Status of NA64++

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Outline

• Searches with $e, \mu, \pi, K, p$ beams
• Summary
NA64 designed to search for new physics in missing-energy events was approved in March’16. A wider program of searches with e\(^-\), \(\mu\), \(\pi\), K, p beams was proposed at PBC’16.
e$^-$ beam

- dark pseudoscalar(s), vector(A$'$) $\rightarrow$ invisible decays
- s, A$'$ $\rightarrow$ e$^+$e$^-$ decays
- $^8$Be$^*$ anomaly: a new light boson?
- ALP: a $\rightarrow$ $\gamma\gamma$
- milli-Q
Search for $A' \rightarrow$ invisible decays at the CERN SPS

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

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

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

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
2016 Results, Projected Sensitivity

Exact tree-level calculations of cross sections $\sigma(eZ\rightarrow eZ\leftarrow \gamma)$. Large corrections to the WW approximation for $m_{A^{'}} > \sim 100$ MeV.

Plans to accumulate $\sim 4\times10^{12}$ EOT after LS2

Projected Sensitivity for Light Thermal Dark Matter

\[ \alpha_D \sim \alpha_S = 0.5, \ m_{A'} = 0.3 m_\chi \]

\[ \alpha_D \sim \alpha_{EM} = 0.005, \ m_{A'} = 0.3 m_\chi \]

- Sensitivity of a beam-dump \( \sim \varepsilon^2 \varepsilon^2 \alpha_D (m_\chi / m_{A'})^4 = \varepsilon^2 y \), NA64 \( \sim \varepsilon^2 \)
- Bounds from LSND, SLAC, MiniBooNE for \( \sim 10^{22}, 10^{19}, 10^{20} \) POT
- NA64 can cover significant area with \( \sim \) a few \( 10^{12} \) EOT
2016 Results and Expected Bounds on $\alpha_D$

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

![Graph showing bounds on $\alpha_D$ and $\alpha_{EM}$ as a function of $m_\chi$.](image)

Sensitivity to p-s, $A' \rightarrow $ invisible decays, $m_{ps,A'} < 1$ MeV

Thanks to J. Jaeckel.

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

- Calculation of $\sigma_{A'}/\sigma_S$,
- Full simulation in progress

\[ g_{ps} = m_e/f_a = \varepsilon \varepsilon \]

\[ \mathcal{L} \supset \frac{\partial \mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi \]

8Be* anomaly: a new light X boson?

\[ \Gamma(\pi^0 \rightarrow X \gamma) \sim (\varepsilon_u q_u - \varepsilon_d q_d)^2 \sim 0 \]

if \(2\varepsilon_u = -\varepsilon_d\) -> protophobic X

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

7Li(p, γ)8Be, \(M_X = 16.7\) MeV

X cannot be \(A'\) due to constraints from \(\pi^0 \rightarrow X \gamma\) decay:

S.N. Gninenko – NA64 Status Report, SPSC Open Meeting, CERN, June 20–21, 2017
Expected Bounds on $X, A'$ $\rightarrow$ $e^+e^-$

Could be covered by using Si pixels
Under study.

**2016** $\rightarrow$ test run

**2017** $\rightarrow$ $\sim 5 \times 10^{10}$ EOT at 100 GeV. Analysis in progress.

**2018 +..** $\rightarrow$ $\sim 10^{11}$ EOT at 150 GeV required

\( \mu \) beam

- (pseudo)scalar, \( Z_{\mu\tau} \rightarrow \) invisible decays
- (pseudo)scalar, \( Z_{\mu\tau} \rightarrow \mu^+\mu^- \) decays
- \( \mu - \tau \) conversion

\[ Z_{\mu\tau} = L_\mu - L_\tau \]  
gauge boson
Search for $Z_{\mu\tau}$ in missing energy events with M2 beam

Main components:
- clean, mono-energ. 160 GeV $\mu^-$ beam
- in $\mu$ tagging: MM/GEM tracker
- out $\mu$ tagging: GEM/Straw tracker
- $4\pi$ fully hermetic detector

Signature:
- in: 160 GeV $\mu^-$ track
- out: $<100$ GeV $\mu^-$ track
- no energy in the ECAL, Veto, HCAL
- Sensitivity $\sim g_Z^2$

S.G. Krasnikov, Matveev PRD(2015)
Update on PBC’16 list of issues

Thanks to C. Vallee and COMPASS

- $P_{\mu}^{in}$ momentum measurements. Cross-check: available COMPASS data sample vs MC under study.

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

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

- HCAL size optimization:
  - Hermeticity. HCAL transverse, longitudinal size
  - HCAL length vs $P_{\mu}^{out}$ accuracy

- Target size optimization vs $P_{\mu}^{out}$ precision measurement

Important feedback from PBC EHN2 muon-WG meetings.
$P_{\mu}^{\text{in}}$: BMS vs SM2 test in COMPASS. Data sample 2016.

