Searching for dark sector with missing mass technique in fixed target experiments

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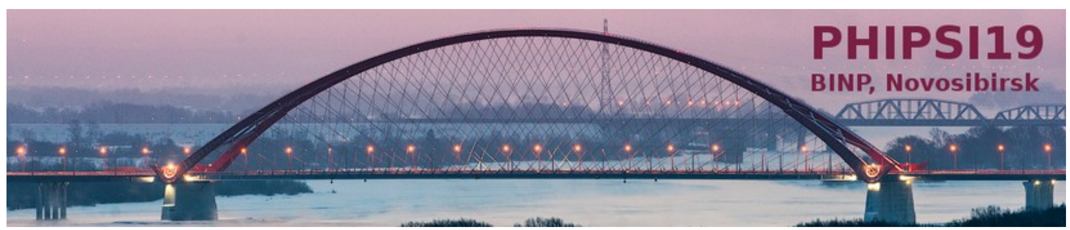


28.02.2019

** partially supported by BG NSF, DN08-14/14.12.2016 & LNF-SU 70-06-497/07-10-2014*

Outline

- Motivation
- Technique
- Positron-on-target experiments
- Meson decay in flight

Particle physics

- **Standard Model is complete: 2012 LHC - Higgs boson**
- **But unknowns:**
  - Matter-antimatter asymmetry
  - Dark Matter
  - Dark Energy
- The Standard Model is a low energy approximation of a more fundamental theory.

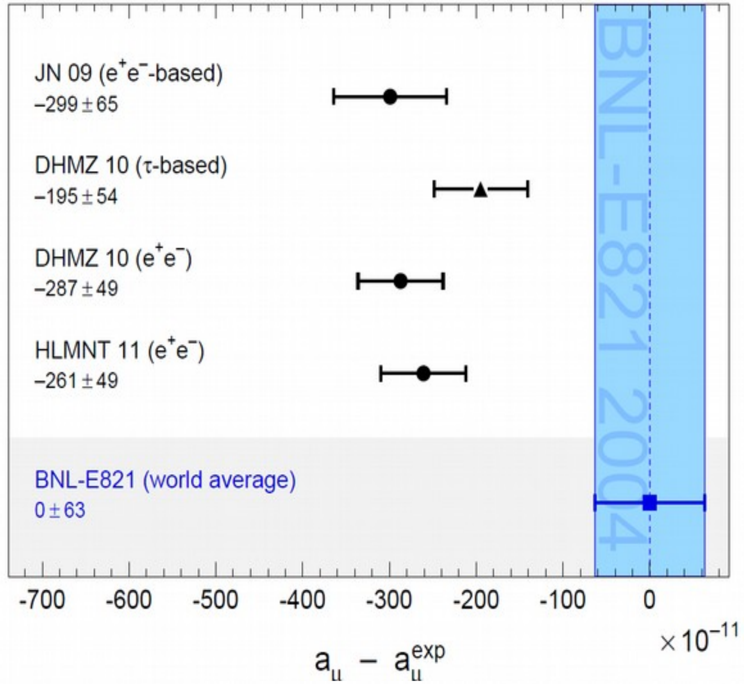
But which theory?

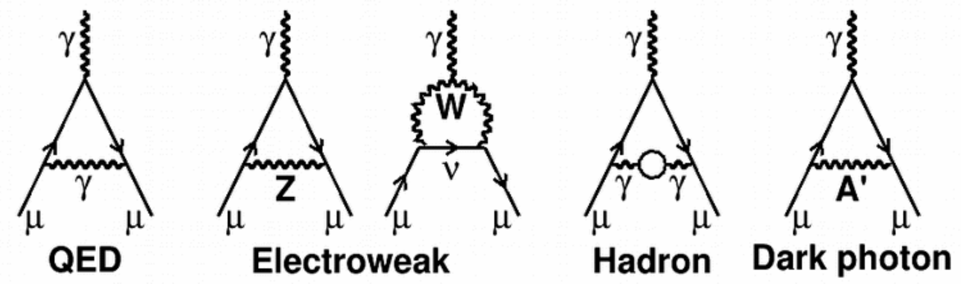
- Despite the highest energy reach LHC did not provide any convincing evidence for new degrees of freedom … yet?

Where to look? How to proceed?

New information on anything that has not been checked so far is extremely valuable!

Why Dark Photon?





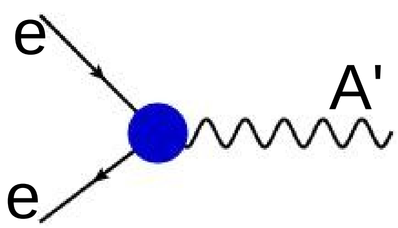
- About 3 σ discrepancy between theory and experiment (3.6 σ, if taking into account only $e^+e^- \rightarrow$ hadrons)

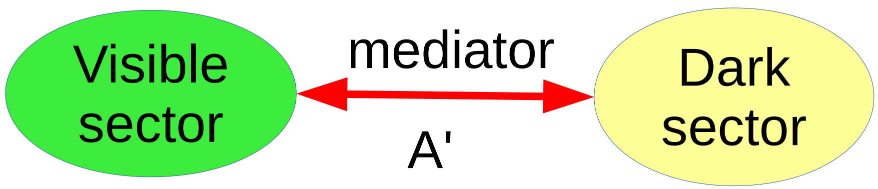
$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. 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

Hidden sector and Dark Photon

- The effective interaction that can be studied is





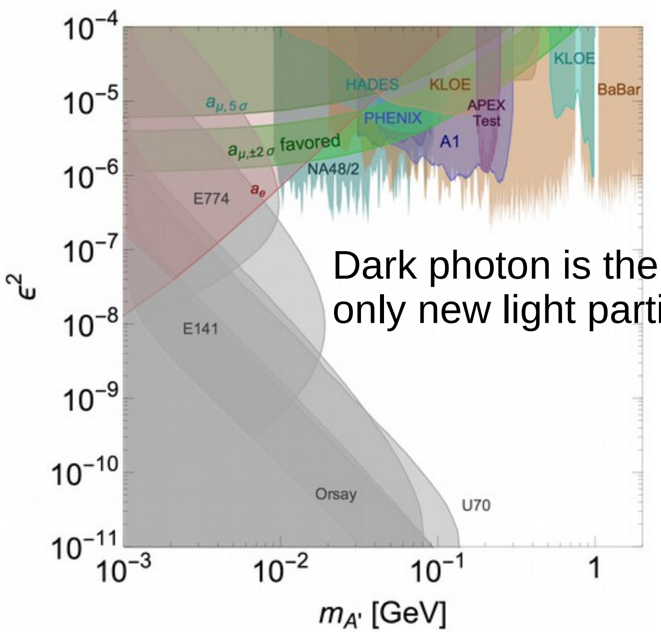
$$\boldsymbol{L} \sim g'q'\,\overline{\Psi}\,(\gamma_\mu + \alpha'_a\,\gamma_\mu\,\gamma^5)\Psi\,A'^{\,\mu},\ \ usually\ \alpha'_a = 0$$

  – $q_f \rightarrow 0$ 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. Lμ - Lτ , B – L)**
- Related to Dark matter and its interactions

Variety of Dark Photons ...

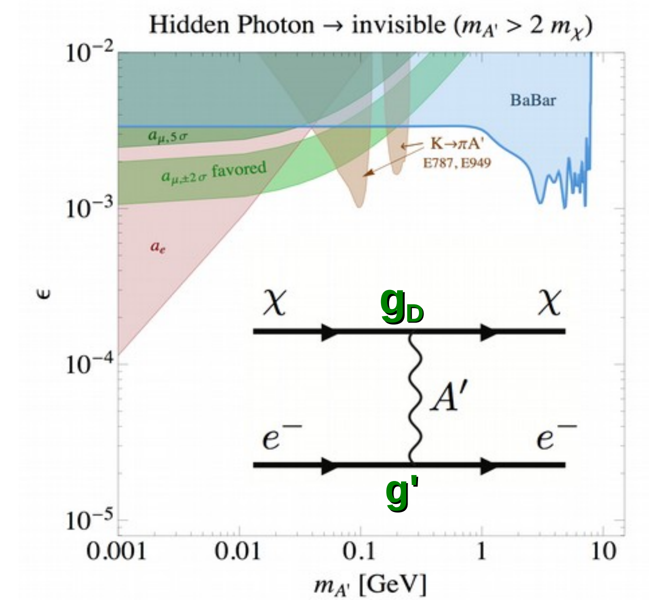


Dark photon is the only new light particle

- 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

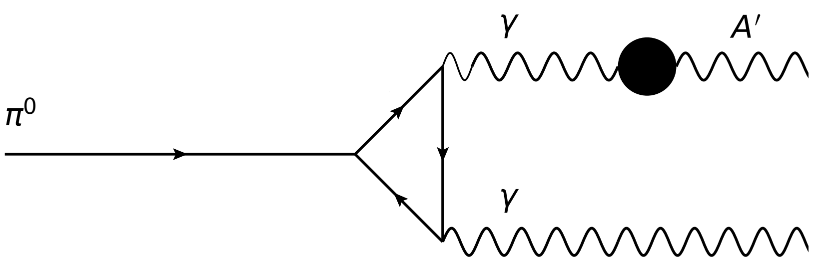
Heavy

Constrained initial process

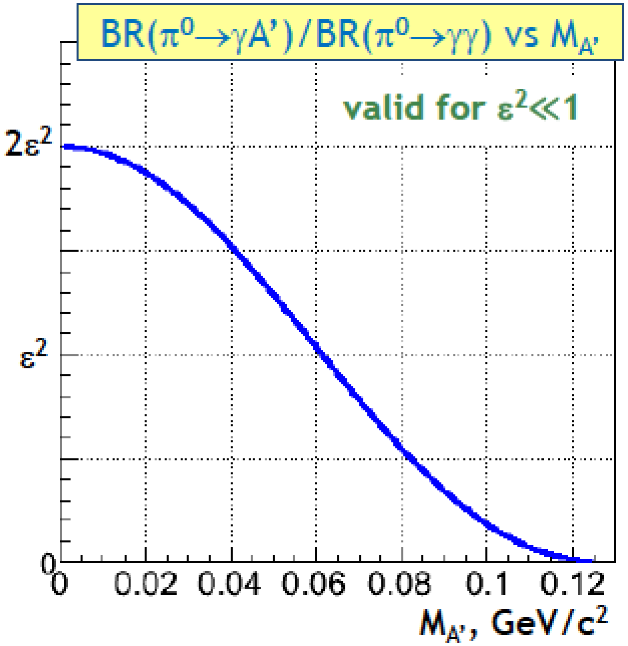
- Initial state is carefully prepared
  - A' as a product of SM particles decays: π^0, ρ, η….
  - e^+e^- colliders
  - Annihilation
- Possible A' final states
  - A' $\rightarrow$ SM particles, all states reconstruction
    - Provides significant background suppression
  - A' $\rightarrow$ DM particles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

