The Theory and Phenomenology of Dark Forces at the GeV Scale

Frascati Seminar
April 14, 2010

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 & 1003.4729)
R. Essig, N. Toro, B. Wojtsekhowski (1001.2557)
R. Essig, J. Kaplan, N. Toro (1004.0691)

Dark Forces at the GeV Scale

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

The Search for New Forces – Summary

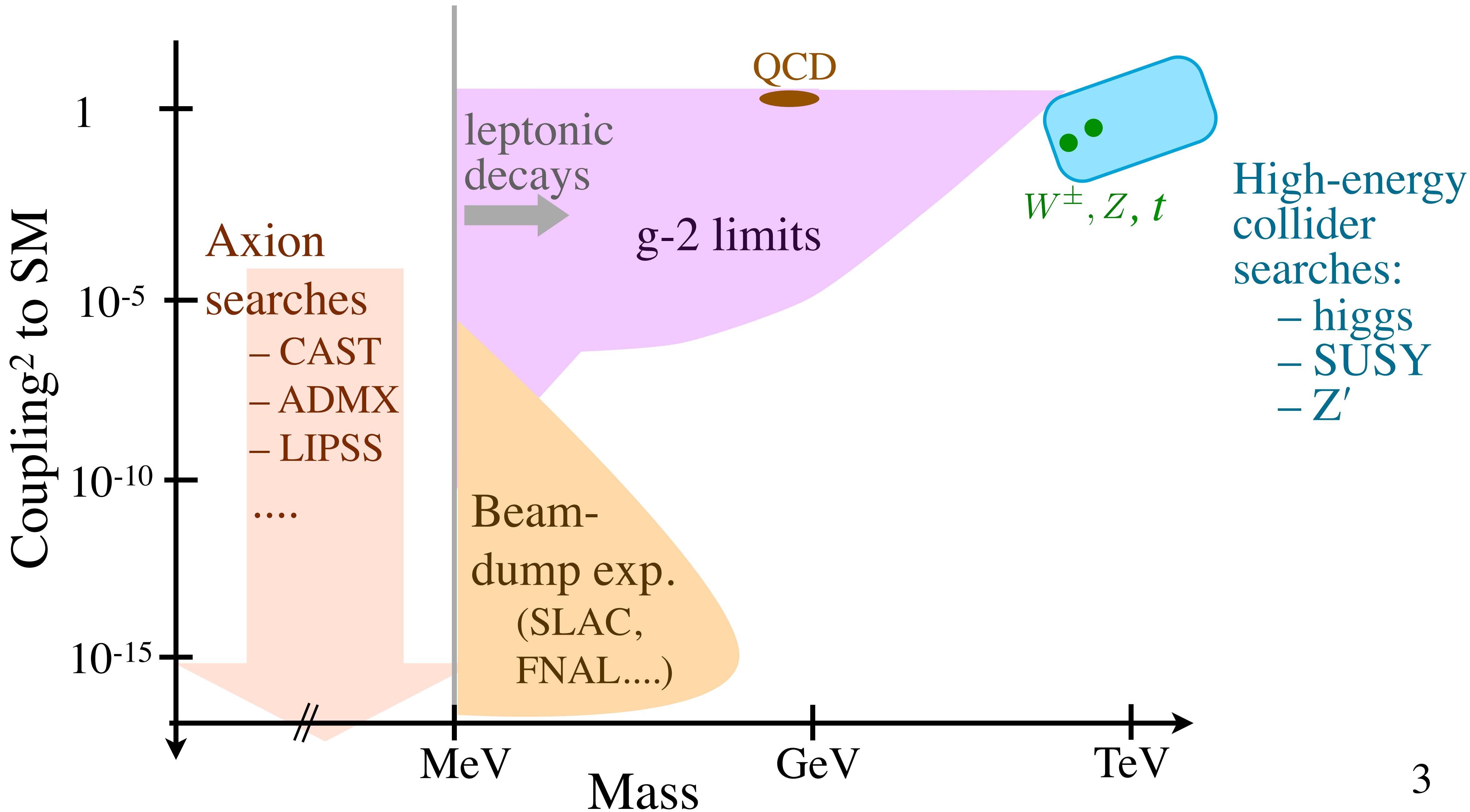
Standard Model | **New Forces?**

strong — g

weak — $W^{\pm}, Z$

electromagnetic — γ

??? — A'

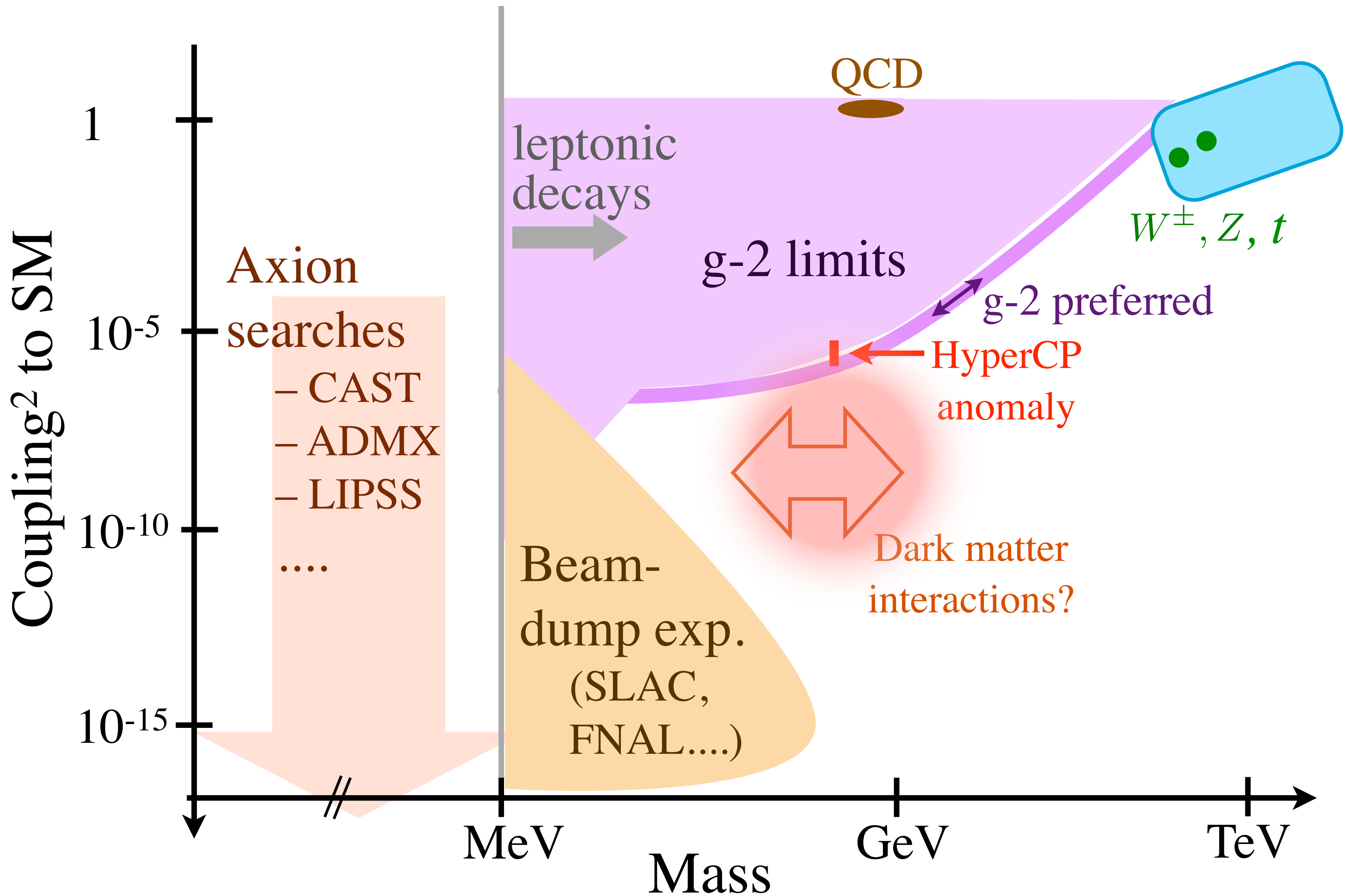


Standard Model

New Forces?

strong weak electromagnetic ???

g $W^{\pm}, Z$ γ A'

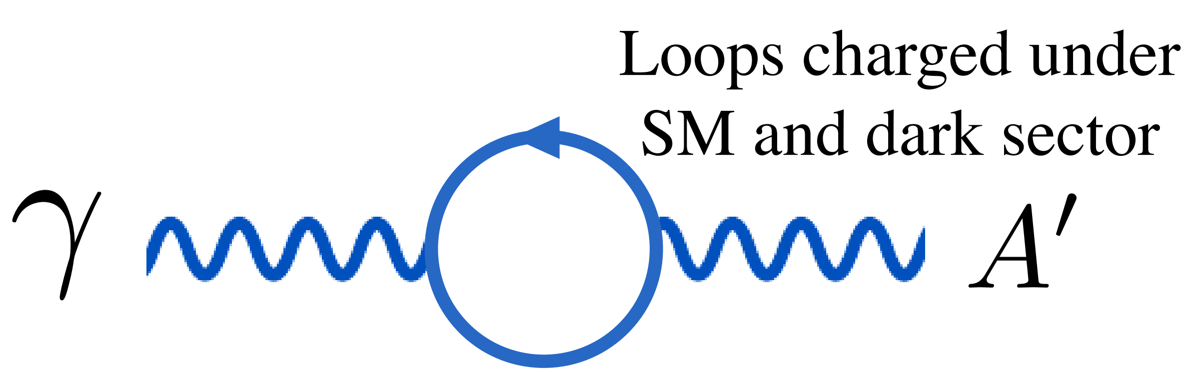


High-energy collider searches:
- higgs
- SUSY
- Z'

A Simple U(1) Example

Gauge kinetic mixing is a "portal" that can link the Standard Model to new dark forces

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



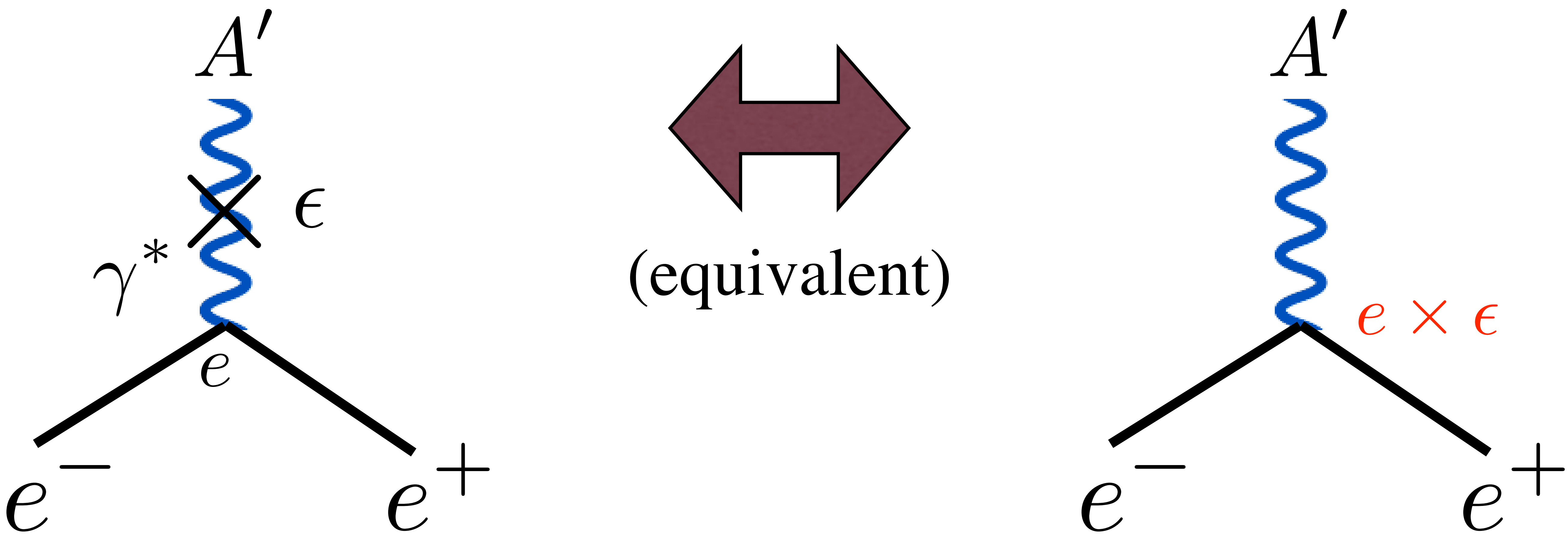
GUT or Planck scale quantum corrections

[Holdom '86]

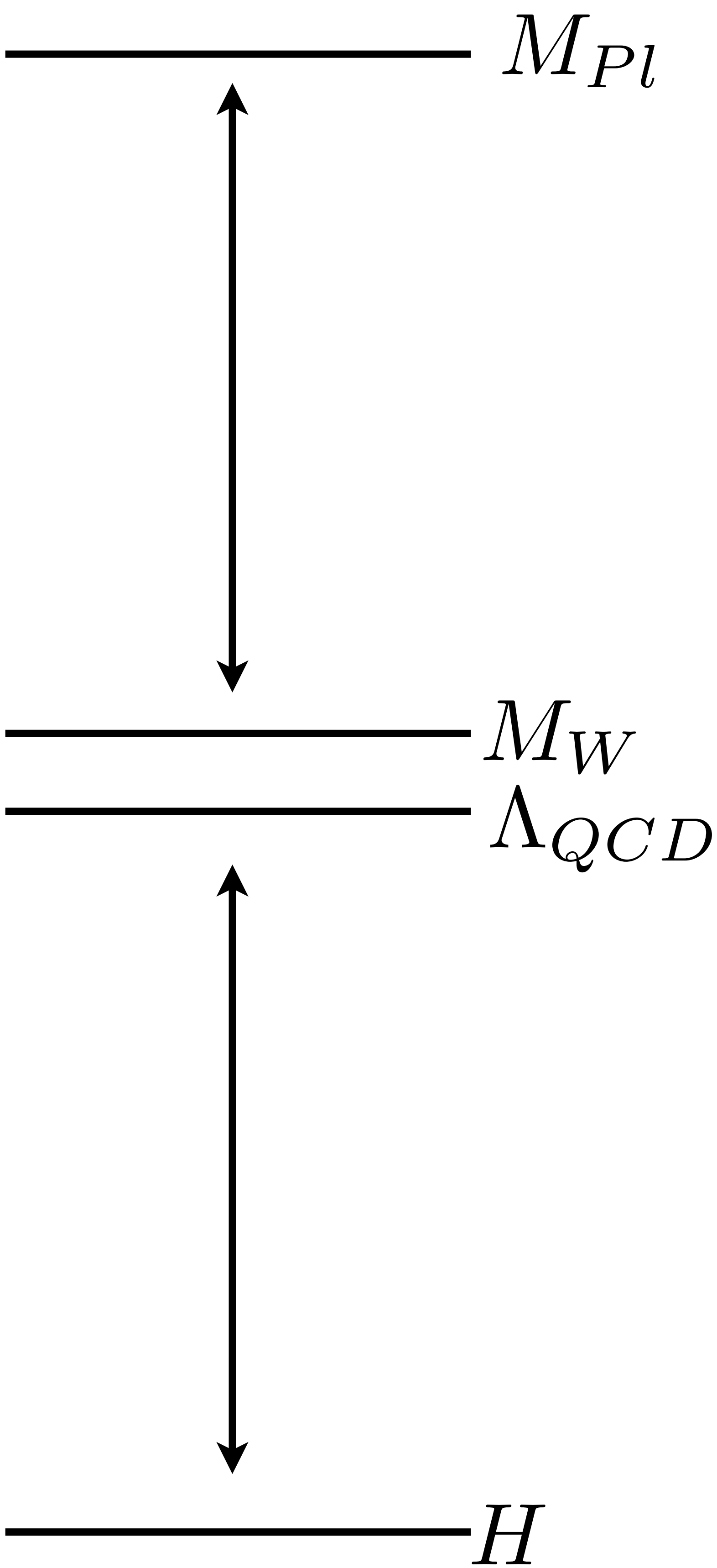
$$\epsilon \approx \frac{g_D g_Y}{16\pi^2} \sum_i q_{D,i} Y_i \; \ln \frac{\Lambda^2}{\mu_i^2} \quad \sim 10^{-4} - 10^{-3}$$

Ordinary Matter and Dark Forces

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



Mass Scales



Weak coupling to dark sector is natural, but what about the mass scale?

GUT or Planck scale?

Massless?

Nearly massless?

Anywhere (technicolor like dark sector) ?

What about the weak-scale?

New U(1) Near The Weak-Scale

Assume that weak-scale SUSY exists, and couple the Standard Model to a dark sector via kinetic mixing.

Supersymmetric kinetic mixing:

$$\mathcal{L} \supset \int d^2\theta \frac{\epsilon}{2} W_Y^\alpha W_{A'\alpha} + \text{h.c.}$$

Dark sector matter:

$W = \mu_D H_+ H_-$ or $W = \lambda S H_+ H_-$

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

New U(1) Near The Weak-Scale

Dark U(1) and hypercharge U(1) D-terms mix

Dark Sector D-term Potential:

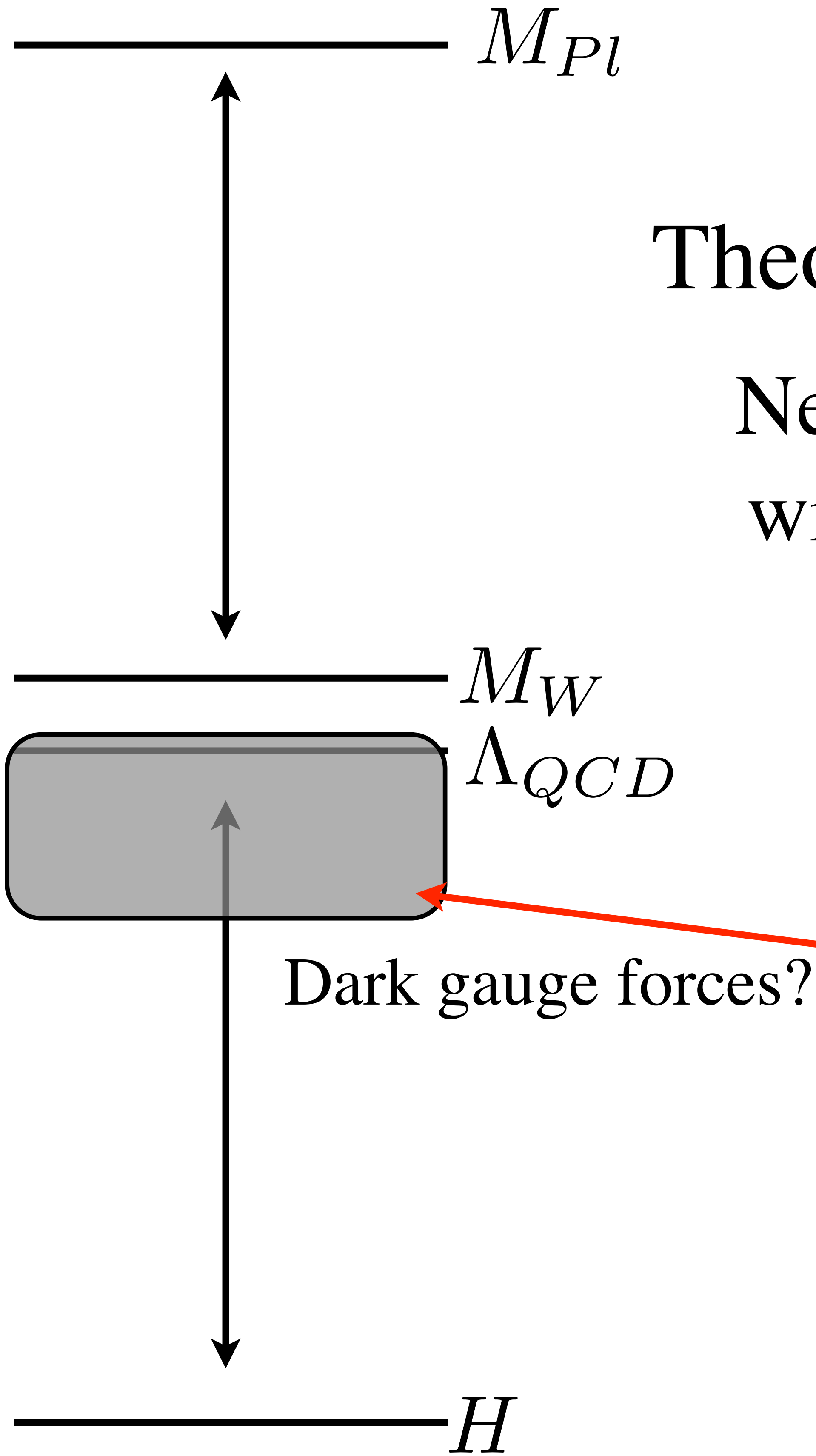
$$V_D \sim g_D^2(|\phi_D|^2 - \frac{\epsilon g_Y}{g_D}|H_{SM}|^2)^2$$

Electro-weak symmetry breaking triggers dark U(1) breaking:

$$m_{A'}^2 \sim \epsilon \frac{g_D}{g_Y} M_W^2 \lesssim (1\mathrm{GeV})^2$$

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

New Dark Gauge Forces - Where to Look?



