GEANT4-based full simulation of the PADME experiment at the DAΦNE BTF

Emanuele Leonardi$^1$, Venelin Kozhuharov$^2$, Mauro Raggi$^{1,3}$, Paolo Valente$^1$

$^1$INFN Roma, $^2$University of Sofia, $^3$Sapienza University of Rome
The Dark Matter problem

The Standard Model only includes <20% of the matter in the universe. From cosmological measurements we know that visible matter only accounts for a small part of the observed gravitational effects.

Can some kind of "Dark Matter" provide the missing contribution?

Galaxy rotation curve

Many open questions:
- What is Dark Matter made of?
- How does DM interact with SM particles?
- Do one or more new Dark Forces exist?
- How complex is the Dark Sector spectrum?
- …
The simplest Dark Sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the “dark photon” or $A'$

Two possible modes of interaction with the SM

- Direct coupling to fermions
- Mixing with the QED gauge boson

In $e^+$ collisions on target, $A'$ can be produced by:
- Bremsstrahlung
- Annihilation
- Meson decay

If no dark matter particles lighter than $A'$ exist, $A'$ can only decay into SM particles.

If any dark matter particle $\chi$ has $2M_\chi < M_{A'}$, then SM decays are strongly suppressed.
The PADME experiment

• PADME (Positron Annihilation into Dark Mediator Experiment) will look for invisible $A'$ production in the annihilation channel $e^+e^-\rightarrow A'\gamma$

• A 550 MeV $e^+$ beam from the DAΦNE Beam Test Facility (BTF) will interact with the (at rest) $e^-$ of a thin (100μm) diamond target.

• An electromagnetic calorimeter will measure the energy $E_{\gamma}$ and angle $\theta_{\gamma}$ of the recoil photon.

• Evaluate the (invisible) $A'$ mass from $M_{A'}^2 = (p_{e^-} + p_{\text{beam}} - p_{\gamma})^2$

• Goal: collect $O(10^{13})$ $e^+$ in 2018-2019
The PADME detector

Dipole MBP-S from the CERN SPS transfer line

Thin active diamond target 100 μm

Positron veto
1 cm scintillators with SiPM readout

Electron veto
1 cm scintillators with SiPM readout

EM Calorimeter
21×21×230mm³ BGO crystals with PMT readout

Small Angle Calorimeter
20×20×200mm³ PbGl with PMT readout

High Energy Position veto with SiPM readout

Positron beam

γ

A'
The diamond target

• Diamond (Z=6) is the rigid material with the best $ee(\gamma\gamma)/\text{bremsstrahlung}$ ratio

• Measure charge and position of the beam
  • $O(10^4) \ e^+/\text{bunch} @ 50 \ Hz$
  • <1mm spatial resolution
  • <10% charge measurement

• $20\times20\text{mm}^2$ polycrystalline diamond with 50-100µm thickness.

• 19 readout strips per side (X/Y readout) with 1mm pitch.

• Strips are graphitized with laser to avoid metallization.

• First prototypes for PADME tested in October 2015 and April 2016.
The electromagnetic calorimeter

- 616 BGO crystals
  - Recovered from one EM end-cap of the L3 experiment
  - Reshaped to $21 \times 21 \times 230 \text{mm}^3$

- BGO: high LY, high $\rho$, small $X_0$ and MR, long $\tau_{\text{decay}}$

- Calorimeter with a cylindrical shape (R~300mm)
  - Inner hole (~$10 \times 10 \text{cm}^2$) to avoid bremsstrahlung pile-up
  - Angular acceptance: 20-75 mrad
  - Ø 19mm PMT readout

- Expected performances:
  - $\sigma(E)/E < 2\%/\sqrt{E}$
  - $\sigma(\theta) < 2$ mrad

A 5x5 crystals prototype was tested at BTF in July 2016
The Small Angle Calorimeter

- The bremsstrahlung rate along the beam axis is too high for BGO.
  - Cut a $\sim 10 \times 10 \text{cm}^2$ hole in EM calorimeter.
  - Add a fast Small Angle Calorimeter behind it.
  - Must tolerate a rate of $\sim 10$ clusters in 40ns.
- A good (i.e. fast and cheap) solution is represented by a Cherenkov radiator with fast PMT readout.
- Use 49 lead-glass blocs cut to $20 \times 20 \times 200 \text{mm}^3$ size.
  - Recovered from the Opal EM calorimeter, courtesy of NA62.
The charged particles veto system

- The PADME veto system will detect charged particles to reduce background from bremsstrahlung and Bhabha scattering.
- 3 detectors: electrons, low energy positrons, high energy positrons
- Use extruded plastic scintillator fingers
  - $10 \times 10 \times 184 \text{mm}^3$
  - SiPM readout
  - Time resolution $< 300 \text{ ps}$
  - Momentum resolution $O(\text{few\%})$ based on impact position along $Z$.
  - Efficiency better than 99.5\% for MIPs.

These sections are inside the magnetic field region.
GEANT4 simulation

• A GEANT4-based simulation of the full experiment was available since the early stages of the project (2014).

