Dark Forces at New Experimental Frontiers

The Search for New States and Forces of Nature Conference,
GGI, October 2009

Philip Schuster (SLAC Theory Group)

with J.D. Bjorken, R. Essig, and N. Toro (0906.0580)
R. Essig, and N. Toro (0903.3941)
N. Toro and I. Yavin (0910.1602)
D. Alves, S. Behbahani, and J. Wacker (0903.3945)

Dark Forces at New Experimental Frontiers

- Theory of New Vector Bosons
  (and hints from dark matter)
- e+e- Collider Searches
  (Babar, Belle, KLOE)
- Fixed-Target Experiments
  (e.g. @ JLab)

New Forces?

Known interactions:

$$SU(3) \times SU(2) \times U(1) \times ?$$

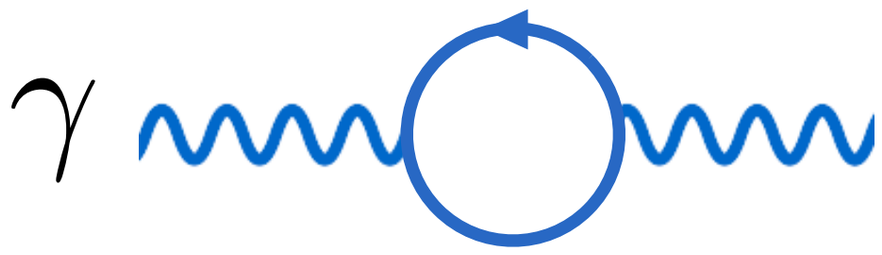
(Strong) (Electro-weak)

If ordinary matter is charged under a new force, we would have seen it (for masses ~TeV or less)

What about forces we are **not** charged under?

Photon Mixing with New Vector Boson

New vector bosons couple to the Standard Model by mixing with the photon

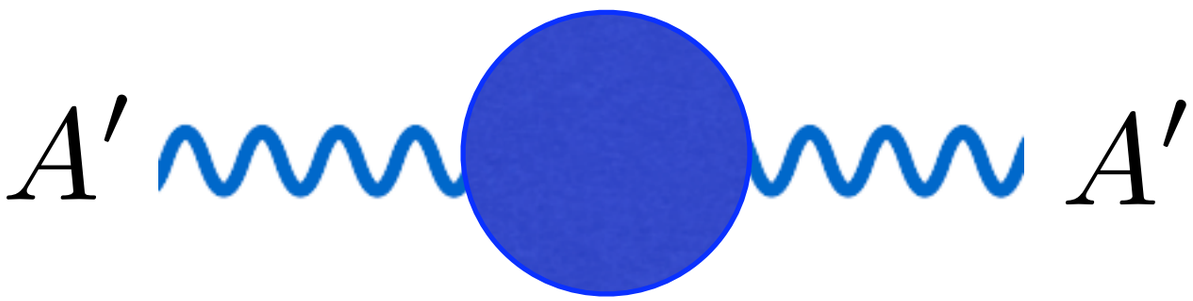


$$\delta L = \epsilon F_Y F_{A'}$$

GUT or Planck scale quantum corrections

[Holdom '86]

$$\epsilon \lesssim \frac{e g_D}{16\pi^2} \sim 10^{-4} - 10^{-3}$$



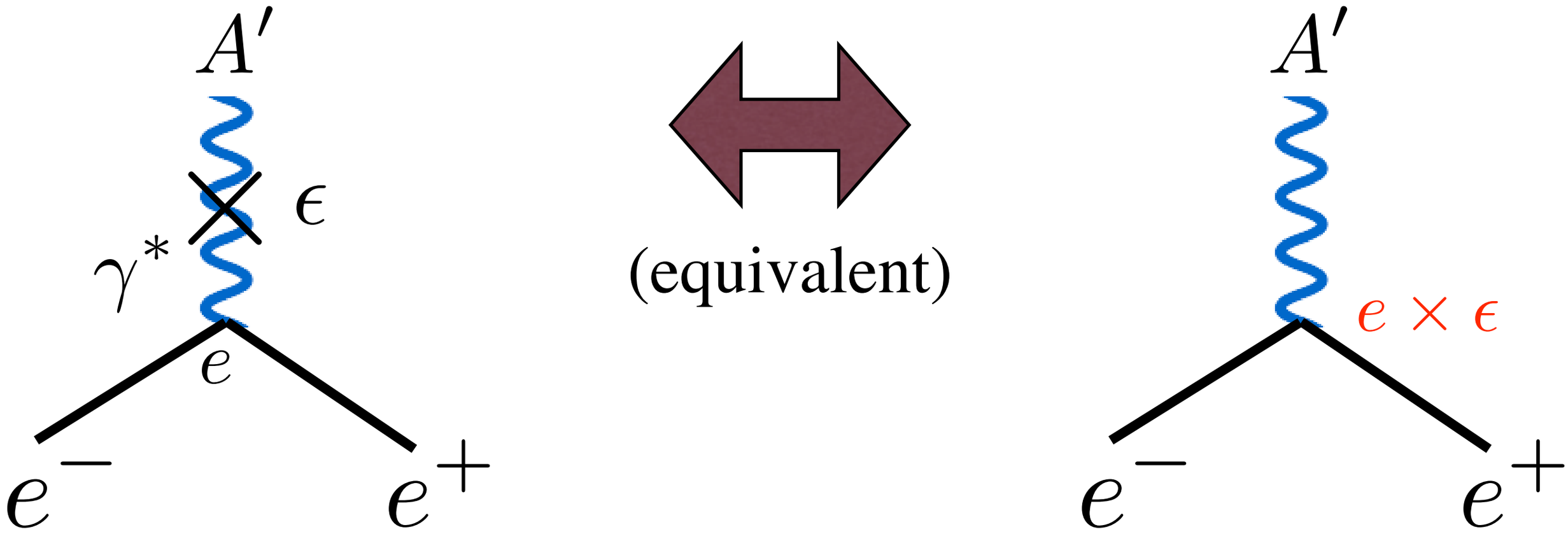
$$m^2_{A'} \sim \epsilon M^2_W$$

(mass inherited from "electro-weak" scale)

[Cheung, Ruderman, Wang, Yavin; Katz and Sundrum; Morrissey, Poland, Zurek]

Ordinary Matter is Milli-Charged

Photon mixing with A' is equivalent to electrically charged matter acquiring a milli-charge under the A'



What about the rest of the matter in the Universe?

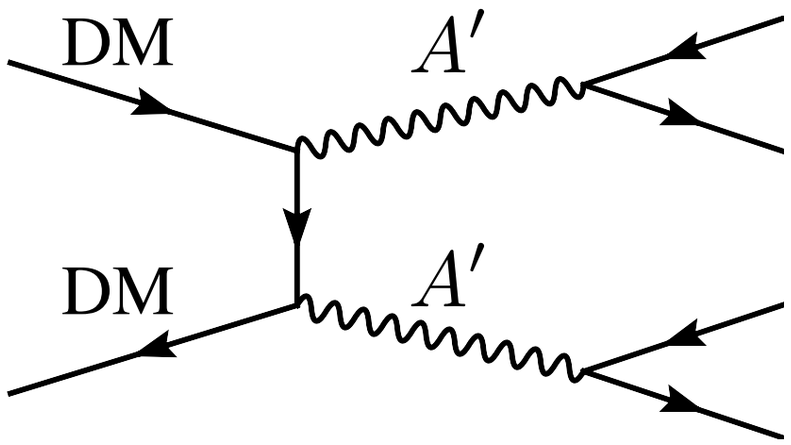
Suppose Dark Matter is Charged Under a GeV-Scale Gauge Force

Several Striking Consequences:

- Annihilation enhanced at low velocities
- Annihilation into light, not heavy states

- Excited states split by O(MeV)
- Scattering off matter:
  - rate similar to neutral current
  - scattering into excited state, enhanced modulation

