Experiment on Positronium Invisible decay Channels (EPIC)

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UZH – ETHZ – PSI PhD Seminars 2016
November 24, 2016, Zürich

Dark Matter

- Several cosmological observations suggest the existence of Dark Matter, e.g. galaxy rotation curves[1]and gravitational lensing
- This matter cannot have barionic or SM neutrino origin, but it is still ~ 5 times more abundant than ordinary matter
- Dark Matter strongly suggests the existence of new physics beyond the Standard Model

Gravitational lensing, from Hubble mission

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Some candidates for DM

- Axions
- Supersymmetric particles
- Sterile neutrinos
- Hidden sectors

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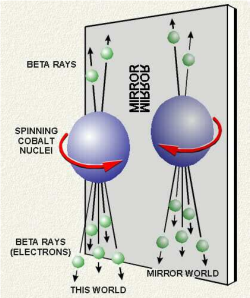
- Sterile neutrinos
- Hidden sectors
  - **Mirror Sector**
  - Dark photons (talk by D. Banerjee)



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What is the Mirror Sector?

- Postulated by Lee and Yang in 1956 to restore parity conservation in the weak interaction
- The model introduces a new set of mirror particles having the same properties as ordinary ones, such as mass and charge, but opposite chirality
- Interactions among mirror particles would be the same as ordinary ones except that only right-handed particles couple with the weak interaction
- Gravity and kinetic mixing of colorless, neutral particles (e.g. photons or neutrinos) are the only possible interactions between sectors[2]

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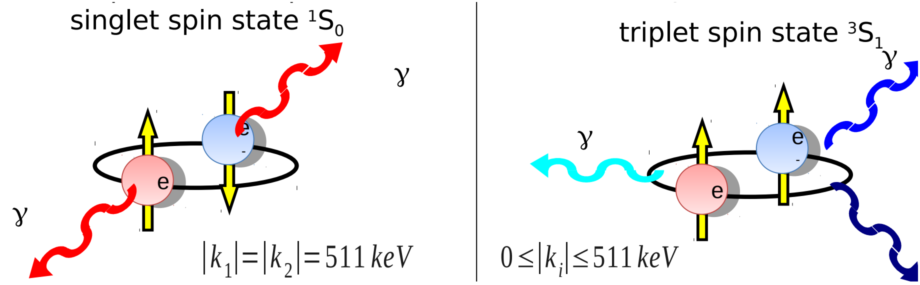
Why do we seek Mirror Matter?

- Suitable DM candidate since it provides massive, stable and barely interacting particles
- The model can also explain the similarity between matter and DM abundances
- Kinetic mixing of photons opens up some possibilities to detect oscillation of matter into its mirror partners[3]

[2] S.L. Glashow, Physics Letters B 167, 1 (1986)
[3] P. Crivelli et al., JINST 5,(2010)

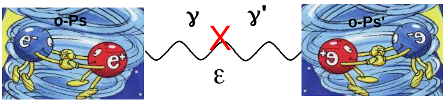
Positronium...

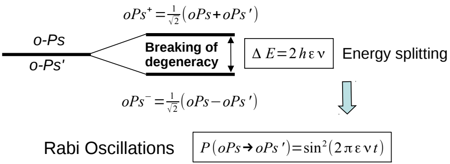
- Bound state of electron and positron (particle – anti-particle system)
- Purely leptonic atom, almost free of finite size effects inaccuracy (ideal for precision bound state QED tests)
- Two different spin configurations:
  - Singlet state: para-positronium (p–Ps) $\rightarrow \tau = 124$ ps, decays into $2, 4, 6 \ldots$ photons
  - Triplet state: ortho-positronium (o–Ps) $\rightarrow \tau = 142$ ns, decays into $3, 5, 7 \ldots$ photons



as a portal into the Mirror Sector

- If photon – mirror-photon mixing can occur, it can eliminate the degeneracy of o–Ps and o–Ps' so that the vacuum energy eigenstates would be a linear combination of the mass eigenstates
- This mixing would induce o−Ps $\longleftrightarrow$ o–Ps' Rabi oscillations with a frequency proportional to the coupling constant ϵ
- The oscillation would result in the decay into three mirror photons
- The experimental signature is therefore the apparent disappearance (missing energy) of o–Ps with a branching ratio Br(o–Ps→invisible)$= \frac{2(2\pi\epsilon f)^2}{\Gamma_{SM}^2+4(2\pi\epsilon f)^2}$





