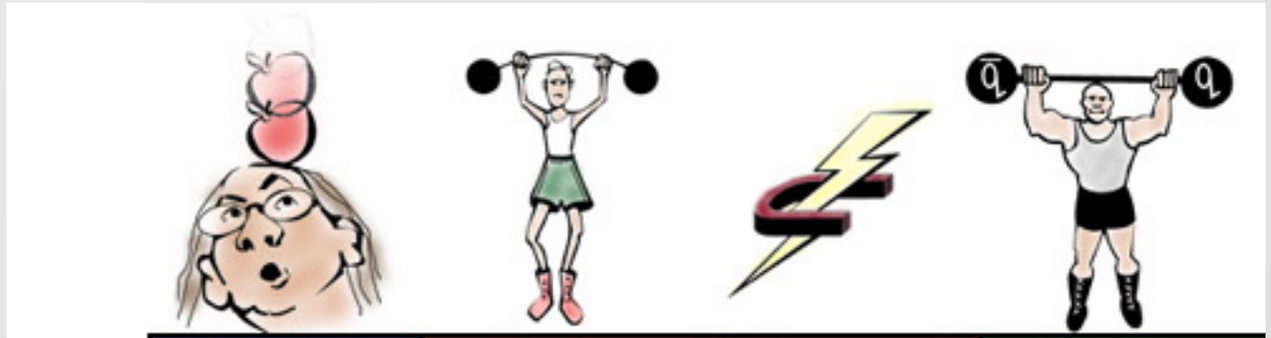
~~Hidden~~ ~~Secluded~~ Dark Sectors and Heavy Photons

Mathew Graham
SLAC Summer Institute
July 30, 2012

Where does an extra force fit?

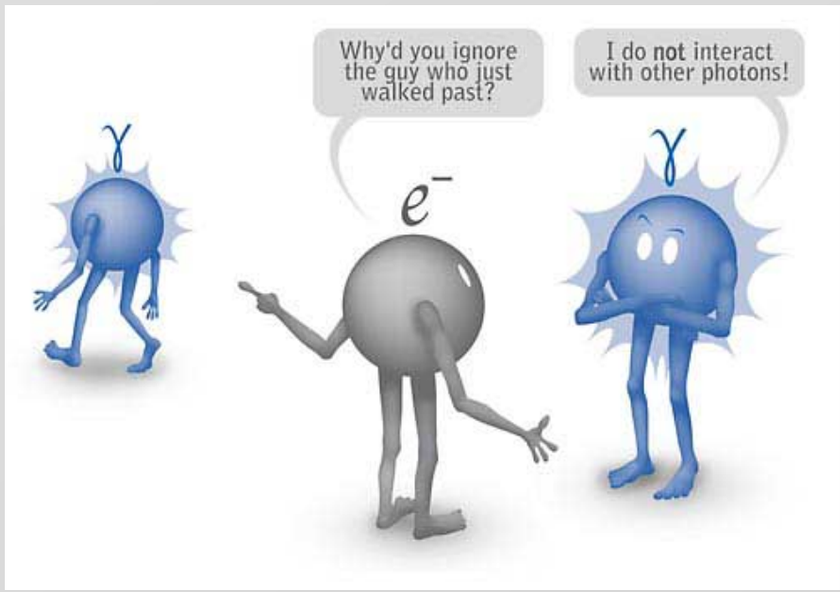


	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

http://www.particleadventure.org/inter_summary.html

How could additional forces have escaped detection?

- very high mass force carrier
- small coupling to SM particles



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Dark Forces

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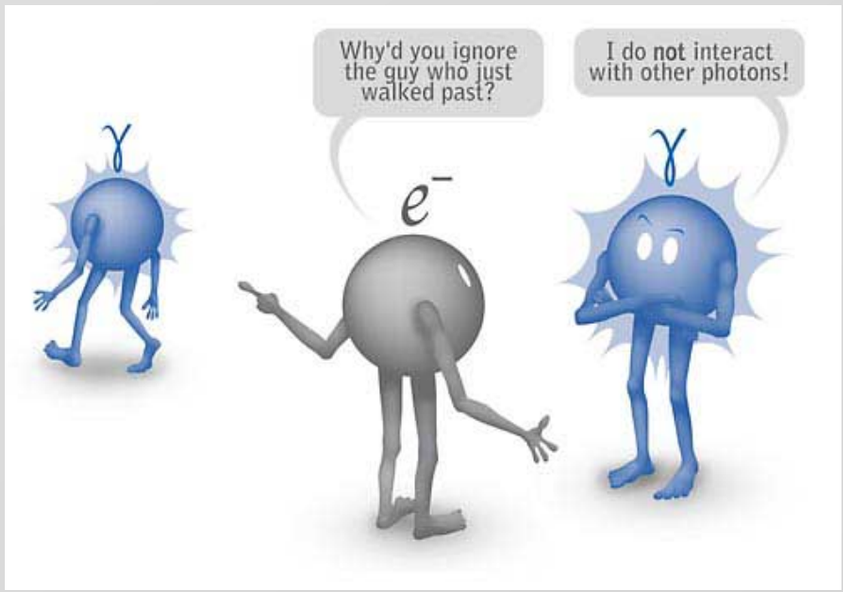
- very high mass force carrier
- small coupling to SM particles
  - ***0 (direct) coupling to SM!***



Portals to a hidden sector

vector → $\frac{1}{2}\epsilon F^{Y}_{\mu\nu}F'^{\mu\nu}$ **dark photon**

Higgs → $\epsilon_h |h|^2 |\phi|^2$ **dark scalar**

neutrino → $\epsilon_\nu (hL)\psi$ **sterile neutrino**

axion → $\frac{1}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$ **ALPSs**

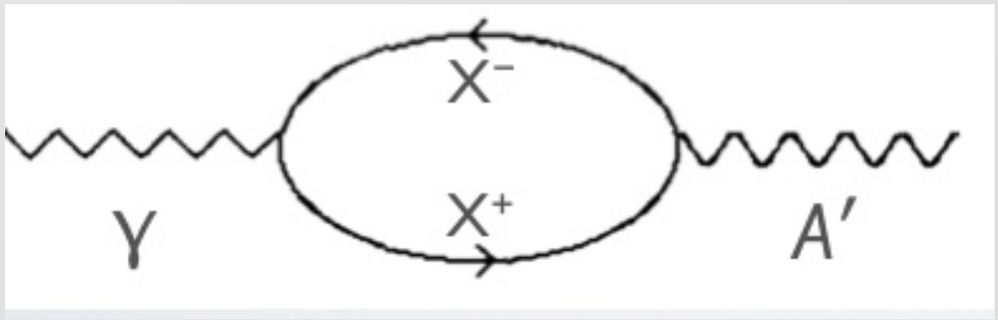
Kinetic mixing from the vector portal

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

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

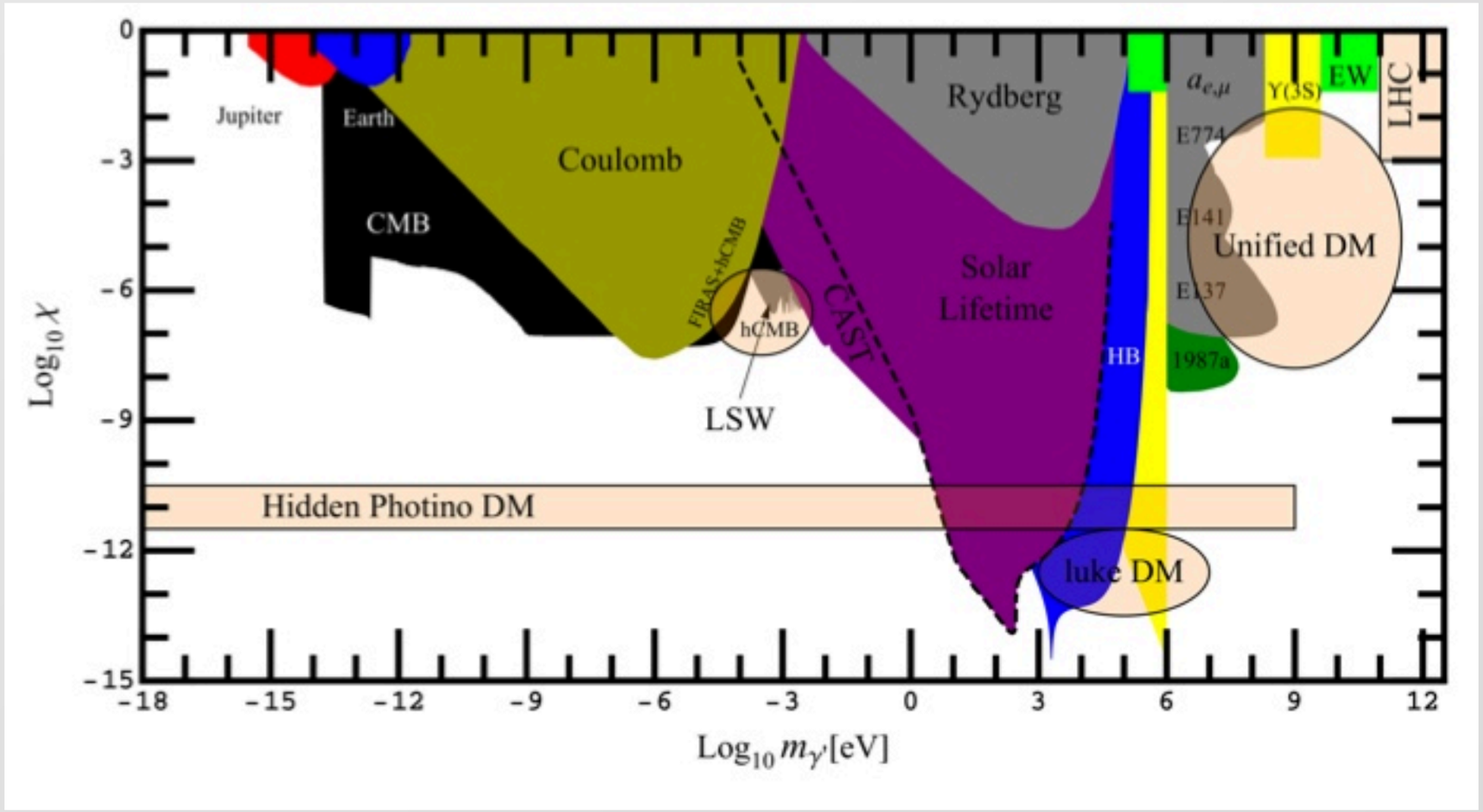
Kinetic Mixing term



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

30 decades of heavy photons

...there is a lot of physics here!

