Physics with a GeV positron beam

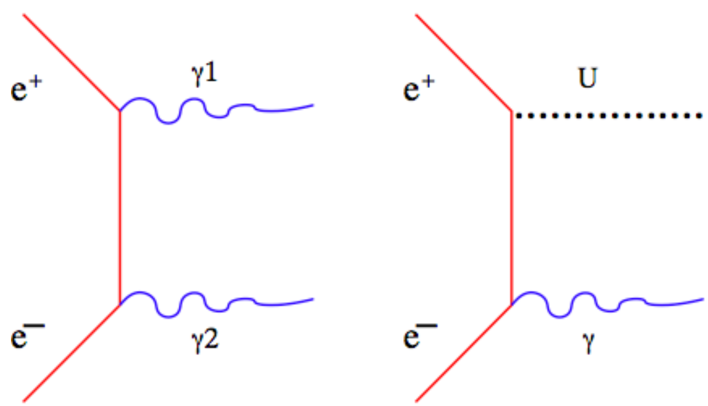
B. Wojtsekhowski and L. Pentchev

The positron beam on atomic electrons

1. Diagram, kinematics, cross section
2. Photons for nuclear physics; Saclay photon beam
3. “Collider” for U-boson from 2006 to 2023
4. Self tagged photons for hadron physics

Dirac analysis of the process

$$\boldsymbol{\sigma} = \frac{\pi r_e^2}{\gamma_+^2 - 1} \cdot \left[\frac{\gamma_+^2 + 4\gamma_+ + 1}{\gamma_+^2 - 1} \ln(\gamma_+ + \sqrt{\gamma_+^2 - 1}) - \frac{\gamma_+ + 3}{\sqrt{\gamma_+^2 - 1}} \right]$$



a) b)

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

$$\frac{d\sigma}{d\cos\theta_\gamma^{cm}} = \frac{\pi r_e^2}{(\gamma_+^{cm})^2} \cdot \left[\frac{1}{\sin^2\theta_\gamma^{cm}} - \frac{1}{2} \right]$$

$$\frac{d\sigma}{dy} \approx \frac{\pi r_e^2}{2\gamma_+} \left[\frac{1-y}{y} + \frac{y}{1-y} \right] \qquad \mathbf{y} = \frac{\mathbf{E}_\gamma}{\mathbf{E}_{\mathbf{positron}}}$$

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THE PHOTON SPECTRUM FROM POSITRON ANNIHILATION IN FLIGHT *

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Received 12 July 1968

Figures are presented which enable the target parameters of a positron annihilation in flight system to be chosen to obtain the maximum photon yield consistent with the required photon energy spread in the annihilation "spike".

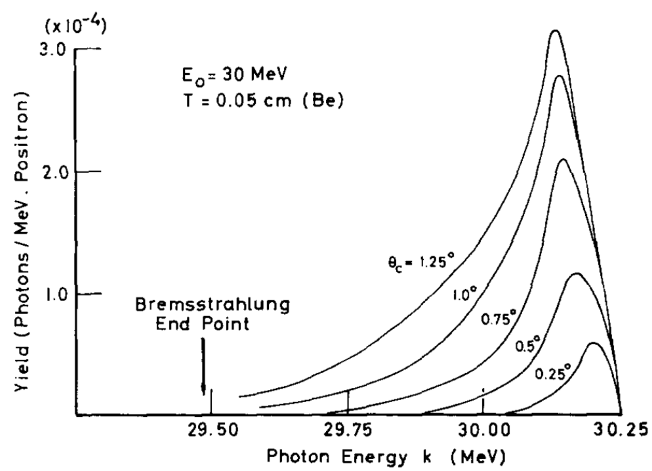

Fig. 1. Annihilation photon spectra from a beryllium target for monoenergetic incident positrons.

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A 130 to 530 MeV tagged photon beam obtained by in flight positron annihilation

P. Argan [*, a], G. Audit [a], J. Bechade [a], A. Bloch [a], N. de Botton [a], G. Colin [a], J.L. Faure [a], D. Foucaud [a], M.L. Ghedira [a], C. Guerra [a], J. Martin [a], E. Mazzucato [a], C. Schuhl [a], G. Tamas [a], E. Vincent [a]

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Abstract

We have developed a tagged annihilation photon facility at the 720 MeV Saclay Linear Accelerator, delivering 130 to 530 MeV tagged photons. The typical flux produced in 25 MeV around 300 MeV is 10^4 photons per second with a 2 MeV energy resolution. The positron transport system is described; the tagging and tagged photon beams are detailed; we present some measurements of their characteristics, and illustrative examples of photonuclear experiments using this tagging facility.

High resolution e-m calorimeters at JLab allow the design of an experiment for a sensitive search of the U-boson (A')

No assumption about the A' decay

Hall B – PRAD-II -1600 crystals
Hall C – NPS - 1080 crystals
Hall D – 1600 crystals (under construction)
Each calorimeter will use fADC-based DAQ
High energy and coordinate resolution, pulse width ~40 ns

Using 100 nA of 11-12 GeV positron beam in Hall B, or C, or D
U-boson search will cover mass range up to 100 MeV
The proposal for U-boson (A') search will be on the list for PAC51

