ПОИСК ЛЕГКОЙ ТЕМНОЙ МАТЕРИИ

Эксперимент NA64 в ЦЕРНе

Н.В. Красников
ИЯИ РАН

В последние 5-7 лет модели с легкой темной материей стали привлекать большое внимание специалистов.

Один из наиболее часто обсуждаемых вариантов – модели с дополнительным массивным векторным бозоном.

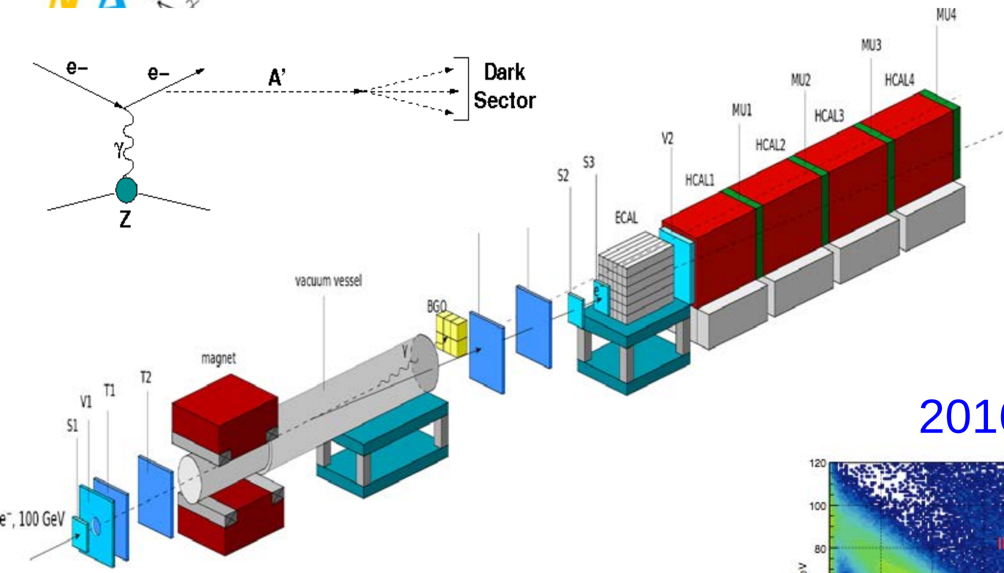
NA64

NA64 designed to search for new physics in missing-energy events was approved in March’16. A wider program of searches with e^-, μ, π, K, p beams was proposed at PBC’16.

e^- beam

- dark pseudoscalar(s), vector(A´) → invisible decays
- s, A´→ e+e- decays
- ^{8}Be* anomaly: a new light boson?
- ALP: a → $\gamma\gamma$
- milli-Q

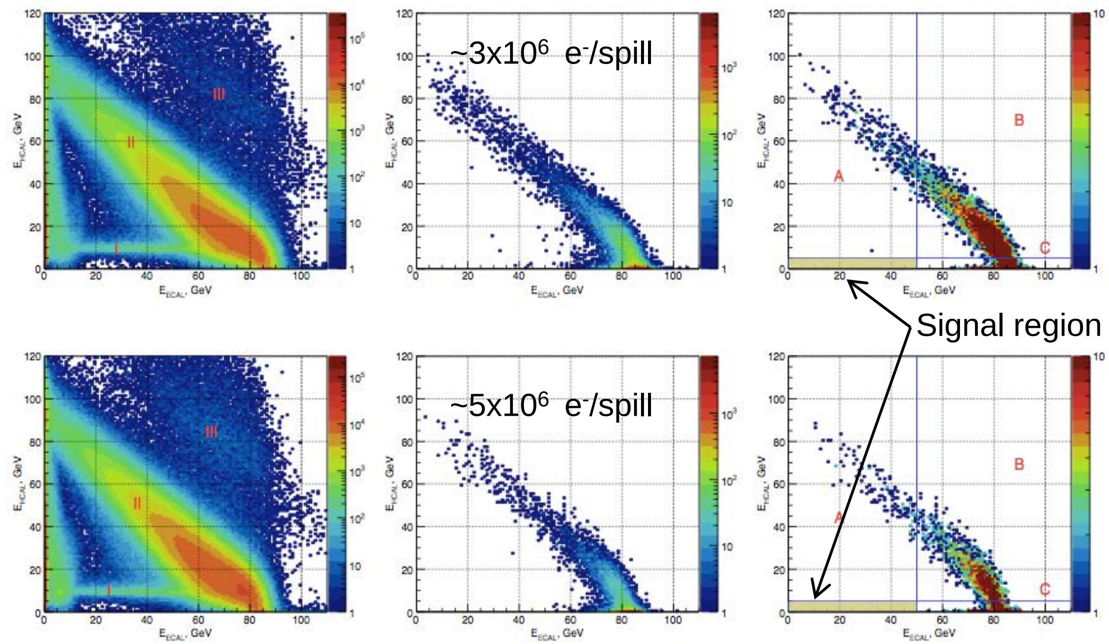
Search for A´->invisible decays at the CERN SPS



Signature:

- in: 100 GeV e- track
- out: $E_{ECAL} < E_0$ shower in ECAL
- no energy in Veto and HCAL

2016 run: $0.3\text{x}10^{10}$(July)+$4\text{x}10^{10}$(Oct) EOT



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

Main components :

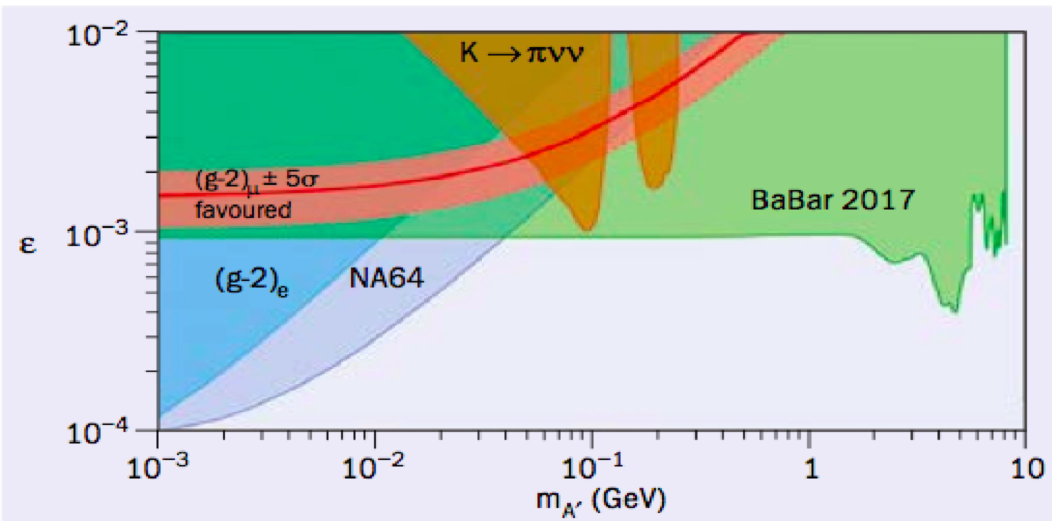
- clean 100 GeV e- beam
- e- tagging: tracker+SRD
- fully hermetic ECAL+HCAL

No A´signal for $4.3\text{x}10^{10}$ EOT

July’16 run: A´explanation for$(g-2)_\mu$ is ruled out

CERN Courier April 2017

News



Regions of the dark-photon parameter space (mixing strength versus mass) excluded by BaBar (green) compared with the previous constraints. The new analysis rules out dark-photon coupling as the explanation for the muon (g-2) anomaly and places stringent constraints on dark-sector models.

of Caltech, who has worked on dark-photon models. “In contrast to massless dark photons, which are analogous to ordinary photons, this experiment constrains a slightly different idea of dark force-carrying particles that are associated with a broken symmetry, which therefore get a mass and then can decay. They are more like ‘dark Z bosons’ than dark photons.”

Further reading

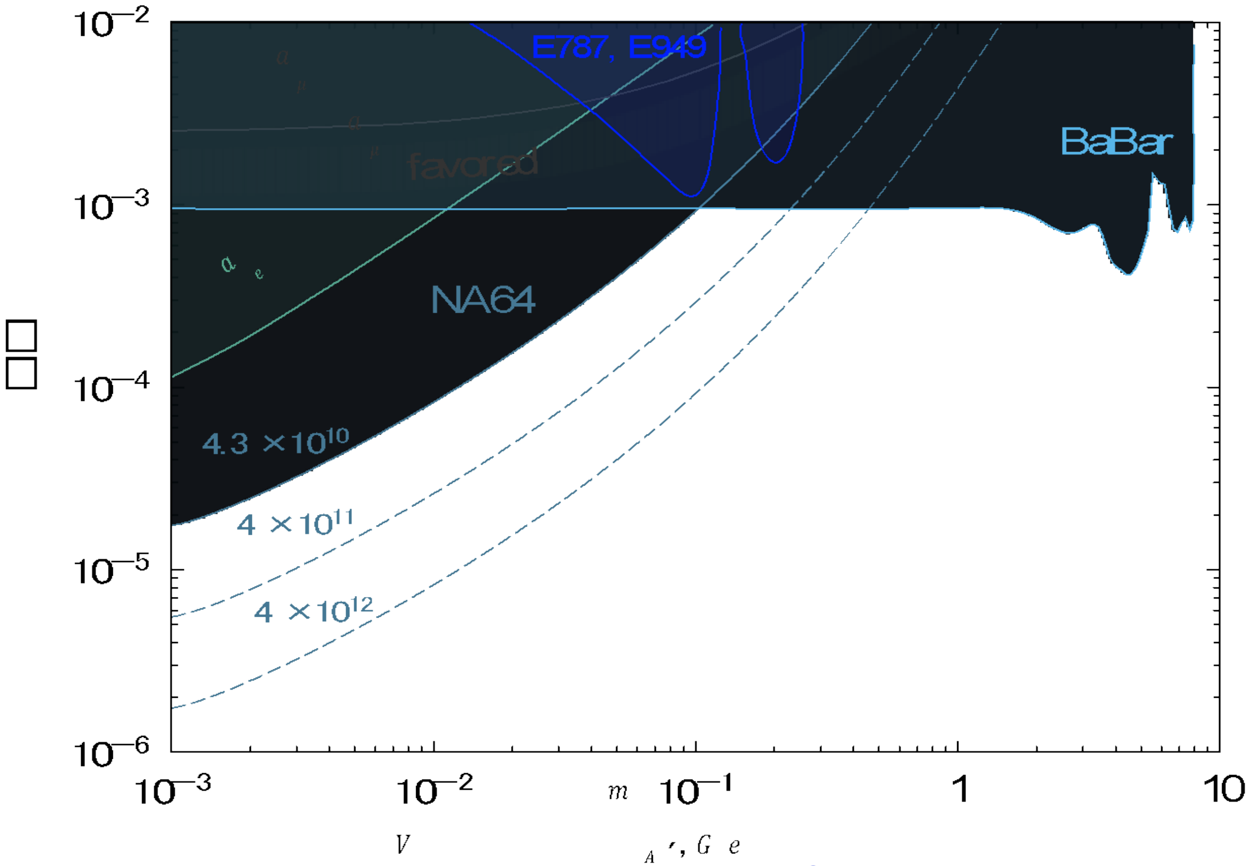
BaBar Collaboration 2017 arXiv:1702.03327.
NA64 Collaboration 2017 *Phys. Rev. Lett.* **118** 011802.

2016 Results, Projected Sensitivity

arXiv: 1710.00971

Exact tree-level calculations of cross sections $\sigma(eZ \to eZA')$.

