The light dark vector boson and muon g-2 anomaly

N.V.Krasnikov

INR RAS, Moscow
and
JINR. Dubna

Dubna
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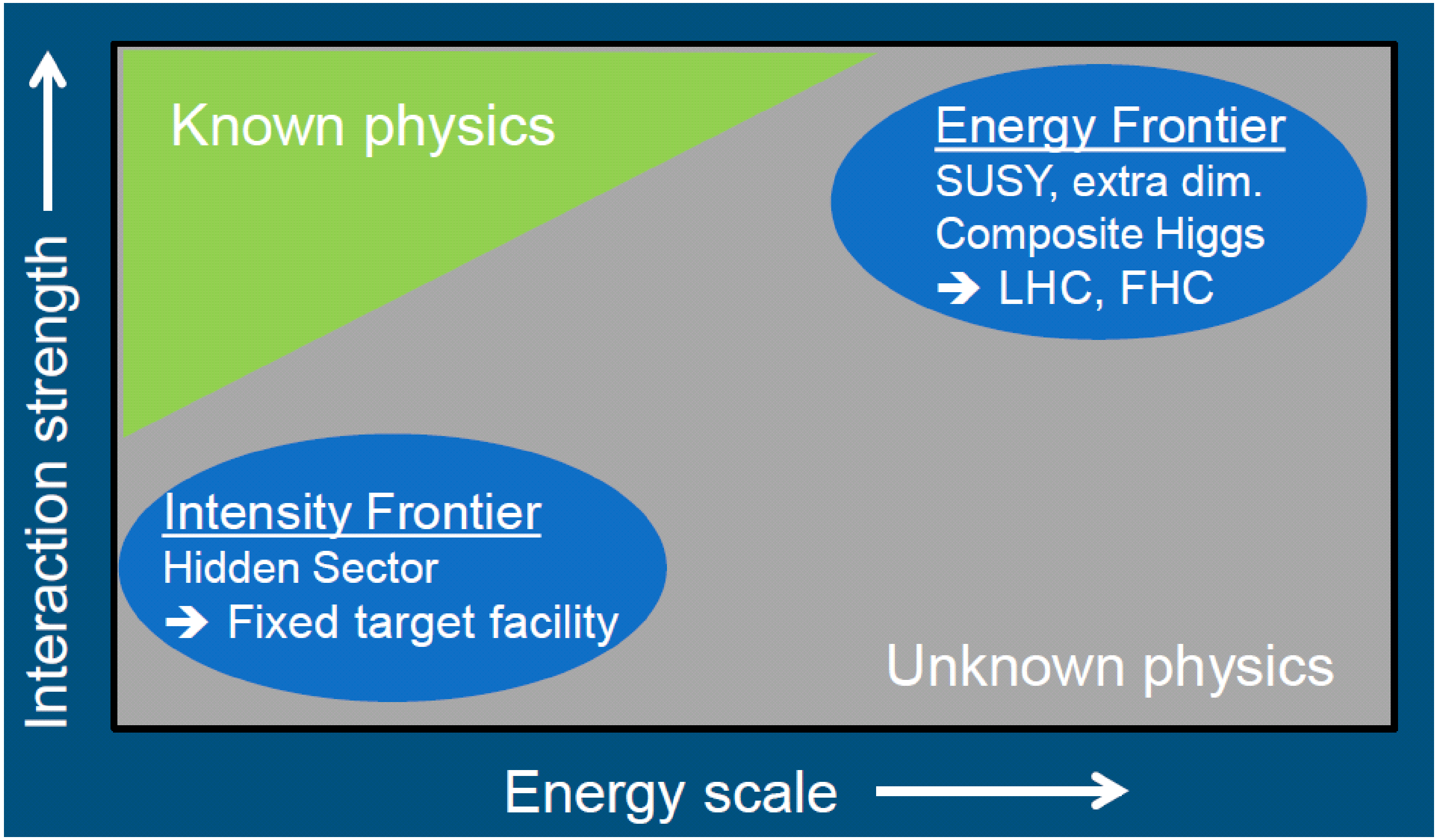
1.Introduction

Two lines of research in experimental elementary particle physics

1. High energies → search for new massive particles (LHC mainly)
2. Relatively low energies → search for new relatively light O(10) GeV or less new particles with small coupling constants


Interaction strength
Known physics
Energy Frontier
SUSY, extra dim.
Composite Higgs
➔ LHC, FHC
Intensity Frontier
Hidden Sector
➔ Fixed target facility
Unknown physics
Energy scale

1.Introduction

Light particles:

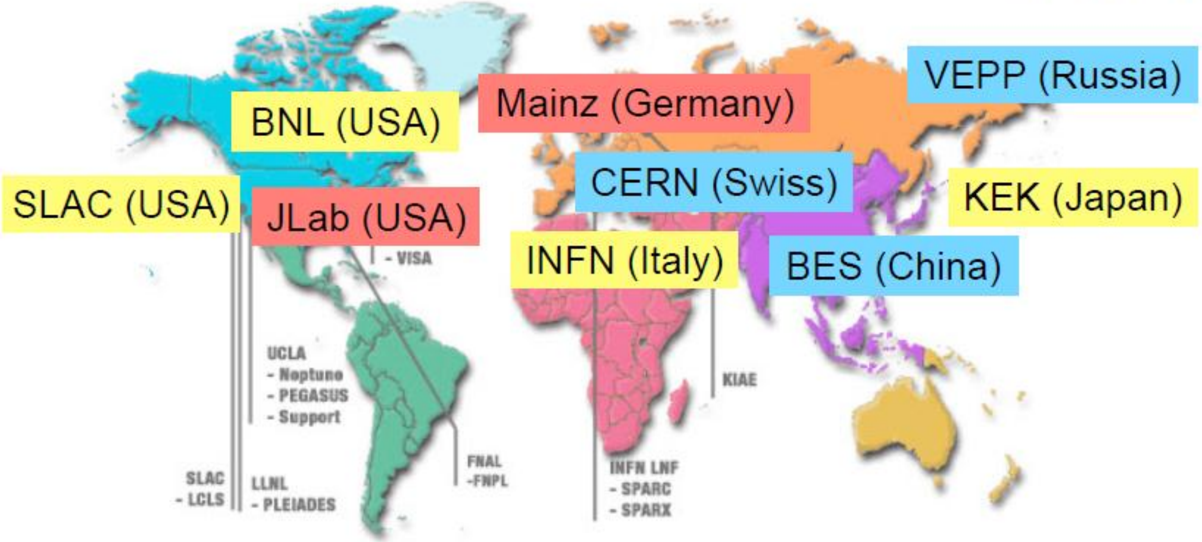
1. S= 0 - scalar portal – axions, higgs like states
2. S = ½ - neutrino portal - neutral leptons (sterile neutrino)
3. S =1 - vector portal – light dark vector boson

As a review: arXiv:1504.04855

1.Introduction

Dark Force searches in the Labs

Many searches for Dark Force in the Labs around the world (ongoing/proposed).



Experimental bounds

- Astrophysical bounds
- Photon Regeneration Experiments
- K-meson decays
- Upsilon decays
- Electron Beam Dump experiments
- Electron Fixed-Target Experiments
- Proton Beam Dump Experiments

1.Introduction

- The aim of this talk is the discussion
- of the vector portal (theoretical arguments and experimental searches of light vector particles
- There are several motivations
- 1. Dark matter motivations(excess of positrons, hint in favor of dark matter selfinteraction

General idea

Besides SM we have some hidden sector and this sector interacts with our world due some dark force exchange. The most popular mediator is massive vector boson (dark photon)

L.Okun(1982), B.Holdom(1986), …

For a recent review: P.Hansson Adrian, et al., arXiv:1311.0029(2013)

Muon (g-2) anomaly.

The muon g-2 anomaly discovered at BNL AGS experiment 821

$$a_\mu^{\exp} - a_\mu^{SM} = 288(80) \times 10^{-11}$$

gives 3.6 σ difference with the SM prediction

A lot of explanations exist:

Supersymmetry, leptoquarks, additional vector boson(dark boson)

1.Introduction

- An explanation of g-2 with additional light vector boson(S.N.Gninenko & N.V.K., Phys.Lett. B513,119, 2001) assumes vector like interaction

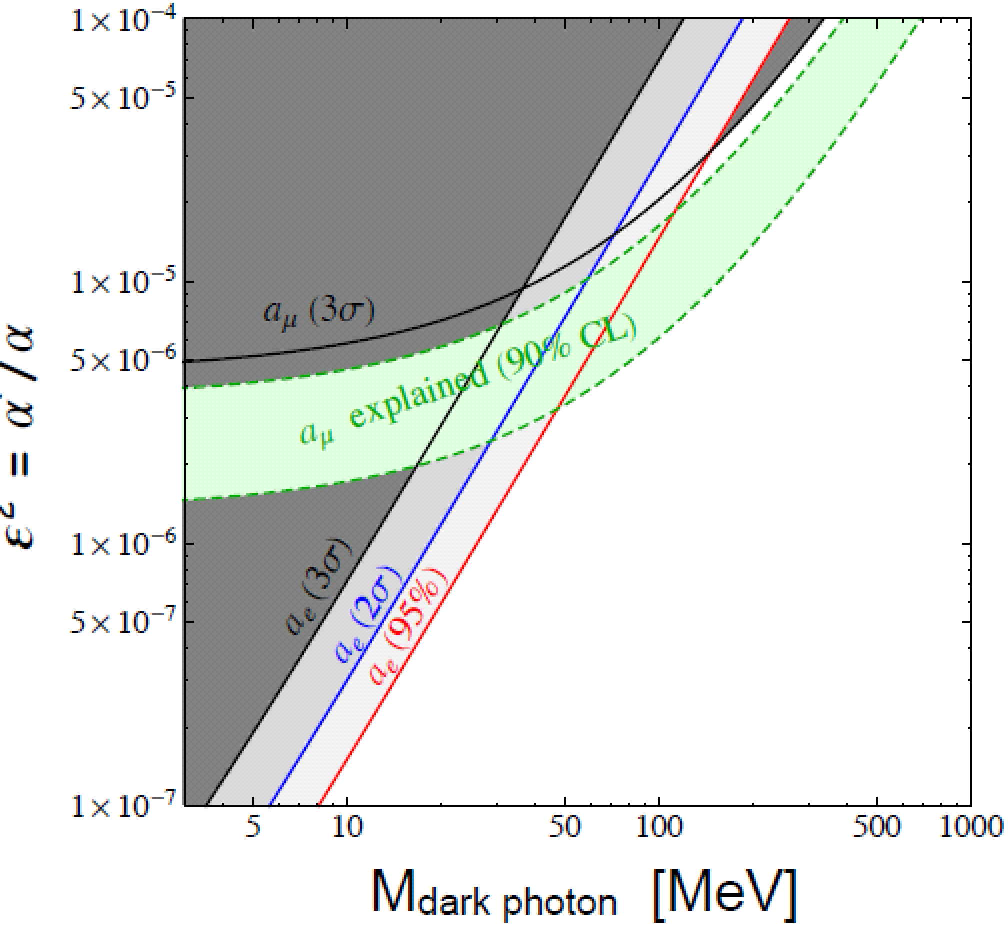
  of new light boson A` with muons with

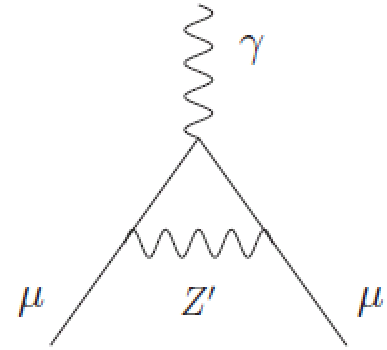
  coupling constant $\alpha_\mu \approx O(10^{-8})$

  For instance for, very light (much lighter than µ-meson) vector boson

$$\alpha_\mu = (1.8 \pm 0.8) \times 10^{-8}$$

Anomalous Magnetic Moment





$(\text{magnetic moment}) = -\frac{g\mu}{}$

Green band: explains the 3.6σ devi

(possibly early hint of Dark Fo

[Gninenko, Krasnikov (2001); Pospe

a_μ **= (g_μ - 2) / 2** : Always an important motivation/constraint for New Physics.

- One of the major motivations for the <u>light Dark gauge boson (Z')</u>.

1.Introduction

$$L_{Z_\mu} = e_\mu \bar{\mu} \gamma_\nu \mu Z_\mu^\nu \,. \qquad (2)$$

The interaction (2) gives additional contribution to the muon anomalous magnetic moment $a_\mu \equiv \frac{g_\mu - 2}{2}$

$$a_l^{Z_\mu} = \frac{\alpha_\mu}{\pi} \int_0^1 \frac{x^2(1-x)}{x^2 + (1-x)M_{Z_\mu}^2/m_l^2} \,, \qquad (3)$$

where $\alpha_\mu = (e_\mu)^2/4\pi$ and M_{Z_μ} is the mass of the Z_μ-boson. Equation (3) allows to determine the α_μ which explains $g_\mu - 2$ anomaly. For $M_{Z_\mu} \ll m_\mu$ we find from Eq.(1) that

$$\alpha_\mu = (1.8 \pm 0.5) \times 10^{-8} \qquad (4)$$

For another limiting case $M_{Z_\mu} \gg m_\mu$ Eq.(1) leads to

$$\alpha_\mu \frac{m_\mu^2}{M_{Z_\mu}^2} = (2.7 \pm 0.8) \times 10^{-8} \qquad (5)$$

1.Introduction

But the postulation of the interaction of dark boson with muon is not the end of the story. What about the interaction of the new boson with other quarks an leptons? Very popular scenario in which Z_μ -boson interact with electromagnetic current of leptons and hadrons

$$L_{\text{int}} = e_\mu J_\nu^{em} Z_\mu^\nu$$

The most popular scenario

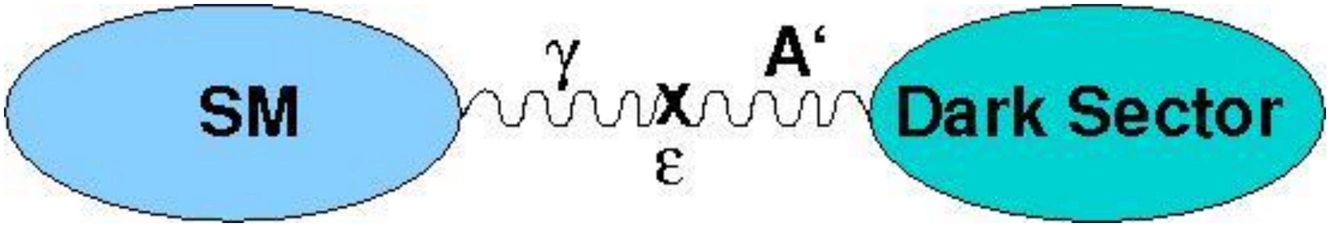
New hidden vector boson A` interacts with our world only due to kinetic mixing with photon(or maybe with Z boson)

$$2\Delta L = \varepsilon F^{\mu\nu} A`_{\mu\nu}$$

Due to this mixing dark photon interacts with our matter with the εe charge

An example of dark mediator A`

Holdom'86, earlier work by Okun, ..



- extra U`(1), new gauge boson A`(dark or hidden photon,…)
- $2\Delta L = \varepsilon F^{\mu\nu} A`_{\mu\nu}$ - 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

Decay modes and signatures

- Unfortunately theory can’t predict the mass
- of A` and its coupling constants with our world and hidden sector. We shall be interested in the region when the A’ mass
- is between 1 MeV and O(1) TeV. For A` mass lighter than 210 MeV A` boson decays into electron-positron pair, invisible modes if A` acquires a mass by Stueckelberg mechanism

2. Experimental bounds

For this scenario there are several bounds which exclude possible g-2 anomaly explanation

1. Bound from electron magnetic moment excludes masses below 30 MeV
2. Phenix collaboration excluded masses between 36 MeV and 90 MeV

2. Experimental bounds

3. The A1 and NA48 collaborations excluded masses

between 30 MeV and 300 MeV

BaBar collaboration excluded masses

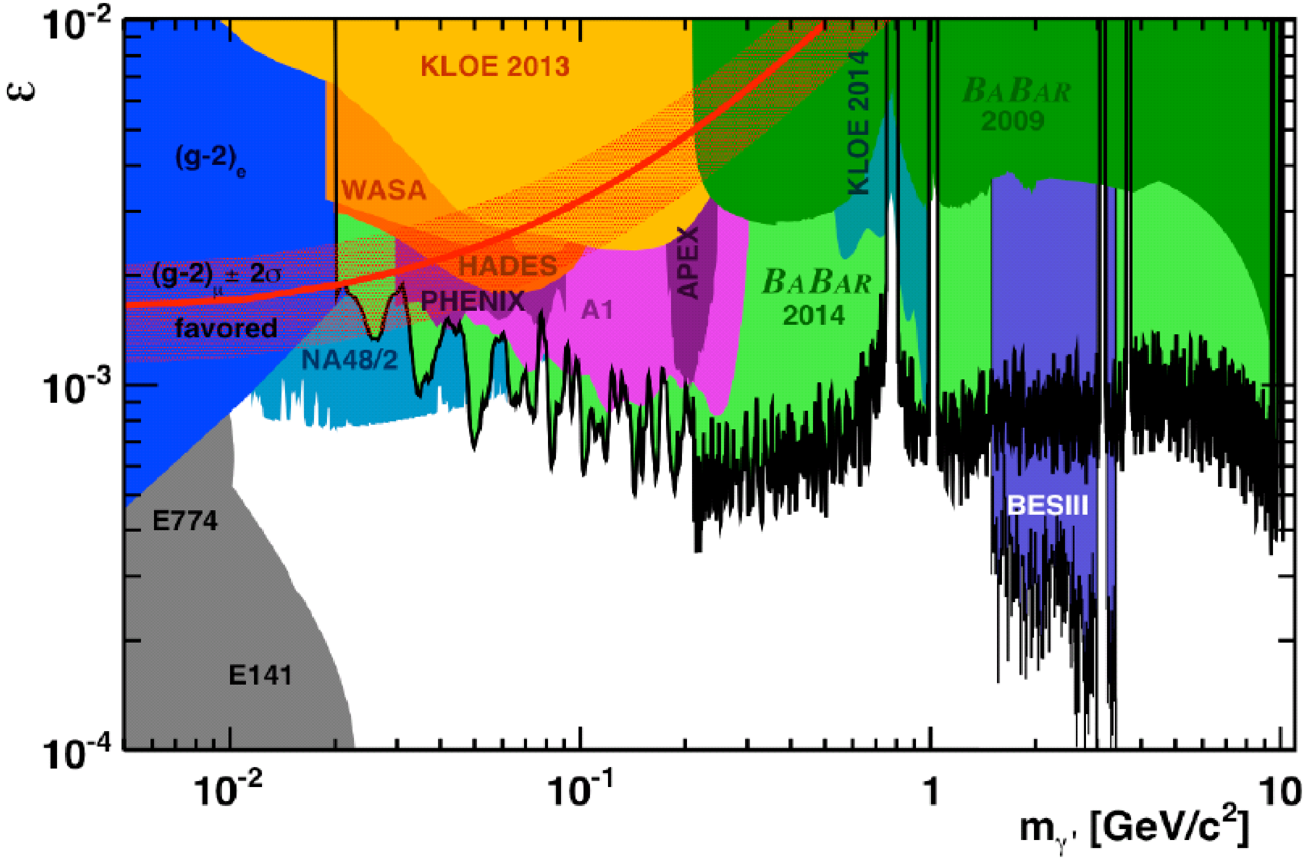
between 32 MeV and 10.2 GeV

So the possibility of g-2 anomaly

explanation due to existence of light

vector boson is excluded

Exclusion plot



2.Experimental bounds

It should be noted that in the considered model for A` boson lighter than 210 MeV the A` boson decays mainly into electron positron pair

