Physics at the SPS

Lau Gatignon / CERN-EN-EA
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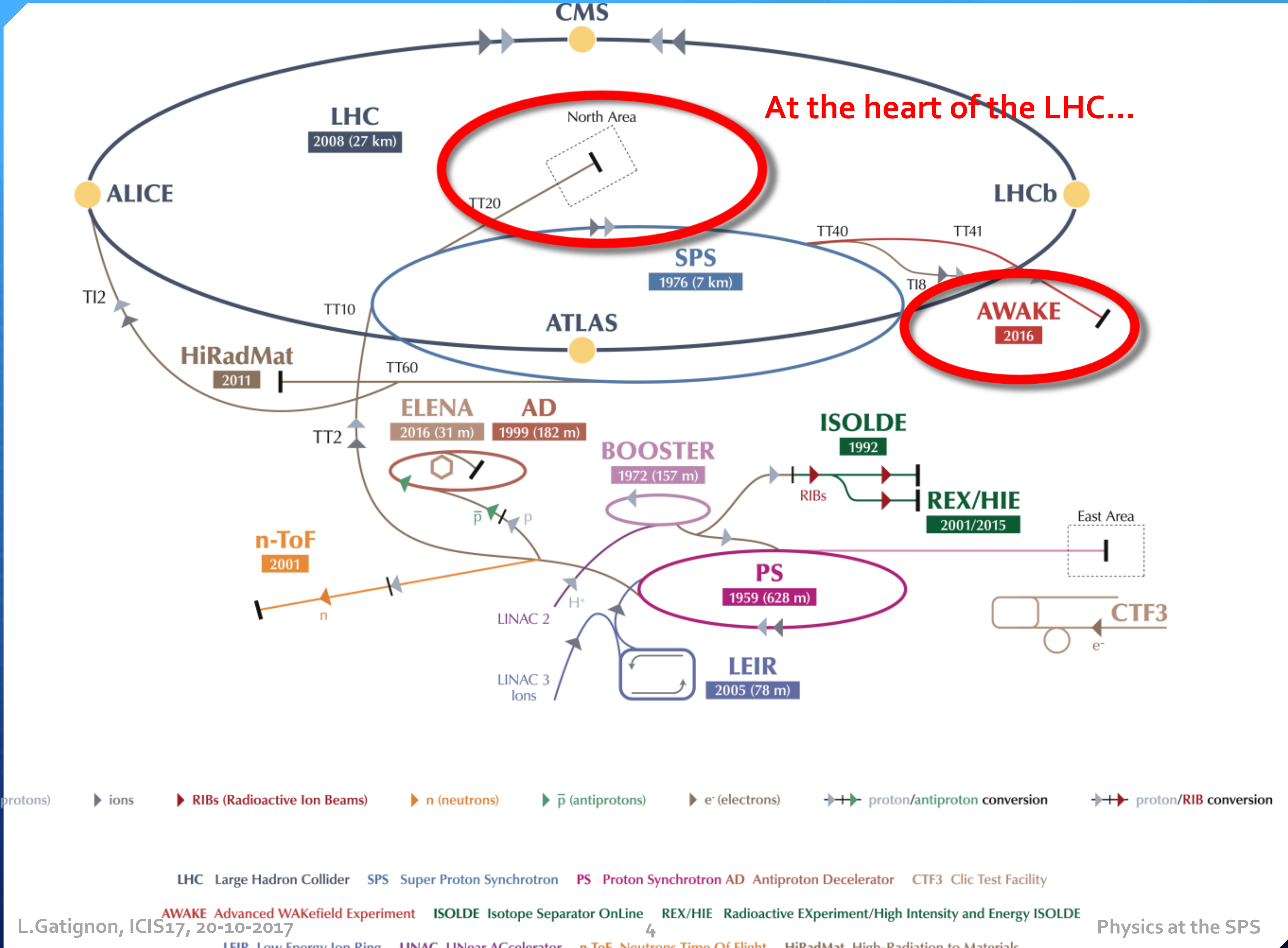
Outline

- Introduction
- Spin structure of the Nucleon (COMPASS)
- Dark Matter (NA64)
- Very rare Kaon decays (NA62)
- Transition to a new state of matter, QGP (NA61/SHINE)
- Accelerator physics studies – PDPWA (AWAKE)

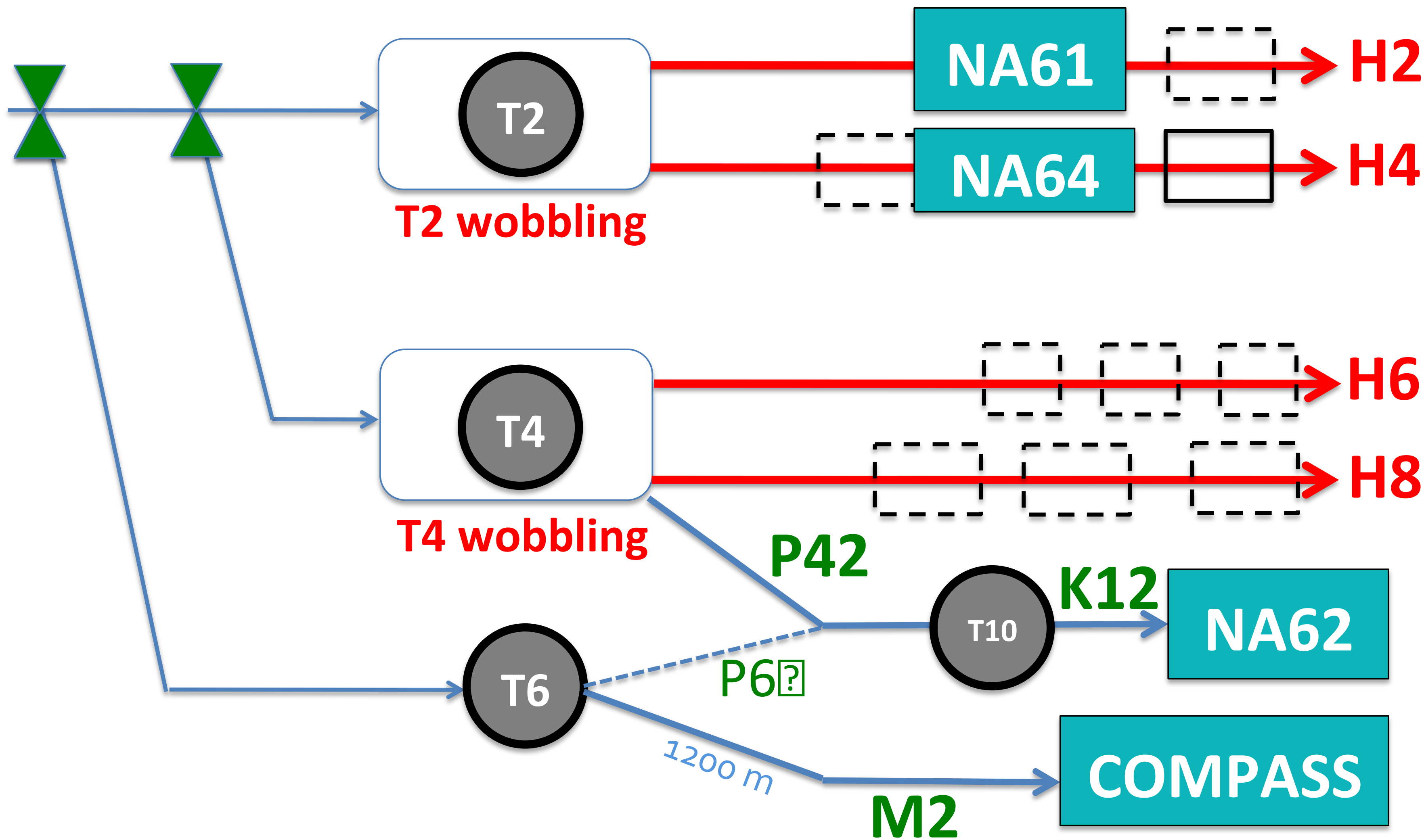
Introduction

- Colliders address the high-energy frontier: $E_{CMS} \sim E_{beam}$
  Fixed target address **high-intensity frontier**: $E_{CMS} \sim \sqrt{E_{beam}}$
  Fixed target experiments use many more protons than LHC!
- Fixed target allows a **variety of beams**: p, π, $K^{\pm}$, K^{o}, e, μ, ions, …
- Therefore fixed target can address a large variety of specific questions with high precision or for rare processes
- Typical FT experiments include vertex or incoming particle definition, tracking, particle identification, calorimetry and muon identification in that order.
- They address e.g. hadron structure, rare processes, dark matter or other new physics, dense nuclear matter (early universe), etc

