Dark Forces:
Past, Present and Future

Natalia Toro

work with Bjorken, Essig, Schuster, Yavin

Workshop webpage:

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

All talks are posted at:

http://indico.cern.ch/event/darkforces


Dark Forces: Searches for New Forces at the GeV-scale

Description: Theoretical models related to dark matter have proposed that there are long-range forces mediated by new gauge bos
ordinary matter. The experimental constraints on the existence of these new gauge bosons are quite weak. This works
searching for these "dark forces" in three arenas:
1. new fixed-target experiments at electron and proton accelerators such as JLab, SLAC, and Fermilab;
2. searches at high-luminosity e+e- experiments, including BaBar, BELLE, CLEO-c, KLOE, and BES-III;
3. searches at the Tevatron experiments.

Material: Working Group discussion topics; Working group discussion topics (PDF)

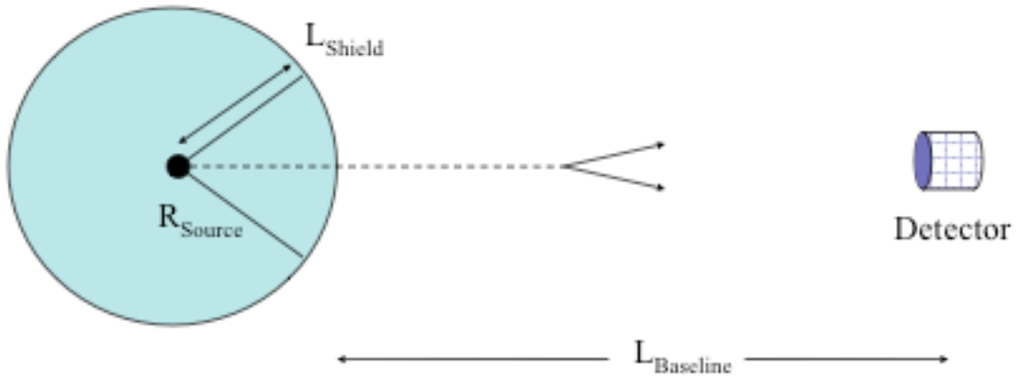
Thursday

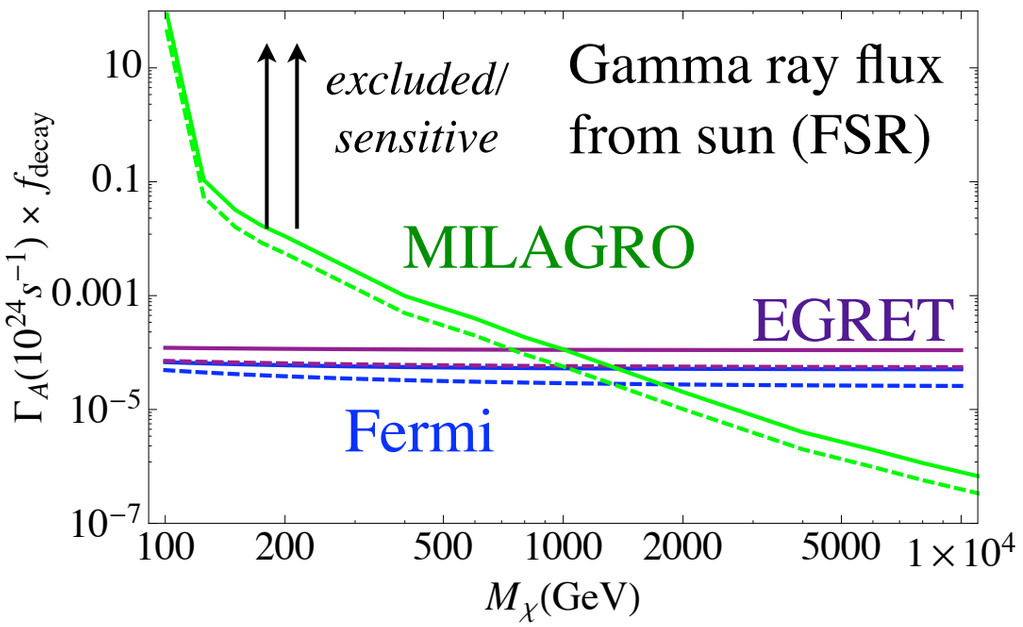
Thursday 24 September 2009

08:00 Registration (45')
08:45 Welcome and Overview (15') (Slides)
09:00 Motivations for a dark force from astrophysics and WIMP searches (30') (Slides (22MB))
09:35 Theories of Dark Forces (30') (Slides)
10:10 Coffee Break (25')
10:35 Searching for the Light Dark Gauge Boson in GeV-Scale Experiments. (25') (Slides)

Very Long-Lived Species

Constraints on decays outside the sun

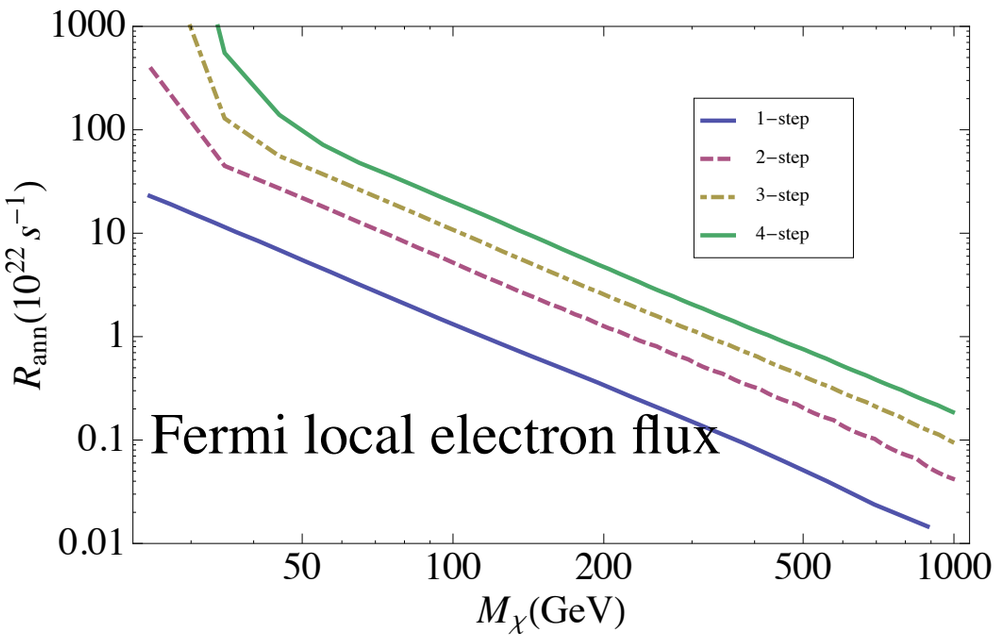


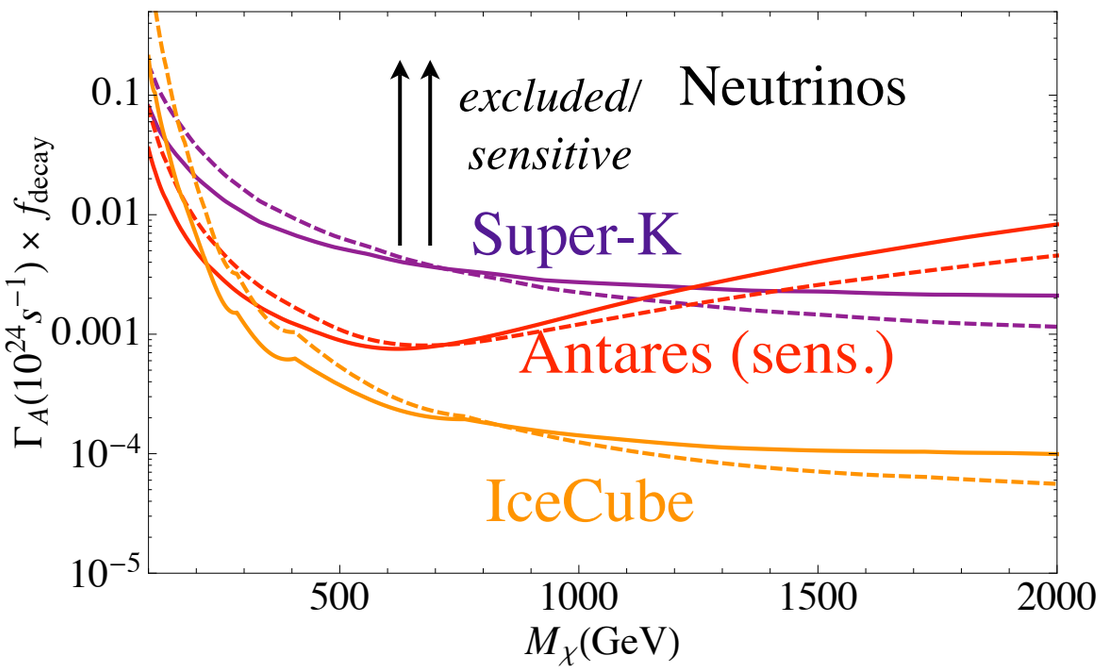


Capture rates:

~10^{24}/s for DAMA-like inelastic cross-section (very common in these models)

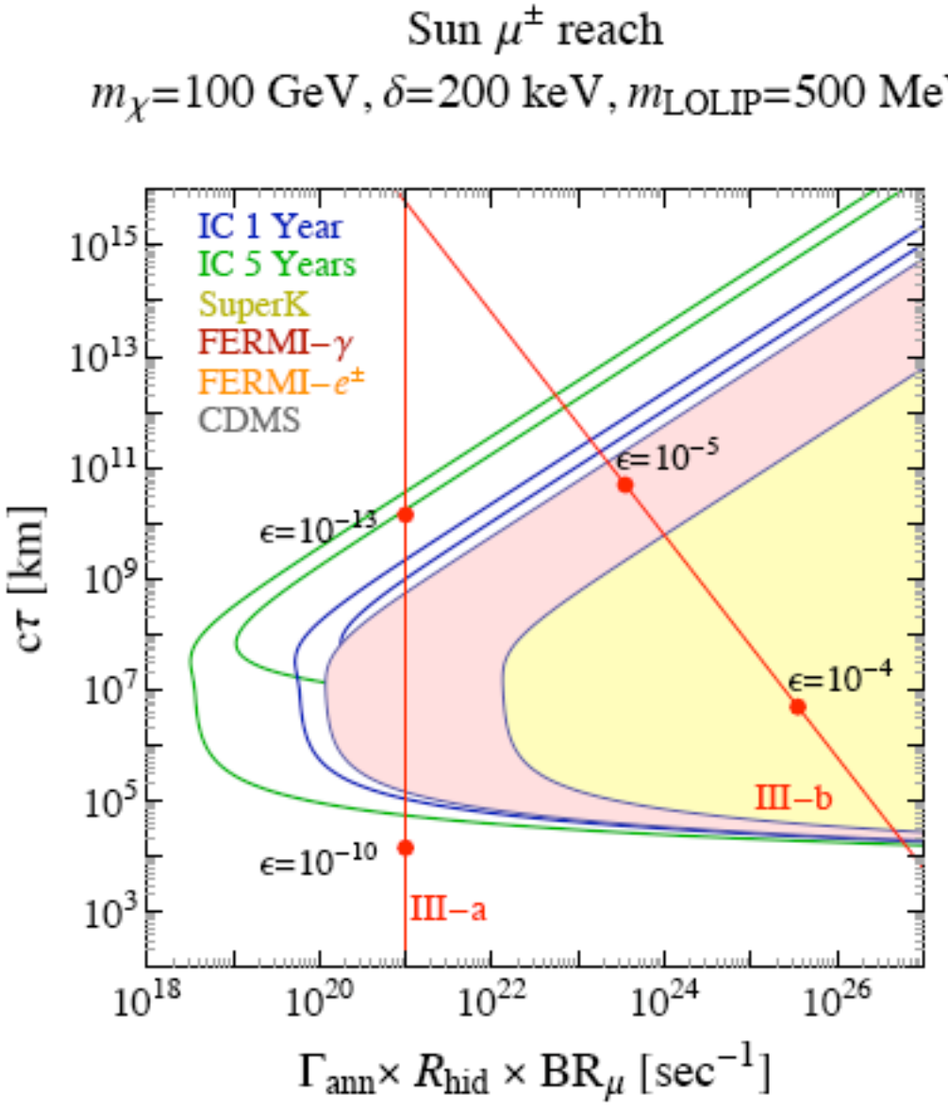
~10^{21}/s for elastic cross-section at CDMS limit

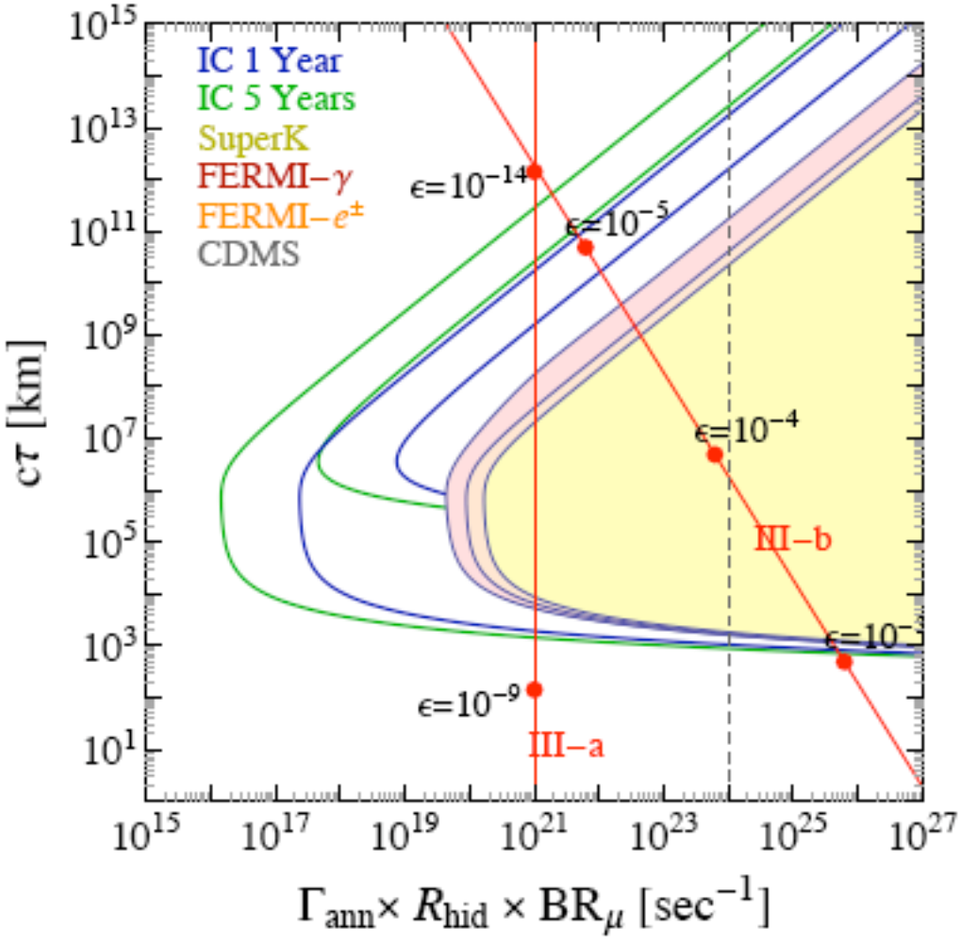




[Schuster, NT, Yavin; see also Batell, Pospelov, Ritz, Shang]