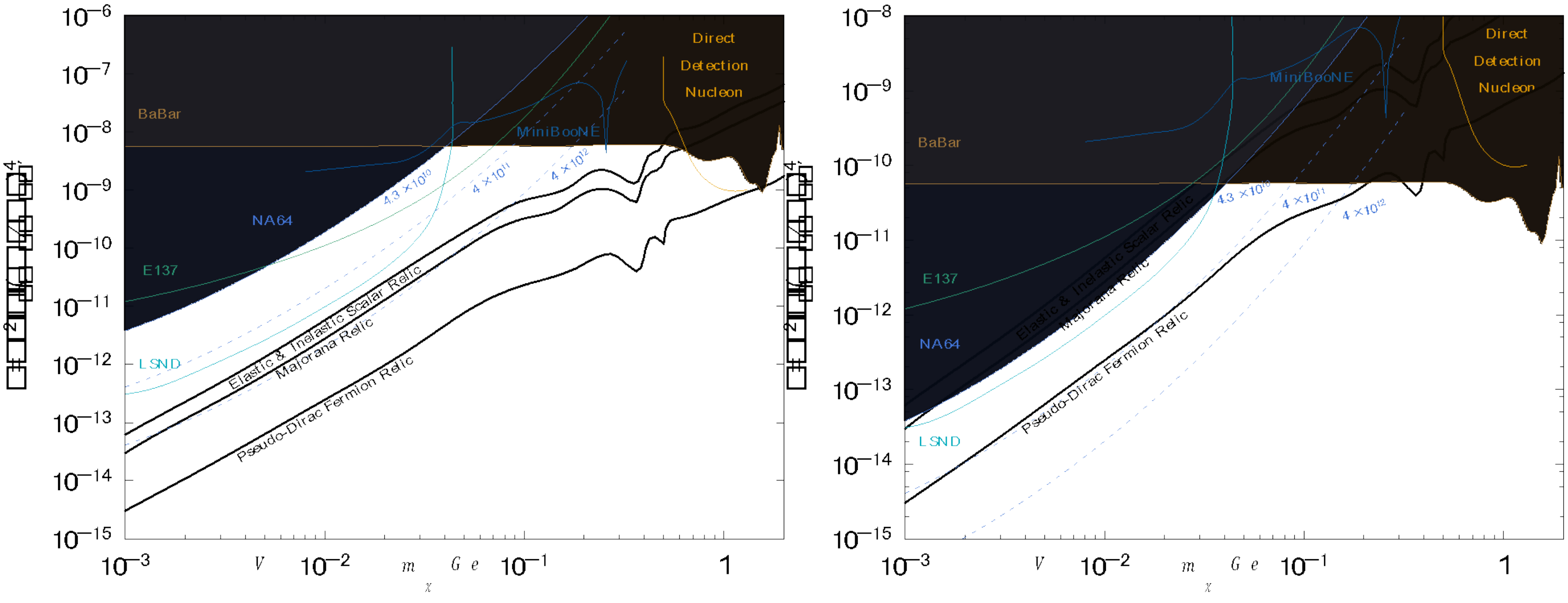
Large corrections to the WW approximation for $m_{A'} > \sim 100$ MeV.



Plans to accumulate ~ 4×10^{12} EOT after LS2

Projected Sensitivity for Light Thermal Dark Matter

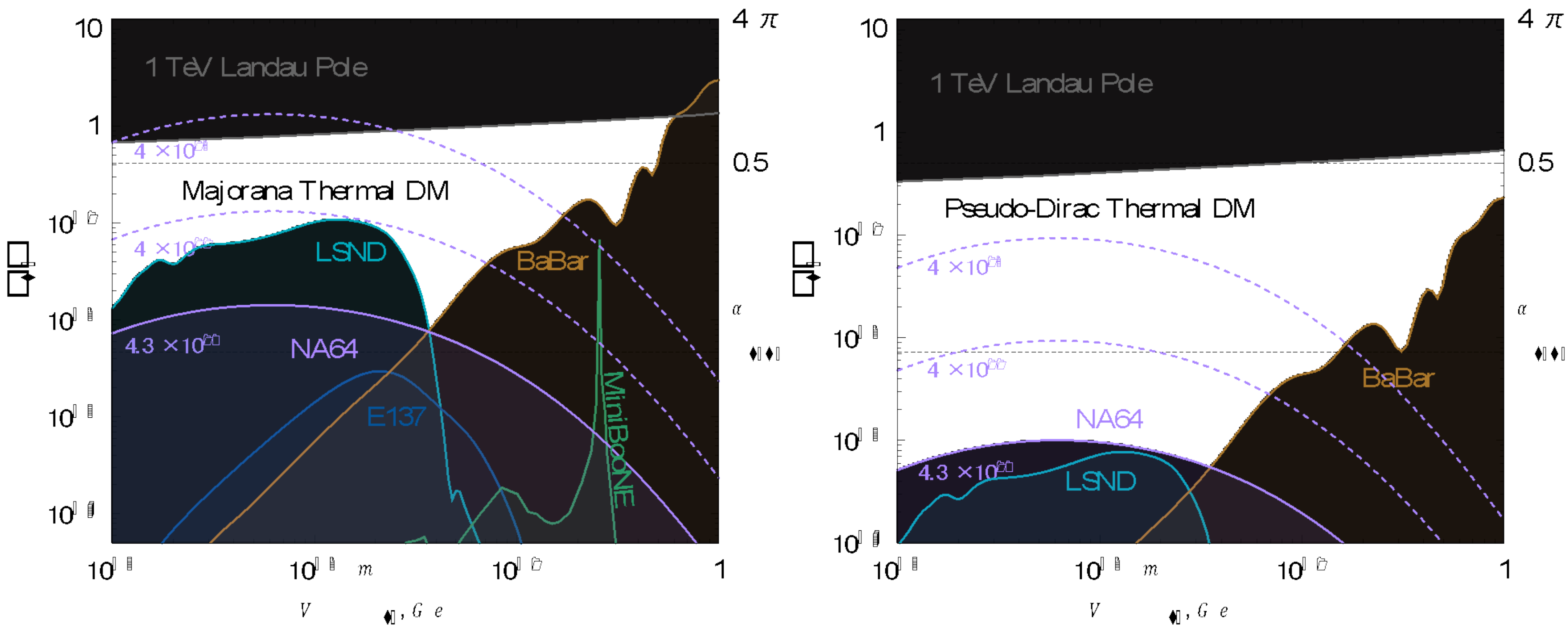
α_D (~ α_S) = 0.5, $m_{A'}$ = 0.3m_χ α_D (~ α_{EM}) = 0.005, $m_{A'}$ = 0.3m_χ



- Sensitivity of a beam-dump ~$\varepsilon^2 \times \varepsilon^2 \alpha_D (m_\chi/m_{A'})^4 = \varepsilon^2 y$, NA64~$\varepsilon^2$
- Constraints on relic adandance from freeze out annihilation
- Bounds from LSND, SLAC, MiniBooNE for ~10^{22}, 10^{19}, 10^{20} POT
- NA64 can cover significant area with ~ a few 10^{12} EOT

2016 Results and Expected Bounds on α_D

$m_{A'} = 0.3\ m_\chi$



Sensitivity to p-s, A´->invisible decays, $m_{ps,A´}$ <1MeV

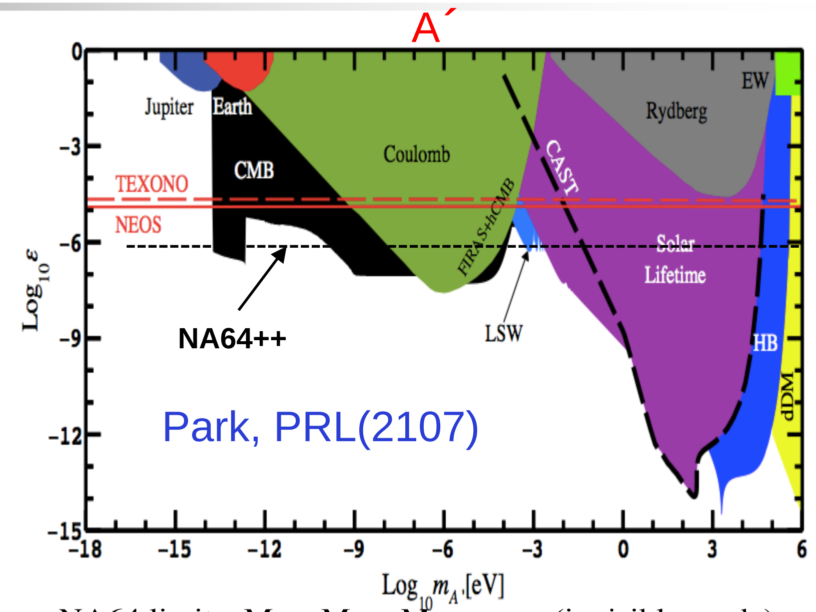
Thanks to J. Jaeckel.

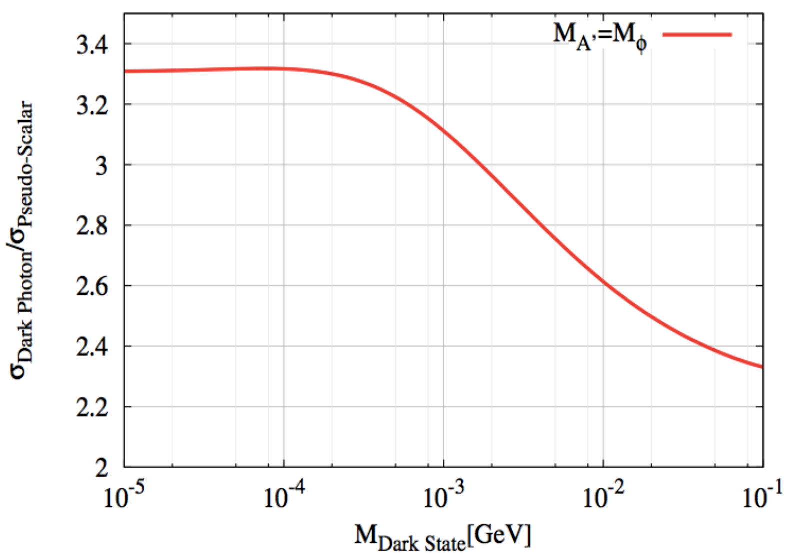
Pseudoscalar case, $m_{ps,V}$<1 MeV

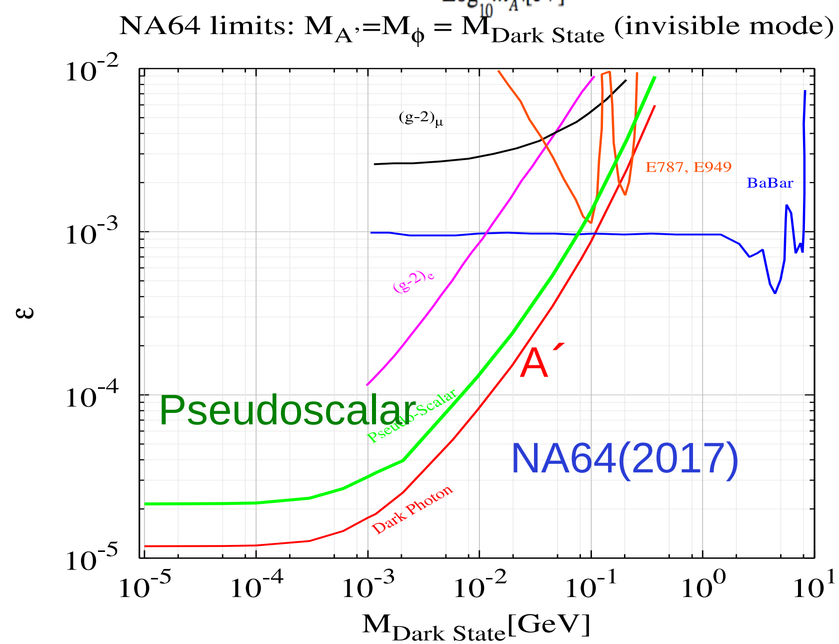
- Calculation of $\sigma_{A´}/\sigma_{S}$,
- Full simulation in progress

