Title: Beyond the Standard Model â€“ Experiment: BSM in neutrino experiments

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Abstract:

Experimental Searches for Dark Sector Particles

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SLAC
TRISEP 2015
July 2015

What I will talk about

- Introduction to dark sectors & portals to the SM
  - kinetic mixing!
- Dark sector DM interactions
  - Constraints (and hints) from astrophysics
- Dark sector particle production & decays
- ……………

What I will talk about

- Introduction to dark sectors & portals to the SM
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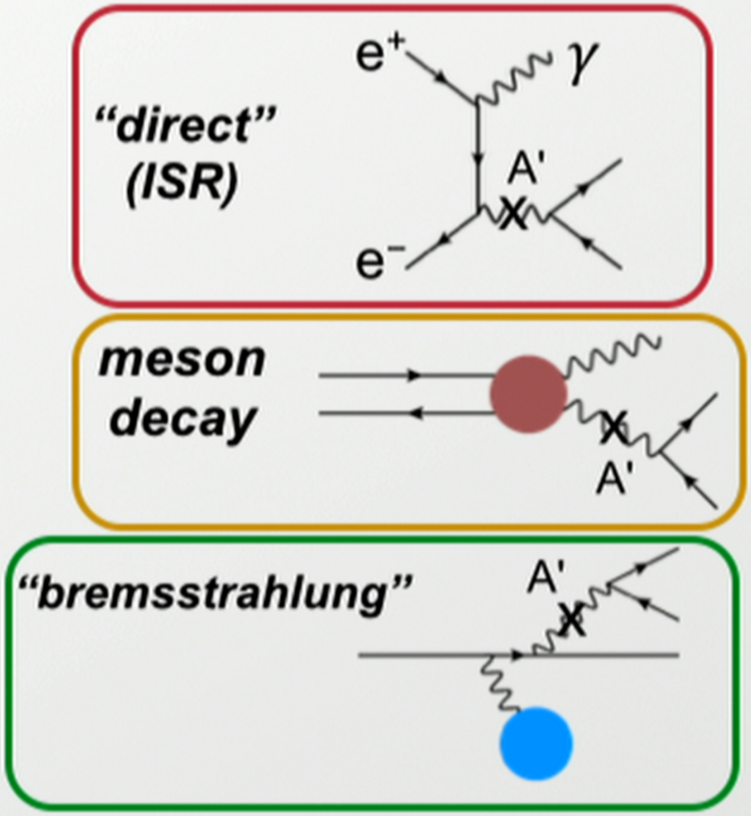
  - Constraints (and hints) from astrophysics
- Dark sector particle production & decays

- How to produce dark photons in the lab (if they exist)
- How to detect dark photons in the lab (if they exist)
- Current experiment constraints on dark photons & future (near and far) plans
  - upcoming fixed target experiments
- Light dark matter & dark matter beams

Dark Photon Particle Production:
The Experimentalist View

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



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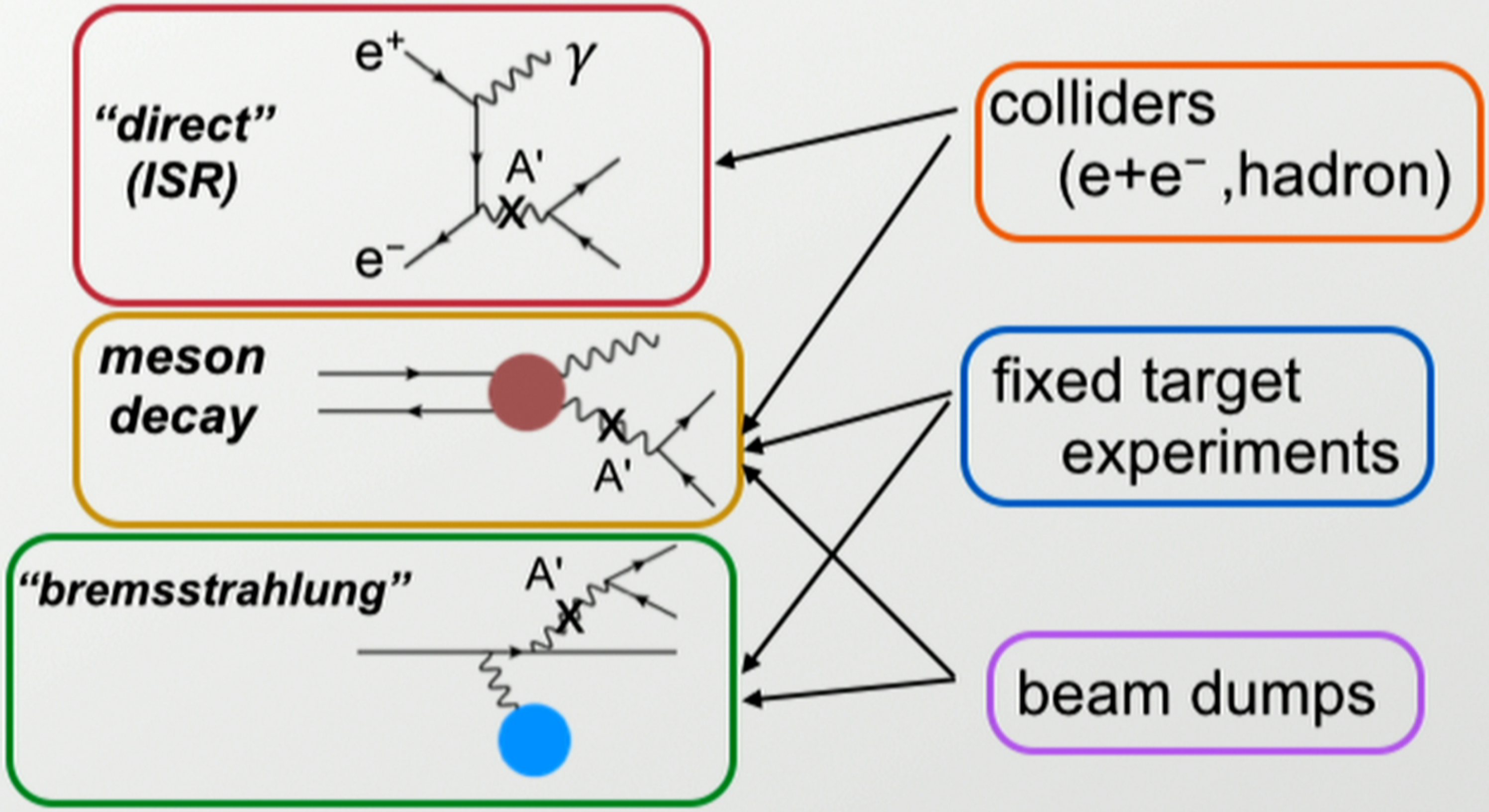
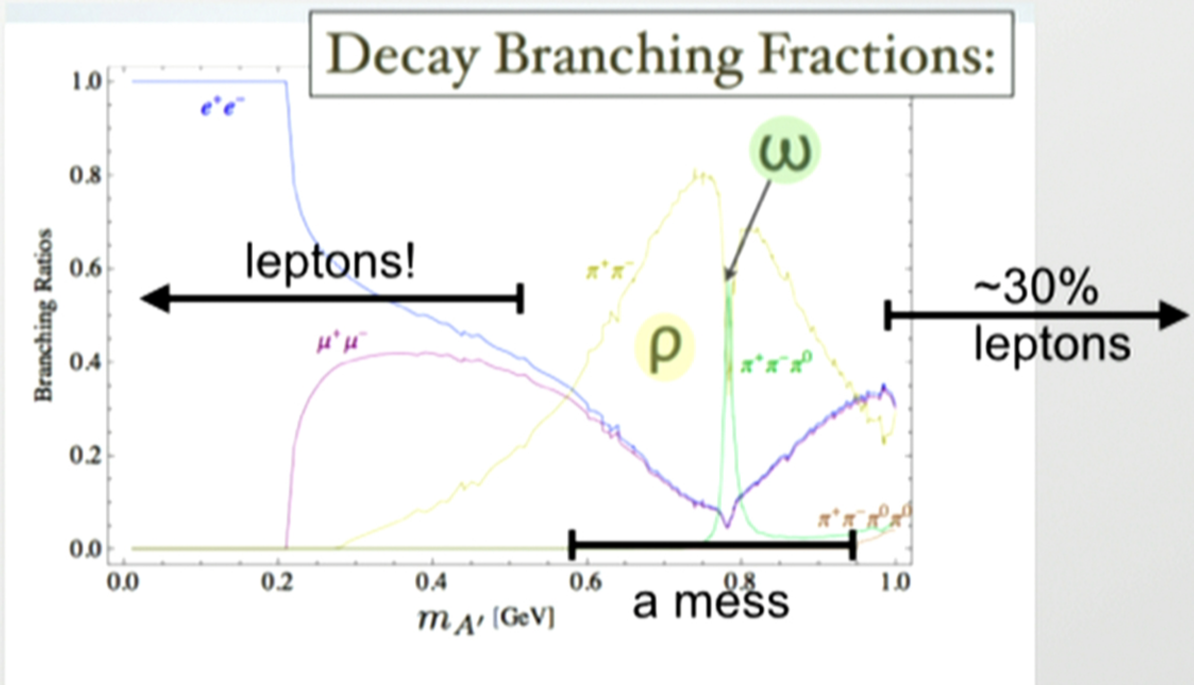
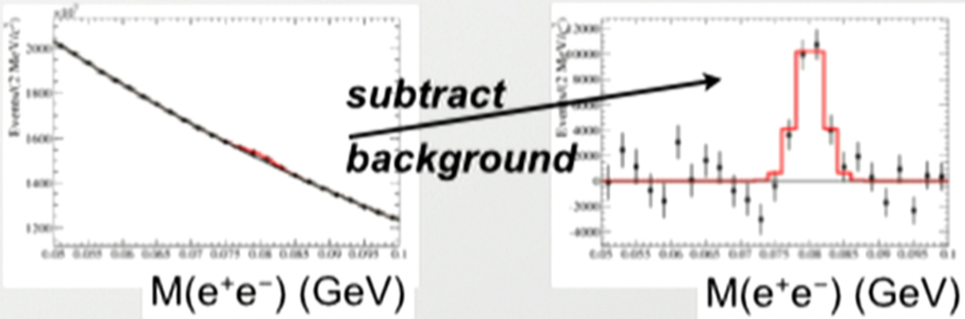


