Легкий векторный бозон и g-2 мюонная аномалия

Н.В.Красников

ИЯИ РАН

1.Introduction

Outline

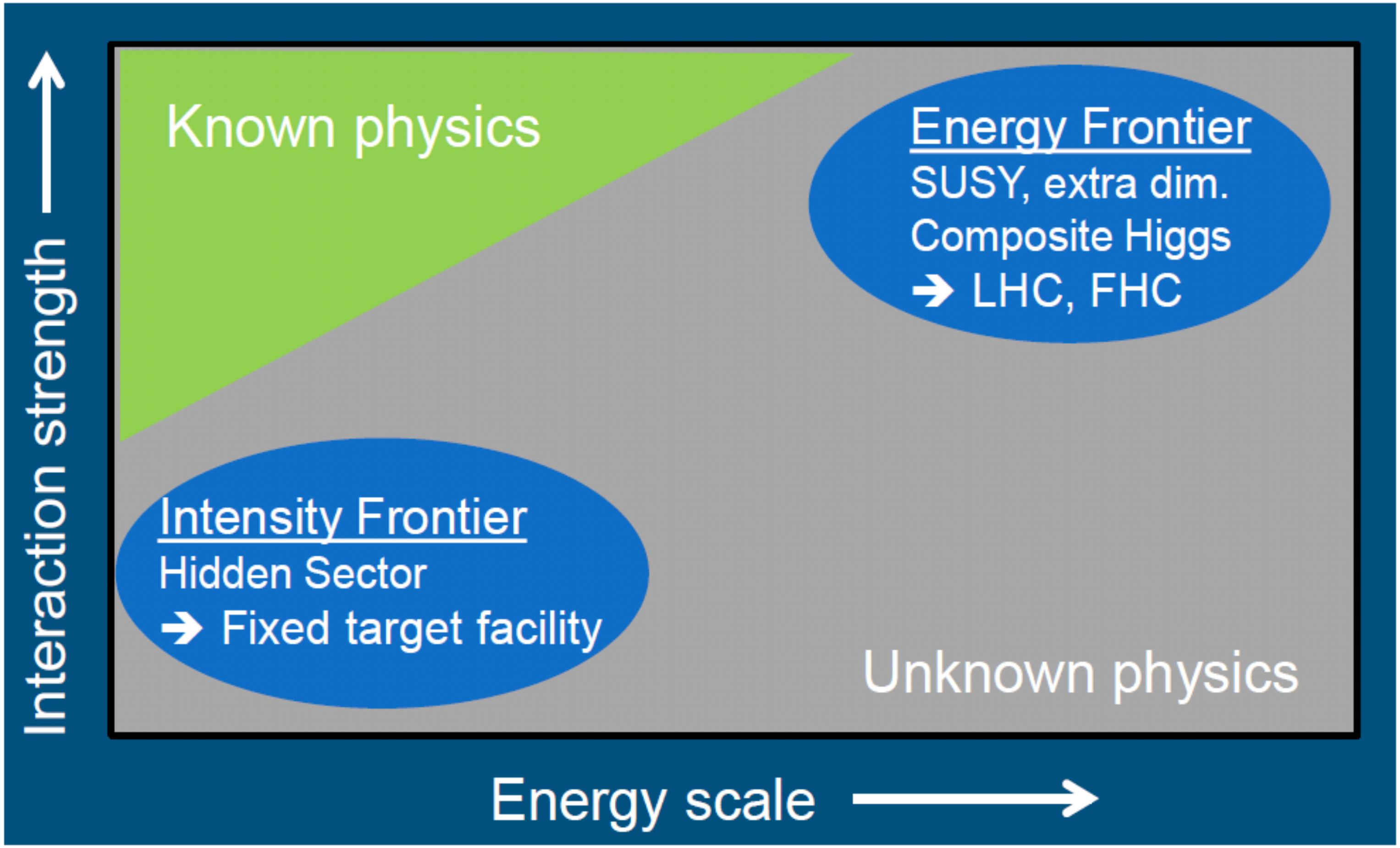
1. Introduction
2. Experimental bounds
3. P348(NA64) experiment
4. Conclusion

1. Introduction

Two lines of research in experimental elementary particle physics:

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

1. Introduction



1. Introduction

Light particles:

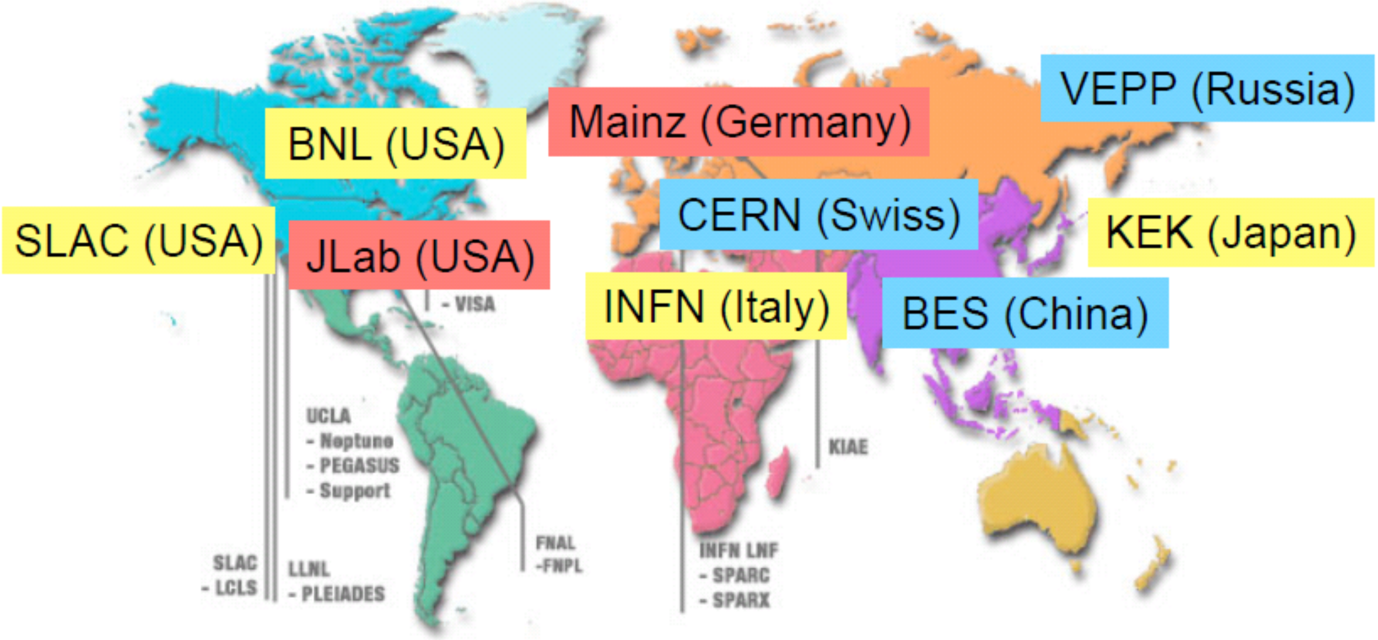
1. S = 0 – scalar portal – axions, flavons, ...
2. S = ½ – neutrino portal – neutral leptons (sterile neutrino)
3. S =1 – vector portal – light dark vector boson
4. S = 3/2 – gravitino

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

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

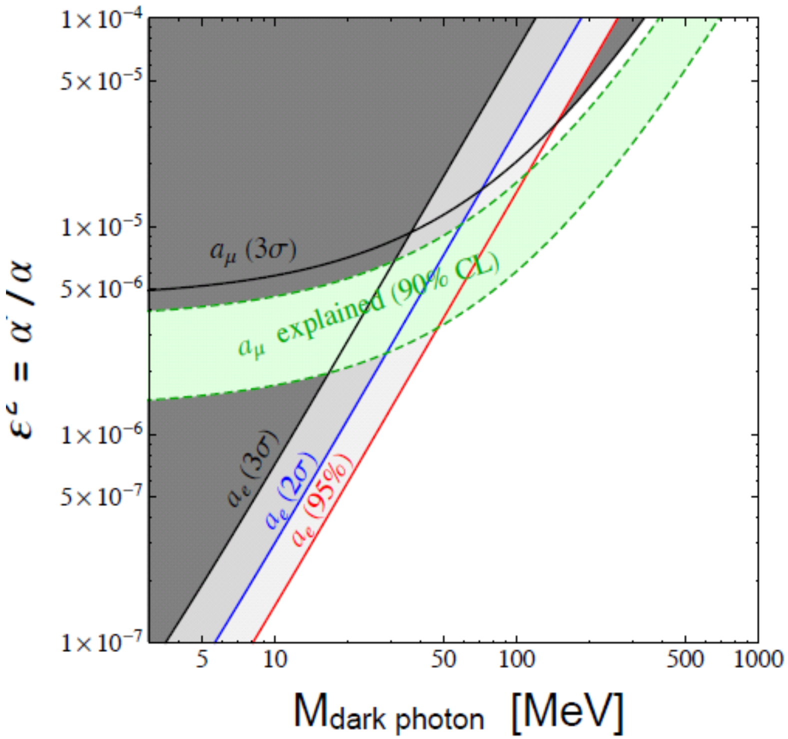
  of new light boson A`(Z`) with muons with $\alpha_\mu \approx O(10^{-8})$

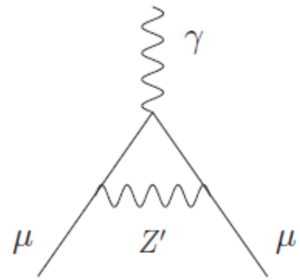
  coupling constant

  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





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

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.

Эксперим. указания на существование A´

- (g-2 M $_{A´}$ < ~100 MeV
- ^{7}Li(p, M $_{A´}$ =16.7 MeV
- astrophysical observations

PRL 116, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

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(Received 7 April 2015; published 26 January 2016)

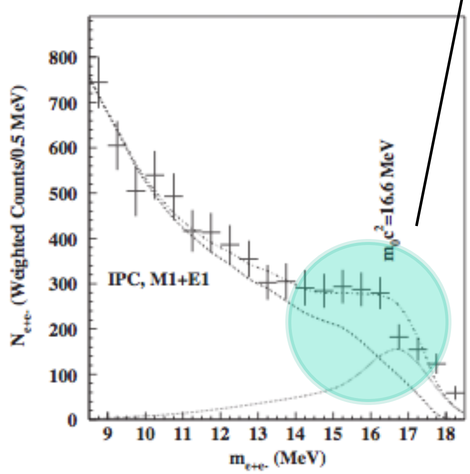

FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.

Br(A´→ e$^+$e$^-$)=1, ε^2~ 10^{-7}

Br(A´→ inv)=0.9, ε^2~10^{-6}
Br(A´→ e$^+$e$^-$)=0.1

$m_0c^2 = 16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV. The branching ratio of the e^+e^- decay of such a boson to the γ decay of the 18.15 MeV level of ^{8}Be is found to be 5.8×10^{-6} for the best fit.

Such a boson might be a good candidate for the relatively light $U(1)_d$ gauge boson [4], or the light mediator of the secluded WIMP dark matter scenario [5] or the dark Z (Z_d) suggested for explaining the muon anomalous magnetic moment [7].

Very recently dark photon (DP) signals were searched for in the $\pi^0 \to \gamma e^+e^-$ decay [2]. No signal was observed, and the obtained upper limits ruled out the DP as an explanation for the muon (g-2) measurement under the assumption that the DP couples to quarks and decays predominantly to standard model fermions. However, in the case of the dark Z, the predominant decay to e^+e^- is not assumed [42].

Our observed branching ratio can also be related to the mixing parameter ε^2 [2]. A somewhat similar calculation was performed by Donnelly *et al.* [43] for nuclear deexcitations via axions. When we use Eq. 22a of that article, our experimental branching ratio gives an ε^2 in the 10^{-7} range, which is already below the best upper limit published recently [2]. If we consider a vector or axial vector dark Z particle, which decays only with 10% branching to e^+e^- pairs, than our ε^2 is consistent with the description of the g-2 anomaly [7].

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1. Introduction

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

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

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

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

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

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

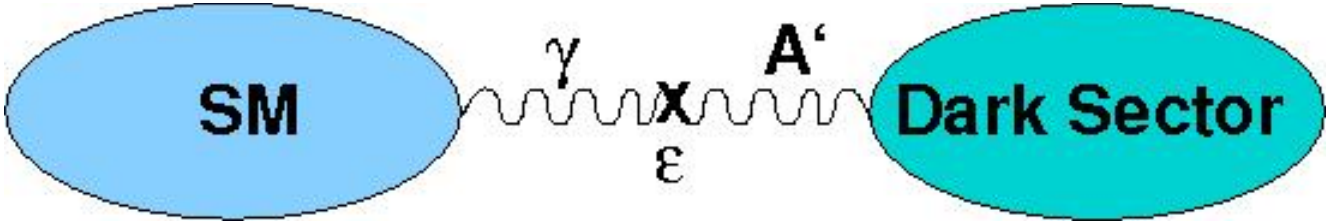
New hidden vector boson A`(Z`) interacts with our world only due to kinetic mixing with photon(or maybe with Z boson)

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

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`(Z`) 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

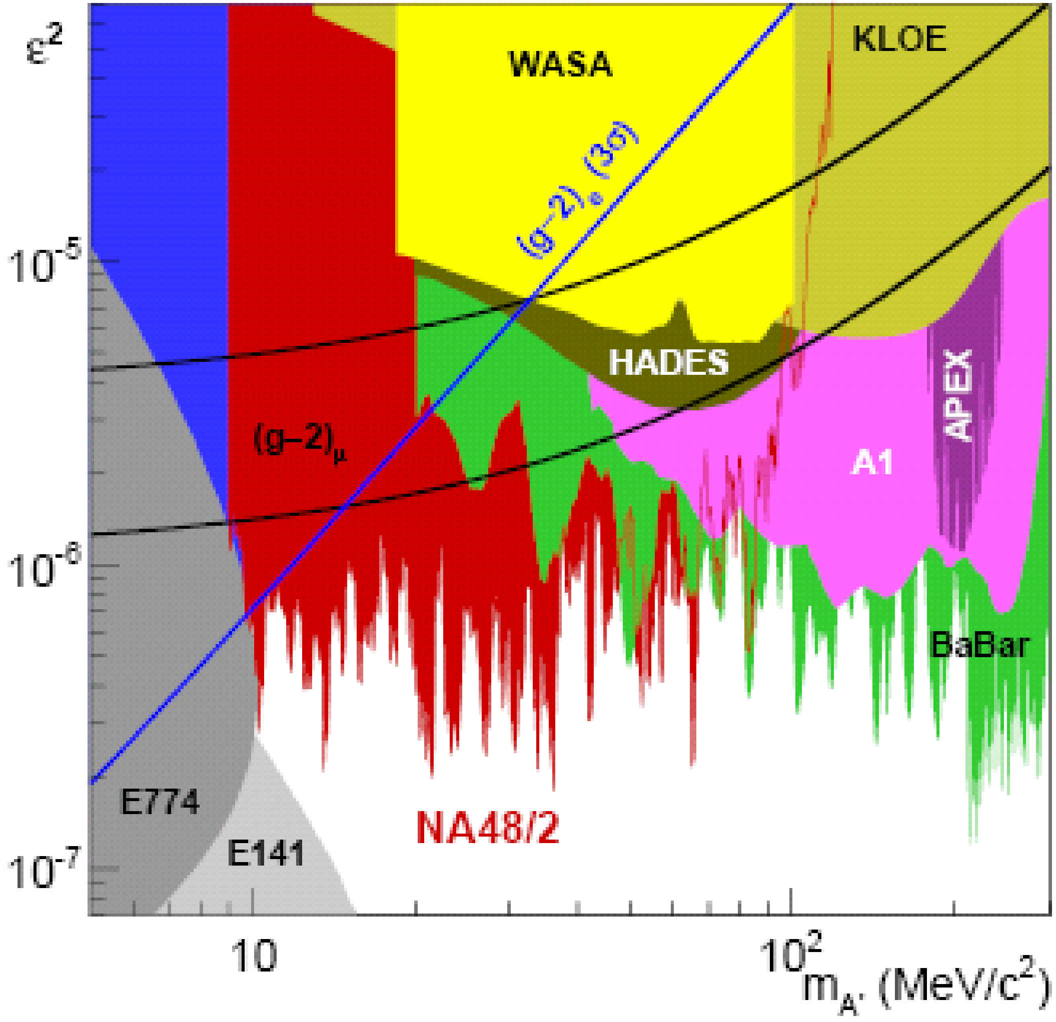
For this scenario there are several bounds which exclude possible g-2 anomaly explanation

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 in the model is excluded.