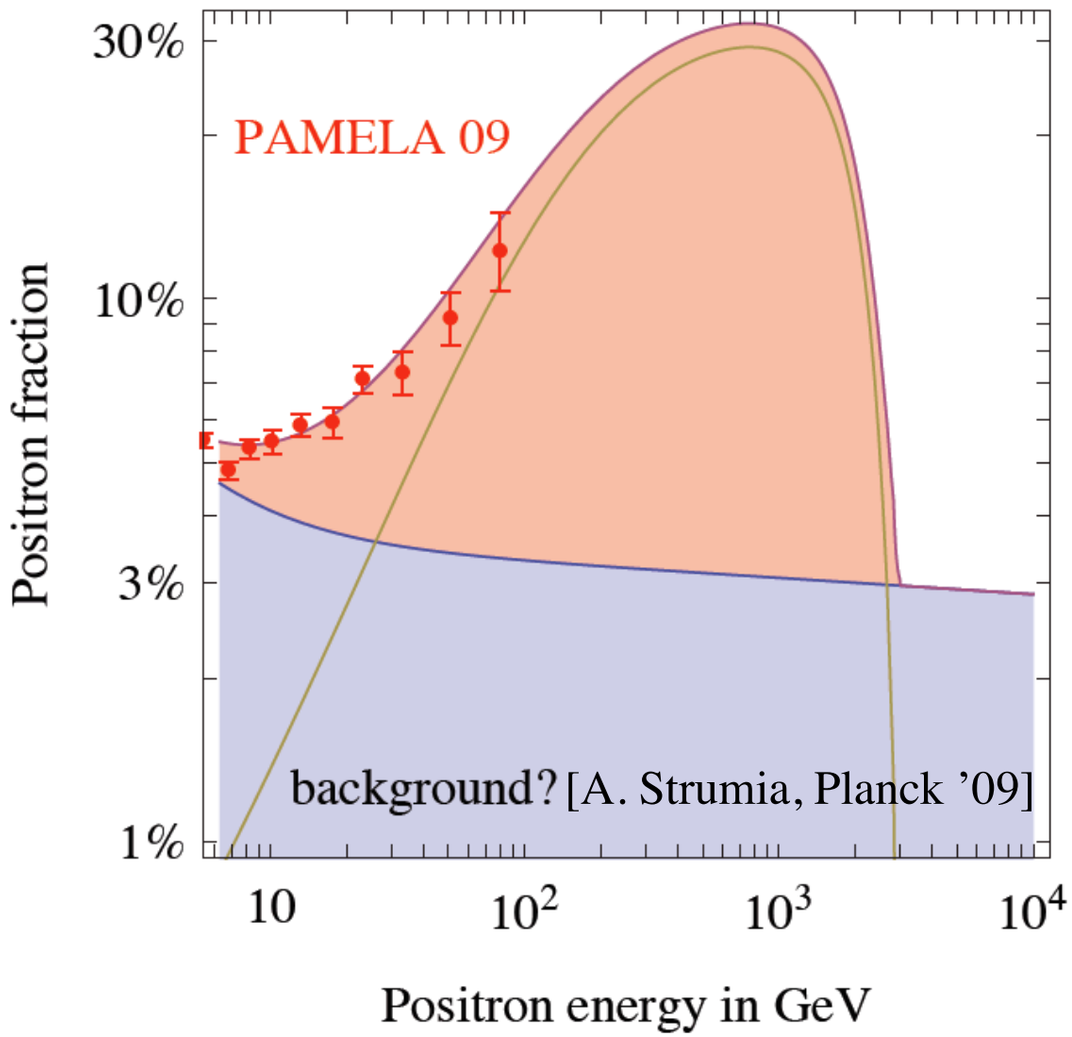
Annihilation into Leptons

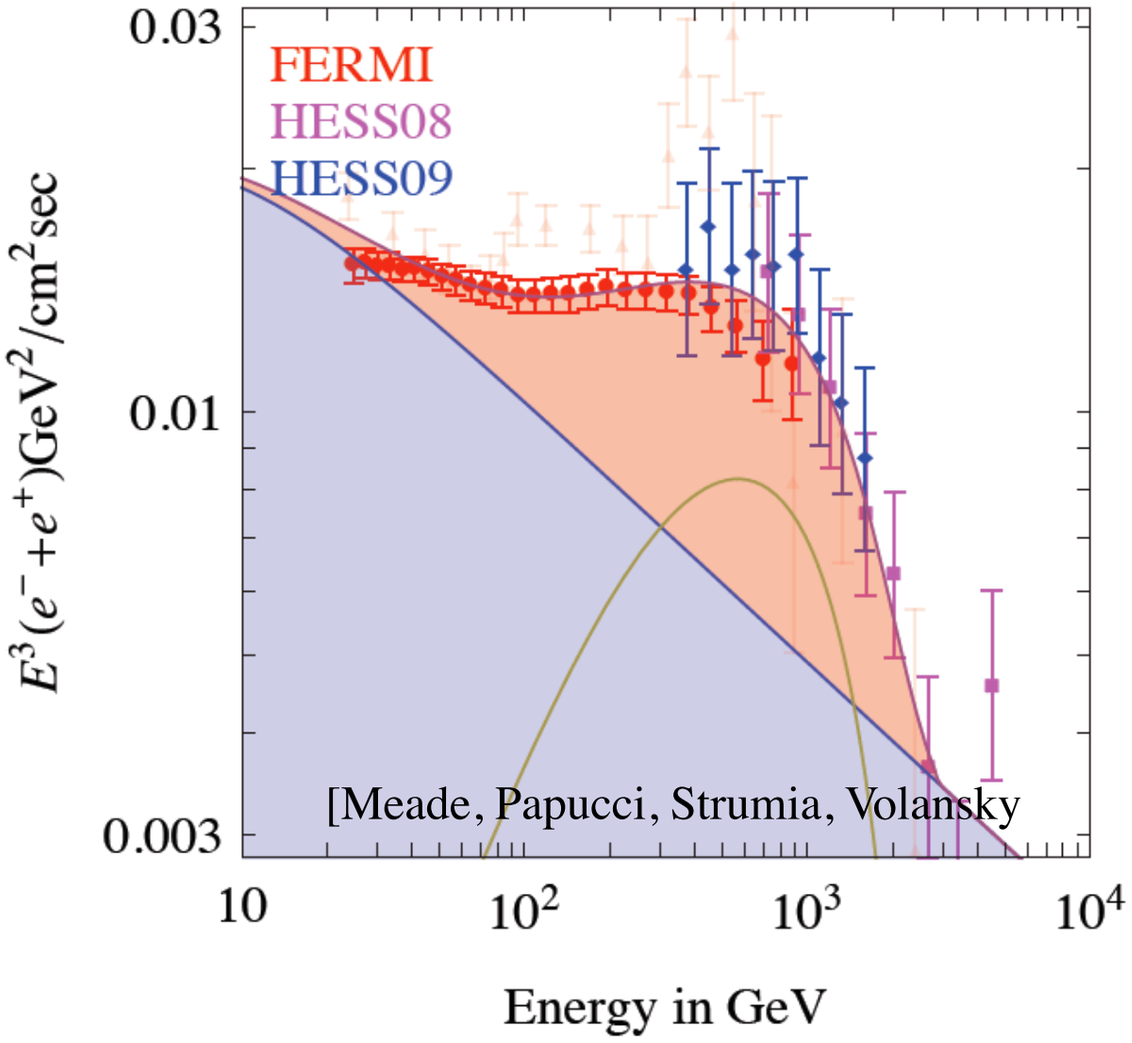


Standard Model Particles

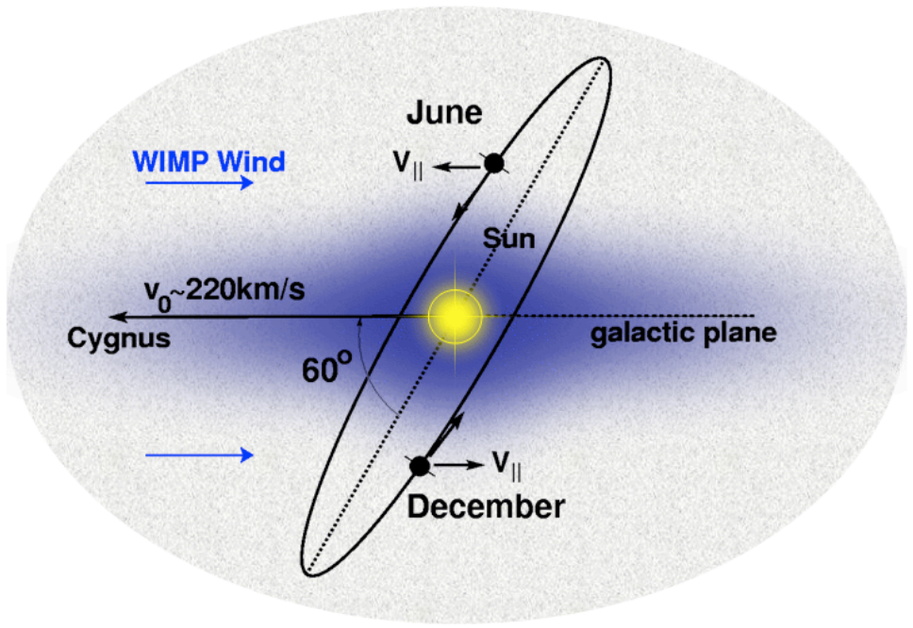
($m<m_{A'}/2$)

[Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Cholis, Finkbeiner, Goodenough, Weiner; Pospelov & Ritz]





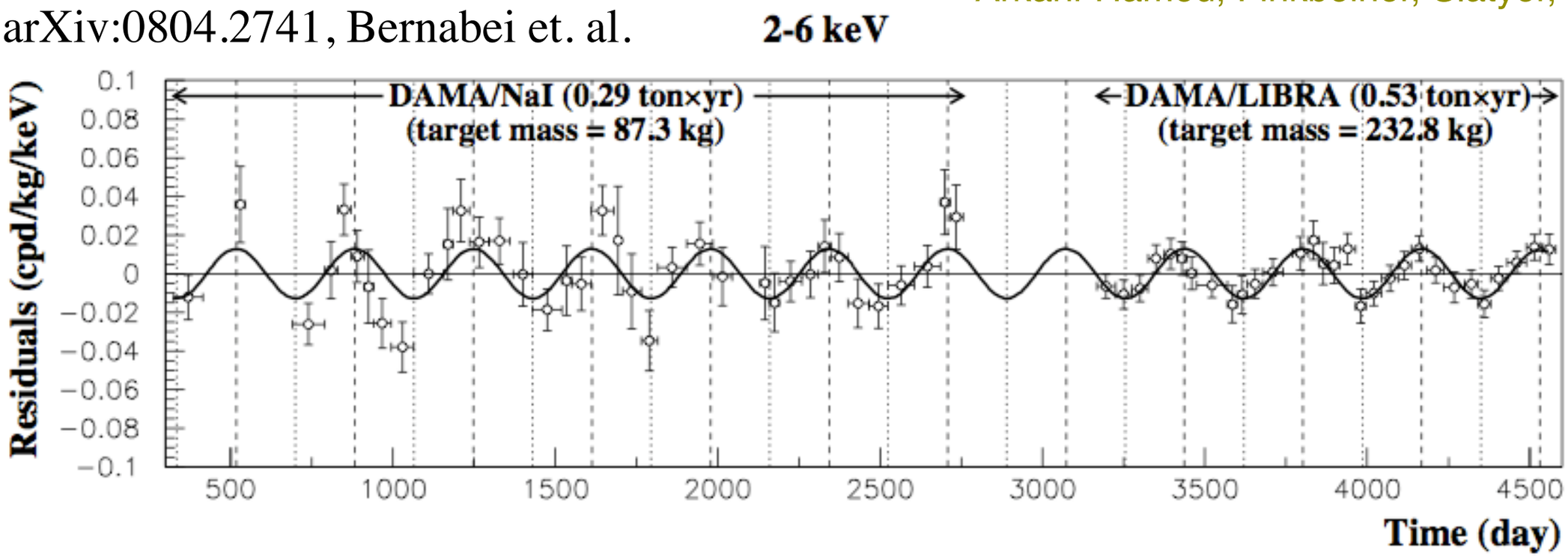
A' Mediation of Inelastic DM-Nuclei Scattering



Dark matter mass splitting:
~100 keV

Large modulation amplitude, characteristics of recoil spectrum, and null results of other experiments explained by inelastic collisions
[Tucker-Smith and Weiner;
Arkani-Hamed, Finkbeiner, Slatyer, Weiner]

arXiv:0804.2741, Bernabei et. al.



The Origin of a 100 keV Dark Sector Splitting

Non-Abelian Higgsed Sector:

Dark matter is a charged multiplet [Arkani-Hamed, Finkbeiner, Slatyer, Weiner]

$$\delta M_{DM} \sim \alpha_D \delta M_{gauge} \sim \alpha_D^2 M_{gauge} \sim 100 \text{ keV}$$

(radiative splittings) (custodial symmetry breaking)

Non-Abelian Confined Sector:

Dark matter is a dark heavy flavor meson [Alves, Behbahani, PS, Wacker]

$$\delta M_{DM} \sim \frac{\Lambda_{Dark}^2}{M_{DM}} \sim 100 \text{ keV} \rightarrow \Lambda_{Dark} \sim \text{GeV}$$

(hyperfine splittings)

New particles at the GeV-scale are required

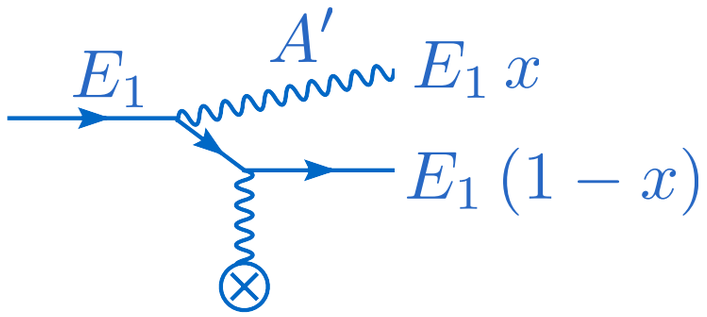
New Gauge Forces

Are there new gauge forces? – an intriguing possibility

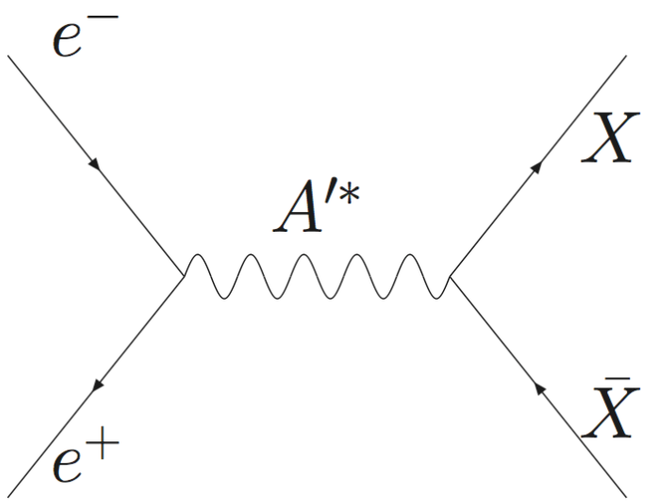
Do new gauge forces explain astro/direct-detection data?

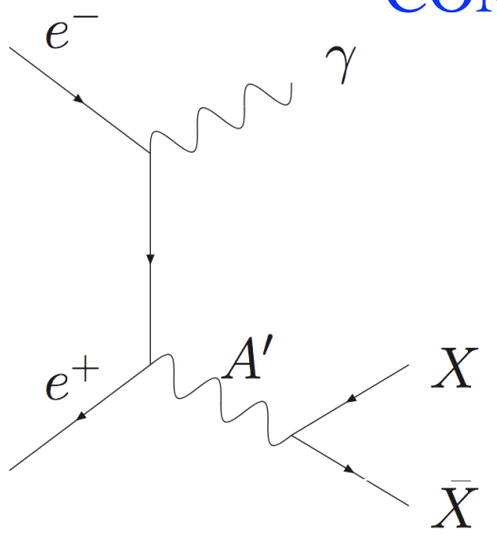
Insight from laboratory experiments needed!

Production Mechanisms

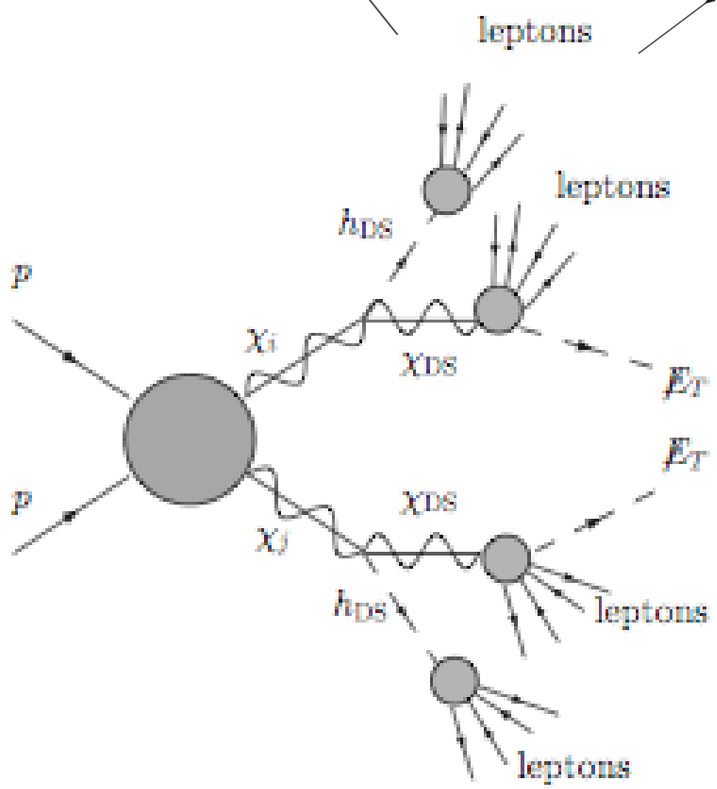


Fixed-Target: Electron or Proton collisions,
A' decays to di-lepton, pions, multiple channels
(Jefferson Lab (Hall A, Hall B/CLAS), SLAC, MAMI (Mainz), ELSA (Bonn), XFEL (DESY), COMPASS (CERN), FNAL, ...)





Colliding e+e-: On- or Off- shell A',
X=dark sector or leptons & pions
(BELLE, BaBar, BES-III, KLOE, CLEO)



High Energy Hadron Colliders:
New heavy particles decaying into dark sector (lepton jets) (CDF & D0)
(see talk by Itay Yavin)

See SLAC Dark Forces Workshop for Reference

Organizers:

R. Essig, M. Graham, M. Peskin, A. Roodman, P. Schuster, N. Toro, J. Wacker

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

All talks are posted at:
http://indico.cern.ch/event/darkforces

Dark Forces at New Experimental Frontiers

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  (and hints from dark matter)