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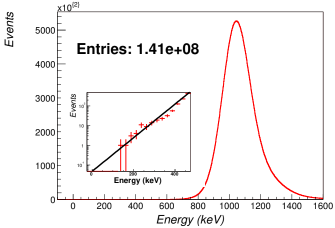
Previous search for o–Ps → o–Ps' oscillations

- Best limit set with Ps confined in **aerogel**: Br(o–Ps→inv.)$< 4.2 \times 10^{-7}$
- $\sim 10^4$ collisions per lifetime for Ps confined in aerogel destroy the coherence of the oscillation reducing sensitivity to ϵ by a factor $\sqrt{N_{coll}}$
- Limit on coupling constant $\epsilon < 1.55 \times 10^{-7}$ far from cosmological suggestions $\epsilon \simeq 4 \times 10^{-9}$



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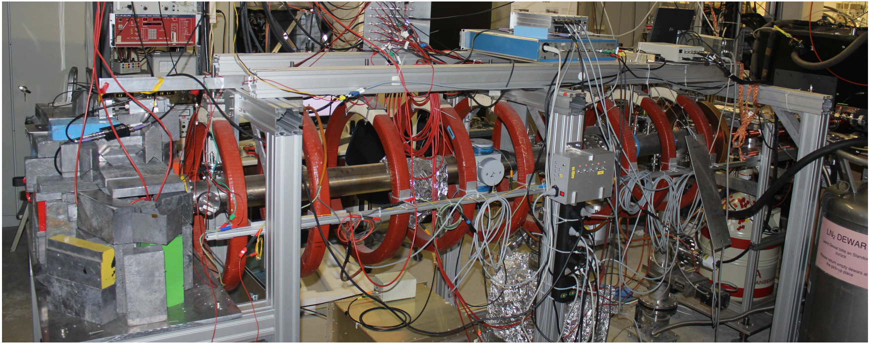
Goal:

- Measure Br(o–Ps→inv.) in vacuum to improve limit on coupling constant ϵ
- Use signal modulation via collision rate to confirm signal observation

The slow positron beam at ETHZ

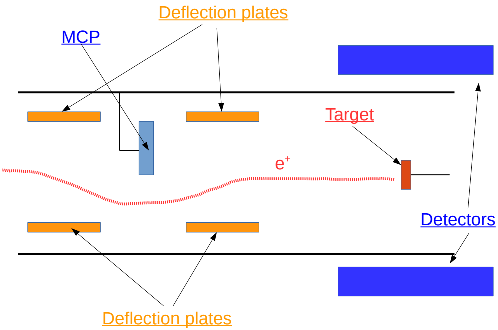
- Na-22 β^+ source coupled to W moderator produces slow, monoenergetic positron beam[4]
- Velocity selector to discard fast positrons
- Magnetic confinement to guide positrons to detector region
- Electrons released by positron reaching the target detected by an upstream MCP to precisely tag arrival time



[4] More on L. Gerchow's talk

Positron Tagging System

1. Positrons reach the target and release secondary electrons



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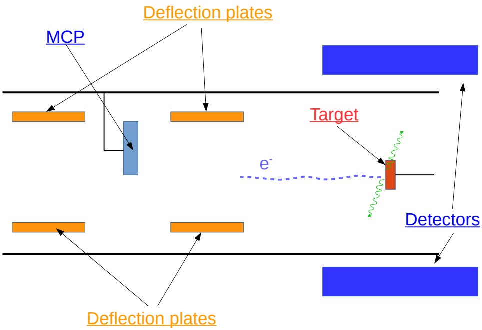

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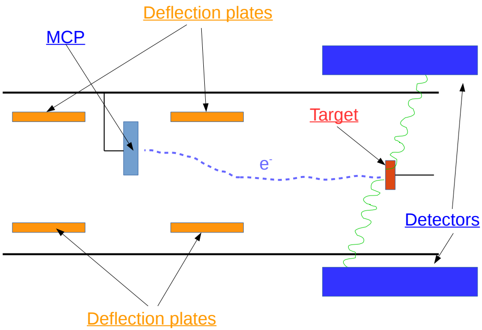

