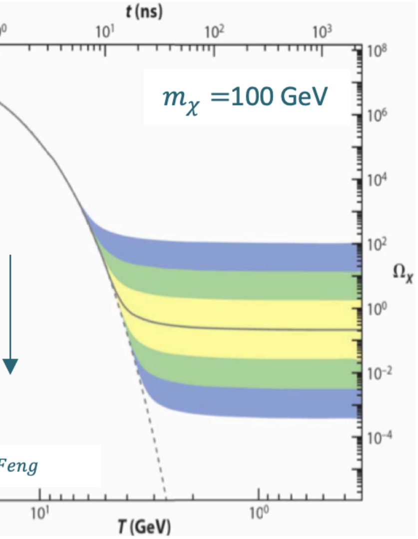
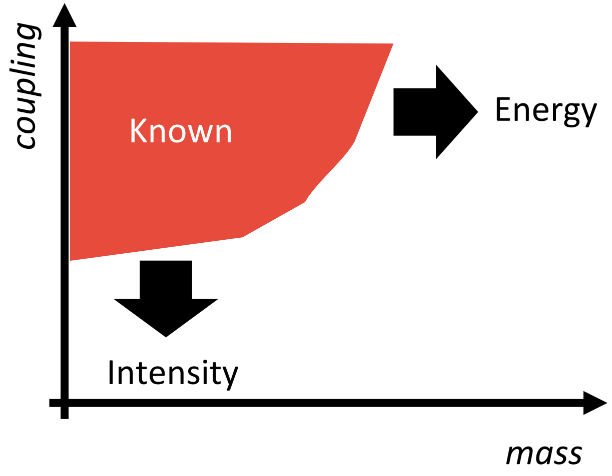
Status of PADME
and review of dark photon searches

Paolo Valente

FCCP 2019, Anacapri

Why searching for dark photons





Dark matter

spite its abundance, we don't yet know what is made of

eze-out mechanism predicts DM to be WIMPs, which ven't yet shown up

- Models indicating that DM could be **lighter** than 100 GeV - TeV

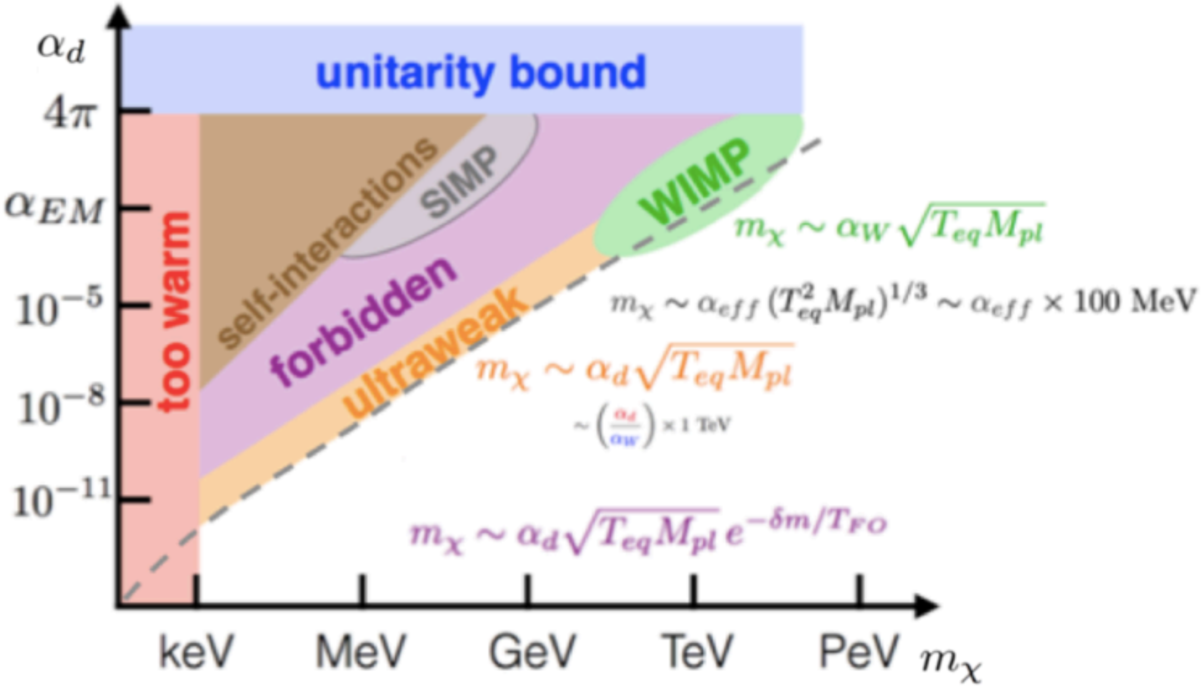
Dark or hidden sector

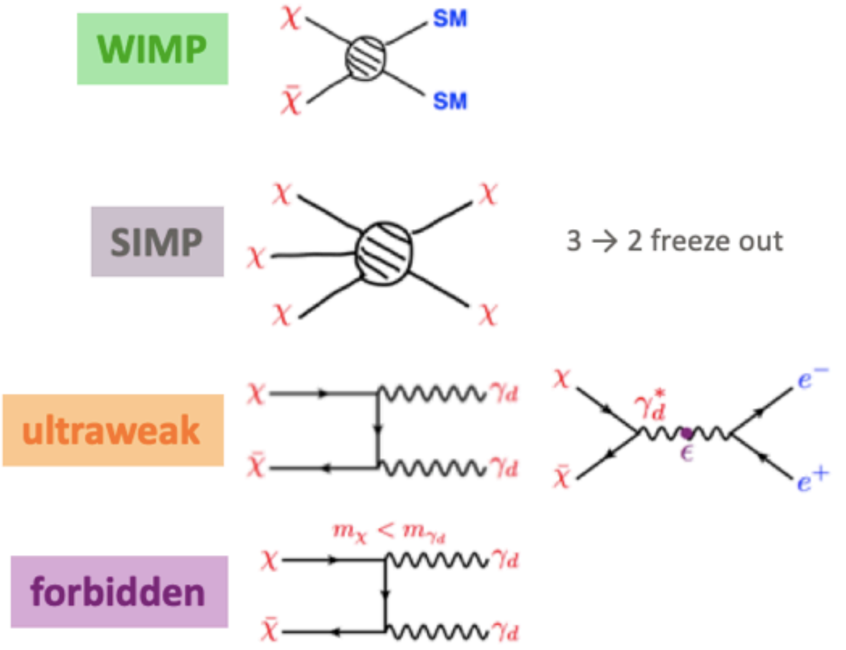
- DM living in an almost completely decoupled sec
  - Some mediator particle or "portal", can be **feebly** coupled to ordinary matter
  - Dark freeze-out mechanism allows to have a light mediator: MeV to GeV scale
- It could be a **dark photon** (vector), a axion (or AL dark Higgs (scalar), heavy neutral leptons, …

Look for signals in previously unexplored regions

- Do not rely on a single experiment
- Small, dedicated experiments very useful

Dark freeze-out



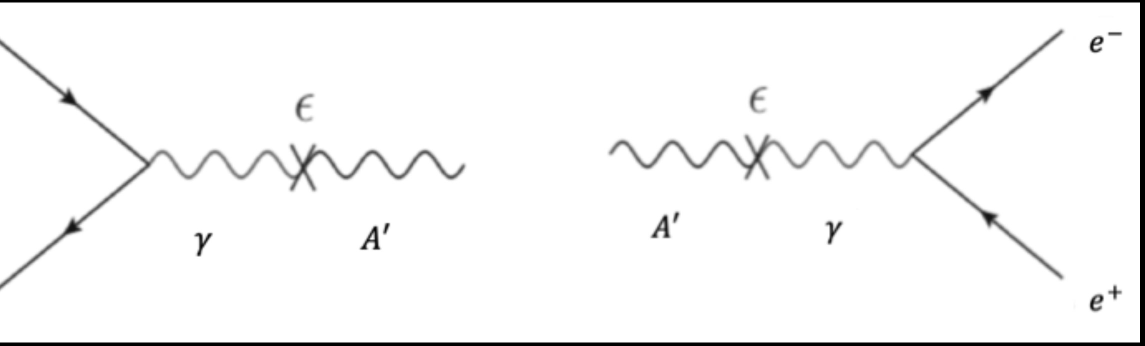


J. Ruderman

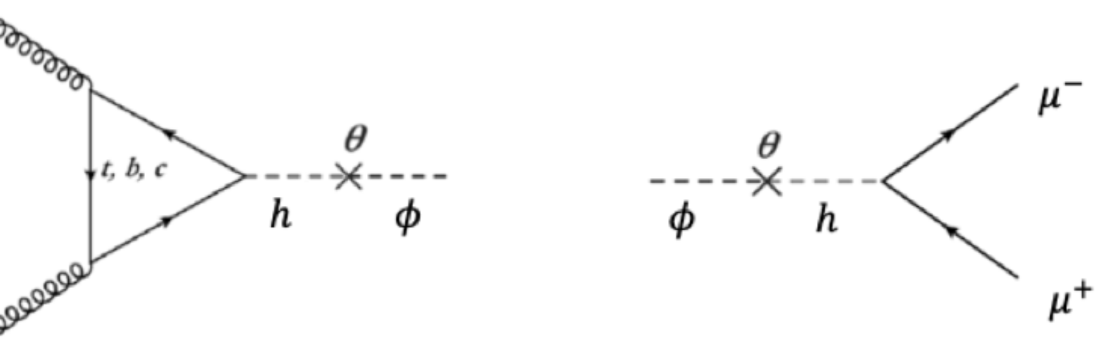
Dark photon, dark Higgs, ALP

could be a **dark photon** (vector), a axion (or ALP's), dark Higgs (scalar), heavy neutral leptons, …

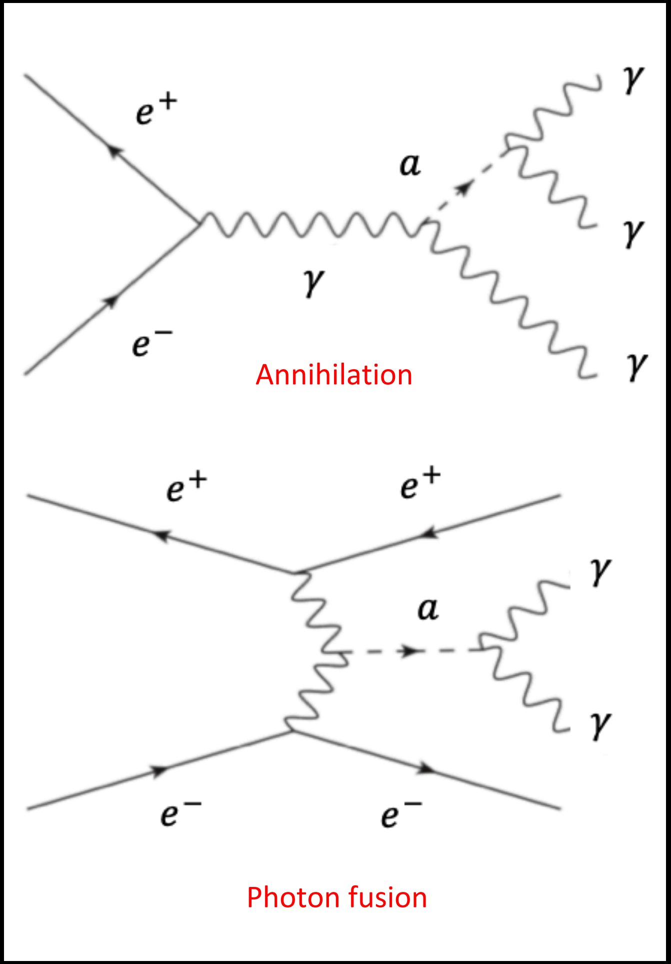
Dark photon



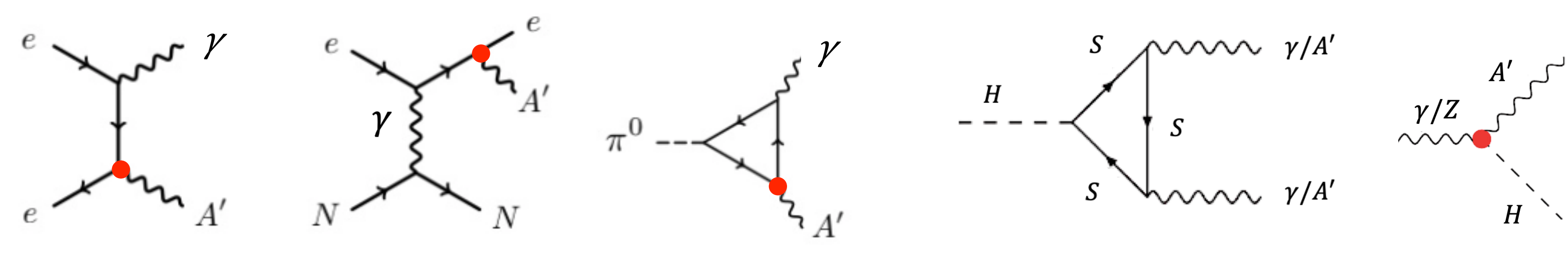
Dark Higgs



Axion-Like Particle



Dark photon production and decay



Annihilation

$e^+ e^-$ colliders

Bremsstrahlung

Fixed target e^- beam

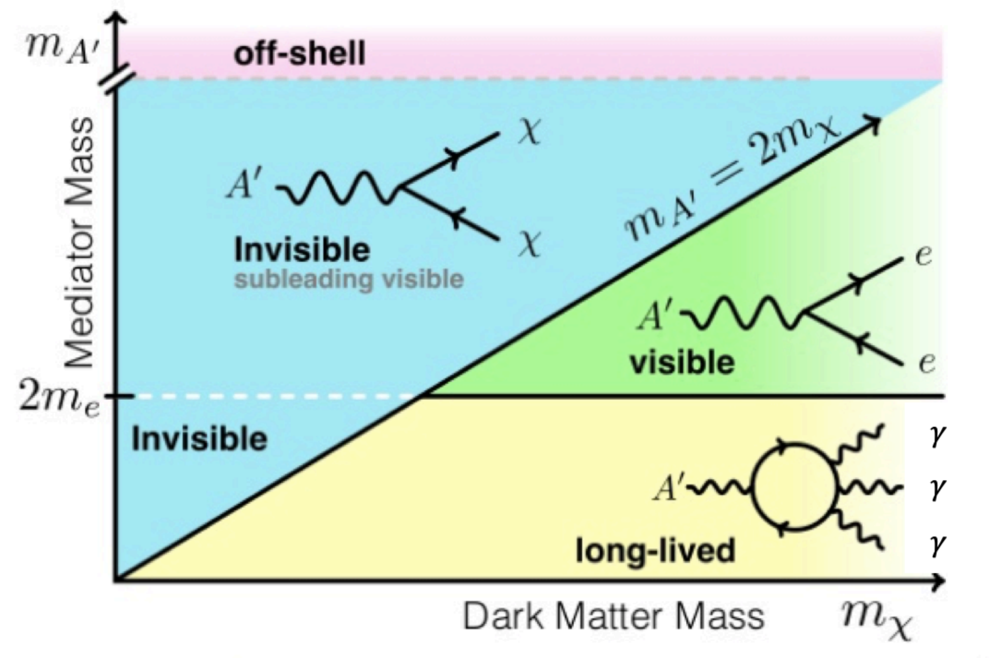
Meson decay

Hadron beams, ν experiments

+ same diagrams with

LHC

e decay will be ( ) if can decay
bly into dark sector particles…

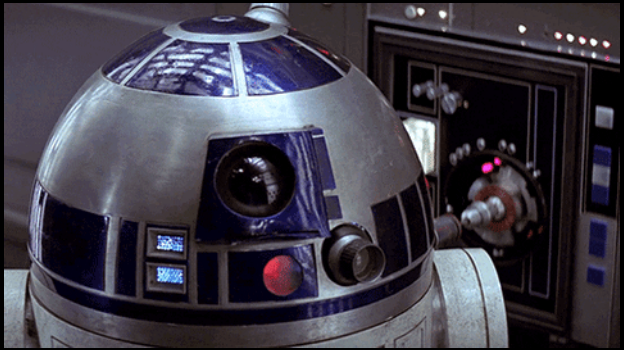


…otherwise it will decay t
lepton pairs, hadrons

Dark photon and muon $g-2$

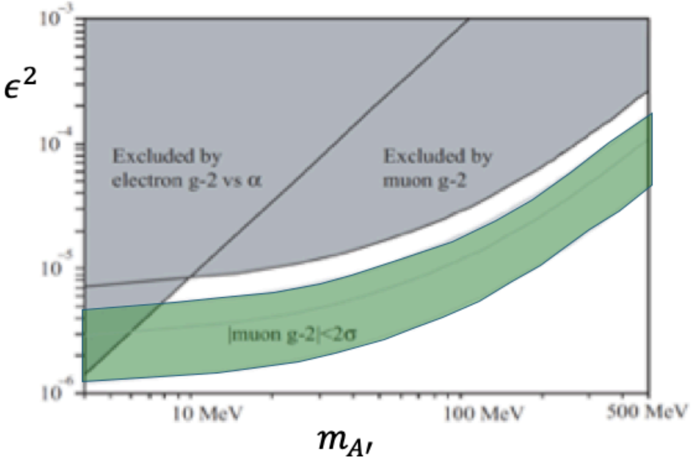
most appealing solutions to the DM problem are models which **he same time** can fix other anomalies:

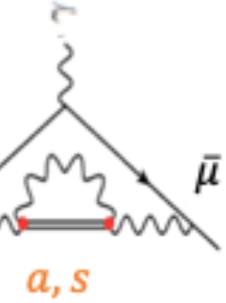
- Peccei-Quinn (light) axion would solve the strong problem
- n additional particle coupling to leptons, like a DP, could match the uon discrepancy



M. Pospelov: **Phys.Rev.D80 (2009) 095002**

$$a_\mu = \frac{\alpha\epsilon^2}{2\pi}\int_0^1 dz \frac{2m_\mu^2 z(1-z)^2}{m_\mu^2(1-z)^2 + m_{A'}^2 z}$$

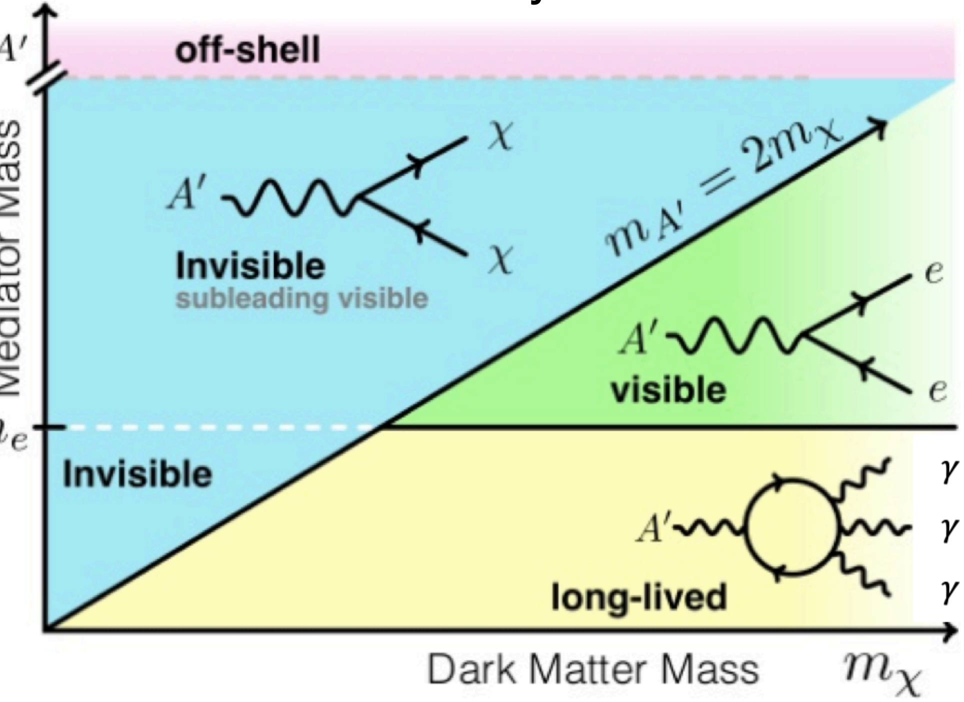




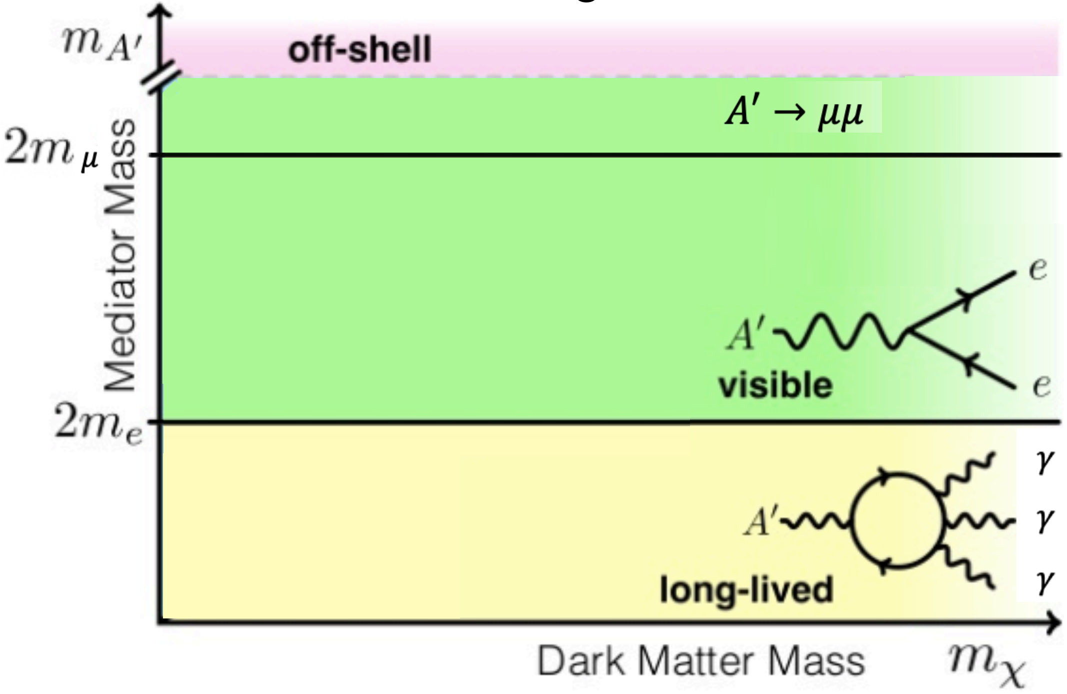
DP and ALP contributions to $(g-2)_\mu$

DP visible and invisible decays

“Heavy” DP

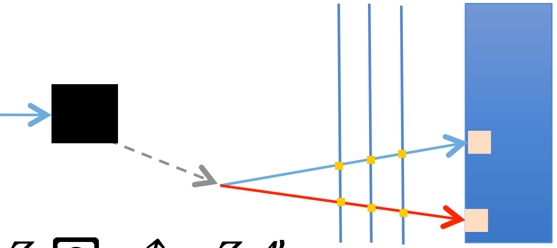


“Light” DP



DP visible decays

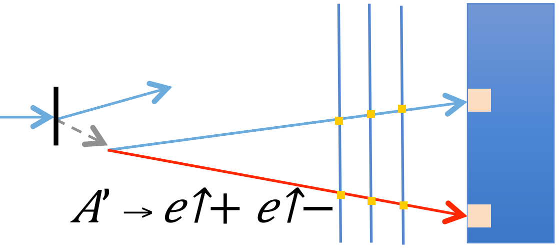
Visible decays



Z ? $e^{-} Z A'$

A' ? $e^{+} e^{-}$

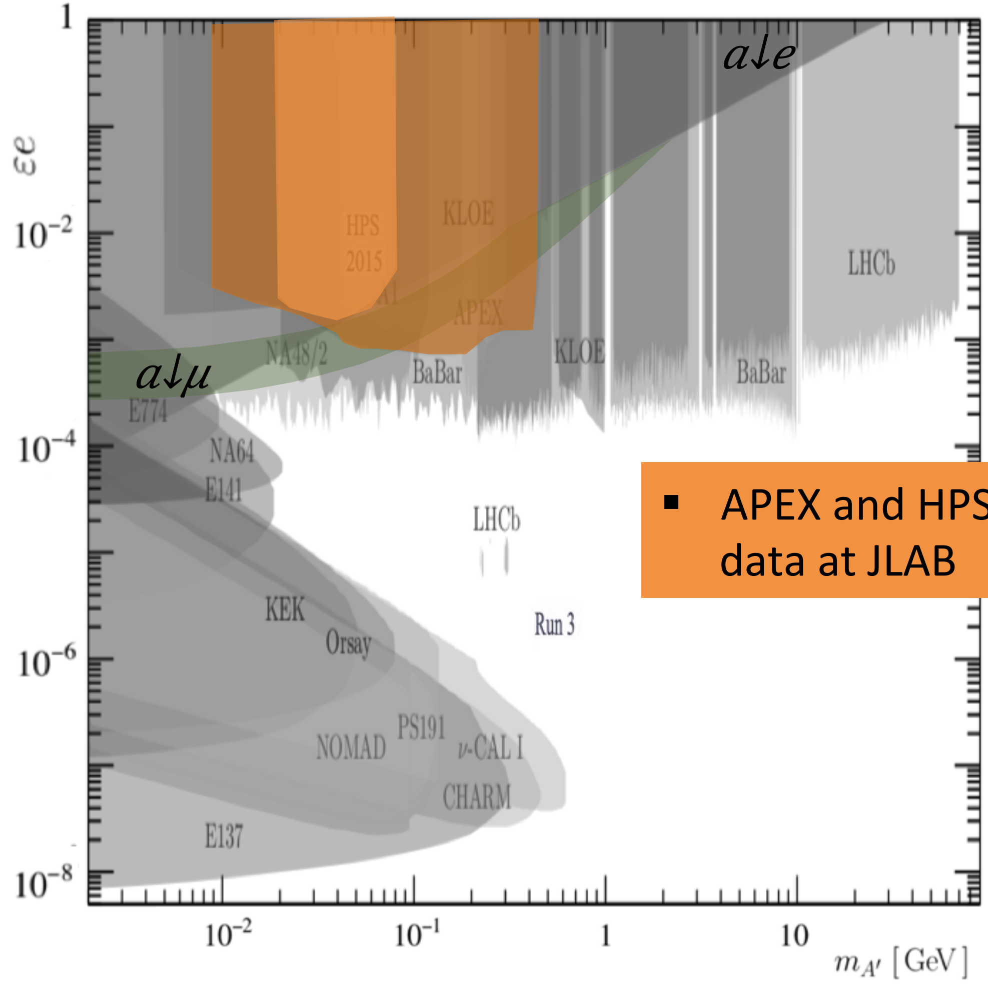
Dump E-137, E-141, E-774, Orsay, …



$A' \to e^{+} e^{-}$

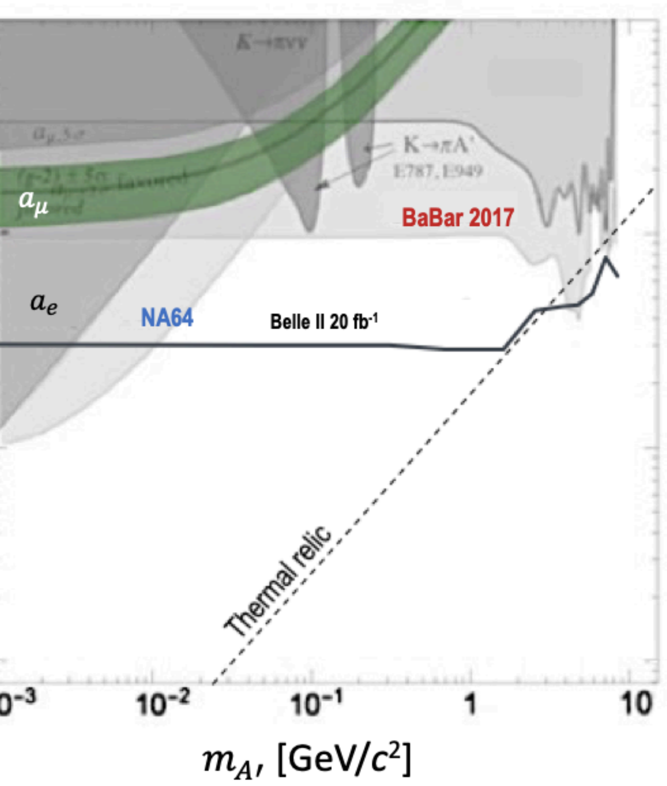
Thin target APEX, HPS, A1

+meson decays



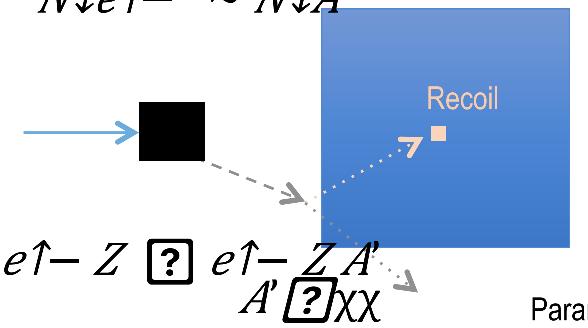
- APEX and HPS still taki
data at JLAB

DP invisible decays



Invisible decays

- Large luminosity: $N_{e^-} \sim N_A$



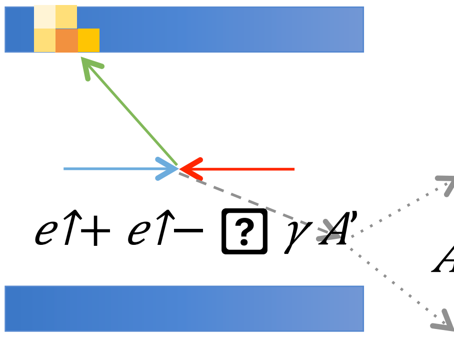
$e^{-} Z \boxed{?} e^{-} Z A'$

$A' \boxed{?} \chi\chi$

Dump + recoil (BDX)

