Searching for dark photons with PADME

Andre Frankenthal on behalf of the
PADME Collaboration

Outline

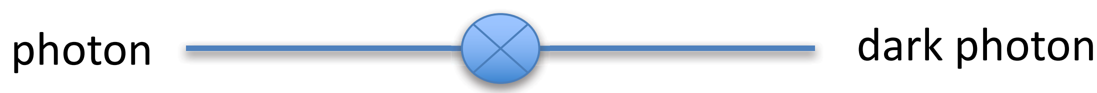
- Motivation: dark photons
- Fixed-target experiments
- PADME
- Status

Dark photons

- Renormalizable extension of the SM
- Additional U(1) gauge symmetry
- Kinetic mixing with SM $U(1)_Y$

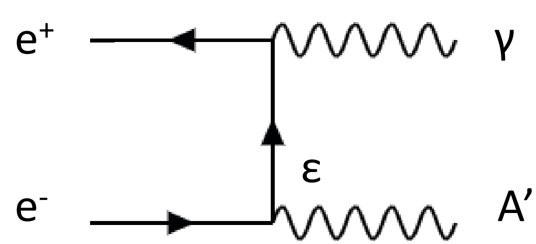
$$-\epsilon F'_{\mu\nu} B^{\mu\nu}$$

- Leads to coupling between photon and dark photon:



ε = kinetic mixing coefficient

- Allows for processes such as:



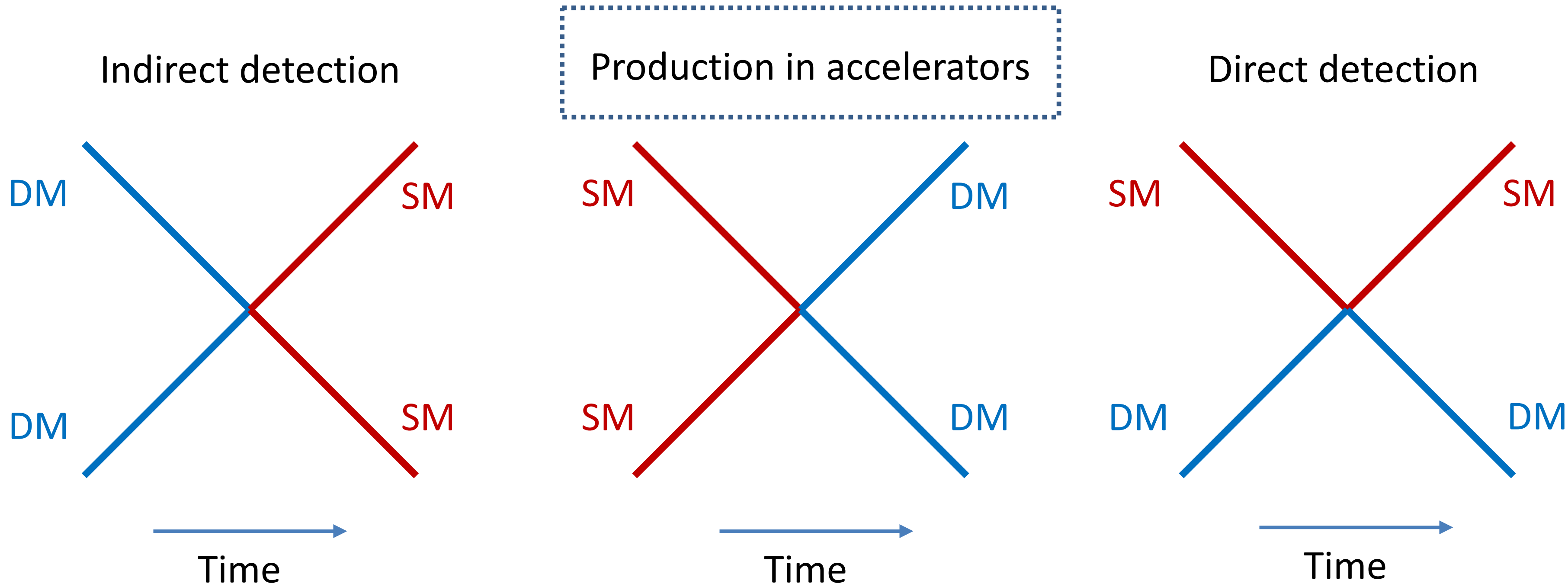
$$+\frac{1}{2} m_{A'}^2 A'^{\mu} A'_{\mu}$$

(Mass term also allowed)

$$+\epsilon e A'^{\mu} J_{\mu}^{EM}$$

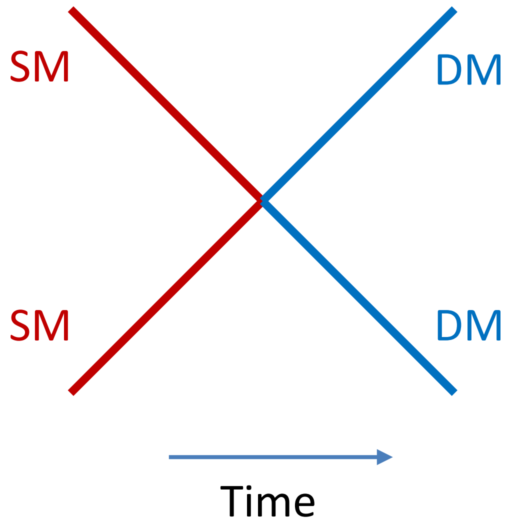
DM search pathways

- Different DM search modes via interaction with SM particles:

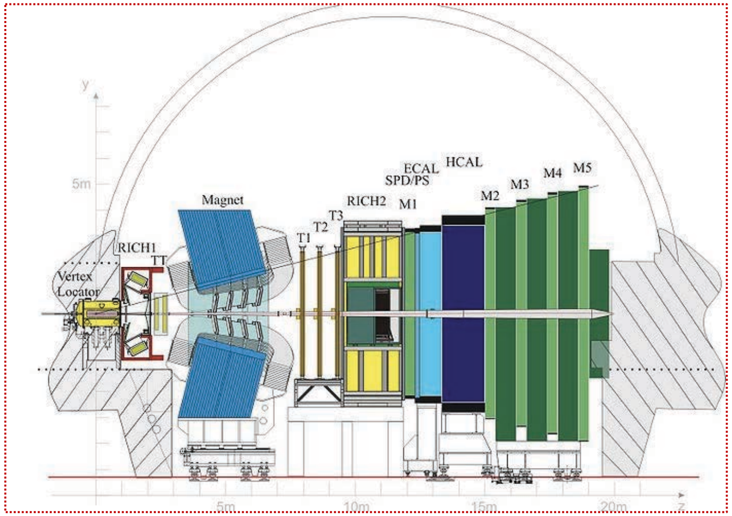


DM search pathways

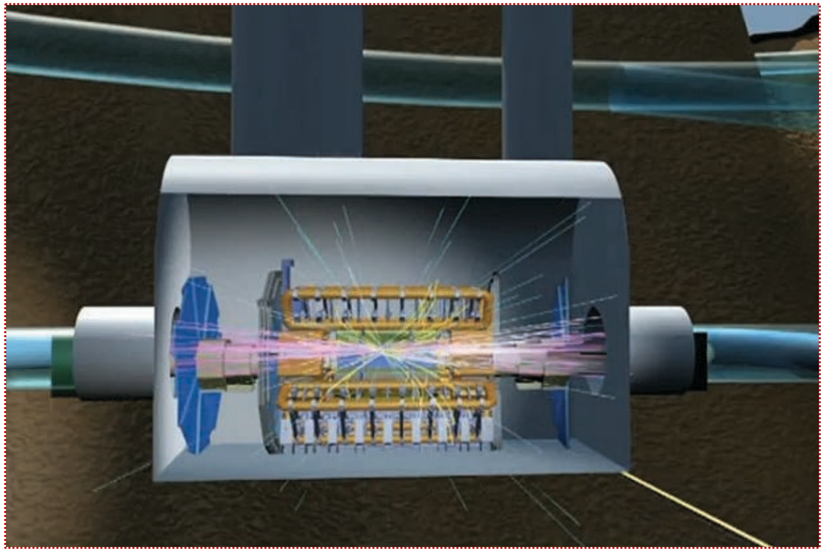
Production in accelerators



Fixed-target



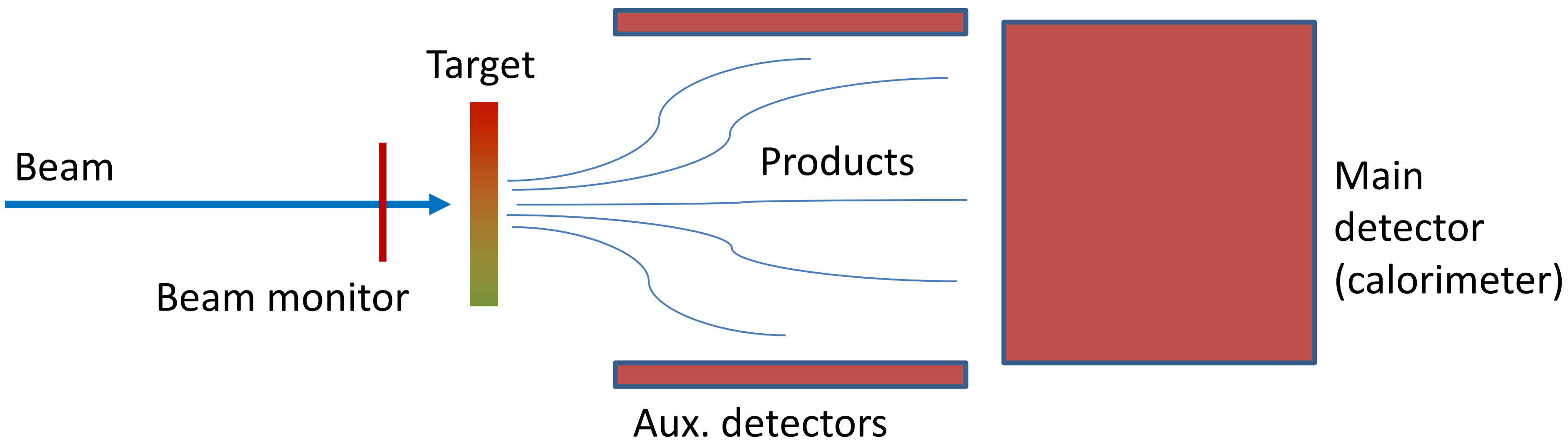
Colliders



Fixed-target experiments

- General principles:
  - One beam (e-, e+, protons, neutrinos, …)
  - One target (C, Be, W, …)
  - Detectors in front of target to measure beam
  - Detectors behind the target to measure products

