Proposal for an Experiment to Search for Light Dark Matter at the SPS

S.N. Gninenko
INR Moscow

SPSC Open Session
CERN, January 14, 2014.

PREPARED FOR SUBMISSION TO SPSC

Proposal for an Experiment to Search for Light Dark Matter at the SPS

S. Andreas[a,b], S.V. Donskov[c] , P. Crivelli[d], A. Gardikiotis[e], S.N. Gninenko[f1], N.A. Golubev[f], F.F. Guber[f], A.P. Ivashkin[f], M.M. Kirsanov[f], N.V. Krasnikov[f], V.A. Matveev[f,g], Yu.V. Mikhailov[c], Yu.V. Musienko[e], V.A. Polyakov[c], A. Ringwald[a], A. Rubbia[d], V.D. Samoylenko[c], Y.K. Semertzidis[h], K. Zioutas[e]

[a]*Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Notkestrasse 85, Germany*
[b]*Institut d'Astrophysique de Paris IAP, 75014 Paris, France*
[c] *State Research Center of the Russian Federation, Institute for High Energy Physics, 142281 Protvino, Russia*
[d]*ETH Zurich, Institute for Particle Physics, CH-8093 Zurich, Switzerland*
[e]*Physics Department, University of Patras, Patras, Greece*
[f]*Institute for Nuclear Research, Moscow 117312, Russia*
[g]*Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[h]*Center for Axion and Precision Physics, IBS, Physics Dept., KAIST, Daejeon, Republic of Korea*

CERN-SPSC-2013-034 / SPSC-P-348
06/12/2013

December 6, 2013

[1]Contact person, Sergei.Gninenko@cern.ch

Plan

- New physics at sub-GeV scale: SM portals to dark sectors
- Search for visible and invisible decays of dark photons
  - setup
  - background
  - expected sensitivity
- Schedule
- Summary

Dark matter portals to SM

- The question of Dark Matter (DM):
  What makes up most of the Universe's mass? is still open

- LHC Phase I: no DM candidates so far.
  Expectations for further searches at Phase II.

- Can one expect a hint from high intensity experiments at sub-GeV scale?

- Models: dark sectors of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields, coupled to SM by gravity, and possibly by other very weak forces.
  Search for dark forces is an additional way to detect DM.

- SM allowed portals to DS: Higgs, RH neutrino couplings, kinetic mixing between $U(1)_Y$ and new $U(1)_x$

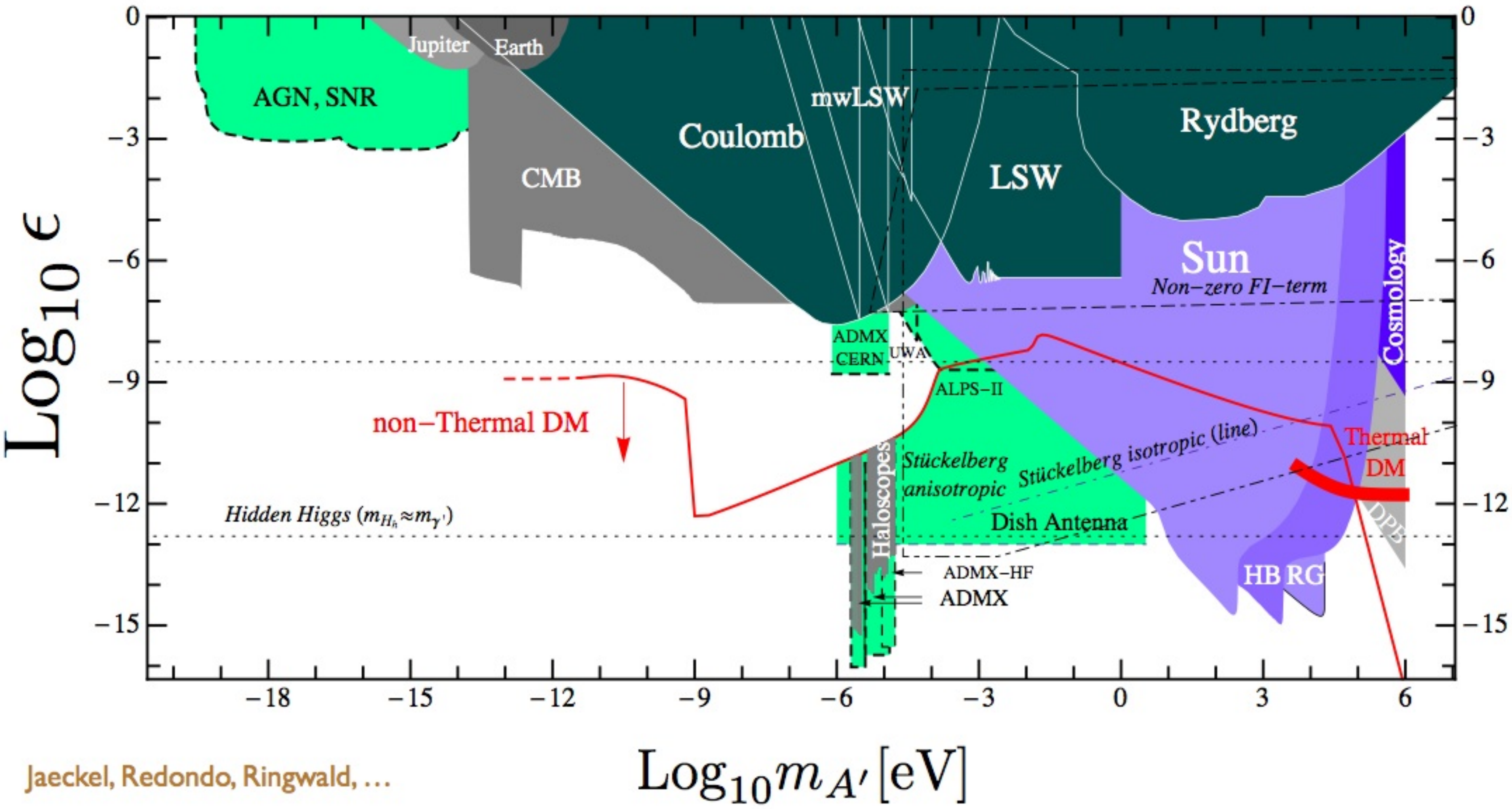
An example of dark mediator A`

Holdom'86, earlier work by Okun, ..

- extra U`(1), new gauge boson A` (dark or hidden photon,...)
- $\Delta L = \varepsilon F^{\mu\nu} A`_{\mu\nu}$ - kinetic mixing
- γ-A` mixing, ε - strength of coupling to SM
- A` could be light: e.g. $M_{A`} \sim \varepsilon^{1/2} M_Z$
- new phenomena: γ-A` oscillations, LSW effect, A` decays,..
- A` decay modes: e+e-, μ+μ-, hadrons,.. or A` -> DM particles, i.e. A` -> invisible decays

Large literature, >100 papers /few last years, many new theoretical and experimental results

