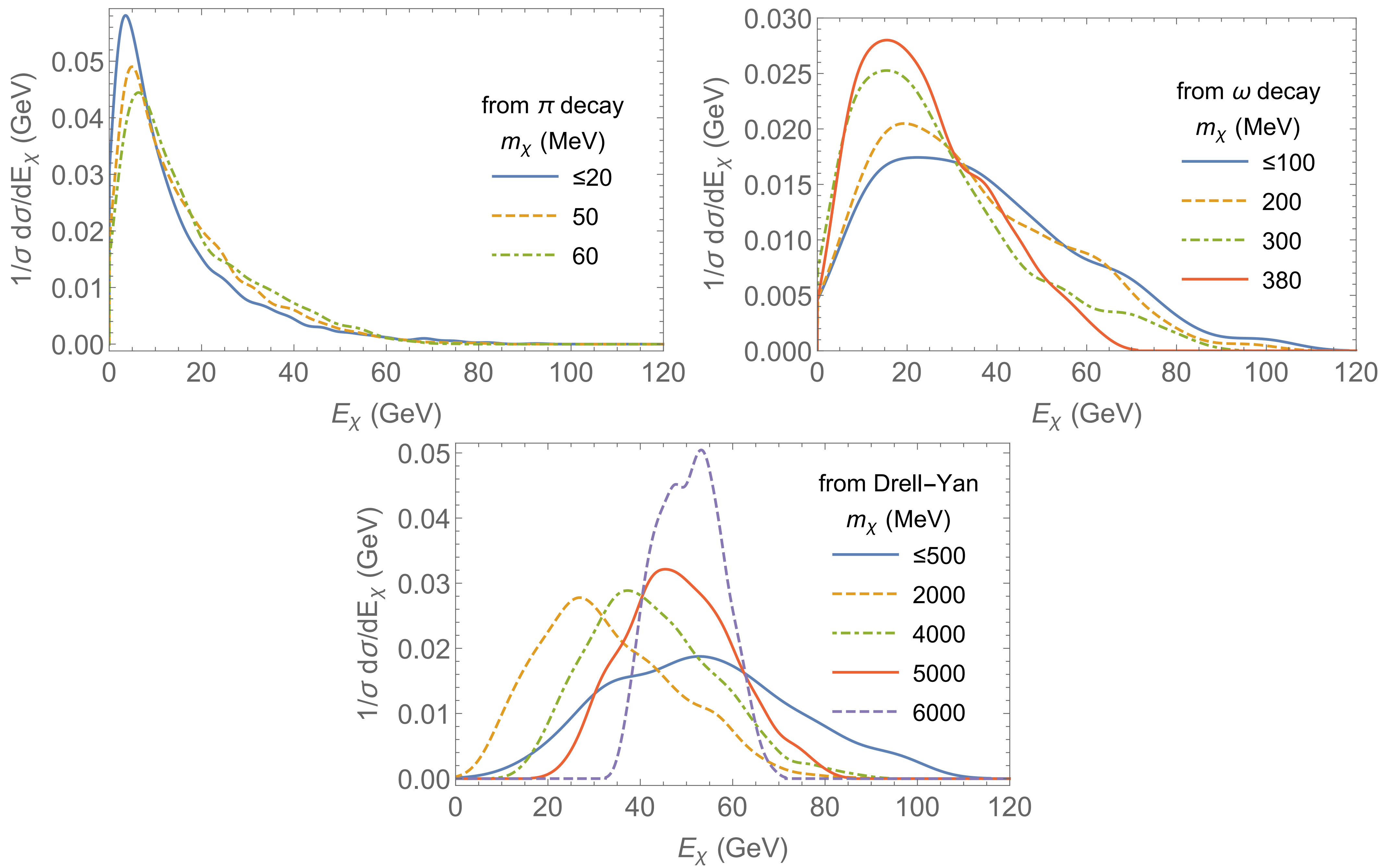
Production



Many many mCPs!!

thanks Pythia.

