Searching for Hidden Sectors via the Vector Portal

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SLAC Experimental Seminar
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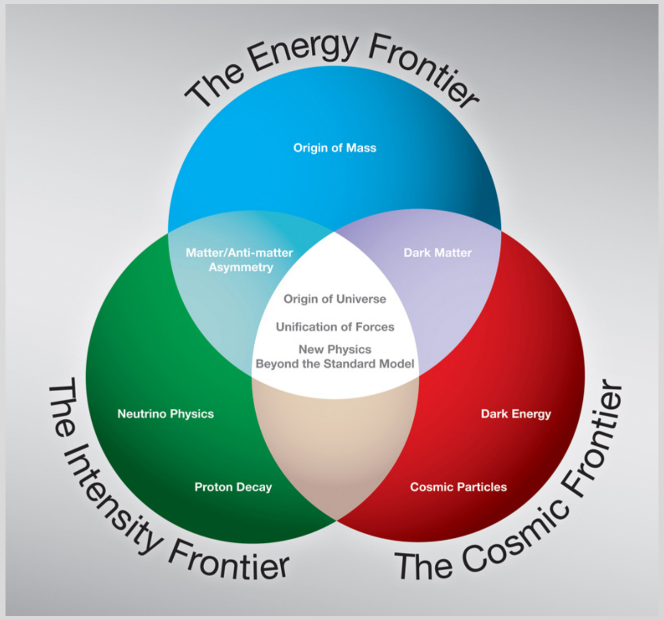
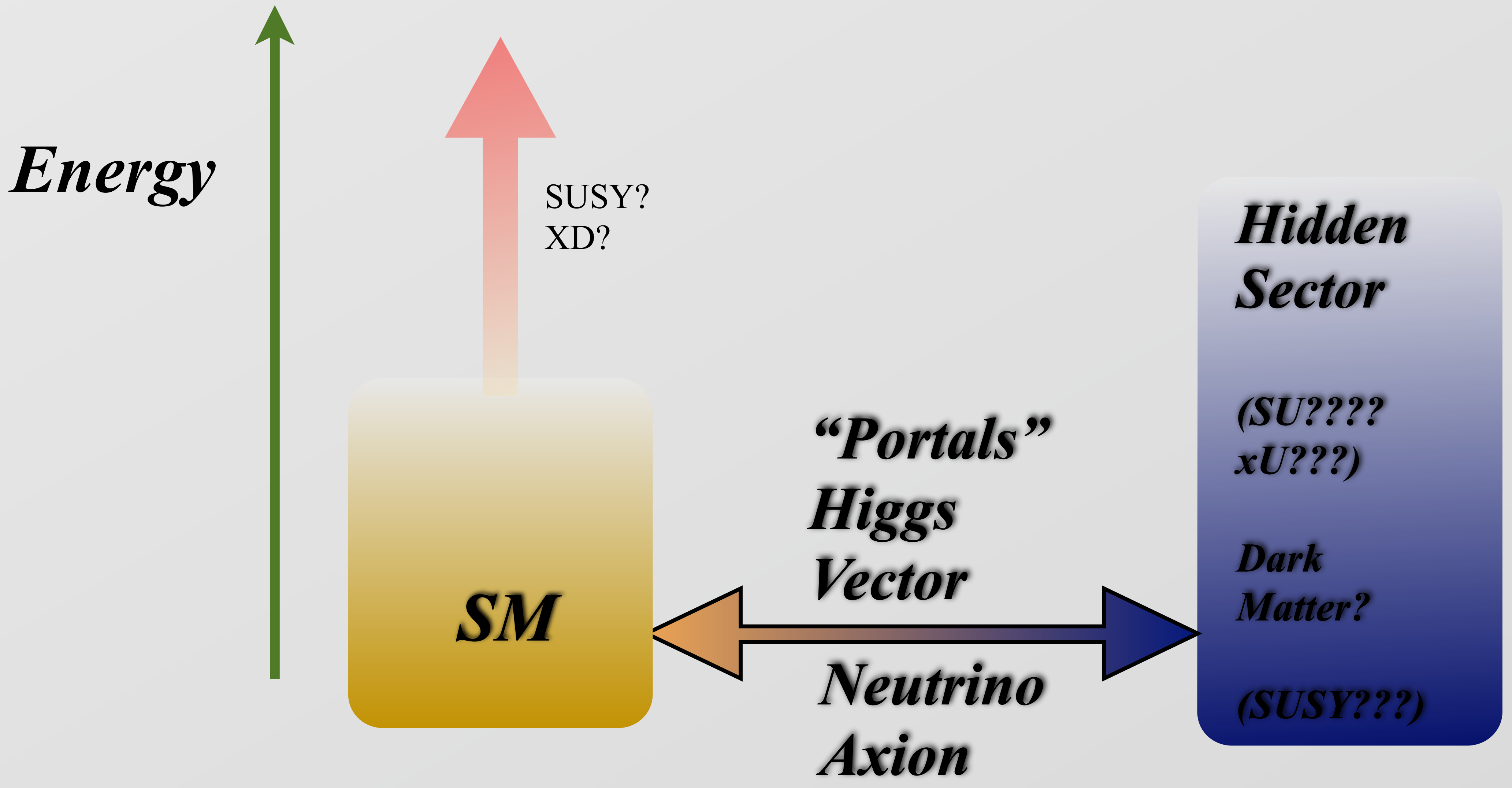
Introduction, Outline, Disclaimers…

- The goals of this talk are three-fold
  - Convince you (again? even more?) that searches for hidden sectors are interesting & worthwhile (and not crazy at all)
  - Update you on heavy photon & beam-based neutrino groups' activities
    - HPS (& APEX), LBNE, microBoone
  - Attempt to convince you that there are some interesting physics links between the two programs
  - Discuss some (possible) future directions
- Much of the material comes from Snowmass & followups
  - This topic was mostly discussed in the NLWCP subgroup
    - NLWCP=New Light, Weakly Coupled Particles



New Physics on the Side



$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{HS}} + \mathcal{L}_{\mathrm{portal}}$$

Portals to a hidden sector

$\underline{\mathcal{L}_{\text{portal}}}$

Higgs portal $\longrightarrow$ $\epsilon_h |h|^2 |S|^2$ $\longrightarrow$ rare higgs decays

neutrino portal $\longrightarrow$ $\epsilon_\nu (hL)\psi$ $\longrightarrow$ "sterile neutrino"

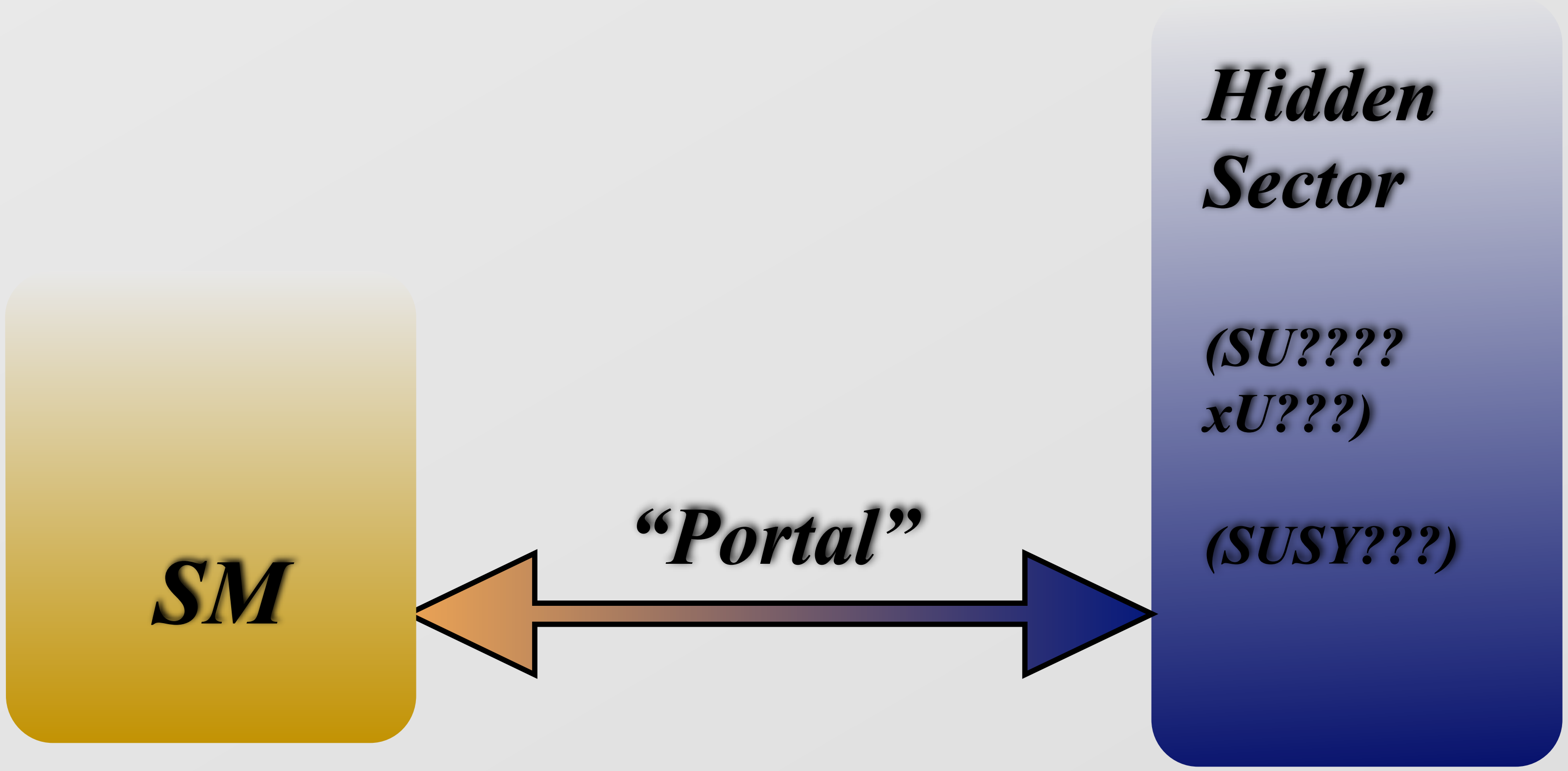
vector portal $\longrightarrow$ $\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$ $\longrightarrow$ massive "photon"

axion portal $\longrightarrow$ $\frac{1}{f_a} a_h F_{\mu\nu} \tilde{F}^{\mu\nu}$ $\longrightarrow$ axion-like particle

Experimental hidden sector probes

	$\underline{\mathcal{L}_{\text{portal}}}$	
Higgs portal $\longrightarrow$	$\epsilon_h \lvert h\rvert^2 \lvert S\rvert^2$	$\longrightarrow$ higgs factory
neutrino portal $\longrightarrow$	$\epsilon_\nu (hL)\psi$	$\longrightarrow$ ν oscillations/very rare meson decays
vector portal $\longrightarrow$	$\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$	$\longrightarrow$ everywhere (almost)
axion portal $\longrightarrow$	$\frac{1}{f_a} a_h F_{\mu\nu} \tilde{F}^{\mu\nu}$	$\longrightarrow$ axion searches

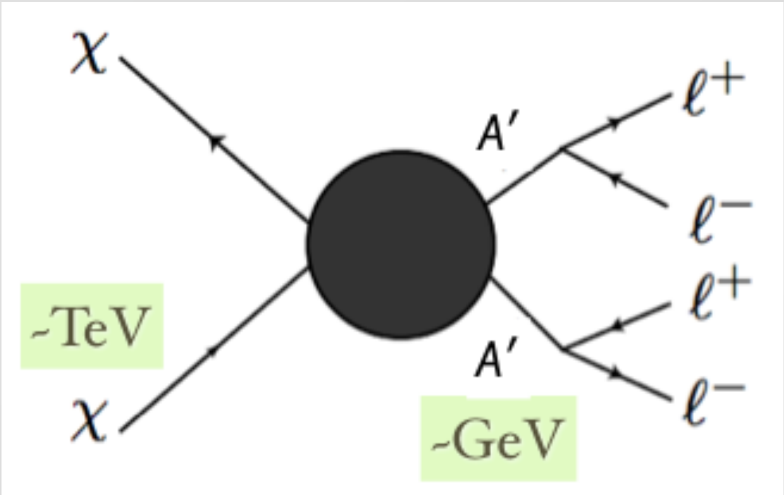
Hidden Sector ⇒ Dark Matter?



link between SM and hidden sector is weak…good place for DM to hide!

WIMP miracle⇒wiMP miracle

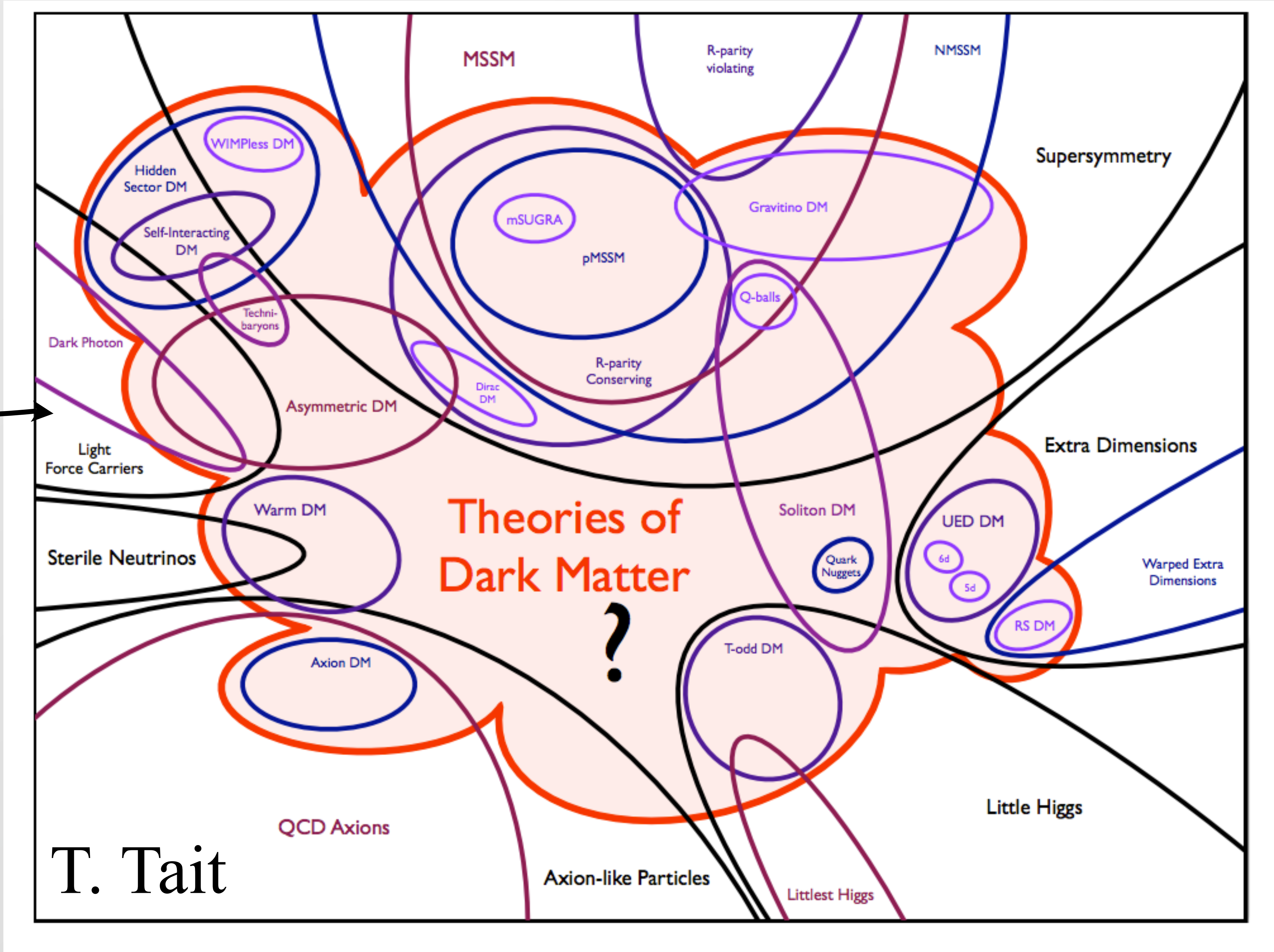
N. Arkani-Hamed *et al.*, PRD **79**, 015014 (2009).



M. Pospelov and A. Ritz, Phys. Letters B **671**, 391 (2009).

My favorite Venn diagram from Snowmass

Here we are



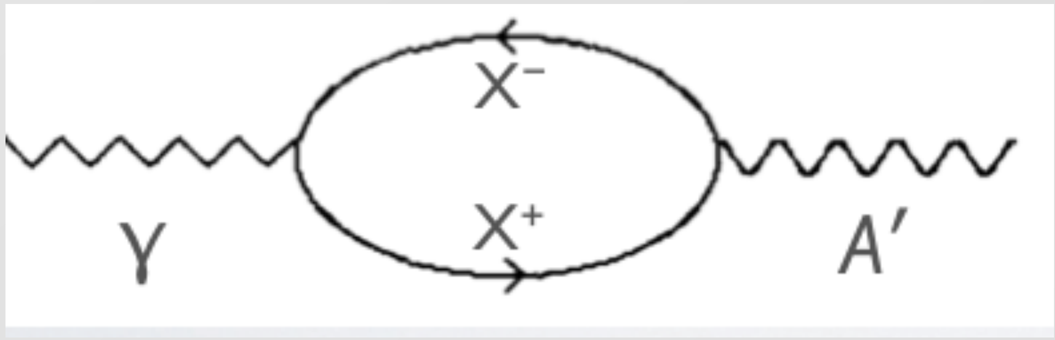
U(1)´ and kinetic mixing

an old idea: if there is an additional U(1) symmetry in nature, there will be mixing between the photon and the new gauge boson

Holdom, Phys. Lett B166, 1986

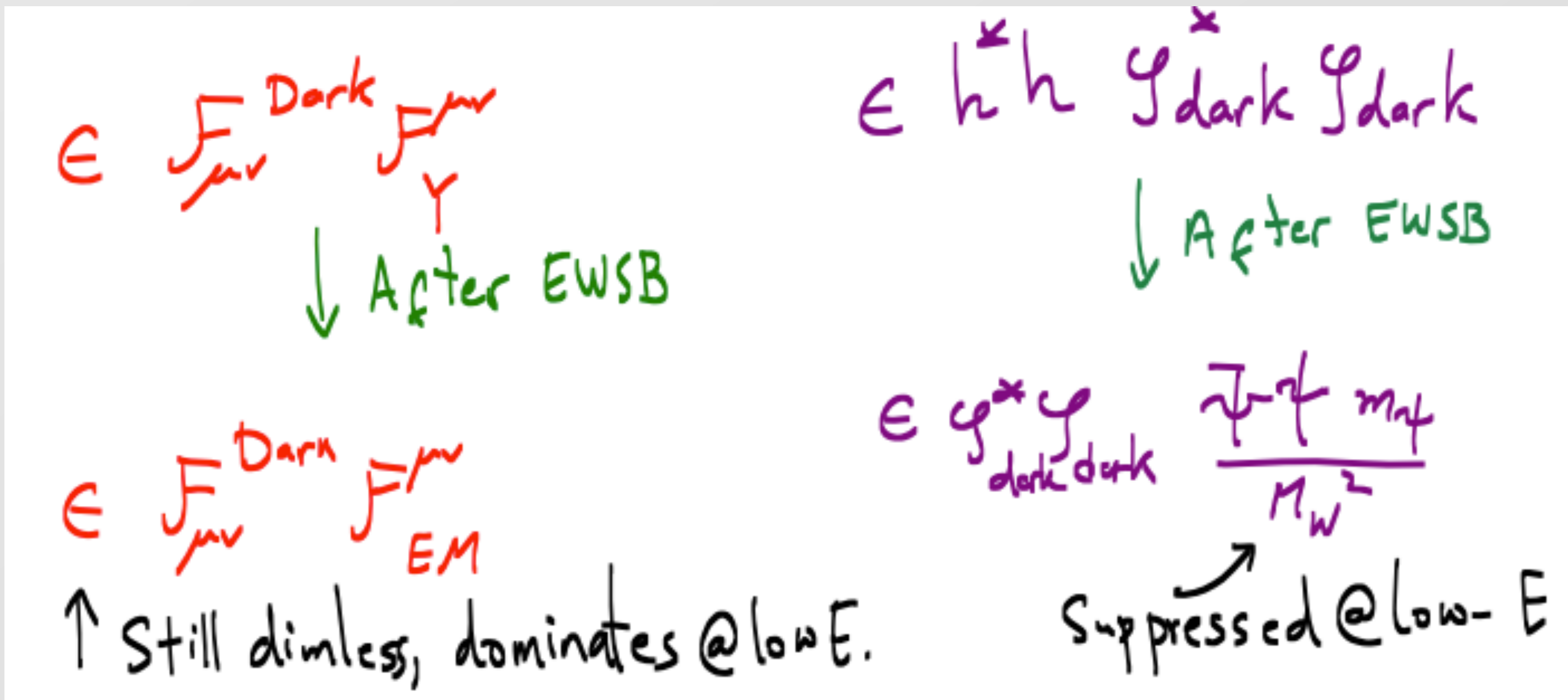
$$\mathcal{L}_{U(1)'} = -\frac{1}{4}V_{\mu\nu}^2 - \boxed{\frac{\epsilon}{2}V_{\mu\nu}F^{\mu\nu}} + |D_\mu\phi|^2 - V(\phi)$$

Kinetic Mixing term



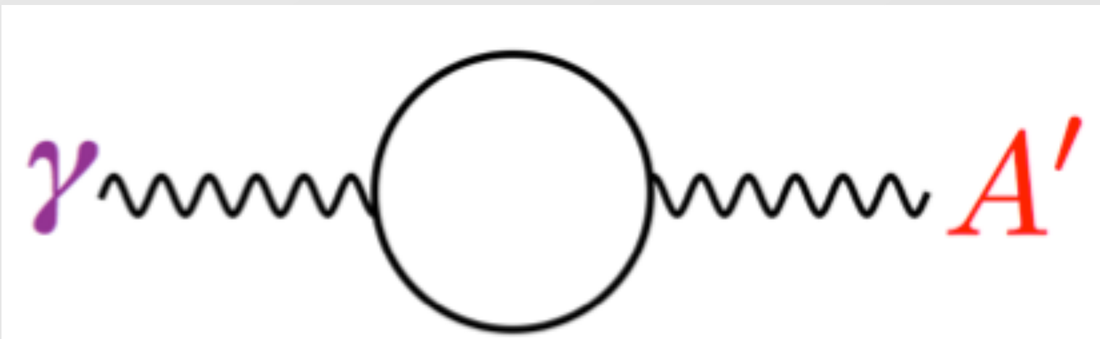
- extremely general conclusion...even arises from broken symmetries
- gives coupling of normal charged matter to the new "heavy photon" q=εe

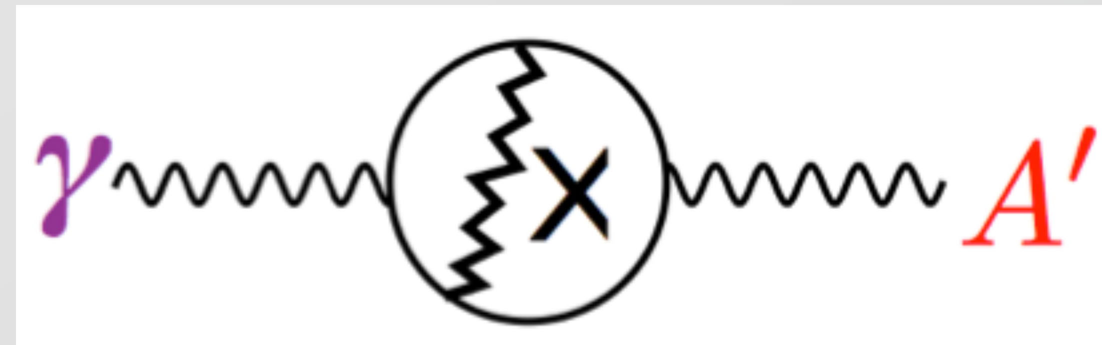
Why the vector portal is special



…from somebody's slide at the NLWC closeout session….

"Natural" coupling and mass





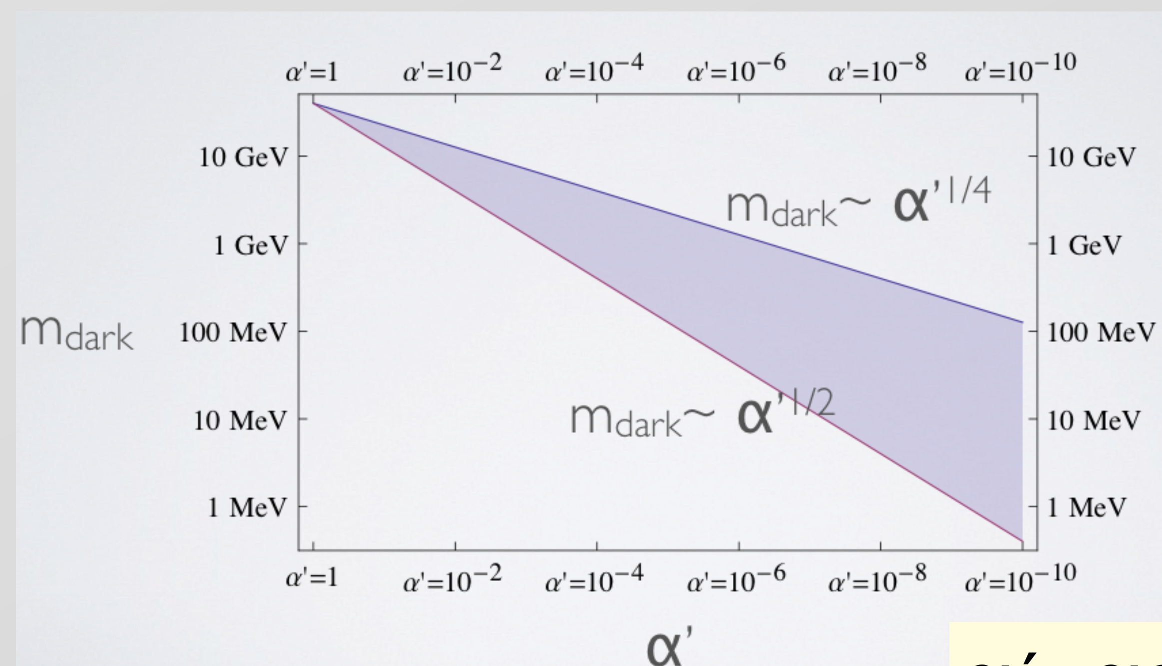
$$\epsilon \sim 10^{-3} - 10^{-2} \xrightarrow[\text{symmetry}]{\text{enhanced}} \epsilon_{GUT} \sim 10^{-5} - 10^{-3}$$

Depending on model, mass scales like:

M(A′)/M(W)~ε^{1}-$\varepsilon^{1/2}$

leading to

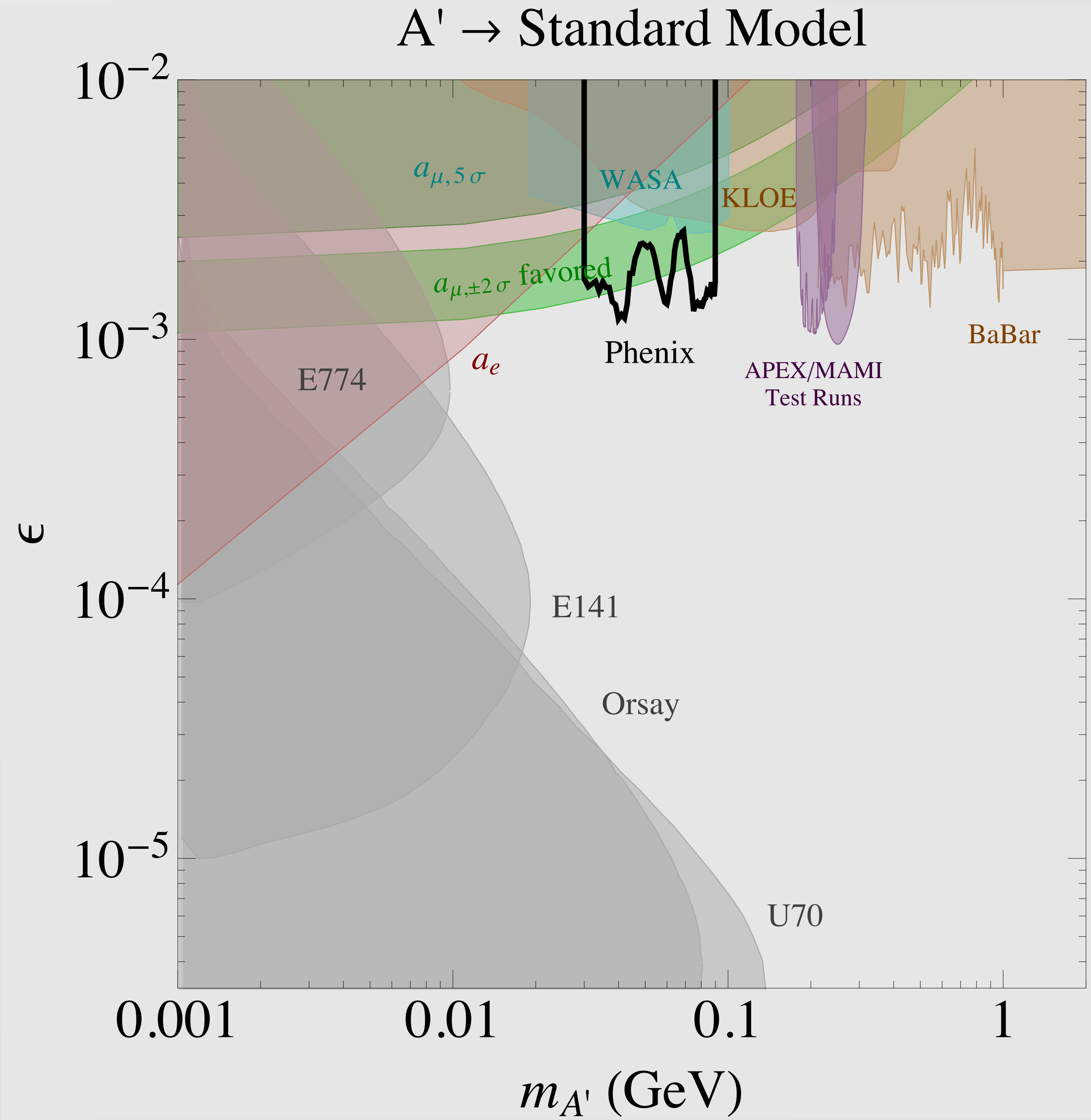
M(A′)~MeV-GeV



N. Weiner, JLAB PAC37 Talk

$\alpha' = \alpha\varepsilon$

The coupling-mass sweet spot



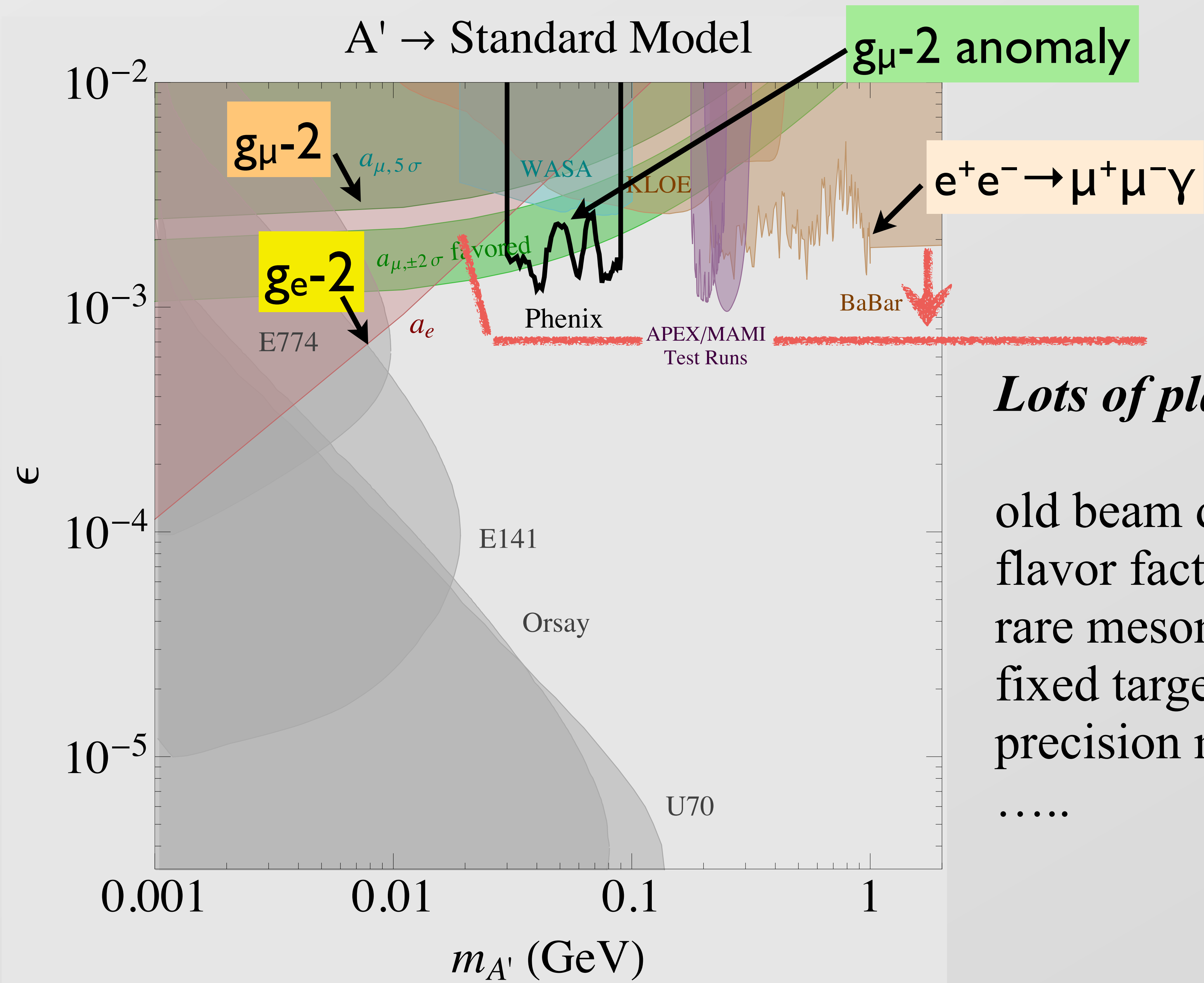
Both "naturalness" arguments and hints from experiments block out the same region in mass-coupling space:

$\varepsilon \sim 10^{-2} - 10^{-5}$

$m(A') \sim$ MeV – GeV

Most of this region is unexplored!

Some existing constraints (A′ → visible)



Lots of places to look for the A′

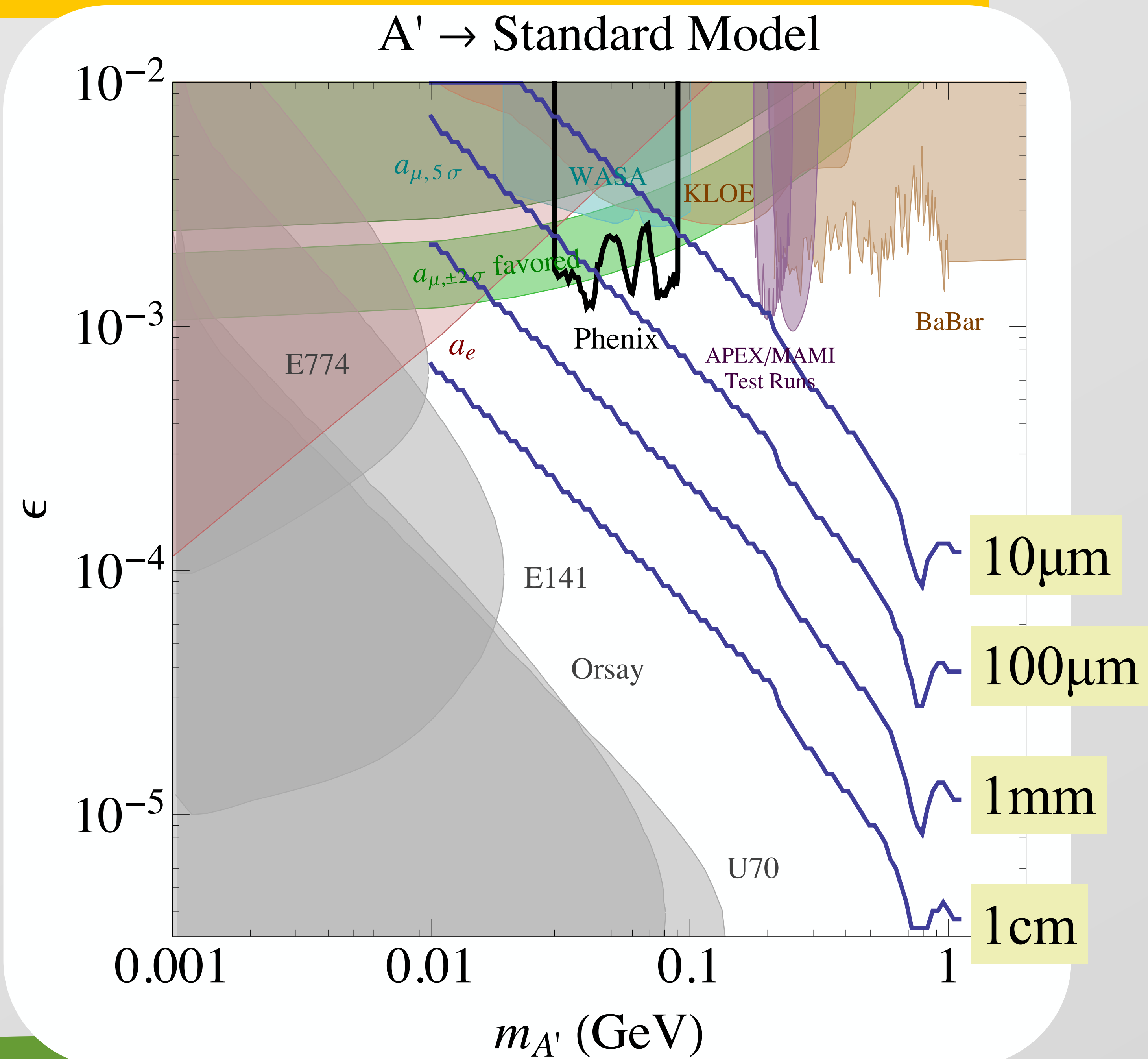
old beam dumps *(EXXX)*
flavor factories *(BaBar/Belle/KLOE)*
rare meson decays *(WASA,Phenix)*
fixed target expts. *(APEX/MAMI)*
precision measurements *(g-2)*
…..

A' decay length

$$\ell_0 \equiv \gamma c\tau \simeq \frac{3E_1}{N_{\text{eff}} m_{A'}^2 \alpha \epsilon^2}$$

$$\simeq \frac{0.8\text{cm}}{N_{\text{eff}}} \left(\frac{E_0}{10\text{GeV}}\right)\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{100\,\text{MeV}}{m_{A'}}\right)^2$$

lower ε, lower mass
→ longer lifetime

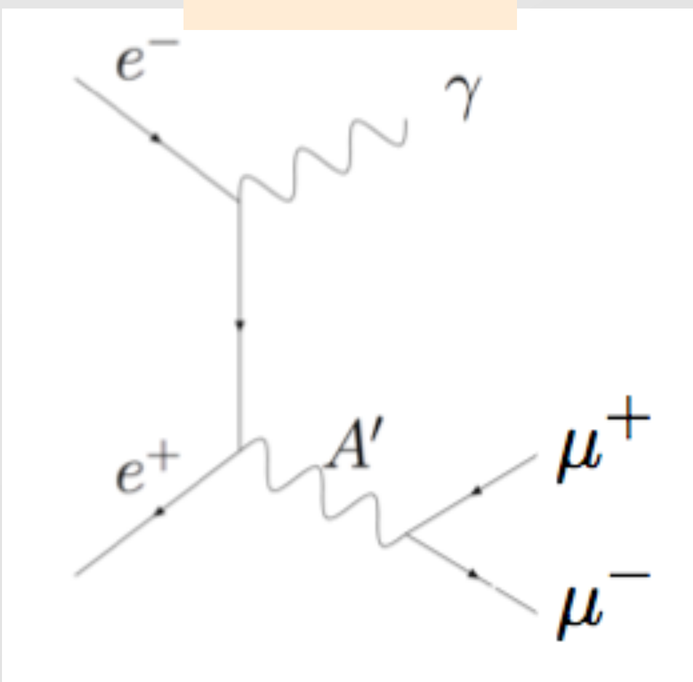


Much of parameter space will have displaced vertex

Collider vs. Fixed Target

Wherever there is a photon there is a dark photon...

Collider

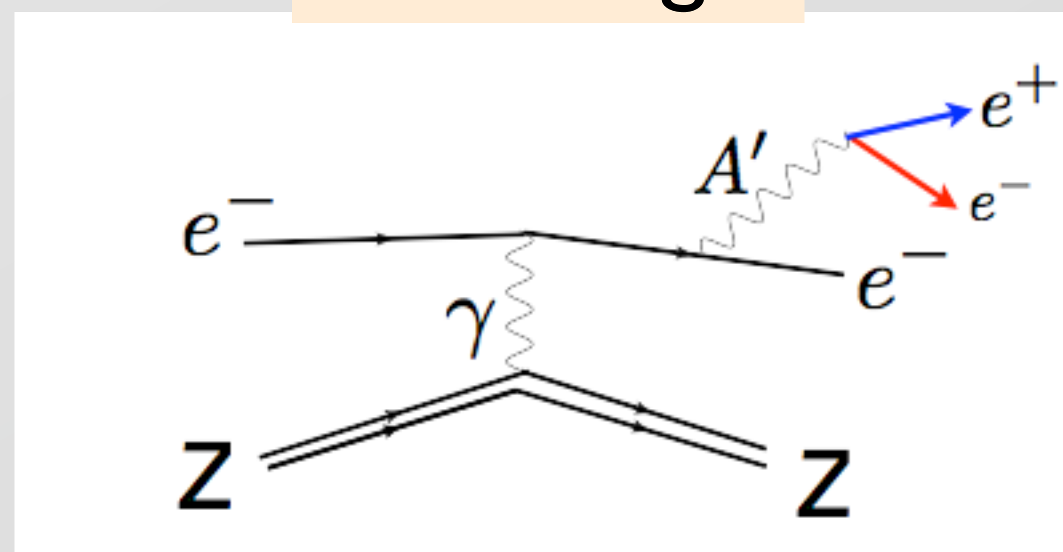


$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

$$O\ ab^{-1} \text{ per } \cancel{\text{decade}}$$

month

Fixed Target

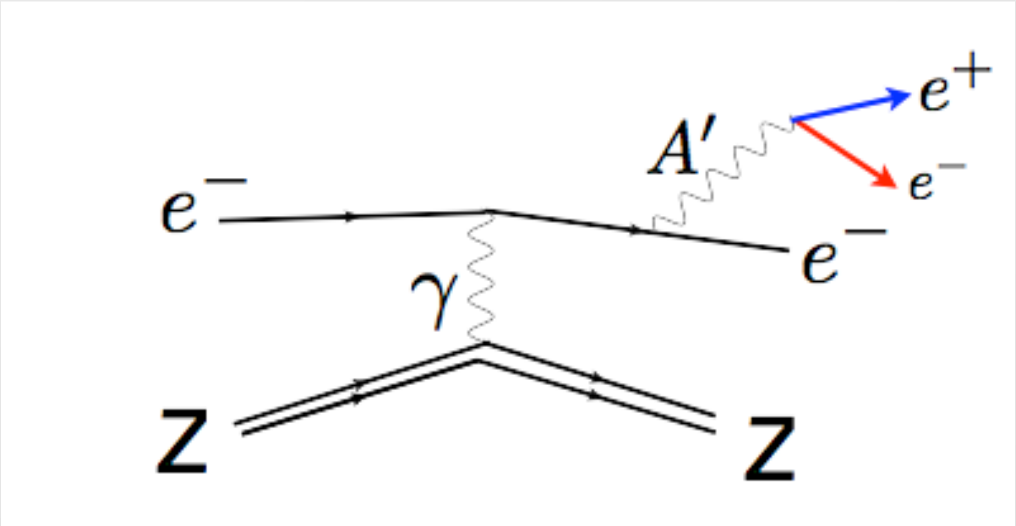


$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

$$O\ ab^{-1} \text{ per day}$$

...much higher backgrounds

A' production & decay



Production is analogous to bremsstrahlung:

$$\frac{d\sigma}{dx} \approx \boxed{\frac{8Z^2\alpha^3\epsilon^2 x}{m_{A'}^2}} \left(1 + \frac{x^2}{3(1-x)}\right) \mathcal{L}og$$

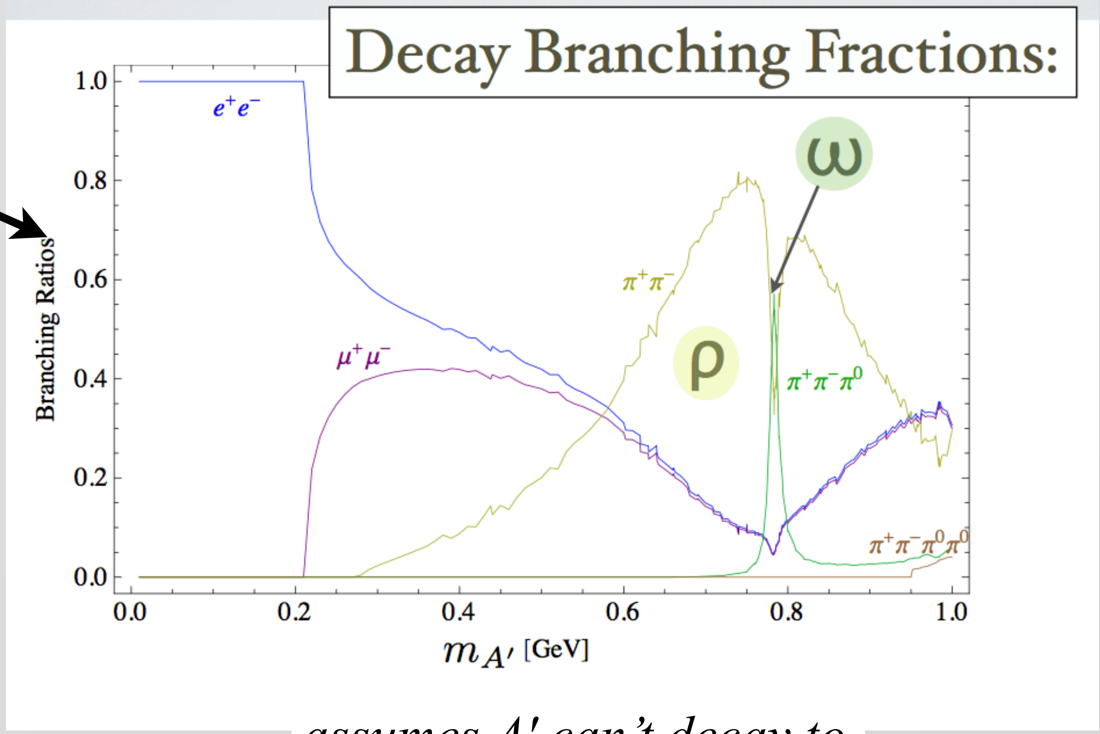
- prefers x~1 (i.e. $E_{A'} = E_{beam}$)
- small angle emission dominates

A' ***decays*** back to charged SM fermions with BFs taken from $R(e^+e^- \rightarrow \text{hadrons}/e^+e^- \rightarrow \mu^+\mu^-)$

The decay length depends on $m_{A'}$ and ε:

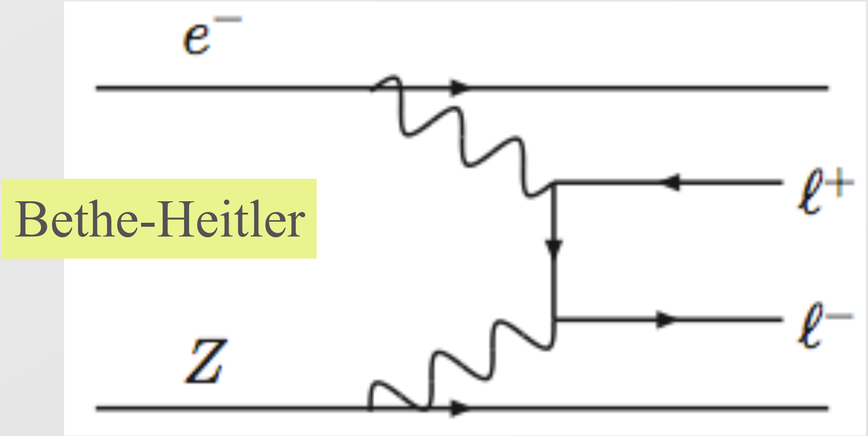
$$\ell_0 \equiv \gamma c\tau \simeq \frac{3E_1}{N_{\text{eff}} m_{A'}^2 \alpha \epsilon^2} \simeq \frac{0.8\text{cm}}{N_{\text{eff}}} \left(\frac{E_0}{10\text{GeV}}\right) \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\text{ MeV}}{m_{A'}}\right)^2$$

HPS is sensitive to A's with decays ~5-100mm

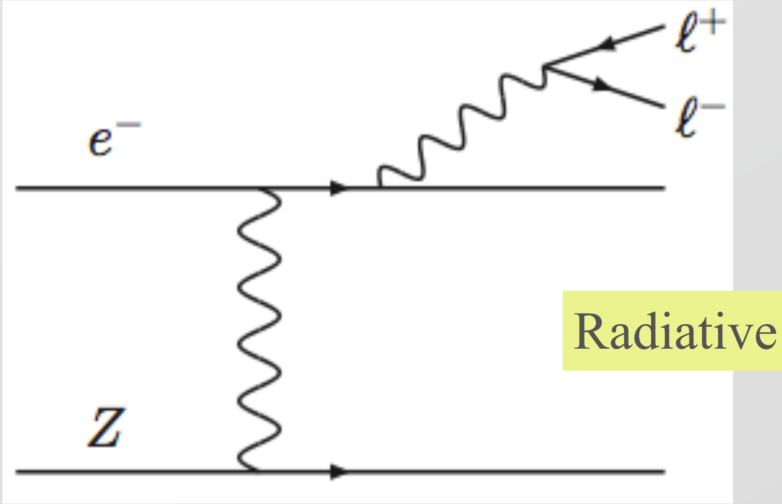


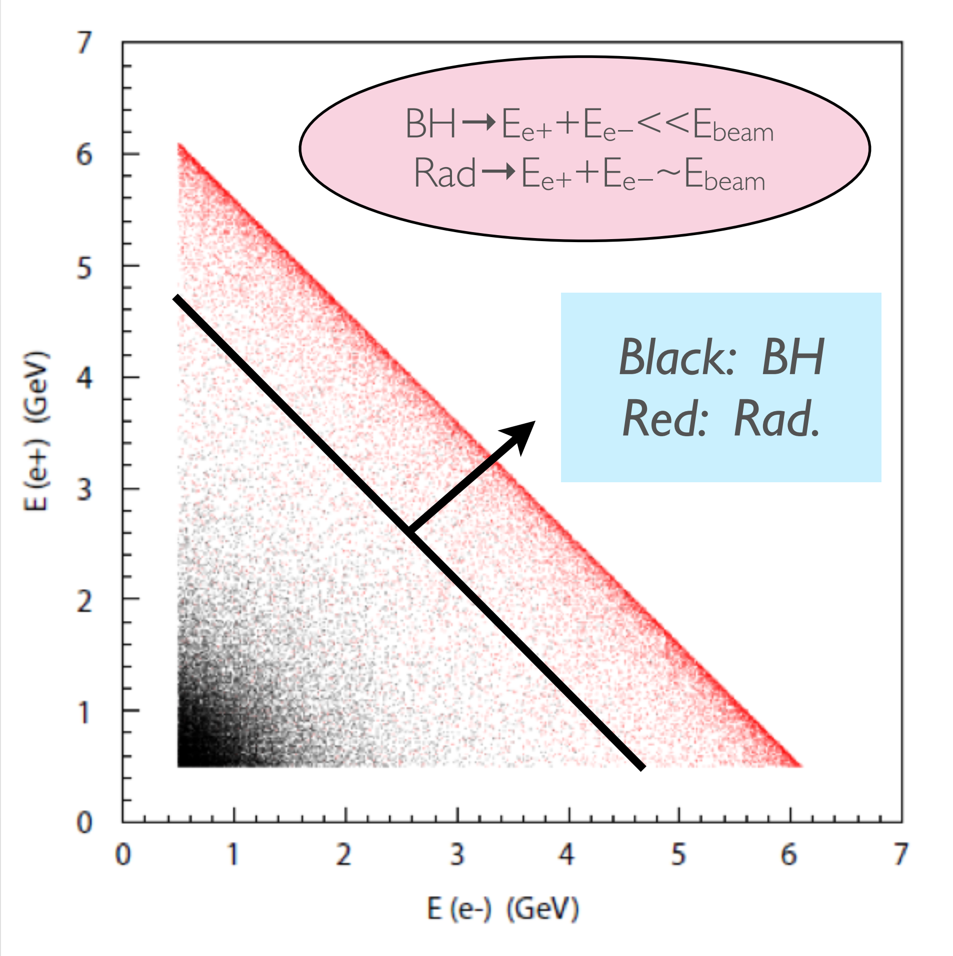
assumes A' can't decay to hidden sector particles

Backgrounds @ fixed target



Two physics backgrounds, collectively known as "tridents"





- BH and Radiative cross-sections calculated by MadGraph at NNLO
- BH cross section is huge, but dominated by $E(e^+)+E(e^-)<<E_{beam}$
  - this background is reducible, but still large (~2x radiative) after $E(e^+)+E(e^-)>0.8E_{beam}$
- Radiative tridents have the same kinematics as A' decays...only invariant mass & decay vertex can resolve these two
- All trident events decay promptly!

The HPS experiment

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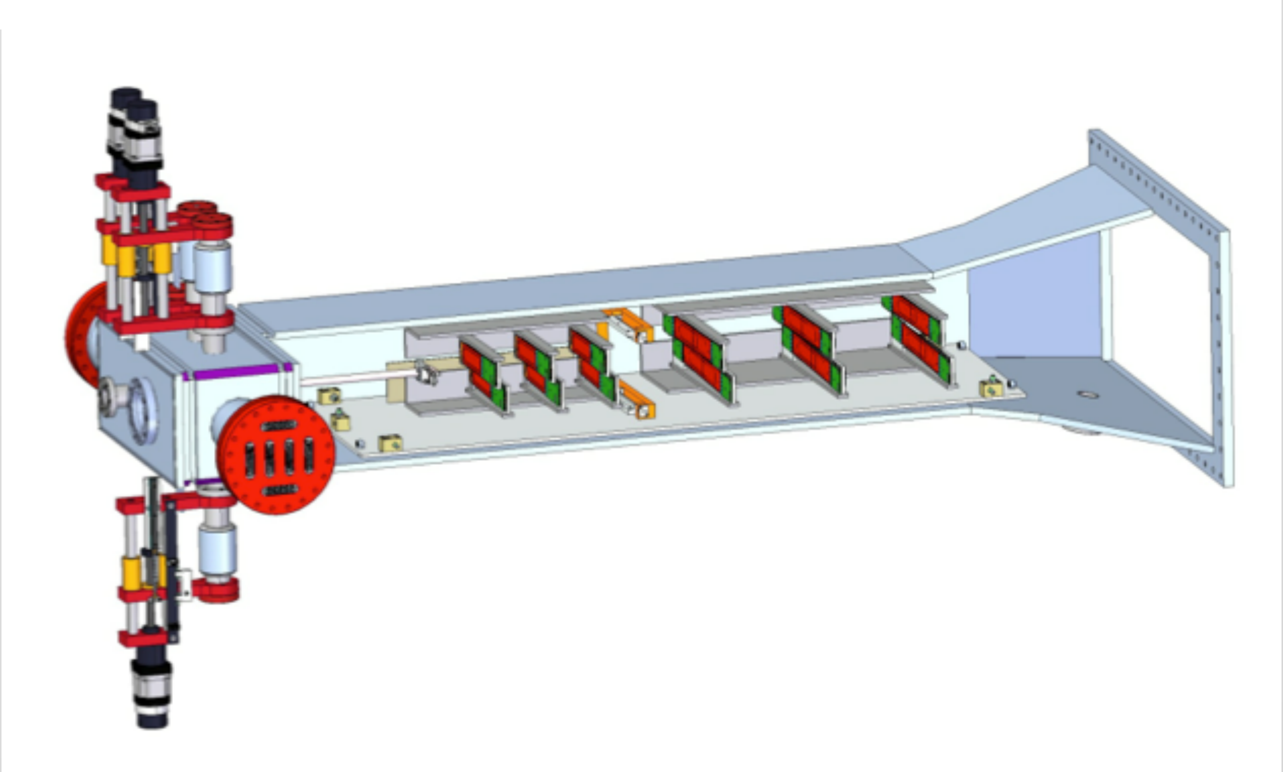
(Dated: May 10, 2013)

Broad-brush Responsibilities

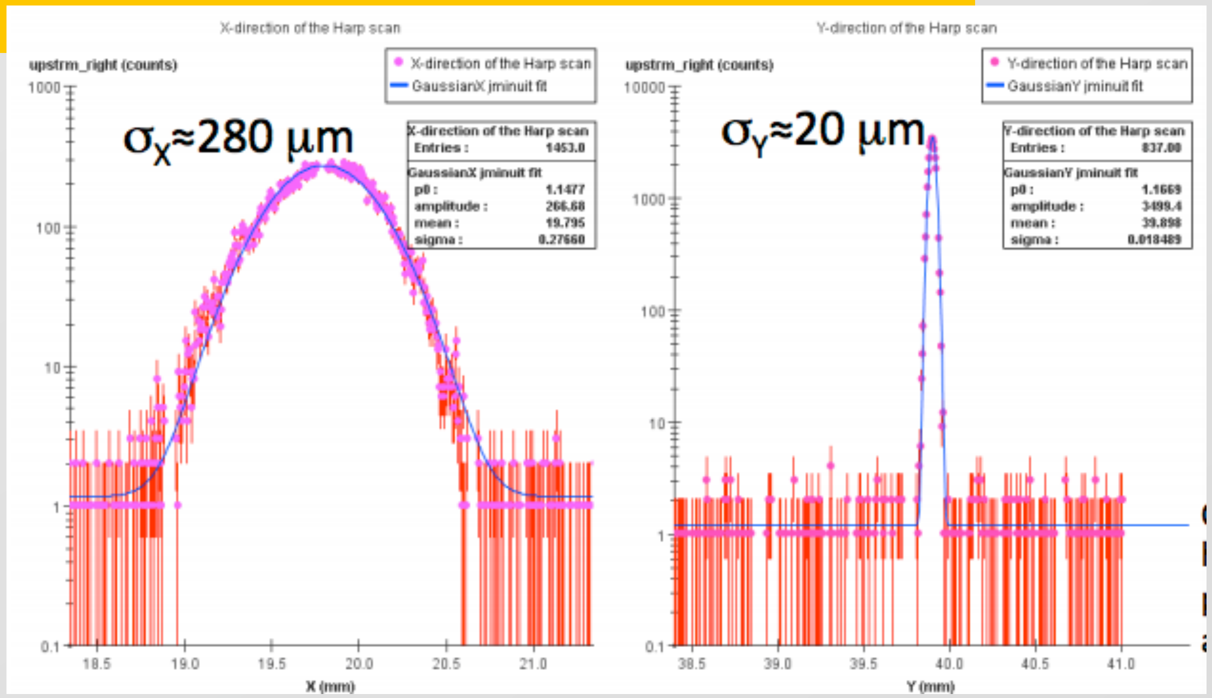
SLAC: SVT(daq), Sim&Reco
JLAB: Beam, Trigger, DAQ
Orsay&INFN: ECAL