Visible decays of the dark photon

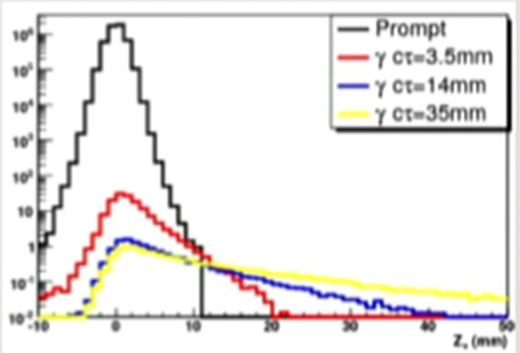


Two characteristics of the dark photon

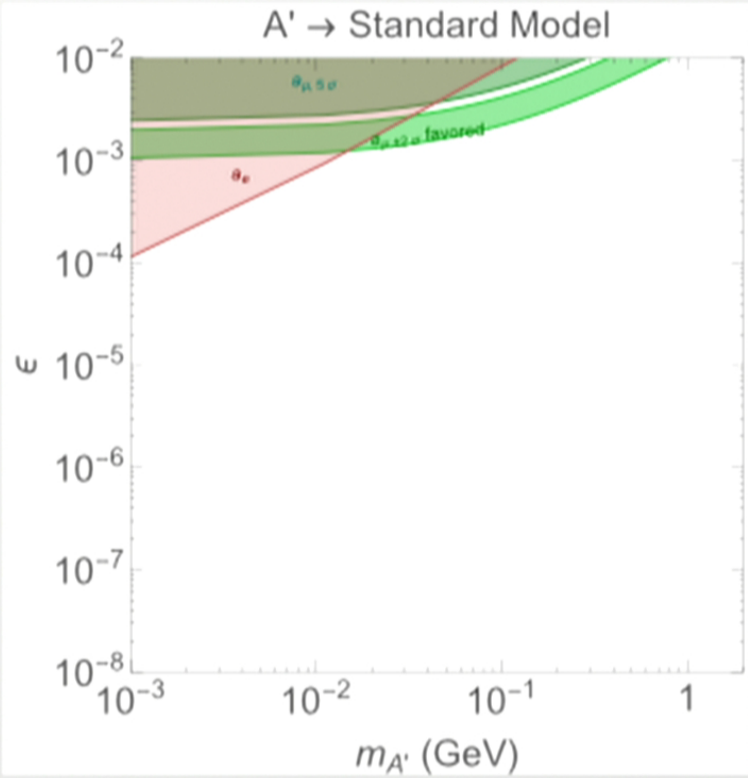
- Massive
  - when we say "dark" photon we typically also mean "heavy"
  - look for peak in the invariant mass spectrum



- Non-zero lifetime
  - some regions of parameter space will have decays that happen far from production target
  - backgrounds typically decay promptly



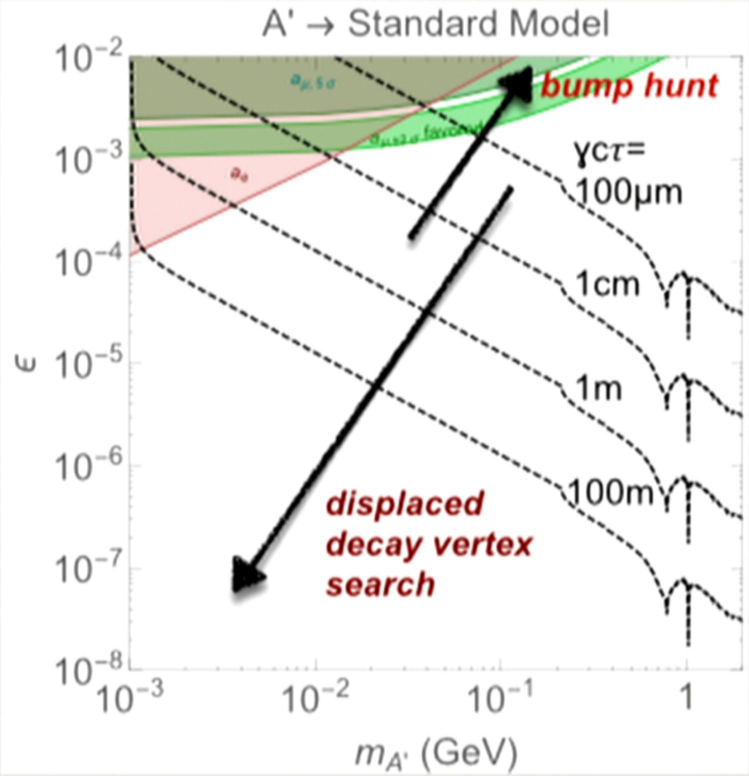
Reach plot: v0



Start off with 2 indirect constraints: g-2 of electron & muon

But! A ~3σ anomaly in g_μ-2 …interesting territory!

Reach plot: v0



assume $E_{A'}$=20GeV

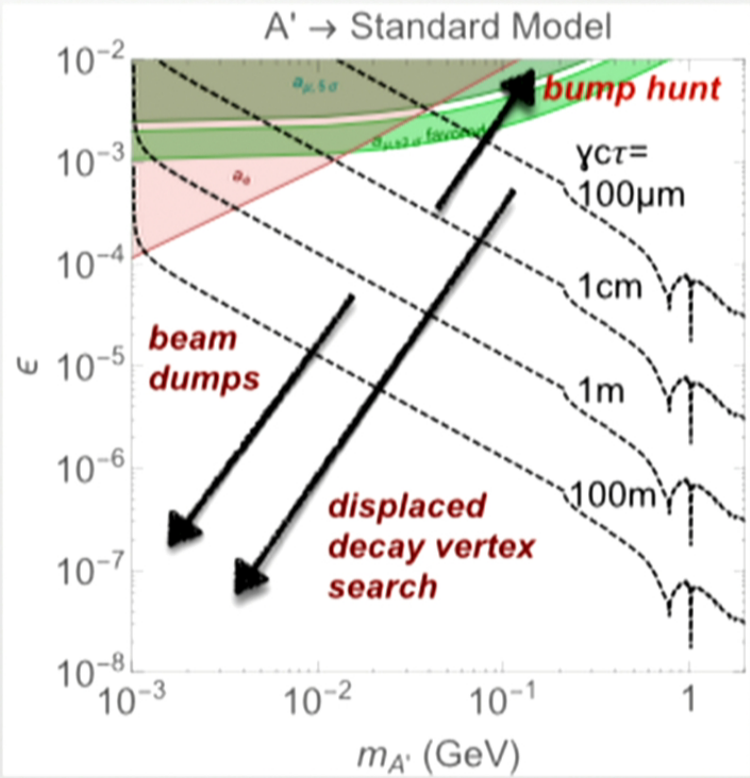
thinking about direct searches…

if (ɣcτ<~100 μm) bump-hunt;

if (ɣcτ > 1 m) displaced decay;

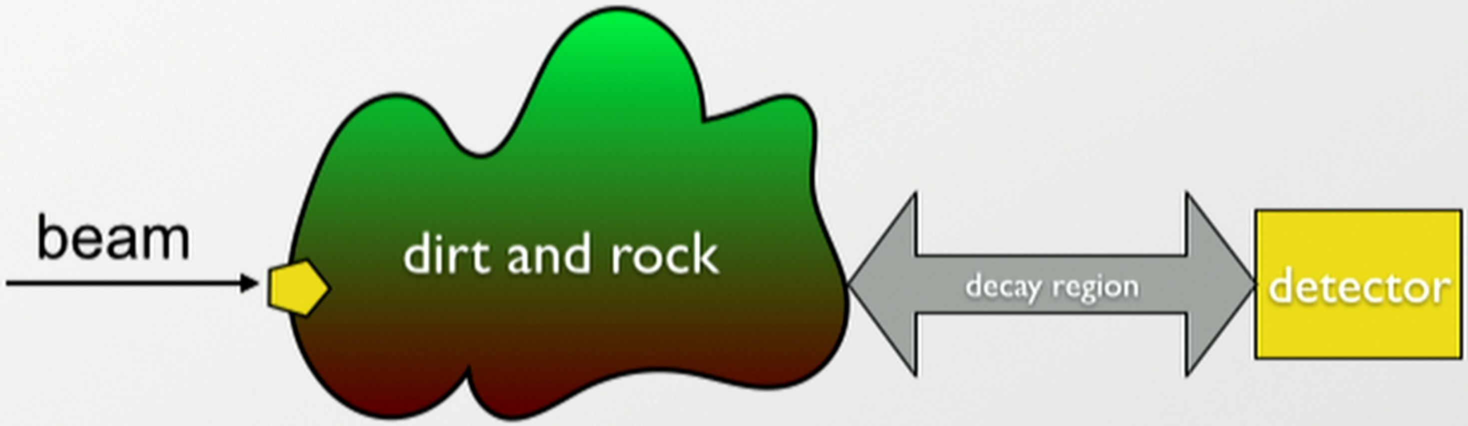
…some mushy middle where both handles are useful;