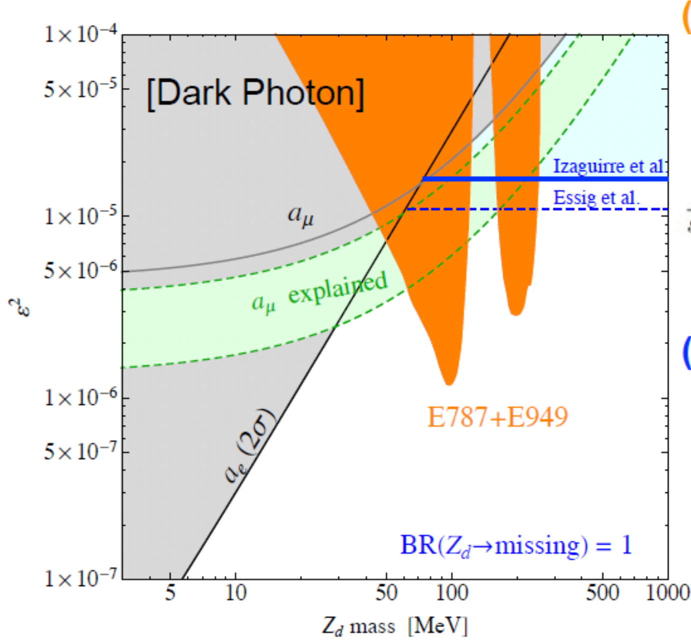
2.Experimental bounds

There is also possibility that new boson A` decays mainly into invisible modes, new light particles χ. For such scenario bound from $K^+ \to \pi^+ + nothing$ decay and the off resonance Ba Bar result exclude masses except 30 MeV and 50 and around 140 MeV

2.Experimental bounds

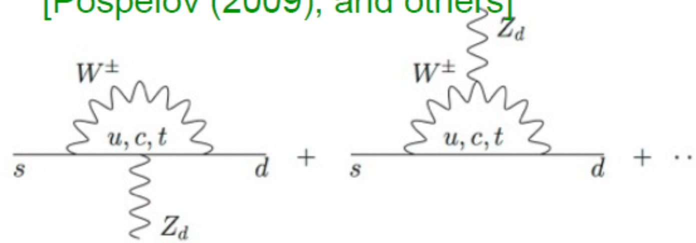
Invisibly decaying Dark gauge boson

(ii) Missing Energy (Z' $\rightarrow \chi\chi$) searches



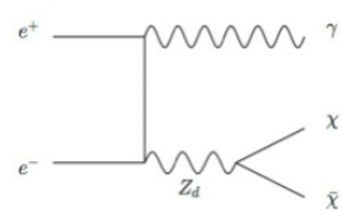
(i) $K^+ \rightarrow \pi^+$ + nothing (BNL E787+E949)

[Pospelov (2009); and others]



(ii) $e^+e^- \rightarrow \gamma$ + nothing (BABAR)

[Izaguirre *et al* (2013); Essig *et al* (2013)]



2.Experimental bounds

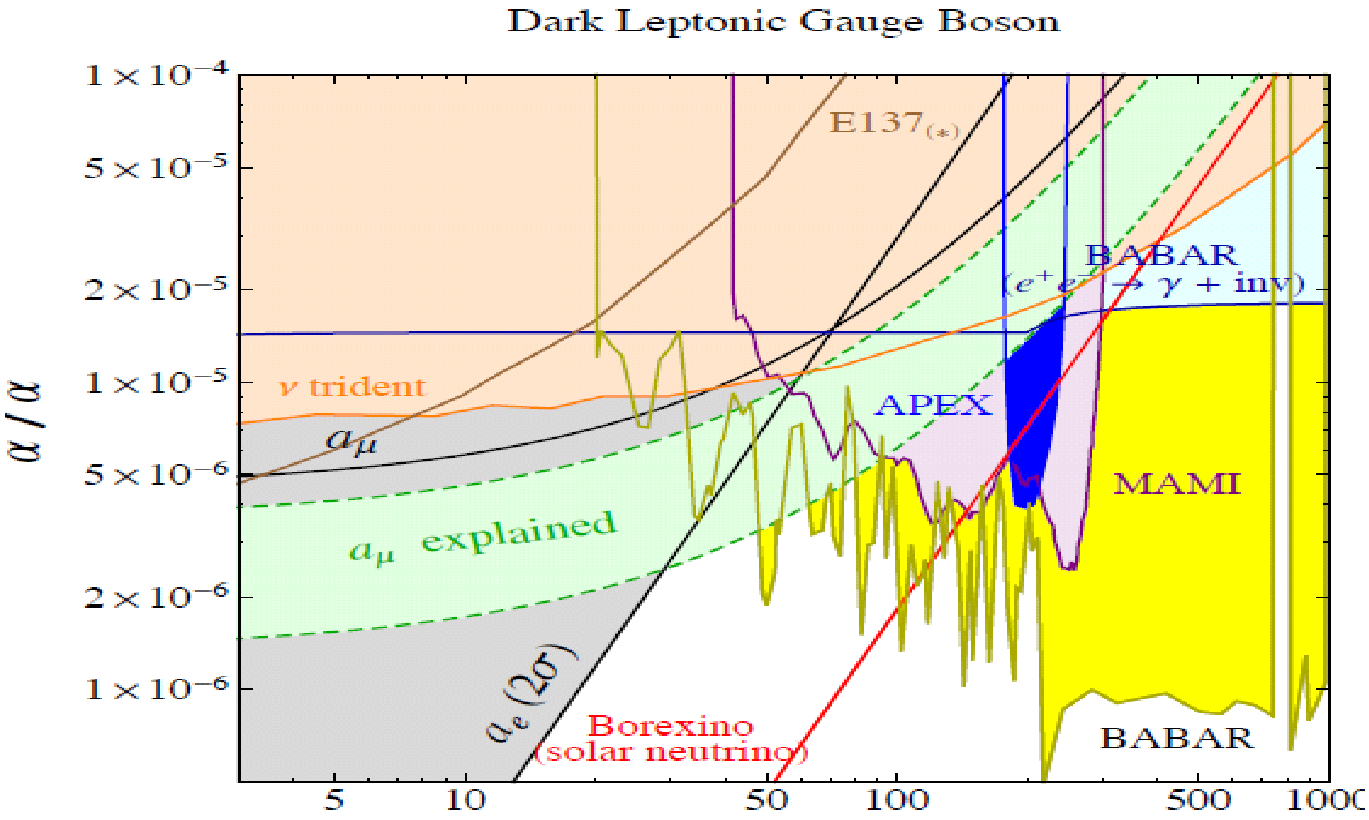
Other possibility is that new boson Z\` interacts only with leptonic current

$$L_{Z_\mu} = e_\mu[\bar{e}\gamma_\nu e + \bar{\nu}_{eL}\gamma_\nu\nu_{eL} + \bar{\nu}\gamma_\mu\mu + \bar{\nu}_{\mu L}\gamma_\nu\nu_{\mu L} + \bar{\tau}\gamma_\nu\tau + \bar{\nu}_{\tau L}\gamma_\nu\nu_{\tau L}]Z^\nu_\mu$$

The bound from $862\ KeV\ {}^7Be$ Borexino experiment excludes the possibility of g-2 explanation

2.Experimental bounds

[LEE (2014)]



Experimental bounds

There is possibility that new boson Z\` interacts only with $L_\mu - L_\tau$ current

$$L_{Z_\mu} = e_\mu [\bar{\mu}\gamma_\nu\mu + \bar{\nu}_{\mu L}\gamma_\nu\nu_{\mu L} - \bar{\tau}\gamma_\nu\tau - \bar{\nu}_{\tau L}\gamma_\nu\nu_{\tau L}] Z_\mu^\nu$$

For this model the most nontrivial bound (W.Almannsofer et. al) comes from CCFR data on neutrino trident $\nu_\mu N \to \nu_\mu N + \mu^+\mu^-$ production. Masses $m_{Z_\mu} \geq 400\ MeV$ are excluded

3. EXPERIMENT P348 at CERN SPS

Experimental proposal(S.Andreas et al.,arXiv:1308.6521

We proposed to use SPS secondary e-beams with an energy of electrons 30 -300 GeV to produce A` bosons in reaction eZ ---→ eZA` (A` bremsstrahlung) and to use decays A` ---→e+e- and A`-→invisible

Research program of P348 (still under developme

1. Searches for A`->e+e- and A`->invisible decay
of massive dark photons (Dark matter)

2. Search for electrophobic new gauge boson
Z`(muon g-2 anomaly)

3. Searches for the decays π^0, η, η' -> invisible

4. Searches for the decays K_S, K_L -> invisible and
test of the Bell-Steinberger relation

Program is based on the missing-energy approac
developed for fixted-target experiments

Focus of this talk on items 1. and 2.

SPSC recommended to focus on A`->invisible decay

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[f 1], 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[c], 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

arXiv:1312.3309[hep-ex]

December 6, 2013

CERN

MINUTES of the 113th Meeting of the SPSC
Held on Tuesday 8 April and Wednesday 9 April 201

7. FOLLOW-UP ON EXPERIMENTS AND PROPOSALS

7.1 P348

The SPSC **received with interest** the answers to the referees' question P348, describing the search for light dark matter using the SPS.

The Committee **recommends** that the Collaboration place more focus channel, the more competitive of the two channels.

The SPSC **recommends** a test run of two weeks at the SPS for the mea backgrounds, a study of the performance of the apparatus and an initial matter.
The Committee also **recommends** that the results of the test run, as we simulation studies, should serve as input for a technical design report t SPSC.

P348 Collaboration (preliminary)

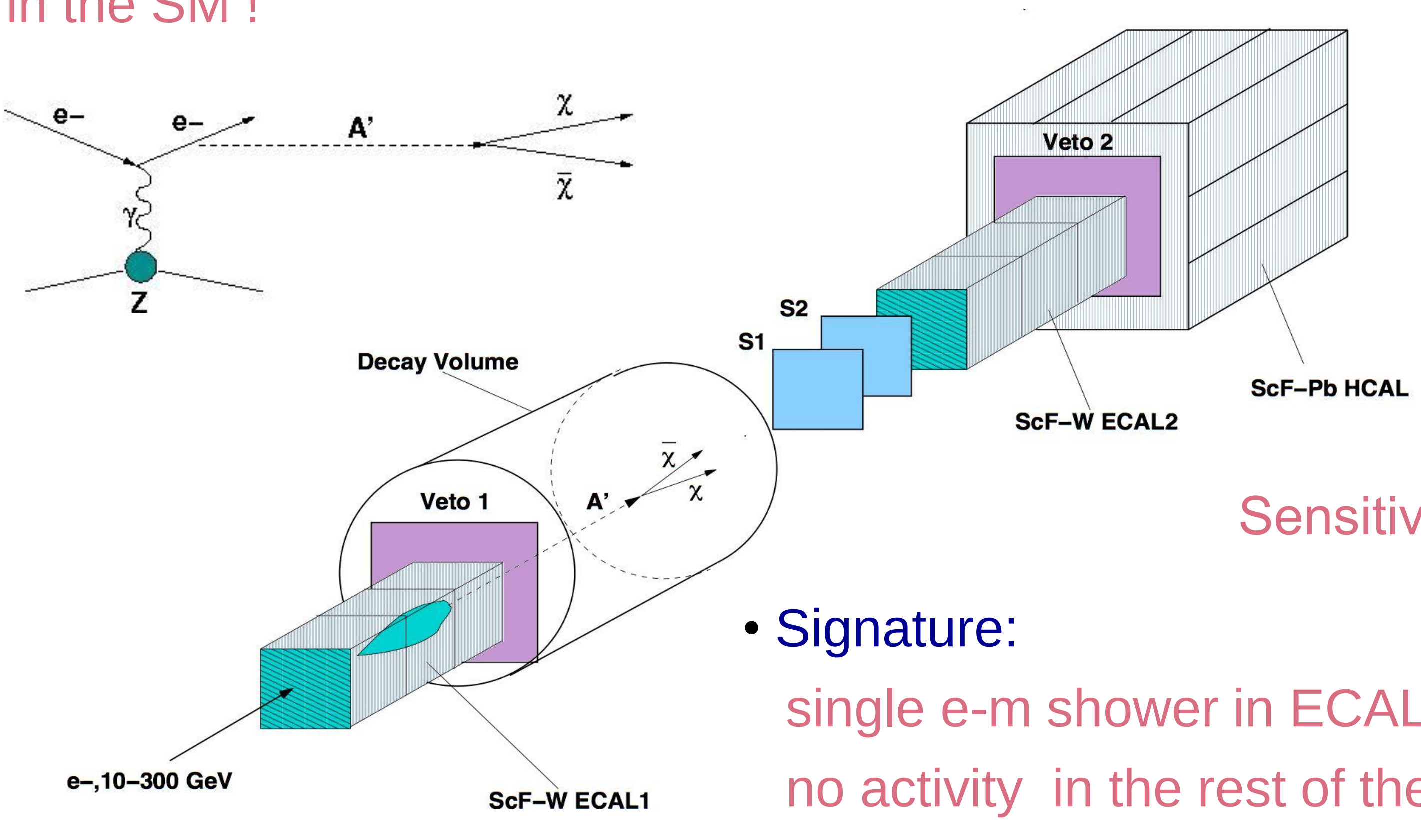
Technical University UTFSM, Valparaiso, Chile
W. K. Brooks, H. Hakobyan, S. Kuleshov, R. Rios
Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany
S. Andreas, A. Ringwald
Physics Department, University of Patras, Patras, Greece
A. Gardikiotis, K. Zioutas
Center for Axion and Precision Physics, IBS, Physics Depart., KAIST, Republic o
Y.K. Semertzidis
State Research Center of the Russian Federation, Institute for High Energy Ph
IHEP, 142281 Protvino Russia
S.V. Donskov, V.A. Kachanov, Yu.V. Mikhailov, V.A. Poliakov, V.D. Samoyle
Joint Institute for Nuclear Research (JINR) , 141980 Dubna, Russia
G.D. Kekelidze, V.A. Matveev, V.V. Myalkovskiy, D.V. Peshekhonov,
V.D. Peshekhonov, A.A. Savenkov, I.A. Zhukov
Institute for Nuclear Research (INR) RAS, Moscow 117312, Russia
A.V. Dermenev, S.N. Gninenko, F.F. Guber, A.P. Ivashkin, A.E. Karneyeu,
M.M. Kirsanov, N.V. Krasnikov, D.A. Tlisov
ETH Zurich, Institute for Particle Physics, CH-8093 Zurich, Switzerland
D. Banerjee, P. Crivelli, A. Rubbia
P.N.Lebedev Physical Institute of the Russian Academy of Sciences, Moscow 1
Russia *V.O.Tikhomirov*

Search for invisible decay $A' \to \chi\bar{\chi}$

Remember Z-->invisible

in the SM !