Production



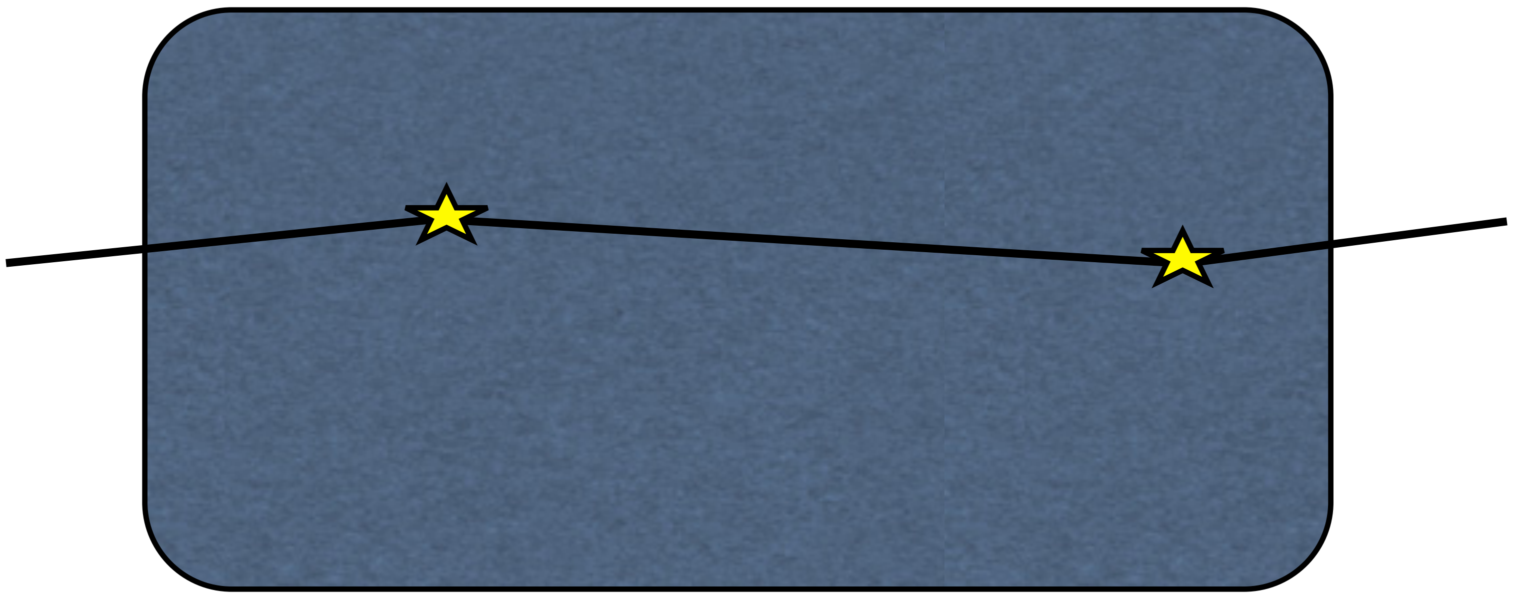
mCPs produced boosted, w/ energy ~ 5- 50 GeV.

thanks Pythia.

Milli-Charge Interactions

- What do milli-charged do in matter?
- Same as charged particles. Ionize, Scintillation...
- But they do it in "slow motion".

Most "hits" are soft.



$$\frac{d\sigma}{dE_r} \propto \frac{\varepsilon^2}{E_r^2}$$

$$\sigma(E_{th}) \propto \frac{\varepsilon^2}{E_{th}}$$

Matter Effects

- En route to the detector, mCPs travel through ~500 meters of dirt.
- A random walk of soft scatterings (off nuclei) leads to small **angular deflection**

$$\Delta\theta_\chi \sim \langle\theta_\chi\rangle\sqrt{N_{\rm col}}$$

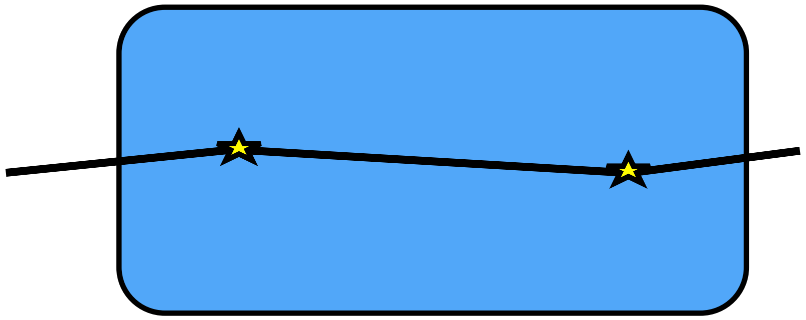
= average deflection per collision. × sqrt # of collisions.

$$\sim 2\times 10^{-3}\left(\frac{5\ \text{GeV}}{E_\chi}\right)\left(\frac{\epsilon}{10^{-2}}\right)\left(\frac{L_{\rm dirt}}{500\ \text{meters}}\right)^{1/2}$$

The mCPs point back to the target.

