Searching for new light particles with positrons on target

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for the PADME collaboration

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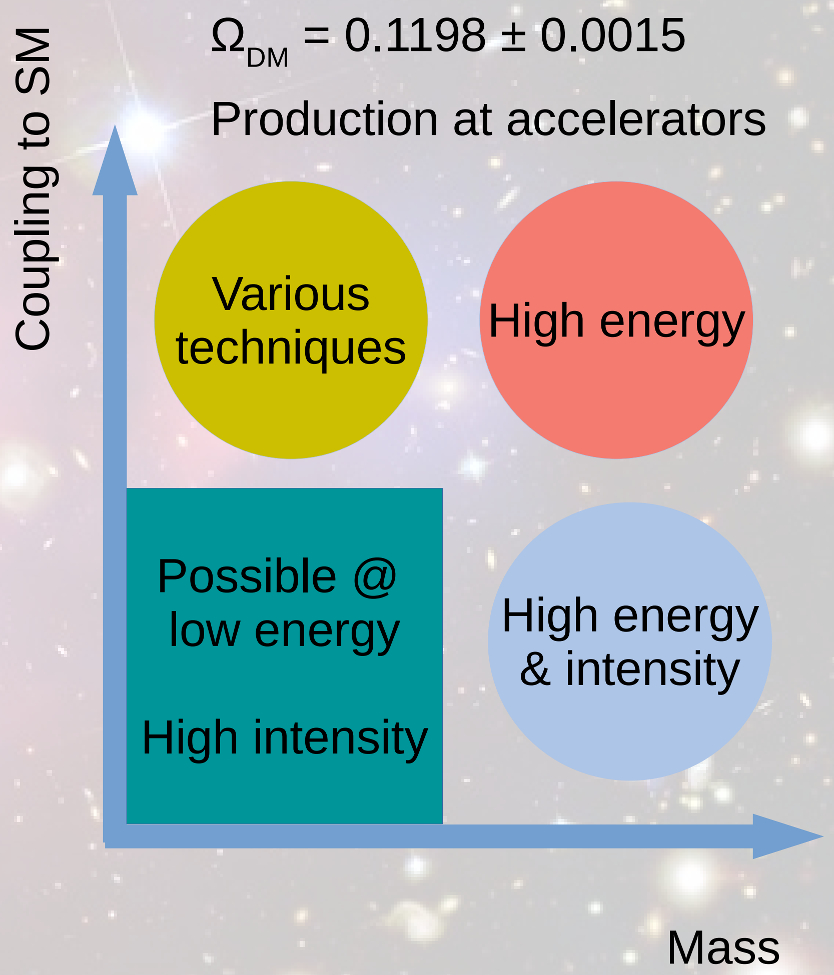
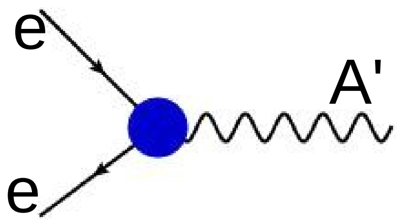
Outline

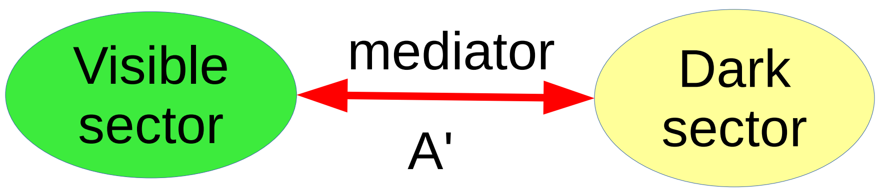
- Motivation
- Technique
- PADME @ LNF
- Further options
- Conclusions



Hidden sector and Dark Photon

- The effective interaction that can be studied is





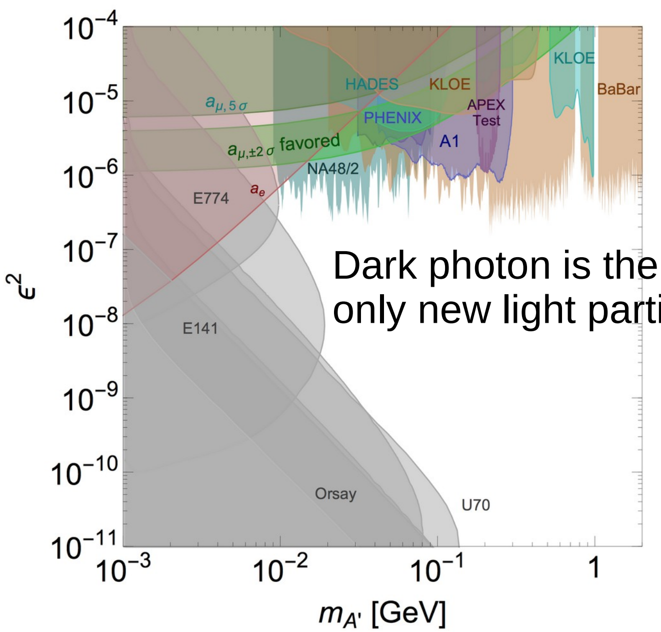
$$\boldsymbol{L} \sim g'q'\,\overline{\Psi}\,(\gamma_\mu + \alpha'_a\,\gamma_\mu\,\gamma^5)\Psi\, A'^{\,\mu},\ \ usually\ \alpha'_a = 0$$

  - $q_f \to 0$ for some flavours
- Textbook scenario, could address the (g_μ-2) discrepancy, abundance of antimatter in cosmic rays, signals for DM scattering
  - **General U'(1) and kinetic mixing with B (A', Z')**
    - Universal coupling proportional to the q_{em}
    - Just single additional parameter – ε

$$L_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

  - **Leptophilic/leptophobic dark photon**
    - **„Gauging“ SM accidental symmetries: (e.g. $L\mu$ - $L\tau$, B – L)**
- Related to Dark matter and its interactions

Variety of Dark Photons ...

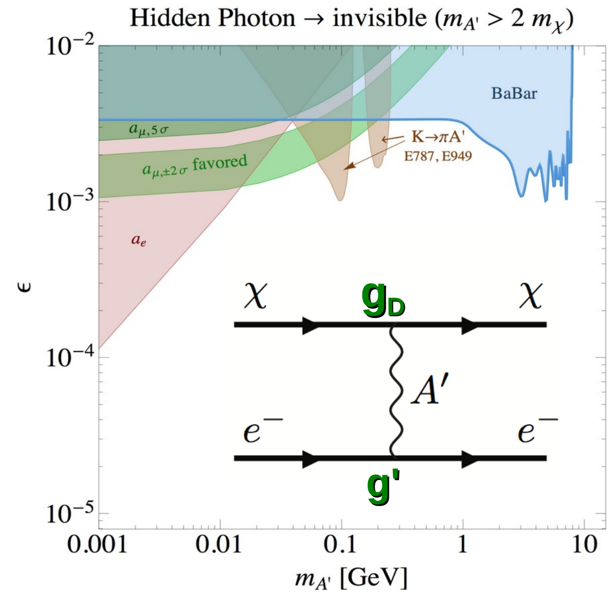


Dark photon is the only new light particle

- Two parameters
  $M_{A'}$, g',

  vs

- Four parameter space
  $M_{A'}$, g', g_D, M_χ



- Part of the phenomenology of the Dark Photon depends on what we don't know
  - Is it really a mediator between the visible and the hidden world?
  - Is it a manifestation of a Fifth Force?
  - How does it come to couple to SM particles?
    - Mixing with SM gauge boson?
    - Universal versus non-universal couplings?
- And moreover – what the hidden world looks like?

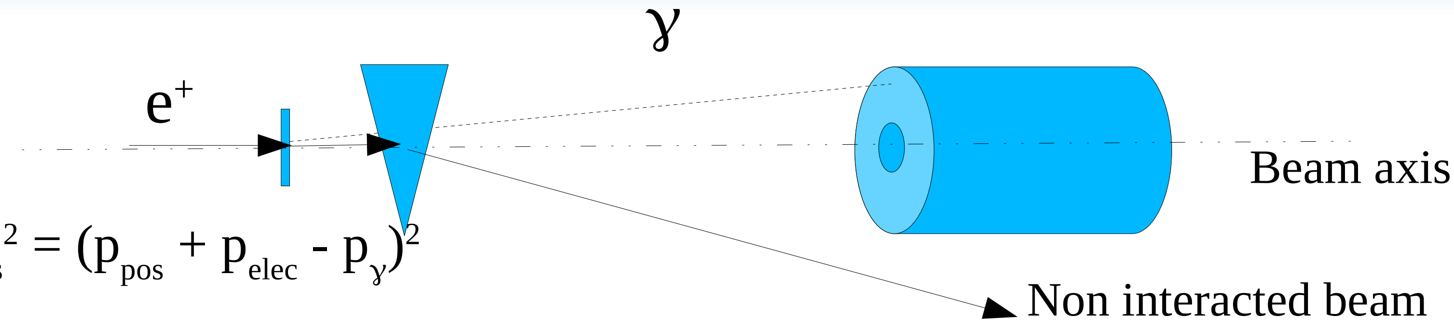
Light

Heavy

Constrained initial process

- Initial state is carefully prepared
  - A' as a product of SM particles decays: π^0, ρ, η….
  - e^+e^- colliders
  - Annihilation
- Possible A' final states
  - A' $\rightarrow$ SM particles, all states reconstruction
    - Provides significant background suppression
  - A' $\rightarrow$ DM particles
    - Determination of A' properties through missing momentum/energy/ mass

A' in annihilation



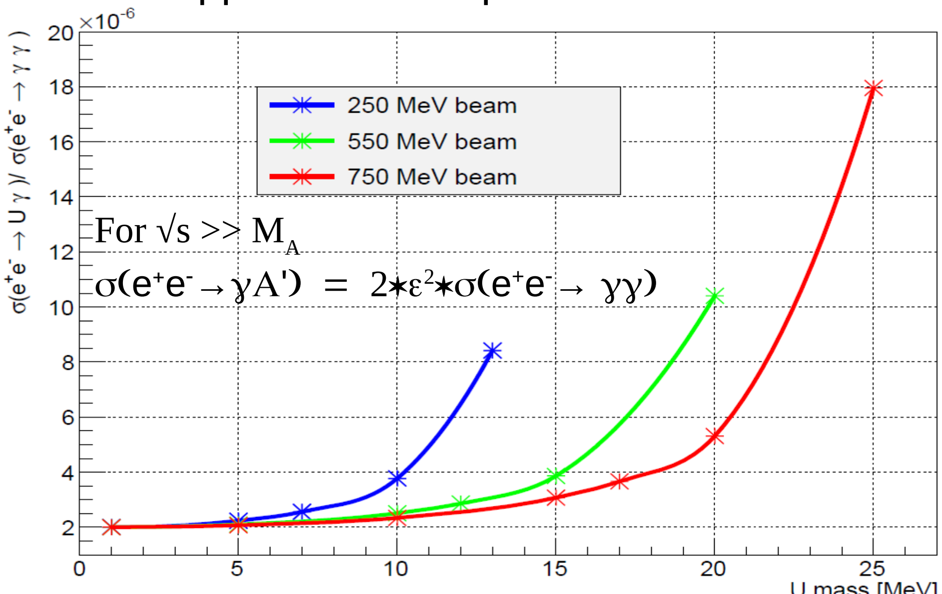
$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

- Positron beam on a thin target
- Positron momentum is determined by the accelerator characteristics
- Missing mass resolution: annihilation point, E_γ, φ_γ

$$\frac{\sigma(e^+e^- \to U\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta,$$