Internal report on U boson search, summer, 2006

Search of U boson in electron-positron annihilation in flight

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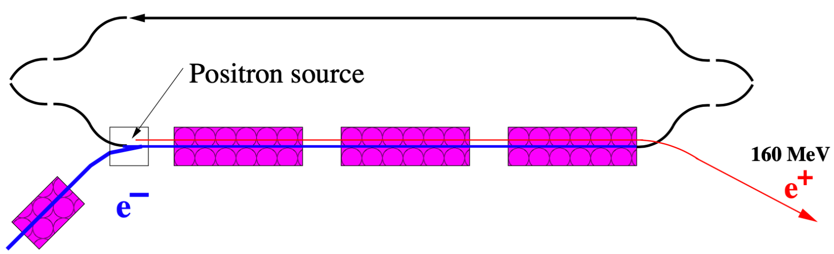
Abstract

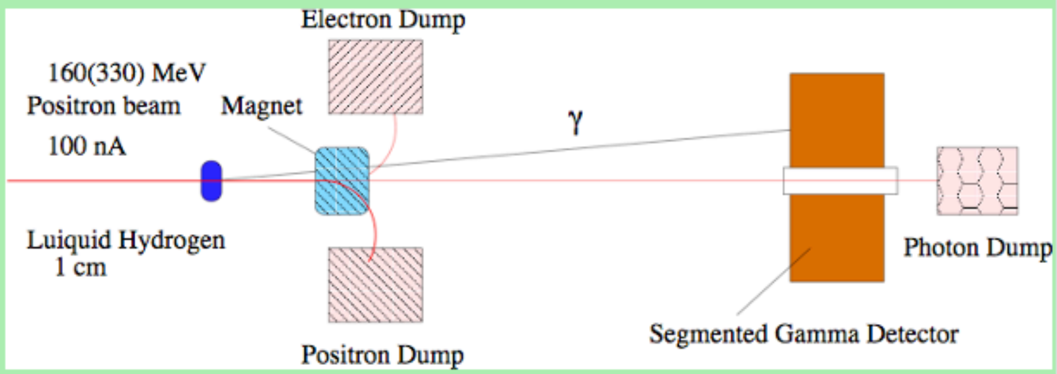
An experiment is proposed to search for a new gauge boson U in reaction $e^+e^- \rightarrow U\gamma$ in the mass range from 2 to 15 MeV. The data could determine the particle mass and the coupling constant f_e^2 (or its upper limit). The experiment could utilize a 160-330 MeV positron beam in JLab FEL. It needs a low-power liquid hydrogen target and a high-resolution gamma detector. With 240 hours of beam-time and full detector, this measurement will find the U boson or provide an upper limit for the coupling constant f_e^2 to the level of $\mathbf{10^{-8}}$ or **almost seven orders** smaller than the electromagnetic one e^2. Such a measurement will be a very important step in the investigation of the origin of the abundant 511 keV photons in Galactic Center.



U boson analyzed by P. Fayet, Phys. Lett. B 95, 285 (1980); Nucl. Phys. B 187184 (1981).

Schematic of the proposed experiment

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

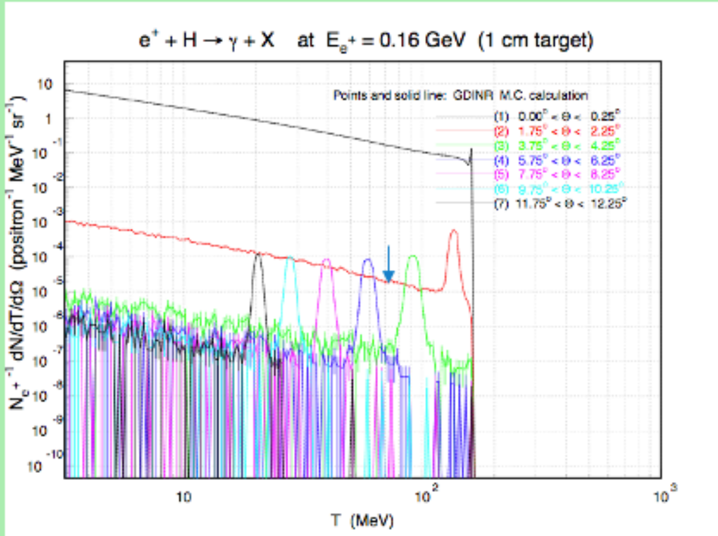


- Segmented photon detector ~ 1000 modules, ~2% energy resolution.
- Parallel DAQ for the total rate of ~50 MHz.

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

Oct. 27, 2006 DNP APS Nashville

Expected accuracy of the result



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

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

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

$f_e^2 < 0.3 \times 10^{-7} e^2$, which is "100+" improvement relatively to the upper limit obtained from g-2 results

The photo-production processes

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

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

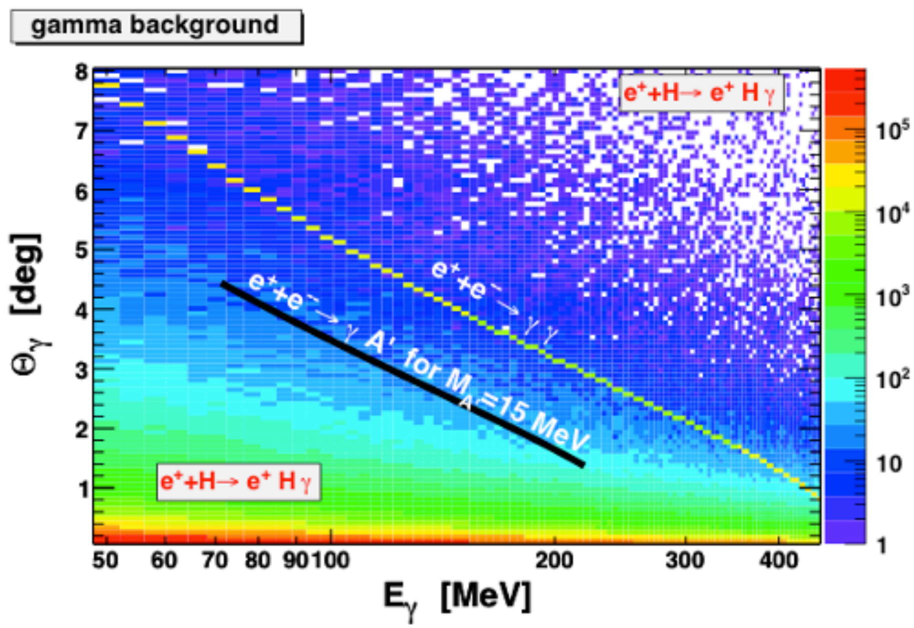
Basic QED: $e^+Z \to \gamma$ (smooth brems.)

