Introduction to Secondary Beams

Beamline for Schools 2023

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A brief introduction – and who am I, anyway?

- **A brief introduction**
  - I am one of the Secondary Beamline Physicists that work at CERN
  - I am one of the (Secondary Beamline) Physicists that work at CERN
- **Things covered today**
  - A little bit of physics, a little bit of context
- **What about you?**
  - You are considering applying for the BL4S program
  - And some information about physics and the beamlines is helpful for this!

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Topics of this talk

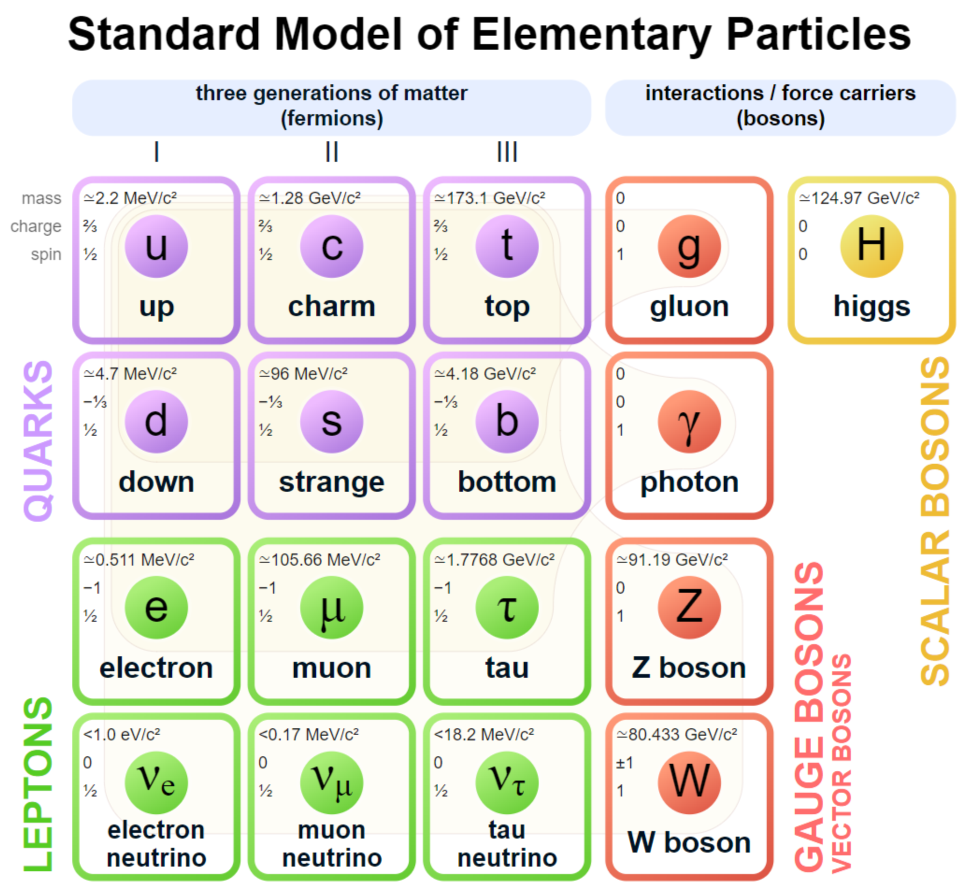
- **Secondary beams are complicated things**
  - What is a particle?
  - What are secondary beams?
  - Where do they come from?
    - Fixed target, *not* a collider
  - What can we expect to find in a secondary beam?
- **Detectors and detectors – interactions of particles with matter**
  - What is a detector and how does it work?
  - Different particles in different detectors
  - BL4S detectors
- **Proposals for BL4S?**

Particle physics in context

Let’s start from the beginning (?)

- **Standard model of elementary particles contains all of the wisdom of the last 100 years or so**
  - Clearly, this is a bit much to start from
  - And usually we don’t need all of it

- **A few things that will keep returning**
  - Elementary particles cannot be split further
  - **You will never see a quark alone**
  - However, we can glue quarks together
    - Glue two quarks together = a meson
    - Glue three quarks together = a baryon
    - Particles made from quarks are hadrons

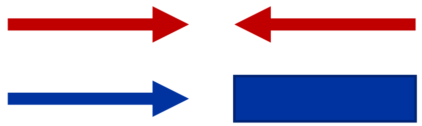


How do you do particle physics?

- **Put a lot of energy in a very small space**
  - Use electric and magnetic fields to push a particle to high energy
  - Nature will do the rest of the work for you
- **Two possible configurations for using this energy**
  - Smash into other particles (moving also at high speed)
  - Smash into fixed (non-moving) target

Collider

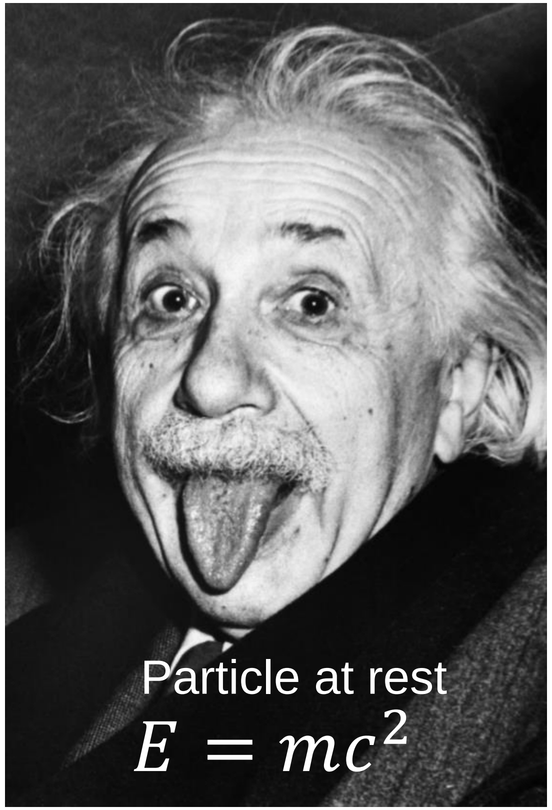
Fixed target



- **Collider is good at concentrating energy**
  - Energy scaling is much more efficient due to special relativity
  - Ask your teacher if you would like to know more about this!
- **Fixed target is good at “many” collisions – all particles will interact**
  - Good for producing large numbers of **secondary** particles (!)

Energy, momentum and all that jazz

- **Mass and energy are not the same**
  - But they are **equivalent and exchangeable**
  - Momentum is *also* a form of energy!
  - Add it to equation
  - Momentum and mass are ALSO exchangeable!
- **In particle physics, we express energy in GeV**
  - 1 GeV = 1.60218 × 10^{-10} Joule
  - And following the equation, we can also see that we can also do this for mass and momentum
  - Mass GeV/c^2
  - Momentum GeV/c
  - 1 proton mass = 1.673 × 10^{-27} kg = 0.938 GeV/c^2



