Dark matter searches at (low energy) accelerators

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The long quest for dark matter

Zwicky, Coma cluster (1933)

$M/L \approx 660\ M_\odot/L_\odot$

Hubble Space Telescope (2007)
Cluster Cl 0024+17

Lensing of background galaxies

Estimate masses using velocities

$\Sigma_i m_i \langle v_i^2 \rangle = \Sigma_i \Sigma_{j<i} G m_i m_j \; 1/\langle |\mathbf{r}_i - \mathbf{r}_j| \rangle$

$\langle v_{r,i}^2 \rangle_\Omega = 1/3 \; v_i^2$

projected along radial direction, averaged over solid angle Ω

- We see only radial component of motion, $\langle v_i \rangle \approx \sqrt{3}\, v_r$
- We see projected radii: $r = \theta d$

$1/\langle |\mathbf{r}_i - \mathbf{r}_j| \rangle = 1/|\mathbf{r}_i - \mathbf{r}_j| \langle 1/\sin\theta_{ij} \rangle_\Omega$

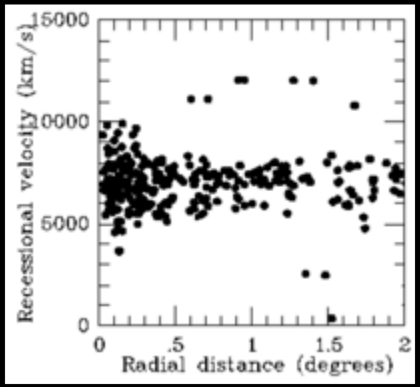
Assuming N equal masses $\Sigma_i m_i = N m$

$M_{VT} = 3/2\pi \, G^{-1} N \, \Sigma_i v_i^2 / \Sigma_{j<i} 1/r_{ij}$

Coma cluster (Zwicky):

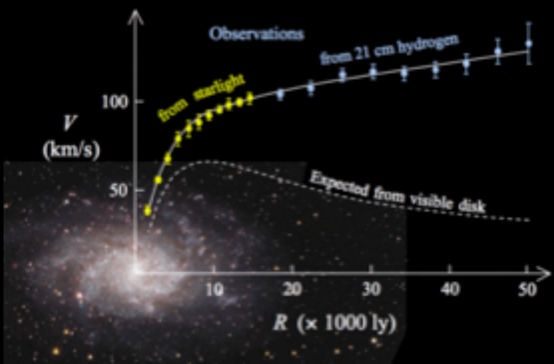
$\sigma \approx 1000$ km/s, $R \approx 3$Mpc, $M_{VT} = 3\; 10^{15}\, M_\odot$

$L = 5\; 10^{12}\, L_\odot$

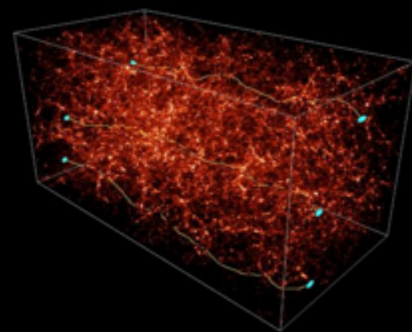


Many pieces of evidence for dark matter

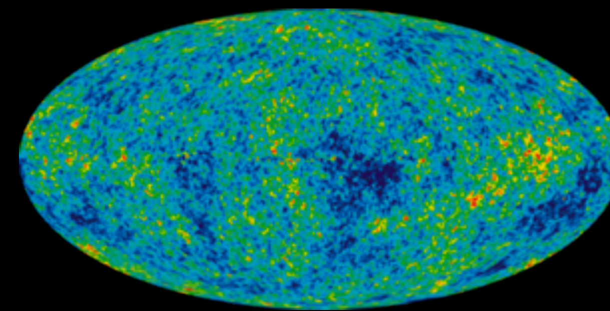
Rotation curves

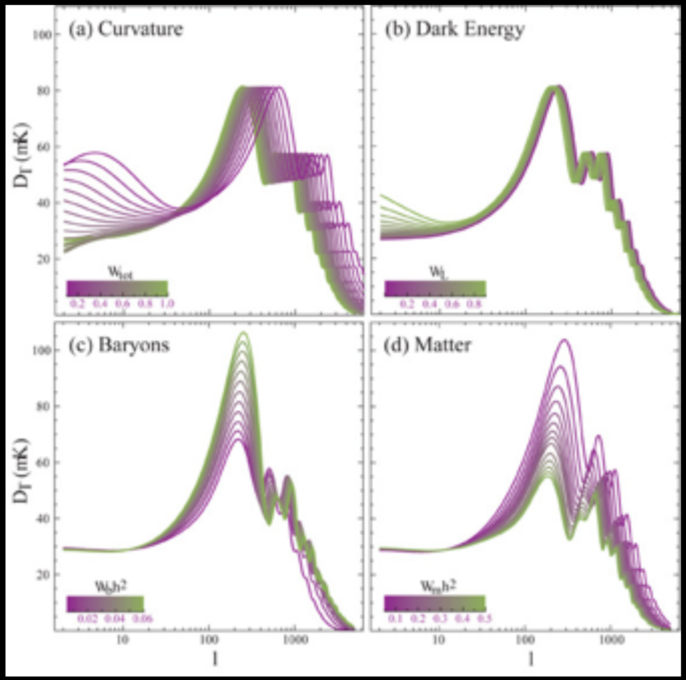


Large scale structures

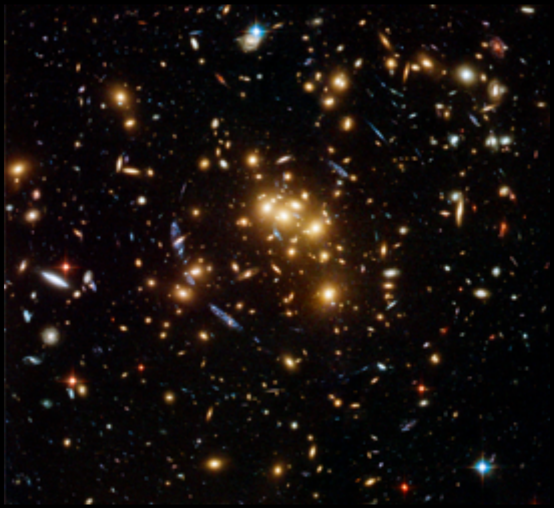


Cosmic Microwave Background





Lensing



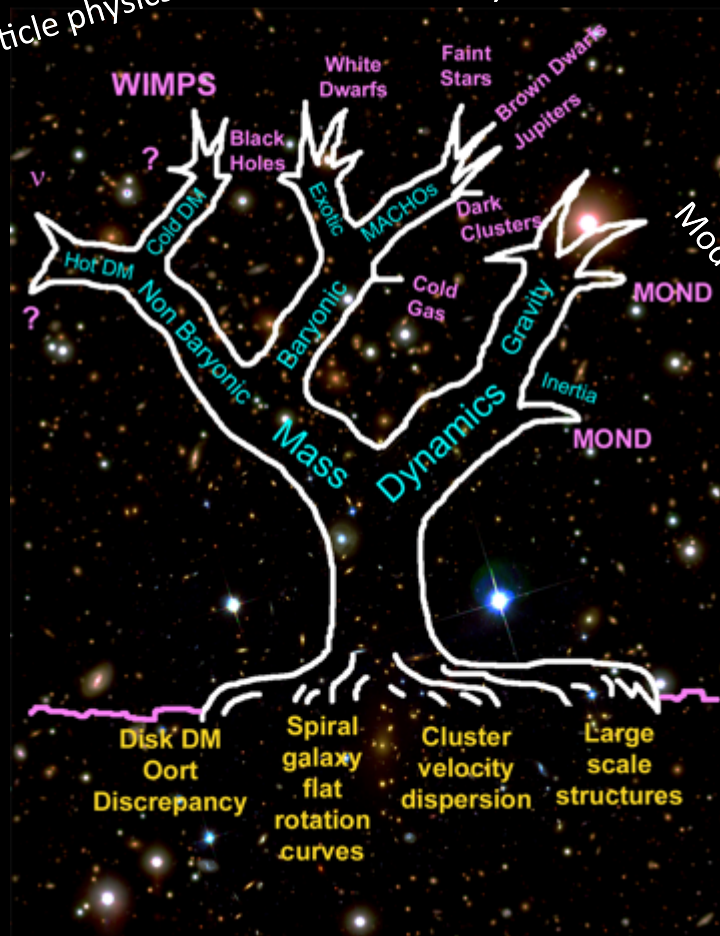
Colliding clusters (Chandra)

The dark matter problem

Original drawing by Stacy McGaugh (1995)

Particle physics

Astrophysics

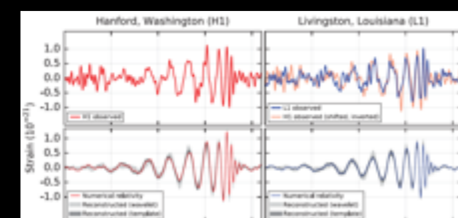


Modify gravity

Several hypothesized solutions

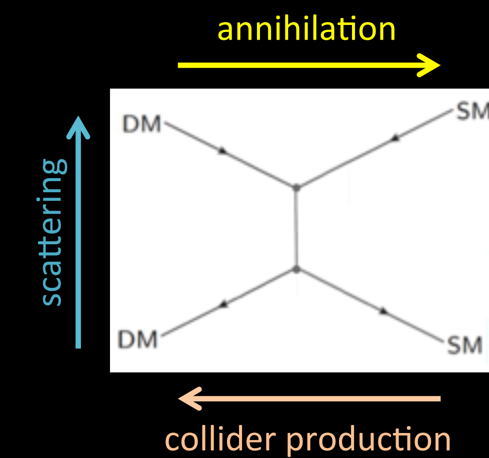
Roots are the empirical observations

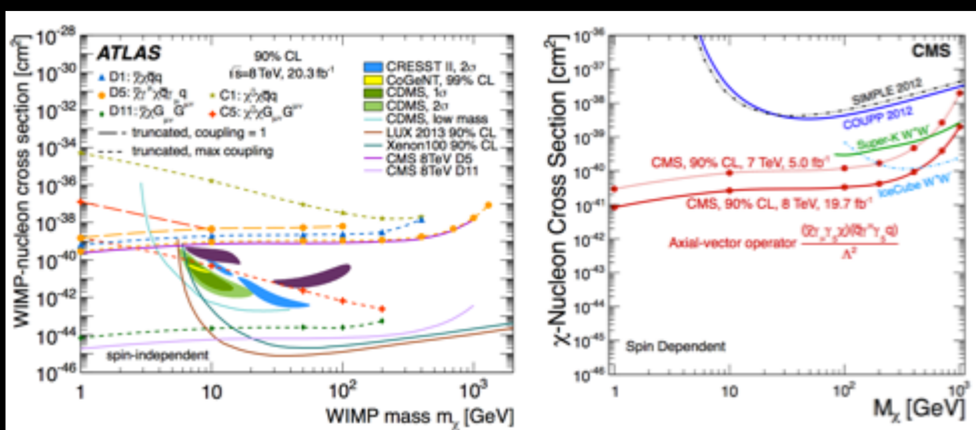
Particle physics is not the only possible solution…

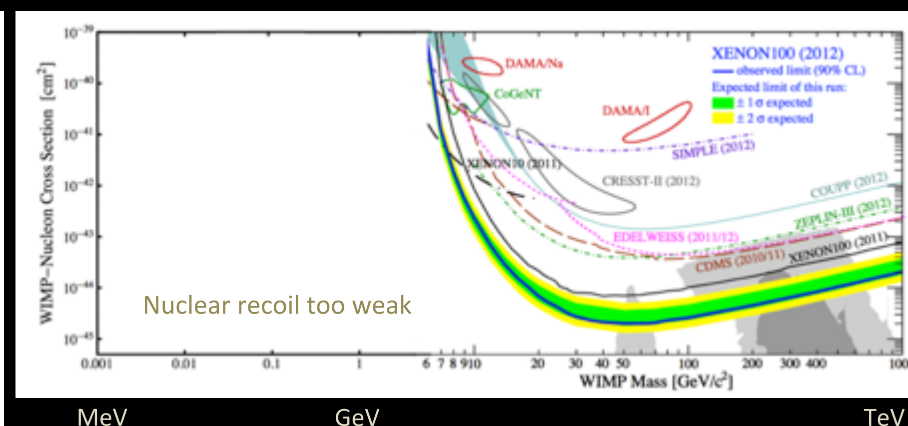


Where to search for dark matter

- **Without** modifying the SM structure: $U(1)_Y + SU(2)_L + SU(3)_C$
  - Dark matter can't be strong interacting (scattering cross section too high)
  - Cannot be electrically charged, otherwise it would not be dark!
  - It can be **weakly interacting** and massive!
- **WIMP** has all the characteristics to solve the DM problem…
- … but so far more than 20 years of unsuccessful searches
  - Apart from DAMA-LIBRA annual modulation
  - Strong constraints from the **LHC** and **direct searches** up to TeV scale







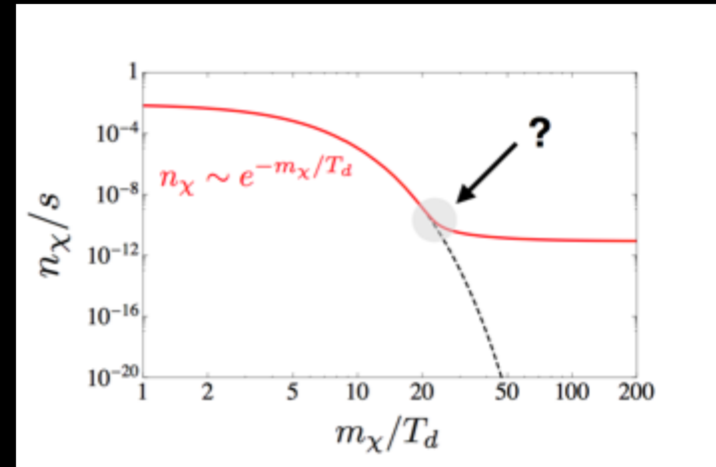
What about introducing a **new force**?

Thermal relic dark matter

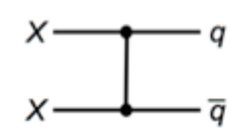
DM particles

- were created **thermally** in the early universe
- They are in chemical equilibrium with SM particles through 2 → 2 annihilations

- At thermal equilibriums same number density as photons: $T_d \sim T_\gamma$
- As the Universe cooled the number of DM particles and photons would decrease together as long as $T_d \gtrsim m_{DM}$
- When the temperature dropped below m_{DM} the number density started to exponentially decrease
- No relics today, unless transition out of equilibrium or "freeze-out", when the probability of annihilation has become small
- Freeze-out should complete before neutrino decoupling and Big Bang Nucleosynthesis

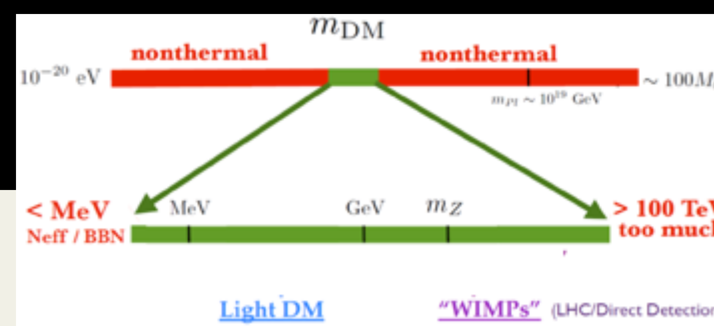


$$\Omega_X \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_X^2}{g_X^4}$$



m_χ=100 GeV, g_χ=0.6, Ω_χ = 0.1

- The annihilation cross section is just what would be predicted for particles with electroweak scale interactions: the WIMP miracle



Types of DM

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

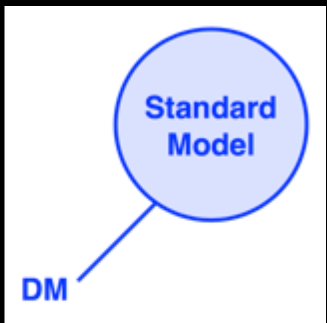
Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_{\gamma}=1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM --> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. Asymmetric DM is also in this category.

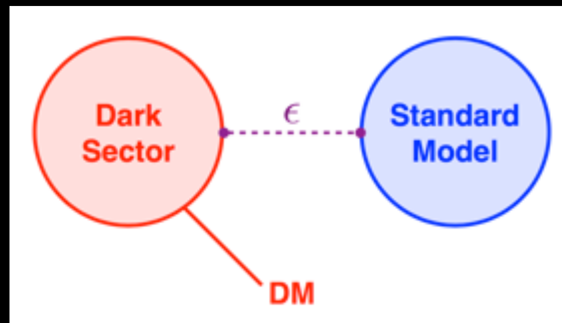
Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **superweakly interacting MPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_{\gamma}\sim10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

M. Pospelov

From WIMP to "portal" to hidden sector





- A mediator particle, very weekly interacting with SM particles, and connecting with a hidden sector
- It can be light… where direct detection gets into trouble

vector	$\frac{1}{2}\epsilon F^{Y}_{\mu\nu}F'^{\mu\nu}$	**dark photon**
Higgs	$\epsilon_h \lvert h \rvert^2 \lvert \phi \rvert^2$	dark scalar
neutrino	$\epsilon_\nu (hL)\psi$	sterile neutrino
axion	$\frac{1}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$	ALPs

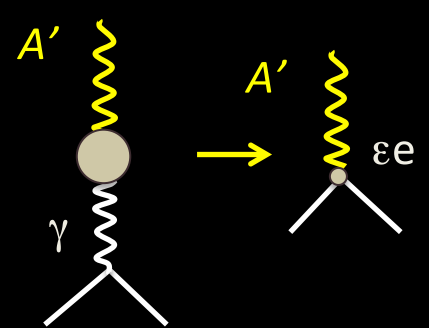
Dark photon

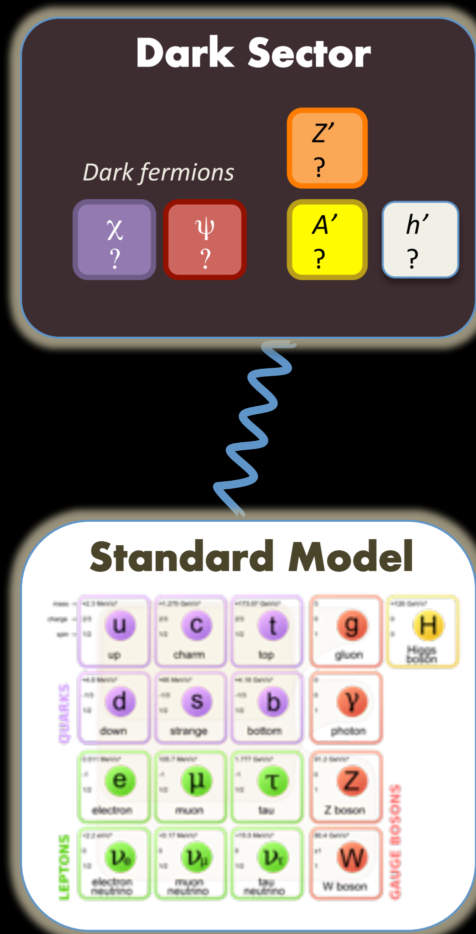
- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the "dark photon" or U boson or heavy photon (γ' or A')
- An extra U(1) symmetry implied in many Standard Model extensions, some classes of string theory, etc.
- Two types of interactions with SM particles should be considered

1. As in QED, generates interactions of the type:
    - Not all the SM particles need to be charged under this new symmetry $\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$
    - In the most general case q_f is different in between leptons and quarks and can even be 0 for quarks

    [P. Fayet, Phys. Lett. B 675, 267 (2009).]

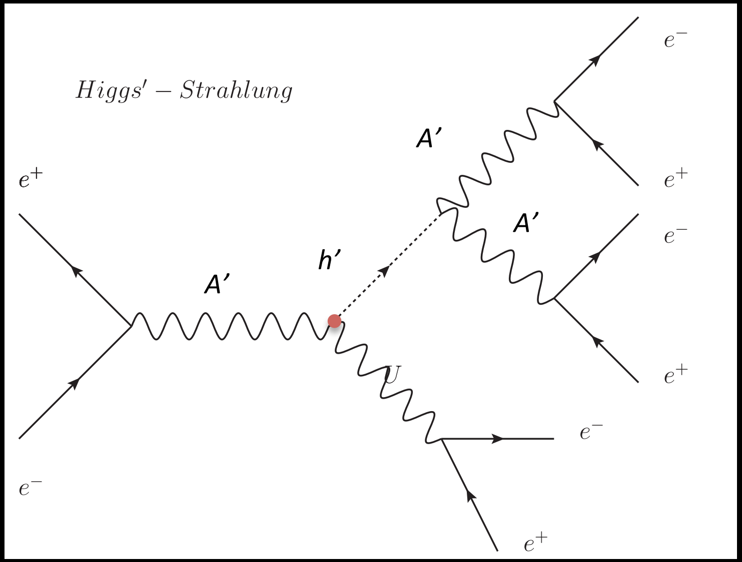
2. Couples to SM hypercharge through kinetic mixing operator, acquiring a (small) SM charge:
    - $\frac{1}{2}\, \varepsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$; $F'^{\mu\nu} = \partial_\mu A'_\nu$
    - $A_\mu \rightarrow A_\mu + \varepsilon a_\mu$; $\alpha' = \varepsilon^2 \alpha$



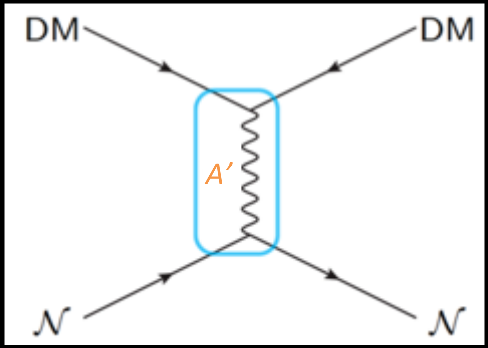


Dark photon with dark Higgs

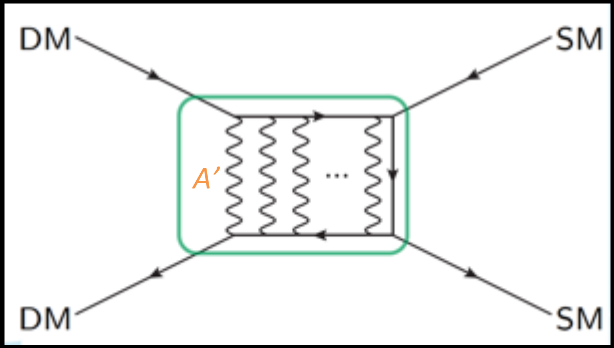
- Model assumes the existence of an elementary dark Higgs boson *h'*, which spontaneously breaks the U(1) symmetry.
  PRD 79, 115008 (2009)
- *A'* boson produced together with a dark Higgs *h'* through a Higgs-strahlung $e^+e^- \to A' h'$
  - Cross section $=20\text{fb}\times(\alpha/\alpha_D)(\varepsilon^2/10^{-4})(10\text{GeV})^2/s$
  - For light *h'* and *A'* ($M_{U,h'}<2M\mu$) final state with 3(e^+e^- pair) are predicted
  - Background events with 6 leptons are very rare at this low energies
  - Due to *A'*,*h'* being very narrow resonances strong kinematical constraints are available on lepton pair masses
- Experimental search by **BaBar** and **KLOE-2** for *A'* masses above 200 MeV



A dark matter "messenger"

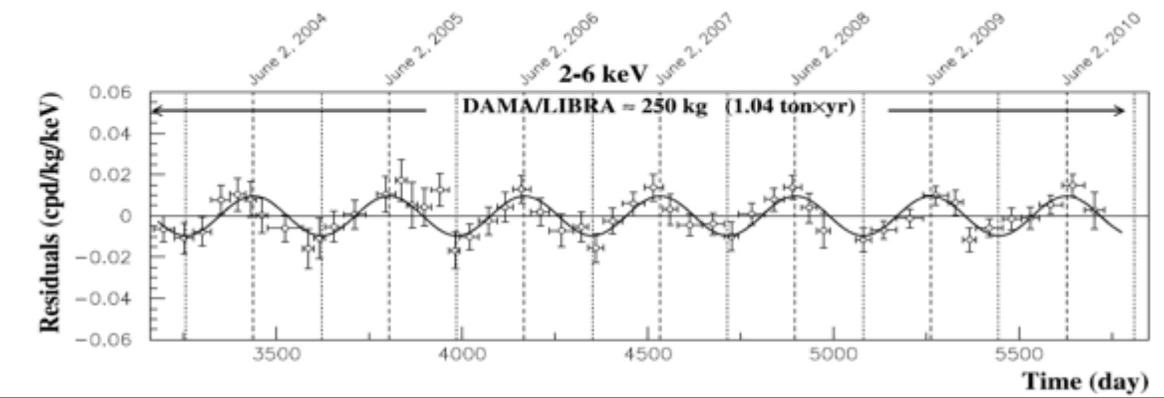


Dark Matter scattering on nuclei

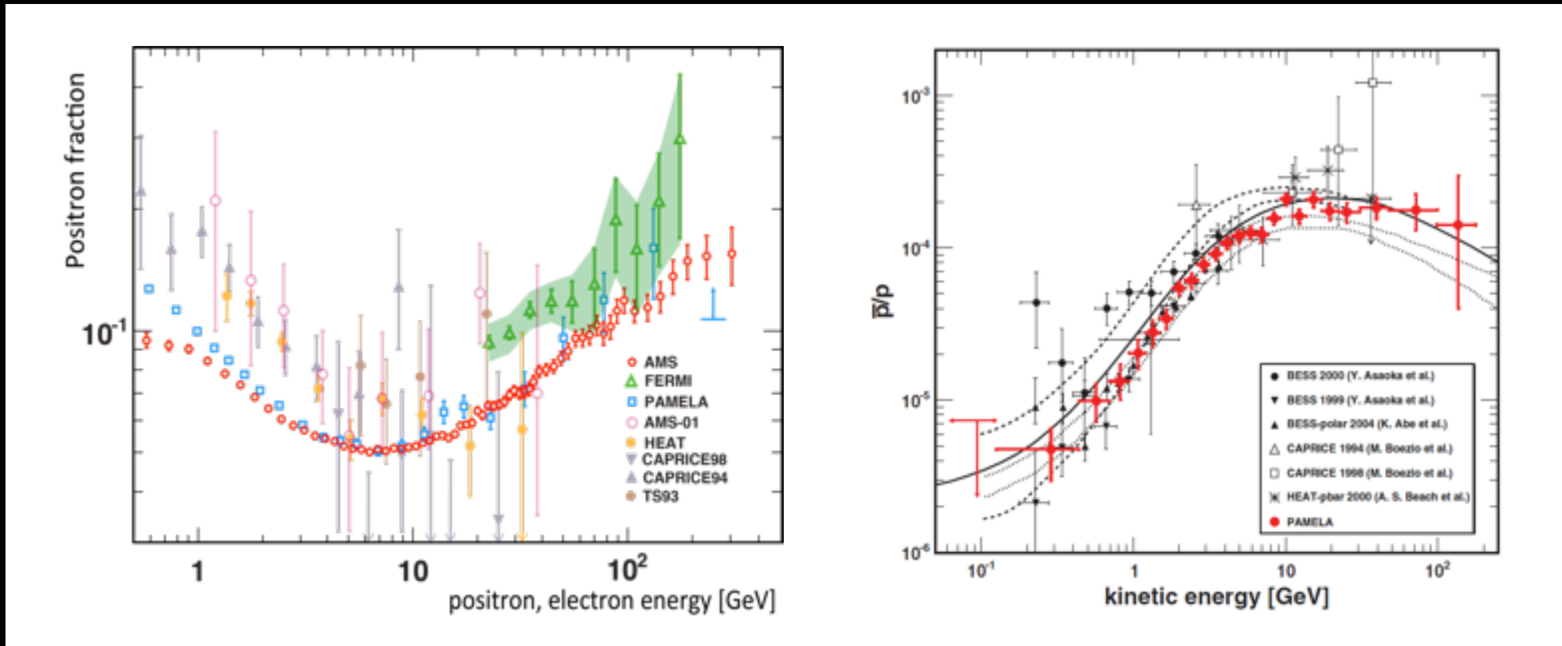


Dark Matter annihilation…

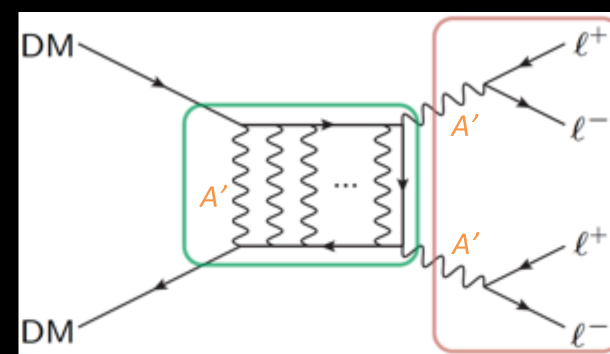
- Nuclear recoil by the exchange of a dark photon
- Independent of χ mass value



Particle astrophysics: PAMELA, AMS

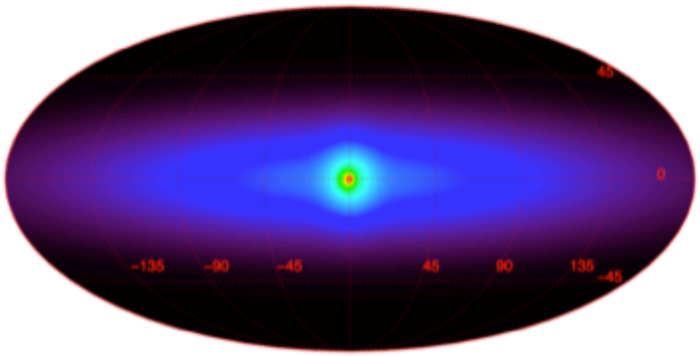


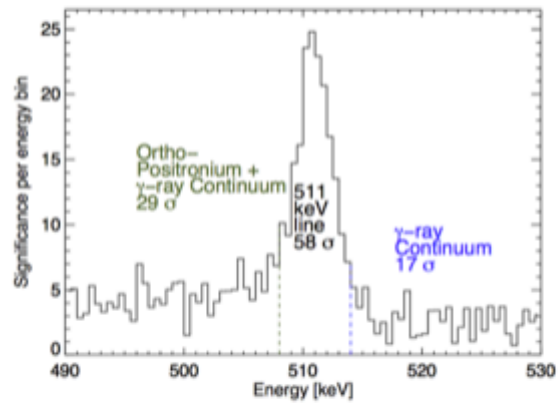
- Positron eccess: PAMELA, FERMI, AMS-02
- No significant excess in antiprotons
  - Consistent with pure secondary production
- Leptofilic dark matter annihilation?
- If DM is the explanation, the **mediator should be light**, < $2m_{\text{proton}}$



…naturally leptophilic

511 keV signal (INTEGRAL/SPI)



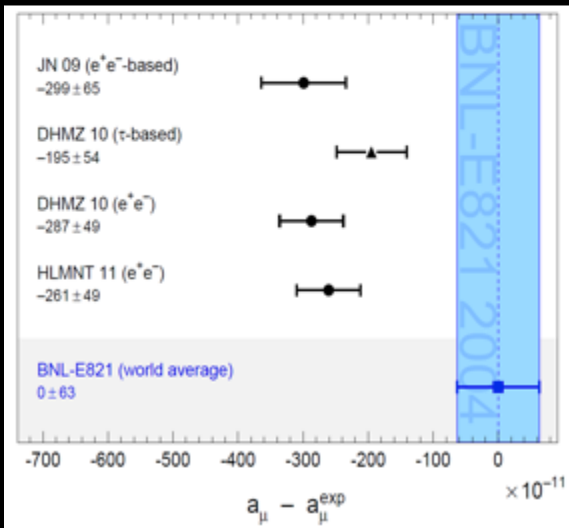


Siegert et al. 2016

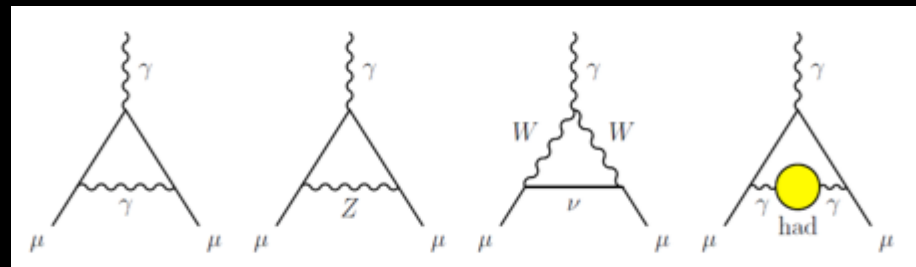
Source (Requirement)	Process	Intensity $\sim 10^{43} e^{+} s^{-1}$	Spectrum $E_{e^+} \lesssim 3$ MeV	Morphology B/D $\gtrsim 1.4$
Massive Stars	^{26}Al β^+ decay	✓	✓	×
SNe	^{44}Ti β^+ decay	✓	✓	×
SNIa	^{56}Ni β^+ decay	?	✓	×
Novae	β^+ decay	×	✓	×
Hypernovae/GRBs	^{56}Ni β^+ decay	?	✓	×
Cosmic rays	p–p collisions	?	×	×
Low-mass X-ray Binaries	γ–γ pair creation	✓	✓	×
Microquasars	γ–γ pair creation	✓	✓	×
Pulsars	γ–γ pair creation	✓	×	×
Central black hole	γ–γ pair creation	?	×	✓(?)
Dark Matter*	annihilation	?	✓	✓