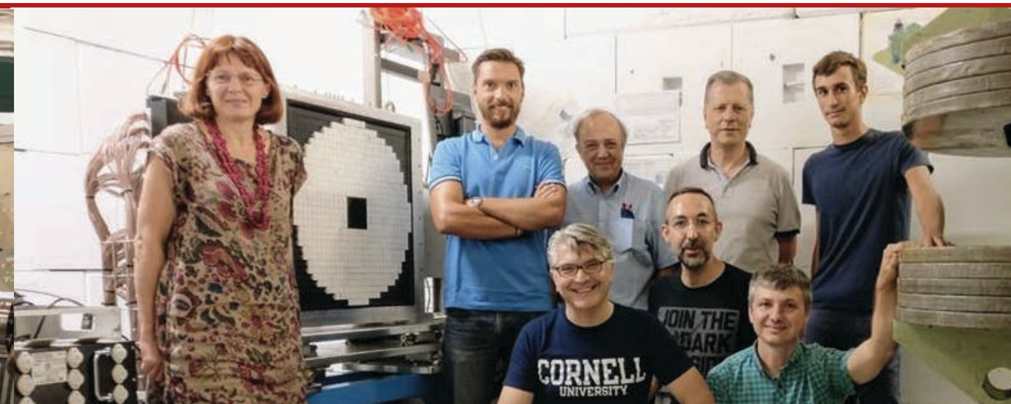
SM + SM → DM + DM

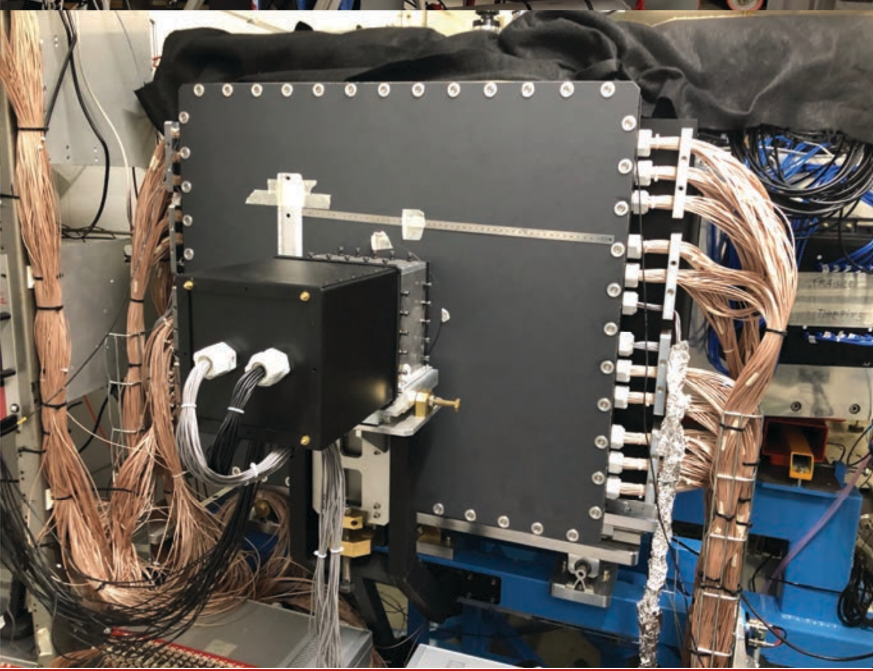


PADME

- *Positron Annihilation into Dark Matter Experiment*
- Goal: look for dark photons
- Fixed-target, missing-mass experiment
- Beam: 550 MeV e^+, 20k e^+/bunch @ 50 Hz
- Target: Diamond (C)
- Detectors: Electromagnetic calorimeter (ECAL), Small-Angle Calorimeter (SAC), vetos, active target
- 0.45 T B-field to bend beam after target

PADME

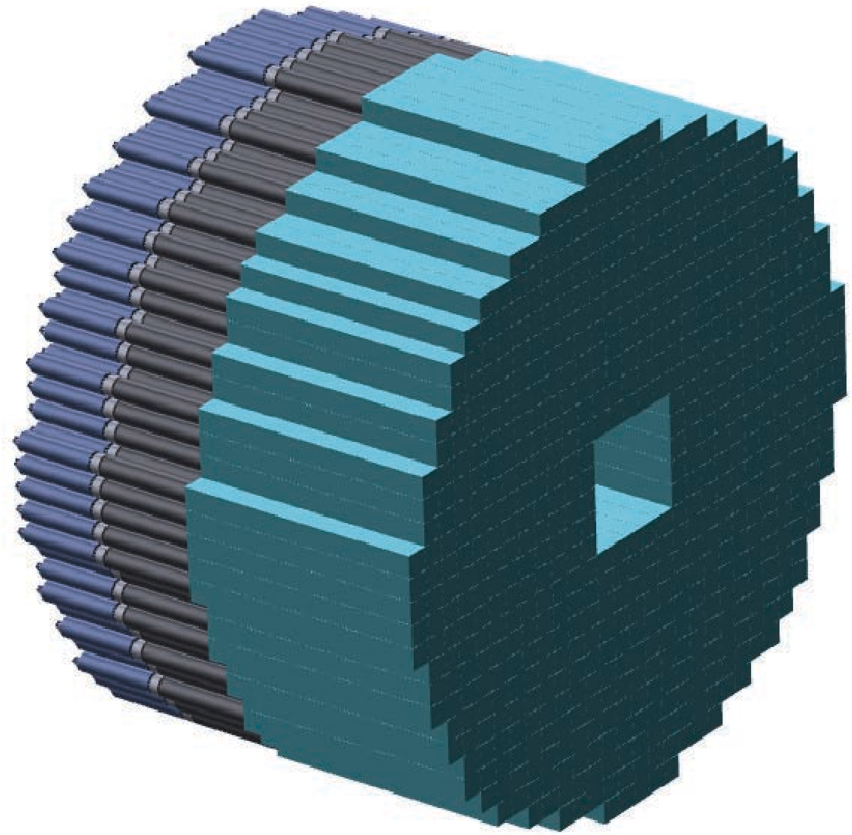




- Located near Rome, Italy
- ~ 30 people collaboration
- 550 MeV positrons

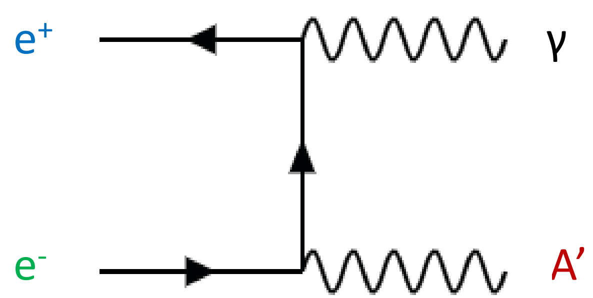
PADME ECAL

- Goal: measure energy and transverse position of photon
- Central detector
- 616 BGO crystals ($21 \times 21 \times 230$ mm^3)
- HZC PMTs for readout
- Square hole in middle to handle Bremsstrahlung background (via SAC)
- With energy and position, determine angle and hence momentum of photon

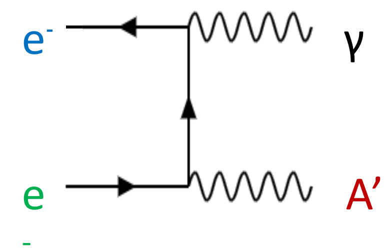


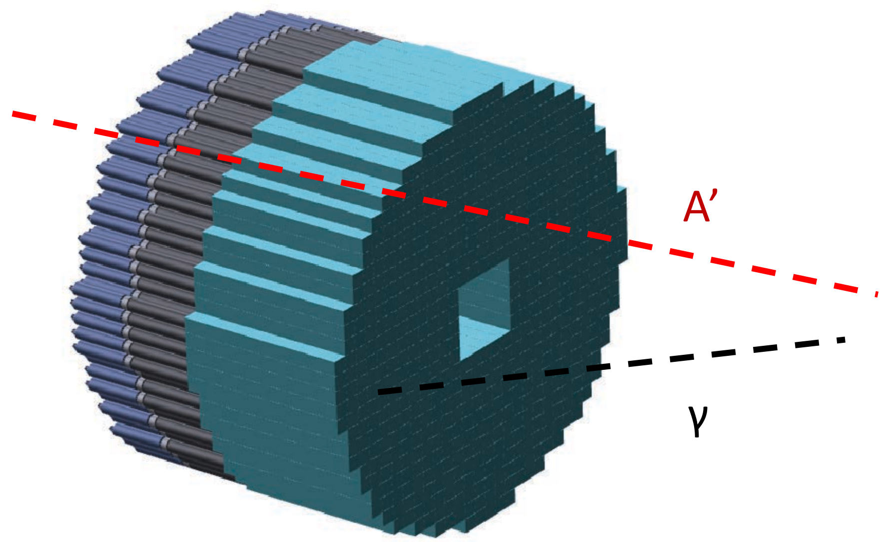
PADME: how it works

- e^+ and e^- scatter, produce a photon and a dark photon



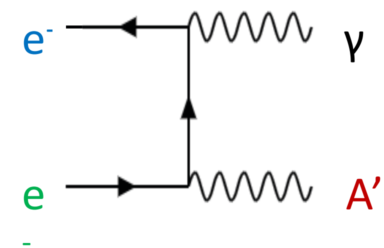
- e^+ and e^- scatter, produce a photon and a dark photon
- Dark photon invisible, escapes detector