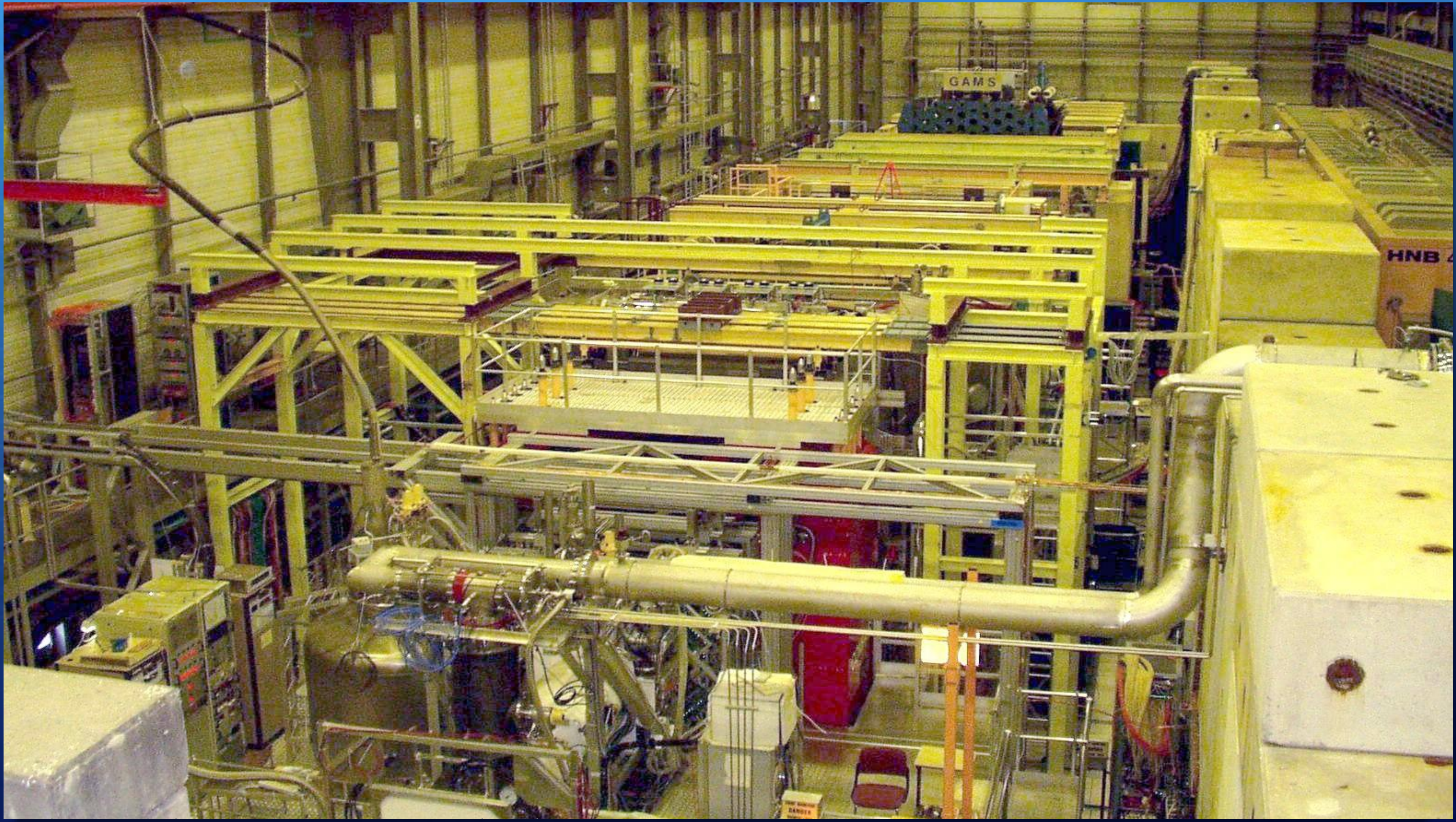
At the heart of the LHC…



NA Beam Lines – Schematic view



Spin structure of the Nucleon - COMPASS



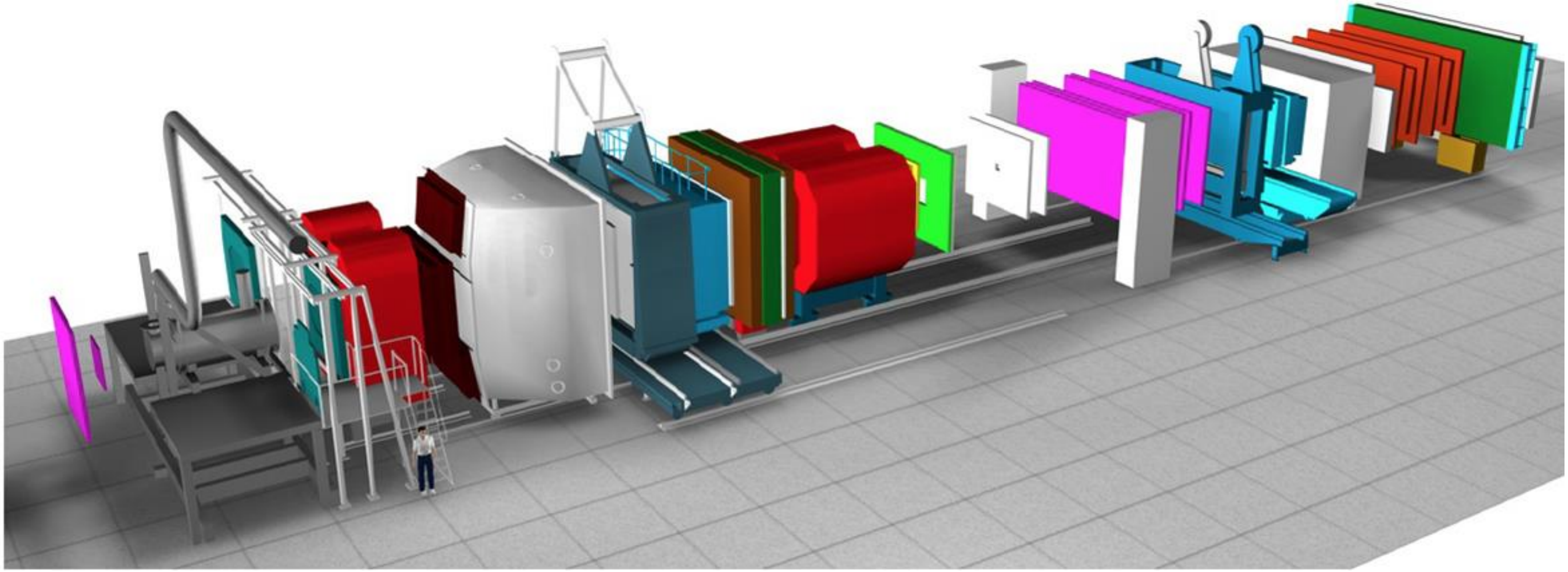
The COMPASS experiment

COMPASS (~250 physicists) is a multi-purpose set-up with a widespread physics program:

- Hadron spectroscopy with pion and kaon beams
- Photon scattering (Primakoff) with hadron beams (π polarisability)
- **Nucleon spin structure**
  - with muon beams on unpolarised target (DVCS),
  - with **polarised muon beams** (Longitudinal and transverse: DIS, SIDIS),
  - with hadron beams (DY) impinging on a **polarised target**

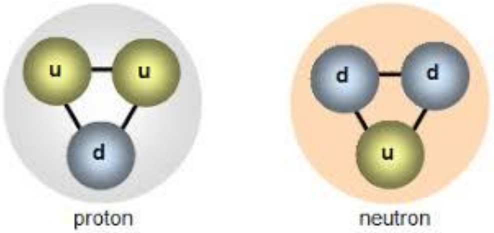
    Note: *muon beams are naturally polarised (80% for COMPASS)*

COMPASS set-up

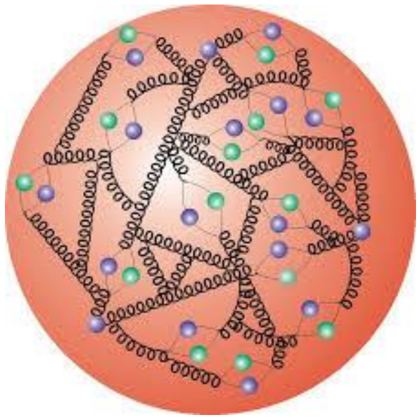


Nucleon spin structure

- A nucleon can be seen as a compound of **3 (valence) quark**s. They explain the quantum numbers.



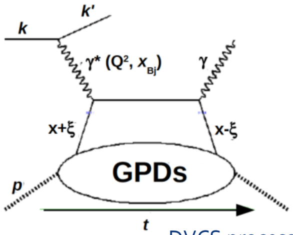
- If you look in more detail, there are also sea quarks and gluons.
- The **nucleon spin**, value ½, is made by the spins of valence quarks, sea quarks, gluons and orbital angular momentum



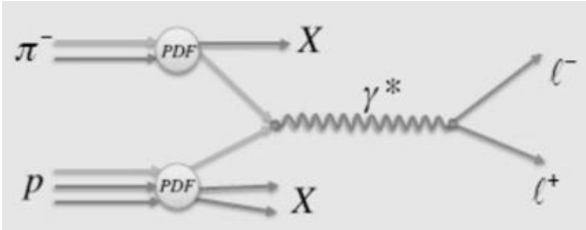
- The **quark contributions** do not sum up to ½ (spin puzzle).
- COMPASS studies the nucleon spin in great detail.