$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$$

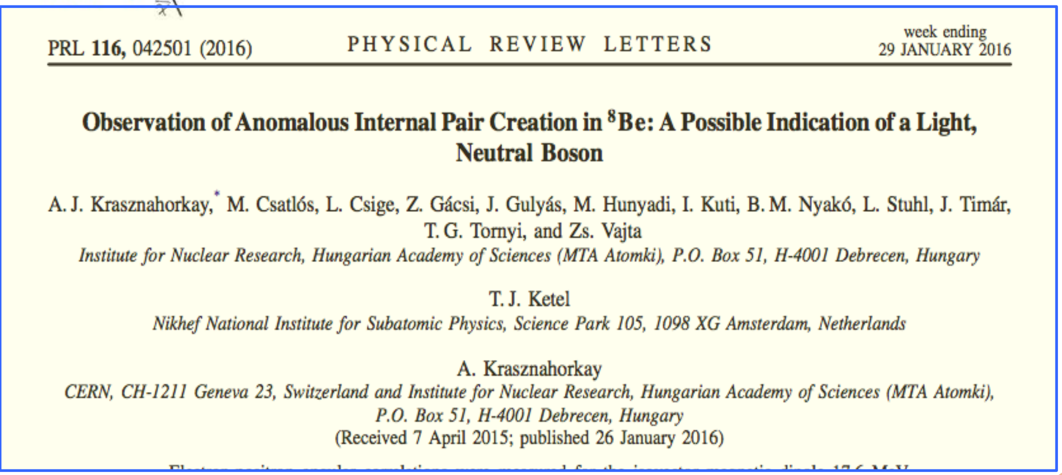
$$g_{ps} = m_e/f^e_a = \varepsilon e$$







$^{8}Be^{*}$ anomaly: a new light X boson?



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

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
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(Received 7 April 2015; published 26 January 2016)

^{7}Li(p,γ)^{8}Be, M_X =16.7 MeV

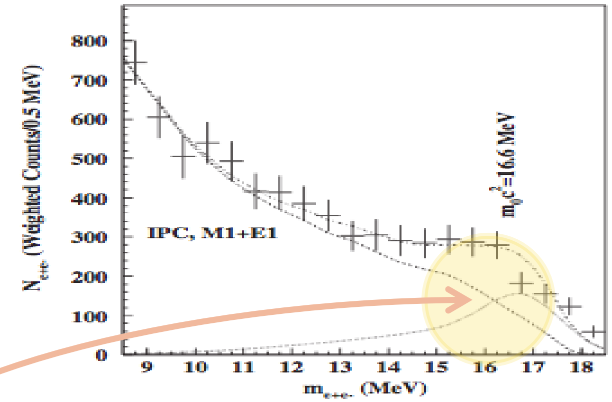
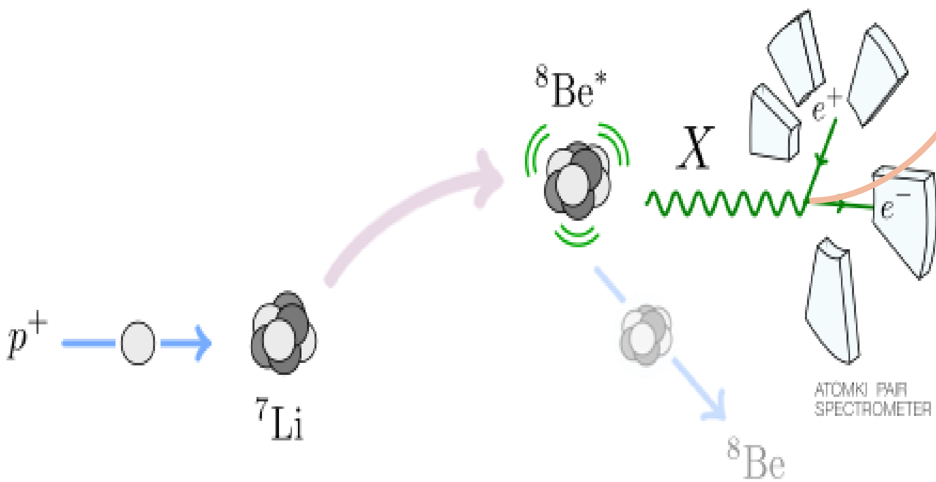


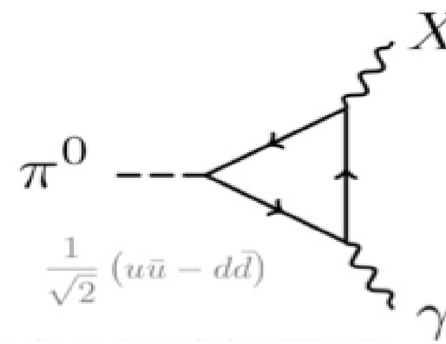
FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.



Feng et al, 2016

$2 \times 10^{-4} < \varepsilon_e < 1.4 \times 10^{-3}$

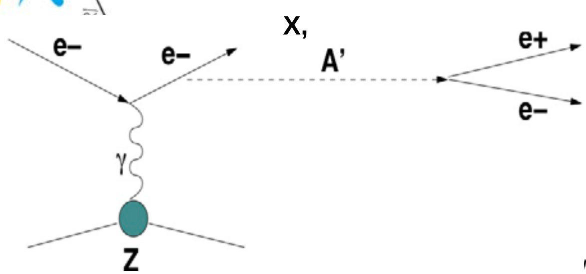
X cannot be A´ due to constraints from $\pi^0 \to X\gamma$ decay:



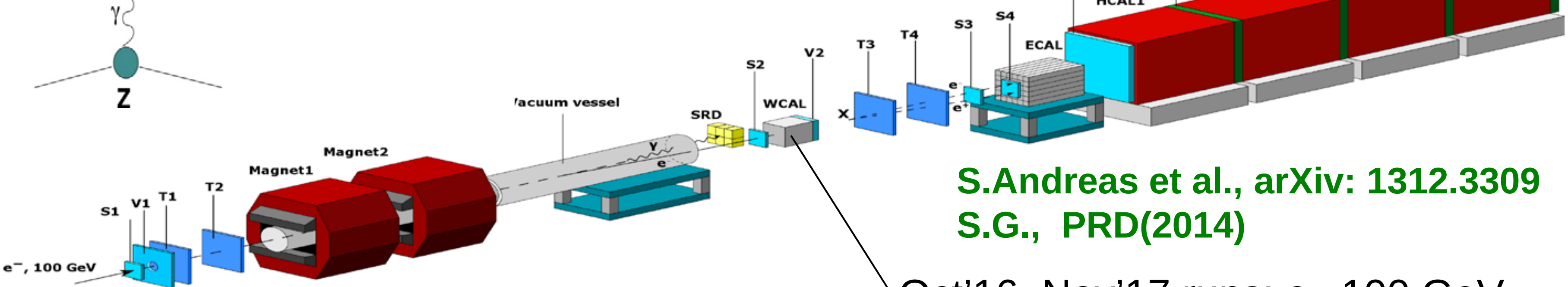
$\Gamma(\pi^0 \to X\gamma) \sim (\varepsilon_u q_u - \varepsilon_d q_d)^2 \sim 0$

if $2\varepsilon_u = -\varepsilon_d$ -> protophobic X

Search for the X,A´->e^+e^- and a ->$\gamma\gamma$ decays

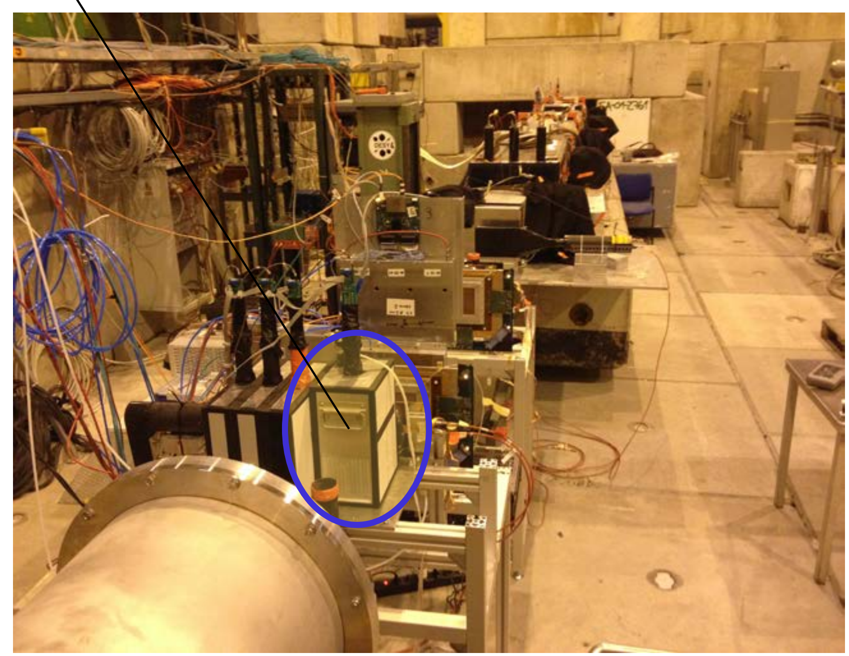


$\sigma_X/\sigma_\gamma \sim 10^{-10}$, $\tau_X \sim 10^{-13}$ s



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

Oct'16, Nov'17 runs: e^-, 100 GeV



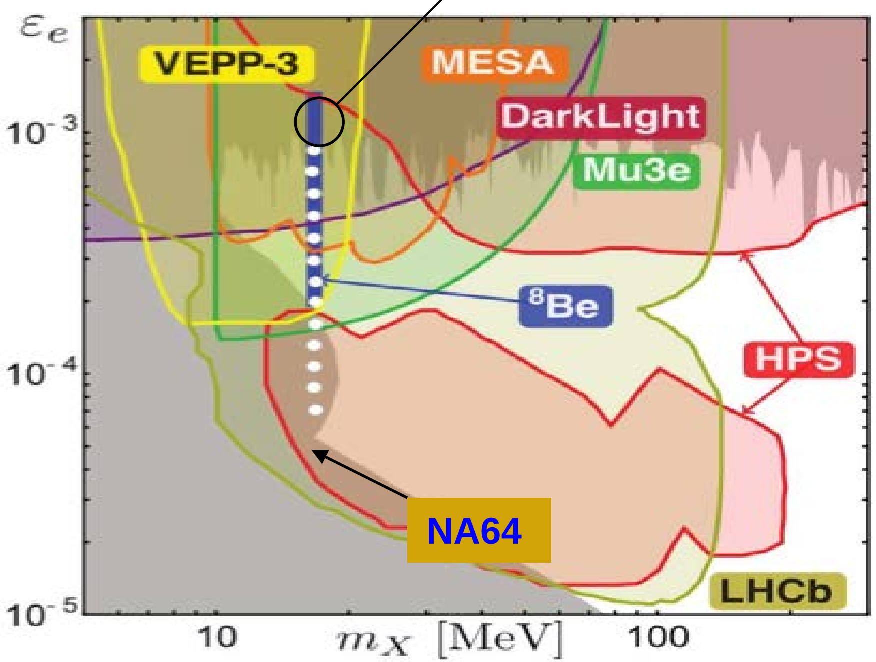
- X's decay mostly outside WCAL
- Signature: two separated showers from a single e-
- $E_{WC} < E_0$, and $E_0 = E_{WC} + E_{EC}$
- θ_{e+e-} too small to be resolved
- background mainly from

