The muon g-2 and searches for a new sub-GeV dark boson in a missing-energy experiment at CERN

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Plan

- Introduction
- A little bit of theory
- Experimental bounds
- Search for visible and invisible decays of dark photons

  P348 experiment

The use of CERN SPS muon beam

- 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 $U(1)_x$

The most popular scenario

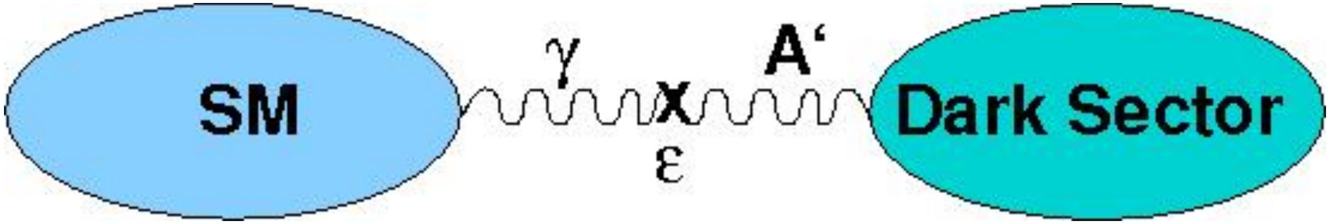
New hidden vector boson A\` interacts with our world only due to kinetic mixing with photon(or maybe with Z boson)

$$\Delta L = 0.5\varepsilon F^{\mu\nu} A`_{\mu\nu}$$

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,...)
- $\Delta L = \varepsilon F^{\mu\nu} A`_{\mu\nu}$ - 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

Decay modes for BEH mechanism

- For the case when hidden symmetry is broken by BEH(Brout-Englert-Higgs) mechanism additional decays are possible(for light A` boson)

  A` --→ A`*h` -→e+e- h’ ,

  h` ---→ invisible,

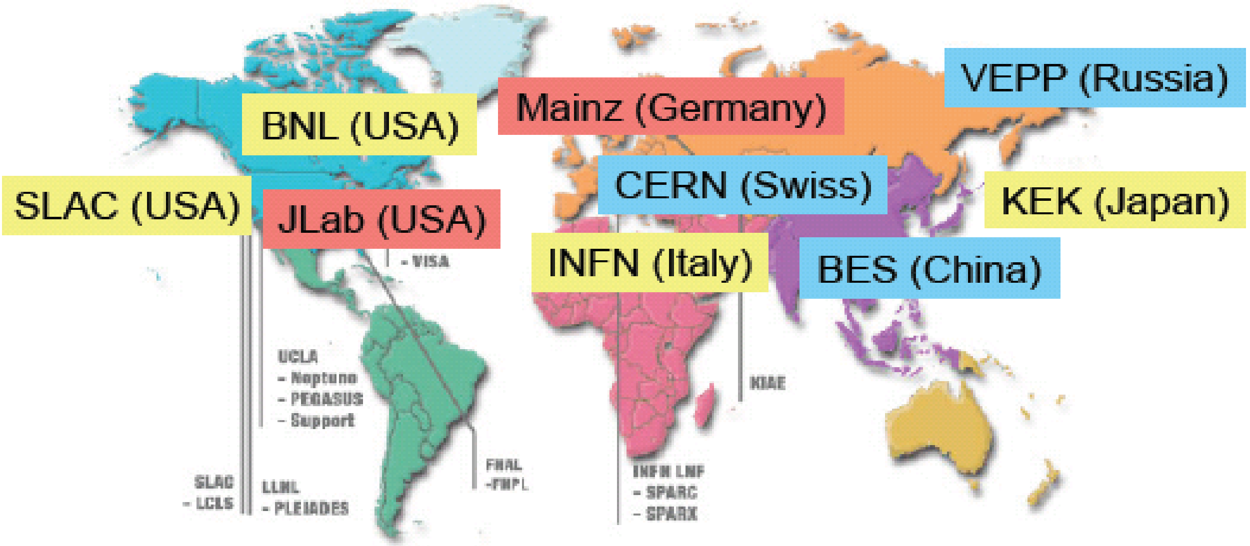
  h` ----> e+e-e+e-, pi+pi-pi+pi-

Experimental bounds

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

Dark Force searches in the Labs

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



Typical searches for Dark Force exploit the small Z' coupling to the SM particles (rather than using the DM particles).

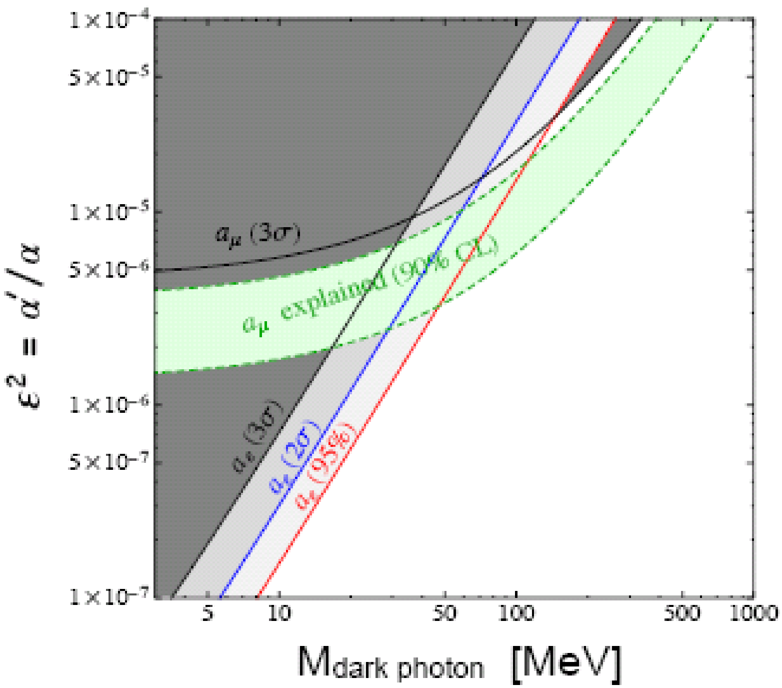
Particularly attractive feature: a New physics scenario that can be tested at both High-E & Low-E experimental facilities (Nuclear/Hadronic physics labs).

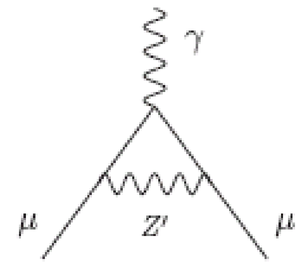
[Dark force carrier Z' scale (GeV) ≈ 1/1000 × Typical new physics scale (TeV)]

"various Low-E Labs" "LHC"

1. Introduction

Anomalous Magnetic Moment





$$(\text{magnetic moment}) = -\frac{g\mu_B S}{\hbar}$$

Green band: explains the 3.6σ deviation in a_μ (possibly early hint of Dark Force)

[Gninenko, Krasnikov (2001); Pospelov (2008)]

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

- One of the major motivations for the light Dark gauge boson (Z').
- Unlike other motivations, it is independent of the unknown Dark Matter properties.
- It is independent of the Z' decay branching ratios.

- An explanation of g-2 anomaly with additional vector light boson(massive photon) assumes vectorlike interaction

of new light boson Z_{μ} with muons with $\alpha_{\mu} \approx O(10^{-8})$

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

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

$$L_{Z_\mu} = e_\mu \bar{\mu} \gamma_\nu \mu Z^\nu_\mu \, . \tag{2}$$

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

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

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

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

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

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

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

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

2. Experimental bounds

For this scenario there are several bounds which almost exclude possible g-2 anomaly explanation except narrow region between 30 and 32 MeV

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 collaboration excluded masses

between 40 MeV and 300 MeV

BaBar collaboration excluded masses

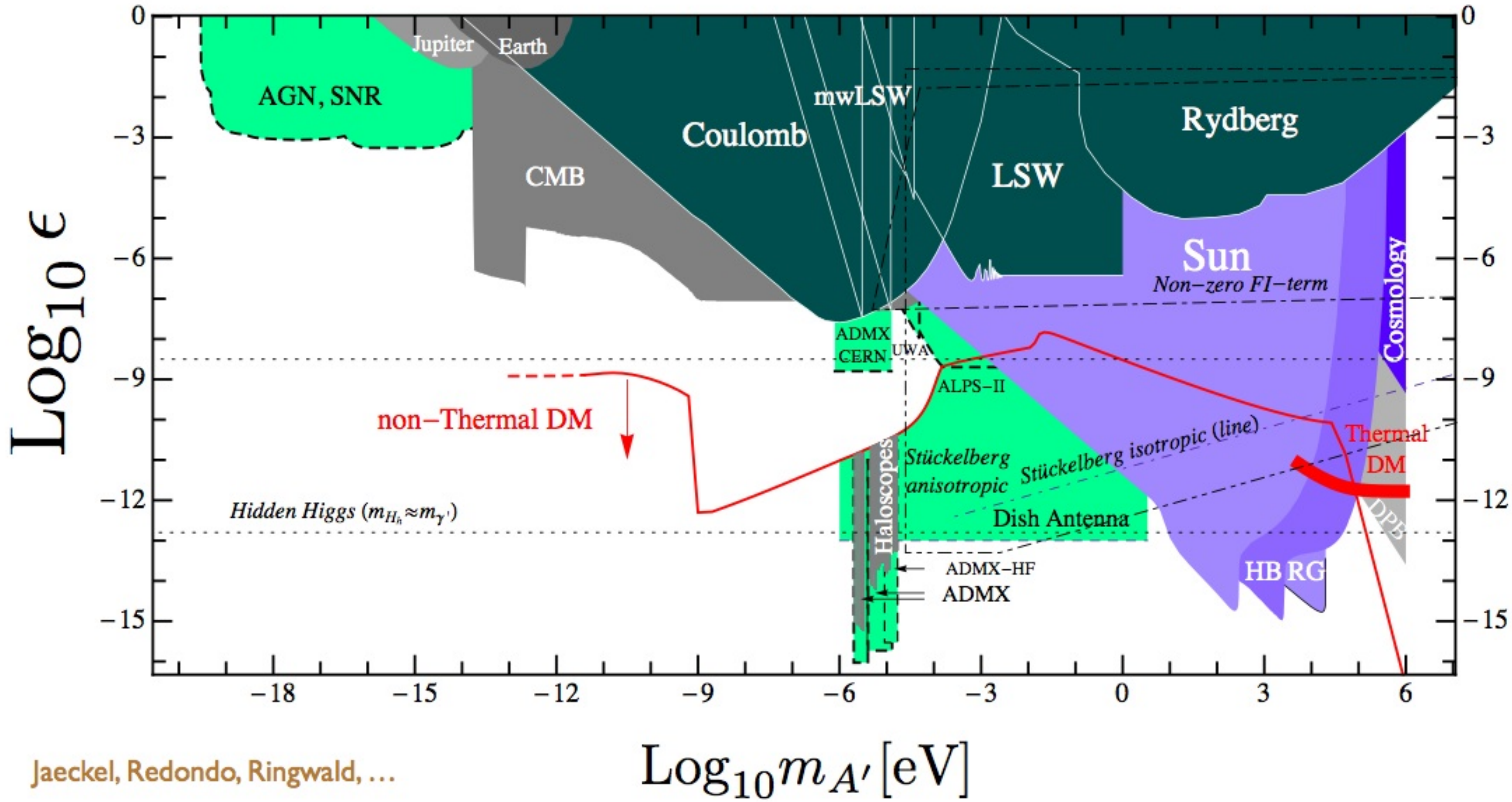
between 32 MeV and 10.2 GeV

So the possibility of g-2 anomaly

Explanation due to existence of light

vector boson is almost excluded

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

2. Experimental bounds

Constraints on the Parameter Space

Mostly from the Z' $\to \ell^+\ell^-$ searches

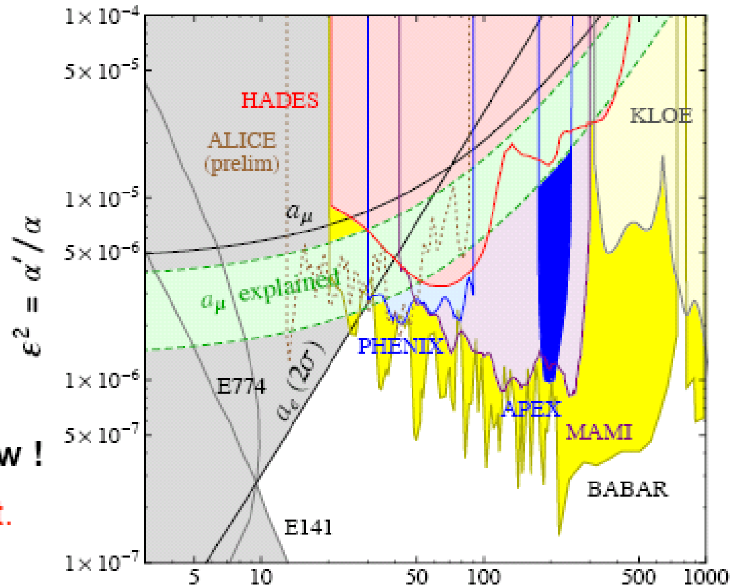
- (i) Electron, Muon g-2
- (ii) Beam-dumps
- (iii) Meson (quarkonium) decays
- (iv) e+e- collision (ISR)
- (v) Fixed target experiments

With 2014 results: whole green band (g_μ-2 favored) is almost excluded now !

Only a small spot (mZ' ~ 30 MeV) is left.
[PHENIX arXiv:1409.0851 v2]

We need to keep searching inside/outside of the green band.

[2014 constraints]



Z' mass [MeV]

[Dark Photon & Dark Z boson]

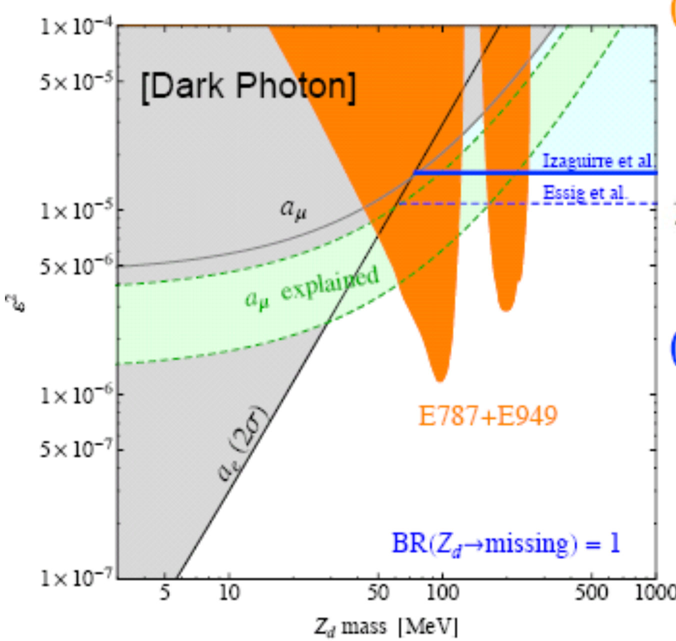
2.Experimental bounds

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

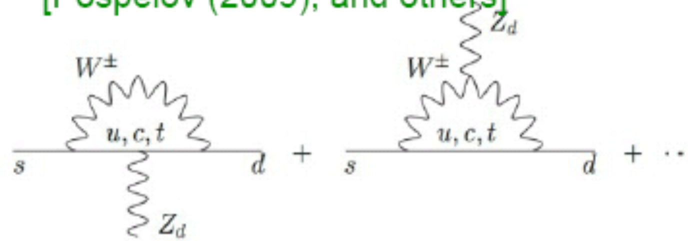
2. Experimental bounds

Invisibly decaying Dark gauge boson

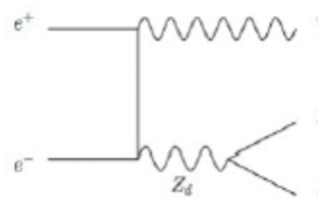
(ii) Missing Energy (Z' → $\chi\chi$) searches



(i) $K^+ \to \pi^+$ + nothing (BNL E787+E949)
[Pospelov (2009); and others]



(ii) $e^+e^- \to \gamma$ + nothing (BABAR)
[Izaguirre *et al* (2013); Essig *et al* (2013)]



(More constraints through χ interaction at detectors in some beam dump experiments are possible, but they depend on the χ couplings.)

In Dark Photon model, small portion of the green band survives the constraints.

2. Experimental bounds

There is also possibility that new boson Z_μ 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

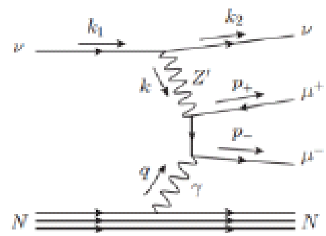
2. Experimental bounds

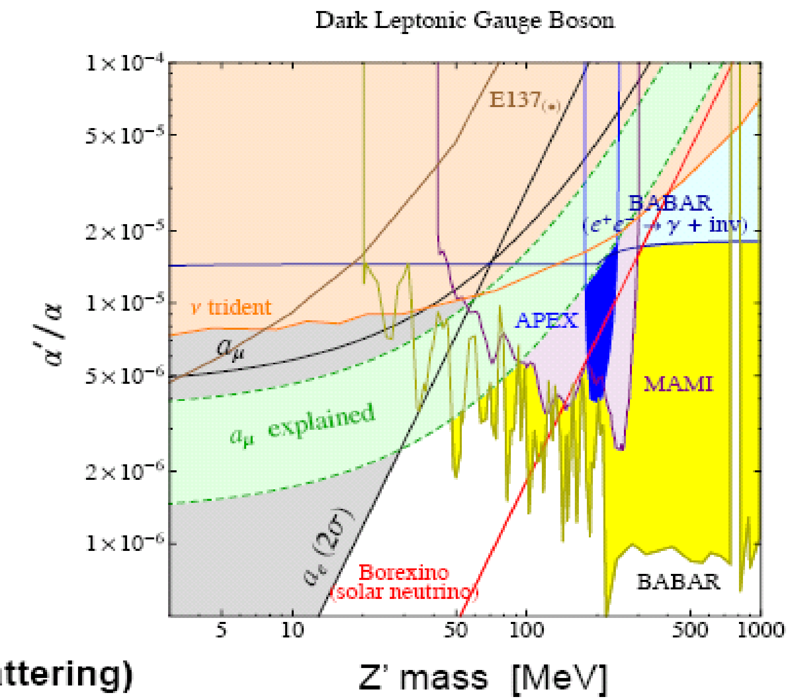
Constraints on the $U(1)_L$ Parameter Space

[LEE (2014)]

$U(1)_L$ is constrained by the followings.