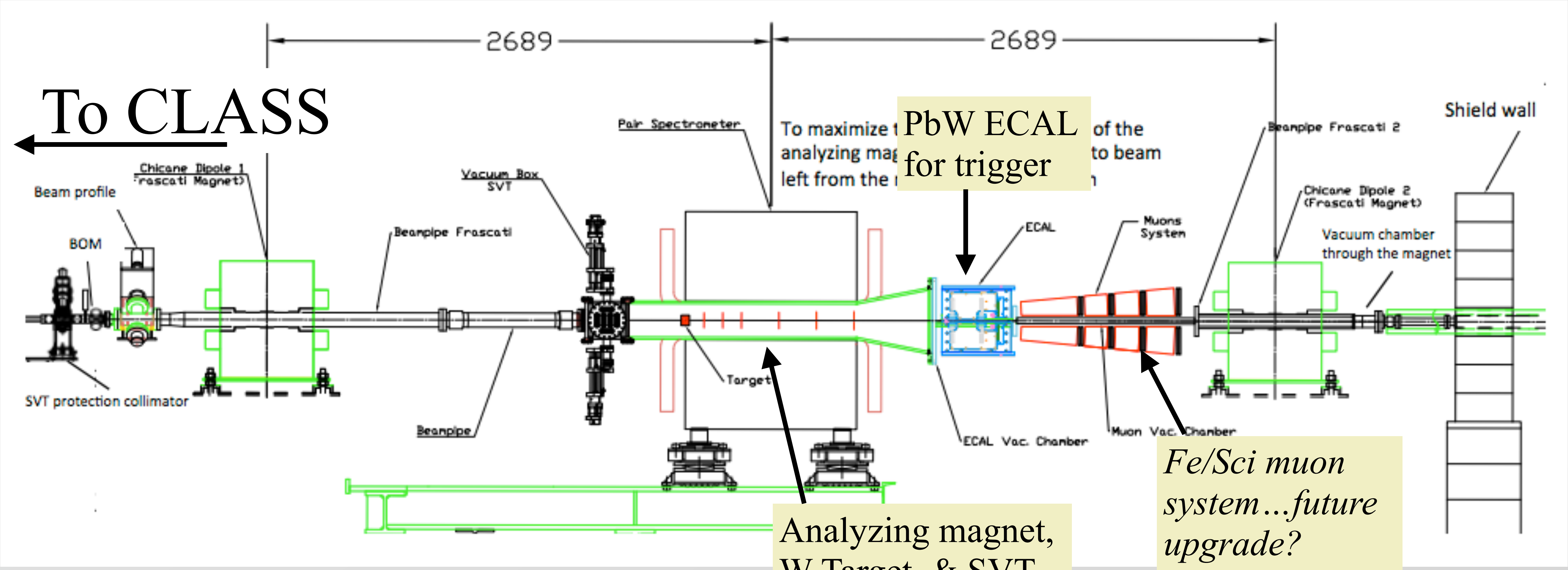


HPS beam & detector

HPS will sit in an alcove in ***JLAB Hall-B***
…behind CLASS, in front of beam dump

- energy: ***1.1-11.1 GeV***
- current: up to ***~700nA***
- roughly CW…***2ns*** bunch spacing
- can focus beamspot ~ ***300μ × 40μ***



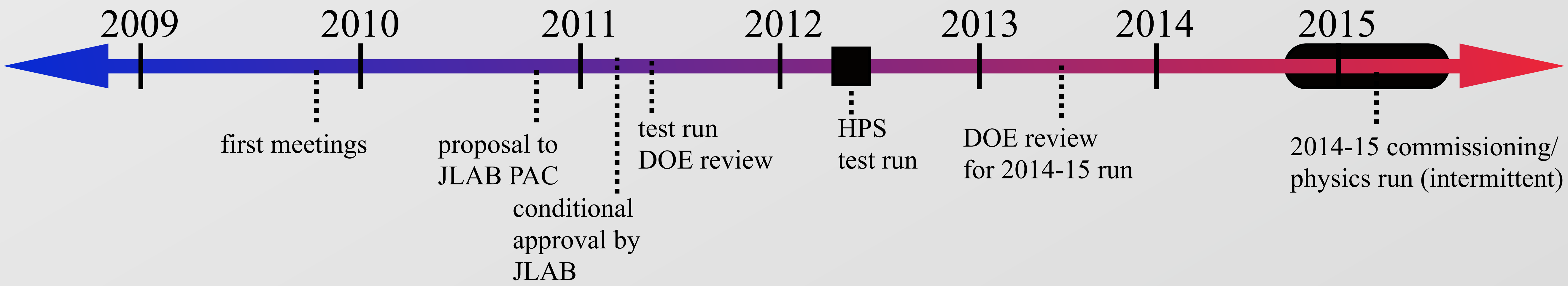


PbW ECAL for trigger

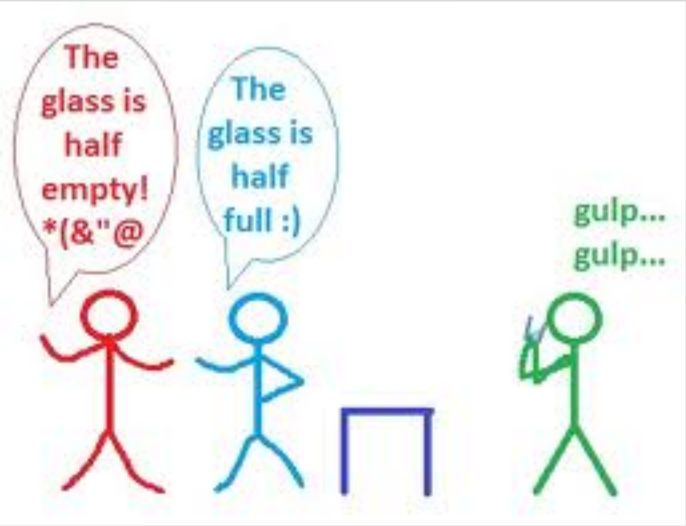
Analyzing magnet, W Target & SVT (in vacuum)

Fe/Sci muon system…future upgrade?

HPS Timeline



- The CLASS toroid magnets are late…this gives us an opportunity between CEBAF beam turn-on (Fall 2014) and when CLASS is ready to take date
- DOE proposal to build HPS detector for running late 2014-2015 — submitted April 2013, reviewed/accepted July 2013.
    - proposed a commissioning run @ 1.1, 2.2GeV (2 weeks beam time) followed by a data run @ 2.2, 6.6 GeV (4 weeks)
- Our goal is to get installed ~Sept 2014 and "be ready" to take data. CLASS toroid installation will take precedence (to put it lightly)…nights & weekends through 2015 (and nights may be tricky).



The HPS SVT

SVT is the key ingredient! Needs to measure momenta & vertex pairs with extreme purity in a busy environment. **Require low material & very fast.**

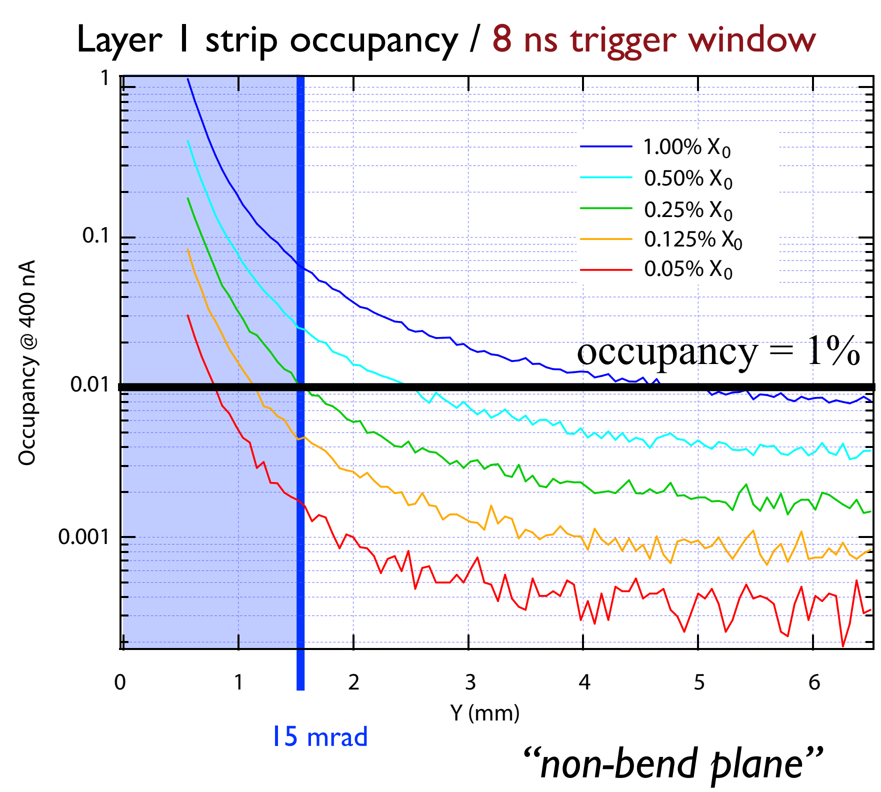
Si μstrip sensors

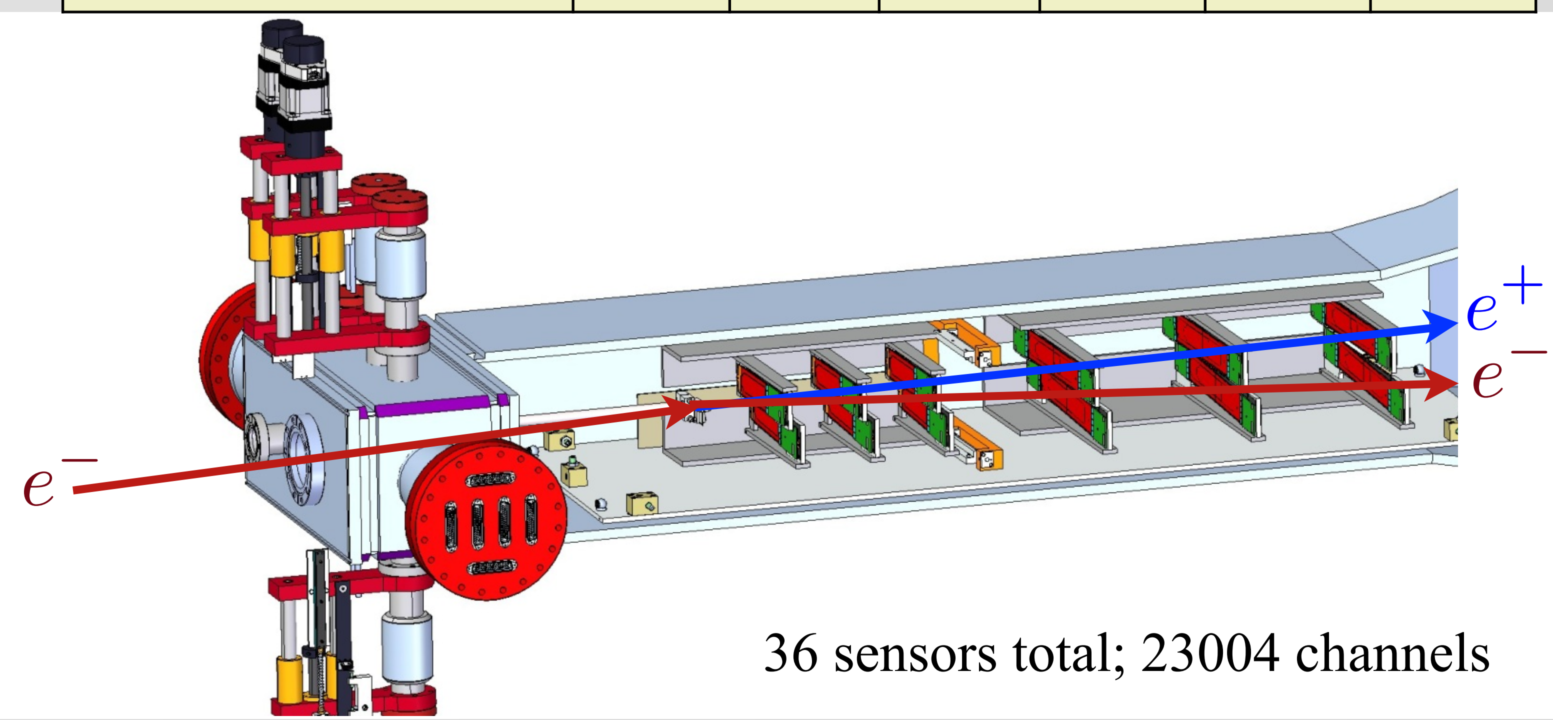
- Rad hard, thin (320μ), 60μ/30μ readout/sense pitch & $$$=Free (from RunIIb)

APV25 readout chip

- S/N>25 & ~2ns timing resolution

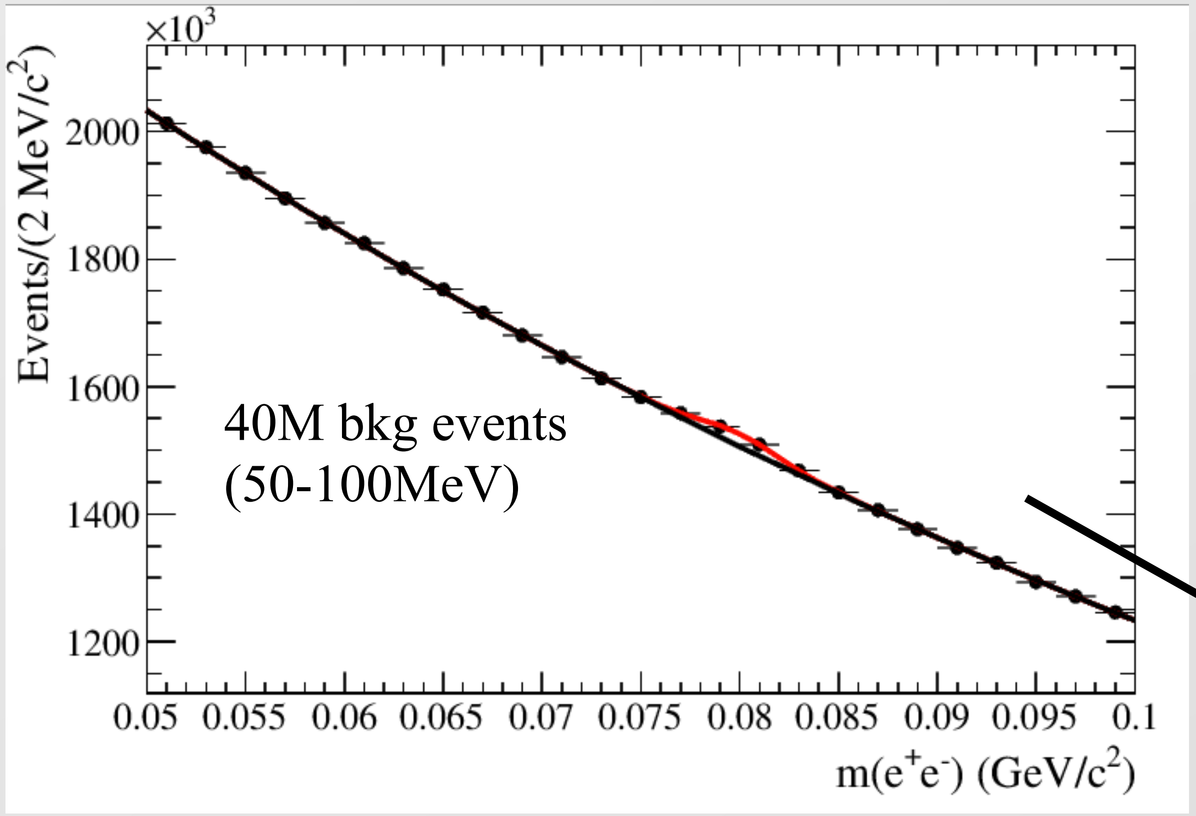
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
z position, from target (cm)	10	20	30	50	70	90
Stereo Angle (mrad)	100	100	100	50	50	50
Bend Plane Resolution (μm)	≈ 60	≈ 60	≈ 60	≈ 120	≈ 120	≈ 120
Non-bend Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
# Bend Plane Sensors	2	2	2	4	4	4
# Stereo Sensors	2	2	2	4	4	4
Dead Zone (mm)	±1.5	±3.0	±4.5	±7.5	±10.5	±13.5





36 sensors total; 23004 channels

Heavy photon signatures: bump hunt



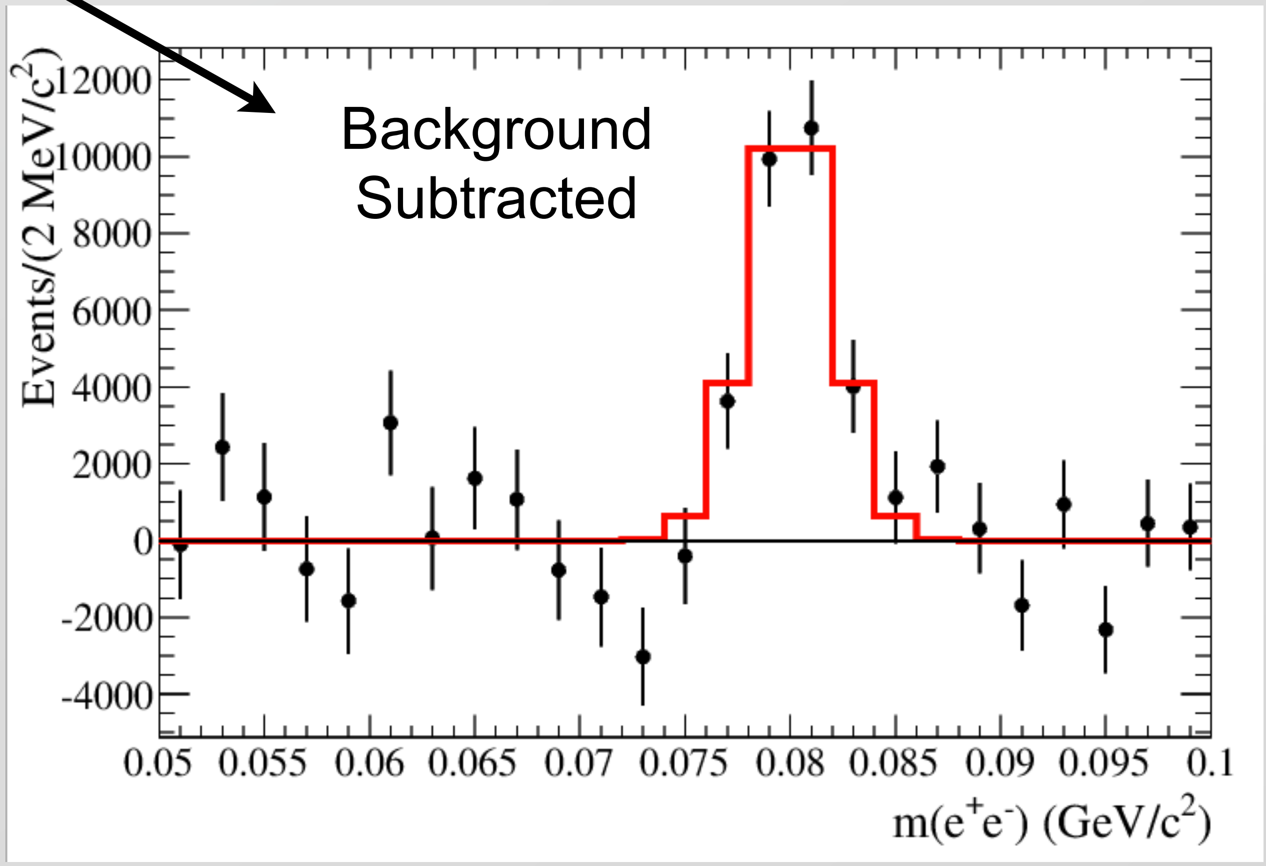
Pure bump hunt in m(e^+e^-)

⟶ large coupling region

(α>10^{-7})

mass resolution is the key…

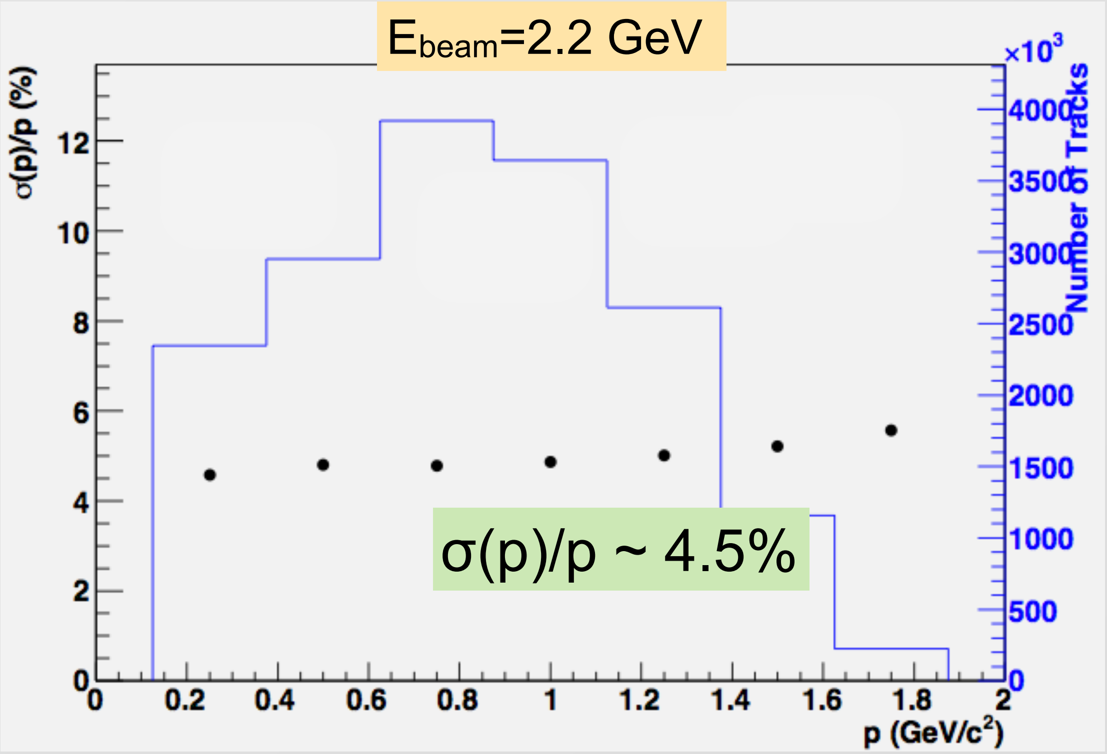
toy MC for example only...
does not reflect reality



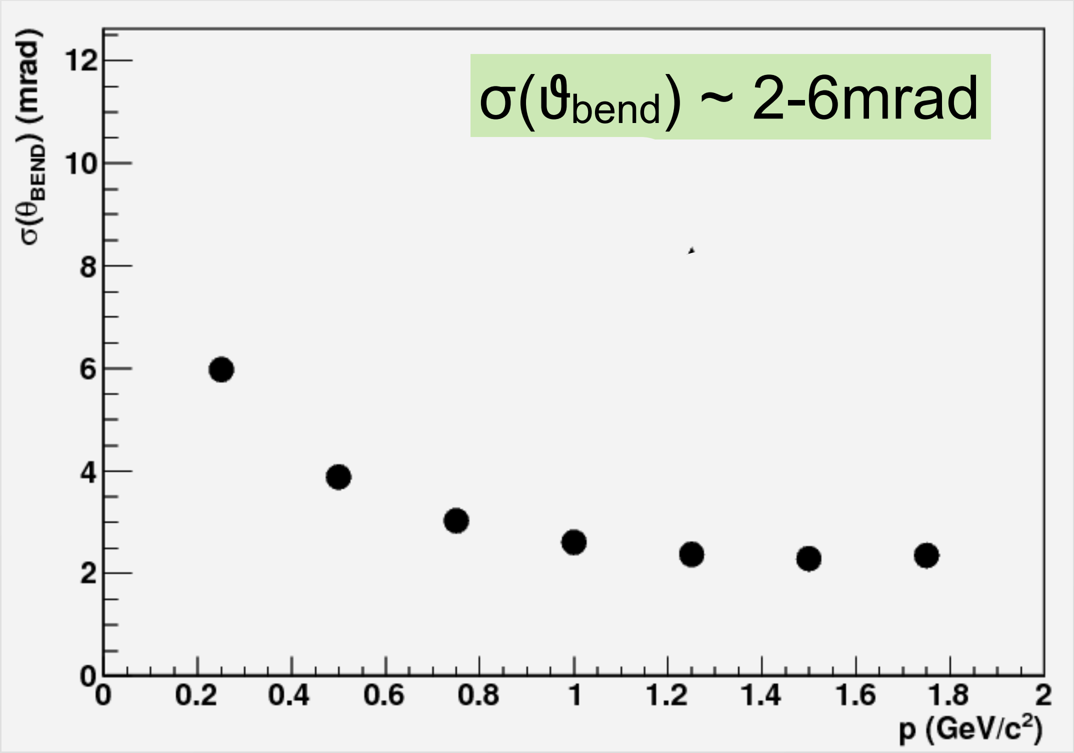
HPS momentum/angular resolution

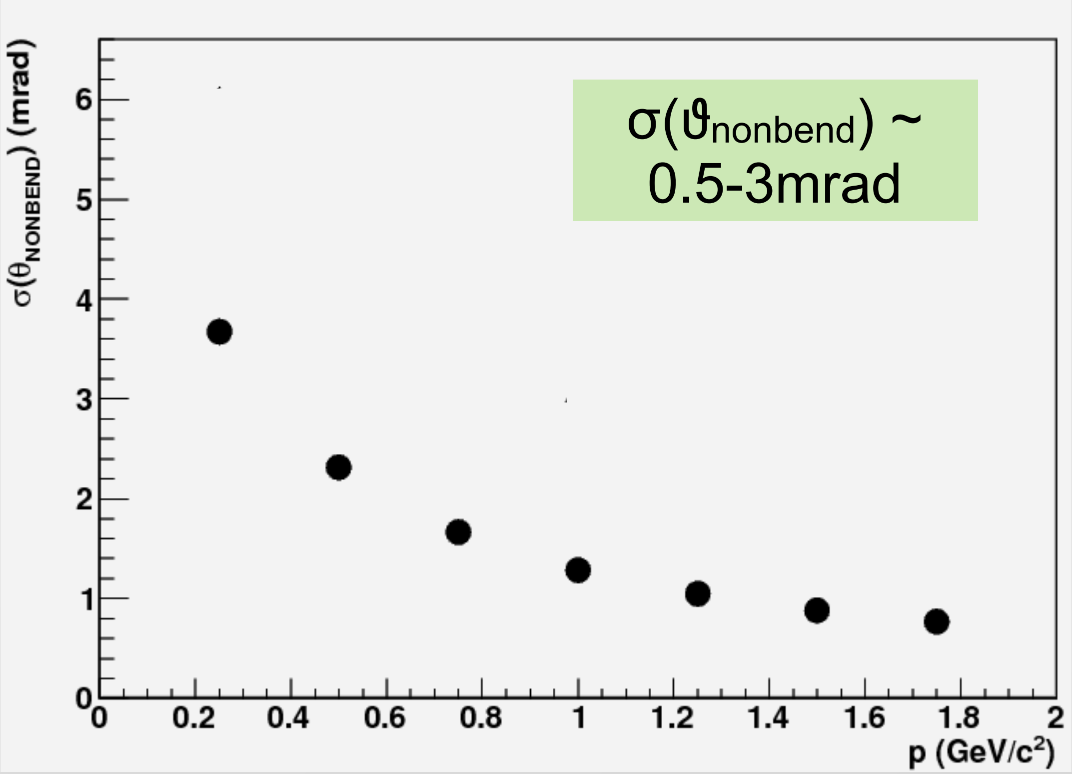
$$M = 2p_{e^+}p_{e^-}(1 - cos\theta)$$

$$\left(\frac{\Delta M}{M}\right)^2 \sim \left(\frac{\Delta p}{p}\right)^2 + \left(\frac{\Delta \theta}{\theta}\right)^2$$