Exclusion plot



2. Experimental bounds

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

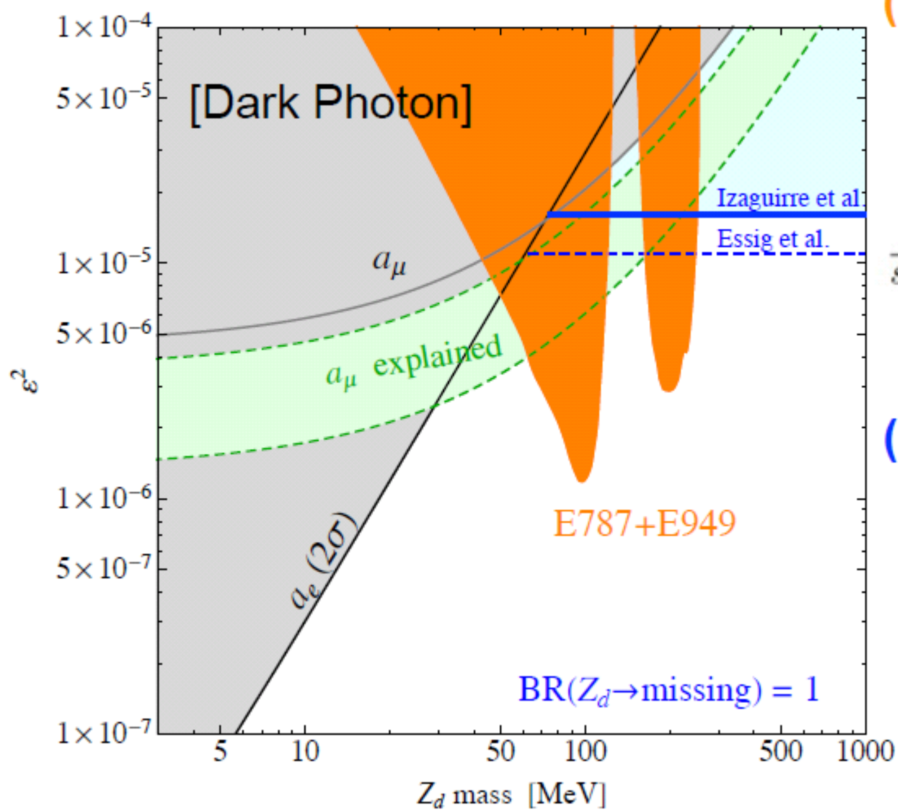
2. Experimental bounds

There is also possibility that new boson A`(Z`) 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

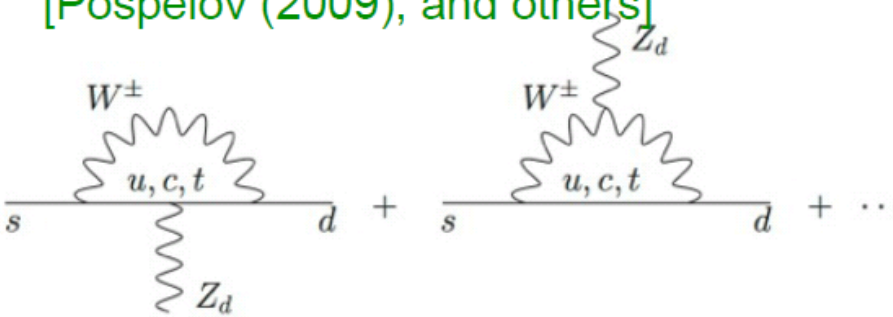
2. Experimental bounds

Invisibly decaying Dark gauge boson

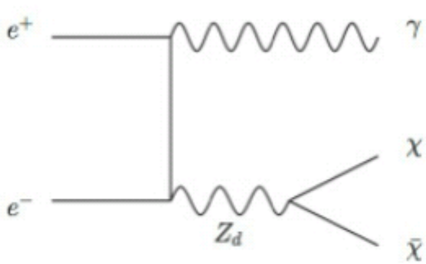
(ii) Missing Energy (Z' → $\chi\chi$) searches



(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)]



2. Experimental bounds

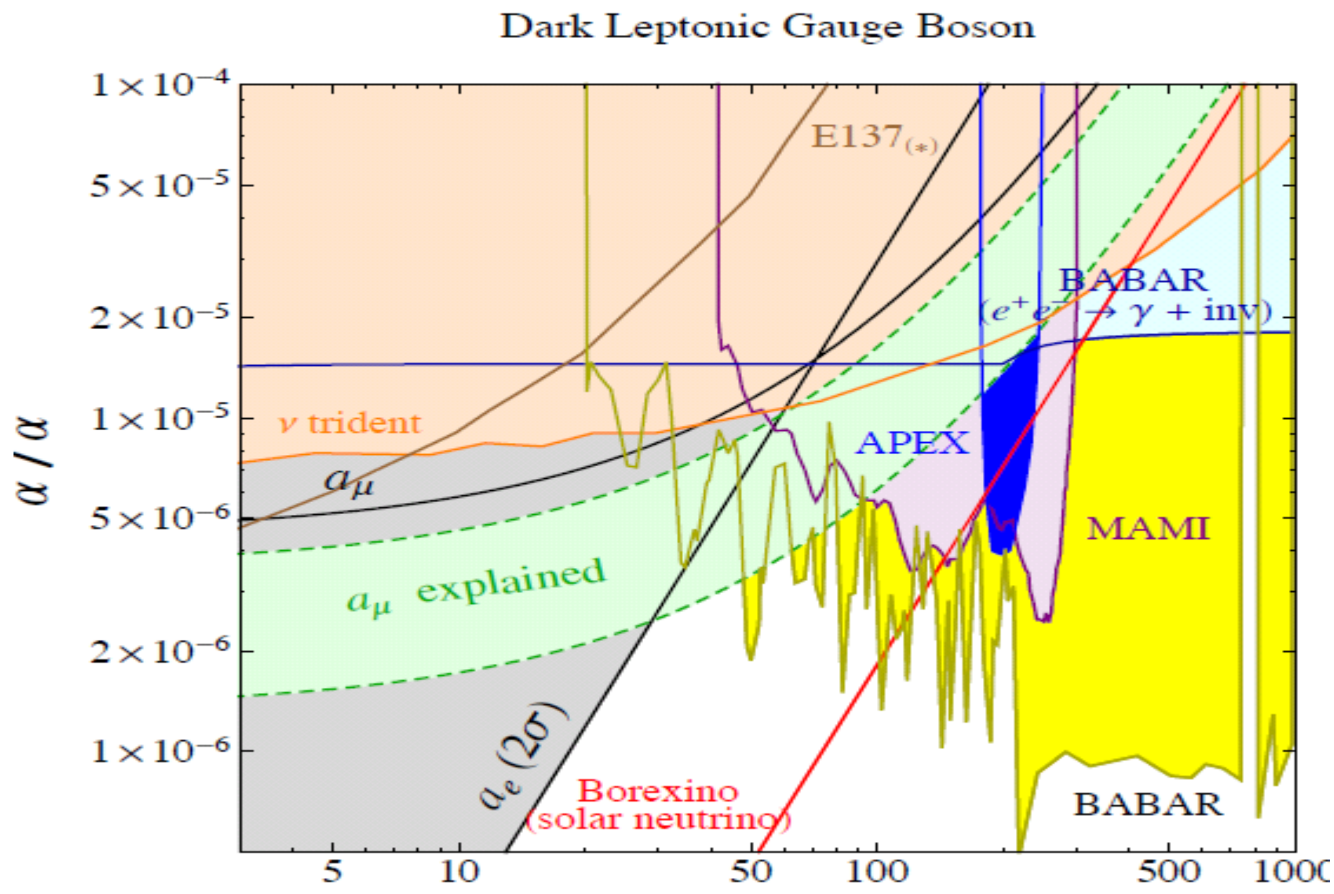
Other possibility is that new boson Z` interacts only with leptonic current

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

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

2. Experimental bounds

[LEE (2014)]



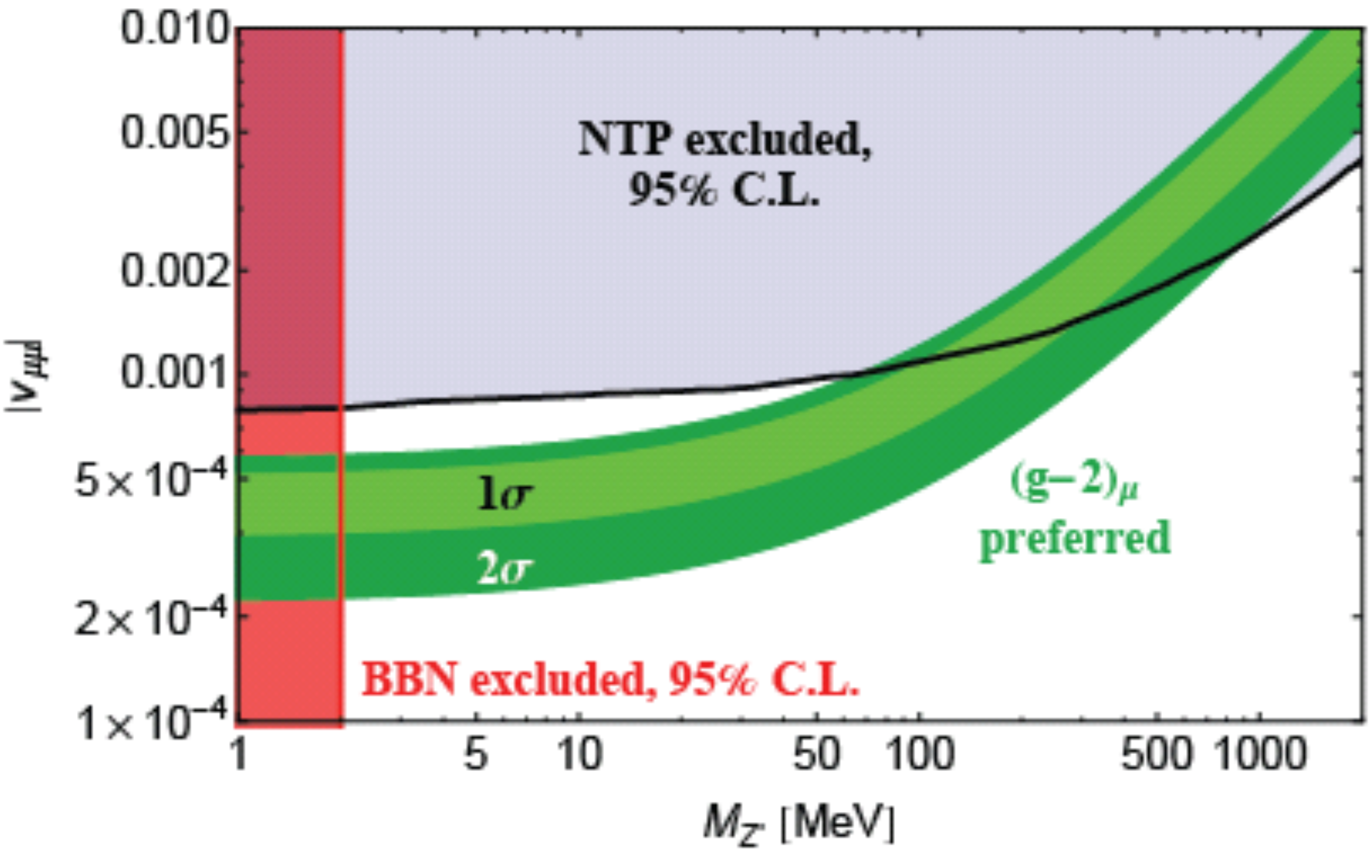
Experimental bounds

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

2.Experimental bounds



2.Experimental bounds

Light vector boson explanation of g-2 muon anomaly is strongly restricted but not excluded

3. EXPERIMENT P348(NA64) at CERN SPS

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

(Search for A´->e+e- and A´-> invisible Decays of Dark Photons)

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[e] *Physics Department, University of Patras, Patras, Greece*
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CERN-SPSC-2013-034 / SPSC-P-348
06/12/2013

December 6, 2013

Краткая История NA64

Dec' 13 – proposal to SPSC

Apr' 14 – SPSC recommendation for tests in 2015.
Обращение в Рабочую Группу. Протокол №02/14, 30.05.2014

Apr.' 14 - design, production, delivery at CERN, assembly,
Sept' 15 commisioning. Обмен письмами ЦЕРН, РГ, МОН.

Oct' 15 – two weeks run. Two reports: *CERN-SPSC-2015-037 / SPSC-SR-172;*
CERN-SPSC-2015-042 / SPSC-P-348-ADD-1

Jan' 16 – SPSC recommendation to the Reasearch Board to approve
as a SPS experiment with the focus on the A´ invisible mode.

March' 16 – **CERN Research Board approved NA64,**
as a part of the CERN Research Programme.

Коллаборация NA64 (2015)

Technical University UTFSM, Valparaiso, Chile
S. Kuleshov, W. K. Brooks, H. Hakobyan, R. Rios,

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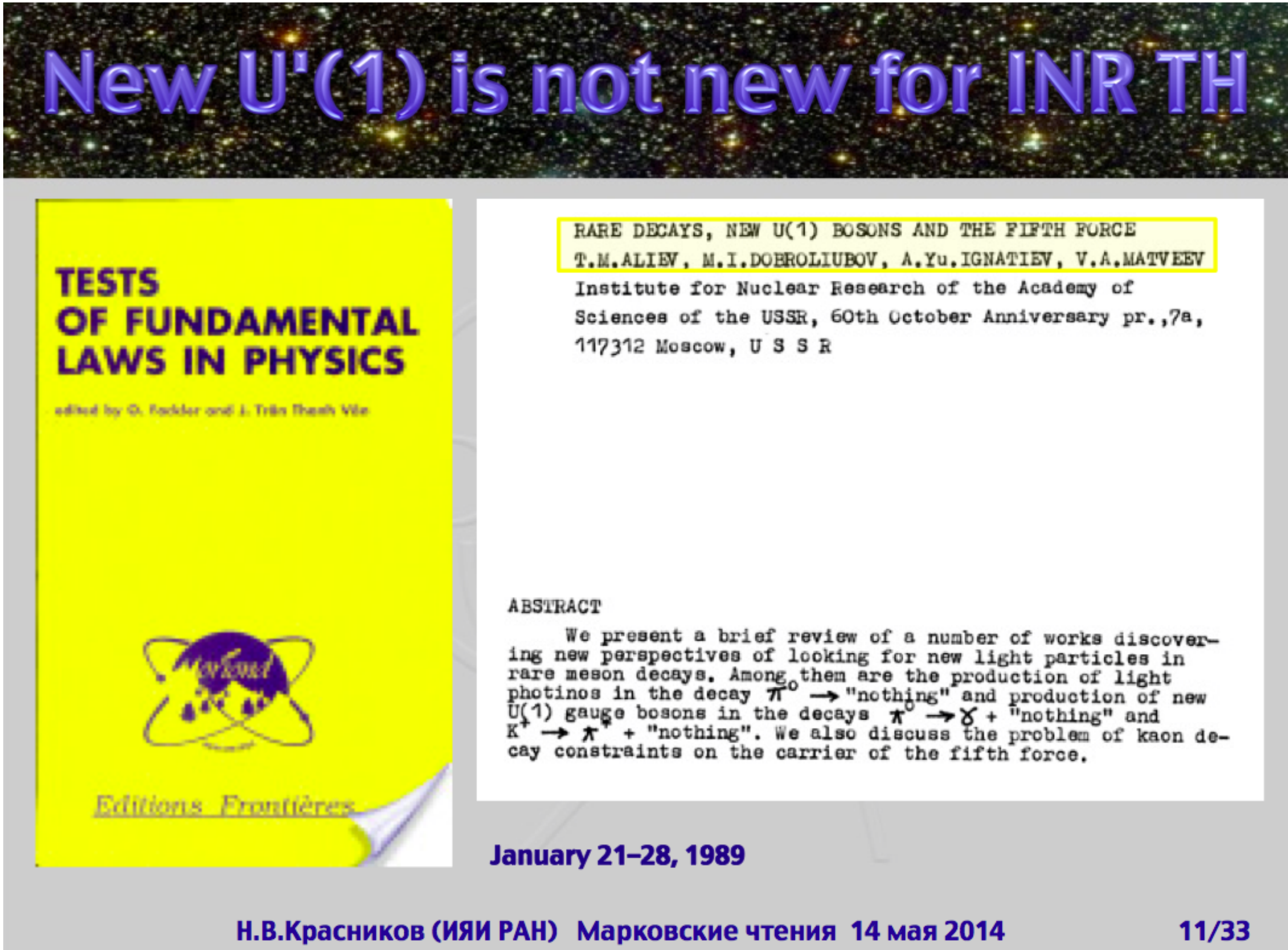
D. Banerjee, E. Depero, P. Crivelli, H-S. Cheng, A. Rubbia

2016: ~ 35 участника, MoU в процессе подготовки
Chile, Greece, Germany, South Korea, Switzerland, and JINR.
РФ: ИФВЭ, ИЯИ, ФИАН, ТПУ, ~ 20 физик + 5 аспир. + 4 магистр-студента.
Вклад РФ Институтов: ~ 370 kCHF / 520 kCHF ≈ 70 %.