- Detect γ at fixed angle with the beam:

  reconstruct the mass
- Variation with the angle:

  control systematic
- Target Z

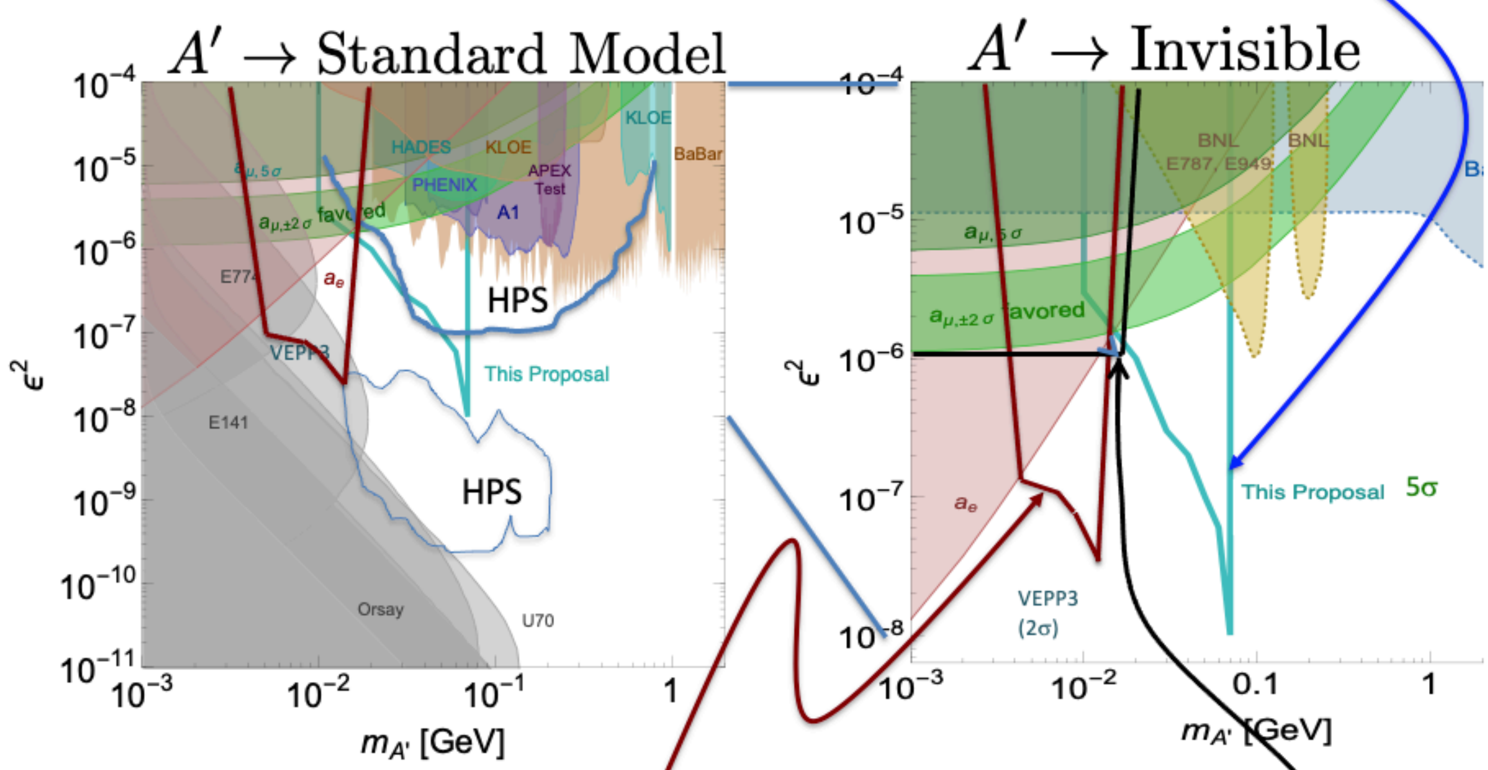
  Hydrogen vs. ^{12}C



Estimated reach for expt at Cornell

Based on GEANT4 simulation with all bkgs and pileup included

E_{beam}=5.3GeV, I_{beam}^{avg}=2.3nA, Lumi = 1.0x10^{34}, T = 10^{7}sec, 5-sigma excl



Novosibirsk (proposed)

PADME @ Frascati (proposed)