Beam trigger: interactions in target

No selections

Downstream counter 4 cm/45 m

Thanks to S. Gerassimov

Measurements of $\pi, K$ contamination in the M2 beam

A few days run in October’17
- empty LiH target
- HCAL calibration, $\pi^-$ 160 GeV
- Statistics ~ 5x10^8 MOT
- Sensitivity (rough)estimate: $\pi/\mu \sim 6 \times 10^{-5}/(n_{MOT}/10^6)^{0.5}$

Preliminary results: $\pi, K / \mu = (9.7 \pm 1.4) \times 10^{-5}$ (6 absorbers)
Background from $\pi, K \to \mu \nu$ decays is expected to be small (prelim.)
Expected sensitivity to: $Z_{\mu\tau}$, dark(pseudo)scalars, $\mu - \tau$

$Z_{\mu\tau} \rightarrow $ invisible, $\sim 10^{12}$ MOT

$p-s \rightarrow$ invisible

$$g_{ps} = \frac{m_\mu}{f^\mu_a} = \varepsilon \ e$$

$$\zeta_{e,\mu} = \varepsilon \ e \ \frac{v}{m_{e,\mu}}$$

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

H1, ZEUS e-\tau vs NA64 $\mu - \tau$ bounds:

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

Battel et al. 1606.04943

Plans: Proposal to the SPSC in 2018

\pi, \ K, \ p \ beams

- \pi^0, \eta, \eta' \rightarrow \text{invisible}
- K_S, K_L \rightarrow \text{invisible}
- Leptophobic light Dark Matter in p+A \rightarrow \text{DM+X}
Copious and important results from experiments performed in 70–80’s at IHEP, Protvino

Table 1
Cross sections for the reactions (1) and (2) at $P = 48$ GeV/c (in $\mu$b)\(^a\)

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>H [3, 5]</th>
<th>Li</th>
<th>C</th>
<th>Al</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(\pi^- A_2 \to \pi^0 A_{2-1})$, reaction (1)</td>
<td>$9.1 \pm 0.4$</td>
<td>$22.0 \pm 1.1$</td>
<td>$28.7 \pm 1.4$</td>
<td>$36 \pm 2.0$</td>
<td>$39 \pm 8$</td>
</tr>
<tr>
<td>$\sigma_2\gamma(\pi^- A_2 \to \pi A_{2-1})$, reaction (2)</td>
<td>$1.20 \pm 0.07$</td>
<td>$3.5 \pm 0.4$</td>
<td>$4.4 \pm 0.4$</td>
<td>$5.6 \pm 1.0$</td>
<td>$4.8 \pm 2.9$</td>
</tr>
<tr>
<td>$\sigma(\pi^- A_2 \to \eta A_{2-1})$ (^b)</td>
<td>$3.2 \pm 0.2$</td>
<td>$9.2 \pm 1.0$</td>
<td>$11.6 \pm 1.0$</td>
<td>$14.7 \pm 2.6$</td>
<td>$12.6 \pm 7.5$</td>
</tr>
<tr>
<td>$Z_{\text{eff}}(\pi^0)$</td>
<td>$2.4 \pm 0.1$</td>
<td>$3.2 \pm 0.2$</td>
<td>$4.0 \pm 0.2$</td>
<td>$4.3 \pm 0.8$</td>
<td></td>
</tr>
<tr>
<td>$Z_{\text{eff}}(\eta^0)$</td>
<td>$2.9 \pm 0.3$</td>
<td>$3.7 \pm 0.3$</td>
<td>$4.7 \pm 0.7$</td>
<td>$4.0 \pm 2.4$</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Cross sections were determined within the range of four-momentum transfer $0 < -t < 2 (\text{GeV}/c)^2$.

\(^b\) All $\eta^0$ decay channels are considered, $\Gamma_{2\gamma}/\Gamma_{\text{all}} = 0.38$.

Estimate for the yield of $\pi^0$, $\eta$, $\eta^\prime$, and possibly for $K_L$, $K_S$. Measurements of the yield in situ in 2018 run is under study.
Projected sensitivity for $\pi^0$, $\eta$, $\eta'$, $K_L, K_S \rightarrow$ invisible