Dark Photon in meson decays

Batell, Pospelov and Ritz, PRD 80, 095024 (2009)



$$\mathcal{B}(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathcal{B}(\pi^0 \to \gamma\gamma)$$

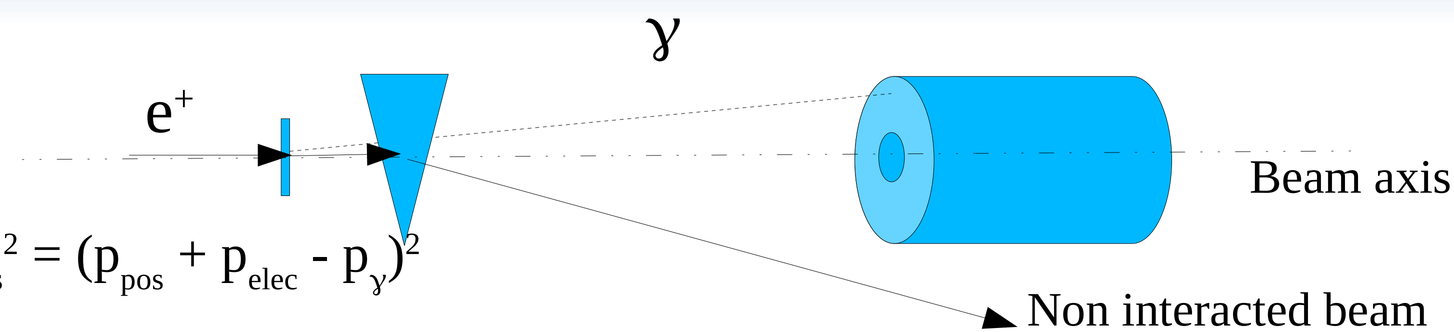


- Identify a solid source of π^0
  - @ colliders: $e^+e^- \to$ Υ, ρ, η, ϕ
  - In target production
    - Background from beam-target interaction
  - Use a cascade process, where π^0 is one of the products
    - $K^\pm \to \pi^\pm\pi^0$, $K^\pm \to \mu^\pm\pi^0\nu$ (Kμ3)

$\pi^0 \to ee\gamma$ (π^0_D)

- $Br(K^\pm \to \pi^\pm\pi^0 \to \pi^\pm e^+e^-\gamma) = 2.4 \times 10^{-3}$
- Sensitive both to visible and invisible DP, depending on the requested final state

A' in annihilation



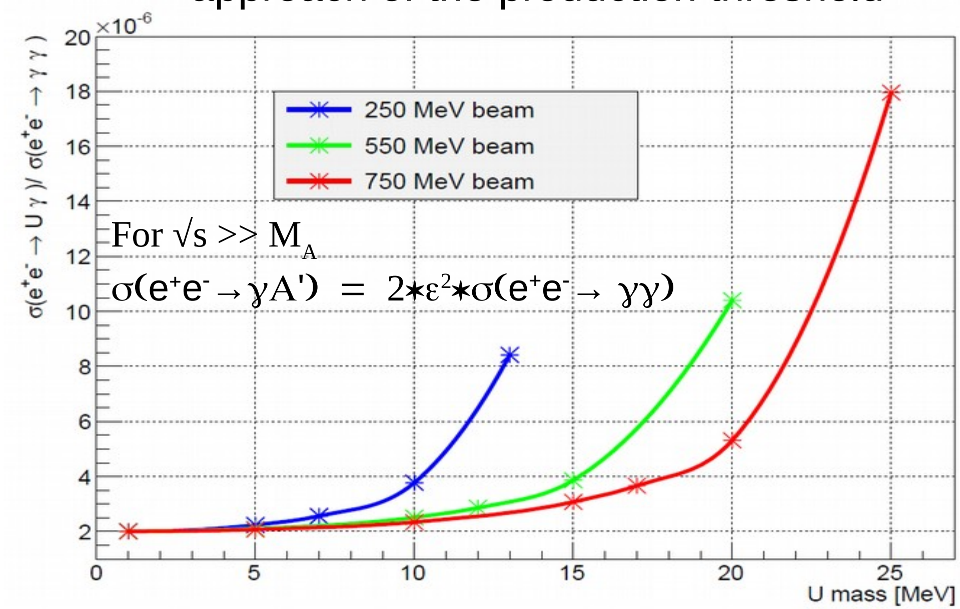
$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

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

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

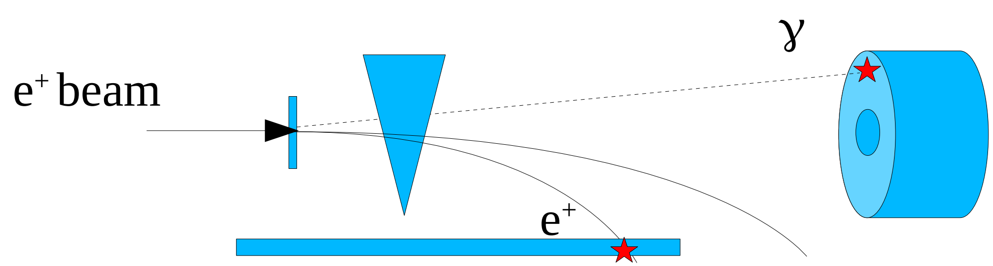
- Clear 2 body correlation
- Background minimization
  - Best possible resolution on energy/angle measurement
  - **Dominant process in e+/e- interactions with matter is bremsstrahlung**
  - Photons vetoing
  - Minimize the interaction remnants + vetoing

Cross section enhancement with the approach of the production threshold

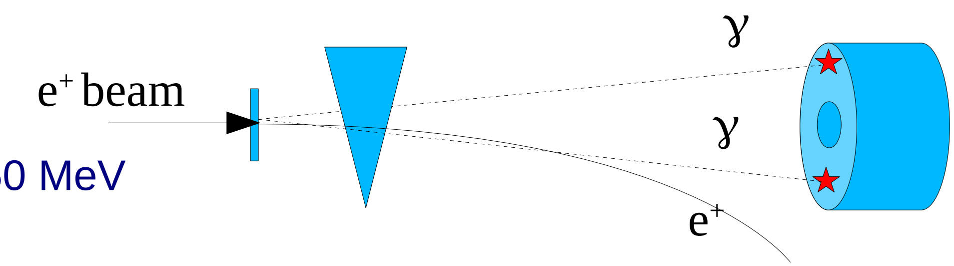


Backgrounds

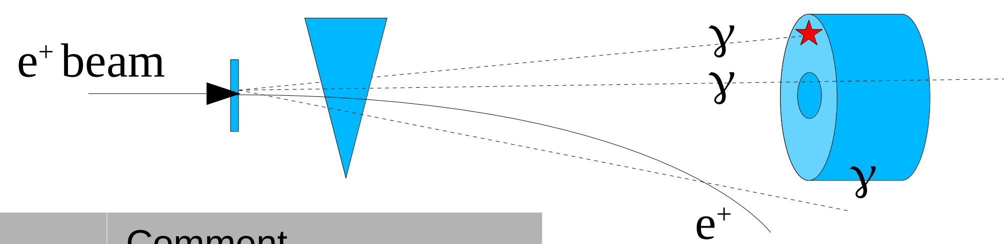
- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection



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

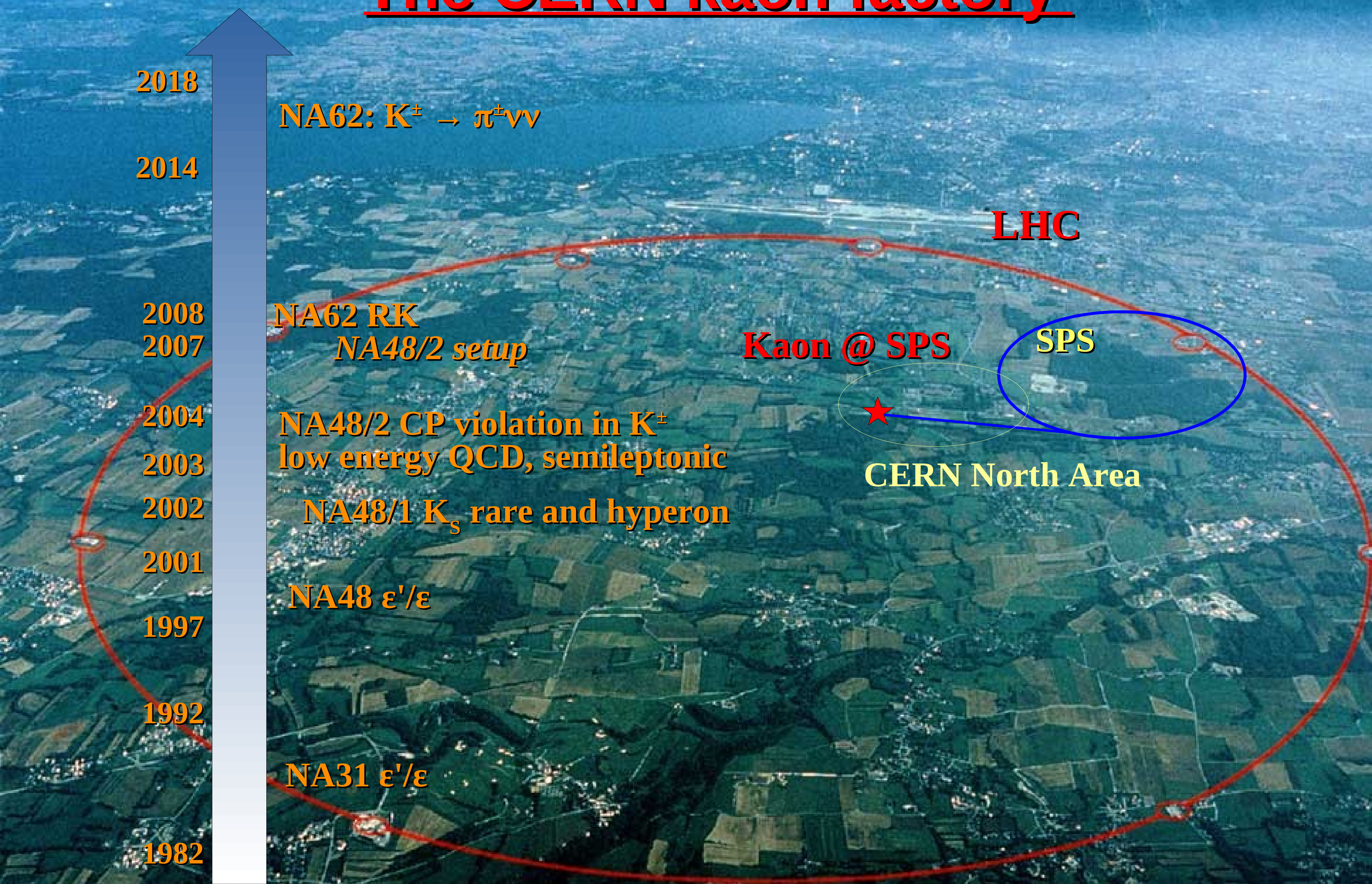


- 3 photon annihilation
  - Symmetry is lost – decrease in the vetoing capabilities
- Radiative bhabha scattering
  - Topology close to bremsstrahlung



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	$E\gamma$ > 1MeV
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma$ > 1MeV
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb	CalcHEP, $E\gamma$ > 1MeV

The CERN kaon factory



NA62 experiment

JINST 12 (2017) P05025

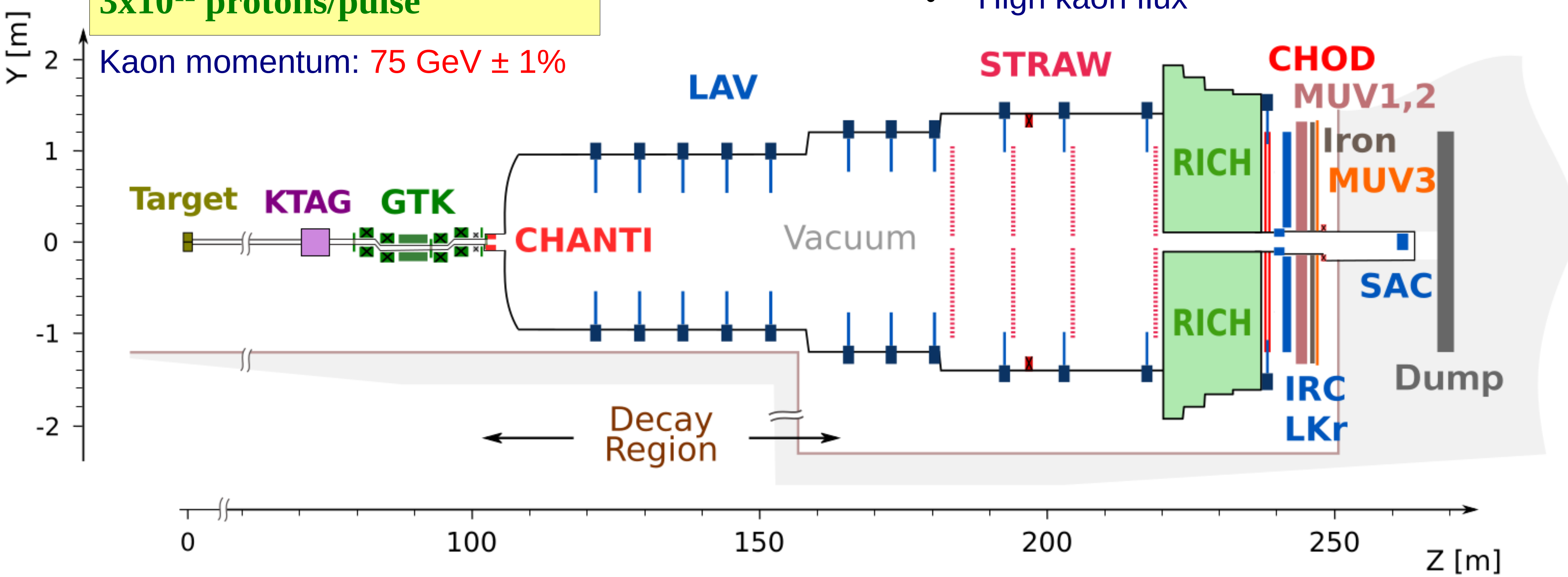
- Main goal: BR($K^+ \rightarrow \pi^+\nu\nu$) with 10% precision
  - Collect O(100) signal events ⇒ 10^{13} kaon decays
  - Measure $|V_{td}|$ with ~10% accuracy

arXiv:1811.08508

- Excellent particle veto efficiency
- Excellent momentum resolution
- Particle ID efficiency
- High kaon flux