Theoretical Region of Interest:

New weakly coupled gauge interactions with mass scale beneath the weak scale

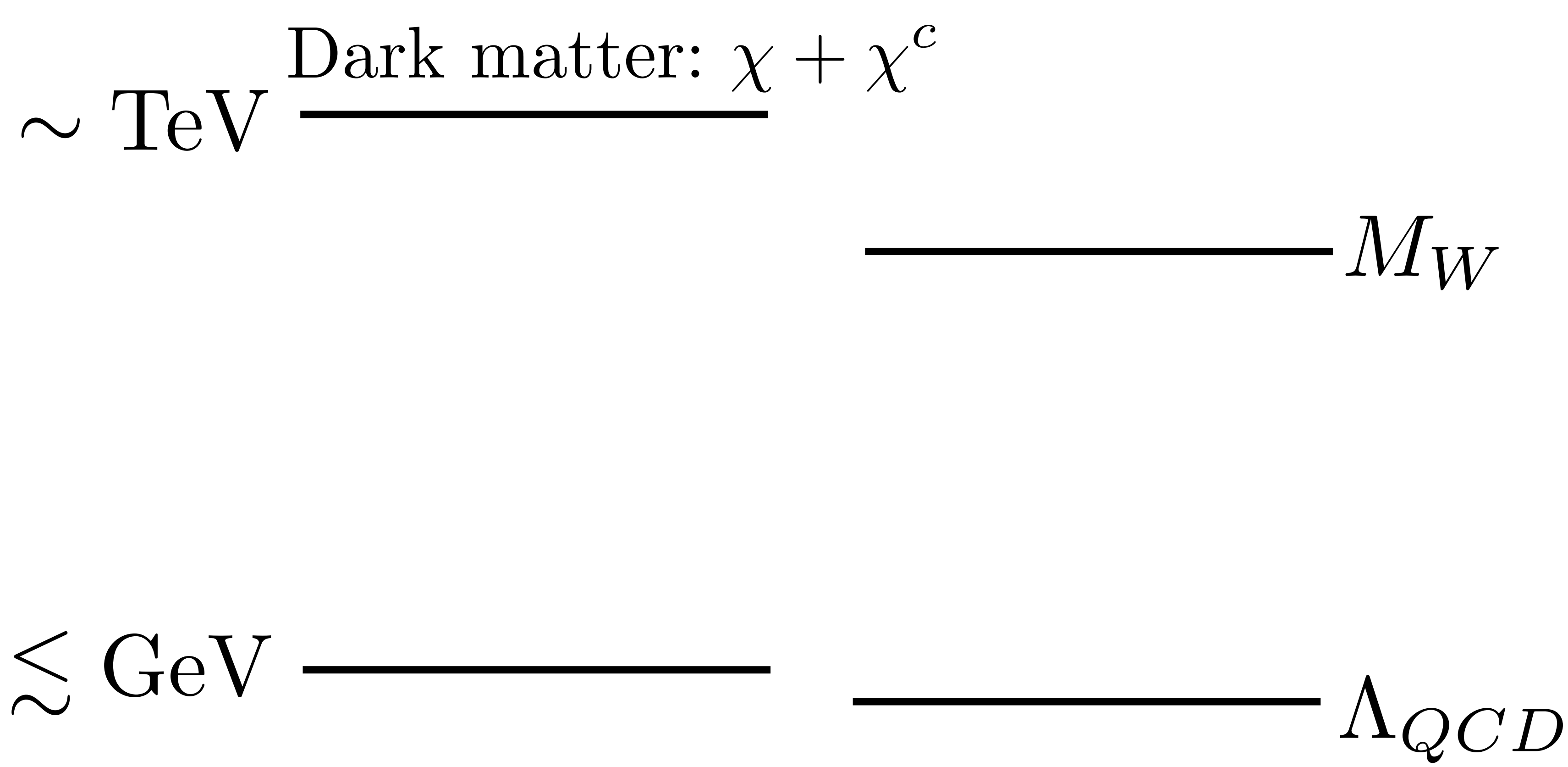
A good place to explore!

Phenomenological Motivation

What if dark matter belongs to a dark sector

Suppose that dark matter is a TeV mass thermal relic charged under a dark U(1) that kinetically mixes with the photon

Dark Sector   Standard Model



Dark Matter Charged Under a GeV-Scale Gauge Force

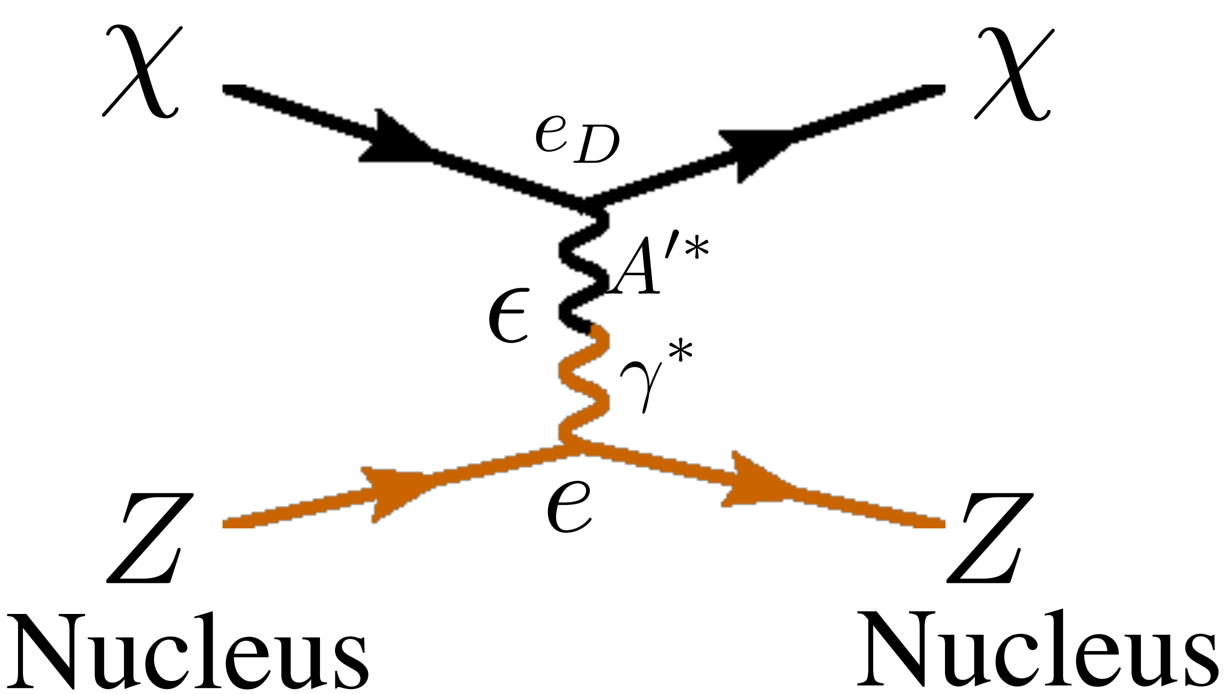
Several Striking Consequences:

- Annihilation enhanced at low velocities
- Annihilation or decay into light, not heavy states
- Additional GeV-scale Dark Matter species

- Excited states split by O(MeV)
- Scattering off matter:
  - rate similar to neutral current
  - inelastic scattering

Dark Matter and Dark Forces

Direct Detection Rates:



$$m_{A'}^2 = \epsilon \frac{q_i g_D \cos 2\beta}{2 g_Y} M_W^2$$

$$\downarrow$$

$$A \sim \frac{e_D e \epsilon}{m_{A'}^2} \sim \frac{e^2}{M_W^2}$$

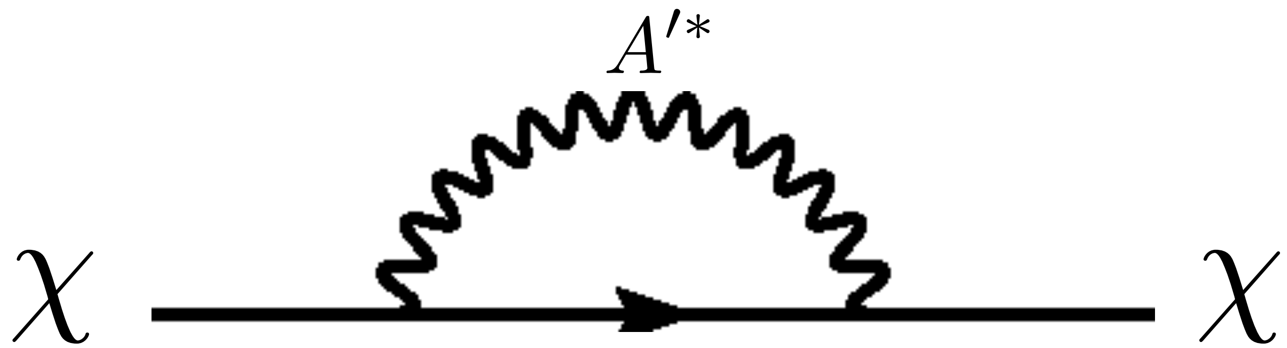
Despite lack of SM charge, dark matter can naturally have weak-scale scattering rates with ordinary matter!

Dark Matter and Dark Forces

Very small dark matter mass splittings:

[Tucker-Smith and Weiner;
Arkani-Hamed, Finkbeiner, Slatyer, Weiner]

In Non-Abelian dark sectors, radiative effects can split dark matter states



$$\delta M_{DM} \sim \alpha_D \delta M_{gauge} \sim \alpha_D^2 M_{gauge} \sim O(\mathrm{keV}-\mathrm{MeV})$$

(radiative splittings) (custodial symmetry breaking)

Dark Matter and Dark Forces

Very small dark matter mass splittings:

TeV-scale dynamics also generates small splittings from higher-dimension operators:

$$\delta W = \frac{1}{M_{\mathrm{TeV}}} h_d^2 \Phi_{DM}^2$$

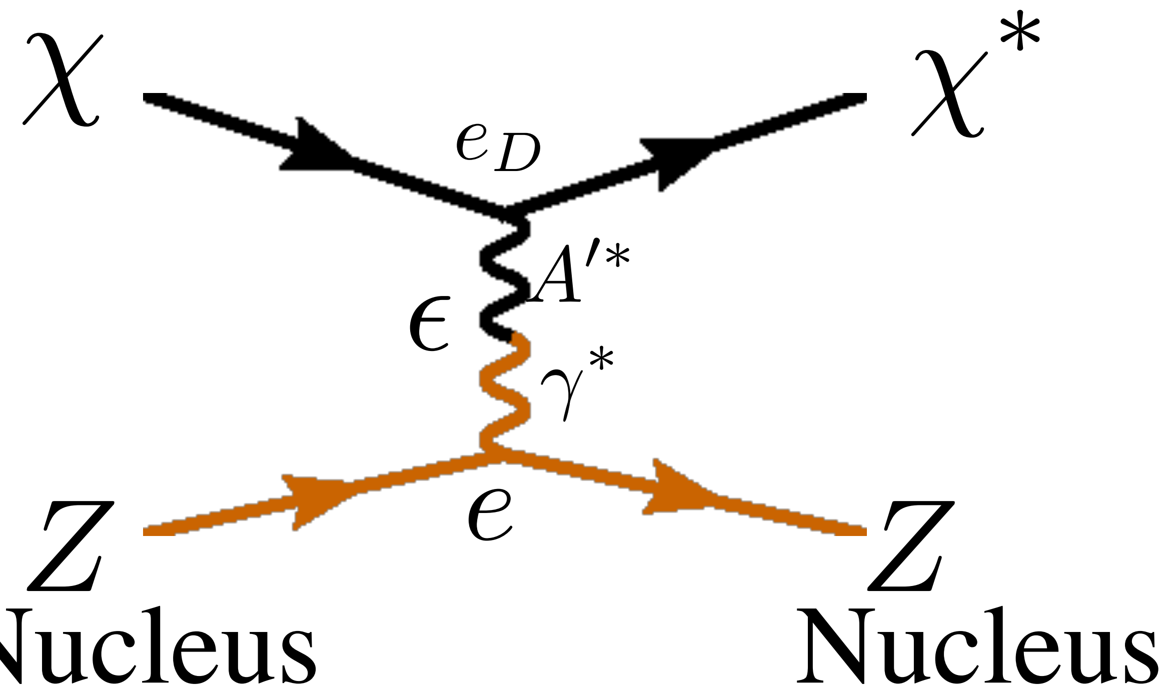
(super-potential term)

$$\delta M_{DM} \sim \frac{\langle h_{dark} \rangle^2}{M_{\mathrm{TeV}}} \sim O(\mathrm{keV} - \mathrm{MeV})$$

Dark Matter and Dark Forces

Inelastic Scattering:

$$\delta M_{DM} \sim O(\mathrm{keV} - \mathrm{MeV})$$



Vector mediated scattering is automatically inelastic

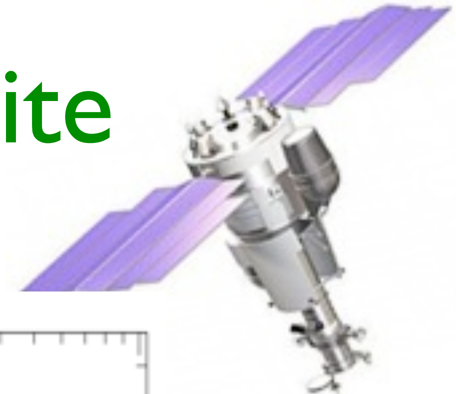
Dark Forces at the GeV Scale

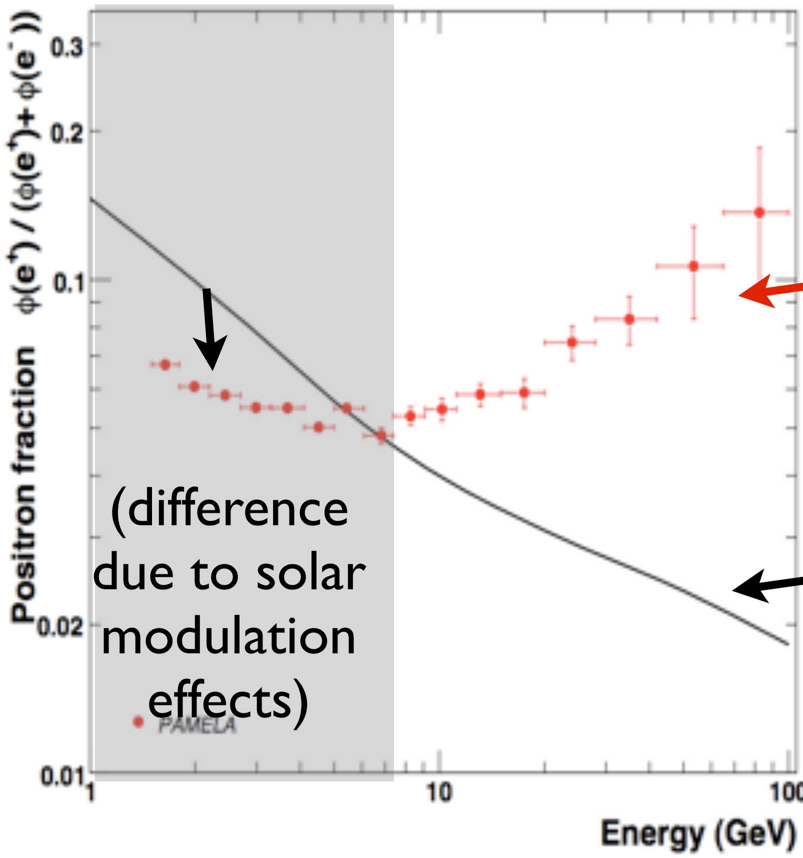
- Theory of New Vector Bosons (**and hints from dark matter**)
- e+e- Collider Searches (Babar, Belle, KLOE)
- Fixed-Target Experiments (e.g. @ JLab)

Satellite Data – Dark Matter Anomalies?