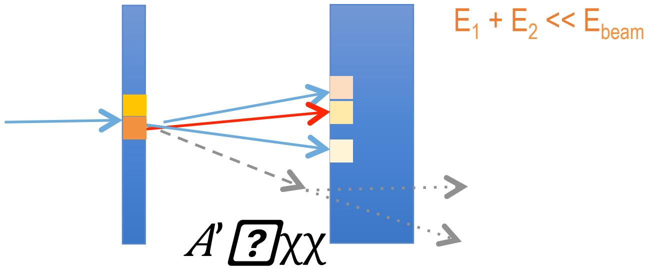
Parametri aggiuntivi: α_{d} e m_{χ}

- Fix



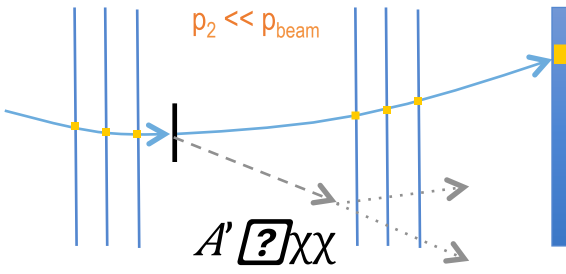
$e^{+} e^{-} \boxed{?} \gamma A'$

Missing mass BaBar, KLOE



$A' \boxed{?} \chi\chi$

Missing energy NA64

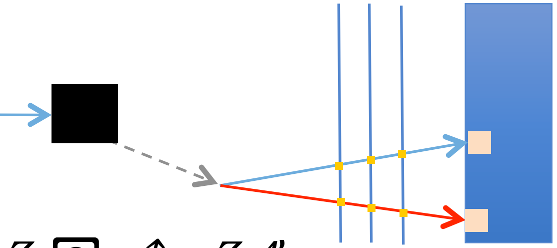


$A' \boxed{?} \chi\chi$

Missing momentum (LD

DP experiments

Visible decays

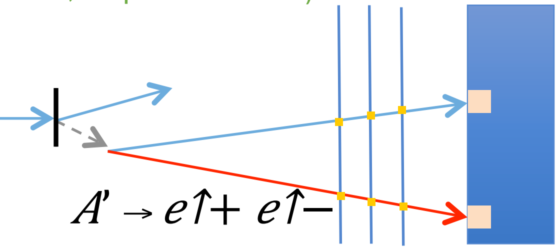


$Z \boxed{?} e\uparrow - Z A'$

$A' \boxed{?} e\uparrow + e\uparrow -$

Dump E-137, E-141, E-774, Orsay, …

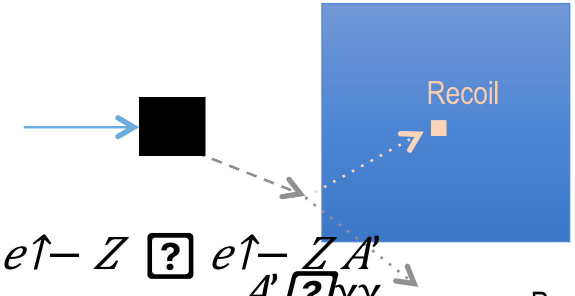
e evidence
hunt, displaced vertex)



$A' \rightarrow e\uparrow + e\uparrow -$

Thin target APEX, HPS, A1

Invisible decays



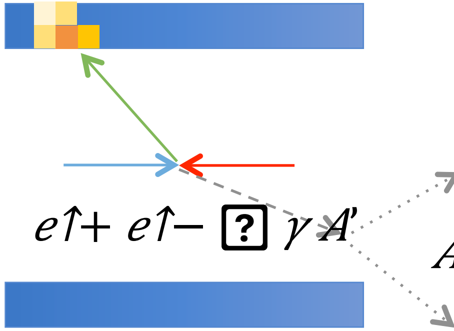
$e\uparrow - Z \boxed{?} e\uparrow - Z A'$

$A' \boxed{?} \chi\chi$

Dump + recoil (BDX)

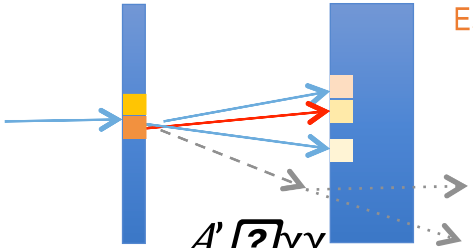
Parametri aggiuntivi:

$\alpha\downarrow d$ e $m\downarrow\chi$



$e\uparrow + e\uparrow - \boxed{?} \gamma A'$

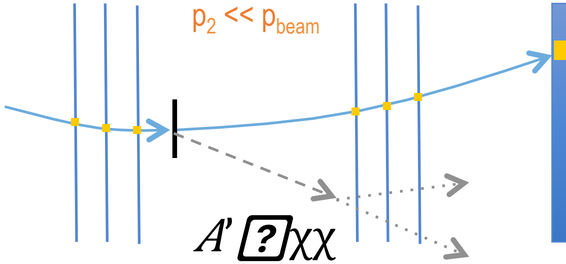
Missing mass BaBar, KLOE



$E_1 + E_2 << E_{beam}$

$A' \boxed{?} \chi\chi$

Missing energy NA64



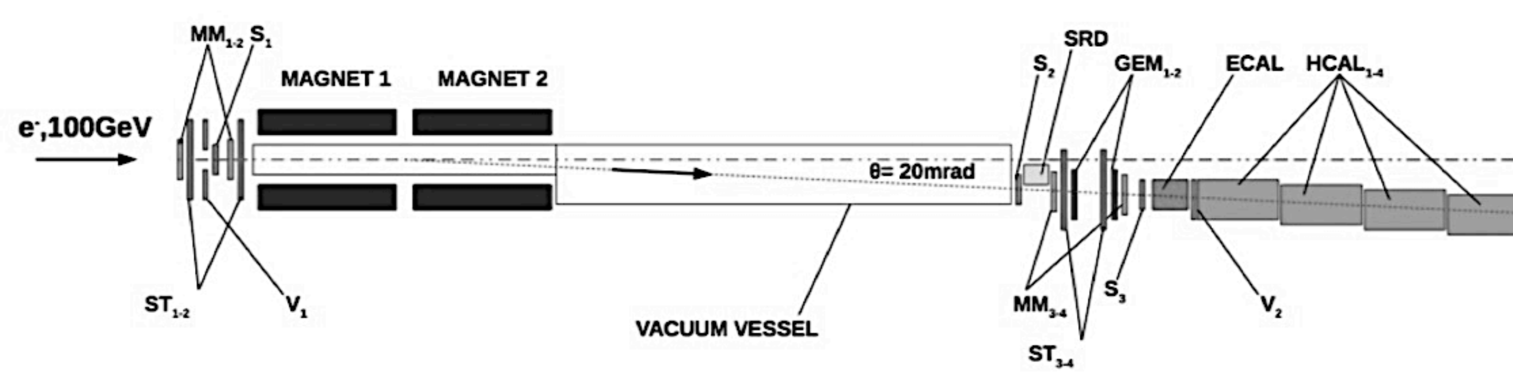
$p_2 << p_{beam}$

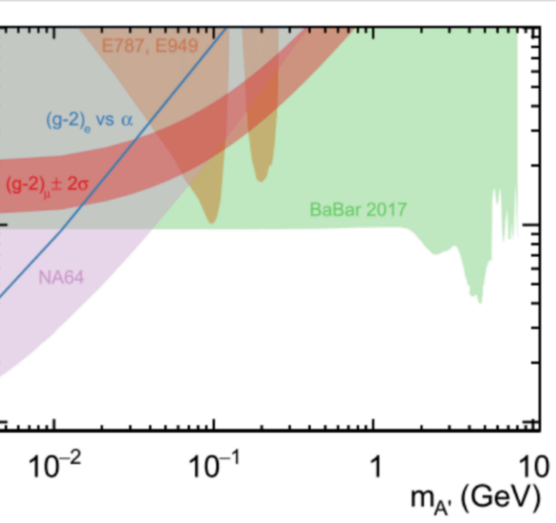
$A' \boxed{?} \chi\chi$

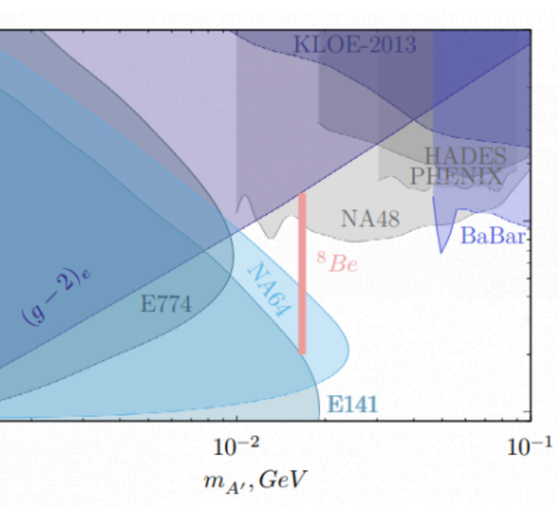
Missing momentum (LD

NA64

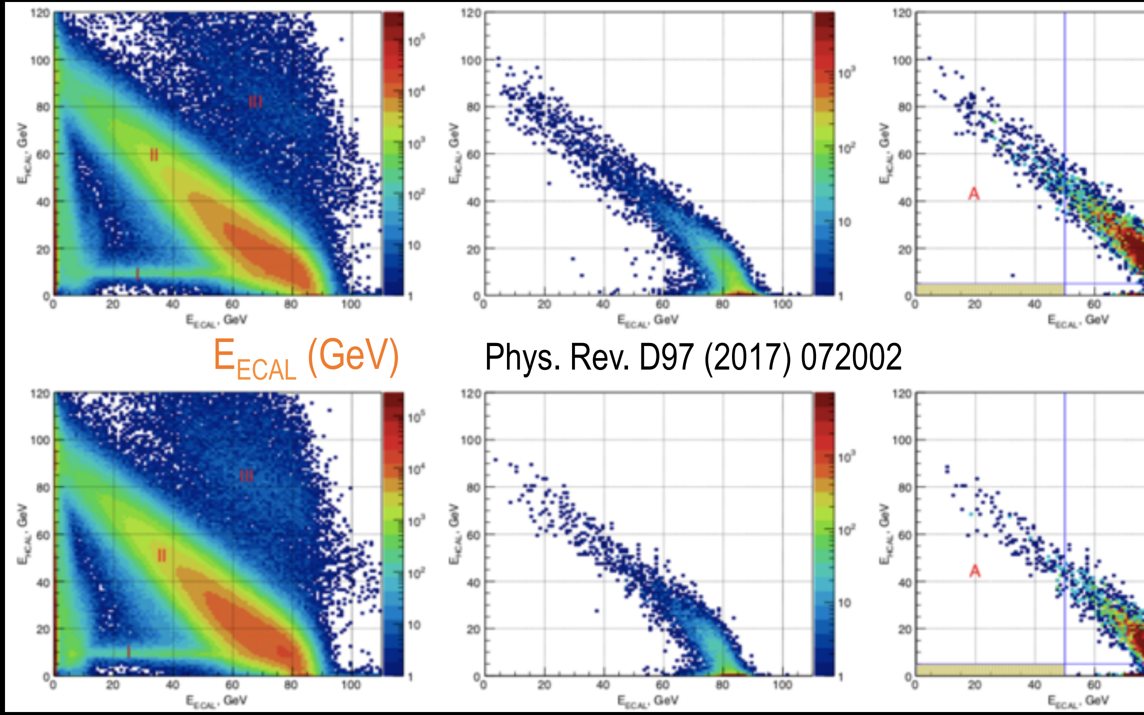
ing energy:
4 at H4, 100 GeV electron beam







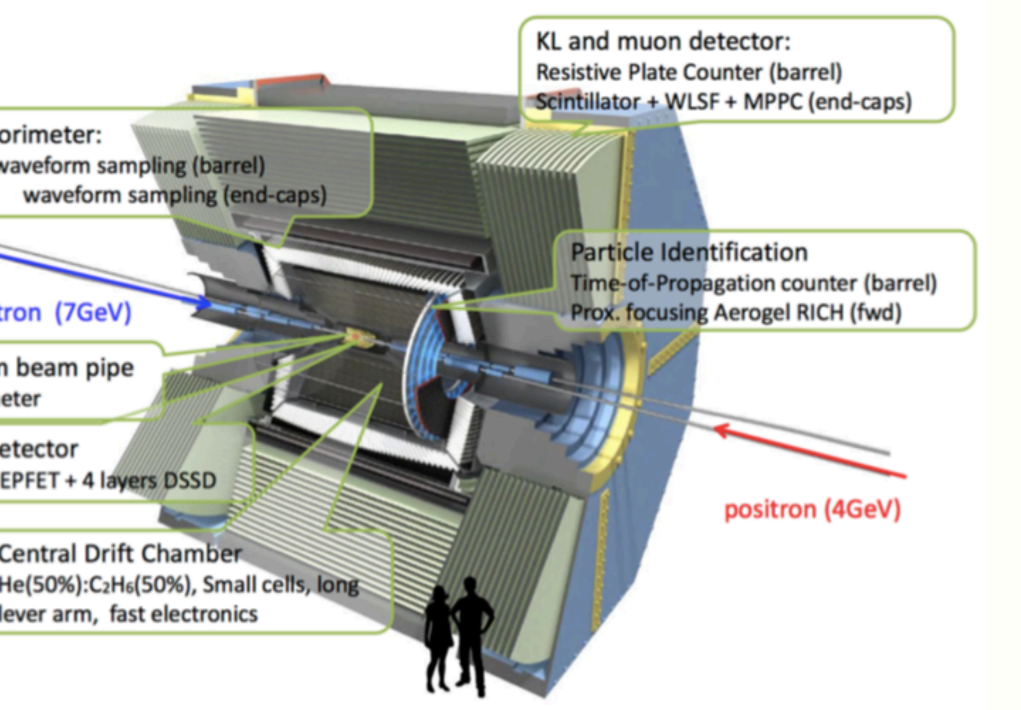
Corresponding to 4.3 ×10^{10} electrons on target

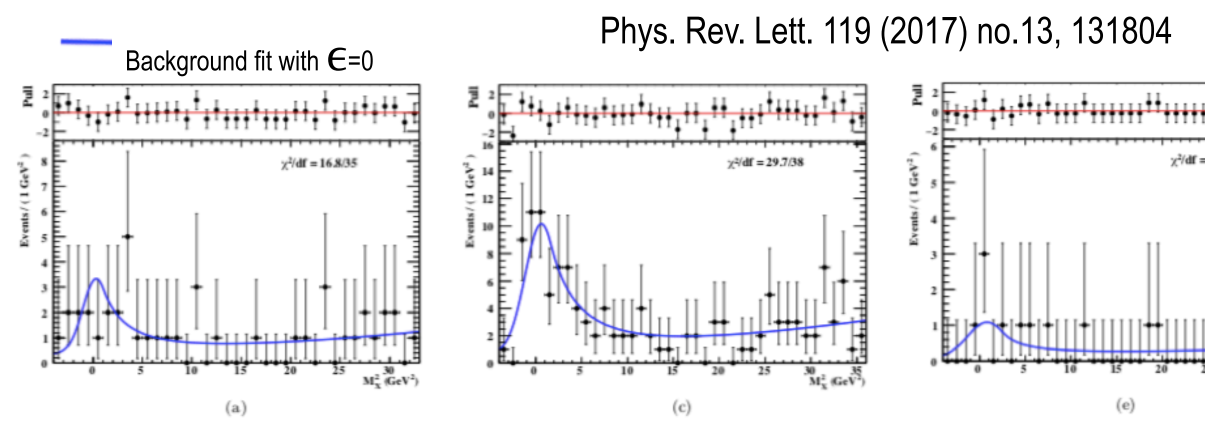


Phys. Rev. D97 (2017) 072002

BaBar/Belle II

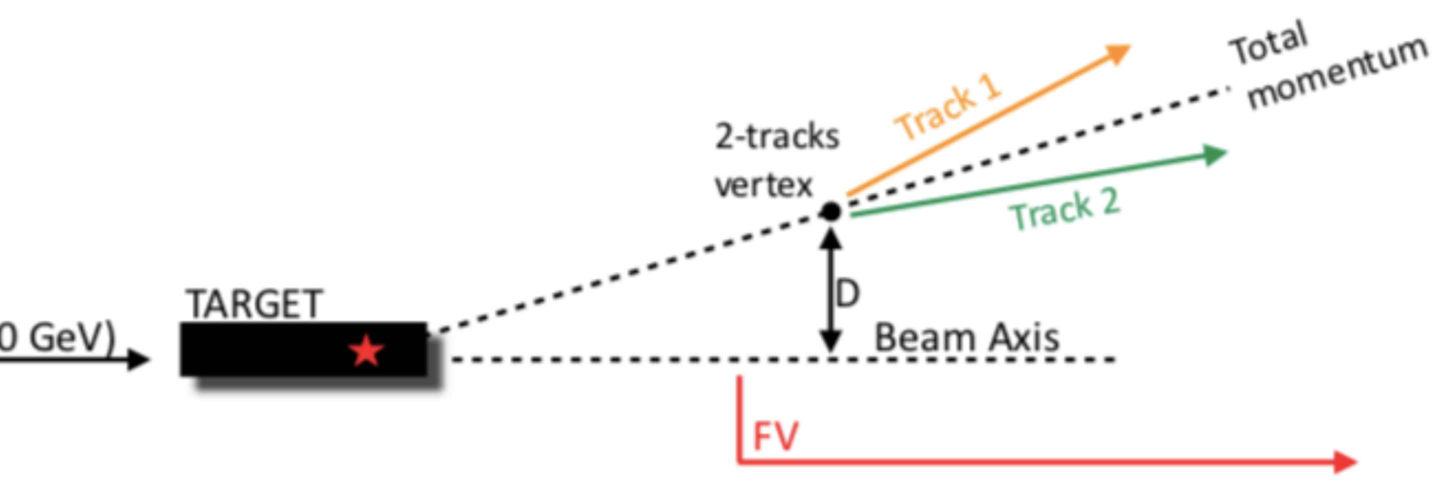
BaBar: 53 fb^{-1} near , , with mono-photon trigger, missing mass with boosted decision tree



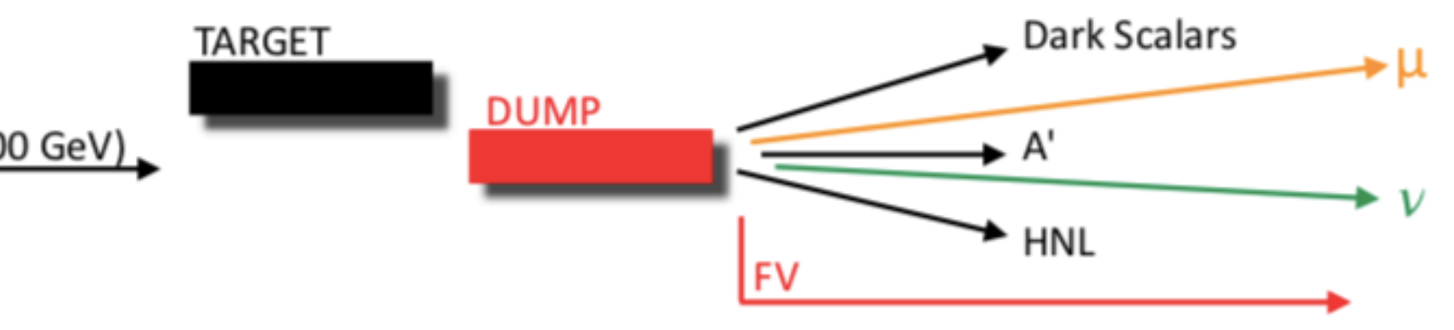

Phys. Rev. Lett. 119 (2017) no.13, 131804

- Belle-II taking data, will **soon** improve
  10^{-7} reachable with 20 fb^{-1} (statistics only

NA62

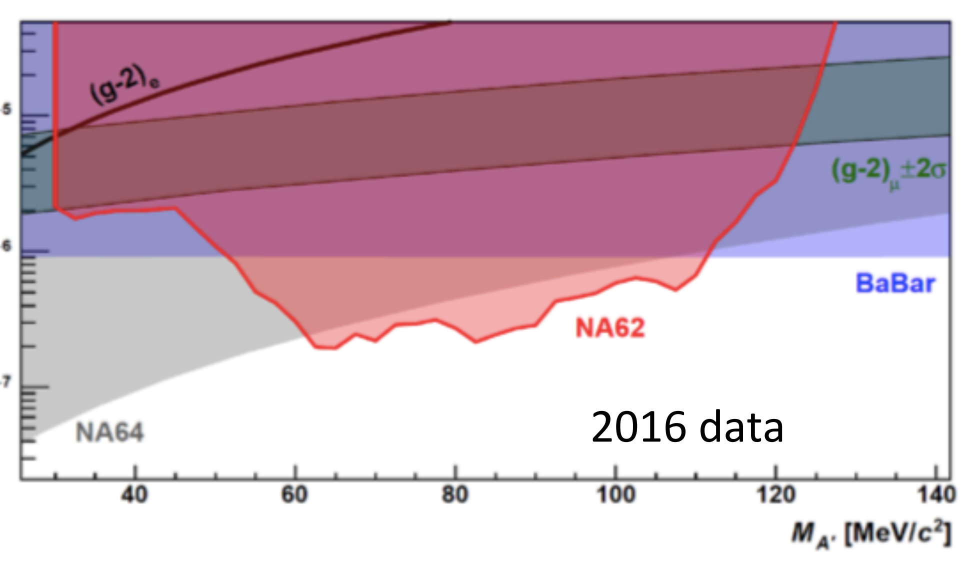


NA62 standard running
Recorded in parallel to the standard data-taking using dedicated low bandwidth triggers that select configuration topologies with pair of tracks in the final state



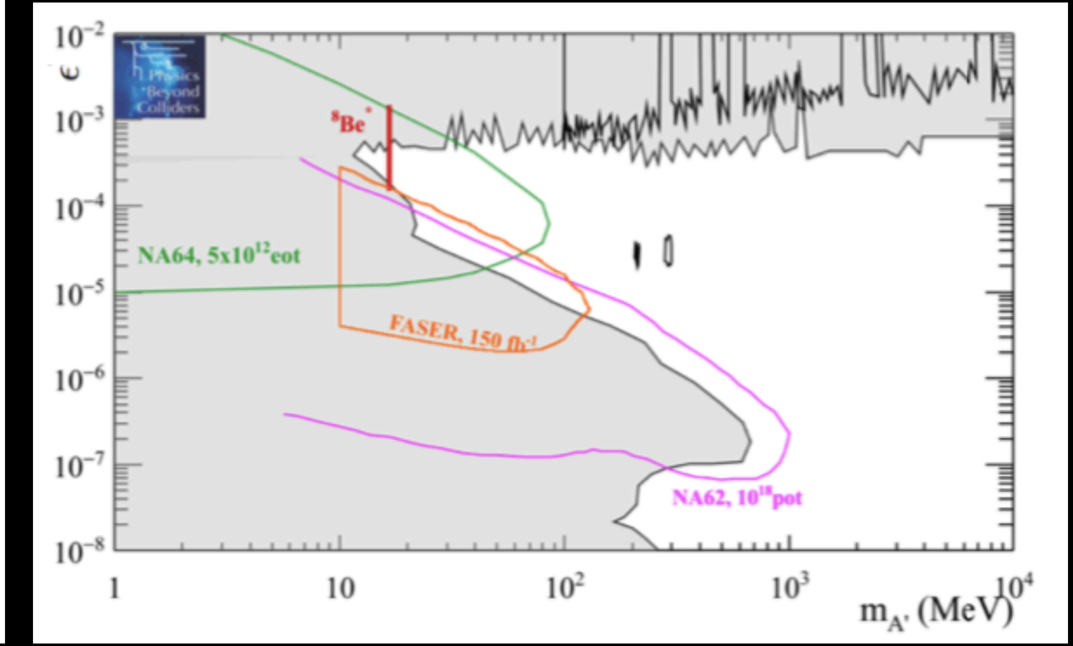
Dump mode
The target may be lifted and the copp
collimators closed, so that the whole
interacts in a higher Z material (~11 λ
closer to the detector (20 m downstre
the target), increasing the sensitivity
All beam-induced backgrounds are st
but muons and neutrinos and any kin
feebly-interacting long-lived particle