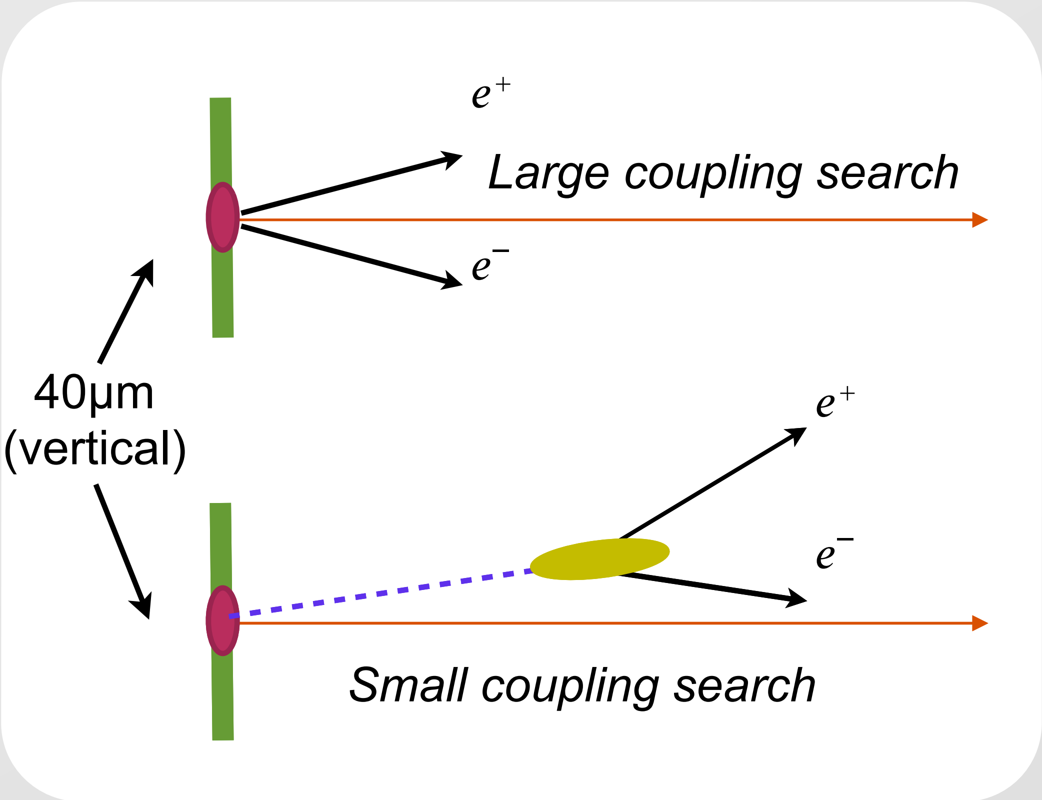


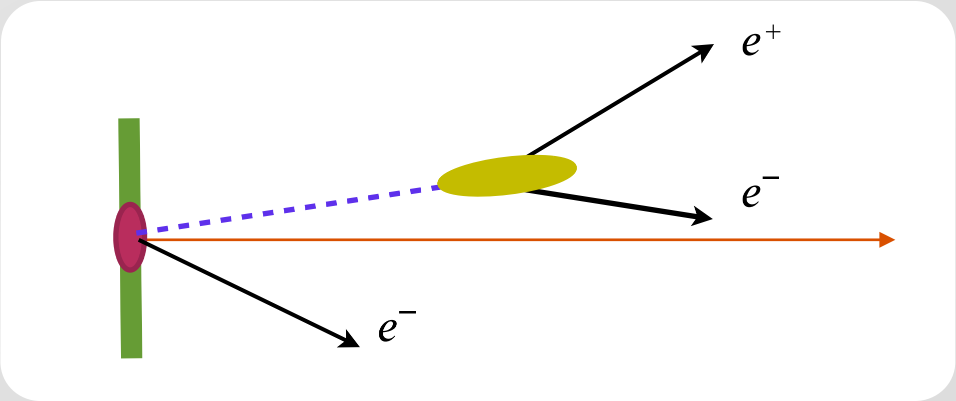
- momentum resolution→ material throughout whole tracker & ∫L×B
- angular resolution→ material in first few layers





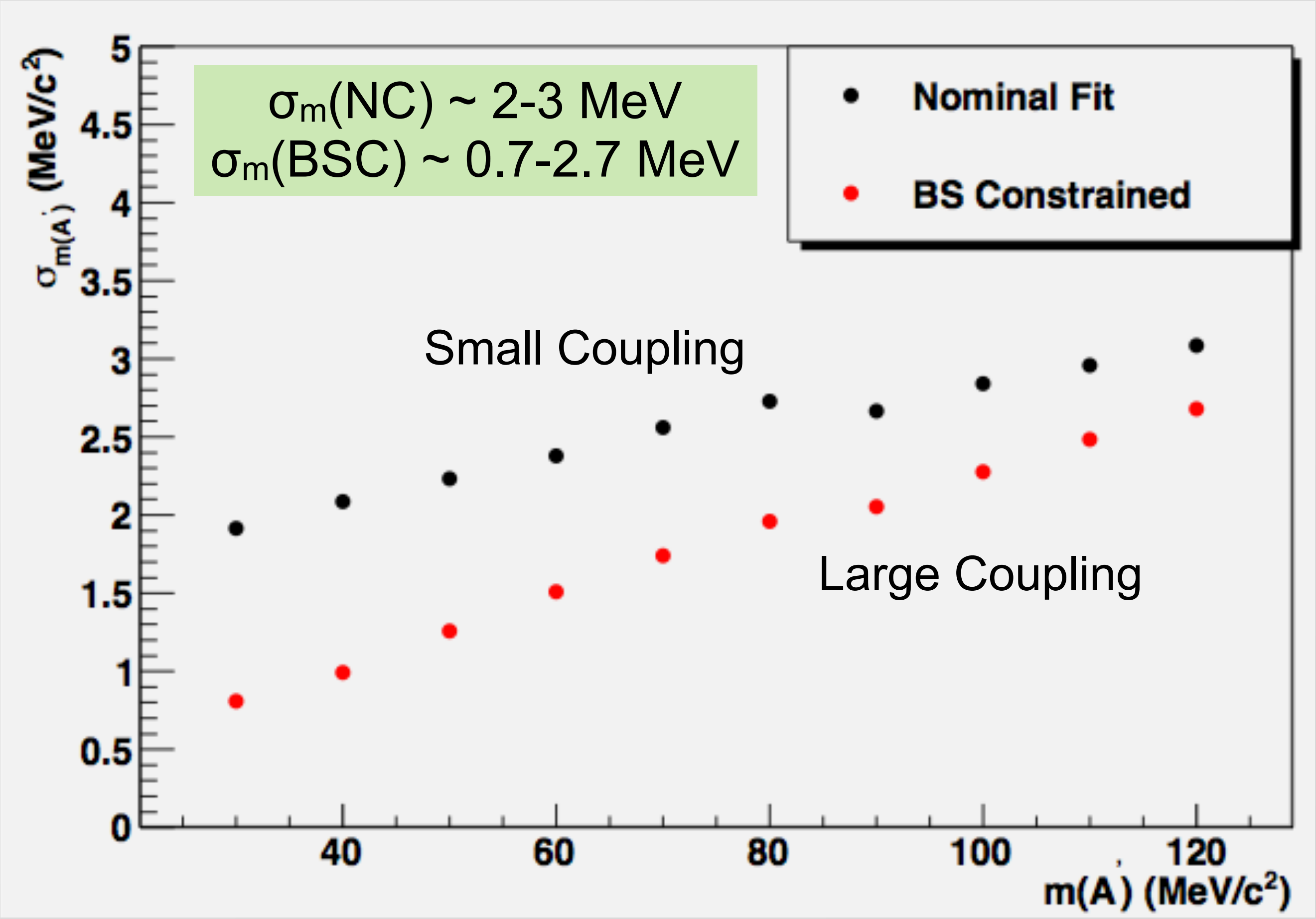
Mass Resolution: Bump-Hunt vs Vertexing



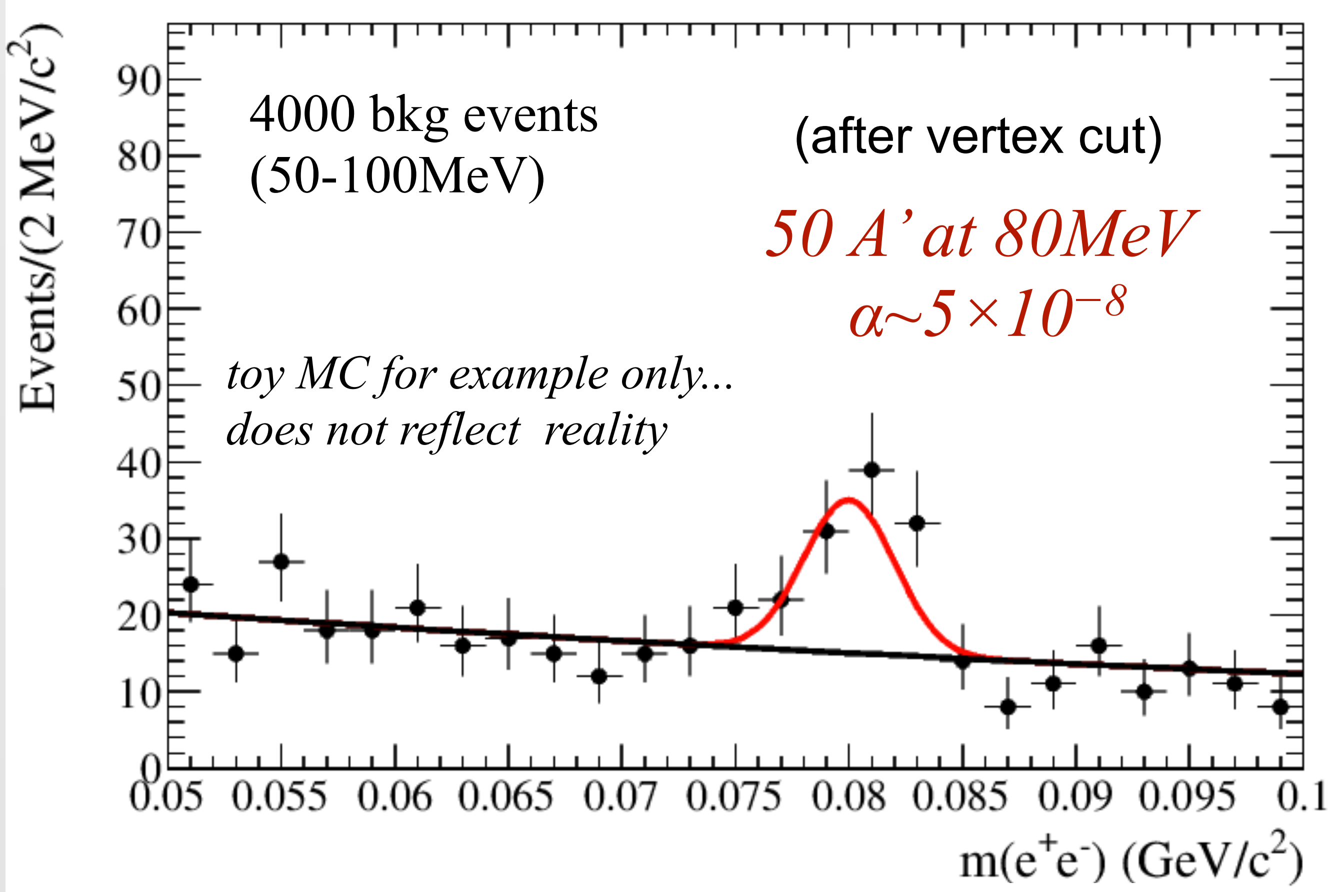


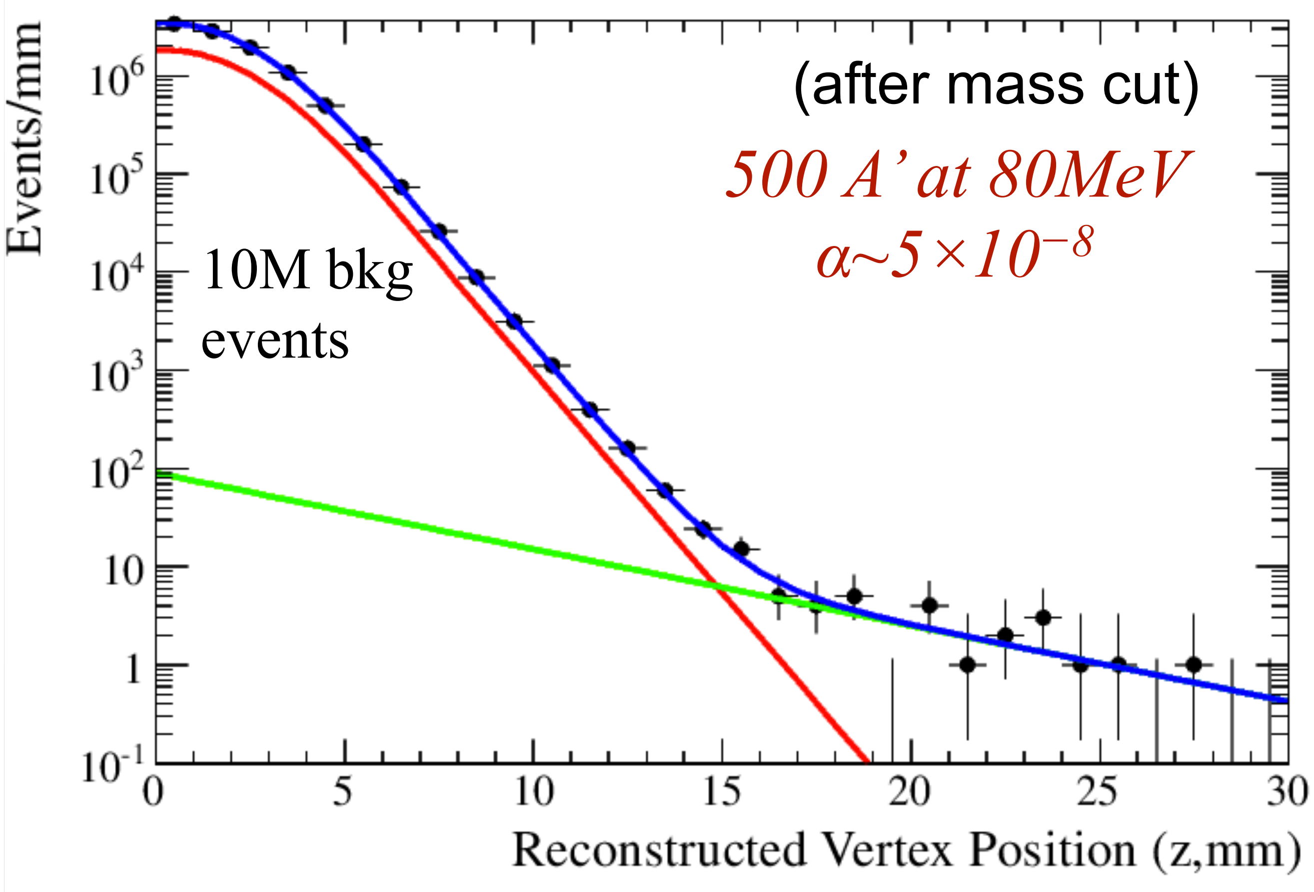
not included yet…recoil electron!
⟹adds mass resolution/BH discrimination

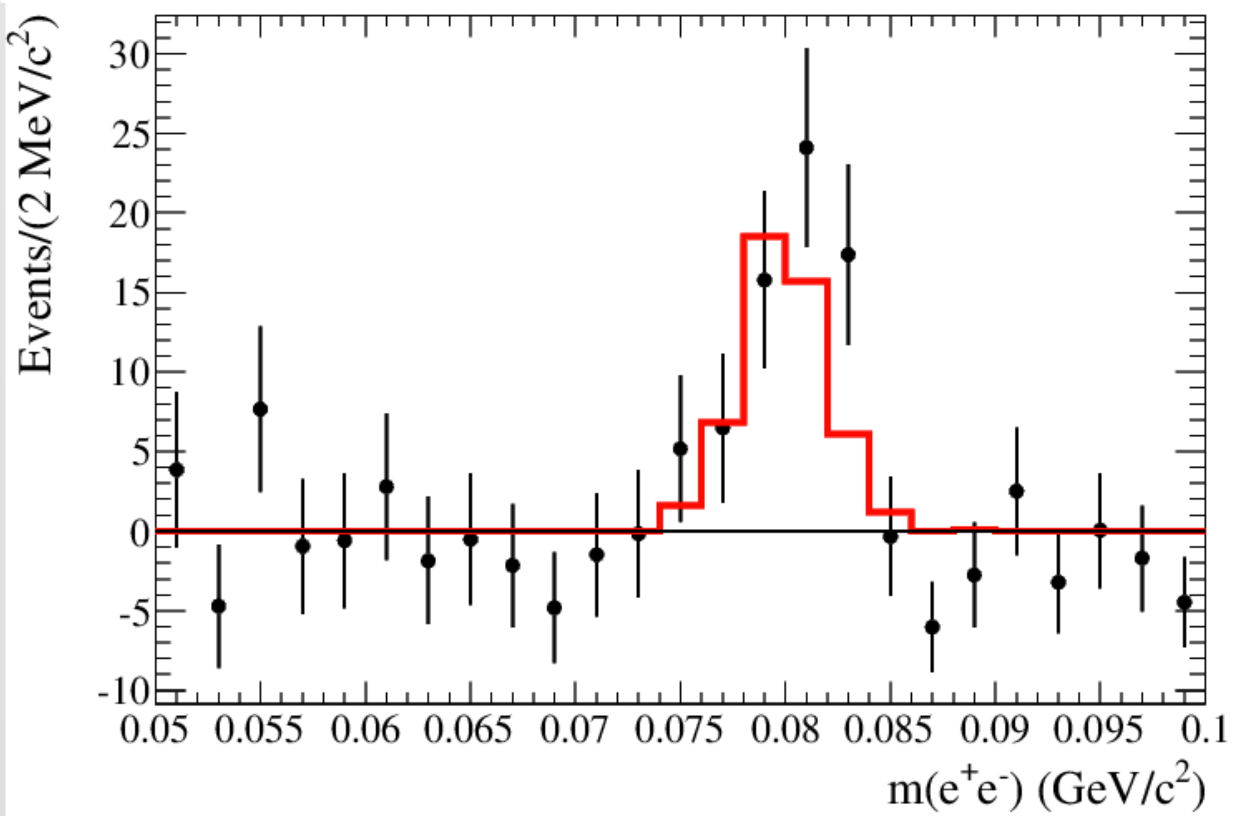
- two types of searches → two kinematic fits →two mass resolutions
  - Large coupling A's decay in the target → constrain the e^+ & e^- to originate from beamspot
    - very good constraint on angles
  - Small coupling A's decay outside of target → point decay products back to target
    - good at removing poorly reconstructed tracks



Heavy photon signatures: displaced vertex







2D search in mass & vertex position (z)

⟶ small coupling region ***(α~10^{-8} – 10^{-10})***

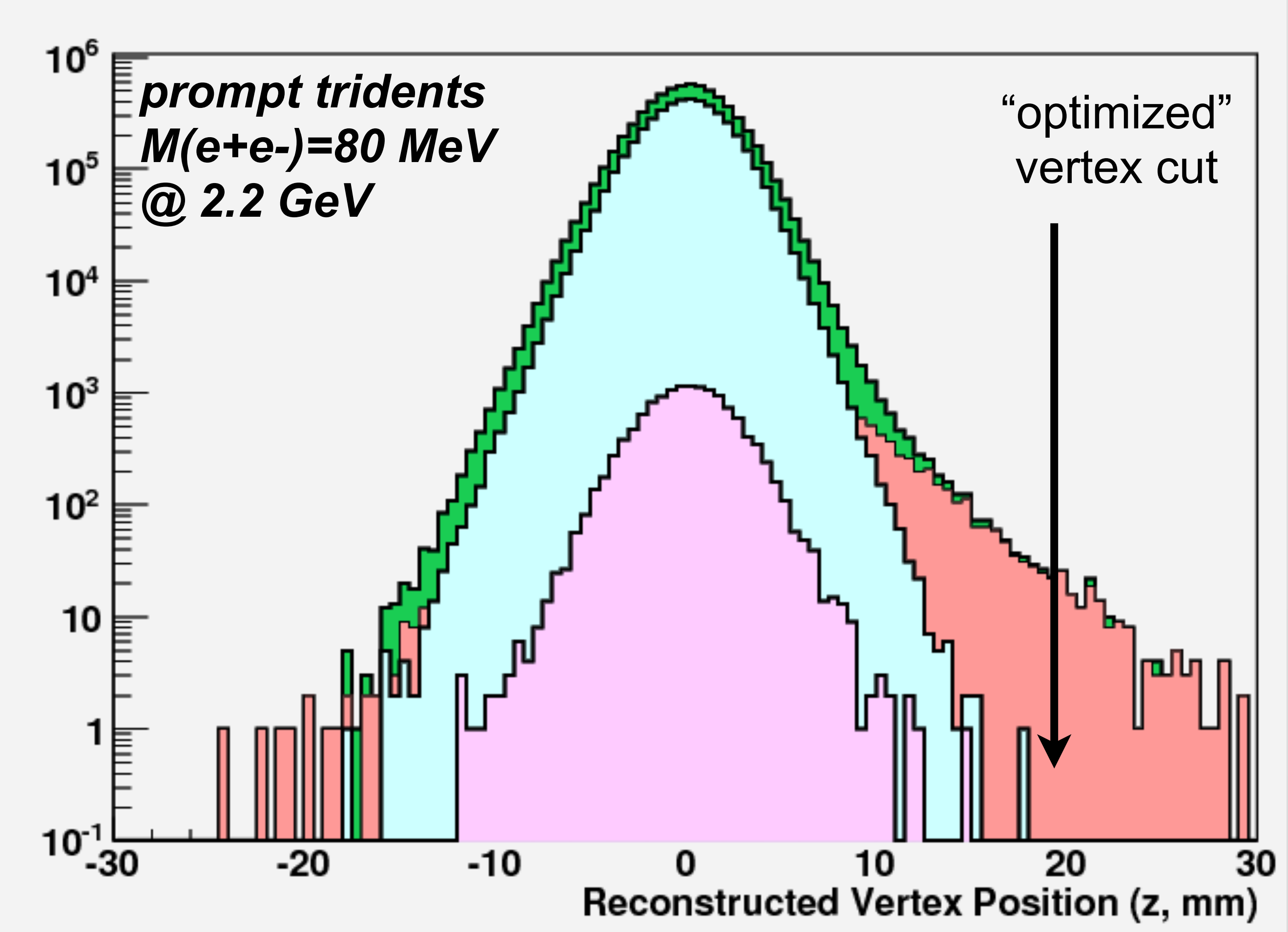
good mass and (more importantly) vertex resolution are the keys here

HPS Vertex Resolution

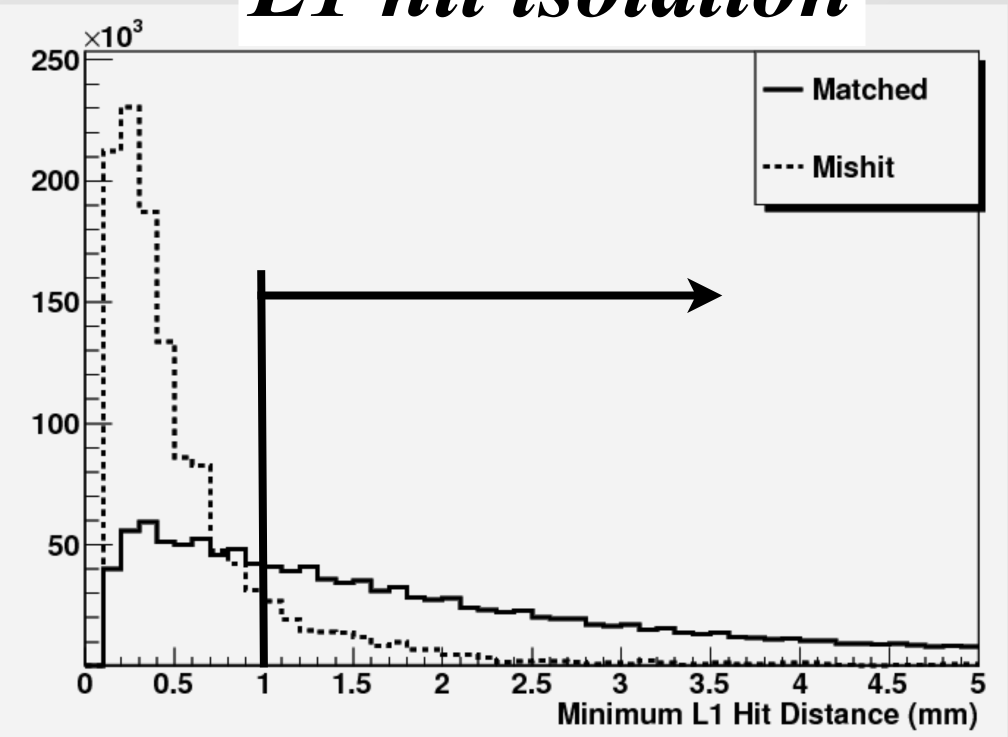
Huge prompt trident background⇒cut on the ***extreme*** tails of the vertex Δz distribution.

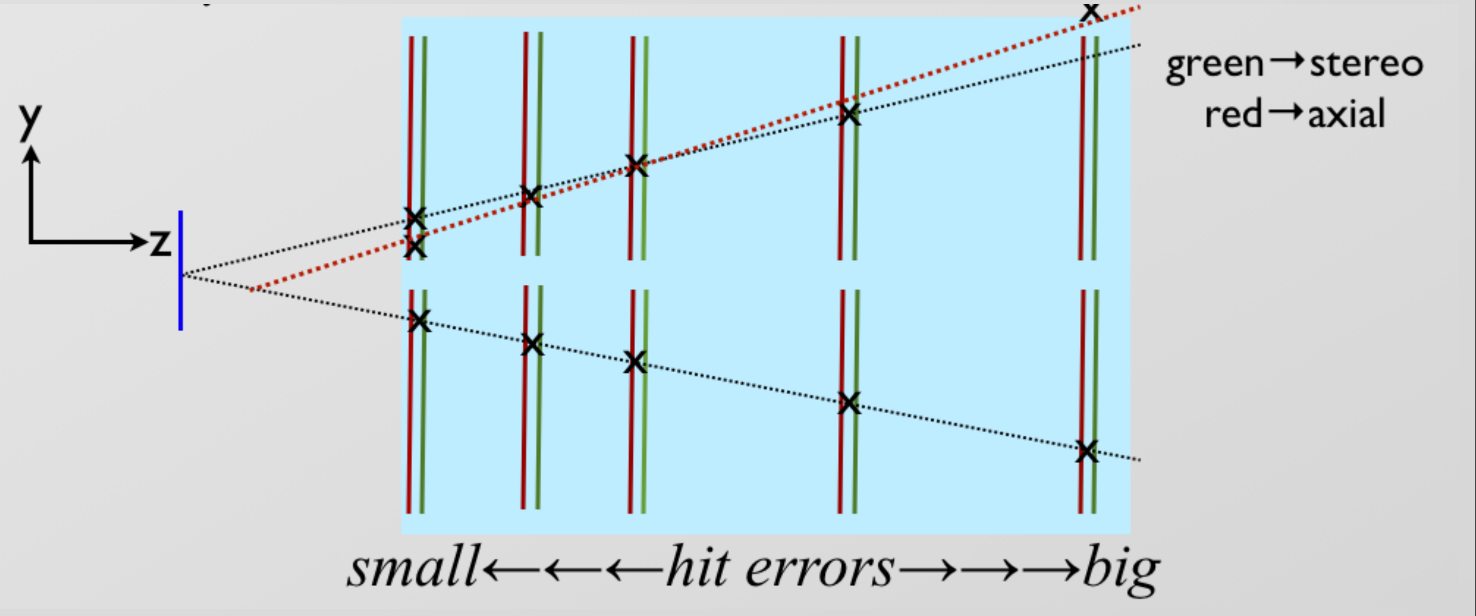
Need the tracks to be extremely pure:
•dark green: “reasonable” cuts ... e.g. track chi^2, vertex chi^2 etc
•dark red: >0 hits not matched to the true e^+ or e^- ; “mishits”

•light green: all pairs after isolation cut
•light red: mishits after isolation cut
…after isolation cut: ***>99.9% track purity***