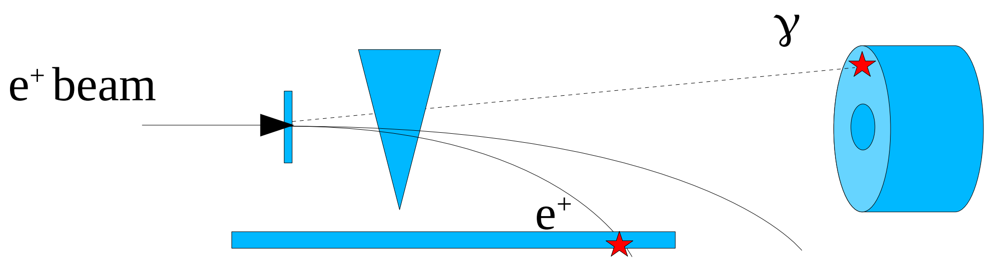
- Clear 2 body correlation
- Background minimization
  - Best possible resolution on energy/angle measurement
  - **Dominant process in e+/e- interactions with matter is bremsstrahlung**
  - Photons vetoing
  - Minimize the interaction remnants + vetoing

Cross section enhancement with the approach of the production threshold

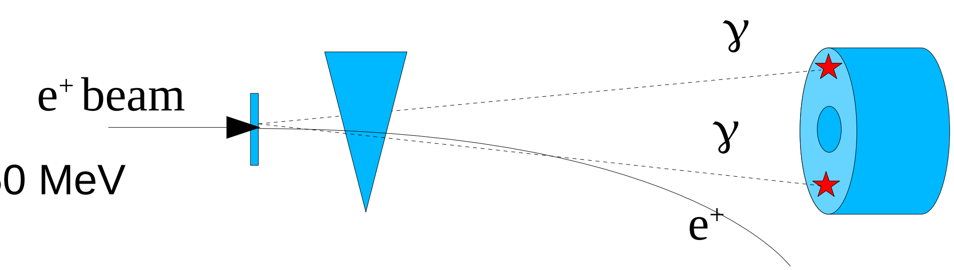


Backgrounds

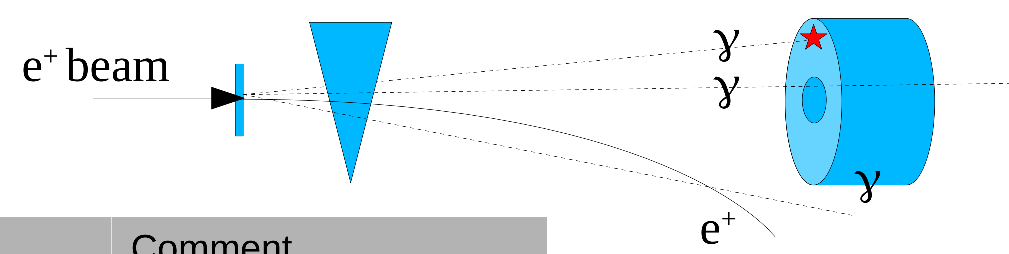
- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection



- 2 photon annihilation
  - Peaks at $M_{miss} = 0$
  - Quasi symmetric in gamma angles for $E\gamma > 50$ MeV



- 3 photon annihilation
  - Symmetry is lost – decrease in the vetoing capabilities
- Radiative Bhabha scattering
  - Topology close to bremsstrahlung

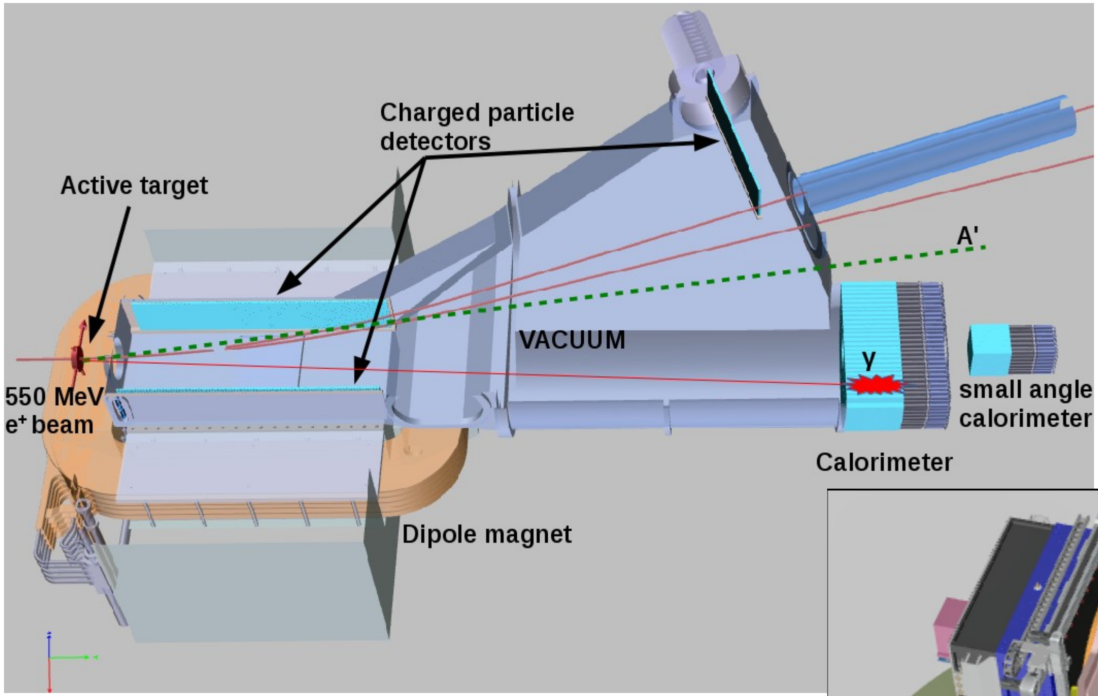


Background process	Cross section e^+@550 MeV beam	Comment *Carbon target*
$e^+e^- \rightarrow \gamma\gamma$	1.55 mb	
$e^+ + N \rightarrow e^+ N \gamma$	4000 mb	$E\gamma > 1$MeV
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma > 1$MeV
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb	CalcHEP, $E\gamma > 1$MeV

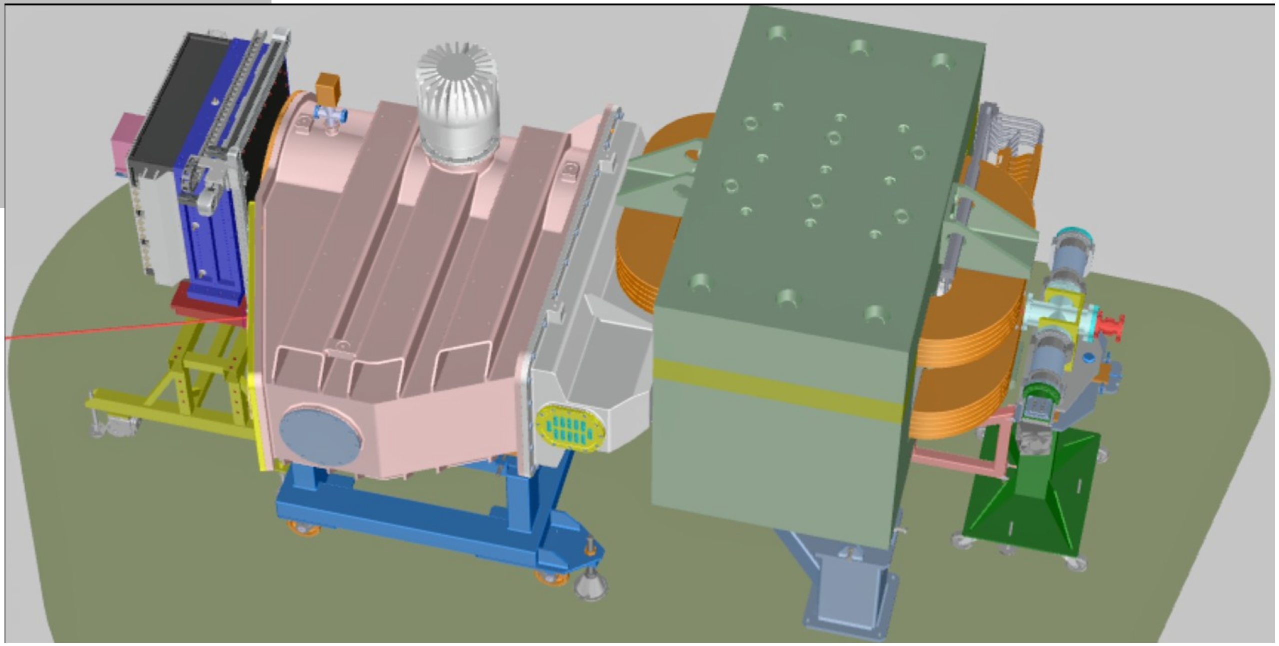
PADME

Positron Annihilation into Dark Matter Experiment

Adv. HEP 2014 (2014) 959802

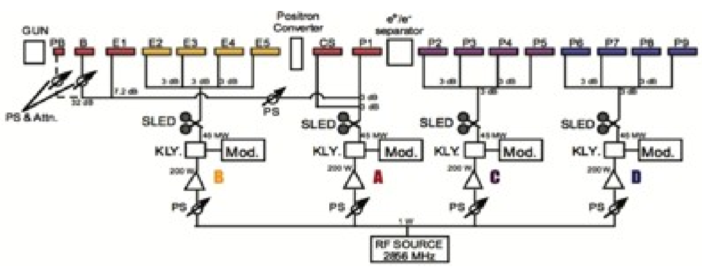


- Small scale fixed target experiment
  - e^+ @ Frascati Beam test facility
  - Solid state target
  - Charged particles detectors
  - Calorimeter

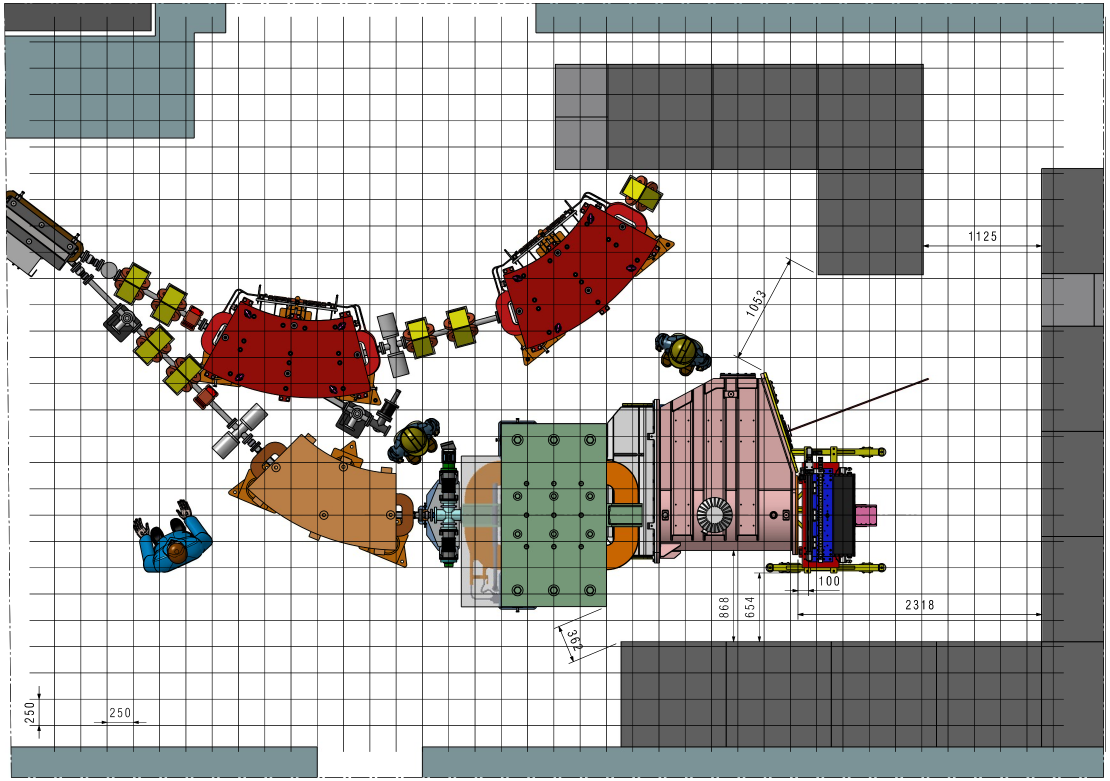


- Vacuum: ~$2*10^{-7}$ mbar
  - Two major sections: inside and outside the dipole magnet
  - Austenitic steel, thermally treated to reach the desired magnetic permeability