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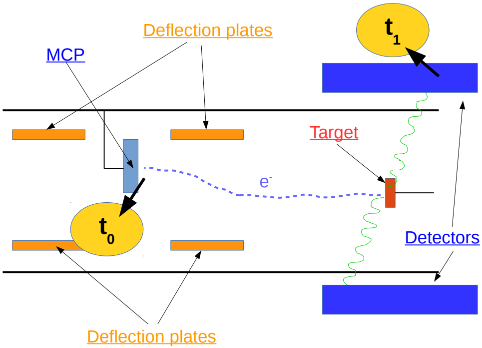
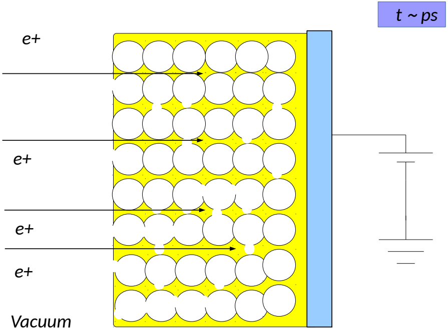
4. MCP provides t_0 and gamma detectors provide t_1



Positronium Formation in Porous Silica Thin Films

1. Implantation with few keV energy (20 to 200 nm) and rapid (ps) thermalization in the bulk



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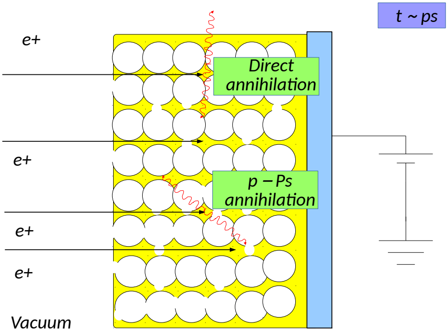
Positronium Formation in Porous Silica Thin Films

1. Implantation with few keV energy (20 to 200 nm) and rapid (ps) thermalization in the bulk
2. Diffusion through the porous structure with either direct annihilation or Ps formation (25 % p–Ps, 75 % o–Ps) by ionized electron capture in SiO_2



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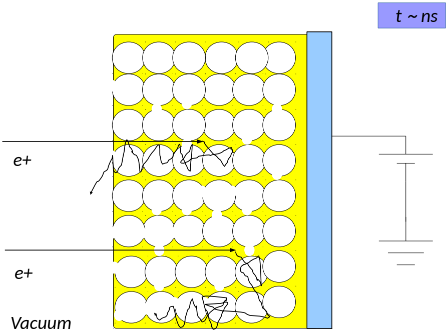

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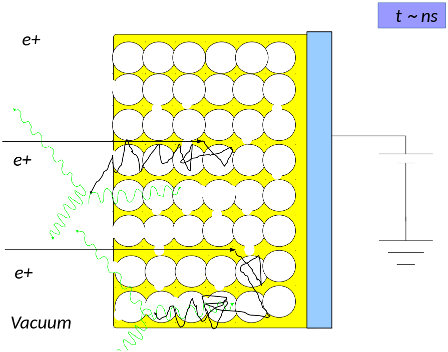
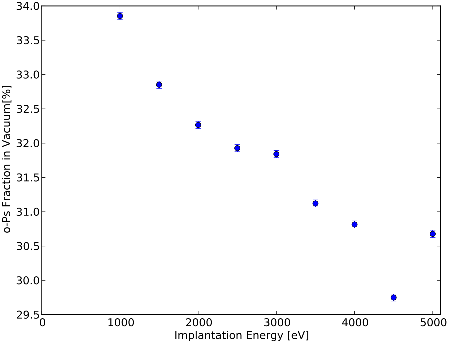
4. o–Ps annihilation in a pore or escape to vacuum



Extra–thin o–Ps formation target

- A new target was prepared on a specially thin glass substrate (100 µm) target
  - Fraction of o–Ps measured via Positronium Annihilation Lifetime Spectroscopy (PALS): $\sim 30\,\%$, depends on positron implantation energy



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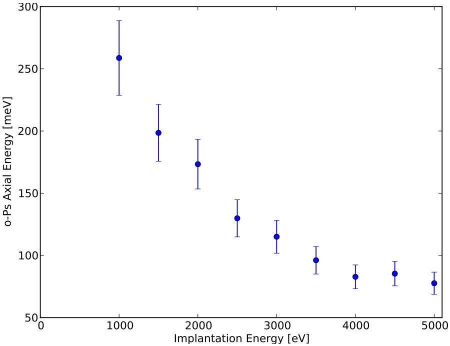
  - Fraction of o–Ps measured via Positronium Annihilation Lifetime Spectroscopy (PALS): ∼ 30 %, depends on positron implantation energy
  - o–Ps axial energy measured with Time-Of-Flight principle[5] (assuming isotropic emission total energy can be found) ⟶ implantation energy changes collision rate ⟶ signal modulation

