



Search for dark sector physics in missing-energy events

S.N. Gninenko
INR, Moscow
(for the NA64 Collaboration)

Outline

- Introduction
- Searches with e , μ , π , K , p beams
- Summary

The NA64 Collaboration

Universidad Tecnica Federico Santa Maria (UTFSM), Valparaiso, Chile

S. Kuleshov, W. K. Brooks, H. Hakobyan, S. Kovalenko, G. Vasquez Arenas, P. Ulloa

Rheinische Friedrich-Wilhelms- Universität Bonn, Germany

M. Ball, M. Hösgen, B. Ketzer

Institute for High Energy Physics, Protvino, Russia

S.V. Donskov, V.A. Kachanov, Yu.V. Mikhailov, V.A. Poliakov, V.D. Samoylenko, A.P. Filin.

Joint Institute for Nuclear Research (JINR), Dubna, Russia

G.D. Kekelidze, V.Yu. Karjavine, V.A. Kramarenko, V. Lysan, V.A. Matveev, V.V. Myalkovskiy, D.V. Peshekhonov, V.D. Peshekhonov, A.A. Savenkov, I.A. Zhukov

P.N. Lebedev Physical Institute of the RAS (LPI), Moscow, Russia

V.O. Tikhomirov, K. Zhukov

Institute for Nuclear Research of the RAS (INR), Moscow, Russia

A.V. Dermenev, S.N. Gninenko, A.E. Karneyeu, M.M. Kirsanov, N.V. Krasnikov, L.V. Kravchuk, O. Petukhov, I.I. Tkachov, D.A. Tlisov, A.N. Toropin

Tomsk Polytechnic University (TPU), Tomsk, Russia

V.E. Burtsev, R.R. Dusaev, V.E. Lyubovitsky, A.Yu. Trifonov, B.I. Vasilishin

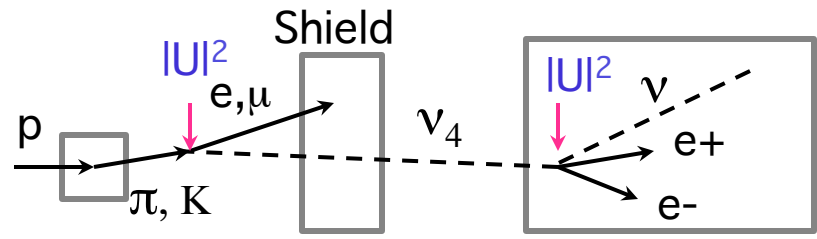
ETH Zurich, Institute for Particle Physics, Zurich, Switzerland

D. Banerjee, D.A. Cooke, P. Crivelli, B. Radics, A. Rubbia

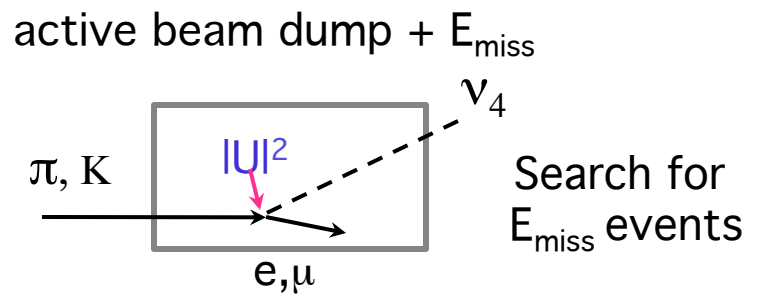
NA64 approach to search for new physics

The NA64 is a new fixed-target experiment aiming to search for dark photon A' -> invisible decays at the CERN SPS with a new approach: **the active beam dump combined with missing energy technique.**

Beam dump: \leftarrow **Complementary to each other** \rightarrow NA64 approach:



Sensitivity $\sim |U|^4$
e.g. SHIP, A. Golutvin talk



Sensitivity $\sim |U|^2$

Goal of the talk: to show that this approach allows a sensitive probe of “light new physics“ (dark sector physics, new symmetries, new WI sub-GeV particles coupled to e, μ, q 's) by using $e, \mu, \pi, K,$ and p beams from existing facilities at CERN.



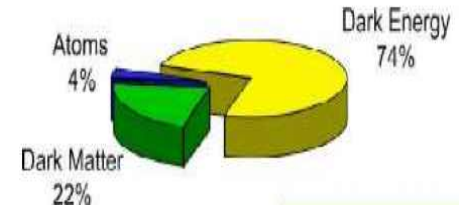
e^- beam

Search for
 $A' \rightarrow$ invisible and $A' \rightarrow e^+e^-$
decays of dark photons

Motivation

M. Shaposhnikov talk

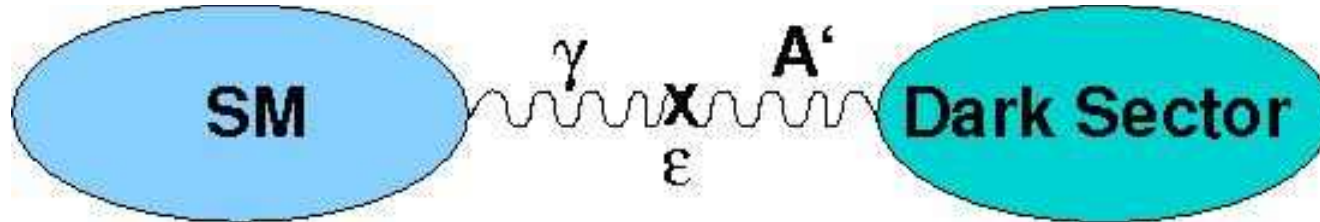
- Dark Matter (DM) puzzle:
What makes up most of the Universe's mass?
- LHC Run I: no DM candidates so far.
LHC Run II: focus on searching for “heavy” new physics.
- Various models for DM motivate “light” new physics that could be observed in lower energy experiments.



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.

The A'

Okun, Holdom' 86 ..



- extra (broken) $U(1)'$, new massive boson A' (dark photon)
 - $\Delta\mathcal{L} = \epsilon F^{\mu\nu} A'_{\mu\nu}$ - kinetic γ - A' mixing, ϵ - coupling strength
 - $\epsilon \sim 10^{-8} - 10^{-3}$
 - A' could be light: e.g. $M_{A'} \sim \epsilon^{1/2} M_Z$
 - new phenomena: γ - A' oscillations, LSW effect,... or A' decays:
 - i) $A' \rightarrow e^+e^-, \mu^+\mu^-, \text{hadrons}, \dots$
 - ii) $A' \rightarrow \text{invisible}$ if $M_{A'} > M_{\text{DM}}$ and $\alpha_{\text{DM}} \gg \epsilon$.
- Can explain $(g-2)_\mu$, astrophys. observations, ... (M. Pospelov talk)

Growing activities of high intensity/sensitivity experiments at sub-GeV scale, e.g. JLab, SLAC, INFN,

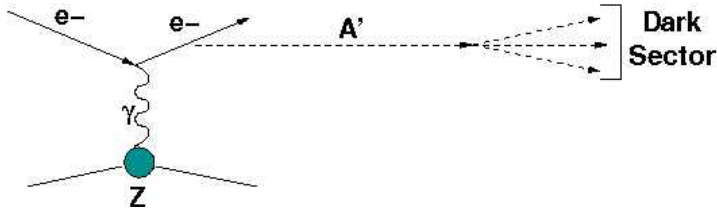
Large literature, many theoretical and experimental results.

e.g. Jaeckel, Ringwald review.