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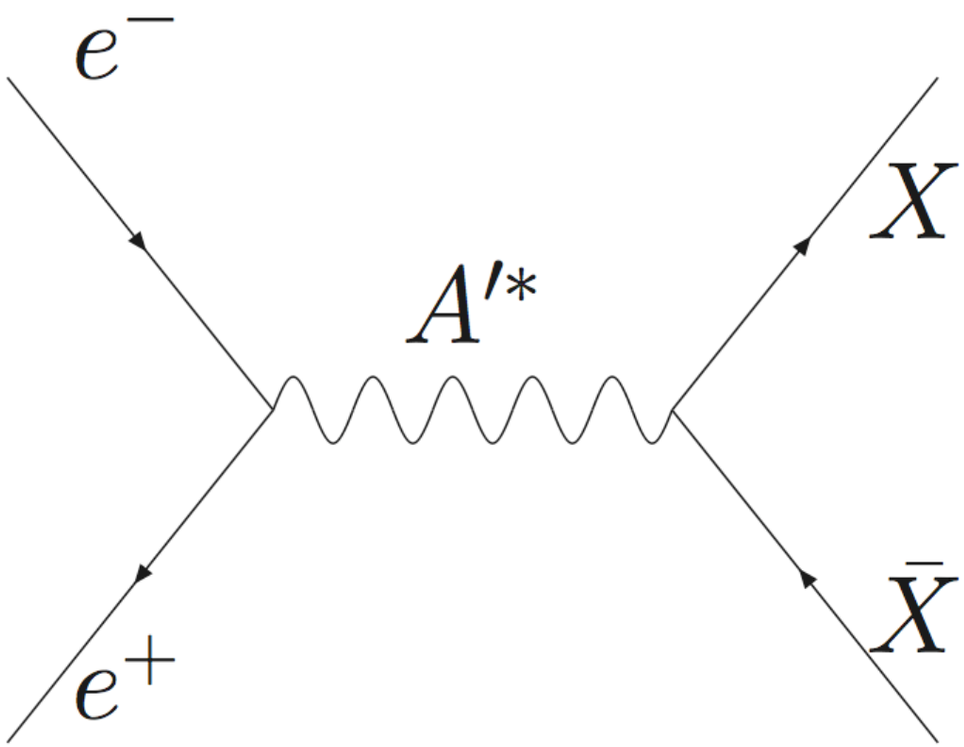
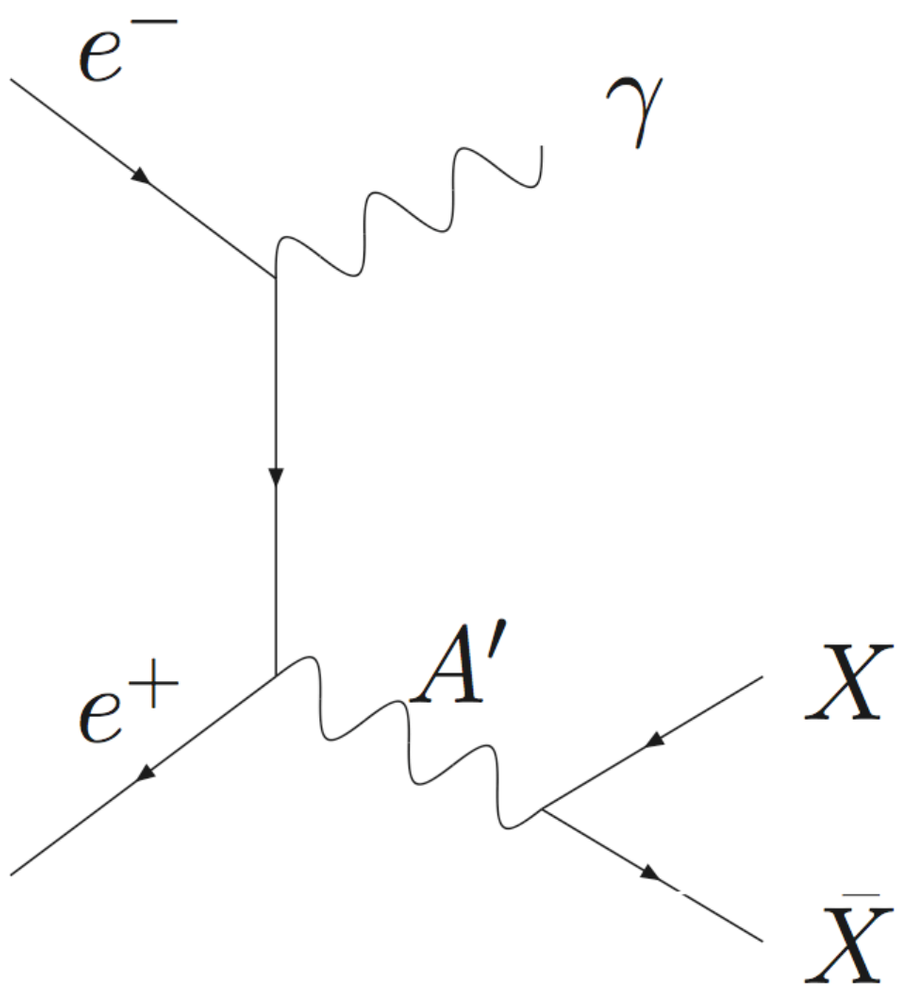
- Fixed-Target Experiments
  (e.g. @ JLab)

Dark Sector Collider Production



Off-Shell A′

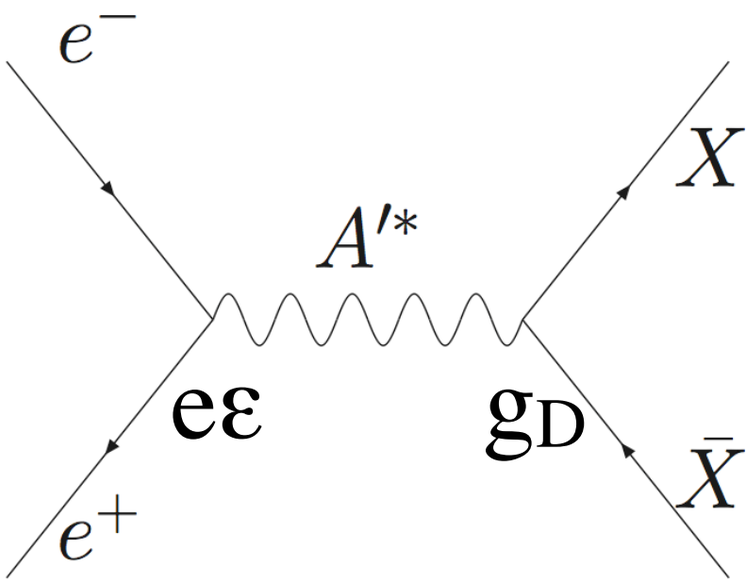


Radiative return

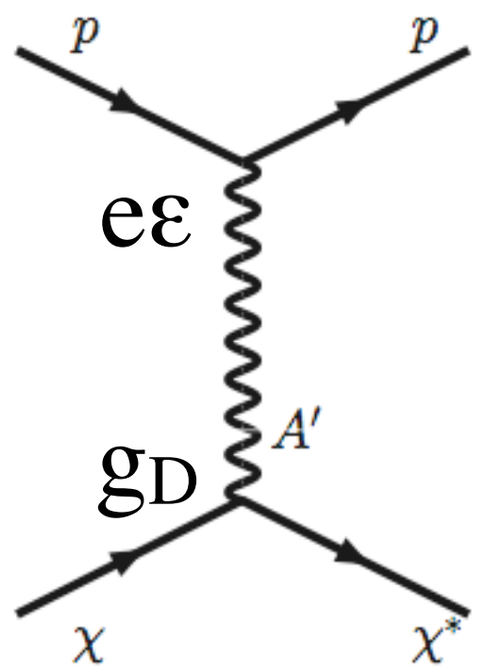
$$\sigma \propto \epsilon^2/s \rightarrow$$

High-luminosity
GeV-scale colliders

Normalizing Production Rates from DAMA/LIBRA



$$\propto$$

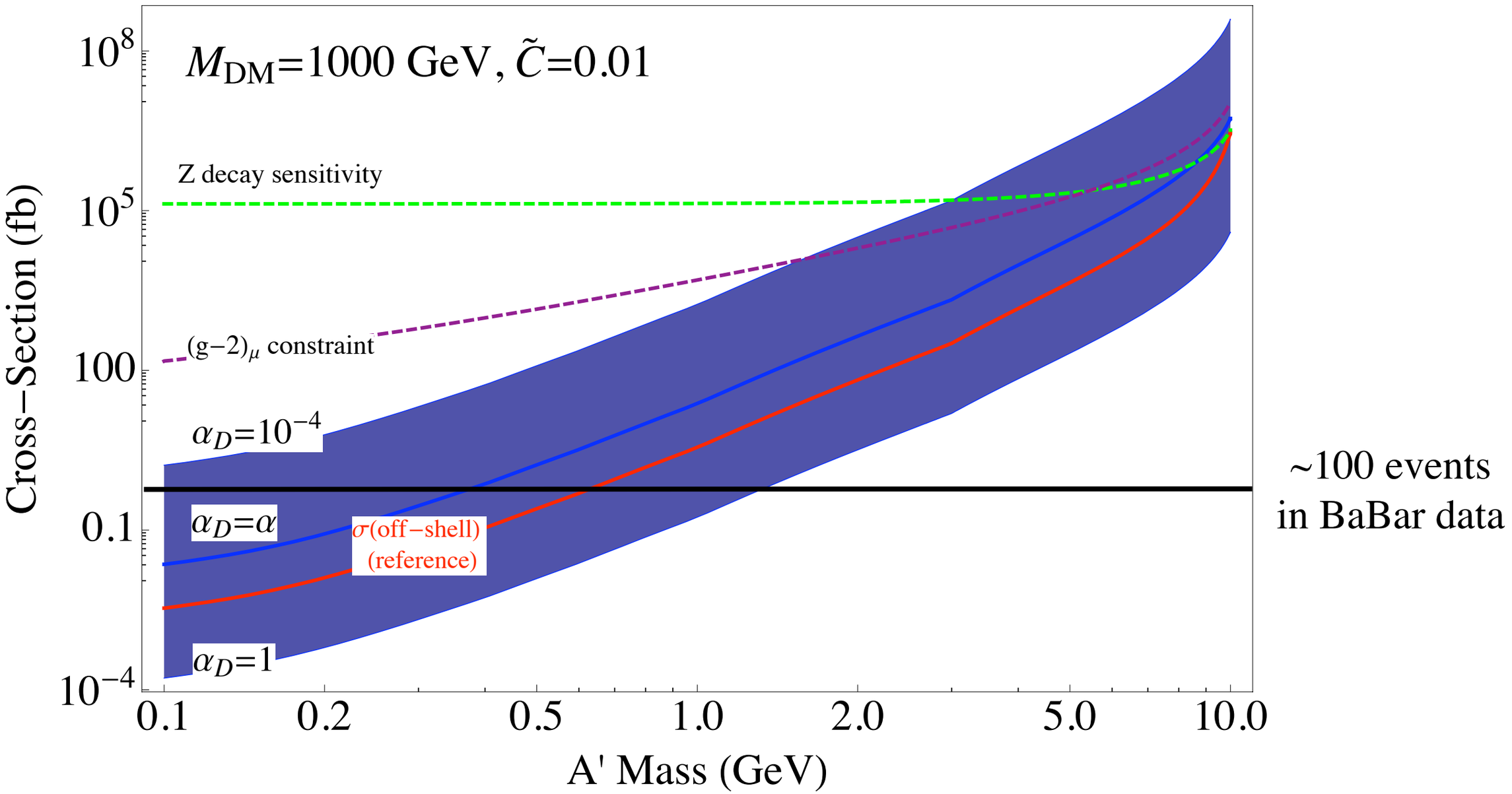


$q^2 = s = (10.58\ \mathrm{GeV})^2$

$q^2 = \mu^2 v^2 \ll m_{A'}^2$

Can estimate production cross-section from DAMA/LIBRA scattering cross-section

DAMA-Normalized Production Rates



[see: Essig, PS, Toro]

GeV-Scale Colliders

Figure of Merit is: $\mathcal{L}_{int}/s$

BELLE	BaBar	KLOE	CLEO-C	BES III
$\frac{725\ \text{fb}^{-1}}{(10.6\ \text{GeV})^2}$	$\frac{430\ \text{fb}^{-1}}{(10.6\ \text{GeV})^2}$	$\frac{2.5\ \text{fb}^{-1}}{(1\ \text{GeV})^2}$	$\frac{\approx 1\ \text{fb}^{-1}}{(4\ \text{GeV})^2}$	$\frac{??\ \text{fb}^{-1}}{(4\ \text{GeV})^2}$

No. of events for $\alpha_D = \alpha$, $\epsilon = 10^{-2}$ (approx):

170,000	100,000	50,000	1,000

Missing from numerical comparison:

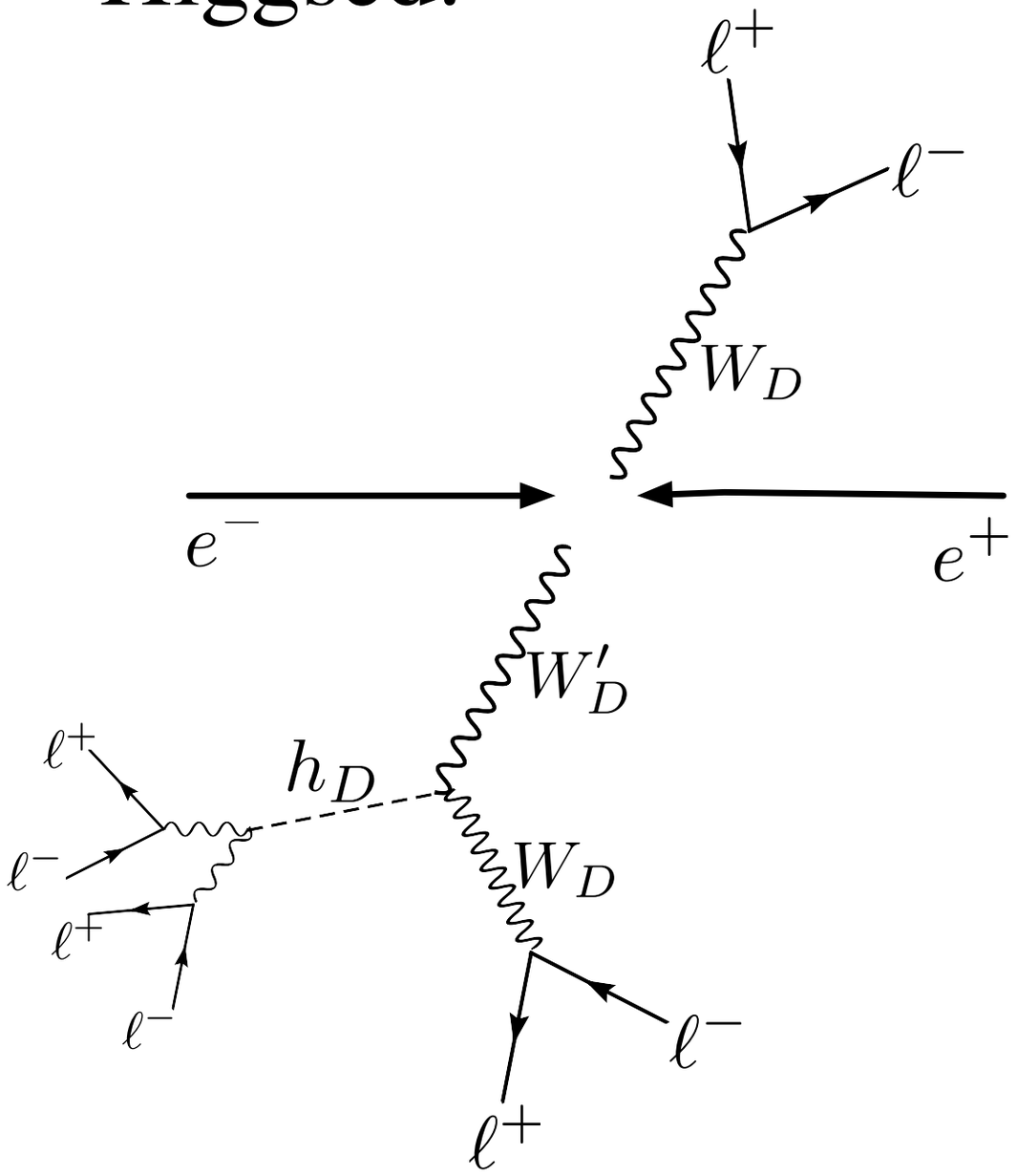
– accessible mass range

– kinematic acceptance & **visibility** of events

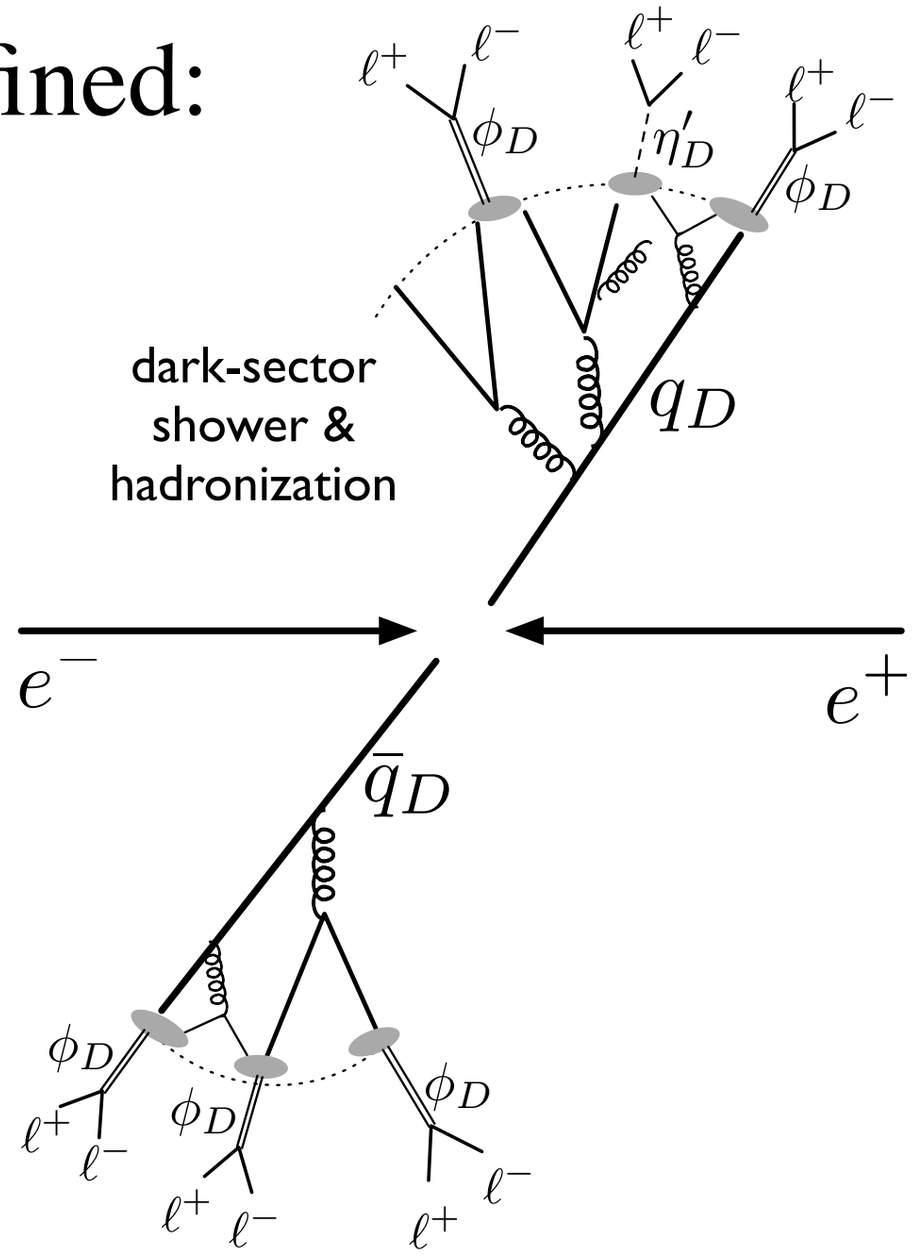
Broad range of searches needed

Higgsed/Confined Dark Sector Signatures

Higgsed:



Confined:

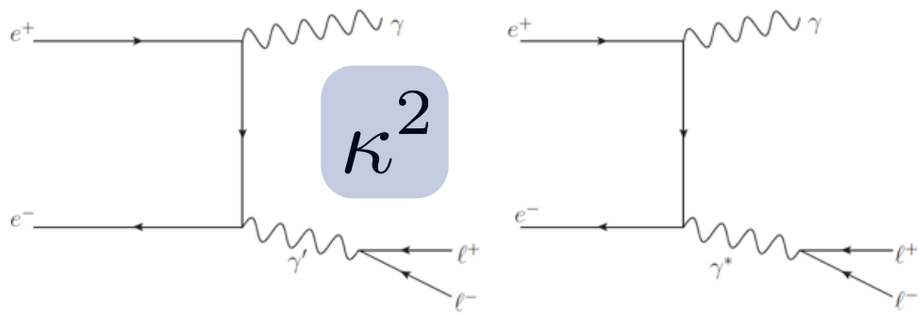


[see: Essig, PS, Toro; Batell, Pospelov, Ritz]

Wide variety of multi-lepton final states

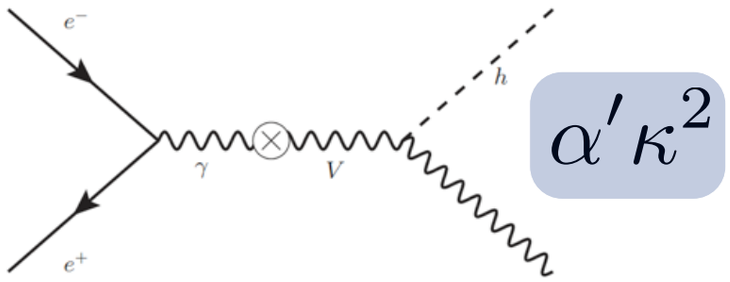
Final States (direct production)

- "Generic": $e^+e^- \to \gamma l^+ l^-$



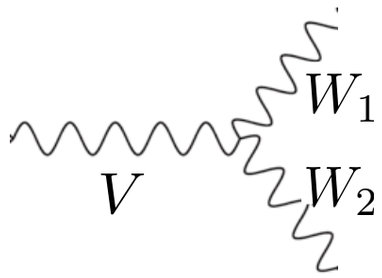
- BaBar [via Υ-decay search, H. Kim] ✓?
- Belle [Y. Kwon, J. Rorie]
- BES-III [H. Li, Y. Zheng]
- KLOE [F. Bossi]

- "Generic + higgs": $e^+e^- \longrightarrow Vh' \longrightarrow 6l \ \ (or\ 2l + \not{E})$



- not yet!
  [interest from BaBar, Belle, BES-III, KLOE]

- "Nonabelian": $e^+e^- \to V^* \to 4l$



- BaBar [4l, M. Graham] ✓

Also: higher multiplicity (confining), 4l + $\not{E}_T$, ...

From e+e- working group summary (DF workshop)

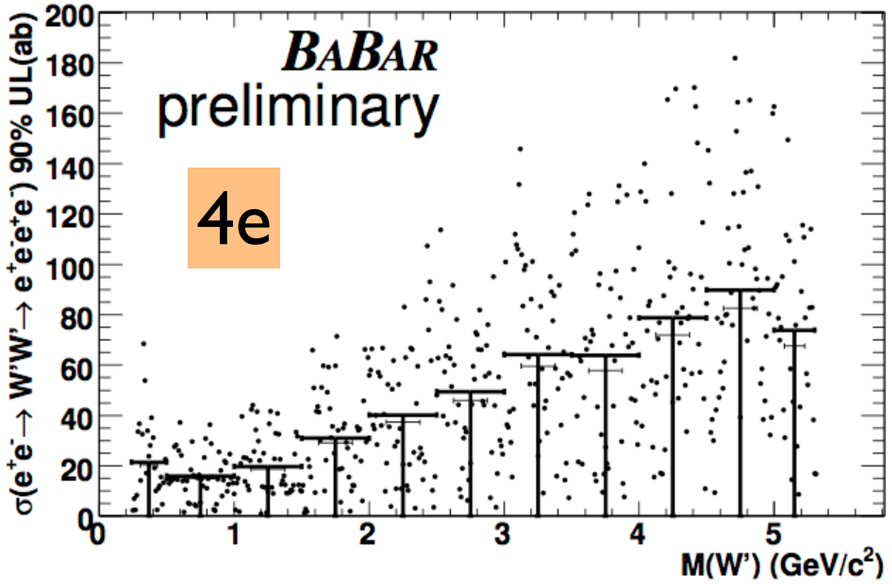
Search for narrow resonance pairs in $e^+e^- \to 4$ lepton @ BaBar

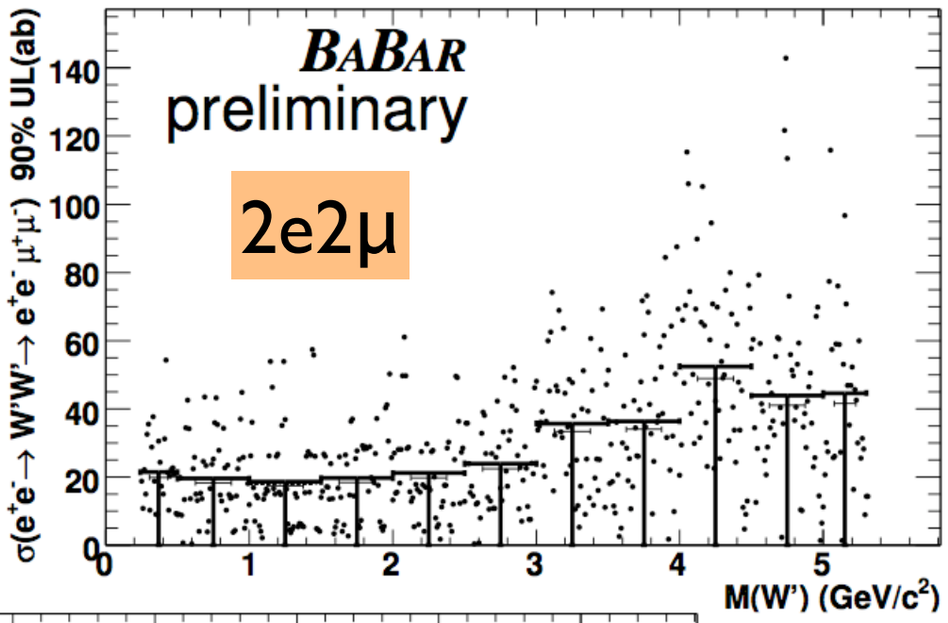
Matt Graham, SLAC
September 25, 2009

Sensitivity to $\epsilon \sim 10^{-4}$

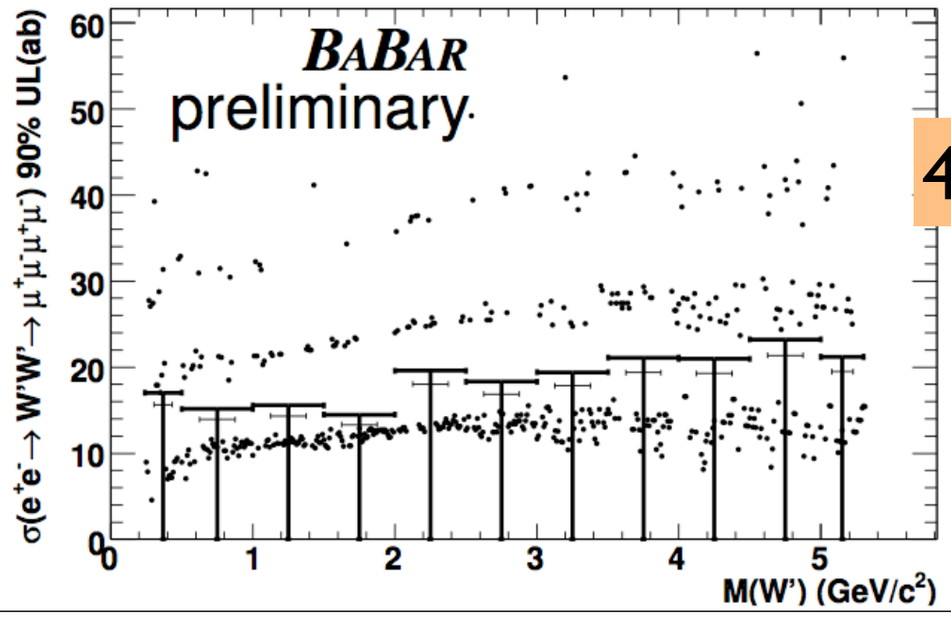
[M. Graham, arXiv:0908.2821]

Cross Section Upper Limits





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



Rare Meson Decays

Existing data sets provide sensitivity to $\epsilon \sim 10^{-3}$

$X \to YU$	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}	7×10^{-8a}	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 '09]

Good sensitivity in additional channels:

$\pi \to ee\gamma$ Sensitivity to $\epsilon \lesssim 10^{-3}$ (Babar, Belle, kTeV)

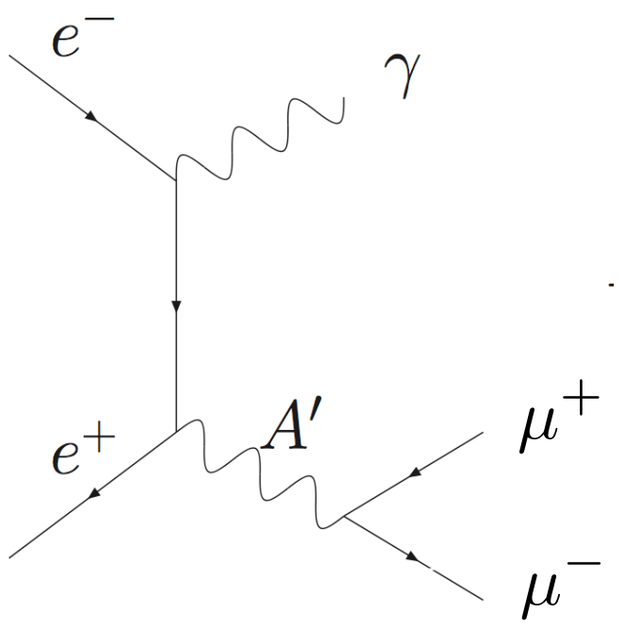
$J/\psi \to 6l$ Sensitivity to $\epsilon \sim 10^{-4} - 10^{-3}$ (BES-III in 1 year)

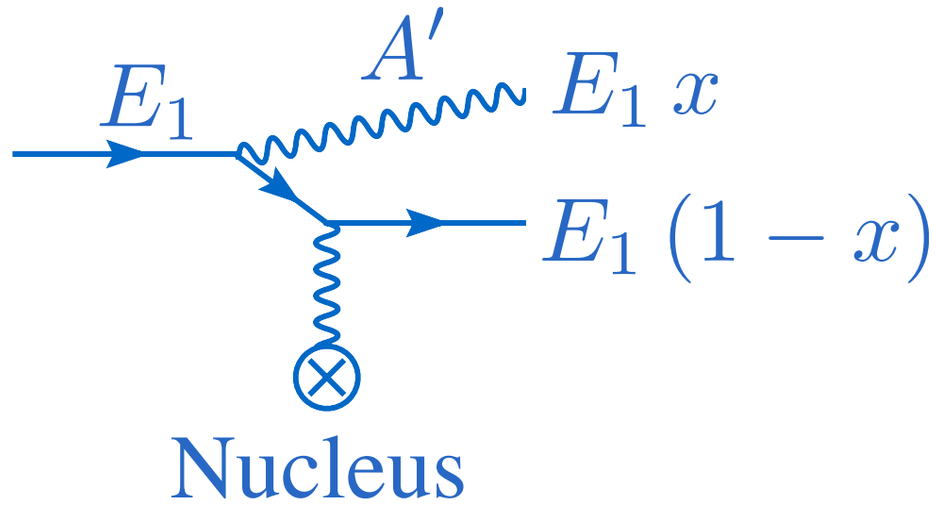
Searches ongoing...

