Эксперимент Р348 в ЦЕРНе: поиск взаимодействий темной материи

И.В.Красников
ИЯИ РАН

Марковские чтения
ИЯИ РАН, Москва, 14 мая 2014 года

Plan

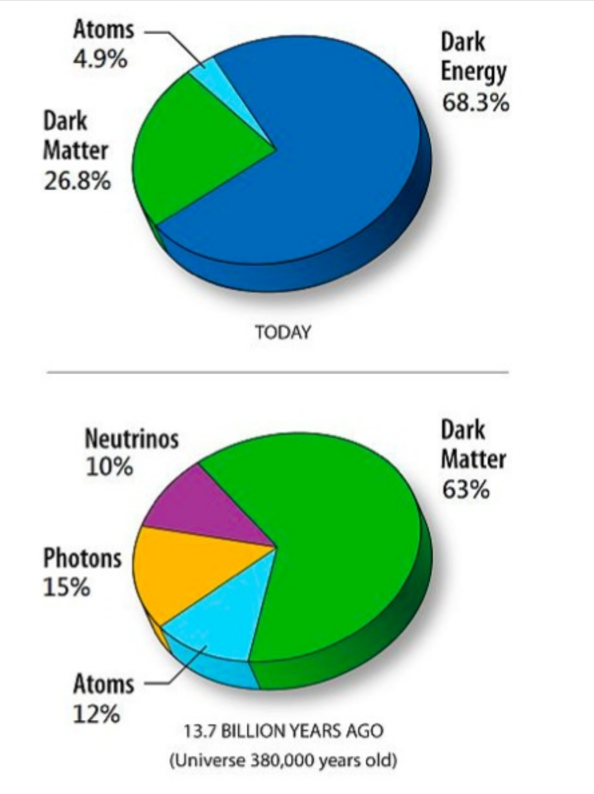
- SM portals to Dark sectors at sub-GeV scale
- Search for visible and invisible decays of dark photons
  - setup
  - background
  - expected sensitivity
- Status and goals
- Summary

Higgs boson and SM

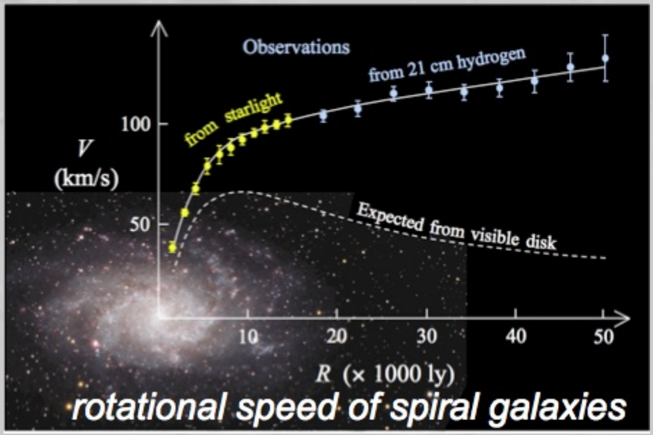
The great LHC discovery –
Higgs boson discovery in 2012.
Standard Model is complete.
But it is not the end of the history…

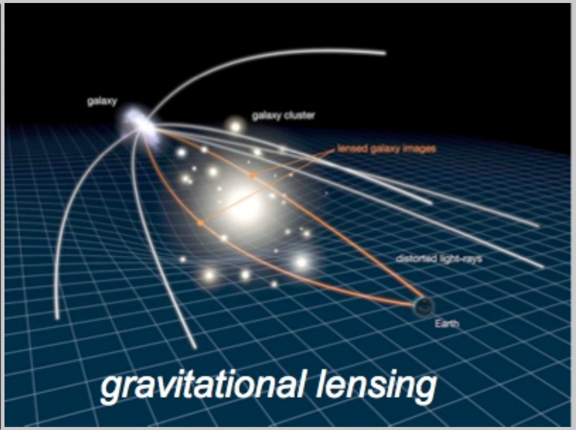
1. Dark matter
2. Muon (g-2) magnetic moment

Dark matter puzzle in the SM



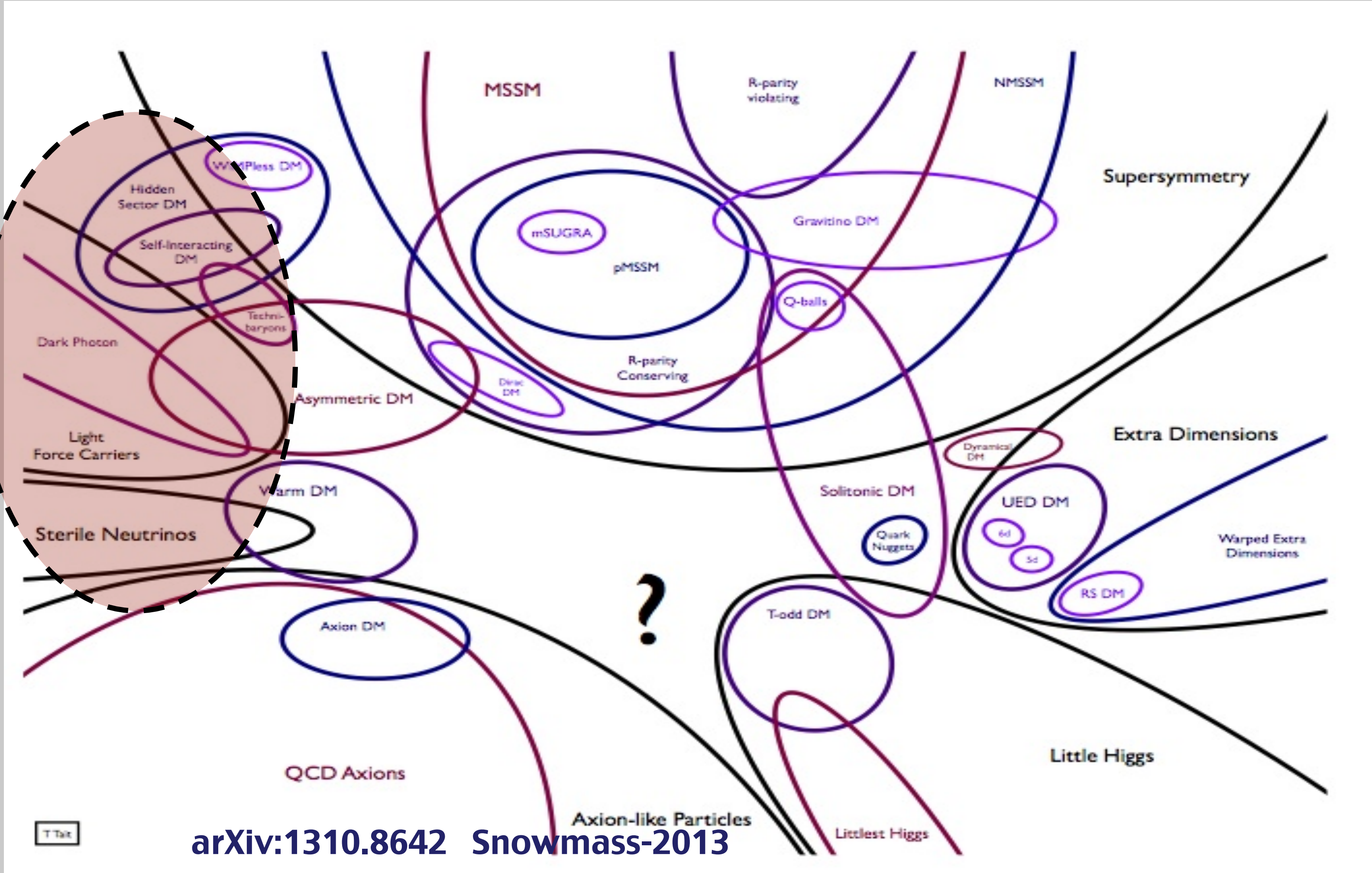
What makes up most of the Universe's mass?





The question is still open: no SM explanation of the Origin of Dark Sector of the Universe

The (incomplete) landscape of Dark Matter candidates



arXiv:1310.8642 Snowmass-2013

SM extension?

Another hint in favour of the SM extension is (g-2) muon anomalous magnetic moment.