Direct Search for A' \rightarrow invisible decays at CERN SPS

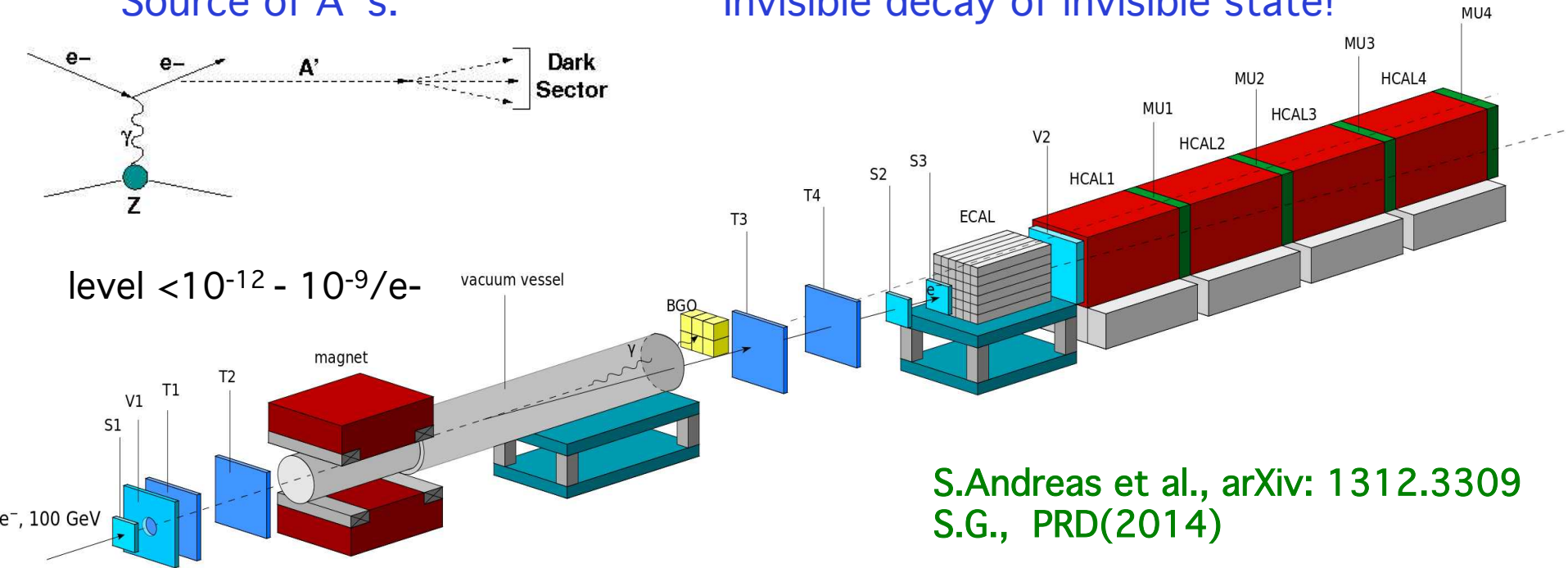
7.

Source of A' 's:



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

Invisible decay of invisible state!



S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

Main components :

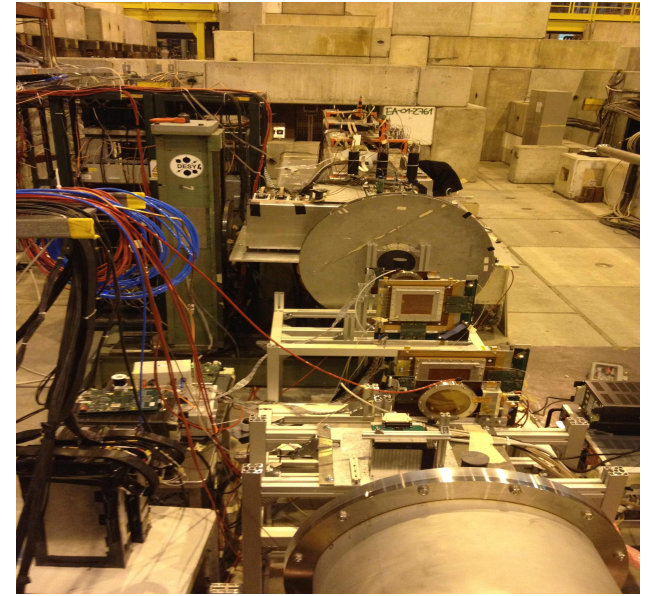
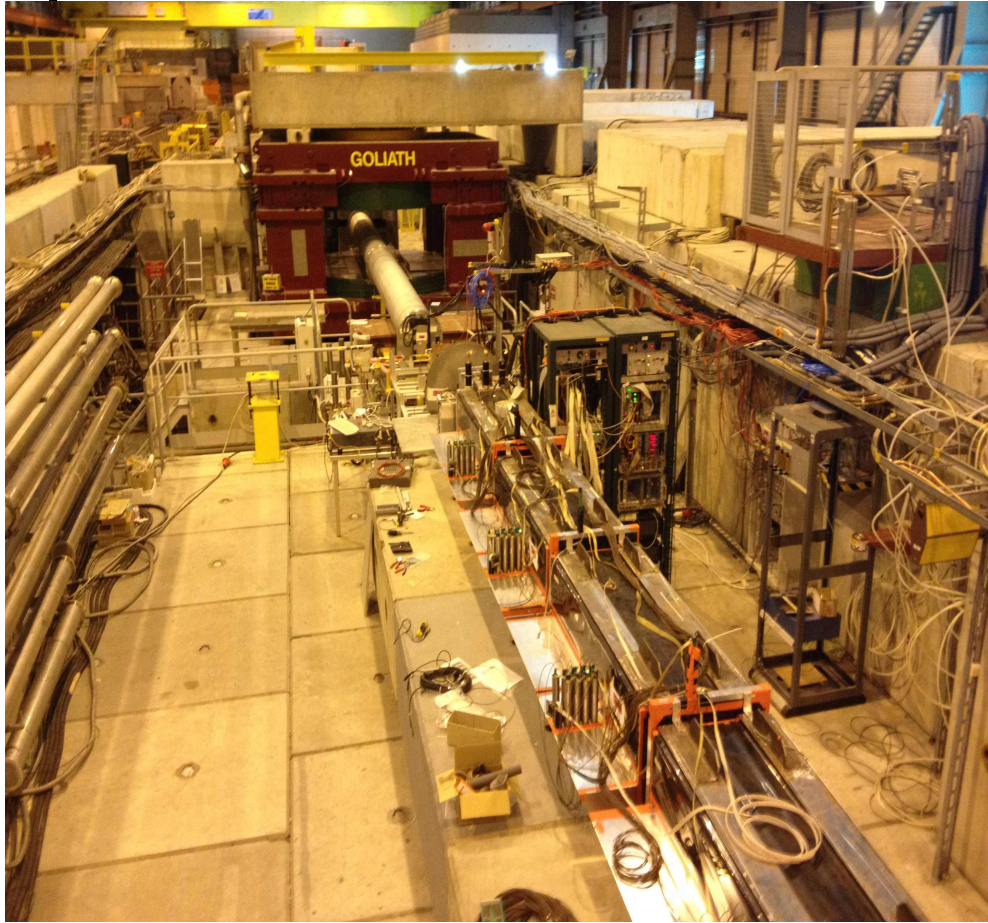
- clean, mono-energ. 100 GeV e^- beam
- e^- tagging system: MM/GEM/Straw tracker + SRD (BGO, LYSO; Pb-SC)
- 4π fully hermetic ECAL+ HCAL

Signature:

- in: 100 GeV e^- track
- out: < 50 GeV e -m shower in ECAL
- no energy in the Veto and HCAL
- Sensitivity $\sim \epsilon^2$
- same signature for milli-q, APLs,