Dark sector studies with the PADME experiment

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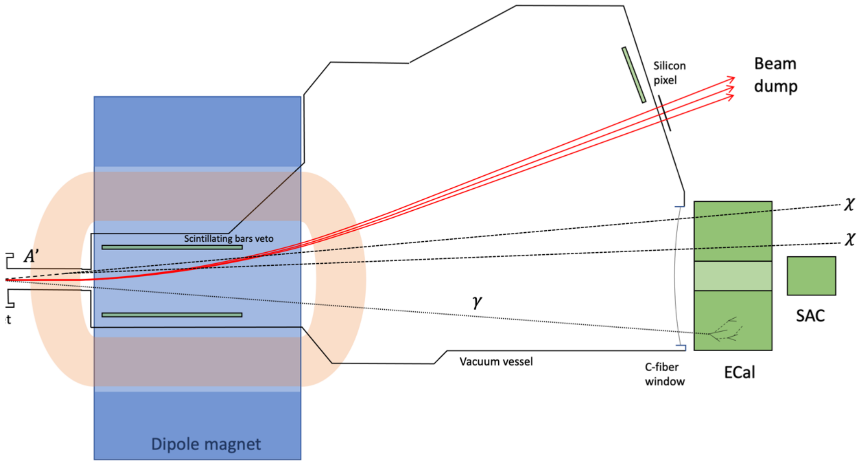


2. PADME experiment status

PADME has taken data in two periods, in fall 2019 (Run I) and fall 2020 (Run II), collecting a similar statistics of $\approx 5 \times 10^{12}$ positrons on target (pot), but with different beam configurations: with a secondary beam of 490 MeV positrons, produced onto the attenuating target of the BTF yielding a high beam-induced background, in Run I, and by using the "primary" beam produced at the positron converter of the Frascati LINAC and accelerated to 430 MeV, in Run II. In order to reduce the pile-up, the density of positrons in a single beam pulse was limited to $\sim 10^2$ particles/ns, trying to produce the maximum lenght of the macro-bunches, up to $\sim$ 300 ns [6].

Many, 10^8 -10^9 , pulses!

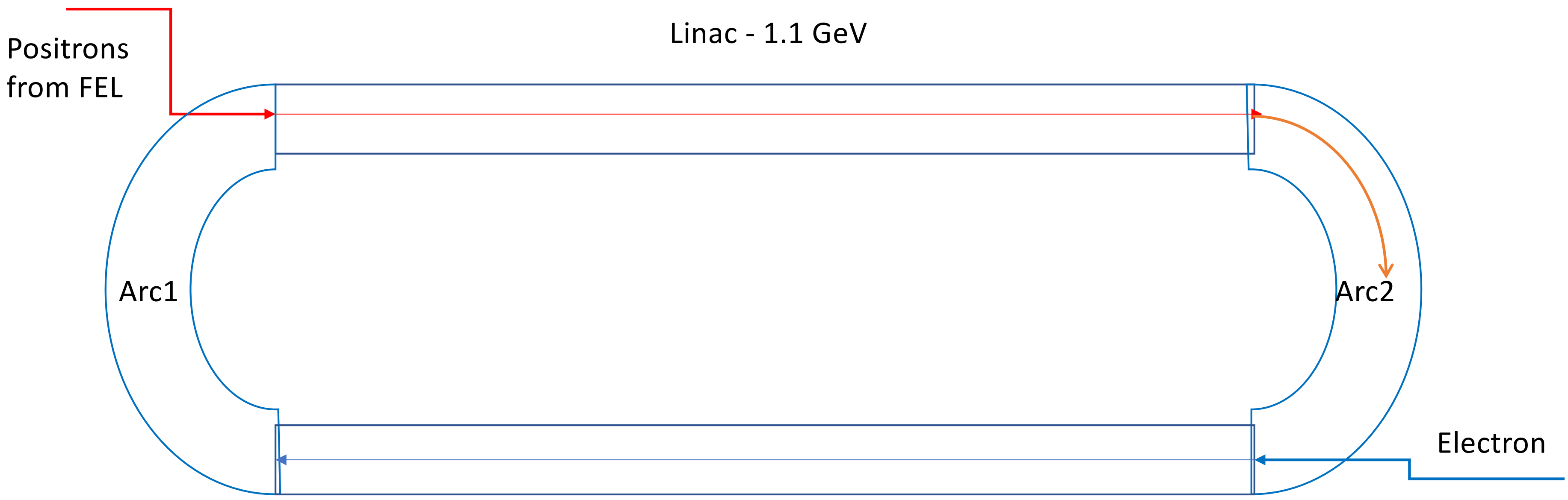
The charge is as with

0.1 μA x 10 seconds

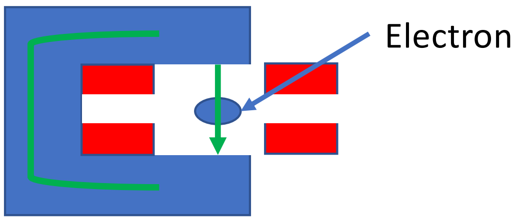
A concept with the focus on staging of the project

Why start the positron program with P3?