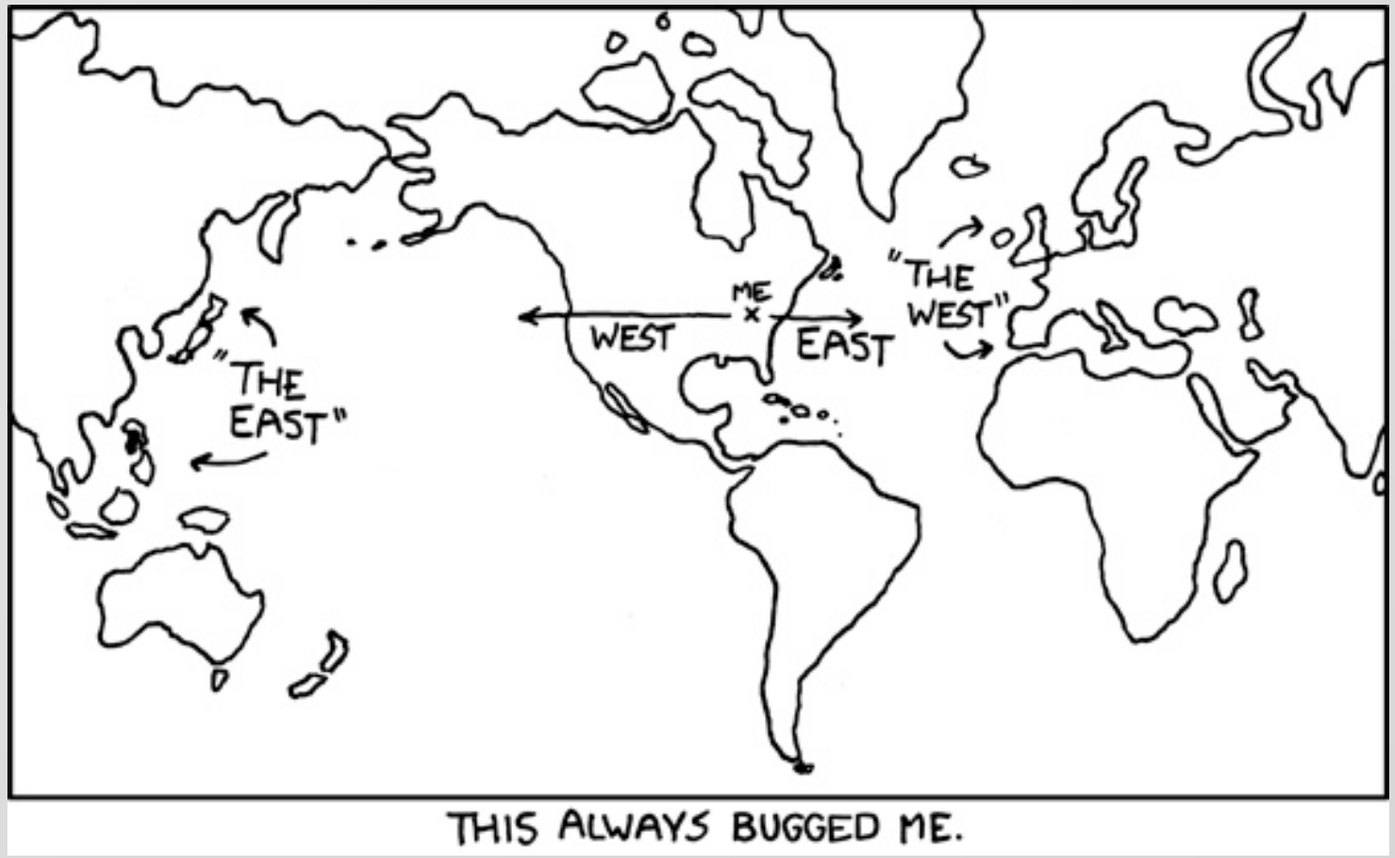


Jaeckel and Ringwald, hep-ph/1002.0329

Terminology break

- The literature is infested with different terms for (basically) the same things...
  - dark sector=hidden sector=secluded sector
  - dark photon=hidden photon=heavy photon=A′=U-boson
  - $\varepsilon^2=\kappa^2=\alpha'/\alpha$

I will try to stick to dark sector, A′, and ε!



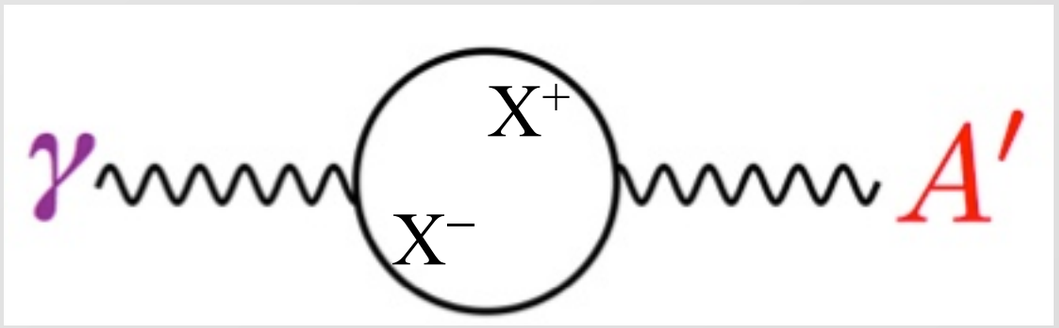
$\frac{1}{2}\epsilon F^{Y}_{\mu\nu}F'^{\mu\nu}$ *What coupling?*

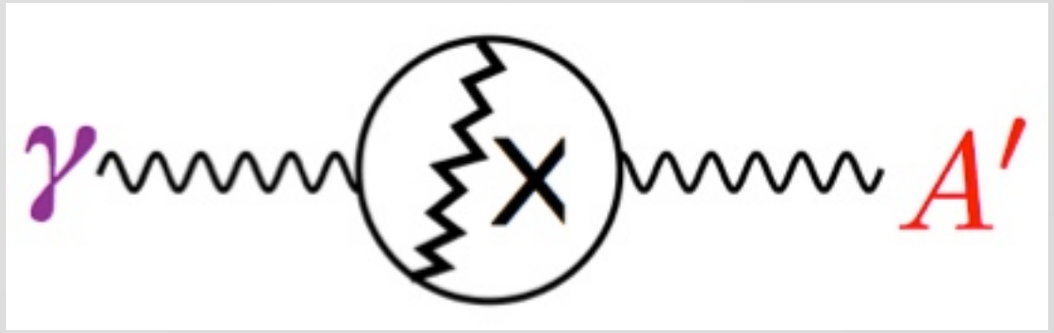
- Coupling is generated from non-perturbative loops
  - One-loop if the heavy particle is charged under both U(1)s

$$\epsilon \sim \frac{e g_D}{16\pi^2}$$

...depends on coupling in dark sector

  - Two-loop if one of the U(1)s is embedded into a higher symmetry...





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

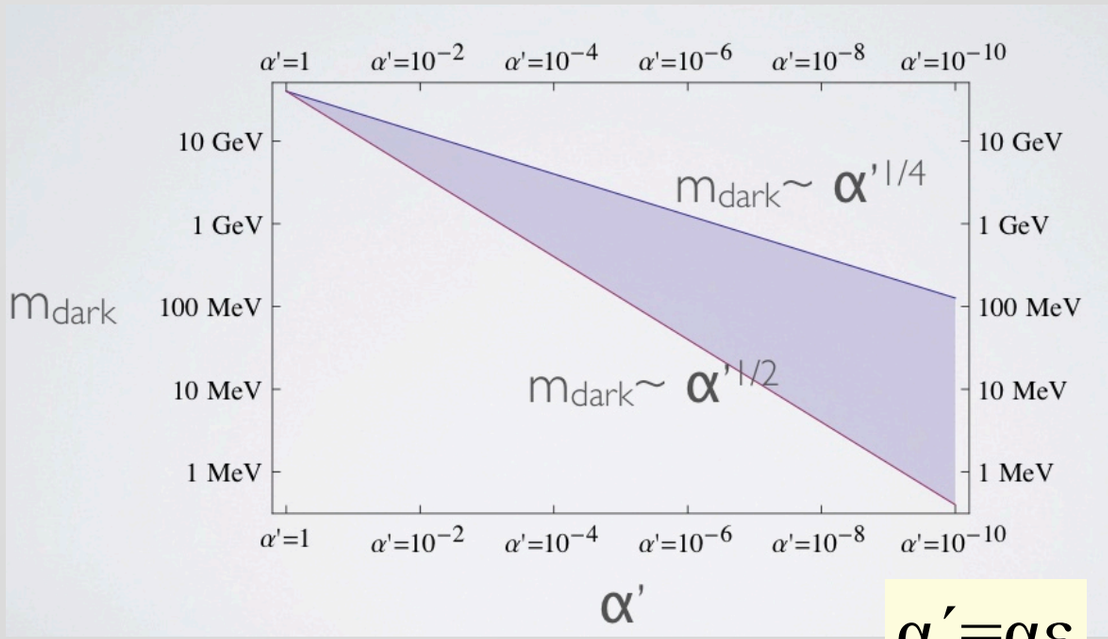
Ok, what about the mass?