PADME @ BTF



	Electrons	Positrons
Maximum beam energy (E_{beam})[MeV]	750 MeV	550 MeV
Linac energy spread [Dp/p]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 – 40 (can reach 200 in 2016)	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot s [mm]	<1 mm	
Beam divergence	1-1.5 mrad	

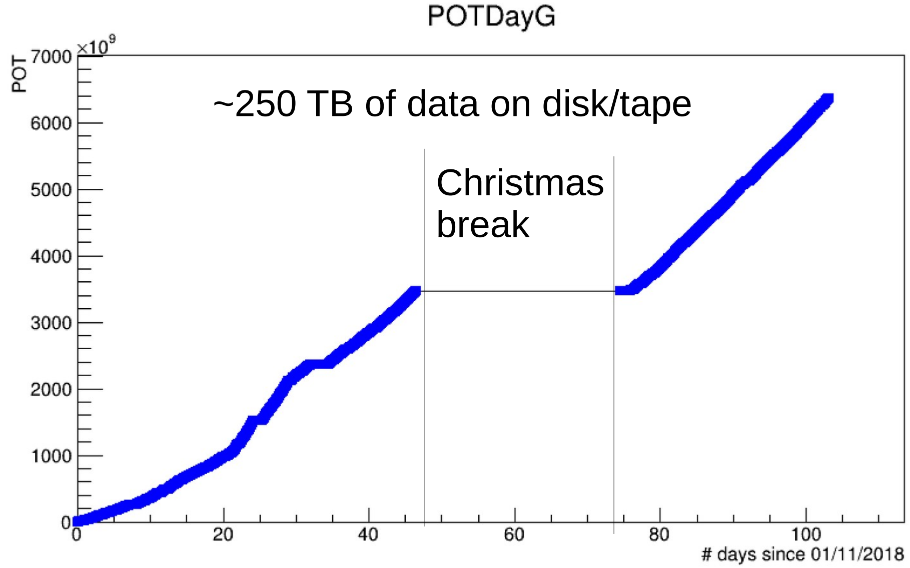


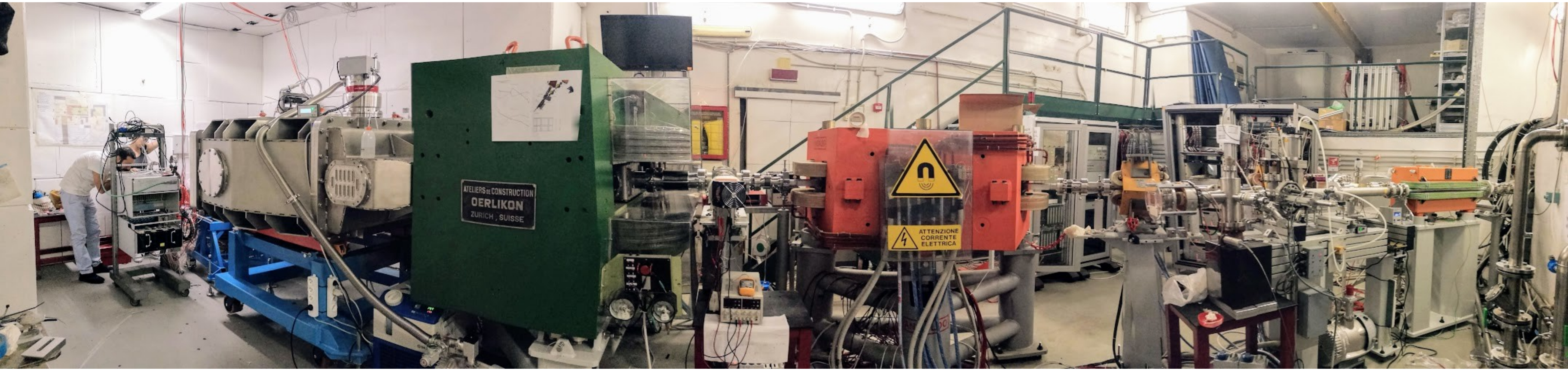
- BTF line completely dismounted
- Hall and infrastructure refurbished, control room moved
- All the components placed to their new nominal position

Outstanding support from the laboratory!

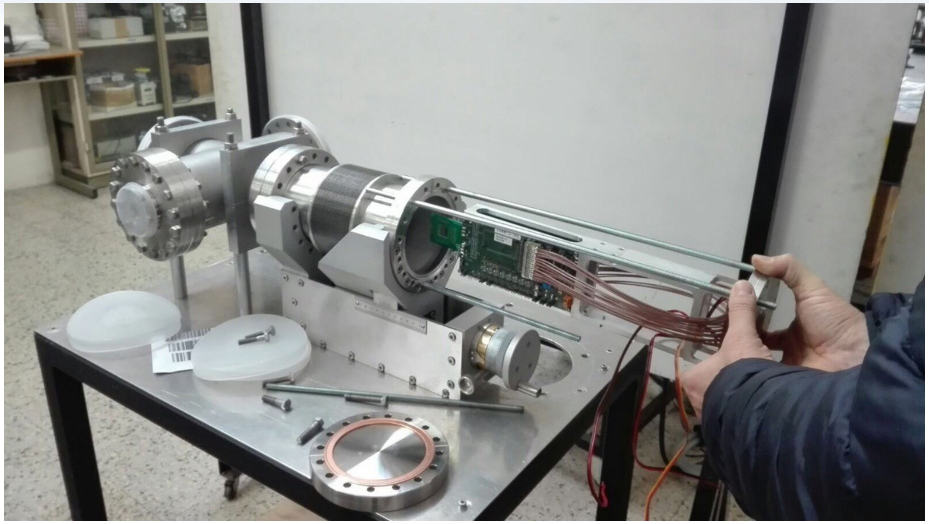
Data taking

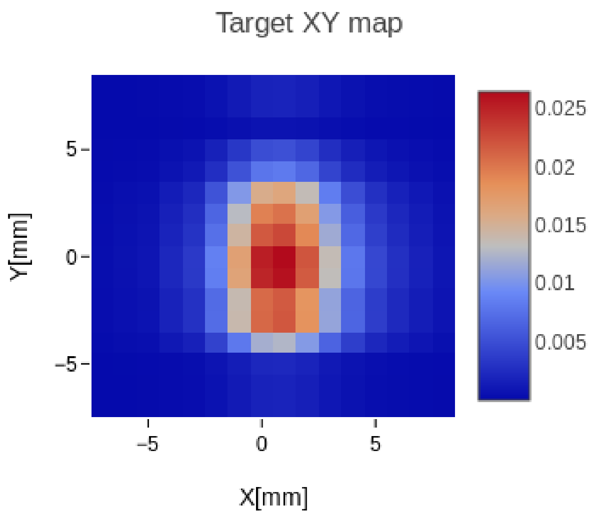
- PADME commissioning and Run-1 started in Autumn 2018 and ended on February 25th
  - ~7 x 10^{12} positrons on target recorded
  - Data quality and detector calibration in progress
- PADME Run-2
  - July 2019, few days of data
  - Detector performance/calibration checks





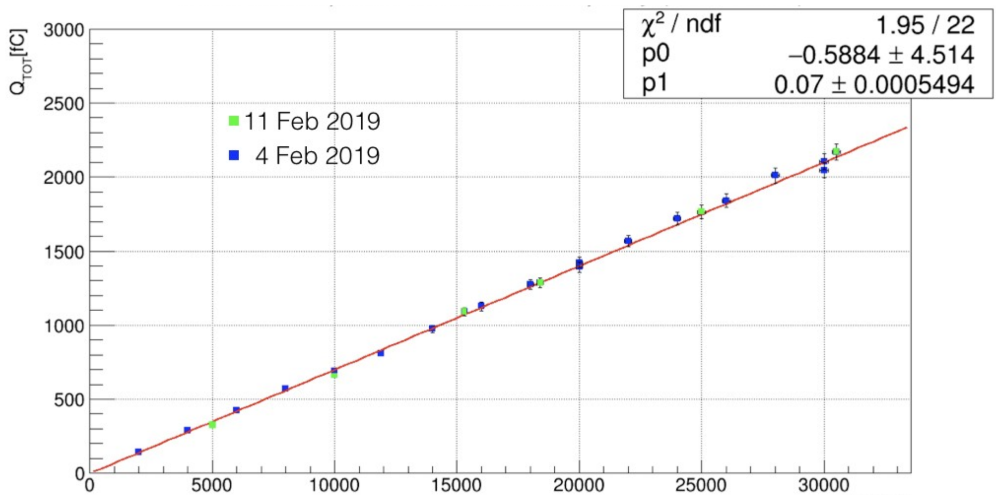
Active diamond target



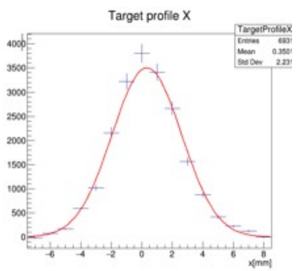


Polycrystalline diamonds

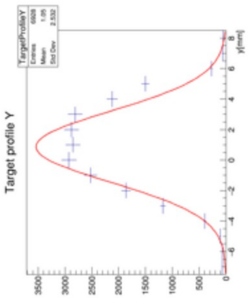
- 100 μm thickness:
- 16 × 1 mm strip and X-Y readout in a single detector
- Graphite electrodes using excimer laser (Lecce)
- PADME prototype 20 × 20 mm² produced and tested 2015
- Low noise CSA integrated in the 16 channel chip AMADEUS from IDEAS