PAMELA satellite

Nature, 2009
(~1 citation/day)

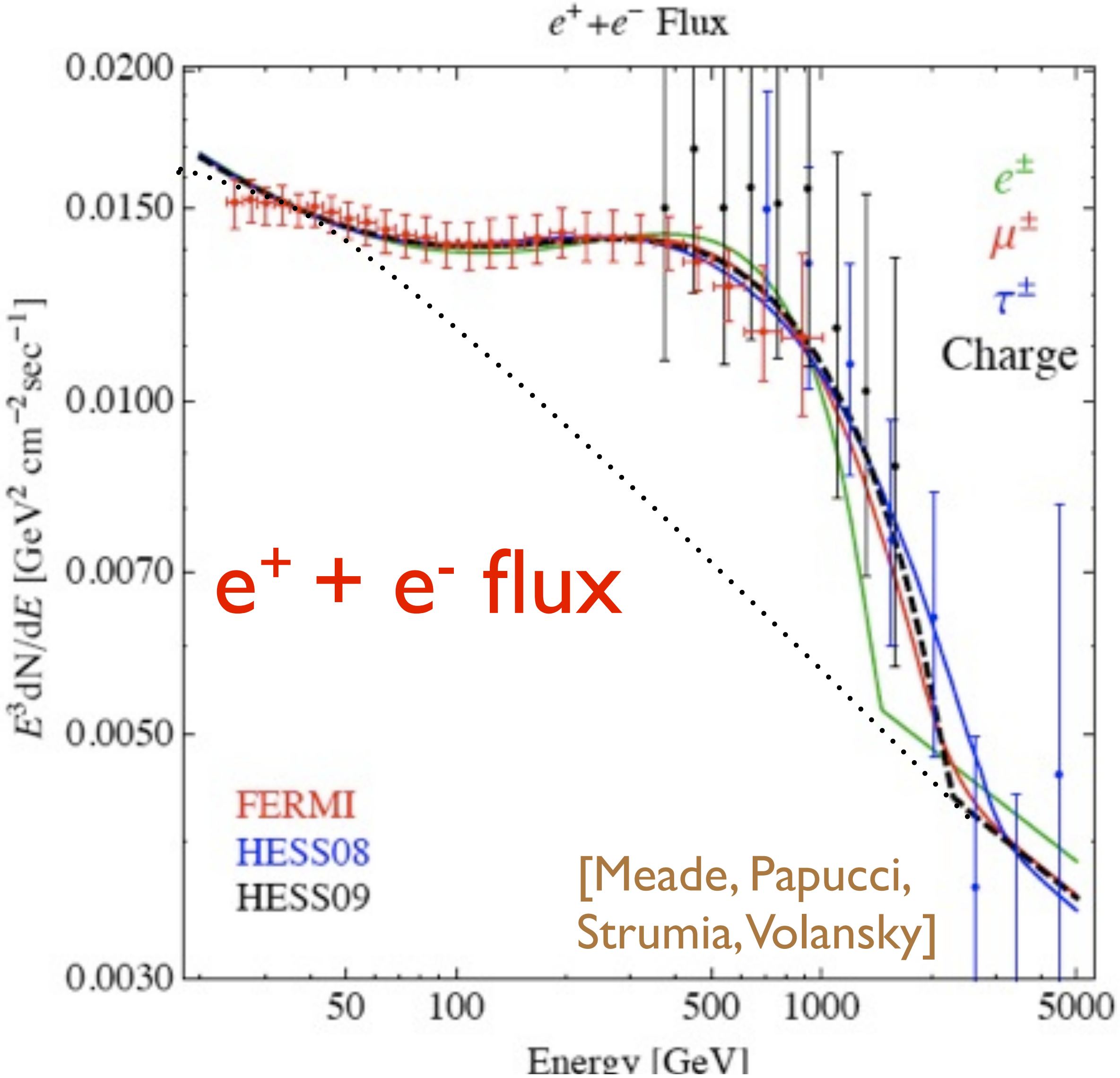




New e+ source

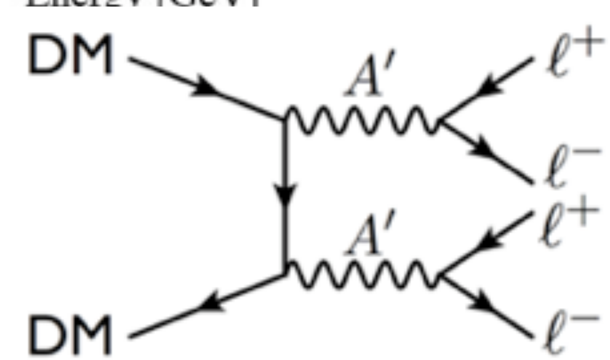
theory expectation

Fermi satellite, HESS



$e^+ + e^-$ flux

[Meade, Papucci, Strumia, Volansky]



e^+, e^- energy $\sim m_{DM} \sim$ TeV

These and related anomalies are compatible with annihilation of ~TeV dark matter into Standard Model leptons. (also compatible with diffuse microwave, gamma-ray sources claimed by Finkbeiner et. al.)

Dark Matter Anomalies – why a new force?

1) No antiproton excess observed!

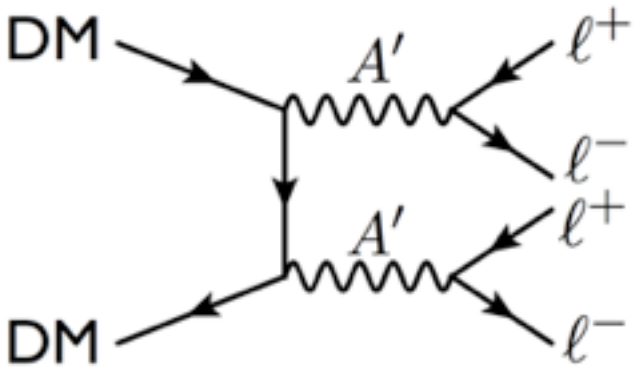
– not consistent with annihilation into g, $W^{\pm}$, Z

$\Rightarrow$ new force?

– suggests $m_{A'} \lesssim 1$ GeV

$\Rightarrow$ decay to protons is kinematically forbidden,

$$A' \to \ell^+\ell^-, \pi^+\pi^-$$

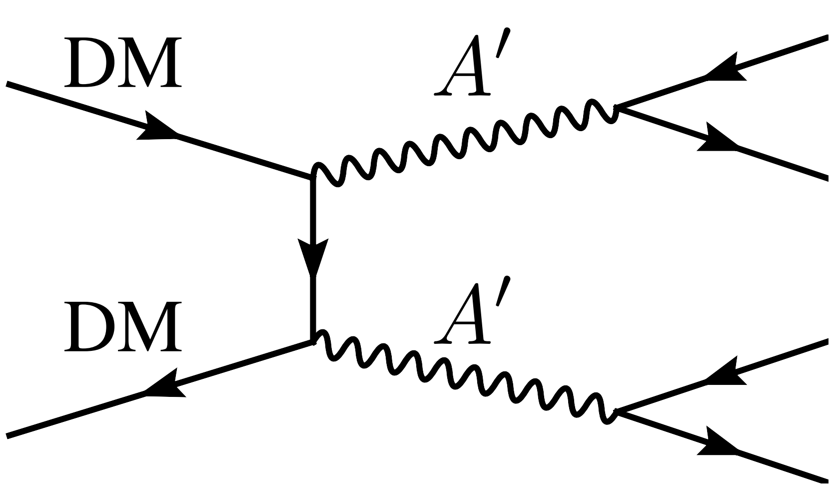


2) Observed annihilation rate is large!

– consistency with standard cosmology requires attractive force with range $\gg 1/m_{DM} \Rightarrow$ again suggests $m_{A'} \lesssim 1$ GeV

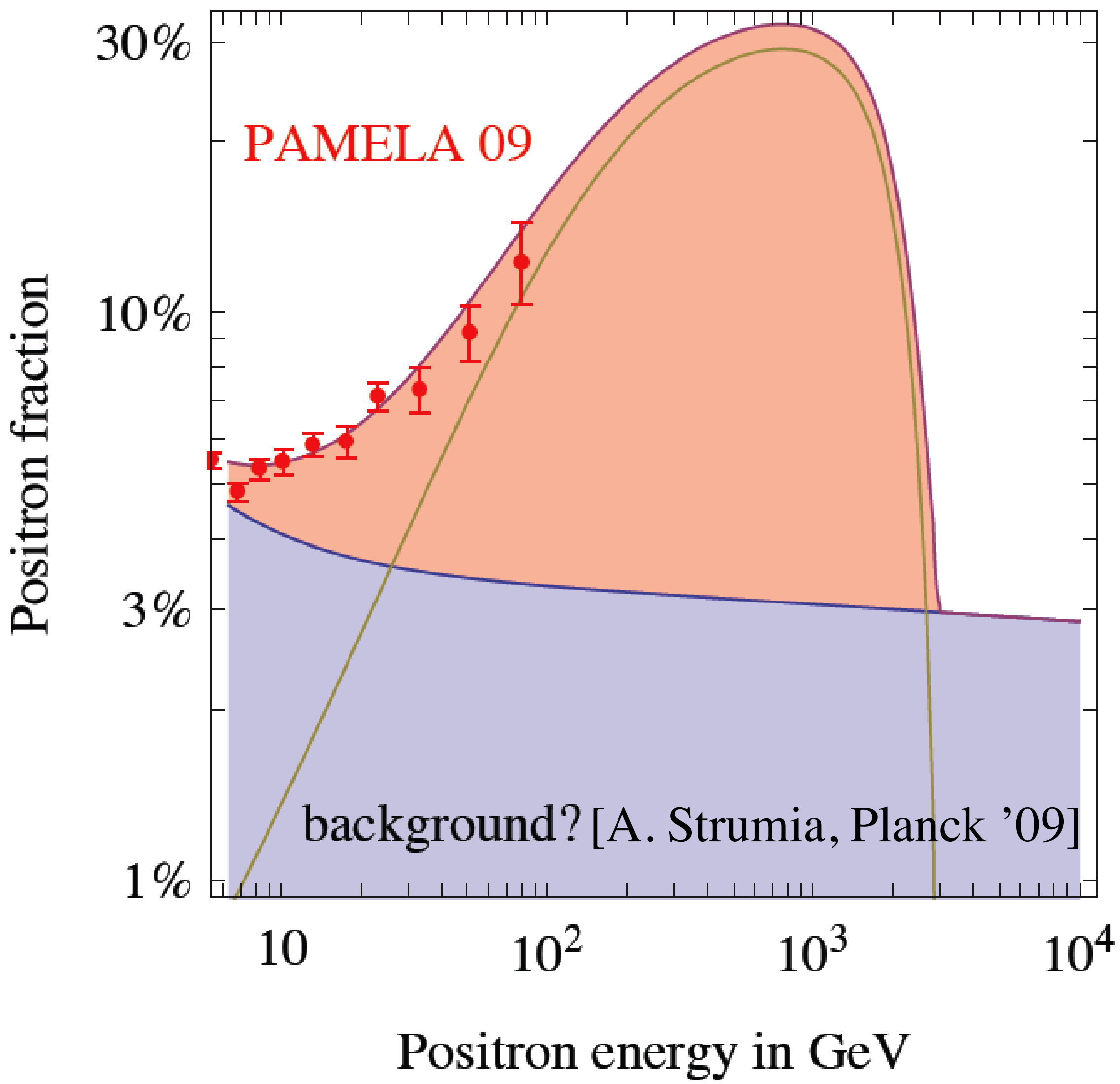
[Cholis, Goodenough, Weiner;
Arkani-Hamed, Finkbeiner, Slatyer, Weiner;
Pospelov & Ritz]

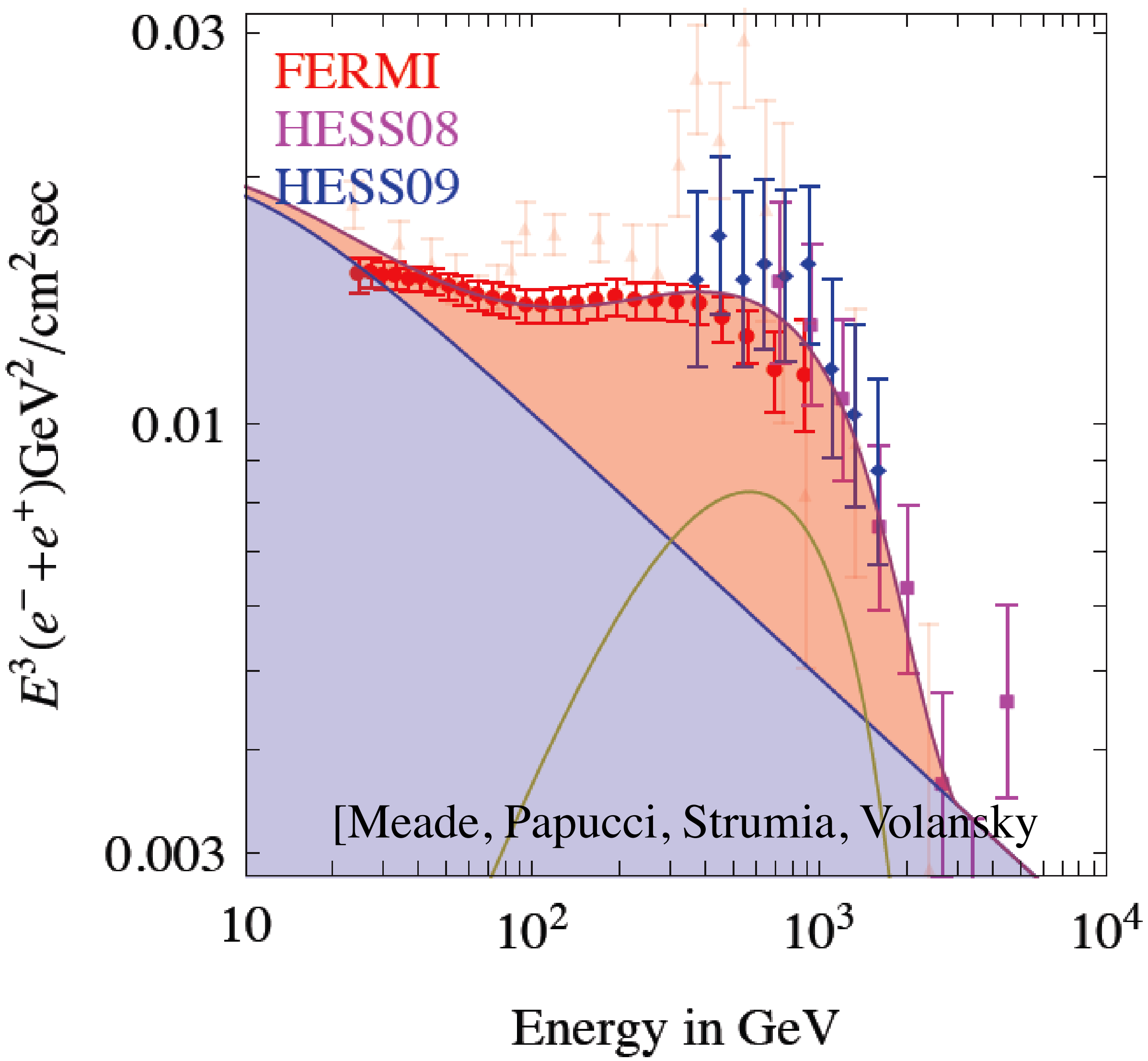
Dark Matter Annihilation or Decay into Leptons