New U'(1) is not new for INR TH
TESTS OF FUNDAMENTAL LAWS IN PHYSICS
Editions Frontières
RARE DECAYS, NEW U(1) BOSONS AND THE FIFTH FORCE
T.M.ALIEV, M.I.DOBROLIUBOV, A.Yu.IGNATIEV, V.A.MATVEEV
Institute for Nuclear Research of the Academy of Sciences of the USSR, 60th October Anniversary pr.,7a, 117312 Moscow, U S S R
ABSTRACT
We present a brief review of a number of works discovering new perspectives of looking for new light particles in rare meson decays. Among them are the production of light photinos in the decay $\pi^0 \to$ "nothing" and production of new U(1) gauge bosons in the decays $\pi^0 \to \gamma +$ "nothing" and $K^+ \to \pi^+ +$ "nothing". We also discuss the problem of kaon decay constraints on the carrier of the fifth force.
January 21–28, 1989
Н.В.Красников (ИЯИ РАН) Марковские чтения 14 мая 2014 11/33

Программа исследований NA64 (II)

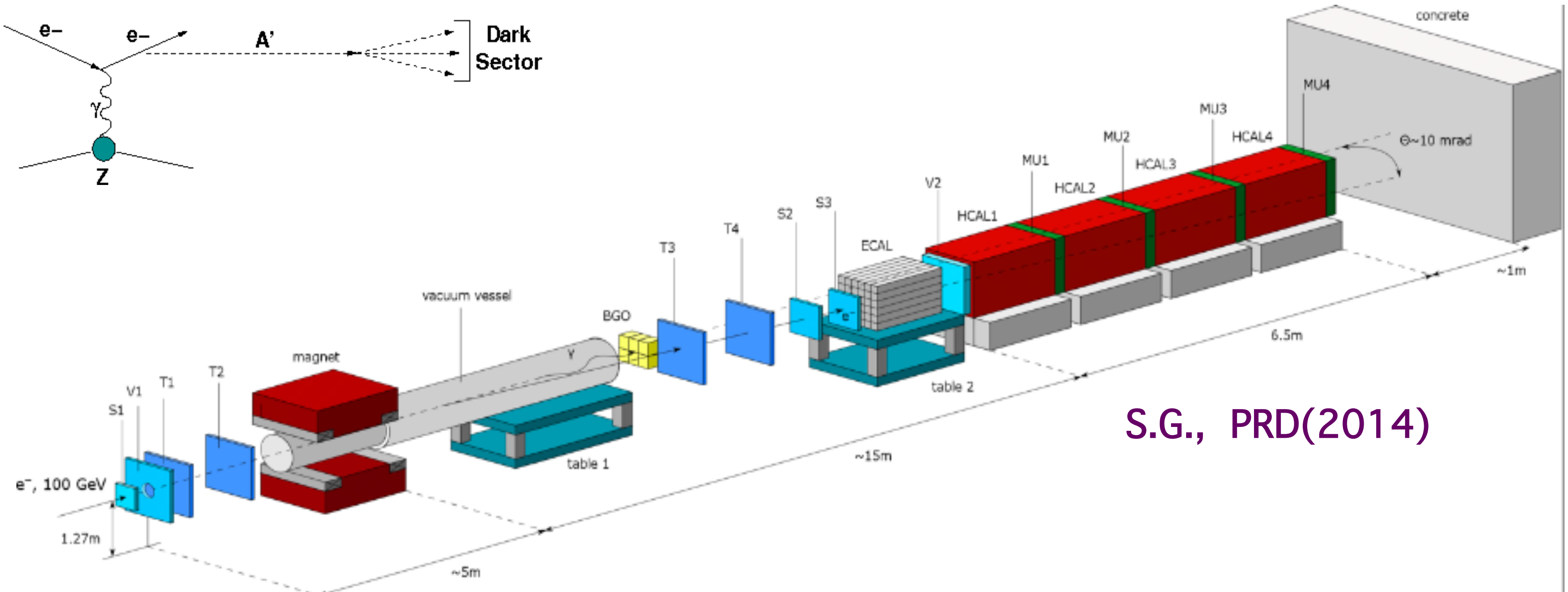
Reasearch program: Searches for sub-GeV Z`boson, NHL,... coupled to e, μ, q’s.
New method: Active beam dump combined with missing-energy technique

1. Beam Purity for Light Dark Matter Search in Beam Dump Experiment
   D. Banerjee, P. Crivelli, and A. Rubbia (Zurich, ETH) Adv.High Energy Phys. 2015(2015)105730
2. On detection of narrow angle e+e- pairs from dark photon decays
   A.V. Dermenev, S.V. Donskov, S.N. Gninenko, S.B. Kuleshov, V.A. Matveev, V.V. Myalkovskiy, V.D. Peshekhonov, V.A. Poliakov, A.A. Savenkov, V.O. Tikhomirov, I.A.Zhukov
   IEEE Trans.Nucl.Sc. 62 (2015) 3283;
3. The K_L invisible decays as a probe of new physics
   S.N. Gninenko and N.V. Krasnikov
   Phys. Rev. D92 (2015) 034009;
4. Search for invisible decays of π0, η, η', K_S and K_L: A probe of new physics and test using the Bell-Steinberger relation
   S.N. Gninenko,
   Phys. Rev. D91 (2015) 015004;
5. Muon g-2 and searches for a new leptophobic sub-GeV dark
   S.N. Gninenko, N.V. Krasnikov, V.A. Matveev,
   Phys. Rev. D91 (2015) 095015;
6. Search for MeV dark photons in a light-shining-through-walls experiment at CERN
   S.N. Gninenko,
   Phys. Rev. D89 (2014) 075008
7. The Muon anomalous magnetic moment and a new light gauge boson,
   S.N. Gninenko and N.V. Krasnikov,
   Phys. Lett. B420 (2000) 9;
8. Proposal for an Experiment to Search for Light Dark Matter at the SPS
   S. Andreas, D. Banerjee, S.V. Donskov, P. Crivelli, A. Gardikiotis, S.N. Gninenko, F. Guber et al.,
   arXiv:1312.3309[hep-ex]

Поиски распадов *A´-> invisible* и *A´-> e^+e^-* на SPS CERN

Установка для поиска *A´->invisible* на CERN SPS

Invisible decay of Invisible State!



S.G., PRD(2014)

3 main components :

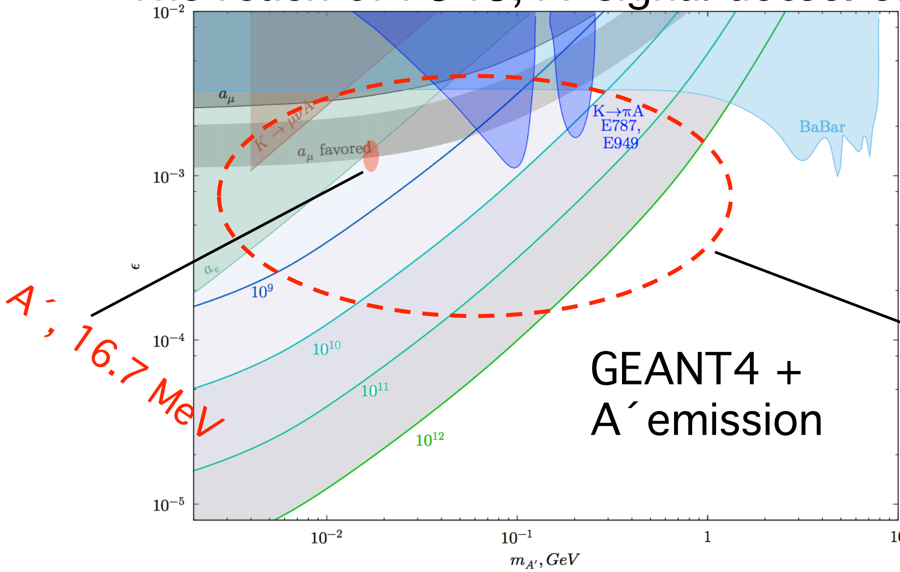
- clean, mono-energ. 100 GeV e- beam
- e- tagging system: MM tracker + SR
- 4π fully hermetic ECAL+ HCAL

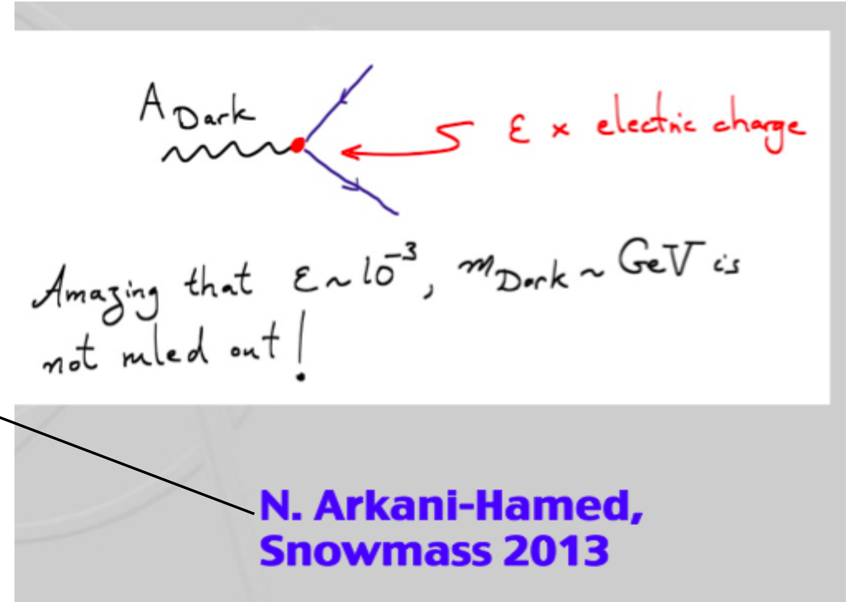
Signature:

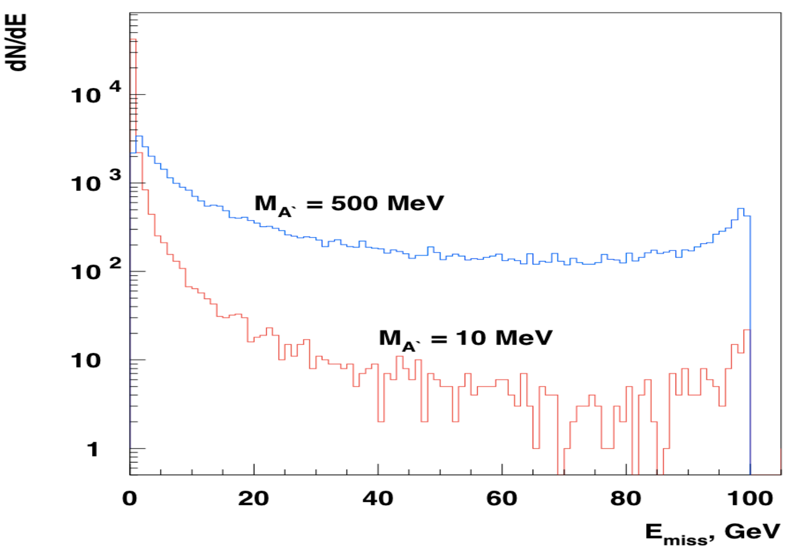
- in: 100 GeV e- track
- out: < 50 GeV e-m shower in ECAL
- no energy in the Veto and HCAL
- Sensitivity ~ ε^2

Exclusion plots

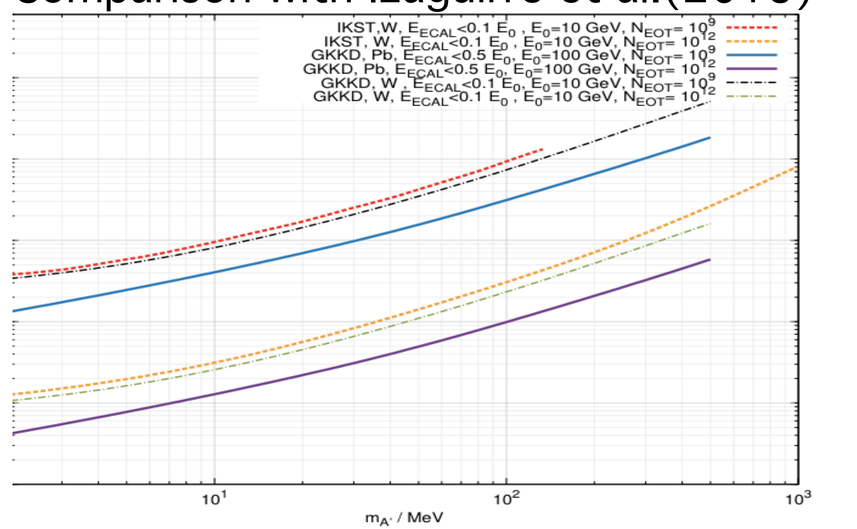
The reach of P348, A´signal detec. eff. ~0.5



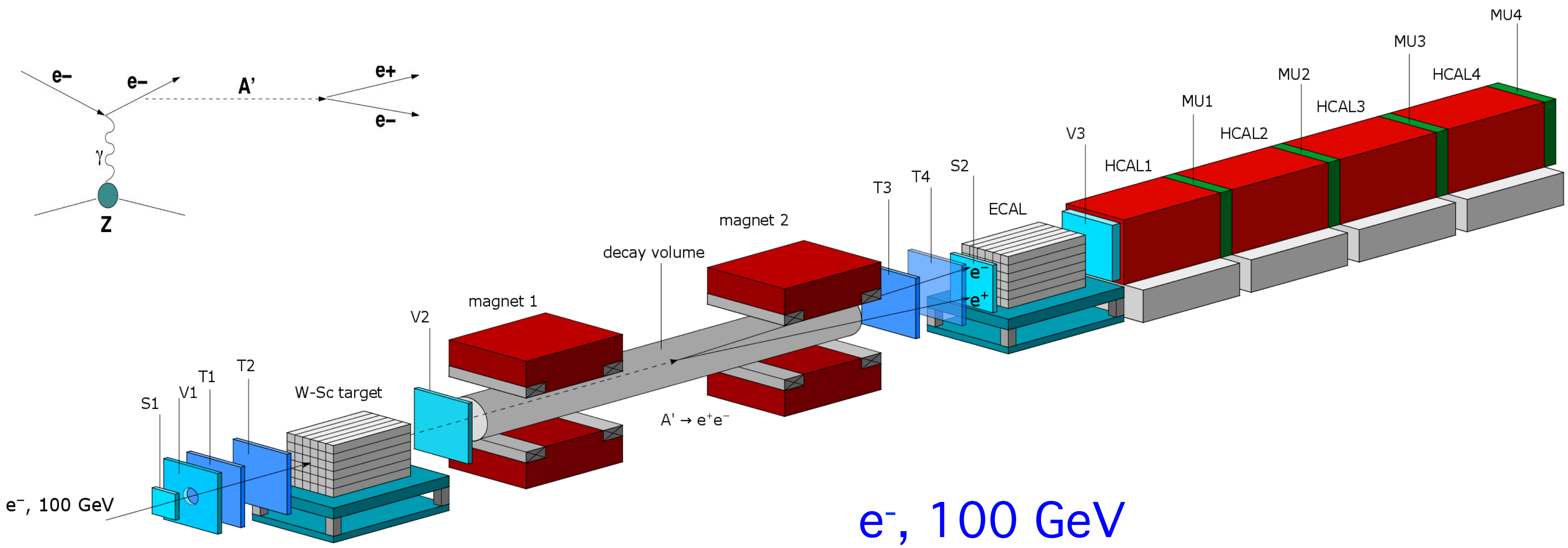




Comparison with Izaguirre et al.(2015)



Поиски распада $A' \to e^+e^-$



e^-, 100 GeV

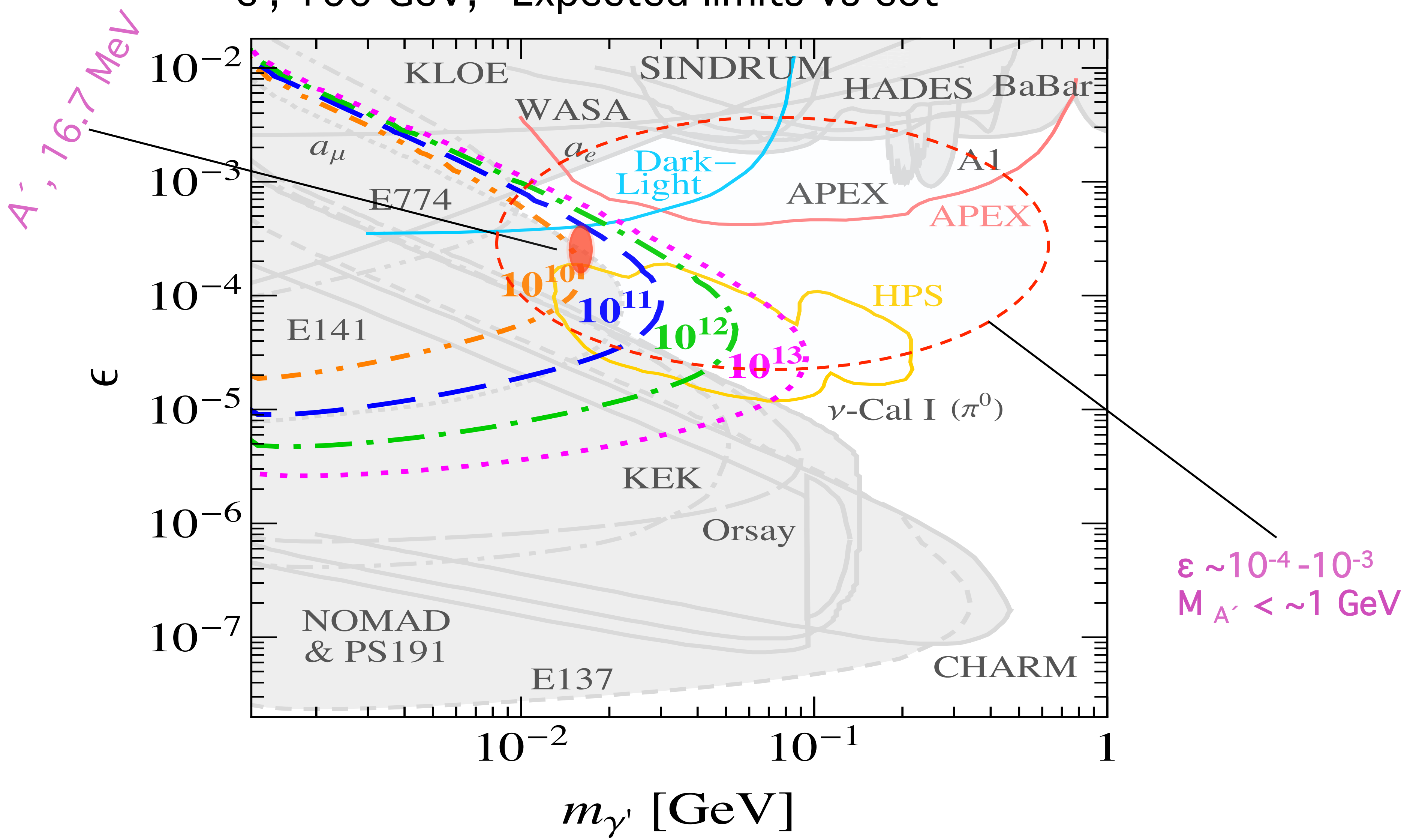
- A´ decay outside W-Sc ECAL1
-
- Signature: two separated e-m showers from a single e^-