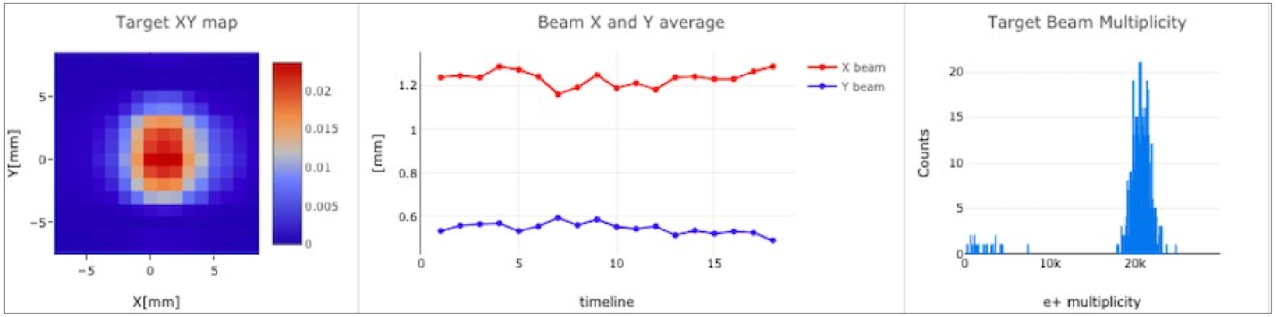


Target performance

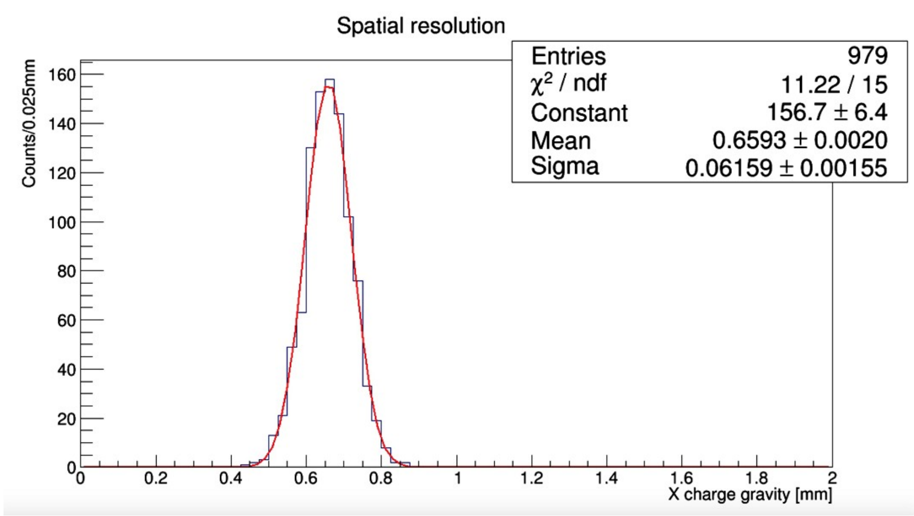


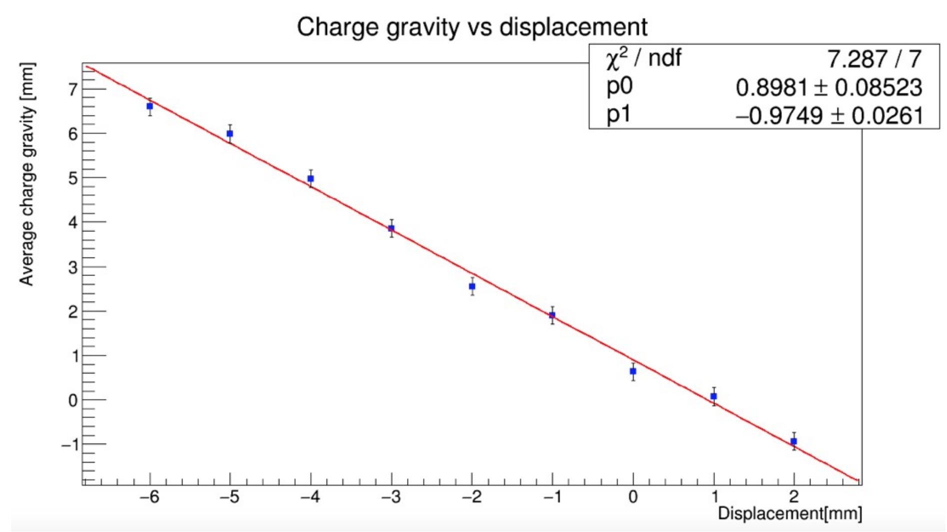
- Precise measurement and control of the beam parameters
  - Position
  - Multiplicity
  - Beam steering diagnostics
- Extensive work on calibration



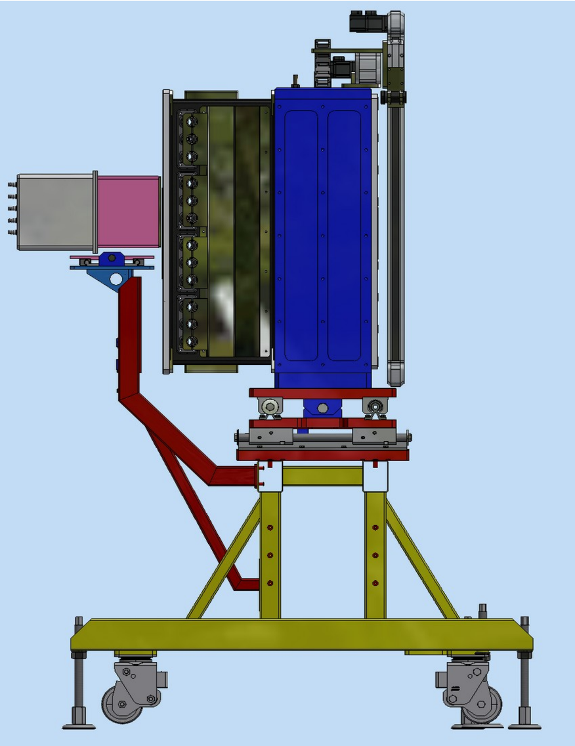


<u>PADME Diamond</u>
CCD ≈ 12 μm

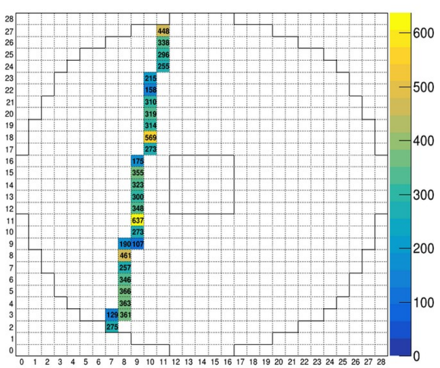




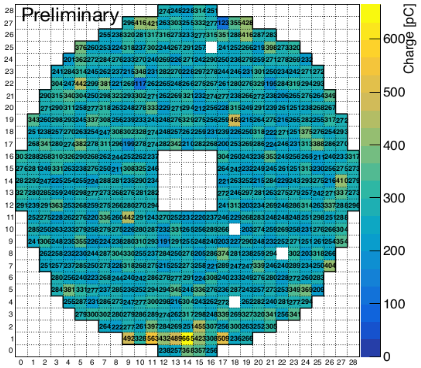
Calorimeter: ECal

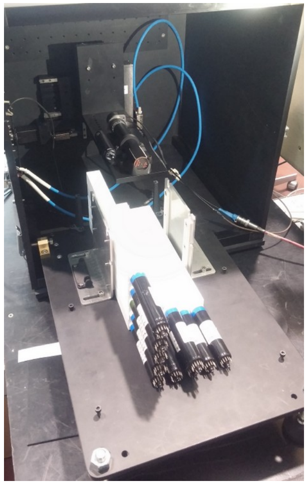


- ECAL: The heart of PADME
- 616 BGO crystals, 2.1 x 2.1 x 23 cm^3
- BGO covered with diffuse reflective TiO_2 paint
  - additional optical isolation: 50 – 100 μm black tedlar foils



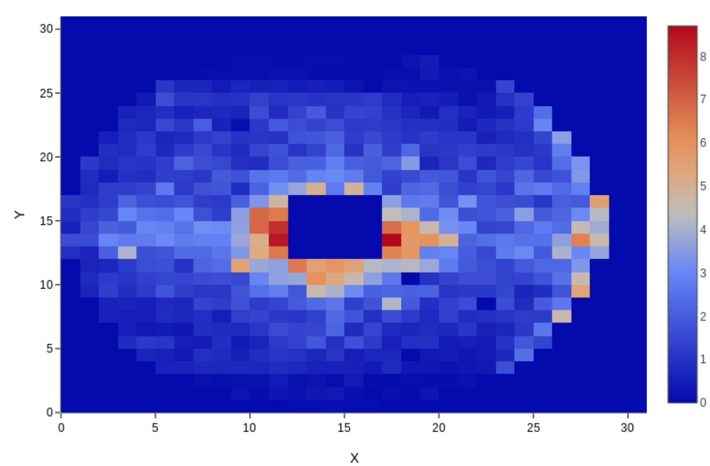
ECal ev. 11 (0 3032)

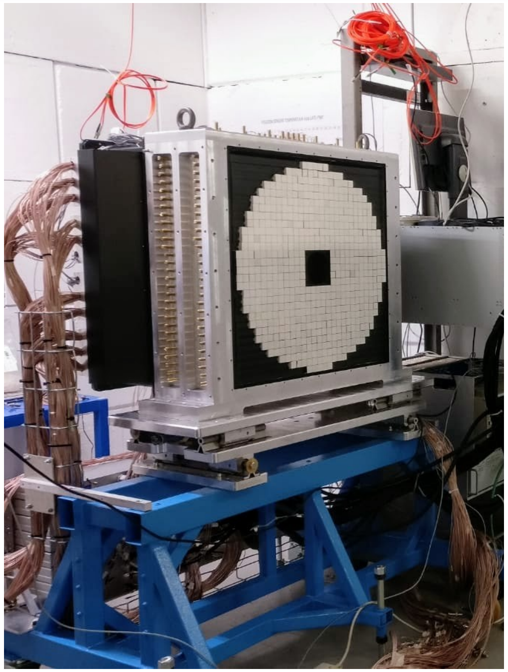




- Calibration at several stages:
  - BGO + PMT equalization with 22Na source before constructio
  - Cosmic rays calibration using the MPV of the spectrum

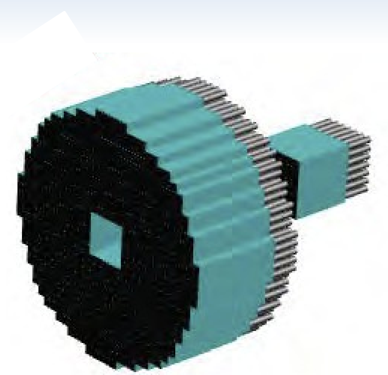
ECal Energy map (approx. MeV)

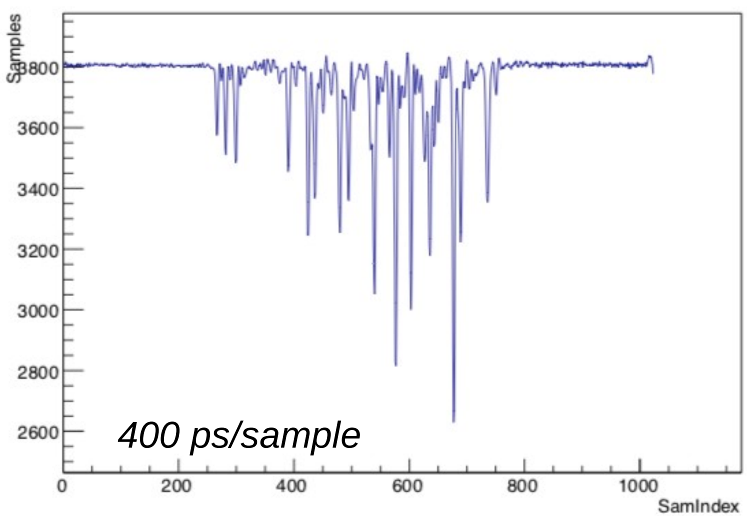


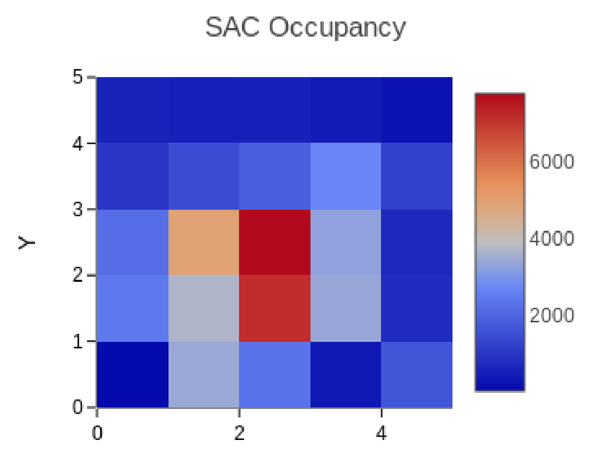


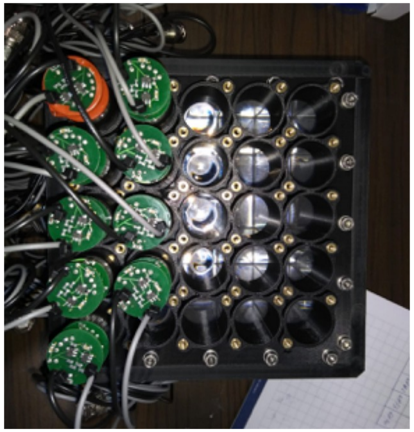
Small angle calorimeter

- 25 crystals - 5 x 5 matrix, Cherenkov PbF_2
- Dimensions of each crystal: 3 × 3 × 14 cm^3
- 50 cm behind ECal
- PMT readout: Hamamatsu R13478UV with custom dividers
- Angular acceptance: [0,19] mrad