Prantzos et al. 2011

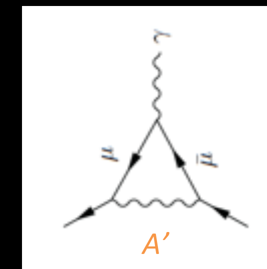
Muon g-2 SM discrepancy



g-2 in the **Standard Model**



g-2 and ***A'***

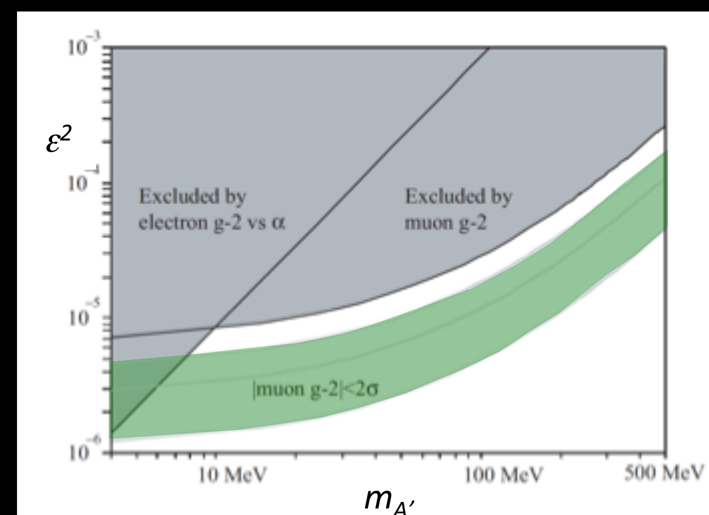


About 3σ discrepancy between theory and experiment (3.6σ, if taking into account only e+ e- → hadrons)

Additional diagram with dark photon exchange can fix the discrepancy (with sub GeV *A'* masses)

Contribution to **g-2** from **dark photon**

$$\Delta a_\mu = \frac{\varepsilon^2 \alpha}{2\pi} \times \begin{cases} 1 & \text{for} \quad m_\mu \ll m_{A'} \\ \frac{2m_\mu^2}{3m_{A'}^2} & \text{for} \quad m_\mu \ll m_{A'} \end{cases}$$



g-2 electron

Caution with $(g-2)_e$ constraint

- The two most precise determinations of fine structure constant disagree at 1.5σ level

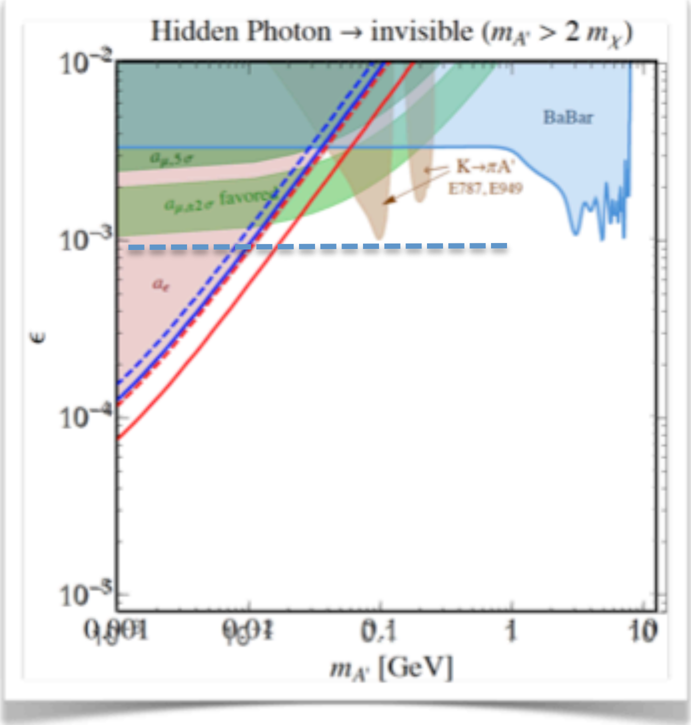
- One can reasonably argue for a more conservative constraint

$$\Delta a_e = (-1.05 \pm 0.82) \times 10^{-12}$$

Aoyama et al. 1205.5368

Or just using error

$$\Delta a_e = \pm 0.82 \times 10^{-12}$$



Important to also have a direct probe of this region of parameter space!

Brian Batell

M. Pospelov

Some examples

- Scalar dark matter talking to the SM via a dark photon (variants: L_{mu}-L_{tau} etc gauge bosons). With $2m_{DM} < m_{mediator}$.

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 - \frac{\epsilon}{2} V_{\mu\nu} F_{\mu\nu}$$

- Model 1: one step process:

$$\chi\chi^* \rightarrow \text{off shell dark photon} \rightarrow e^+e^-$$

Main signature: mediator [dark photon] can be produced in collisions and it decays to DM

- Fermionic dark matter talking to the SM via a "dark scalar" that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

$$\mathcal{L} = \overline{\chi}(i\partial_\mu \gamma_\mu - m_\chi)\chi + \lambda \overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - AS(H^\dagger H)$$

After EW symmetry breaking S mixes with physical h, and can be light and weakly coupled provided that coupling A is small.

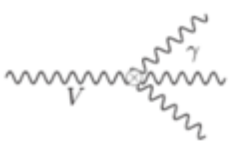
- Model 2: two-step process: annihilation to mediators with subsequent decay

$$\chi\overline{\chi} \rightarrow S + S \rightarrow \ldots \rightarrow (e^+e^-) + (e^+e^-)$$

Main signature: Production of scalar mediator in meson decays (e.g. K or B mesons) with missing energy signal [if long lived], or displaced decays.

Superweakly interacting Vector Dark Matter

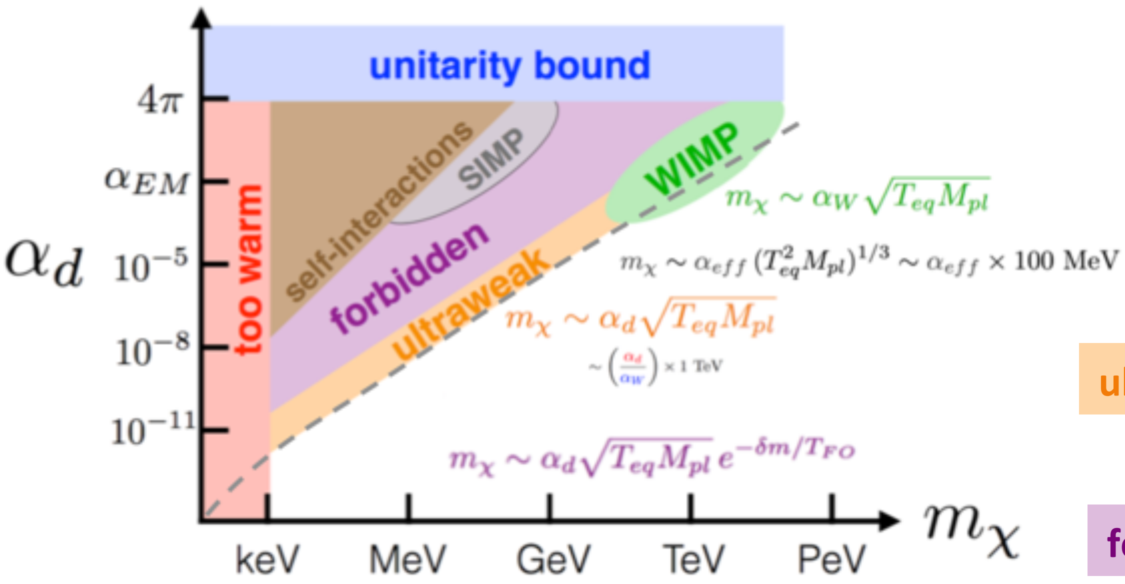
$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu}^2 - \frac{\kappa}{2} V_{\mu\nu} F_{\mu\nu} + \mathcal{L}_{h'} + \mathcal{L}_{\dim>4},$$

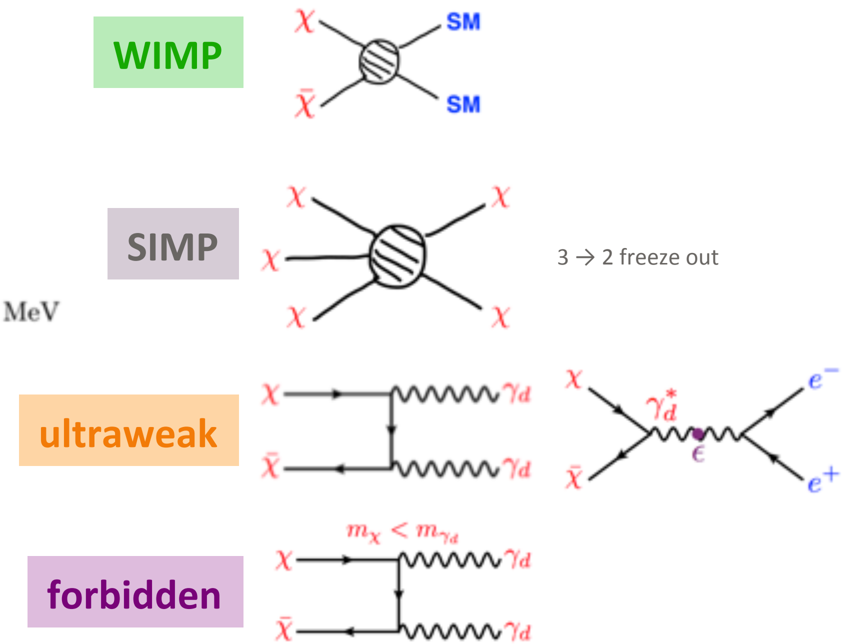


$$\tau_U \Gamma_{V\to 3\gamma} \lesssim 1 \implies m_V\, (\alpha')^{1/9} \lesssim 1\,\text{keV}$$

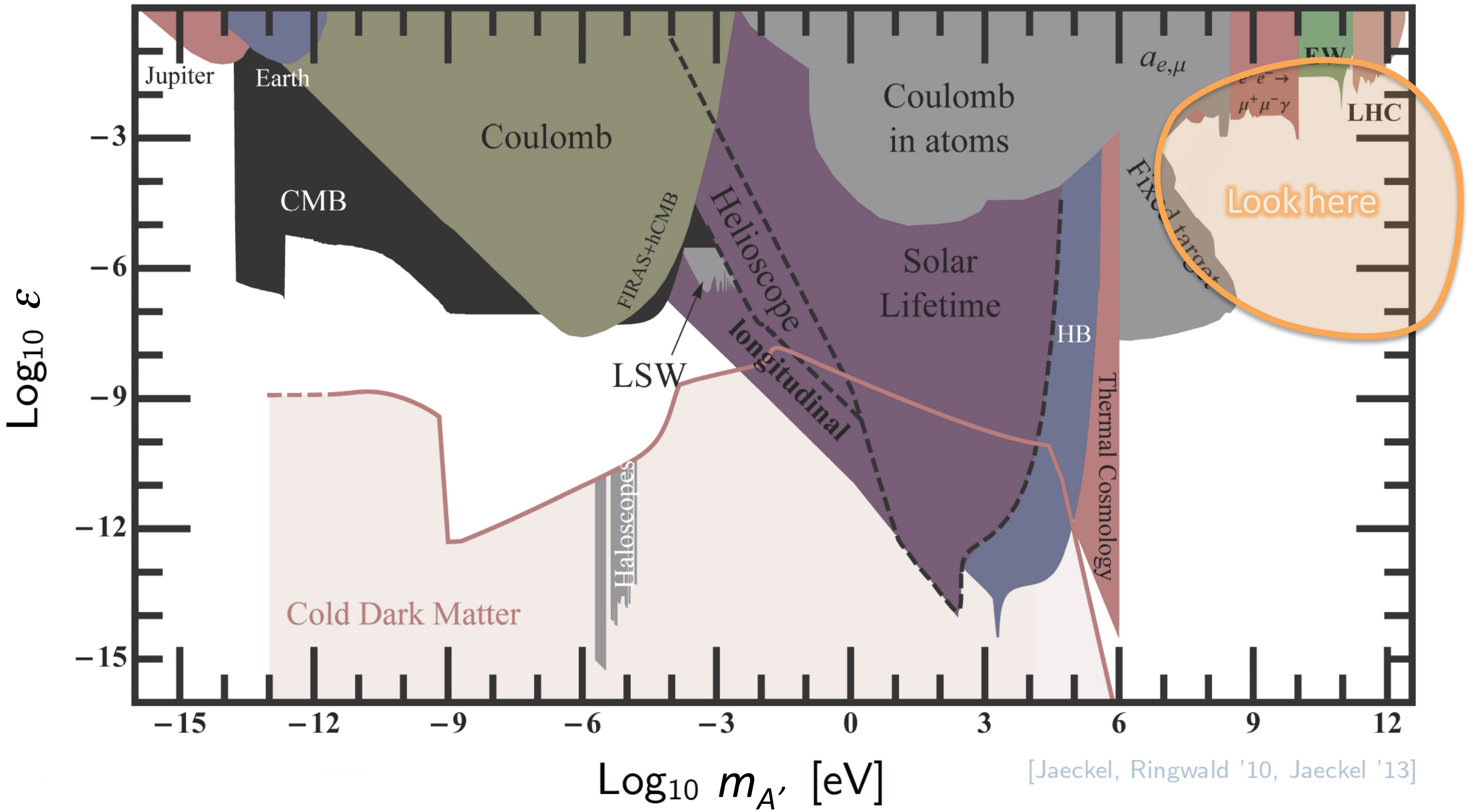
Dark freeze-out

J. Ruderman (NYU)

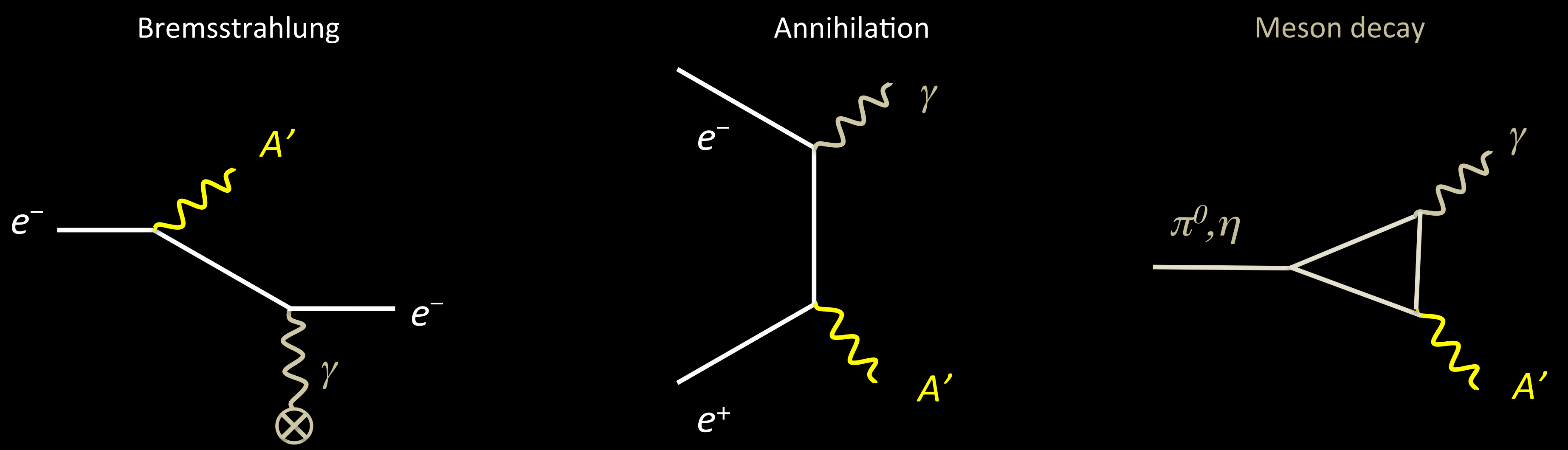




Where to look for dark mediators?



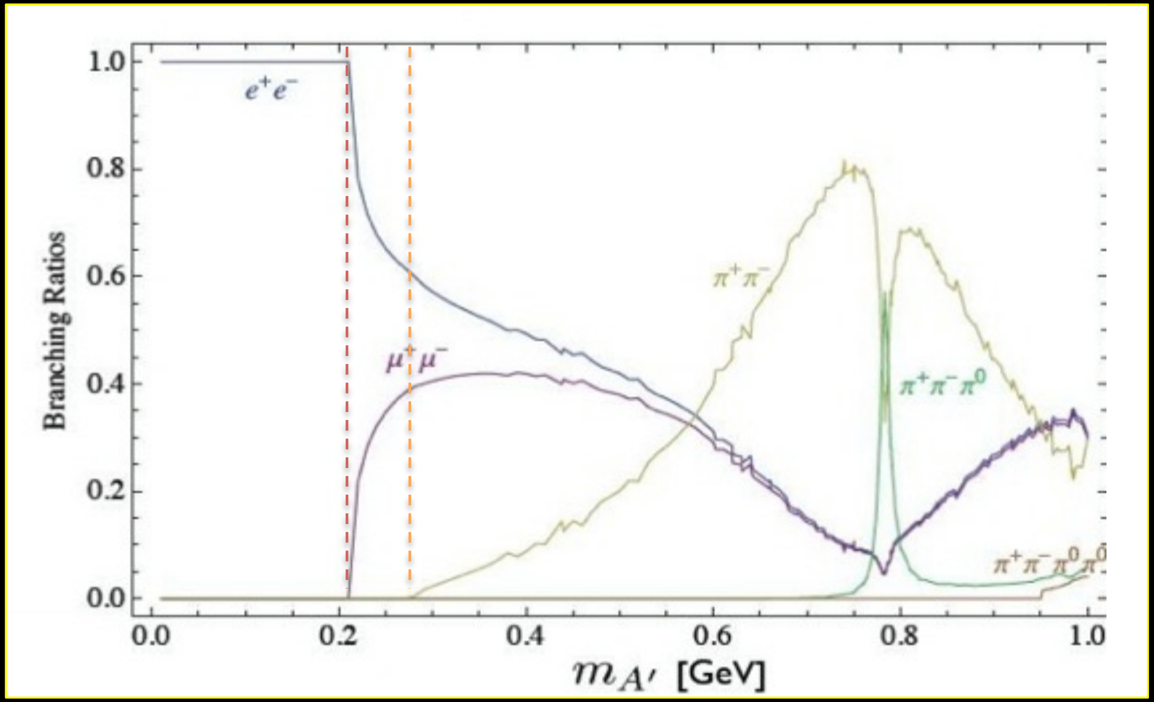
Dark photon production



- *A′* can be produced in electron collision on target by:
  - Bremsstrahlung: e N → e N *A′*
  - Annihilation: $e^+ e^- \to \gamma$ *A′*
  - Meson decays

Dark photon visible decays

- Assume that no additional **lighter** states exists in the dark sector with $m_\chi < m_{A'}/2$
- Dark photon couples to SM particles through kinetic mixing only (with same coupling εq)
- For $m_{A'} < 2\,m_\mu$ only decays to e^+e^-



Dark photon invisible decays

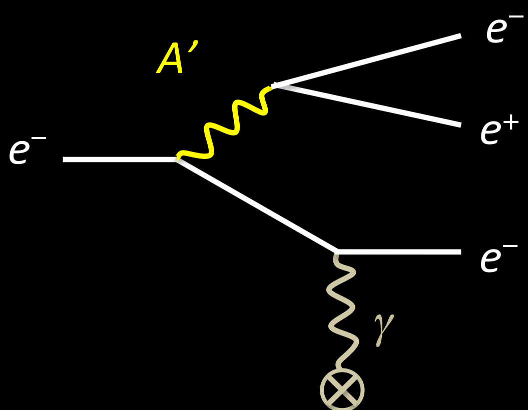
- If χ state with U(1) charge q_U and coupling constant g_U exists in the dark sector with $m_\chi < m_{A'}/2$, the coupling to the A' will be: $q_U g_U$
- $A' \rightarrow \bar{\chi}\chi$ will be dominant wrt to visible decays for $\alpha_D > \alpha$, i.e. $|q_U g_U| > \varepsilon e$

Dark sector experiments

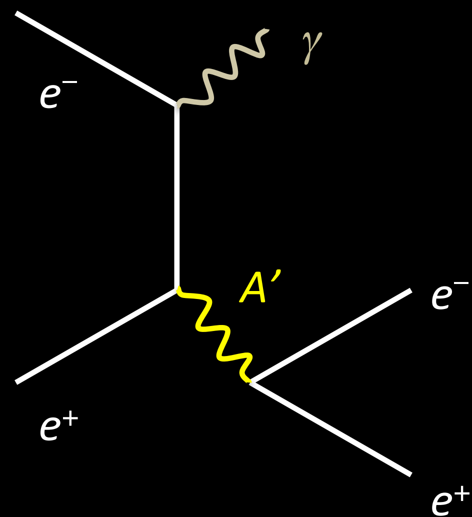
- Thick target (beam-dump)
  - **Produced by electron beam**
  - **Absorb all SM backgrounds**
  - Look for visible decays ($e^+ e^-$, $\mu^+ \mu^-$, …)
- Thin target + decay:
  - **Produced by electron beam**
  - **Do not absorb shower**
  - Decay to visible particles ($e^+ e^-$, $\mu^+ \mu^-$, …)
    - "Bump hunting", looking for a peak in the invariant mass
    - Displaced vertices, looking for long-lived particles
  - Decay to invisible particles
    - Look for missing mass
    - DM particles recoil
- Meson decays (visible and invisible)
- Dark particles scattering (invisible)

Why fixed target?

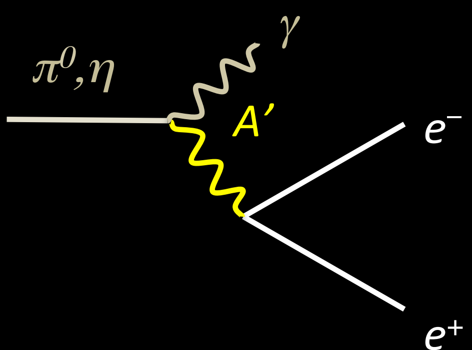
Bremsstrahlung



Annihilation



Meson decay



$$\sigma^{\mathrm{ft}}_{\gamma'} \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2_{A'}}$$

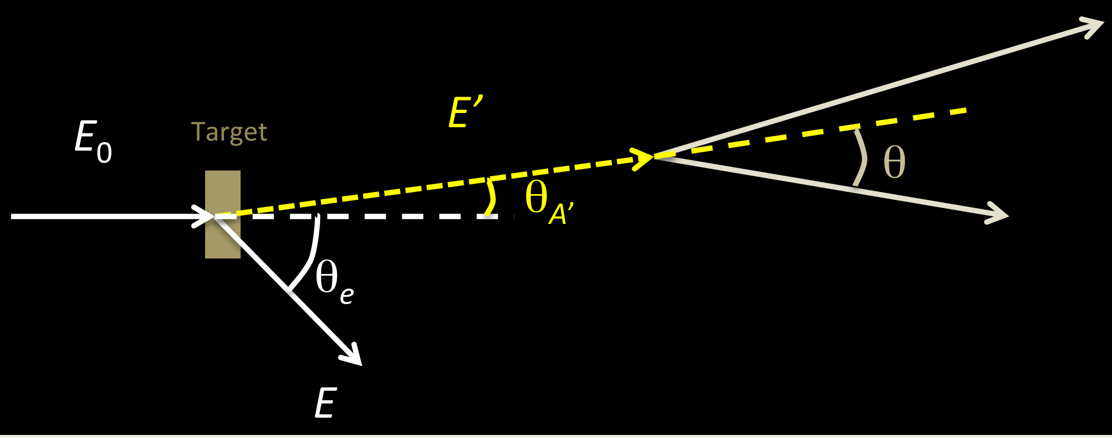
O(pb)

$$\sigma^{\mathrm{coll}}_{A'} \sim \frac{\alpha^2 \varepsilon^2}{E^2}$$

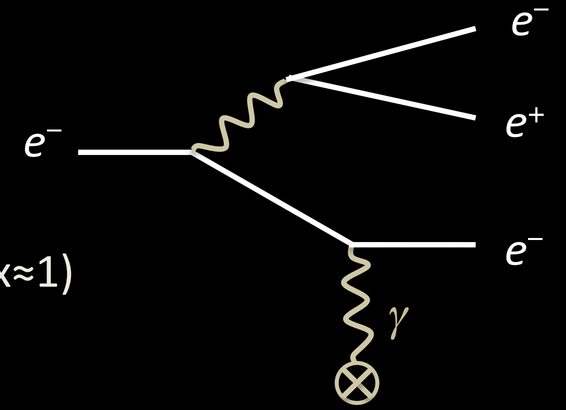
O(fb)

Fixed target experiments

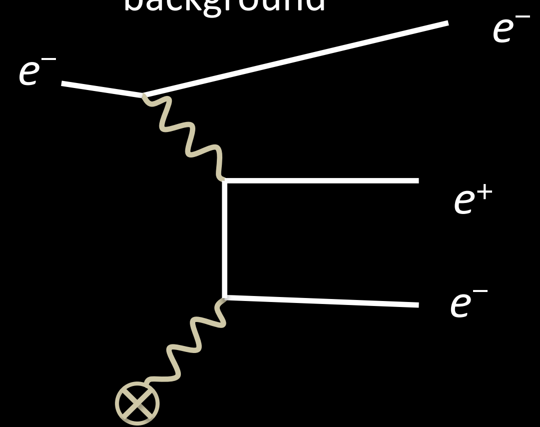
- Main backgrounds: SM Bremsstrahlung + Bethe-Heitler
- Kinematics:
  - A' takes nearly all the beam energy E_0 (sharply peaked at x≈1)
  - Electron takes a small energy ≈ $m_{A'}$
  - A' emission almost collinear to the beam: $\theta_{A'}=(m_{A'}/E_0)^{3/2}$
  - Electron going at "wide" angle: $\theta_e=(m_{A'}/E_0)^{1/2}$
  - A' decay products open by $\theta \approx m_{A'}/E_0$



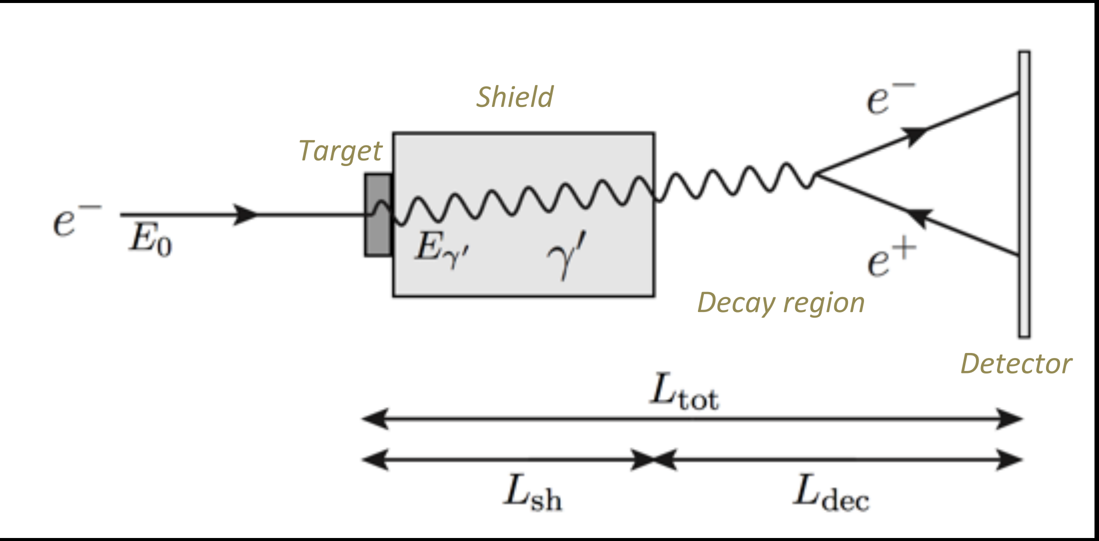
Radiative background



Bethe-Heitler background



Electron beam-dump experiments

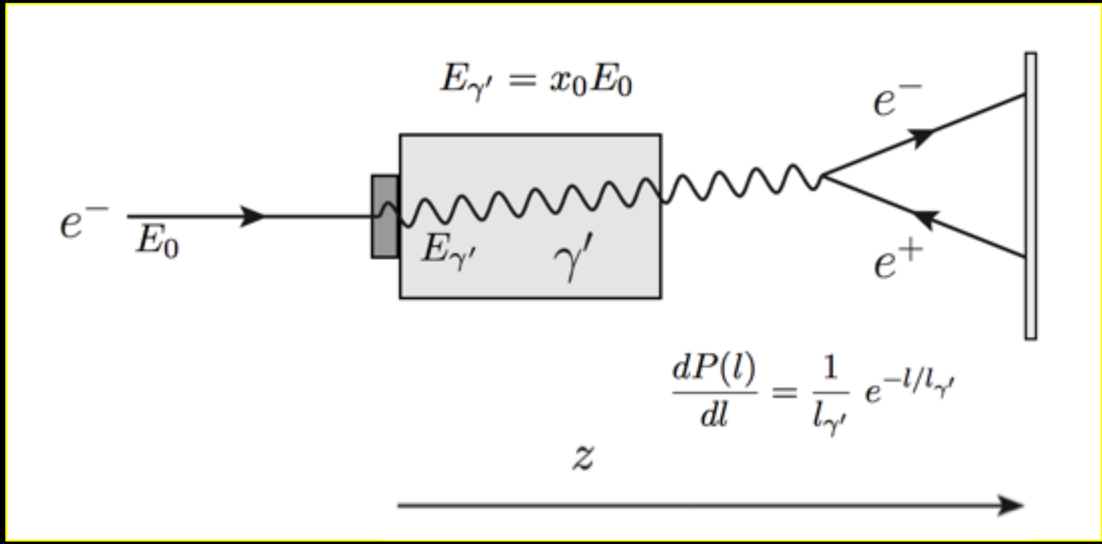


Luminosity: $\mathcal{L}^{\rm ft} \simeq N_e \frac{N_0 \rho_{\rm sh} l_{\rm sh}}{A}$

At colliders: $\mathcal{L}^{\rm coll} \simeq \frac{N_e^2}{\mathcal{A}_b}$ → Beam section

