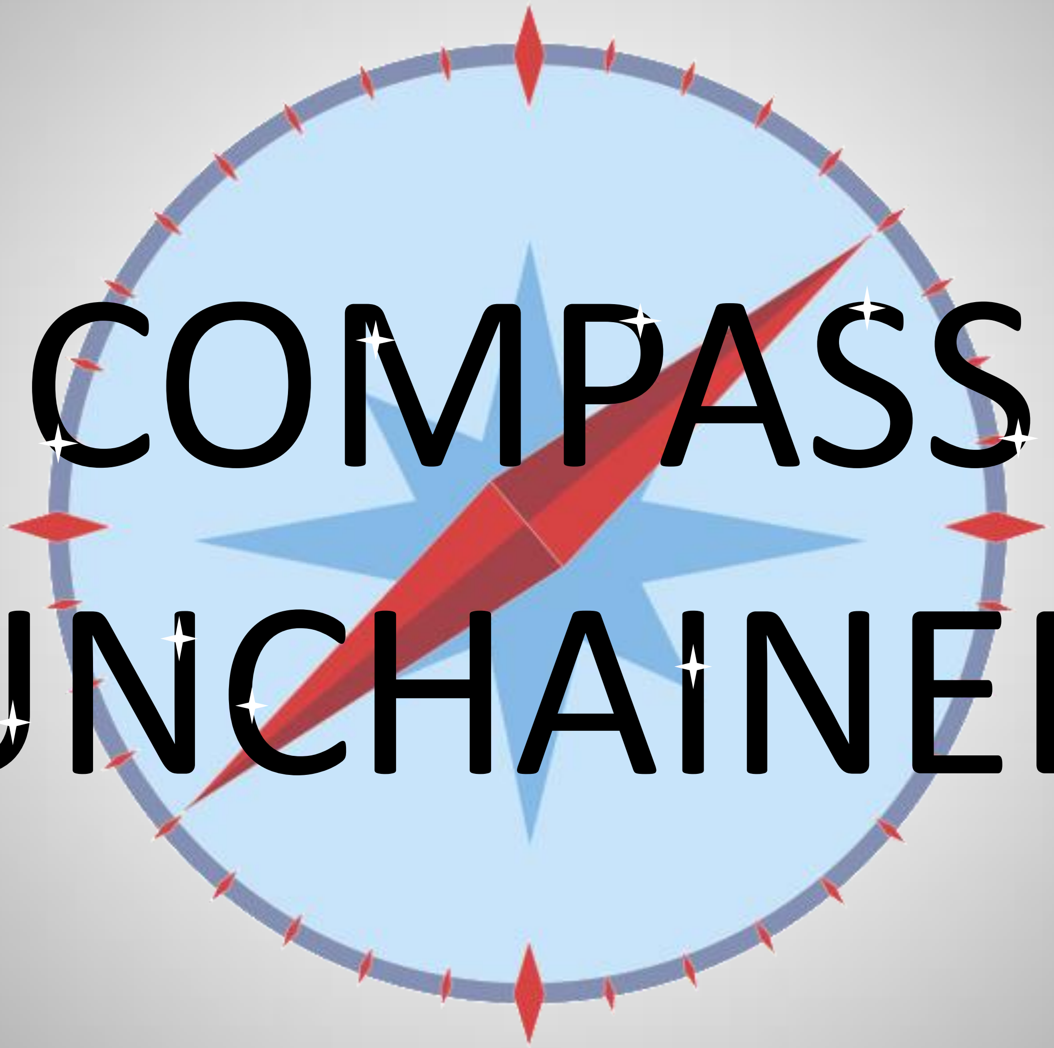


COMPASS UNCHAINED

most slides from E. Bielert, A. Bressan, F. Kunne, G.Mallot

A few processes and the detectors needed

- Spin asymmetry of DIS cross sections

→ Need polarized beams and polarized targets

- Gluon spin contribution to nucleon spin,

via photon gluon fusion → charmed mesons → π K pairs

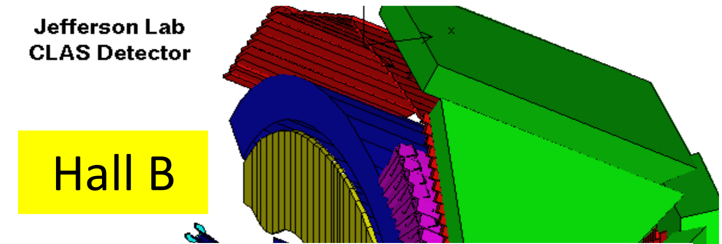
Need kaon identification

- Strange quark spin contribution to nucleon spin, via kaon production (K=u-sbar)

