Searching for Dark Forces at the B-Factories and Beyond

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On behalf of the BaBar Collaboration

Outline

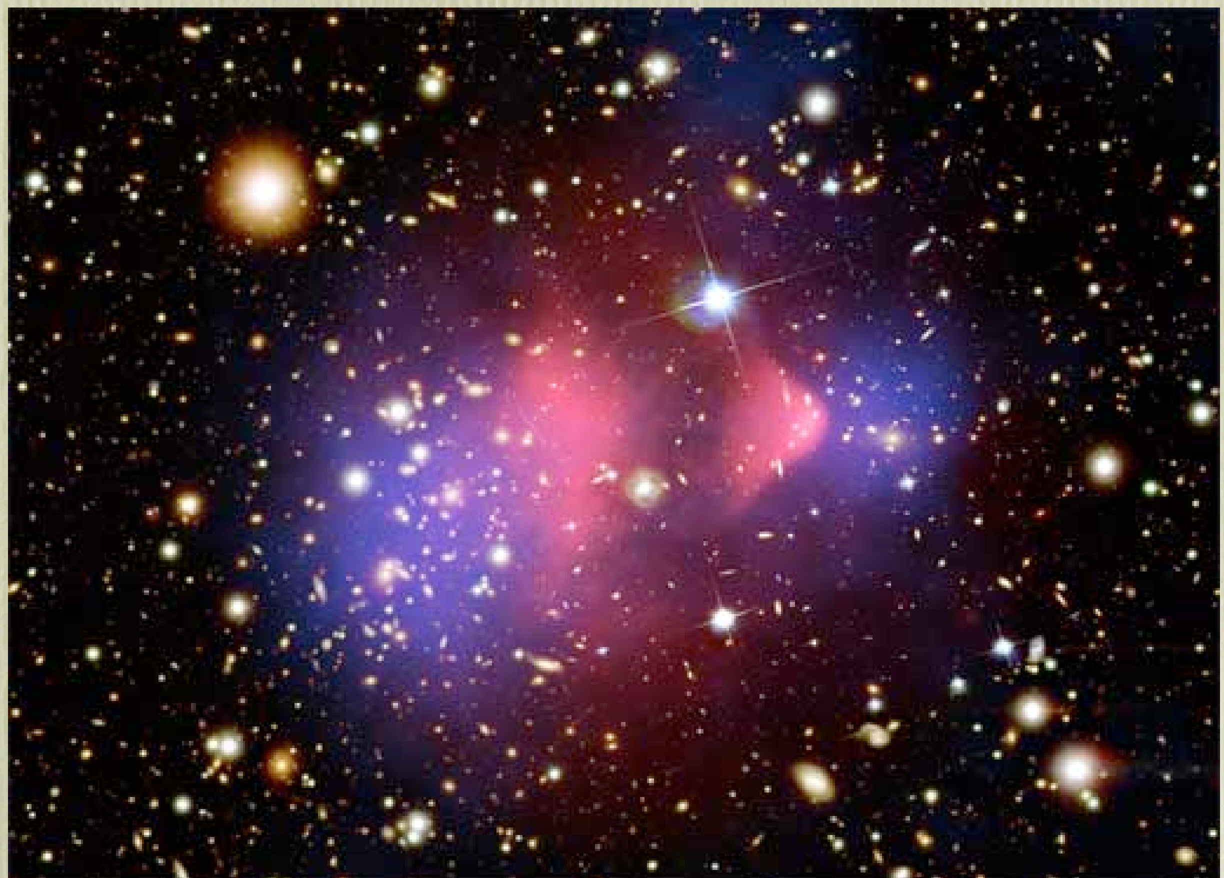
- Dark matter: what and why?
- Are we seeing dark matter do something interesting? A selection of recent observations
- Dark forces: what and why?
- Looking for dark forces at e^+e^- machines
- Other places to search: rare decays, fixed target, and the Tevatron/LHC

The visible universe

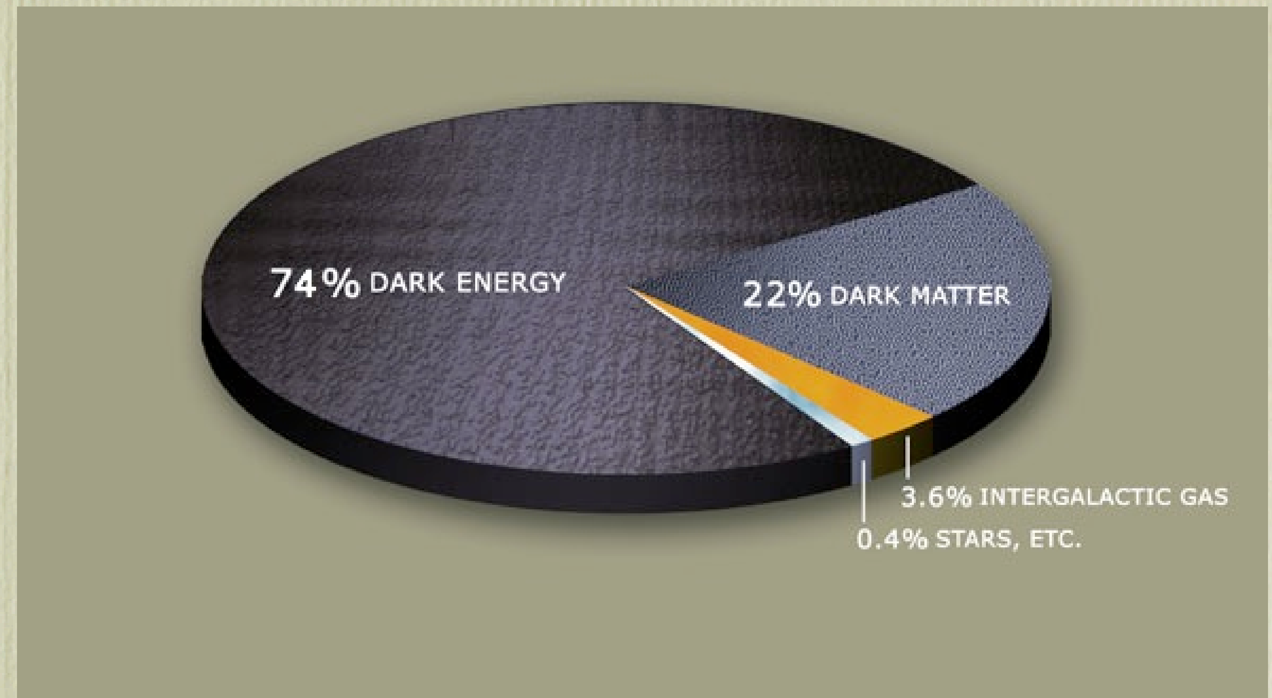
- Stars, planets, (lots of) dust...

The *in*visible universe

- ...and even more matter that we can't see...



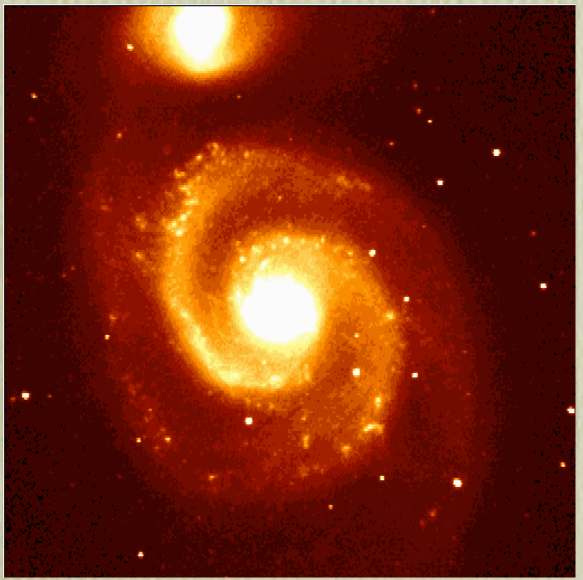
Composition of the Universe

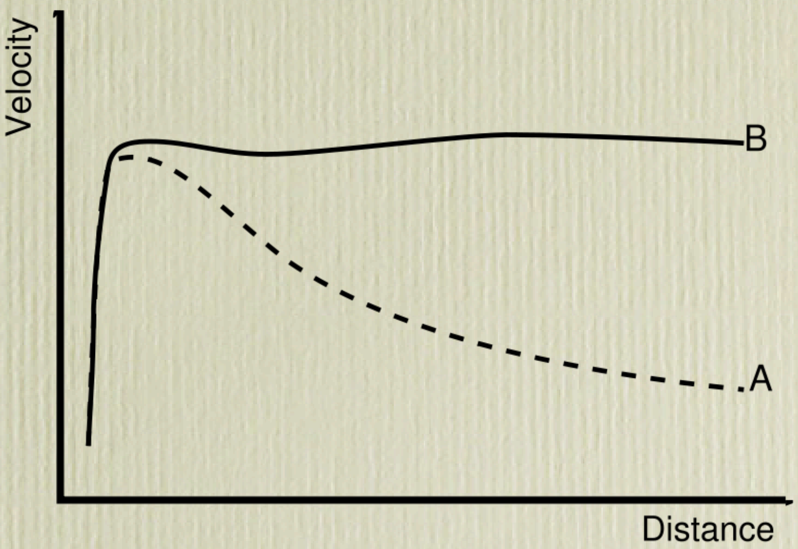


We are ignorant to ~95% of the universe...

Why do we think dark matter exists?

- Galactic rotation: stars on the outskirts of galaxies seem to move too fast...





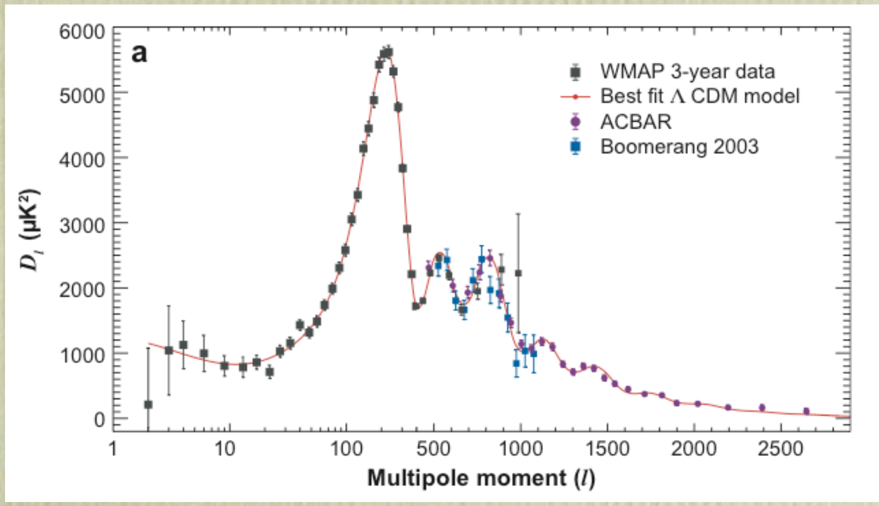
Why do we think dark matter exists?

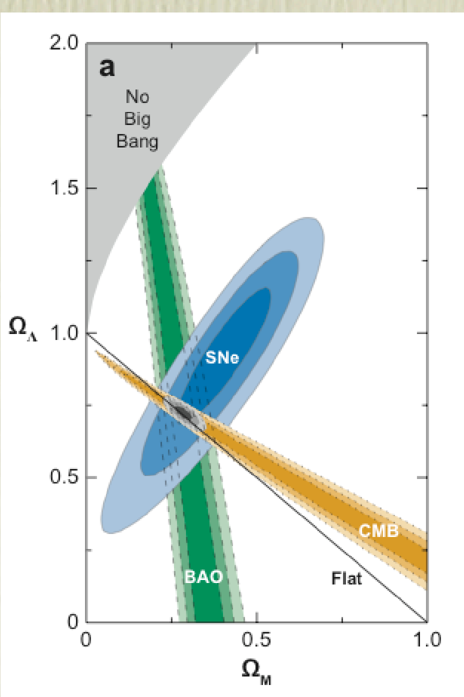
- Galactic rotation: stars on the outskirts of galaxies seem to move too fast...
- Evidence from gravitational lensing

Hubble Space Telescope + Chandra X-Ray Observatory
http://www.nasa.gov/images/content/155244main_HSTplusLensBlueChandraPink2blur.jpg

Why do we think dark matter exists?

- Galactic rotation: stars on the outskirts of galaxies seem to move too fast...
- Evidence from gravitational lensing
- Cosmic Microwave Background





Why do we think dark matter exists?

- Galactic rotation: stars on the outskirts of galaxies seem to move too fast...
- Gravitational lensing from galaxy clusters
- Cosmic Microwave Background
- DM needed to explain large-scale structure formation

We've never "seen" a dark matter particle in the wild.

What we do(n't) know about dark matter

✓ It doesn't glow (i.e. it's dark!)

- doesn't participate in the EM or strong forces...just gravity and (maybe) weak force

✓ It's *probably* cold (non-relativistic)

✓ It is stable compared to the lifetime of the universe

✓ There is a lot of it...galaxies congregate around it

– Doesn't seem to match any SM particle

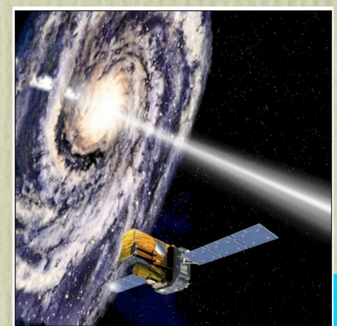
So what could DM be?

- Weakly Interacting Massive Particles
    - heavy DM particle (~TeV) that interacts via the Weak (or some other, new) force
    - Is stable due to some, as yet undetermined symmetry

    ➡ In supersymmetry with R-Parity conservation, the Lightest Supersymmetric Particle (LSP) is a prime candidate
- (sterile) neutrinos or axions
- MAssive Compact Halo Object
    - astronomical bodies that emit no light (i.e. not particle physics)

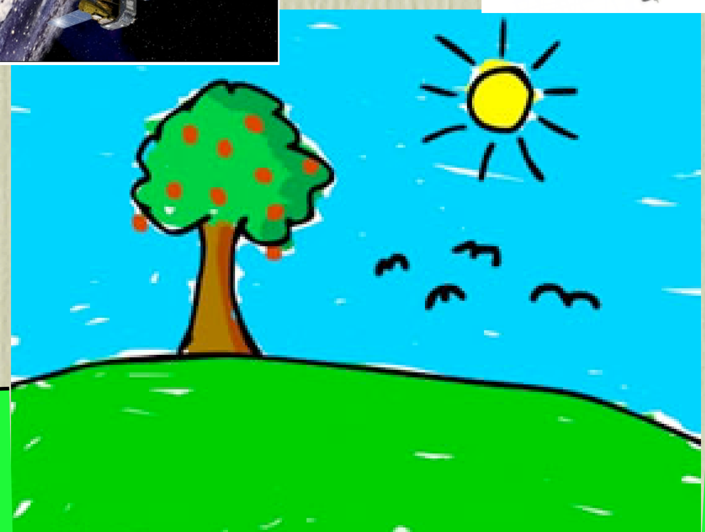
Detecting Dark Matter

In the Sky:



PAMELA
ATIC
HESS

Fermi/GLAST
INTEGRAL

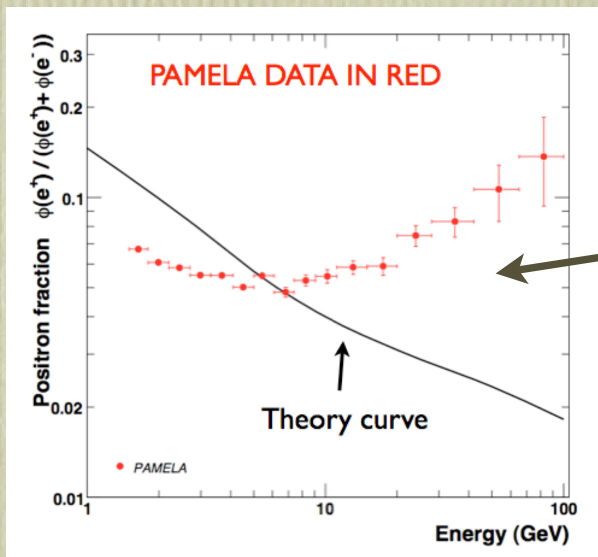


Underground:

