The *PADME* experiment at DAFNE LINAC

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The dark matter problem

Several hypothesized solutions

Deep roots in strong empirical observations

Particle physics

Astrophysics

Particle physics is not the only possible solution

However...

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Portals to a hidden sector

A new, very weak interaction, connecting the ordinary matter with a (almost) hidden sector (by the smallness of the coupling constant, not by the mass scale)

Standard Model

SU(3) × SU(2) × U(1)

“portal”

Dark Sector

Not so many possibilities:

- **vector**
  \[
  \frac{1}{2} \varepsilon F_{\mu\nu}^{\gamma} f^\gamma_{\mu\nu}
  \]

- **Higgs**
  \[
  \epsilon_h |h|^2 |\phi|^2
  \]

- **neutrino**
  \[
  \epsilon_\nu (hL) \psi
  \]

- **axion**
  \[
  \frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}
  \]

- **dark photon**
  \[
  \frac{1}{2} \varepsilon F_{\mu\nu}^{\gamma} f^\gamma_{\mu\nu}
  \]

- **dark scalar**
  \[
  \epsilon_h |h|^2 |\phi|^2
  \]

- **sterile neutrino**
  \[
  \epsilon_\nu (hL) \psi
  \]

- **ALPs**
  \[
  \frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}
  \]
Dark photon

- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the “dark photon" or U-boson or heavy photon (\(\gamma'\) or \(A'\))
- An extra U(1) symmetry is implied in many extensions of the SM, some classes of string theory, etc.
- Appealing explanation of the muon g-2 discrepancy in the 1 MeV – 1 GeV mass range

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Dark photon decays: “visible”

- Assume that no additional lighter state exists in the dark sector with $m_\chi < m_{A^{'}}/2$
- $A'$ couples to SM particles through kinetic mixing only (with universal coupling $\epsilon q$)
- For $m_{A^{'}} < 2 m_\mu$ only decays to $e^+e^-$

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Dark photon decays: “invisible”

- If at least one $\chi$ state exists in the dark sector with $U(1)$ charge $q_U$ and coupling constant $g_U$ and $m_\chi < m_{A'}/2$, the coupling to the $A'$ will be: $q_U g_U$
- $A' \rightarrow \chi \chi$ will be dominant wrt to the visible decays for $\alpha_D > \alpha$, i.e. for $|q_U g_U| > \varepsilon e$
In any electromagnetic interaction, just replace one $\gamma$ with $A'$, replacing $\alpha$ with $\varepsilon^2\alpha$.
We have to add experiments using meson decays: $\eta, \pi^0 \rightarrow \gamma A'$ with dark photon "visibile" decay;

Or $A'$ coming from dark Higgs decays

Thin target, visible decays
(APEX, HPS, A1)

Dump, visible decays
(E-137, E-141, E-774, Orsay, ...)

Dump, invisible decays, recoil
(BDX)
Decay to visible states ($e^+e^-$)

- Bremsstrahlung on thick target (dump experiments)
  - Requires the dark photon to decay beyond the dump
- Bremsstrahlung on thin target
  - Look for $e^+e^-$ excess over Standard Model background (bump hunt, displaced vertices)
  - Requires $m_{A'} > 2m_e$
- Meson decays (collider experiment)
  - Requires coupling to quarks

Practically, all the $(g-2)_\mu$ favored band already excluded
Still large interest for excluding the uncovered parameter space
Decay to invisible states

- Direct searches for $A'$ invisible decays only depend on $\varepsilon^2$ and $m_{A'}$.
- No assumptions on coupling to quarks (Both $Y_{3S}$ and $K^\pm$ results rely on that)

- $\chi$ scattering (indirect) searches instead depend on 4 parameters: $\varepsilon^2, m_{A'},$ and $m_{\chi}, \alpha_D$
Missing mass approach

Look for \textbf{one photon} + nothing else in positron on target electrons annihilations

\[ e^+e^- \rightarrow \gamma (E_{\text{miss}}) \]