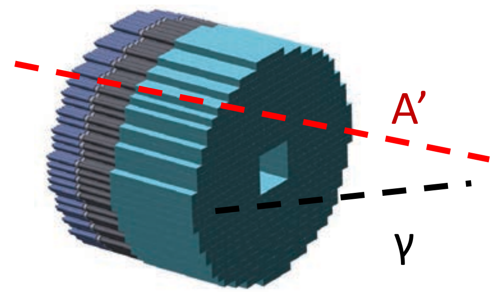


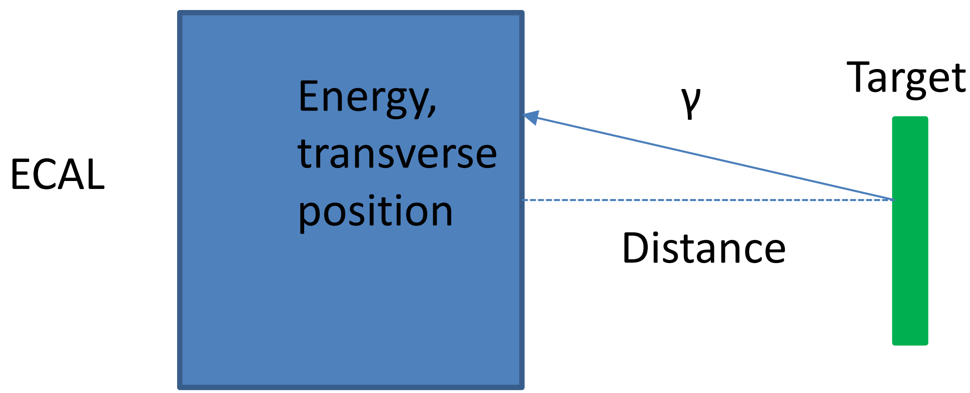


PADME: how it works

- e^+ and e^- scatter, produce a photon and a dark photon
- Dark photon invisible, escapes detector
- Photon momentum measured by ECAL

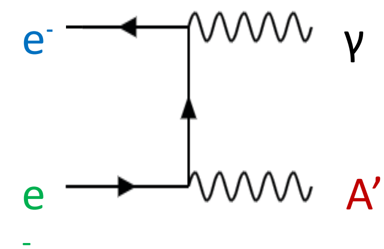


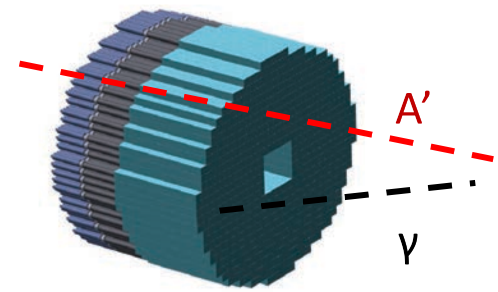


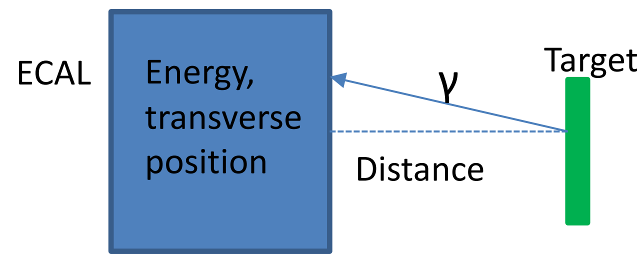


PADME: how it works

- e$^+$ and e$^-$ scatter, produce a photon and a dark photon
- Dark photon invisible, escapes detector
- Photon momentum measured by ECAL
- Subtracting from beam and target momentum, missing mass is inferred:

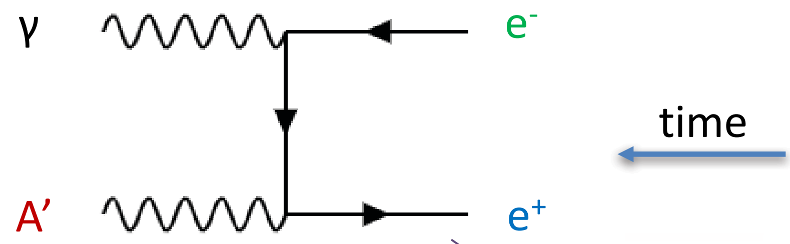


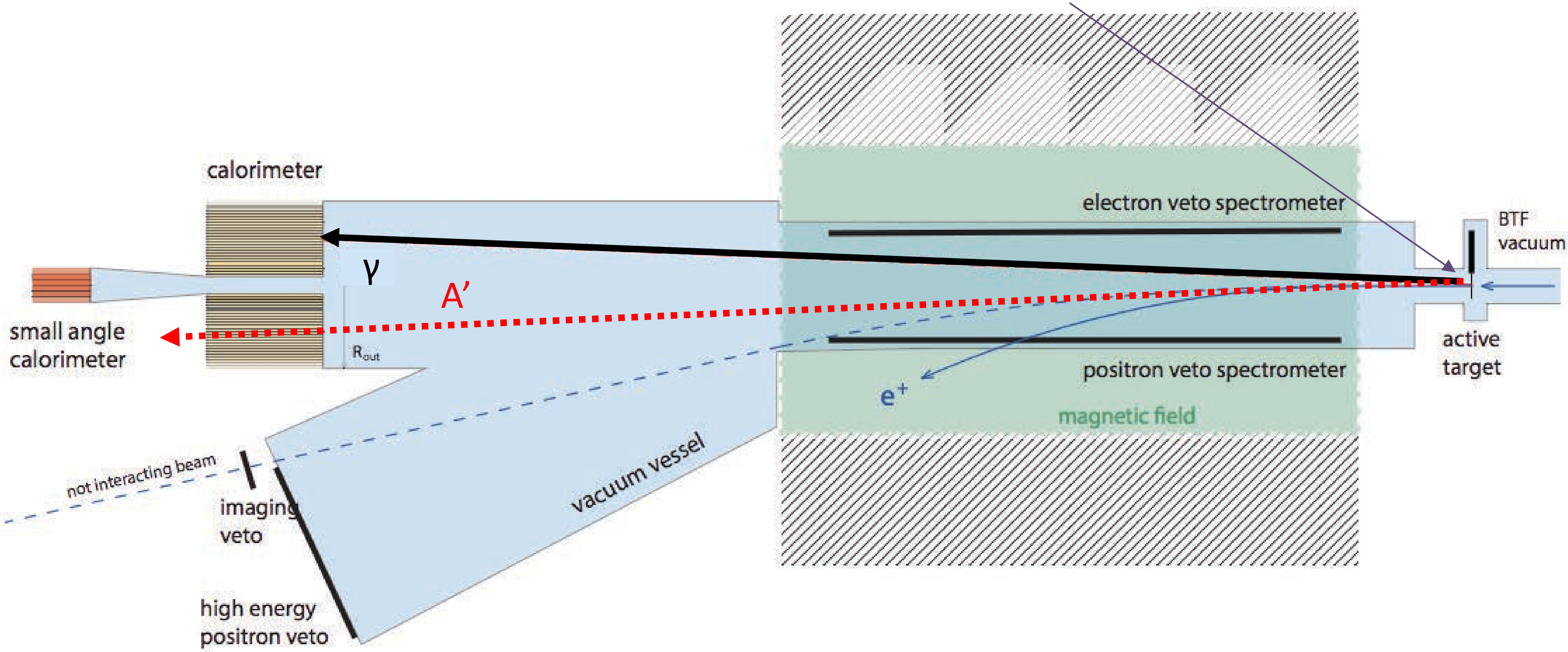




$$m^2_{\text{miss}} = (p_{e^-} + p_{e^+} - p_\gamma)^2$$

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

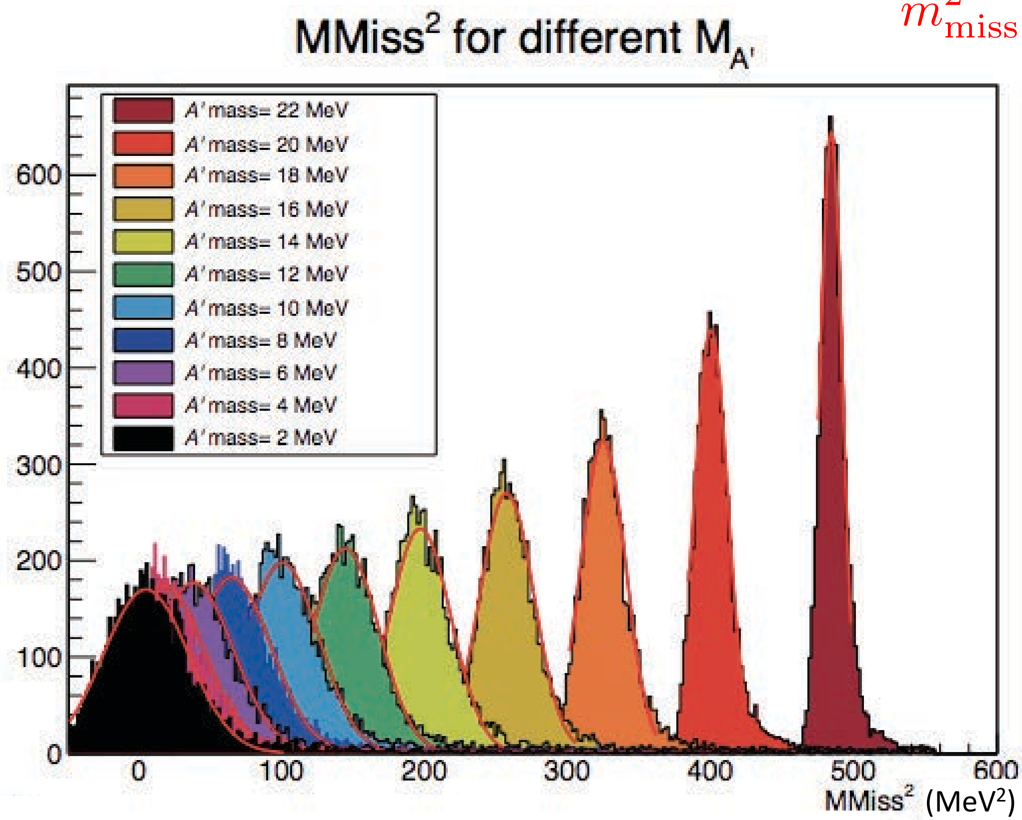




Missing mass

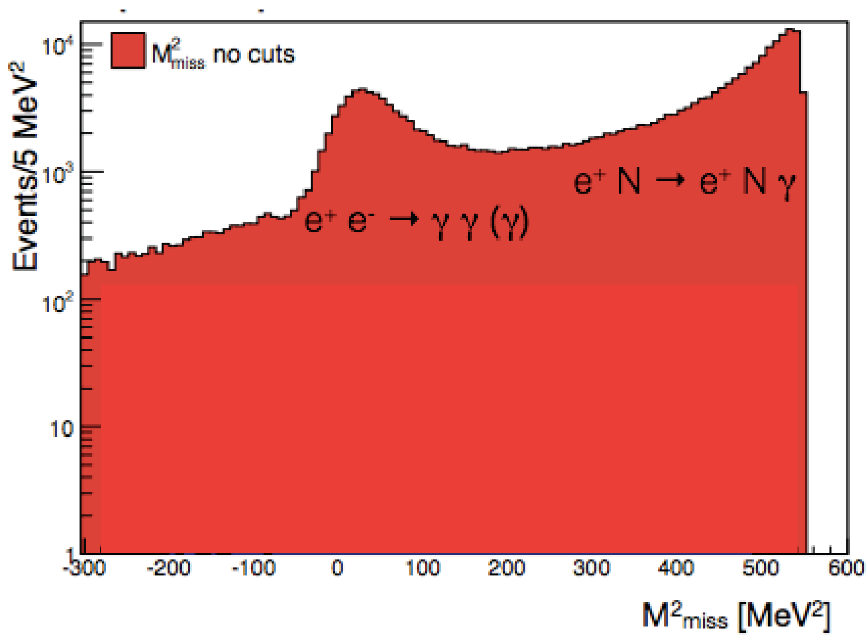
- Geant4-based PADME MC simulation, for different dark photon masses:

$$m^2_{\text{miss}} = (p_{e^-} + p_{e^+} - p_\gamma)^2$$



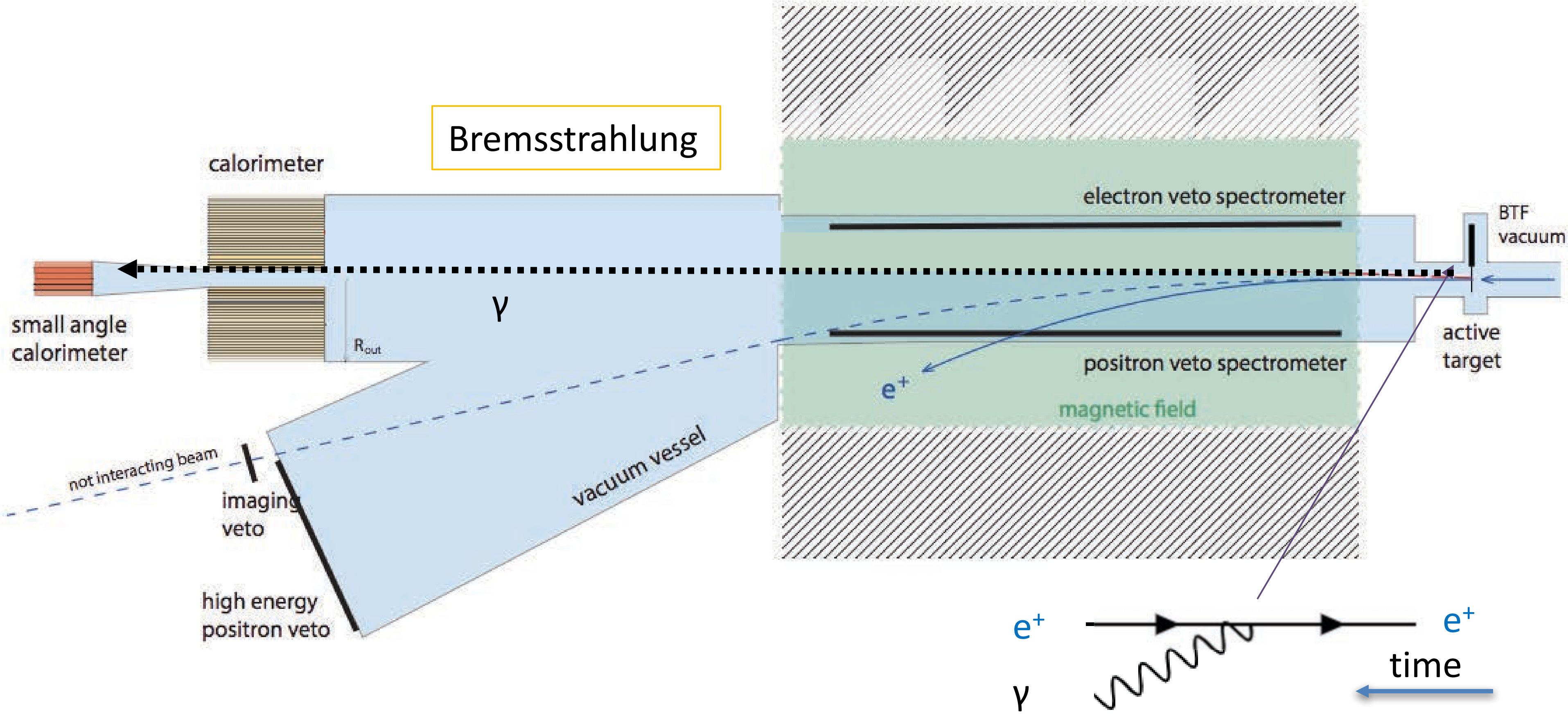
Missing mass

- Major backgrounds:
  - Bremsstrahlung — $e^+ + N \rightarrow e^+ + N + \gamma$
  - 2- and 3-gamma production — $e^+ + e^- \rightarrow \gamma + \gamma$
  - **Beam-induced backgrounds**