-bremss γ punchthrough

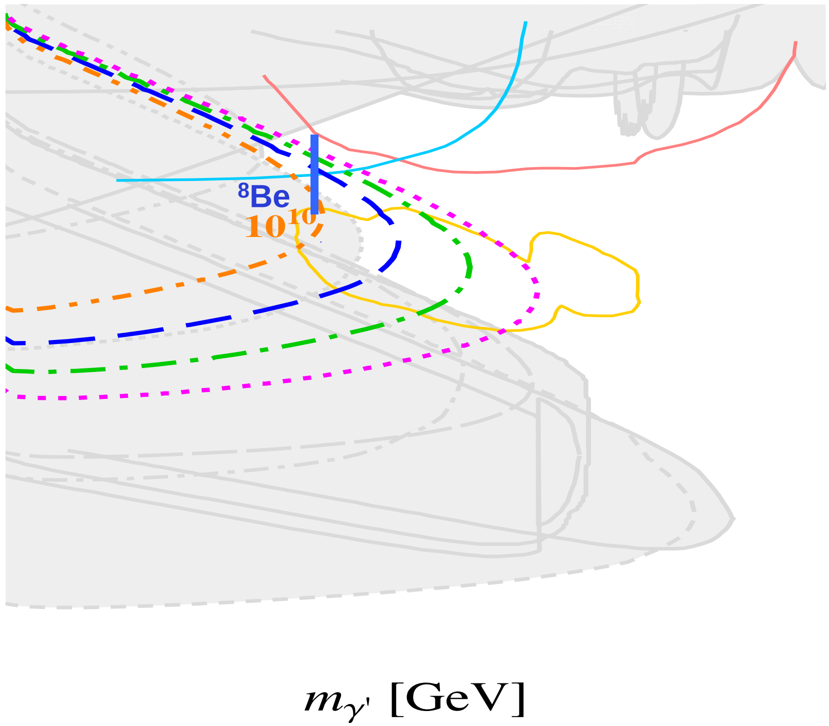
-beam and secondary hadrons

Expected Bounds on X, A´→ e+e

Could be covered by using Si pixels Under study.



X, A´→ e+e-



2016 – test run

2017 - ~ 5 10^{10} EOT at 100 GeV. Analysis in progress. 2018+beyond LS2 - ~ 10^{11} EOT at 150 GeV required

μ beam

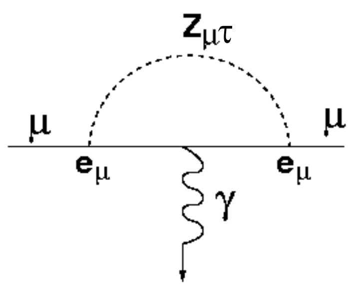
- (pseudo)scalar, $Z_{\mu\tau}$ → invisible decays
- (pseudo)scalar, $Z_{\mu\tau}$ → $\mu^+\mu^-$ decays
- μ - τ conversion

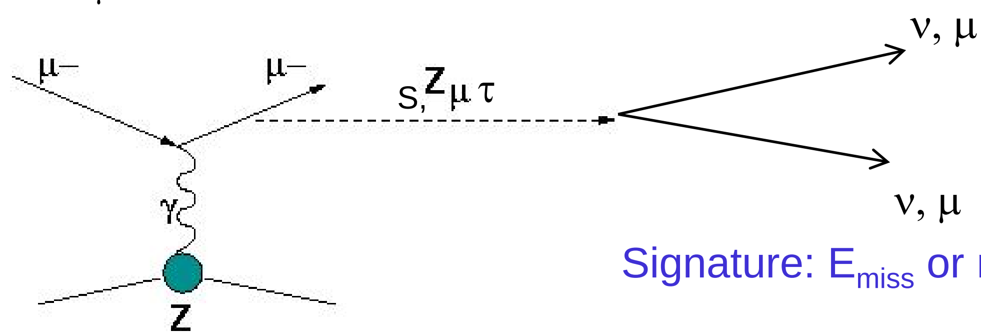
$Z_{\mu\tau} = L_\mu - L_\tau$ gauge boson

Searches for E_{miss} in muon events

Motivated by g_μ-2 and other anomalies, Dark Matter, LFV, ..

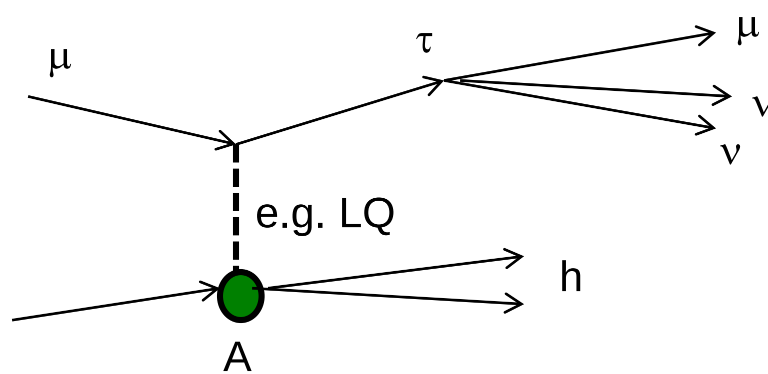
1. Search for a new sub-GeV $Z_{\mu\tau}$, (pseudo)scalars coupled to μ and τ





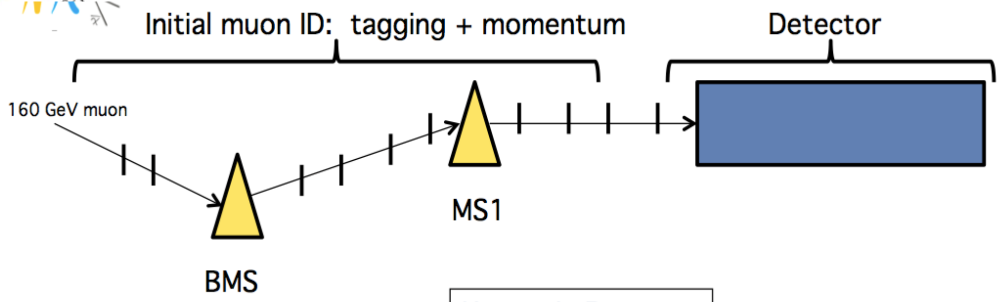
Signature: E_{miss} or $m_{\mu\mu}$

2. Search for LFV: μ-τ conversion, complementary to e-τ at HERA

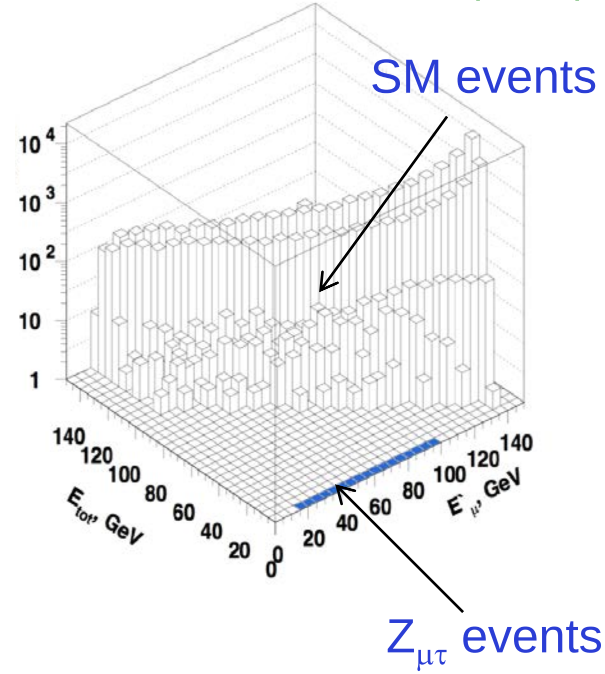


Signature: E_{miss}

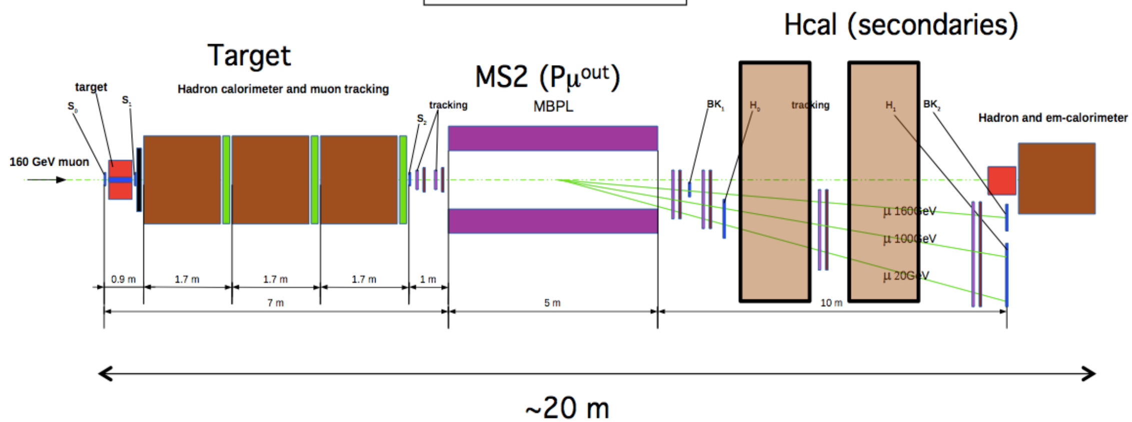
Search for $Z_{\mu\tau}$ in missing energy events with M2 beam



SG, Krasnikov, Matveev PRD(2015)



Hermetic Detector



Main components :

- clean, mono-energ. 160 GeV μ- beam
- in μ tagging: MM/GEM tracker
- out μ tagging: GEM/Straw tracker
- 4π fully hermetic detector

Signature:

- in: 160 GeV μ- track
- out: < 100 GeV μ- track
- no energy in the ECAL, Veto, HCAL
- Sensitivity ~ g_Z^2

Update on PBC'16 list of issues

Thanks to C. Vallee and COMPASS

- P_μ^{in} momentum measurements.
  Cross-check: available COMPASS data sample vs MC under study.

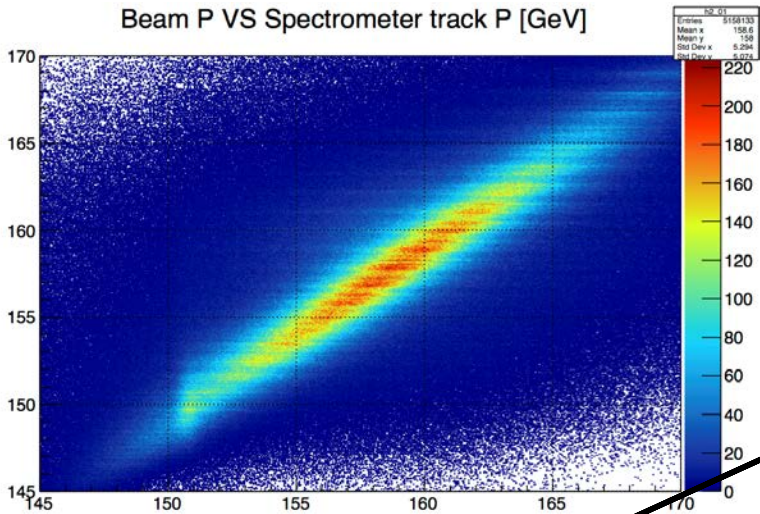
- M2 μ intensity: $I_\mu \sim 10^7 – 10^8$ μ/spill. Trigger rate.