In addition to cross section advantage

Electron beam-dump experiments



$$N_{\gamma'} = \sigma_{\gamma'} N_e \frac{N_0}{A} \rho_{\rm sh} L_{\rm sh}$$

Electron energy distribution due to the interaction in target+shield

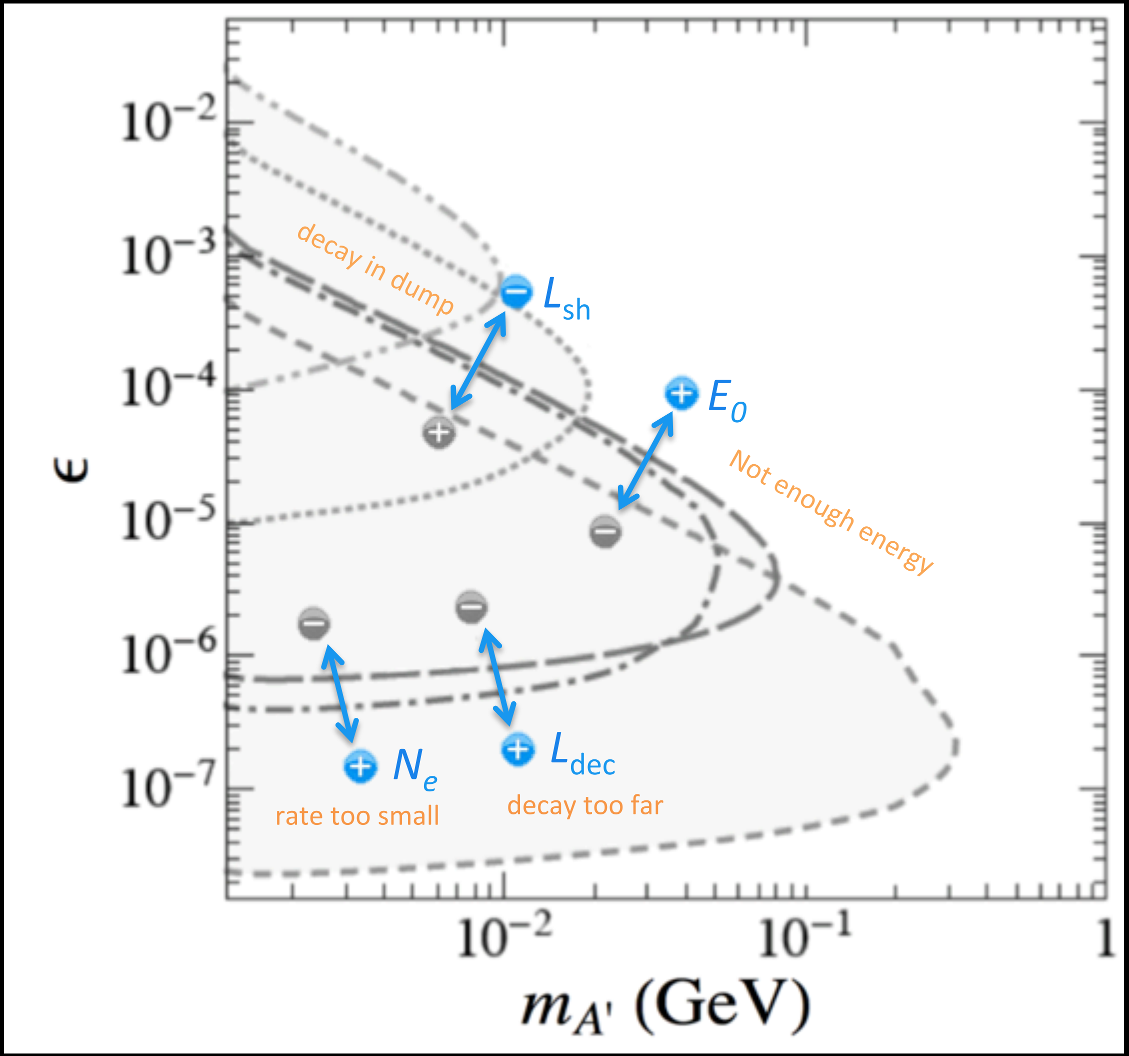
Decay probability of γ' after shield

$$\frac{dN_{\gamma'}}{dx_0\, dz} = N_e \frac{N_0 X_0}{A} \int_{E_{\gamma'}+m_e}^{E_0} dE_e \int_0^{T_{\rm sh}} dt_{\rm sh} \left[I_e(E_0, E_e, t_{\rm sh}) \frac{E_0}{E_e} \frac{d\sigma}{dx_e}\bigg|_{x_e = \frac{E_{\gamma'}}{E_e}} \frac{dP(z - \frac{X_0}{\rho_{\rm sh}} t_{\rm sh})}{dz} \right]$$

$$T_{\rm sh} \equiv \rho_{\rm sh} L_{\rm sh} / X_0$$

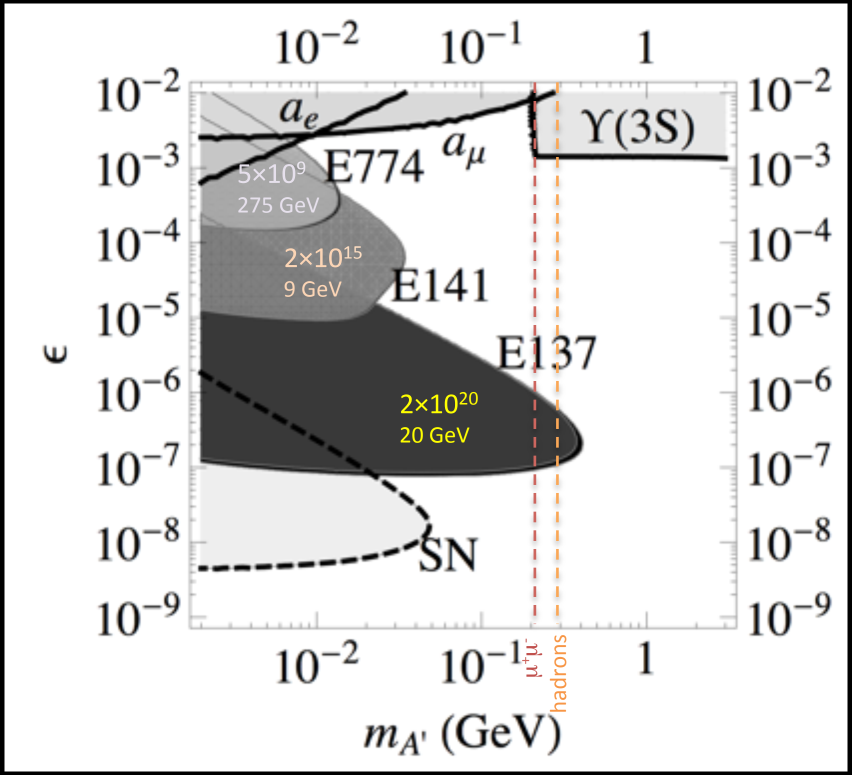
$d\sigma/dx$ for γ' production by Bremsstrahlung

Limits from electron beam-dump experiments

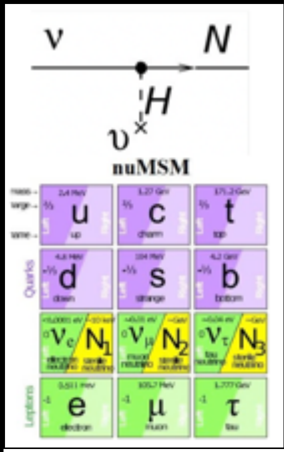


Limits from electron beam-dump experiments

- Beam-dump experiments: looking for decay products of "rare penetrating particles" behind a **stopped electron beam**
- SLAC **E141** (1987) and SLAC **E137** (1988), Fermilab **E774** (1991)

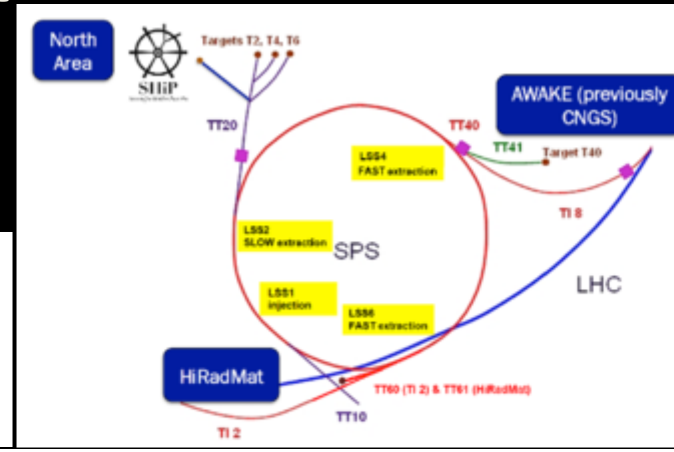


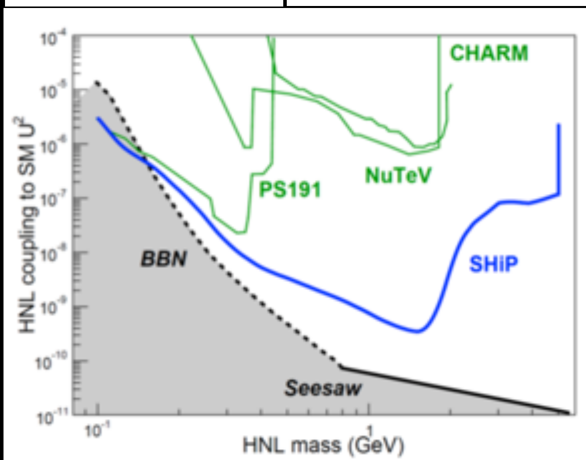
Proton beam dump: SHIP



Main aim: look for heavy neutral leptons

- νMSM introduces 3 right-handed Majorana HNLs: N1, N2 and N3
  - N_1 light, O(1 keV) : Dark Matter candidate
  - $N_{2,3}$ degenerate, O(100 MeV - few GeV) : neutrino masses via see-saw
  - $N_{2,3}$ leptogenesis → baryogenesis by increased CP violation (BAU)

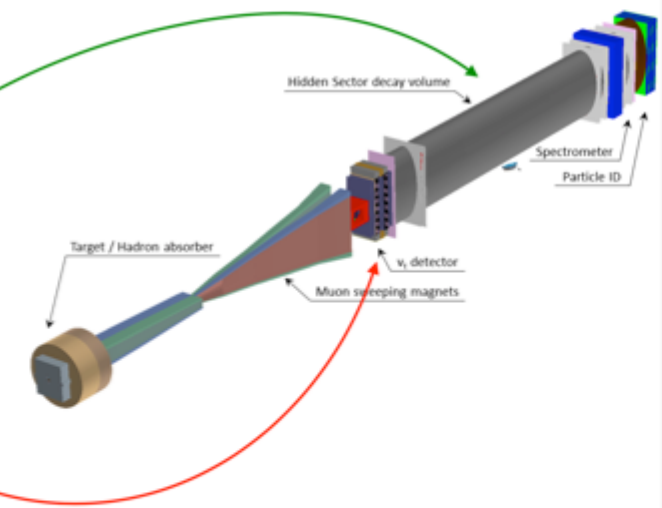


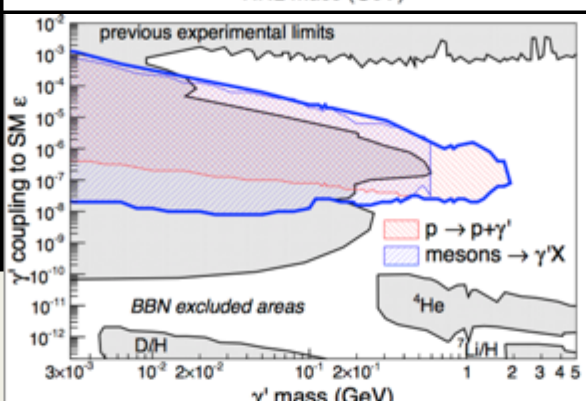


5×10^{13} protons per spill @ 400 GeV
→ 2×10^{20} collisions in 5 years

Hidden particle detector will consist of a long evacuated decay volume with a magnetic spectrometer, calorimeters, and a muon detector located on the far end

Neutrino detector consists emulsion target with tracking in a magnetic field followed by a muon spectrometer $N\nu_\tau \sim 10^4$





Dark photon sensitivity

Thin target experiments

Running:

- APEX at JLAB Hall-A, test run done, full run coming
- A1 at MAMI
- HPS at JLAB Hall-B, first runs done in 2015 and 2016

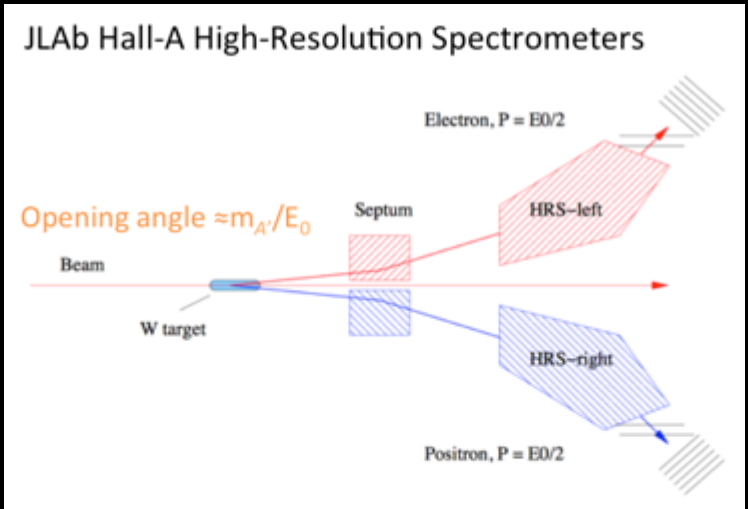
Coming soon:

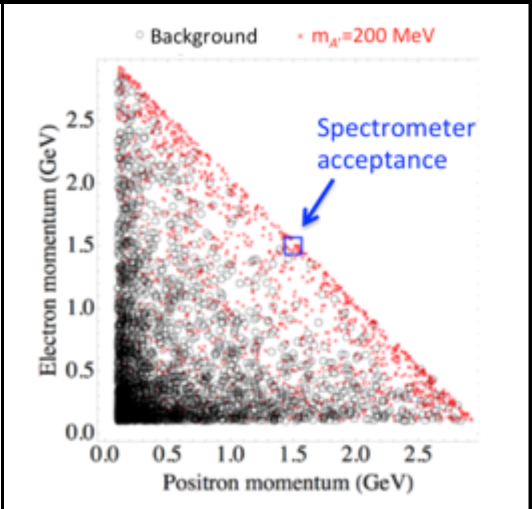
- PADME at Frascati (approved)

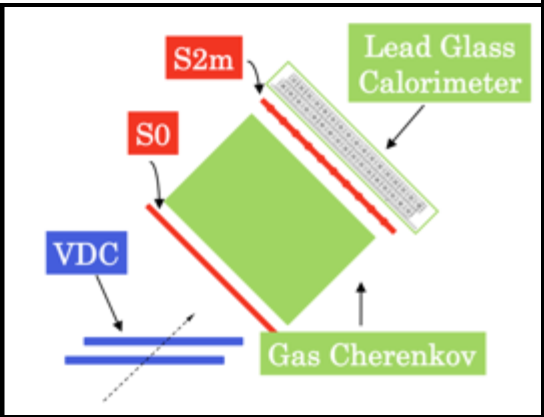
Proposed:

- DarkLight at JLAB FEL (electron on gas jet target)
- VEPP3 (electron on gas jet target)
- Cornell (positron extracted from synchrotron)

APEX







$0.3<p<4.0$ GeV, $\theta_0=5°$
Acceptance=4.5 msr
$\delta p/p < 2\times10^{-4}$
$\delta\phi$=0.5 mrad, $\delta\theta$=1 mrad

APEX

Background rejection and final dataset

Reducible backgrounds

- Electron singles from inelastic or electron-nucleon scattering
- Pions from virtual photon decays
- Proton singles
- Accidental e^+e^- coincidences
- e^+e^- pairs from real photon conversions

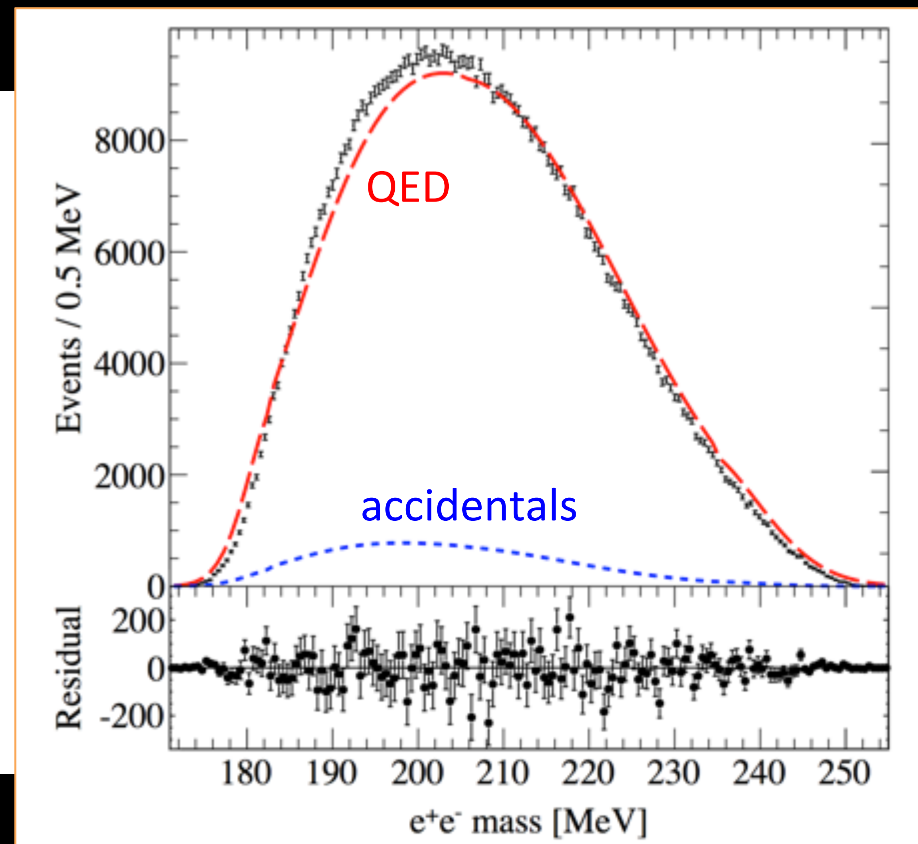
Pion rejection:

- Production ratio in right HRS: $e^+/\pi^+ > 1/100$
- Online pion rejection: factor of 30
- Offline rejection > 1/100 using both gas Cherenkov and calorimeters

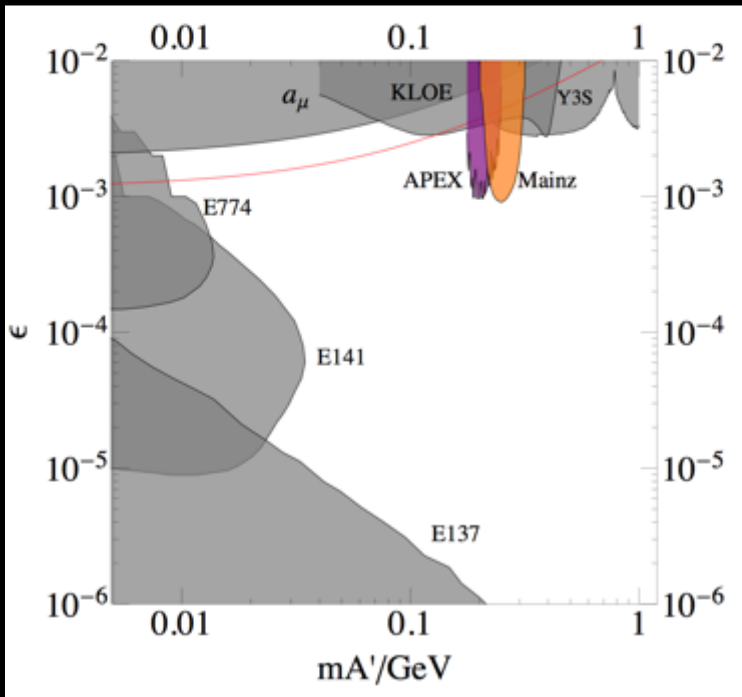
Final event sample trigger:

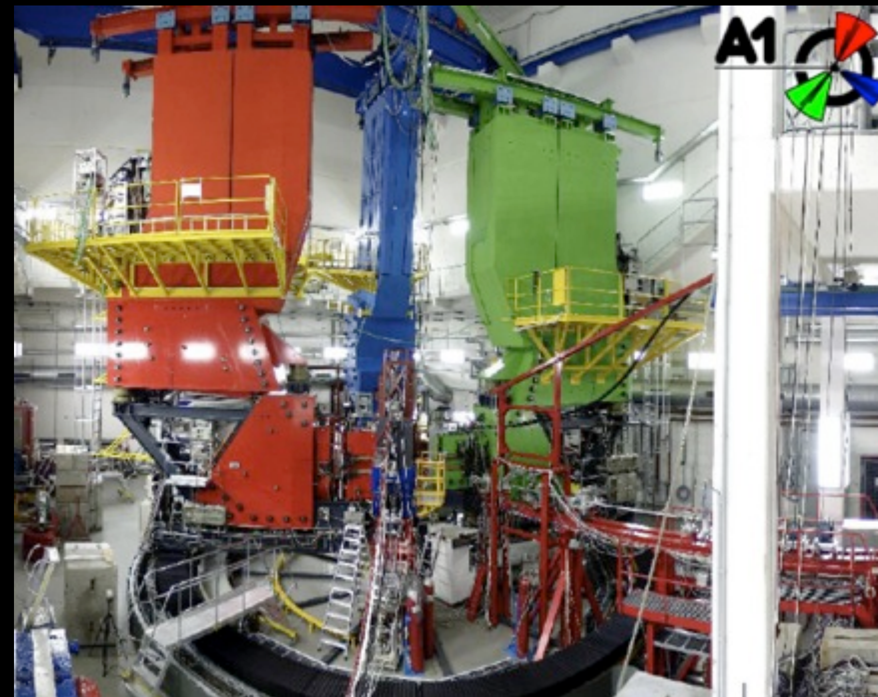
- Double coincidence gas Cherenkov signal within 12.5 ns window in each arm

Final data sample consisted of 770500 true e^+e^- coincident events with 0.9% (7.4%) meson (accidental e^+e^- coincidence) contamination



MAMI A1

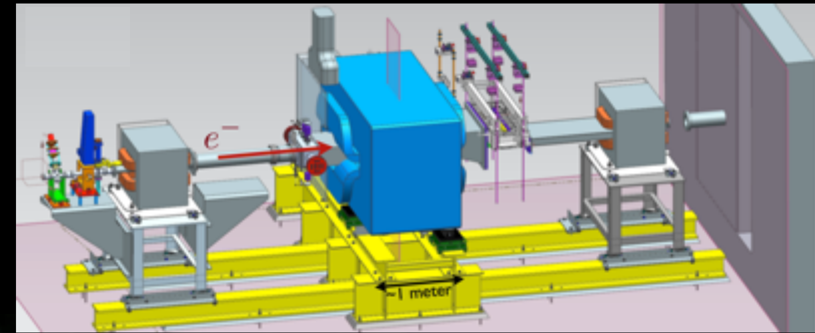




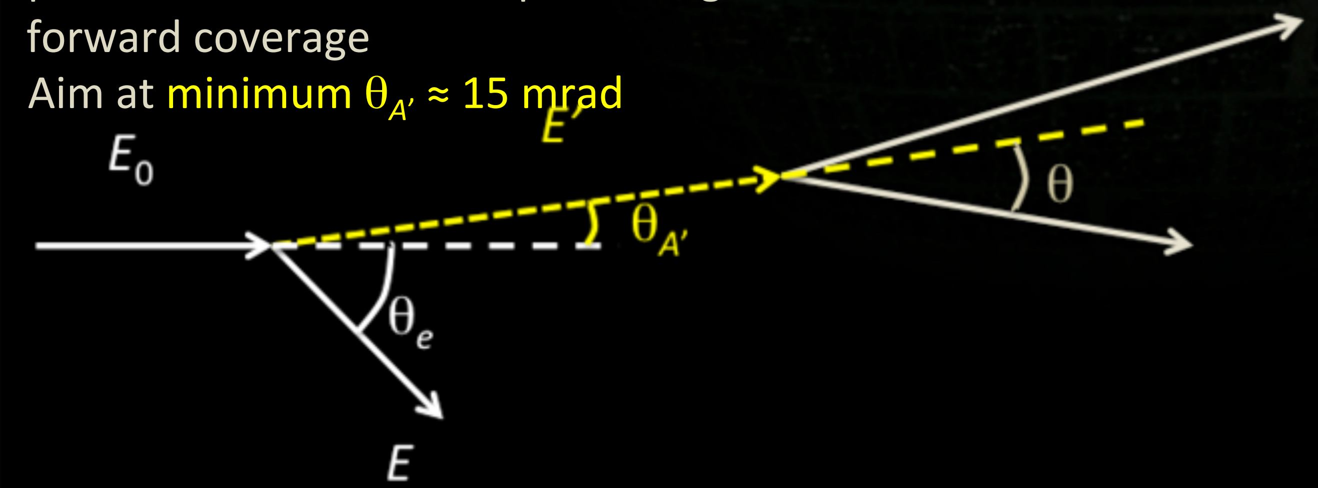
JLAB Hall-A APEX
n×1.1 GeV, continuous, 200 μA beam

MAMI A1
855 MeV, continuous, 90 μA beam

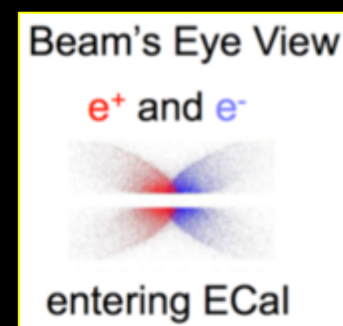
HPS



- Increase acceptance wrt double arm spectrometer
- Look for displaced vertex
- θ of the decay is small:
  - put detectors as close as possible, good forward coverage
  - Aim at minimum $\theta_{A'} \approx 15$ mrad

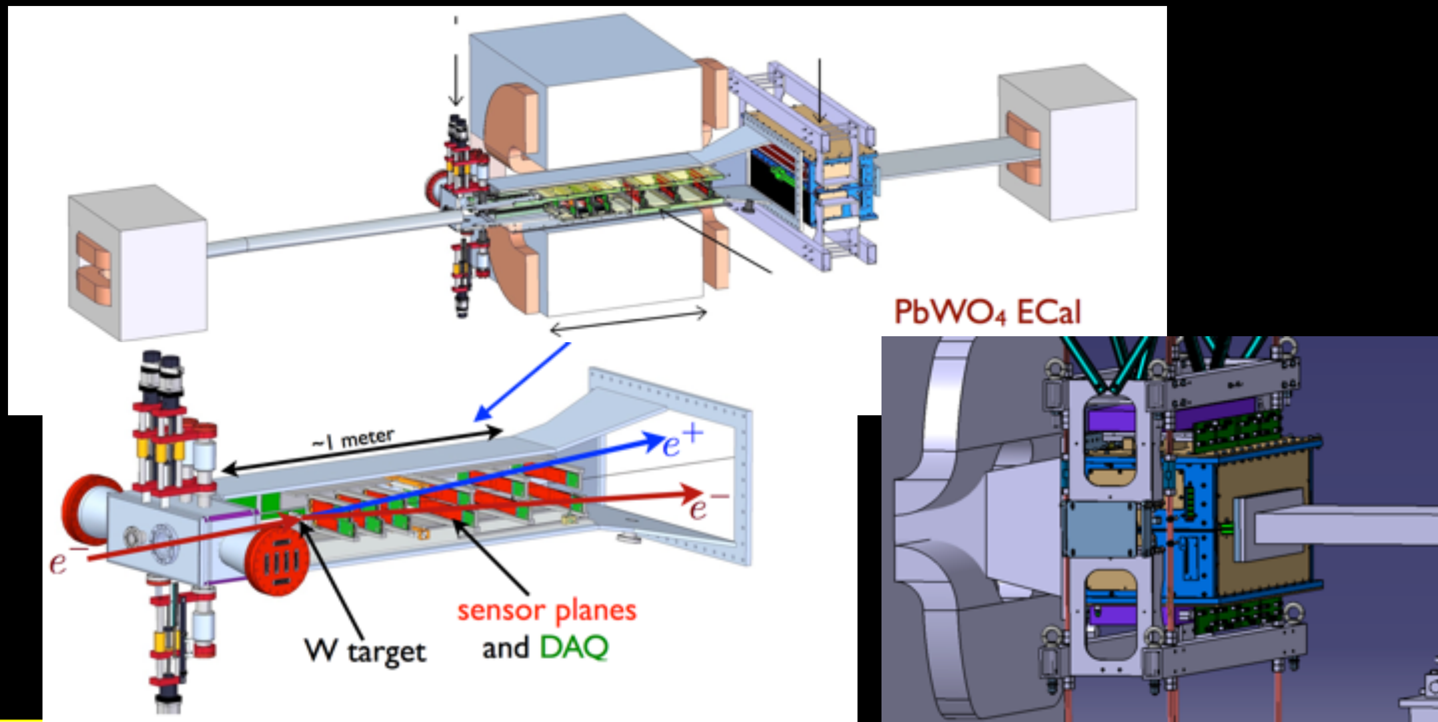


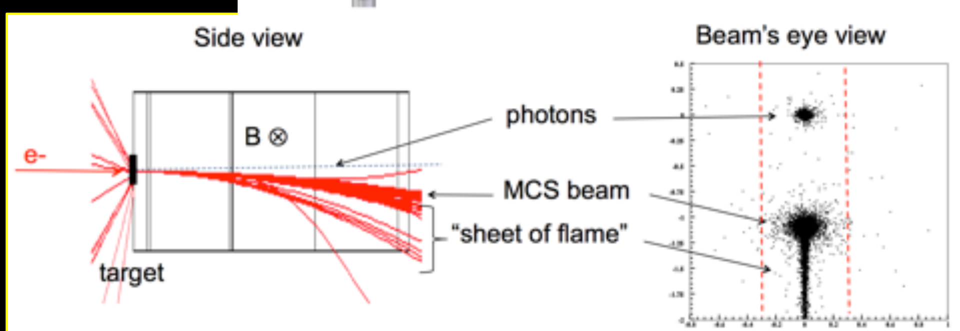
- Bump hunting needs good momentum/mass resolution
- Good tracking and analyzing magnet
- Aim at $\Delta m/m \approx 1\%$ and $\Delta z \approx 1$ mm



- Trigger with a high rate ECAL
- Magnet+ECAL to select e^+ and e^-
- Magnet+muon detector to select μ^+ and μ^-