Reach plot: v0

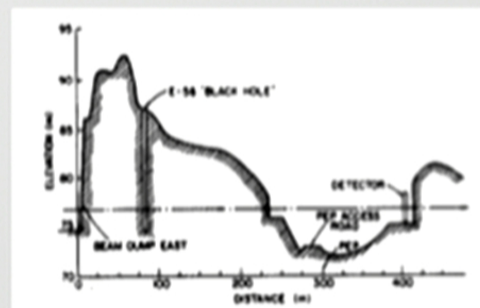


…for very long-lived decays, beam dump experiments are useful

Beam-dump Experiments



- Beam energy & integrated current
- Length of absorber region
  - enough to absorb primary beam
- Length of decay region
  - effects acceptance



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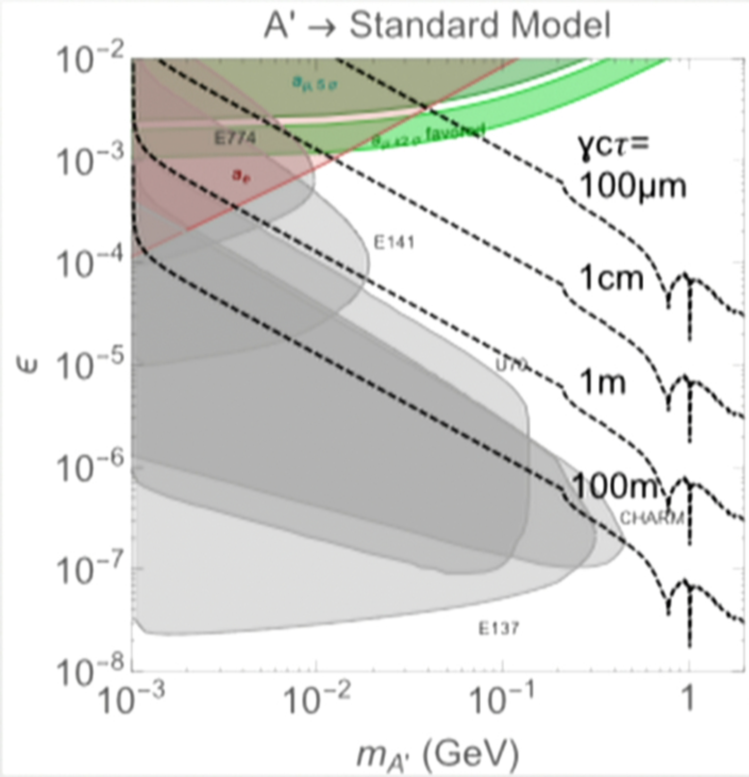
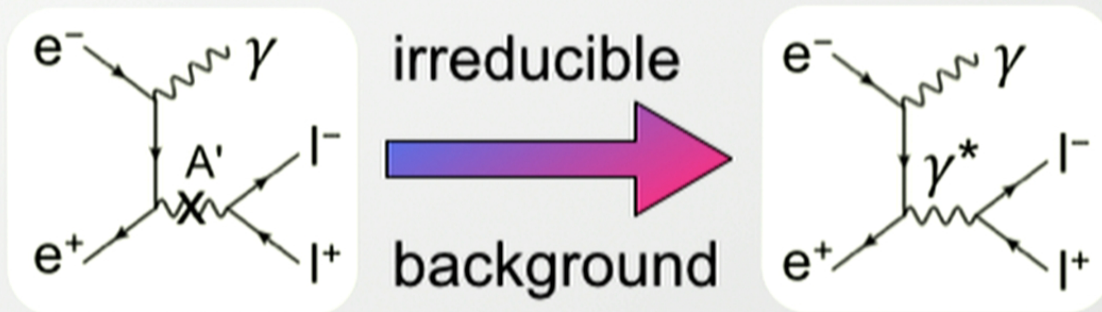
Beam dump reach



	Beam Energy (GeV)	particles-on-target	Length (m)
E774 (FNAL)	275	0.5×10^{10}	7.25
E141 (SLAC)	9	2×10^{15}	35
E137 (SLAC)	20	1.9×10^{20}	400
U70 (IHEP)	70	1.7×10^{18}	64
CHARM (CERN)	400	2.4×10^{18}	480

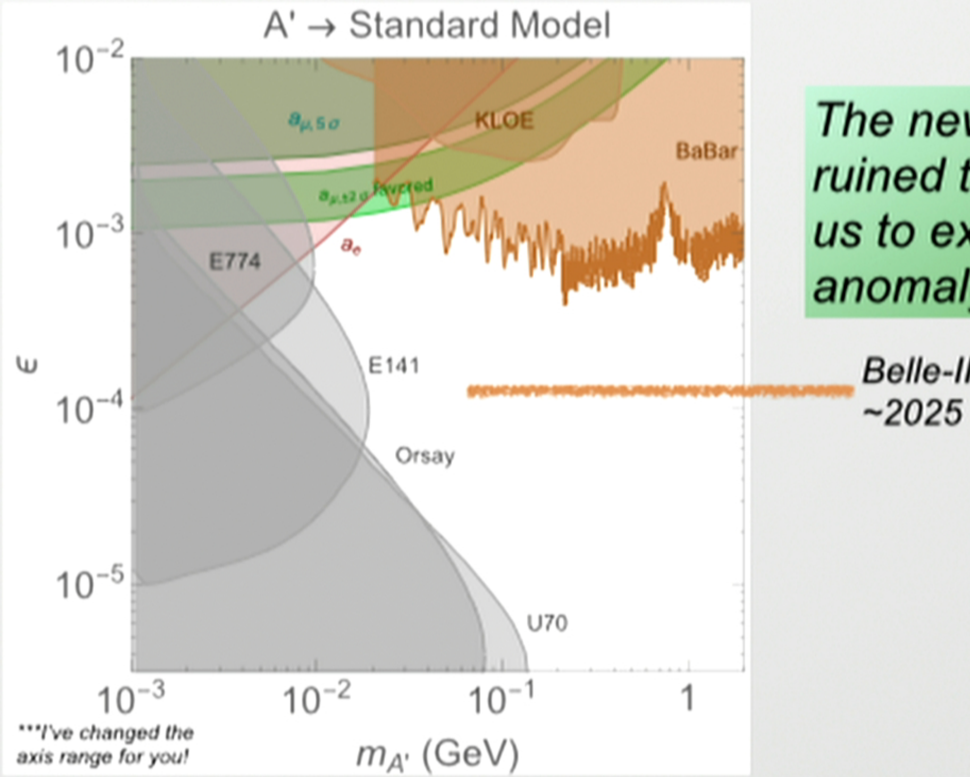
Other experiments too…
NOMAD, Orsay, KEK, etc

e+e- collider searches (flavor factories)



- The flavor factories (BaBar, Belle(-II), KLOE) are great places to look for dark photons:
  - high luminosity
    - not quite high enough to get to displaced-vertex regions
  - excellent acceptance & PID
    - also makes them good places to look for non-minimal dark sector (A'h, non-Abelian, etc)
  - good mass resolution ~ few MeV
  - see F. Porter's talk last Monday for the recent BaBar result!

Reach from flavor factories



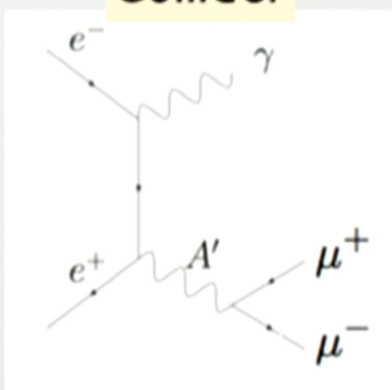
The new BaBar result has ruined the party for those of us to explain the g-2 anomaly with dark photons…

→KLOE result shown is from η decays

Collider vs. Fixed Target

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

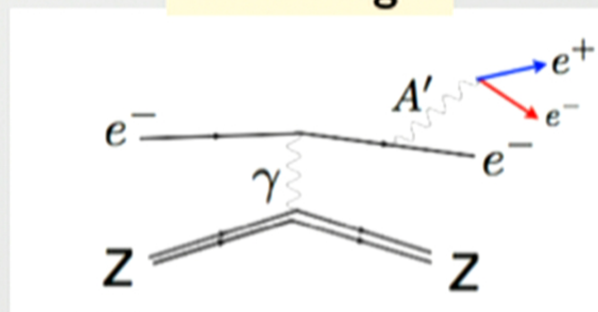
Collider



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

$O\ ab^{-1}$ per ~~decade~~ month

Fixed Target



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

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

...much higher backgrounds

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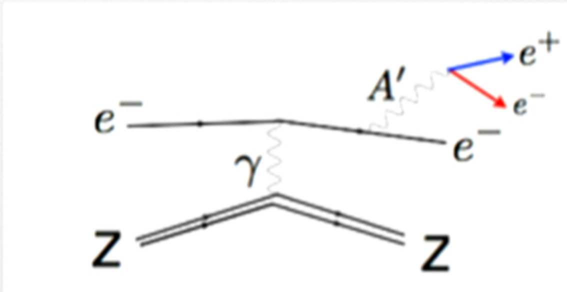
17

A' production & fixed target



Production is analogous to bremsstrahlung:

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

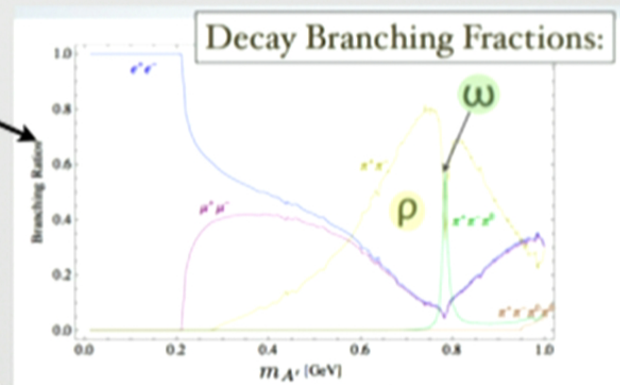
- prefers x~1 (i.e. $E_{A'} = E_{beam}$)
- small angle emission dominates

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

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

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

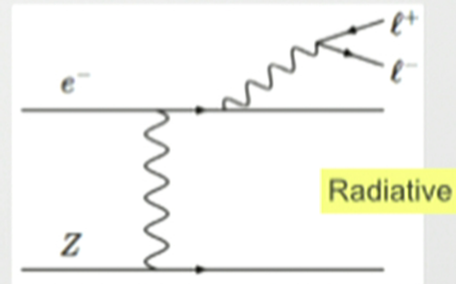
HPS is sensitive to A's with decays ~5-100mm

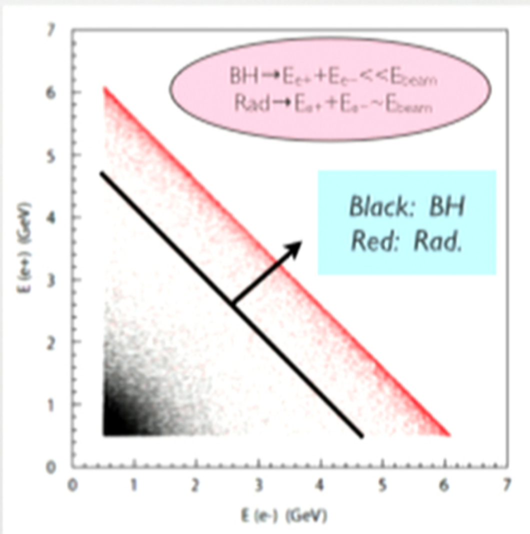


assumes A' can't decay to hidden sector particles

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!

Optimizing a fixed-target search…

Increasing Signal

high Z target (for low E_{beam})

Low m(A'), e^+e^- fine
add muons, pions at higher masses

High acceptance x current x target thickness

$$\frac{S}{\sqrt{B}} \sim \frac{\sigma(e^- Z \to A' e^- Z) \times B(A' \to f^+ f^-) \times \epsilon_{A'} \times \int I \times T}{\sqrt{(\sigma(Rad)\epsilon_{Rad}\delta M + \sigma(BH)\epsilon_{BH}\delta M) \times \int I \times T}}$$

Reducing Background

reduce mass resolution

reduce mass resolution
& exploit different kinematics

Mass resolution depends on detector momentum & angular resolution and multiple scattering in target (for prompt decays)

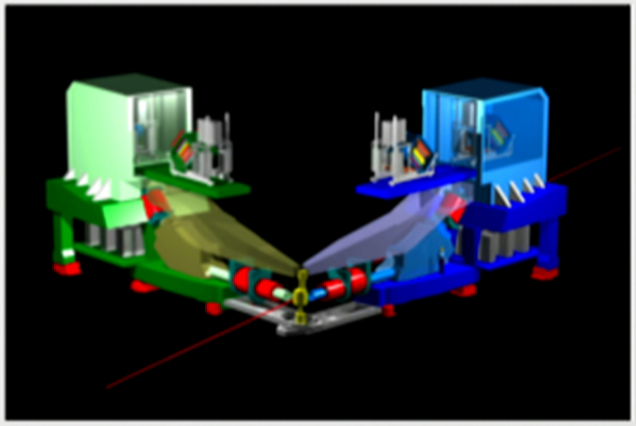
ALL OF THE BACKGROUND IS PROMPT! Detector with good vertex position resolution can reduce the background to effectively 0!

Background is really the "Radiative" + "BH" diagrams added coherently… numerically, this is REALLY IMPORTANT; for experimental optimization, less so

Two regions, two approaches

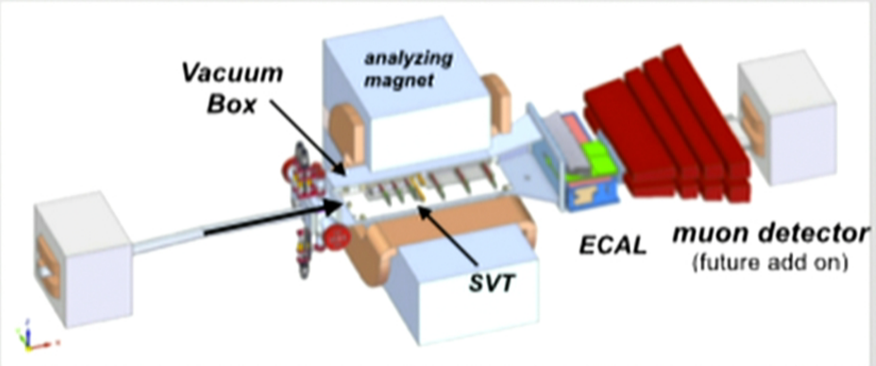
✓high-current, excellent mass resolution
- low acceptance, no vertexing

APEX @ JLAB, A1 @ Mainz



✓high acceptance, vertexing capability
- middling currents & mass resolution

HPS @ JLAB



The APEX experiment

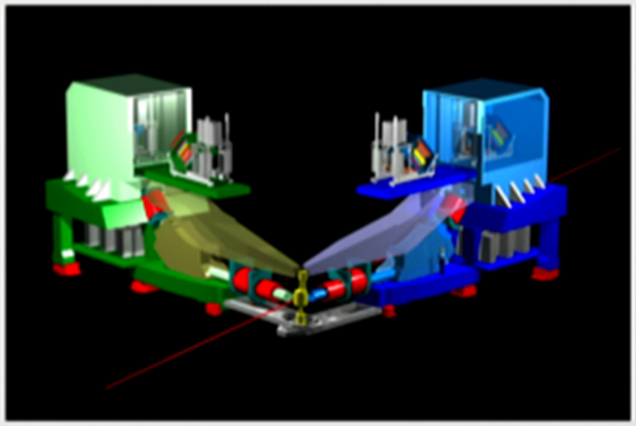
A **P**rime **EX**periment (I know…) takes the high current x thickness path

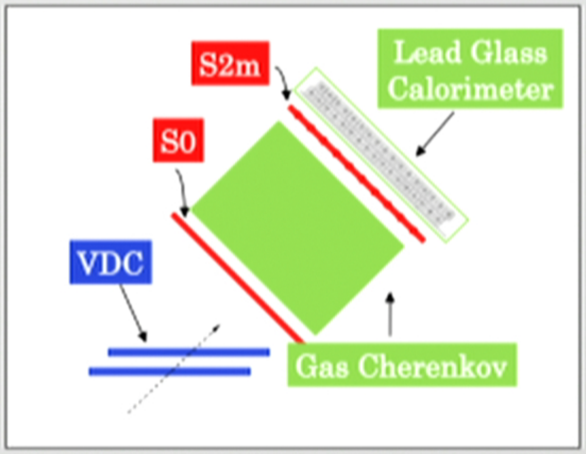
APEX uses the HALL A dual armed spectrometers to reconstruct the e^+e^- pair.

➡HALL A beam: <200 μA with 2 ns bunch spacing
➡drift chamber (tracking), gas Cherenkov (PID), hodoscopes(trigger)
➡great mass resolution (~1%), small acceptance (~0.1%)
➡mass resolution dominated by angular resolution (optics+tracker), MS in target

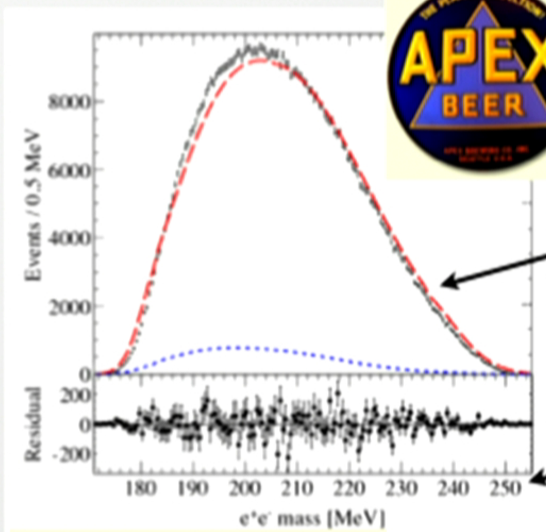
In July, 2010, APEX completed successful test run

- primary goal was to confirm calculated background rates; make sure we wouldn't burn down the detector hall for full run
- we were also able to take some interesting physics data





The APEX Test Run



Phys. Rev. Lett. 107 (2011) 191804.

APEX has taken successful test runs and published physics results!

