



# Beamlines for Fixed Target Experiments

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On behalf of CERN BE-EA-LE



partrec



university of  
groningen

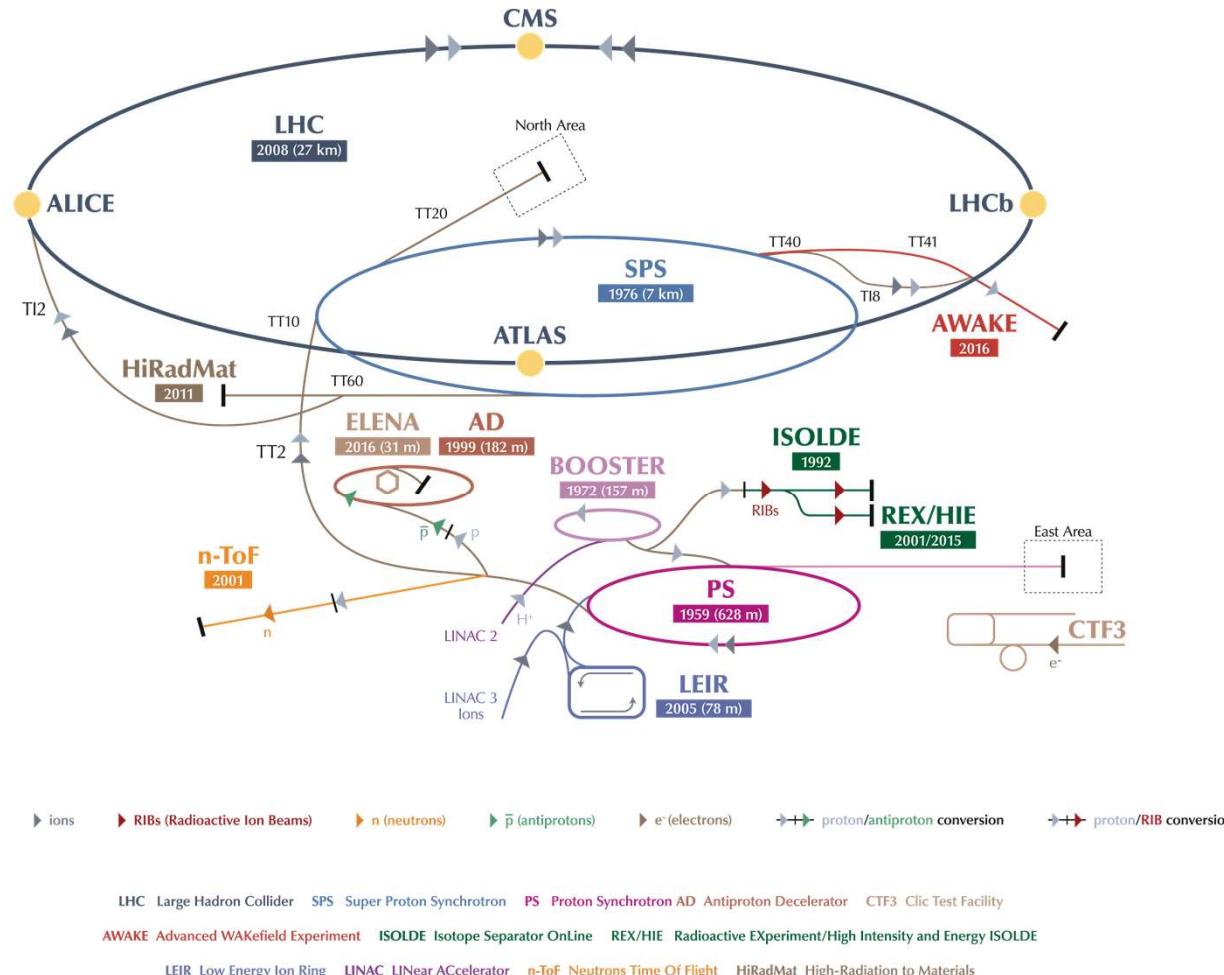


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# Overview

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



# 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:

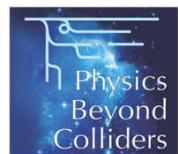
$$E_{CM} \approx \sqrt{2 m_0 E_{beam}}$$

## 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**



# Purpose and Users

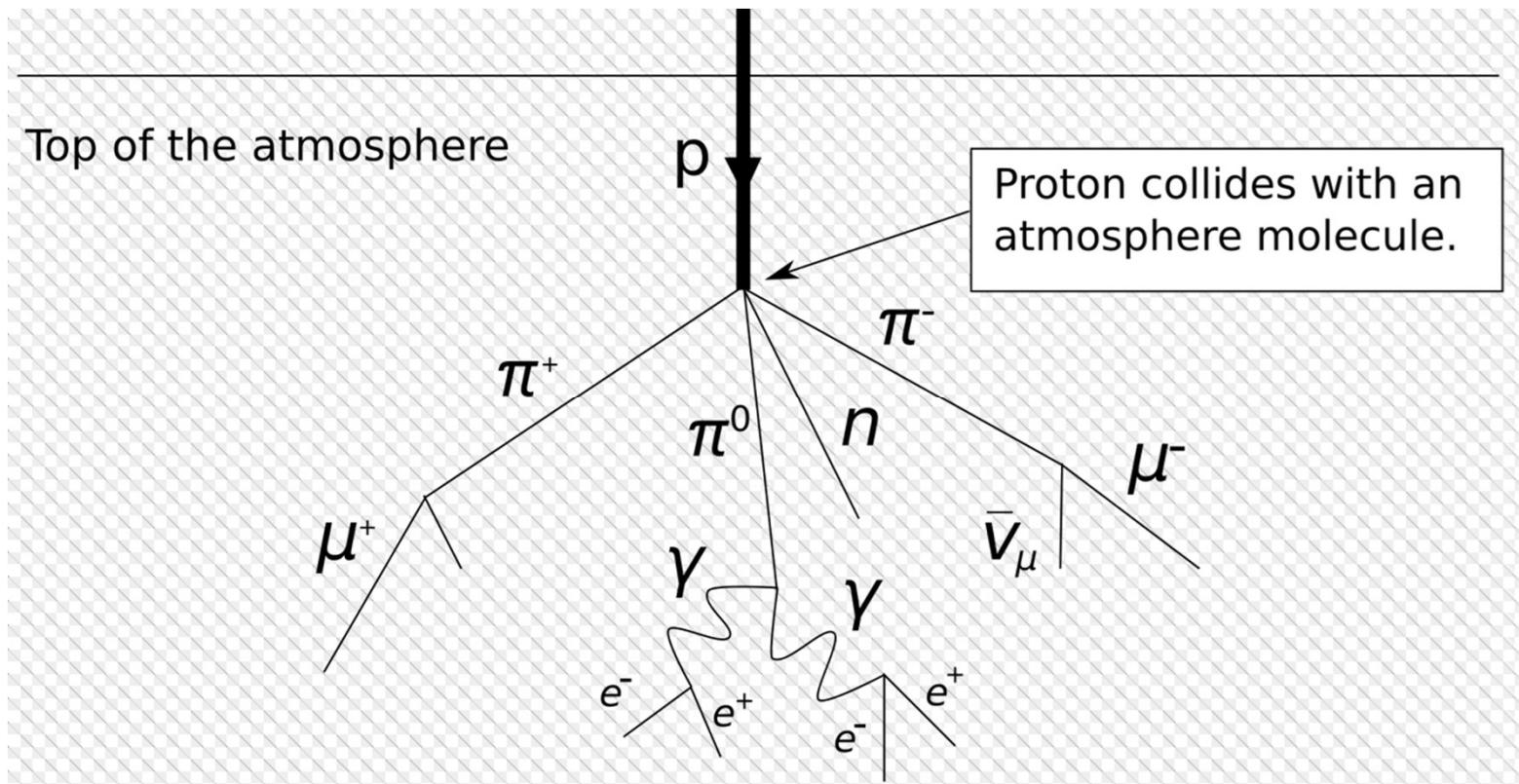
Secondary Beam Areas (SBA) are hosting:

- **FT experiments:** COMPASS, NA61, NA62, NA63, NA64, CLOUD, ...
  - Precision studies (QCD, standard model, BSM physics)
  - Stable beam conditions for weeks and months
- **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