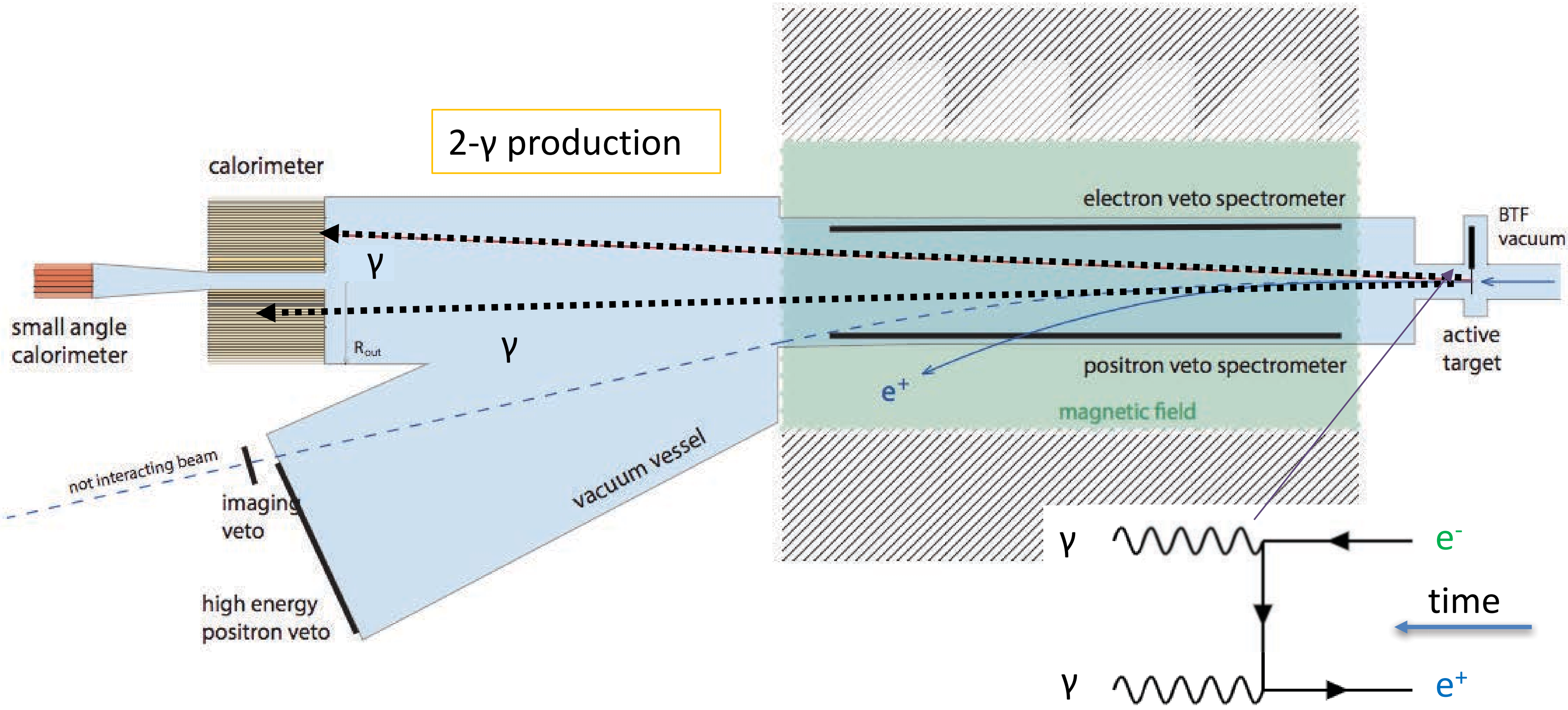
Mitigating backgrounds

- Auxiliary detectors tag background events
- Tagged events are rejected



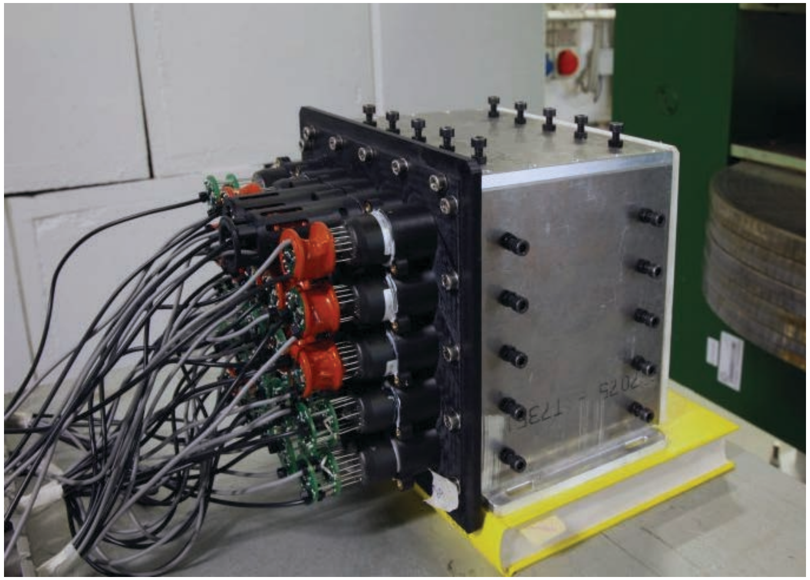
Mitigating backgrounds

- Auxiliary detectors tag background events
- Tagged events are rejected



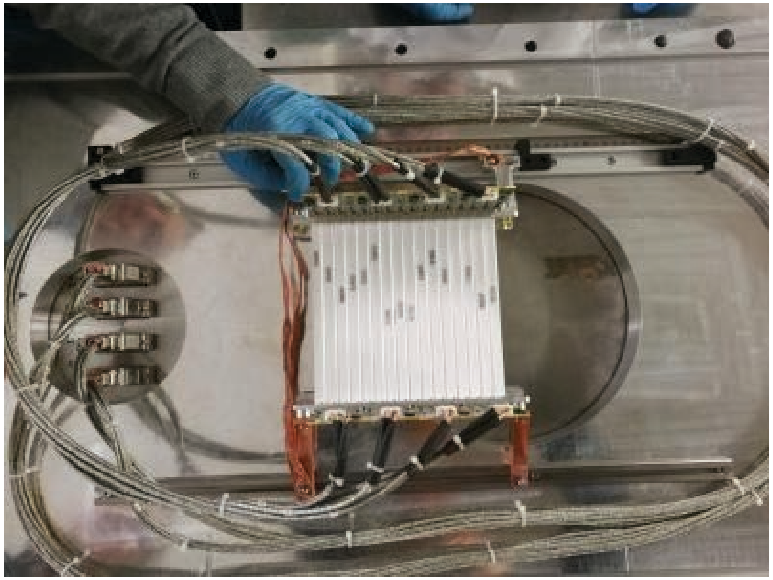
Auxiliary detectors

Small-Angle Calorimeter (SAC)



- Sits behind main ECAL
- Fast (~ 80 ps res., < 1 ns peak separation)
- 5x5 PbF_2 Cherenkov detector
- 30 x 30 x 140 mm^3 crystals
- Identifies Bremsstrahlung photons

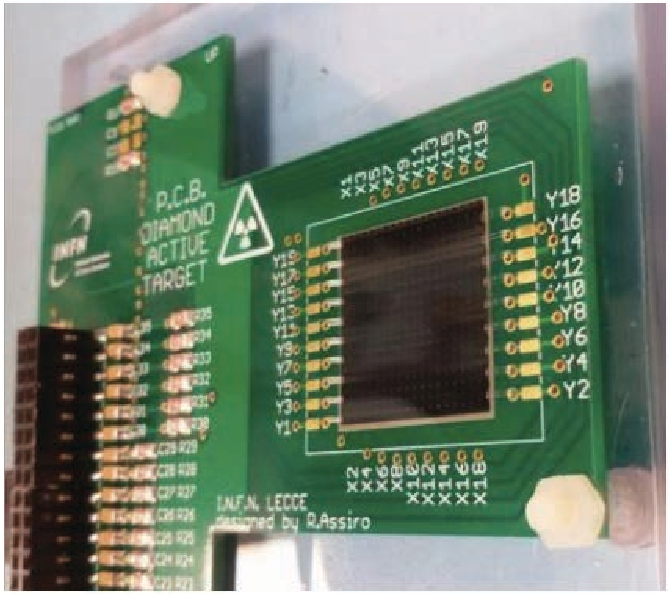
Electron/Positron/HEP vetoes



- Inside walls of magnet and by beam dump
- Plastic scintillator bars w/ SiPM readout
- Detect e^+ and e^- that radiated photons and lost momentum, bending under B field

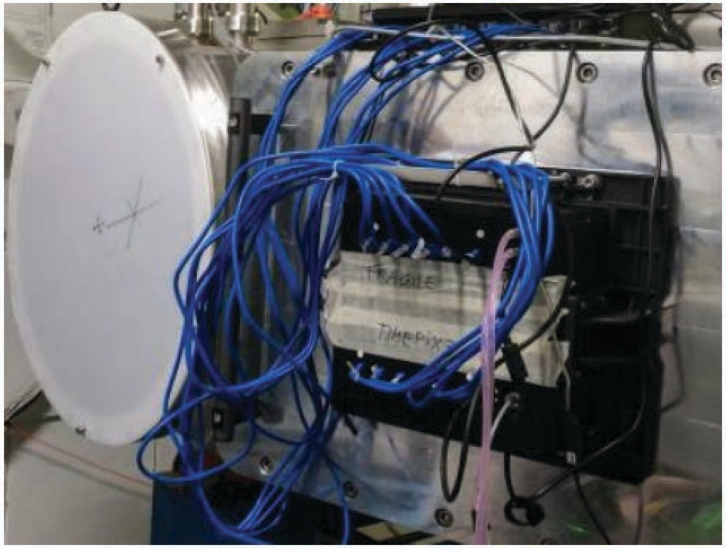
Auxiliary detectors

Active diamond target



- 100 um thick policrystalline diamond
- 19 x 19 (x and y) graphite stripes on surface
- Active target: charge measured proportional to beam intensity, plus profile information

TimePix3 beam monitor



- In a single sensor: matrix of 256 x 256 pixels, 55 um in size
- Whole detector: 12 such sensors (786,432 pixels), 8.4 x 2.8 mm2
- Monitors non-interacting beam

