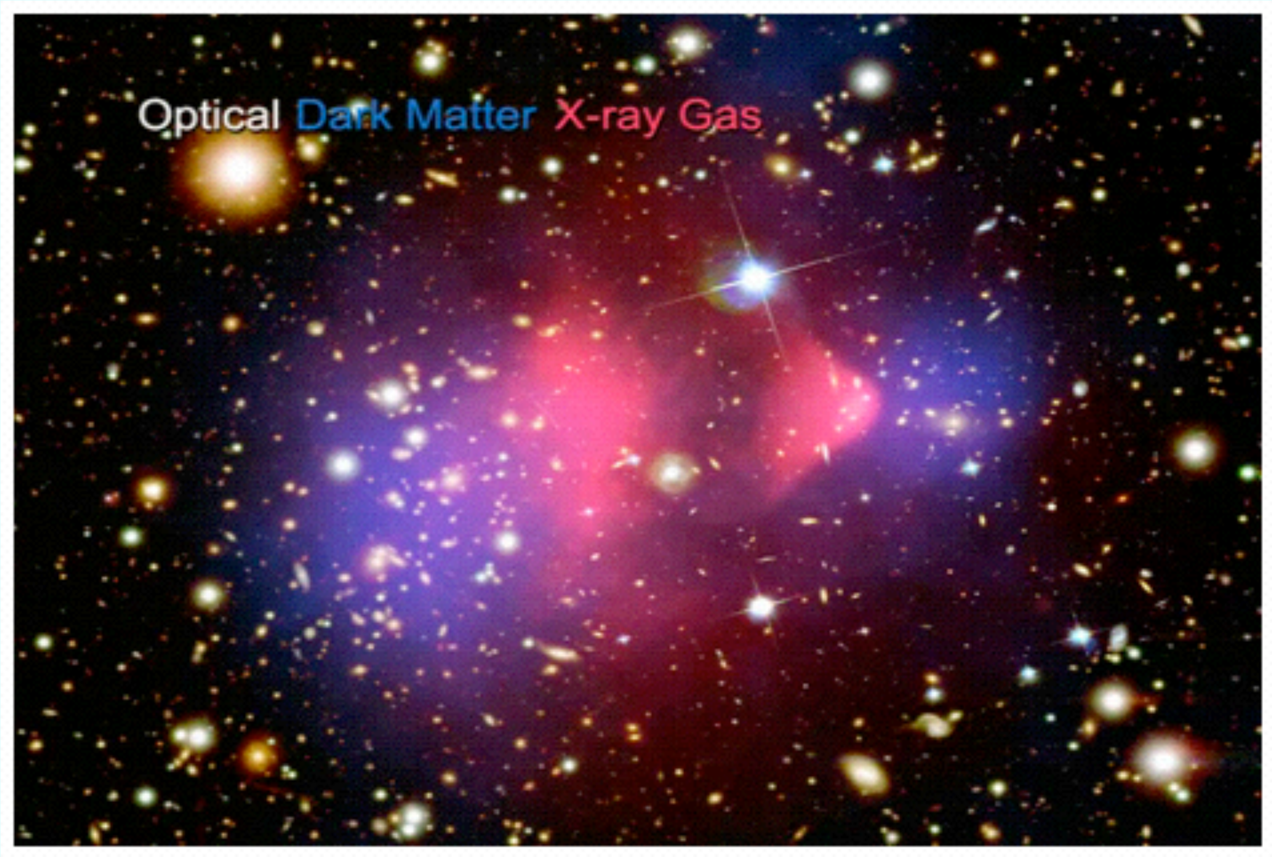
Searching for a **U**-boson with a positron beam

Bogdan Wojtsekhowski
Thomas Jefferson National Accelerator Facility

- The light dark matter
- Properties of a U-boson
- Design of the experiment and expected sensitivity

SLAC, September 25, 2009

From September 2006, NASA/SLAC



From September 2006, NASA/SLAC

SLAC, September 25, 2009

From September 2006, NASA/SLAC

NASA Finds Direct Proof of Dark Matter

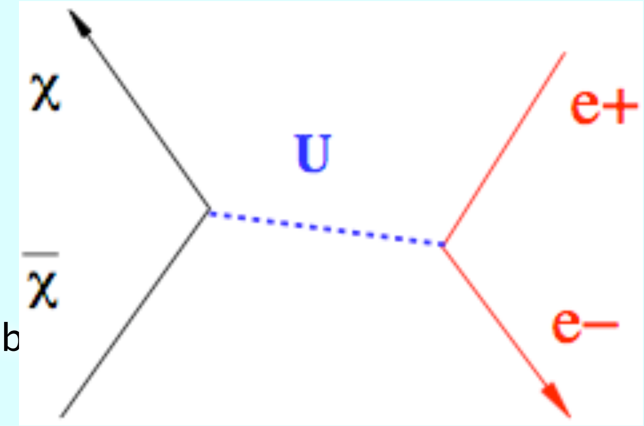
Dark matter and normal matter have been wrenched apart by the tremendous collision of two large clusters of galaxies. The discovery, using NASA's Chandra X-ray Observatory and other telescopes, gives direct evidence for the existence of dark matter.

"This is the most energetic cosmic event, besides the Big Bang, which we know about," said team member Maxim Markevitch of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass.

These observations provide the strongest evidence yet that most of the matter in the universe is dark. Despite considerable evidence for dark matter, some scientists have proposed alternative theories for gravity where it is stronger on intergalactic scales than predicted by Newton and Einstein, removing the need for dark matter. However, such theories cannot explain the observed effects of this collision.

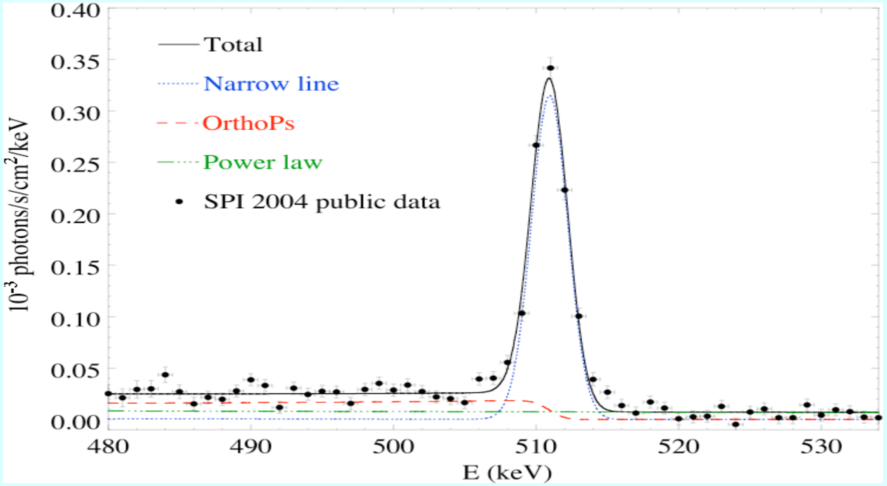
DARK matter directly observed in gravitational experiment
What is the nature and parameters of the constituents?

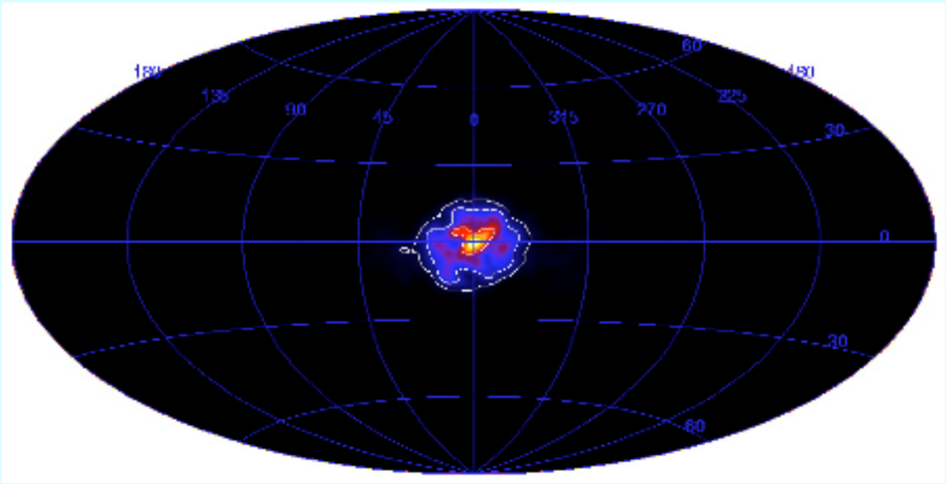
We will discuss the process:



The case of the Light Dark Matter

The 511 keV line in the spectra of photons





Photon energy spectrum

Location of the source

P. Jean etal, Astron. Astrophys. 445, 579 (2006)

The case of the Light Dark Matter

VOLUME 92, NUMBER 10 PHYSICAL REVIEW LETTERS week ending 12 MARCH 2004

MeV Dark Matter: Has It Been Detected?

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(Received 1 October 2003; published 12 March 2004)

We discuss the possibility that the recent detection of 511 keV γ rays from the galactic bulge, as observed by INTEGRAL, is a consequence of low mass (1–100 MeV) particle dark matter annihilations. We discuss the type of halo profile favored by the observations as well as the size of the annihilation cross section needed to account for the signal. We find that such a scenario is consistent with the observed dark matter relic density and other constraints from astrophysics and particle physics.

The most commonly discussed DM candidates are weakly interacting particles with masses typically in the range of a few GeV to several TeV, the most popular example of this being the lightest supersymmetric particle [15] made stable by the virtue of *R* parity [16]. This particle, along with other fermionic DM particles, is not expected to be significantly lighter than a few GeV if they are to provide the measured density of DM in the Universe [17]. This constraint does not strictly apply to all particle candidates, however. Light particles (MeV–GeV), in some cases, may be able to satisfy relic density and other constraints [18,19]. In particular, light scalar DM candidates are an interesting and viable possibility [19].