Detecting mCPs

$$\frac{d\sigma}{dE_r} \propto \frac{\varepsilon^2}{E_r^2} \qquad \sigma(E_{th}) \propto \frac{\varepsilon^2}{E_{th}}$$

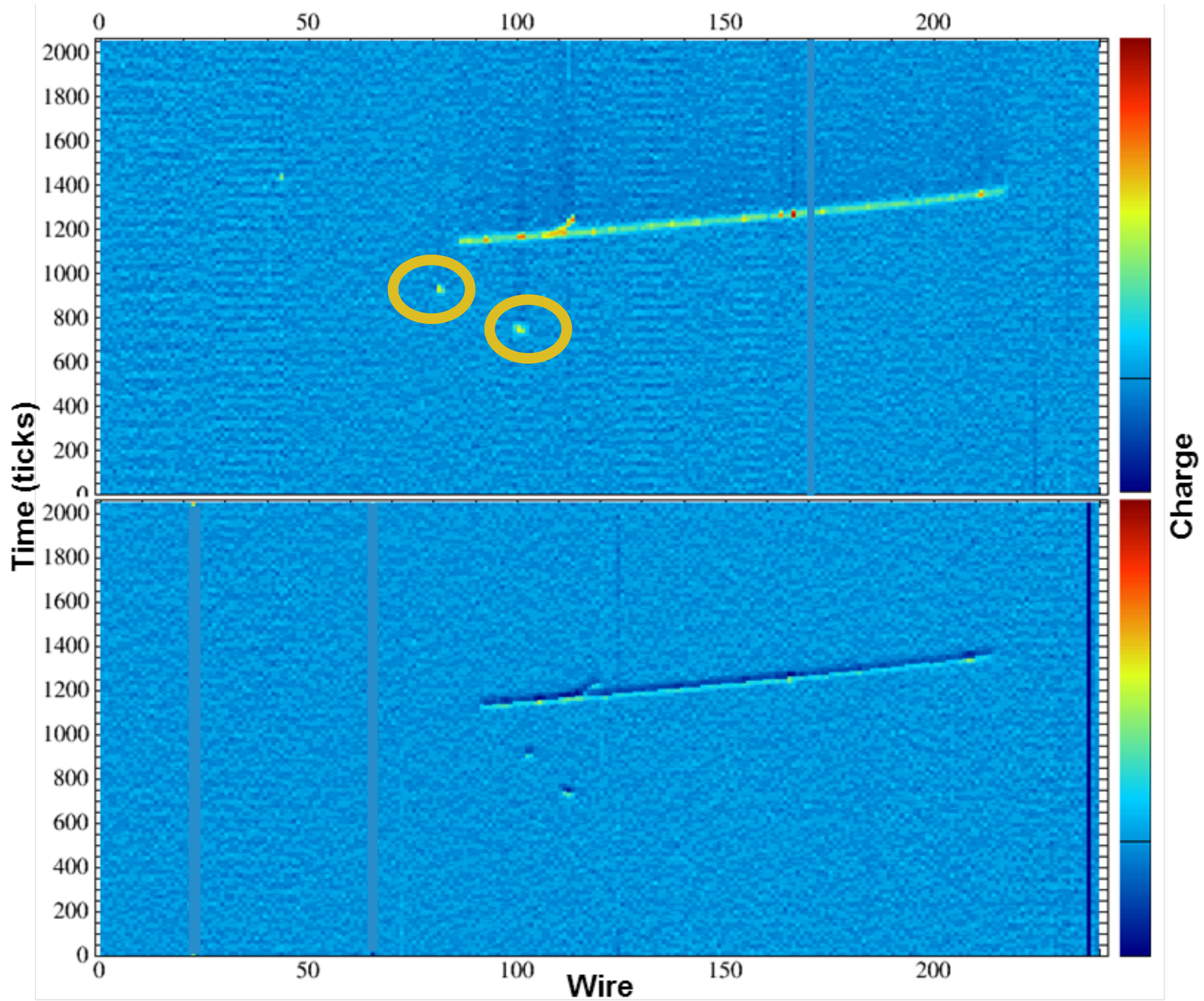


Again, most "hits" are soft.

