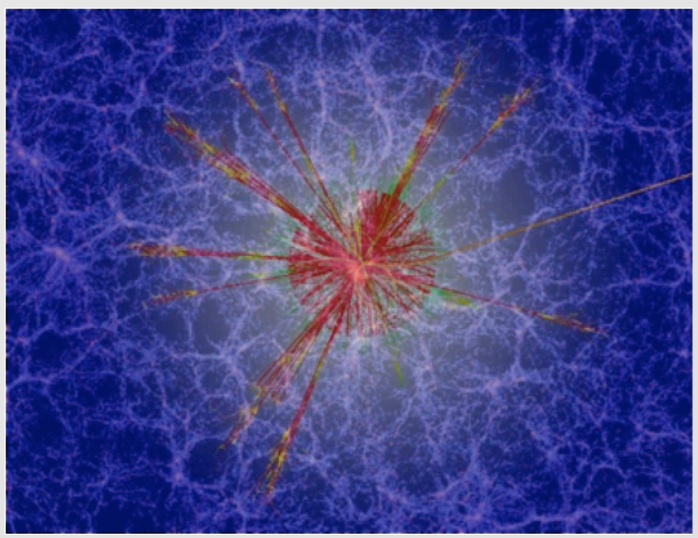
Searching for Dark Forces



Matt Graham
SLAC

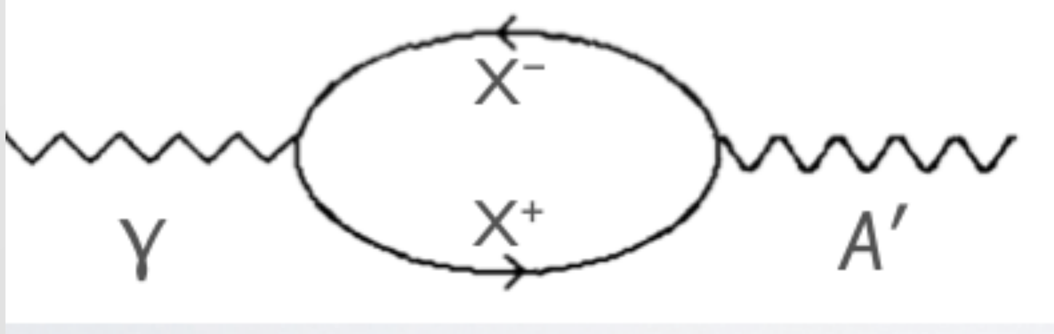
Physics in Collision 2011
August 31, 2011
Vancouver, Canada

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

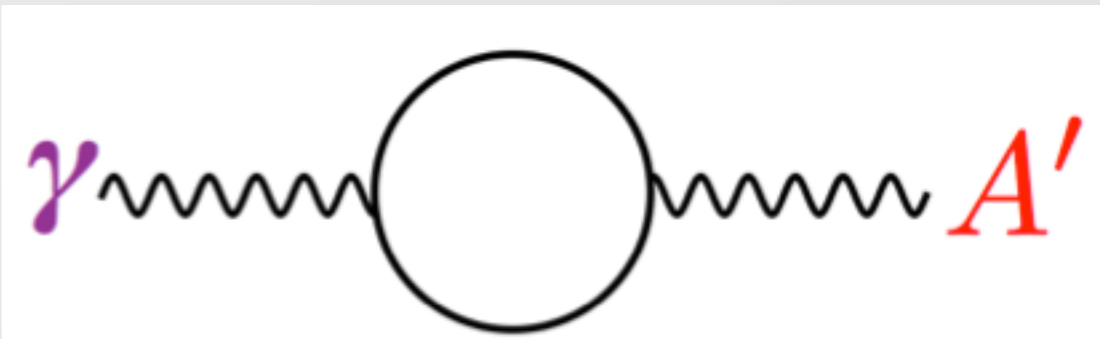
$$\mathcal{L}_{U(1)'} = -\frac{1}{4}V_{\mu\nu}^2 - \boxed{\frac{\epsilon}{2}V_{\mu\nu}F^{\mu\nu}} + |D_\mu\phi|^2 - V(\phi)$$

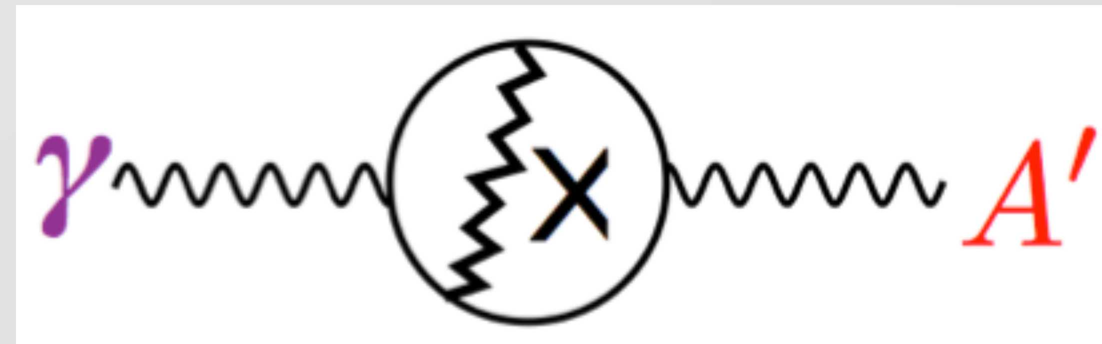


Kinetic Mixing term

- extremely general conclusion...even arises from broken symmetries
- one of the very few portals for a new force to communicate with the standard model
- gives coupling of normal charged matter to the new “heavy photon” q=εe

"Natural" coupling and mass





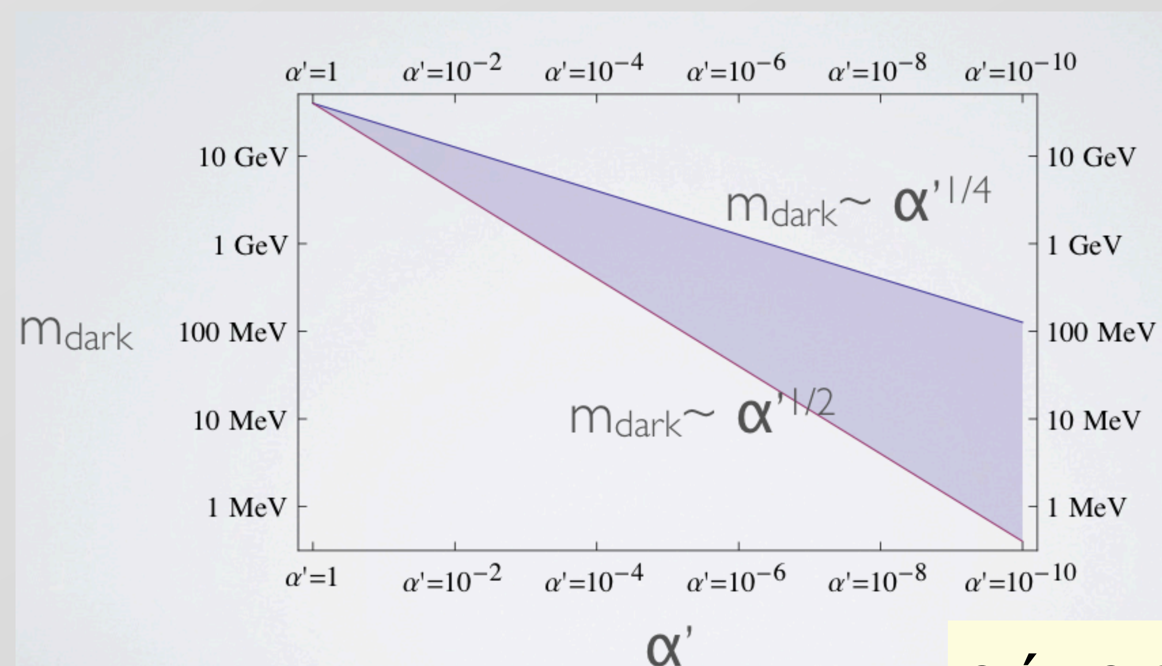
$$\epsilon \sim 10^{-3} - 10^{-2} \xrightarrow[\text{symmetry}]{\text{enhanced}} \epsilon_{GUT} \sim 10^{-5} - 10^{-3}$$

Depending on model, mass scales like:

$M(A')/M(W) \sim \varepsilon^{1}$-$\varepsilon^{1/2}$

leading to

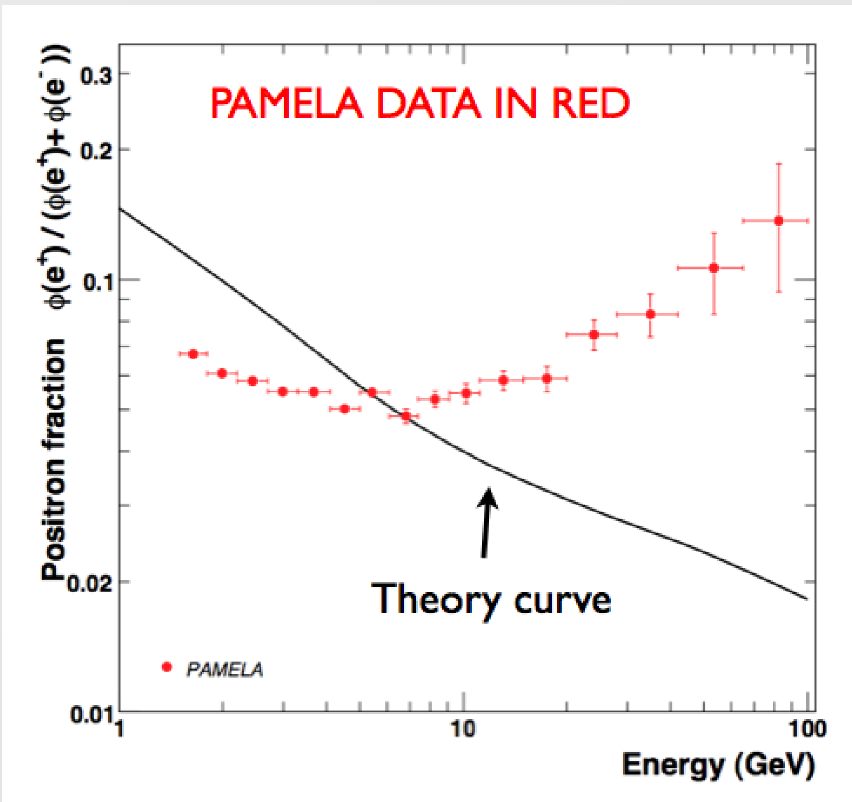
$M(A') \sim$ MeV-GeV



N. Weiner, JLAB PAC37 Talk

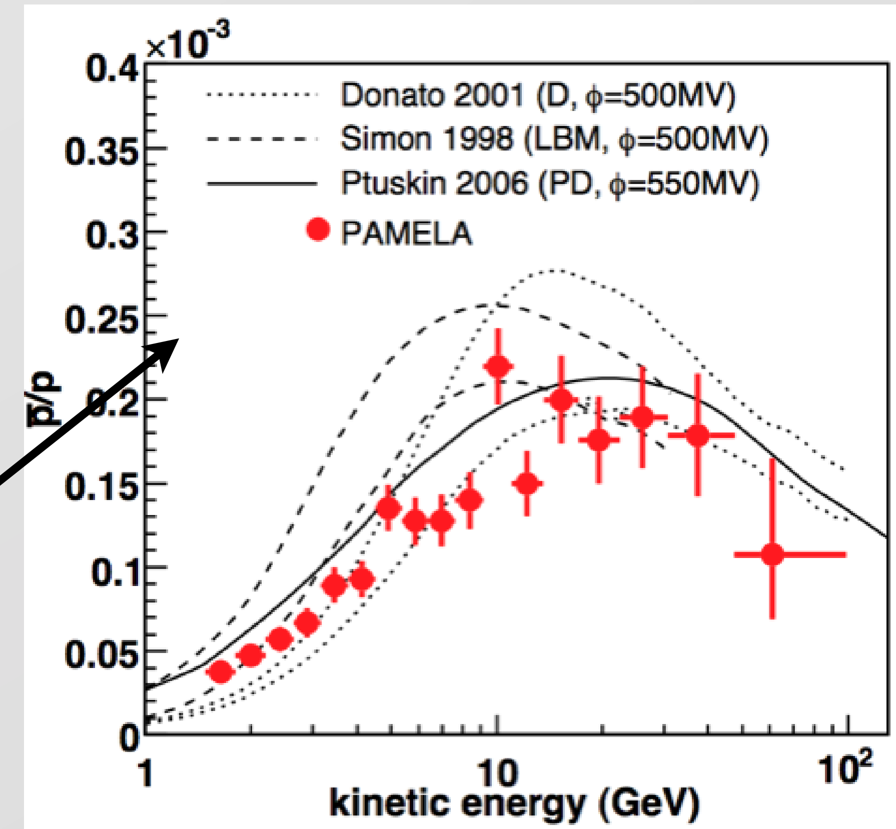
$\alpha' = \alpha\varepsilon$

Hint from astrophysics?

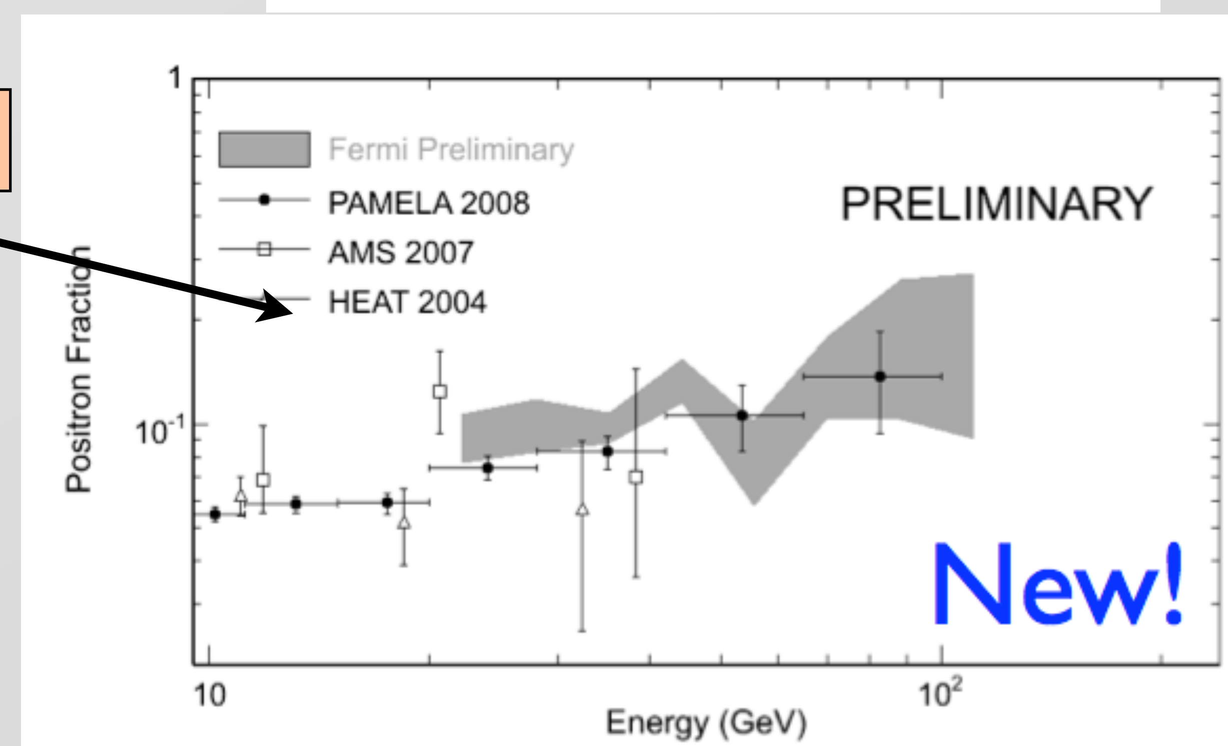


excess in e^+/e^- ratio

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



•FERMI sees it too!

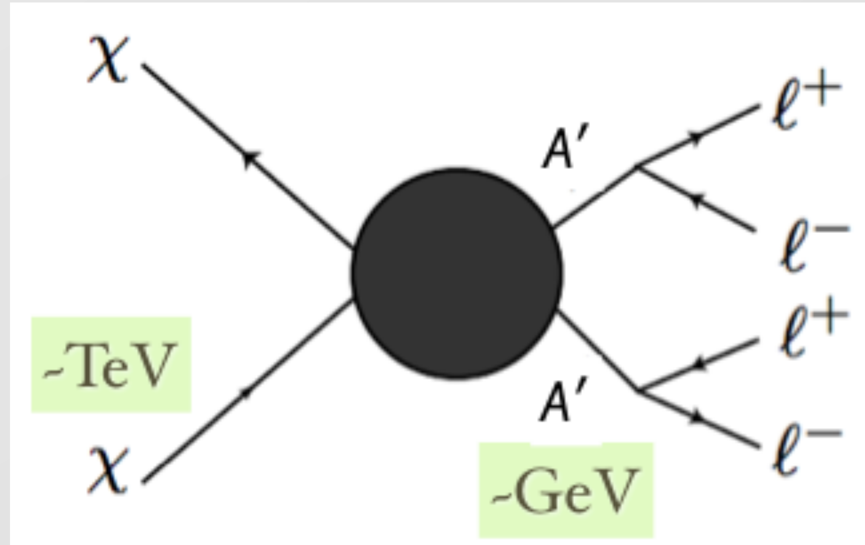


Unknown source of high energy positrons...

Is this astrophysics or particle physics?

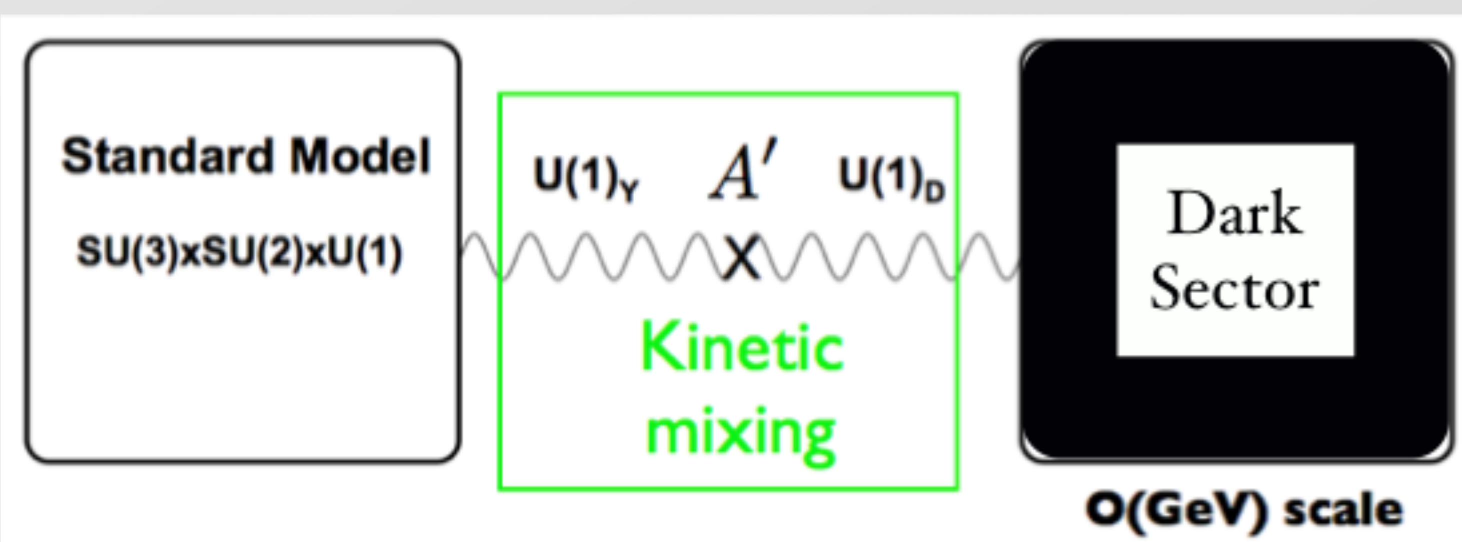
Dark matter annihilation and the dark sector

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−, μ+μ−) but $p\bar{p}$ decays are kinematically forbidden