(i) Electron, Muon g-2
(ii) Beam-dumps
(iii) e+e- collision (ISR)
(iv) Fixed target experiments
(v) No meson decays
(vi) ν scattering (Borexino, ν trident)





Whole green band (g_μ-2 favored)
is excluded by the Borexino (ν-e scattering)
in both $U(1)_L$ and $U(1)_{B-L}$.

Experimental bounds

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

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

For such model the most untrivial 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

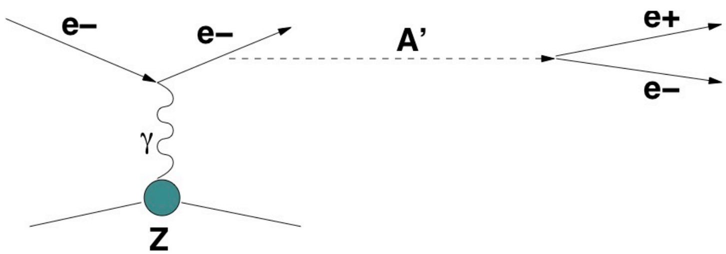
Experimental bounds

Existing experimental data restrict rather strongly (but not completely close) dark boson g-2 explanation

3. Experiment

- 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: $\sigma_{A`}/\sigma_\gamma < 10^{-13}$-$10^{-9}$
- 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

Research program of P348 (still under development)

1. Searches for A`->e+e- and A`->invisible decays 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 approach developed for fixted-target experiments

Focus of this talk on items 1. and 2.

SPSC recommended to focus on A`->invisible decay in 2015

PREPARED FOR SUBMISSION TO SPSC

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

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06/12/2013

arXiv:1312.3309[hep-ex]

December 6, 2013

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CERN-SPSC-2014-017
SPSC-113
April 2014

MINUTES of the 113th Meeting of the SPSC
Held on Tuesday 8 April and Wednesday 9 April 2014

7. FOLLOW-UP ON EXPERIMENTS AND PROPOSALS

7.1 P348

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

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

The SPSC **recommends** a test run of two weeks at the SPS for the measurement of backgrounds, a study of the performance of the apparatus and an initial search for light dark matter.
The Committee also **recommends** that the results of the test run, as well as detailed simulation studies, should serve as input for a technical design report to be submitted to the SPSC.

P348 Collaboration (preliminary)

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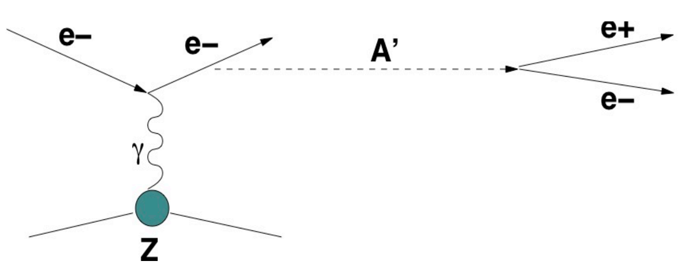
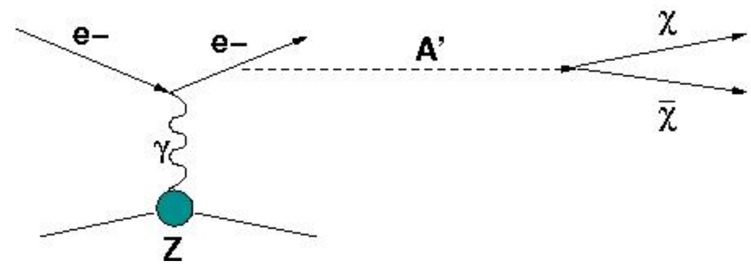
Bremsstrahlung A` production and decays

a)



b)



- e Z->e Z A`cross section $\sigma_{A`} \sim \varepsilon^2 (m_e/M_{A`})^2 \sigma_\gamma$; Bjorken' 09, Andreas' 12
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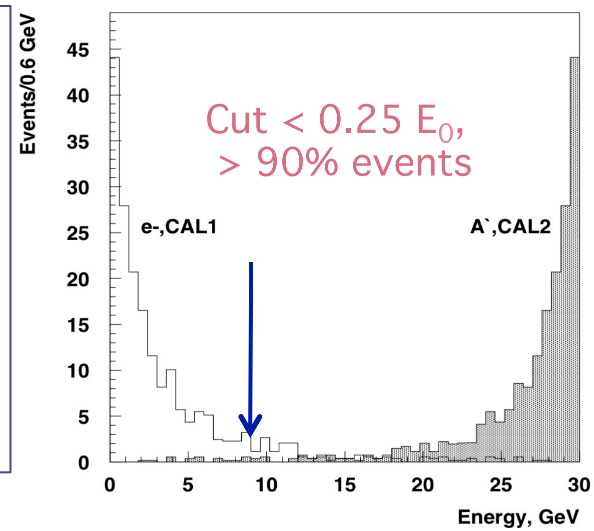
For $10^{-5} < \varepsilon < 10^{-3}$, $M_{A`} < \sim 100$ MeV

- 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,

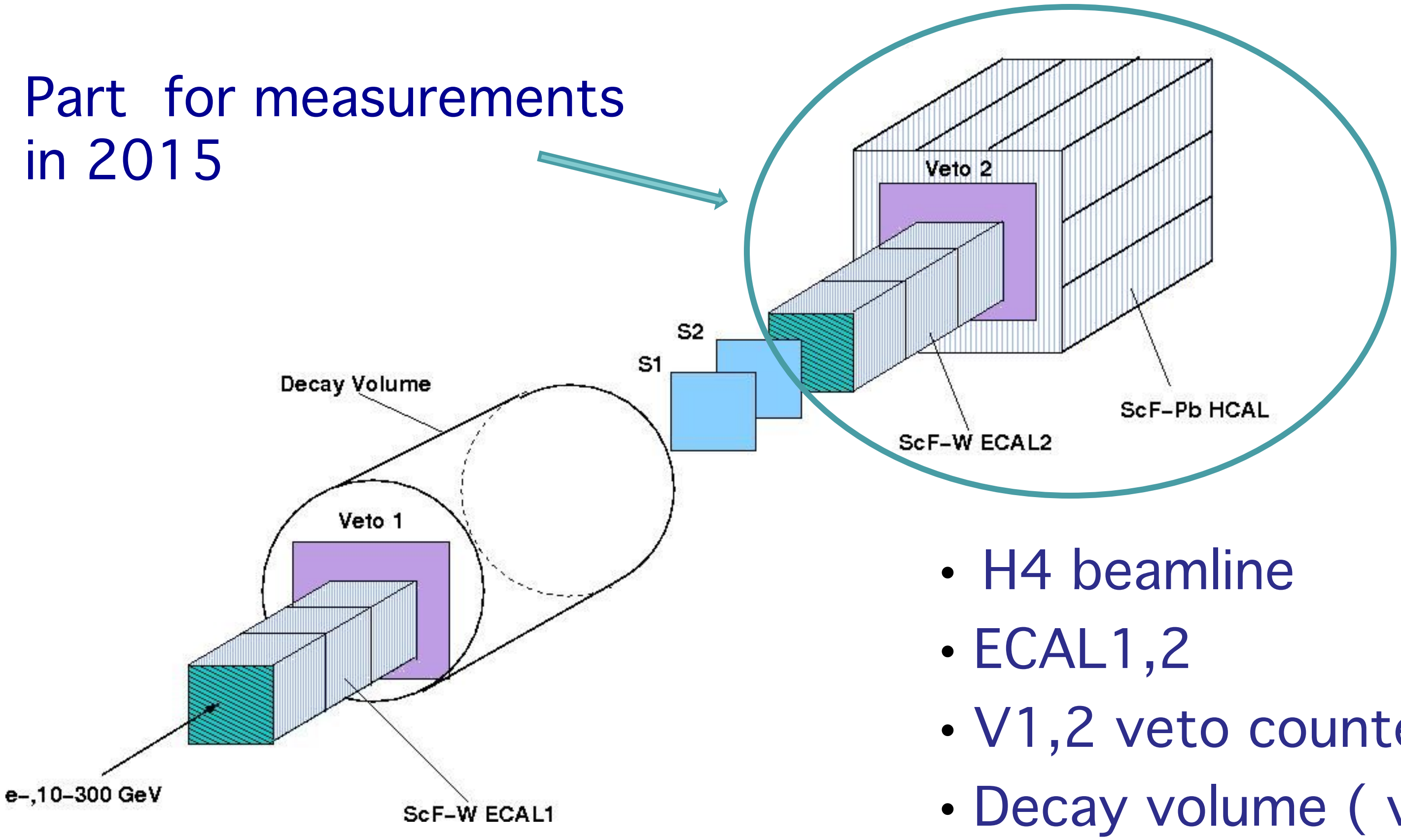
$\varepsilon \sim 10^{-4}$, $M_{A`} \sim 50$ MeV, $E_{A`} \sim 100$ GeV, $L_d \sim 1$ m

e Z-> e Z A`, 30 GeV



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

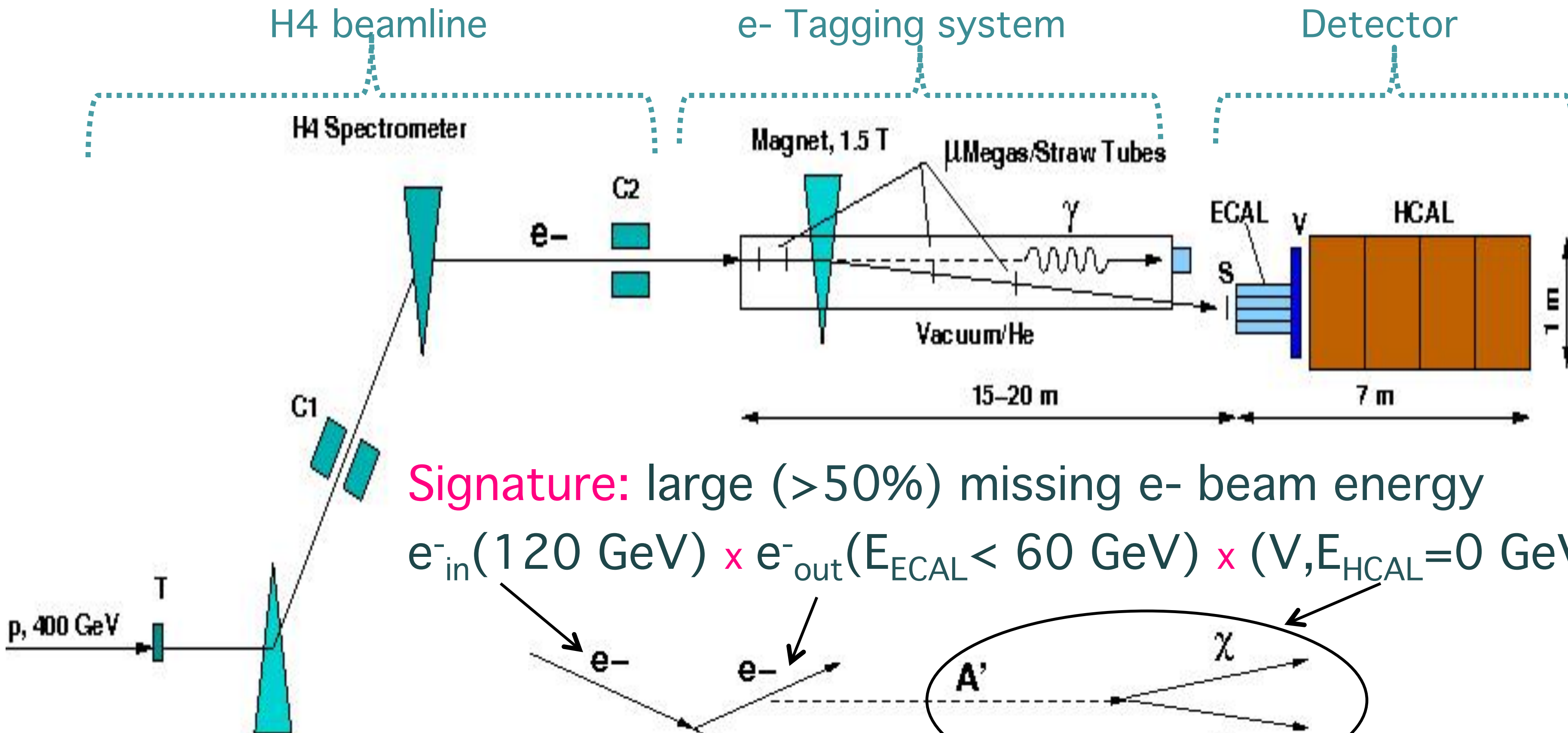
Part for measurements in 2015



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

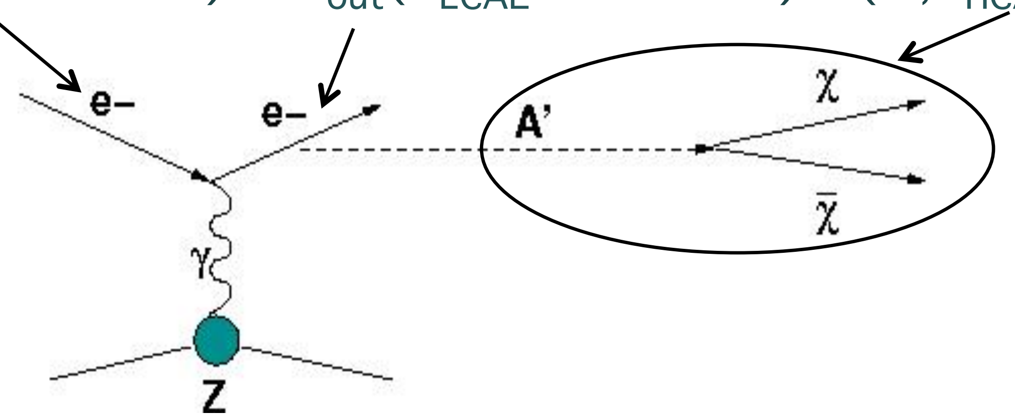
Setup for invisible A` decay in 2015

Three basic components



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

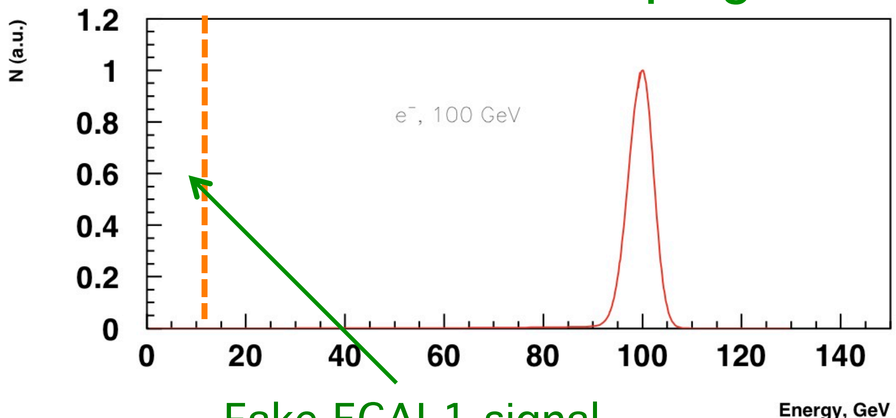
$e^-_{in}(120\text{ GeV}) \times e^-_{out}(E_{ECAL} < 60\text{ GeV}) \times (V, E_{HCAL} = 0\text{ GeV})$



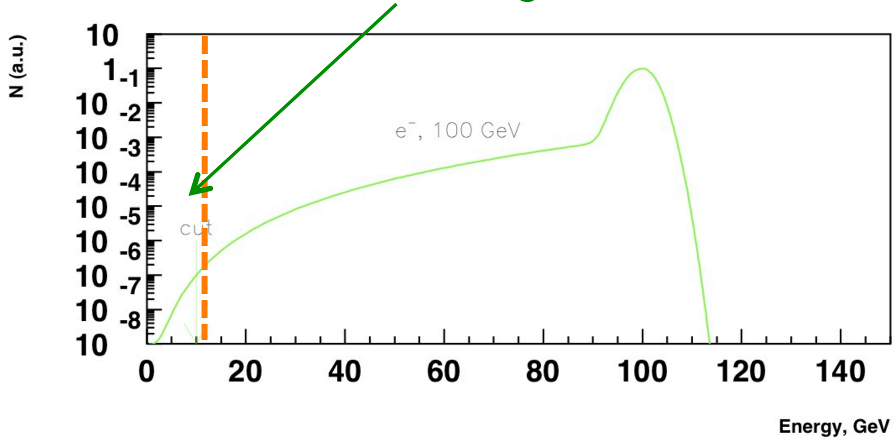
Electron tagging with SR photons

- enhancement of the e- tagging
- suppression of π,K -> eν decays

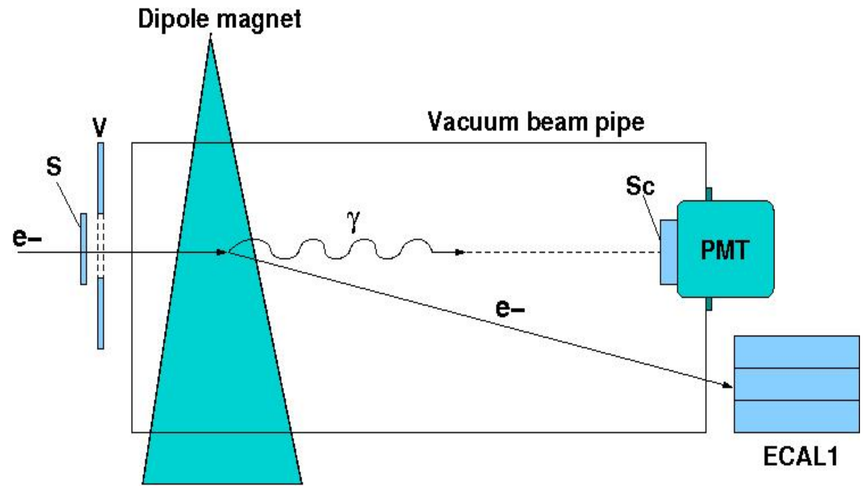
Detailed simulations in progress



Fake ECAL1 signal .