Summary of background sources for $A' \rightarrow$ invisible

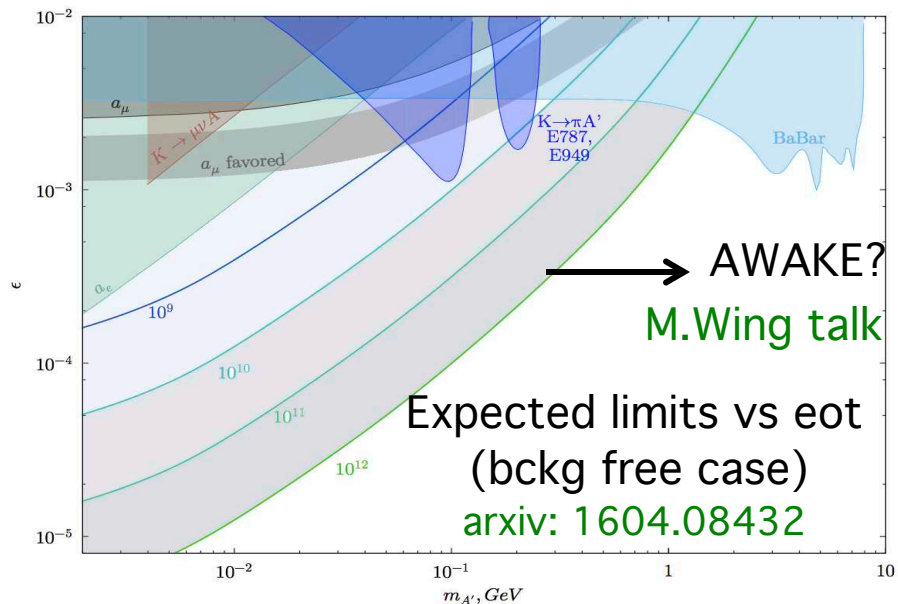
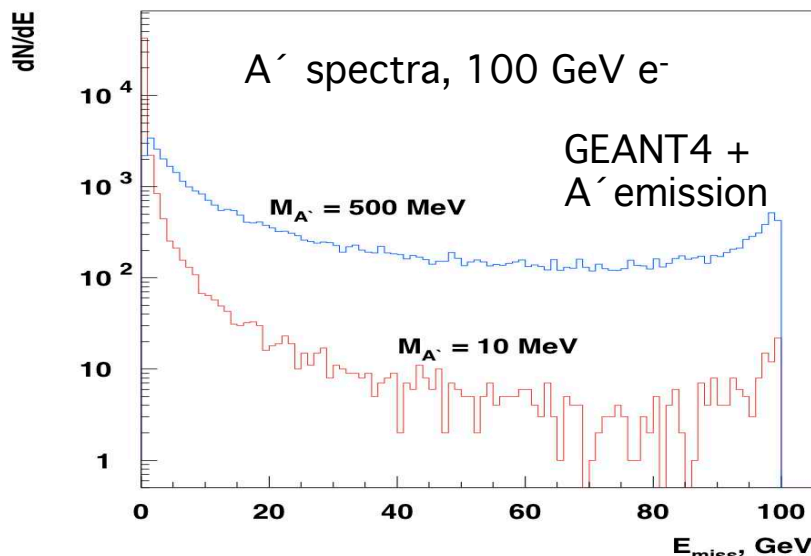
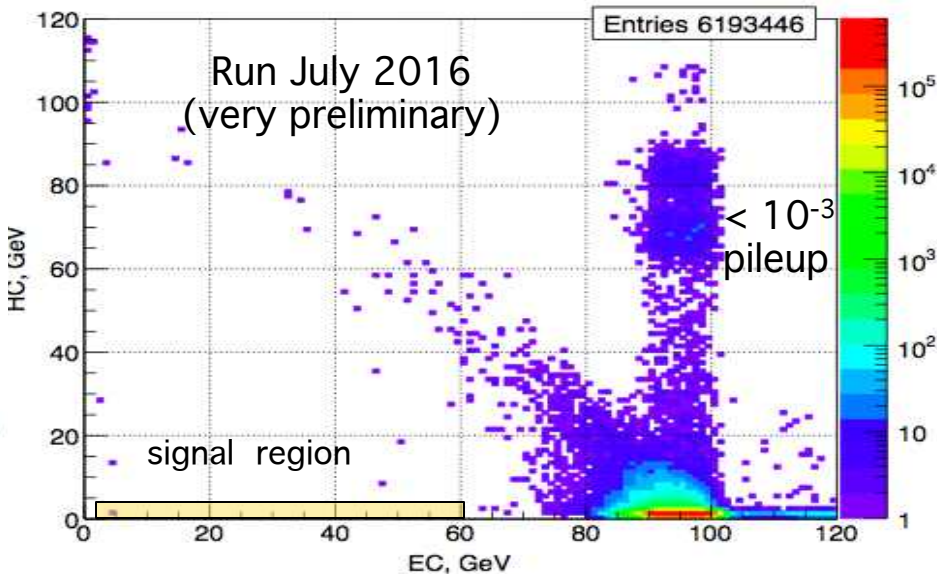
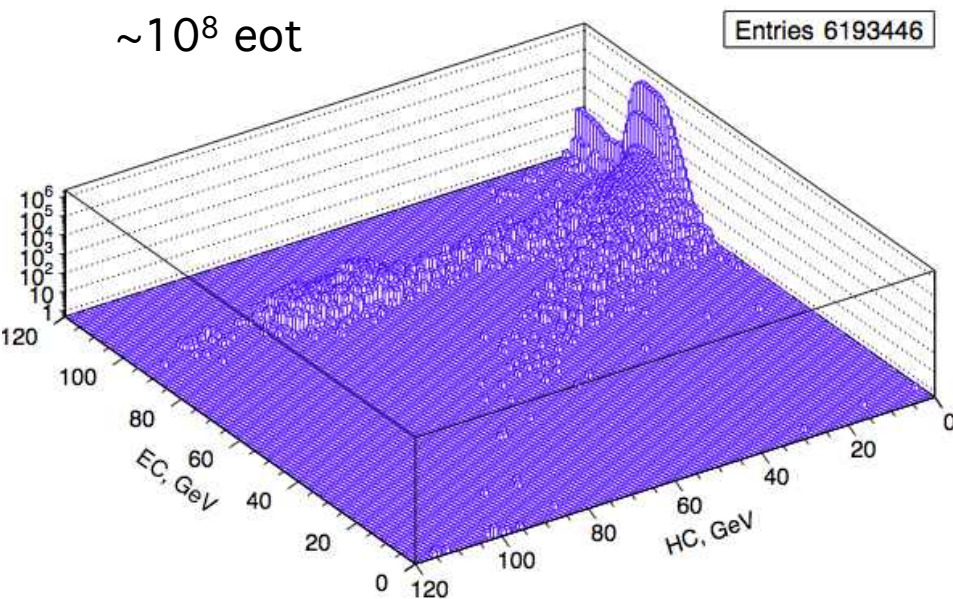
Source	Expected level	Comment
Beam contamination		
<ul style="list-style-type: none"> - π, ρ, μ reactions and punchthroughs,... - e^- low energy tail due to brems., π, μ-decays in flight... 	$< 10^{-13}$ - 10^{-12} $< 10^{-12}$	Impurity $< 1\%$ high precision MM tracker + e^- SR photon tag
Detector		
ECAL+HCAL energy resolution, transverse hermeticity, holes, dead material, cracks...	$< 10^{-13}$	Full upstream coverage
Physical		
<ul style="list-style-type: none"> - hadron electroproduction, e.g. $e^- A \rightarrow e^- A^* + n, \pi, \rho, J/\psi$ - n punchthrough, μ inefficiency - WI process: $e^- Z \rightarrow e^- Z \nu \nu$ 	$< 10^{-13}$ $< 10^{-13}$	HERA ep-data (H1 Collaboration) WI σ estimated.
Total	$< 10^{-12}$	