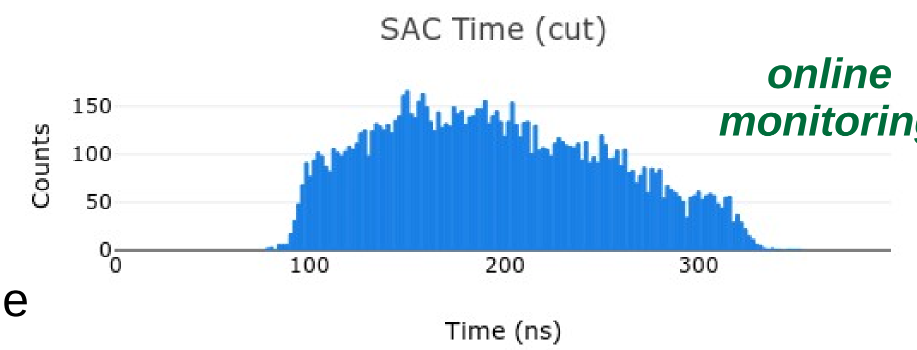








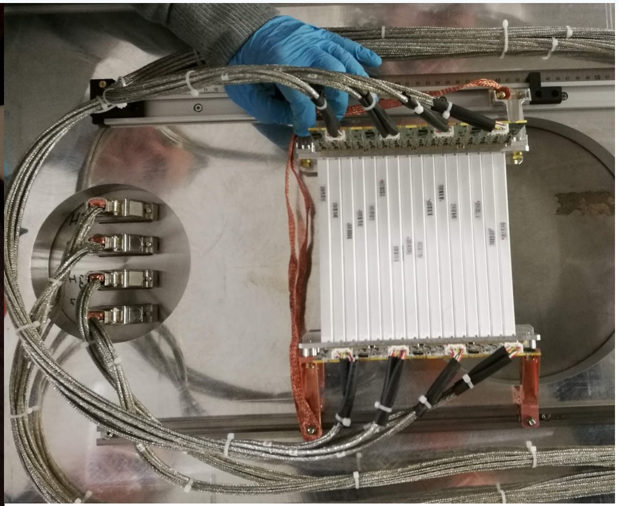
- Multiphoton events suppression
- Bremsstrahlung events identification
- Provides online information of the beam profile

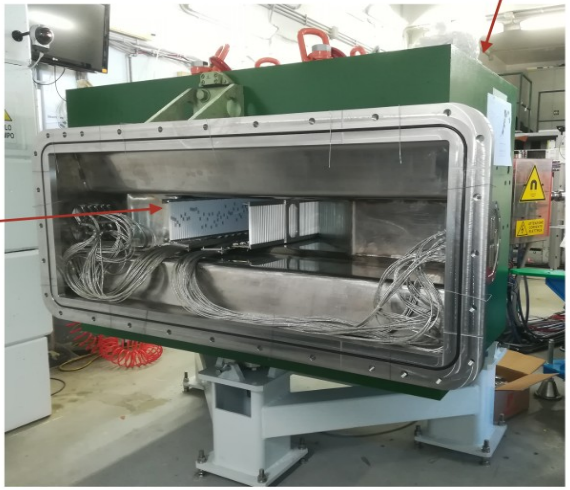


online monitoring

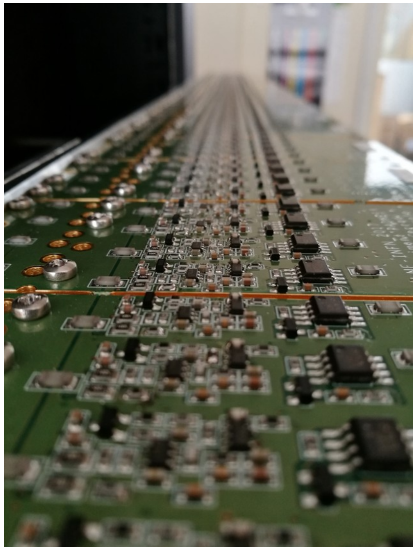
Charged particle detectors

- An extensive work on the preparation, test and commissioning of the individual detecting elements
- 96 + 96 (90) + 16 (x2) scintillator-WLS-SiPM RO channels
- Segmentation provides momentum measurement down to ~ 5 MeV resolution

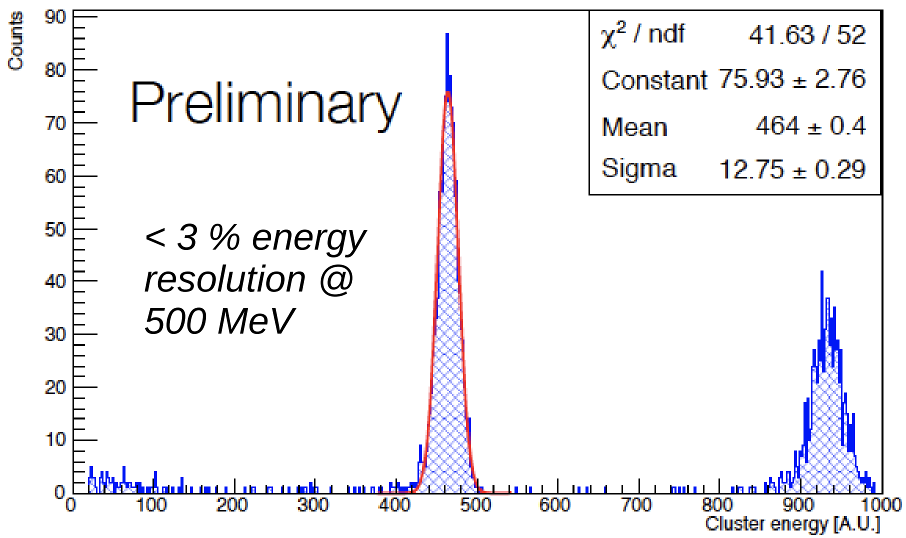


- Custom SiPM electronics, Hamamatsu S13360 3 mm, 25μm pixel SiPM
- Differential signals to the controllers, HV, thermal and current monitoring

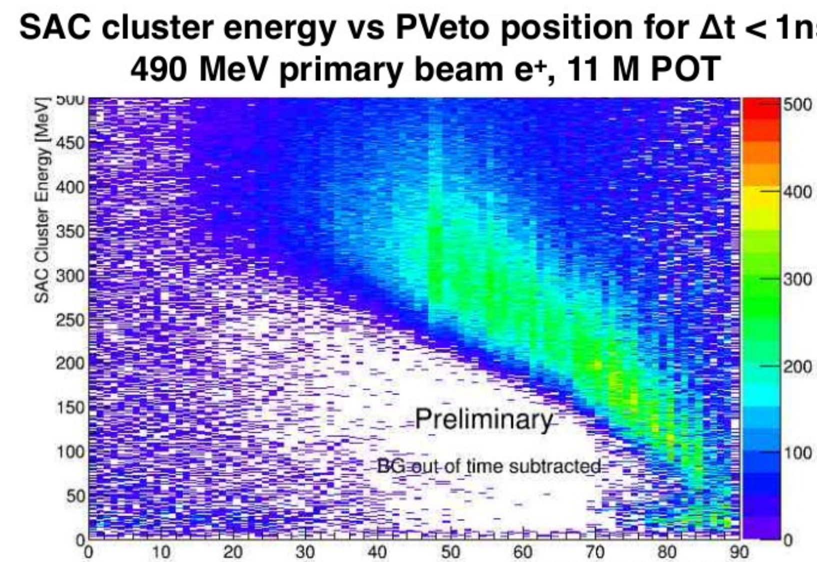


- Online time resolution: ~ 2 ns
- Offline time resolution after fine T_0 calculation – better than 1 ns

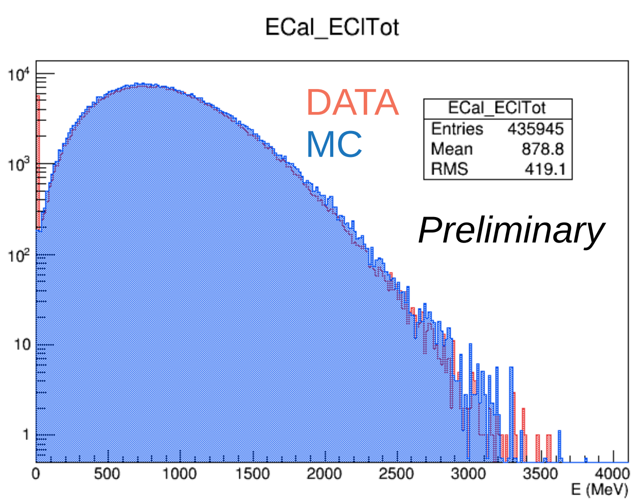
PADME data



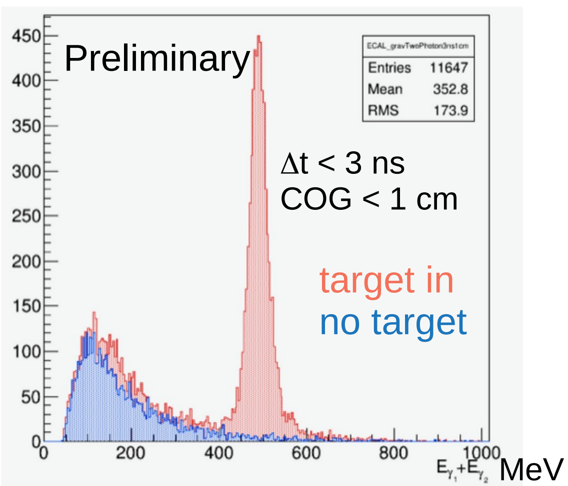
Counts
Preliminary
< 3 % energy resolution @ 500 MeV
χ^2 / ndf 41.63 / 52
Constant 75.93 ± 2.76
Mean 464 ± 0.4
Sigma 12.75 ± 0.29
Cluster energy [A.U.]



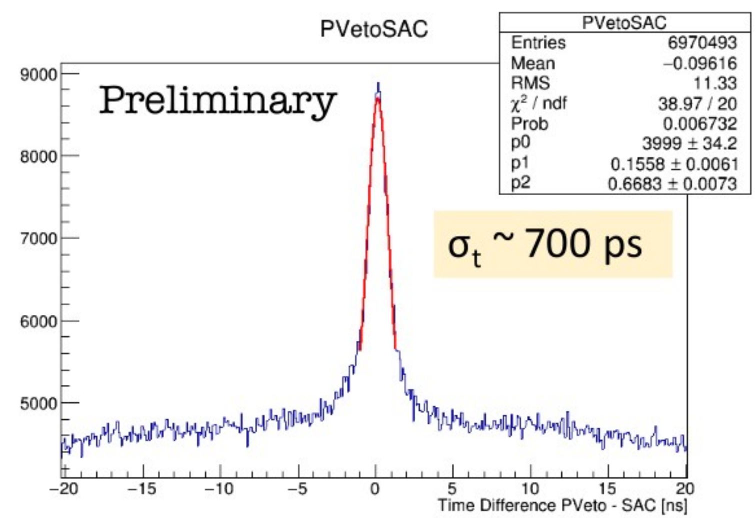
SAC cluster energy vs PVeto position for Δt < 1ns
490 MeV primary beam e+, 11 M POT
SAC Cluster Energy [MeV]
Preliminary
BG out of time subtracted



ECal_ECITot
DATA
MC
ECal_ECITot
Entries 435945
Mean 878.8
RMS 419.1
Preliminary
E (MeV)



Preliminary
Entries 11647
Mean 352.8
RMS 173.9
Δt < 3 ns
COG < 1 cm
target in
no target
$E_{\gamma_1}+E_{\gamma_2}$ MeV



PVetoSAC
Preliminary
PVetoSAC
Entries 6970493
Mean −0.09616
RMS 11.33
χ^2 / ndf 38.97 / 20
Prob 0.006732
p0 3999 ± 34.2
p1 0.1558 ± 0.0061
p2 0.6683 ± 0.0073
σ_t ~ 700 ps
Time Difference PVeto - SAC [ns]