COMPASS measurements of nucleon spin

- COMPASS-II uses mainly two processes to study the spin:



DVCS process



Drell-Yan process

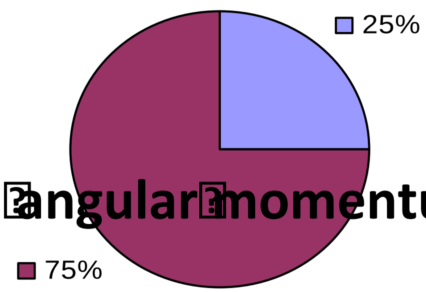
- DVCS is studied with a **high-intensity muon beam**,
  Drell-Yan is done with a **hadron beam** (π^-) on a polarised target

- In Drell-Yan one measures $\mu^+\mu^-$ pair production (absorb the rest).
  In DVCS one measures the outcoming μ and the photon produced (exclusive production).

- The M2 muon beam is the highest-intensity high-energy muon beam in the world

What did one learn about nucleon spin?

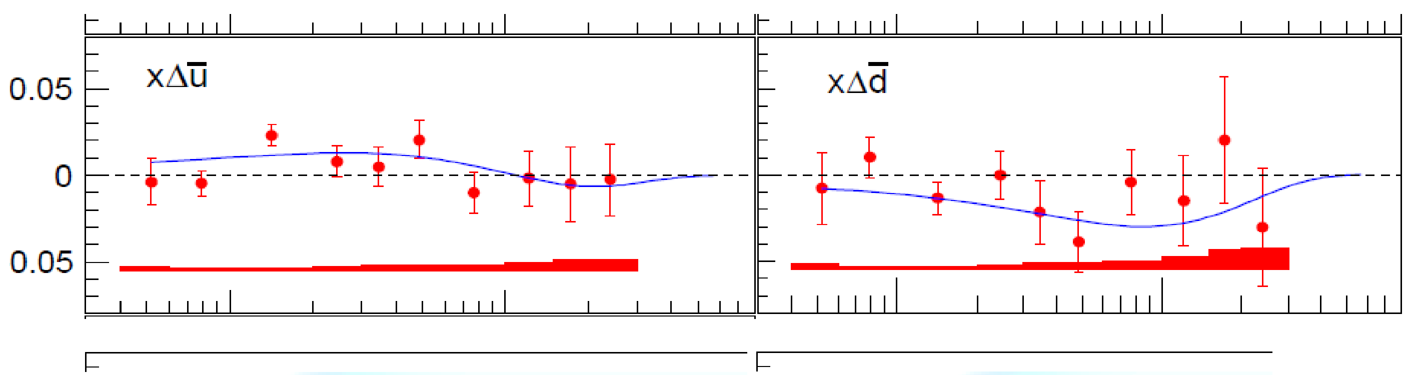
Total proton spin = 1/2



Quark spin measured
In DIS

"Dark" angular momentum?

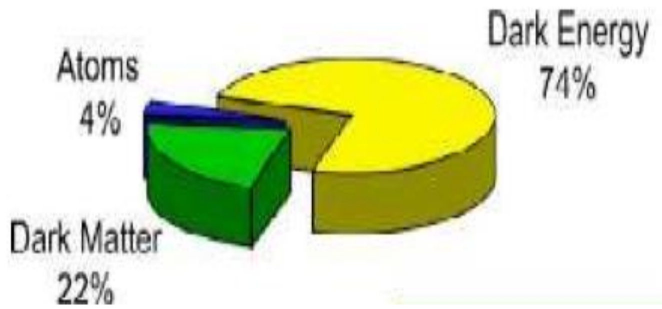
And many features of the proton structure and its spin!



Dark Matter – NA64

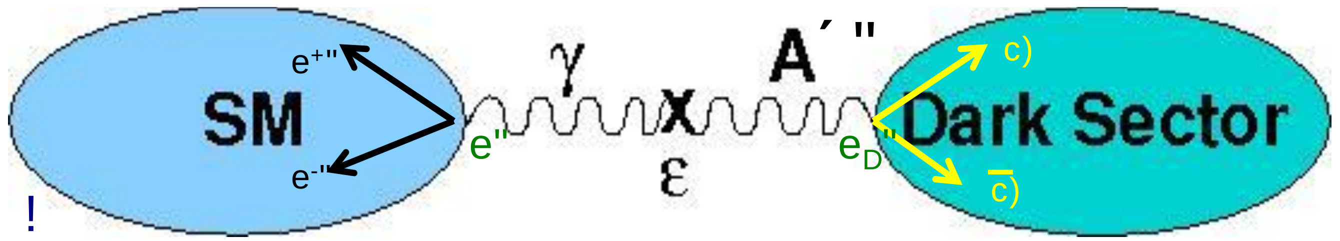
The NA64 experiment

- In spite of its omnipresent successes, the Standard Model is far from complete: it only explains a small fraction of the **mass in the Universe**. Most of the mass is carried by Dark Matter and Dark Energy.



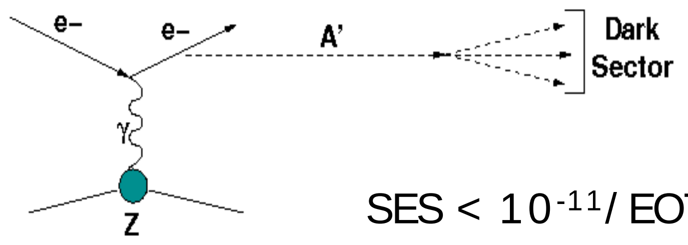
- NA64 searches for the decay if the A', responsible for the transitions between normal matter and Dark Matter.

- Fixed target experiments can explore the **high-intensity frontier**



Experimental approach

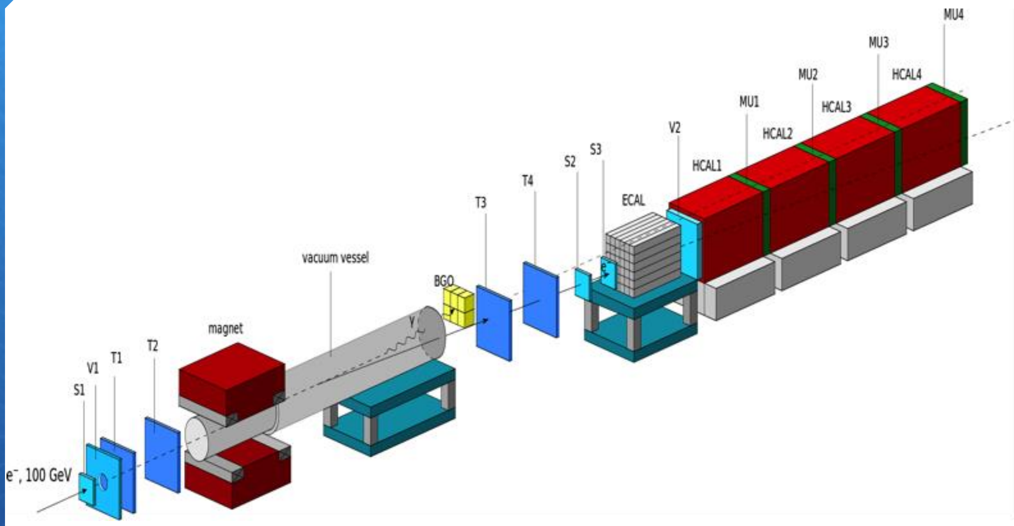
- The initial approach is to look for the **invisible decay mode**:
  An electron emits an A′ which remains undetected.
  The signal events deposit less than 50 GeV in an e.m. calorimeter, where the initial electron has 100 GeV/c.



SES < 10^{-11}/ EOT "

- The main problem is the **beam purity**. Need to reduce non-e component to the ~10^{-12} level, where the physical contamination is O(1%). Use synchrotron radiation and tracking.
- They also look for the **visible decay** A′ $\rightarrow$ e^+e^- with a slightly modified set-up

NA64: Invisible mode



Signature:

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

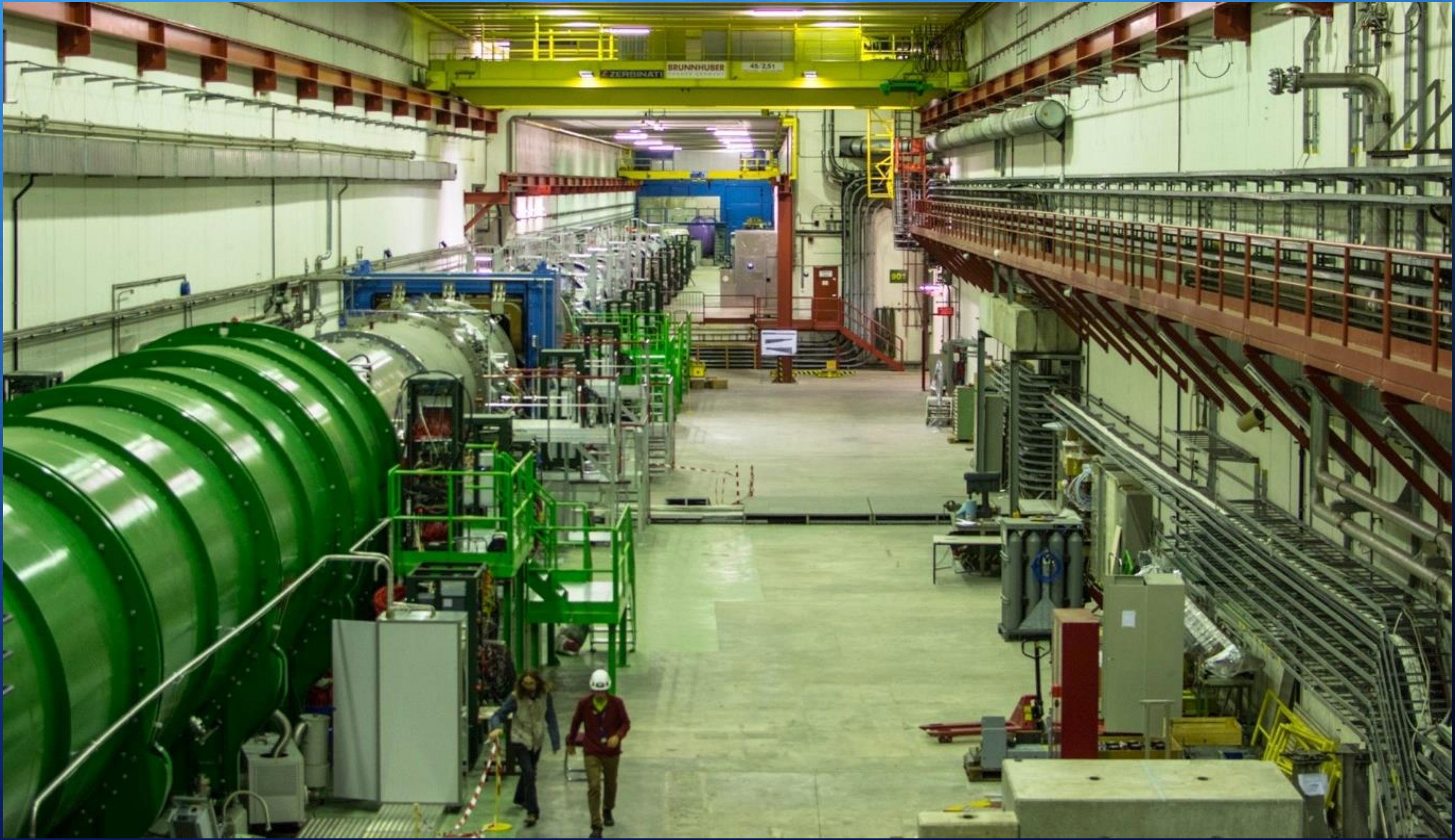
Main components :

- clean 100 GeV e- beam
- e- tagging system: tracker+SRD
- 4π fully hermetic ECAL+ HCAL

Background:

- μ, π, K decays in flight
- Tail < 50 GeV in the e- beam
- Energy leak from ECAL+HCAL

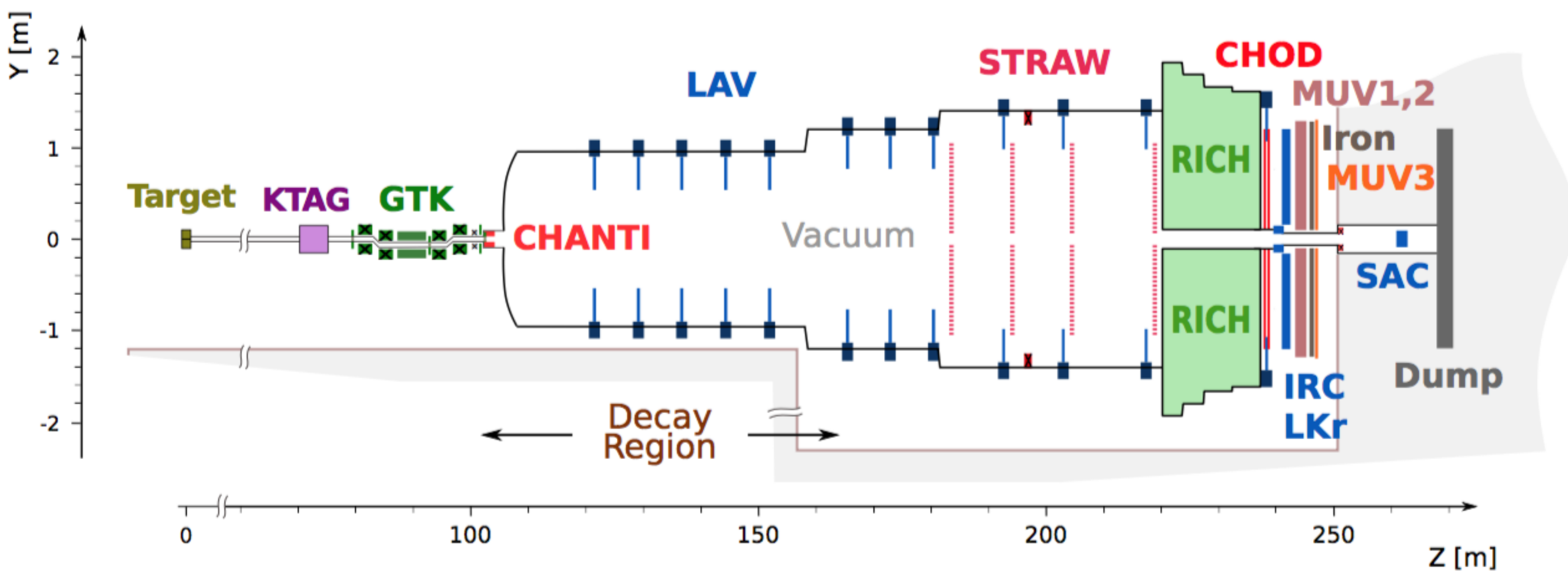
Very rare Kaon Decays – NA62



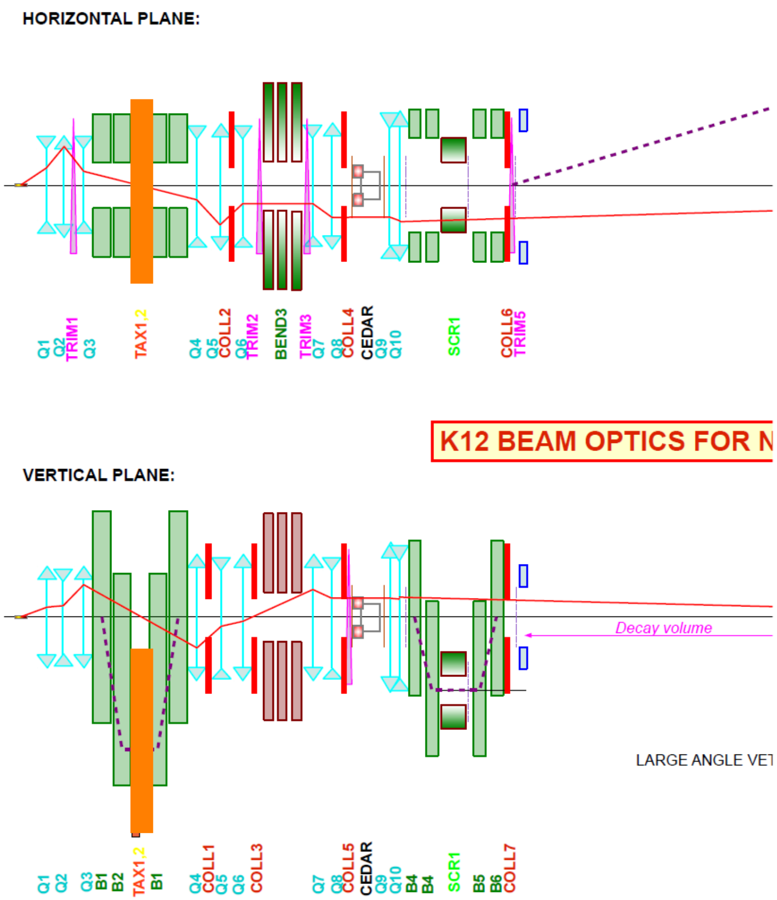
The NA62 experiment

- NA62 has its roots in the NA31 and NA48 experiments, studying Direct CP Violation. CPV is one of the main ingredients in explaining matter dominance in the universe.
- NA48 has also studied **rare Kaon decays**.
- NA62, a completely new experiment, studies the very rare K^+ decay into $\pi^+\nu\nu$. The branching ratio is very small ($\sim 10^{-10}$) and calculable with very good precision in the Standard Model. Therefore it is an ideal place to **look for New Physics**.
- NA62 spends part of its beam time in looking for Dark Matter.

