Search for dark sector physics in missing-energy events

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Outline

- Introduction
- Direct search for the A´->invisible decay
- First results (preliminary)
- Physics prospects
- Summary

Motivation

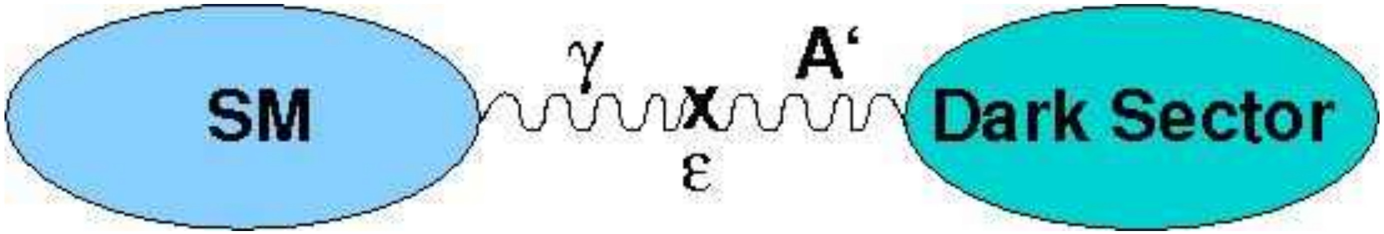
- Dark Matter (DM) puzzle:
  What makes up most of the Universe's mass?
- LHC Run I: no DM candidates so far.
  LHC Run II: focus on searching for “heavy” new physics.
- Various models for DM motivate “light” new physics that could be observed in lower energy experiments.

One possibility is dark sector of SM singlet fields, coupled to ordinary matter by gravity, and possibly by other very weak forces. Searches for such dark forces and their mediators provide an additional way to solve the DM problem.

Growing activities of high intensity/sensitivity experiments at sub-GeV scale, e.g. many in Jlab, SHIP at CERN, ….

The A´

Okun, Holdom'86 ..



- extra (broken) U(1)´, new massive boson A´(dark photon)
- $\Delta L = \varepsilon F^{\mu\nu} A'_{\mu\nu}$ - kinetic γ-A´mixing , ε - coupling strength
- natural coupling $\varepsilon \sim 10^{-4} - 10^{-3}$
- A´ could be light: e.g. $M_{A'} \sim \varepsilon^{1/2} M_Z$
- new phenomena: γ-A´oscillations, LSW effect,... or A´decays:

i) $A' \to e^+e^-, \mu^+\mu^-$, hadrons,..

ii) A´ → invisible if $M_{A'} > M_{DM}$ and $\alpha_{DM} >> \varepsilon$. Can explain: $(g-2)_\mu$, hint on 17 MeV A´, astrophys. observations, ...

Large literature, many new theoretical and experimental results

The P348 Collaboration, timeline

Reasearch program

Searches for sub-GeV Z`, NHL,... coupled to e, μ, q, by using New method: active beam dump combined with missing-energy technique.

PREPARED FOR SUBMISSION TO SPSC

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

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

Proposal to search for the A´->e+e- and A´-> inv decays

December 6, 2013

[1] Contact person, Sergei.Gninenko@cern.ch

Dec'13 – proposal to SPSC

Apr'14 – recommen.for tests

Apr.'14 – March'15 - design, production, delivery at CERN

March -Sept'15 – assembly, installation, commisioning

Oct'15 – 2 w test run

Jan'16 – recommended to RB for approval as a SPS experiment

March'16 - final approval?

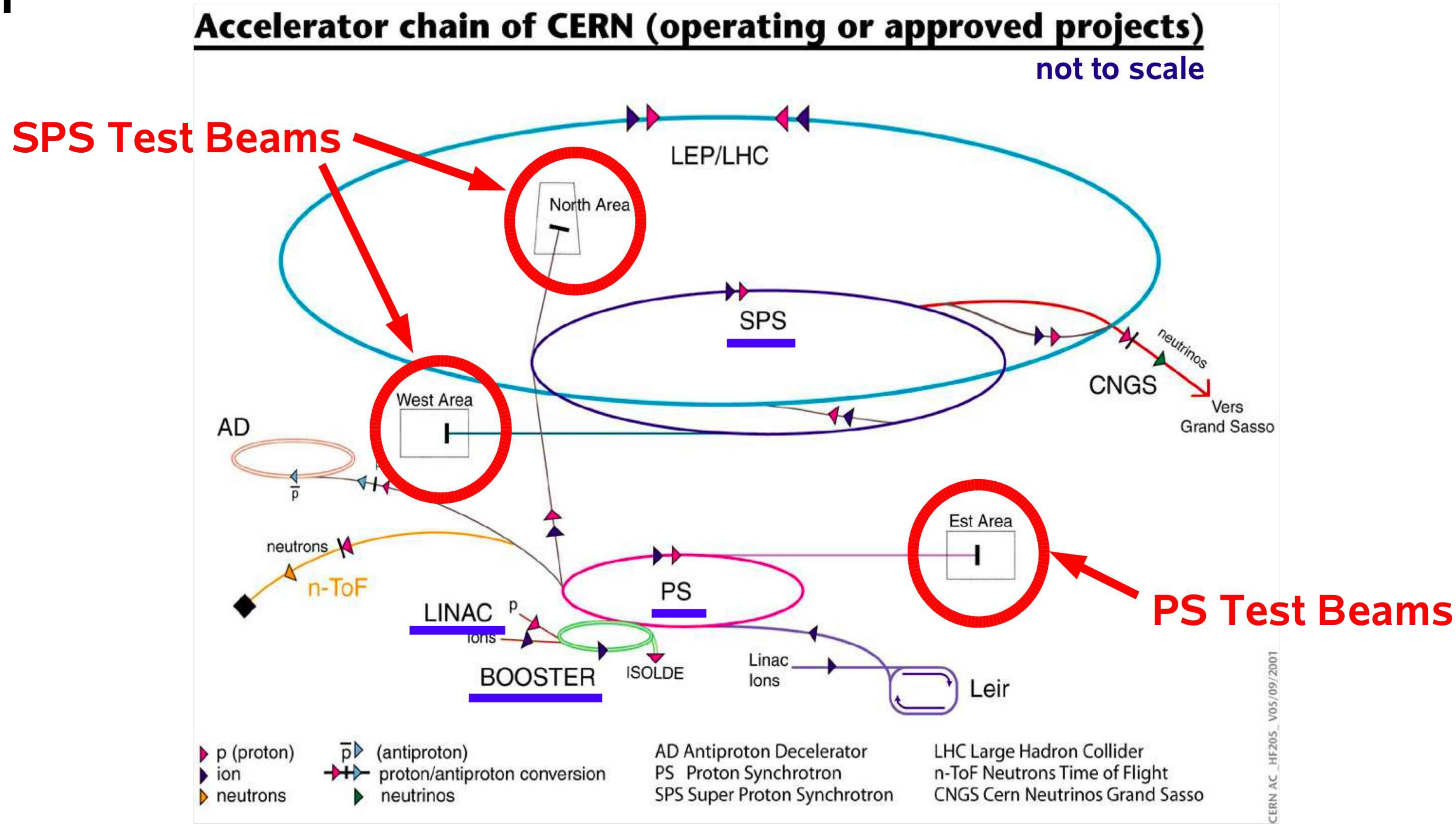
if yes, P348 -> NA64.

July, October'16 - 2 beam runs

Currently ~30 members from Chile, Greece, Germany, Russia, South Korea, Switzerland.

Search for A´-> invisible decay

Test Beams at CERN

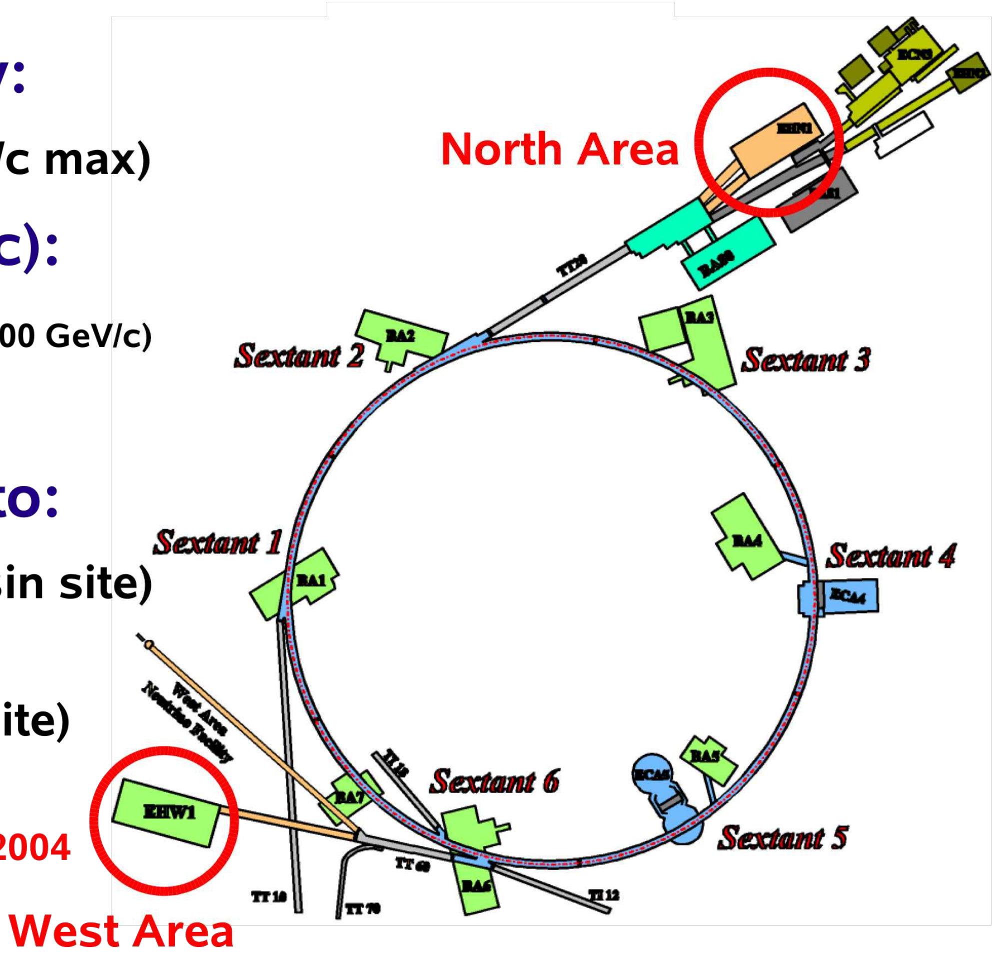


Test Beams at CERN

Michael Hauschild, LCWS04, Paris, 22-Apr-2004, page 1

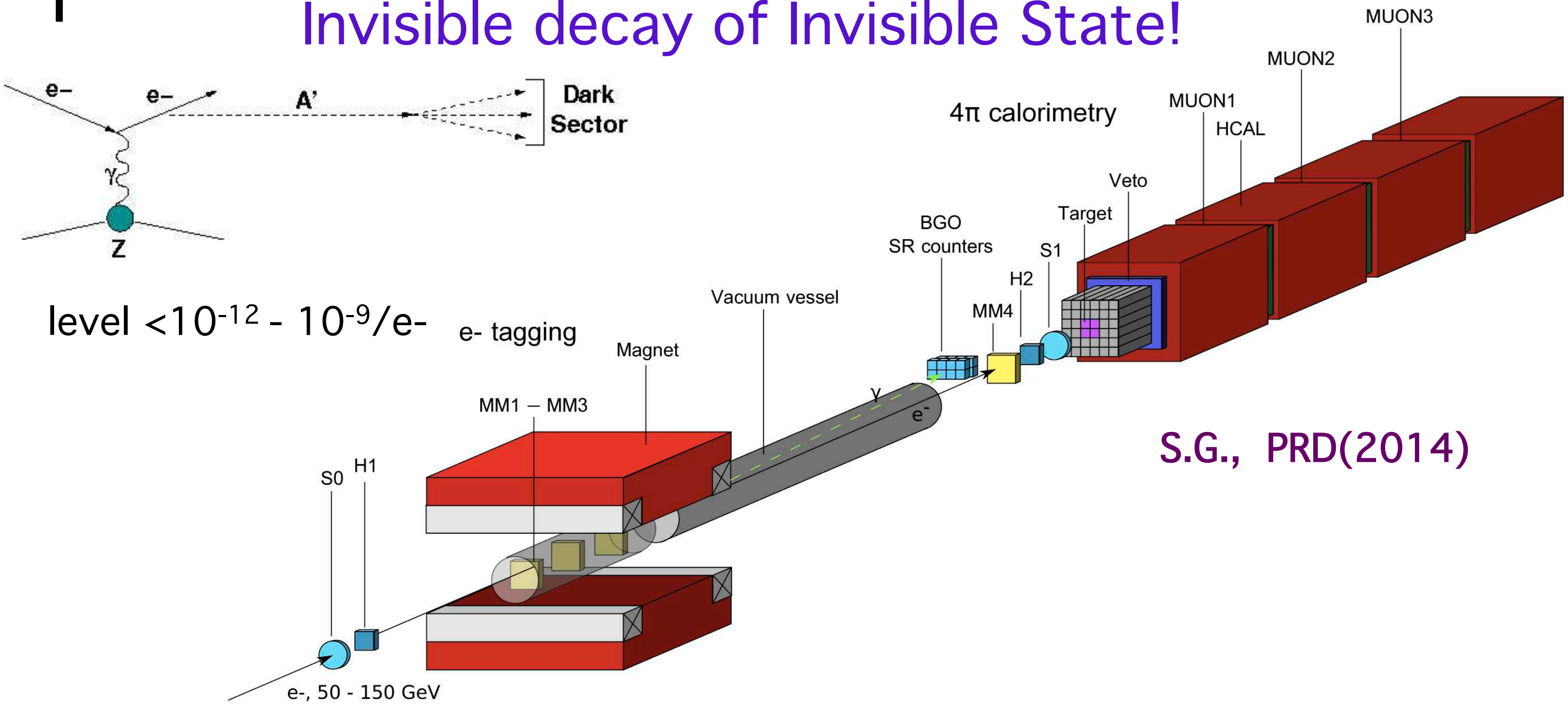
SPS Layout

- **SPS beam energy:**
  - 400 GeV/c (450 GeV/c max)
- **Spill (at 400 GeV/c):**
  - 4.8 s spill length (at 400 GeV/c)
  - 1 spill every 16.8 s
- **Beam extraction to:**
  - North Area (Prevessin site)
    - physics + test beams
  - West Area (Meyrin site)
    - test beams only
    - will be closed end of 2004