Hypothetical e- beam energy Distribution (not simulated).

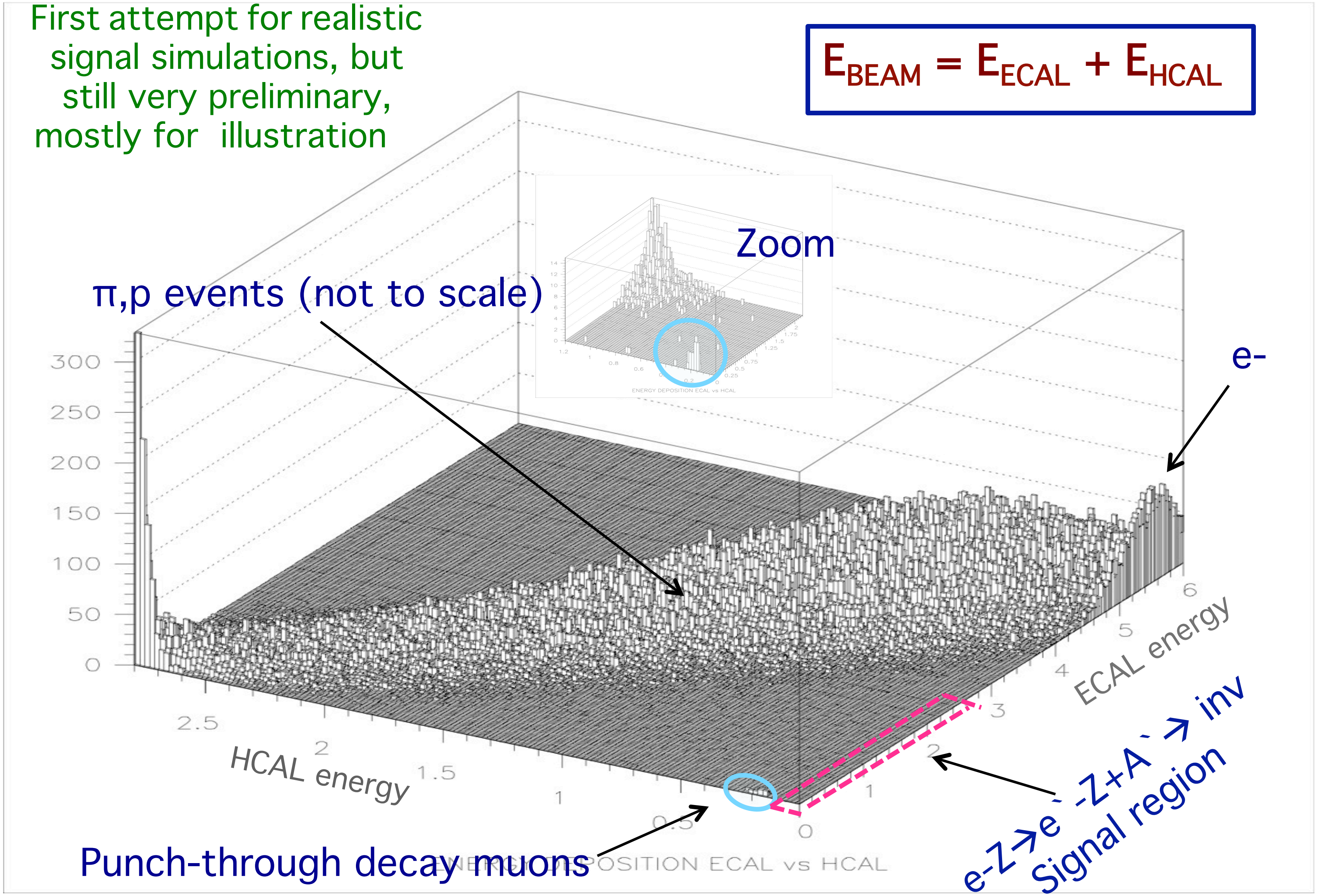


- B field ~ 0.1- 1T
- $(\hbar\omega)_\gamma^c \sim E^2 B$, $n_\gamma/m \sim 6\ B(T)$
- cut $E_\gamma > 0.1\ (\hbar\omega)_\gamma^c$ ~100 keV
- LYSO crystal, good resolution for > ~50 keV γ
- suitable for vacuum

A`->invisible Signal Region in the ECAL vs HCAL Plane

First attempt for realistic signal simulations, but still very preliminary, mostly for illustration

$E_{BEAM} = E_{ECAL} + E_{HCAL}$



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

Source	Expected level	Comment
Beam contamination		
- π, μ reactions, e.g. πA-> 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->eν	$< 10^{-13}$	
Total	$< 10^{-12}$	

Required performance of the beam and detector

- H4 e- beam at 120 GeV, 10^{12} pot per SPS spill.

- monochromaticity: very small low energy tail $<10^{-?}$
- intensity: $\sim 10^{6}$ e- per spill expected
- purity: $\pi/e < 10^{-2}$ expected or lower
- beam divergency, sport size at ECAL a few cm^2

- e- Tagging system

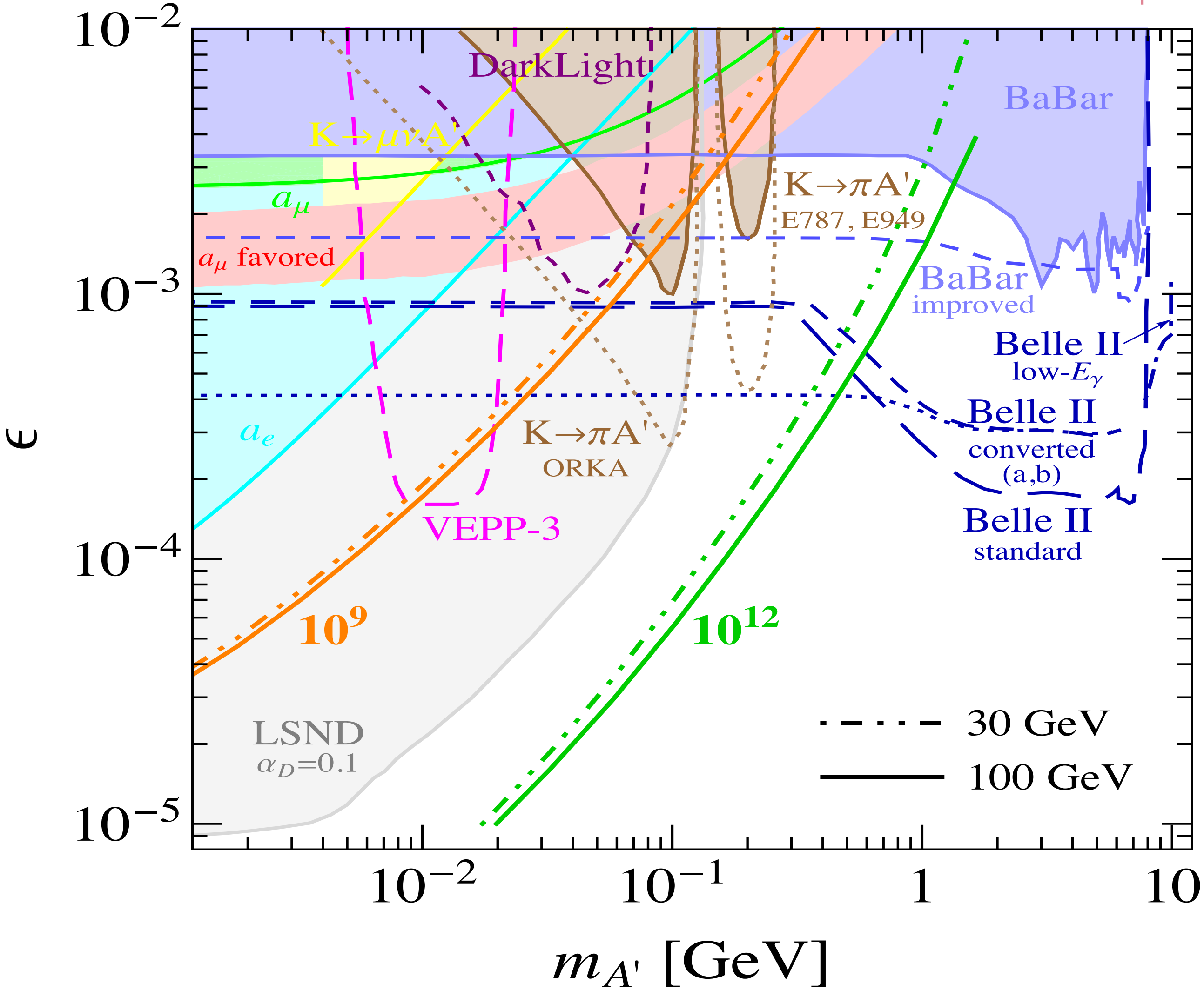
- H4+magnetic spectrometer: low energy tail $<10^{-10}$ per e-
- synchrotron γ-counter: ~ MeV range, good timing and efficiency
- H4+MS+SR tag : low energy tail $<10^{-12}$/e-, hadron suppresson

- Detector

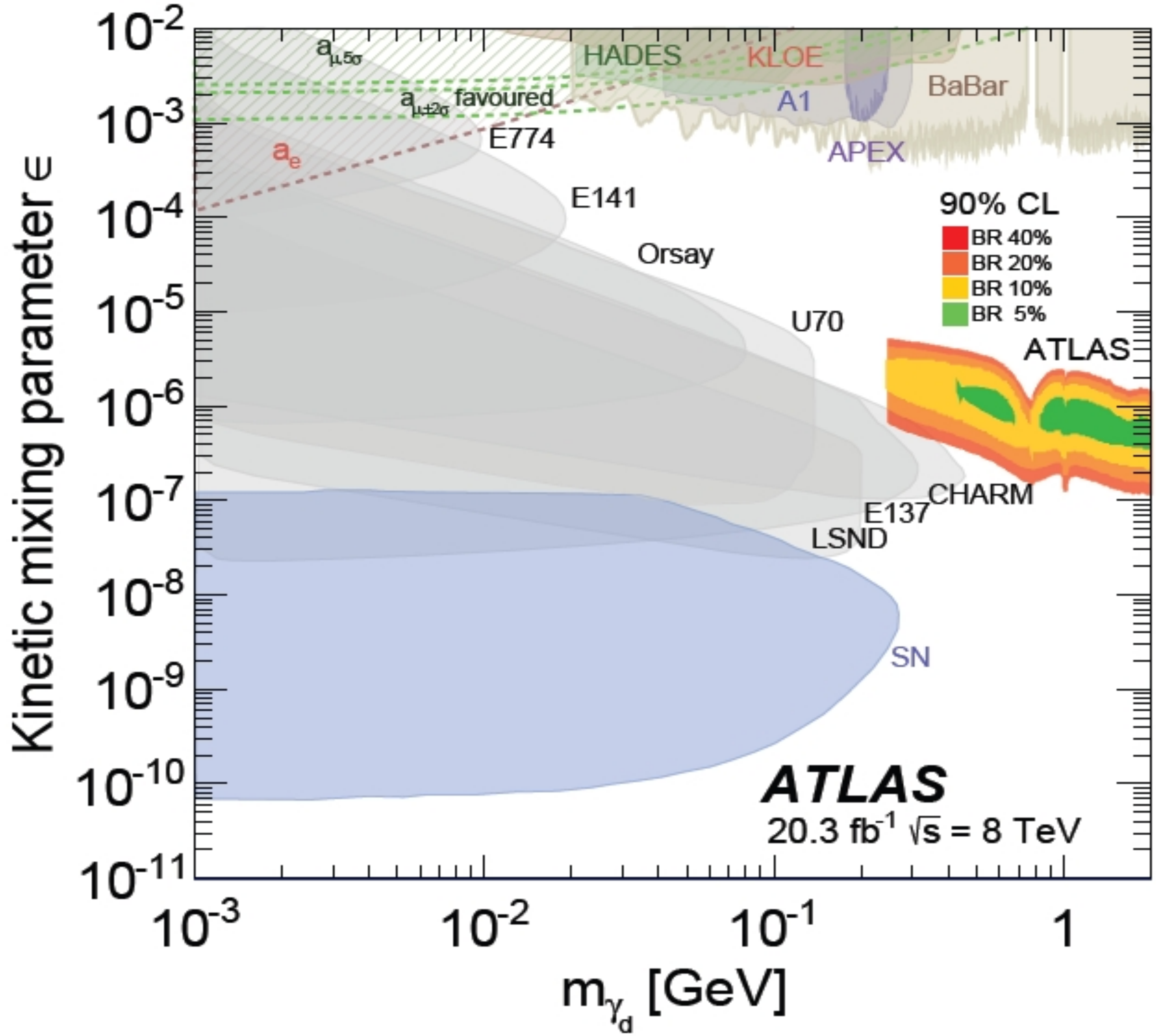
- ECAL e,γ– , HCAL π,n–hermiticity: $< 10^{-10}$
- HCAL number of ph.e. per mip: $>10^{2}$/module
- good ECAL resolution and shape: intrinsic low energy tail $< 10^{-10}$
- good e- ID, π/e rejection $<10^{-3}$
- ECAL first level trigger: E < Eo
- Veto inefficiency for mip $<10^{-4}$

Expected limits for A`-> invisible decays

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



Current limits for A` -> e+e- decays



Status of preparation for beam in 2014

- Detector design for the search for A`->invisible decay

  is completed

- Currently in production:

- Micromegas
- Strow tube chambers
- ECAL + preshower
- HCAL modules
- Synchrotron radiation counters
- parts of DAQ system

- The plan is :

- to assemble the setup during summer 2015
- to have first beam time period at H4 in autumn 2015

Experiment. Muon beam

The second aim of this talk is short review of our recent proposal to look for dark boson at collisions of CERN SPS muon beams

$$\mu(p) \; + \; Z(P) \rightarrow Z(P^{'}) \; + \; \mu(p^{'}) \; + \; Z_\mu(k)$$

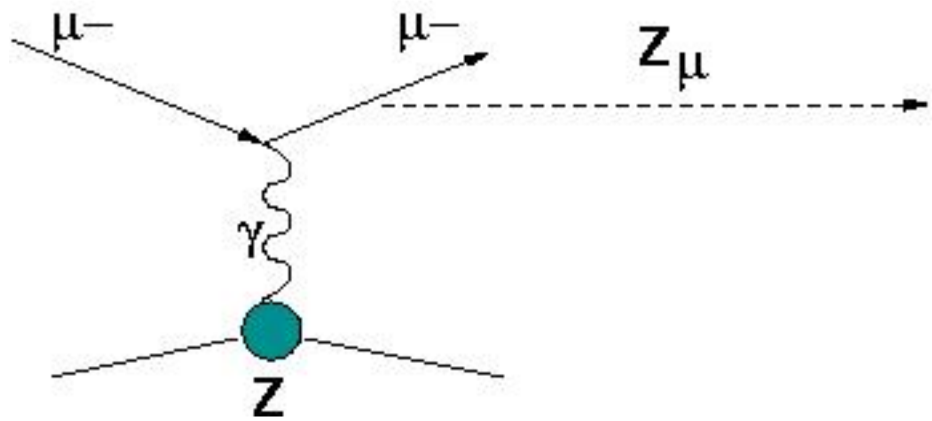
This part is based on our recent paper

S.N.Gninenko, N.V.Krasnikov and V.A.Matveev,

The muon g-2 and searches for a new electrophobic sub-GeV dark boson in a missing-energy experiment at CERN, arXiv:1412.1400(2013).

Most relevant references are contained in this paper.