Scalar DM particles: $\chi / \overline{\chi}$

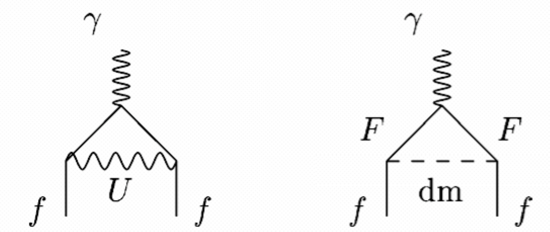
Both the *U* boson and the DM particle evade colliders limits despite their small masses, as studied in [19]. Indeed, the direct production of *U* bosons ($e^+e^- \to \gamma U$) is likely to remain unobserved due to the large background associated with the photon pair production.

The processes which could has U-boson

C.Boehm, P.Fayet, Nuclear Physics B 683 (2004)

g_e-2, g_μ-2
π,η decays to $U\gamma$
π,φ,ψ decays to γ + invisible

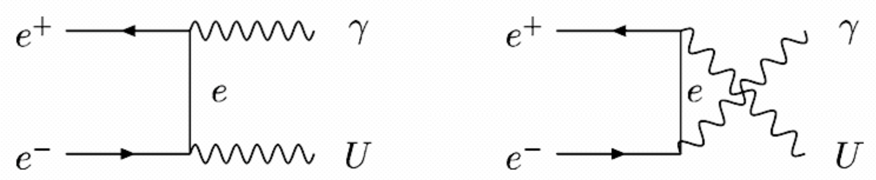
A.4. Constraints from g − 2



If the U boson mainly decays into dark matter, then the U production process turns out to be of the type $e^+e^- \to \gamma + \not{E}$, where $\not{E}$ is missing energy, which is of interest in experiments searching for single photon production events. But, in the case of a light dark matter candidate, such a process is likely to remain unobserved, owing to the large background associated with $e^+e^- \to \gamma\gamma$, in which one of the two photons escapes detection.

Upper limit for the coupling constant $|f_{eU}|^2 < 2\ 10^{-8}\,(m_U)^2$

A.6.1. Direct U boson production



The processes which could has U boson

P.Fayet, arXive:0607094 (2006)

U-boson detectability, and LDM

$$\delta a_\mu \simeq \frac{f_{\mu V}^{\,2}}{4\,\pi^2} \int_0^1 \frac{m_\mu^2\, x^2\,(1-x)\, dx}{m_\mu^2\, x^2 + m_U^2\,(1-x)} \simeq \frac{f_{\mu V}^{\,2}}{8\,\pi^2}\, G(\frac{m_U}{m_\mu})$$

→ $|f_{\mu V}| \lesssim$ (.7 up to 1.5) 10^{-3}

by searching for the decay $K^+ \to \pi^+ U$

$$|f_{sA}| \lesssim 2\;10^{-7}\; m_U\,(\text{MeV}) \;.$$

$$|f_{eV}| \lesssim 1.3\;10^{-4}\; m_U\,(\text{MeV})$$

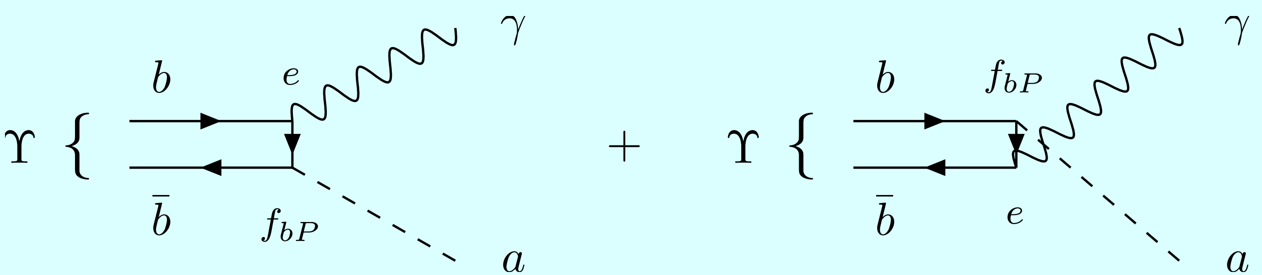
Having $f_e^{\,2} \lesssim 10^{-5}\, e^2$ makes the detection of U production in e^+e^- colliders difficult. The prospects for actually producing and detecting such very weakly coupled U bosons in $e^+e^- \to \gamma\, U$, as well as in other reactions, appear as challenging. Still efforts should be pursued in this direction.

The processes which could has U-boson

P.Fayet, arXive:0812390 (2008)

Y decays to γ + invisible

BABAR: $B_{inv} < 3\ 10^{-6}$

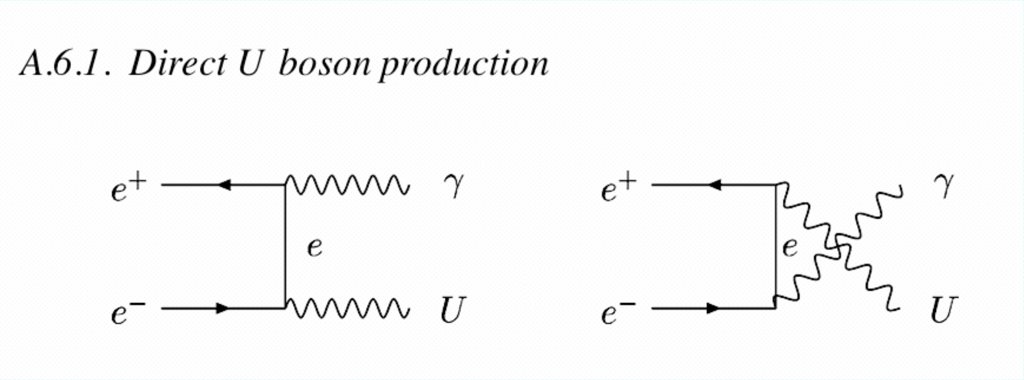


universality of couplings leads to restriction on

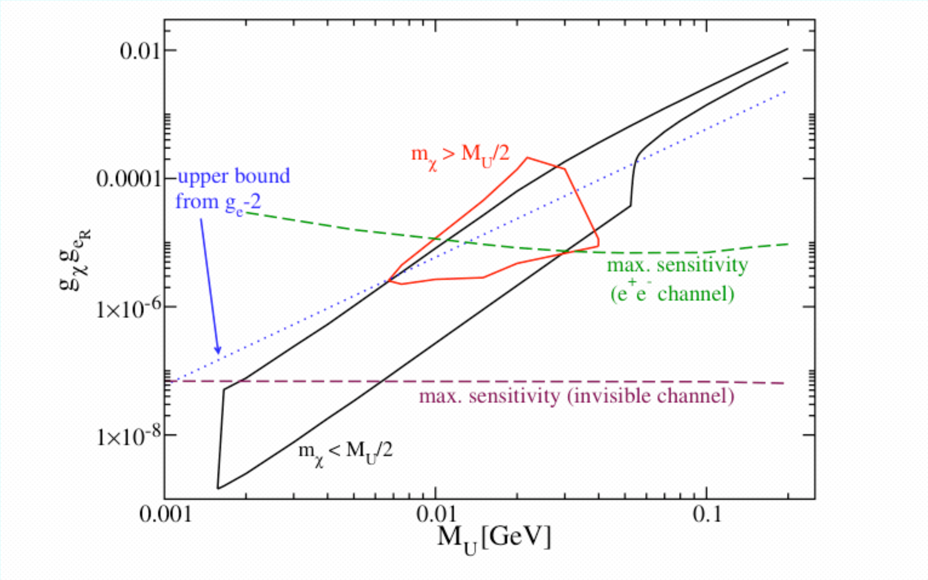
the coupling constant $|f_{eU}|^2 < 5\ 10^{-8}\ (m_U[\mathrm{MeV}])^2$

The search for the–U boson in e^+e^-

C.Boehm, P.Fayet, Nuclear Physics B 683 (2004)



N.Borodatchenkova, D.Choudhury and M.Drees, PRL 96 (2006)



suggestion: to search in data from DAΦNE and CLEO; the potential sensitivity for the coupling $f_e^2 \sim 10^{-6}$

The search for new physics in e^+e^-

An Improved Limit on Invisible Decays of Positronium

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Abstract

The results of a new search for positronium decays into invisible final states are reported. Convincing detection of this decay mode would be a strong evidence for new physics beyond the Standard Model (SM): for example the existence of extra–dimensions, of milli-charged particles, of new light gauge bosons or of mirror particles. Mirror matter could be a relevant dark matter candidate.

In this paper the setup and the results of a new experiment are presented. In a collected sample of about $(6.31 \pm 0.28) \times 10^6$ orthopositronium decays, no evidence for invisible decays in an energy window [0,80] keV was found and an upper limit on the branching ratio of orthopositronium $o - Ps \rightarrow$ invisible could be set:

$$Br(o - Ps \rightarrow \text{invisible}) < 4.2 \times 10^{-7} \text{ (90\% C.L.)}$$

Our results provide a limit on the photon mirror-photon mixing strength $\epsilon \leq 1.55 \times 10^{-7}$ (90% C.L.) and rule out particles lighter than the electron mass with a fraction $Q_x \leq 3.4 \times 10^{-5}$ of the electron charge. Furthermore, upper limits on the branching ratios for the decay of parapositronium $Br(p - Ps \rightarrow invisible) \leq 4.3 \times 10^{-7}$ (90% C.L.) and the direct annihilation $Br(e^+e^- \rightarrow invisible) \leq 2.1 \times 10^{-8}$ (90% C.L.) could be set.