Direct Search for the A´->invisible decay at CERN SPS

Invisible decay of Invisible State!



level <10^{-12} - 10^{-9}/e-

S.G., PRD(2014)

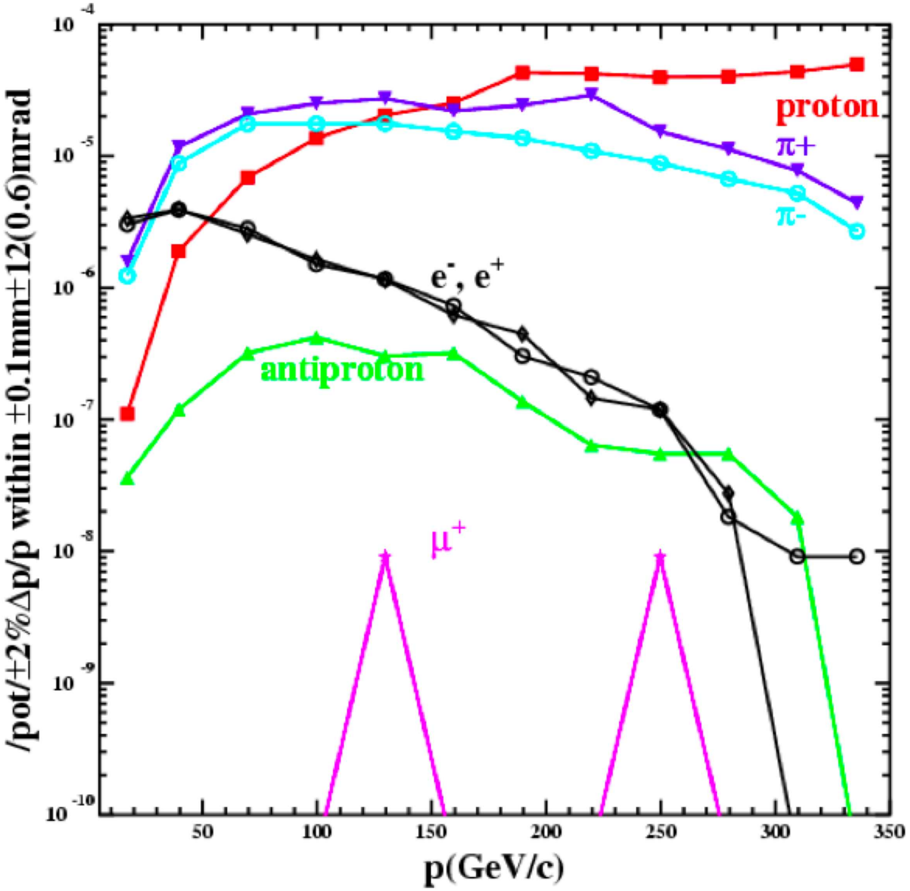
3 main components :

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

Signature:

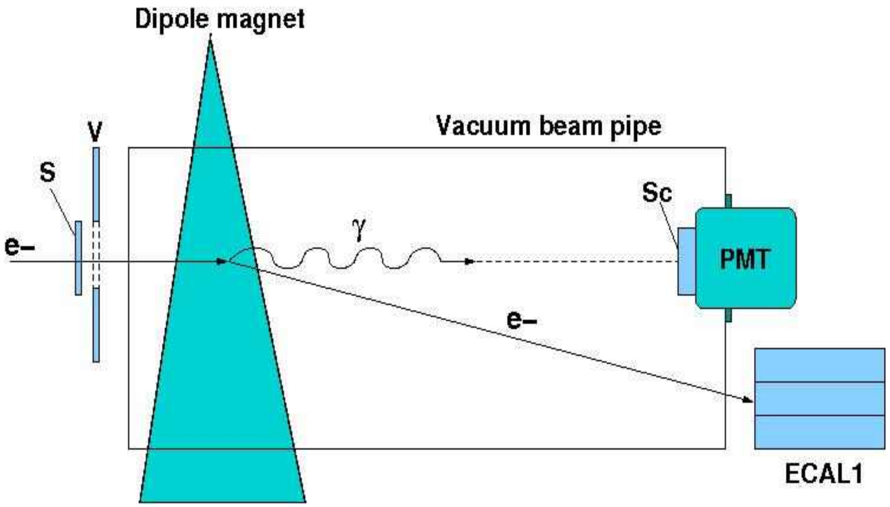
- in: 100 GeV e- track
- out: < 50 GeV e-m shower in ECAL
- no energy in the Veto and HCAL
- Sensitivity ~ ε^2

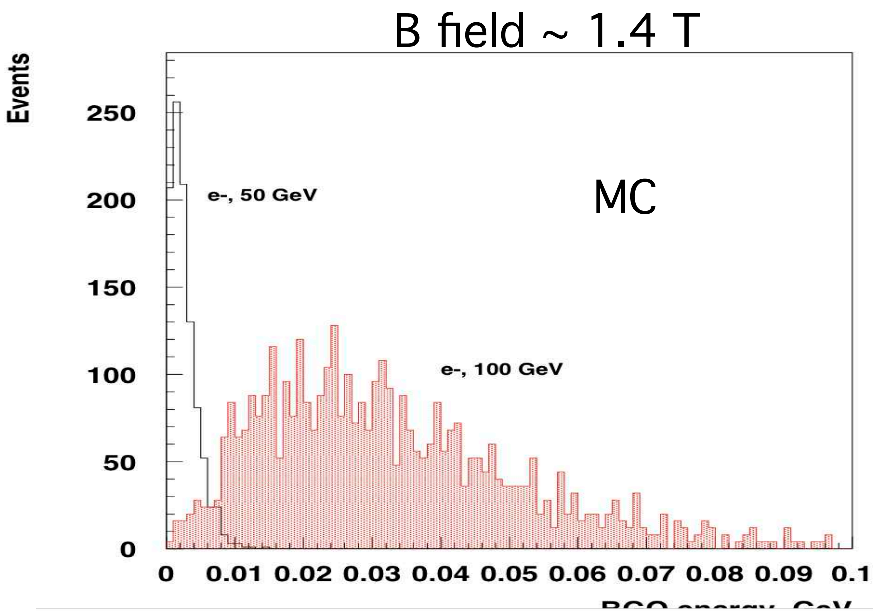
H4 beamline

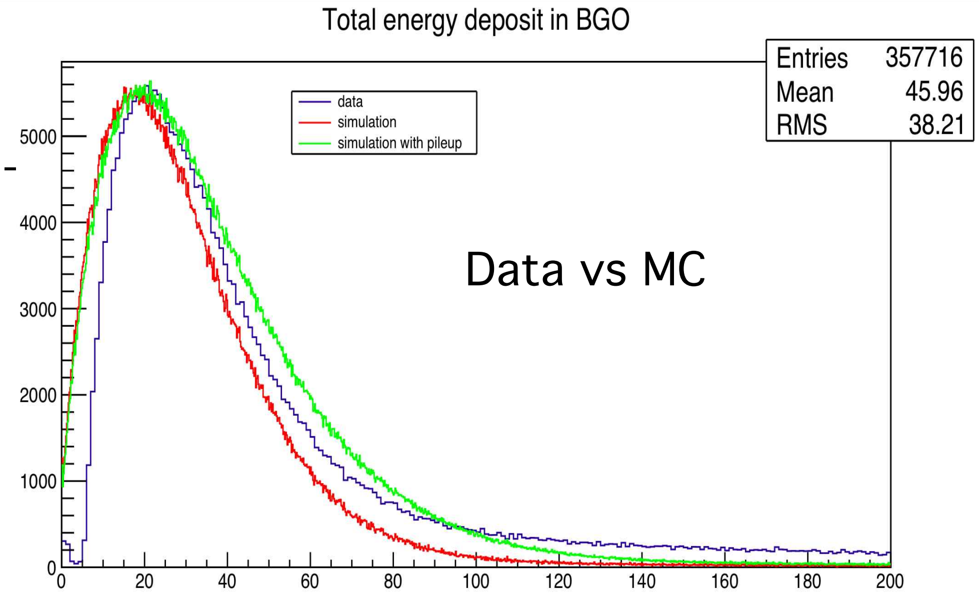


- e- , I_{max} at ~ 50 GeV, Now tuned to ~100 GeV
- for 3–4 10^{12} pot/spill, I_{max} ~ 10^6 e^- /spill
- duty cycle is ~ 0.25
- ~10^{11} e^- /month additional tunning by a factor 2–3 ?
- beam spot ~ cm^2
- hadron admixture < 1 %

Tagging of e-`s with SR photons







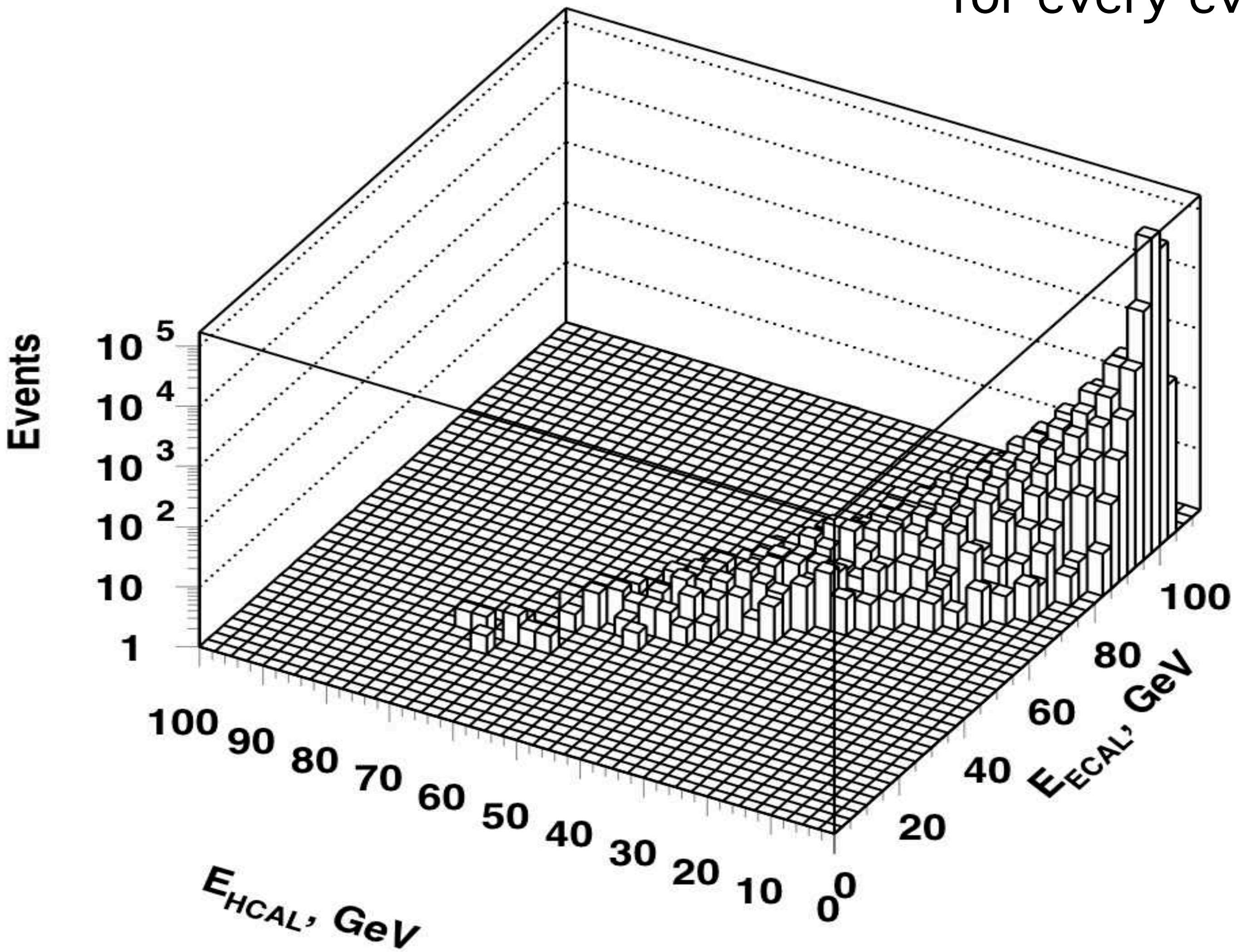
BGO crystal for SR detection:

- $<\Delta E> \sim E_0^3$, ~1(50) : 8(100) GeV e^-
- B field~1.4 T, max1.8 T
- $<\Delta E>$~30 MeV/100 GeV e^-
- E_γ^{min} ~1 MeV ; n_γ ~10
- $(\hbar\omega)_\gamma^c$ ~10 MeV

Response to eZ->eZ+X in (E_{HCAL};E_{ECAL}) plane

GEANT4

SM: $E_{ECAL}+E_{HCAL} = E_0$ for every event

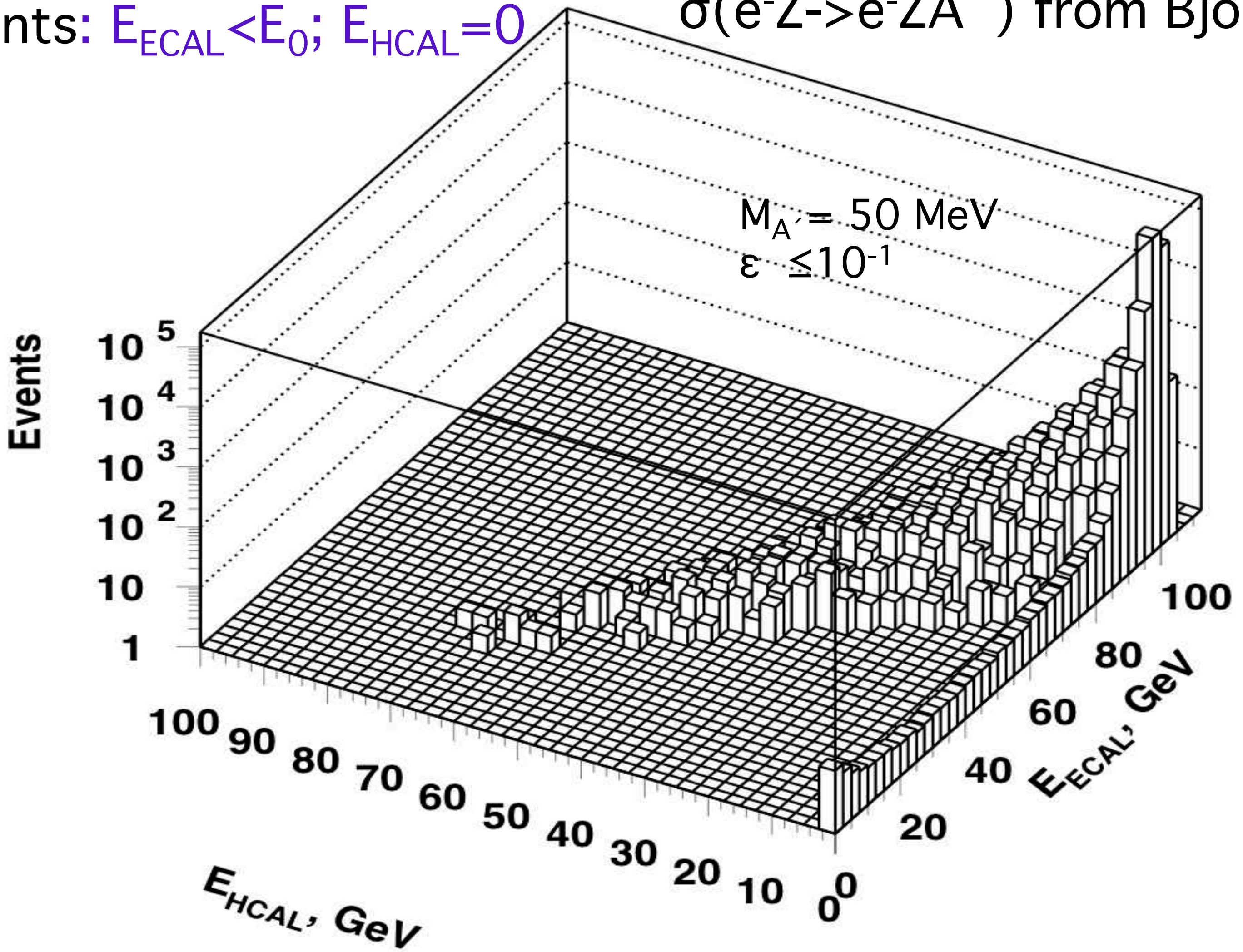


Signature for eZ->eZA´

SM events: $E_{ECAL}+E_{HCAL} = E_0$

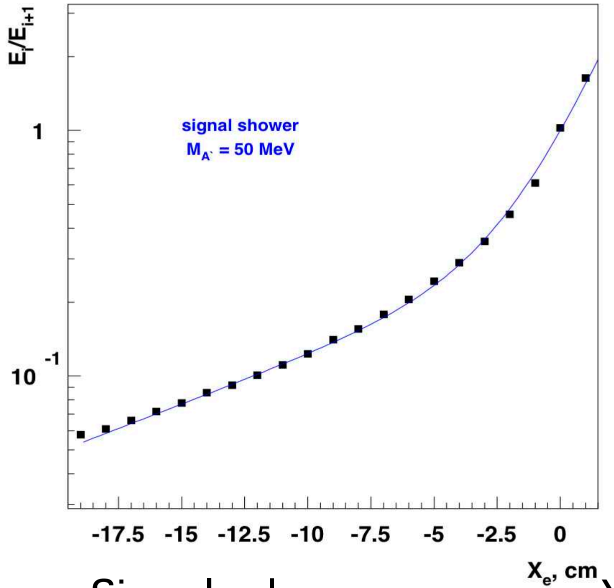
A´events: $E_{ECAL}<E_0$; $E_{HCAL}=0$

GEANT4+code for A´emission in the process of e-m shower development $\sigma(e^-Z\to e^-ZA')$ from Bjorken et al.`09

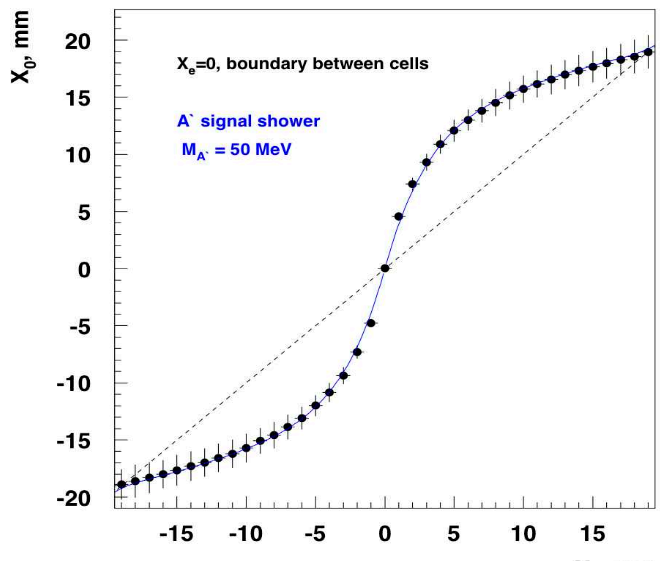


ECAL response to eZ->eZA´ (Geant4+A´emission)