Signal modulation S_{A-B}

Given o–Ps with different energies E_A and E_B, then:

$$S_{A-B} \sim \frac{N_{coll,A}}{N_{coll,B}} = \frac{v_A}{v_B} = \sqrt{\frac{E_A}{E_B}}$$



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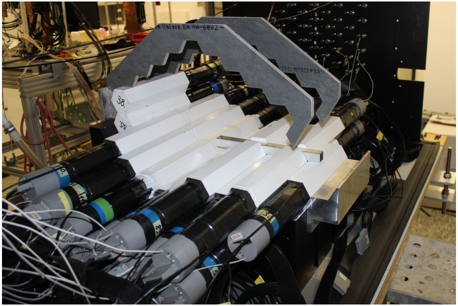
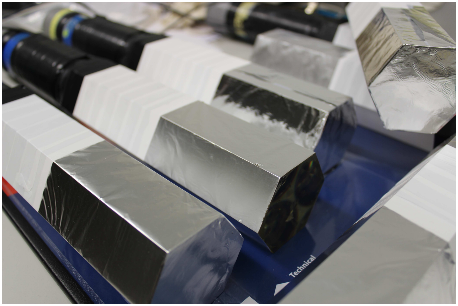
4π hermetic calorimeter: features

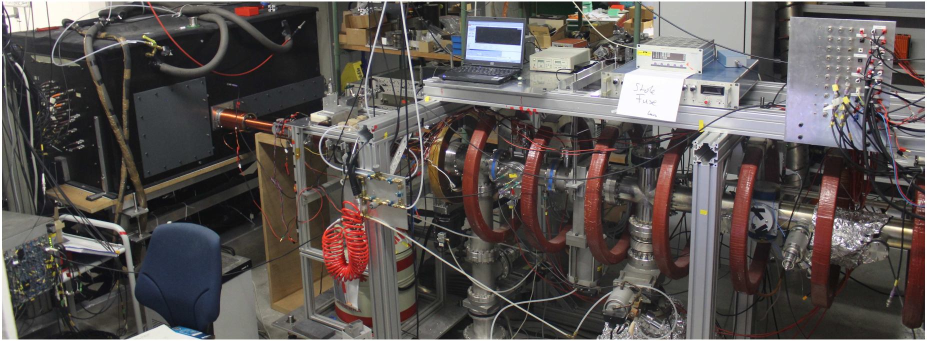
- About ~ 100 BGO scintillators in a honeycomb structure surrounding the o–Ps target. Inner crystals were refurbished with thinner wrapping to reduce dead material





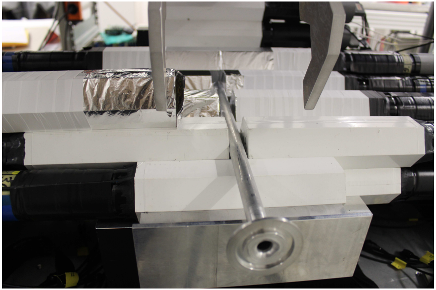
4π hermetic calorimeter: features

- About $\sim$ 100 BGO scintillators in a honeycomb structure surrounding the o–Ps target. Inner crystals were refurbished with thinner wrapping to reduce dead material
- PVC box to operate PMTs in complete darkness and keep temperature constant, providing signal and power feedthroughs and aperture for beam pipe



Construction of insertion pipe

- Last vacuum pipe to guide positrons into ECAL, form positronium and extract SE for tagging
- Small pipe diameter to maximize detector hermeticity
- Keep dead material to the minimum (e.g. pipe structure or coils)