- Background due to π , K -> $\mu\nu$ decays.
  Hadron contaminantion, expected $\pi/\mu \sim 10^{-6}$ or so.
  Beam test at COMPASS in October. Currenly under study.

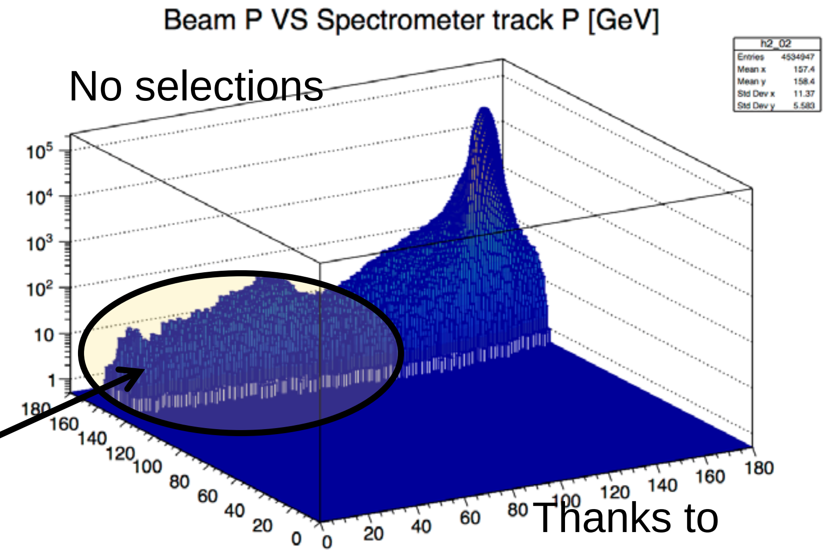
- HCAL size optimization :
  - Hermeticity. HCAL transvserse, longitudinal size
  - HCAL length vs P_μ^{out} accuracy
- Target size optimization vs P_μ^{out} precision measurement

Important feedback from PBC EHN2 muon-WG meetings.

P_μ^{in}: BMS vs SM2 test in COMPASS. Data sample 2016.

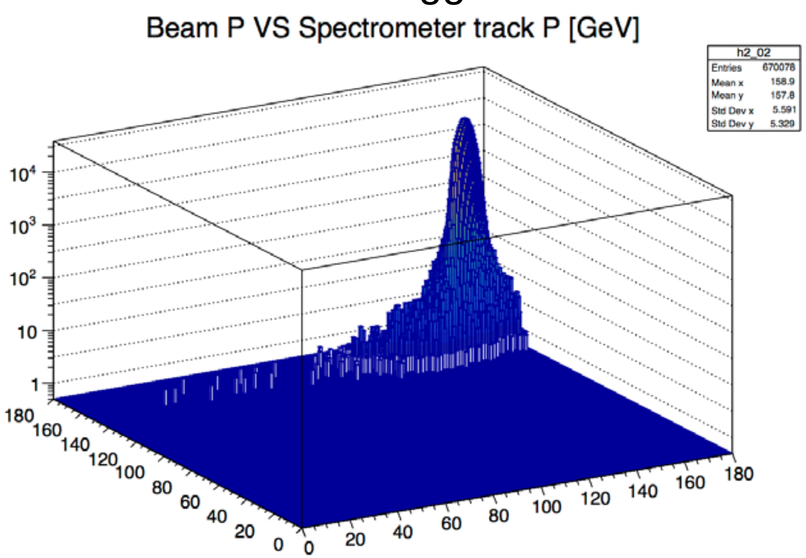


No selections

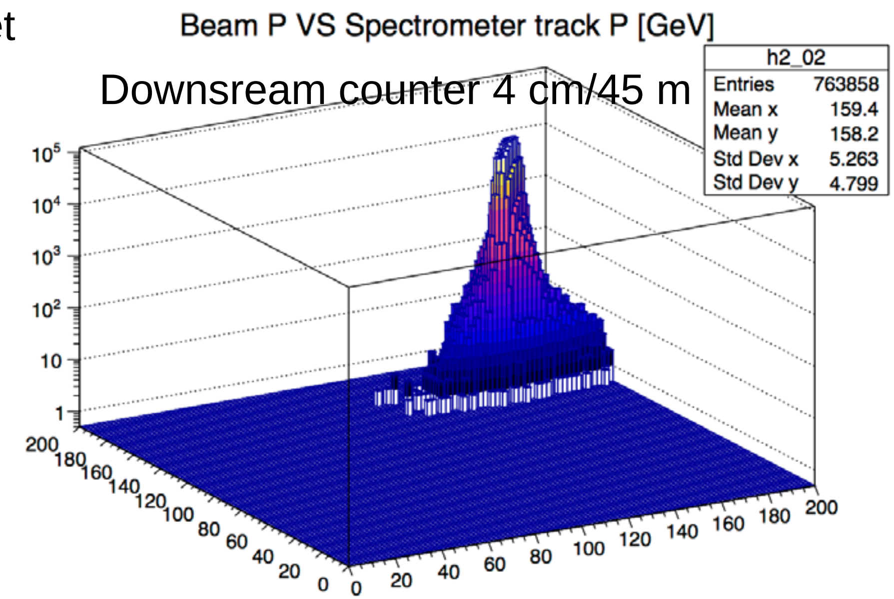


Thanks to
S. Gerassimov

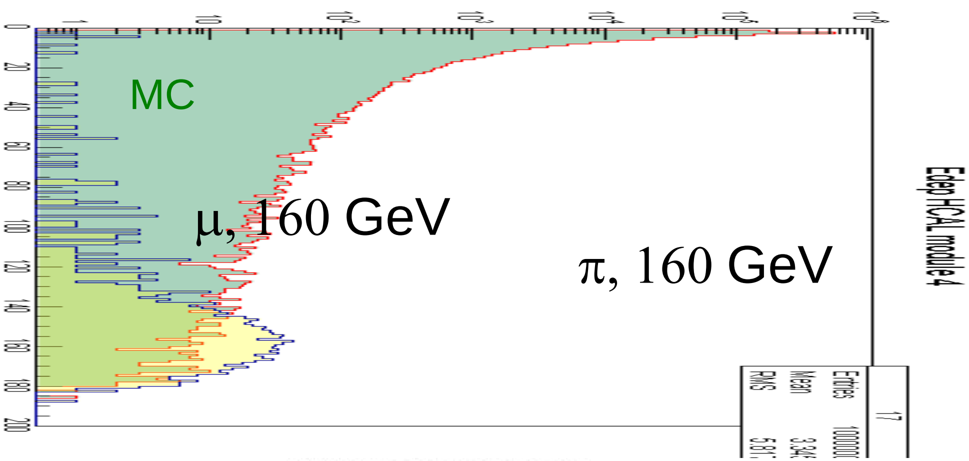
Beam trigger: interections in target



Downsream counter 4 cm/45 m

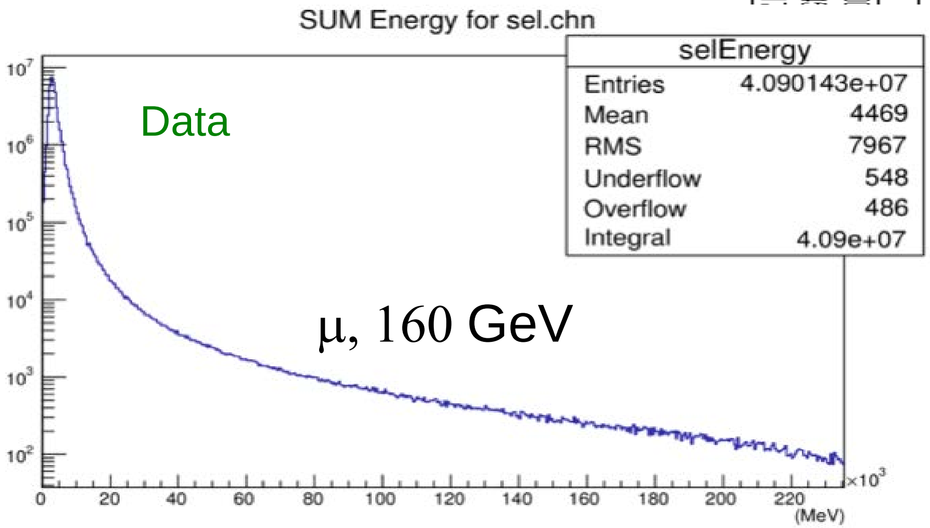


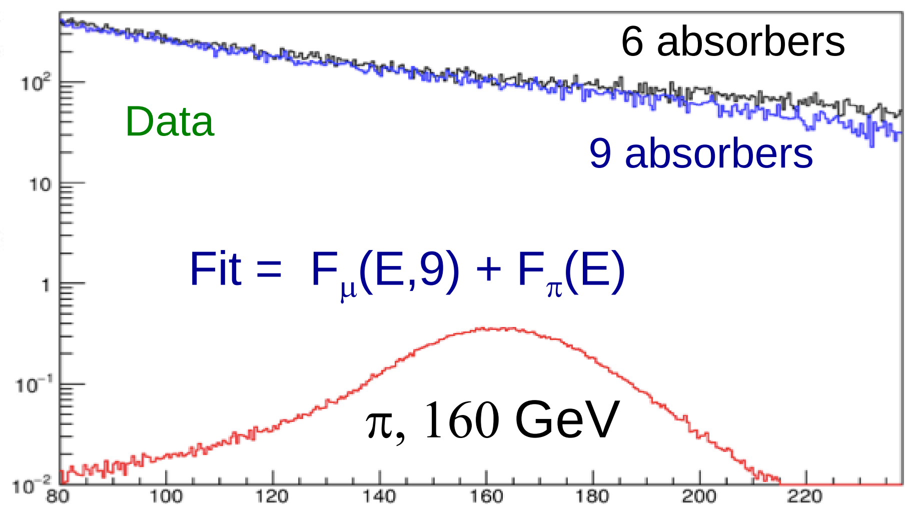
Measurements of π,K contamination in the M2 beam



A few days run in October'17

- empty LiH target
- HCAL calibration, π^- 160 GeV
- Statistics ~ 5×10^8 MOT
- Sensitivity (rough)estimate: $\pi/\mu \sim 6\times10^{-5}/(n_{MOT}/10^6)^{0.5}$