- Could be massless ⇒ millicharges!
- Non-perturbative ⇒ chaos!
- Same origin as weak scale

⇒ $O(\mathrm{M_Z})$

Depending on model, mass scales like:
$\mathbf{M(A')/M(W)\sim\varepsilon^{1}\text{-}\varepsilon^{1/2}}$
leading to

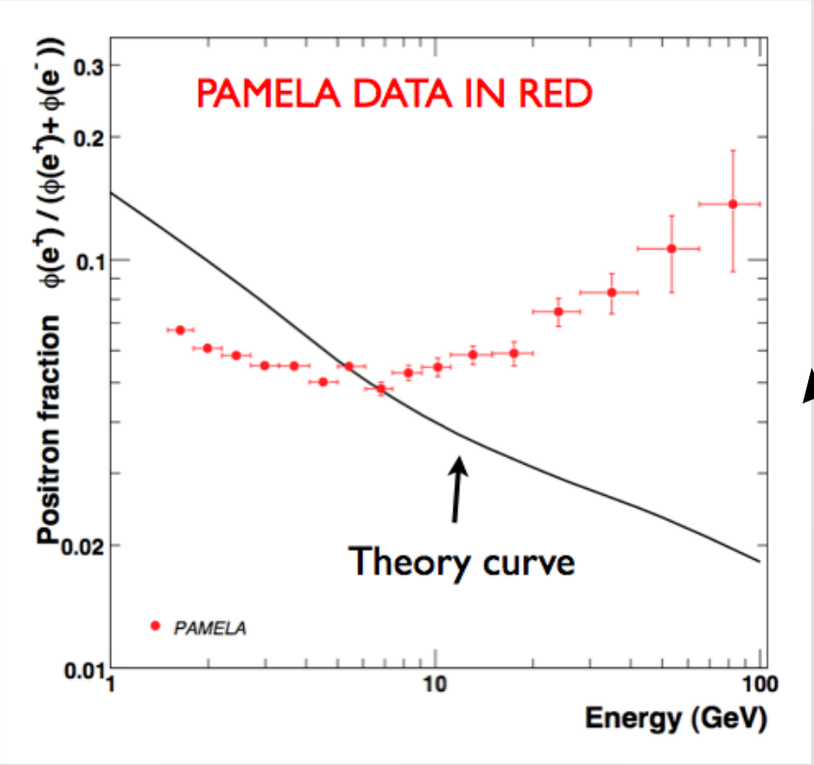
M(A′)~MeV-GeV



N. Weiner, JLAB PAC37 Talk

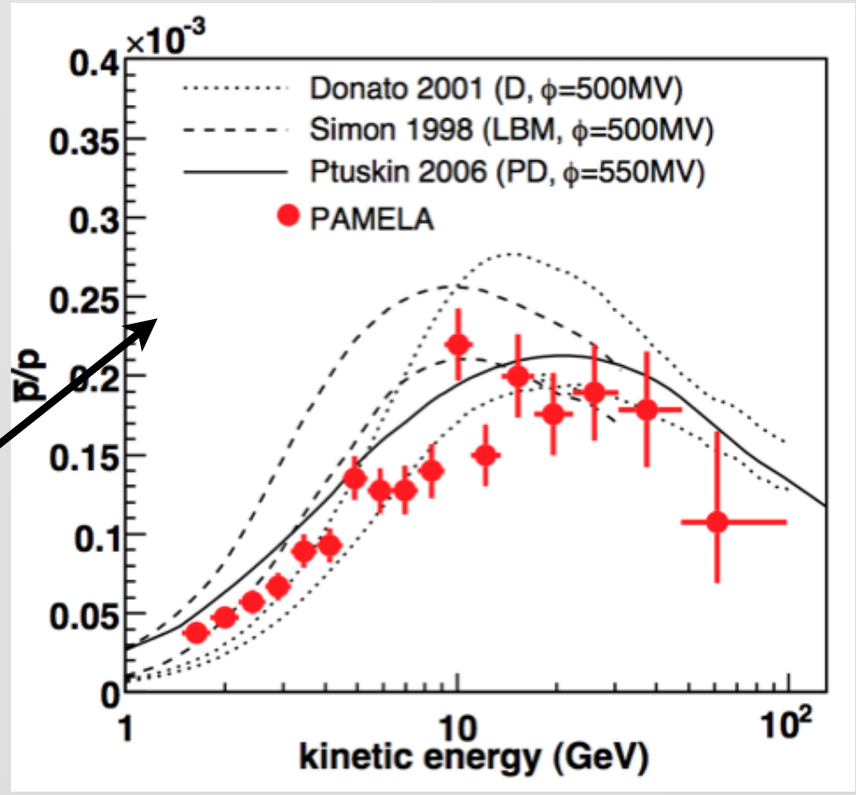
$\alpha' = \alpha\varepsilon$

A hint from above?

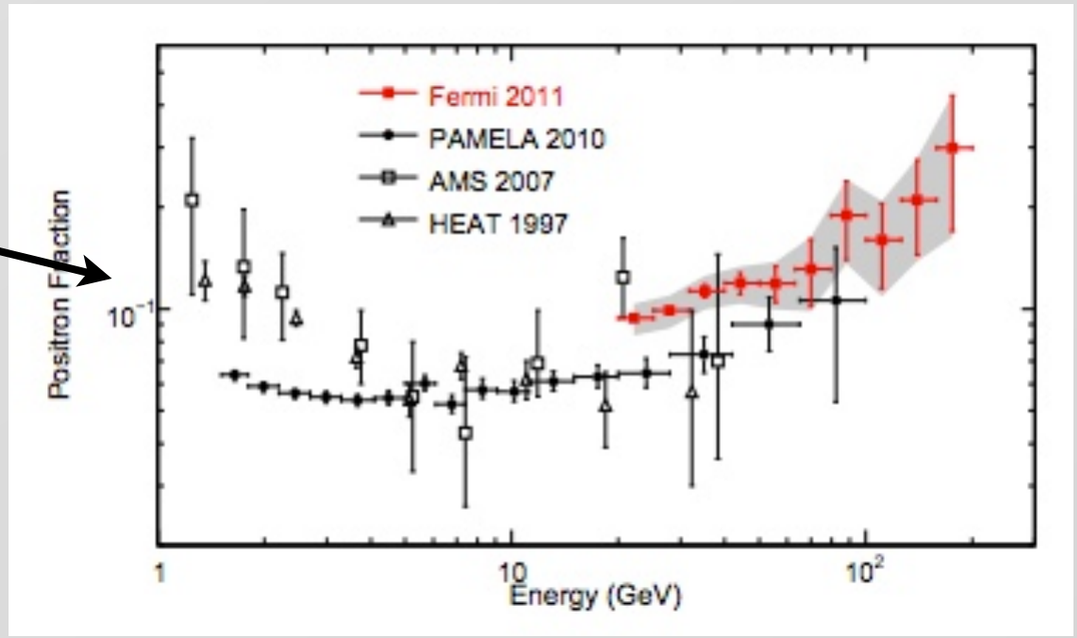


excess in e^+/e^- ratio

...but not in $\overline{p}/p$ ratio



•FERMI sees it too!

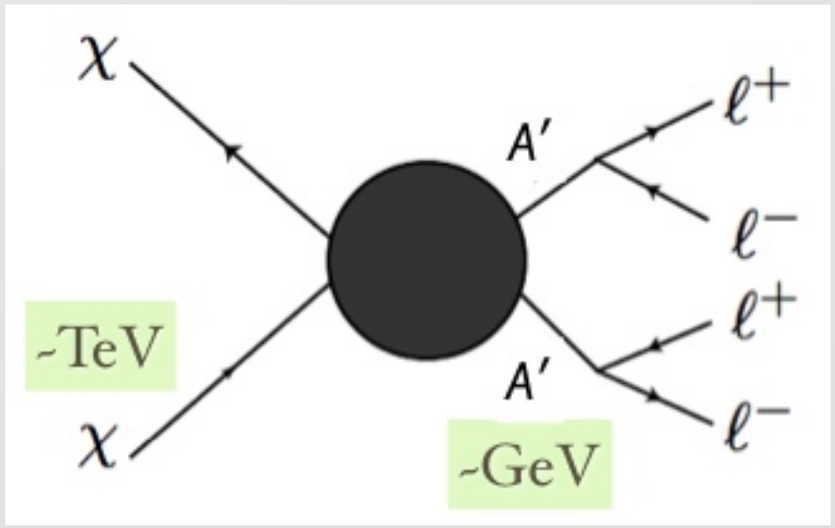


Unknown source of high energy positrons...

Is this astrophysics or particle physics?

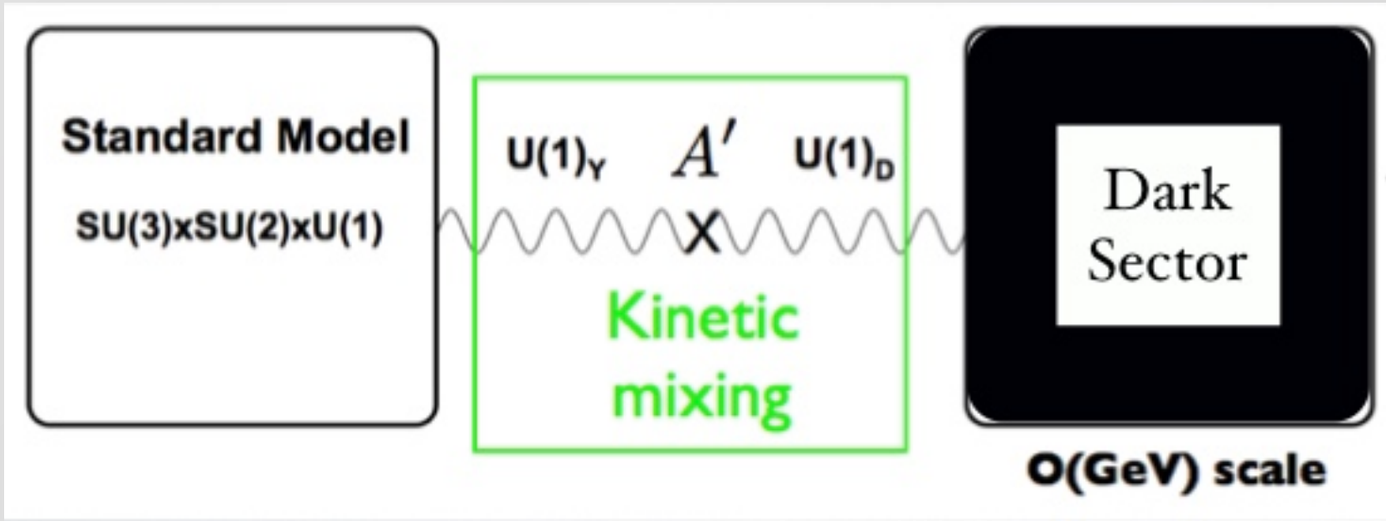
Dark matter annihilation and the dark sector