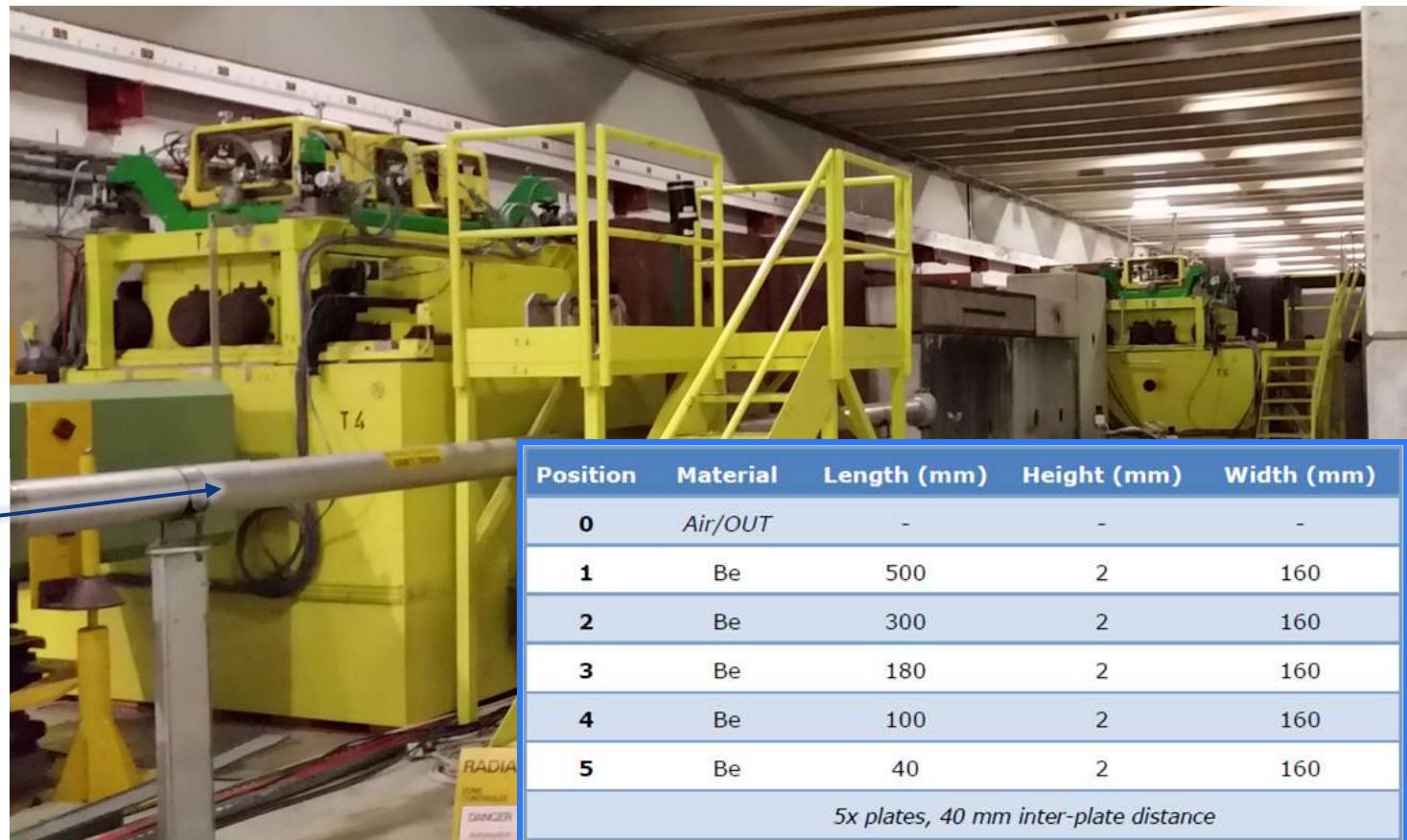
# Targets and particle production

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



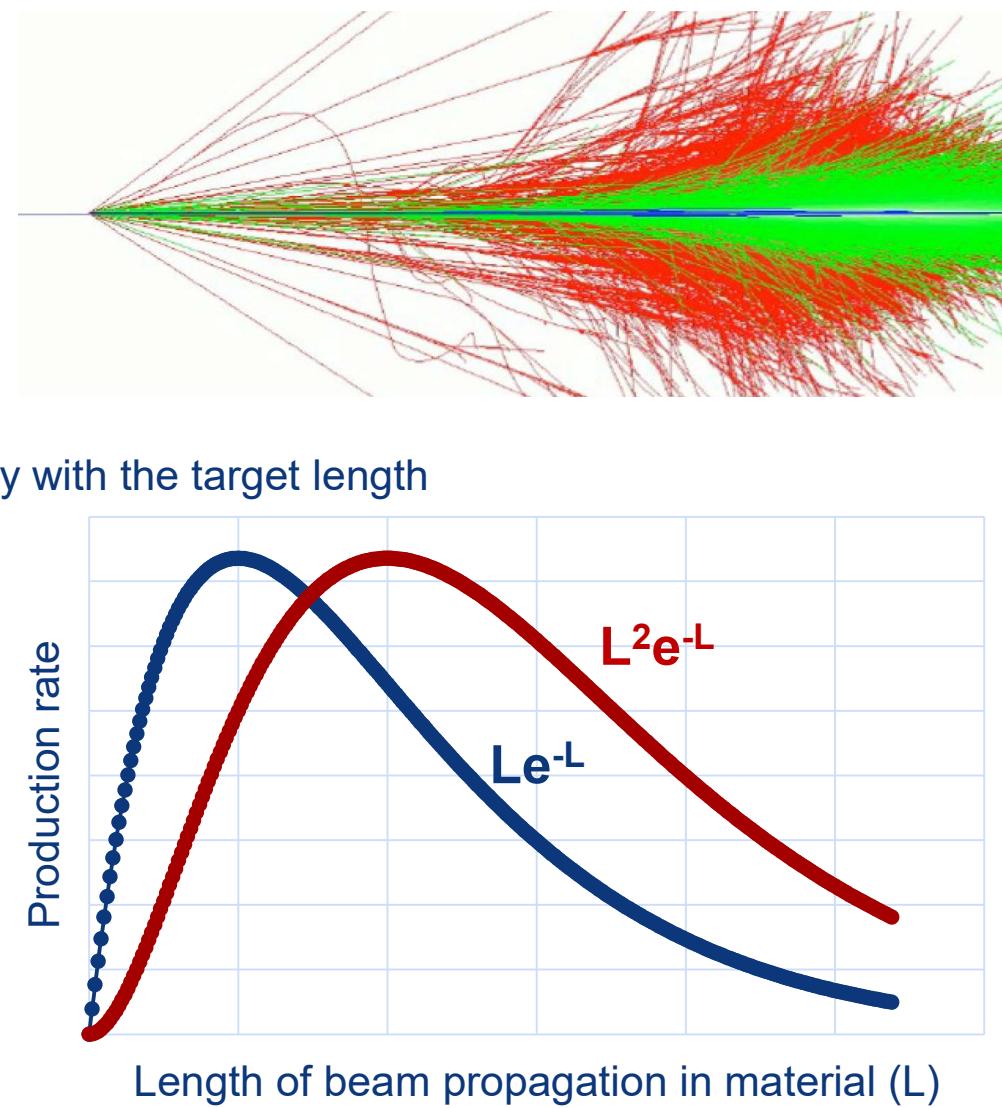
# Targets and particle production

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



# Target length and production rates

- Beryllium has
  - radiation length  $X_0 = 35.3$  cm,
  - nuclear interaction length  $\lambda_I = 42.1$  cm,  
=> high  $X_0/\lambda_I$  ratio
  - low density ( $1.848 \text{ g/cm}^3$ )
  - high melting point (1560 K)
- The  $e/\pi$  ratio increases approx. linearly with the target length
- Hadrons
  - are produced via  $p + N \rightarrow \text{hadron}$  (rate  $\sim L$ )
  - reabsorbed (rate  $\sim e^{-L}$ )  
=> Overall rate  $\sim Le^{-L}$  (maximum at  $L \approx \lambda_I$ )
- Electrons are mainly produced via
  - $p + N \rightarrow \pi^0 \rightarrow \gamma\gamma$  (rate  $\sim L$ )
  - $\gamma$  converts to  $e^+ + e^-$  (rate also  $\sim L$ )
  - reabsorbed (rate  $\sim e^{-L}$ )  
=> Overall rate  $\sim L^2 e^{-L}$  (maximum at  $L \approx 2\lambda_I$ )



# Targets and hadron production

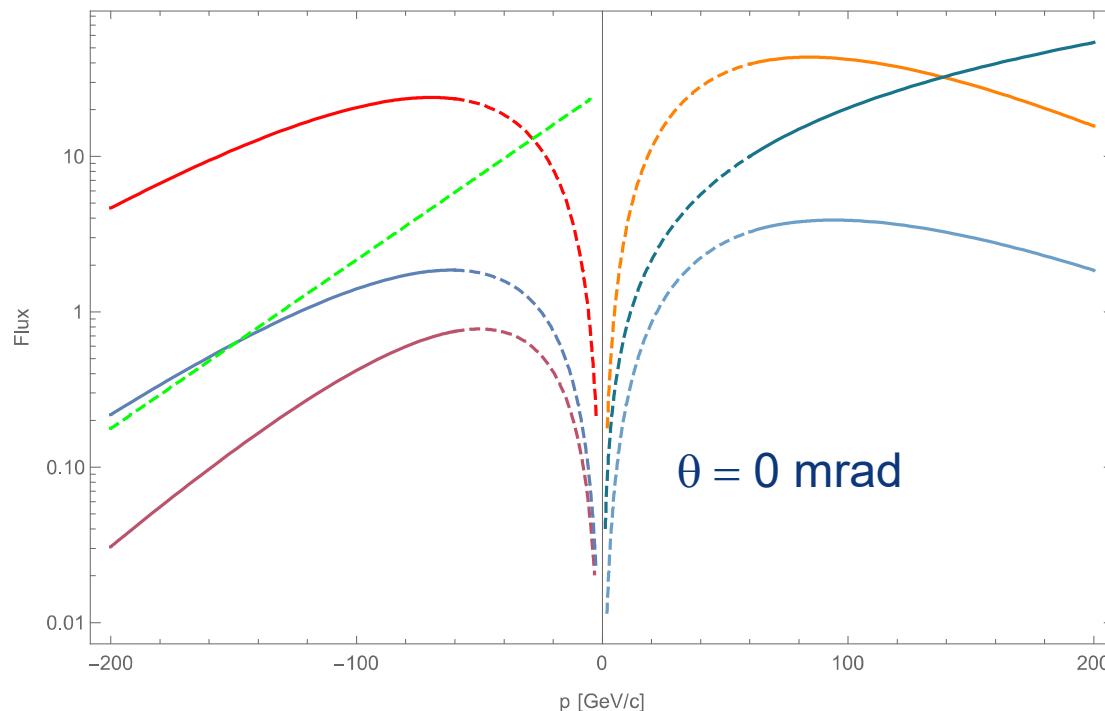
Atherton parameterisation (CERN 80-07):

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

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

with primary momentum  $p_0$  and production angle  $\theta$

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
$\pi^+$	1.2	9.5	5.0
$\pi^-$	0.8	11.5	5.0
$\bar{p}$	0.16	8.5	3.0
$p$	0.10	13.0	3.5
$K^+$	0.06	16.0	3.0
$K^-$			
$e^-$			

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



# Targets and particle production

	Name	Q	Mass [MeV/c <sup>2</sup> ]	Mean life (τ)		cτ	Mean decay distance [m/GeV/c]	Decays		
				[s]	[m]					
Hadrons	Leptons	Electron	e	±e	0.511		stable			
	Mesons	Muon	μ	±e	105.6	$2.2 \times 10^{-6}$	659.6	$K^+ \rightarrow e^+ \bar{v}_e v_\mu$ (100%)		
		Pion	π	±e	139.6	$2.6 \times 10^{-8}$	7.8	$\pi^+ \rightarrow \mu^+ v_\mu$ (100%)		
		Kaon	K	±e	493.6	$1.23 \times 10^{-8}$	3.7	$K^+ \rightarrow \mu^+ v_\mu$ (63%) $\pi^0 e^+ v_e$ (5%) $\pi^0 \mu^+ v_\mu$ (3%) $\pi^+ \pi^0$ (...) (28.9%)		
			K <sup>0</sup>	0	497.6	K <sub>s</sub> <sup>0</sup> K <sub>L</sub> <sup>0</sup>	8.9 × 10 <sup>-11</sup> 5.12 × 10 <sup>-8</sup>	0.02 15.34	0.060 34.4	$K_s^0 \rightarrow \pi^0 \pi^0$ (30.7%) $\pi^+ \pi^-$ (69.2%)  $K_L^0 \rightarrow \pi^\pm e^\mp v_e$ (40.5%) $\pi^\pm \mu^\mp v_\mu$ (27.0%) $3\pi^0$ (19.5%) $\pi^+ \pi^- \pi^0$ (12.5%)
	Baryons	Proton	p	±e	938		stable			
		Lambda	Λ	0	1115.6	$2.63 \times 10^{-10}$	0.079	$0.237^*$	$\Lambda^0 \rightarrow p \pi^-$ (63.9%)	
		Sigma	Σ <sup>+</sup>	+e	1189.3	$8.02 \times 10^{-11}$	0.024	$0.068^*$	$\Sigma^+ \rightarrow p \pi^0$ (51.57%)	
		Hyperons	Σ <sup>-</sup>	-e	1197.4	$1.48 \times 10^{-10}$	0.044	$0.125^*$	$\Sigma^- \rightarrow n \pi^-$ (99.84%)	

(\*) for 10 GeV/c



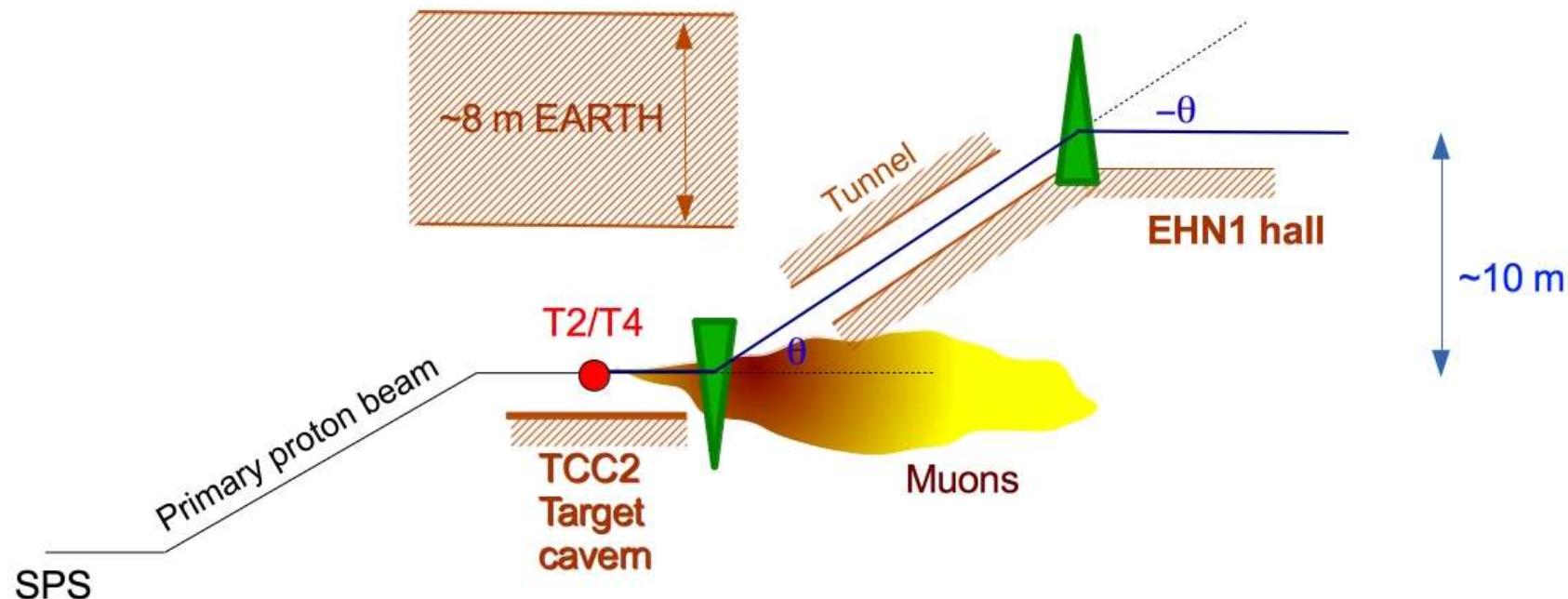
# Beamlines

- 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



# 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 ( $2 \cdot 10^{-4}$ )



# Dipoles

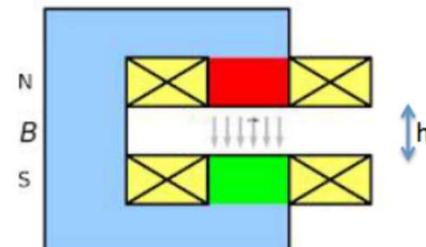
Basic beam design

- Transport and momentum ( $p$ ) selection: bending magnets

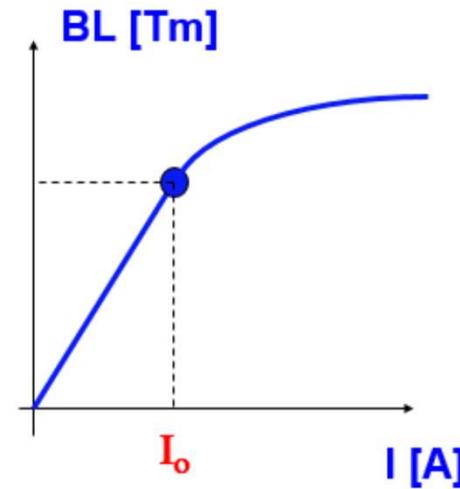


Dipole electro-magnets:

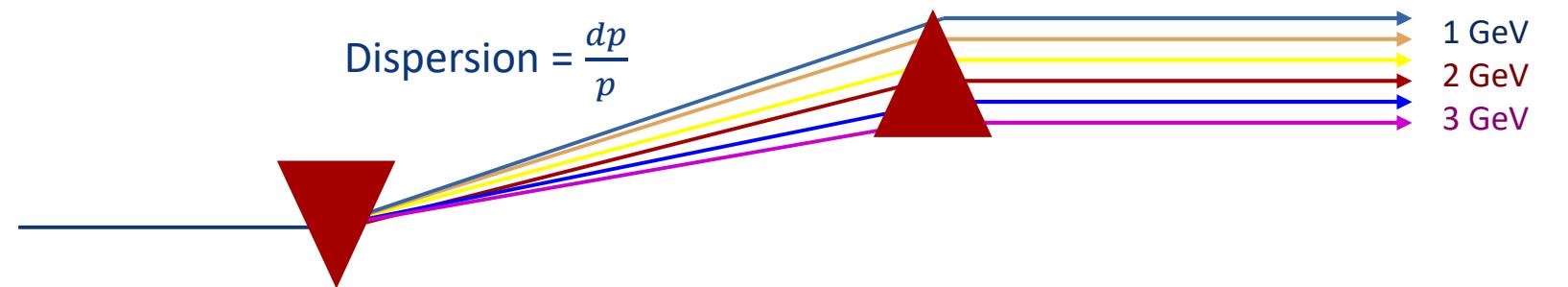
$$\vec{F} = q \cdot \vec{v} \times \vec{B}$$