- black points → data
- red → MC (madgraph)
- blue → e+e− accidentals

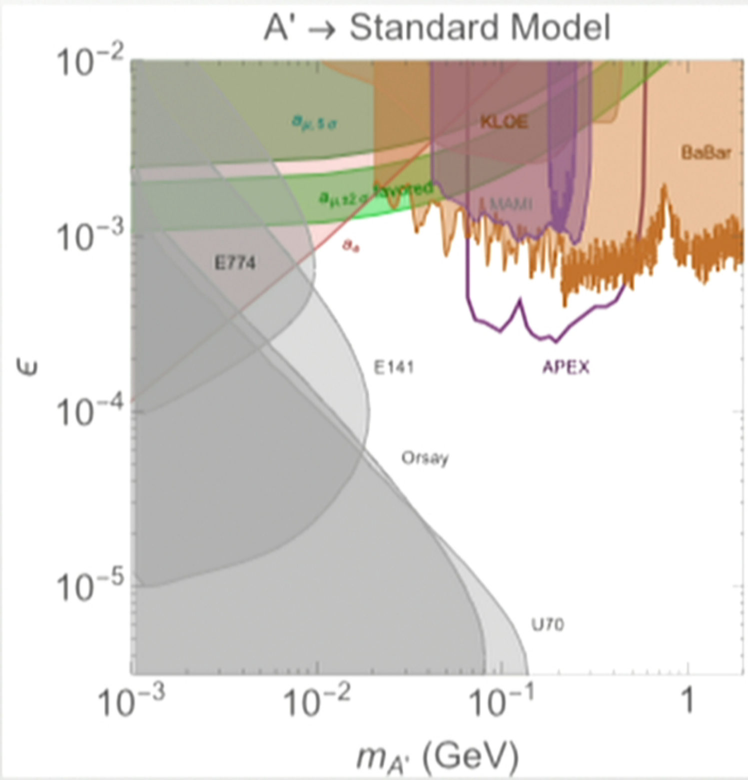
small mass range... reflects small acceptance.

- We were able to take quality data at ~high rate (4kHz; DAQ limited), and the trident backgrounds were as expected. Physics data taken at 2.2GeV on X_0~0.3% Ta target
- Excellent mass resolution(→angular resolution) is the key for physics...for test run:

in mrad	optics	tracking	MS in target
σ(horiz)	0.11	~0.4	0.37
σ(vert)	0.22	~1.8	0.37

→ ***σ(M)~1 MeV***

APEX & A1 Results & Plans



APEX Run Plan:
Low acceptance→run at various E_{beam} and spectrometer angles

Settings	A	B	C	D
Beam energy (GeV)	2.2	4.4	1.1	3.3
Beam current (μA)	70	60	50	80
Nominal central angle	5.0°	5.0°	5.0°	5.0°
Time Requested (hrs)				
Energy change	–	4	4	4
Magnet setup	4	4	4	4
Optics calibration	16	16	16	16
10% $\mathcal{L}$	2	2	2	2
Normal $\mathcal{L}$	144	288	144	144
Total	166	314	170	170

in total, 33 days of beam

Recent results from A1 @ MAMI:

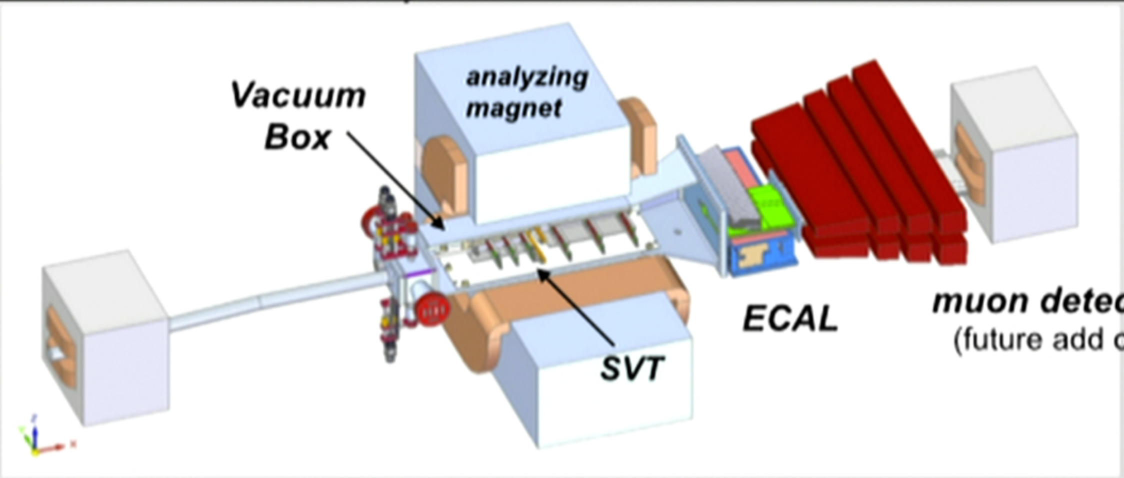
http://arxiv.org/pdf/1404.5502v1.pdf

…had best reach for a few days before BaBar released their result!

The HPS Experiment

The **H**eavy **P**hoton **S**earch uses the lower current beam on a thin target with a high precision vertexing & tracking detector to search for displaced vertices

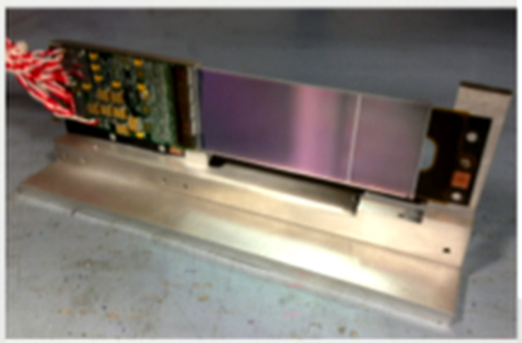
- ➡HALL B beam: <700 nA with 2 ns bunch spacing; $\sigma_{x,y}$ <50um
- ➡12-layer Si microstrip detector inside 0.5T magnet measures momentum & decay vertex
- ➡PbW crystal calorimeter w/APD readout used for triggering
- ➡decent mass resolution (~2-10%), decent acceptance (up to ~20%)
- ➡vertex resolution ~few mm; 10^{-6} rejection of prompt decays
- ➡mass resolution dominated by MS in tracker

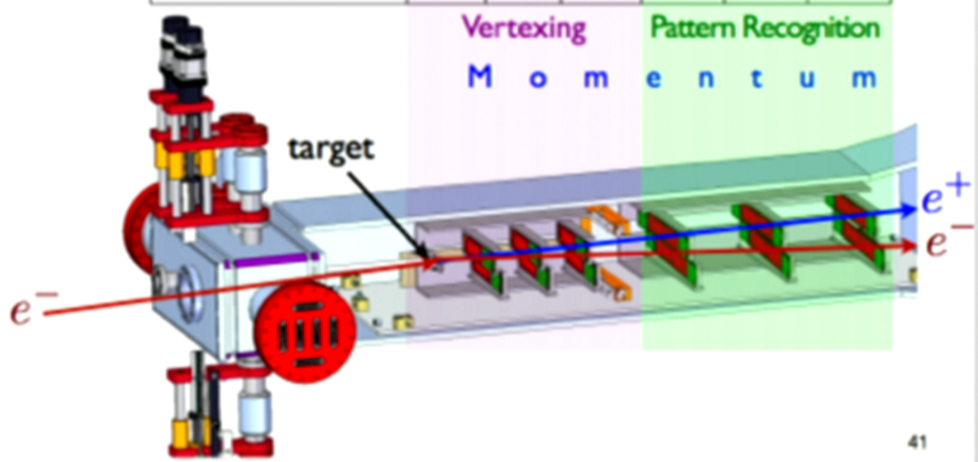


HPS SVT

- 6 dual-sensor layers, top/bottom symmetric about beam
- sensors from Run-IIb production, donated by FNAL (60μm)
- 36 Si strip sensors in total
  - 180 APV25 chips
  - 23004 channels
- ~6μm hit resolution
- ~2.5ns time resolution

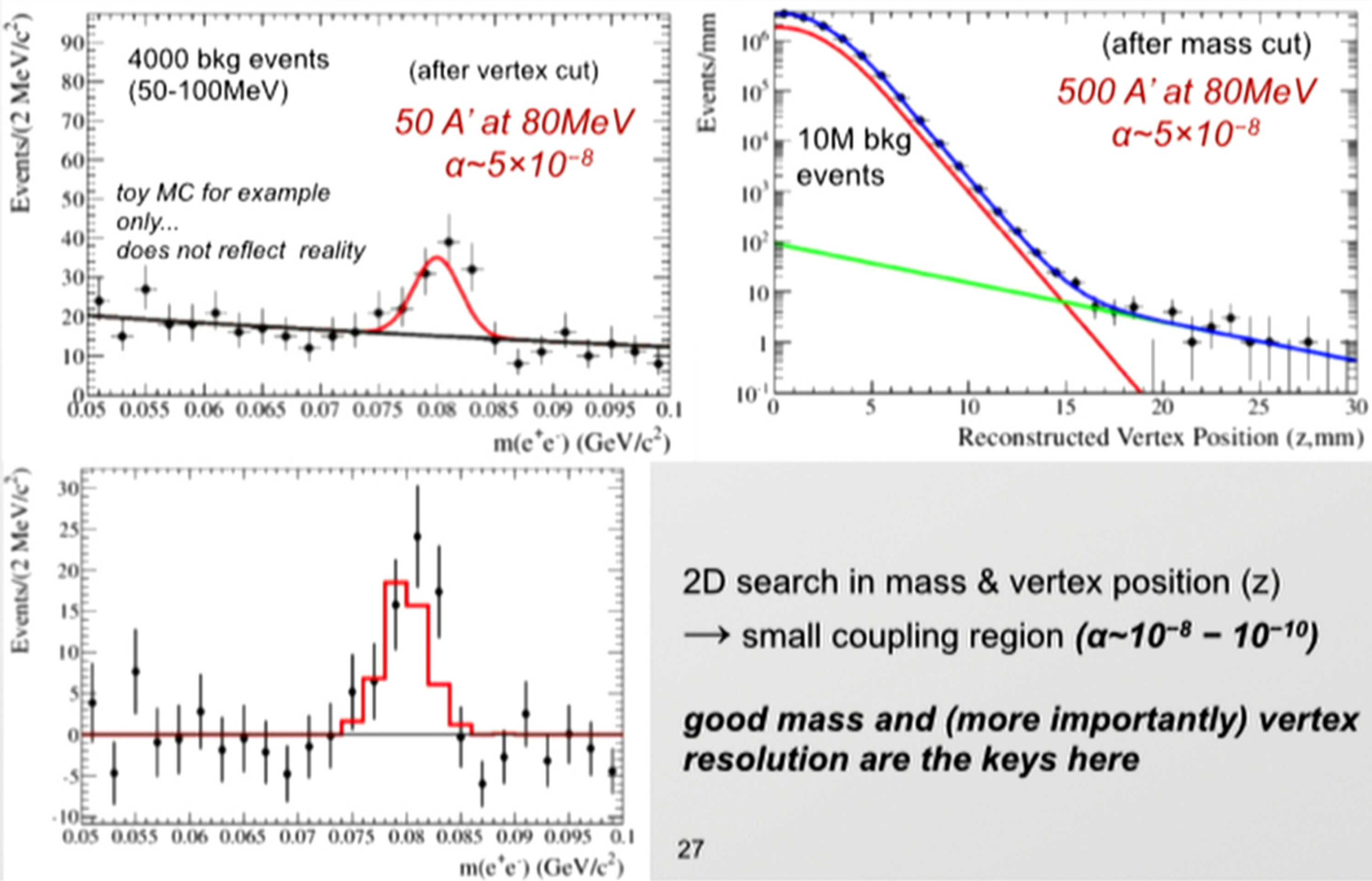
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
z position, from target (cm)	10	20	30	50	70	90
Stereo Angle (mrad)	100	100	100	50	50	50
Bend Plane Resolution (μm)	≈ 60	≈ 60	≈ 60	≈ 120	≈ 120	≈ 120
Non-bend Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
# Bend Plane Sensors	2	2	2	4	4	4
# Stereo Sensors	2	2	2	4	4	4
Dead Zone (mm)	±1.5	±3.0	±4.5	±7.5	±10.5	±13.5
Power Consumption (W)	7	7	7	14	14	14