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

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



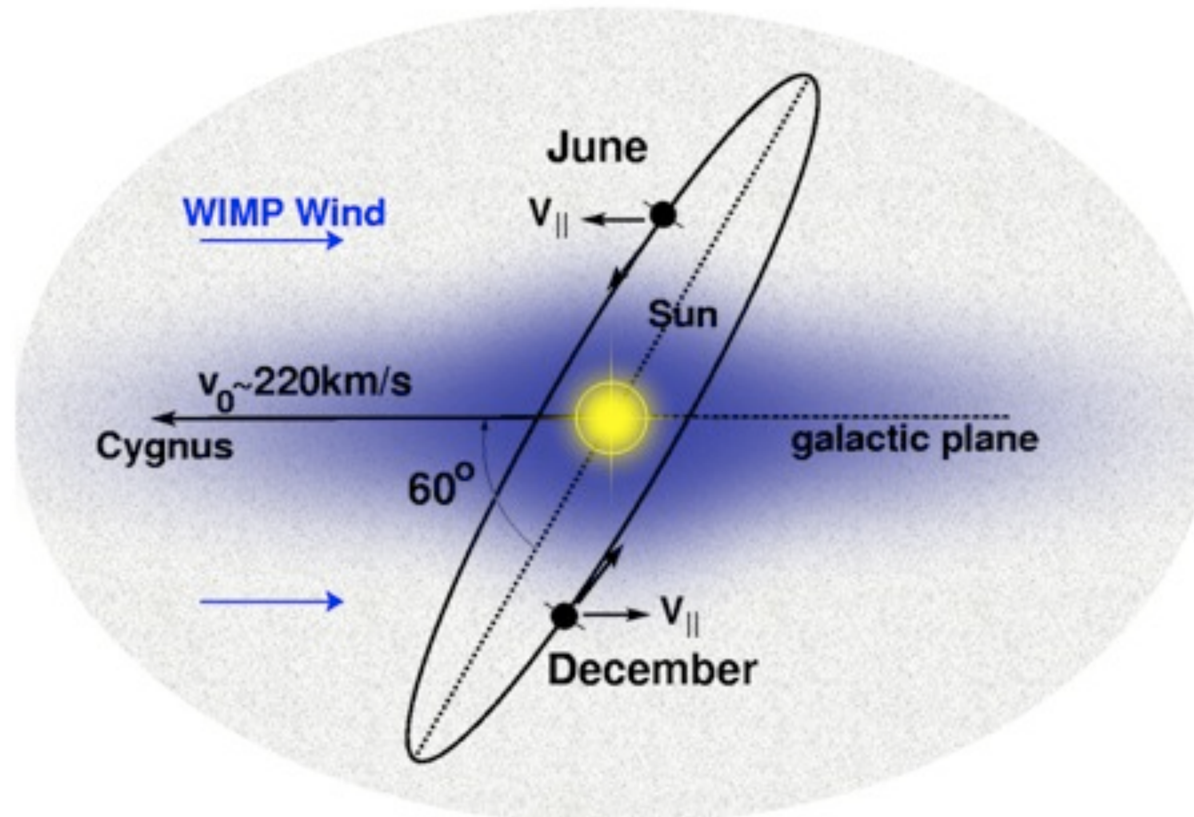


DAMA Annual Modulation

A decade of modulation

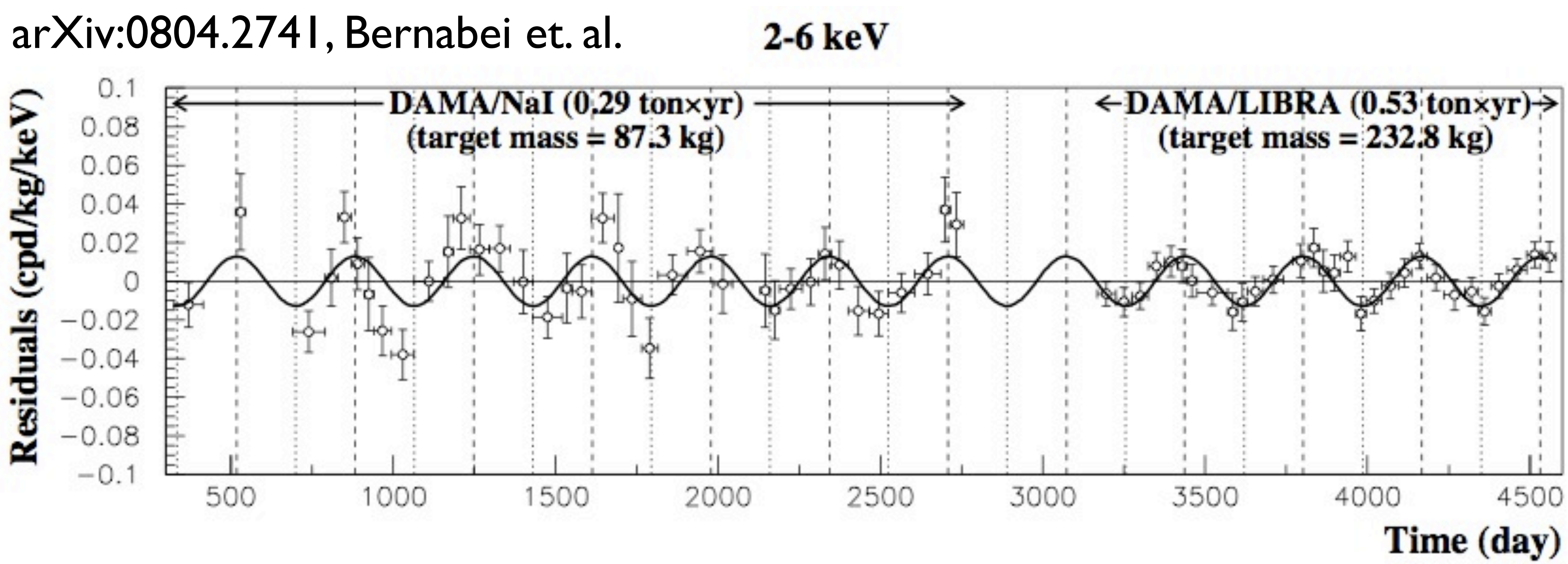
Precisely in phase

...but unusual



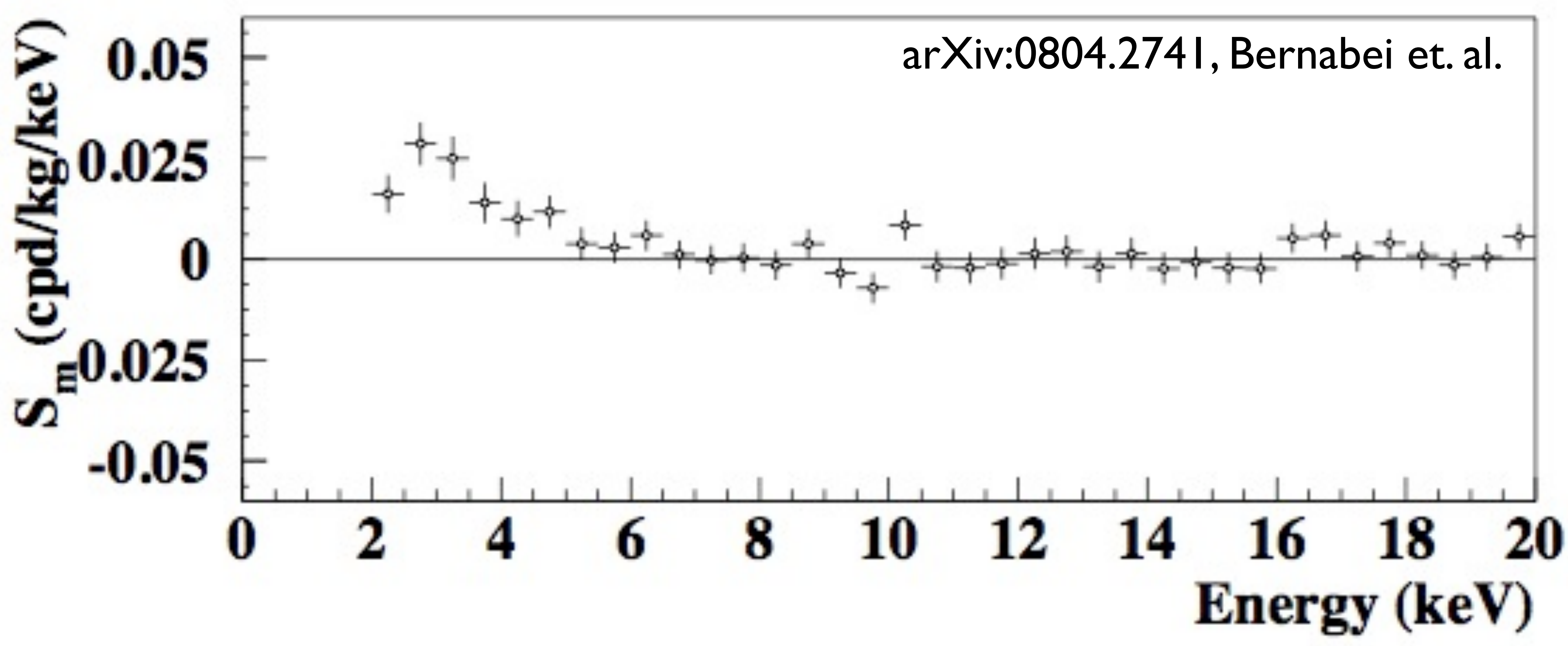
Sheffield PPPA Group WebSite

arXiv:0804.2741, Bernabei et. al.



A Distinctive Recoil Spectrum

Modulation
Amplitude

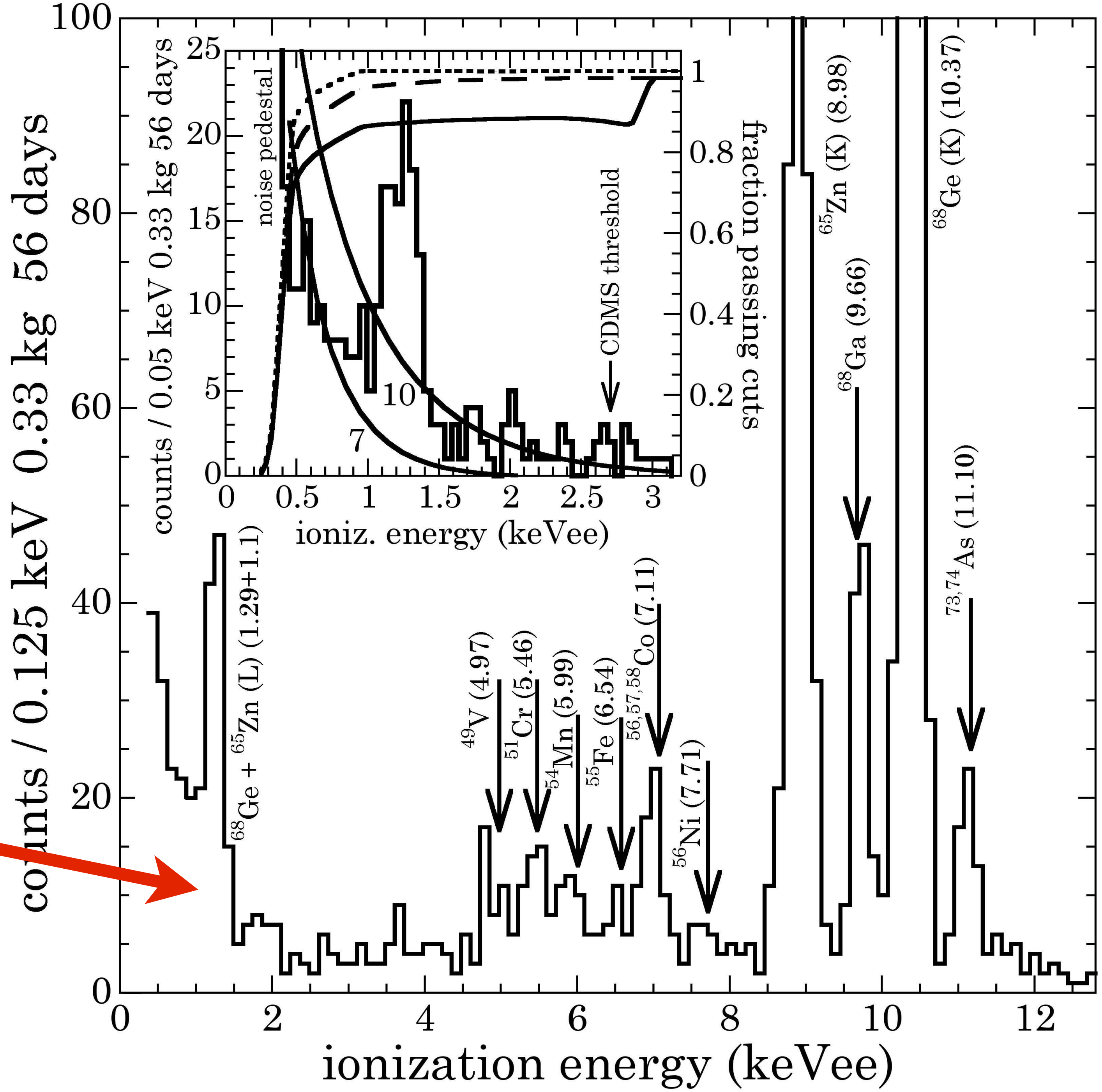


A dip at low energy?

The CoGeNT Anomaly

[arXiv: 1002.4703]

Falling component of events



Suggestive, but much more needs to be done to rule out background possibilities...

Can GeV-scale dark sectors possibly explain direct detection data?

Possible Origin of Light Dark Matter Species

Dark Sector:

$\sim$ TeV ———————

Dark matter: $\chi + \chi^c$

Heavy (~TeV) stable components dominate the dark matter mass density

(small annihilation cross-sections)

Particles from the dark-force sector (the dark higgs sector for example) can be stable

$\lesssim$ GeV ———————

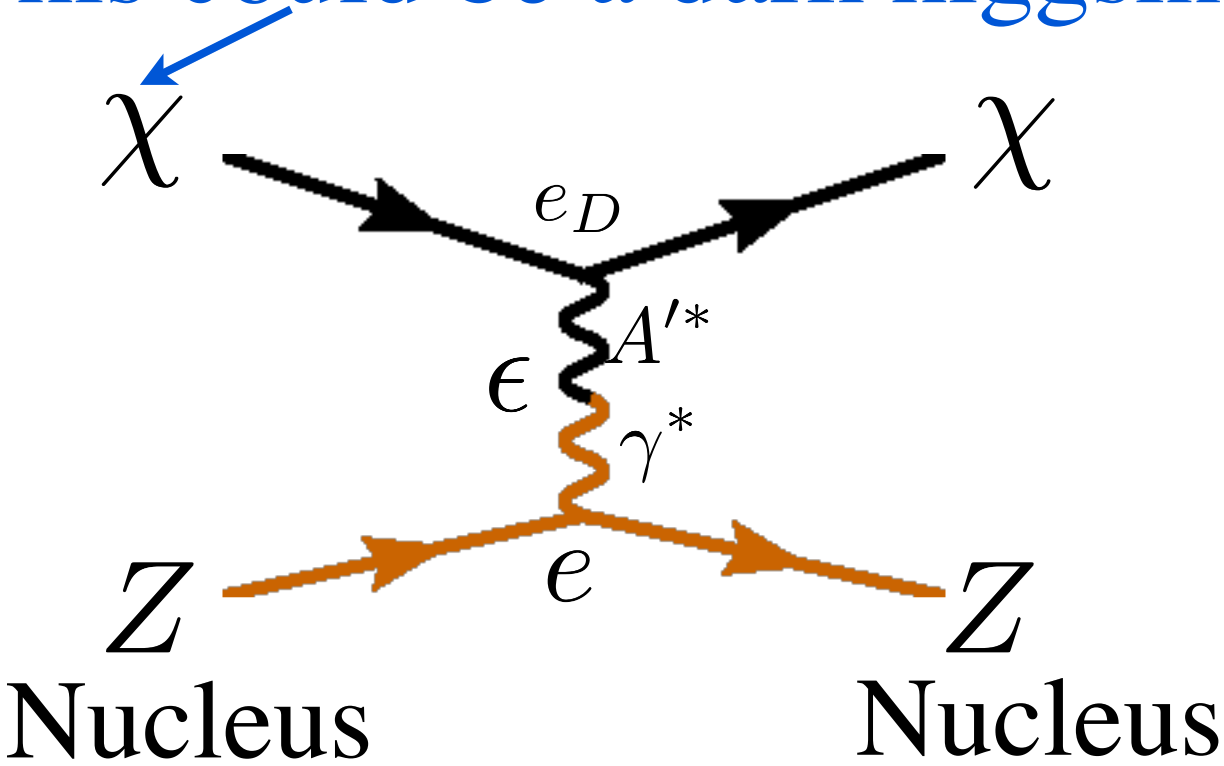
vector, dark higgs particles, SUSY partners...etc

GeV-scale stable particles are a small fraction (~1%) of the dark matter mass density

(larger annihilation cross-sections)

A’ Mediation of Inelastic DM-Nuclei Scattering

This could be a dark higgsino!

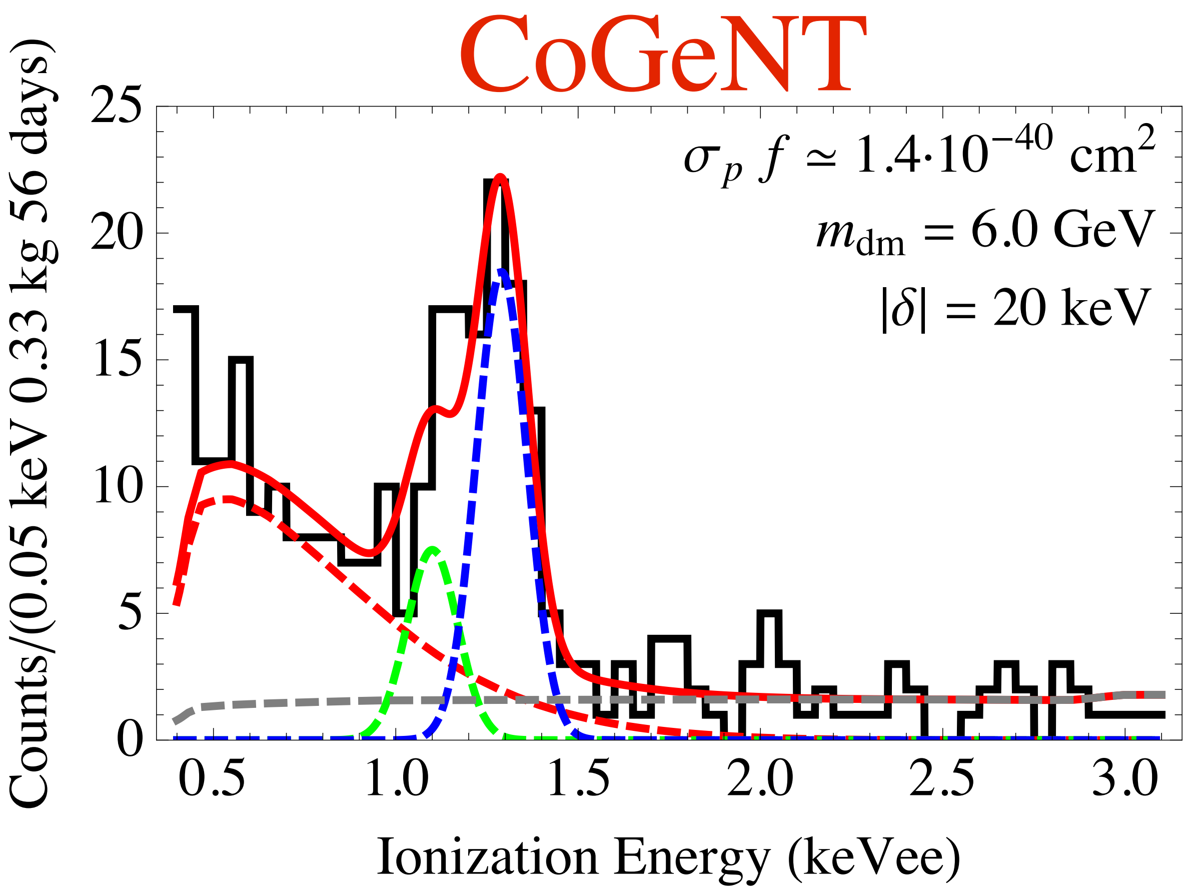


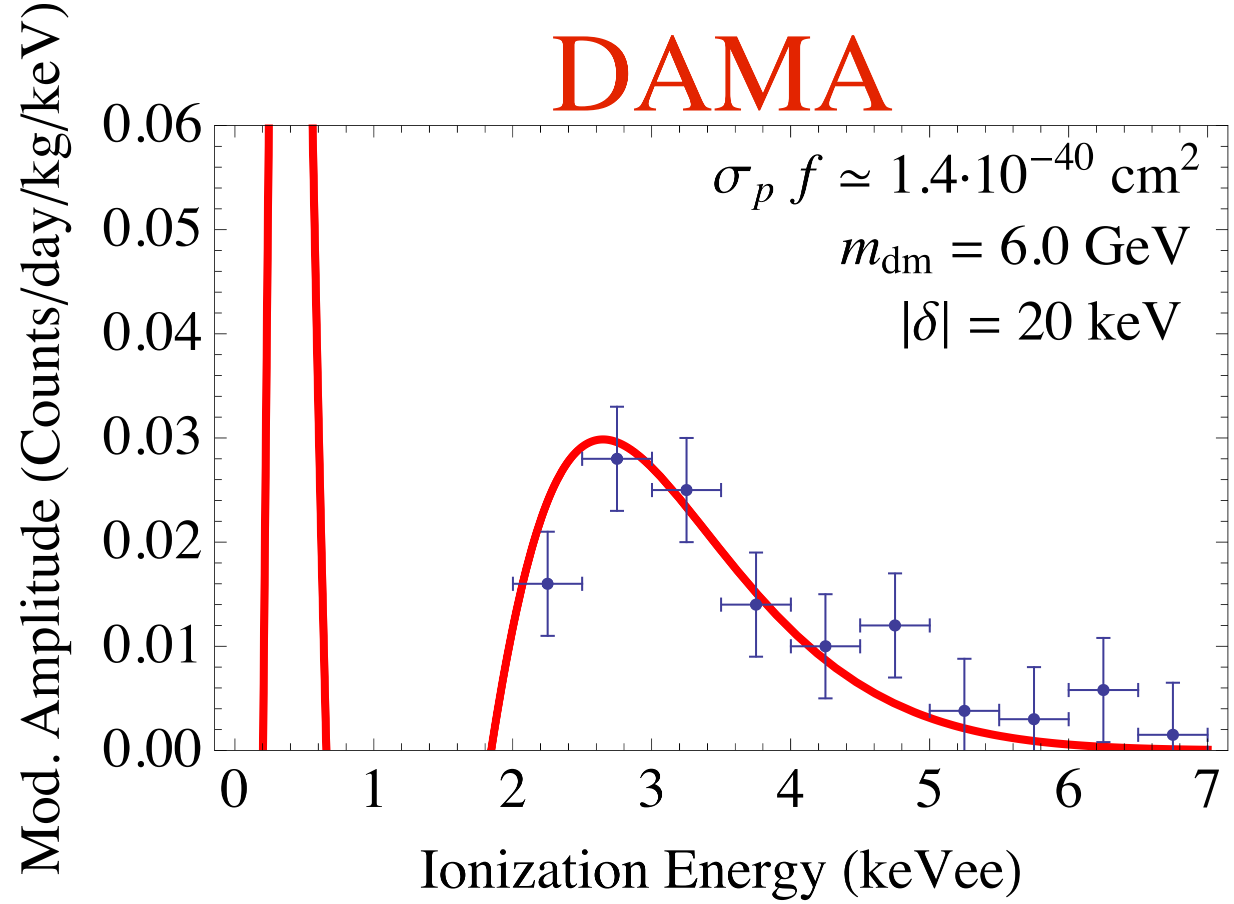
$$A \sim \frac{e_D e \epsilon}{m_{A'}^2} \sim \frac{e^2}{M_W^2}$$

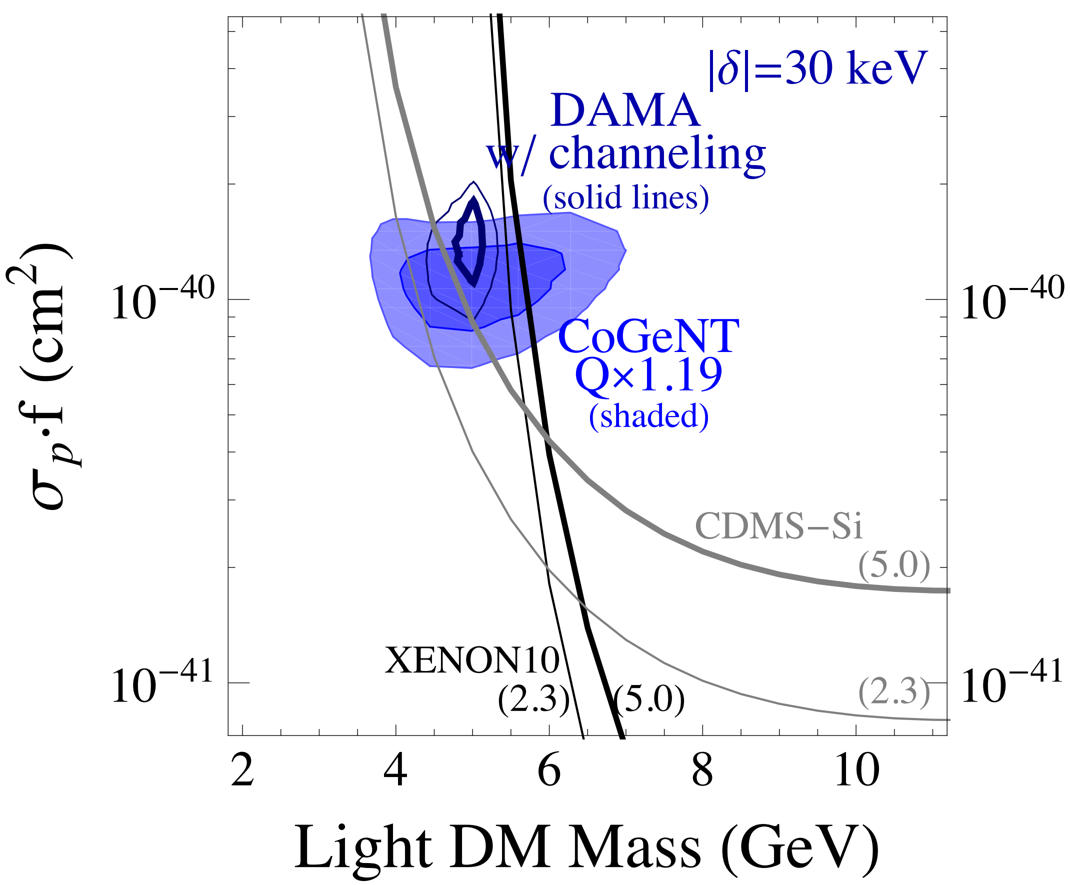
GeV-scale stable particles scatter via A’ exchange off protons. The cross-section is large, so even a small number density can be visible

