Physics prospects at the CERN North Area

Eckhard Elsen
Director Research and Computing

1974 survey of Lab II site; geodolite on loan from Fermi Laboratory
The longevity of the North Area programme is explained by the fact that the first run in March 1978, and the first physics publications were reported at the start of the commissioning run in March 1978, and the first physics publication was North Area at 40, where each machine is not only used to inject the protons by the unique complex of proton accelerators at CERN, the North Area's physics programme is as vibrant as ever.

Yan – was published in 1979 by the NA3 experiment. Today, by quark–antiquark annihilation as predicted by Drell and Yan – a measurement of the production rate of muon pairs in parallel to collider facilities. Among these were the first studies of the quark–gluon plasma, the first evidence of direct CP violation and a detailed understanding of how nucleon spin arises from quarks and gluons. The first muons in the dark sector. As the North Area marks 40 years since the first muons and hadrons. With respect to collider experiments, fixed-target experiments tend to be more specialised and focus on precision measurements that demand very high statistics, such as those involving ultra-rare decays. High-energy machines like the SPS, which produces proton–antiproton collider in the early 1980s, and again during the LEP and now LHC eras. As has been the case sequentially named, they range from the pioneering NA1, which measured the photoproduction of vector and scalar bosons, to today's NA64, which studies hadronic production of particles with large transverse momentum (NA3); inelastic hadron scattering (NA7); hadronic production of particles with large toproduction (NA1); electromagnetic form factors of pions and kaons (NA6); and neutron scattering (NA6). In EHN2 there were studies and EHN2 for muon experiments. The first round involved two large experimental halls: EHN1 for hadronic experiments NA10 (bottom) showing with a view from 1980 (top) and the same experiment NA62 today, showing underground hall T2, T4, T6 targets.