41

Heavy photon signatures: displaced vertex



2D search in mass & vertex position (z)
⟶ small coupling region ***(α~10^{-8} – 10^{-10})***

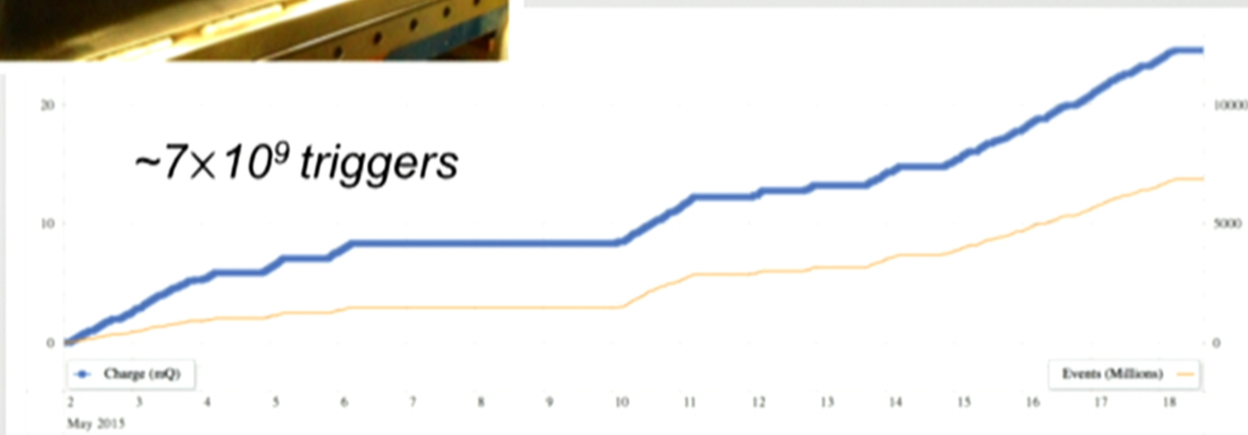
good mass and (more importantly) vertex resolution are the keys here

27

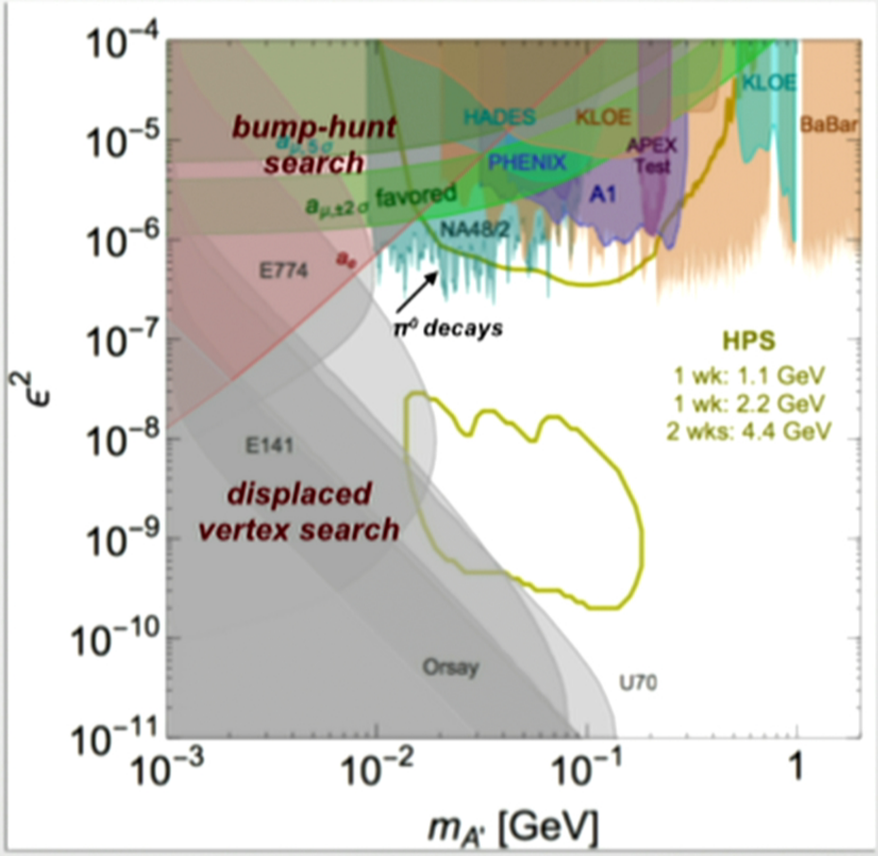
HPS Engineering Run

we installed & took some beam data @ 1.1GeV this spring

pretty successful! Some kinks to work out…



Expected HPS ('15-'16) Reach

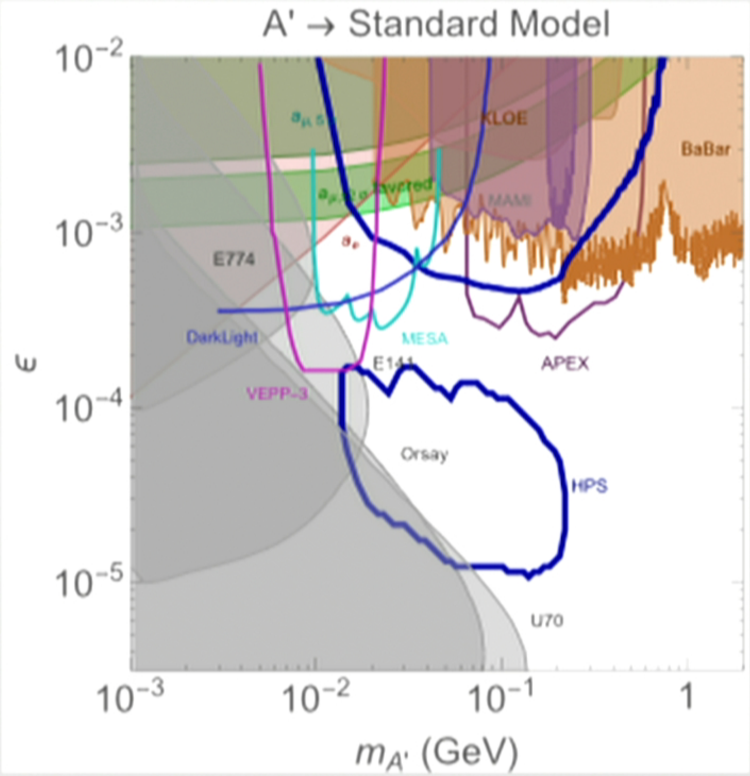


2015 - 2016 Running (Yellow)

1 week with 50nA @ 1.1 GeV
1 week with 200nA @ 2.2 GeV
2 weeks with 300nA @ 4.4 GeV

time given is beam time=floor time/2

One, two, many…



Lots of dedicated experiments planned/ proposed for the next few years. Should be interesting.

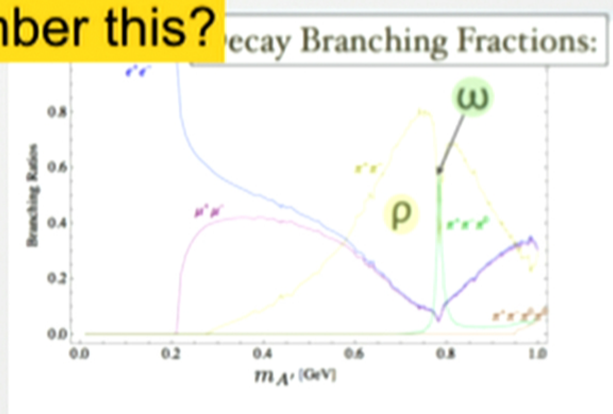
HPS should be the first experiment online…should have beam by end of 2014.

