An Experiment to Search for the Muonium Decay $\mu^+e^- \to \nu_\mu\nu_e$

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INR Moscow

Open Users Meeting
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PREPARED FOR SUBMISSION TO PSI

Letter of Intent for an Experiment to Search for the Muonium Decay $\mu^+ e^- \to \overline{\nu}_\mu \nu_e$

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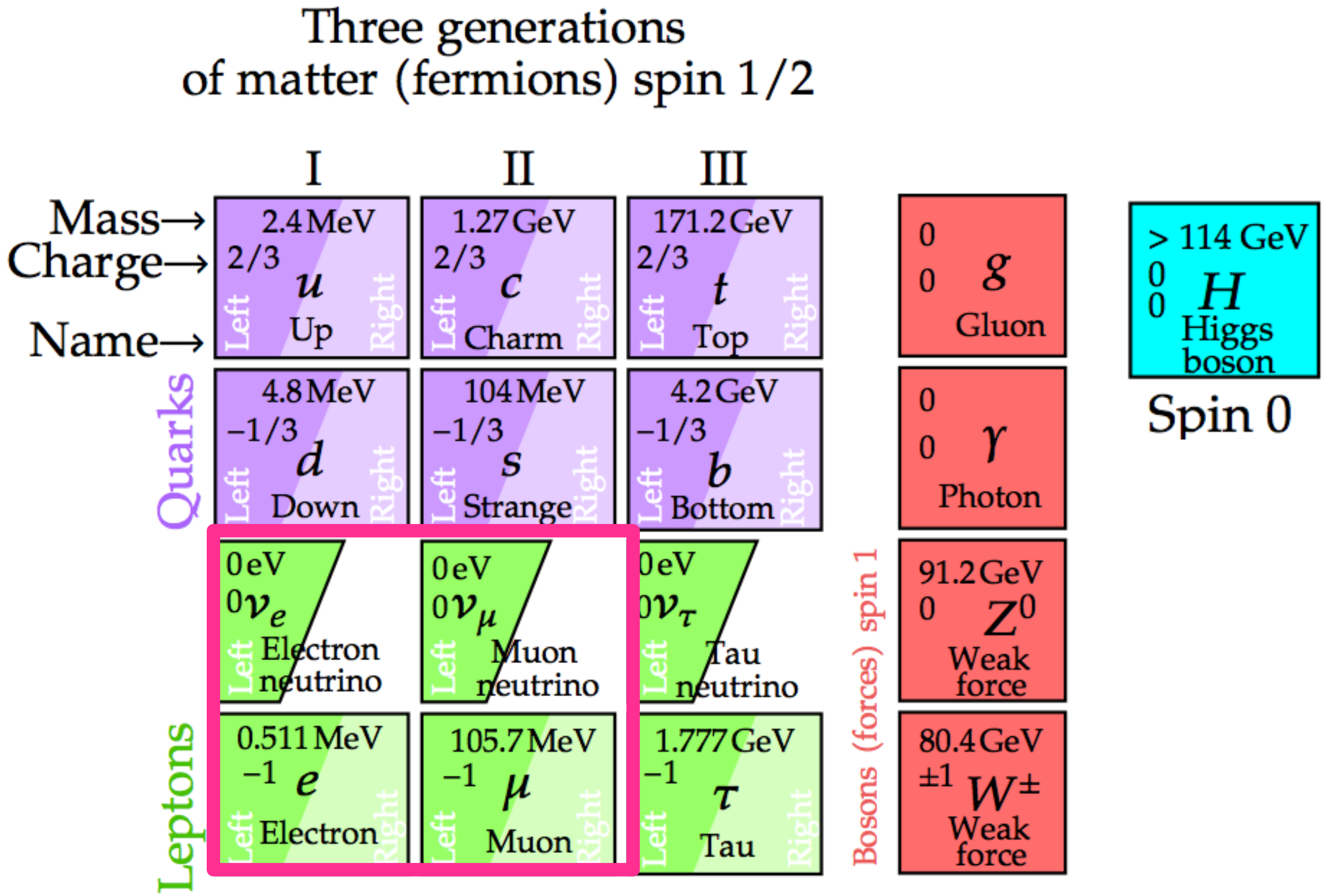
Plan

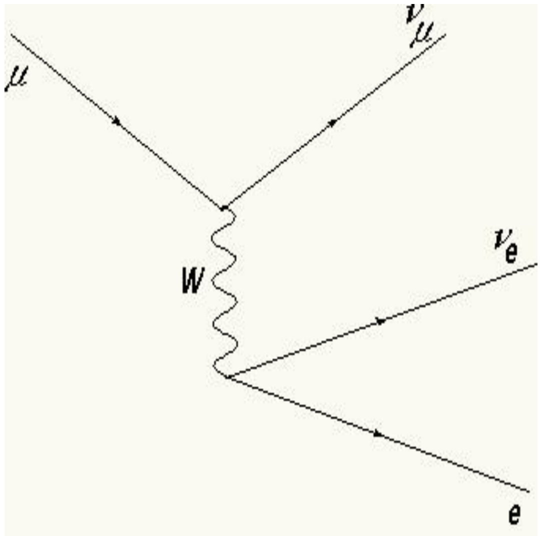
- introduction
- muonium decay $\mu^+e^- \to \nu_\mu \nu_e$ in the SM
- μ^+e^- decays beyond the SM
- experimental techniques
- background
- sensitivity
- schedule

Physics with first two lepton generations



in the electroweak theory transitions between two generations are induced by interactions of charged currents $(e\nu_e)$ and $(\mu\nu_\mu)$ resulting in several canonical processes connected by crossing symmetry: $\mu^+ \to e^+\nu_\mu\nu_e$ <---- > $\nu_\mu e^- \to \mu^-\nu_e$ <----> $\mu^+e^- \to \nu_\mu\nu_e$

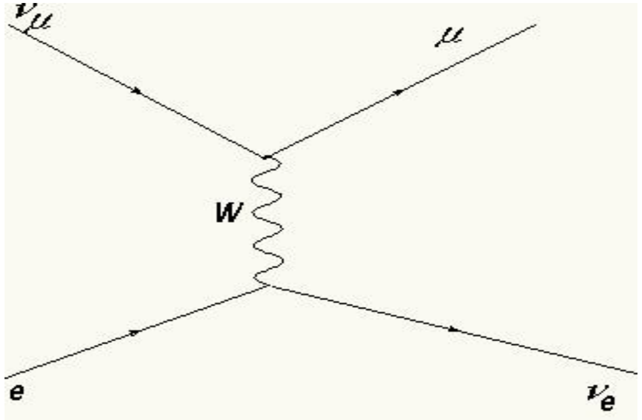
Muon decay μ -> e $\nu_\mu \nu_e$



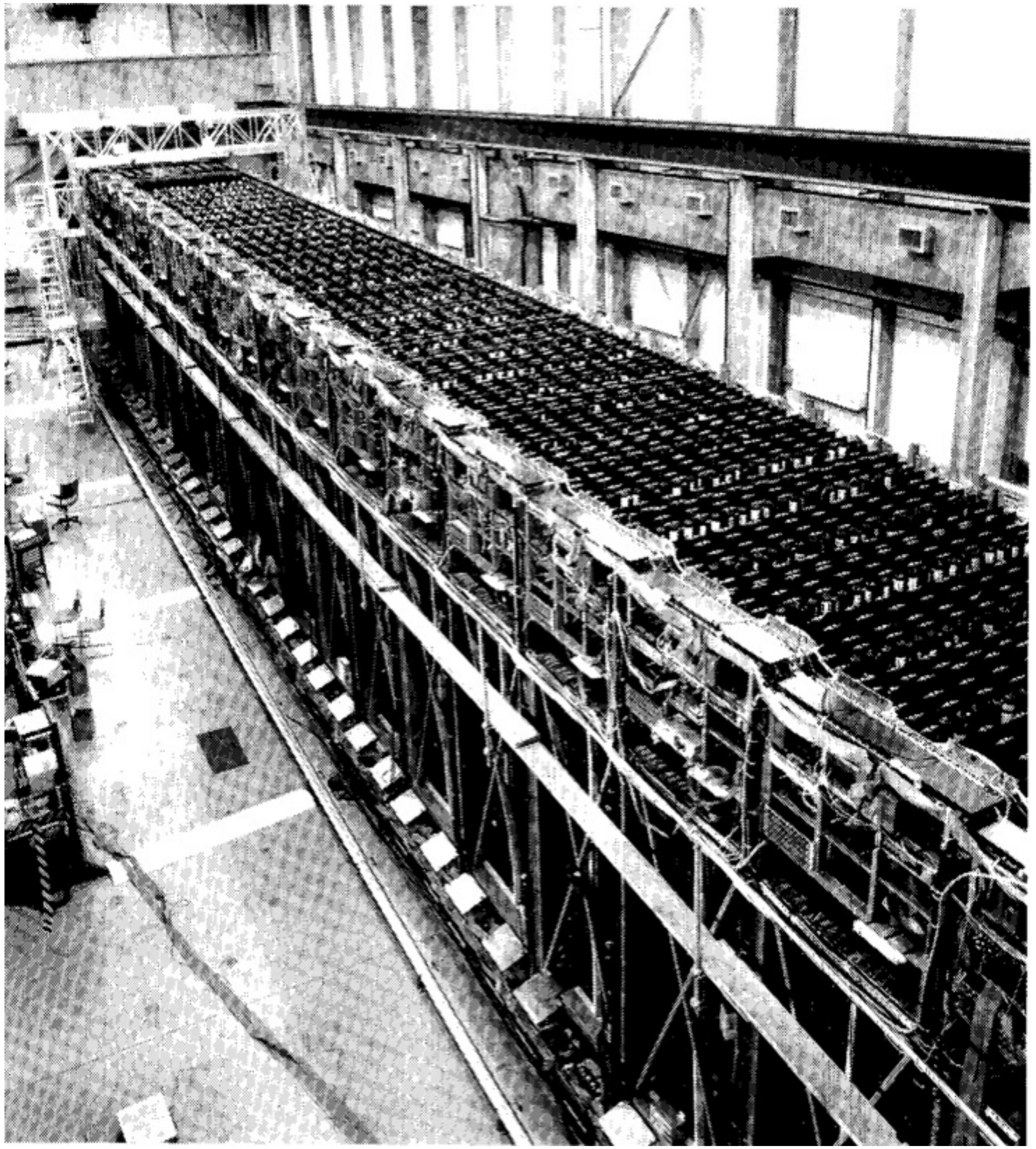
Discovered in 1948. Today, it is one of the best studied processes in history of Particle Physics . It has great importance for the development of the modern electroweak theory.