The E821 experiment at BNL :

$$(g\text{-}2)_{obs} - (g\text{-}2)_{SM} = (287 \pm 80)\cdot 10^{-11}$$

A lot of explanations:

1. Supersymmetry
2. New massive vector boson
3. ...

New vector boson – Dark force

New vector massive boson interacting with muon explains (g-2) muon magnetic moment

S.Gninenko, N.Krasnikov (2001)

E.Ma, D.P.Roy, S.Roy (2002)

J.Heeck, W.Rodejohann (2011)

$$\alpha_X = O(10^{-8} - 10^{-6})$$

New vector boson – Dark force

Dark Forces: additional way to detect DM

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

- Can one expect a hint from high intensity and precision experiments at low energy, e.g. 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. E.g. old idea: Mirror Matter Model.

- Search for dark forces, other than Gravity that connect our Universe to the Dark Sector, is an additional way to detect DM.

The SM Portals to Dark Sectors

Generic low-energy forces of any Dark Sector

- **Neutrino Portal** $\Delta L = \varepsilon_\nu (hL)\psi$ sterile neutrinos?
- **Higgs Portal** $\Delta L = \varepsilon_h (h)^2 \phi^2$ exotic Higgs decays?
- **Vector portal** $\Delta L = \varepsilon F^{\mu\nu} A'_{\mu\nu}$ Okun'85, Holdom'86

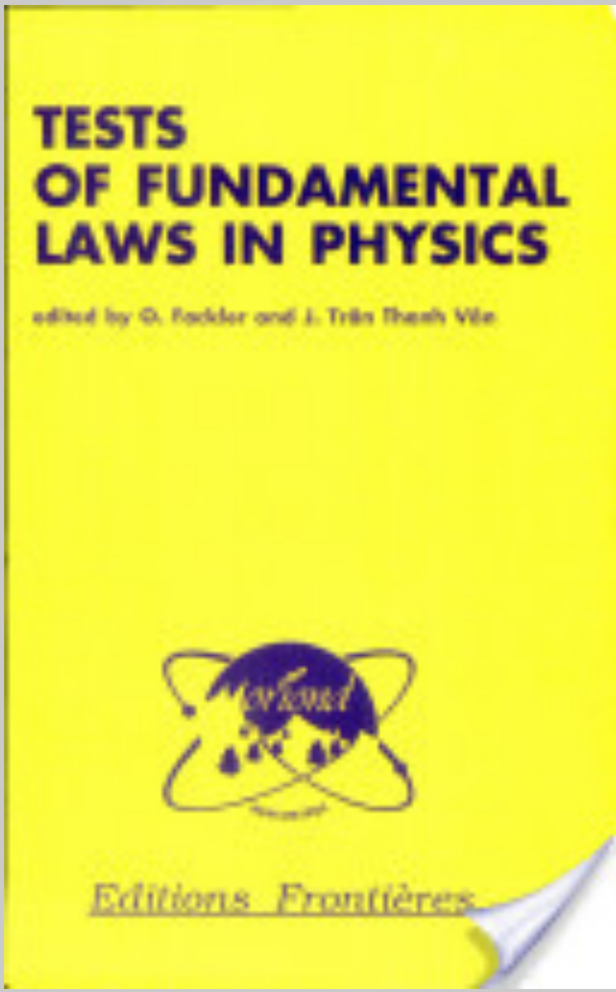
Only light vector portal is really accessible at low energy, ε_ν and ε_h couplings are very small

Dark vector mediator A'

- 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^-, $\mu^+\mu^-$, hadrons,.. or A'-> DM particles, i.e. A'-> invisible decays

Extensive literature, more than 100 papers over the past few years, many new theoretical and experimental results

New U'(1) is not new for INR TH



RARE DECAYS, NEW U(1) BOSONS AND THE FIFTH FORCE

T.M.ALIEV, M.I.DOBROLIUBOV, A.Yu.IGNATIEV, V.A.MATVEEV

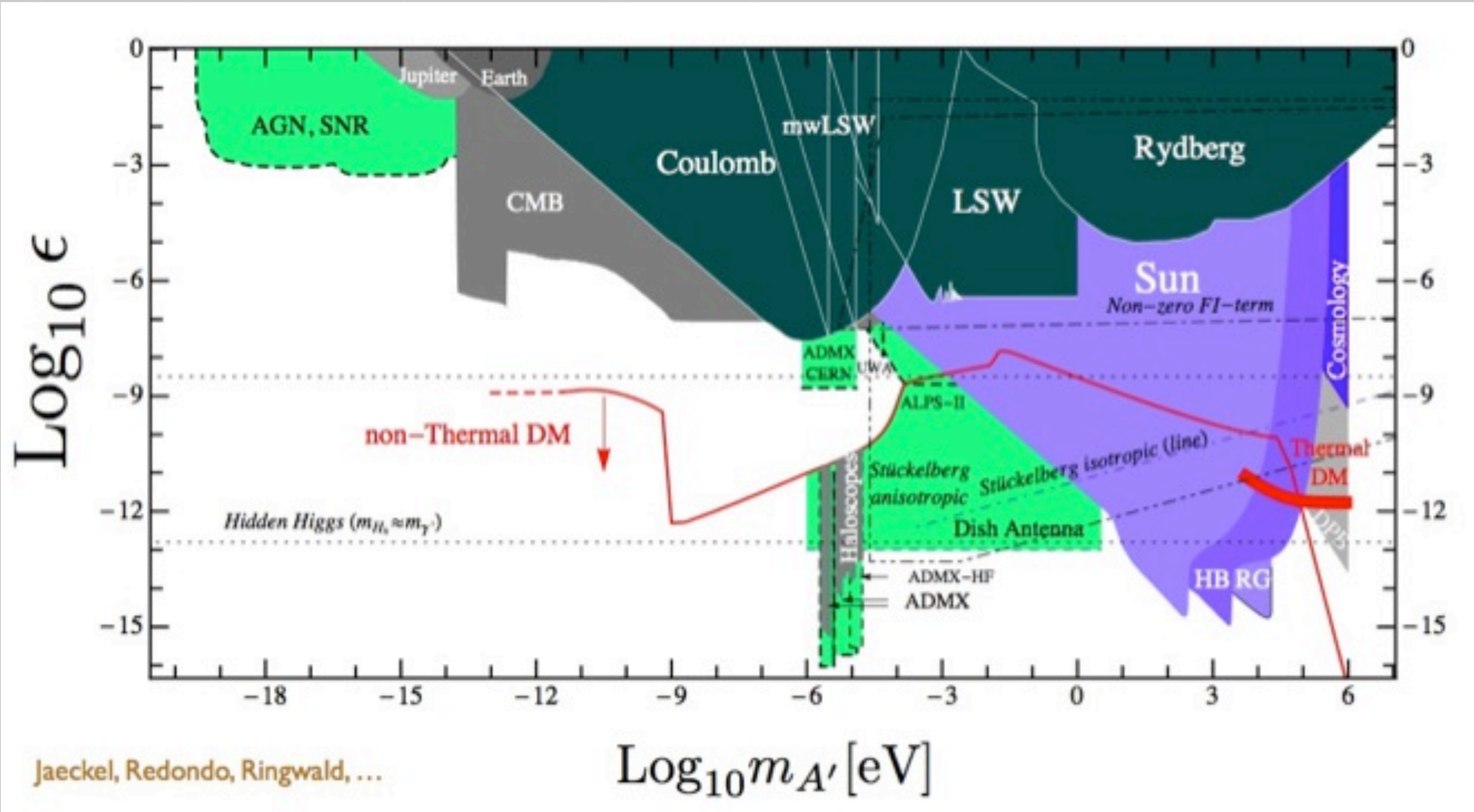
Institute for Nuclear Research of the Academy of Sciences of the USSR, 60th October Anniversary pr.,7a, 117312 Moscow, U S S R

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.