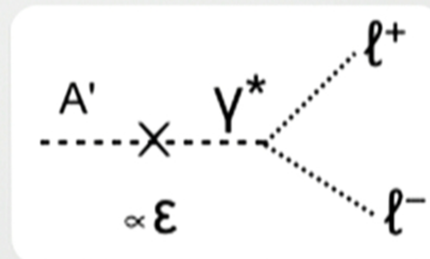
HPS with additional Running (Blue):

2 weeks with 200nA @ 2.2 GeV
2 weeks with 300nA @ 4.4 GeV
3 weeks with 450nA @ 6.6 GeV

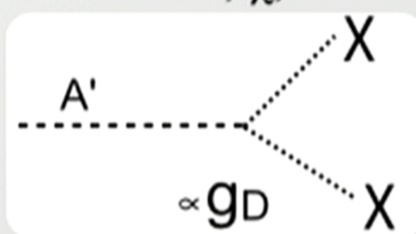
Another scenario…

Remember this?





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

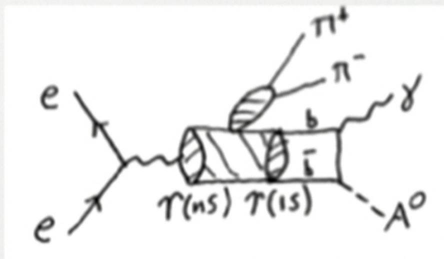


χ = light, hidden sector dark matter

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

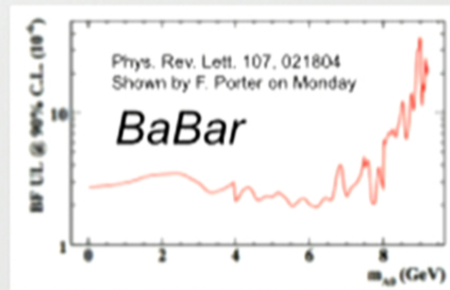
Searching for light DM @ colliders

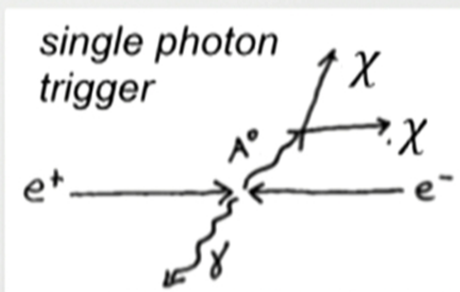
- Both hadron & electron colliders have been looking for DM for a long time…typically look for "missing mass" from well-controlled initial state. This requires excellent energy resolution and hermeticity



$\Upsilon(3s)\rightarrow$

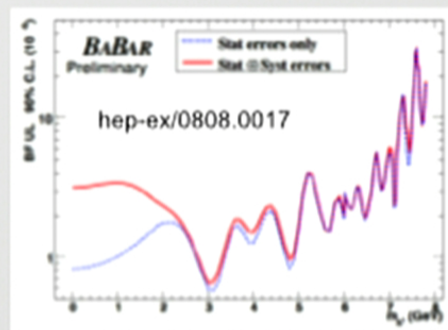
$\pi\pi\Upsilon(1s)\rightarrow$
γ+invisible





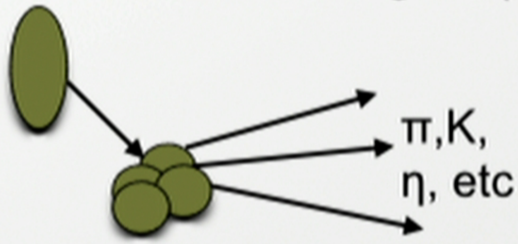
$e^+e^-\rightarrow$

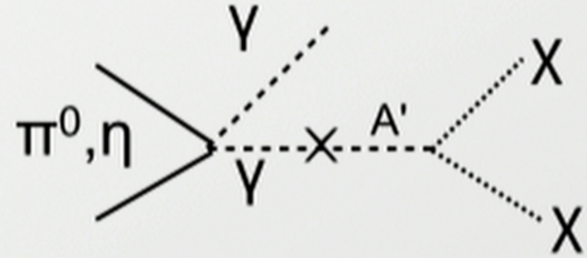
γ+invisible



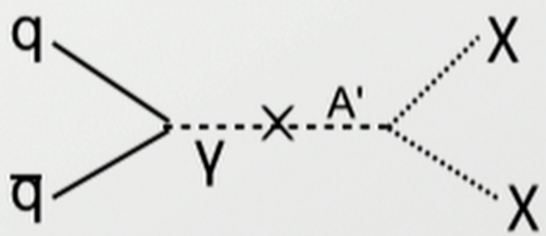
Light dark matter from proton beam dumps

…at low energies (8 GeV=FNAL Booster)



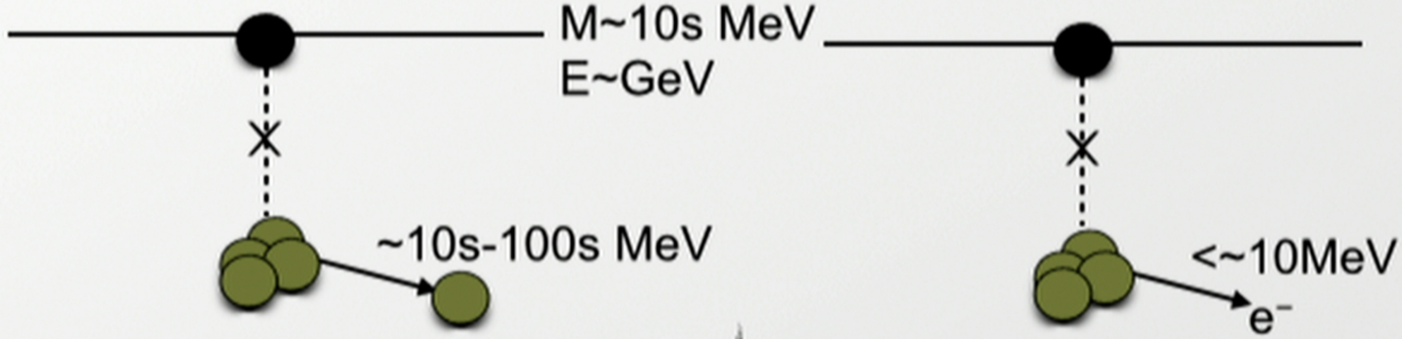


…at high energies (120 GeV=FNAL Main Injector)



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)

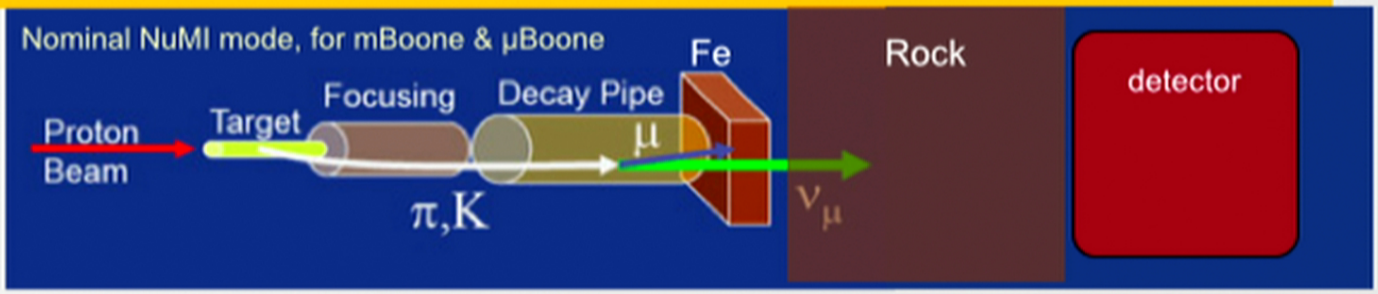


nuclear recoils	**electron recoils**
coherent—low mA',low E_{recoil}, Z^2 enhanced *quasi-elastic*—mid mA',mid E_{recoil} *DIS*—high energies (both χ and recoil) …QE has received most attention	low mA',low E_{recoil}, low background

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

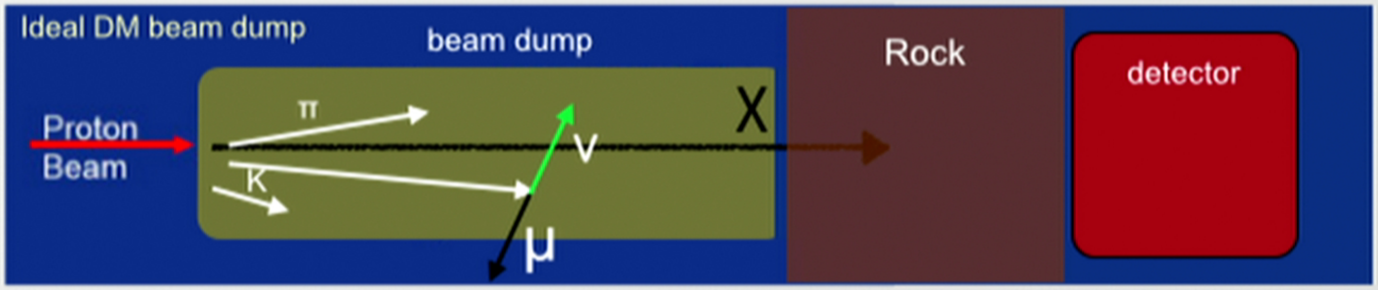
Very convenient!