[Essig, Kaplan, PS, Toro]

Simultaneous Explanations of DAMA & CoGeNT







Specific models with ~5 GeV mass particle from the dark force sector can explain all anomalies

[Essig, Kaplan, PS, Toro]

New Gauge Forces

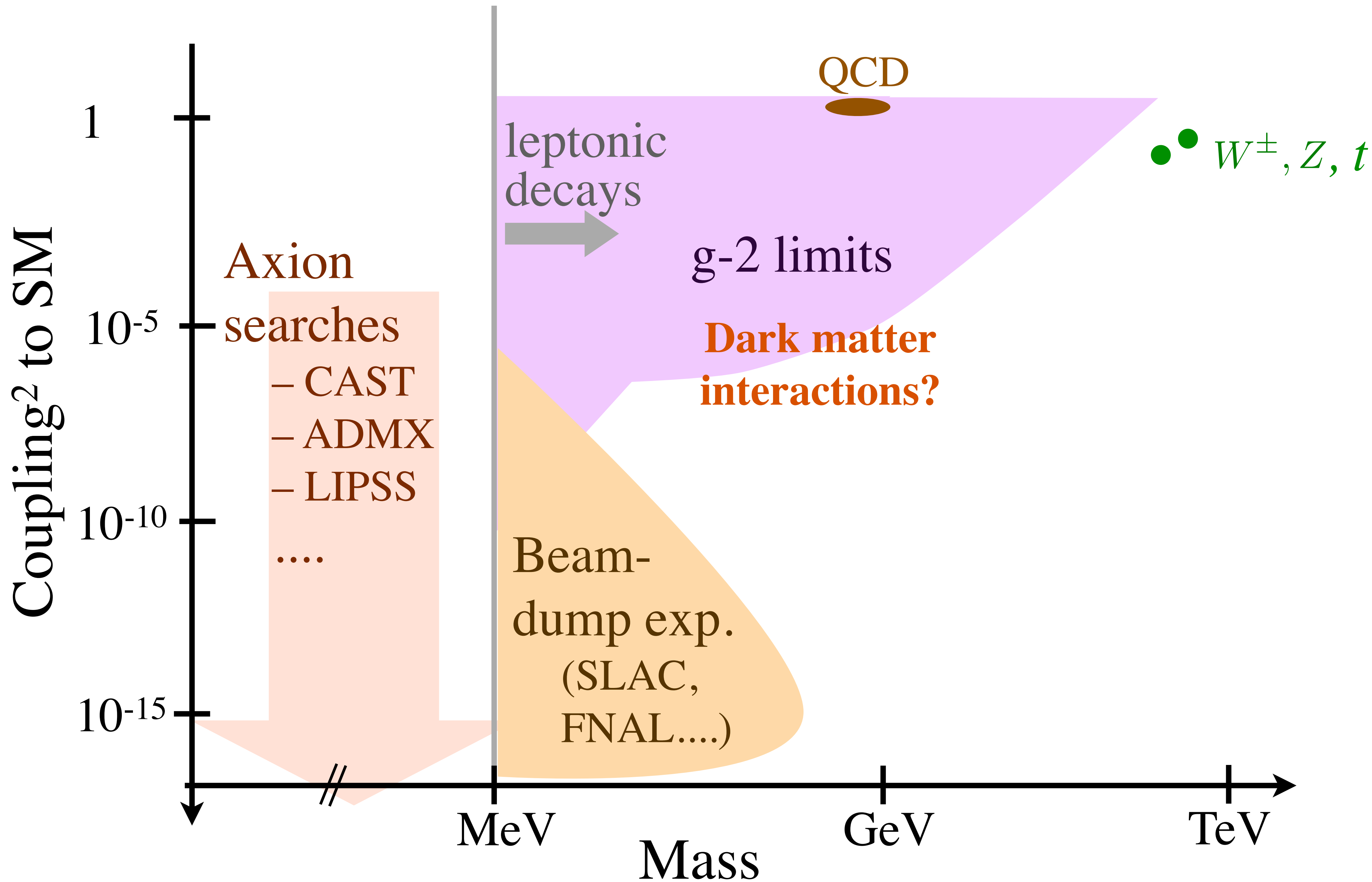
Are there new gauge forces? – an intriguing possibility

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

Insight from laboratory experiments needed!

The Search for New Forces – Summary

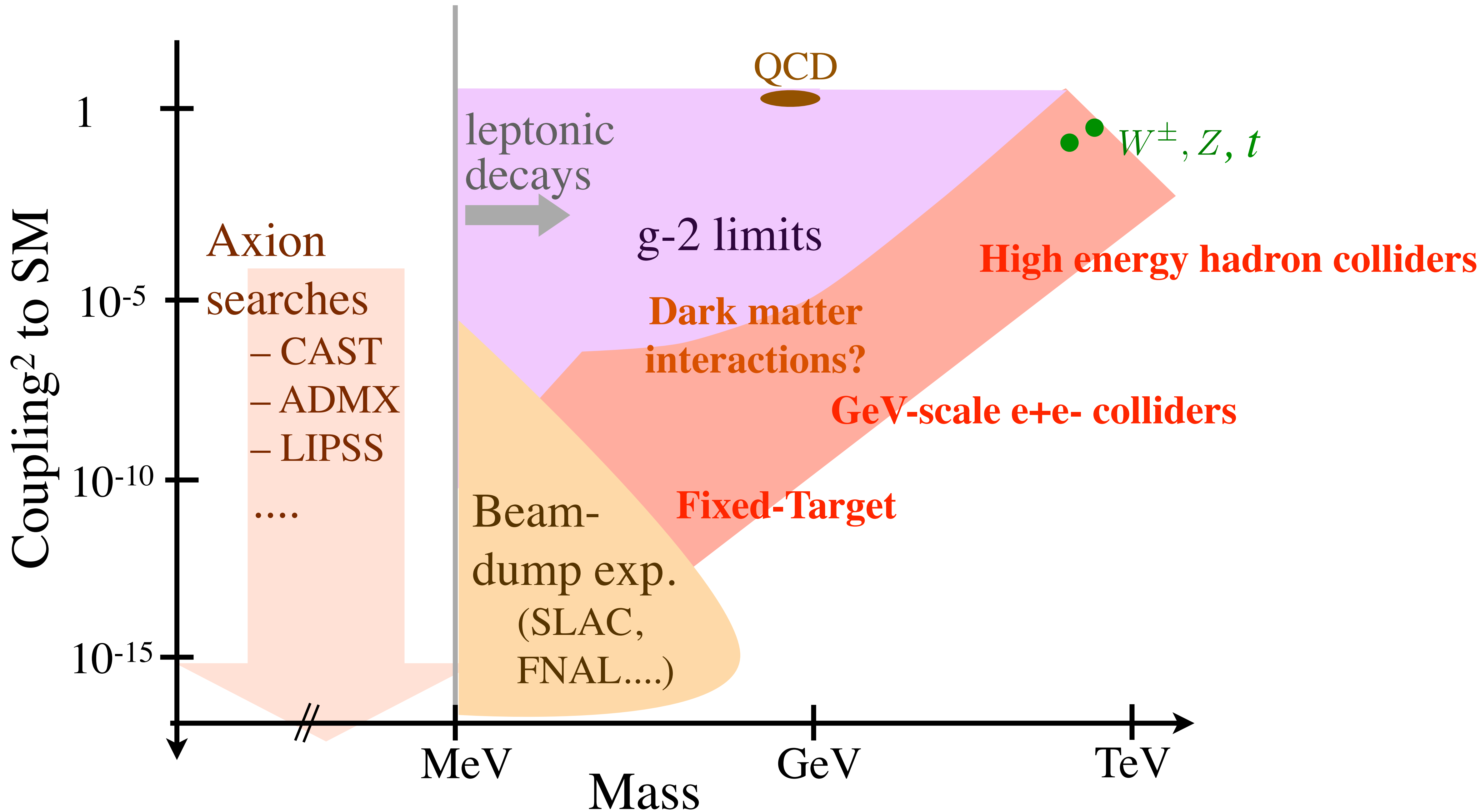
A new program of collider and fixed-target searches can cover:



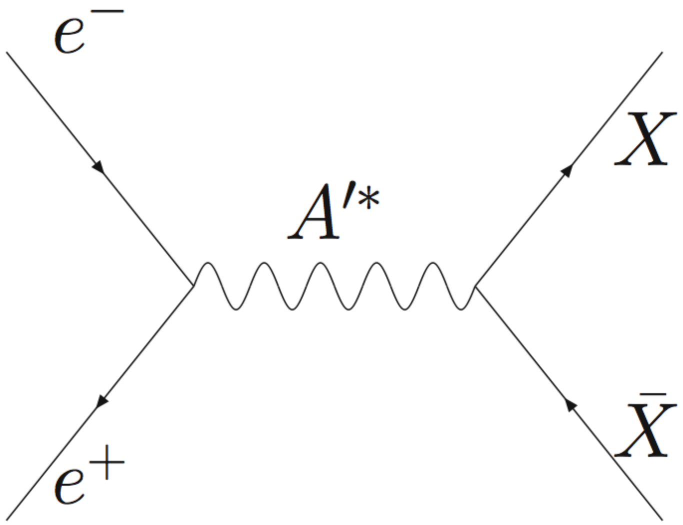
The Search for New Forces – Summary

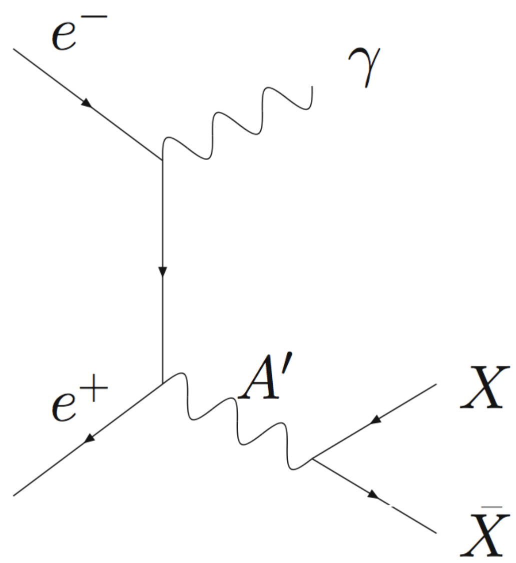
A new program of collider and fixed-target searches can cover:

4-6 decades in mass
3-5 decades in coupling strength
Region of interest for dark matter interactions

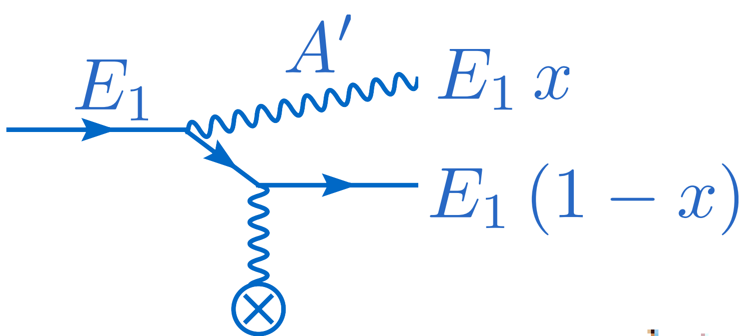


Broad Array of Signatures and Searches!

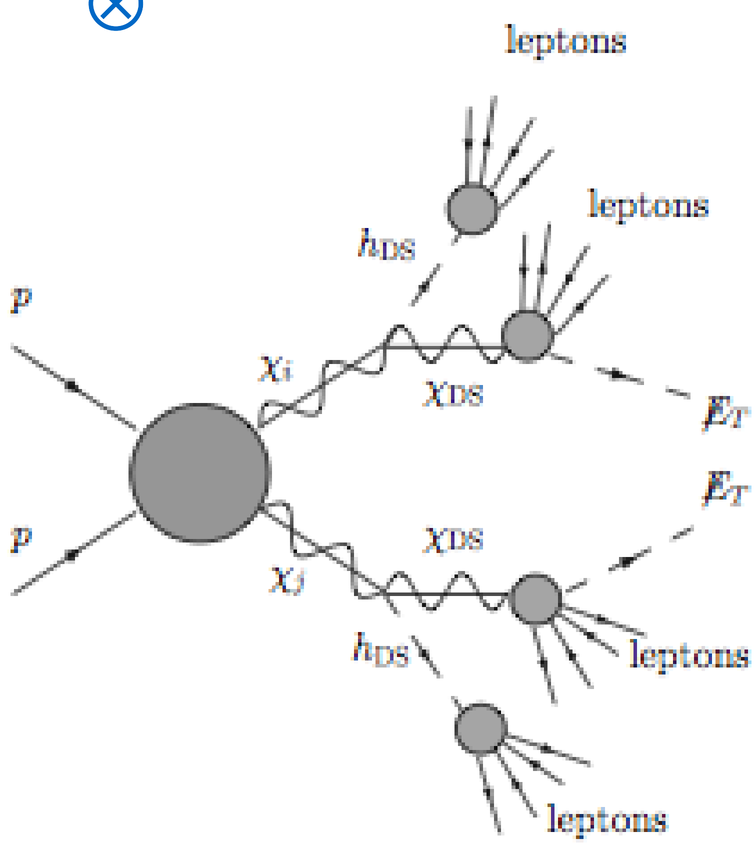




Colliding e+e-: On- or Off- shell A’, X=dark sector or leptons & pions (BELLE, BaBar, BES-III, KLOE, CLEO)



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, ...)



High Energy Hadron Colliders: New heavy particles decaying into dark sector (lepton jets) (CDF & D0)

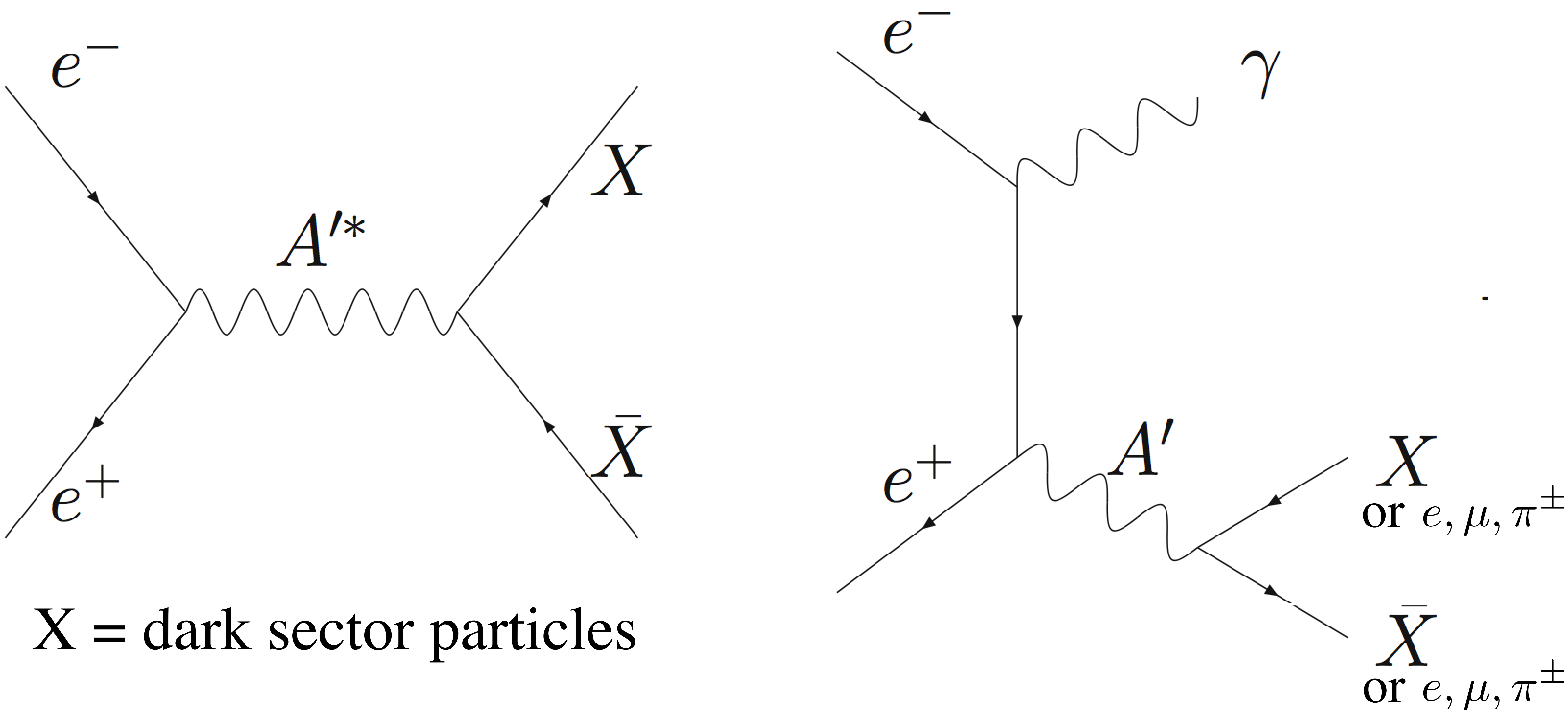
(very interesting, but no time in this talk)

Dark Forces at the GeV Scale

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

Dark Sector Collider Production

Off-Shell A′ | Radiative return



X = dark sector particles

$\sigma \propto \epsilon^2 / s$ → High-luminosity GeV-scale 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):

BELLE	BaBar	KLOE	CLEO-C	BES III
170,000	100,000	50,000	1,000	

Missing from numerical comparison:

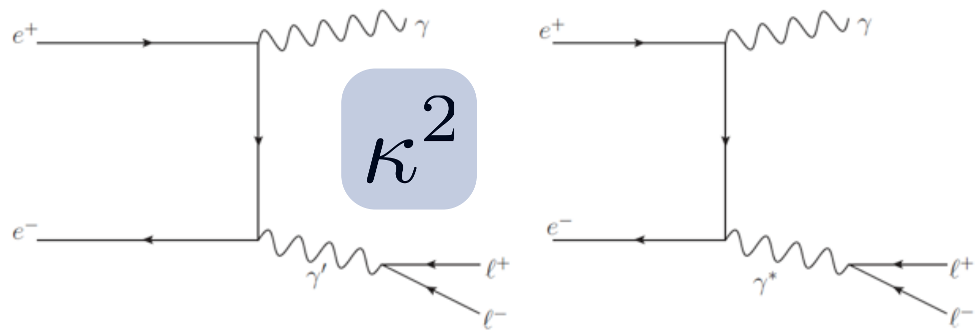
– accessible mass range

– kinematic acceptance & **visibility** of events

Broad range of searches needed

Final States (direct production)