3.The experiment at CERN SPS muon beam



Bremsstrahlung $Z\mu$ production in high energy muon scattering off nuclei

3.The experiment at CERN SPS muon beam

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

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

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

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

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

3.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]

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

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

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

3.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

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

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

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

3.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

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

$\chi = Z^2 \cdot Log$

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

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

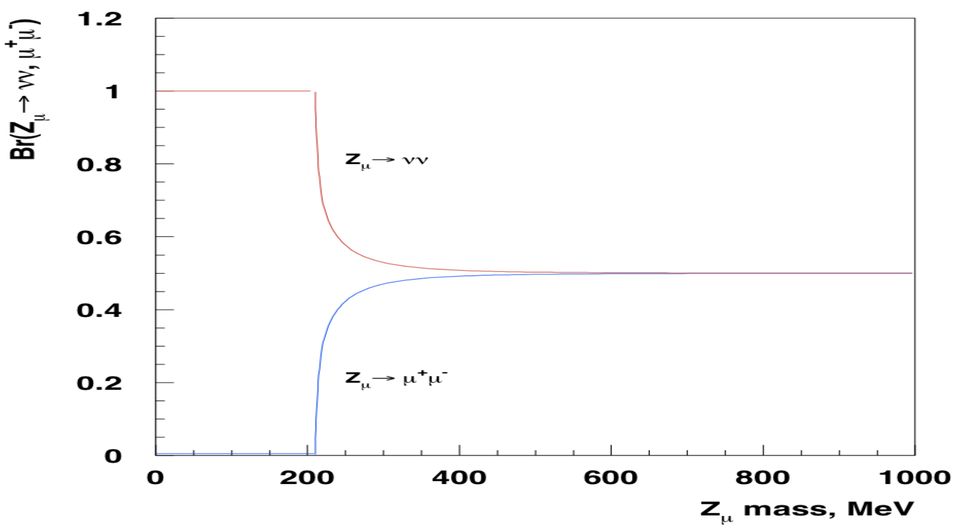
3.The experiment at CERN SPS muon beam

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

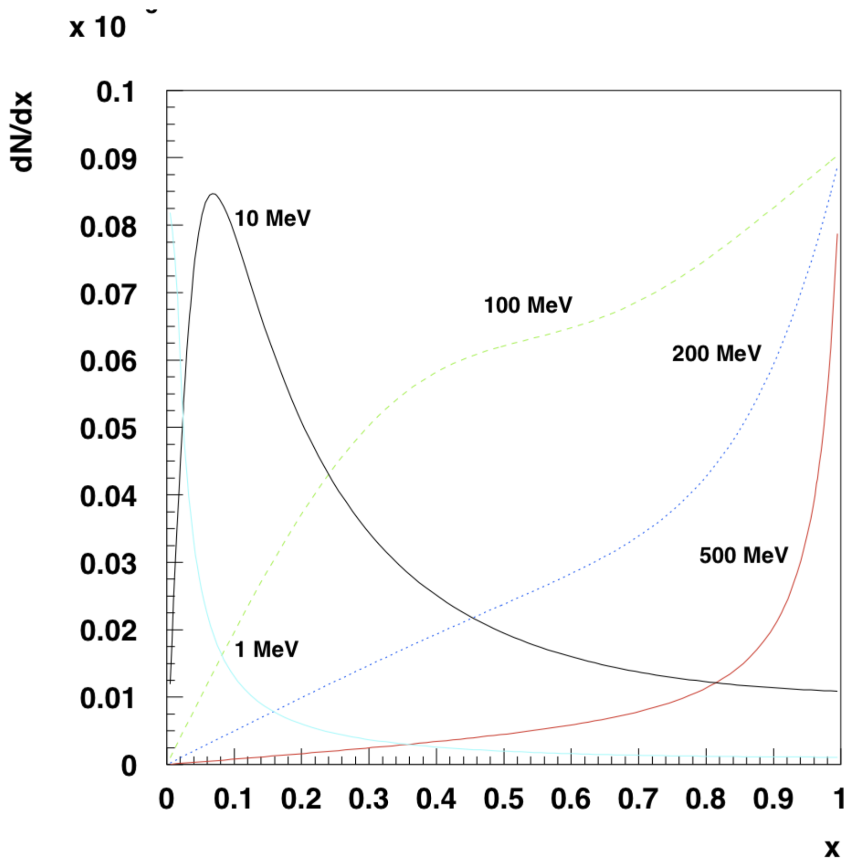
$$Br(Z_\mu \to \mu^-\mu^+) = \frac{K(\frac{m_\mu}{M_{Z_\mu}})}{1 + K(\frac{m_\mu}{M_{Z_\mu}})}, \qquad (32)$$

where

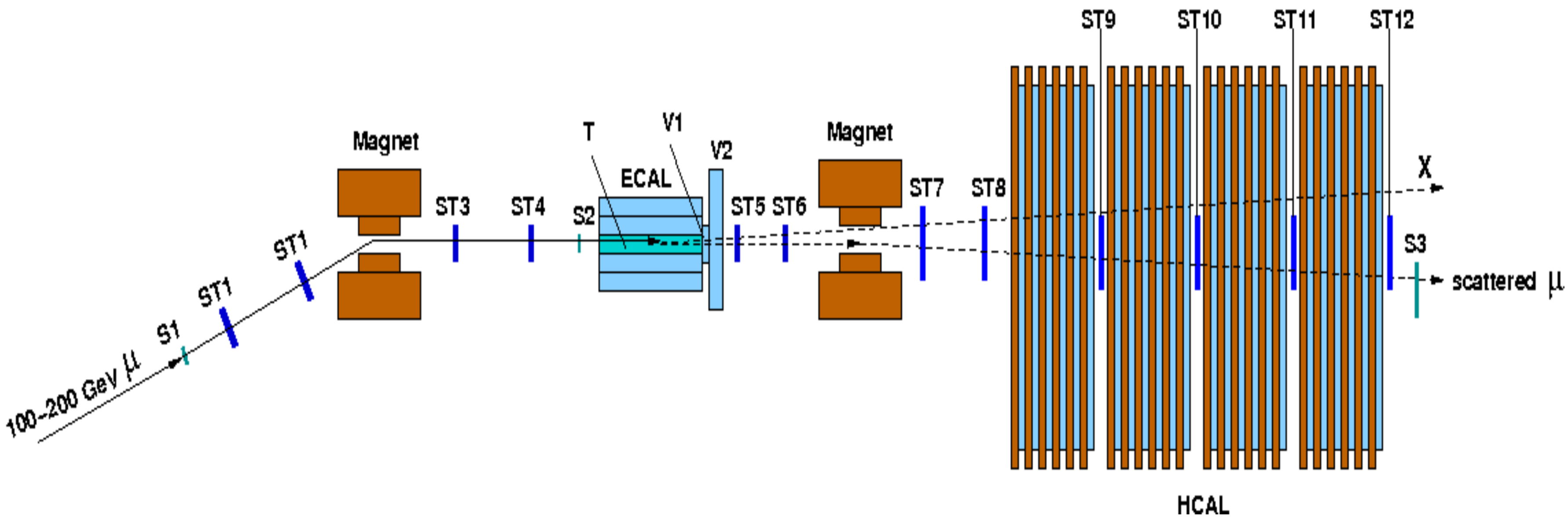
$$K(\frac{m_\mu}{M_{Z_\mu}}) = (1 + \frac{2m_\mu^2}{M_Z^2}) \cdot \sqrt{1 - 4\frac{m_\mu^2}{M_Z^2}}. \qquad (33)$$



3.The experiment at CERN SPS muon beam



Schematic illustration of the setup to search for dark boson



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

3a. 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

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

3a. 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}

3a. backgrounds

The crucial point – backgrounds

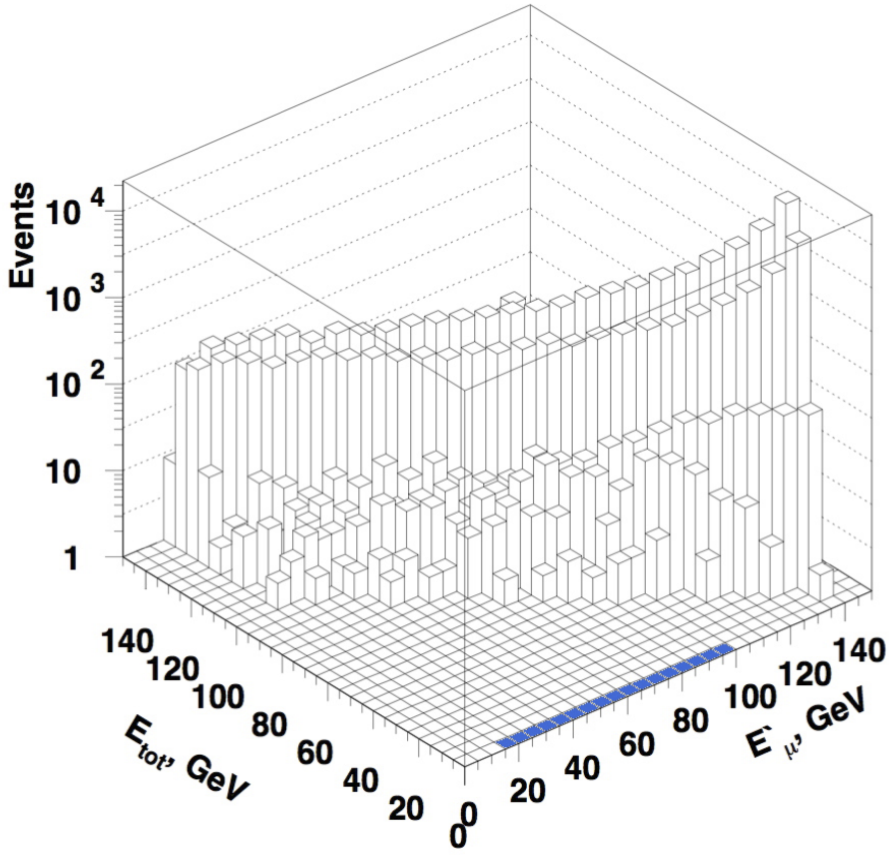
Two type of backgrounds

1. Beam related – nonexact knowledge of muon momentum – low energy tails
2. The presence in the beam of kaons and pions decaying into muons

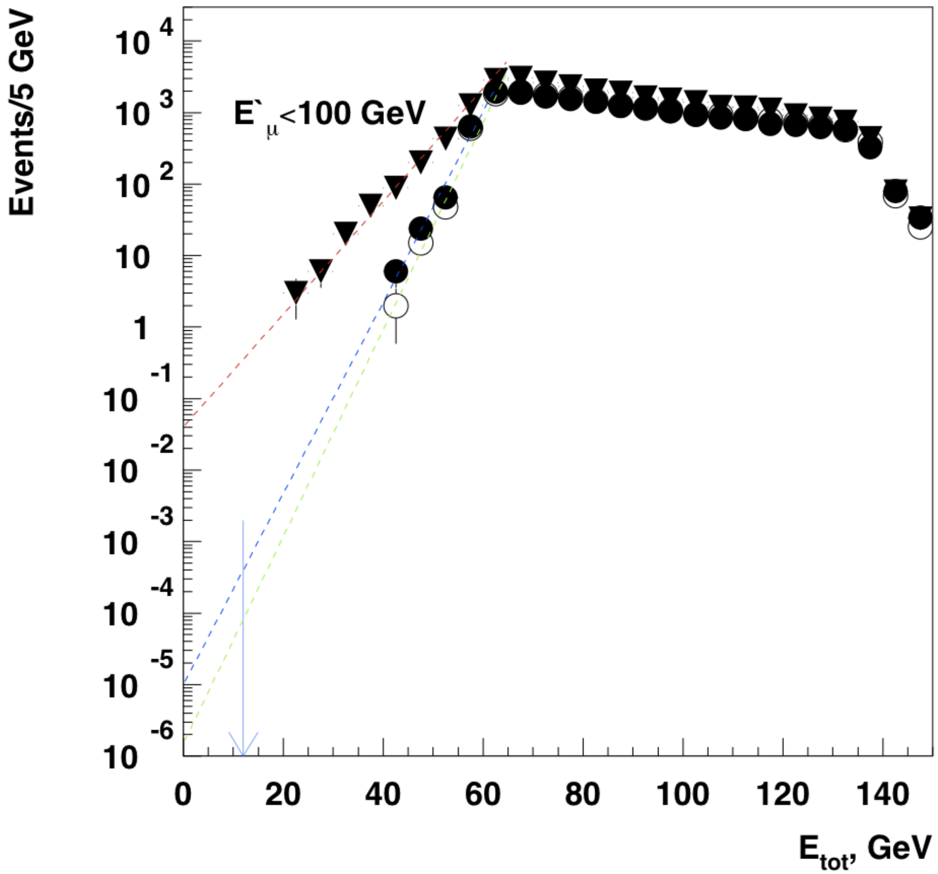
Simulations show that it is possible to get rid of such backgrounds at the level

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

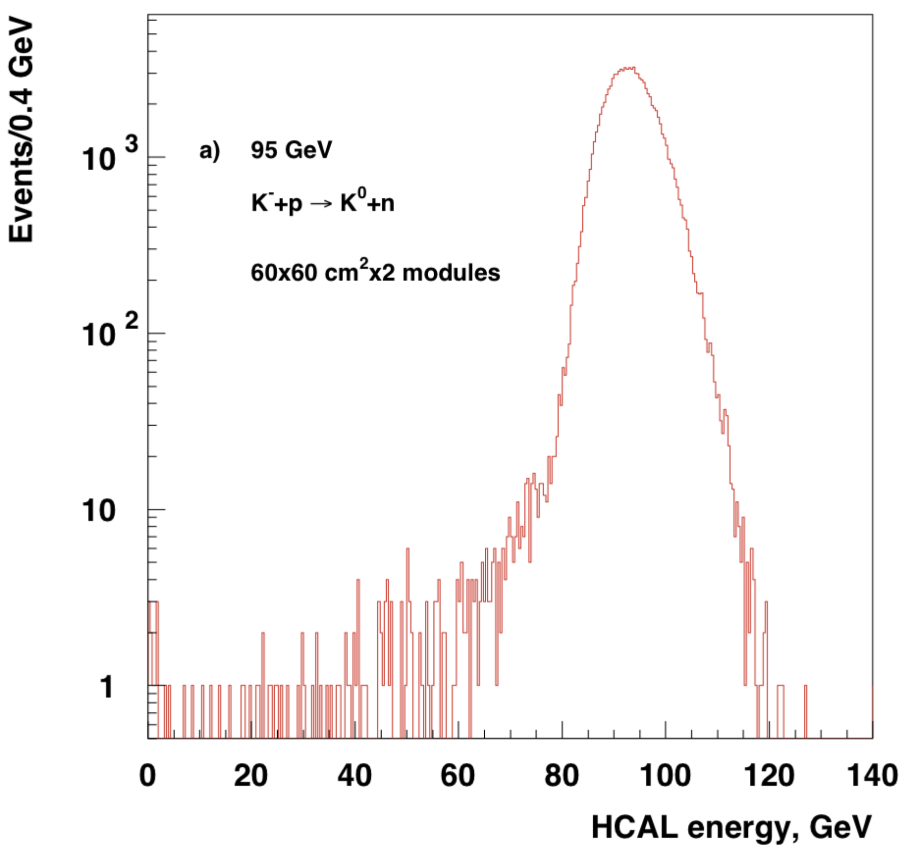
3a. backgrounds



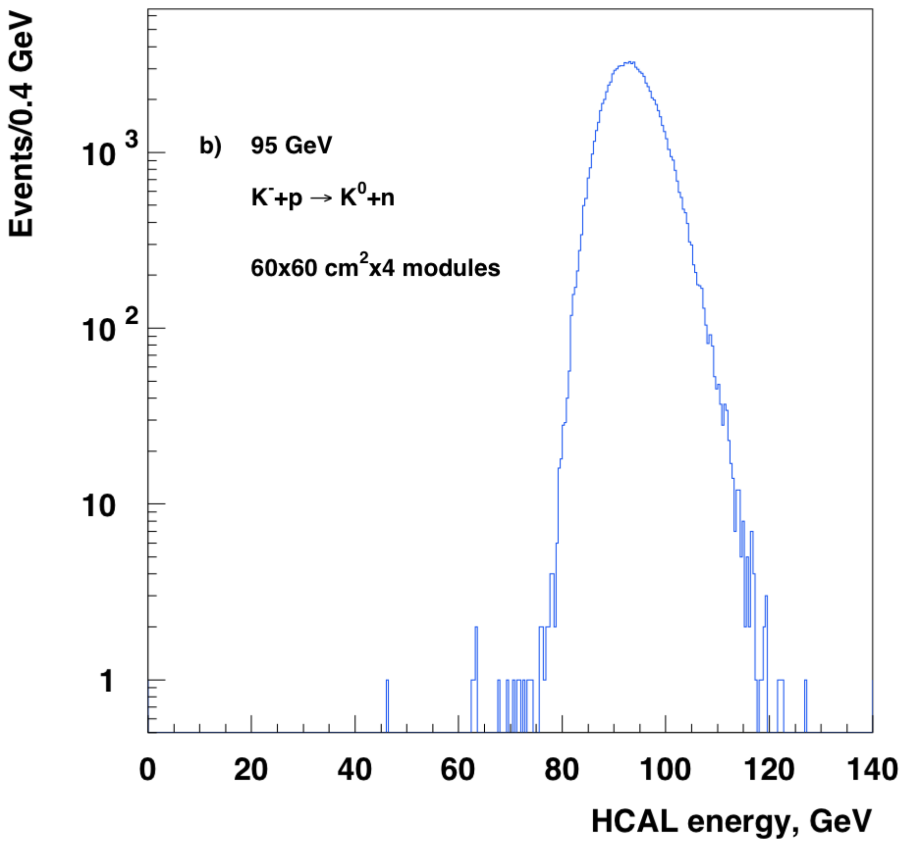
3a. backgrounds



3a. backgrounds



3a. backgrounds



3a.backgrounds

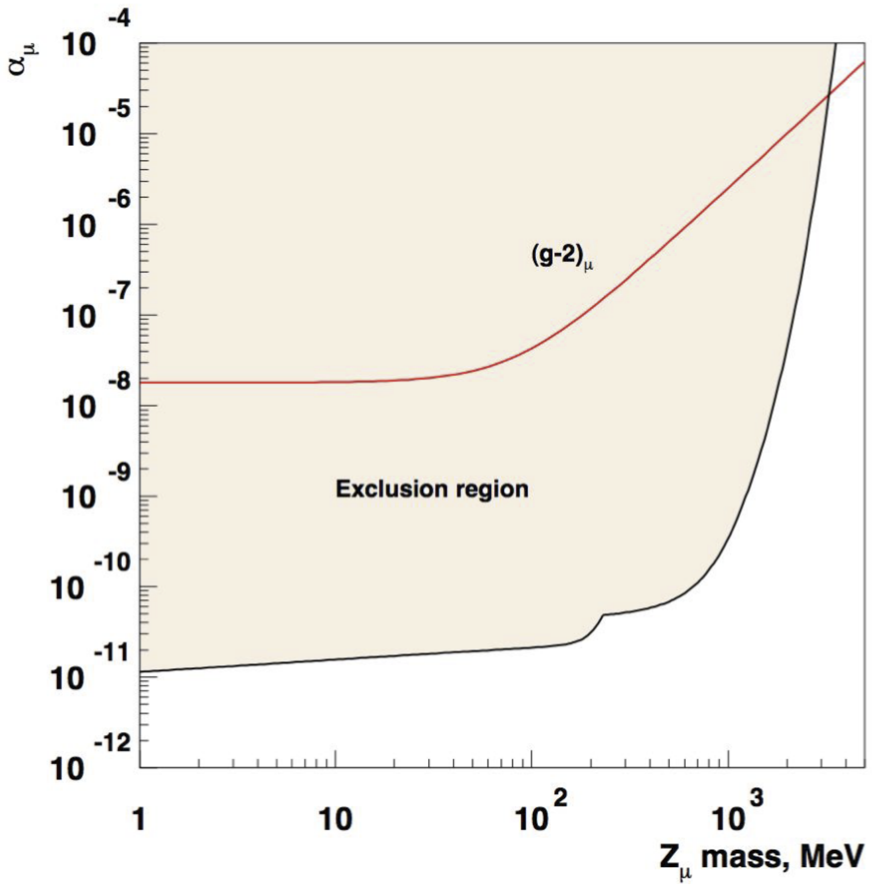
TABLE I: Expected contributions to the total level of background from different background sources estimated for the beam energy 150 GeV (see text for details).