Moving particle

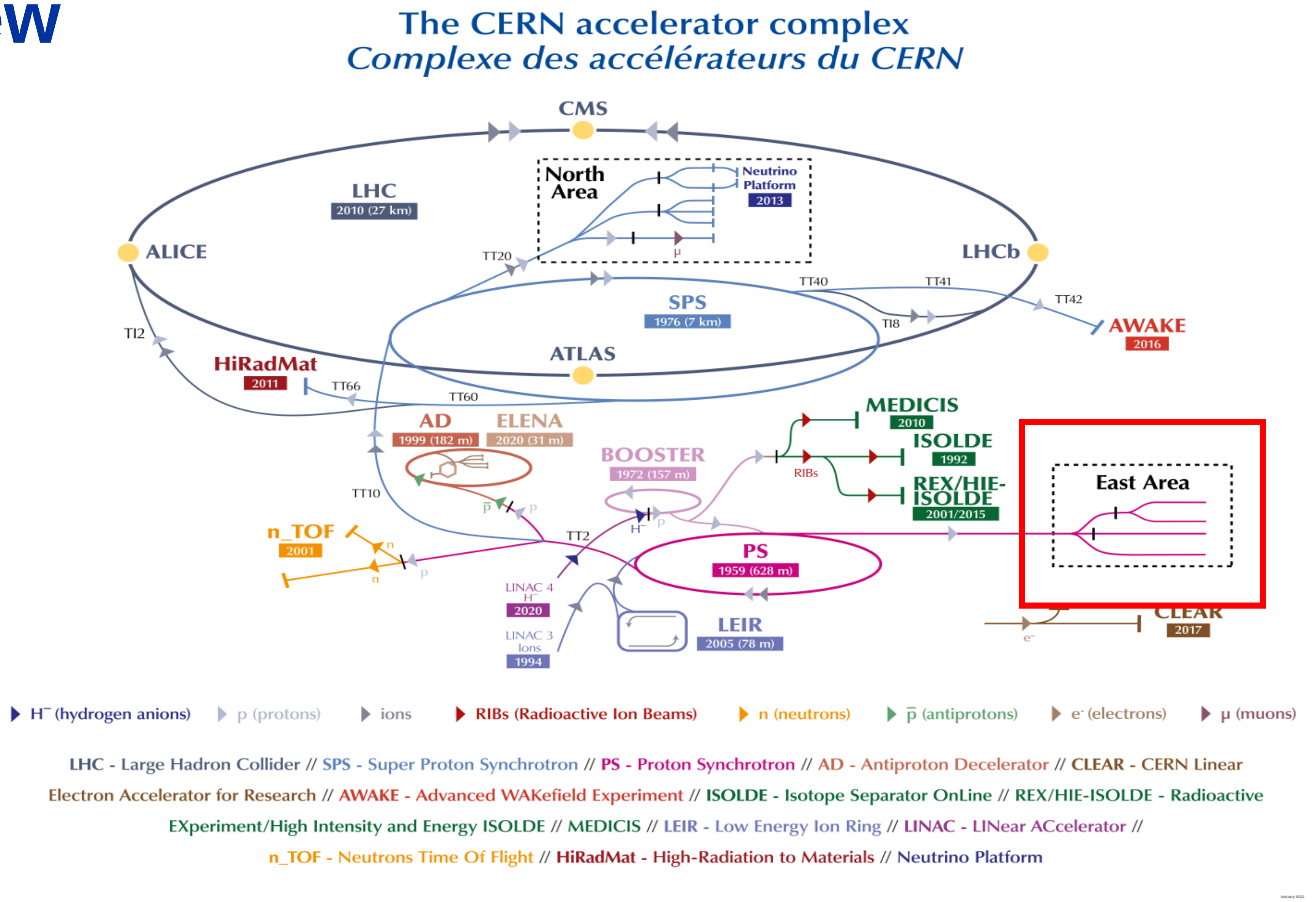
$$E^2 = (mc^2)^2 + (pc)^2$$

$$E^2 = m^2c^4 + p^2c^2$$

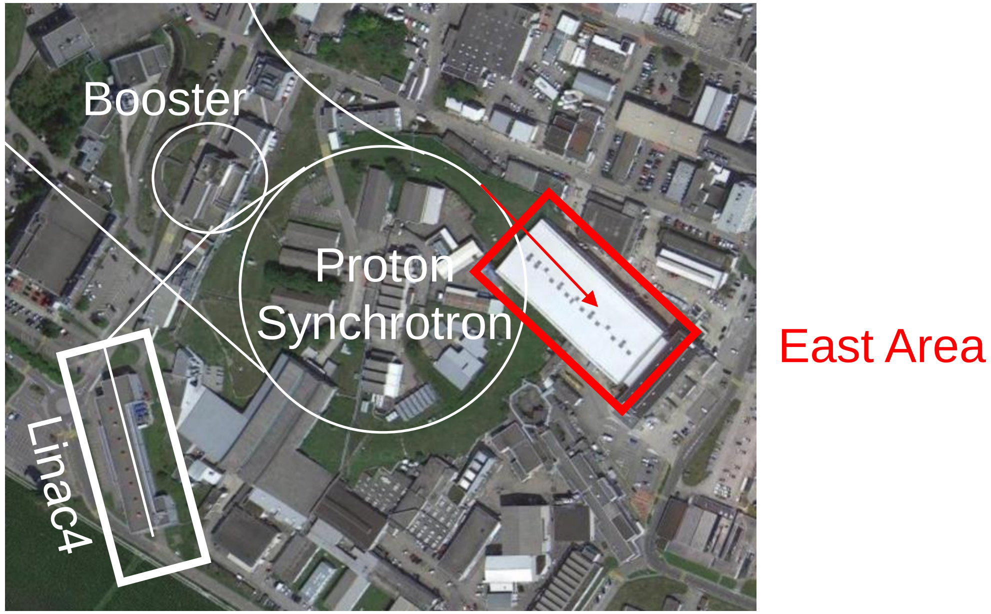
$$E = \sqrt{m^2c^4 + p^2c^2}$$

The CERN accelerator complex

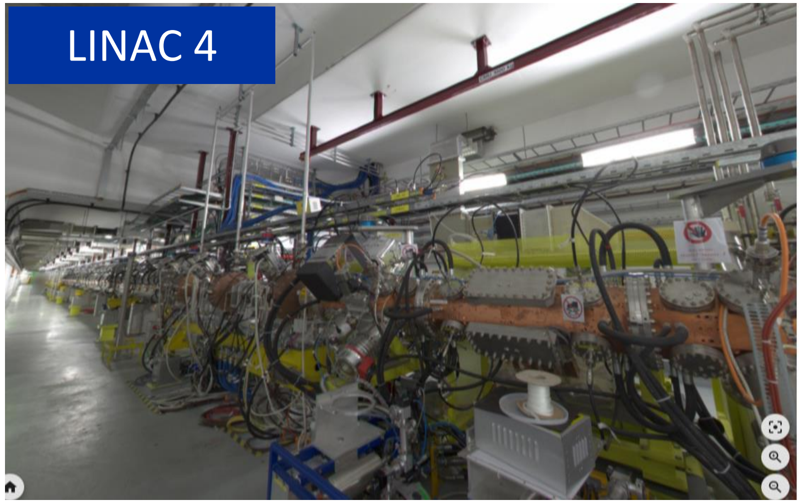
Overview

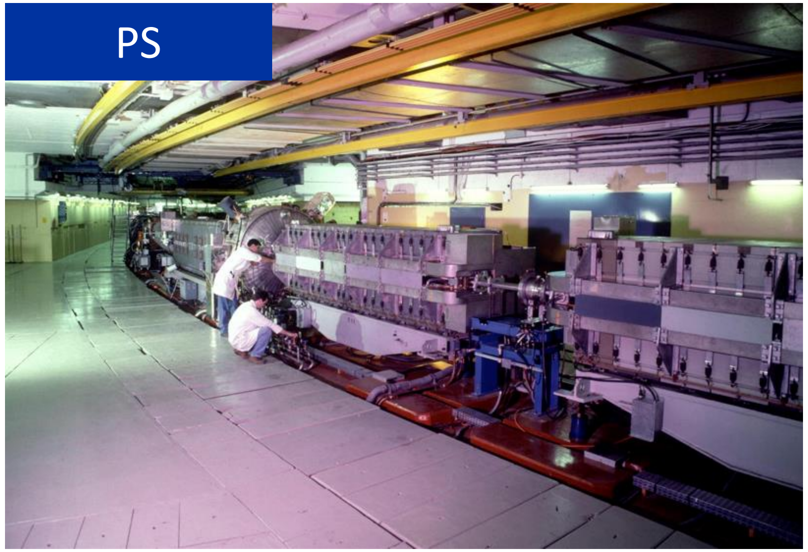

The CERN accelerator complex
Complexe des accélérateurs du CERN
CMS
LHC
2010 (27 km)
ALICE
LHCb
North Area
Neutrino Platform
2013
TT20
μ
SPS
1976 (7 km)
TT40
TT41
TT42
TI8
AWAKE
2016
TI2
HiRadMat
2011
TT66
ATLAS
TT60
AD
1999 (182 m)
ELENA
2020 (31 m)
BOOSTER
1972 (157 m)
MEDICIS
2010
ISOLDE
1992
RIBs
REX/HIE-ISOLDE
2001/2015
East Area
TT10
n_TOF
2001
TT2
PS
1959 (628 m)
LINAC 4
H⁻
2020
LINAC 3
Ions
1994
LEIR
2005 (78 m)
CLEAR
2017
e⁻
H⁻ (hydrogen anions)
p (protons)
ions
RIBs (Radioactive Ion Beams)
n (neutrons)
p̄ (antiprotons)
e⁻ (electrons)
μ (muons)
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

Geography of CERN

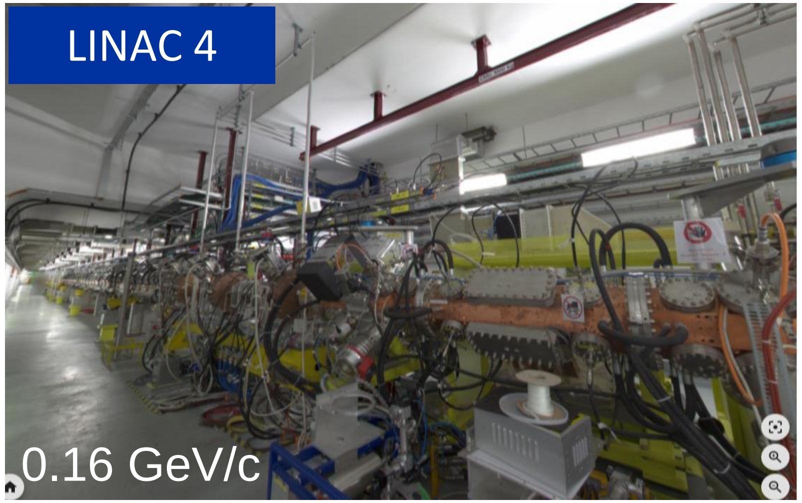


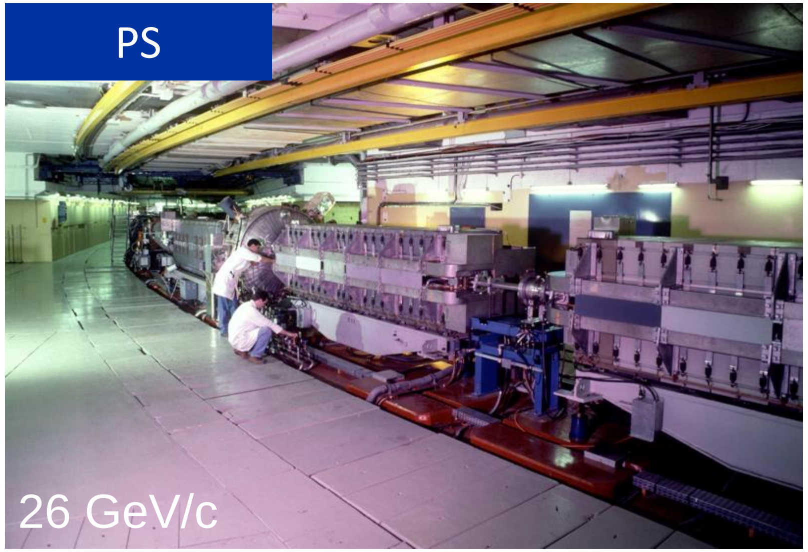
The life of a proton at CERN





Energy scales in the CERN machines



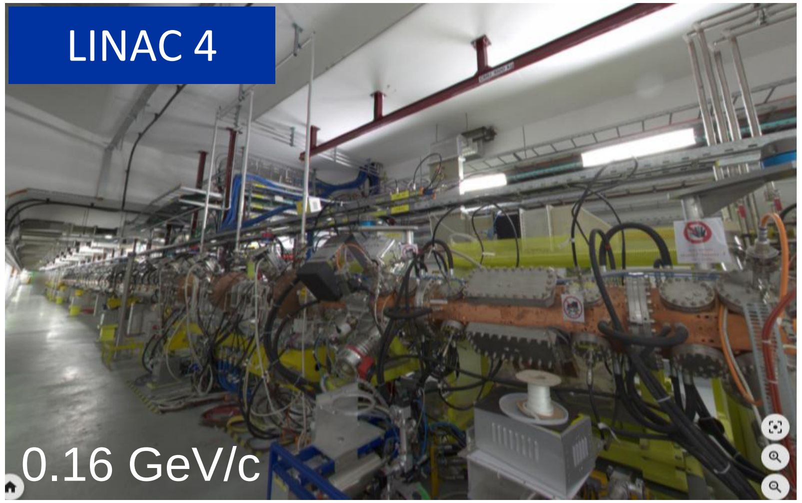


7000 GeV/c

The life of YOUR proton at CERN?

