**DARK SECTOR (DS)** charged under a new U(1)' gauge symmetry and interacts with SM through kinetic mixing ($\epsilon$) of a MASSIVE VECTOR MEDIATOR ($A'$) with our photon.

Dark matter with mass ($m_\chi$), part of DS. Four parameters: $m_{A'}$, $m_\chi$, $\alpha_D$, $\epsilon$

\[
\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_{A'}^2}{2} A_\mu A'^\mu + i \bar{\chi} \gamma^\mu \partial_\mu \chi - m_\chi \bar{\chi} \chi - \alpha_D \bar{\chi} \gamma^\mu A'_\mu \chi,
\]
In this framework DM can be produced thermally in the early Universe.

\[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \]

Large range for \( g_X \) and \( m_X \)

J. Feng and J. Kumar Phys.Rev.Lett.101:231301,2008
SEARCHES FOR DARK SECTORS AT ACCELERATORS

1) BEAM DUMP APPROACH (MiniBooNE, LSND, NA62...)

Flux of X generated by decays of A's produced in the dump.

**Signal:** X scattering in far detector

\[ \sigma \propto \epsilon^4 \alpha_D \]
SEARCHES FOR DARK SECTORS AT ACCELERATORS

INVISIBLE DECAY MODE \[ m'_A > 2m_X \]

2) NA64/LDMX APPROACH

NA64 **missing energy**: produced A's carry away energy from the active dump used to measure recoil e- energy

\[ \sigma \propto \varepsilon^2 \]
EXPLICIT TARGET FOR NA64 \((y,m_X)\) DM PARAMETER SPACE

\[ y = \epsilon^2 \alpha_D \left( \frac{m_X}{m_{A'}} \right)^4 \]

Recent review https://arxiv.org/pdf/1707.04591.pdf

Cross sections DM -> SM annihilation is \(\sim Y\), useful variable to compare exp. sensitivities

Solid lines predictions from DM relic abundance
EXPLICIT TARGET FOR NA64 \((y,m_X)\) DM PARAMETER SPACE

\[ y = \epsilon^2 \alpha_D (m_X/m_A')^4 \]

**Thermal and Asymmetric Targets at Accelerators**

- **Probed**
- **Solid lines**
- **predictions from DM relic abundance**

**NA64e TARGET**

higher mass region could be covered by NA64mu (pilot run in 2021, see report from Laura)

*PLB796, 117 (2019)*

recent review https://arxiv.org/pdf/1707.04591.pdf
The NA64 method to search for $A' \rightarrow \chi\bar{\chi}$

- TAGGED 100 GeV
- Requested ECAL ENERGY < 50 GeV

Active Dump

ELECTROMAGNETIC CALORIMETER (ECAL)

"BREMSSTRAHLUNG" OF A'

$\sqrt{\alpha_D} = g\chi$
Signature for the invisible decay \( A' \rightarrow \chi \bar{\chi} \) - large missing energy

\[ \sqrt{\alpha_D} = g \chi \]

**HADRONIC CALORIMETER (HCAL)**

**STANDARD MODEL:**
\[ E_{ECAL} + E_{HCAL} = 100 \text{ GeV} \]

**A’ → MISSING ENERGY:**
- ECAL < 50 GeV
- HCAL < 2 GeV
The NA64 setup to search for $A' \rightarrow \chi \bar{\chi}$

**Active target**

100 GeV electrons (tagged with $S_{1,2,3}$)

HCAL: High hermeticity due to Lorentz boost

Particle identification
SR emission $\sim 1/m^4$

Two bending magnets in series
7 T.m field $\rightarrow$ reconstruction of $e^-$ incoming momentum
Combined results (2016-2018)

TOT: 2.84 x 10^{11} EOT

First time NA64 constraints on light thermal DM exceeding sensitivity of beam dump exp. (suppressed by $\varepsilon^2 \alpha_D$)

NA64 collaboration, Phys. Rev. Lett. 123, 121801 (2019), selected as Editor suggestion
Current bounds on thermal relic DM & projected NA64 sensitivity

\[ \alpha_D = 0.1 \]

\[ m_{A'} = 3m_\chi \]

Setup and beam upgrade required (status in few slides)
2) The NA64 search for $X/A' \rightarrow e^+e^-$

VISIBLE DECAY MODE  \[ m_{A'} < 2m_X \]