Inverse muon decay $\nu_\mu e^- \to \mu^- \nu_e$

E_ν > 10 GeV, small cr.sec.



CHARM'80 at CERN, 178 events



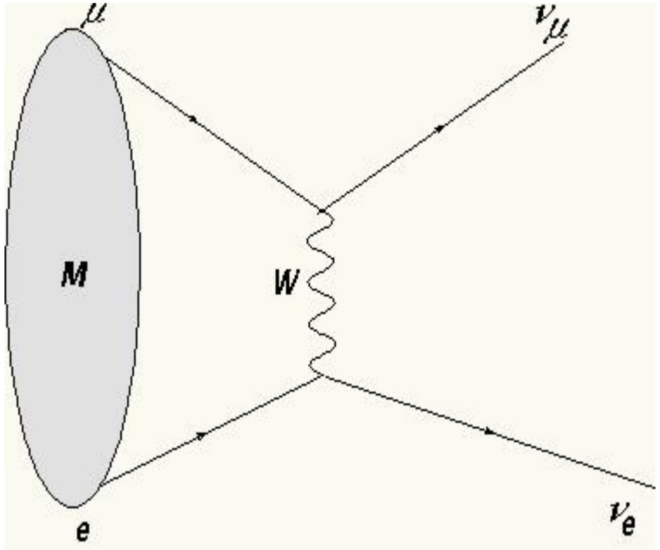
- ν_μCC scattering off e-'s
- pure leptonic process
- no hadronc corrections
- CHARM, CCFR, NuTeV
- test of V-A , LFV, ...

Muonium and its annihilation $\mu^+ e^- \to \nu_\mu \nu_e$

The decay $\mu^+ e^- \to \nu_\mu \nu_e$ has never been tested

- at low energy $\mu^+ e^-$ could form an atomic bound state – muonium (M)
- at the current level of theoretical and experimental precision the only forces that are present in this system are e-m and WI.
- M is bounded by e-m, but can self-annihilate through CC weak interactions: $\mu^+ e^- \to \nu_\mu \nu_e$

$^1S_0 \not\to \nu_\mu \nu_e$; $^3S_1 \to \nu_\mu \nu_e$



Useful for

- tests of QED bound state theory
- measurements of fundamental constants
- searches for symmetries violation: LFV, LV, ..
- probe of new physics: are there new forces in muonium?
- testing gravity with muonium

Rate of $\mu^+ e^- \to \nu_\mu \nu_e$ in the SM

muonium properties can in principle be calculated precisely, due to the purely leptonic nature of muon...

Br ($\mu^+ e^- \to \nu_\mu \nu_e$)	Ref.
$\sim 10^{-10}$	B. Pontecorvo, Zh. Eksp. Teor. Fiz. **33, 549 (1958); Sov.Phys. JETP 6, 429 (1958)**
1.045×10^{-10}	L. Chatterjee, A. Chakrabarty, G. Das, and S. Mondal, Phys. Rev. D **46, 5200 (1992)**
6.6×10^{-12}	P.-J. Li, Z.-Q. Tan, and C.-E. Wu, J. Phys. G **14, 525 (1988).**
6.6×10^{-12}	A. Czarnecki, G. P. Lepage, and W. Marciano, Phys. Rev. D **61, 073001 (2000)**

A lesson from $\mu^+e^- \to \nu_\mu\nu_e$ for heavy quarks annihilation

Modern bound state theory connects decay properties of QED (atomic) and QCD (e.g. heavy q-qbar) systems bound by gauge forces.

Brodsky, Marciano,....

Rate of $\mu^+e^- \to \nu_\mu\nu_e$:

$$\Gamma(\mu^+e^- \to \nu_\mu\nu_e) = 48\pi(\alpha\, m_e/m_\mu)^3\, \Gamma(\mu \to e\, \nu_\mu\nu_e)$$

......Although that effect is tiny ~ 6.6×10^{-12}, it demonstrates an important feature. The two- vs three-body final state gives rise to a very large (48π) enhancement fact. This type of capture effect can be quite important for b-hadron lifetimes where two- body annihilation or scattering can play a significant role.

Marciano'04

In the SM the $\mu^+e^- \to \nu_\mu\nu_e$ decay is strongly enhanced by Coulomb interaction. Combined with other tests of QED bound state theory its measurement would provide a sensitive testing ground for our basic understanding of the QCD q-qbar bound systems.

Testing new physics with $\mu^+ e^-$->invisible, γ`s

Reminder: Z-->invisible decay rate play fundamental role in determination of lepton families number in the SM.

Other searches for invisible decays of (qqbar) bound state systems (motivated by various models of physics beyond the SM) :

Ps at CERN, π^0 , K mesons at E949, η , η `mesons at BES, heavy B meson decays at Belle, BaBAR, BES and decays of Upsilon(1S) resonances at CLEO...

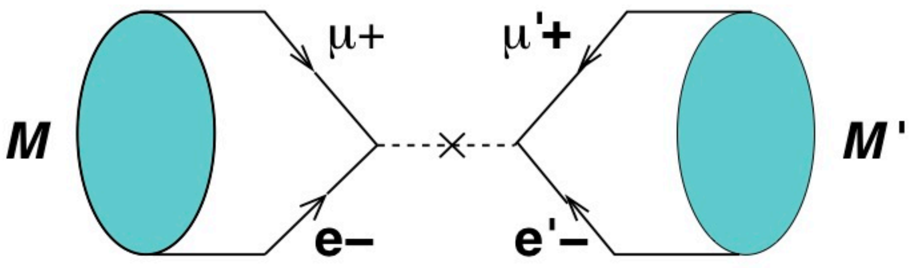
$\mu^+ e^-$ decays

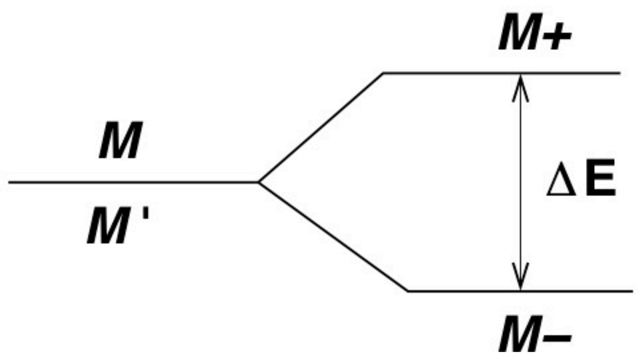
Process	Present limit	Expected limit
μ^+e^--> $\nu_\mu\nu_e$	~< 10^{-5}	~ 10^{-11}, observation
μ^+e^--> (μ^+e^-)` ocsillations	---	~ < 10^{-12}, MMM μ^+e^-->invisible in vacuum
μ^+->invisible	~< 10^{-3}	~ < 10^{-12}, Extra Dim.
μ^+e^--> $\nu\nu$, XX, ...	---	ν mag.mom., light X boson,..
μ^+e^- -> 2,3γ	---	S=0,1states
μ^+e^-->γ+a	---	search for γ-peak
μ^+e^-->γ+invisible	---	

Under Study (last four rows)

$\mu^+e^- \to \mu^{+`}e^{-`}$ oscillations

S.G., N. Krasnikov, V.Matveev 1209.0060





phenomenology is similar to
M-Mbar, Ps-Ps`, n-n`... oscillations

- new mass eigenstates: $M\pm = (M\pm M`)/\sqrt{2}$
- energy splitting: $\Delta E = 1.5\text{x}10^{-12}\ (G_{MM`}/G_F)$ [eV], n=1
- oscillation probability: $P(M\text{-}M`)(t) = 2.56\text{x}10^{-5}\,(G_{MM`}/G_F)^2$
- exp. signature is different from M-Mbar: $\mu^+e^- \to$ invisible decay
- the search must be in vacuum: no collisional quenching, B,E-fields.

Limits on charge nonconserving decays

- τ (e --> inv) > 2.4 10^{24} y DAMA`99
- τ (p --> inv) > 9.2 10^{34} y SuperK`03
- Br(n-->p$\nu\nu$) < 8.0 10^{-27} Solar ν exp.`96
- τ (n --> inv) > 5.8 10^{29} y KamLand`06

No experimental limits for μ and τ,

- Br(μ --> inv)< 5.2 10^{-3} from comparison of G_F and Γ_μ
- Br(τ --> inv)< 1.6 10^{-3} (MuLan at PSI vs (indirect) LEP)

SG, PRD'07

Could be improved by ~9 orders of magnitudes by this experiment.