The NA62 in-flight technique



NA62 Dump Mode



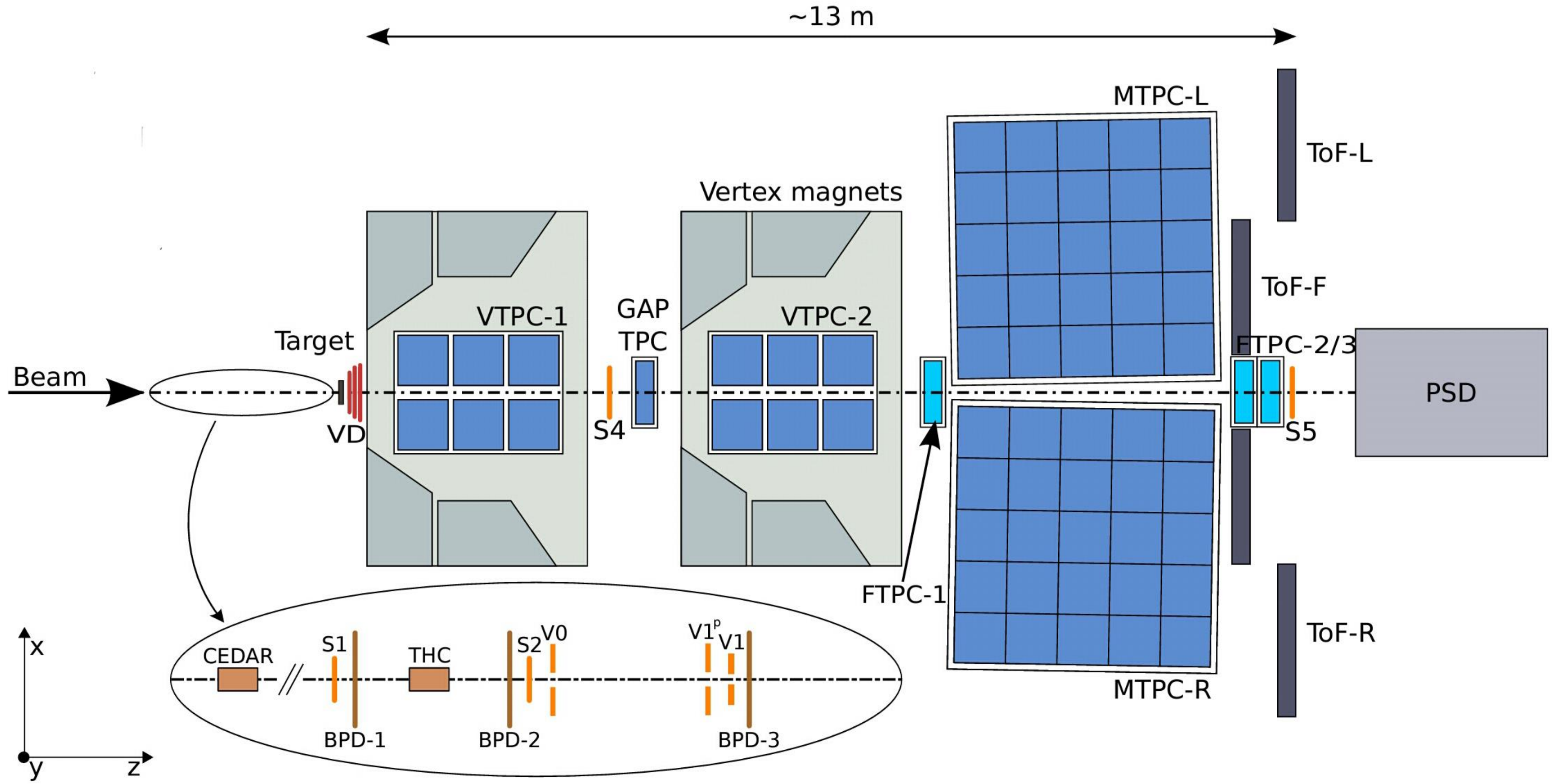
- Beam dump can be closed to stop all hadrons
- As no charged beam needs to be transported, muon sweeping can be optimised (under study)
- Hence possibility to look for HNL (heavy neutral leptons), Dark Matter candidate) via decay into $\pi\mu$
- Also possibility of $A' \rightarrow e^+e^-$
- Some data-taking during 2017, 2018 Maybe more after LS2.

A new state of Matter: QGP (NA61/SHINE)

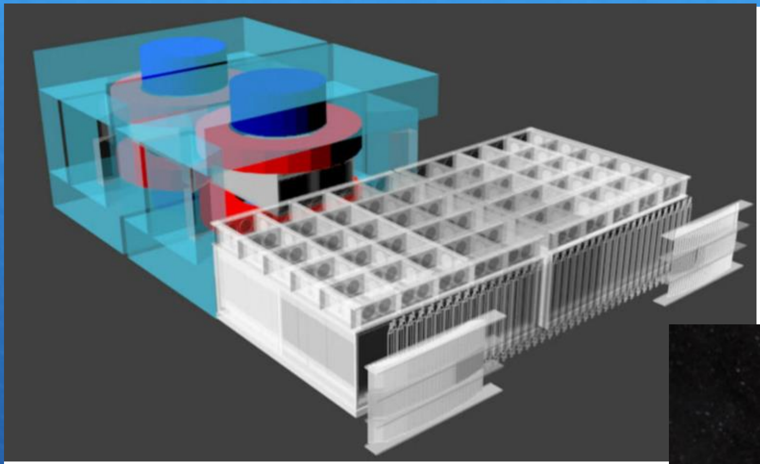
The NA61 / SHINE experiment

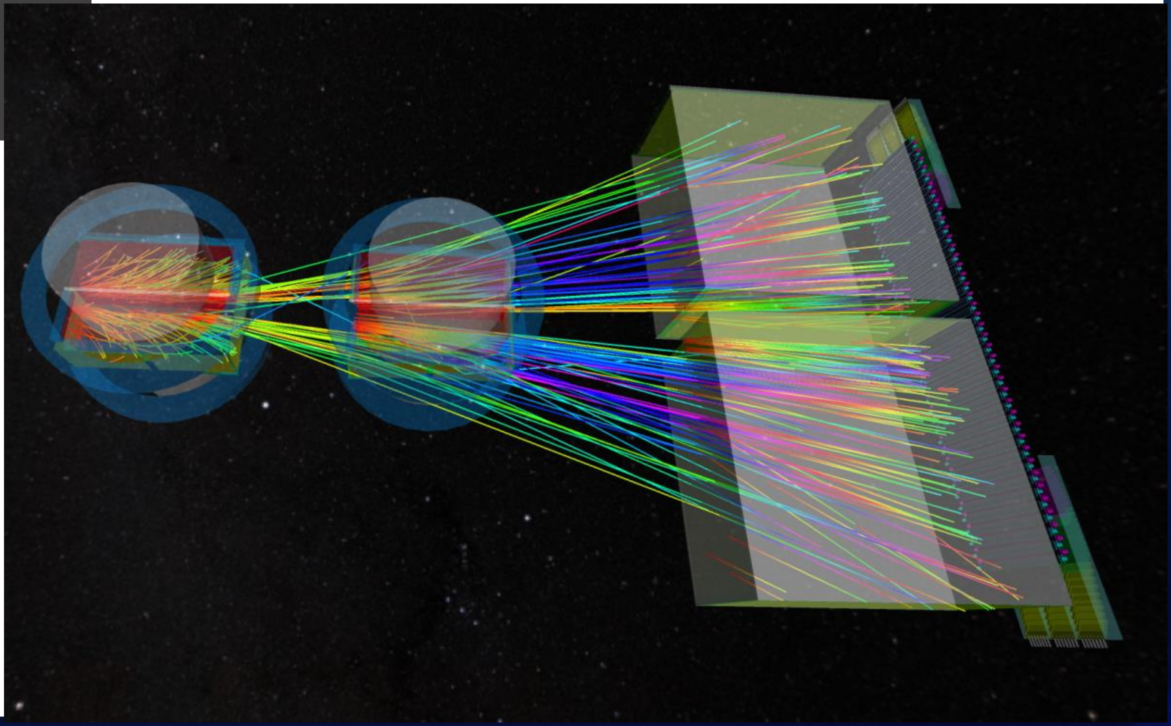
- NA61 has 3 components:
  - Hadroproduction studies for cosmic ray experiments
  - Hadroproduction measurements for neutrino beams
  - Studies of the **Onset of Quark Gluon Plasma** with ion beams
- **QGP is a new state of matter** where quarks and gluons move freely. The study of the phase transition is of particular interest. In particular NA61 searches for the critical point of strongly interacting matter, signalled e.g. by increased event-by-event fluctuations of the number of particles.
- NA61 explores the phase space in analogy to thermodynamics with (P, T) replaced by (A, E). **They use primary Pb, Ar and Xe beams, as well as proton and fragmented Be beams.**

