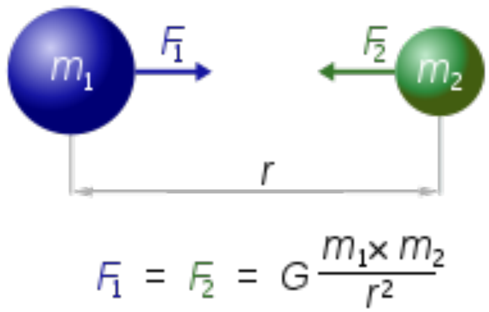
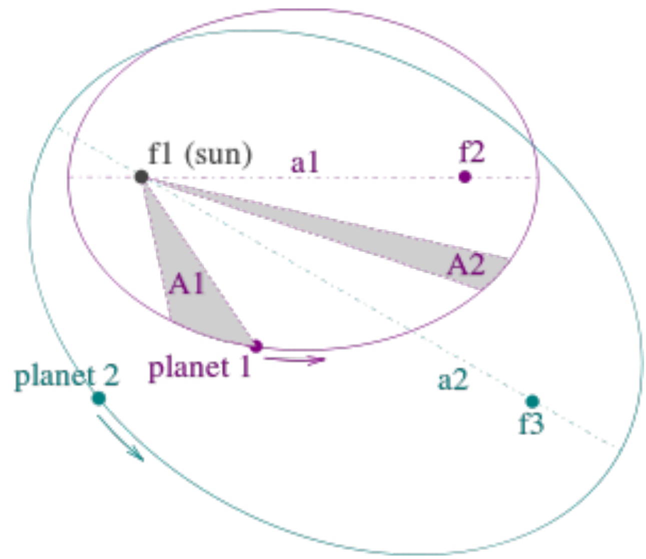
Searches for a hidden sector photon

Bogdan Wojtsekhowski, Jefferson Lab

- Motivation
  - Possible new forces
  - Dark matter observations/indications
  - A theory of DM (one of them)
  - Heavy photon
- Axion-like/Heavy photon searches
- APEX – the experiment to run
- An experiment with a positron beam

Where is new physics





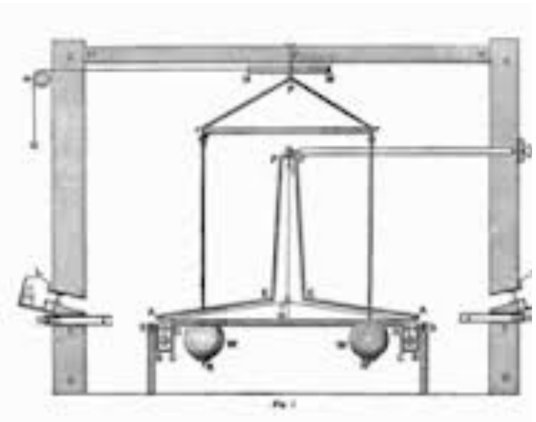
In the middle of the 18th century:

Clairaut suggested that the strength of gravity was proportional not to $\frac{1}{r^2}$, but the more complicated

$$\frac{1}{r^2} + \frac{c}{r^4}$$

for some constant c. Over large distances, the c/r^4 term would effectively disappear, accounting for the utility of the inverse square law over large distances. He then began

Where is new physics



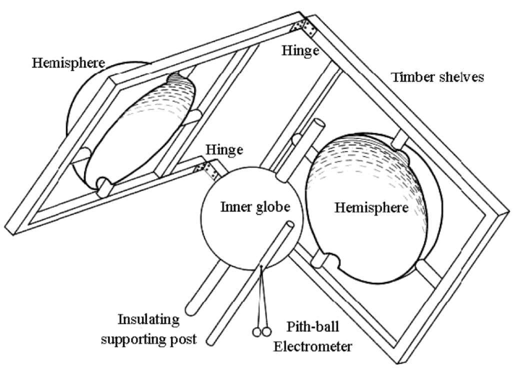


Table I. Results of various tests of Coulomb's law and tests for a nonzero photon rest mass.

	Coulomb's Law violation of form r^{2+q} q	$\mu^2 = (\frac{m_o c}{\hbar})^2$	Photon rest mass m_o
Cavendish (1773)	2×10^{-2}		
Coulomb (1785)	4×10^{-2}		
Maxwell (1873)	4.9×10^{-5}		
Plimpton and Lawton (1936)	2.0×10^{-9}	1.0×10^{-12} cm^{-2}	$\leq 3.4 \times 10^{-44}$ g
Cochran and Franken (1967)	9.2×10^{-12}	7.3×10^{-15} cm^{-2}	$\leq 3 \times 10^{-45}$ g
Bartlett, Goldhagen, Phillips (1970)	1.3×10^{-13}	1×10^{-16} cm^{-2}	$\leq 3 \times 10^{-46}$ g
Williams, Faller, Hill	$(2.7 \pm 3.1) \times 10^{-16}$	$(1.04 \pm 1.2) \times 10^{-19}$ cm^{-2}	$\leq 1.6 \times 10^{-47}$ g
Schroedinger (1943)	Test of Ampere's Law from Geo-magnetic Data	3×10^{-19} cm^{-2}	$\sim 2 \times 10^{-47}$ g
Gintsburg (1963)		5×10^{-20} cm^{-2}	$\leq 8 \times 10^{-48}$ g
Nieto and Goldhaber (1968)		1.3×10^{-20} cm^{-2}	$\leq 4 \times 10^{-48}$ g
Feinberg (1969) [a]	Dispersion of light	8×10^{-14} cm^{-2}	10^{-44} g

SM tests, constraints on new physics (per PDG)

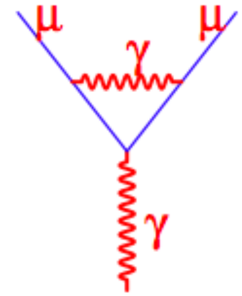
column denoted Pull gives the standard deviations for the principal fit with M_H free, while the column denoted Dev. (Deviation) is for $M_H = 124.5$ GeV [215] fixed.

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	-0.1	-0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		-0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\mathrm{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

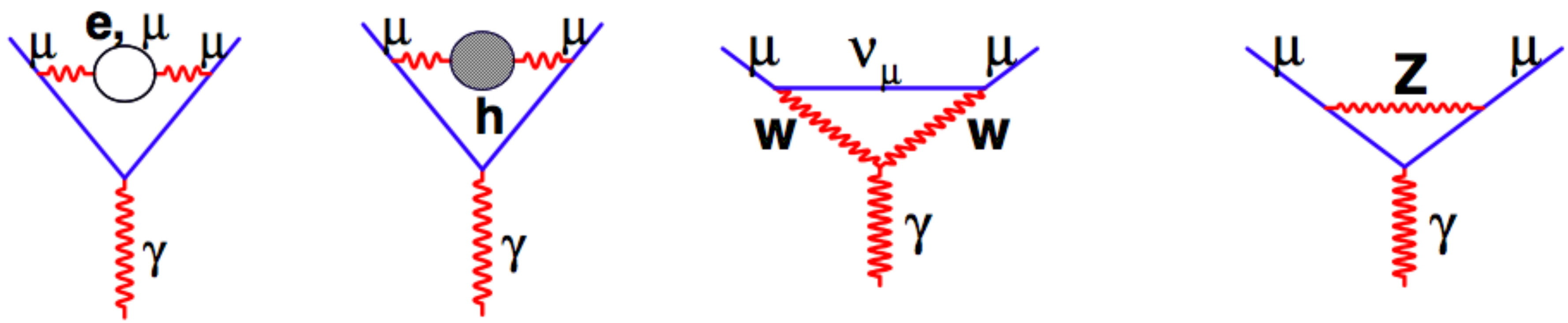
SM tests, constraints on new physics (per PDG)

g - 2 for the muon

Largest contribution : $a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$



Other standard model contributions :



QED hadronic weak

from STORY05, Y. Semertzidis

The motivation is the nature of dark matter

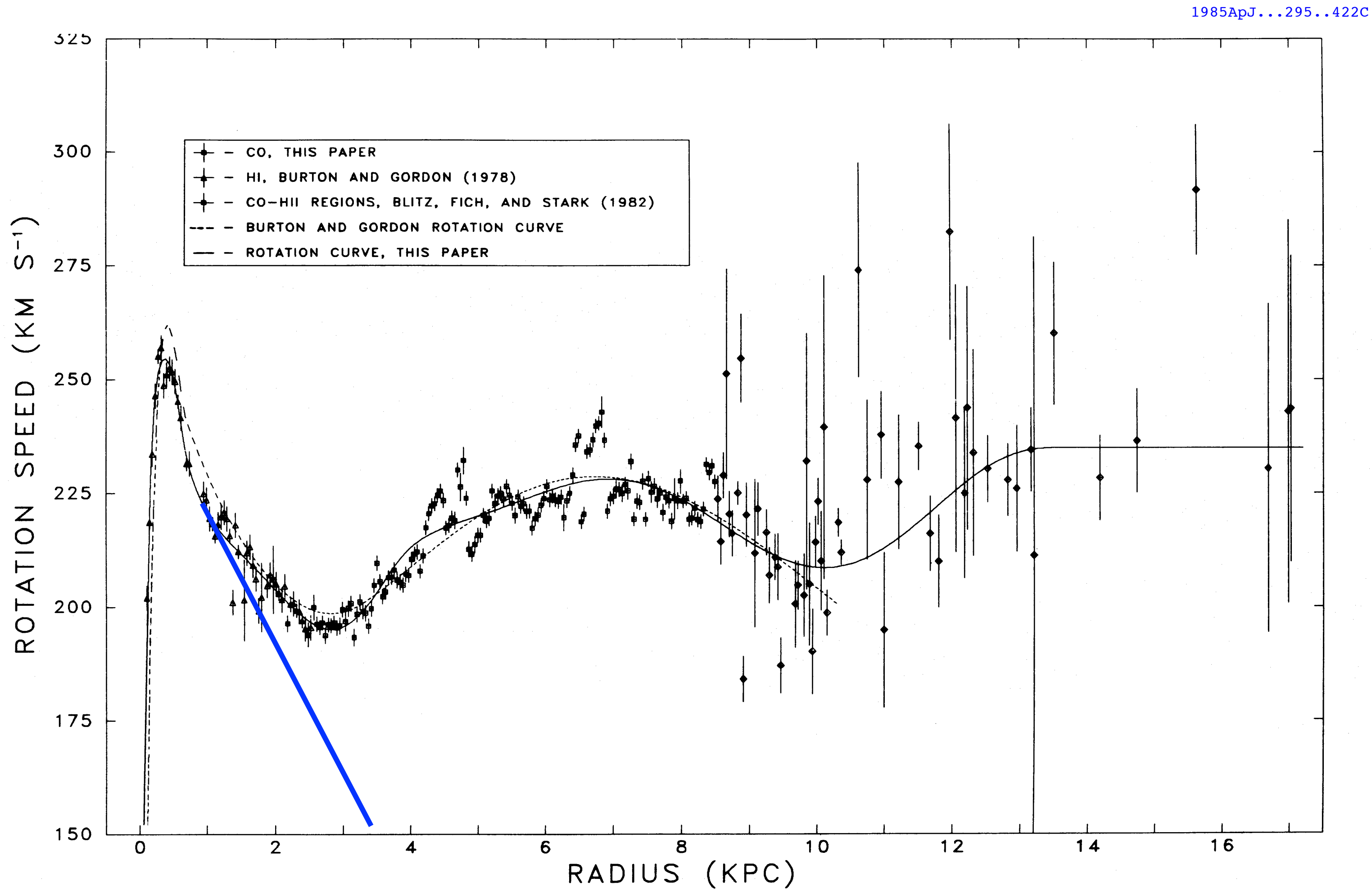
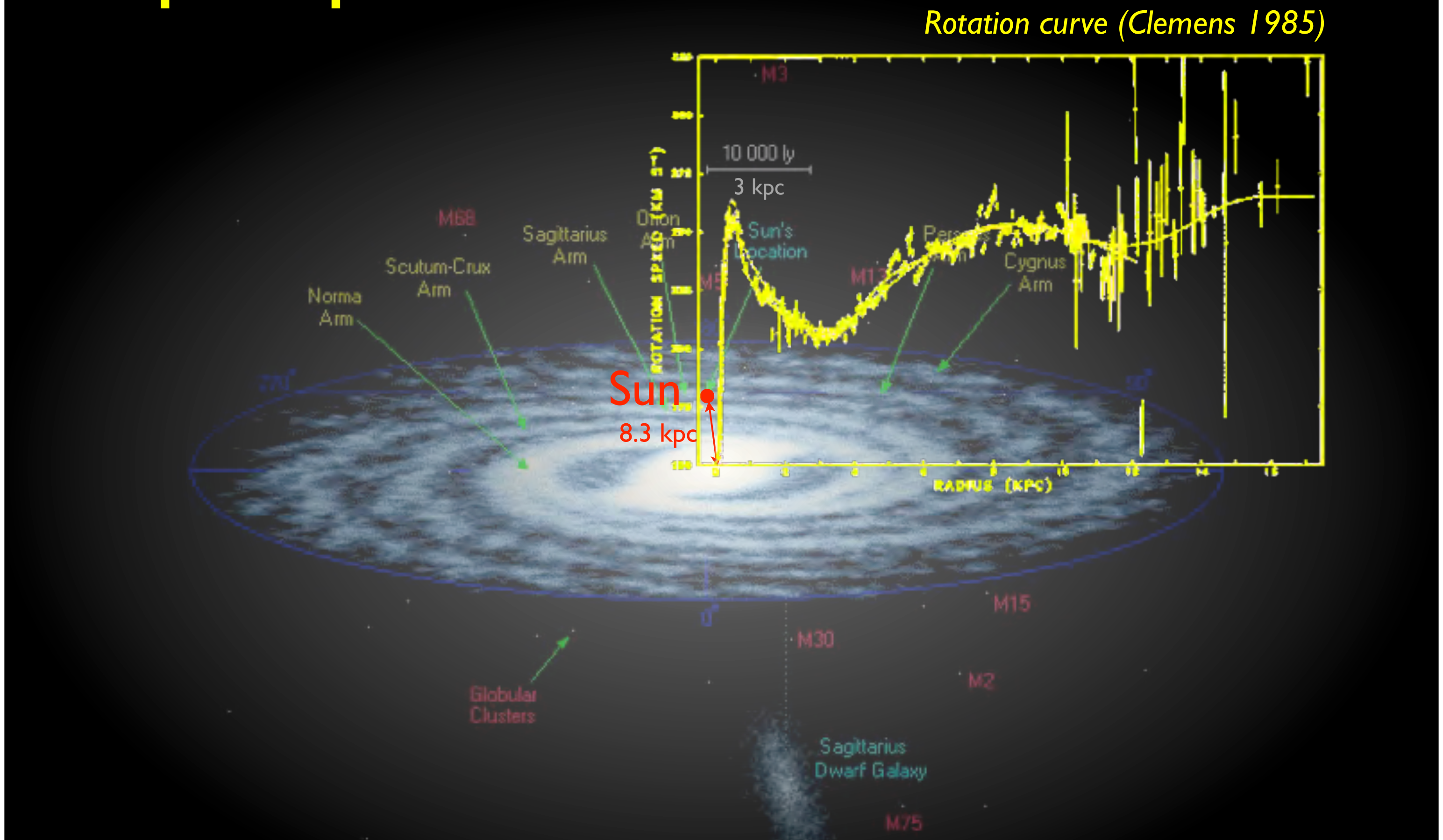


FIG. 3.—Plots of the rotation speed versus galactocentric radius. The solid lines correspond to the polynomials, and the dashed lines are the BG rotation curve. (*upper panel*)(R_0, θ_0) = (10 kpc, 220 km s^{-1}); (*lower panel*) (8.5 kpc, 220 km s^{-1}).

Dark Matter: In 1933 by F. Zwicky. This plot from D. Clemens, 1985

The motivation is the nature of dark matter

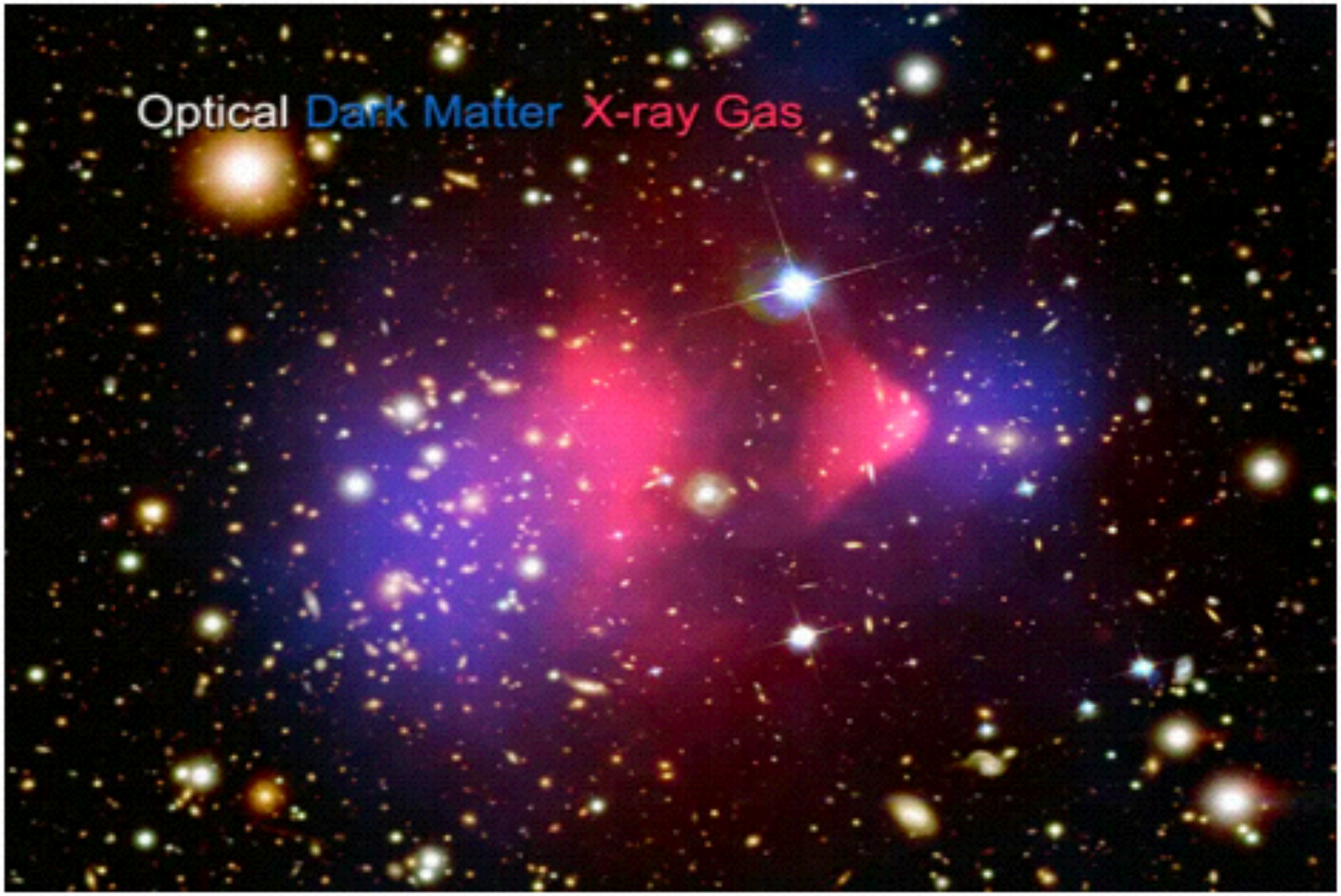
The principle



Our galaxy is inside a halo of dark matter particles

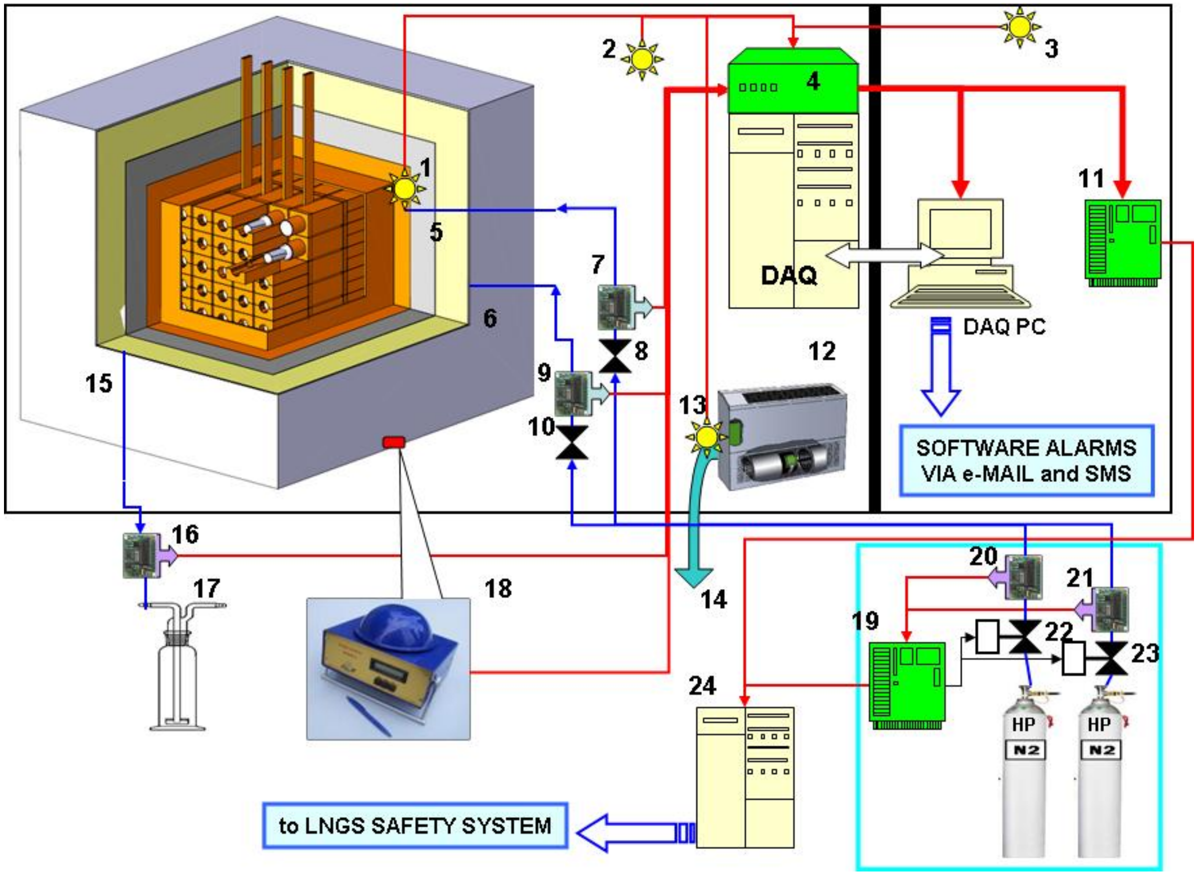
Image by R. Powell using DSS data

The motivation is the nature of dark matter



D. Clowe et al., "A direct empirical proof of the existence of dark matter", Astrophys. J., Vol.648, L109 (2006). doi:10.1086/508162