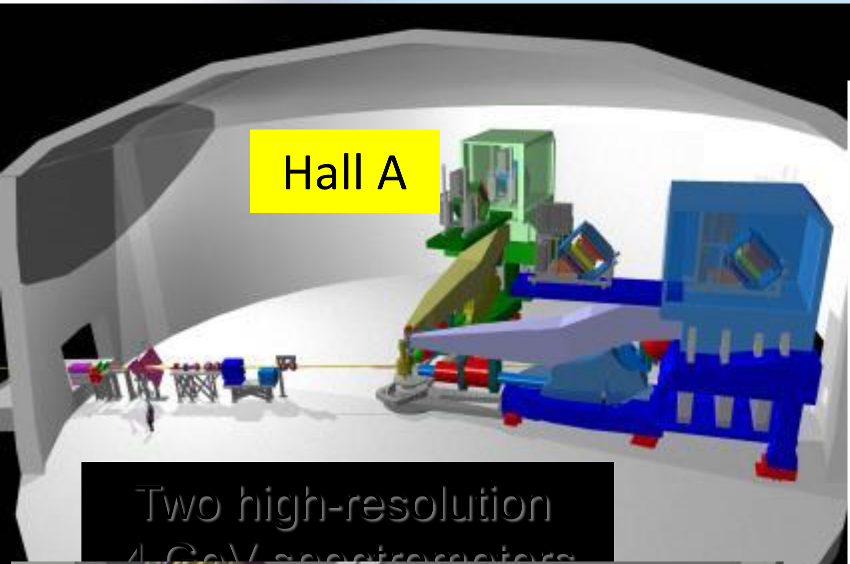
Need kaon identification

- Exclusive reactions, like Pion polarisability, 3D structure of the nucleons: Need photon detection, recoil proton detection around the target, need full Monte-Carlo description of apparatus

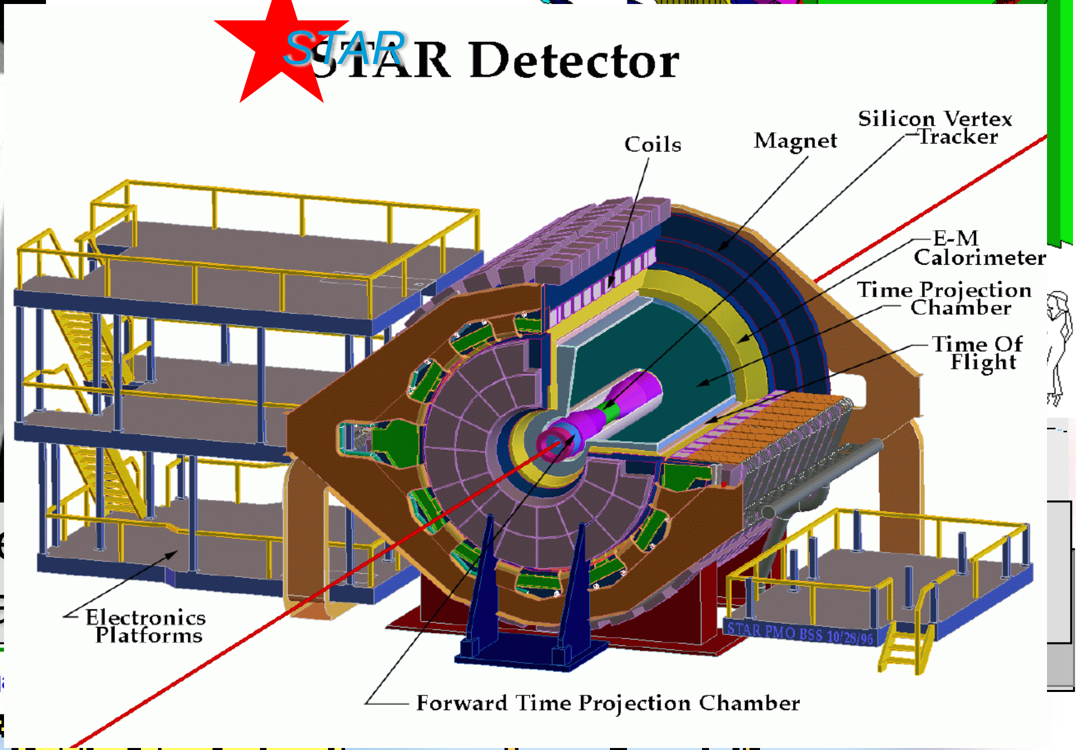
Who are the players?



