PADME project at DAΦNE BTF

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Dark Matter, Hadron Physics and Fusion Physics

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Positron Annihilation into Dark Matter Experiment
http://www.infn.infn.it/acceleratori/padme/
The simplest hidden sector model just introduces one \textbf{extra U(1) gauge symmetry} and a corresponding \textbf{gauge boson}: the “dark photon” or U boson.

Two type of interactions with SM particles should be considered.

As in QED, this will generate new interactions of the type:

\[ \mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu \]

Not all the SM particles need to be charged under this new symmetry.

In the \textbf{most general case} \( q_f \) is different in between leptons and quarks and can even be 0 for quarks. (P. Fayet, Phys. Lett. B 675, 267 (2009).)

The coupling constant and the charges can be generated effectively through the \textbf{kinetic mixing} between the QED and the new U(1) gauge bosons.

\[ \mathcal{L}_{\text{mix}} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{\mu\nu}^{\text{dark}} \]

In this \textbf{case} \( q_f \) is just proportional to electric charge and it is equal for both quarks and leptons.
U boson production and decays

- **U boson** can be produced in $e^+$ collision on target by:
  - Bremsstrahlung: $e^+A \rightarrow e^+AU$
  - Annihilation : $e^+e^- \rightarrow \gamma U$

If no dark matter candidate lighter than the U boson exist:

- $U \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ the so called “Visible” decays
- For $M_U < 210$ MeV $U$ only decay to $e^+e^-$ $BR(e^+e^-) = 1$

If any dark matter $\chi$ with $2M_\chi < M_U$ exist

- $U$ will dominantly decay into pure dark matter and $BR(l^+l^-)$ becomes small suppressed by $\epsilon^2$
- $U \rightarrow \chi\chi \sim 1$ so called “Invisible” decays”
Dark photon searches status

- Favored parameters values explaining g-2 (red band)
  - U-boson light 10-100 MeV

- Status of dark photon searches
  - Beam dump experiments (grey)
  - Fixed target
    - Peak search in BG
  - Mesons decays
    - Peaks in $M(e^+e^-)$ or $M(\mu^+\mu^-)$

- Indirect exclusion from $g_e - 2 \ g_\mu - 2$
  - Recent tight limit in blue filled area

- Many different techniques, assumptions on dark photon interaction models
Status $\varepsilon_q \neq 0$ and $U \rightarrow e^+e^-$

Valid for the next 1.30 hours see E. Goudzovski talk
Status $\epsilon_q = 0$ and $U \rightarrow e^+e^-$

Identical exclusion in case of $\epsilon_q = 0$ (still for 1.30 hours)
Status regardless $\varepsilon_q$ and U decays

\[ \sigma(3e^-) - (g-2)_B(3\gamma) \]

$\varepsilon$ vs $M_\mu$ (GeV/c^2)
**Why dark photon invisible decays?**

- In this scenario U boson keeps all the necessary characteristics to explain positron excess, g-2
- The invisible search technique remove any assumption except coupling to leptons
- U boson increase its capability of having escaped detection so far
- No data in the minimal assumptions

- At present there are no experimental limit for the $U \rightarrow$ invisible decay
  - Just a never published ArXiv 0808.0017 by Babar ‘08 with very limited sensitivity on $\varepsilon^2$ ($\Upsilon_{3S} \rightarrow \gamma U$ assumes coupling to quarks!)
  - Indirect limit from $K^+ \rightarrow \pi^+ \nu \nu$ (assumes coupling to quarks!) arXiv:1309.5084v1

- New approach by BDX with direct detection of dark matter (arXiv:1406.3028v1)
**DAΦNE Beam Test Facility (BTF)**