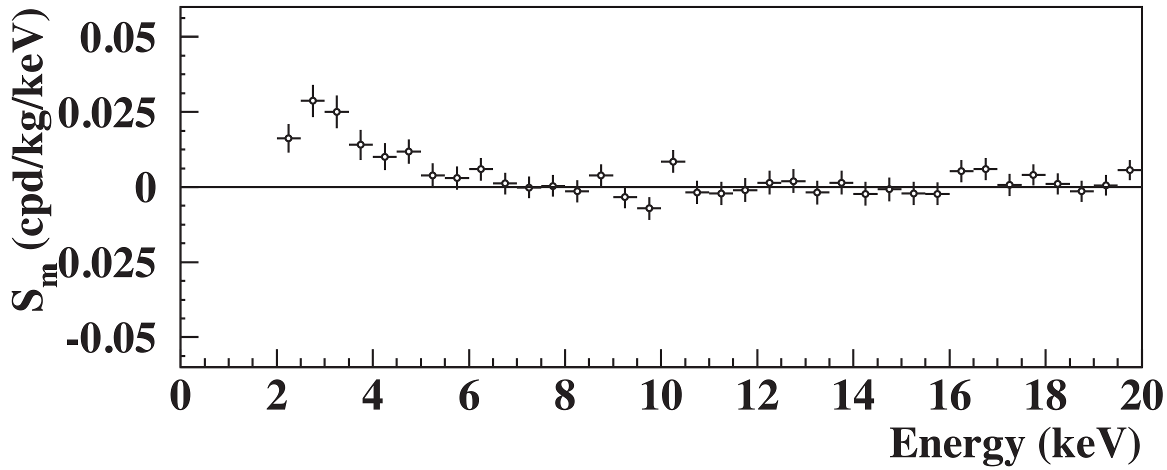
The DAMA/LIBRA experiment

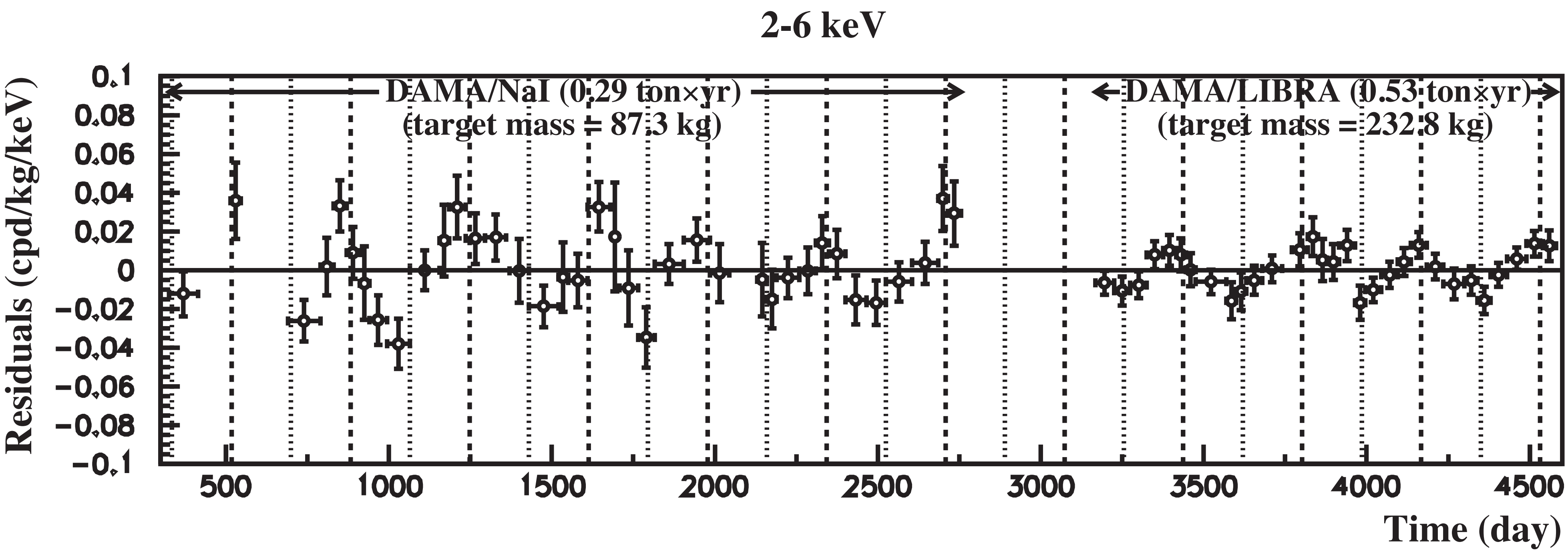


Bernabei et al.
250 kg radiopure NaI(Tl)
the Gran Sasso

NIM A592:297-315,2008

The DAMA/LIBRA experiment





DAMA collab., arXiv:0884.2741

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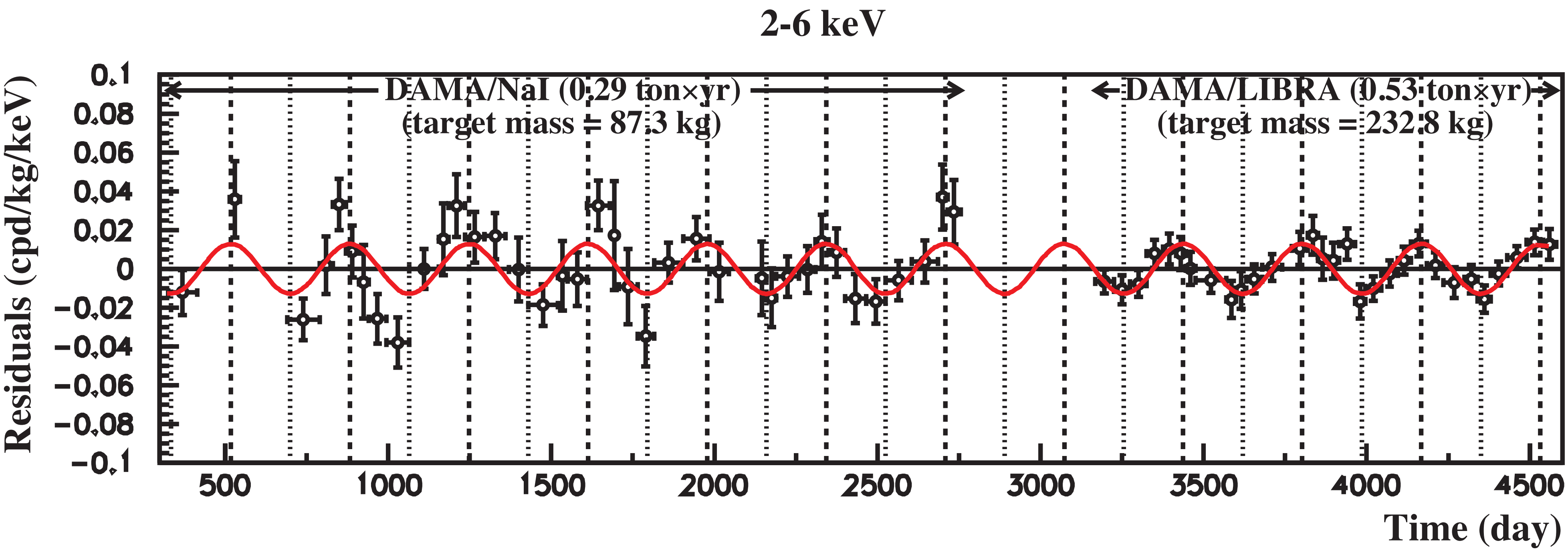
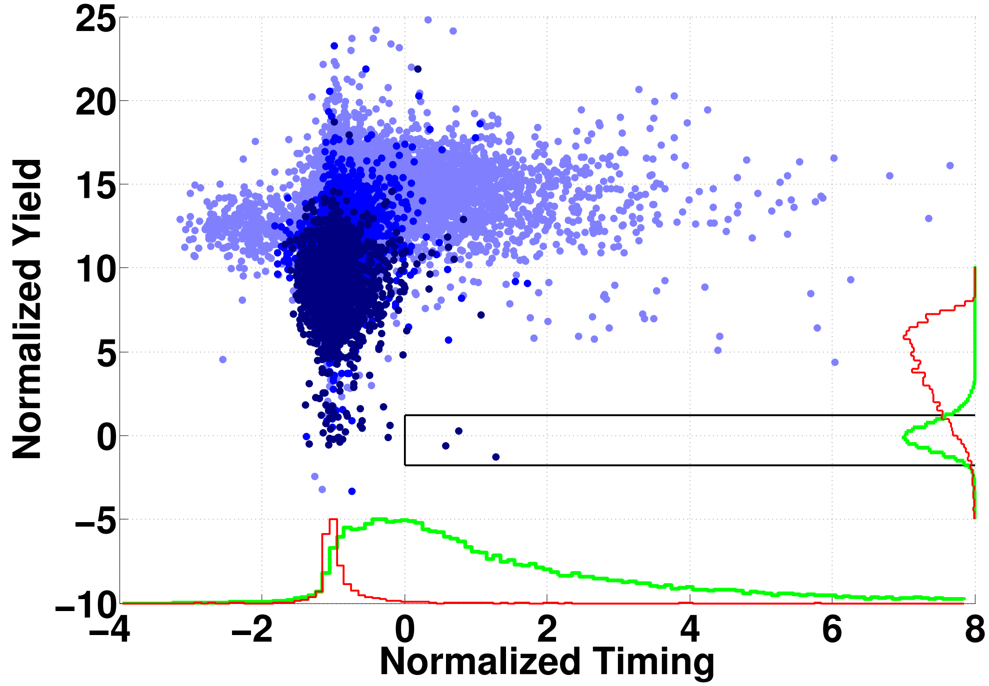


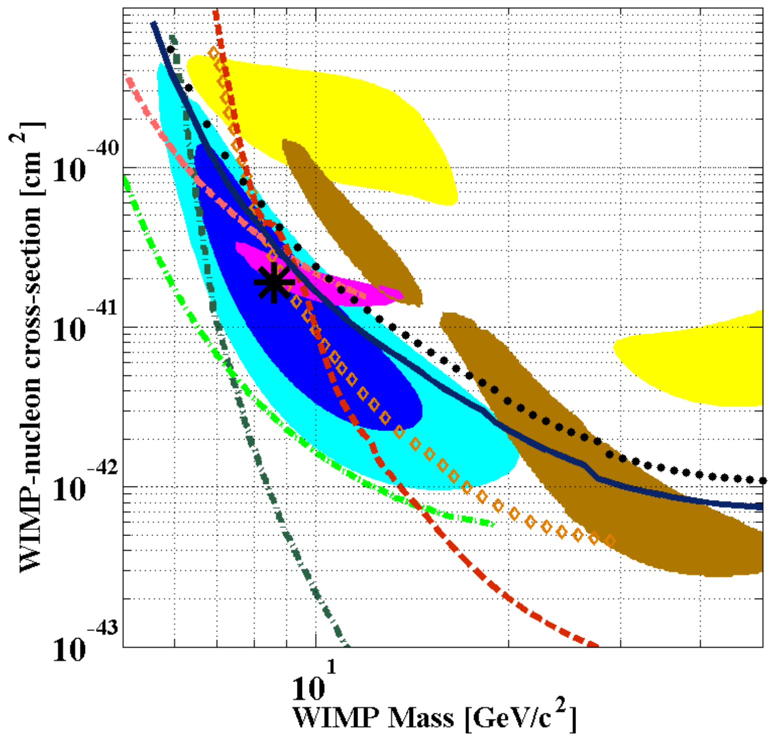
DAMA collab., arXiv:0884.2741

Recoil detection of the massive particle.

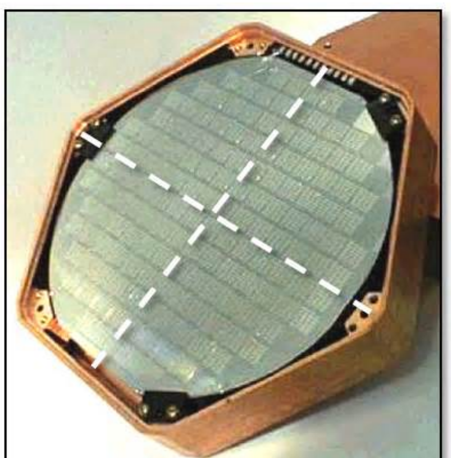
Where is the gauge boson?

The CDMS experiment





CDMS collab., arXiv:1304.4279

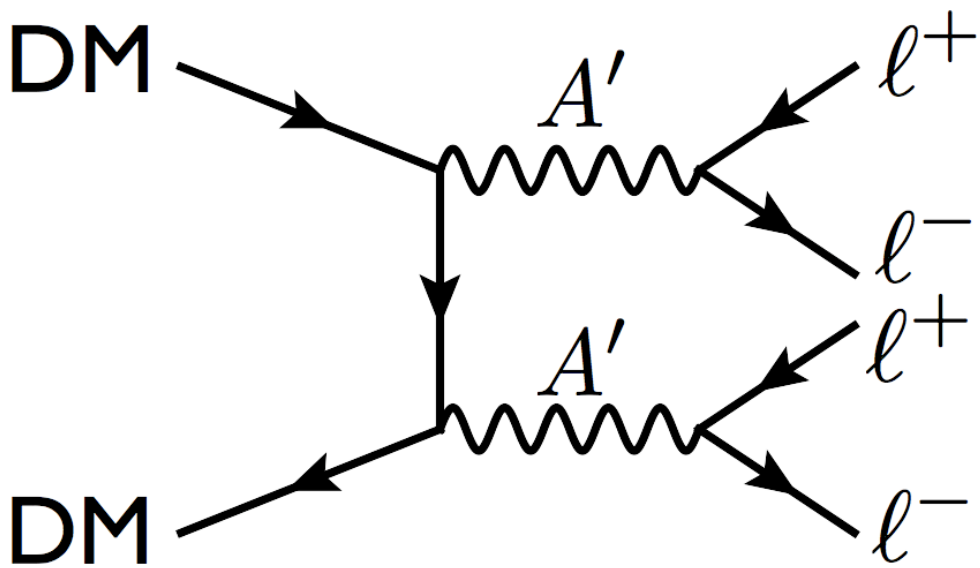


Recoil detection of the massive particle, 8.6 GeV.

Where is the gauge boson?

The theory of DM

Arkani-Hamed, Finkbeiner, Slatyer, Weiner
Pospelov & Ritz

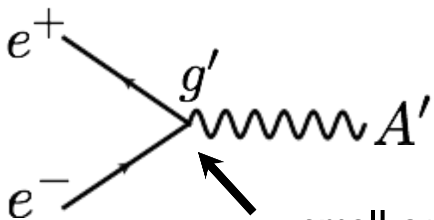


$m_{DM} \sim$ TeV $\quad$ $m_{A'} \sim$ GeV $\quad$ no anti-protons

also: A′ generates long-range force
(Sommerfeld enhancement)

$$\langle \sigma v \rangle \propto \frac{1}{v}$$

Motivation for light dark photon



("dark photon")

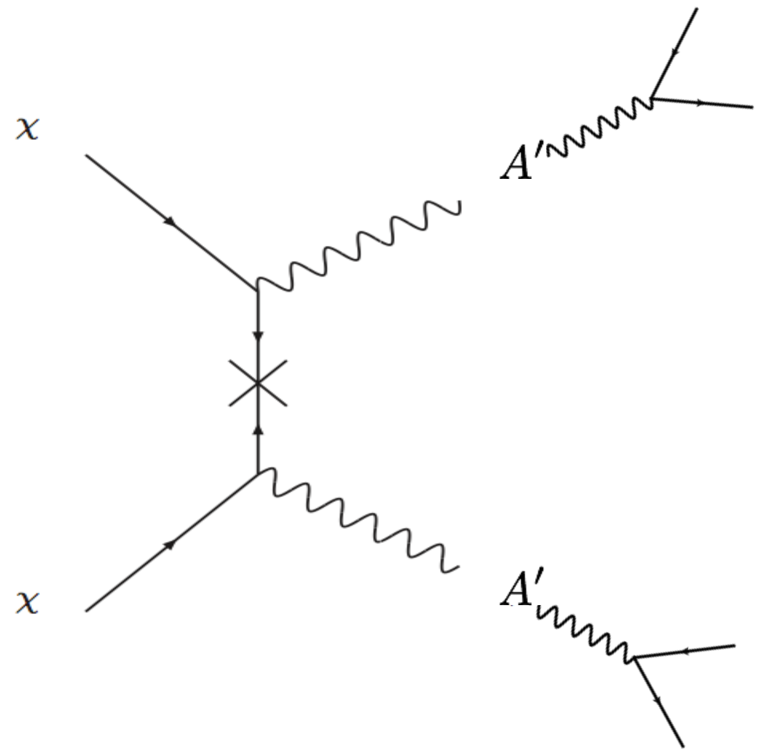
small coupling

$$\alpha' \equiv \frac{g'^2}{4\pi}$$

- Large interest in A′ search
- Number of considerations

naturally give A′ mass ~ 1 - 100s MeV

DM annihilation



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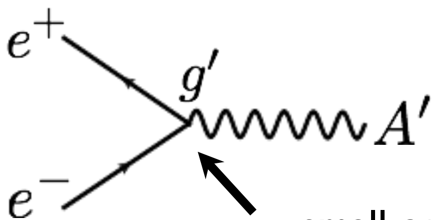