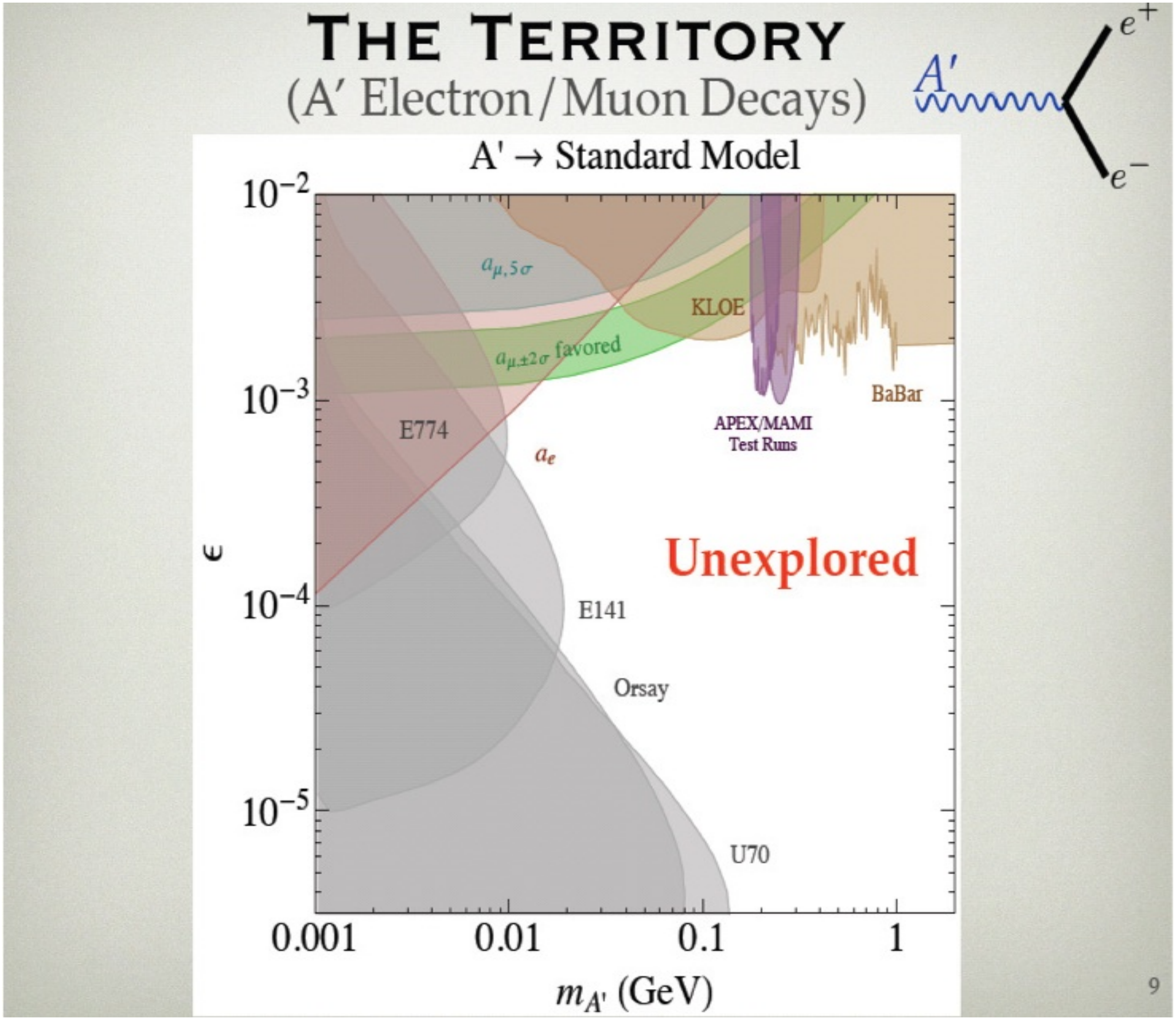
low-mass (< MeV) A′ parameter space

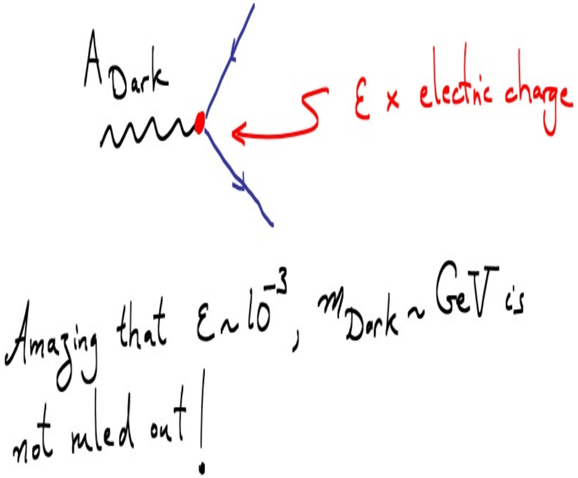


Jaeckel, Redondo, Ringwald, …

\+ M. Betz et al., First results of the CERN Resonant WISP search (CROWS) arXiv:1310.8098

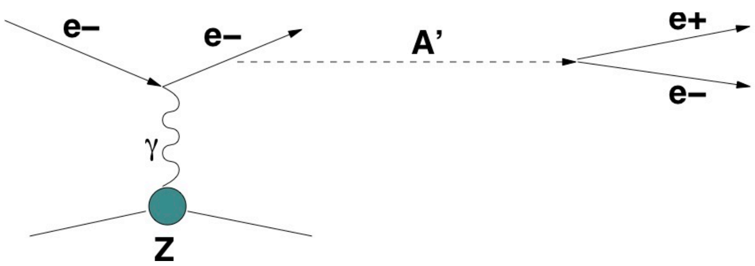
High mass (> MeV) A` parameter space





N. Arkani-Hamed,
Snowmass 2013

MeV A` production and decay



bremsstrahlung A`

- e Z->e Z A`cross section $\sigma_{A`} \sim \varepsilon^2 (m_e/M_{A`})^2 \sigma_\gamma$; Bjorken'09, Andreas'12
- decay rate $\Gamma(A` \to e+e-) \sim \alpha\varepsilon^2 M_{A`}/3$ is dominant for $M_{A`} < 2\, m_\mu$
- sensitivity $\sim\varepsilon^4$ for long-lived A`, typical for beam dump searches

For $10^{-5} < \varepsilon < 10^{-3}$, $M_{A`} < \sim 100$ MeV

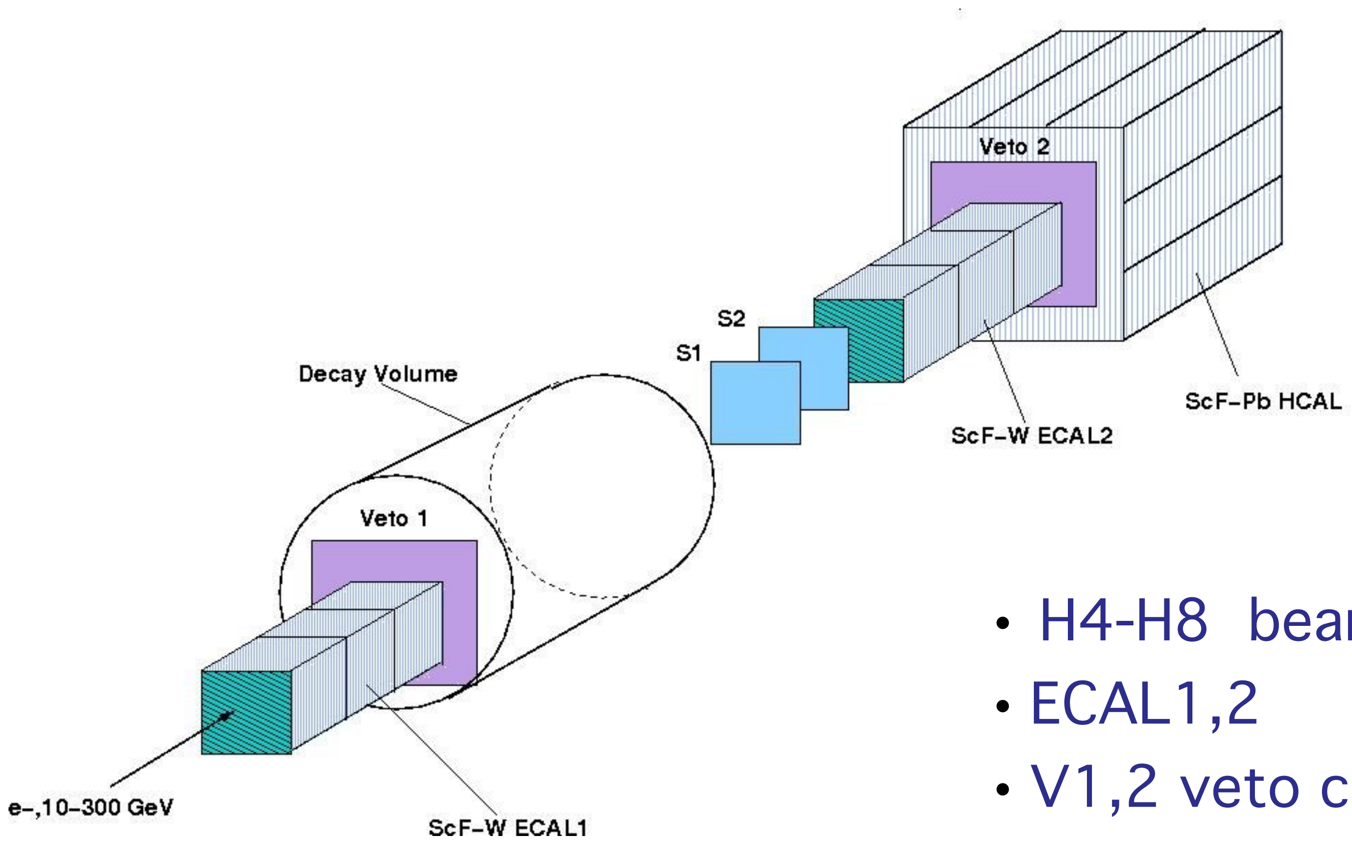
- very short-lived A`: $10^{-14} < \tau_{A`} < 10^{-10}$ s
- very rare events: $\sigma_{A`}/\sigma_\gamma < 10^{-13}$-$10^{-9}$

