CERN Beamlines for Fixed Target Experiments

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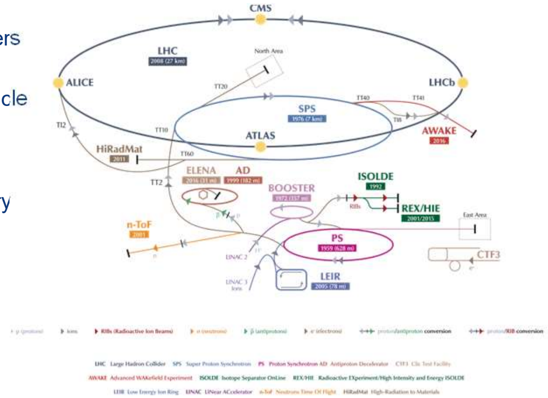
Overview

- Introduction: Purpose and users
- Targets and particle production
- Design of secondary/tertiary beamlines
- Experiments at CERN



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Introduction

Fixed Target (FT) setup

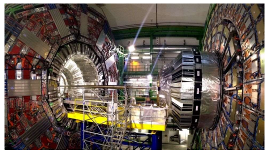
- Easier installation, easier access
- Less space restrictions
- Larger flexibility
  - Large momentum range
  - Flexible particle types

But only fraction of beam energy available for physics:

$E_{CM} \approx \sqrt{(2\ m_0\ E_{beam})}$

Collider

- All beam energy available for producing new particles/physics
- $E_{CM} \approx 2\ E_{beam}$



Physics at FT and collider are both useful and needed

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Purpose and Users

Secondary Beam Areas (SBA) are hosting:

- **FT experiments**: COMPASS,NA61, NA62, NA63, NA64, CLOUD, …
  - Precision studies (QCD, standard model, BSM physics)
  - Stable beam conditions for weeks and weeks
- **Radiation facilities**: HiRadMat, Charm, Irrad, GIF++
- **Test beams:**
  - Detector prototype tests
  - Detector calibration

    e.g. for LHC, linear colliders, space & balloon experiments
  - Outreach
  - Usually require a large spectrum of beam conditions within few days

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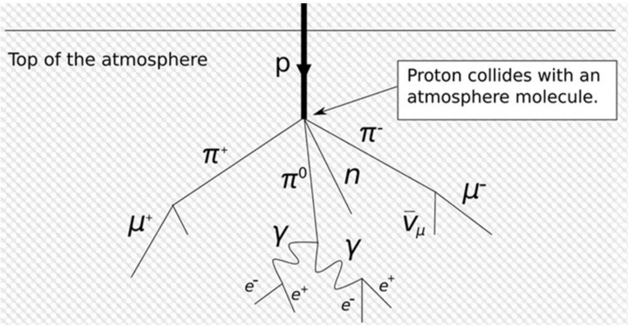
Targets and particle production

- Principle taken from cosmic radiation
  - Primary proton beam initiating hadronic cascade
  - Always followed by an electro-magnetic cascade



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Targets and particle production

- Principle taken from cosmic radiation
- Particles are produced in a large momentum range

SPS beam

Position	Material	Length (mm)	Height (mm)	Width (mm)
0	*Air/OUT*	-	-	-
1	Be	500	2	160
2	Be	300	2	160
3	Be	180	2	160
4	Be	100	2	160
5	Be	40	2	160
5x plates, 40 mm inter-plate distance				

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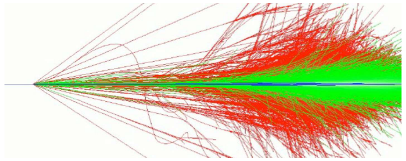
Target length and production rates

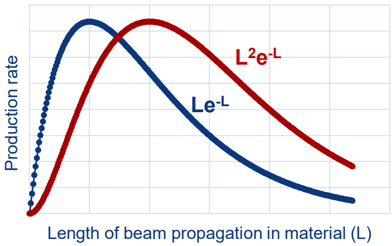
- Beryllium has
  - radiation length X_0 = 35.3 cm,
  - nuclear interaction length λ_I = 42.1 cm,
    => high X_0/λ_I ratio
  - low density (1.848 g/cm³)
  - high melting point (1560 K)



- The e/π ratio increases approx. linearly with the target length
- Hadrons
  - are produced via p + N -> hadron (rate ~ L)
  - reabsorbed (rate ~ e^{-L})