<table>
<thead>
<tr>
<th></th>
<th>electrons</th>
<th>positrons</th>
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<tbody>
<tr>
<td>Maximum energy [MeV]</td>
<td>750 MeV</td>
<td>550 MeV</td>
</tr>
<tr>
<td>Charge [nC]</td>
<td>5 nC</td>
<td>0.85 nC</td>
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<tr>
<td>Bunch length [ns]</td>
<td>1.5 - 40</td>
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<tr>
<td>Repetition rate</td>
<td>25/50 Hz</td>
<td>25/50 Hz</td>
</tr>
<tr>
<td>Typical emittance [mm mrad]</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Beam spot σ [mm]</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

- **Longer Duty Cycle**
  - **Standard BTF** duty cycle = 50*10 ns = $5 \times 10^{-7}$ s
  - Already obtained upgrade 50*40ns= $20 \times 10^{-7}$ s (Thanks to BTF team)
  - Any increase of duty cycle increase linearly experiment statistics

- **Possibility for single particle beam to** $10^{10}$
  - Packed in 50 bunch of ~10ns

- **The accessible $M_u$ region is limited by beam energy**
  - Region from 0-22 MeV can be explored with 550 MeV $e^+$ beam
Basic detector components

- Active 50\(\mu\)m diamond target
- \(10^3\)-\(10^4\) \(e^+\) on target per bunch at 50 bunch/s (\(10^{13}\)-\(10^{14}\) \(e^+/\text{year}\))
- GEM based magnetic spectrometer \(~1\text{m length}\)
- Conventional 0.6T magnet
- 15 cm radius cylindrical LYSO calorimeter with 1x1x15 cm\(^3\) crystals
Search in annihilation production

\[ e^- \quad \rightarrow \quad U \quad \rightarrow \quad e^+ \quad \gamma \]

*Annihilation*
Experimental technique

- Search for the process: $e^+e^- \rightarrow \gamma U$ on target $e^-$ at rest electrons
- $550$ MeV positron beam on a $50 \, \mu$m diamond target
- Measure in the ECal the $E_\gamma$ and $\theta_\gamma$ angle wrt to beam direction
- Compute the $M_{\text{miss}}^2 = (P_{e^-}^4 + P_{\text{beam}}^4 - P_{\gamma}^4)^2$
  - $P_{e^-}^4 = (0,0,0,m_e)$ and $P_{\text{beam}}^4 = (0,0,550,\sqrt{550^2 + m_e^2})$
Signal selection

Selection cuts (all decay modes)

- Only one cluster in EM calo
  - Rejects $e^+e^- \rightarrow \gamma\gamma$ final state

- $5 \text{ cm} < R_{\text{Cl}} < 13 \text{ cm}$
  - Improve shower containment

- Cluster energy within: $E_{\text{min}}(M_U) < E_{\text{Cl}} < 400 \text{ MeV}$
  - Removes low energy bremsstrahlung photons and pile up clusters

- Positron veto in the spectrometer
  - $E_{e^+} < 500 \text{ MeV}$ then $(E_{\text{beam}} - E_{e^+} - E_{\text{cl}}) > 50 \text{ MeV}$
  - Reject BG from bremsstrahlung identifying primary positrons

- Missing mass in the region: $M_{\text{miss}}^2 \pm \sigma M_{\text{miss}}^2$
BG sources are: $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \gamma\gamma\gamma$, $e^+N \rightarrow e^+N\gamma$, Pile up

Pile up contribution is important but rejected by the maximum cluster energy cut and $M_{Miss}^2$.

Veto inefficiency at high missing mass ($E(e^+) \approx E(e^+)_{beam}$)

- New Veto detector introduced to reject residual BG
- New sensitivity estimate ongoing
PADME sensitivity estimate

- Based on $1 \times 10^{11}$ fully GEANT4 simulated $e^+$ on target events

- Number of BG events is extrapolated to $4 \times 10^{13}$
  - Using $N(U\gamma) = \sigma(N_{BG})$
  - $\delta$ enhancement factor $\delta(M_U) = \sigma(U\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon = 1$

\[
\frac{\Gamma(e^+e^- \rightarrow U\gamma)}{\Gamma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} \times \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \varepsilon^2 \times \delta
\]
Search in bremsstrahlung production