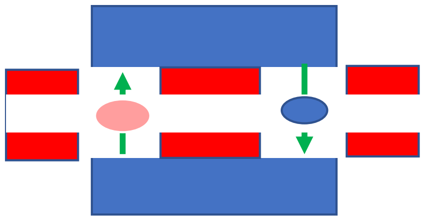
- It is a cost effective plan: $10M vs. $100M
- It will be first time a cw positron beam
- It will have a tiny energy spread
- It will have 3.4 GeV energy (great for the TPE and the A'/X-17 boson)
- It will be in parallel to the electron beam 11 GeV program
- It could be delivered to the halls via the existing beam lines
- It has a clear prospect of reaching higher beam energy when ready
- It needs a modest funding for the P3 stage
- It ought to be done when the opportunity exists



Magnet Arc2



Combined e+ and e-



Previous reports/proposals on U/A’ search with e^+ beam

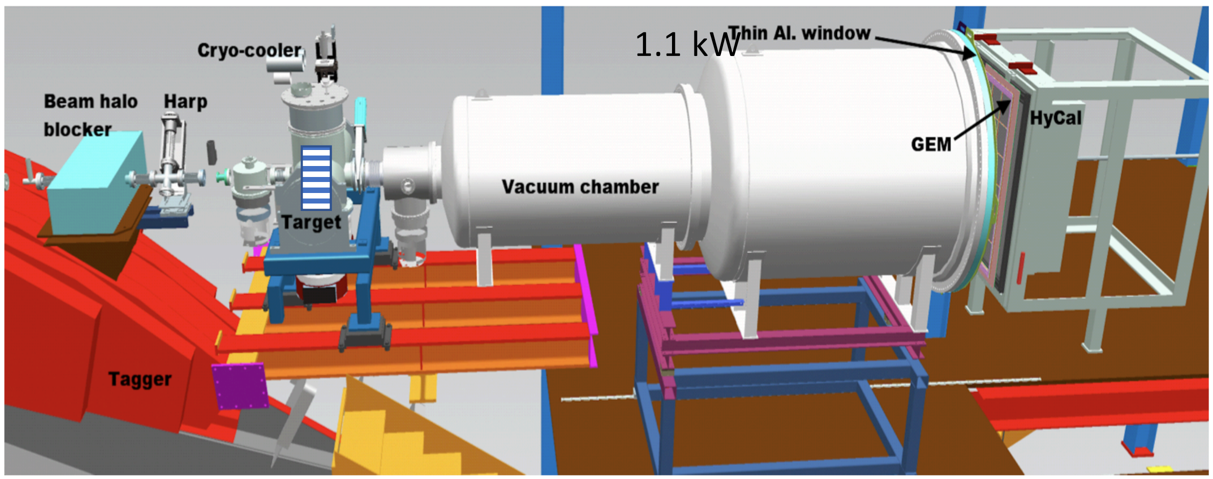
- *Searching for the dark matter U boson with a positron beam*, at *Mini-symposium on Identifying Dark Matter II: Axionic and Sterile Neutrino Dark Matter*, DNP/APS meeting, Nashville, October 25–28, 2006.
- JPOS 2009 - arXiv:96.5265
- SLAC, 2009 – option with SLAC damping ring
- Cornell, 2013 – BNP, VEPP-3, J. Instrum. 13 (02) (2018) P02021
- Cornell, 2013 – positrons for A’ search in CESR
- Positron source for solid state research, arXiv:1404.1534
- Cornell, 2015 - Very Asymmetric Collider, NIM-A 1049 (2023) 168035
- SLAC, 2016 – Cornell project MMAPS

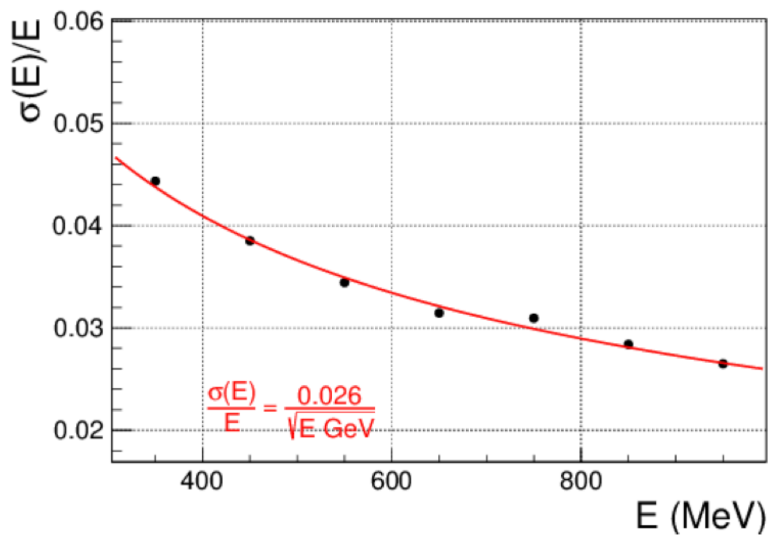
  SLAC 2009 => PADME now taking data with 50 Hz pulsed e+ beam
- JLab, 2021 3.5 GeV positron beam with extra arcs in “between” existing