  => Overall rate ~ Le^{-L} (maximum at L≈ λ_I)
- Electrons are mainly produced via
  - p + N -> π^0 -> γ γ (rate ~ L)
  - γ converts to e^+ + e^- (rate also ~ L)
  - reabsorbed (rate ~ e^{-L})

  => Overall rate ~ $L^2 e^{-L}$ (maximum at L ≈ $2\lambda_I$)



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Targets and hadron production

Atherton parameterisation (CERN 80-07):

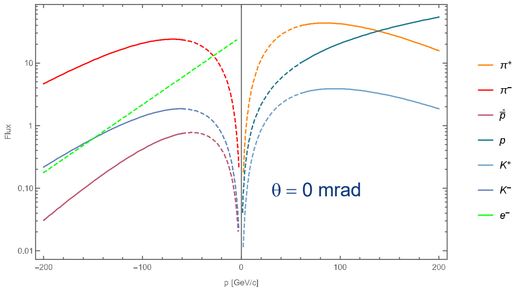
$$\frac{d^2N}{dp\,d\Omega} = A\left[\frac{B}{p_0}\, e^{-Bp/p_0}\right]\left[\frac{2Cp^2}{2\pi}\, e^{-C(p\theta)^2}\right]$$

$$\frac{d^2N}{dp\,d\Omega} = A\left[\frac{(B+1)}{p_0}\left(\frac{p}{p_0}\right)^B\right]\left[\frac{2Cp^2}{2\pi}\, e^{-C(p\theta)^2}\right]$$

with primary momentum p_0 and production angle θ

Flux per solid angle [steradian], per interacting proton, and per dp [GeV/c]

	A	B	C
p	0.8	-0.6	3.5



	A	B	C
π^+	1.2	9.5	5.0
π^-	0.8	11.5	5.0
K^+	0.16	8.5	3.0
K^-	0.10	13.0	3.5
$\bar{p}$	0.06	16.0	3.0

Note: Valid for primary interactions only!
Extrapolation for momenta below 60 GeV/c

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Targets and particle production

Category	Name		Q	Mass [MeV/c²]	Mean life (τ) [s]	cτ [m]	Mean decay distance [m/GeV/c]	Decays
Leptons	Electron	e	±e	0.511	stable			
Leptons	Muon	μ	±e	105.6	2.2×10^{-6}	659.6	6.3×10^{3}	$\mu^+ \to e^+ \bar{\nu}_e \nu_\mu$ (100%)
Hadrons / Mesons	Pion	π	±e	139.6	2.6×10^{-8}	7.8	56.4	$\pi^+ \to \mu^+ \nu_\mu$ (100%)
Hadrons / Mesons	Kaon	K	±e	493.6	1.23×10^{-8}	3.7	8.38	$K^+ \to \mu^+ \nu_\mu$ (63%); $\pi^0 e^+ \nu_e$ (5%); $\pi^0 \mu^+ \nu_\mu$ (3%); $\pi^+ \pi^0$ (...) (28.9%)
Hadrons / Mesons	Kaon	K^0	0	497.6	K^0_S: 8.9×10^{-11}	0.02	0.060	$K^0_S \to \pi^0 \pi^0$ (30.7%); $\pi^+\pi^-$ (69.2%)
					K^0_L: 5.12×10^{-8}	15.34	34.4	$K^0_L \to \pi^\pm e^\mp \nu_e$ (40.5%); $\pi^\pm \mu^\mp \nu_\mu$ (27.0%); $3\pi^0$ (19.5%); $\pi^+\pi^-\pi^0$ (12.5%)
Hadrons / Baryons	Proton	p	±e	938	stable			
Hadrons / Baryons	Lambda	Λ	0	1115.6	2.63×10^{-10}	0.079	0.237*	$\Lambda^0 \to p\,\pi^-$ (63.9%)
Hadrons / Baryons	Sigma Hyperons	Σ^+	+e	1189.3	8.02×10^{-11}	0.024	0.068*	$\Sigma^+ \to p\,\pi^0$ (51.57%)
Hadrons / Baryons	Sigma Hyperons	Σ^-	-e	1197.4	1.48×10^{-10}	0.044	0.125*	$\Sigma^- \to n\,\pi^-$ (99.84%)