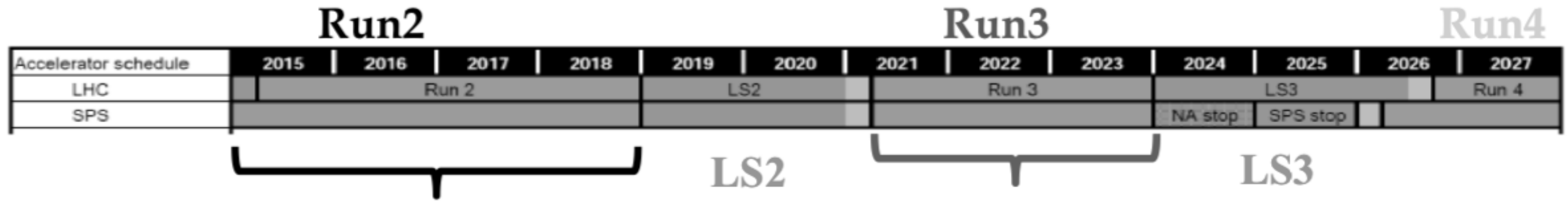
NA62 and NA62++



2016 data

arXiv:1903.08767 (JHEP)

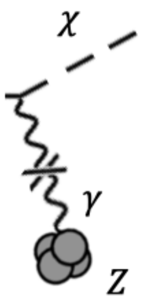




NA62: $K^+ \to \pi^+ \nu \nu$, LNV/LFV decays +
~3x10^{16} POT run in “beam-dump” mode

$K^+ \to \pi^+ \nu \nu$, LFV/LNV +
~10^{18} POT run in “beam-dump” mode

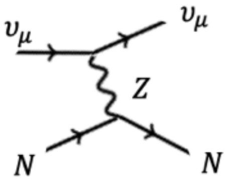
DP at neutrino experiments



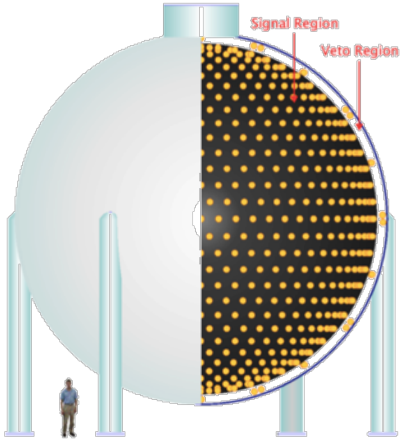
- MiniBooNE run with booster neutrino beam in **off-target** mode (2014)
- $1.86 \cdot 10^{20}$ POT in 10 months run (8 GeV protons)

scattering

ar to neutrino neutral-current elastic scattering

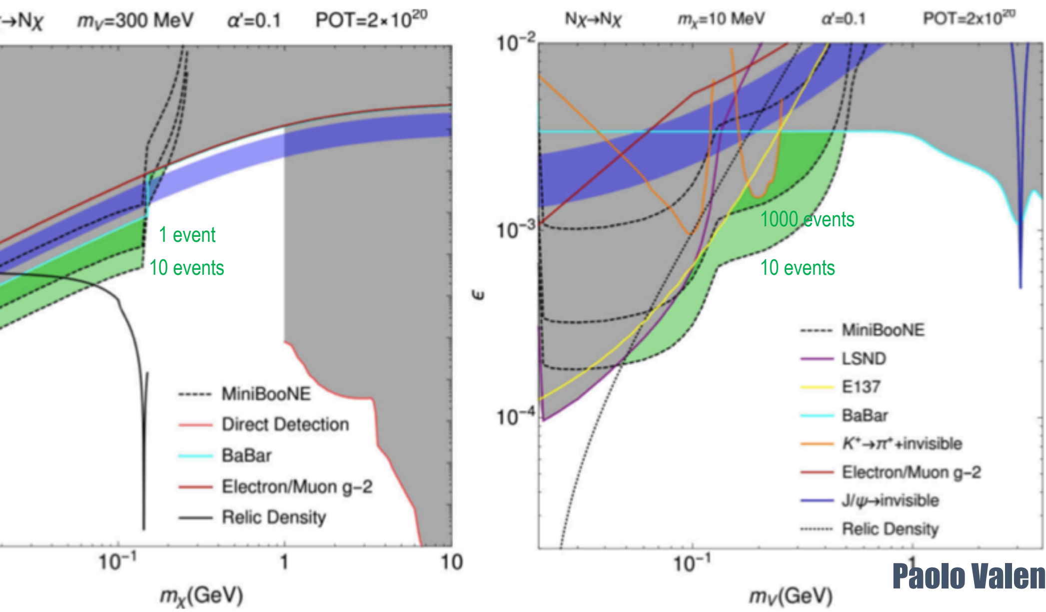


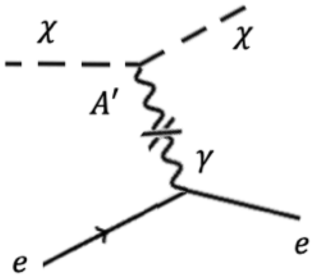
MiniBooNE Detector



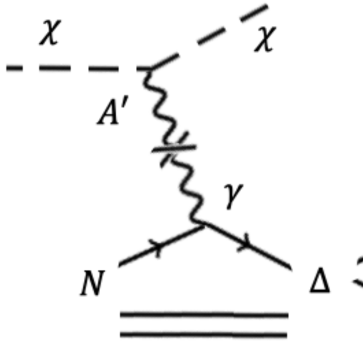
Cherenkov in mineral

Nuclear scattering sensitivity





Electron scattering



π↑0 cha

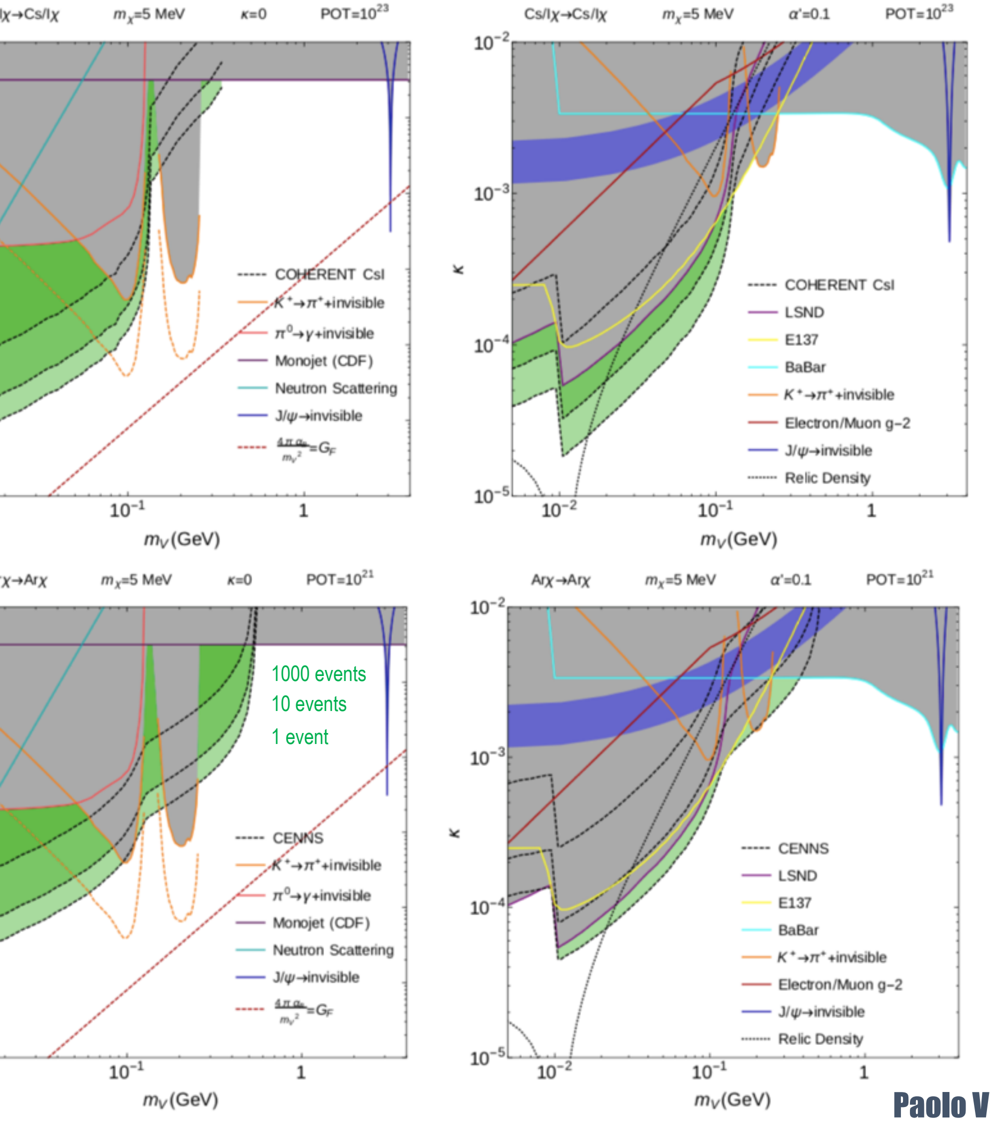
Further improvement form CEυNS:

- COHERENT@SNS Oak Ridge
- CENNS@Fermilab

DP at neutrino experiments

$U(1)\downarrow B$ model

Dark photon



COHERENT@SNS Oak Ridge
1 ton CsI

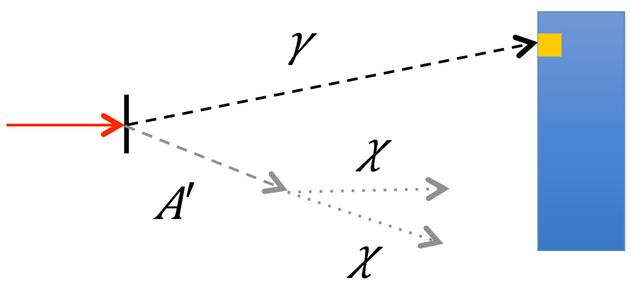
CENNS@Fermilab
1 ton ^{39}Ar

Phys. Rev. D 92, 095005 (2015)

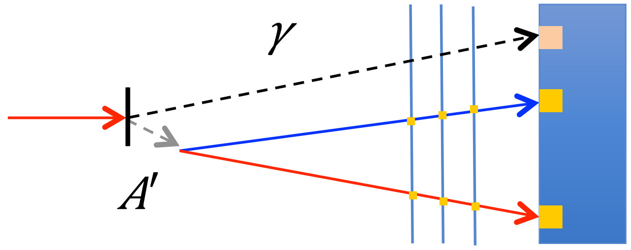
PADME@BTF

Approach: produce the DP in events,
but use positron beam on the atomic electrons of a fixed target, for increasing the luminosity

invisible decays

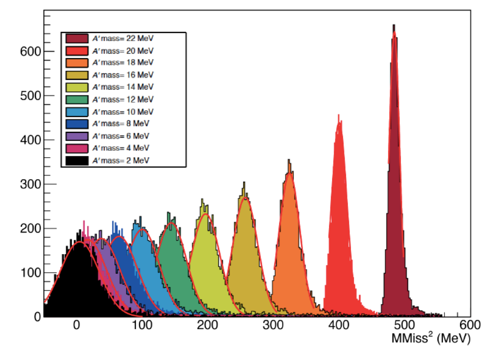


visible decays



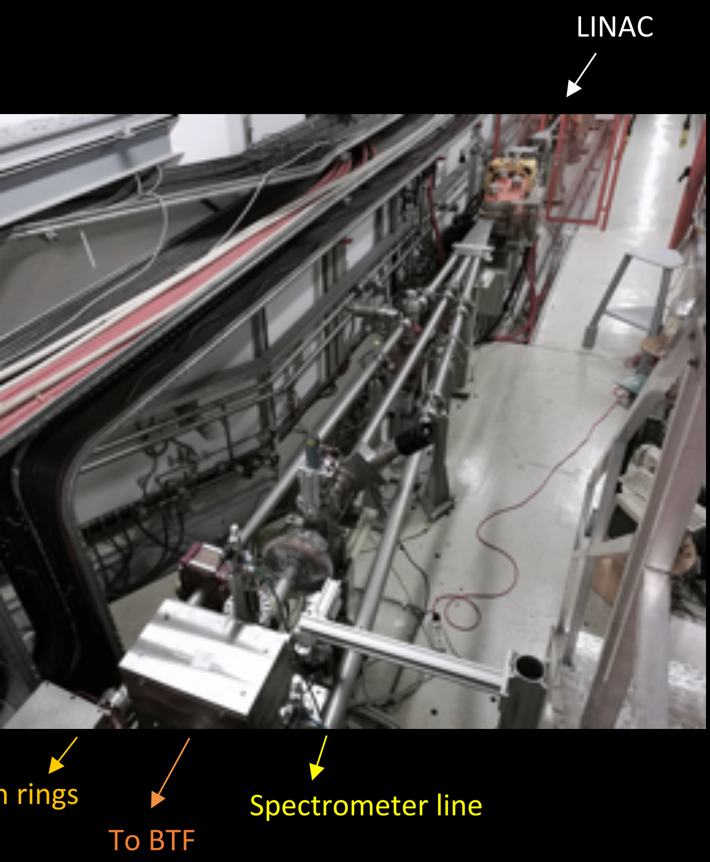
- No assumption on the *A′* decays and coupling to quarks (just assume coupling to leptons for production)
- Limits the coupling of **any new light particle** produced in annihilations: scalars (*h'*), vectors (*A′*) and ALPs

- Of course one can also look for pairs in the final state



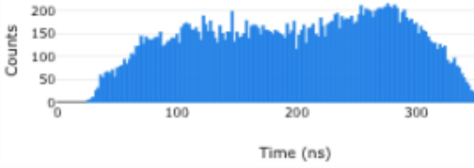
- To compute $m^2_{miss} = (\underline{P}_{\gamma} - \underline{P}_{e+})^2$ we need a positron beam with known 4-momentum, and:
  1. Small energy and angular spread
  2. Small transverse spot
- We also need to precisely measure the photon momentum

Positron beam-line



- Positrons produced on two alternative targets:
  - Beam Test Facility target
    - Maximum energy ~700 MeV (intensity strongly reduced increasing the selected energy)
    - Much easier to tune energy
    - Less sensitive to LINAC optics variations
  - DAΦNE LINAC positron converter:
    - Maximum **energy 550 MeV**
    - Up to 0.5 nC/pulse
    - Less beam-induced background, better momentum spread

- **Low repetition rate**: **50 Hz** LINAC (−1 shot/s, used for monitorin
- Short pulses due to RF compression for getting high energy i relatively short S-band LINAC:

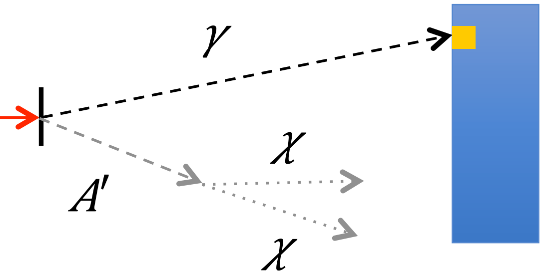


  - Generally 10 ns for injections into the collider rings
  - Optimization for PADME: **pulse length up to 200 ns**
- Good beam quality: **2-3 mm** $\sigma_{x,y}$, **1 mrad** divergence

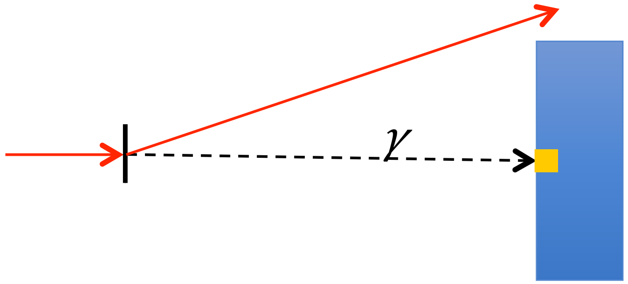
Signal vs. backgrounds

Istituto Nazionale

l: invisible decay of *A'*



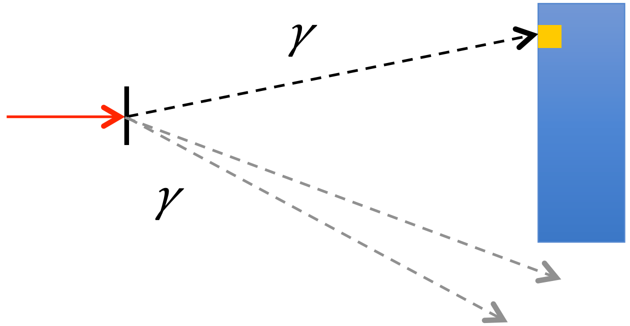
Background: Bremsstrahlung + lost e↑+



Bremsstrahlung background:

- Detect the irradiating positron
- Cut on the photon energy

Background: 2 or 3 photons, 1 de



2+ photons background:

- **Ermeticity**
- Granularity
- Energy resolution

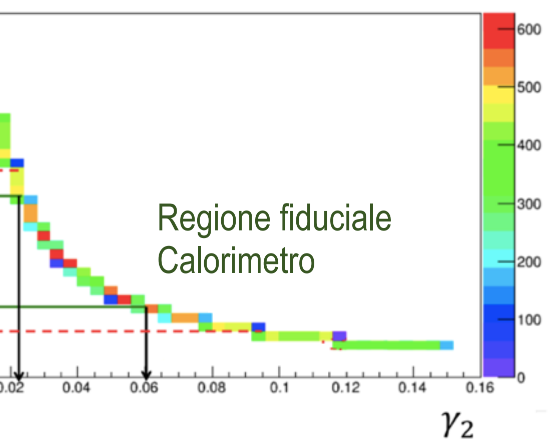
For cleaning away positron beam (not interacting with the target):

- Central hole

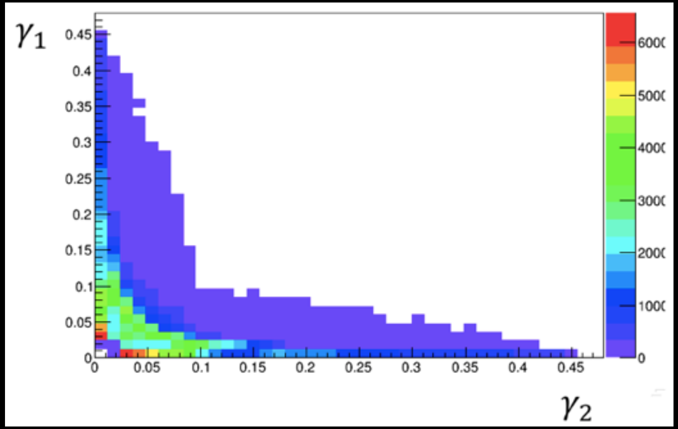
  or

- Sweeping magnetic field

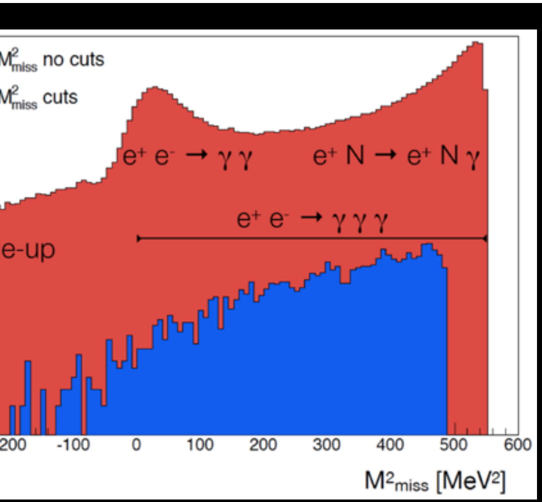
PADME: fighting the background



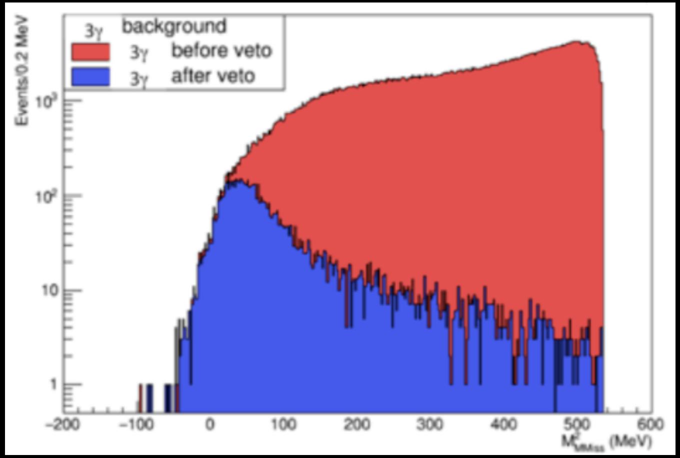
For events: given one photon in the fiducial region, the second is always in the acceptance



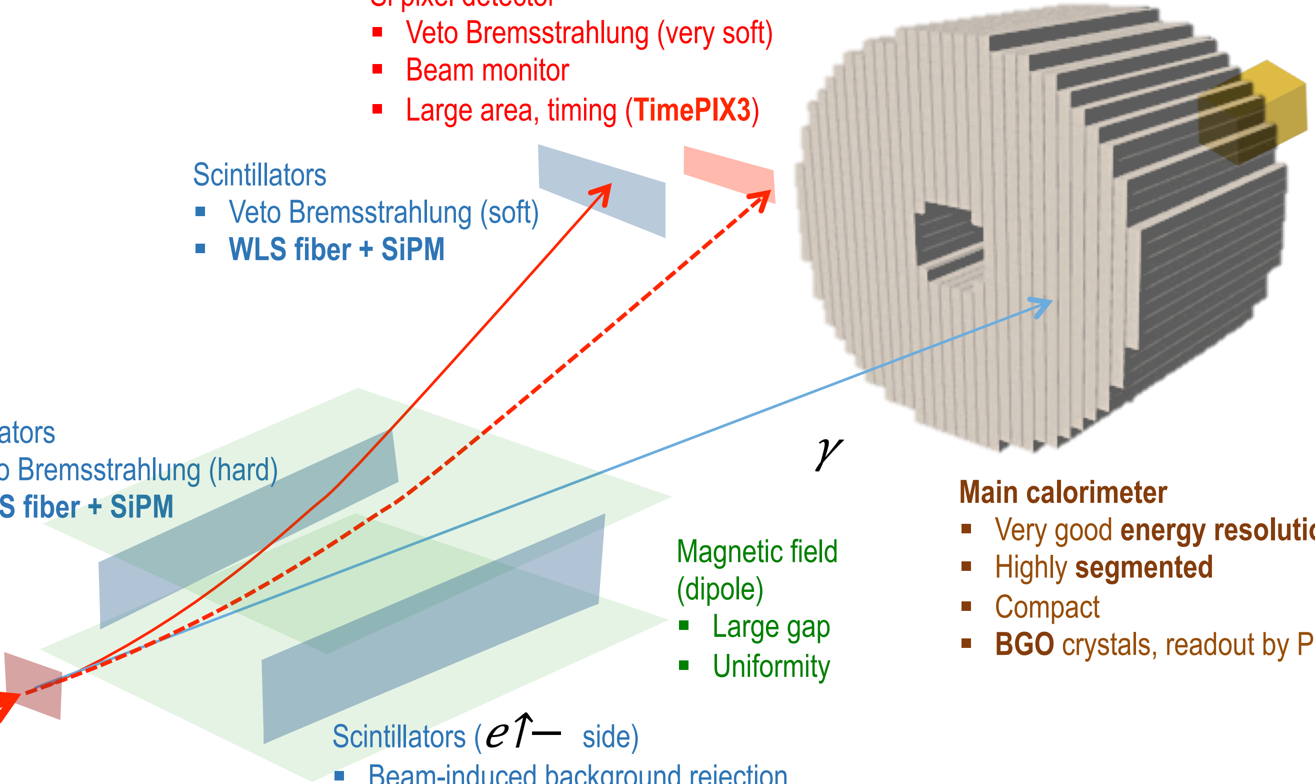
For events: given one photon in the fiducial region, the small angle region is crucial



Residual background dominated by Bremsstrahlung with the positron escaping detection in the scintillating bars veto



PADME layout



Si pixel detector
- Veto Bremsstrahlung (very soft)
- Beam monitor
- Large area, timing (**TimePIX3**)

Scintillators
- Veto Bremsstrahlung (soft)
- **WLS fiber + SiPM**

Small-angle calorimeter
- Veto Bremsstrahlung (hard)
- Recover 3 photons events acceptance
- **Fast** (Cherenkov)
- Good light yield: **PbF_2**

ators
o Bremsstrahlung (hard)
S fiber + SiPM

Magnetic field (dipole)
- Large gap
- Uniformity

Main calorimeter
- Very good **energy resolution**
- Highly **segmented**
- Compact
- **BGO** crystals, readout by PMT's

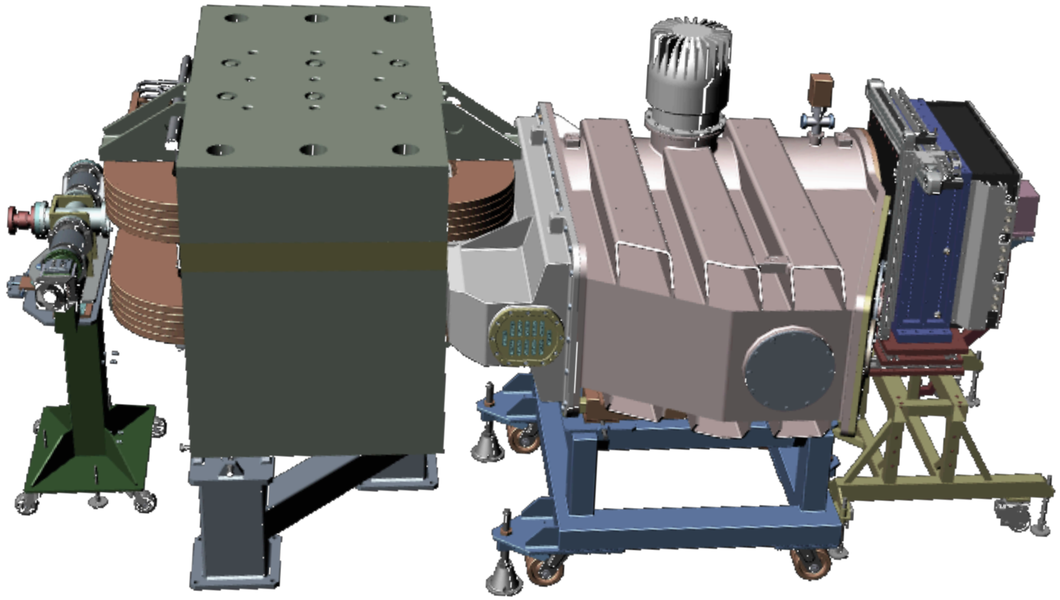
Scintillators ($e\uparrow-$ side)
- Beam-induced background rejection
- Detect visible decays: $A' \rightarrow e\uparrow + \ e\uparrow -$

Active target
- 100 μm diamond
- Graphitic strips

Design choices

- Beam intensity × target thickness = luminosity, it is limi
  the maximum tolerable occupancy and veto probability:
  - Driven by the distribution and **rate of photons** + by t
    resolution of detectors
- $M{\downarrow}miss$ resolution determined by **spatial** (Moliére r
  and **energetic resolution** of main calorimeter + **lever-a**
  (calorimeter-to-target distance)
  - Aim at 4-5 MeV/$c\uparrow 2$
  - Distance + magnet **gap** fix the photon **acceptanc**
- Hole in the main calorimeter (BGO)
  - To limit the Bremsstrahlung rate
  - Covered by fast, small-angle calorimeter (PbF_2)
- Everything in **vacuum**: avoid parasitic interactions of po
  (other than in target), losing photons, showering, etc.