Lower threshold is better.
How low can LAr go?

Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT

arXiv:1810.06502v1 [hep-ex] 15 Oct 2018



Detection of de-excitation γs and neutrons.

find a detection efficiency of 50% and energy resolution of 24% at 0.5 MeV, and an efficiency of almost 100% and energy resolution of 14% at 0.8 MeV.

see also Nov 30th wine and cheese talk by I. Lepetic and Palamara's talk on Friday.

mCP Signal in ArgoNeut

$$\lambda(E_r^{\min}) = \frac{1}{Z n_{\rm det}\sigma(E_r^{\min})} \simeq \left(\frac{10^{-2}}{\epsilon}\right)^2 \left(\frac{E_r^{\min}}{1\ \text{MeV}}\right) 1\ \text{km}.$$

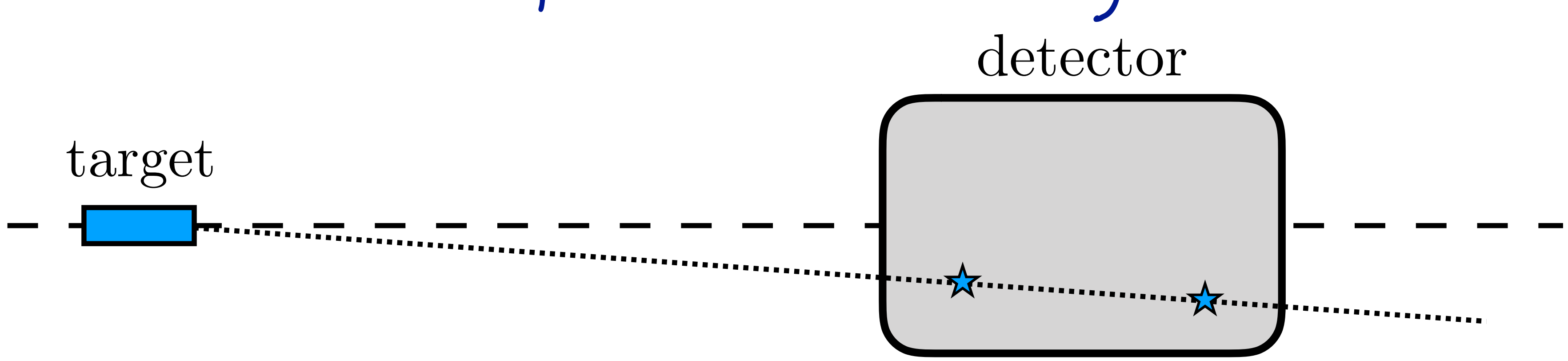
for $\varepsilon = 10^{-2}$: 1 in 10^3 mCPs hit once.

1 in 10^6 mCPs hit twice.

...

(recall, for $\varepsilon \sim 10^{-2}$ we can have billions of mCPs)

Double hits point back to target:



mCP search in ArgoNeuT

- For ArgoNeuT's 10^{20} POT run, most events were "empty frames" (no neutrino).
  A few x 10^6