Positron beam with PRAD calorimeter in Hall B

No assumption about the A' decay

B. Wojtsekhowski and A. Gasparian





Positron beam with PRAD calorimeter in Hall B

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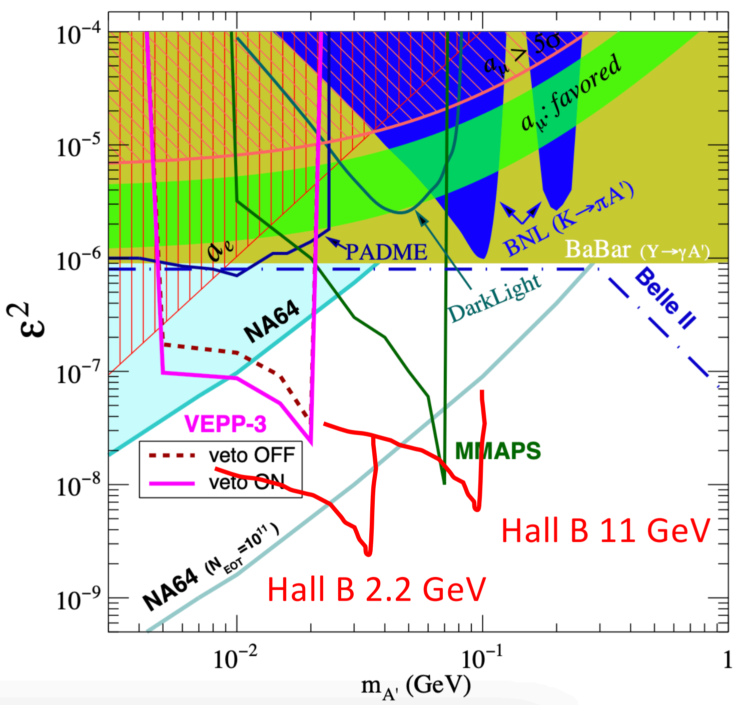
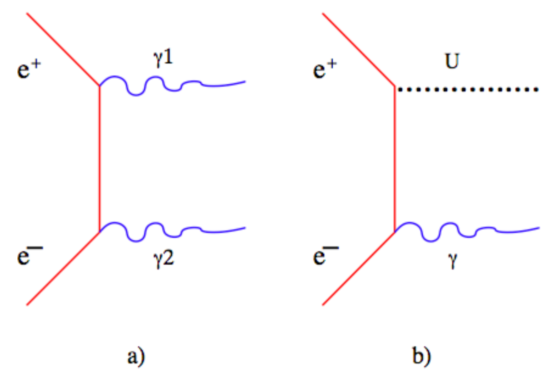
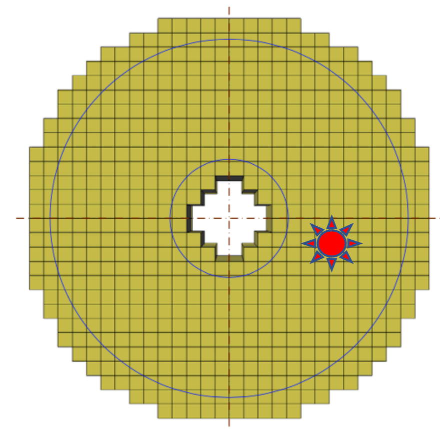






Luminosity: 0.1 μA x 15 cm LH2 ~ 4 x 10^{35} cm^{-2}/s

which is 400 times that of VEPP3, ~ 10^6 of PADME, ~ 40 times that of Cornell's

DAQ for clusters: 100 kHz of single high-energy hits

Self tagged photons for hadron physics

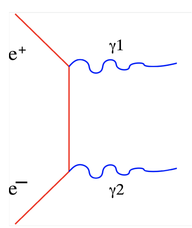
Positrons for the energy tagged photons

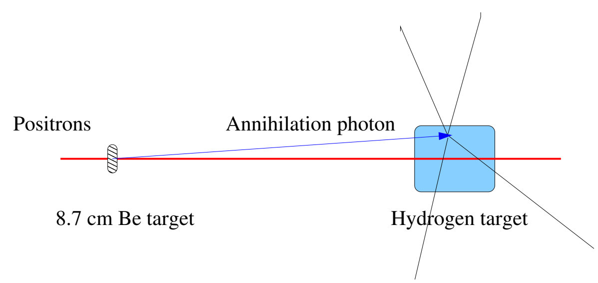
B. Wojtsekhowski and L. Pentchev
(Dated: November 29, 2022)

The annihilating photons produced by the positrons on the Be target have a large advantage in counting rate relative to the tagged photon beam method. For example with the 5 μA positron beam intensity, the gain is about 10+, considering that an intensity of 10^8 is the upper limit for the tagged beam intensity. The annihilating photon energy could be accurately reconstructed using a correlation of the photon energy and emission angle, which is obtained from the transverse coordinate of the event vertex at the target.

I. MOTIVATION

The study of photo-production of the excited $c\bar{c}$ and the recently discovered XYZ states [1, 2] with mass range 4-6 GeV presents an important field of hadron study which will became accessible at JLab with the positron beam. The primary process for production a few GeV states will be photo-production of the hadron final state using photons of known energy. For a traditional photon beam, the rate limitation comes from the flux of tagged photons due to operation of the electron tagger on the level of 10^8 per second. The intensity is also very limited near the end-point. We propose using positron annihilation in which the photon energy is correlated with its emission angle and could be reconstructed from the transverse coordinate of the event vertex. The reaction for the two-photon final state is shown in the left panel of Fig. 1.





In the annihilation process the energy in the electron-positron cm. system is $\sqrt{2 * m_e * E_{positron}}$ and is about 140 MeV for a 22 GeV positron beam. The use of positrons for a photon source for nuclear physics experiments was discussed in Ref. [3]. The resulting size of the photon cone is about $0.14/22 \sim 0.4$ degrees. Using a 500 cm distance between the annihilation target and physics target, the diameter of the photon beam could be estimated at 6 cm. With achievable accuracy of the vertex coordinate of 0.6 mm, the projected photon energy accuracy is 1%. The scheme of the layout is shown in the right panel of Fig. 1.