PADME layout

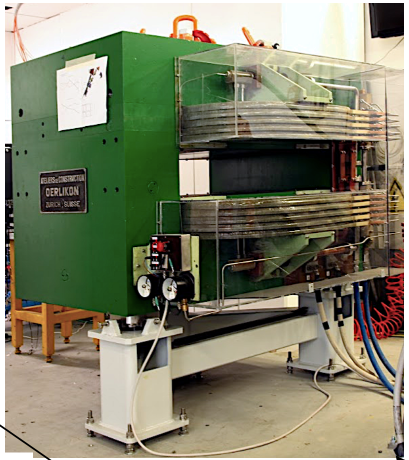


Main constraints

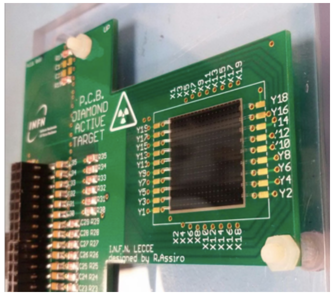
- Maximum length and transverse size
    - Available space in the BTF experimental hall
- Available magnet
    - Large gap dipole from CERN (23 cm)
    - Moderate field needed (<0.5 T)
- Available BGO crystals
    - From L3 electromagnetic calorimeter (endcap)

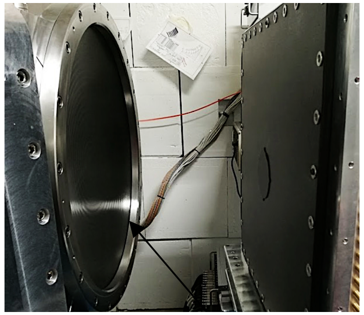
PADME components

Dipole
(CERN TE/NSC-MNC)

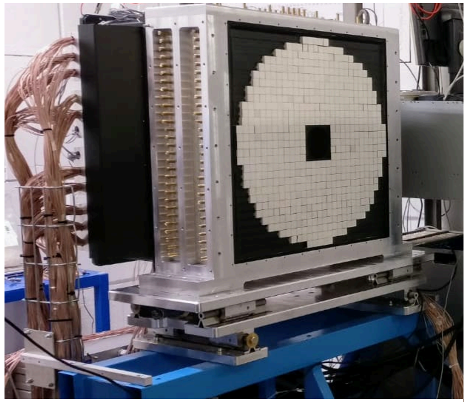


Active target
Lecce & University Salento



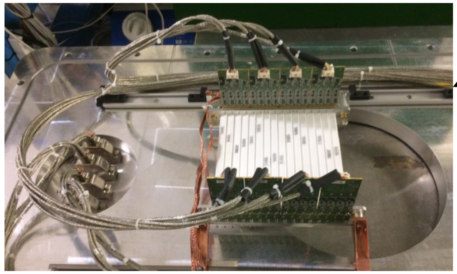


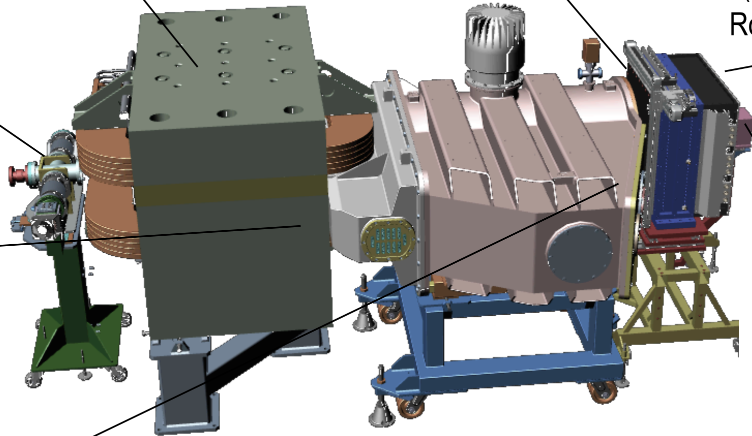
C-fiber window

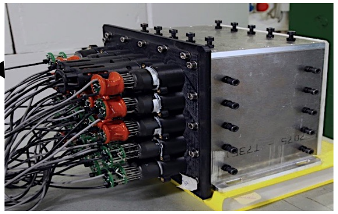


BGO calorimeter
(616 L3 endcap crystals:
Roma, Cornell U., LNF, LE)

Veto scintillators
(University of Sofia, Roma)



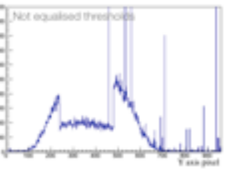




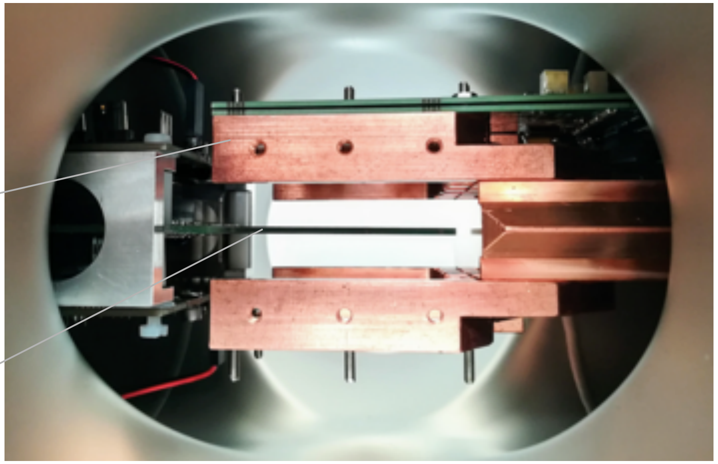
PbF_2 calorimeter
(MTA Atomki, Cornell U., LNF)

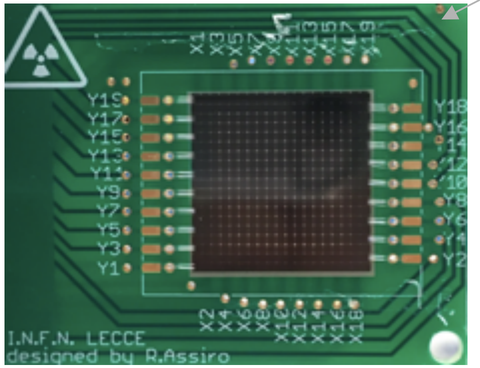
TimePIX3 array
(ADVACAM, LNF)

tive target

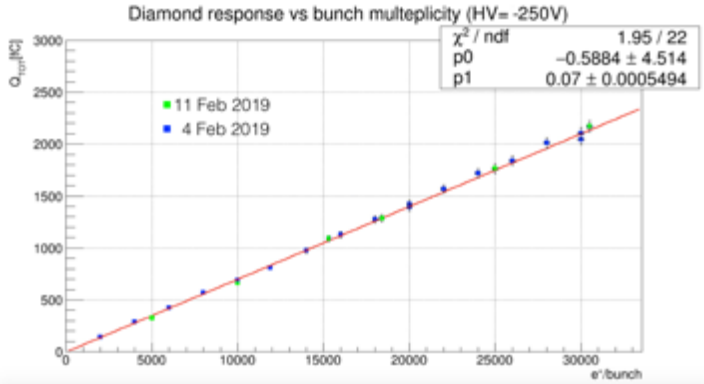


MIMOSA pixel tracker
(under commissioning)

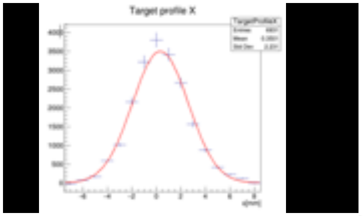




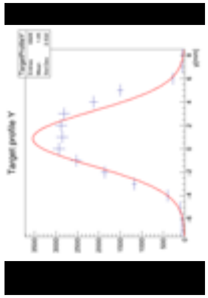
- CVD diamond, detector grade
- 1 mm graphitic strips (laser-burning)
- x and y views
- Pre-amplified analog signals sampled by waveform digitizer
- Gives beam spot position, size and intensity pulse by pulse

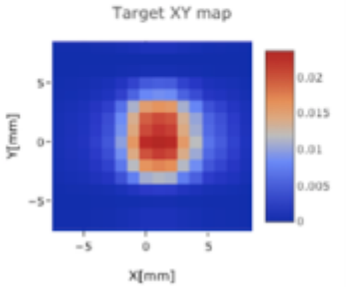


- Absolute calibrations referred to the BTF Cherenkov detector (not used online)
- Very good linearity, no saturation
- Good stability

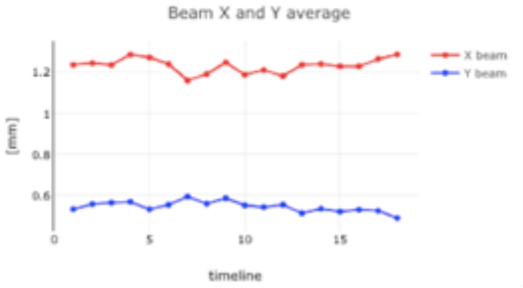


veighted strips





Online x and y



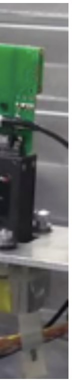
Online intensity

Average intensity vs. time

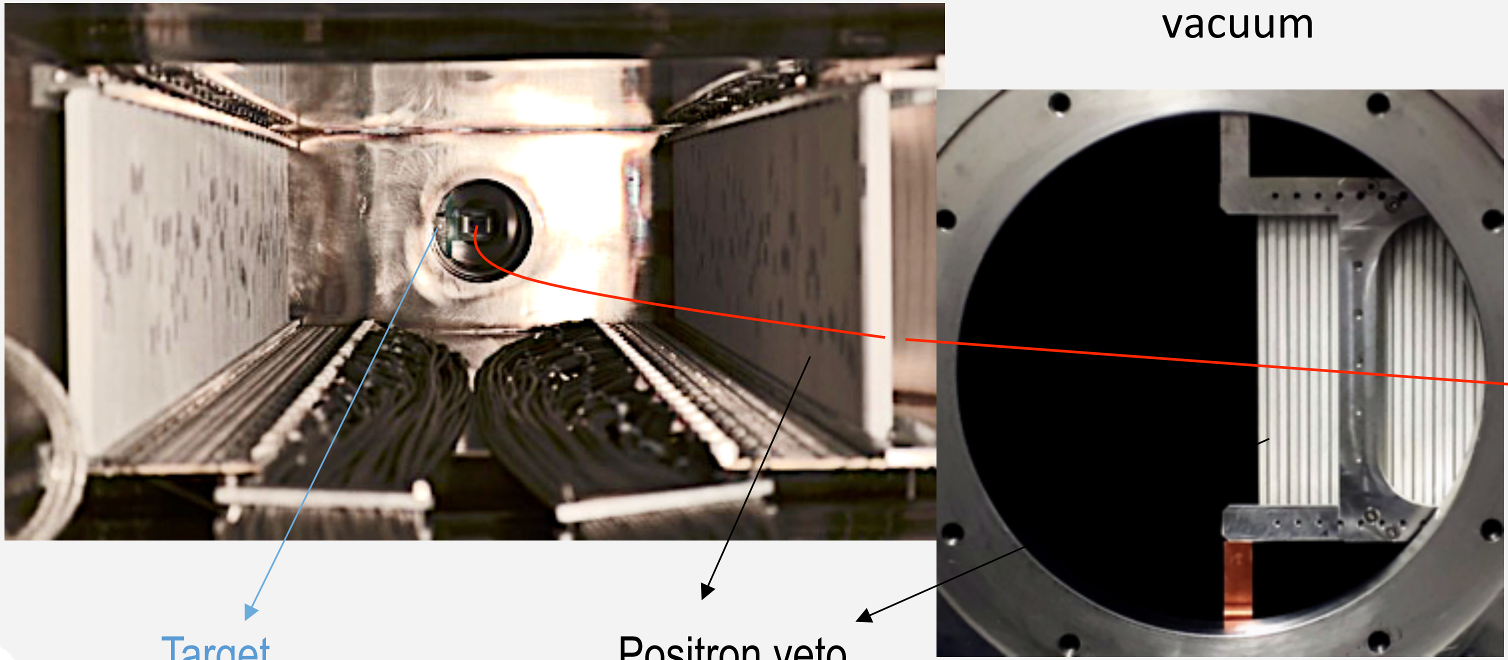
am monitoring, luminosity measurement

Beam close to design v

- ~2 mm RMS in both x
- <1% energy spread
- <1 mrad divergence



agnostics:

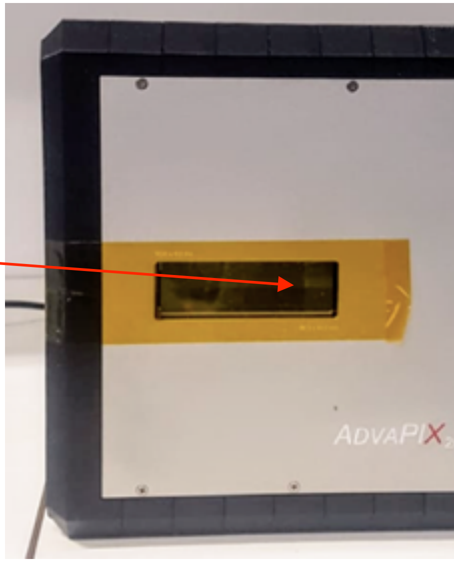


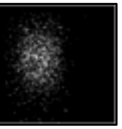
vacuum

Target

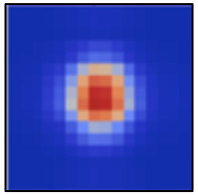
Positron veto

Timepix

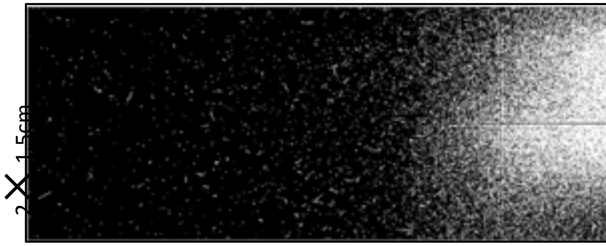




.5 × 1.5 cm²



2 × 2 cm²



6 × 1.5cm

PADME detectors: TimePix3 beam monitor

ray of 6 horizontal ×2 vertical TimePix3

in features single detector:

brid detector

µm pitch pixels

6 rows × 256 col. (1.408×1.408 cm^2)

uivalent tickness: 700-800 µm

tector+indium ball bonding+readout chip)

fo about amplitude and ToA(<0.5 ns)

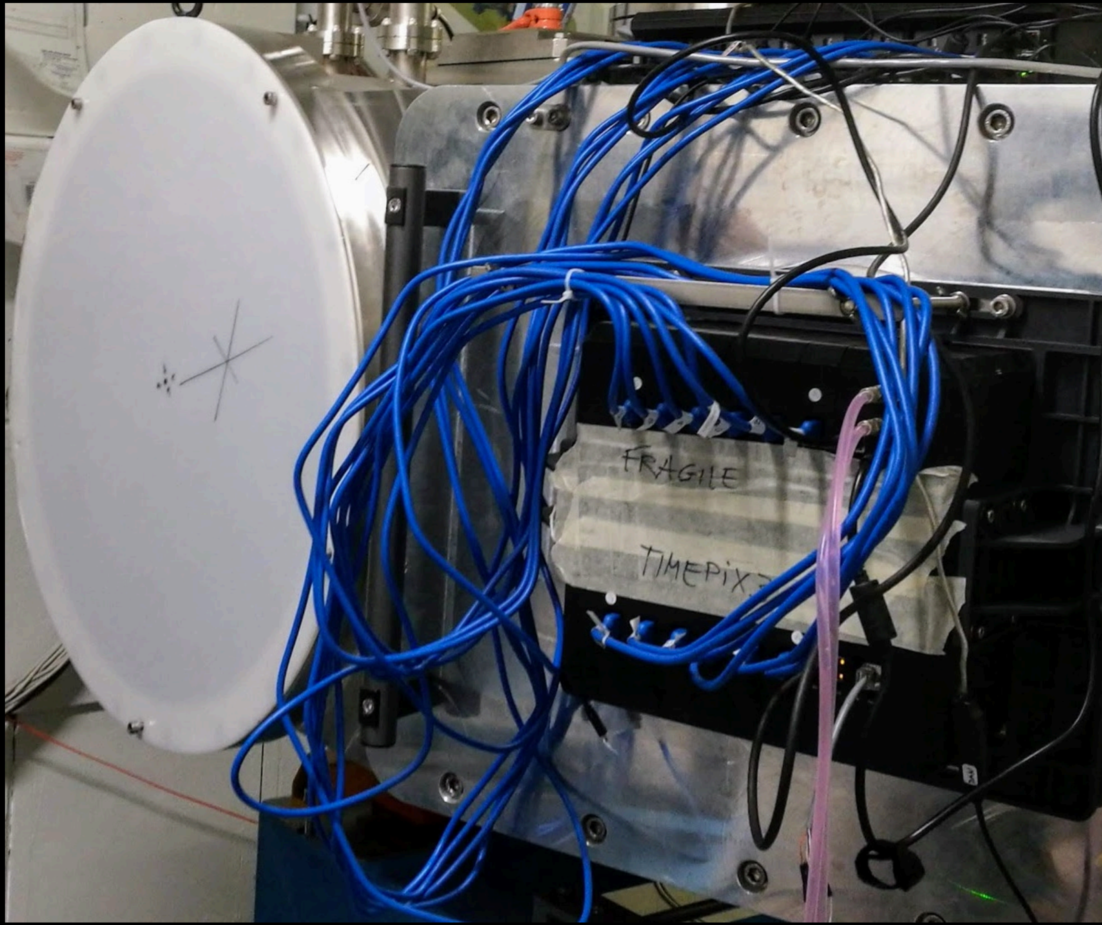
in features of the assembly:

sensors

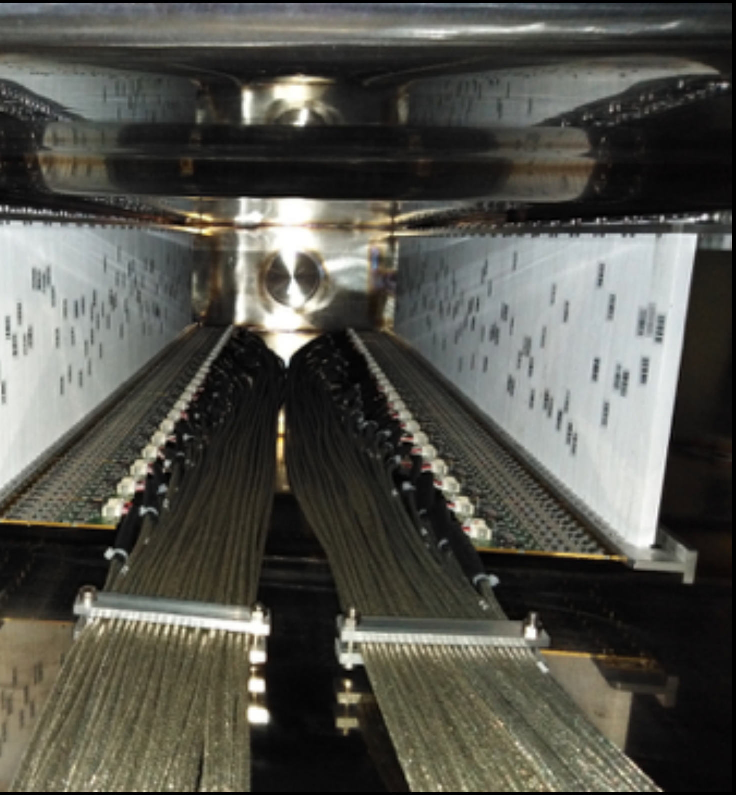
6432 pixels

tal surface 8.4 x 2.8 mm

ry important for monitoring beam divergence and **omentum spread**



PADME detectors: $e^{\pm}$ vetos

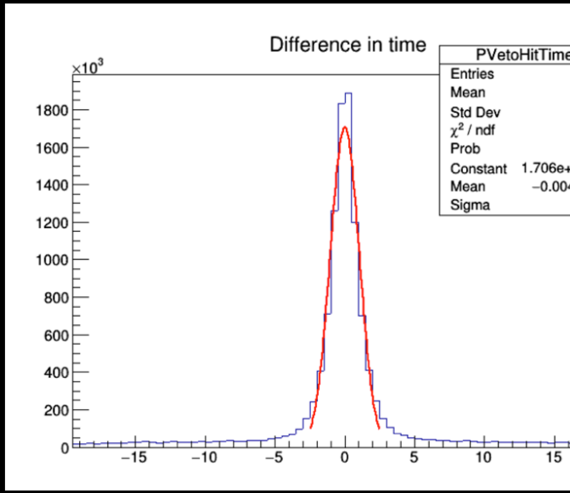


Main features:

- 96 (e^- veto) + 90 (e^+ veto) + 16 (high energy e^+ veto) 1.1×1×17.8 scintillating plastic bars
- WLS fibers 1.2 mm in diameter glued to the scintillator ($\tau_{\text{signal TOT}}$ = 70-100
- In vacuum and magnetic field
- FADC sampling: 2.5 GS/s, 1024 samples
- SiPM: Hamamatsu S13360 3x3 mm^2 25 μm cell
- Custom FEE with differential output

First timing response calibration

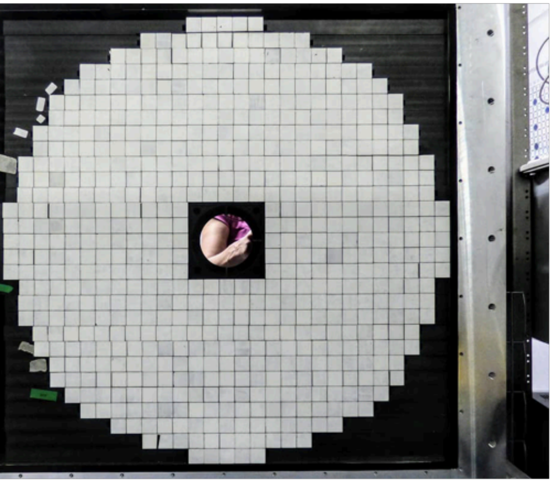
- Compensate for different cable length
- Compensate for different trigger time in different digitizers
- Compute time from digitizers signals
- Achieved resolution 700ps

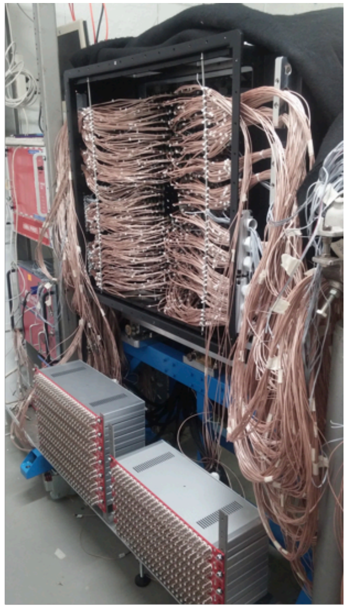


PADME detector: calorimeters

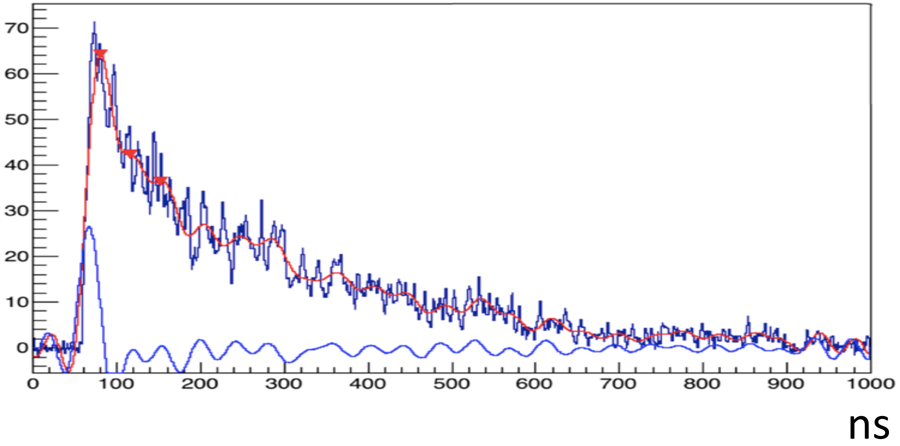
Main BGO calorimeter

Front view, opened



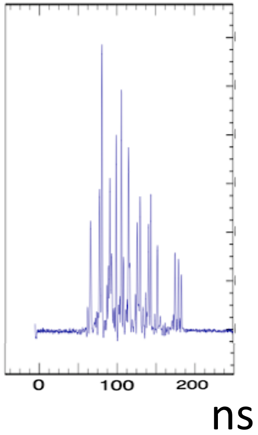


Back view, opened



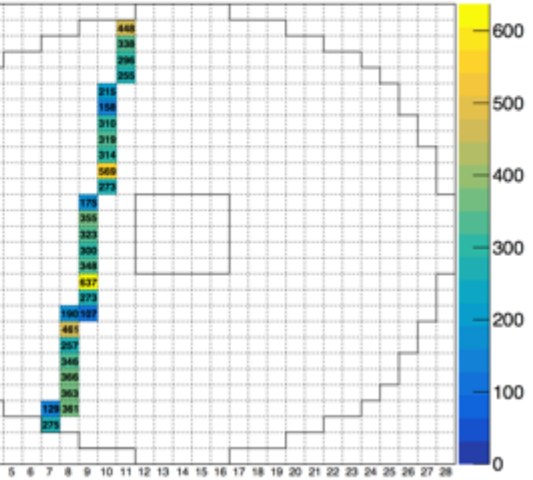
n Features:

- 16 2.1×2.1×23 cm^3 scintillating BGO (τ_{decay} = 300 ns)
- eadout PMT: HZC XP1911
- adius: ≈ 29 cm at 3.45 m from the target
- entral hole (10.5×10.5 cm^2) for letting Bremsstrahlung go to he small angle calorimeter
- ngular coverage: [20,93] mrad acceptance: [26,83] mrad
- eadout sampling: 1GS/s, 1024 samples
- urrent gain (≃15 pC/MeV) single BGO crystal E_γ < 511 keV

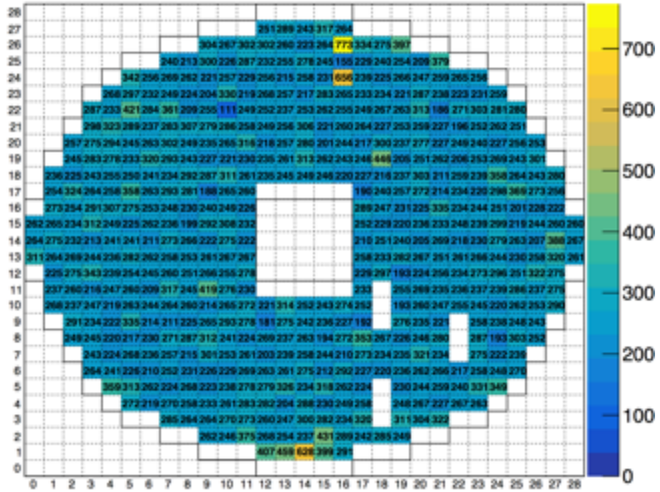


Small angle, PbF_2 calorimeter

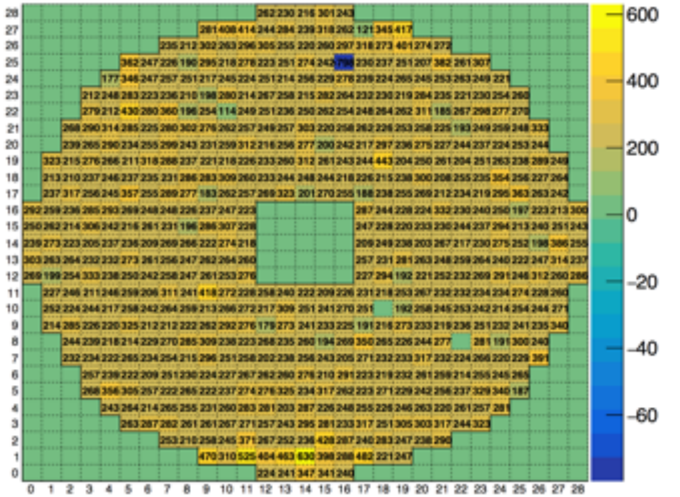
lorimeters performance



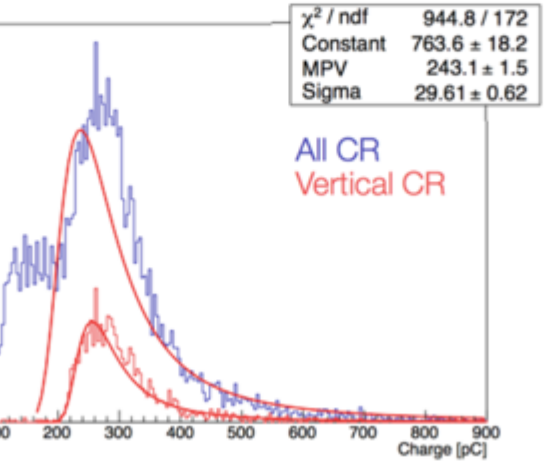
ics calibration of calorimeter

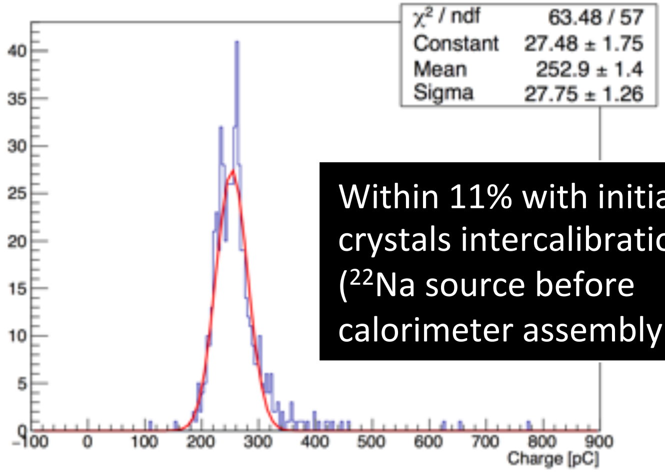


Full calibration map

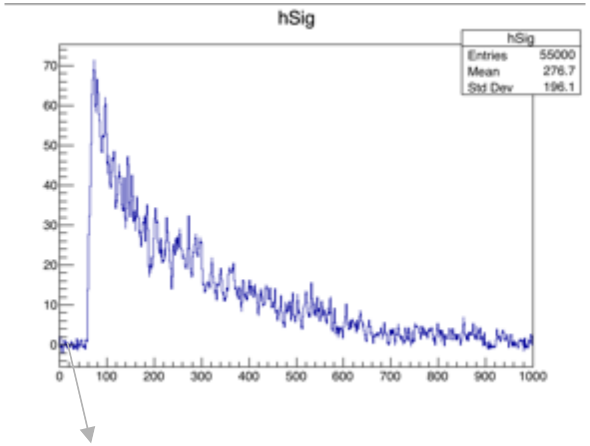


<1% dead/very inefficient cells





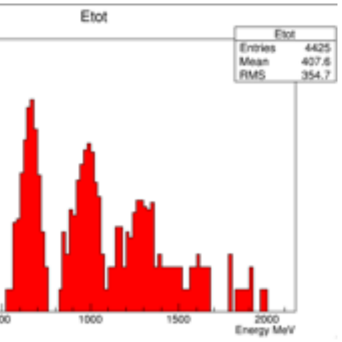
Within 11% with initial crystals intercalibration (^{22}Na source before calorimeter assembly)

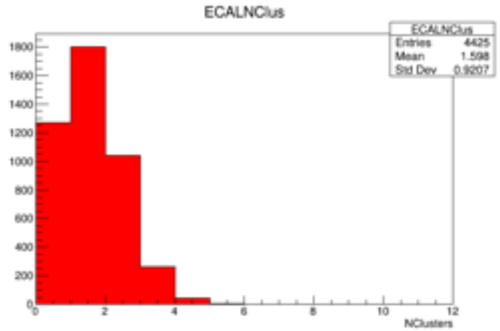


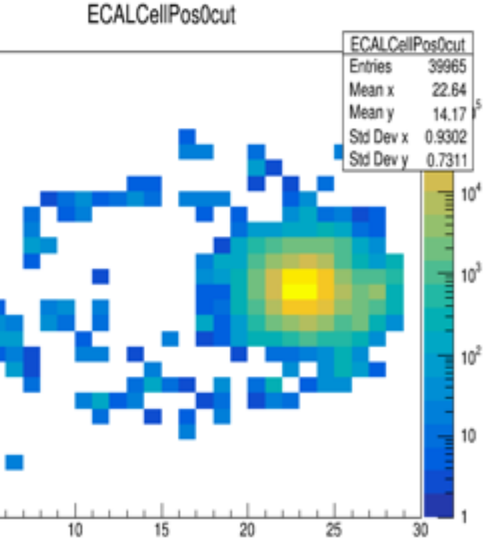
Pedestal from first samples, width ~500 keV

lorimeters performance

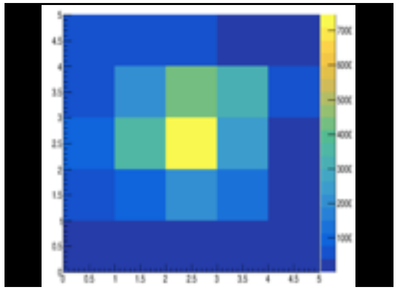
- gle positrons directly shot inside the calorimeter
- ergy resolution: 4% at 490 MeV already with rough intercalibration

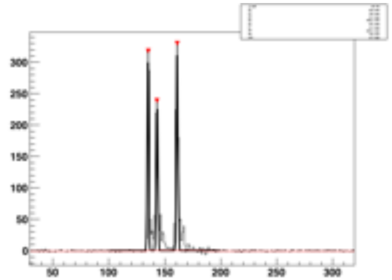




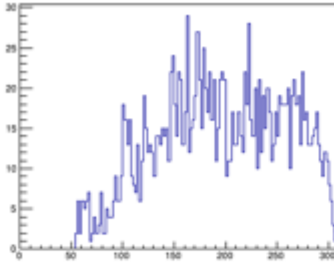


- Similarly, on small angle Cherenkov calorimeter:
  - Recognize multi-peaks
  - Timing
- Also needed for veto scintillating detectors



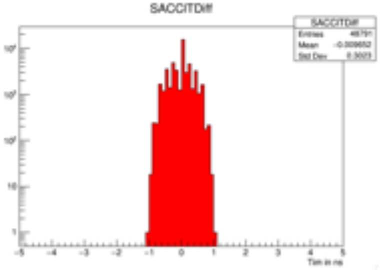


- 0-angle peaked
- Very low pileup up to 40-50 g/bunch

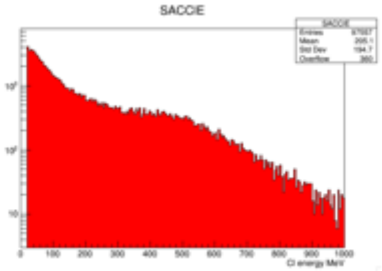


Cumulative distribut

≈200 ns beam puls



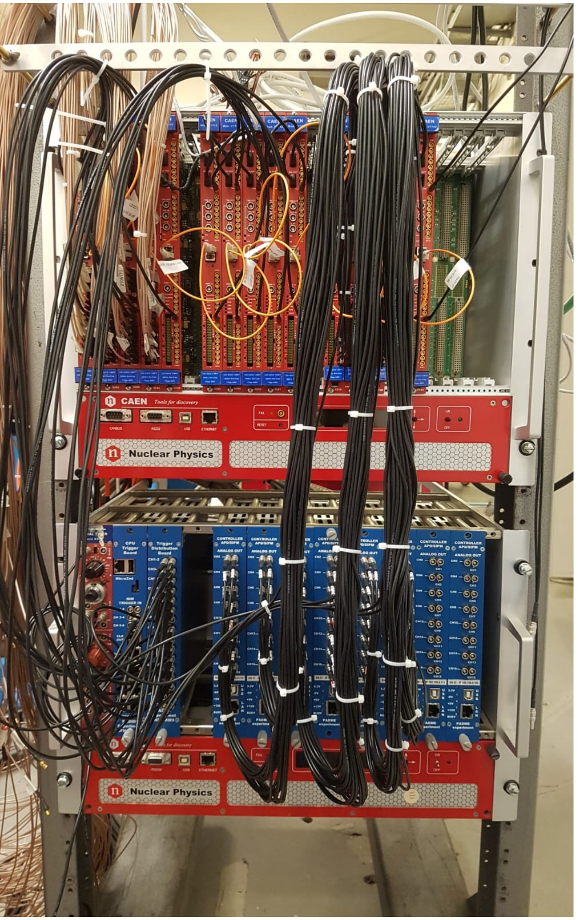
300 ps time resolution



Cluster energy: Bremsstrahlung distribution

Trigger and DAQ systems

30 VME 1-5Gs/s digitizers



00 KB/bunch

0 MB/s sustained data throughput

0 TB collected, tapes @LNF & CNAF

Trigger is produced using two types of board:
- CPU Trigger Board (6 inputs)

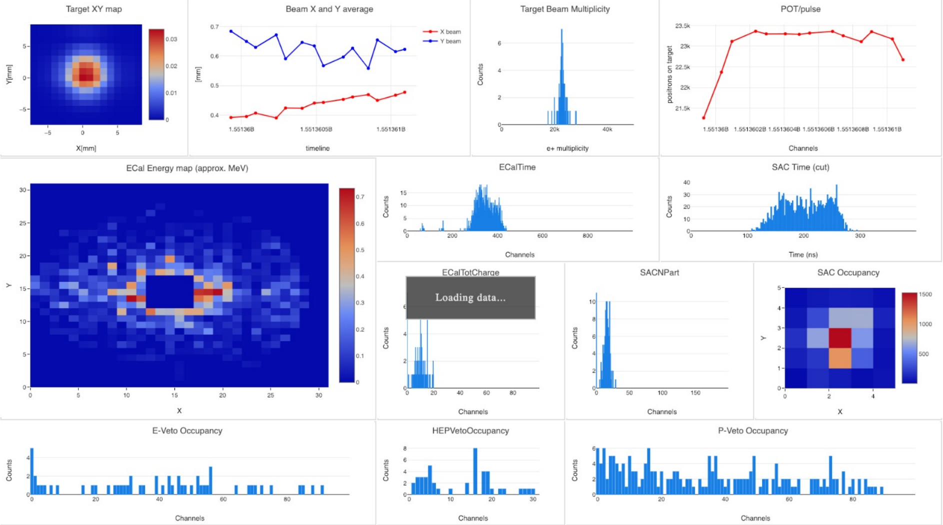
- Trigger distribution boards (2 32 channels)

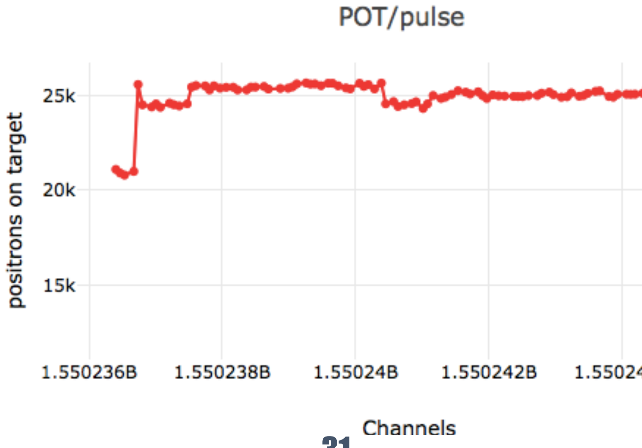
CPUTP generates the trigger signal based on:
- Physics (BTF bunch)
- Cosmics (Calibration)
- Random (Pedestals)

Data collected by two level readout system

- L0 PCs perform data collection from single boards and zero suppression
- L1 PCs perform event merging and eventually further selection based on full event information

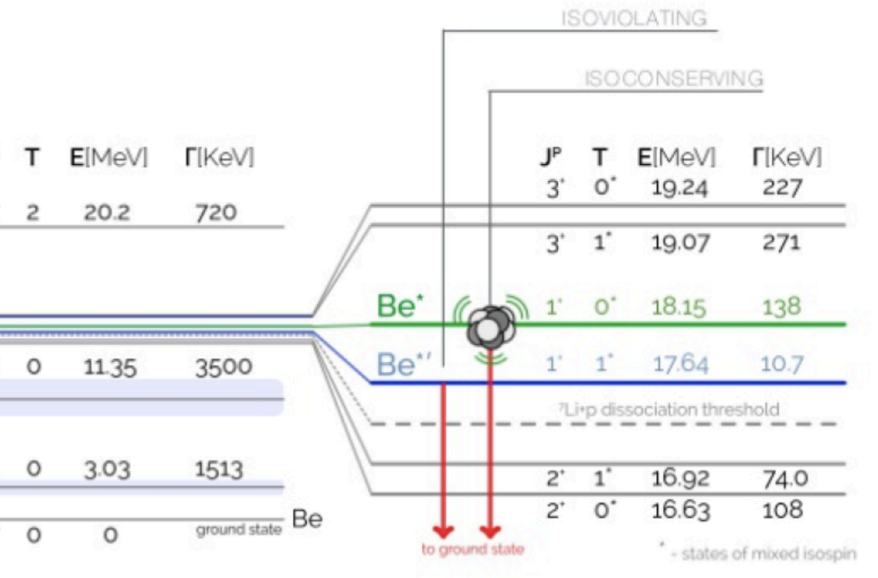
Online reconstruction and monitoring

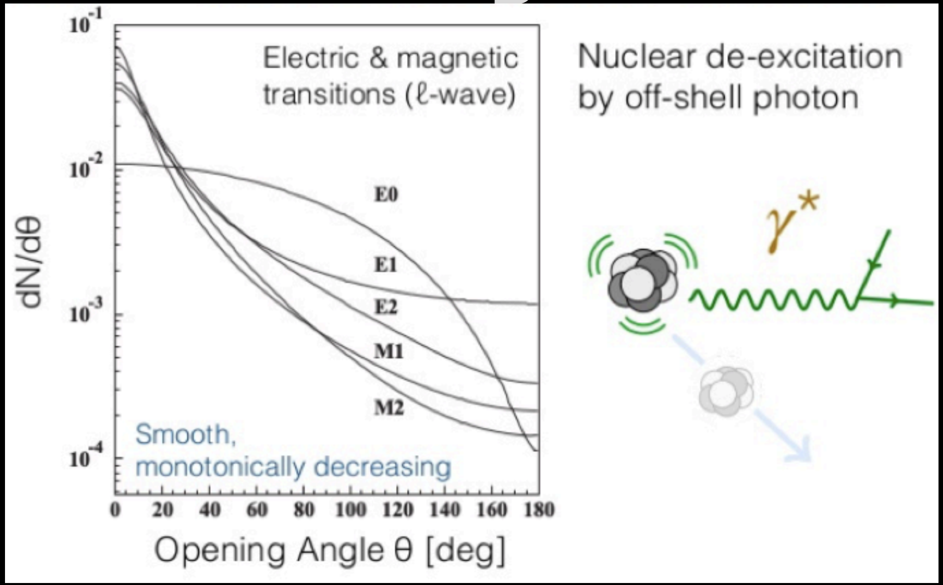


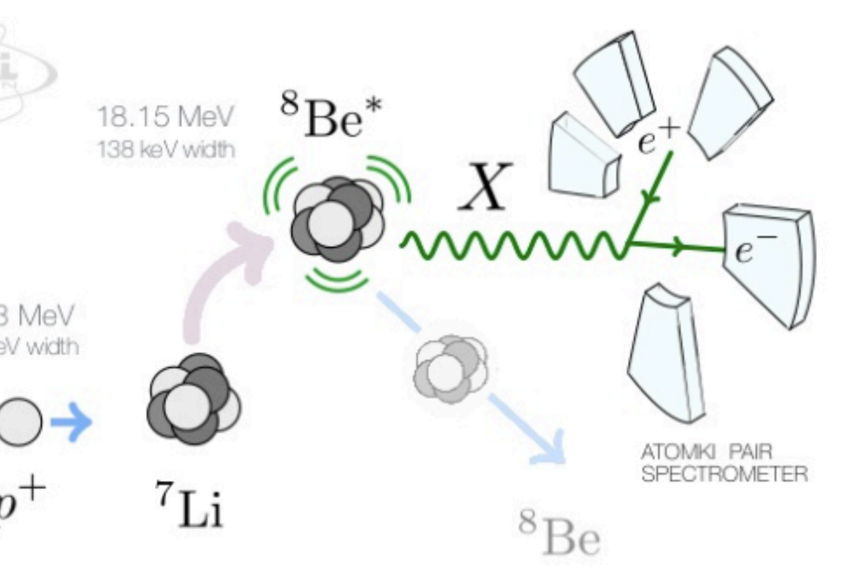


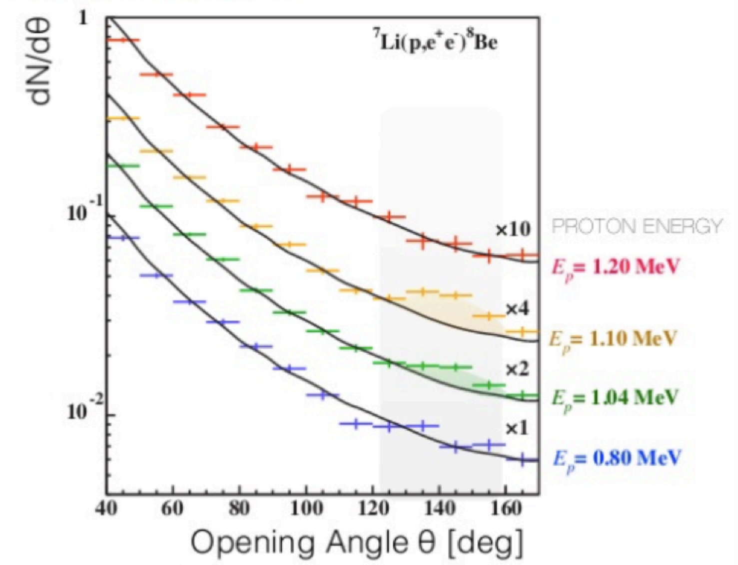
More physics

^{8}Be anomaly

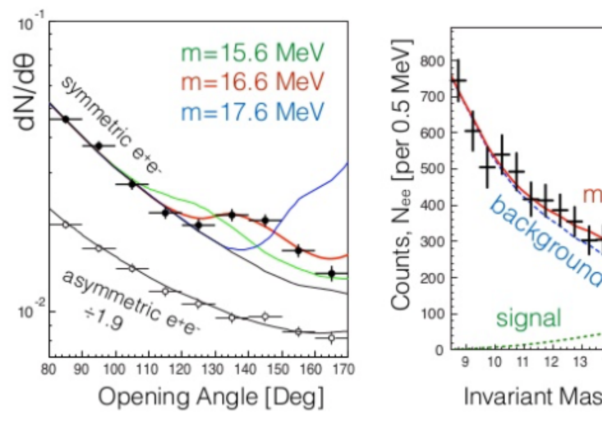






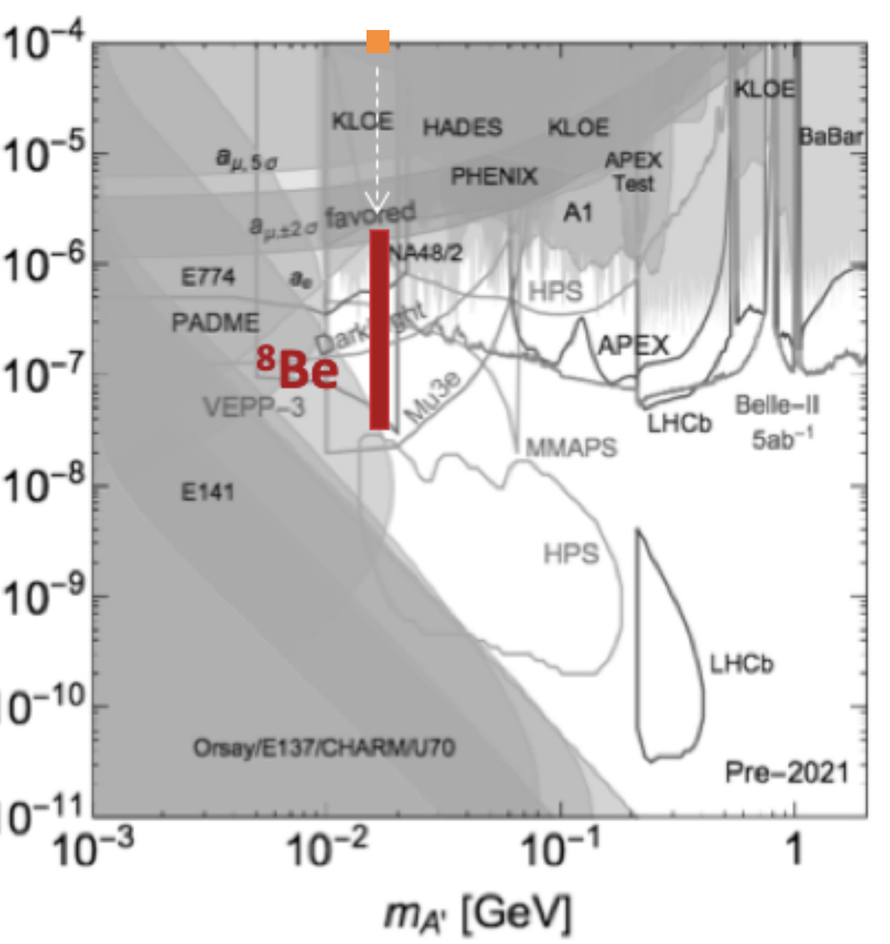


Krasznahorkay et al. Phys. Rev. Lett 116 (2016) 042501



6.8   effect

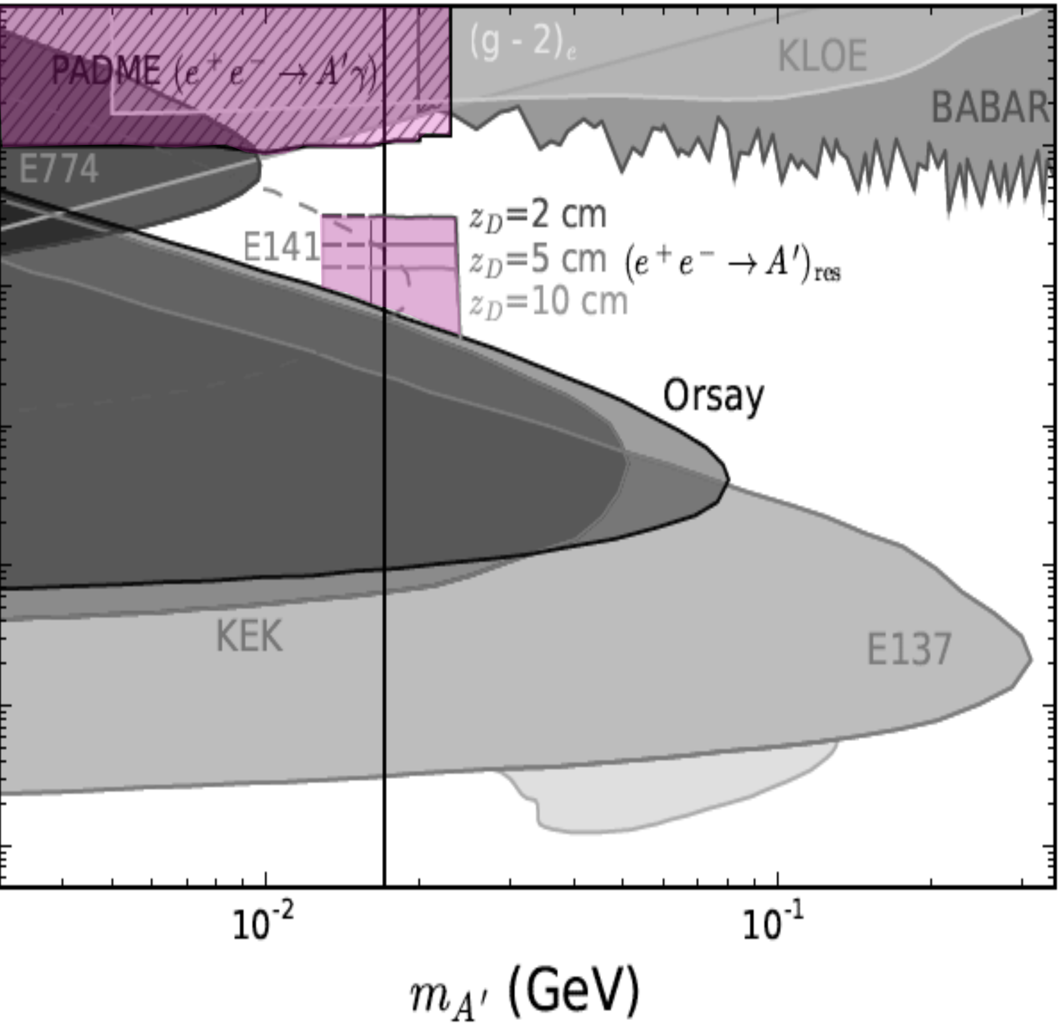
^{8}Be anomaly



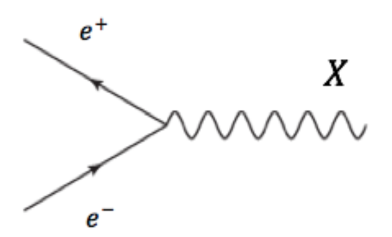
- Not the «minimal» dark photon:
  - Coupling way too high, already excluded by visible decay experiments)
  - Unless we give up universal coupling of the c photon to quark and leptons