(*) for 10 GeV/c

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Beamlines

- Experiments and test beams require "clean" beams with high purity (one particle type) and small momentum spread
- Beam lines design ("optics")
  1. Collect produced particles from target
  2. Select momentum
  3. Select particle type
  4. Transport beam to experiment
  5. Select beam spot size for experiment

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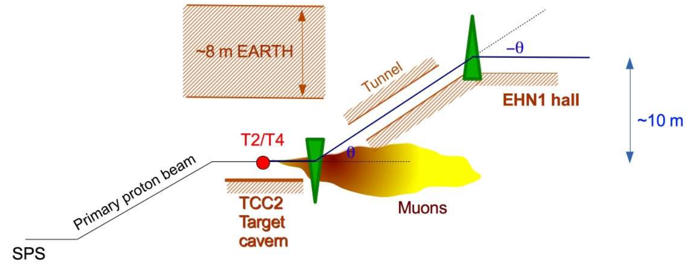
NA beamline design considerations

- NA beams were originally (end of 1970's) designed for the fixed target experiments. Design considerations were
  - Muon range (absorb underground)
  - Charged pion lifetime
  - Momentum selection ($2\cdot10^{-4}$)



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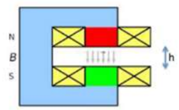
Dipoles

Basic beam design

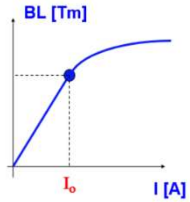
- Transport and momentum (p) selection: bending magnets

Dipole electro-magnets:

$$\vec{F} = q \cdot \vec{v} \times \vec{B}$$



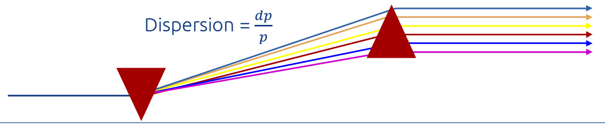
$$B = \frac{\mu_0 n I}{h}$$



$$\theta\,[mrad] = \frac{299.79 Bl\ [T \cdot m]}{p[GeV]}$$

For example:

$$\text{Dispersion} = \frac{dp}{p}$$



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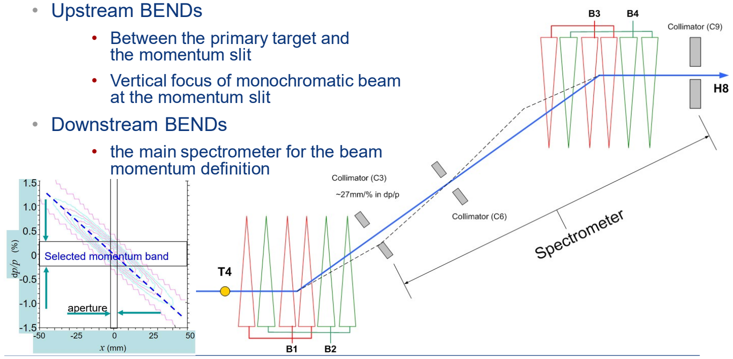
Momentum selection

Basic beam design

- momentum selection in the vertical plane
- two sets of bending magnets
  - Upstream BENDs
    - Between the primary target and the momentum slit
    - Vertical focus of monochromatic beam at the momentum slit
  - Downstream BENDs
    - the main spectrometer for the beam momentum definition



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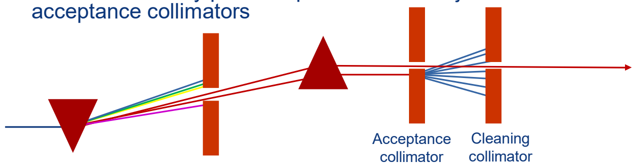
Secondary beamlines - collimators

- TAX (Target attenuator)
  - Define initial acceptance of the beam line

- Acceptance collimators
- Cleaning collimators
  - Absorb secondary particles produced on the jaws of acceptance collimators



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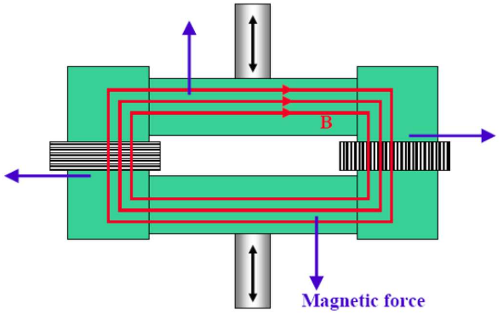
Secondary beamlines – muon sweepers