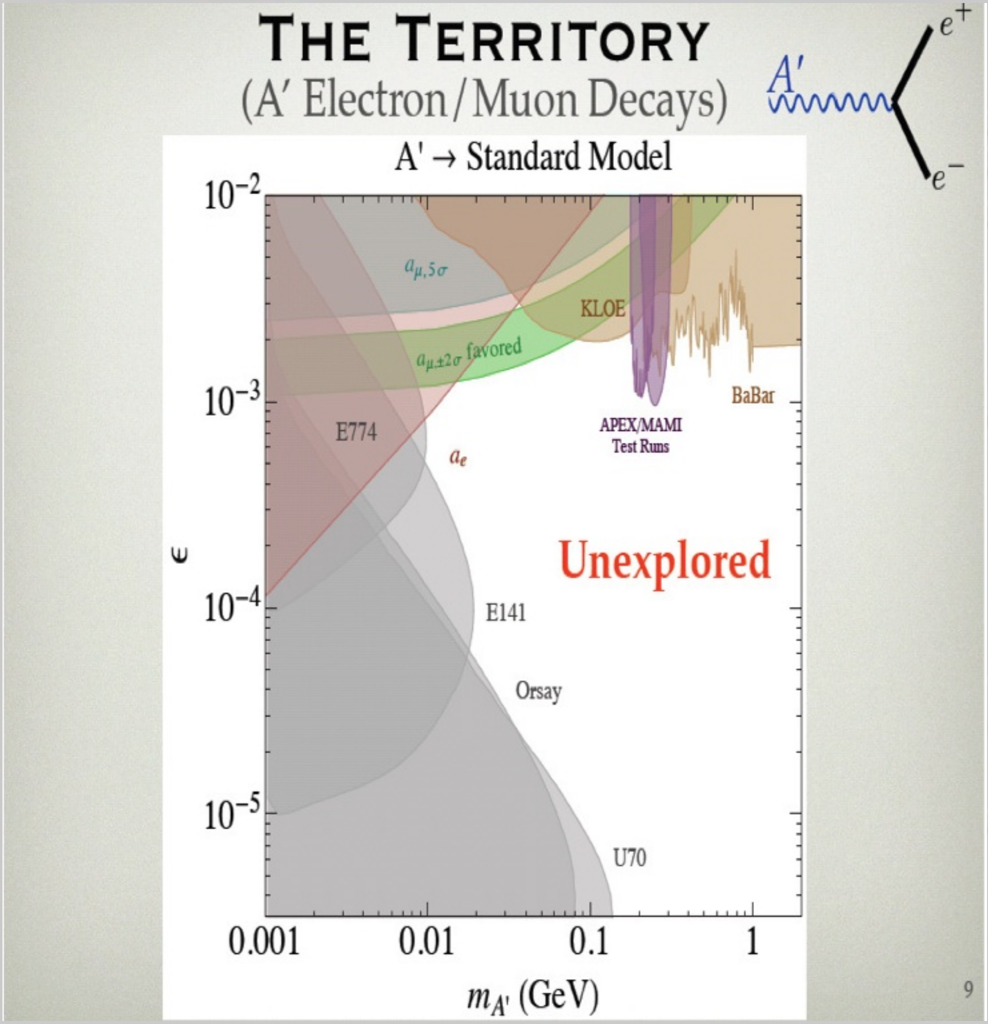
January 21–28, 1989

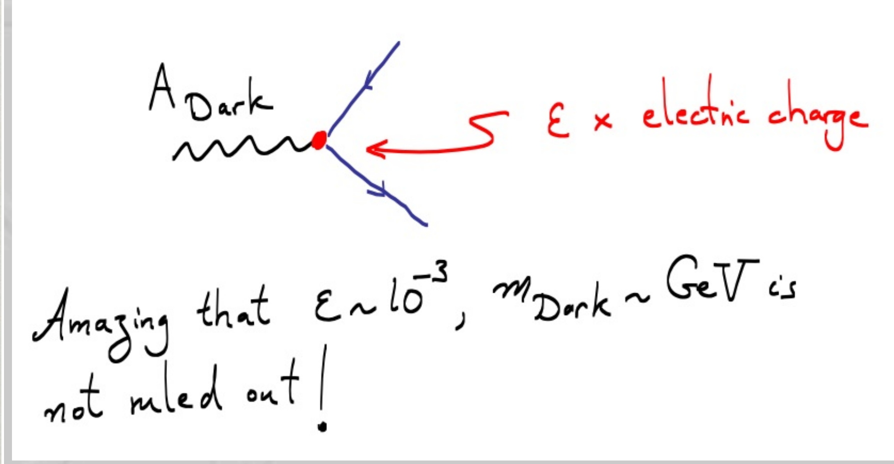
Low mass (<MeV) A' parameter space



+ 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

Search for Visible and Invisible DM particles at CERN

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[e], V.A. Polyakov[c], A. Ringwald[a], A. Rubbia[d], V.D. Samoylenko[c], Y.K. Semertzidis[h], K. Zioutas[e]

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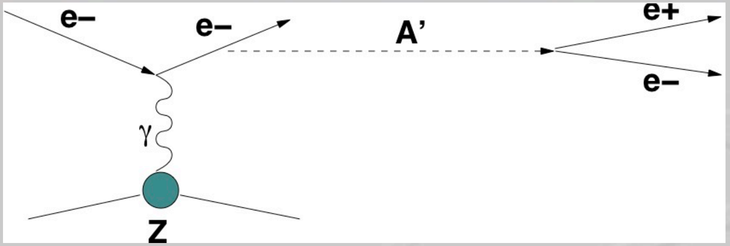
[h] *Center for Axion and Precision Physics, IBS, Physics Dept., KAIST, Daejeon, Republic of Korea*

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

December 6, 2013

Experiment P348, arXiv: 1312.3309

MeV A' production and decay



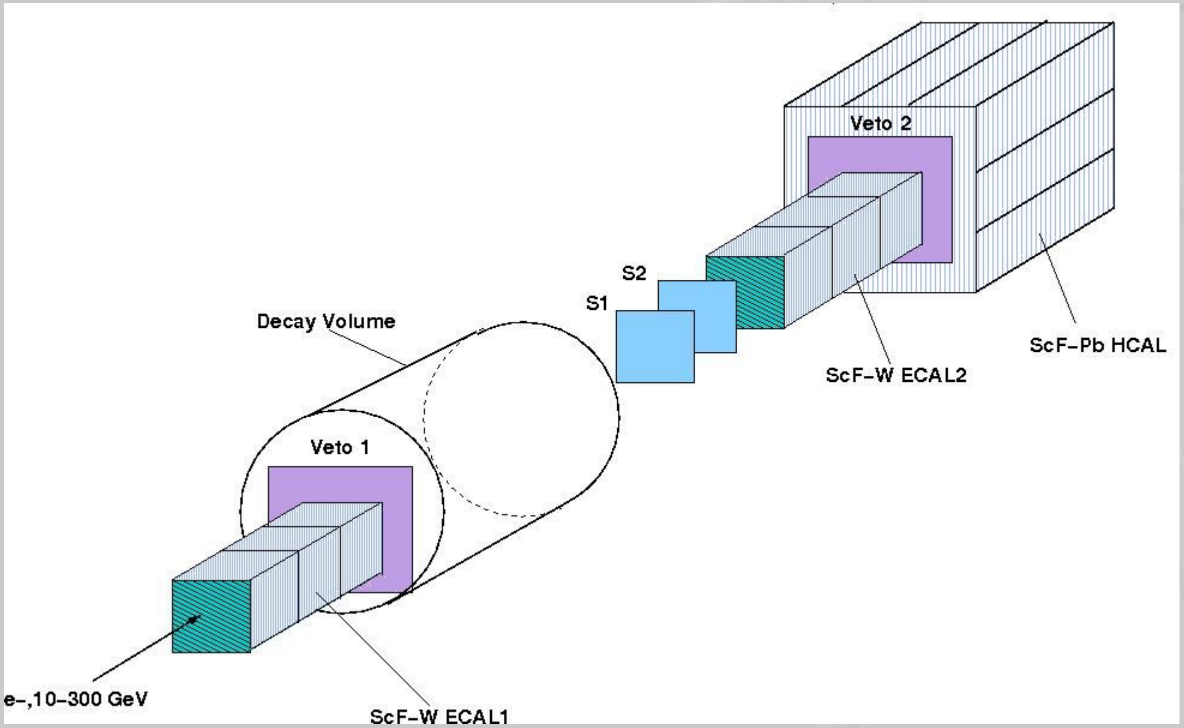
bremsstrahlung A'

- 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 ~ ε^4 for long-lived A', typical for beam dump searches