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

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

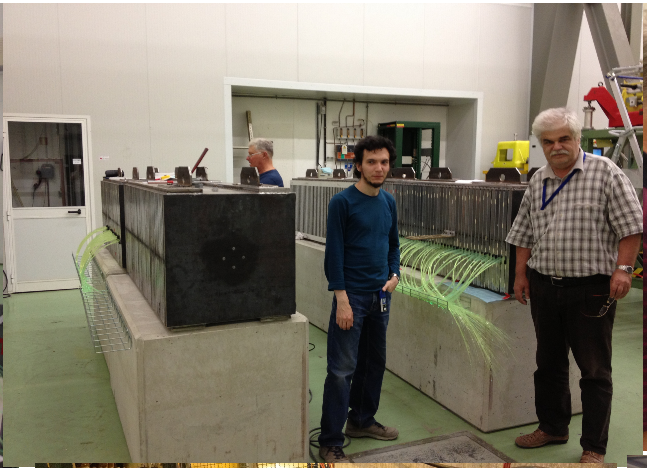
Exclusion plot $A' \to e^+e^-$

e⁻, 100 GeV; Expected limits vs eot

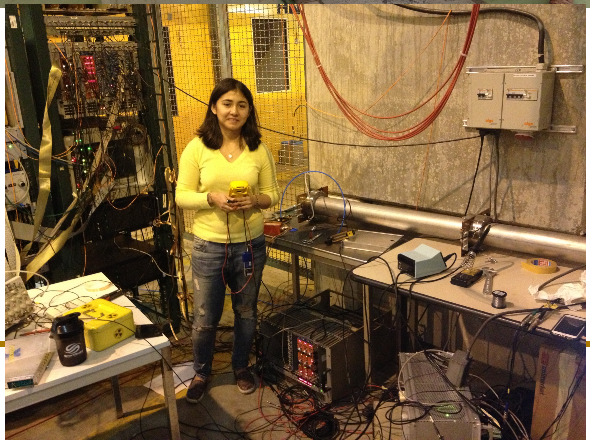


Сеанс 2015


April 9, 2015



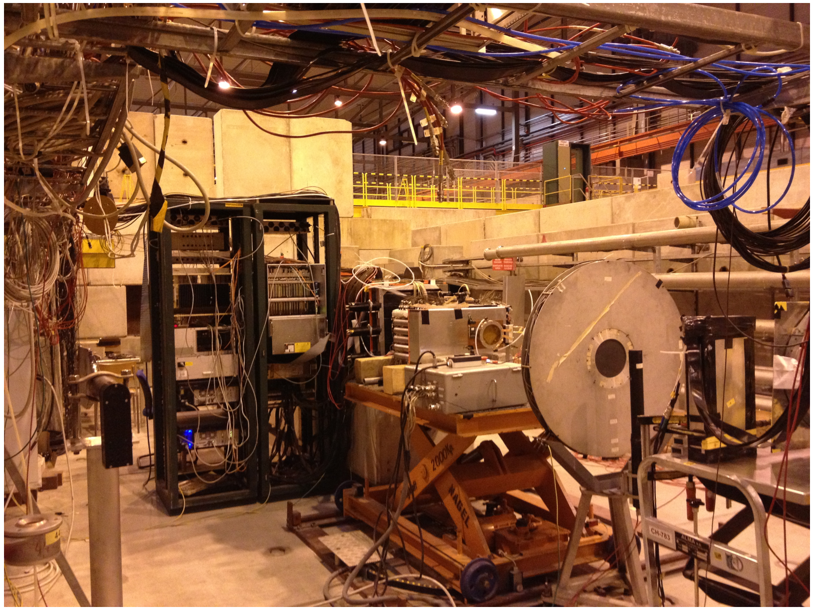

Dubna, April 14, 2016

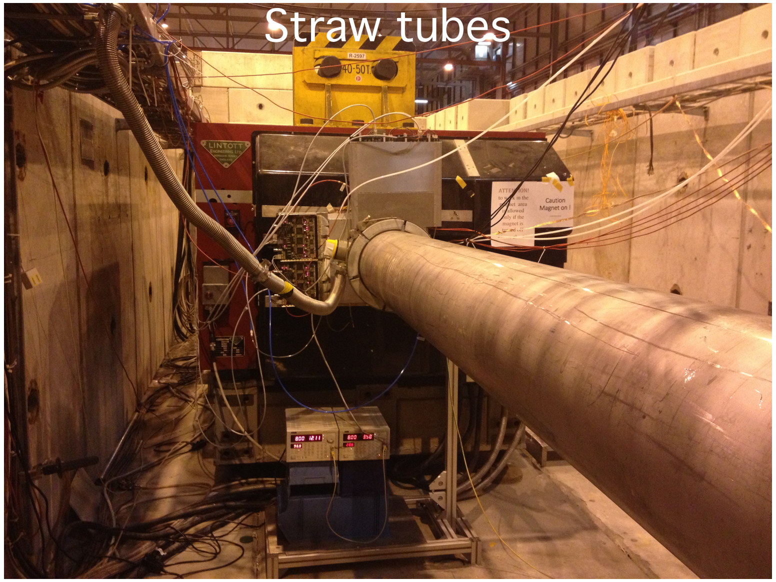


Установка NA64 (2015)

Установка NA64 (2015)

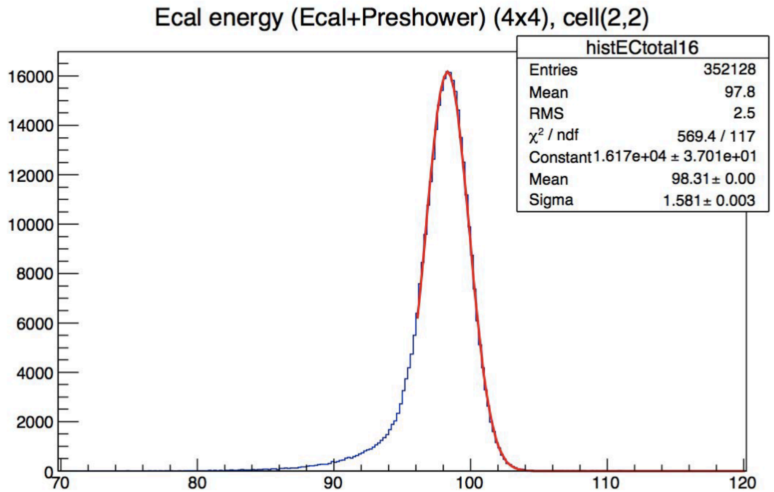
BGOs, Micromegas, straws, hodoscopes, ...