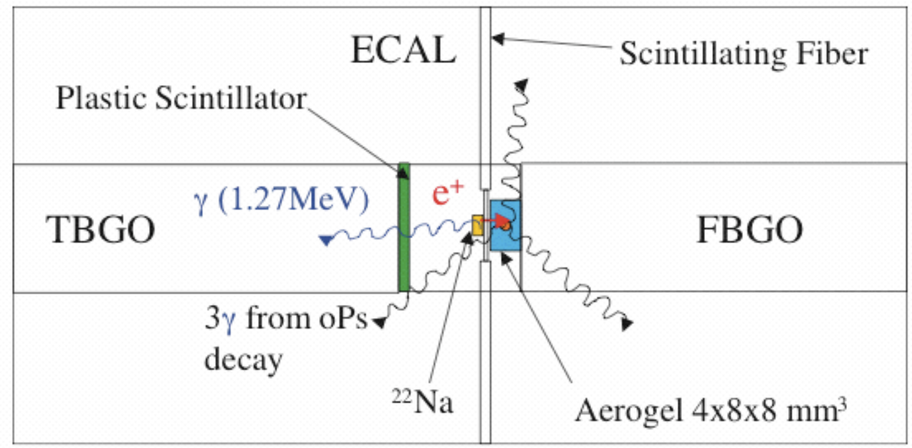

Fig. 2. *Schematic illustration of the positron tagging system and the* o-Ps *formation target of the setup.*

The search for the resonances e^+e^-

UME 69, NUMBER 12 PHYSICAL REVIEW LETTERS 21 SEPTEMBER 1992

Search in s Channel for Production of 1–2 MeV/c^2 Long-Lived e^+e^- Resonances

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(Received 3 March 1992)

The search for s-channel production of light neutral particles coupled to e^+e^- has been extended by more than 3 orders of magnitude in lifetime beyond the region which is accessible to elastic e^+e^- scattering. The whole mass range $1500 \lesssim M_{\chi^0} \lesssim 1860$ keV/c^2 suggested by the observation of anomalous e^+e^- pairs in heavy-ion collisions has been investigated. These measurements find no evidence for e^+e^- states within lifetime ranges (90% C.L.) of $1.4\times10^{-12} \lesssim \tau \lesssim 4\times10^{-10}$ sec ($J=0$) and $1.4\times10^{-12} \lesssim \tau \lesssim 6\times10^{-10}$ sec ($J=1$), assuming that the state does not break up by interacting within the target.

JME 69, NUMBER 12 PHYSICAL REVIEW LETTERS 21 SEPTEMBER 1992

Search for Low-Mass States in Elastic e^+e^- Scattering

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(Received 3 March 1992)

We report results of an experiment to search for a resonance enhancement of the e^+e^- scattering cross section in a metallic Li target utilizing an energy-tunable monoenergetic positron beam. Within statistical uncertainties (0.27%) no evidence has been observed for deviations from Bhabha scattering over the entire invariant-mass region 1560 keV/$c^2 < M_{\chi^0} <$ 1860 keV/c^2 that can be associated with the e^+e^- sum-peak energies in GSI heavy-ion experiments. Under the assumption that the e^+e^- channel dominates, we deduce lower limits on lifetimes $\tau > 3.3\times10^{-13}$ sec ($J=0$) and $\tau > 8.2\times10^{-13}$ sec ($J=1$), at 90% C.L.

Another search for the boson

e^+e^- pairs from a nuclear transition signaling an elusive light neutral boson

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Abstract. Electron-positron pairs have been observed in the 10.95-MeV $0^- \to 0^+$ decay in ^{16}O. The branching ratio of the e^+e^- pairs compared to the 3.84-MeV $0^- \to 2^+$ γ decay of the level is deduced to be $20(5) \times 10^{-5}$. This magnetic monopole (M0) transition cannot proceed by γ-ray decay and is, to first order, forbidden for internal pair creation. However, the transition may also proceed by the emission of a light neutral 0^- or 1^+ boson. Indeed, we do observe a sharp peak in the e^+e^- angular correlation with all the characteristics belonging to the intermediate emission of such a boson with an invariant mass of 8.5(5) MeV/c^2. It may play a role in the current quest for light dark matter in the universe.

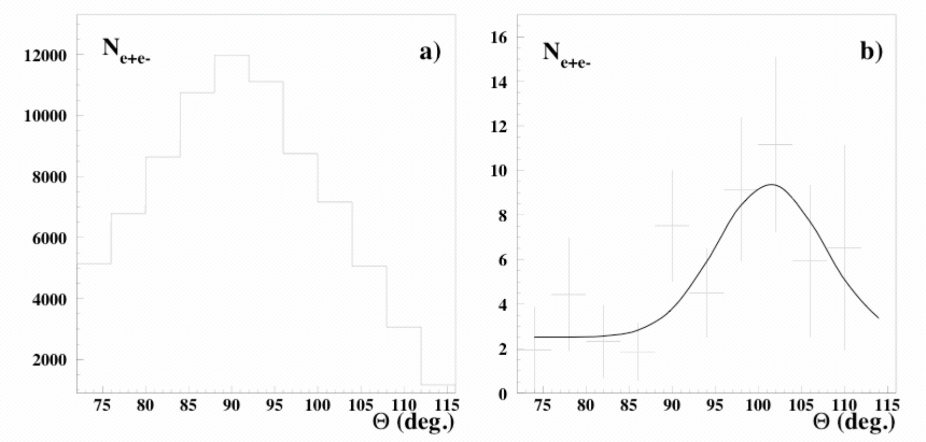
Keywords: magnetic monopole transition, anomal IPC, light boson, dark matter
PACS: 23.20.Ra, 23.20.En, 14.70.Pw

INTRODUCTION

Internal pair creation (IPC) can be instrumental in assigning spins and parities to nuclear levels. It was described with QED [1] long time ago. When an excited nuclear level does not decay by γ radiation or by conventional IPC, an emission of a light neutral particle which in turn decays into an e^+e^- pair is still a possible form of the deexcitation.

Such a light boson might be identified with a light and very weakly coupled neutral spin-1 gauge boson U, introduced by Fayet [2] more than two decades ago and revisited by Boehm and Fayet [3]. It was first argued by Boehm et al. [4] and recently by Fayet [5] and Beacom et al. [6] that light dark matter particles with masses between 1 and 20 MeV/c^2 annihilating through such bosons into e^+e^- pairs may be the source of the observed 511 keV emission line in the galactic bulge [7]. They find that such a scenario is consistent with the observed dark matter relic density and other constraints from astrophysics and from particle physics.

In 1988, de Boer and van Dantzig [8] analyzed the emulsion results produced in relativistic heavy ion bombardments, an emulsion study, in which a distinct cluster of e^+e^- pairs was observed at a short distance from the interaction vertex. These events were attributed to the emission and subsequent decay of a light neutral boson with a



Search experiment with BaBar data

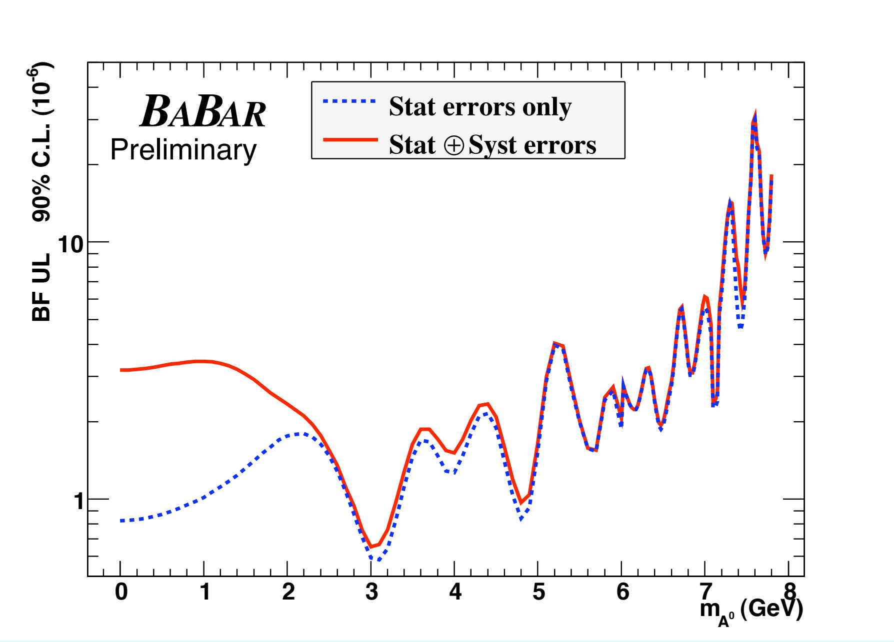
Search for Invisible Decays of a Light Scalar in Radiative Transitions $\Upsilon(3S) \to \gamma A^0$

The *BABAR* Collaboration

July 31, 2008

Abstract

We search for a light scalar particle produced in single-photon decays of the $\Upsilon(3S)$ resonance through the process $\Upsilon(3S) \to \gamma + A^0$, $A^0 \to$ invisible. Such an object appears in Next-to-Minimal Supersymmetric extensions of the Standard Model, where a light *CP*-odd Higgs boson naturally couples strongly to *b*-quarks. If, in addition, there exists a light, stable neutralino, decays of A^0 could be preferentially to an invisible final state. We search for events with a single high-energy photon and a large missing mass, consistent with a 2-body decay of $\Upsilon(3S)$. We find no evidence for such processes in a sample of 122×10^6 $\Upsilon(3S)$ decays collected by the *BABAR* collaboration at the PEP-II B-factory, and set 90% C.L. upper limits on the branching fraction $\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \text{invisible})$ at $(0.7-31) \times 10^{-6}$ in the mass range $m_{A^0} \le 7.8$ GeV. The results are preliminary.