400 GeV protons from SPS
$3x10^{12}$ protons/pulse

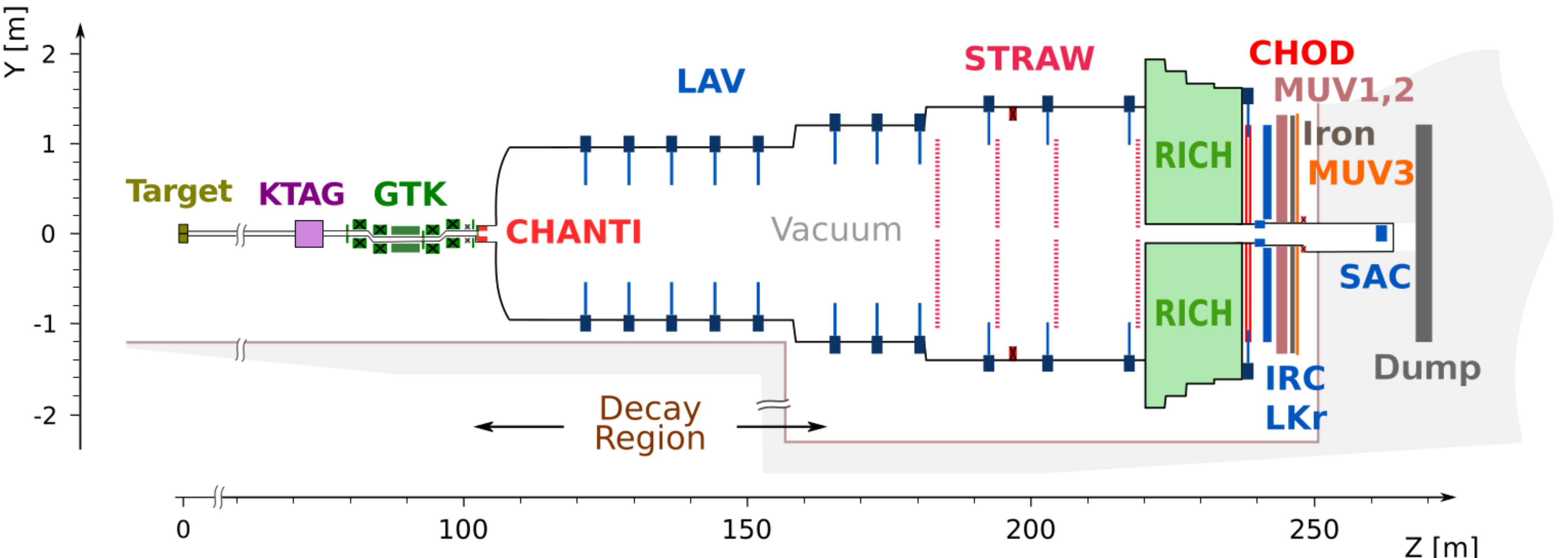
Kaon momentum: 75 GeV ± 1%



Unseparated hadron beam: kaon component 6%

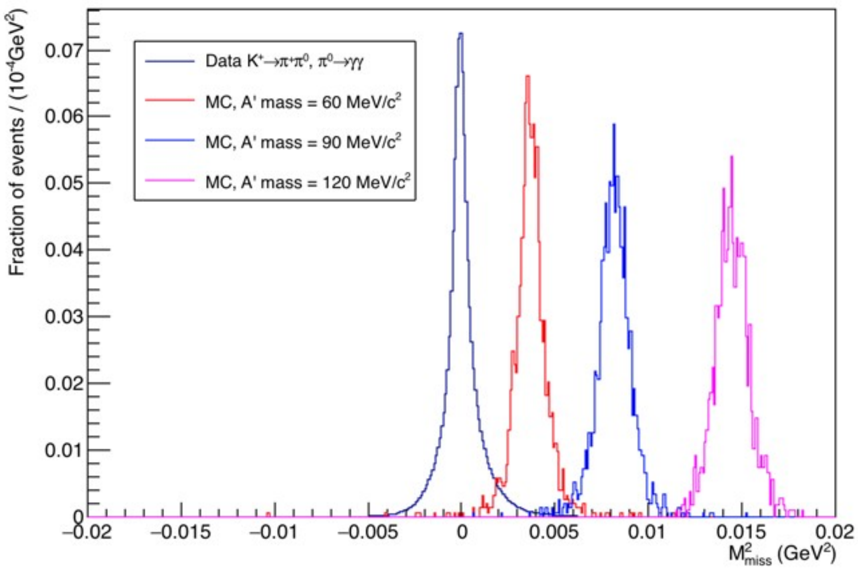
NA62 experiment

see talk of A. Shaikhiev

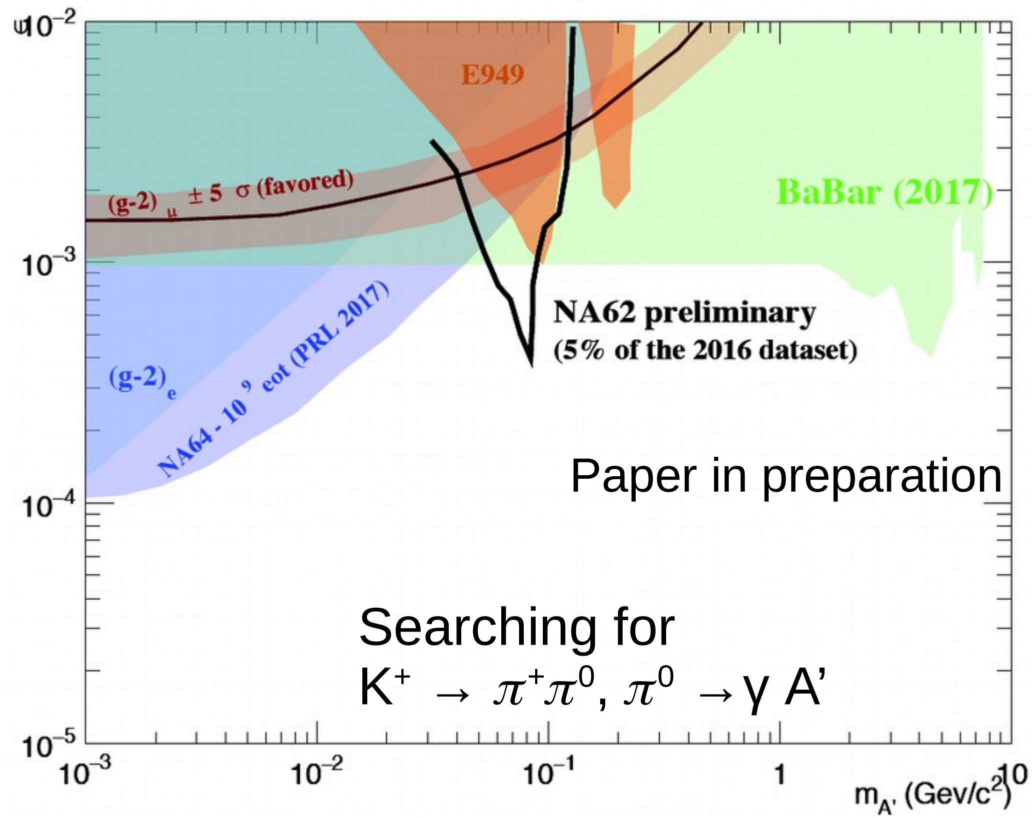


- Charged particle tracking:
  - Gigatracker: Si pixel
  - Straw chambers in vacuum
- Charged particle identification
  - KTAG: Differential Cherenkov
  - CHOD & RICH, MUVs for π/μ/e
- Hermetic photon veto
  - LAV, LKR, IRC/SAC
  - θ_{part} ~ 50 mrad
- Charged particle veto: CHANTI
  - extra activity in downstream detectors

NA62: extensive search for NP



$M^2_{miss} = (P_K - P_\pi - P_\gamma)^2$

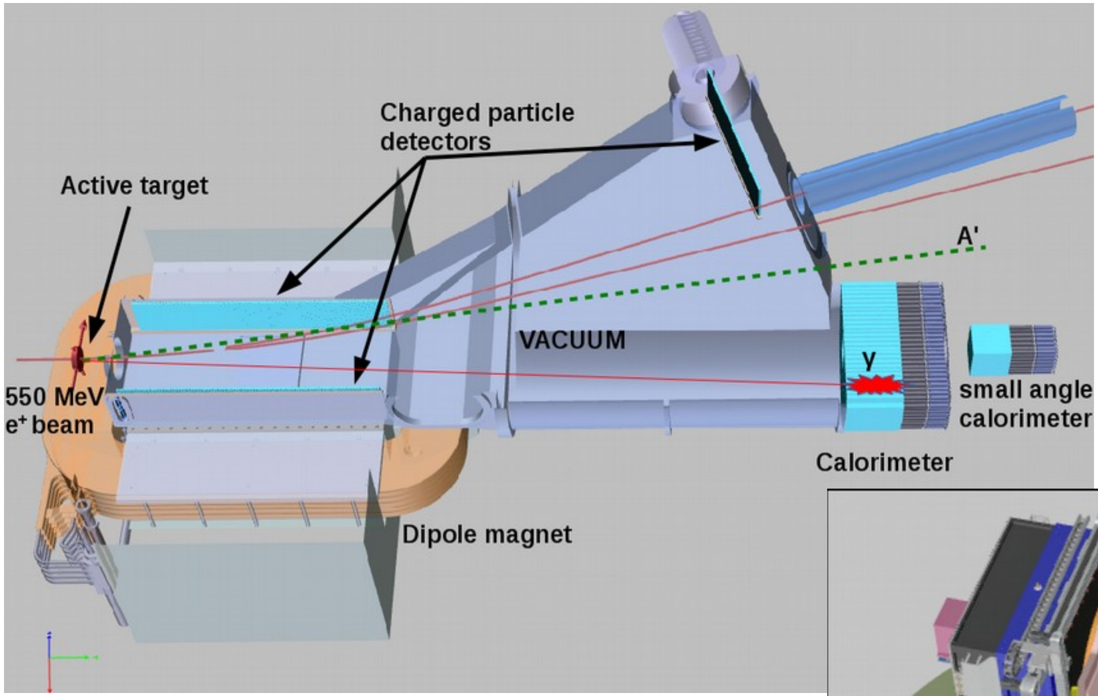


- Total number of kaons in the fiducial region – X*10¹³
- Different searches for light new states: HNL, scalars
- Lepton number violating and Lepton flavour violating channels studies