0 GeV/c

LINAC 4

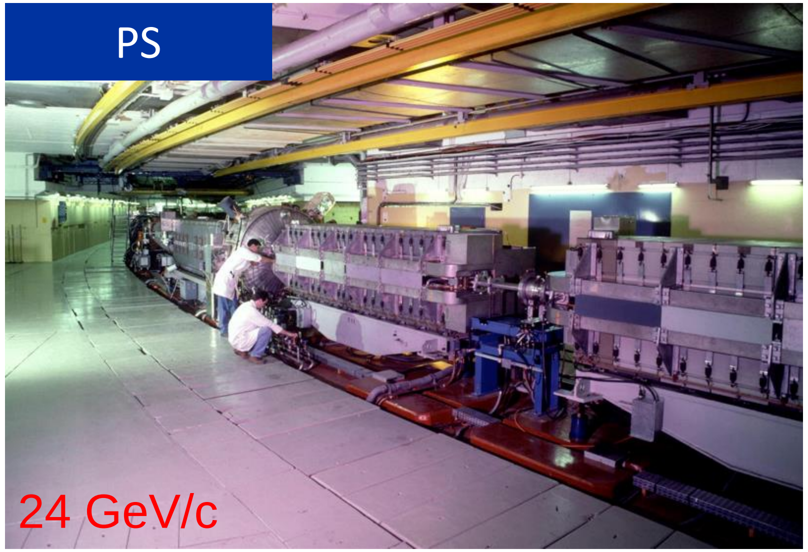


0.16 GeV/c

BOOSTER

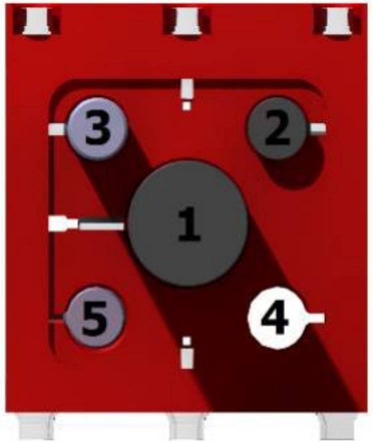
2 GeV/c

PS



24 GeV/c

East Area Multi-target



YOUR experiment!

What particles can we see in T9?

Targets and particle production

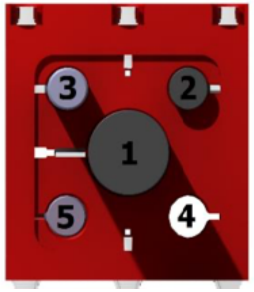
HADRON TARGET

Mainly Hadrons (p, π, K,..)

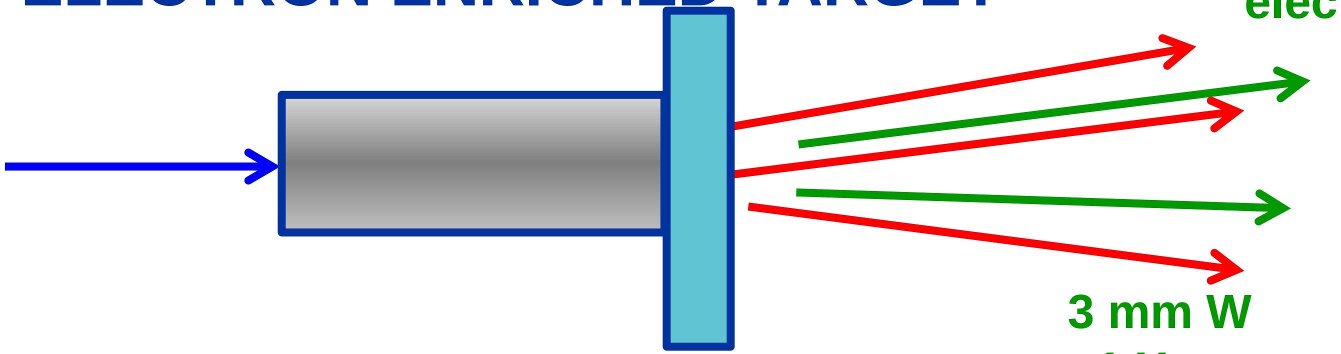
100-200 mm AL or BE, i.e. Low-Z material
Up to 1 L_{int} and 0.5 Xo

T9/T10/T11 Multitarget Configuration

Head	Material	Length (mm)	Diameter (mm)	Comments
1	Be	200	10 + Al case	Electron enriched
	W	3		
2	Al	100	10	Electron enriched
	W	3		
3	Al	200	10	Hadron
4	Air	-	-	Empty
5	Al	20	10	Hadron