↓

- A`energy boost to displace decay vertex,

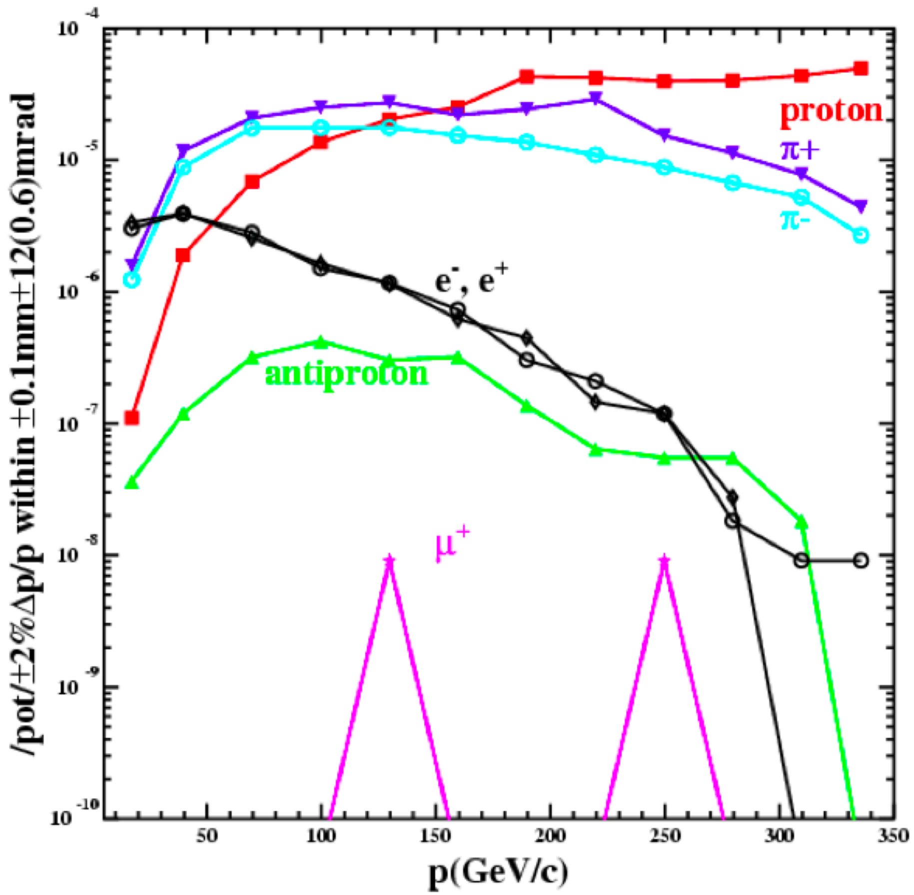
  $\varepsilon \sim 10^{-4}$, $M_{A`} \sim 50$ MeV, $E_{A`} \sim 100$ GeV, $L_d \sim 1$ m
- background suppression

Setup



- H4-H8 beamline
- ECAL1,2
- V1,2 veto counters
- Decay volume (vacuum)
- HCAL
- S1,S2 fiber-tracker

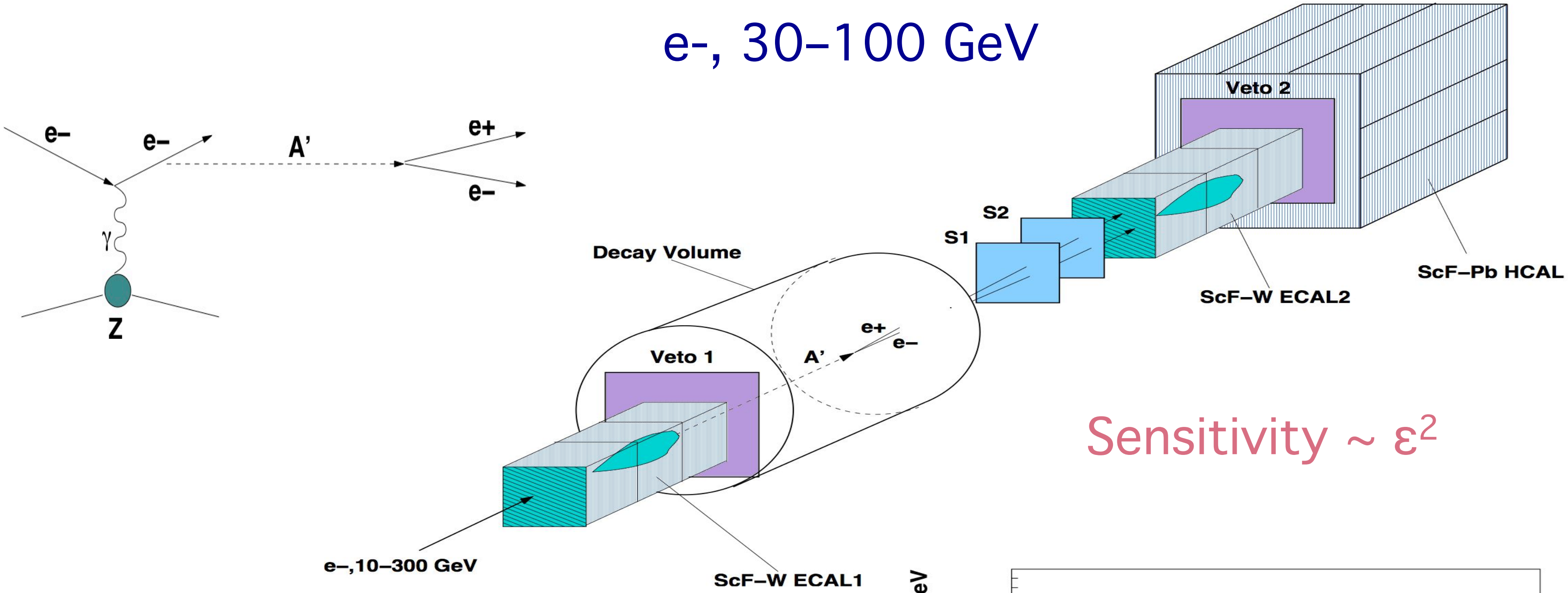
SPS e- beams



- H4, I_{max}~ 50 GeV e-
- 10^{12} pot per SPS spill,
- ~ $5x10^6$ e- per spill
- duty cycle is 0.25
- ~10^{12} e- / month
  additional tunning by
  a factor 2–3 ?
- beam spot ~ cm^2
- beam purity < 1 %