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

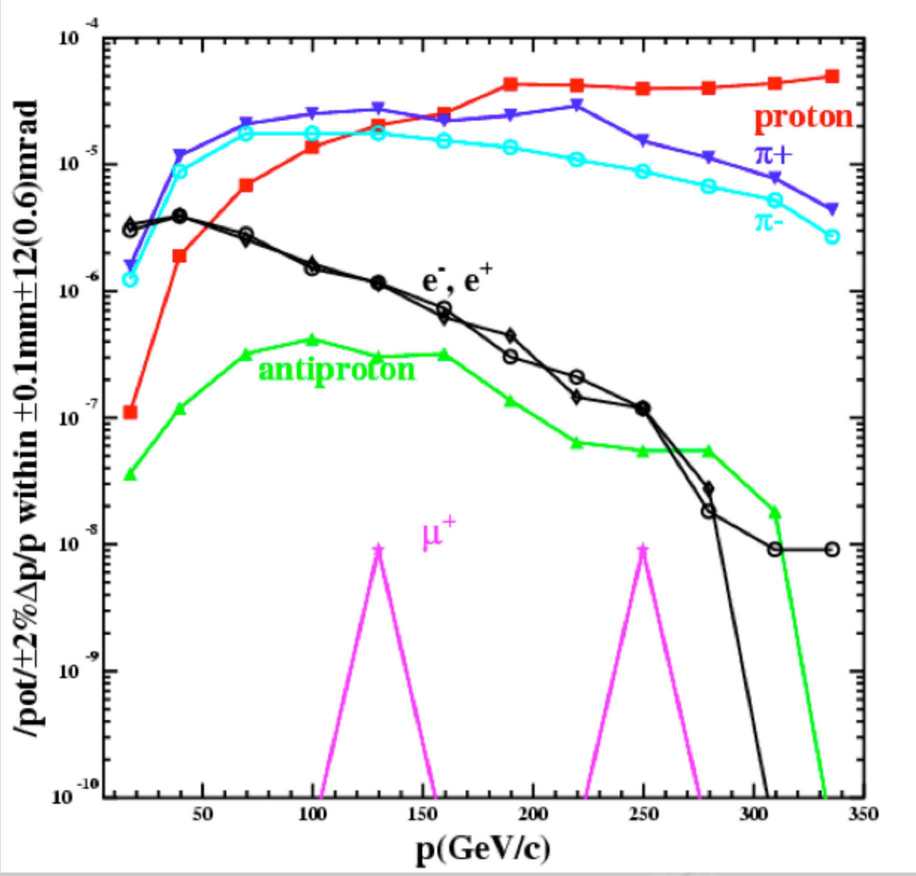
- very short-lived A': $10^{-14} < \tau_{A'} < 10^{-10}$ s
- very rare events: $\sigma_{A'}/\sigma_\gamma < 10^{-13} - 10^{-9}$
- A' energy boost to displace decay vertex,
  $\varepsilon \sim 10^{-4}$, $M_{A'} \sim 50$ MeV, $E_{A'} \sim 100$ GeV, $L_d \sim 1$ m
- background suppression

Setup



- H4-H8 beamline
- Magnetic spectrometer (not shown)
- ECAL1,2
- V1,2 veto counters
- Decay volume (vacuum)
- HCAL
- S1,S2 fiber-tracker

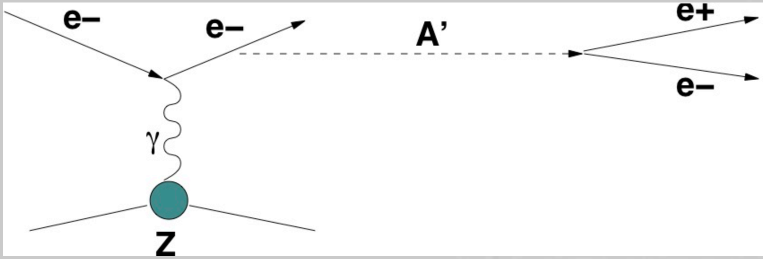
SPS e^- beams

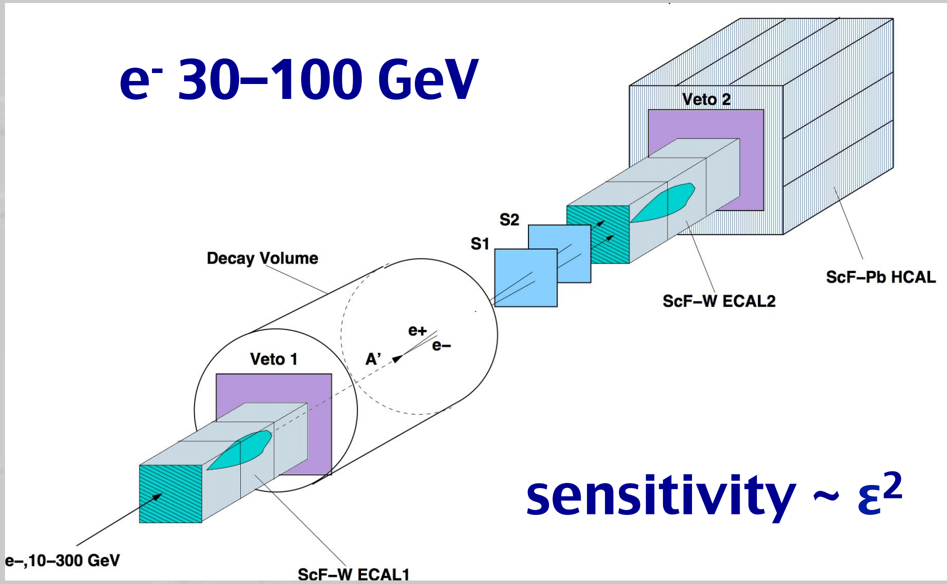


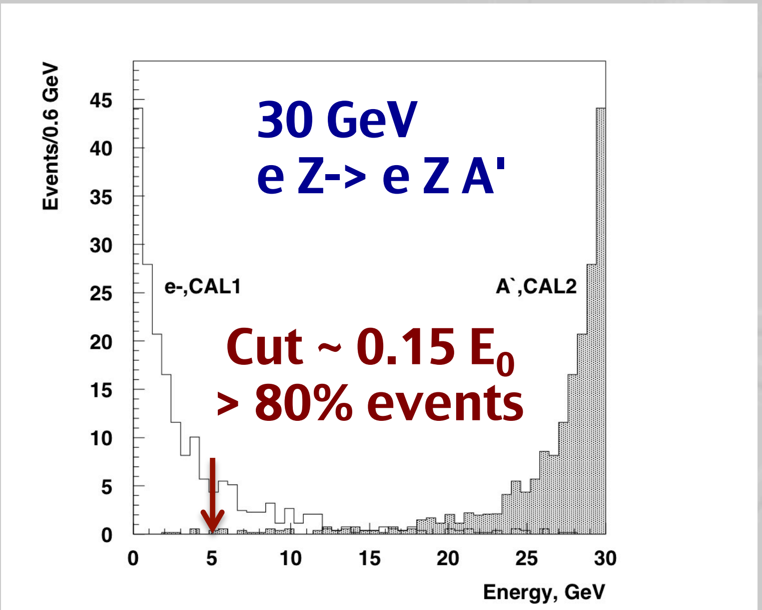
- H4, I_{max}~ 50 GeV e^-
- 10^{12} pot per SPS spill
- ~ 5×10^6 e^- per spill
- duty cycle is 0.25
- ~10^{12} e^- / month
  additional tunning
  by a factor 2–3 ?
- beam spot ~ cm^2
- beam purity < 1 %

Search for $A' \to e^+e^-$ in a LSW experiment

S.N. Gninenko, PRD (2014)





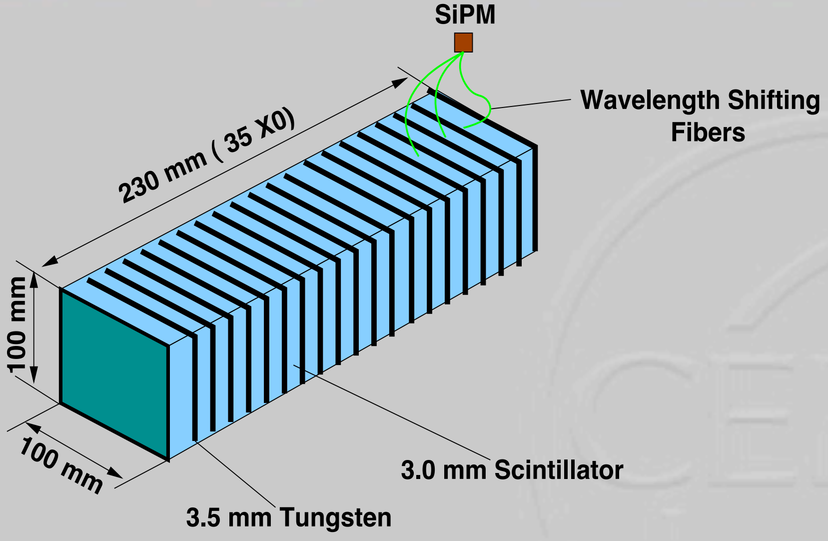


- A's decay mostly outside ECAL1
- Signature: two separated em showers from a single e^-