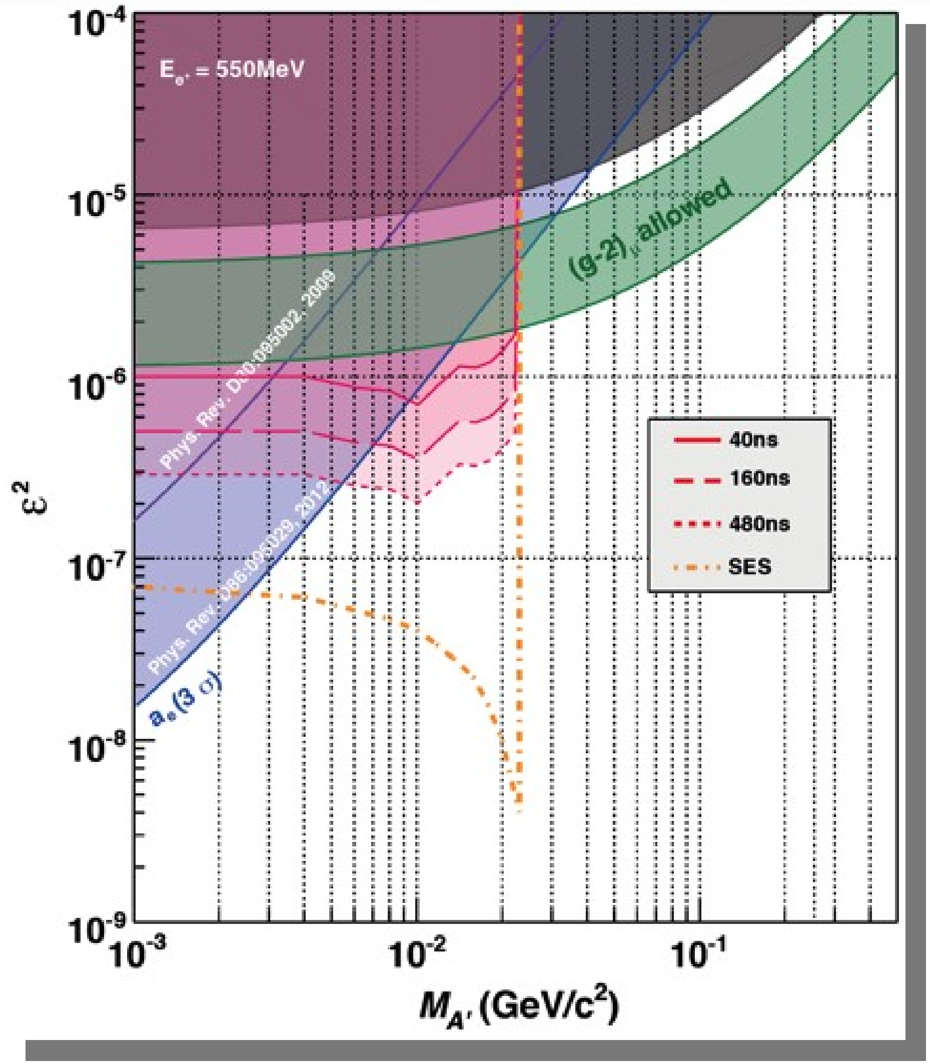
PADME sensitivity

2.5x10^{10} fully GEANT4 simulated 550MeV e+ on target events

Number of BG events is extrapolated to 1x10^{13} electrons on target

$$\frac{\Gamma(e^+e^- \to A'\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma)} \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon \cdot \delta$$

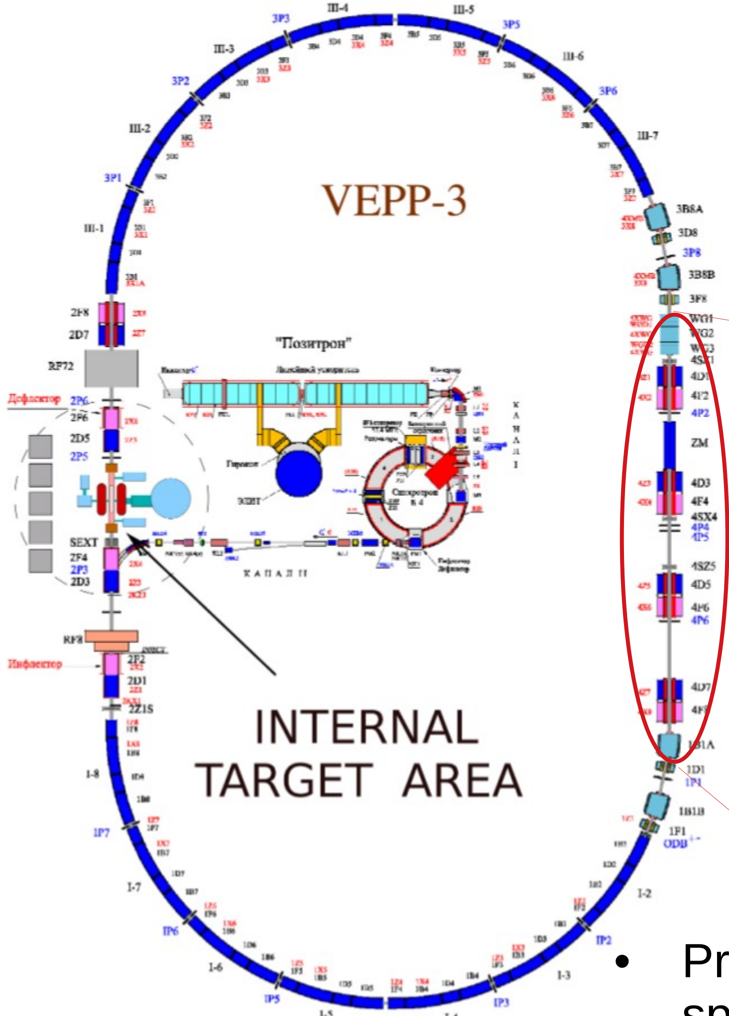
PADME:
2 years of data taking at 60% efficiency with bunch length of 200 ns
4x10^{13} EOT = **20000 e$^+$**/bunch × 2 × **3.1 · 10^7**s x 0.6 · **49 Hz**

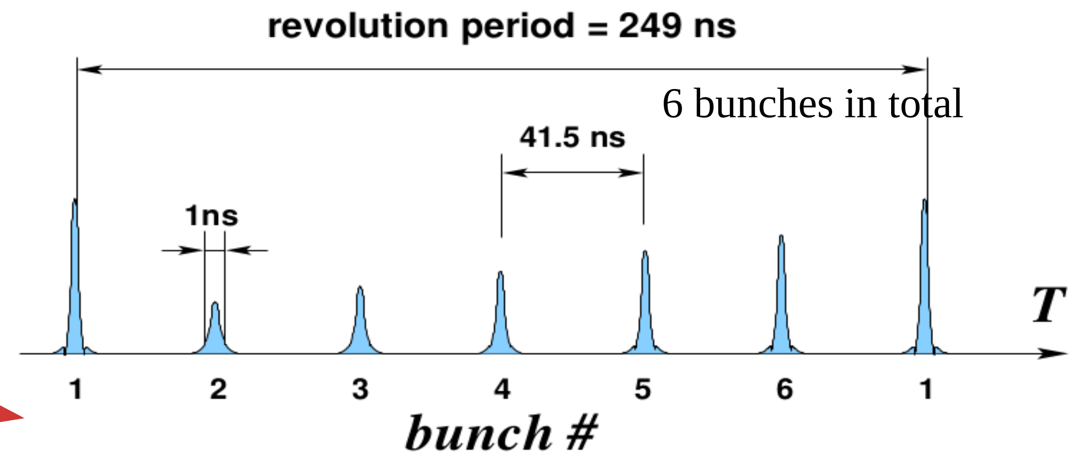


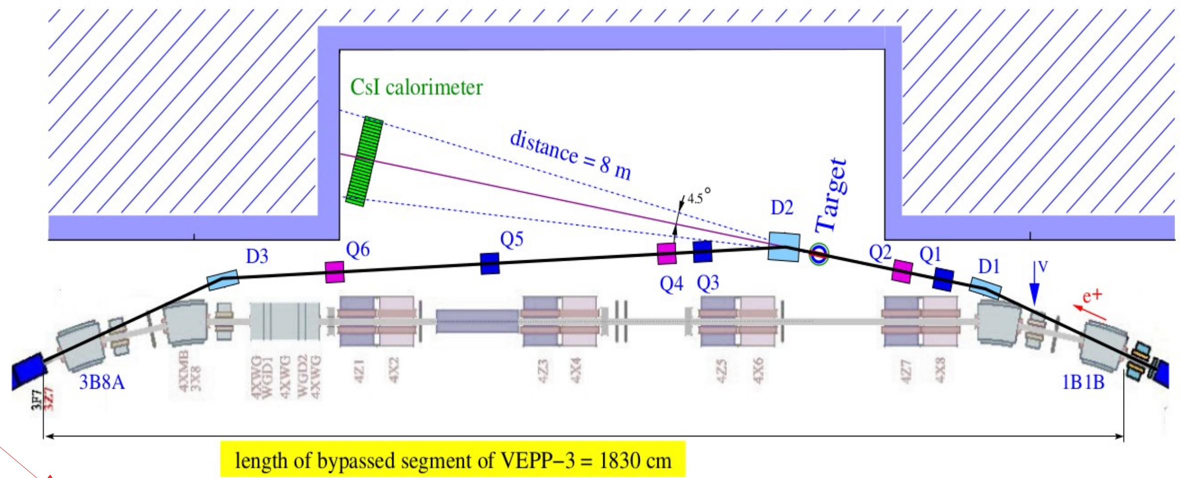
VEPP 3

arXiv:1708.07901

- 500 MeV storage ring @ Novosibirsk



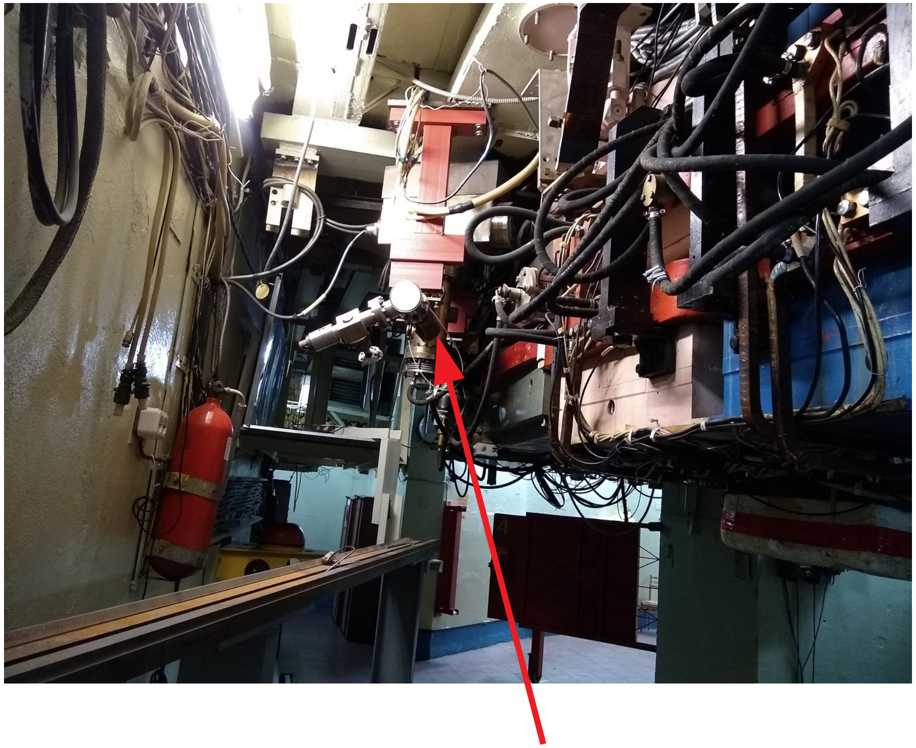




- Proposed to construct a ByPass, allowing to utilize available space for a crystal calorimeter and shielding
- Operating in paralel with the ongoing VEPP-3 activities