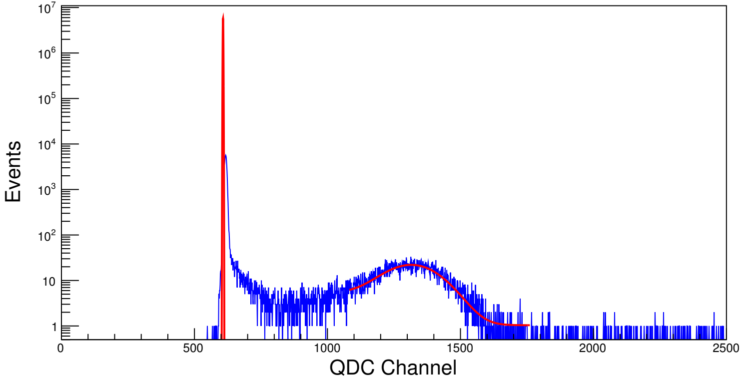
Preliminary tests with simple MCP tagging to check ECAL

Background dominated by fake triggers (i.e. MCP triggers uncorrelated with a positron): expected at a level of $\sim 10^{-3}$. Nevertheless data very useful to:

- Perform energy calibration of each individual BGO
- Estimate background and pile-up inefficiencies
- Monitor stability over long periods of time
- Cross-check data with Geant4 simulation

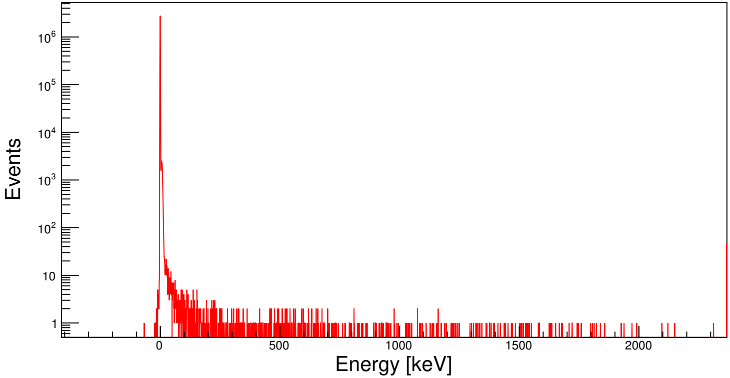
BGO Energy Calibration

- Internal BGOs can be self-calibrated with the data itself
- External BGOs are too shielded from the annihilation target and are calibrated with an external Na-22 source



Background measurements (pile-up, cosmic rays, noise. . .)

- Individual background spectra can be used to set different thresholds for each BGO



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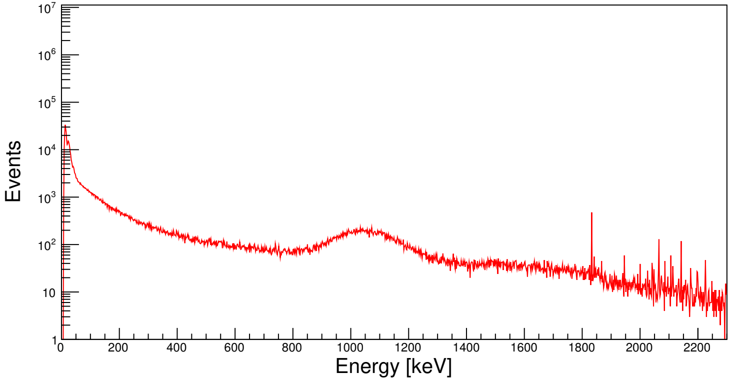
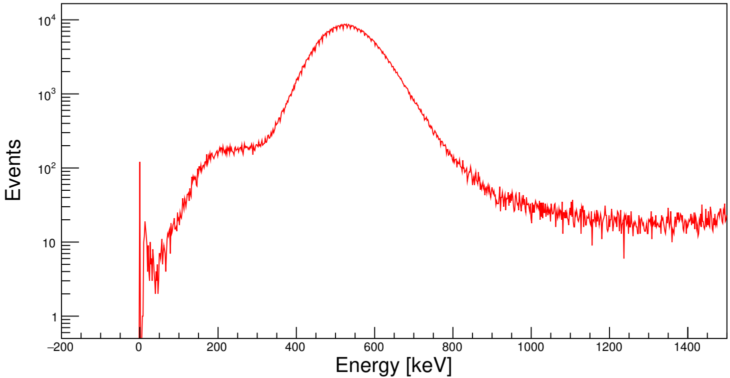
Background measurements (pile-up, cosmic rays, noise. . .)