Search for A`->e⁺e⁻ in a LSW experiment

e-, 30–100 GeV

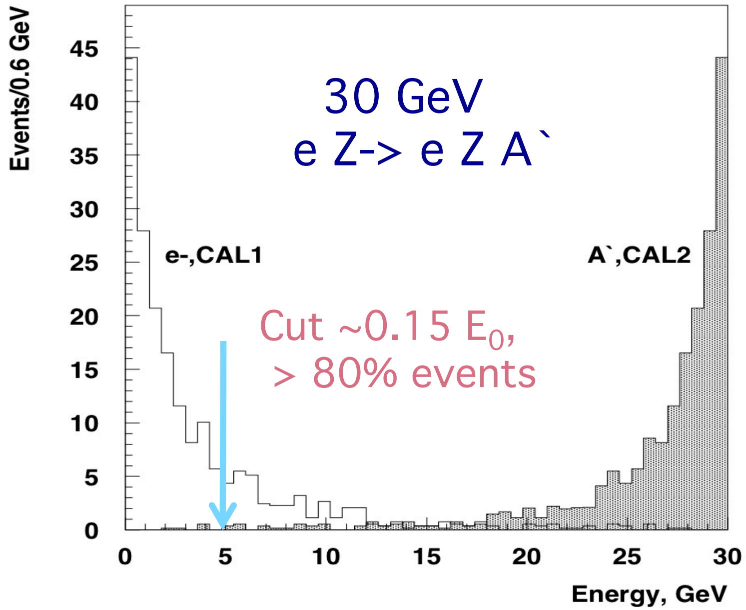


Sensitivity ~ ε^2

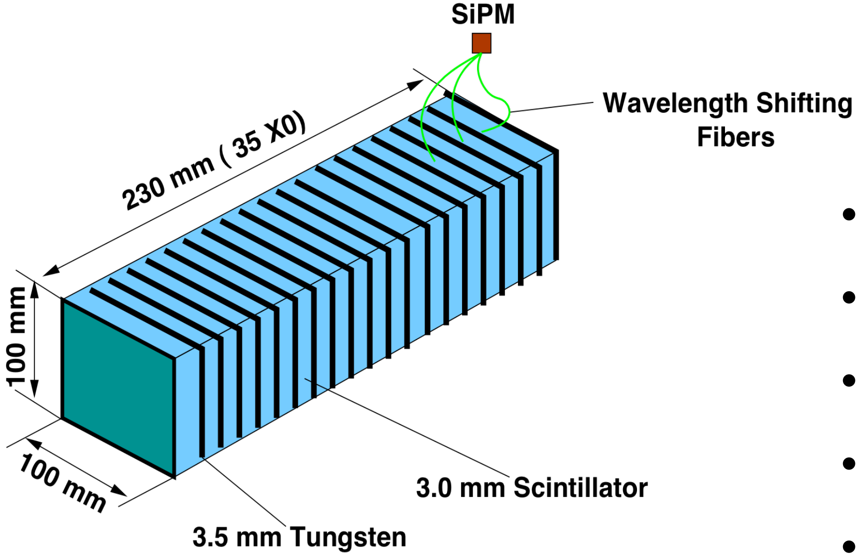
- A`s decay mostly outside ECAL1
- Signature: two separated e-m showers from a single e-

S= ECAL1xS1xS2x ECAL2 $\overline{\text{xV1xV2xHCAL}}$

- $E_1 << E_0$, and $E_0 = E_1 + E_2$
- θ_{e+e-} too small to be resolved



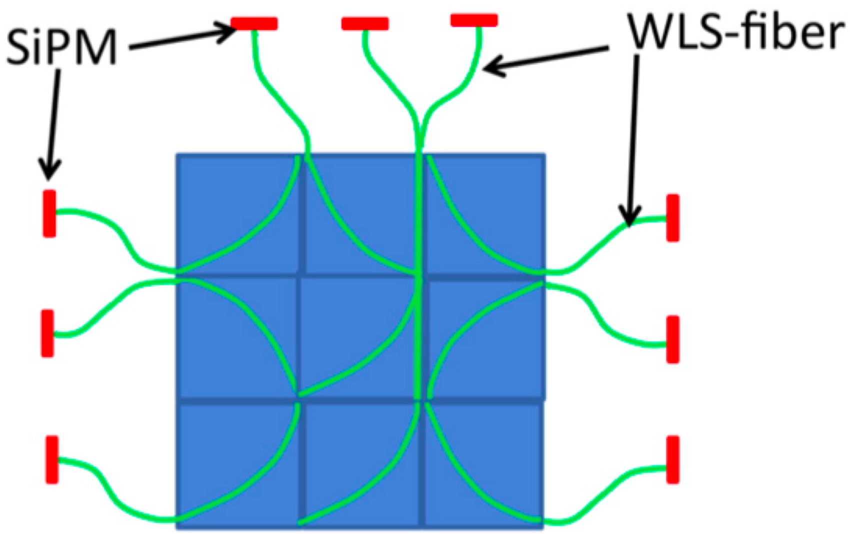
Specially designed ECAL

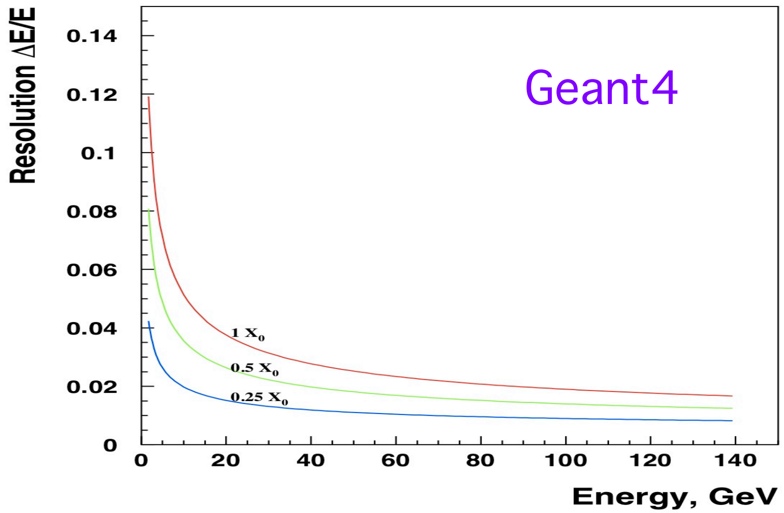


ECAL1 "bubble chamber"

W-Sc sandwich + fiber readout

- compact, hermetic, dense, fast
- rad. hard, side SiPM readout
- lateral and longitudinal segmentation
- elementary cell V ~ R^2_M x few X_0
- good energy, space resolution
- e/π rejection < 10^{-3}