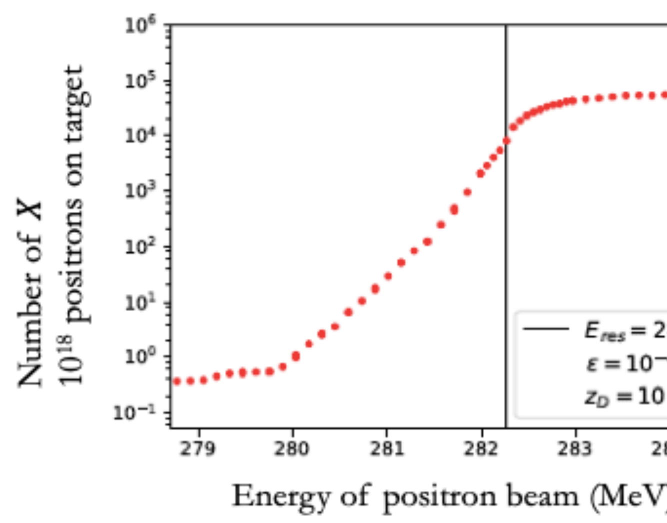
J. Feng et al., "Protophobic Fifth Force Interpretation of th Observed Anomaly in ^{8}Be Nuclear Transitions", Phys. Rev. Lett. 117, 071803 (2016)

^{8}Be boson at PADME



- Exploit knowledge of the mass $\sim$17 MeV/c^2
- Exploit the possibility of tuning the beam energy at BTF for si
  the resonance: E_{e^+} =282.7 MeV
- Produced on-shell throught the direct annihilation diagram
  - Parametric enhancement of cross section wrt $e^+ e^- \to X$
  - Effect of threshold crossing can provide solid evidence (if the b does exist…)
- The electro-magnetic shower background must be absorbed
  - Optimization of the target (thickness, material)

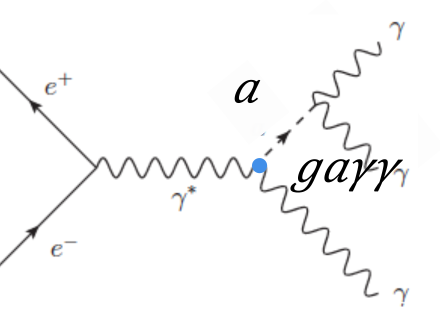


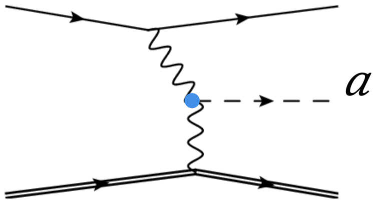


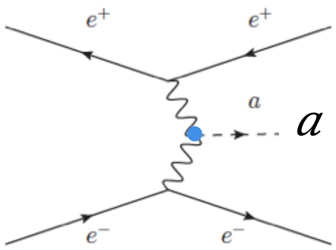
E. Nardi et al. Phys.Rev. D97 (2018) no.9, 0

ALPs at PADME

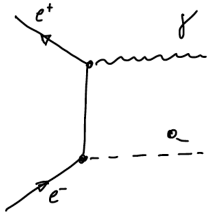
axion-like particles coupled to photons different production mechanisms: annihilation and photon fusion







e promising for PADME ALPs coupled to electrons.



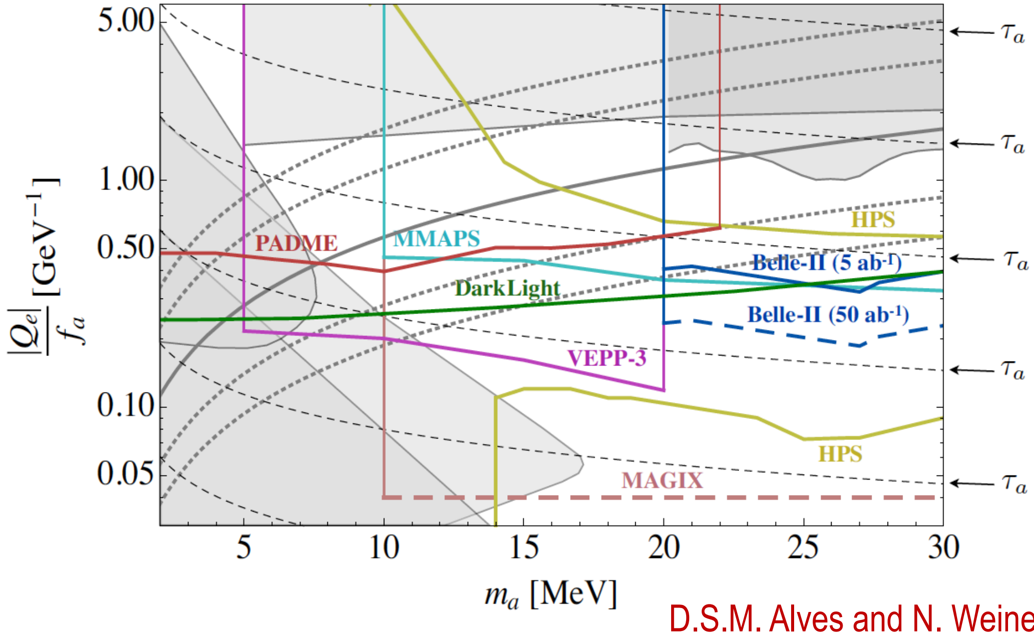
$$\mathcal{L}_a^{\text{eff}} \supset \frac{Q_e}{f_a}\, m_e\, a\, \bar{e}\, i\gamma_5 e\,,$$

states observable at PADME:

Visible ALP decays (a→$\gamma\gamma$): $\gamma\gamma\gamma$, e↑+ $\gamma\gamma$, e↑+ e↑− $\gamma\gamma$

Invisible ALP decays: γ + missing mass

background is $\gamma\gamma$, but limited by invariant mass (24 MeV)



D.S.M. Alves and N. Weine
JHEP07(2018)092

es ongoing at LNF theory division, promising (good granularity and resolution of calorimeters)

PADME status

All detectors installed and working

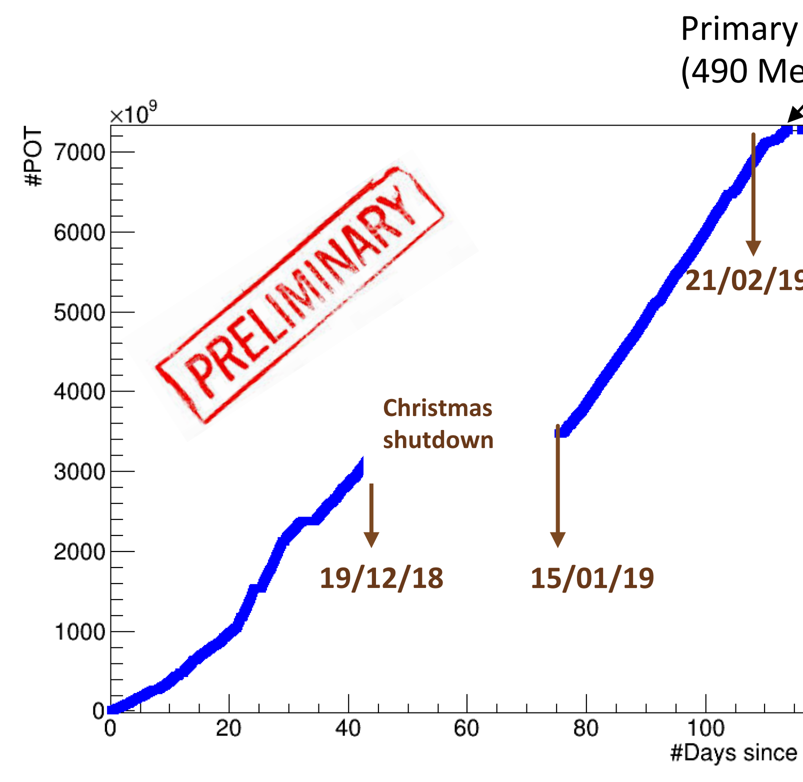
Beam commissioning and optimization for long beam pulses

545 MeV (secondary, BTF target) positrons

Up to 2.5 10^4 / 200 ns pulse

Stable data taking Oct. 2018-Feb. 2019

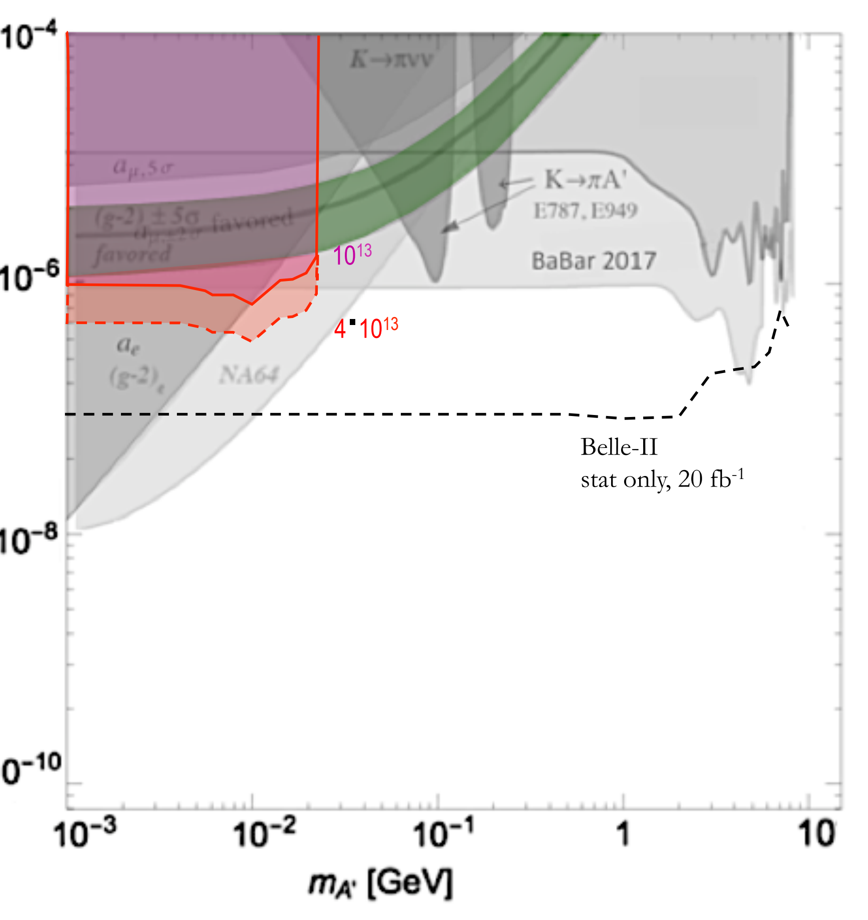
- 0.7 10^{13} positrons on target for **Run-1** (before quality cuts)



Future perpectives

- **Run-2** before the end of 2019?
- Positron beam energy scan?
- Thick target run for ^{8}Be anomaly testing?

PADME status



Nota bene:

PADME requires long (∼200 ns ≫ 10 ns) LINAC pulses a E≳510 MeV, which is not compatible with continuous injections for DAΦNE topping-up

Future projects

PADME@DAΦNE

ME luminosity mainly limited by the positron beam intensity, due
ne need of limiting **pile-up** and **over-veto**

ated by the time resolution of the **detectors** and the time structure
ne positron **beam**

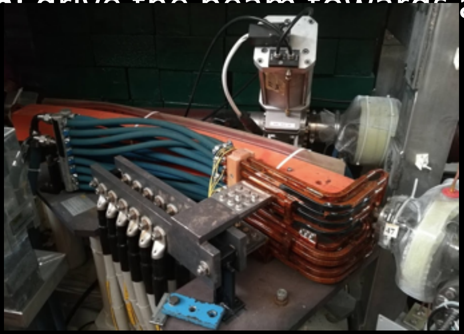
l limits:

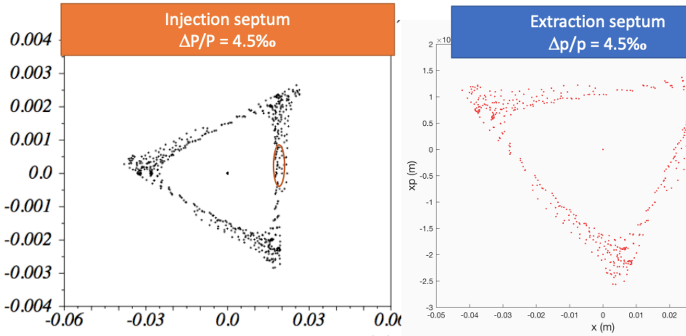
- LINAC maximum repetition rate is **50 Hz**
- LINAC maximum pulse length is ~**300 ns** (due to RF compression)

c idea: inject the LINAC positron beam in one of the DAΦNE rings
"stretch" it by extracting particles as slowly as possible.

main options:

- **Resonant extraction**: drive the beam towards a $n+1/3$ tune resonance and "spill" unstable particles out of the ring (with electric/magnetic septa)
- **Non-resonant extraction**: drive the beam towards a bent crystal and use channeling deflection





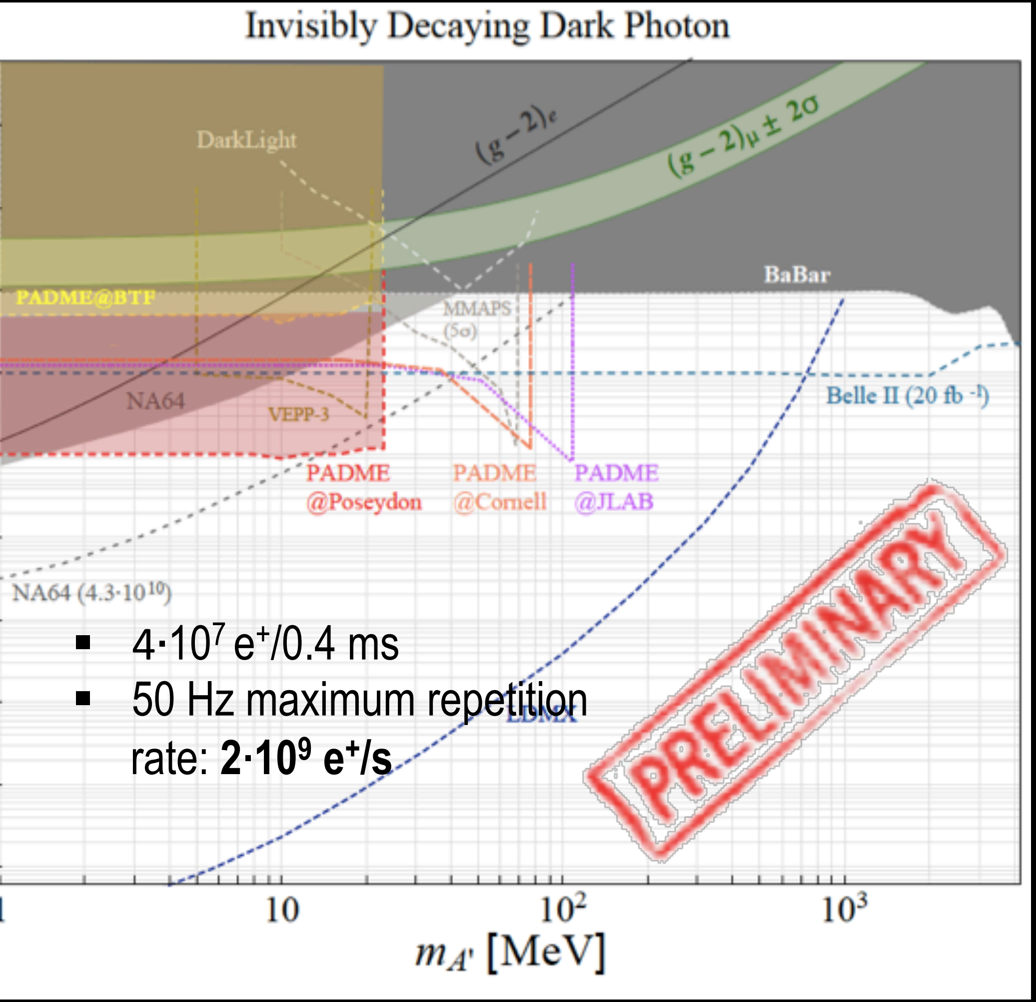
J.Phys.Conf.Ser. 1067 (2018) no.6, 062006

- Use synchrotron radiation loss and chroma to drive the resonance
- RF and wigglers off → significant savings o operations cost
- All beam extracted in 660 turns = 0.2 ms
- $\Delta p/p = 1.4\ 10\uparrow -3$

- Discussion on future use of DAΦNE accelerator complex is ongoing:
    - Positron extracted beam could be used other purposes (**arXiV:1711.06877**)
    - Workshop on DAΦNE Test Facility: **http agenda.infn.it/event/16334/**
- Crystals for positron channeling also interesting for radiation production

PADME@DAΦNE

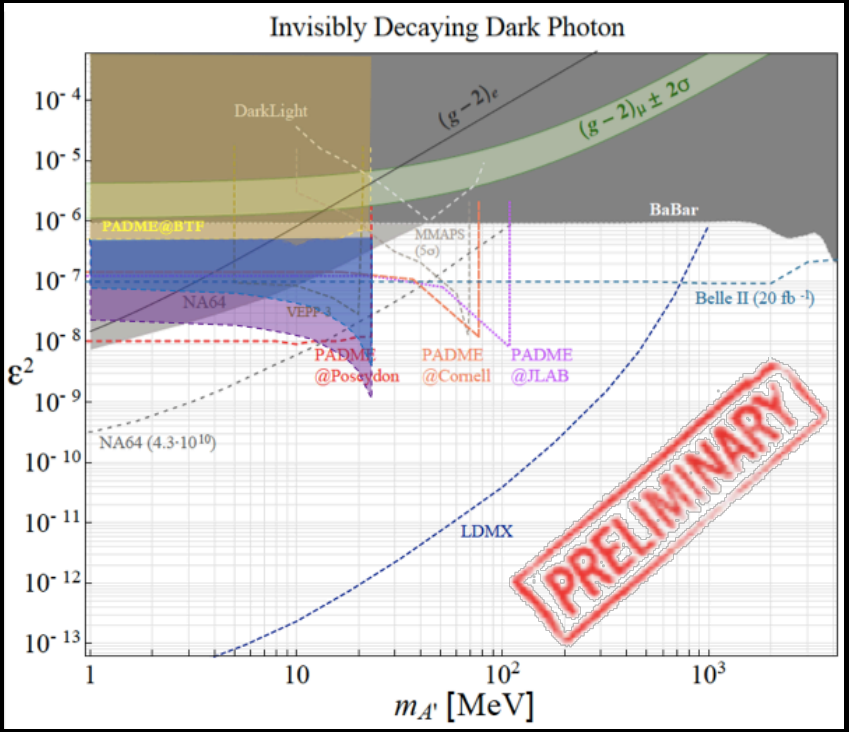
Resonant extraction



- $4 \cdot 10^7$ e⁺/0.4 ms
- 50 Hz maximum repetition

rate: **$2 \cdot 10^9$ e⁺/s**

Crystal channeling ultra-slow extraction



- **At least** similar intensity (if $>10^{-4}$ extraction efficiency) but with a much diluted time-structure
- Virtually a 0-background experiment
- Expect better sensitivity close to kinematic threshold

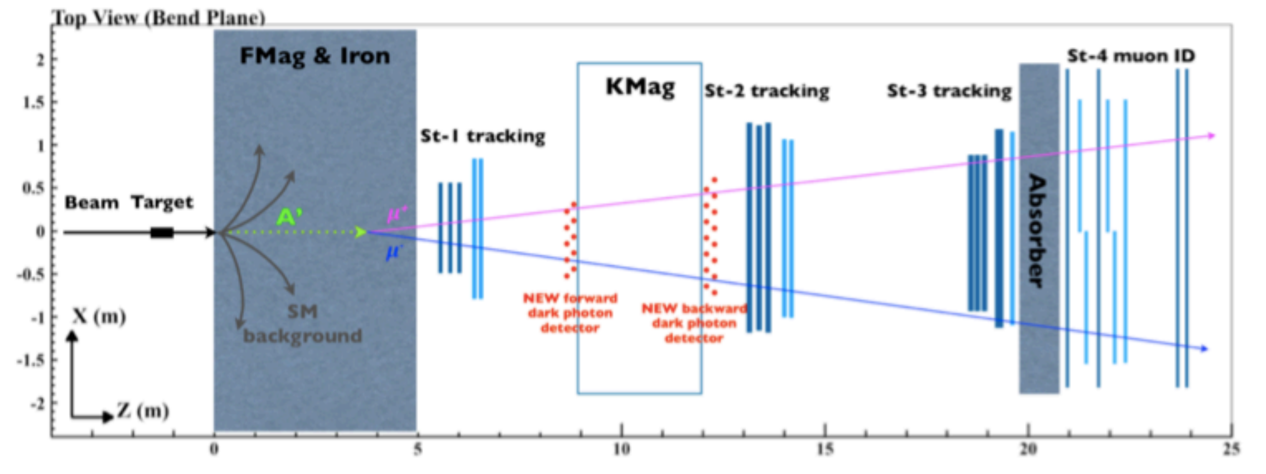
Visible decays: SpinQuest

un parasitically to **SpinQuest** (fka **SeaQuest**) Drell-Yan di-muon experiment

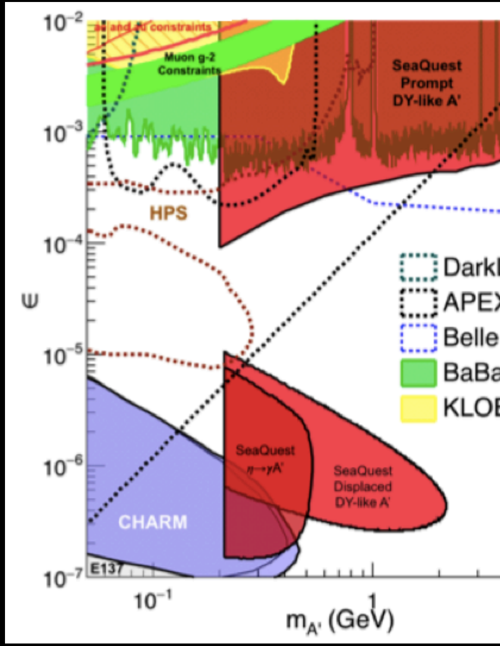
ssume 1.4 10^{18} POT

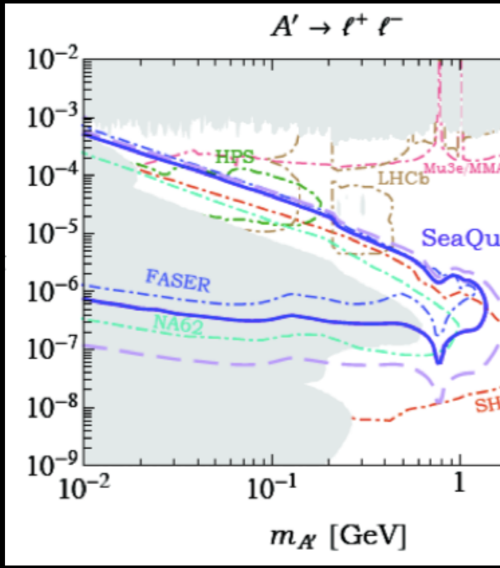
   120 GeV protons from Fermilab Main Injector

xperiment being installed, expected to take data in dump mode in
)20-2021



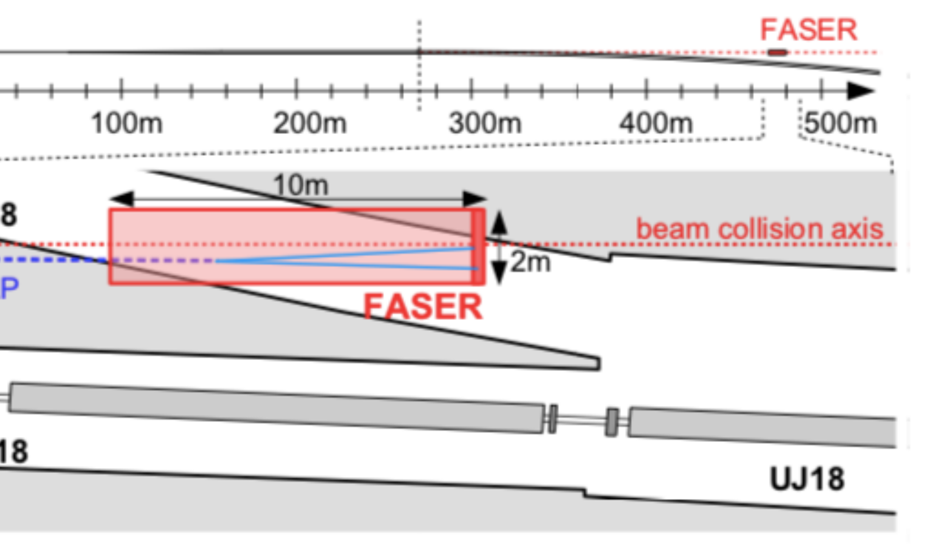
roposal (**DarkQuest**) for adding electromagnetic calorimeter for
xtending the reach to   <   <