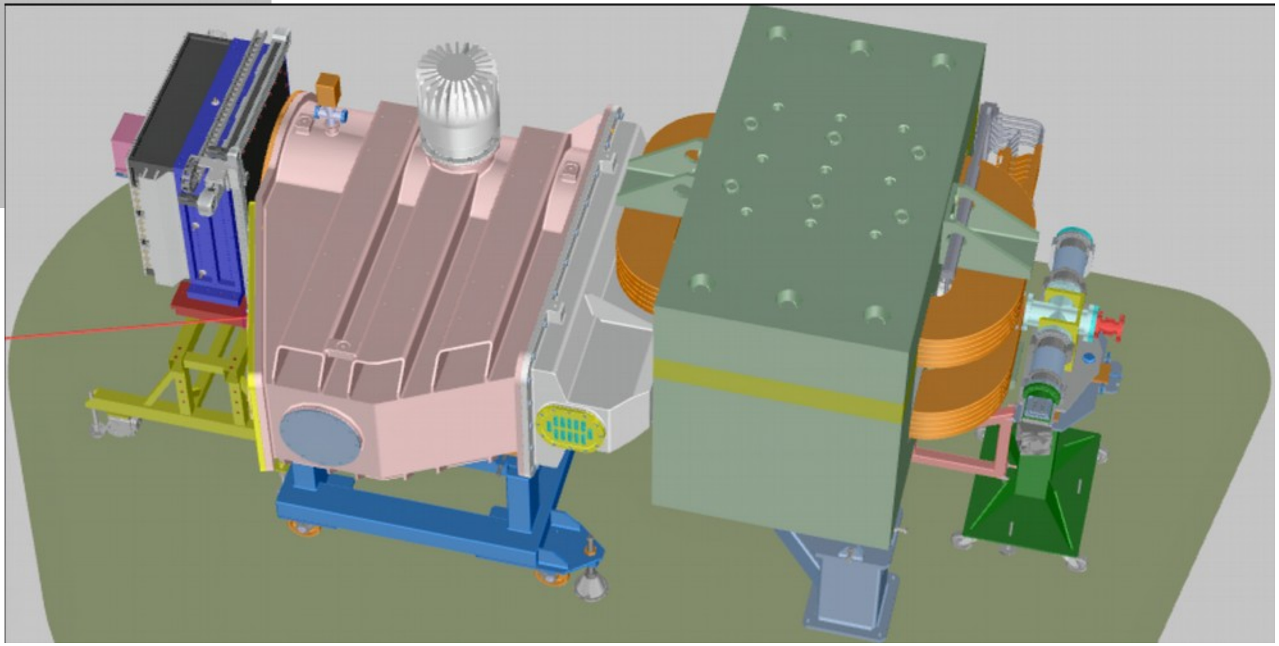
PADME

Positron Annihilation into Dark Matter Experiment

Adv. HEP 2014 (2014) 959802



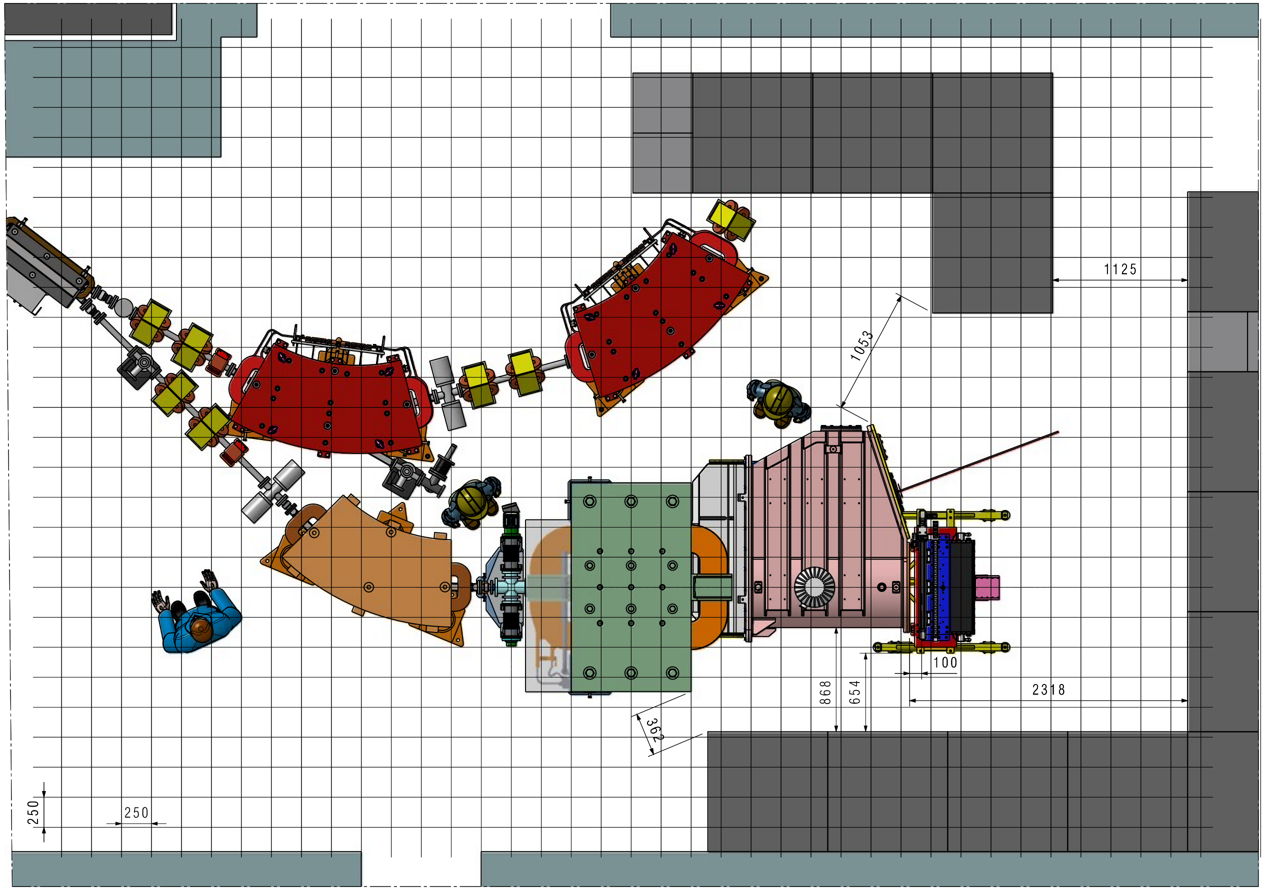
- Small scale fixed target experiment
  - e^+ @ Frascati Beam test facility
  - Solid state target
  - Charged particles detectors
  - Calorimeter



- 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

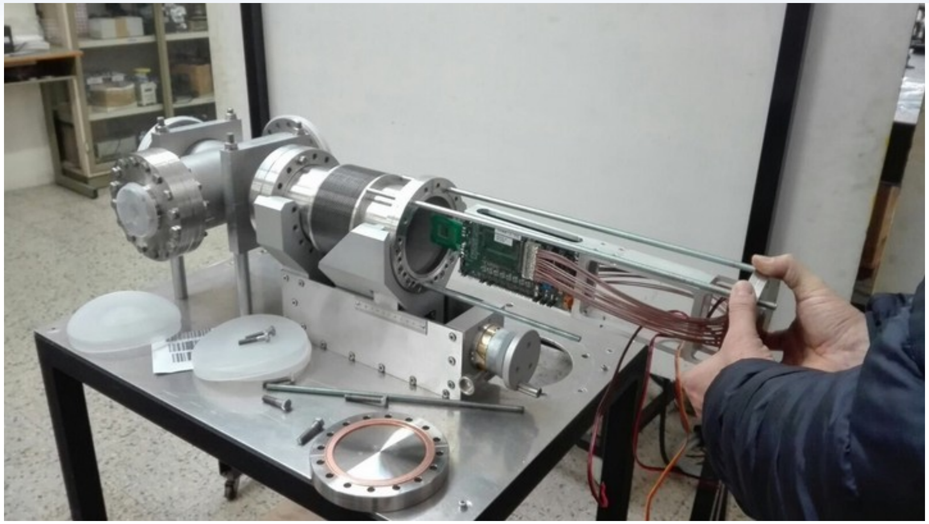
	Electrons	Positrons
Maximum beam energy (E_{beam})[MeV]	750 MeV	550 MeV
Linac energy spread [Dp/p]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 – 40 (can reach 200 in 2016)	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot s [mm]	<1 mm	
Beam divergence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

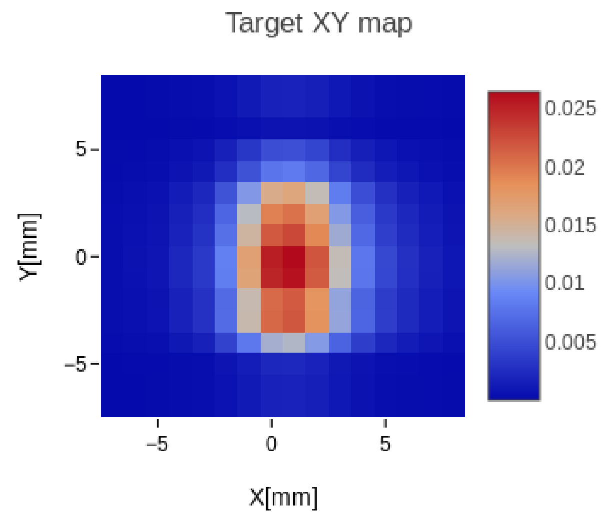


- BTF line completely dismounted
- Hall and infrastructure refurbished, control room moved
- All the components placed to their new nominal position

Outstanding support from the laboratory!

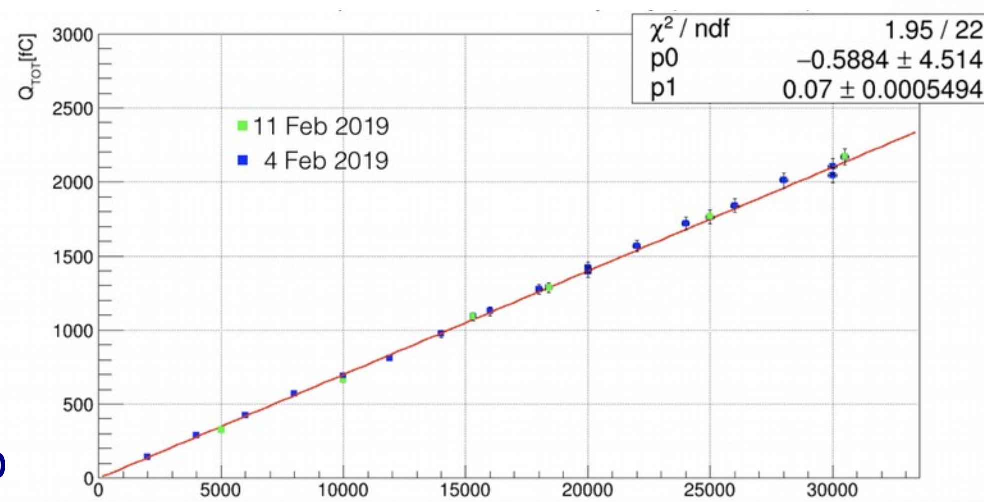
Active diamond target





Polycrystalline diamonds

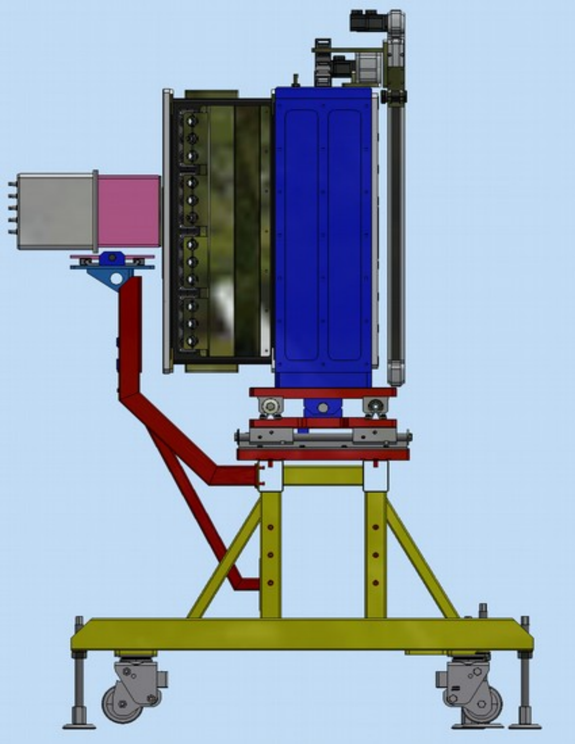
- 100 μm thickness:
- 16 × 1 mm strip and X-Y readout in a single detector
- Graphite electrodes using excimer laser (Lecce)
- PADME prototype 20 × 20 mm^2 produced and tested 2015
- Low noise CSA integrated in the 16 channel chip AMADEUS from IDEAS