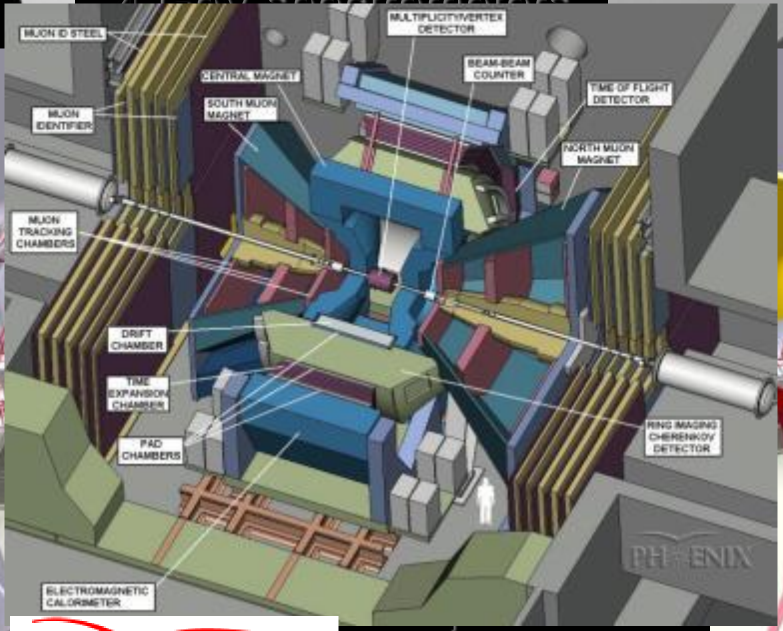
Hall B


Hall A

Two high-resolution
4 GeV spectrometers


STAR Detector

Be
Ta



PHENIX

Beams: 250 GeV pp; <60>% polarization
Lumi: 1.2 $10^{31} cm^{-2} s^{-1}$

COMPASS (NA58 CERN experiment):

COmmon

Muon

Proton

Apparatus for

Structure and

Spectroscopy

- ~ 230 members
- 13 countries
- 28 universities and research institutes

COMPASS is the ***largest surface experiment*** at CERN

COMPASS – some facts

- Located at CERN North Area beam line
- **Possible beams: μ^+, μ^-, π^+, π^-, K → Several physics programs**
  - 1996: COMPASS proposal
  - 2001: commissioning run

- Experiments with muon beam
- Experiments with hadron beams

COMPASS - I (2002 – 2011)

Nucleon spin structure:
  - Gluon polarization
  - u,d,s quark flavor decomposition of the nucleon spin
  - Transverse spin
  - Quark transverse momentum

- **Pion polarizability**
- **Search for exotic states:**
  - Light meson spectroscopy
  - Baryon spectroscopy

COMPASS - II (2012 – 2018)

'3D' structure of the nucleon (DVCS)

Quark transverse momentum distribution

Strangeness in the nucleon

- **Pion and kaon polarizabilities**
- **Universality of transverse momentum distribution**-polarized Drell-Yan