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

A "very" low energy s ~ 10-30 MeV

a) Search in existing data from good detector => problem with resolution at low s
b) 5 MeV x 5 MeV collider of e+e- => very low luminosity < 10^{29}
c) Sliding beams of e+e- (200 MeV x 200 MeV)=> need specialized accelerator with two rings
d) Positron beam and atomic electrons

The focus now on a positron beam of several 100s MeV incident on the hydrogen target

JLab positron beam considerations

$$\epsilon^n = \gamma \frac{\sigma_x^2}{\beta_{SRF}}$$

$$\sigma_x \sim 2 \text{ mm}, \; \beta_{SRF} \sim 5 \text{ m}$$

$$\epsilon^n = 60 \frac{4[mm]^2}{5000[mm]} = 50 \; \mu m \times rad$$

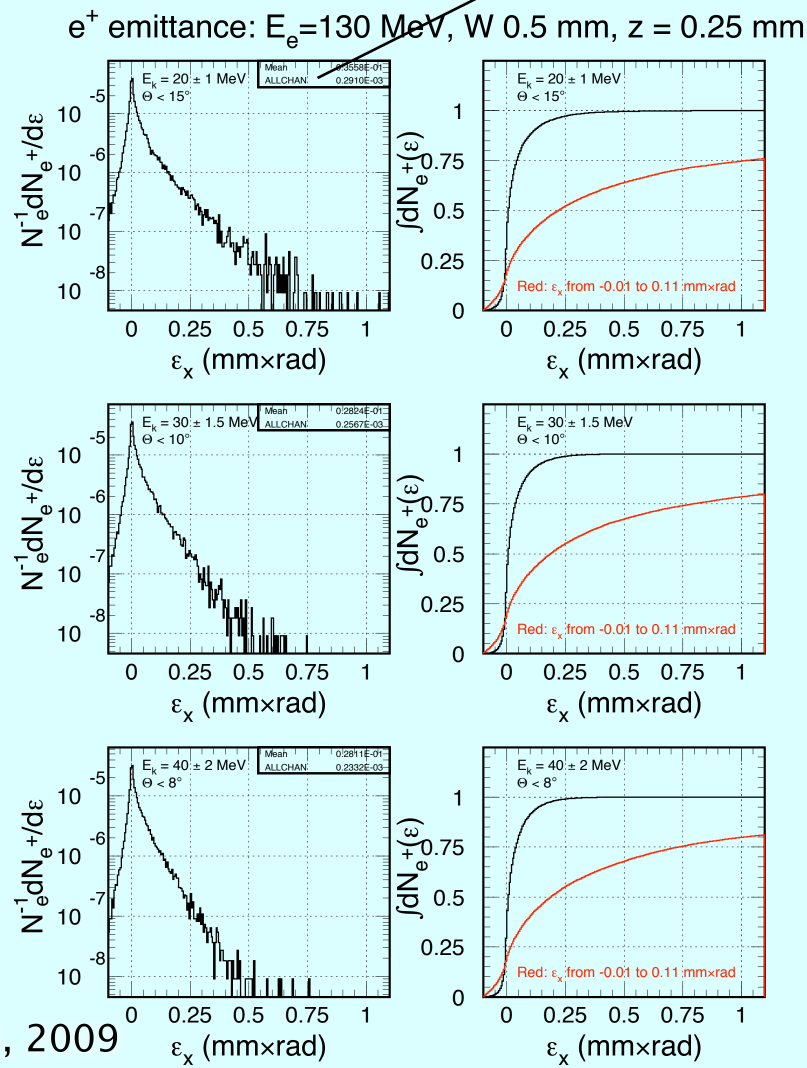
$$E_e = 130 \text{ MeV}, \; E_+ = 20 \pm 1 \text{ MeV}, \; \theta_+ < 15^\circ$$

$$\epsilon_x = \gamma \, x \, \theta_x$$

$$J_+ = J_- \times (\epsilon_x^{max})^2 \times N_+/N_-$$

Production: $\sim 10^{-4}$ positrons per each 160 MeV electron into acceptance SRF

P.Degtyarenko & BW $N_+/N_- \sim 3 \times 10^{-4}$



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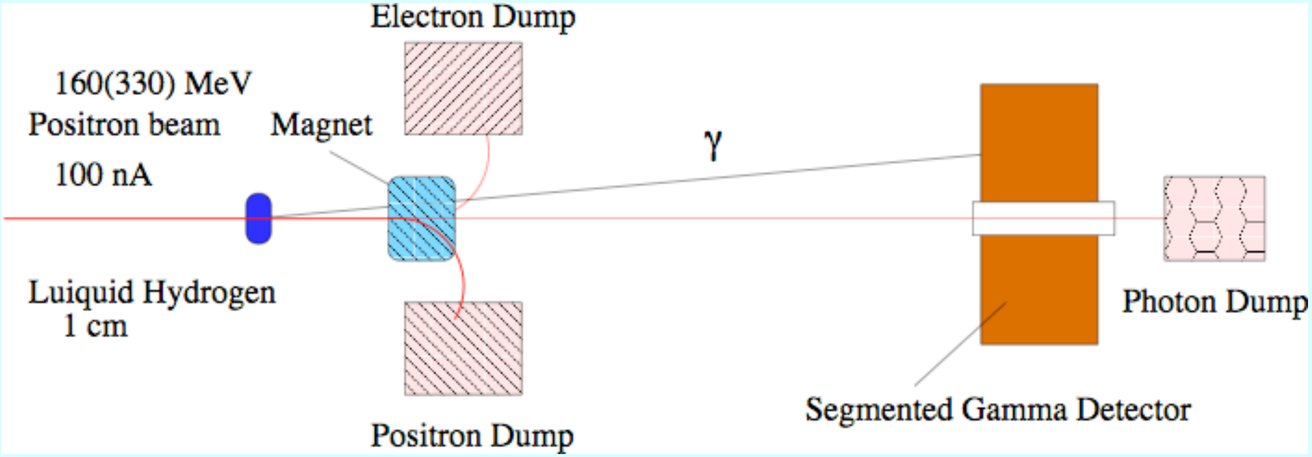
Schematic of the proposed experiment

- Positron beam with 1-2 MeV spread
- Thin – 1 cm liquid hydrogen target
- Direct the rest of the beam to the dumps



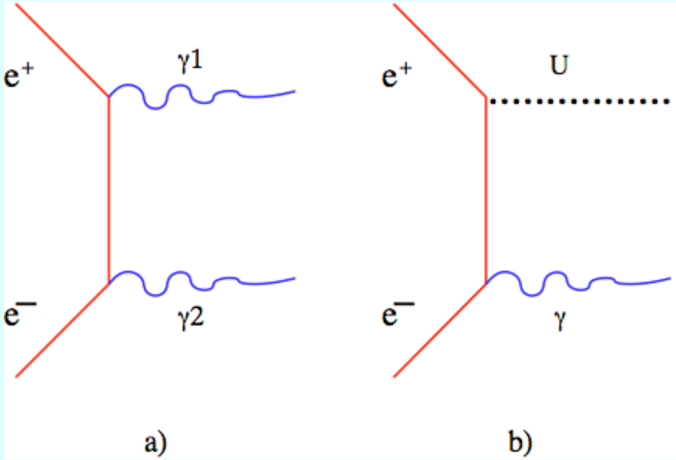
- Segmented photon detector ~ 1000 modules, ~2% energy resolution.
- Parallel DAQ for the total rate of ~50 MHz. Example from kTeV used CsI

Makes use of high luminosity: 1000 parallel 1-d spectra.

Singles Rates

Rates are calculated for the luminosity = $3 \times 10^{34}\ cm^{-2}\ s^{-1}$

Calculations are based largely on the GEANT3 code



- Dominant rate in the peak of two-gamma process. Intensity drops 100 times below the peak.
- The rate per module is about 50 kHz