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



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



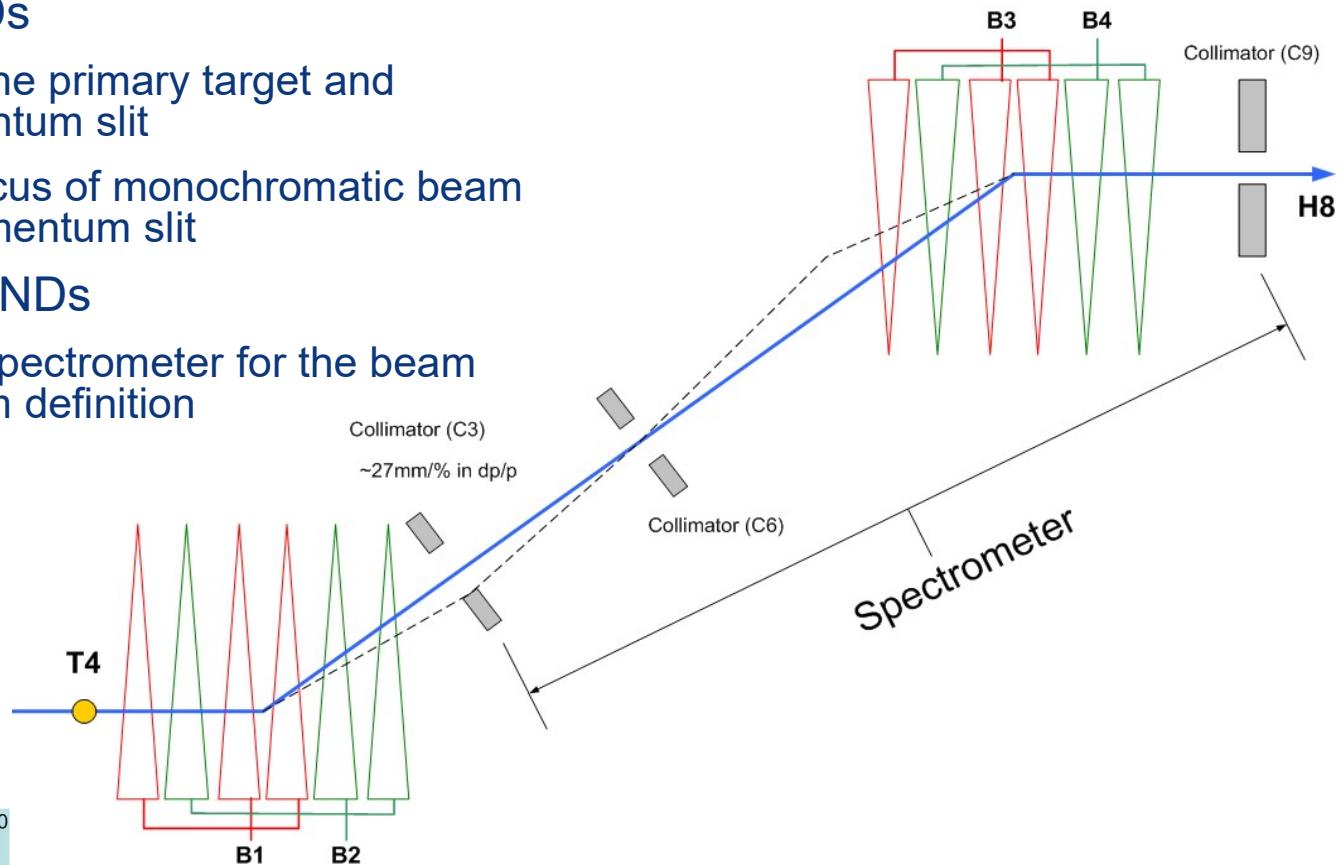
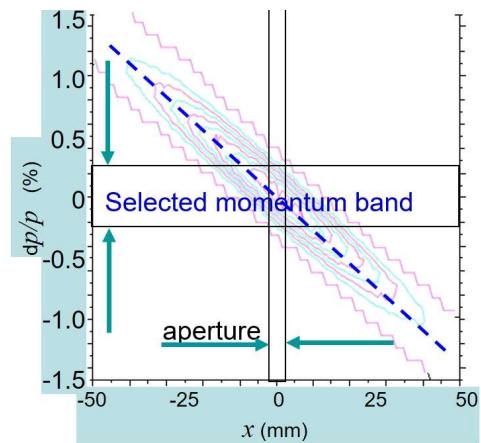
For example:



# 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

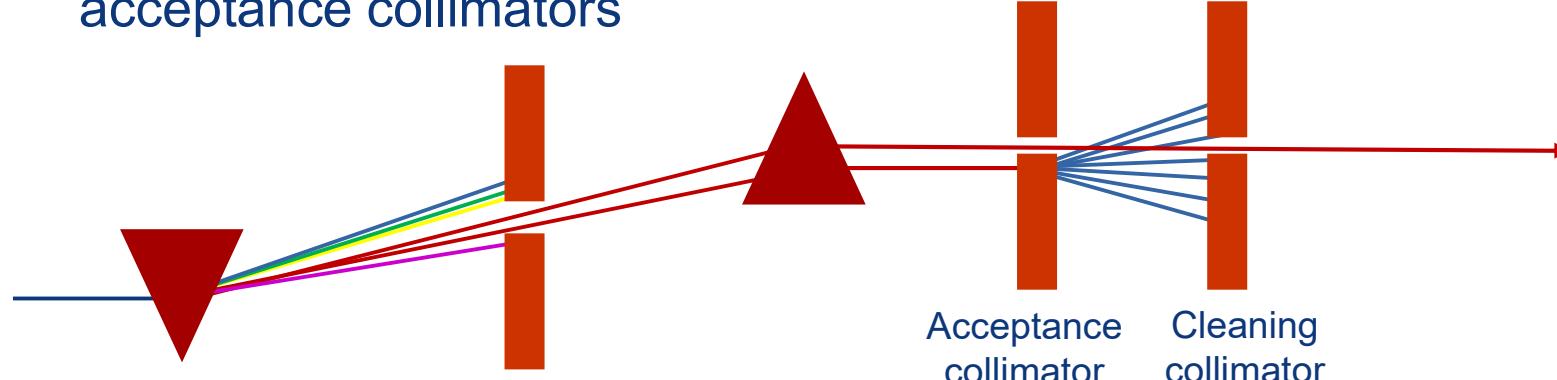


# Secondary beamlines - collimators

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

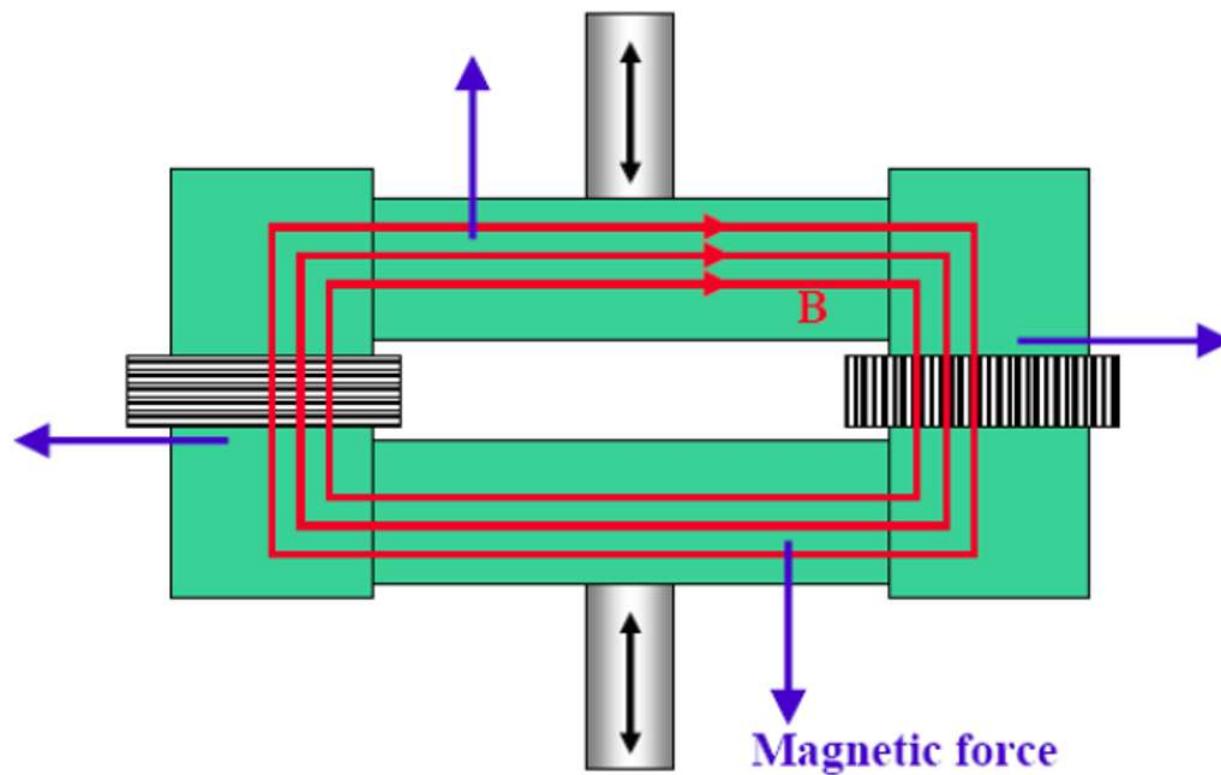


- Acceptance collimators
- Cleaning collimators
  - Absorb secondary particles produced on the jaws of acceptance collimators