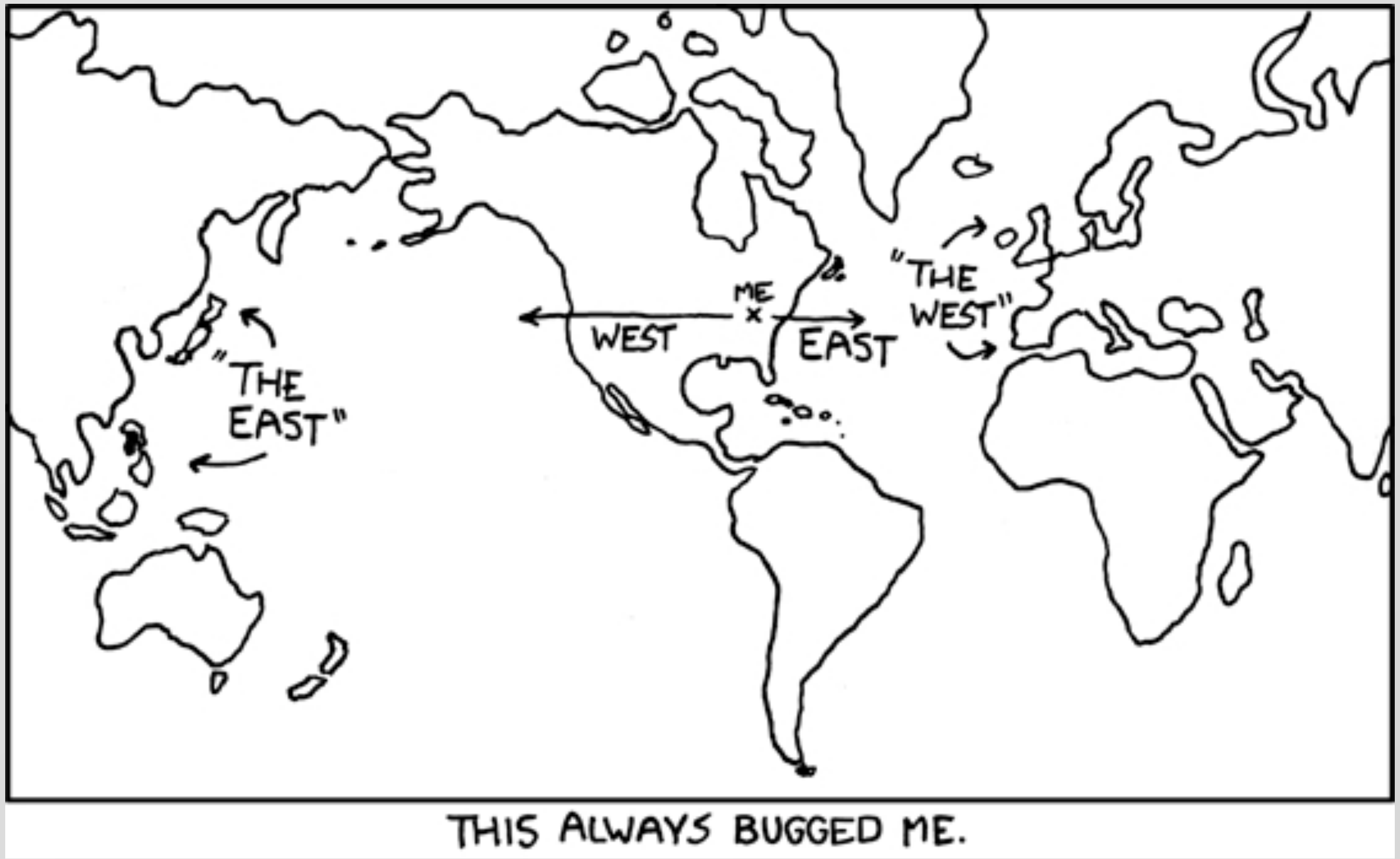


The idea of a dark sector has generated intense interest from both theory and experiment communities

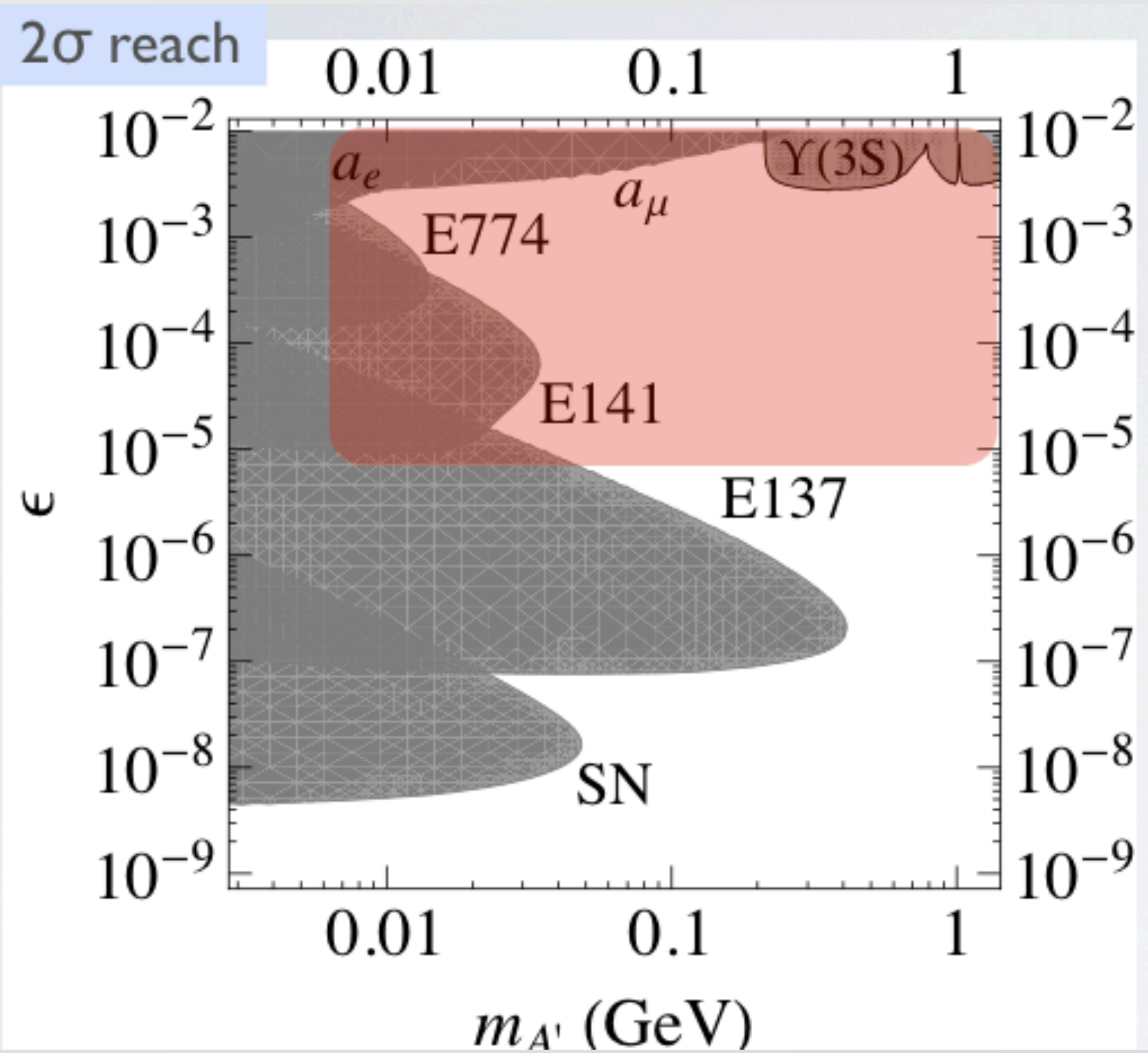
Terminology break

- 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!



The coupling-mass sweet spot



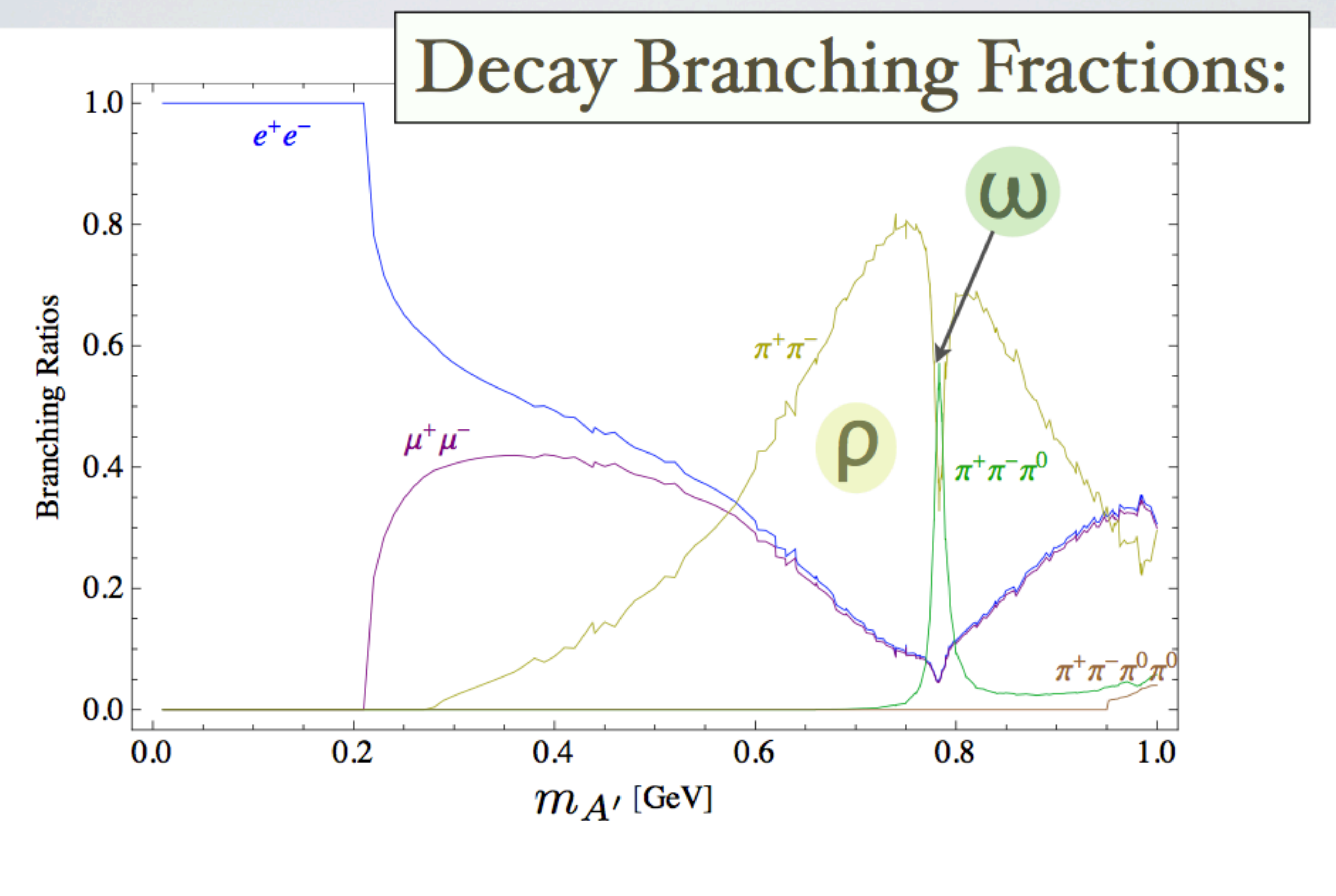
Both "naturalness" arguments and hints from experiments block out the same region in mass-coupling space:

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

m(A´) ~ MeV – GeV

Most of this region is unexplored!

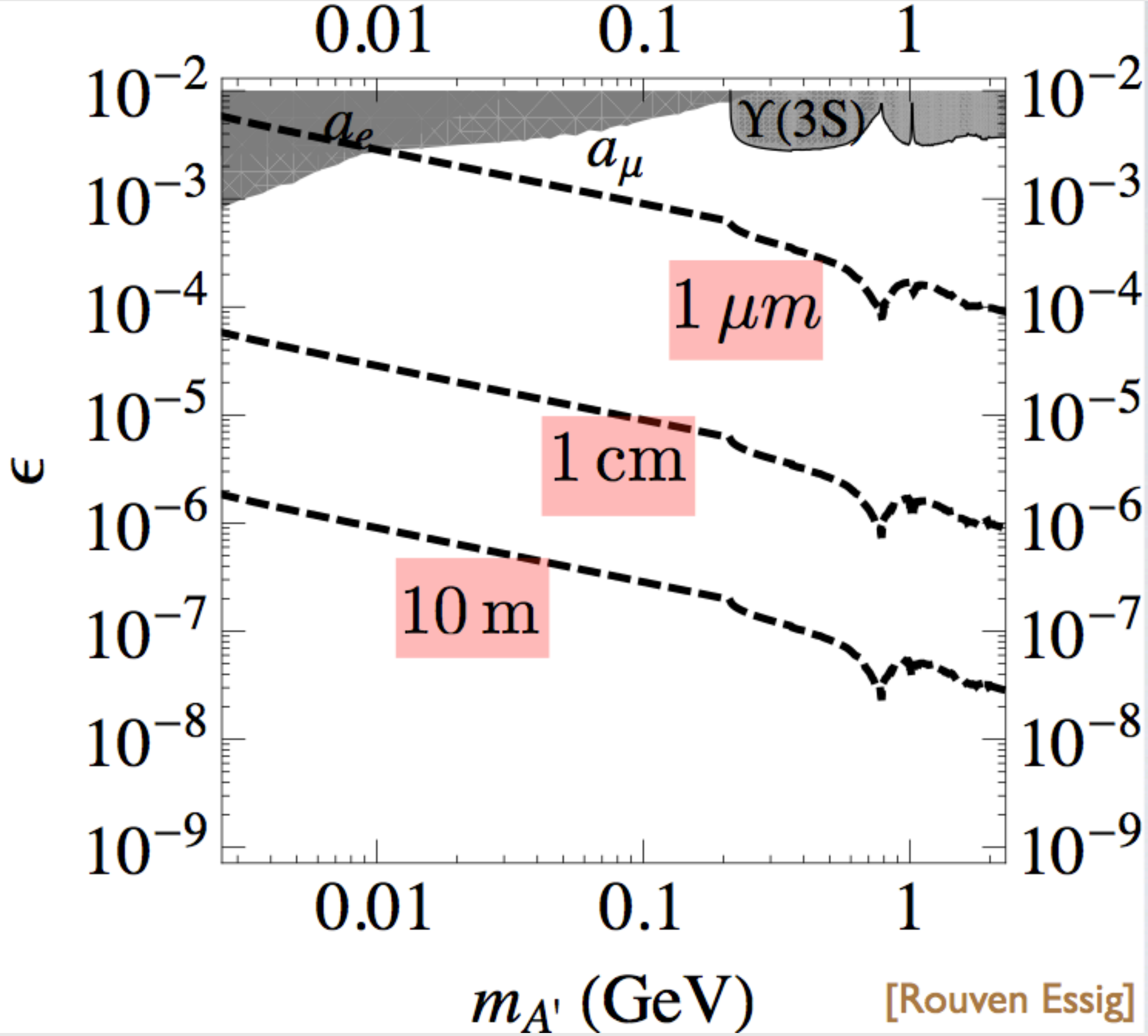
A´ decay products



A′ lifetime

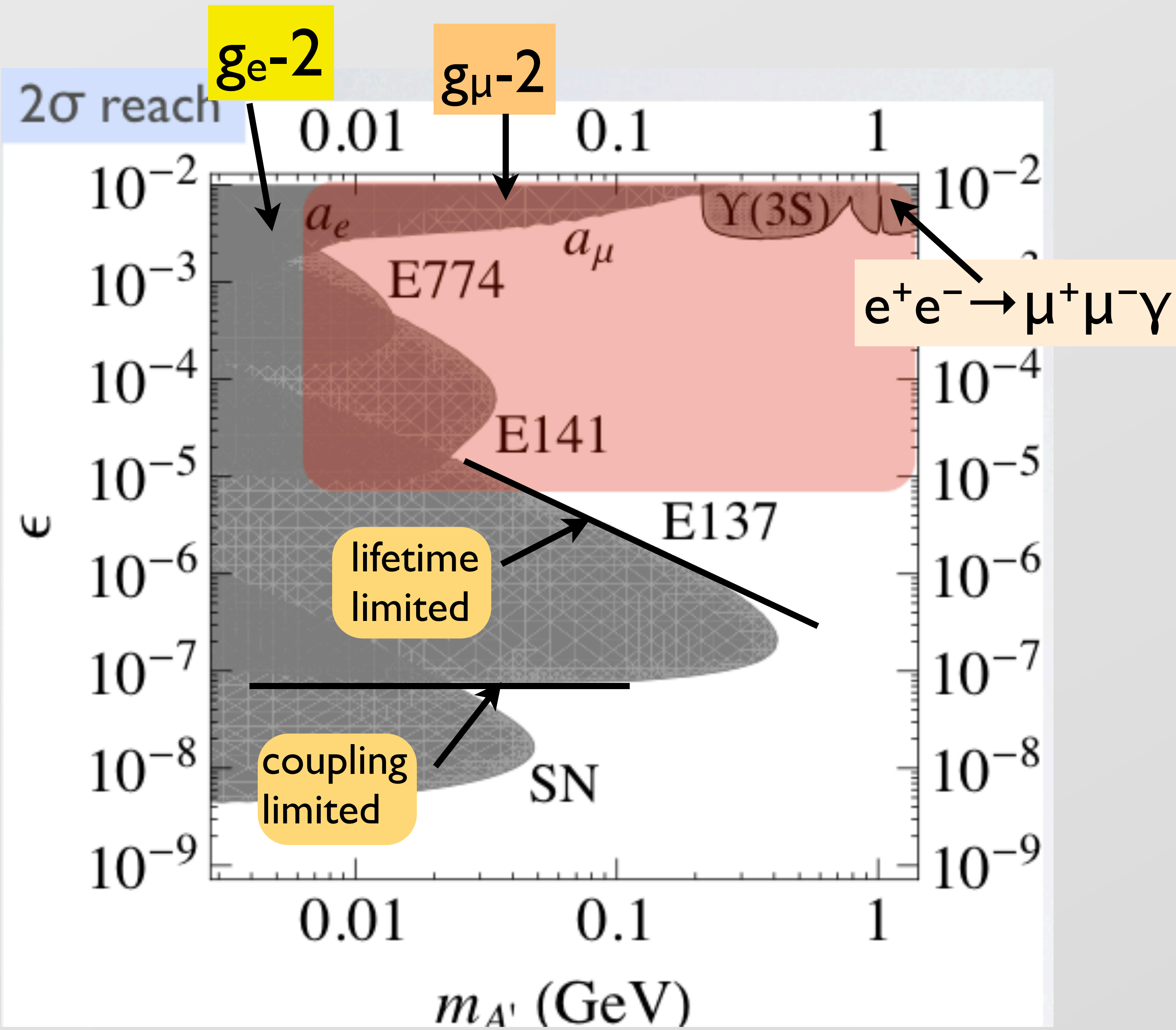
$$\gamma c\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{A'}}\right)^2$$

lower ε, lower mass
→ longer lifetime



[Rouven Essig]

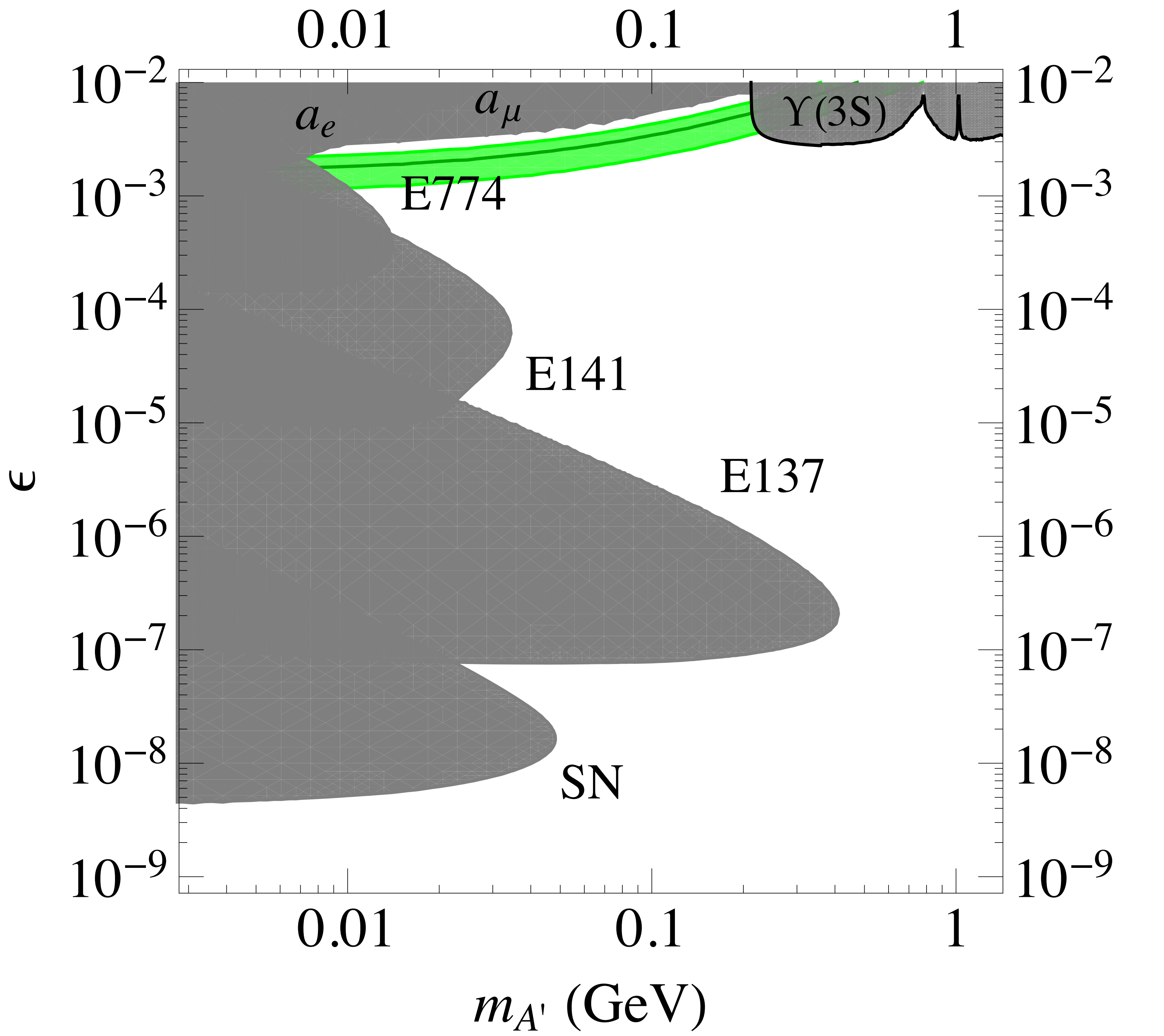
Some existing constraints



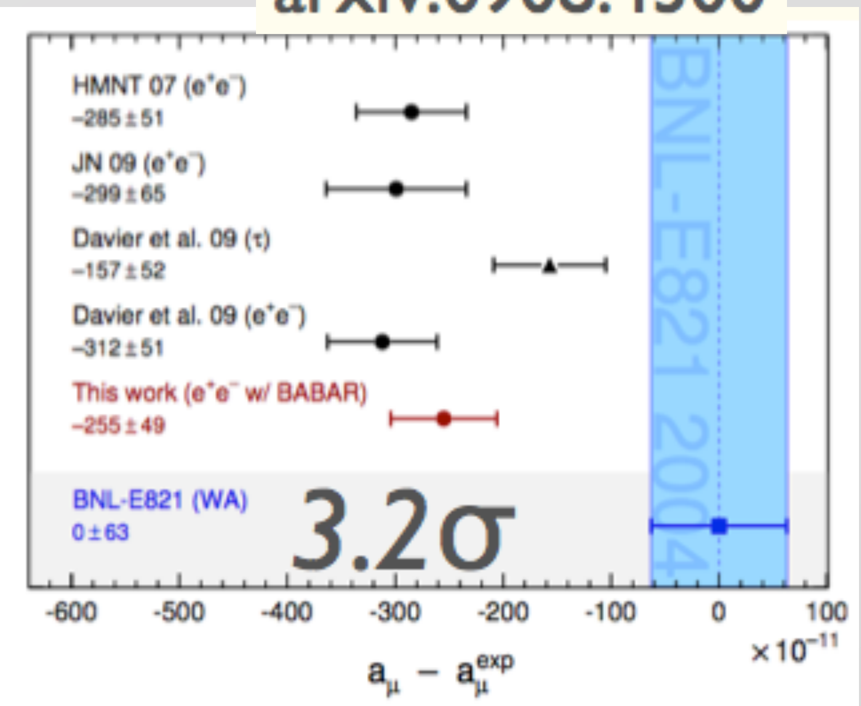
	Shield (m)	E_{beam} (GeV)	Lumi (e^-)
E137	200	20	10^{20}
E141	0.12	9	2×10^{15}
E774	0.3	27.5	5×10^{9}