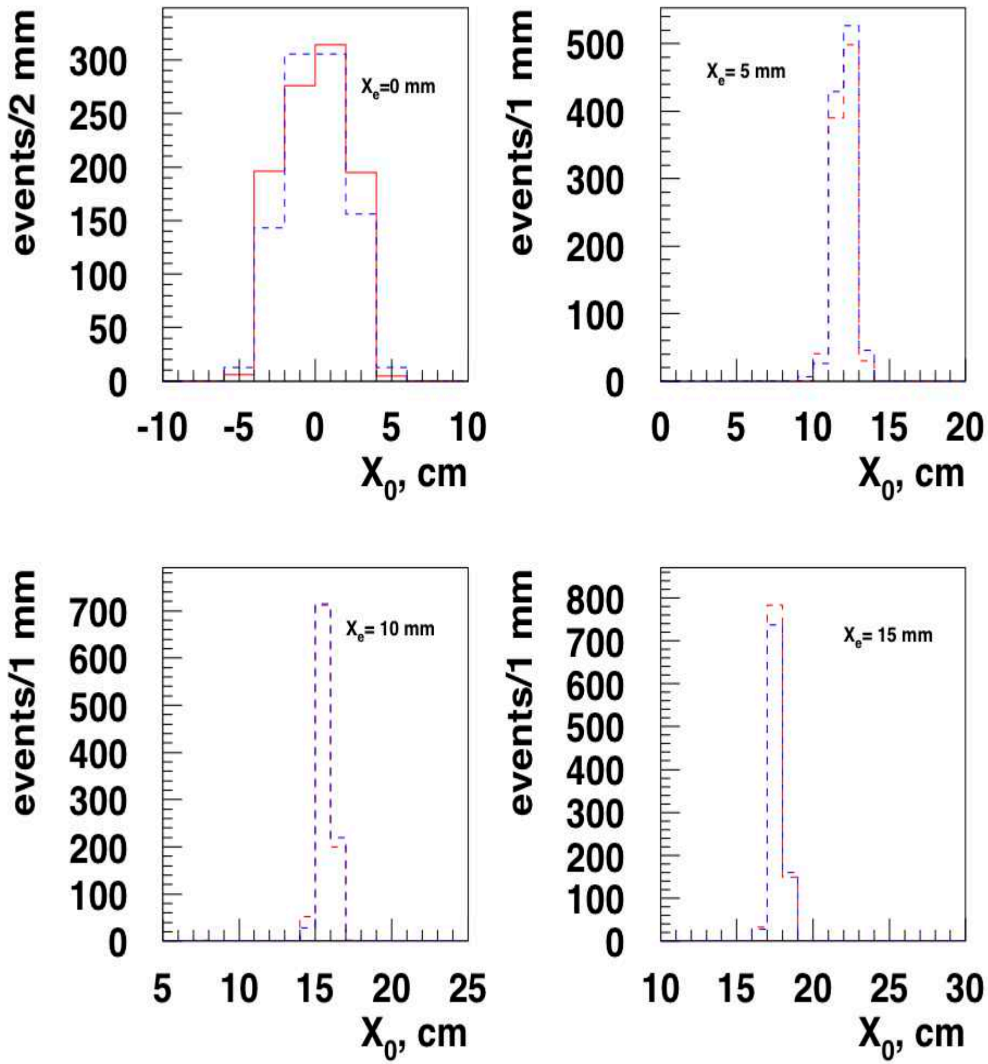
Signal shower profile



Signal shower c-o-g vs X_e

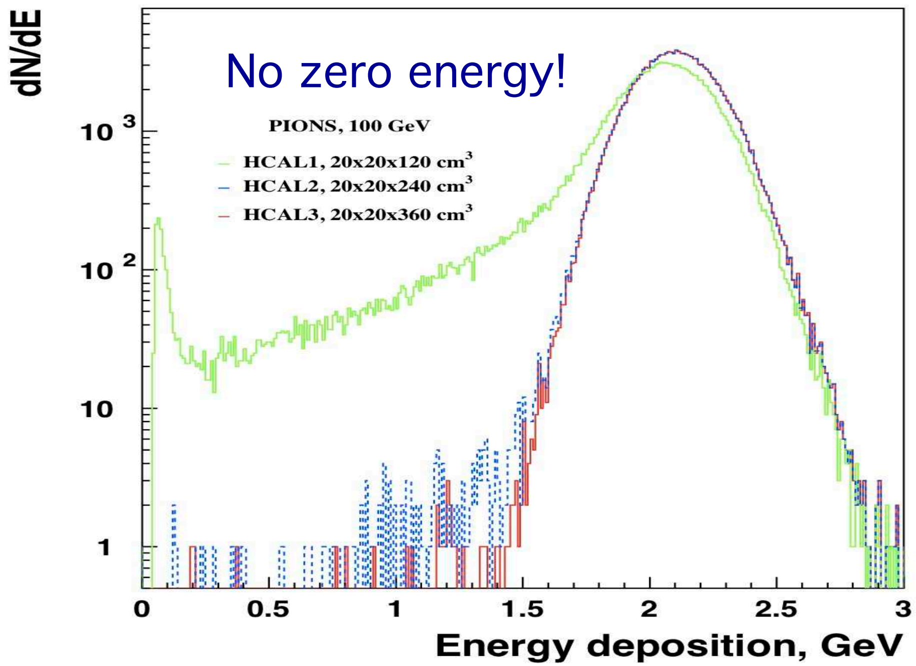


X_e reconstruction: e^- and e^-+A´ showers

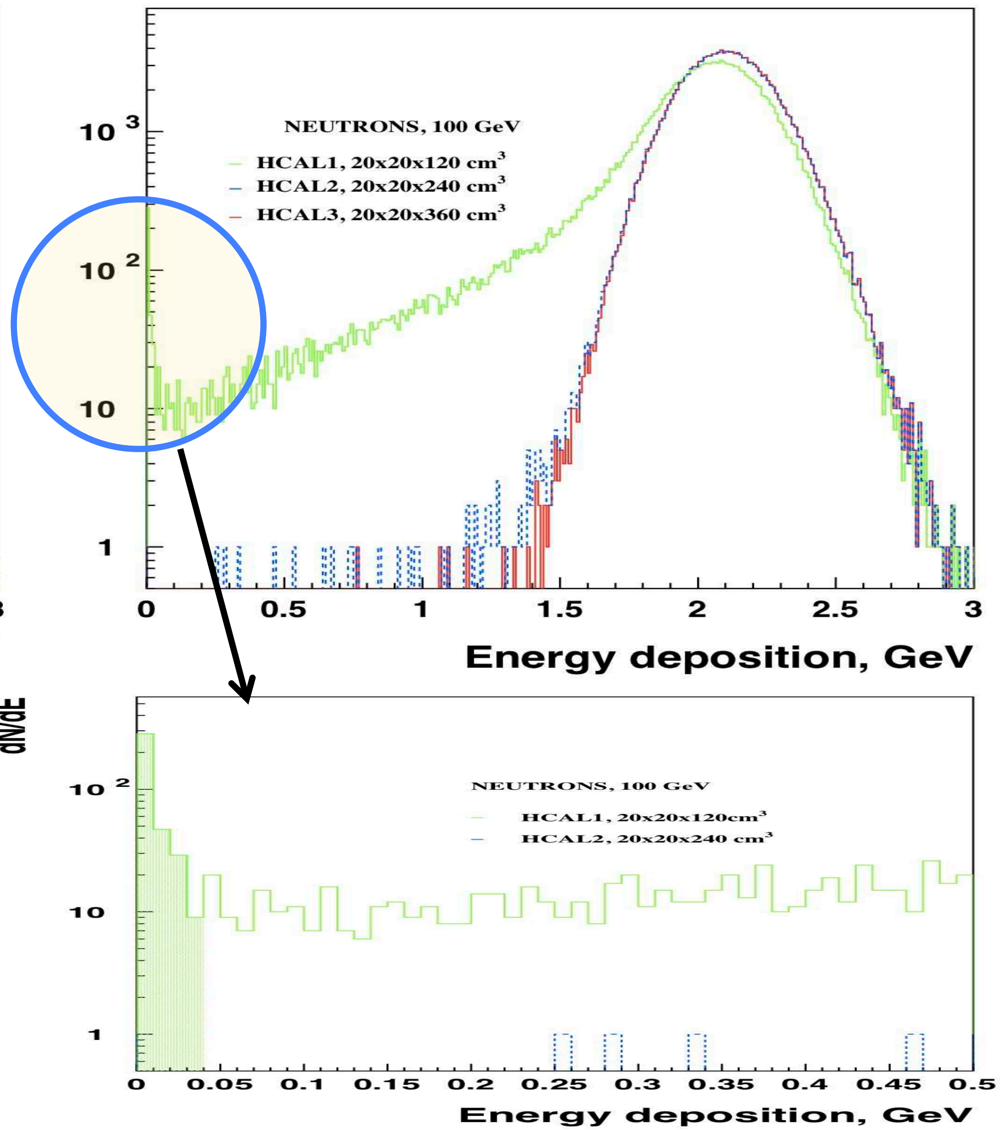


HCAL hermeticity

Pions, 100 GeV



Neutrons, 100 GeV



Expected HCAL energy threshold ~ 0.3-0.5 GeV (in units of hadronic energy) determined by electronics noise and pileups.

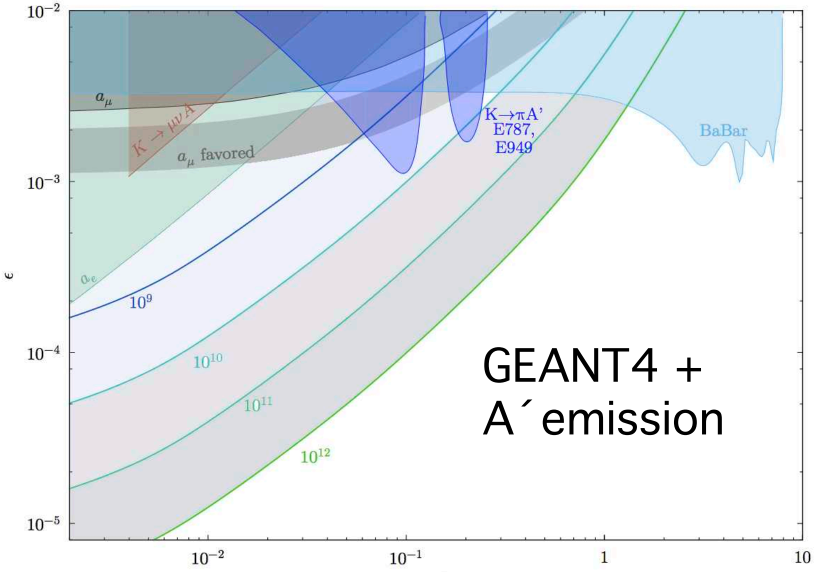
P(full E-leakage) < 10^{-7} / n

Summary of background sources for A´-> invisible

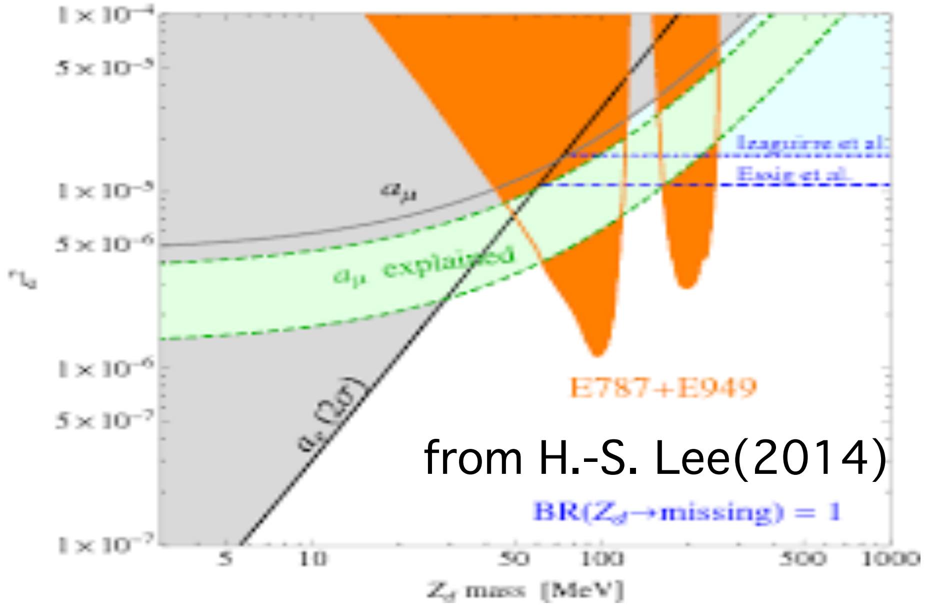
Source	Expected level	Comment
Beam contamination		
- π , p, μ reactions and punchthroughs,... - e^- low energy tail due to bremss., π , μ decays in flight,..	$< 10^{-13}$-10^{-12} $< 10^{-12}$	Impurity < 1% high precision MM tracker + e^- SR photon tag
Detector		
ECAL+HCAL energy resolution, hermeticity: holes, dead materials, cracks...	$<10^{-13}$	Full upstream coverage
Physical		
-hadron electroproduction, e.g. e^-A->ne^-A^*, n punchthrough; - WI process: $e^- Z$->$e^- Z \nu\ \nu$	$< 10^{-13}$ $< 10^{-13}$	~10 mb x nonherm. WI σ estimated. textbook process, first observation?
Total (conservative)	$< 10^{-12}$	

Exclusion plots

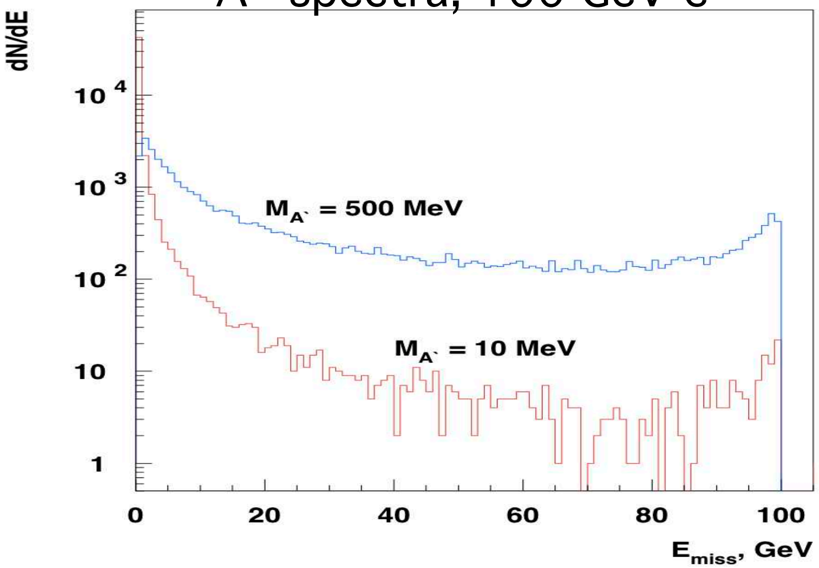
The reach of P348, A´signal detec. eff. ~0.5



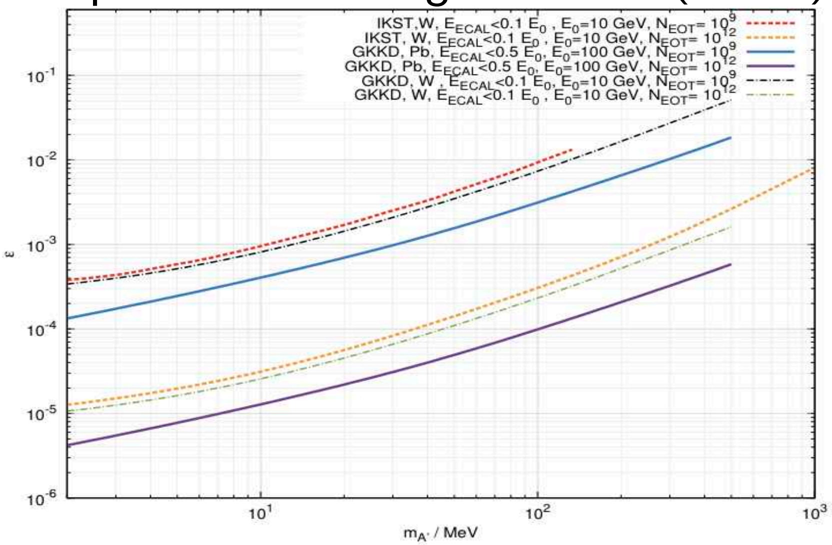
Current direct limits



A´ spectra, 100 GeV e-



Comparison with Izaguirre et al.(2015)



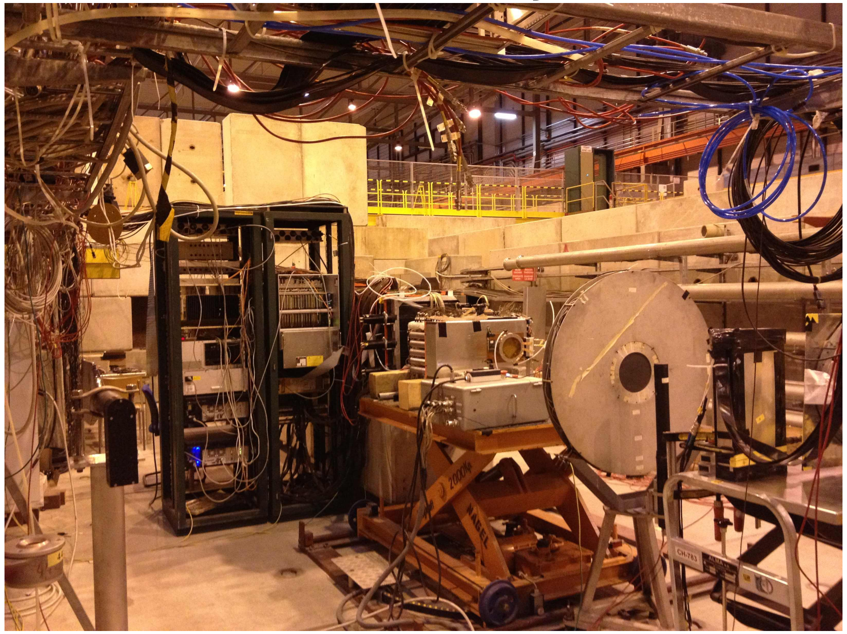
Test Run 2015

The P348 detector

The P348 detector

BGOs, Micromegas, straws, hodoscopes, ...