North Area
EHN1

1980s

now
Completed NA Experiments

<table>
<thead>
<tr>
<th>Name</th>
<th>Synonym</th>
<th>Title</th>
<th>Date of Approval</th>
</tr>
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<tbody>
<tr>
<td>NA1</td>
<td></td>
<td>Measurement of the Photoproduction of Vector and Scalar Bosons</td>
<td>12.03.75</td>
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<td>NA2</td>
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<td>Electromagnetic Interactions of Muons</td>
<td>12.03.75</td>
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<td>NA3</td>
<td></td>
<td>Hadronic Production of High p T Leptons and Hadrons</td>
<td>12.03.75</td>
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<td>NA4</td>
<td>NA14/2</td>
<td>Inclusive Deep-Inelastic Muon Scattering</td>
<td>07.03.75</td>
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<td>NA5</td>
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<td>Inelastic Hadron Reactions Using a Streamer Chamber Triggered by a Single-Arm Spectrometer</td>
<td>04.08.75</td>
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<td>NA6</td>
<td></td>
<td>Neutron Elastic Scattering at Very Small Angles</td>
<td>20.01.77</td>
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<td>NA7</td>
<td></td>
<td>Measurement of the Electromagnetic Form Factors of p and K Mesons at the SPS</td>
<td>22.09.77</td>
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<tr>
<td>NA8</td>
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<td>Hadron Elastic Scattering at Small Angles</td>
<td>08.12.77</td>
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<td>NA9</td>
<td></td>
<td>Study of Final States in Deep-Inelastic Muon Scattering</td>
<td>16.02.78</td>
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<tr>
<td>NA10</td>
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<td>High Res. St. of the Inclusive Prod. of Massive Muon Pairs by Intense Pion Beams</td>
<td>16.03.78</td>
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<td>NA11</td>
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<td>Measurement of Charm Particle Production in Hadronic Reactions</td>
<td>25.05.78</td>
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<tr>
<td>NA12</td>
<td></td>
<td>GAMS Study of p-p Interactions with Neutral Final States</td>
<td>16.11.78</td>
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<td>NA13/2</td>
<td></td>
<td>GAMS Search for Mesons and Gluon Decaying into Multiphoton Final States Produced in Central Hadron Collisions and Study of Inclusive Production of Heavy Quark Mesons</td>
<td>06.02.86</td>
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<tr>
<td>NA13</td>
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<td>Search for Direct Evidence for Charm in Hadronic Interactions using a High-Resolution Bubble Chamber</td>
<td>16.11.78</td>
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<tr>
<td>NA14</td>
<td></td>
<td>PHOTOPRODUCTION Photoproduction at High Energy and High Intensity</td>
<td>14.12.78</td>
</tr>
<tr>
<td>NA14/2</td>
<td></td>
<td>PHOTOPRODUCTION A Programme of Heavy Flavour Photoproduction</td>
<td>25.04.83</td>
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<tr>
<td>NA15</td>
<td></td>
<td>Search for Charmed Hadron Production in p-p Nucleus Interactions in Nuclear Emission</td>
<td>14.06.78</td>
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<tr>
<td>NA16</td>
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<td>Study of the Hadronic Production and Properties of New Particles with a Lifetime 10-13 to 10-10 x using LEBIC-EHS</td>
<td>20.09.79</td>
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<td>NA17</td>
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<td>Momentum and Angular Correlations Study in p-p Nuclear Jets at High Energies using Emulsion Telescopes Technique with Magnetic Field</td>
<td>20.09.79</td>
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<td>NA18</td>
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<td>Search for Short-Lived Particles Produced on Nuclei with a Heavy Liquid Mini Bubble Chamber</td>
<td>15.11.79</td>
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<tr>
<td>NA19</td>
<td></td>
<td>Direct Observation of Beauty Particles Selected by Muonic Decay in Emulsion</td>
<td>15.11.79</td>
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<tr>
<td>NA20</td>
<td></td>
<td>Measurements of p-p, K-+K-, p+e0 - Yields in 400 GeV Proton Beryllium and Copper Collisions</td>
<td>15.11.79</td>
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<td>NA22</td>
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<td>The Influence of Parton Structure on Hadronic Interactions in EHS with a K-&gt;p+p Beam at 350 GeV/c</td>
<td>16.10.80</td>
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<td>NA23</td>
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<td>Study of Diffusive Dissociation Especially into Strange and Charmed Particles with EHS</td>
<td>16.10.80</td>
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<td>NA24</td>
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<td>Investigation of Deep Inelastic Scattering Processes Involving Large p T Direct Photons in the Final State</td>
<td>27.11.80</td>
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<td>NA25</td>
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<td>Study of Charm and Bottom Particle Production Using a Holographic Bubble Chamber</td>
<td>23.04.81</td>
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<td>NA26</td>
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<td>A Prototype Experiment to Study Charmed Particle Production and Decay using a Holographic High-Resolution Hydrogen Chamber (HOLBEC) and the European Hybrid Spectrometer</td>
<td>21.05.81</td>
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<td>NA27</td>
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<td>An Experiment to Measure Accurately the Lifetime of the D0, D+, F-- LambdaCharm Particles and to Study their Hadronic Production and Decay Properties</td>
<td>08.12.81</td>
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<td>NA28</td>
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<td>Study of Shadowing and Hadron Production in High Energy Mu Scattering Using Nuclear Targets</td>
<td>17.02.82</td>
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### Ongoing NA Experiments

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<tr>
<td>NA58</td>
<td>COMPASS</td>
<td>Common Muon and Photon Apparatus for Structure and Spectroscopy</td>
<td>06.02.97</td>
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<tr>
<td>NA61</td>
<td>SHINE</td>
<td>Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS</td>
<td>21.02.07</td>
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<tr>
<td>NA62</td>
<td></td>
<td>Proposal to Measure the Rare Decay K+ → π+ νν at the CERN SPS</td>
<td>21.02.07</td>
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<tr>
<td>NA63</td>
<td></td>
<td>Electromagnetic Processes in strong Crystalline Fields</td>
<td>21.02.07</td>
</tr>
<tr>
<td>NA64</td>
<td></td>
<td>Search for dark sectors in missing energy events</td>
<td>09.03.16</td>
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</tbody>
</table>

- **Designing the experiment.**
  - **How does this setup measure photon energies?**
  - All you know is the position where some charged particles hit the detector.