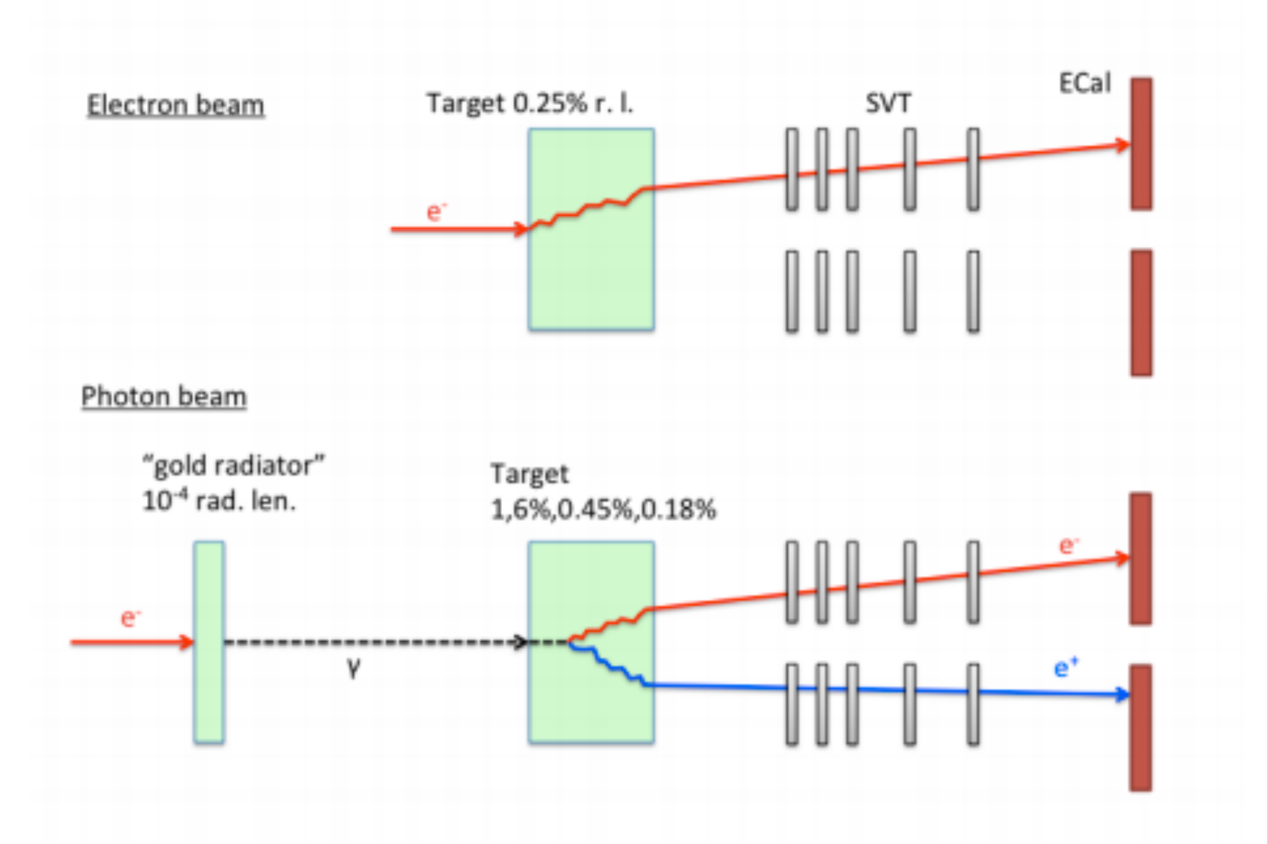
L1 hit isolation

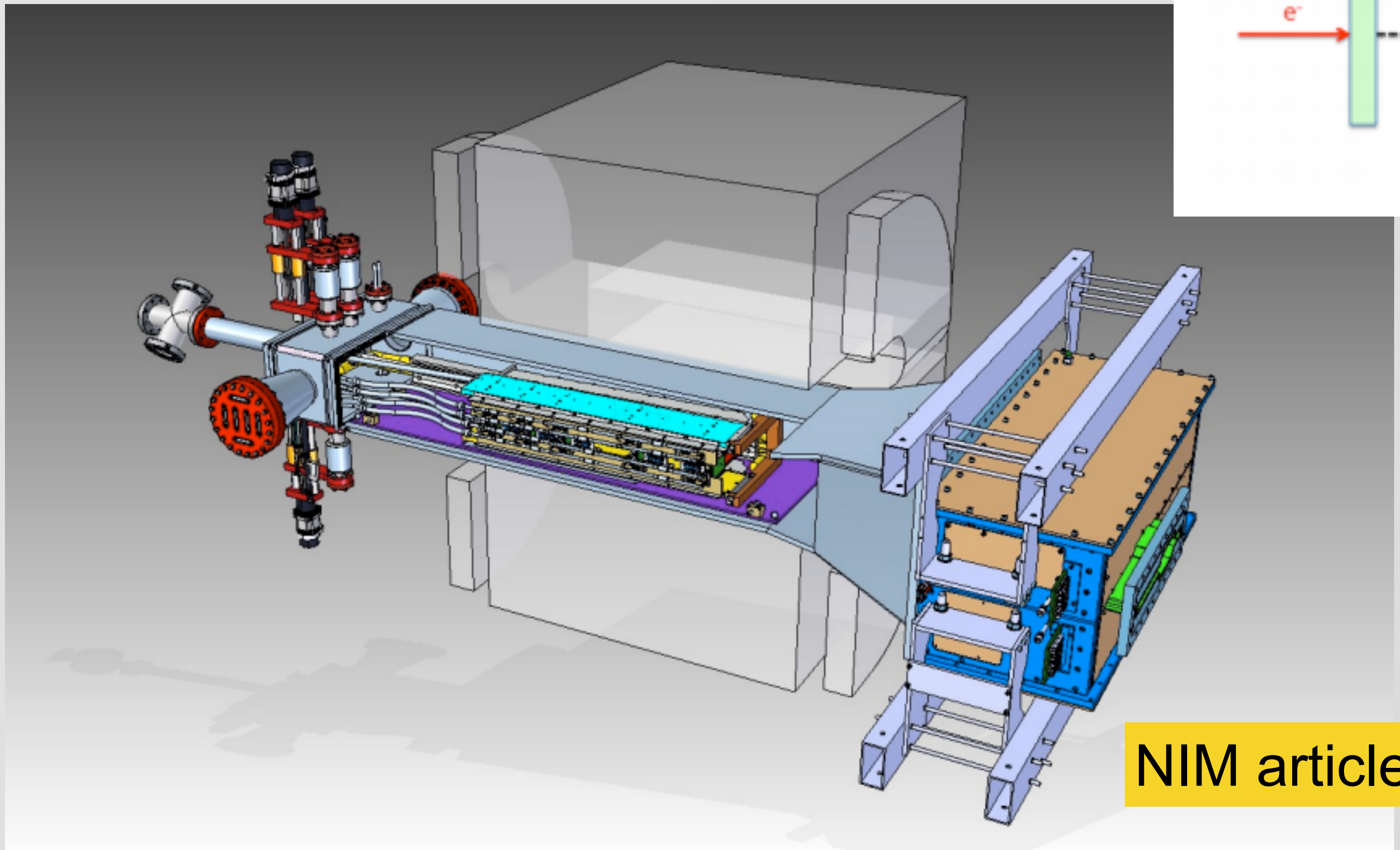




HPS Test Run (May 2012)

We built a test detector & installed May 2012…
…unfortunately, parasitic to another experiment using photon beam





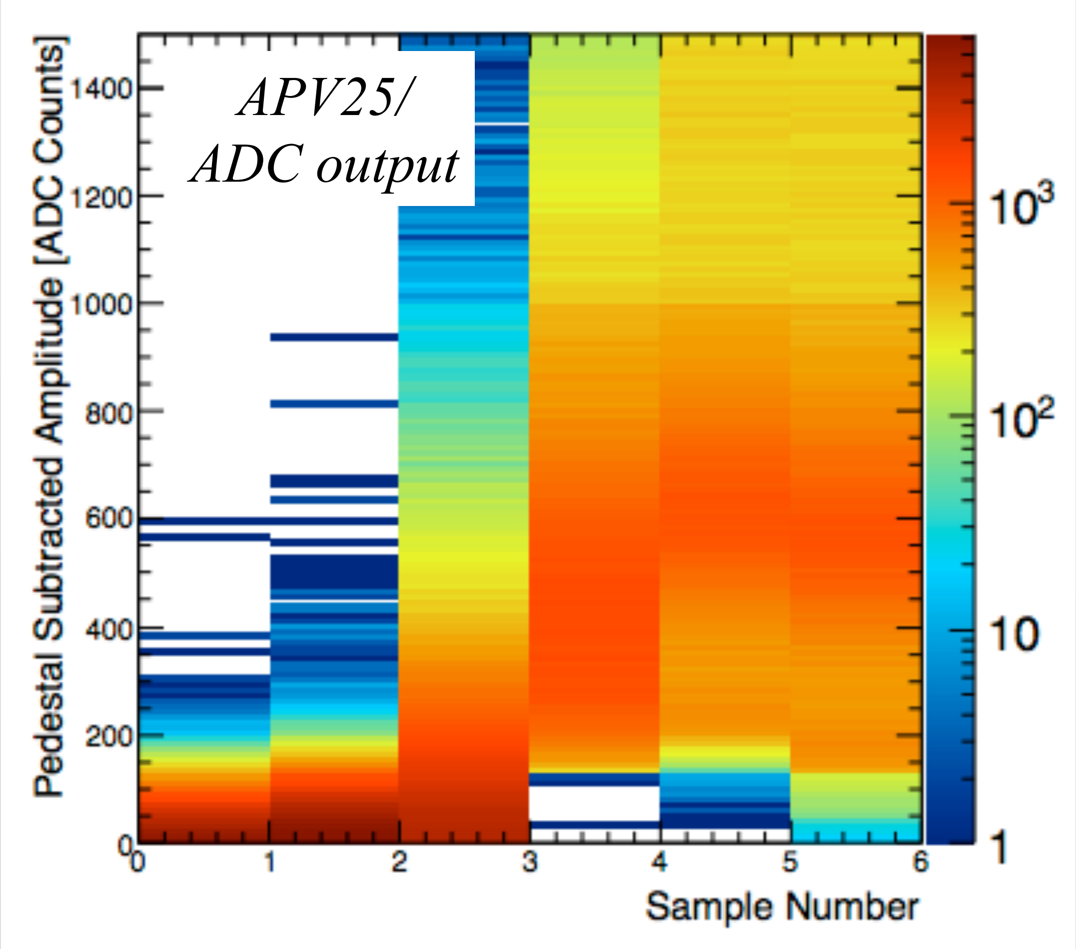
…still, able to take data, find tracks and even pairs.
Got some useful data ***(all in the last 8 hours before JLAB shut down)***.

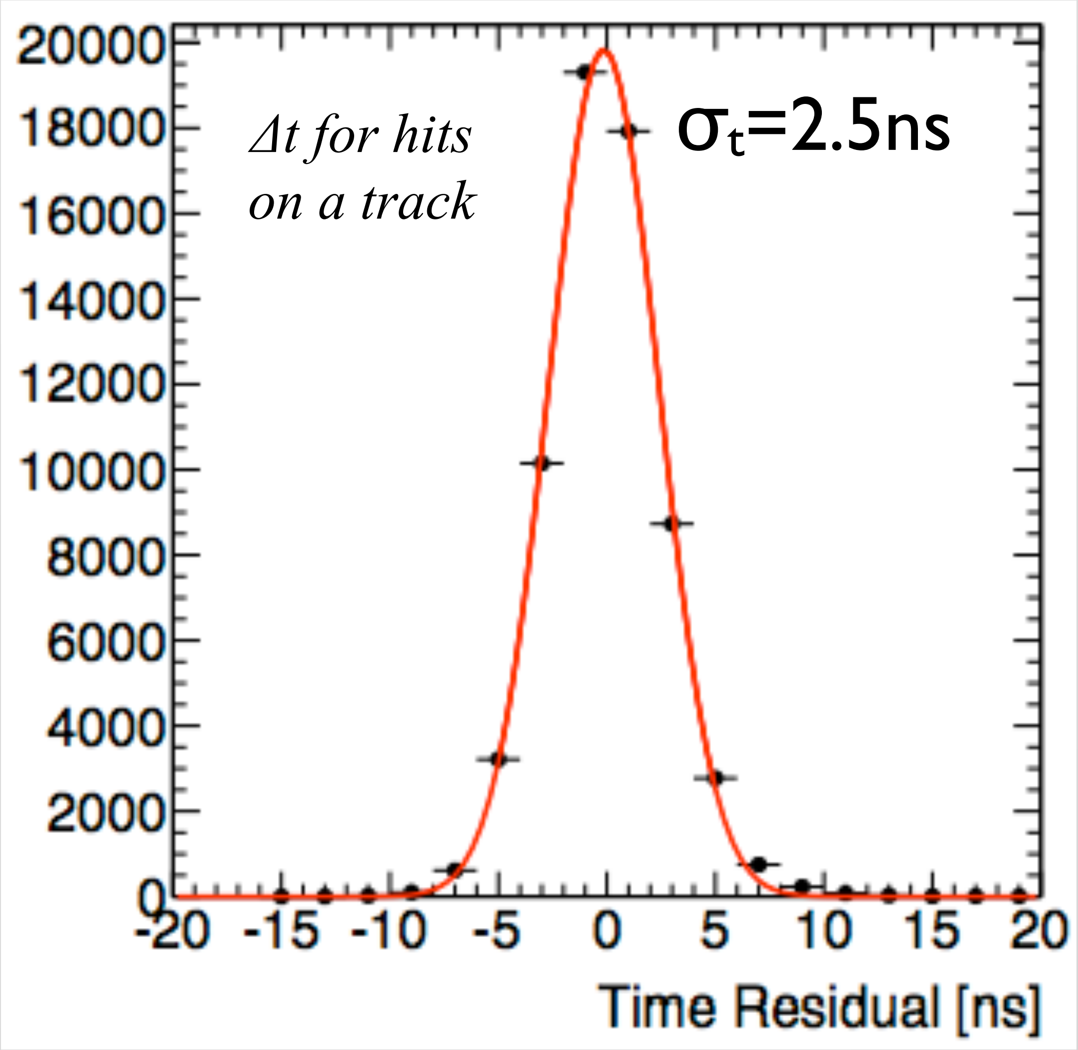
NIM article in progress

SVT Test Run Performance

SVT worked reasonably well…

- S/N ~ ***21-25***
- timing resolution ~ ***2.5ns***
- hit efficiency > ***98%***
- similarly high tracking efficiency

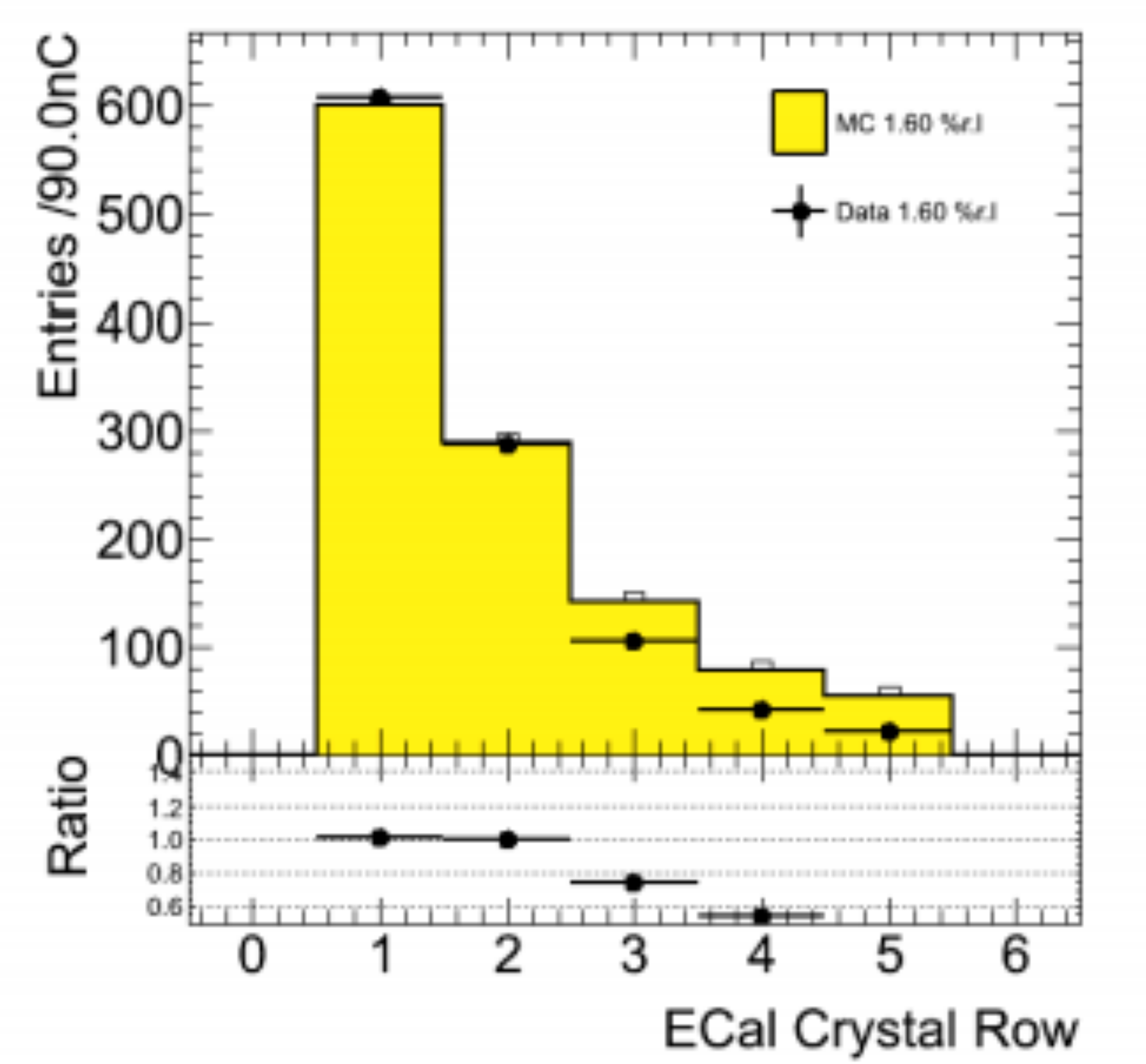


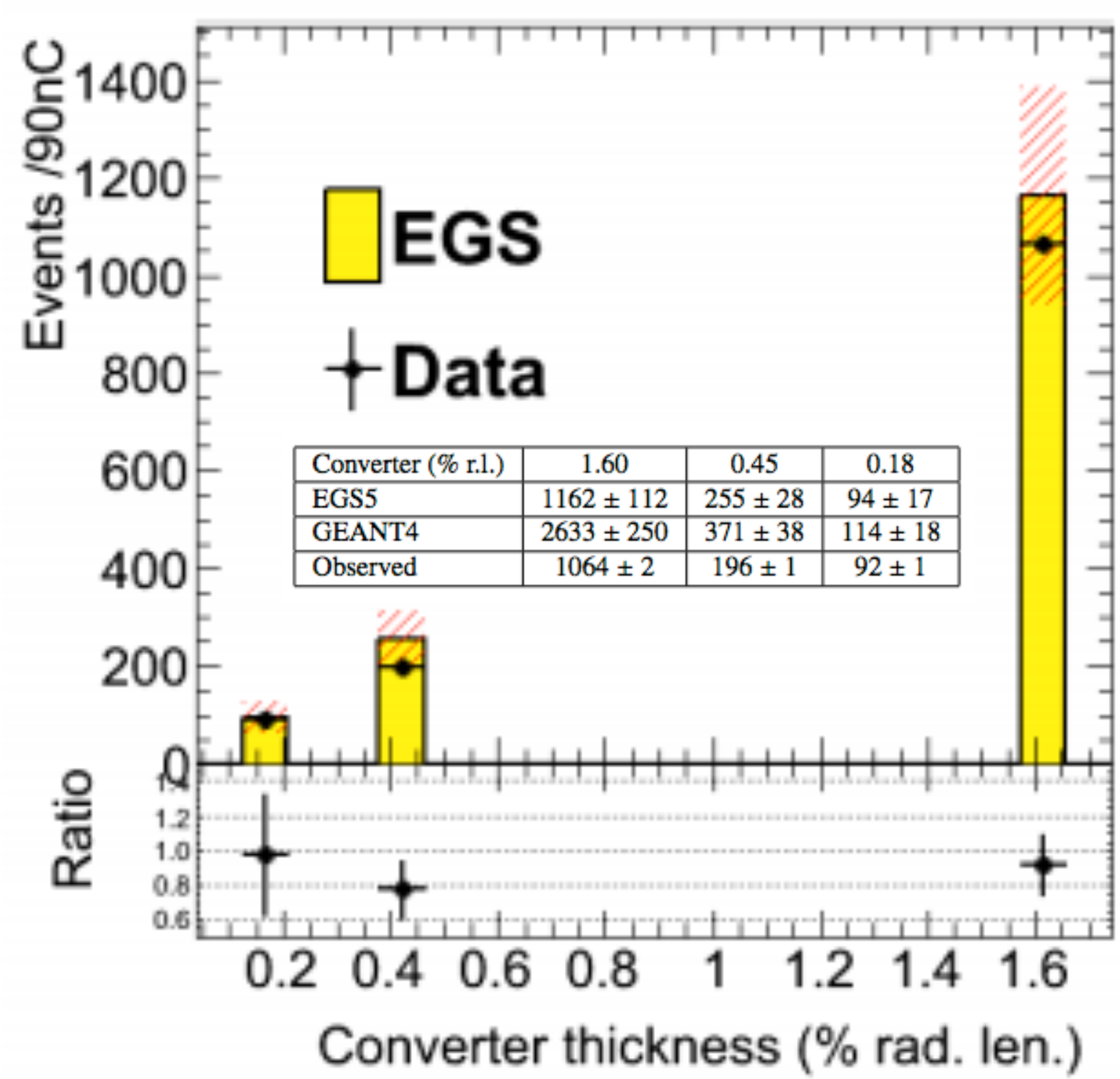


Beam scattering model

HPS Si is very close to beam…L1 guard ring is ***500μm*** from beam center. How well do we know what the occupancy will be? ***GEANT and EGS give different answers!***

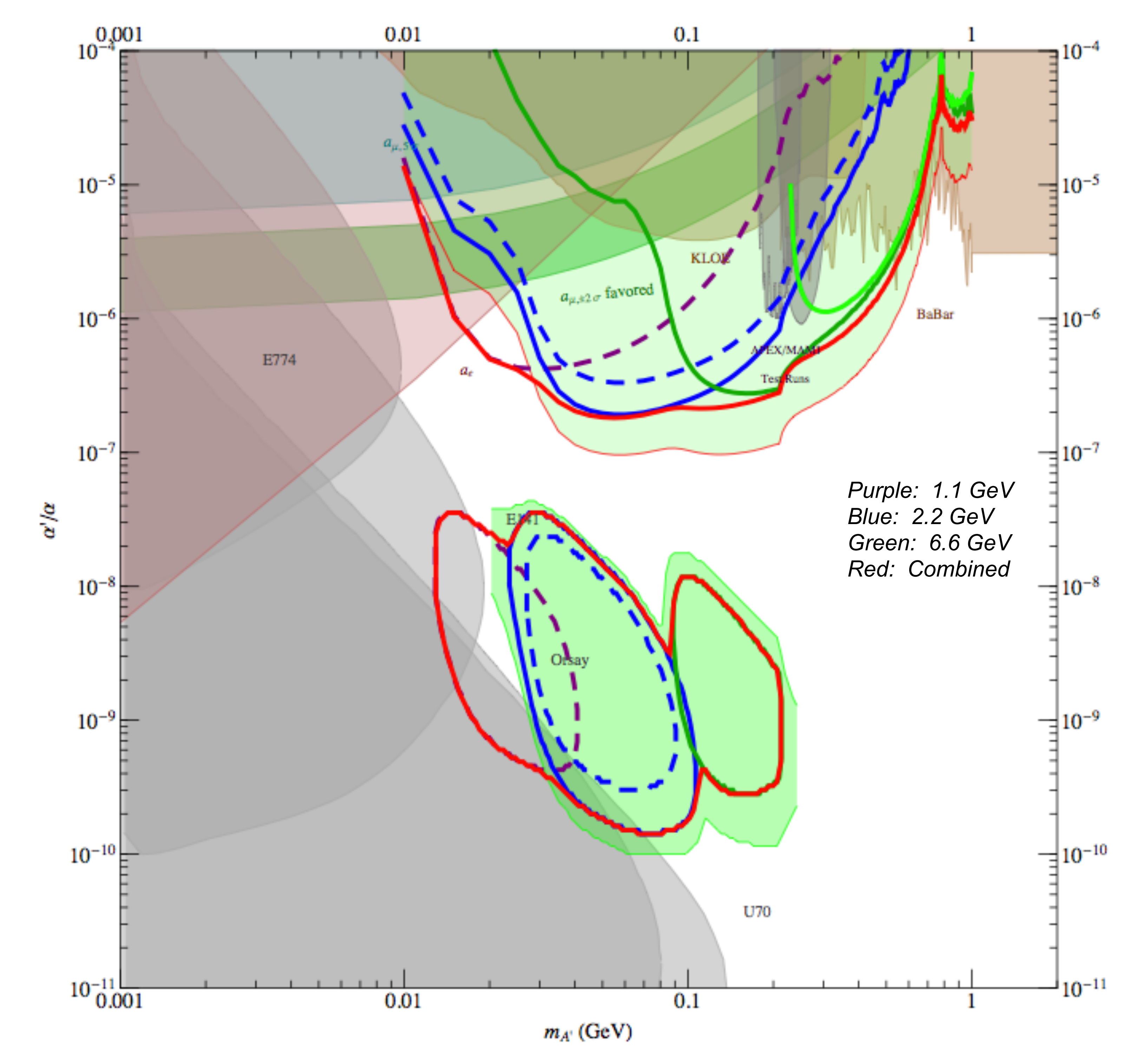
During our 8 hours, ran the photon beam through different converter thicknesses…compare with MC. ***EGS is correct!*** Good news…lower occupancy.





Converter (% r.l.)	1.60	0.45	0.18
EGS5	1162 ± 112	255 ± 28	94 ± 17
GEANT4	2633 ± 250	371 ± 38	114 ± 18
Observed	1064 ± 2	196 ± 1	92 ± 1

Expected HPS ('15-'16) Reach



Commissioning Run (dashed):

1 week with 50nA @ 1.1 GeV
1 week with 200nA @ 2.2 GeV

Production Run (solid):

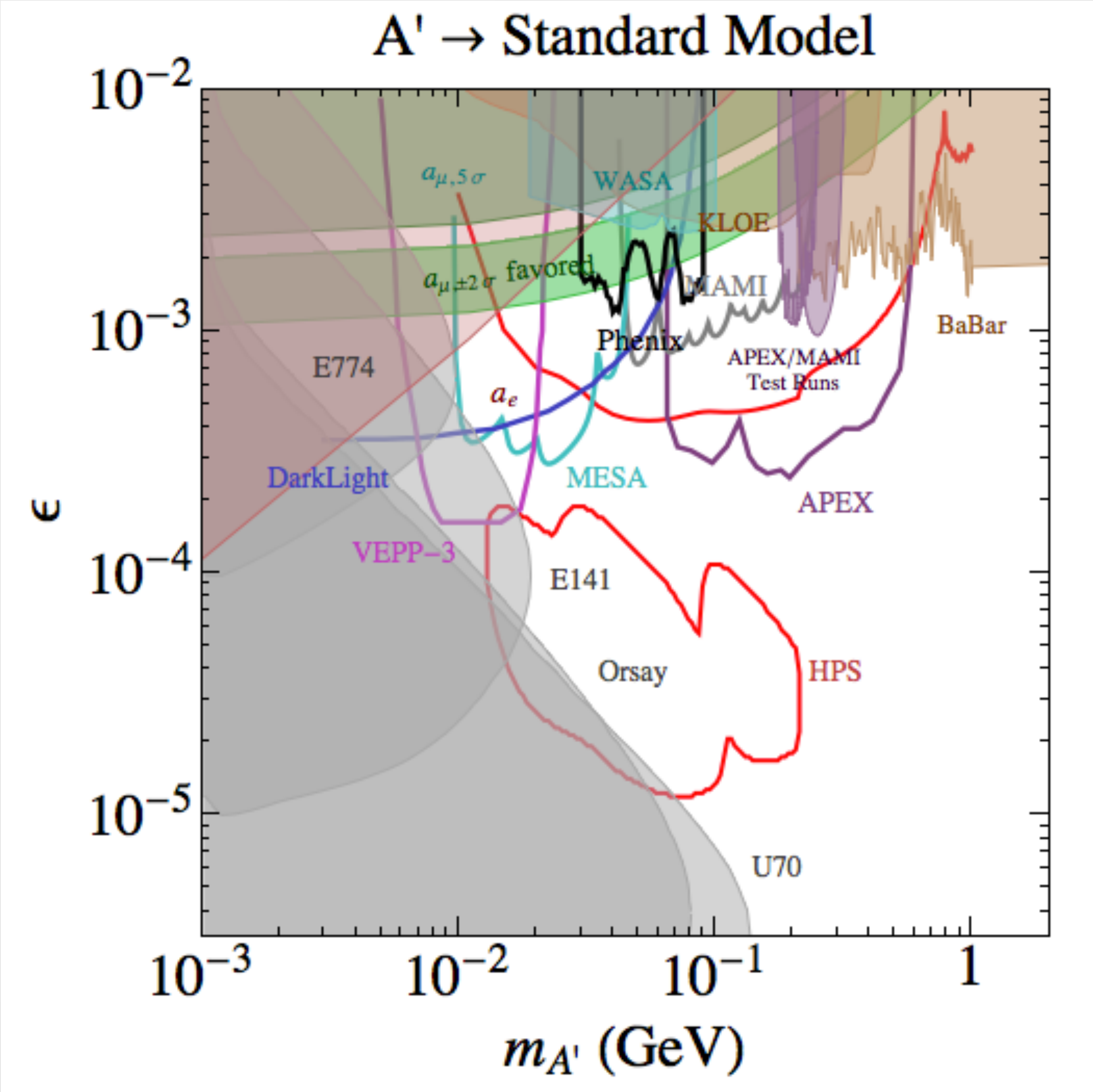
2 weeks with 200nA @ 2.2 GeV
2 weeks with 450nA @ 6.6 GeV

Shaded green:

3 months with 200nA @ 2.2 GeV
3 months with 450nA @ 6.6 GeV

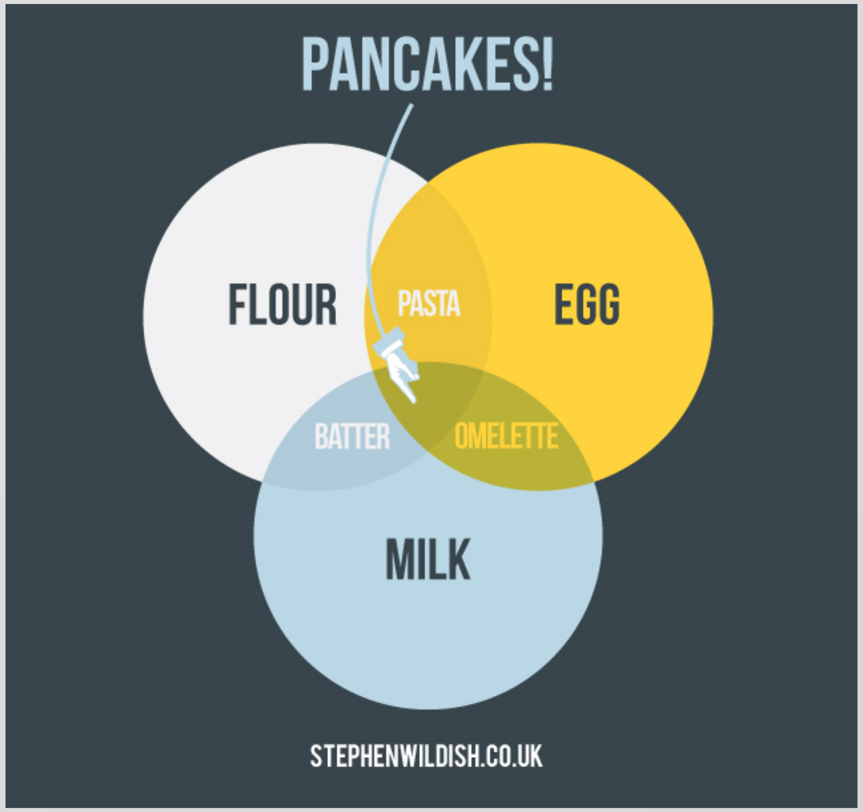
time given is beam time=floor time/2

The Competition/Compliments



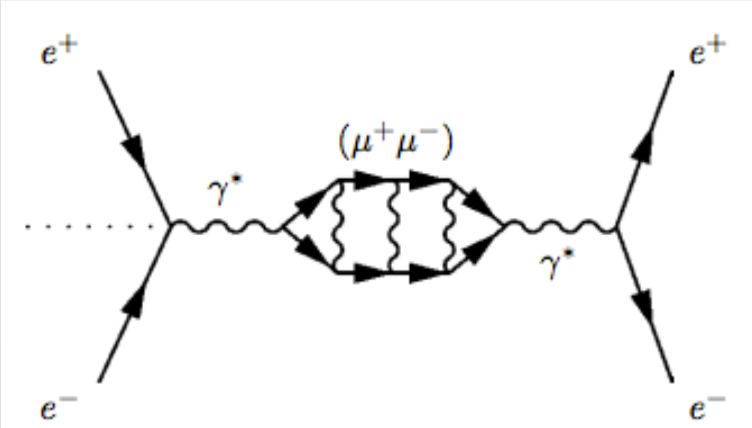
Lots of dedicated experiments planned, however…

HPS searches a region no other experiment can!