Mitigating backgrounds

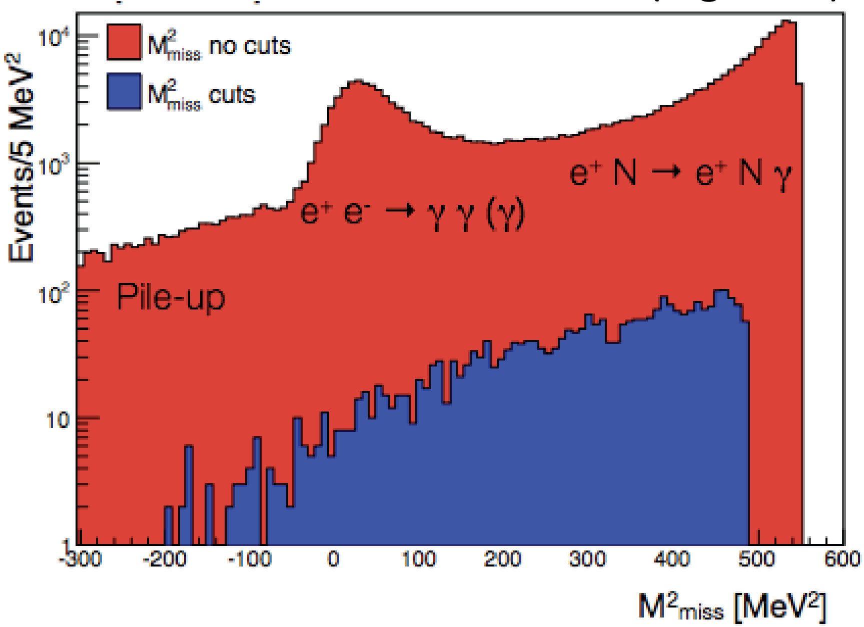
PADME

J. Phys. Conf. Ser. 770 (2016) 012039

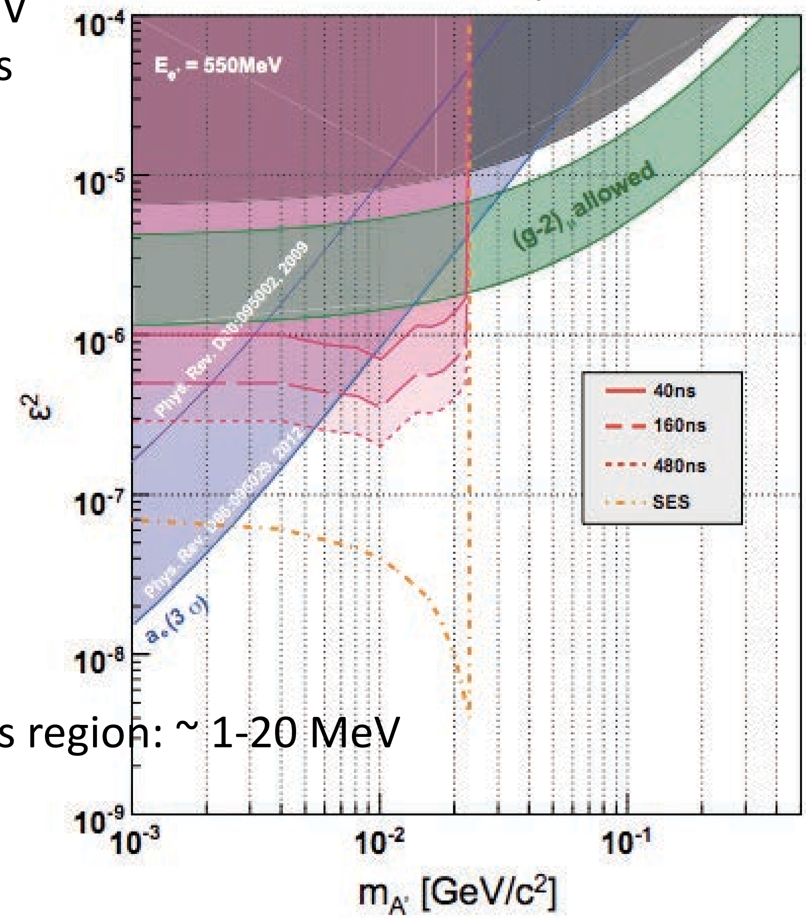
- Backgrounds limited after mitigation:

- 1 cluster in ECAL
- No hits in vetos
- No γ in SAC w/ energy > 50 MeV
- 20-150 MeV < ECAL energy < 120-350 MeV depending on A' mass

Simulation (log scale)



Sensitivity:



A' mass region: ~ 1-20 MeV

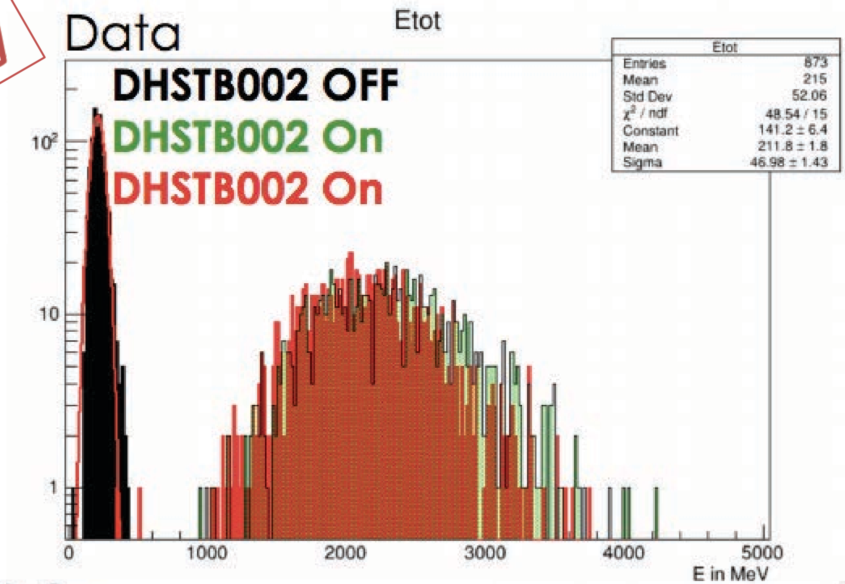
Beam-induced backgrounds

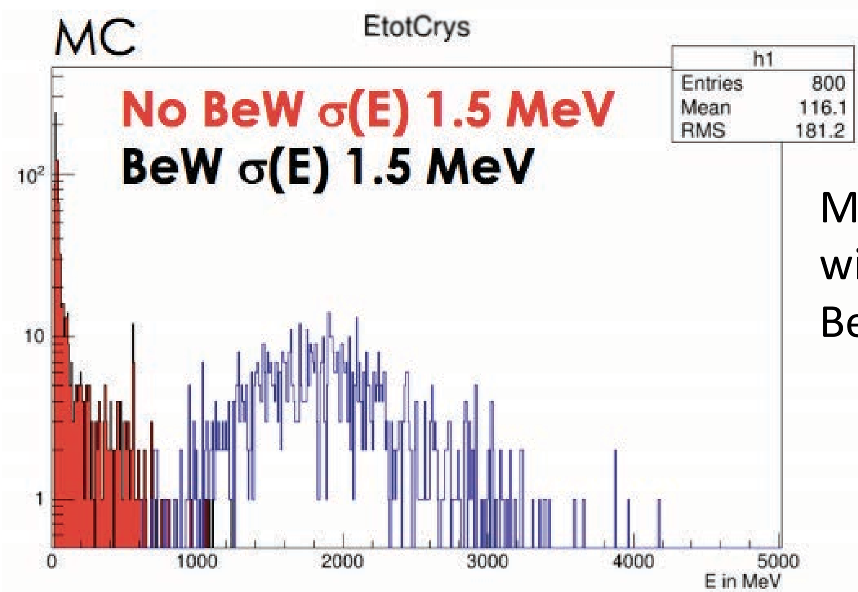
- Over the course of first data-taking run, observed additional background due to beam
- Extended MC simulation to understand causes
- Found three main culprits:
  - Beryllium window separating detector vacuum from accelerator vacuum
  - Steering beam magnet from accelerator structure
  - Early showers when using a secondary beam
- Mitigation now being applied, 3x lower already

Beam-induced backgrounds PADME

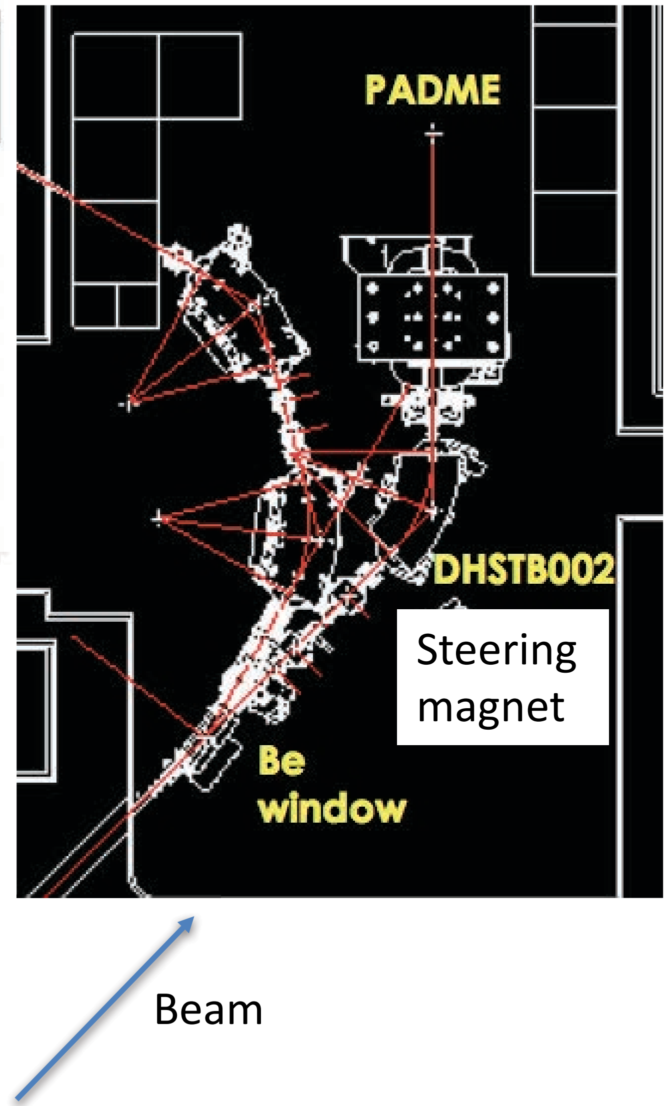
preliminary

Total energy deposition in ECAL





MC comparison with and without Be window



Summary

- PADME is a **fixed-target**, **missing-mass** experiment to look for low-mass dark photons
- Model-independent (kinetic mixing)
- Run 1 just finished in early March
- ~ 4 months of data
- Data reconstruction and analysis ongoing
- Calibration run ongoing and starting physics run 2 in early November
- Plan to have first physics results next year