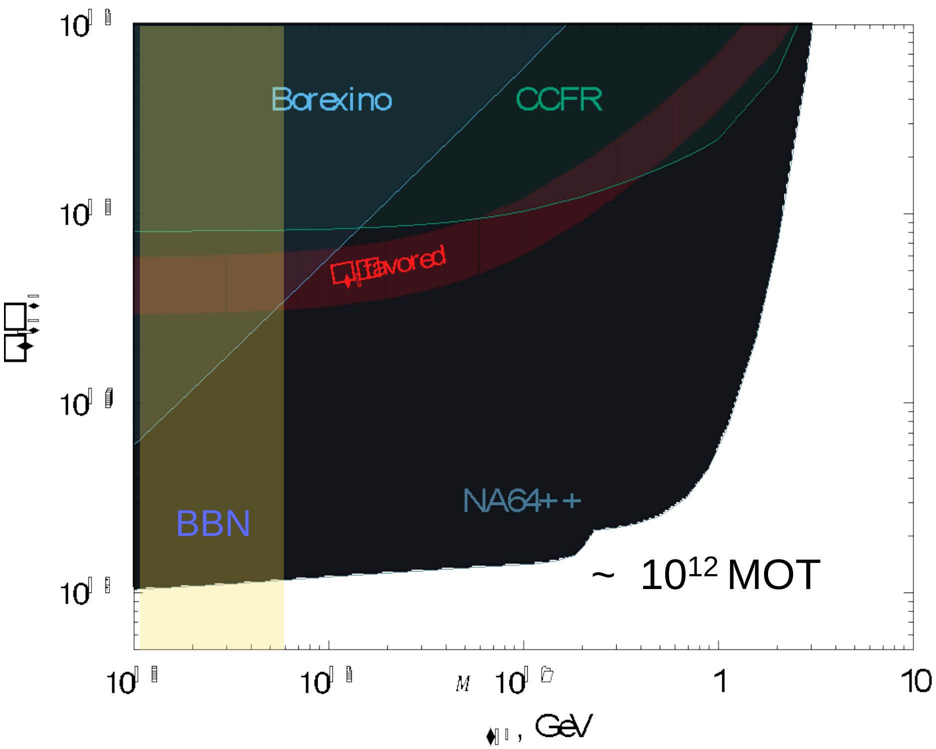


Preliminary results: $\pi,K/\mu = (9.7\pm1.4)\times10^{-5}$ (6 absorbers)

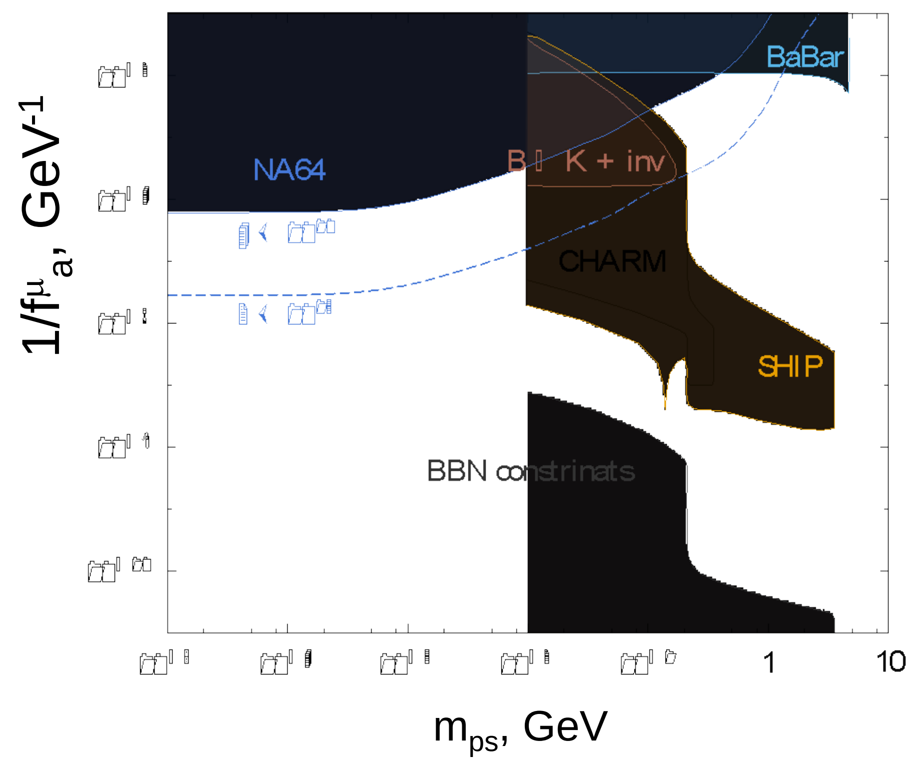
Background from $\pi,K \to \mu\nu$ decays is expected to be small (prelim.)

Projected sensitivity: $Z_{\mu\tau}$, dark leptonic (pseudo)scalars

$Z_{\mu\tau} \rightarrow$ invisible



(pseudo)scalars → invisible



Plans: Proposal to the SPSC in 2018

μ A -> τ X conversion (preliminary)

The $e-\tau$ and $\mu-\tau$ Lagrangians read:

$$\mathcal{L}_{\ell\tau} = \sum_{I,if,XY} \left(\Lambda^{\ell\tau}_{I_{if},XY}\right)^{-2} \mathcal{O}^{\ell\tau}_{I_{if},XY} + \text{H.c.}$$

where $\mathcal{O}^{\mu\tau}_{I_{if}}$ - dimension-6 operators:
$360 = 6 \times 6 \times 10$ operators for the 6 quark flavors for each quark field and 10 possible chirality $P_{X,Y} = (1 \pm \gamma_5)/2$ combinations

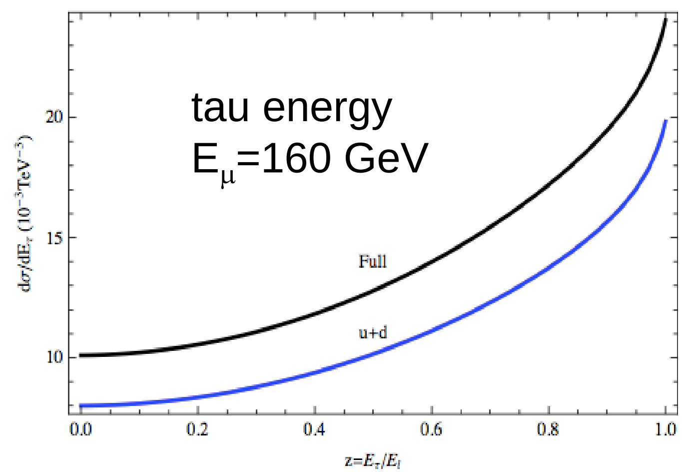
$$\mathcal{O}^{\ell\tau}_{I_{if},XY} = (\bar{\tau} P_X \Gamma_I l)(\bar{q}_f P_Y \tilde{\Gamma}_I q_i)\,, \quad \Gamma_I \otimes \tilde{\Gamma}_I = I \otimes I\,, \quad \gamma^\mu \otimes \gamma_\mu\,, \quad \sigma^{\mu\nu} \otimes \sigma_{\mu\nu}$$

Mass scale $\Lambda^{\ell\tau}_{I_{if},XY}$ set strength of low-energy effect of corresponding operator

$R_{\mu\tau}=\sigma(\mu A\to\tau X)/\sigma(\mu A\to\mu X) < \sim 10^{-12}$

H1, ZEUS vs NA64 bounds:

- *S* operators: $\Lambda^{e\tau} \geq 0.2$ TeV; $\Lambda^{\mu\tau} \geq 1.3$ TeV
- *V* operators: $\Lambda^{e\tau} \geq 0.3$ TeV; $\Lambda^{\mu\tau} \geq 2.4$ TeV
- *T* operators: $\Lambda^{e\tau} \geq 0.3$ TeV; $\Lambda^{\mu\tau} \geq 2.6$ TeV



π, K, p beams

- π^0, η, η' → invisible
- K_S, K_L → invisible
- Leptophobic light Dark Matter

  in pA->DM+X reactions

Update on charge-exchange cross sections

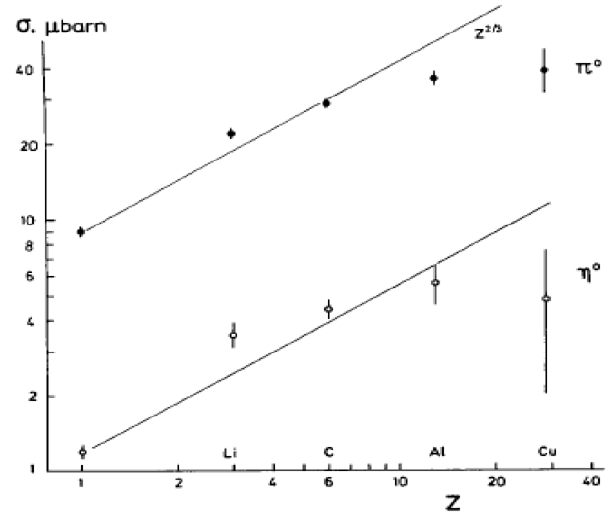
Copious and important results from experiments performed in 70-80’s at IHEP, Protvino

V.N. Bolotov et al., π^- charge exchange 159

Table 1
Cross sections for the reactions (1) and (2) at $P = 48$ GeV/c (in μb)[a)]

Cross section \ Nucleus	H [3, 5]	Li	C	Al	Cu
$\sigma(\pi^- A_Z \to \pi^0 A_{Z-1})$, reaction (1)	9.1 ± 0.4	22.0 ± 1.1	28.7 ± 1.4	36 ± 2.0	39 ± 8
$\sigma_{2\gamma}(\pi^- A_Z \to \eta A_{Z-1})$, reaction (2)	1.20 ± 0.07	3.5 ± 0.4	4.4 ± 0.4	5.6 ± 1.0	4.8 ± 2.9
$\sigma(\pi^- A_Z \to \eta A_{Z-1})$ [b)]	3.2 ± 0.2	9.2 ± 1.0	11.6 ± 1.0	14.7 ± 2.6	12.6 ± 7.5
$Z_{eff}(\pi^0)$		2.4 ± 0.1	3.2 ± 0.2	4.0 ± 0.2	4.3 ± 0.8
$Z_{eff}(\eta^0)$		2.9 ± 0.3	3.7 ± 0.3	4.7 ± 0.7	4.0 ± 2.4

a) Cross sections were determined within the range of four-momentum transfer $0 < -t < 2\,(\mathrm{GeV}/c)^2$.
b) All η^0 decay channels are considered, $\Gamma_{2\gamma}/\Gamma_{all} = 0.38$.



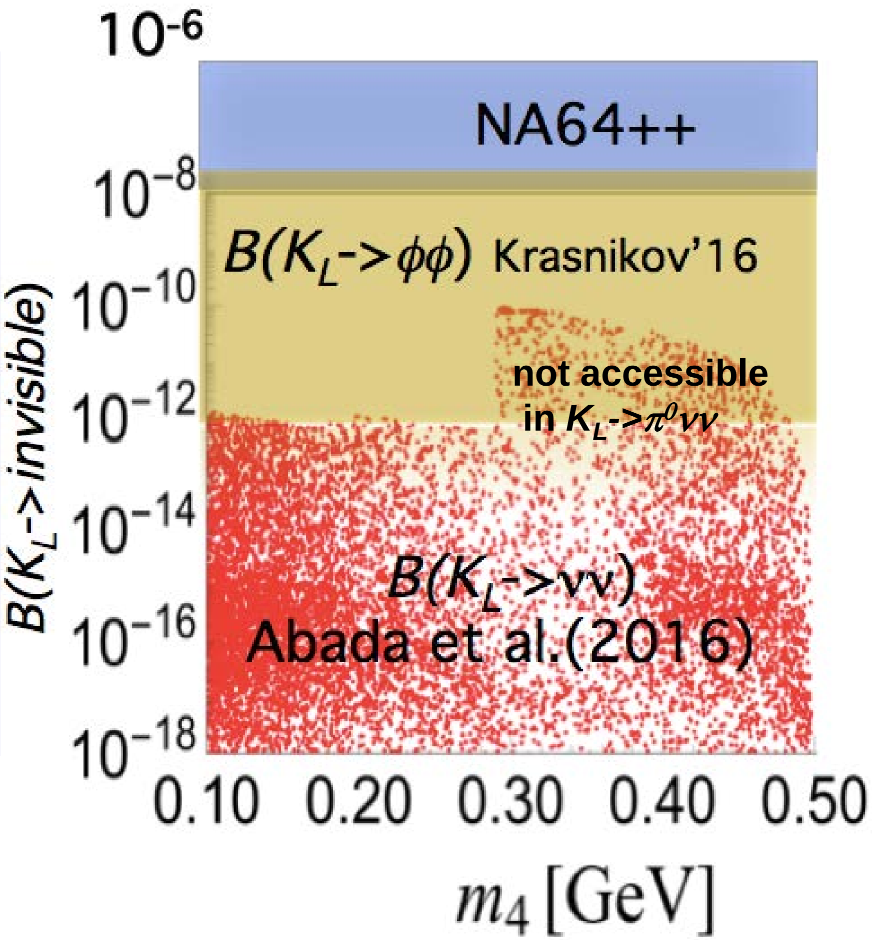
Cross sections for the reactions (1) (black points) and (2) (circles) at $P = 48$ GeV/c. The straight lines are dependences $\sigma \sim Z^{\frac{2}{3}}$.