Principle of measurements

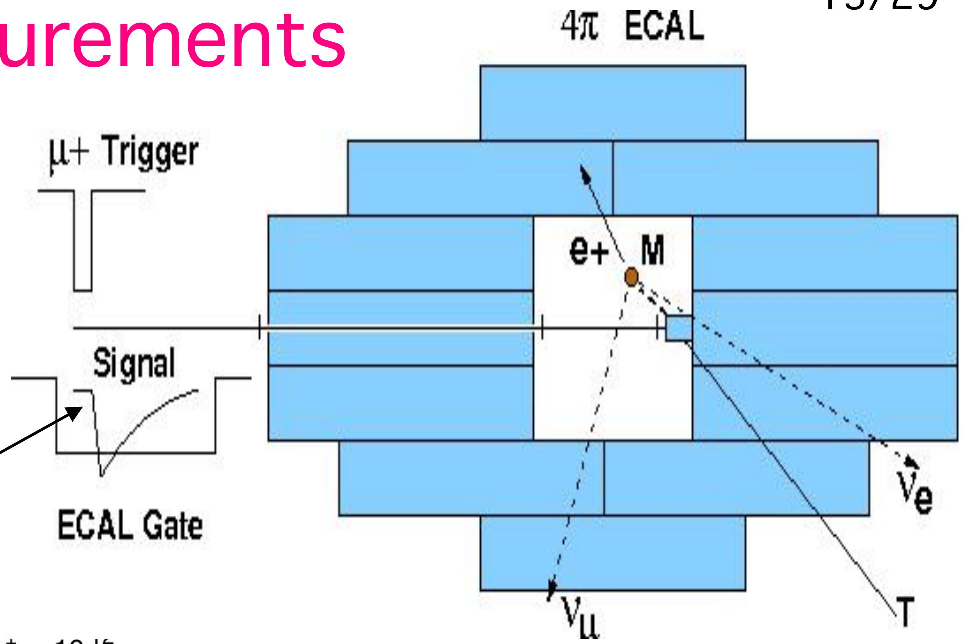
No measurement of neutrino from

$\mu^+ e^- \to \nu_\mu \nu_e$!

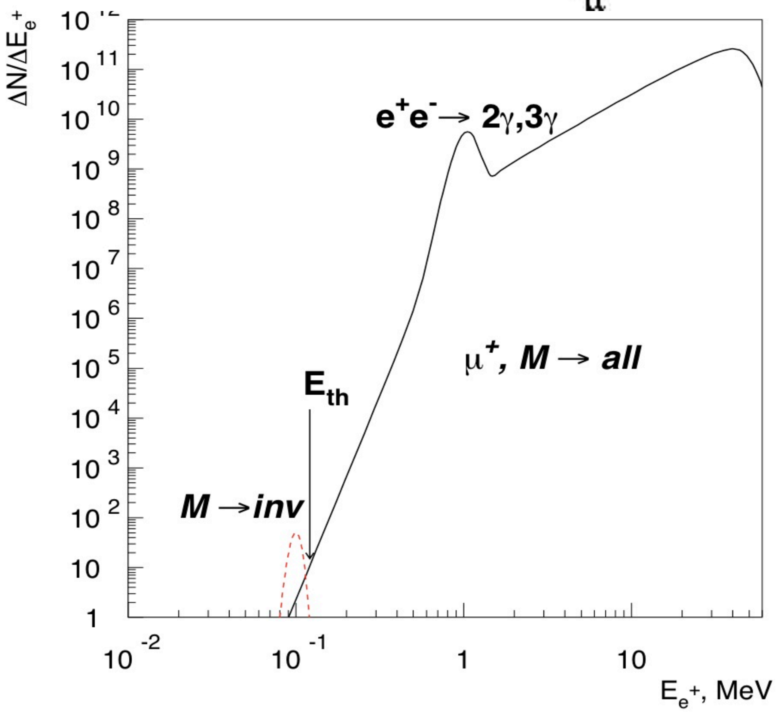
Instead, search for the signal from

$\mu^+ e^- \to$ nothing: invisible final state

Experimental signature: no energy in a hermetic ECAL($E < E_{th}$)



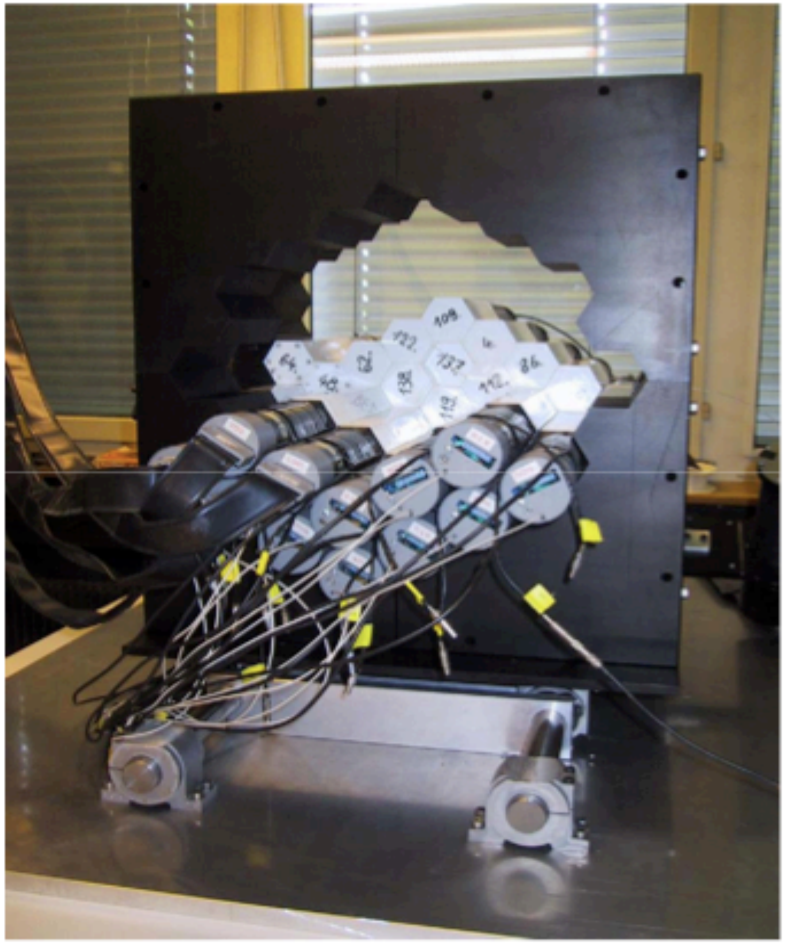
- decays outside the gate: >~50 μs N_μ (~10^{12-13}) vs intensity. L1trigger
- low energy e+ from
  $\mu+ \to e+\nu\ \nu \to e+e- \to 2,3\gamma$:
  E_{th}~100-200 keV for E ~ 1MeV
- ECAL thickness: ~ 20 λ for γ's
- no high-Z dead material:
  $\sigma^\gamma_{ph.abs} \sim Z^5$