- Know \( e^+ \) beam \textbf{momentum and position}
  - Tunable intensity (in order to optimize annihilation vs. pile-up)
- Measure the recoil photon \textbf{position and energy}
- Calculate \( M^2_{\text{miss}} = (\mathbf{p}_{e^+} + \mathbf{p}_{e^-} - \mathbf{p}_\gamma)^2 \)
  - Only minimal assumption: \( A' \) couples to leptons
  - \textbf{PADME} will limit the coupling of \textbf{any new light particle} produced in \( e^+e^- \) annihilations: scalars (\( h' \)), vectors (\( A' \)) or pseudoscalars (ALPs)

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Signal and background

Dark photon event

We need to fight the backgrounds: one photon + something else, typically one or more photons going undetected.

Bremsstrahlung

\( \gamma \gamma (\gamma) \)
Of course, also visible decays can be searched for

Present **PADME** detector has been optimized for the *invisible* search

However, we foresee scintillator detectors both on the “electron” and “positron” side of the analyzing magnet to allow detection of decays to $\ell^+\ell^-$ pairs

$$e^+e^- \rightarrow \gamma A'$$
$$A' \rightarrow e^+e^-$$

**Annihilation, visible decays**
The beam test facility

530/730 MeV $e^+/e^-$ from the DAFNE LINAC

To the DAFNE collider main rings

BTF

10 m

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BTF positron beam

- Energy spread $\Delta p/p \sim 1\%$
- Beam spot: <1 mm RMS
- Divergence: 1 – 1.5 mrad
- Beam position: 0.25 mm RMS
- Pulse duration: 1.5 – 40 ns
  - 10 ns during collider operations
- Two intensity ranges (with and without attenuation target)
  - PADME will be limited by the pile-up anyhow

Beam spot after Be window

<table>
<thead>
<tr>
<th>Parasitic mode</th>
<th>Dedicated mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>With target</td>
<td>With target</td>
</tr>
<tr>
<td>Without target</td>
<td>Without target</td>
</tr>
<tr>
<td>Particle species</td>
<td>e$^+$ or e$^-$ Selectable by user</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>25–500</td>
</tr>
<tr>
<td>Energy spread</td>
<td>1% at 500 MeV</td>
</tr>
<tr>
<td>Rep. rate (Hz)</td>
<td>Variable between 10 and 49</td>
</tr>
<tr>
<td>Pulse duration (ns)</td>
<td>10</td>
</tr>
<tr>
<td>Intensity (particles/bunch)</td>
<td>$1\times10^5$ Depending on the energy</td>
</tr>
<tr>
<td>Max. average flux</td>
<td>$3.125\times10^{10}$ particles/s</td>
</tr>
<tr>
<td>Spot size (mm)</td>
<td>0.5–25 (y) x 0.6–55 (x)</td>
</tr>
<tr>
<td>Divergence (mrad)</td>
<td>1–1.5</td>
</tr>
</tbody>
</table>

Beam parameters

See poster on Saturday:

The Frascati LINAC beam facility performance and upgrades

Speaker: Paolo Valente (Università e INFN, Ro.)

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Thin, segmented, full Carbon target

Monitor beam **intensity** and **spot** position/size

- 20×20×0.050 mm³ sensor
- 1 mm pitch x-y **graphitic strips** produced by UV laser
- Moveable inside vacuum

Beam position scan
Sweeping/analysing magnet

- MBP-S series, **on loan from CERN**
  - Many thanks to TE-MSC-MNC, R. Lopez, D. Tommasini
- Poles: 100 cm length, 52 cm width
- Variable gap 11 to 20 cm, **further extended to 23 cm**
- Detailed field mapping
  - Good B field quality
  - **Fringe field** not negligible, even outside the coils, relevant for the precise beam steering onto the active target
Measuring the recoil photon

Our main detector is of course a calorimeter, with two basic requirements:

1. Measure $E_\gamma$ and $\theta_\gamma$
   - Good energy resolution: 1-2%/√E[GeV])
   - High Photo-statistics
   - Containment
   - Good angular resolution: ≈1 mrad

2. Fight pile-up
   - Sub-ns timing resolution

Moreover:
- The material choice fixes the Molière radius determines granularity
- The granularity + required angular resolution, set the distance from the target
- Given the distance, the lateral size fixes the angular coverage (i.e. acceptance)
- The material choice also fixes the light yield, time resolution, and $X_0$

Moreover:
- The overall size of the experiment is limited by the hall length (<5 m)
- Cost, complexity, time schedule, man-power

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Crystal choice

Small Molière radius and high light yield: BGO and LYSO

- **BGO**: high LY, high $\rho$, small $X_0$ and small $R_M$, long $\tau_{\text{decay}}$
  - $\sigma(E)/E$ in 1-2%/\sqrt{E} range
- **LYSO(Ce)**: high LY, high $\rho$, small $X_0$ and small $R_M$, short $\tau_{\text{decay}}$
  - $\sigma(E)/E = 1.1%/\sqrt{E} \oplus 0.4%/E \oplus 1.2%$

**Granularity $\approx R_M \rightarrow 2$ cm**

- $\sigma_{\text{point}} = 6$ mm $\rightarrow 2$ mrad at 3 m distance (too much!)

But we have clusters:

- Center of gravity should have a better resolution
- Most of the energy will be in a single crystal, pulling the cog towards the center of the most energetic one)

LYSO would be faster and with higher light yield but...
L3 BGO crystals

- BGO crystals available from the electromagnetic calorimeter of the former L3 experiment at LEP
- Reshape to square section $21 \times 21$ mm$^2$, 220 mm long
Beam tests

- First tests of diamond target and of 5×5 crystals matrix
- DAQ based on 1 GS/s digitizer (DRS-4)

2.3%/√E already achieved without inter-calibration

HZC and Hamamatsu PMT’s under test

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Small angle calorimeter/Positron veto

- BGO calorimeter cannot tolerate the Bremsstrahlung rate in the very central crystals
  - Inner hole 5×5 crystals
  - Small angle calorimeter: sustain a rate of $O(10)$ clusters (40 ns pulses)
  - The only fast enough inorganic crystal is $\text{BaF}_2$ with a fast PMT readout
  - A possible alternative: Cherenkov detector

- Scintillating bars for detecting irradiating positrons in the magnetic field region (low energy $e^+$) and close to beam path (high energy $e^+$)
PADME experiment in summary

- 10^3-10^4 e^+ on target per bunch, at 50 bunches/s (10^{13}-10^{14} e^+/year), limited by pile-up, mainly due to Bremsstrahlung events

- Positron annihilations on target: thin and active (50-100 μm) diamond with graphite strips

- Magnetic spectrometer ~ 1m length × 0.5 T for sweeping away the 550 MeV beam
  - Conventional magnet with large gap for gaining acceptance
  - Possibility to increase field for LINAC upgrade to ~ 1 GeV

- Positron veto (from Bremsstrahlung events)
- Cylindrical crystal calorimeter
- Optimized radius vs. distance by looking at the background rejection vs. acceptance
  - In order to have an acceptable rate, central hole
- Small angle detector for Bremsstrahlung veto
- Vacuum decay volume
- Positron veto detectors
- Compute missing mass from the momenta of the incoming positron and of the recoil photon

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Signal vs. background

Simple cuts:
- 1 cluster in fiducial region (angle and momentum)
- no hit in positron veto in ±2ns
- <50 MeV in small angle
- 2-σ missing mass cut

Pile up

$e^+e^+ \rightarrow \gamma\gamma(\gamma)$
$e^+N \rightarrow e^+N\gamma$

Signal acceptance
Residual background

Bremsstrahlung

A high-resolution imaging veto could help rejecting $E=E_{\text{beam}}$ events

3 photons decay

$\gamma\gamma$ events can be cleanly selected for measuring the beam flux, in addition to the diamond