III. COUNTING RATE OF THE PHOTON BEAM

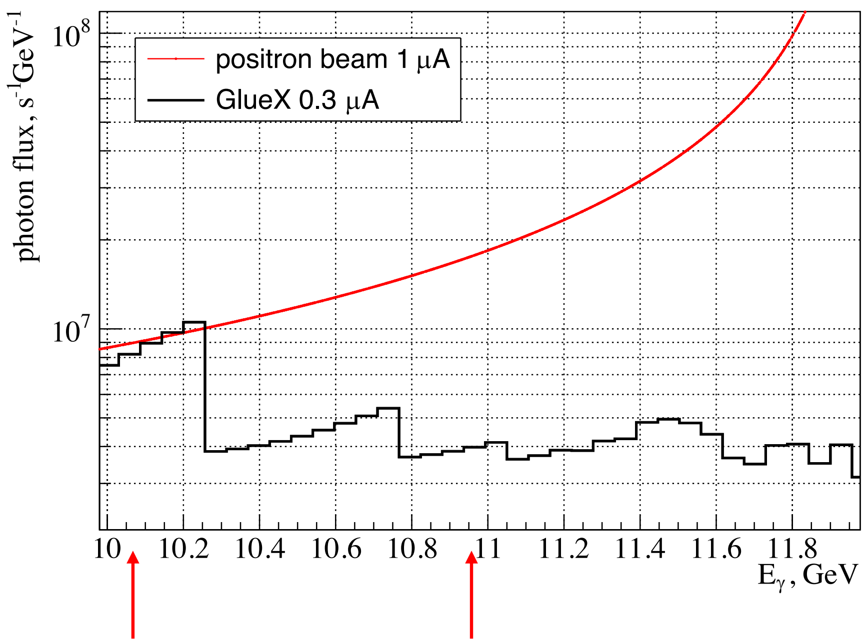
The energy in the center of mass system $\sqrt{s} = \sqrt{2m^2 + 2E_+ m}$, where m is the electron mass and E_+ the positron energy, and the emission angle of the final photon θ_γ with respect to the direction of the positron beam defines the value of the photon energy E_γ. In the case of two-photon production: $E^{lab}_{\gamma(\gamma\gamma)} \approx E_+(1 - \cos\theta^{cm}_\gamma)/2$.

The total cross section of the process for $E_\gamma > E_+/2$ is:

$$\sigma = \frac{\pi\, r_e^2}{2(E_+/m_e)} \cdot [\ln 2\,(E_+/m_e) - 1] \tag{1}$$

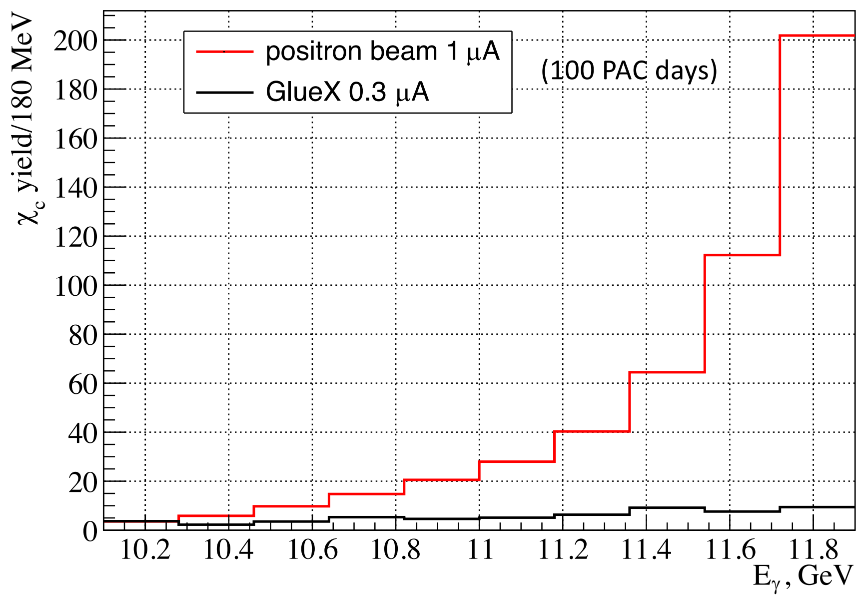
For a selected 500 cm distance between the Be (annihilation target) and LH2, where XYZ states will be produced, the Be target length of 8.8 cm will be used (resulting in 0.5% contribution to the energy resolution).