e-, 30-100 GeV



Sensitivity ~ ε^2

- Signature:

  single e-m shower in ECAL1 +

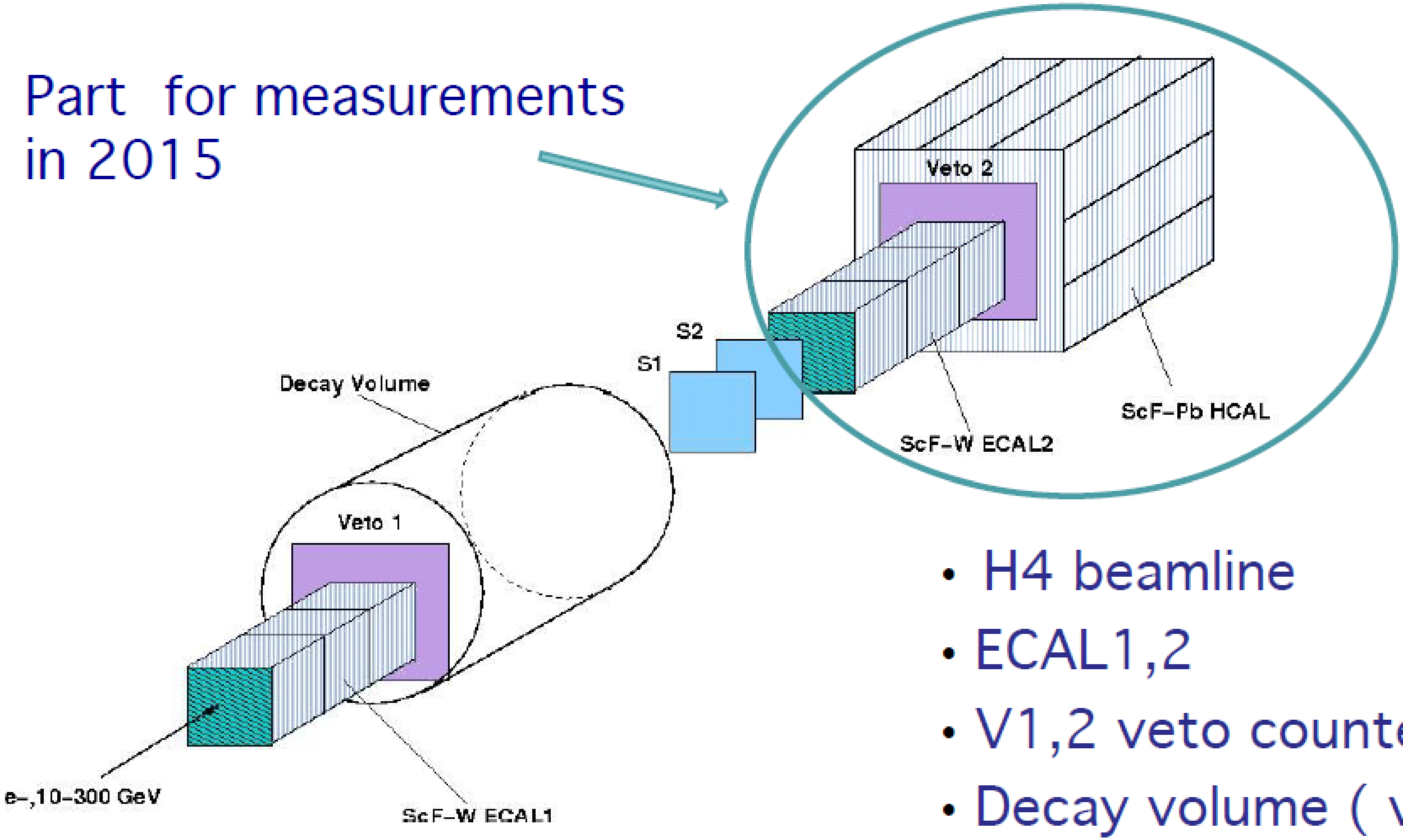
  no activity in the rest of the detector

  S= ECAL1xV1xS1xS2x ECAL2x V2xHCAL

- $E_1 \ll E_0$, and $E_0 \neq E_1 + E_2 \approx E_1$
- detector hermeticity is a crucial item

Setup to search for A`->e+e- and A`-> invisible de

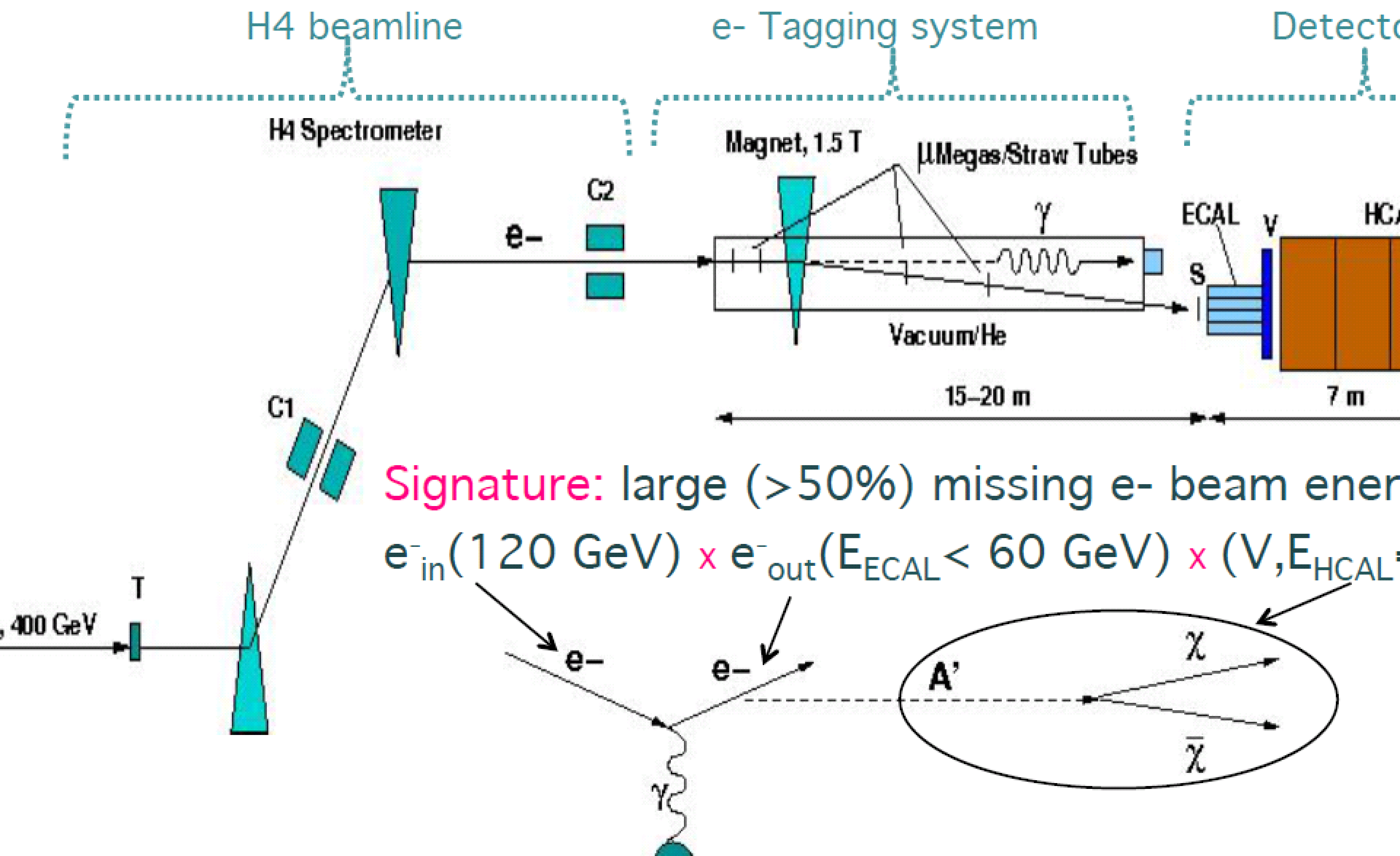
Part for measurements in 2015



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

Setup for invisible A` decay in 2015

Three basic components

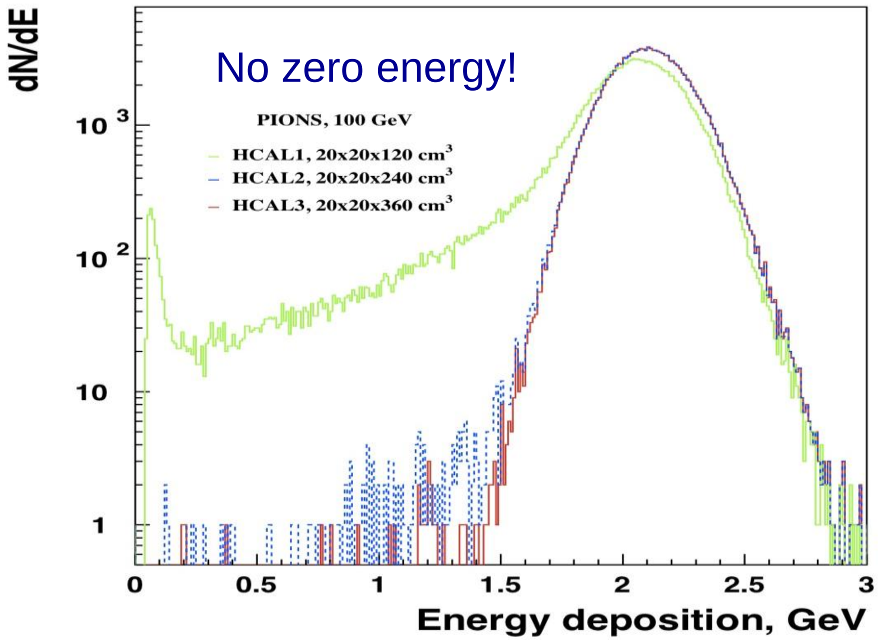


Signature: large (>50%) missing e- beam ener

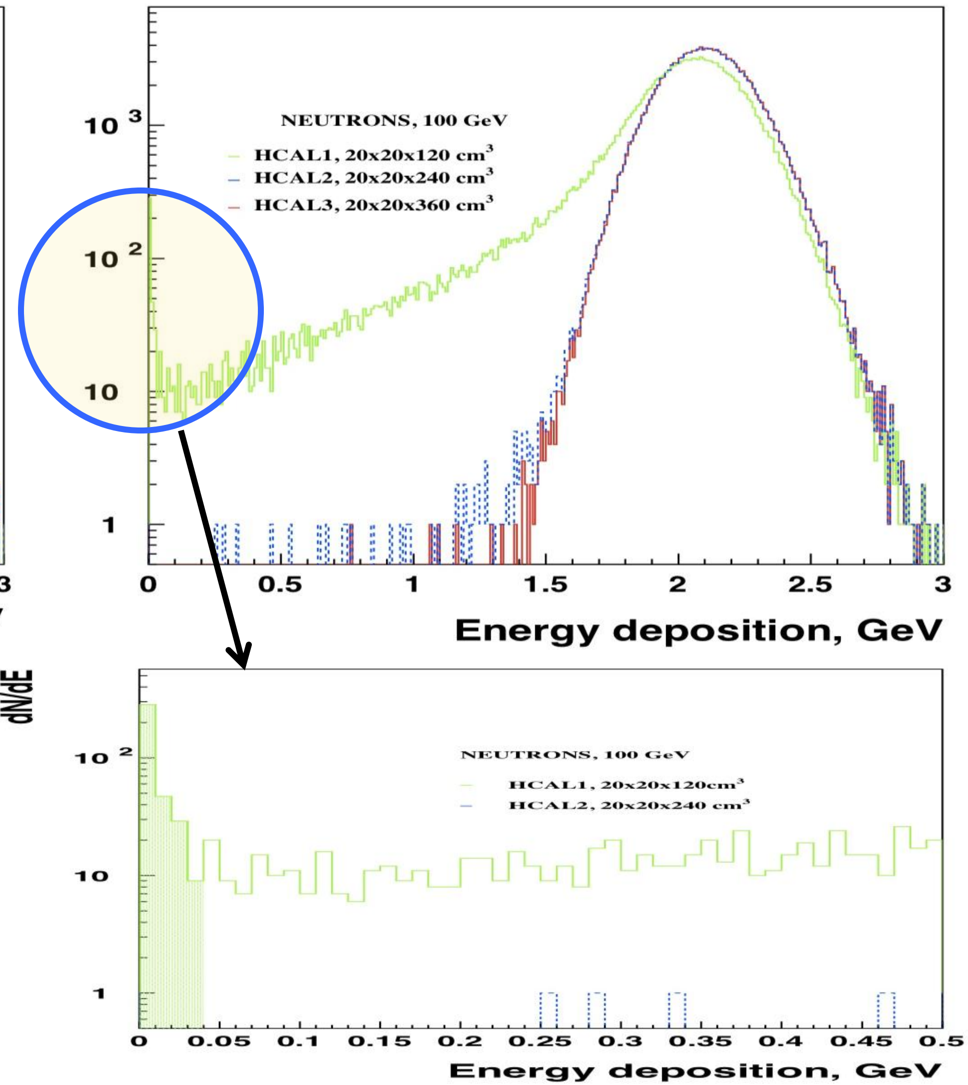
$e^-_{in}(120\ GeV) \times e^-_{out}(E_{ECAL} < 60\ GeV) \times (V, E_{HCAL}$

HCAL hermeticity for 3 consequtive modules

Pions, 100 GeV

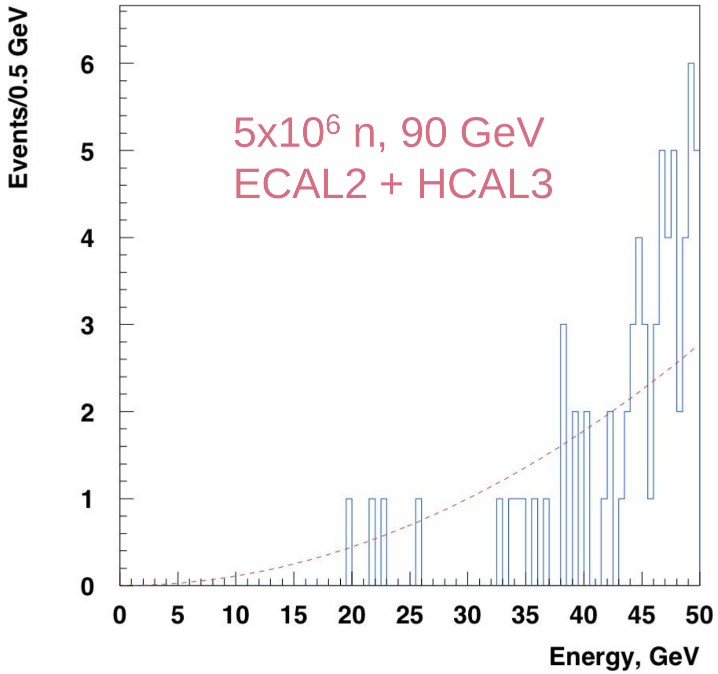


Neutrons, 100 GeV

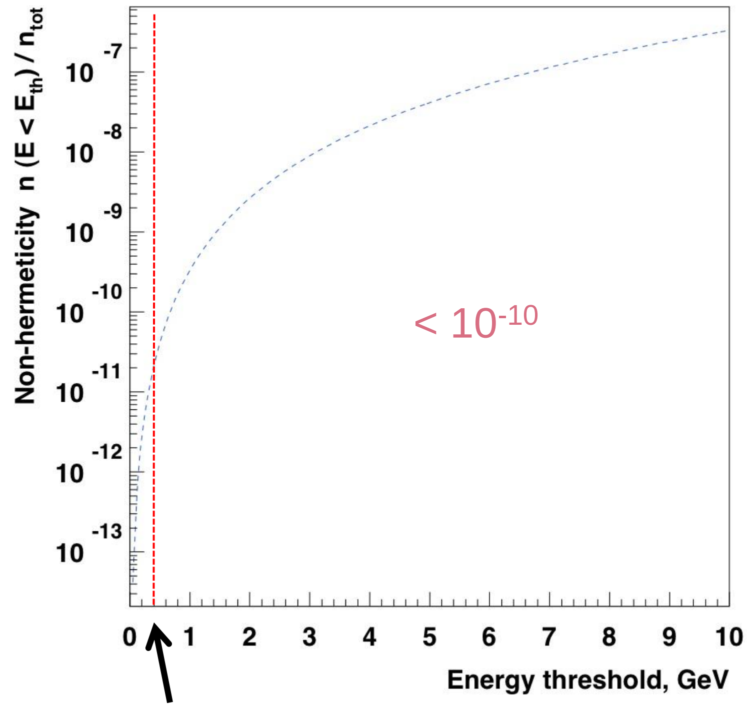


Expected HCAL energy threshold ~ 20-50 keV determined by noise and pileups.

Estimated ECAL2+ HCAL3 nonhermeticity



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

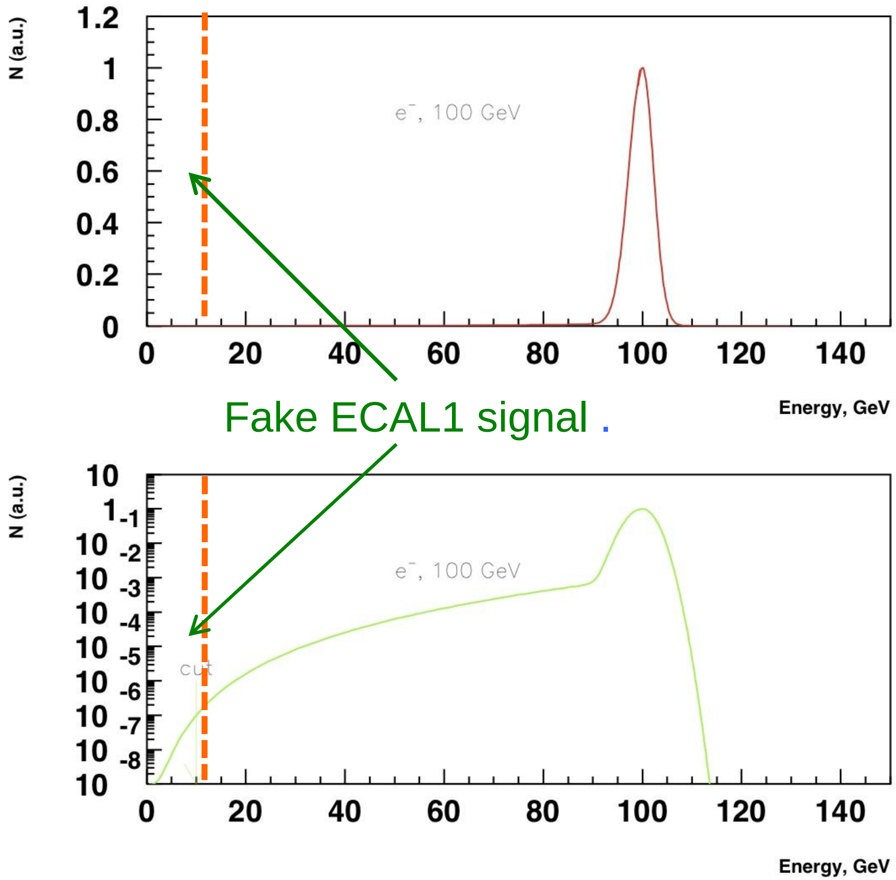


ECAL2+HCAL3 nonhermeticity as a funcion of the energy threshold

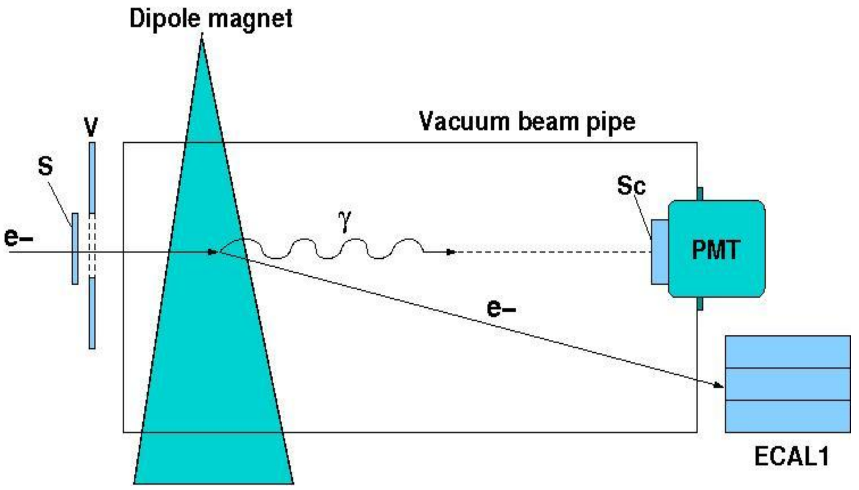
Summary of background sources for A`-> invisible

Source	Expected level	Comment
Beam contamination		
-π, *p*, μ reactions and punchthroughs,… - e- low energy tail due to bremss., π,μdecays 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 Zνν	$< 10^{-13}$ $< 10^{-13}$	~10 mb x nonherm. WI σ estimated. textbook process, first observation?
Total	$< 10^{-12}$ + ?	