- Individual background spectra can be used to set different thresholds for each BGO
- Complete background spectra to estimate pile-up inefficiency ($< 10\,\%$)



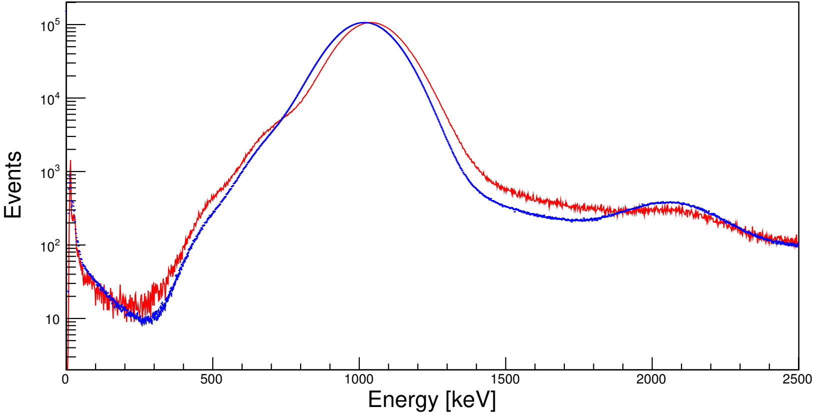
511 keV-photon escape probability

Checking that a 511 keV photon is detected in one BGO and then looking at the energy deposition in the rest of the ECAL, one can estimate the probability to lose one photon to be $\sim 10^{-4}$ (compatible with simulation and previous experiments)



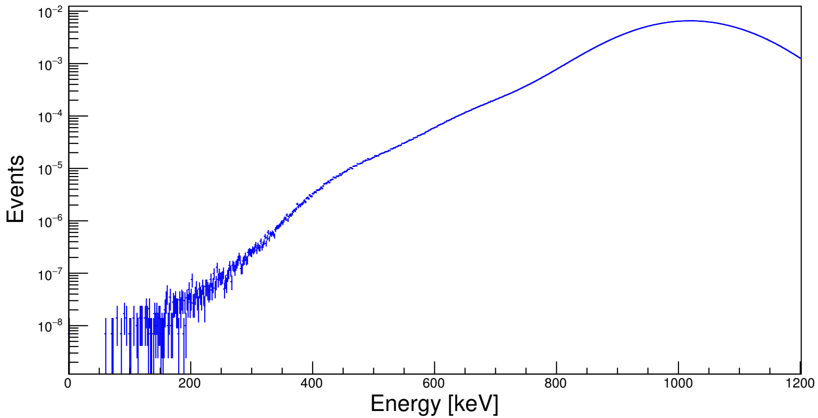
Preliminary data – simulation agreement

Very preliminary results with energy deposition in complete ECAL fairly agree with simulation
Large tails expected due to fake trigger completely non-suppressed (background sampling)



Preliminary data – simulation agreement

Simulation shows that reducing fake trigger, losses in the ECAL should be well below 10^{-7} and thus we should be able to reach the sensitivity $\epsilon \leq 4 \times 10^{-9}$



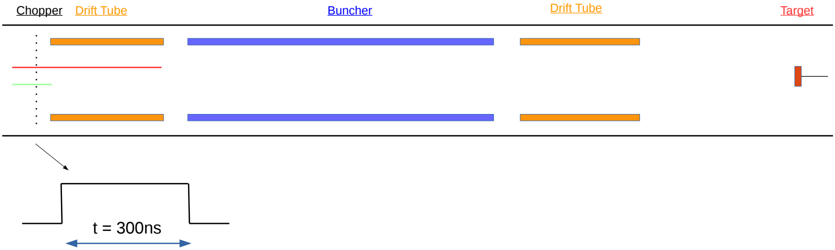
Reduce background from uncorrelated triggers with two strategies

- Implement positron bunching to compress beam

The positron buncher

A double-gap electrode where a time dependent potential is applied slows down early positrons and accelerates late ones

A compression from $\sim 300\,\text{ns}$ down to $\sim 2\,\text{ns}$ is possible (suppressing fake triggers by a factor 150)



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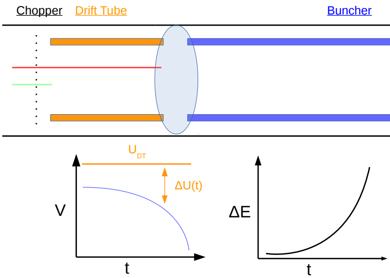