Dark Forces at New Experimental Frontiers

- Theory of New Vector Bosons
  (and hints from dark matter)
- e+e- Collider Searches
  (Babar and Belle)
- Fixed-Target Experiments
  (e.g. @ JLab)

Collider vs. Fixed-Target





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

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

O(few) ab^{-1} per decade

O(few) ab^{-1} per day

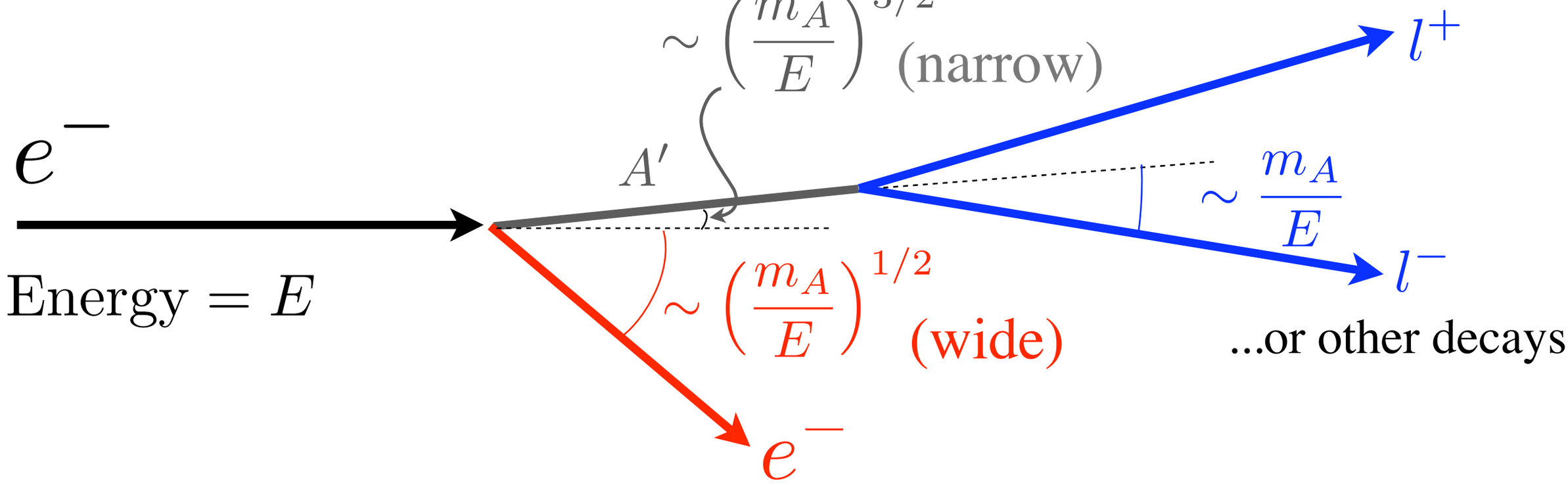
Unique Fixed-Target Kinematics

[see: Bjorken, Essig, PS, Toro]

$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2(1-x)/x}$$

$$x = \frac{E_A}{E}$$

Kinematics **very different** from massless photon bremsstrahlung



Heavier product (here A') takes most of beam energy

$$E_A \sim E - m_A$$
$$E_e \sim m_A$$

Lifetime

A' decays directly back to Standard Model:

$$\gamma c\tau \approx 1 \text{ mm } (\gamma/10)\ (10^{-4}/\epsilon)^2\ (100\text{MeV}/m_{A'})$$

A' decay to dark scalars: $h_D \to l^+ l^- \qquad l = e, \mu, \pi$

$$\gamma c\tau \approx 2 \times 10^8 \text{ cm } (\gamma/10)\ (\alpha/\alpha_D) \times (10^{-3}/\epsilon)^4\ (m_{A'}/\text{GeV})^2\ (\text{GeV}/m_{h_D})$$

...etc

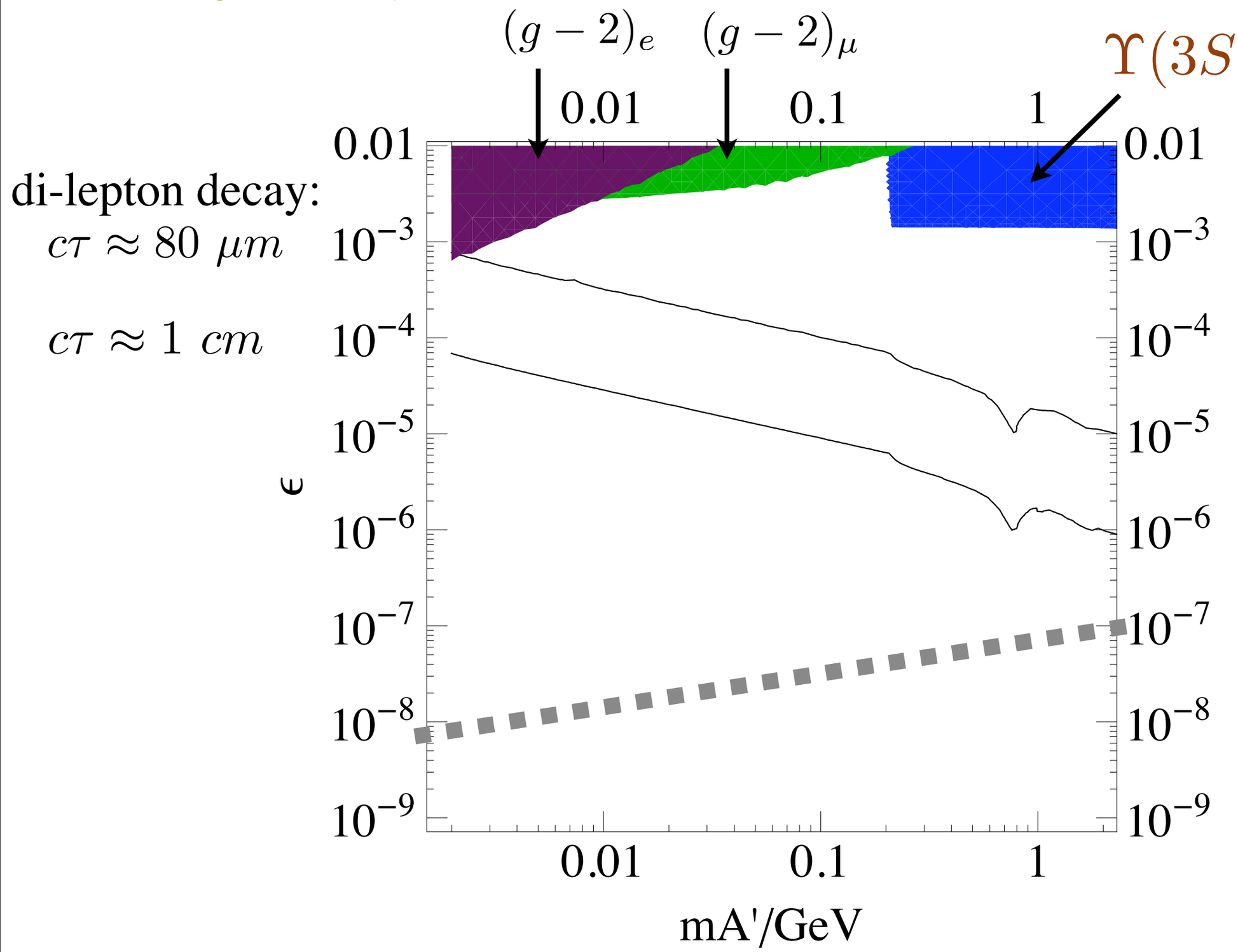
A' production vs. decay product lifetime determine existing constraints and search strategies

Fixed-Target Territory

[see: Bjorken, Essig, PS, Toro;
Reece, Wang; Batell Pospelov, Ritz]

BABAR

$\Upsilon(3S) \to (\mu^+\mu^-)\gamma$



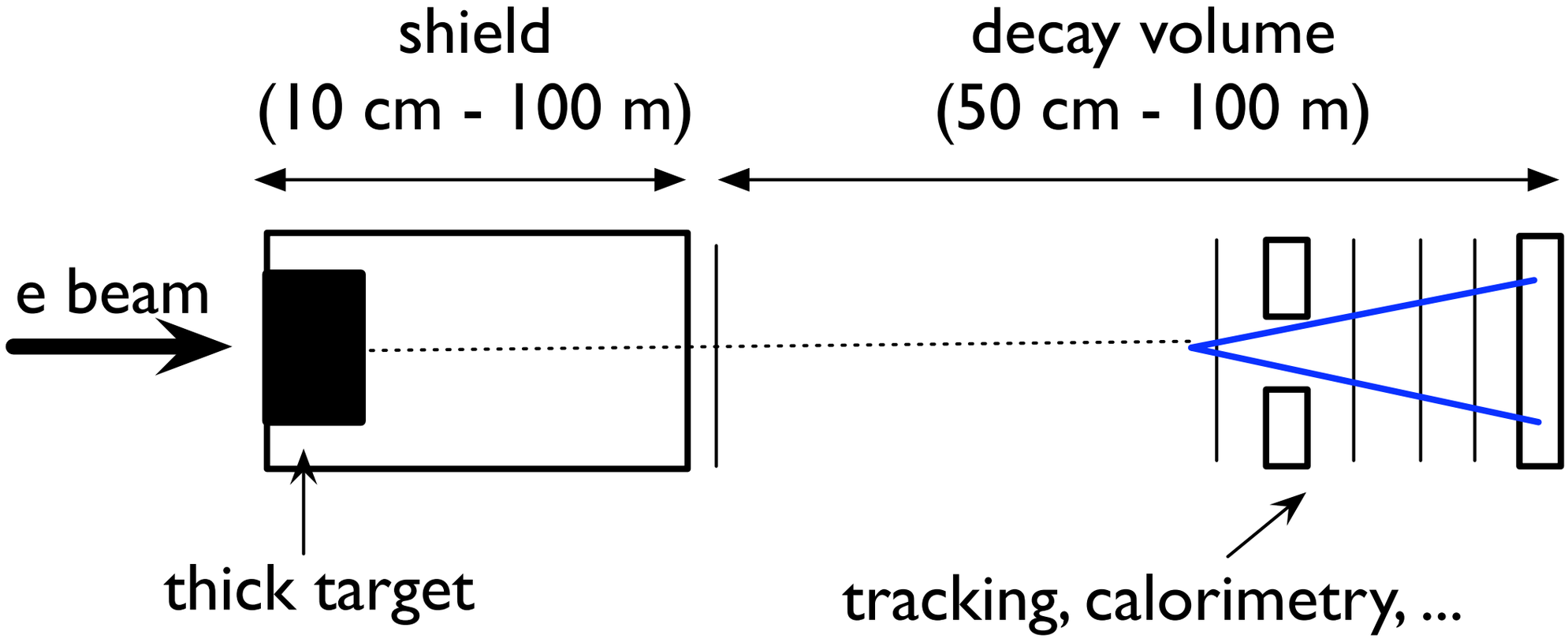
di-lepton decay:

$c\tau \approx 80\ \mu m$

$c\tau \approx 1\ cm$

MegaWatt x Year
lower limit for
seeing >10 events

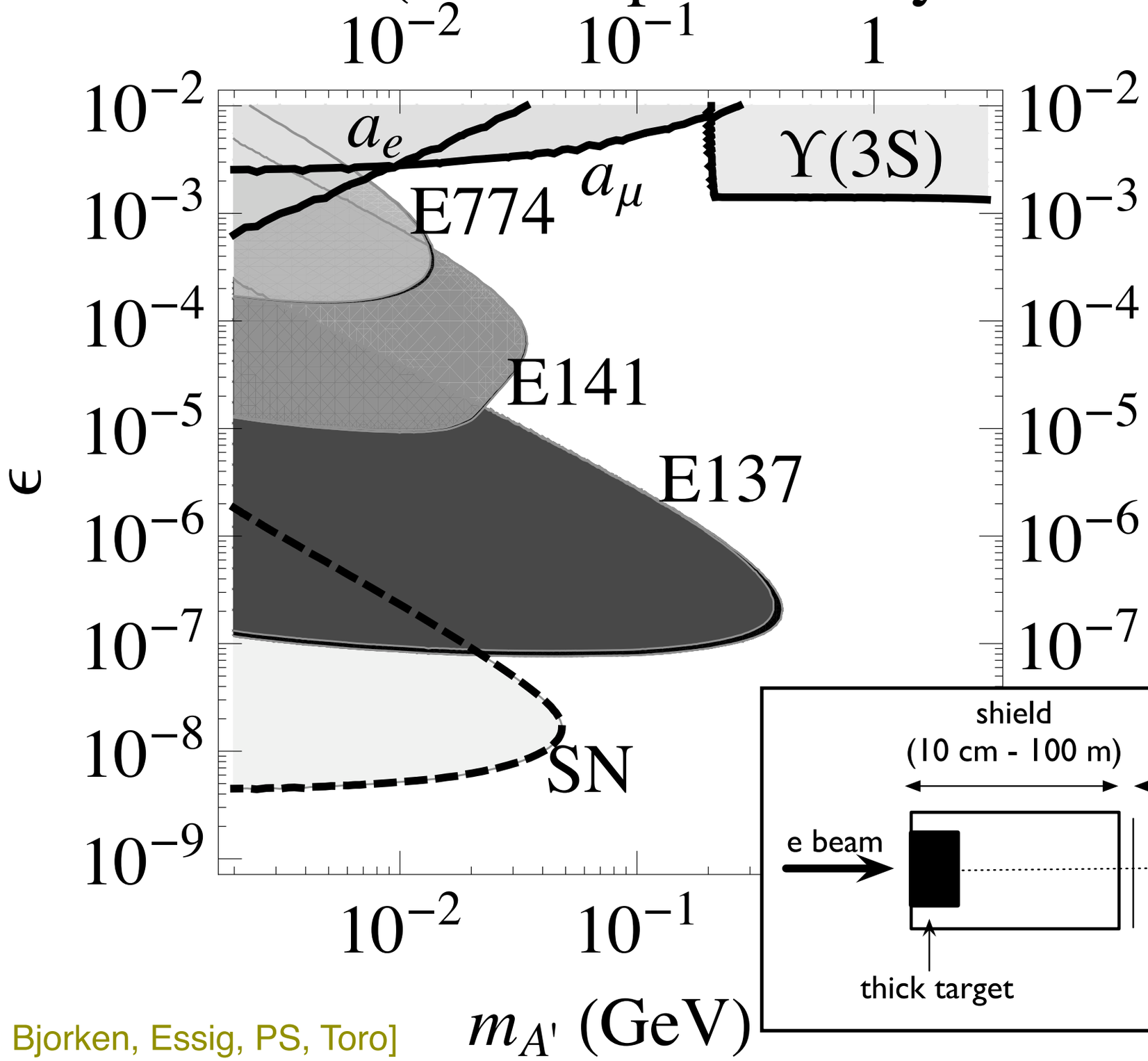
Beam Dump Experiments



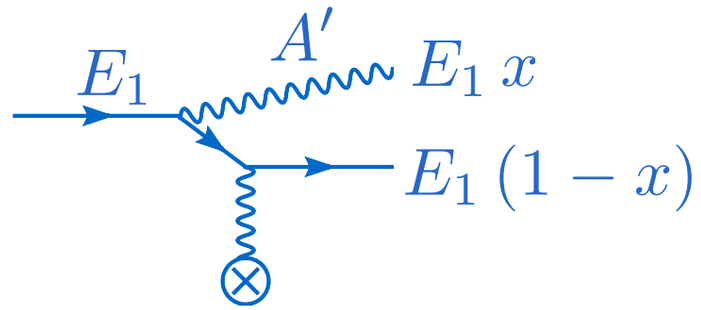
SLAC E137:	10^{20} e^- (30 C)	at 20 GeV,	200m shield
SLAC E141:	10^{16} e^-	at 9 GeV,	12 cm W target
FNAL E774:	10^{10} e^-	at 275 GeV,	20 cm W target

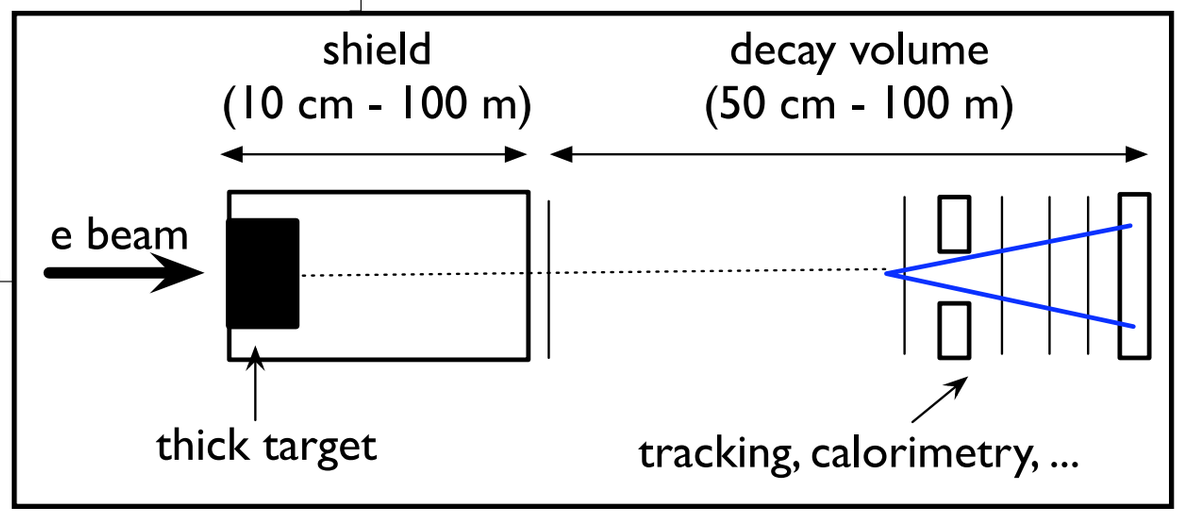
Past Beam Dump Limits

(A' di-lepton decay modes)



Production Mode:





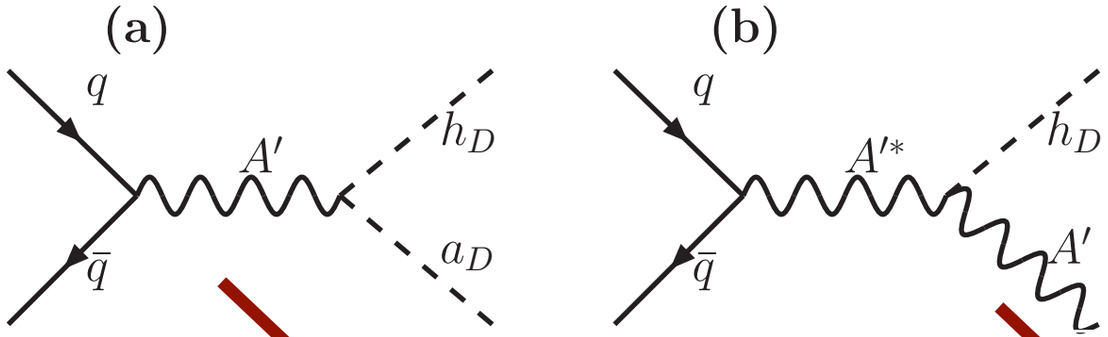
[see: Bjorken, Essig, PS, Toro]

Past Beam Dump Limits

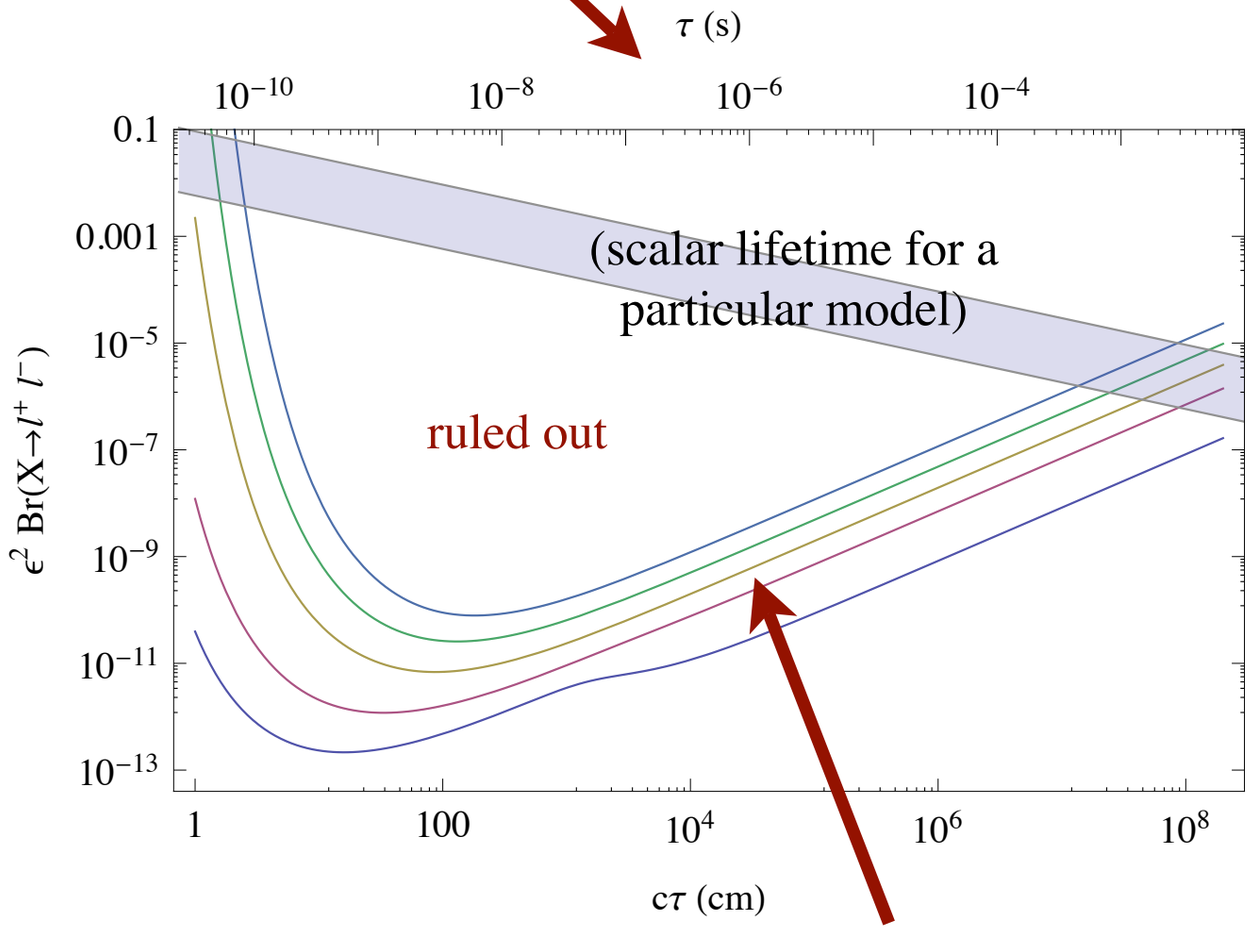
(scalar decay modes)

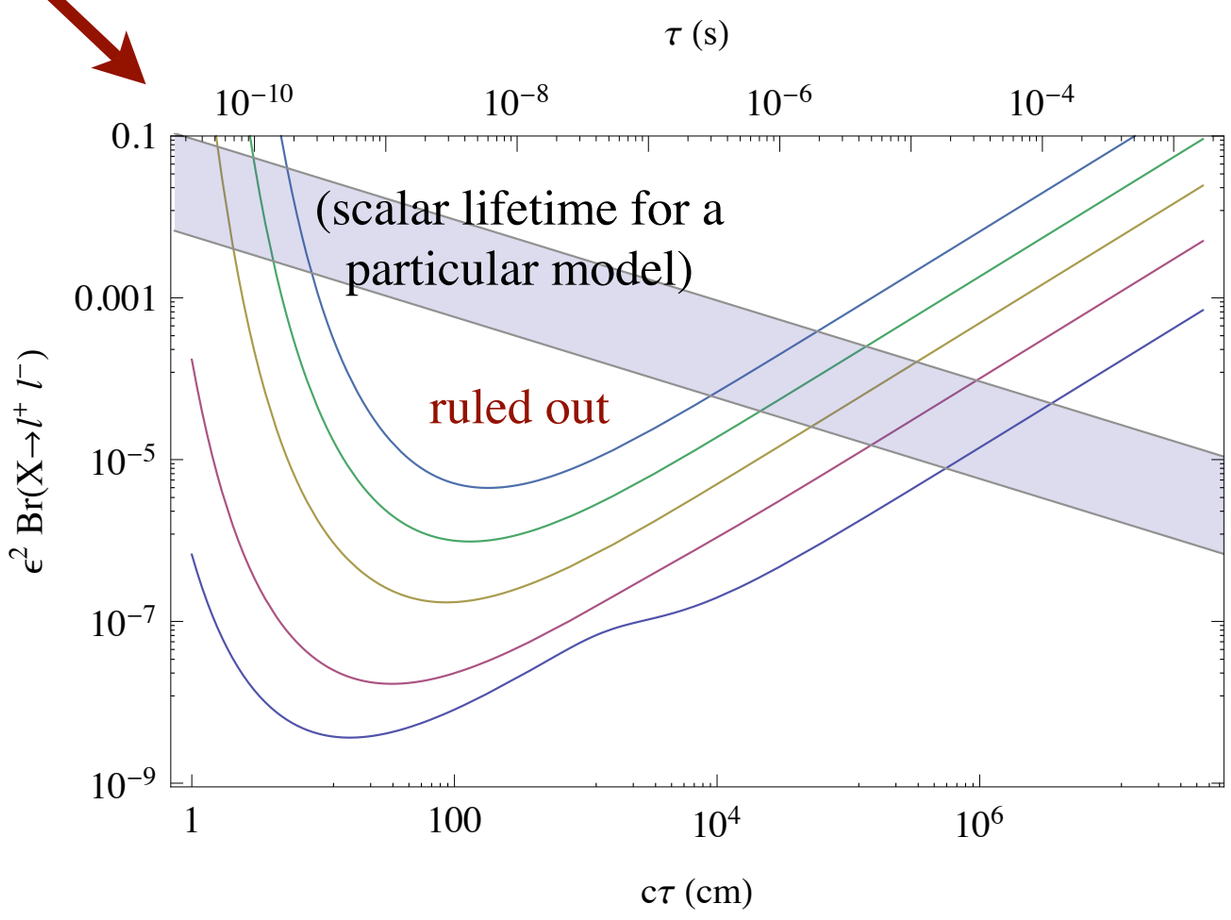
[see: PS, Yavin, Toro]

Production Mode:



CHARM axion search:
proton beam dump,
~1 C at 400 GeV



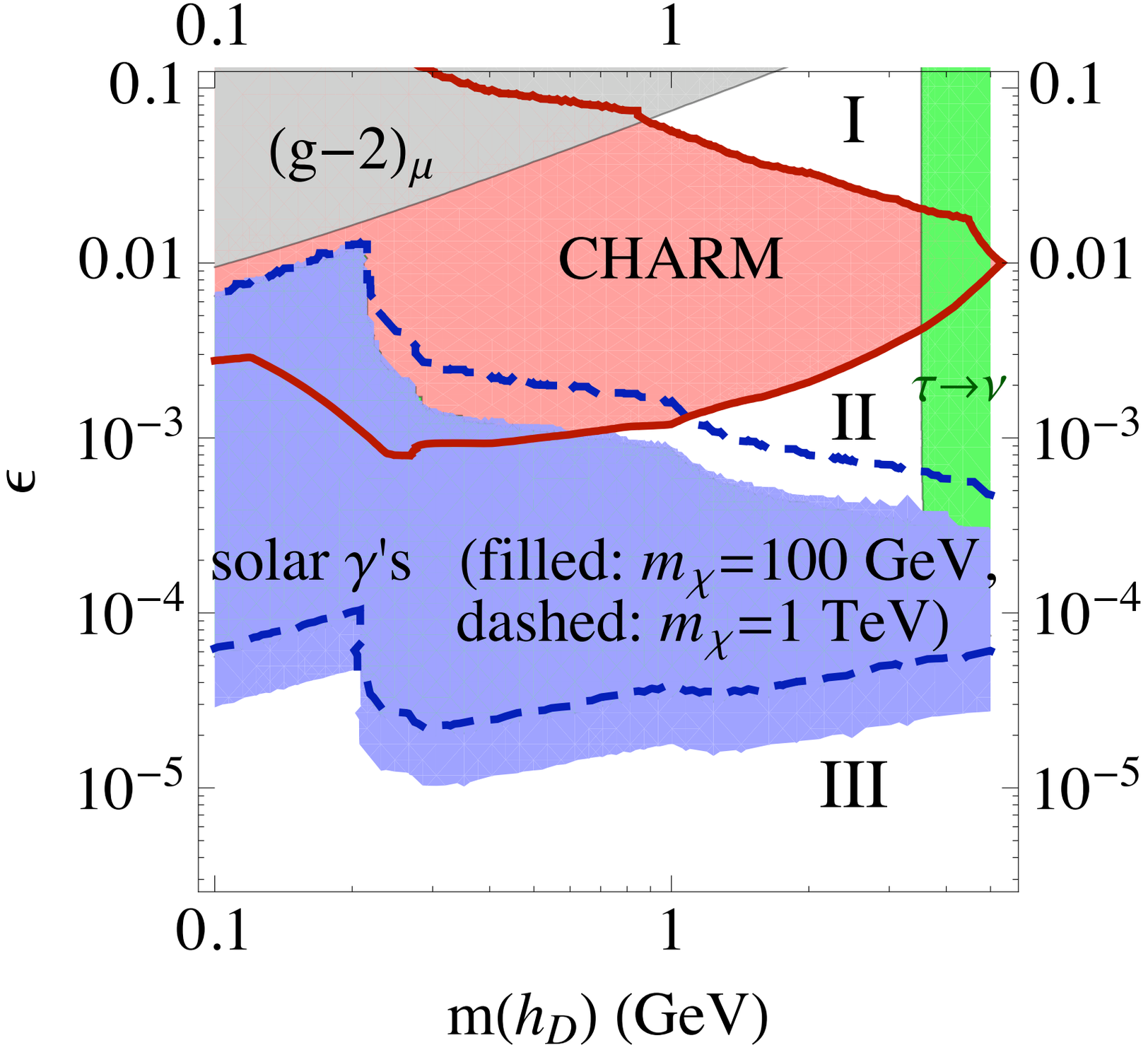


curves from bottom to top: $m_{A'} = 0.6, 1, 2, 3, 4$ GeV

Past Beam Dump Limits

(scalar decay modes)

[see: PS, Yavin, Toro]



Strong laboratory constraints in the DAMA/LIBRA region of interest

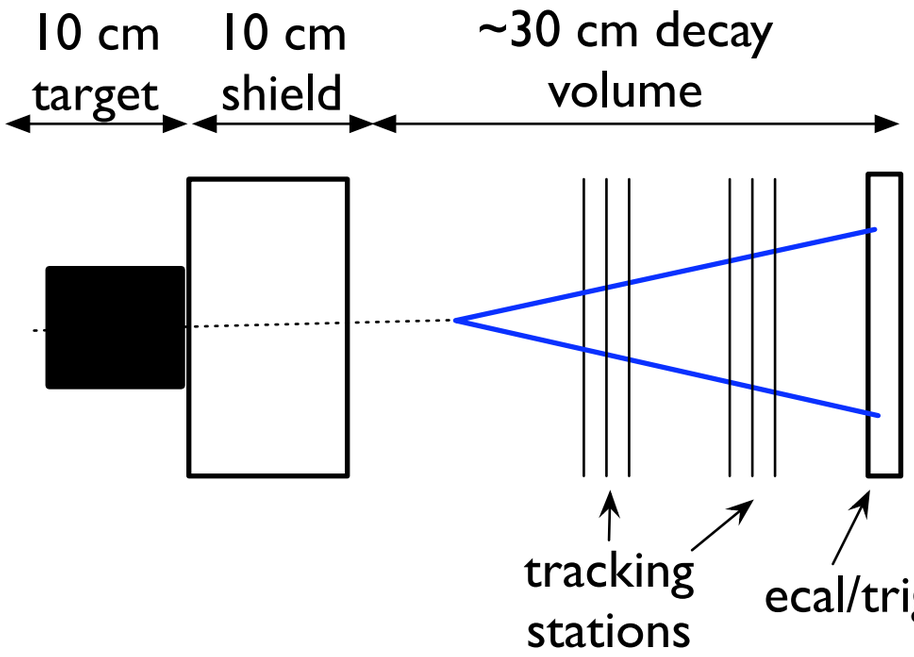
If dark matter can annihilate into dark sector states, then there are constraints from solar capture of dark matter

New Experiments?

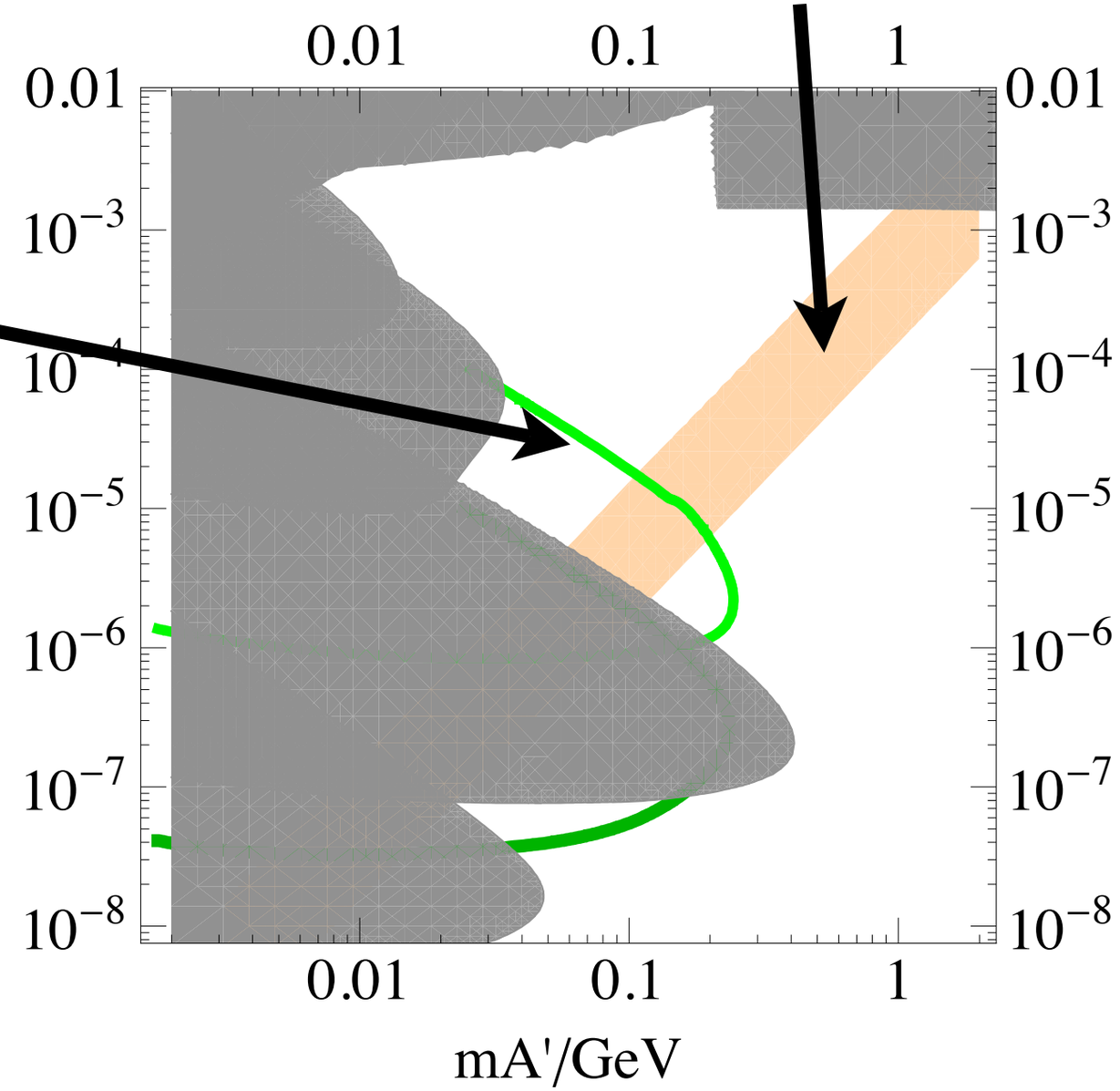
Focus on di-lepton (electron, muon, pion) parameter space given existing constraints on non-direct dark sector decay modes

New Beam Dump Reach

Di-lepton
decay channel



"D-term" line – also explains
DAMA/LIBRA



Good Beams:

FEL at JLab
SLAC
ELSA, Mainzer Mikrotron (MAMI), Max-lab

[see: Bjorken, Essig, PS, Toro]

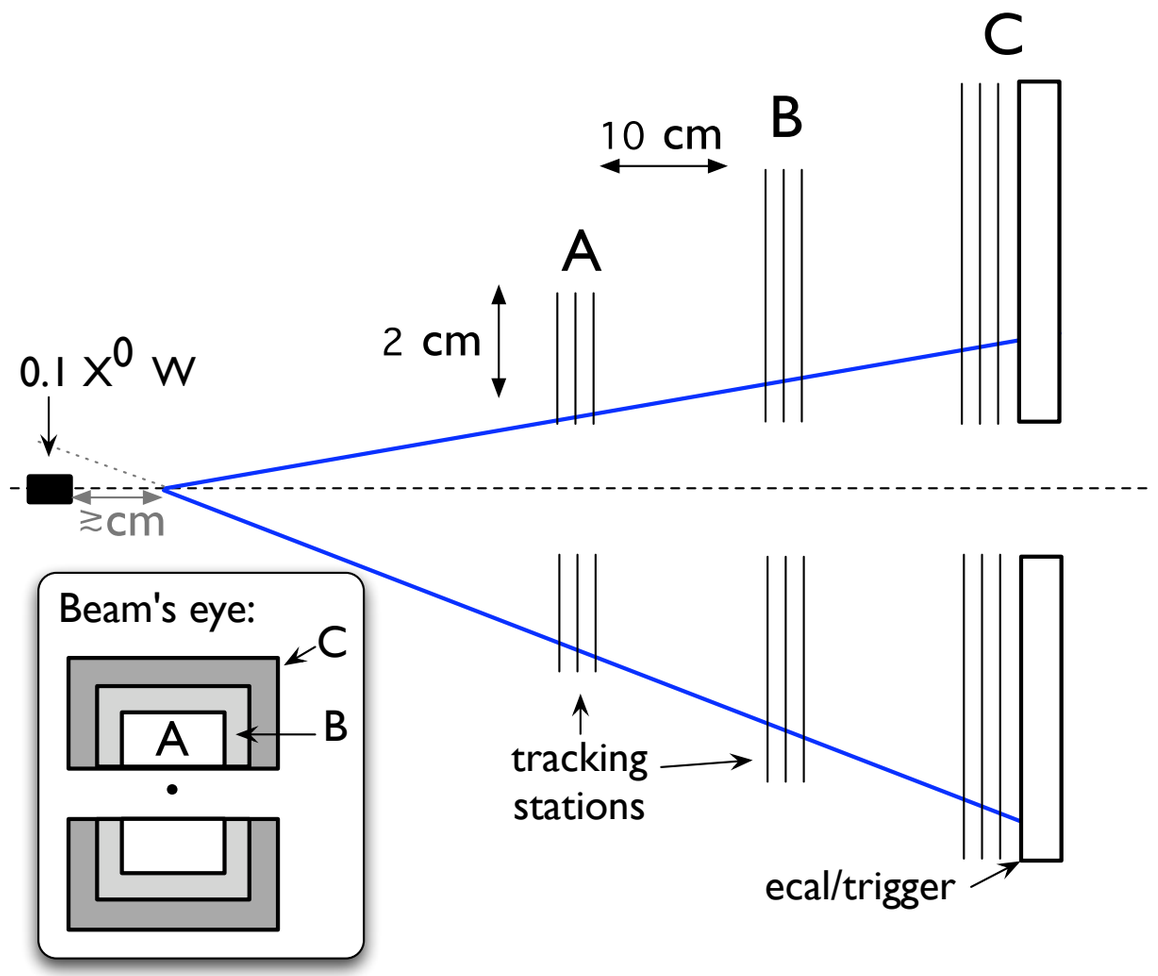
Beyond Beam Dumps

- Electron beam dump experiments set strongest bounds.
- To see higher ϵ, m_A (best DM region) need thinner target – now beam gets through, too!
  (work hard to keep S/B large, not just stat. significance!)
- Two strategies:
  - Resonance Search
  - Vertex and recoil tagging

Approaches for New Experiments

Features of conceptual design: Two-arm spectrometer

- Very good forward coverage
  (signal production is peaked forward)
- Fast trigger (high event rate)
- Fast detector and continuous beam
  (control coincidence backgrounds)
- 1% or better mass resolution
  (kinematic discrimination)
- Silicon good for fast precision tracking (use vertex discrimination)