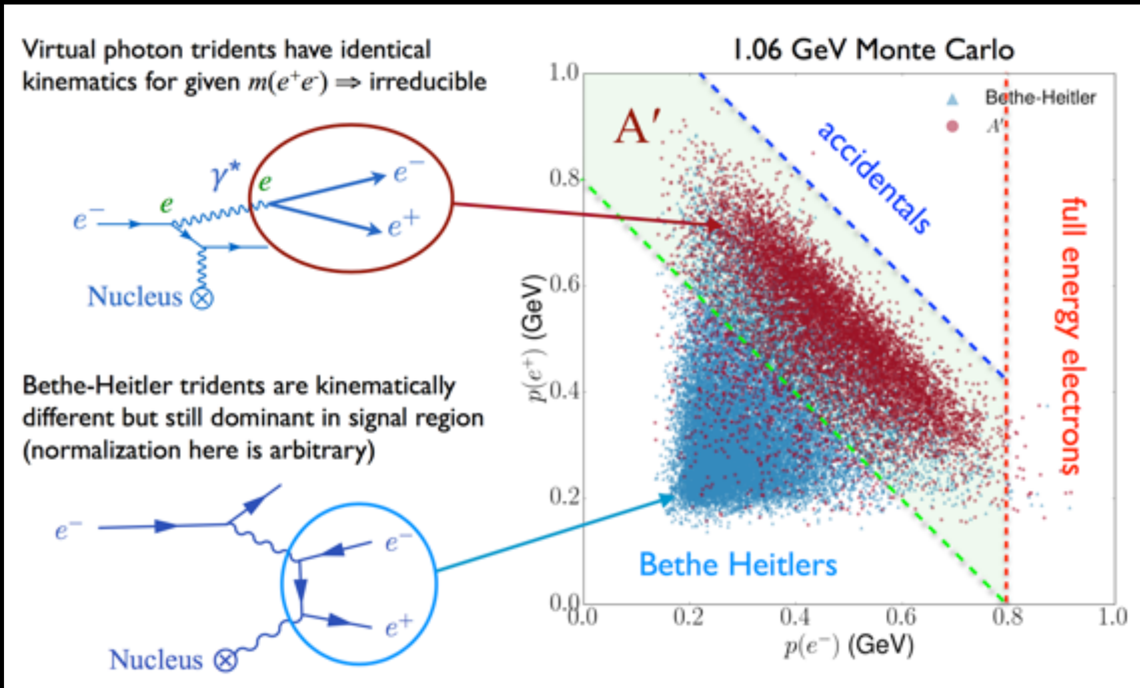
HPS

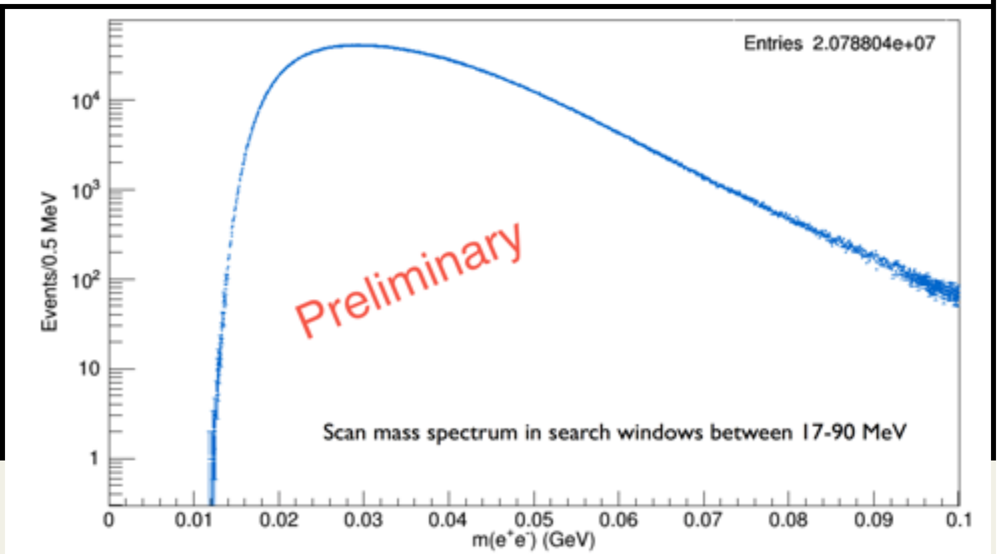


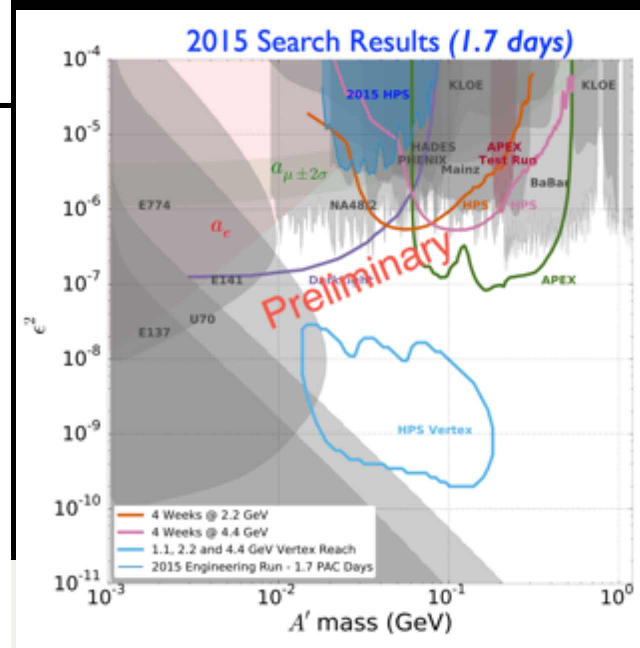


Detectors split in two halves to let the beam pass through

HPS background & exclusion



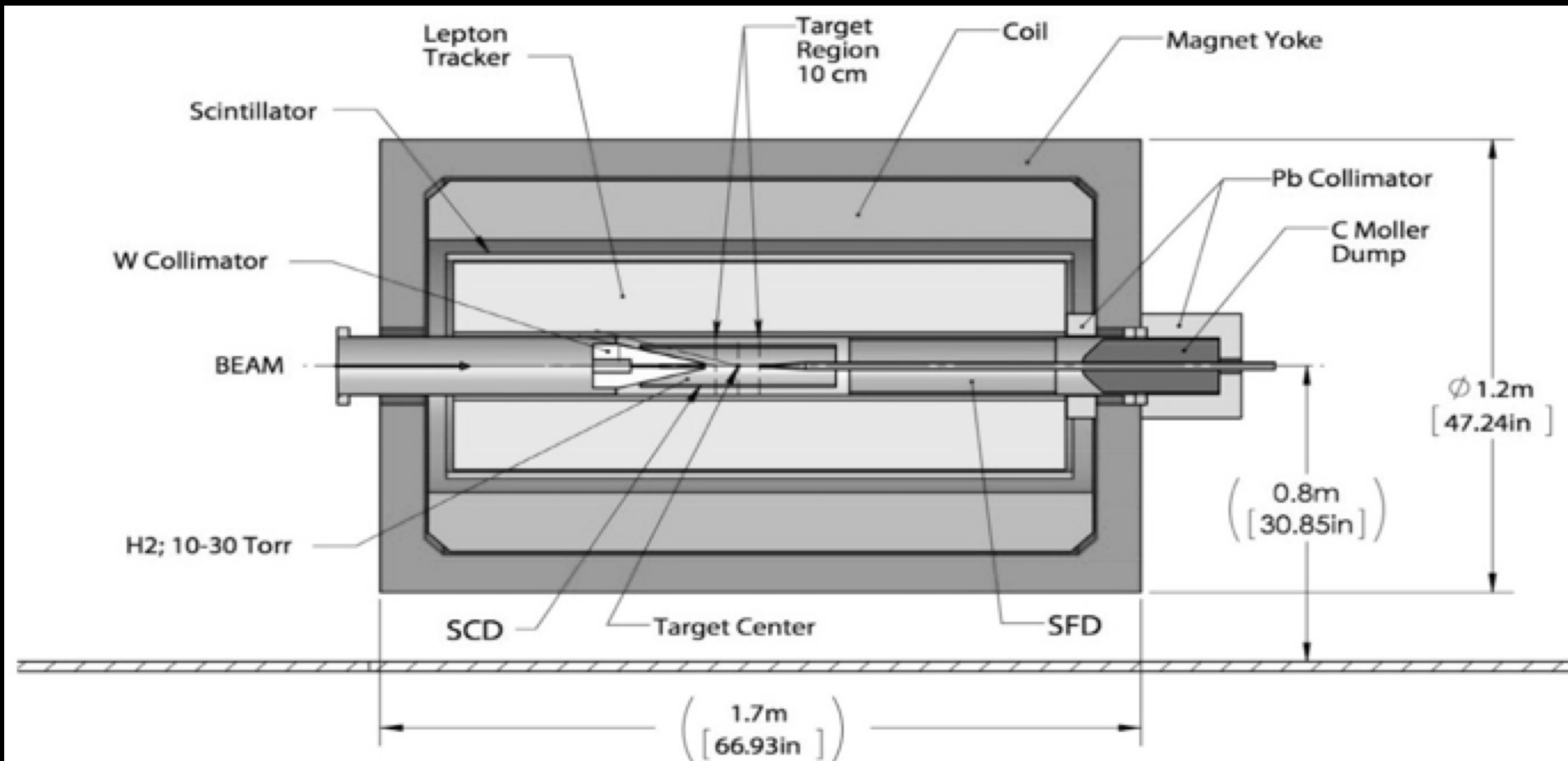




DarkLight

FEL electron beam, 100 MeV, continuous, 10 mA, onto 10^{19} H_2/cm^2 gas jet target

- Proton recoil detector. Full reconstruction of event for background rejection
- Vertexing and low momentum lepton tracker: TPC
- Outer trackers

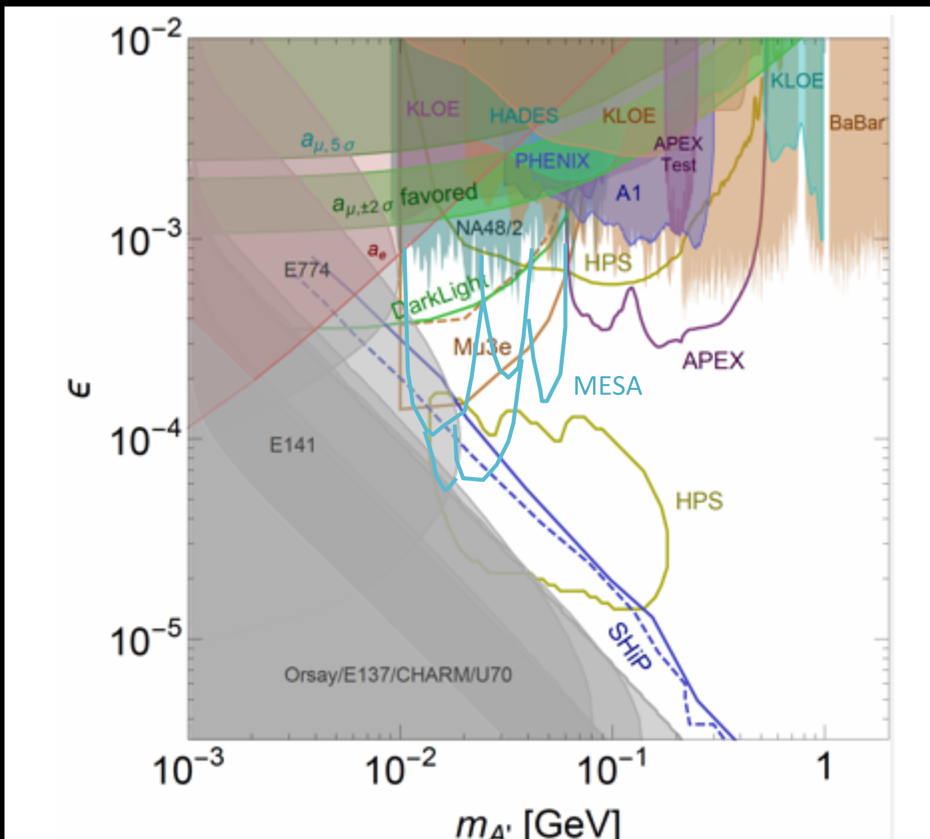


Test performed on prototype vacuum chamber to assess beam transport feasibility

Summary on visible decays

Practically, all the $(g-2)_\mu$ favored band already excluded

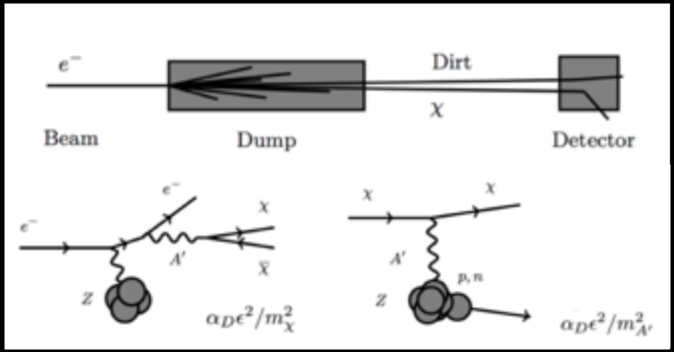
Still large interest for excluding the uncovered parameter space



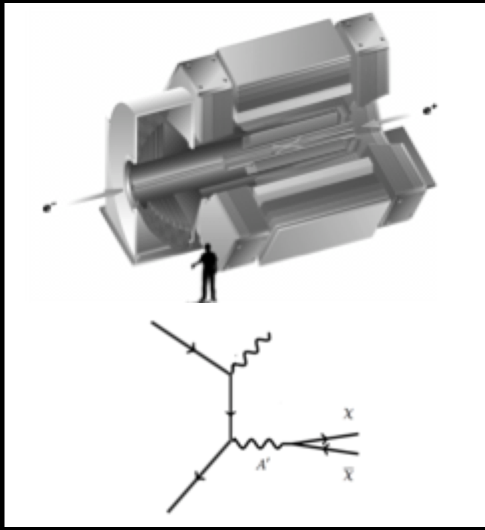
… but limits work **only** if the dark photon is the **lightest particle** in the hidden sector

Invisible decays: a dark matter beam

Positive evidence



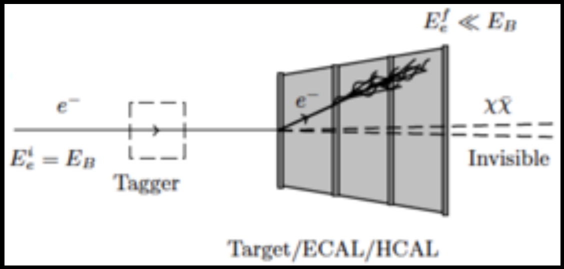
Dump & scattering, $N \sim \varepsilon^4$ BDX



BaBar,
Belle-II,
PADME

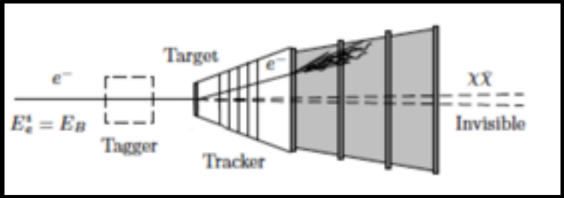
Missing mass, $N \sim \varepsilon^2$

Negative evidence



NA64

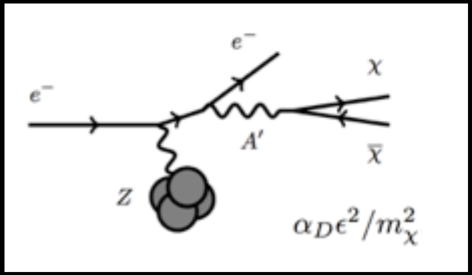
Missing energy, $N \sim \varepsilon^2$

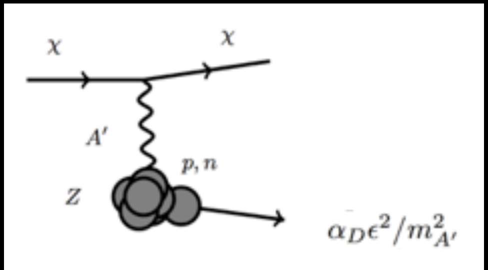


LDMX

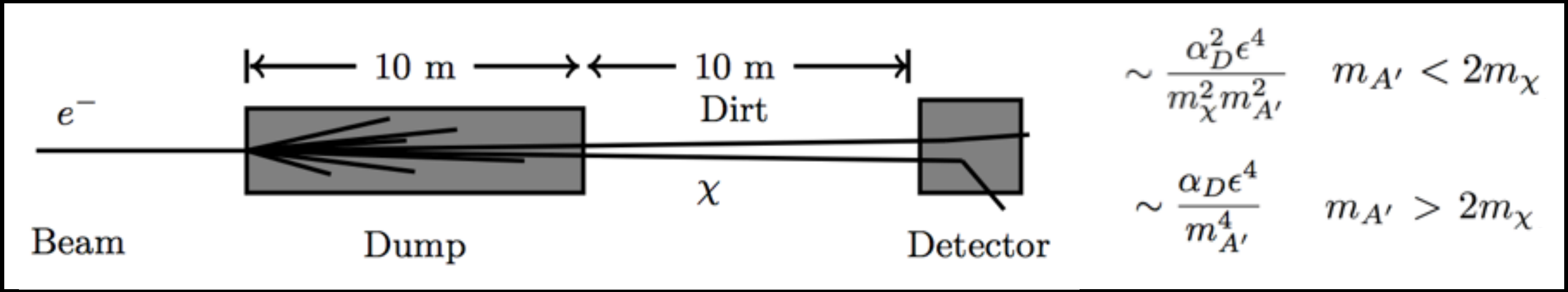
Missing momentum, $N \sim \varepsilon^2$

DM scattering experiment: BDX at JLAB





Scattering on nuclei



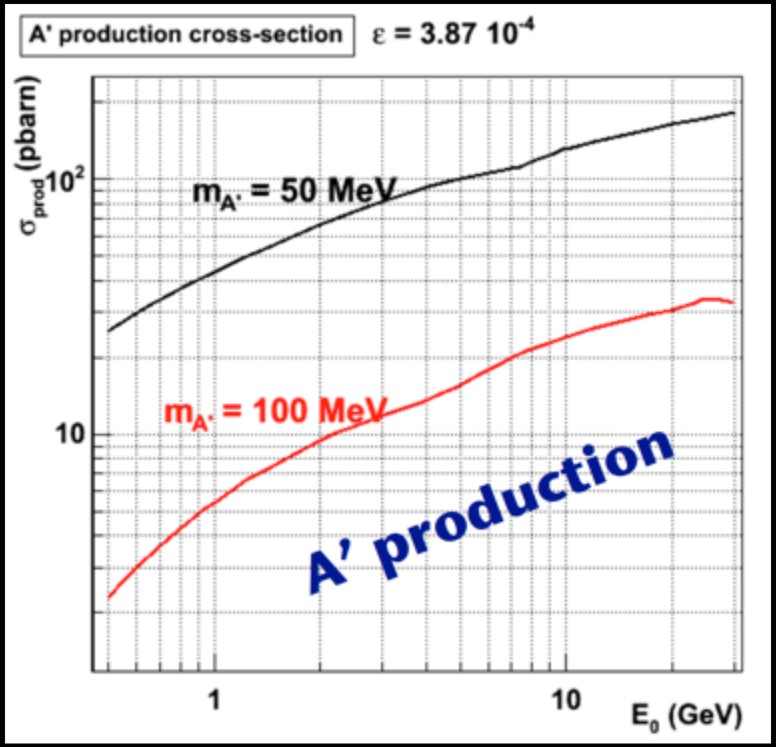
Backgrounds:
- Neutrino production
- Cosmogenic muons and neutrons

Scintillator 1 m^3
1 MeV/10 MeV e^+e^- detection threshold

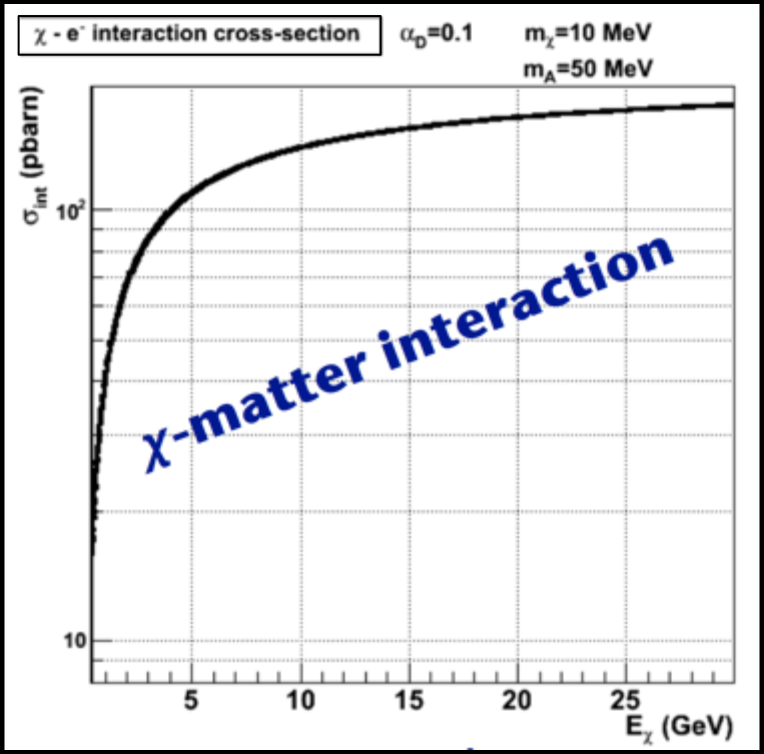
LOI presented to JLAB PAC

Scattering experiment: BDX at JLAB

High energy beam advantages:
- Higher cross sections
- χ beam boosted, larger acceptance

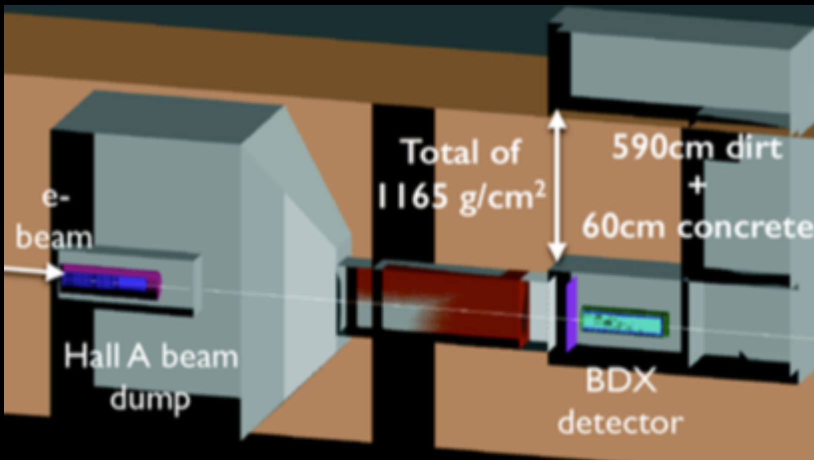


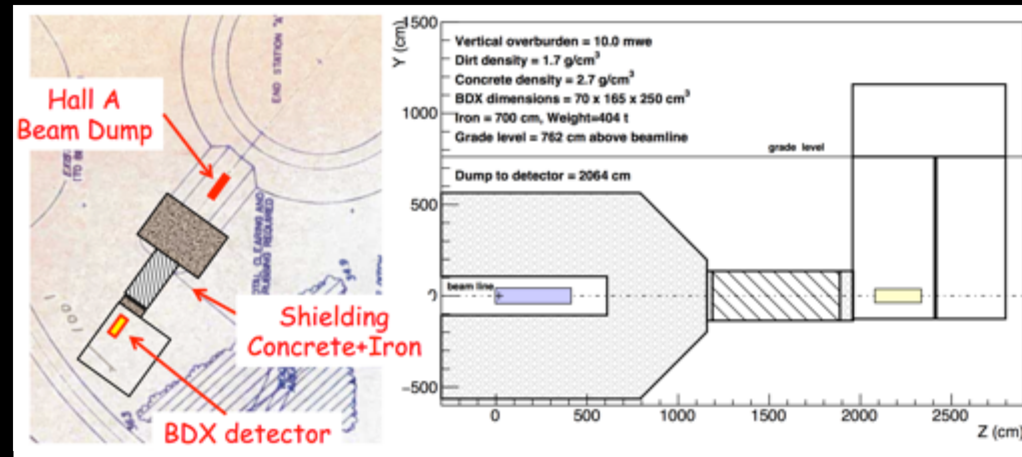
Cross section dependence from *A′* mass

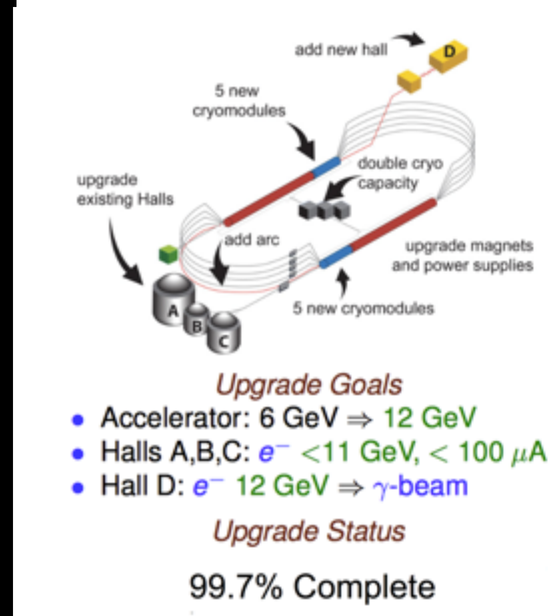


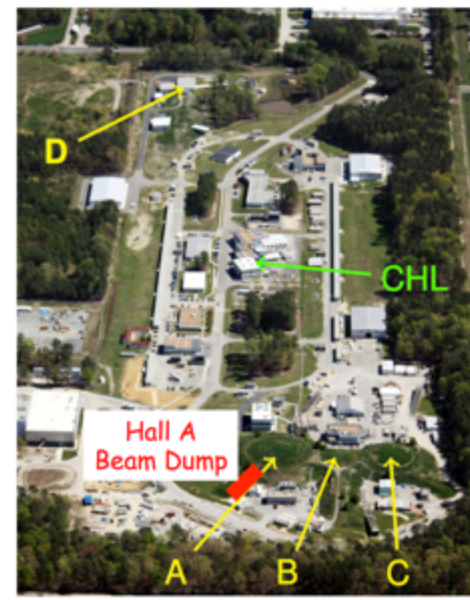
Cross section dependence from *A′* mass, χ mass, coupling constant

BDX





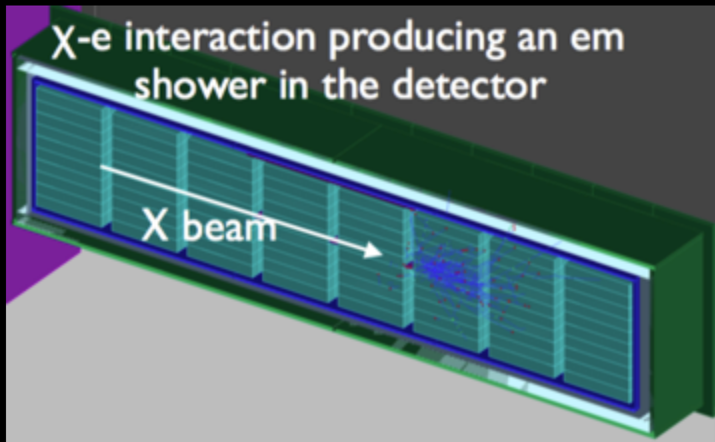




10^{22} EOT = 1 beam-year at Hall-A

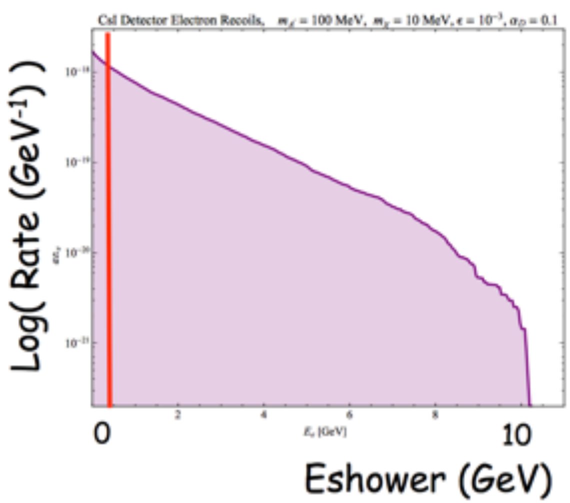
3 beam-years at Hall-C?

BDX signal



$\simeq$ 800 CsI(Tl) crystals, total interaction volume $\simeq 0.5m^3$

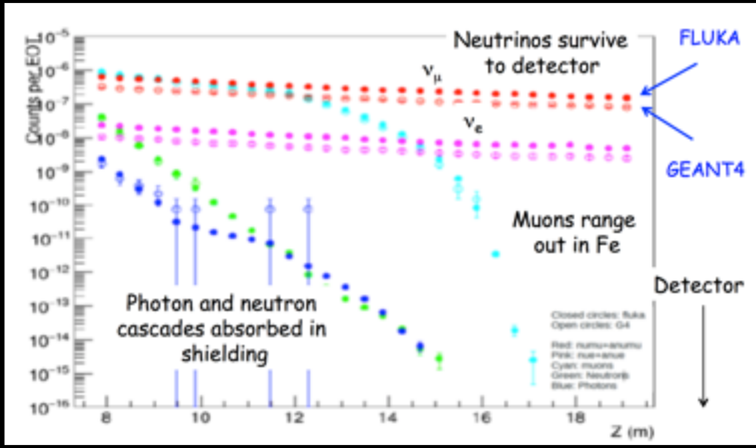
Modular detector: change front-face dimesions and total lenght by re-arranging crystals



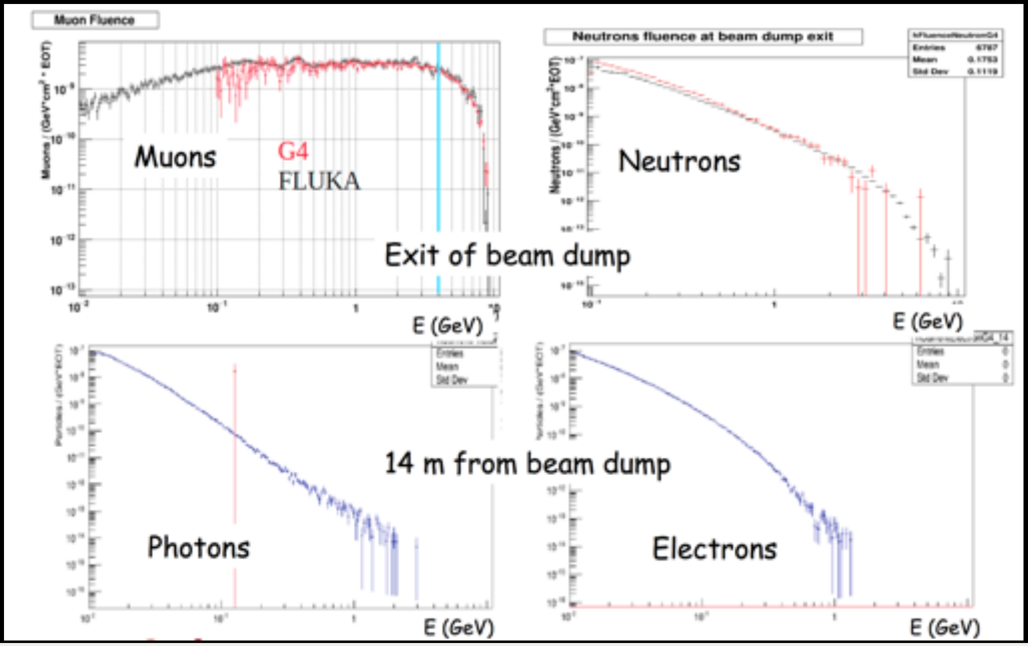
Signal Efficiency ~ 20% for E_{thresh} > 0.3 GeV