BGO SR array

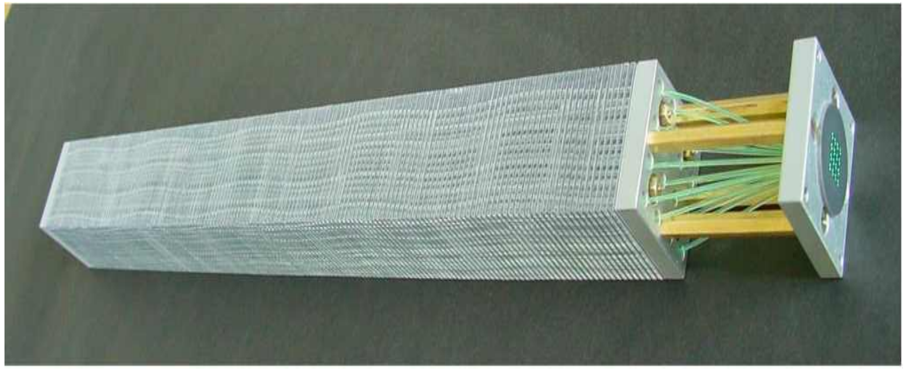


Micromegas

Straw tubes

Shashlik ECAL

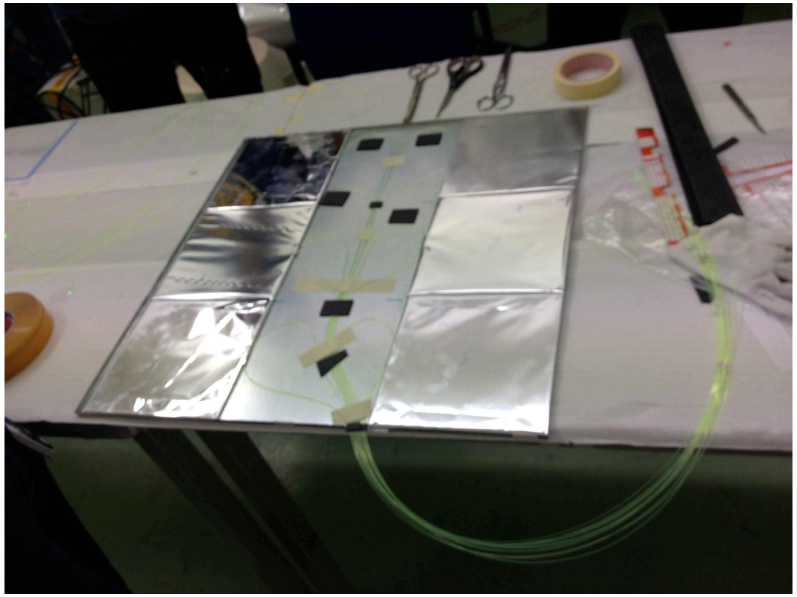
- Matrix of 6x6 cells, PS+ECAL
- Cell: Pb-Sc sandwich, 38x38x450 mm^3
- WLS fiber readout
- (1.5mm Pb+1.5mm Sc)x150 layers
- Hermetic, 40 X_0, no leak to HCAL
- fibers are inserted in a spiral
- Uniform, no cracks, holes
- Energy resolution~9% $E(GeV)^{-0.5}$
- Spatial resolution: 0.5- a few mm
- e/π rejection < 10^{-3}
- lateral and longitudinal segmentation



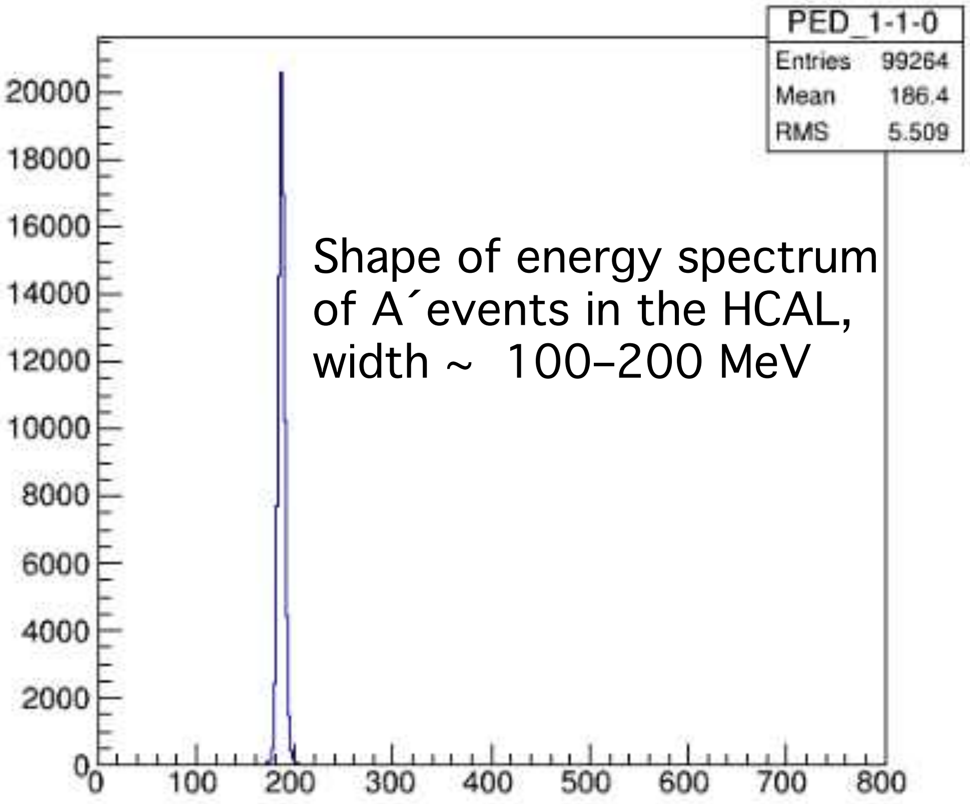
HCAL modules

Single HCAL module :

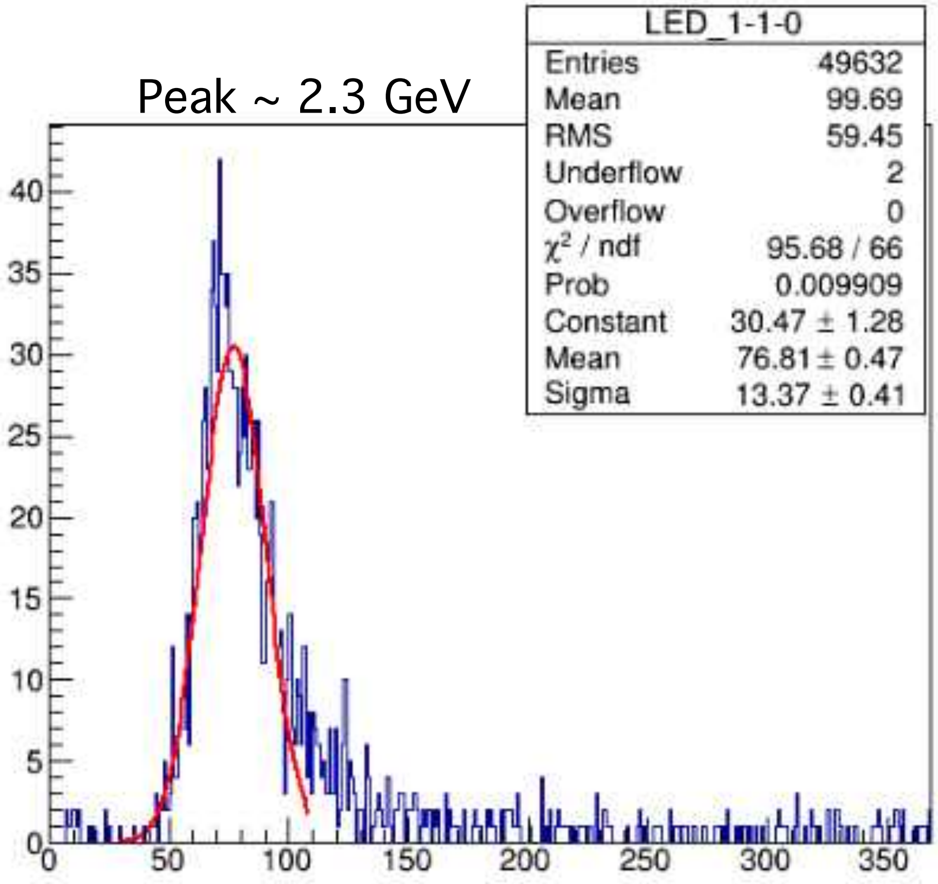
- Fe-Sc sandwich, 60x60x150 cm^3
- Matrix 3x3 cells
- WLS fiber readout
- (25mm Fe + 4mm Sc) x 48 layers
- Hermetic, ~7λ
- Uniform, no cracks, holes
- Energy resolution ~ 60% $E(GeV)^{-0.5}$
- Full HCAL: 4 modules, ~15 tons