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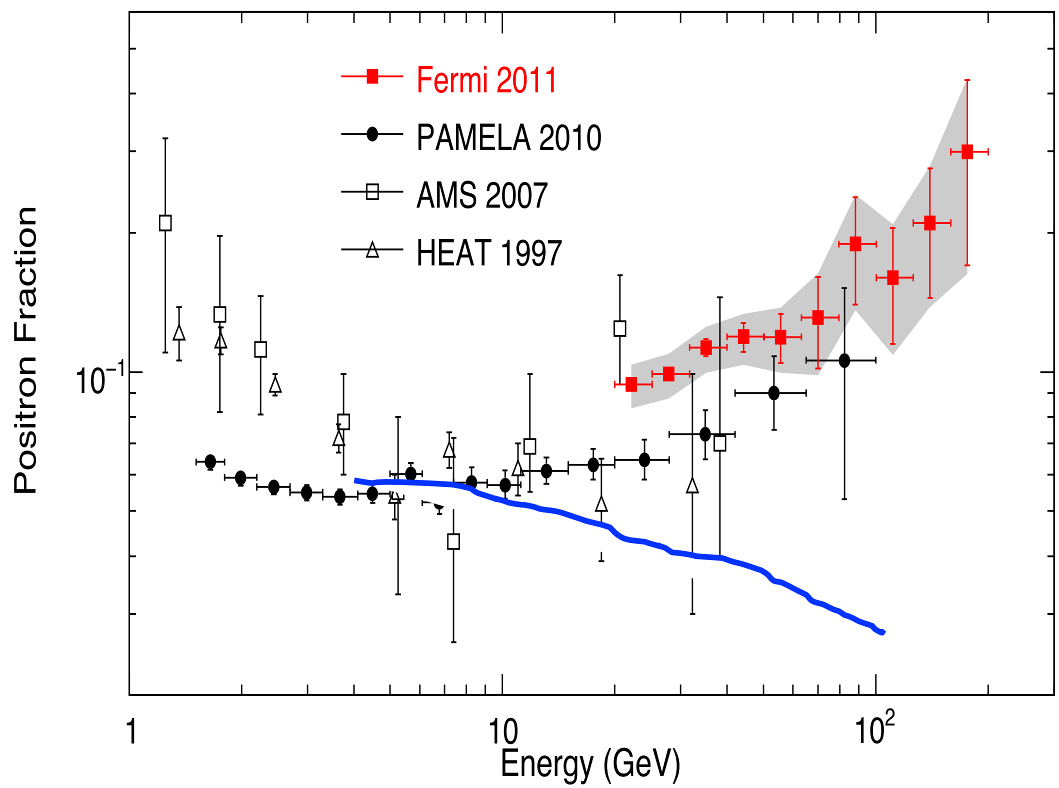
Positron/electron intensity ratio



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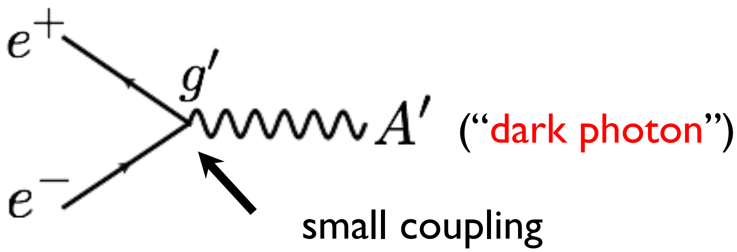

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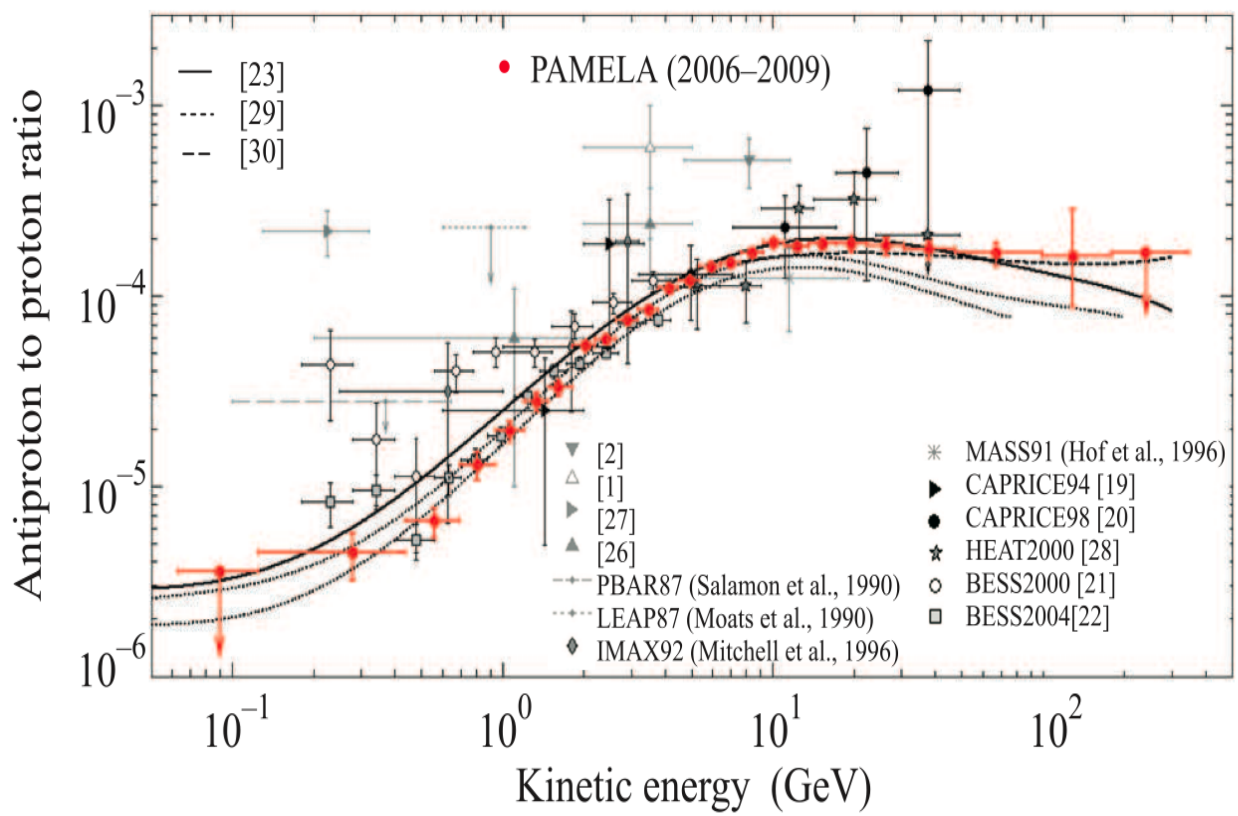
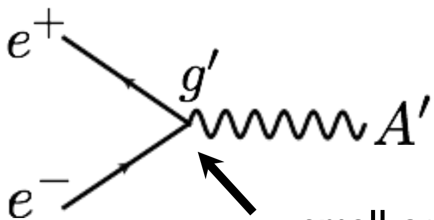


Motivation for light dark photon



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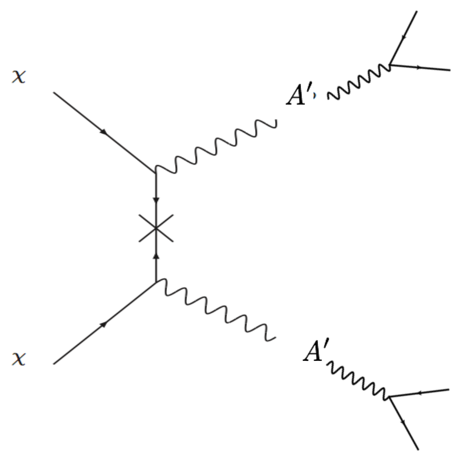
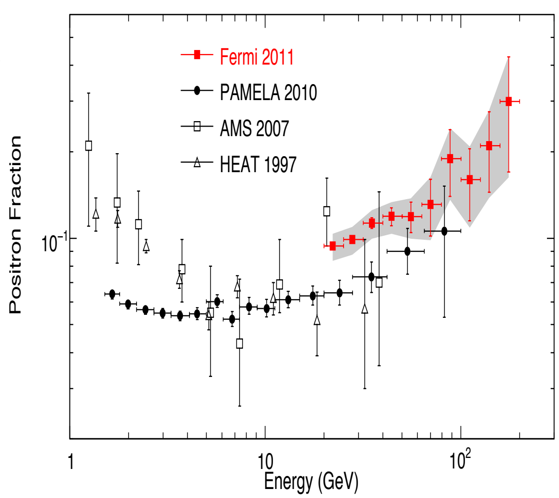


Positron/electron



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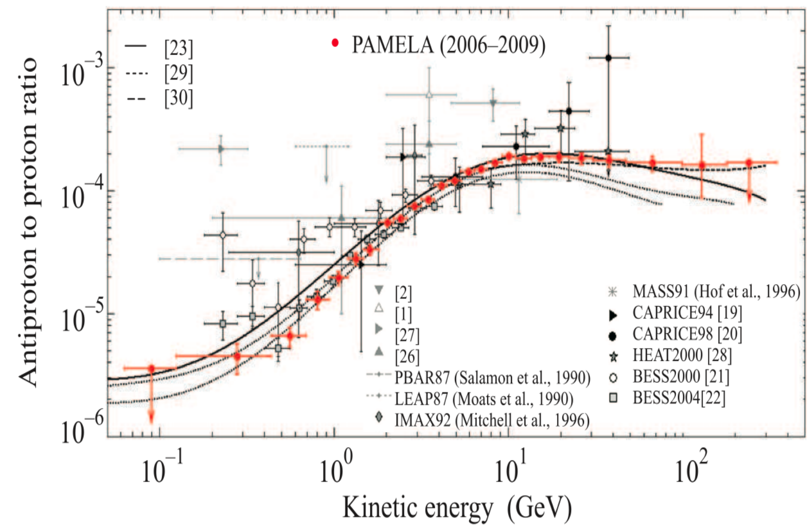

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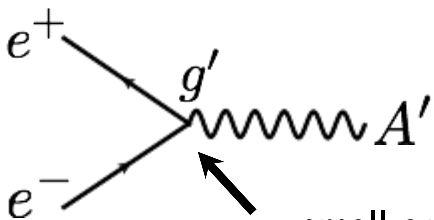

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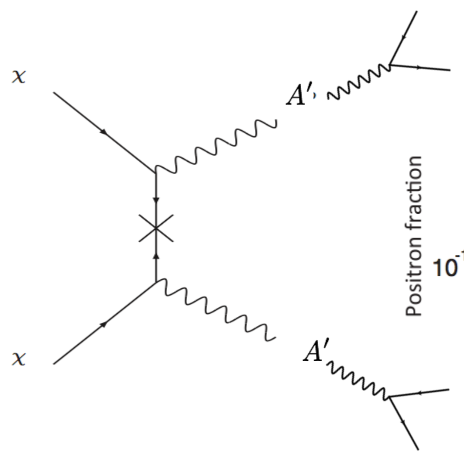
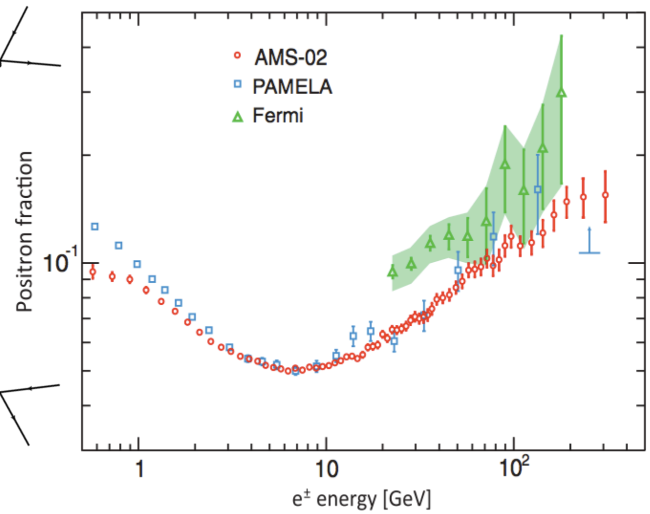
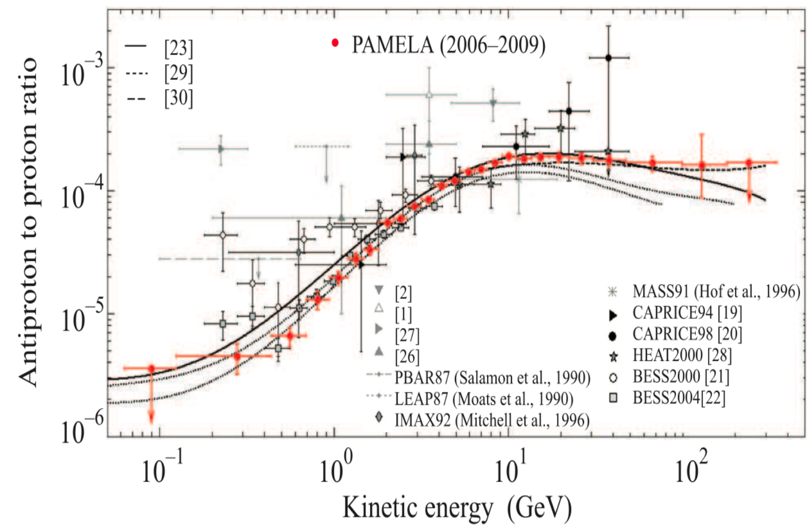
DM annihilation   Positron/electron   Antiproton/proton







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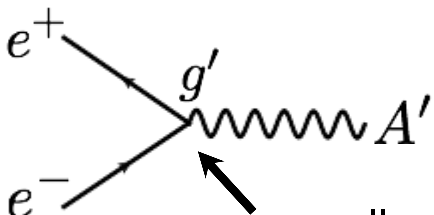

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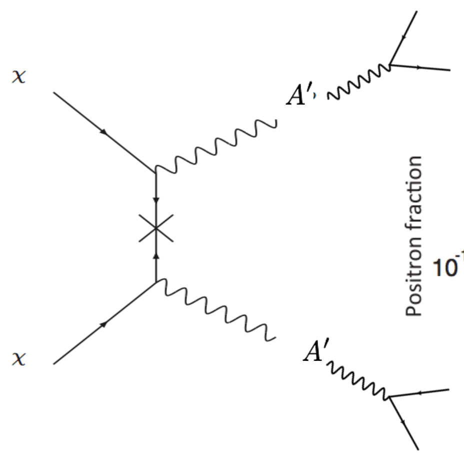
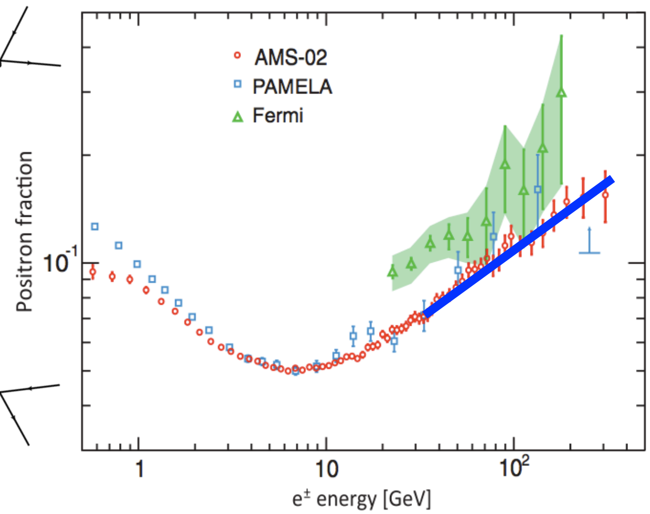
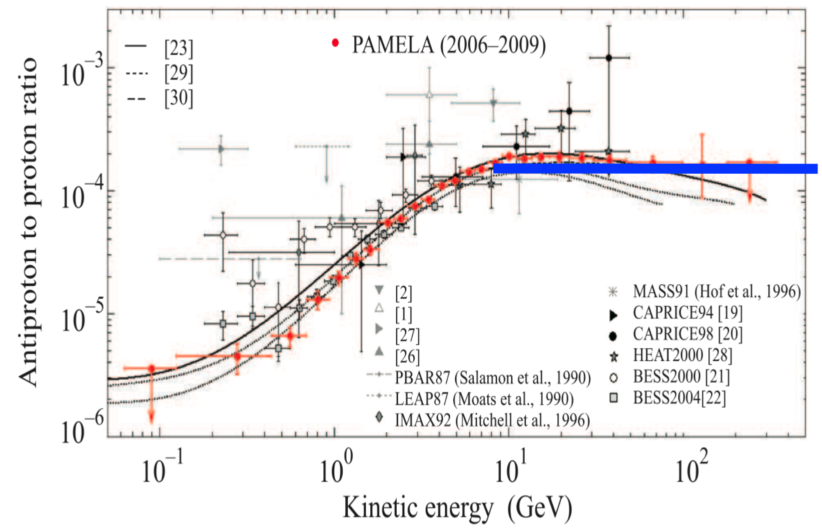
DM annihilation Positron/electron Antiproton/proton



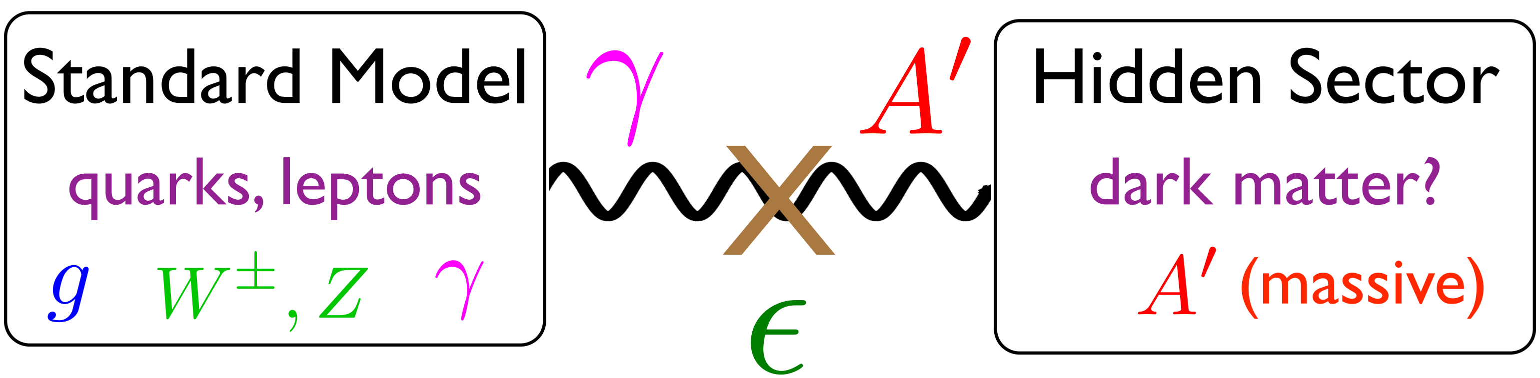




How to search for new physics

The photon and A′ can mix !