Parameters:
M_χ=10 MeV, $m_{A'}$=100 MeV

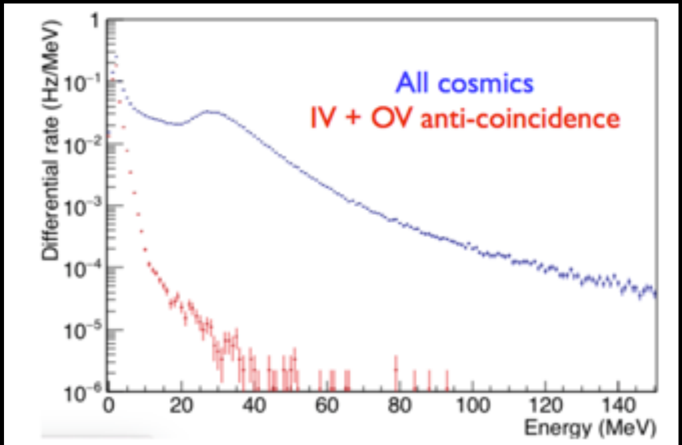
BDX backgrounds



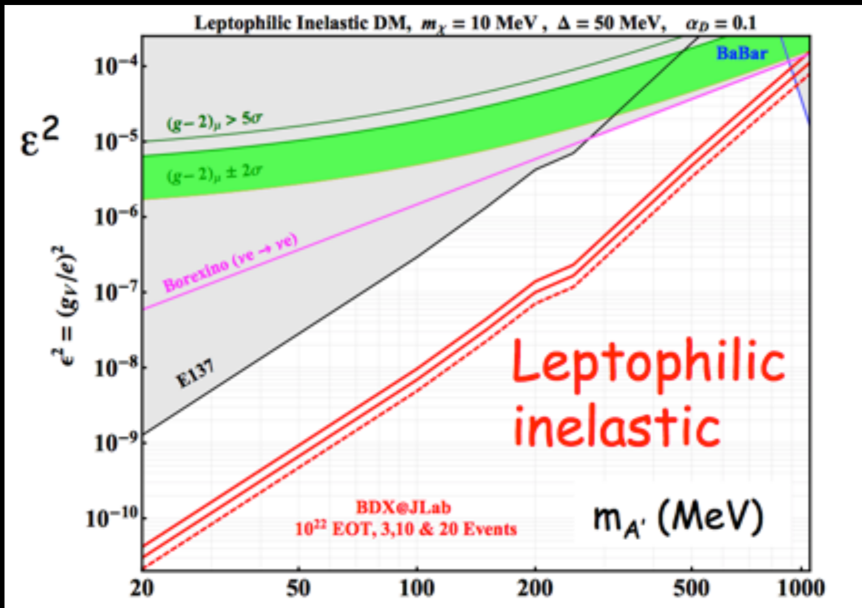
Beam related

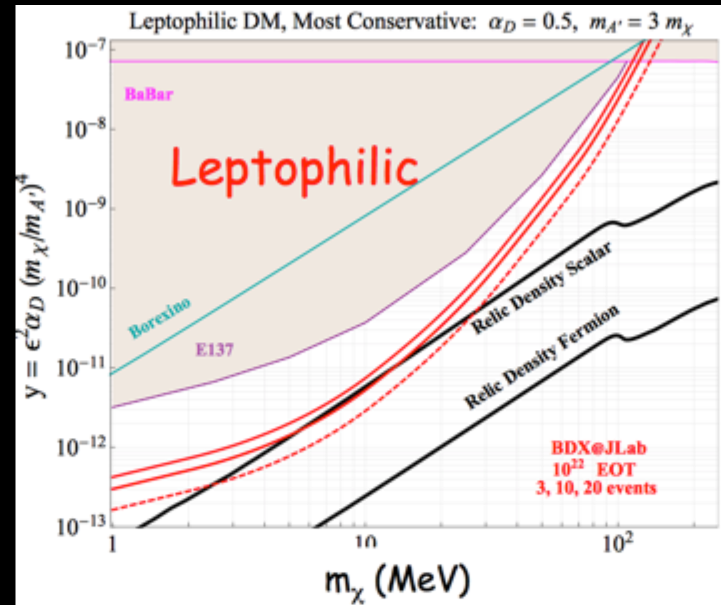


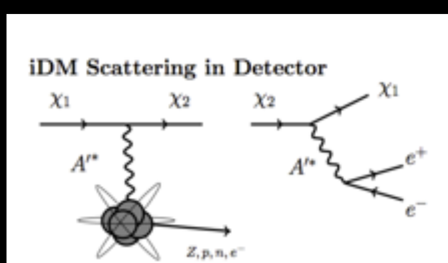
Cosmogenic

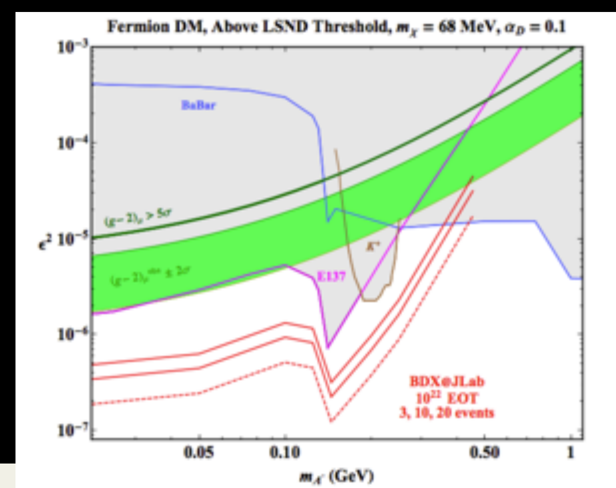


BDX sensitivity





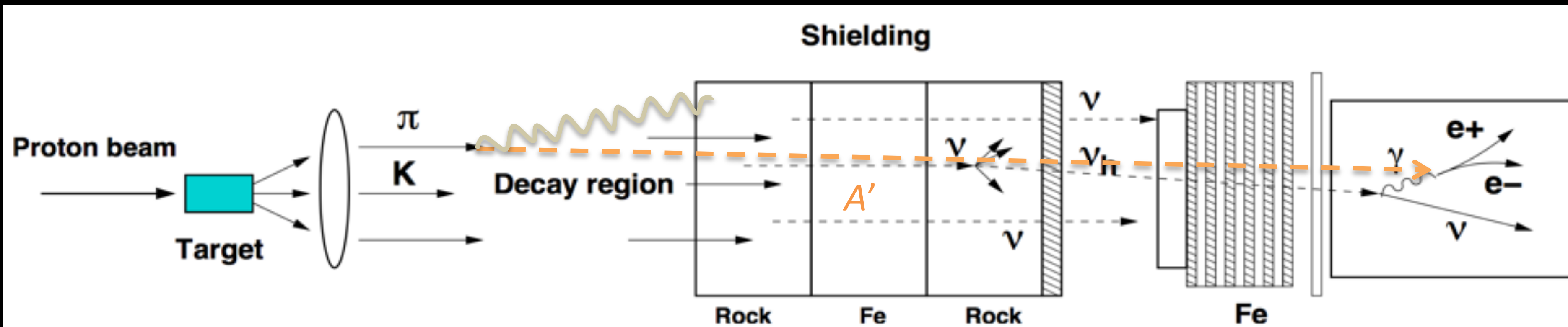


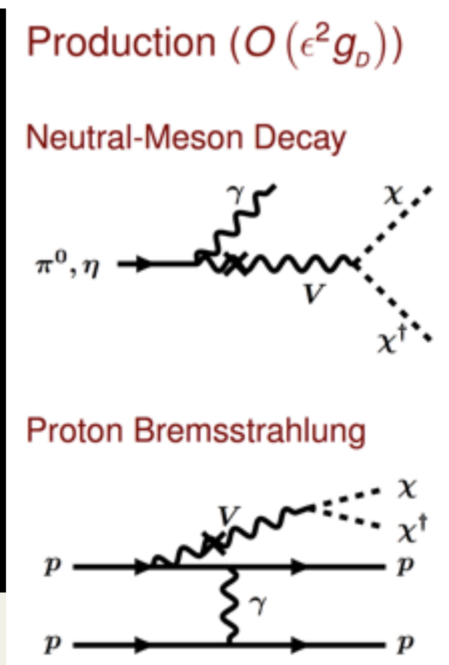


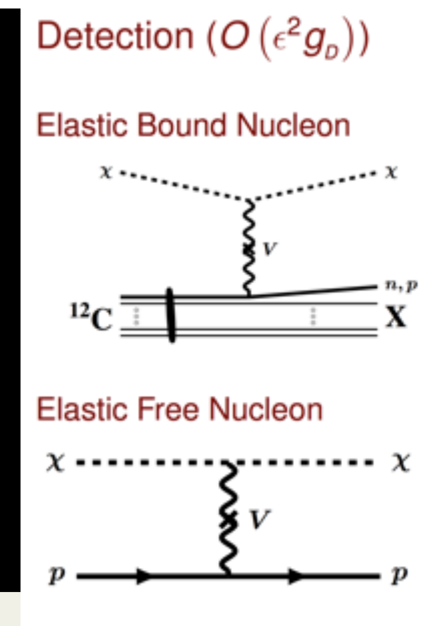
Proton beam dump experiments

Use data of the search of $\nu_H \rightarrow \nu e^+ e^-$ for looking for $P \rightarrow \gamma A'$

Pseudoscalar decaying to spin 0 or ½ particles negligibly small







Limits from past experiments: proton beam dump

NOMAD and PS191 looked for decay of and heavy neutrino $\nu_H \rightarrow \nu e^+ e^-$

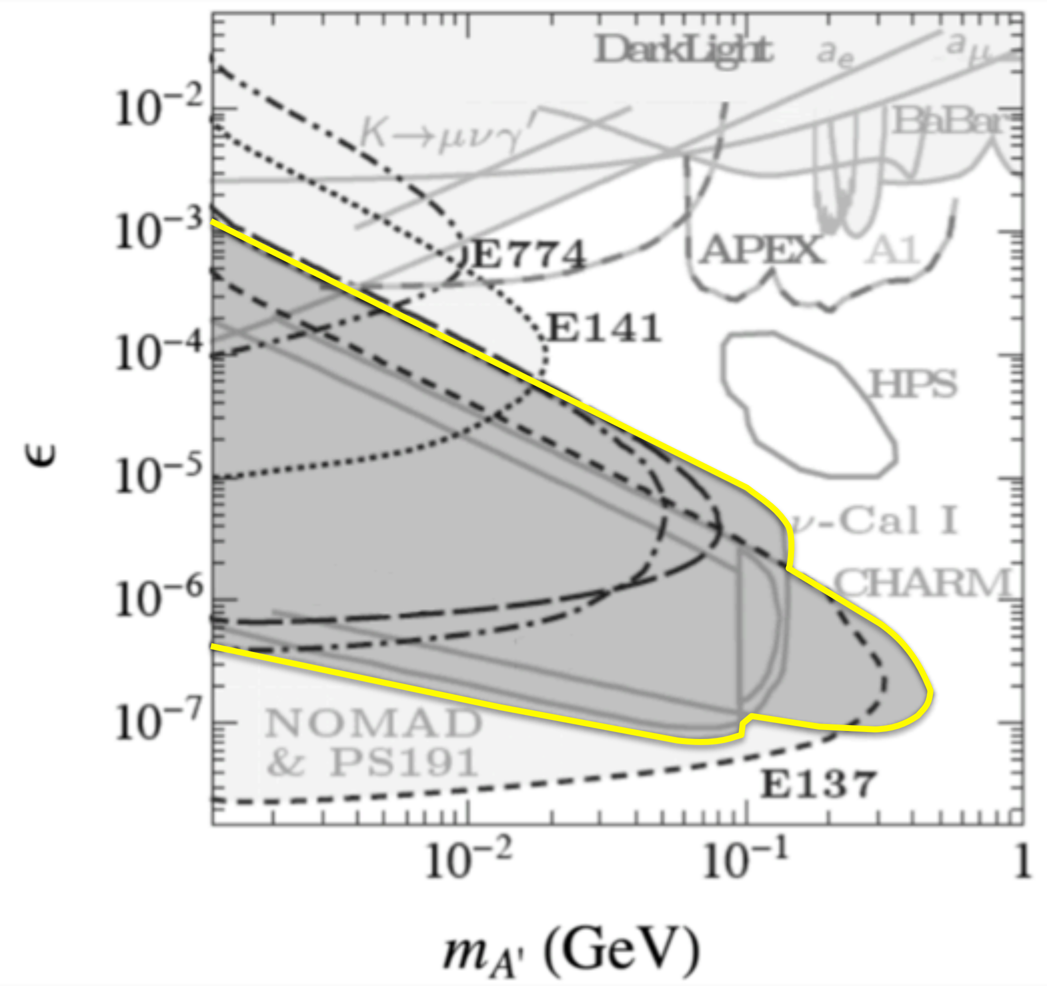
Look for $\pi^0 \rightarrow \gamma A'$

NOMAD: $4.1 \cdot 10^{19}$ POT

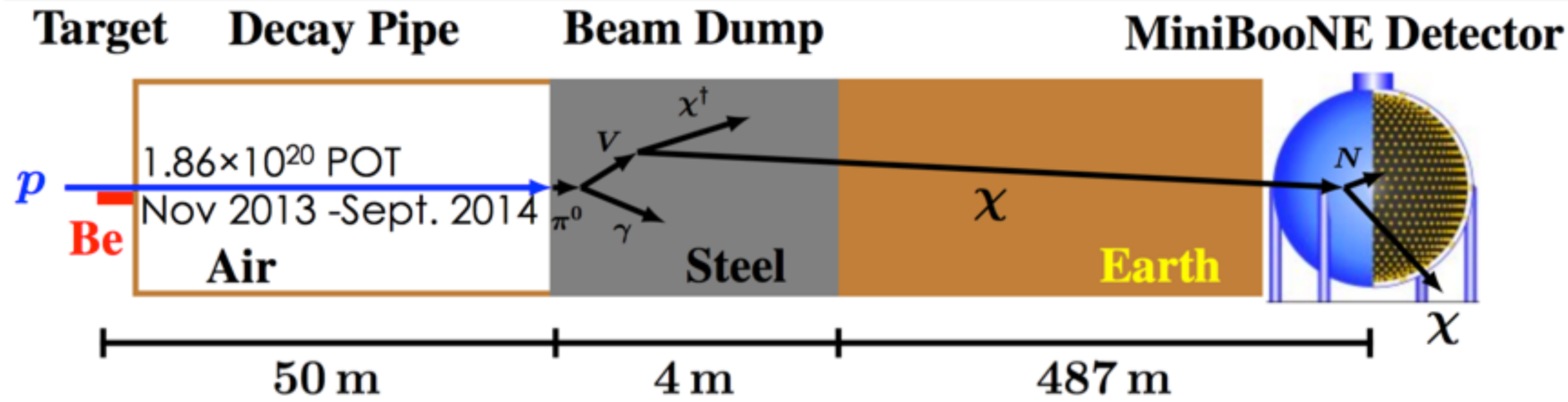
E>4 GeV, m_{ee}<95 MeV

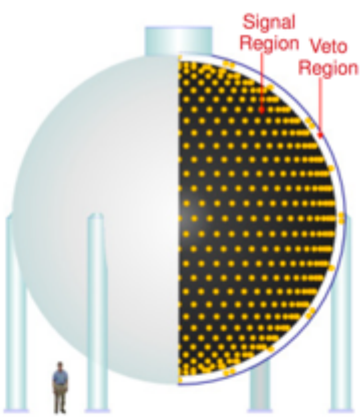
PS191: $0.89 \cdot 10^{19}$ POT

$$Br(\pi^0 \to \gamma A') = 2\epsilon^2 Br(\pi^0 \to \gamma\gamma)\left(1 - \frac{M_{A'}^2}{M_{\pi^0}^2}\right)^3$$

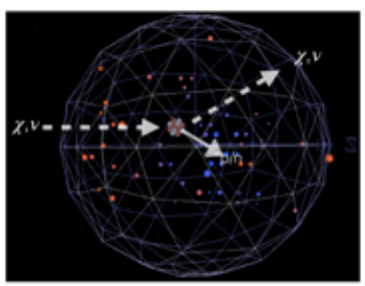


Beam dump: MiniBooNE

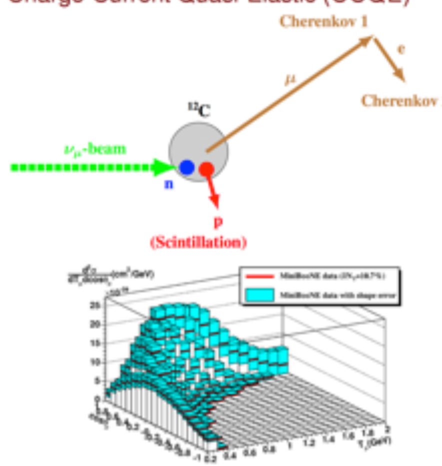




Neutral-Current Nucleon (NCE)

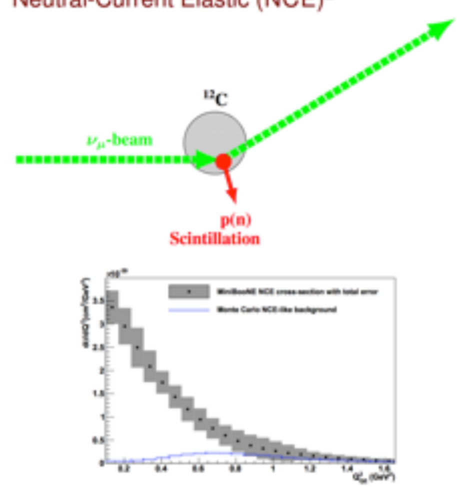


Charge-Current Quasi-Elastic (CCQE)[1]



First ν double-differential CCQE cross section measurement

Neutral-Current Elastic (NCE)[2]

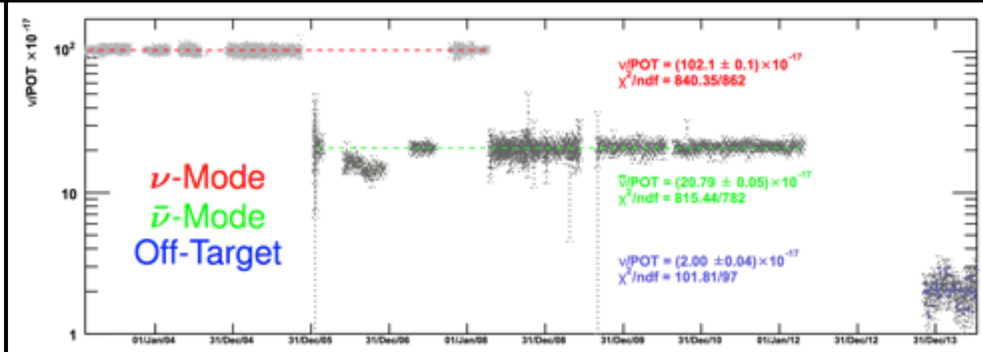


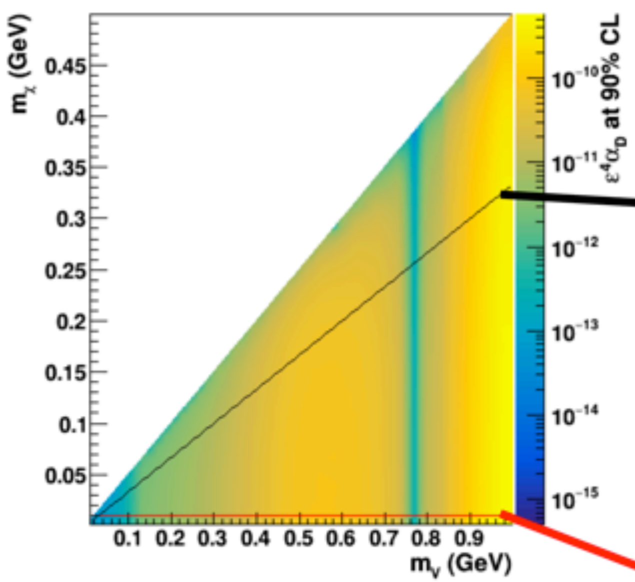
Produced absolute and relative cross sections

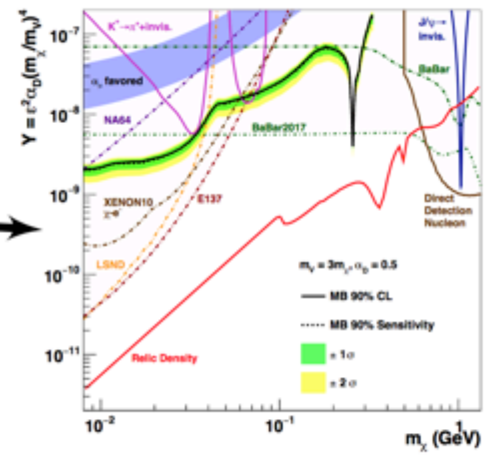
- 800 tons of mineral oil (CH_2)
- Cherenkov tracking detector with scintillator component
- 1280 inner and 240 veto PMTs.
- Ran for a decade in $\nu/\bar{\nu}$ Modes and has obtained/published 27 papers

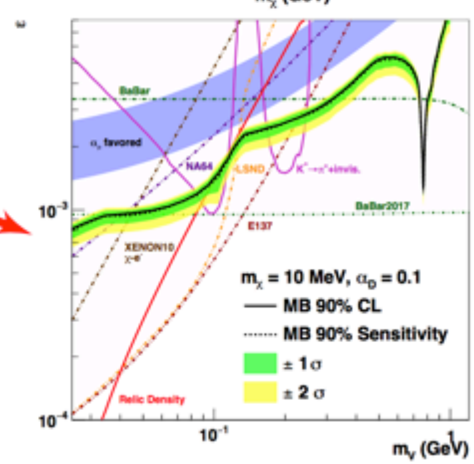
MiniBooNE

- Ran 9 months, Nov 2013 to begining of Sept. 2014, collected 1.86×10^{20} POT
- CCQE ν "event"/POT decreased by $\sim$50 compared to ν-Mode



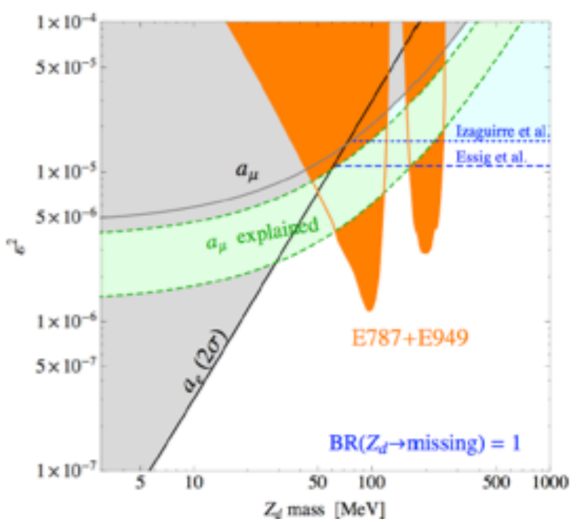




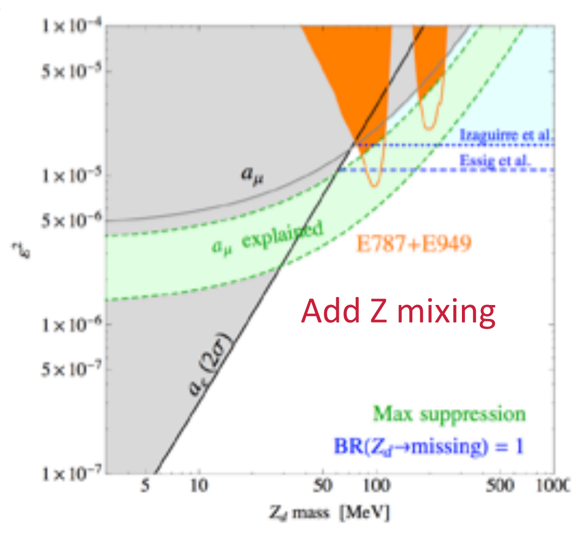


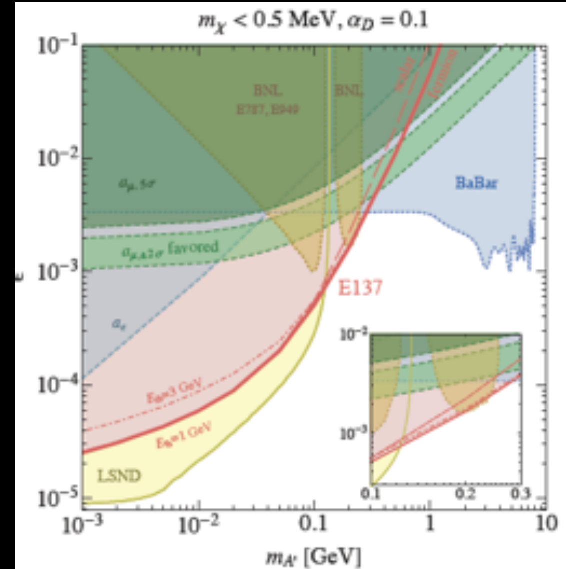
- Only considered on-shell decay ($m_V > 2m_\chi$)
- CL in $\epsilon^4\alpha_D$ for a given m_V, m_χ
- Slice space to compare to other experiments

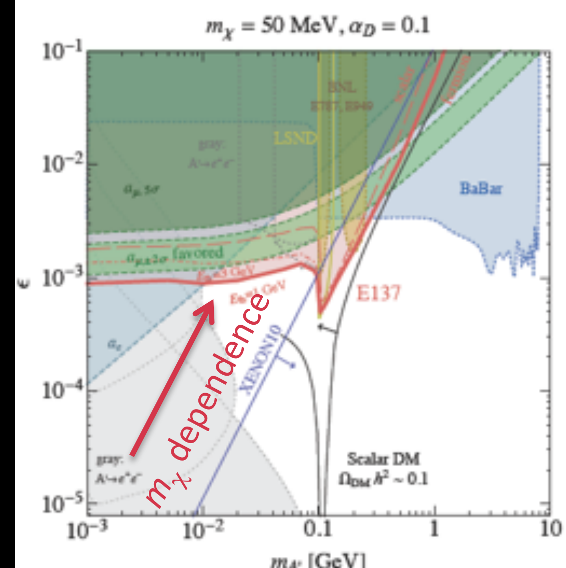
Invisible decays, model dependence of limits



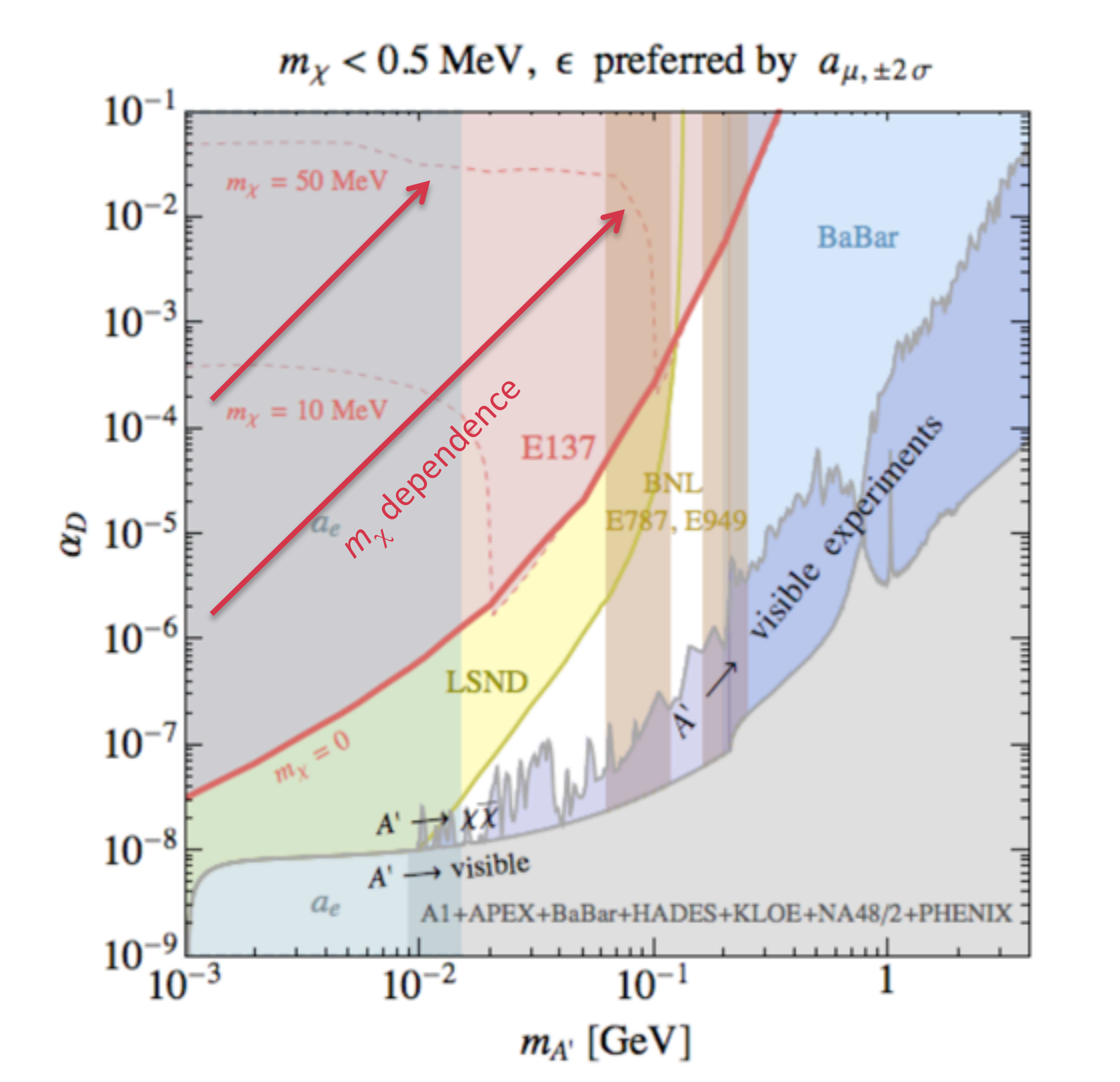
$K^{\pm}\to\pi^{\pm}\nu\nu$ used to constrain $K^{\pm}\to\pi^{\pm}A'$ assuming kinetic mixing and coupling to quarks ≠ 0



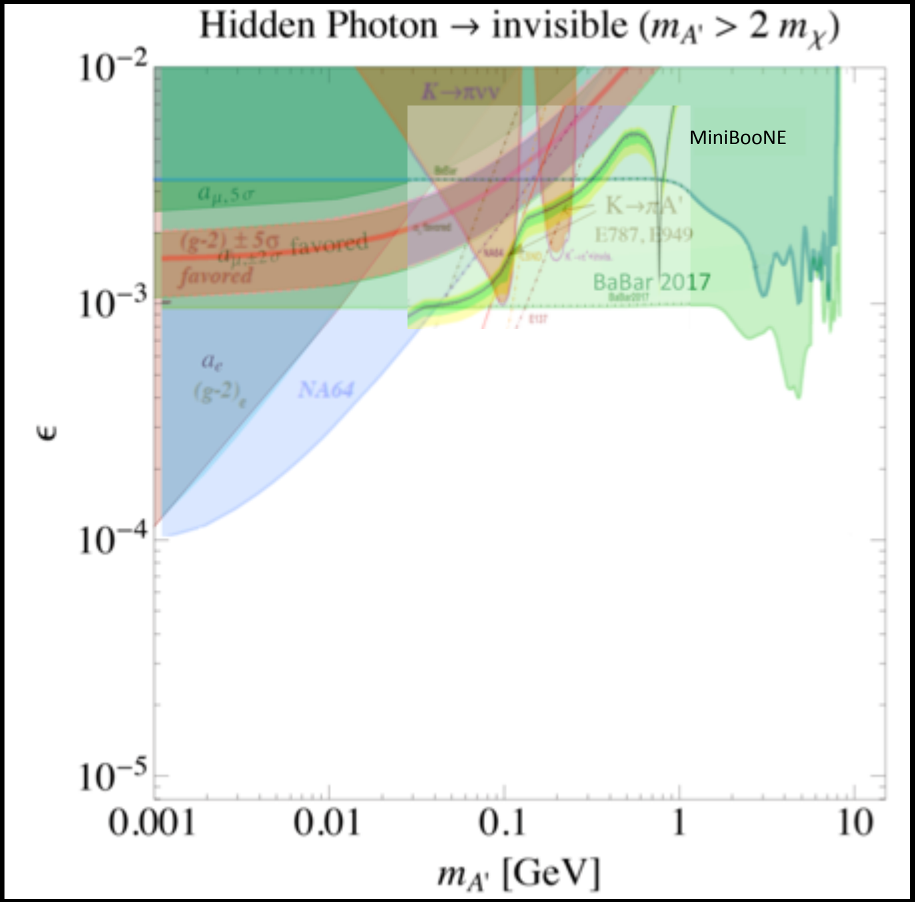




Combine visible and invisible decays



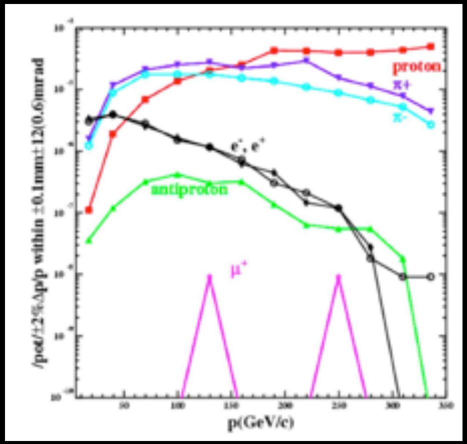
Model independent limits from invisible decays