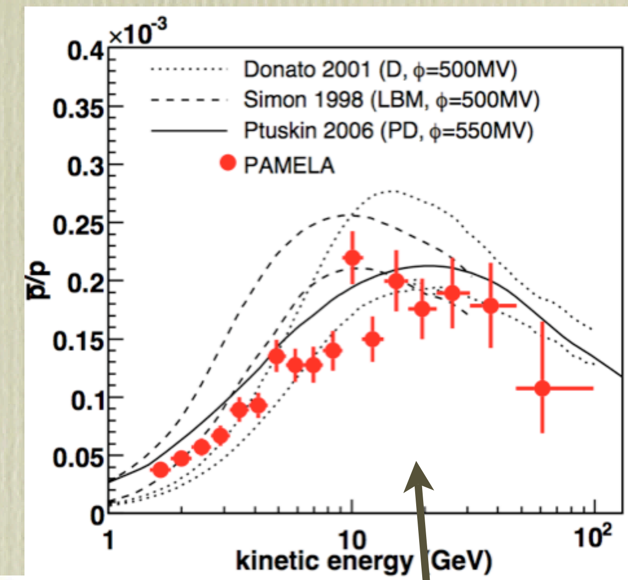
CDMS
ZEPLIN

DAMA
XENON

e^+/e^- and $\bar{p}/p$ from PAMELA



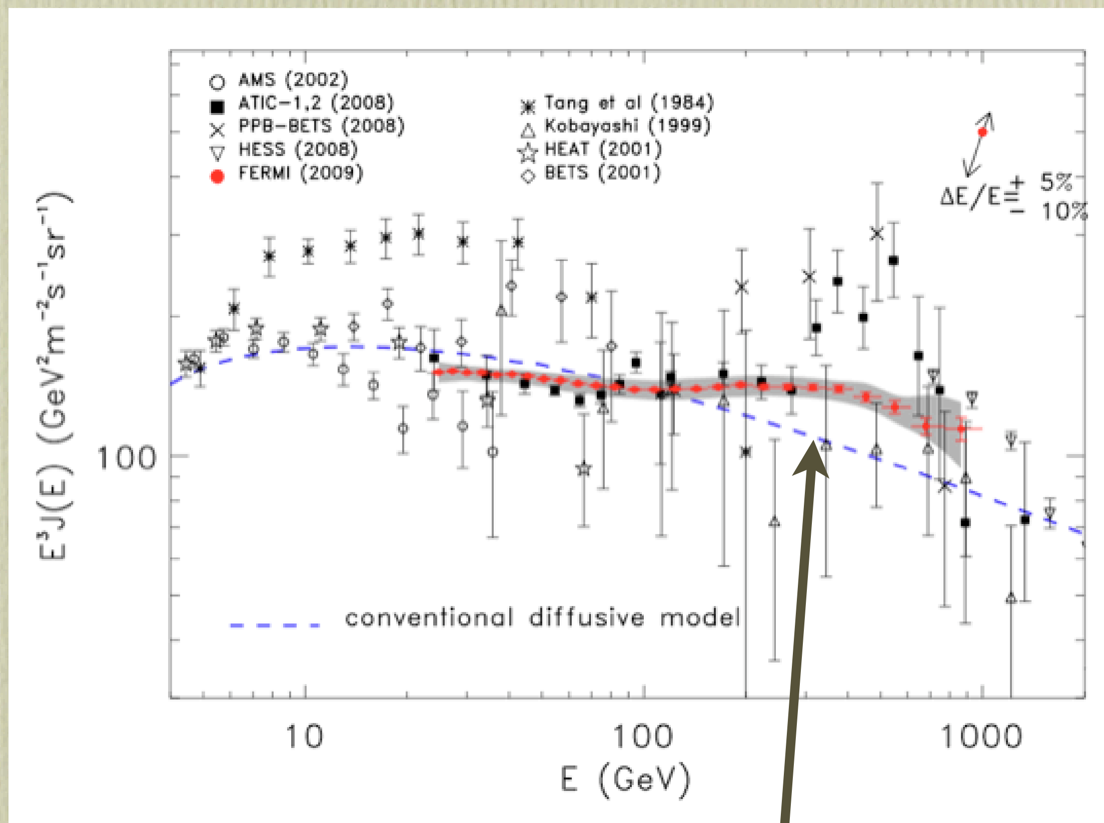
Excess observed in e^+/e^-



O. Adriani *et al.*, Nature **458**, 607 (2009).

...but not in p/p

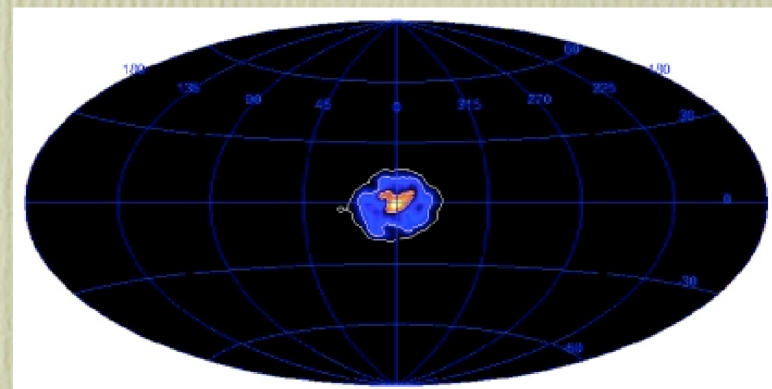
Electron flux from Fermi and ATIC

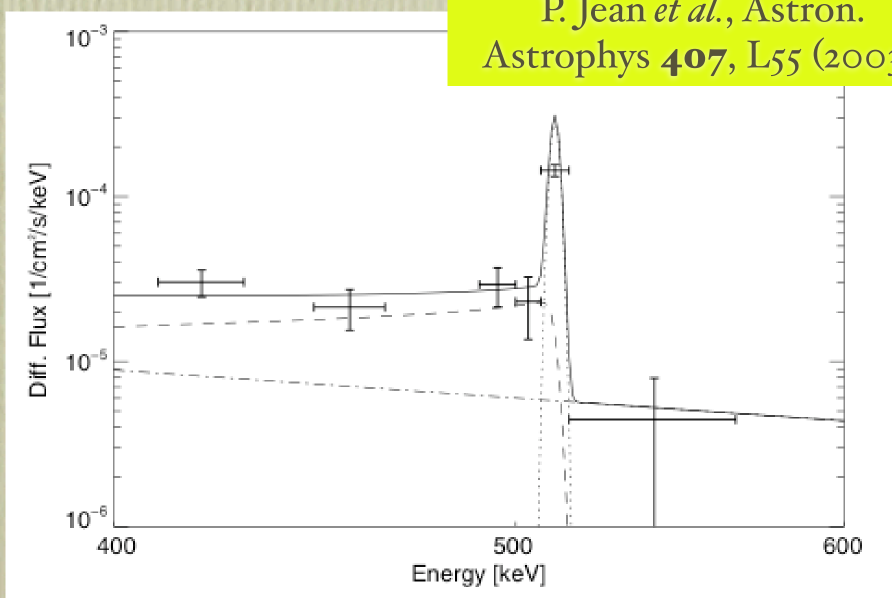


Fermi LAT, ATIC, and HESS observe excess in total $e^+ + e^-$ flux at high energy

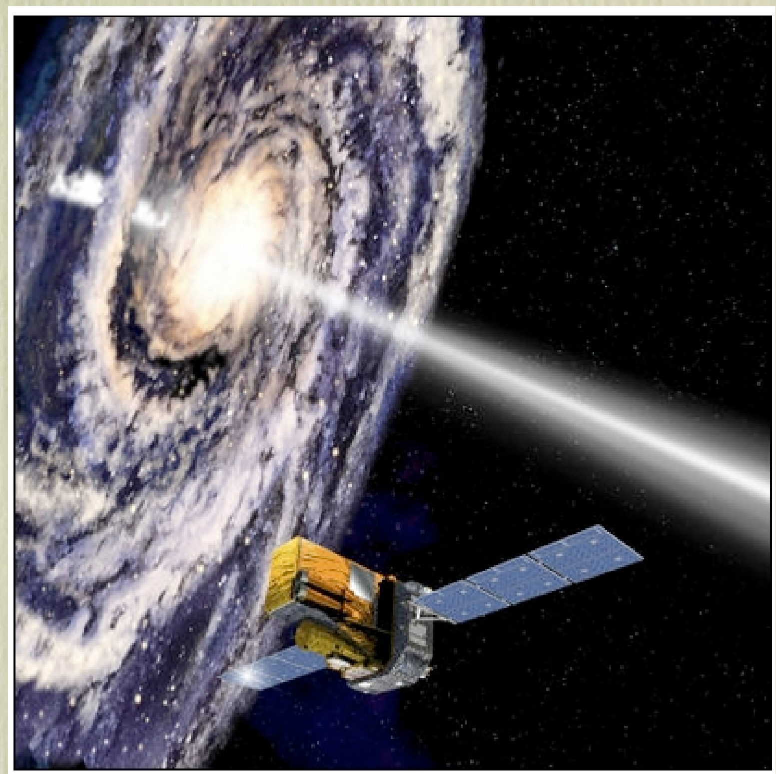
A. Abdo *et al.*, astro-ph/0905.025.

The INTEGRAL 511keV signal



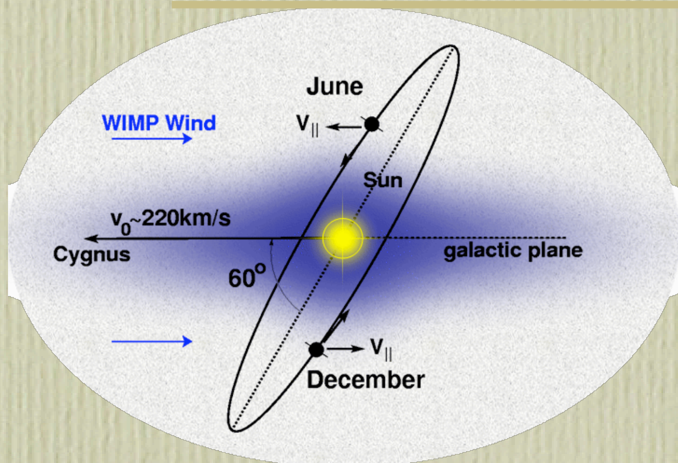


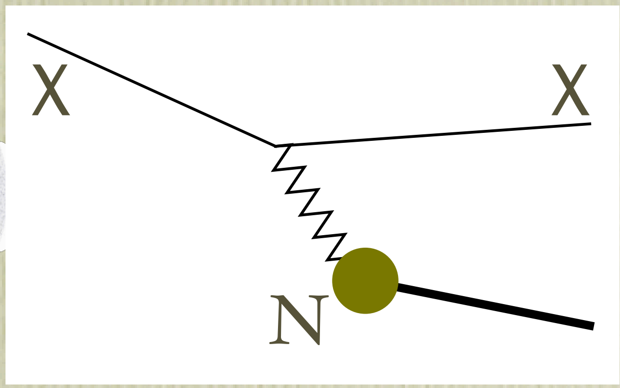
P. Jean *et al.*, Astron. Astrophys **407**, L55 (2003).

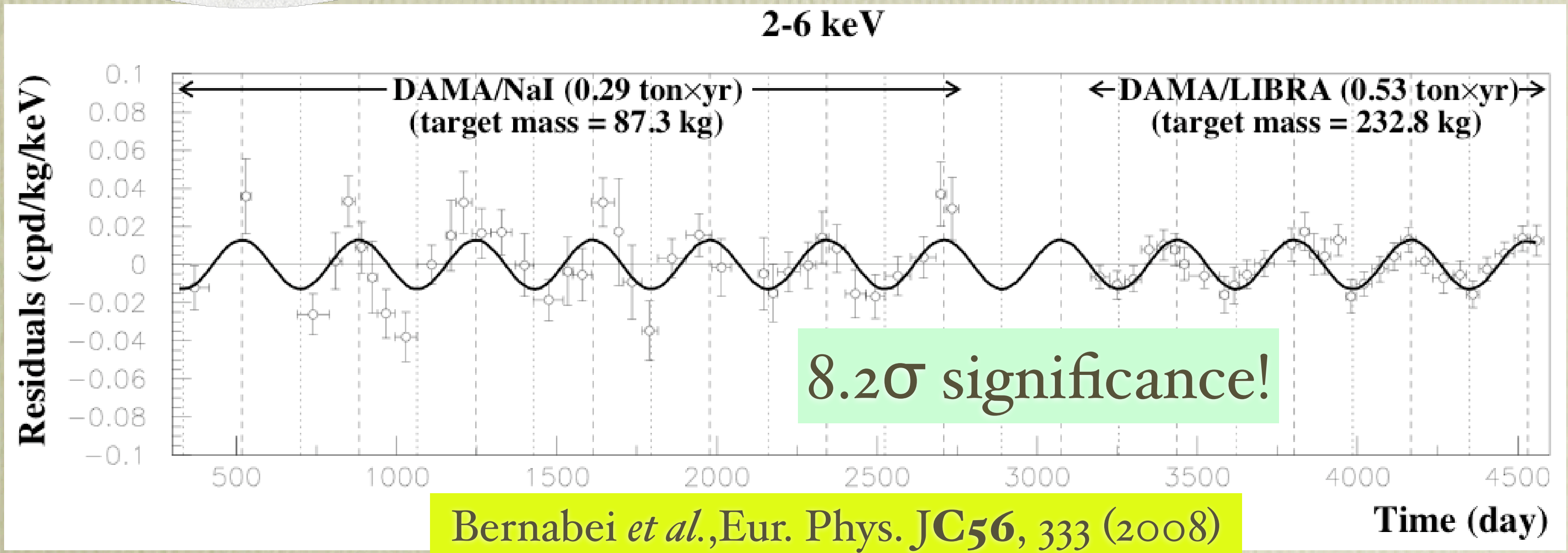


...low energy e^+e^- annihilation at the galactic center

Direct Detection and DAMA







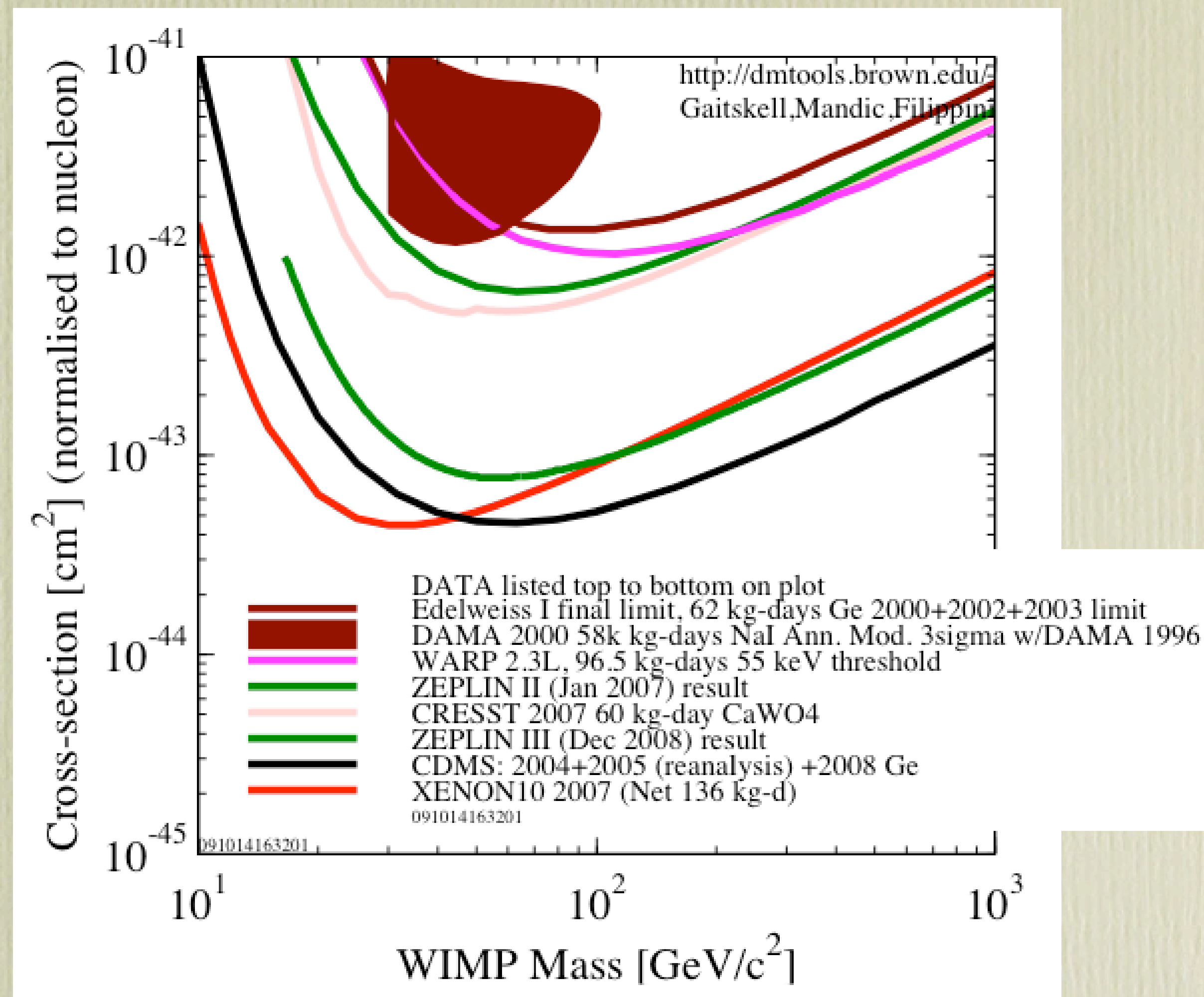
8.2σ significance!

Bernabei *et al.*,Eur. Phys. **JC56**, 333 (2008)

DAMA vs the World...

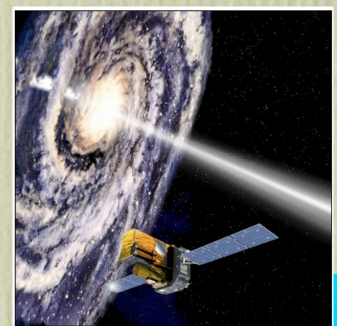
...observed DAMA cross section is ruled out by a number of other, similar experiments!?!?

Techniques are different...is DAMA sensitive to different physics?

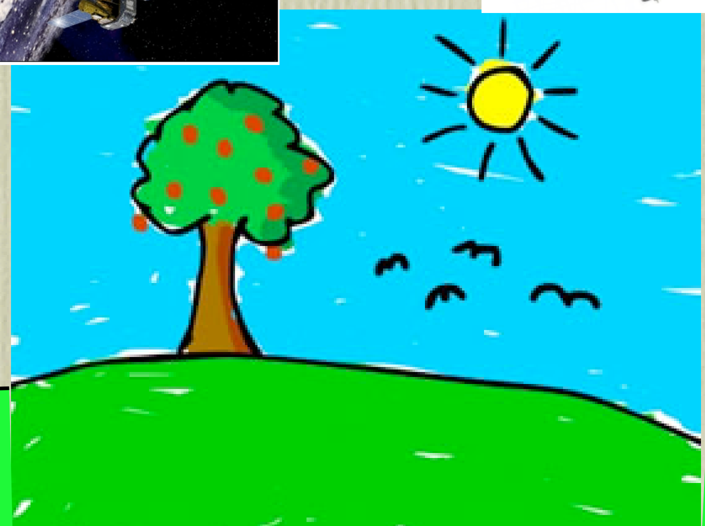


Lots of anomalies...