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PADME sensitivity

Based on $2.5 \times 10^{10}$ fully GEANT4 simulated 550 MeV $e^+$ on target events

- Number of background events is extrapolated to $1 \times 10^{13}$ electrons on target
- Room for improvement by looking at the **single event sensitivity** (zero-background)

**PADME $10^{13}$ EOT**

- Bunch length of 40 ns:
  
  $5000$ $e^+/bunch \times 2 \cdot 10^7$ s $\times 49$ Hz

Lengthening the beam pulse would **LINEARLY**:

- Either **reduce** the run time for reaching $10^{13}$ EOT
- Or **increase the sensitivity** for the same running time of $2 \cdot 10^7$ s

$E_{e^+} = 550$ MeV: $M_{A'} < 23.7$ MeV/c$^2$

$E_{e^+} = 1$ GeV: $M_{A'} < 32$ MeV/c$^2$
ALPs at PADME

PADME can search for **invisible** decaying or long-lived ALPs looking at $1\gamma + M_{\text{miss}}^2$ final states

In the **visible** final state $a \rightarrow \gamma\gamma$ all production mechanisms can be explored, extending the mass range in the region of $\sim 100$MeV

The observables at PADME will be: $e\gamma\gamma$ or $\gamma\gamma\gamma$
Dark Higgs production at PADME

\[ e^+ + e^- \rightarrow A'h', \text{ with } h' \rightarrow A'A', \]

Depending on dark Higgs and dark photon masses:

**a)** \( 2M_{A'} < M_{h'} \)
Dominant \( A'h' \rightarrow A'A'A' \rightarrow 6 \) leptons

**b)** \( 2M_{A'} > M_{h'} \)
Dominant \( A'h' \rightarrow A' \) Invisible \( \rightarrow 2 \) leptons

In PADME just count the number of events with:

- 6 leptons in time
- With zero total charge
- And sum of the momenta \( < E_{\text{beam}} \)

No data below \( m_{A'} = 250 \) MeV
Outlook

- **PADME** detector construction fully funded by INFN
- Aim at a first **physics run in 2018**, immediately after the KLOE-2 run
- Construction schedule tight but still respected
  - Mainly dominated by BGO calorimeter construction
  - Well advanced R&D activities on diamond thin target
  - Finalizing the design for vacuum vessel, positron veto, small angle calorimeter

Even though the sensitivity we have estimated is for the **presently available beam** parameters and energy, there is still **room for improvement**:

- **Beam**:
  - New gun pulser installation due in September for **extending the beam pulse** from 40 ns to hopefully 100-150 ns (linear increase of sensitivity)
  - **LINAC consolidation** and **energy upgrade** proposed (increase \(A'\) mass accessible range)
  - **BTF beam-line splitting** (increase the availability of the beam, i.e. the data-taking efficiency)

- **Detector**:
  - PADME is being designed in order to be capable of searching also **visible decays** of the dark photon
  - And also to replace the target with a thicker one in order to perform a “classical” **dump experiment**
PADME is looking forward to new jedi