- **Position sensitive detectors**

- **NA61**

- **NA63**

- **NA64**
Continuing Interest in SPS fixed target experiments
Physics interest in Fixed Target Programme at SPS

• Intensities
  • ~40% of all protons go to SPS

• Variety
  • many targets from hydrogen to heavy elements
  • many projectiles:
    • $p, \bar{p}, \pi, K, e, \mu$
  • and ion beams
SPS is no longer energy frontier

- while SPS with 450 GeV was conceived to address energy frontier

  - on the long run there was no way to compete against collider programmes
    - SppS, HERA, Tevatron, LHC

- **but** the boost of the centre-of-mass system (in Fixed-Target experiments) provides a superb handle for measuring/exploiting short-lived particles, in particular charm

  - ACCMOR introduced Si-detectors

  - Principle often used: asymmetric B-factories
and then R&D

- SPS test beams lines are regularly fully subscribed
  - example North Area use for
    - LHC, CLIC, ILC, … detectors
    - general calorimeter and tracker studies
  - EHN1 extension serves the neutrino platform
Physics Activities
NA62  \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \)

- ultra rare decay in SM
- sensitive to new physics

\[
K^+ \rightarrow \pi^+ \nu \bar{\nu} (\gamma) \quad 8.4 \pm 1.0
\]
\[
K_L \rightarrow \pi^0 \nu \nu \quad 3.00 \pm 0.31
\]

SM branching ratios
Buras et al., JHEP 1511 (2015) 033

**Mode**  | **BR\(_{SM} \times 10^{11} \)**
--- | ---
\( K^+ \rightarrow \pi^+ \nu \nu (\gamma) \) | 8.4±1.0
\( K_L \rightarrow \pi^0 \nu \nu \) | 3.00±0.31
NA62 - Search for Dark Photons

- tagged $\pi^0$ from $K^+$ decays

![Graphical representation of dark photon analysis](attachment:image.png)

$$K^+ \rightarrow \pi^+ \pi^0, \quad \pi^0 \rightarrow \gamma A'$$

$$\frac{BR(\pi^0 \rightarrow \gamma A')} {BR(\pi^0 \rightarrow \gamma \gamma)} = 2\epsilon^2 (1 - \frac{M_{A'}^2}{M_{\pi^0}^2})^3$$

- Most abundant background due to $\pi^0$ decays with undetected photon
- Data-driven approach: select $\pi^0 \rightarrow \gamma \gamma$ with lost $\gamma$ due to conversions in the detector to study background. Background scaled from sideband to signal region
- $A'$ search region: $0.00075 < M_{\text{miss}}^2 < 0.01765 \text{GeV}^2/c^4$ for all mass hypotheses
- Subsample of 2016 data, corresponding to 1% of 2016 data
- No statistically significant excess: observed upper limit @ 90% CL compatible with fluctuations from background only hypothesis

[Moriond QCD 2019]
NA64 – missing energy final states

- Initial experiment
  - $eZ \rightarrow eZ A'$

- NA64µ proposal
  - $\mu Z \rightarrow \mu Z Z \mu$ where $Z\mu$ is a gauge particle

rules out dark photon as explanation for g-2 anomaly

- NA64 detector
  - Main components:
    - $160$ GeV $\mu$-beam, $I\mu \sim 10^7 \mu/$spill.
    - In $\mu$ tagging: BMS+MS1 (MBPL+tracker)
    - Out $\mu$ tagging: MS2 (2MBPL+tracker)
    - 4-hermetic ECAL, VHCAL, Veto, HCAL
    - Location upstream of COMPASS (PBC EHN2 WG)

Signature:
- In: 160 GeV $\mu$-track
- Out: < 80–100 GeV $\mu$-track
- No energy in the ECAL, Veto, HCAL...

Sensitivity $\sim g_{\mu}^2$, SES $\leq 10^{-10}$
Proposal SHiP: Search for Hidden Particles

- search for Heavy Neutral Lepton (HNL) and dark photon $A'$
  - access to extended mass range
- also equipped with emulsion layers for $\nu_\tau$-measurements
- vast physics potential has been thoroughly explored during PBC studies
- requires a Beam Dump Facility (BDF) on the North Area beam lines
QCD and Heavy Ion Physics
COMPASS

• approved in 1997
• QCD facility in M2 beamline
  • (polarised) Drell-Yan
  • SiDIS
  • exklusive processes
• DVCS
COMPASS: Feasibility test of proton radius measurement

Form factor measurement in high-E muon-proton elastic scattering $10^{-3} \ldots 10^{-2}$ GeV$^2$/c$^2$

TPC for measuring proton recoils down to 0.5 MeV: Gatchina / GSI silicon microstrip detectors for muon scattering angle measurement: COMPASS

very preliminary
Future plans – COMPASS++/AMBER

- extended measurements with a variety of beams (rf-separated beams of π, K, anti-p...)
- various targets
- There is also a proposal for an ultra-precise MuOnE ($10^{-5}$) to address the measurement of $g_{\mu}-2$ from a different angle
NA61 – Shine