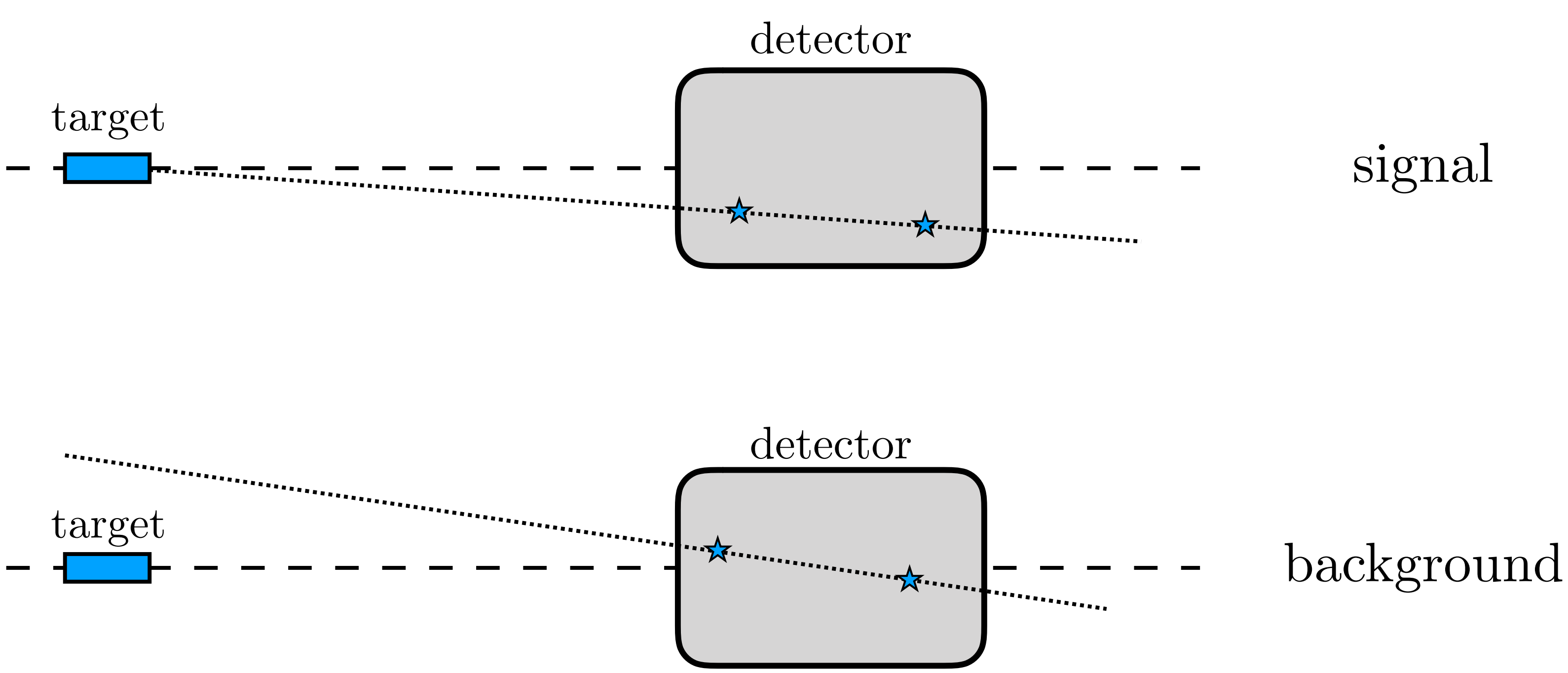
- Control sample → signal region!

- **Of empty frames:**
  12% had one MeV hit.
  About 1% had two MeV hits.
  ...

A <u>large</u> background.
Orders of magnitude more than ν BG.