S= ECAL1xS1xS2x ECAL2 xV1xV2xHCAL

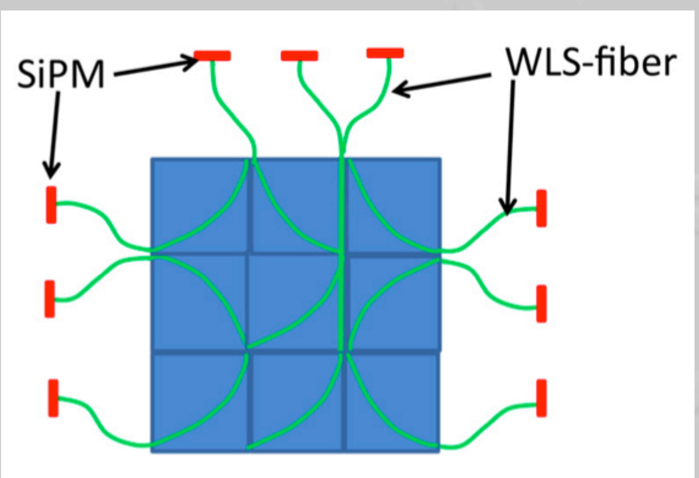
- $E_1 << E_0$ and $E_0 = E_1 + E_2$
- Θ_{e+e-} too small to be resolved

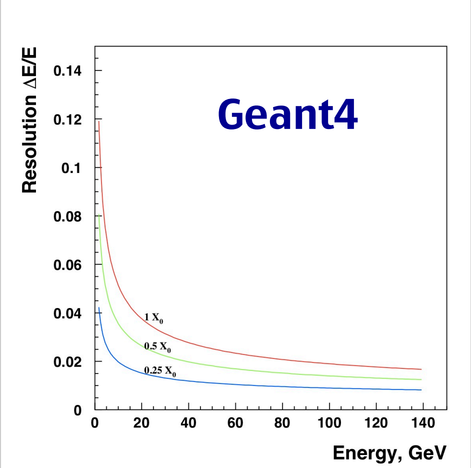
Specially designed ECAL



ECAL1 “bubble chamber”
W-Sc sandwich + fiber readout

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

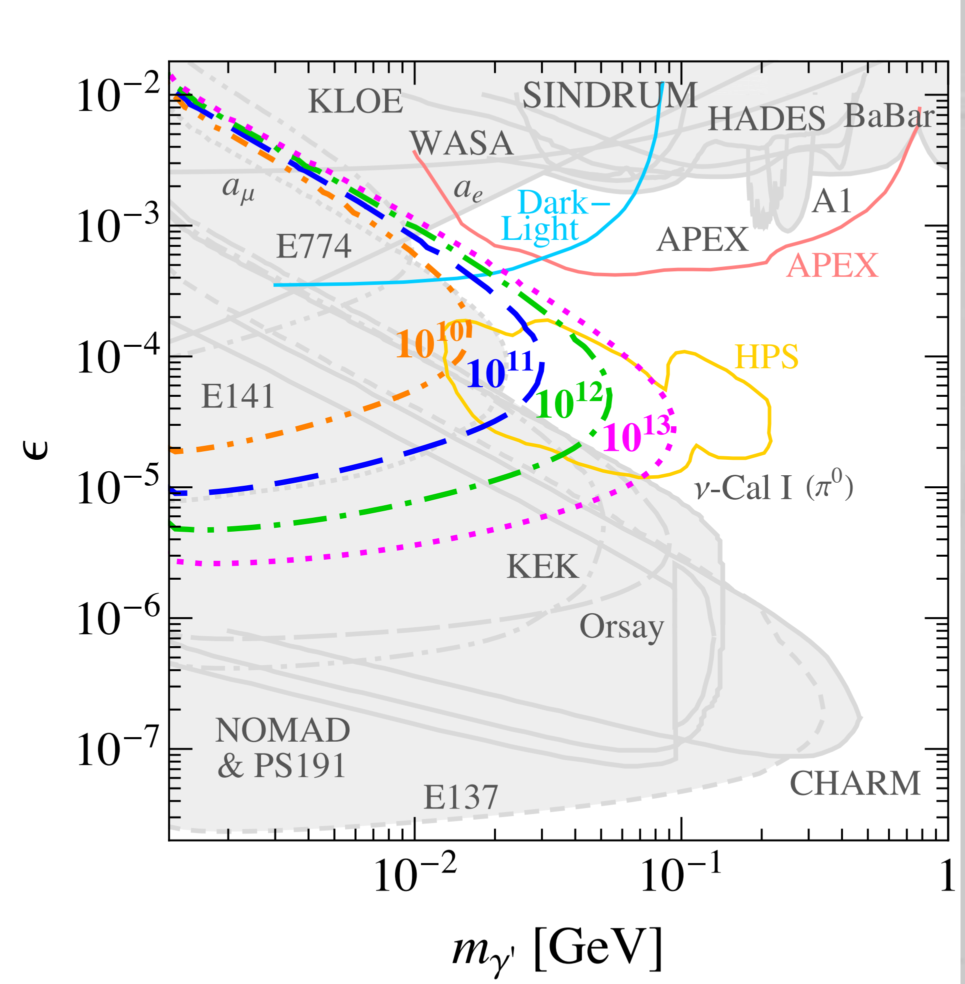




Summary of background sources for $A' \to e^+e^-$

Source	Expected level	Comment
Beam contamination		
- π, μ reactions, e.g. $\pi A \to \pi^0 n + X$, … - 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	$< 10^{-12}$	

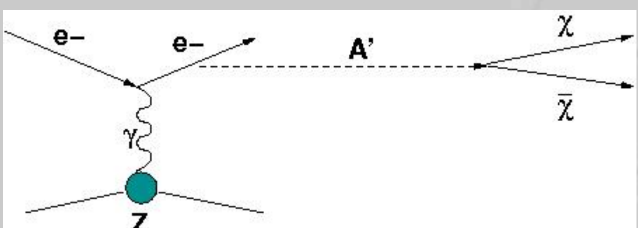
Expected limits on $A' \to e^+e^-$ decays vs accumulated N_{e-}

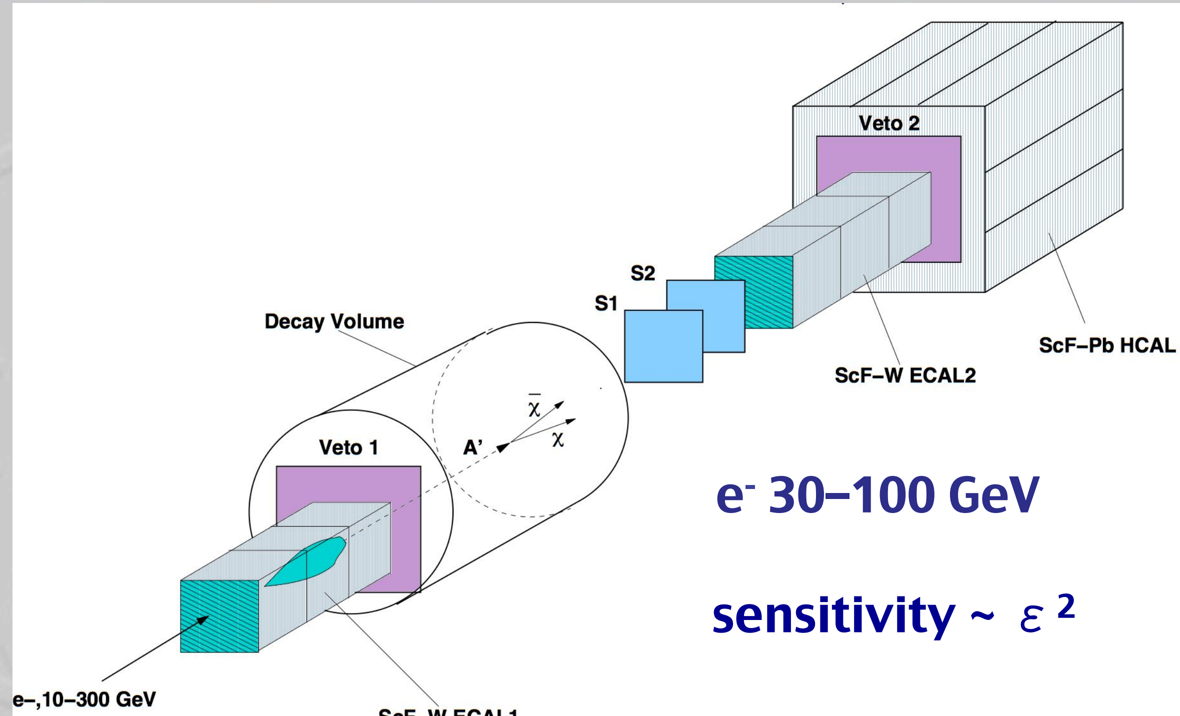


background free case

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

Remember
Z—>invisible
in the SM !