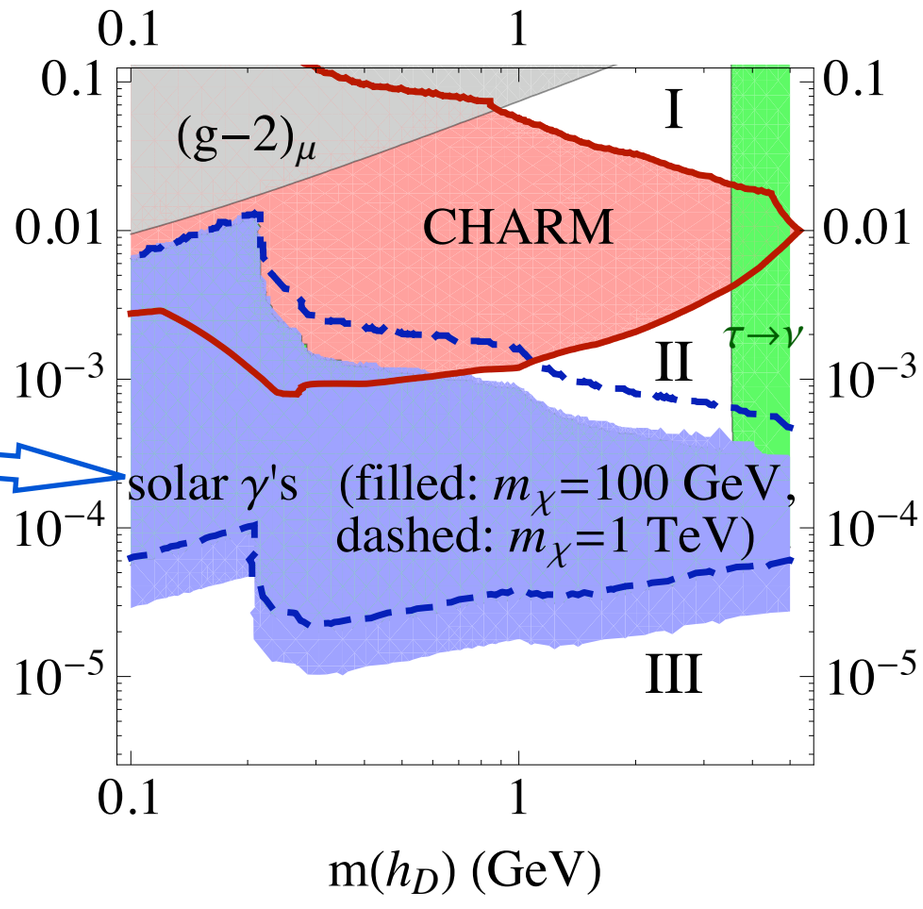
- Exclude $R_{sun}(10^{11}\mathrm{cm}) \lesssim \gamma c\tau \lesssim 10\ \mathrm{AU}\ (10^{14}\mathrm{cm})$ depending on annihilation rate
- Also look for decays to $\mu\mu$ in front of neutrino detector – exciting signature!





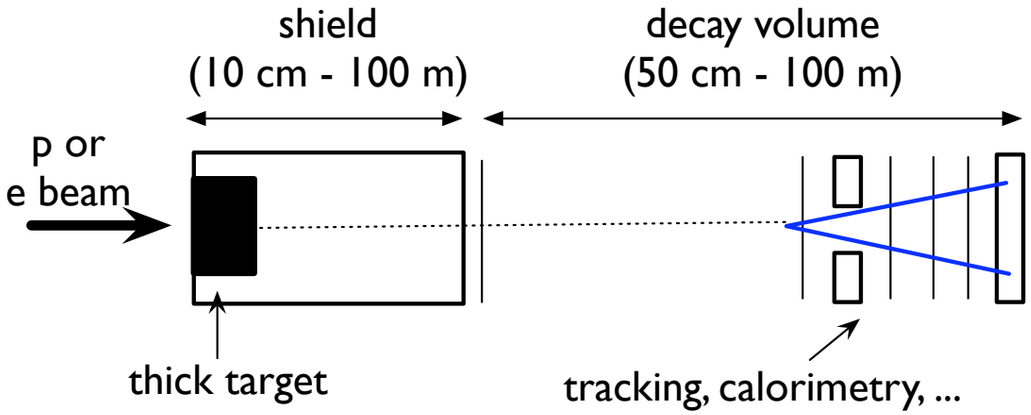
[Meade, Nussinov, Papucci, Volansky]

Constraint in scalar-decay scenario

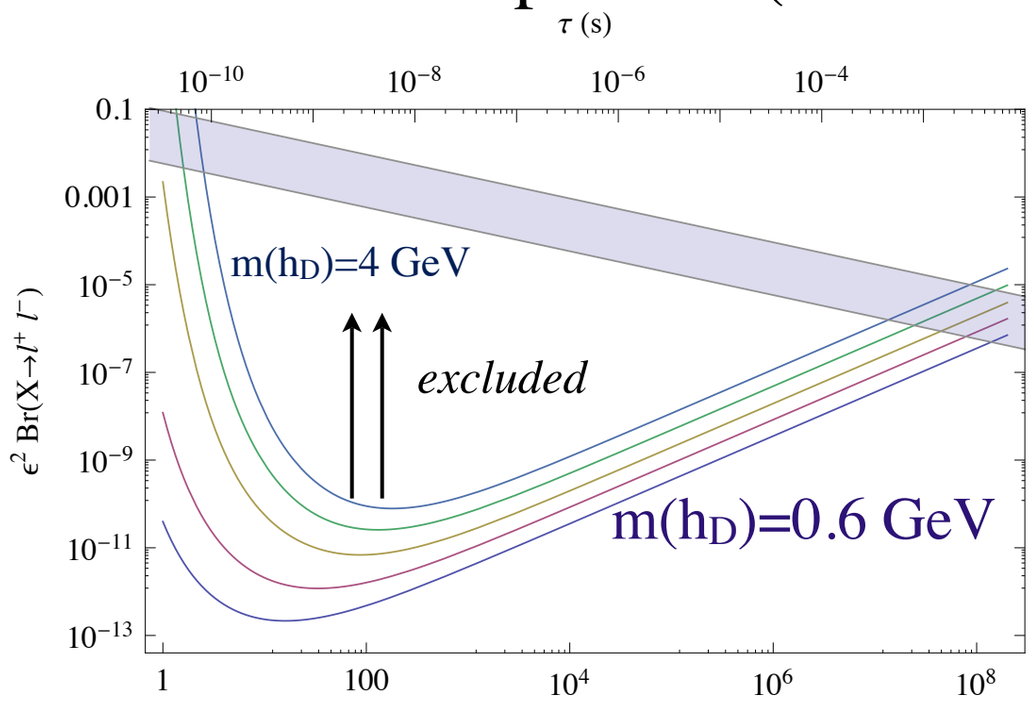


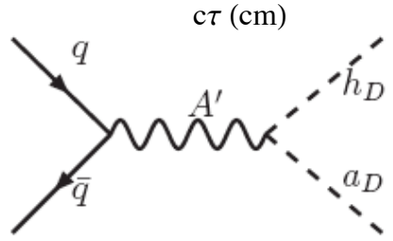
[Schuster, NT, Yavin]

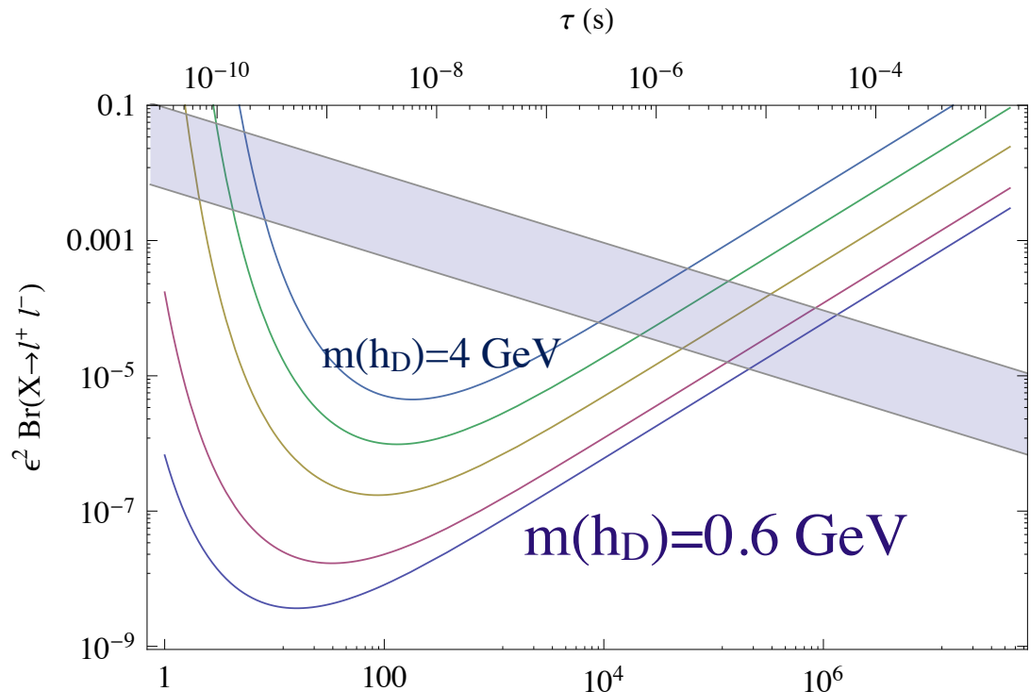
Beam Dump Constraints

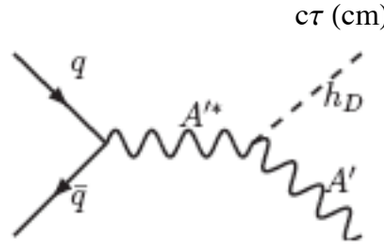


CHARM: 10^{21} protons (400 GeV)



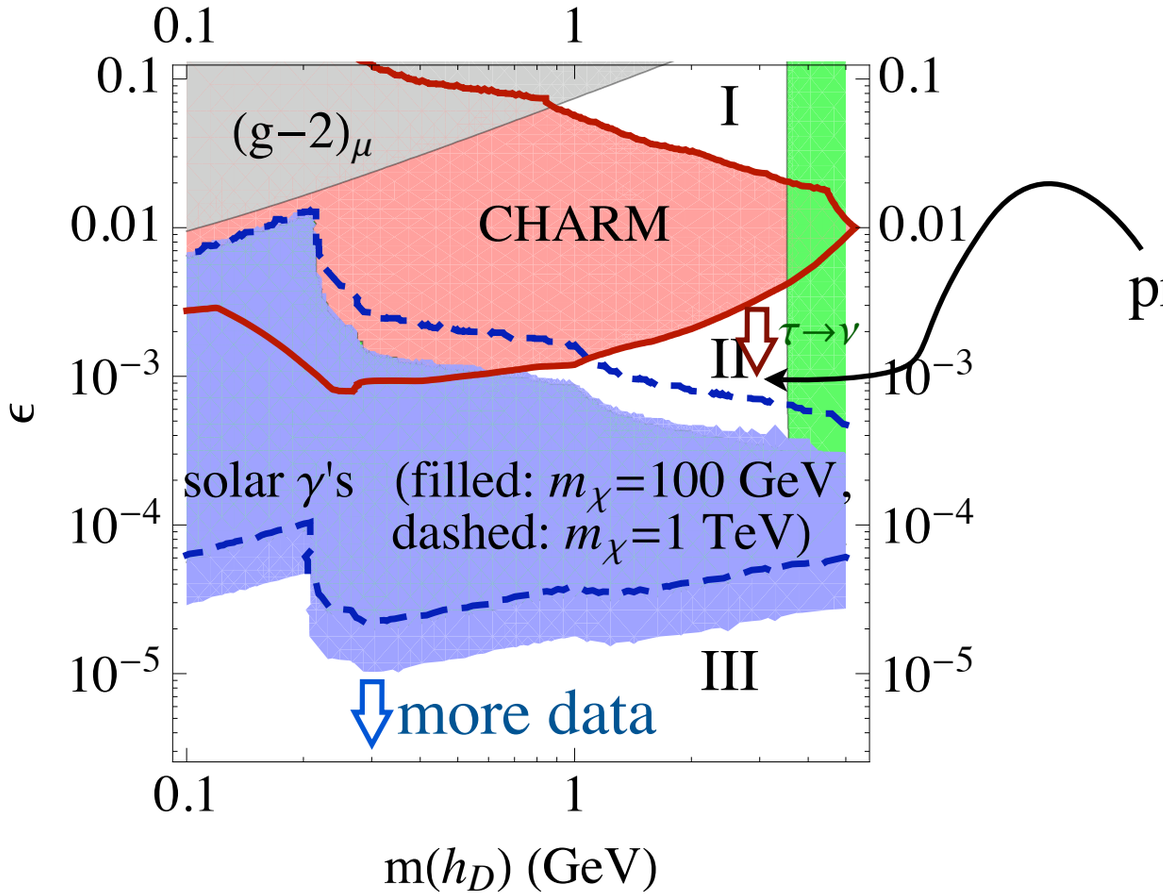






[Schuster, NT, Yavin; see also Batell, Pospelov, Ritz]

Constraints and prospects in scalar-decay scenario



production by cosmic rays?
(sweet spot in lifetime)

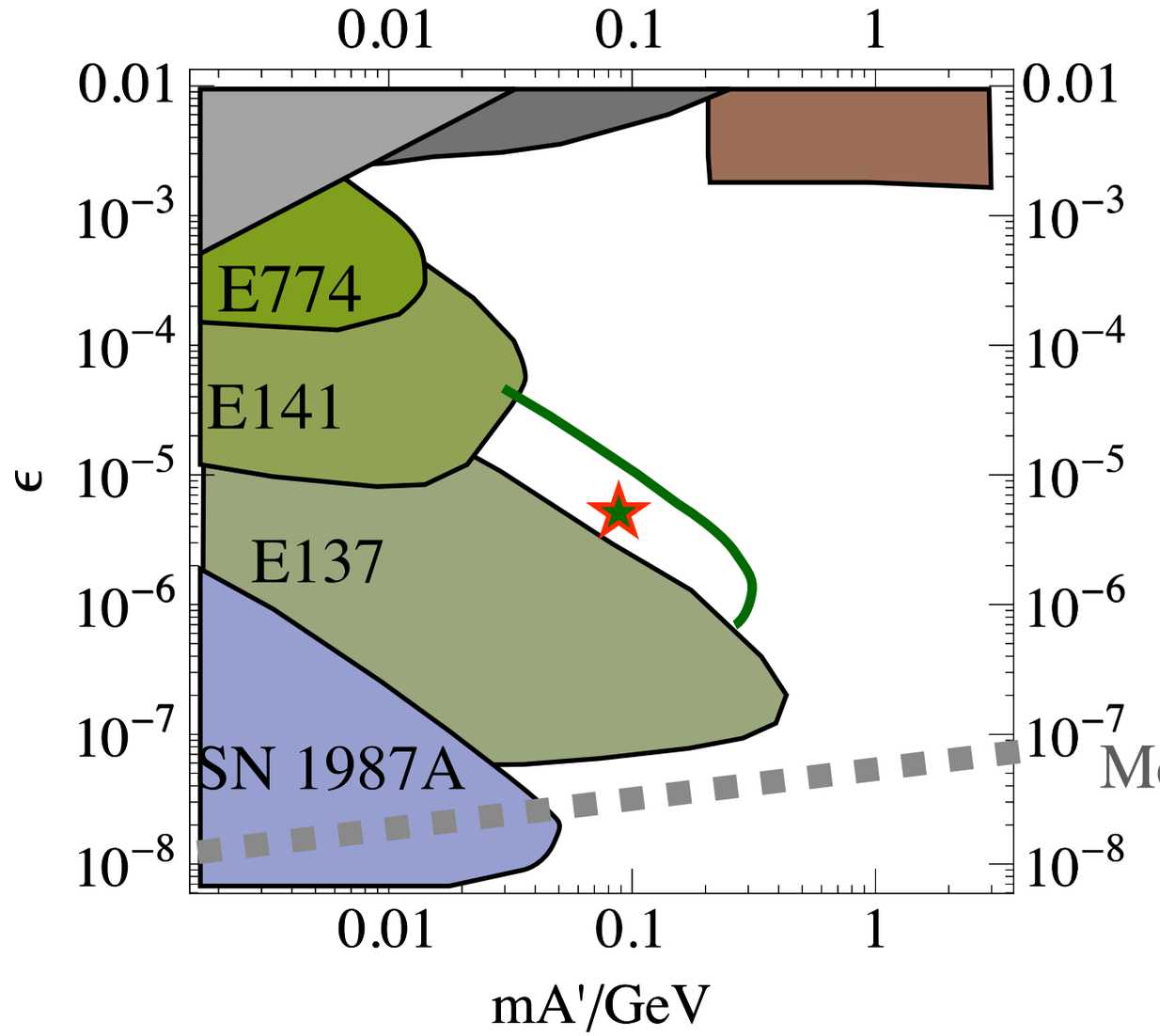
see e.g. Yin and Zhu

[Schuster, NT, Yavin]

Long-Lived Direct Decays

(very small mixing ~10^{-7}!)