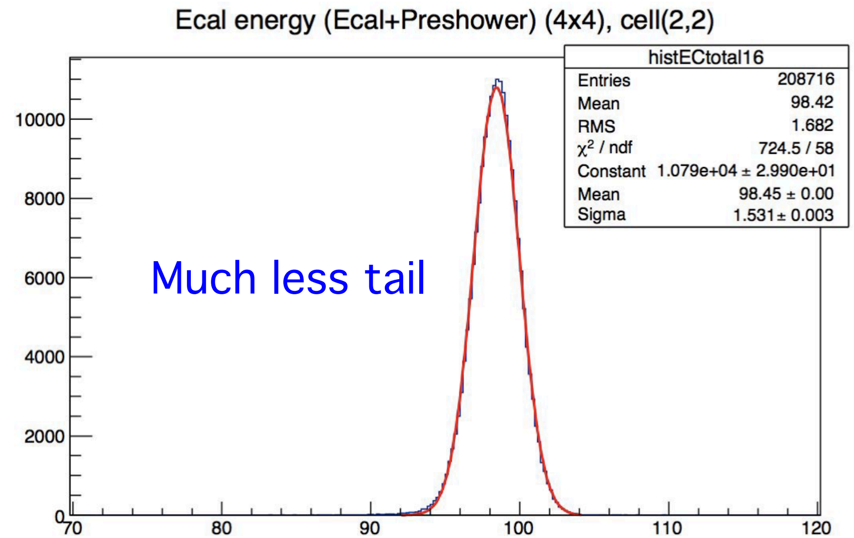


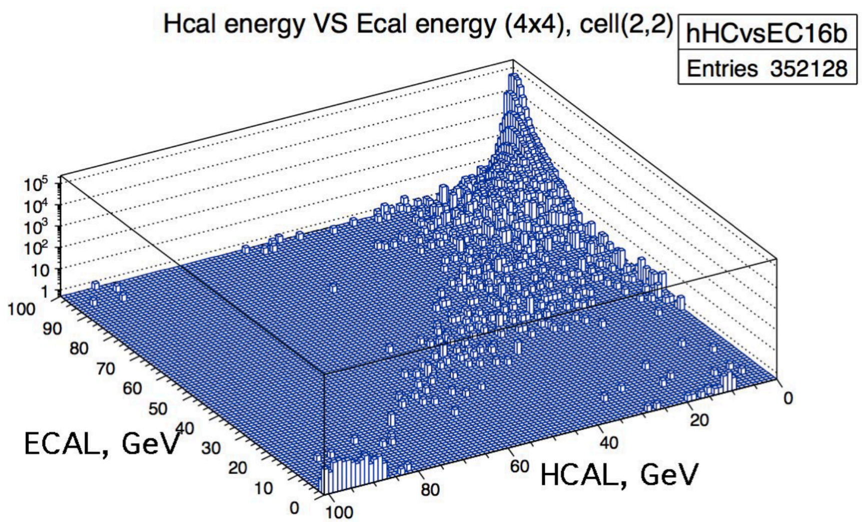
Performance of the SR tagging system

No SR tagging of e^-'s

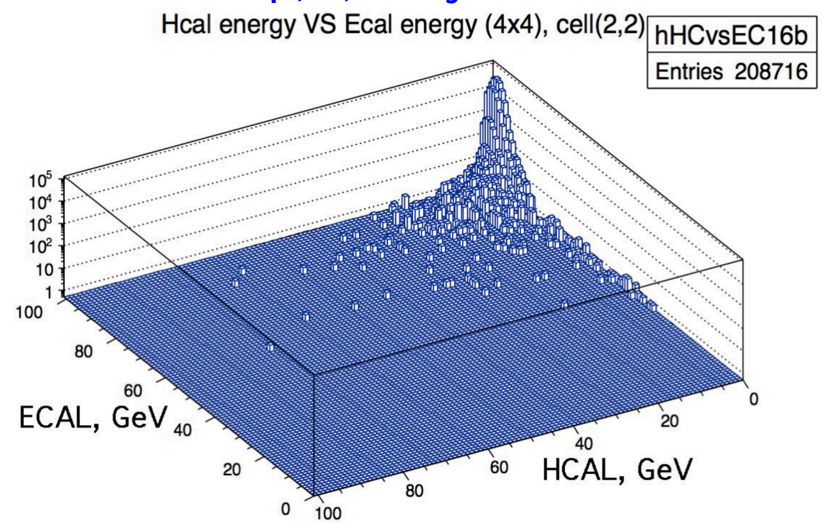


With SR tagging of e^-'s



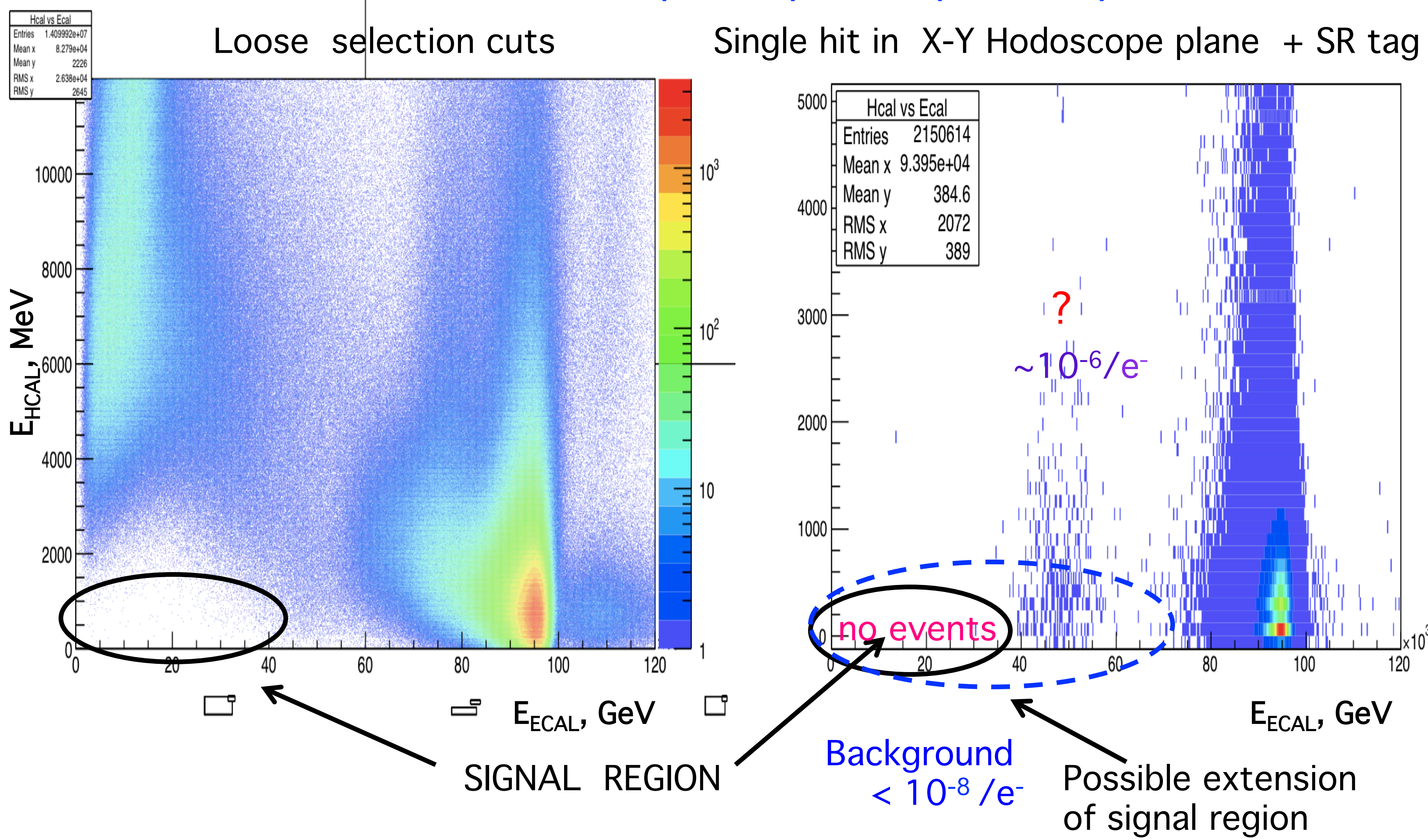


μ,π,.. rejection > 100



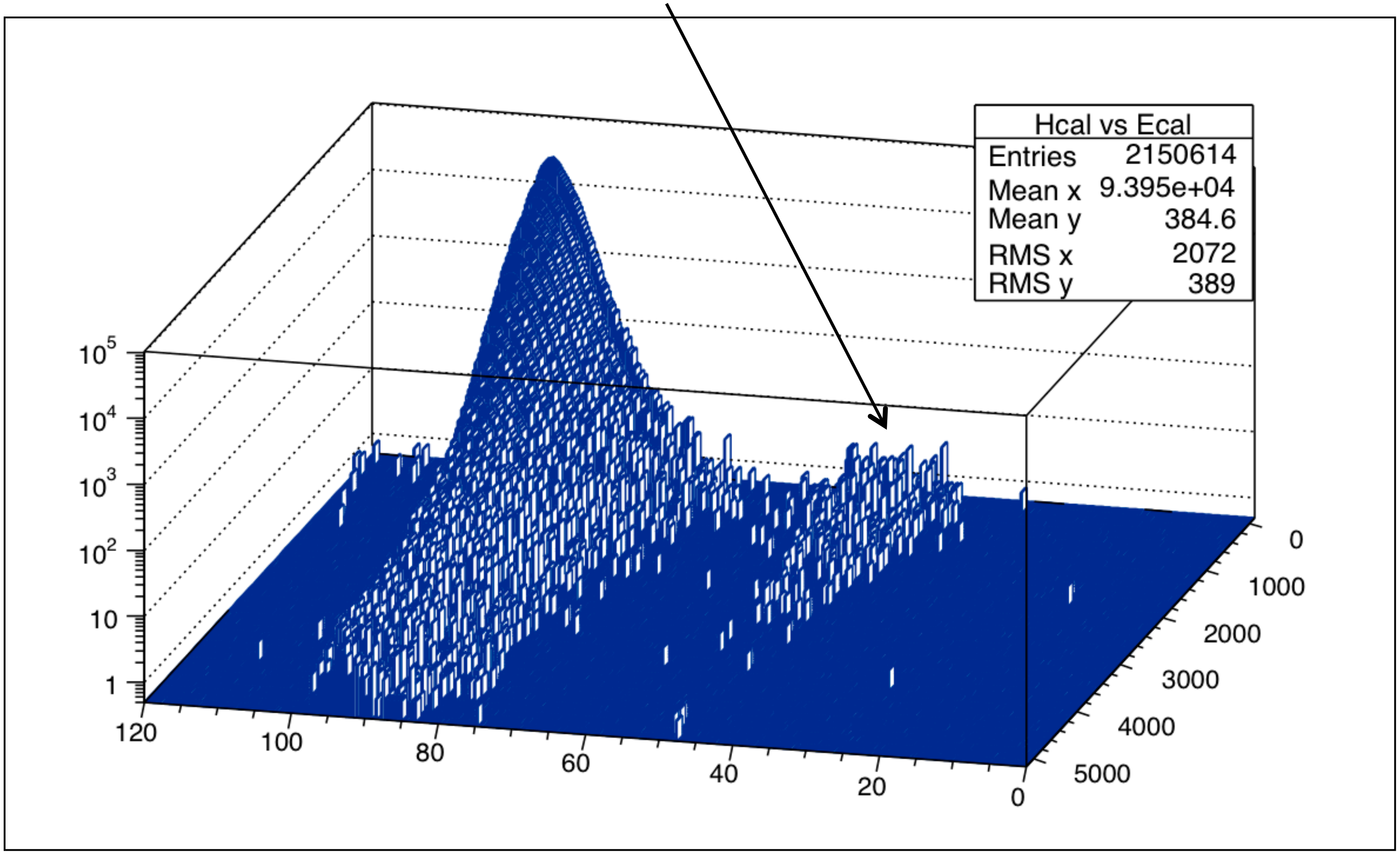
Сигнал A´в плоскости (E_{HCAL}; E_{ECAL})

Tr = S0 x S1x PS(>2 GeV) x ECAL(< 95 GeV)



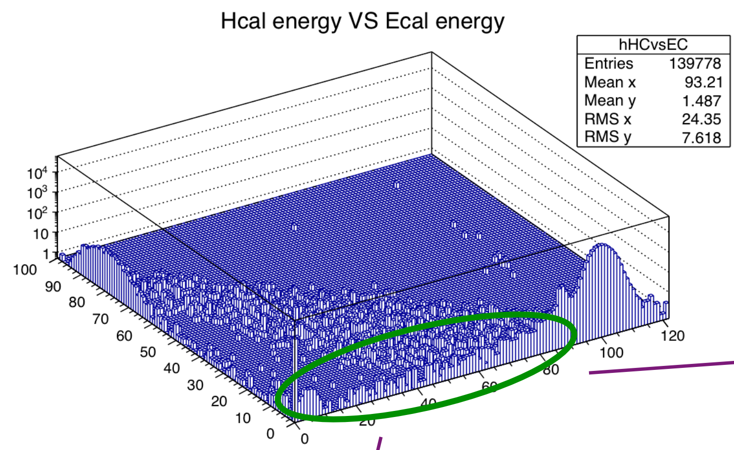
Сигнал A´в плоскости (E_{HCAL}; E_{ECAL})

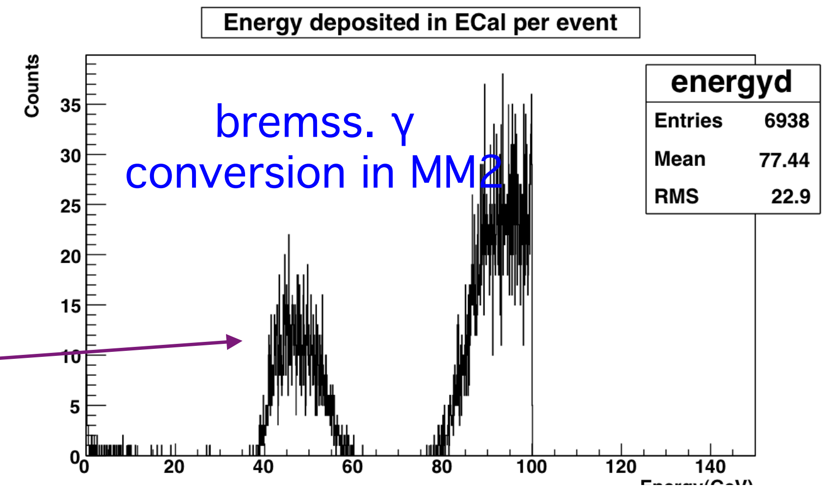
Conversion of bremss. γ ->e^+e^- in ~200 μm MM2 inside the magnet

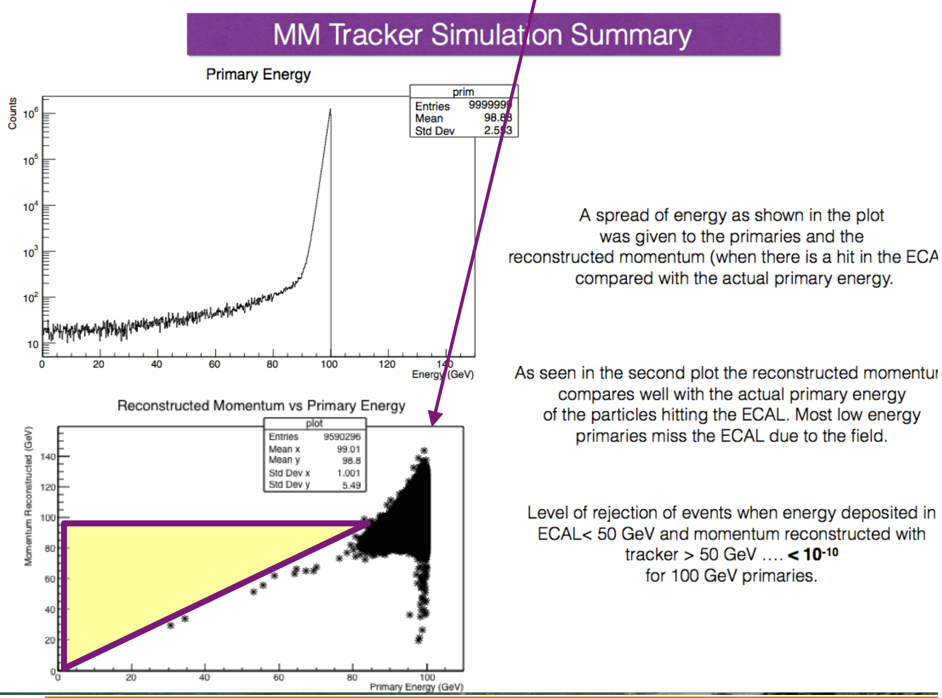


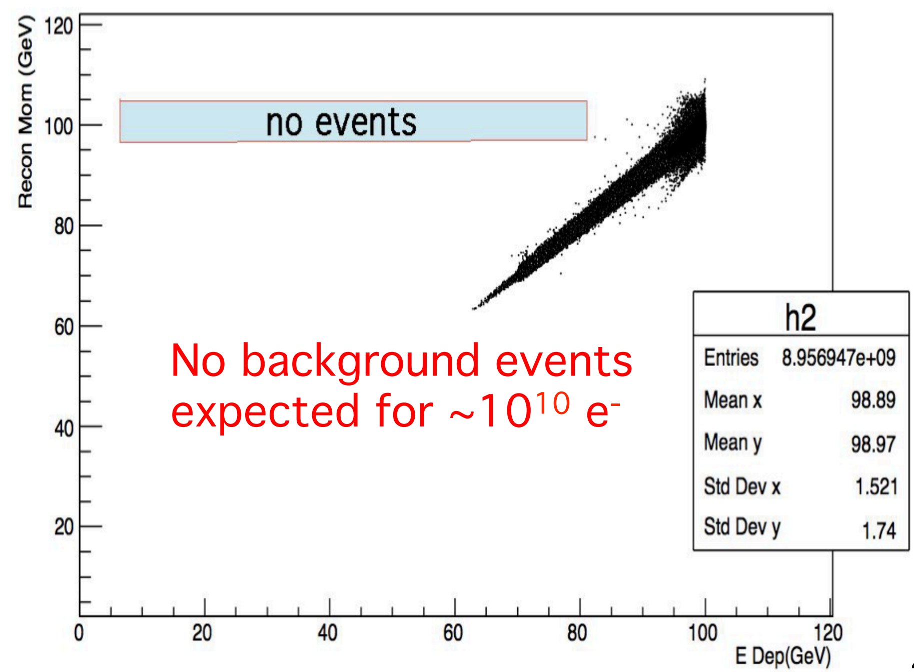
SR tag is triggered by either SR γ from 50 GeV ,
or by low energy bremss. γ/knock-on .

MM tracker: tail background rejection









SPS: July 2016

schedule issue date: 21-Jan-2016 Version: 1.0

Weeks 26–30 (Mon 27 Jun – Sun 31 Jul)

Machine: UA9

North Area

- **T2 - H2**: Calice (Sdhcal) | NA61 VD — A. Aduszkiewicz | A. Aduszkiewicz | NA61 FTPC | SHiP
- **T2 - H4**: CMS ECAL | P348 — S. Gninenko | PHOTAG — M. Prest, PPE134 | CHANNEL — V. Guidi, PPE134 | CMS ECAL
- **T4 - H6**: Clic pix | ATLAS AFP — S. Vlachos | ATLAS Strip Tk — S. Vlachos | ATLAS NSW — S. Vlachos | AIDA WP7
- **T4 - H8**: ATLAS Tilecal | UA9 Totem — W. Scandale, M. Bozzo | ATLAS μ — S. Vlachos | TOTEM PPS — M. Bozzo | ATLAS TRT — S. Vlachos | LHCb
- **T4 - K12**: NA62 — A. Ceccucci
- **T6 - M2**: NA58 COMPASS — J. Bernhard

SPS: October 2016

schedule issue date: 21-Jan-2016 Version: 1.0

Weeks 39–43 (Mon 26 Sep – Sun 30 Oct)

Machine: UA9

North Area

- **T2 - H2**: CMS HB & HE — D. Lazic | NA61 pp — A. Aduszkiewicz | NA61 neutrino
- **T2 - H4**: CMS ECAL | P348 — S. Gninenko | RD51 & GIF
- **T4 - H6**: ATLAS AFP | CMS Outer Tracker — D. Lazic | XSEC — M. Silari | ALICE PHOS — V. Manko | ALICE & ATLAS muons — A. Tauro, S. Vlachos | ATLAS ITK
- **T4 - H8**: RD52 DREAM — R. Wigmans | ATLAS Tilecal — S. Vlachos | LHCb — H. Schindler
- **T4 - K12**: NA62 — A. Ceccucci
- **T6 - M2**: NA58 COMPASS — J. Bernhard

TT41: AWAKE Commissioning — E. Gschwendtner | AWAKE — P. Muggli

For further information contact the PS/SPS Coordinator. Email: Sps.Coordinator@cern.ch, Tel: +41 75 411 3845.

NA64 in the Grey Book !

The CERN Experimental Programme

Grey Book database

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- Neutrino Platform
- CTF3
- R&D
- Non-accelerator experiments

RESEARCH ACTIVITIES

- Experiments and Projects under Study
- Recognized Experiments
- Completed Experiments

RELATED LINKS

- PH Department
- Users' Office
- Scientific Committees
- Conditions for experiments

NA64

Search for dark sectors in missing energy events

SYNONYM:

RESEARCH PROGRAMME: SPS

APPROVED: 09-03-2016

BEAM:

STATUS: Preparation

Overview | Institutes | Participants

SPOKESPERSON:

Sergei GNINENKO

DEPUTY SPOKEPERSON(S):

CONTACT PERSON:

Sergei GNINENKO

TECHNICAL COORDINATOR:

Vladimir POLIAKOV

RESOURCES COORDINATOR:

GROUP LEADER IN MATTERS OF SAFETY (GLIMOS):

DEPUTY GLIMOS:

DEPARTMENTAL FLAMMABLE GAS

NUMBER OF INSTITUTES: 0

NUMBER OF AUTHORS: 0

NUMBER OF PARTICIPANTS: 0

NUMBER OF COUNTRIES: 0

Status history

Status	Start date	End date
Preparation	15-03-2016	

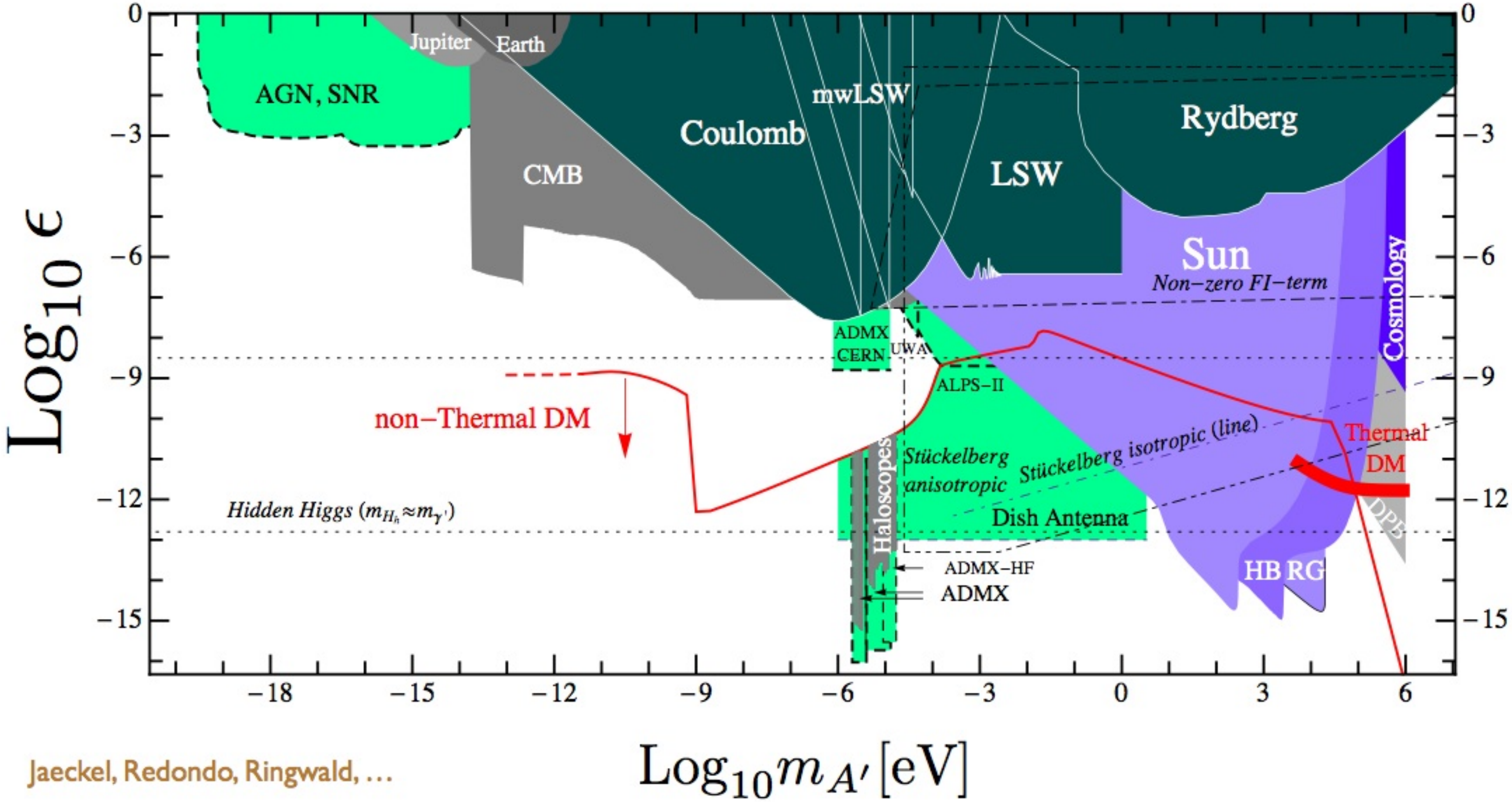
http://cern.ch/na64
http://na64.web.cern.ch

5. Conclusion

(g-2) anomaly explanation due to existence of hypothetical light vector boson is severely restricted (but not excluded by current experiments). P348(NA64) experiment at CERN and(or) experiment with muon beams will allow to discover new light vector boson or reject this explanation of (g-2) anomaly.