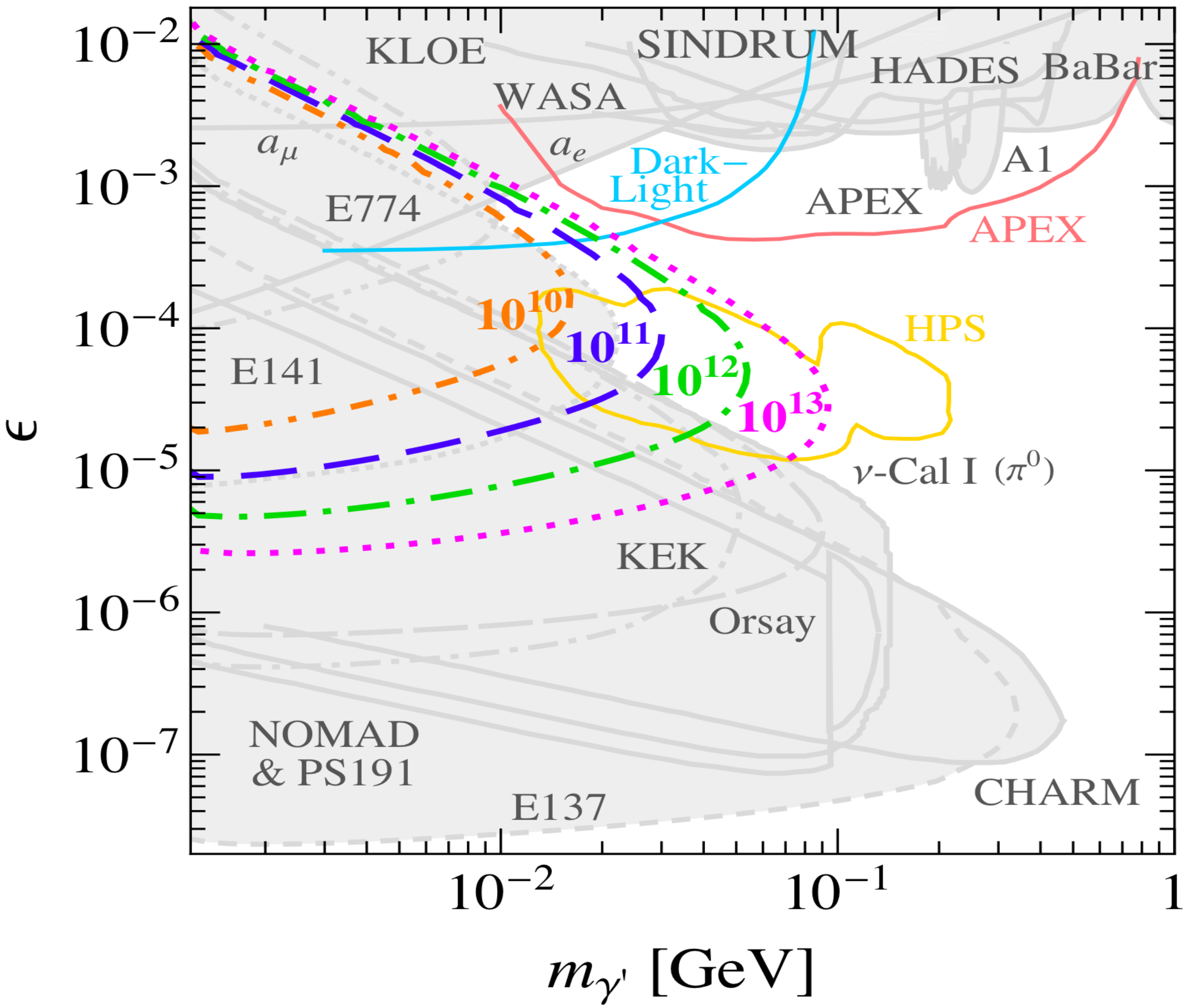




Summary of background sources for A`-> e+e-

Source	Expected level	Comment
Beam contamination		
- π , μ reactions, e.g. π A-> π^0n+X, … -accidentals: $\pi\ \pi$, $\mu\ \mu$, … decays, e-n pairs, …	< 10^{-12} < 10^{-13}	Impurity < 1% Leading n cross sect. ISR data
Detector		
- e,γ punchthrough, - ECAL thickness, dead zones, leaks	< 10^{-13}	Full upstream coverage
Physical		
hadron electroproduction: - eA->neA*, n -> ECAL2, - eA-> e+ π +X, π ->e ν	< 10^{-13}	
Total	< 10^{-12}	

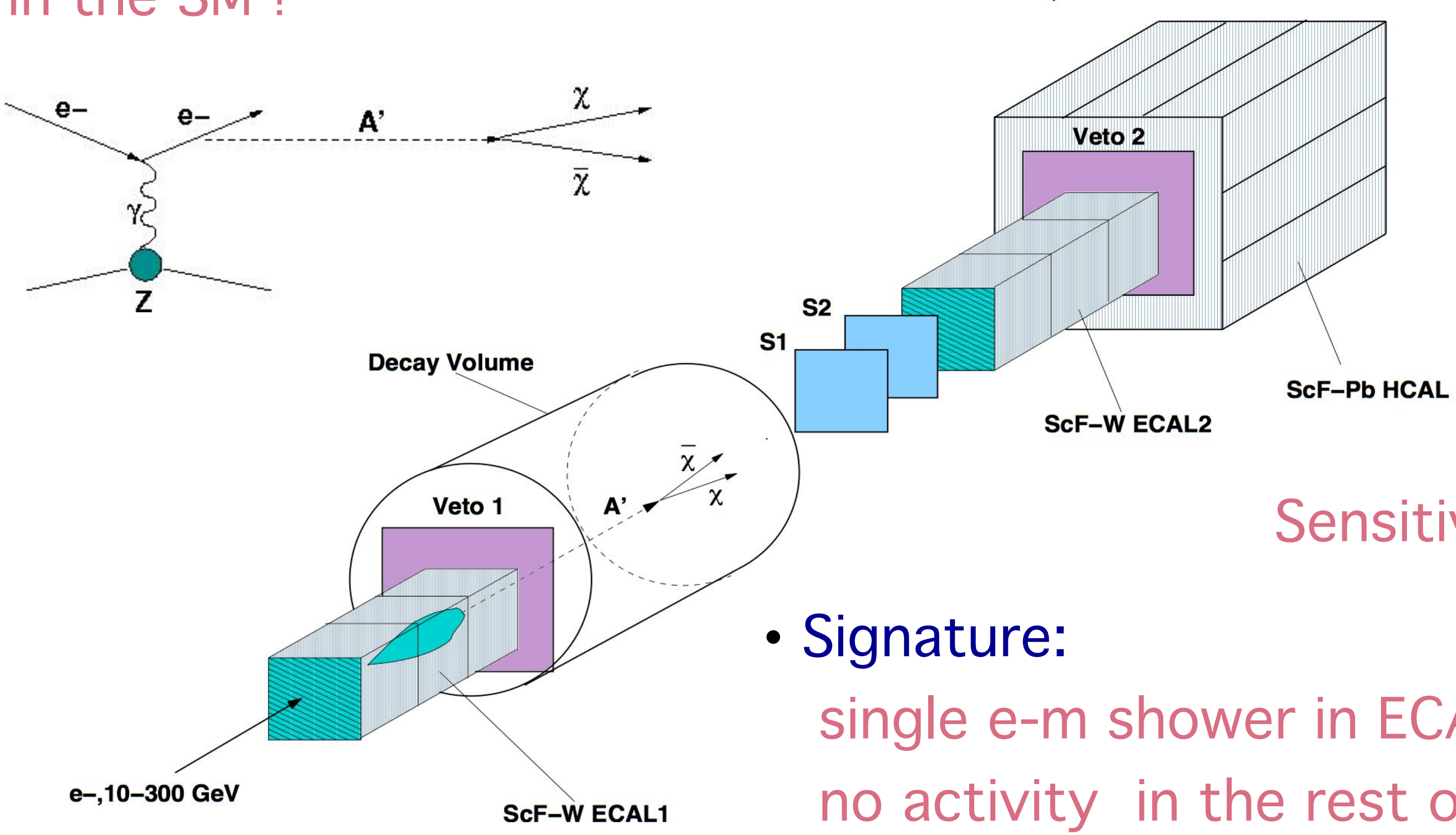
Expected limits on A` -> e+e- decays vs accumulated N_{e-} (background free case)



Search for invisible decay A` -> $\bar{\chi}\chi$

Remember Z-->invisible

in the SM !



Sensitivity ~ ε^2

- Signature:

  single e-m shower in ECAL1 +

  no activity in the rest of the detector

  $S = ECAL1 \times \overline{V1 \times S1 \times S2 \times ECAL2 \times V2 \times HCAL}$
- $E_1 \ll E_0$, and $E_0 \neq E_1 + E_2 \approx E_1$
- detector hermeticity is a crucial item

“β decay“ analogy

^{210}Bi β decay e- spectrum

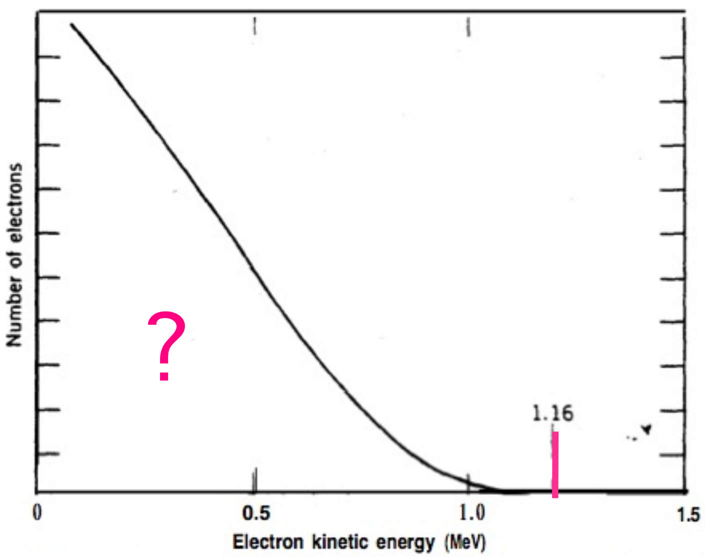
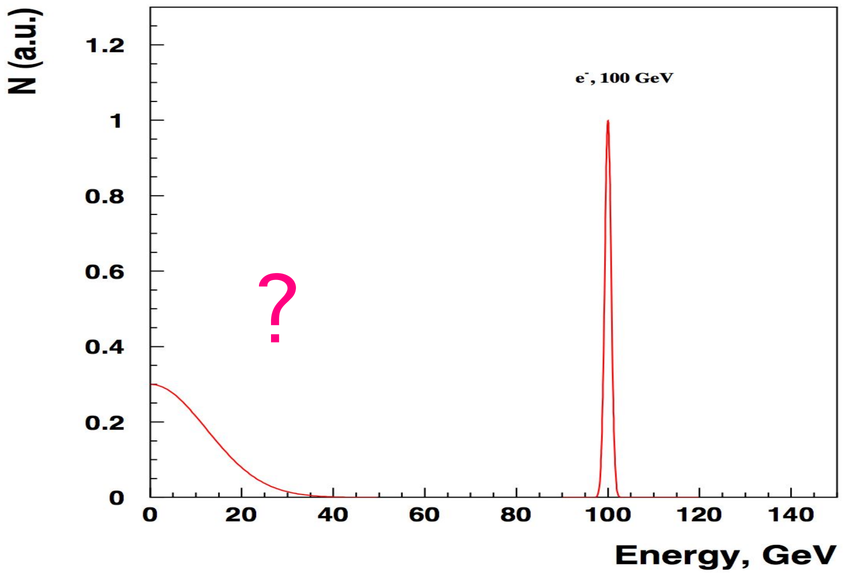


Figure 9.1 The continuous electron distribution from the β decay of ^{210}Bi (also called RaE in the literature).