<table>
<thead>
<tr>
<th>TABLE I: Expected upper limits on the branching ratios of different decays into invisible final states calculated for the $5 \times 10^{12}$ incident $\sim 40$ GeV $\pi^-$ or $K^-$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected limits on the branching ratio</td>
</tr>
<tr>
<td>$\text{Br}(K_S \rightarrow \text{invisible}) \lesssim 10^{-9}$</td>
</tr>
<tr>
<td>$\text{Br}(K_L \rightarrow \text{invisible}) \lesssim 10^{-8} - 10^{-7}$</td>
</tr>
<tr>
<td>$\text{Br}(\pi^0 \rightarrow \text{invisible}) \lesssim 10^{-9}$</td>
</tr>
<tr>
<td>$\text{Br}(\eta \rightarrow \text{invisible}) \lesssim 10^{-8}$</td>
</tr>
<tr>
<td>$\text{Br}(\eta' \rightarrow \text{invisible}) \lesssim 10^{-7}$</td>
</tr>
</tbody>
</table>

Under study: Possibility to search for $K_L \rightarrow$ invisible at lower energy with $> 10^{13}$ KOT
## Beam and process

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Required number of POT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. (e^- Z)</strong></td>
<td>~5x10^{12} EOT</td>
</tr>
<tr>
<td>(A' \rightarrow) invisible</td>
<td>~5x10^{12} EOT</td>
</tr>
<tr>
<td>(X(16.7), A' \rightarrow e^+e^-)</td>
<td></td>
</tr>
<tr>
<td>(\text{pseudoscalar} \rightarrow\text{invisible})</td>
<td></td>
</tr>
<tr>
<td>(a \rightarrow \gamma\gamma)</td>
<td></td>
</tr>
<tr>
<td>(\text{milli-Q})</td>
<td></td>
</tr>
<tr>
<td><strong>2. (\mu^- Z)</strong></td>
<td>10^{12}-10^{13} MOT</td>
</tr>
<tr>
<td>(Z_{\mu\tau} \rightarrow \nu\nu, \mu^+\mu^-)</td>
<td></td>
</tr>
<tr>
<td>(\text{pseudoscalar} \rightarrow\text{invisible})</td>
<td></td>
</tr>
<tr>
<td>(\mu \rightarrow \tau) conversion</td>
<td></td>
</tr>
<tr>
<td>(\text{LFV})</td>
<td></td>
</tr>
<tr>
<td><strong>3. (\pi (K) p \rightarrow M^0 n + E_{\text{miss}})</strong></td>
<td>~5x10^{12} P(K)OT</td>
</tr>
<tr>
<td>(K_L \rightarrow) invisible</td>
<td></td>
</tr>
<tr>
<td>(K_S \rightarrow) invisible</td>
<td></td>
</tr>
<tr>
<td>(\pi^0, \eta, \eta \rightarrow) invisible</td>
<td></td>
</tr>
<tr>
<td>(\text{NHL, } \phi\phi,) Bell-Steinberger Unitarity, CP, CPT symmetry</td>
<td></td>
</tr>
<tr>
<td><strong>4. (p A \rightarrow X + E_{\text{miss}})</strong></td>
<td>~5x10^{12} POT</td>
</tr>
<tr>
<td>(\text{leptophobic } X)</td>
<td>~ GeV DM</td>
</tr>
</tbody>
</table>
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 $e$, $\mu$, $\pi$, $K$, and $p$ beams at CERN in the medium term future. The physics results promise to be rich, and might be unexpected.

**NA64++ provisional time schedule**


- **$e^-$, H4 $\rightarrow$ (g-2)$_\mu$, 8Be, Dark Sector LS2 8Be, Dark Sector LS3 Dark Sector**

- **$\mu^-$, M2 $\rightarrow$ Proposal, Preparation $g_{\mu}-2$, Dark sector, $m-\tau$ LS3 Dark sector, $m-\tau$**

- **$\pi^-$, $K^-$, H2-H8,T9 $\rightarrow$ Proposal $\pi^0,\eta,\eta',K_L\rightarrow inv$ LS3 $\pi^0,\eta,\eta',K_S,K_L\rightarrow inv$**
BACKUP
The NA64 detector in 2017

S.N. Gninenko – NA64 Status Report, SPSC Open Meeting, CERN, June 20–21, 2017
Neutral events:
- background from punchthrough $\gamma$’s
- Search for short-lived ALPs: $a \rightarrow \gamma \gamma$

Results from Oct’16 run, $\sim 0.5 \times 10^{10}$ EOT.

$E_0 = E_W + E_{ECAL}$ signature

Br($X \rightarrow e^+e^-$) = 1

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

Could be covered by using Si pixels
Under study.

Exclusion area for $A' \rightarrow e^+e^-$

AWAKE
Search for GeV Dark Matter in pA interactions (prelim.)

$pA \rightarrow X + Z'; Z' \rightarrow \chi\chi$

$Z'$ – leptophobic boson

$\alpha_{Z'}$ – q-$Z'$ coupling const.

$p, 150 \text{ GeV}$

$E_{\text{miss}}$

$10^9 \text{ pot}$

Exclusion region in $(M_{Z'}; \alpha_{Z'})$ plane