ELECTRON ENRICHED TARGET



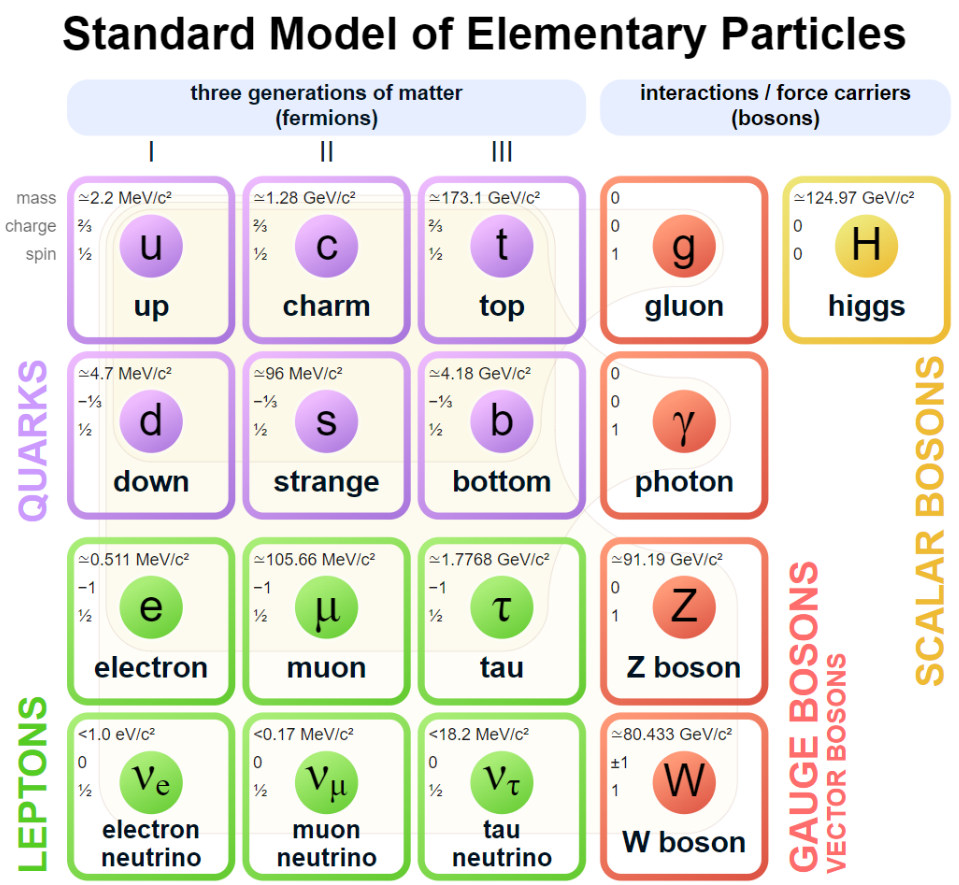
More electrons

3 mm W
+1 X_o to convert photons

π^+, π^-, π^o $\gamma + \gamma$ $e^+ + e^-$

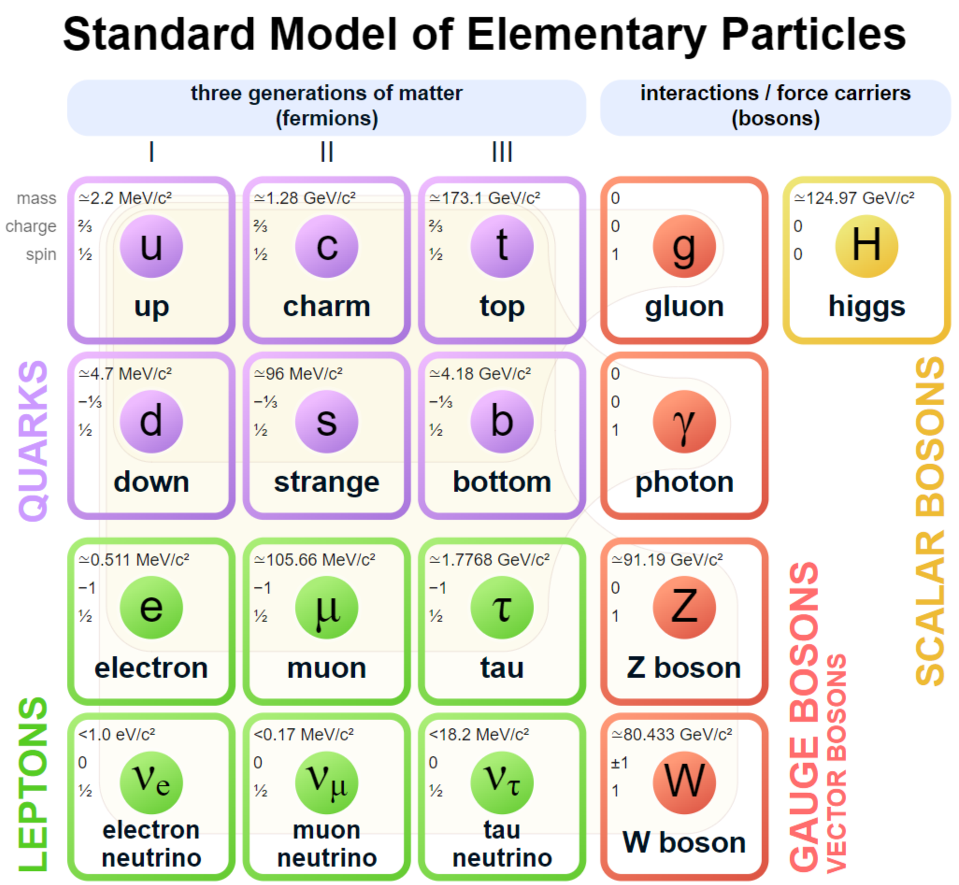
So, what comes out of the T9 target?

- **Let's combine what we have seen so far**
  - Mass, momentum and energy are equivalent
  - Energy scale expressed in GeV
  - 1 GeV ~ 1 proton mass
  - Secondary beams are made by smashing primary protons into a target
  - Primary protons used in the East Area carry 24 GeV/c
    - Fixed target experiment
    - *Only produce particles of much lower mass!*
- **Beams are steered with magnets**
  - Magnets only affect charged particles
  - Cannot make neutral particle beams in T9



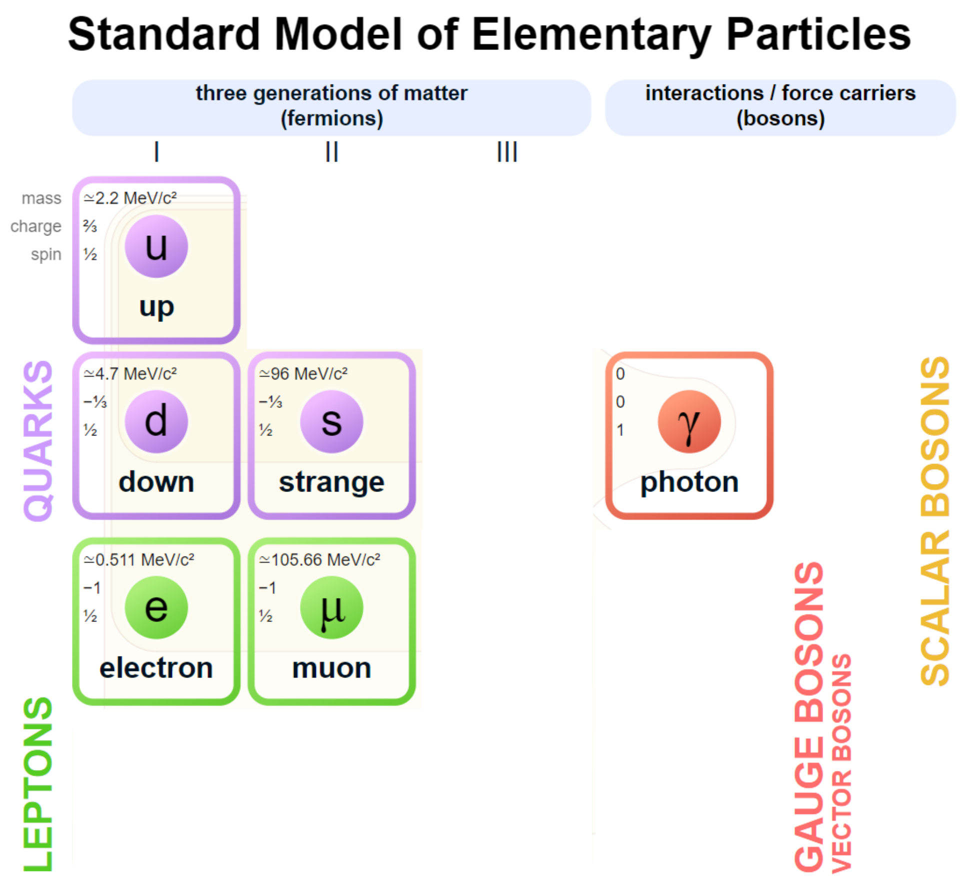
Now let’s edit the Standard Model a bit for T9

- **Keep only particles we will see in T9**
- **Boson sector**
  - Higgs, Z-boson and W-boson are too heavy
  - Gluon we cannot see
- **Quark sector**
  - Top, bottom and charm quarks are too heavy
- **Lepton sector**
  - Tau is too heavy
  - Neutrinos are (close to) undetectable



The final products

- **Hadrons (particles containing quarks)**
  - Mesons (two-quark particles)
    - Pions (ud), kaons (us)
  - Baryons (three-quark particles)
    - Proton (uud)
- **Leptons**
  - Electrons, muons
- **Photons produced when beam meets detector**
- **Neutral particles will not make it to T9 (magnets)**
  - Neutral kaons (ds)
  - Neutrons (udd)