Estimate for the yield of π^0, η, η´, and possibly for K_L, K_S.
Measurements of the yield in situ in 2018 run is under study.

Projected sensitivity for π^0, η, η', K_L, K_S-> invisible

TABLE I: Expected upper limits on the branching ratios of different decays into invisible final states calculated for the 5×10^{12} incident $\simeq 40$ GeV π^- or K^-.

Expected limits on the branching ratio	Present limit PDG(2017)
$Br(K_S \to invisible) \lesssim 10^{-9}$	no
$Br(K_L \to invisible) \lesssim 10^{-8} - 10^{-7}$	no
$Br(\pi^0 \to invisible) \lesssim 10^{-9}$	$< 2.7 \times 10^{-7}$
$Br(\eta \to invisible) \lesssim 10^{-8}$	$< 1.0 \times 10^{-4}$
$Br(\eta' \to invisible) \lesssim 10^{-7}$	$< 5.2 \times 10^{-4}$



Under study: Possibility to search for
K_L -> invisible at lower energy with > 10^{13} KOT

Summary of NA64++ Physics Prospects beyond LS2

Beam and process	Motivation	Required number of POT
1. $e^- Z$		
✧ A´-> invisible ✧ X(16.7), A´ -> e^+e^- ✧ pseudoscalar ->invisible ✧ a -> $\gamma\gamma$ ✧ milli-Q	S,V mediator of light DM production ^{8}Be anomaly, Leptonic pseudogoldstone, ALP decays, miii-Q	~5x10^{12} EOT ~5x10^{12} EOT
2. $\mu^- Z$		
✧ $Z_{\mu\tau}$ -> { ν, $\mu^+\mu^-$ ✧ pseudoscalar -> invisible ✧ μ->τ conversion	$(g-2)_\mu$, New gauged symmetry L_μ-L_τ. Leptonic pseudo-goldstone, LFV	10^{12}-10^{13} MOT
3. π(K) p-> M^0 n + E_{miss}		
✧ K_L-> invisible ✧ K_S-> invisible ✧ π^0, η,η-> invisible	NHL, ϕϕ, Bell-Steinberger Unitarity, CP, CPT symmetry	~5x10^{12} P(K)OT
4. p A -> X+ E_{miss}		
✧ leptophobic X	~ GeV DM	~5x10^{12} POT

Summary

New physics (dark sector, new symmetries, hidden particles, ..) at a scale of the visible sector can be effectively probed with the NA64 approach by using e, μ, π, *K*, and *p* beams at CERN in the medium term future. The physics results are expected to be rich. In some cases they might be unexpected.

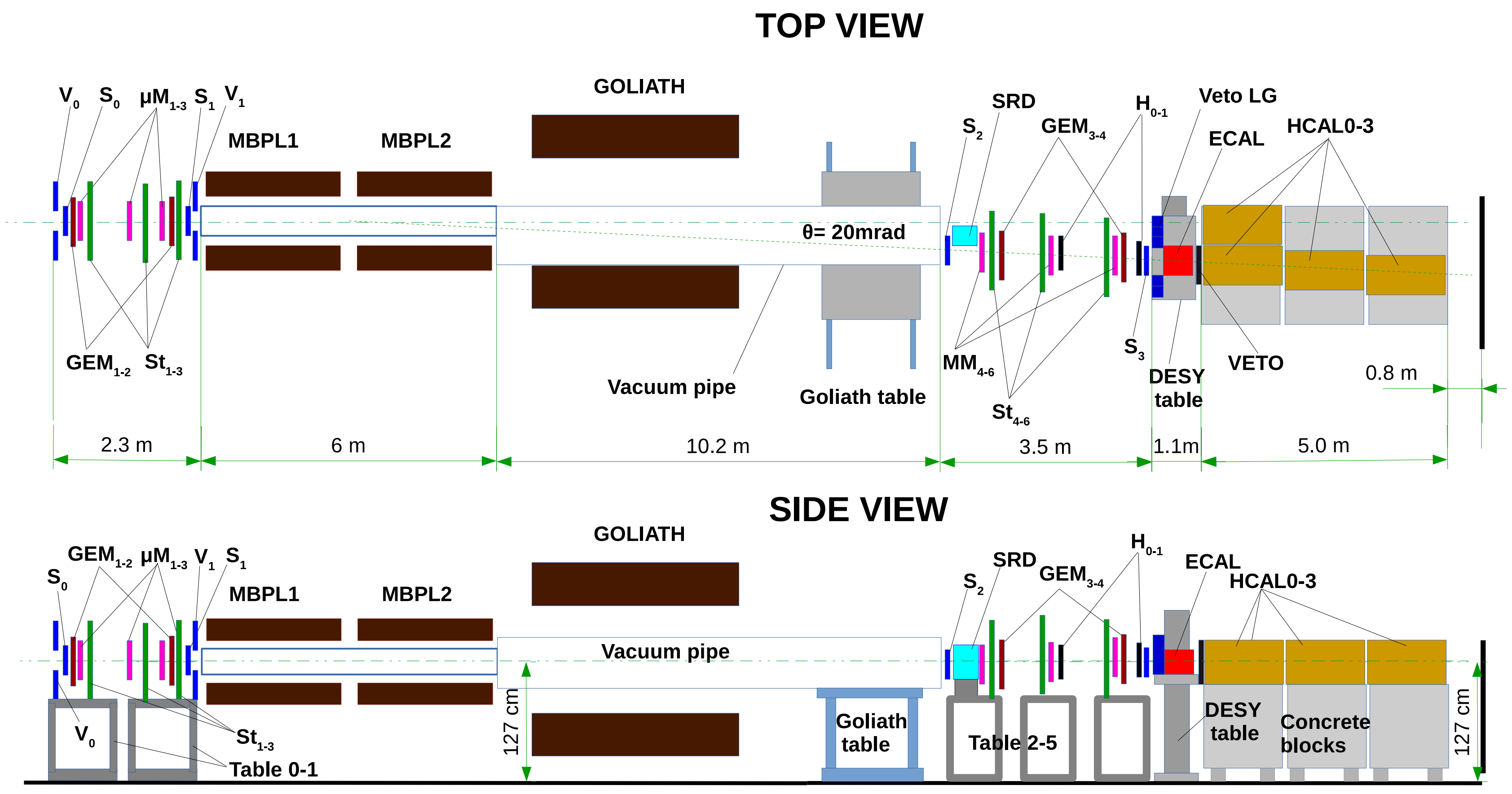
NA64++ provisional time schedule

2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 |

Beam						
e^-, H4 →	$(g\text{-}2)_\mu$, 8Be, Dark Sector	LS2		8Be, Dark Sector	LS3	Dark Sector
μ^-, M2 →		Proposal, Preparation		g_μ-2, Dark sector, m-τ	LS3	Dark sector, m-τ
π^-, K^-, H2-H8,T9 →			Proposal	$\pi^0,\eta,\eta',K_L \to inv$	LS3	$\pi^0,\eta,\eta',K_S,K_L \to inv$

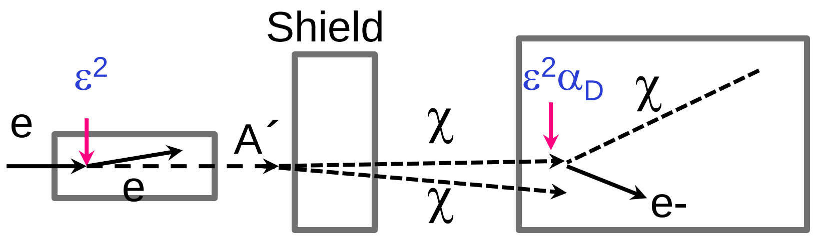
BACKUP

The NA64 detector in 2017



Beam dump vs NA64++

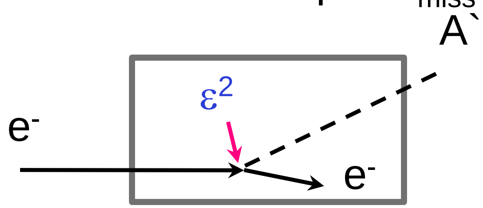
Beam dump:



Sensitivity $\sim \varepsilon^2 \times \varepsilon^2 \alpha_D (m_\chi / m_{A'})^4 = \varepsilon^2 y$

NA64 approach:

active beam dump + E_{miss}



Search for E_{miss} events

Sensitivity$\sim \varepsilon^2$

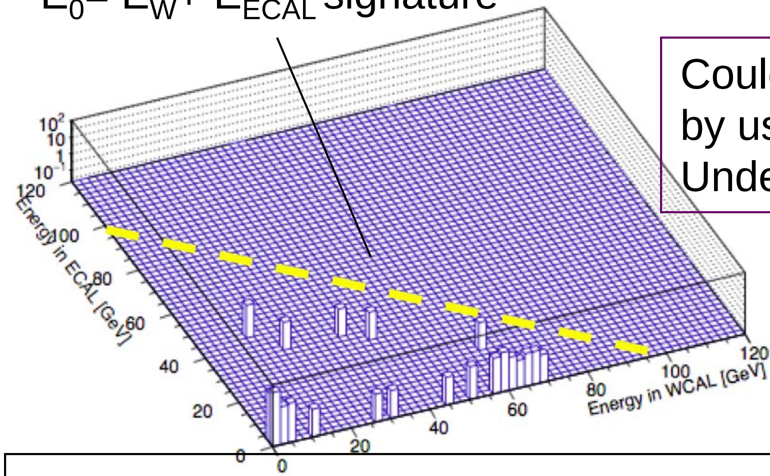
active beam dump + missing energy

Results from Oct'16 run, ~$0.5x10^{10}$ EOT.