HCAL PED, muons

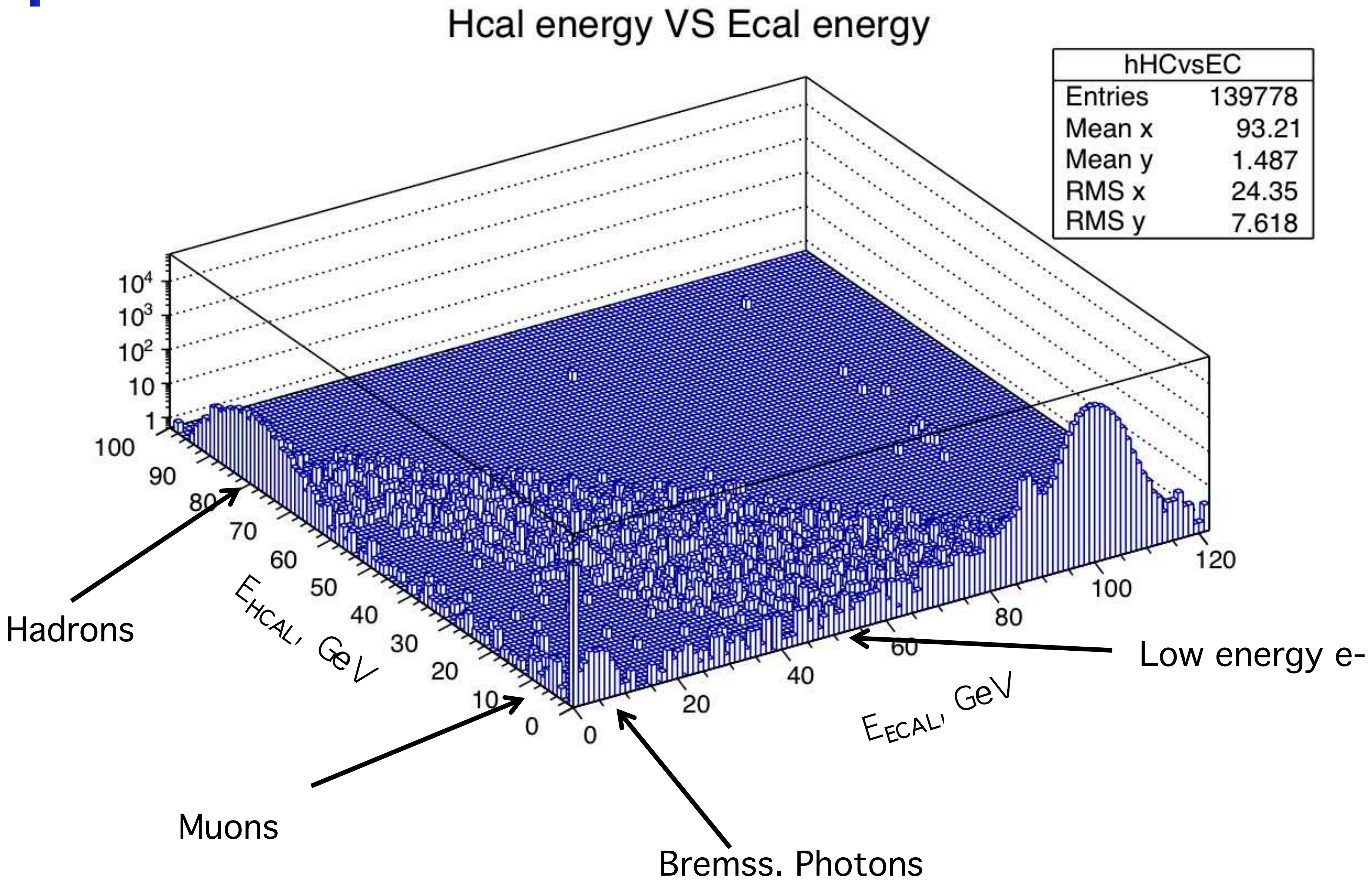


Peak ~ 2.3 GeV



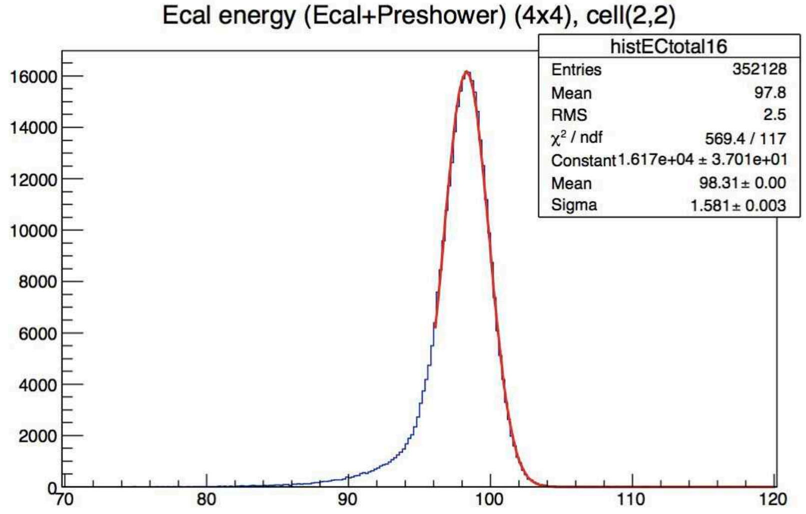
$N_{ph.e.}$~ 150 / MIP

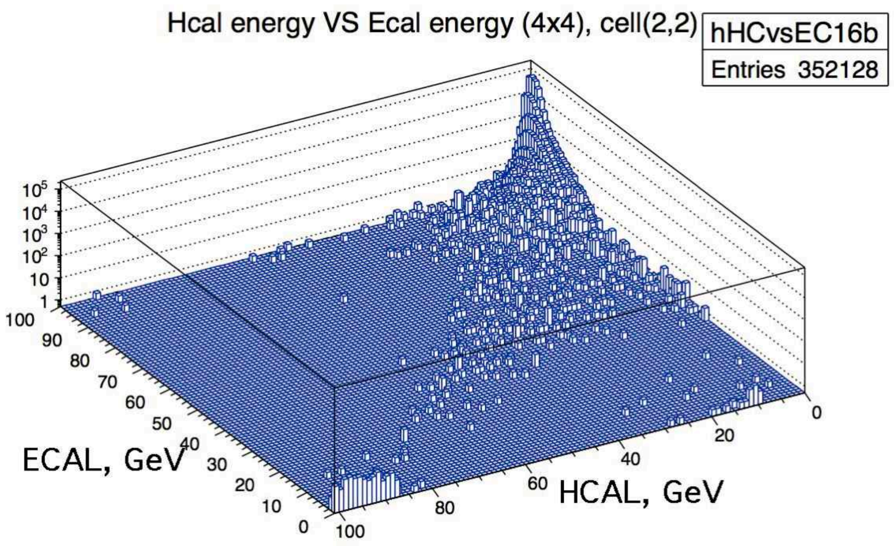
First look, B-field off.



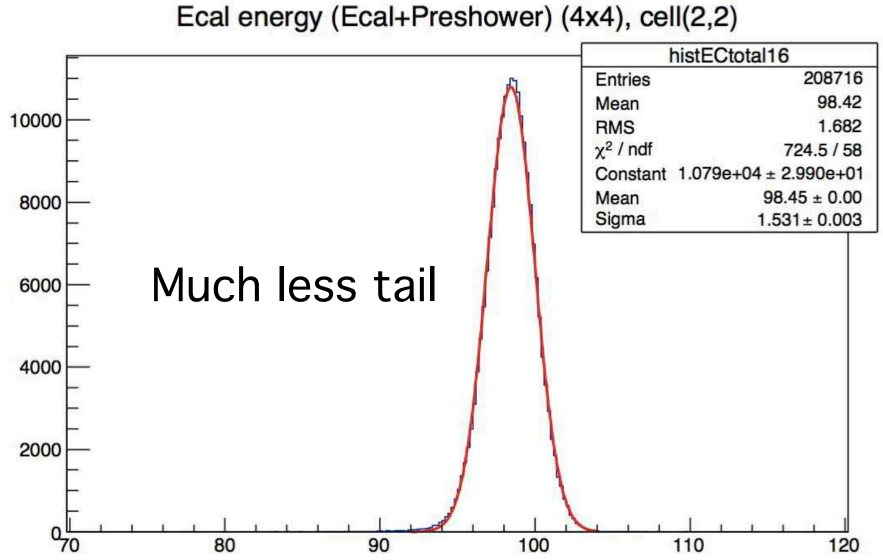
Performance of the SR tagging system

No SR tagging of e⁻'s



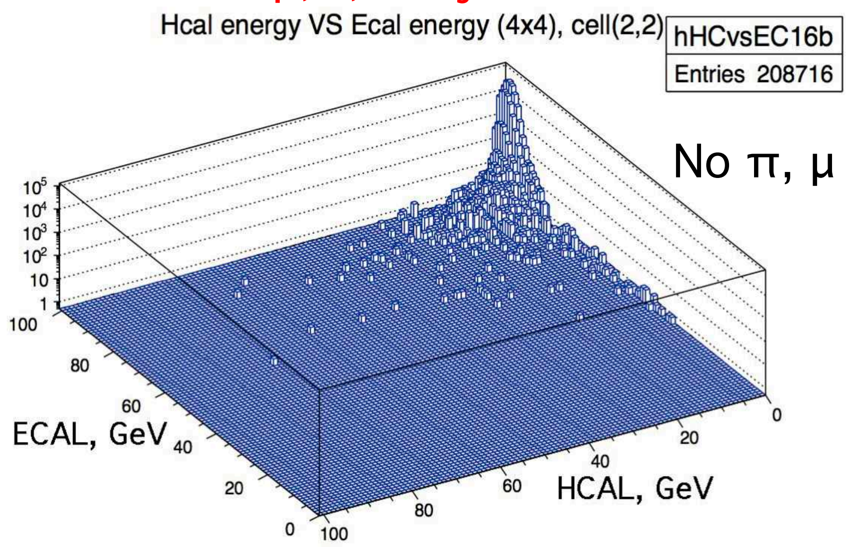


With SR tagging of e⁻'s



Much less tail

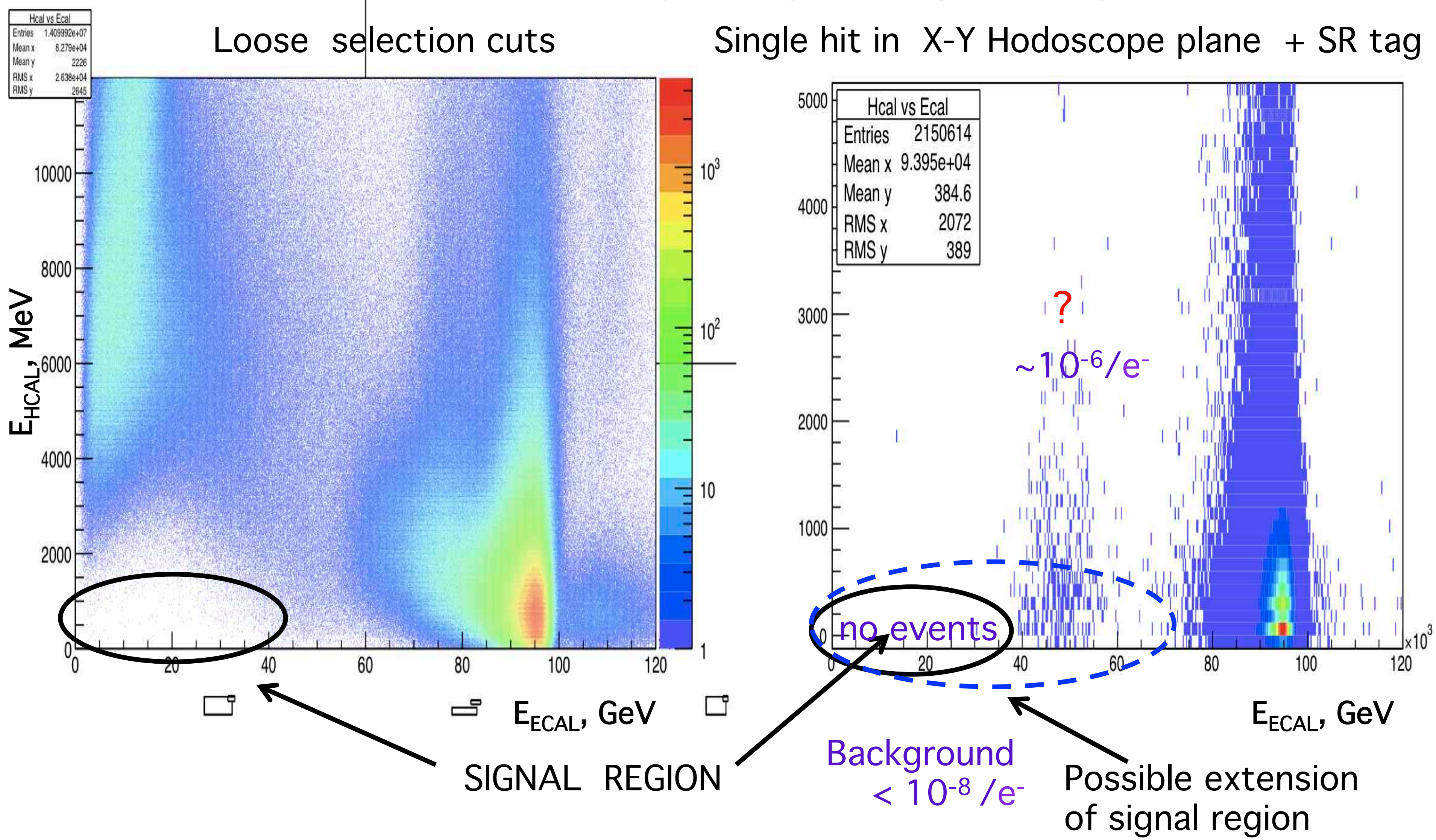
μ,π,.. rejection > 100



No π, μ

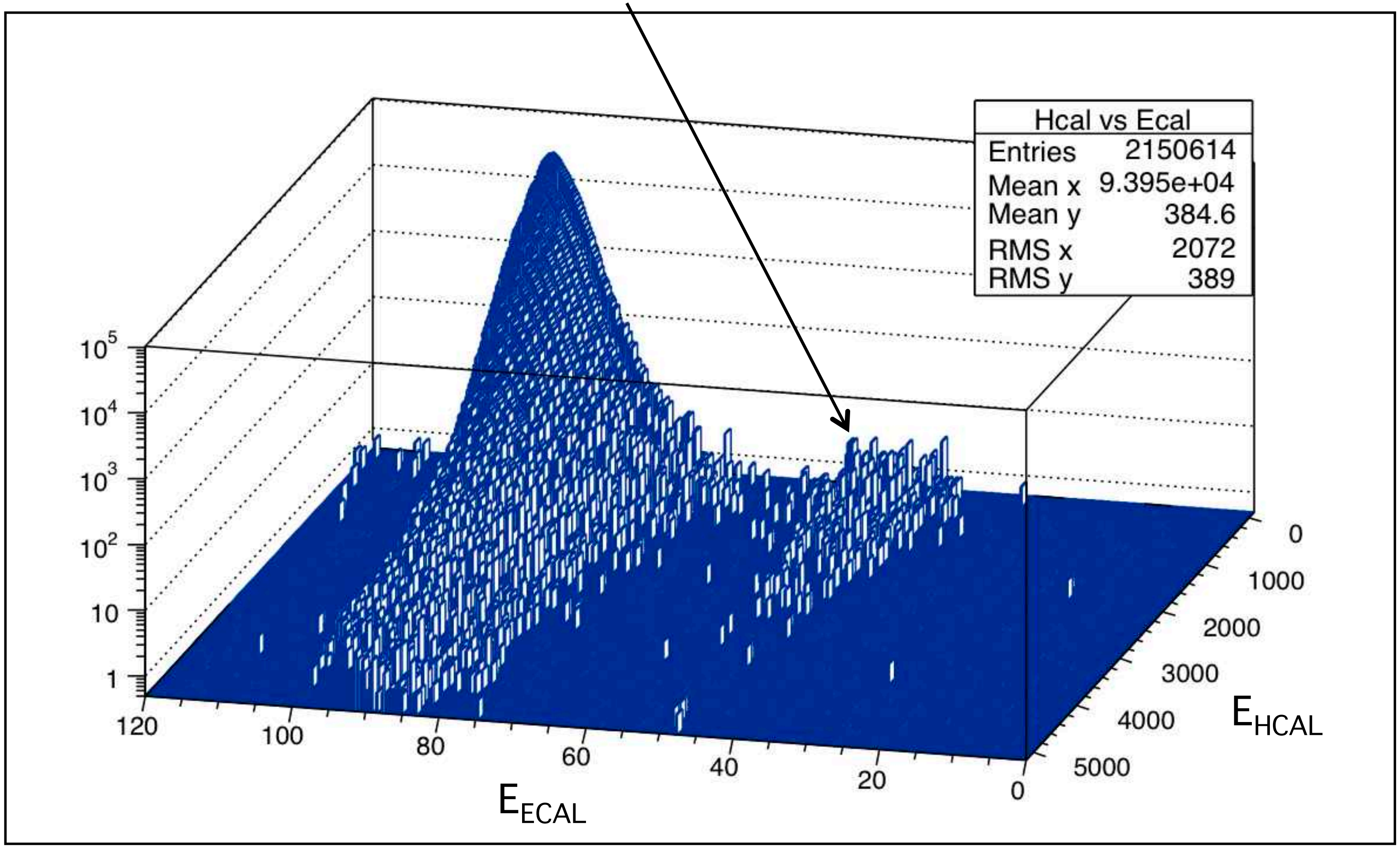
A´ signal in the (E_{HCAL};E_{ECAL}) plane