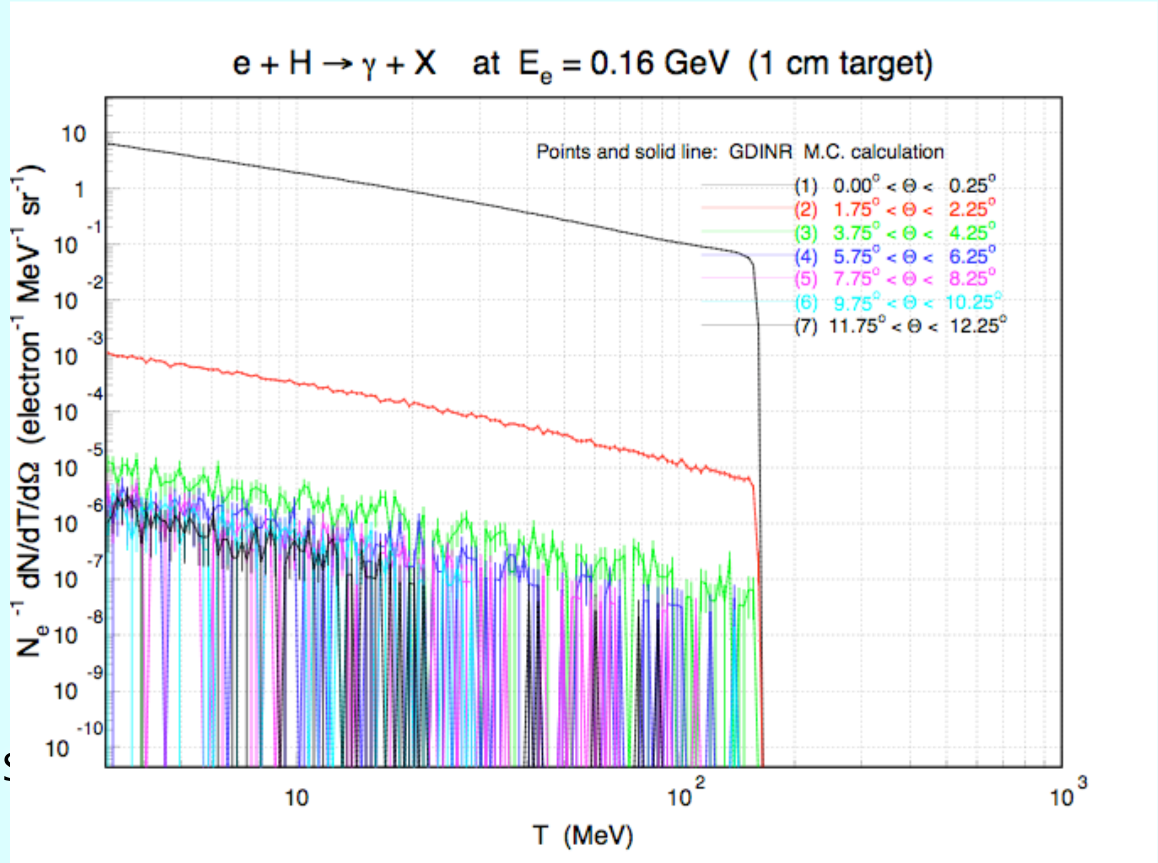
The photo–production

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

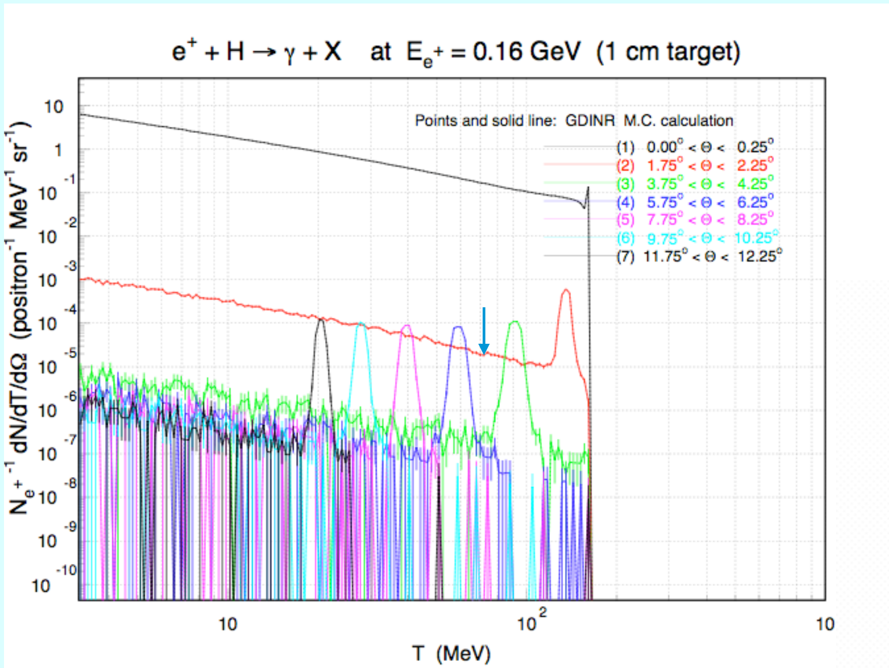
Search for : $e^+e^- \rightarrow \gamma\,U$ (*peak below main*)

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



Expected accuracy of the result



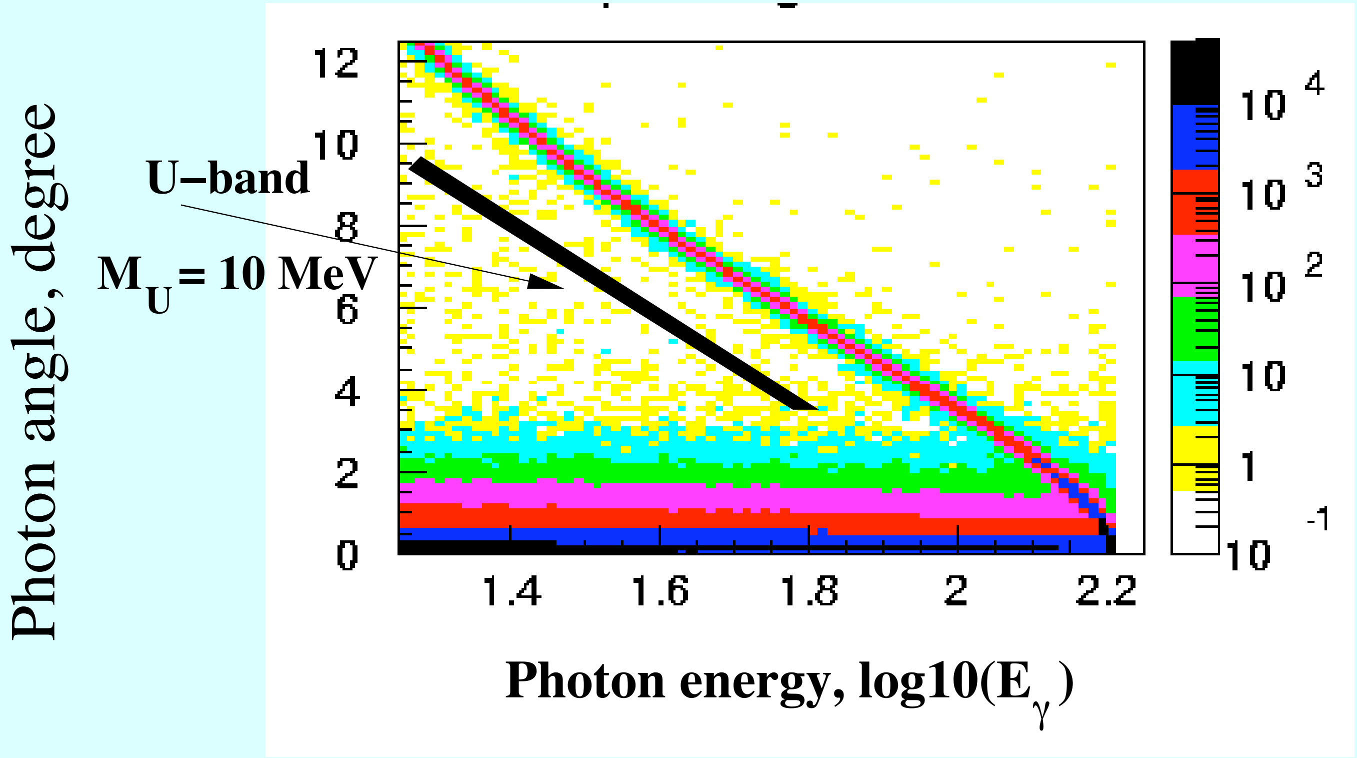
$$N_{U\gamma} = 2\frac{f_e^2}{e^2} \cdot N_{\gamma\gamma}$$

$$N_{\gamma\gamma} = 63 \text{ MHz} \cdot 10^6 \text{ sec} = 6.3 \cdot 10^{13} \text{ events}$$

$$N_{background} = R \times N_{\gamma\gamma} \approx 6.3 \cdot 10^{11} \text{ events}$$

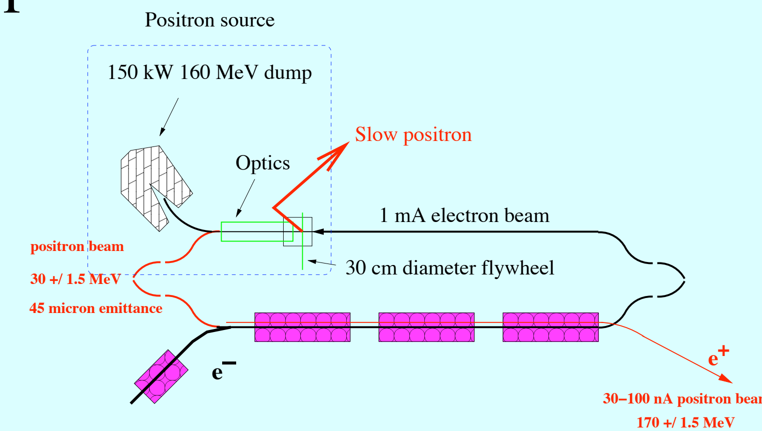
$f_e^2 < 3 \times 10^{-8}\, e^2$ (it is 5 sigma), which is "100+" improvement relatively to the upper limit obtained from g-2 results at m_U = 10 MeV

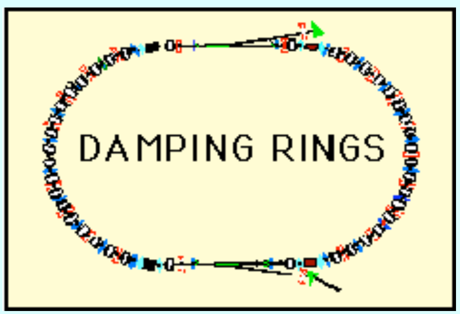
What is proposed ?