SCRAPERS
(Magnetic Collimators)



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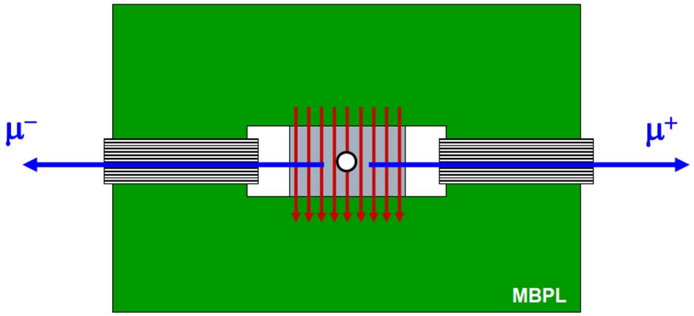
Secondary beamlines – muon sweepers



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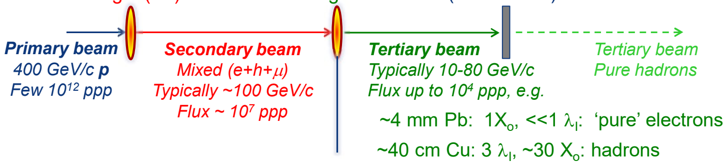
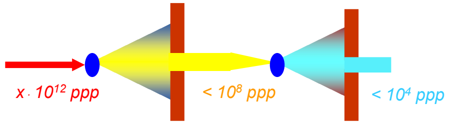
Secondary beamlines - intensities

Basic beam design

- Selection of particle types



- Intensities



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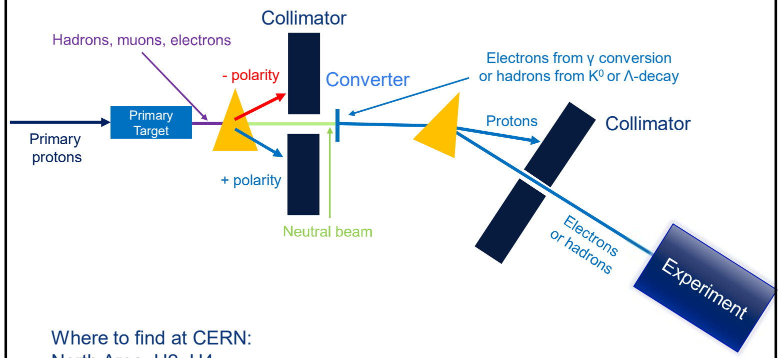
Selection of particle type - Converter



Where to find at CERN:
North Area: H2, H4
East Area: T9

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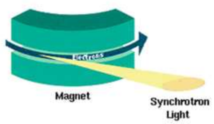
Selection of particle type - Synch. rad.

- Synchrotron radiation

(for one full revolution)

$$P_s = \frac{e^2 c}{6\pi\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho^2}$$



- E.g. e± at 200 GeV lose in 1° bending magnet of 1 T field 590 MeV
  - => With beamline momentum acceptance of Δp/p < 0.3 % it is possible to separate them from (heavier) hadrons and muons. So set up the following bends either
    - at the constant energy to select heavier particles or
    - scale it with energy loss of electrons.

  Works only for p_e > 120-150 GeV/c

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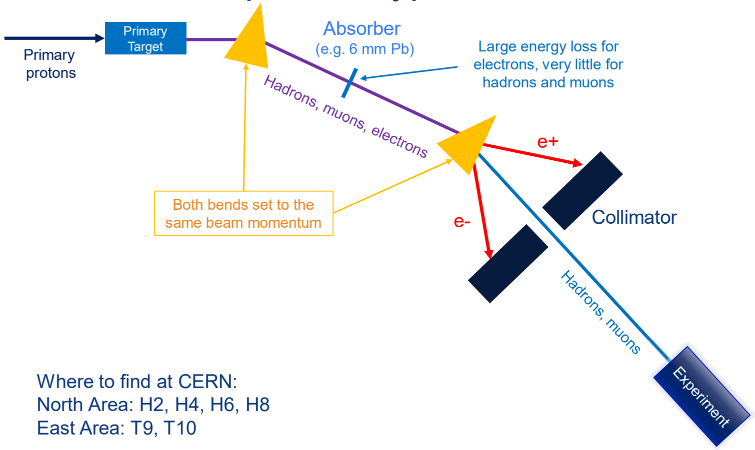
Selection of particle type - Absorber