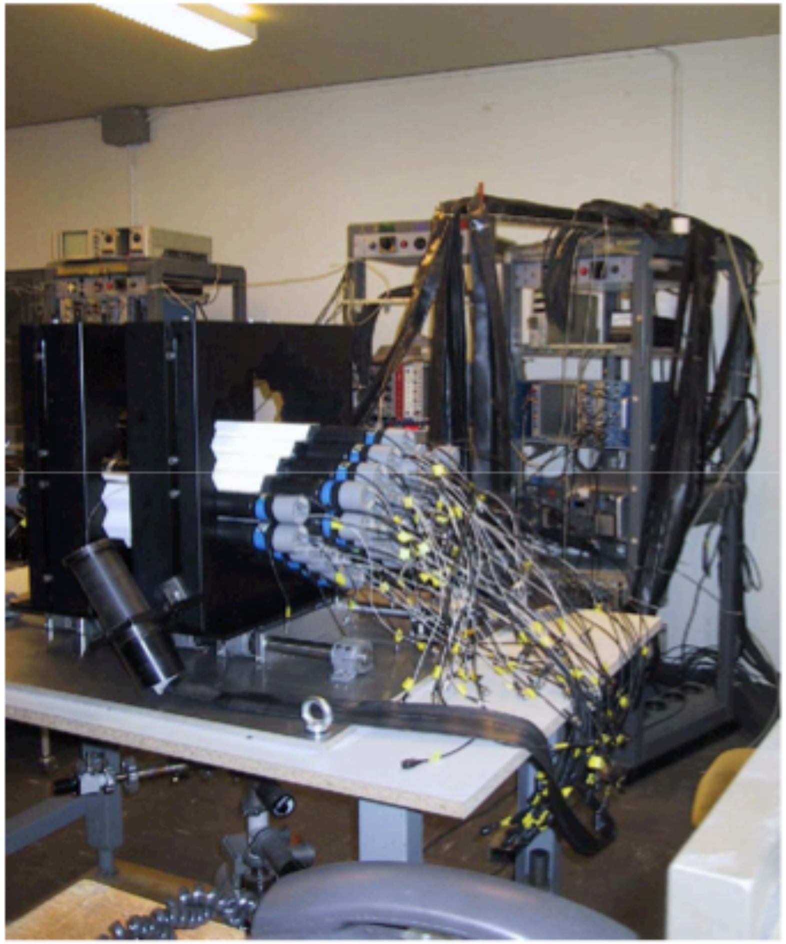


Good example: search for Ps->invisible decays

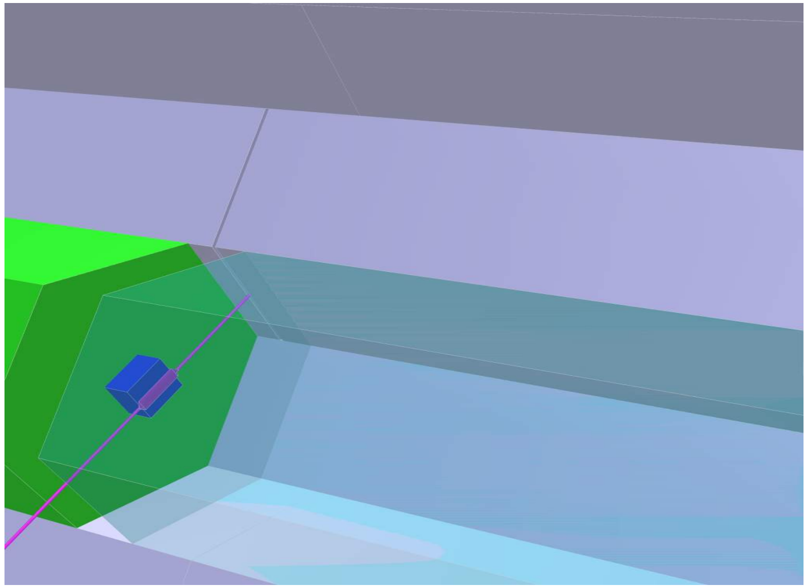
BGO Calorimeter (PSI)

Photograph of the calorimeter (assembling phase)

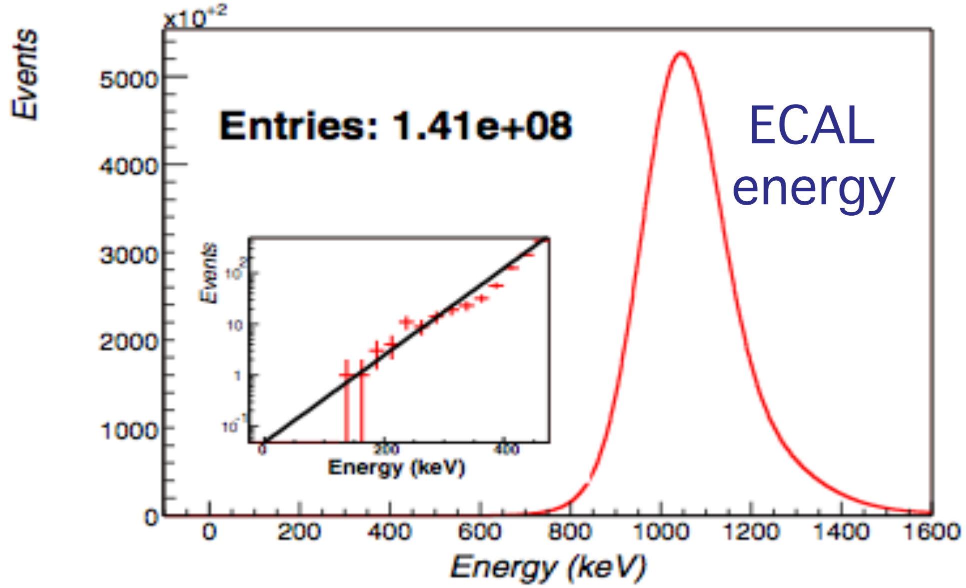


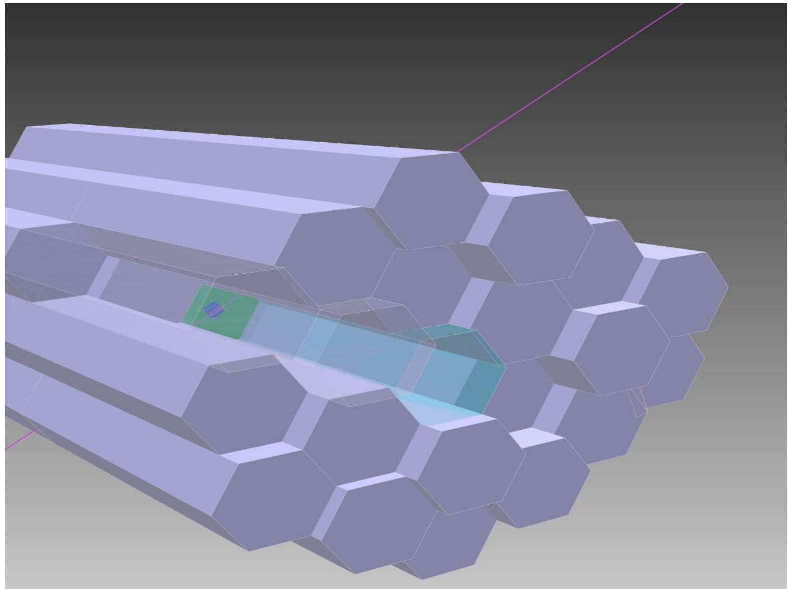


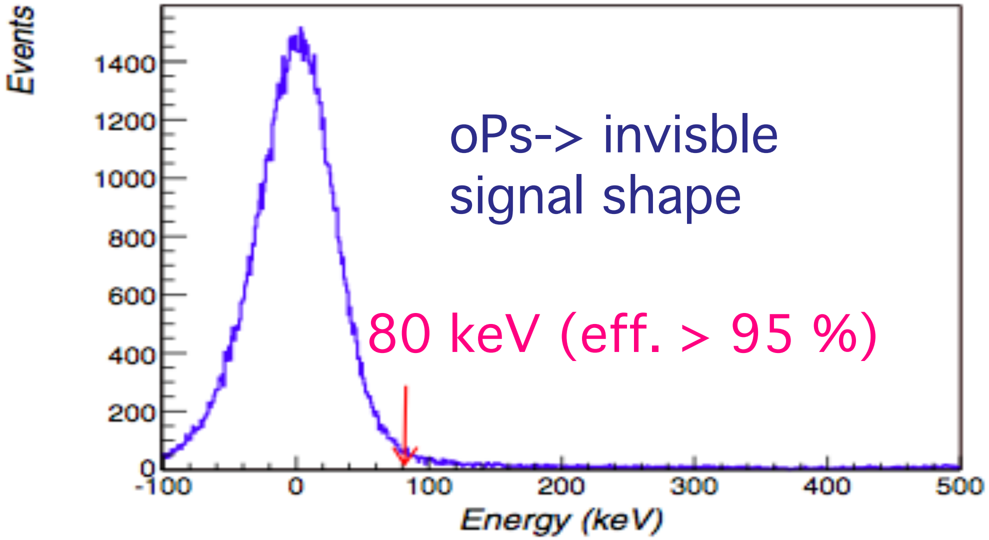
Energy deposition in the ECAL from e^+e^- -> all



A. BADERTSCHER *et al.*







Direct measurements of e+e- -> invisible in the ECAL

PHYSICAL REVIEW D **75,** 032004 (2007)

Improved limit on invisible decays of positronium

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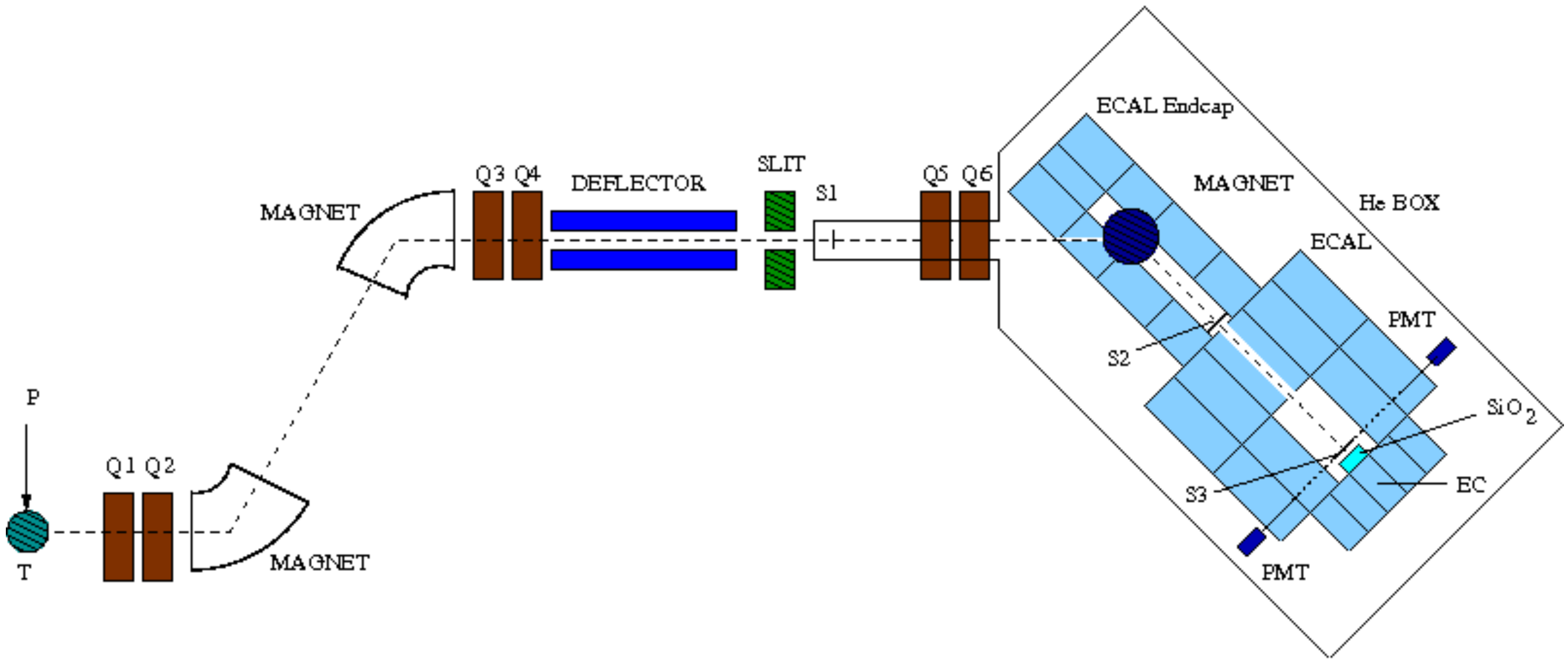
(Received 9 October 2006; published 13 February 2007)