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)	$\lesssim 10^{-12}$

3b. Expected sensitivity

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

3b. Expected sensitivity



4. Conclusions

- We proposed to perform an experiment dedicated to the search for dark boson coupled with lepton generation(s) by using CERN SPS electron(muon) beams. If the dark boson exists it could be produced at electron(muon) nuclei collisions with the specific signature – the missing of the large fraction of the beam energy in the detector. A feasibility study of the experimental setup shows that using this signature

4. Conclusions (cont)

it is possible to reach the sensitivity in the coupling constant of dark boson with muon $\alpha_{\mu} \geq 10^{-11}$.

BACKUP

"Dark Z" effects on Weak Neutral Current phenomenology

[Davoudiasl, LEE, Marciano (2012)]

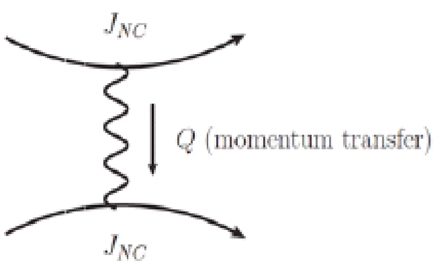
Dark Z : $\mathcal{L}_{\rm int} = -[\varepsilon\, e J^{\mu}_{em} + \varepsilon_Z\,(g/2\cos\theta_W) J^{\mu}_{NC}]\, Z'_{\mu}$

Dark Z **modifies** the effective Lagrangian of Weak Neutral Current scattering.

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} J^{\mu}_{NC}(\sin^2\theta_W) J^{NC}_{\mu}(\sin^2\theta_W)$$

$$G_F \to \left(1 + \delta^2 \frac{1}{1+Q^2/m^2_{Z'}}\right) G_F \quad \left(\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta\right)$$

$$\sin^2\theta_W \to \left(1 - \varepsilon\delta \frac{m_Z}{m_{Z'}} \frac{\cos\theta_W}{\sin\theta_W} \frac{1}{1+Q^2/m^2_{Z'}}\right) \sin^2\theta_W$$



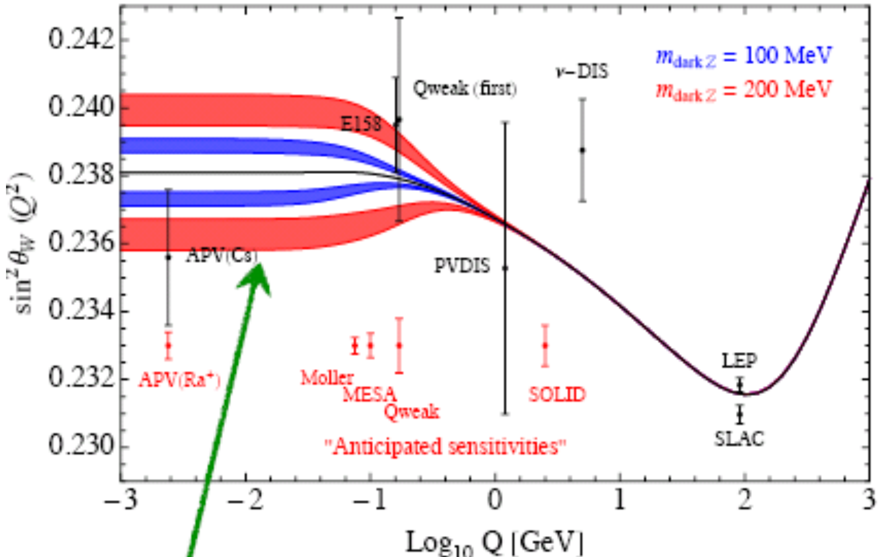
$$\frac{g_X^2}{m_X^2 + Q^2} \longrightarrow 0 \quad (\text{for } Q^2 \gg m_X^2)$$

- Sensitive only to Low-Q^2 (momentum transfer). (Effect negligible for $Q^2 >> mZ'^2$)
- Low-Q^2 Parity-Violating experiments (measuring $\sin^2\theta_W$) are good place to look.

Dark Z effectively changes the weak neutral current scattering (including parity), but only for the "Low" momentum transfer (Q).

Weinberg angle shift in Low-Q^2

[Davoudiasl, LEE, Marciano (2014)]



(Example)
For invisibly-decaying Dark Z.

Colored regions are predictions for the Weinberg angle shift by the Δa_μ solution (green band).

$$\Delta \sin^2\theta_W(Q^2) \simeq -0.42\,\varepsilon\delta\,\frac{m_Z}{m_{Z'}}\,\frac{1}{1+Q^2/m_Z^2}$$

Deviations from the SM prediction (due to Dark Z) can appear **"only" in the Low-E experiments.**

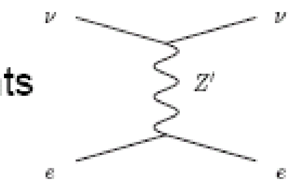
For the Low-Q^2 Parity Test (measuring Weinberg angle), we can use

(i) Atomic Parity Violation (Cs, Ra^+, …)

(ii) Low-Q^2 Polarized Electron Scattering (E158, Qweak, MESA P2, Moller, …)

independent of Z' decay BR (good for both visibly/invisibly decaying Z').

Neutrino - Electron scattering



Large flux ν experiments (Borexino, etc.) may give strong constraints on the new gauge boson if it couples to ν & e.
[Harnik, Kopp, Machado (2012)]

Borexino experiment: measures the solar ν flux through ν-e elastic scattering.

Standard Solar Model (with global fit for ν mixing parameters) predicts the ^{7}Be neutrino (862 keV) events to be 47.5±3.4 [counts/(day . 100 ton)].

New physics contribution to the ν-e scattering is constrained by the Borexino data (less than 8% of the SM).

TABLE I. Average fit results [counts/(day · 100 ton)].

^{7}Be	$46.0 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{syst})$
^{85}Kr	$31.2 \pm 1.7(\text{stat}) \pm 4.7(\text{syst})$
^{210}Bi	$41.0 \pm 1.5(\text{stat}) \pm 2.3(\text{syst})$
^{11}C	$28.5 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$

[Borexino (2011)]

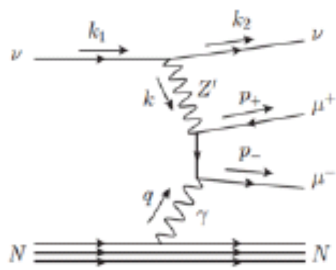
Borexino (~270ton Liquid Scintillator) in Gran Sasso

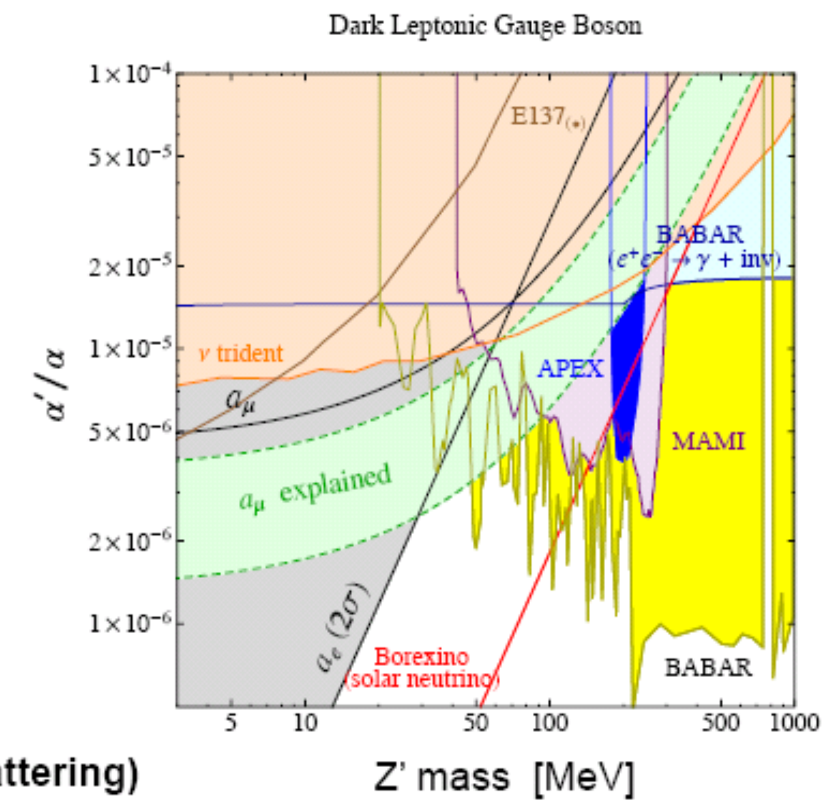
Constraints on the $U(1)_L$ Parameter Space

[LEE (2014)]

$U(1)_L$ is constrained by the followings.

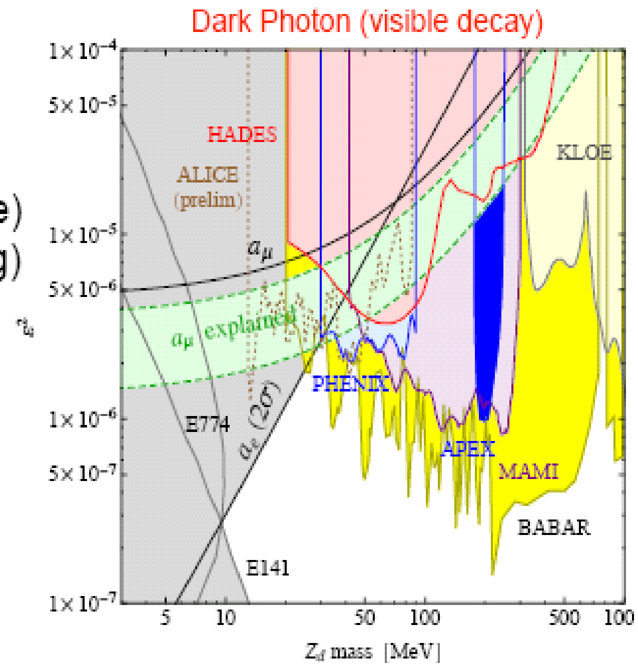
(i) Electron, Muon g-2
(ii) Beam-dumps
(iii) e+e- collision (ISR)
(iv) Fixed target experiments
(v) No meson decays
(vi) ν scattering (Borexino, ν trident)





Whole green band (g_μ-2 favored)
is excluded by the Borexino (ν-e scattering)
in both $U(1)_L$ and $U(1)_{B-L}$.

Dark gauge boson Models:
(1) Dark Photon (~ standard model of Dark force)
(2) Dark Z (Dark Photon w/ generalized coupling)
(3) B-L, L (constrained by neutrino physics)
…



"Dark gauge boson searches" include

(i) g-2 : 3.6σ deviation in a_μ may be explained by Dark gauge boson (Green band).

(ii) Z' → $\ell^+\ell^-$: Direct bump searches. (Green band is almost excluded now.)

(iii) Z' → MET : Requires light Dark particles (m$\chi \lesssim$ mZ'/2). (Green band survives.)

(iv) Z'-mediated scatterings (polarized electron scattering, ν scattering, …) :
independent of Z' decay BR
(with axial coupling or coupling to the neutrinos).

Plan

- Introduction
- A little bit of theory
- Experimental bounds
- 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 $U(1)_X$

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)

The most popular scenario

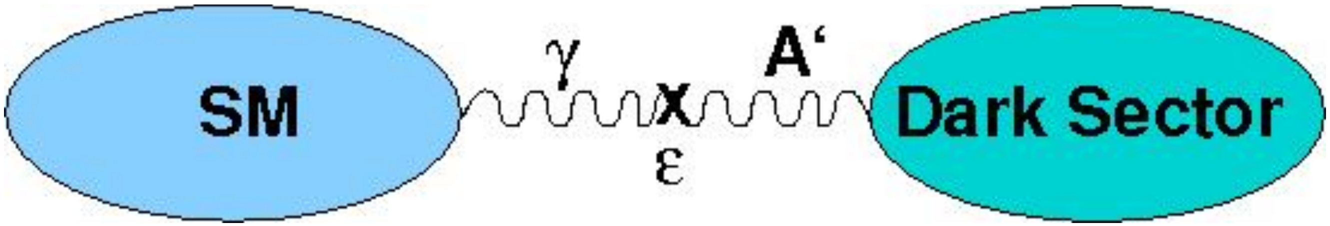
New hidden vector boson A\` interacts with our world only due to kinetic mixing with photon(or maybe with Z boson)

$$\Delta L = 0.5\varepsilon F^{\mu\nu} A`_{\mu\nu}$$

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,...)
- $\Delta L = \varepsilon F^{\mu\nu} A`_{\mu\nu}$ - 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

Decay modes for BEH mechanism

- For the case when hidden symmetry is broken by BEH(Brout-Englert-Higgs) mechanism additional decays are possible(for light A` boson)

  A` --→ A`*h` -→e+e- h’ ,

  h` ---→ invisible,

  h` ----> e+e-e+e-, pi+pi-pi+pi-

Experimental bounds

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

Decay modes for BEH mechanism

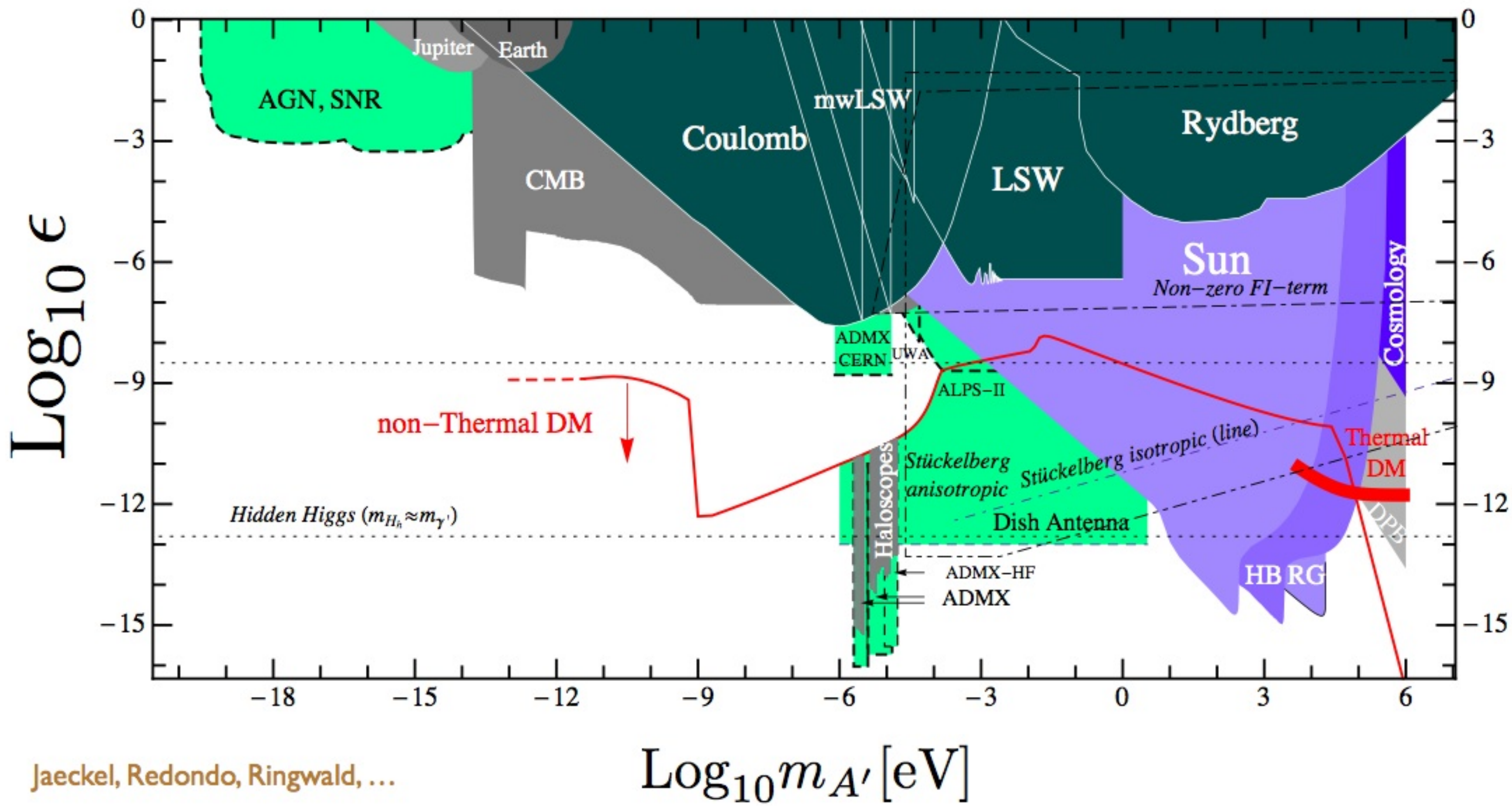
- For the case when hidden symmetry is broken by BEH(Brout-Englert-Higgs) mechanism additional decays are possible(for light A` boson)