- Because of kinematics, electron beam dumps are ideal
- Experiments to search for 1.8 MeV pseudoscalars in the 80's



★ Small, low-power beam dump scenario:
Duke? INFN Frascati? DESY?

[Bjorken, Essig, Schuster, NT]

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

Shorter Lifetimes:

- flavor factories
- fixed-target
- Tevatron/LHC

e+e- Colliders

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:

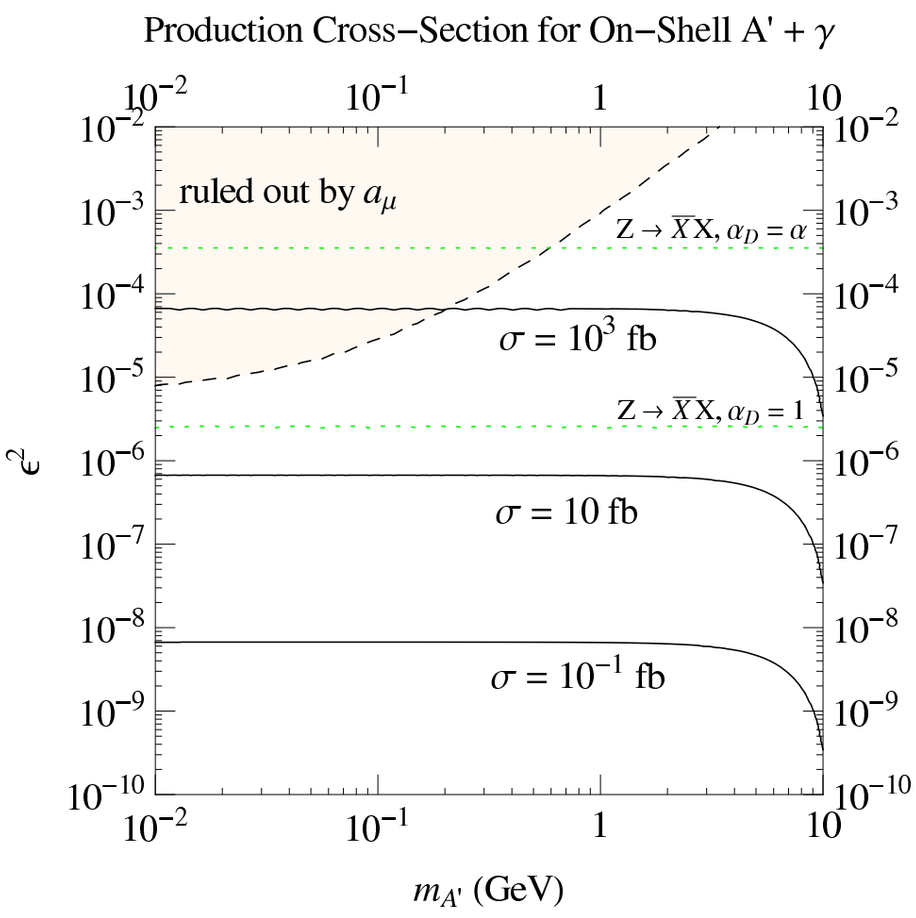
– accessible mass range

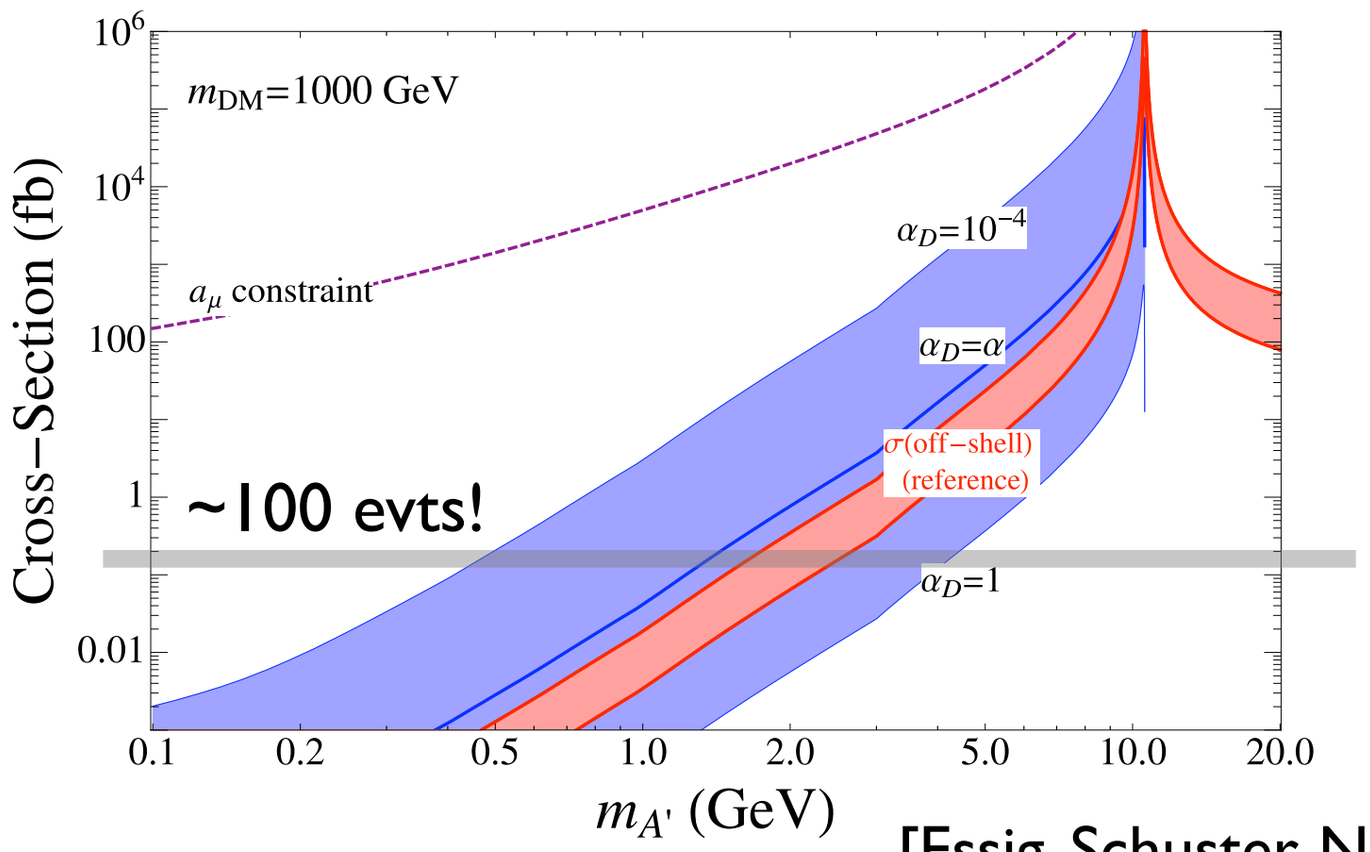
– kinematic acceptance & **visibility** of events

Broad range of searches needed

Continuum Production Xsecs

$$\sigma \sim \alpha^2 \epsilon^2 / E_{cm}^2$$





[Essig, Schuster, NT]

In large parameter range, enough statistics to see distinctive high-lepton-multiplicity events!

Rare meson decays

Various facilities have sensitivity (~$\mathscr{L}$/s) through rare decays

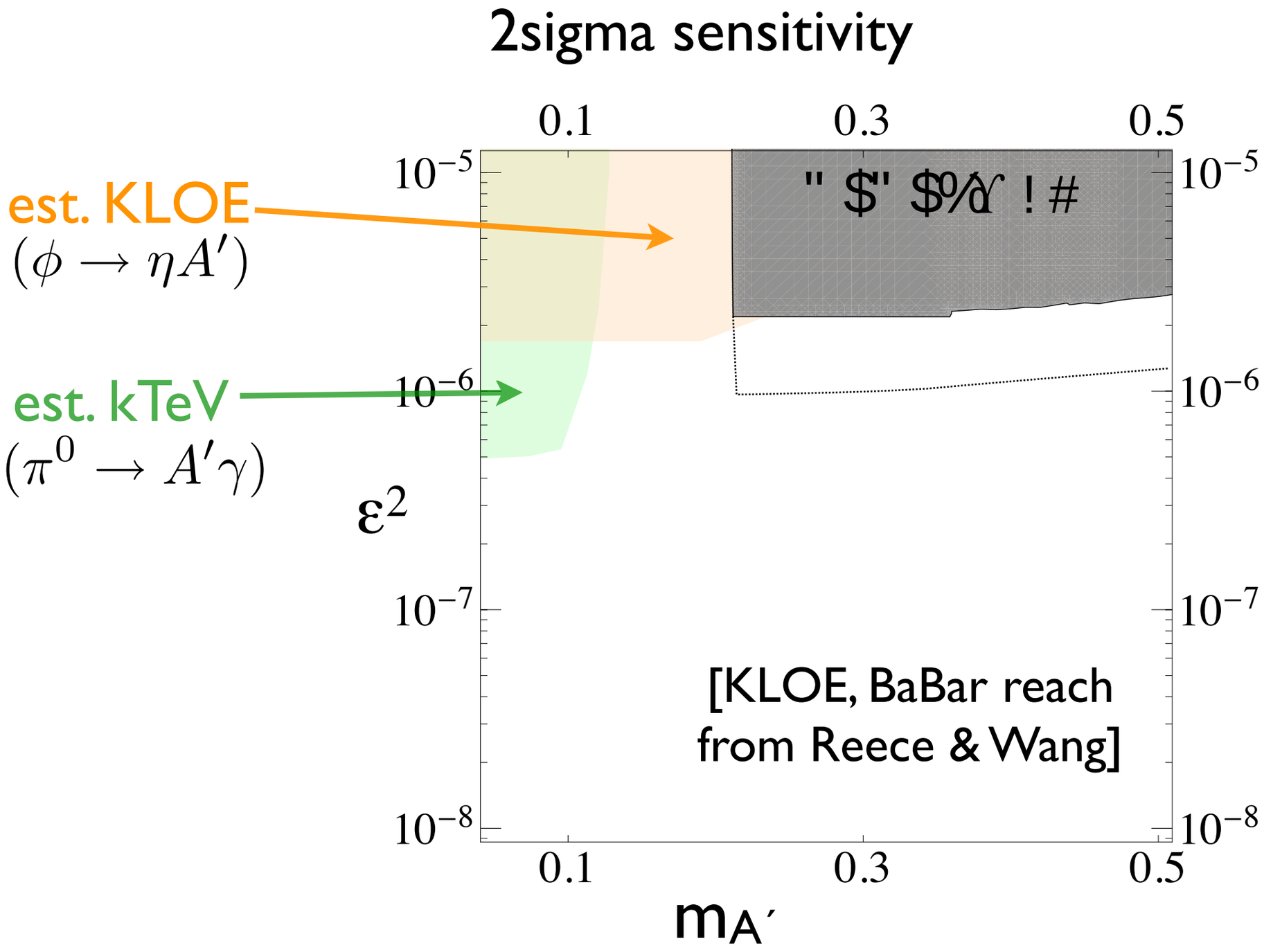
$X \to YU$	n_X	$m_X - m_Y$ (MeV)	BR($X \to Y + \gamma$)	BR($X \to Y + \ell^+\ell^-$)	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	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]

- More existing data - K → eeγ , π → ee, η → ... (kTeV, BaBar/Belle, KLOE?)
  - J/ψ→ 6l via higgs'strahlung ⇒ sensitivity to κ~10^{-3}-10^{-4} given 10^{10} at BES-III in 1yr!
  - Rare B-decays....

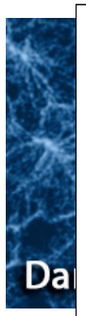
[M. Graham and A. Ritz]

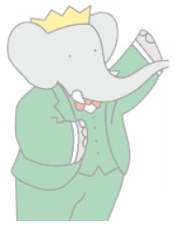
BaBar Upsilon(3s) Search and *Possible* Improvements