- **Signature:** **single em shower in ECAL1 + no activity in the rest of 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**

Analogy with β–decay

^{210}Bi β-decay e^- spectrum

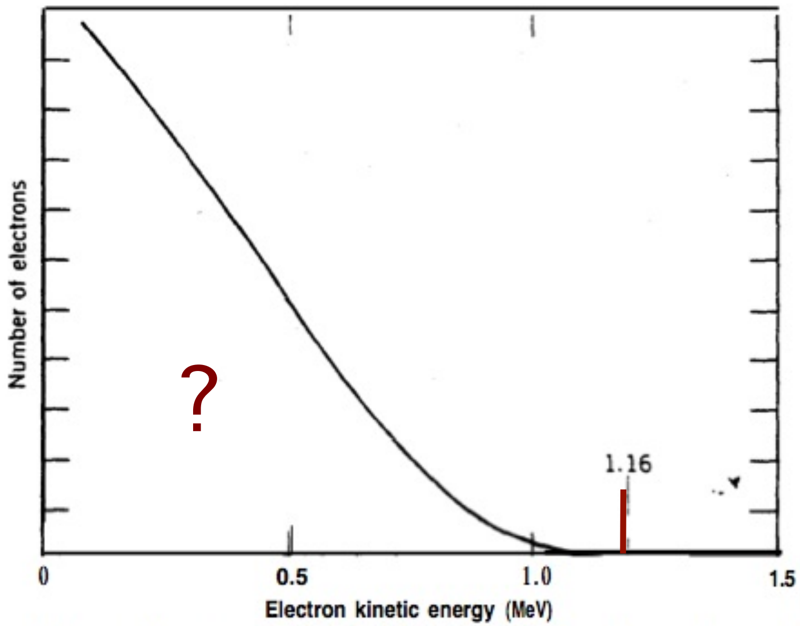
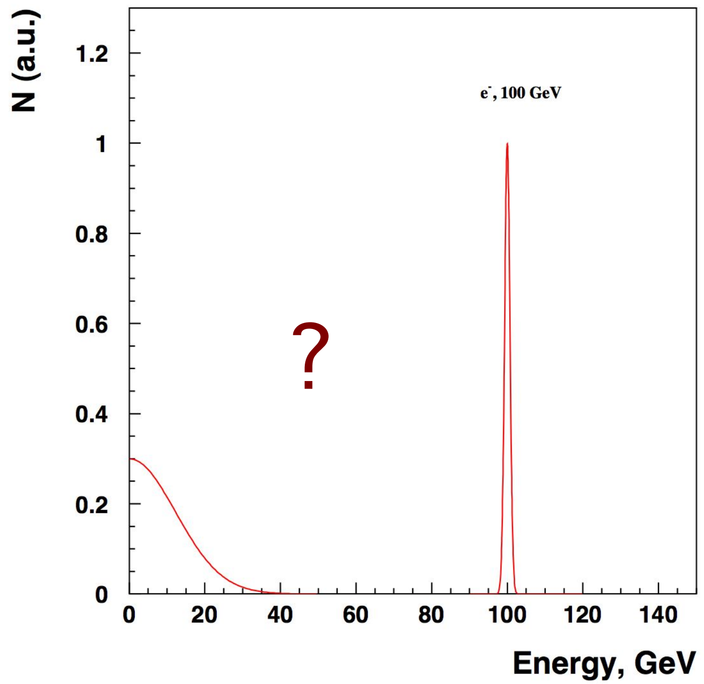


Figure 9.1 The continuous electron distribution from the β decay of ^{210}B
called RaE in the literature).

SPS e^- spectrum



W.Pauli, 1931

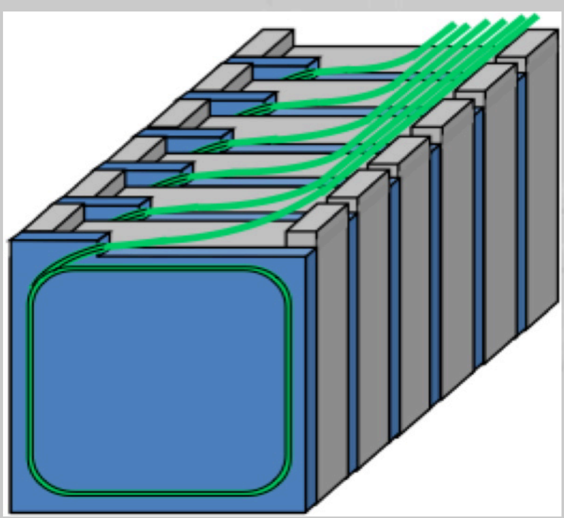
? = invisible ν

Massive HCAL to enhance longitudinal hermeticity

Single module of the hadronic calorimeter (F.Guber et al. INR):