Additional tag of electrons with SR photons



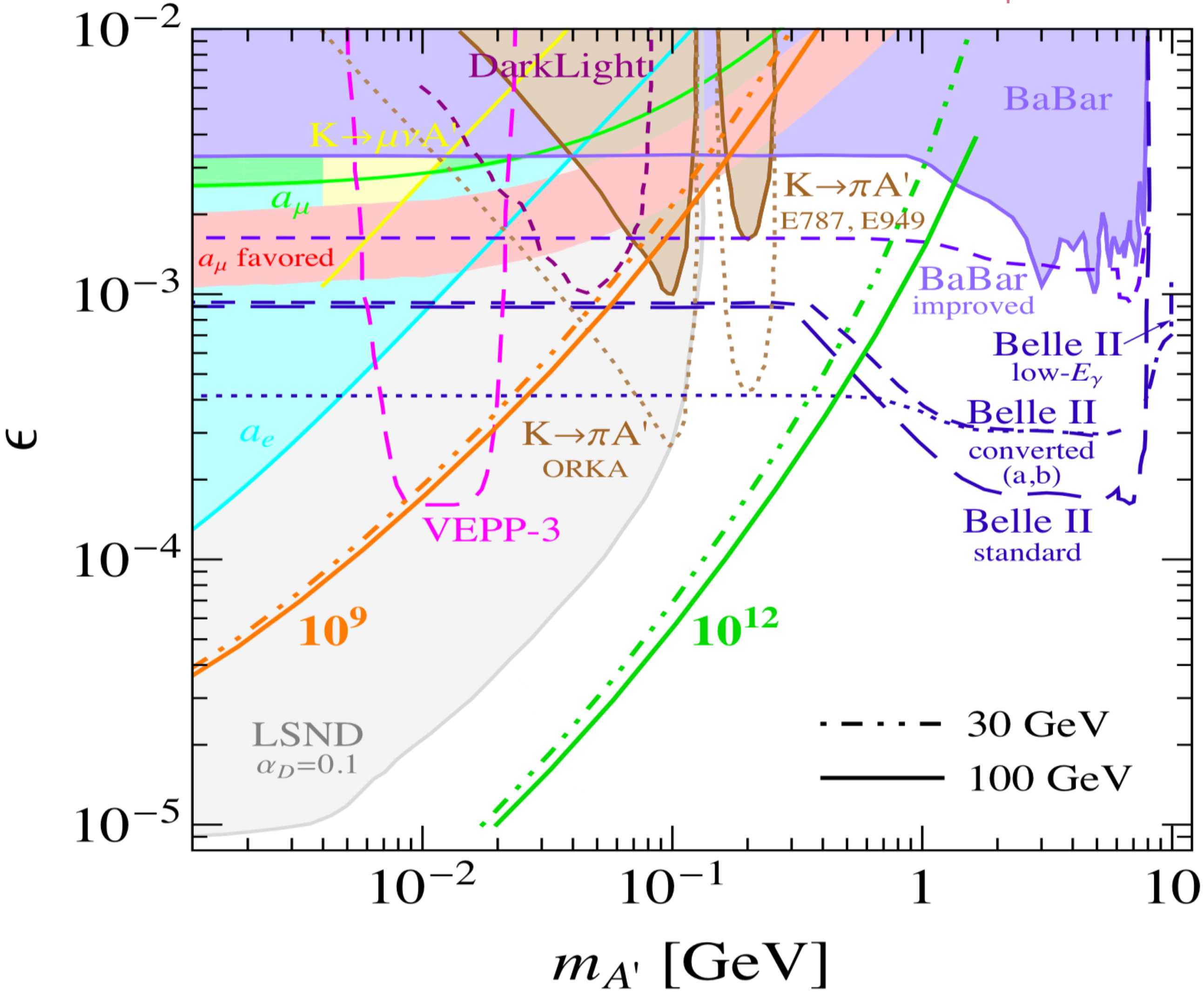
Hypothetical e- beam energy distribution (not simulated).



- 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 $E_\gamma > 0.1\ (\hbar\omega)_\gamma^c \sim 100$ 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)

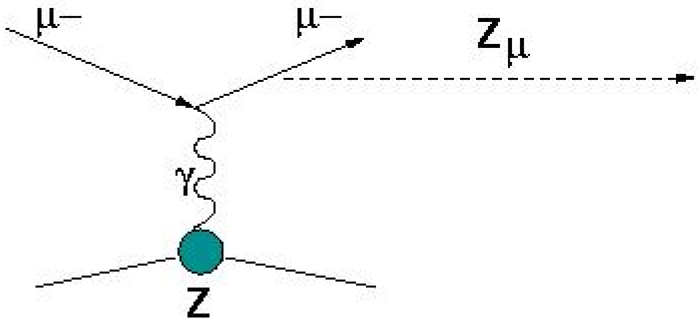
With one day of running we could cover completely the $(g\text{-}2)_\mu$ favored region!



3. P348 experiment

P348 experiment is able to completely eliminate the possibility with invisible A` decays

4.The experiment at CERN SPS muon beam



4. The experiment with muon **beam**

Existing experimental data restrict rather strongly(but not comletely close) dark vector boson g-2 explanation.The aim of this part is short review of our recent proposal

(S.Gninenko, N.K and V.Matveev, Phys.Rev. D91(2015)095015)

to look for dark boson at collisions of CEF $\mu(p) + Z(P) \rightarrow Z(P') + \mu(p') + Z_\mu(k)$

4.The experiment at CERN SPS muon beam

In the Weizsaker-Williams approximation the Z_μ-production cross section is (J.Bjorken et al.)

$$\frac{d\sigma(\mu + Z \to \mu + Z_\mu + Z)}{dE_{Z_\mu}\, d\cos\theta_{Z_\mu}} = \frac{\alpha\chi}{\pi}\frac{E_0 x \beta_{Z_\mu}}{1-x} \times \frac{d\sigma(p + q \to p' + k)}{d(pk)}\Big|_{t=t_{min}}$$

$$x \equiv E_{Z_\mu}/E_0\,,$$

$$t \equiv -q^2\,,$$

$$\beta_{Z_\mu} = \sqrt{(1 - m^2_{Z_\mu}/E_0^2)}$$

4.The experiment at CERN SPS muon beam

$$q^0 = \frac{|\vec{q}|^2}{2M} \approx 0 \,,$$

$$U \equiv U(x, \theta_{Z_\mu}) = E_0^2 \theta_{Z_\mu}^2 x + m_{Z_\mu}^2 \frac{1-x}{x} + m_\mu^2 x$$

$$|\vec{q}| = \frac{U}{2E_0(1-x)} \,,$$

At the q^2_{min} kinematics [31]

$$-\tilde{u} = m_\mu^2 - u_2 = 2p \cdot k - m_{Z_\mu}^2 = U \,,$$

$$\tilde{s} = -m_\mu^2 + s_2 = 2p^{'} \cdot k + m_{Z_\mu}^2 = \frac{U}{1-x} \,,$$

$$t_2 = (p - p^{'})^2 = -\frac{Ux}{1-x} + m_{Z_\mu}^2 \,.$$

4.The experiment at CERN SPS beam

$$\frac{d\sigma}{dt_2} = \frac{2\pi\alpha\alpha_\mu}{\tilde{s}^2}[\frac{\tilde{s}}{-\tilde{u}} + \frac{-\tilde{u}}{\tilde{s}} + 4(\frac{m_\mu^2}{\tilde{s}} + \frac{m_\mu^2}{\tilde{u}})^2 \;\; +4(\frac{m_\mu^2}{\tilde{s}} + \frac{m_\mu^2}{\tilde{u}})$$
$$+\frac{2m_{Z_\mu}^2 t_2}{-\tilde{u}\tilde{s}} + 2m_{Z_\mu}^2 m_\mu^2((\frac{1}{\tilde{s}})^2 + (\frac{1}{\tilde{u}})^2)]. \qquad (23)$$

In the Weizsacker-Williams approximation the cross section of the $\mu(p) \; + \; Z(P) \to Z(P') \; + \; \mu(p') \; + \; Z_\mu(k)$ reaction is given by

$$\frac{1}{E_0^2 x}\frac{d\sigma}{dx\,d\cos\theta_{Z_\mu}} = 4(\frac{\alpha^2\alpha_\mu\chi\beta_{Z_\mu}}{1-x})[\frac{C_2}{U^2} + \frac{C_3}{U^3} + \frac{C_4}{U^4}], \quad (24)$$

where

$$C_2 = (1-x) + (1-x)^3, \qquad (25)$$

$$C_3 = -2x(1-x)^2 m_{Z_\mu}^2 - 4m_\mu^2 x(1-x)^2, \qquad (26)$$

$$C_4 = 2m_{Z_\mu}^4(1-x)^3 + (1-x)^2[4m_\mu^4 x^2 + 2m_\mu^2 m_{Z_\mu}^2(x^2 + (1-x)^2)]. \qquad (27)$$

4.The experiment at CERN SPS muon beam

By integrating with respect to θ_{Z_ν} we find that

$$\frac{d\sigma}{dx} = 2(\frac{\alpha^2\alpha_\mu\chi\beta_{Z_\mu}}{1-x})[\frac{C_2}{V} + \frac{C_3}{2V^2} + \frac{C_4}{3V^3}], \qquad (28)$$

where

$$V = U(x, \theta_{Z_\mu} = 0) = m^2_{Z_\mu}\frac{1-x}{x} + m^2_\mu x \qquad (29)$$

For a general electric form factor $G_2(t)$ [30] an effective flux of photons χ is

$$\chi = Z^2 \cdot Log$$

$$\chi = \int_{t_{min}}^{t_{max}} dt \frac{(t - t_{min})}{t^2} G_2(t)\,. \qquad (30)$$

For the $M_{z_\mu} < 2m_\mu$ the decays $Z_\mu \to \mu\mu$ are prohibited and Z_μ decays mainly into $Z_\mu \to \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$. For $2m_\mu < M_{Z_\mu} < 2m_\tau$ besides decays into neutrino pairs Z_μ also decays into $\mu^+\mu^-$-pair with decay width

$$\Gamma(Z_\mu \to \mu^-\mu^+) = \frac{\alpha_\mu M_{Z_\mu}}{3}(1 + \frac{2m^2_\mu}{M^2_{Z_\mu}})\sqrt{1 - 4\frac{m^2_\mu}{M^2_{Z_\mu}}} \quad (31)$$

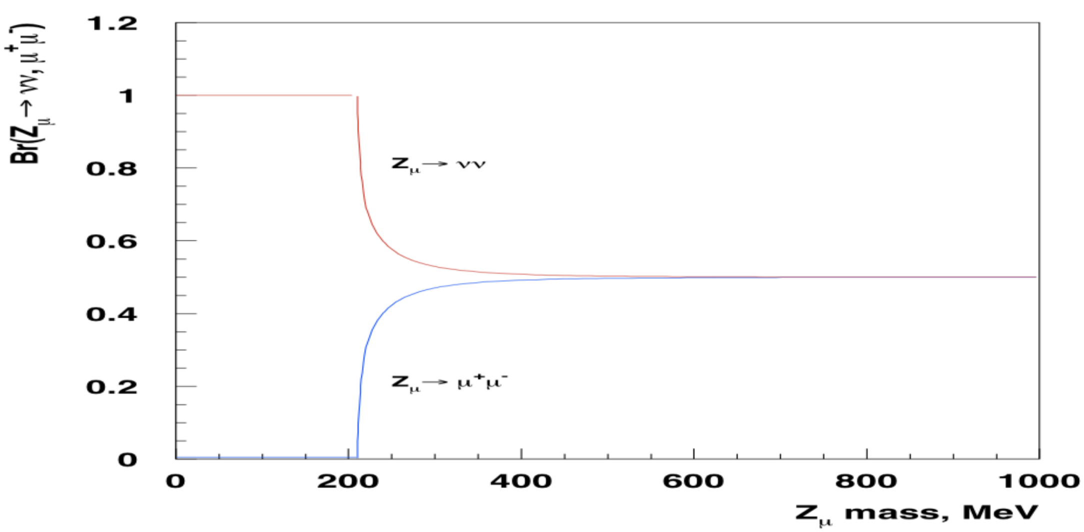
4.The experiment at CERN SPS muon beam

The branching ratio into $\mu^-\mu^+$ pair is determined by the formulae

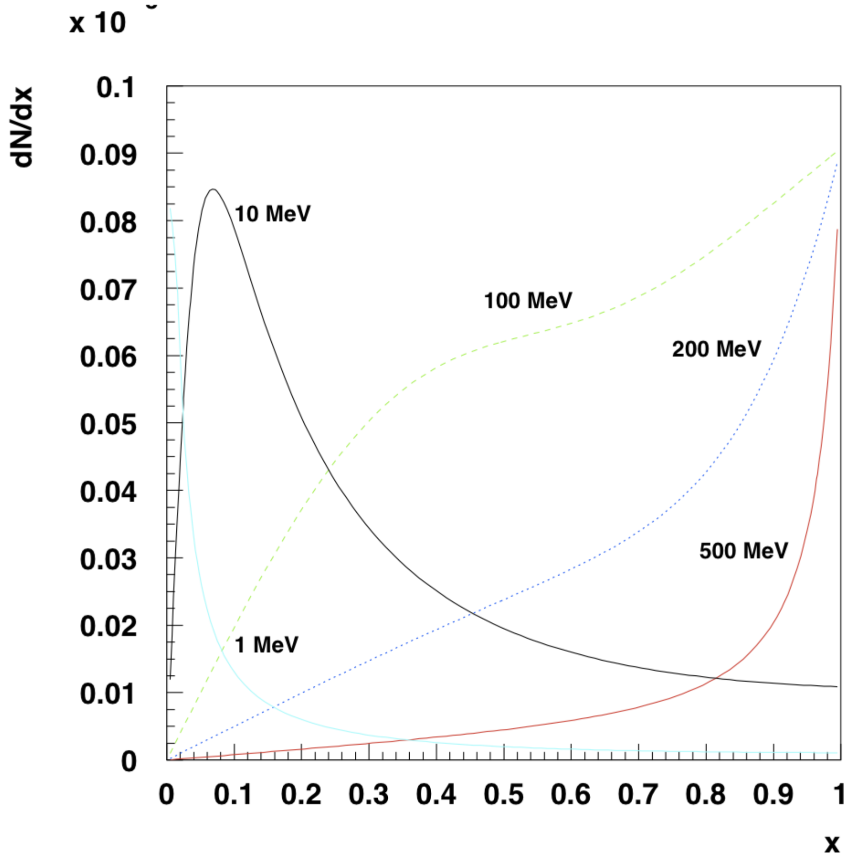
$$Br(Z_\mu \to \mu^-\mu^+) = \frac{K(\frac{m_\mu}{M_{Z_\mu}})}{1 + K(\frac{m_\mu}{M_{Z_\mu}})}, \qquad (32)$$

where

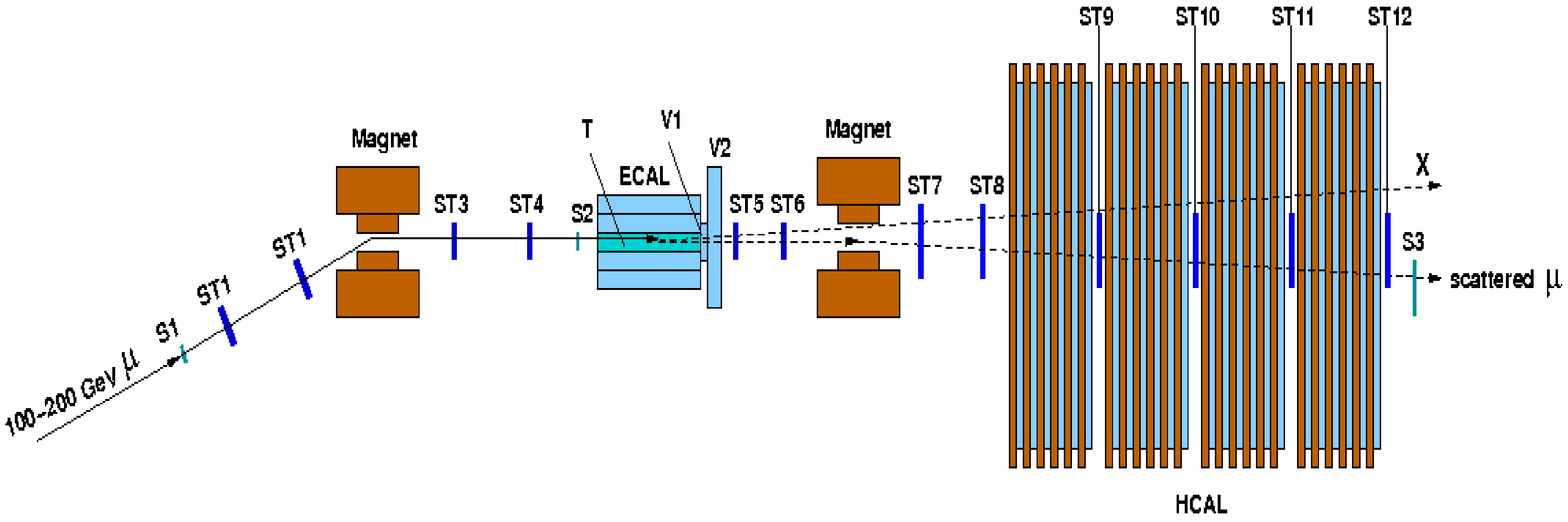
$$K(\frac{m_\mu}{M_{Z_\mu}}) = (1 + \frac{2m_\mu^2}{M_{Z_\mu}^2}) \cdot \sqrt{1 - 4\frac{m_\mu^2}{M_{Z_\mu}^2}}. \qquad (33)$$