Beam intensity measurement with high precision and linearity

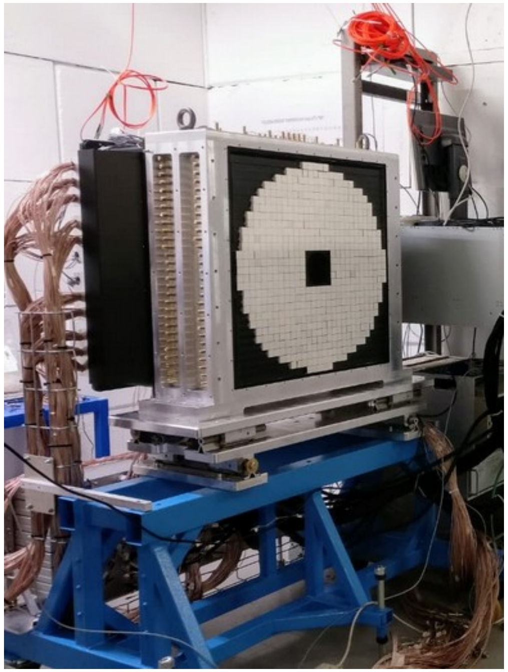
Calorimeters

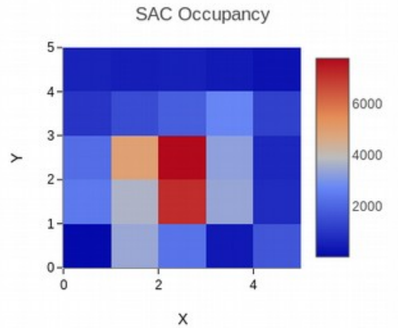
616 BGO crystals,
2.1 x 2.1 x 23 cm^3

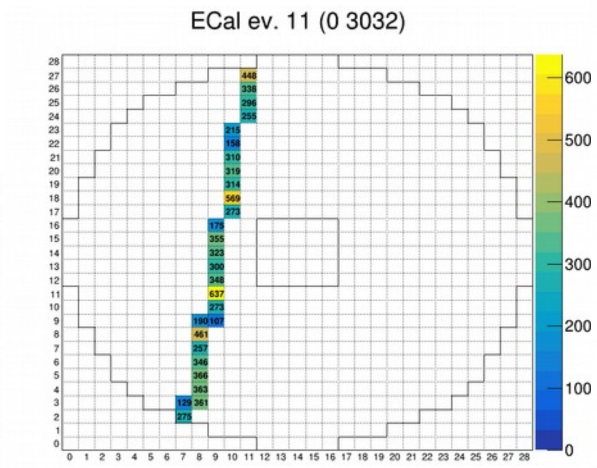


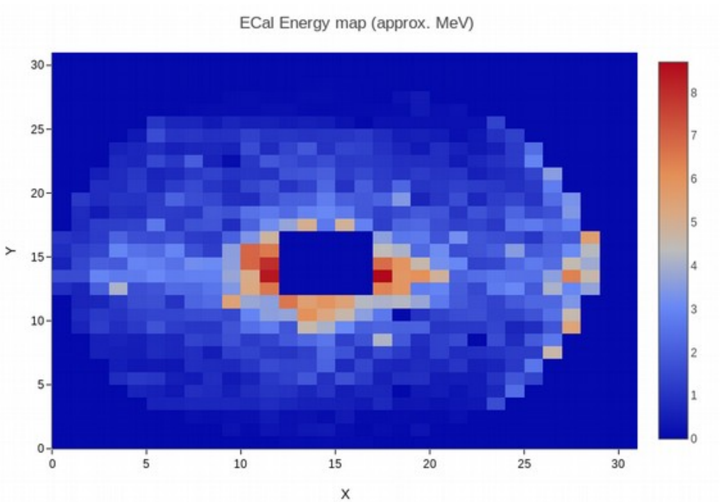
- ECAL: The heart of PADME
- BGO covered with diffuse reflective TiO_2 paint
  - additional optical isolation: 50 – 100 µm black tedlar foils

- SAC: forward photon detector
  - 5 x 5 matrix of PbF_2 crystals
  - 30 x 30 mm^2 front face
  - Hamamatsu R13478UV-11 with custom dividers



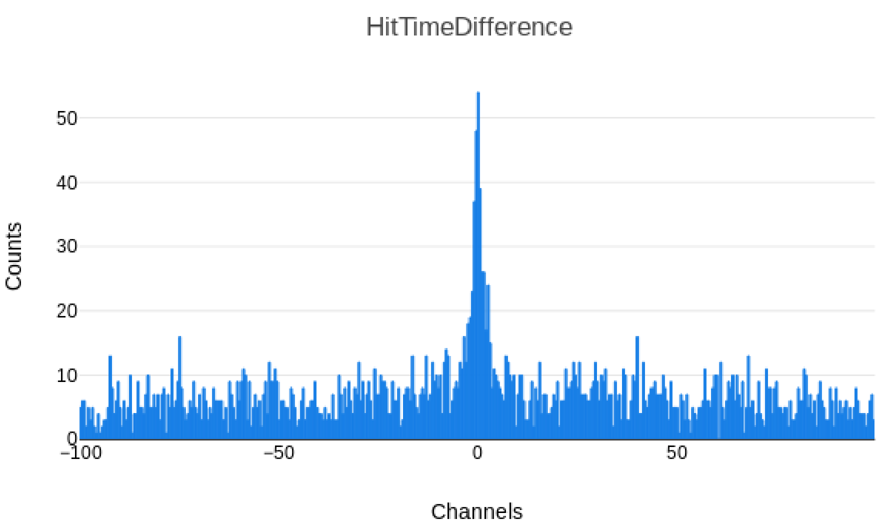


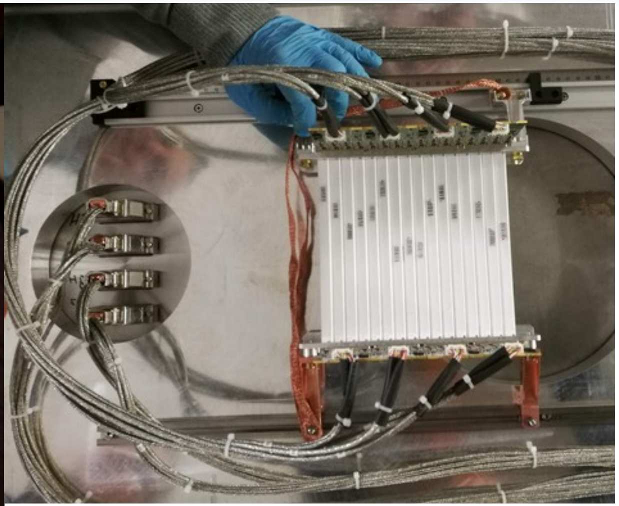




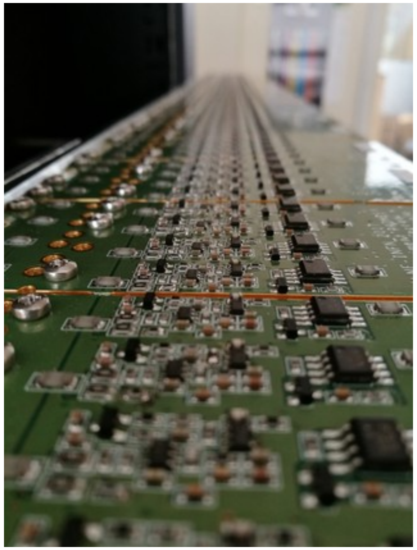
Charged particle detectors

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





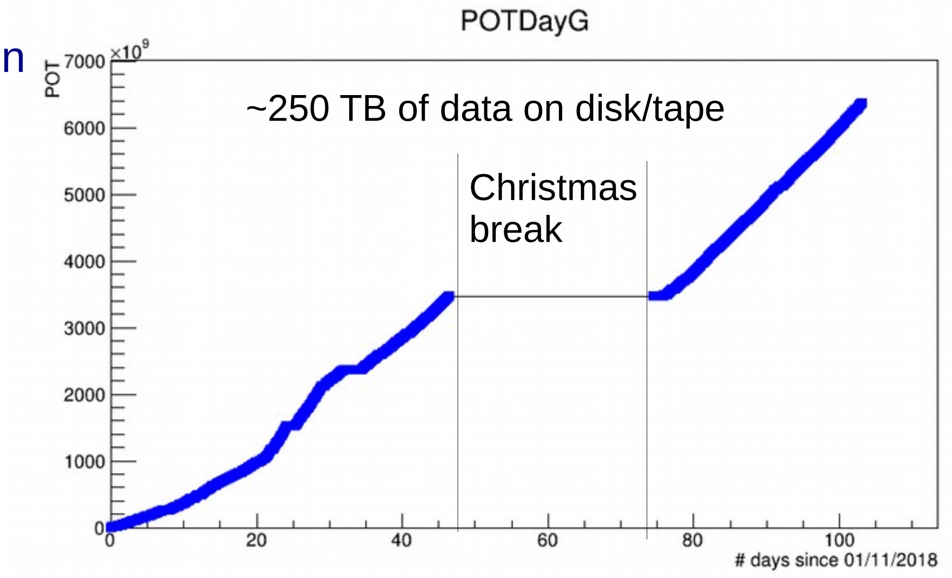
- Custom SiPM electronics, Hamamatsu S13360 3 mm, 25μm pixel SiPM
- Differential signals to the controllers, HV, thermal and current monitoring