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

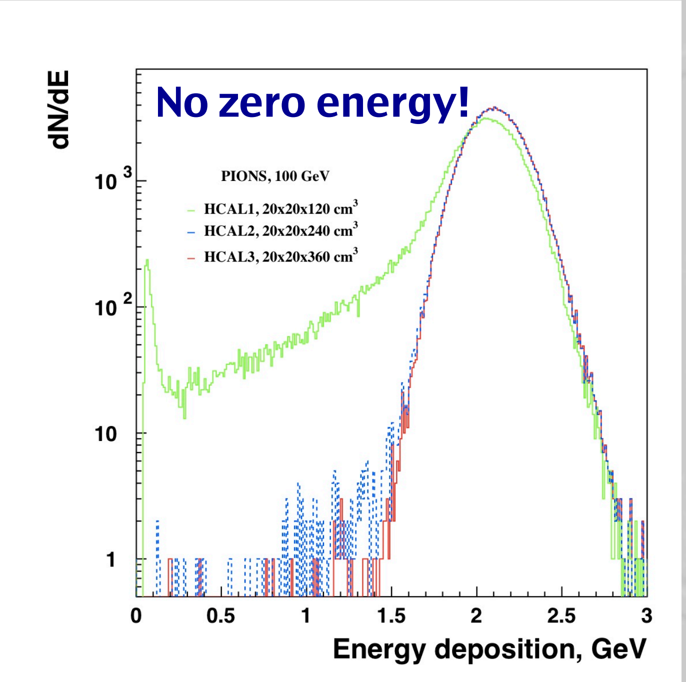
Full HCAL : 2x2x3 modules, ~ 7 tons



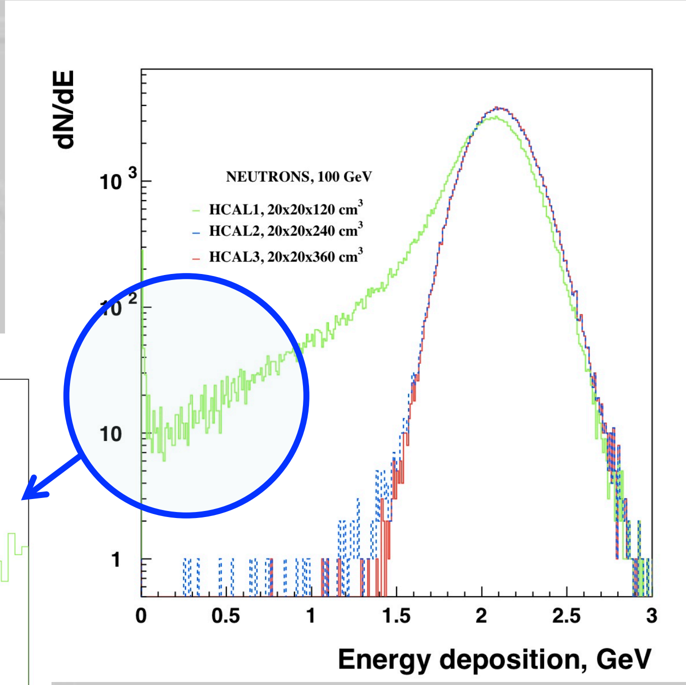
Prototype →

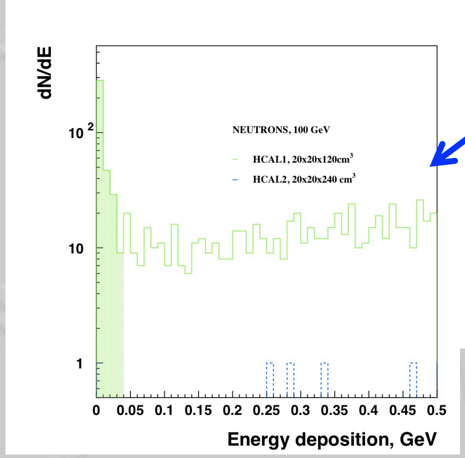
HCAL hermeticity for three consecutive modules

Pions, 100 GeV



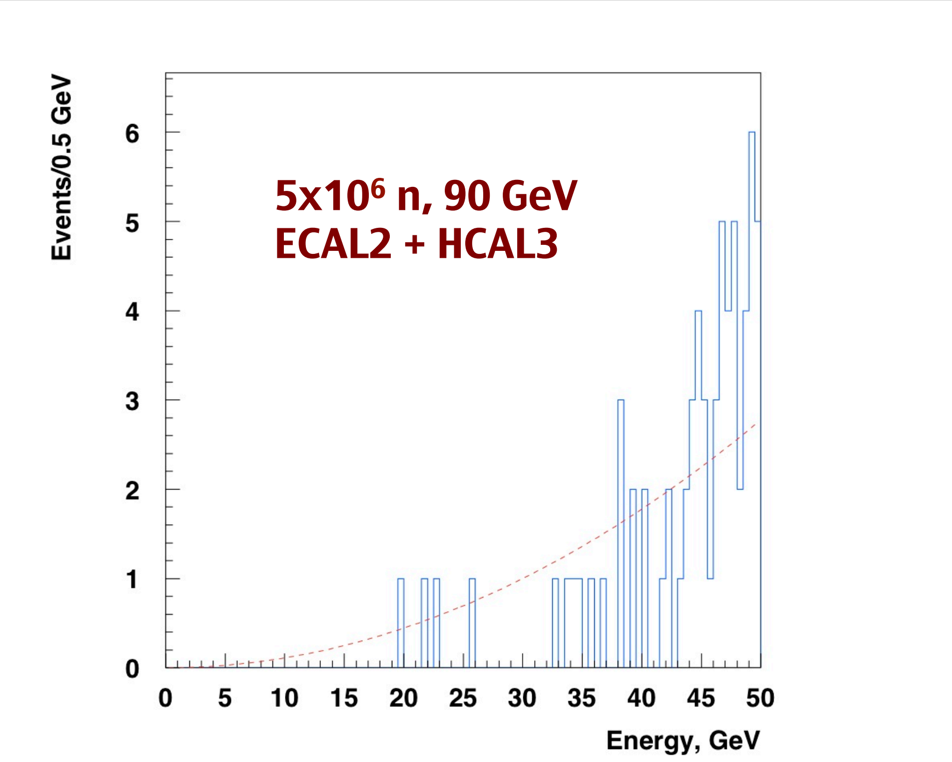
Neutrons, 100 GeV

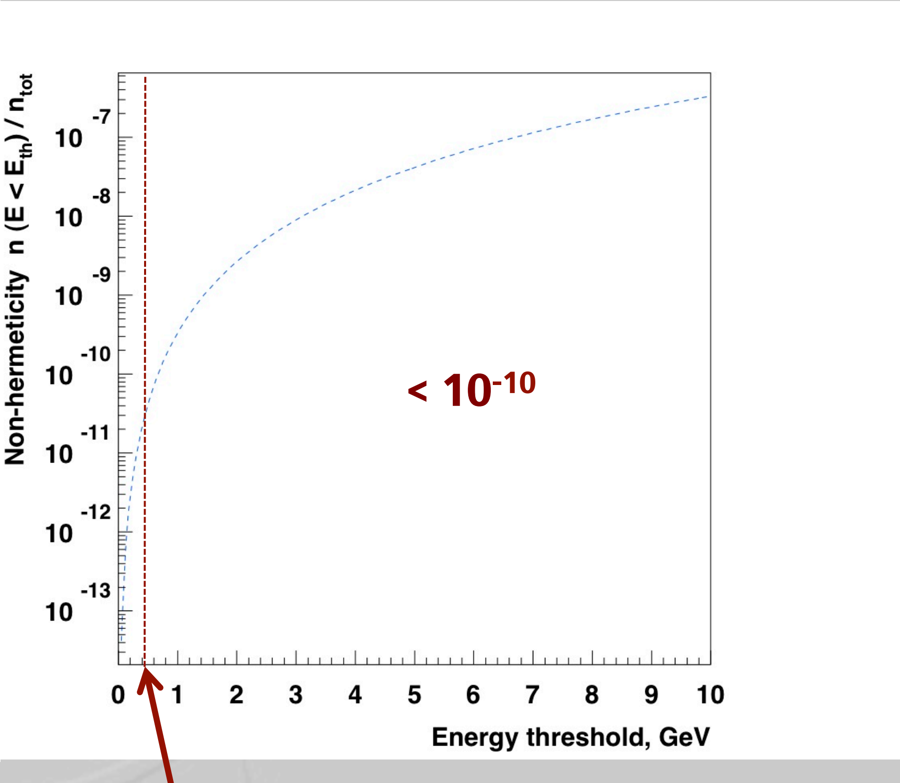




Expected HCAL energy threshold ~ 20–50 MeV determined by noise and pileup

Estimated ECAL2 + HCAL3 nonhermeticity





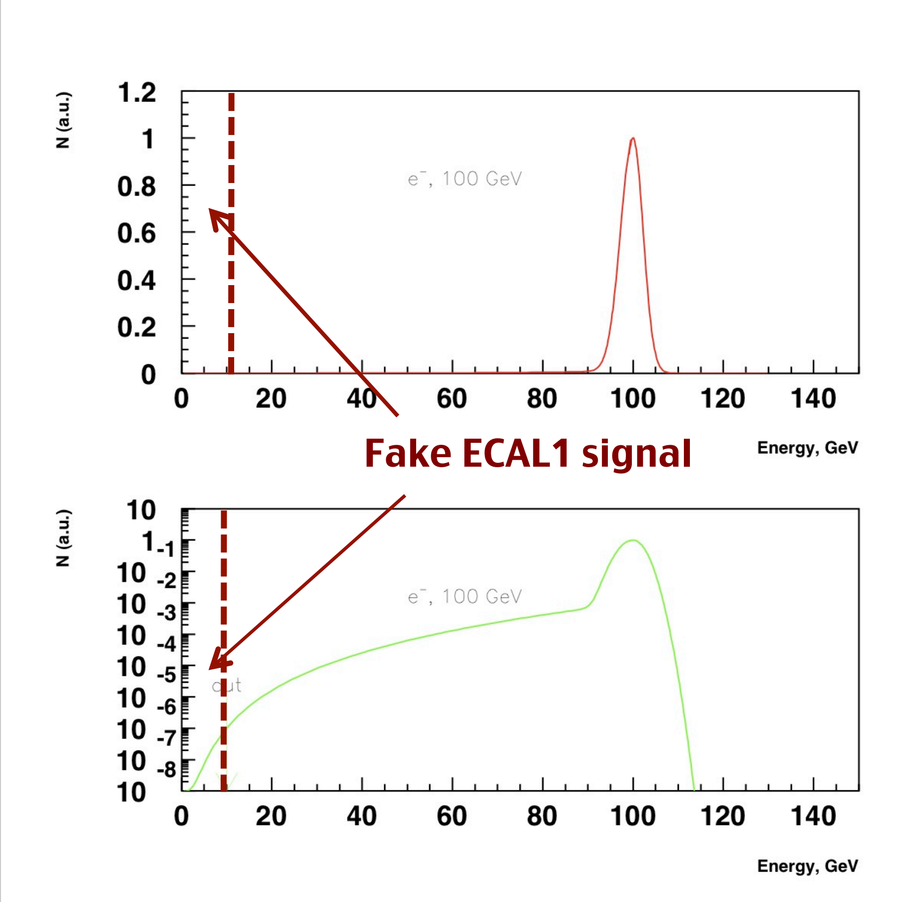
Fit of the low energy tail with a smooth function f(E)