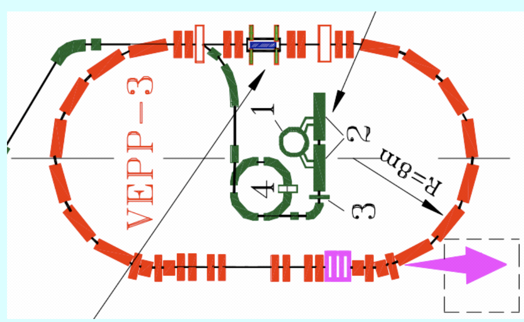


Positron Beams

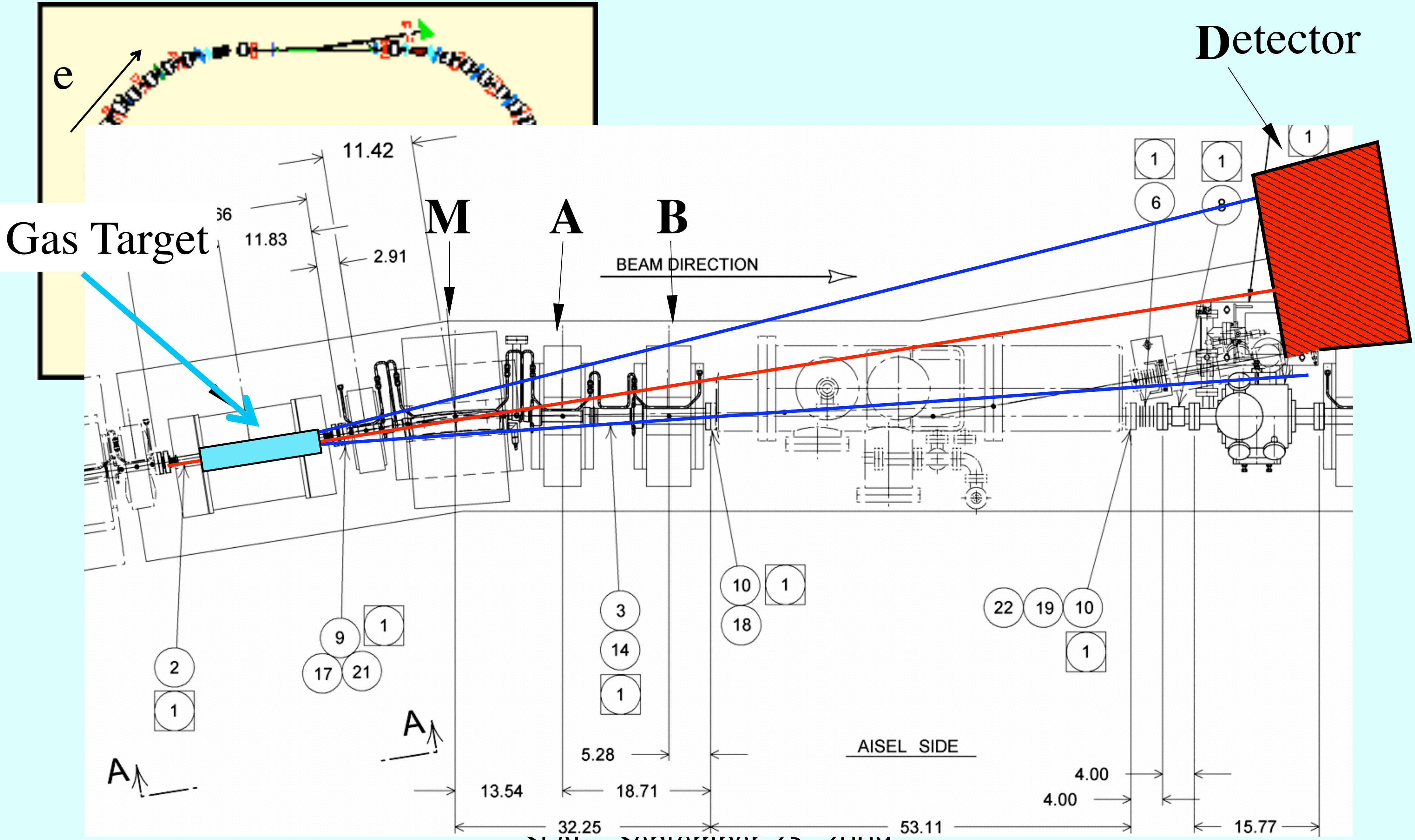
- A beam of 25 nA 400 MeV was produced at Saclay in 1980
- Beam of 1 μA was used for SLC (120 Hz), we need d.f. 100%
- Positron damping ring up to 1.2 GeV, 200 mA
- VEPP-3 energy of 0.6-2 GeV, 10 mA positrons







Positron Damping Ring Setup



Summary

- Observation of a U-boson signal on the level of 5 sigma (statistical), assuming $f_e^2 = 3*10^{-9}$, requires 3 month production running (total~ six-month experiment).
- For m_U in range 2-25 MeV, this experiment has unique sensitivity, which about 1-2 orders higher than (g-2).
- Experiment will explore exciting explanation of the 511 keV signal, light dark matter and search for particle beyond Standard Model.

See also in **arXiv:0906.5265**

Spectrometers and beam in the Hall A

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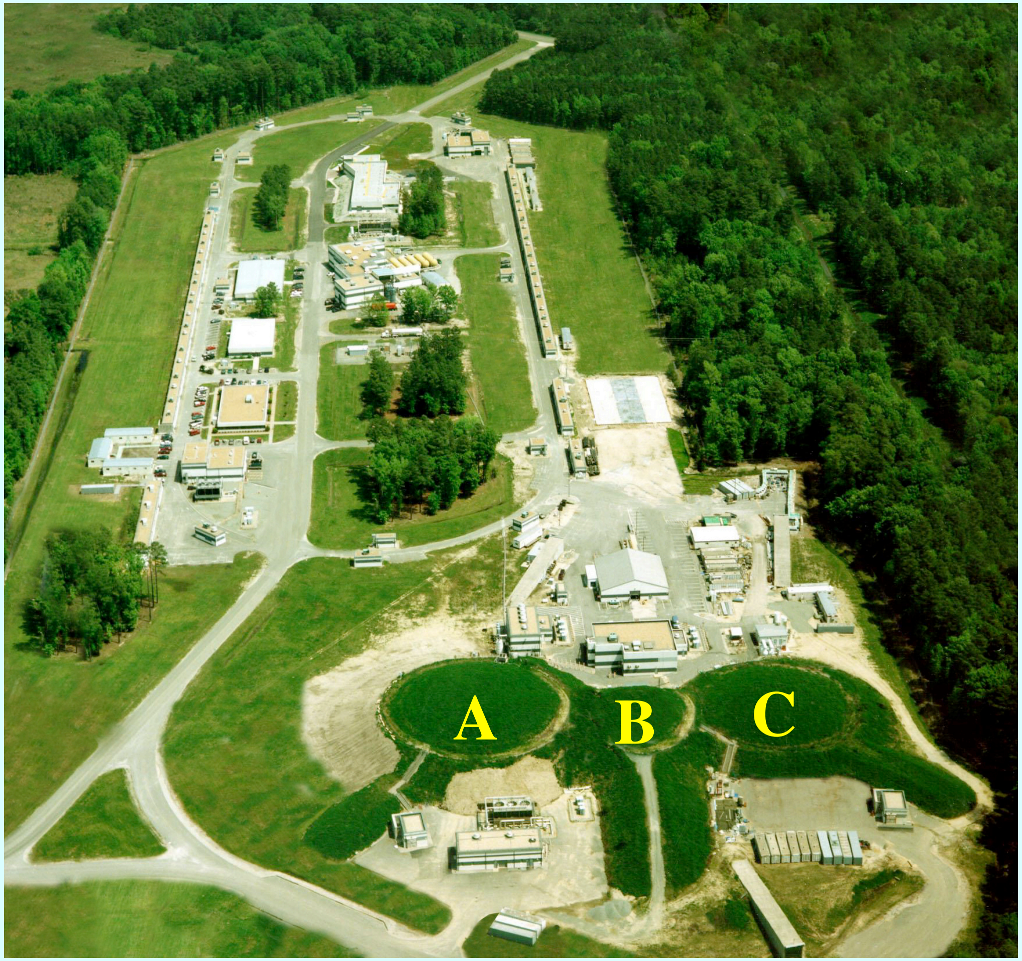
Thomas Jefferson National Accelerator Facility

- The HRS spectrometer
- Configuration for Pb-skin with septa magnet
- H(e,e’K) experiments
- Design and expected sensitivity