Where to find at CERN:
North Area: H2, H4, H6, H8
East Area: T9, T10

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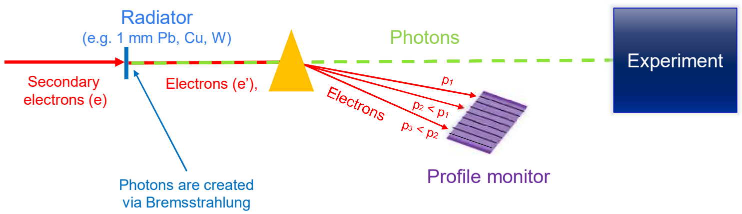
Selection of particle type - Radiator



- Time resolution - electron by electron
- Transverse position gives information on e- momentum
- $p_\gamma = p_e - p_{e'}$
- Result : tagged photon beam

Where to find at CERN:
(Ad hoc installation, but usually used at)
North Area: H2, H4
East Area: T9

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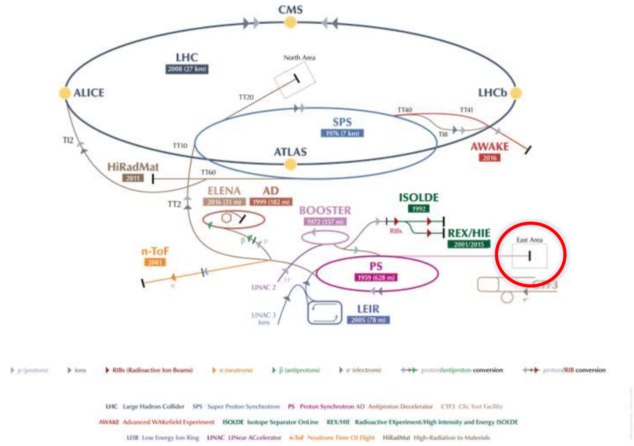
Beams from PS



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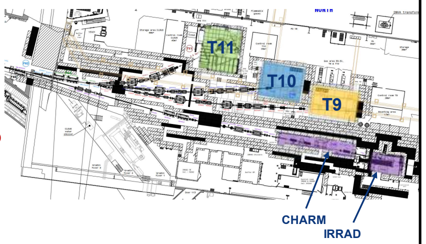
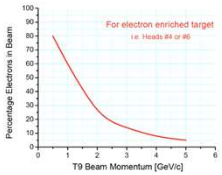
East Area

Area under renovation

After LS2

- Secondary beams:
  - Momentum < 15 GeV/c
  - Irradiation facilities CHARM and IRRAD
  - Test beamlines T9 and T10
  - T11 beamline for CLOUD experiment
  - Horizontal momentum selection
- Particle types and intensity
  - Pure electrons, hadrons, muons
  - Max. ~$5 \cdot 10^6$ particles per spill
- Spill structure from PS
  - 400ms spill length
  - Typically 1 spill every 18s (15bp), more on request
- Quick access from control room to experimental area (< 1 minute)
- Short cables





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The CLOUD Experiment in T11 Beam

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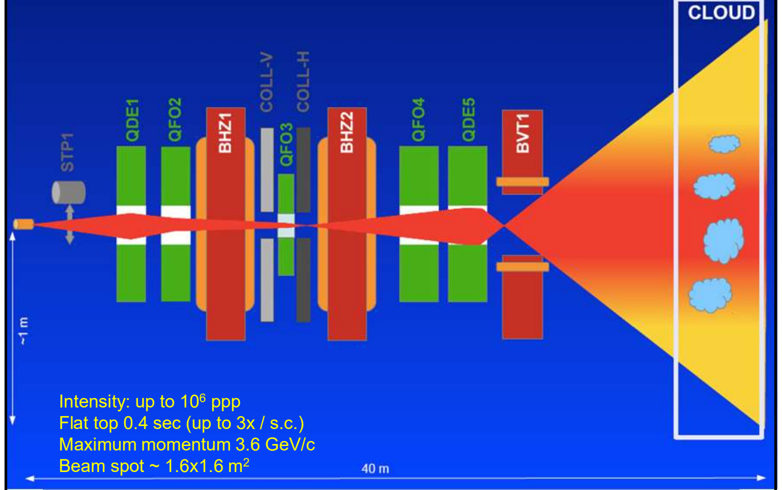
The Beam Line for CLOUD