The results of a new search for positronium decays into invisible final states are reported. Convincing detection of this decay mode would be a strong evidence for new physics beyond the standard model (SM): for example, the existence of extra–dimensions, of milli-charged particles, of new light gauge bosons or of mirror particles. Mirror matter could be a relevant dark matter candidate. In this paper the setup and the results of a new experiment are presented. In a collected sample of about $(6.31 \pm 0.28) \times 10^6$ orthopositronium decays, no evidence for invisible decays in an energy [0,80] keV was found and an upper limit on the branching ratio of orthopositronium o-Ps → invisible could be set: Br(o-Ps → invisible) $< 4.2 \times 10^{-7}$(90%C.L.) Our results provide a limit on the photon mirror-photon mixing strength $\epsilon \leq 1.55 \times 10^{-7}$(90%C.L.) and rule out particles lighter than the electron mass with a fraction $Q_x \leq 3.4 \times 10^{-5}$ of the electron charge. Furthermore, upper limits on the branching ratios for the decay of parapositronium Br(p-Ps → invisible) $\leq 4.3 \times 10^{-7}$(90%C.L.) and the direct annihilation Br($e^+e^- \rightarrow$ invisible) $\leq 2.1 \times 10^{-8}$(90%C.L.) could be set.

DOI: 10.1103/PhysRevD.75.032004 PACS numbers: 13.40.−f, 13.40.Hq

probability to lose two photon energy : $P_{2\gamma} \sim 10^{-8}$

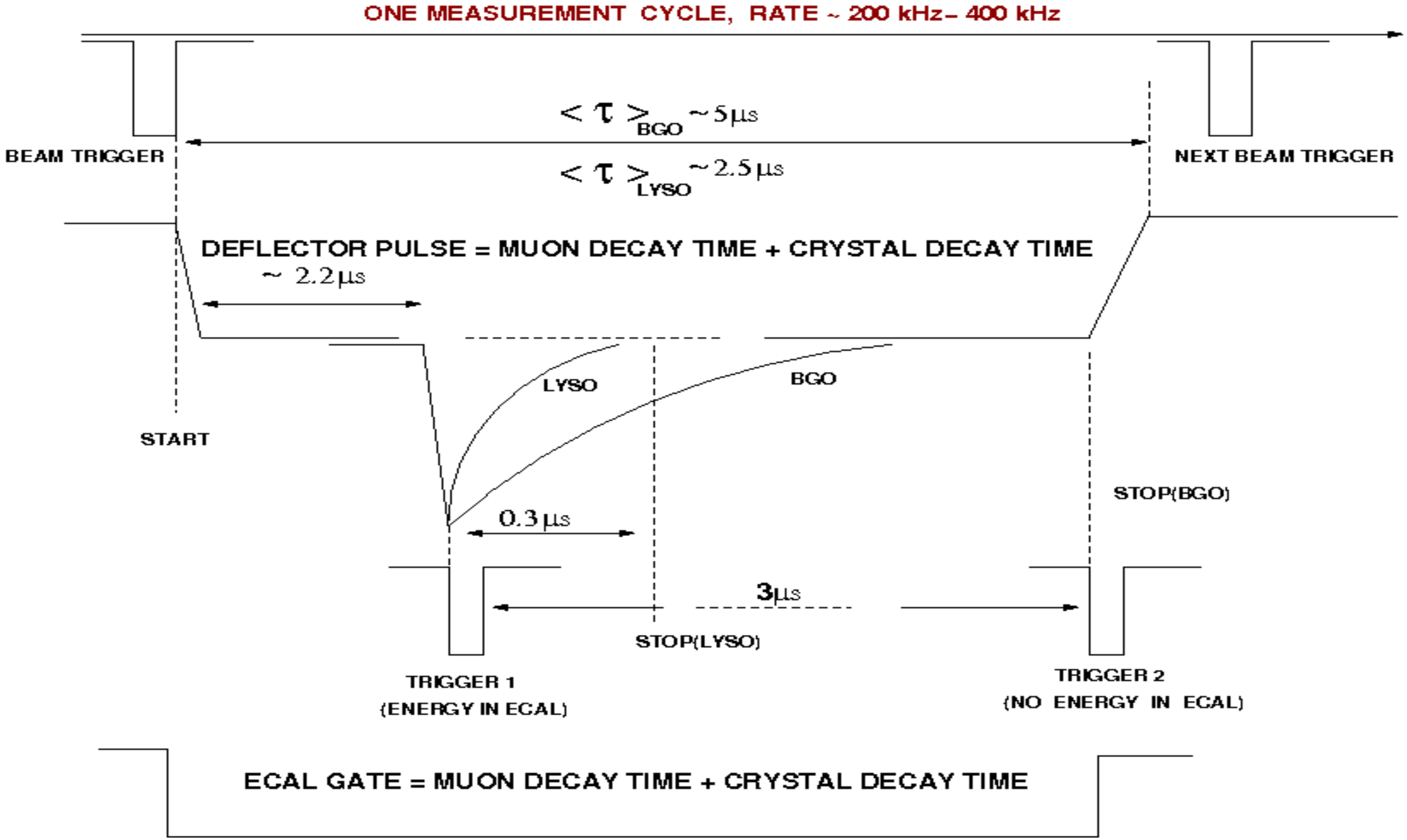
Setup to search for $\mu^+e^- \to \nu_\mu \nu_e$



- muon beamline
- deflector, μ^+ on request
- beam definig counters (μ^+ tag)
- magnet system

- 4π-hermetic ECAL
- ECAL Endcap
- SiO_2 target
- DAQ, electronics

Event sequence



Gate ~60 *μs* is required to avoid muon decays outside the gate for 10^{-12} limitation of beam intensity~$(2\text{-}4)10^5$ *μ/s*

Muon beam

- μ^+ , μ^-
- momentum 30-50 MeV/c, fwmh < 5%
- intensity up to ~300-400 kHz
- beam purity p, e, μ^- , π, .../μ < 10^{-7}-10^{-5} (t.b.c.)
- low emittance (at the entrance to deflector)
- beam spot < 1-2 cm^2

Magnet

- aimed for the ECAL hermeticity and μ+ ID.
- permanent or electromagnet
- B field ~ 1T
- distance between poles ~10 cm

Deflector

- electrostatic type
- effective frequency 300-400 kHz
- external trigger
- pulse duration ~400 ns – 100 mks
- pulse rising/fall time 50-100 ns
- extinction > 95 %
- stability ~ 1 %

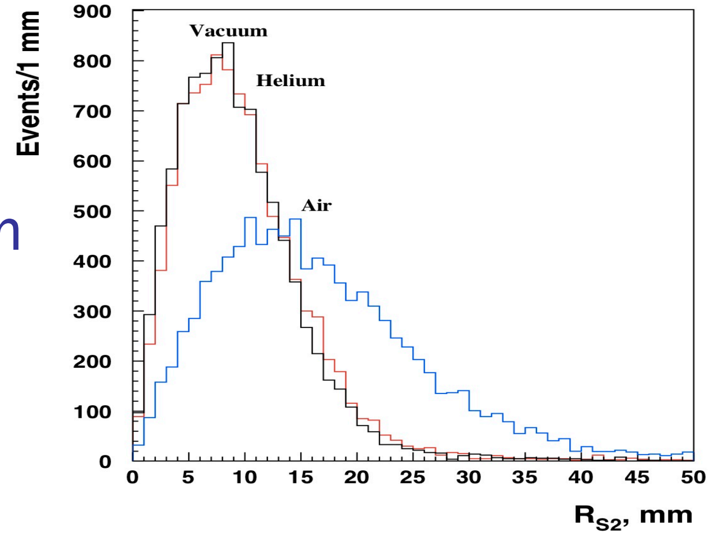
MuLan design at 400 kHz

- MOSFETs overheating
- cooling vs timing?

Currently under consideration at INR
to minimize power small muon beam emittance at the deflector position is required.

Beam counters/simulation.