Dark matter @ neutrino beams



⇒ target/horn/decay pipe optimized to produce neutrino beam

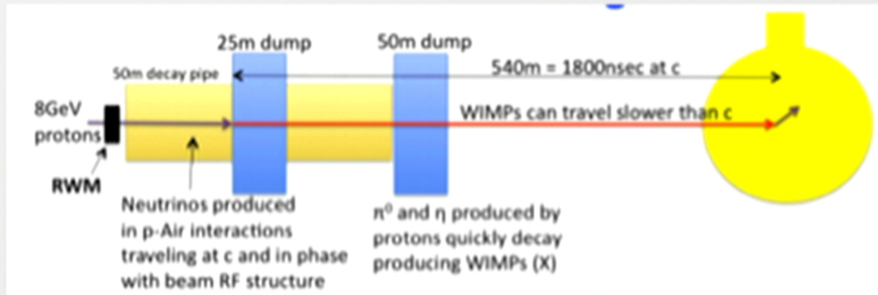
BUT! neutrino NC events are ~irreducible background



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

The off-target miniBoone proposal

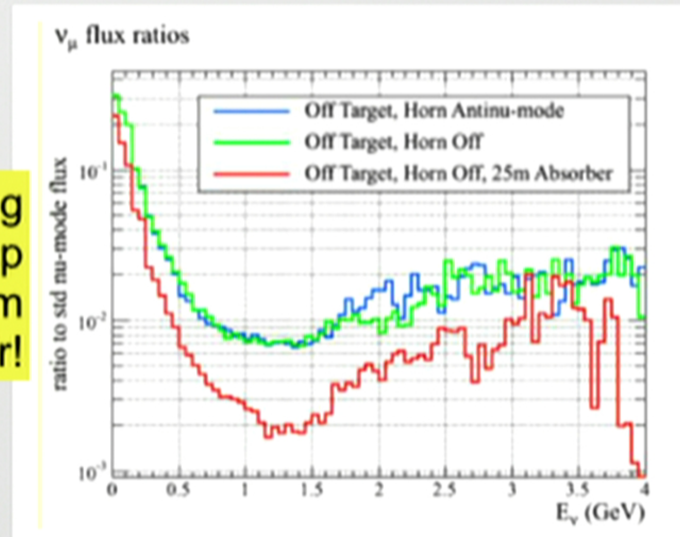
miniBoone proposal to run in "off-target mode" … not quite ideal beam dump, but better than neutrino mode!



miniBoone with beam off target

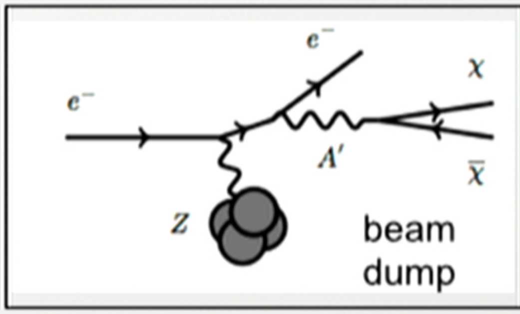
$$\frac{\text{Rate}\,(\text{events/POT})^{\nu\ \text{mode}}}{\text{Rate}\,(\text{events/POT})^{\text{beam}-\text{off}-\text{target mode}}} = 42 \pm 7.$$

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

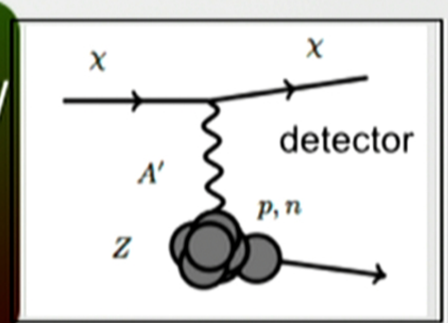


R. Van de Water et al.
arXiv/hep-ex 1211.2258

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

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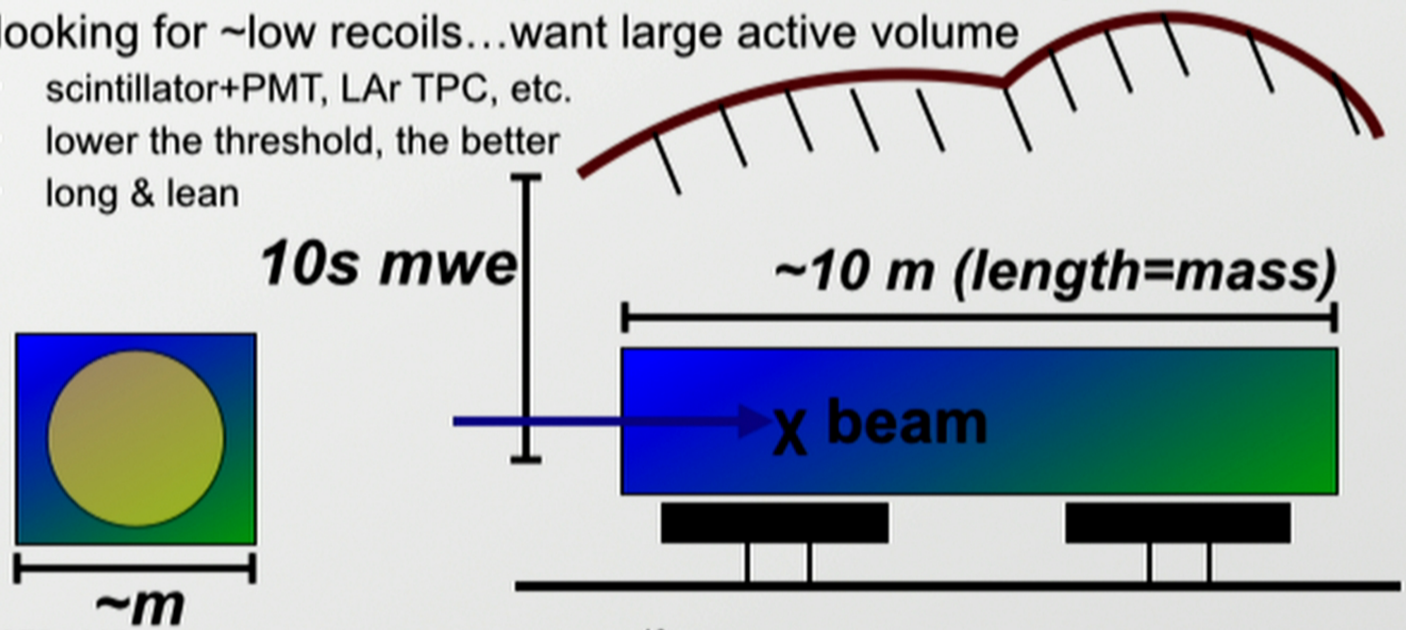
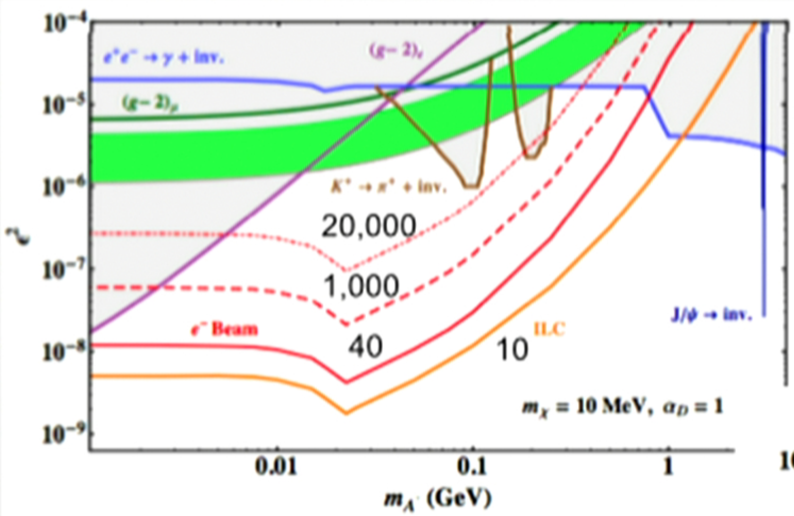
Building a detector

- 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

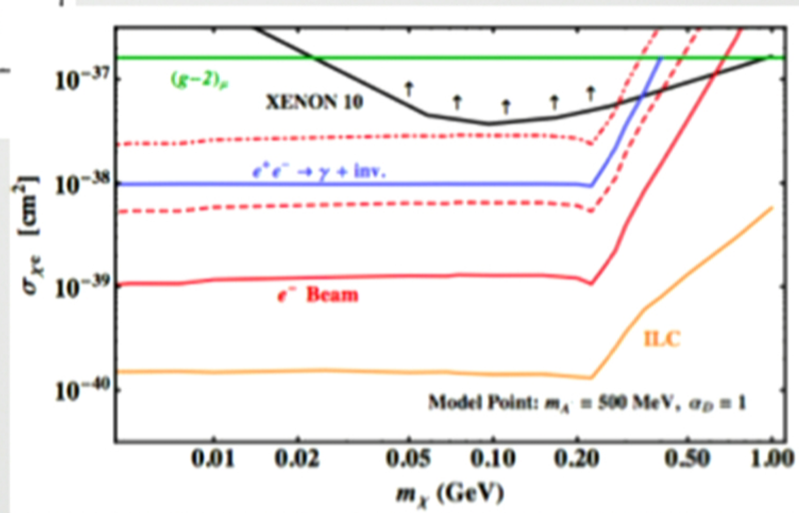


e^- Beam :

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

Summary

- 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
- Past few years, the community has done a good job of mining data to look for dark photons…some of the experiments go back decades
- Results from dedicated experiments are starting to come (A1) and more are expected in the next few years
- 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!
- There has been a lot of thinking about light dark matter searches (not just vector-portal) in the past ~year or so, including specific experimental setups…Natalia will talk about that this afternoon.