4.The experiment at CERN SPS muon beam



Schematic illustration of the setup to search for dark boson



4. The experiment at CERN SPS muon beam

ST1- ST4, ST5-ST6 –straw tubes

S1,S2 ,S3 –fiber hodoscopes

V1,V2 –veto counters

The experiment at CERN SPS muon beam

Coming muon produce dark boson at the target. Dark boson decays into neutrino and escapes the detection. So the signature is imbalance in energy for incoming and outcoming muons without big activity in HCAL and ECAL

4a.backgrounds

The crusial point - backgrounds

Two type of backgrounds

1. Beam related – nonexact knowledge of muon momentum – low energy tails

2. The presence in the beam of kaons and pions decaying into muons

Simulations show that it is possible to

get rid of such backgrounds at the level

$$10^{-12} \leq$$

4a.backgrounds

Second type of backgrounds include:

1. Hard bremsstrahlung
2. Pair production
3. Photonuclear production of of neutral

penetrating particles (photons,neutrons,K-mesons)

Simulations show that for good ECAL and HCAL it is possible to get rid of such instrumental backgrounds at the level 10^{-12}

4a.backgrounds

The crusial point - backgrounds

Two type of backgrounds

1. Beam related – nonexact knowledge of muon momentum – low energy tails

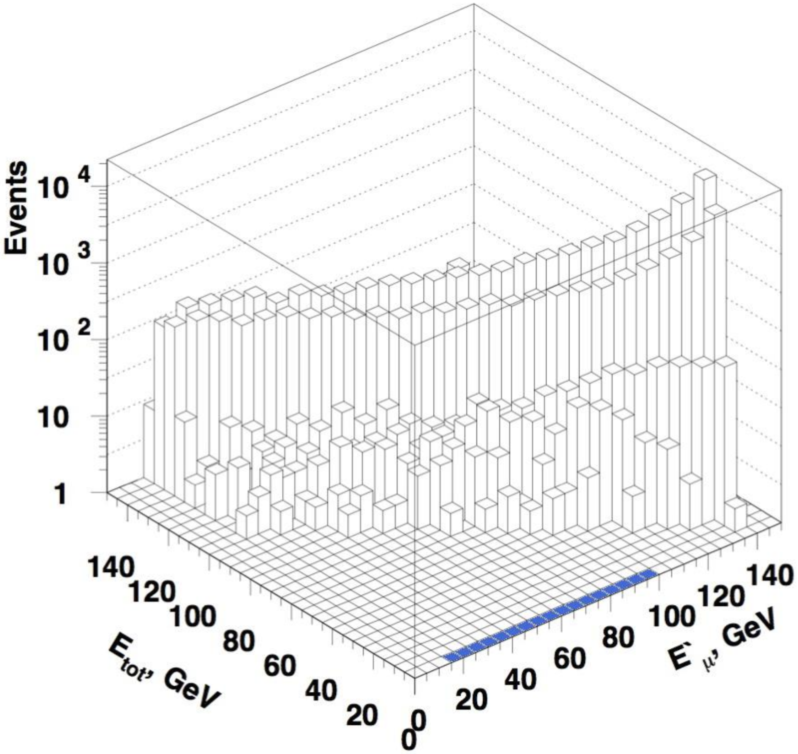
2. The presence in the beam of kaons and pions decaying into muons

Simulations show that it is possible to

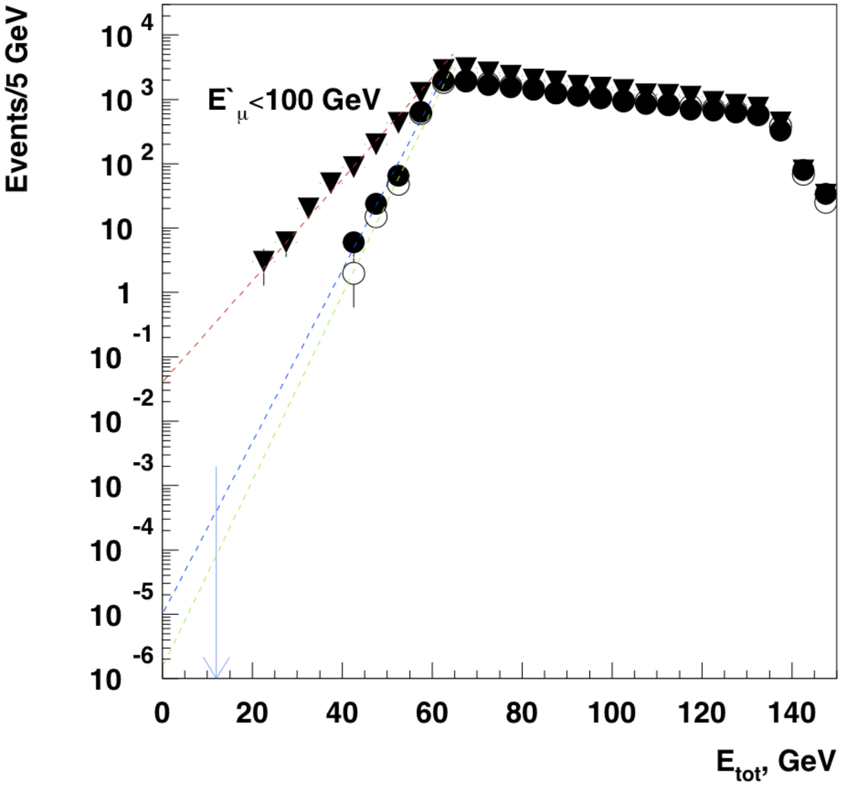
get rid of such backgrounds at the level

$$10^{-12} \leq$$

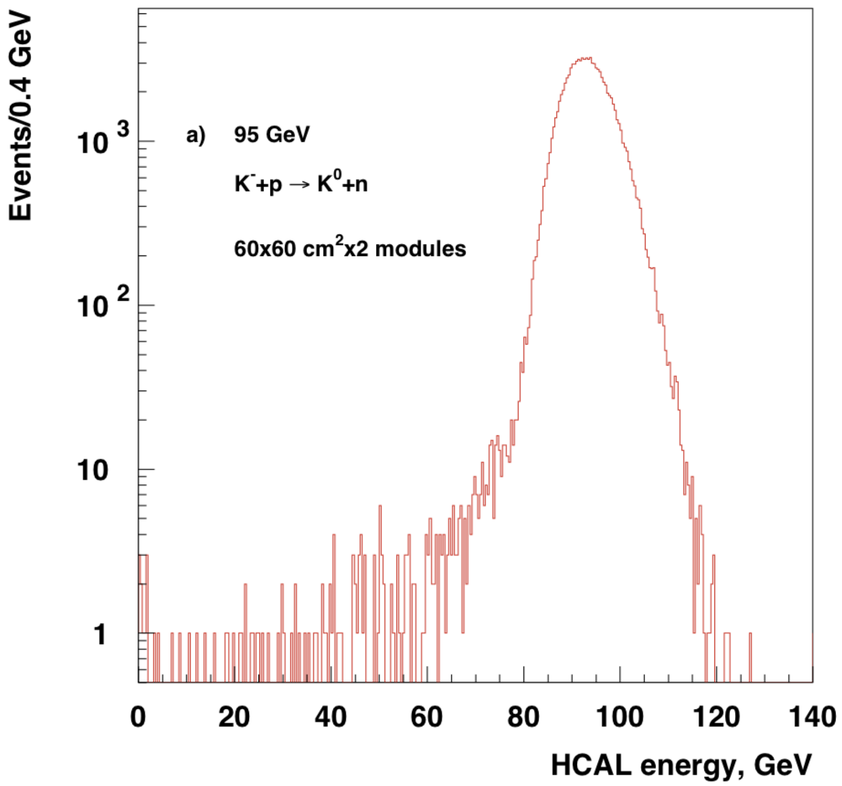
4a.backgrounds



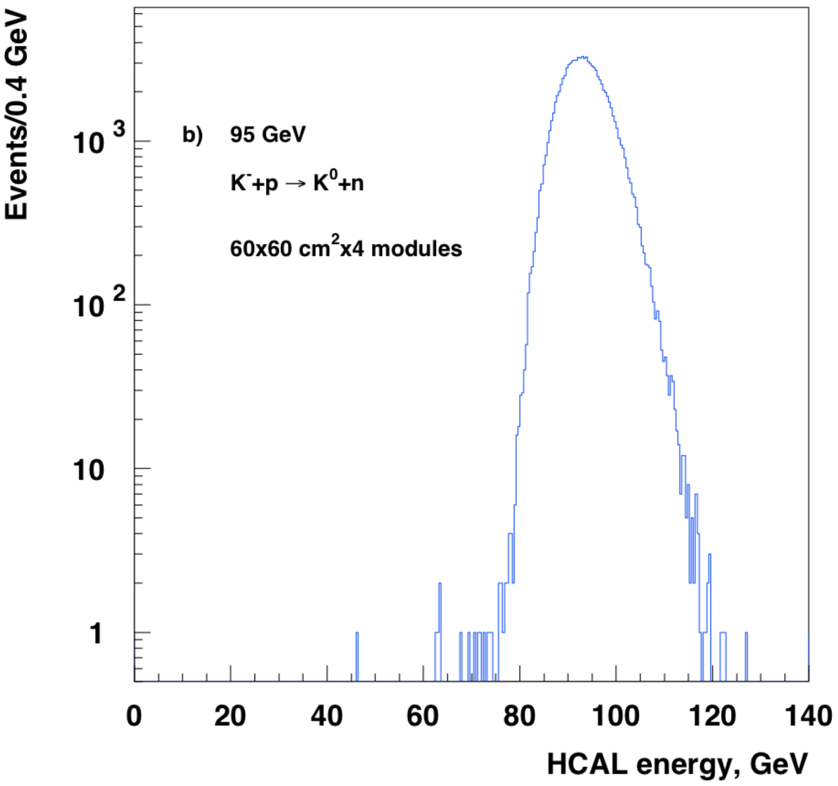
4a.backgrounds



4a.backgrounds



4a.backgrounds



4a.backgrounds

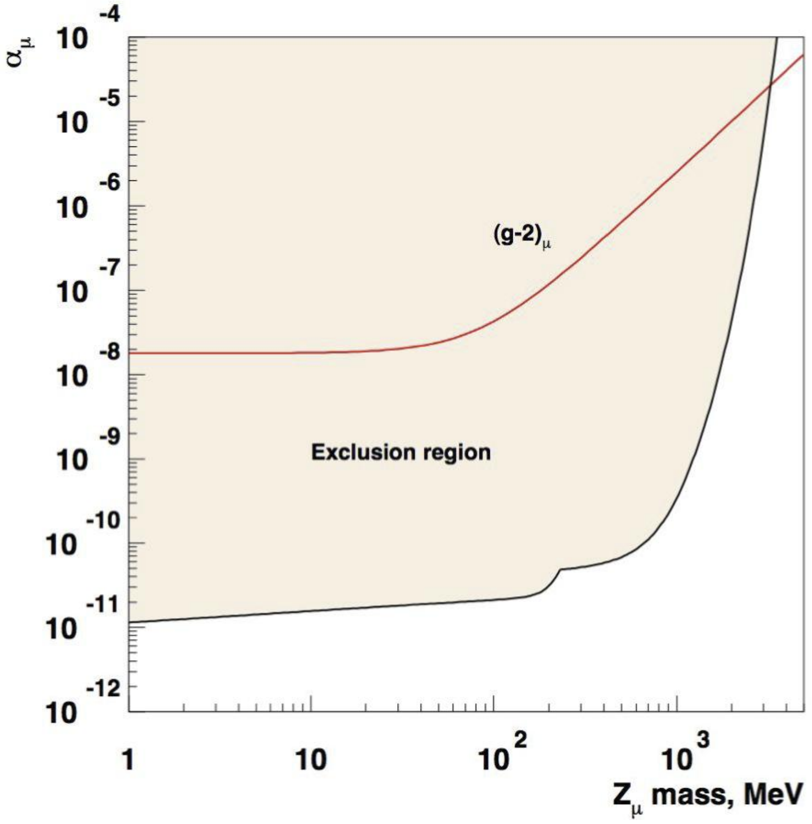
TABLE I: Expected contributions to the total level of background from different background sources estimated for the beam energy 150 GeV (see text for details).

Source of background	Expected level
μ low energy tail	$\lesssim 10^{-13}$
HCAL non-hermeticity	$\lesssim 10^{-13}$
μ induced photo-nuclear reactions	$\lesssim 10^{-13}$
μ trident events	$\lesssim 10^{-12}$
Total (conservatively)	$\lesssim 10^{-12}$

4b.Expected sensitivity

For 10^{12} muons with average energy 150 GeV and in the assumption of zero background we find that it is possible test dark boson muon coupling constant up to $\alpha_\mu \geq 10^{-11}$

4b.Expected sensitivity



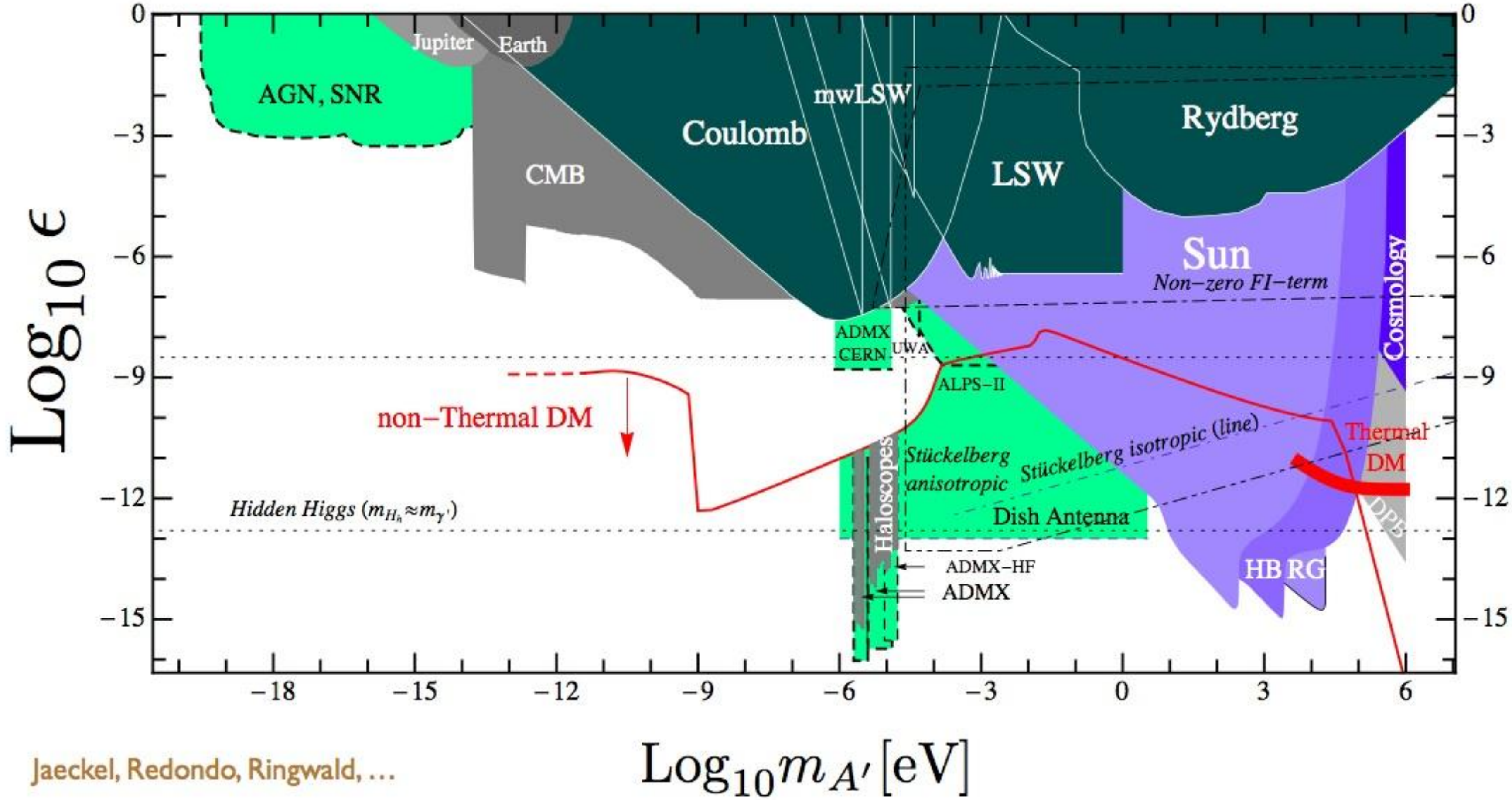
5.Conclusion

(g-2) anomaly explanation due to existence of hypothetical light vector boson is severely restricted(but not excluded by current experiments).

P348 experiment at CERN and(or) an experiment with muon beams will allow to discover new light vector boson or reject this explanation of (g-2) anomaly.