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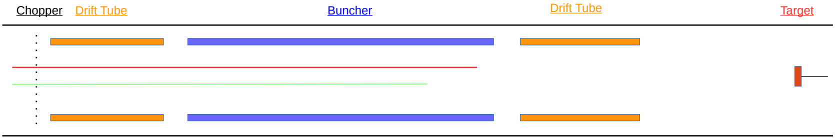

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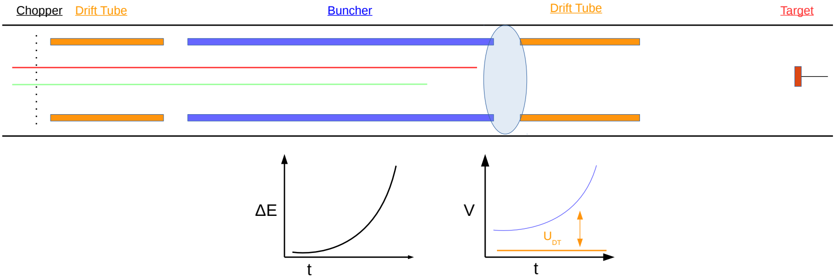

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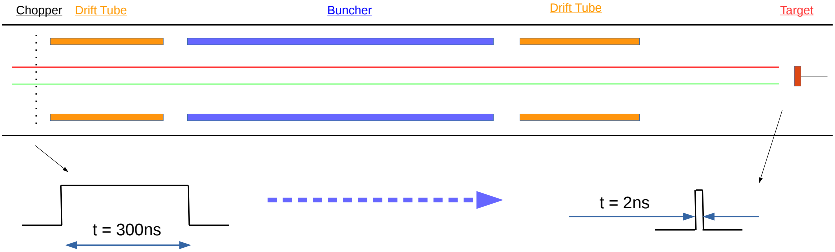
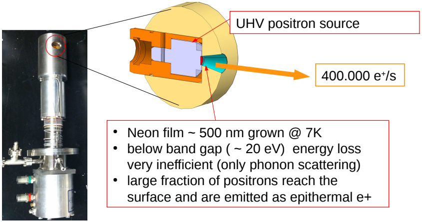


Reduce background from uncorrelated triggers with two strategies

- Implement positron bunching to compress beam
- Upgrade W moderator to deliver 20 times more positrons

A new solid Argon moderator

- Replace W moderator by a more efficient solid noble gas film
- Flux increase by factor 20 reduces both fake trigger and data taking time
- Design is ready, construction ongoing and installation planned in February 2017



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Where do we get?

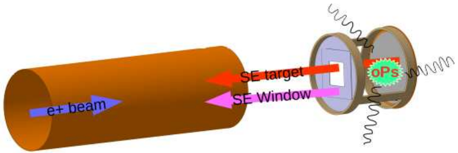
These two upgrades will reduce background from fake triggers below 10^{-6}
It will be possible to improve current limit on ϵ (1.55×10^{-7}) about one order of magnitude
To completely cover the ROI ($\epsilon \simeq 4 \times 10^{-9}$) more enhancements are necessary

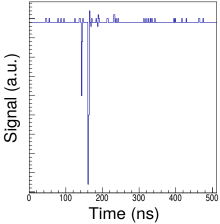
- Further reduce fake trigger by implementing a coincidence logic
- Refurbish target region to reduce dead material

Positronium confinement and coincidence requirement

A very thin (few nm) membrane is placed in front of the o–Ps formation target at a lower potential.

- Positrons are accelerated by the film and are able to go through it with $E \sim 2\,\text{keV}$ and then are further accelerated into the target
- Secondary electrons released in both the membrane and the target reach the MCP
- A time coincidence between the two signals can be required to suppress fake triggers more than 2 orders of magnitudes
- The membrane provides o–Ps confinement reducing its possibility to escape detection region
- Preliminary tests with 30 nm Si_3N_4 show excessive scattering. Thickness can be reduced to $\sim 10\,\text{nm}$ with carbon foils





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- Calorimeter refurbished, assembled and tested
- DAQ system fully operational

Conclusions

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Data Taking and Results

- Successful engineering runs for calibration and background monitoring
- Preliminary results with expected high background
- Two upgrades for the tagging system coming $\rightarrow$ improve by a factor 10 the current limit on ϵ by Feb. 2017

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Outlook

- Last upgrade for tagging system under design
- Complete coverage of interesting parameter space possible

Thank You!

Questions?