Small with variable geometry

Heavy Photon Search Working Group

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

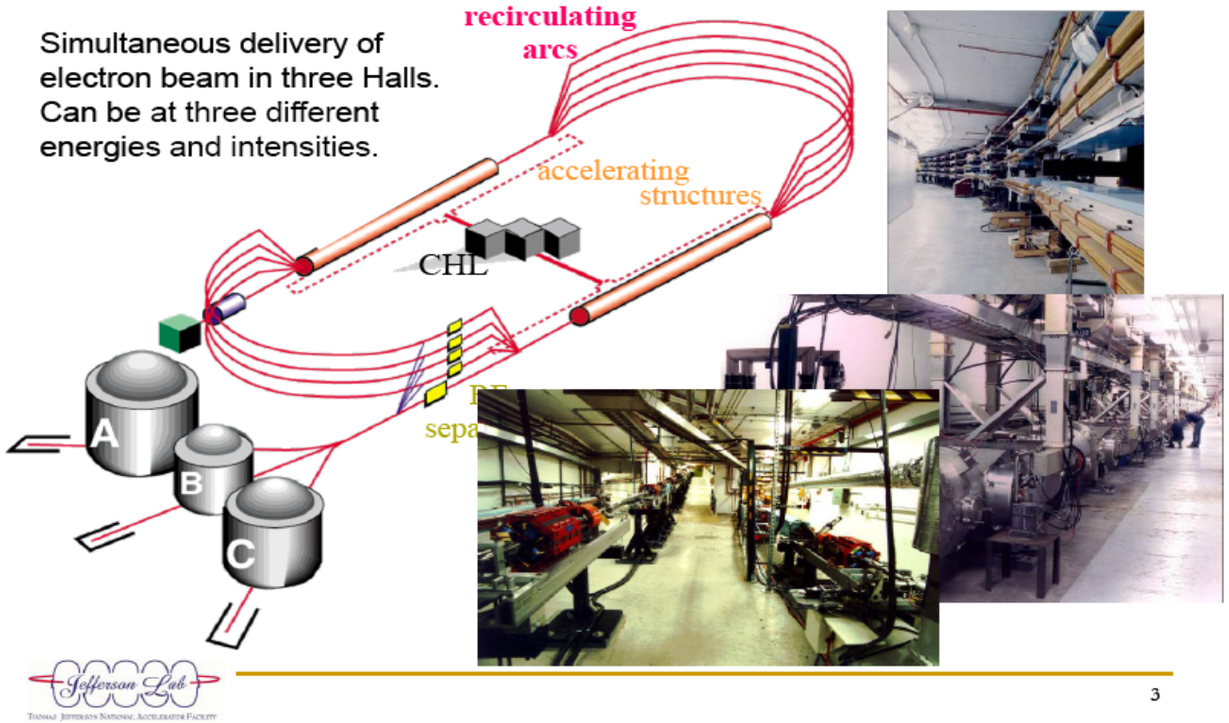
FNAL
M. Demarteau

JLab
P. Bosted
S. Stepanyan
L. Weinstein
B. Wojtsekhowski

U. Oregon
R. Frey

Developing:

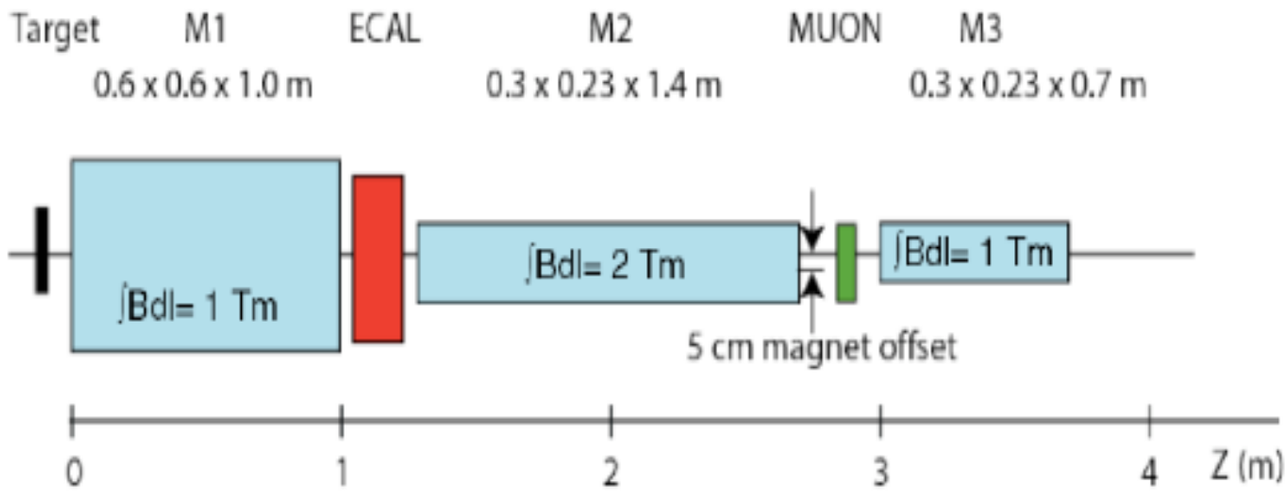
- Hall A search with existing spectrometers
- New experiment (parasitic) in Hall B
- Short baseline beam-dump in Hall C



New Parasitic Experiment in JLab Hall B

- Introduction
- Available beam
- JLab Hall B "Photon Dump"
- Experimental Apparatus
- Simulation
- Backgrounds
  - Occupancy
  - Track multiplicity
- Performance
  - Acceptance
  - Mass resolution
  - Vertex resolution
- Experimental reach
- Conclusions

Experimental Apparatus

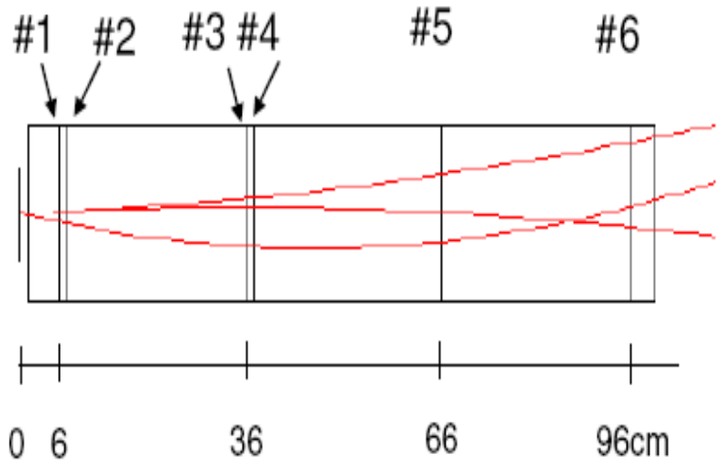


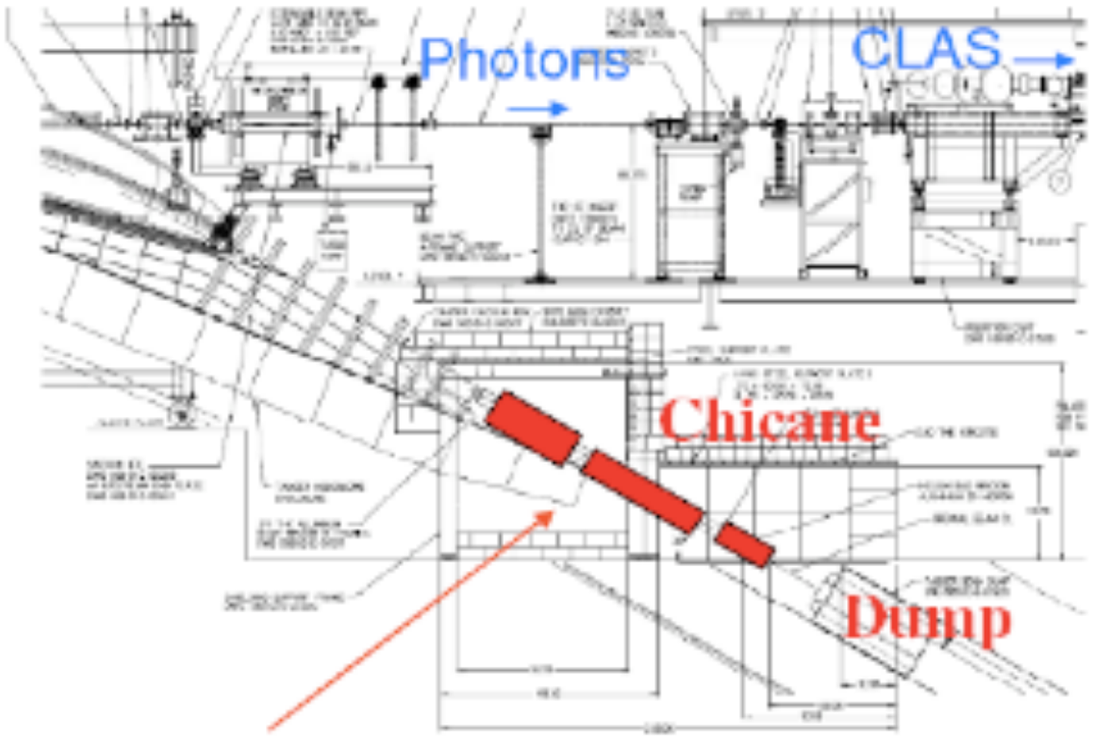
Beam:

- 6 GeV e- 100 nA

Target:

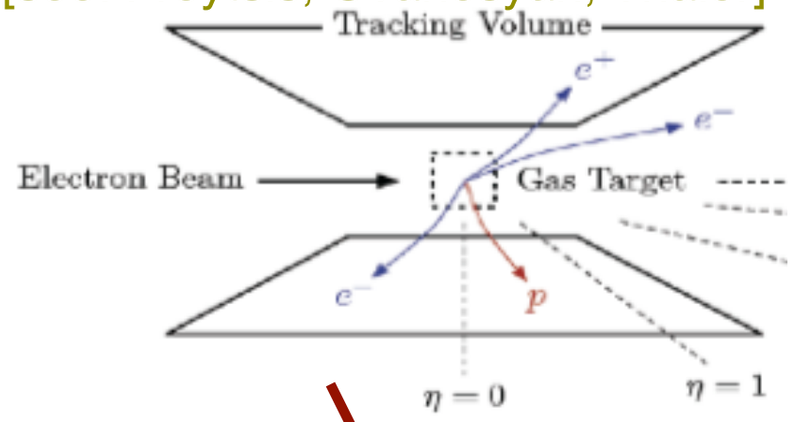
- 0.01 X_0 Tungsten



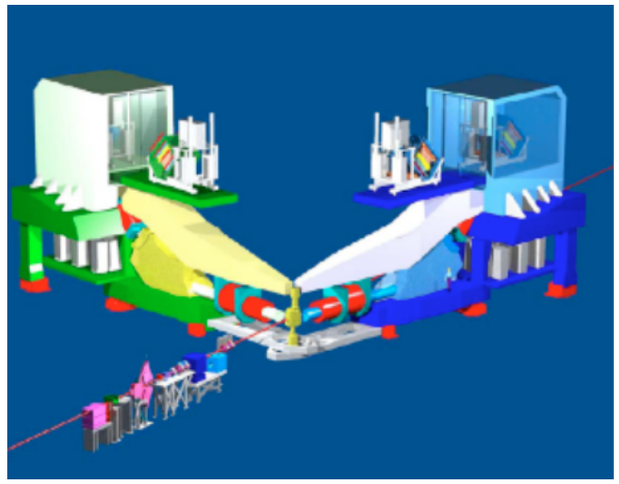


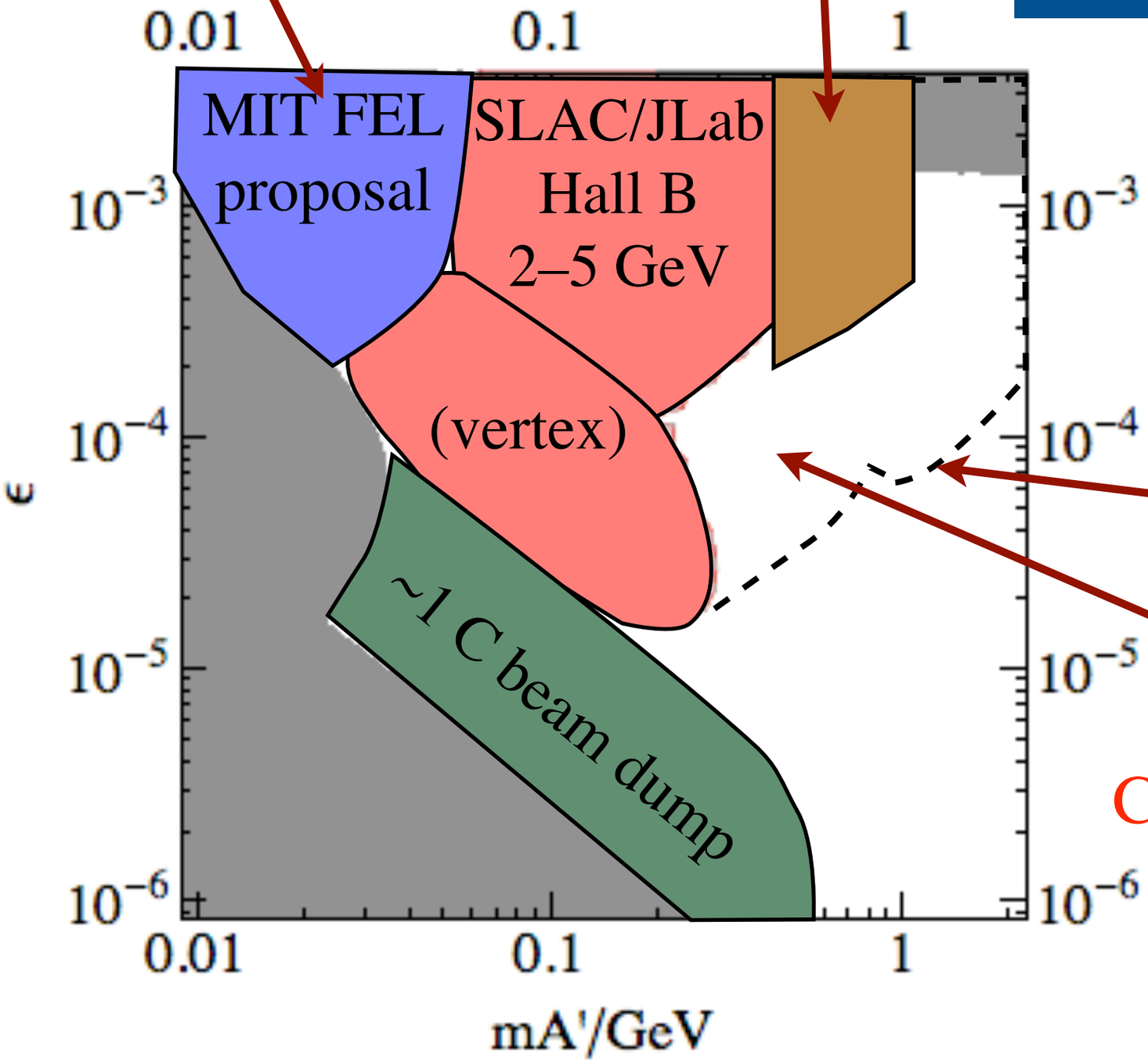
See T. Maruyama Talk at the SLAC Dark Fores Workshop

[see: Freytsis, Ovanesyan, Thaler]



JLab
Hall A
(20 days)





Sensitivity and Improvements:

Sensitivity with existing beams but better acceptance

Pixel tracking extends reach

Complementary coverage from B-factories: higher mass, multi-lepton channels

Summary

- Dark forces are an intriguing possibility, well-motivated by existing data
- Laboratory tests are crucial and complementary to additional astro/direct-detection data

- Broad array of experimental investigation is possible
- Considerable sensitivity to dark forces with existing data and new small-scale experiments

New searches and experiments on ~year timescale!

Further Information

SLAC Dark Forces Workshop

All talks are posted at:
http://indico.cern.ch/event/darkforces

Thanks!