SPS e- spectrum



Pauli, 1931

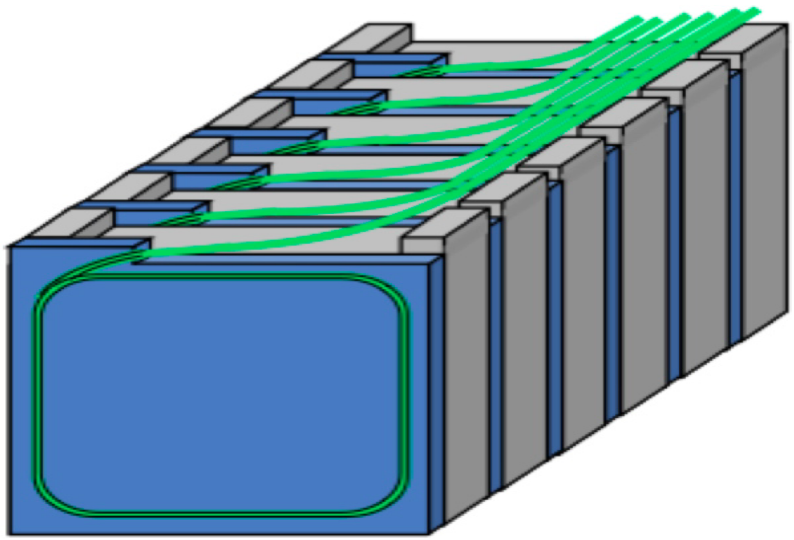
? = invisible ν

Massive HCAL to enhance longitudinal hermeticity

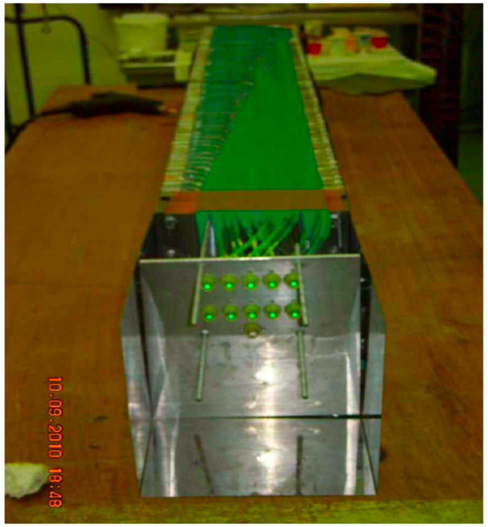
Single module of the hadronic calorimeter:

- Pb-Sc sandwich + fiber readout
- 20x20 cm^2 x (16mm Pb + 4mm Sc) x 60 layers
- hermetic at ~6 λ
- uniform, no cracks, holes
- good energy resolution