Dark photons and the g-2 anomaly

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

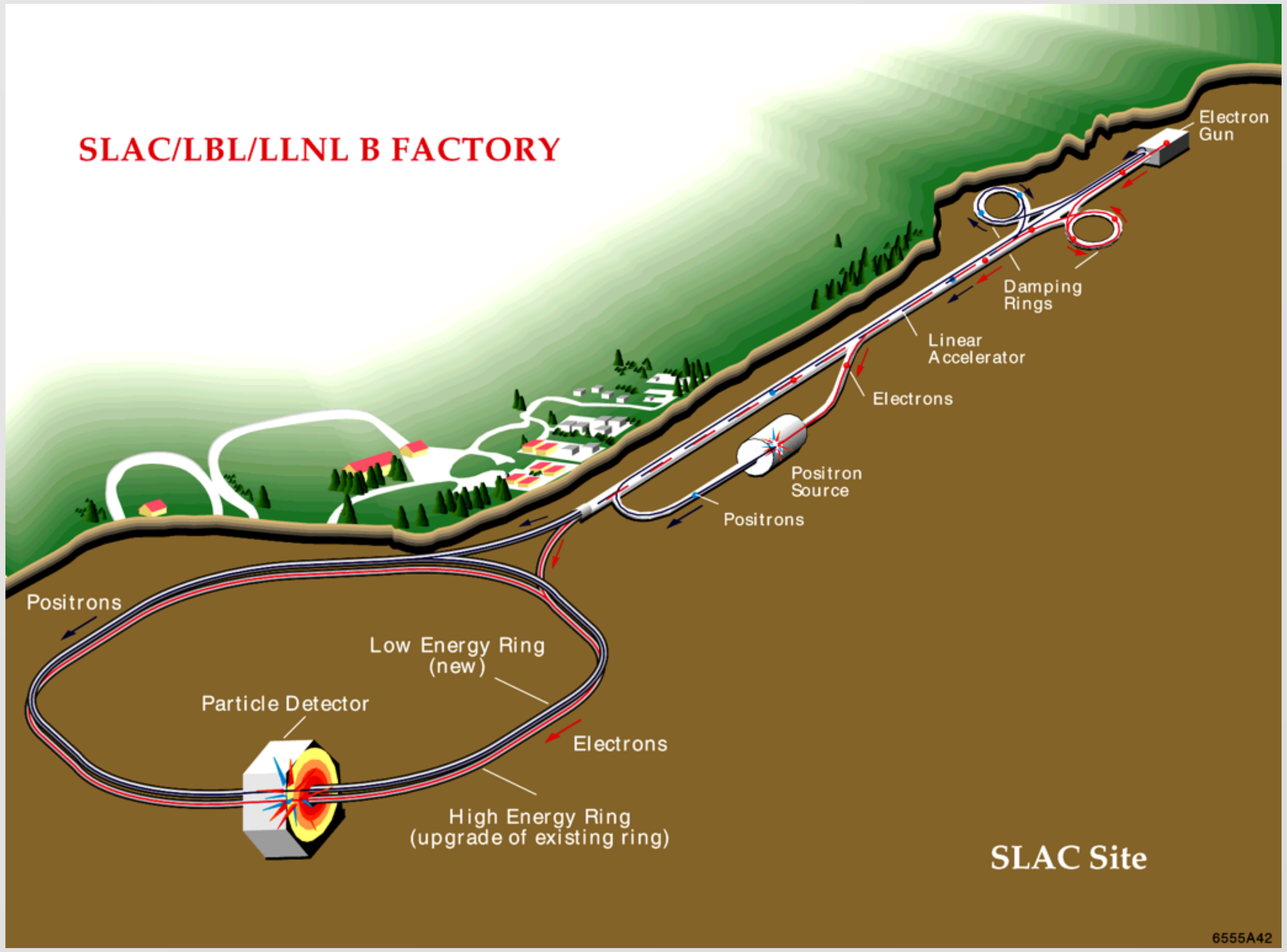


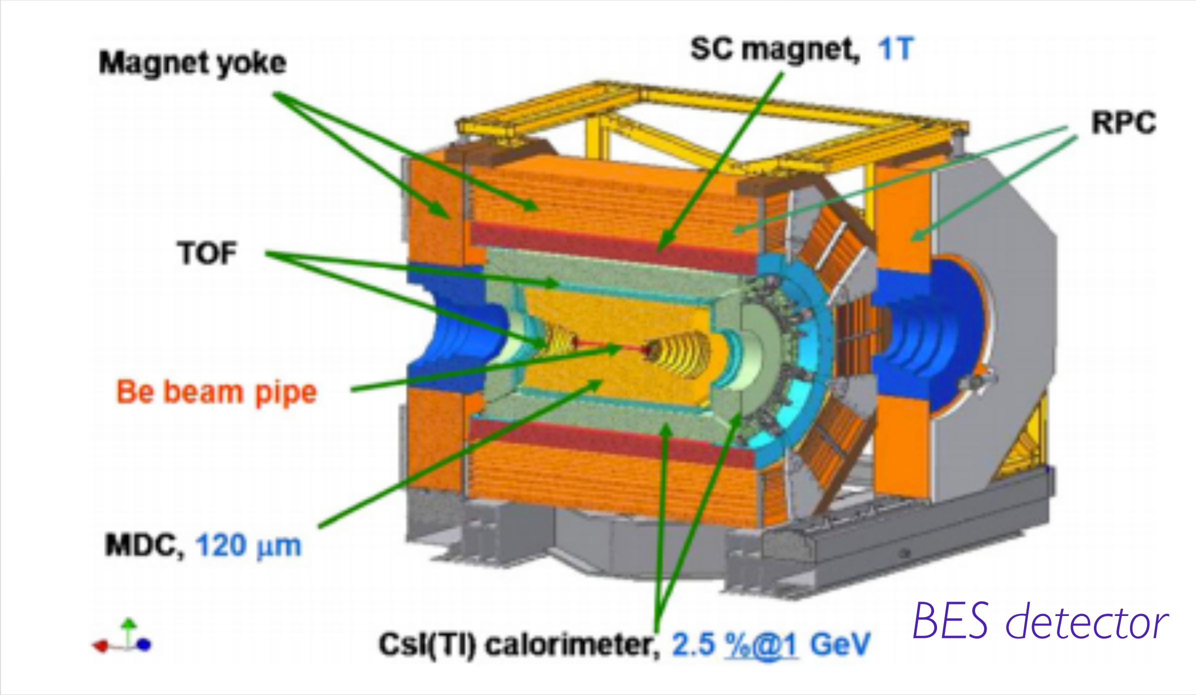
Davier *et al.*, arxiv:0908.4300



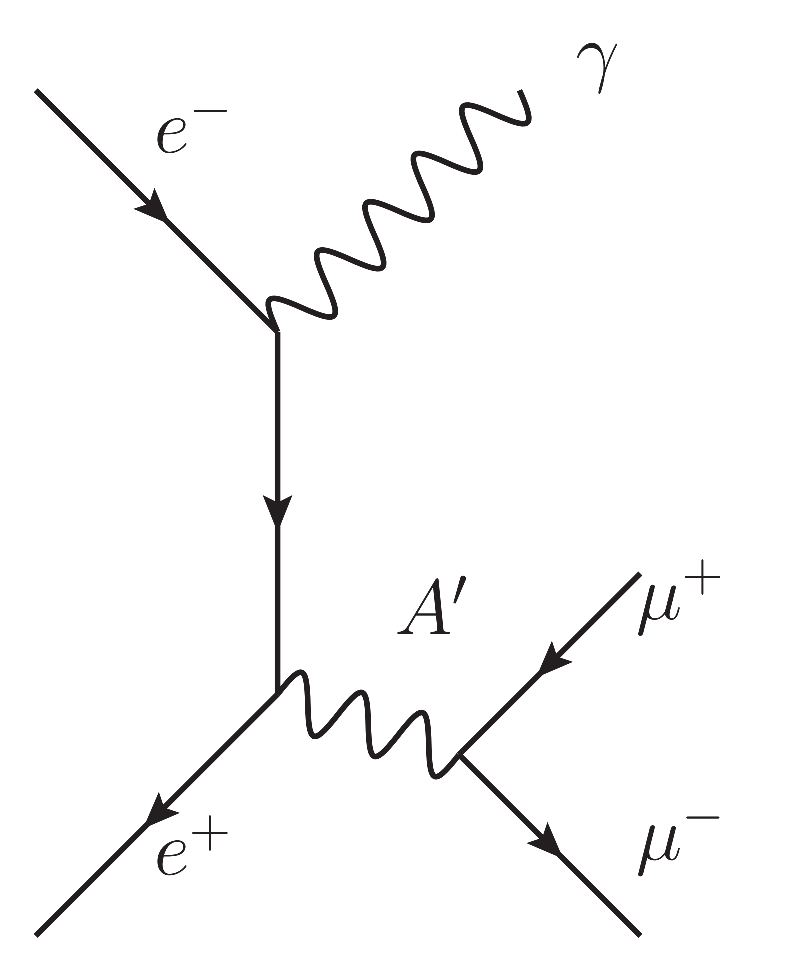
Where to look for dark forces?

- at e^+e^- colliders
  - BaBar, Belle, KLOE, BES...





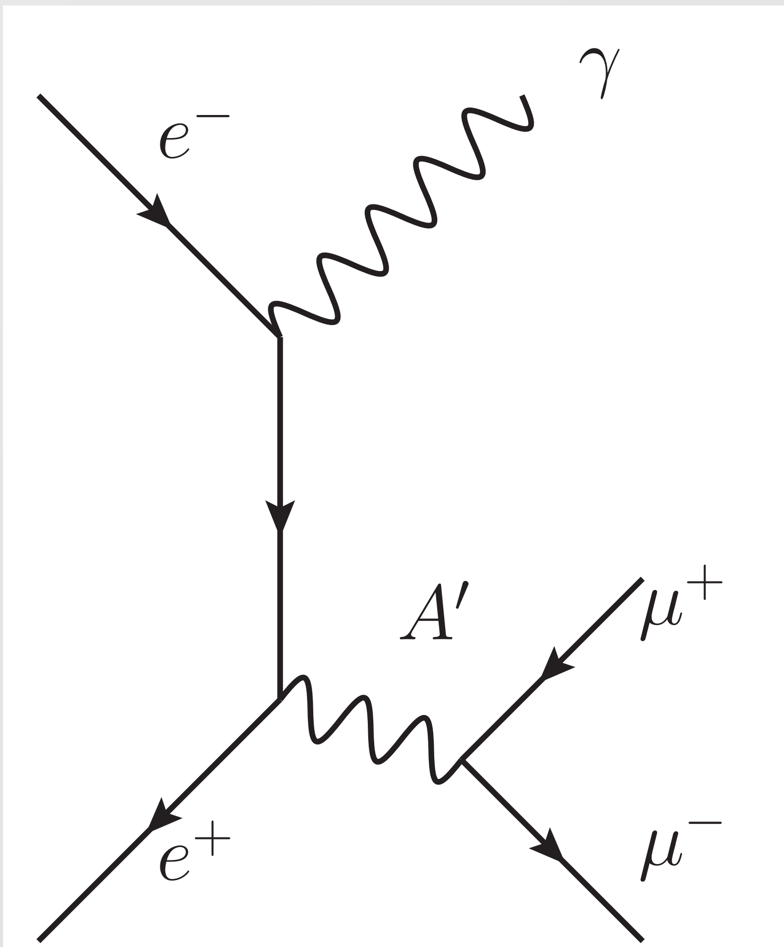
Dark forces production at e⁺e⁻ colliders

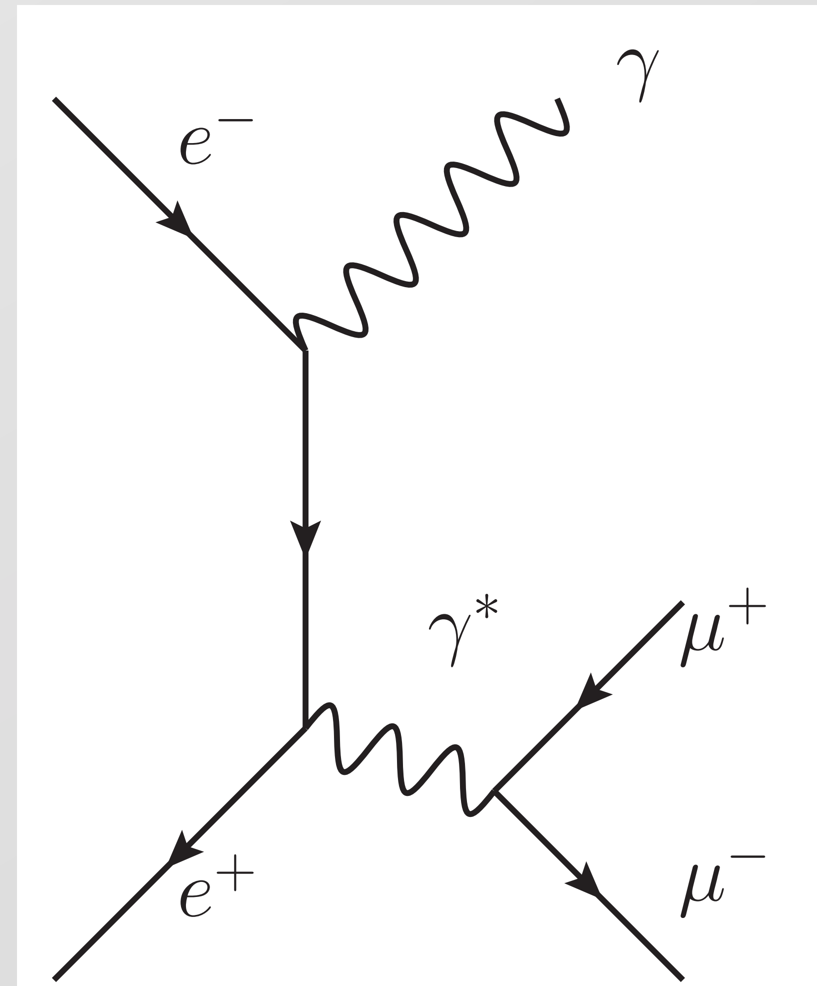


$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

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

Dark forces production at e⁺e⁻ colliders





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

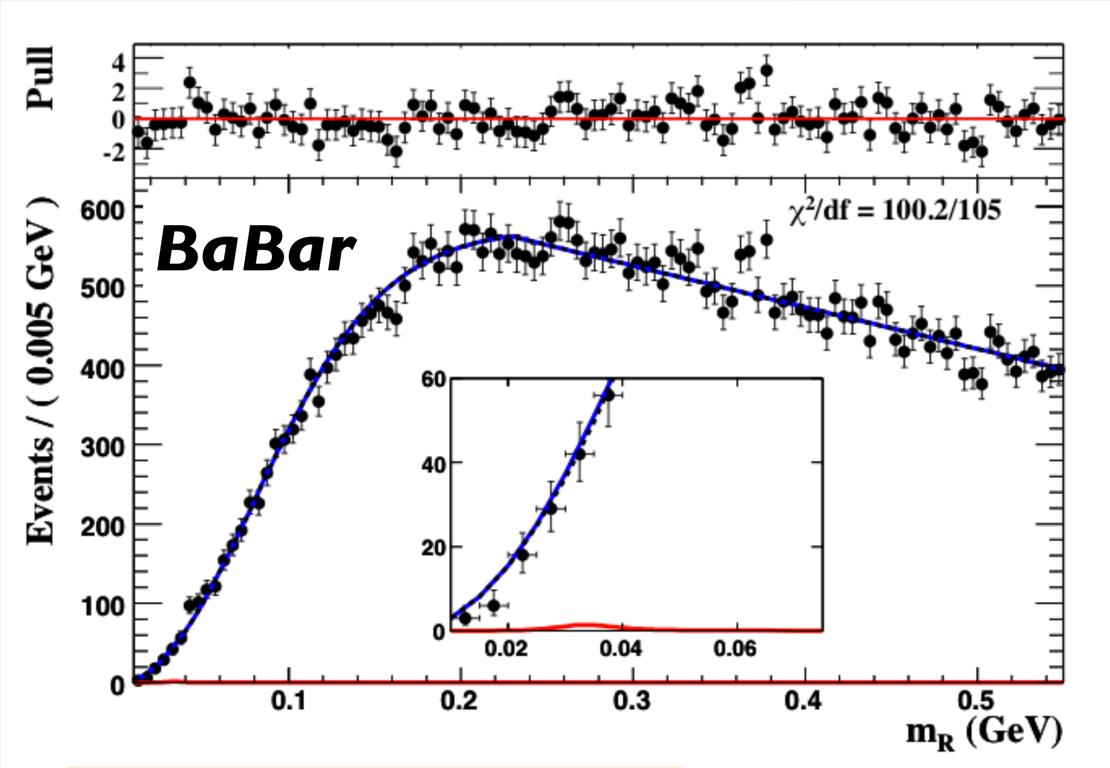
$O\ ab^{-1}$ per ~~decade~~ month

...but a large, irreducible background

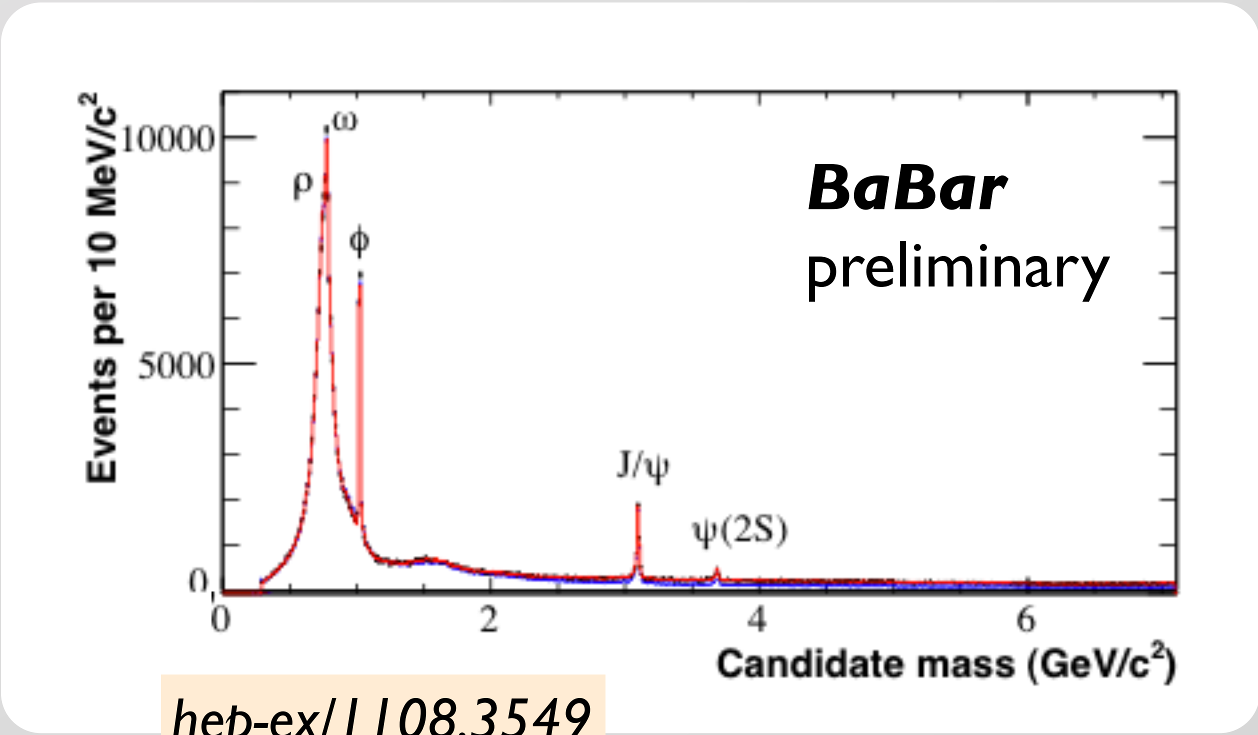
⇨look for a bump spectrum

$e^+e^- \to \gamma(narrow)$

- BaBar has done a few searches for $\Upsilon(nS) \to \gamma A_0$, looking for a light, narrow scalar from Υ decays
- Simple searches...look for a bump in the $\mu\mu/\pi\pi/\tau\tau$ (etc) spectrum
    - No (unexpected) peaks found in any of these searches
- Very close to the same analysis one would use to look for $e^+e^- \to \gamma A'$
    - Acceptance and selection efficiency different for scalar vs vector...
    - BaBar has not published results specifically for $e^+e^- \to \gamma A'$
        - ➡All ε vs $m(A')$ exclusions using results from BaBar are estimates!
- Only a fraction (~10%) of all BaBar data has been used...nothing from Belle yet. Hopefully more to come!