BACKUP

Future ideas

- PADME could also potentially be used for ALP searches, studies underway to assess sensitivity and reach
- Could be sensitive to both g_{aee} and $g_{a\gamma\gamma}$ couplings
- Signal: three gammas or a gamma and e^+/e^- pair in the calorimeter

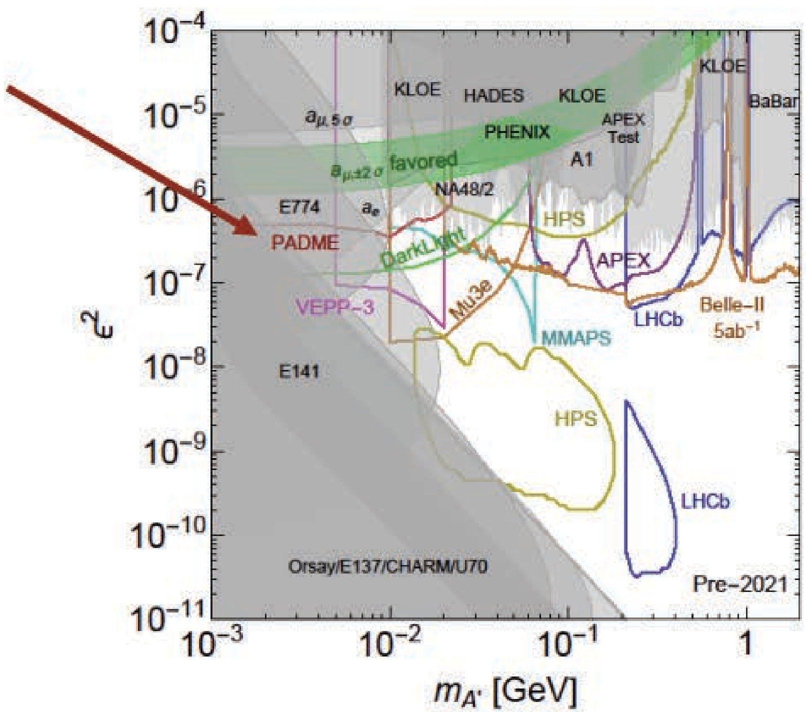
Future ideas

- Tentative plans to bring the PADME detector to higher energy and intensity beams
- For example, Cornell has a 6 GeV e+ beam (10x more energy)
- With resonant extraction, could distribute beam intensity over longer periods, decreasing pile-up and maximizing efficiency of event collection

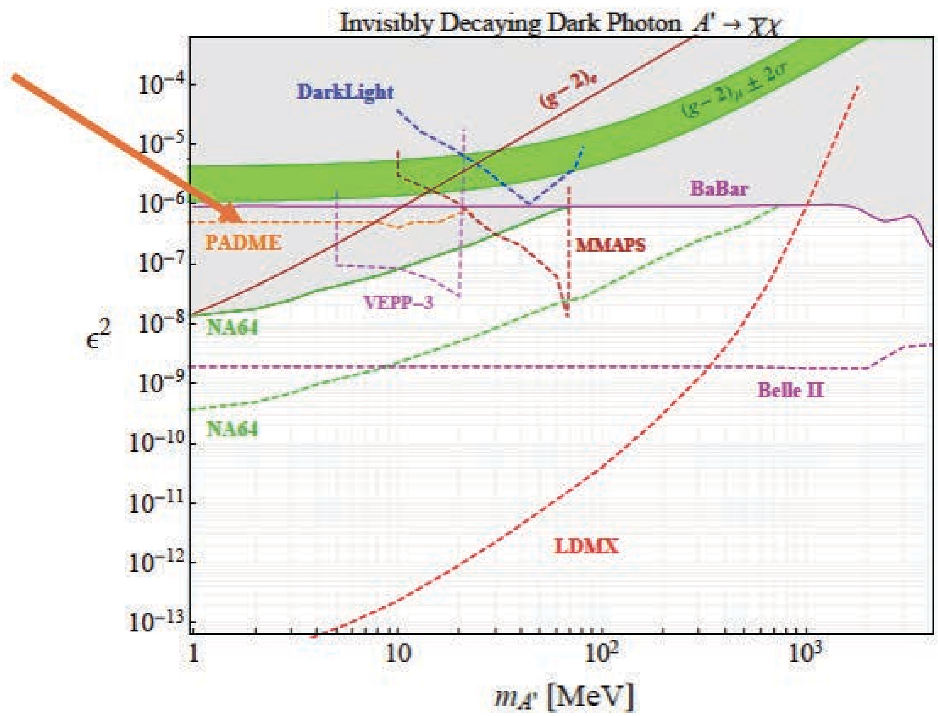
Future ideas

- With Cornell beam, sensitivity would increase significantly ('MMAPS' label):