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

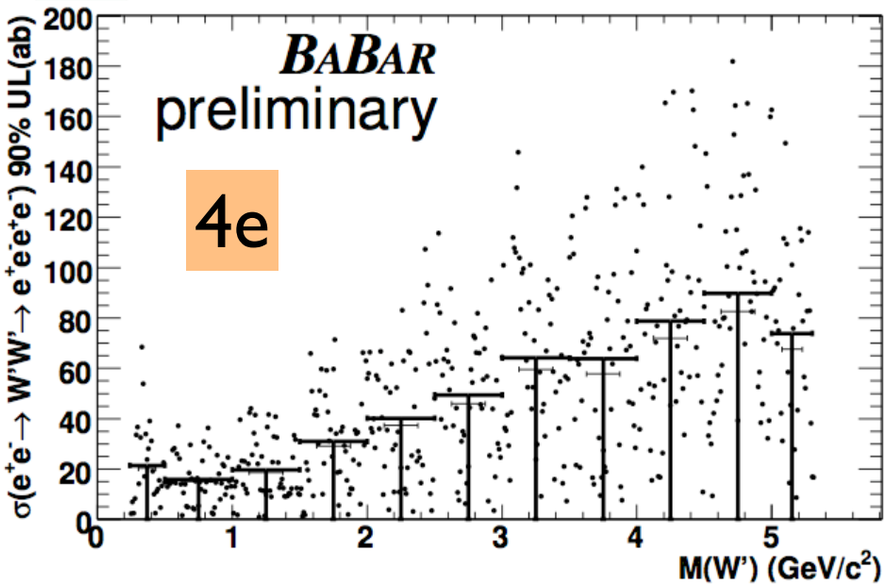
Matt Graham, SLAC
September 25, 2009

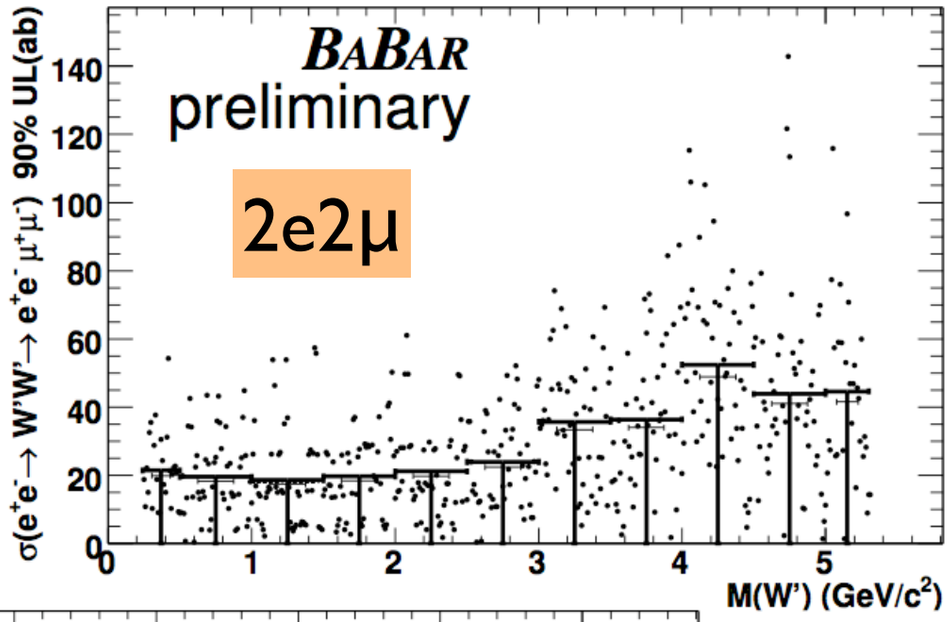




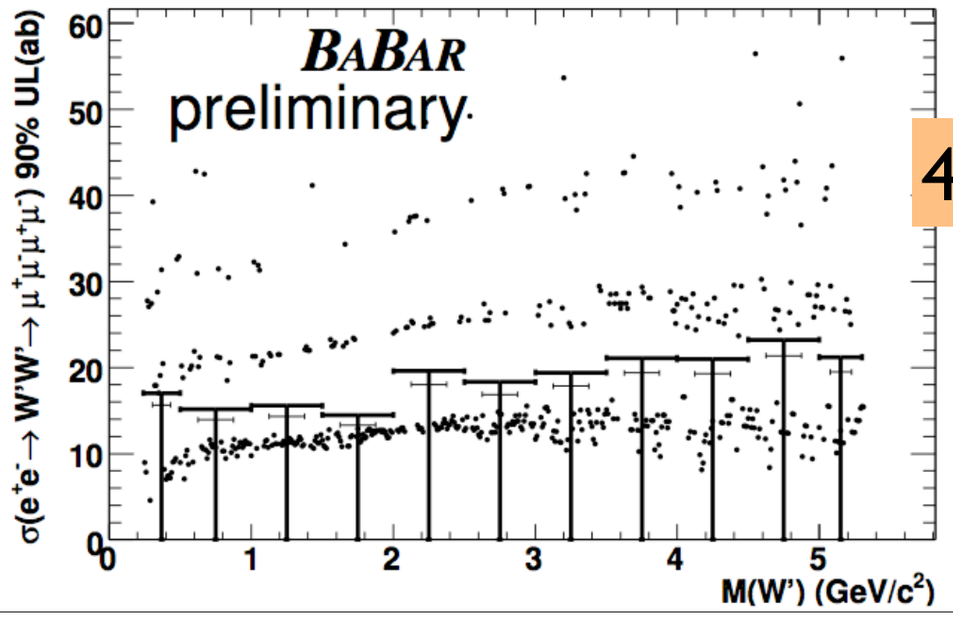
Cross Section Upper Limits

SLAC NATIONAL ACCELERATOR LABORATORY





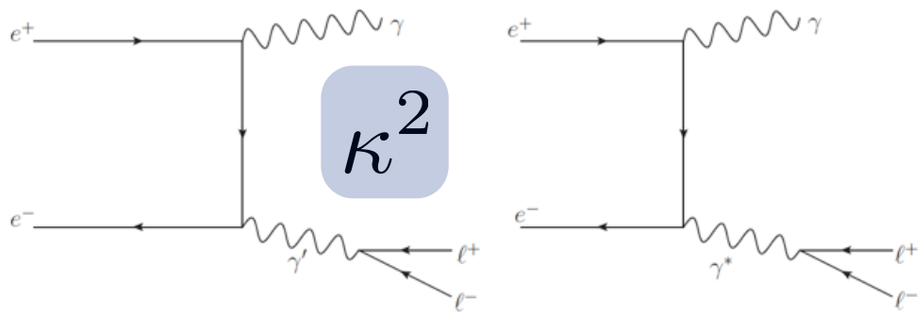
Points: bin UL
Lines: average UL
(smaller line shows statistical error only)



[M. Graham]

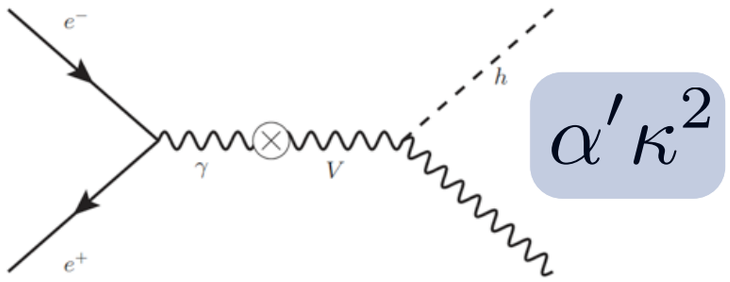
Final States (direct production)

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



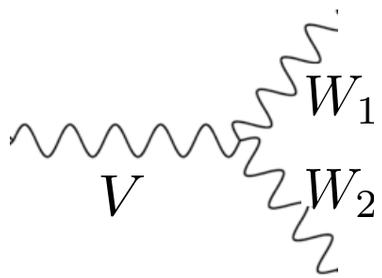
- BaBar [via Υ-decay search, H. Kim] ✓?
- Belle [Y. Kwon, J. Rorie]
- BES-III [H. Li, Y. Zheng]
- KLOE [F. Bossi]

- "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] ✓

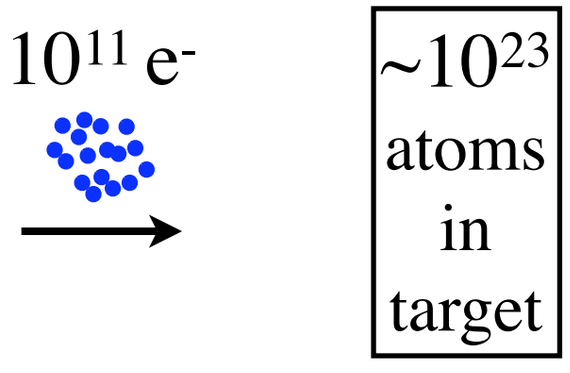
Also: higher multiplicity (confining), 4l + $\not{E}_T$, ...

[M. Graham and A. Ritz]

Fixed-Target Experiments

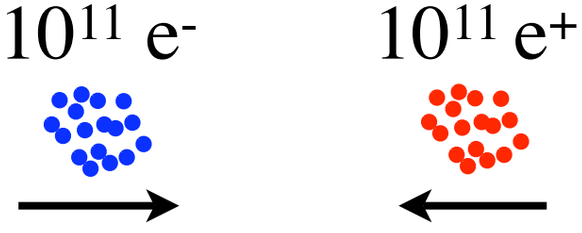
Higher Luminosity

Fixed-Target



N(hard scatter) ~ 0.01 – 1
per electron

e^+e^-



N(hard scatter) ~ 1
per crossing

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

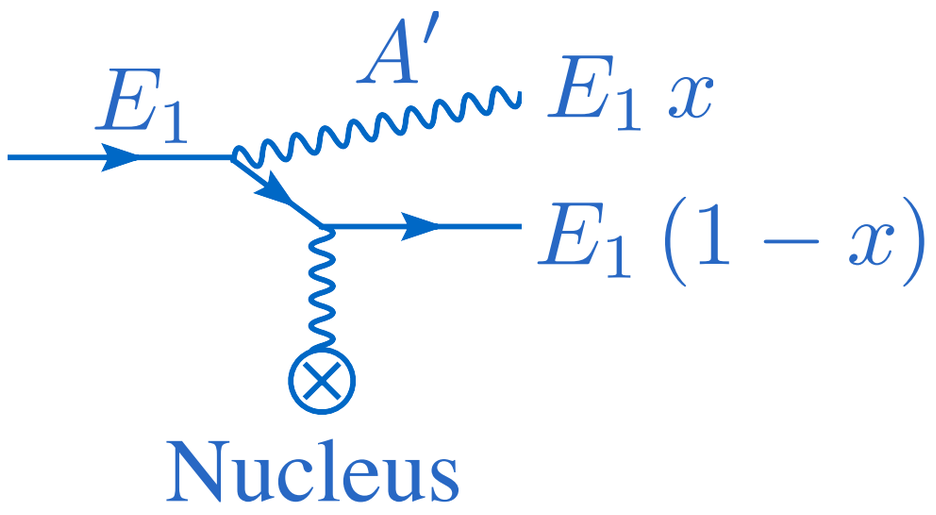
O(few) ab^{-1} per decade

High rate most important when few A´ are produced or for high-background modes

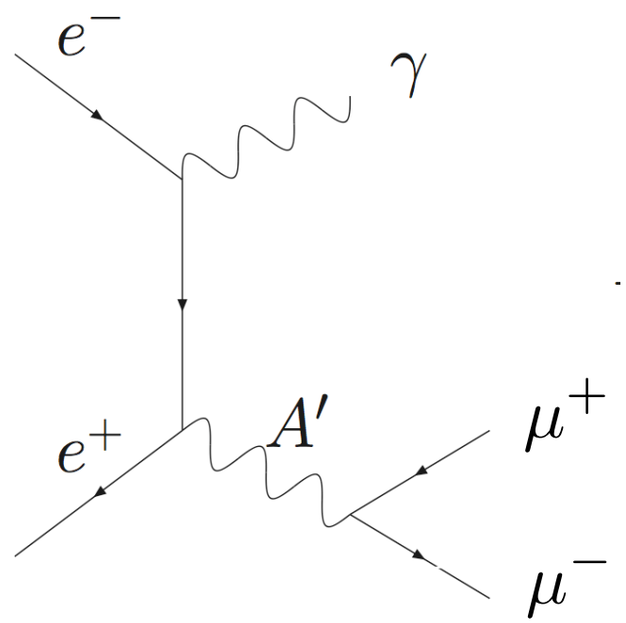
(e^+e^- ideal for larger-rate/low-background decay modes)

Larger Cross-Sections

Fixed-Target



e^+e^-



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

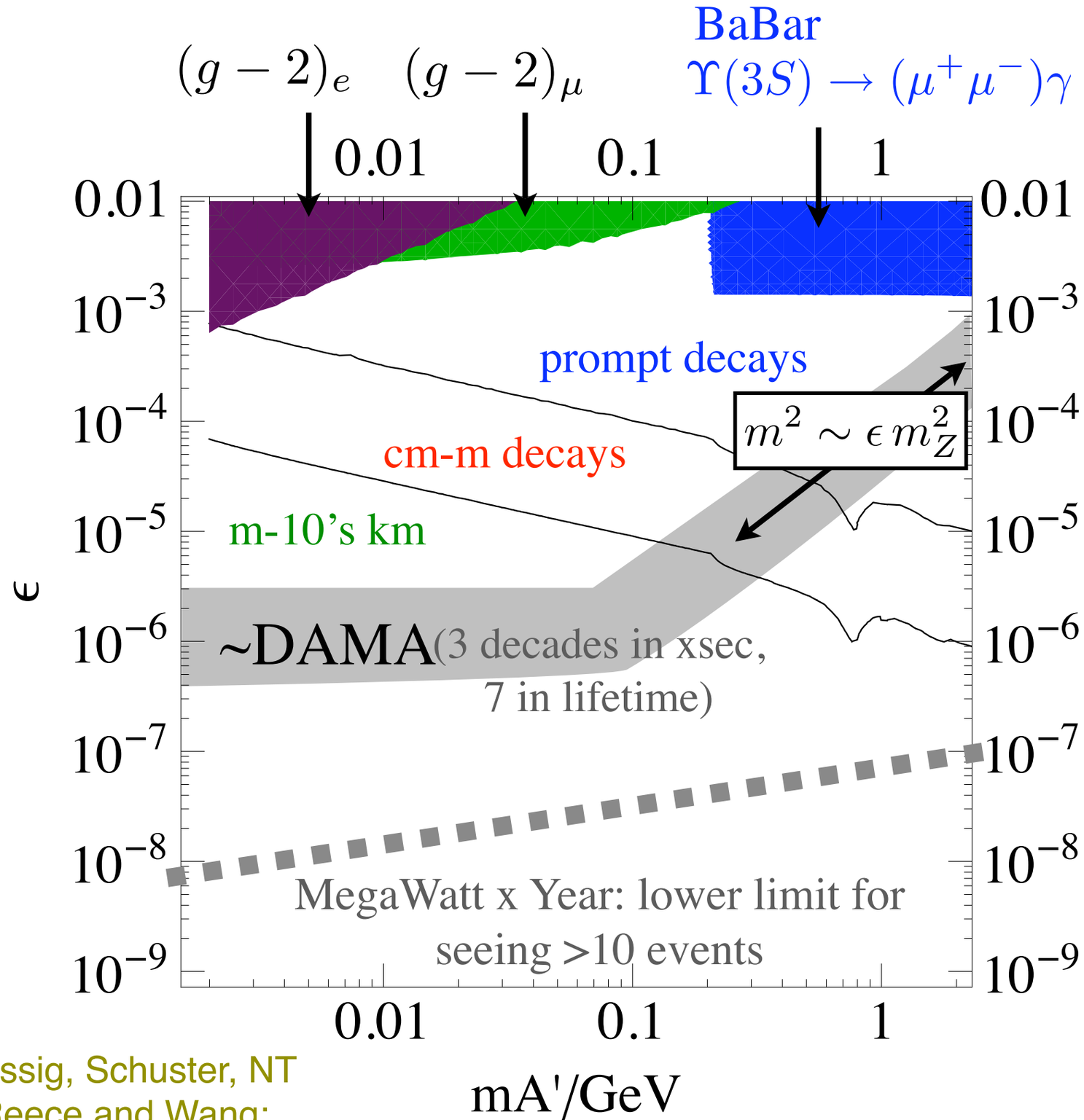
- Scales as A´ mass, not beam energy
- Coherent scattering from nucleus

Fixed-Target Territory

- Lifetime

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

  varies over 15 decades
- Kinematics depends on mass
- Multiple detectors needed



[Bjorken, Essig, Schuster, NT
see also: Reece and Wang;
Batell, Pospelov, Ritz]

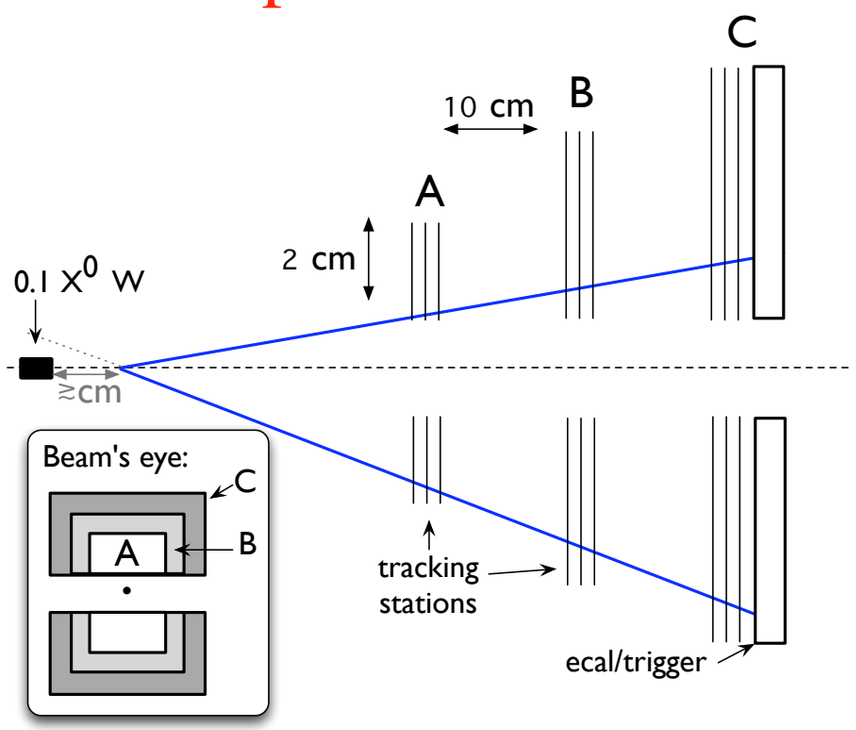
Approaches for New Experiments

To maximize search reach:

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

  [T. Maruyama will discuss these technical challenges]

Forward two-arm spectrometer



Heavy Photon Search Working Group

SLAC
R. Essig
C. Field
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A. Odian
R. Partridge
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JLab
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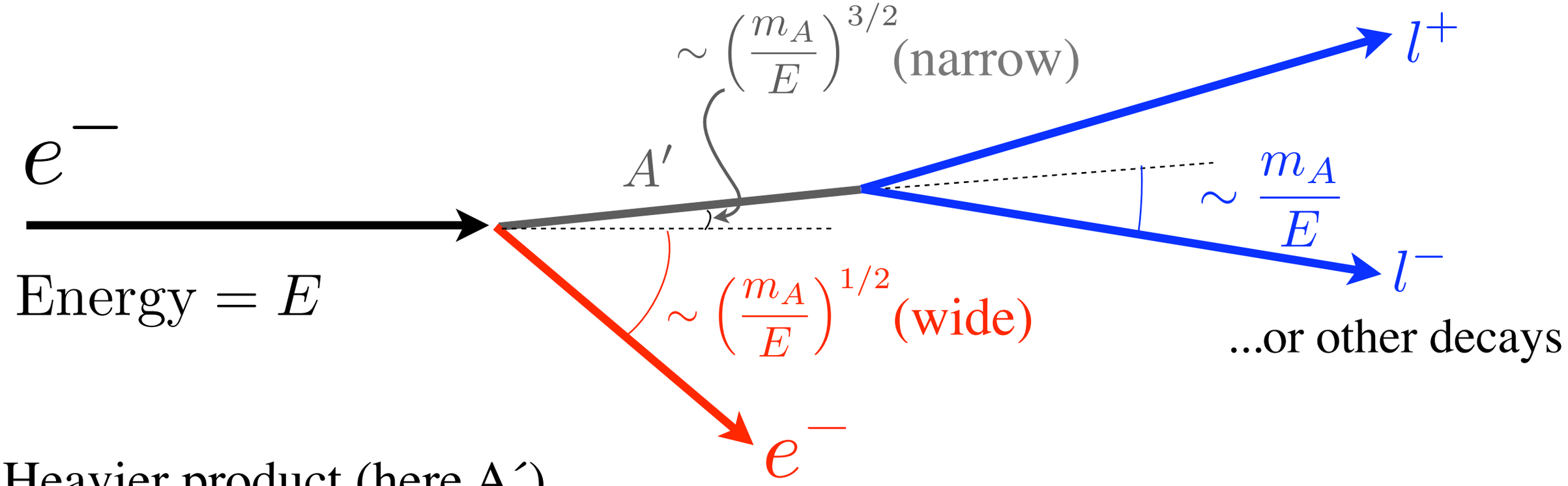
L. Weinstein
B. Wojtsekhowski

U. Oregon
R. Frey

Kinematics and Geometry



Heavier product (here A´)
takes most of beam energy:

$E_{e\text{-}} \simeq m_{A'}$ $E_{A'} \simeq E_{beam}$

$m_{A'} \gg m_e$ vs. $m_e \gg m_\gamma = 0$
for bremsstrahlung

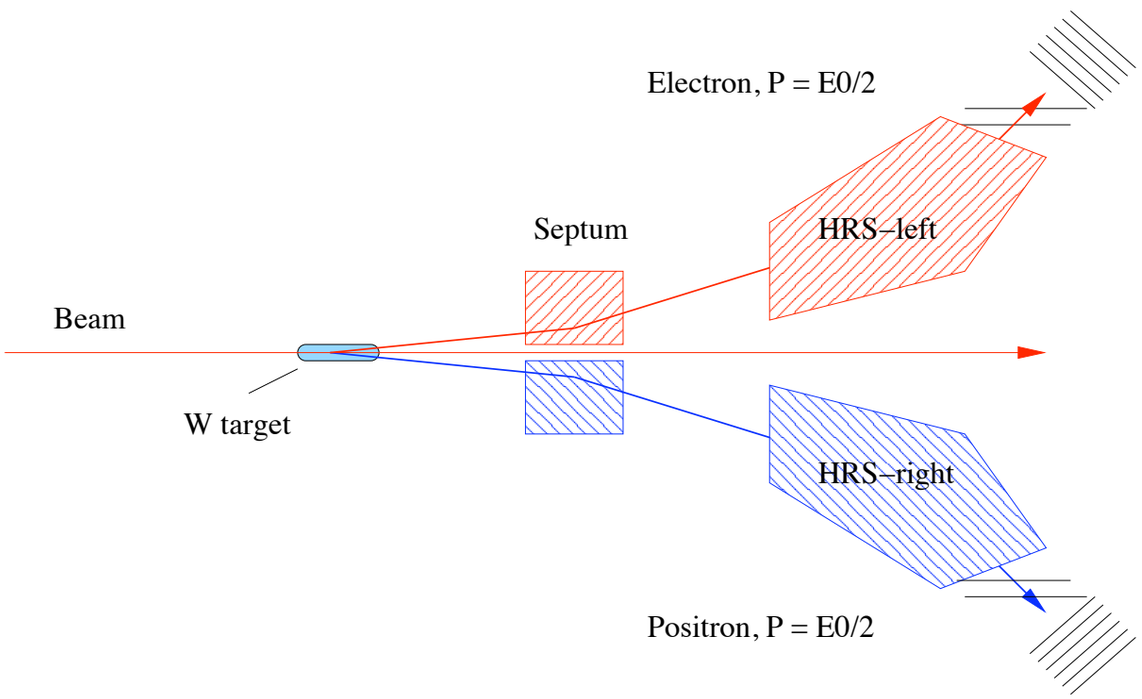
- Forward geometry allows small, purpose-built detector
- Limitation: Beam products also forward!

Proposal to JLab (Hall A)

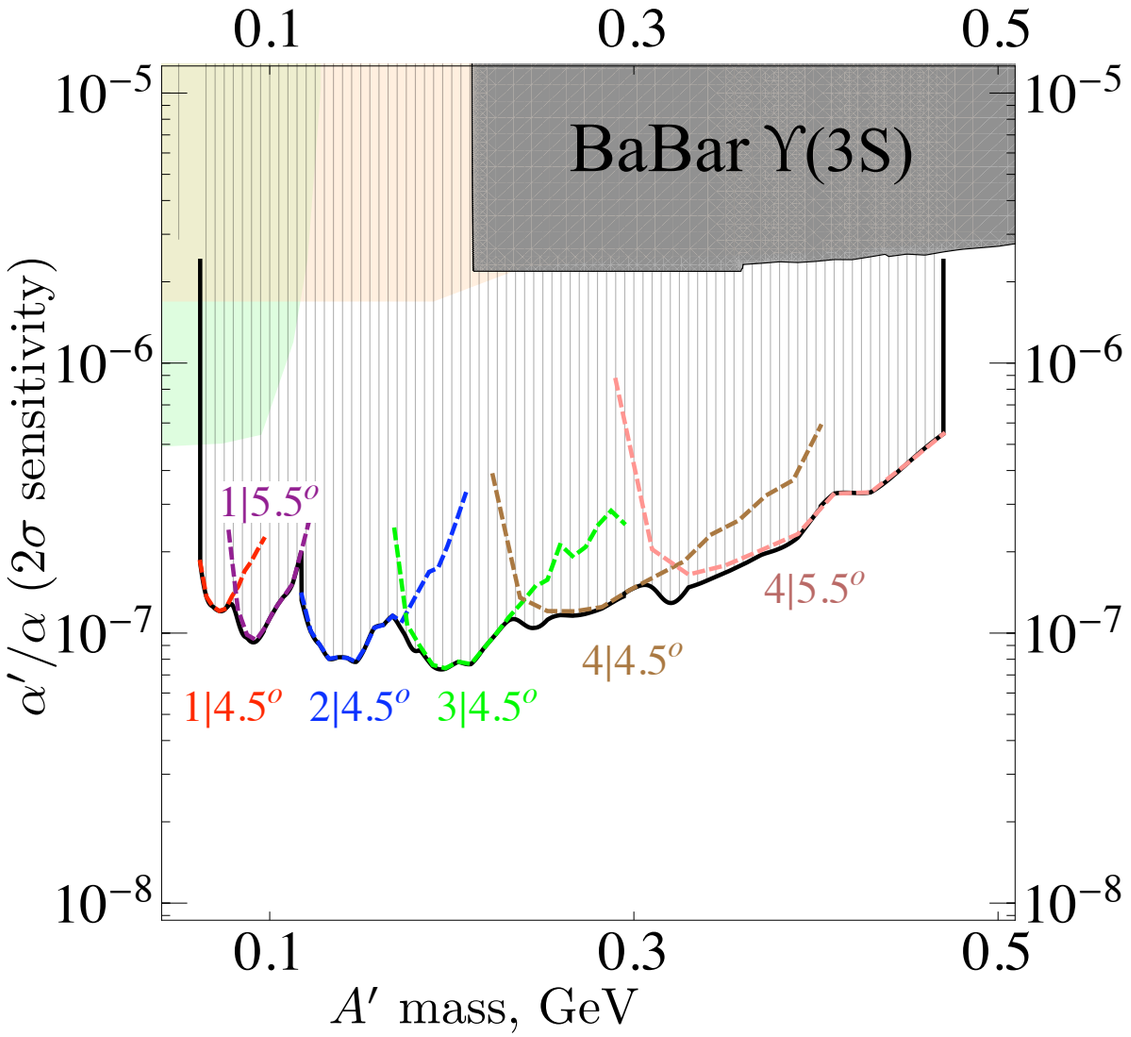
Essig, Schuster, NT, Wojtsekhowski

JLab Hall A advantages

- Ready to do experiment
- High resolution and forward acceptance
- Select high momentum in spectrometer
  $\Rightarrow$ optimal signal-to-background
- Unprecedented statistics achievable



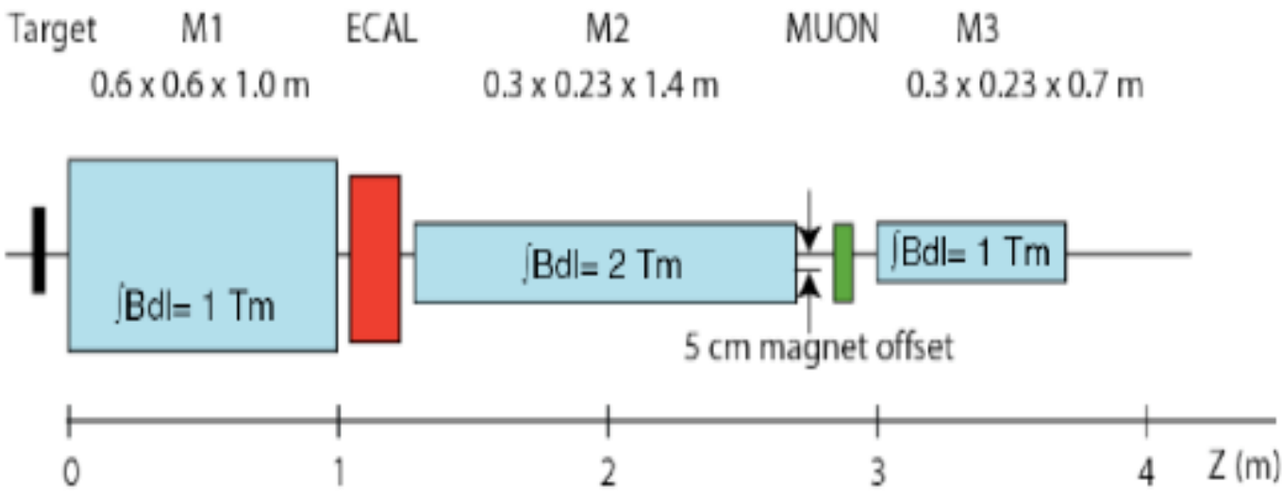
reach in 24-day run (2010?)



Forward Electro-Production of A' at J Lab T. Maruyama

- 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

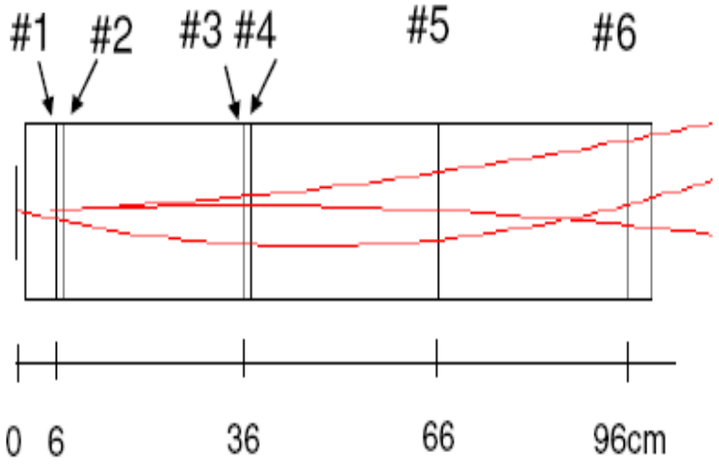


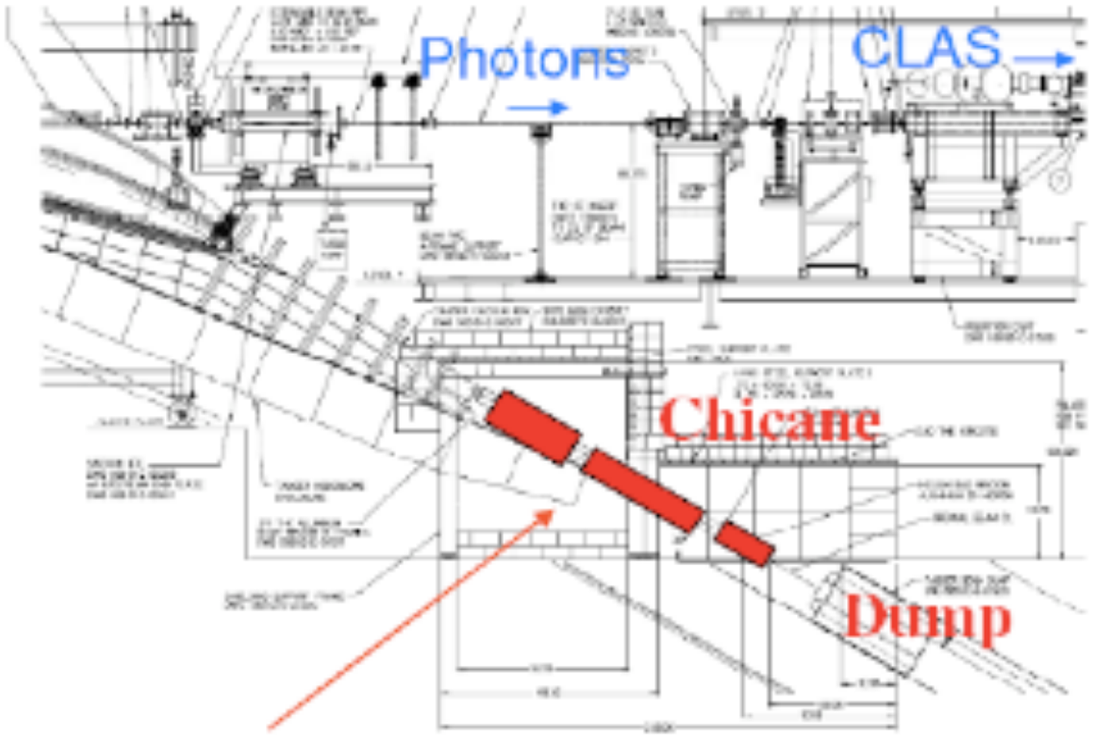
Beam:

- 6 GeV e- 100 nA

Target:

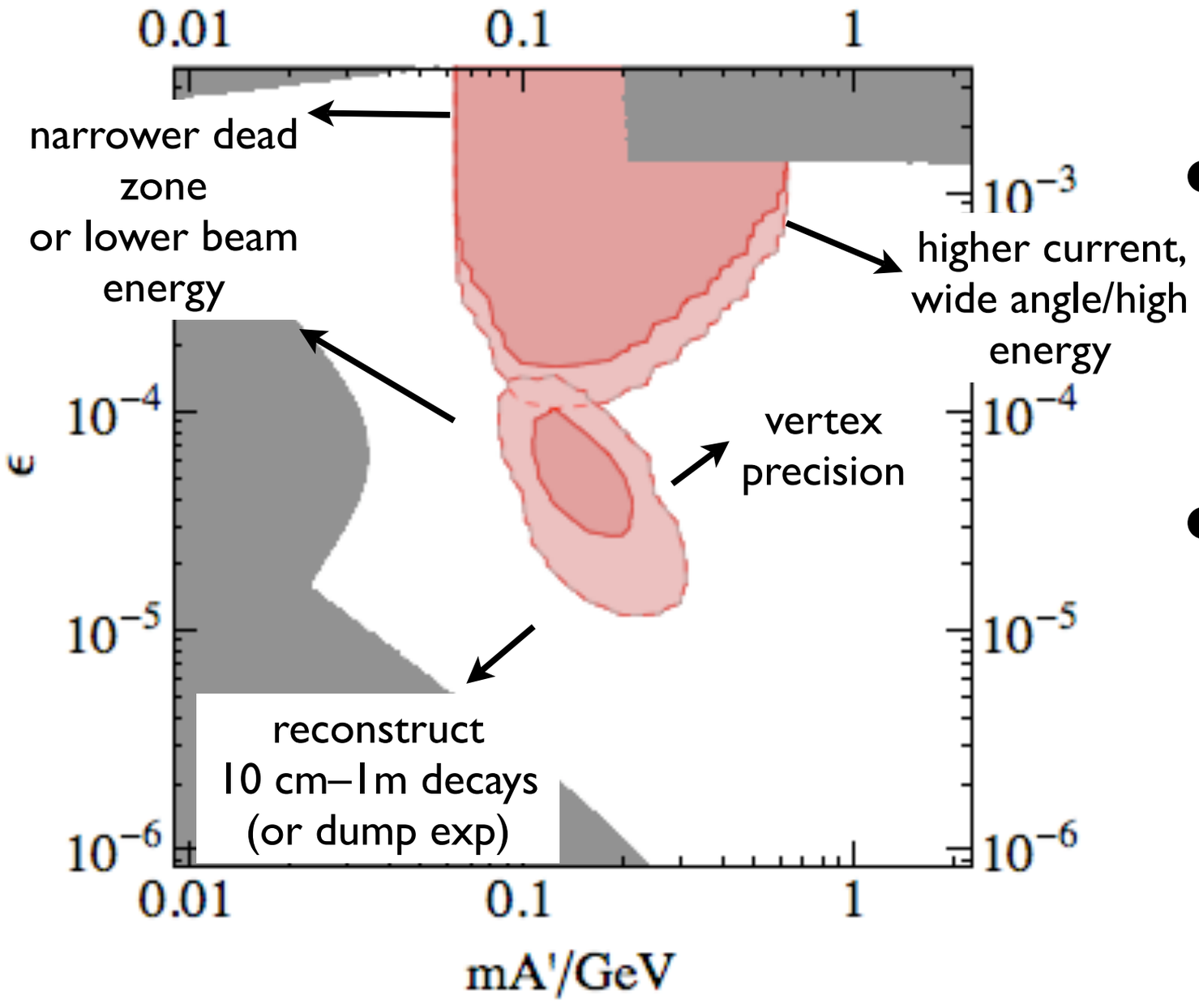
- 0.01 X_0 Tungsten





[T. Maruyama]

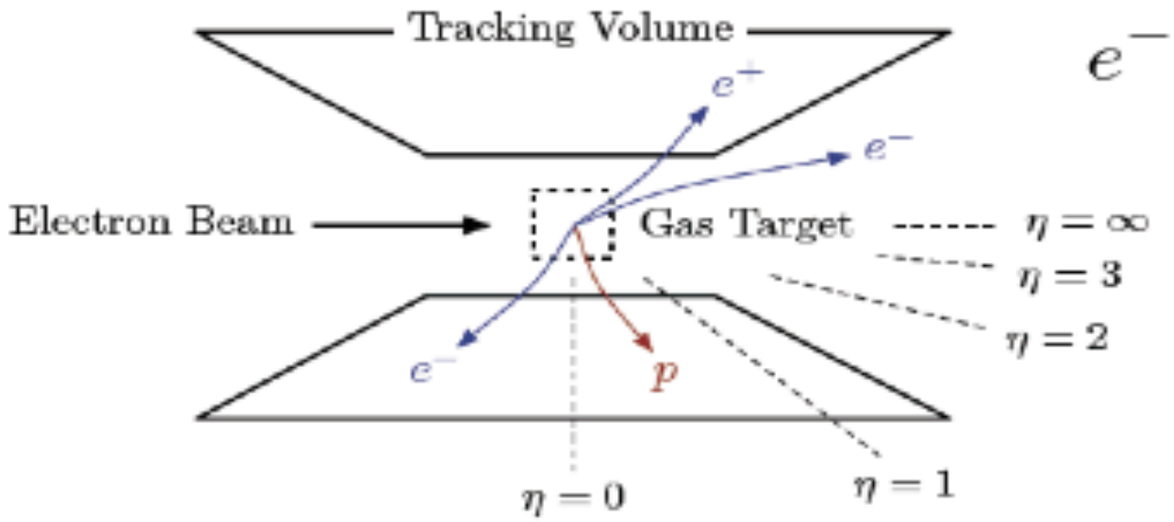
Potential Sensitivity



- For one geometry in 100 nA beam, 0.01 radiation-length target for 10^7 s (14–100 mrad acceptance)
- Different regions can be probed by varying beam energy and/or angular acceptance

U Boson Search at JLab FEL J. Thaler and P. Fisher

Electron-Proton Collisions

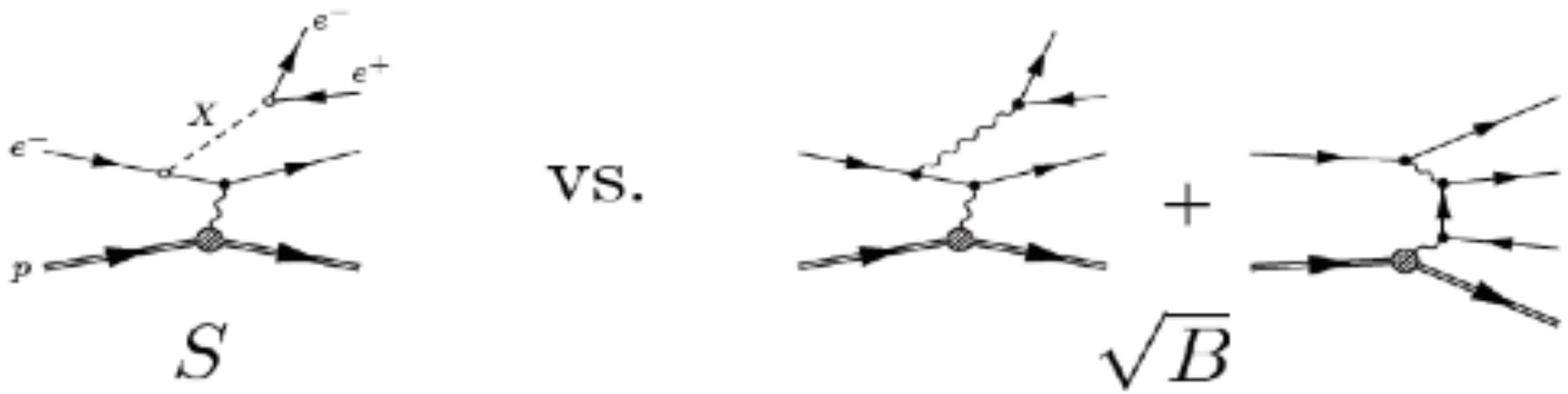


$$e^- p \to e^- p + X$$
$$\hookrightarrow e^+ e^-$$

$$E_{\text{beam}} \lesssim 140 \text{ MeV}$$

$$\text{ab}^{-1}/\text{month}$$

Narrow Resonance on Huge QED Background

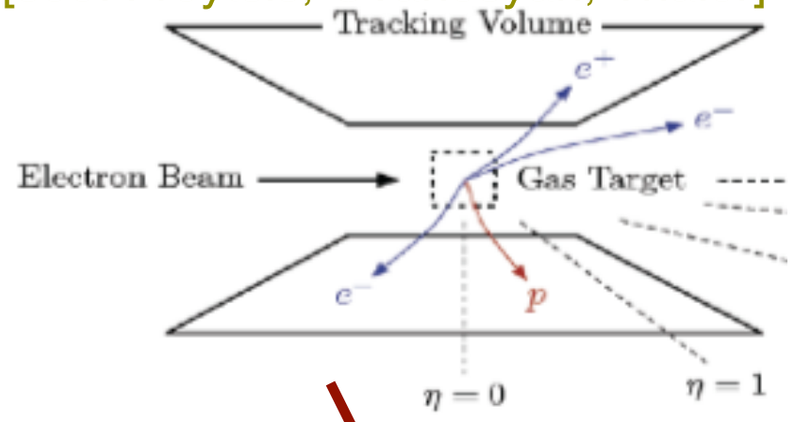


S

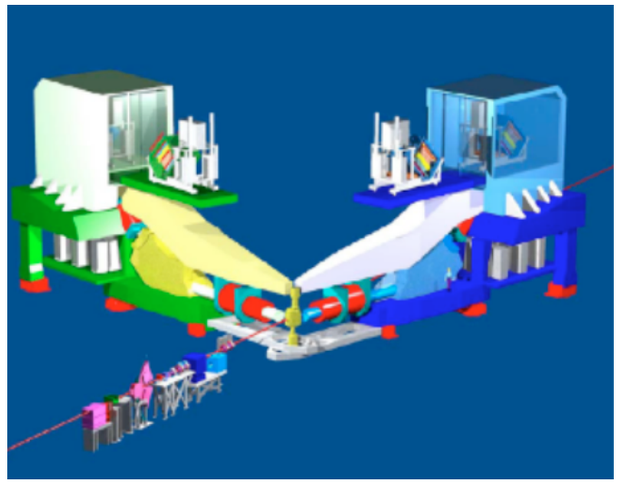
$\sqrt{B}$

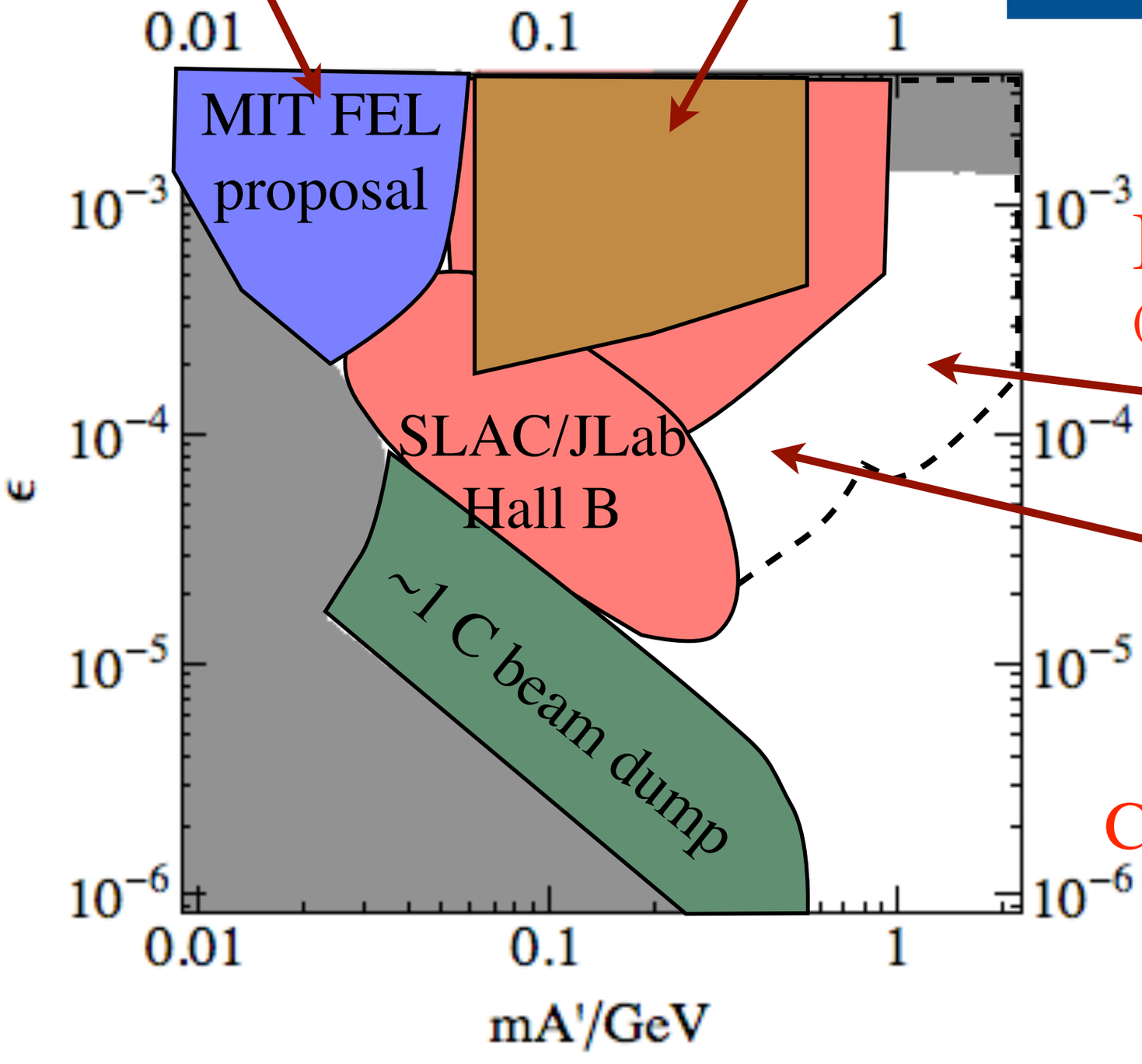
[P. Fisher, J. Thaler]

[see: Freytsis, Ovanesyan, Thaler]



JLab
Hall A
(24 days)





Improvements:

(not 1-year time scale, maybe <<5)