PRL 103:081802, 2009.



hep-ex/1108.3549
Submitted to PRL

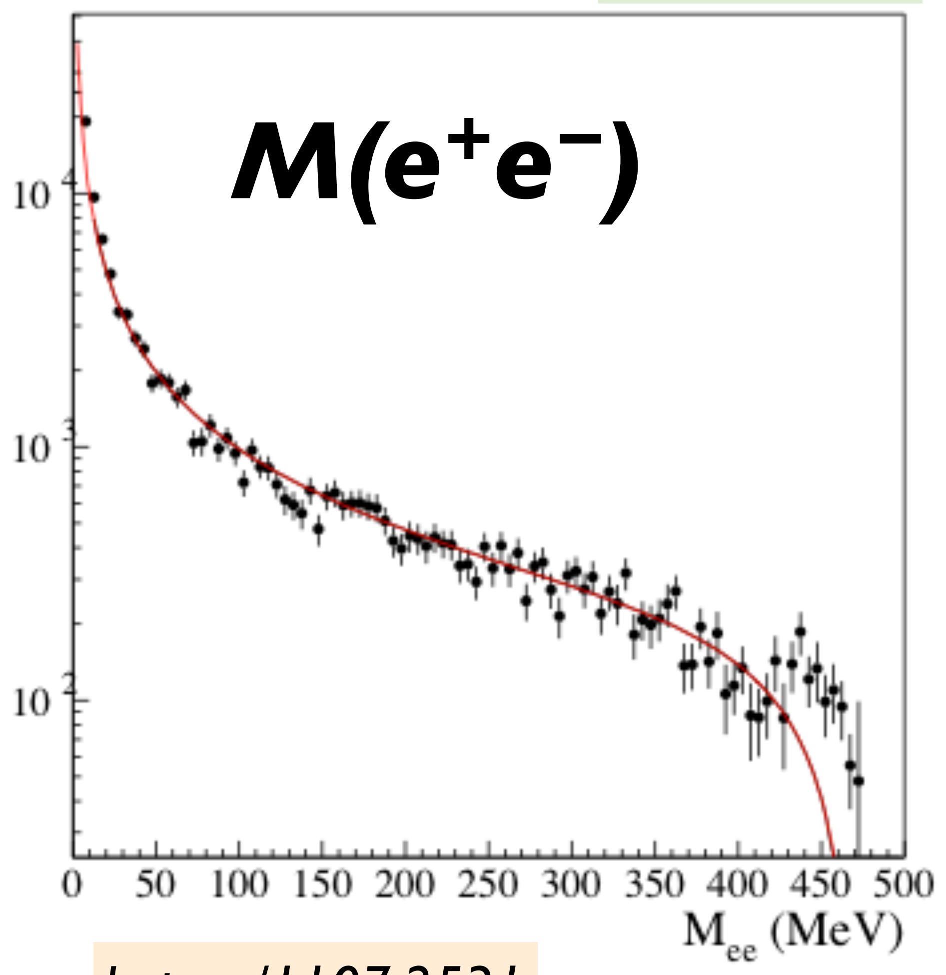
KLOE $\phi \rightarrow \eta A'$

- looked for $\eta \rightarrow \pi^+\pi^-\pi^0$ & $A' \rightarrow e^+e^-$
- primary background is $\phi \rightarrow \eta e^+e^-$ which has ***σ~700fb*** (~14k events)
- signal cross-section ($\varepsilon = 10^{-3}$):

$$\sigma(\phi \to \eta U) = \epsilon^2 \, |F_{\phi\eta}(m_U^2)|^2 \, \frac{\lambda^{3/2}(m_\phi^2, m_\eta^2, m_U^2)}{\lambda^{3/2}(m_\phi^2, m_\eta^2, 0)} \, \sigma(\phi \to \eta\gamma) \sim 40 \text{ fb}$$

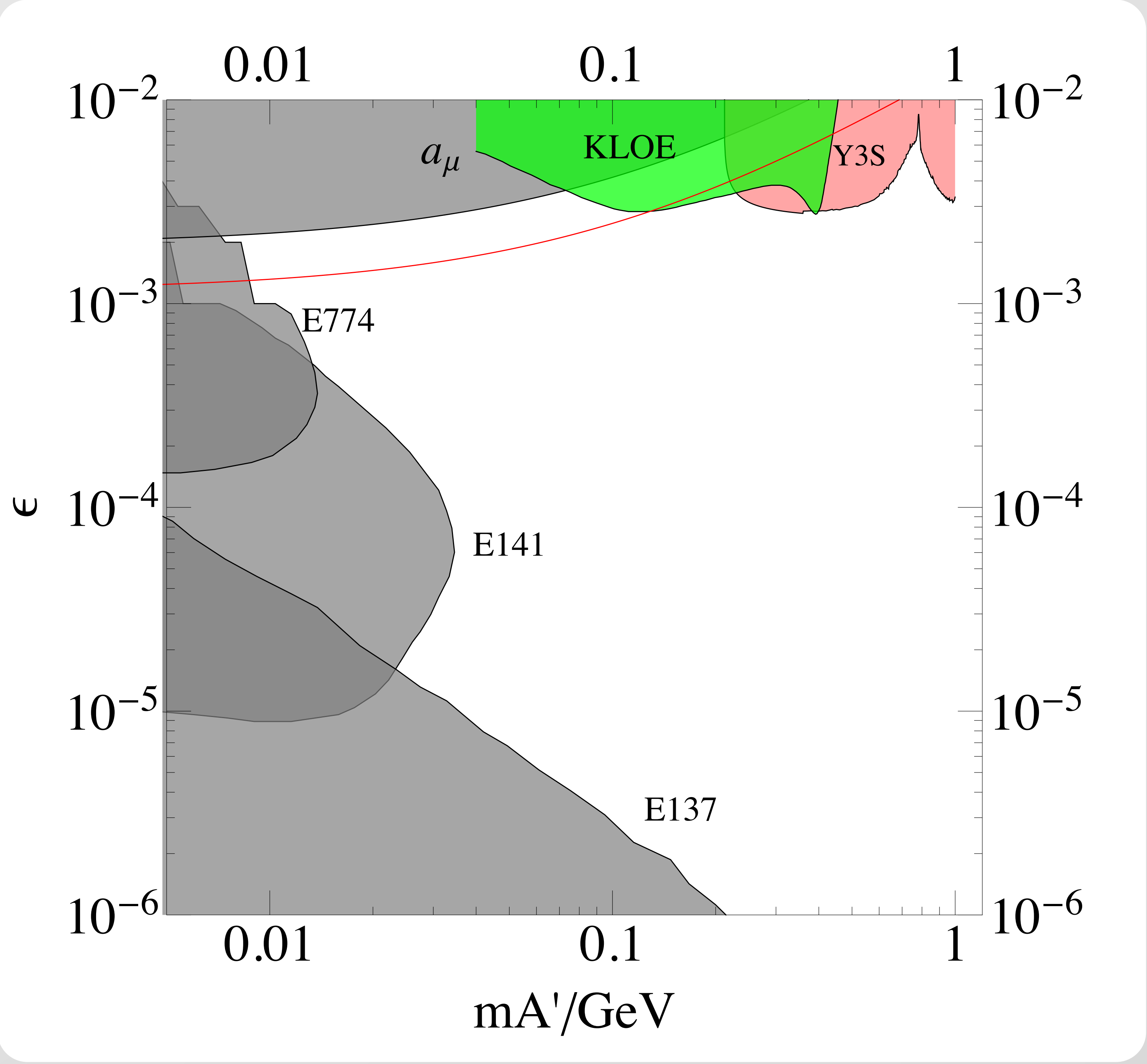
- look for bump in $M(e^+e^-)$
  - mass resolution ~ MeV
  - background is parameterized with a phenomenological model...safer to fit an arbitrary smooth polynomial???

1.5 fb⁻¹



hep-ex/1107.2531

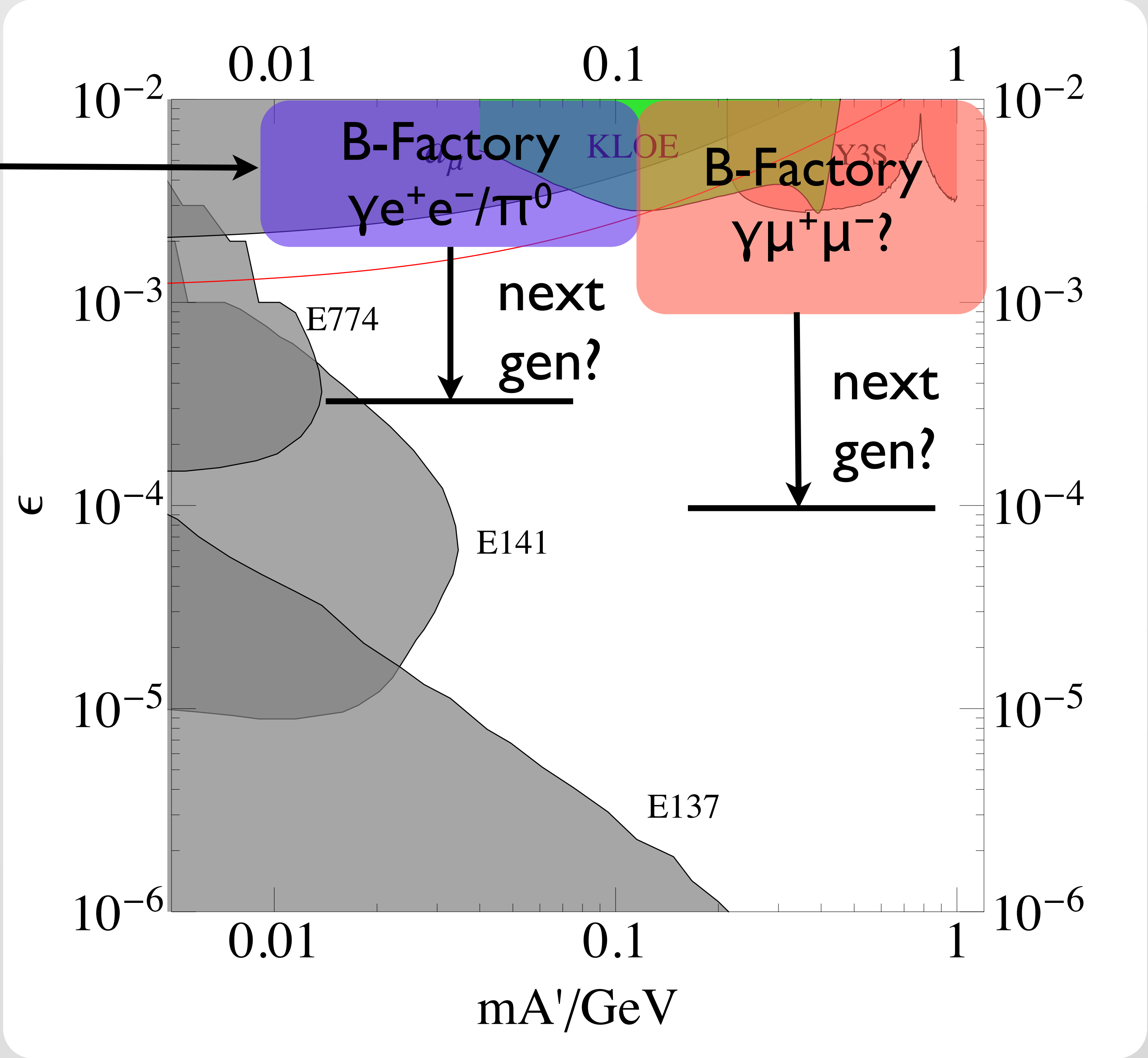
Constraints...now



Constraints...and later?

How low???

(mass & ε)



Where to look for dark forces?

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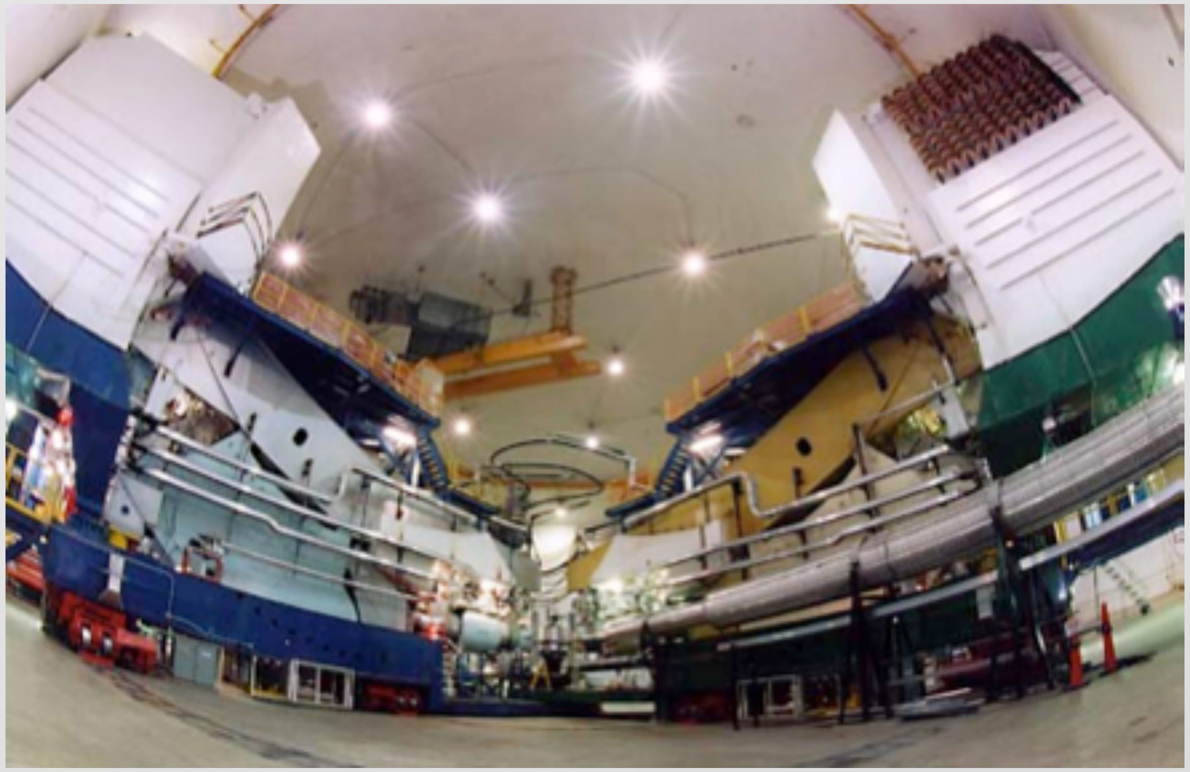
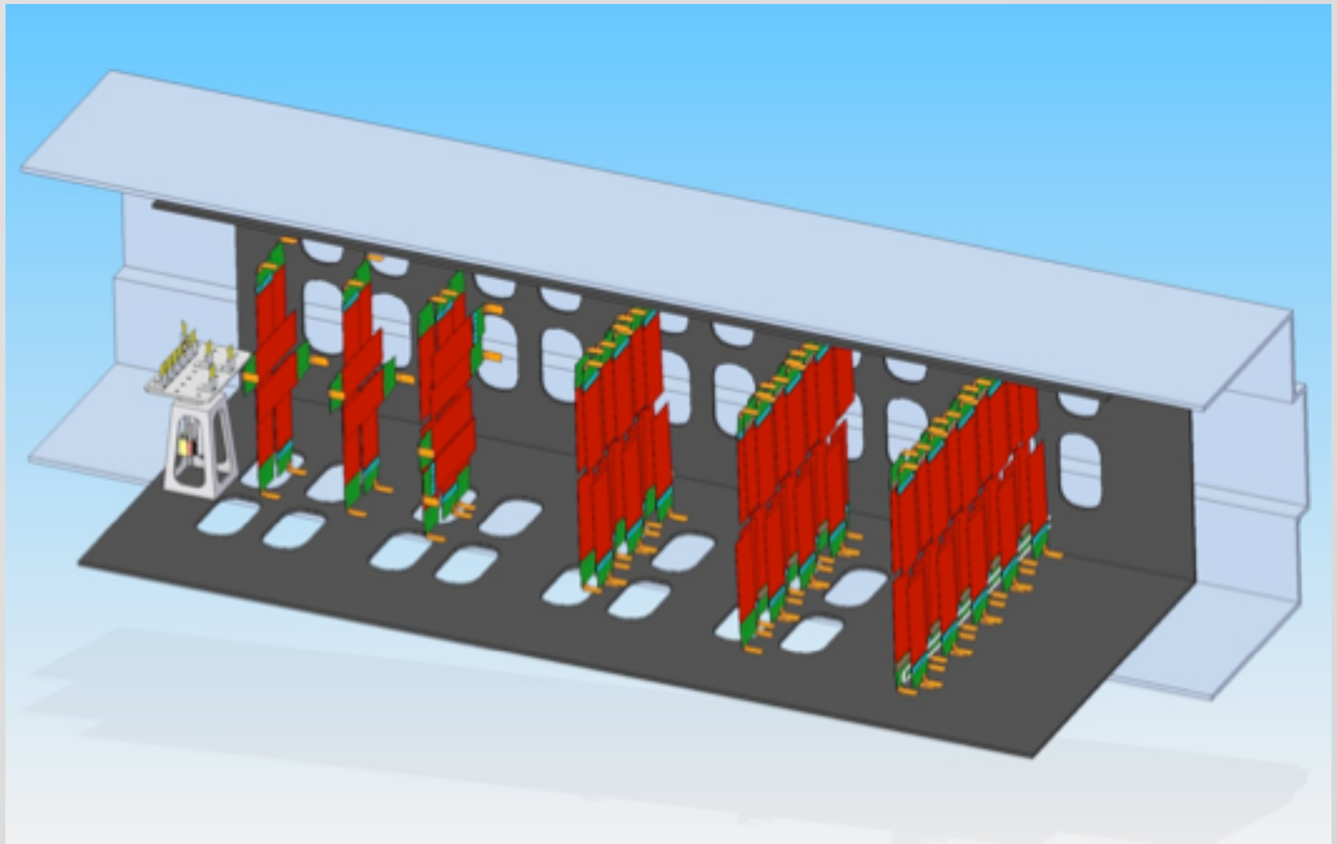
  - BaBar, Belle KLOE, BES...
- fixed target experiments
  - E137, E141, APEX, Mainz, MAMI, DarkLight...