Bremsstrahlung
Visible analysis strategy

- Search for the process: $e^+N \rightarrow Ne^+U \rightarrow Ne^+e^+e^-$
- 550 MeV positron beam on a 50 µm diamond target
- Measure in the spectrometer only the $P_{e^-}^4 + P_{e^+}^4$
- Compute the $M_U^2 = (P_{e^-}^4 + P_{e^+}^4)^2$
Ratio of bremsstrahlung wrt to annihilation at 1MeV ~ 400

Scaling low of the U-strahlung is $1/M_U^2$

Final state is more constrained by invariant mass of the $e^+e^-$ pair

Naively a limit down to $\sim \varepsilon < 4 \times 10^{-4}$ is expected at low masses
  - Only an indication no real simulation so far!
Early study for a beam dump experiment @ LNF (Sarah Andreas)

- 1E7 electrons of energy 750 MeV per bunch in 50 bunch/s over 1 year
- Total e\textsuperscript{-} on target being: 50*1\times10^7*3.15\times10^7 = 1.6\times10^{16}  (we use 1\times10^{16})
- Study based on 0 events observed after the dump. (not easy to achieve)
- Much better sensitivity can be achieved using a total 10^{20} e\textsuperscript{-} on target
- Further improvement by using longer decay region
<table>
<thead>
<tr>
<th>Experiment</th>
<th>target</th>
<th>$E_0$ [GeV]</th>
<th>$N_{el}$ electrons</th>
<th>Coulomb</th>
<th>$L_{sh}$ [m]</th>
<th>$L_{dec}$ [m]</th>
<th>$N_{obs}$</th>
<th>$N_{95%up}$</th>
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<tbody>
<tr>
<td>E141 [47]</td>
<td>W</td>
<td>9</td>
<td>$2 \times 10^{15}$</td>
<td>0.32 mC</td>
<td>0.12</td>
<td>35</td>
<td>1126</td>
<td>$^{+1312}_{-1126}$ 3419</td>
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<tr>
<td>E137 [48]</td>
<td>Al</td>
<td>20</td>
<td>$1.87 \times 10^{20}$</td>
<td>30 C</td>
<td>179</td>
<td>204</td>
<td>0</td>
<td>3</td>
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<td>E774 [49]</td>
<td>W</td>
<td>275</td>
<td>$5.2 \times 10^{9}$</td>
<td>0.83 nC</td>
<td>0.3</td>
<td>2</td>
<td>0$^{+9}_{-0}$ 18</td>
<td></td>
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<tr>
<td>KEK [39]</td>
<td>W</td>
<td>2.5</td>
<td>$1.69 \times 10^{17}$</td>
<td>27 mC</td>
<td>2.4</td>
<td>2.2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Orsay [40]</td>
<td>W</td>
<td>1.6</td>
<td>$2 \times 10^{16}$</td>
<td>3.2 mC</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>3</td>
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<td>PADME dump</td>
<td>W</td>
<td>0.8</td>
<td>$1 \cdot 10^{16}$</td>
<td>~1.6 mC</td>
<td>0.1</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PADME dump+</td>
<td>W</td>
<td>1.2</td>
<td>$2 \cdot 10^{20}$</td>
<td>~30 C</td>
<td>0.1-2</td>
<td>5-10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Due to authorization of LNF site we cannot exceed
  - Total limit on Year at BTF = $9.8 \times 10^{17}$ e$^-$/Year

- PADME dump+ (E upgrade, improved authorization)
  - BTF maximum current $1.2 \times 10^{11}$ e$^-$/bunch (40ns):
  - e$^-$/Year=$1.2 \times 10^{11} \times 50 \times 3.15 \times 10^7$=$1.9 \times 10^{20}$ e$^-$/Year
  - We can get $4.5 \times 10^{17}$ in 3 days at $3 \times 10^{10}$ e$^-$/bunch
Project status

- Project has been presented as a What Next Project in INFN CSN1
  - The project has received referees and its under study
  - Proposal for R&D financing will be discussed in the next CSN1 meeting

- Proto collaboration formed including
  - LNF, Rome1, Lecce and Sofia university

- Interesting synergy with BDX project identified (BDX at LNF?)