http://www.lnf.infn.it/acceleratori/padme
The Frascati LINAC

**LINAC parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam final energy</td>
<td>800 MeV</td>
<td>510 MeV (750)</td>
</tr>
<tr>
<td>Positron beam final energy</td>
<td>550 MeV</td>
<td>510 MeV (550)</td>
</tr>
<tr>
<td>RF frequency</td>
<td>2856 MHz</td>
<td></td>
</tr>
<tr>
<td>Positron conversion energy</td>
<td>250 MeV</td>
<td>220 MeV</td>
</tr>
<tr>
<td>Beam pulse rep. rate</td>
<td>1 to 50 Hz</td>
<td>1 to 50 Hz</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>10 nsec</td>
<td>1.4 to 40 nsec</td>
</tr>
<tr>
<td>Gun current</td>
<td>8 A</td>
<td>8 A</td>
</tr>
<tr>
<td>Beam spot at converter</td>
<td>1 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Normalized Emittance (mm mrad)</td>
<td>1 (electron)</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td></td>
<td>10 (positron)</td>
<td></td>
</tr>
<tr>
<td>rms Energy spread</td>
<td>0.5% (electron)</td>
<td>0.5% (electron)</td>
</tr>
<tr>
<td></td>
<td>1.0% (positron)</td>
<td>1.0% (positron)</td>
</tr>
<tr>
<td>electron current on converter</td>
<td>5 A</td>
<td>5.2 A</td>
</tr>
<tr>
<td>Max. electron current (10 ns)</td>
<td>&gt;150 mA</td>
<td>200 mA</td>
</tr>
<tr>
<td>Max. positron current (10 ns)</td>
<td>36 mA</td>
<td>85 mA</td>
</tr>
<tr>
<td>Trasport efficiency</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Accelerating structure</td>
<td>SLAC-type, CG, 2π/3</td>
<td></td>
</tr>
<tr>
<td>RF source</td>
<td>4x45 MWp SLED-ed klystrons</td>
<td></td>
</tr>
</tbody>
</table>

50 Hz repetition rate

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BTF experimental hall

Approximately $<5.5\,\text{m total}$ length
($<3\,\text{m lateral width}$)
Decay to invisible states, scattering searches
Fix $\varepsilon$ to the preferred value from $a_\mu$ (±2σ), limits are represented in the plane $\alpha_D$ versus $m_{A'}$.

Still different curves due to the mass dependence of the dark sector particles $m_\chi$.

N.B. $\varepsilon$ is fixed to the minimum value of the $a_\mu$ band.
DAΦNE complex in Frascati

- DAΦNE, replacing ADONE (operational until 1993), has been running as $e^+e^-$ collider at 1.02 GeV since 1999, for KLOE, DEAR, FINUDA, Siddharta, and now KLOE/2 ...
- Synchrotron light source operational with 3 lines (X, UV, IR)
- Hi...
BTF beam-line upgrade
BTF users

[Luckily] BTF is already extensively used by many experimental groups in HEP and astro-particles...
Linac energy upgrade

Proposal of exploiting drift space at the end of accelerating structures put forward

Adding **four** more SLAC-type *accelerating sections* (3 m length)

- Fed by a 5\textsuperscript{th} RF station: 45 MWp klystron + SLED: 17.5 MV/m \times 12 m = **210 MeV**

**Or/And**

- Increasing the accelerating gradient splitting the RF power of one station /2 instead that /4 sections
  - Assuming 27 MV/m: **110 MeV** (4 accelerating sections)
  - **1 to 3 more RF stations** for the last 4 to 12 sections

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Magnet gap (– vacuum pipe depth): fixes the maximum (vertical) acceptance together with the target position

Given the gap, the minimum magnetic field is given by beam momentum and needed sweeping angle, depending on the calorimeterangular acceptance (in the bending, horizontal, plane)
Calorimeter: signal acceptance

N=616 crystals, 2×2 cm² size

Central hole to keep under control pile-up, mainly due to Bremsstrahlung events

Fraction of energy loss, leaving at least 1.5 cells for lateral containment

\[ \chi^2 / \text{ndf} = 382.5 / 94 \]

\[ p_0 = 0.02414 \pm 0.00053 \]
Calorimeter $2\gamma$ and $3\gamma$ backgrounds

Recoil $\gamma$ definition:
- $10$ MeV $< E < 400$ MeV
- $30$ mrad $< \theta < 65$ mrad

Region 1
- $\theta < 20$ mrad

Region 2
- $20$ mrad $< \theta < 75$ mrad

Region 3
- $\theta > 75$ mrad

Lost: $\theta > 100$ mrad

No $2\gamma$ events

Per-mil $3\gamma$ background

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Increasing linac beam pulse length

- Diluting the same number of positrons in a longer pulse is a plus from the point of view of pile-up.
- Main limitation coming from the SLac Energy Doubling system (SLED) used to reach higher energy in our linac.
- Uncompressed RF field 4.5 µs long, but with a 1/9 lower accelerating field increases the energy spread.