  A` —→ A`*h` -→e+e- h’,

  h` —-→ invisible,

  h` ——> e+e-e+e-, pi+pi-pi+pi-

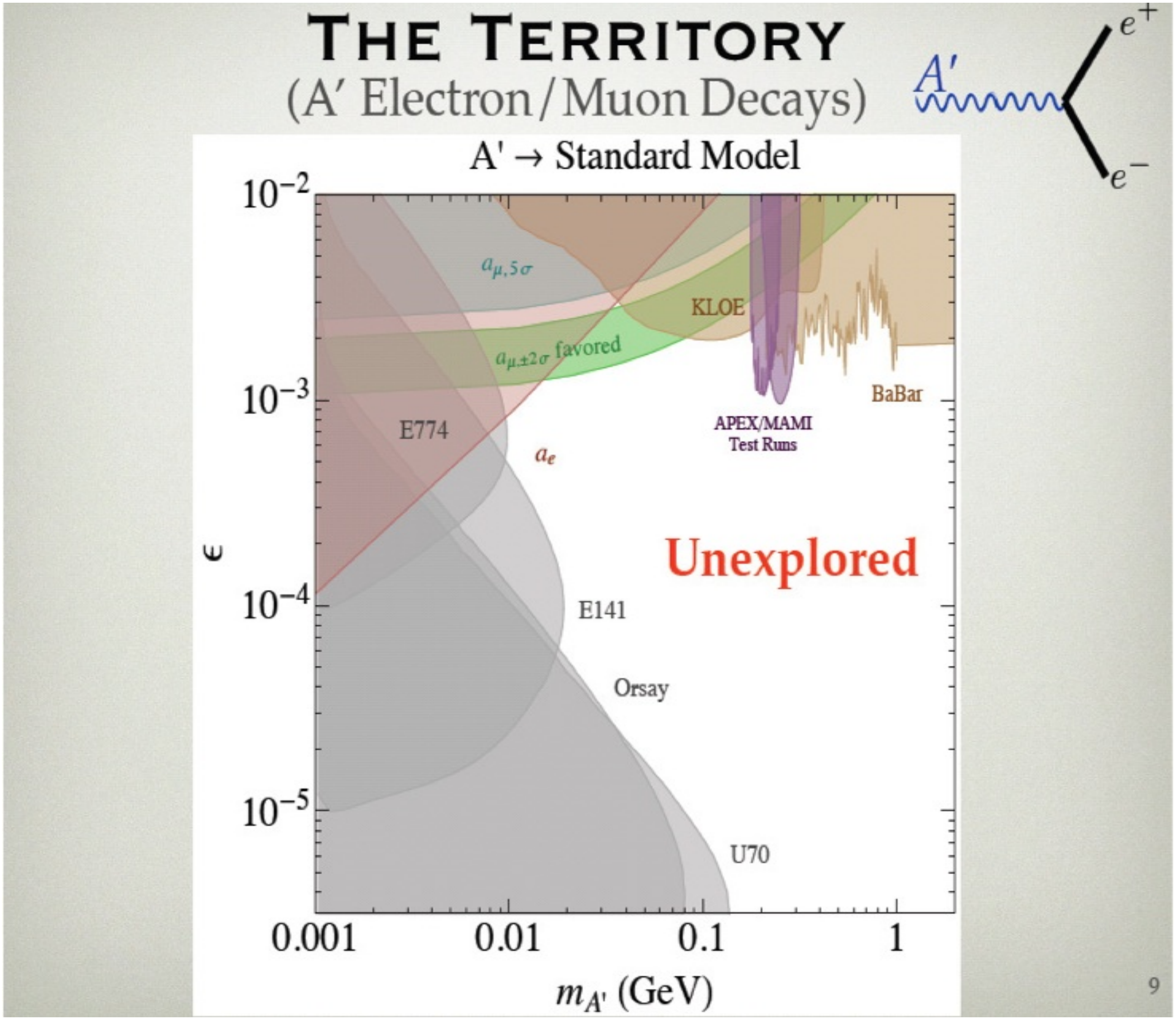
low-mass (< MeV) A′ parameter space

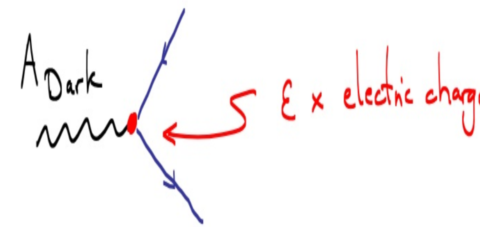


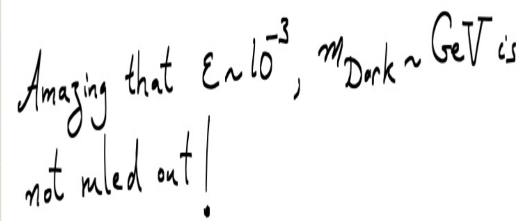
Jaeckel, Redondo, Ringwald, …

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

High mass (> MeV) A` parameter space





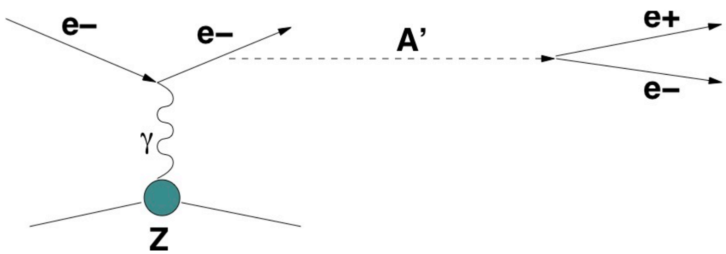


N. Arkani-Hamed,
Snowmass 2013

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`

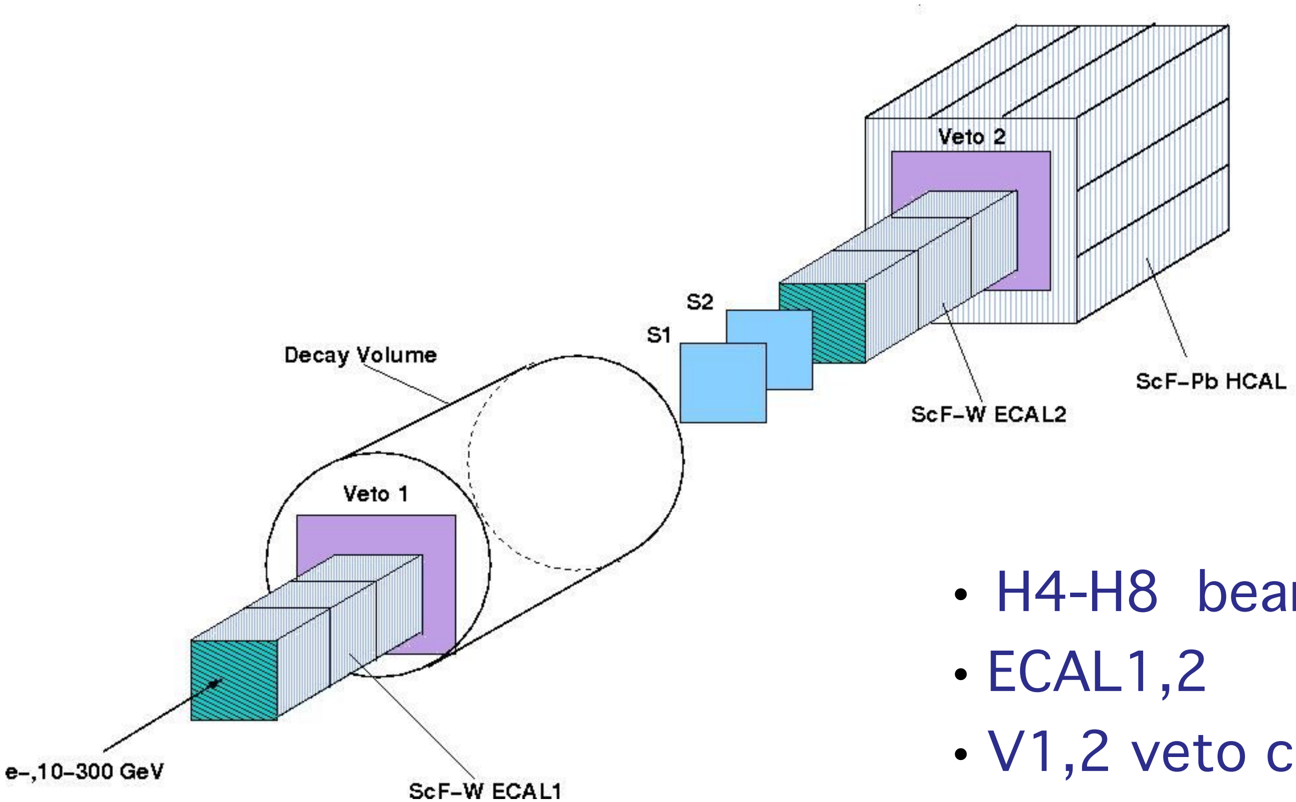
- e Z->e Z A`cross section $\sigma_{A`} \sim \varepsilon^2 (m_e/M_{A`})^2 \sigma_\gamma$; Bjorken' 09, Andreas' 12
- decay rate $\Gamma(A` \to e^+e^-) \sim \alpha\varepsilon^2 M_{A`}/3$ is dominant for $M_{A`} < 2\, m_\mu$
- sensitivity $\sim\varepsilon^4$ for long-lived A`, typical for beam dump searches

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: $\sigma_{A`}/\sigma_\gamma < 10^{-13}$-$10^{-9}$

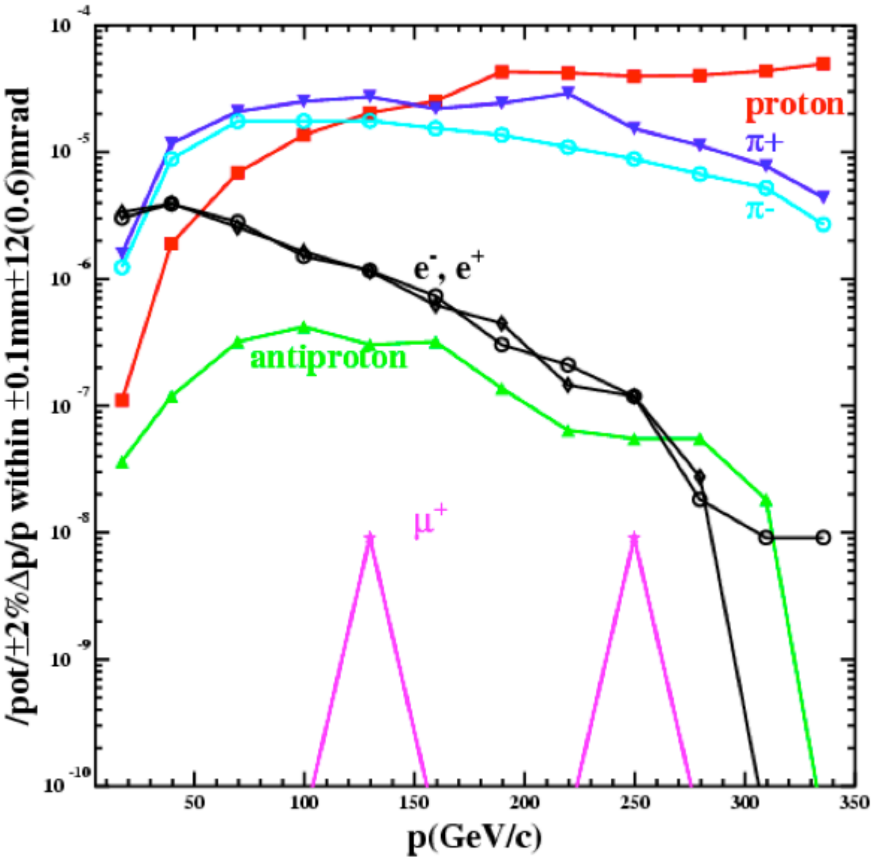
- A`energy boost to displace decay vertex,
  $\varepsilon \sim 10^{-4}$, $M_{A`} \sim 50$ MeV, $E_{A`} \sim 100$ GeV, $L_d \sim 1$ m
- background suppression

Setup



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

SPS e- beams



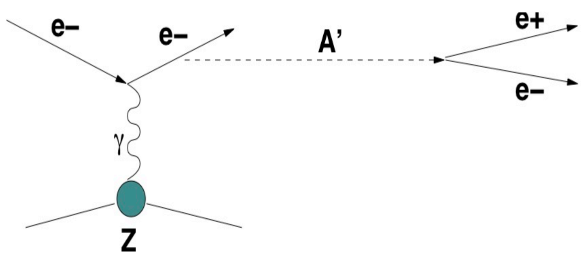
- H4, I_{max}~ 50 GeV e-
- 10^{12} pot per SPS spill,
- ~ $5x10^6$ e- per spill
- duty cycle is 0.25
- ~10^{12} e- / month