Low energy
e+e−:
INTEGRAL



Excess of high
energy electrons:
PAMELA
ATIC
Fermi



DAMA vs Everyone

Lots of anomalies...

Low energy electrons: INTEGRA

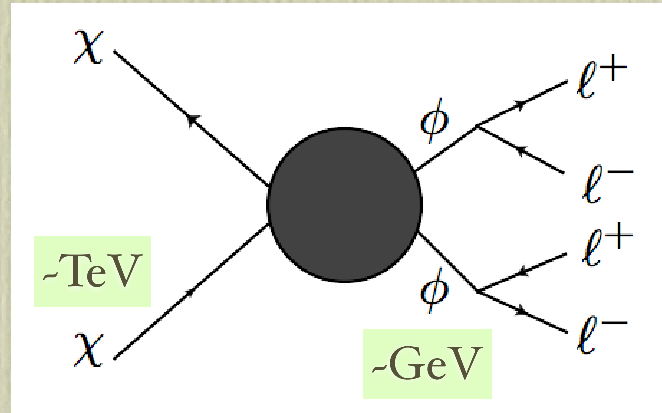
Excess of high energy electrons:
PAMELA
ATIC
Fermi

Is this particle physics or astrophysics???

DAMA vs Everyone

"A Theory of Dark Matter"

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

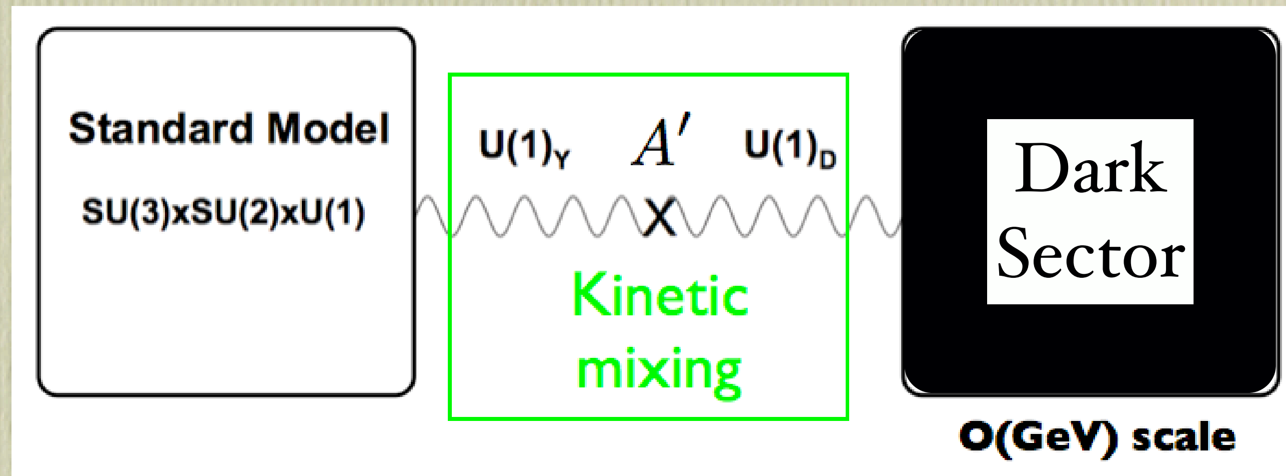


M. Pospelov and A. Ritz, Phys. Letters B **671**, 391 (2009).

- new "dark force" with (vector) gauge boson φ~ GeV while the dark matter particle is ~TeV scale
- gauge boson decays to lepton pairs (e^+e^-, $\mu^+\mu^-$) but not $p\bar{p}$ because φ is below $p\bar{p}$ threshold (2GeV)

Would explain the high energy positrons but no antiprotons...

Structure of the Dark Sector

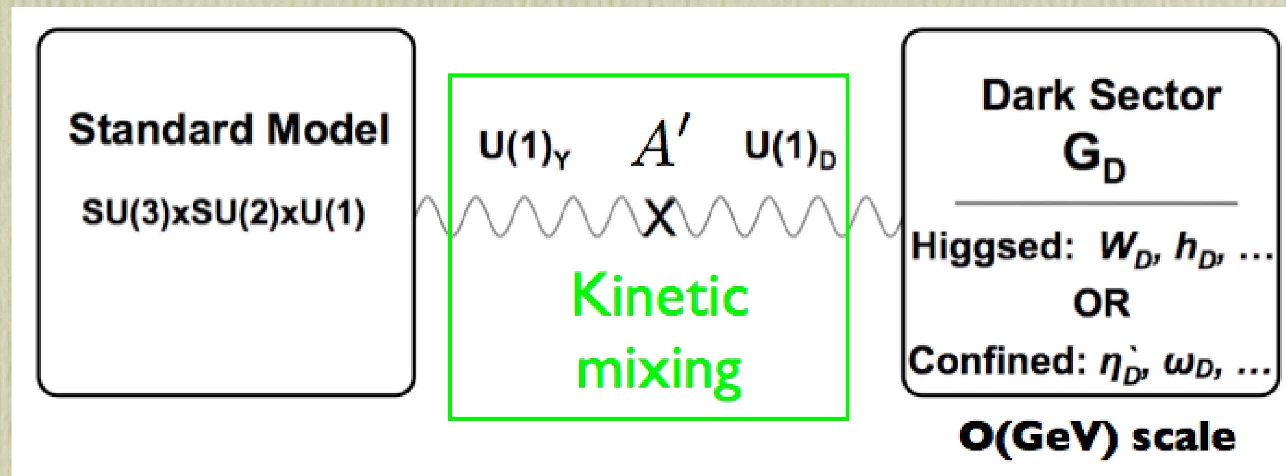


•Abelian U(1)$_D$ common to all models...mixes with SM hypercharge with coupling κ (or ϵ depending on the paper); "dark higgs" to give mass

•The main mixing goes via "Kinetic Mixing"...i.e. terms like this:

$$\mathcal{L}_{\text{mix}} = \epsilon\, F^{\mu\nu}_{\text{dark}} F_{Y\ \mu\nu}$$

Structure of the Dark Sector



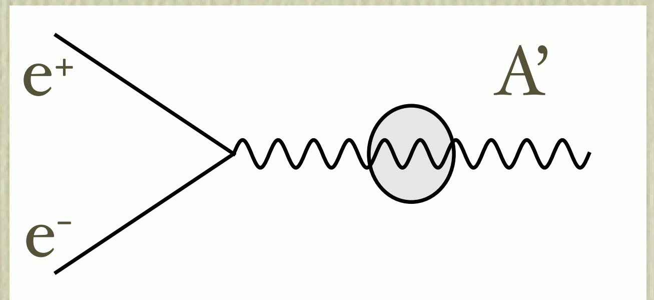
- Structure in the dark sector is wide open...
  - could have nothing (else) interesting (just U(1))
  - Higgsed non-abelian SU(2): "dark EW"
    - Arkani-Hamed, Finkbeiner, Slatyer, Weiner (hep-ph/0810.0713)
  - Confined non-abelian SU(N): "dark color"
    - Alves, Behbahani, Schuster, Wacker (hep-ph/0903.3945)
  - Or....?

Dark forces and you
(if you work at an e^+e^- collider)

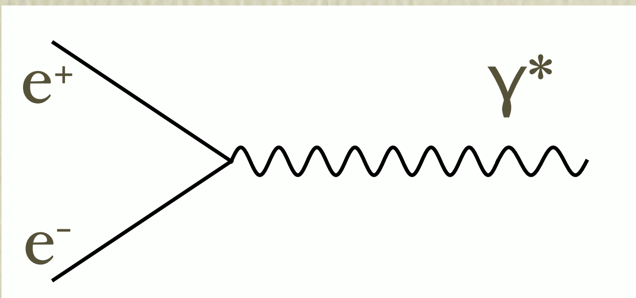
Low energy/high luminosity e+e- colliders are a great place to look for dark forces...

Batell *et al.*, PRD**79**, 115008, 2009.

Essig *et al.*, PRD**80**, 015003, 2009.



$\sim\epsilon^2 \times$

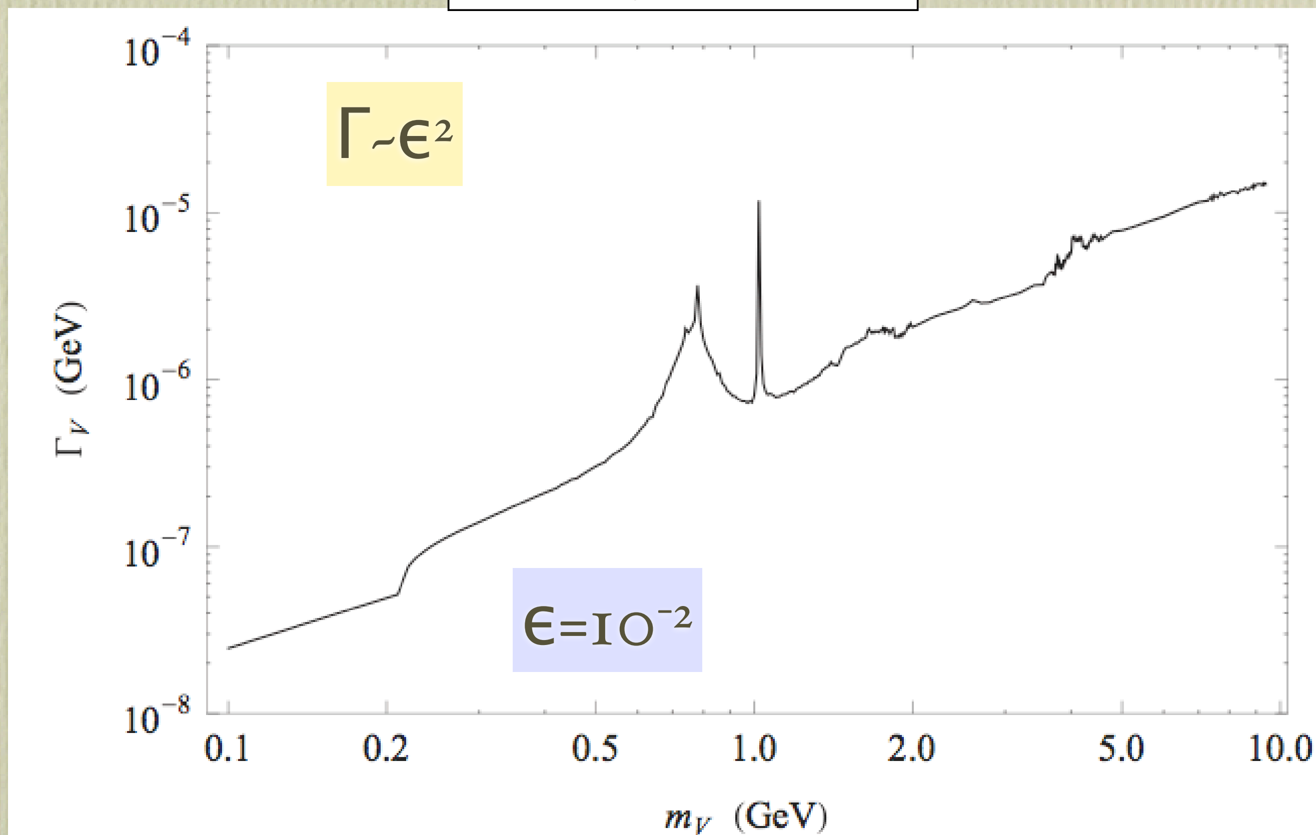


- ★ Very high luminosity+great efficiency
- ★ Great momentum resolution+vertexing
- ★ Good PID
- – High QED backgrounds

Properties of the "Dark Photon"

Batell *et al.*, PRD**79**, 115008, 2009.

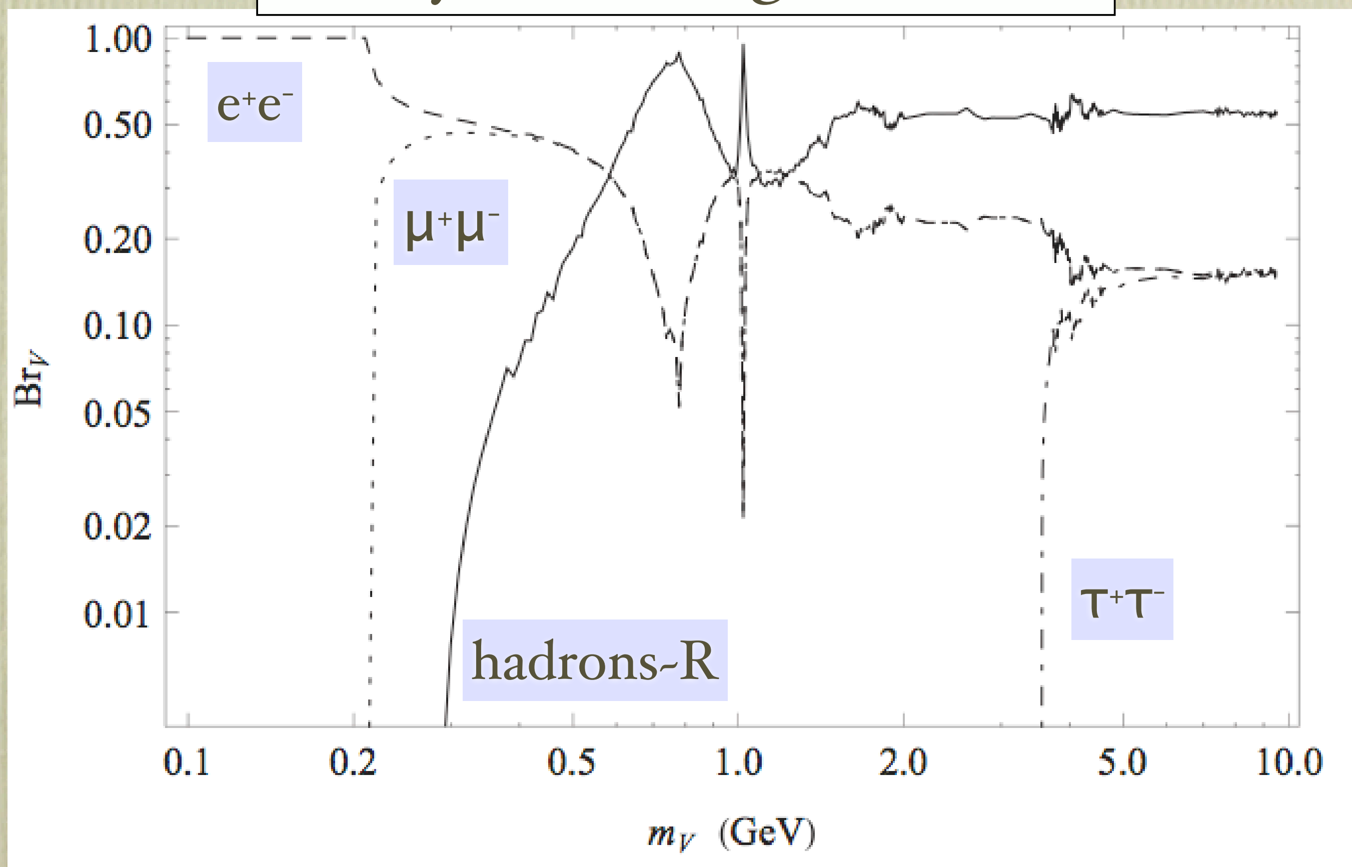
Decay Width:



Very narrow, but generally prompt (for this value of mixing)

Properties of the "Dark Photon"

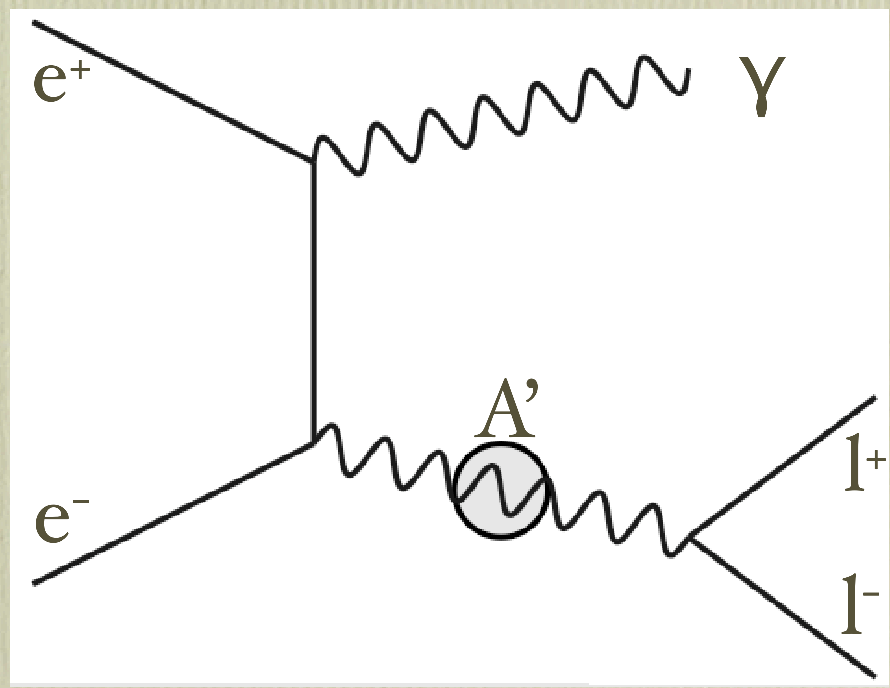
Decay Branching Fractions:



Batell *et al.*, PRD**79**, 115008, 2009.