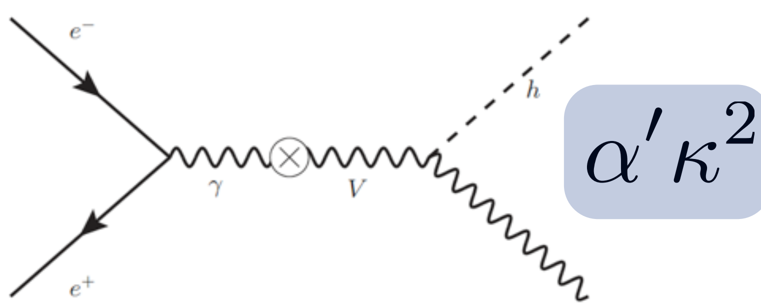
- "Generic": $e^+e^- \to \gamma l^+ l^-$



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

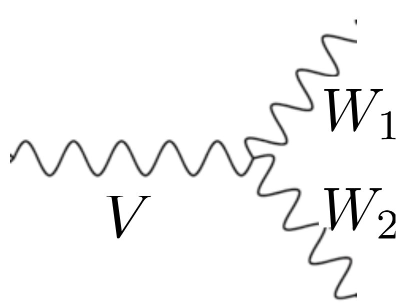
Reach: $\epsilon \sim 10^{-3}$

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



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

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



Reach: $\epsilon \sim 10^{-4}$

- BaBar [4l, M. Graham] ✓

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

From e+e- working group summary (SLAC Dark Forces workshop)

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)

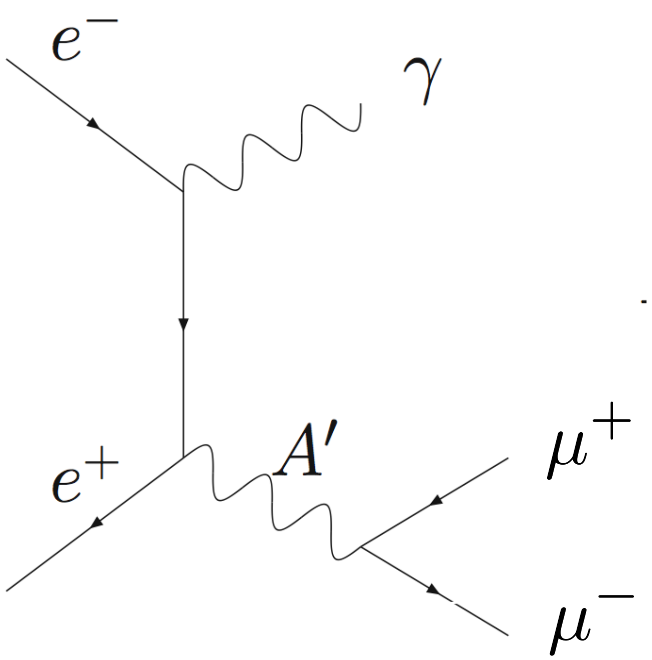
$J/\psi \to 6l$ Sensitivity to $\epsilon \sim 10^{-4} - 10^{-3}$ (BES-III in 1 year)

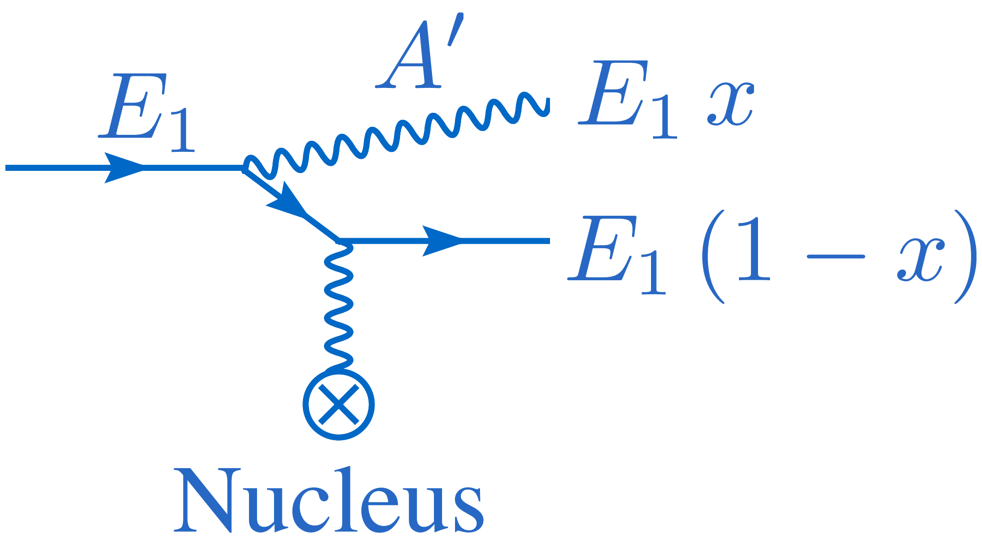
Searches ongoing...

Dark Forces at the GeV Scale

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

Collider vs. Fixed-Target





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

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

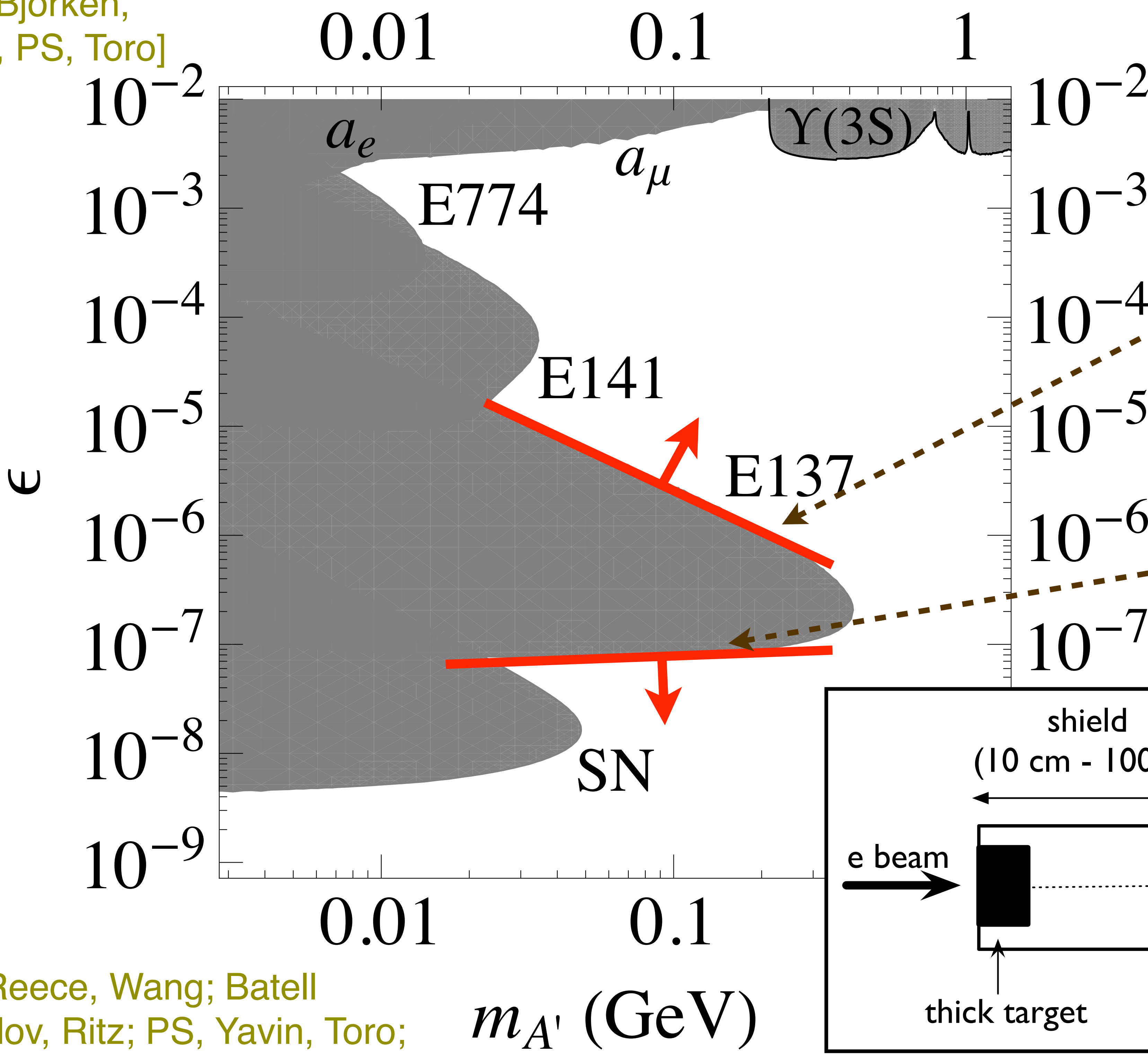
O(few) ab^{-1} per decade

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

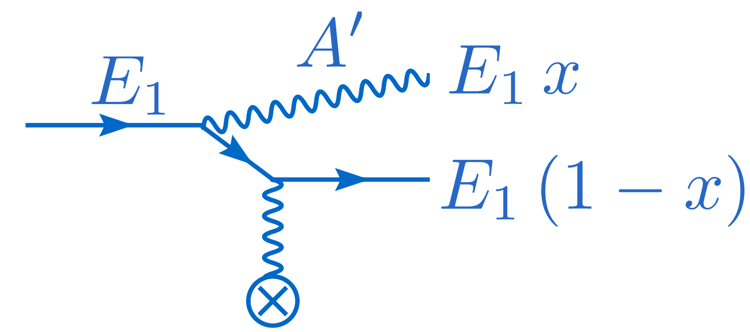
Past Beam Dump Limits

(A' di-lepton decay modes)

[see: Bjorken, Essig, PS, Toro]

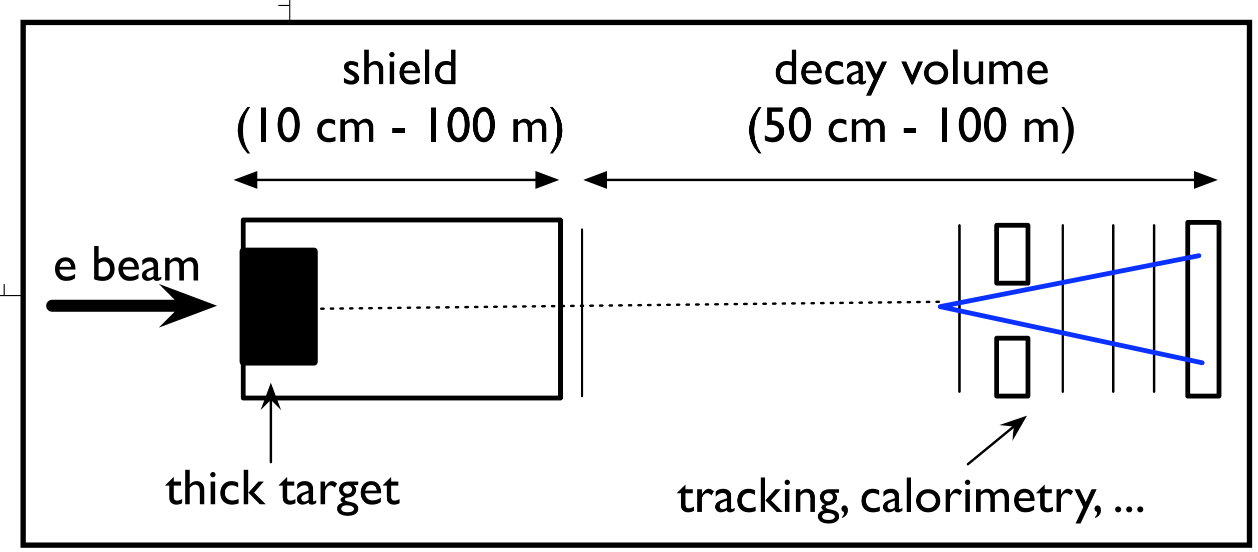


Production Mode:



Lifetime small compared to shield length: decay products stop

Lifetime large compared to shield length, and lower cross-section: run out of statistics



[see; Reece, Wang; Batell Pospelov, Ritz; PS, Yavin, Toro; Batell, Pospelov, Ritz, Shang for additional constraints]

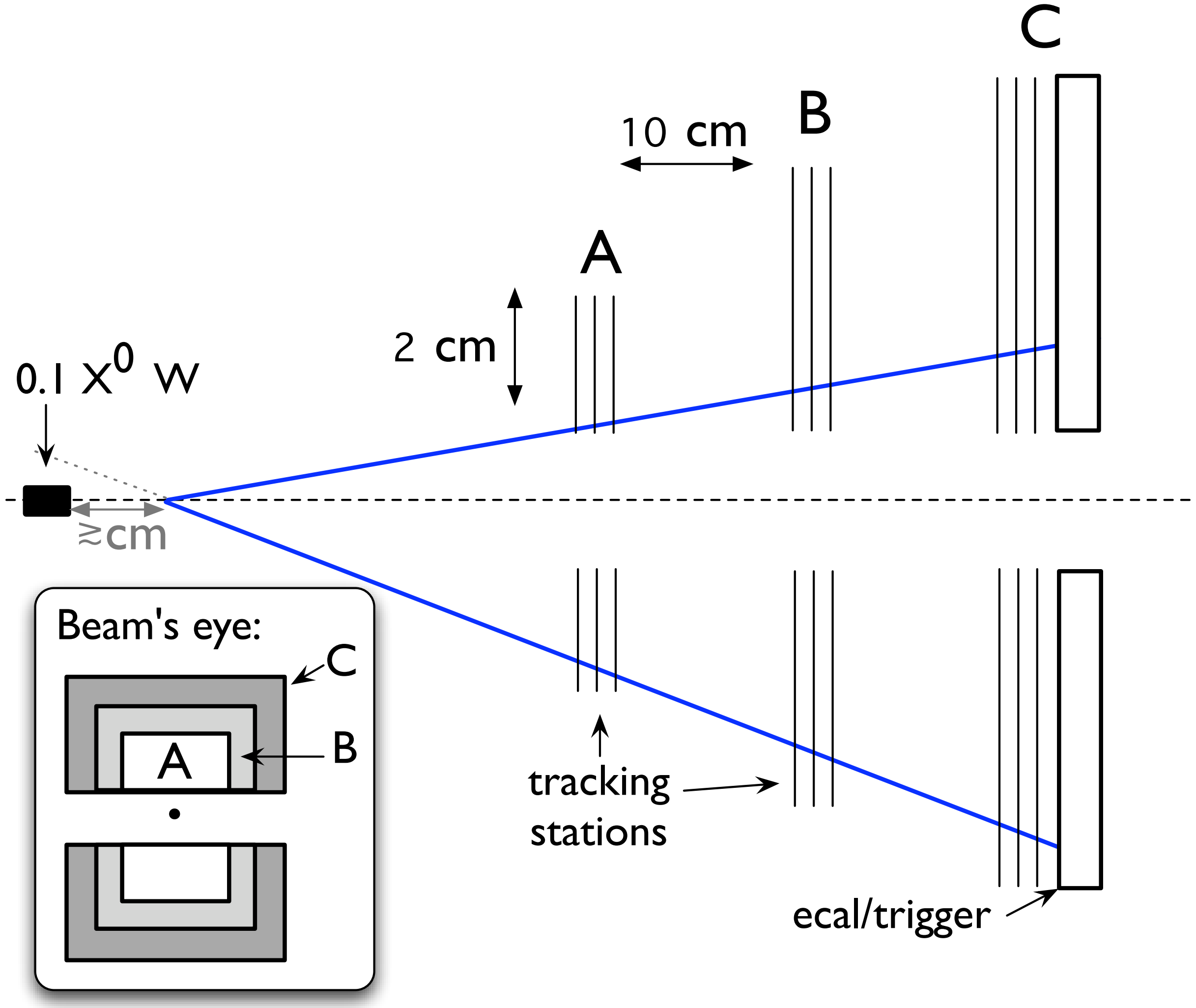
SLAC E137: 10^{20} e^- (30 C) at 20 GeV, 200m shield

Approaches for New Experiments

- Electron beam dump experiments set strongest bounds.
- To see higher ϵ, m_A (best DM region) need thinner target – now beam gets through, too!

- Two strategies:
  - Resonance Search
  - Vertex and recoil tagging

Two-arm spectrometer



Features of conceptual design:

- 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

Dark Forces at the GeV Scale

- Theory of New Vector Bosons (and hints from dark matter)
- e+e- Collider Searches (Babar, Belle, KLOE)
- Fixed-Target Experiments **A' Experiment (APEX)**

Search for a New Vector Boson A' Decaying to e^+e^-

The A' Experiment (APEX) Collaboration

http://hallaweb.jlab.org/experiment/APEX/

(arXiv:1001.2557)

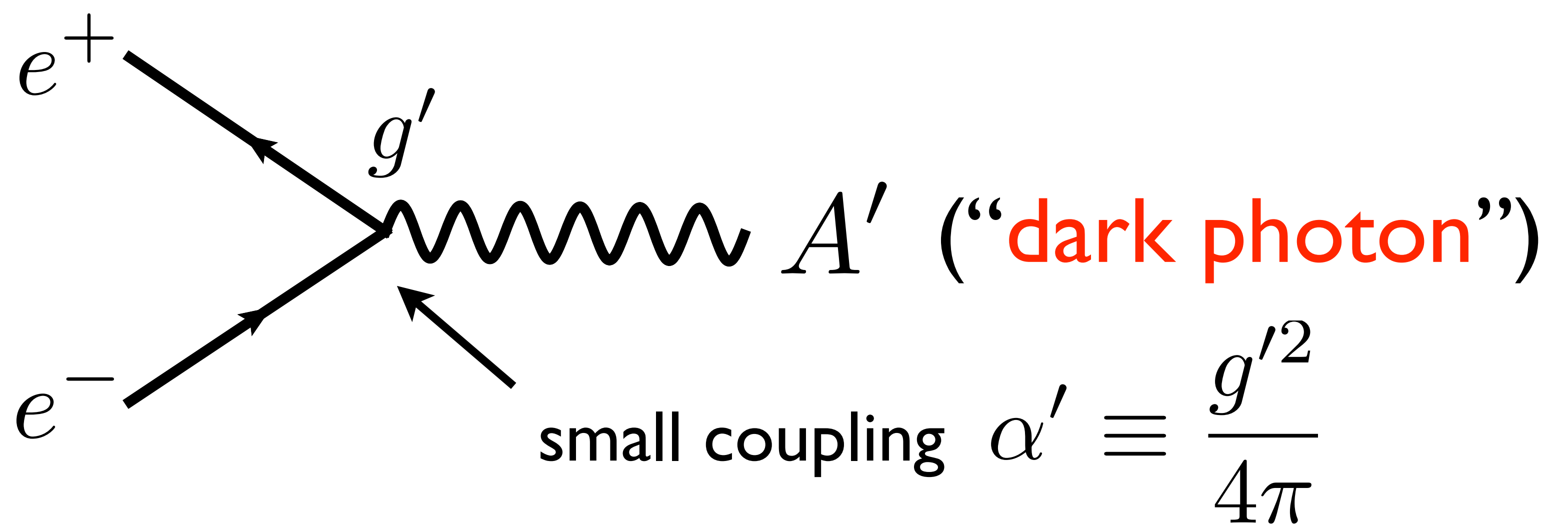
Spokespeople: R. Essig, P. Schuster, N. Toro, B. Wojtsekhowski