The NA61/SHINE detector

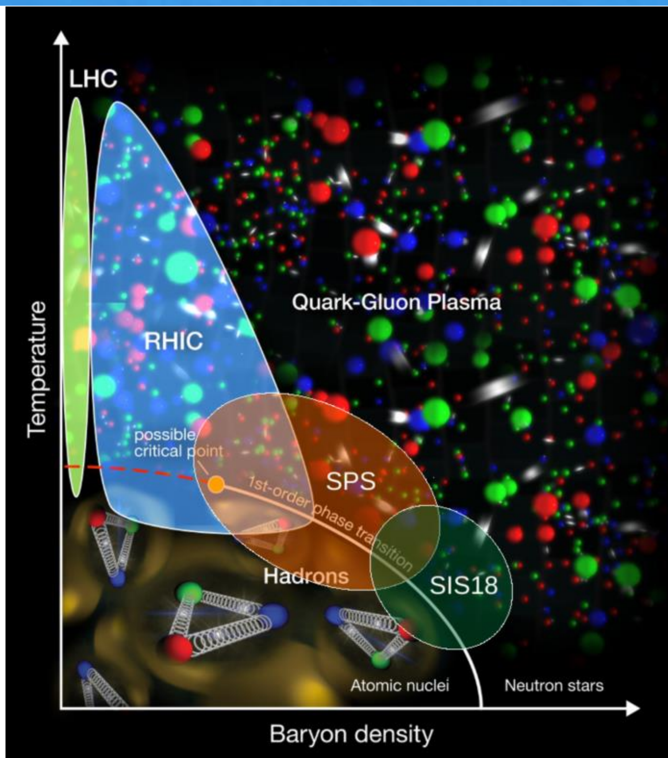


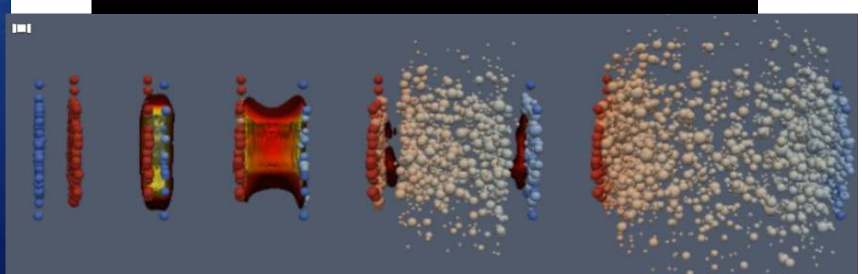
What do events look like in NA61?

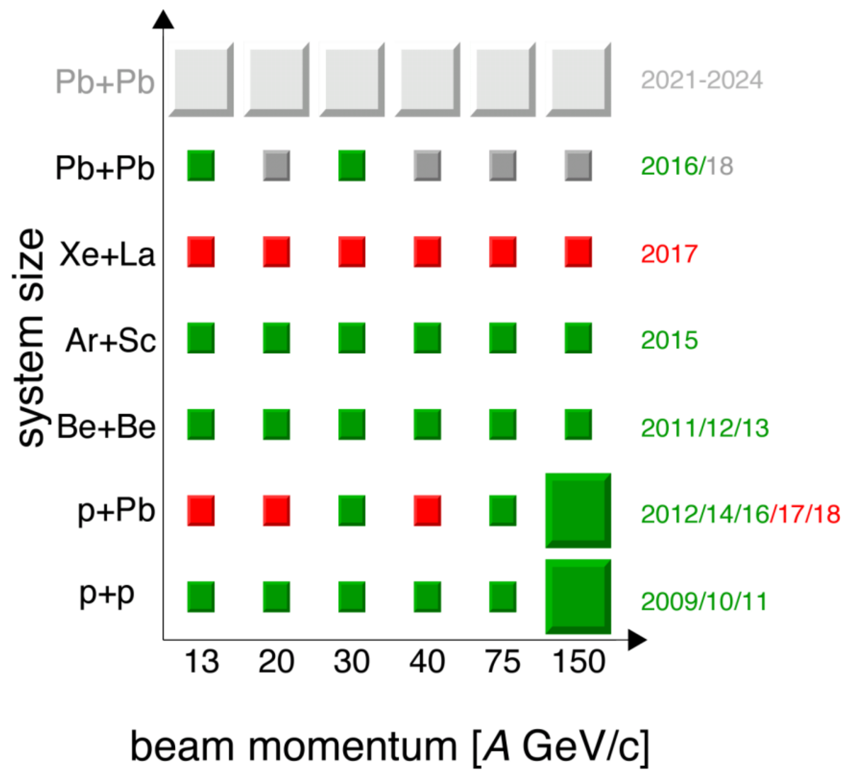




Phase diagram

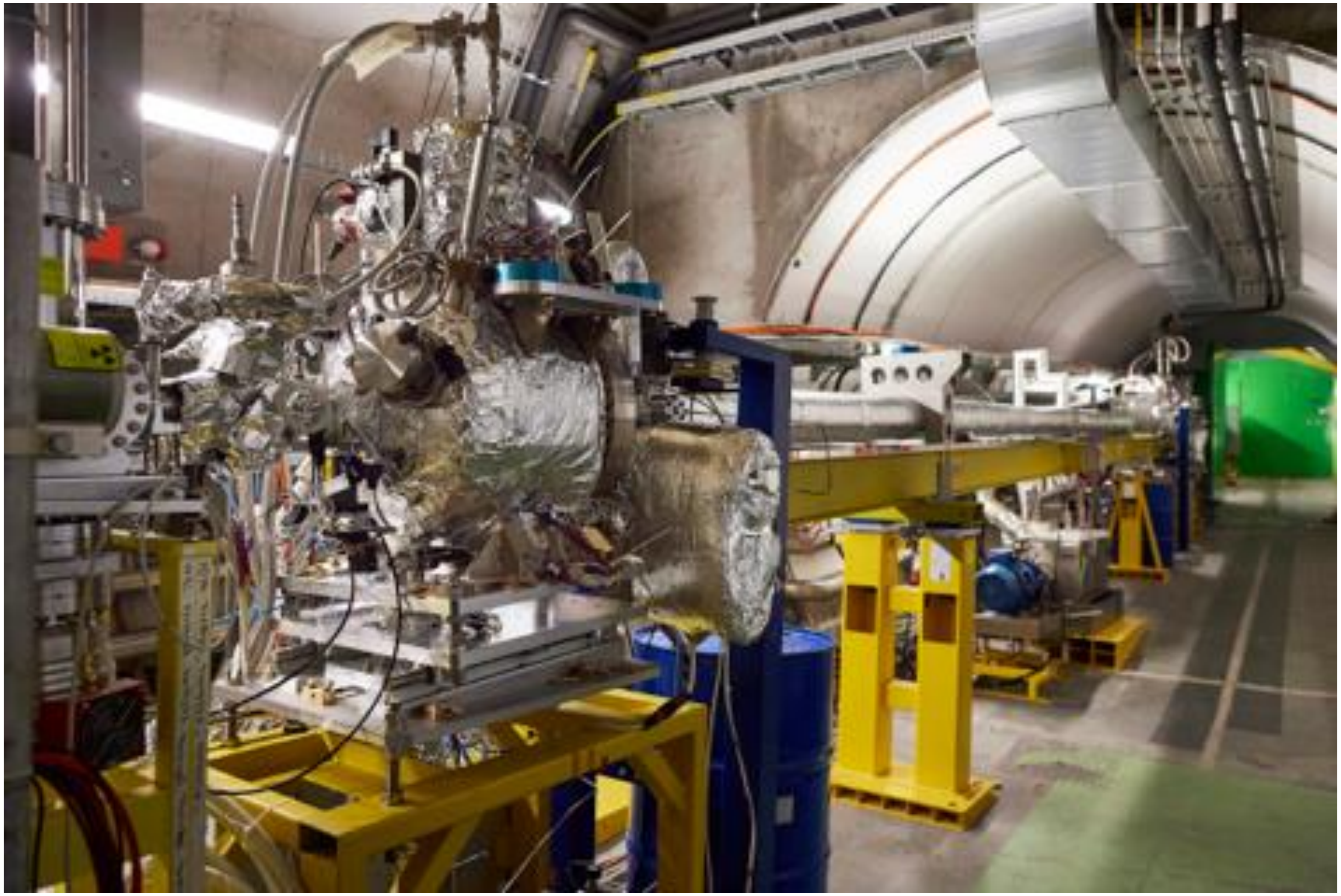






Unique 2-D parameter scan

Proton Driven Plasma Wakefield Acceleration (AWAKE)

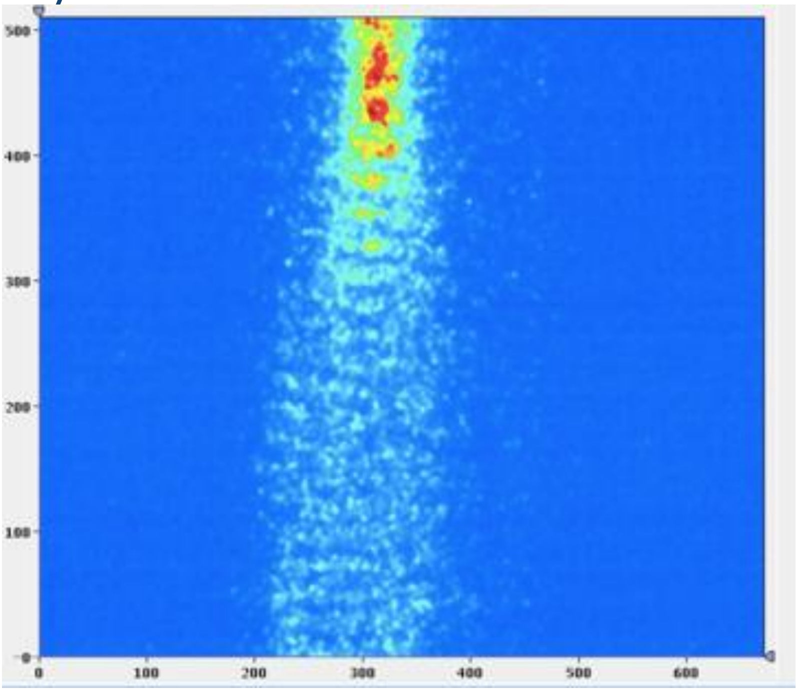


The AWAKE experiment

- Modern particle physics is largely possible thanks to the developments in particle accelerators towards **higher luminosity and energy.** However, the exponential increase of top energy vs time (Livingston plot) is no longer respected.
- A fundamentally new approach to acceleration is required.
- **Plasma Wakefield Acce**leration is a particularly promising avenue with potential accelerating gradients of many GV/m.
- Laser and electron driven PWA requires many stages of acceleration. Proton driven plasma wakefield acceleration can in principle accelerate electrons to very high energies **in a single plasma stage**.
- The AWAKE experiment at CERN studies the feasibility of this technique and started first tests a year ago.

