Searches for exotic particles at NA62

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ICHPE 2018
Seoul – 7 July 2018
Why search for exotic particles?

No hints of new physics at high energy so far?

- Strong constraints on SUSY, extra dimensions, technicolor, etc.
- Constraints on new $Z'$ bosons push new gauge groups into multi-TeV territory

Yet, SM is obviously incomplete:

- **Neutrino masses and oscillations**
  - See-saw mechanism with RH neutrinos with masses from $10^{-9}$ to $10^{15}$ GeV, with Yukawa couplings to the Higgs and SM leptons?

- **Matter-antimatter asymmetry**
  - Requires violation of baryon number, $C$, and $CP$ in the early universe. Not enough non-equilibrium $CP$ violation in the SM to explain it.

- **Dark Matter**
  - SM particles alone cannot account for the observed matter in the universe
  - Masses for viable DM candidates: $10^{-31}$ GeV (ultralight scalars) to $10^{20}$ GeV (black holes) (10 keV to 100 TeV if from thermal origin)

- **Strong CP problem**
  - Apparent conservation of $CP$ in QCD requires fine tuning
  - Axion (pseudo-Goldstone boson of spontaneously broken Peccei-Quinn symmetry) may resolve strong $CP$ problem while providing DM candidate
Searches for exotic particles

Distinguish searches by mass scale:

1. **Sub-eV**: Search for axions or axion-like particles (ALPs) via EDMs or in direct laboratory searches

2. **MeV-GeV**: Search for heavy neutrinos, ALPs, light DM particles and mediators (dark photons, dark scalars) in fixed-target or collider experiments

3. **10-1000 TeV**: Search for NP in clean and very rare flavor processes or in EDMs

Much attention has been dedicated to TeV-scale models and ideas. Need a systematic approach for NP at the intensity frontier.

Adapted from M. Pospelov

**NA62** designed to be sensitive to $K^+$ BRs of order $10^{-12}$

Well suited to explore new physics portals in the MeV-GeV scale.

<table>
<thead>
<tr>
<th>Portal</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark photon</td>
<td>$\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$</td>
</tr>
<tr>
<td>Scalar</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
</tr>
<tr>
<td>Axion</td>
<td>$\frac{a}{f_a} F'<em>{\mu\nu} \tilde{F}^{\mu\nu}, \frac{a}{f_a} G</em>{i,\mu\nu} \tilde{G}^{i\mu\nu}, \frac{\partial_{\mu} a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>Neutrino/HNL</td>
<td>$\gamma_N LHN$</td>
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</tbody>
</table>

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The NA62 experiment at the SPS

Primary beam:
- $p = 400$ GeV SPS protons
- $10^{12}$ protons/effective second

Secondary beam:
- $p = 75$ GeV positive, unseparated
- Total rate: 750 MHz
- $K^+$ rate: 45 MHz

- Large angle photon vetoes
- OPAL lead glass
- 1 atm Ne
- Dipole spectrometer
- 4 straw-tracker stations
- Forward $\gamma$ veto
- NA48 LKr
- KTAG
- CHANTI
- Forward $\gamma$ veto
- SAC
- IRC
- GIGATRACKER
- Beam tracking Si pixels, 3 stations
- MUV
- $\mu$ veto
- Fe/scint
The NA62 experiment at the SPS

- Beam and secondary particle tracking

Beam tracking:
- Si pixels, 3 stations
- GIGATRACKER: $\sigma_i < 200$ ps

Kinematic rejection of $10^4$ for $K^+ \rightarrow \mu^+\nu$ and $K^+ \rightarrow \pi^+\pi^0$ decays

Fiducial volume $\sim 60m$ 10$^{-6}$ mbar

5 MHz $K^+$ decays

Dipole spectrometer:
- 4 straw-tracker stations

LAV
- Large angle photon vetoes
- OPAL lead glass

RICH
- RICH $\mu/\pi$ ID
- 1 atm Ne

MUV
- $\mu$ veto
- Fe/scint

Forward $\gamma$ veto
- NA48 LKr

KTAG
- Differential Cerenkov for $K^+$ ID in beam

CHANTI
- Charged veto

GIGATRACKER

STRAW
- IRC

SAC

K0

0 50 100 150 200 250 m

Fiducial volume $\sim 60m$ 10$^{-6}$ mbar
The NA62 experiment at the SPS

- Hermetic photon vetoes

- Photon veto rejection of $10^8$ for $\pi^0$ from $K^+ \to \pi^+\pi^0$ with $E(\pi^0) > 40$ GeV
The NA62 experiment at the SPS

- Beam and secondary particle identification
- Muon vetoes

- Beam tracking
  - Si pixels, 3 stations
  - Differential Cerenkov for $K^+$ ID in beam