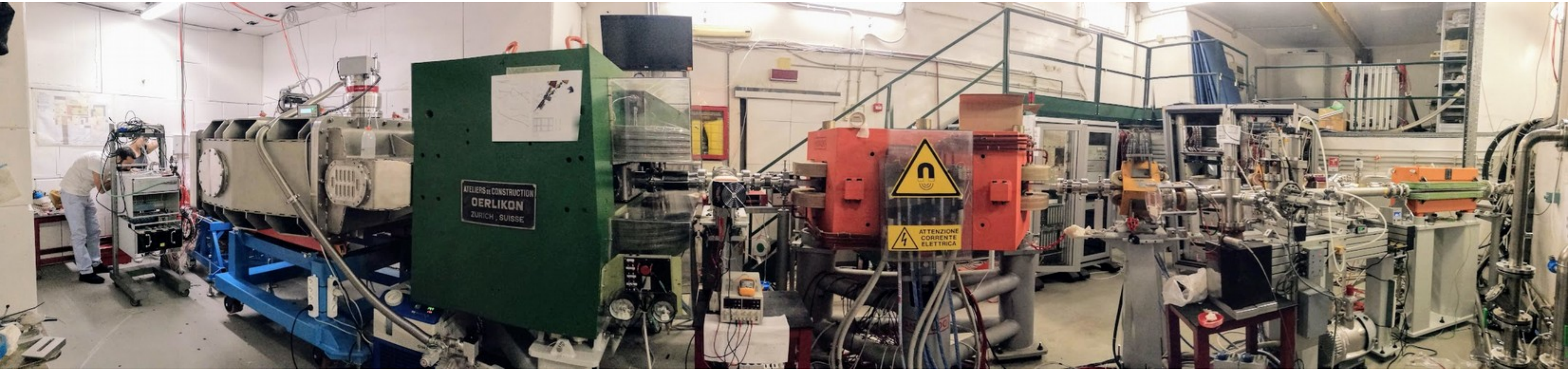


- Online time resolution: ~ 2 ns
- Offline time resolution after fine T_0 calculation – better than 1 ns

Data taking

- PADME commissioning and Run-1 started in Autumn 2018 and ended on February 25th
- > 6×10^{12} positrons on target recorded
- Data quality and detector calibration in progress
- 2 months of stop before PADME Run-2
  - At least the same amount of running time expected
  - Time for analysis and deeper understanding of the collected data





PADME sensitivity

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

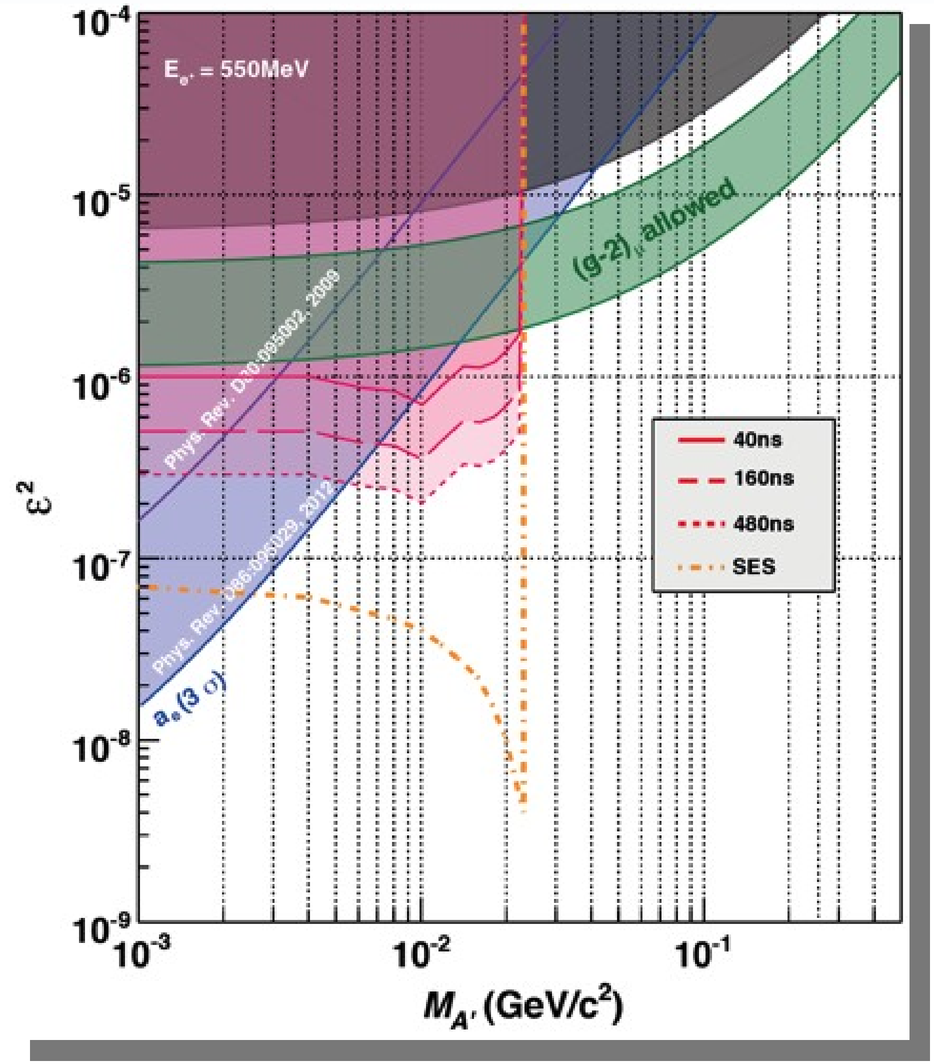
Number of BG events is extrapolated to 1x10^{13} electrons on target

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

PADME:

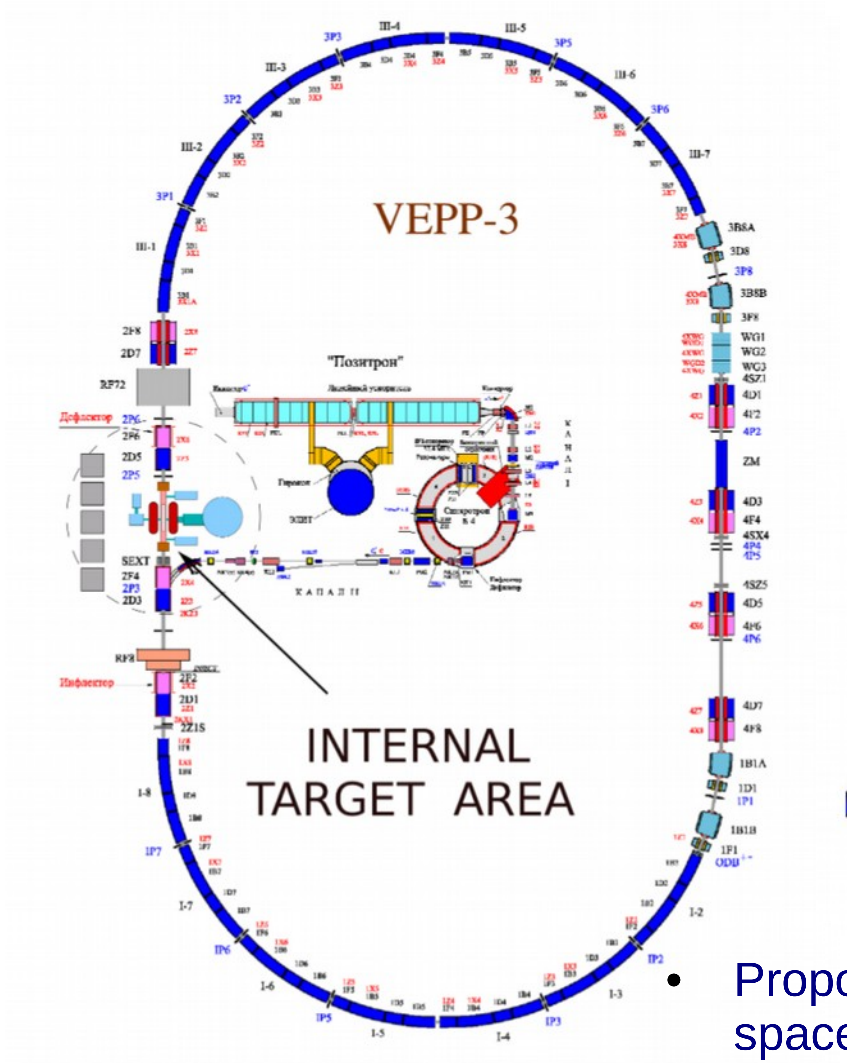
2 years of data taking at 60% efficiency with bunch length of 200 ns

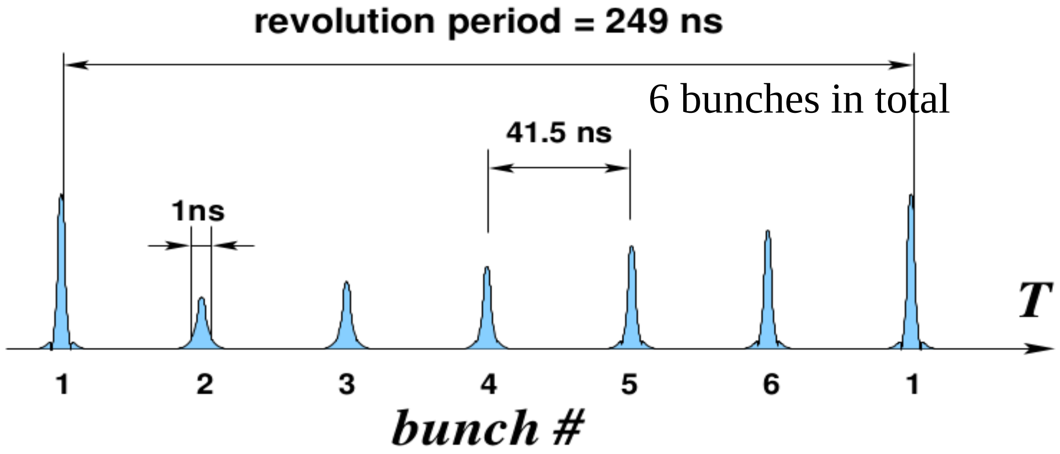
4x10^{13} EOT = **20000 e**$^+$/bunch × 2 × **3.1 · 10^7**s x 0.6 · **49 Hz**