VEPP 3: first option

- Storage ring is on top, easy access below



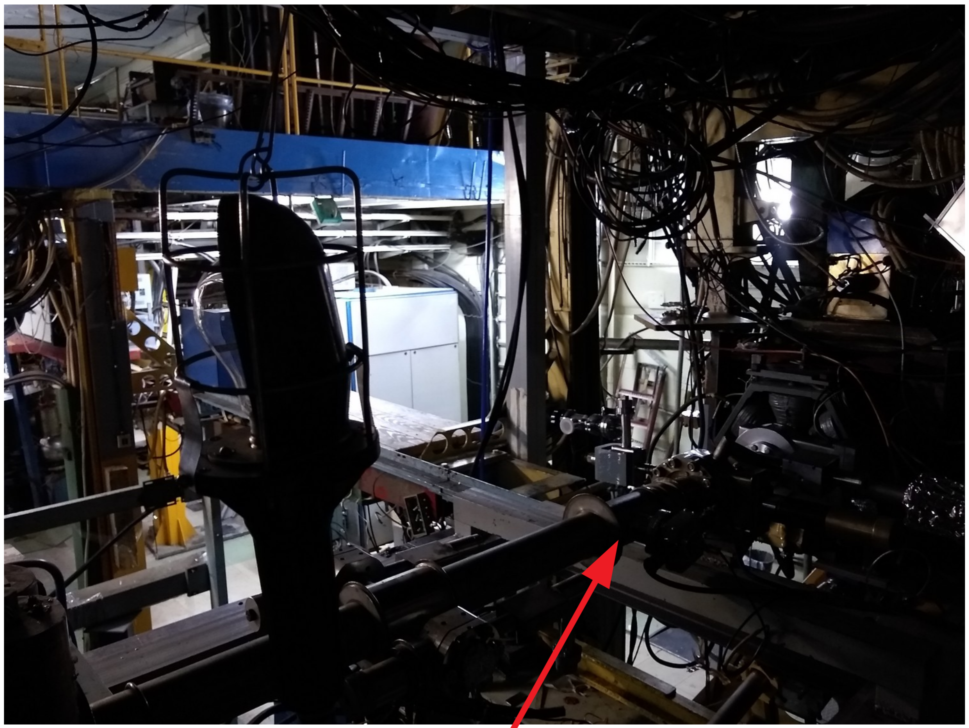
Extraction line

Experiment region

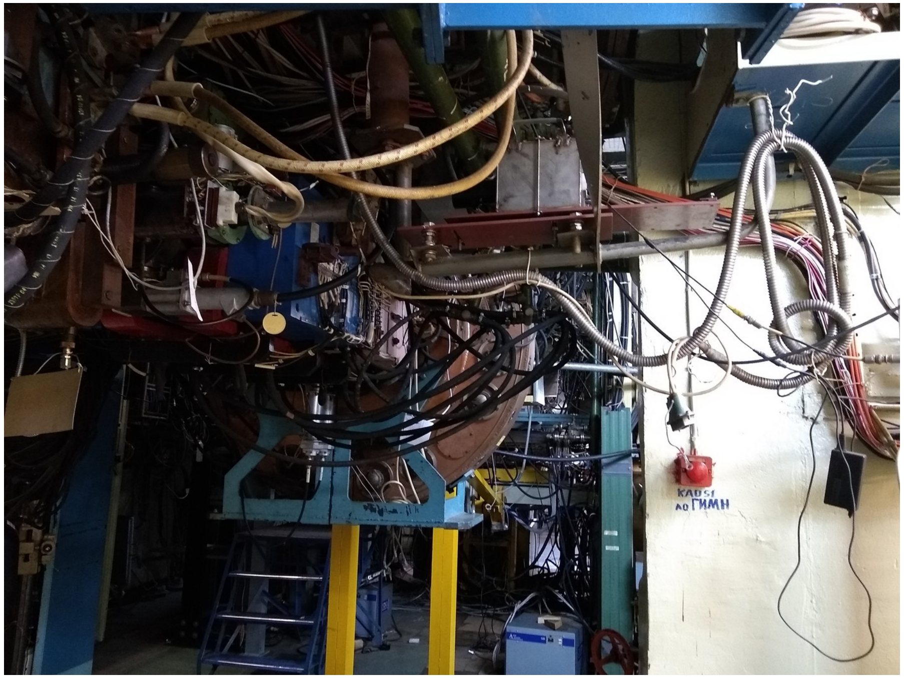
- Suitable place to install the experimental setup
  - Support and infrastructure exists
  - Detector wanted....

VEPP 3: second option

- A relatively „free“ region exists also on the opposite side of the storage ring



New extraction place - @ internal target area

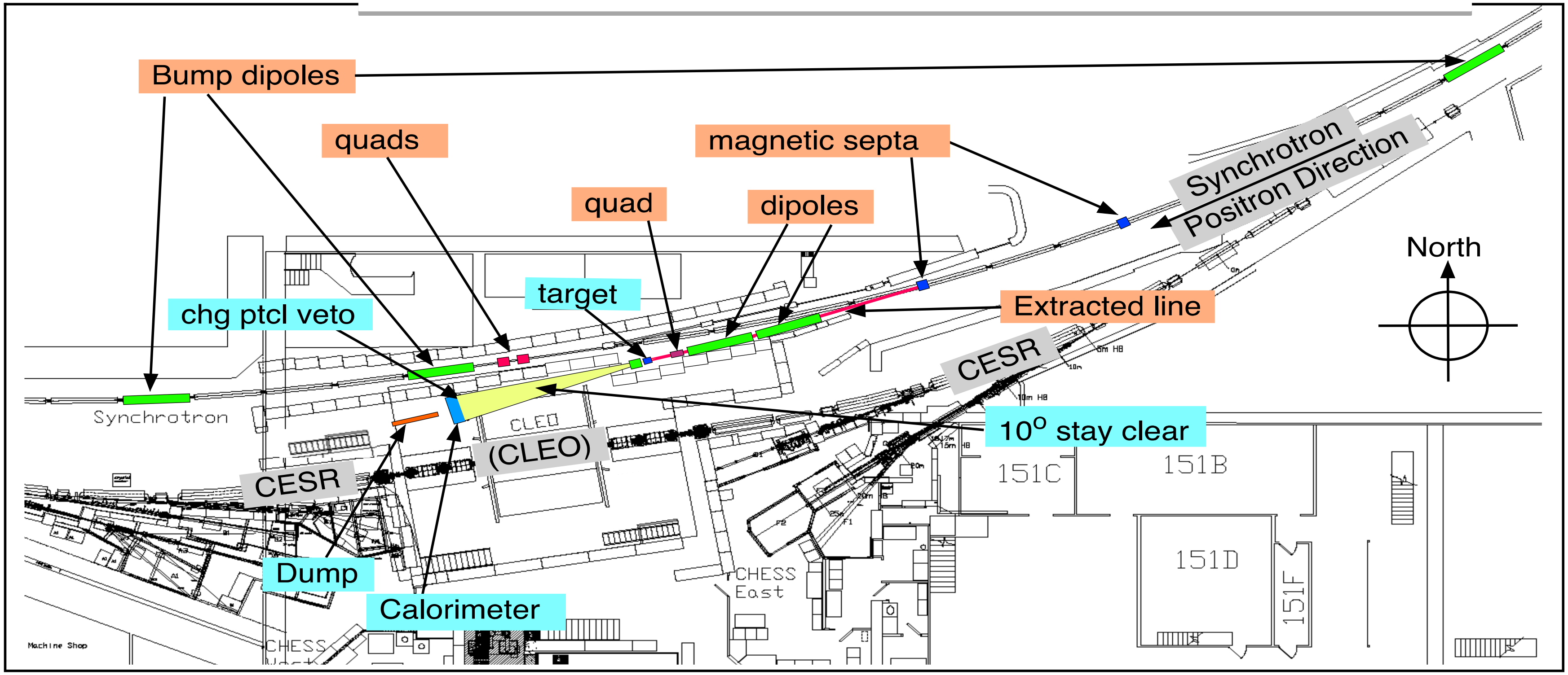


Potential experiment region

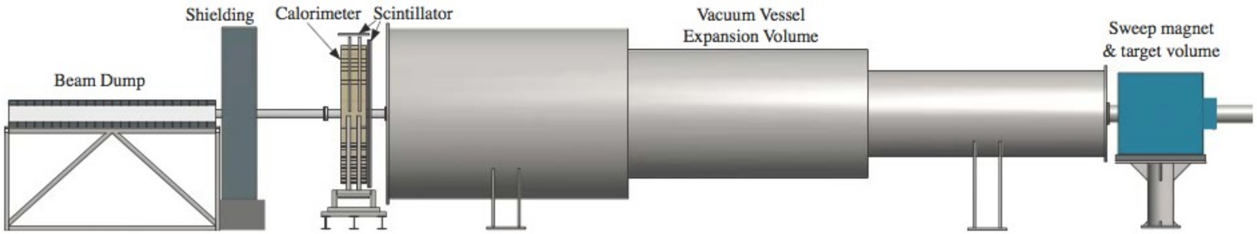
- However, non-negligible amount of work necessary
  - New extraction line (but a magnet exists)
  - Cut part of the wall … and detector installation

Cornell positron beam

EPJ Web Conf. 142 (2017) 01001

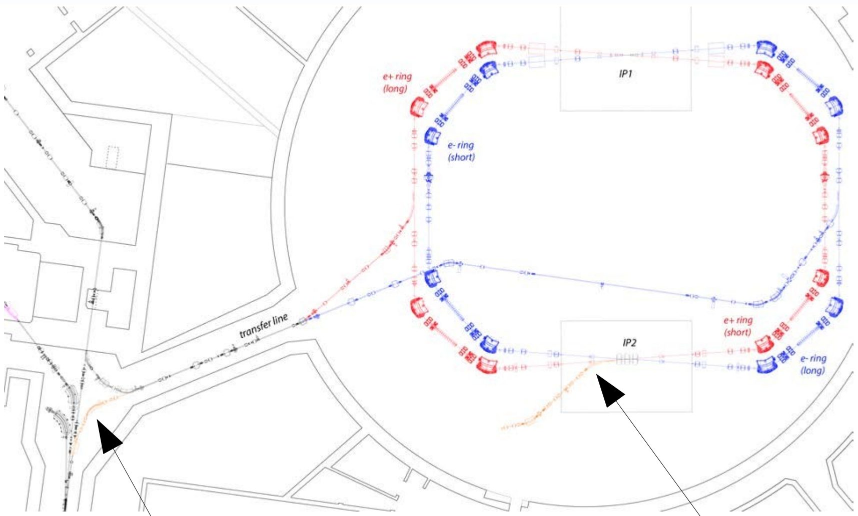


- Extract positron beam from synchrotron (between CESR fills for xray program)
  - E_{beam} = 1.8 - 5.3 GeV
  - I_{beam} ~ 2.3 nA at target
  - pulse structure: 168ns



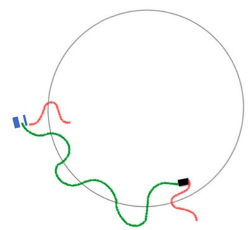
PADME @ DAΦNE

- DAΦNE – the Frascati ϕ-factory
  - LINAC + e+/e- storage ring
- LINAC rate – 50 Hz, 49 Hz for users
- Beam energy – O(550 MeV)



arXiv:1711.06877

POSEYDON



DAΦNE resonant extraction

- Long beam from the Linac (up to 324 ns)
  - 0.5 % momentum spread at injection
- RF off - monochromatic extraction due to synchrotron losses
- Wigglers off (on), losses ~ 3 (6) keV per turn
  - Spill length: 0.4 (0.2) ms
- $\Delta p/p = 1.4 \times 10^{-3}$
- Requires new injection and extraction lines

Ultra slow extraction

- Use crystal channelling
- $N_{e+} = 2 \times 10^{12}$ (1 A current in 120 bunches)
- Revolution time – 324 ns
- 1 extracted particle per turn per bunch → ~3×10^{8} e^{+} per second