- Charged veto

- KTAG $\sigma_t < 100$ ps

- Large angle photon vetoes
  - OPAL lead glass

- Forward $\gamma$ veto
  - OPAL lead glass
  - 1 atm Ne

- $\mu$ vs $\pi$ rejection of $10^7$ for $15 < p(\pi^+) < 35$ GeV

- $\mu$ veto
  - Fe/scint

- Dipole spectrometer
  - 4 straw-tracker stations
  - LKr

- RICH
  - $\mu/\pi$ ID
  - $1$ atm Ne

- Forward $\gamma$ veto
  - NA48 LKr

- MUV
  - $\mu$ veto
  - Fe/scint

- Fiducial volume $\sim 60$m
  - $10^{-6}$ mbar

- 5 MHz $K^+$ decays

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Exotic particle searches at NA62

Standard data taking during $K^+ \rightarrow \pi^+ \nu \nu$

• Possible approaches:

  1. Invisible exotic particles seen as missing mass from $K$ decays
     
     E.g. $K^+ \rightarrow \pi^+ X$, with $X =$ dark photon, HNL, etc.

  2. Exotic particles produced in target and reconstructed in FV

     • Dedicated triggers ($\mu \mu$, $ee$, $\pi \mu$, $\pi e$) using small fraction of $K^+ \rightarrow \pi^+ \nu \nu$ bandwidth
     
     • Currently existing samples on order of $10^{17}$ pot

1 $\lambda_{\text{int}}$ Be target for standard data taking

Fiducial volume $\sim 60$ m

Reasonable acceptance for long-lived states
Exotic particle searches at NA62

Data taking with dumped beam

- Exotic particles produced from interactions of 400 GeV protons in closed collimator
- Dedicated data taking for short periods during $K^+ \rightarrow \pi^+ \nu \nu$ running
  
  Target lifted and collimator closed in 15-minute, reversible operation
- Background reduced enough to reconstruct exotic final states with open kinematics (proven for $4 \times 10^{15}$ pot)
- Contemplate longer periods of dedicated data-taking in dump mode $\rightarrow 10^{18}$ pot

$22 \lambda_{\text{int}}$ Cu collimator (TAX) closed for dump-mode data taking

Fiducial volume $\sim 60$ m
Reasonable acceptance for long-lived states

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Dark photons

Simplest hidden sector model introduces a new U(1) gauge symmetry with one extra gauge boson: the dark photon $A'$

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2 \cos \theta_W} F'_{\mu \nu} B_{\mu \nu}$$

$$\mathcal{L}_{\text{DS}} = -\frac{1}{4} (F'_{\mu \nu})^2 + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 + |(\partial_\mu + i g D A'_\mu) \chi|^2 + ...$$

Interaction of $A'$ with visible sector through kinetic mixing with SM hypercharge

- QED-like interactions with SM fermions
- Free parameters: $\epsilon$ and $m_{A'}$

NA62 can search for dark photons:

- With no decays to SM particles, in $K^+ \rightarrow \pi^+ X$ or $K^+ \rightarrow \pi^+ \pi^0$ with $\pi^0 \rightarrow \gamma X$
- With dedicated trigger for decays such as $A' \rightarrow e^+ e^-$ or $A' \rightarrow \mu^+ \mu^-$
Search for $K^{+} \rightarrow \pi^{+}\pi^{0}$ with $\pi^{0} \rightarrow \gamma A'$ and $A'$ invisible

- Sensitivity for $m_{A'} < m_{\pi^{0}}$
- Signal: 1 track + 1 $\gamma$ + missing energy
- Search for missing mass peak corresponding to $A'$
- Main background: $\pi^{0} \rightarrow \gamma\gamma$ with 1 $\gamma$ lost

Preliminary result with 5% of 2016 data sample

- $1.5 \times 10^{10}$ $K^{+}$ decays
- Background from negative $m_{\text{miss}}$ resolution tail from control data
- No significant excess observed
- 90% CL UL within expected statistical uncertainty band
- Analysis with full 2016 data set in progress
Dark photons with visible decays

Search for $A'$ produced in target or dump with decay to $e^+e^-$ or $\mu^+\mu^-$ in FV
- Meson decays: From primary beam secondaries, e.g., $pN \rightarrow X\pi^0$, $\pi^0 \rightarrow \gamma A'$
- Bremsstrahlung from primary beam: $pN \rightarrow XA'$

Sensitivity estimate assumes:
- $10^{18}$ pot on Be target
- Production in meson decays and bremsstrahlung
- Reconstruction of both $e^+e^-$ and $\mu^+\mu^-$ channels
- 90% CL exclusion in zero-background assumption

Sensitivity estimate does not include contributions from:
- $A'$ from QCD processes
- $A'$ produced in TAX

Data from 2016-2017 runs
- $3 \times 10^{17}$ pot with $\mu\mu$ trigger
- $5 \times 10^{16}$ pot with $ee$ trigger
Dark scalar particles