A. Afanasev, D. Armstrong, T. Averett, S. Beck, J. Bjorken, P. Bosted, P. Brindza, N. Bubis, A. Camsonne, O. Chen, E. Chudakov, C. Curtis, M. Dalton, K. De Jager, A. Deur, R. C. Field, E. Folts, A. Gavalya, S. Gilad, R. Gilman, S. Glamazdin, J. Gomez, M. Graham, O. Hansen, D. Higinbotham, T. Holmstrom, J. Huang, J. Jaros, E. Jensen, M. Khandaker, I. Korover, G. Kumbartzki, J. LeRose, R. Lindgren, N. Liyanage, P. Markowitz, T. Maruyama, V. Maxwell, D. Meekins, R. Michaels, M. Mihovilovic, K. Moffeit, S. Nanda, V. Nelyubin, B. Norum, A. Odian, M. Oriunno, M. Paolone, R. Partridge, E. Piasetzky, I. Pomerantz, A. Puckett, V. Punjabi, Y. Qiang, R. Ransome, S. Riordan, G. Ron, A. Saha, R. Schneor, J. Segal, A. Shahinyan, S. Sirca, S. Stepanyan, V. Sulkosky, D. Walz, L. Weinstein, B. Zhao

and The Hall A Collaboration

Goal:

Search for a new ~100 MeV vector boson (A′) with weak coupling to electrons



Significant new reach in α' (~2-3 orders of magnitude)
Broad interest in particle physics community

- new gauge force
- dark matter interactions?
- $(g\text{-}2)_\mu$ and HyperCP anomalies

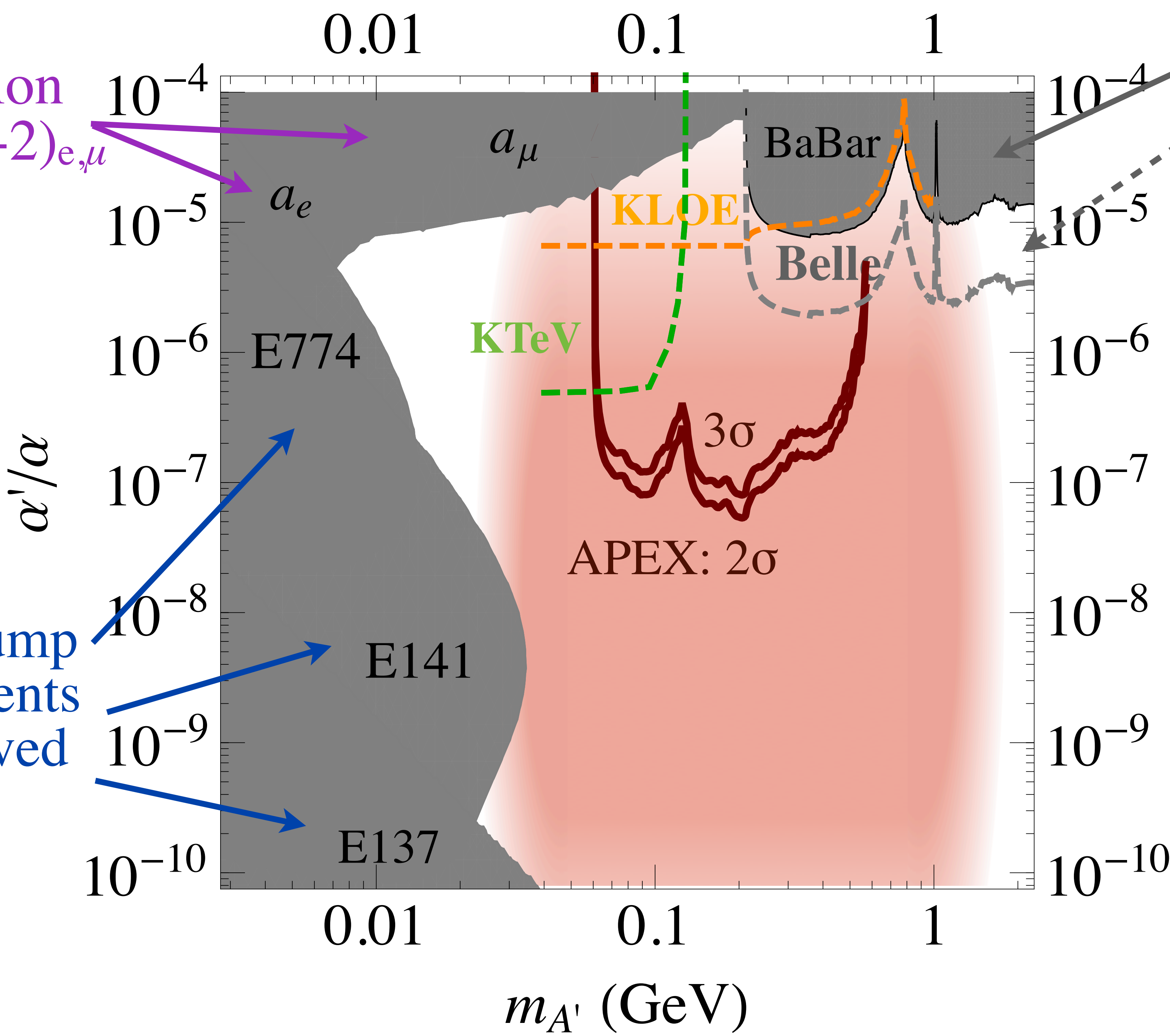
see also Dark forces workshop, SLAC Sept. 2009:
http://www-conf.slac.stanford.edu/darkforces2009/

Existing limits and APEX Sensitivity

Direct production: $e^+e^- \to \gamma A'$

precision QED $(g\text{-}2)_{e,\mu}$

beam-dump experiments (long-lived A′)



Gray regions: excluded (2σ) by past experiments

Dashed lines: estimated 2σ sensitivity of other possible searches in existing **KLOE**, **KTeV**, and **Belle** data.

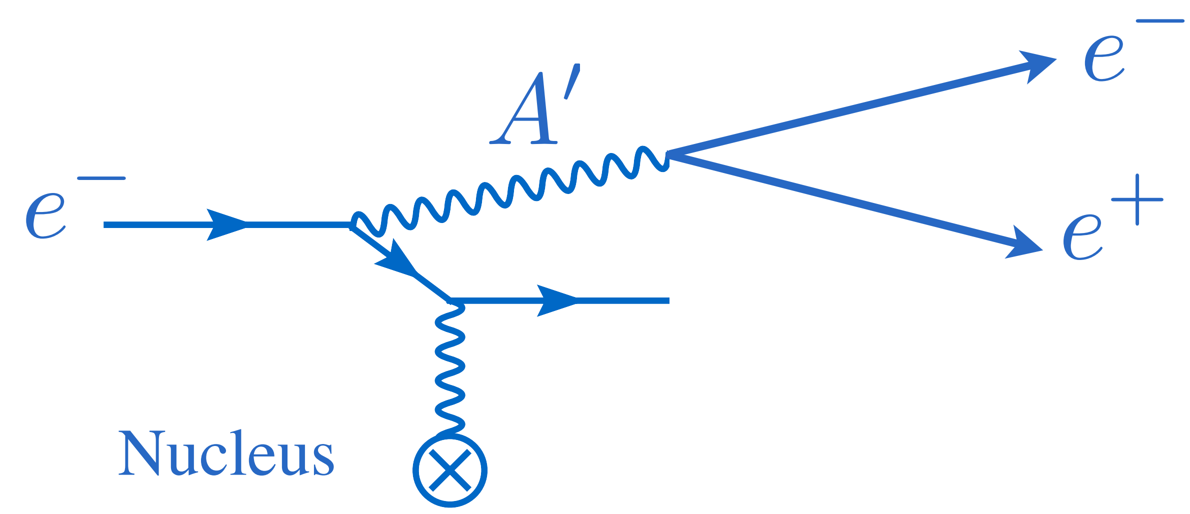
No past experiment has **sufficient statistics and mass resolution** to see A′ if its coupling is below the dotted lines.

This is a theoretically motivated region

– relevant for dark matter – predicted by grand unification

A′ Properties in APEX Search Region ($\alpha'/\alpha > 10^{-7}$)

- Produced abundantly through bremsstrahlung
  (e.g. >1/second for 75 μA beam, 0.1 X_0)

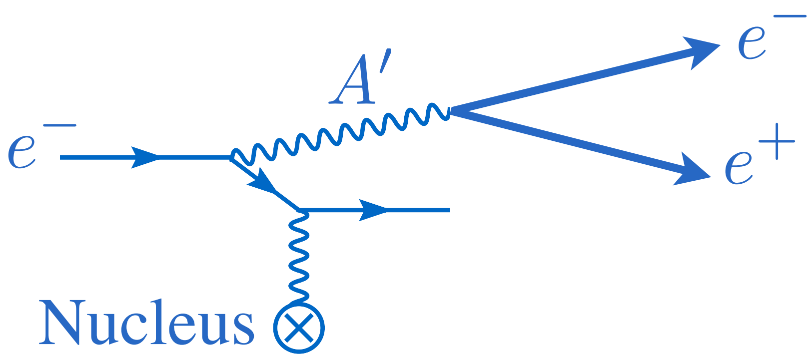


- A′ decays promptly to e^+e^-, $\mu^+\mu^-$, or $\pi^+\pi^-$
  ⇒ large QED background

Strategy: measure e^+e^- mass spectrum precisely, in kinematic region optimized for A′ acceptance and QED background suppression

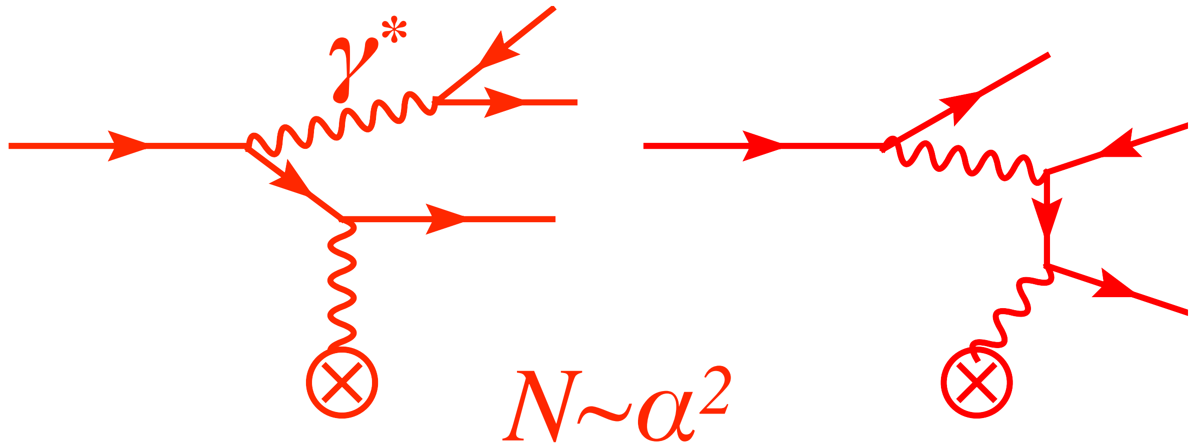
Approach: A′ Production and Background Kinematics

Production diagrams analogous to photon bremsstrahlung



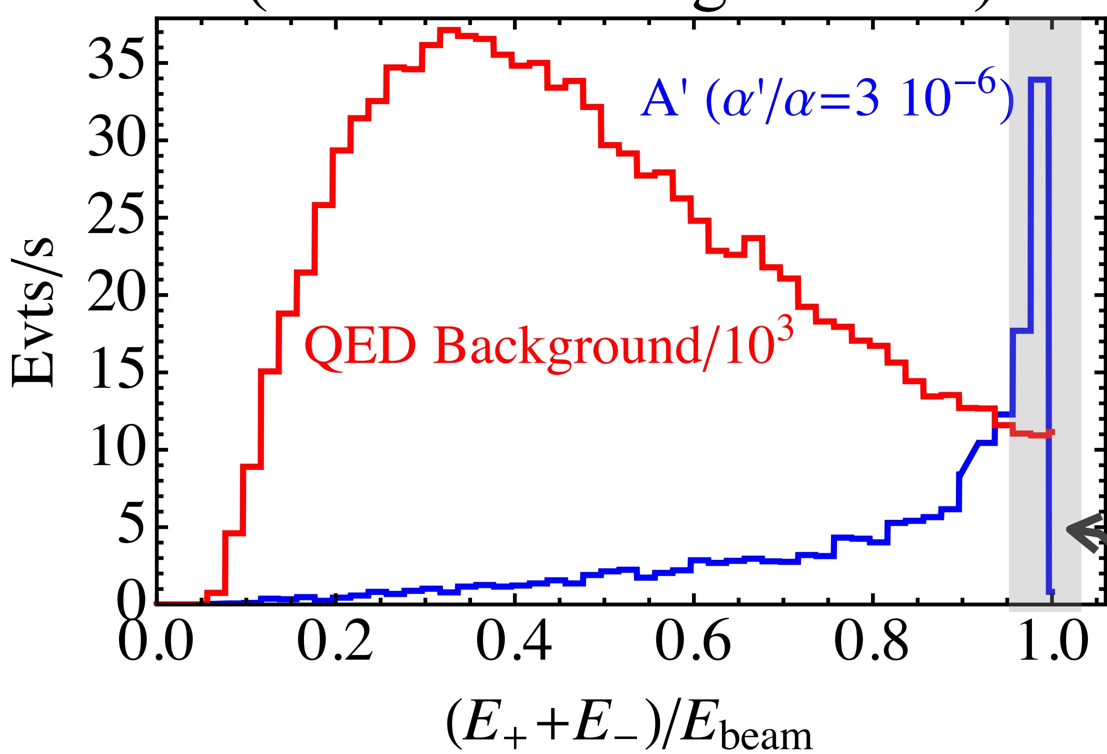
$N \sim \alpha'$ x Branching → O(1)

QED Backgrounds



$N \sim \alpha^2$

(rates before angular cuts)



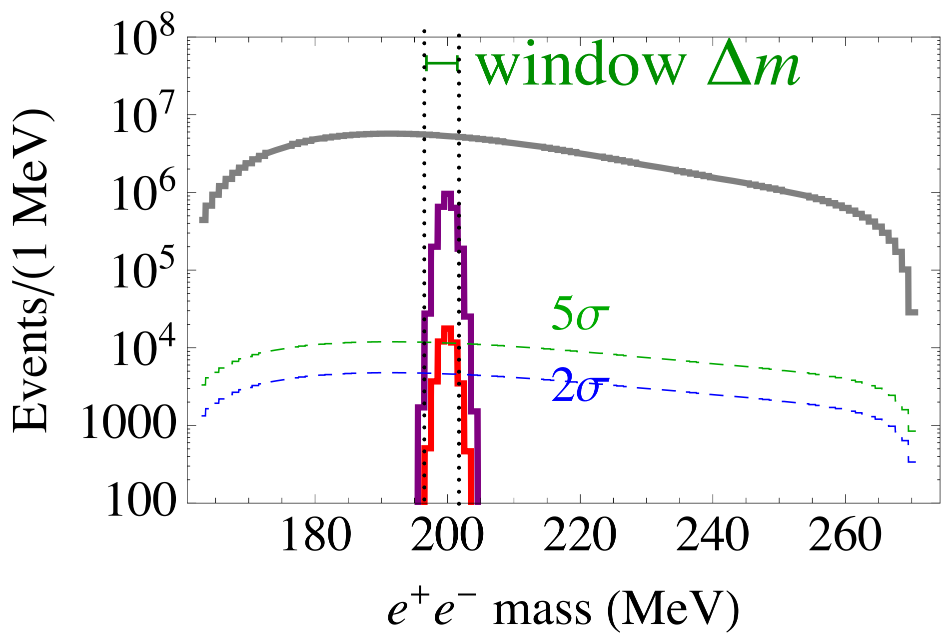
A′ products carry full beam energy!

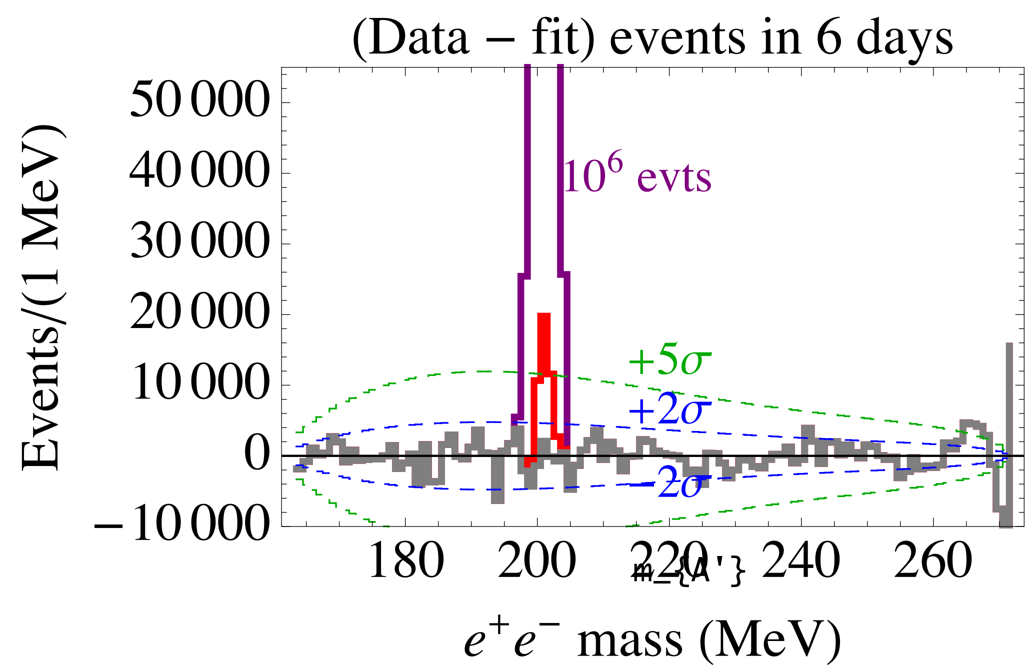
– Distinctive kinematics
– Assists in background suppression

Best kinematics to select events for A′ search

To identify A′ signal, must study invariant mass distribution

$$m_{A'} \approx \sqrt{E_+ E_-}(\theta_+ + \theta_-)$$





In mass window Δm: $\dfrac{S}{\sqrt{B}} \sim \dfrac{\alpha'}{\alpha^2}\sqrt{N_{QED}\left(\dfrac{m_{A'}}{\Delta m}\right)}$