Pair production of SM particles
8Be anomaly and X boson

Could be explained by new ‘protophobic’ gauge boson X with mass around 17 MeV

J. L. Feng et al., Phys. Rev. D95, 035017 (2017)
J. L. Feng et al., arXiv 2006.01151

A. J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015) and new evidence for X17 from measurements with 4He
arXiv:1910.10459
The NA64 setup to search for $X \rightarrow e^+e^-$ - calorimetry approach

Addition of W calorimeter
Short in length to allow X to escape

Zooming in (next slide)
The NA64 search for $X \rightarrow e^+e^-$ - experimental signature

**Signature:**
1) $E_{WCAL} + E_{ECAL} = 100$ GeV
2) No activity in $V_2, V_3$ and HCAL
3) Signal in $S_3, S_4$
4) e-m shower in ECAL

**WCAL:** 30 $X_0$ Sandwich W-Sc
The NA64 search for $X \rightarrow e^+e^-$ - NEW results (2017-2018)

No signal-like event in signal box

~ $8 \times 10^{10}$ EOT

NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) (2020)
The NA64 search for $X \rightarrow e^+e^-$ - prospects (2021)

Feasibility under study (in few slides)

NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) (2020)
3) The NA64 search for ALP

Production via Primakoff effect

\[ e^{-}Z \rightarrow e^{-}Z\gamma; \gamma Z \rightarrow aZ; a \rightarrow \gamma\gamma \]

NA64 collaboration, CERN-EP-2020-068 arXiv:2005.02710 submitted to PRL

Closing the gap between beam dump and colliders

\[ \sim 2.84 \times 10^{11} \text{ EOT} \]

Search expected to be BKG free up to ~ 5 x 10^{12} EOT, allowing to probe ALP masses up to ~ 200 MeV
Additional publications - Theory working group

(i) S. Demidov, S. Gninenko and D. Gorbunov, “Light hidden photon production in high energy collisions,” JHEP 1907 (2019) 162, [arXiv:1812.02719 [hep-ph]].

(ii) S. N. Gninenko, D. V. Kirpichnikov, M. M. Kirsanov and N. V. Krasnikov, “Combined search for light dark matter with electron and muon beams at NA64,” Phys. Lett. B 796 (2019) 117 [arXiv:1903.07899 [hep-ph]].

(iii) S. N. Gninenko, N. V. Krasnikov and V. A. Matveev, “Search for dark sector physics with NA64,” arXiv: 2003.07257 [hep-ph].

(iv) S. N. Gninenko, D. V. Kirpichnikov and N. V. Krasnikov, “Probing millicharged particles with NA64 experiment at CERN,” Phys. Rev. D 100 (2019) no.3, 035003 arXiv:1810.06856 [hep-ph].

(v) R. R. Dusaev, D. V. Kirpichnikov and M. M. Kirsanov, “Photoproduction of axion-like particles at NA64,” arXiv: 2004.04469 [hep-ph].

(vi) D. V. Kirpichnikov, V. E. Lyubovitskij and A. S. Zhevlakov, “Implication of the hidden sub-GeV bosons for the (g−2)_\mu, ^8\text{Be}-^4\text{He} anomaly, proton charge radius, EDM of fermions and dark axion portal,” arXiv:2002.07496 [hep-ph].

(vii) N. V. Krasnikov, “Implications of last NA64 results and the electron ge−2 anomaly for the X(16.7) boson survival,” arXiv:1912.11689 [hep-ph].
Status of Preparation of new area in H4

- Design of beam line and the experimental area was performed in a **strong collaboration with the EN-EA-LE and EN-EA-DC groups**.
- MC studies: to **maximize electron flux**, reduce beam halo and **minimize background** from hadron contamination in the beam.
- **New H4 zone** will allow for even wider range of searches for new physics with NA64e than was foreseen in the proposal.

installation expected to be completed in 2021 when SPS will resume.
New DAQ: to improve in data-taking efficiency. At the moment the DAQ allows to collect about 8 kHz with a dead time of 20%. After the upgrade we plan to reach more than 50 kHz with less than 1% dead time.
Setup upgrade A’ → $\chi \bar{\chi}$

**GOAL**: increase the overall performance and improve background rejection

**New VHCAL**: to improve detector hermiticity and reject high-$p_t$ hadronic secondaries from beam interactions upstream the ECAL dump. Search expected to be BKG free up to $\sim 10^{13}$ EOT