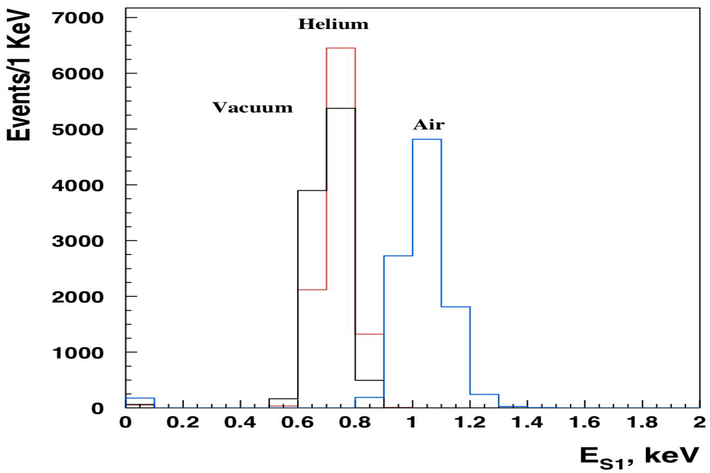
- 0.1-0.4 mm thick scintillatiors
- photoreadout PMT, SiPM, HPD,...
- number of photoelectrons > 10 ph.e.
- time resolution 0.5 ns, tof~0.13 ns/cm



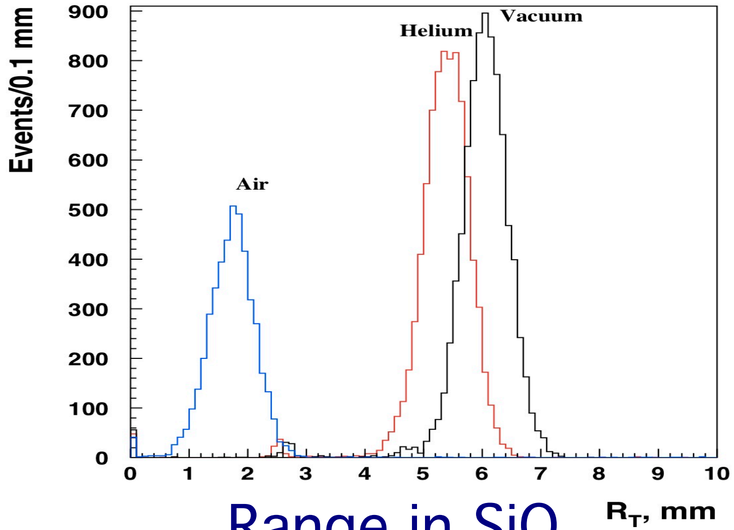
Radius at target position

Target

- target SiO_2 ,10 mm, 0.1 g/cm^3,
- efficiency of M formation 60 % per μ

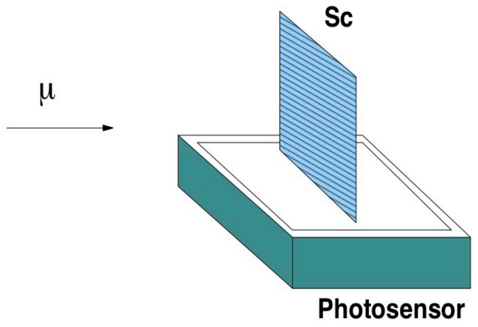


Energy loss in S1

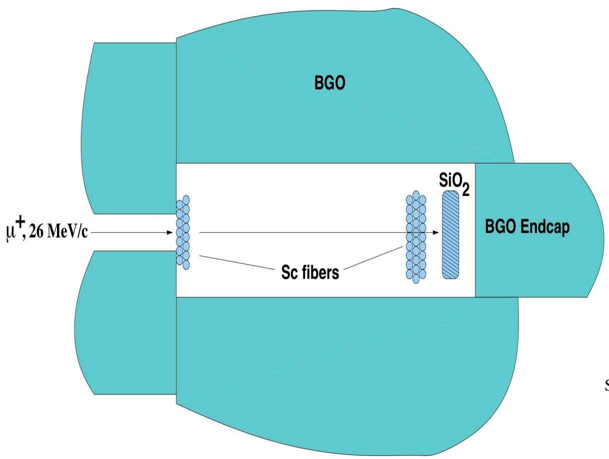


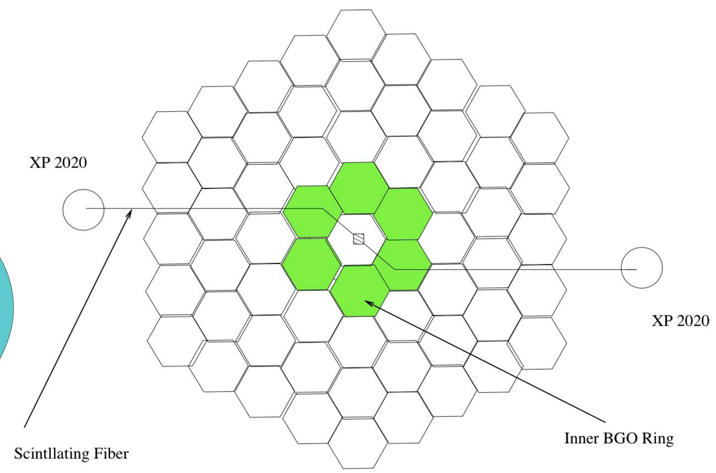
Range in SiO_2

Beam counters arrangement

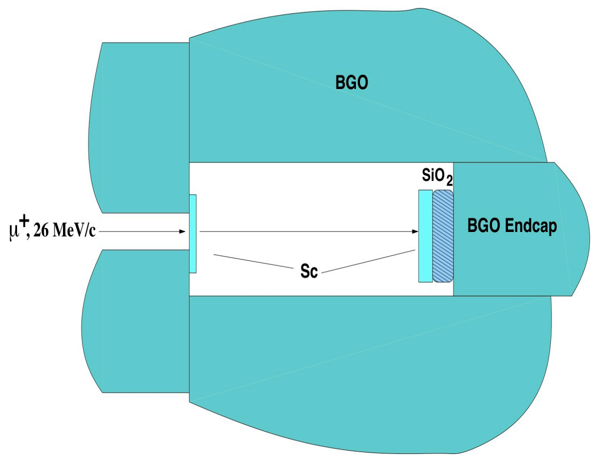


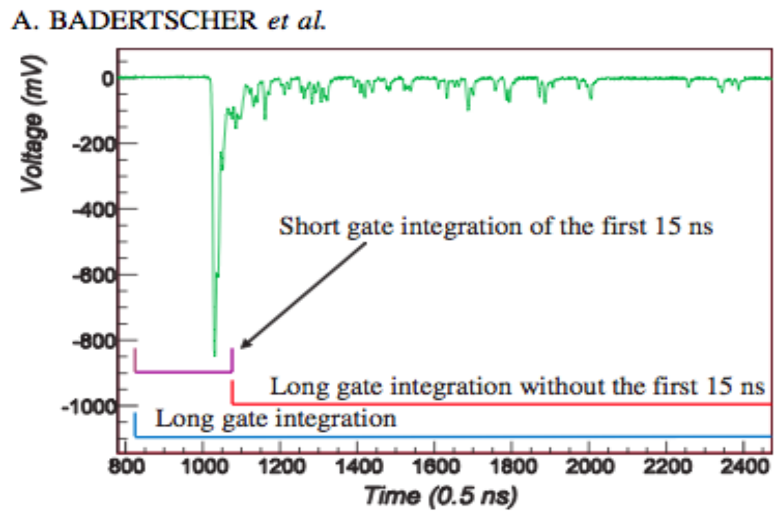
- thickness ~ 0.1 mm
- N ph.e. >10 /mip
- photodetector PMT, HPD, SiPM





- 0.1-0.3 mm sci.fibers
- PMT's outside ECAL
- S shape: reject back-to-back γ`s
- N ph.e. >15 /mip





- EC as a light guide
- Sc and BGO signals differ in shapes

ECAL

- ~100 BGO crystals, ~ 400 kg
- each hexagonal shape diam. 5.6 x 25 cm^3
- energy resolution ΔE/E~ 7-10% at 511 keV
- probability to lose annihilation photons: $P_{2\gamma} \sim 10^{-8}$
- decay time 300 ns
- afterglow < 0.005 % at 6 ms
- photon attenuation length (511 keV) ~1.14 cm
- refractive index 2.3
- not hygroscopic

LYSO (internal crysals)

- light yield a factor 3 higher
- decay time 40 ns
- ....

BGO, LSO and LYSO Crystals

~3x3x20 cm3

R.Zhu's CMS talk

Three categories of background

Beam: fake muons

- μ^+ beam purity: admixture *p, e^+, e^-, μ^-...*
- accidentals: PMT noise, cosmics, ...

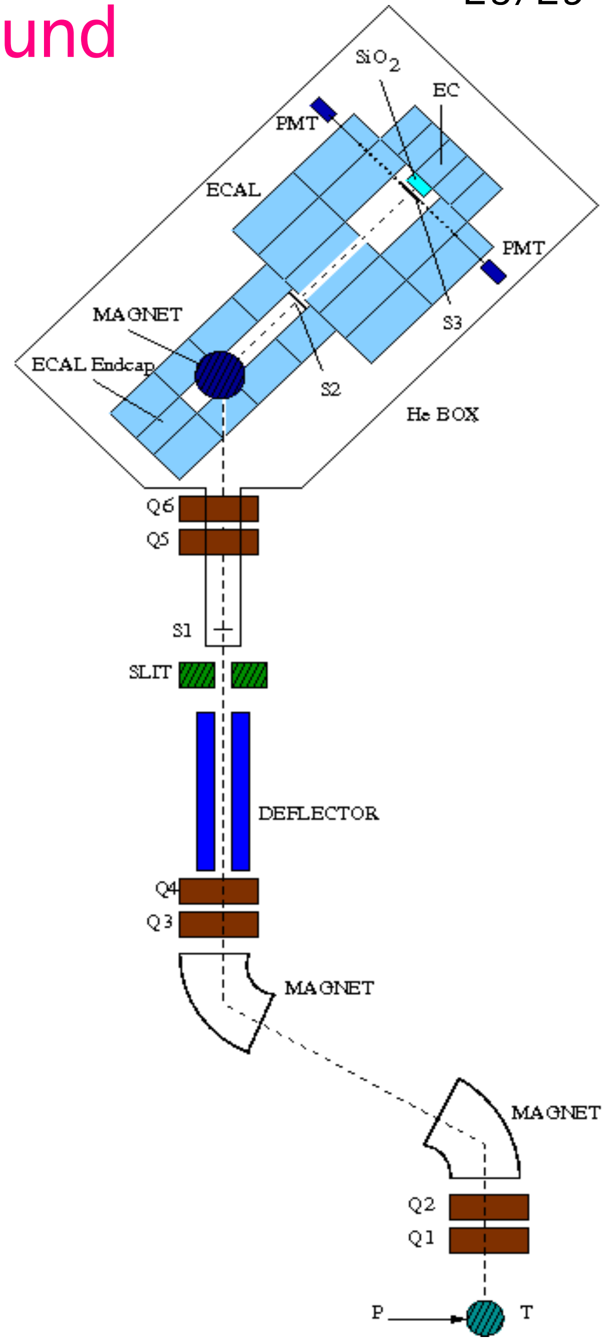
Rejection by energy deposition in S1, S2, S3 and time of flight

Detector: energy leak, absorption, ..