BACKUP

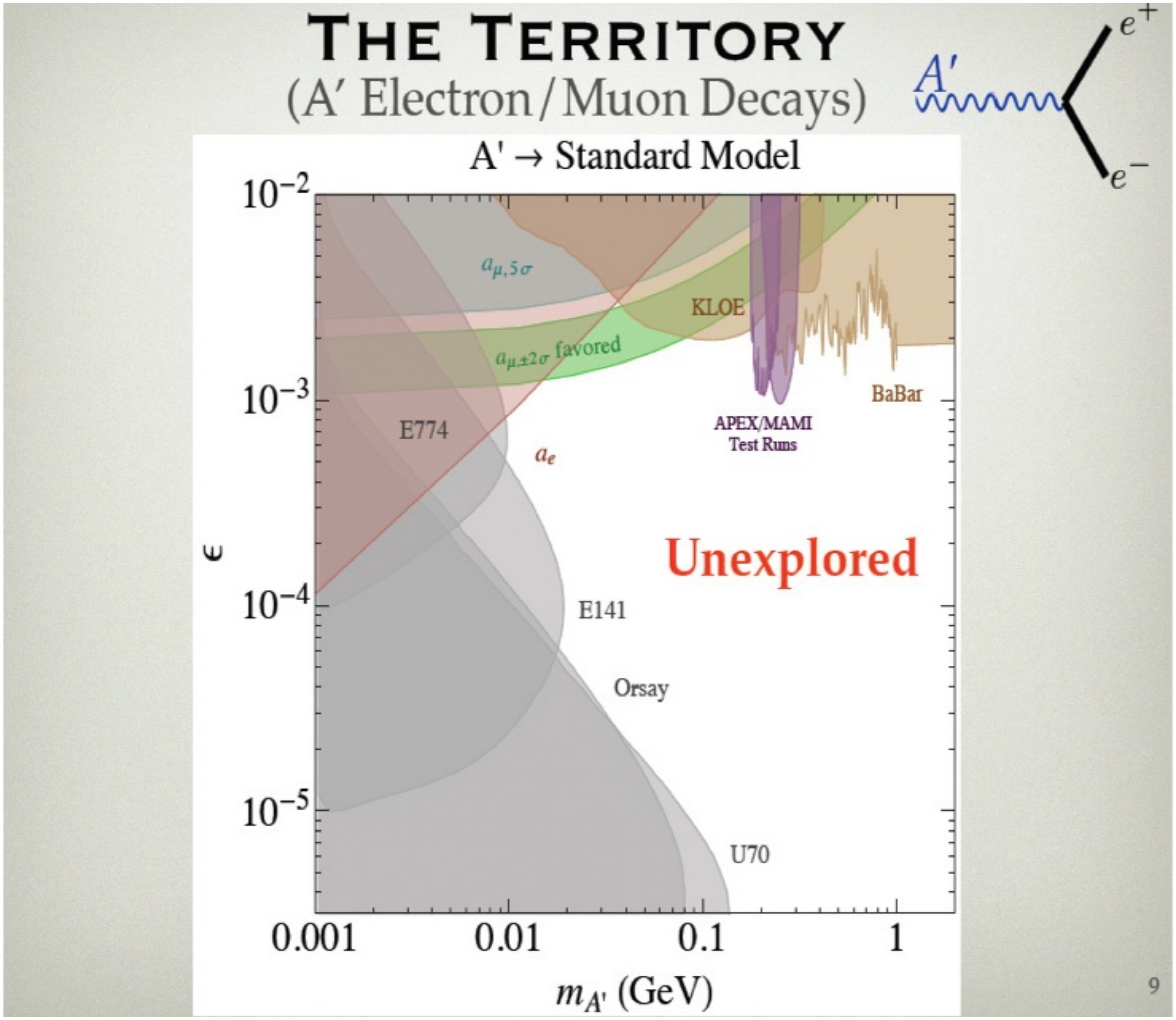
low-mass (< MeV) A′ parameter space

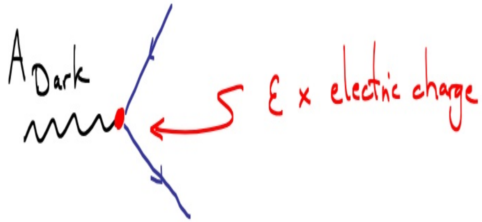


Jaeckel, Redondo, Ringwald, …

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

High mass (> MeV) A` parameter space





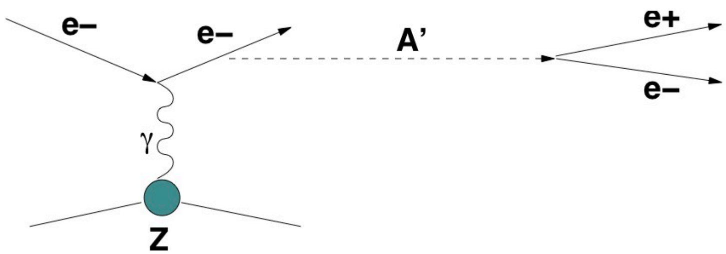
Amazing that $\varepsilon \sim 10^{-3}$, $m_{Dark} \sim$ GeV is not ruled out!

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



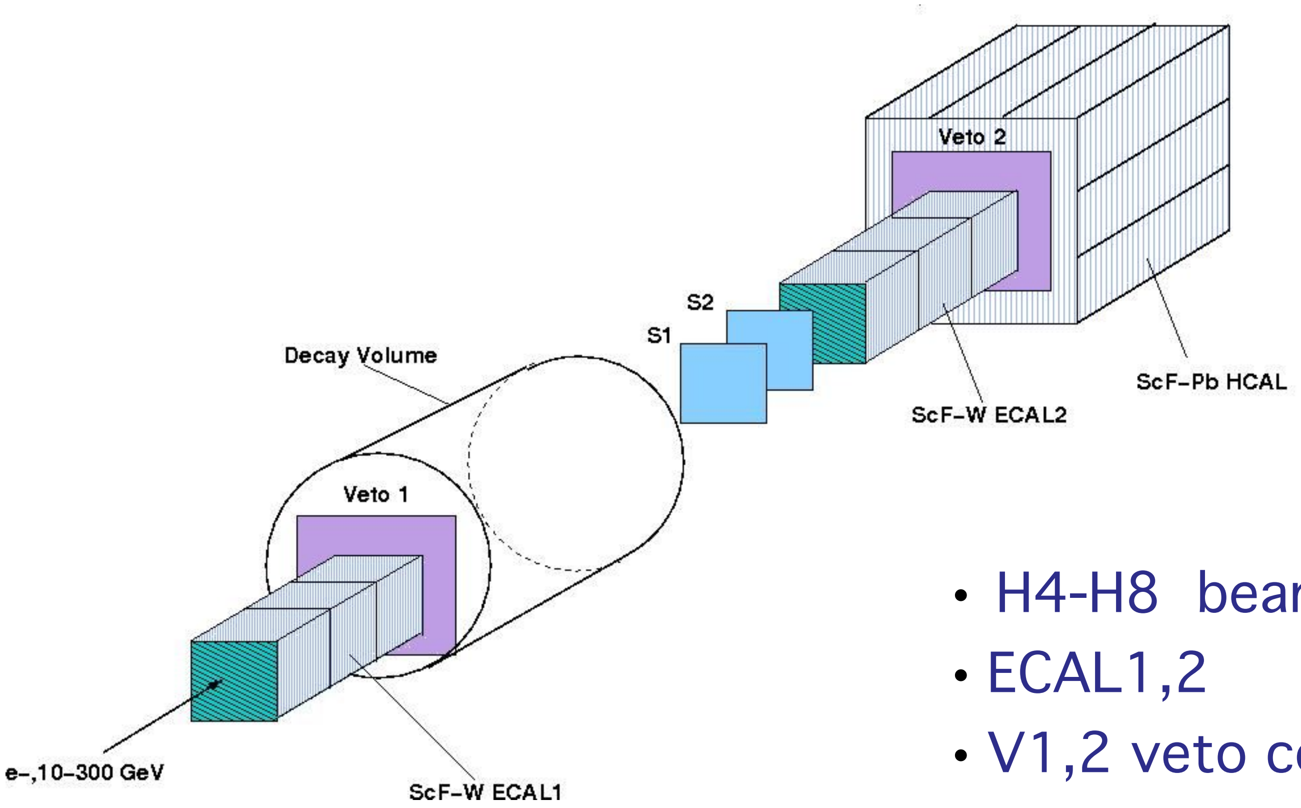
bremsstrahlung A`

- 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

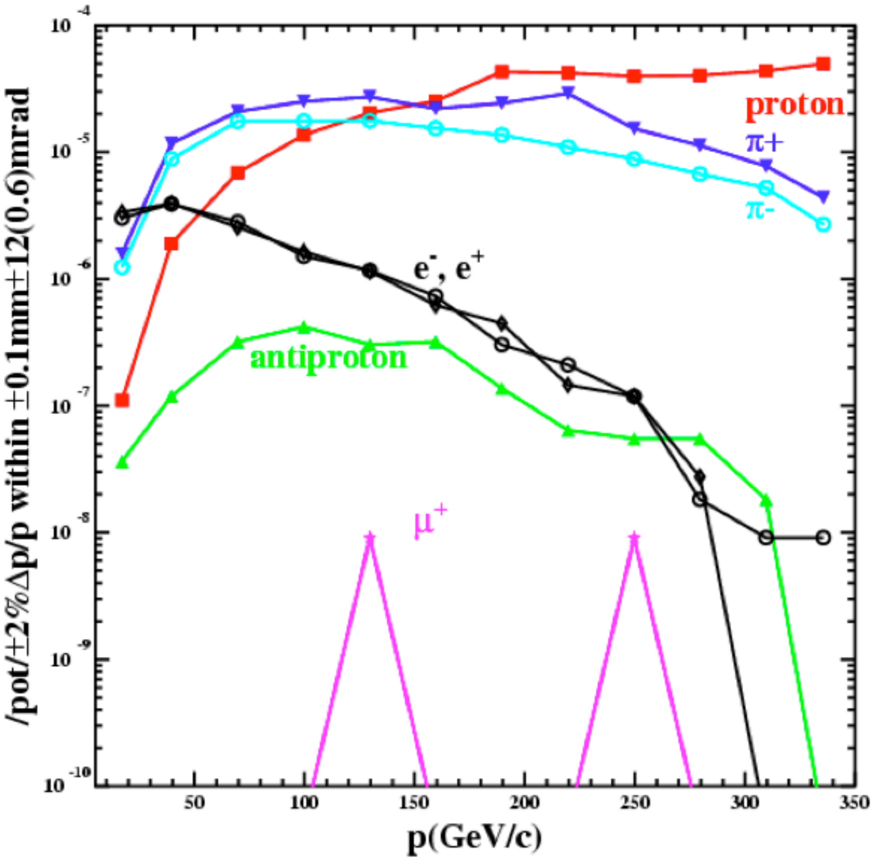
- very short-lived A`: $10^{-14} < \tau_{A`} < 10^{-10}$ s
- very rare events: $\sigma_{A`}/\sigma_\gamma < 10^{-13}$-$10^{-9}$
- A`energy boost to displace decay vertex,
  $\varepsilon \sim 10^{-4}$, $M_{A`} \sim 50$ MeV, $E_{A`} \sim 100$ GeV, $L_d \sim 1$ m
- background suppression

Setup



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

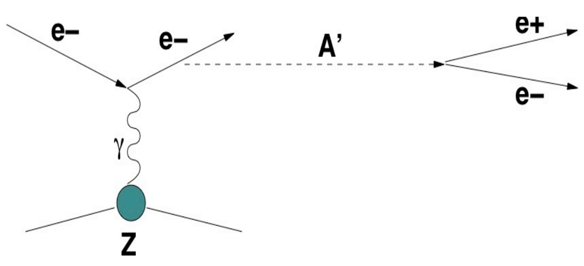
SPS e- beams

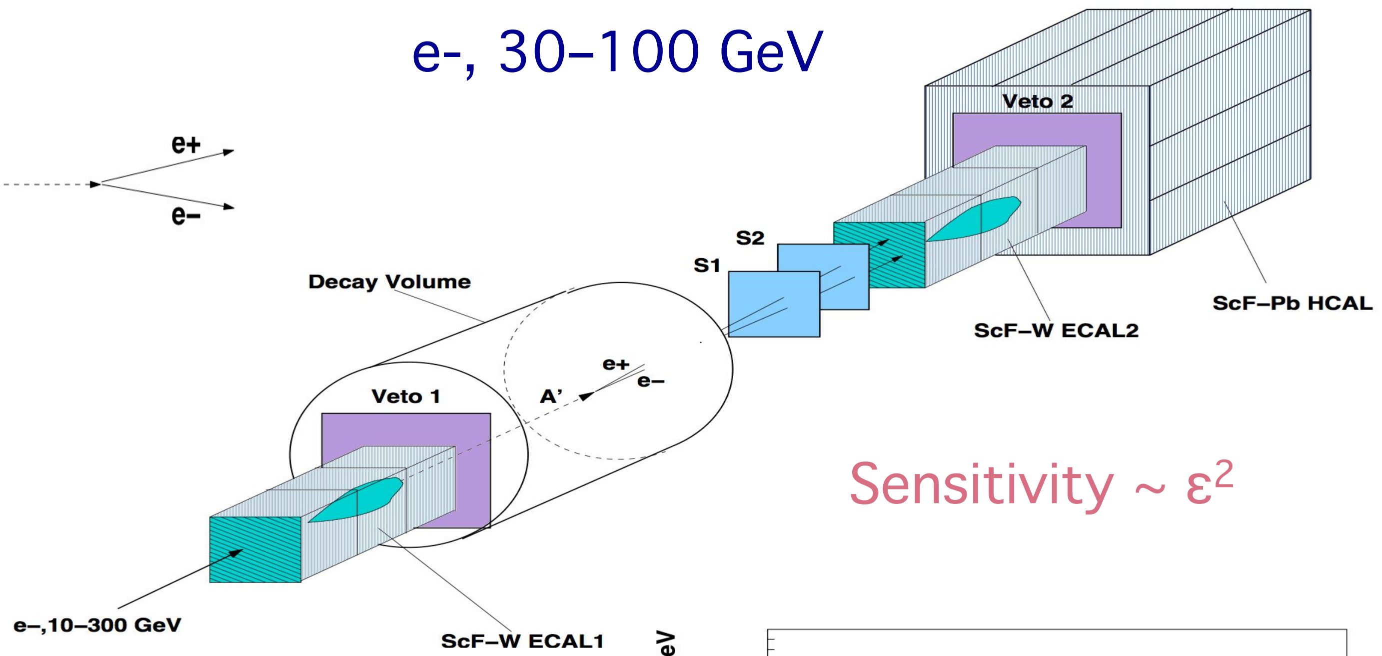


- H4, I_{max}~ 50 GeV e-
- 10^{12} pot per SPS spill,
- ~ $5x10^{6}$ e- per spill
- duty cycle is 0.25
- ~10^{12} e- / month
  additional tunning by
  a factor 2–3 ?
- beam spot ~ cm^2
- beam purity < 1 %

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

e-, 30–100 GeV



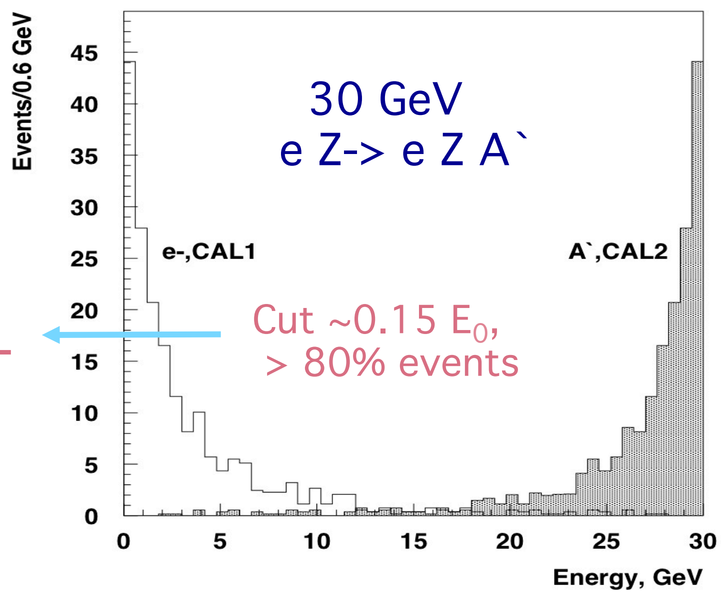


Sensitivity ~ ε^2

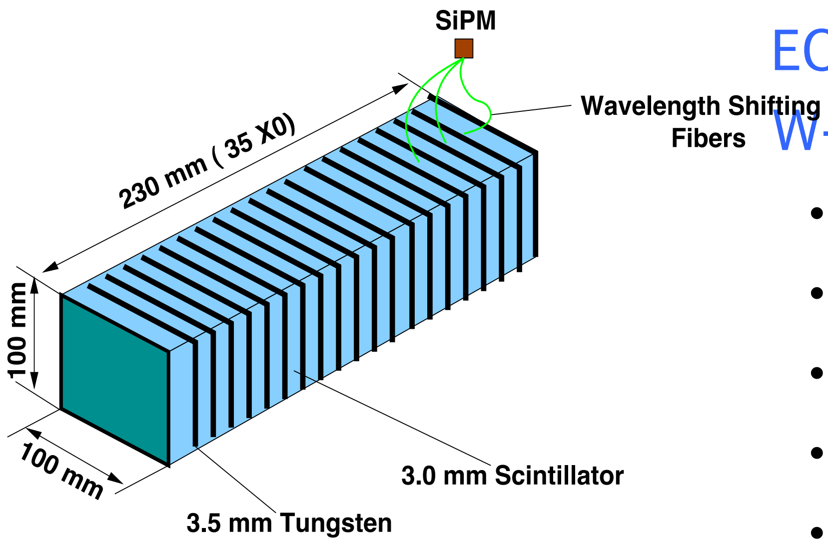
- A`s decay mostly outside ECAL1
- Signature: two separated e-m showers from a single e-