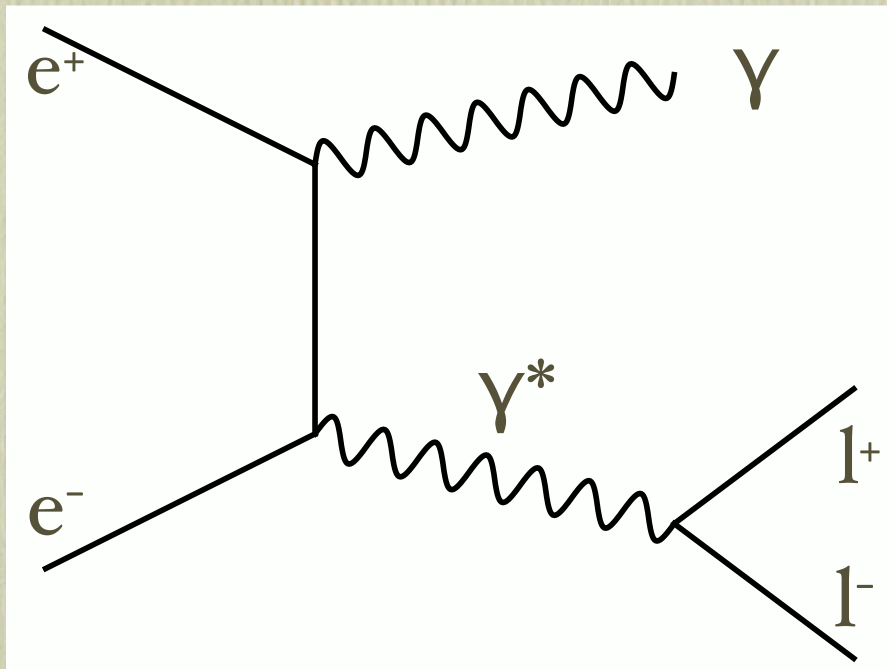
Direct Production: $\gamma l^+ l^-$

The most generic (model independent) signature...

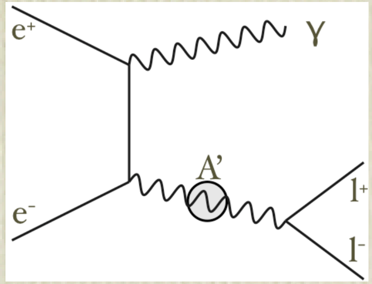


Direct Production: γl^+l^-

But a huge QED background...

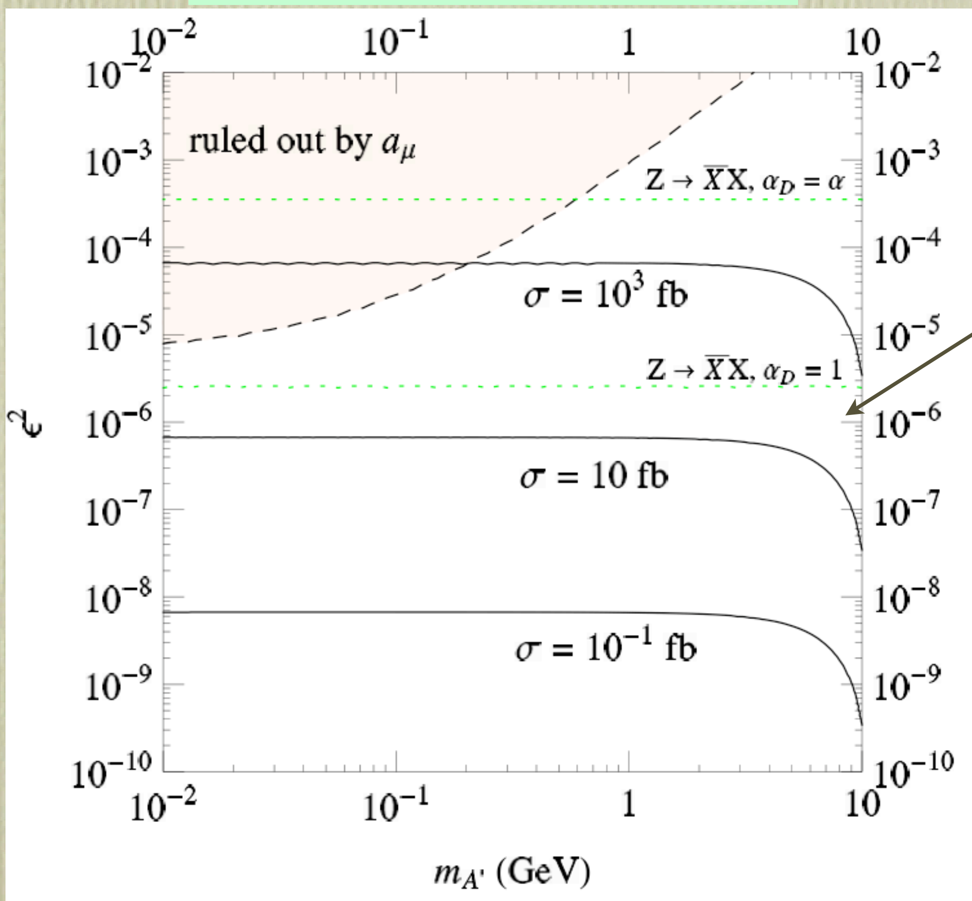


...still, we should look. The A' would show up as a spike in the l^+l^- spectrum...



Direct Production: γA'

@ B-Factory Energy

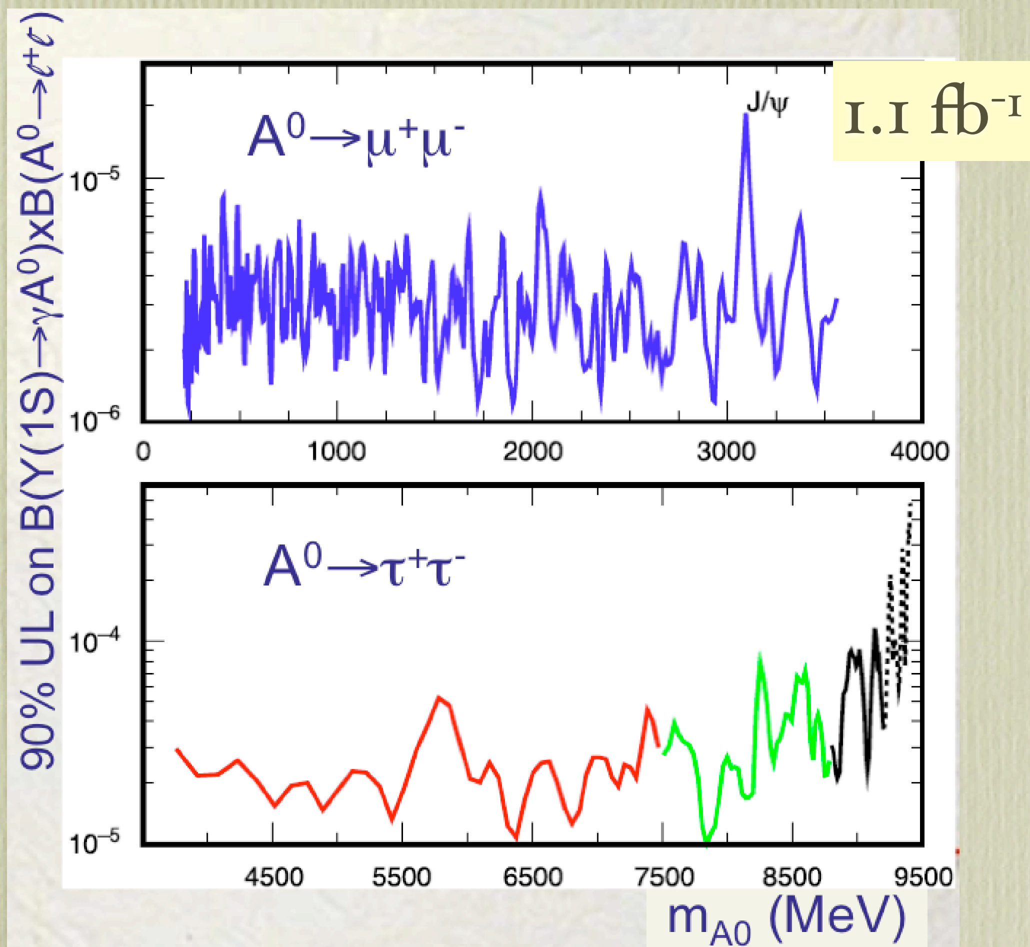


Essig *et al.*, PRD**80**, 015003, 2009.

Even with large background should be able to reach ~here

Cross sections scale like s^{-1}...lower energy is better (good for BES)!

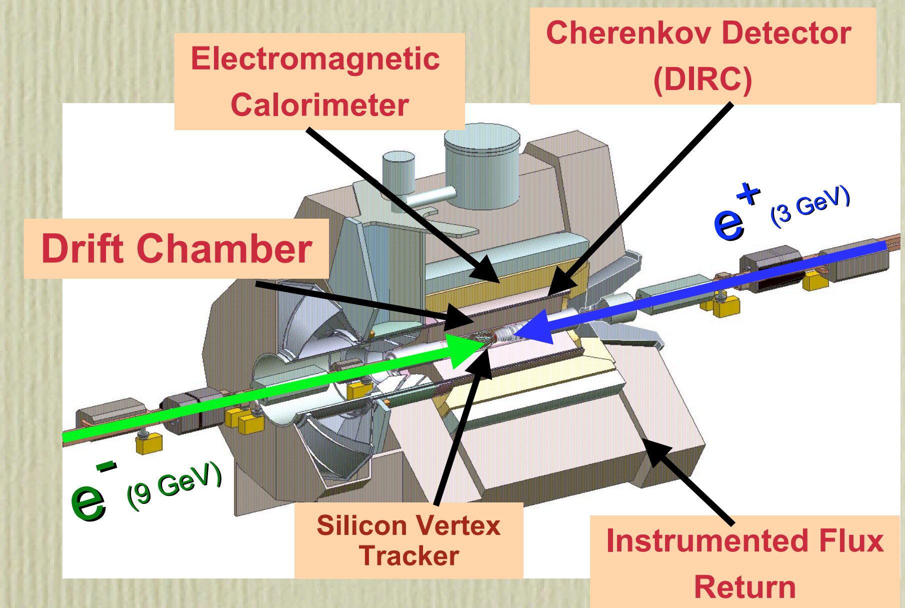
Search for Narrow Resonance in $e^+e^- \rightarrow \gamma l^+ l^-$ (CLEO)



W.Love *et.al*, PRL**101** 151802 (2008)

Analysis designed to look for light higgs (A_o), but works for this too…but big QED bkg.

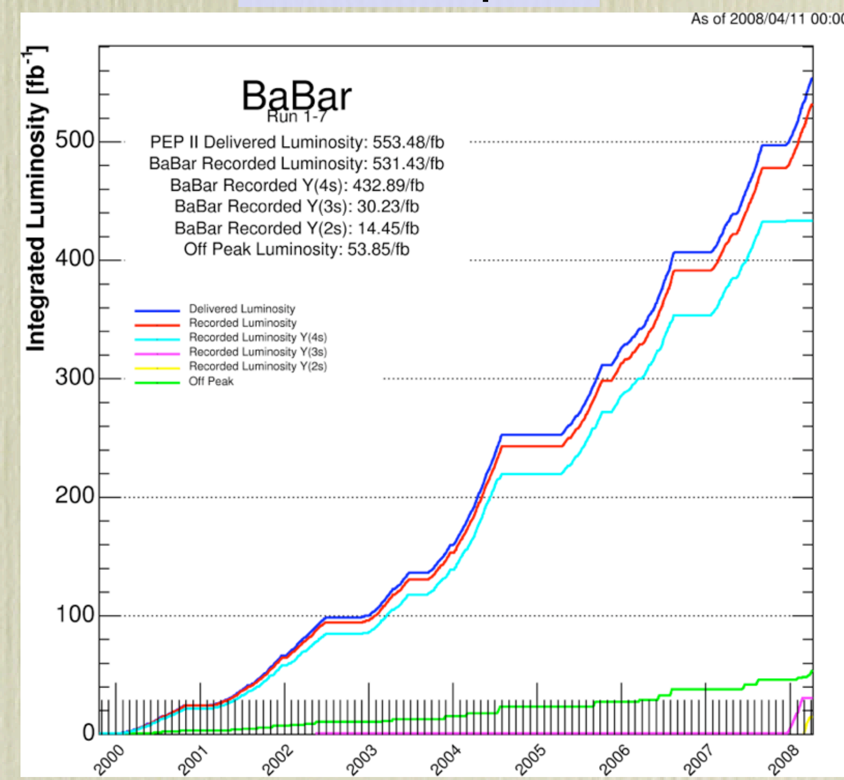
BaBar and PEP-II

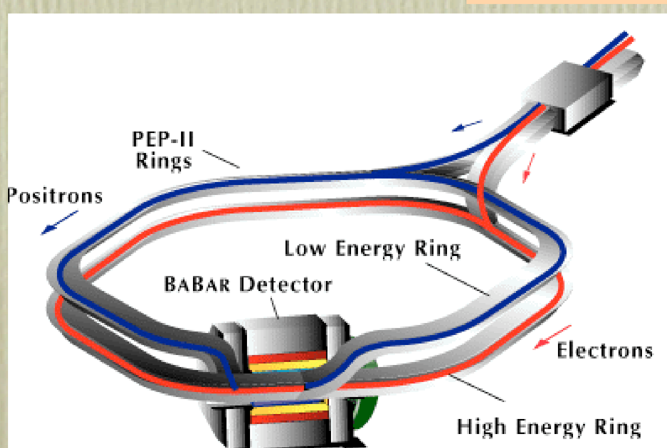


ran from 1999→2008

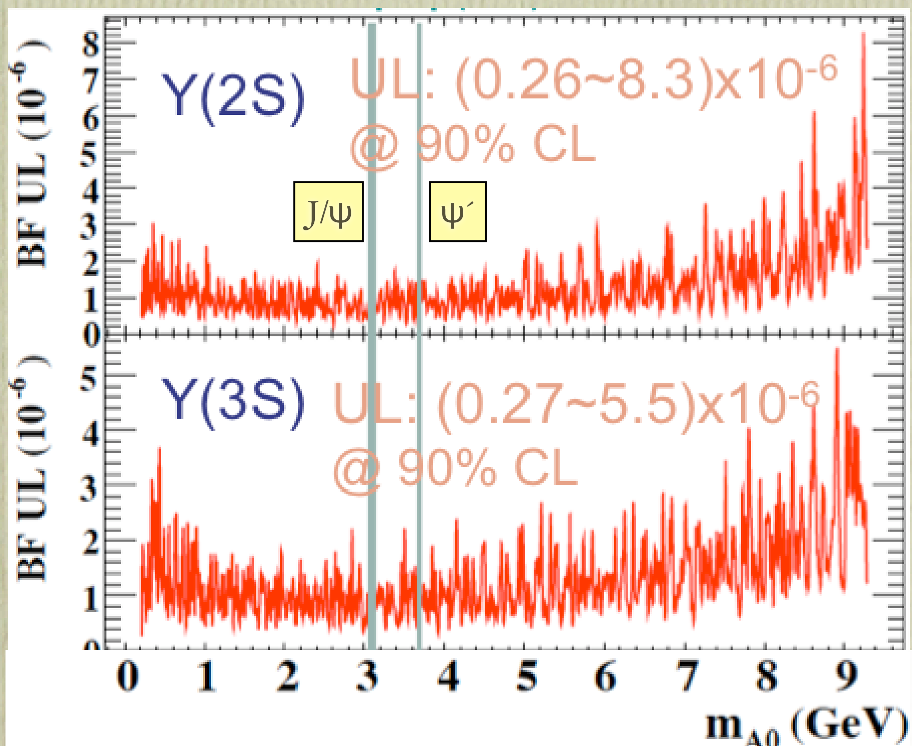
540/fb collected including

465M $B\bar{B}$ pairs





Search for Narrow Resonance in $e^+e^- \to \gamma\mu^+\mu^-$



30.22/fb @ Υ(3s)
14.45/fb @ Υ(2s)

PRL 103, 081803 (2009)

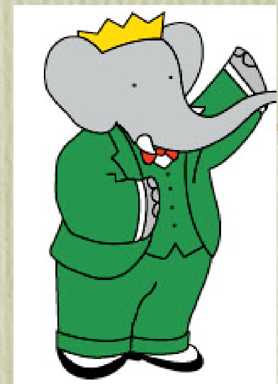
Analysis designed to look for light higgs (A_0), but works for this too...but big QED bkg.