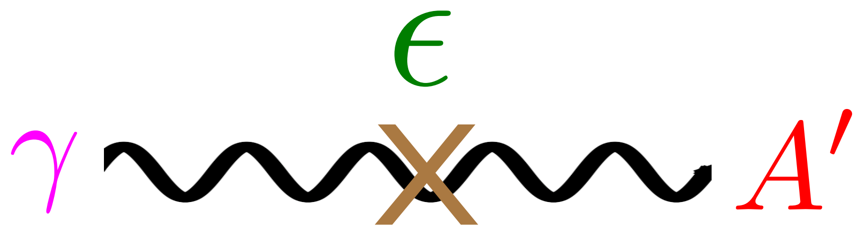
Holdom
Galison, Manohar



mixing induces coupling between
ordinary matter and hidden sector matter

How to search for new physics

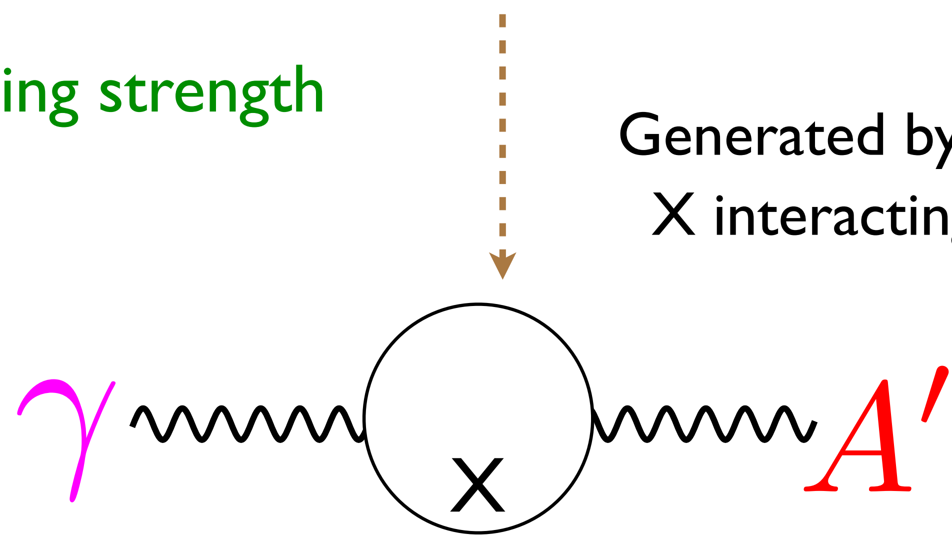
our photon



"heavy photon"

ϵ = mixing strength

Generated by heavy particles X interacting with γ and A'



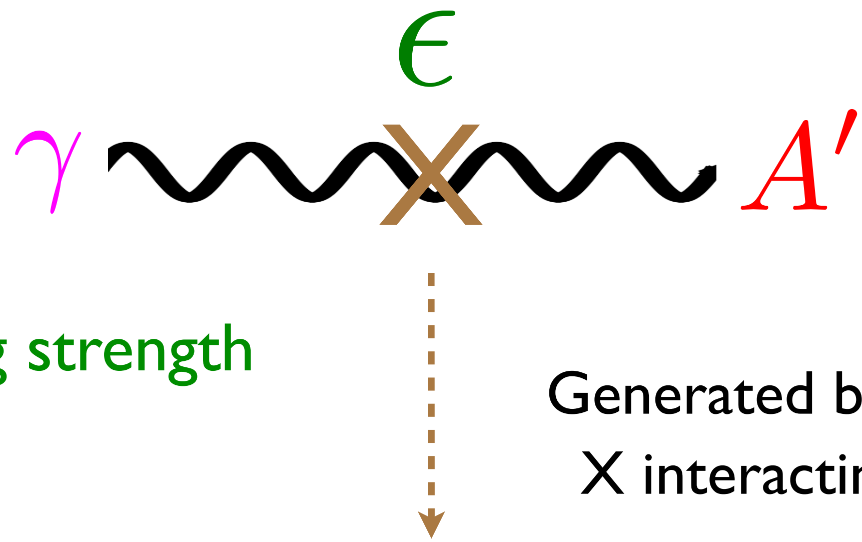
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic Mixing"

ϵ could even be O(1) (theoretically)

How to search for new physics

our photon



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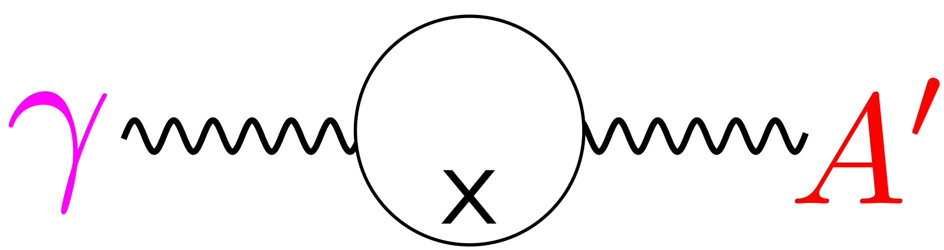


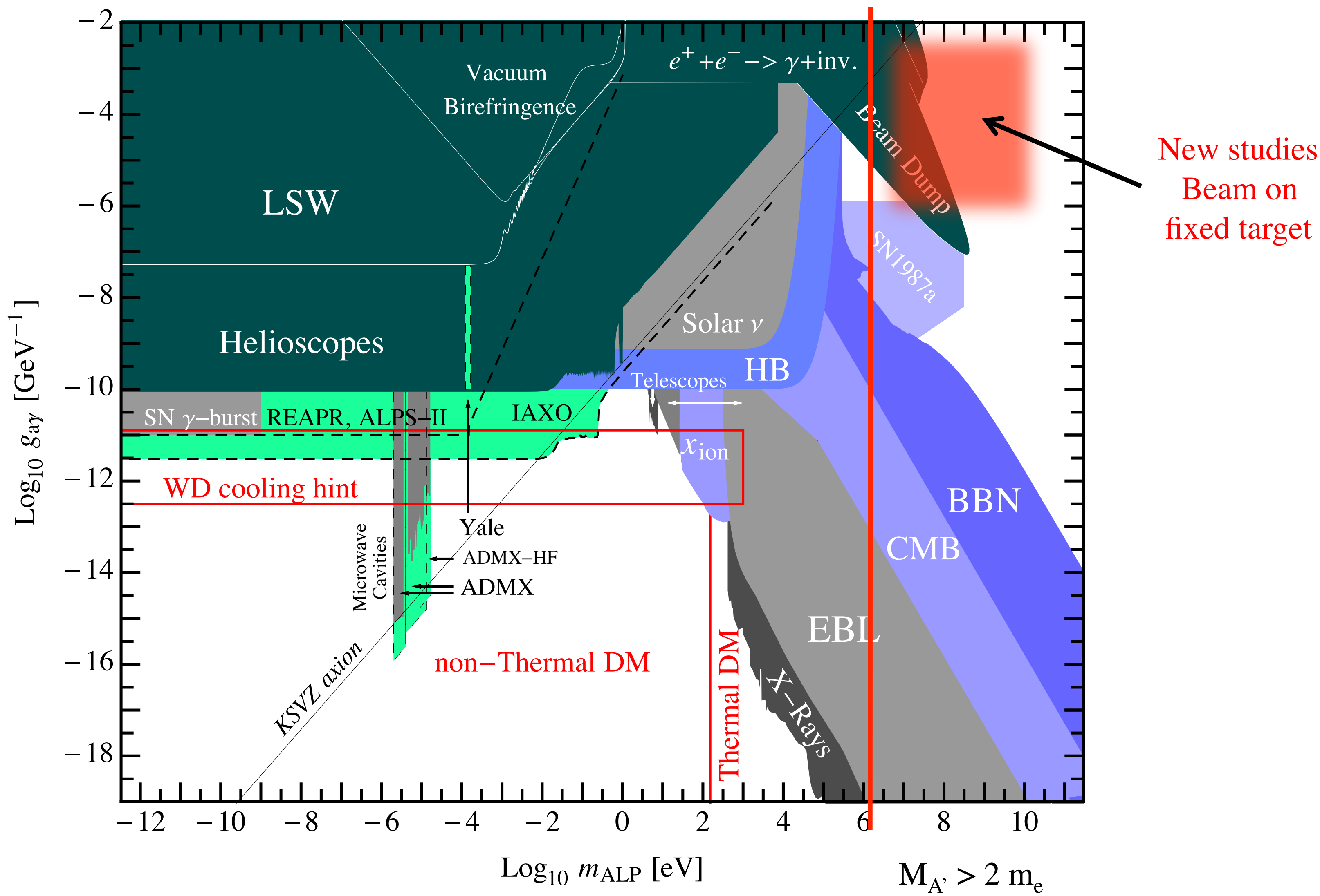
$$\epsilon \sim 10^{-8} - 10^{-2}$$

natural from quantum fluctuations of heavy particles

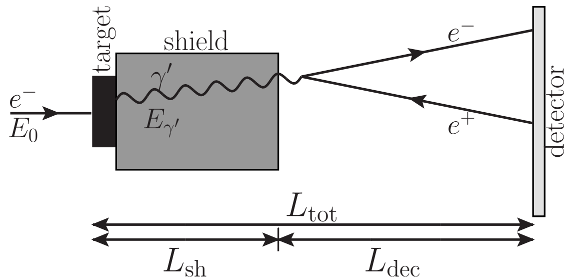
Where to search for new physics

Report of the Workshop held December 2011 in Rockville, MD

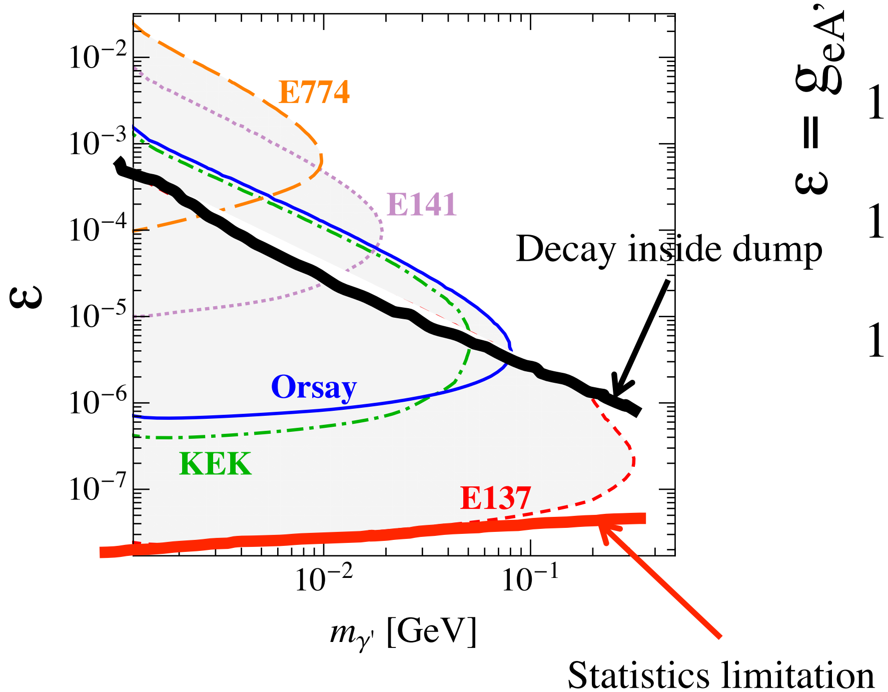
arXiv:1205.2671v1 [hep-ex] 11 May 2012

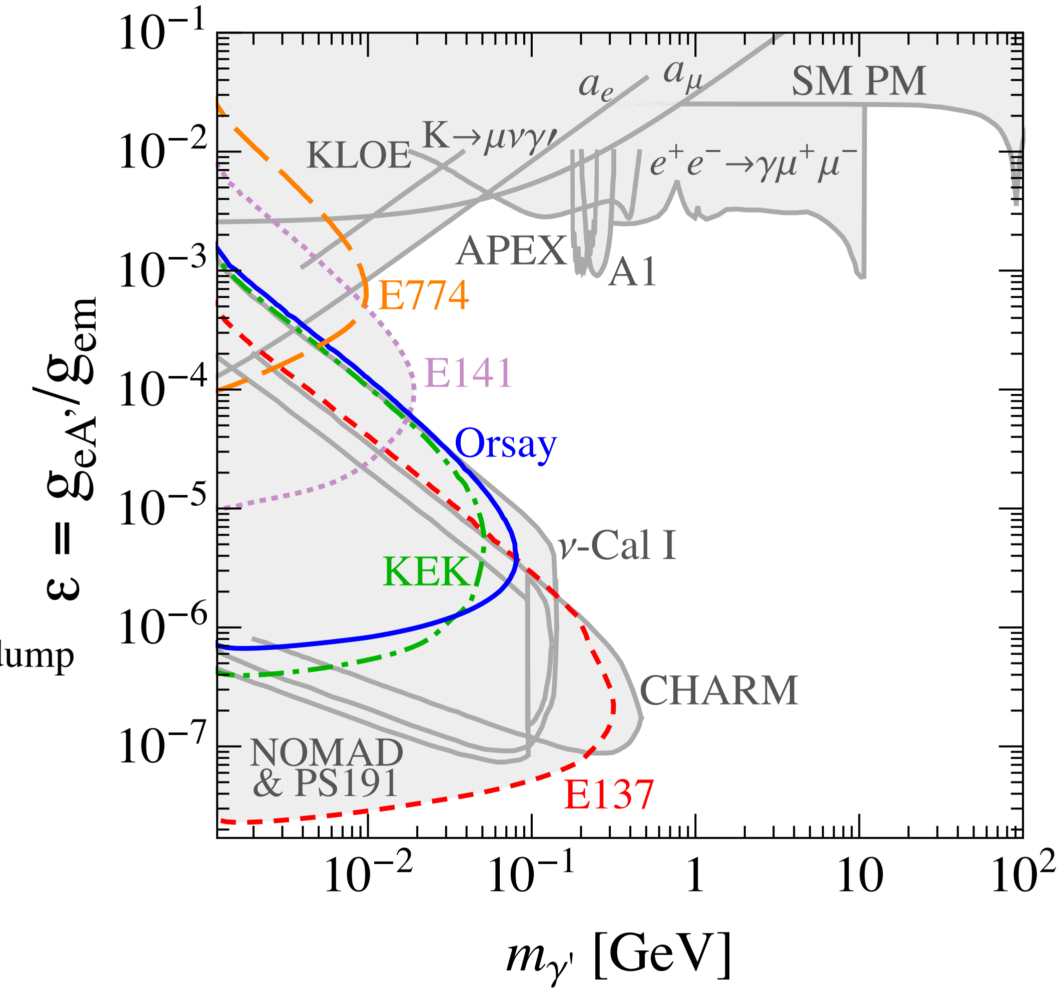


Recent summary of the searches



No mass reconstruction





S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083

Recent summary of the searches

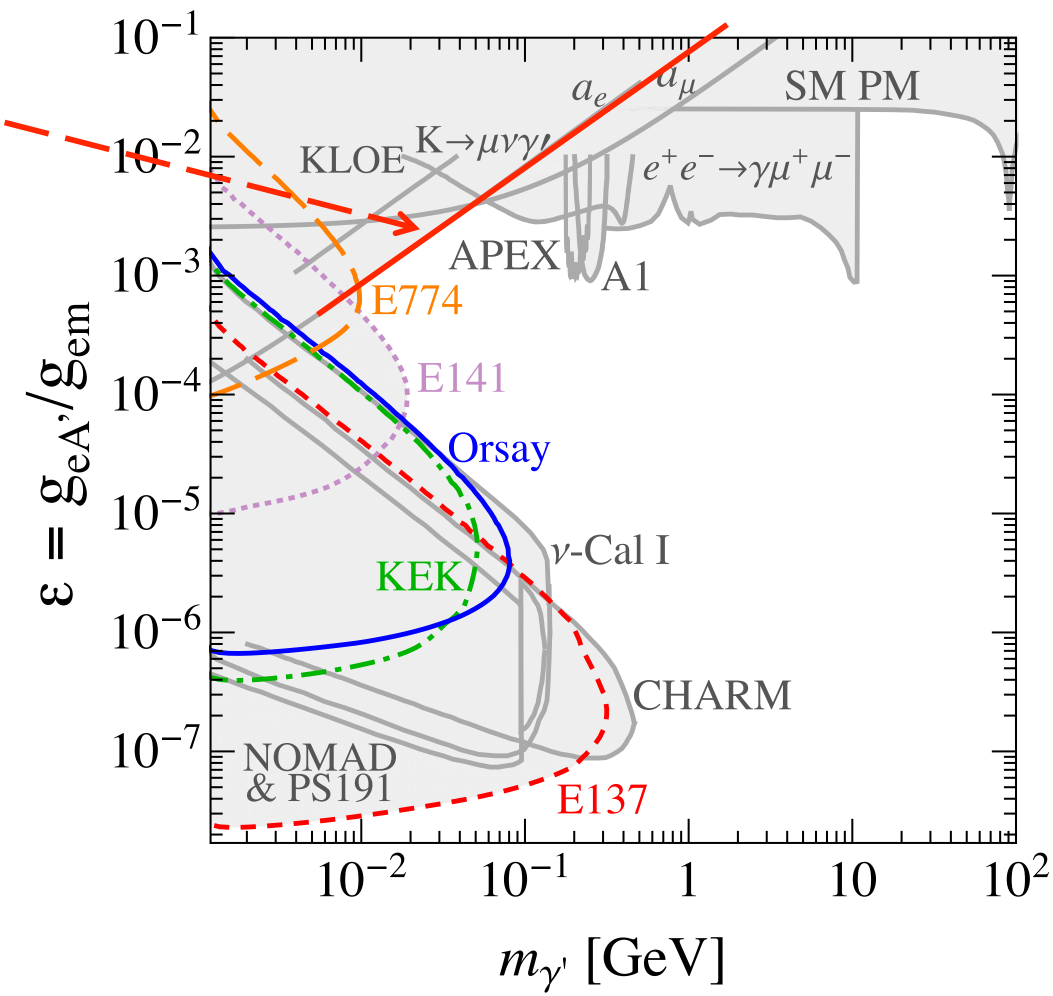
g-2 of muon and electron

Missing particle in e+e- to ..

Decay to SM (e+/e-) -

Beam Dump

Mass reconstruction



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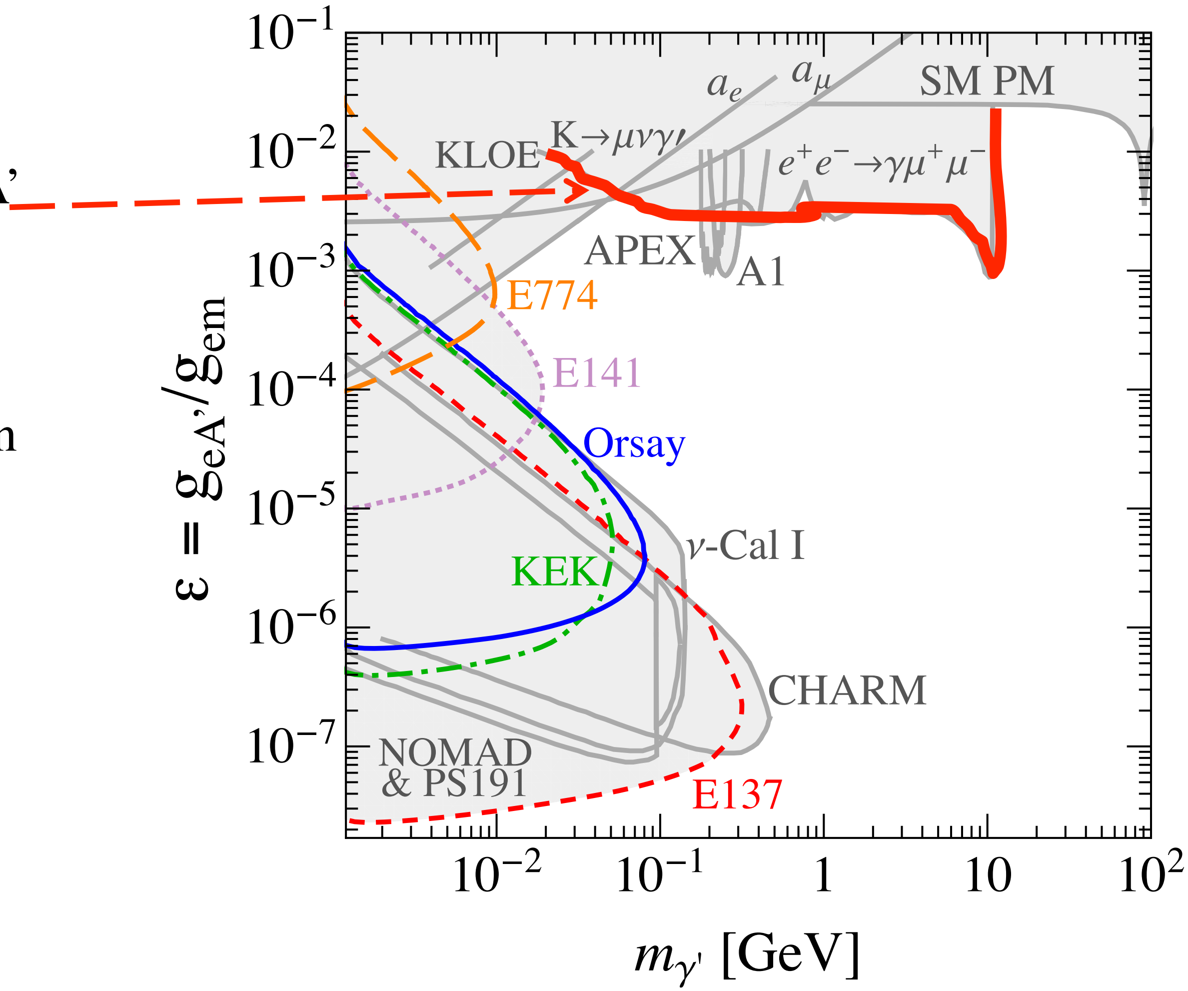