Thanks to
CERN: two MBPL, SR vessel, beam tuning,
E18 TUM, Munich (I.Konorov , D. Levit) for DAQ

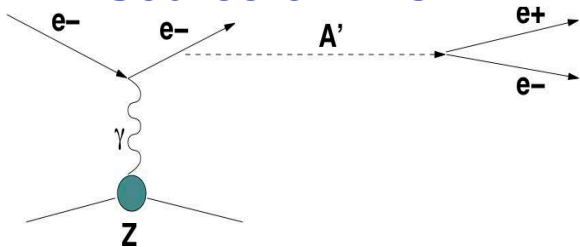
A' signal in the (E_{HCAL}; E_{ECAL}) plane

~10⁸ eot



Search for the $A' \rightarrow e^+e^-$ decay

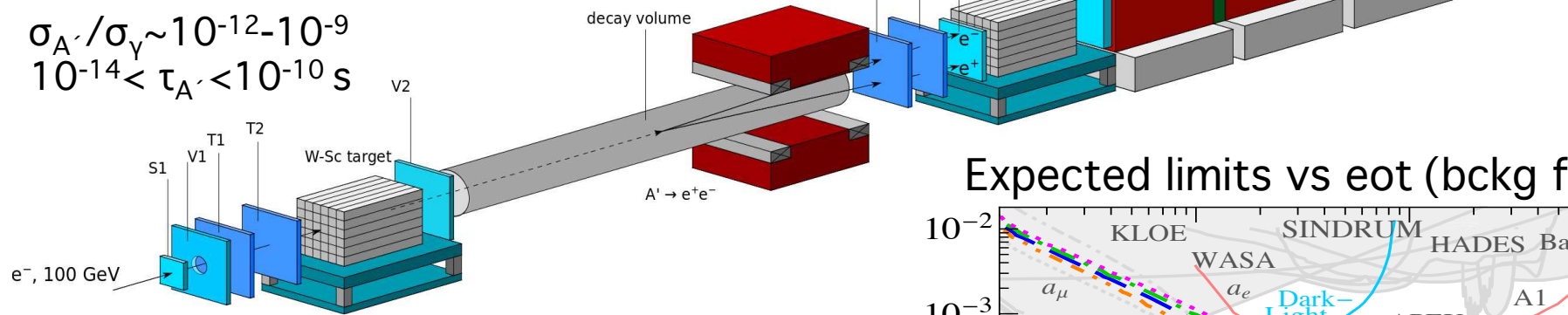
Source of A' 's:



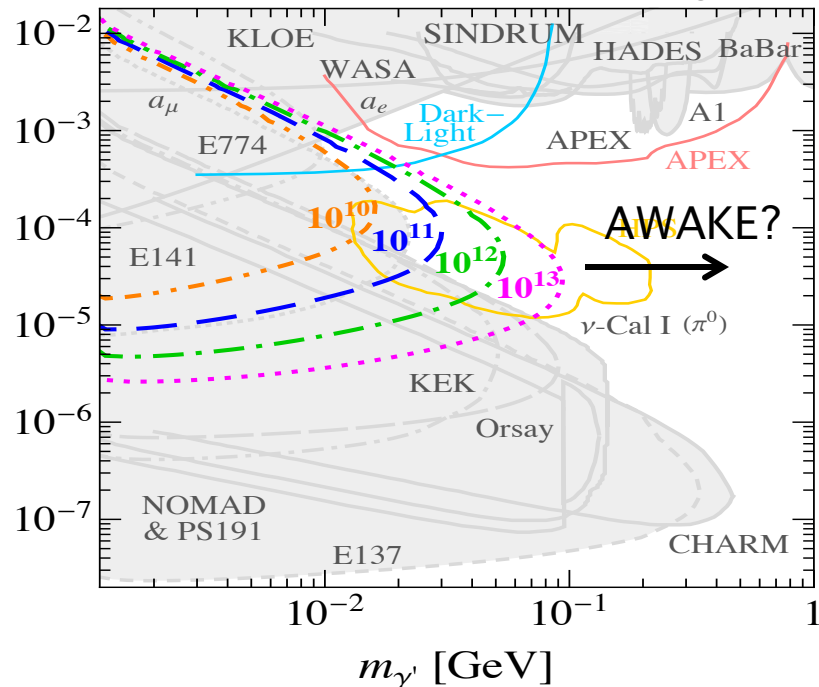
$$\sigma_{A'} / \sigma_Y \sim 10^{-12} - 10^{-9}$$

$$10^{-14} < \tau_{A'} < 10^{-10} \text{ s}$$

$e^-, 100 \text{ GeV}$



Expected limits vs $e\theta$ (bckg free)



Signature:

- $S = S1 \times \text{Target} \times S2 \times \text{ECAL} \times V2 \times V3 \times \text{HCAL}$ ϵ
two separated showers in target and ECAL from a single e^-
- $E_0 = E_T + E_{\text{ECAL}}$
- magnet to separate e^+e^-
- $\theta_{e^+e^-}$ is small to be resolved



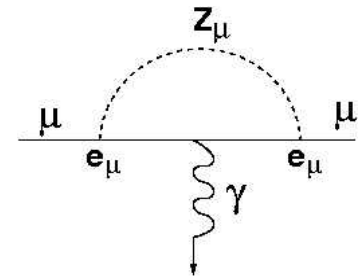
μ beam

Search for a new
 L_{μ} - L_{τ} gauge boson

(see M. Pospelov talk)

New leptonic Z' (or Z_μ) from gauged $L_\mu - L_\tau$

- Class of $U(1)'$ models: in SM it's possible to gauge one of $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ LN differences. No anomaly.
- Extra (broken) $U(1)'$, new massive boson Z' coupled predominantly to μ and τ through the $L_\mu - L_\tau$ current (leptonic dark photon)
- $M_{Z'}$ could be in sub-GeV range
 $Z' \rightarrow \mu^+\mu^-$ or $Z' \rightarrow \nu\nu$ if $M_{Z'} < 2 m_\mu$
- Impact on: ν -physics, explanation of $(g-2)_\mu$



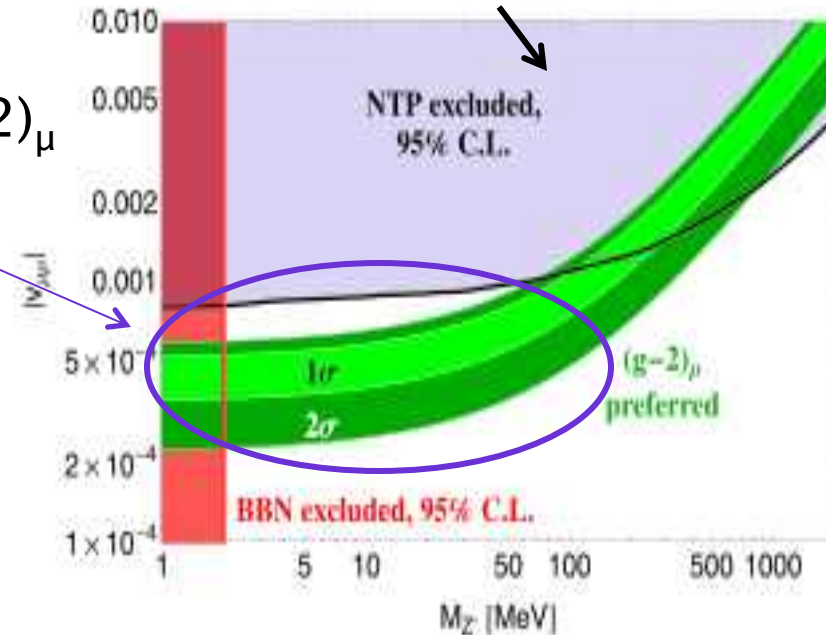
Strong motivation for a sensitive search for $Z' \rightarrow \nu\nu$, $\mu^+\mu^-$ in a near future experiment by using (unique) high intensity muon beam at CERN.