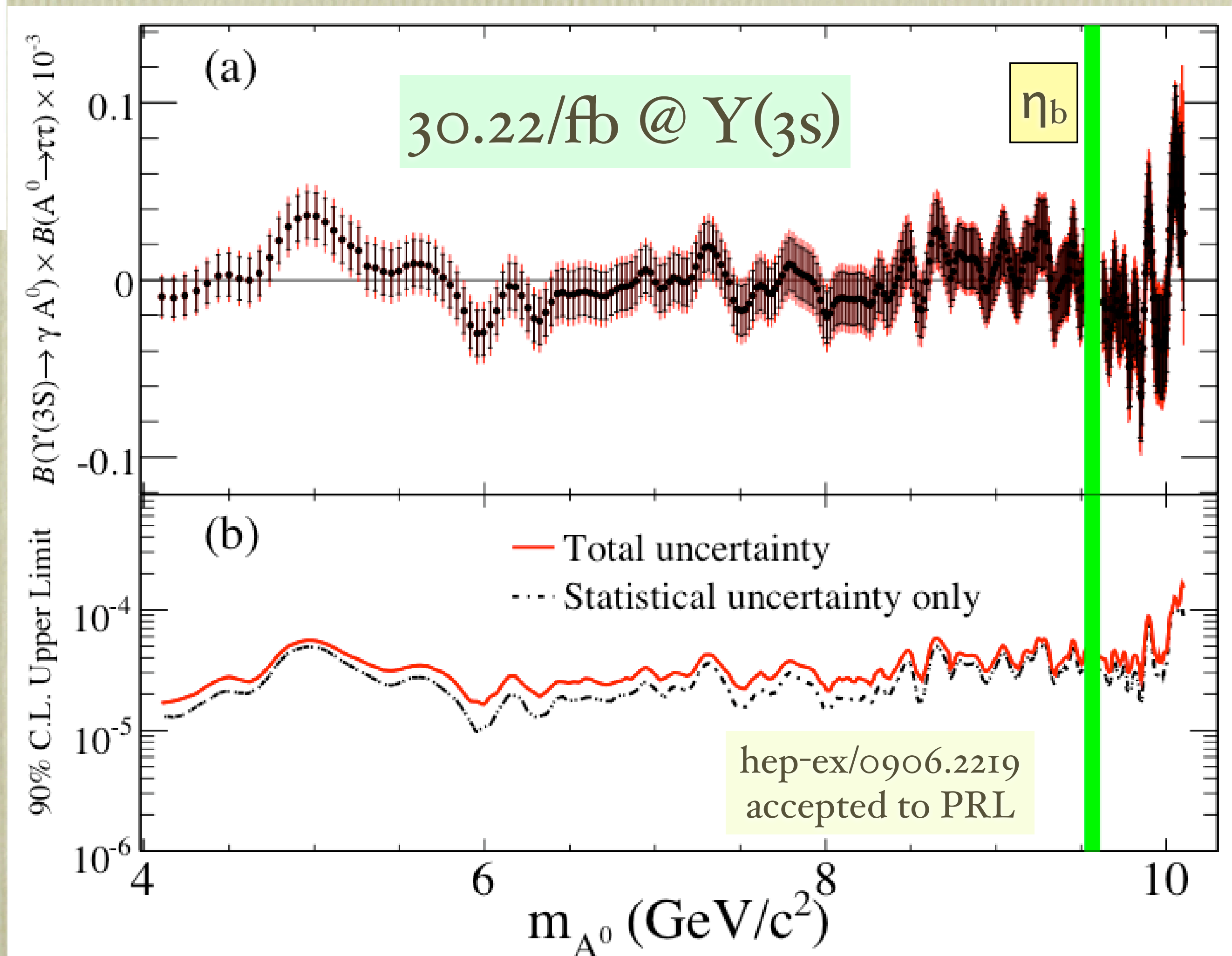
→corresponding limit on ϵ~5×10^{-3}

Remember...scaling of ϵ goes as: $\sqrt[4]{\mathcal{L}}$ so adding full dataset (x10) reduces limit by ~x 1.8.

...even "super" B-Factories only gets it down to ~1×10^{-3}...

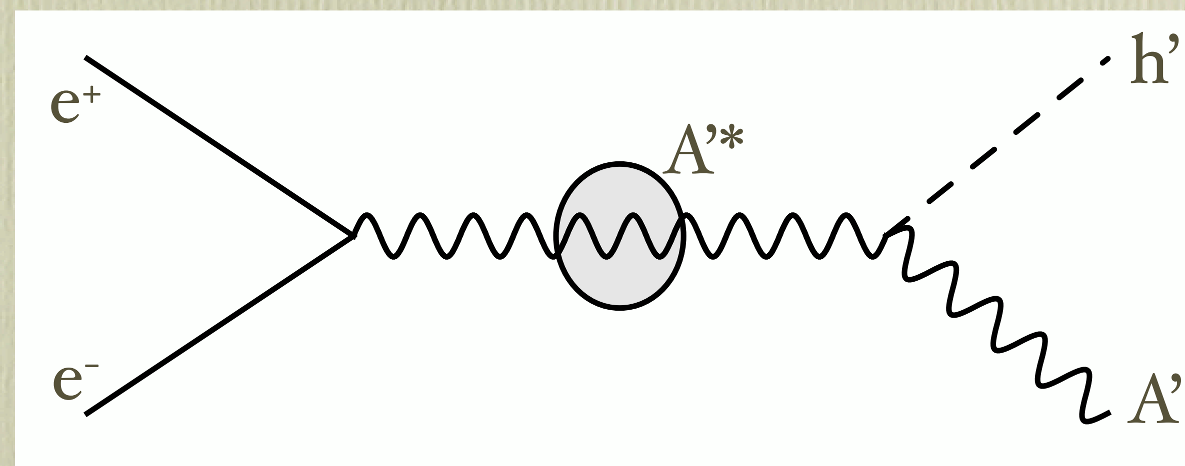
Search for Narrow Resonance in $e^+e^- \rightarrow \gamma\tau^+\tau^-$





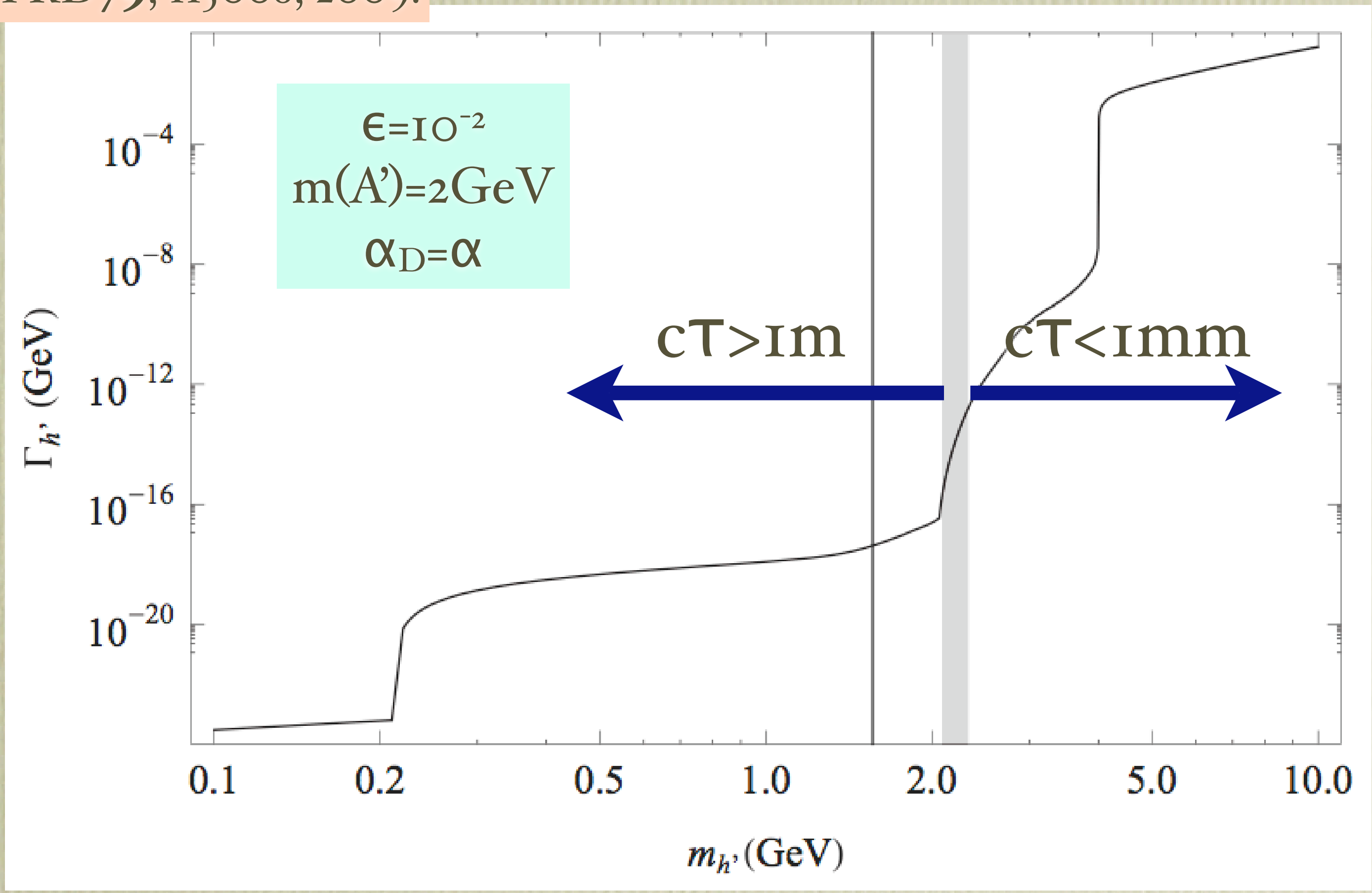
Direct Production: Dark Higgs-strahlung

Another potentially great signature:



Properties of the “Dark Higgs”

Batell *et al.*, PRD**79**, 115008, 2009.



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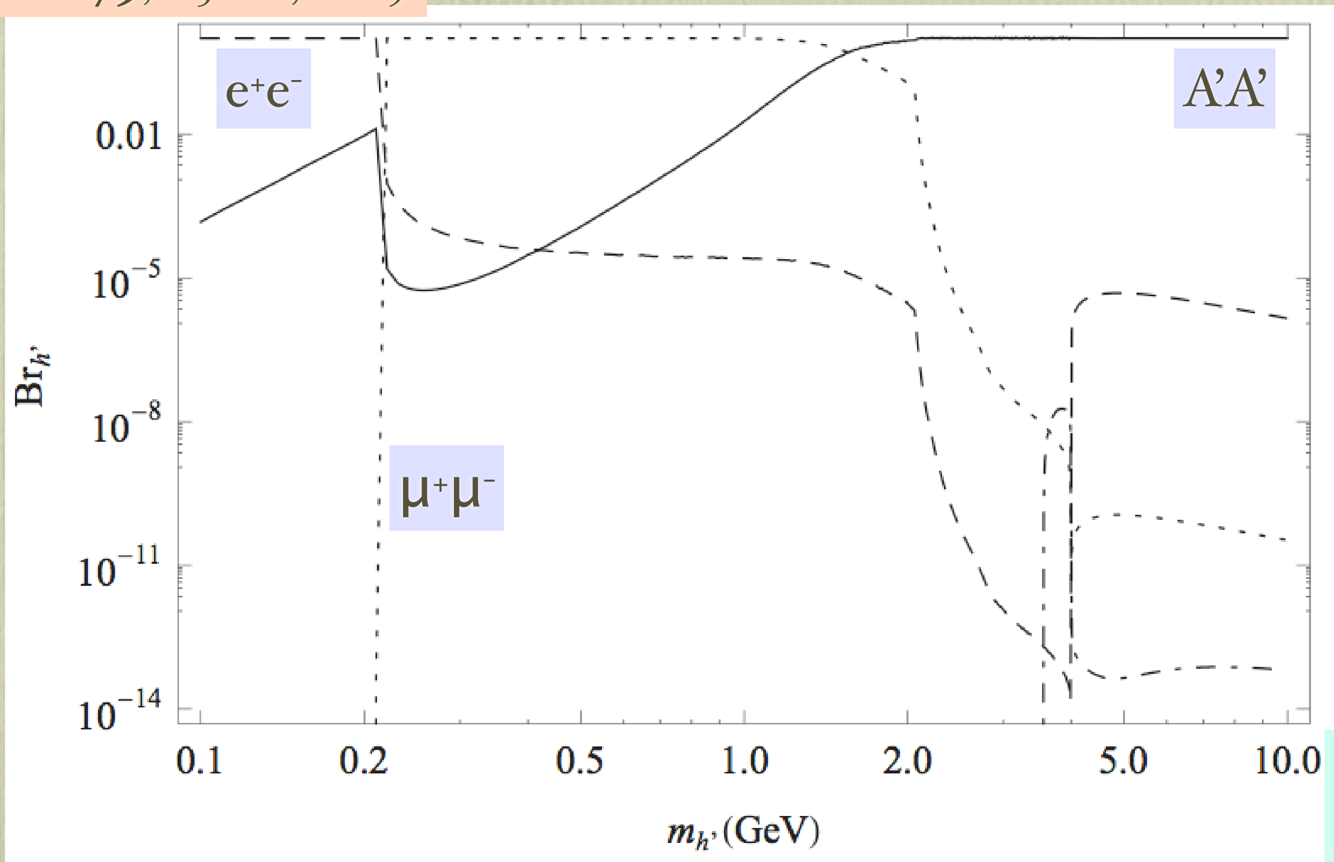
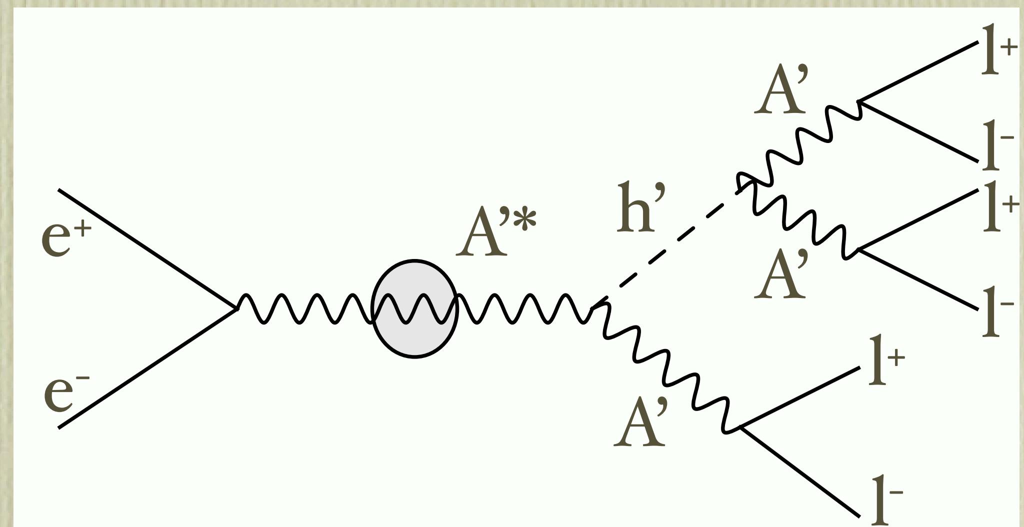


$\epsilon = 10^{-2}$
m(A’)=2GeV
$\alpha_D = \alpha$

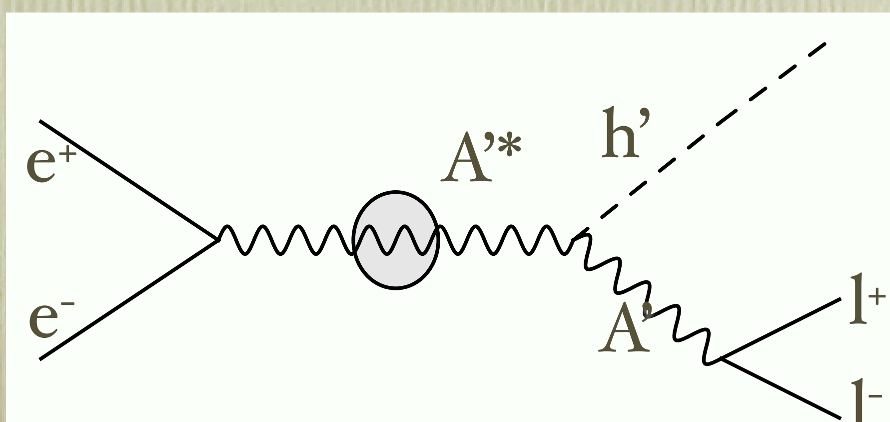
Direct Production:
Dark Higgs-strahlung



m(h´)>m(A´)

$e^+e^- \rightarrow$ 6-leptons

- 1, 2, or 3 pairs making A'
- 4-lepton resonance
- Very small QED bkg

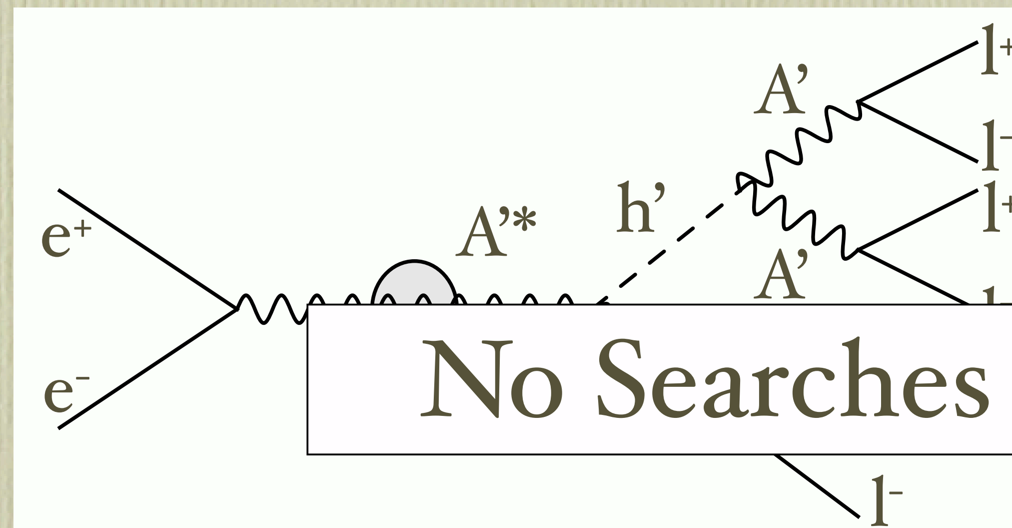


m(h´)<m(A´)

$e^+e^- \rightarrow$ 2-leptons+$\not{E}$

- 1 pair making A'
- large missing energy...
- pretty hard...triggering issues?