• Exploration of the second order phase transition in the formation of the QGP

• Measurement of pA cross sections relevant for neutrino precision physics (LBNF and J-PARC)

• ...
NA60++ plans

- Study of dimuon and charm production in nuclear collisions at the CERN SPS (muon + vertex spectrometer)
- Document submitted to the ESPPU
- End of life (EoI) prepared

Vertex spectrometer (MAPS)
Development in synergy with ALICE (upgrade of ITS in LS3)

Toroid magnet
Conceptual design existing
NA60+ Physics Goals

Study the finite-$\mu_B$ region of the QCD phase diagram (critical point, first-order phase transition, chiral symmetry), via a high-luminosity energy scan from low to top SPS energy.

- Thermal di-muons from the QGP
- Open charm and Charmonium Production

$\mu\mu$ invariant mass spectrum (after combinatorial background subtraction)
Experiment proposals examined during PBC study

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Primary</th>
<th>PoT/year</th>
<th>Secondary</th>
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<td>ions/p scan</td>
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<td>ions/hadrons &lt; 120 GeV</td>
<td>ENH1</td>
<td>H2</td>
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<td>400 GeV p</td>
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<td>hadrons &lt; 10 GeV (tertiary)</td>
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<td>H2</td>
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<td>NA64++(e)</td>
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<td>$1 \times 10^{18}$</td>
<td>100 GeV e-</td>
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<td>H4</td>
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<td>COMPASS+</td>
<td>400 GeV p</td>
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<td>muons, pions</td>
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<td>M2</td>
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<tr>
<td>COMPASS++</td>
<td>400 GeV p</td>
<td></td>
<td>100 GeV K; $\bar{p}$; RF-separated</td>
<td>EHN2</td>
<td>M2</td>
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<td>20-50 GeV $\pi$; $K^-$; 200 GeV p</td>
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<td>H4</td>
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<td>NA64++($\mu$)</td>
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<td>100 GeV muons</td>
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<td>Hidden sector</td>
<td>ECN3</td>
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<td>KLEVER</td>
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<td>$K_L$</td>
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<td>2-3 GeV p</td>
<td>$1 \times 10^{18}$</td>
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<td>PS</td>
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</table>
Neutrino Platform
From civil construction to first beam in two years

March 2016, construction of EHN1 extension

February 2018, detector assembly and installation

November 2016, cryostat structure assembly

August 2018, LAr filling and purification

September 2017, cryostat completion

September 2018, beam ready & detector ready for beam!
protoDUNE Single Phase Detector – LArTPC

- Charged particles ionise LAr
- Ionisation electrons drift to the anode in ultra pure LAr
- Calorimetry and Particle Identification (dE/dx)
- \( T_0 \) from externally or internally from prompt scintillation light
Some impressions of interactions in LArTPC

- Bubble chamber-like events
- $dE/dx$
- Track length
- Decays

LAr-TPC data of unprecedented quality
Towards cross section measurements in LAr – protoDUNE-SP

Cross Section Measurements

• The precision hadron cross section measurements will help the DUNE physics in many ways - Provide input to the neutrino generators to improve the final state interaction models.

• For example: the charge exchange process $p + p \rightarrow Ar^* + p + p_0$ is an important background to the $n$e signals - Validate the GEANT simulation of hadron interactions in the LAr.

![Graphs and Images]

- $dE/dx$ of Beam Protons and Positrons
- Proton $dE/dx$ distribution for 1 GeV beam data after applying the calibration derived using cosmic ray muons.
- The expected most probable value of $dE/dx$ vs residual range is superimposed (red).
- Deviation from expectation due to residual non-corrected Space Charge effect.
- $dE/dx$ of electrons (before showering) agrees well with expectations.

- Data: Run 5387
- MC (SCE ON)
- ProtoDUNE Preliminary

1 GeV proton

![Graphs and Images]
protoDUNE dual phase detector – Principle

- 6 m drift; 300 kV
- 15 mm amplification stage (LEM)
protoDUNE dual phase cryostat preparation
Happy Anniversary, North Area
Summary

• At the age of 40 the North Area shows no sign of ageing

• made and continues to make significant contributions to understanding of the Standard Model in QCD and Electroweak measurements

• reaches beyond the Standard Model in searches for new physics

• continues to be the site for developing advanced detector techniques that benefit even more ambitious experiments