The upgraded muon beam at the SPS

N. Doble, L. Gatignon*, G. von Holtey, F. Novoskoltsev¹
 CERN, SL Division, CH-1211 Geneva 23, Switzerland

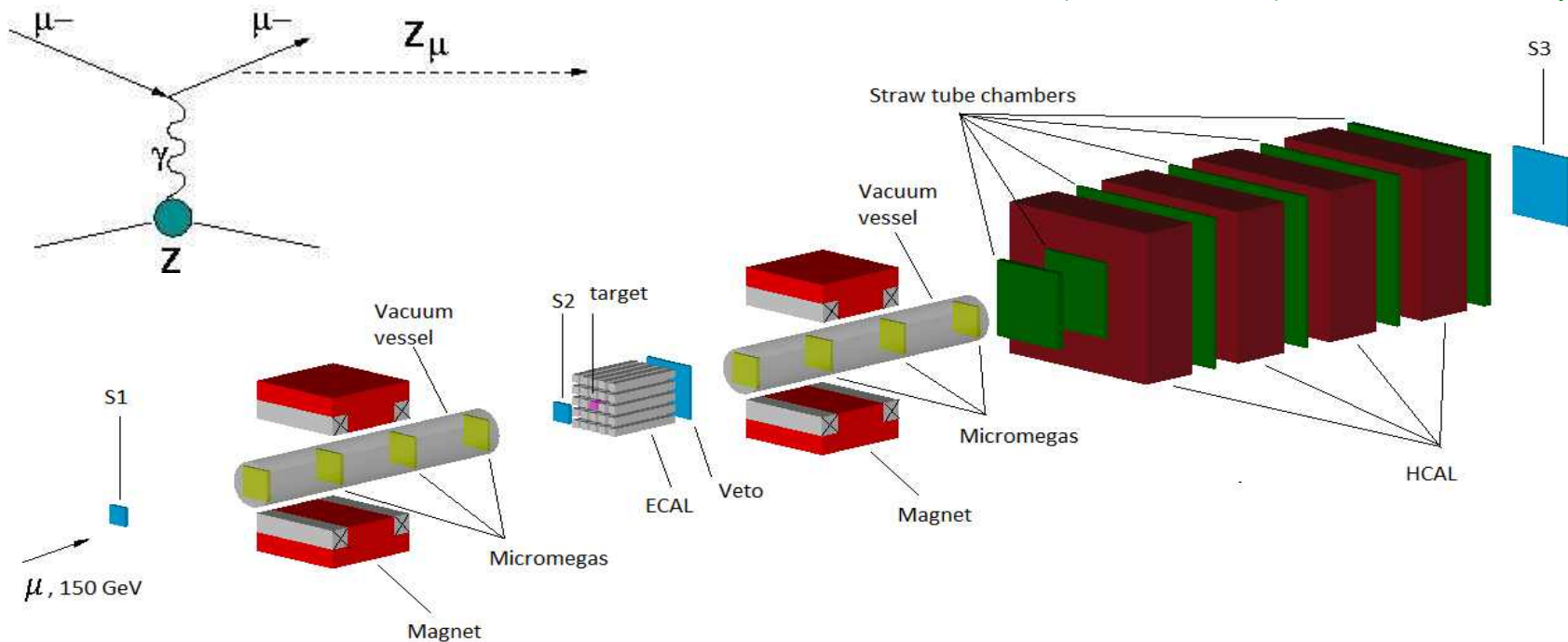
Altmannshofer et al.,
 arXiv:1406.2332



From J.Heeck PLB'16

Source of Z_μ :

SG, Krasnikov, Matveev PRD(2015)



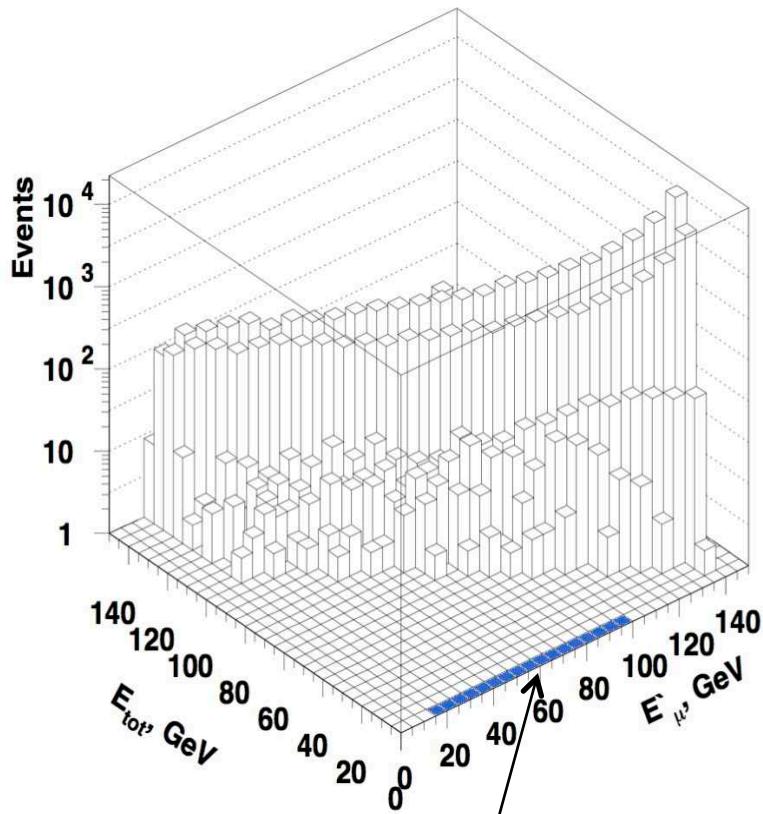
Main components :

- clean, mono-energ. 150 GeV μ^- beam
- in μ tagging: MM/GEM tracker
- out μ tagging: GEM/Straw tracker
- 4π fully hermetic ECAL+ HCAL

Signature:

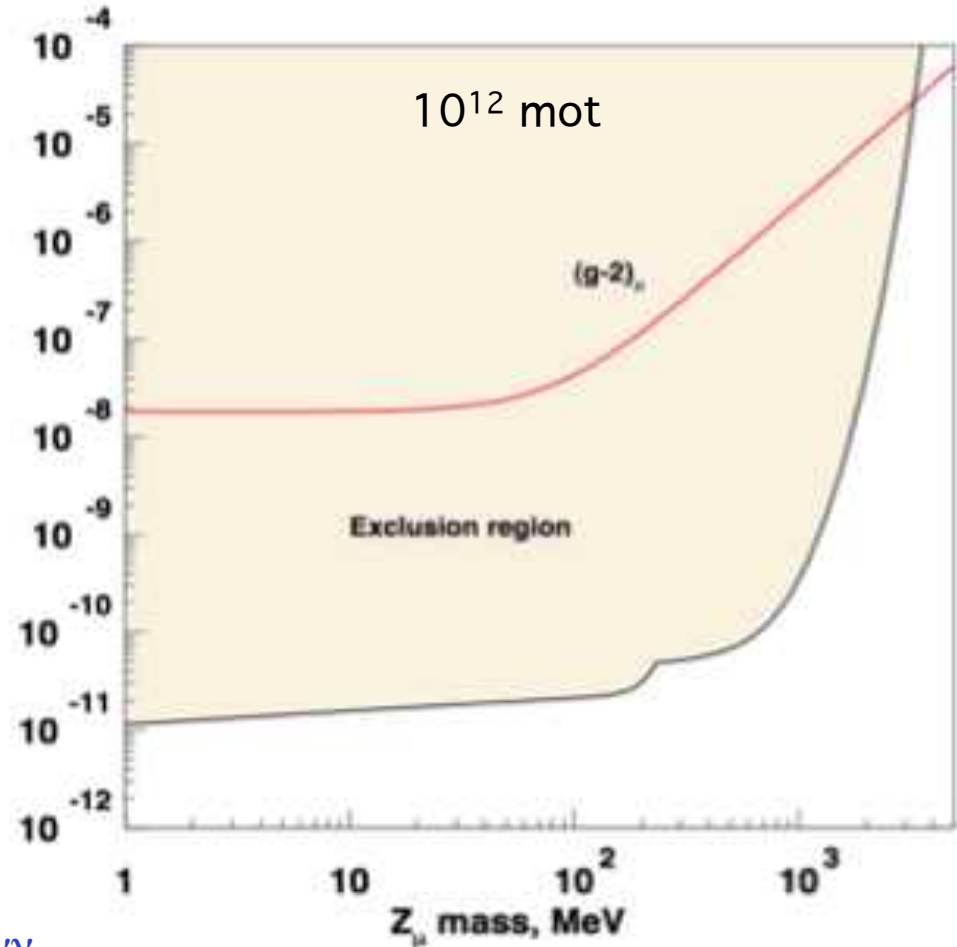
- in: 150 GeV μ^- track
- out: < 100 GeV μ^- track
- no energy in the ECAL, Veto, HCAL
- Sensitivity $\sim g_\mu^2$

Expected exclusion area



Signature for $\mu Z \rightarrow \mu' Z Z'$; $Z' \rightarrow \nu\nu$
in $(E_{\mu'}; E_{\text{tot}})$ plane

Same signature for LFV $\mu \rightarrow \tau \rightarrow \mu\nu\nu$
conversion





π , K , p beams

Search for
 $\pi^0, \eta, \eta', K_S, K_L \rightarrow$ invisible
decays and
light Dark Matter

Rare π, η, η' $\rightarrow l_i l_j$ decays (PDG' 15) as a probe of NP ^{17.}

$P \rightarrow l_i l_j$	
Visible	
$\pi^0 \rightarrow ee$	6.46×10^{-8}
$\pi^0 \rightarrow e\mu$	$< 3.8 \times 10^{-10}$
$\eta \rightarrow ee$	$< 5.6 \times 10^{-6}$
$\eta \rightarrow \mu\mu$	5.8×10^{-6}
$\eta \rightarrow e\mu$	6.0×10^{-6}
$\eta' \rightarrow ee$	$< 5.6 \times 10^{-6}$
$\eta' \rightarrow e\mu$	$< 4.7 \times 10^{-4}$
Invisible	
$\pi^0 \rightarrow \nu\nu$	$< 2.7 \times 10^{-7}$
$\eta \rightarrow \text{invis}$	$< 1.0 \times 10^{-4}$
$\eta' \rightarrow \text{invis}$	$< 5 \times 10^{-4}$

Motivation for π^0, η, η' ($J^P=0^-$) \rightarrow invisible

- In SM $\pi, \eta \rightarrow \nu\nu$ strongly suppressed
 $\text{Br}(\pi^0, \eta \rightarrow \nu\nu) \sim 10^{-10} - 10^{-11}$ if $m_\nu = 18$ MeV
- ideal to test pseudoscalar WI
- final state could be sub-GeV DM
- $\pi^0=(u,d)$, η has admixture of s-quarks
- Impact on: ν -Physics, cosmology.

- E949 BNL, LSND
- BESII, BABAR, CLEO
- BESIII

Rare $K^0 \rightarrow l_i l_j$, $\pi l_i l_j$ decays (PDG'15) as a probe of NP ^{18.}

$K^0 \rightarrow l_i l_j$	BR	$K^{0,+} \rightarrow \pi l_i l_j$	BR
Visible		Visible	
$K^0_S \rightarrow ee$	$< 9 \times 10^{-9}$	$K^0_S \rightarrow \pi^0 ee$	3.0×10^{-9}
$K^0_S \rightarrow \mu\mu$	$< 9 \times 10^{-9}$	$K^0_S \rightarrow \pi^0 \mu\mu$	3.0×10^{-9}
$K^0_L \rightarrow ee$	9.0×10^{-12}	$K^0_L \rightarrow \pi^0 ee$	$< 2.8 \times 10^{-10}$
$K^0_L \rightarrow \mu\mu$	6.8×10^{-9}	$K^0_L \rightarrow \pi^0 \mu\mu$	$< 3.8 \times 10^{-10}$
$K^0_L \rightarrow e\mu$	$< 4.7 \times 10^{-12}$	$K^+ \rightarrow \pi \mu e$	$< 1.3 \times 10^{-11}$
		$K^0_L \rightarrow \pi^0 \mu e$	$< 7.6 \times 10^{-11}$
Invisible		Invisible	
$K^0_S \rightarrow \nu\nu$	never	$K^+ \rightarrow \pi^+ \nu\nu$	1.7×10^{-10}
$K^0_L \rightarrow \nu\nu$	tested	$K^0_L \rightarrow \pi^0 \nu\nu$	$< 2.6 \times 10^{-8}$

Motivation

- In SM $K^0 \rightarrow \nu\nu$ suppressed
 $\text{Br}(K^0 \rightarrow \nu\nu) \sim 10^{-10}$ $m_\nu = 18$ MeV
- could occur in 2HDM, 2HDM+ light scalars, mirror model, ..
- in some scenarios could be at $\text{Br}(K^0 \rightarrow \text{inv}) \sim 10^{-8} - 10^{-6}$ and not constrained by $K \rightarrow \pi \nu\nu$.
- clean probe of NP scales above **100 TeV**,
 Complementary to $K \rightarrow \pi \nu\nu$

(NA62)

Rare kaon decays with “missing energy”

William J. Marciano and Zohreh Parsa

PRD(R)'96.

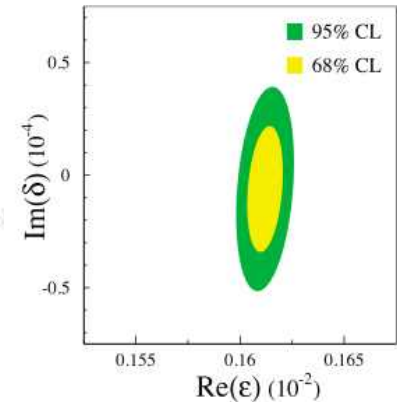
and $K_L \rightarrow \nu \bar{\nu}$ (if neutrinos have mass). Those decays would be interesting to explore, but their detection looks essentially impossible. New ingenious experimental ideas are required.

Bell-Steinberger relation (PDG'15)

Sensitive test of CPT symmetry.

$$\left[\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan \phi_{sw} \right] \left[\frac{\Re(\epsilon)}{1 + |\epsilon|^2} - i \Im(\delta) \right] = \frac{1}{\Gamma_S - \Gamma_L} \sum \langle \Gamma | T | K_L \rangle \langle \Gamma | T | K_S \rangle^*$$

CPV
CPTV



Unitarity implies a link between CP and CPT-violating parameters and the (CPV) physical decay amplitudes in the K system.

arXiv:1401.6938v1 [hep-ex]

MITP/13-089
12 July 2013

$$\Re(\epsilon) = (161.1 \pm 0.5) \times 10^{-5},$$

$$\Im(\delta) = (-0.7 \pm 1.4) \times 10^{-5}.$$

(assuming no significant undiscovered K_S, K_L decays!)