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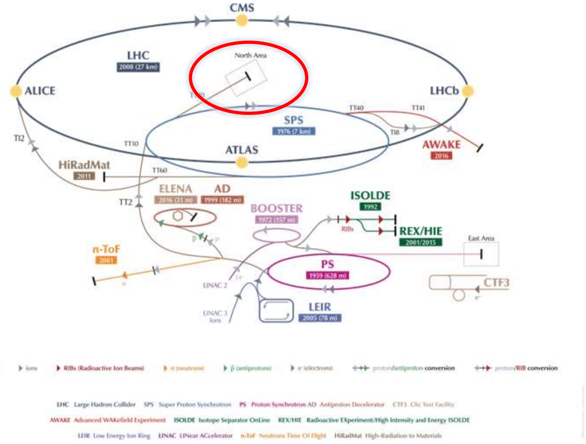
Beams from SPS



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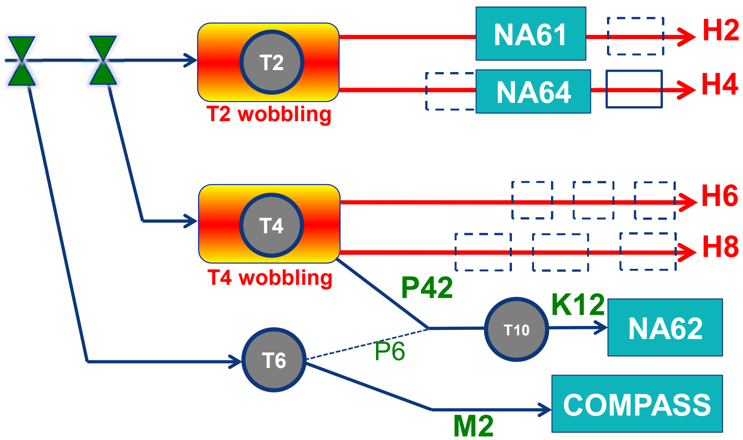
North Area beamlines - schematic



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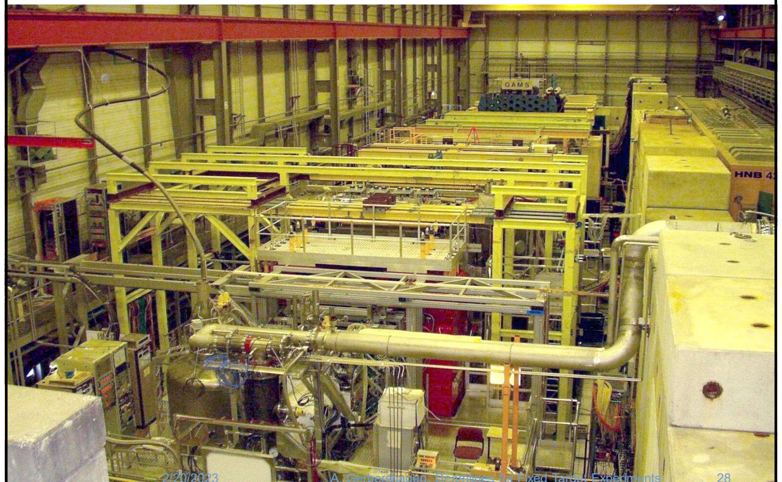
EHN2: COMPASS



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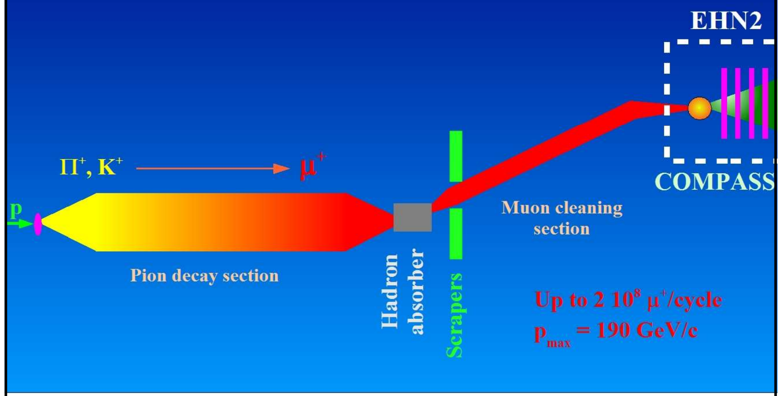
THE M2 MUON BEAM