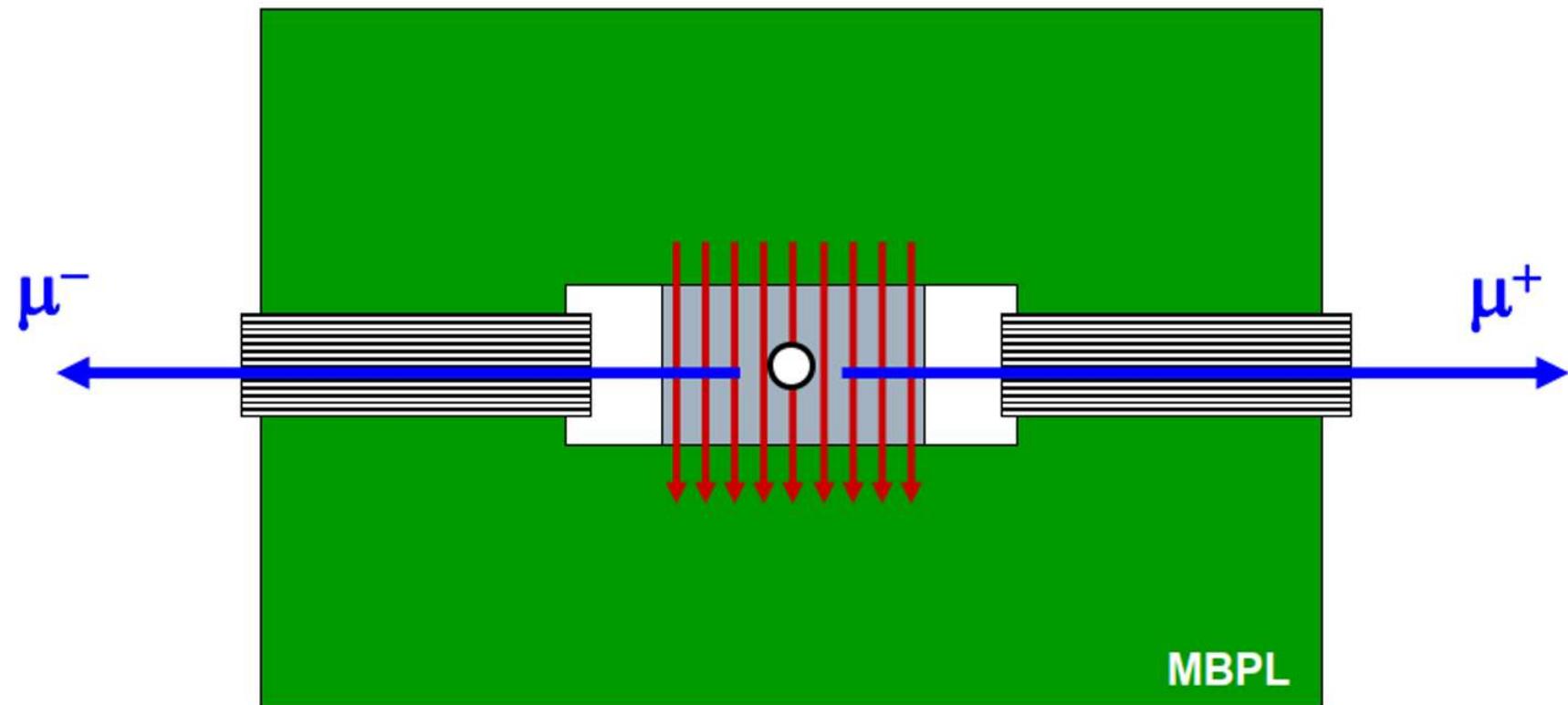


# Secondary beamlines – muon sweepers

## SCRAPERS (Magnetic Collimators)



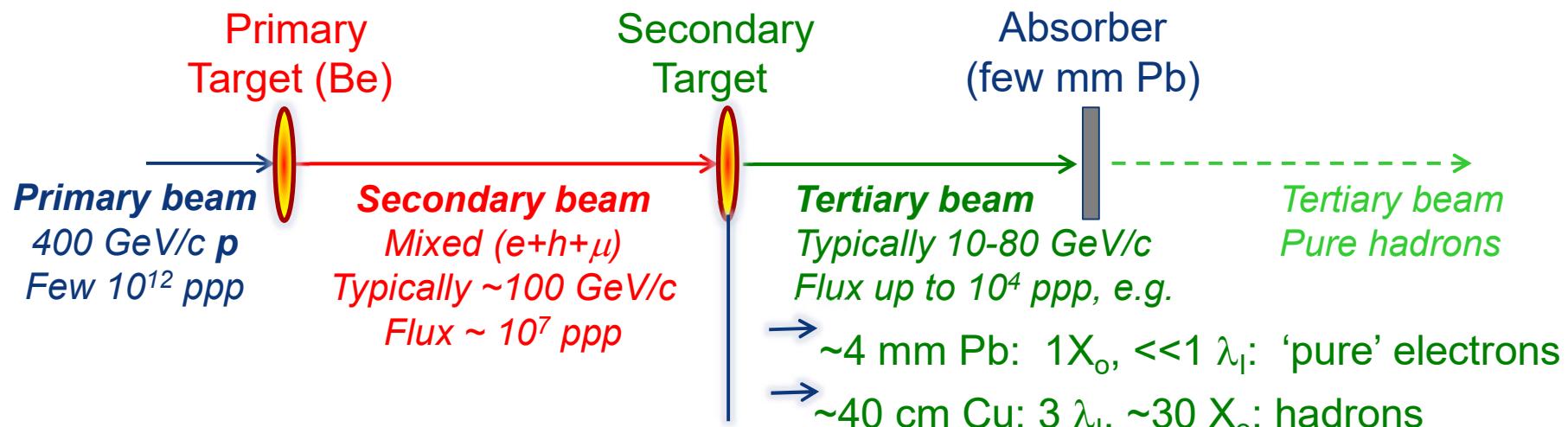
# Secondary beamlines – muon sweepers



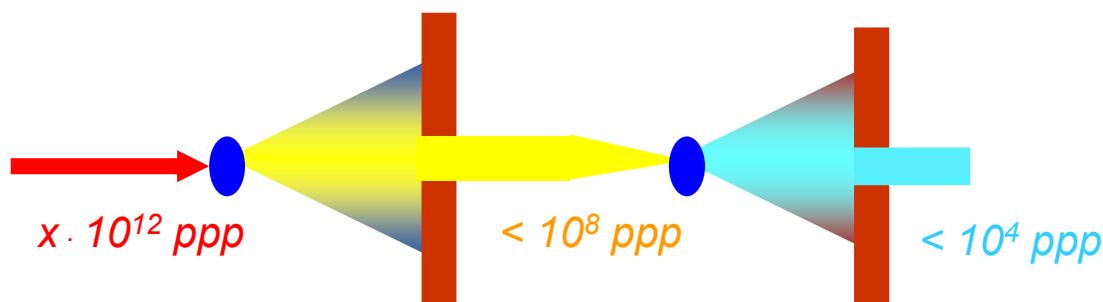
# Secondary beamlines - intensities

Basic beam design

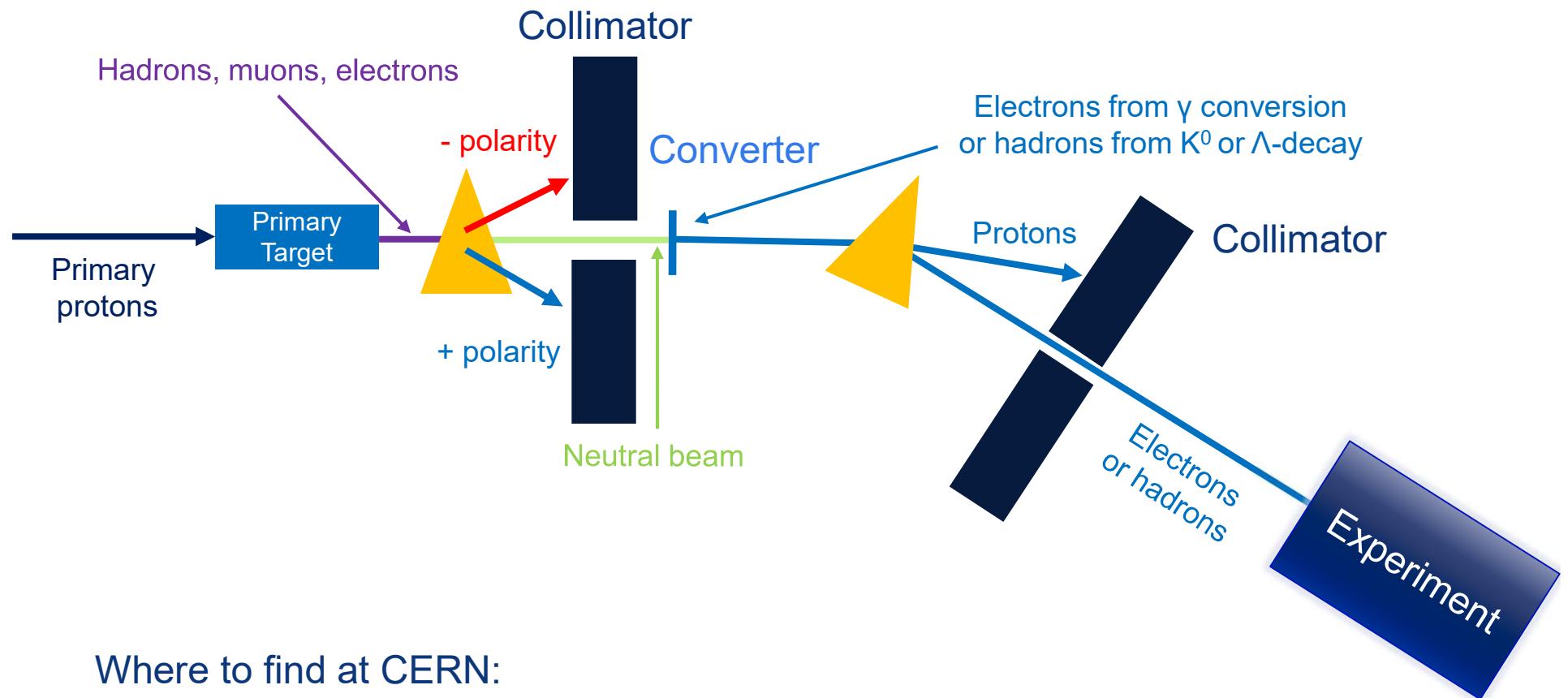
- Selection of particle types



- Intensities



# Selection of particle type - Converter



Where to find at CERN:

North Area: H2, H4

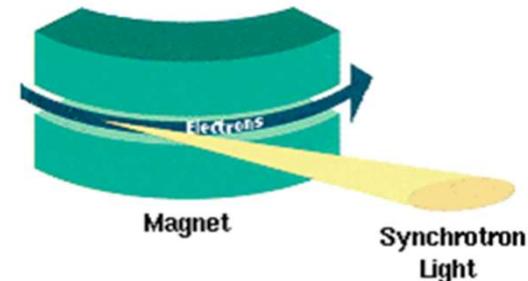
East Area: T9 (starting 2021)



# Selection of particle type - Synch. rad.

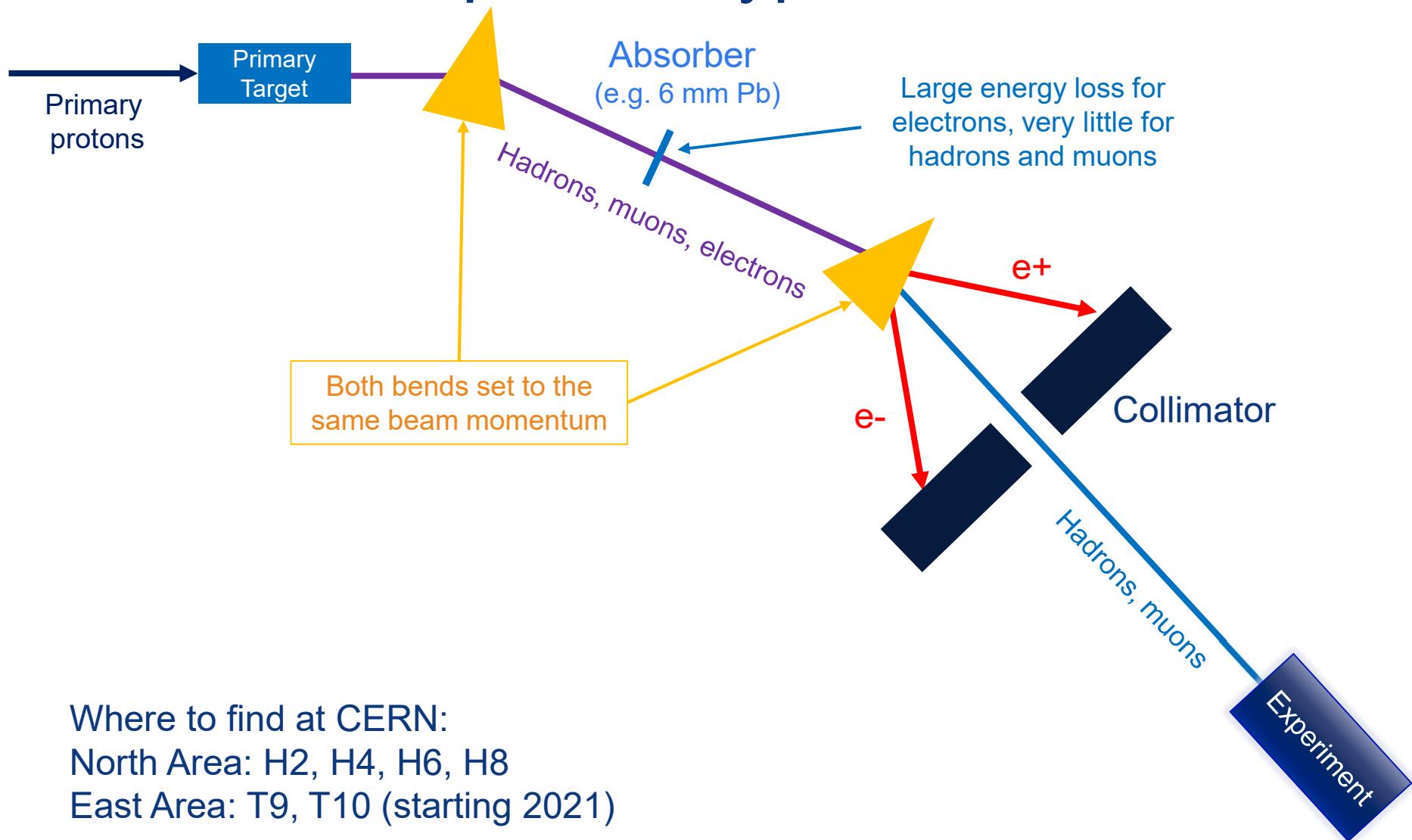
- Synchrotron radiation  
(for one full revolution)

$$P_s = \frac{e^2 c}{6\pi\epsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho^2}$$



- E.g.  $e^\pm$  at 200 GeV lose in 1° bending magnet of 1 T field 590 MeV
  - => With beamline momentum acceptance of  $\Delta p/p < 0.3 \%$  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  $p_e > 120-150 \text{ GeV}/c$

# Selection of particle type - Absorber



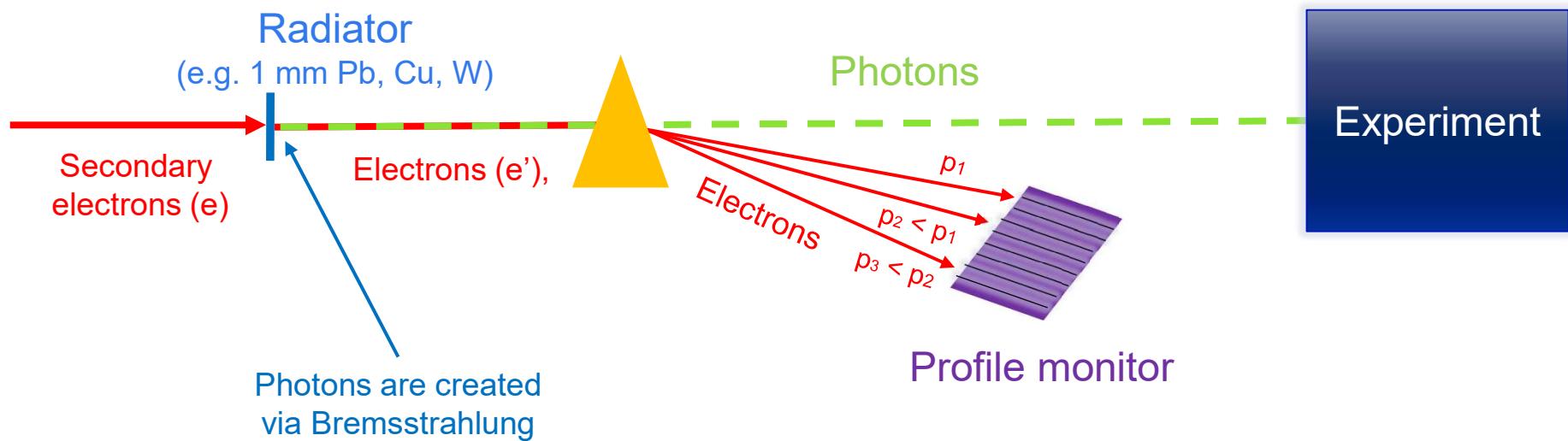
Where to find at CERN:

North Area: H2, H4, H6, H8

East Area: T9, T10 (starting 2021)



# Selection of particle type - Radiator



Where to find at CERN:

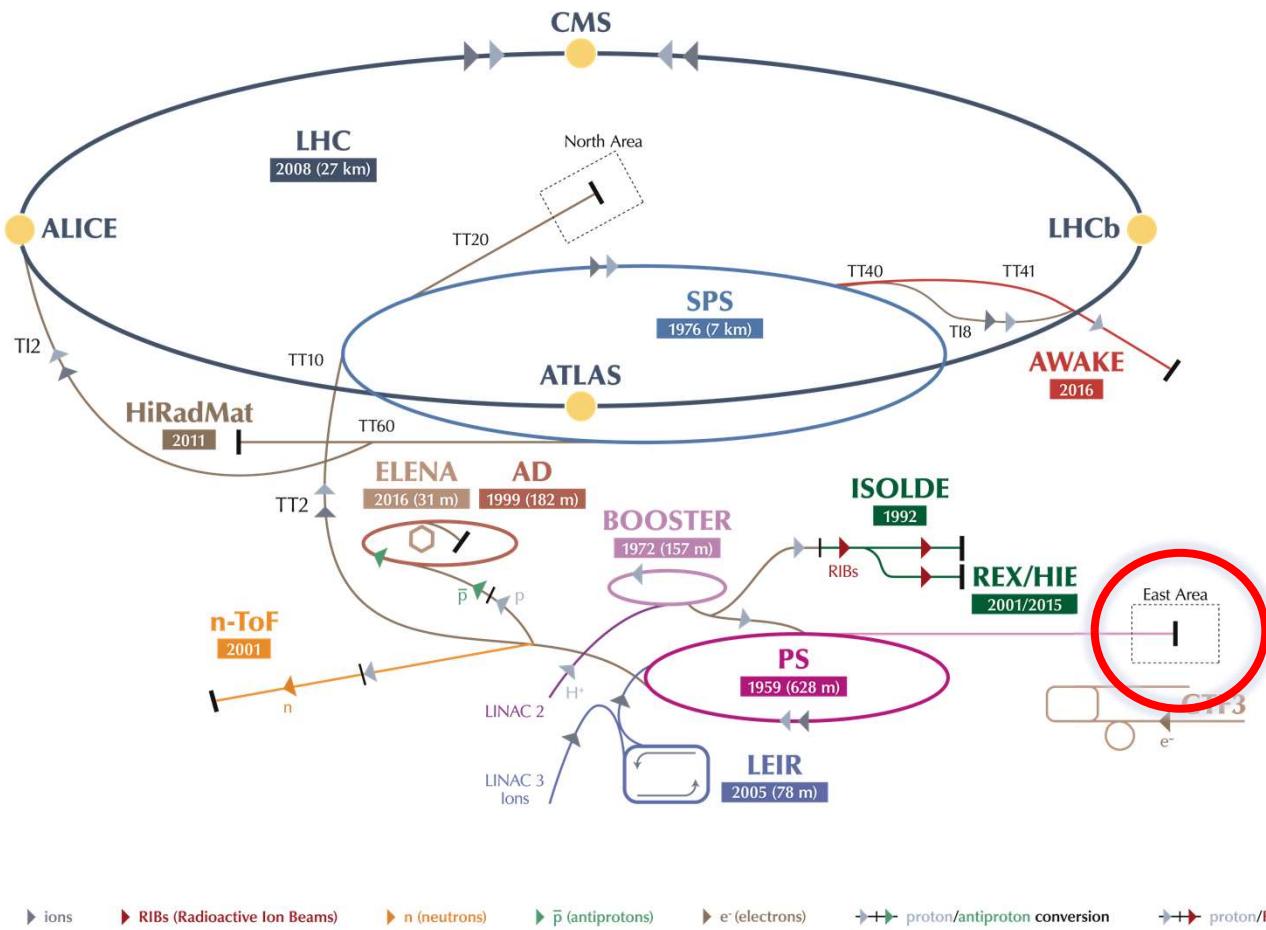
(Ad hoc installation, but usually used at)

North Area: H2, H4

East Area: T9

- Time resolution - electron by electron
- Transverse position gives information on  $e$ - momentum
- $\mathbf{p}_y = \mathbf{p}_e - \mathbf{p}_{e'}$
- Result : tagged photon beam

# Beams from PS



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKEfield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

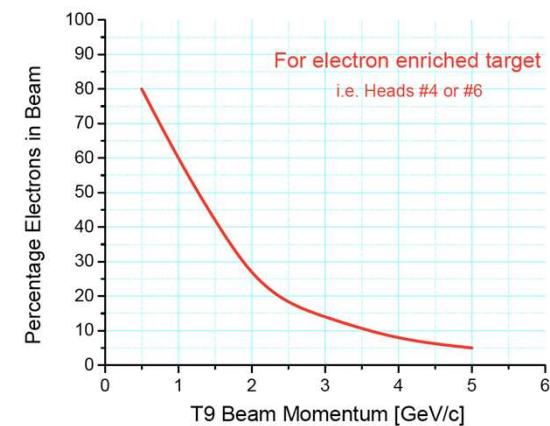
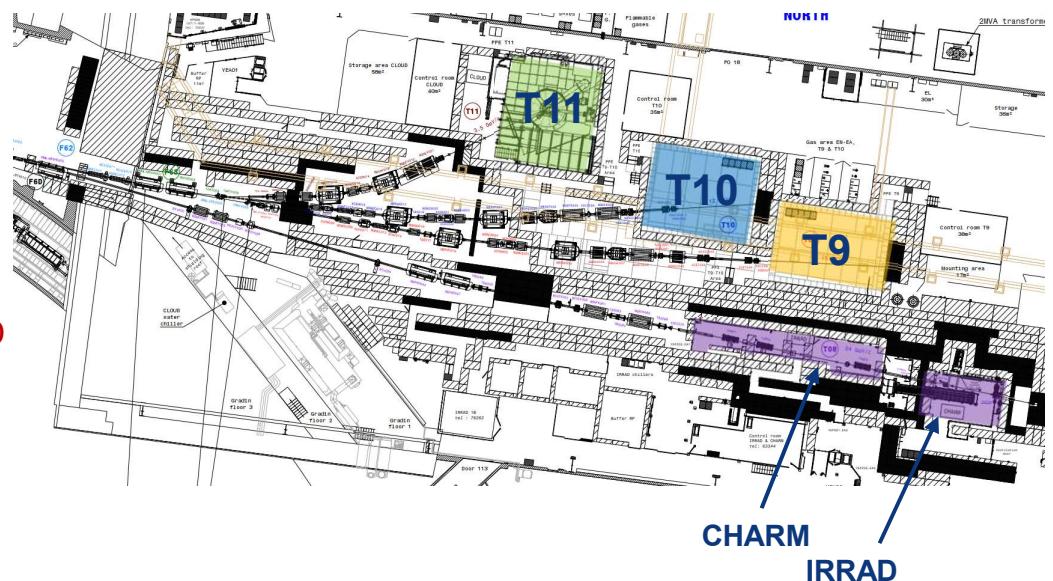
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# East Area

## Area under renovation

After LS2

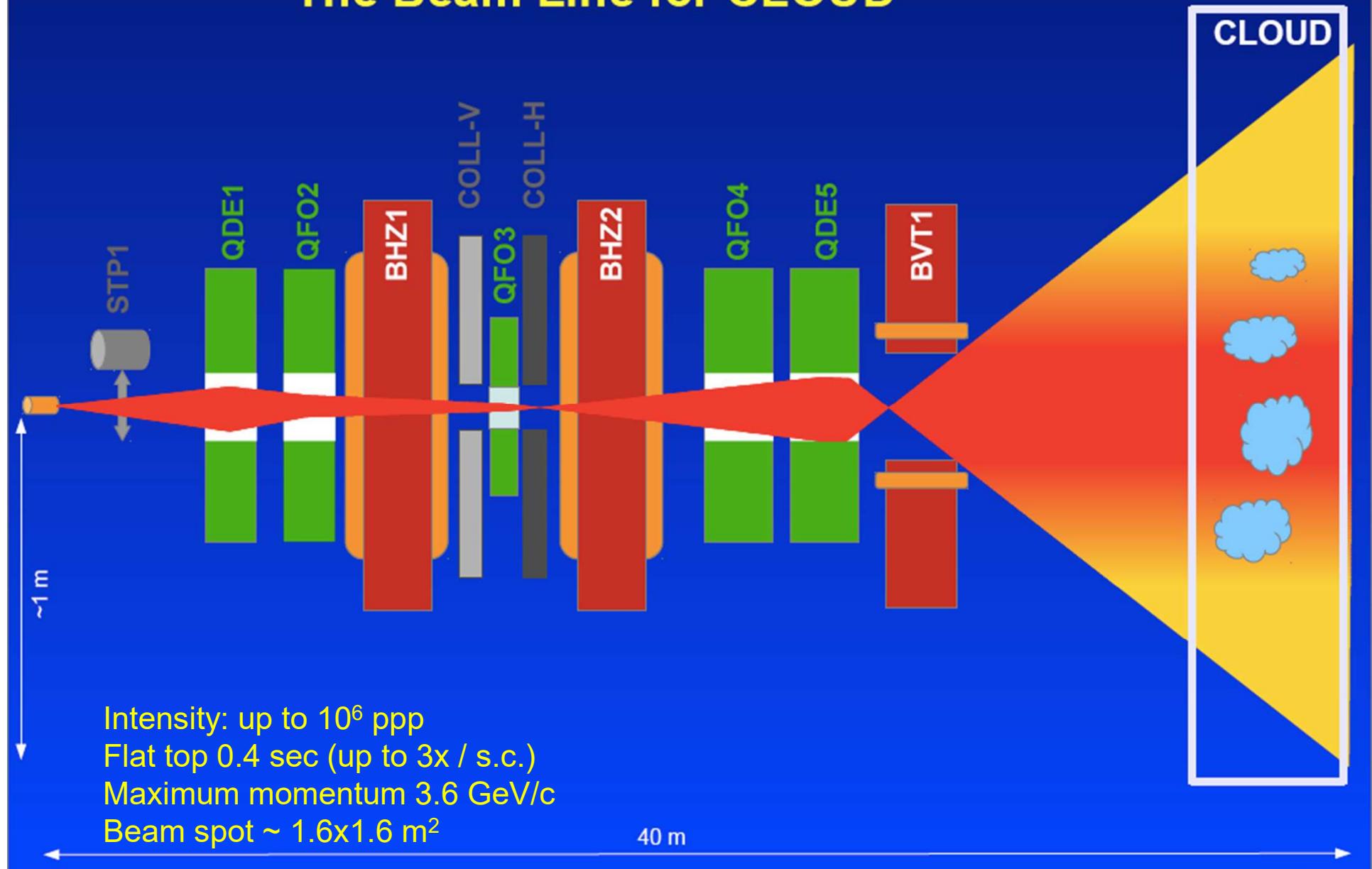
- Secondary beams:
    - Momentum < 15 GeV/c
    - Irradiation facilities CHARM and IRRAY
    - Test beamlines T9 and T10
    - T11 beamline for CLOUD experiment
    - Horizontal momentum selection
  - Particle types and intensity
    - Pure electrons, hadrons, muons
    - Max.  $\sim 5 \cdot 10^6$ 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



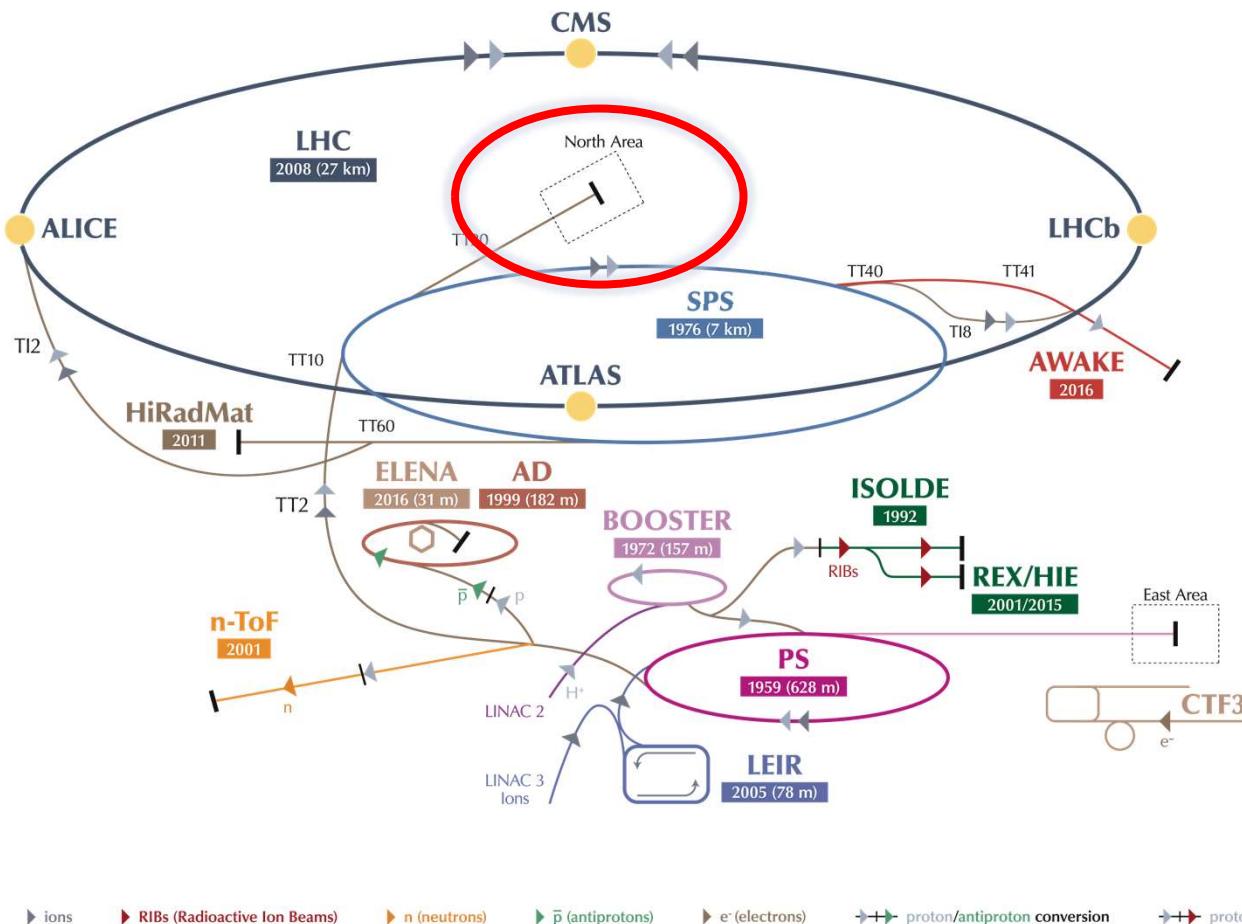
# The CLOUD Experiment in T11 Beam



# The Beam Line for CLOUD



# Beams from SPS



► p (protons)   ► ions   ► RIBs (Radioactive Ion Beams)   ► n (neutrons)   ►  $\bar{p}$  (antiprotons)   ►  $e^-$  (electrons)   ►↔ proton/antiproton conversion   ►↔ proton/RIB conversion