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

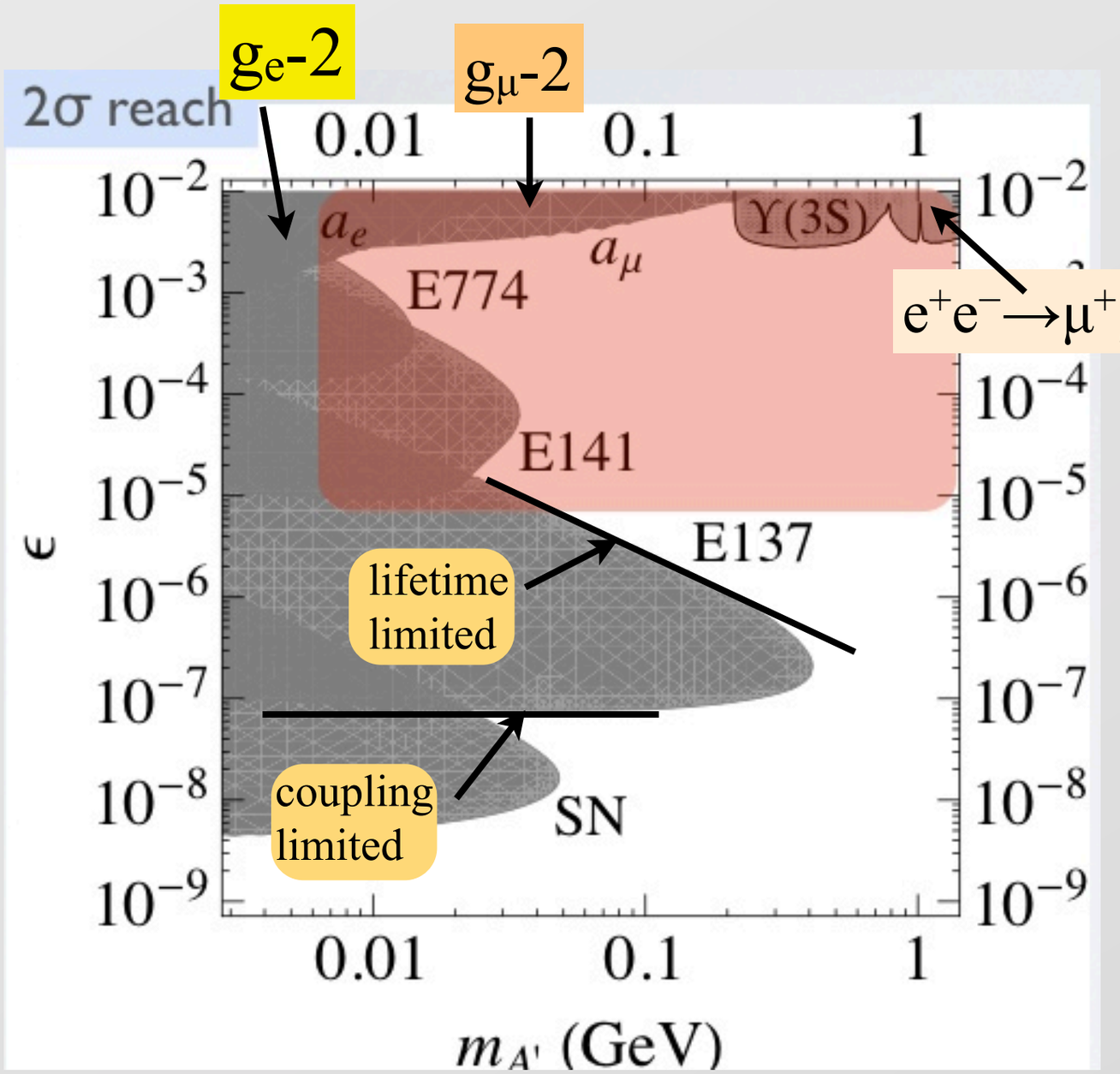


M. Pospelov and A. Ritz, Phys. Letters B **671**, 391 (2009).

- new "dark force" with gauge boson ~ GeV while the dark matter particle (charged under the new force) ~ TeV
- decays to lepton pairs (e^+e^-, $\mu^+\mu^-$) but $p\bar{p}$ decays are kinematically forbidden



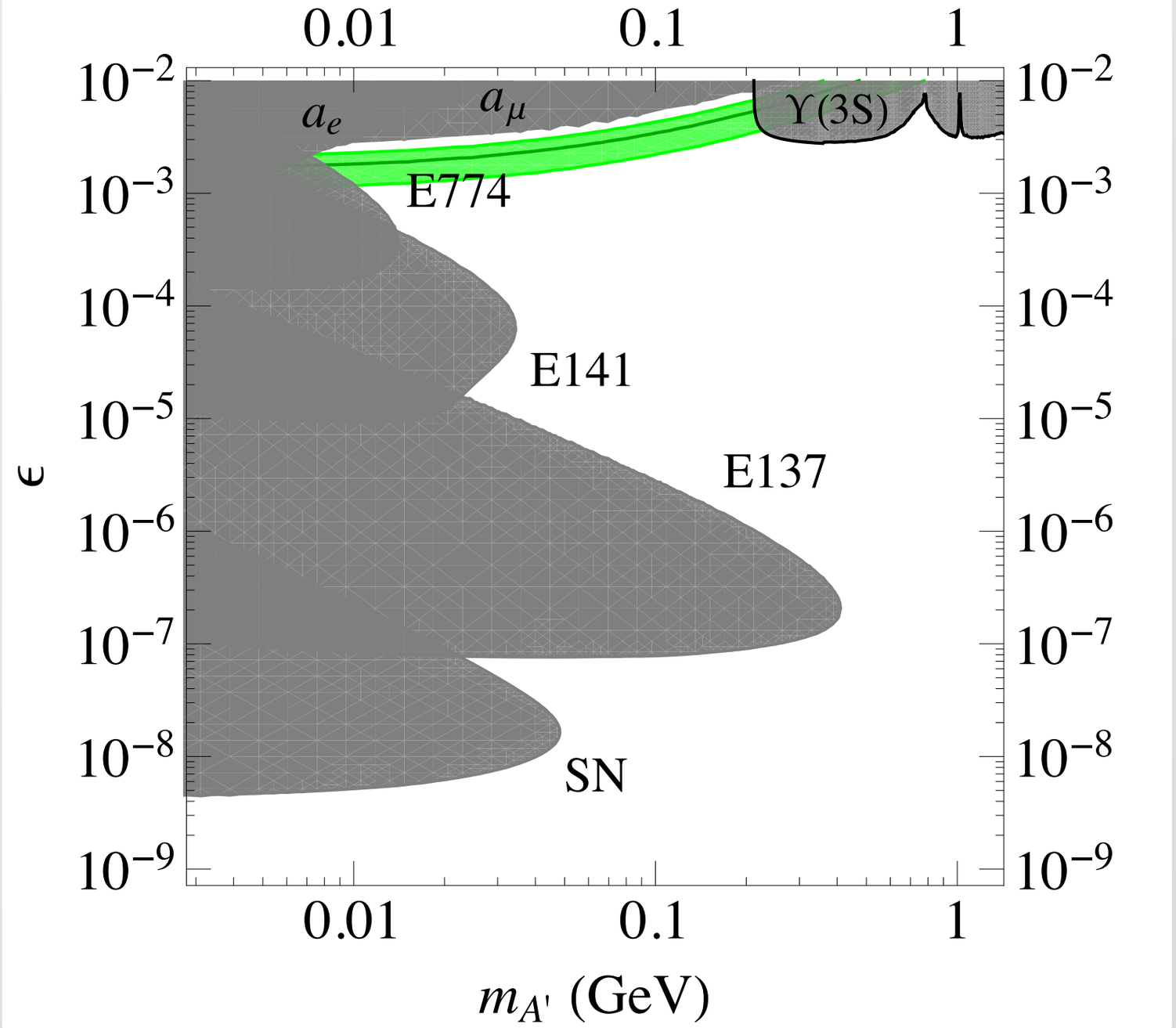
Some existing constraints



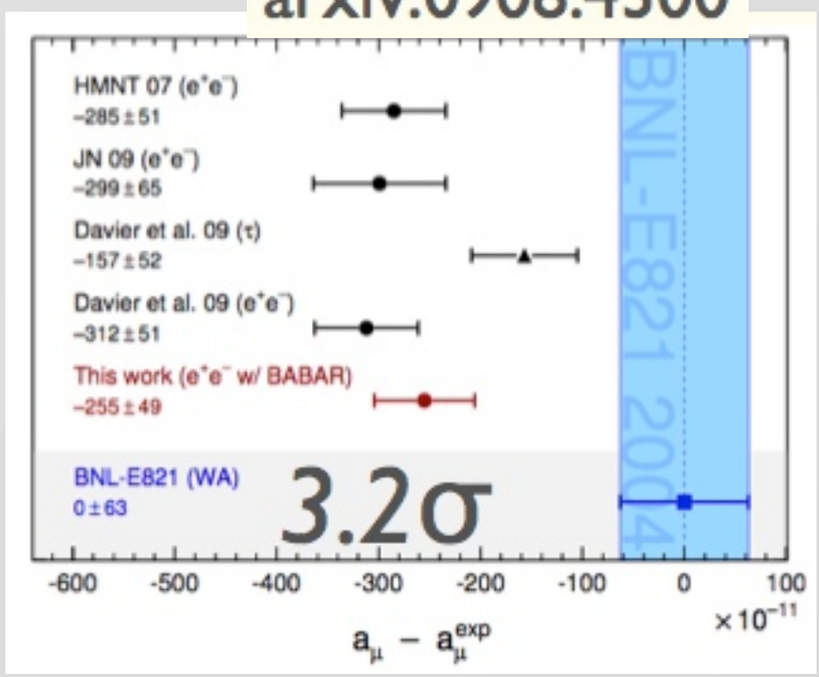
	Shield (m)	E_{beam} (GeV)	Lumi (e^-)
E137	200	20	10^{20}
E141	0.12	9	2×10^{15}
E774	0.3	27.5	5×10^{9}