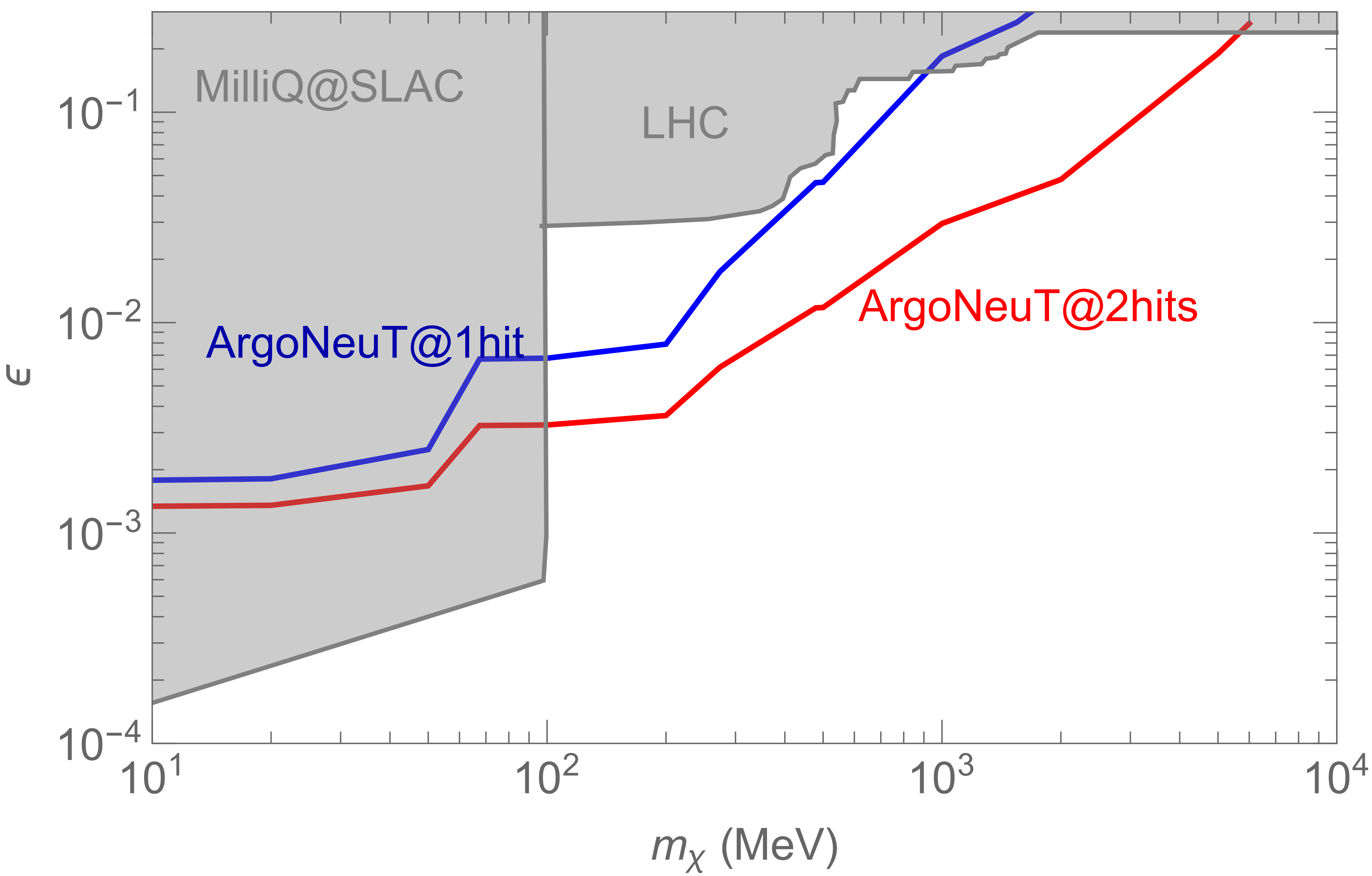
1 vs 2 hits

- Excellent spatial resolution → BG can be reduced by requiring alignment with target.



In going from 1 to 2 hits, BG can be reduced by 10^5 or more!

ArgoNeuT Sensitivity



An ArgoNeuT analysis is underway.