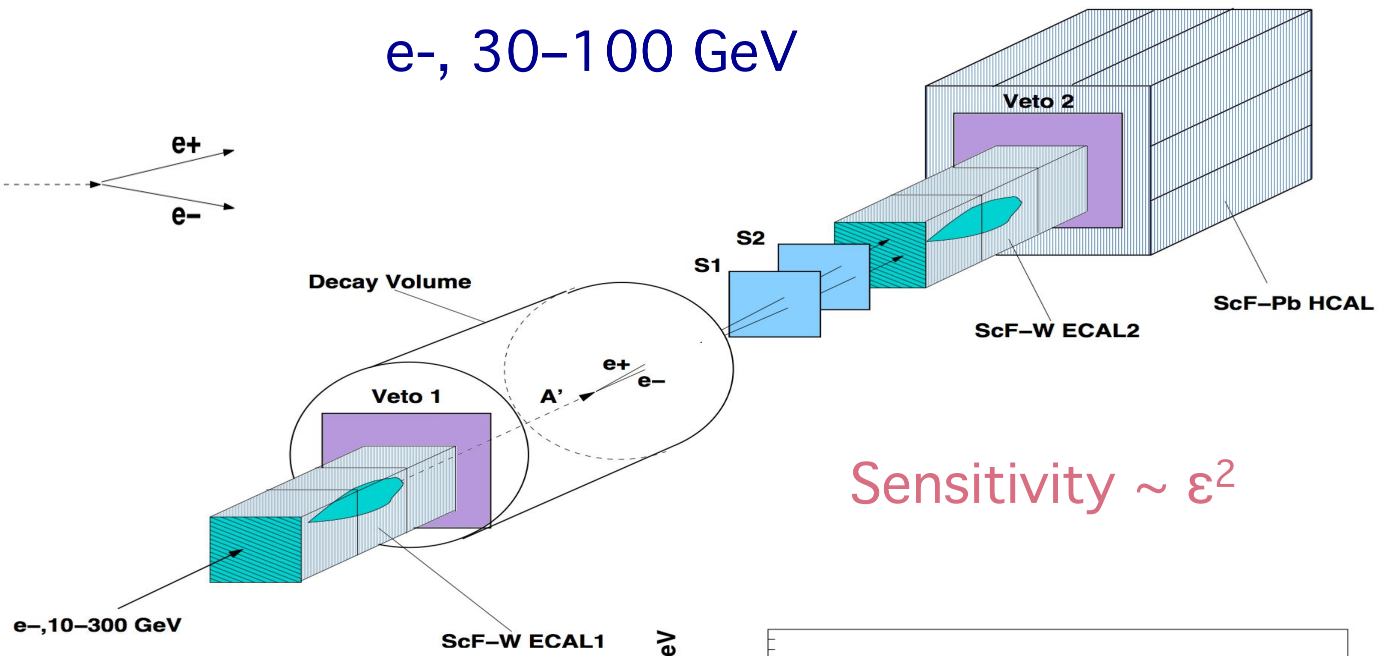
  additional tunning by

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

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

e-, 30–100 GeV



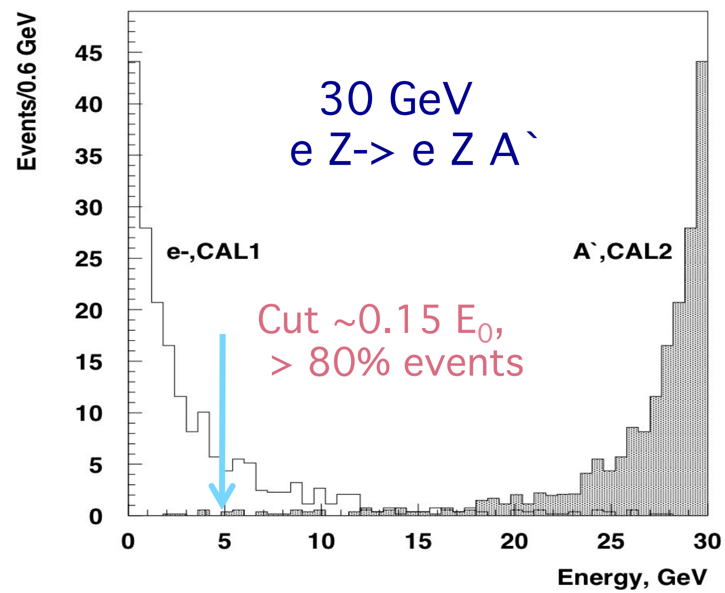


Sensitivity ~ ε^2

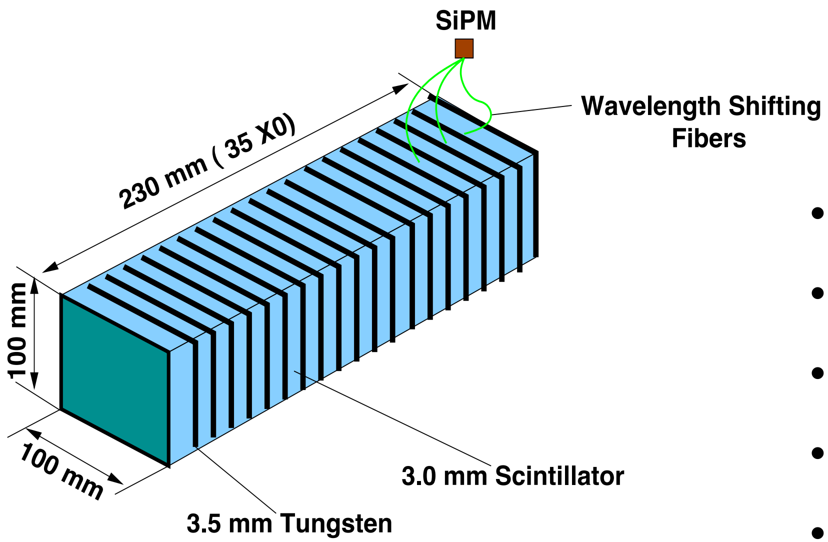
- A`s decay mostly outside ECAL1
- Signature: two separated e-m showers from a single e-

$S= ECAL1 x S1 x S2 x ECAL2 \overline{x V1 x V2 x HCAL}$

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



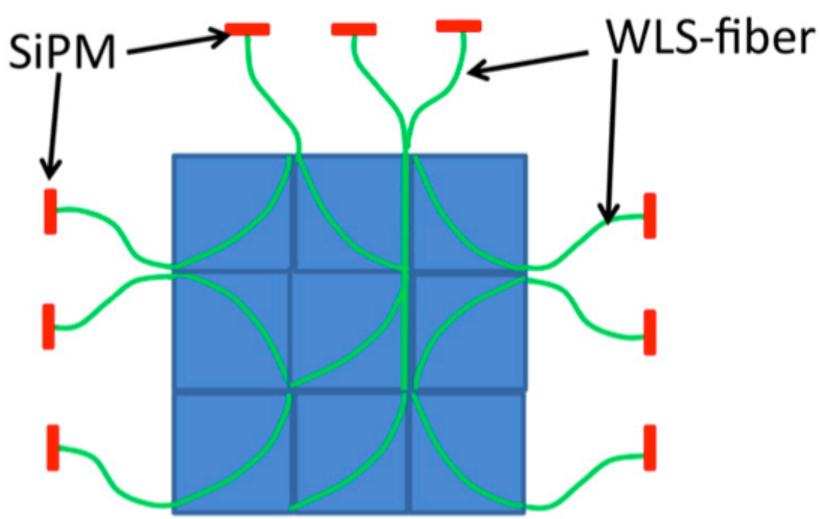
Specially designed ECAL

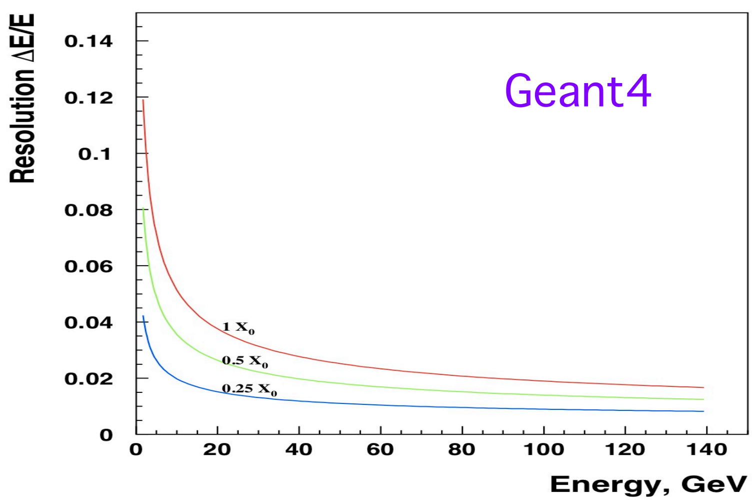


ECAL1 "bubble chamber"

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}

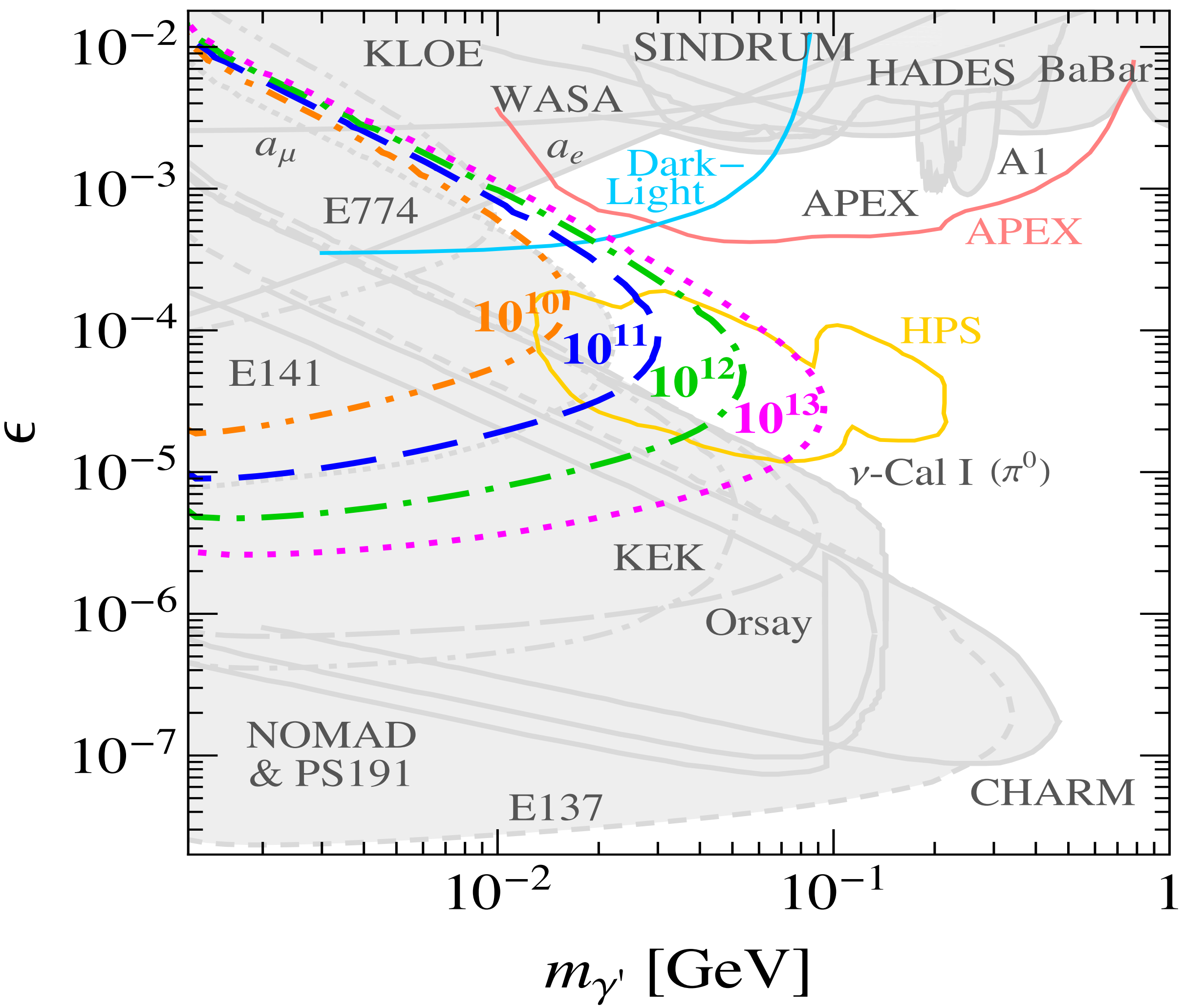




Summary of background sources for A` -> e+e-

Source	Expected level	Comment
Beam contamination		
- π, μ reactions, e.g. πA-> 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->eν	$< 10^{-13}$	
Total	$< 10^{-12}$	

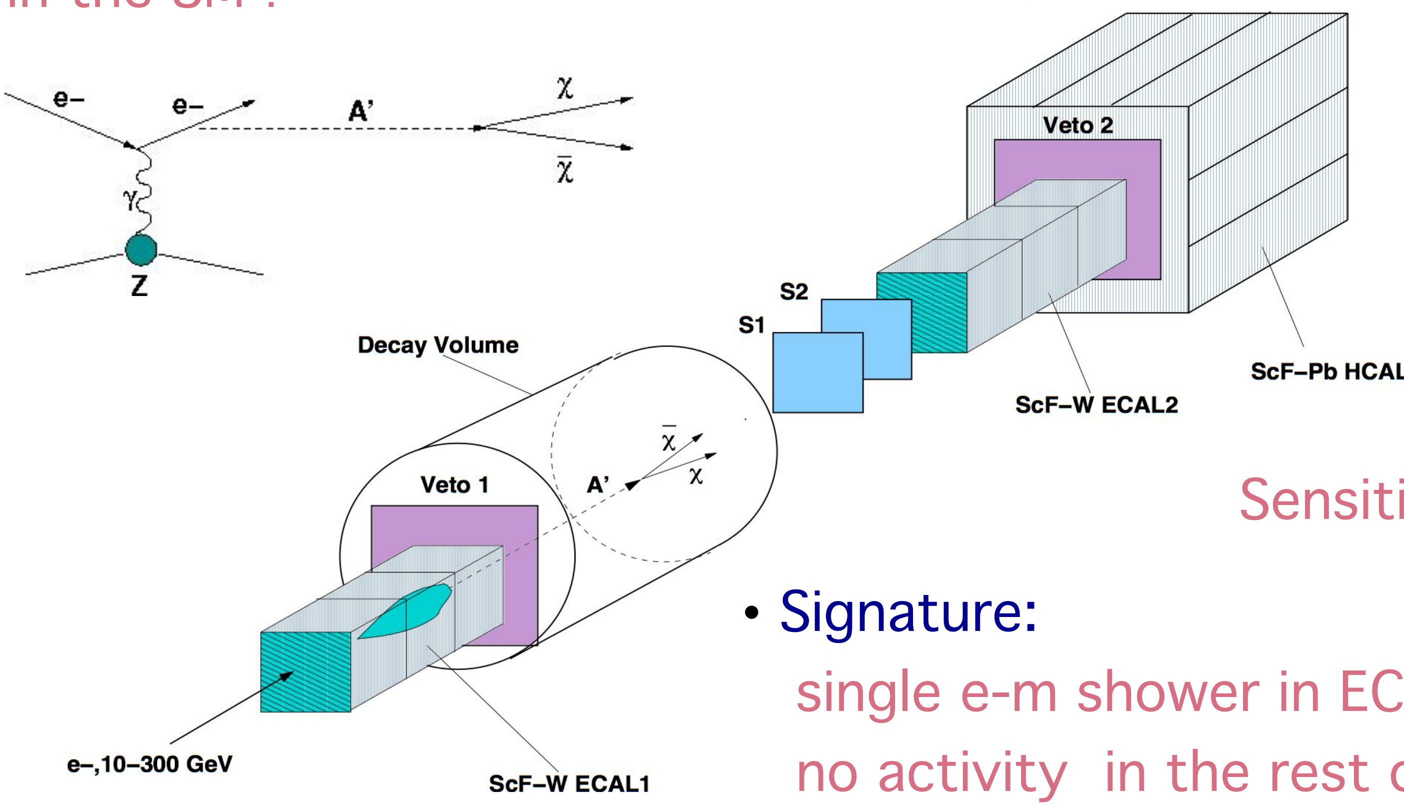
Expected limits on A` -> e+e- decays vs accumulated N_{e-} (background free case)



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

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
  $S = ECAL1 \times \overline{V1 \times S1 \times S2 \times ECAL2 \times V2 \times HCAL}$
- $E_1 << E_0$, 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

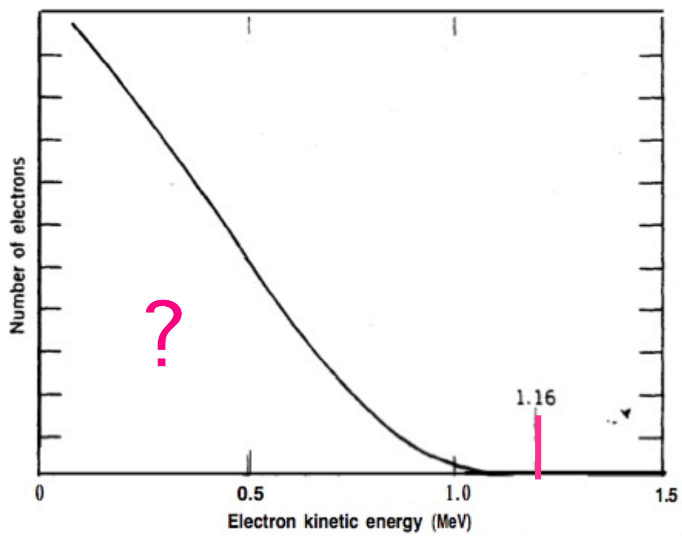
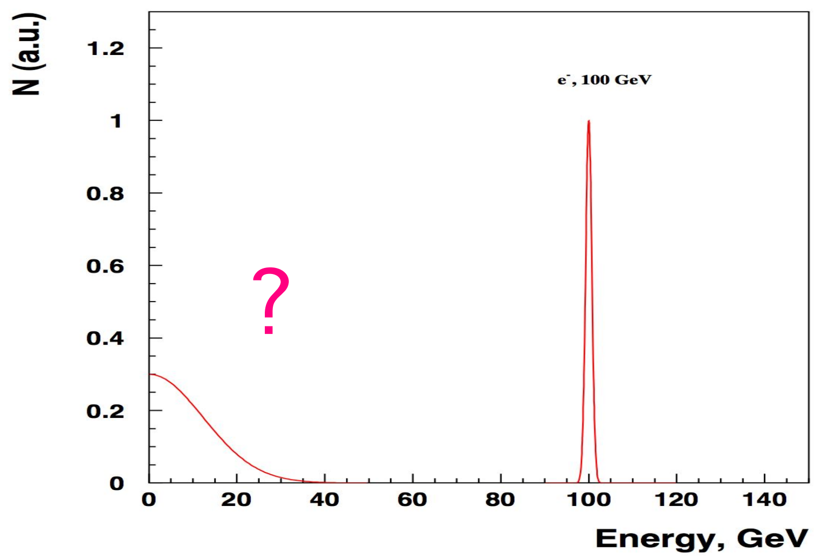


Figure 9.1 The continuous electron distribution from the β decay of ^{210}E. called RaE in the literature).