BACKUP

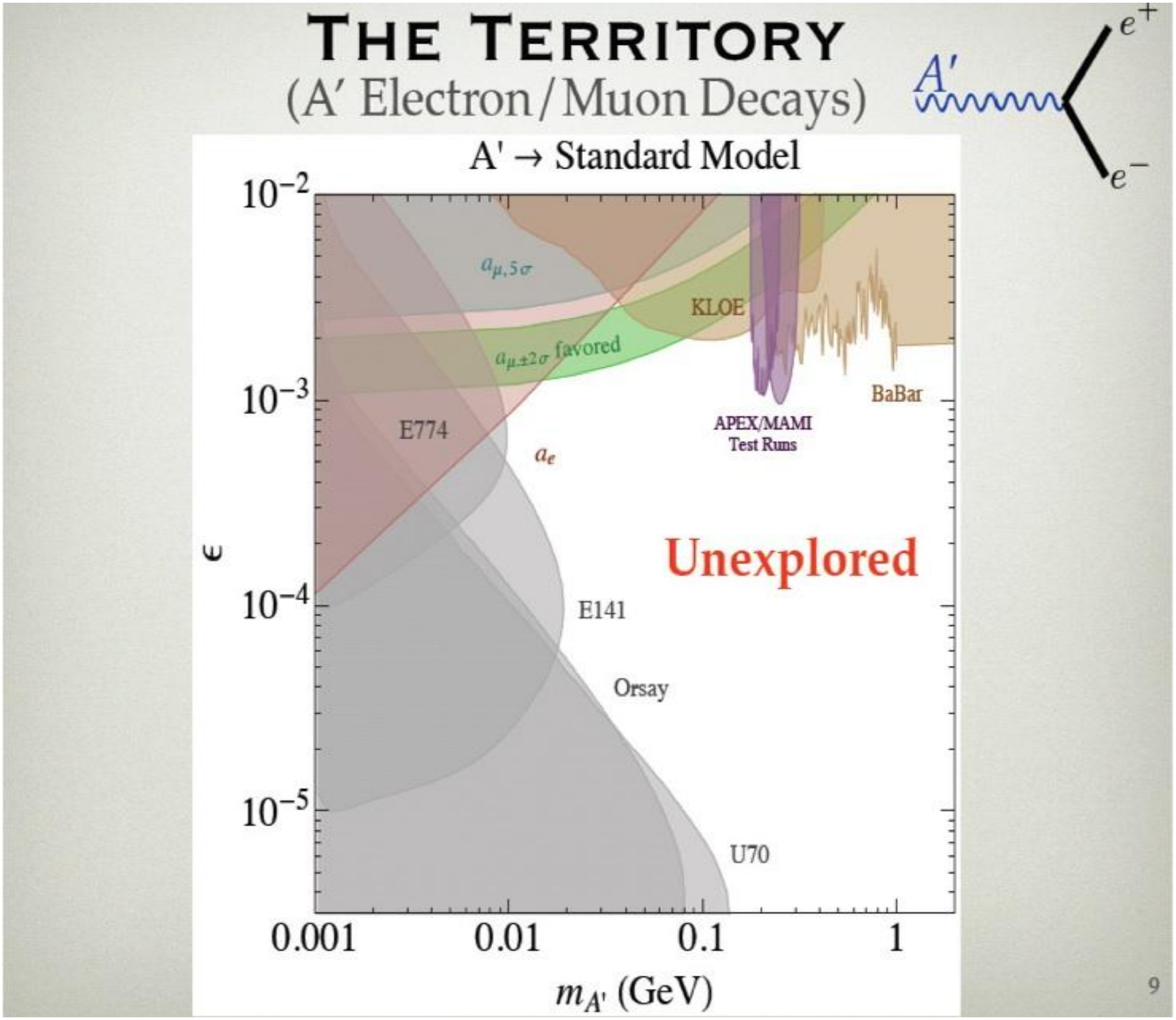
low-mass (< MeV) A′ parameter space

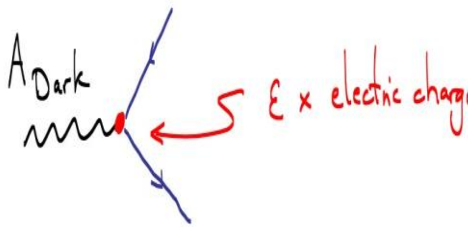


Jaeckel, Redondo, Ringwald, …

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

High mass (> MeV) A` parameter space





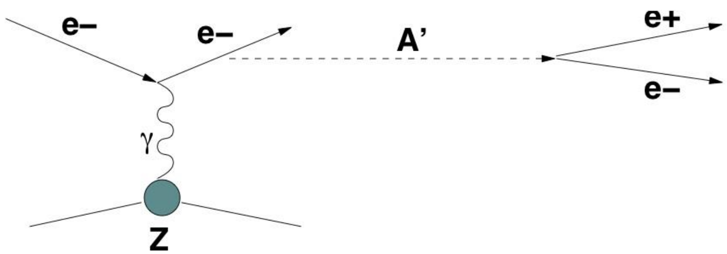
Amazing that $\varepsilon \sim 10^{-3}$, $m_{Dark} \sim$ GeV is not ruled out!

N. Arkani-Hamed, Snowmass 2013

Experiment proposal

- We propose to use SPS e-beams with
- an energy of electrons 30 – 300 GeV to produce A` bosons in reaction
- eZ ---→ eZA` (A` bremsstrahlung)
- and to use decays
- A` ---→e+e-
- A`-→invisible
-

MeV A` production and decay



bremsstrahlung A`

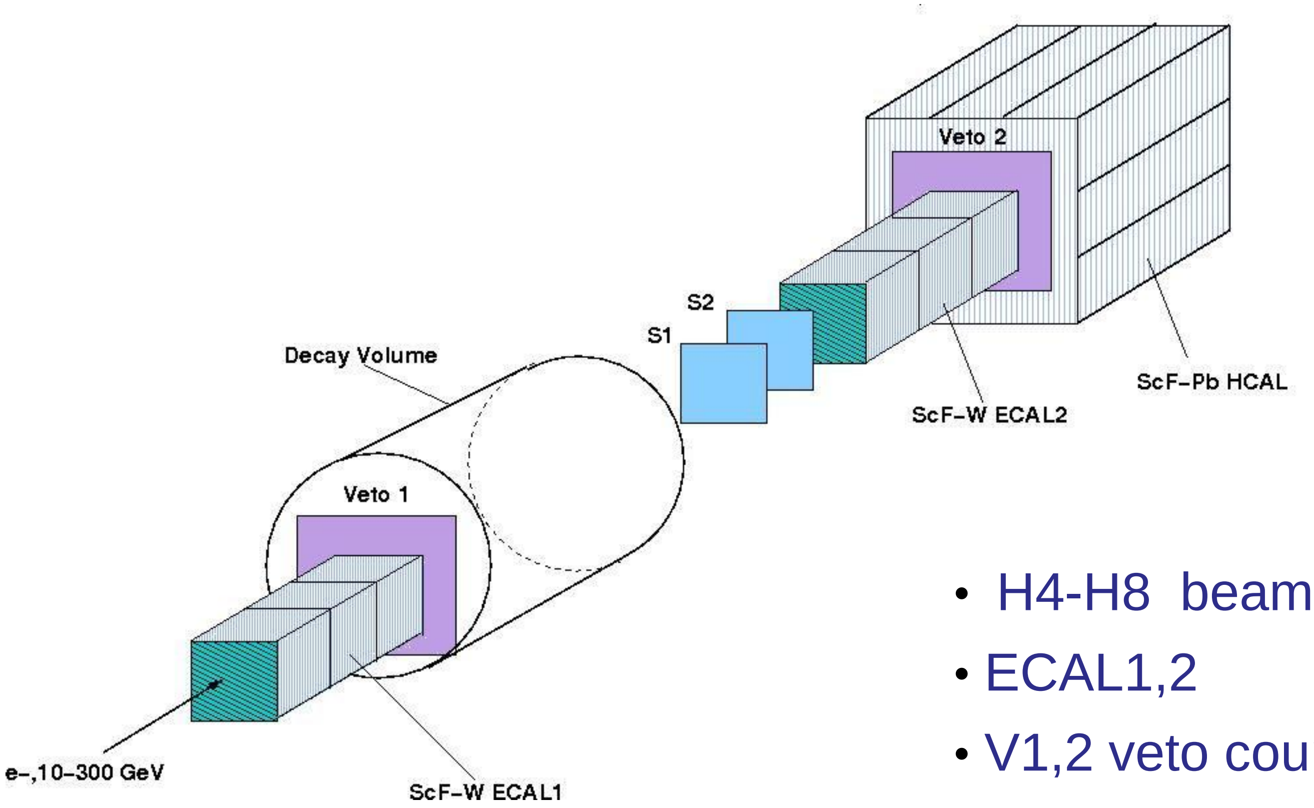
- e Z->e Z A`cross section $\sigma_{A`} \sim \varepsilon^2 (m_e/M_{A`})^2 \sigma_\gamma$; Bjorken'09, Andreas'12
- decay rate $\Gamma(A` \to e^+e^-) \sim \alpha\varepsilon^2 M_{A`}/3$ is dominant for $M_{A`} < 2\ m_\mu$
- sensitivity $\sim\varepsilon^4$ for long-lived A`, typical for beam dump searches

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: $\sigma_{A`}/\sigma_\gamma < 10^{-13}\text{-}10^{-9}$
- A`energy boost to displace decay vertex,

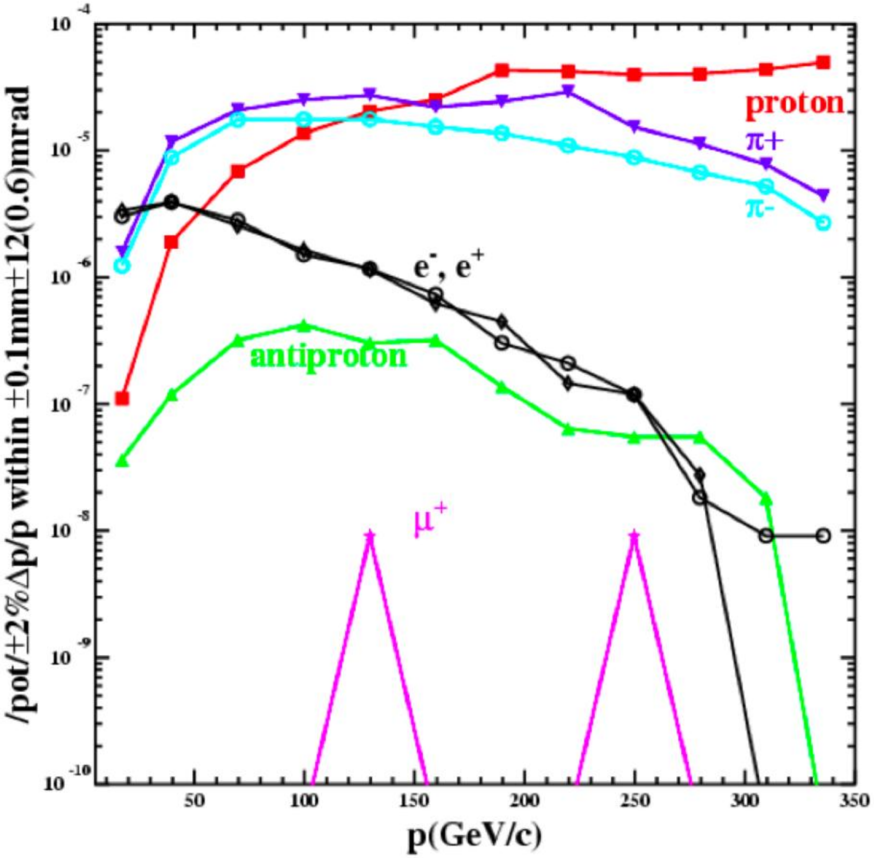
  $\varepsilon \sim 10^{-4}$, $M_{A`} \sim 50$ MeV, $E_{A`} \sim 100$ GeV, $L_d \sim 1$ m
- background suppression

Setup



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

SPS e- beams



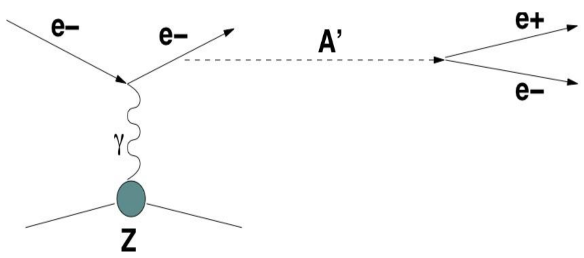
- H4, I_{max}~ 50 GeV e-
- 10^{12} pot per SPS spill,
- ~ $5x10^{6}$ e- per spill
- duty cycle is 0.25
- ~10^{12} e- / month

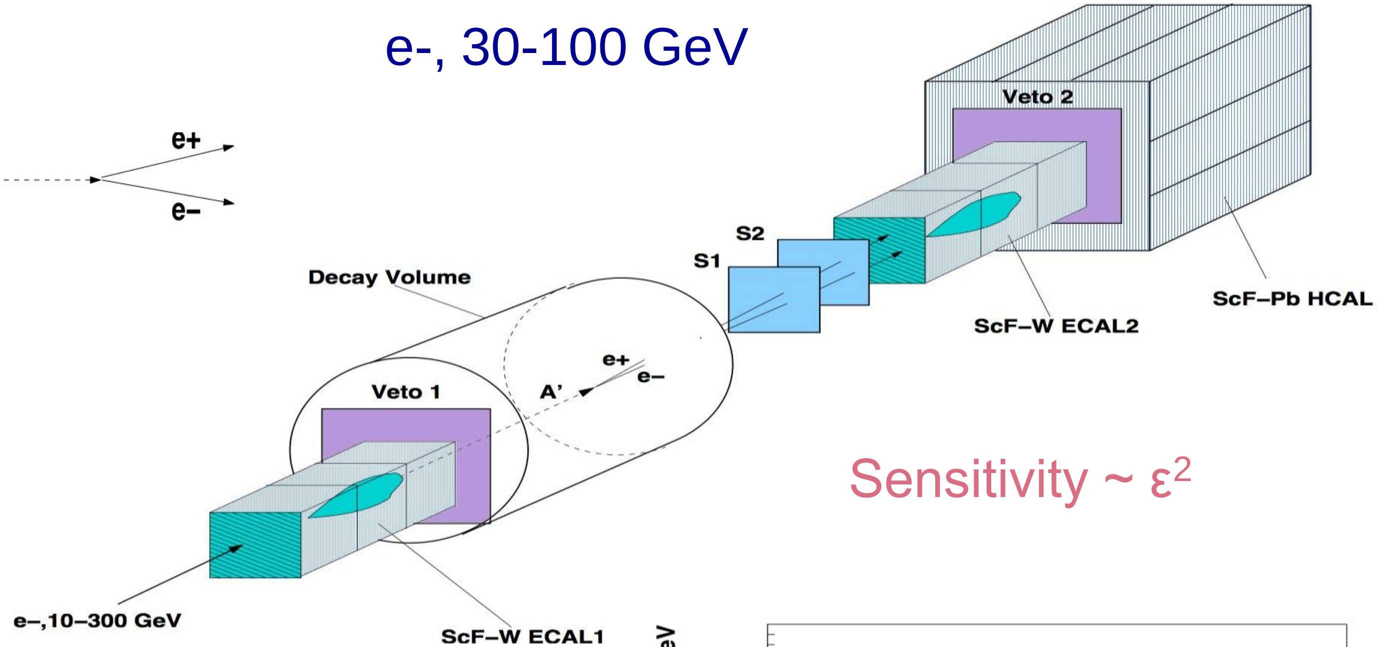
  additional tunning by

  a factor 2-3 ?
- beam spot ~ cm^2
- beam purity < 1 %

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

e-, 30-100 GeV



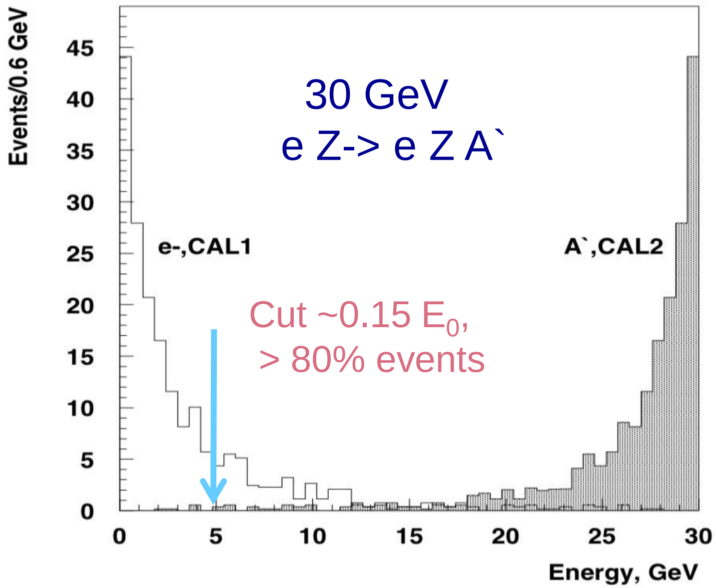


Sensitivity ~ ε^2

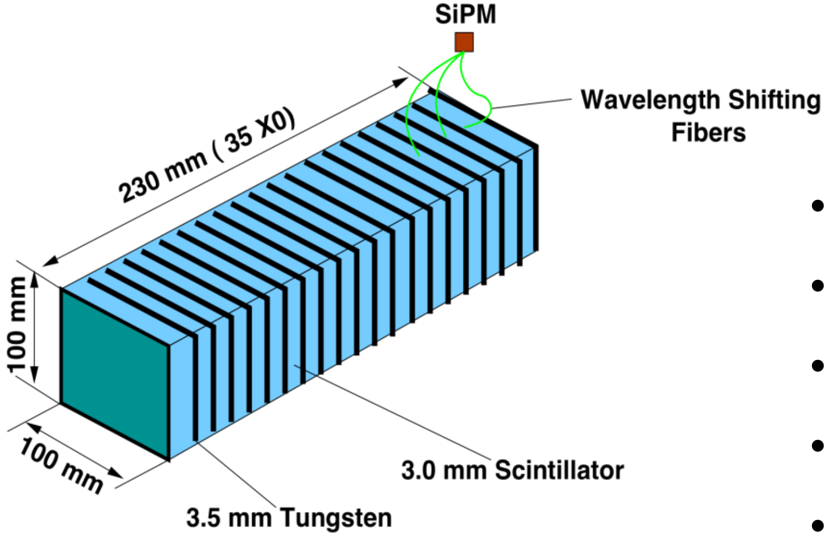
- A`s decay mostly outside ECAL1
- Signature: two separated e-m showers from a single e-