Dark sector coupled to Higgs by new singlet scalar field \( S \)

Expansion of the field \( H \) around VEV \( v \) gives mixing of physical \( h \) and \( S \) with parameter \( \theta \)

Sensitivity estimate assumes:

- **10^{18}** pot on Be target
- Reconstruction of 2-track final states \((ee, \mu\mu, \pi\pi, KK)\) with vertex pointing back to TAX:
  \( S \) produced most efficiently by decays of \( B \)-mesons from interactions in TAX
- 90\% CL exclusion in zero-background assumption

Data from 2016-2017 runs

- **3 \times 10^{17}** pot with \( \mu\mu \) trigger
- **5 \times 10^{16}** pot with \( ee \) trigger

**NA62 estimated sensitivity for 10^{18} pot**
Axion-like particles

Light pseudoscalar ALP may act as a mediator between SM and dark matter

\[ \mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{4f_\gamma} F_{\mu\nu} \tilde{F}_{\mu\nu} + \frac{a}{4f_G} \text{Tr} G_{\mu\nu} \tilde{G}_{\mu\nu} + \frac{\partial \mu a}{f_l} \sum_\alpha \bar{l}_\alpha \gamma_\mu \gamma_5 l_\alpha + \frac{\partial \mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta \]

NA62 can explore ALP masses in the MeV-GeV range

Focus on pseudoscalar ALPs whose dominant interaction is with photons:
- Dedicated running in beam dump mode (TAX closed)
- Primakoff (\(\gamma\gamma\) fusion) production from interaction in TAX with \(a \rightarrow \gamma\gamma\) decay
- ALP produced at low \(p_\perp\) \(\rightarrow\) good acceptance even if detector far from production point

Sensitivity estimate assumes:
- \(10^{18}\) pot on closed TAX
- 90% CL exclusion in zero-background assumption

Significant results obtainable with only 1 day of data taking (1.3 \(\times\) \(10^{16}\) pot)
- Analysis of 2017 data in progress:
  - 5 \(\times\) \(10^{15}\) pot in dump mode

\[ g_{\gamma\gamma} = 1/f_\gamma \]
HNLs with visible decays

\[ \mathcal{L}_{DS} \] may include mass terms for one or more HNLs \( N \) (Dirac or Majorana)

\( N_s \) mix with \( \nu_{1,2,3} \) to give \( \nu_{e,\mu,\tau} + \text{RH "sterile" neutrinos} \)

Search for \( N \) produced in TAX with decays to two-track final states:

- Assume \( 10^{18} \) pot on closed TAX
- Reconstruct two-track final states, including open channels
- 90\% CL exclusion in zero-background assumption
- Derive sensitivity for coupling scenarios in Shaposhnikov & Gorbunov 0705.1729v2

Data from 2016-2017 runs: \( 10^{17} \) pot with \( \pi\mu \) trigger; few \( 10^{16} \) pot with \( \pi e \) trigger

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DS} + \sum F_{\alpha I} (\bar{L}_\alpha H) N_I \]

\[ \nu_\alpha \rightarrow \sum I U_{\alpha I} N_I \]
Summary and outlook

Main goal of NA62 is to measure $\text{BR}(K^+ \rightarrow \pi^+\nu\nu)$ with 10% accuracy

- Physics runs in 2016, 2017, and 2018 – data taking in progress!

Hidden-sector physics program before LS2:

- Dedicated triggers compatible with $\pi\nu\nu$ program to search for dark photons, dark scalars, and HNLs
- Short, dedicated beam-dump runs to search for ALP decays to $\gamma\gamma$

After LS2, collection of $10^{18}$ pot in beam-dump mode will provide sensitivity to various hidden-sector models

- Expected sensitivity beyond that of other initiatives with same time scale

Results from the current NA62 run will be exploited to:

- Evaluate background rejection capability up to $10^{17} \rightarrow 10^{18}$ pot
- Define setup optimizations for future beam-dump mode running, including, if needed, minor modifications to the existing apparatus
The zero-background assumption

Sensitivity estimates for channels with visible decays (dark photons, scalars, ALPs, HNLs) are based on zero-background assumption for $10^{18}$ pot

- Baseline selection: 2 tracks, opposite sign, vertex far from beamline

Test zero-background assumption using combinatorial background to $A' \rightarrow \mu\mu$ from halo muons

Halo rates from upstream decays/interactions: 3 MHz $\mu^+$ and 150 kHz $\mu^-$

Cuts:
- Track quality & acceptance
- Vertex quality
- Total momentum from target
- Veto extra LKr energy
- Photon veto: SAC/IRC/LAV
- Upstream charged particle veto (CHANTI)

No events selected in signal region for $10^{15}$ pot, even with standard $K^+$ beam
Assumption valid for $10^{15}$ pot in standard running (4 $\times$ $10^{15}$ pot in dump mode)