- ECAL hermeticity (thickness, ...)
- energy resolution and threshold
- dead materials (crystal wrapping, target, walls..)
- muon backscattering and migration out
- decay e^+,e^-, γ\`s leak through the entrance
- M leak through the entrance aperture

Physical Background: invisible channels

- e^+\`s in the target, ECAL,.. *-> $\gamma$\`s -> n\`s*
- exitation of long-lived nuclei: e.g. *$(e^+ + e^-) + A \to A'$*
- e^+ weak reactions, e.g. *$e^+ n \to p \nu_e$*, ...



background summary

Source	Expected level	Comment
Fake muons		
Accidentals e- from μ decays Beam purity	$\leq 10^{-13}$ $\leq 10^{-12}$	 time res.0.5 ns, purity < 0.01%
Detector		
Hermeticity: ECAL thickness Dead materials, leak Resolution	$\leq 10^{-12}$	probability to lose $P_{2\gamma} \sim 10^{-8}$. Full Endcap upstr. coverage
Physical		
Nuclei excitations Weak reactions	$\leq 10^{-13}$	cross sect. t.b.c.
Total:	$\leq 2x10^{-12}$	

Estimated sensitivity in Br($\mu^+e^- \to \nu_\mu \nu_e$)

Item	Value	comment
beam momentum	~ 30 MeV /c	
intensity	~ 350 kHz	
data taking period	1 month	
M formation eff.	~ 60 %	triplet state
ECAL threshold	~100 keV	
signal efficiency	~ 90 %	overall
background	≤ 1.5 events	prelim. study
signal	4 events	
Significance for $\mu^+e^- \to \nu_\mu \nu_e$ observation	> 3 σ	after 3 months of runing

Schedule

- **Test period** 2013- 2014. Beam intensity $\sim 10^{4}$.
  Debugging of the detector
  first limit on $\mu^+ \to$ invisible
  Design and fabrication of the deflector.

- Measurement period **2014-2015.**
  - deflector installation and commisioning
  - search for $\mu^+ e^- \to \nu_\mu \nu_e$
  - improved limit on $\mu^+ \to$ invisible
  - search for other decay modes
- Measurement period **> 2015.**
  Search for $\mu^+ e^- \to$ invisible in vacuum. Test of M-M' oscillations.

PSI participation at any level would be of great importance

Summary:

The decay $\mu^+e^- \to \nu_\mu\nu_e$ is a textbook example of the electroweak reaction between first two lepton generations, which, however has never been experimentally tested. In the SM it predicted to be at the level 6.6×10^{-12}, still very small although the decay rate is enhanced by a large (48π) factor due to Coulomb interaction.

Our primary goal is to observe this process. Feasibility study of the experimental setup shows that the sensitivity of the search for this decay mode in Br(μ^+e^-->invisible) at the level of 10^{-12} could be achieved.

The decay rate might be enhanced by non-SM contributions. If the proposed search results in a substantially higher Br(μ^+e^-->invisible) than predicted, this would unambiguously indicate the presence of new physics. A result in agreement with the SM prediction would be

- quite important for our understanding of the bound theory based on universal principles of gauge symmetry, which connect decay properties of QED-bound states to those of heavy quark-antiquark systems bound by the QCD gauge force. It provides a sensitive testing ground for this theory.

- a theoretically clean check of the pure leptonic bound state annihilation through the charged current weak interactions, which place constraints for further attempts beyond the SM.

Overall, the experiment would be complementary to other tests of bound state theory and searches for new physics with muonium.

Backup Slides

Hidden sector

Extentions of the SM that suggests the existence of so- called "hidden" sectors consisting of $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ singlet fields. Sectors of WIMPs that do not interact, but coupled to SM by gravity and possibly by other very weak forces. Could be light.

Mirror Matter Models (MMM)

Great mistery: why only left-handed fermions feel week interactions?
Wu et al.'56: decays of polarized $^{60}Co \to {}^{60}Ni\ e^- \nu$. Another
LRSM model (parity at high energy, W_R, N), but no indication at LHC.

- old idea: Nature is intrinsically L-R symmetric with L-R particle properties exchanged: V-A->V+A
  SM fermions and gauge bosons are accompanied
  by identical mirror partners. MM is a good candidate for DM
- ordinary-mirror particles interactions: h-h\`, $\gamma$-$\gamma$\` ν-ν\`,
  interactin between neutral particles allowed: n-n\`, oPs-oPs\`, ...
  see: L.Okun hep-ph/0606202

MMM effects:

- Higgs mixing

Ignatiev, Volkas ’01; Barbieri et al. ’05, Wilczek’ 07, Li et al. ‘07.....

- γ-γ` mixing

Ps-Ps` Glashow ‘86, SG ‘95, Foot, SG ’01; Atoyan et al. ‘89, Mitsui et al. ‘95, Badertsher et al. 07

- n-n` oscillations

Berezhiani, Bento ‘05; Pokotilovski ‘06, Ben et al.(PSI) ‘07, Serebrov et al. (PNPI) ‘07, Mohapatra et al. ‘05.

- dark matter interaction

DAMA ’05; DAMA/LIBRA ‘07, Foot ‘01-07; Ignatiev,Volkas’03, Mitra’03-06,...

- ν-ν` mixing

Berezhiani, Mohapatra ‘95, Foot, Volkas ’00; Mohapatra, Nasri ‘05

- cosmology

Blinnikov, Khlopov’82,83, Khlopov’91,00, Berezhiani’95-08, Ciarcelluti’03-05,....

- millicharged particles

Holdom ’85; Ignatiev ‘91; Gninenko et al.’07....

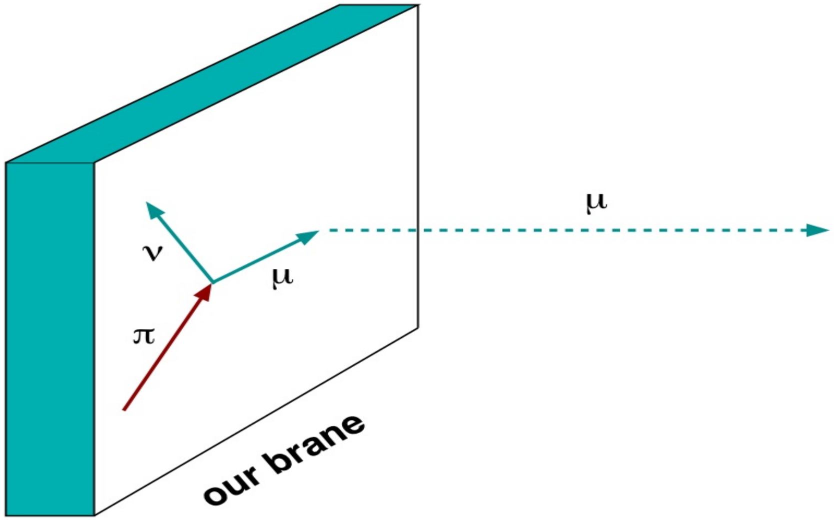
- anomalous events

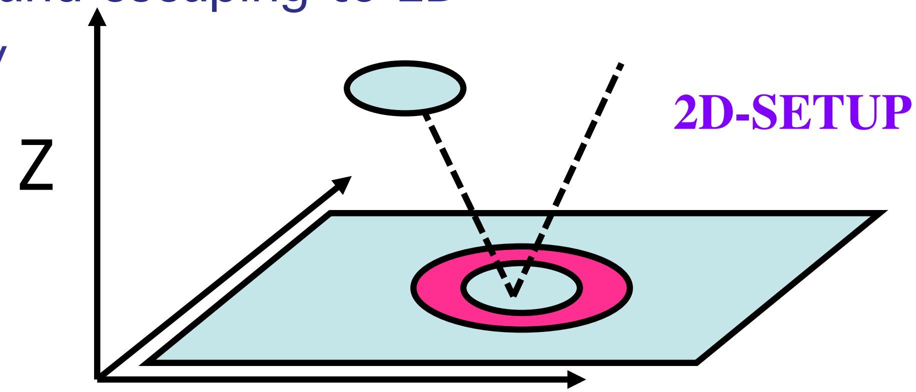
Foot, Silagadze’01-05, Foot,Mitra’02-03,...

Muon tunneling to Extra Dimensions: Is the electric charge conserved in brane world?