COMPASS – some facts

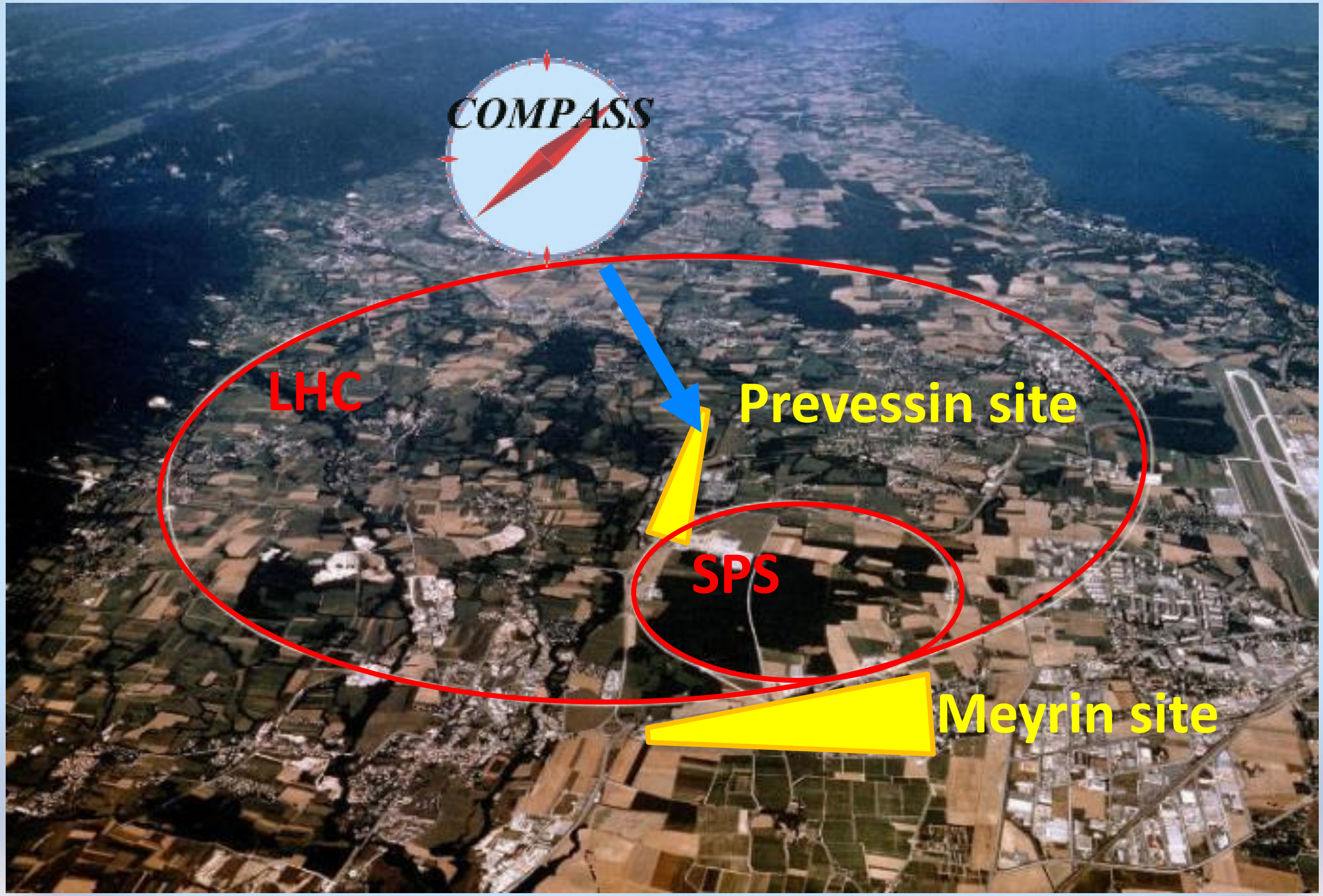
- **Targets**

Experiments with muon beam	Experiments with hadron beams
COMPASS - I (2002 – 2011)	
Nucleon Spin structure	Hadron spectroscopy
p, d polarized target (L & T)	**40cm LH2 or nuclear targets**
COMPASS - II (2012 – 2017)	
Unpolarised (3D, strangeness …)	Polarized Drell-Yan studies
2.5m long LH2 target	**Polarized target (T)**