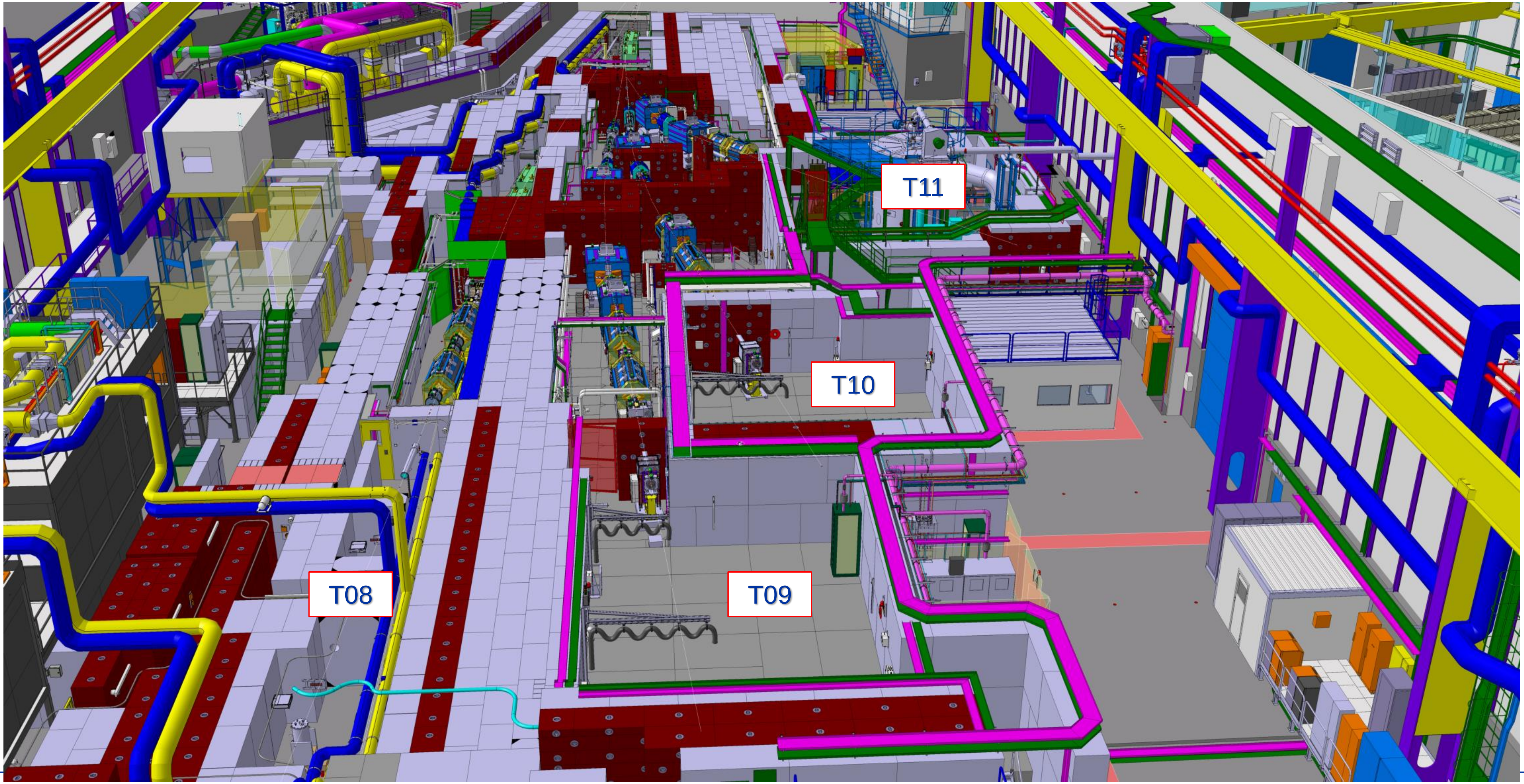


Targets and particle production

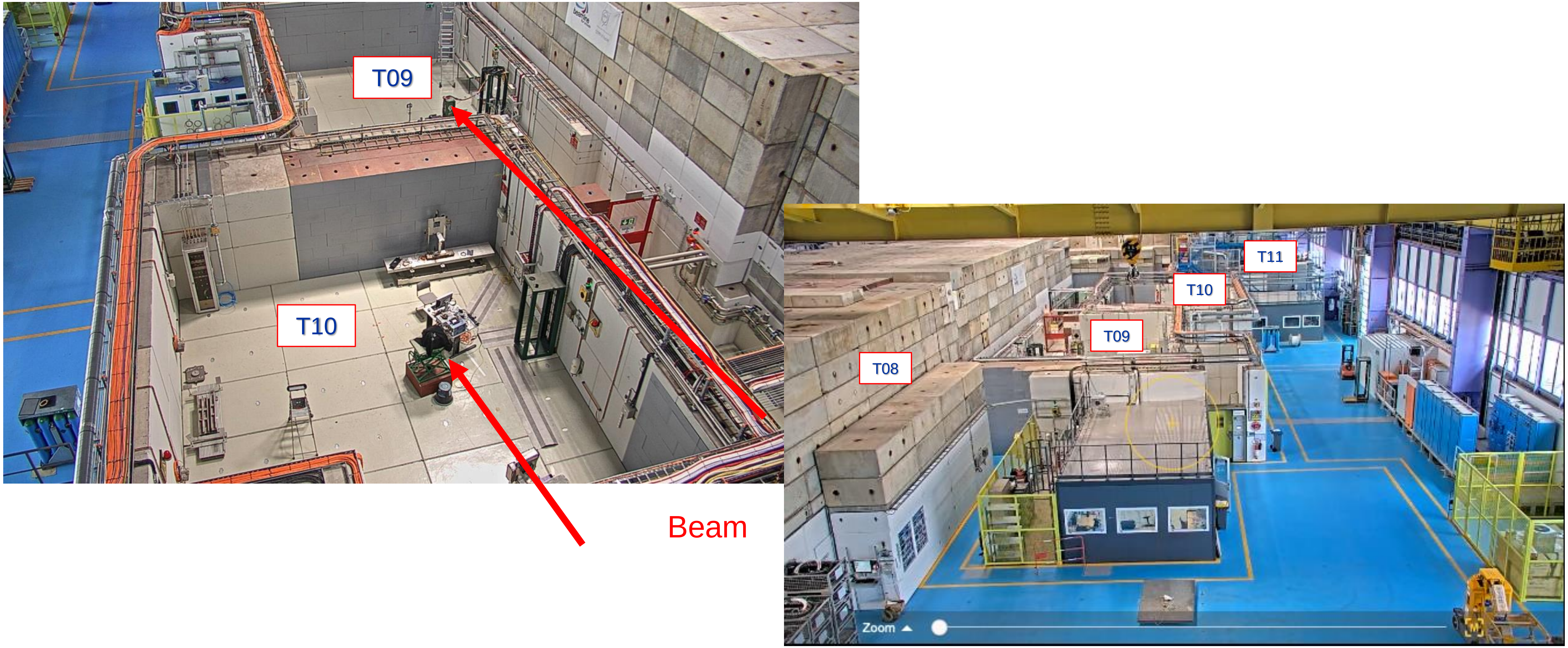
Category	Name	Symbol	Q	Mass [MeV/c²]	Mean life (τ) [s]	cτ [m]	Mean decay distance [m/GeV/c]	Decays
Leptons	Electron	e	±e	0.511	stable			
Leptons	Muon	μ	±e	105.6	2.2×10^{-6}	659.6	6.3×10^{3}	$\mu^+ \longrightarrow e^+ \bar{\nu}_e \nu_\mu$ (100%)
Hadrons / Mesons	Pion	π	±e	139.6	2.6×10^{-8}	7.8	56.4	$\pi^+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

(*) for 10 GeV/c

Layout of the East Area



Layout of the East Area



How do we build a beamline?

Beam lines

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

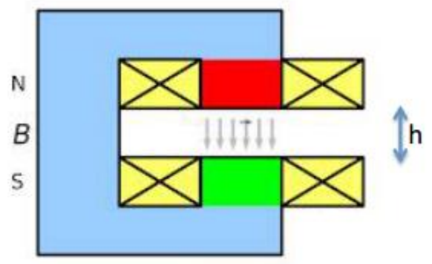
Secondary beam line - layout

Basic beam design

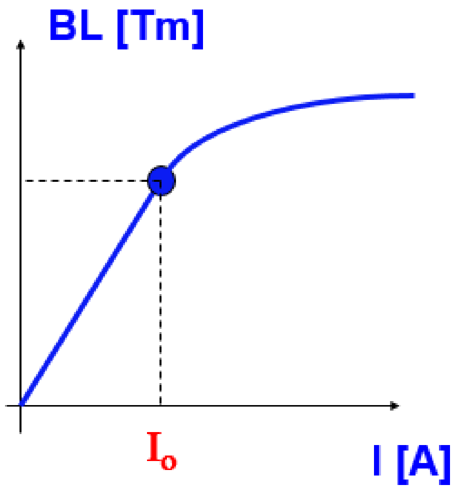
Transport and momentum selection: bending magnets

Dipole electro-magnets:

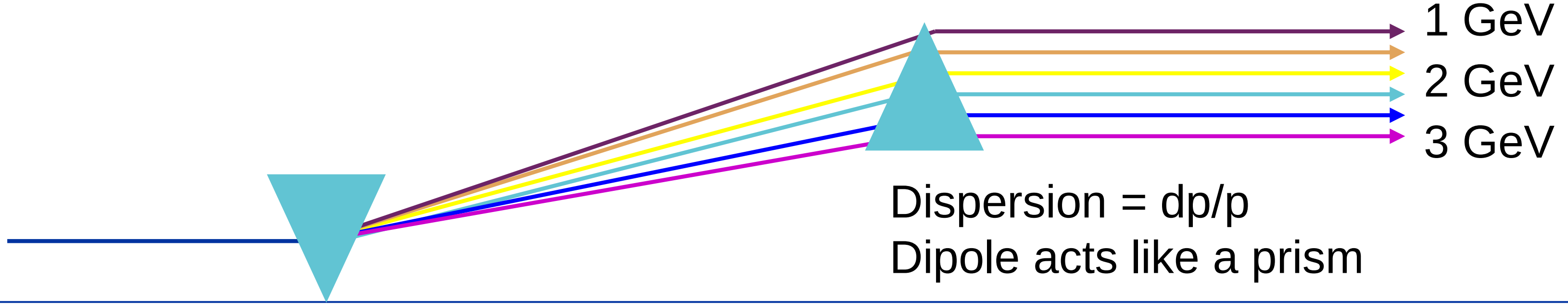
$$\vec{F} = q \cdot \vec{v} \times \vec{B}$$



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



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



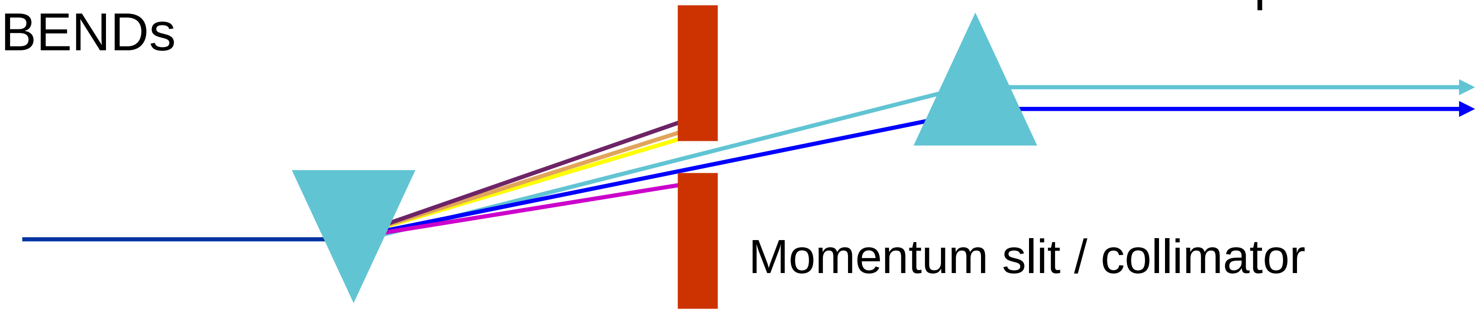
Dispersion = dp/p
Dipole acts like a prism