Dark photons and the g-2 anomaly

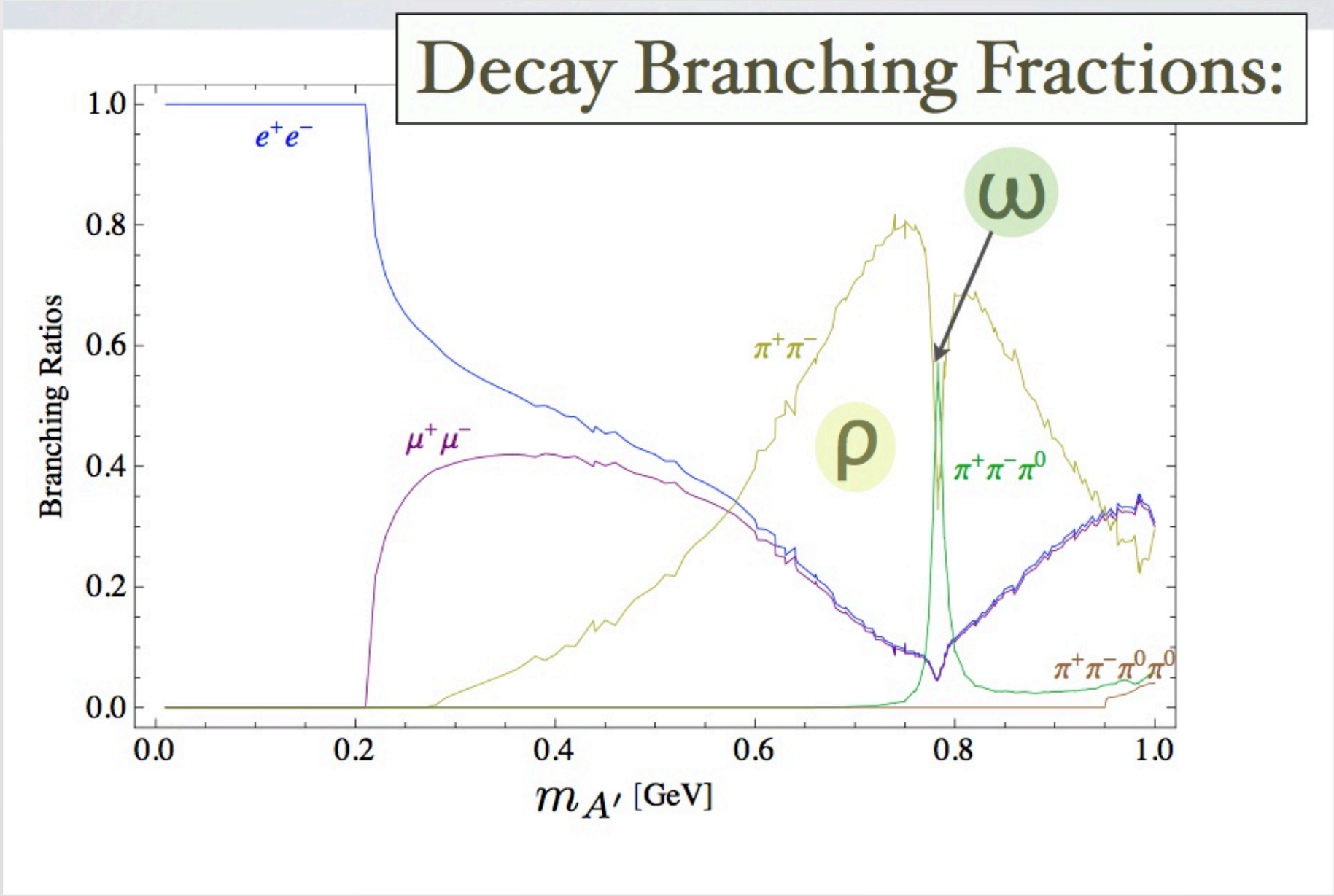
If the g-2 anomaly is due to a heavy photon



Davier *et al.*, arxiv:0908.4300



A′ decay products

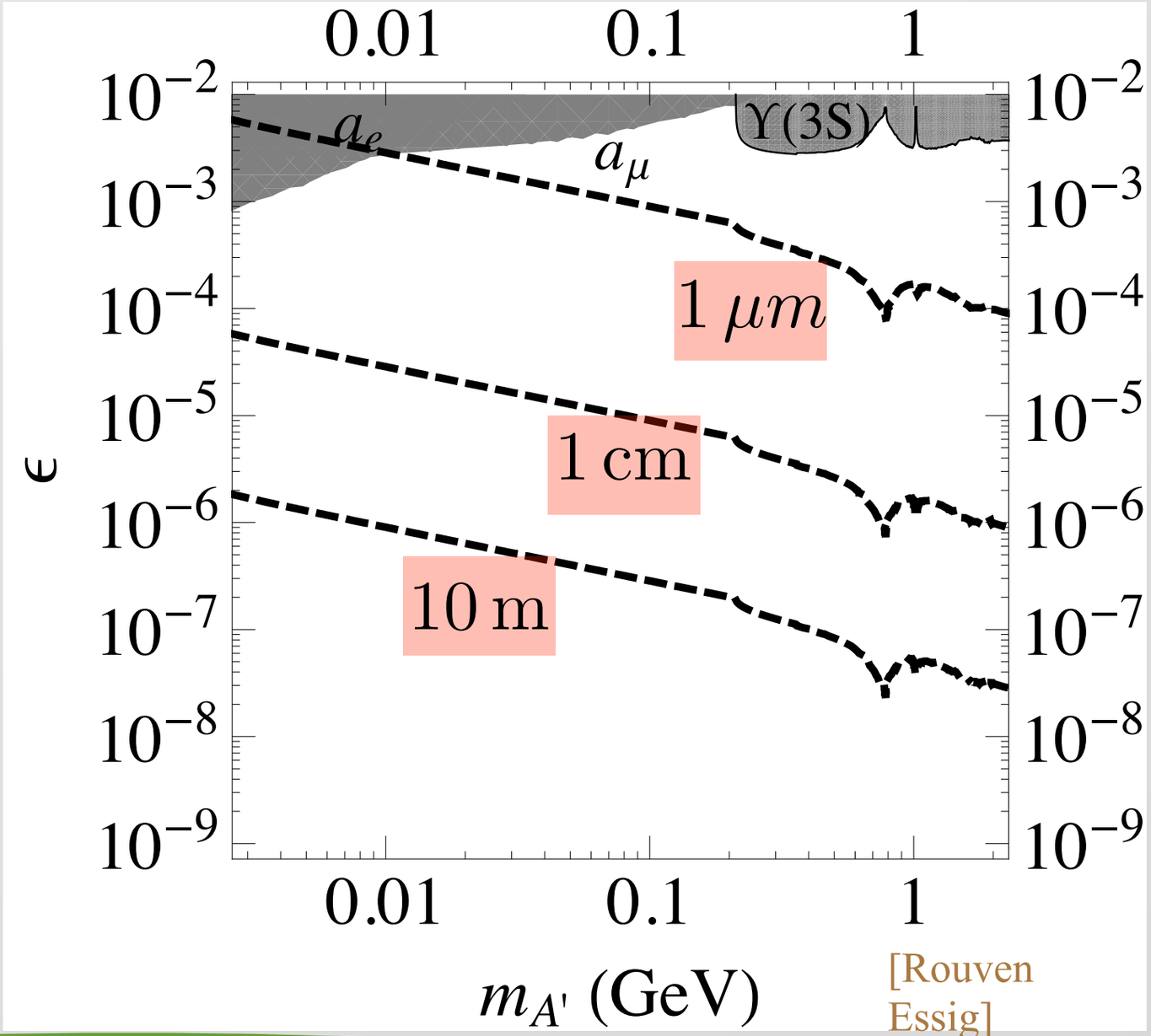


...up to ~500 MeV, decay to leptons dominates

A′ Lifetime

$$\gamma c\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2$$

lower ε, lower mass
→ longer lifetime



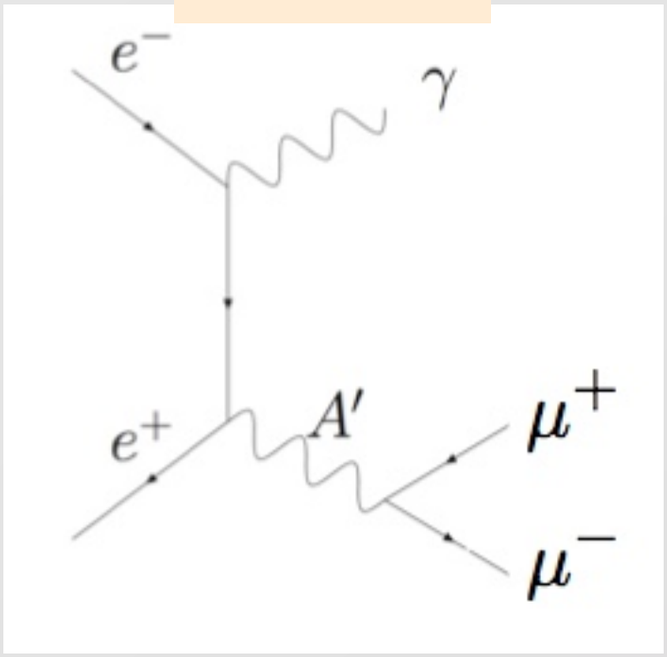
[Rouven Essig]