FOR COMPASS / NA58



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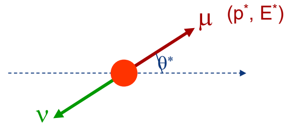
Muons from pion decay

- Pion decay in π center of mass:

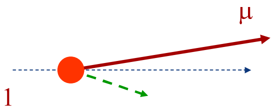
$$p^* = \frac{m_\pi^2 - m_\mu^2}{2\,m_\pi} = 30 \text{ MeV/c}$$

$$E^* = \frac{m_\pi^2 + m_\mu^2}{2\,m_\pi} = 110 \text{ MeV}$$



- Boost to laboratory frame:

$$E_\mu = \gamma_\pi\,(E^* + \beta_\pi\, p^* \cos\theta^*) \quad \text{with } \beta_\pi \approx 1$$



- Limiting cases:

$\cos\theta = +1 \rightarrow E_{max} = 1.0\, E_\pi$

$\cos\theta = -1 \rightarrow E_{min} = 0.57\, E_\pi$

➡ $0.57 < E_\mu / E_\pi < 1$

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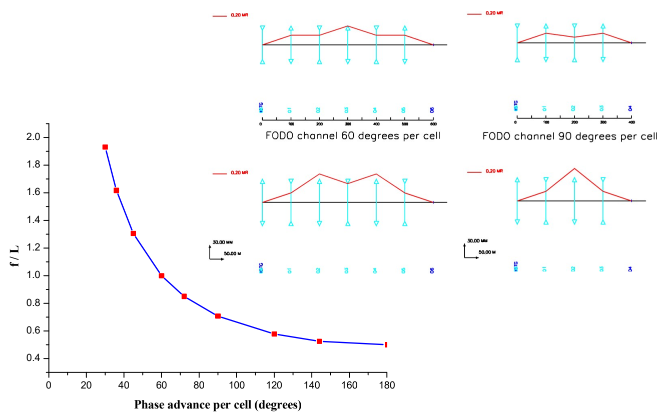
Momentum acceptance of FODO cells



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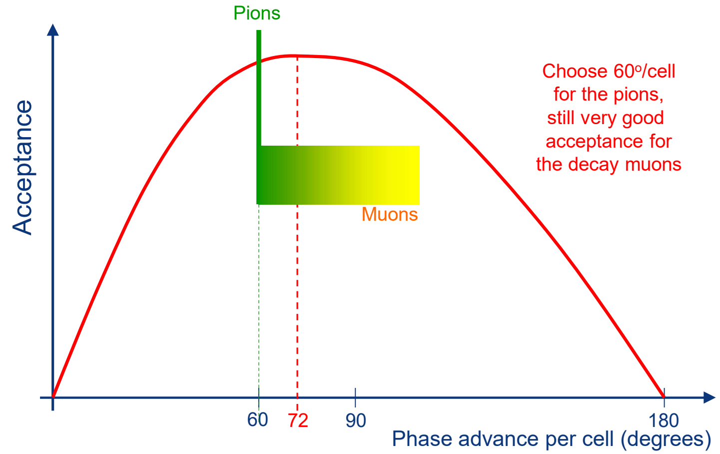
Phase advance for M2 beam



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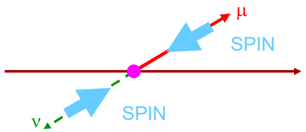
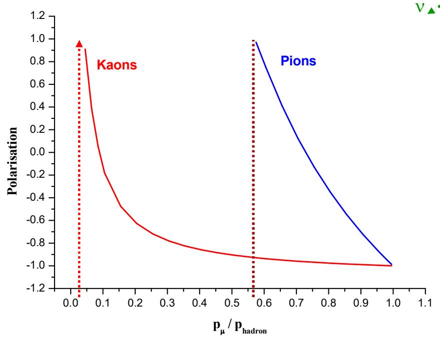
Muon Polarisation

- Pions and kaons have spin zero
- Neutrinos are left-handed
  - => Muons from pion decay are naturally polarised





For the typical COMPASS conditions, p_μ / p_π = 0.92 and the measured muon polarisation is about -80%