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



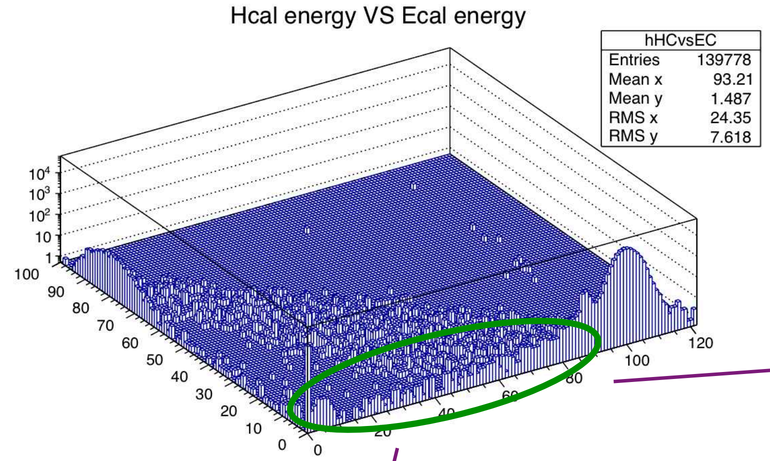
A´signal in the (E_{HCAL};E_{ECAL}) plane

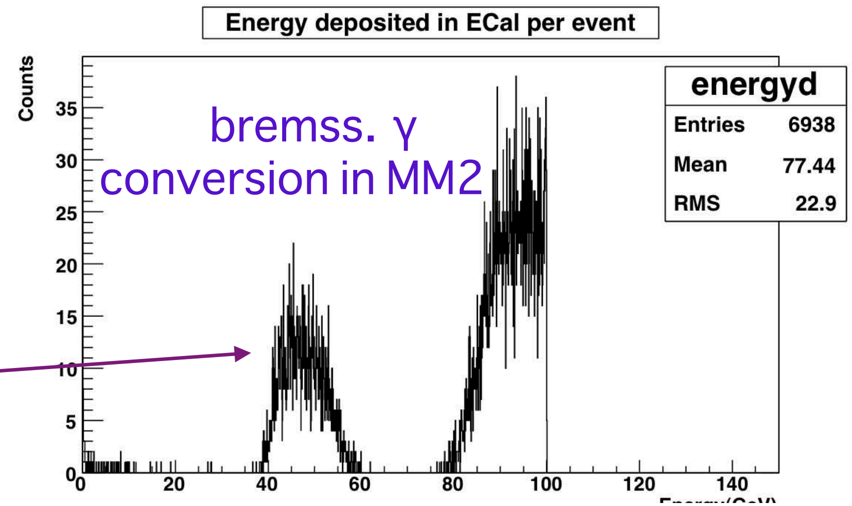
Conversion of bremss. γ ->e^+e^- in ~200 μm MM2 inside the magnet

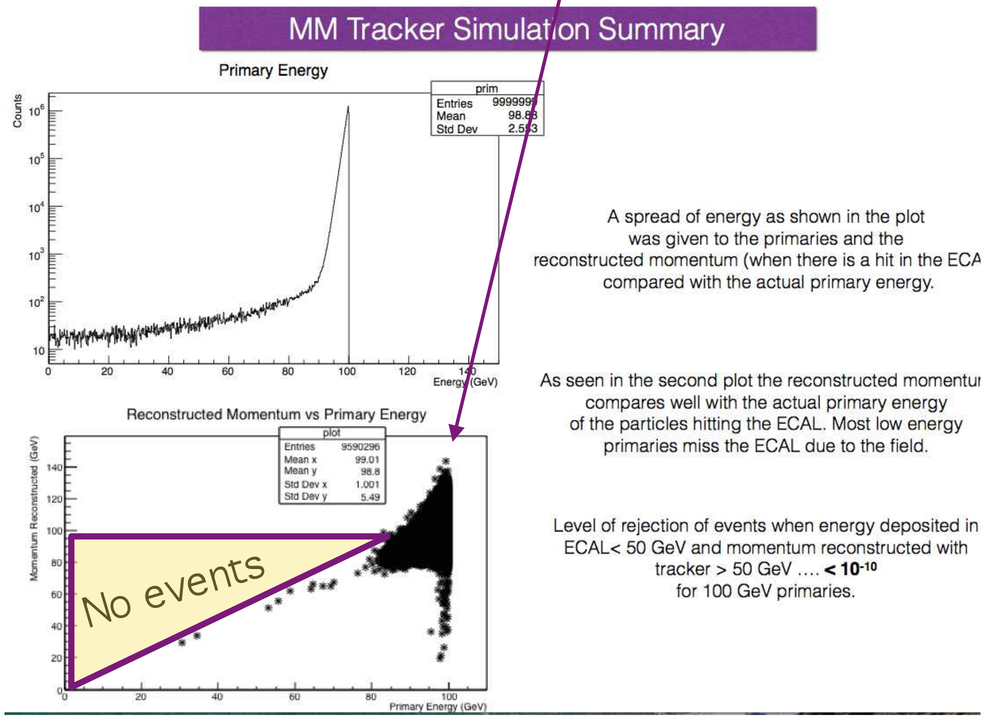


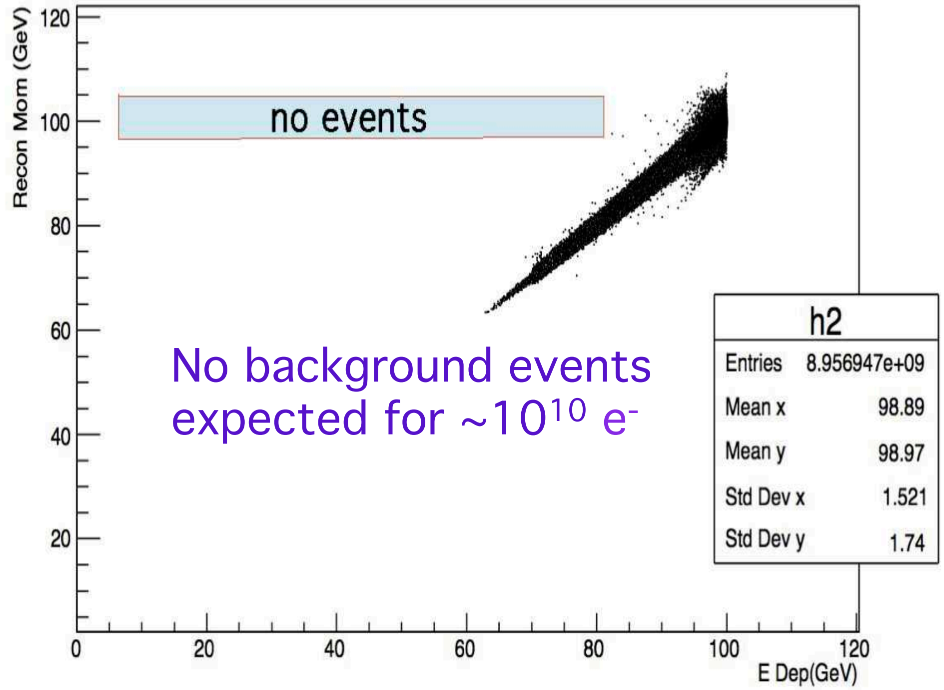
SR tag is triggered by either SR γ from 50 GeV e^-,
or by low energy bremss. γ/knock-on e^- .

MM tracker: tail background rejection









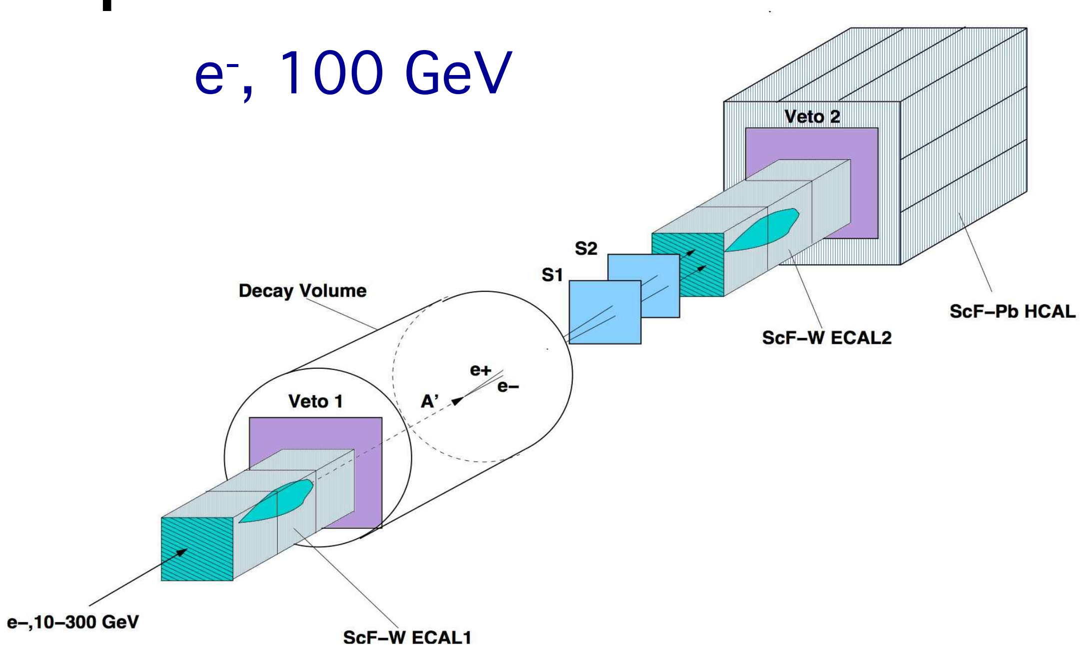
Physics prospects and plans

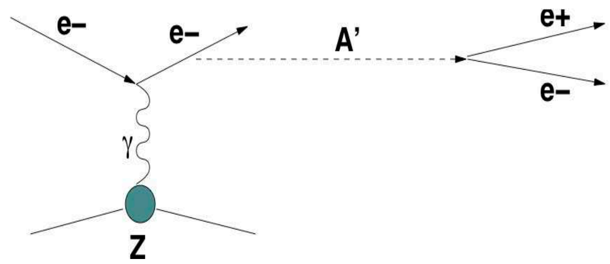
Physics prospects

Process	New Physics	Sensitivity
1. *$e^-Z \to e^-Z + E_{miss}$*		
✧ *A´-> e^+e^-* ✧ *A´-> invisible* ✧ *alps* ✧ *mQ*	Dark photons, Hidden sectors, $(g-2)_\mu$ new particles, milli-q	$10^{-4} < \varepsilon < 10^{-5}$ $M_{A'} \sim$ sub-GeV e´ $< 10^{-5}$-10^{-7}
2. *$\mu^- Z \to \mu^- Z + E_{miss}$*		
✧ $Z_\mu \to \nu\nu,\ \mu^+\mu^-$ ✧ $\mu \to \tau$	$(g-2)_\mu$, gauged L_μ-L_τ, L-phobic boson Z_μ, LFV	$\alpha_\mu < 10^{-11}$-10^{-9} $< 10^{-9}$-$10^{-8}/\mu$
3. *$\pi(K)p \to M^0 n \to E_{miss}$*		
✧ *K_L-> invisible* ✧ *K_S-> invisible* ✧ *π^0, η, η -> invisible*	Bell-Steinberger Unitarity, CP, CPT , NHL, 2HDM,	$\sim 10^{-5}$ Br $< 10^{-8}$ $< 10^{-8}$-10^{-7}
4. *pA -> X+ E_{miss}*		
✧ *leptophobic X +h*	~ GeV DM	$< 10^{-7}$-10^{-8} /p