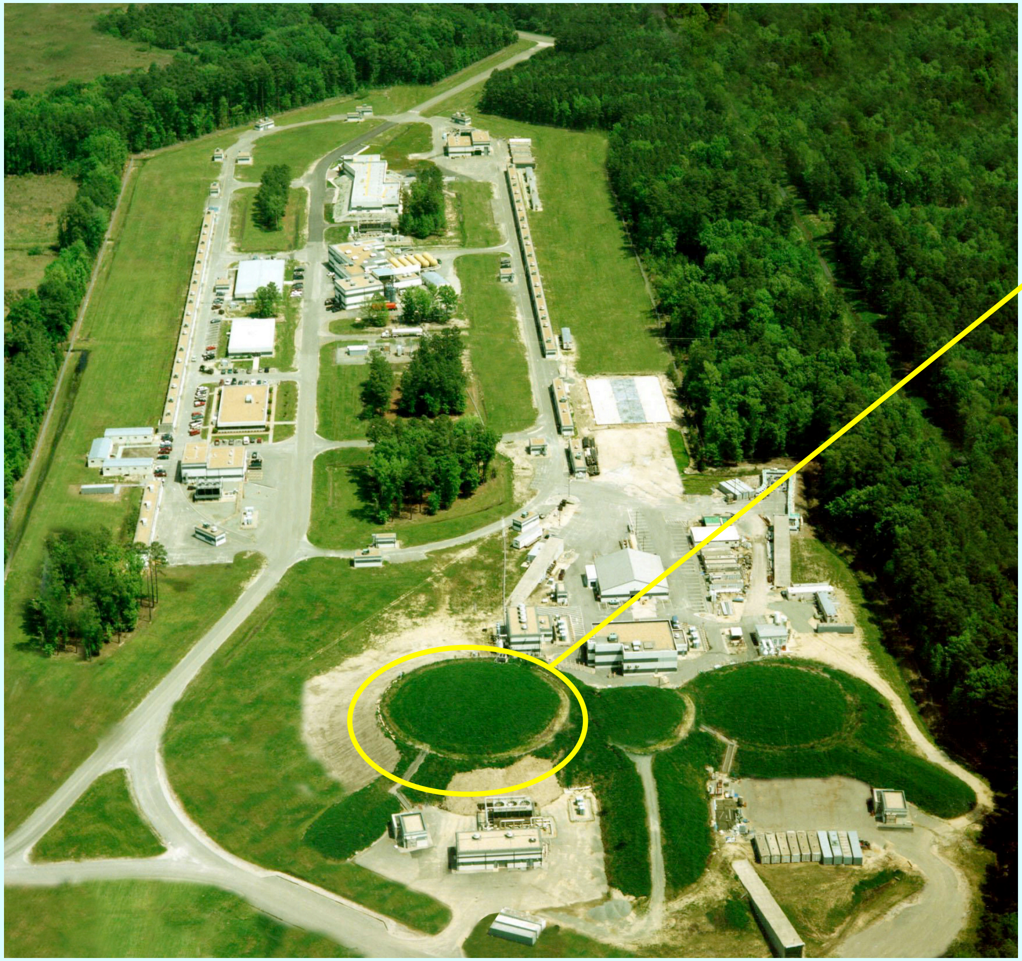
SLAC, September 25, 2009

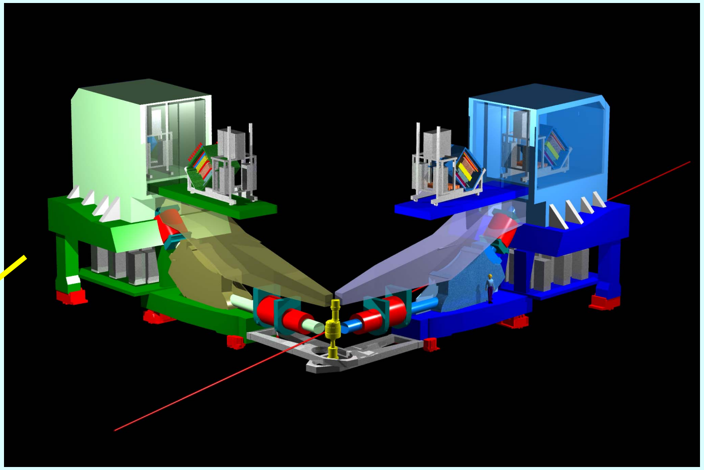
CEBAF Accelerator



- Re-circulating linac design
- Up to 5 pass, 0.3 to 1.2 GeV per pass.
- 6.0 GeV max beam energy
- 100% duty cycle
  - 2ns microstructure
- $\sigma_E/E < 1 \cdot 10^{-4}$ (Halls A & C)
- Beam polarization up to 85%
- 180 μA max current

Hall A at Jefferson Lab



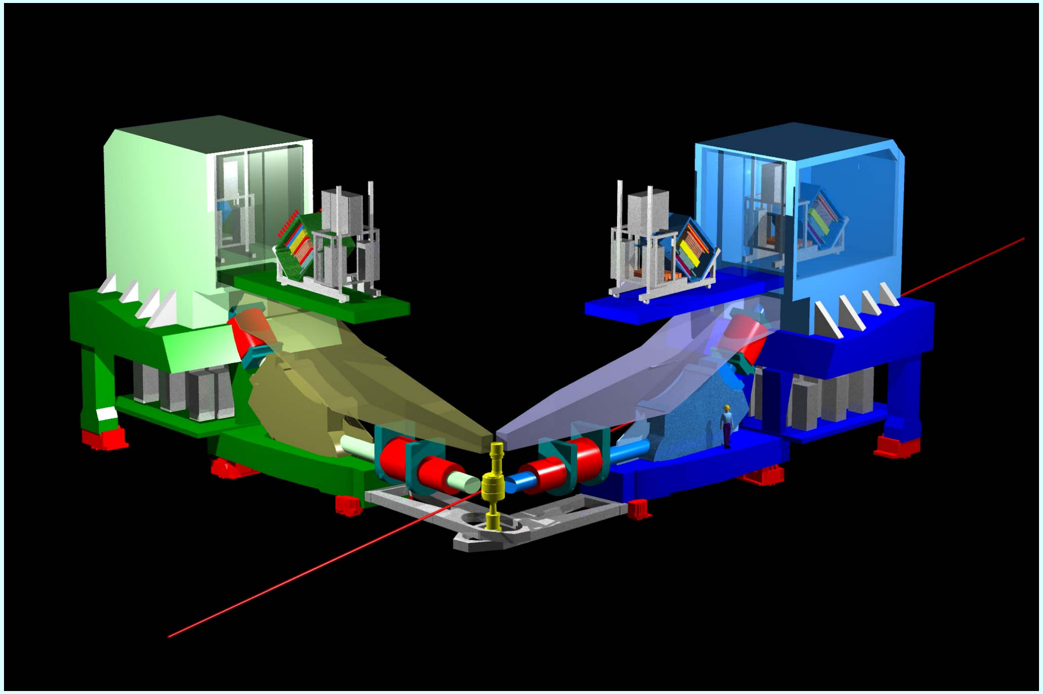


Beamline

- $\sigma_E/E < 2 \cdot 10^{-4}$ (absolute)
- Non-invasive 3% polarization measurement

Two High Resolution Spectrometers originally designed for (e,e´p) expts.

Hall A at Jefferson Lab



Two HRS Spectrometers

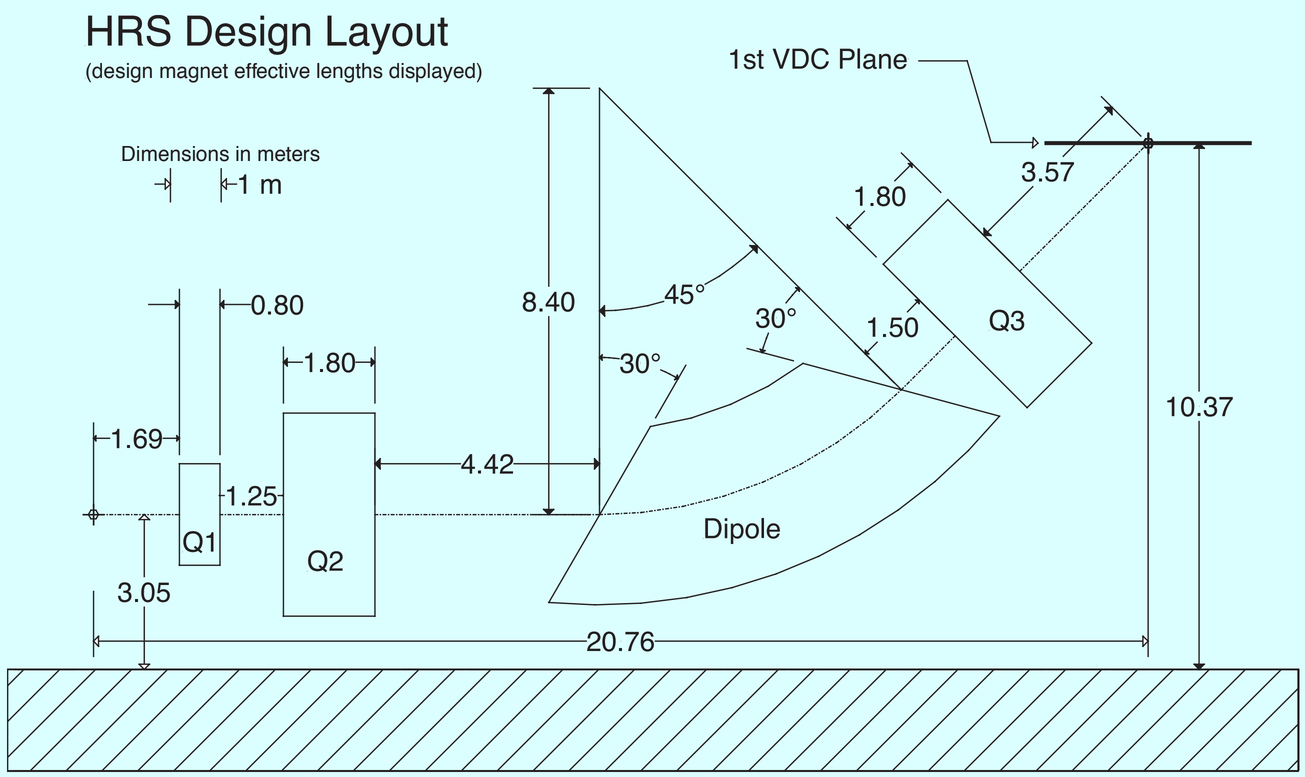
- $0.3 < p < 4.0$ GeV/c
- $-4.5\% < \Delta p/p < 4.5\%$
- 6 msr at $12.5° < \theta < 150°$
- 4.5 msr at $\theta = 6°$ with septum
- $-5\text{cm} < \Delta y < 5\text{cm}$

Optics: (FWHM)

- $\delta p/p \leq 2 \cdot 10^{-4}$ (achieved)
- $\delta\vartheta = 0.5$ mrad, $\delta\varphi = 1$ mrad
- $\delta y = 1\text{mm}$