S= ECAL1xS1xS2x ECAL2 x$\overline{\text{V1xV2xHCAL}}$

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



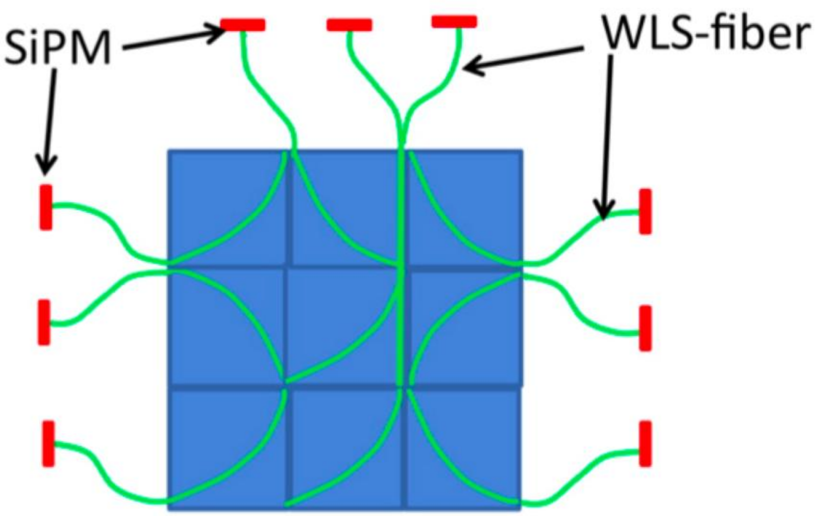
Specially designed ECAL

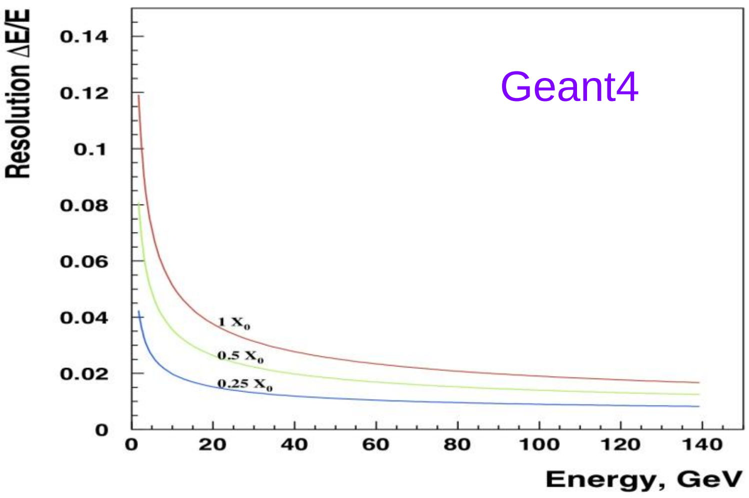


ECAL1 "bubble chamber"

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}

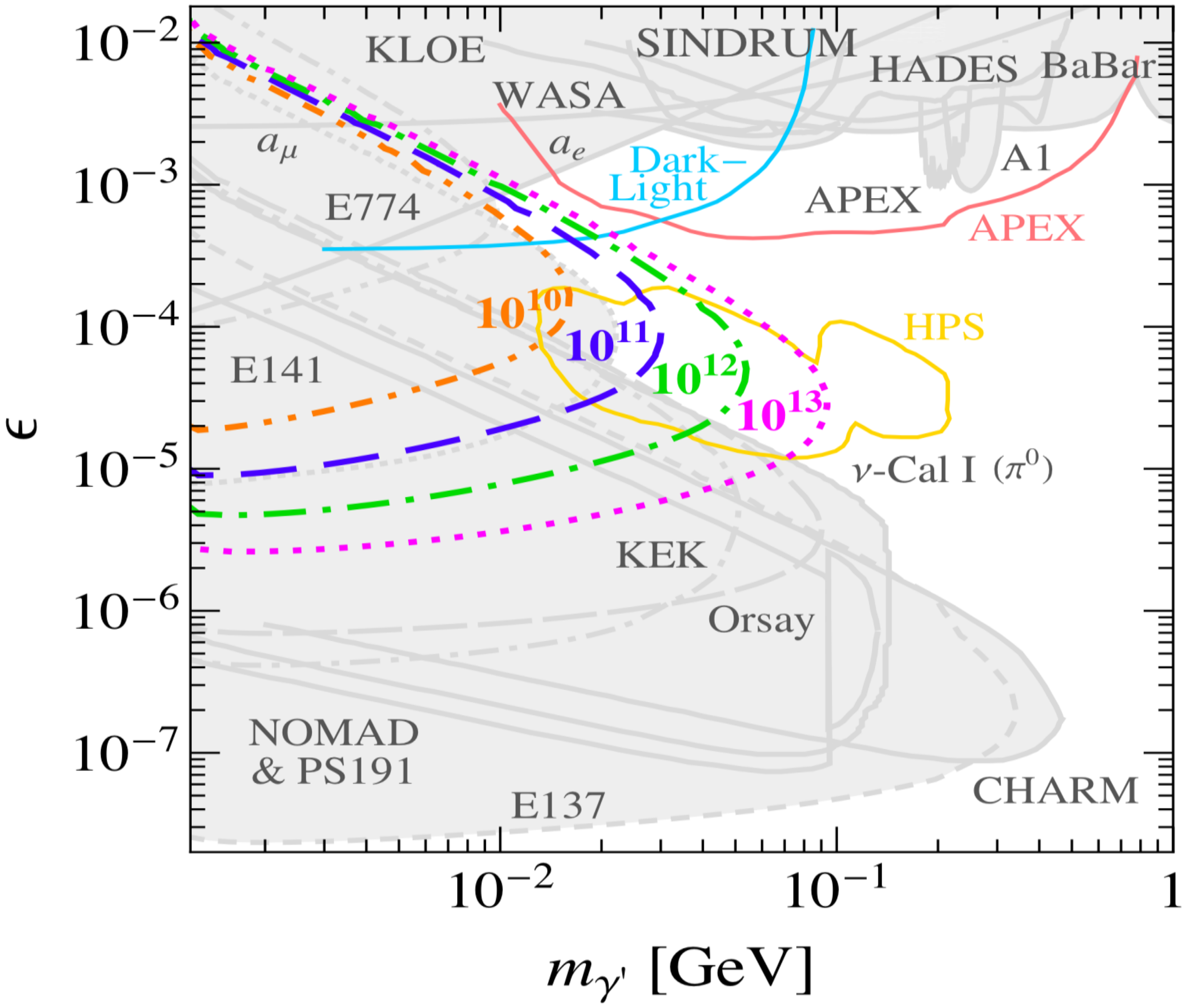




Summary of background sources for A`-> e+e-

Source	Expected level	Comment
Beam contamination		
-π,μ reactions, e.g. πA->π^0n+X, … -accidentals: ππ,μμ, ... 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->eν	< 10^{-13}	
Total	< 10^{-12}	

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

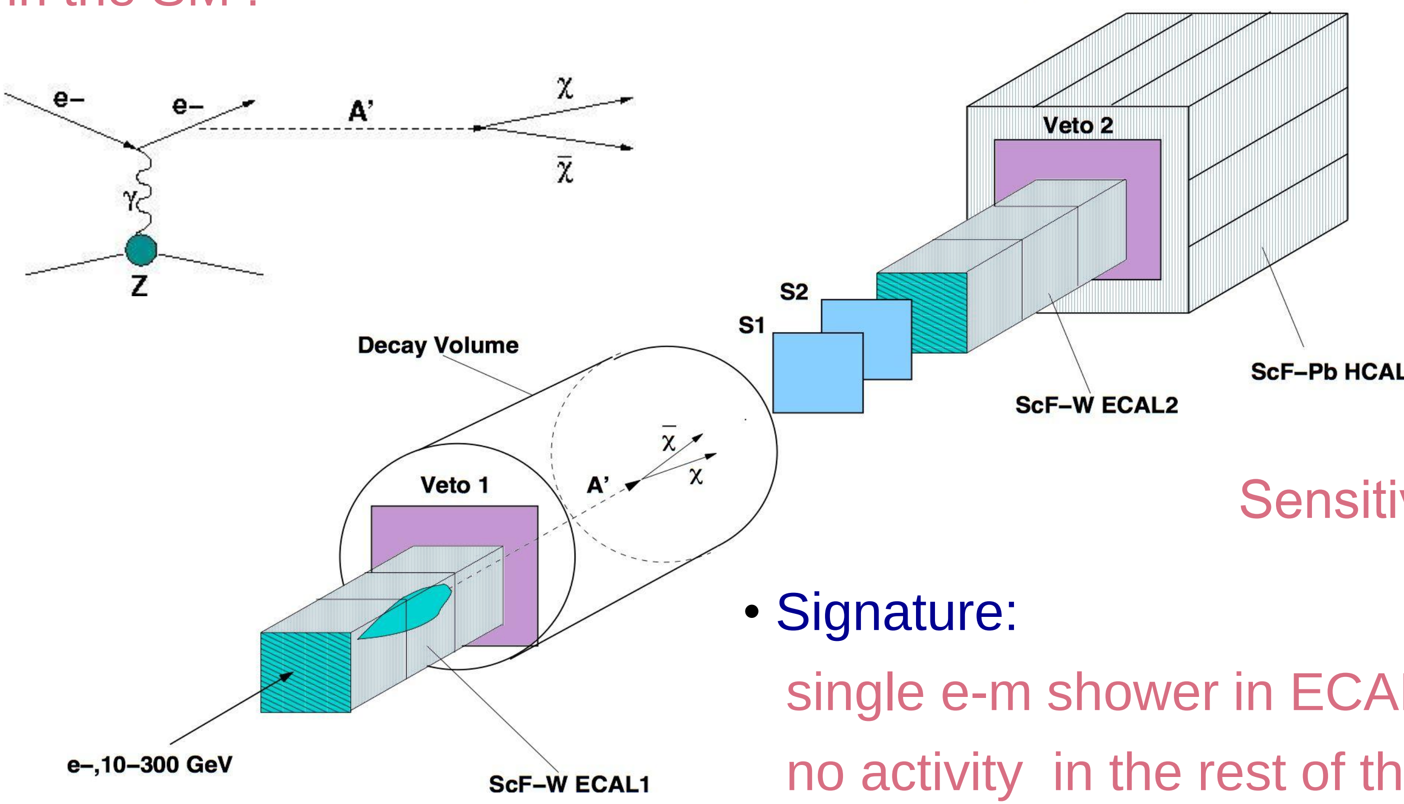


Search for invisible decay A`-> $\chi\bar{\chi}$

Remember Z-->invisible

in the SM !

e-, 30-100 GeV



Sensitivity ~ ε^2

- Signature:

  single e-m shower in ECAL1 +

  no activity in the rest of the detector

  S= ECAL1xV1xS1xS2x $\overline{\text{ECAL2x V2xHCAL}}$

- $E_1 \ll E_0$, 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

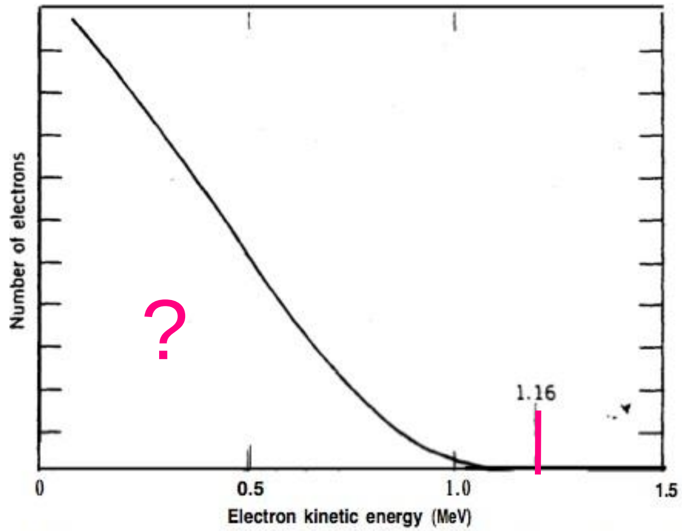
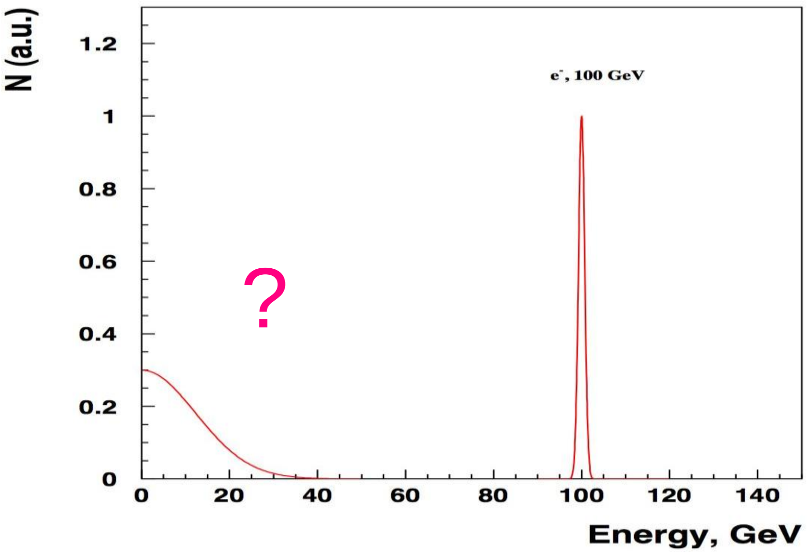


Figure 9.1 The continuous electron distribution from the β decay of ^{210}E. (also called RaE in the literature).

SPS e- spectrum



Pauli, 1931

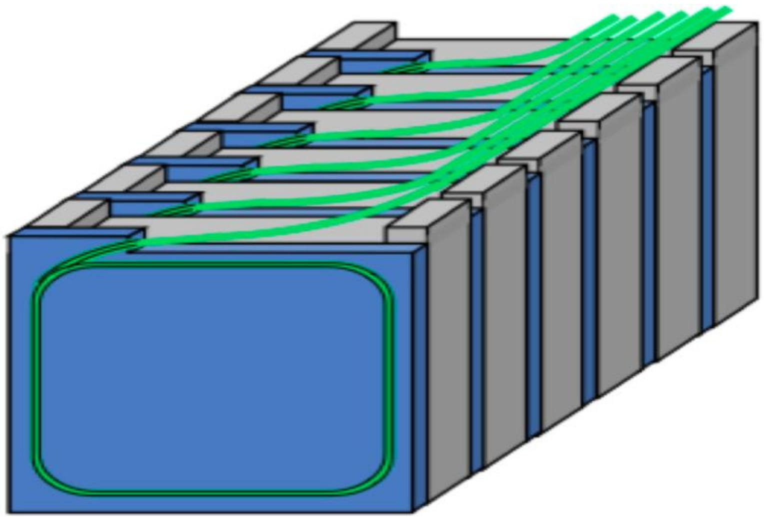
? = invisible ν

Massive HCAL to enhance longitudinal hermeticity

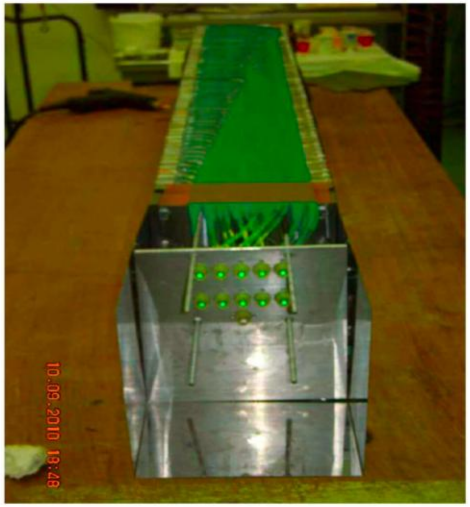
Single module of the hadronic calorimeter:

- 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



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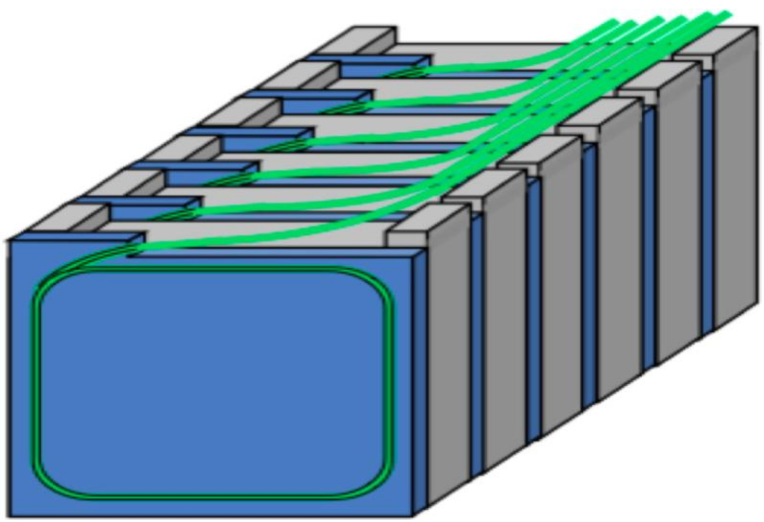
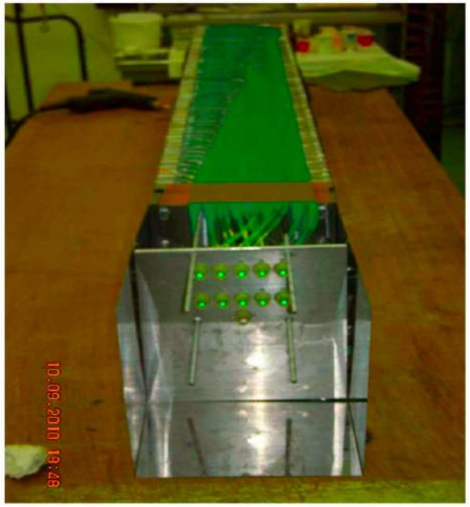