- Dimensions $\sim 50 \times 50$ cm$^2$, 16 cells, matrix 4x4 cells
- Central hole size $12 \times 6$ cm$^2$
- Cell size $12 \times 12$ cm$^2$
- Length $\sim 100$ cm, 5 $\lambda$
- 30 layers, 25 mm copper + 2 mm scintillator
- Read out WLS fiber, 12 fibers per scintillator
- Light yield $\sim 15$ photoelectrons per MIP
Setup upgrade for $X/A' \rightarrow e^+e^-$ - Calorimetry + mass reconstruction

**GOALS**

i) probe remaining X17 parameter space

ii) claim an unambiguous observation of X17 by reconstructing its invariant mass.

**WCAL optimisation**: shorter WCAL dump with the total thickness $\simeq 30X_0$, and a new WCAL veto counter

| WCAL structure [mm][layers] | WCAL length [mm] | $\epsilon$ | EOT to cover X17 at 90% confidence [$10^{10}$] |
|-----------------------------|------------------|------------|-----------------------------------------------|
| ECAL1:3+2(34)              | 178              | 0.001      | $174.3\pm4$                                  |
| ECAL1:6+2(17)              | 148              | 0.001      | $7.4\pm0.9$                                  |
| ECAL1:9+2(12)              | 138              | 0.001      | $6.7\pm0.7$                                  |
| ECAL1:3+2(34)              | 178              | 0.0012     | $85.4\pm4.7$                                 |
| ECAL1:6+2(17)              | 148              | 0.0012     | $24.6\pm6.9$                                 |
| ECAL1:9+2(12)              | 138              | 0.0012     | $19.5\pm5$                                   |
GOALS
i) probe remaining X17 parameter space
ii) claim an unambiguous observation of X17 by reconstructing its invariant mass.

New large area trackers at 18 m from vertex:
measurement of the e+e- opening angle.

Additional spectrometer using MBPL magnet:
momentum reconstruction + increase track separation at the ECAL.

New ECAL with larger transverse size:
measurement of two separate em showers
SUMMARY & PLANS FOR 2021

- Preparation of the **new NA64 area at H4** and the detector upgrade is in progress.

- **Summer of 2021:** we plan to request three-weeks run for detector commissioning and accumulation of ≃ $10^{11}$ EOT in **invisible mode** in order to cover yet unexplored areas in the sub-GeV Dark Matter parameter space.

- **Autumn of 2021:** about six-seven weeks for detector commissioning and accumulation of ≃ $10^{11}$ EOT **for visible mode at 150 GeV** to perform a more sensitive search for the $A'(X) \rightarrow e^+e^-$ decays.

The exploitation of the NA64 physics potential has just begun!

- **Before LS3:** Assuming intensity up to ≃ $10^7$ e$^-$/spill and on average ≃ 4000 good spills per day means accumulation of up to $5 \times 10^{12}$ EOT during 6 months of running is feasible. The results obtained with such number of EOT will allow us to **probe full parameter space for scalar and Majorana sub-GeV dark matter models.**
Backup slides
Summary of setup upgrade

**DETECTORS & DAQ UPGRADES**: To increase the overall performance and improve background rejection the following upgrade of the setup are ongoing:

(i) additional number of the MM, GEM, ST stations are planned to be installed.
(ii) using of a new ECAL with larger transverse dimensions and new WCAL dump for the visible mode
(iii) using of a higher transversely segmented SRD detector with improved readout
(iv) large Veto HCAL (VHCAL) in front of the ECAL to reject large angle neutral secondaries from the upstream e$^-$/hadronic interactions
(v) further improvement of the DAQ and the analysis program are foreseen to ensure a substantial data collection of $n_{EOT} \approx 5 \times 10^{12}$ events in 2021-2023.
2018: NA64 search for $X \rightarrow e^+e^-$ - optimised for very short lived $X$

Beam energy: 100 GeV (2017) → 150 GeV

Setup optimization:
shorter WCAL, thinner veto (W2) after WCAL, vacuum pipe installed, additional trackers and increased WCAL- ECAL distance.
2018: Improvement of setup $A' \rightarrow \chi \bar{\chi}$

ST1,2: New straw-tube trackers: VETO against hadron electro-production in the beam material upstream the ECAL.

HCAL0: Rejection of events with hard neutral from upstream e- interactions