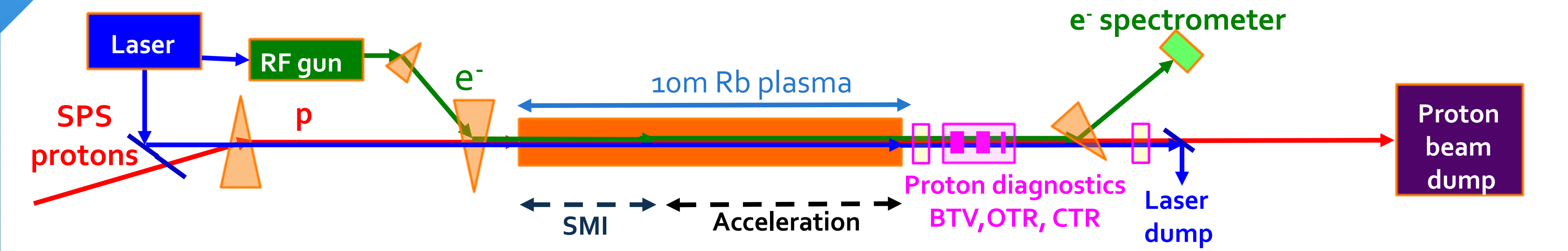
AWAKE principle

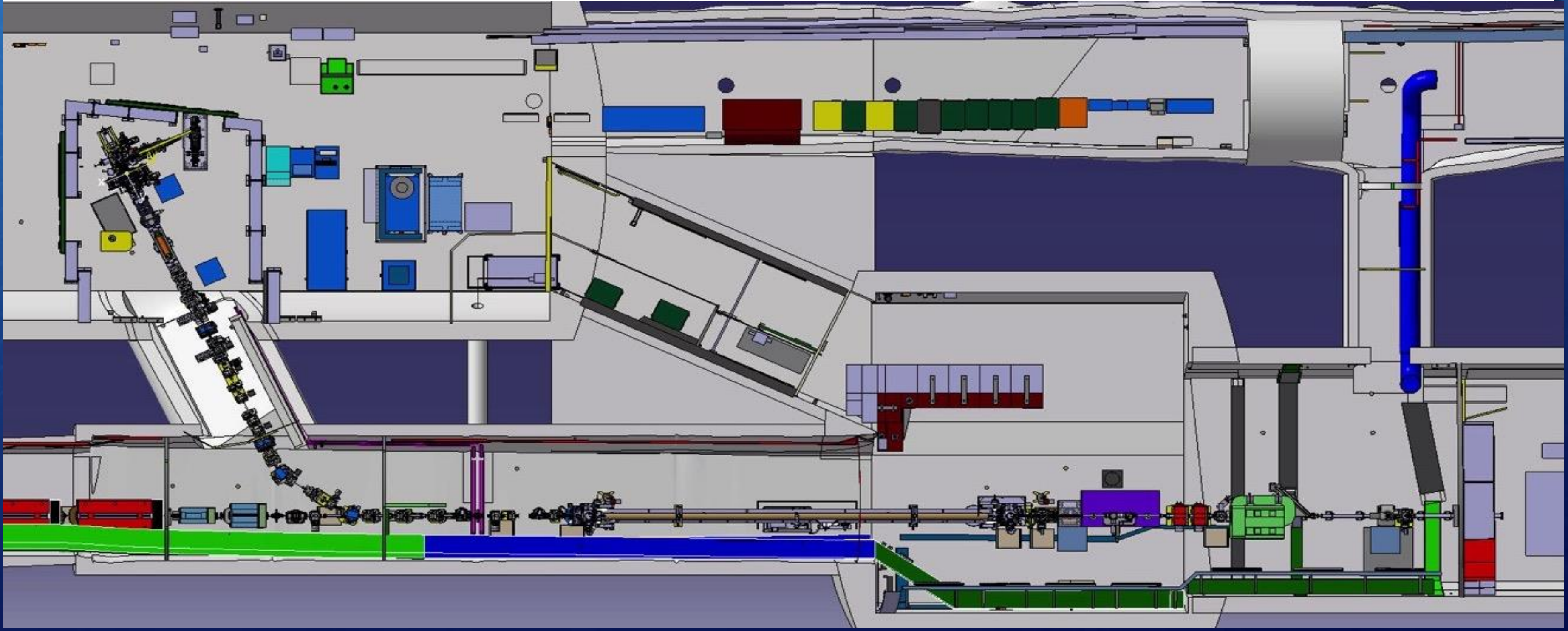
- A very short proton bunch can create a **wake field in a plasma** that accelerates charged particles very fast.



- Fast extracted bunches from the SPS are too long (~1 nsec), but via a process called **self-modulation** they split in a series of much shorter bunches that should allow PWA.
- AWAKE has already demonstrated self-modulation and will exploit this to demonstrate and optimise the acceleration of externally injected electrons.

Experimental set-up





Final words

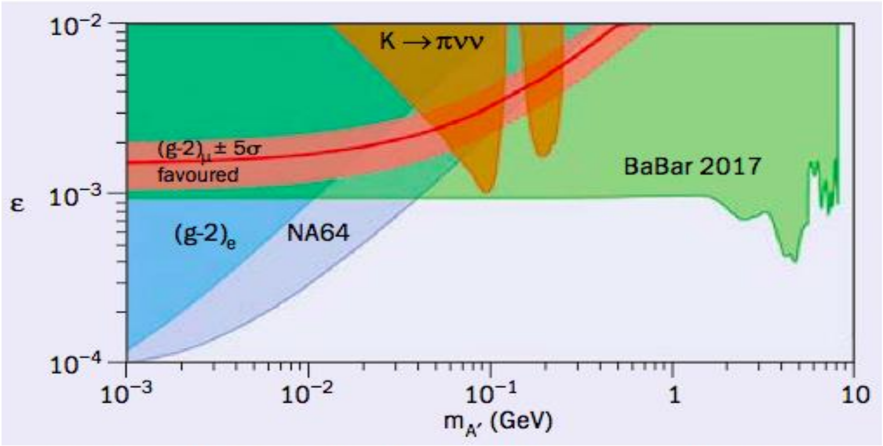
- In addition to the physics experiments (apologies to those I could not mention) there is an intense program of test beam activities in EHN1, for FT, LHC and LC experiments, space research and so forth.
- The Physics Beyond Colliders study at CERN aims at ensuring a bright future of the fixed target programme at CERN.
- Nothing of this rich physics program would be possible without performant and reliable particle sources, both protons, electrons and heavy ions
- Many thanks to the colleagues in the EN-EA-LE Section and colleagues from the experiments in preparing this overview.

Thanks for your attention!