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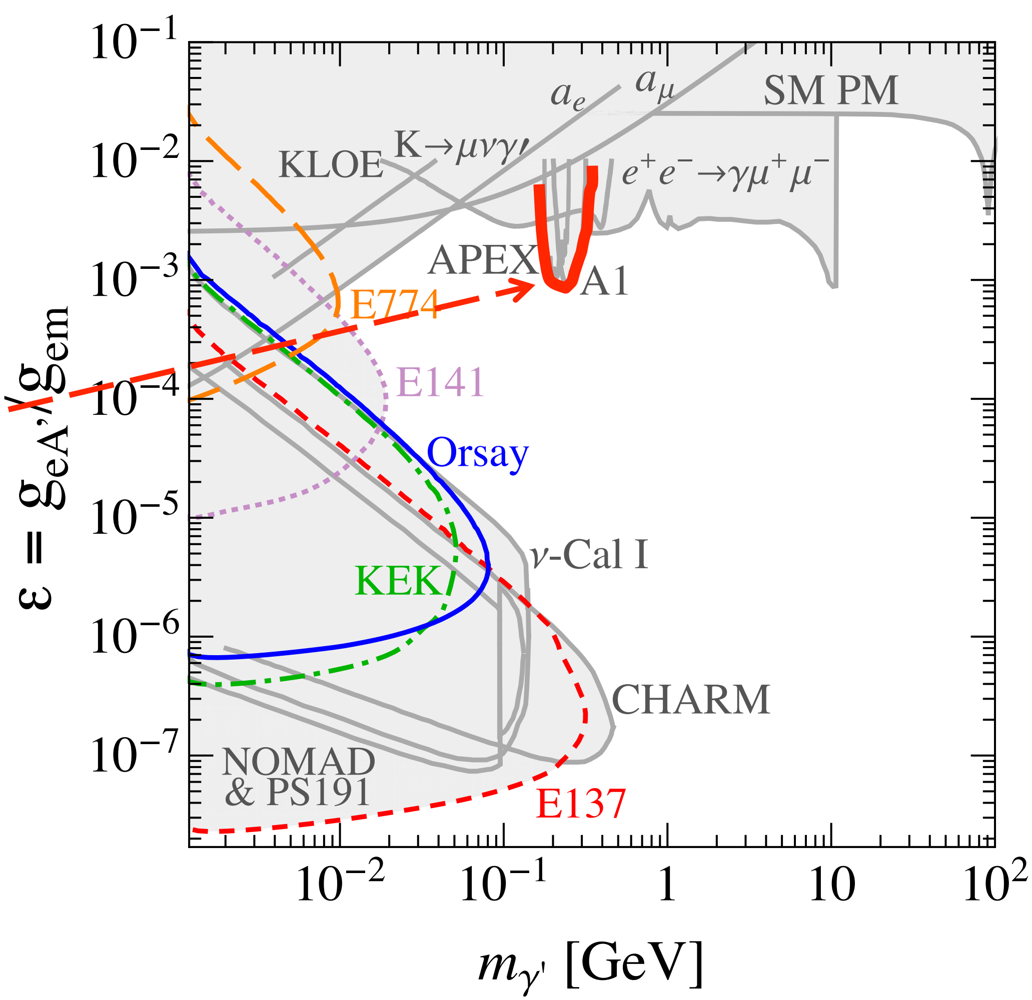


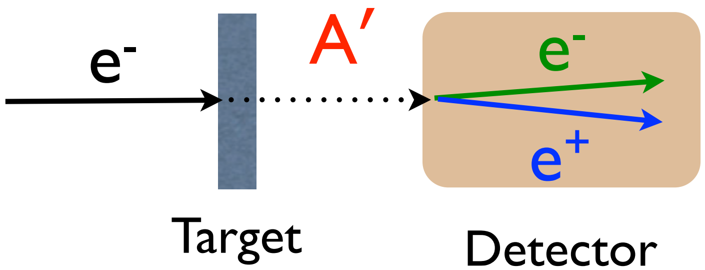
S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083

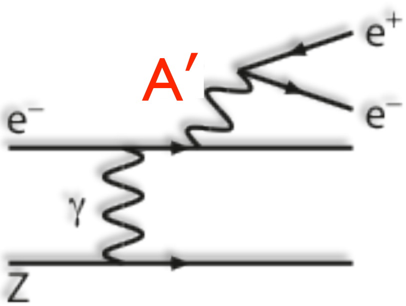
How look for A′ with MeV-GeV mass?

New e⁻ fixed target experiments

Bjorken, RE, Schuster, Toro
Freytsis, Ovanesyan, Thaler
Reece & Wang

Detect both e^+ and e^-: mass reconstruction





Experiments done/planned at

- Jefferson Lab (APEX, HPS, DarkLight)

slide from R.Essig lecture at PATRAS2012

APEX: A Search for Dark Photons in Hall A

Why do a search for new physics at JLab?

Proposal: PR12-10-009

Scientific Rating: A
Recommendation: Approval

The PAC approves the proposal contingent on a successful solution of the radiation issue. The PAC feels that the experiment should be carried out as early as possible (ideally before the 6 GeV shut down in 2012).

Title: "Search for new Vector Boson *A'* Decaying to e^+e^-"

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

Motivation: The proposal is to search for a vector boson *A'* with weak coupling of about 10^{-3} e or smaller to electrons in the mass region 65-525 MeV. The proposed search is motivated by recent developments of models trying to explain inconsistencies observed in astrophysical data and dark matter search experiments. Such a vector boson would couple to charged leptons as it will mix with photon. If *A'* is produced by radiation off an electron beam, it would decay producing very narrow resonance in the invariant mass e^+e^- spectrum.

The proposal is very interesting and has the potential to make an important discovery. There are not many places where such measurement can be done, as it requires very high integrated luminosity and good control of the electromagnetic background. Part of the plane of coupling constant *versus* mass of the boson has already been excluded, but the region available for the proposed experiment coincides with the domain of greatest theoretical interest, for example explaining the deviation from SM expectations observed in the latest *g-2* experiment.

APEX: A Search for Dark Photons in Hall A

Why do a search for new physics at JLab?

• It is the most interesting thing that a physicist can do.

• Our nuclear physics lab has the only 100% d.f. high energy electron accelerator existing in the US.

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There are two ways to search for new physics:

i) Direct search, as done for VMs, Z, W, top, Higgs
ii) Deviation in some well-known observable, such as Θ_W

The LHC results indicate a Great Desert beyond SM
The focus is shifting to Dark Matter: WIMPs, A', Z_d … Dark forces

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The parameter space: the mass and the coupling constant.
Direct search often covers a limited range of mass and could be very sensitive to small coupling.

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• Heavy photon is a window which our electromagnetic community has a chance of opening. It is like the searches for new physics with the Qweak and future Moller exp-ts.

• A' is the chance of a lifetime for the electron scattering nuclear community to contribute to searches using the standard available equipment.
Only one other experiment is a big Moller project.

APEX: A Search for Dark Photons in Hall A

Why do a search for new physics at JLab?

What are the A' particle status and perspectives?

October 2012, Dark Forces at Accelerators (Frascatti):
http://www.lnf.infn.it/conference/dark/

November 2011, Intensity Frontier workshop (DC):
Fundamental Physics at the Intensity Frontier:
arXiv:1205.2671

September 2010, Searching for a New Gauge Boson at JLab:
http://www.jlab.org/conferences/boson2010/

September 2009, Dark Forces Workshop (SLAC):
http://www-conf.slac.stanford.edu/darkforces2009/

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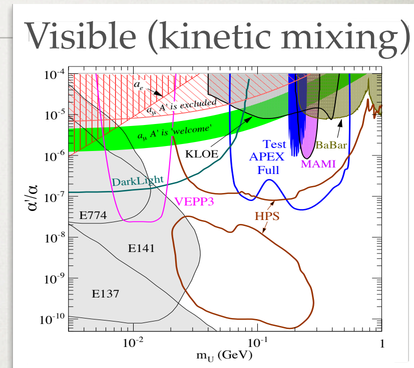
N. Toro: LOOKING FORWARD

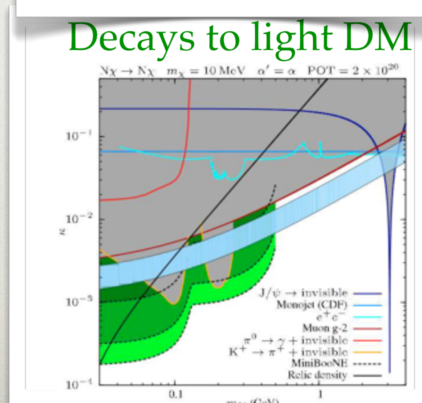
Parameter space too big for one plot!

- Different searches apply to different couplings (e.g. kinetic mixing vs. baryon # vs. e-τ …)
- Especially important distinction
  - visible
  - invisible (to DM)
  - cascade (e.g. multileptons)

very different experiments!

A lot left to do!





Parameter space too big for one class of experiments!

Invisible: cf. Fayet; Battell, Pospelov, Ritz; C. Wallace's talk

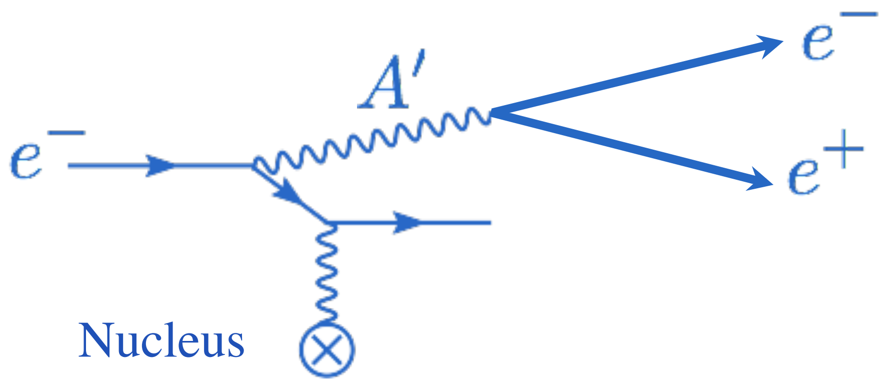
Cascade: BaBar 0908.2821 …

APEX: A Search for Dark Photons in Hall A

Why do a search for new physics at JLab?

What are the A' particle status and perspectives?

What is the APEX search method?



Strategy: measure $e^{+}e^{-}$ mass spectrum precisely,

in kinematic region optimized for A′ acceptance

and QED background suppression.

APEX: A Search for Dark Photons in Hall A

Why do a search for new physics at JLab?

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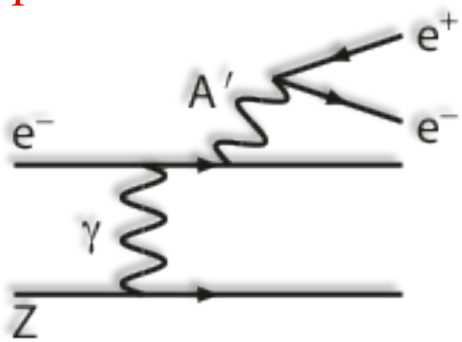
Why will Hall A do a very good experiment?

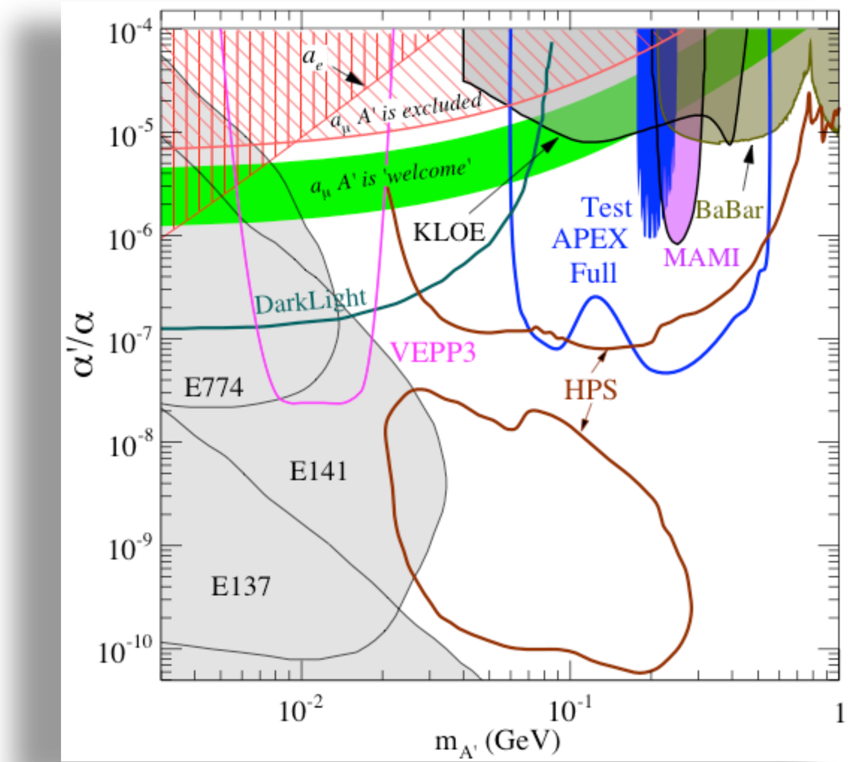
• Large Acceptance	- forward: m_A/E_b , $E_+=E_-=E_b/2$
• Best Detector	- rate capability: VDC~ 8MHz
• Best Intensity	- can use 80 μA x 8%X0
• Strong Collaboration	- test run, analysis, PRL

Searches for a gauge boson A' – APEX Test Run Result

Electroproduction of A'



decay



Published results :

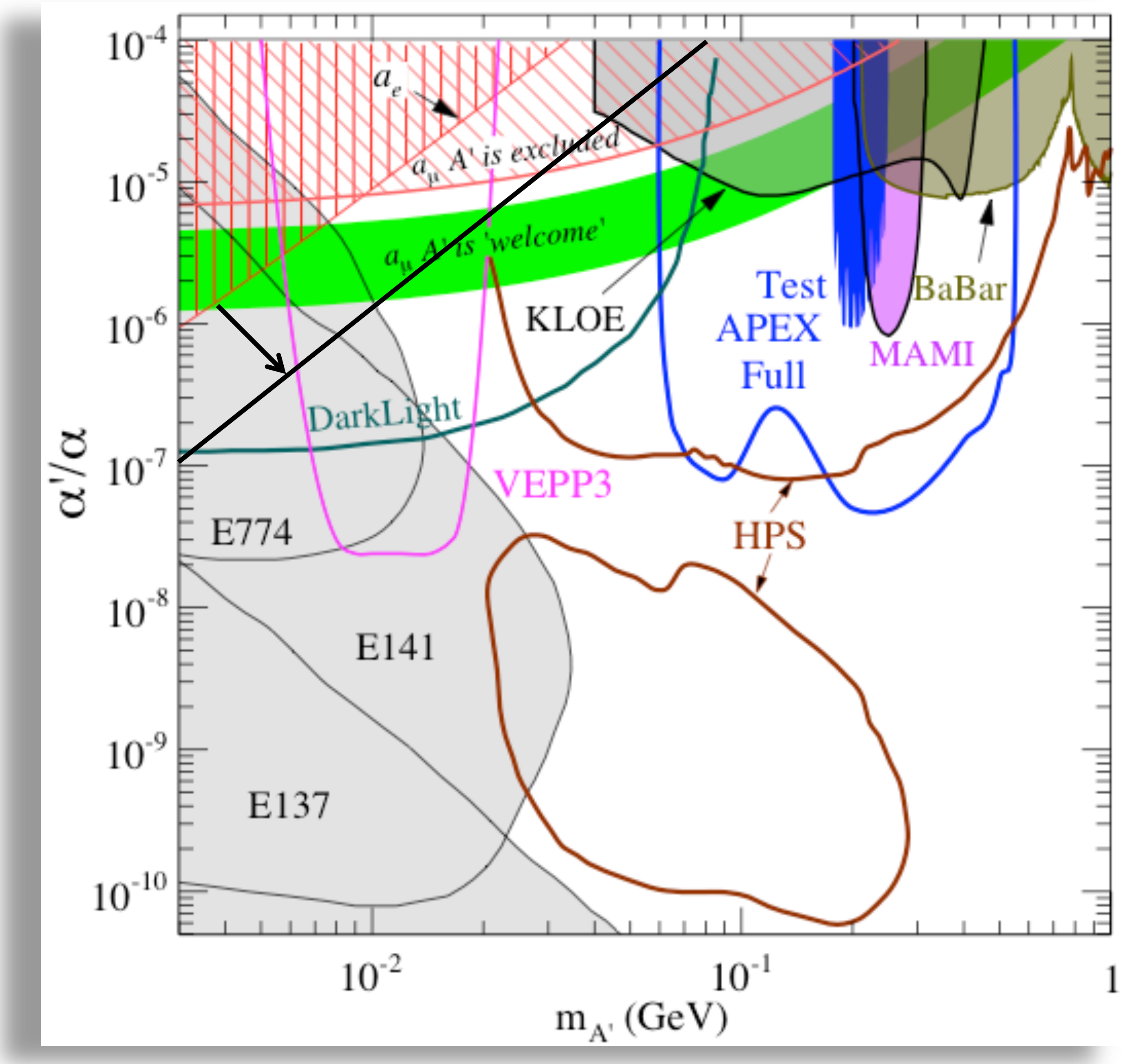
- Beam dump searches: SLAC:E137, 141; FNAL: E774
- electron and muon (g-2), limits
- BaBar, Υ(3s)-> γ and μ+μ- (inferred limit)
- KLOE, mass of e+e- pair (bump search)
- **APEX test run, mass of e+e- pair – in publication**
- MAMI – APEX type scheme

Future searches for a new force carrier:

- APEX – electron-nucleus fixed-target, a e+e- pair in two focusing spectrometers
- HPS – same, the e+e-, μ+μ- pairs in a custom Si-tracker magnetic spectrometer
- DarkLight – an internal target with an electron beam in Jefferson Lab ERL, detect a e+e- pair and e'p
- VEPP3 – a positron beam incident on an internal H_2 target, missing mass in (e+e-, γ X)
- MAMI – APEX type scheme with lower beam energy

Mont's slide

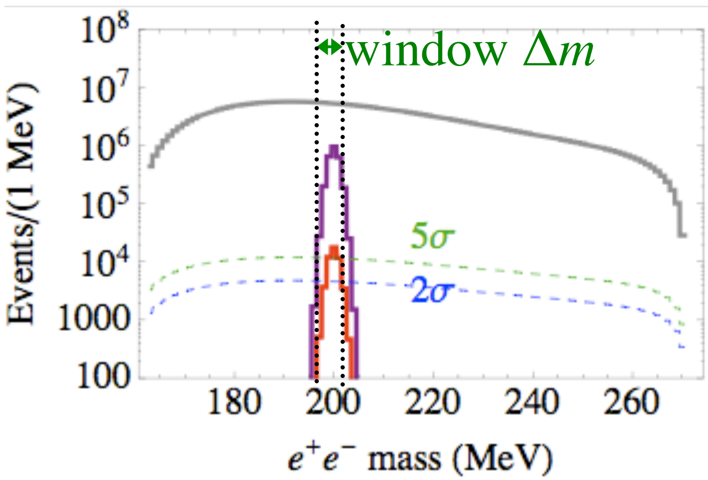
Searches for a gauge boson A'

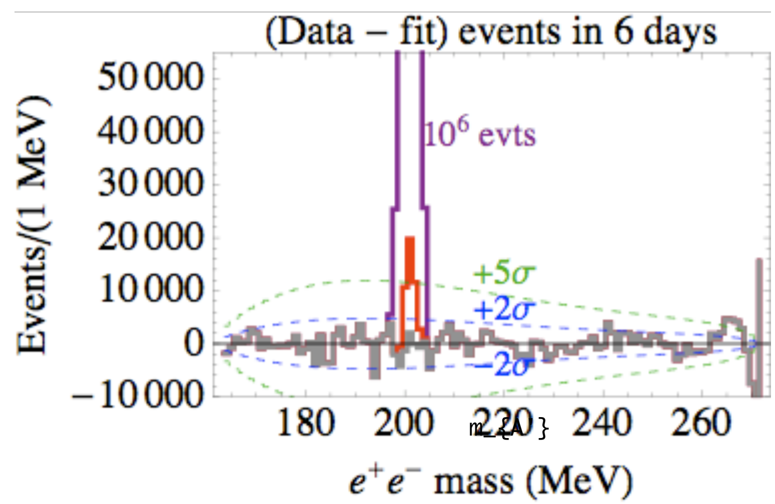


Narrow Resonance Search

To identify A′ signal, must study invariant mass distribution

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





In mass window Δm:

$$\frac{S}{\sqrt{B}} \sim \frac{\alpha'}{\alpha^2}\sqrt{N_{QED}\left(\frac{m_{A'}}{\Delta m}\right)}$$