New pulser capable of up to 4.5 µs pulses will be installed during next shutdown (summer 2016).

500 ns pulses with 0.5% energy spread achieved at SLAC.

F.-J. Decker et al.
SLAC-PUB-7214 (1996)

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Vacuum vessel

AI 2219 T851 or AL6082 T6
2 mm side walls
4 mm ribs

Vacuum mandatory for three purposes:

1. Not to spoil beam quality before hitting the target
2. To minimize photon interactions before reaching the calorimeter
3. To minimize positron interactions before hitting the veto detector (in particular showers!)

Different possibilities under study to minimize the material thickness, i.e. increase acceptance (given the magnet gap) for the vessel, with the following requirements:

- Hold the vacuum
- Host the scintillating bars for positron veto detectors
- Interface to target box (upstream) and straight section before calorimeter (downstream)
Positron veto

Time resolution better than 500ps
Momentum resolution of few % based on impact position
Efficiency better than 99.5% for MIPs
Low energy part inside the magnet gap
High energy part close to not interacting beam
Calorimeter

BGO crystals

Small Angle BaF$_2$ or SF57

High Energy positron veto

Positron veto

Target

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Complete GEANT4 simulation
3γ production via CalcHEP
Low momentum losses are reduced for $E_\gamma < 400$ MeV

Interesting positron energy starting at $\sim 150$ MeV

Which granularity?
- 1 cm scintillator bars, readout by SiPM
- Few % momentum resolution in a large part of the spectrum
PADME TDAQ

- Readout based on digitizers CAEN V1742
- ~1000 channels
- ~33 FADC boards

- Trigger and clock distribution to the 33 boards
- Online FADC zero suppression (L0)
- FADC boards synchronization to few 100ps needed
Decay to invisible signal selection

- Only one cluster in calorimeter
  - Rejects $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \gamma\gamma(\gamma)$ final states
- $30 \text{ mrad} < \theta_{\text{Cl}} < 65 \text{ mrad}$
  - Improve shower containment $\sigma(E)/E$
- Positron veto: no tracks in the spectrometer in $\pm 2 \text{ ns}$
  - Reject background from Bremsstrahlung identifying primary positrons
- Photon veto: no $\gamma$ with $E_\gamma > 50 \text{ MeV}$ in time in $\pm 1 \text{ ns}$ in the additional small angle veto (SAV), covering the hole acceptance
- Cluster energy within: $E_{\text{min}}(M_{A'}) < E_{\text{Cl}} < E_{\text{max}}(M_{A'}) \text{ MeV}$
  - Removes low energy bremsstrahlung photons and piled up clusters
- Missing mass in the region: $M^2_{\text{miss}} \pm \sigma(M^2_{\text{miss}})$
**PADME-dump**

- $10^{20}$ EOT, 1.2 GeV; 20 cm aperture at 50 cm from 8 cm W dump
- Zero background hypothesis, in depth production to be refined, not yet a sensitivity plot
From **A. Celentano**

Acceptance limit at \(\approx 100\) MeV coming from beam energy

\[ \alpha_d = 0.1 \quad m_\chi = 10 \text{ MeV} \]

Beam energy **1.2 GeV** (e\(^-\))

CsI detector 60×60×225 cm\(^3\) built with crystals from dismounted BaBar calorimeter?
A new **thin vacuum chamber**

A straight vacuum pipe to the inside of the existing dump cavity

**Additional shielding** for copying with neutron production

Use **DR pumps hall** for shielding and experiment

**LINAC beam dump**