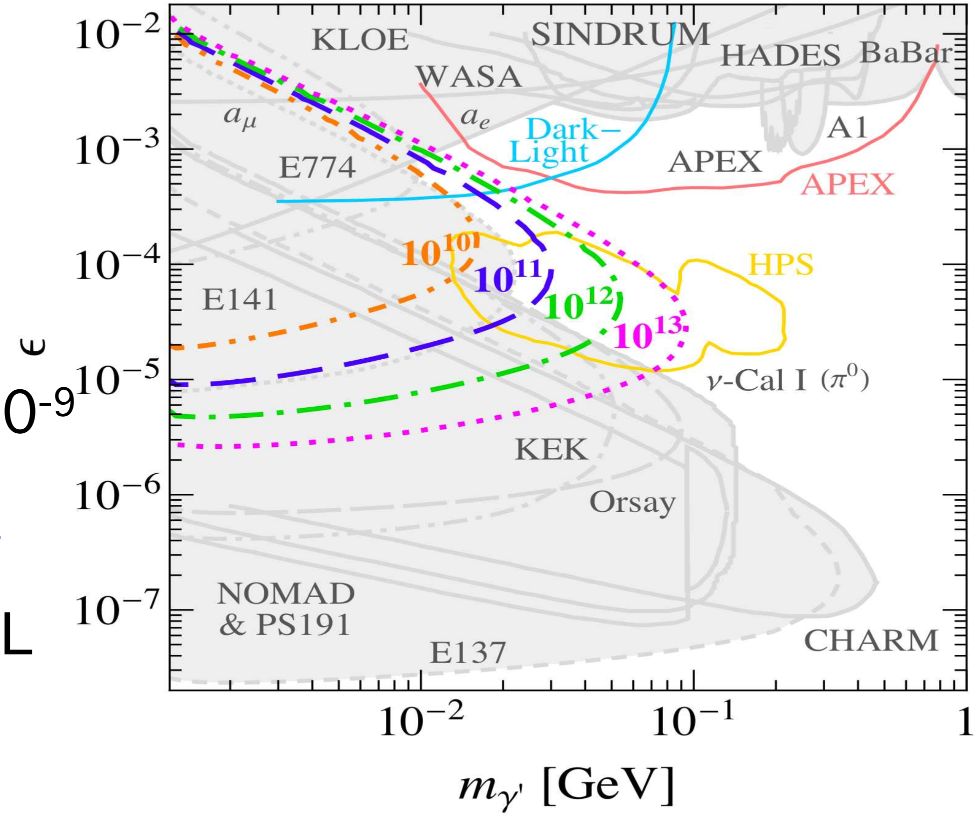
Search for the A´->e⁺e⁻ decay

e⁻, 100 GeV





Expected limits vs eot
(background free case, 30 GeV)



- A´ decay outside W-Sc ECAL1
- $10^{-14} < \tau_{A'} < 10^{-10}$ s, $\sigma_{A'}/\sigma_\gamma < 10^{-13}$-$10^{-9}$
- Signature: two separated e-m showers from a single e⁻

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

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

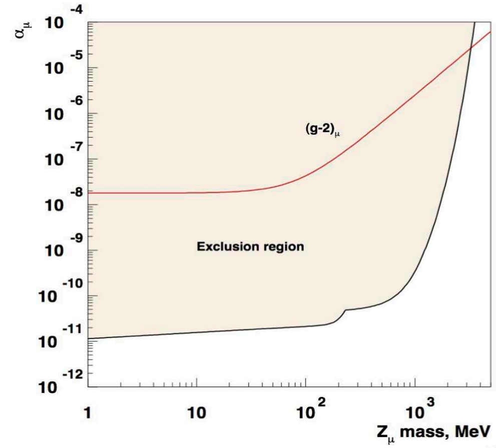
Summary of background sources for A´-> e+e-

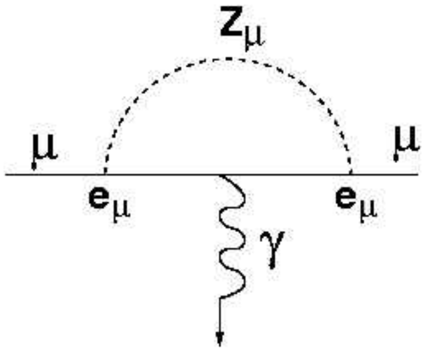
Source	Expected level	Comment
Beam contamination		
- π, μ reactions, e.g. πA->π^0n+X, ... -accidentals: $\pi\pi$, $\mu\mu$, ... decays, e-n pairs, ...	$< 10^{-12}$ $< 10^{-13}$	Impurity < 1% Leading n cross sect. ISR data
Detector		
- e,γ punchthrough, - ECAL thickness, dead zones, leaks	$< 10^{-13}$	Full upstream coverage
Physical		
hadron electroproduction: - eA->neA*, n -> ECAL2, - eA-> e+π+X, π->eν	$< 10^{-13}$	high precision MM tracker + e^- SR photon tag
Total	$< 10^{-12}$	

New leptophobic (muonic) Z_μ from gauged $L_\mu - L_\tau$

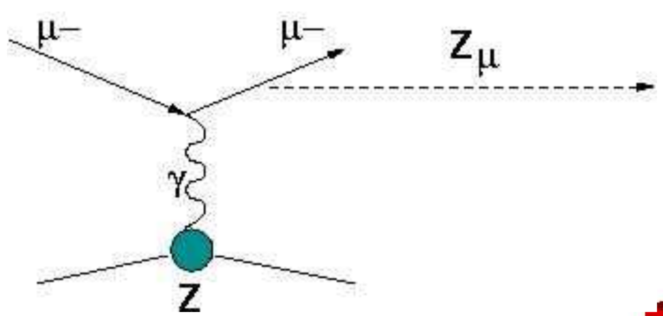
Class of U(1)´models: in SM it's possible to gauge one of $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ LF differences without introducing an anomaly.
Broken U(1)´of $L_\mu - L_\tau$ -> massive Z_μ.
Impact on: $(g-2)_\mu$, ν-Physics, cosmology.
Strong motivation for a sensitive search for $Z_\mu \to \nu\nu$, $\mu^+\mu^-$ in a near future experiment by using (unique) high intensity muon beams at CERN.

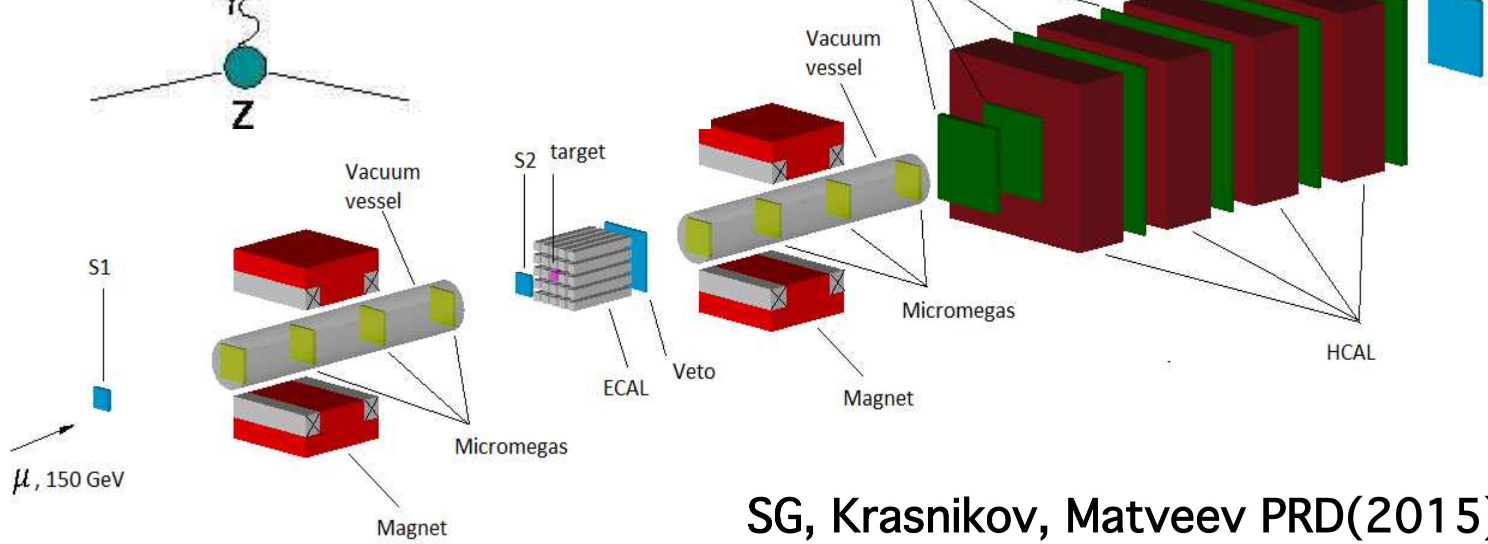
Expected exclusion area





(g−2) μ,





SG, Krasnikov, Matveev PRD(2015)

K_L -> invisible: nothing in, nothing out

Rare kaon decays with "missing energy"

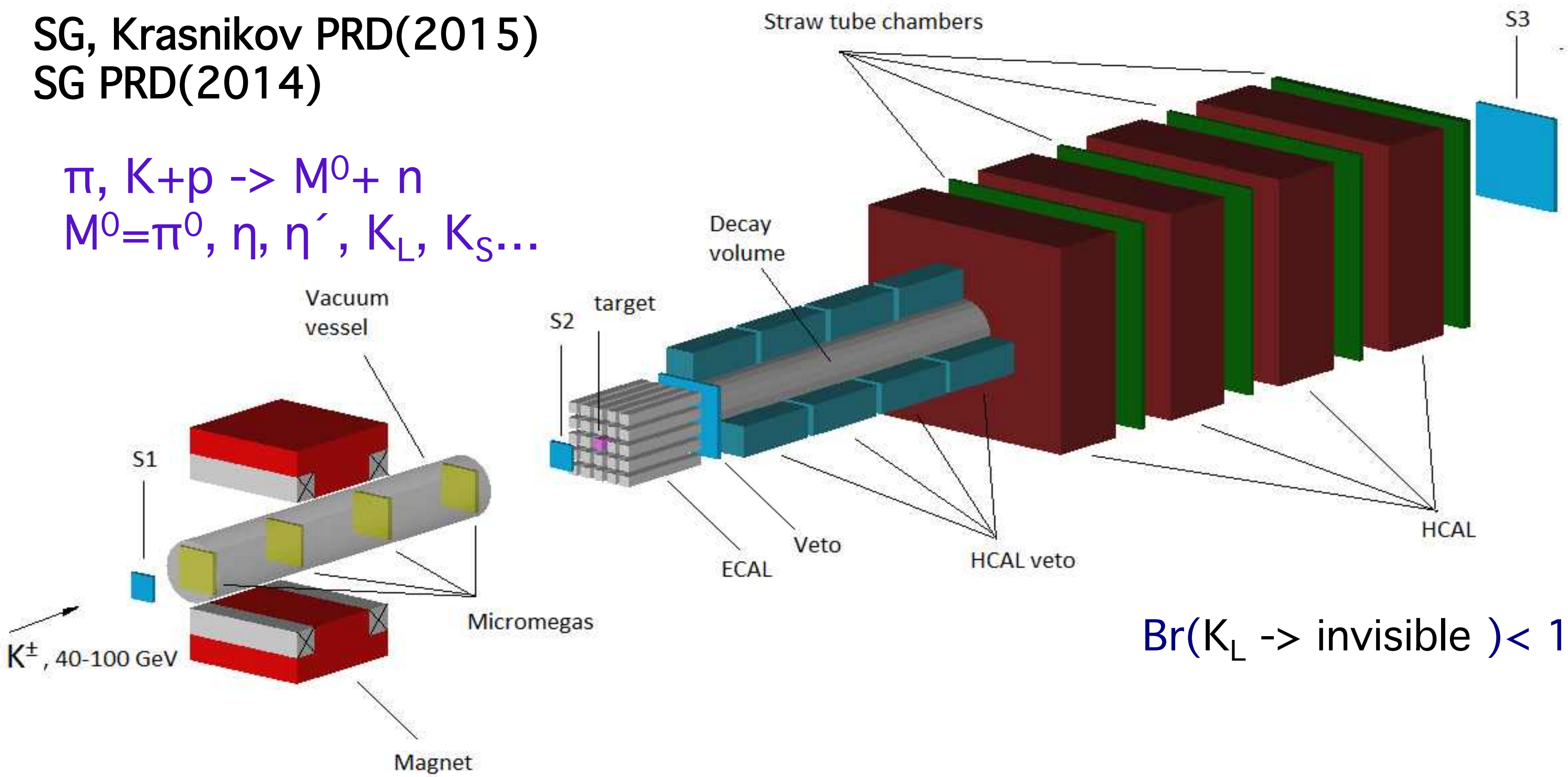
William J. Marciano and Zohreh Parsa

and $K_L \to \nu\bar{\nu}$ (if neutrinos have mass). Those decays would be interesting to explore, but their detection looks essentially impossible. New ingenious experimental ideas are required.

PRD(R)'96.

SG, Krasnikov PRD(2015)
SG PRD(2014)

π, K+p -> M^0+ n
$M^0=\pi^0, \eta, \eta', K_L, K_S$...



Br(K_L -> invisible)< 10^{-8}

Summary

The conceptual idea of P348 is to search for dark sector physics in missing-energy events with an active beam dump experiment.

The test run 2015:

The capability of such approach and background-free operation of the P348 detector have been demonstrated for the first time.

The run 2016:

The further increase in efficiency and sensitivity over 2015 results is expected due to

i) the ability of a high efficiency tagging of initial state,
ii) precise measurement of the incoming electron momentum,
iil) and thus, rejection of all known backgrounds.

Runs >2016 :

Further increases in efficiency and other improvements are in development, including increased beam rate.

These results expand the reach of P348.