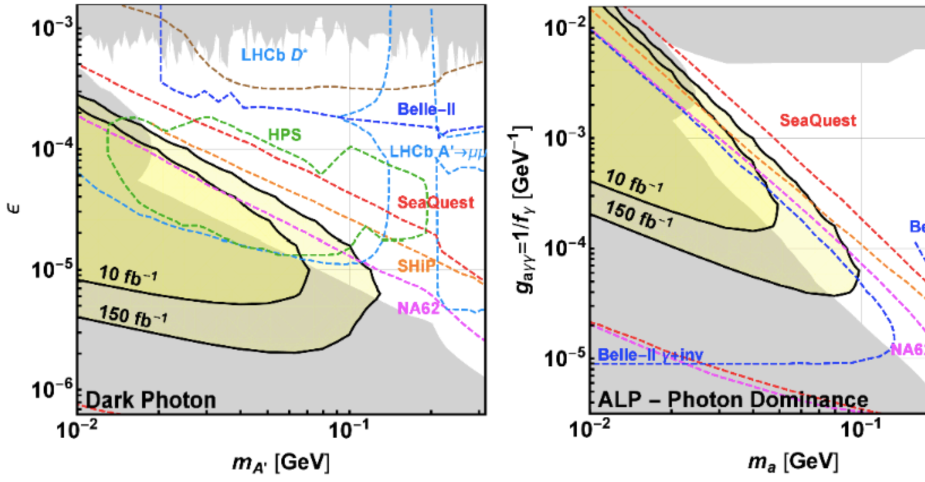


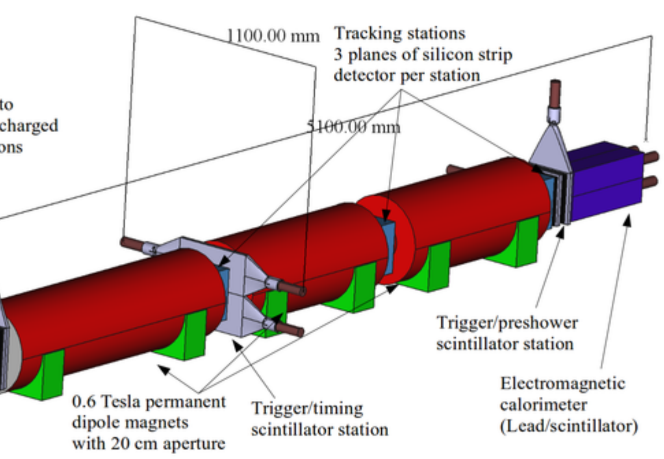
FASER

or Long-Lived Particle escaping ATLAS experiment

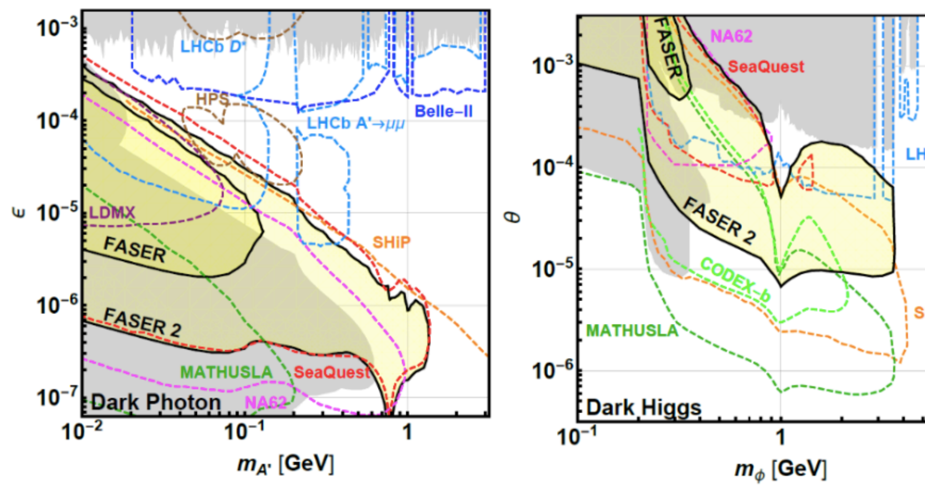


RUN 3





RUN 4

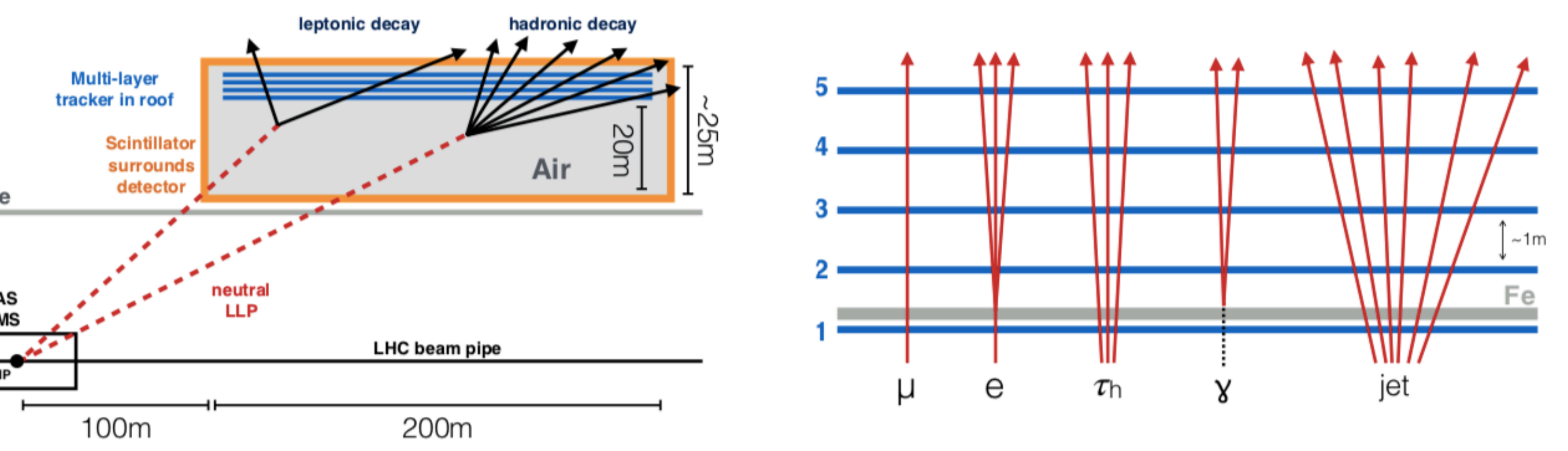


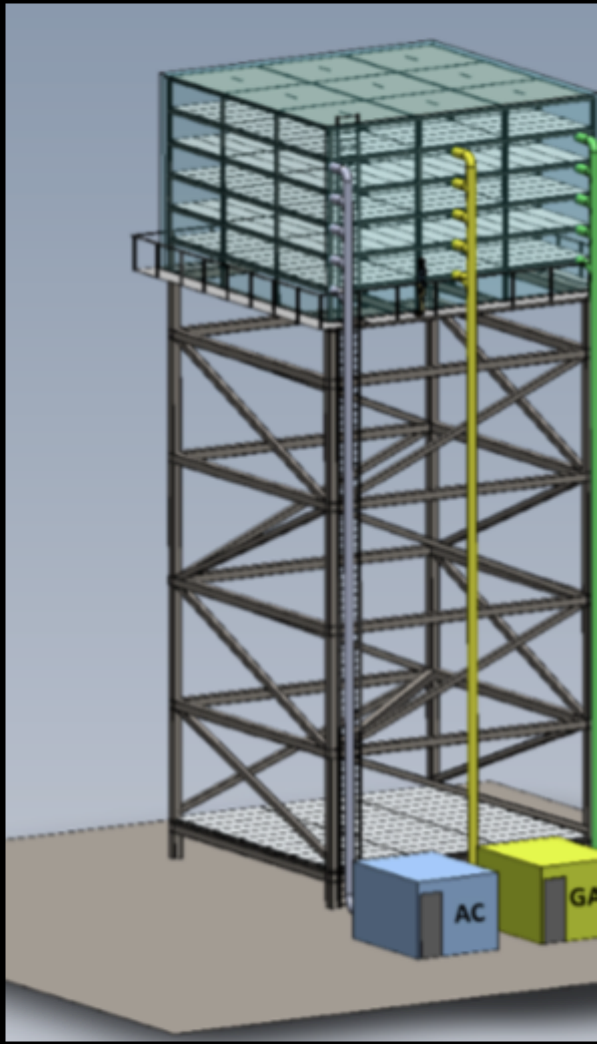
1708.09389, PRD 97 (2018) no. 3, 035001

1710.09387, PRD 97 (2018) no. 5

ts large forward (small angle) cross section enhancement for
cale LLP production processes to probe sub-GeV regime

MATHUSLA





- general-purpose external LLP detector for he HL/HE-LHC
- ery large size with good timing capabilities e.g. RPC-based)

1810.01879, PRD 99 (2019) no. 1, 015021

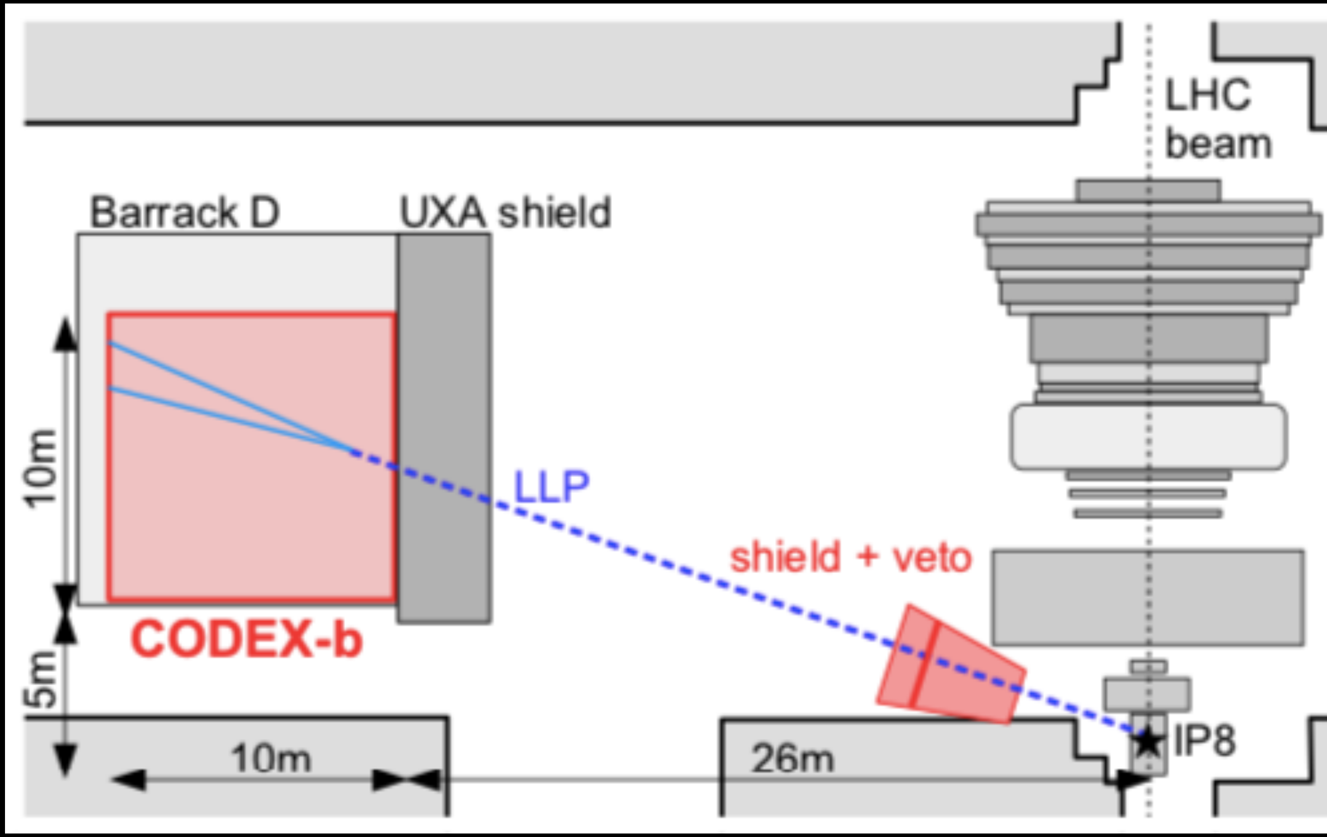
CODEX-b, AL3X ...

EX-b

lar concept, detector in existing cavity
r LHCb

ller, different detectors, possibly lower
s threshold

interface to nearby LHCb



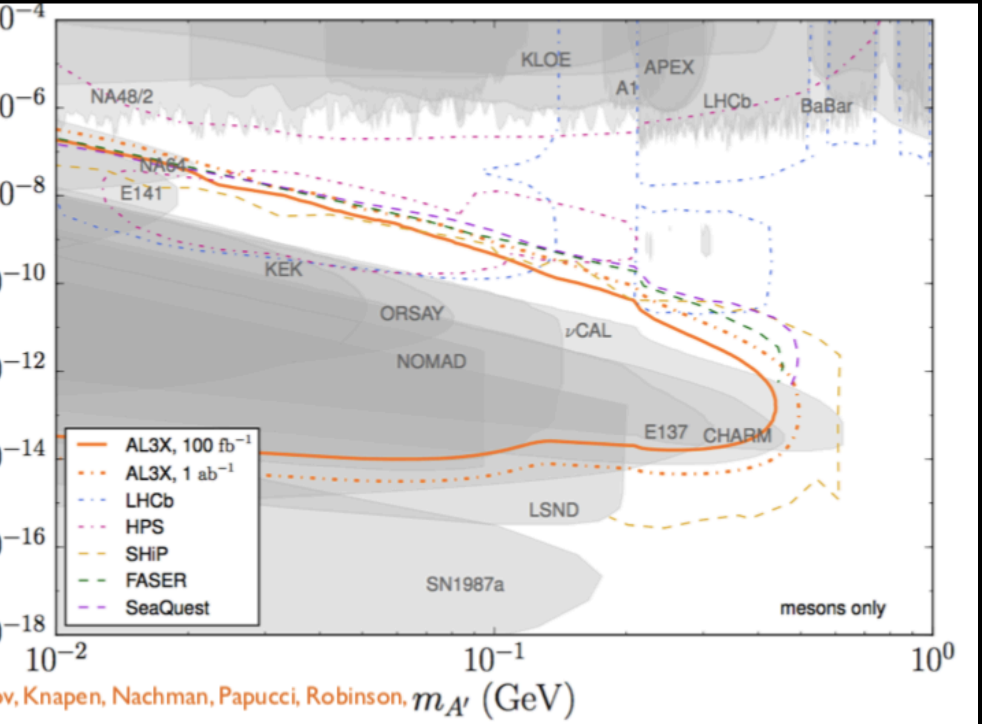
3X

adically reconfigure ALICE detector
d its collision point at HL-LHC for
edicated LLP search

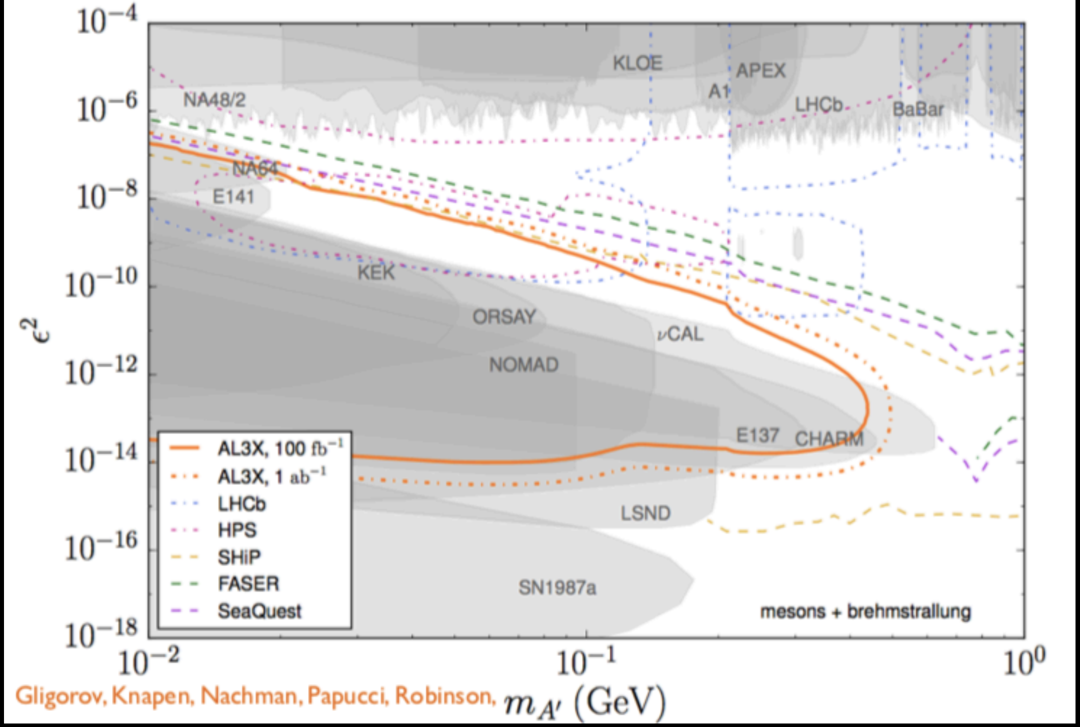
eeds a huge shielding

hallenging

Summary for DP sensitivity

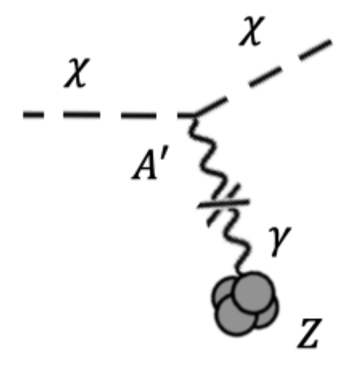


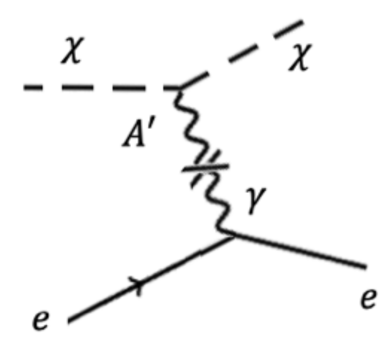
v, Knapen, Nachman, Papucci, Robinson,



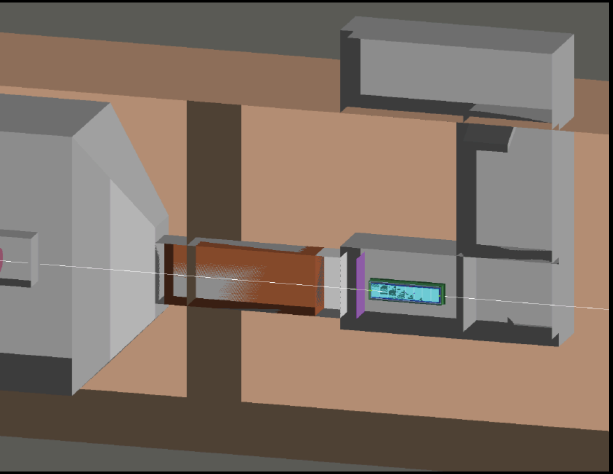
Gligorov, Knapen, Nachman, Papucci, Robinson,

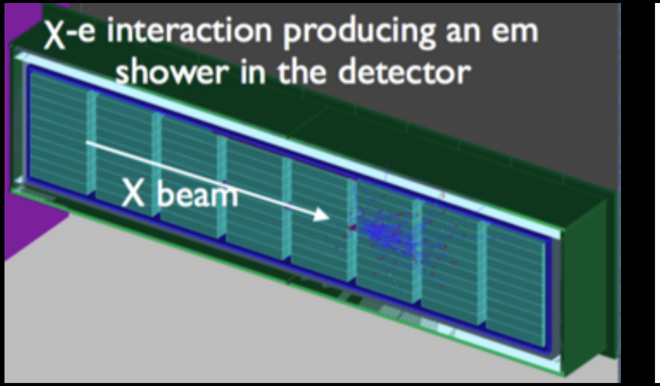
BDX

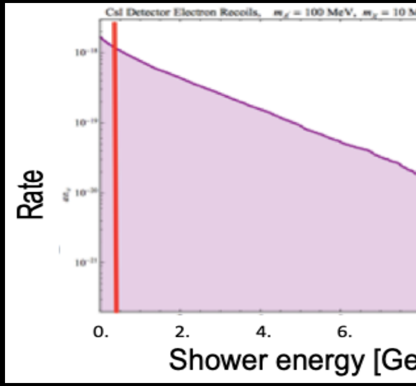




OT = 1 beam-year at JLAB, Hall-A (3 beam-years at Hall-C?)

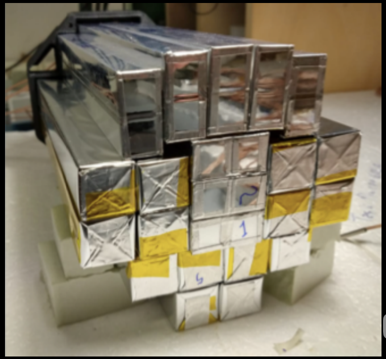






Detector: 800 Cs(Tl) crystals, total interaction volume 0.5

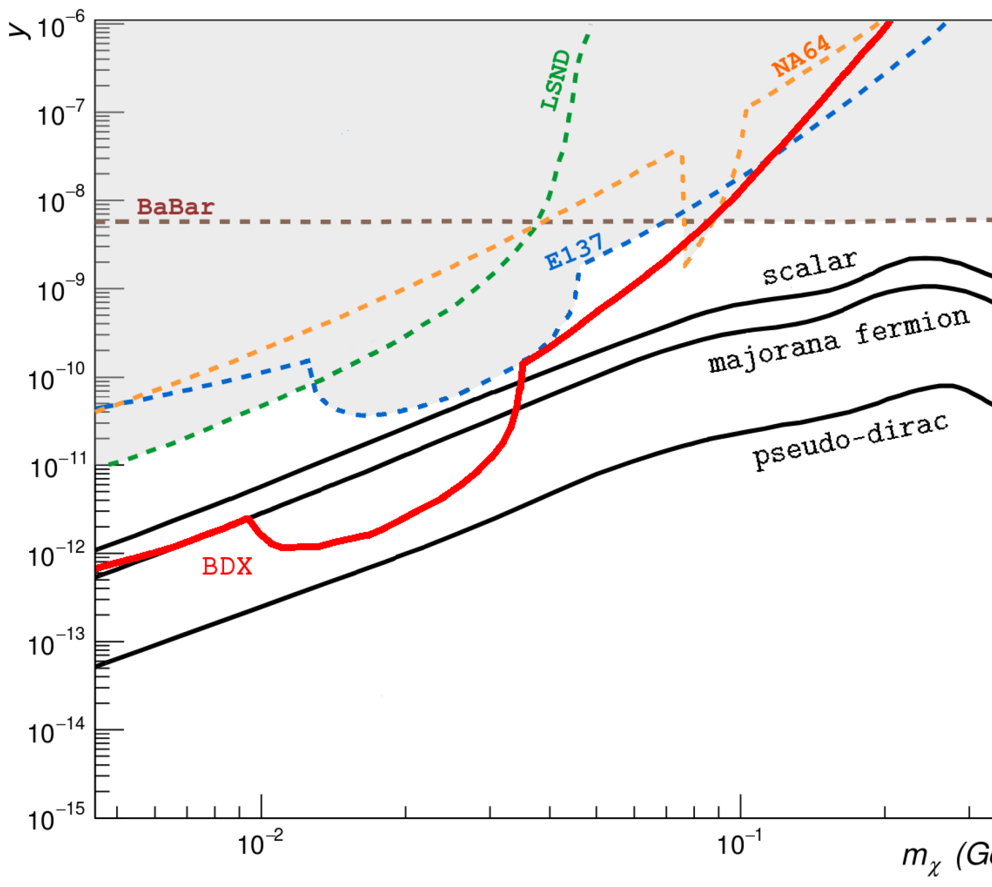
news: BDX-Mini
PbWO4 crystals calorimeter
yer of tungsten
ermetic plastic scintillator veto systems
alled in a well, dug downstream of Hall-A,
ne proposed BDX location



BDX

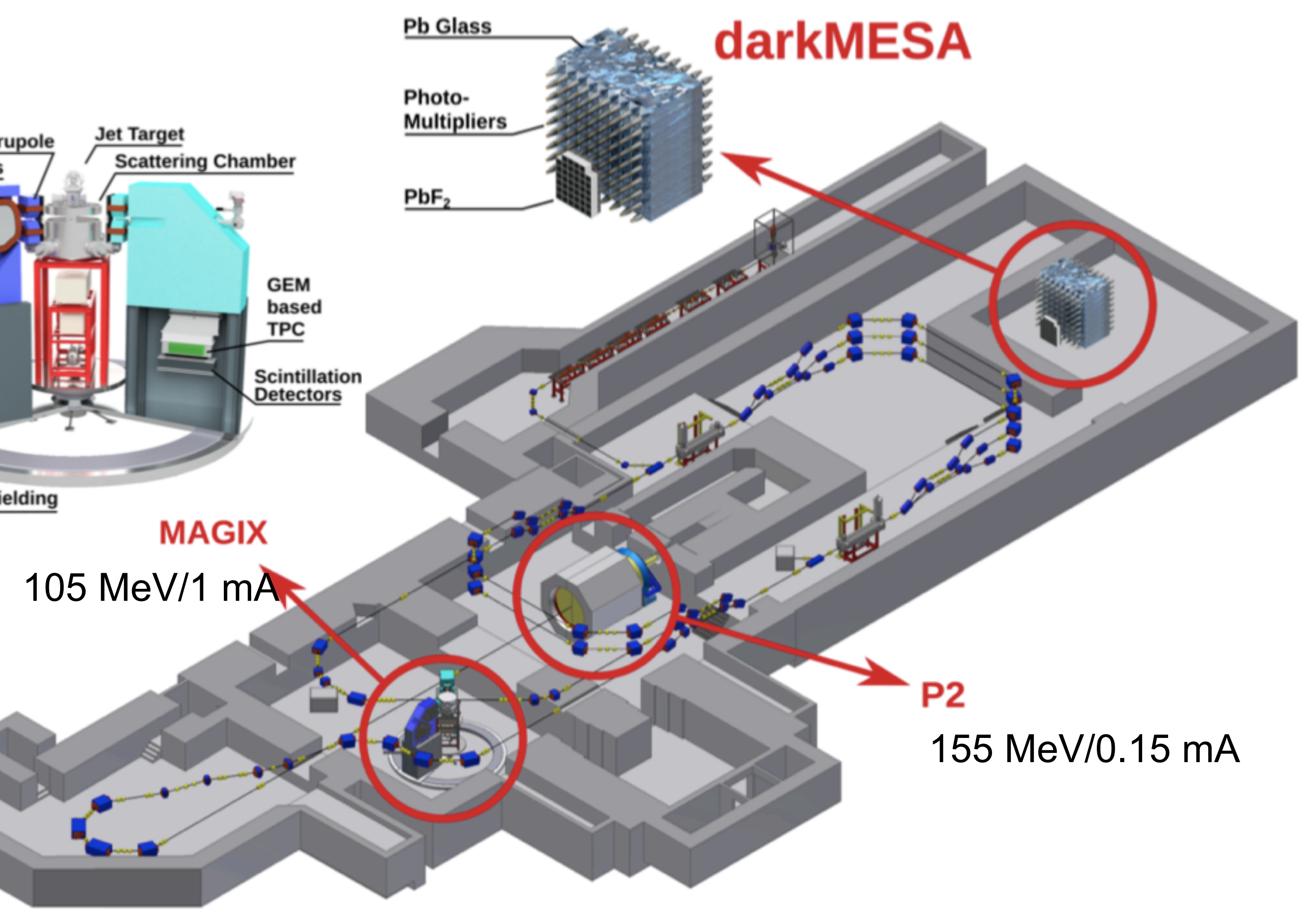
en trying to detect the scattering of DM decay products
he dark photon, two additional parameters:
The mass of the DM particle, χ
ts coupling to the DP, α_D
rder to still representing exclusions on a 2D plot, use the
owing variable:
$\epsilon^2 \alpha_D (m_\chi / m_{A'})^4$
l draw different curves for different choices of two variables
ular choice: $3 m_\chi = m_{A'}$