Conclusions of the MITP Workshop on
T Violation and CPT Tests in Neutral-Meson Systems

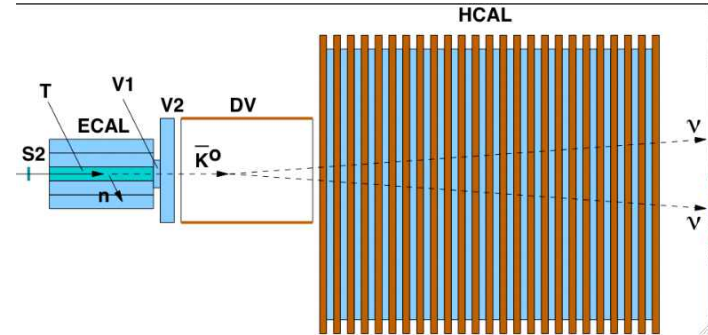
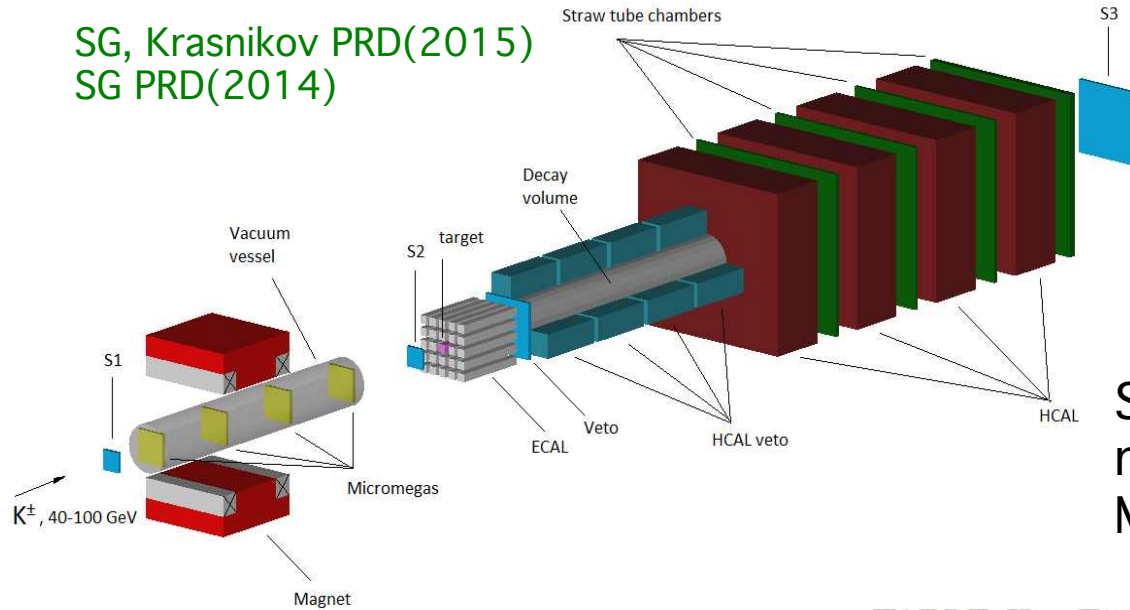
K. R. Schubert^{1,2}, L. Li Gioi³, A. J. Bevan⁴ and A. Di Domenico⁵

The most sensitive tests of CPT symmetry remain the Bell-Steinberger analyses of the $K^0 \bar{K}^0$ system using unitarity which connects the CP-symmetry properties of all observed K_S and K_L decay modes with the CPT- and T-sensitive overlap $\langle K_L | K_S \rangle$. These analyses started in 1970 and have reached the impressive sensitivity of $|m(\bar{K}^0) - m(K^0)| < 4 \cdot 10^{-19}$ GeV at 95% C.L. in 2012, as presented by G. D'Ambrosio at the workshop. An open question remains by how much invisible decays of neutral K mesons can influence the result. How well is unitarity tested experimentally?

$Br(K_S \rightarrow inv) \approx 10^{-5}$, $Br(K_L \rightarrow inv) \Gamma_L / \Gamma_S \approx 10^{-5}$ still can contribute to B-S
NA64 can improve these limits by a few orders of magnitudes

$K_L \rightarrow$ invisible: nothing in, nothing out

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



Source of M^0 : charge exchange reactions: $\pi^-, K^- + p \rightarrow M^0 + n$
 $M^0 = \pi^0, \eta, \eta', K_L, K_S \dots$

Main components :

- 20–50 GeV π, K^- beam
- MM/GEM tracker, ECAL-Veto target
- 4 π fully hermetic ECAL+ HCAL

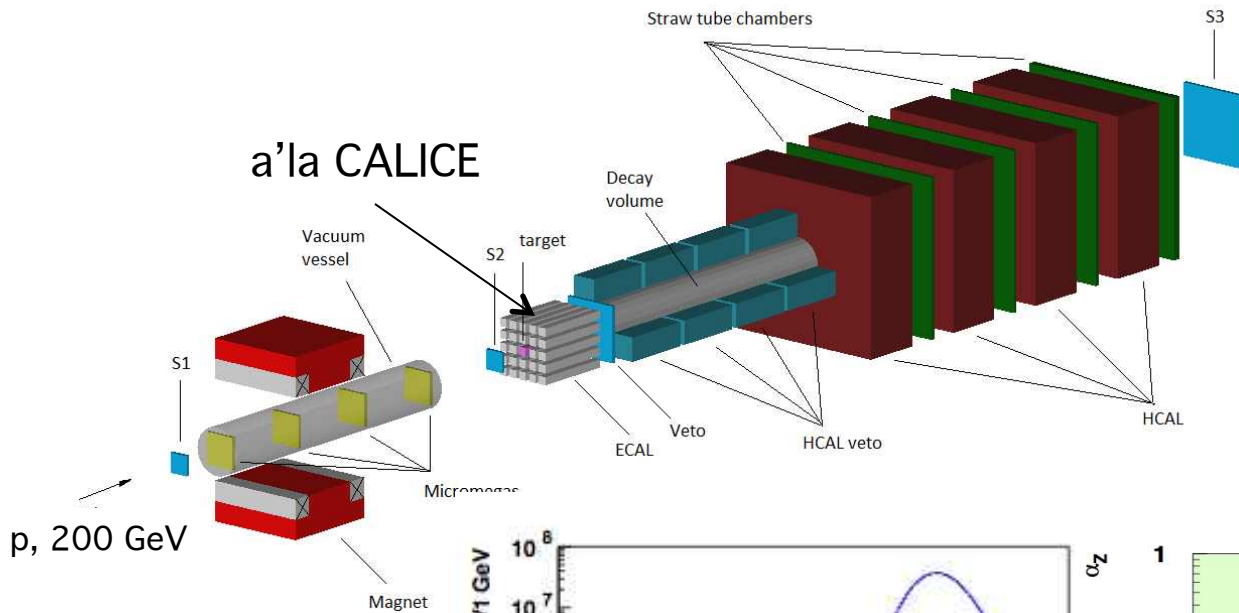
Signature:

- in: 20–50 GeV π, K^- track
- out: no energy in ECAL, Veto, HCAL

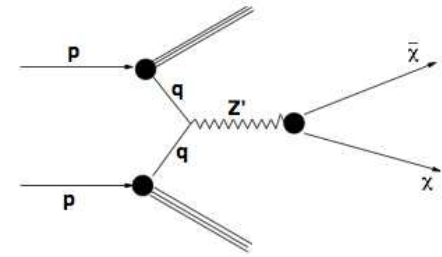
Complete disappearance of beam energy !

TABLE II. Expected upper limits on the branching ratios of different decays into invisible final states calculated for the total number of 10^{12} incident pions or kaons (see text for details).