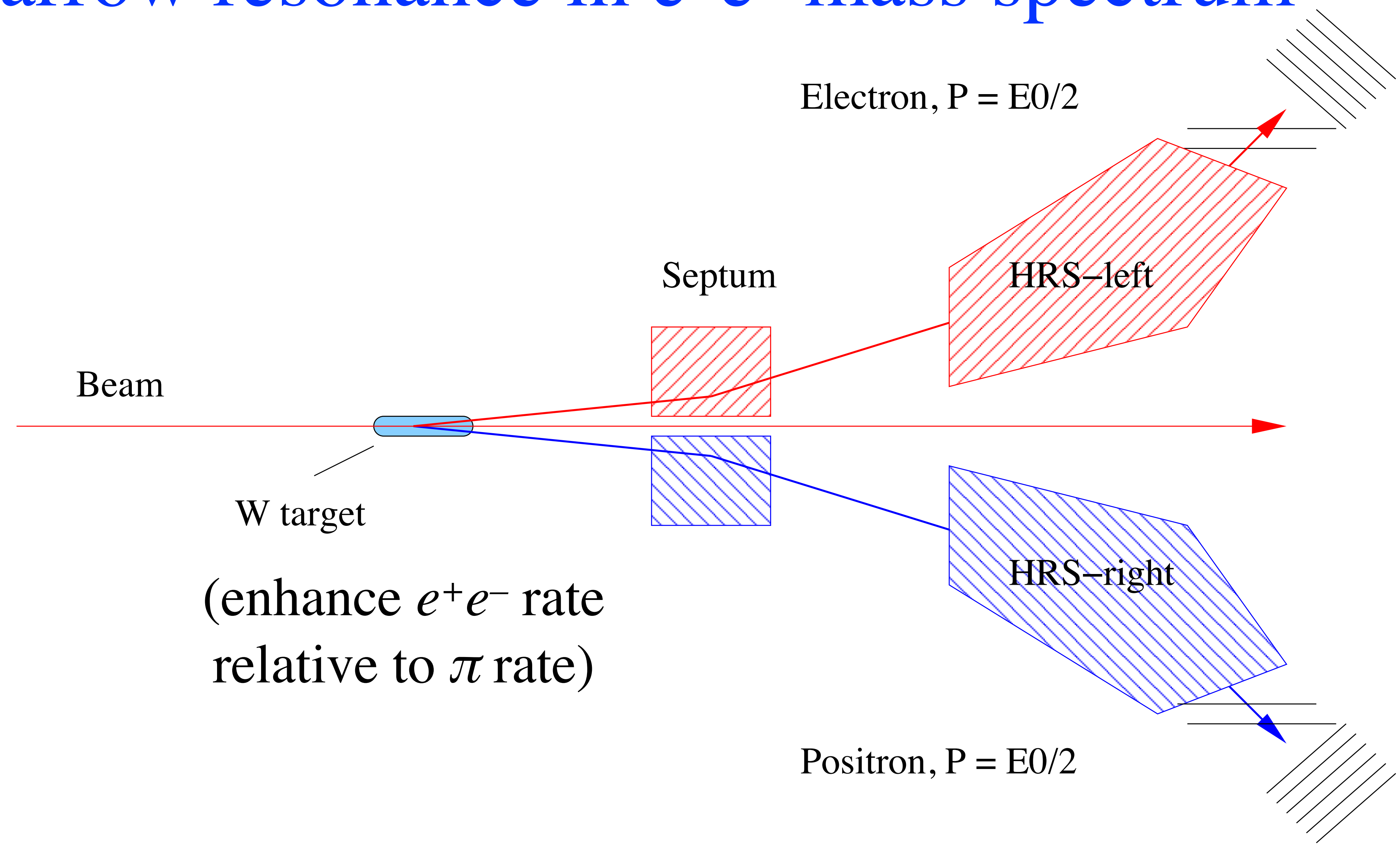
To search at small α′, need:

★High e^+e^- statistics

★Excellent mass resolution

Outline of Experimental Setup

Search for narrow resonance in e^+e^- mass spectrum



(enhance e^+e^- rate relative to π rate)

- Signal dominated at $E_+ = E_- = E_{beam}/2$
- Use septa to achieve 5° central angles ⇒ high statistics
- Mass resolution is critical, controls target design

Experimental Design: HRS Spectrometer Setup

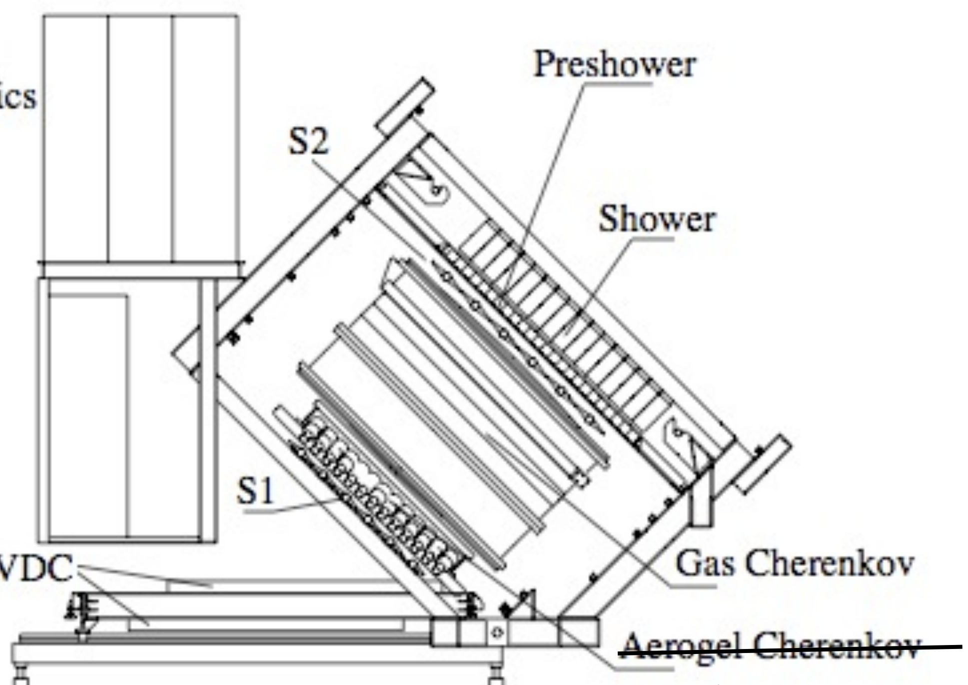
Configuration	QQD_nQ Vertical bend
Bending angle	45°
Optical length	23.4 m
Momentum range	0.3 - 4.0 GeV/c
Momentum acceptance	-4.5% < δp/p <+4.5%
Momentum resolution	1×10^{-4}
Angular range HRS-L	12.5° - 150°
HRS-R	12.5° - 130°
Angular acceptance: Horizontal	±30 mrad
Vertical	±60 mrad
Angular resolution : Horizontal	0.5 mrad
Vertical	1.0 mrad
Solid angle at $\delta p/p = 0$, $y_0 = 0$	6 msr

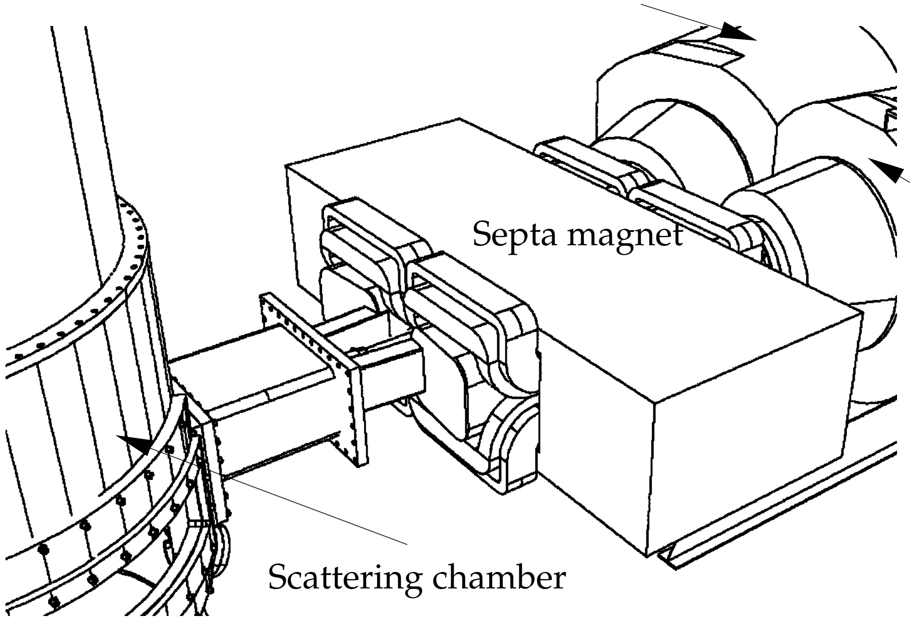
Use PREX septa to achieve smaller central angle (5°)

Excellent momentum and angular resolution

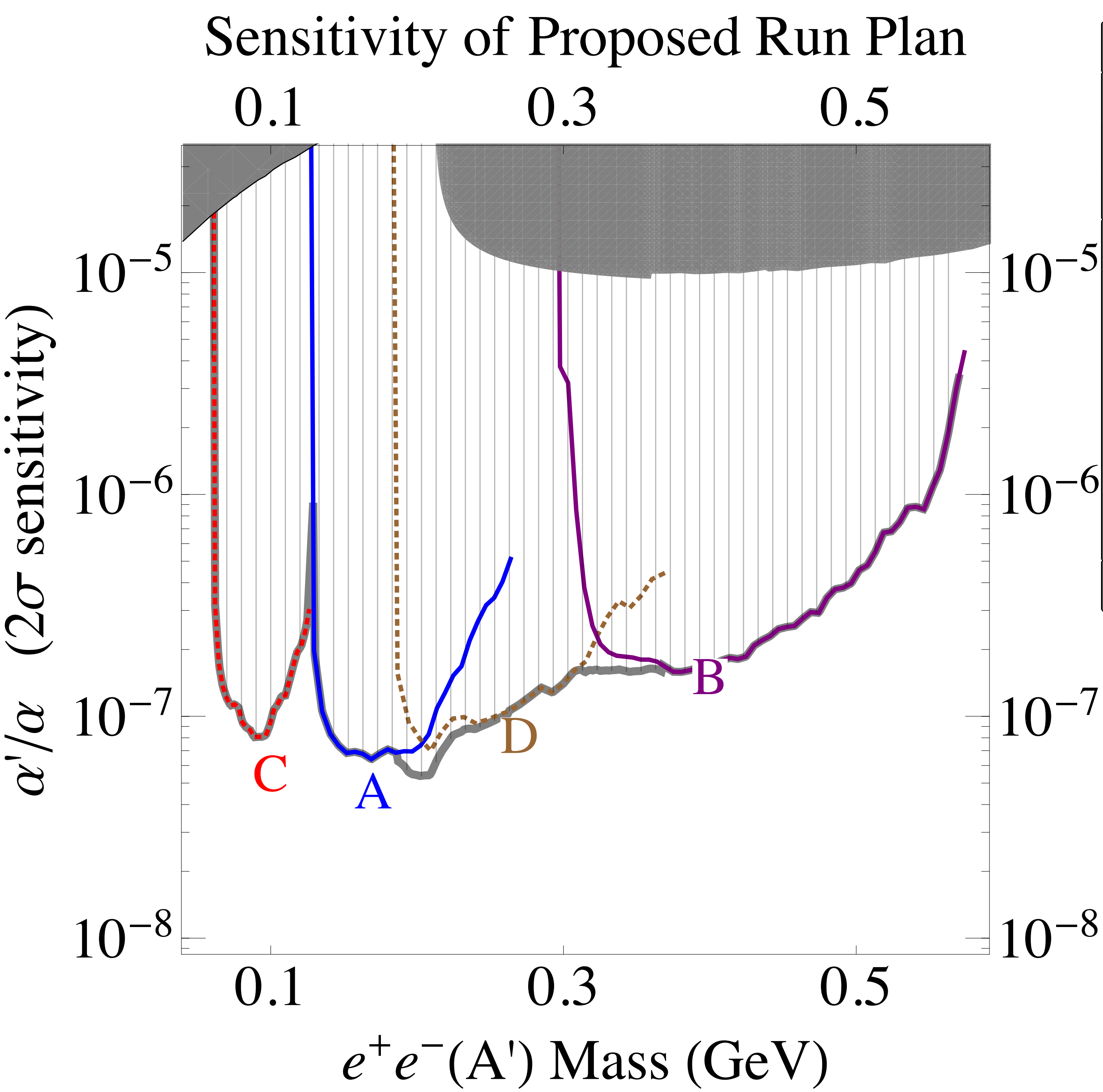
⇒ mass resolution controlled by multiple scattering in target

HRS
Right Arm





Run Plan and Sensitivity



Settings	A	B	C	D
Beam energy (GeV)	2.302	4.482	1.1	3.3
Beam current (μA)	80	80	80	80
Nominal central angle	5.0°	5.5°	5.0°	5.0°
Time Requested (hrs)				
Energy change	–	4	4	4
Angle change	–	16	–	–
Magnet setup	4	4	4	4
Optics calibration	4	4	4	4
10% $\mathcal{L}$	2	2	2	2
Normal $\mathcal{L}$	144	288	144	144
Total	154	318	158	158

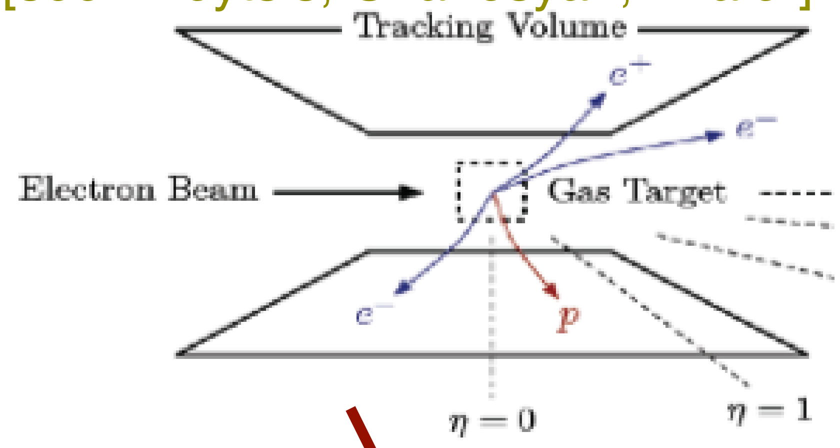
1 Month Beam Time

Conditional Approval from JLab PAC 35:

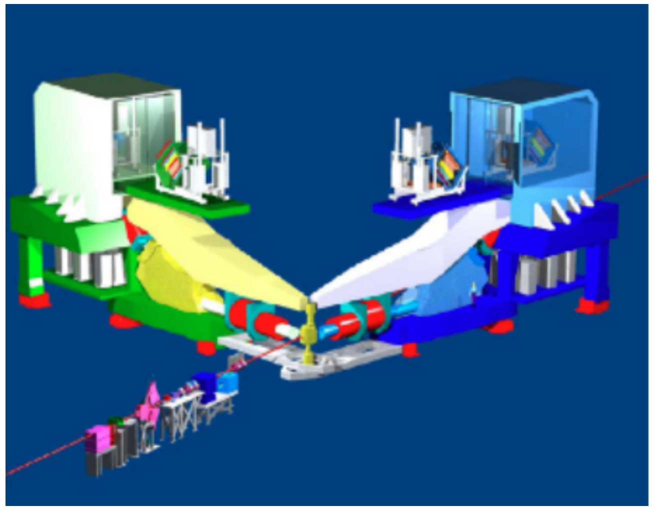
APEX is preparing for a test run in June-July 2010

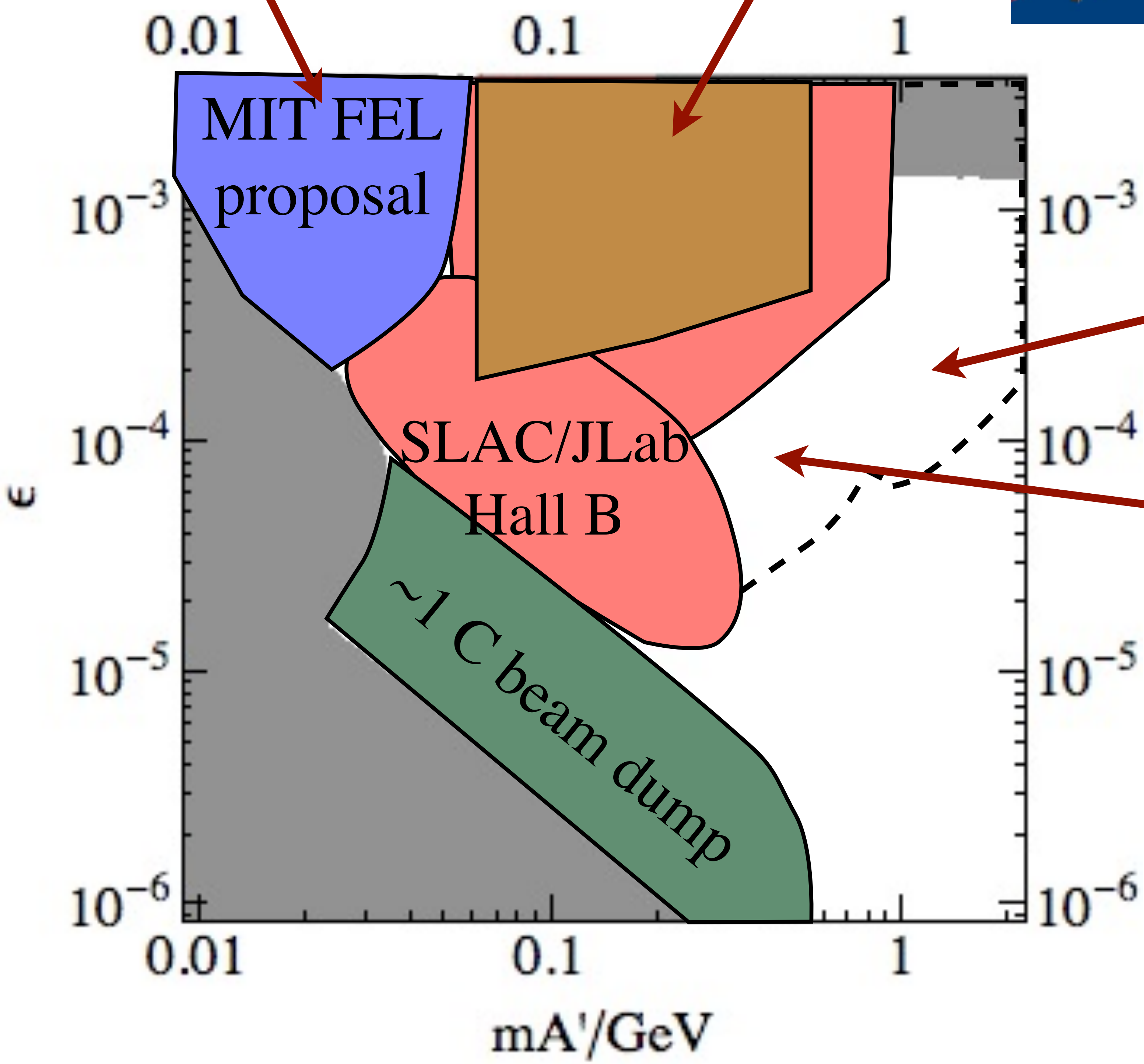
We will fully test all aspects of the experiment needed for the complete run

[see: Freytsis, Ovanesyan, Thaler]



JLab
Hall A
(24 days)





Improvements:

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/phi-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 astro/direct-detection hints and upcoming data

- Broad array of experimental investigation is possible
- Sensitivity to many decades in mass and cross section with existing data and new small-scale experiments

New searches and experiments on ~1-2 year timescale!

Experimental Design: Count Rates and Trigger (80 μA current)

Settings	A	B	C	D
Beam energy (GeV)	2.302	4.482	1.1	3.3
Central momentum (GeV)	1.145	2.230	0.545	1.634
Central angle	5.0°	5.5°	5.0°	5.0°
Target T/X_0	4.25%	10%	0.58%	10%
Singles (negative polarity)				
e^- (MHz)	4.5	0.7	6.	2.9
π^- (MHz)	0.6	2.2	0.4	2.5
Singles (positive polarity)				
$\pi+$ [p] (kHz)	640.	2200	36.	2500.
e^+ (kHz)	31.	3.6	24.	23.
Trigger/DAQ:				
Trigger (kHz)	4.	0.4	3.2	3.4
Signal to background:				
Trident (Hz)	610	70	350	530
Two-step (Hz)	35	15	5	75
Background (Hz)	70	1.3	70	35

70-300 million events!
(6–12 days)

10,000 x more statistics than existing A′ searches in this mass range!

With 2ns offline coincidence timing, **trident dominates** over accidental & pion backgrounds (computed assuming 10^4 π^+ rejection, but true even with 10^3 rejection)