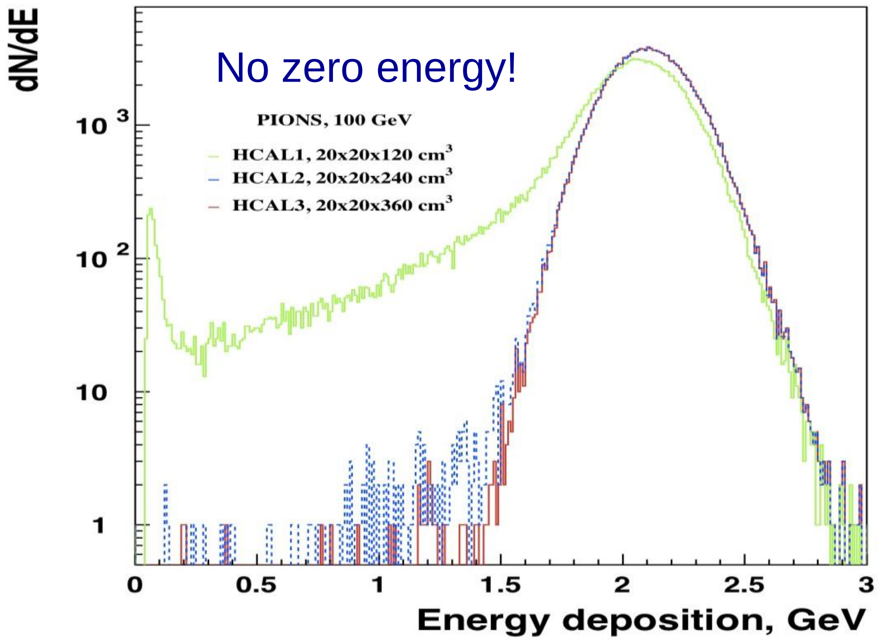
Prototype →

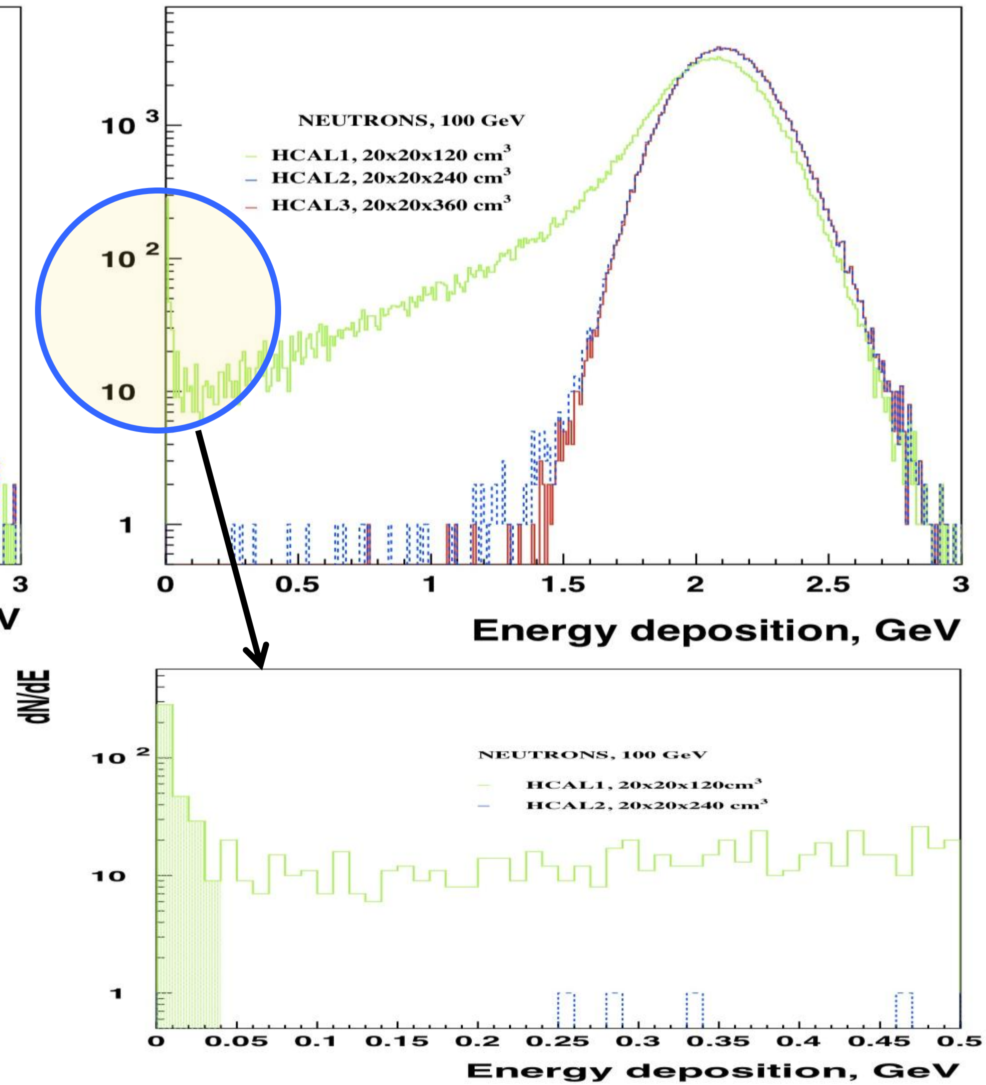


HCAL hermeticity for 3 consequtive modules

Pions, 100 GeV

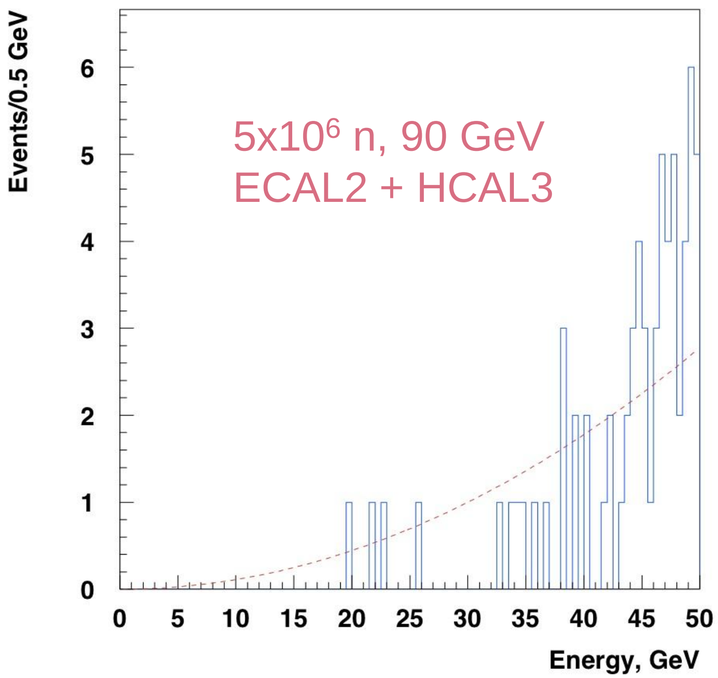
Neutrons, 100 GeV

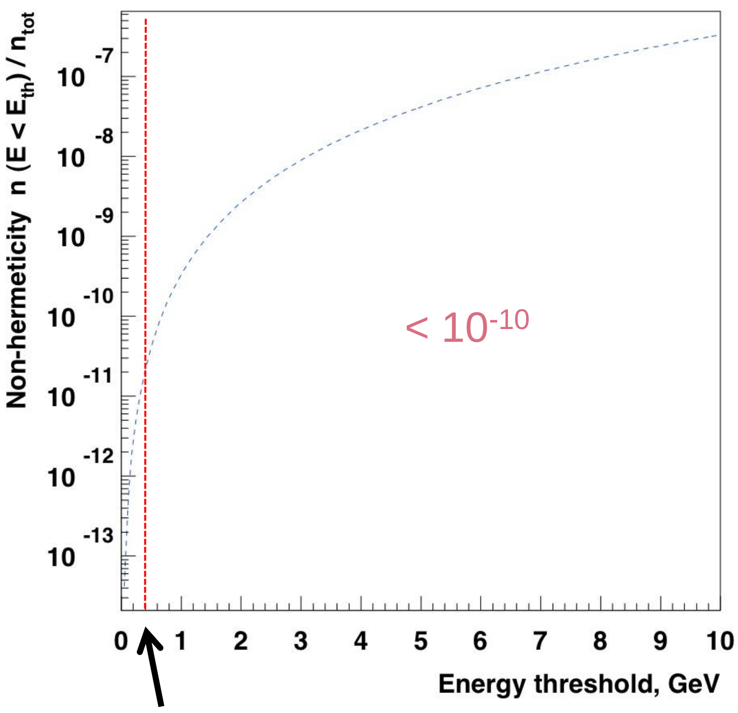




Expected HCAL energy threshold ~ 20-50 keV determined by noise and pileups.

Estimated ECAL2+ HCAL3 nonhermeticity





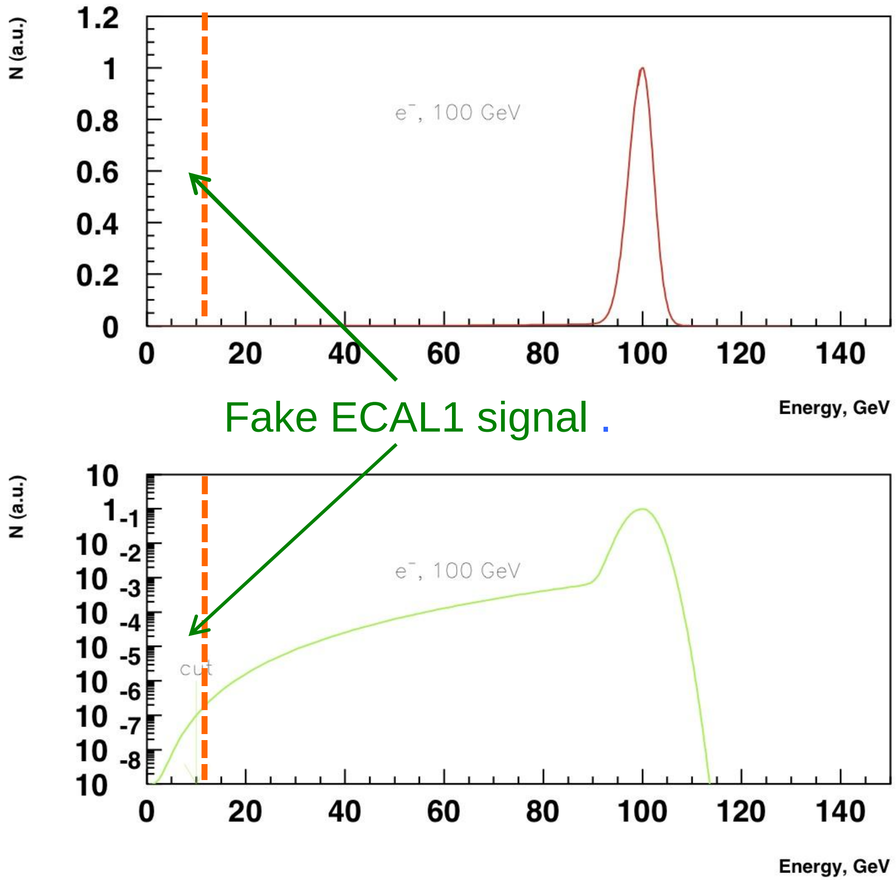
Fit of the low energy tail with a smooth function f(E)

ECAL2+HCAL3 nonhermeticity as a funcion of the energy threshold

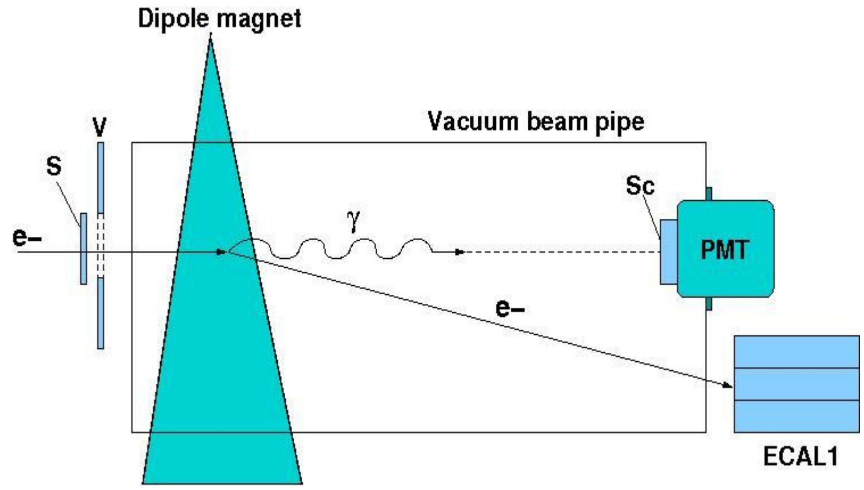
Summary of background sources for A`-> invisible

Source	Expected level	Comment
Beam contamination		
-π, *p*, μ reactions and punchthroughs,… - e- low energy tail due to bremss., π,μdecays 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 Zνν	$< 10^{-13}$ $< 10^{-13}$	~10 mb x nonherm. WI σ estimated. textbook process, first observation?
Total	$< 10^{-12}$ + ?	

Additional tag of electrons with SR photons



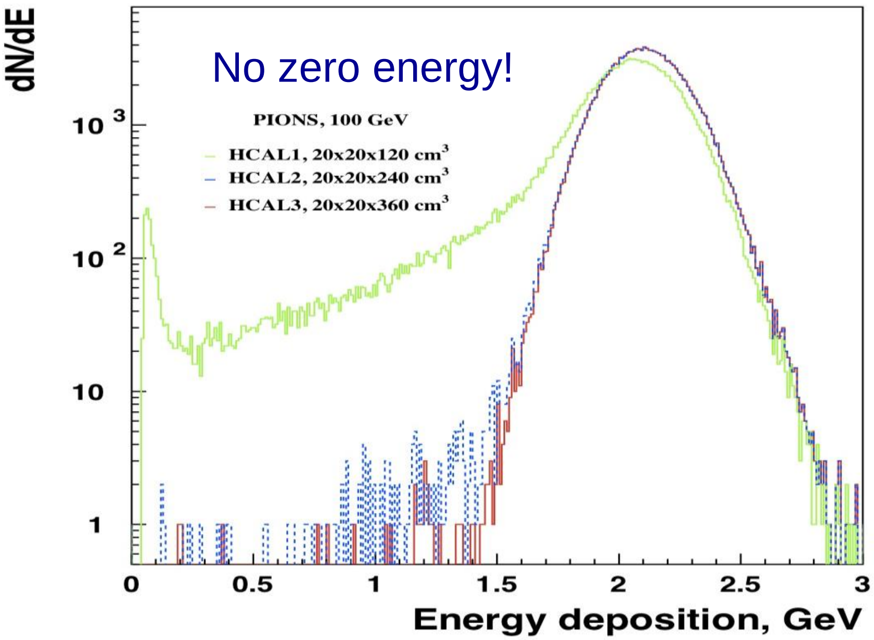
Hypothetical e- beam energy distribution (not simulated).



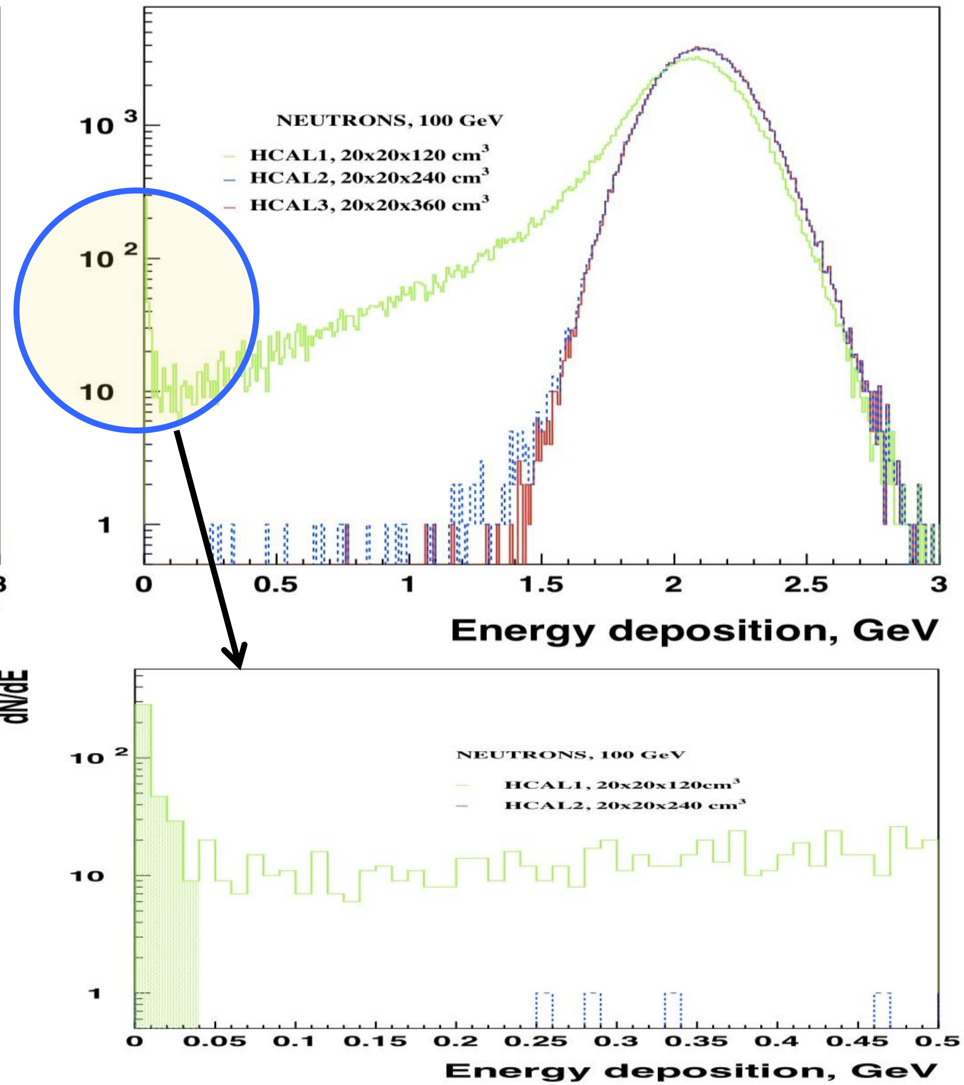
- e- tag enhancement with SR γ
- B field ~ 0.1- 1T
- $(\hbar\omega)_\gamma^c \sim E^2 B$, $n_\gamma/m \sim 6\ B(T)$
- cut $E_\gamma > 0.1\ (\hbar\omega)_\gamma^c \sim 100$ keV
- LYSO crystal, good resolution for > ~50 keV γ
- suitable for vacuum

HCAL hermeticity for 3 consequtive modules

Pions, 100 GeV



Neutrons, 100 GeV



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