Reconfigurable target region - versatile experimental setup

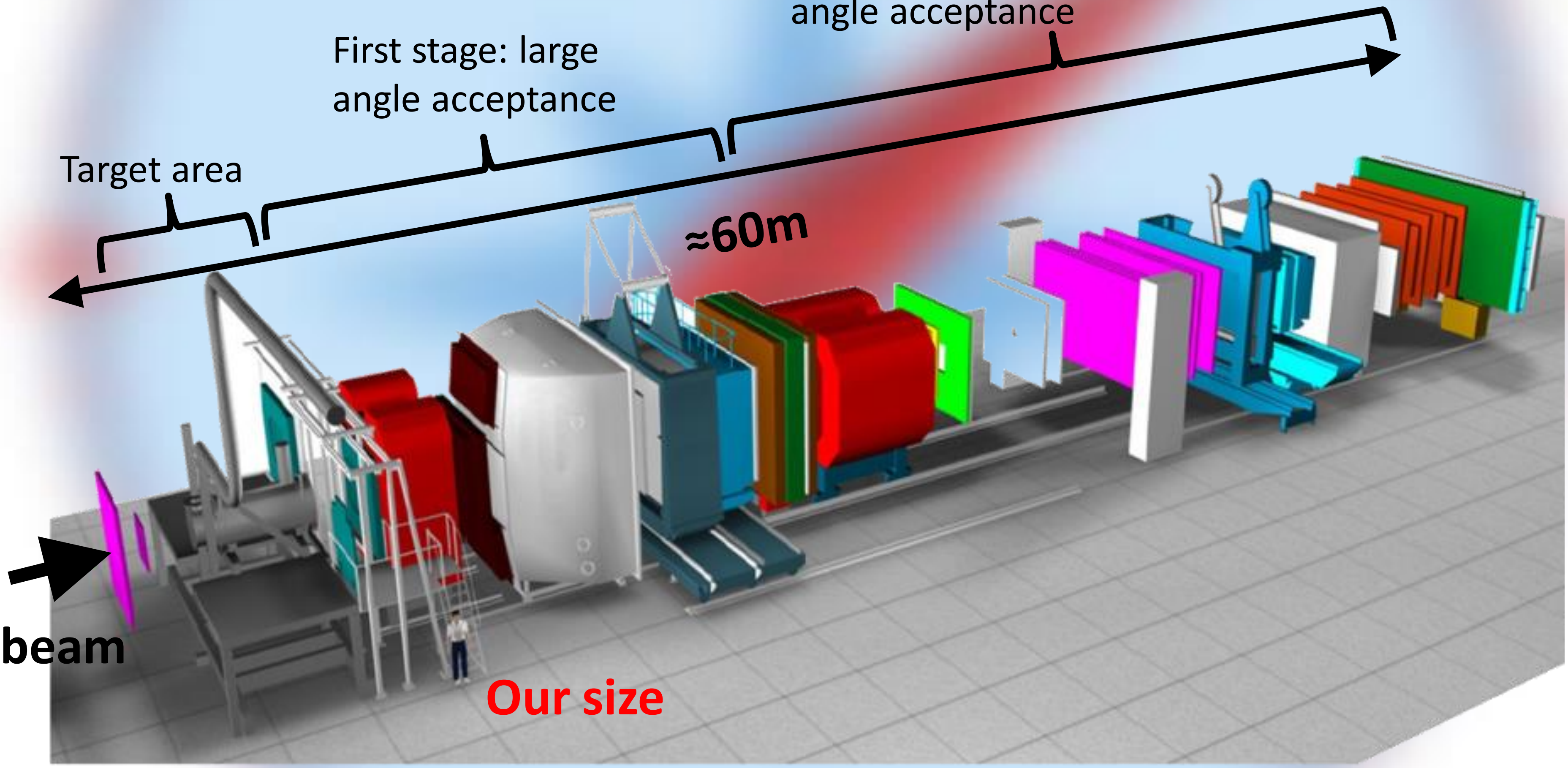
Where is COMPASS located? View from SW

SPS experiment in the North Area at the CERN Prevessin site



What does COMPASS look like?