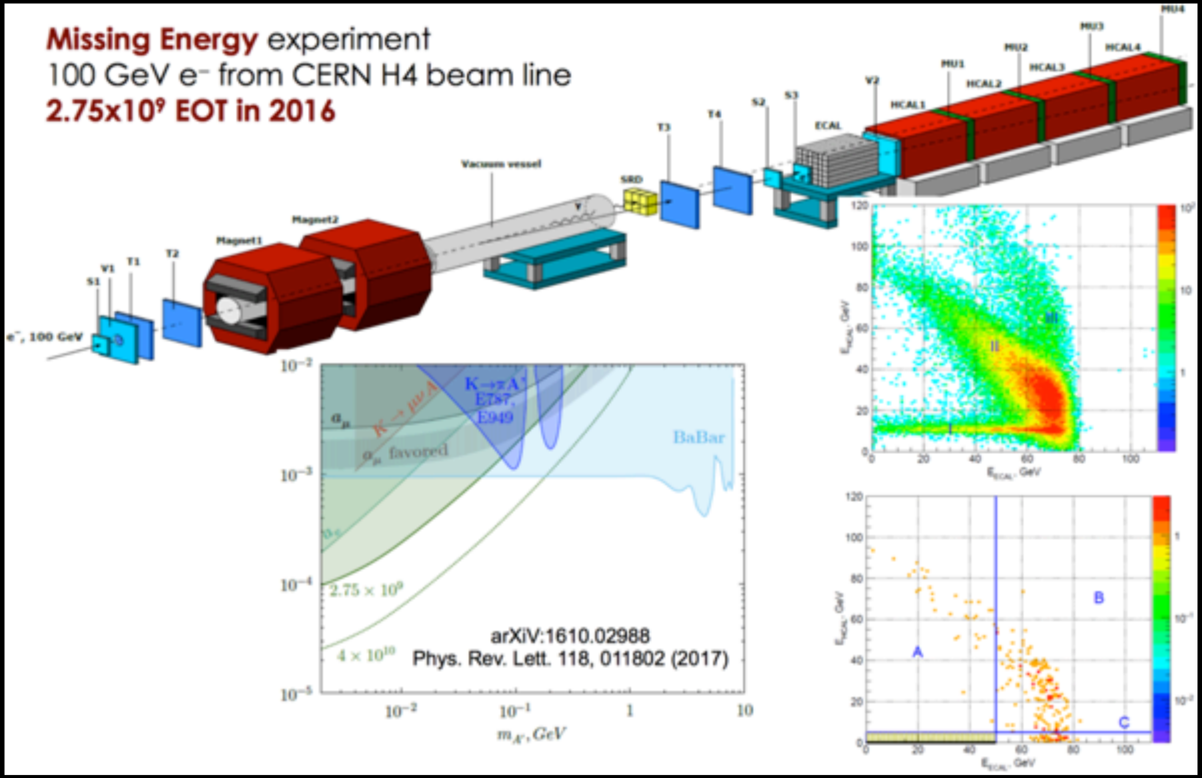


- Direct searches for A' invisible decays only depend on ε^2 and $m_{A'}$
- **No assumptions on coupling to quarks** (Both Υ_{3S} and $K^{\pm}$ results rely on that)
- (g-2)μ favored band excluded
- But still plenty of parameter space unconstrained

NA64 at CERN SPS

H4 high purity electron beam, <1% contamination required
(tertiary, from γ conversions)

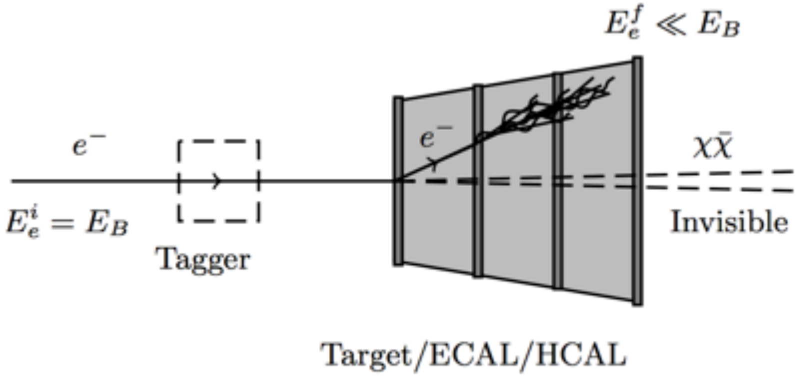


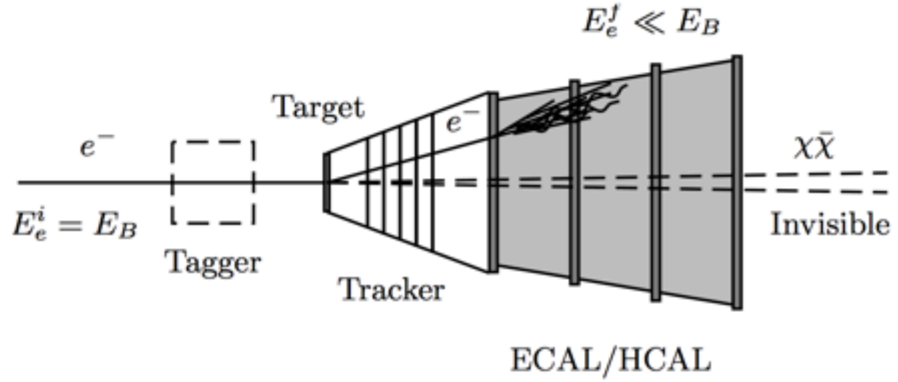


Main backgrounds:

- punch-through of e⁻ or γ
- Non-hermeticity of HCAL
- Low energy tail of e⁻ beam
- e⁻ induced photo-nuclear reactions
- Muon events

Missing momentum vs. missing energy





Missing energy experiments…

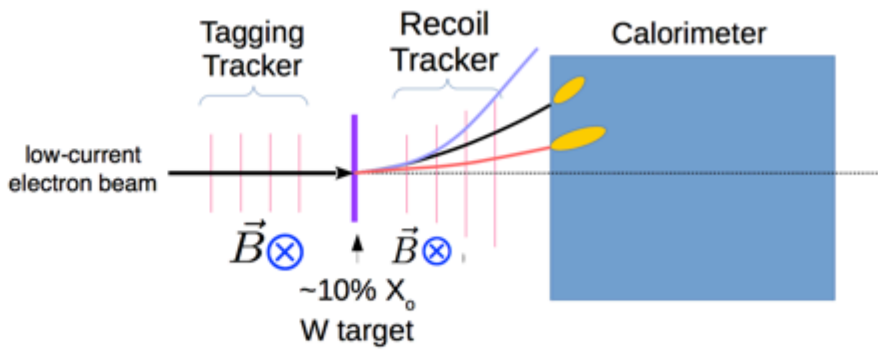
- have higher signal yields/EOT
- have greater acceptance
- *are challenged by backgrounds beyond 10^{14} EOT that require e-γ particle ID*

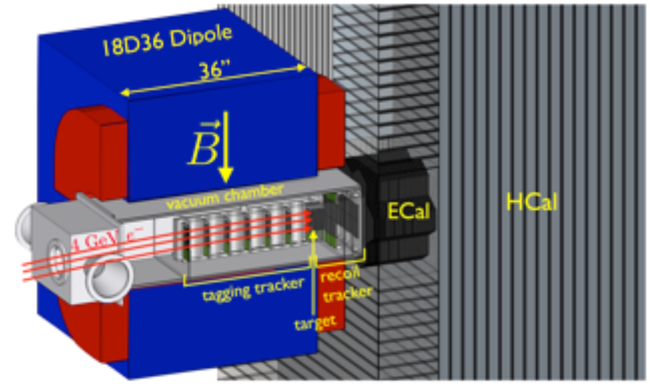
Missing momentum experiments…

- have p_T as a signal discriminator
- have p_T as a signal *identifier*, sensitive to $m_{A'}/m_\chi$
- *are equipped for e-γ particle ID*
- ***include a missing energy experiment***

LDMX can do both

LDMX





Beam that allows individual tagging and reconstruction of 10^{16} incident e^-

- A low-current, multi-GeV, e^- beam with high repetition rate (10^{16}/year ≈ 1 e^-/3 ns). The possibilities are DASEL @ SLAC (4/8 GeV) and CEBAF @ JLab (up to 11 GeV).
- large beamspot (~10 cm²) to spread out otherwise extreme rates and radiation doses

Tracking and calorimetry capable of high rates and radiation tolerance

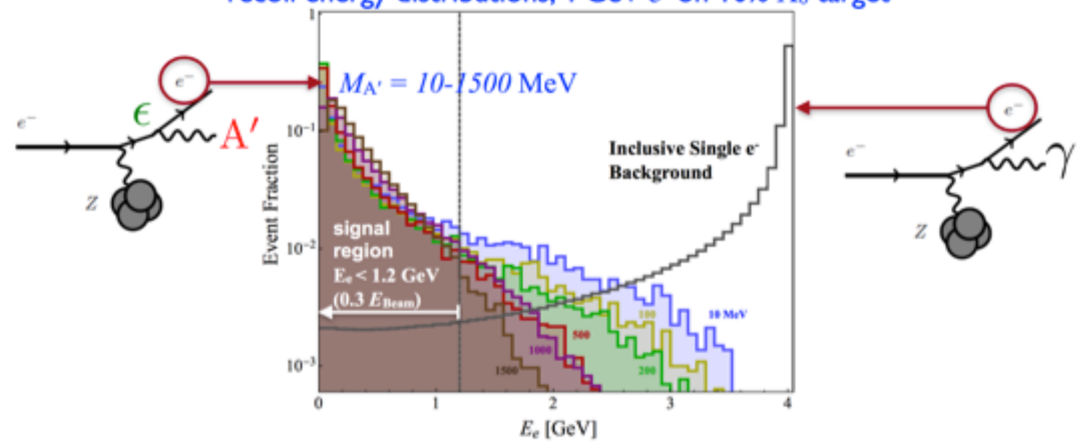
- requirements for 10^{16} experiment close to limits of available technologies

➡ Two-stage approach to LDMX: 4×10^{14} "Phase I" followed by 10^{16} "Phase II"

~1 e^- / 25 ns @ 4 GeV $\mathcal{O}$(1 e^-/ns) , ≳8 GeV

LDMX background rejection

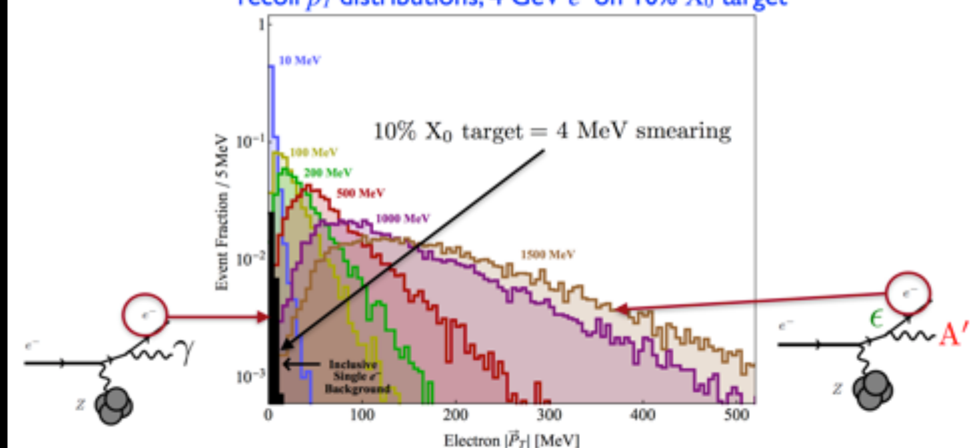
recoil energy distributions, 4 GeV e^- on 10% X_0 target



Recoil kinematics allow efficient signal definition providing ~30× background rejection

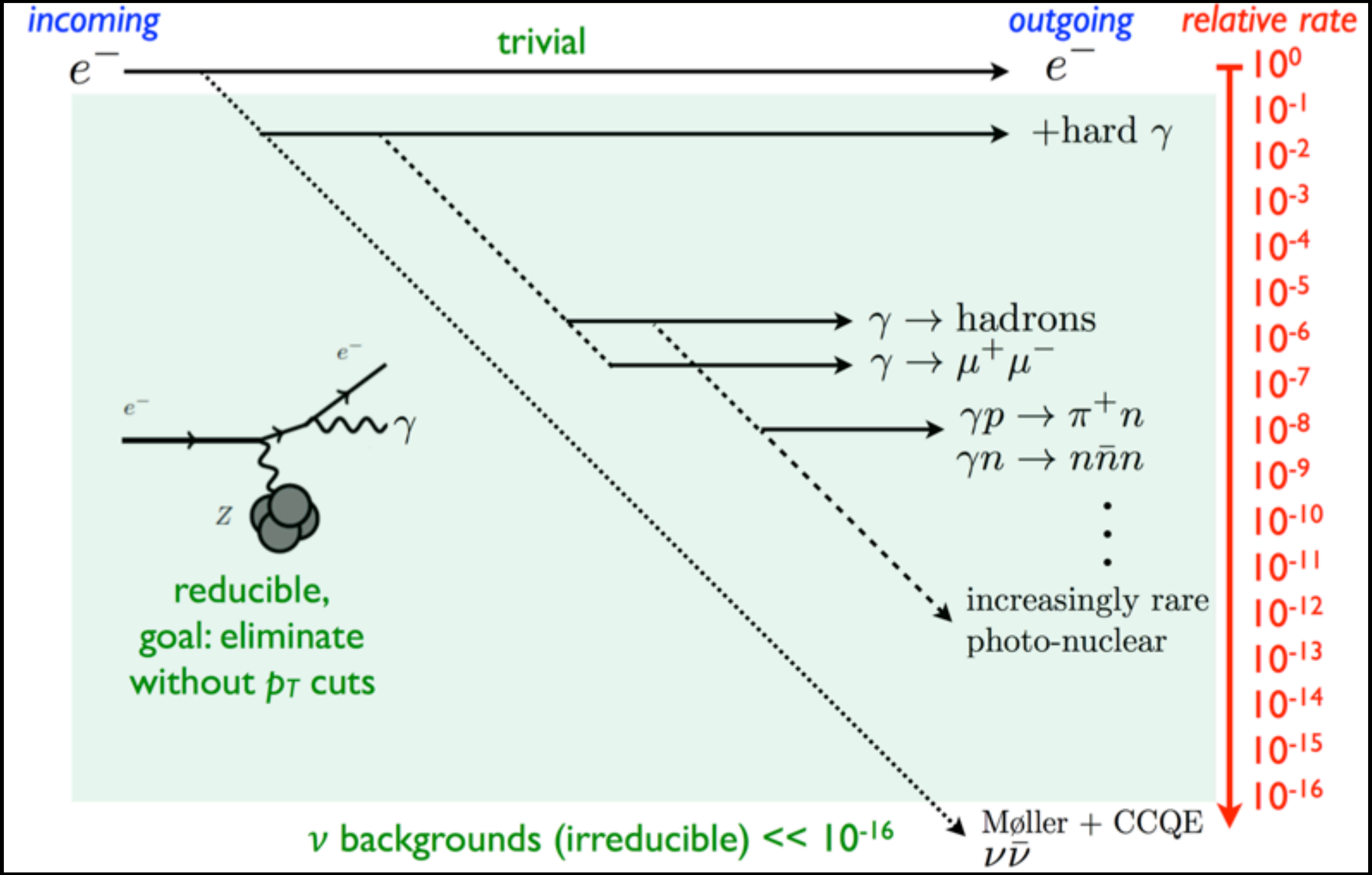
- *Tagging tracker:* track with $|p| = E_{beam}$ on expected trajectory
- *Recoil tracker:* single track, with $|p| < 0.3\ E_{beam}$, that points back to tag in target
- *Calorimeters:* shower consistent with recoil track and no other activity

recoil p_T distributions, 4 GeV e^- on 10% X_0 target



Goal: achieve zero background without using p_T as a signal discriminator

A challenge also for simulation



Tim Nelson

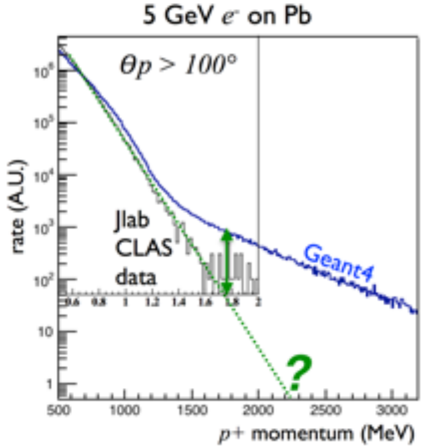
Simulating Rare Photonuclear Events in Geant4

LDMX

Geant4 produces surprising number of events with enormous momentum transfer to recoiling nucleus.

- With high energy secondaries emitted at large angles, these are very difficult events to veto.
- Geant4 is not tuned to data in this regime, which is sparse in the literature.
- Energy/angle spectra from data provide evidence for a universal exponential fall-off, suggesting that Geant4 rates in this regime are overestimated by orders of magnitude.

*The validity of **all** simulations is questionable, so we are working to identify data we can use as a reference point to tune the MC and validate our photonuclear rejection performance.*

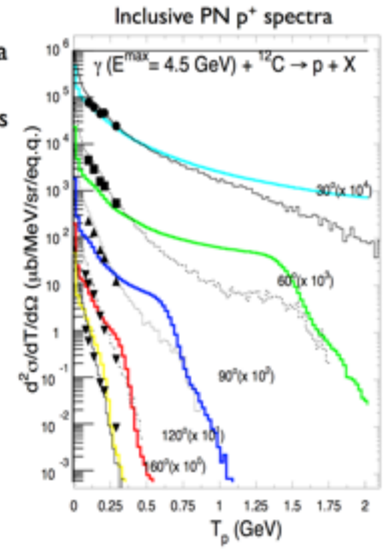


Bertini cascade model in Geant4 (colored lines at right) not tuned to data

Los Alamos code (LAQGSM) (black lines at right) is dedicated photonuclear simulation, tuned to data.

Data for high-energy photonuclear secondaries is sparse to nonexistent, especially at large angles.

*The validity of **all** simulations is questionable: talking to JLab colleagues to identify possibly useful datasets.*



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Muon Conversion Backgrounds in Geant4

LDMX

Can occur in target, recoil tracker or ECal.

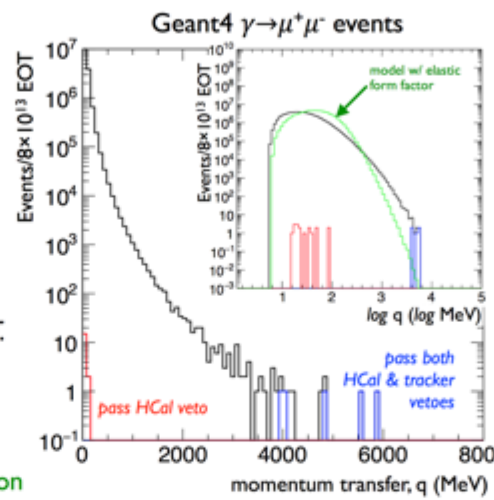
Multiple handles available for veto:

- recoil tracker (for $\gamma\rightarrow\mu^+\mu^-$ in target & recoil tracker)
- ECal
- HCal

An initial veto using only tracker and HCal eliminates all but a few events where both muons are emitted at ≥90° for ~10^{14} EOT.

Geant4 also grossly overestimates rate of $\gamma\rightarrow\mu^+\mu^-$ events with extremely high q^2.

We expect to eliminate muon conversion backgrounds without using p_T.



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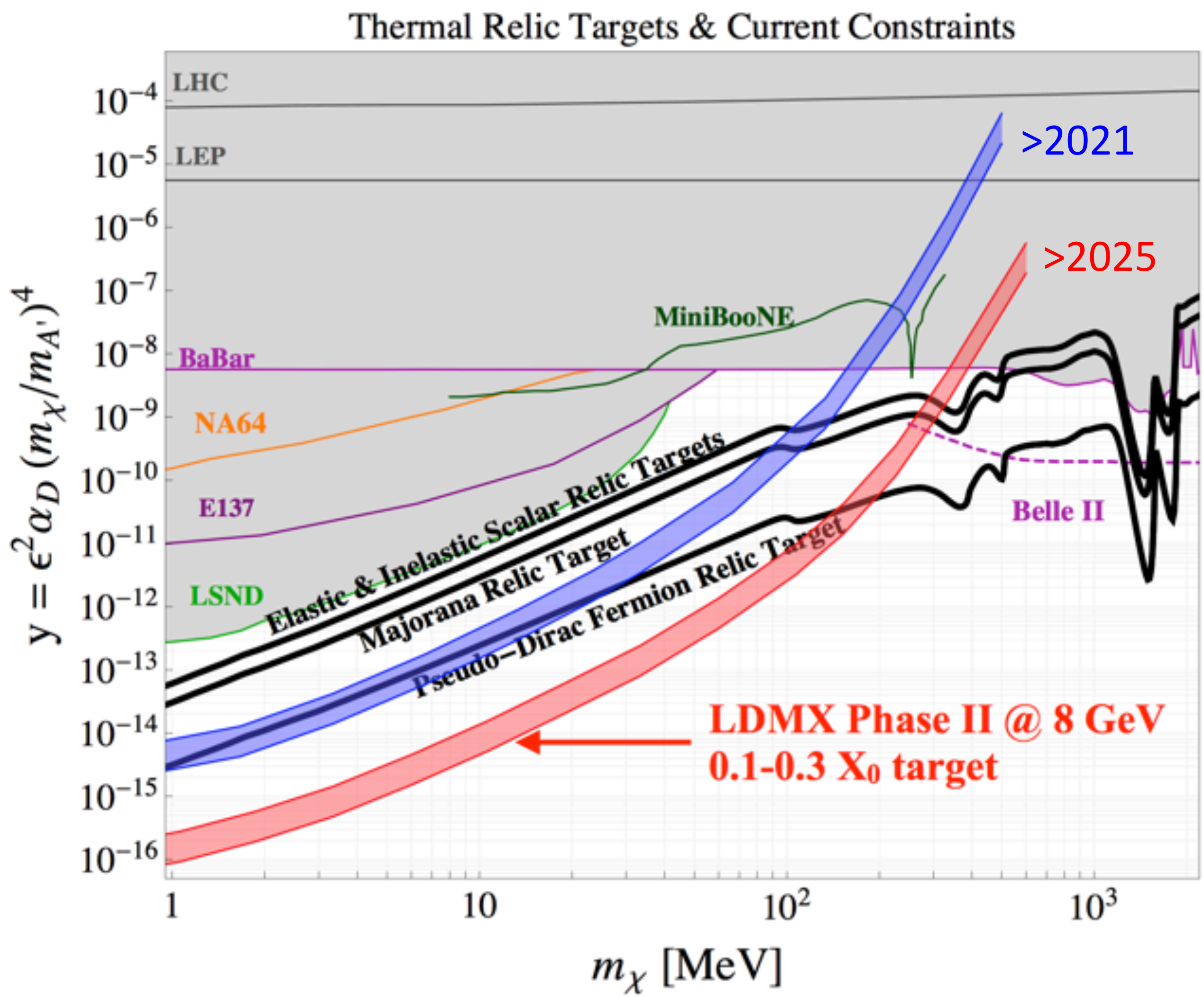
LDMX sensitivity

Phase II
may require faster and more granular detectors, more sophisticated trigger

Higher beam energy (e.g. 8 GeV DASEL) would mitigate the most difficult backgrounds.



The missing mass approach

- No assumption on the *A'* decays products and coupling to quarks
- Only minimal assumption: *A'* bosons couples to leptons
- Limits the coupling of **any new light particle** produced in e^+e^- collision (scalars (H_d), vectors (*A'* and Z_d)

Just detect one photon + missing energy:
$e^+ e^- \rightarrow \gamma$ + nothing

In order to compute $M^2_{miss} = (\underline{P}_{\gamma} - \underline{P}_{e+})^2$ we need:

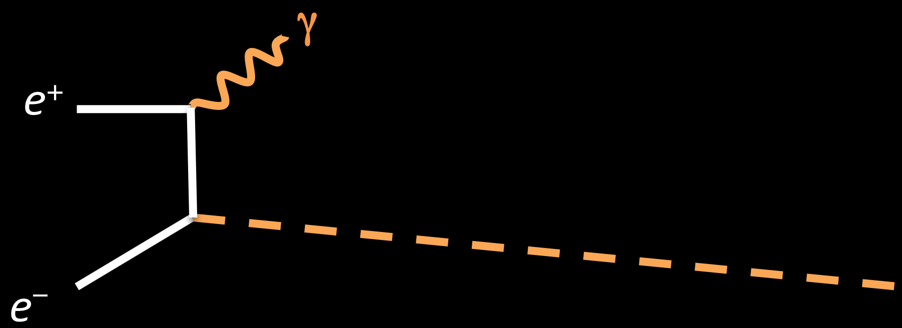
a) A **positron** beam with a well defined four-momentum
   1. Small energy and angular spread
   2. Small transverse spot

      1+2 = small emittance

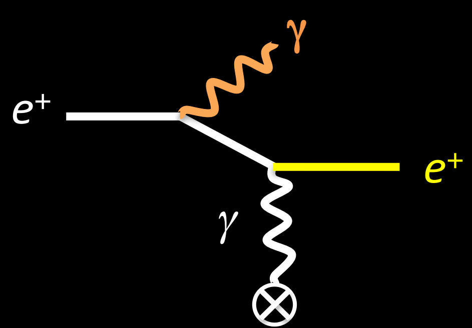
   3. Tunable intensity (in order to optimize annihilation vs. Bremsstrahlung)

b) Measure precisely the photon (tri-)momentum (angle and energy)

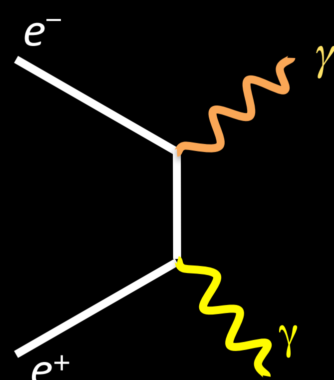
Backgrounds



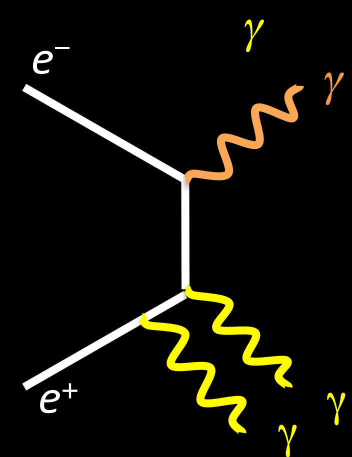
We need to fight the backgrounds
i.e. one photon + something else, eventually going undetected:



+1 electron
Bremsstrahlung process, $\approx Z^2$



+1 γ
$\gamma\gamma$ process, $\approx Z$



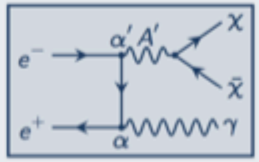
+2 γ
3γ process

BaBar single photon events

Analysis strategy

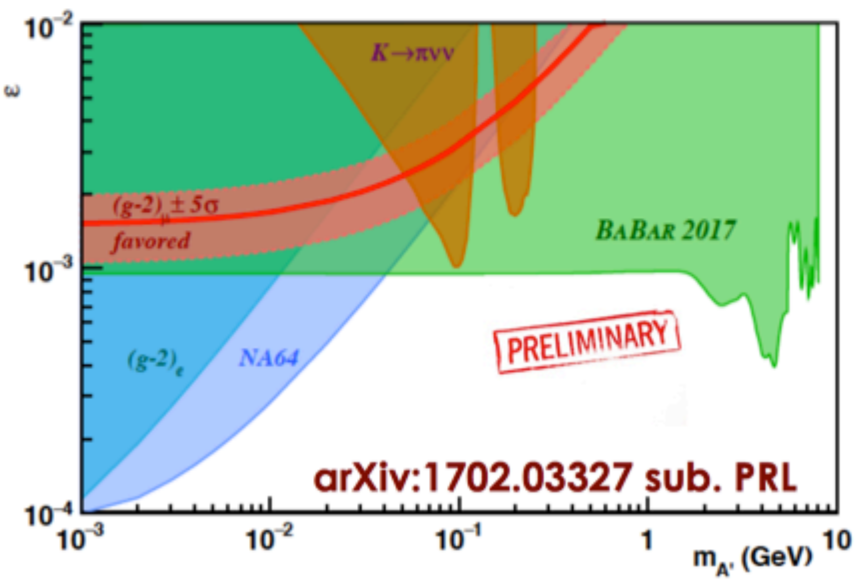
search for

- $e^- e^+ \to \gamma A'$, $A' \to$ invisible (e.g. $\chi\bar{\chi}$)
  i.e. one single photon and nothing else



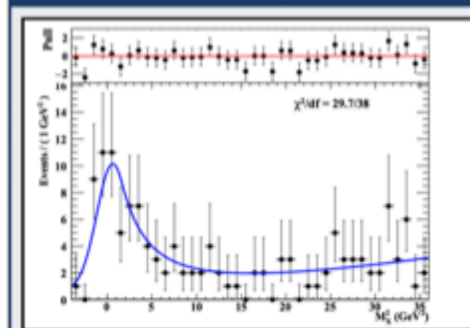
$\sigma \propto \alpha'\alpha = \epsilon^2\alpha^2$

- reconstruct A' mass, $M^2_{A'} = s - 2\sqrt{s}E^*_\gamma$
- scan $M^2_{A'}$ distribution, fitting bumps over smooth background, compute significance
  [A' decay width $\Gamma_{A'}$ expected $\ll$ experimental resolution on $M_{A'}$]

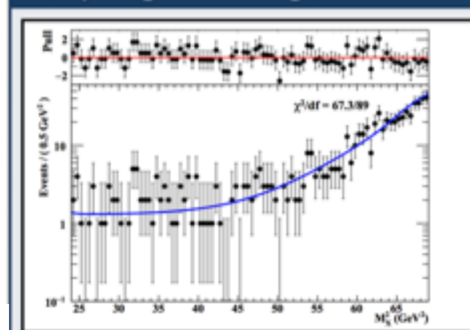


BABAR collected **~53 fb^{-1}** of data with dedicated single γ triggers **Y(3S)** and **Y(2S)** peaks Hard. trigger ≥1 EMC cluster with **E_{LAB} > 800 MeV**

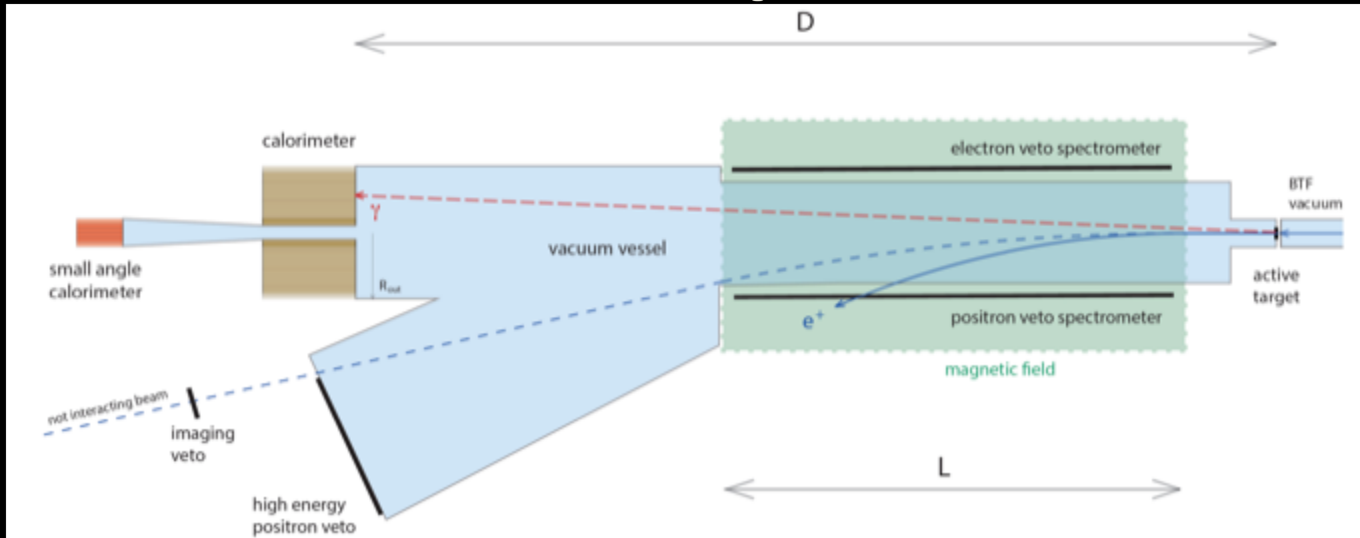
Example low-mass background fit



Example high-mass background fit



The PADME experiment



- 10^3-10^4 e^+ on target per bunch, at 50 bunches/s (10^{13}-10^{14} e^+/year), limited by pile-up, mainly due to Bremsstrahlung events
- Active target, **thin**: e.g. 50-100μm diamond with strips
  - Optimize by looking at **annihilation vs. Bremsstrahlung** cross section
- Magnetic spectrometer/veto ~ 1m length × 0.5 T for sweeping away 550 MeV beam
  - Conventional magnet with **large gap** for gaining **acceptance**
  - Possibility to increase field for energy upgrade to ~ 1 GeV
  - Available from CERN, spare of MBP dipoles of SPS transfer line
- Cylindrical crystal calorimeter
  - Optimize radius vs. distance by looking at **background rejection vs. acceptance**
  - In order to have an acceptable rate, central hole and
- Small angle detector for Bremsstrahlung veto
- Vacuum pipe

First task, measure the recoil photon

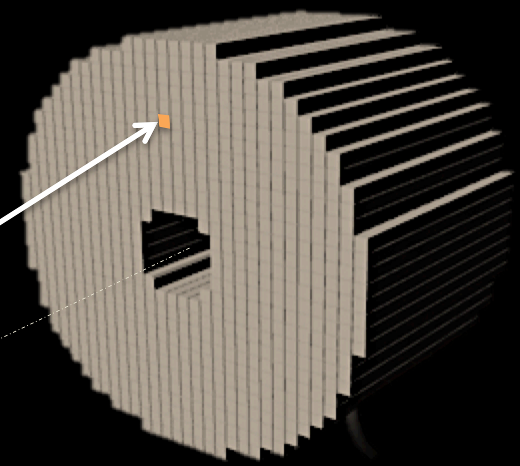
Our main detector is of course a calorimeter, with two basic requirements:

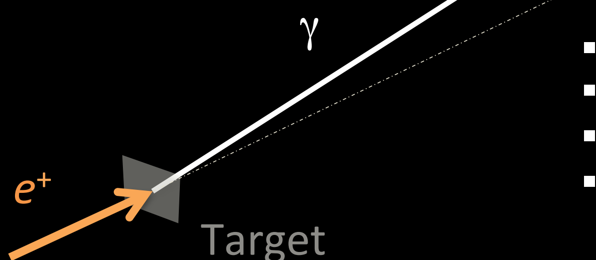
1. Measure E_γ, θ_γ

- Good energy resolution: 1-2%/√E[GeV])
  - High Photo-statistics
  - Containment
- Good angular resolution: ≈1 mrad

2. Fight pile-up

- Sub-ns timing resolution





- The **material** choice fixes **light yield** & **time resolution**, **Moliére radius** & $\boldsymbol{X_0}$
- The **Moliére radius** determines **granularity**
- The **granularity** + required a**ngular resolution**, set the **distance** from the target
- Given the **distance**, the lateral **size** fixes the **angular coverage** (i.e. acceptance)

But…

…we have to take into account two important constraints:

- The **overall size** of the experiment is the hall length (<5 m)
- Another important bound is the **cost**, which is driven by the **material**, **size** and **granularity** (i.e. the number of channels)

So the message is "**keep it compact!**"

The calorimeter

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s	300^s	1.50	36^s	no	-1.9^s
							0.9^f	220^f		4.1^f		0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s	420^s	1.95	3.6^s	slight	−1.4
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

LYSO(Ce): high LY, high ρ, small X_0 and small R_M, short τ_{decay}

- Performance:
  - $\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$

BGO: high LY, high ρ, small X_0 and small R_M, long τ_{decay}

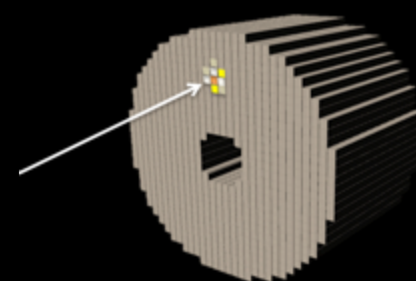
- Resolution also in 1-2%/√E range

Small Moliére radius and high light yield:
LYSO and **BGO**

- **Granularity ≈R_M** → 2 cm
- a=2 cm → **point resolution**: 2 cm/√12=6 mm
- σ_{point}=6 mm → 1 mrad at 6 m **distance** → too much!