Secondary beam line - layout

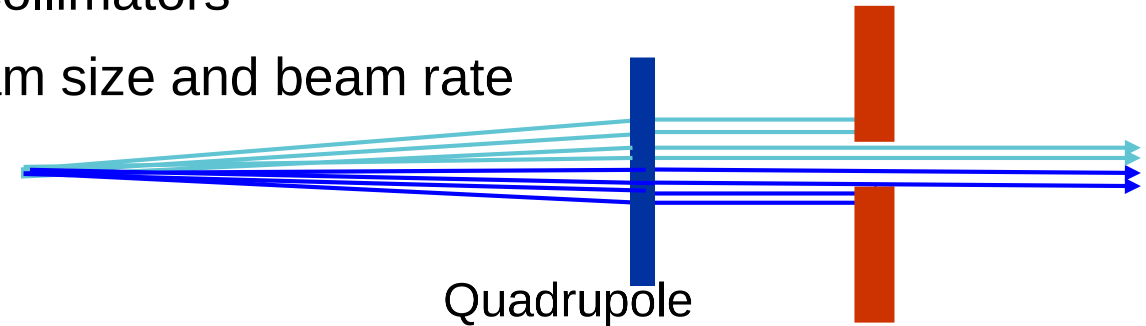
Basic beam design

Momentum selection and acceptance: collimators

- Select small momentum band in combination with dispersion from BENDs



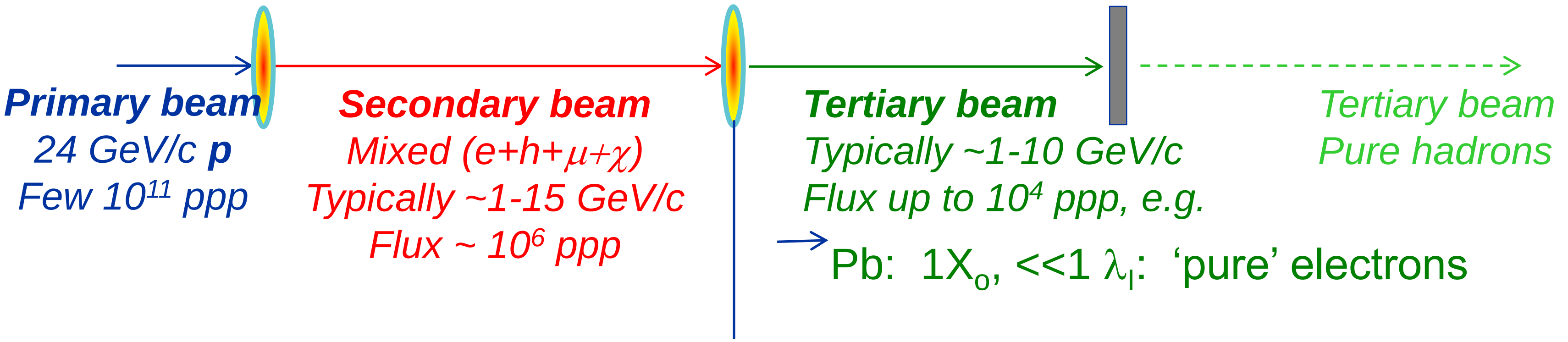
- Acceptance collimators
  - Select beam size and beam rate



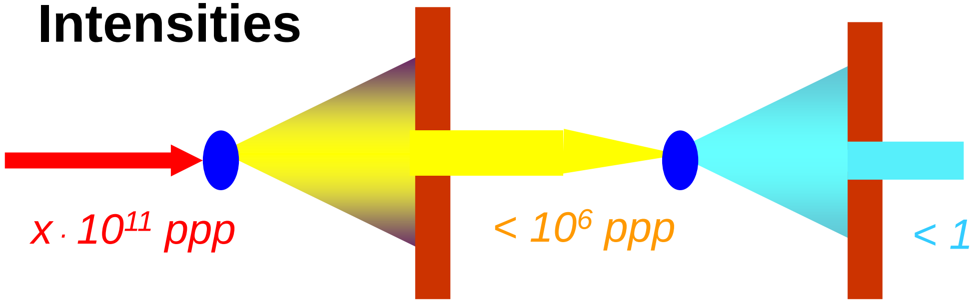
Secondary beam line - layout

Basic beam design

Selection of particle types

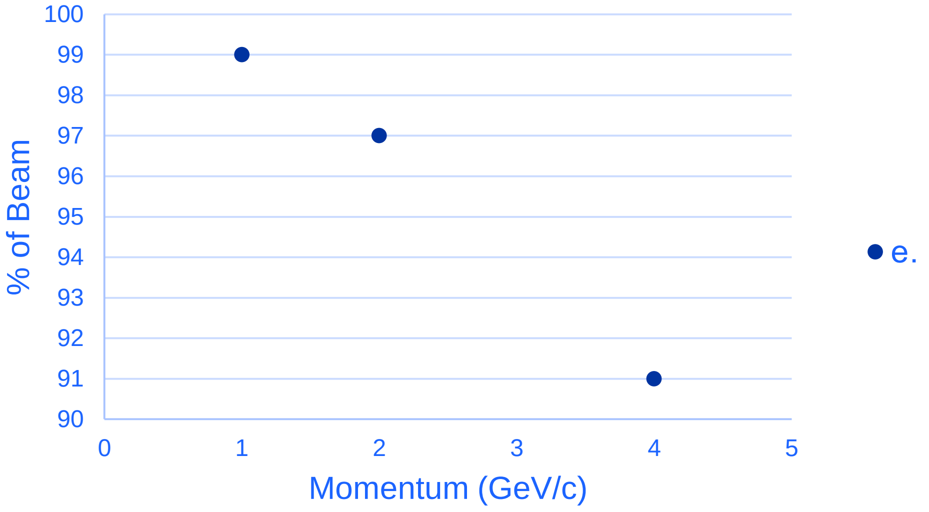


Intensities



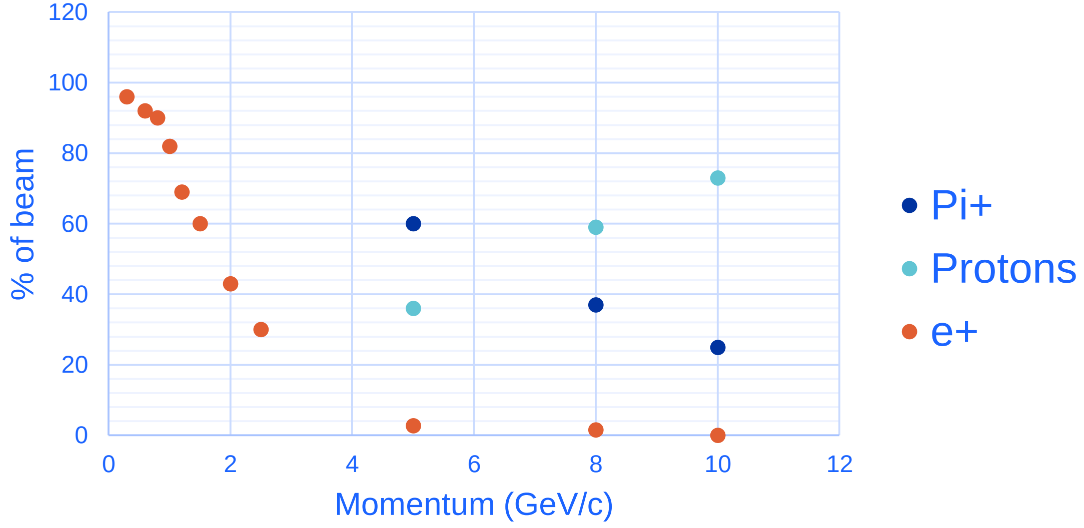
T9 Beam Modes available

- **Electron mode**
  - The charged particles from the secondary target are deflected away selecting the photons. A 5 mm Pb converts the photons into e+/e- pair.
  - Momenta 0.1 GeV/c – 4 GeV/c.
  - > 99% purity for p < 1 GeV/c



Only XCET available for beam composition data

- **Mixed hadron mode**
  - The secondary beam from protons on target can be chosen.
    - Momenta 0.1 GeV/c – 16 GeV/c.
    - At lower momenta electrons dominate.



So…what can we control in the beamline?

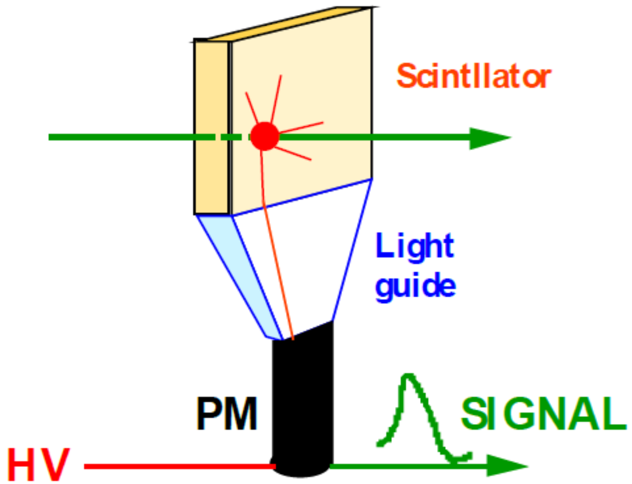
- **Choice of target**
  - More electrons, or more hadrons
- **Momentum of beam**
  - Absolute momentum (up to 16 GeV/c)
  - Spread of momentum (between 0.5% and 7.5% standard deviation around chosen momentum)
- **Particle content of the beam – hadrons, electrons or mixed**
  - Electron only beam (below 5 GeV/c ~90% pure, at 1 GeV/c ~99% pure) or hadron only
  - Tag particle species from beam with threshold Cherenkov counter (see later slide!)
- **Size and quantity of beam**
  - More or fewer particles extracted – between hundreds and millions per spill
  - Beam can be a few mm large, up to a few cm (standard deviation)

How do we see the beam?