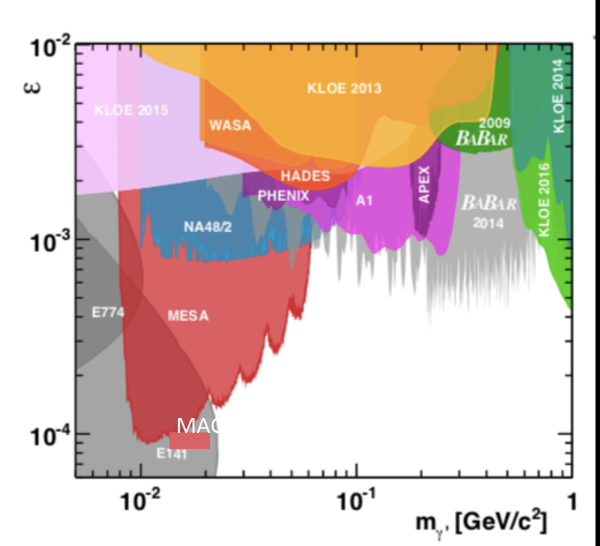
ic density lines assume:
Standard cosmological history
Only a single component of dark matter
nteracting via Dark Photon exchange only

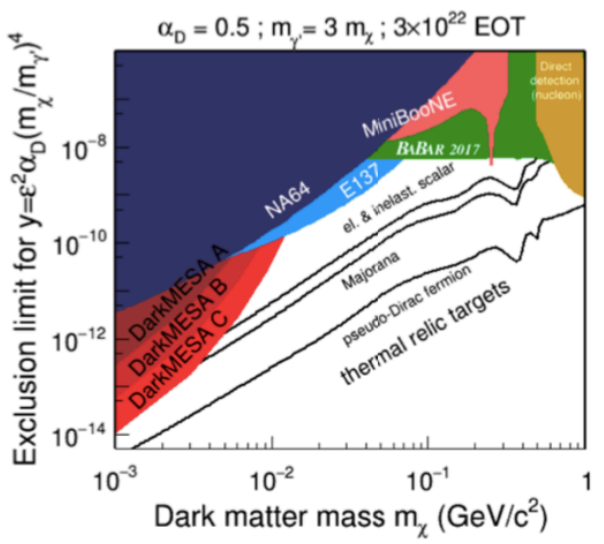


MESA

cw multi-turn energy-recovery electron linac







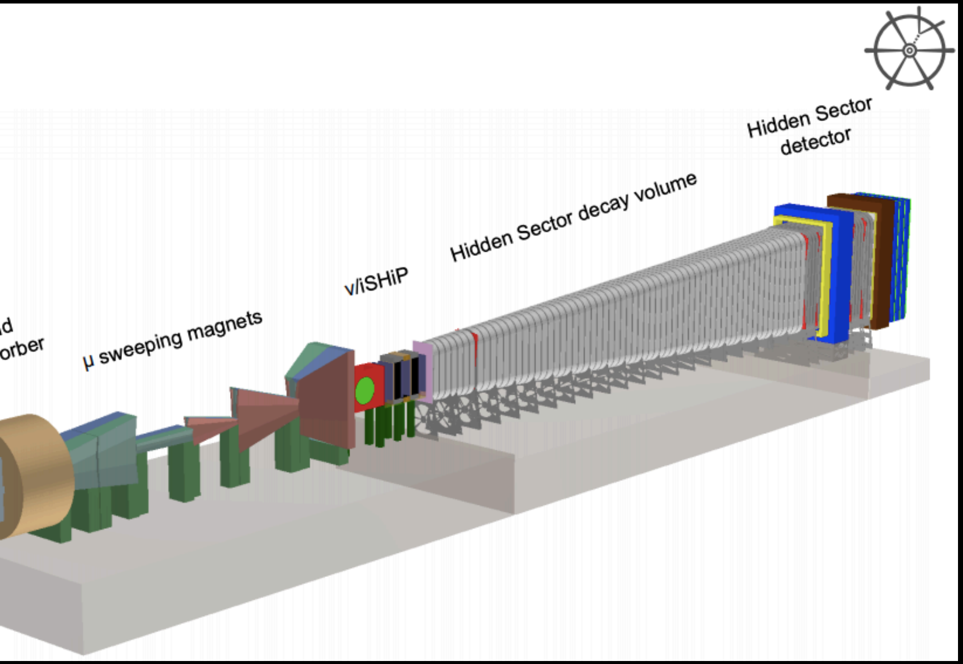
Latest news:

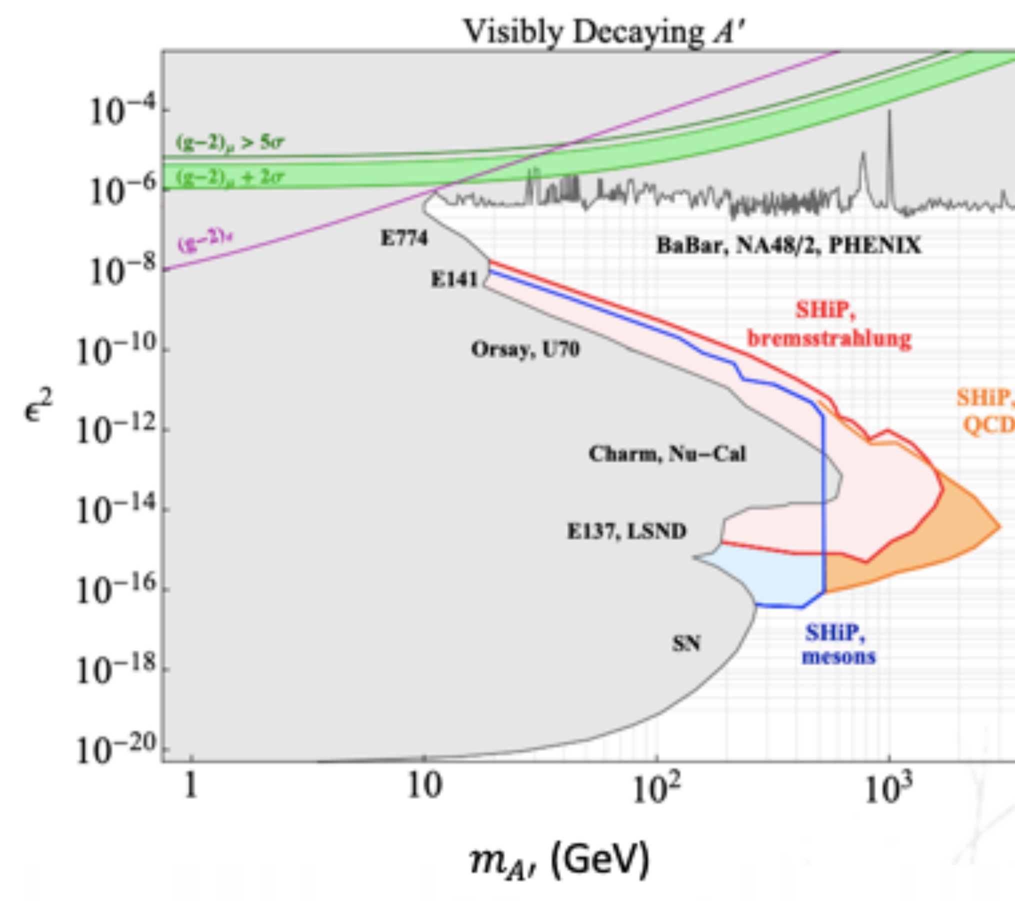
DarkMESA A: existing PbF$_2$ calorimeter, 0.1

DarkMESA B: add lead glass crystals

DarkMESA C: reach 11 m^3 volume

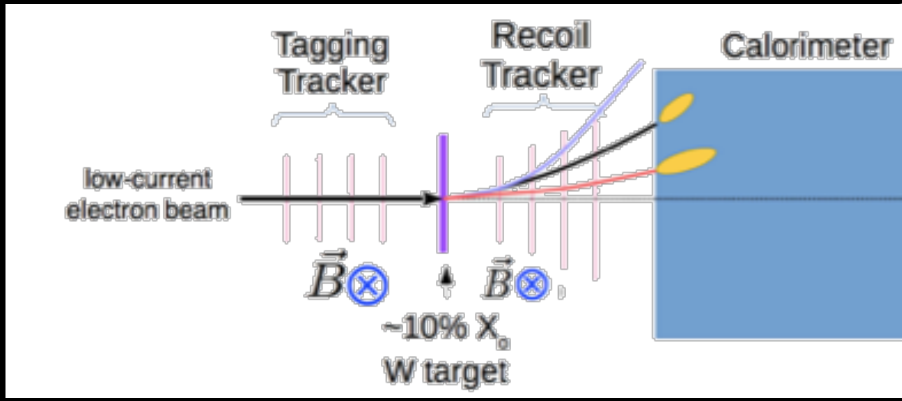
SHIP





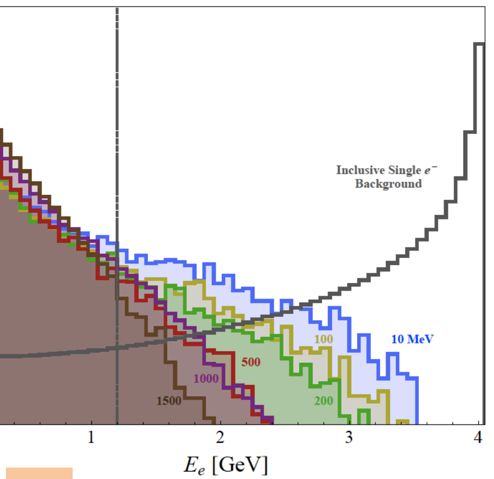
- get peak power 2.5 MW (average 355 kW)
  - Many constraints on the integration, access, thermal stress, radioactivity...
- ve muon shield
  - Reduce by 6 orders of magnitude muon flux
  - High field to minimize length (1.8 T)
- trino detector
- den sector detector
  - Heavy neutral lepton
  - Dark photon

LDMX



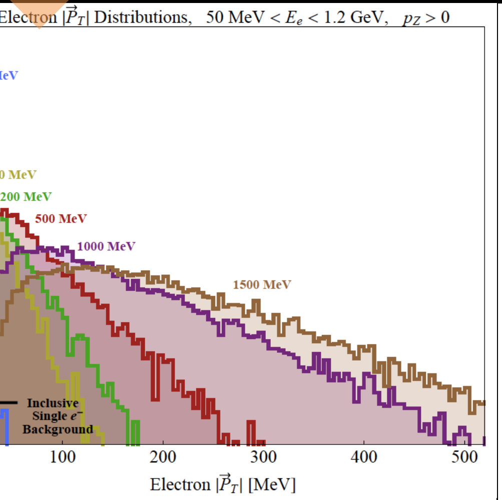
electron beam on 0.1 target

Missing momentum

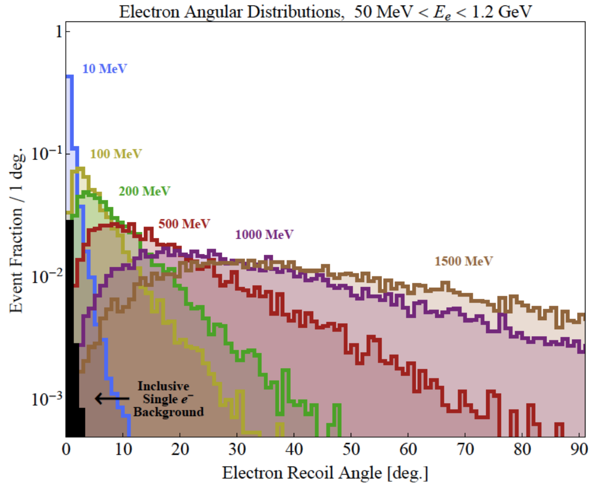


Electron recoil energy [GeV]

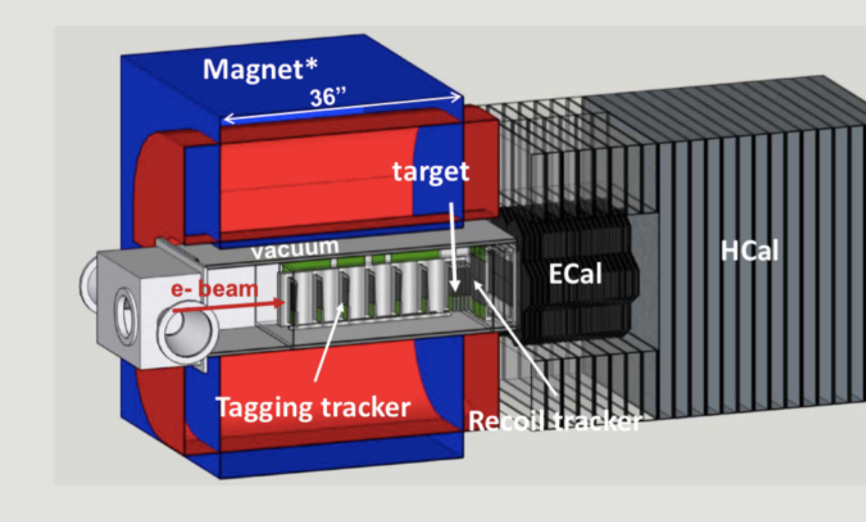
- A multi-GeV, low-current, high repetition rate (10^{16} EOT/year ≈ 1e/3 ns) beam with a large beam spot to spread out the occupancy/radiation dose.
- DASEL@SLAC (4/8 GeV) or CEBAF@JLab (up to 12 GeV)
- First phase (10^{14} EOT) 2022, full intensity of DASEL beam 2026



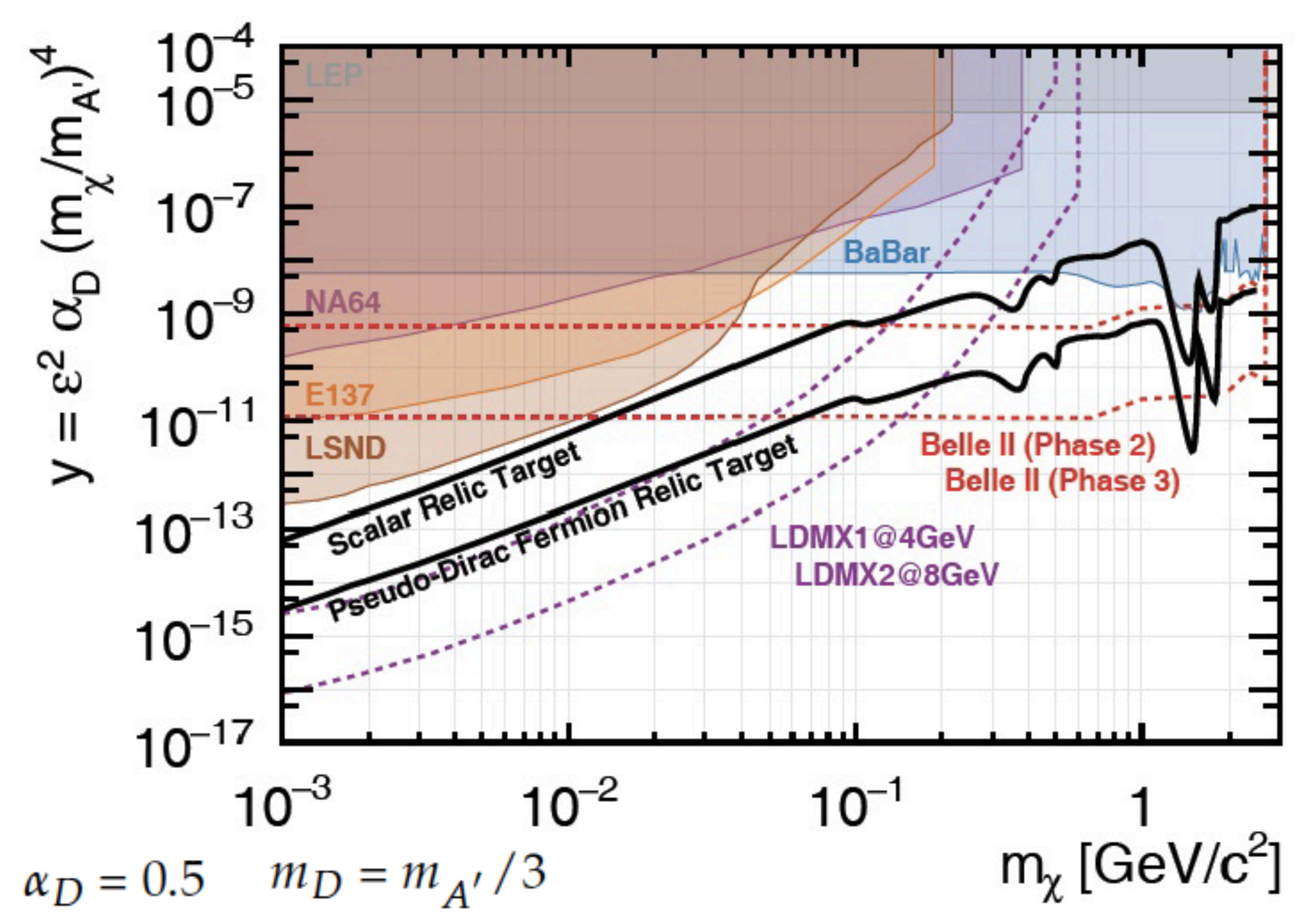
tron transverse momentum [MeV]



Electron recoil angle [deg.]

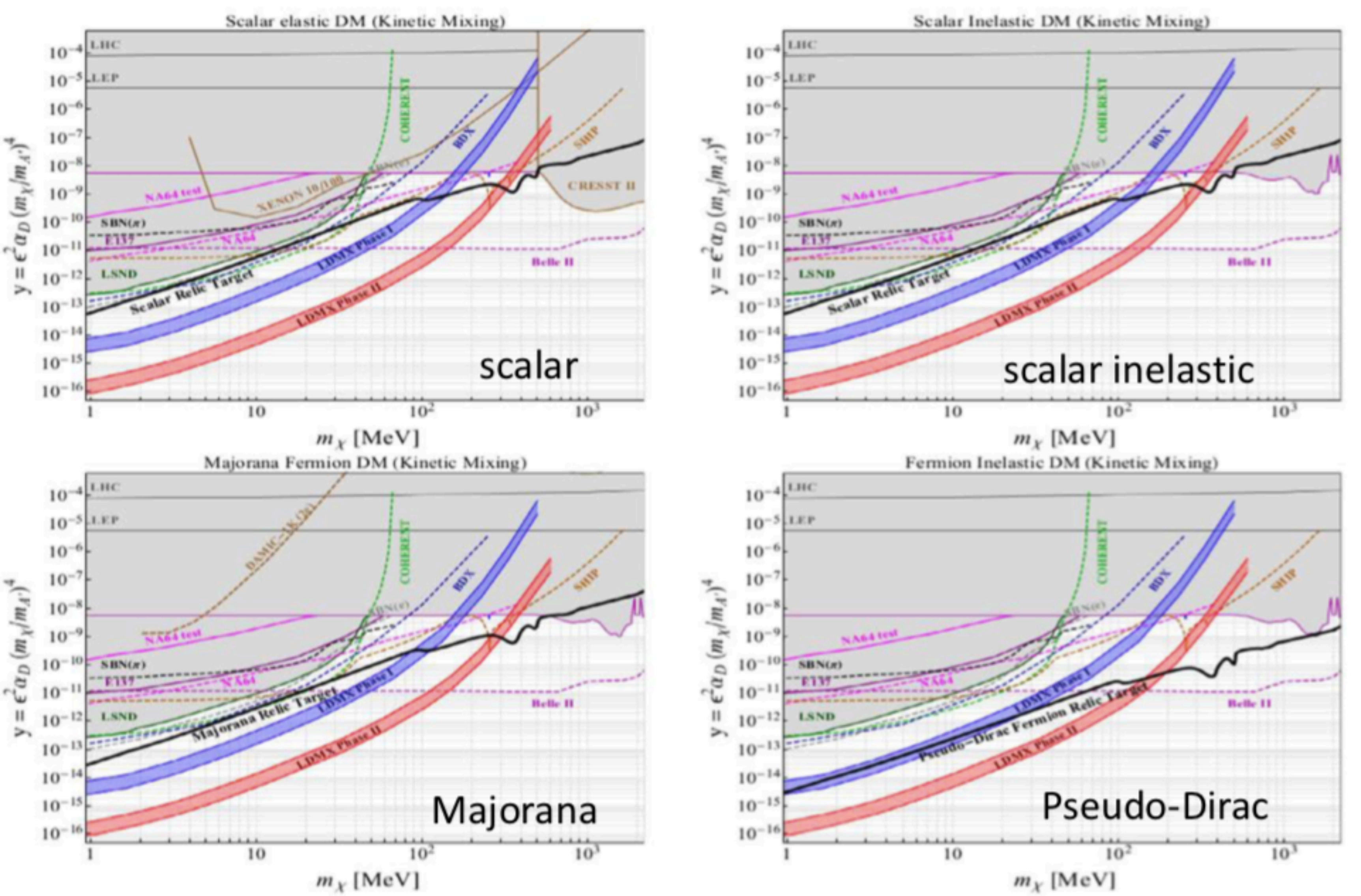


LDMX

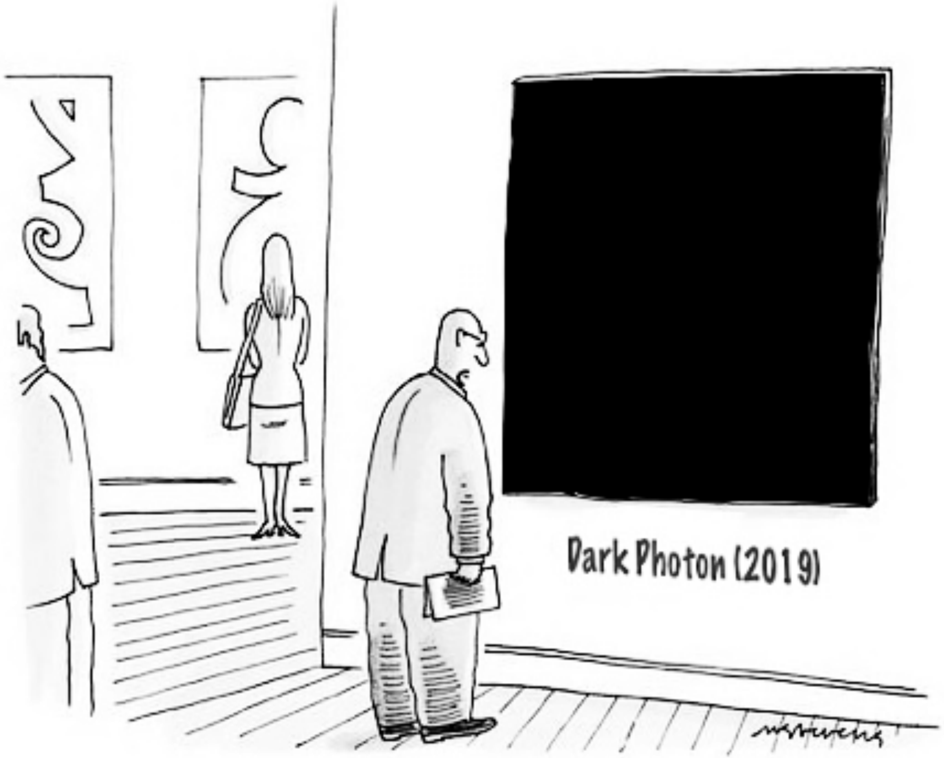


$y = \varepsilon^2 \alpha_D (m_\chi/m_{A'})^4$
10^{-4}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-3}
10^{-2}
10^{-1}
1
m_χ [GeV/c^2]
LEP
BaBar
NA64
E137
LSND
Scalar Relic Target
Pseudo-Dirac Fermion Relic Target
Belle II (Phase 2)
Belle II (Phase 3)
LDMX1@4GeV
LDMX2@8GeV
$\alpha_D = 0.5 \quad m_D = m_{A'}/3$

Summary of future DP experiments



0.5


Dark Photon (2019)

PADME collaboration

INFN
Istituto Nazionale di Fisica Nucleare

nics, DAQ, trigger, mechanics, vacuum,
infrastructure, …

SAPIENZA
UNIVERSITÀ DI ROMA

Simulations, physics, analysis

UNIVERSITA' degli STUDI di ROMA
TOR VERGATA

are, calibrations, calorimeter, analysis

UNIVERSITÀ
DEL SALENTO

Diamond target, analysis

Sofia University St. Kliment Ohridski
Bulgaria

Scintillating bars veto and electronics, DCS, analysis

MTA
atomki
DEBRECEN

Small angle calorimeter, *X* boson analysis

Cornell Laboratory f
Accelerator-based Sc
and Education (CLA

WILLIAM & MARY
CHARTERED 1693

THE
UNIVERSITY
OF IOWA

Simulations
BGO calorimeter
Small angle calorimeter R&D
Analysis