But...
...we have **clusters**!

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



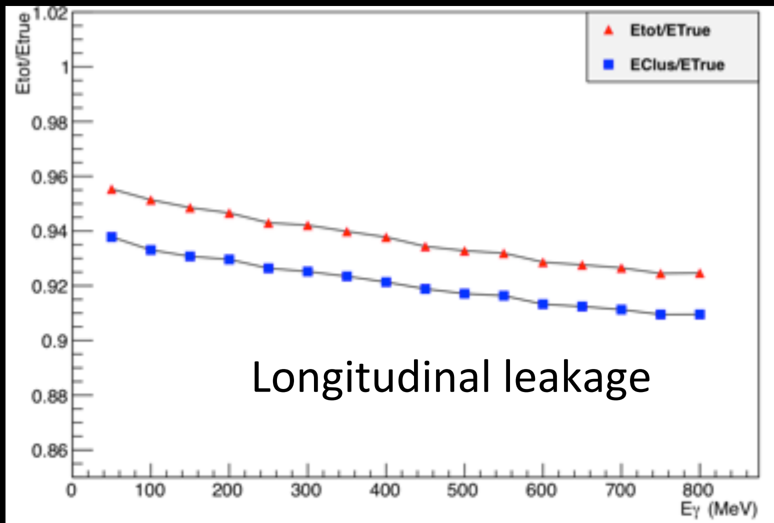
2 cm crystals		
d	$\langle d_{exp} - d\rangle$	RMS
0.0	0.00	0.18
-0.2	0.13	0.18
-0.4	0.24	0.20
-0.6	0.33	0.24
-0.8	0.33	0.29
-1.0	0.10	0.40

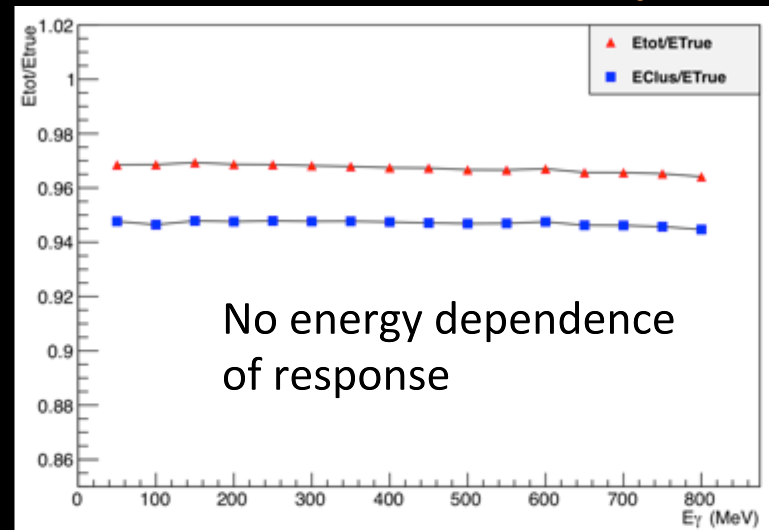
Results with a Geant4 "photon gun", E=500 MeV
$\sigma_{cluster}$≈4.5 mm (including the systematic shift), better than 6 mm

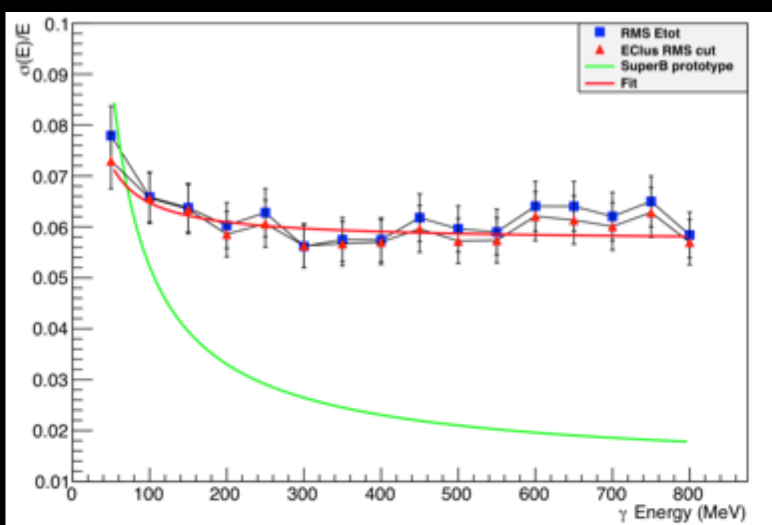
Longitudinal containment

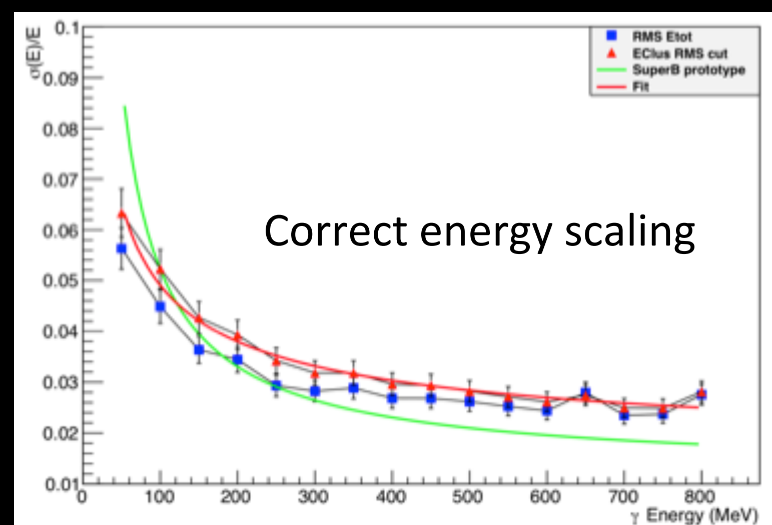
15 cm long crystals (13.2 X_0)

20 cm long crystals (17.5 X_0)

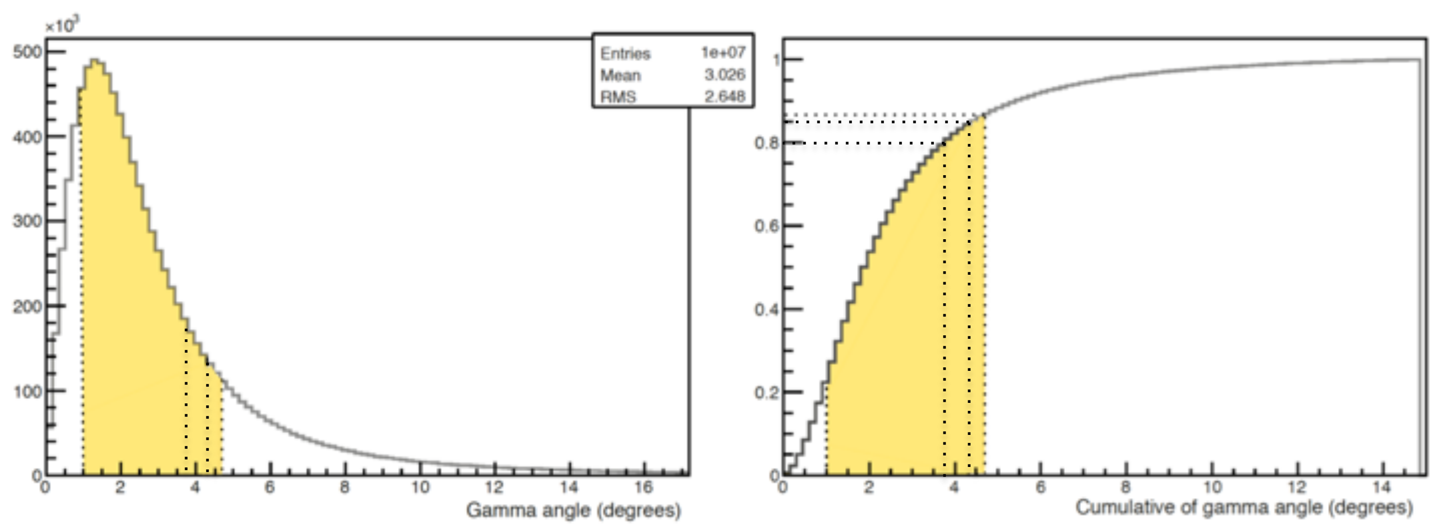








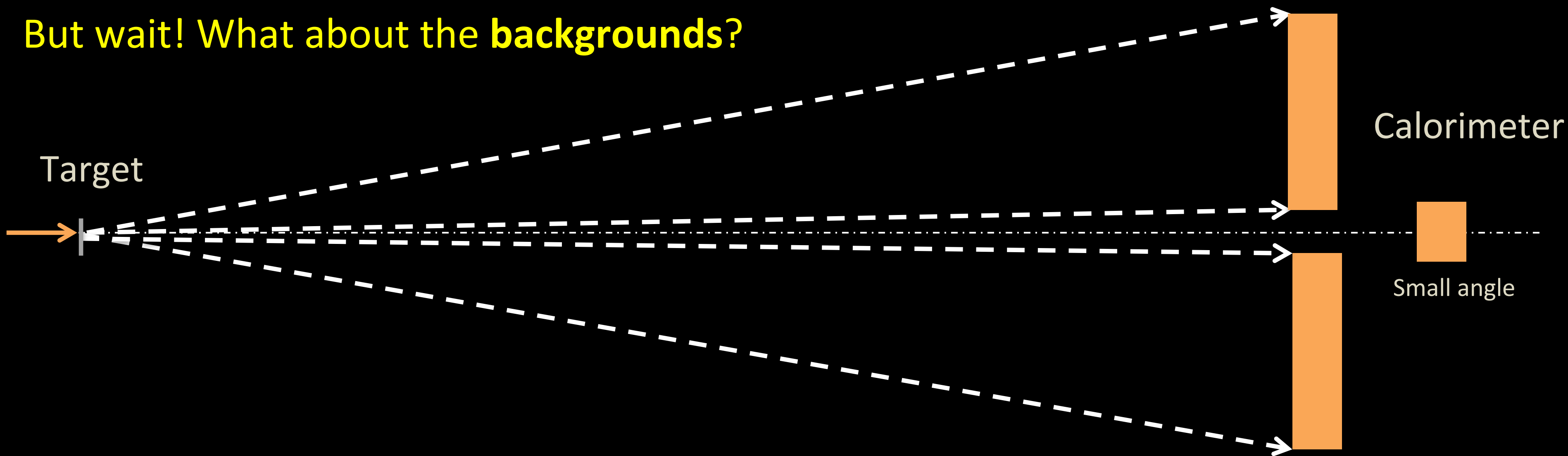
Signal acceptance in calorimeter



Calorimeter hole:
20 mrad

θ_{max}=65, 75, 83 mrad from 58% to 65% acceptance

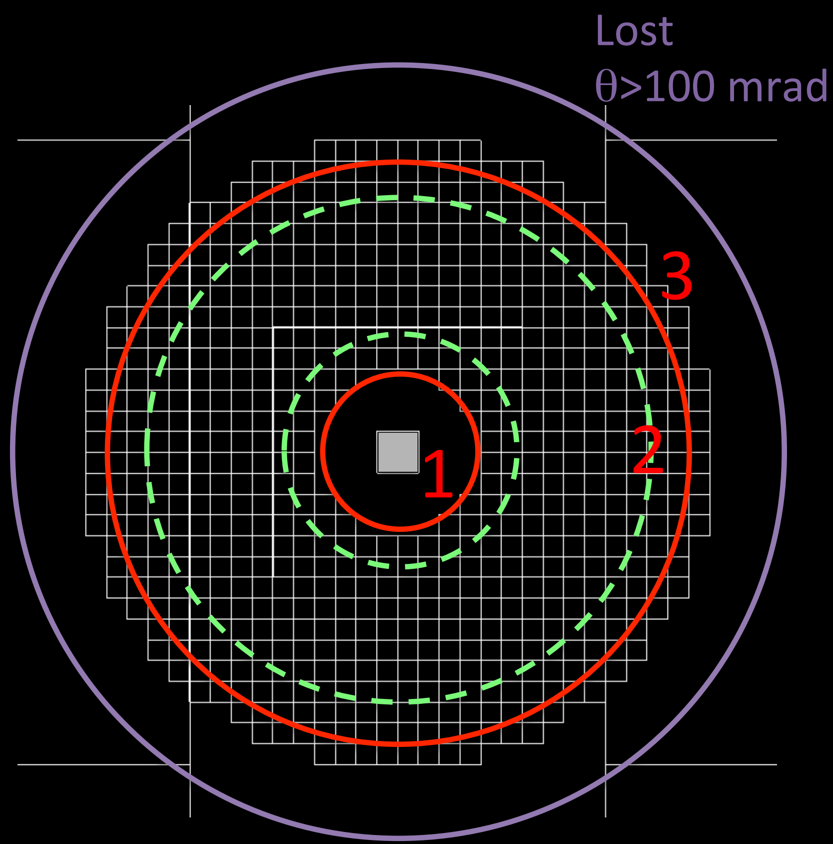
But wait! What about the **backgrounds**?



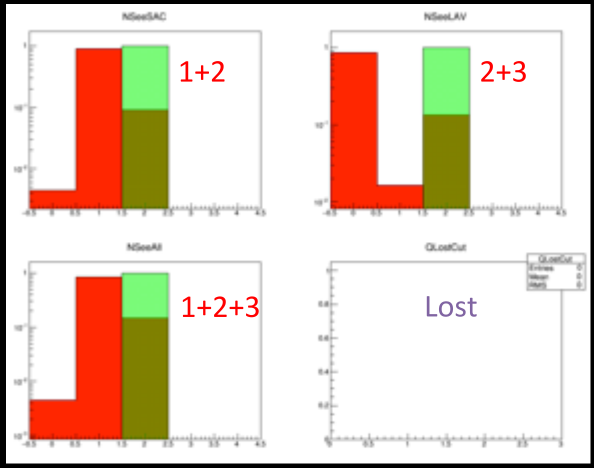
Calorimeter 2γ and 3γ backgrounds

Region 1
<20 mrad

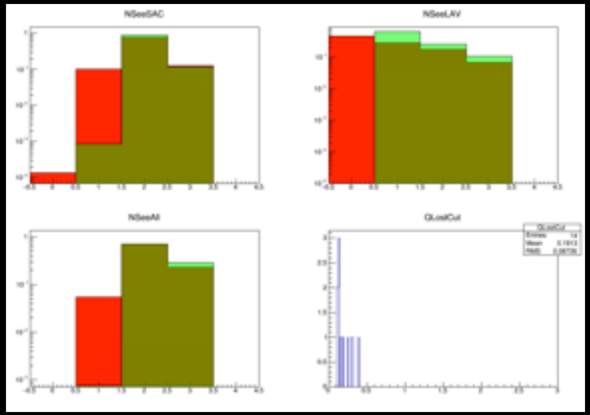
Region 3
θ>75 mrad



Recoil γ definition:
10 MeV < E < 400 MeV
30 mrad < θ < 65 mrad



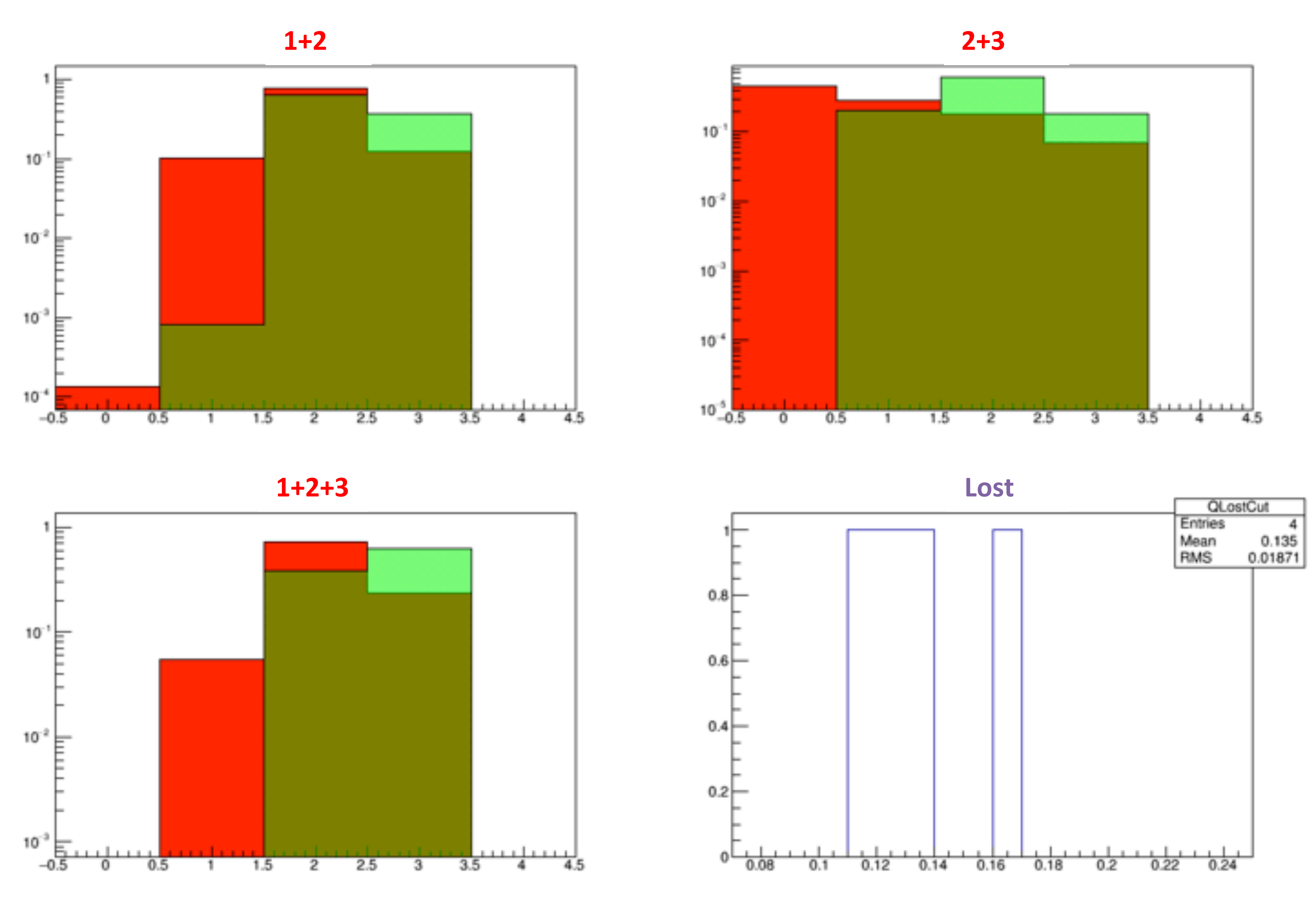
No 2γ events



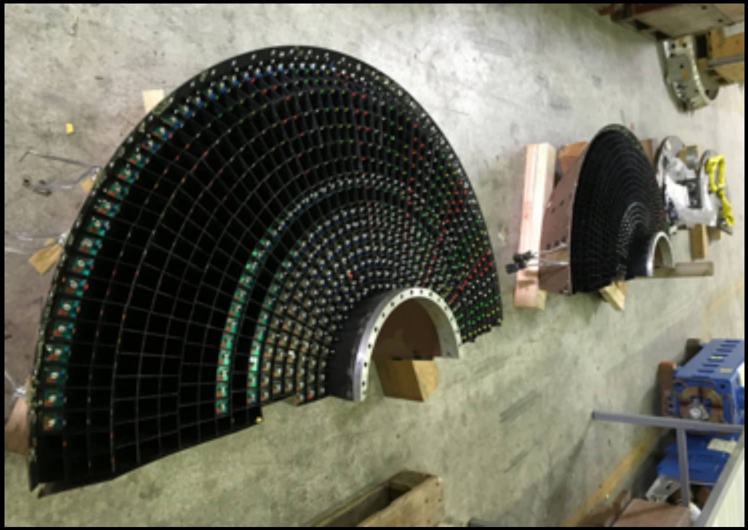
Per-mil 3γ background

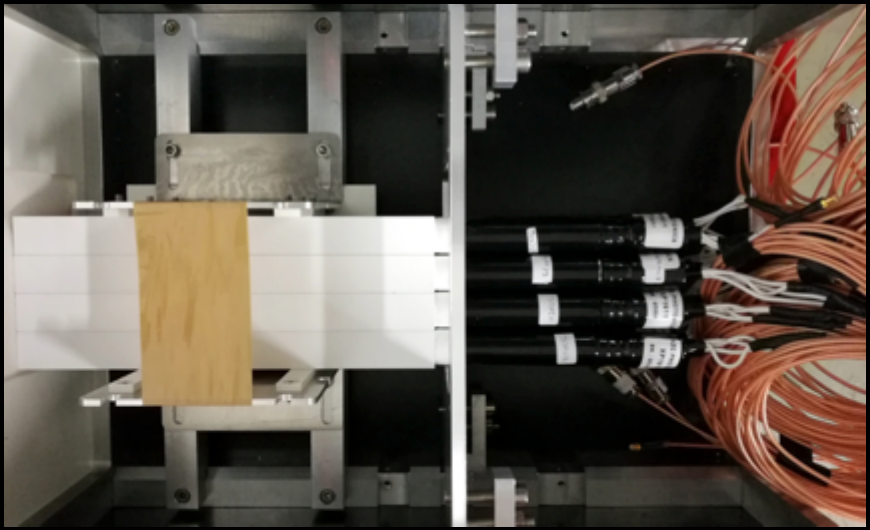
Residual background

Tighter signal definition: in fiducial region **and** 150 MeV < E < 450 MeV



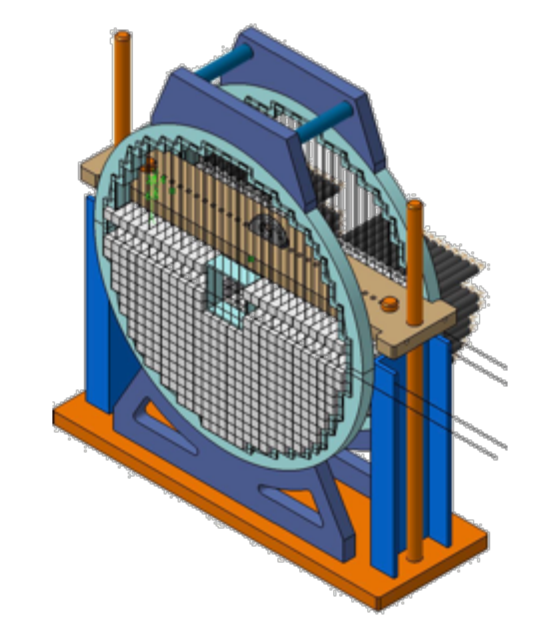
L3 BGO crystals



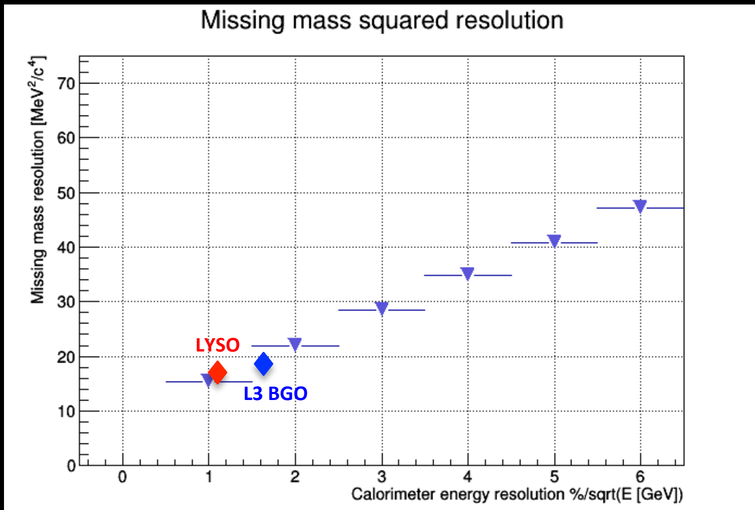


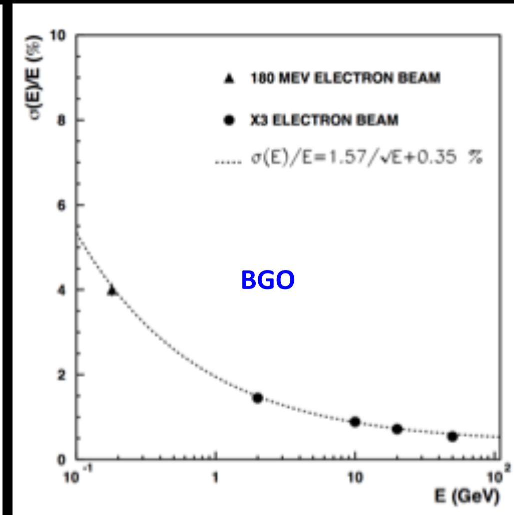
- 700 BGO crystals from former L3 electromagnetic calorimeter
- Cut from trapezoidal prism shape to square section **21×21 mm^2**, **220 mm** long

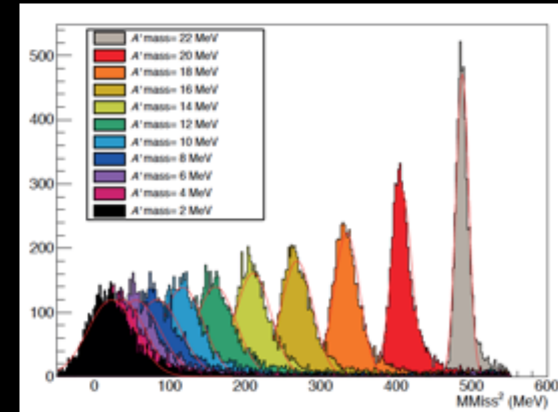
Mounting and support structure



Missing mass resolution

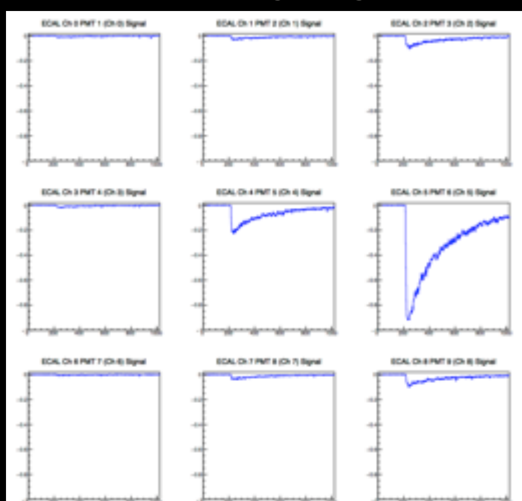




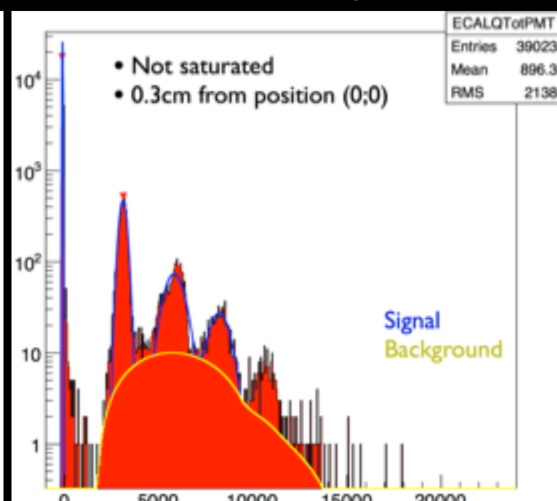


M_{miss} resolution is the result of combination of angular resolution, energy resolution and angle-energy correlation due to production

τ=300 ns light signal



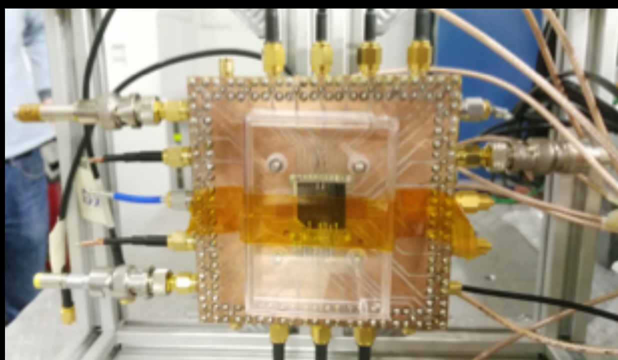
3×3 matrix total charge (150 MeV)

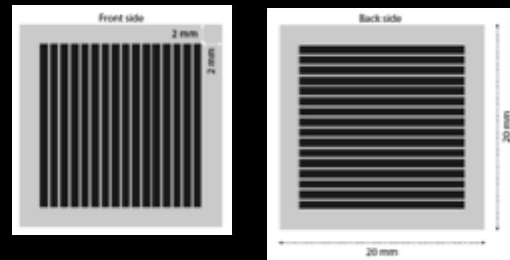


Aim at 1 MeV threshold:
^{22}Na 511 keV calibration

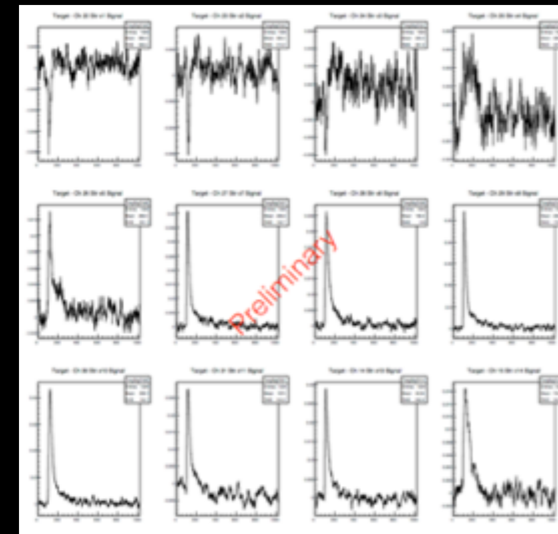
The diamond target

- Given the number of positrons, 50-100 μm of Carbon
- Given the beam spot size and shape, at least cm² area
- 20×20 mm², 50 μm detector tested on beam