- 2 weeks test beam time planned in December at DAΦNE LINAC
  - Asses the maximum beam current per bunch and beam spot

- Many item still to be covered! Search for more collaborators started
Conclusions

- An experiment running at DAΦNE LINAC sensitive to both U→invisible and U→e⁺e⁻ decays is proposed.

- Sensitivity study for U boson produced into annihilation process e⁺e⁻ → γU was presented.
  - The detection through missing mass is independent of the U decay mode and never performed so far.

- Exclusion limit in ε² down to 1-2·10⁻⁶ can be achieved in invisible decays with the present BTF beam parameters in the region M_u 2-20 MeV.

- *M. Raggi and V. Kozhuharov, Advances in High Energy Physics Vol. 2014 ID 959802, 14 pages*

- Possible accessible regions for a bremsstrahlung produced U→e⁺e⁻ were identified to reach 100 MeV.
  - Detailed study of the sensitivity in this channel is planned.
  - Need theoretical guidance to implement a bremsstrahlung generator in the PADME GEANT MC.
Expected results for PADME are shown for annihilation production only. Accessible regions in the decays to lepton pairs are shown.

Many competitors in $e^+e^-$ decay scenario, APEX, HPS, MAMI A1.

Only VEPP3 proposal in the invisible searches (exclusion is a naïve estimate).
The PADME experiments can profit of any upgrade of the BTF beam

- Energy gives access to higher masses both in visible and invisible decays
- Duty cycle gives access to lower $\varepsilon^2$
- In case of Bremsstrahlung production duty cycle helps also in the mass ranges

Mauro Raggi & Venelin Kozhuharov - I.N.F.N. - LNF 27/09/14
Dark sector with dark Higgs

- Model assumes the existence of an elementary dark Higgs $h'$ boson, which spontaneously breaks the $U(1)$ symmetry.

  PRD 79, 115008 (2009)

- $U$ boson can be produced together with a dark Higgs $h'$ through a Higgs-strahlung $e^+e^-\rightarrow Uh'$
  
  - Cross section $=20 fb \times (\alpha/\alpha_D)(\varepsilon^2/10^{-4})(10 \text{GeV})^2/s$
  
  - For light $h'$ and $U$ ($M_{U,h'}<2M_W$) final state with 3($e^+e^-$ pair) are predicted
  
  - Background events with 6 leptons are very rare at this low energies
  
  - Due to $U,h'$being very narrow resonances strong kinematical constraints are available on lepton pair masses

- Experimental search by BaBar and KLOE for $U$ masses above 200 MeV
Production mechanism being bremsstrahlung allows PADME to reach >100 MeV U masses

No data available below 200 MeV in $M_U$

PADME can provide sensitivity in unexplored parameter region.
The $\gamma\gamma$ normalization selection

$$N_{\gamma\gamma}^{tot} = \frac{N_{\gamma\gamma}}{Acc_{\gamma\gamma}} = Flux(e^+) \cdot \sigma_{\gamma\gamma}$$

- Number of calorimeter clusters = 2
- Cluster energy: $100\text{MeV} < E_{cl} < 400\text{ MeV}$
- Cluster radial position $5\text{ cm} < R_{Cl} < 13\text{ cm}$
- $\gamma\gamma$ invariant mass $20\text{ MeV} < M_{\gamma\gamma} < 26\text{ MeV}$

- $Acc_{\gamma\gamma} = 7\%$
- Contamination from bremsstrahlung $< 1\%$

$$M_{\gamma\gamma} = \frac{\sqrt{[(X_{\gamma1} - X_{\gamma2}) + (Y_{\gamma1} - Y_{\gamma2})]E_{\gamma2}E_{\gamma2}}}{Z_{EMcal} - Z_{Target}}$$
Possible BTF upgrades