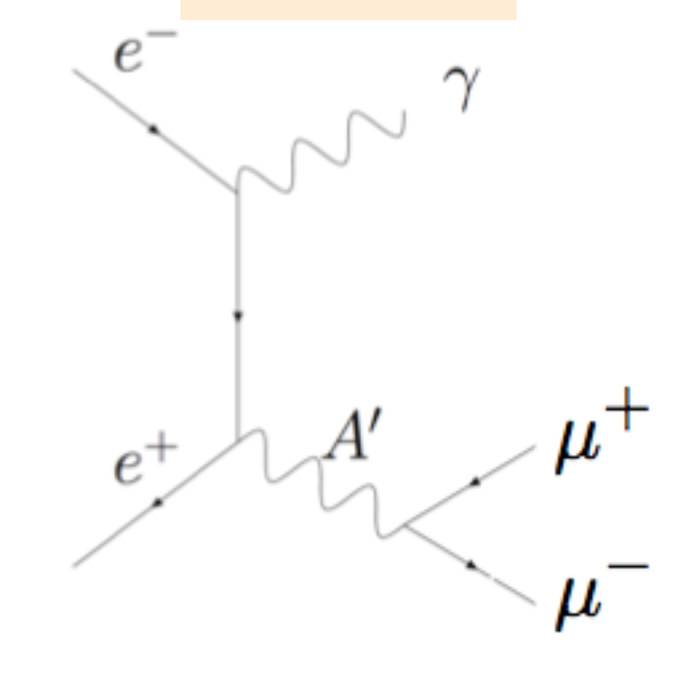




Collider vs. Fixed Target

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

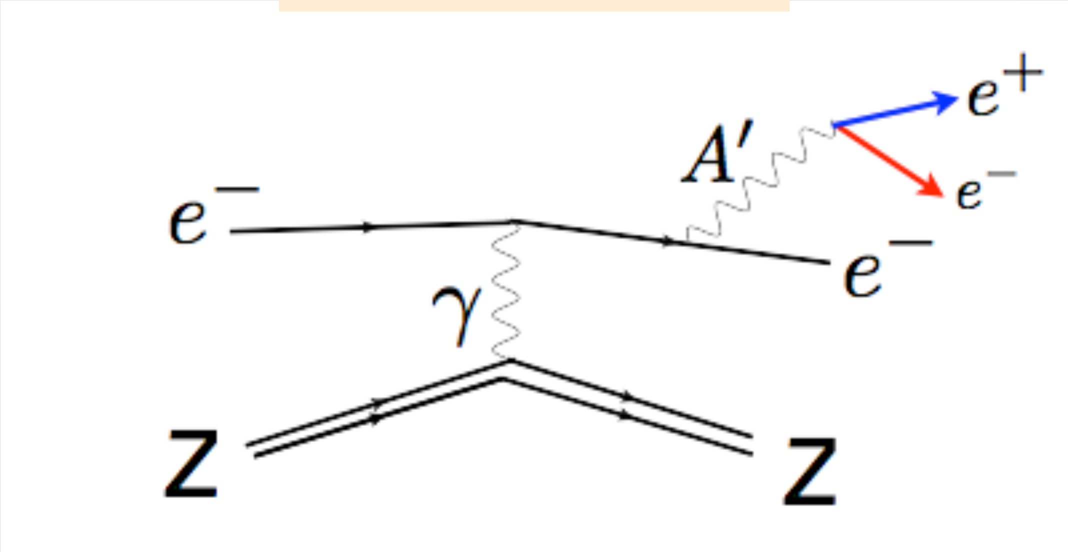
Collider



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

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

Fixed Target



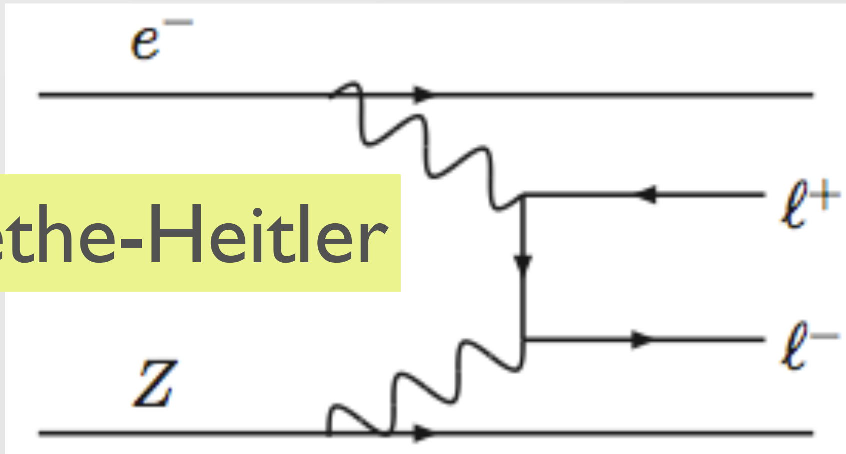
$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

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

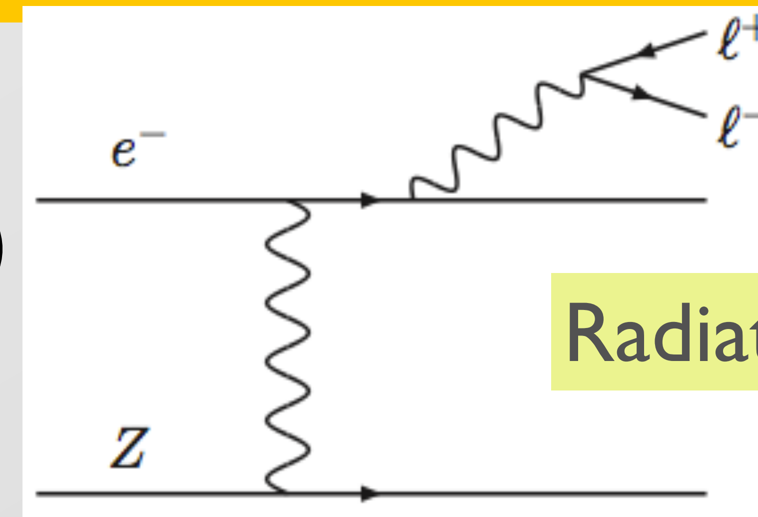
...much higher backgrounds

Backgrounds at fixed target experiments

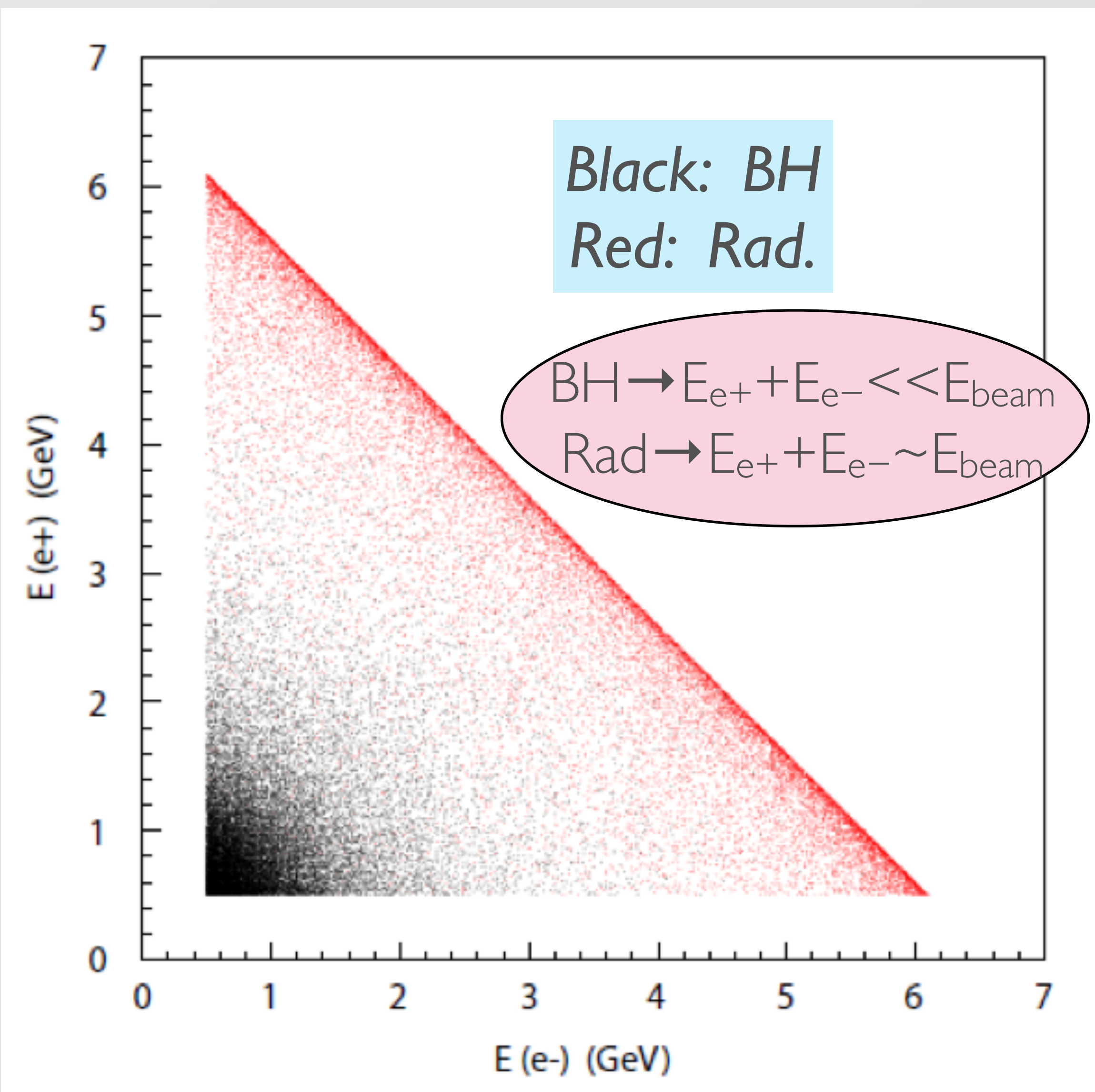
Bethe-Heitler



Two main backgrounds



Radiative



production rates of A' and radiative are related:

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

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

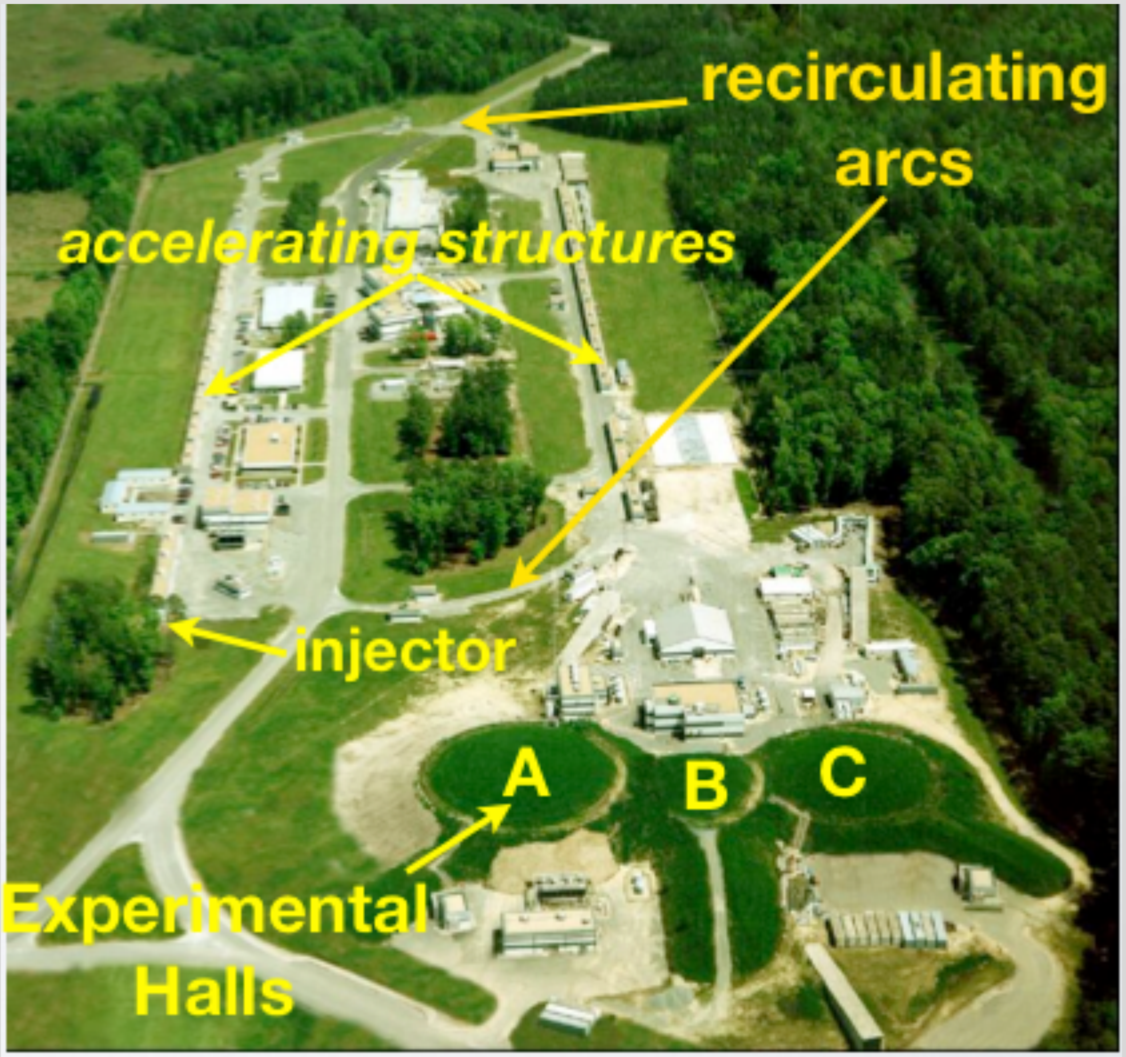
Method #1: brute force

BEST laid out a few methods to look for a dark photon in various ε/m(A´) regions...

Bjorken, Essig, Schuster, Toro, Phys.Rev. D80 (2009) 075018

First...slam a huge number of electrons on a target and look for a bump!

	Hall A	MAMI
Experiment	*APEX*	*A1*
E_{beam}	$n\times1.1$ GeV	0.855 GeV
I_{beam}	$<200\ \mu A$	$90\ \mu A$
bunch separation	~ *Continuous*	



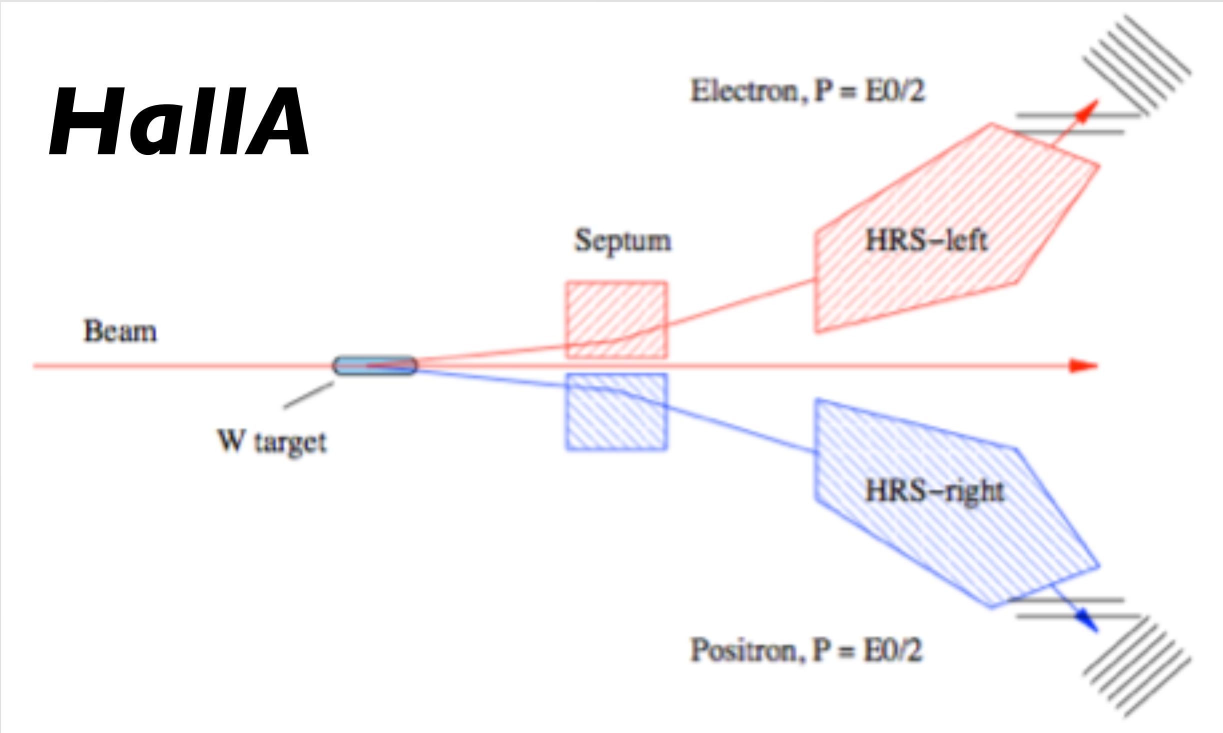
Method #1: APEX & A1/Mami

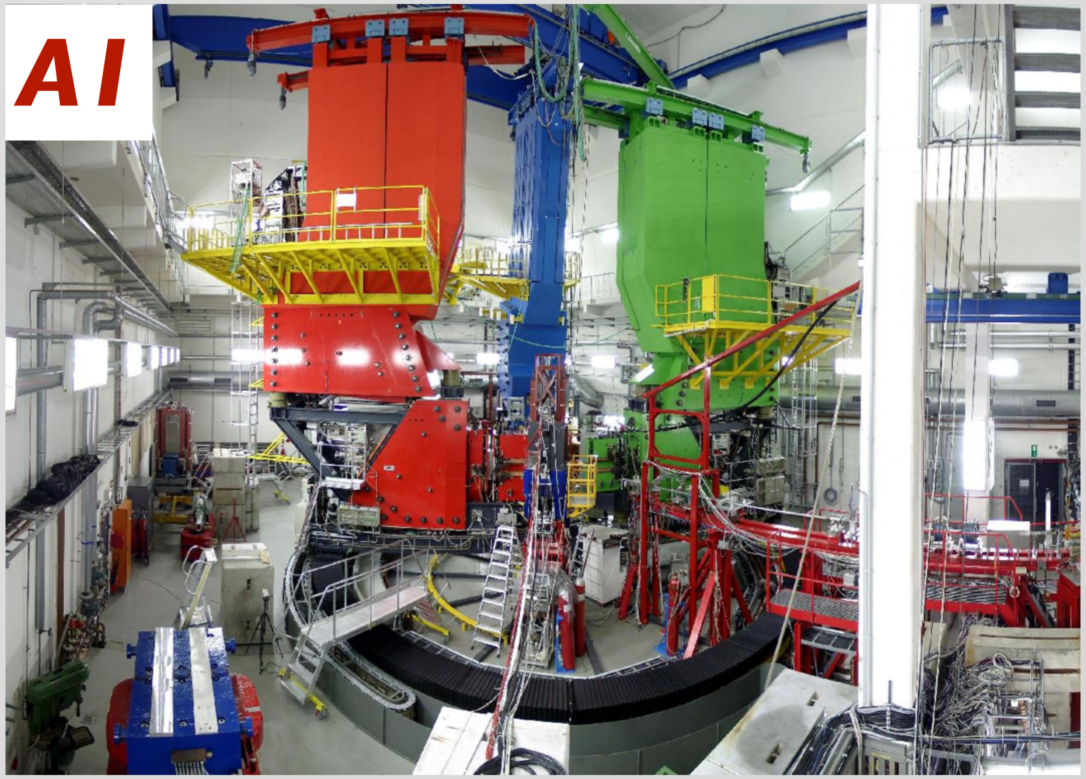
Both APEX and A1 use dual armed spectrometers to reconstruct the e^+e^- pair.

➡drift chamber (tracking), gas Cherenkov (PID), hodoscopes(trigger)
➡great mass resolution (~MeV), small acceptance (~0.1%)
➡mass resolution dominated by angular resolution (optics+tracker), MS in target

Both experiments have completed successful test runs

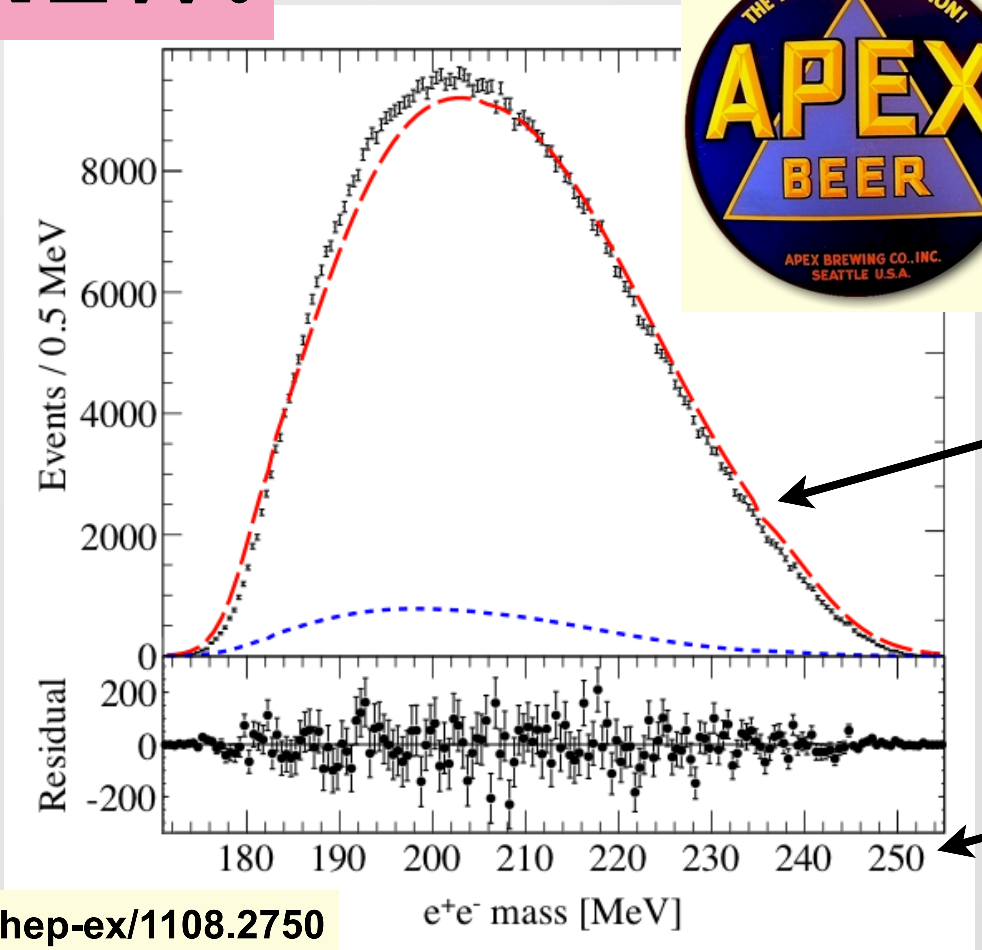
- primary goal was to confirm calculated background rates; make sure we wouldn't burn down the detector hall for full run
- both were also able to take some interesting physics data
  - thick(X/X0~1%) targets⇨plans for data runs using more sophisticated targets





Early brute force results!