ECAL2+HCAL3 nonhermeticity as a function of the energy threshold

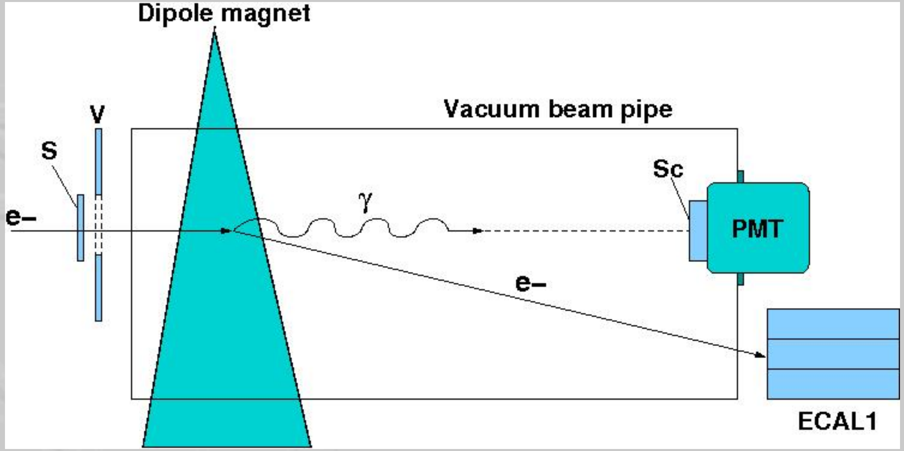
Summary of background sources for *A' → invisible*

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	$< 10^{-12}$ + ?	

Improving of electron tagging with SR photons



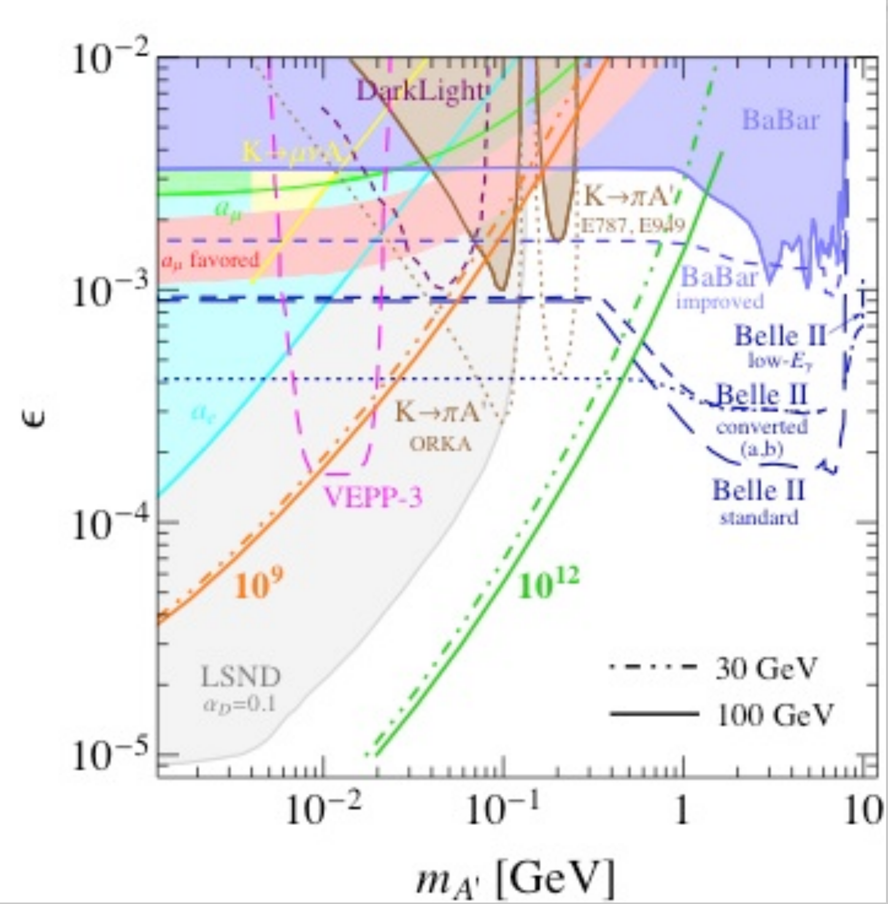
Hypothetical e- beam energy distribution (not simulated)



- 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 $E_\gamma > 0.1\ (\hbar\omega)_\gamma^c$ ~100 keV
- LYSO crystal, good resolution for > ~50 keV γ
- suitable for vacuum

Expected limits on $A' \to$ *invisible* decays vs accumulated N_{e-}

With one day of running the $(g-2)_\mu$ favored region is completely covered!



background free case

P348 Status 2014: SPSC recommends to run Phase I

Feedback from SPSC on P348
Matthew Wing [m.wing@ucl.ac.uk]
Sent: 10 April 2014 09:13
To: Sergei Gninenko
Cc: Gavin Salam; Lau Gatignon

Dear Sergei,

Thank you for your documents and answers to our questions about P348, to search for light dark matter using the SPS. The feedback from the committee is below.

Cheers,
Gavin, Lau and Matthew.

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.

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Goals for Phase I measurements in 2014-2015

- Detector installation and commissioning: upgrade ECAL at CERN, new HCAL modules, magnetic spectrometer (ETH, CERN)
- Tests of the ECAL/HCAL performance with e, π, μ beams
- First tests of background with π, μ beams
- Search for *A'-> invisible*, $n_e \sim 10^{10}$ e^- or more, first limit
- Full coverage of the $(g-2)_\mu$ favored region for *A'-> invisible*
- Preliminary search for *A'-> e^+e^-*, $n_e \sim 10^{10}$ e^- or more
- Preparation of Technical Design Report requested by SPSC for the full-scale searches 2015->

Goals for Phase II in 2015 →

- TDR presentation to the SPSC CERN
- Design and construction of the compact ECAL
- Design and construction synchrotron photon detector
- Full new detector installation and commissioning
- Tests of the ECAL/HCAL performance with e, π, μ beams
- Measurements of background with π, μ beams
- Search for *A'*→ e^+e^-, $n_e \sim 10^{12}$ e^- or more (6 months)
- Search for *A'*→ *invisible*, $n_e \sim 10^{12}$ e^- or more (>6 months)
- Theoretical developments for new rare processes

❖ Full detector construction: 2014 – 2016

❖ Total detector cost : 13.8 Mln. Rub. / 3 years

❖ Needs in 2014: 3.8 Mln. Rub.

Заключение

• Модели новых взаимодействий между обычным веществом и темной материей привлекательны как с теоретической (феноменологически обоснованы, просты, предсказательны,..), так и экспериментальной (четкая сигнатура, низкий уровень фона,..) точек зрения

• Предлагается эксперимент по поиску новых сил и их переносчиков на ускорителе SPS CERN, который планируется осуществить в два этапа (Phase I, II). Проект обладает высокой конкурентноспособностью по сравнению с аналогичными поисками, планируемыми в JLab (США), DESY и ряде других лабораторий в области неисследованных параметров $10^{-5} < \varepsilon < 10^{-3}$, $M_{A'} <\sim 100$ MeV

• Эксперимент был рассмотрен комитетом SPSC CERN и в апреле 2014 г. рекомендован к проведению этапа Phase I с получением первого физического результата в 2015 г. и последующей подготовкой TDR для осуществления полномасштабных поисков

• Суммарная стоимость проекта 13,8 млн. руб. на 2014–2016 гг. Потребности на 2014 г. составляют 3,8 млн. руб.