Secondary beam line - Instrumentation

Scintillating Counter (XSCI)

- Charged particles produce light in scintillator
- Light collected and transported by light guide
- Coupled to photo multiplier tube (PM), light hits photocathode and produces electrons
- Electrons are amplified within a high voltage cascade
- Used to count particles in a range from a few particles up to rates of MHz
- Different shapes and sizes: Some can scan through a beam, other count the total rate

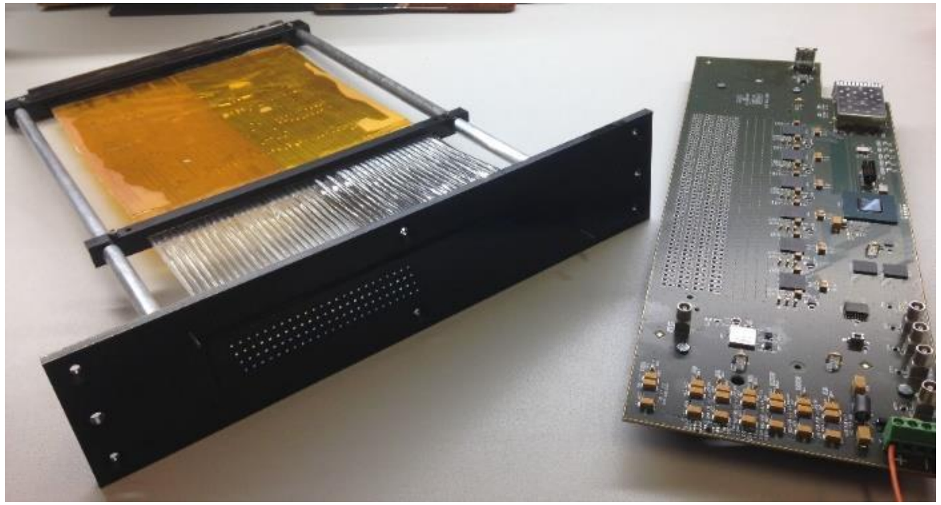


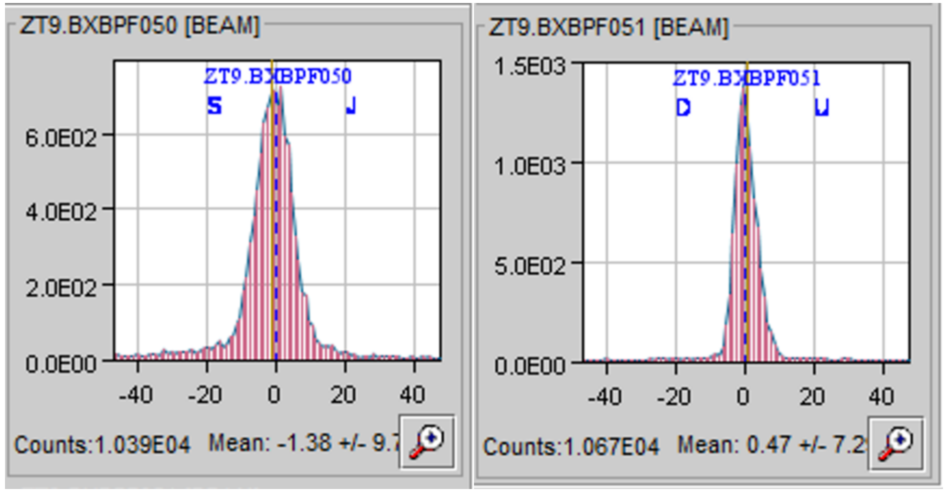
Secondary beam line - Instrumentation

Scintillating fibre hodoscopes (XBPF)

- Particle detection with scintillating fibres from the creation of scintillation light, due to the passage of a charged particle, and the transmission of this light inside the fibre by total internal reflection.

- Composed of 100 or 200 scintillating fibres of 1 mm thickness and square cross-section





Secondary beam line - Instrumentation

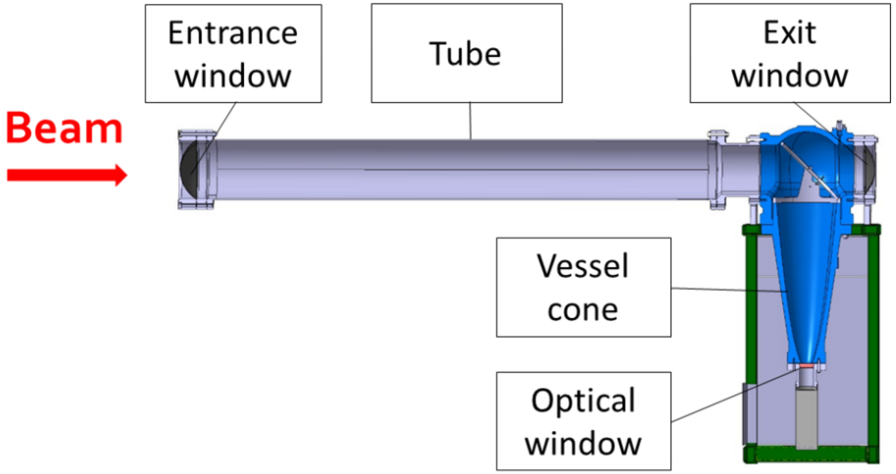
Threshold Cerenkov counters (XCET)

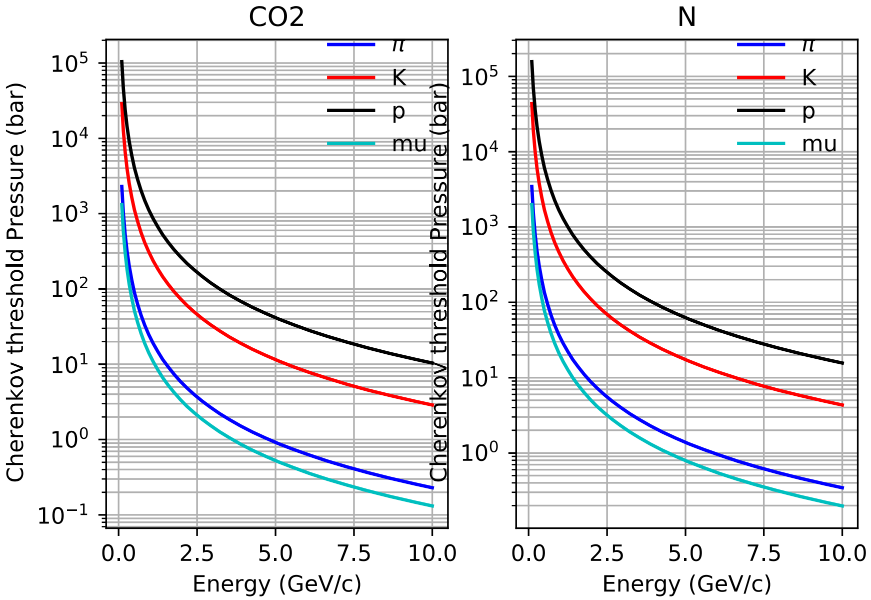
- In a medium (e.g., He or CO2 gas) if a charged particle goes faster than light it emits Cerenkov light in a cone with half-opening angle f:

$$f^2 = 2kP - m^2 / p^2$$

where k depends on the gas, P=pressure.

- By selecting the right operating pressure, one type of particle has good efficiency and the other gives no signal. By making a coincidence with scintillator signals, particle identification can be made.
- Two types of XCET in T09:
  - Low pressure → 0.01 – 4 bars
  - High pressure → 0.01 – 15 bars





Conclusion

- **Core concepts of the CERN beamlines**
  - GeV is everywhere!
  - Secondary beams are made by shooting primary protons on a target and collecting the resulting particles with magnets
  - In T9, most of the beam will be pions, kaons, muons and electrons

- **The user is in control of many of the beam aspects**
  - Particle type in beam, size of beam, momentum, intensity

- **We look forward to reading your proposals!**

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Beam composition

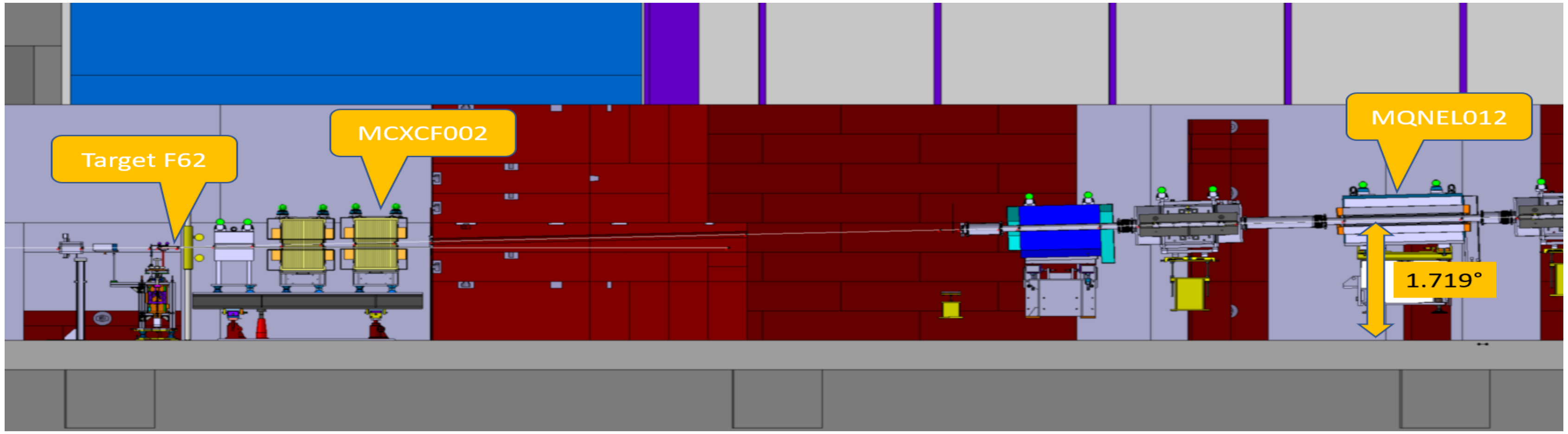
Useful numbers

- **Spill characteristics**
  - The beam will arrive to the T9 zone in “spills” – the beam is taken out of the PS and “spills” to the target
  - Spill length (= time over which particles come to you) is around 400ms
  - You will get 2-4 of these every minute (conditions not static, dependent on other users)
  - Content of the spill is between a few hundred and a few million particles