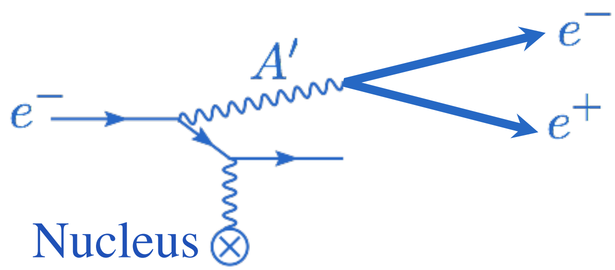
To search at small α′, need:

★ High e^+e^- statistics

★ Excellent mass resolution

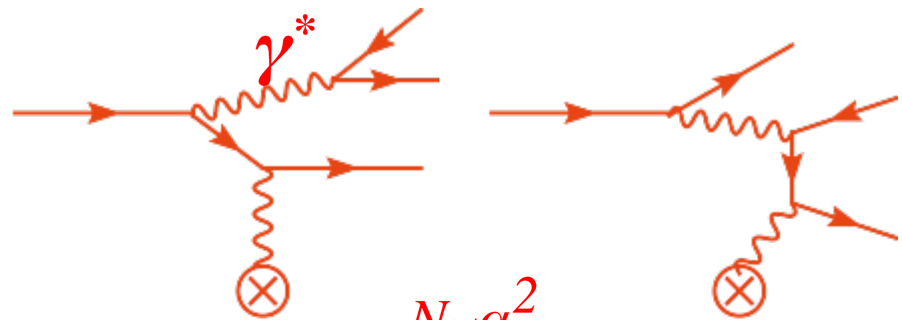
Approach: A′ Production and Background Kinematics

Production diagrams analogous to photon bremsstrahlung



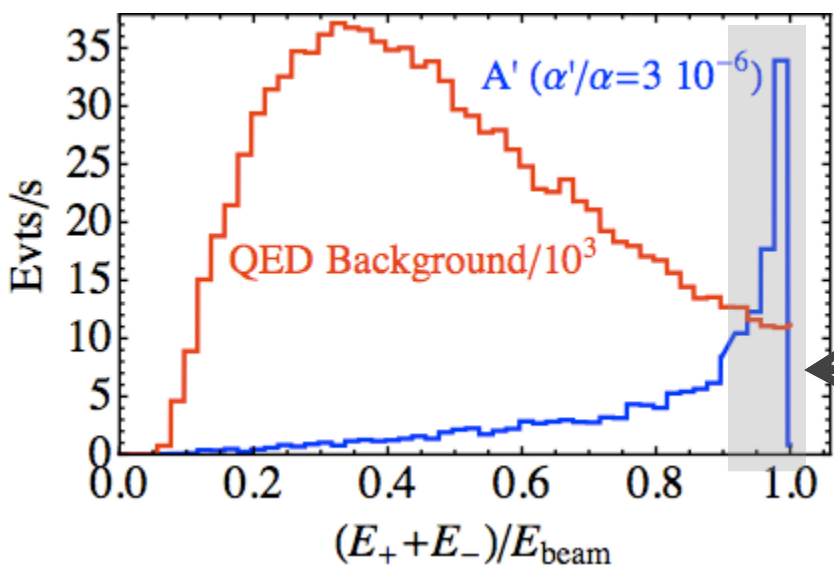
$N \sim \alpha'$ x Branching → O(1)

QED Backgrounds



$N \sim \alpha^2$

(rates before angular cuts)

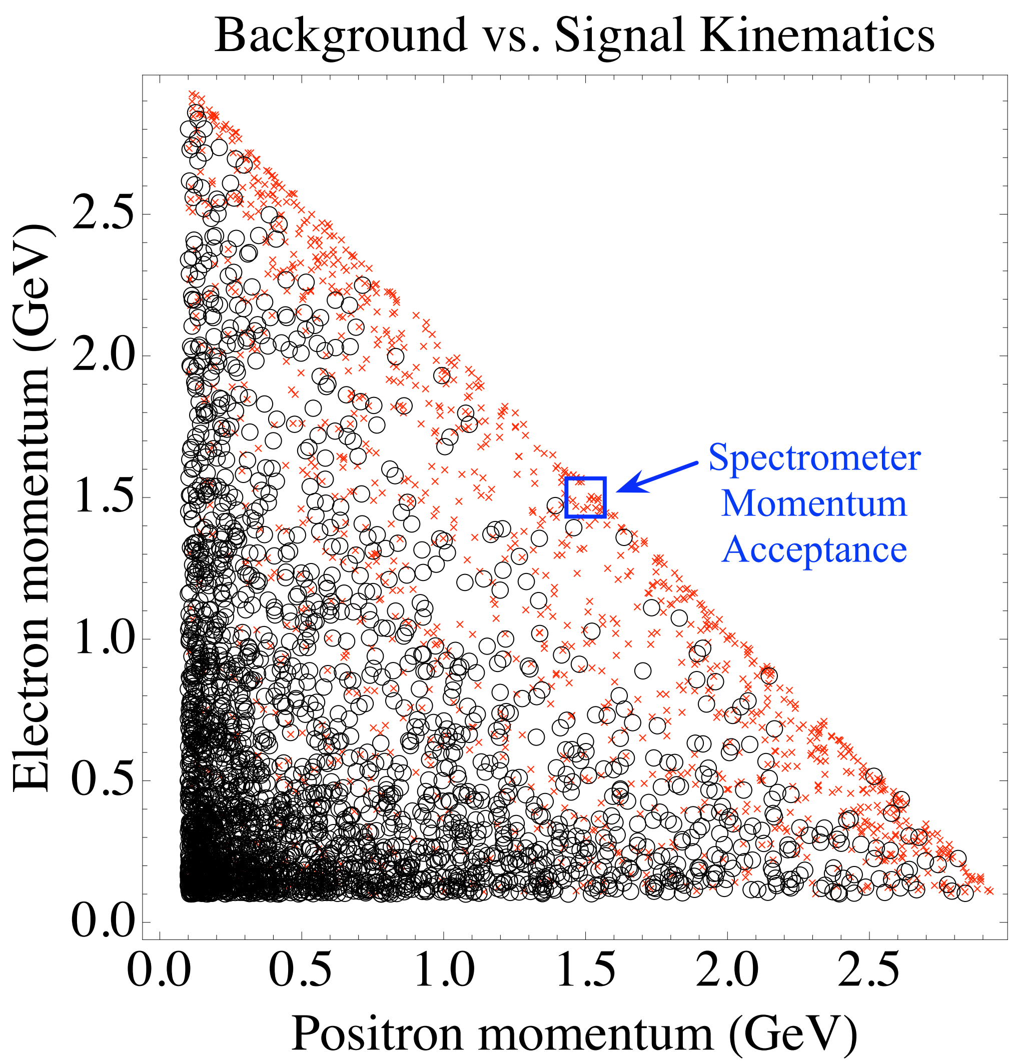


A′ products carry full beam energy!

– Distinctive kinematics
– Assists in background suppression

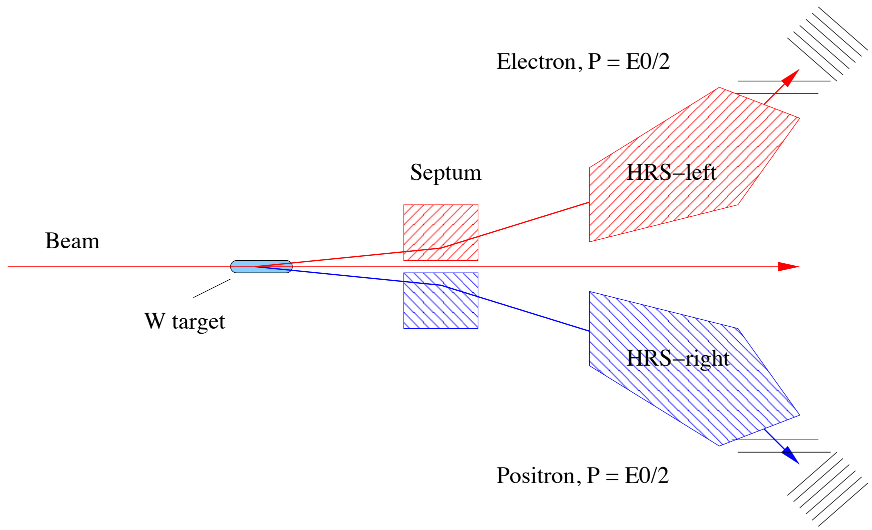
Best kinematics to select events for A′ search

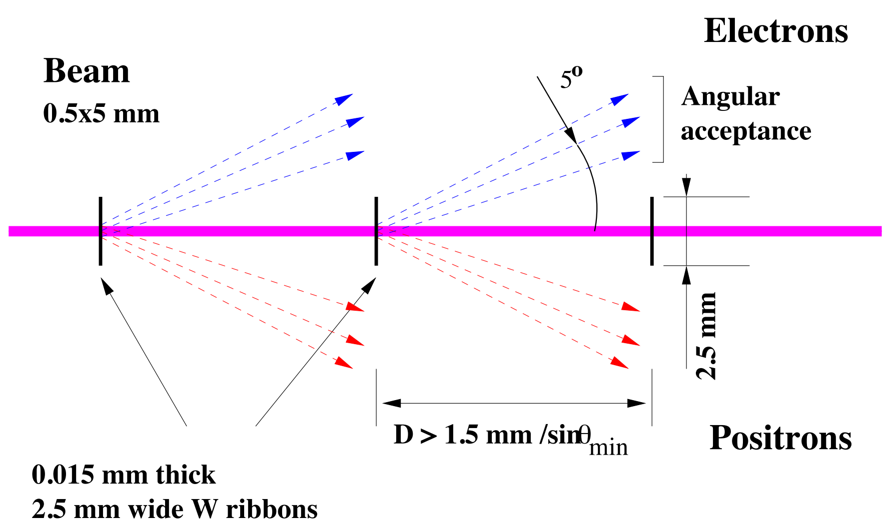
Spectrometer Acceptance and S/N Ratio

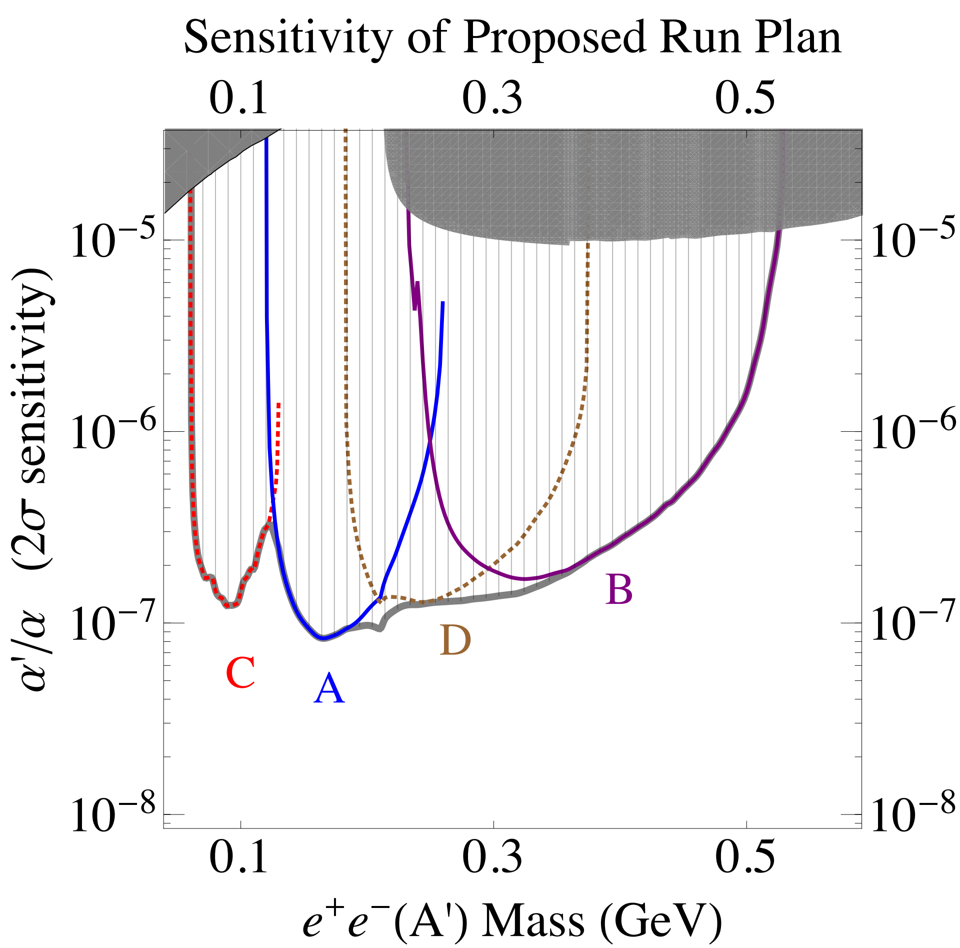


When the productivity reaches the limit of the detector/DAQ capabilities, a modest momentum range is better!

Angular Range and Smooth Mass Acceptance





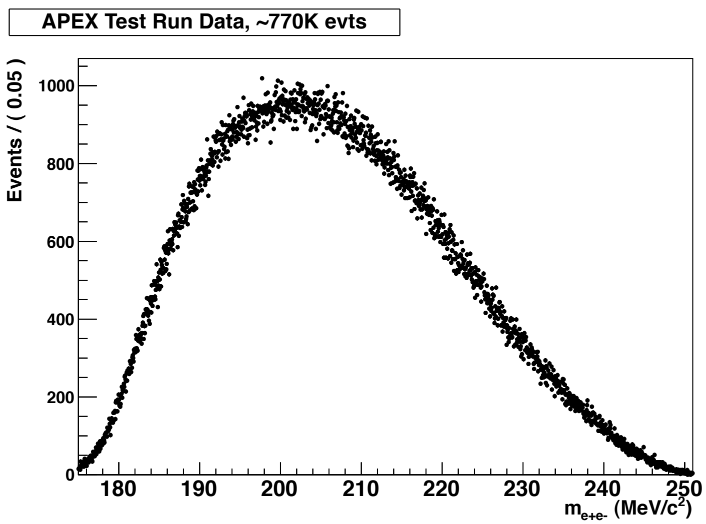


Test run data

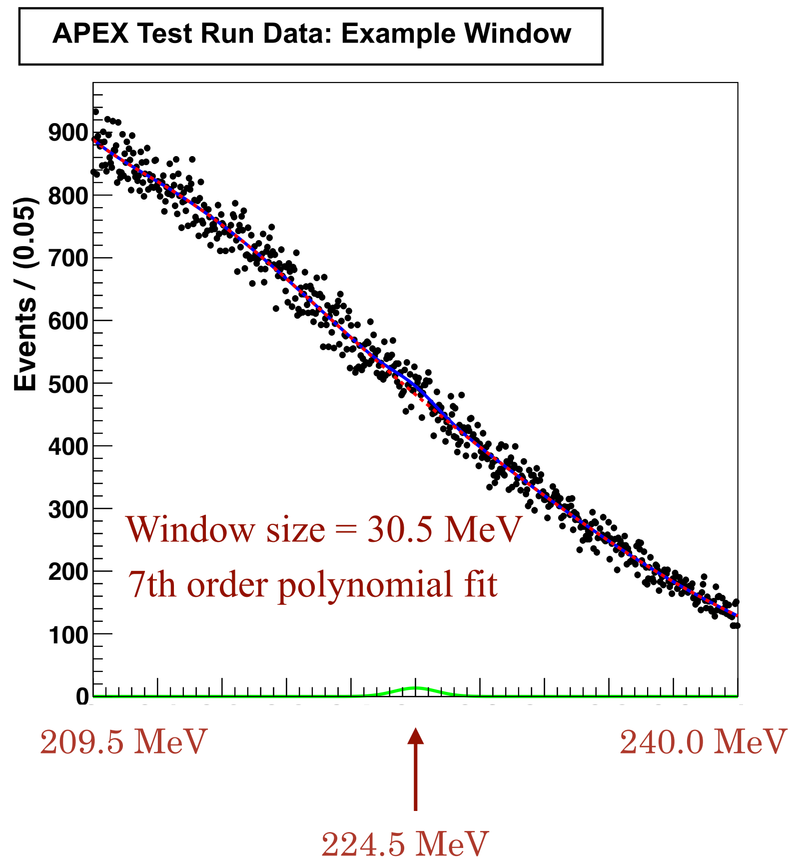
Bump hunt / resonance search

Final invariant mass spectrum QED radiative trident / Bethe-Heitler events

- Bump hunt for small, narrow resonance



Test run mass resolution: $\sigma \sim 0.85$ - 1.11 MeV



APEX: A Search for Dark Photons in Hall A

Why will Hall A do a very good experiment?

What are the results of the 2010 test run?

What is the status of the experimental equipment?

- Spectrometers: maintenance in 2013

APEX: A Search for Dark Photons in Hall A

Why will Hall A do a very good experiment?

What are the results of the 2010 test run?

What is the status of the experimental equipment?

What are the cost of preparation and the sources of funding?

- The total cost of APEX equipment was estimated to be $200-250k.
- There is $120k in Schuster's grant for the APEX experiment.

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Why is APEX the experiment to do in 2014?

APEX: A Search for Dark Photons in Hall A

What are the cost of preparation and the sources of funding?

Why is APEX the experiment to do in 2014?

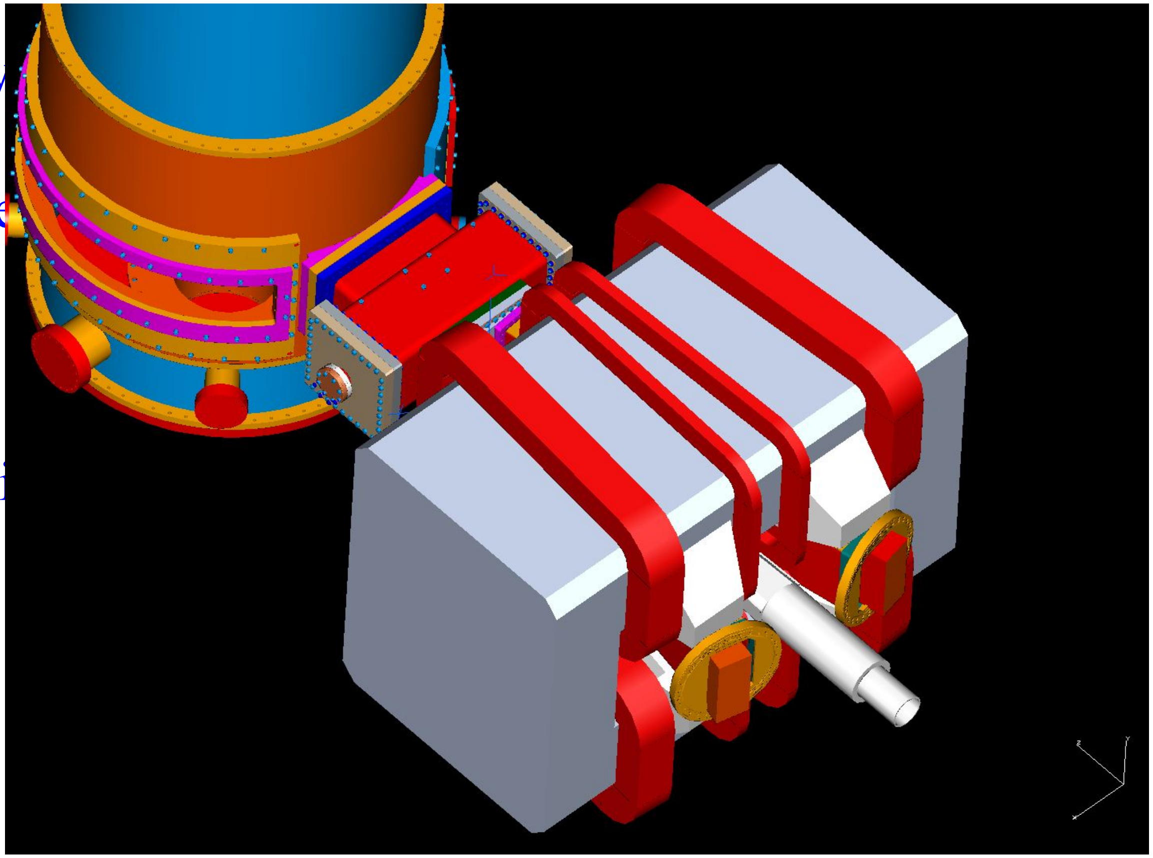
- Because it is very timely and cutting edge physics (PAC37)
- Because it has the best match to the initial beam quality
- Because doing it 2-3 years later could be too late
- Because the required cost of preparation for JLab is low (~$120k)