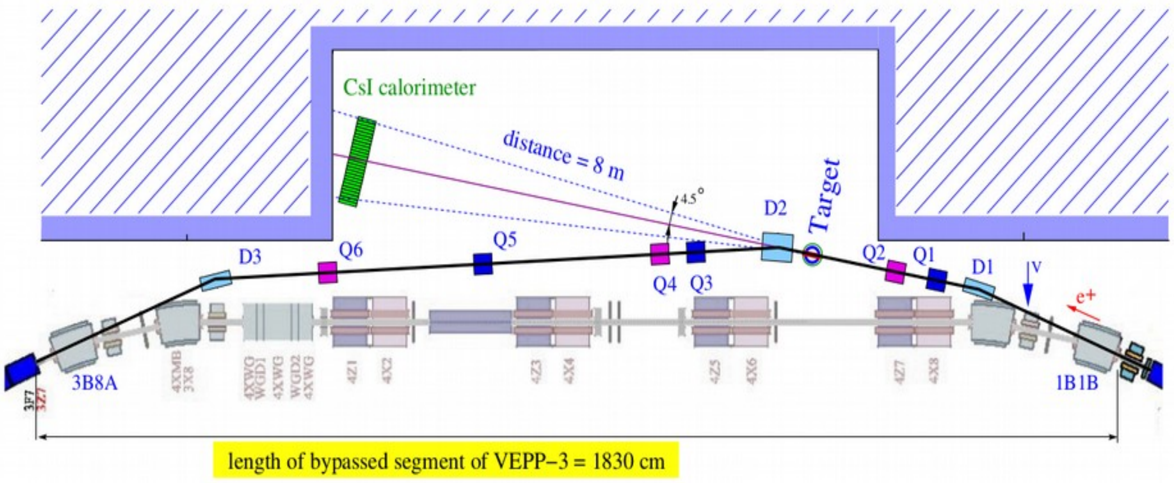


VEPP 3

- 500 MeV storage ring @ Novosibirsk





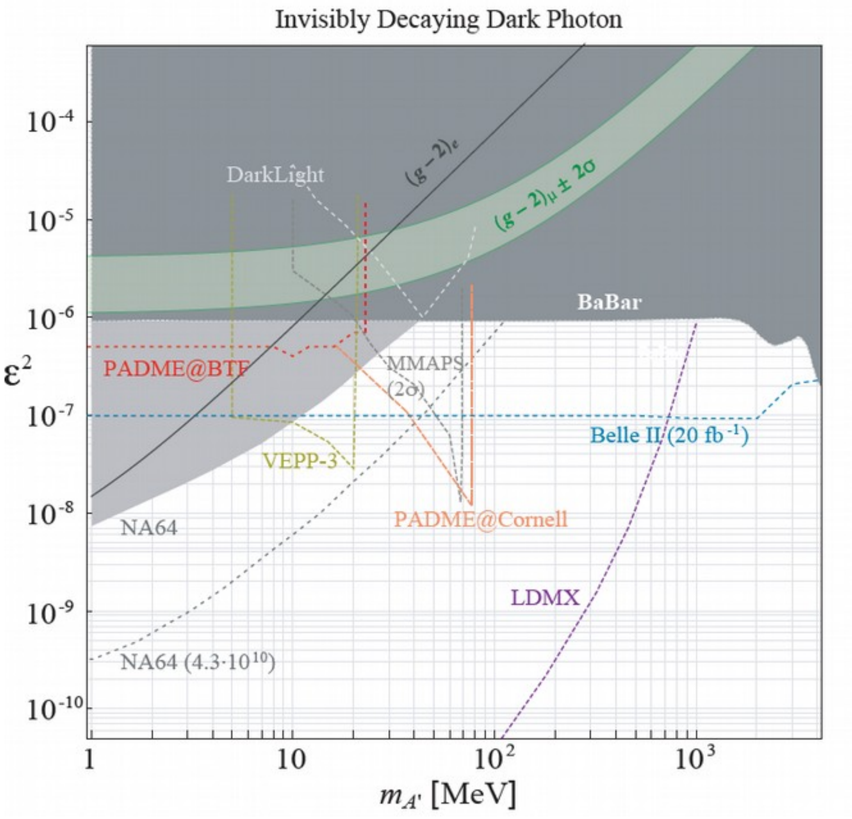


- Proposed to construct a ByPass, allowing to utilize available space for a crystal calorimeter and shielding
- Operating in paralel with the ongoing VEPP-3 activities

Perspectives

- The limit in the PADME sensitivity originates from
  - Statistics, sensitivity ~ sqrt(N)
  - Background – due to overlapping, scales as N
  - e^+ beam energy
- Possible improvements
  - Increase the statistics
    - PADME@VEPP – internal gas target
    - PADME@DAΦNE – slow extraction
  - Increase the beam energy
    - Cornell, Jlab, etc…

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



M_{miss} searches in e^+ on target

	PADME	MMAPS	VEPP3
Place	LNF	Cornell	Novosibirsk
Beam energy	550 MeV	Up to 5.3 GeV	500 MeV
$M_{A'}$ limit	23 MeV	74 MeV	22 MeV
Target thickness	$2x10^{22}$ e^-/cm^2	$O(2x10^{23})$ e^-/cm^2	$5x10^{15}$ e^-/cm^2
Beam intensity	8×10^{-11} mA	2.3×10^{-6} mA	30 mA
$e^+e^- \rightarrow \gamma\gamma$ rate [s^{-1}]	15	2.2×10^6	1.5×10^6
ε^2 limit (plateau)	**10^{-6} (*10^{-7} SES*)**	**$10^{-6} – 10^{-7}$**	**$10^{-7/-8}$**
Time scale	now	?	2020 (ByPass) ?
Status	**Ending run 1 Expecting run 2**	**Not funded Alternatives?**	**ByPass currently suspended?**

Conclusion

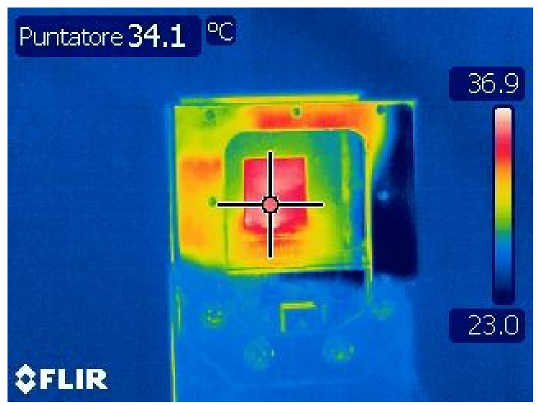
- Missing mass searches provide a universal probe to new light states
- Using constrained initial state allows significant background suppression and control
- NA62 is the present kaon physics laboratory, providing also access to numerous new physics searches, including light states
- PADME just ended Run 1 data taking
  - All systems operational after an intensive effort from the collaboration and the participating laboratories
- Various approaches, complementary techniques

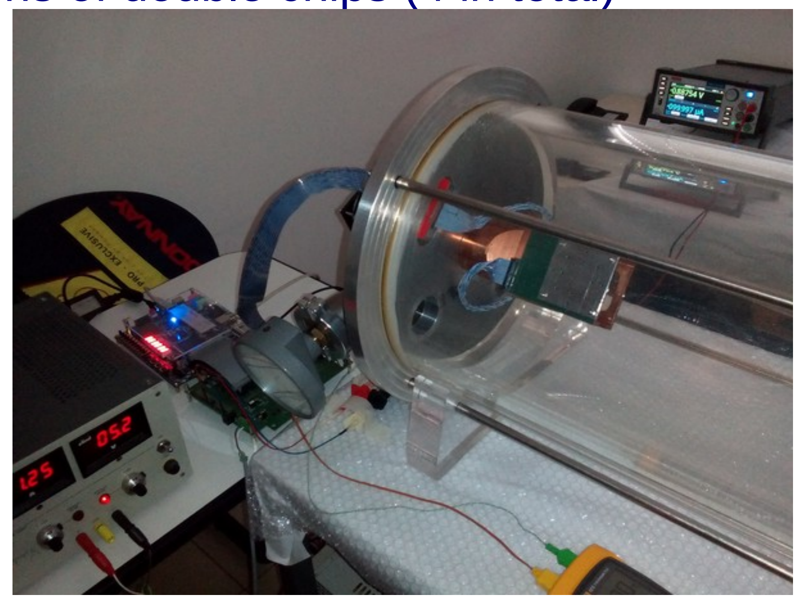
PADME early physics

- The PADME physics program is inevitably related to **precise calibration** and **monitoring of the calibration** of the detectors
- Background understanding
  - The background in the New Physics searches is the calibration tool
  - Understanding the Standard Model processes is the ticket to the “big event”
- Major background sources (or major SM processes)
  - Multiphoton annihilation
    $e^+e^- \rightarrow \gamma\ \gamma$, $e^+e^- \rightarrow \gamma\ \gamma\ \gamma$, $e^+e^- \rightarrow \gamma\ \gamma\ \gamma\ \gamma$, ….
  - Bremsstrahlung in the field of the nuclei – lack of experimental data in the range of O(100 MeV), precision of GEANT4 - ~ (3-4) %
  - Photon emission in the field of orbital electrons
- Bremsstrahlung differential cross-section measurements at different energy in the O(100 MeV) interval and (if possible) materials highly desirable
- Multiphoton annihilation to be studied and compared with MC generators

Beam measurement

- Two detectors provide a particle-by-particle beam information
  - Upstream: 50 µm thick MIMOSA chip, two stations of double chips (4 in total)
  - Downstream: TimePix3 array





- A dedicated support structure for MIMOSA operation in vacuum (Peltier cooling)
- Tested in vacuum for a fist time
  - Difference chip - copper: ~ 10°C and constant