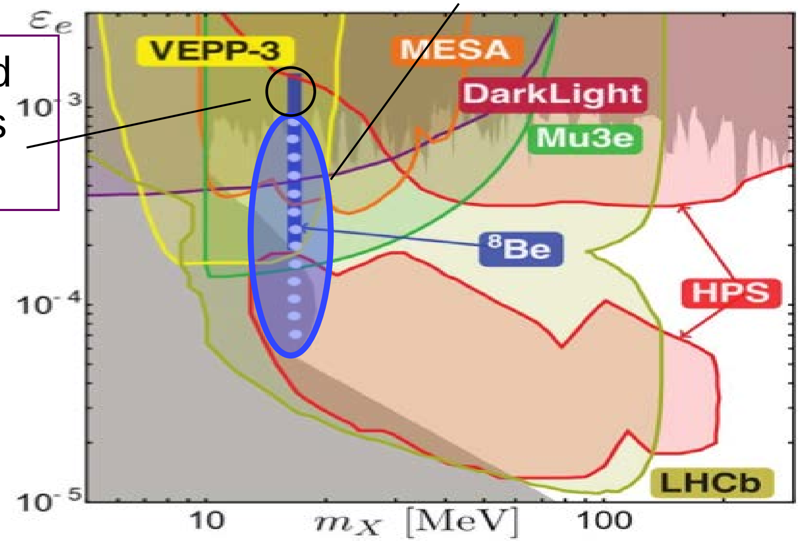
$E_0 = E_W + E_{ECAL}$ signature

Br(X → e^+e^-)=1

Expected X exclusion area (>10^{11} EOT)



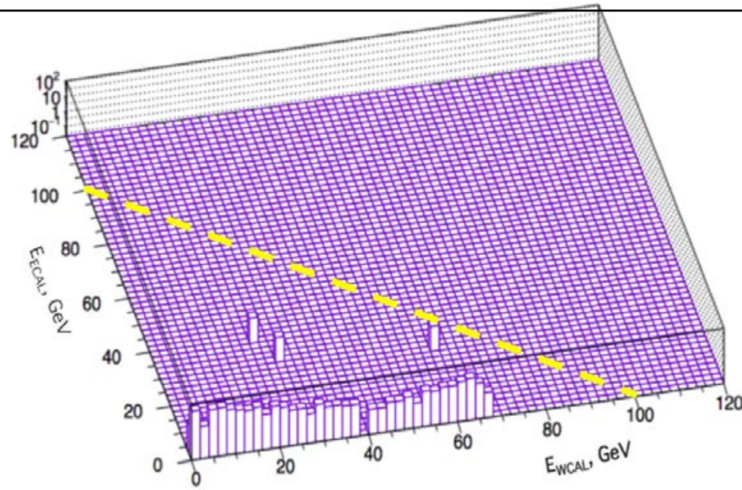
Could be covered by using Si pixels Under study.

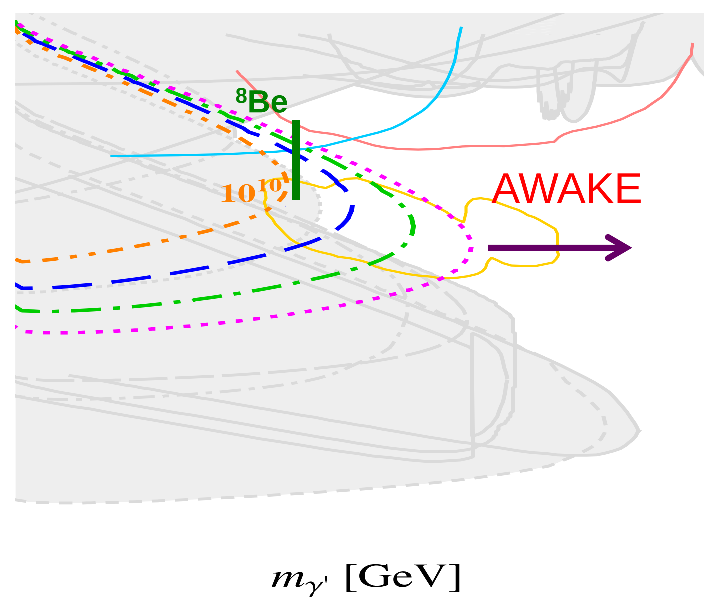


Neutral events:

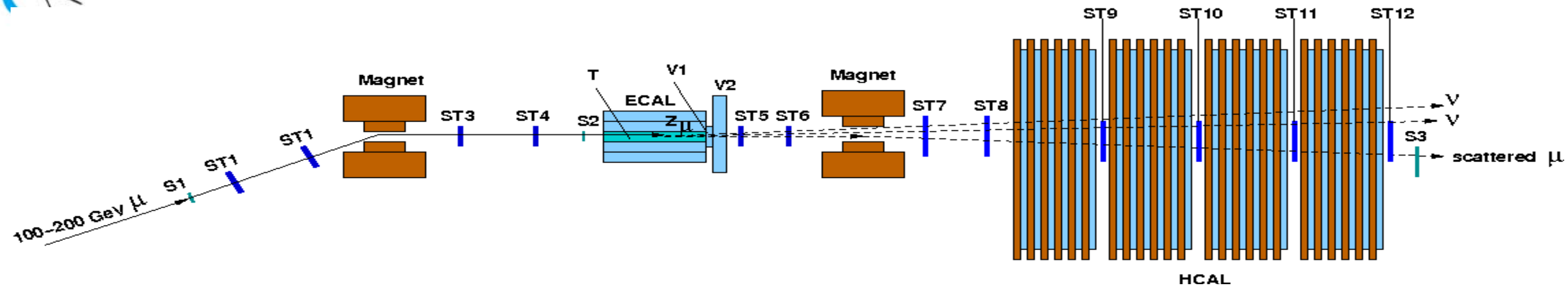
- background from punchthrough γ□s
- Search for short-lived ALPs: a->γγ

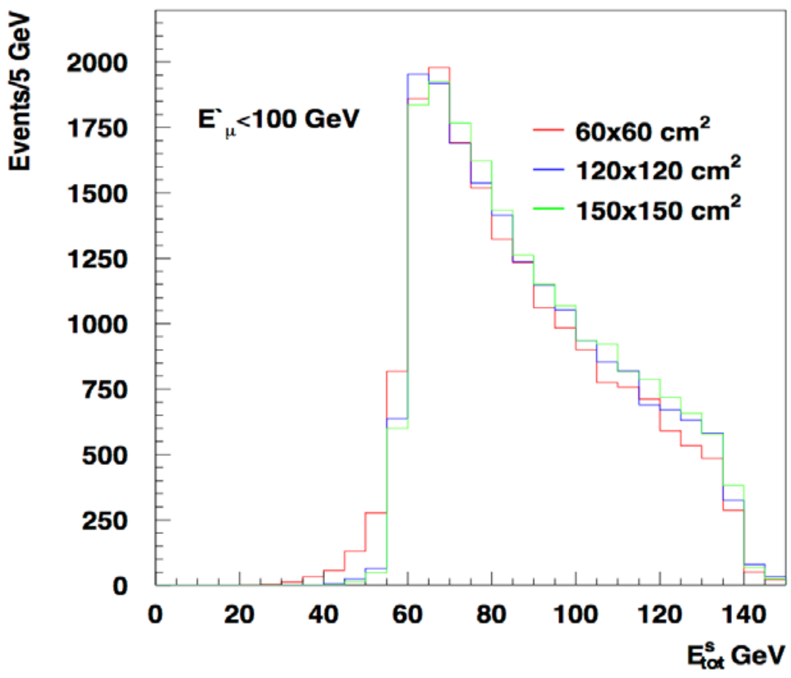
Exclusion area for **A´→ e^+e^-**

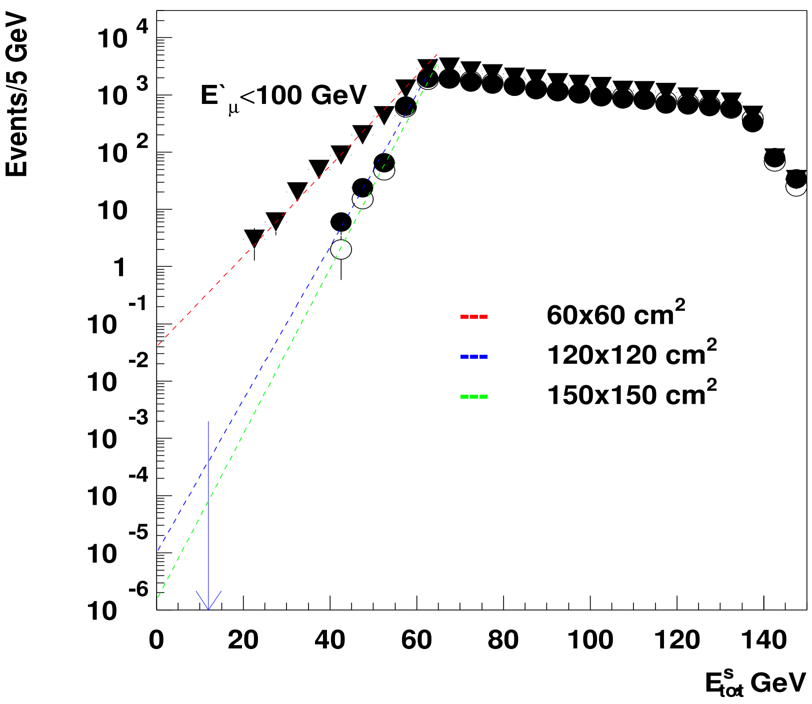




MC: detector hermeticity



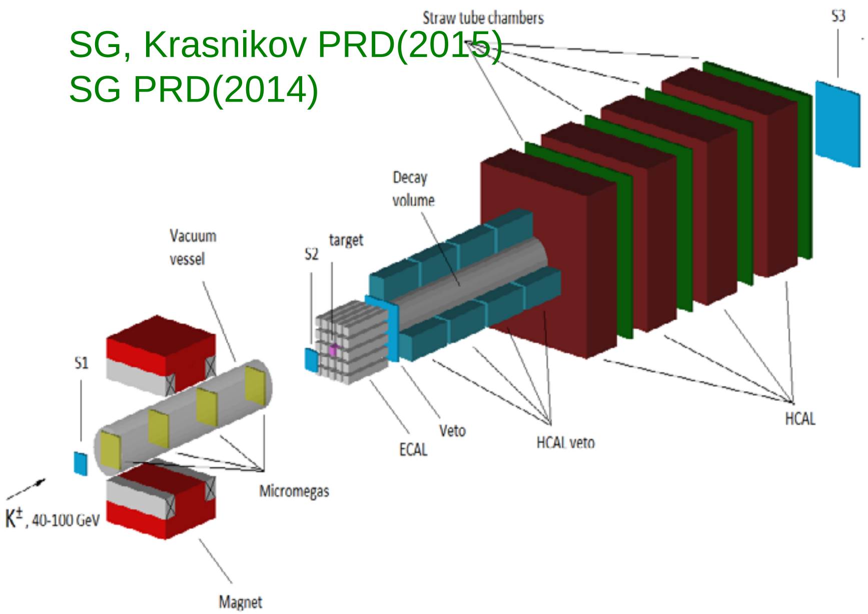




Choice of the HCAL transverse size is a crucial issue !

π^0, η, η´, K_S, K_L -> invisible decays

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



Motivation for K_L:
•complementary to K_L->$\pi^0\nu\nu$
•NHL, ϕ, Bell-Steinberger,…

Source of M^0: charge exchange reactions: π^-, K^-+p -> M^0+ n
M^0=π^0, η, η´, K_L, K_S…

Main components :

- 20-50 GeV π^-,K^- beam
- MM tracker, ECAL target
- 4π fully hermetic system: Veto +ECAL+HCAL

Signature:

- in: 20-50 GeV π, K-track
- out: no energy in ECAL, Veto, HCAL
- Complete disappearance of beam energy !

Status of NA64++

<u>Outline</u>

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