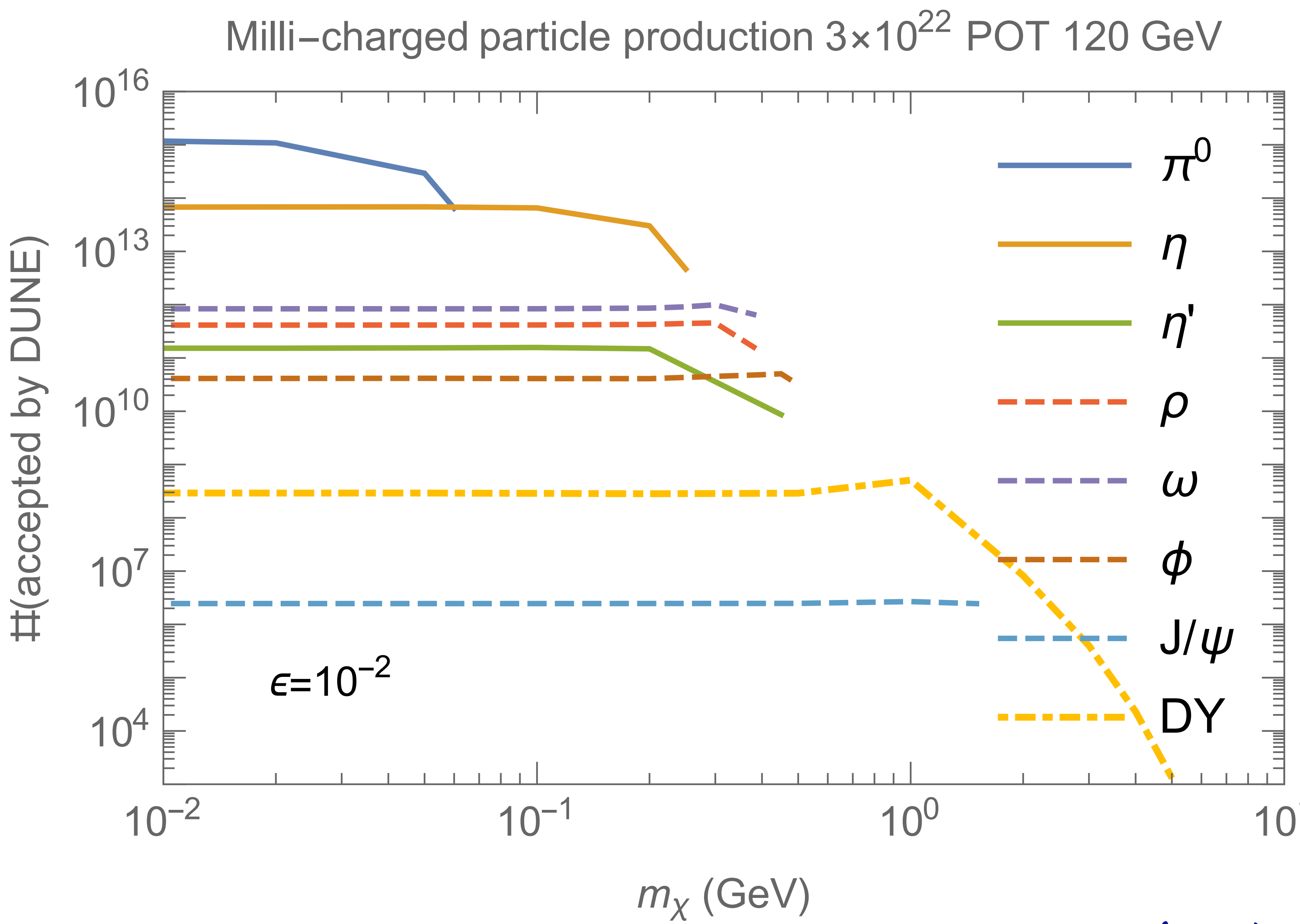
How will this scale for

DUNE ND

?

Production in DUNE

- Detector is a bit closer.
  Different angular coverage.



many many mCPs!

BG at DUNE

- Two benchmarks to scale BG's to DUNE:

  1) ArgoNeuT rate x volume factor.

  2) ArgoNeuT rate x volume x POT. (beam related BG)

  30 - 300 hits per frame..... plus a few neutrino events.

  (10^9-10^{10} total hits. a **very** big background.)