Full HCAL : 2x2x3 modules, ~ 7 tons

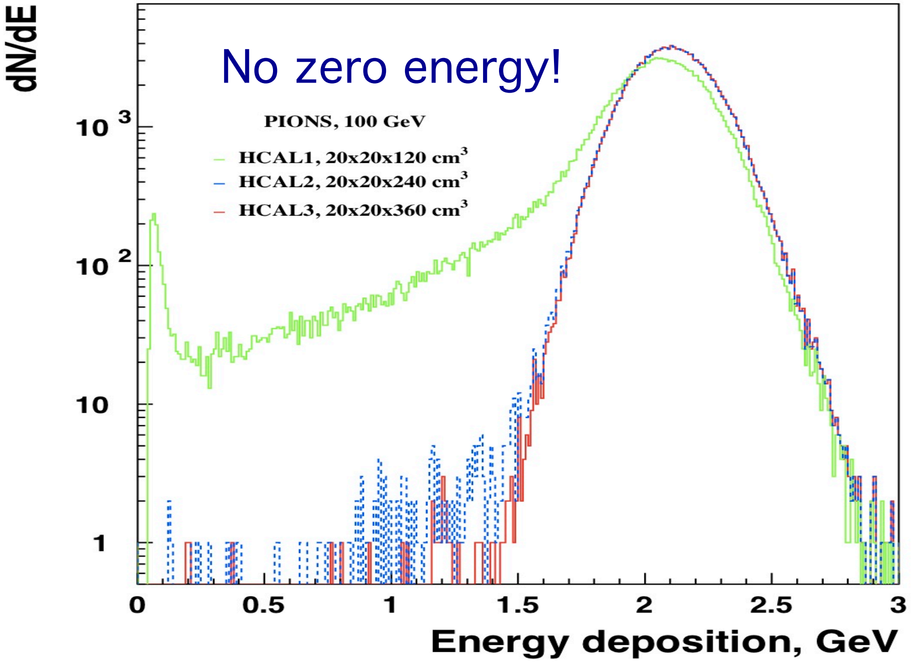


Prototype

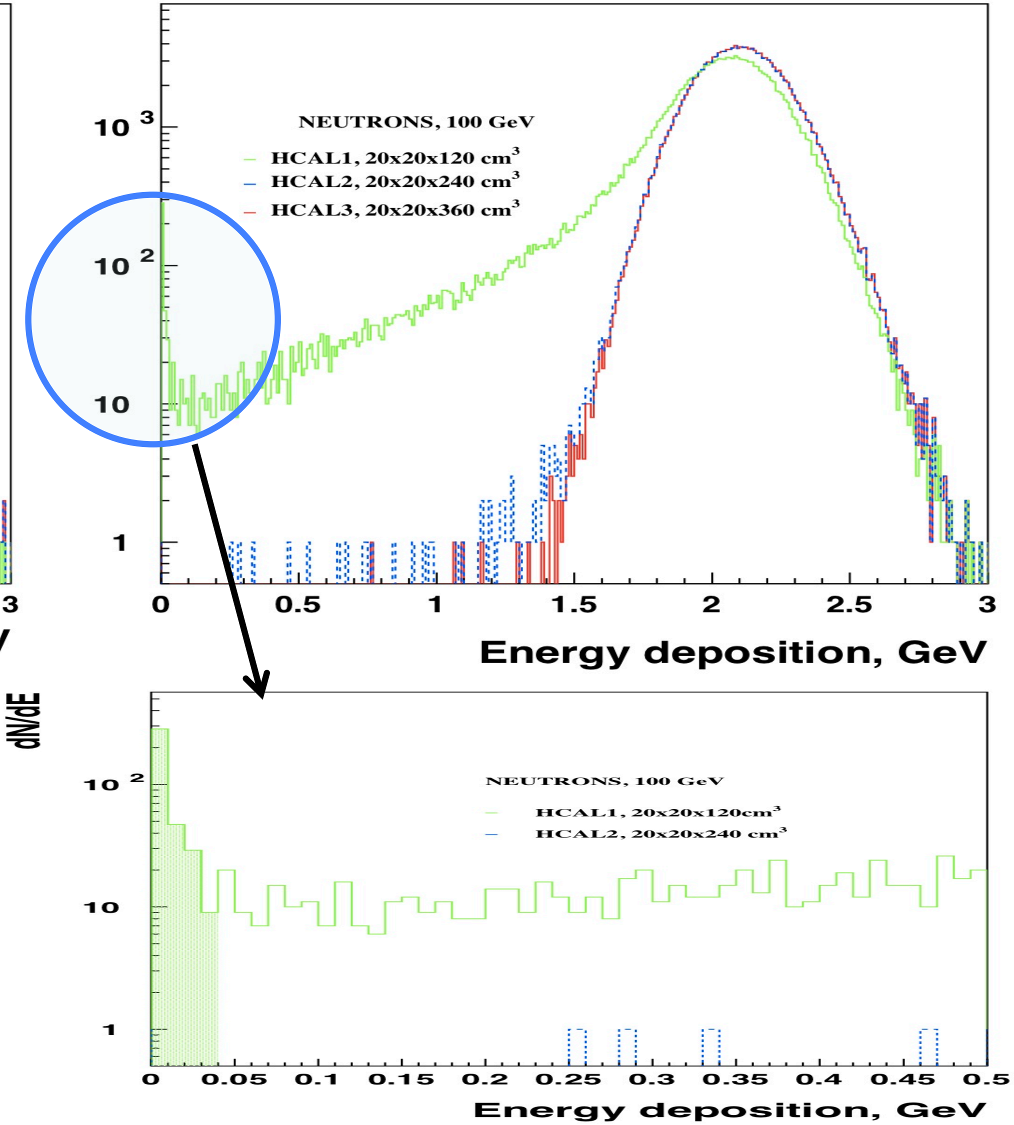


HCAL hermeticity for 3 consequtive modules

Pions, 100 GeV

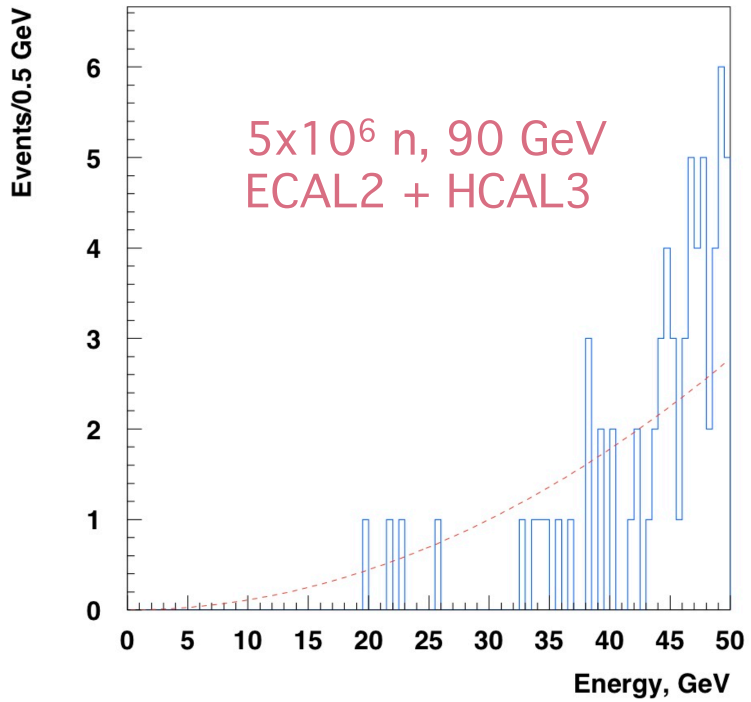


Neutrons, 100 GeV

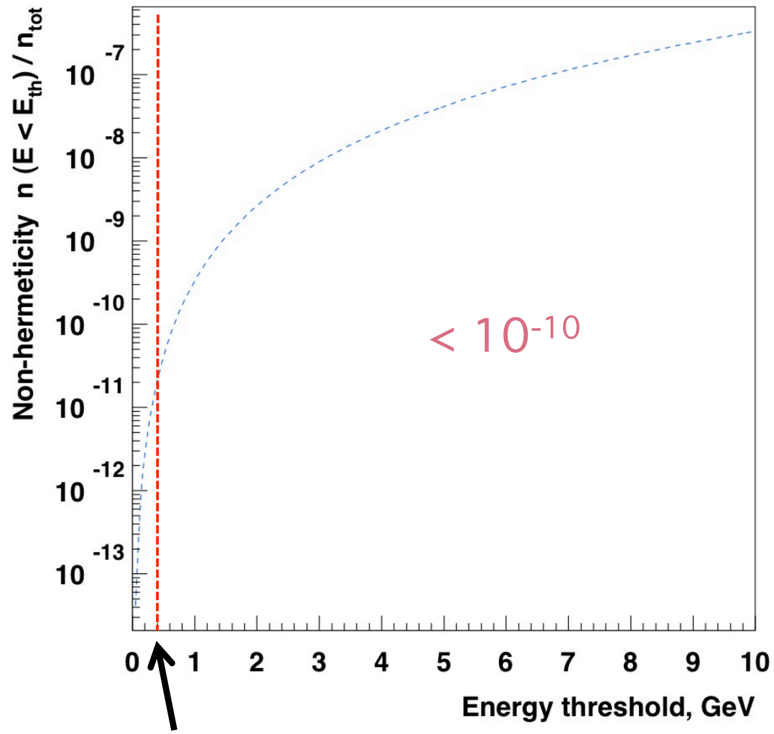


Expected HCAL energy threshold ~ 20-50 keV determined by noise and pileups.

Estimated ECAL2+ HCAL3 nonhermeticity



Fit of the low energy tail with a smooth function f(E)

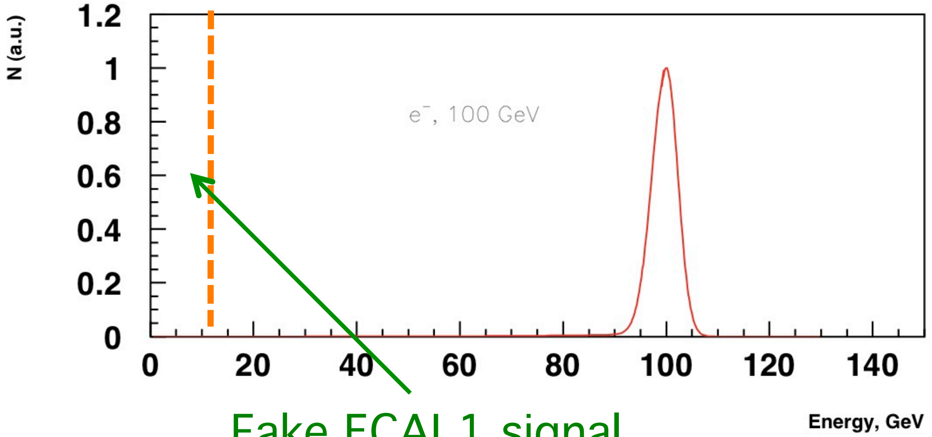


ECAL2+HCAL3 nonhermeticity as a funcion of the energy threshold

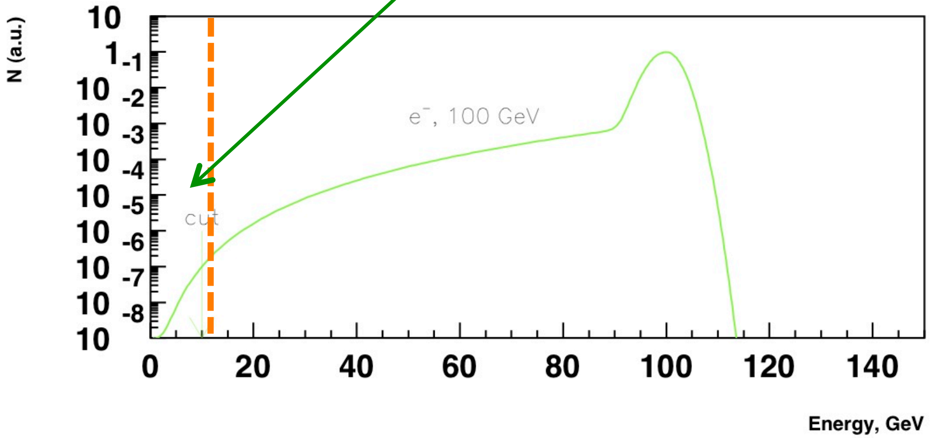
Summary of background sources for A\`-> invisible

Source	Expected level	Comment
Beam contamination		
- π , p, μ reactions and punchthroughs,... - e- low energy tail due to bremss., π , μ decays in flight,..	$< 10^{-13}$-10^{-12} ?	Impurity < 1% SR photon tag
Detector		
ECAL+HCAL energy resolution, hermeticity: holes, dead materials, cracks...	$< 10^{-13}$	Full upstream coverage
Physical		
-hadron electroproduction, e.g. eA->neA*, n punchthrough; - WI process: e Z->e Z ν ν	$< 10^{-13}$ $< 10^{-13}$	~10 mb x nonherm. WI σ estimated. textbook process, first observation?
Total	$< 10^{-12}$ + ?	