- Energy upgrades up to 1.2 GeV electrons
  - Proposal to reach >800 MeV energy for positrons (see V. Buonomo BTF user workshop)

- Longer Duty Cycle
  - **Standard BTF duty cycle = 50*10 ns = 5x10^{-7} s**
  - Already obtained upgrade 50*40ns= 20x10^{-7} s (Thanks to BTF team)
  - Any increase of duty cycle increase linearly experiment statistics

- Collimation system
  - Assure better beam definition for positrons beam

- Maximum current in BTF hall
  - Limited by radio protection to 6.2x10^8 per bunch for long term operation
  - Can reach >3x10^{10} particle per bunch after proper screening

See recent BTF user workshop for details at: https://agenda.infn.it/conferenceOtherViews.py?view=standard&confld=7359
Particle astrophysics PAMELA AMS

- Positron excess: PAMELA, FERMI, AMS02
- No significant excess in antiprotons
  - Consistent with pure secondary production
- Leptofilic dark matter annihilation?

Mauro Raggi & Venelin Kozhuharov - I.N.F.N. - LNF 27/09/14
If Dark Matter is the explanation to the positron excess, then the mediator should be light \((< 2M_{\text{proton}})\).

Coupling constant to DM could be arbitrary (even 0 (1)).

The Lagrangian term can arise through
- Fermions being charged (mili) under this new gauge symmetry \((q_f \to 0\) for some flavors)
- Kinetic mixing between ordinary photon and DM one
- Using simply an effective description

\[
\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu
\]
Muon g-2 SM discrepancy

About 3σ discrepancy between theory and experiment (3.6σ, if taking into account only $e^+e^-\rightarrow\text{hadrons}$)

Contribution to g-2 from dark photon

$$a_{\mu}^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F\left(\frac{m_V}{m_\mu}\right),$$

(17)

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2z] \, dz$. For values of $\varepsilon \sim 1-2 \cdot 10^{-3}$ and $m_V \sim 10-100\,\text{MeV}$, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark
The DAMA-Libra effect

- Nuclear recoil by the exchange of a dark photon
- Independent of $\chi$ mass value
Observation of 3.5KeV X-ray line

- Recently a 3.55 KeV X-ray line ($\sim 3\sigma$) has been reported in the stacks analysis of 73 galaxy clusters from the XMM-Newton telescope [arXiv:1402.2301v1]

- A similar analysis finds an evidence at the $4.4\sigma$ level for a 3.52 KeV line from the analysis of the X-ray spectrum of the Andromeda galaxy (M31) and the Perseus Cluster [arXiv:1402.4119]
Many models have been developed to explain such a line based on sterile neutrinos.

A possible explanation of such a line in terms of the U(1) gauge theory with an Higgs mechanism is proposed in arXiv:1404.2220v1.

- A single new scalar dark matter field $\phi$ of mass 7.1 KeV is introduced.
- $\phi$ couples to SM Higgs through U boson.
- Due to the very small mass $\phi$ can only decay into $\gamma\gamma$ or $\nu\nu$ creating the Xray line at 3.5 KeV.
- After spontaneous symmetry breaking of the U(1) symmetry the U boson becomes massive.
- Due to constraints coming from the relic abundance a mass interval has been identified by authors for the U boson mass:
  - $7\text{KeV} < M_U < 10\text{MeV}$
Indirect limits


\[ \alpha^{-1} = 137.035999037(91) \]

However this is based on a single measurement with drastically improved precision