NEW!

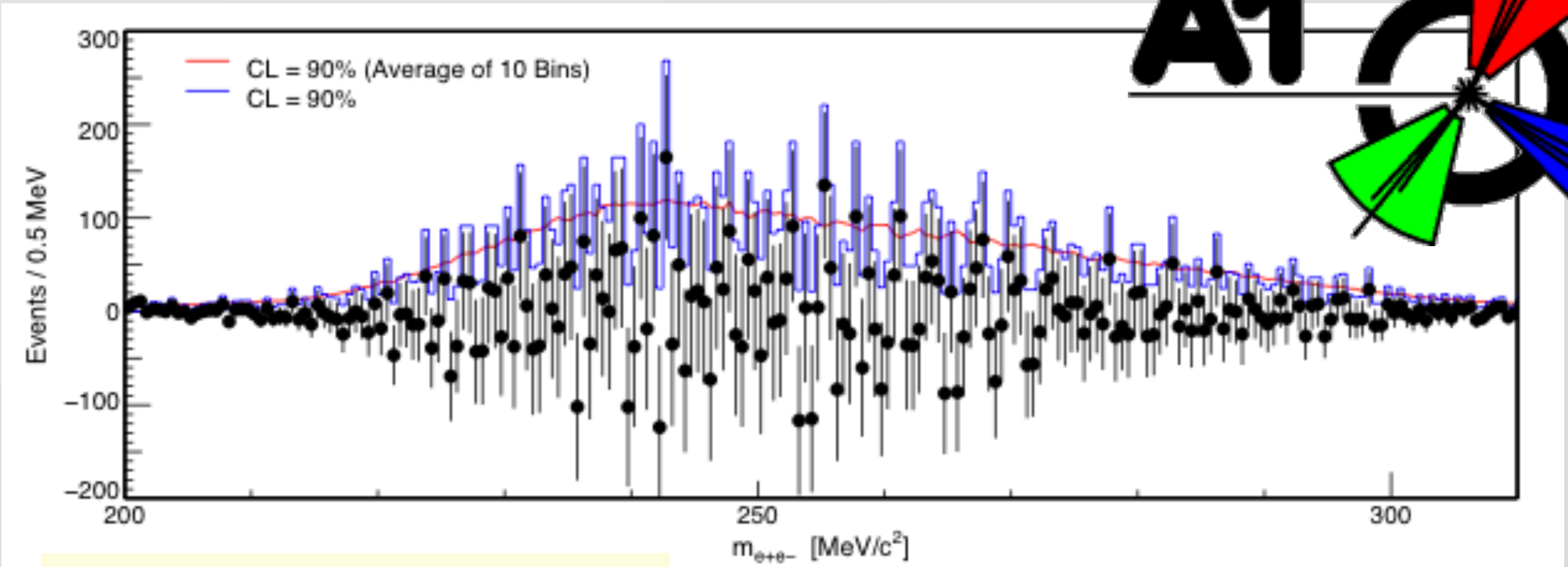


hep-ex/1108.2750

APEX and A1 have taken successful test runs and published (submitted) results!

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

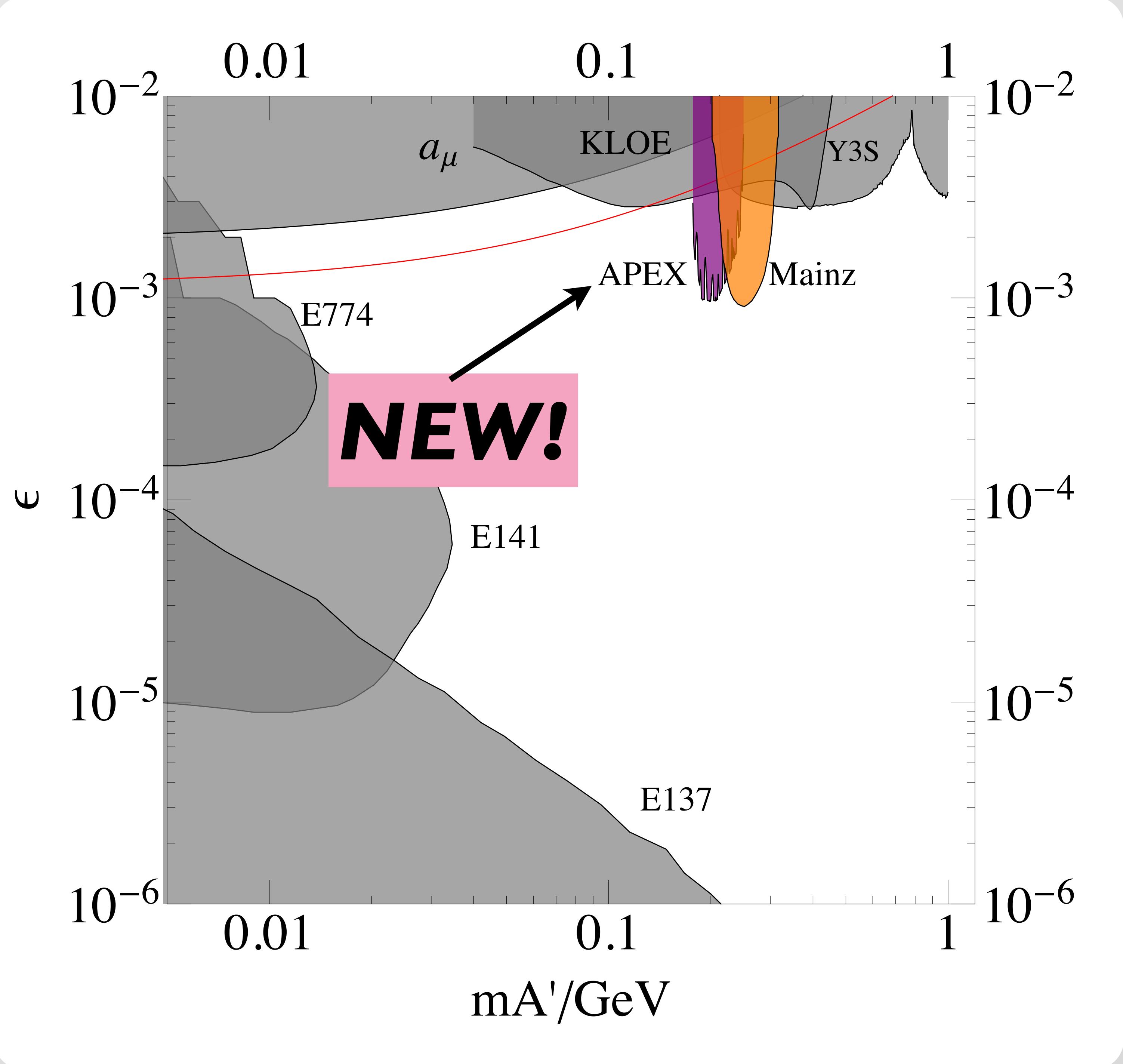
small mass range...
reflects small acceptance.



Phys. Rev. Lett. 106, 251802 (2011)

~ both results from few days of data taking...hope to take more data at various beam/detector settings soon!

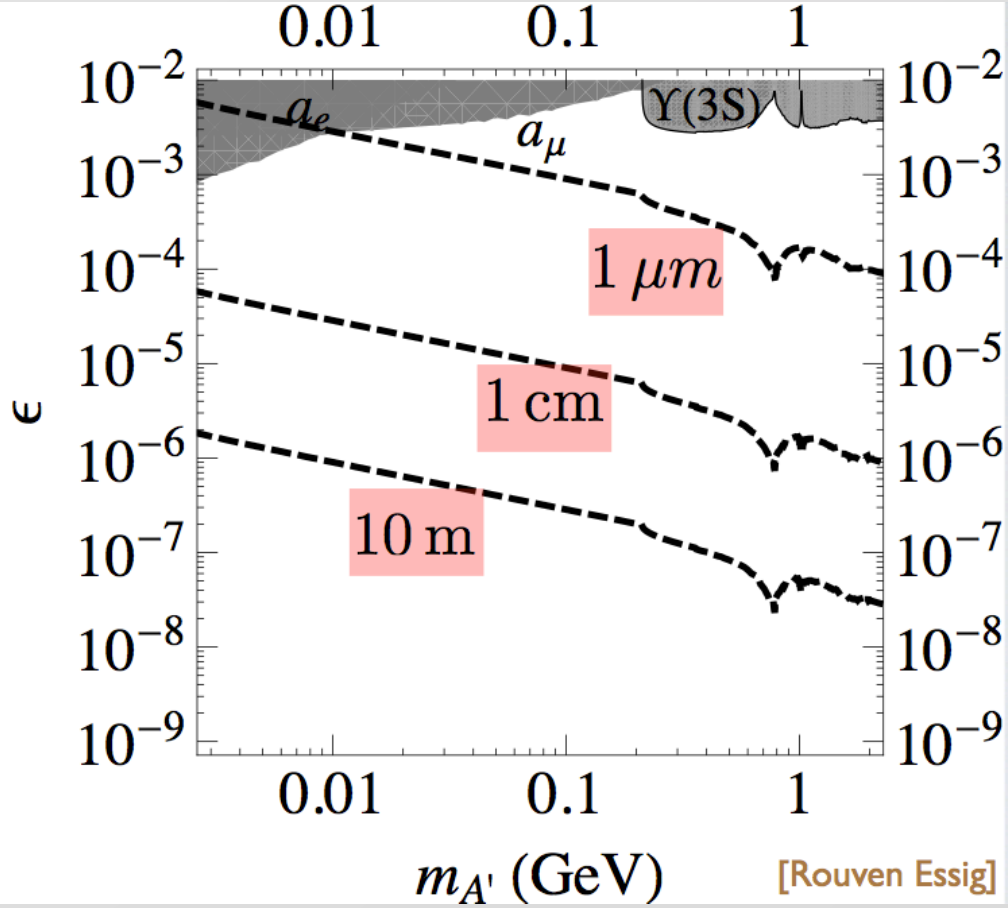
Brute force constraints



Method #2: less brute force

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



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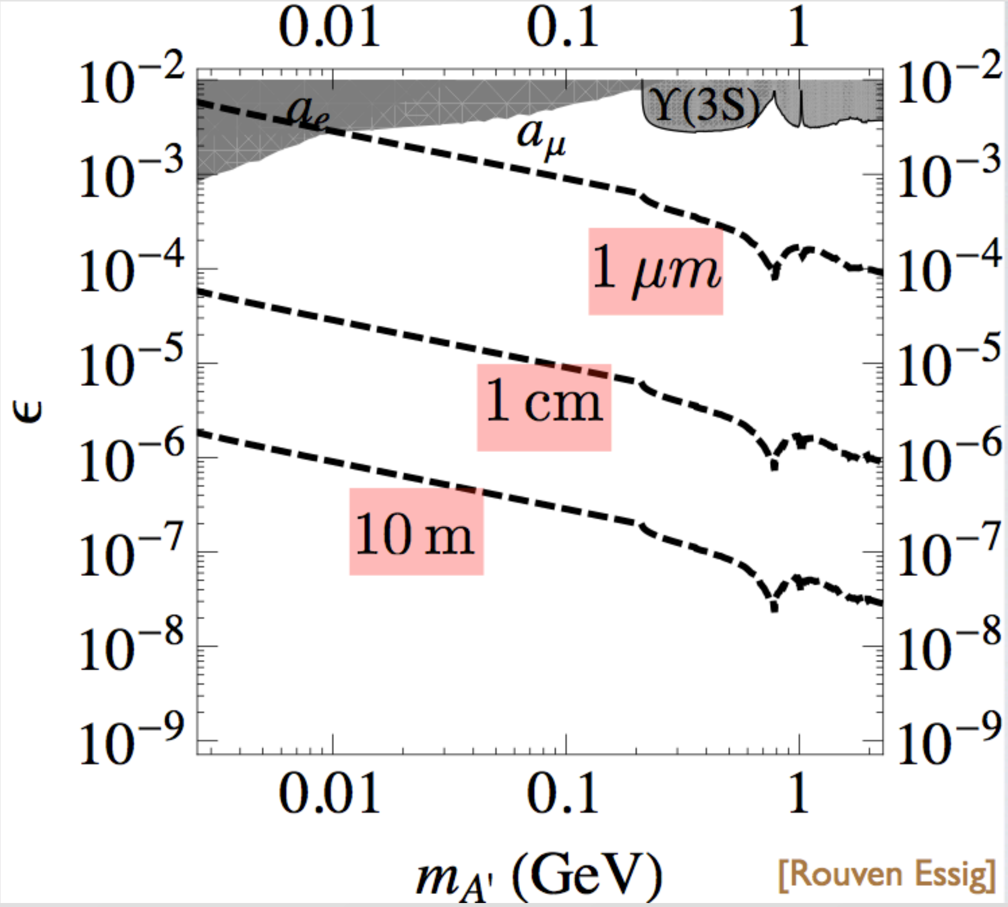
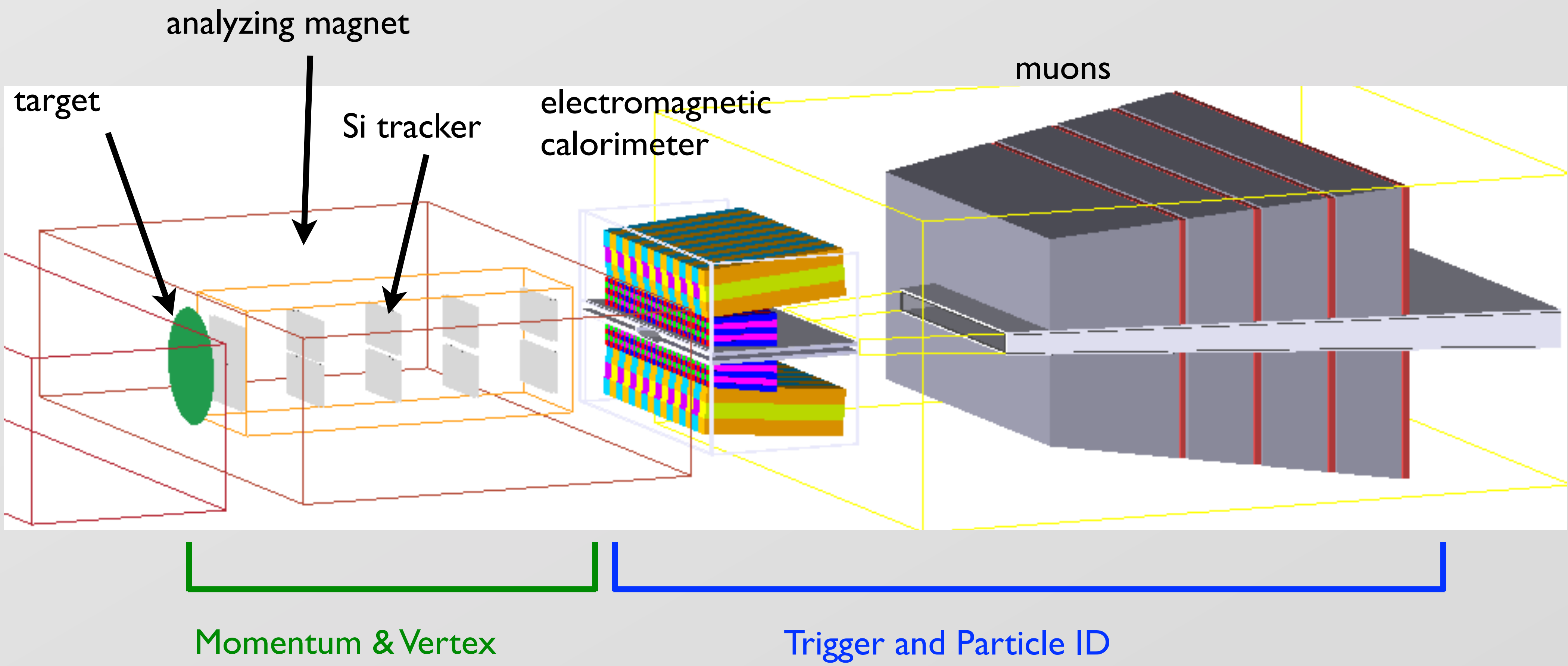


Solution: ***HPS***

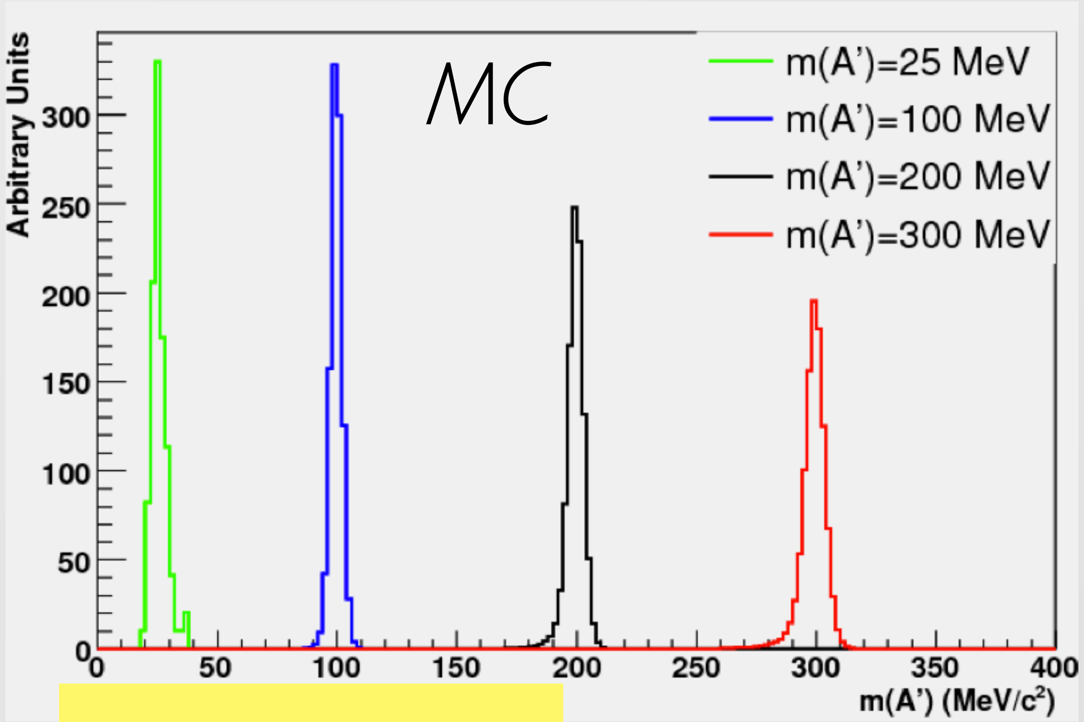
Heavy Photon Search

- collaboration between (many of) JLAB HallB groups, SLAC, UCSC, Fermilab
- high rate, high acceptance, high mass & vertex resolution detector intended to run in Hall B



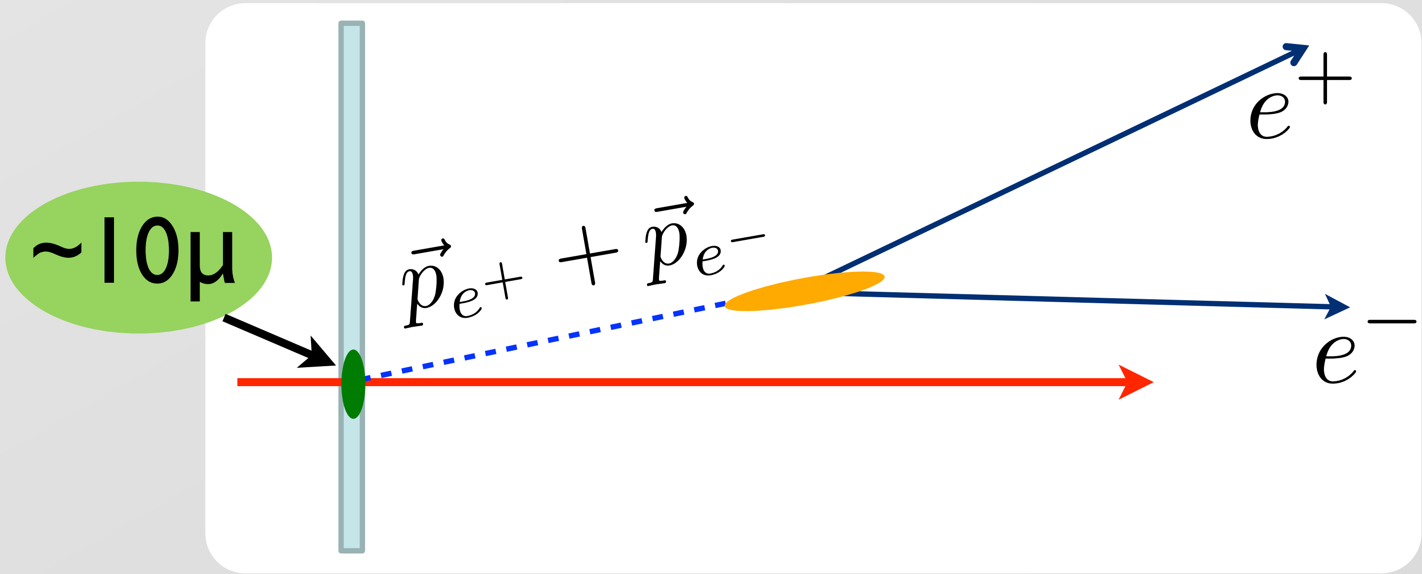
- formal proposal presented to JLAB PAC37 January 2011
- accepted contingent on successful test run, planned for ~March 2012
- received DOE funding to build test run apparatus