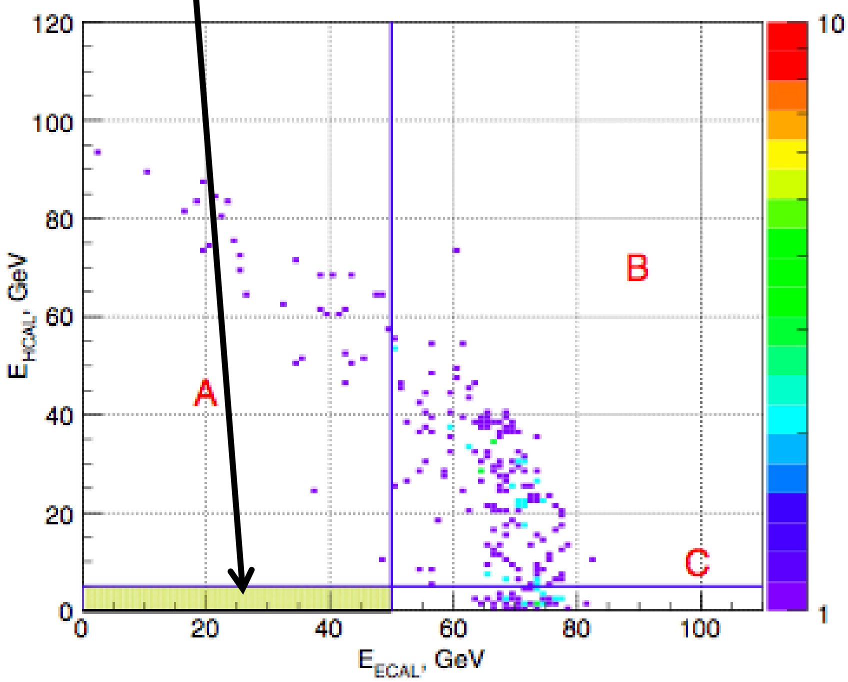
Drell-Yan versus SIDIS and DVCS

- The spin structure of the proton is described by two functions (per quark flavor):
- The Boer-Mulders function describes the structure of unpolarised nucleons.
- The Sivers function (Transverse Momentum Dependent distribution function) describes the spin in transversely polarised nucleons.
  This **changes sign** between SIDIS and DY.
- Therefore SIDIS and Drell-Yan measurements are complementary and from combining and comparing those, one can learn many aspects of the proton spin and disentangle transverse spin components.

Preliminary results

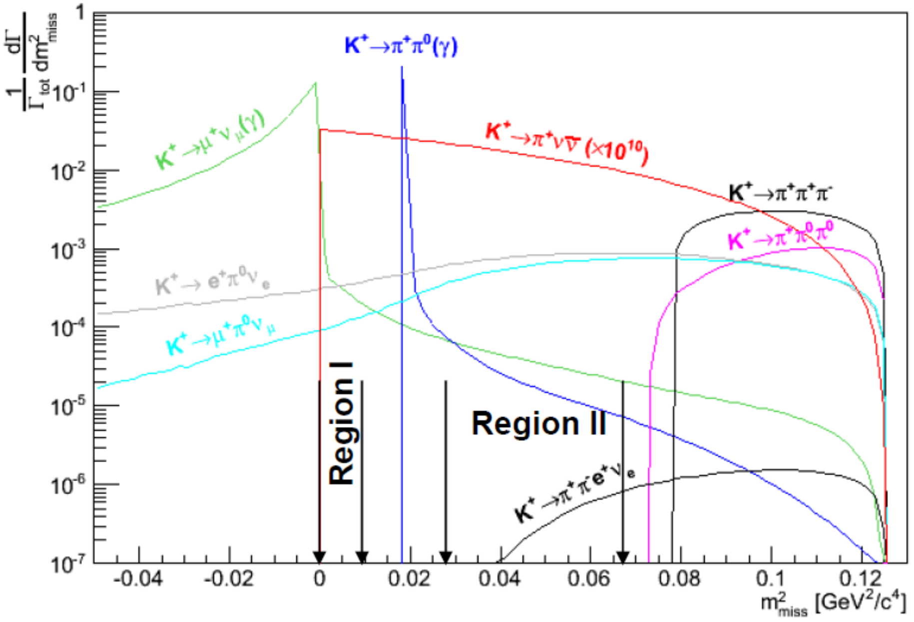


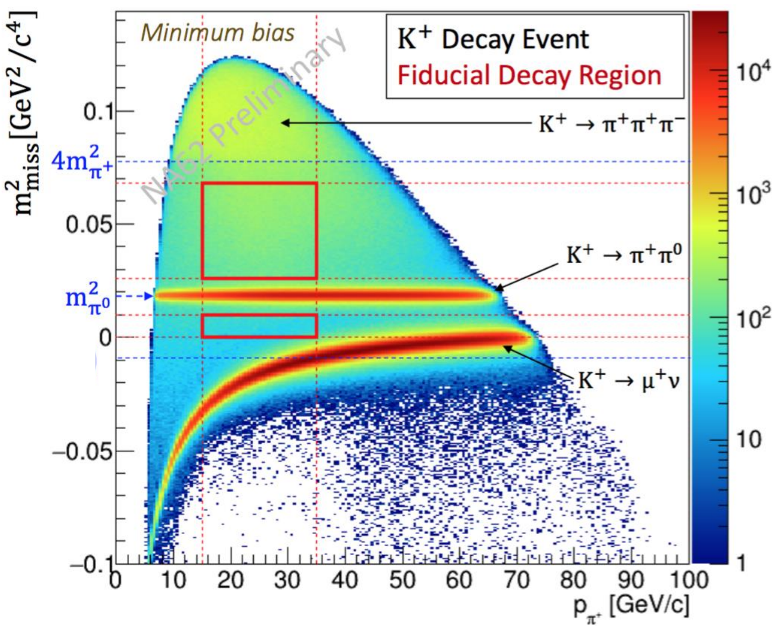
A´ signal box: **E_{EC} < 50; E_{HC} < ~1 GeV** "



Aiming for highest electron fluxes
to push sensitivity down as far as possible.

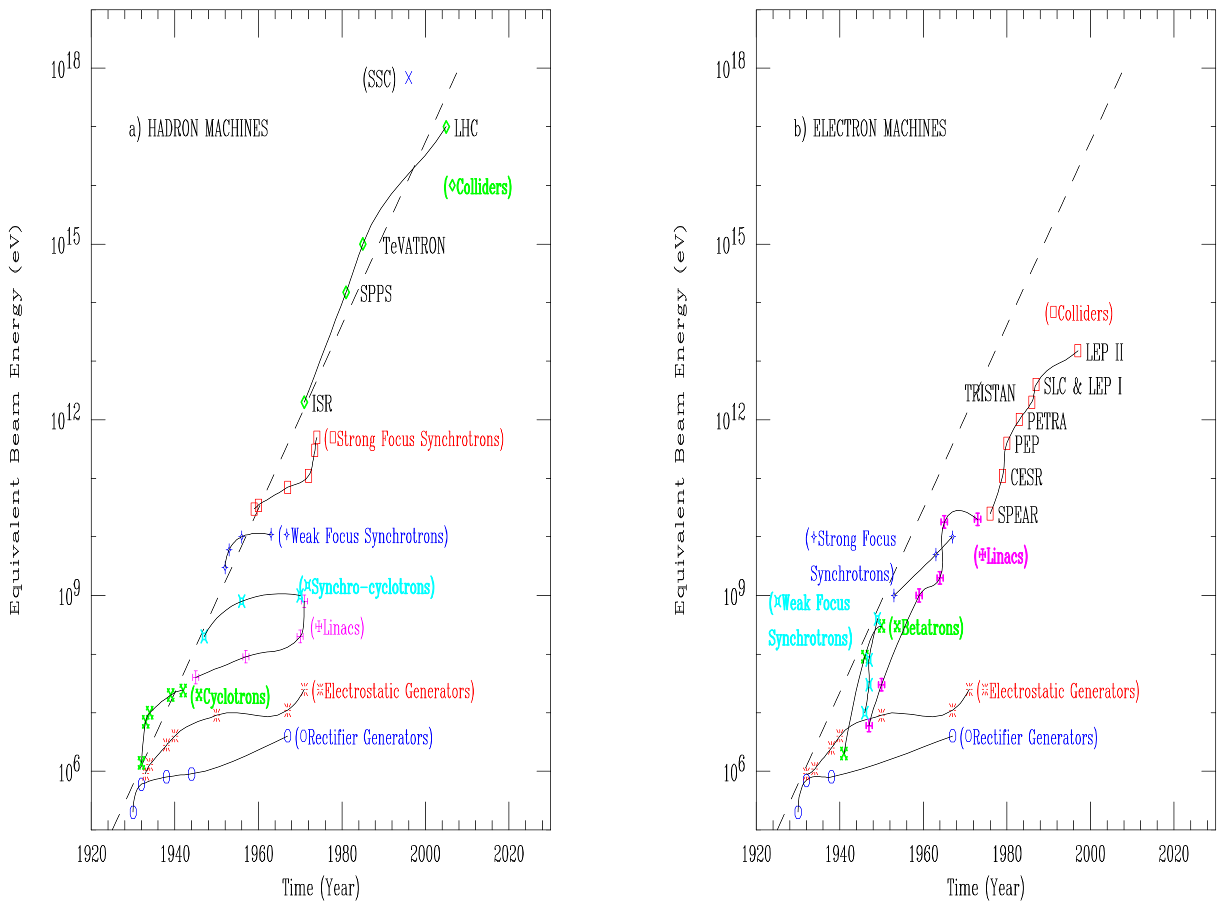
Example of NA62 kinematics





Meets design
Data-taking ongoing

Livingston Plot



Outlook

- Physics Beyond Colliders is mandated by the Directorate to prepare a long-term program at CERN with important physics beyond the physics at the LHC.
- The program contains many working groups. The Conventional Beams and Beam Dump Facility groups are studying a large number of proposed ideas, including:
  - NA62-BEAMDUMP
  - NA62-MU
  - MU-E
  - SHiP
  - KLEVER
  - RF SEPARATED BEAM FOR COMPASS
  - And follow-ups of DIRAC, NA60, SHiNE, etc
- Exploratory study of possible applications of the AWAKE concept