Expected limits on	Present limit
the branching ratio	
$Br(K_S \rightarrow \text{invisible}) \lesssim 10^{-8}$	no
$Br(K_L \rightarrow \text{invisible}) \lesssim 10^{-6}$	no
$Br(\pi^0 \rightarrow \text{invisible}) \lesssim 10^{-8}$	$< 2.7 \times 10^{-7}$ [2]
$Br(\eta \rightarrow \text{invisible}) \lesssim 10^{-7}$	$< 1.0 \times 10^{-4}$ [3] ^a
$Br(\eta' \rightarrow \text{invisible}) \lesssim 10^{-6}$	$< 5.2 \times 10^{-4}$ [3] ^a

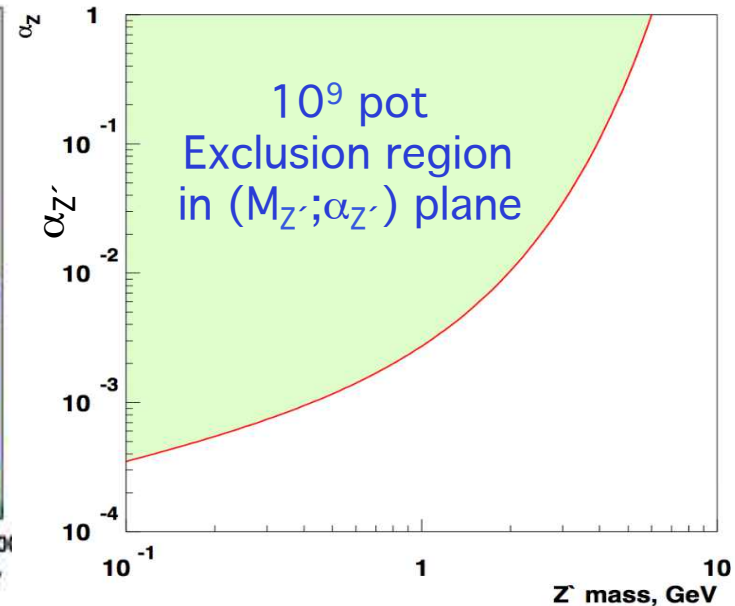
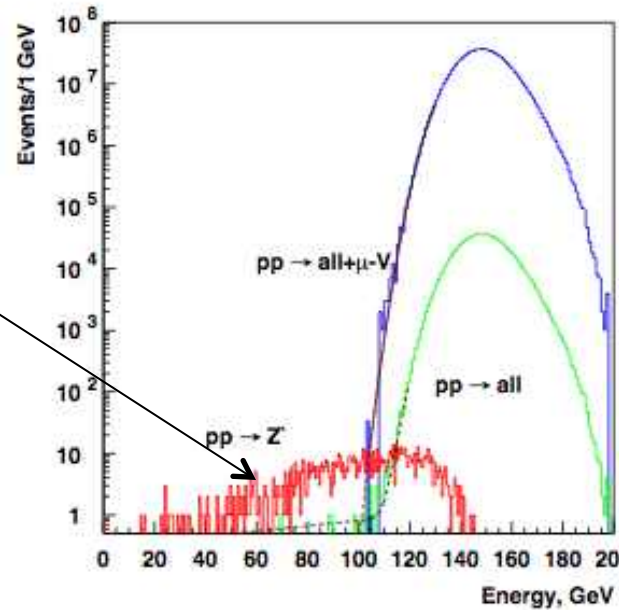


Source of Z' :



E_{miss}

$pA \rightarrow X + Z'$; $Z' \rightarrow \chi\chi$
 Z' – leptophobic boson
 $\alpha_{Z'}$ – q - Z' coupling const.



Physics prospects (<http://na64.web.cern.ch>)

Process	New Physics	Sensitivity
1. $e^- Z \rightarrow e^- Z + E_{\text{miss}}$		
<ul style="list-style-type: none"> ✧ $A' \rightarrow e^+ e^-$ ✧ $A' \rightarrow \text{invisible}$ ✧ alps ✧ milli-q 	Dark Sectors: Dark Photons and DM $(g-2)_\mu$ new particles, Charge Quantization	$10^{-3} < \epsilon < 10^{-6}$ $M_{A'} \sim \text{sub-GeV}$ $e' < 10^{-5} - 10^{-7}$
2. $\mu^- Z \rightarrow \mu^- Z + E_{\text{miss}}$		
<ul style="list-style-type: none"> ✧ $Z_\mu \rightarrow \nu\nu, \mu^+ \mu^-$ ✧ $\mu \rightarrow \tau$ conversion 	New gauged symmetry $L_\mu - L_\tau$ and leptonic forces LFV	$\alpha_\mu < 10^{-11} - 10^{-9}$ $\sigma < 10^{-9} - 10^{-8} / \mu$
3. $\pi (K) p \rightarrow M^0 n + E_{\text{miss}}$		
<ul style="list-style-type: none"> ✧ $K_L \rightarrow \text{invisible}$ ✧ $K_S \rightarrow \text{invisible}$ ✧ $\pi^0, \eta, \eta \rightarrow \text{invisible}$ 	CP, CPT symmetry B-S Unitarity, new particles: NHL, $\phi\phi, VV$	$\text{Br} < 10^{-8} - 10^{-6}$, complementary to $K \rightarrow \pi \nu \nu$ $\text{Br} < 10^{-8} - 10^{-7}$
4. $pA \rightarrow X + E_{\text{miss}}$		
✧ leptophobic X	$\sim \text{GeV DM}$	$\sigma < 10^{-7} - 10^{-8} / p$

Beams and running time

Beam	Energy, GeV	Intensity per spill	Period, months	N_{tot}	Process
e^-	~ 100	$\sim 10^6$	~ 6 ~ 6	$\sim 10^{12}$ $\sim 10^{12}$	$eZ \rightarrow eZA'$; $A' \rightarrow \text{inv}$ $A' \rightarrow ee$
μ^-	~ 150	$\sim 10^6$	~ 6	$10^{12} - 10^{13}$	$\mu Z \rightarrow \mu ZZ'$, $Z' \rightarrow \nu\nu$ $\mu Z \rightarrow \tau Z$ $\tau \rightarrow \mu\nu\nu$
π^-	$\sim 20 - 50$	$\sim 10^6$	~ 6	$10^{12} - 10^{13}$	$\pi A \rightarrow \pi^0, \eta, \eta' A$ $\pi^0, \eta, \eta' \rightarrow \text{inv}$
K^-	$\sim 20 - 50$	$\sim 10^6$	~ 6	$\sim 10^{12}$	$KA \rightarrow K^0 A$ $K_S, K_L \rightarrow \text{inv}$
p	$200 - 400$	$\sim 10^6$	~ 6	$\sim 10^{11}$	$pA \rightarrow pAZ'$ $Z' \rightarrow \chi\chi$

Summary

- The conceptual idea of NA64 is to search for dark photons in missing-energy events with an active beam dump experiment. The capability of the approach has been shown in Runs 2015-16.
- The proposed NA64 research program is significantly extended by the inclusion of measurements with $e, \mu, \pi, K,$ and p beams aiming to search for dark sector physics, new symmetries, and new WI particles with sub-GeV masses that coupled to leptons and/or q' s.
- These are experiments at high-intensity and –sensitivity frontier which can be performed at the existing facilities at CERN in the medium term future. They can deliver rich and compelling physics results, complementary to those at the LHC. In some cases a parameter space in physics beyond the SM, that is inaccessible to direct searches at the LHC or at future colliders can be covered.

Signature for $eZ \rightarrow eZA'$; $A' \rightarrow$ invisible

GEANT4+code for A' emission in the process of e-m shower development $\sigma(eZ \rightarrow eZA')$ from Bjorken et al. '09