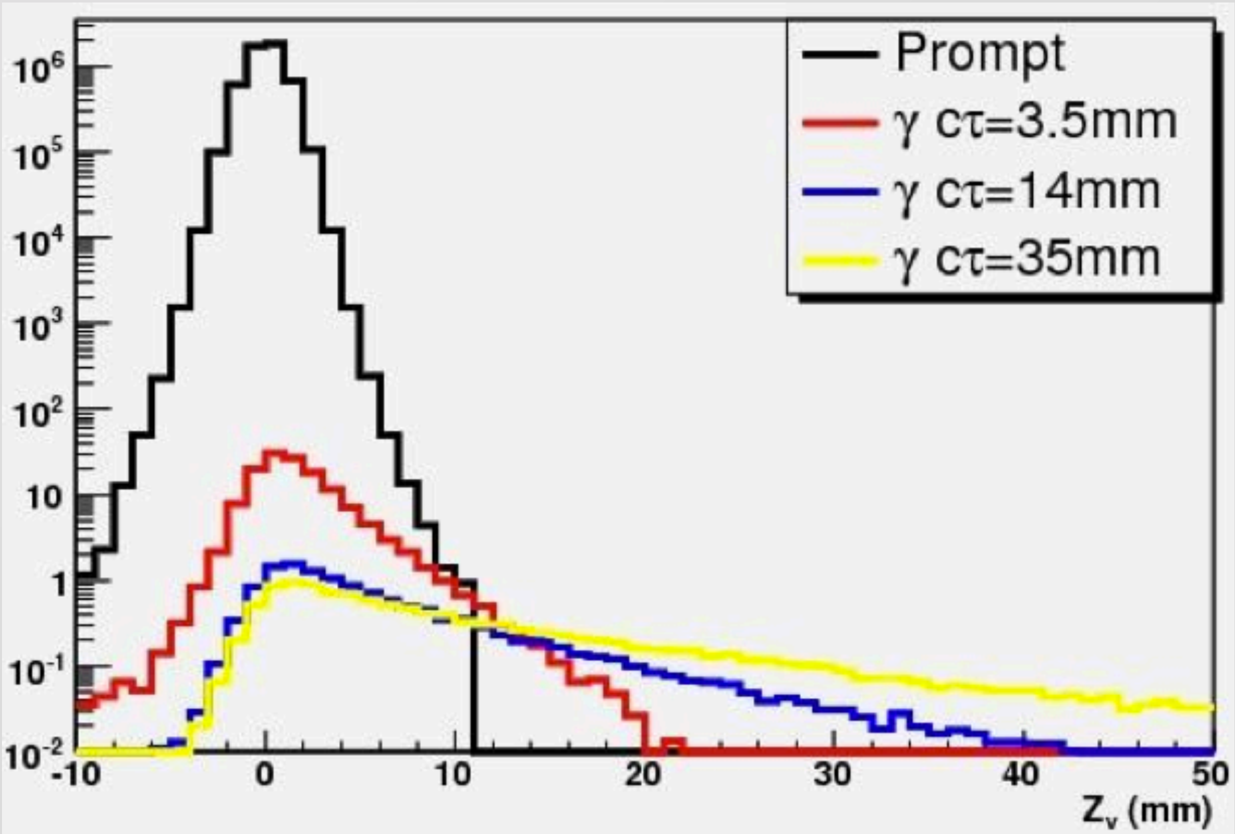
The HPS approach



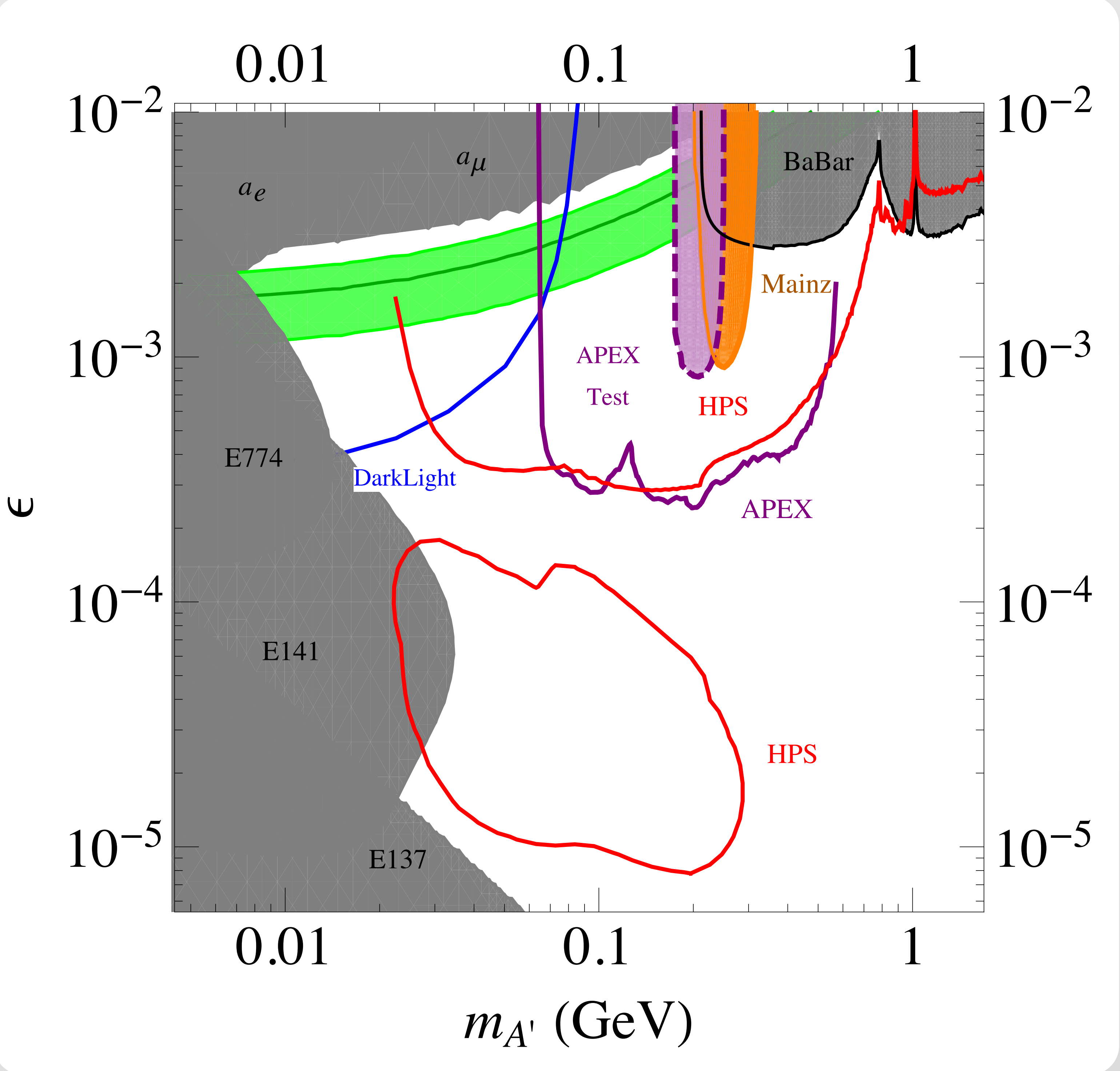
Δm/m~1%

- good mass resolution, dominated by MS in the detector
- use small beam-spot 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´>20MeV
    - running 3 months each at E_{beam}=2.2 and 6.6 GeV





It's getting crowded...

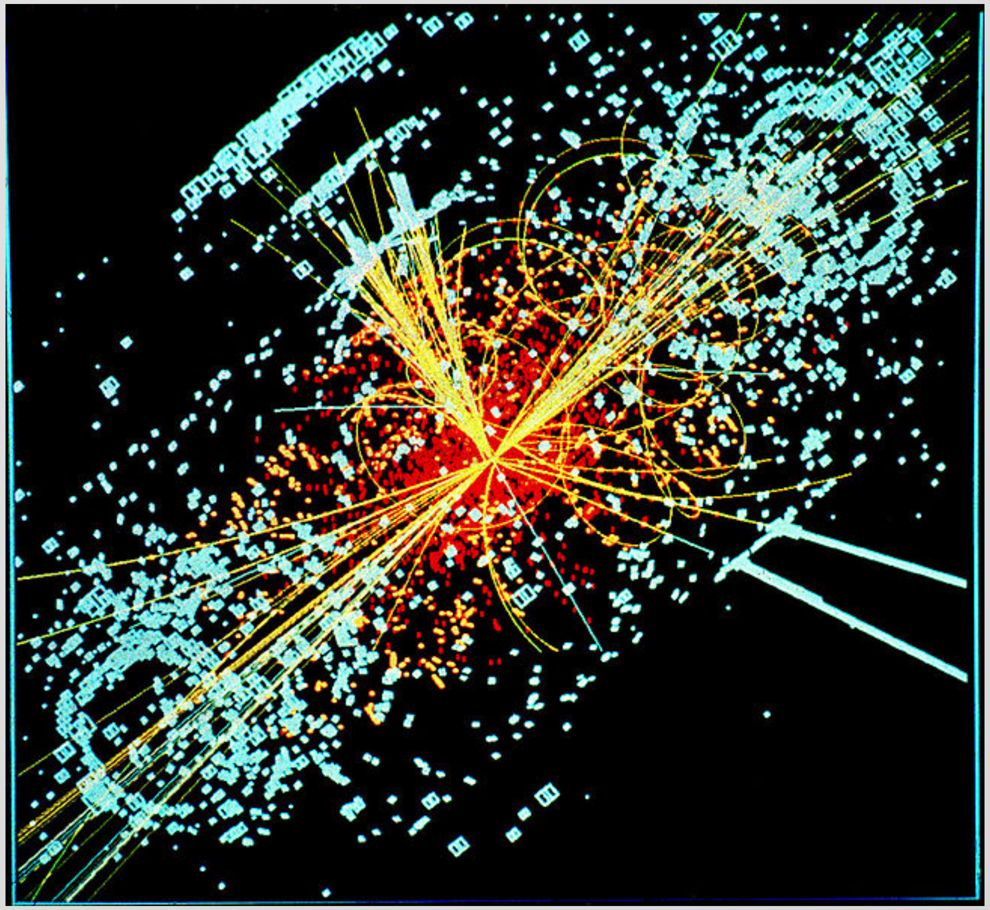


Many experiments in the works to look for Dark Forces:

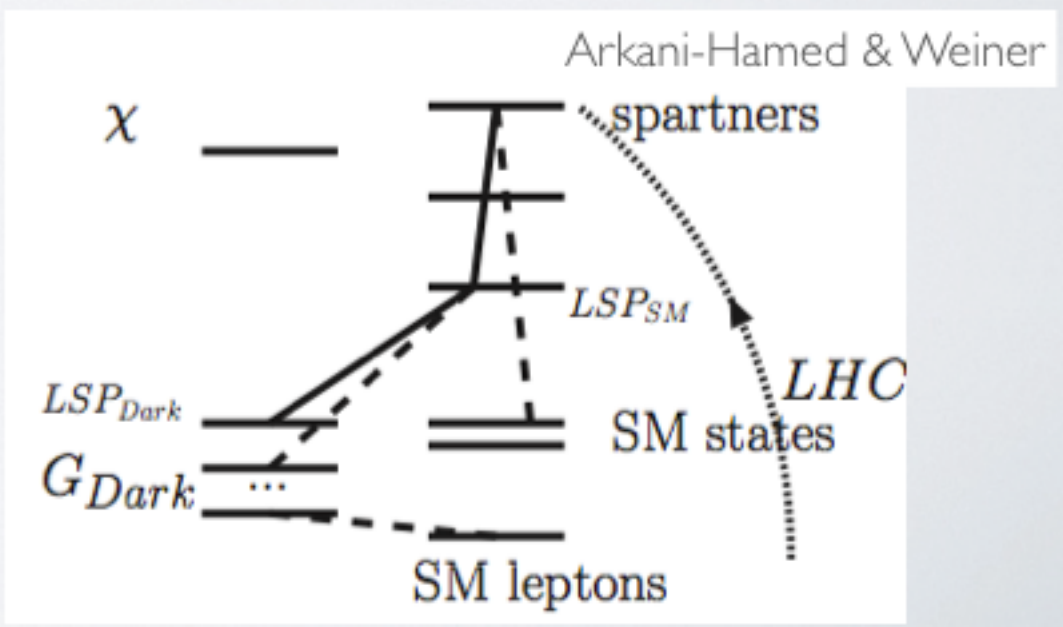
Mainz and APEX (JLab) ~ forward spectrometers
HPS (JLab) ~ compact Si-based vertex-tracker
DarkLight (JLab FEL) ~ high acceptance, H_2 gas target
HIPS(DESY)~ beam dump (not shown)

Where to look for dark forces?

- at e^+e^- colliders
  - BaBar, Belle KLOE, BES...
- fixed target experiments
  - E137, E141, APEX, Mainz, MAMI, DarkLight...
- hadron colliders
  - D0 & CDF, ATLAS & CMS

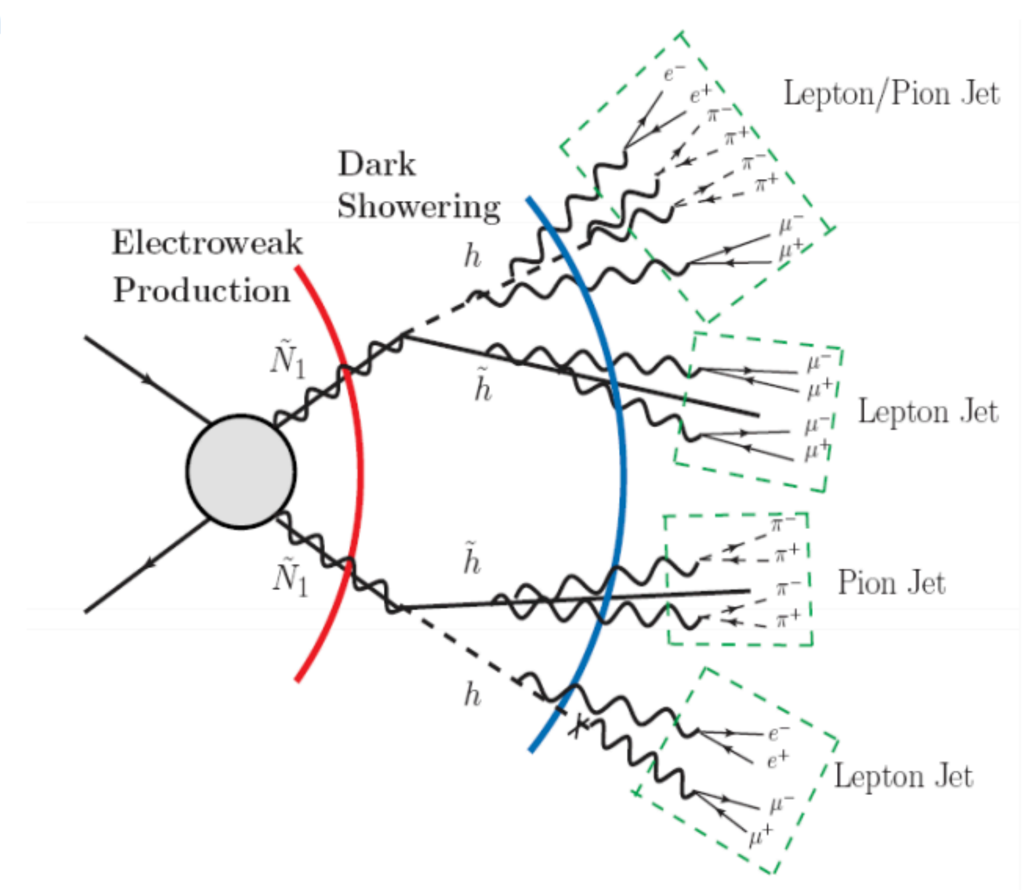


Dark forces & SUSY



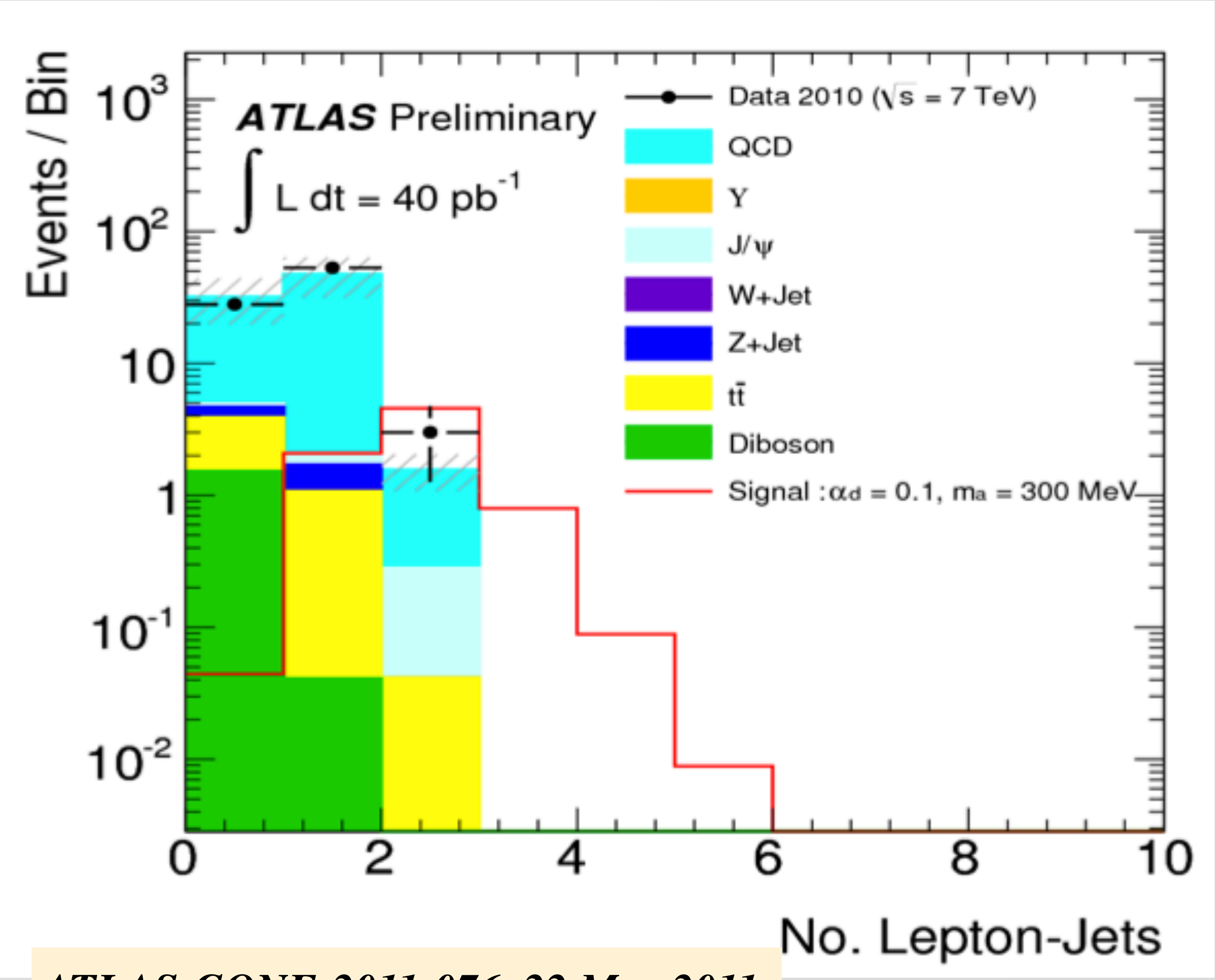
- At high energy hadron colliders, look for dark forces in Z- or Higgs-decays and in SUSY events
- SUSY with a dark sector → rate scales with ε^0 instead of ε^2
  - ✳if: $M(LSP_{Dark})<M(LSP_{SM})$ and R-parity good
    - ✳if: SUSY is correct

- Dark sector events should be quite clear
- highly boosted jets enriched in leptons➪"lepton jets"
- amount of showering depends on α_D (→coupling in dark sector)