Mass-energy initially located at our brane is unstable in some scenarios. Particles allow tunneling off our brane and escaping to ED

Experimental signature: a → invisible decay





Charged lepton escaping rate from the brane- strong mass dependence. (too many paramters to make even an order-of-magnitude prediction)

Putting this result first to Eq. (5) and then to Eqs. (4) and (3) and taking the integral over the masses of bulk modes one gets

$$\Gamma = \beta k \left(\frac{m_e}{M_W}\right)^4 \left(\frac{m_e}{k}\right)^{2\nu-1}$$

where the numerical coefficient β is equal to

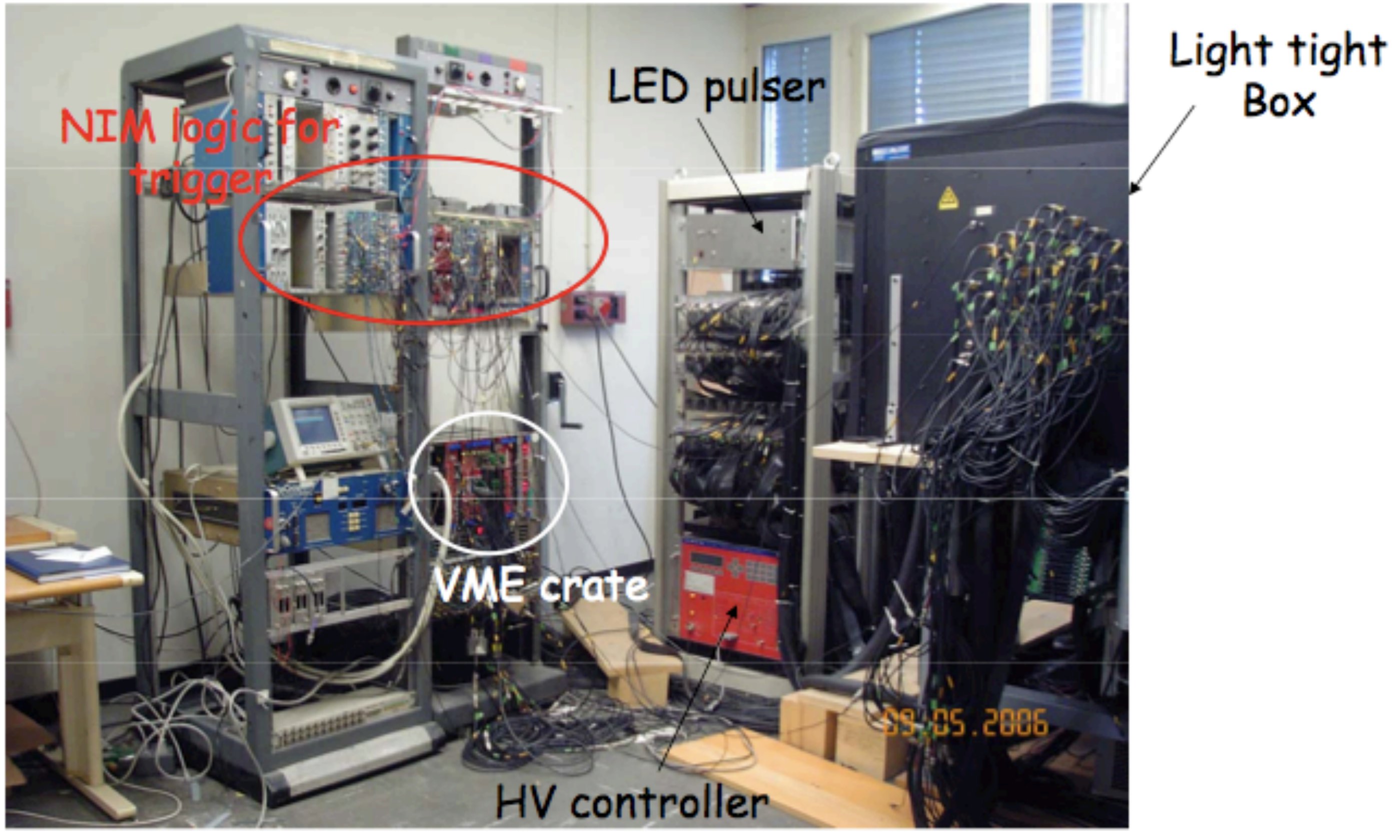
$$\beta = \frac{c g_2^2}{16\pi n\nu(\nu+2)(\nu+3)}$$

Generic property of a class of models with large ED leads to low energy effects complementary to LHC: Electric charge is not conserved in our brane (even for m_γ=0 !), but conserved in multi-D space

S.L. Dubovsky, V.A. Rubakov, P.G. Tinyakov JHEP 0008:041,2000.

Good example: a search for Ps->invisible decays

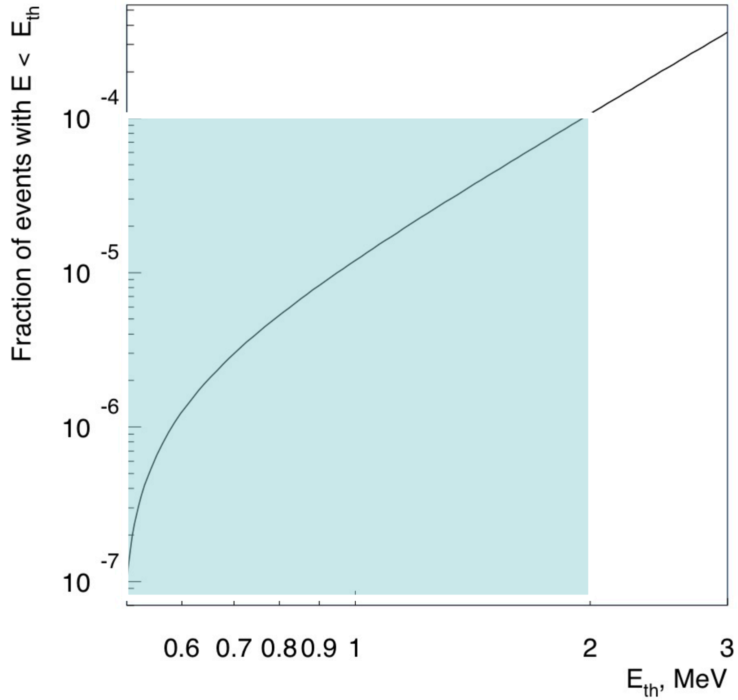
Picture of the lab

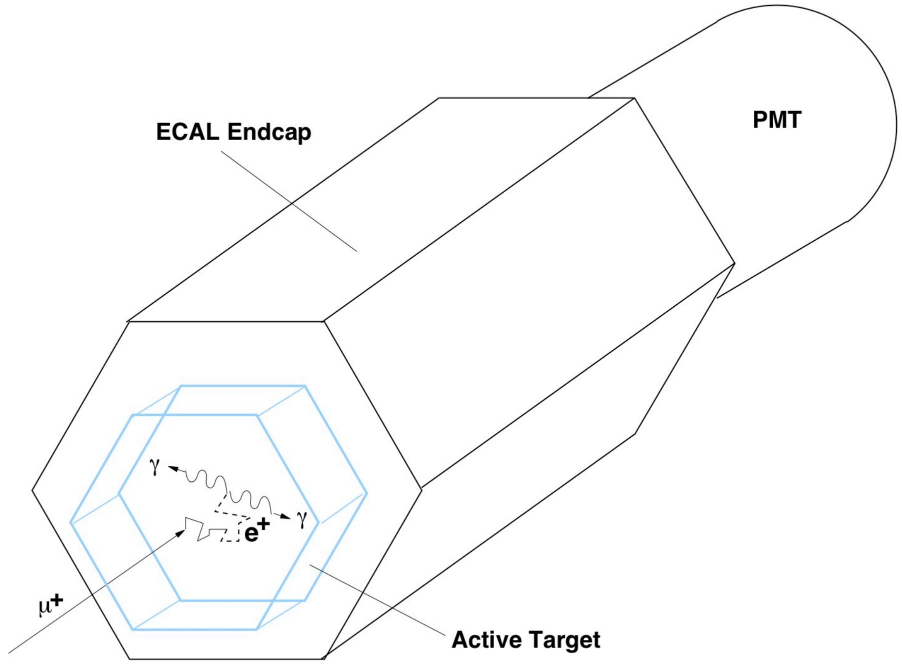


Estimated sensitivity

Process	Expected limit	Present limit
μ^+e^--> *invisible*	~ < 10^{-11}	~ < 10^{-5}
μ^+->*invisible*	~< 10^{-12}	~ < 10^{-3}
μ^+e^--> (μ^+e^-)\` ocsillations	G\`<10^{-5}	—-
μ^+e^- -> 3γ	~10^{-10}	—-
μ^+e^-->γ+*a*	~< 10^{-8}	—-
μ^+e^-->γ+*nothing*	~< 10^{-7}	—-

Low energy e+'s stopped in the target





- μ- -> e-ν ν is invisible if $E_e < E_{th}$ e.g., E_{th} = 2 MeV, $\Delta\Gamma_\mu / \Gamma_\mu \sim 10^{-4}$
- μ+ -> e+ν ν is always visible due to annihilation e-e+ ->2,3γ E_{min} = 1 MeV >> E_{th} ~100 keV

To minimize absorption - as low as possible density and mass of the target is crutial. ($\sigma^{\gamma}_{ph.abs} \sim Z^5$ -> SiO_2, ~0.1 g/cm^3)