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

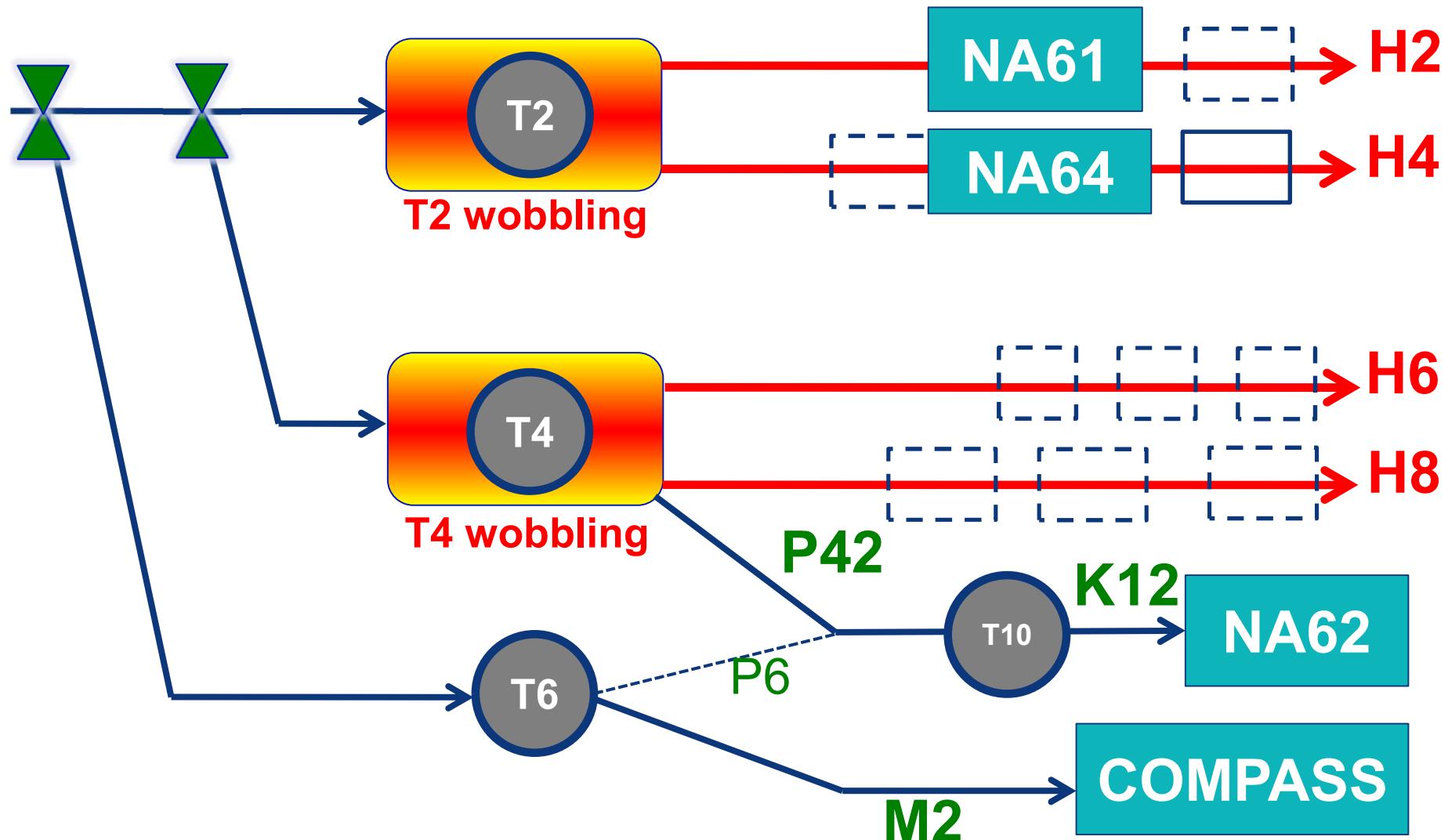
AWAKE Advanced WAvefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

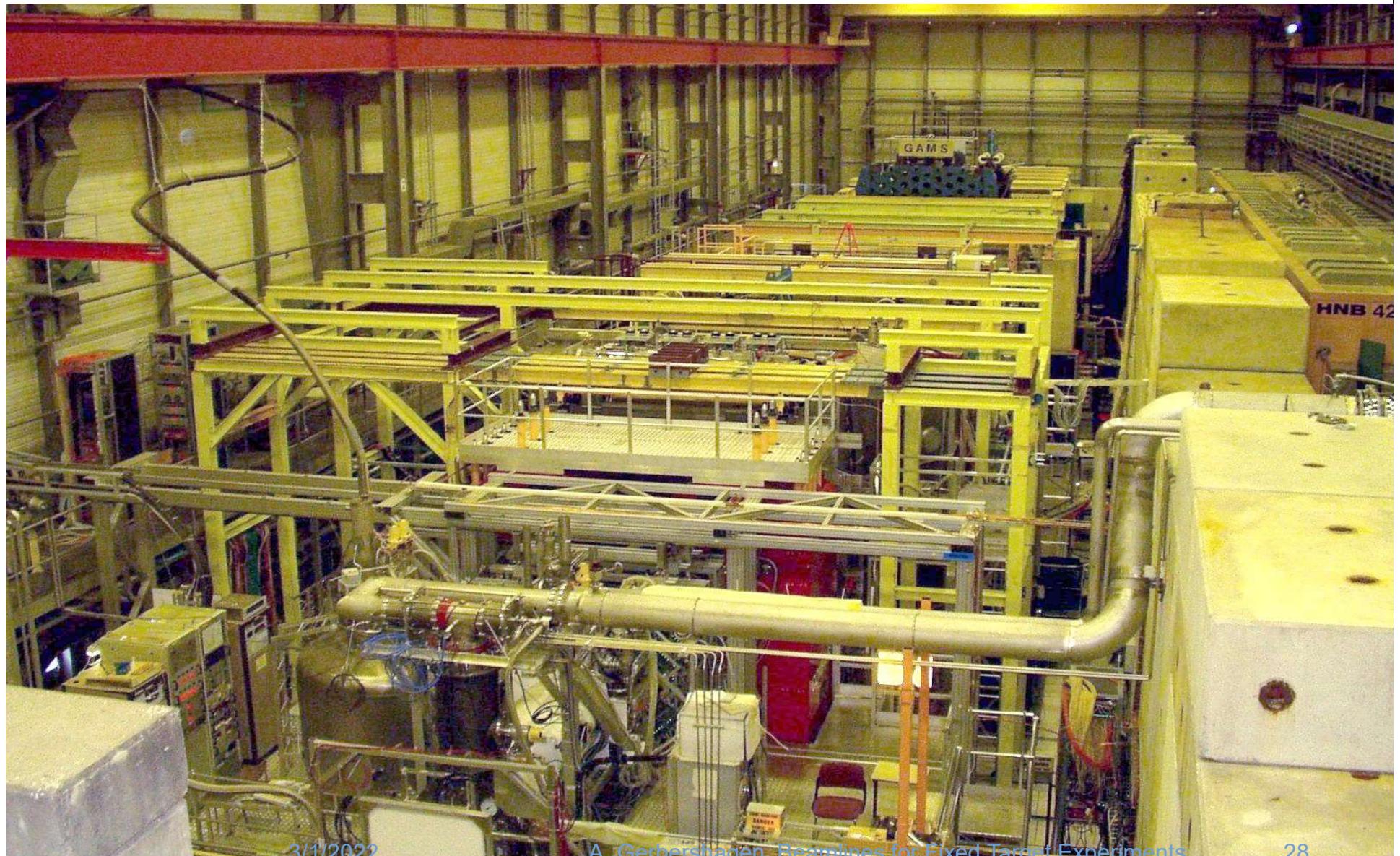
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# North Area beamlines - schematic



# EHN2: COMPASS



✓

PHOTO

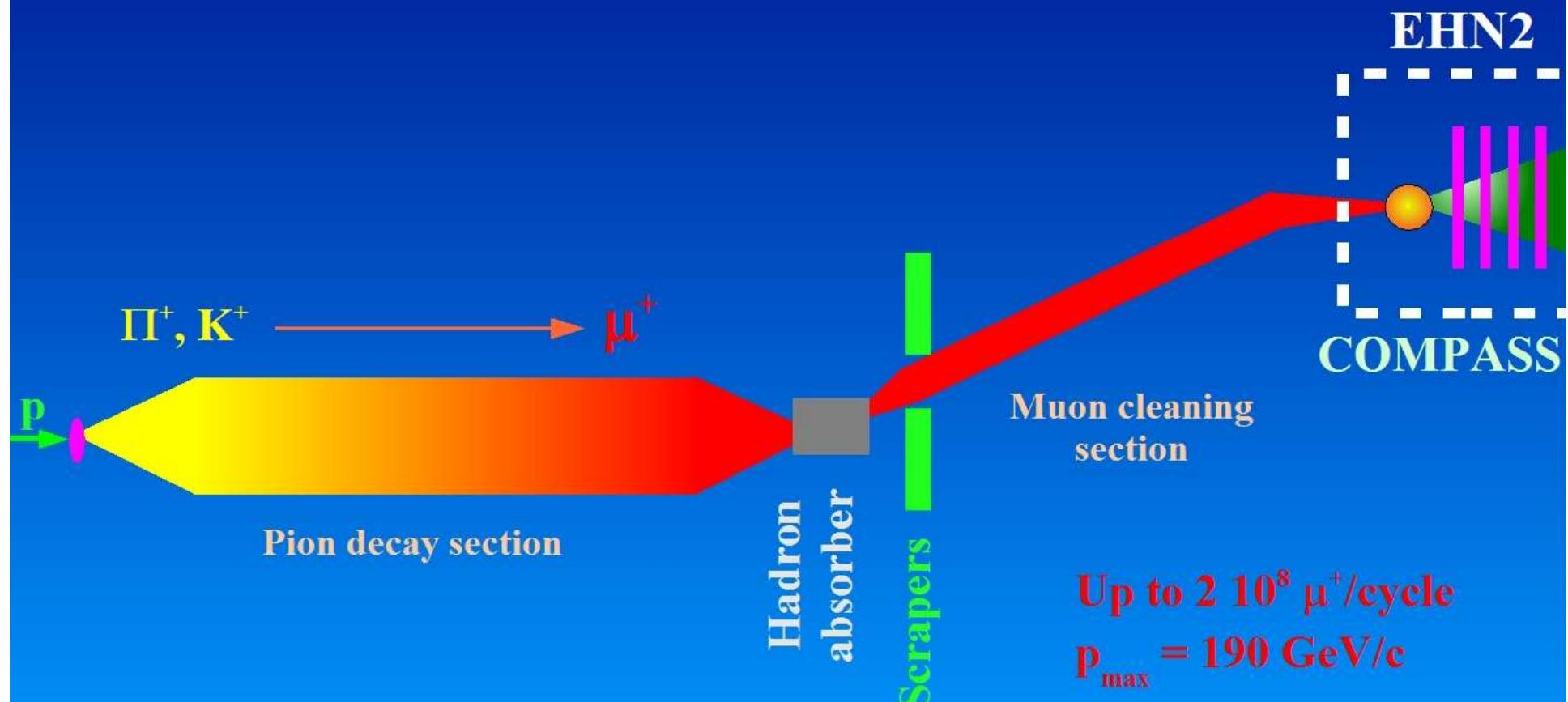
3/1/2022

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# THE M2 MUON BEAM

## FOR COMPASS / NA58



# Muons from pion decay

- Pion decay in  $\pi$  center of mass:

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

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

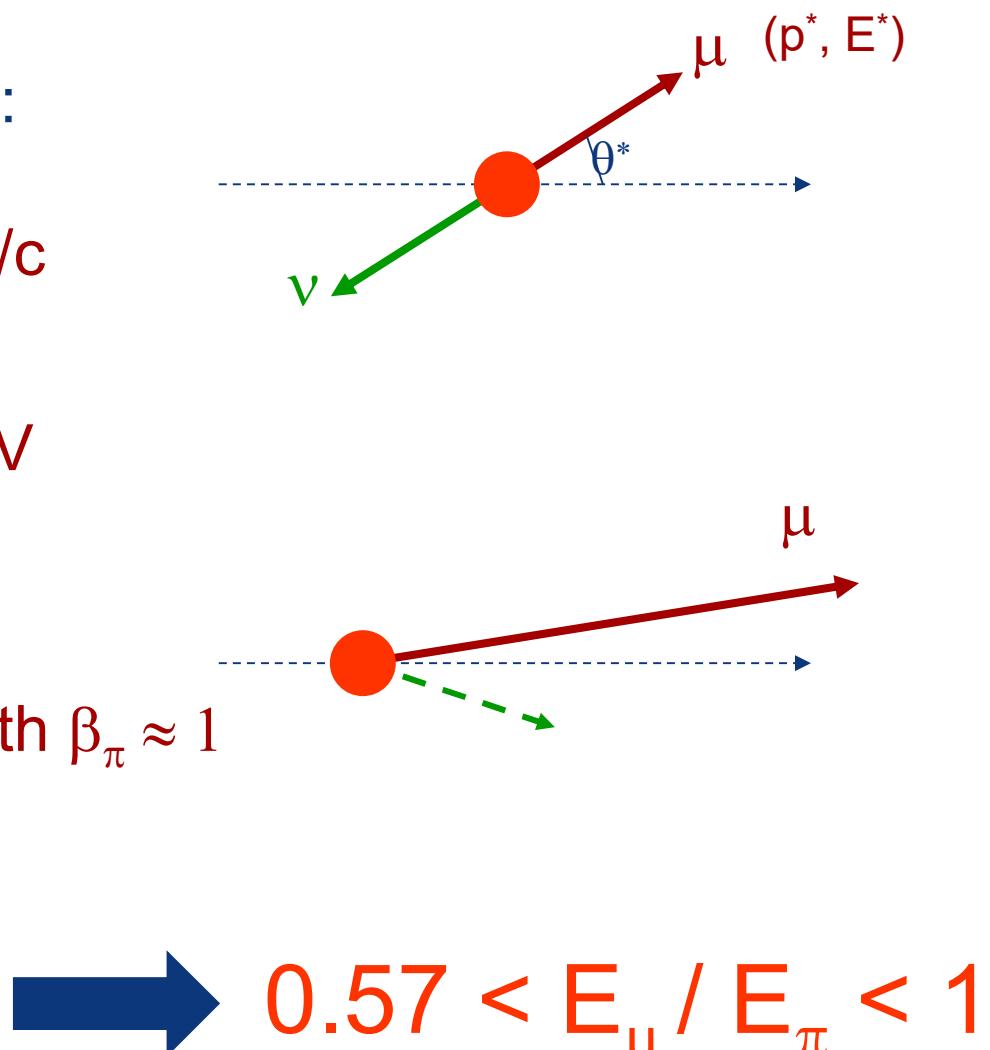
- Boost to laboratory frame:

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

- Limiting cases:

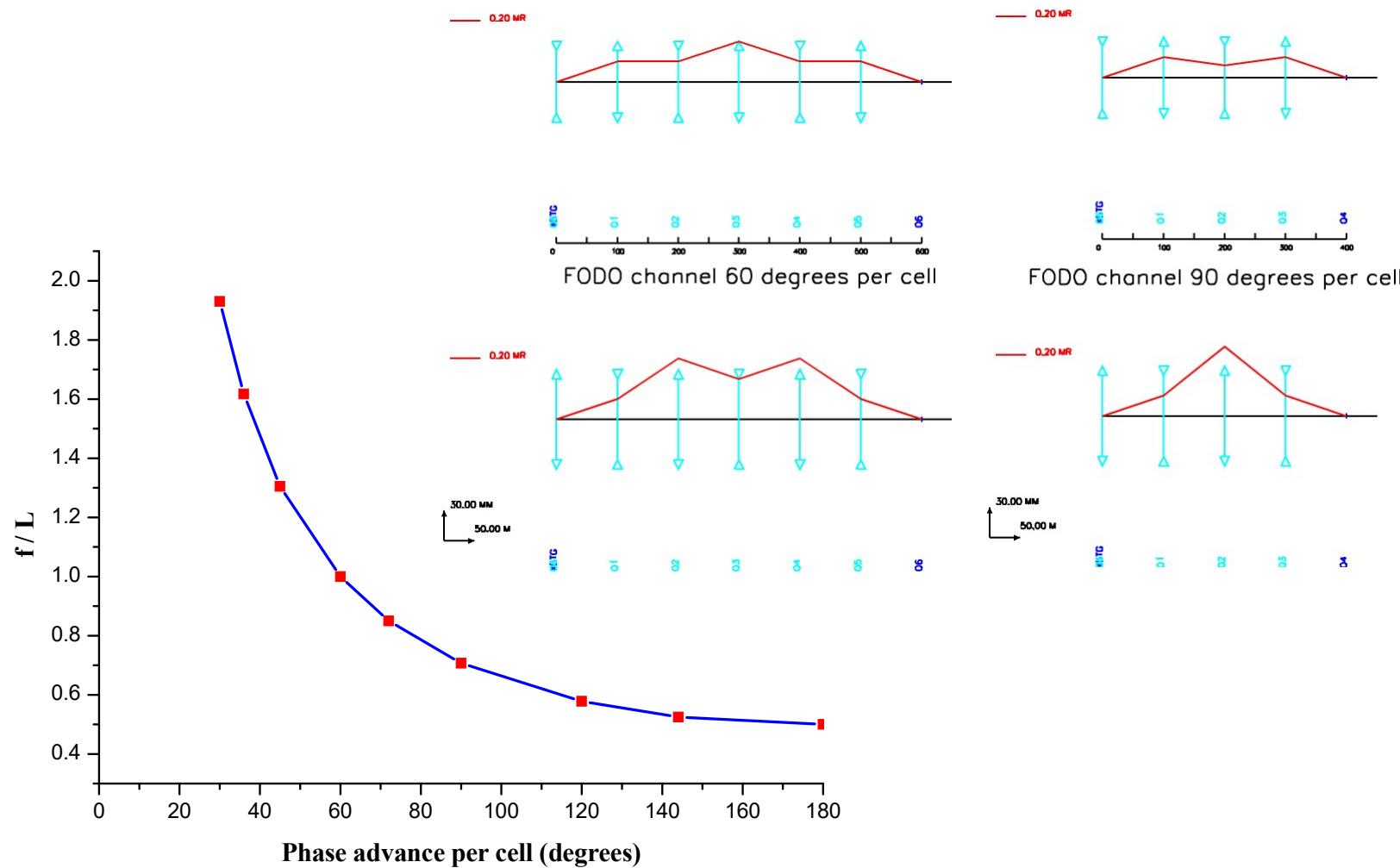
$$\cos \theta = +1 \rightarrow E_{\max} = 1.0 E_\pi$$

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

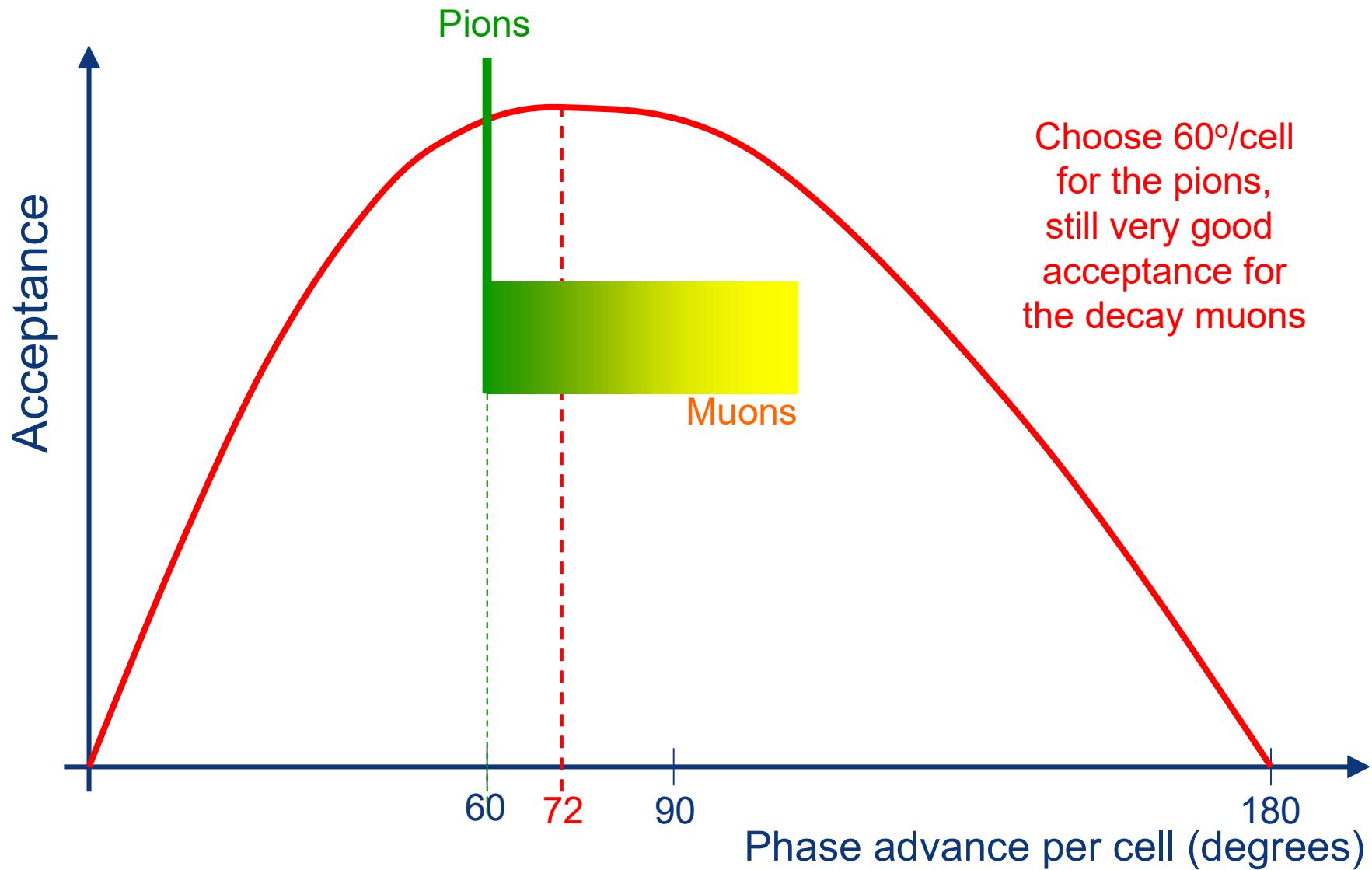


$$0.57 < E_\mu / E_\pi < 1$$

# Momentum acceptance of FODO cells

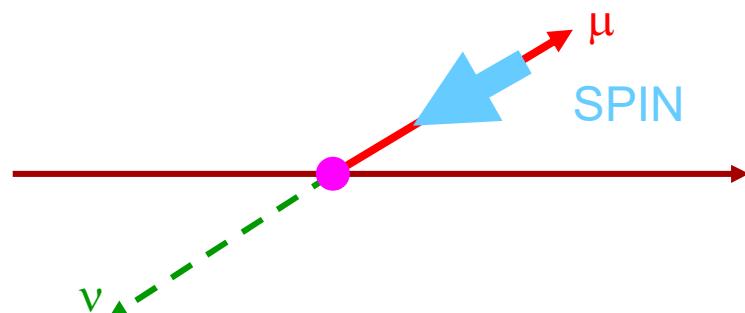
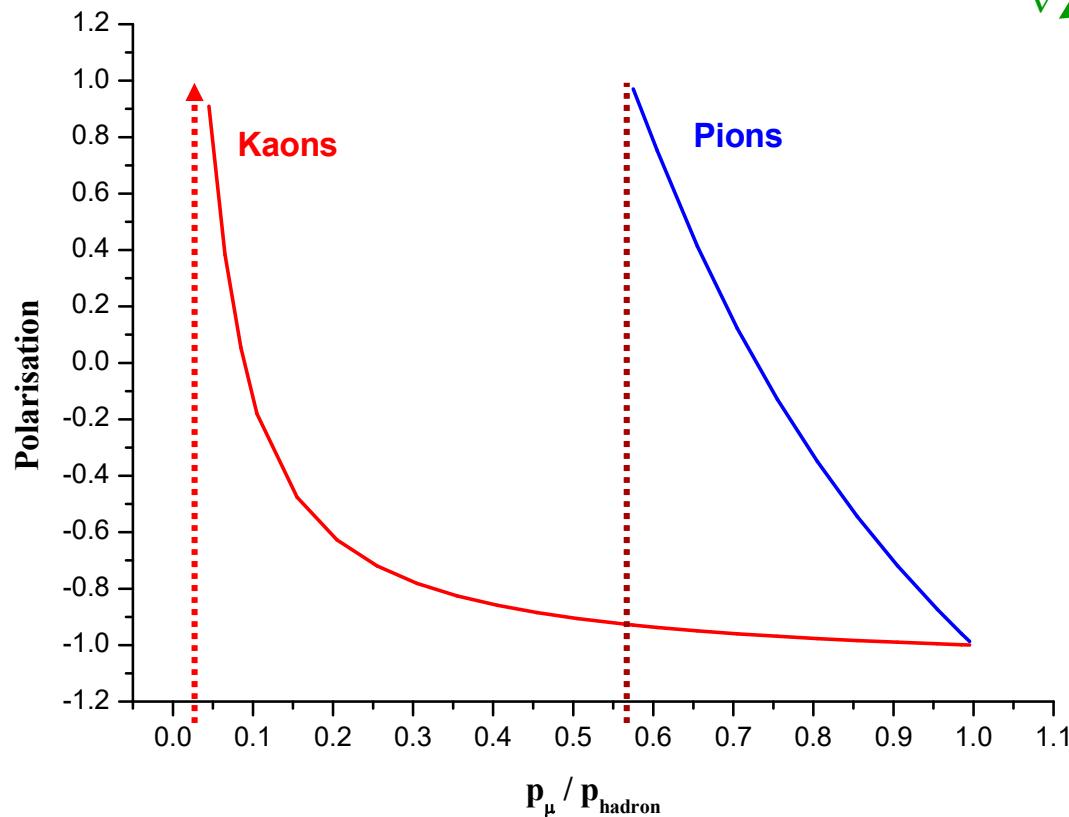


# Phase advance for M2 beam



# Muon Polarisation

Muons from pion decay are naturally polarised through Parity Violation:



For the typical COMPASS conditions,  $p_\mu / p_\pi = 0.92$  and the measured muon polarisation is about -80%