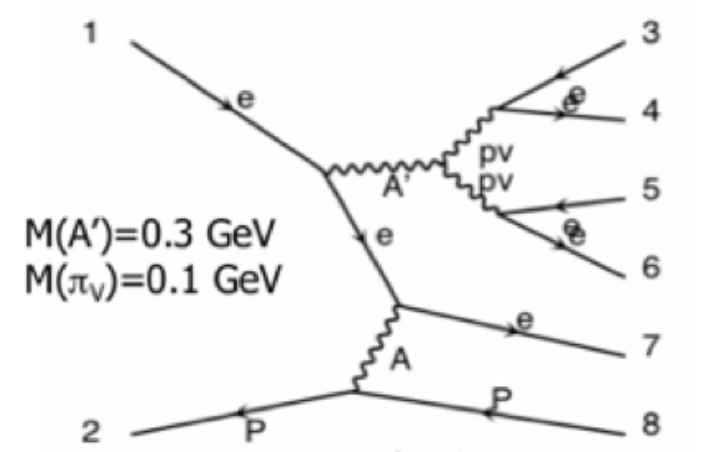


Other physics with the HPS detector

- true muonium: $\mu^+\mu^-$ bound state
- same signature as an A' at di-muon mass
- expect 10-20 accepted events (after vertex cut → no background)

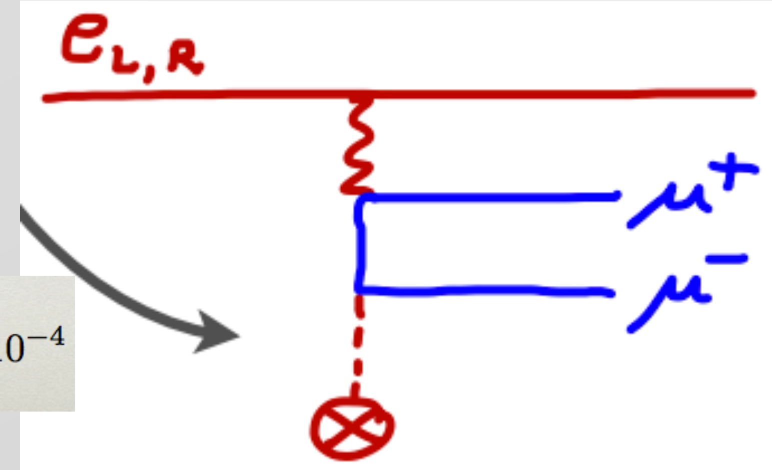


- strongly coupled dark sector could give rise to events with many leptons in final state
- high multiplicity events with many mass peaks
- similar signature if dark higgs is ~ nearby

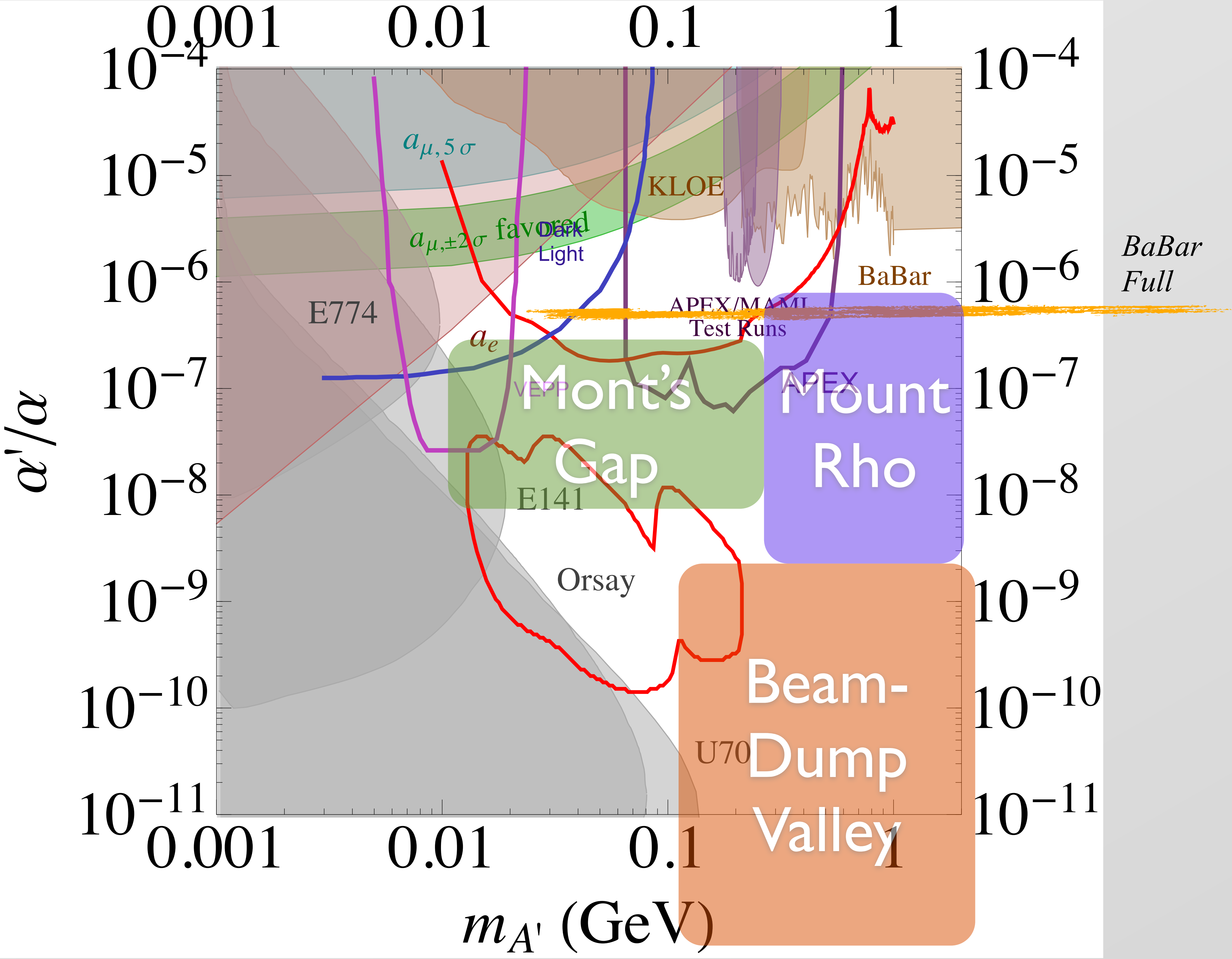


- according to Pospelov et al., MeV-scale force carrier could explain muonic Hydrogen anomaly...could also induce polarization-dependent muon-trident rate

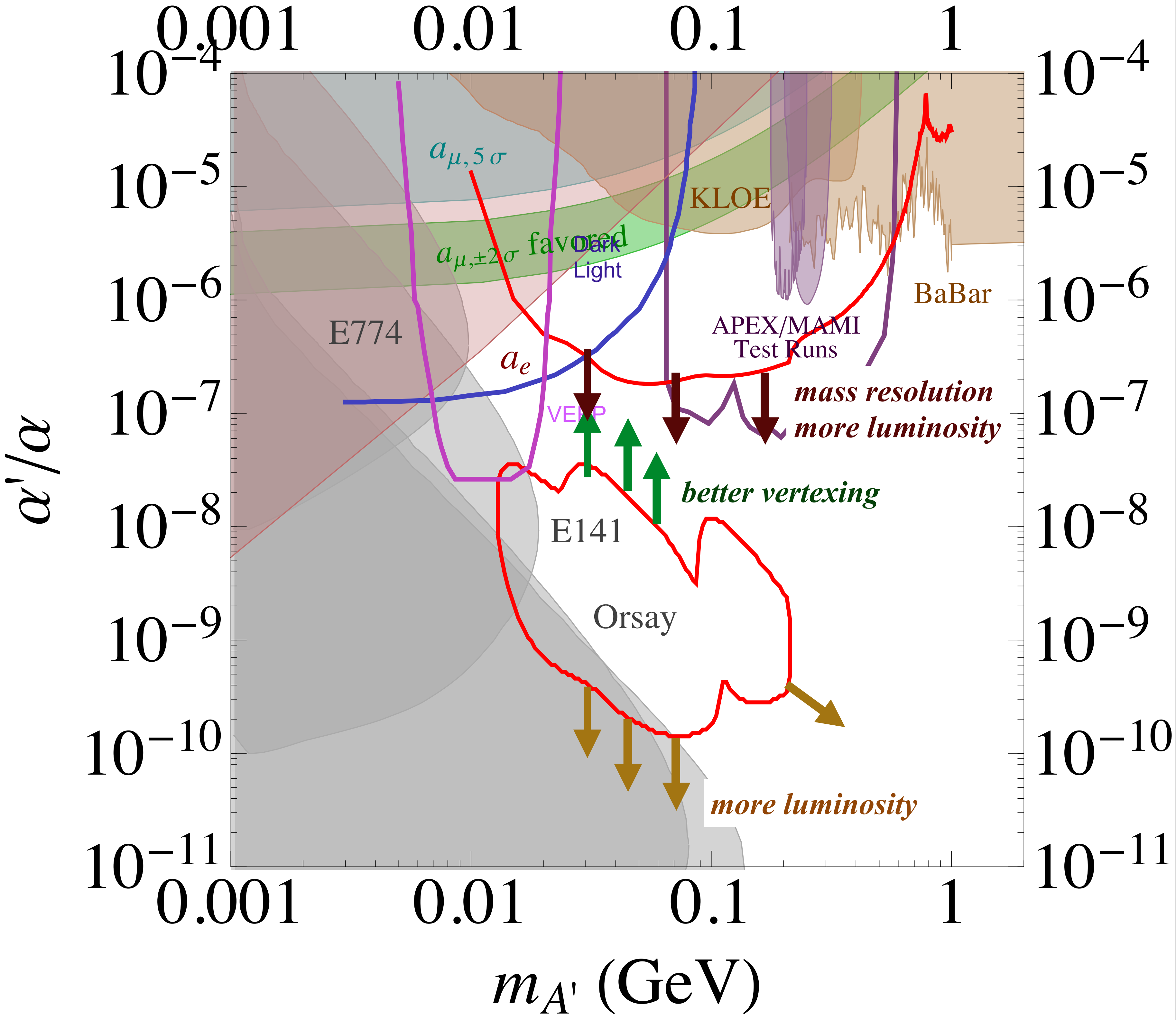
$$\delta = \frac{A_L(\mu^+\mu^-) - A_R(\mu^+\mu^-)}{A_L(\mu^+\mu^-) + A_R(\mu^+\mu^-)} \sim 10^{-3} - 10^{-4}$$



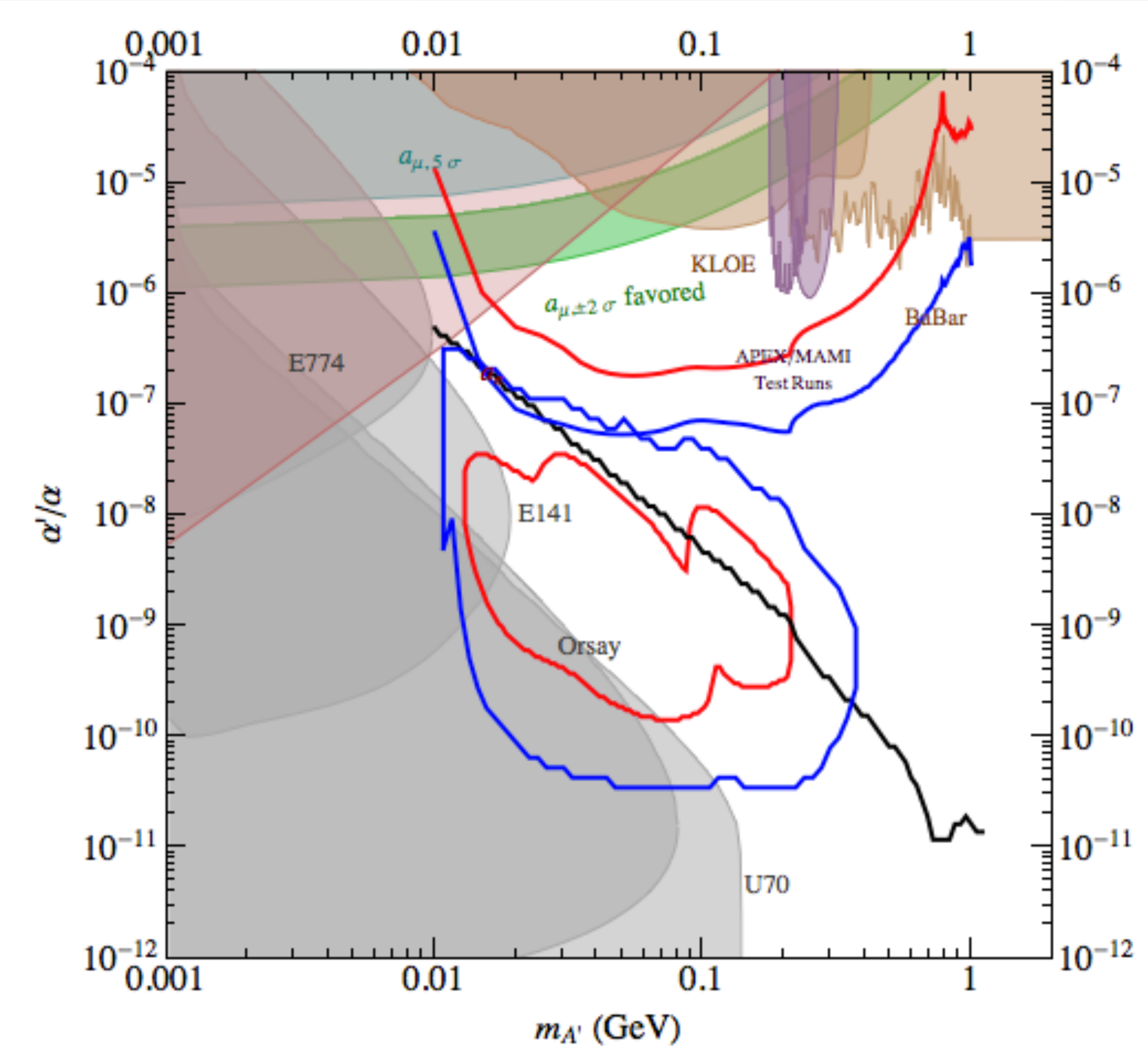
Filling the space…



Pushing HPS to the limit



Something simple…



$\int \mathcal{L} \times 24 \;\Rightarrow$

2 weeks $\times$ 6
(beam current x thickness)
$\times$ 4
…or some other combo.

improve vertex resolution
(i.e. tail rejection) by $\times$ 2 $\Rightarrow$

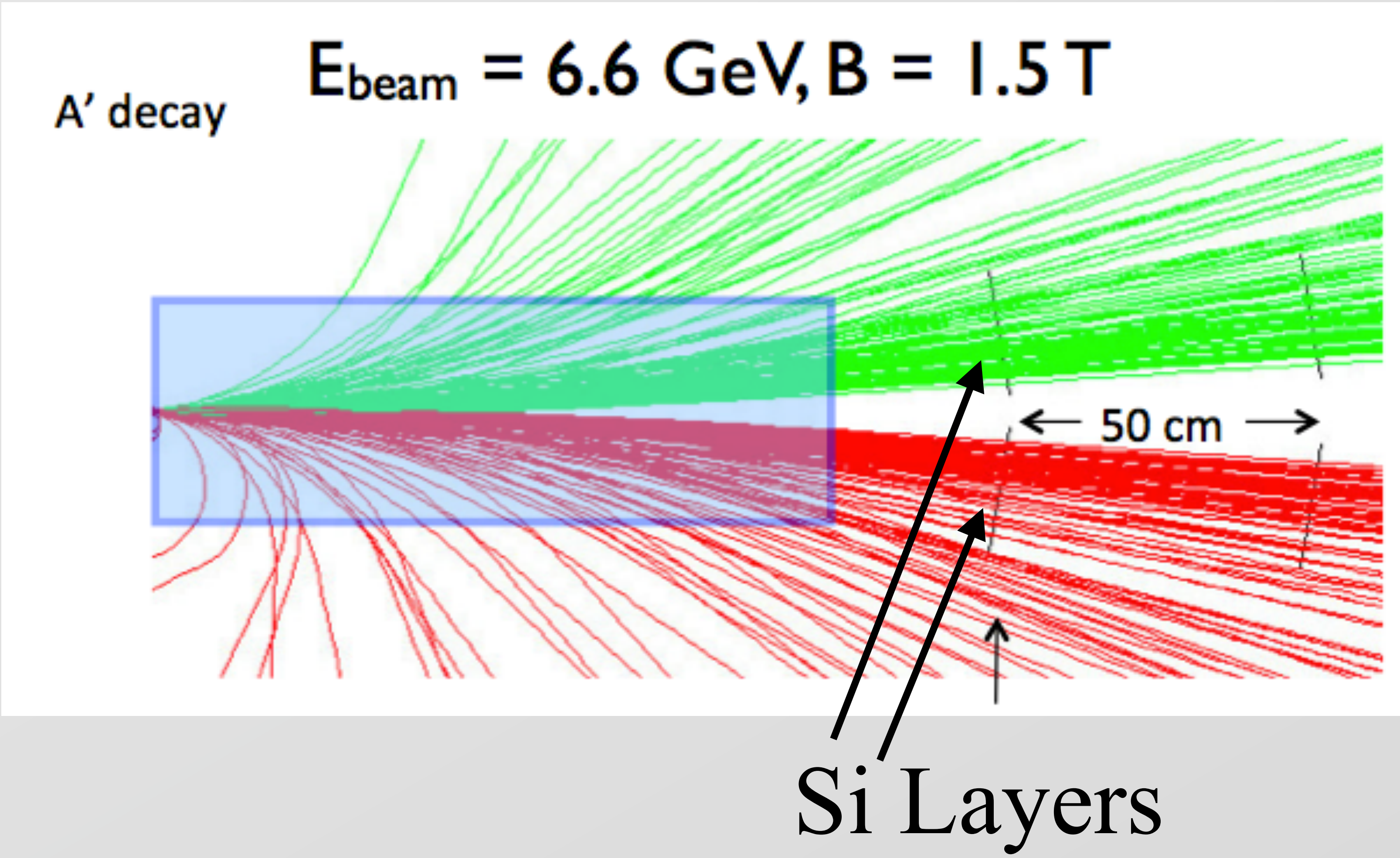
move target from 10 cm to 5cm

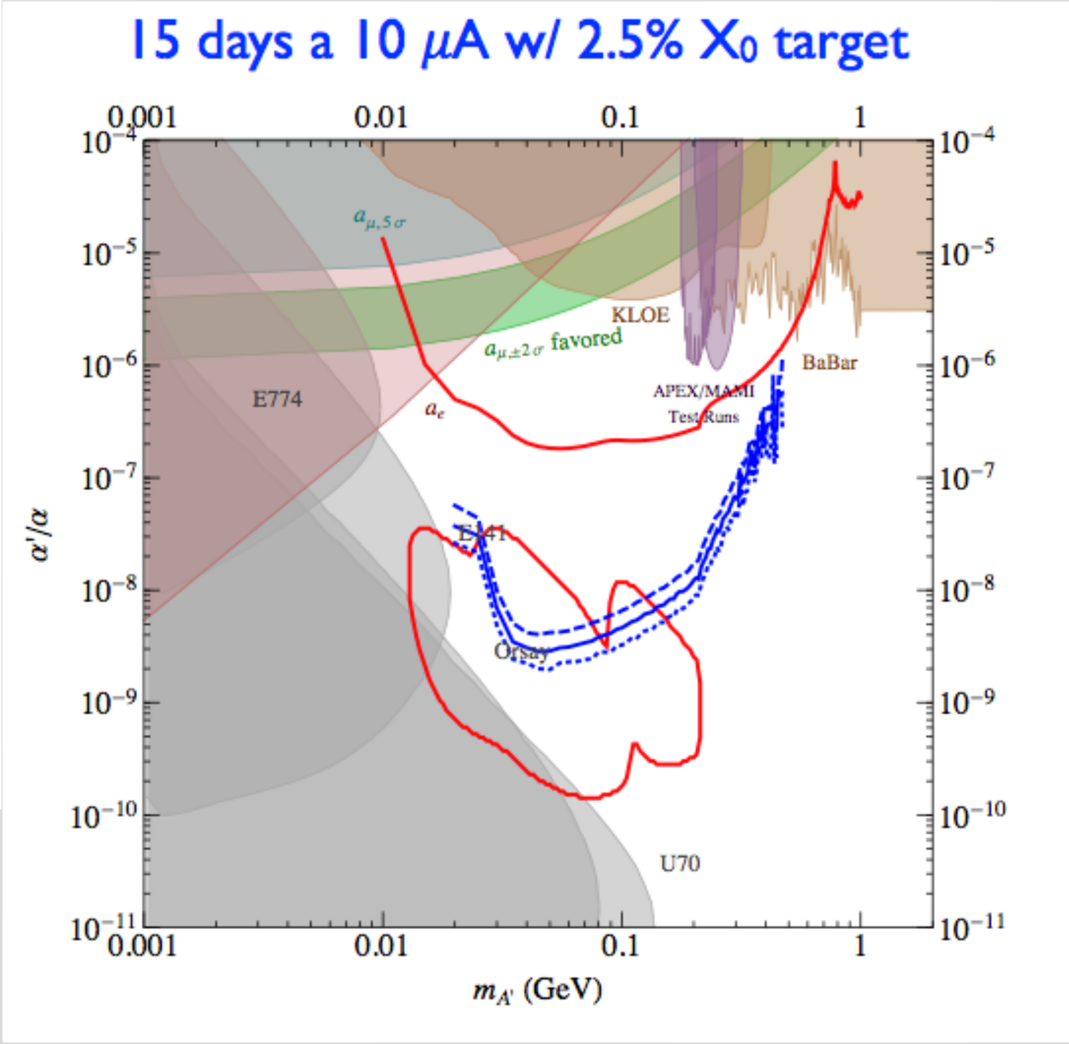
This is an exercise, not a run plan.

Tim's crazy idea #1: HPS^2

Tim's exercise for Snowmass: come up with crazy ideas.

- dual-armed spectrometer, copy of HPS for each "arm"
  - forget about vertexing, open up dead region
  - blast a thick-ish target

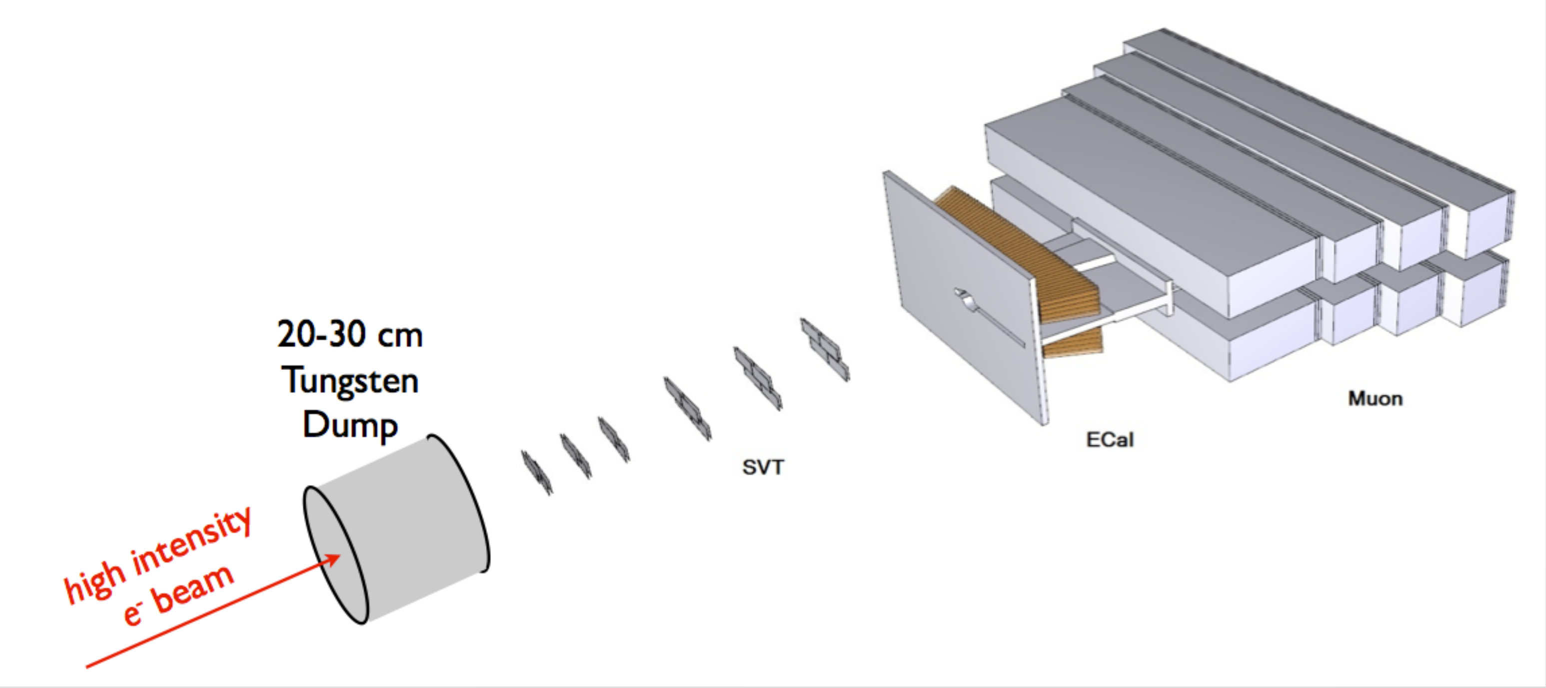


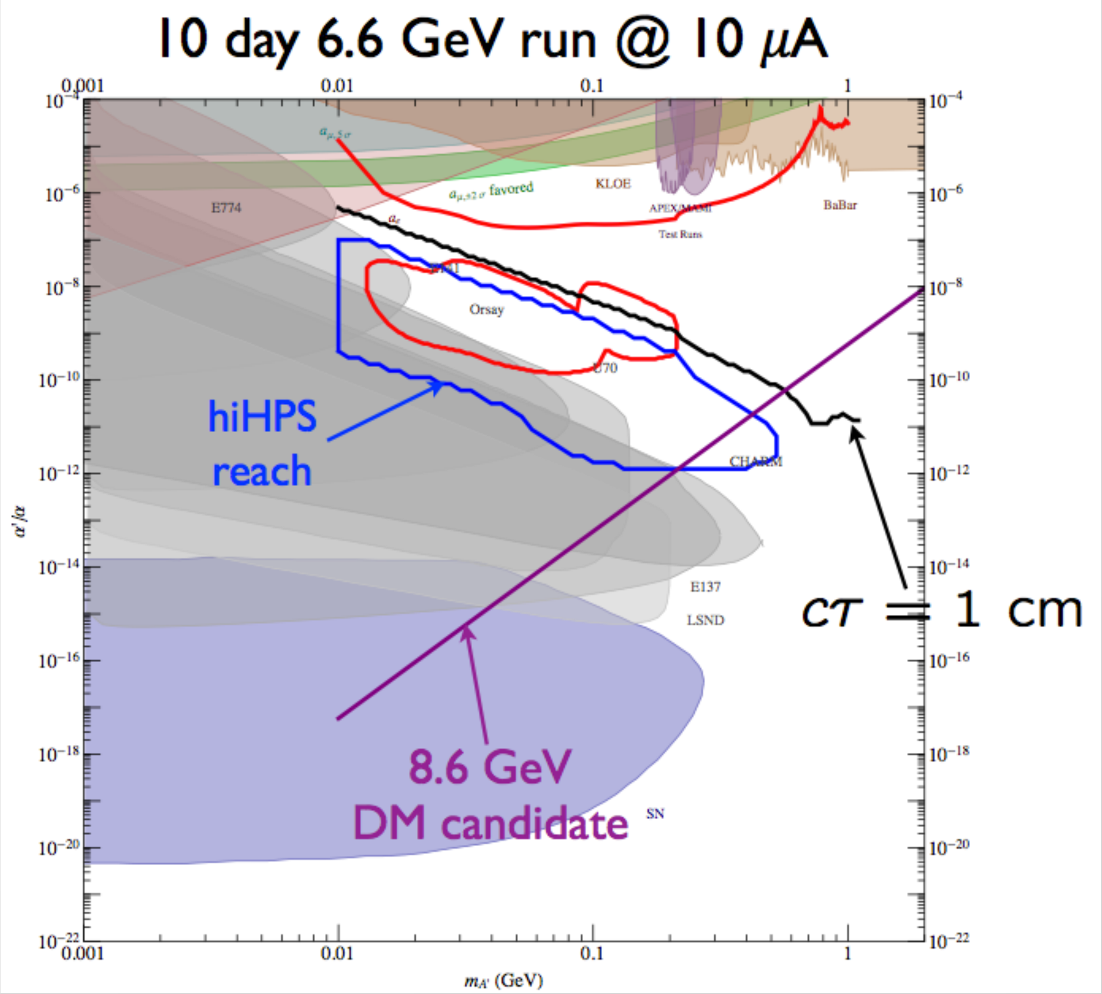


Tim's crazy idea #2: hiHPS

Tim's exercise for Snowmass: come up with crazy ideas.