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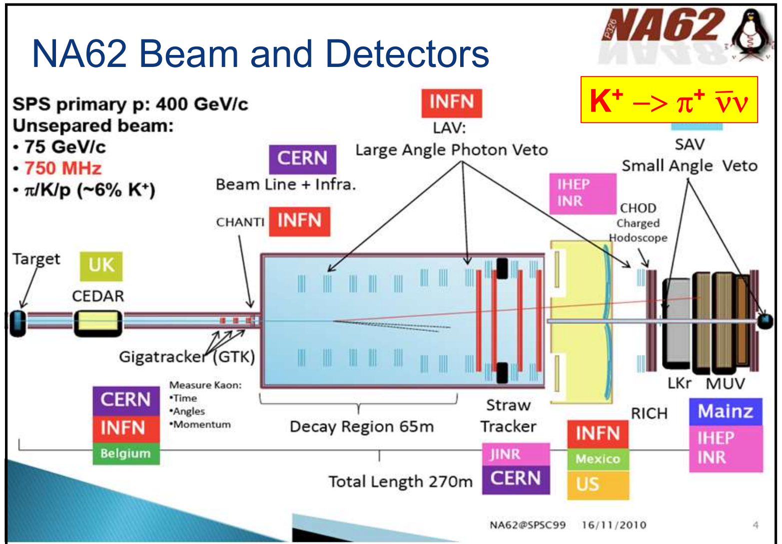
NA62 Beam and Detectors



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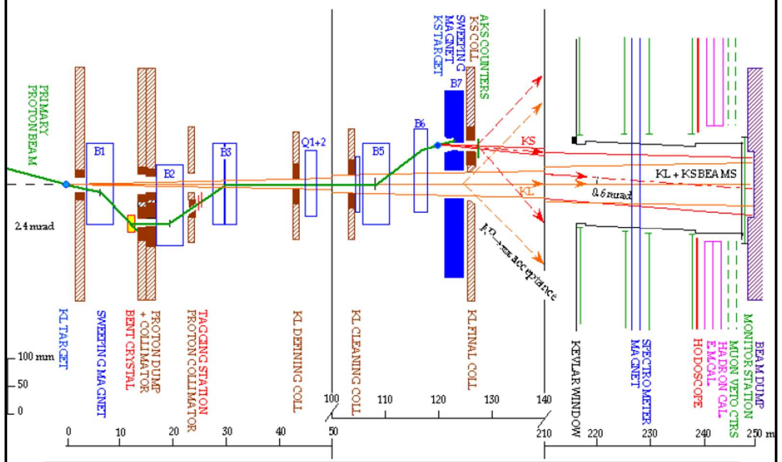
Historical Note - Kaon beam for NA48



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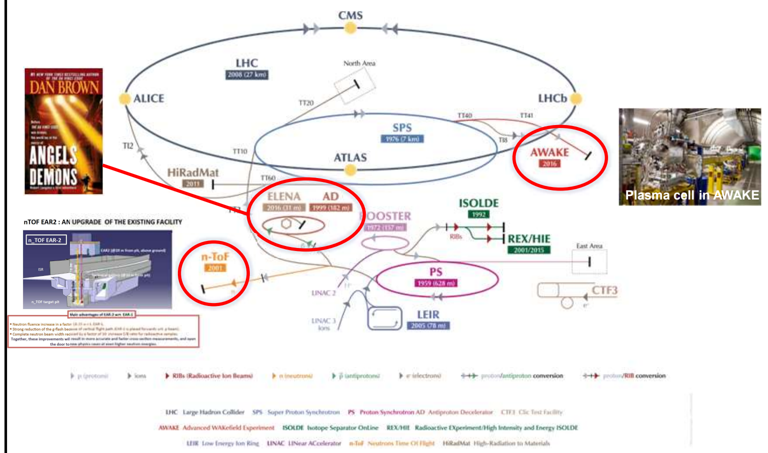
Other experiments with fixed-target beams



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Summary

- Many physics experiments can be performed (only) with fixed targets
- CERN has a rich fixed target complex
  - Beams from PSB, PS or SPS
    - Momenta : <1.4 GeV/c, <15 GeV/c, <400 GeV/c
  - Capable to provide:
    - Protons, electrons, hadrons, pions, tagged kaons, muons, tagged photons
  - Beamlines designed for high flexibility in:
    - Particle type, beam size, divergence, momentum, intensity, (polarization) etc.