2σ limit from new \( \alpha \),

*Phys Rev D 86, 095029 (2012)*

\[ |a_e^{th} - a_e^{exp}| = (1.06 \pm 0.82) \times 10^{-12} \]
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Extra assumptions</th>
<th>Results</th>
<th>Technique</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLOE2</td>
<td>$Q_q \neq 0$ &amp; $U \rightarrow e^+e^-$</td>
<td>YES</td>
<td>$\phi \rightarrow \eta e^+e^-$</td>
<td>Running</td>
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<td>KLOE2</td>
<td>$U \rightarrow \mu^+\mu^-$</td>
<td>Prel.</td>
<td>$e^+e^- \rightarrow \mu^+\mu^-\gamma$</td>
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<td>$e^-$ on target</td>
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<td>A1 (MAMI)</td>
<td>$U \rightarrow e^+e^-$</td>
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<td>WASA (cosy)</td>
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<td>$\pi^0 \rightarrow e^+e^-\gamma$</td>
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<td>DARK LIGHT</td>
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<td>Planned (2016?)</td>
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<td>VEPP3</td>
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<td>Proposal (2016?)</td>
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<tr>
<td>PADME</td>
<td>NONE</td>
<td></td>
<td>$e^+$ on target</td>
<td>Proposal (2016?)</td>
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</table>
Beam conditions

- In the present study we assume that the BTF will be able to deliver:
  - 1E4 positrons of energy 550 MeV per bunch in 50 bunch/s over 1 year
  - Total \( e^+ \) on target being: \( 50 \times 1E4 \times 3.15E7 = 1.6E13 \) (we use 1E13)
  - Beam energy spread \( \sim 1\% \) (BTF can do much better)
  - RMS of beam position 2mm and emittance 1mm*mrad
  - Bunch duration 10 ns (can already go up to 40ns)

**Beam Profile 486MeV**

**Integated beam spot**

**Measurement of the beam spread**

**Medipix detectors**

**FWHM 2.4 \times 1.8 mm**

**Single bunch beam spot**

**Beam E spread**

Missing mass resolution in agreement with toy MC using

\[ \sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\% \] [NIM A 718 (2013) 107–109]

Differences are ~ 10%

Resolution is the result of combination of angular resolution energy resolution and angle energy correlation due to production
PADME active target

- Diamond 50\(\mu\)m thick target
  - Most probably strip detector
- Active area 2x2cm\(^2\)
- Position resolution \(~2\)mm in both X and Y
- Sensitive from few particle to \(10^9\) particle
- Real time beam imaging
- Time resolution below 1ns
- Readout with QDC.

- R&D can start from CIVIDECL Diamond mosaic detector

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**Features:**

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<th>Feature</th>
<th>Value</th>
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<td>Active area</td>
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<tr>
<td>Energy resolution</td>
<td>35 keV FWHM</td>
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<td>Particle rate</td>
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**Detector:**

<table>
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<tr>
<th>Type</th>
<th>sCVD Diamond Mosaic-Detector</th>
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<tbody>
<tr>
<td>Diamond substrates</td>
<td>4.5 mm x 4.5 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>140 (\mu)m</td>
</tr>
<tr>
<td>Electrode structure</td>
<td>3x3 mosaic structure</td>
</tr>
<tr>
<td>Metallization</td>
<td>Au electrodes</td>
</tr>
</tbody>
</table>
- Conventional magnet with B=0.6 Tesla

- Generic cylindrical chamber filled with gas
  - Inner radius 20 cm outer radius 25 cm length 100 cm
  - 5 cylindrical layers of 1 cm each

- Expected to measure track crossing position with 300 µm resolution

- Used in the experiment to veto positron and to reconstruct mass of lepton pairs.
The electromagnetic calorimeter

- **Cylindrical shape:** radius 15 cm, depth of 15-20 cm
  - Inner hole 4 cm radius
  - Active volume 9840 cm\(^3\) total of 656 crystals 1x1x15-20 cm\(^3\)

- **Material LSO(Ce):** high LY, high \(\rho\), small \(X_0\) and \(R_M\), short \(\tau_{\text{decay}}\)

- **Expected performance:**
  - \(\sigma(E)/E = 1.1%/\sqrt{E} \pm 0.4%/E \pm 1.2\%\) superB calorimeter test at BTF [NIM A 718 (2013) 107–109]
  - \(\sigma(\theta) = 3\) mm/1.75 m < 2 mrad
  - Angular acceptance 1.5-5 degrees