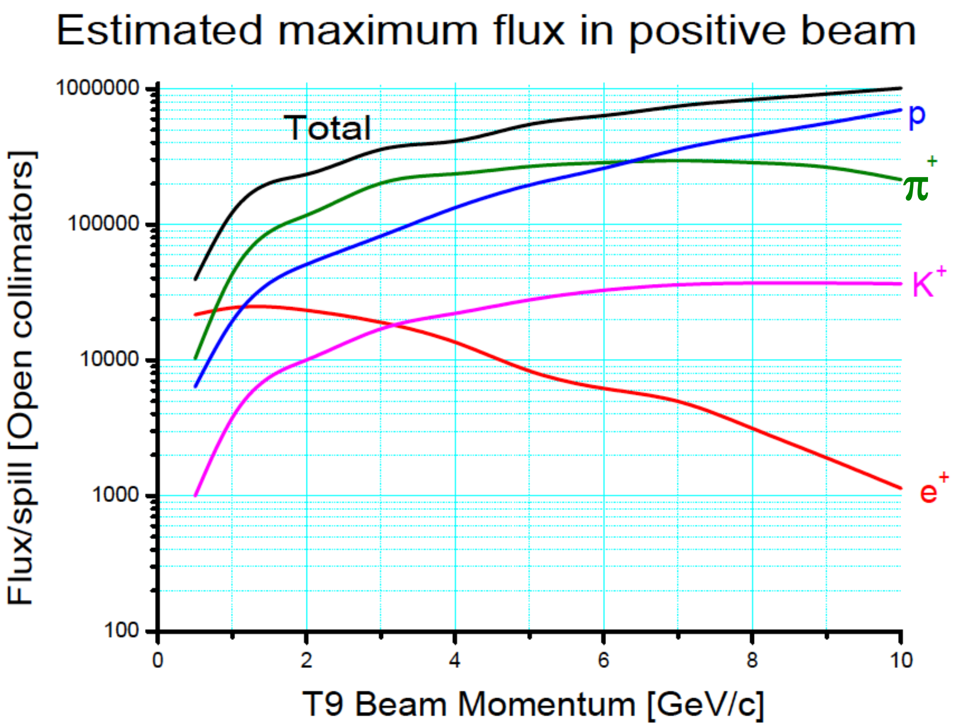
Characteristics of the East Beams

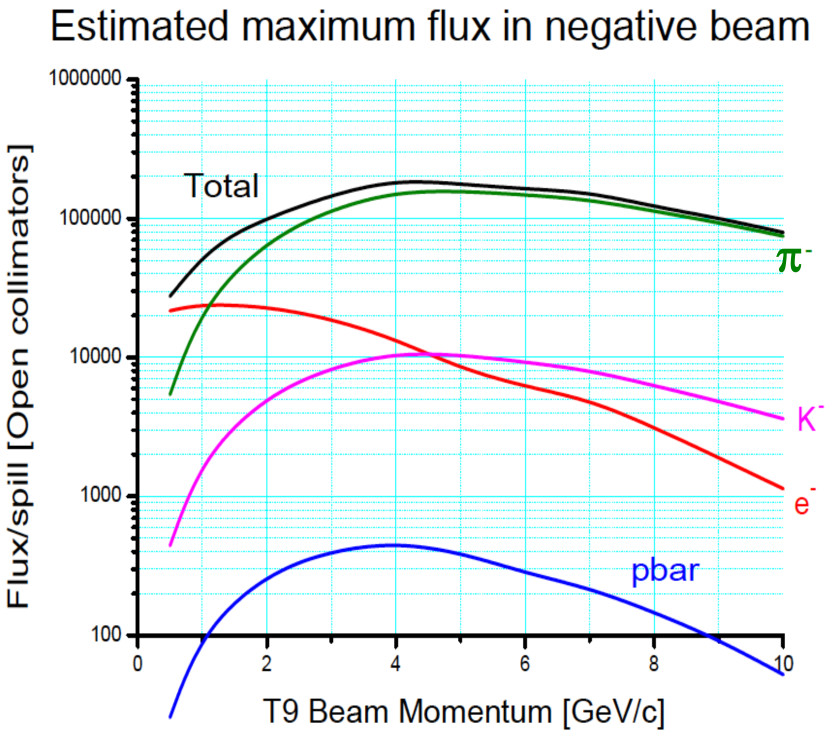
Parameter	T09 Target	T10/T11 Target	
Beam Line	T09	T10	T11
Secondary beam Max Momentum (GeV/c)	16	12	3.5
Δp/p (%)	±0.7 to ±15.0	±0.7 to ±15.0	±0.7 to ±15.0
Maximum intensity/spill (hadrons/electrons)	10^6	10^6	10^6
Available particle types	Pure electrons (T09) or mixed/pure hadrons or pure muons		

30-35 mrad vertical production angle



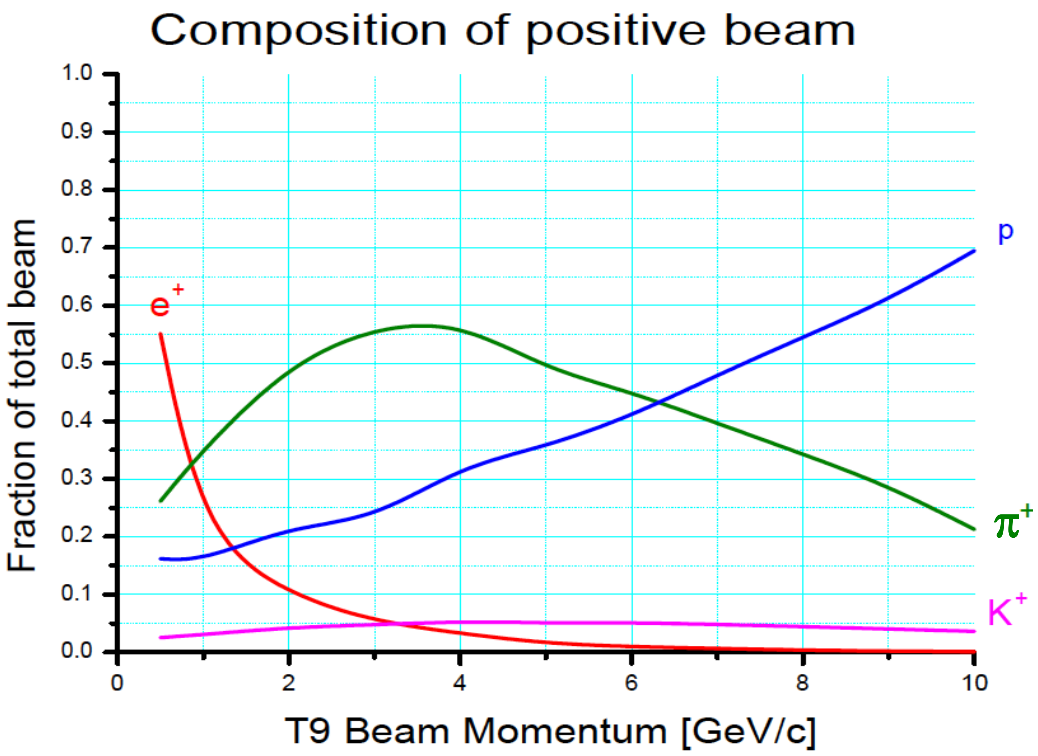
Beam rates

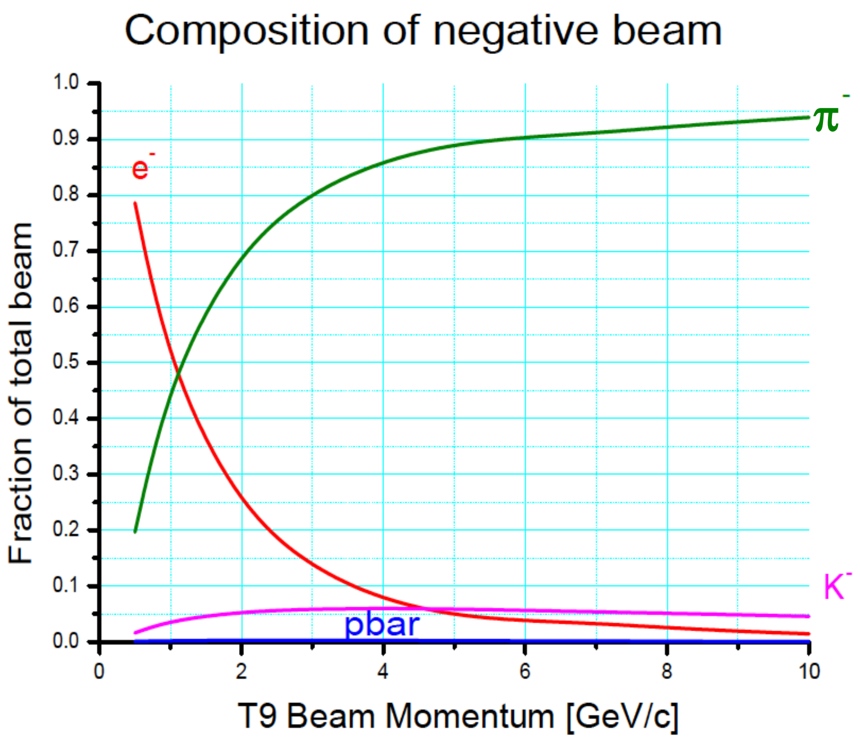




For wide open collimators, i.e. dp/p ≈ ±7.5% (Theoretical Calculation)

Beam composition





With electron enriched target (otherwise $e^{\pm}$ strongly reduced) (Theoretical Calculation)