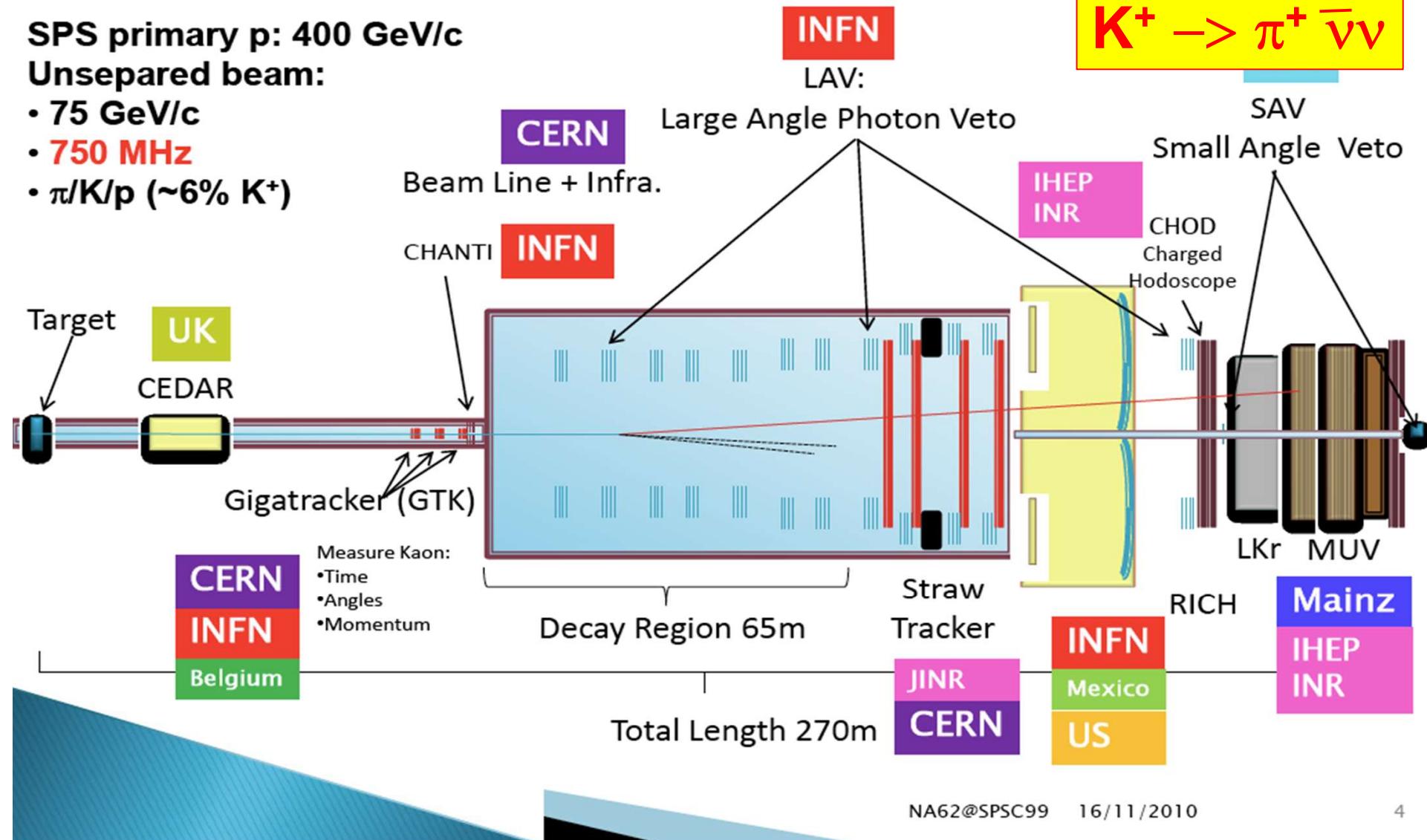
# NA62 Beam and Detectors



SPS primary p: 400 GeV/c

Unseparated beam:

- 75 GeV/c
- 750 MHz
- $\pi/K/p$  (~6%  $K^+$ )



partrec

3/1/2022

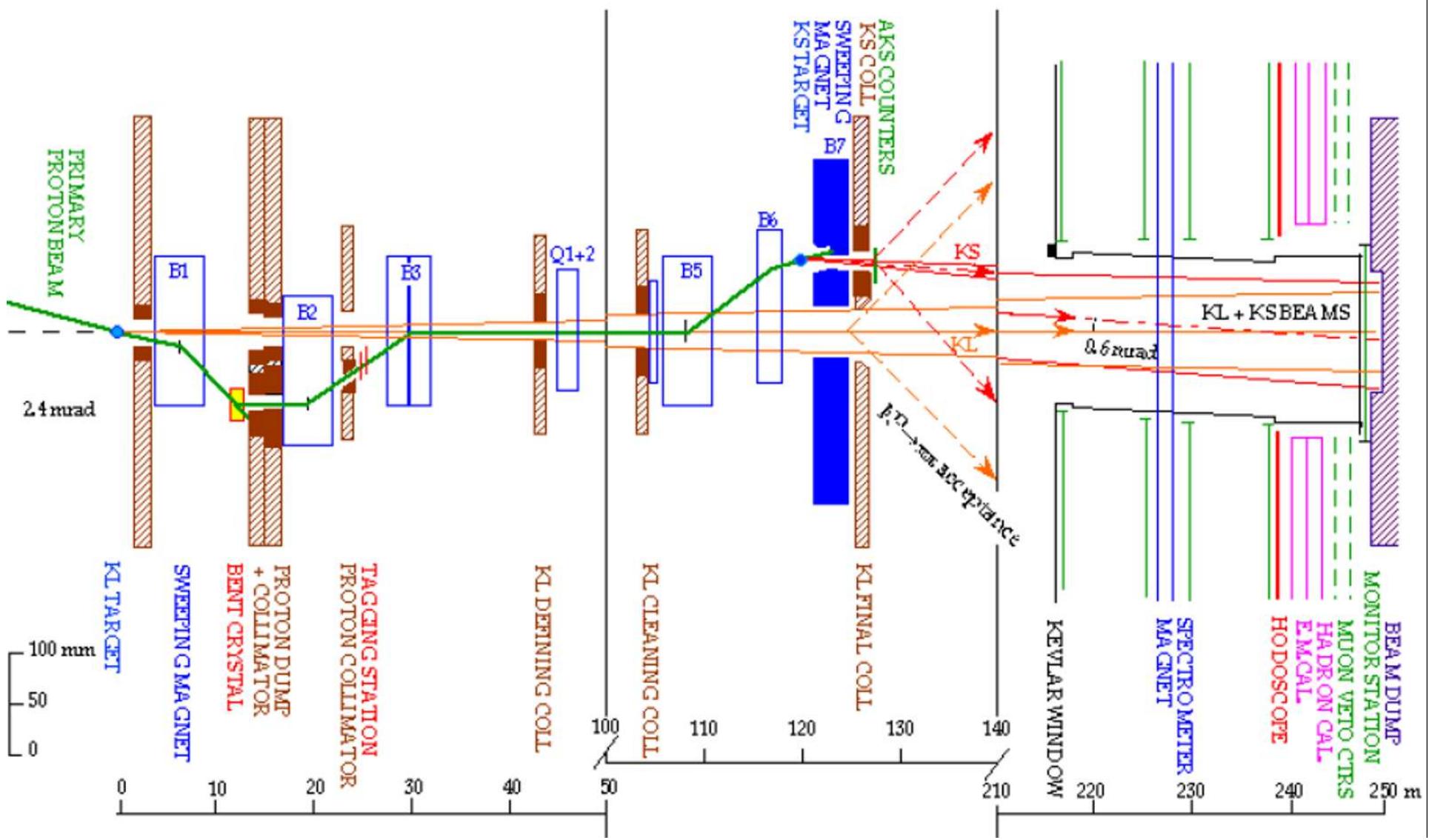
NA62@SPSC99 16/11/2010

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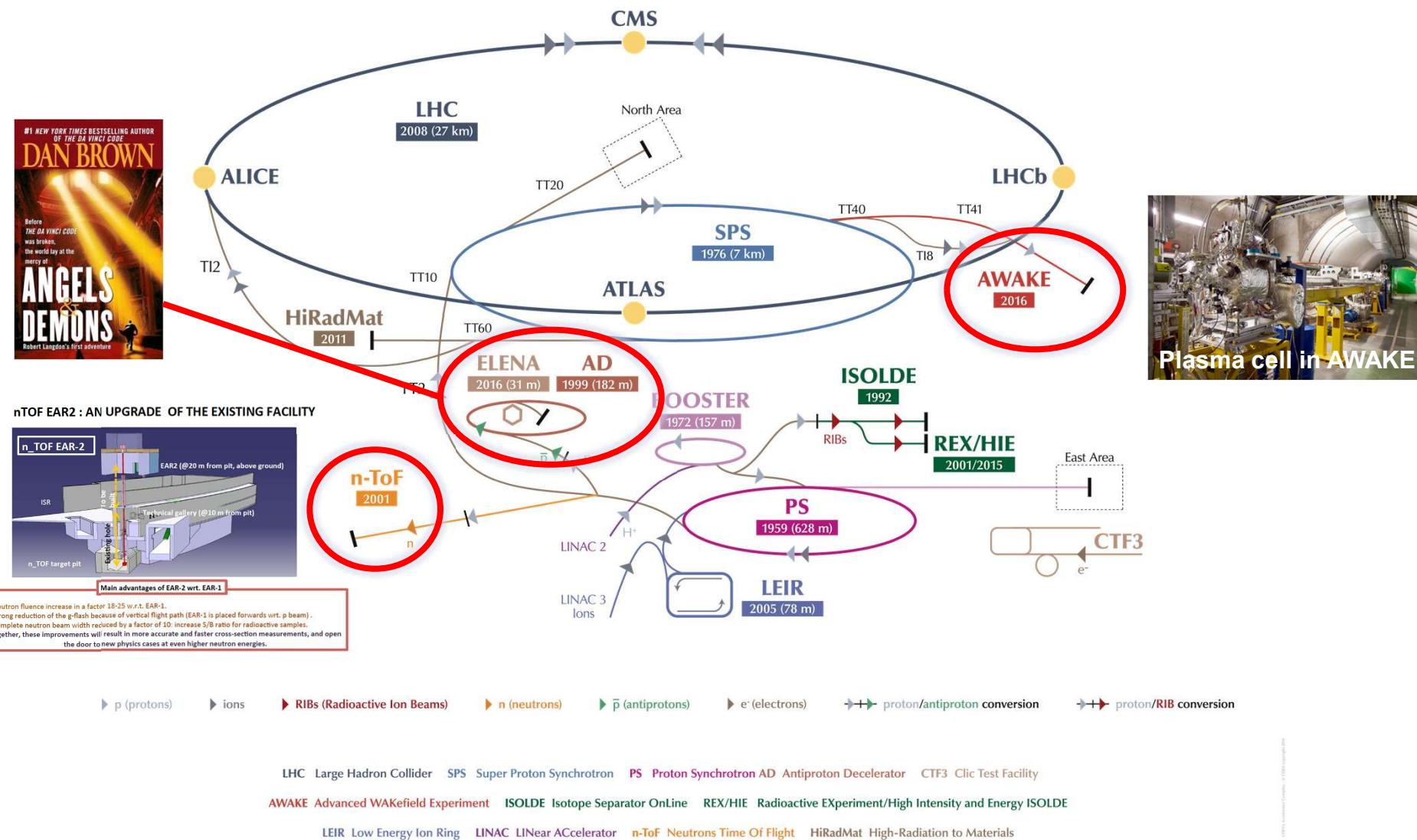
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# Historical Note - Kaon beam for NA48

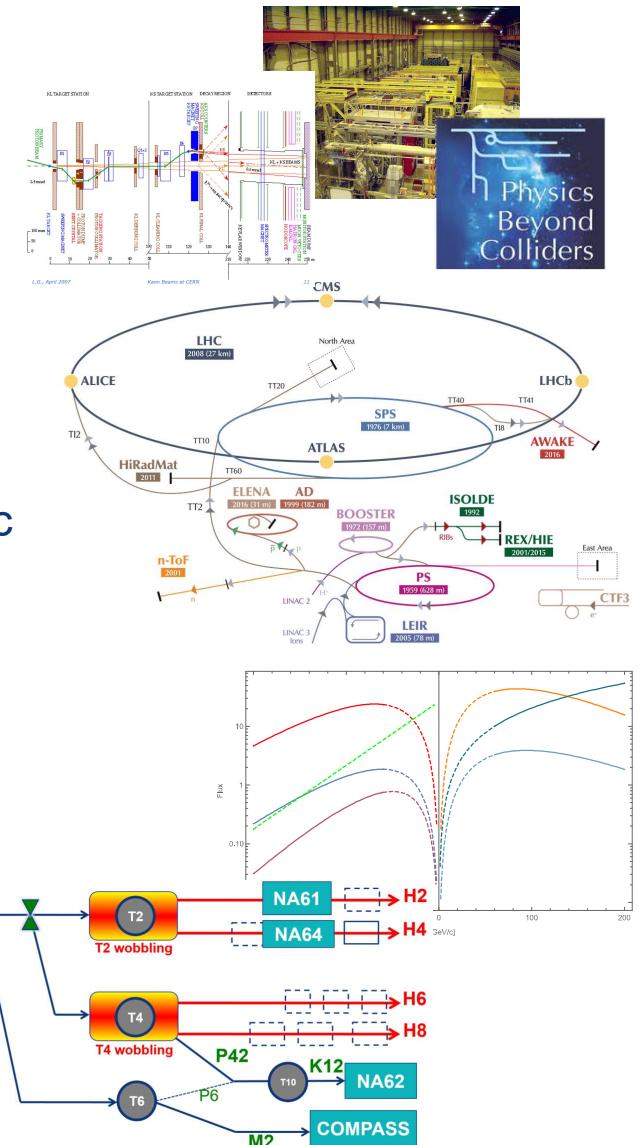


# Other experiments with fixed-target beams



# 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 :  $<1.4 \text{ GeV}/c$ ,  $<15 \text{ GeV}/c$ ,  $<400 \text{ GeV}/c$
  - 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.





Questions?