Direct Production: Dark Higgs-strahlung

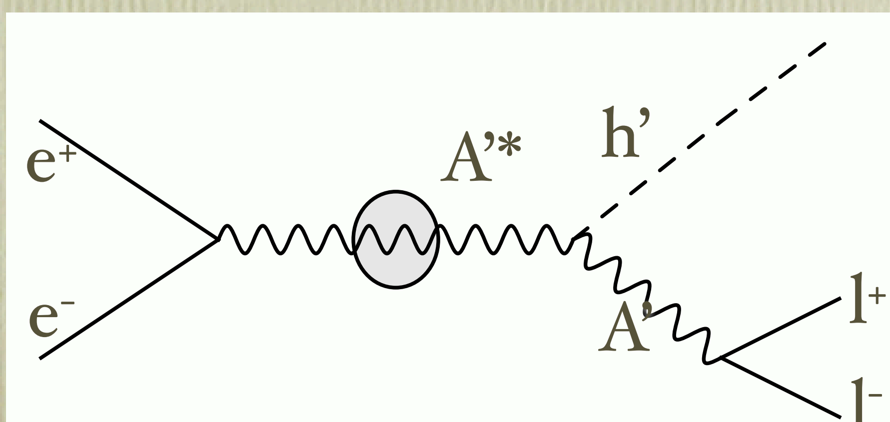


No Searches Yet!

m(h´)>m(A´)

$e^+e^- \rightarrow$ 6-leptons

- 1, 2, or 3 pairs making A'
- ...n resonance
- ...all QED bkg



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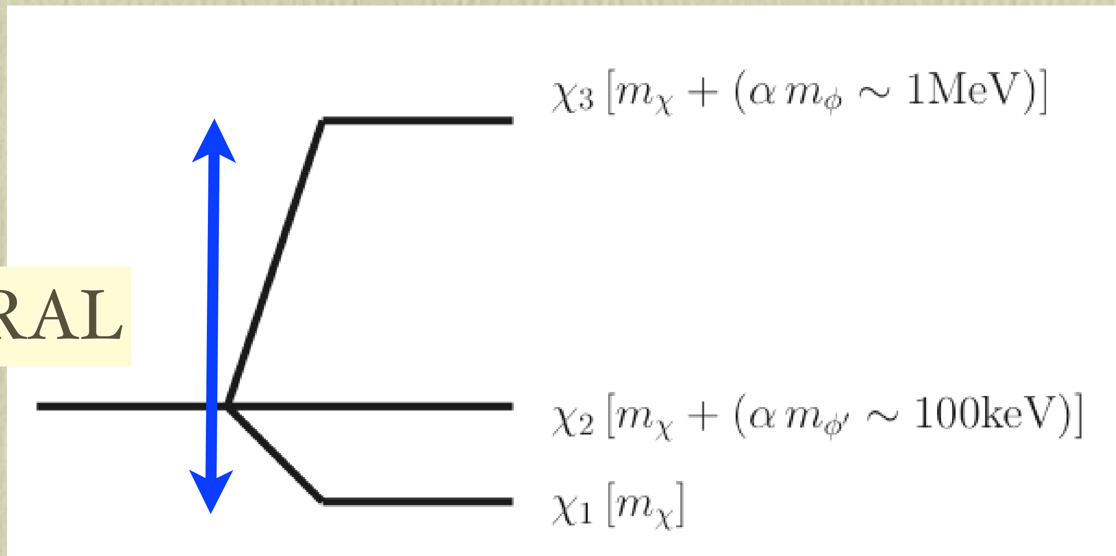
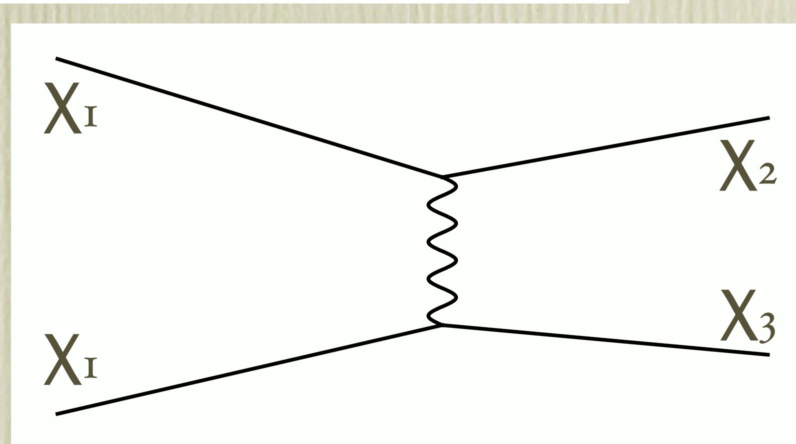
DAMA + INTEGRAL and Non-Abelian Dark Sectors

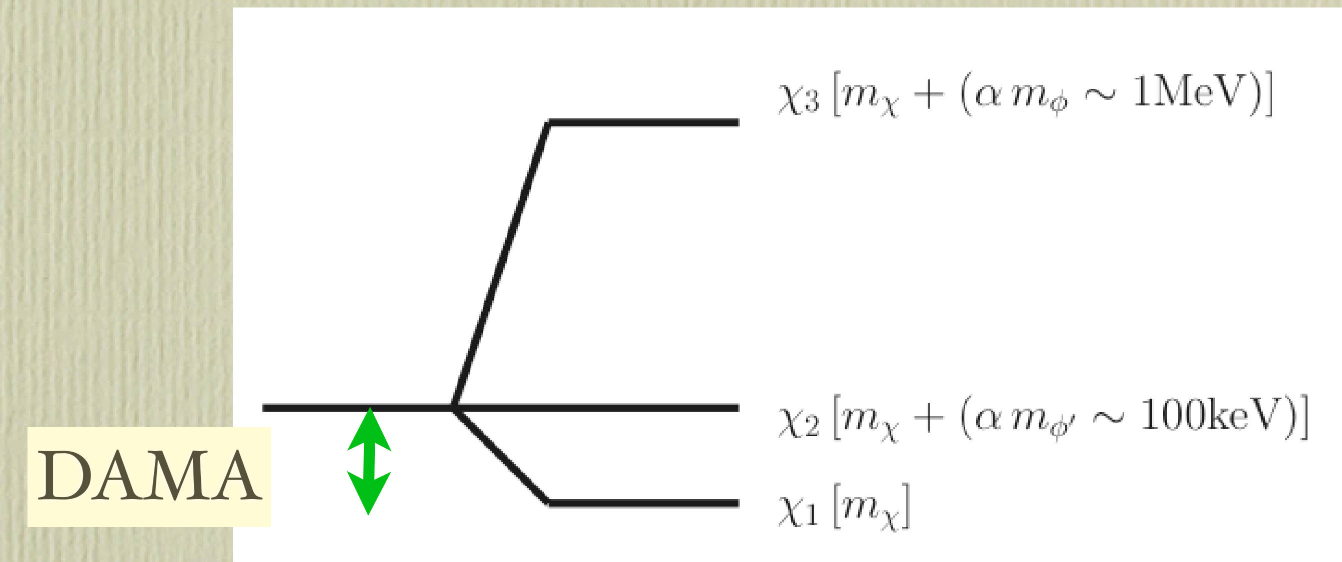


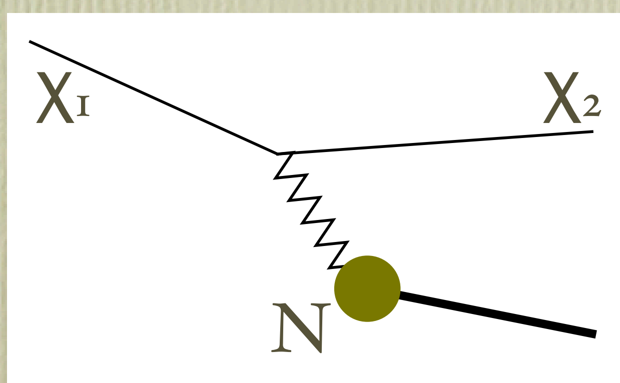
INTEGRAL

eXciting Dark Matter (XDM) can explain 511keV line



DAMA + INTEGRAL and Non-Abelian Dark Sectors





inelastic Dark Matter (iDM) can explain DAMA modulation

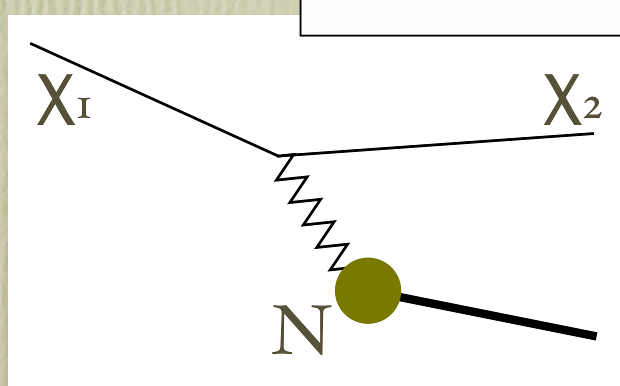
DAMA + INTEGRAL and Non-Abelian Dark Sectors

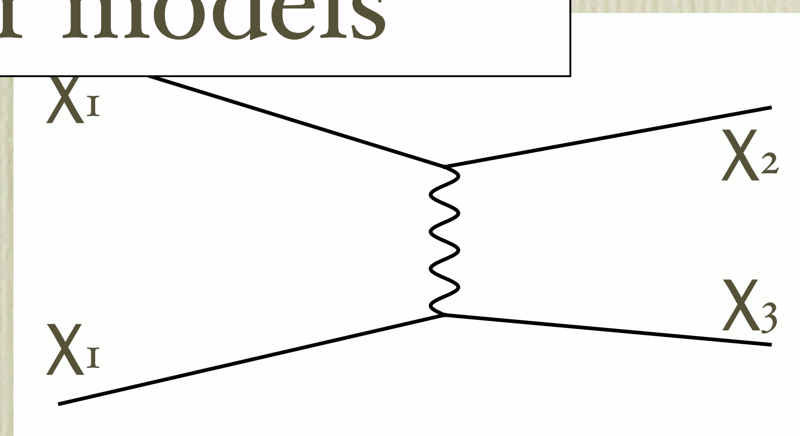
$\chi_3 [m_\chi + (\alpha\, m_\phi \sim 1\mathrm{MeV})]$

INTEGRA

DAMA

XDM and iDM both come naturally in non-Abelian dark sector models



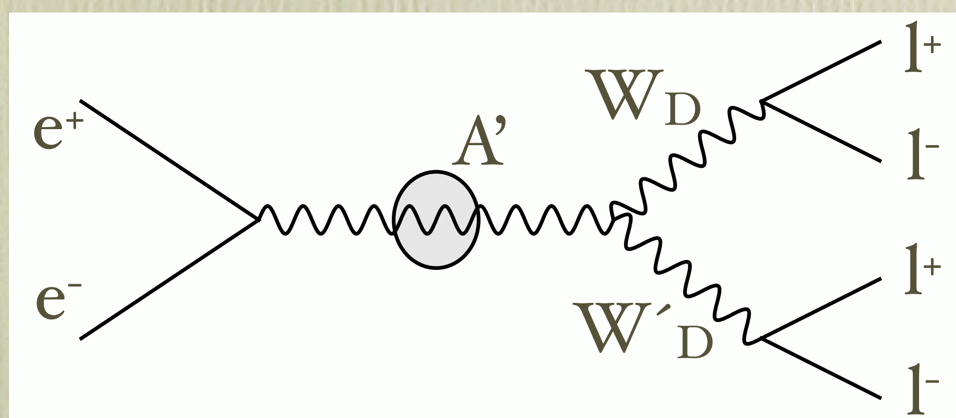


Lowest order non-Abelian signature

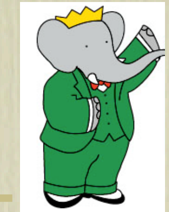
Simplest non-Abelian:

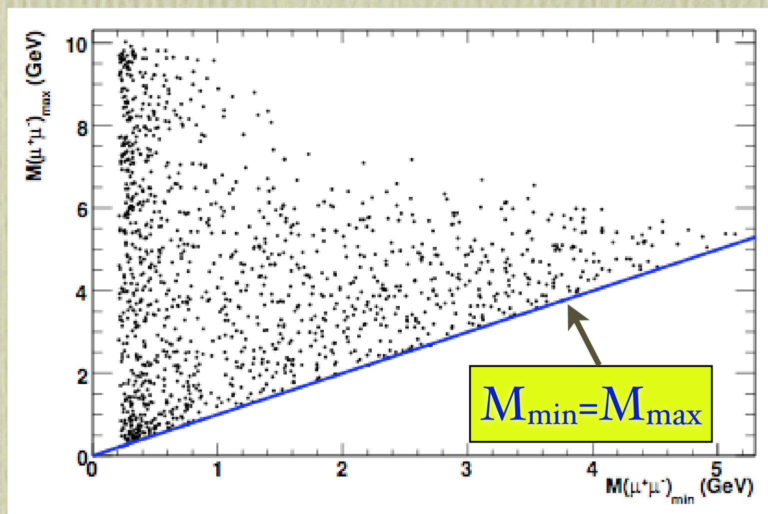
$U(1)_D x SU(2)_D$

...like EW, there are 4 gauge boson force carriers; all potentially mix with the SM photon



$e^+e^- \rightarrow$ 4-leptons

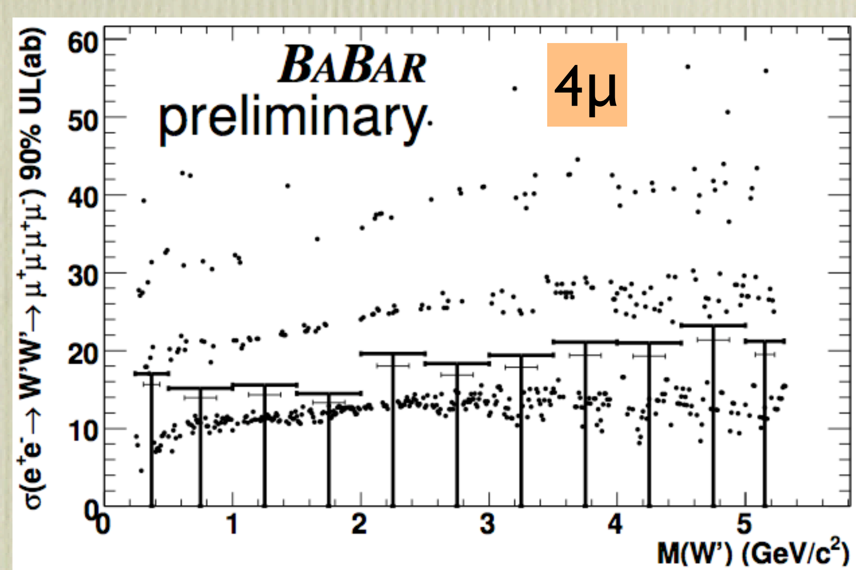




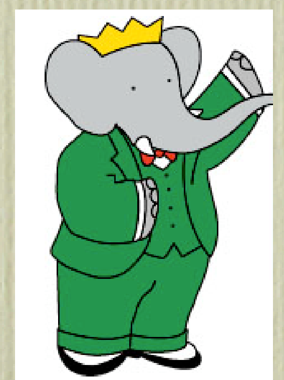
- Very clean modes (esp 4μ) designed to search for a non-Abelian dark sector
- Require 2 resonances within ~50MeV
- include 4e, 2e2μ, and 4μ modes
- Used full BaBar runs 1-7 dataset: ~540/fb

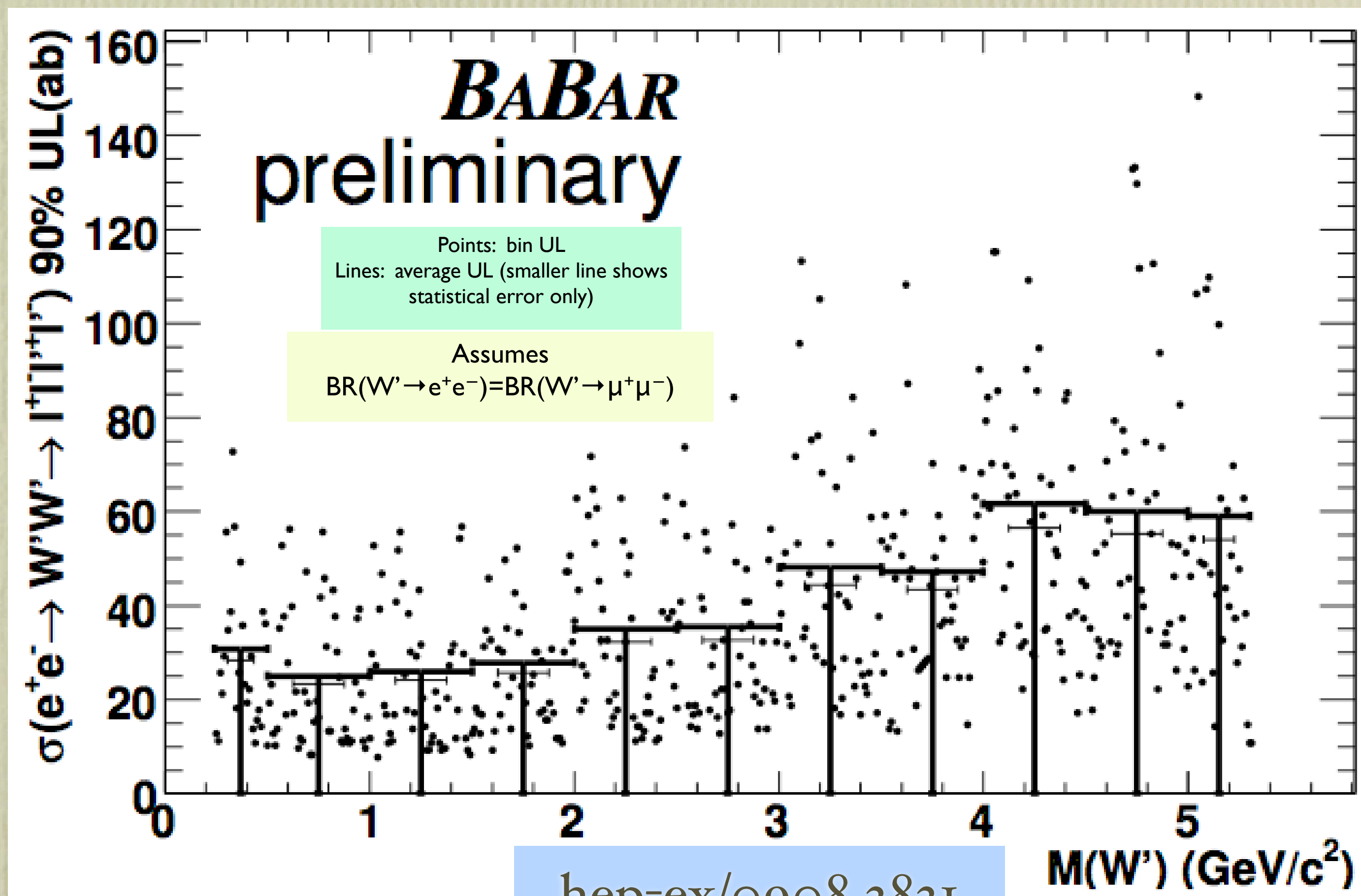
- Signal expected where the two masses are equal
- Simple cut-and-count analysis with background extrapolated from sideband