• It closely followed the evolution of the design and the technical choices of the collaboration.

• Used to verify the effects of proposed solutions on the recoil mass measurement resolution and to optimize construction parameters.
PADME MonteCarlo

- Realistic simulation of BTF beam
  - Bunch length, energy spread, emittance, beam spot, micro-bunching
  - All beam parameters are controlled via datacards

- Kinematics
  - $e^+$ on target simulated by GEANT4
  - Dedicated $A'$ annihilation generator
  - Dedicated $e^+ e^- \rightarrow \gamma \gamma (\gamma)$ generator (CalcHEP)

- Realistic magnetic field map
  - Original field map from CERN
  - Re-measured at INFN-LNF
  - Tunable via datacards

- A fast simulation is available
  - Switch off beam dump simulation
  - Switch off e.m. showers in the SAC

$\text{beam/momentum} \ 550. \text{ MeV}$
$\text{beam/n_e_per_bunch} \ 5000$
$\text{beam/bunch_time_length} \ 40. \text{ ns}$
$\text{beam/position_x} \ 0. \text{ cm}$
$\text{beam/position_y} \ 0. \text{ cm}$
$\text{beam/position_x_spread} \ 1. \text{ mm}$
$\text{beam/position_y_spread} \ 1. \text{ mm}$
$\text{beam/direction} \ 0. \ 0. \ 1.$
Detector simulation

• All active detector parts are fully modeled and simulated
  • Diamond target
  • Vetoes scintillator fingers
  • ECAL BGO crystals
  • SAC lead-glass blocs

• Passive structures being added as they are defined
  • Magnet yoke and coils
  • Vacuum chamber
  • Target support and control structure
  • Vetoes support structures

• All relevant construction parameters are modifiable via datacards
  • Relative position of detectors
  • Size of target, BGO crystals, SAC blocs, veto fingers
  • Gap between BGO crystals

/Injector/ECal/CrystalSize 2.1
/Injector/ECal/CrystalLength 23.
/Injector/ECal/CrystalGap 0.1
/Injector/ECal/FrontFaceZ 230.
/Injector/Target/Size 2.
/Injector/Target/Thickness 100.
/Injector/Target/FrontFaceZ -50.
Detector studies with MC

- Study of EM calorimeter energy collection and resolution.
- Comparison with testbeam results to optimize digitization parameters.
  - ~200 photo-electrons per MeV
  - Zero-suppression if energy in crystal < 2 MeV
  - Cell-to-cell intercalibration errors ~10%
  - Residual difference due to beam energy resolution not included in MC.
A' mass measurement resolution

- Use MC to evaluate resolution on missing mass ($M_{\text{miss}}$) measurement as a function of $M_{A'}$.

- Candidate selection:
  - 1 cluster in ECAL
  - $E_{\text{min}}(M_{A'}) < E_{\text{cluster}} < E_{\text{max}}(M_{A'})$
  - 30 mrad < $\theta_{\text{cluster}}$ < 65 mrad
  - No in-time (± 2 ns) charged tracks in the veto system
  - No in-time (± 2 ns) $\gamma$ with $E\gamma > 50$ MeV in SAC
  - Invariant missing mass in $M_{A'}^2 \pm \sigma(M_{\text{miss}}^2)$

- Use MC to evaluate backgrounds.
Conclusions

• PADME will search for the Dark Photon with mass up to 24 MeV in the $e^+e^-\rightarrow A'\gamma$ channel using the DAΦNE Beam Test Facility at INFN-LNF.

• Data taking will start in 2018 and will collect $10^{13}$ e$^+$ on target in 2 years.

• A full GEANT4-based simulation of the experiment has been available since the first phase of the project (2014).

• All relevant parameters of the detectors and of the beam can be controlled via datacards.

• The simulation is being used to validate and optimize the technical design of the experiment.
Spare slides
PADME Main Backgrounds

- **Signal** $e^+e^- \rightarrow \gamma A'$
  - $M_{\text{miss}} = M_{A'}$

- **BG SM annih.** $e^+e^- \rightarrow \gamma\gamma(\gamma)$
  - 1 lost $\gamma$

- **BG SM Brems.** $e^+N \rightarrow e^+N\gamma$
  - 1 lost $e^+$
PADME Sensitivity

- Based on $2.5 \times 10^{10}$ 550MeV $e^+$ on target events simulated with GEANT4.
- Extrapolated to $10^{13} e^+$ on target, i.e. 2 years of data taking at 50% efficiency with a 40ns bunch length.
- Limit set at $N(A'\gamma) = \sqrt{N_{bg}}$
- Maximum $M_{A'}$ from $M_{A'}^2 = 2m_eE_{\text{beam}}$
  - $E_{\text{beam}} = 550\text{MeV} \rightarrow M_{A'} < 23.7\text{MeV/c}^2$
  - $E_{\text{beam}} = 1\text{GeV} \rightarrow M_{A'} < 32\text{MeV/c}^2$