SPS e- spectrum



Pauli, 1931

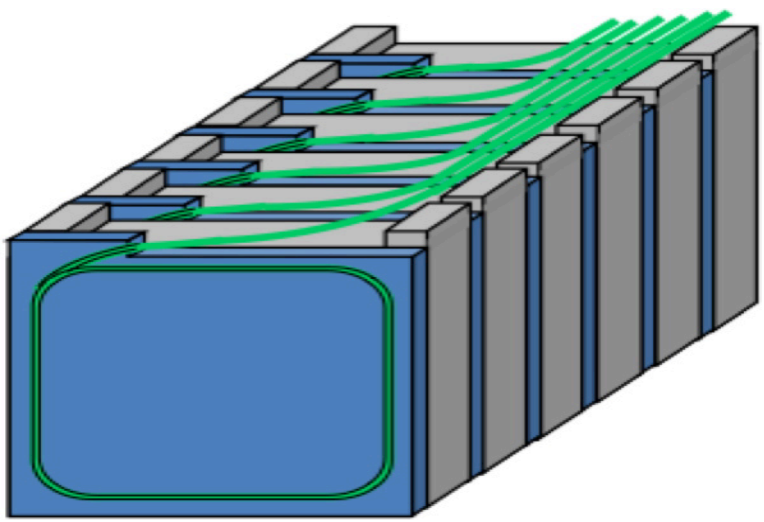
? = invisible ν

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

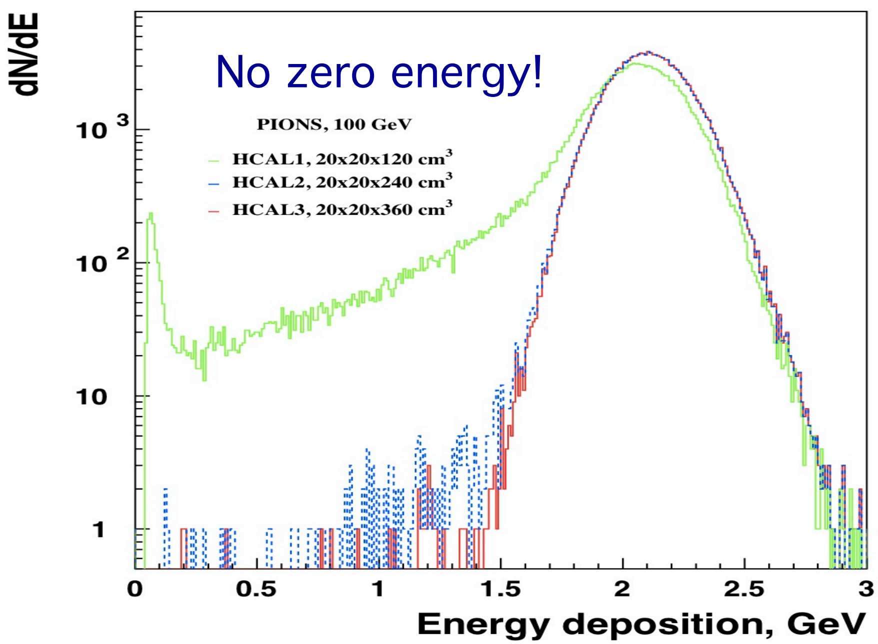
Full HCAL : 2x2x3 modules, ~ 7 tons



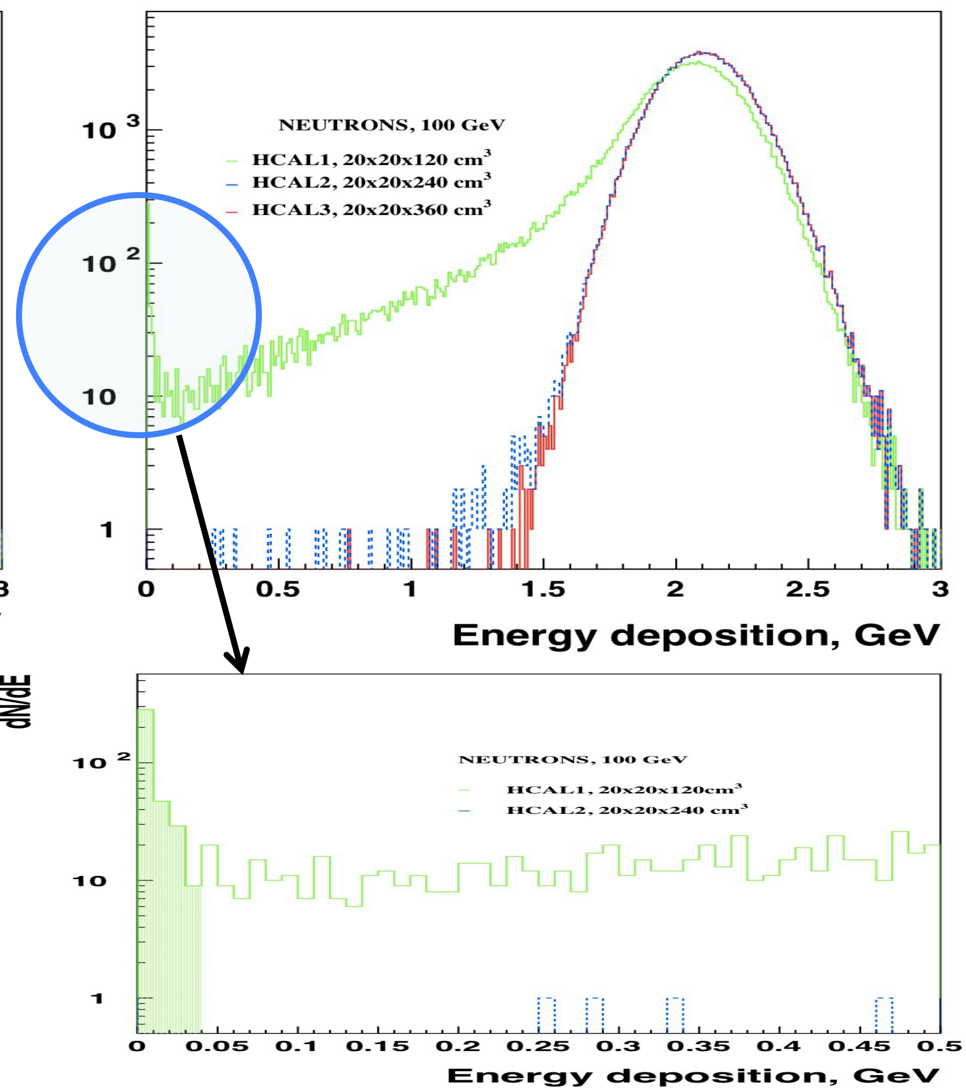
Prototype →

HCAL hermeticity for 3 consequtive modules

Pions, 100 GeV

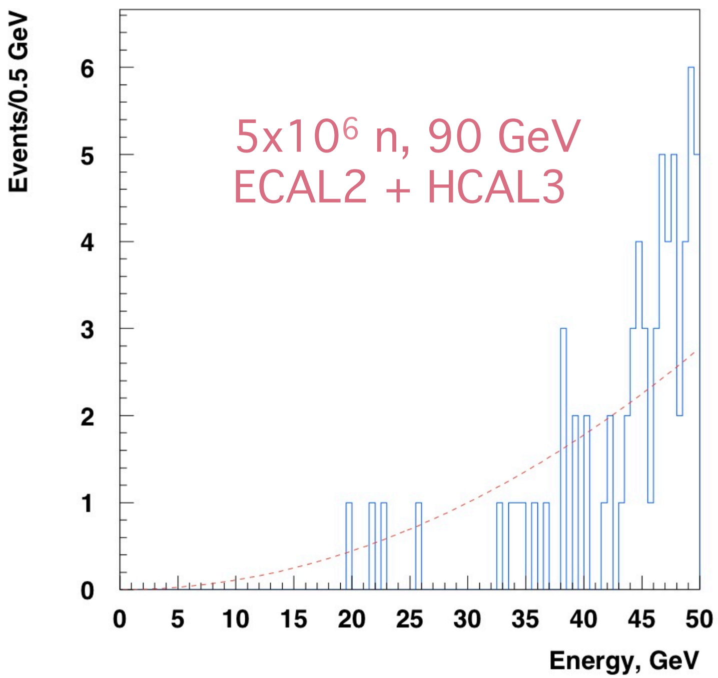


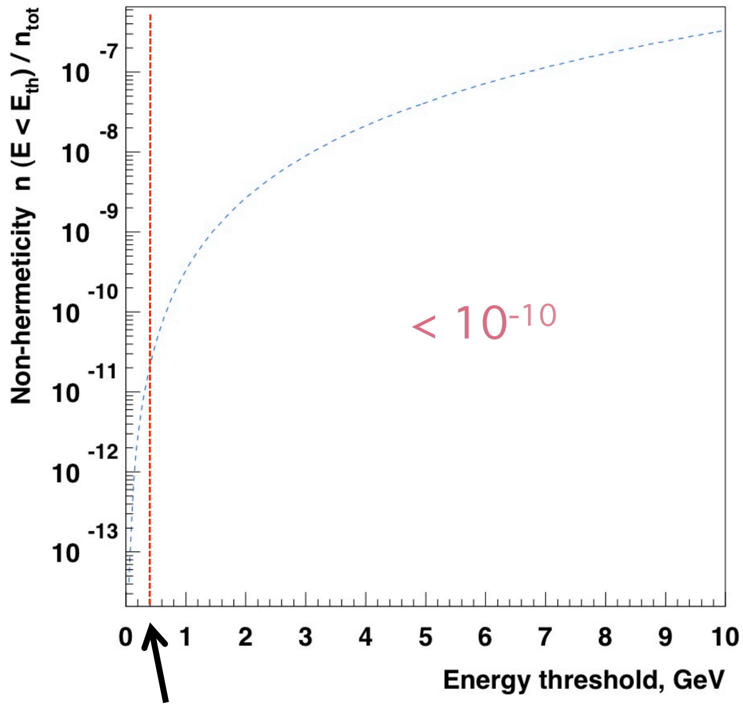
Neutrons, 100 GeV



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

Estimated ECAL2+ HCAL3 nonhermeticity





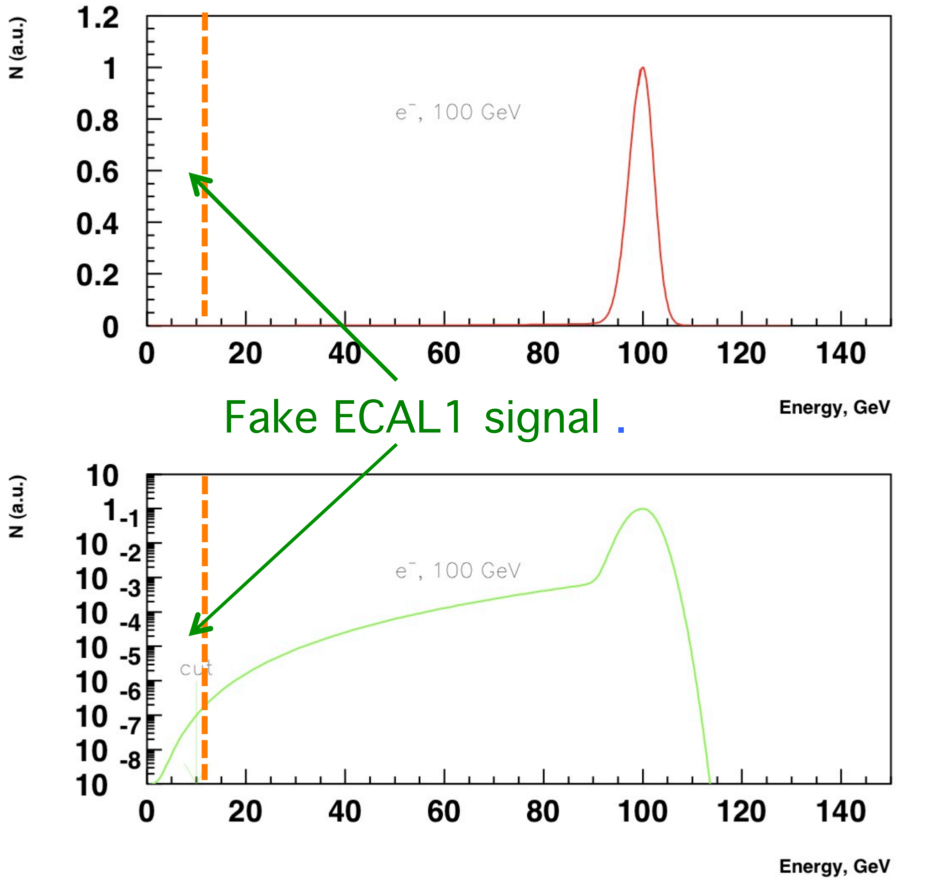
Fit of the low energy tail with a smooth function f(E)

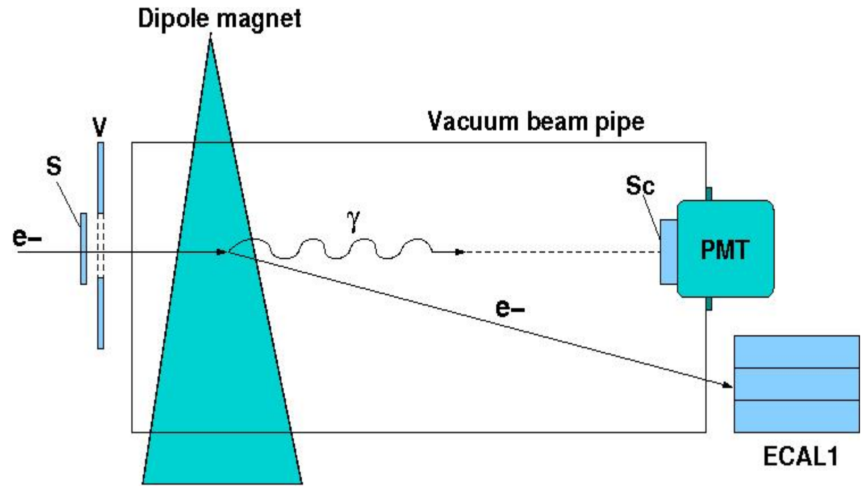
ECAL2+HCAL3 nonhermeticity as a funcion of the energy threshold

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



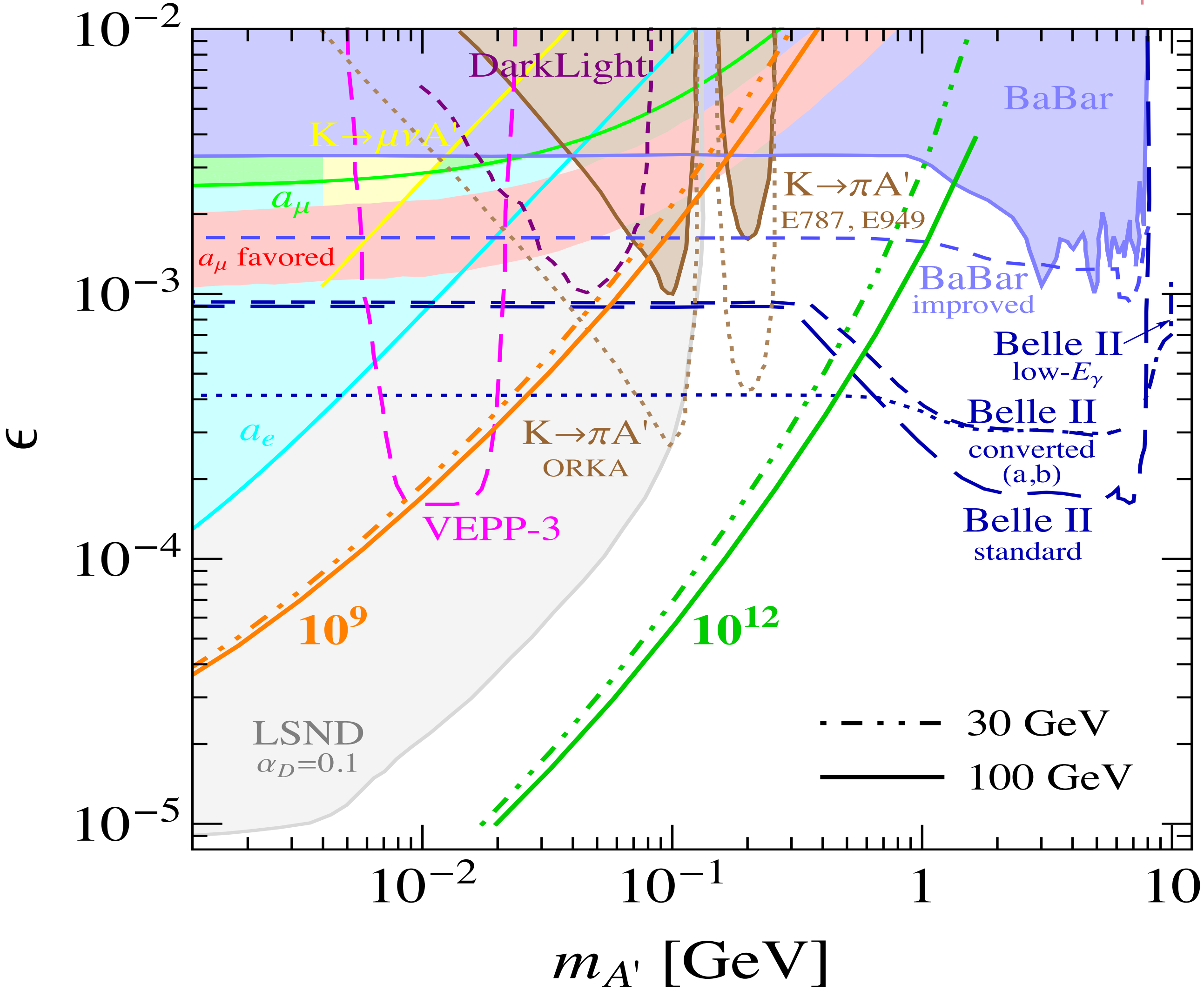


Hypothetical e- beam energy distribution (not simulated).

- 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 $(g-2)_\mu$ favored region!



7. Conclusions

- We proposed to perform an experiment dedicated to the search for dark boson coupled with second lepton generation by using CERN SPS muon beams. If the dark boson exists it could be produced at muon nuclei collisions with the specific signature – the missing of the large fraction of the beam energy in the detector. A feasibility study of the experimental setup shows that using

7. Conclusions (cont)

this signature it is possible to reach the sensitivity in coupling constant of dark boson with muon $\alpha_\mu \geq 10^{-11}$.

This talk is based on our recent paper

S.N.Gninenko, N.V.Krasnikov and V.A.Matveev,

The muon g-2 and searches for a new electrophobic sub-GeV dark boson in a missing-energy experiment at CERN, arXiv:1412.1400(2013).

Most relevant references are contained in this paper.