Points: bin UL
Lines: average UL (smaller line shows statistical error only)



$e^+e^- \to$ 4-leptons: Combined UL



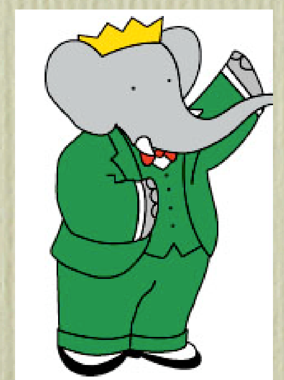


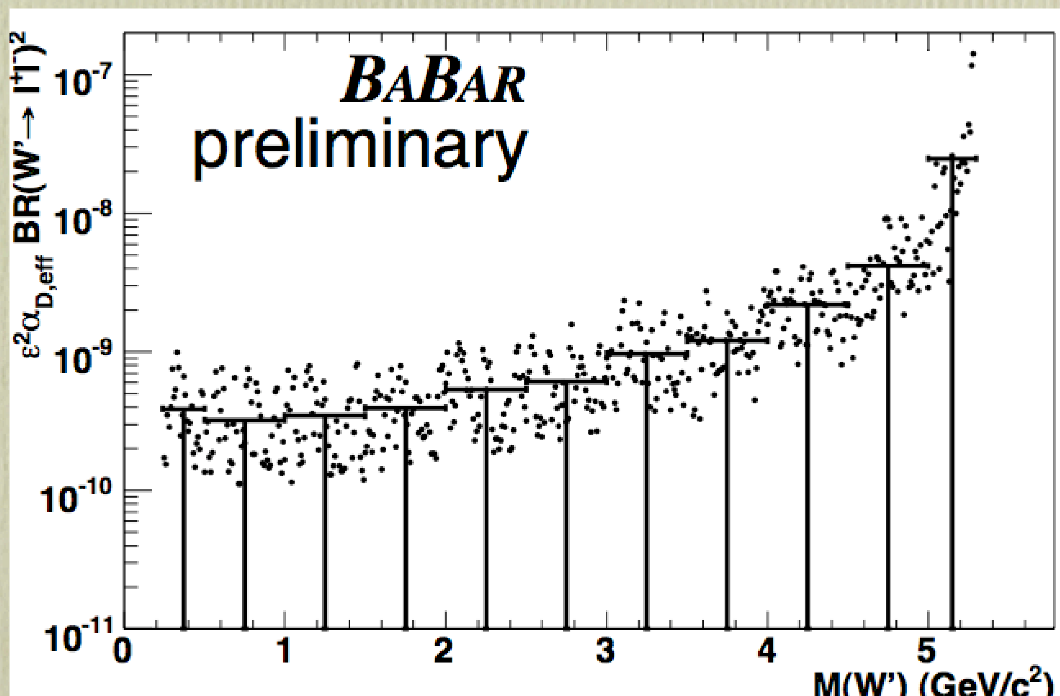
hep-ex/0908.2821

$e^+e^- \to$ 4-leptons: Limits on Coupling

$$\sigma(e^+e^- \to W_D W_D) \sim \frac{\pi\varepsilon^2\alpha\alpha_{D,eff}}{E_{cm}^2}\left(1 - \frac{4m_{W_D}^2}{E_{cm}^2}\right)^{3/2}$$

...some O(1) s dependence absorbed into definition of $\alpha_{D,eff}$



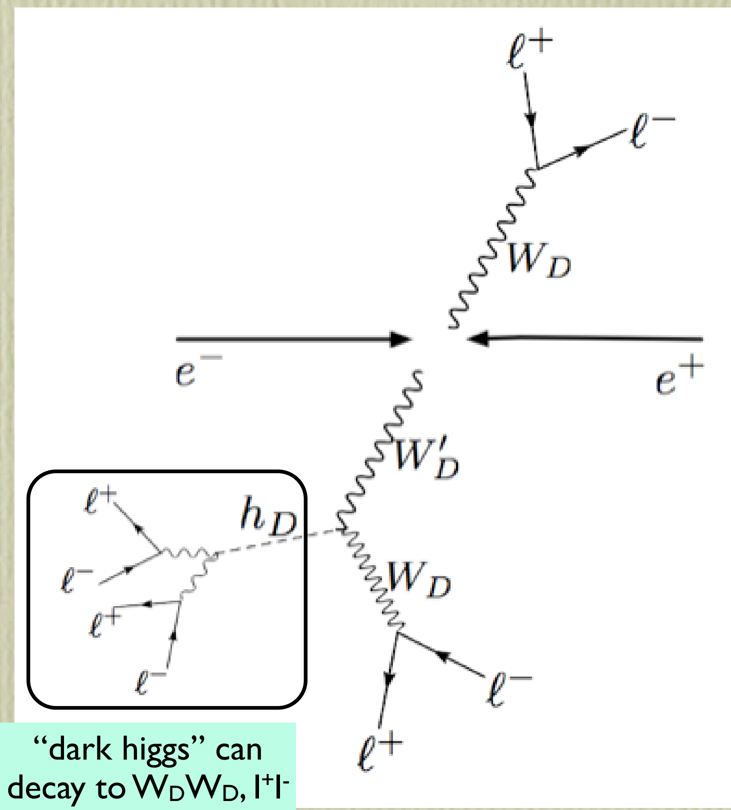


Remove BR(W→ll)^2 by dividing $(2+R)^2$

$\alpha_D \sim 10^{-2}$ →

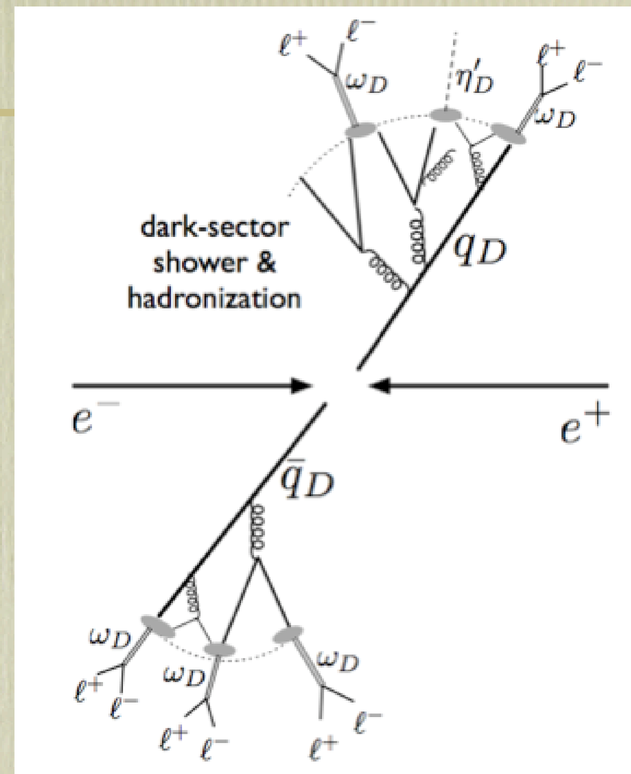
$\epsilon < \sim 10^{-3}$
(for non-abelian hidden sector)

More exotic signatures...



"dark higgs" can decay to W_DW_D, l^+l^- or escape detector!

Non-Abelian Higgsed: 8 leptons or missing mass



Confined: lots of leptons; possibly missing mass depending on lifetimes..

...can also look for muons with a displaced vertex...

Dark Forces in Rare Decays

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

$X \to YU$	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

→High lumi e^+e^- colliders are meson factories!

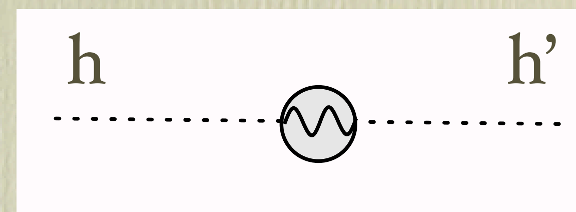
→We have a huge number many of these decays... also other mesons like J/ψ, D, ϒ, and B...

→Also, can look in π^0 decays!

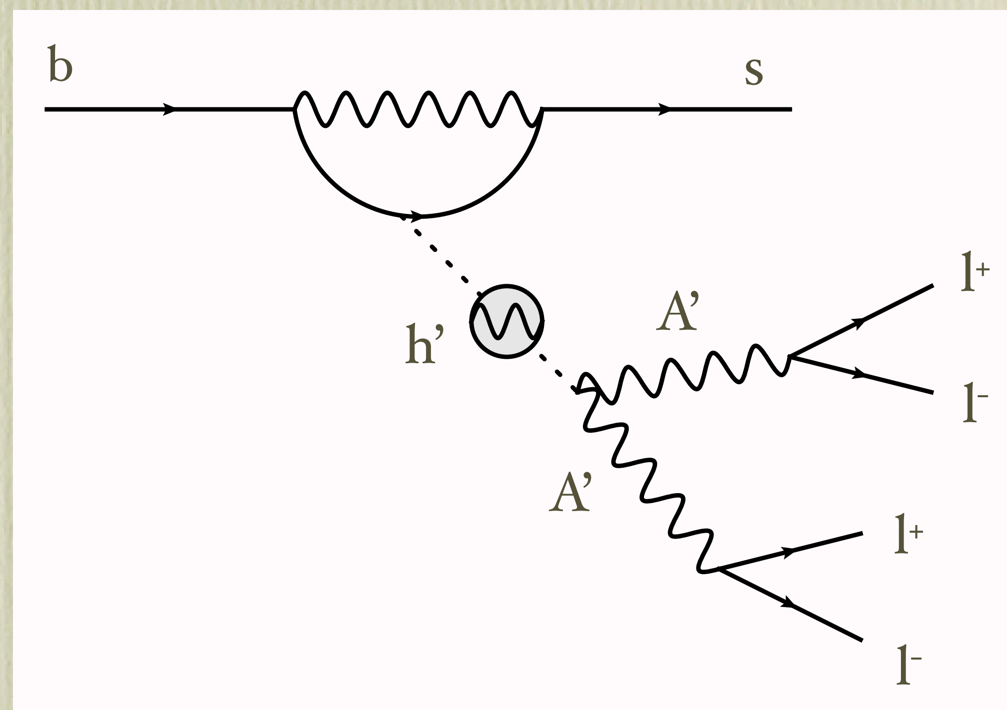
→There is some data mining to do on older experiments (KTeV, JLAB, etc)...maybe there are dark photon events sitting on disk!

Rare B-Decays and the Higgs Portal

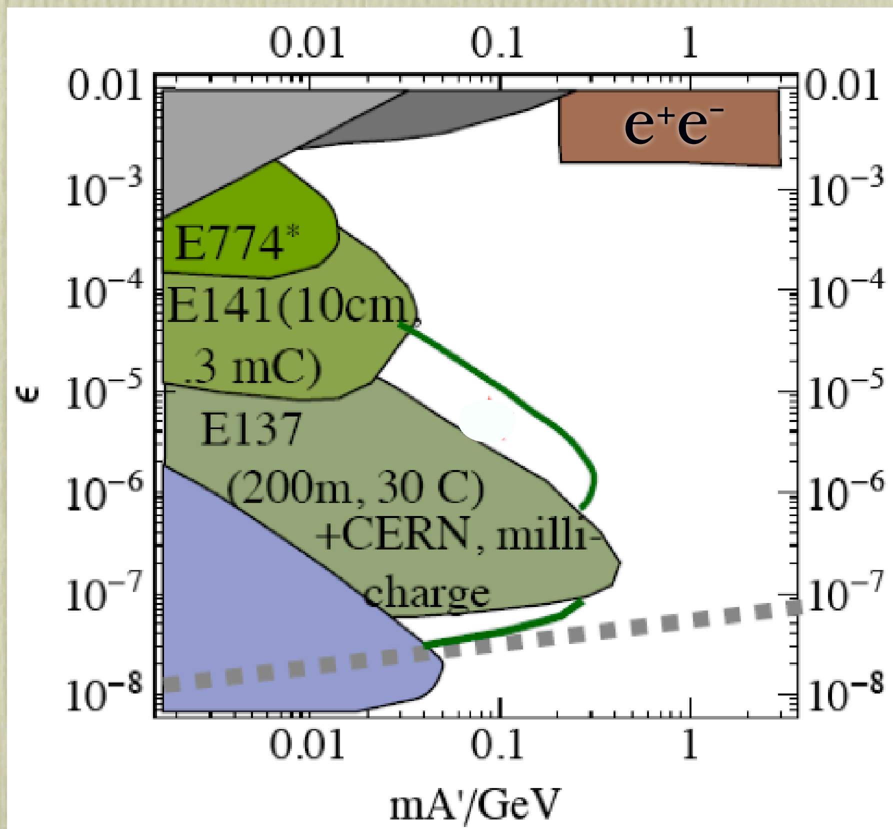
- Vector portal: $\mathcal{L} = -\frac{\kappa}{2} V^{\mu\nu} B_{\mu\nu}$
- Higgs portal: $\mathcal{L} = (-\lambda S^2 + \xi S) H^\dagger H$



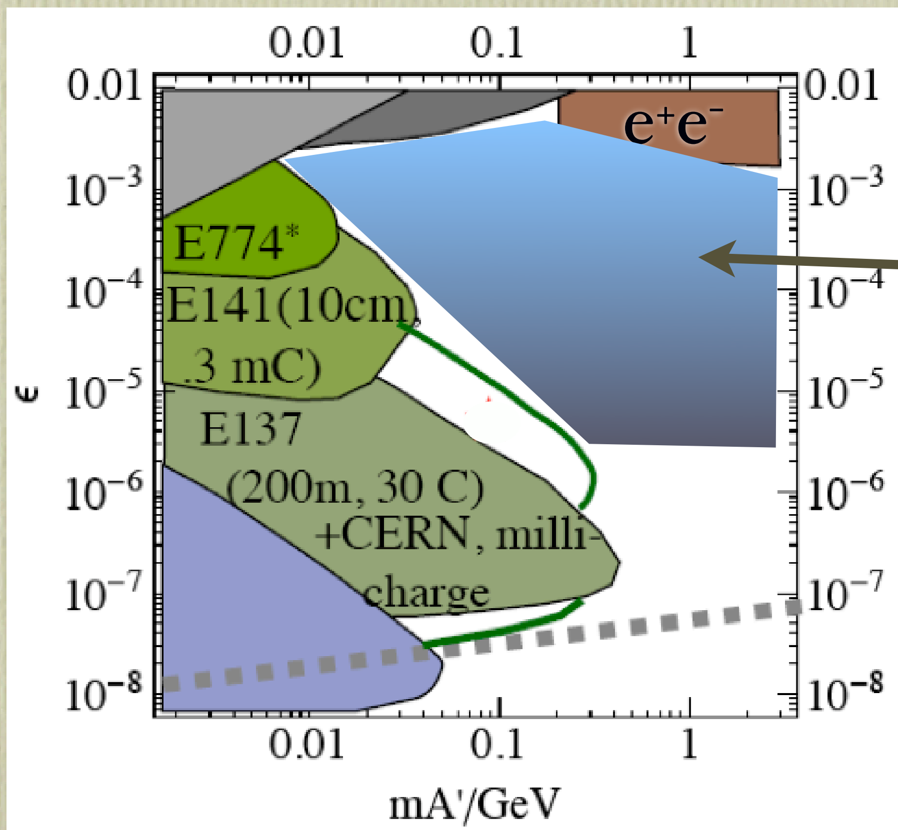
- In addition to kinetic mixing ("vector portal") there must also be a higgs portal.
- Because of the top dominating the loop, FCNC decays may be an interesting place to look for this...
  - modes like $B \to K^{(*)} 4l$ or $B^0 \to 4l$ should be very clean



Lower masses & mixing: Fixed Target and Beam Dumps



Lower masses & mixing: Fixed Target and Beam Dumps



need to probe this parameter space!

Very high flux required so fixed target experiments the way to go...

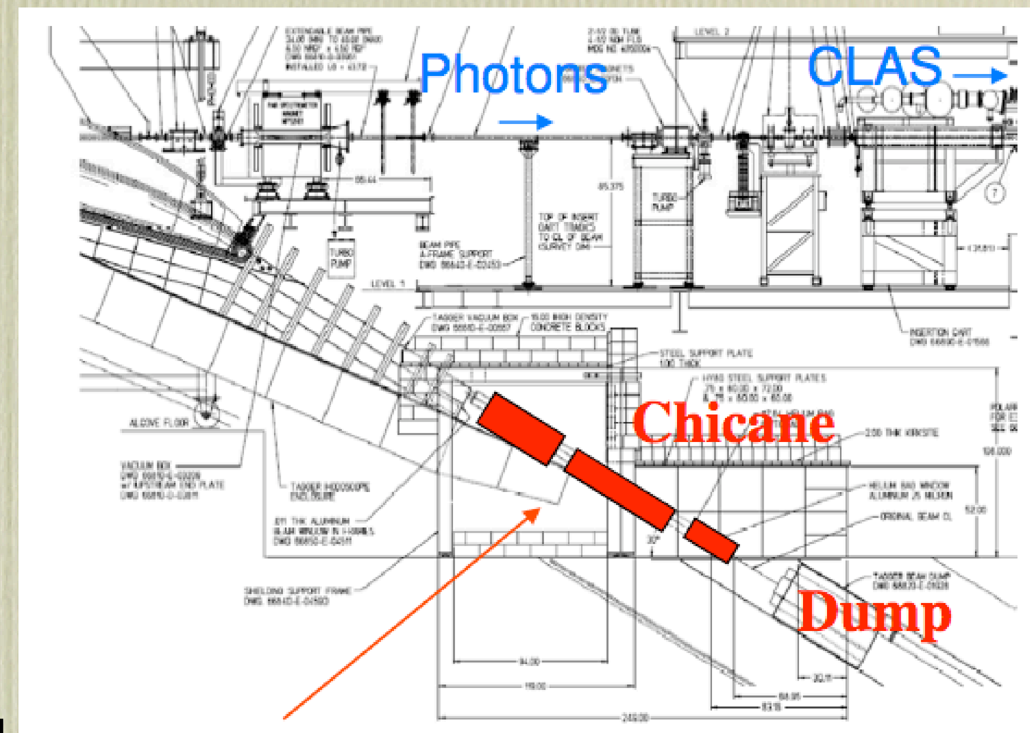
Bjorken, Essig, Schuster, Toro, hep-ph/0906.0580.