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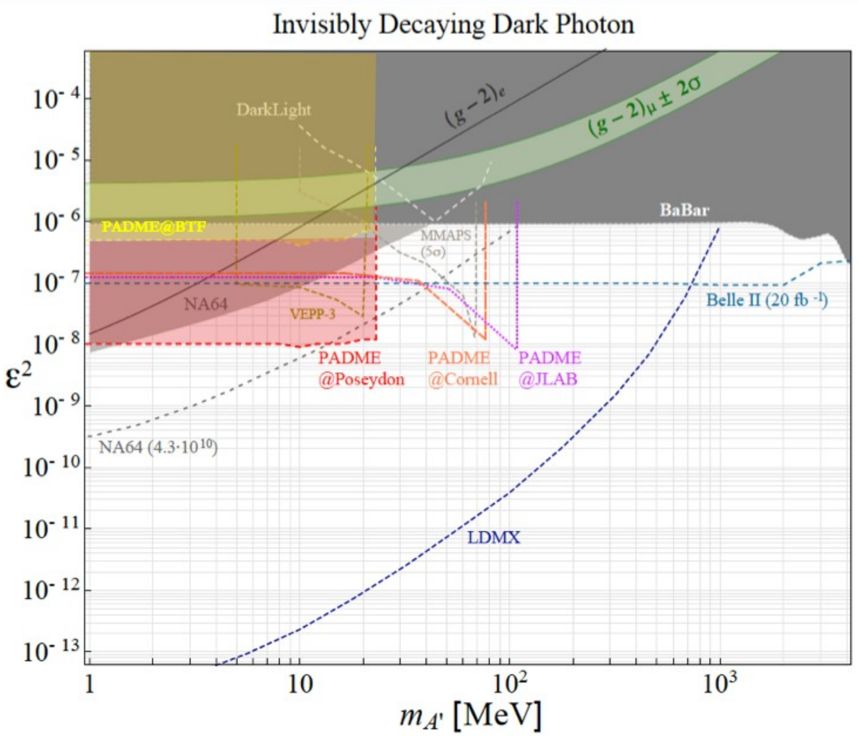
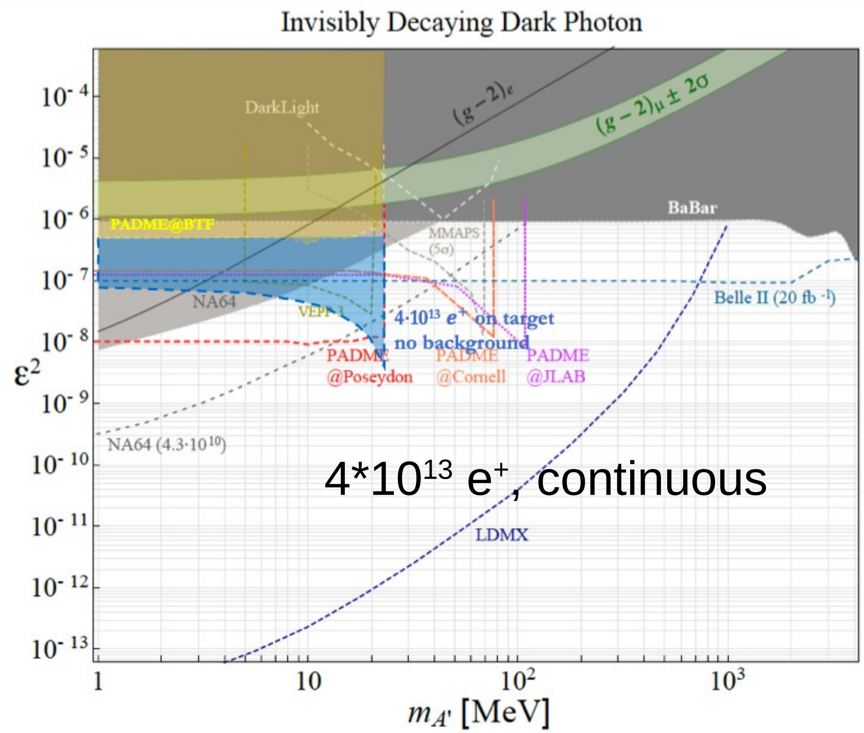
PADME @ DAΦNE





- PADME@POSEYDON
  - Statistics determined by the requirement of ~100 e^+ per 1 ns (due to ECal BGO)
  - $4*10^7$ positrons in a bunch of 400 μs
  - 10^{16} e^+ in 1 year of operation
  - Assuming same background

- PADME @ DAΦNE Ultra slow extraction
  - Single particle mode
    - Single event sensitivity, zero background!
  - Number of positrons – up to few*10^{15}
  - Breakthrough in fixed target and a game changing option!

M_{miss} searches in e^+ on target

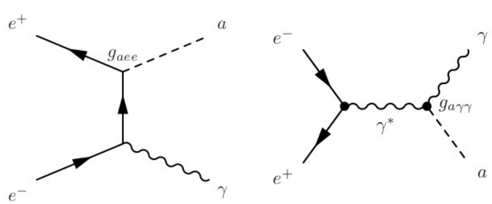
	PADME	MMAPS	VEPP3	PADME @POSEYDON	PADME@DAΦNE Ultra slow
Place	LNF	Cornell	Novosibirsk	LNF	LNF
Beam energy	550 MeV	Up to 5.3 GeV	500 MeV	550 MeV	550 MeV
$M_{A'}$ limit	23 MeV	74 MeV	22 MeV	23 MeV	23 MeV
Target thickness	2×10^{22} e^-/cm^2	$O(2\times10^{23})$ e^-/cm^2	5×10^{15} e^-/cm^2	2×10^{22} e^-/cm^2	2×10^{22} e^-/cm^2
Beam intensity	8×10^{-11} mA	2.3×10^{-6} mA	30 mA	3×10^{-7} mA	4×10^{-8} mA
$e^+e^- \to \gamma\gamma$ rate [s^{-1}]	15	2.2×10^6	1.5×10^6	$4*10^4$	4500
ε^2 limit (plateau)	**10^{-6} (*10^{-7} SES*)**	**$10^{-6} – 10^{-7}$**	**$10^{-7/-8}$**	**10^{-8} ***	***10^{-9} - 10^{-10} SES *****
Time scale	now	?	2020 (ByPass)?		
Status	**Run 1 Next run: 2020**	**Not funded Alternatives?**	**ByPass currently suspended?**	**In discussion**	**In discussion**

**** PADME background level assumption!***

***** with zero background assumption!***

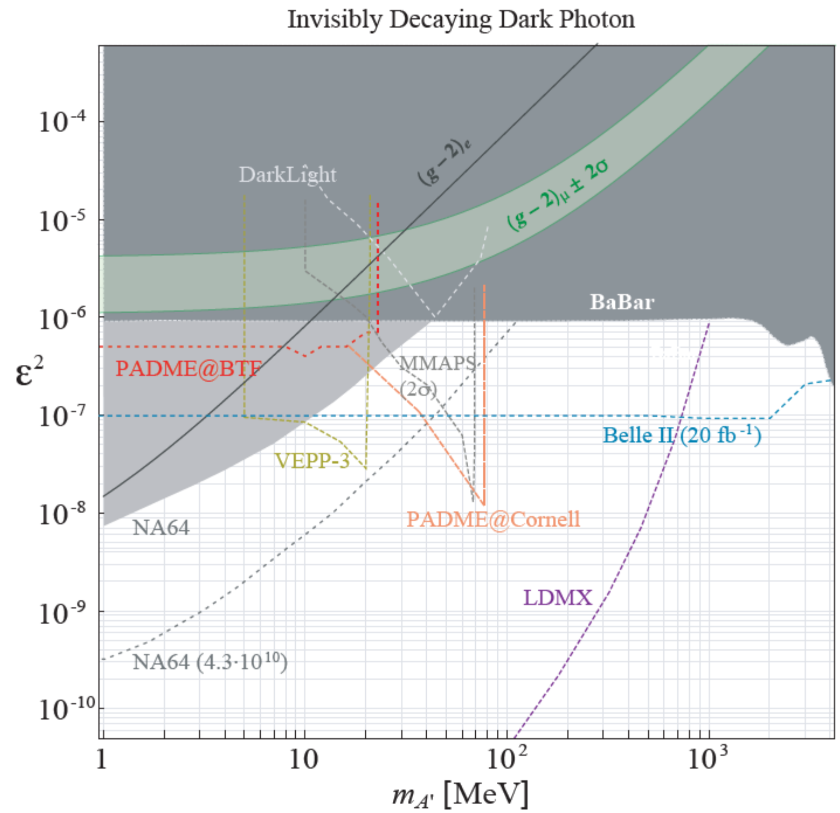
Perspectives

- The limit in the PADME sensitivity originates from
  - Statistics, sensitivity ~ sqrt(N)
  - Background – due to overlapping, scales as N
  - e^+ beam energy
- ALPs at PADME
  - Sensitivity estimation ongoing
  - Any Light Particle with mass below 23 MeV



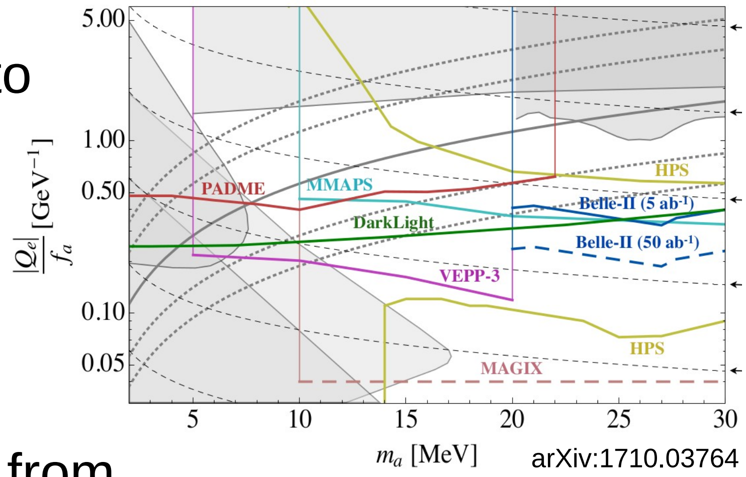
- Possible improvements
  - Increase the statistics
    - PADME@VEPP – internal gas target
    - PADME@DAΦNE
  - Increase the beam energy
    - Cornell, Jlab, etc…

N.B. Different experimental techniques, sometimes different prior assumptions!

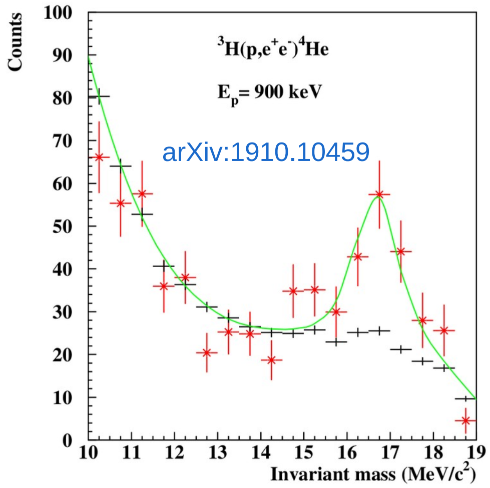


Conclusion

- Missing mass searches provide a universal probe to new light states
- Using constrained initial state allows significant background suppression and control
- PADME detector status:
  - All systems operational after an intensive effort from the collaboration and the participating laboratories
- Data analysis ongoing
  - Detector performance reaching design parameters
- Cross fingers for new insight on Dark Mediators…
  - Various approaches, complementary techniques



arXiv:1710.03764



PADME

P. Albicocco, F. Bossi, B. Buonomo, R. De Sangro, D. Domenici, G. Finocchiaro, L.G. Foggetta, A. Ghigo, F. Giacchino, P. Gianotti, A. Loreti, I. Sarra, B. Sciascia, T. Spadaro, E. Spiriti, E. Vilucchi, A.P. Caricato, F. Gontad, M. Martino, I. Oceano, F. Oliva, S. Spagnolo, C. Cesarotti, A. Frankenthal, J. Alexander, G. Chiodini, F. Ferrarotto, E. Leonardi, E. Long, F. Safai Tehrani, P. Valente, S. Fiore, G. Georgiev, V. Kozhuharov, B. Liberti, C. Taruggi, G.C.Organtini, G. Piperno, M. Raggi, L. Tsankov, S. Ivanov, S. Ivanov, R. Simeonov