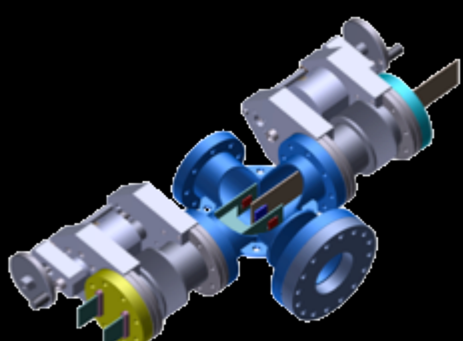


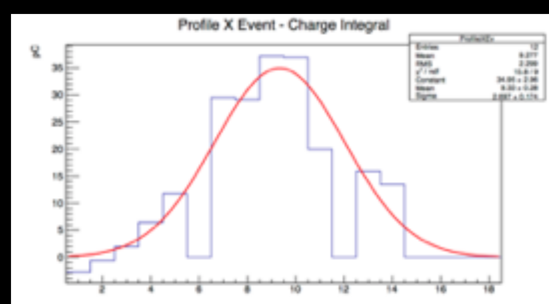


- 16 strips per side, 1 mm pitch is the baseline design
- Resolution adequate for monitoring beam spot

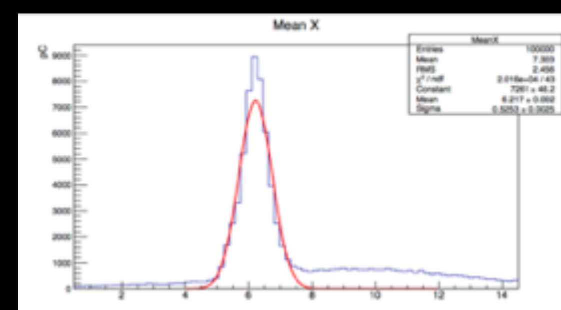


Digitized strips signals





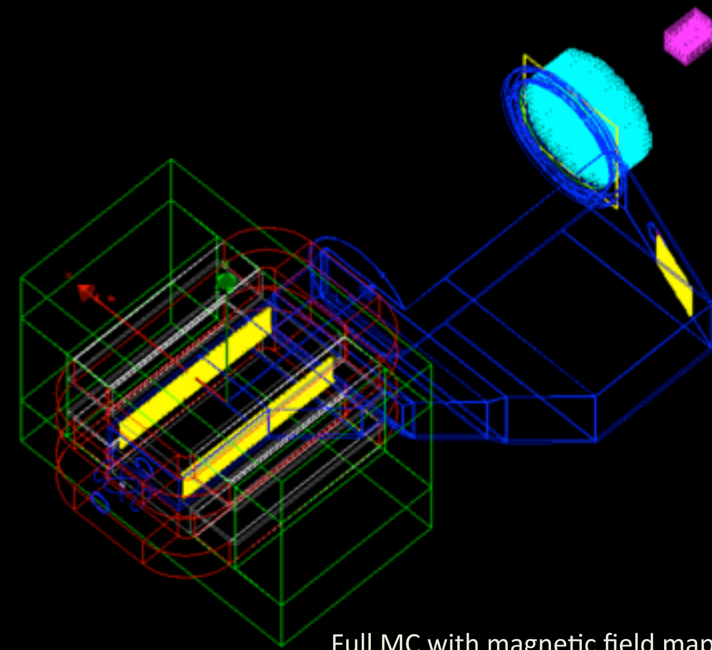
Center of gravity

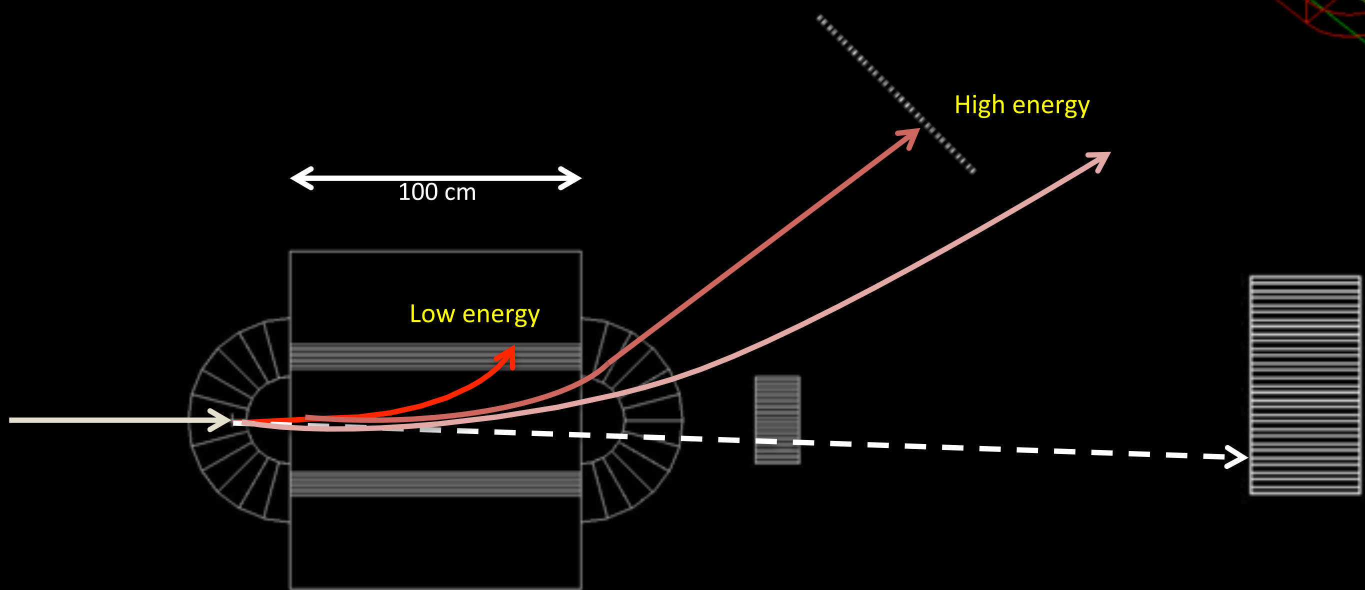


Average position

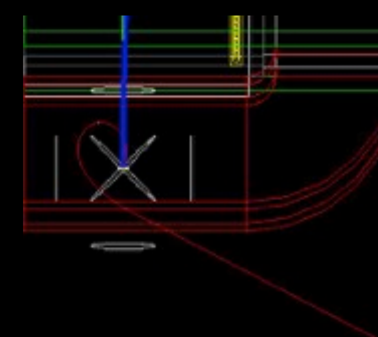
Positron veto

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

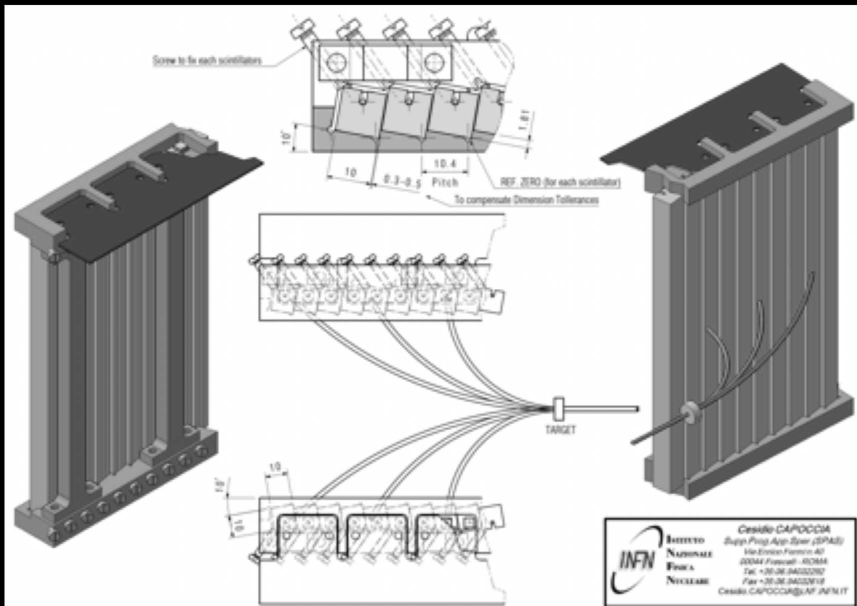


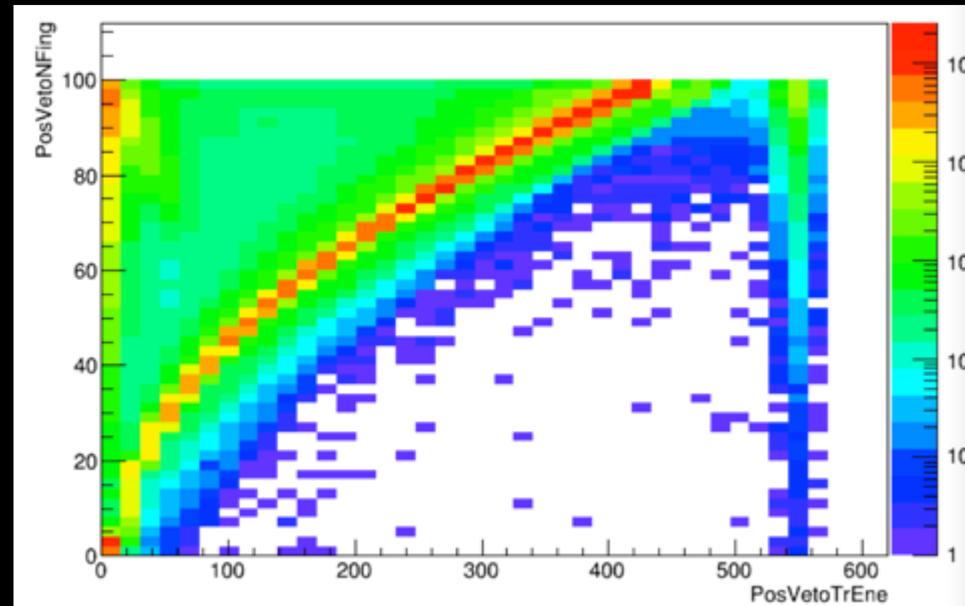


Full MC with magnetic field map



Positron veto



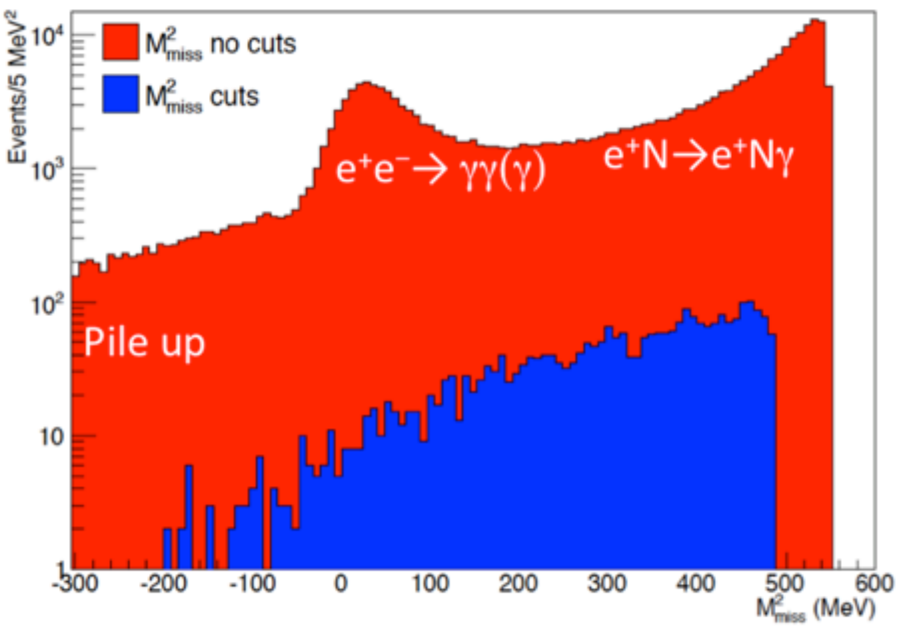


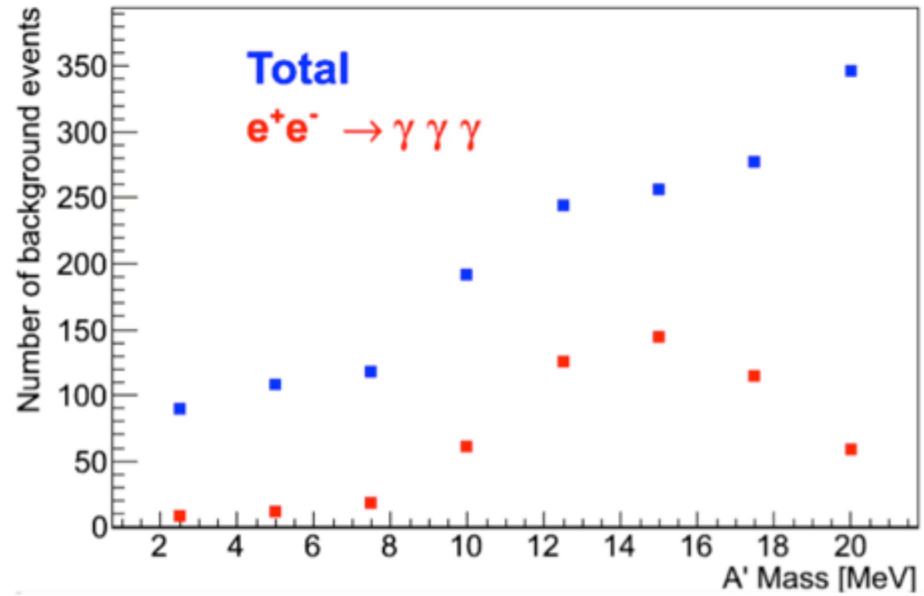
Low momentum losses are reduced for E_γ<400 MeV
Interesting positron energy starting at ~150 MeV

Which granularity?

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

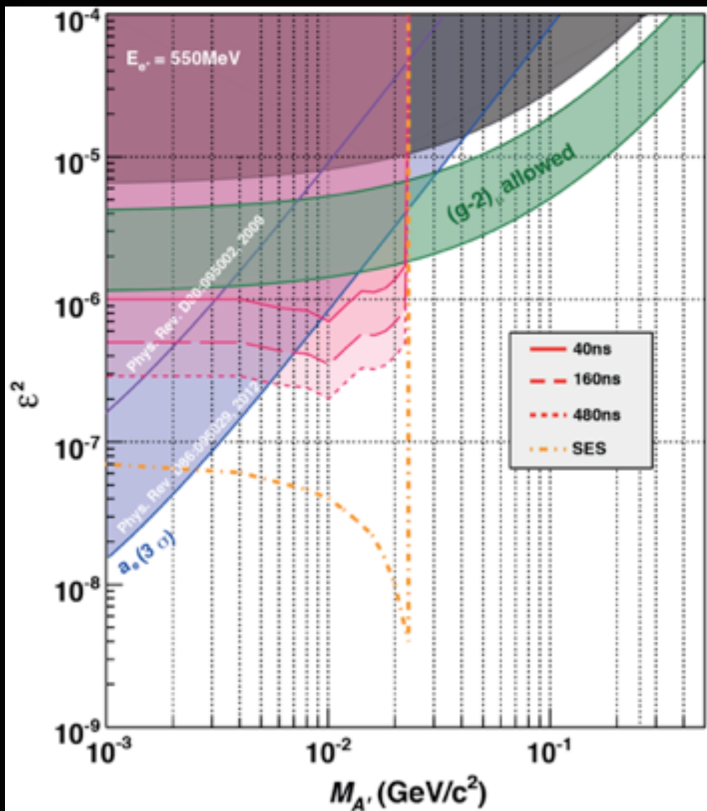
Background estimates





- BG sources are: $e^+e^- \rightarrow \gamma\gamma$, e+e-$\rightarrow \gamma\gamma(\gamma)$, e+N$\rightarrow$e+N$\gamma$, Pile up
- Pile up contribution important; rejected by the maximum cluster energy cut and M^2_{Miss}
- Veto inefficiency at high missing mass (E(e+)≃ E(e+)beam
- Full Geant-4 simulation

PADME-invisible decay sensitivity

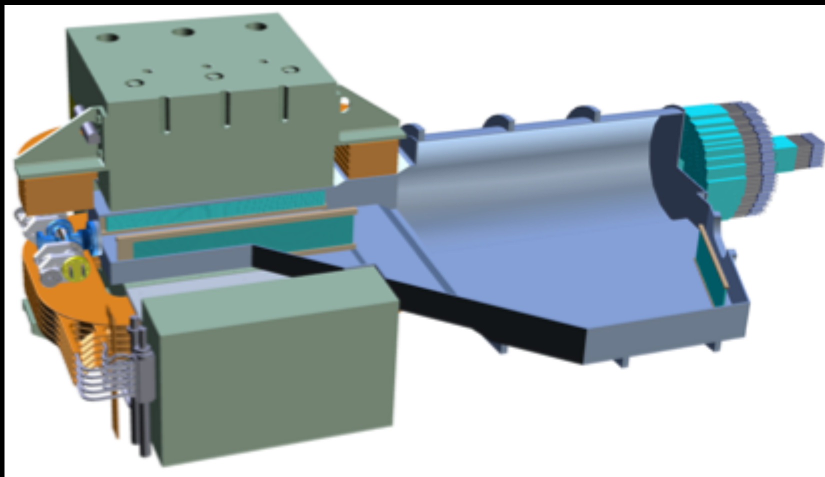


- Based on $2.5\text{x}10^{10}$ fully GEANT4 simulated 550MeV e+ on target events
  - Number of BG events is extrapolated to $1\text{x}10^{13}$ electrons on target
- Using $N(A'\gamma)=s(N_{BG})$
- δ enhancement factor $\delta(M_{A'}) = \sigma(A'\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon=1$

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

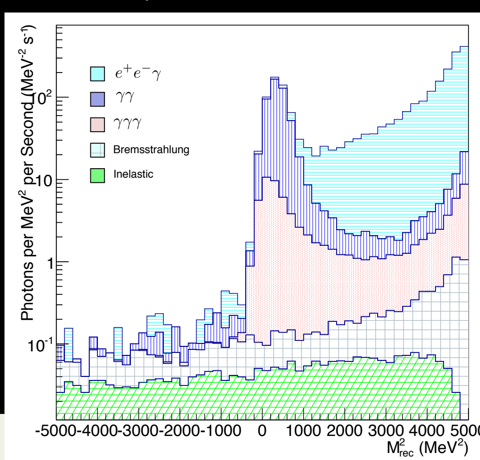
Running time depending linearly on positron pulse length

PADME@Cornell

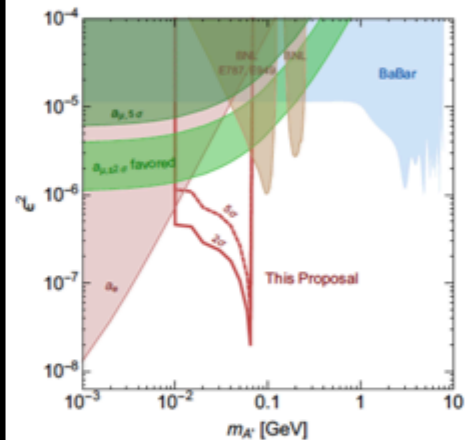


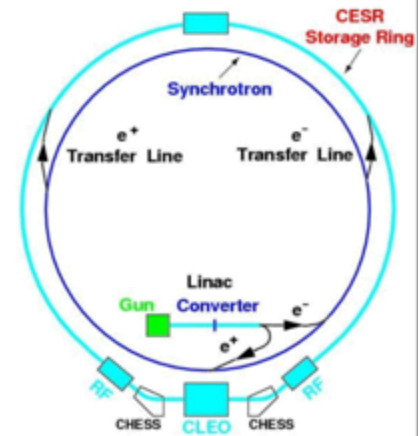
@Cornell

- E_{beam} ~ 6.0 GeV (from 5.3 GeV)
- CM energy ~ 75 MeV
- $2° < \theta_\gamma < 5°$
- 10 MeV < E_γ < 800 MeV

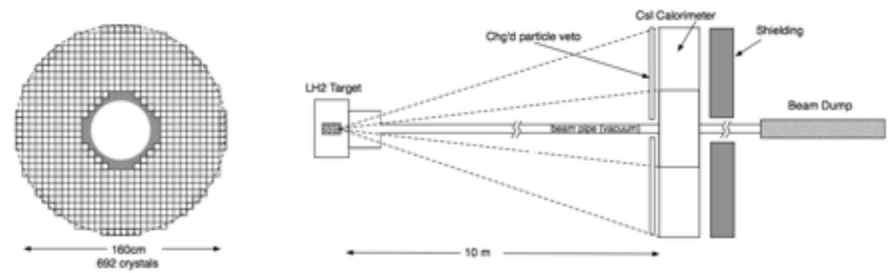


MMAPS @ Cornell





EPJ Web of Conferences 142, 0 01 (2017)



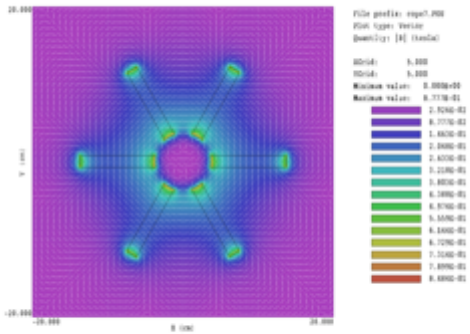
PADME + MMAPS? (2020?)

PADME: E_B~500 MeV, 2 year @ INFN BTF

Cornell: 12x E_B, **10^4x EOT**

PADME: Better M_{miss}, faster detector

A 16.6 MeV boson?

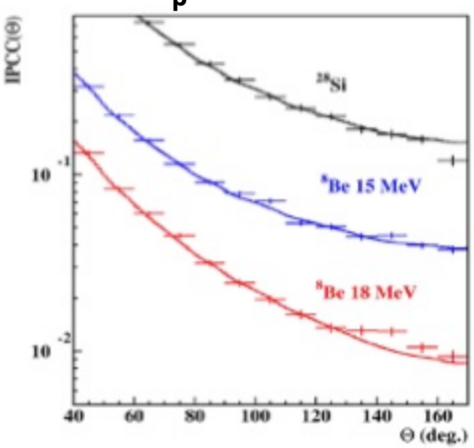


Electron spectrometer
MWPC + scintillators

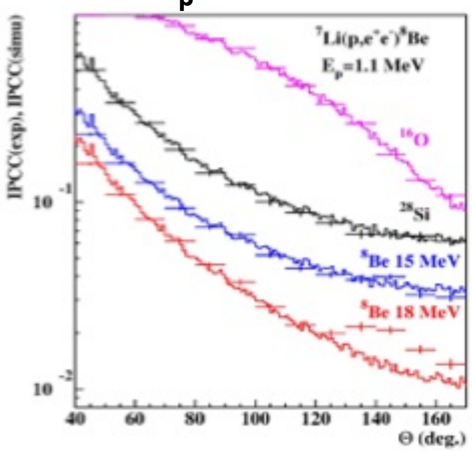
On resonance

Off resonance

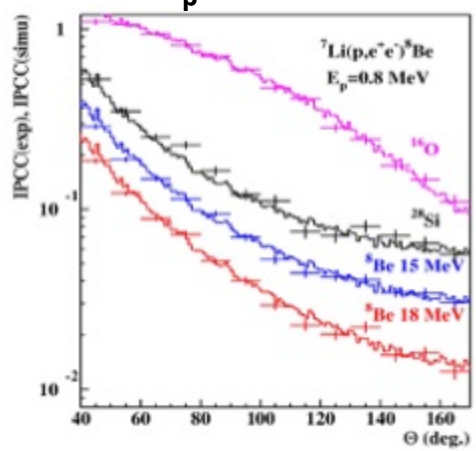
E_p=1.04 MeV



E_p=1.10 MeV



E_p=0.8 MeV

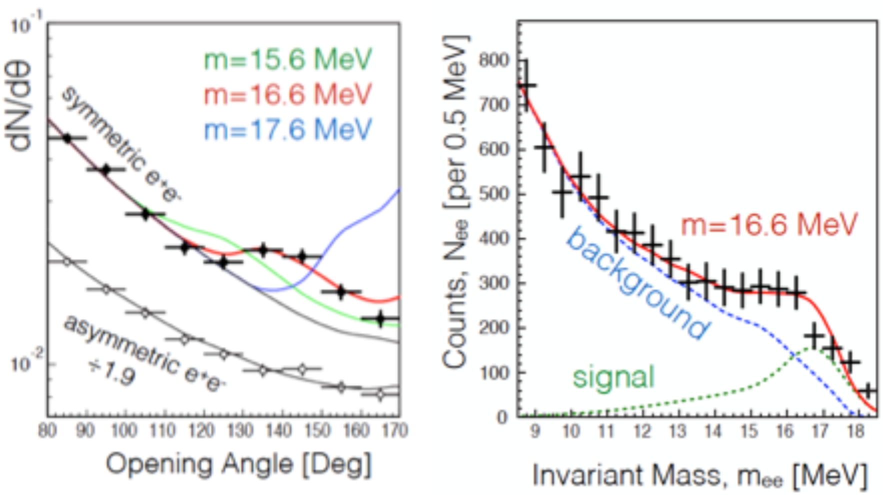


Proto-phobic boson

6.8σ excess, interpred as a new (vector is favored) boson

A. Krasznahorkay et al., “Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson”,

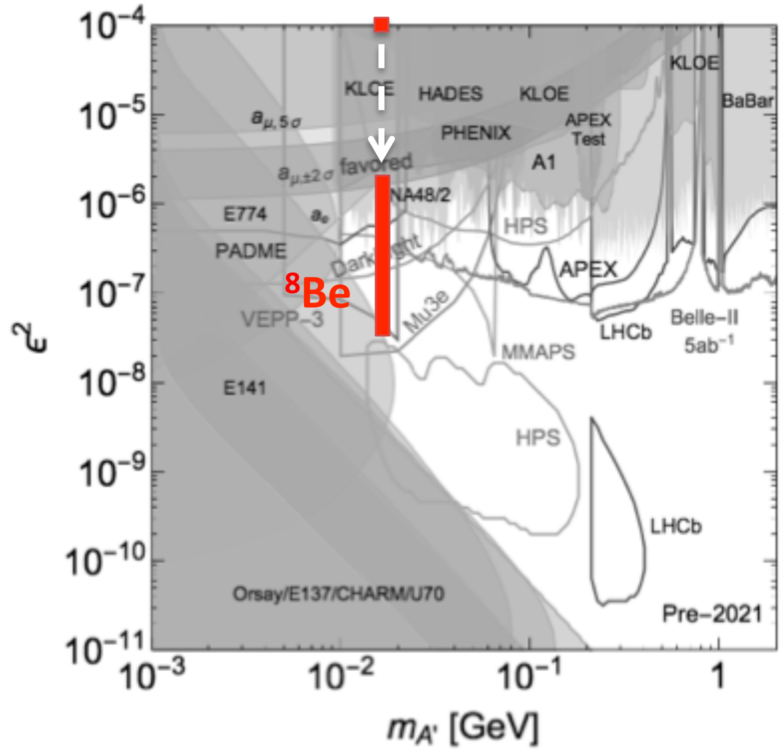
Phys. Rev. Lett. 116, 042501 (2016)



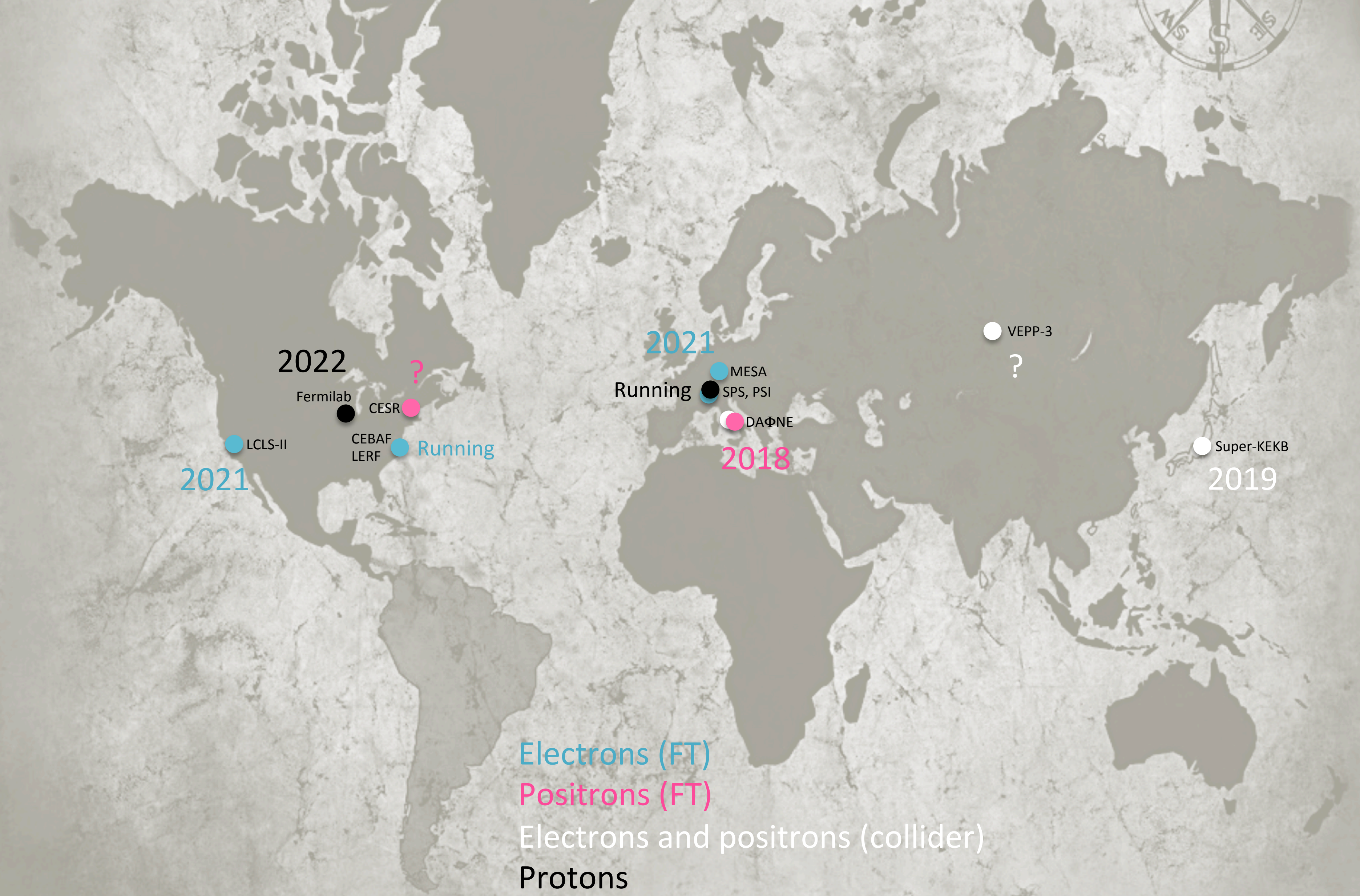
Not compatible with present limits: too high coupling unless…

J. Feng et al., “Protophobic Fifth Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions”,

Phys. Rev. Lett. 117, 071803 (2016)



Time of facilities



Electrons (FT)
Positrons (FT)
Electrons and positrons (collider)
Protons

Facilities for dark sector/LDM searches

Existing accelerators

- CEBAF & LERF@JLAB
- DAΦNE LINAC
- SPS extracted beams@CERN

Approved new accelerators

- MESA@Mainz

Proposed accelerators **upgrades**

- DASEL@SLAC
- BDF@CERN (SHiP)
- Positrons from Synchrotron@Cornell
- VEPP-3 bypass
- Positrons from DAΦNE ring?

INFN

Future projects combined sensitivity