Much of parameter space will have displaced vertex

Collider vs. Fixed Target

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

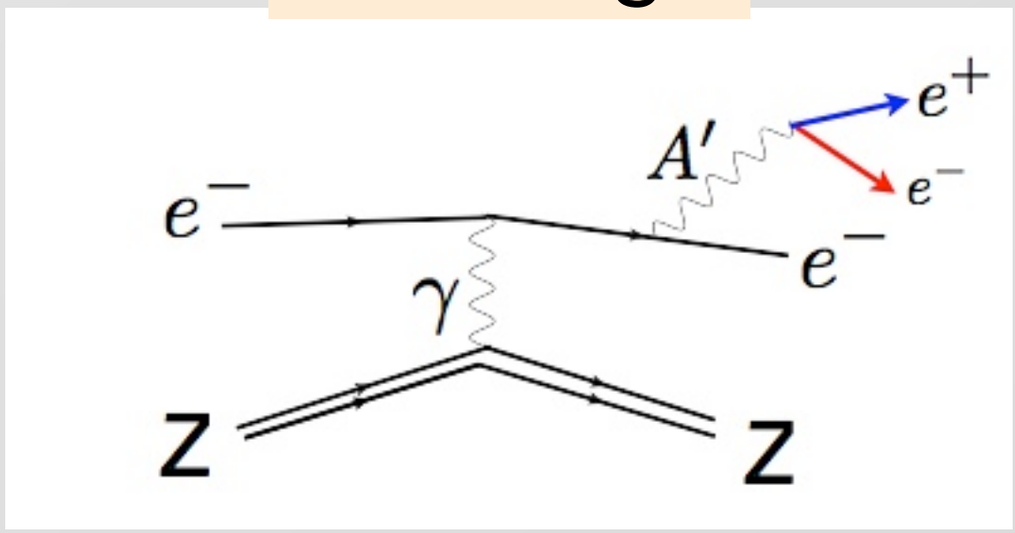
Collider



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

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

Fixed Target

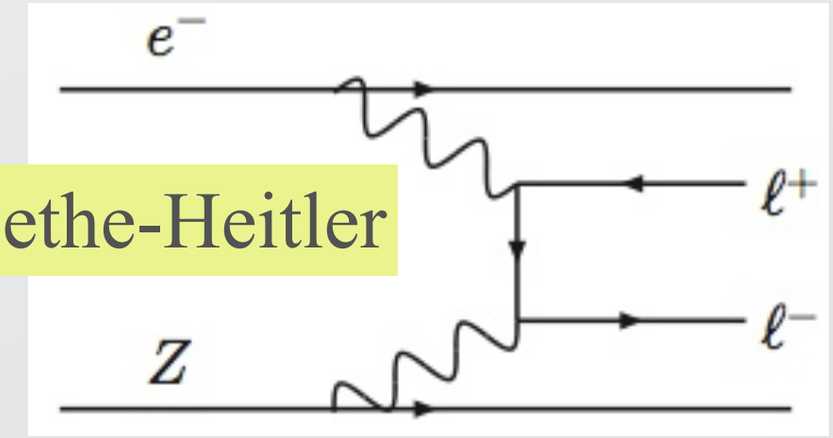


$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

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

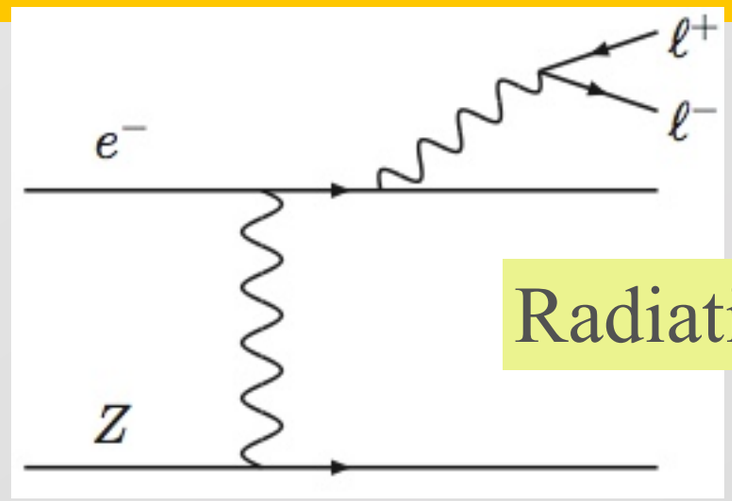
...much higher backgrounds

Backgrounds at fixed target

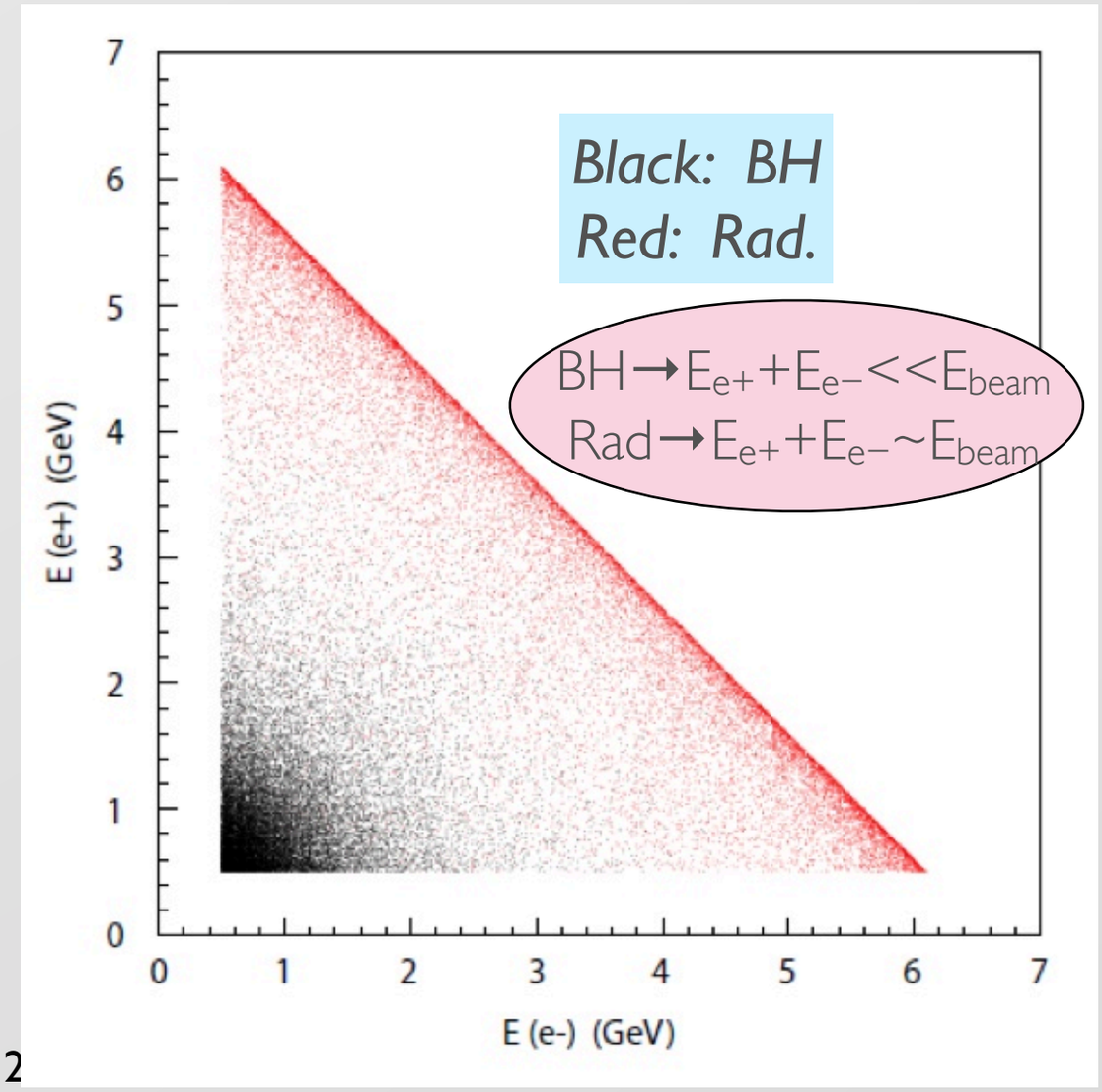


Bethe-Heitler

Two main backgrounds



Radiative



production rates of A' and radiative are related:

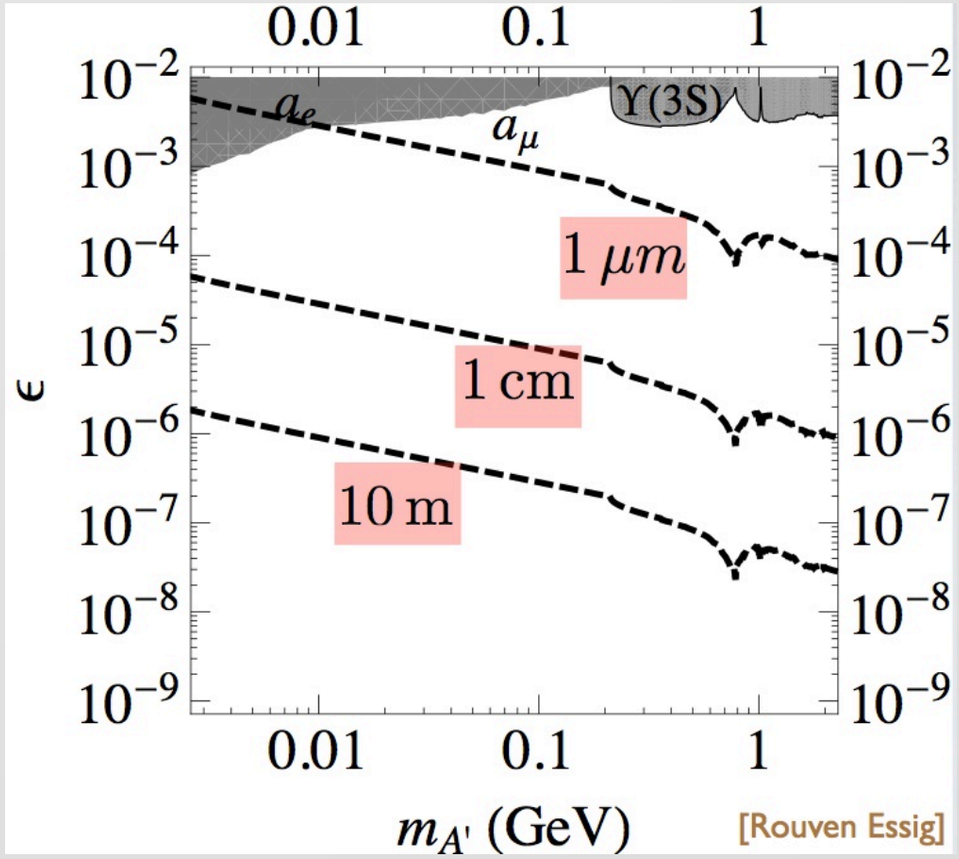
$$\frac{d\sigma(e^- Z \to e^- Z(A' \to \ell^+\ell^-))}{d\sigma(e^- Z \to e^- Z(\gamma^* \to \ell^+\ell^-))} = \left(\frac{3\pi\epsilon^2}{2N_{\rm eff}\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)$$

Cross-section for BH>>Radiative, but kinematics much different... Even after energy cut, BH background ~5x radiative

…a little more subtle…

Problem: cover the low coupling ($<10^{-4}$), intermediate mass (20-200 MeV) region