- **Visible,** in SM particles if $m_{DM} \geq m_{A'}/2$

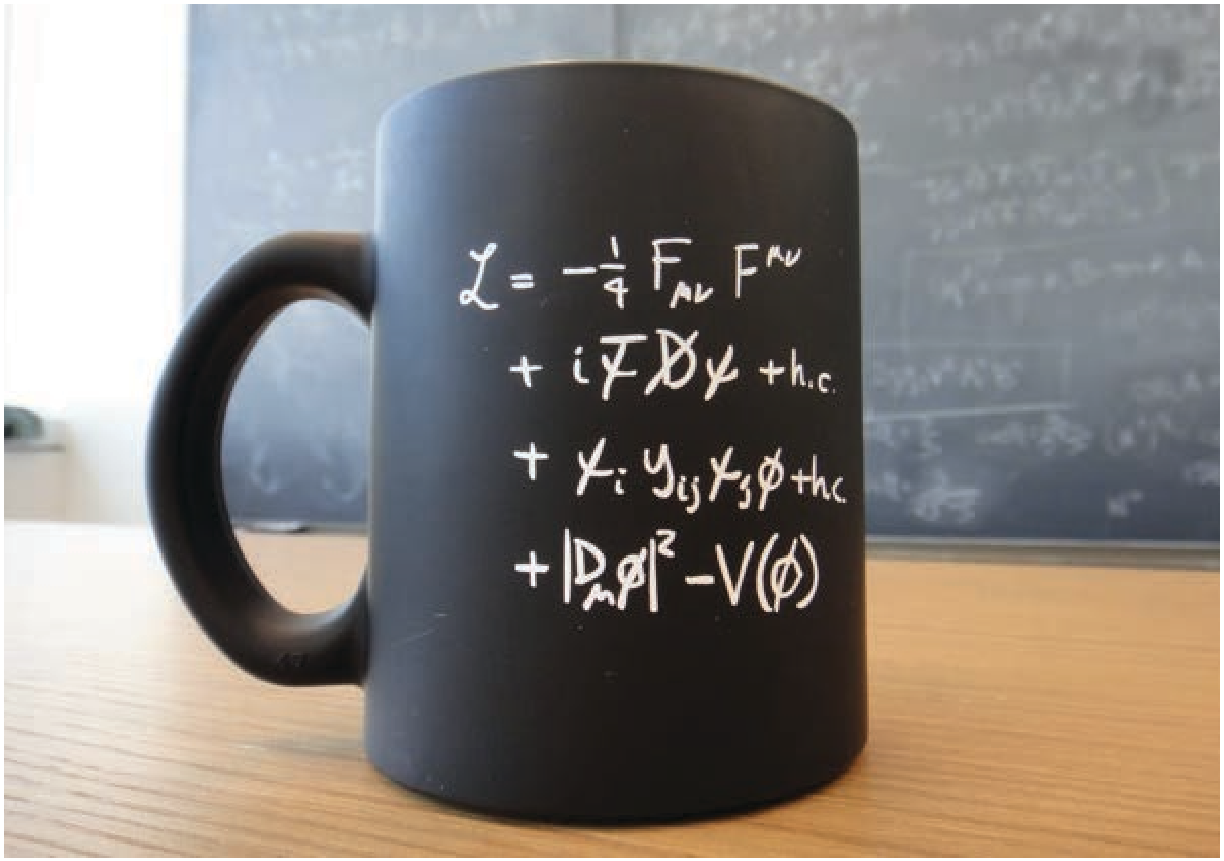


- **Invisible,** in DM particles if $m_{DM} \leq m_{A'}/2$



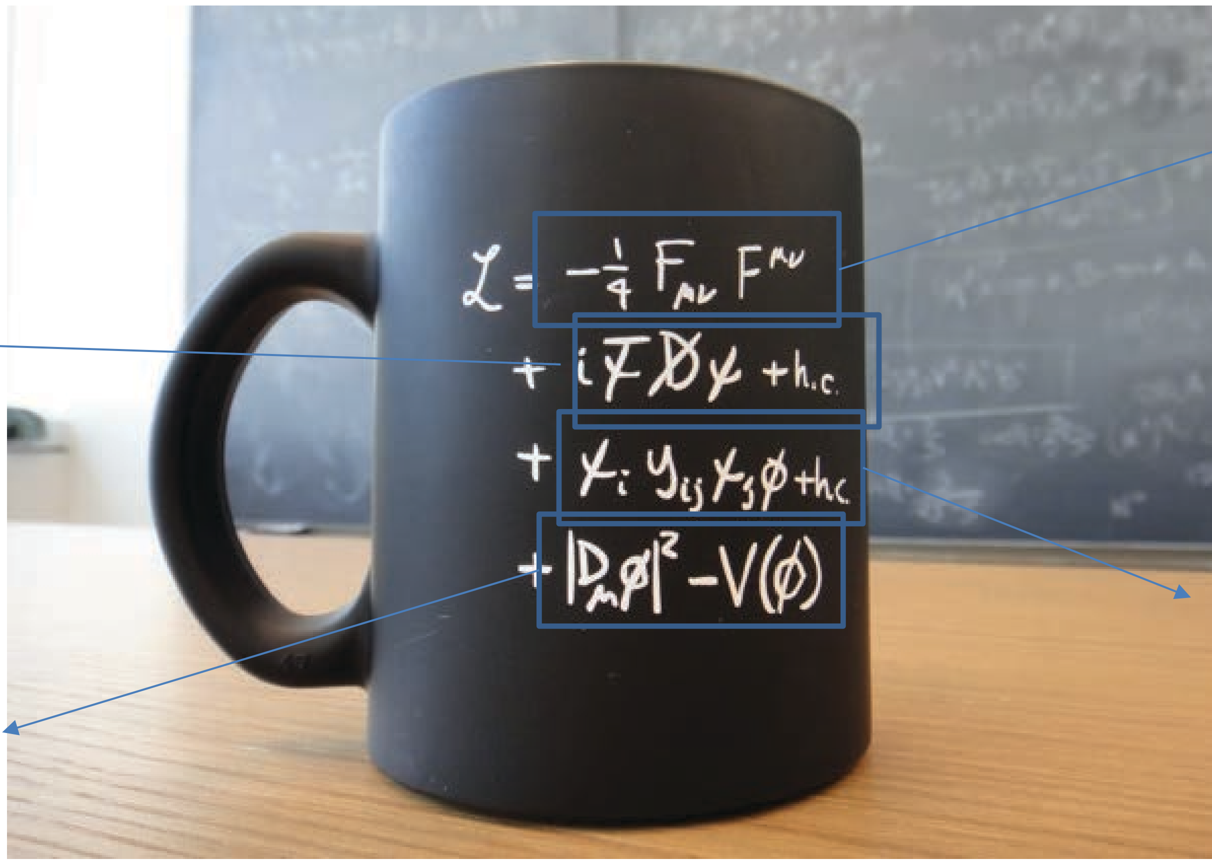
Kinetic mixing

- The SM in a nutshell:



Kinetic mixing

- The SM in a nutshell:



Kinetic terms for bosons (makes fields 'dynamic')

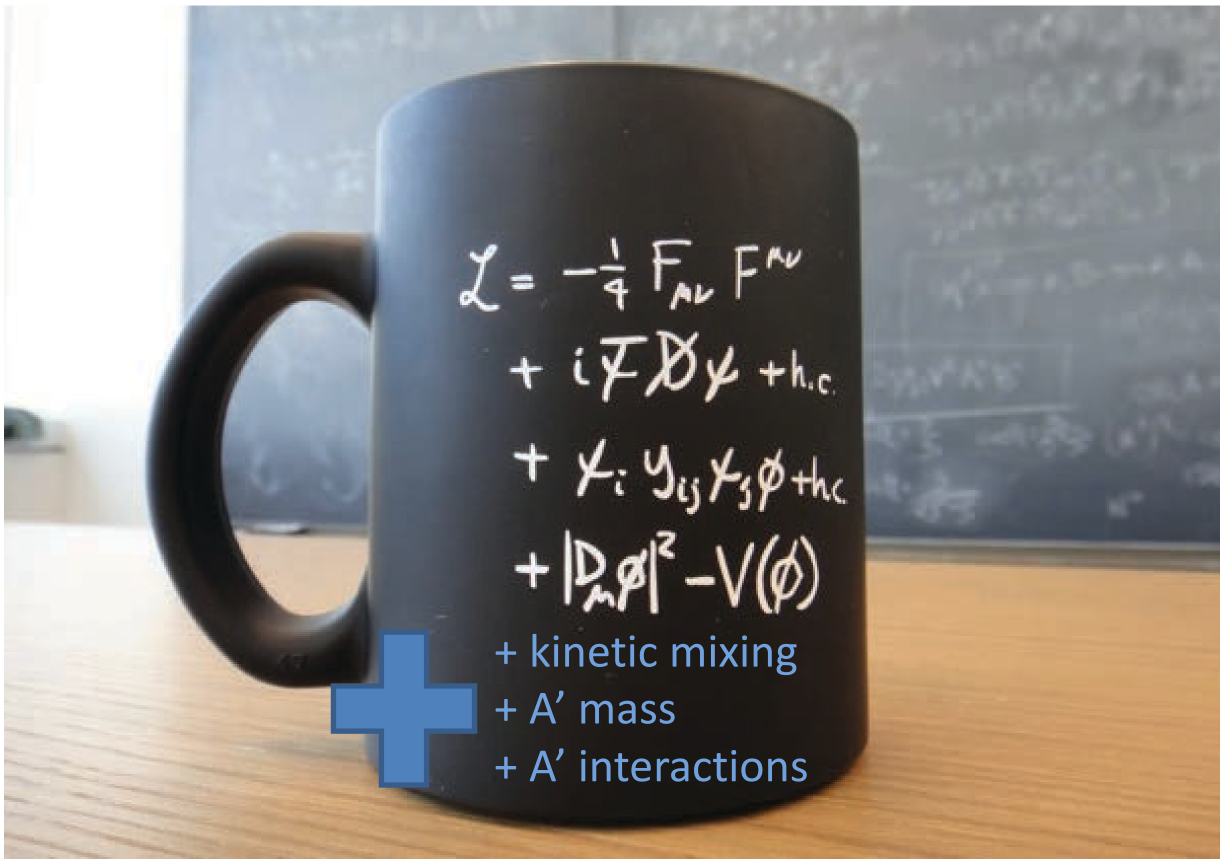
Kinetic terms for fermions

Interaction terms (connects fields together)

Higgs potential

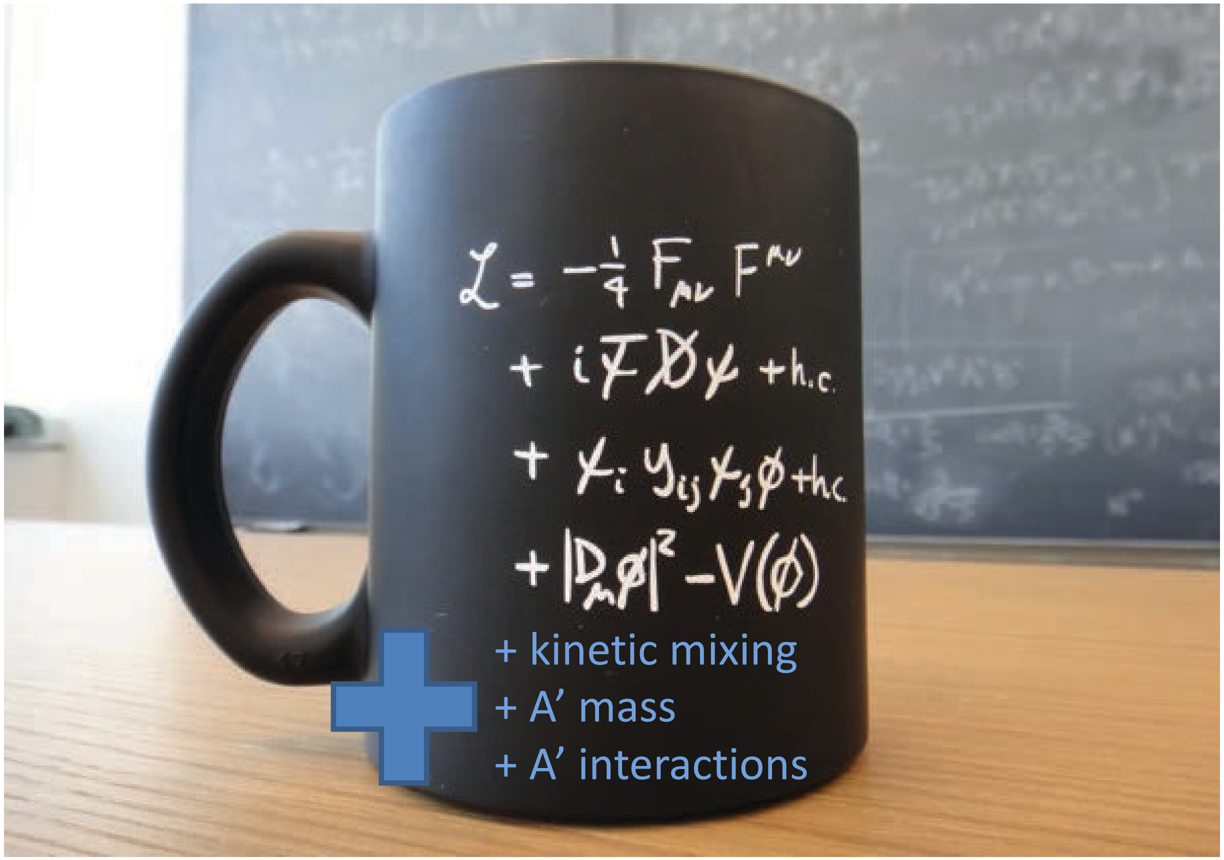
Kinetic mixing

- Add dark photon terms to the Lagrangian:



Kinetic mixing

- All additional A′ terms are allowed



Kinetic mixing

$$-\frac{1}{4} F'_{\mu\nu} B^{\mu\nu}$$

A′ interactions

$$+\epsilon e A'^{\mu} J^{EM}_{\mu}$$

A′ mass

$$+\frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu}$$