Sensitivity with existing beams
but better acceptance

Pixel tracking extends reach

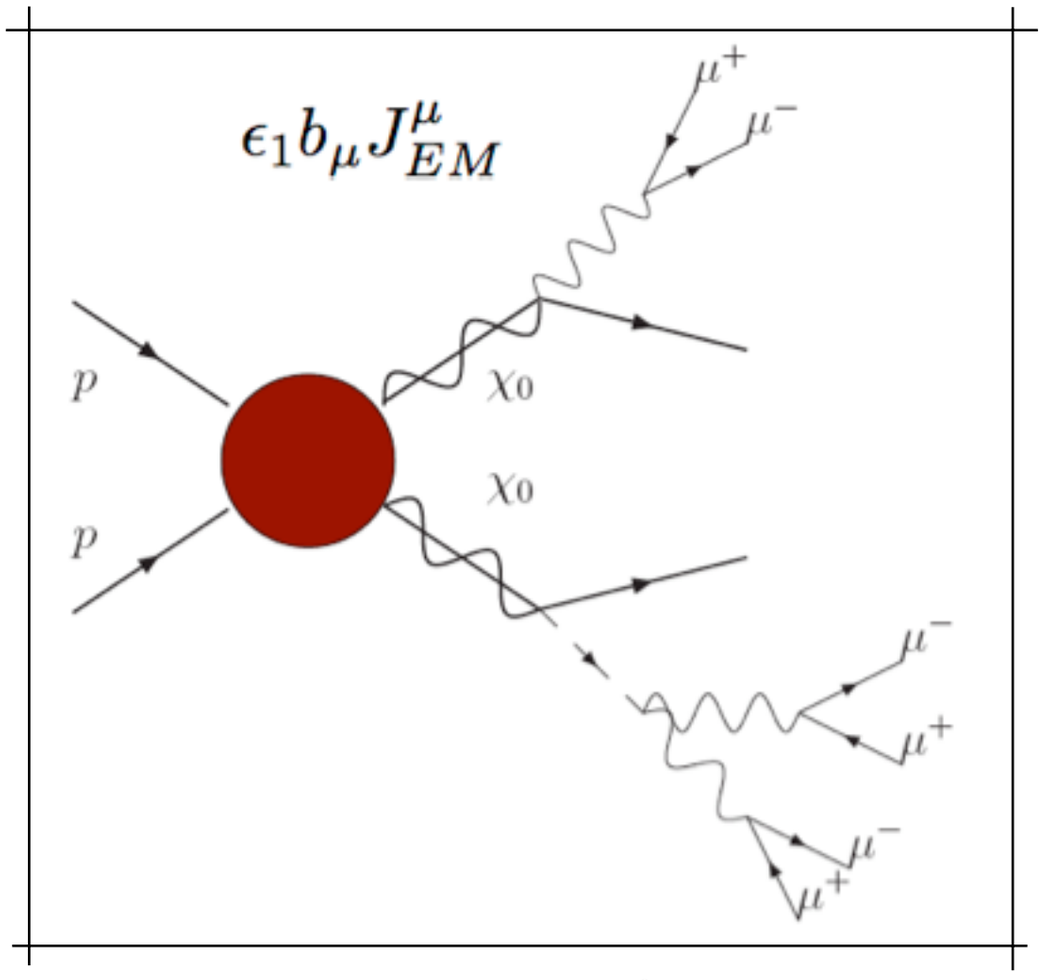
Final version of SLAC/JLab
experiment may have extended reach

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

Indirect Production at Hadron Colliders

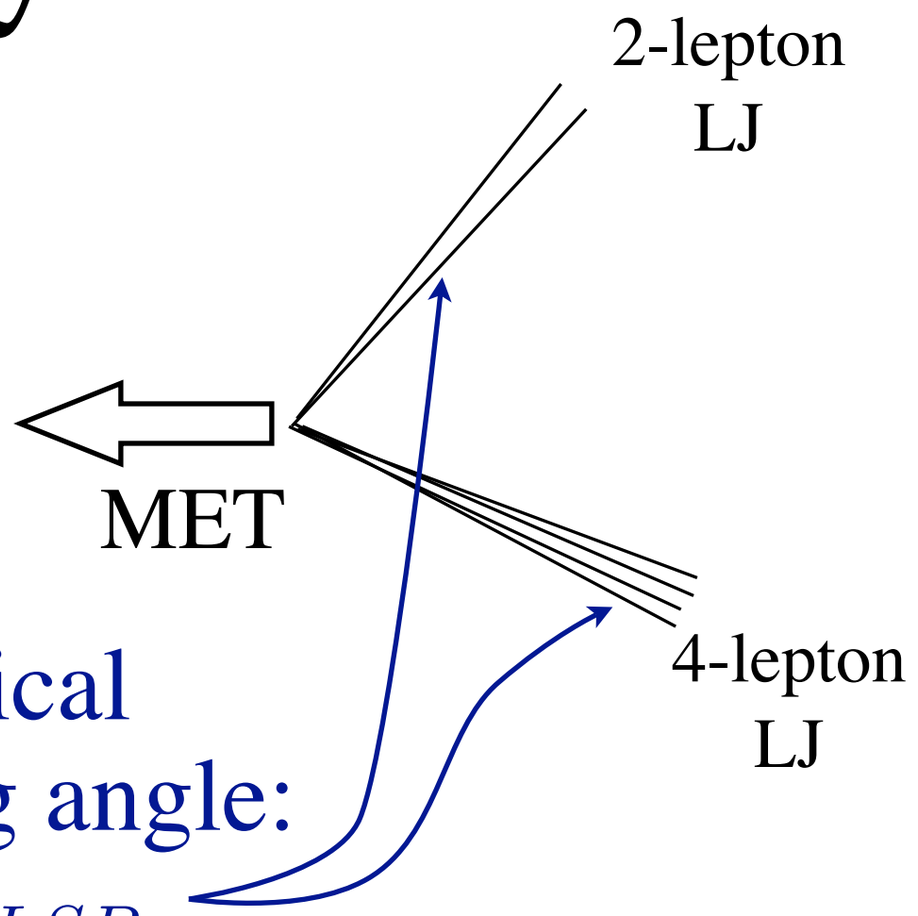
discovering SUSY **and** Dark Forces

LSP Decay



[I. Yavin]

(see Cheung et al 0901.0283)



Branching fraction ~ 100%:
NO dependence on epsilon!

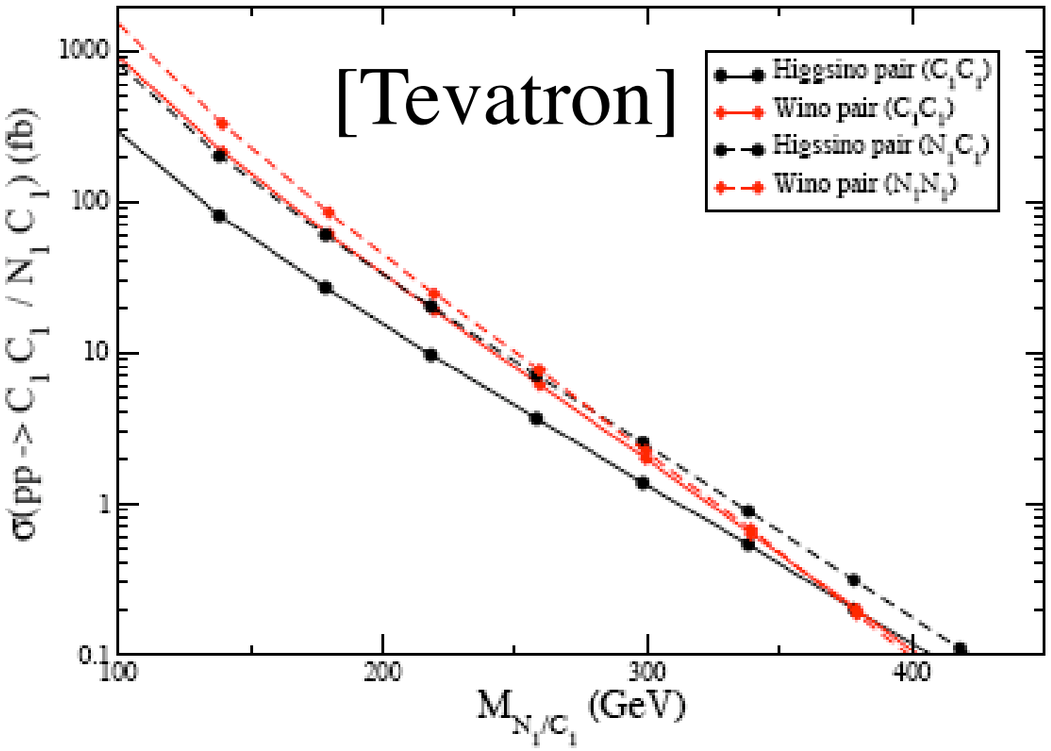
- The only ϵ-dependence is from the A' lifetime:

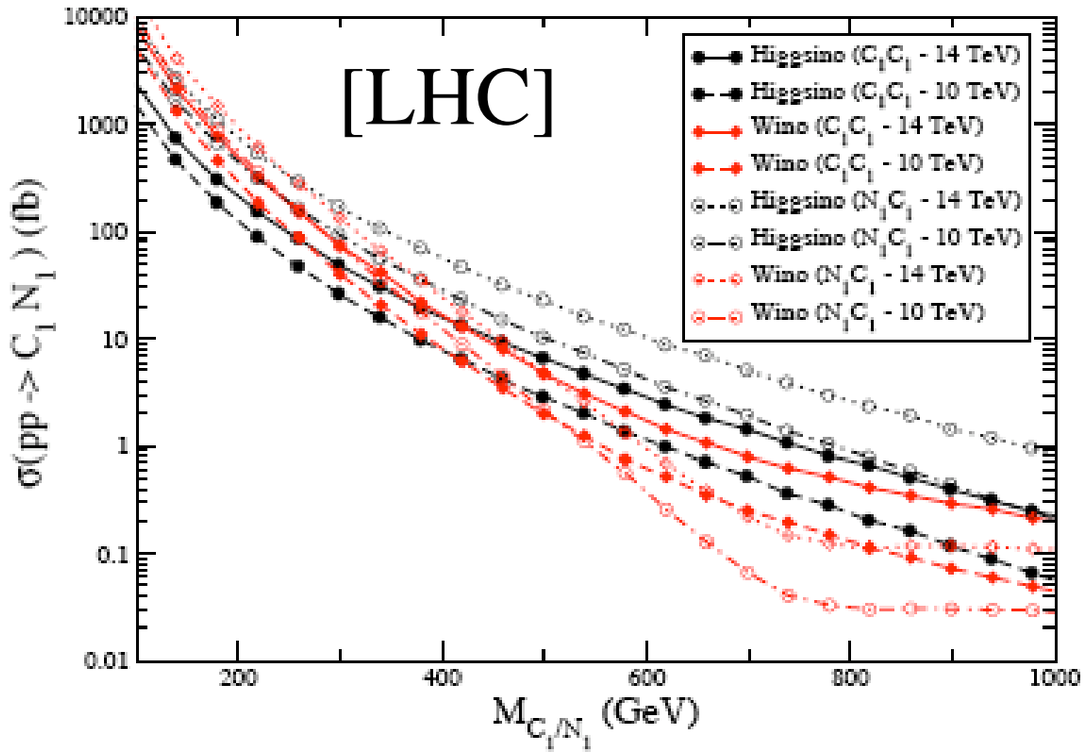
$$\gamma c\tau \approx 1\text{mm}\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{\text{m}_\chi}{100\text{GeV}}\right)\left(\frac{1\text{GeV}}{\text{m}_{A'}}\right)^2$$

  - $\varepsilon \gtrsim 10^{-4}$: Prompt
  - $10^{-4} \lesssim \varepsilon \lesssim 10^{-5}$: Displaced, decay in beam pipe/inner tracker
  - $10^{-5} \lesssim \varepsilon \lesssim 10^{-6}$: Decays in detector (10 cm – 10 m) – no LJ?
- 3-body decays about factor of 10 longer.

- If low-energy SUSY provides the production mode, this is a great way to see dark sectors.

LHC/Tevatron Reach





* This is for a squark mass of 750 GeV.

These are large cross-sections.
Some of the parameter space can already be excluded by Tevatron searches…

Experimental Efforts

Several experimental groups are working on (designing) searches for lepton-jets

1) A. Haas and Y. Gershtein for D0 - Phys. Rev. Lett. 103, 061801 (2009), arXiv:0905:3381

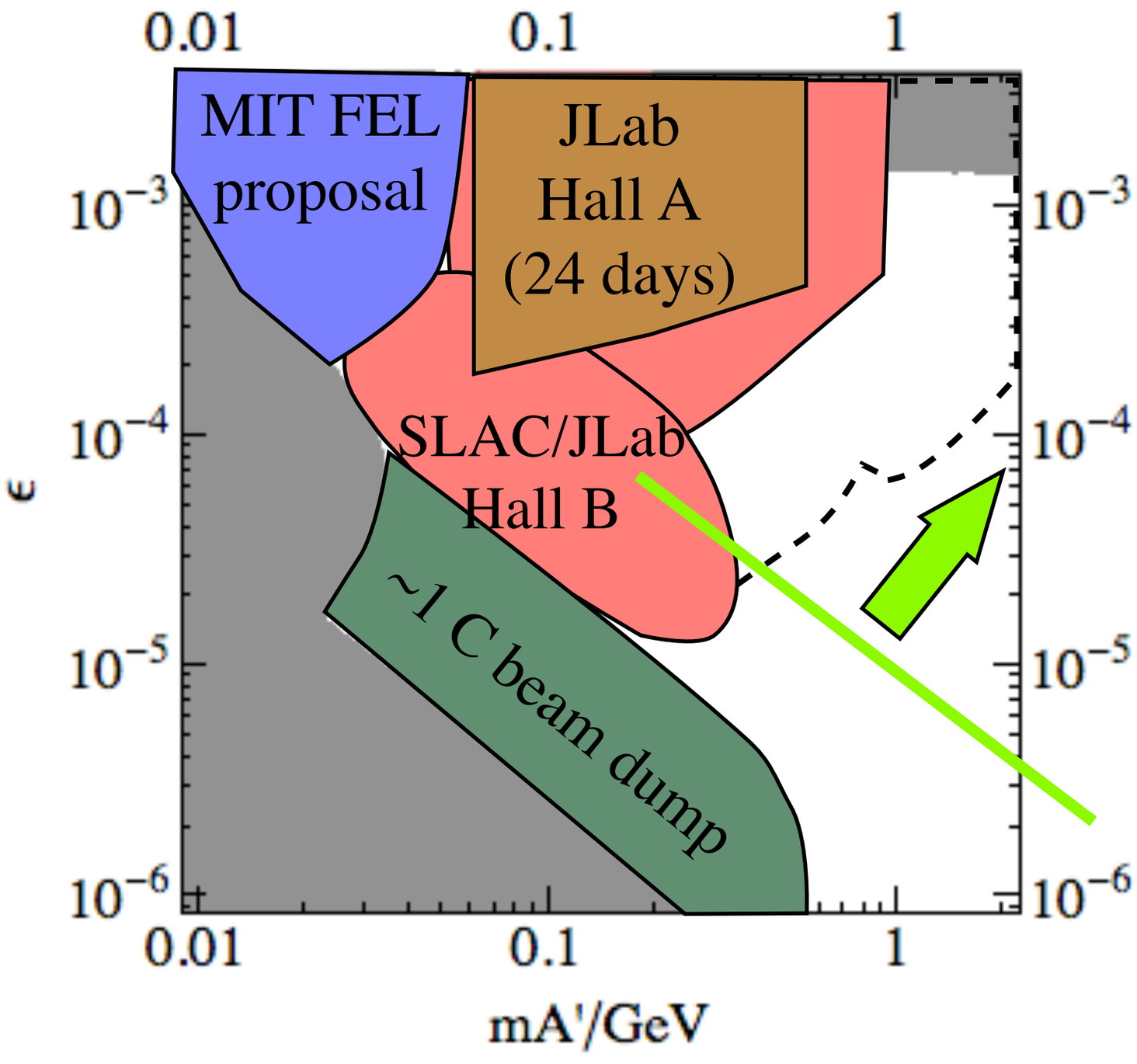
2) B. Demirkoz and R. Moore for ATLAS - designing proper triggers for lepton jets.

3) K. Cranmer and the NYU group - lepton jet gun.

4) H. Lubatti and the Washington group - triggering on long lived neutral particles.

5) V. Halyo for CMS - searches for lepton jets.

6) Searches at BaBar - See all the local experts.