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

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



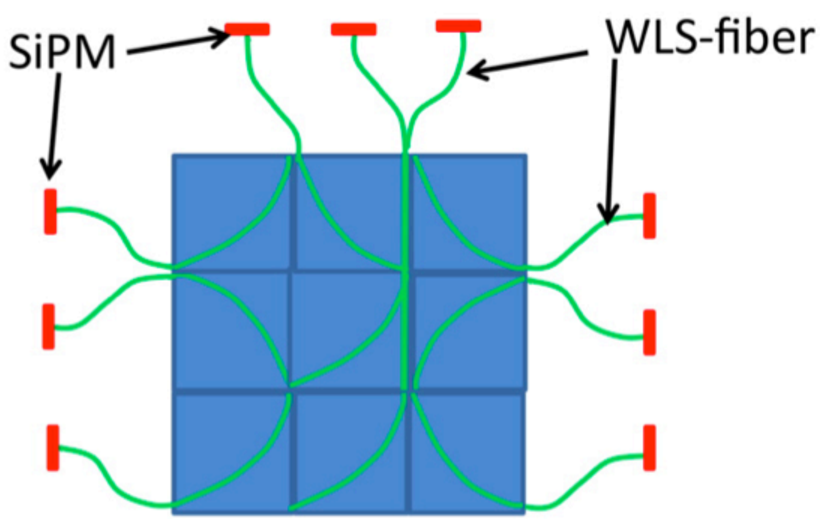
Specially designed ECAL

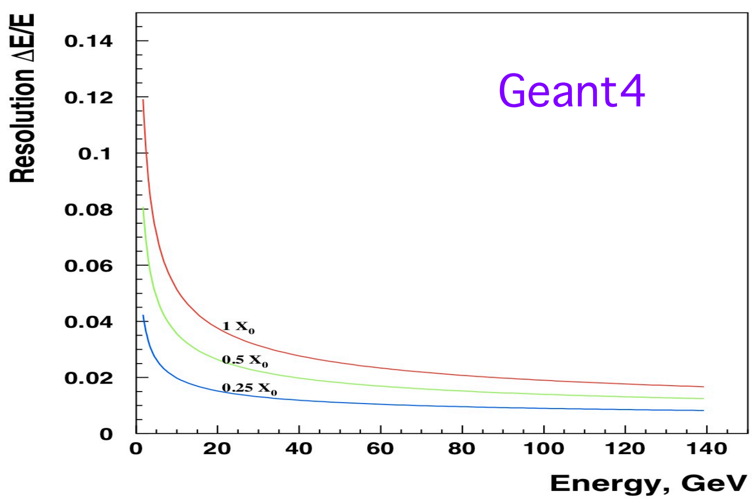


ECAL1 "bubble chamber"

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}

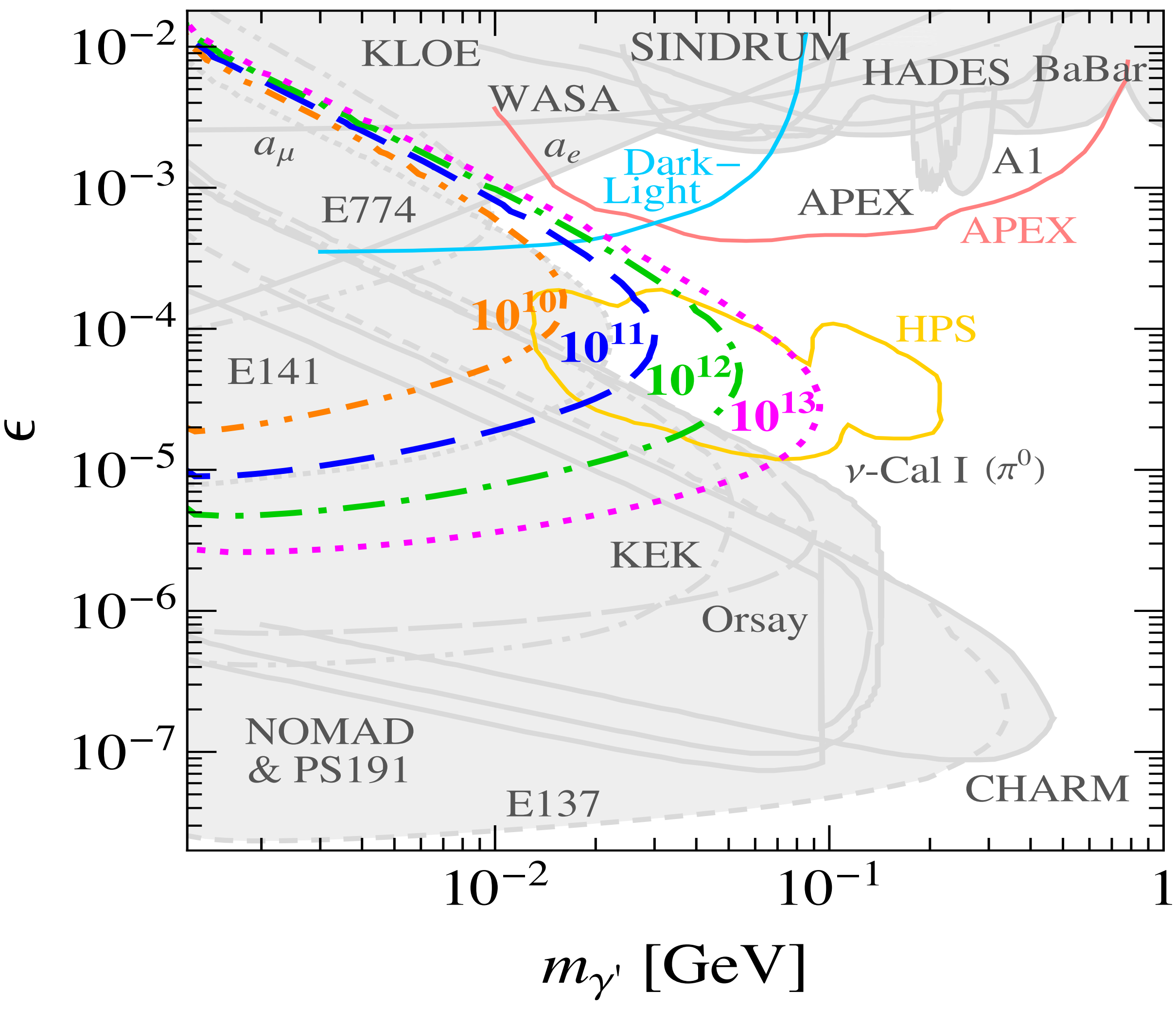




Summary of background sources for A` -> e+e-

Source	Expected leve	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}	

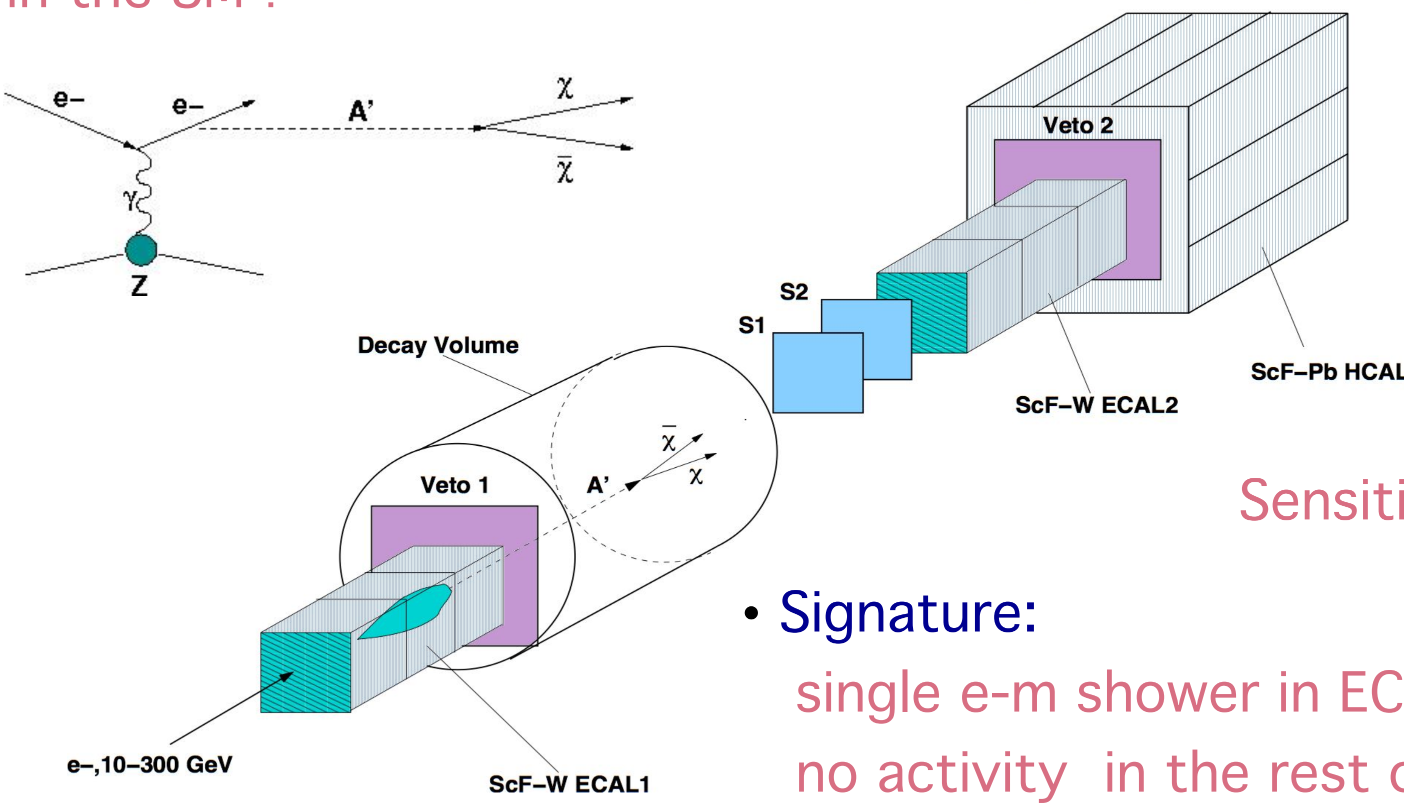
Expected limits on A` -> e+e- decays vs accumulated N_{e-} (background free case)



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= 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

“β decay“ analogy

^{210}Bi β decay e- spectrum

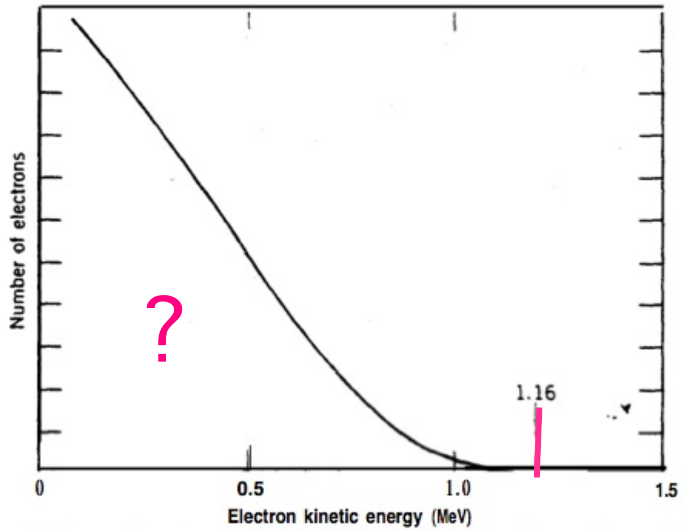
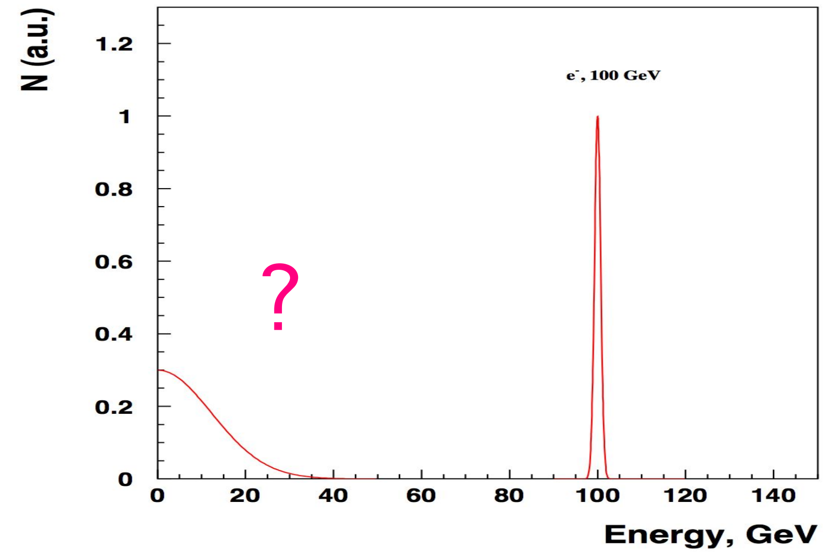


Figure 9.1 The continuous electron distribution from the β decay of ^{210}E. (also called RaE in the literature).

SPS e- spectrum



Pauli, 1931

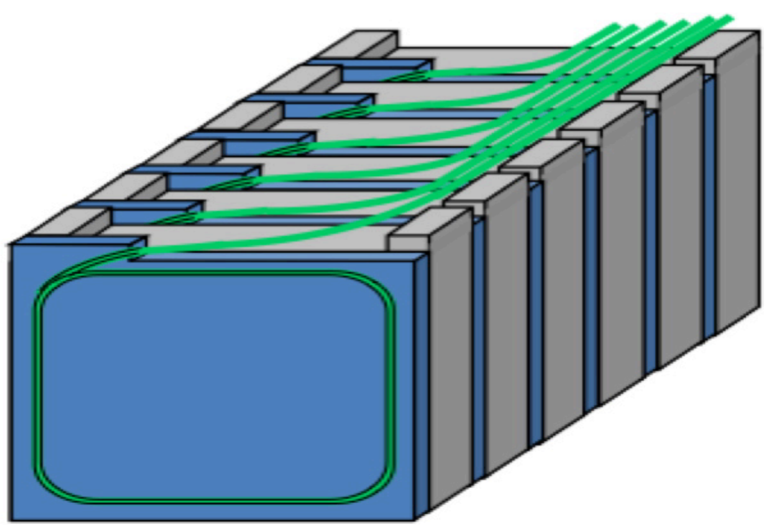
? = invisible ν

Massive HCAL to enhance longitudinal hermeticity

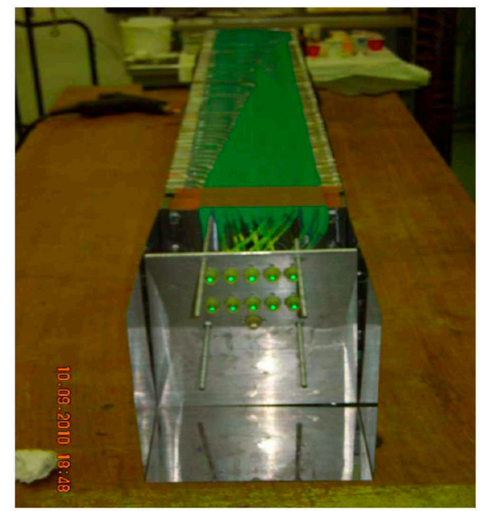
Single module of the hadronic calorimeter:

- 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 →



Massive HCAL to enhance longitudinal hermeticity

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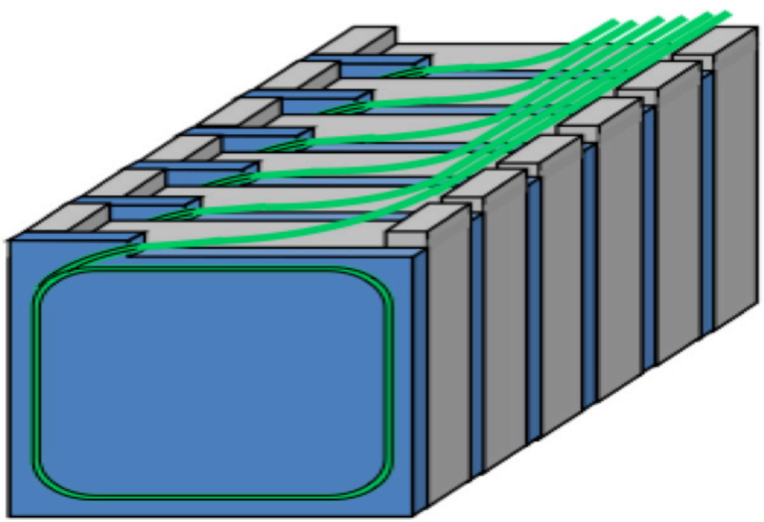
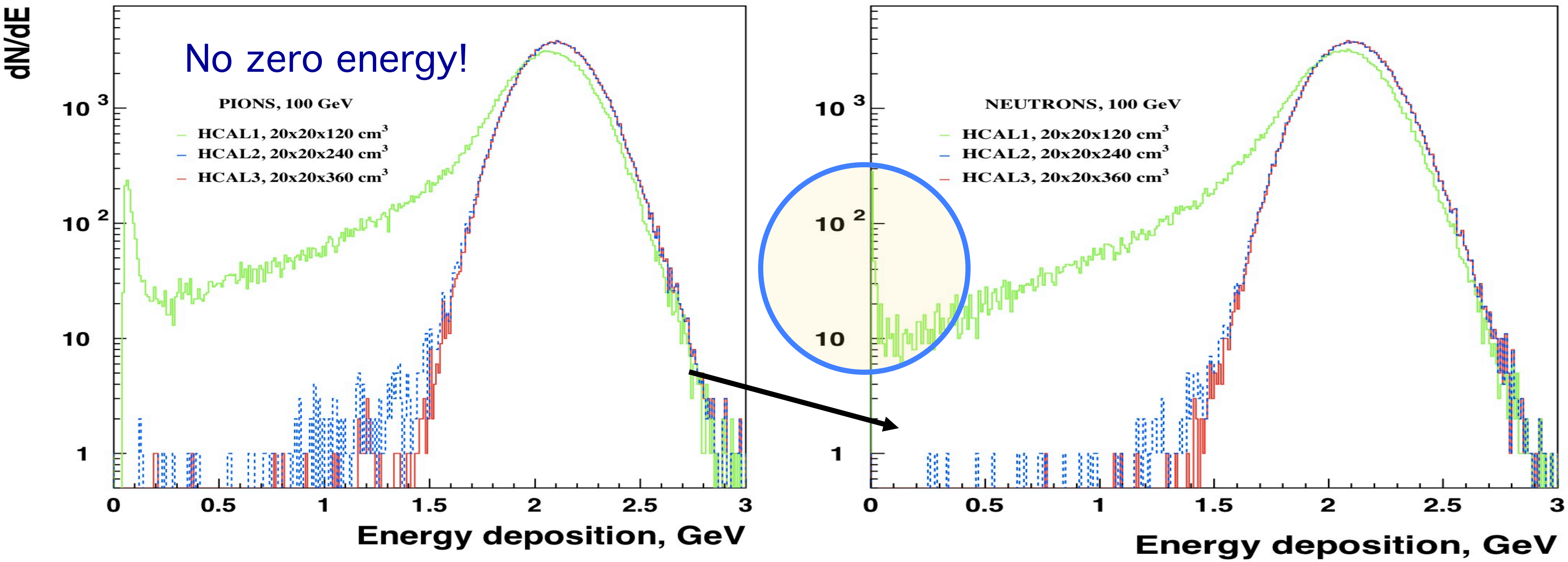


Prototype

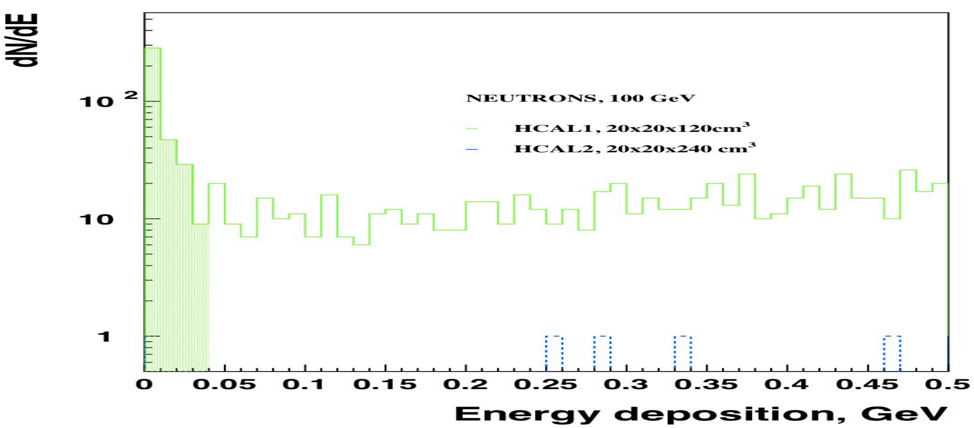
HCAL hermeticity for 3 consequtive modules

Pions, 100 GeV

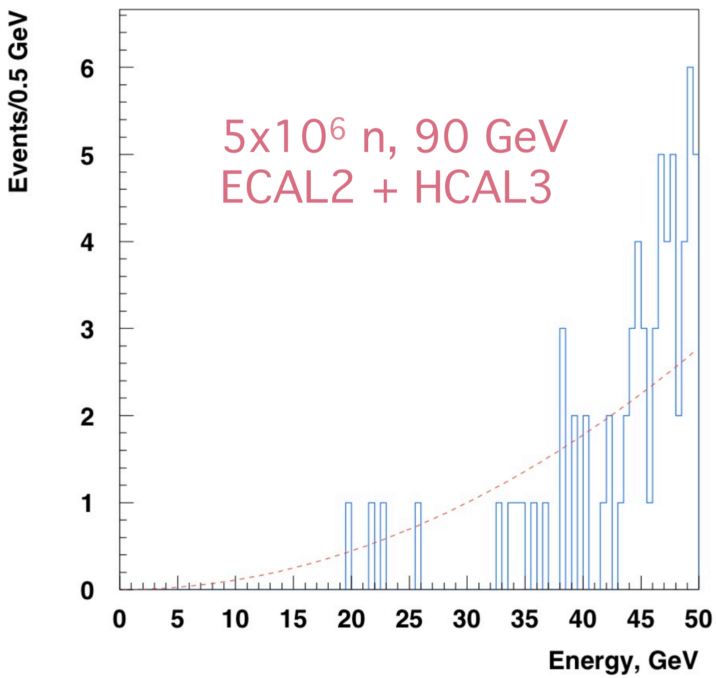
Neutrons, 100 GeV



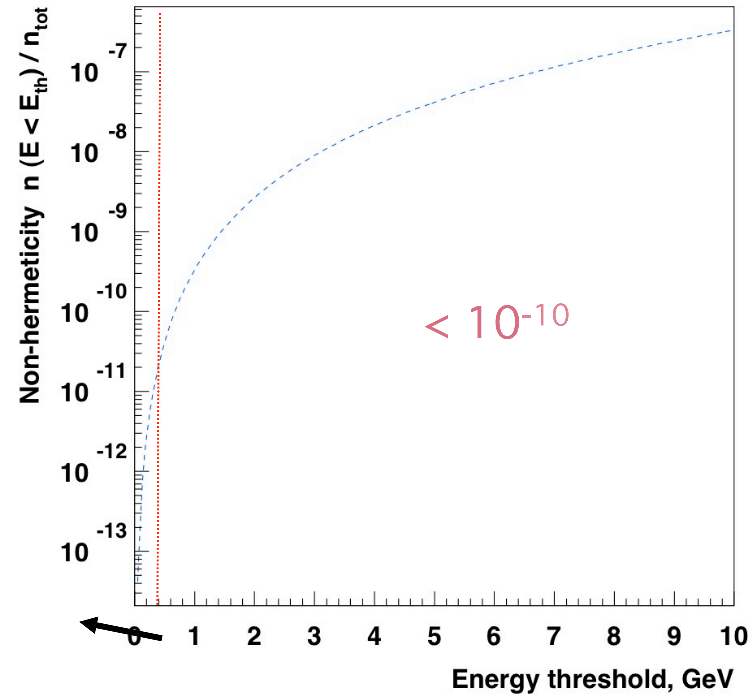
Expected HCAL energy threshold ~ 20-50 keV determined by noise and pileups.



Estimated ECAL2+ HCAL3 nonhermeticity



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

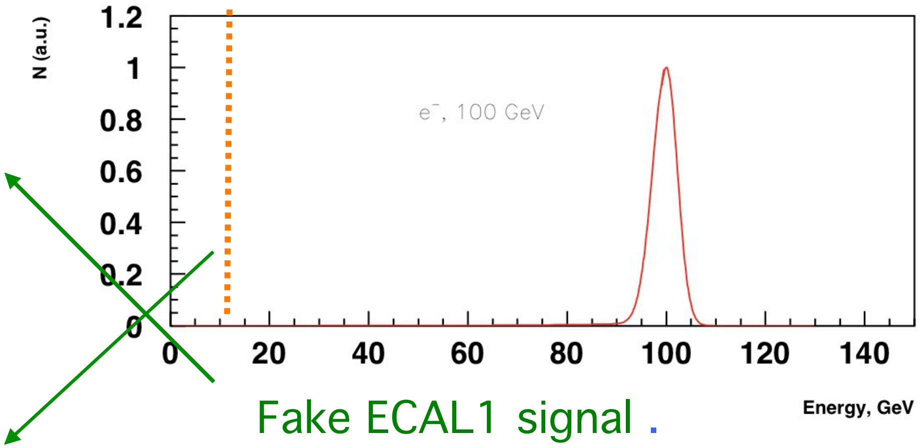


ECAL2+HCAL3 nonhermeticity as a funcion of the energy threshold

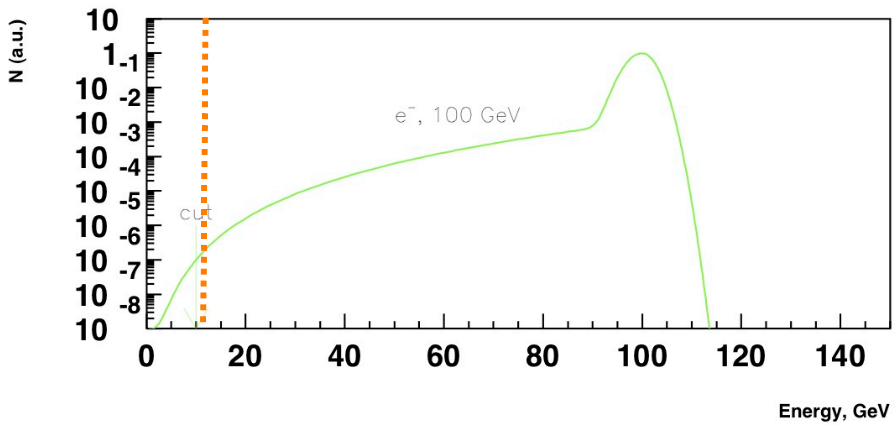
Summary of background sources for A`-> invisible

Source	Expected leve	Comment
Beam contamination		
- π, p, μ reactions and punchthroughs,...	< 10^{-13}-10^{-12}	Impurity < 1%
- e- low energy tail due to bremss., π, μ decays in flight,..	?	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;	< 10^{-13}	~10 mb x nonherm. WI σ estimated.
- WI process: e Z->e Z ν ν	< 10^{-13}	textbook process, first observation?
Total	< 10^{-12} + ?	

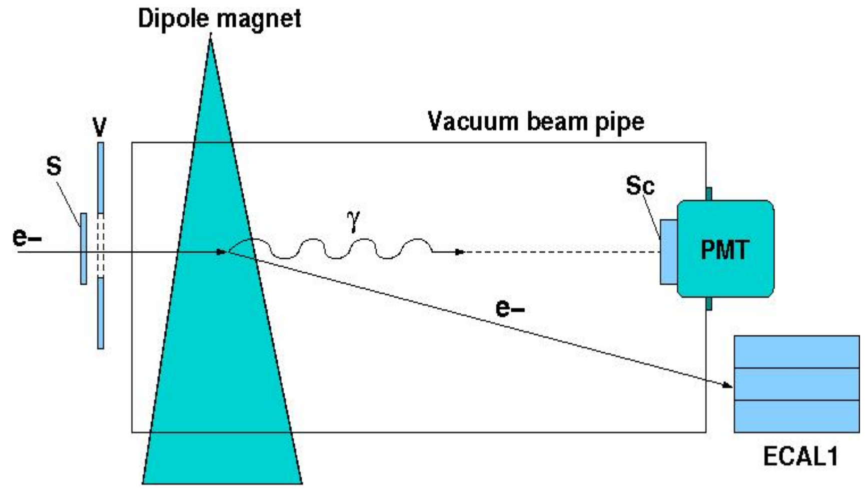
Additional tag of electrons with SR photons



Fake ECAL1 signal .



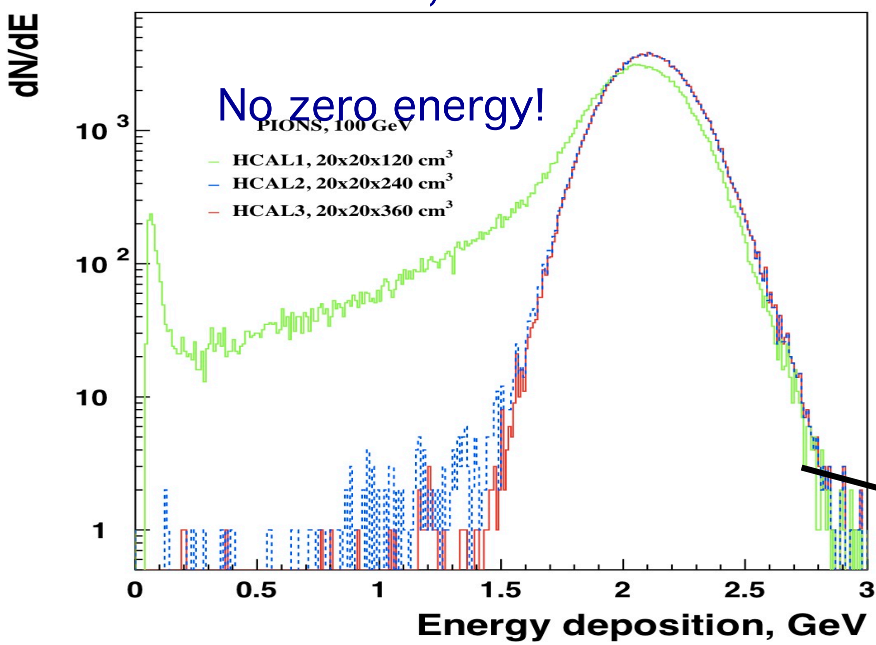
Hypothetical e- beam energy distribution (not simulated).



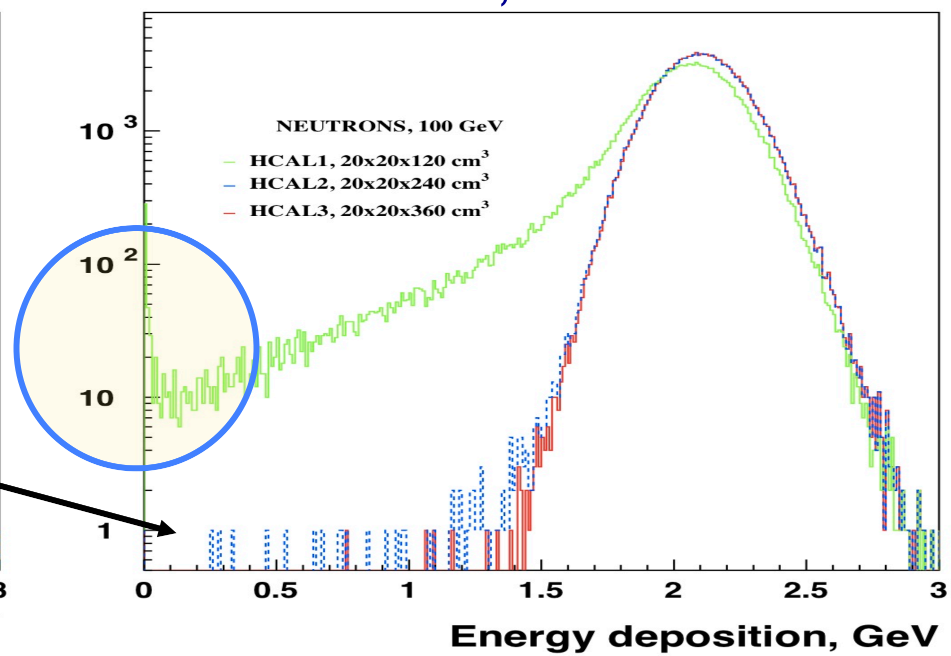
- e- tag enhancement with SR γ
- B field ~ 0.1- 1T
- $(\hbar\omega)_\gamma^c \sim E^2 B$, $n_\gamma/m \sim 6\ B(T)$
- cut $E_\gamma > 0.1\ (\hbar\omega)_\gamma^c$ ~100 keV
- LYSO crystal, good resolution for > ~50 keV γ
- suitable for vacuum

HCAL hermeticity for 3 consequtive modules

Pions, 100 GeV



Neutrons, 100 GeV



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