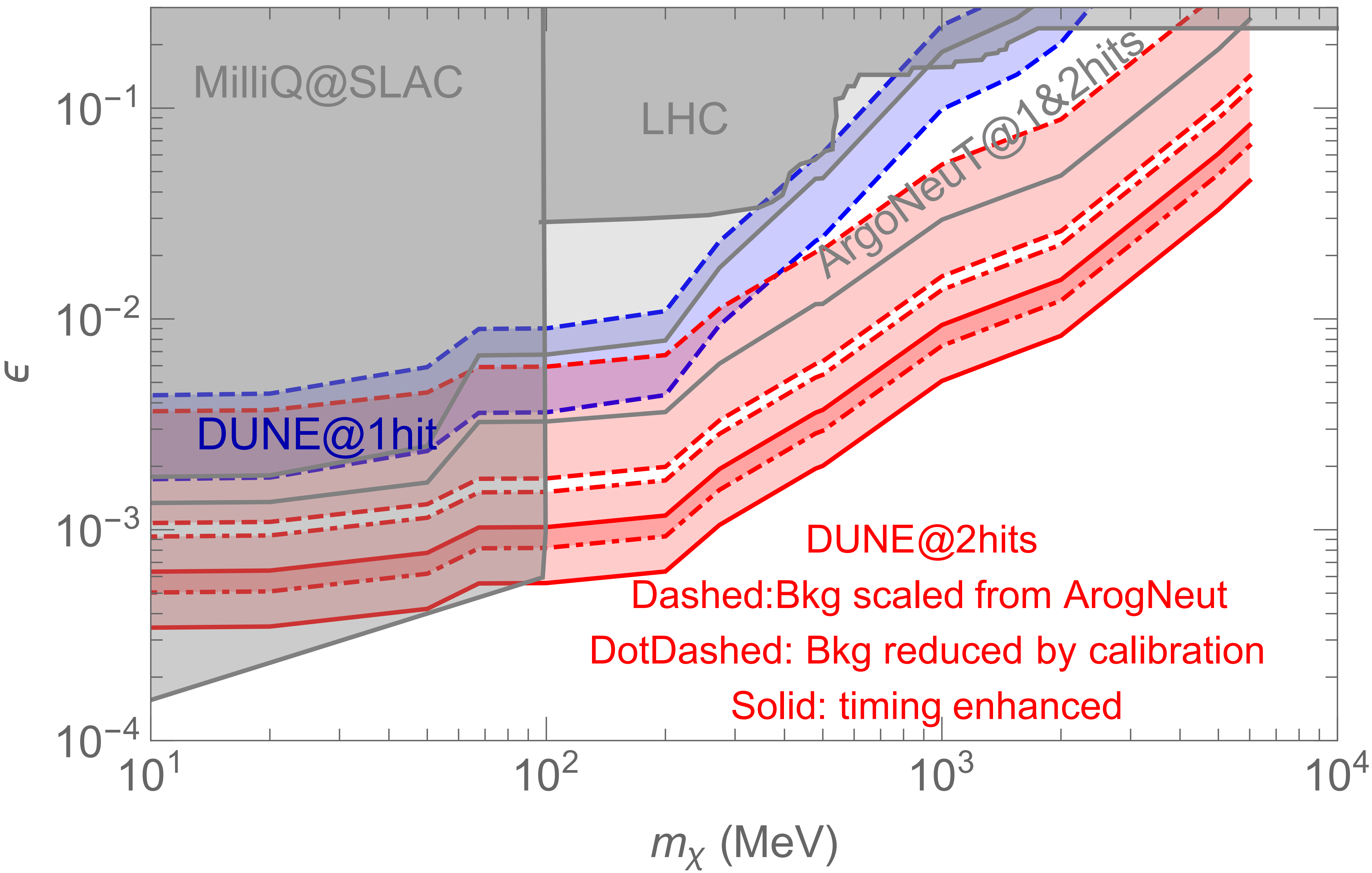
- In our projections we show bands that cover the range of these two benchmarks.

BG at DUNE

- Note: the number of pairs of hits scales as n^2. That is 500-50000 pairs per frame. Diminishing returns for 2-hits?
- **But**: The angular distribution may be a handle. statistical BG uncertainty. $B \to \sqrt{B}$.
- But, occupancy may be reduced with timing using light. Say by a factor of 100.

We study the reach for these 3 options ...

Projections for DUNE



HP Gas Detector

- The HPgTPC will have lower threshold.

$$\lambda(E_r^{\min}) = \frac{1}{Z \underbrace{n_{\rm det}}_{\text{lower}} \underbrace{\sigma(E_r^{\min})}_{\text{higher}}}$$

Signal rates in HPgTPC are parametrically the same as LArTPC.

- But backgrounds may be lower....

Off Axis

- The soft hit background may be beam related and induced by charged pions. May be focused.
- The mCP beam is wide.
- Going off axis may enhance S/B.
- MicroBoone and ICARUS may be ideally located off the NuMI beam.
- DUNE PRISM for LBNF

Applies to a broadest of models (see next talk!)

Dedicated mCP Reconstruction

- A dedicated effort to reconstruct "faint tracks" may allow to lower thresholds.
- Standard analyses start by identifying localized hits above noise floor.
- Looking for an excess above noise along lines may allow to integrate noise down.

none of these hits above noise locally...

but combined charge+light may be above noise along line.

Conclusions

- The ArgoNeuT demonstration of sensitivity to MeV depositions enables searches for new physics.
- Can set new limits on mCPs with exiting data using double hits.
- Interesting prospects for the DUNE ND.

PONDD INDEEDD.