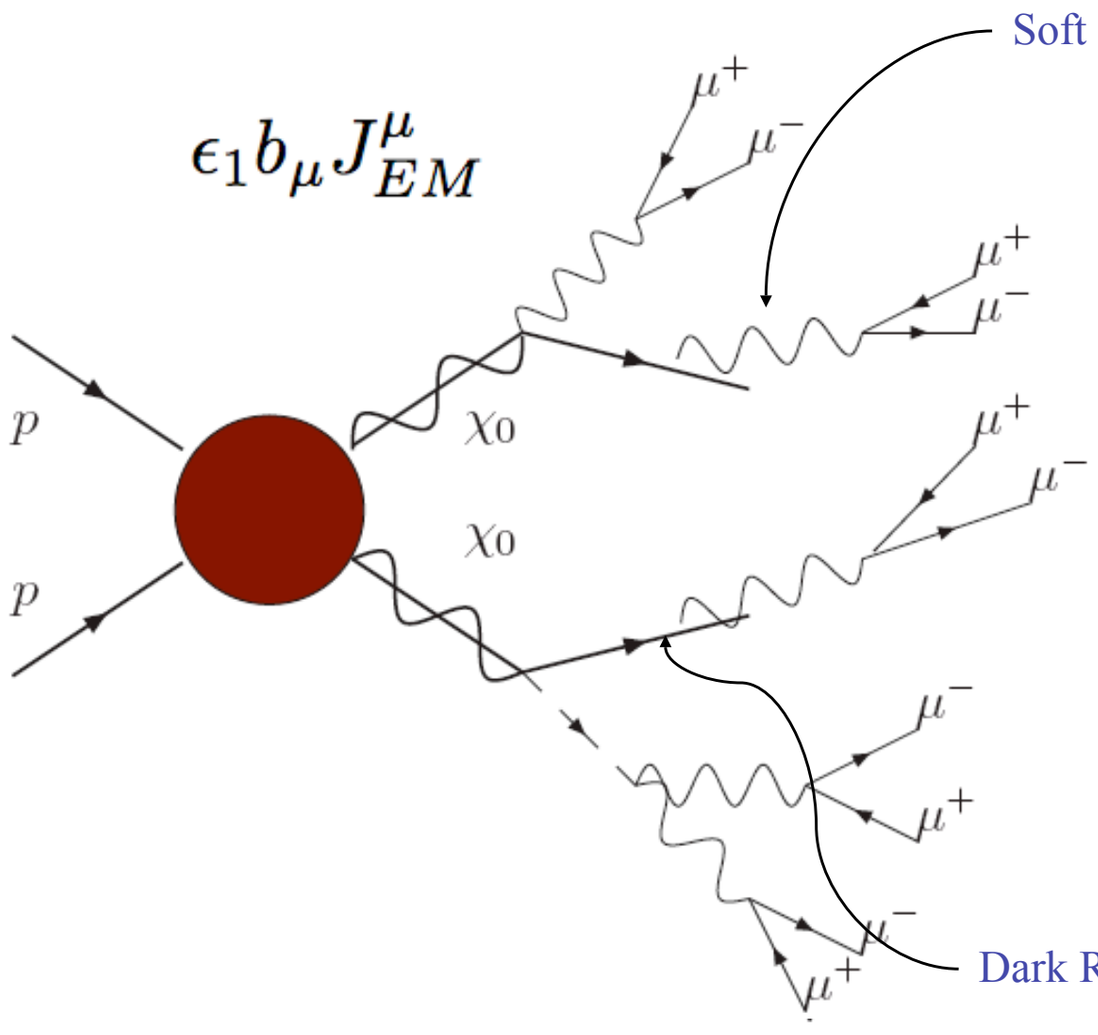


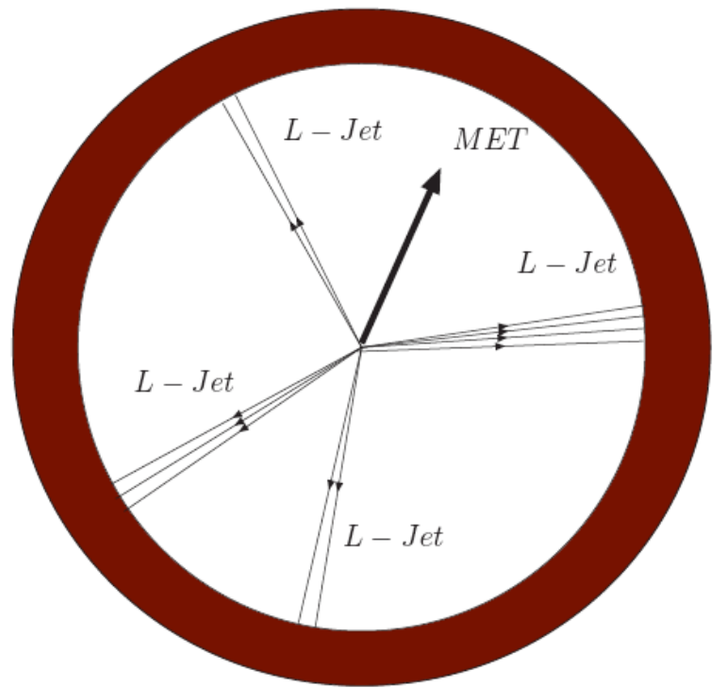
Indirect production from low-energy SUSY **(if it's there)**

LSP Decay with Dark Cascades or Radiation

Neutralino Decay

The bottom of the SUSY cascade is no longer stable (Arkani-Hamed and Weiner). It will decay into the dark sector. A clean channel is electroweak-ino production (Cheung et al.)





Jets + Lepton Jets + MET

- Also sensitive to squark/gluino production (higher cross-section!)

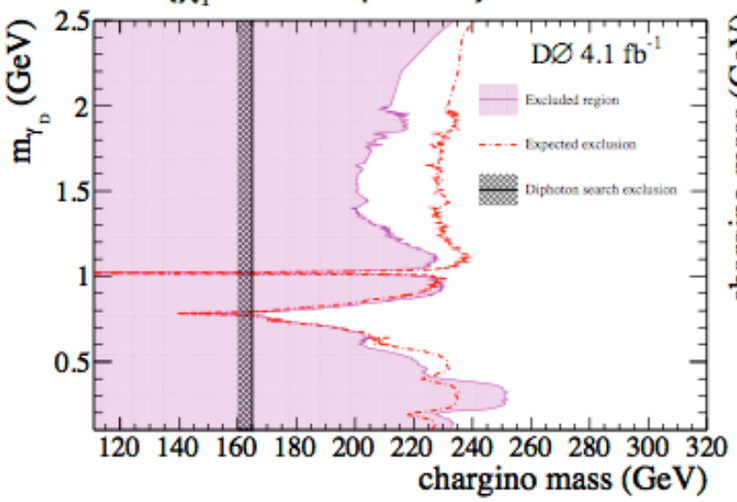
- At the same time, the decays may spoil conventional SUSY searches
  - Lepton jets fail both lepton-veto and isolated-lepton requirements?
  - MET lower than expected, since “LSP” momenta are split between the true-LSP and the lepton-jet.

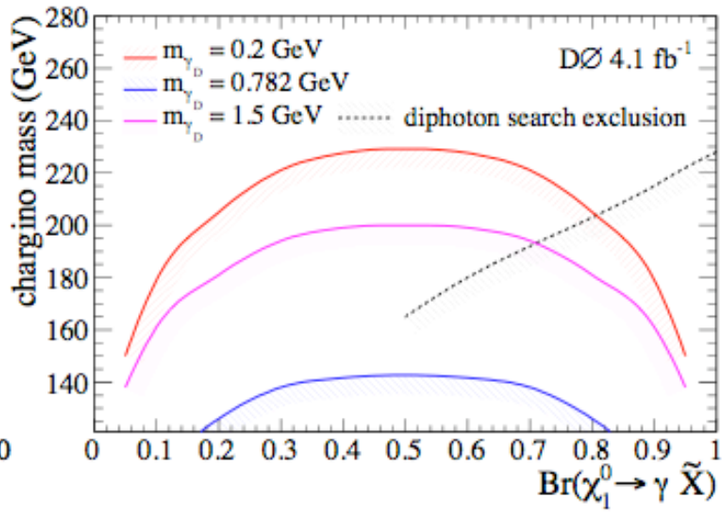
- SUSY bounds probably considerably weakened!

Model Limits

- Use mGMSB model line that was a benchmark for SUSY searches in CDF and DØ – Snowmass Slope SPS8
  - make neutralino decay into a dark photon and a massless invisible particle
- Snowmass slope parameters
  - Λ – varies
  - $M_m = 2 \cdot \Lambda$
  - $N_5 = 1$
  - $\tan\beta = 15$
  - sign $\mu = +1$

Br(χ_1^0 → dark photon) = 0.5

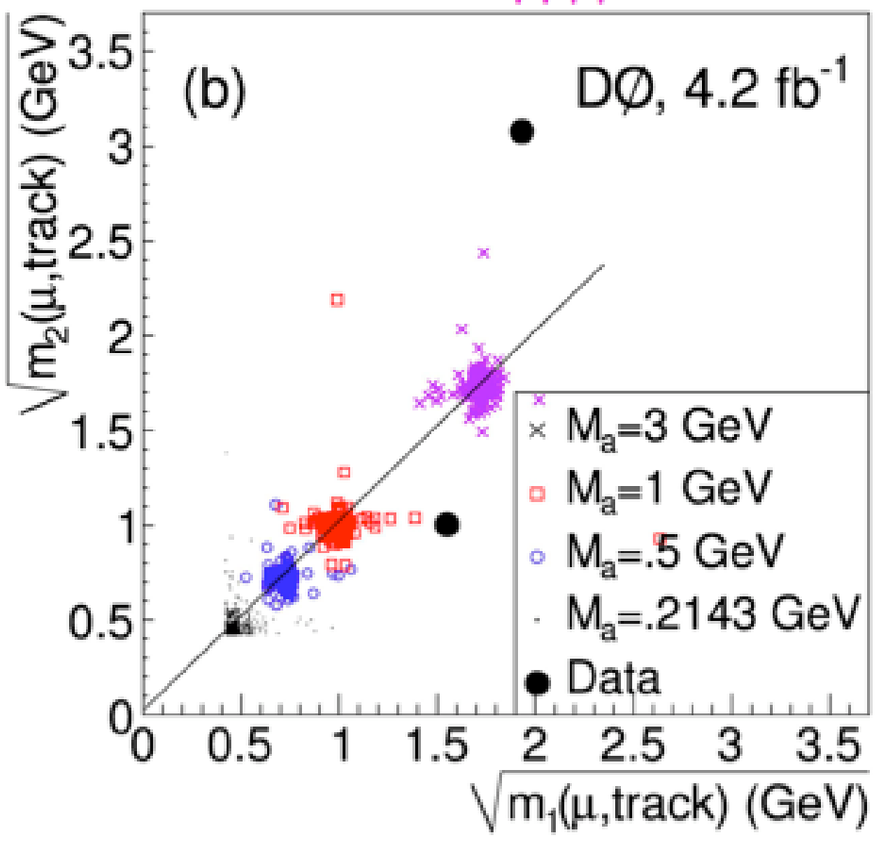




Phys. Rev. Lett. 103, 081802 (2009)

[Y. Gershtein]

h→aa→μμμμ



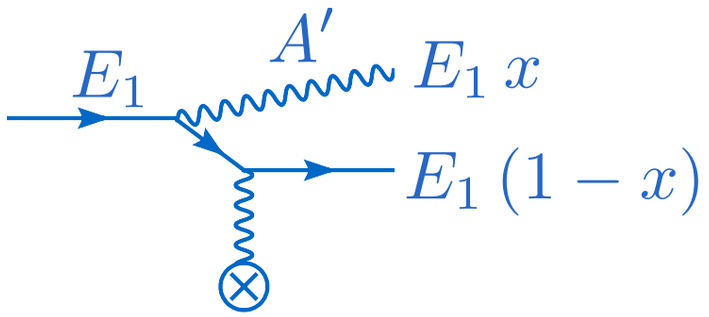
muon p_T>10 GeV,
companion track p_T> 4 GeV
no other significant cuts

[A. Haas]

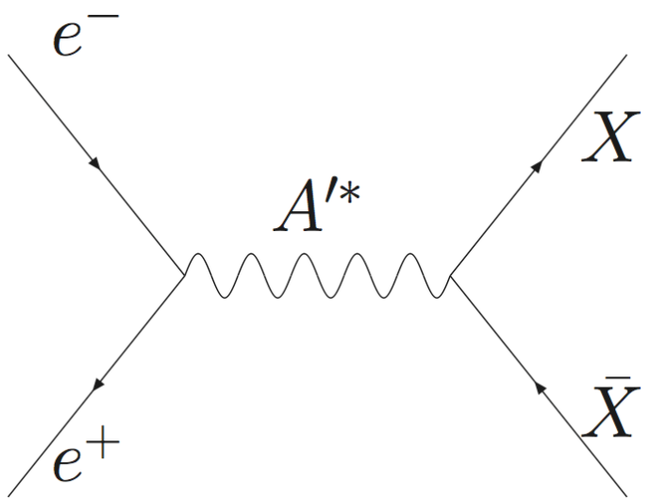
Low backgrounds suggest sensitivity even with no invariant mass requirements on LJ's.

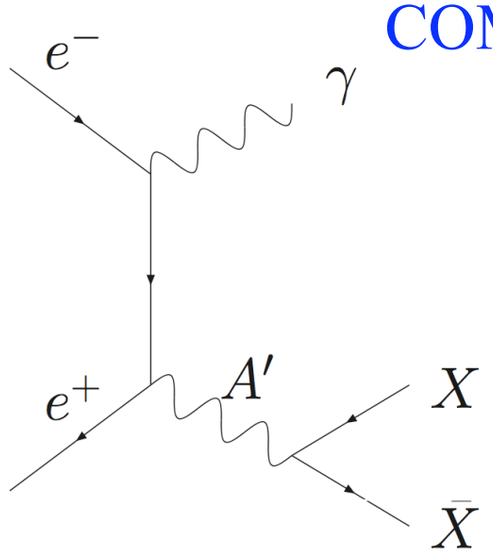
Dark Forces are (Very!) Testable

Dark Matter Observations: Gamma rays, direct detection (Fermi, XENON 100, LUX)

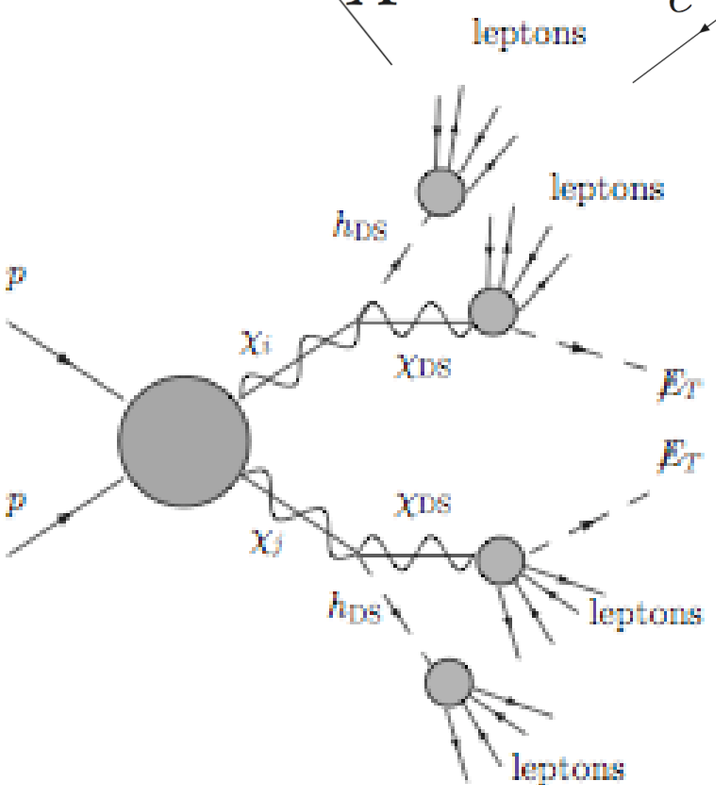


Fixed-Target: Electron or Proton collisions, A' decays to di-lepton, pions, multiple channels (Jefferson Lab (Hall A, Hall B/CLAS), SLAC, MAMI (Mainz), ELSA (Bonn), XFEL (DESY), COMPASS (CERN), FNAL, ...)





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, CMS & ATLAS)