JLAB Hall-B "Proposal"

Run parasitically with photon beam going to class just in front of the electron beam dump...

- 100nA; 6GeV
- very tight space (~5m)
- beam must be steered into the dump...

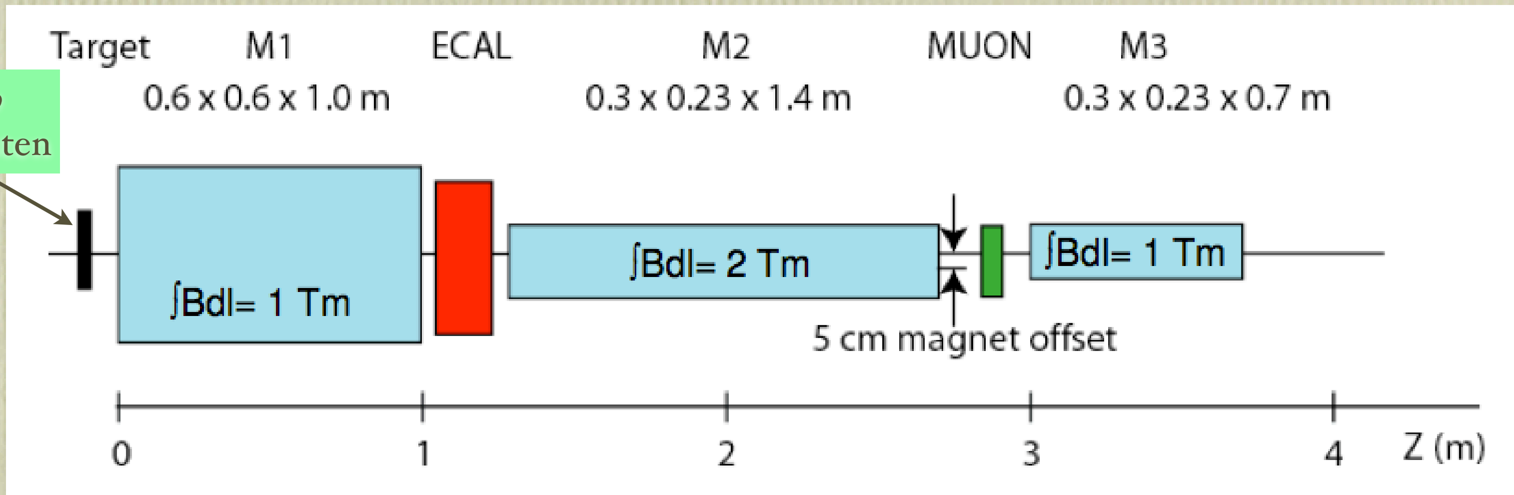
3 considerations: cheap, fast, interesting



Possible location for heavy photon search

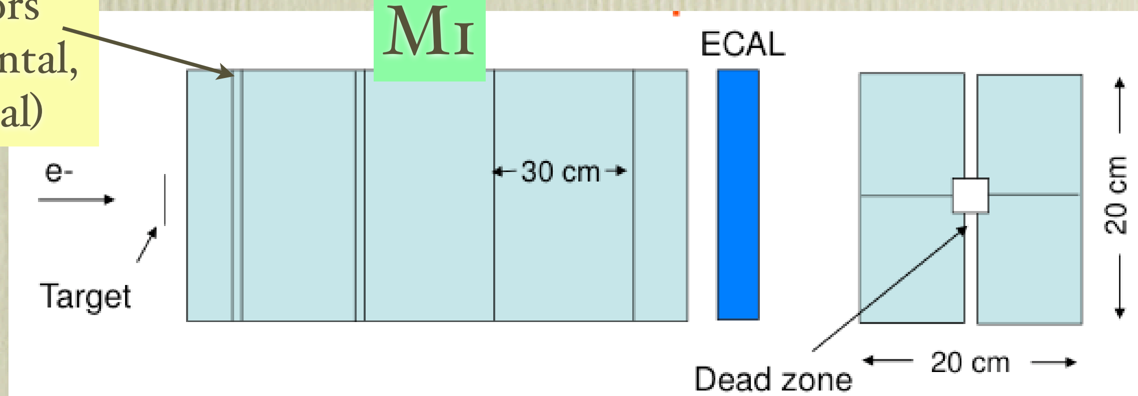
Pre-preliminary detector design

1% Tungsten



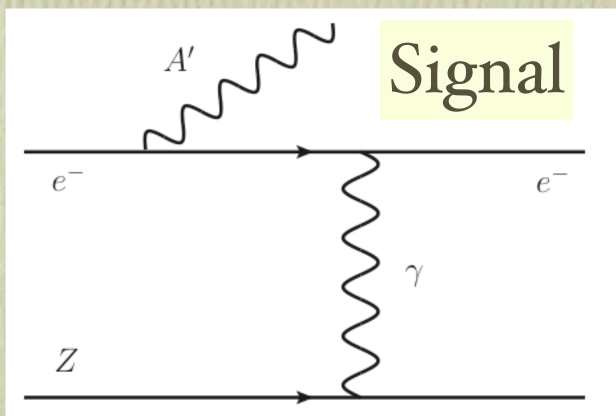
Si microstrip detectors (4 horizontal, 2 vertical)

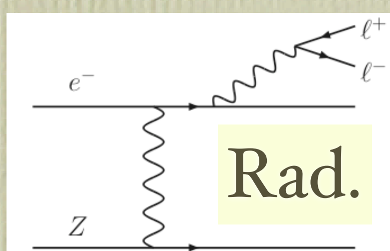
M1

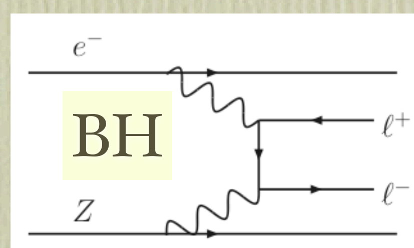


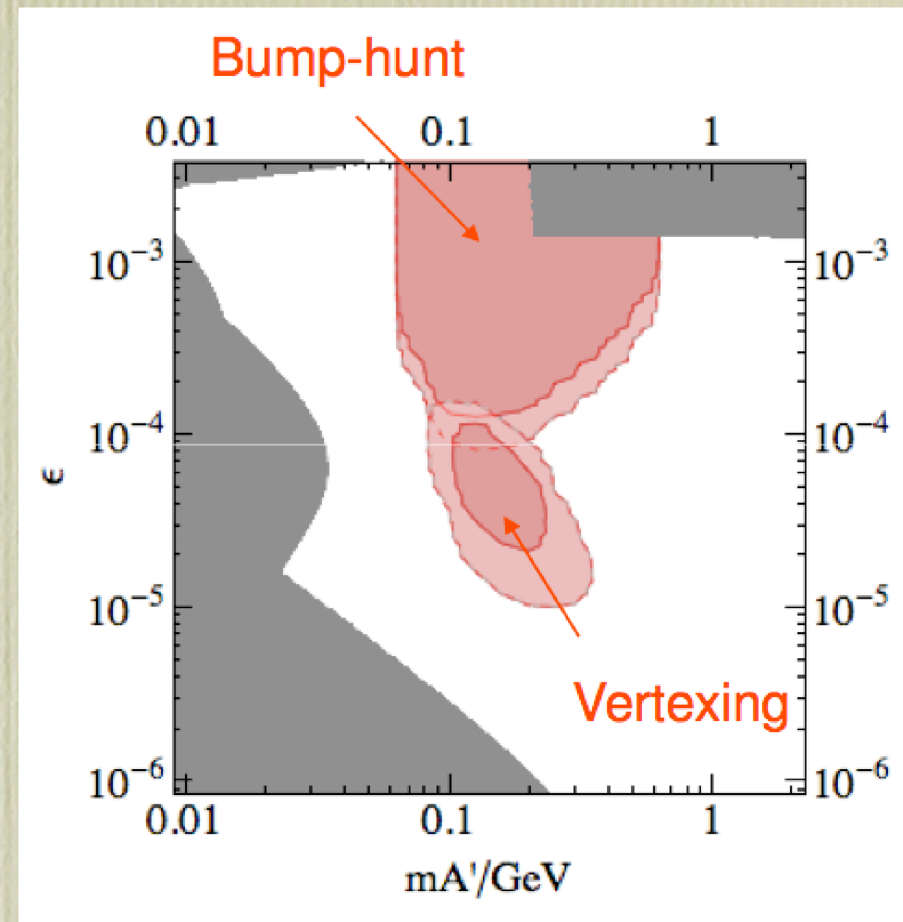
Want both mass and vertex resolution to maximize reach

Expected reach of Hall-B experiment









See talk by T. Maruyama for more details:

http://indico.cern.ch/getFile.py/access?contribId=10&resId=1&materialId=slides&confId=67760

Conclusions

- The idea of a new, “dark”, force has many people excited
  - if it is real, explains a number of recent (and not so recent) anomalies...PAMELA, FERMI, WMAP haze
    - a non-abelian dark sector could explain the DAMA modulation and the INTEGRAL 511kEV peak
- Some searches have been performed at the B-Factories (and elsewhere)...but there is still a lot of parameter space to cover

The Workshop...

- expected ~20-30 people;ended up with 107 (registered)
- about 60%/40% theory/experiment
- experimental talks from BaBar, Belle, BES, KLOE, DØ, ADMX, JLab, MESA
- 3 extremely productive working groups: e^+e^- colliders, hadron colliders, fixed target

http://www-conf.slac.stanford.edu/darkforces2009/

To Do List:

- Data mining older experiments: KTeV, JLAB, etc...
- Perform searches at current experiments: B-Factories, BES, KLOE, Tevatron, LHC
- New experiments to cover the gaps in parameter space
    - there are a number of these being discussed...see workshop program for a more complete taste

Dark Photons Fixed Target Working Group

Dark Forces Workshop
September 24, 2009

Fixed Target Search for Heavy Photons

Takashi Maruyama
SLAC

Heavy photon search working group:*

SLAC
R. Essig
C. Field
M. Graham
J. Jaros (Chair)
C. Kenney
T. Maruyama
K. Moffeit
A. Odian
P. Schuster
C. Spencer
J. Sheppard
N. Toro

JLab
S. Stepanya
L. Weinstein

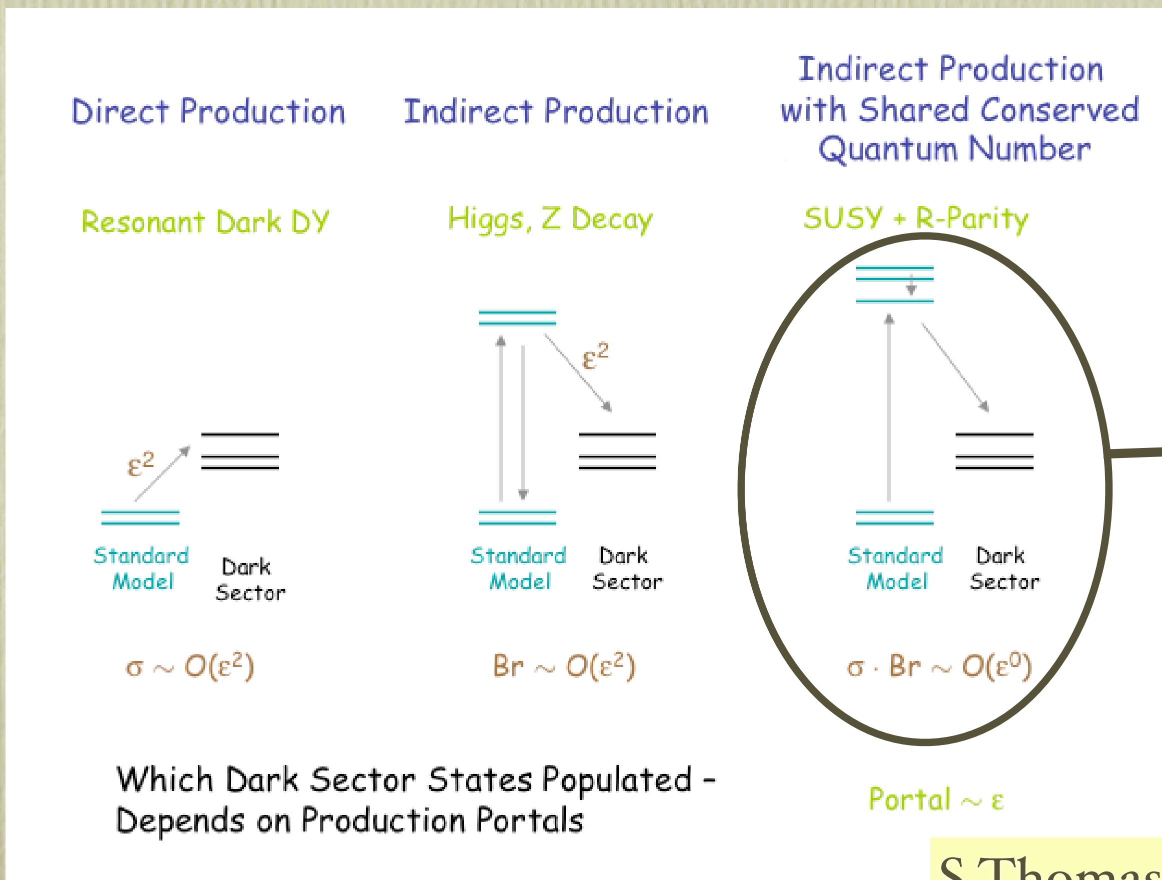
FNAL
M. Demarteau

U. of Oregon
R. Frey

Weekly WebEx meeting on Thursdays

...and growing

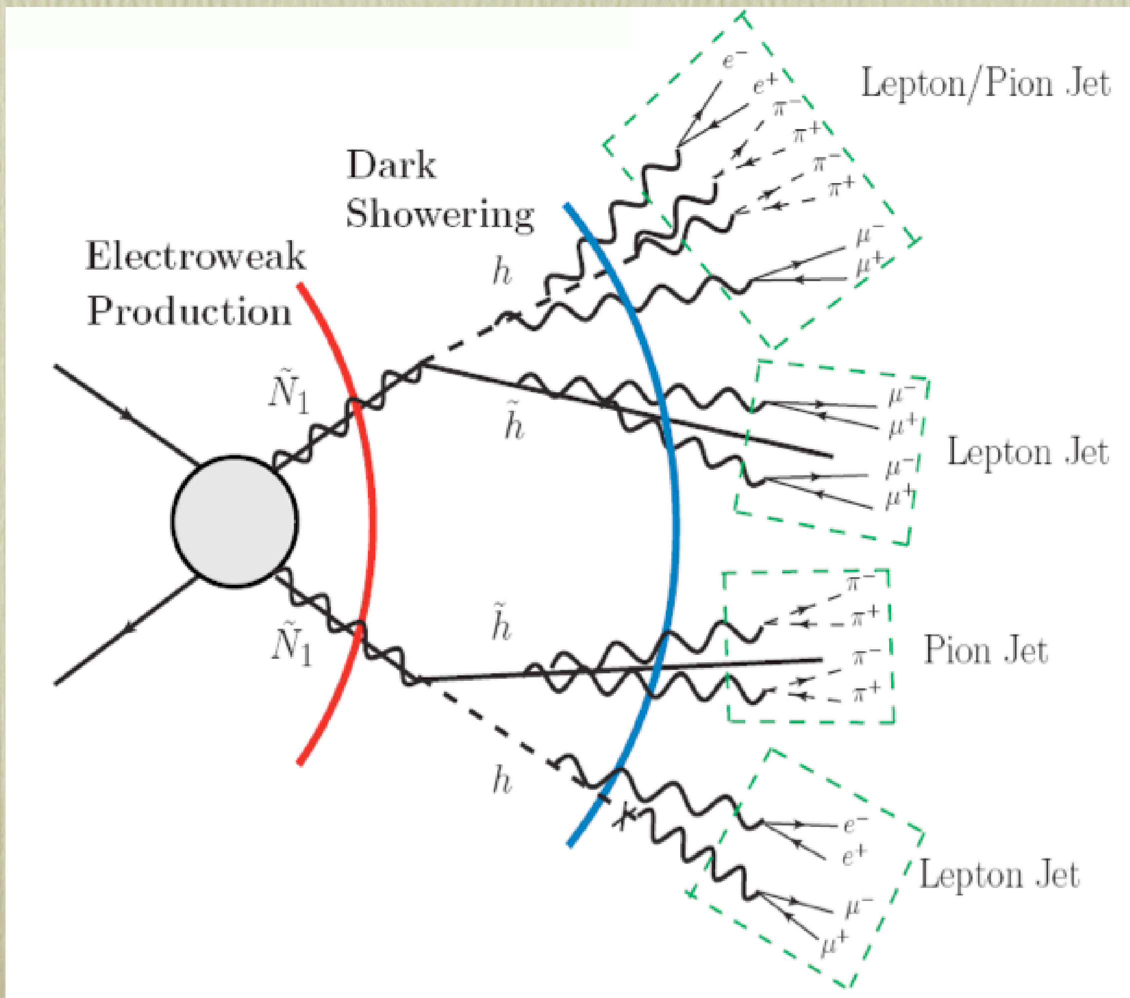
Dark Forces @ the Tevatron/LHC



S.Thomas

no factors of epsilon!

Spectacular lepton jets...



...dark sector events could have very characteristic signatures in hadron colliders.