- HPS with a mini-beam dump
  - minimal dead zone.
  - Require vertexing outside of dump⇒0 background
  - blast the dump…fair bit of power to take away. Still a lot of radiation on SVT…





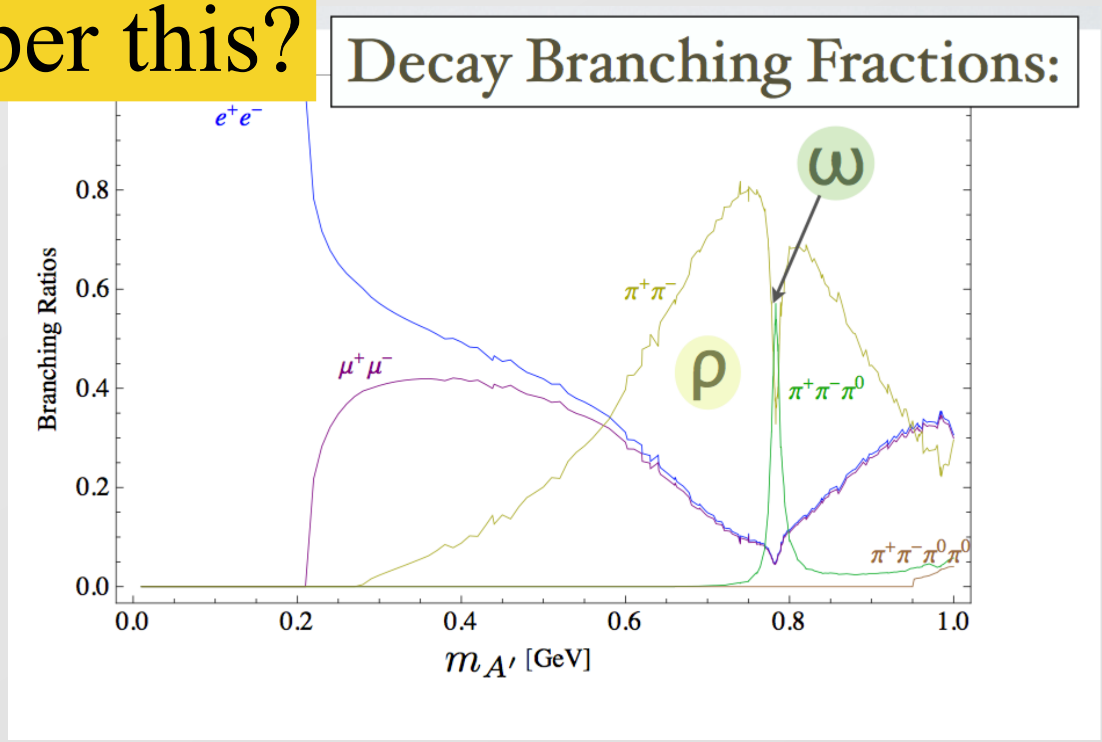
These are good ideas for ***after*** HPS!

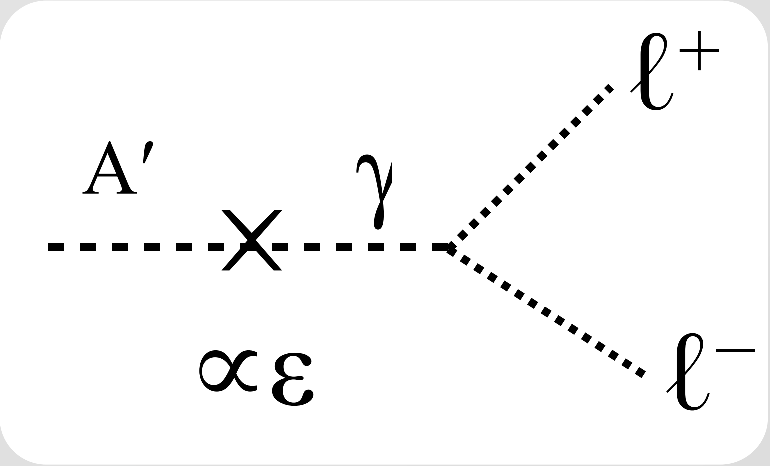
NEUTRINOS!

- SLAC has an Accelerator-Based Neutrino Group (ABNG)
  - M. Convery, D. Muller, JJ Russell, T. Usher, L. Rochester, MG
- We are members of LBNE & microBoone
  - LBNE: 35t physics (MC) & DAQ (MG & RED)
  - μBoone: sim & reco (TU, LR, DM)
  - Joined LBNE first; μBoone chosen for near term physics opportunities and to get into the LAr TPC game
- Why am I bringing this up?
  - μBoone→short-baseline experiment investigating sterile neutrino anomalies
    - sterile neutrino ***could*** be sign of a hidden sector (neutrino mixing with a fermionic singlet)
  - these same experiments can be used to detect hidden sector dark matter

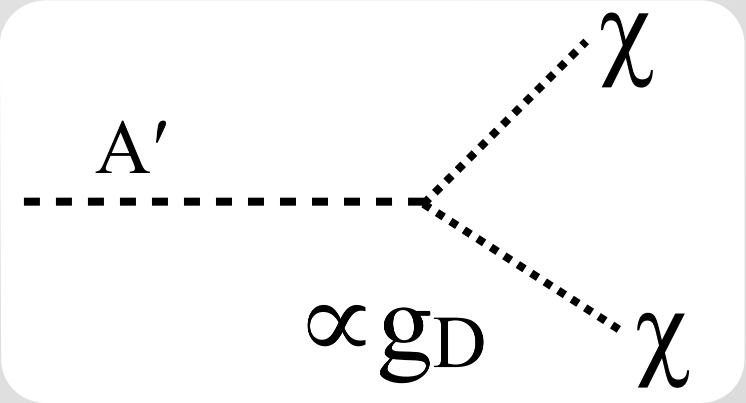
Another scenario…

Remember this?





⇒***BUT,*** if there is a state, χ, with dark charge and is lighter than 2m(A′)

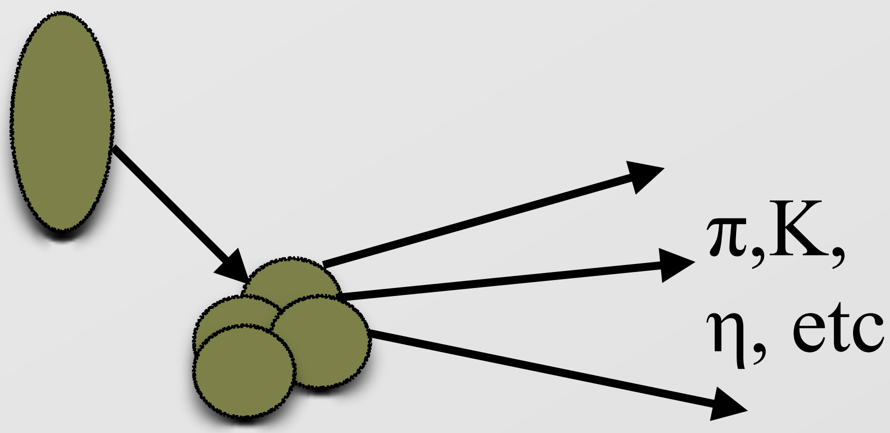


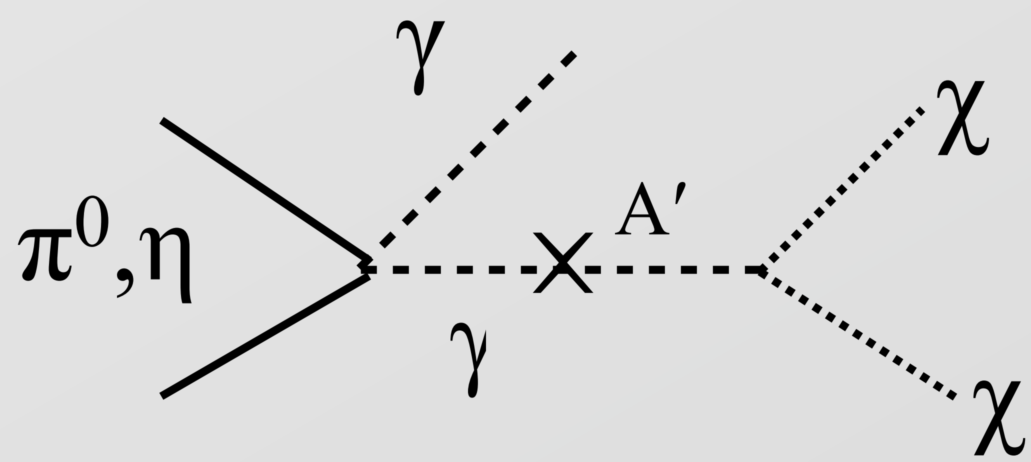
χ = light, hidden sector dark matter

…unless $g_D << \varepsilon$, ***A′ decays to dark sector will dominate***

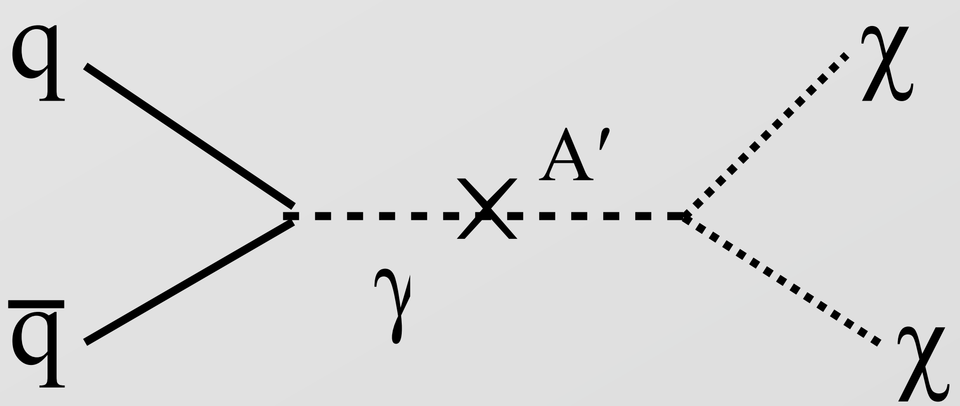
Light dark matter from proton beam dumps

…at low energies (8 GeV=FNAL Booster)



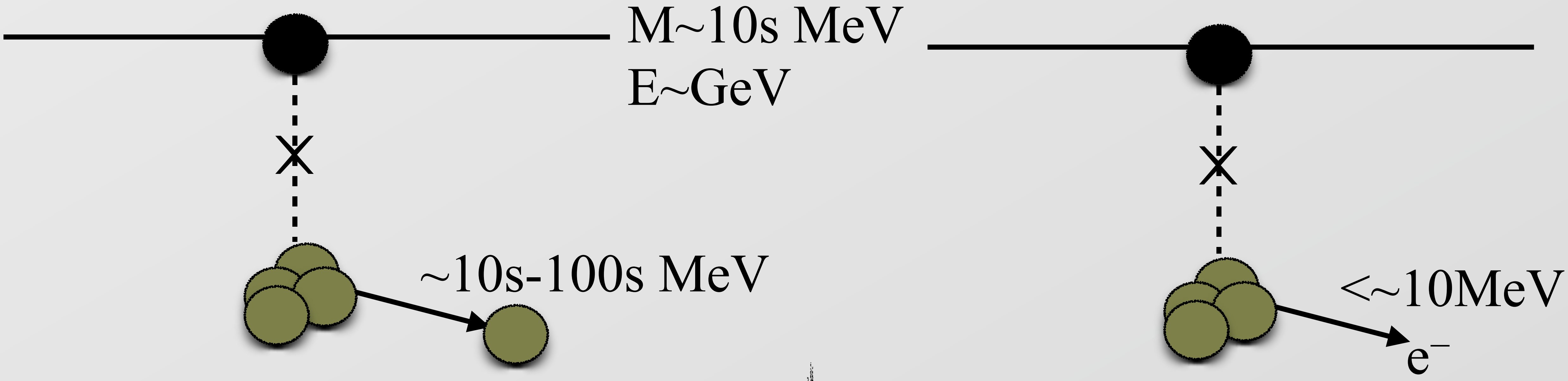


…at high energies (120 GeV=FNAL Main Injector)



There are a few proton beams running in the world now… primarily for neutrino osc:
FNAL Booster & NuMI
JPARC
…SNS too.

Detection of light dark matter (from beams)



nuclear recoils

coherent—low mA′,low E_{recoil}, Z^2 enhanced
quasi-elastic—mid mA′,mid E_{recoil}
DIS—high energies (both χ and recoil)

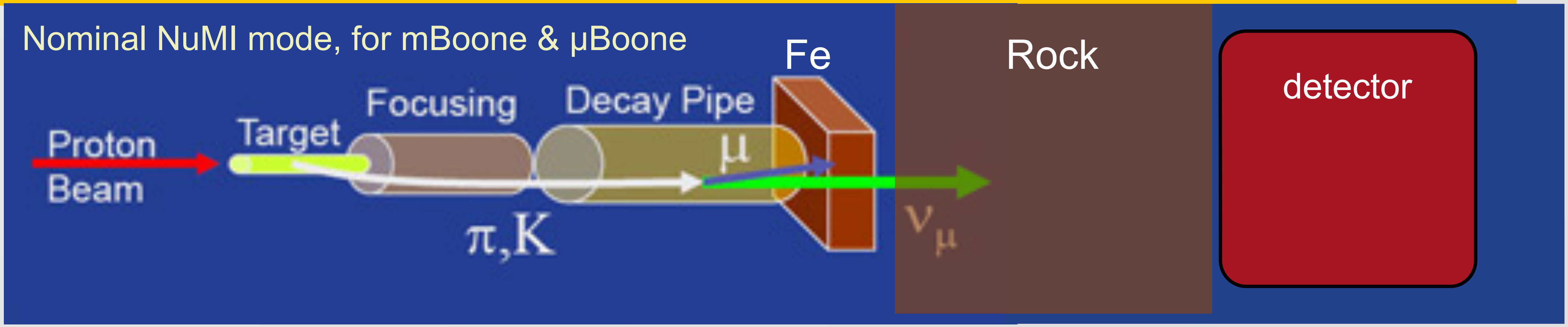
…QE has received most attention

electron recoils

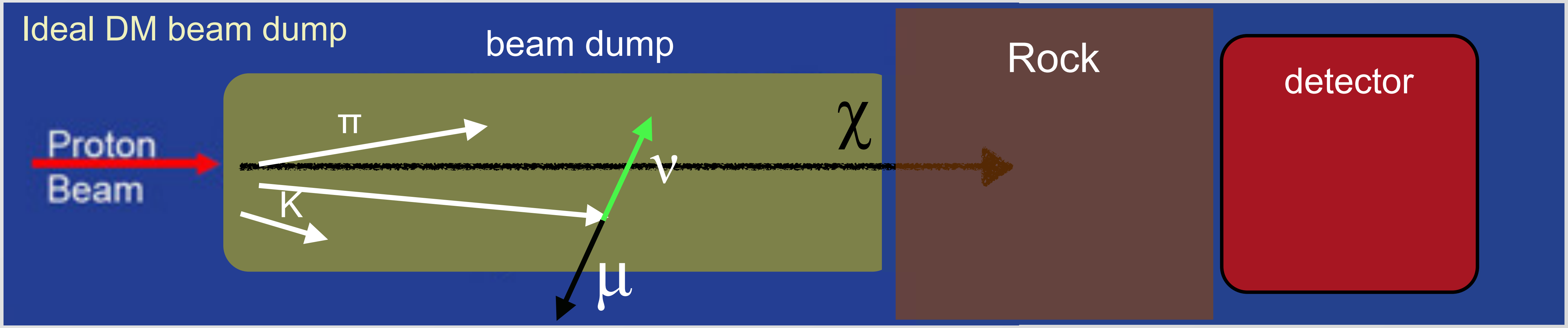
low mA′,low E_{recoil}, low background

These are the sorts of signals neutrino detectors are designed to see.
Very convenient!

Dark matter @ neutrino beams



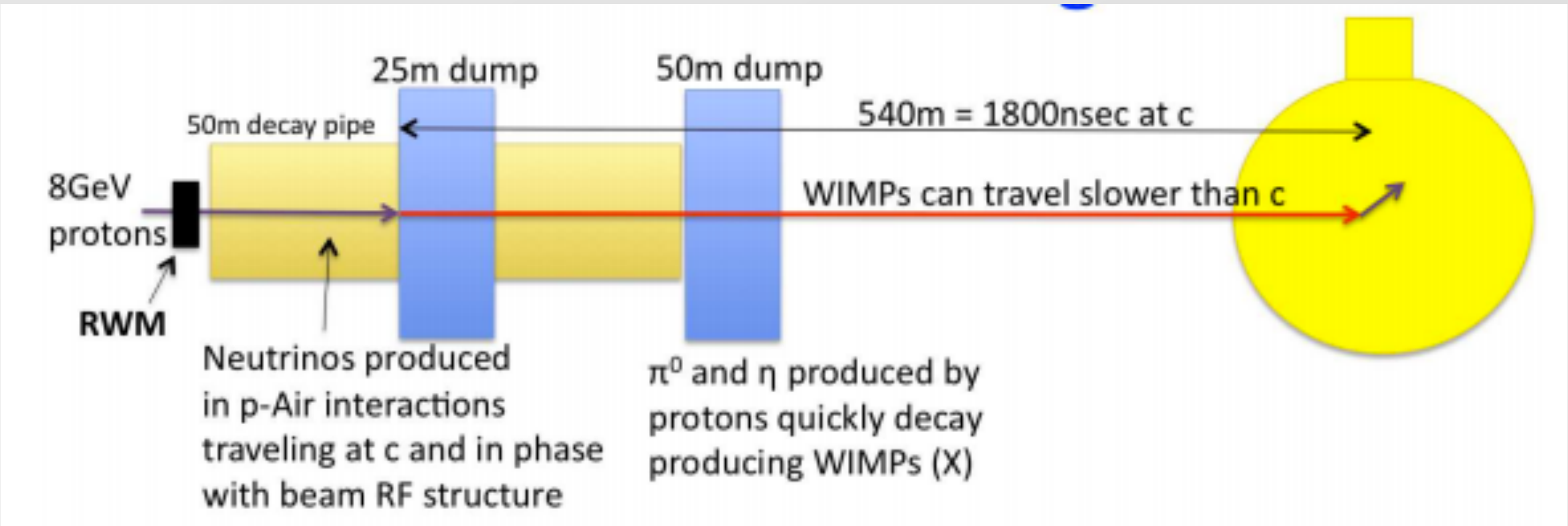
⇒ target/horn/decay pipe optimized to produce neutrino beam
BUT! neutrino NC events are ~irreducible background



⇒ lots of mesons produced, but most of them are captured or are stopped
Greatly reduced neutrino background

The off-target miniBoone proposal

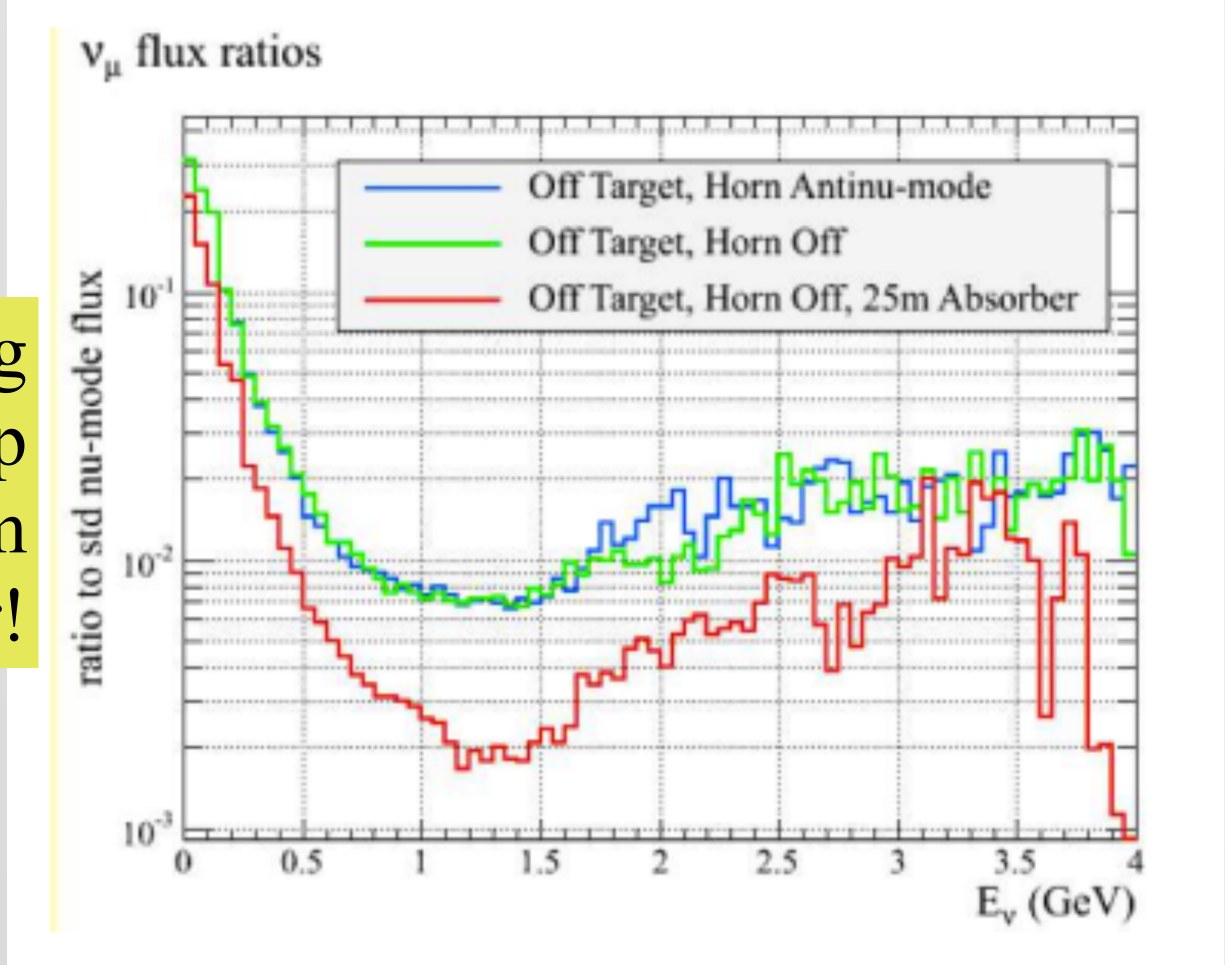
miniBoone proposal to run in "off-target mode" … not quite ideal beam dump, but better than neutrino mode!



miniBoone with beam off target

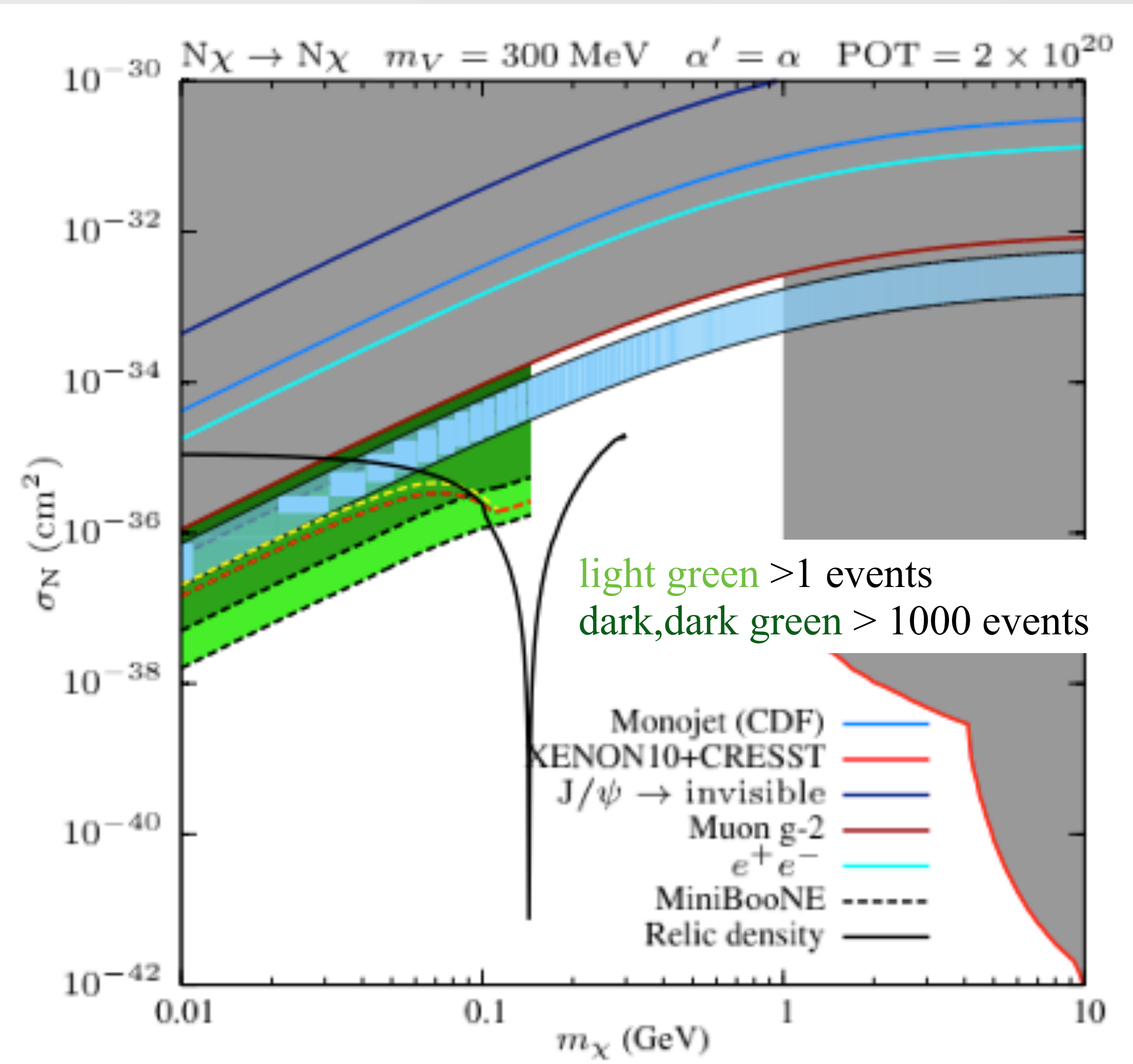
$$\frac{\text{Rate (events/POT)}^{\nu\text{ mode}}}{\text{Rate (events/POT)}^{\text{beam-off-target mode}}} = 42 \pm 7.$$

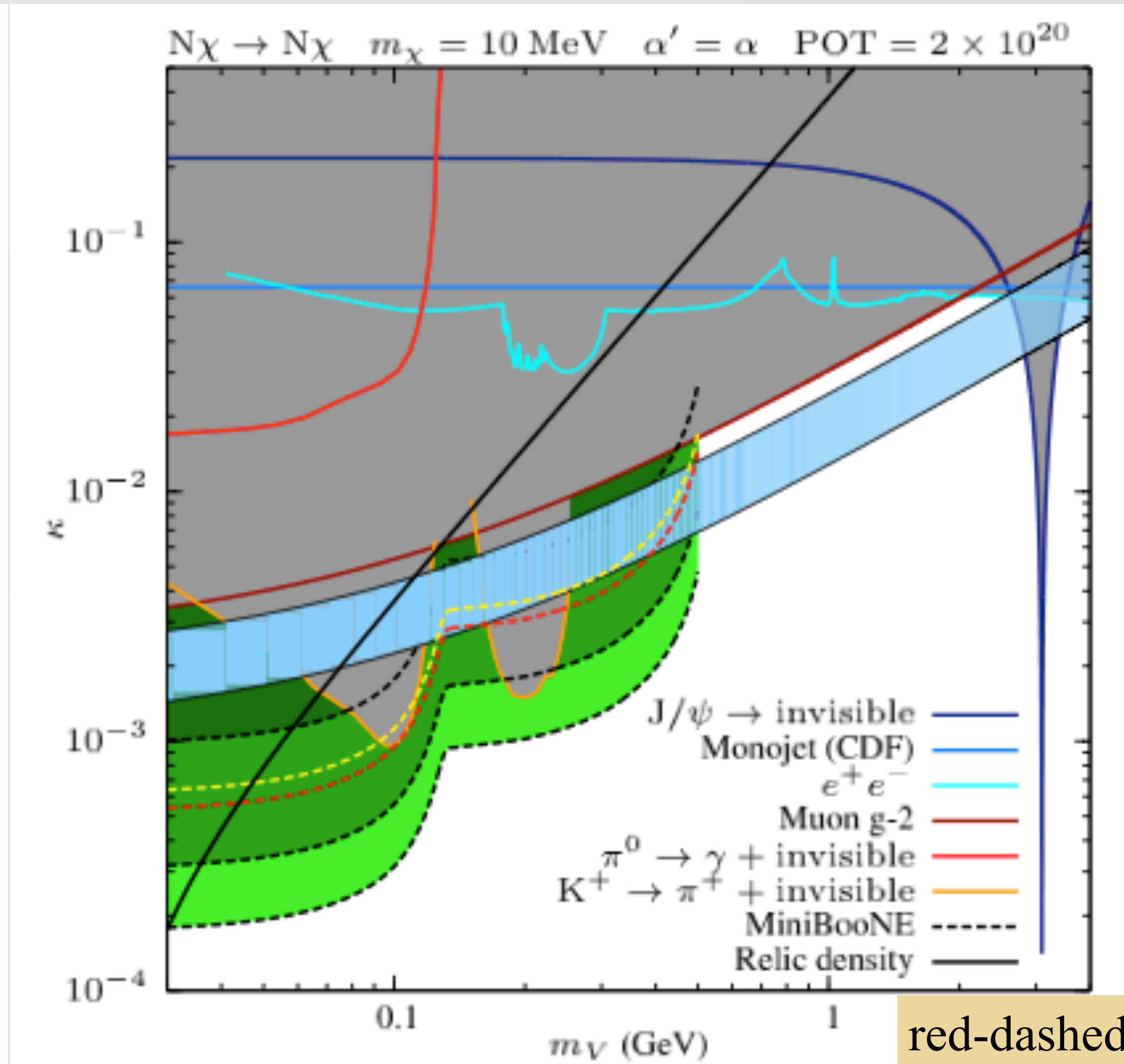
Additional ν suppression by placing absorber upstream (25m) of usual dump (50m)…most of the neutrinos come from interactions with the air!