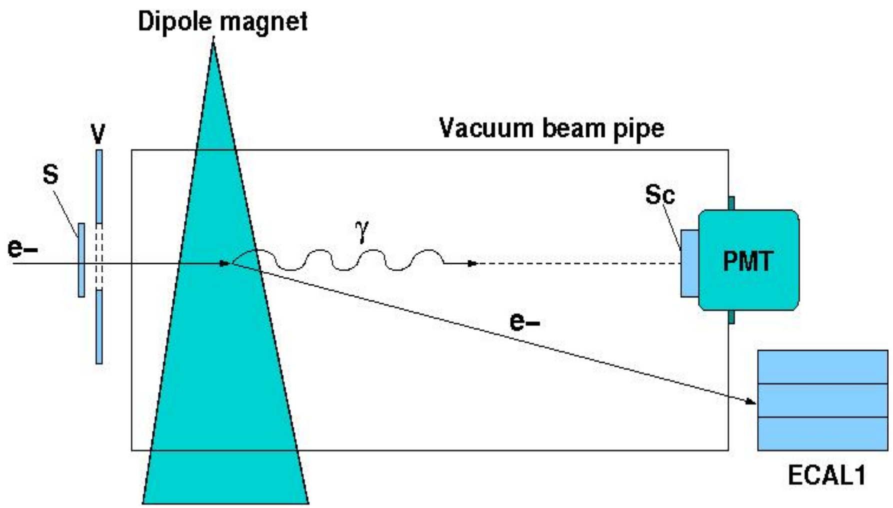
Additional tag of electrons with SR photons



Fake ECAL1 signal .



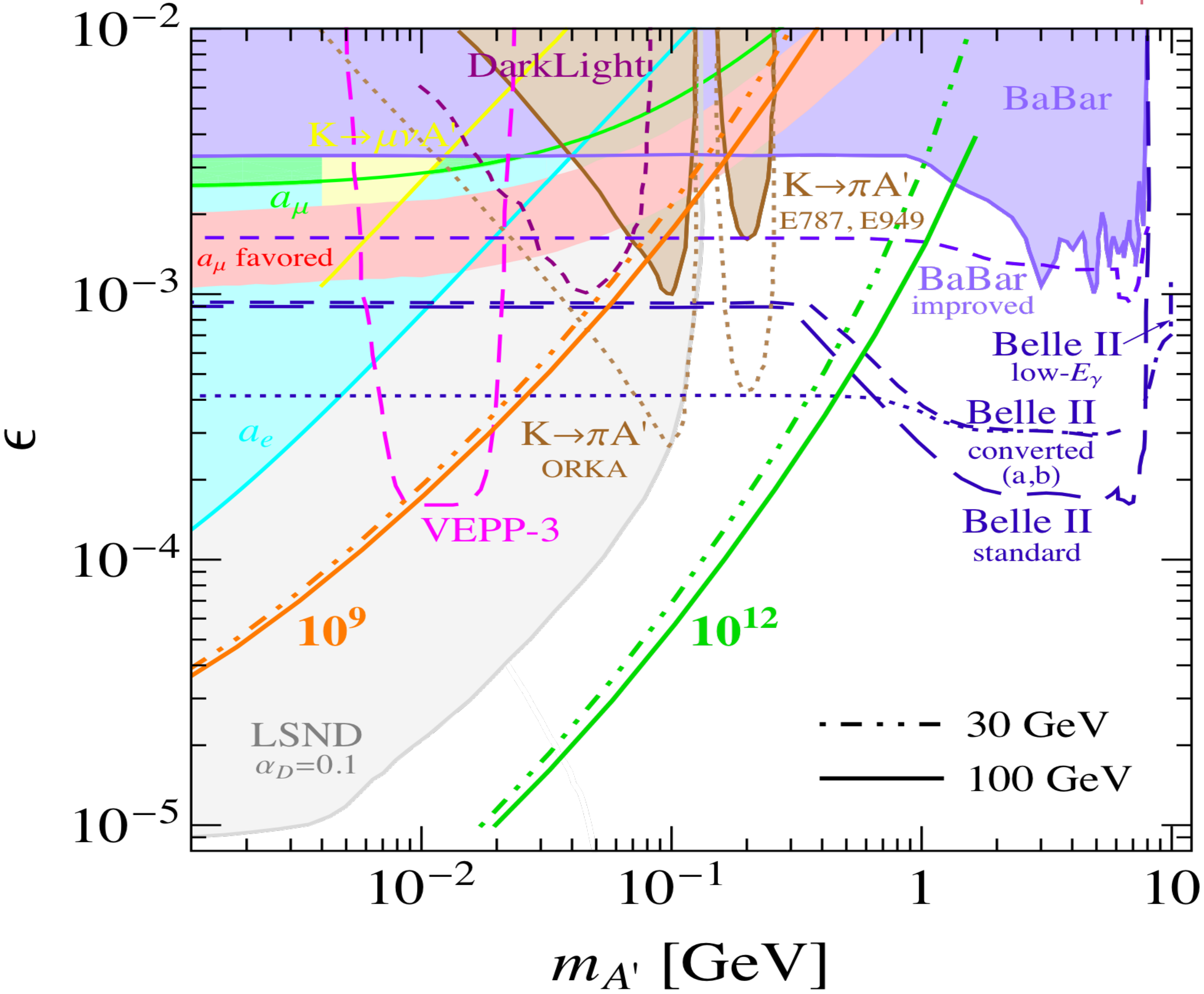
Hypothetical e- beam energy distribution (not simulated).



- e- tag enhancement with SR γ
- B field ~ 0.1- 1T
- $(\hbar\omega)_\gamma^c \sim E^2 B$, $n_\gamma/m \sim 6\ B(T)$
- cut $E_\gamma > 0.1\ (\hbar\omega)_\gamma^c$ ~100 keV
- LYSO crystal, good resolution for > ~50 keV γ
- suitable for vacuum

Expected limits on A`-> invisible decays vs accumulated N_{e-} (background free case)

With one day of running we could cover completely the $(g-2)_\mu$ favored region!



Schedule

- Test period of ~one month in 2014 - 2015 with e, π, μ beams.
  - refurbishing of existing detectors
  - first probe of the background level
  - first search for A` -> invisible
  - full coverage of the $(g-2)_\mu$ favored region
  - first limit on A` -> e+e- decays
  - design and fabrication of the ECAL and HCAL.
- Tests and Measurements period of few months in 2015 - 2017
  - full deflector installation and commisioning
  - tests of the ECAL/HCAL performance with e, π, μ beams.
  - measurements of background with π, μ beams.
  - search for A` -> e+e- , $n_e \sim 10^{12}$ e-, or more
  - search for A` -> invisible, $n_e \sim 10^{12}$ e-, or more

Summary

- The models of dark forces-interactions between the SM and DM- are attractive from both theoretical (motivated, simple, predictive,..) and experimental (indirect detection of DM, clear signature,..) view points.

- We propose experiment to cover the still unexplored area of the parameter space $10^{-5} < \varepsilon < 10^{-3}$, $M_{A`} < \sim 100$ MeV for di-electon and Invisible (into dark matter particles) decays of dark mediator A`s.

- Both decay modes have extraordinary signatures: two separated e-m showers generated by a single e-, or catastrophic e- energy disappearance which have never been tested.

- The search requires using of 30–100 GeV electron beams from the CERN SPS with the total running time of several months during years 2014 – 2017. Additional time of ~ one month is requested for testing of the detectors performance with e, π, μ beams, and direct background measurements with π, μ.

- CERN Beam physicists participation would be a great help.