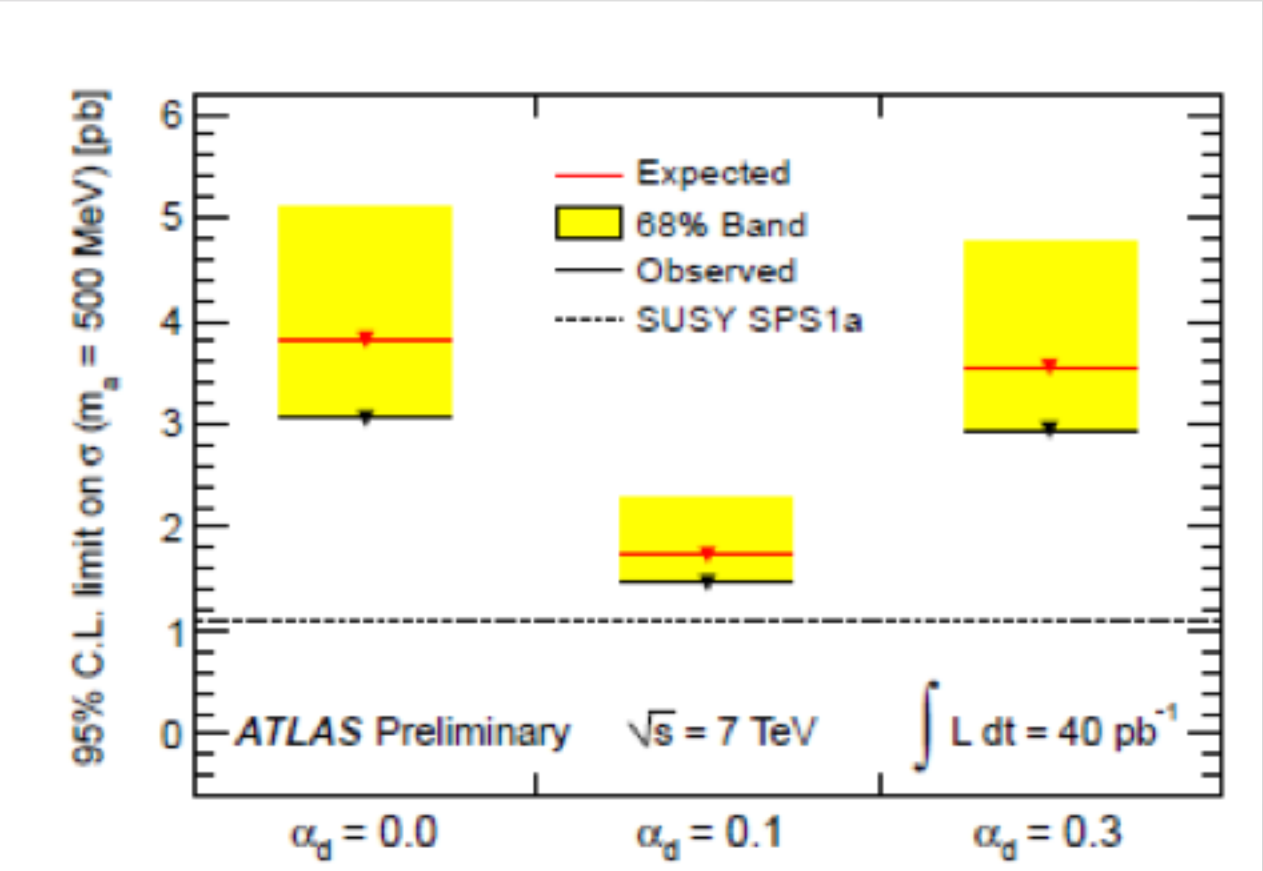


ATLAS lepton-jet search

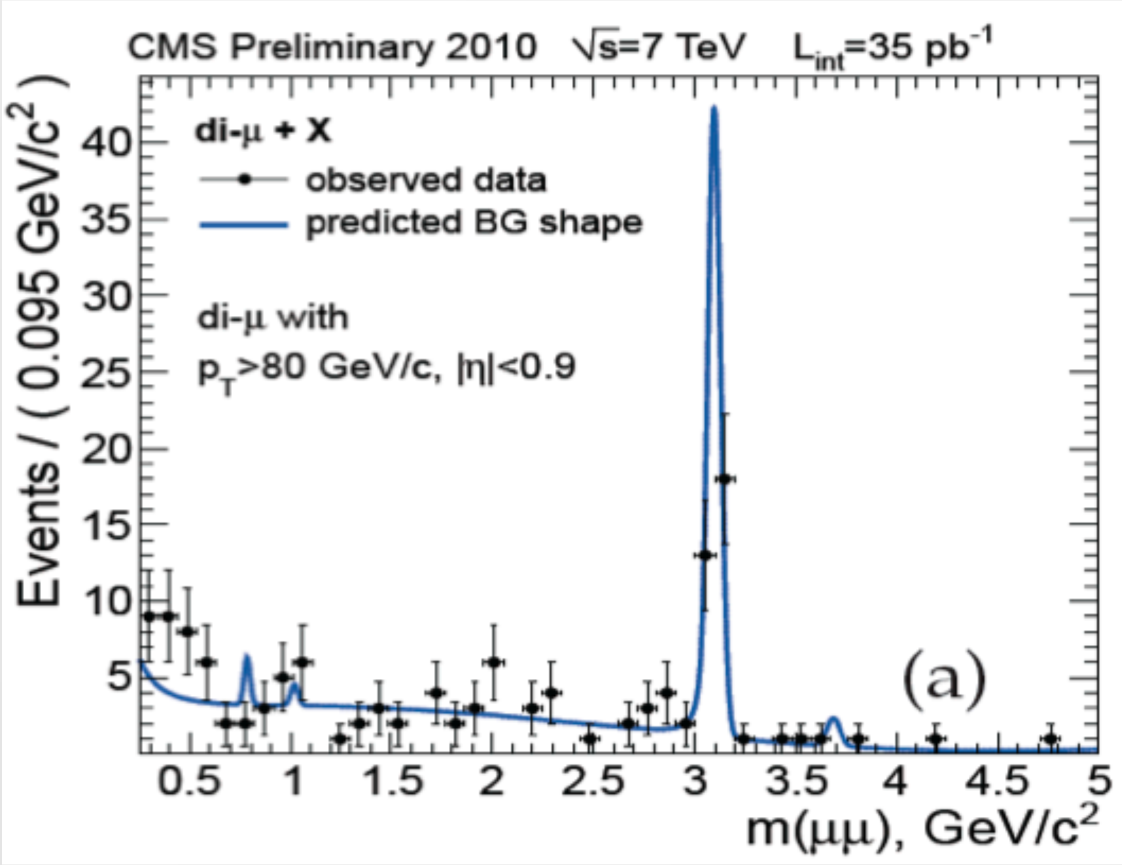
•look for events with 2 or more muon-jets...only a few events observed (and none of them were isolated). No MET required!
•only a small fraction of the data...already coming close to SUSY-dark force models
•much more to come....more data, adding electrons etc.

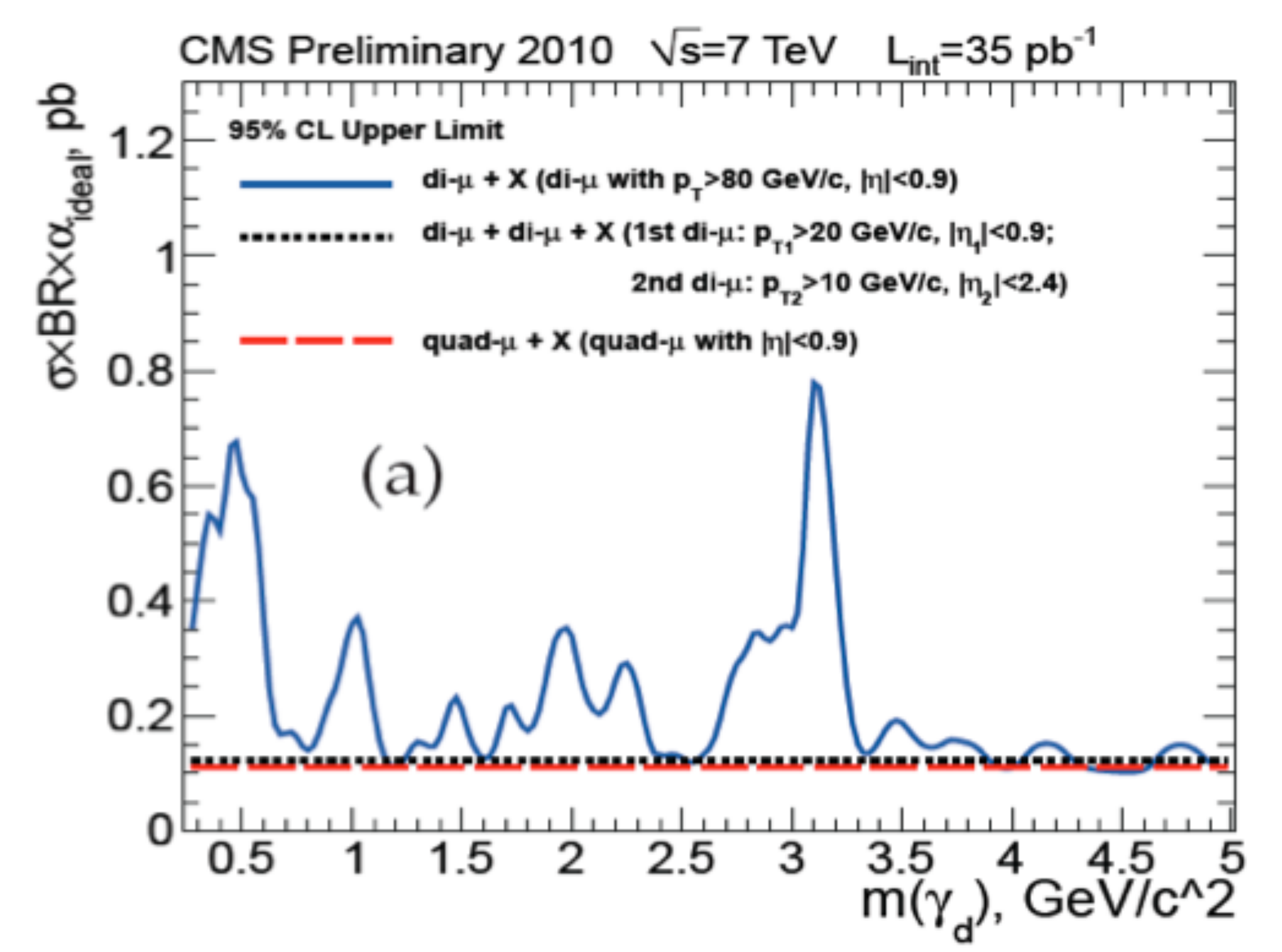


ATLAS-CONF-2011-076, 22 May 2011.



CMS: di- & quad- muon jets

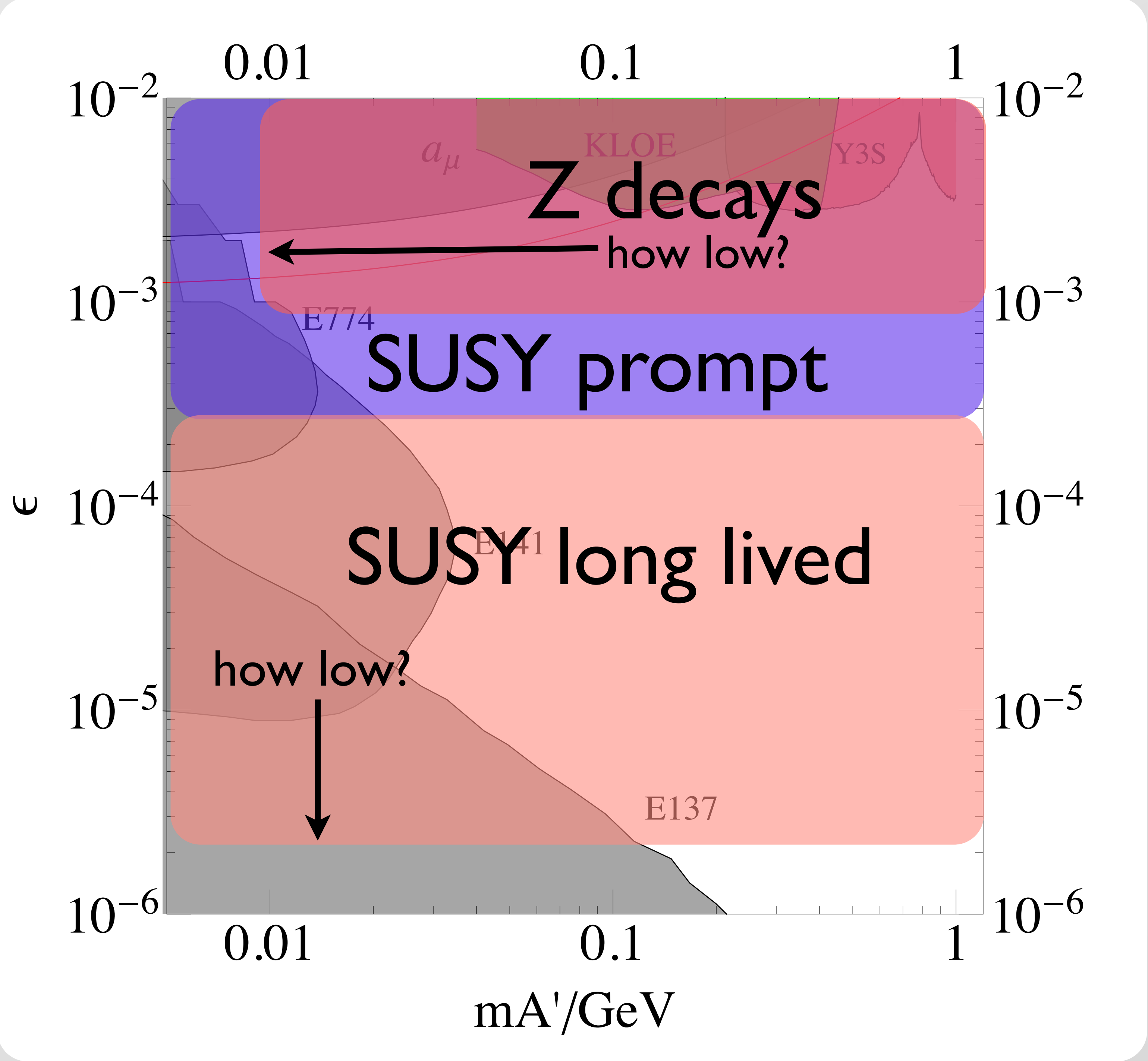




A. Safonov, Boost-2011

- CMS looks at the di-muon mass inside lepton jet for different samples to look for a bump...include single lepton jet events
- no MET requirement, only a pT requirement for di-μ+X
- even less data than ATLAS search

Reach for LHC searches



Where to look for dark forces?

- at e^+e^- colliders
  - BaBar, Belle KLOE, BES...
- fixed target experiments
  - E137, E141, APEX, Mainz, MAMI, DarkLight...
- hadron colliders
  - D0 & CDF, ATLAS & CMS
- "other"
  - neutrino beam + near detectors
  - more astrophysics experiments (FERMI, PLANK)
  - direct DM detection experiments (muddled mess!)

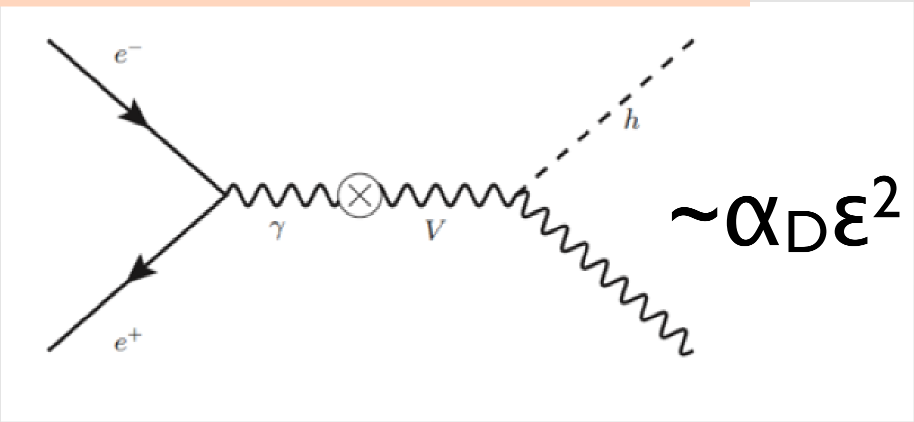
Summary

- The dark sector has been attracting a lot of attention the past few years
  - Average ~ 1 paper a day on hep-ph (is this a good thing?)
  - Many existing experiments have (or plan to have) experimental results directly looking for dark-force particles
  - Groups have come up with NEW experiments to look for dark forces!
    - And some have been approved...and even funded!
- If we live in a world with symmetry higher than SU(3)×SU(2)×U(1), it's likely that something like a heavy-photon exists...finding it will be a huge discovery.
- Sorry for the experiments/results/details I have glossed over...it has become a large enterprise

Questions?

Other production channels

Batell et al., PRD79, 115008, 2009.

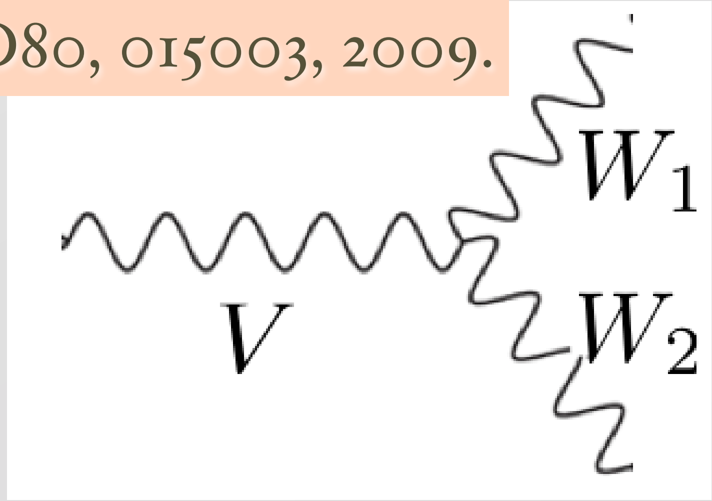


“Dark higgstrahlung”: 6l or 2l+E̸

small QED background

KLOE → hep-ex/1107.2531

Essig et al., PRD80, 015003, 2009.

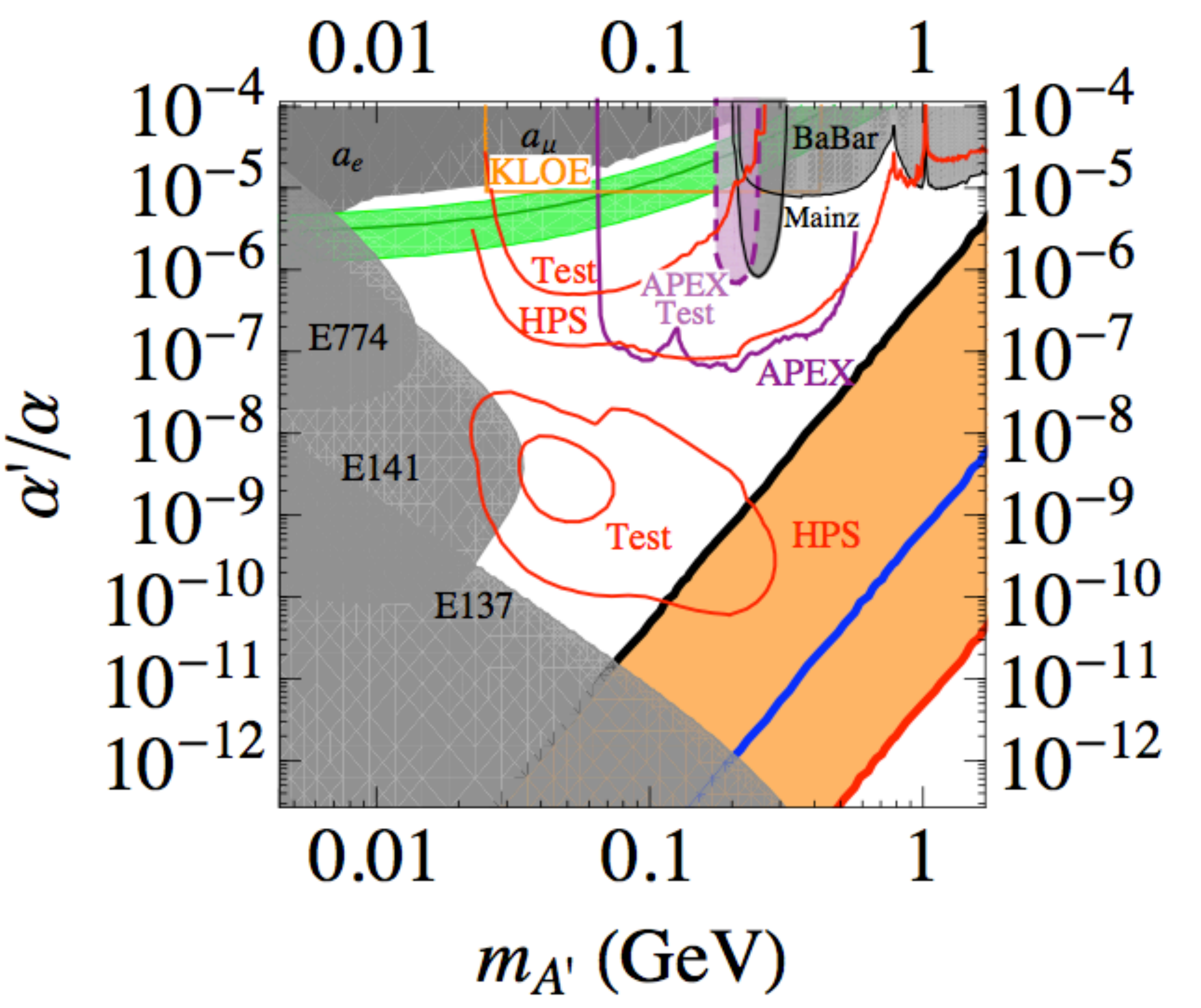


generic non-Abelian: 4l

small QED background

BaBar → hep-ex/0908.2821

…if you believe DAMA



Meson factories ⇨ rare decays

$\pi^0 \to \gamma U$ ~ expect ~10^9; $\varepsilon < 10^{-3}$?

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	BR($X \to Y + \gamma$)	BR($X \to Y + \ell^+\ell^-$)	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	$7 \times 10^{-8\,a}$	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

Reece & Wang 2009

Summary of estimates from existing samples...some of these are from fixed target experiments.