R. Van de Water et al. arXiv/hep-ex 1211.2258

miniBoone off-target reach





red-dashed—90% excl.

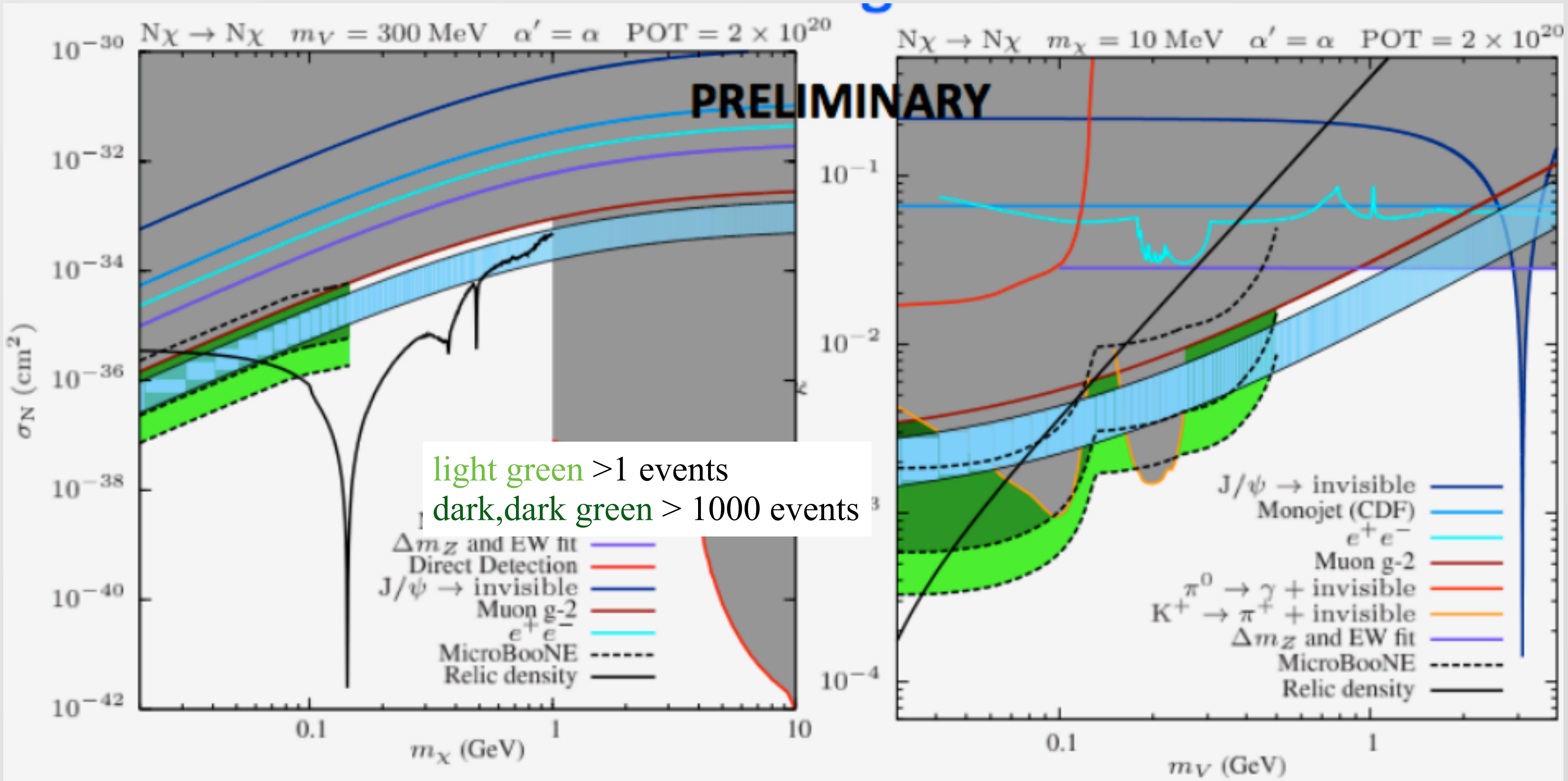
mA′=300MeV

	Scattering Channel	Beam Mode (2.0×10^{20} POT)	WIMP mass (MeV)/ cross section (cm^2)	Signal	Background and Errors	Probability
1	Nucleon	25m	$10/4 \times 10^{-37}$	1859	350±66	$< 10^{-10}$
2	Nucleon	25m	$30/3 \times 10^{-36}$	1453	350±66	$< 10^{-10}$
3	Nucleon	25m	$50/8 \times 10^{-36}$	1326	203±40	$< 10^{-10}$
4	Nucleon	25m	$100/3 \times 10^{-35}$	1186	9.2±3.4	$< 10^{-10}$
1	Electron	25m	$10/4 \times 10^{-37}$	13.2	0.15	$< 10^{-10}$
2	Electron	25m	$30/3 \times 10^{-36}$	7.7	0.15	$\sim 10^{-9}$
3	Electron	25m	$50/8 \times 10^{-36}$	4.8	0.09	$\sim 10^{-6}$
4	Electron	25m	$100/3 \times 10^{-35}$	1.4	0.004	$\sim 10^{-3}$

note: constrain in parameter-space= (κ=ε, α_D,mA′,mχ)

R. Van de Water et al.
arXiv/hep-ex 1211.2258

microBoone off-target reach



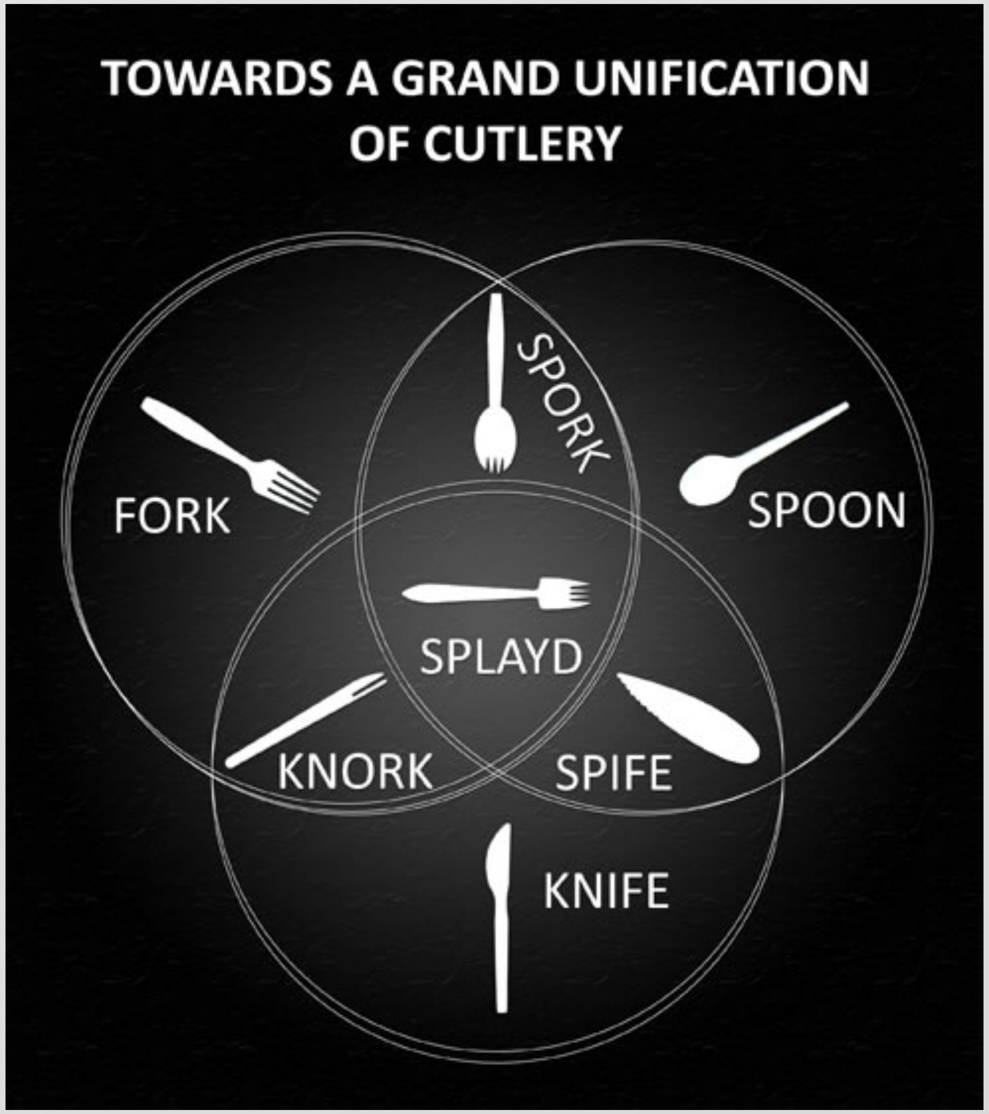
By the way, μBoone people thinking about this too (some are the same people as mBoone)…even though quite a bit smaller, can get decent reach.

Much more information in the LArTPC…may be able to reduce backgrounds significantly. Not included in these plots.

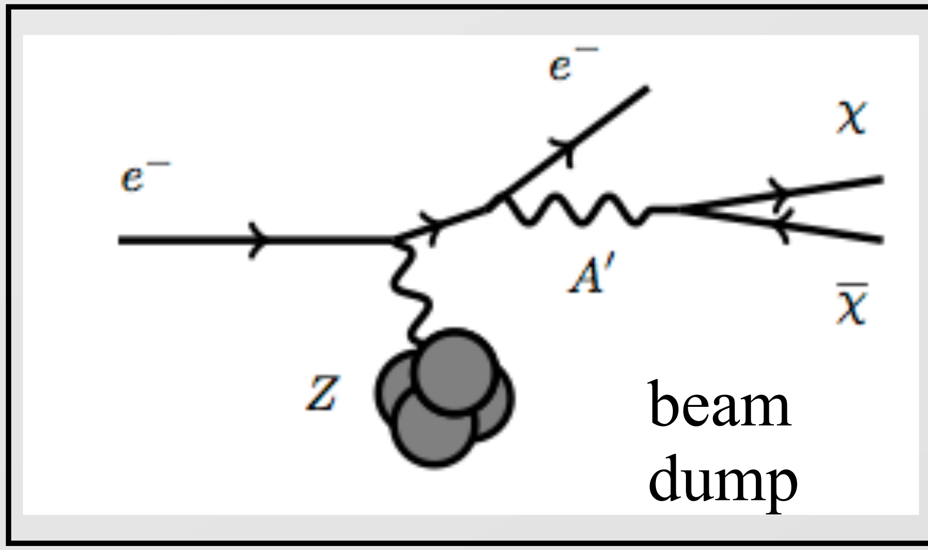
R. Van de Water et al.
microBoone Collaboration Meeting

mBoone & µBoone off-target plans

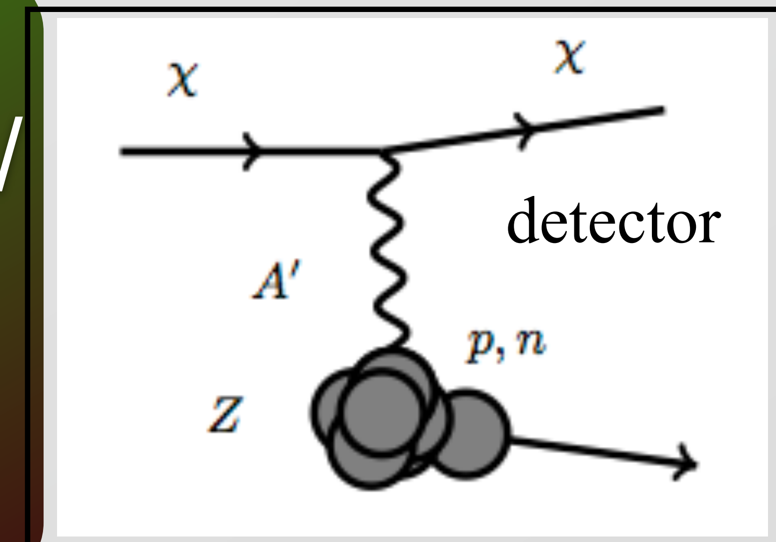
- miniBoone request of a 0.35×10^{20} POT off-target test run was approved by FNAL…this is happening NOW.
- they are proposing to PAC to run until µBoone is ready for beam, mid-late-next year. Hope for ~ 1×10^{20} POT total



Dark matter @ electron beam dumps



X meters of rock/ concrete/dense garbage

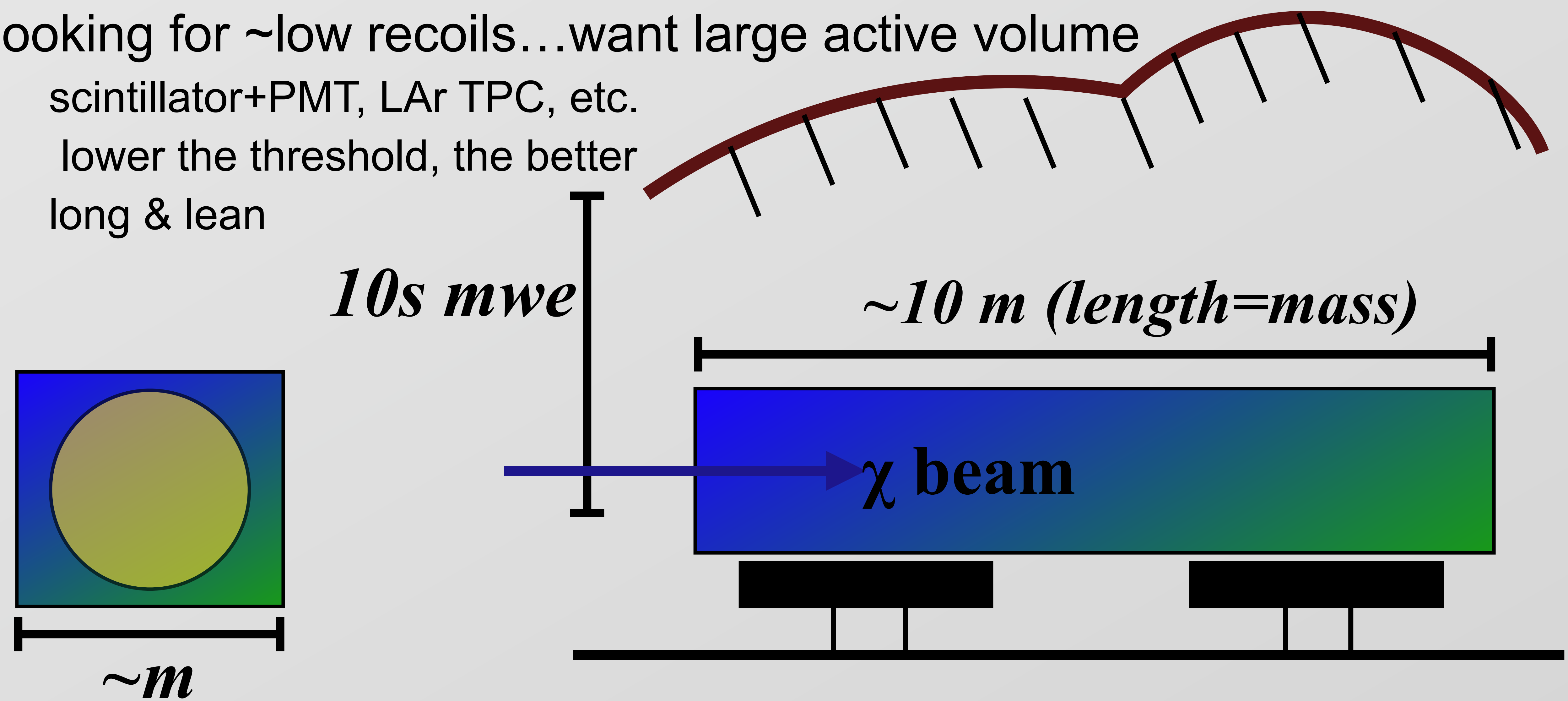


- better than proton beams⇒electron beams
- production mechanism more straightforward…not limited to meson production/decay at low energy
  - (hardly) no neutrinos produced
- high-current electron beams today: JLAB (11GeV) , SLAC (FACET, 20GeV)!
- drawback/opportunity: no detectors on these dumps

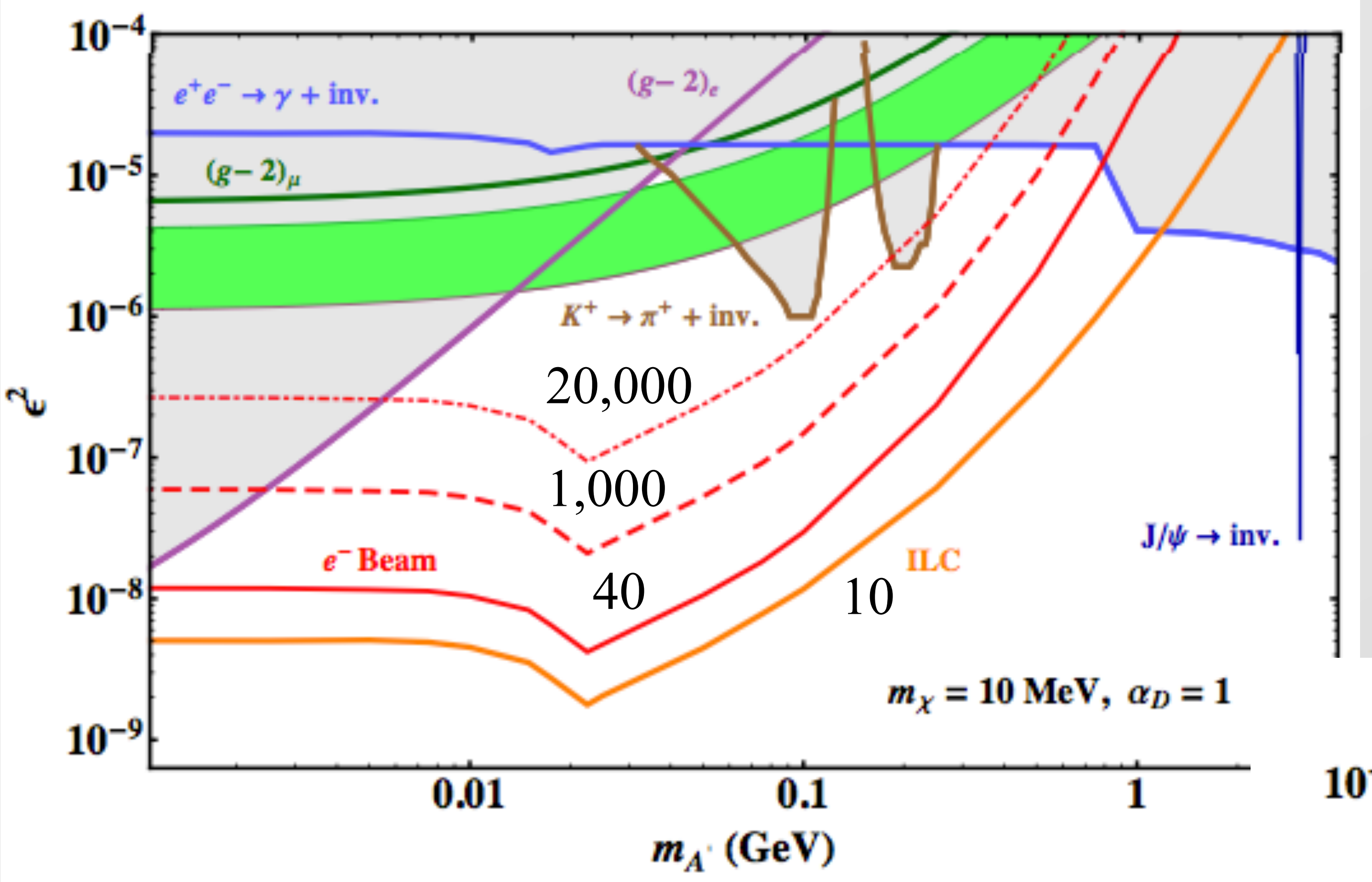
Izaguirre, Krnjaic, Schuster, Toro
hep-ph/1307.6554

Building a detector

- according to IKST, beam related backgrounds are negligible (needs more study)…backgrounds come from cosmics. Particularly cosmogenic neutrons.
- pulsed beam: use beam gate…for 30Hz beam ~10 neutrons/year
- continuous beam: active/passive vetos, directionality?
- looking for ~low recoils…want large active volume
  - scintillator+PMT, LAr TPC, etc.
  - lower the threshold, the better
  - long & lean

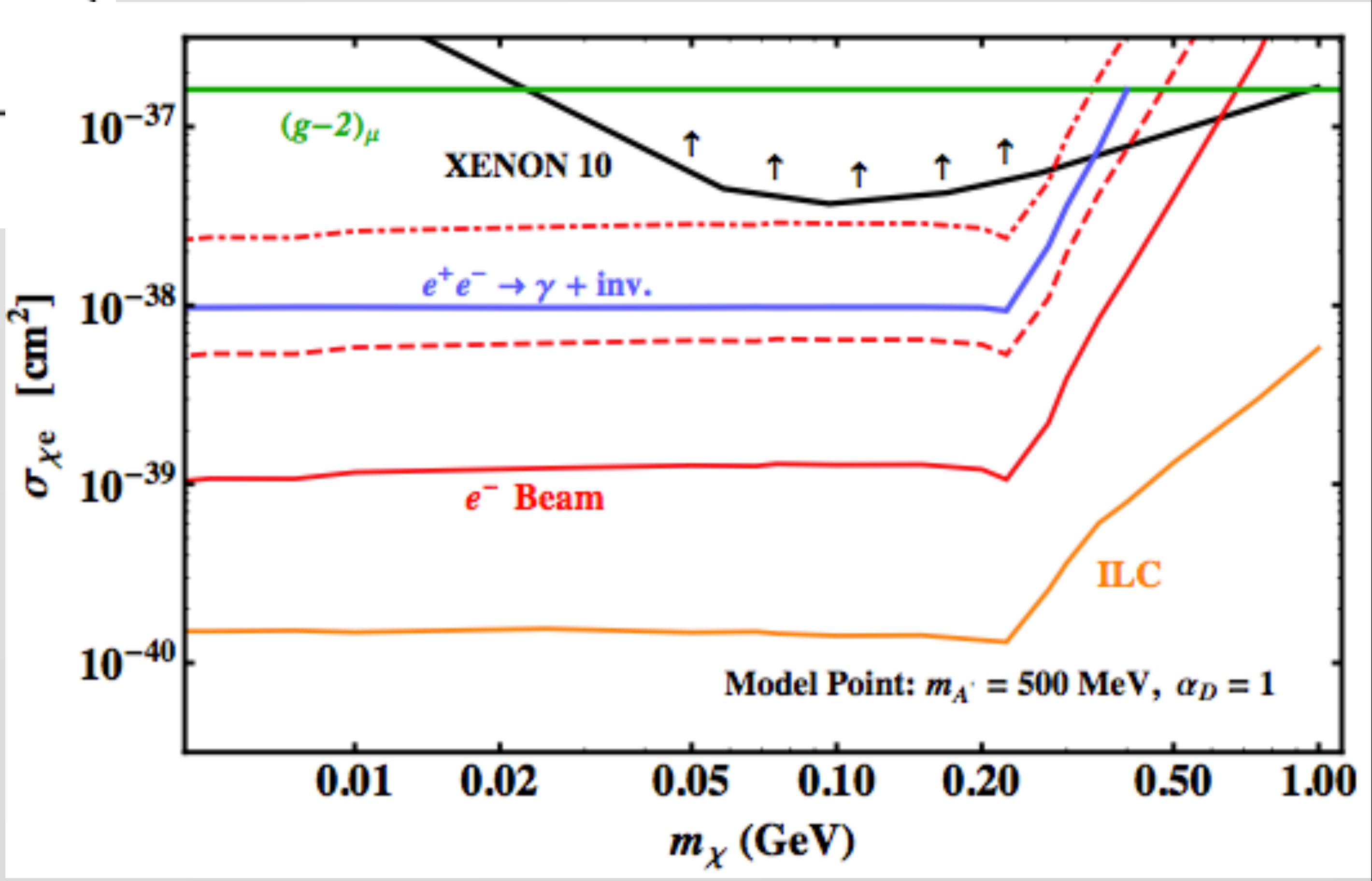


Events from 1 year @ JLAB-type beam



e⁻ Beam :
10^{22} electrons @ 12 GeV
E_{recoil} > 10MeV for QE-NR

detector = 1m x 1m miniBoone

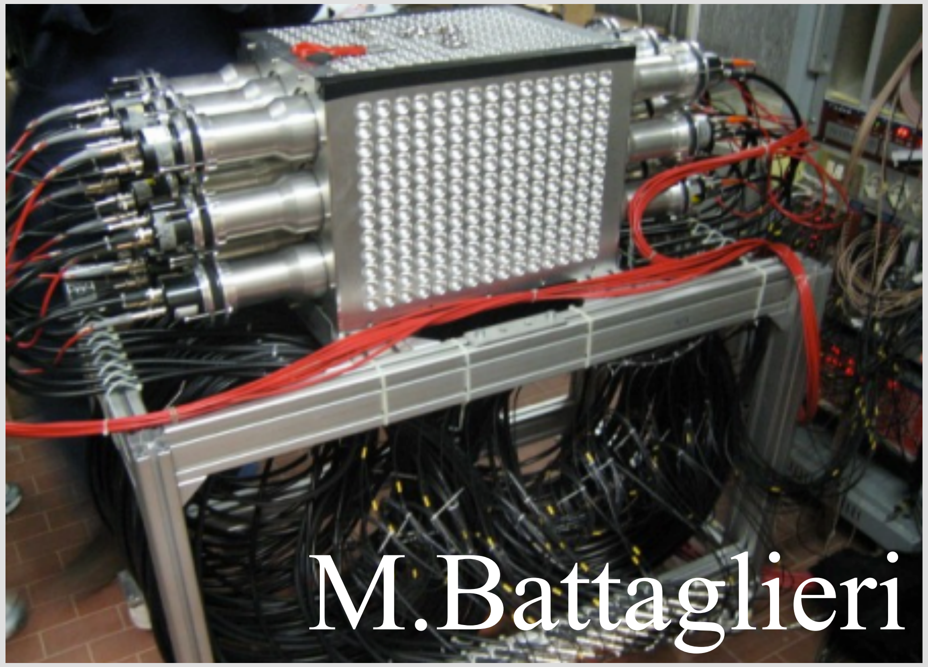


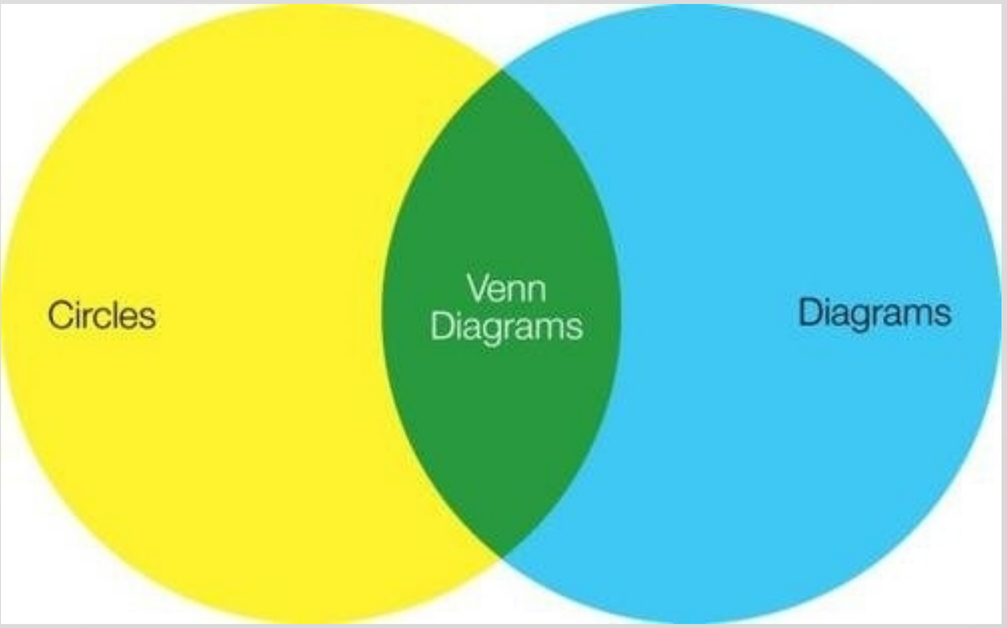
The red contours are events, not reach…expect ~ 10k cosmogenic neutrons without any mitigation

Izaguirre, Krnjaic, Schuster, Toro hep-ph/1307.6554

What's SLACs role in this?

- …not much right now. It's still early and we are focused on getting HPS built and running.
- mini-workshop/offshoot of the MENU conference this year dedicated to this topic (dark matter from electron beams) organized by HPS Italian collaborators.
- proposal to put ***CORMORINO*** detector behind HALL-B beam dump to test beam & cosmic backgrounds
  - HALL-B doesn't work for this type of experiment long term…not enough current. Other halls have different problems.\
- Stay Tuned!





Summary & Sermon

- There are good theoretical arguments for the existence of a hidden sector…particularly one that talks to us via the vector portal
- Dark matter…what is it? Don't believe anyone who tells you they know the answer
  - the answer is that it is a hidden sector particle
- HPS is well on it's way…next few years will be busy and exciting
- To really explore vector portal, need to look for "invisible" decays as well…for low masses, this means beam dumps
- This is good stuff! High impact, low cost…we need more of this in our field!