APEX: A Search for Dark Photons in Hall A

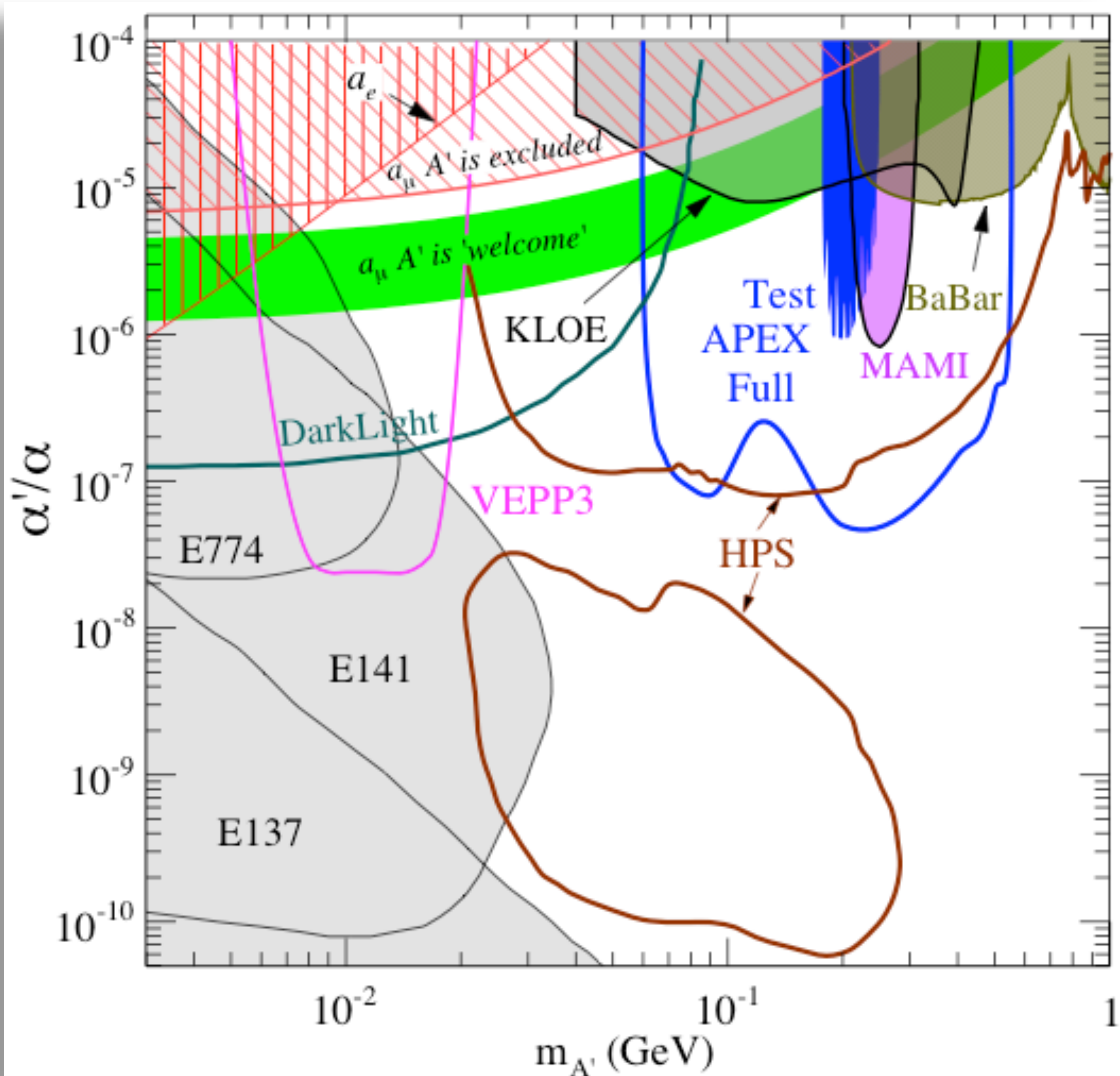
What are the cost of preparation and the sources of funding?

Why is APEX the experiment to do in 2014?

- Because it is very
- Because it has the
- Because doing it
- Because the requi



The parameter space



only g-2= a_e, a_μ,

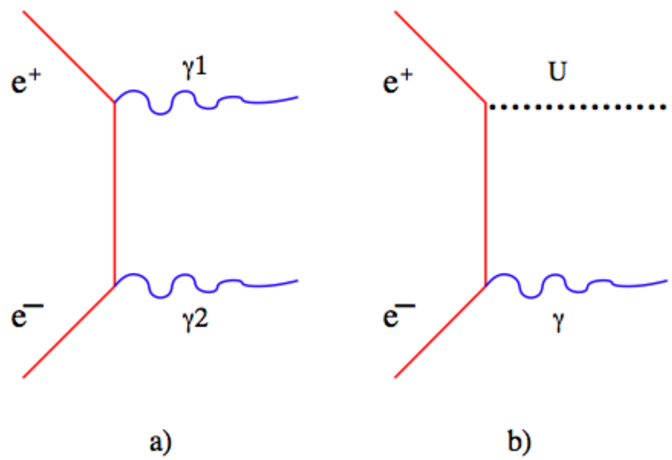
VEPP-3 and
a portion
of DarkLight

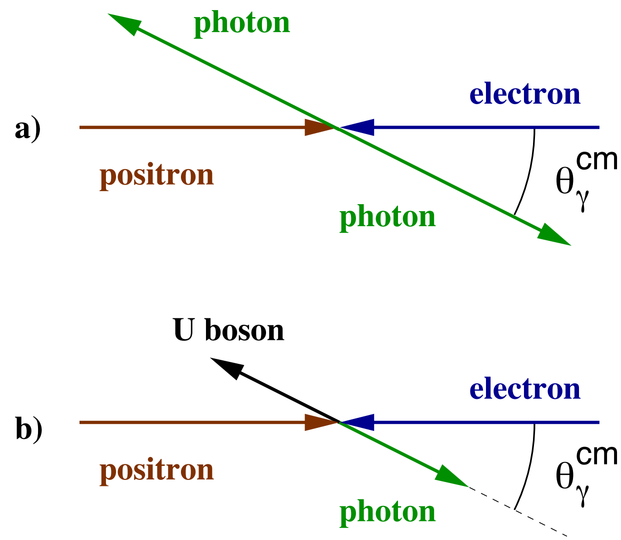
are sensitive

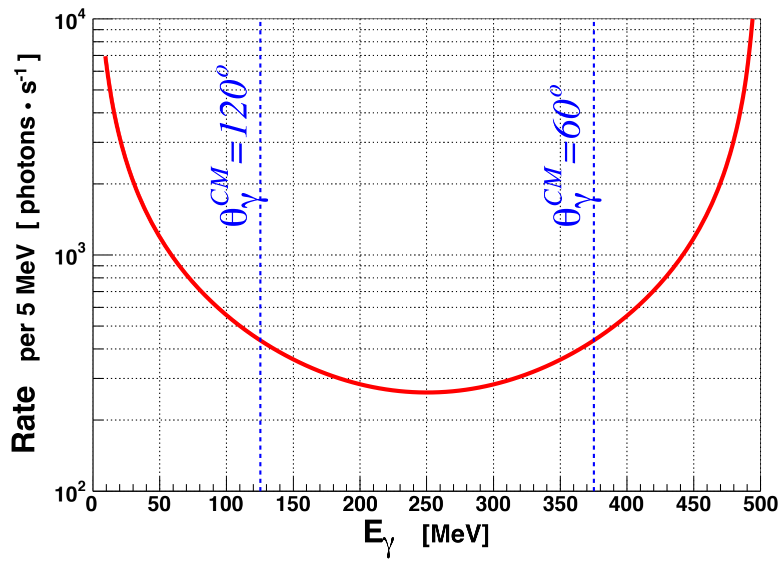
to “invisible”
A’ decay modes

Concept of an experiment with a positron beam

Kinematics







Options for an e^+e^- experiment at low s

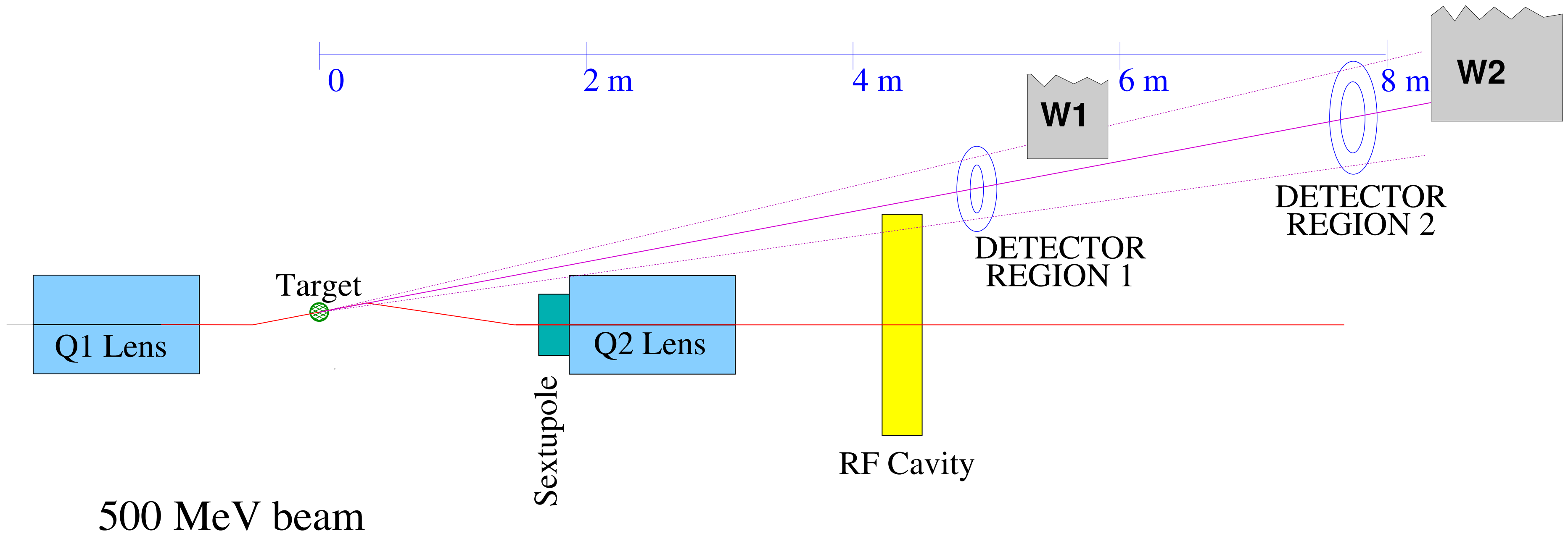
A "very" low energy, $s^{1/2} \sim$ 10-30 MeV

a) 5 MeV x 5 MeV head-head collider of e+e- => $\mathcal{L} \sim 10^{24}$

b) Sliding beams of e+e- (250 MeV x 250 MeV)=>
Project needs a specialized accelerator with two rings

c) Our approach is a positron beam + atomic electrons

Concept of an experiment with a positron beam



Proposal of an experiment at VEPP-3:
BW, Nikolenko, Rachek, arXiv:1207.5089

The photo-production processes

Basic QED: $e^+e^- \rightarrow \gamma\,\gamma$ (mono-energetic)

Search for : $e^+e^- \rightarrow \gamma\,U$ *(peak below main)*

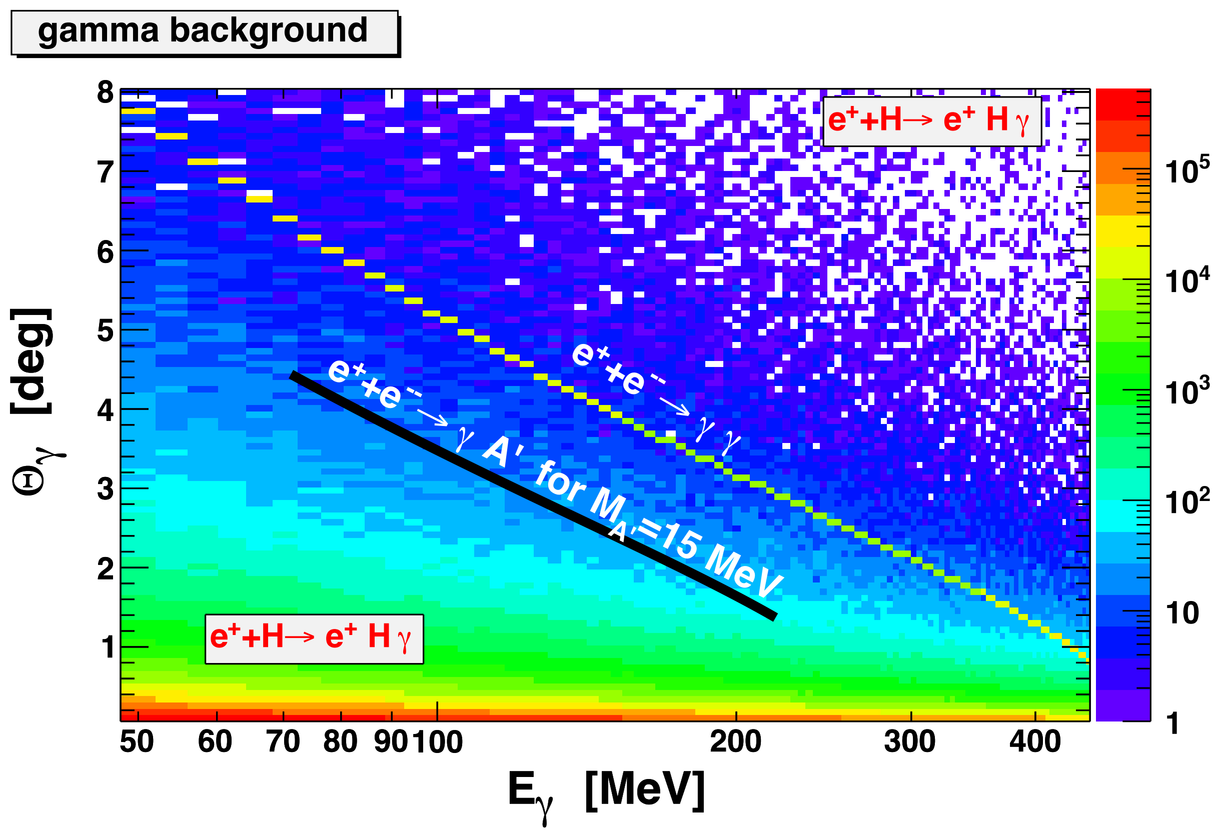
Basic QED: $e^+Z \rightarrow \gamma$ (smooth brems.)

- Detect γ at fixed angle with the beam:

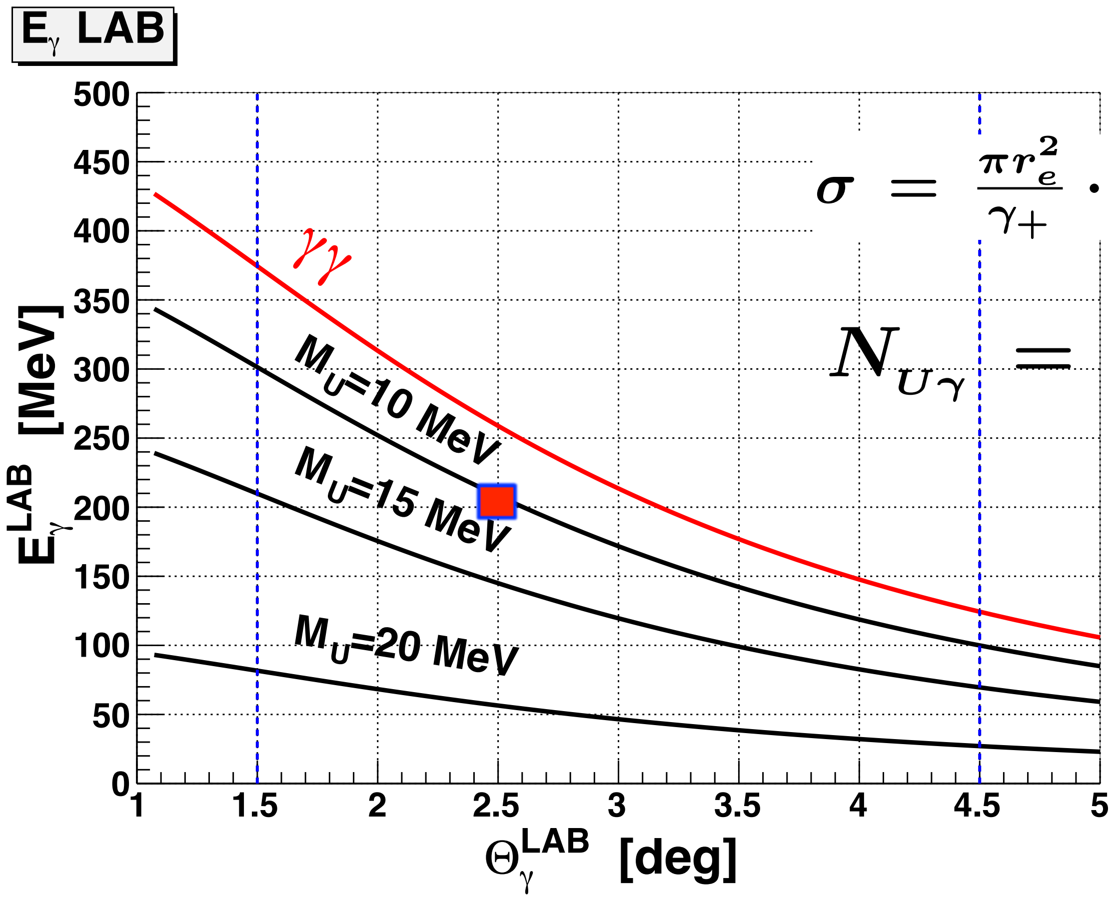
  reconstruct the mass
- Variation with the angle:

  control systematic
- Target Z

  Hydrogen vs. ^{12}C



Kinematical correlation



$$\sigma = \frac{\pi r_e^2}{\gamma_+} \cdot (\ln 2\gamma_+ - 1)$$

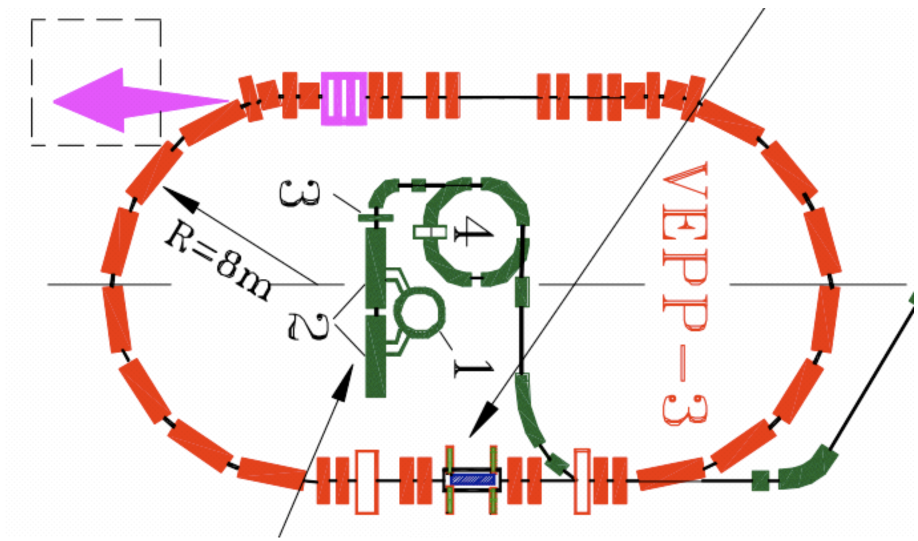
$$N_{U\gamma} = 2\frac{\alpha'}{\alpha} \cdot N_{\gamma\gamma}$$

$$E^{lab}_{\gamma(A'\gamma)} = E^{lab}_{\gamma(\gamma\gamma)} \cdot (1 - M^2_{A'}/s)$$