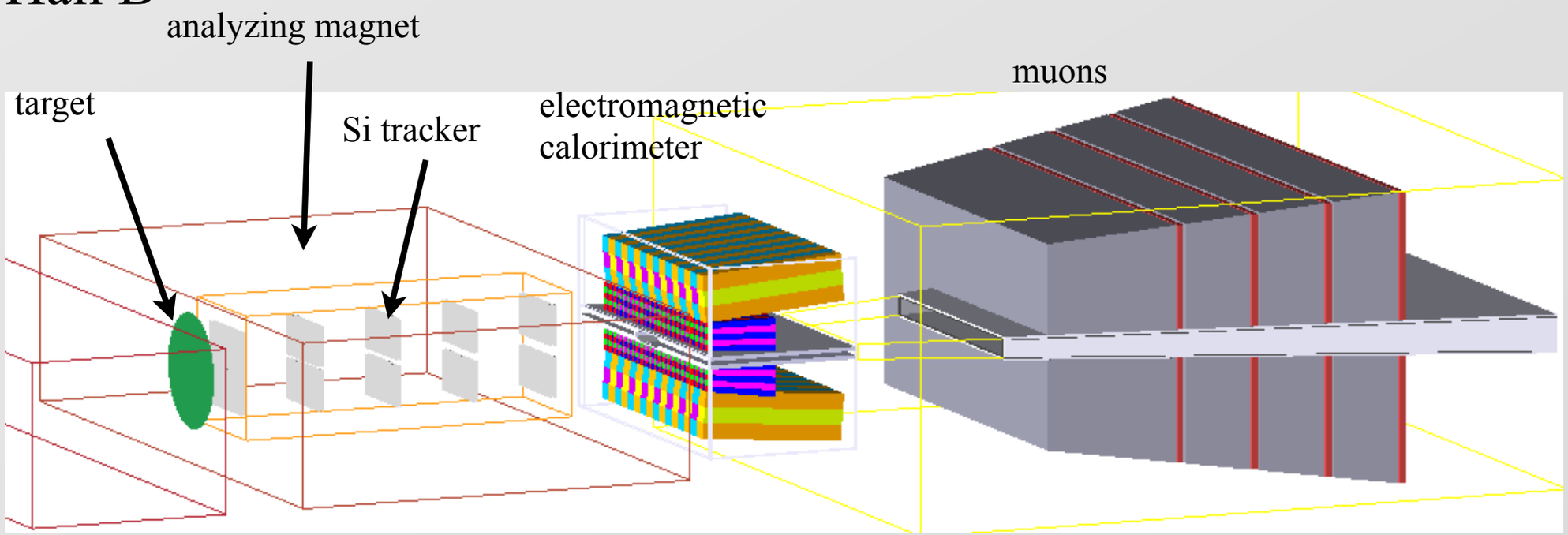
- low rate ➪ intense beam
- high background ➪ high resolution
- ***still*** high background ➪ measure displaced vertex



Solution: HPS

H*eavy* **P***hoton* **S***earch @ Hall*

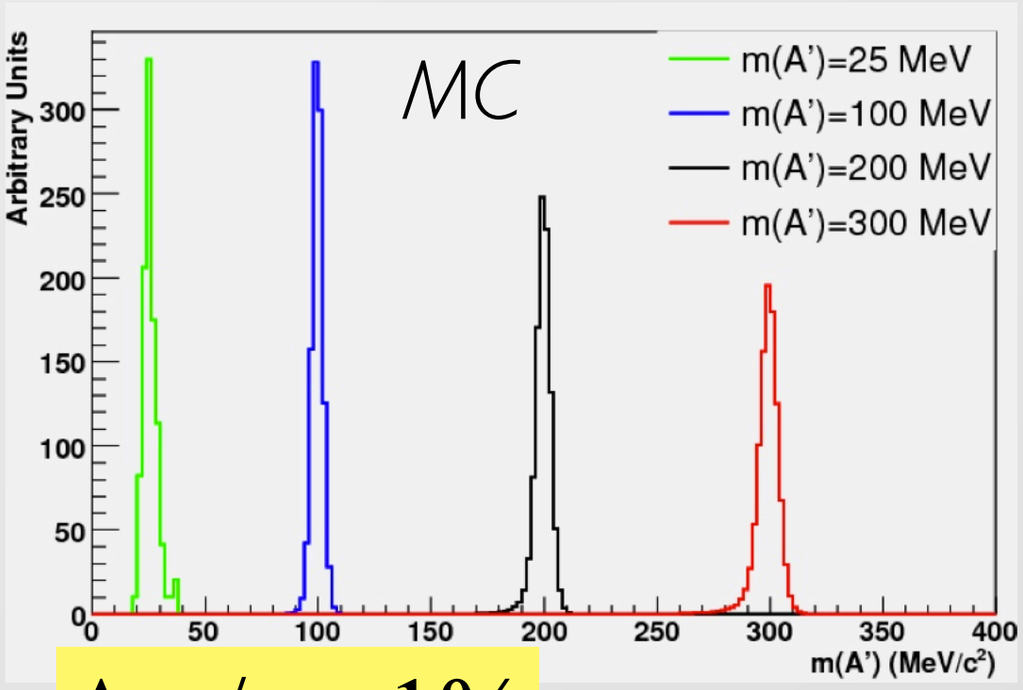
•high rate, high acceptance, high mass & vertex resolution detector intended to run in Hall B



•Silicon strip tracker inside an evacuated dipole for excellent vtx & mom resolution. Use Si sensors donated from Fermilab & APV25 readout chips

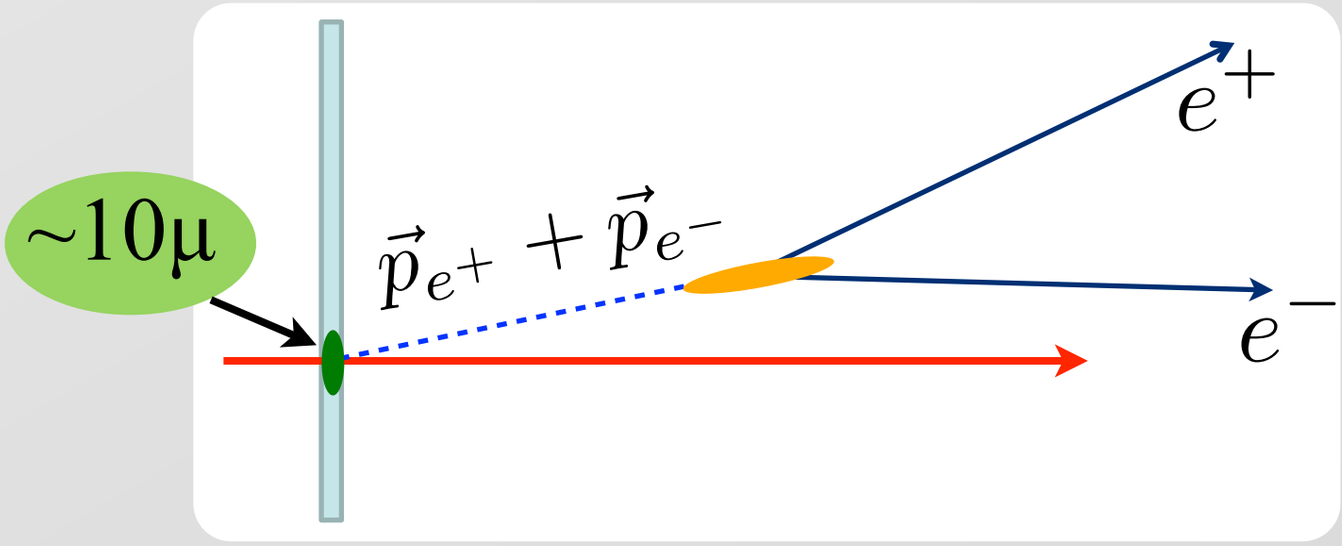
•Borrow & reconfigure the CLAS inner calorimeter for high rate triggering