- Luminosity ~ 10^{38} $\text{cm}^{-2}\text{s}^{-1}$

High Resolution Spectrometer



High Resolution Spectrometer

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}
Dispersion at the focus (D)	12.4 m
Radial linear magnification (M)	-2.5
D/M	5.0
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
Transverse length acceptance	±5 cm
Transverse position resolution	1 mm

PREX : Pb Radius Experiment

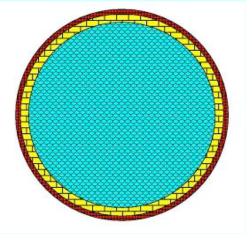
Low Q elastic e - nucleus scattering

E = 850 MeV $\theta = 6$

$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} \approx \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_P(Q^2)} \right]$$

$$\frac{dA}{A} = 3\% \quad ® \quad \frac{dR_n}{R_n} = 1\%$$

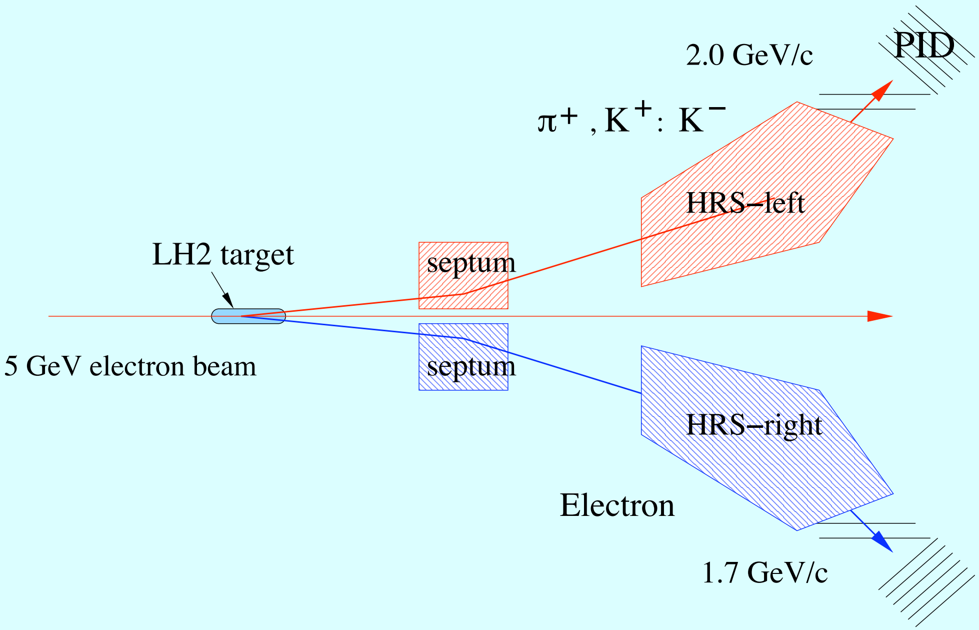
Neutron Star

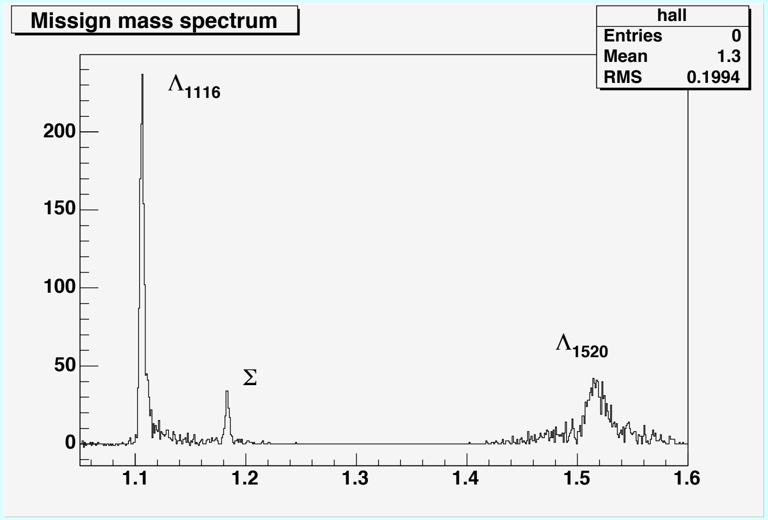


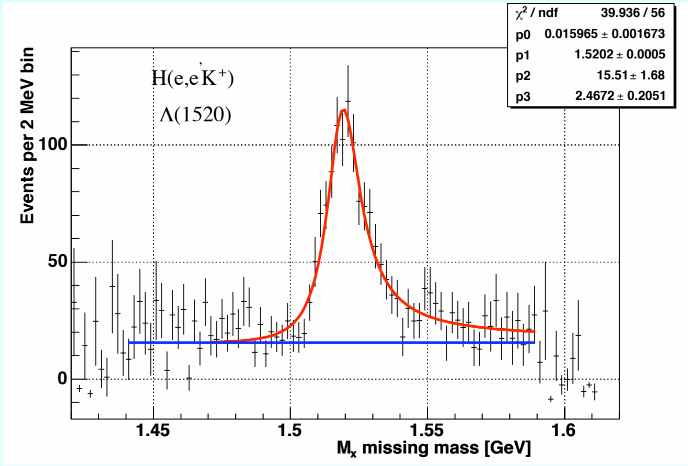
Scheduled for April-May 2010

SLAC, September 25, 2009

2004 experiment H(e,e'K)X







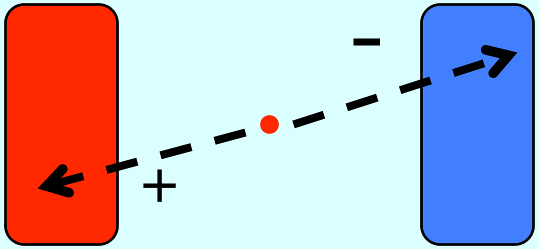
Mass spectra (e+e-) in range 300+/- 20 MeV will be obtained from these existing data

Design of the "A" search

$$m^2_{inv} = (p_+ + p_-)^2 \approx E_+ E_- (\theta_+ + \theta_-)^2$$

$$m_{inv} \sim E_\pm (\theta_+ + \theta_-)$$

Resolution defined by the angle -> 1%



$\delta_+ = E_+ \theta_+$

m_U from 30 to 100 MeV

Design of the "A" search

from arXiv:0906.0580

$$\frac{d\sigma(X \to A'Y \to l^+l^-Y)}{d\sigma(X \to \gamma^*Y \to l^+l^-Y)} = \left(\frac{3\pi\epsilon^2}{2N_f\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)$$

$(10^{-4})^2$

100

~1/1000

Pair in QED =>

$$d\sigma = \frac{8}{\pi} Z^2 \alpha r_e^2 \frac{m^4 \varepsilon_+ \varepsilon_-}{\omega^3 q^4} d\varepsilon_+ \left\{ -\frac{\delta_+^2}{(1+\delta_+^2)^2} - \frac{\delta_-^2}{(1+\delta_-^2)^2} + \frac{\omega^2}{2\varepsilon_+\varepsilon_-} \frac{\delta_+^2 + \delta_-^2}{(1+\delta_+^2)(1+\delta_-^2)} + \left(\frac{\varepsilon_+}{\varepsilon_-} + \frac{\varepsilon_-}{\varepsilon_+}\right) \frac{\delta_+\delta_- \cos\varphi}{(1+\delta_+^2)(1+\delta_-^2)} \right\} \delta_+\delta_- \cdot d\delta_+ d\delta_- \cdot d\varphi,$$

$$\frac{q^2}{m^2} = \delta_+^2 + \delta_-^2 + 2\delta_+\delta_- \cos\varphi + m^2 \left(\frac{1+\delta_+^2}{2\varepsilon_+} + \frac{1+\delta_-^2}{2\varepsilon_-}\right)^2$$

Design of the "A" search

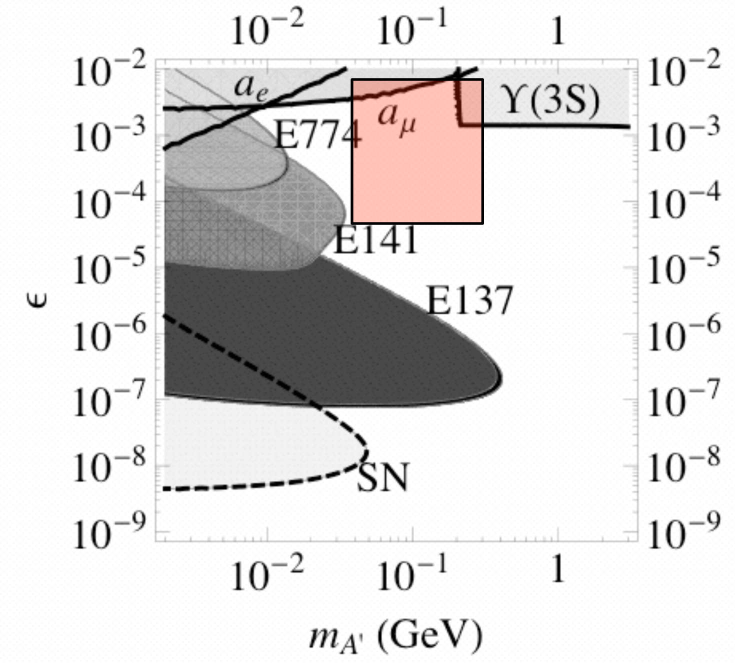
from arXiv:0906.0580

$$\frac{d\sigma(X \to A'Y \to l^+l^-Y)}{d\sigma(X \to \gamma^*Y \to l^+l^-Y)} = \left(\frac{3\pi\epsilon^2}{2N_f\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)$$

$(10^{-4})^2$

100

~1/1000



Detecting e+e- with MSD