The U(or A') mass resolution ~ 3%

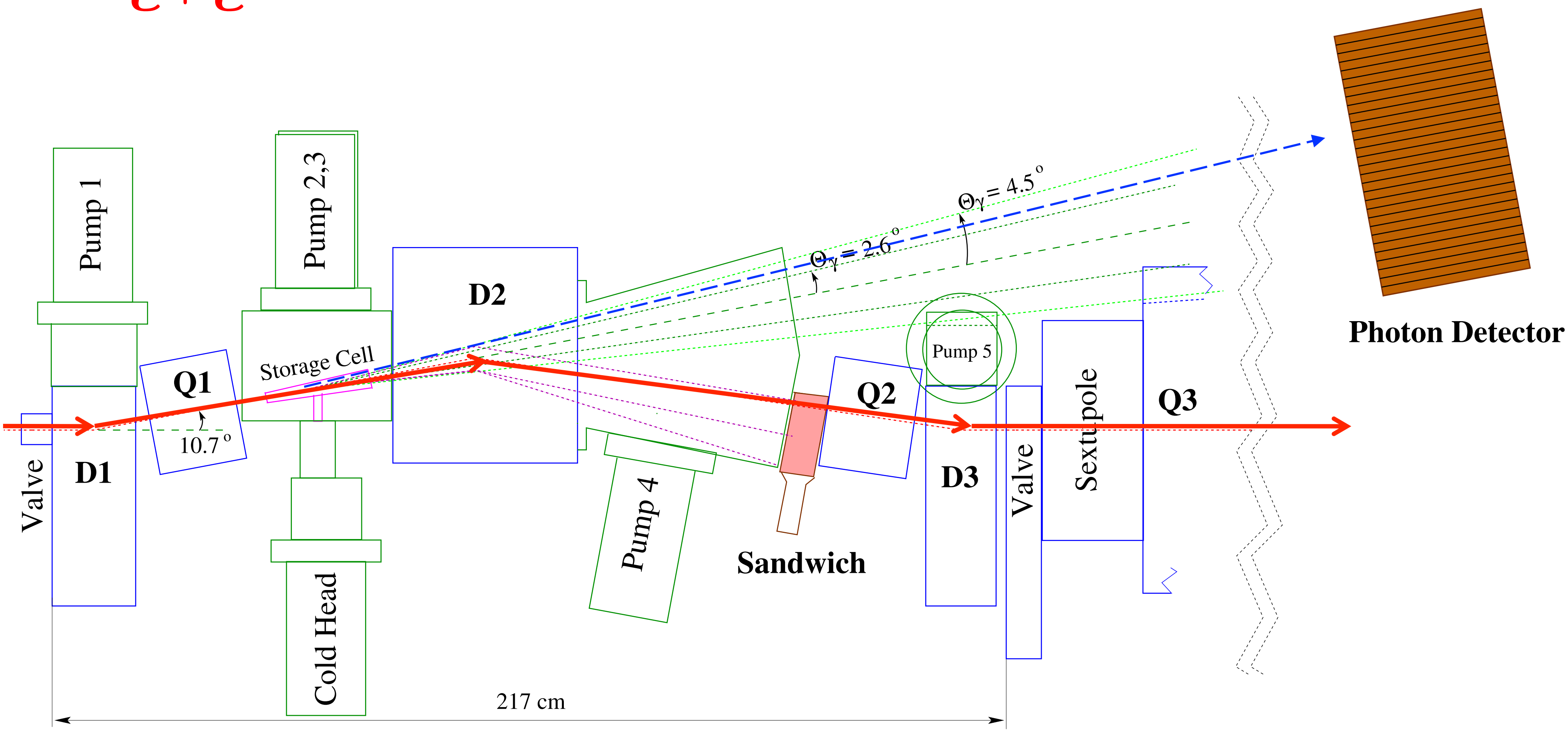
Where to find a positron beam?

- Beam of 1 μA was used for SLC (120 Hz)
- Cornell's positron source (d.f. ?)
- Frascati phi factory positron ring ?
- VEPP-3 energy of 0.5-2 GeV, 50 mA

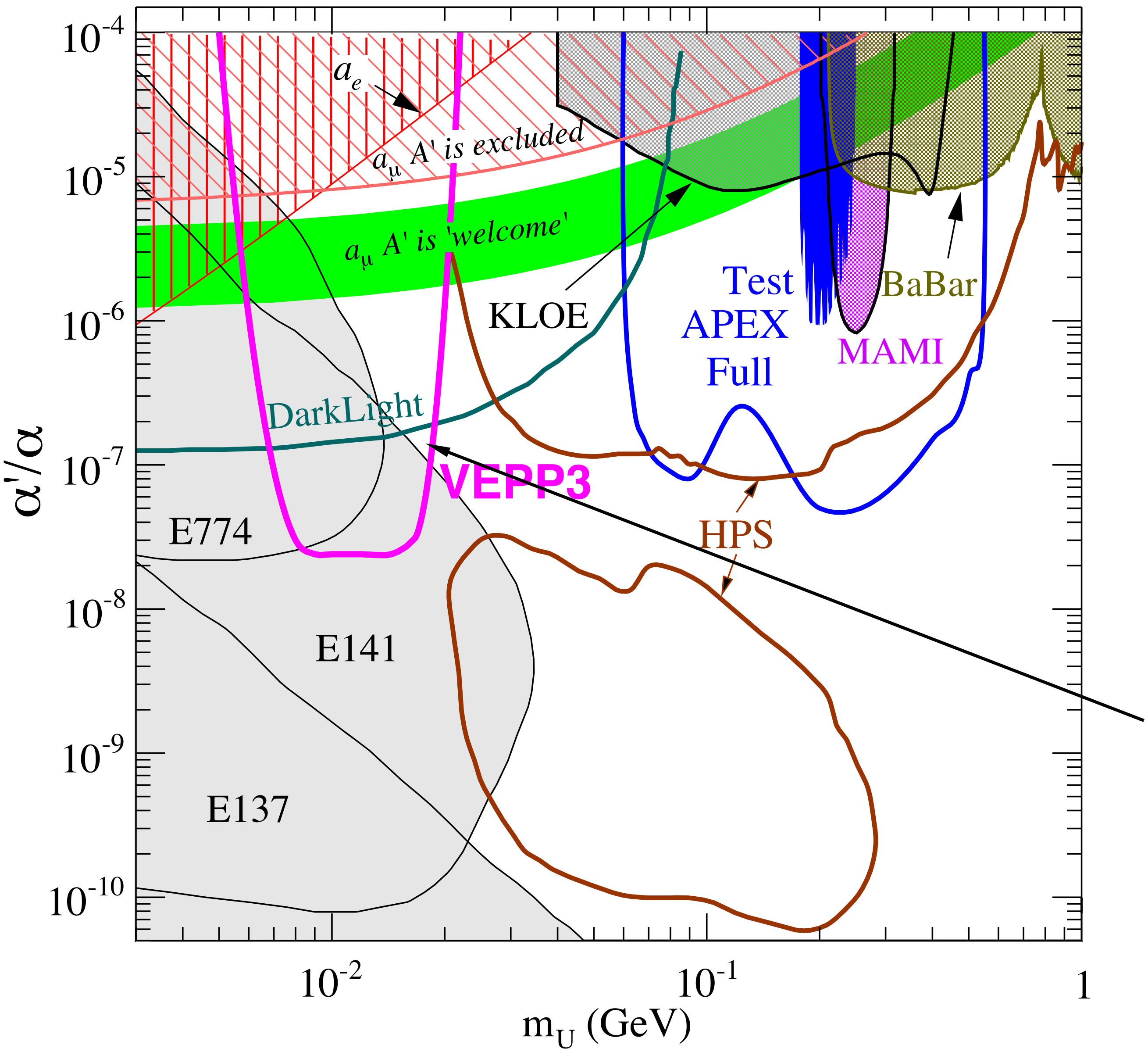


Experimental layout

$\mathcal{L}_{e^+e^-} \sim 10^{32}$

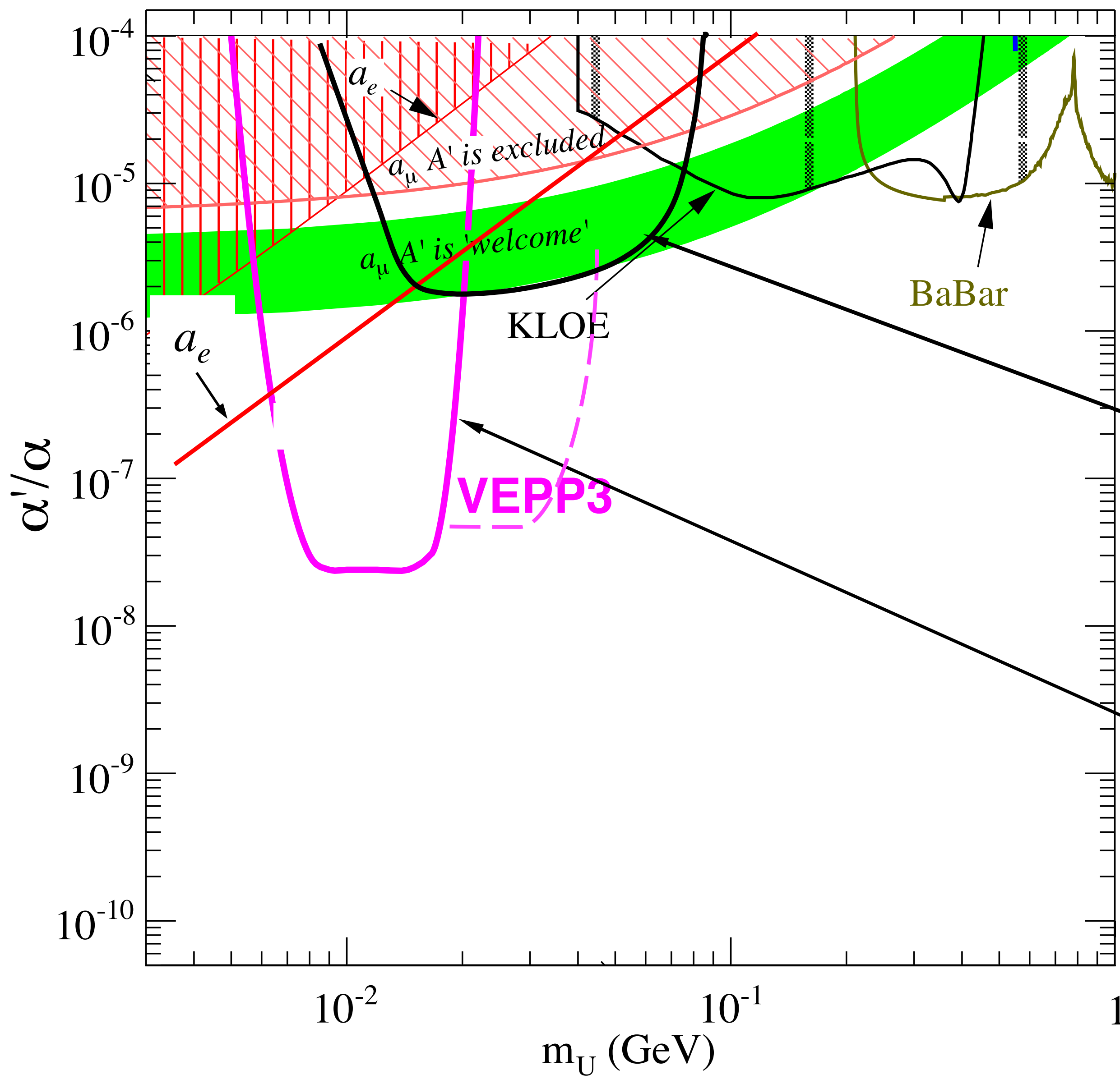


Projected sensitivity in the parameter space



Projected sensitivity for the VEPP-3 measurement at $L_{ep} = 10^{32}$ cm^{-2}/s (aver. current of 25 mA) in the six-month run

Projected sensitivity in the parameter space



These searches are sensitive to "invisible"

DarkLight (to "invisible")
Y. Kahn, J. Thaler, arXiv:1209.0777

Projected sensitivity for VEPP-3 (at 500 MeV) measurement at $L_{ep} = 10^{32}$ cm^{-2}/s (aver. current of 25 mA) in the six-month run

- - - with 5 GeV beam

Outlook

- Experimental search for a hidden photon with a high intensity electron beam will explore an important range of parameters and could discover a new force carrier.
- APEX experiment could be ready to take data in 2014.
- The A' boson bump in the photon recoil spectra is a key to an "invisible" decay case and allows a very sensitive search in the low mass range.

Summary

- I invite you to join the APEX collaboration.
  APEX experiment could discover Hidden Photon.

- I invite you to join the VEPP3 collaboration.
  VEPP3 allows a very sensitive search at low mass.

APEX: A Search for Dark Photons in Hall A

What is the APEX search method?

Why will Hall A do a very good experiment?

What are the results of the 2010 test run?

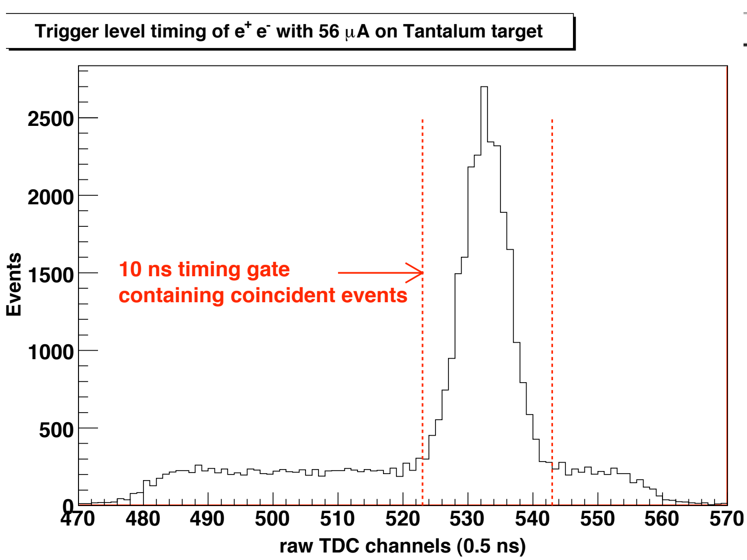
- Validation of every item of the experiment concept
- Full approval by PAC with recommendation to run ASAP
- 3 days of data: PRL, best citation rate in Hall A in the last 3 years

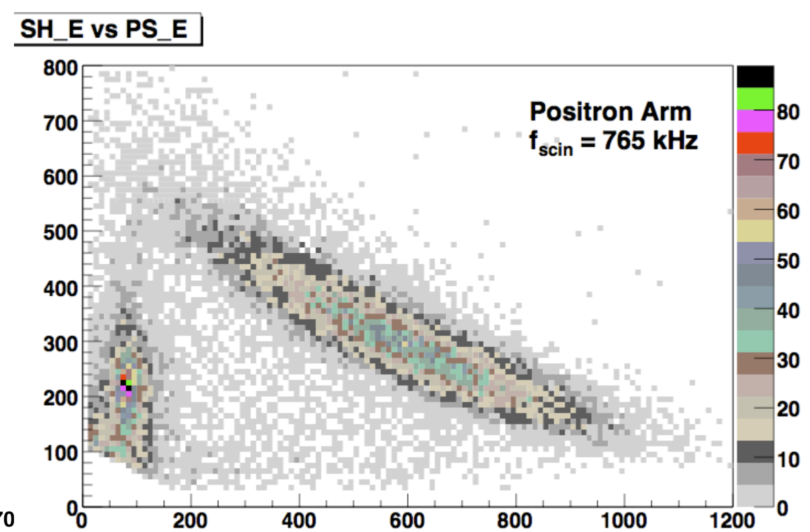
Test Run, June 2010: Collected data to address issues per PAC 35 report

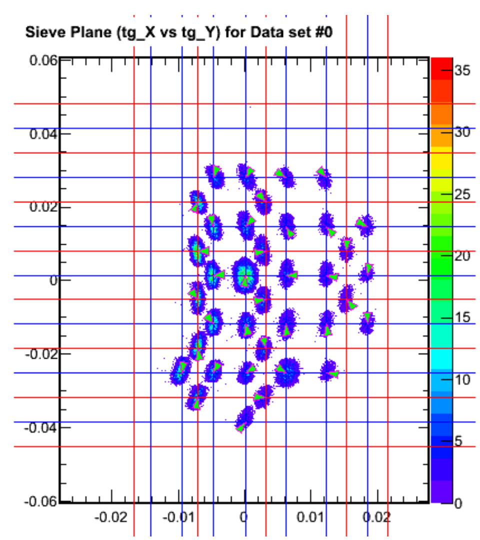
✓ Use of the Gas Cherenkov in trigger, timing – proposed 20 ns, demonstrated 10 ns
✓ Operation of the VDC at 5 MHz track rate – demonstrated up to 8 MHz
✓ Operation of the positron arm PID – demonstrated up to 0.8 MHz (more than needed)
✓ Operation of trigger/DAQ – demonstrated total dead time of 8% at full luminosity

Extended multi-foil target designed and built; not installed due to time, manpower constraints and high radiation left after PREX.

- Also checked: optics calibration, singles rates in the HRS spectrometers, signal to background in trigger and offline analysis, a thin Ta foil with 150 μA beam.
- Accumulated about 2 million true e+e- coincidence events & optics data for new physics result for mass range around 200 MeV.







APEX: A Search for Dark Photons in Hall A

What is the status of the experimental equipment?

• Septa:

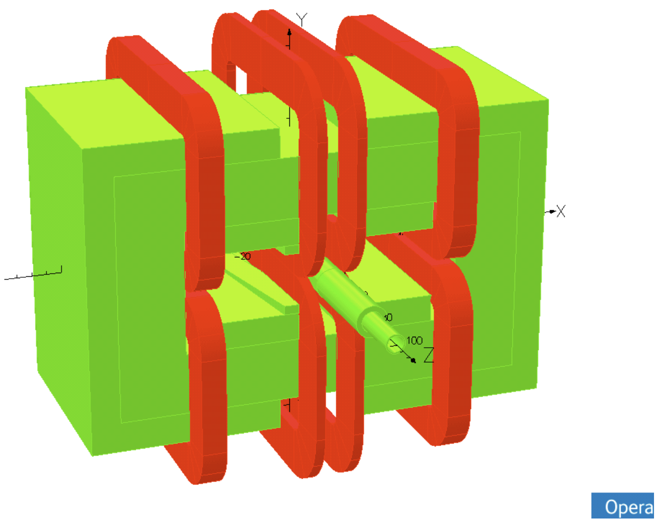
i. The vacuum chamber was disposed of after the PREX-I run due to res. radiation

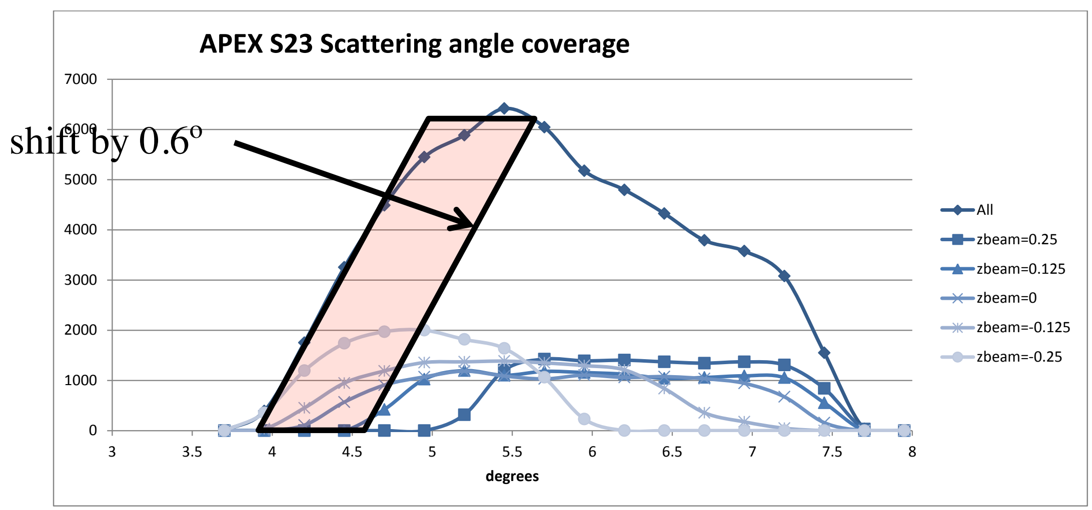
ii. Fire damaged the coils during g2p run -> unsafe coils

iii. The old configuration had a large field on the beam line even for 2.2 GeV run, whose fixing requires a move of the coils to a larger angle and leads to a loss of an important small angle part of the acceptance.

iv. A new design of the coil has been developed: shielded beam; simple coils.

v. A new vacuum chamber conceptual design was prepared.





Recent development: a septa with min angle of 3.7° in APEX mode and 3.4° in PREX mode for 2.2 GeV

APEX: A Search for Dark Photons in Hall A

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- ✓ What are the A' particle status and perspectives?
- ✓ What is the APEX search method?
- ✓ Why will Hall A do a very good experiment?
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