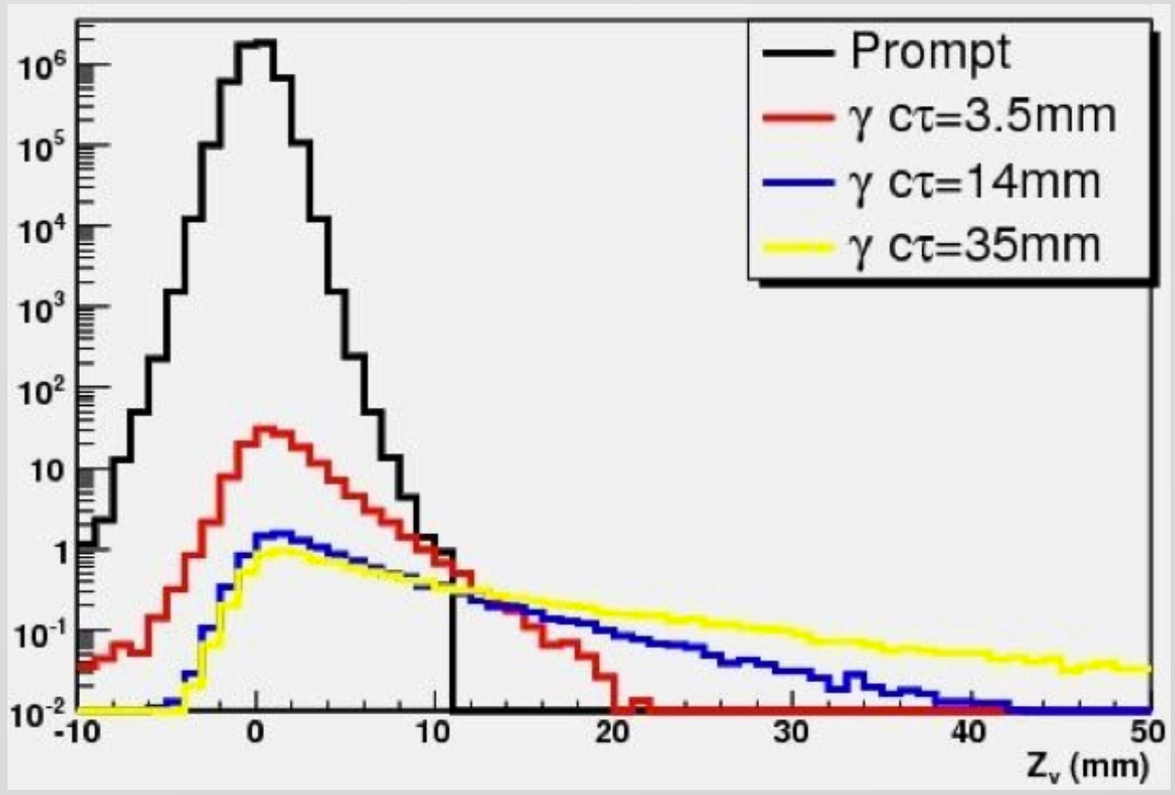
The HPS approach



$\Delta m/m \sim 1\%$

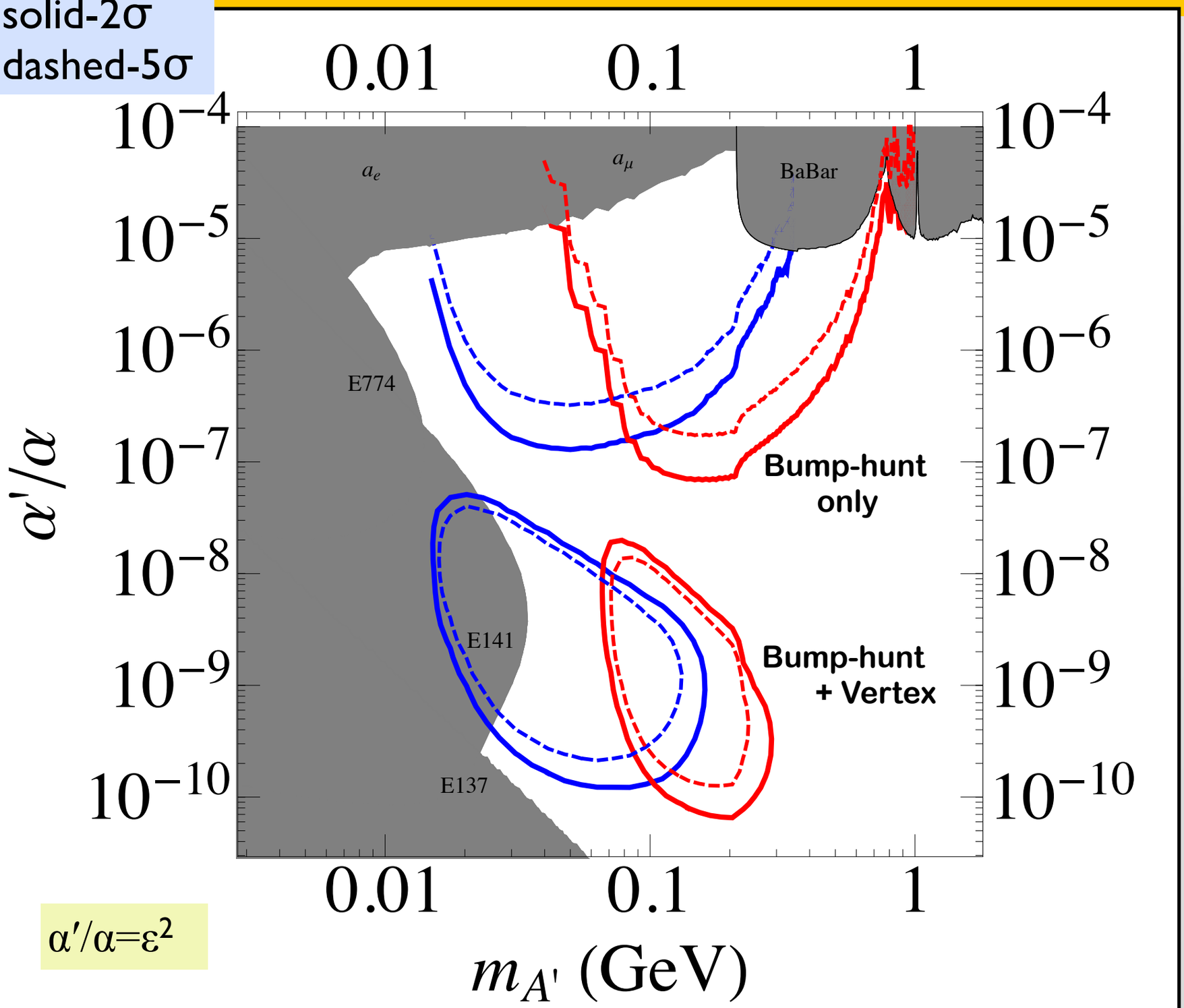
- good mass resolution, dominated by MS in the detector
- use small beam-spot (~10μm) to constrain A′ to point back to IP
  - beat down vertex tails of prompt decays to ~ 0 expected background
  - tails dominated by fake tracks...rate dependent
- Estimate coverage $10^{-4} > \varepsilon > 10^{-5}$ for $200 > mA' > 20$MeV
  - running 3 months each at E_{beam}=2.2 and 6.6 GeV





HPS Expected Reach

solid-2σ
dashed-5σ



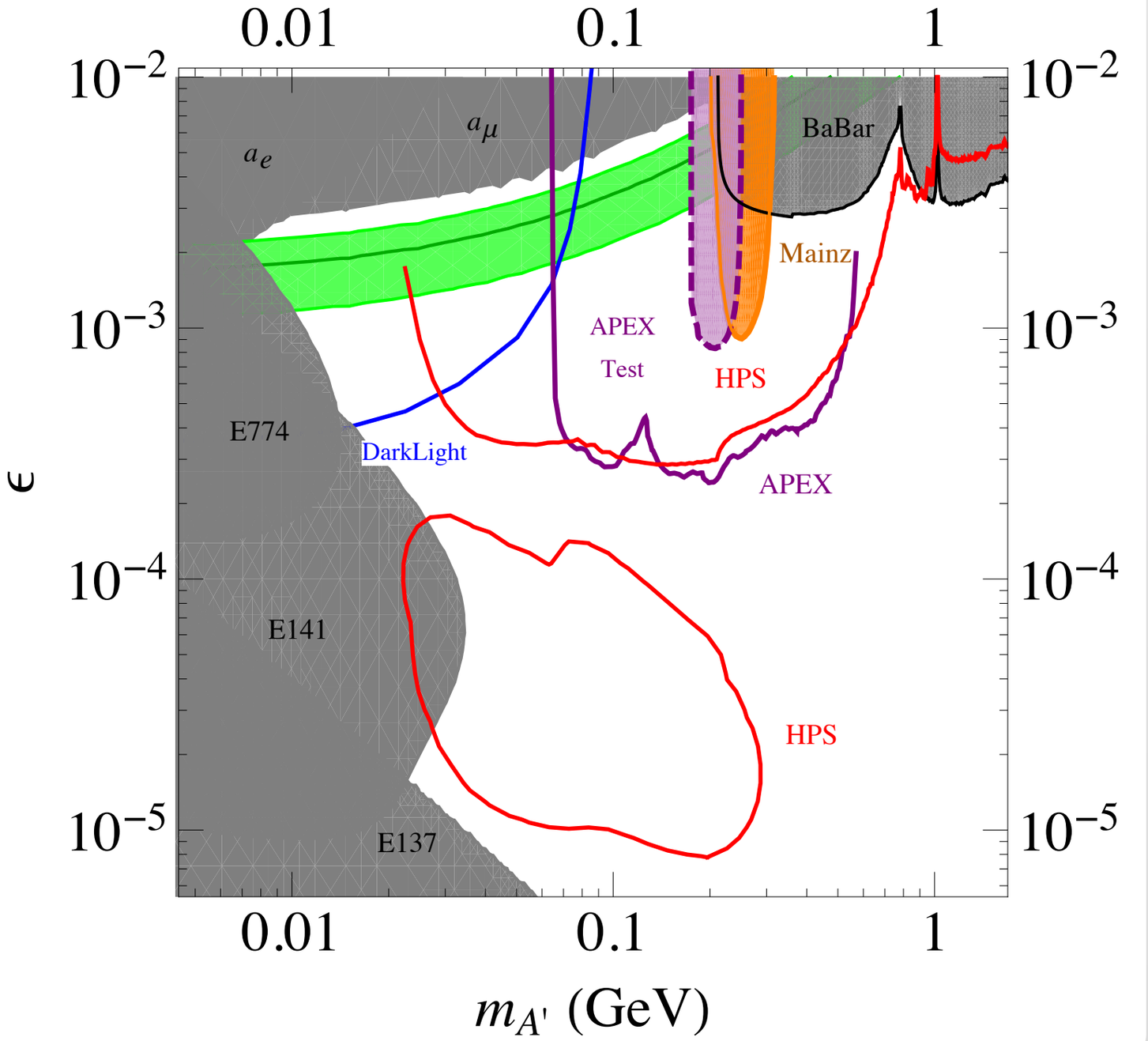
$\alpha'/\alpha=\varepsilon^2$

Blue:
200nA @ 2.2GeV
target: 0.125%

Red:
450nA @ 6.6GeV
target: 0.25%

3 months of beam at each energy

It's getting crowded...



Many experiments in the works to look for Dark Forces:

Mainz and APEX (JLab) ~ forward spectrometers
HPS (JLab) ~ compact Si-based vertex-tracker
DarkLight (JLab FEL) ~ high acceptance, H_2 gas target
HIPS(DESY)~ beam dump (not shown)

Other direct dark force searches

- Searches at e^+e^- colliders: BaBar & Belle(II), KLOE, BES
  - Lower luminosity + lower backgrounds
  - Higher mass reach (up to ~10GeV)
  - "exotic" dark force states: dark higgs, dark mesons
- Searches at hadrons colliders: ATLAS/CMS & CDF/D0
  - possible unique production path ⇒ cascades from SUSY particles
  - "lepton-jets" signatures along with typical di-lepton mass peak
  - potentially covers vast area of coupling-mass space, but with model assumptions

⇒ ***many public results already with more on the way...very active area of study!***

What now? My conclusions

- The search for new gauge bosons has a long history over a huge range of mass scales
- Something like a ***dark photon*** is very well theoretically motivated and if we live in a GU universe it probably exists
  - What coupling? What mass? Who knows? I have my favorite region!
- Dark matter naturally fits in this ***dark sector***
  - by the way, this doesn't override SUSY...dark sector models and SUSY get along fine!
- It's very cool to think that there might be very complicated, very different physics going on all around us which we can't examine but through this weak, tenuous connection

What now next?

- Ok, say we are seeing DM annihilating (maybe via dark photons) in the PAMELA & FERMI data...what else should we see
  - $f(e^+/e^-)$ should cut off at ~ DM mass
  - high energy photons from inverse Compton scattering & final state radiation ⇒ constraints from Fermi are discouraging
  - imprints on the CMB ⇒ PLANK will be crucial...2013?
- Possibly large impact on direct DM experiments
  - iDM ⇒ lower recoil energy
  - DAMA/CoGeNT/CRESST anomalies?
  - Xenon100, CDMS are putting big dent in iDM parameter space

"DM could have shown it's face in many places, and didn't...but has wiggle-room left." - Rouven Essig

Apart from these anomalies, the upcoming direct heavy-photon searches will block out a very interesting part of parameter space...maybe the dark sector will show it's head before dark matter