Intensity vs. photon energy
Access to the high mass states



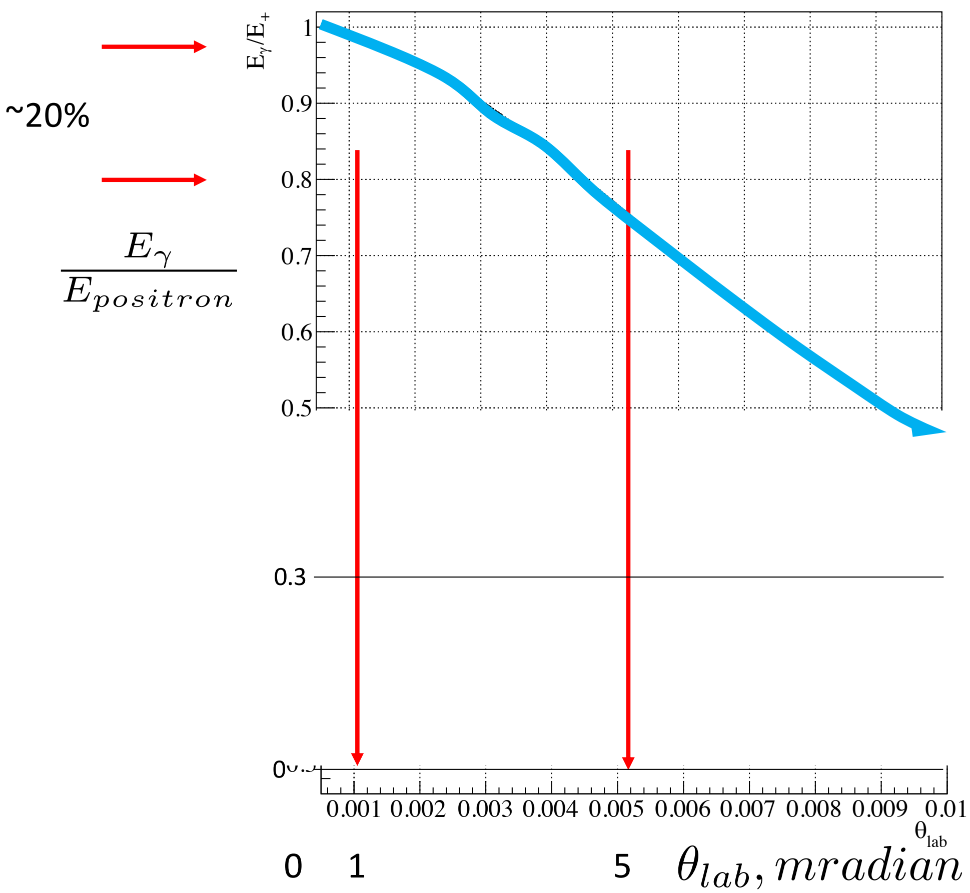
χ_{c1} ψ'

Resonance production rate

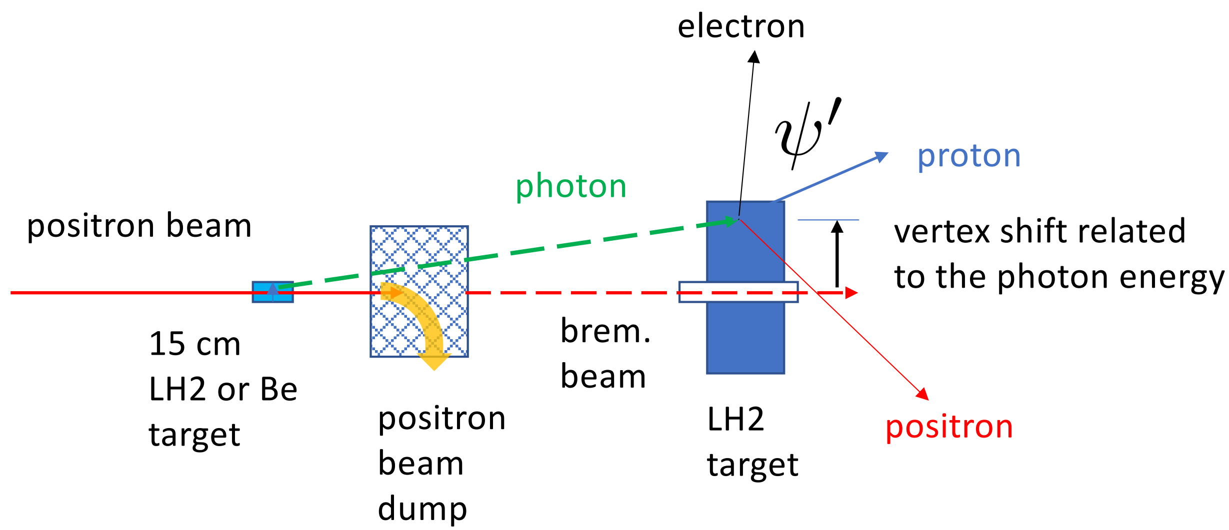


Total integral is larger by x10

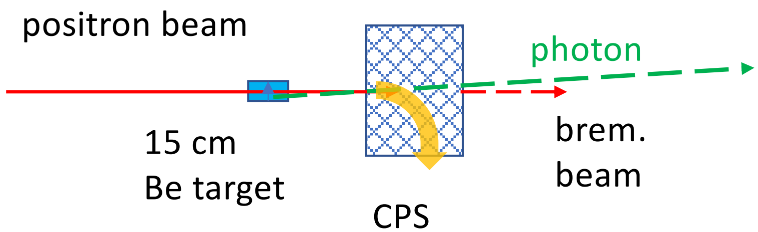
Photon energy vs. emission angle



Self tagged photons - experiment layout



Annihilation photons for TCS



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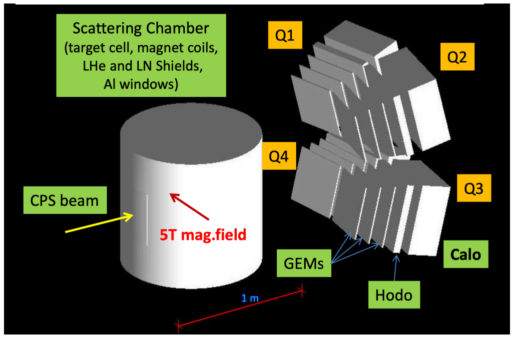

Advantage is large intensity near the end point

Summary

- The productivity gain relative to the GlueX tagger vs. a 1 μA positron beam (ann. photons near the end point 10 (20)%) is 20 (10) times
- Special advantage for study of the XZ states, some accessible with 13 GeV
- Advantage for high sensitivity search of the narrow states
- Positron is a bright plan for hadron physics at JLab