Flexible fixed-target experiment, two-stage forward large-angle spectrometer



Second stage: small angle acceptance

First stage: large angle acceptance

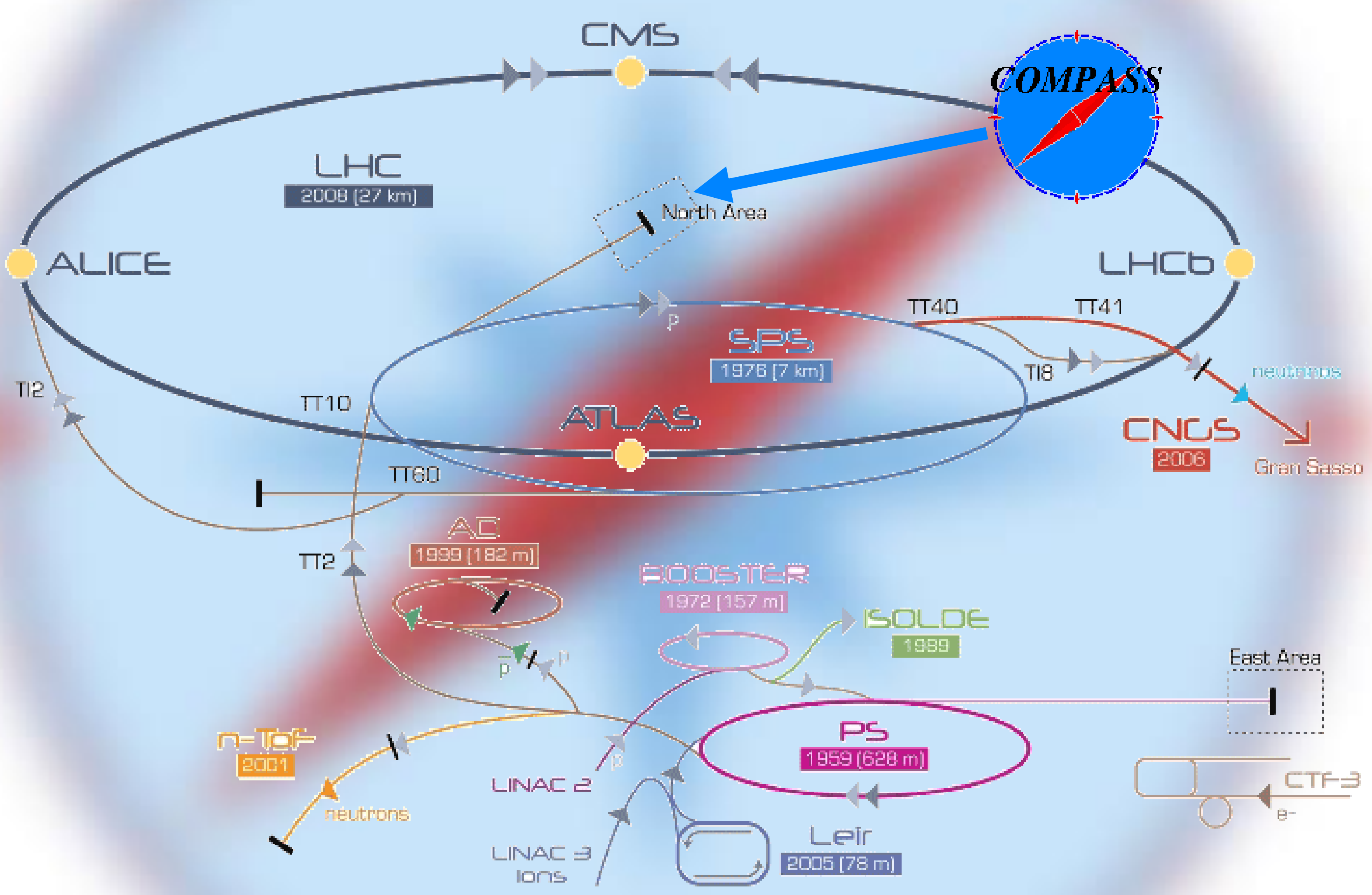
Target area

≈60m

beam

Our size

Where does the COMPASS beam come from?



Types of beams

The beam line can be operated in three different modes, resulting in the desired type of beam:

- **Hadrons:** $p<280$ GeV/c (limited by magnet strength)
  $<10^{8}$ hadrons/SPS cycle at COMPASS
  spot size: ≈3x3 mm
  π, K, p
- **Muons:** $p=60\text{-}190$ GeV/c
  $1.2\cdot10^{13}$ protons/SPS cycle on T6 target
  $2\cdot10^{8}$ muons/SPS cycle at COMPASS
  note: about 1 muon per 100,000 protons!
  spot size: ≈8x8 mm
- **Electrons:** special case: tertiary beam ($p=40$ GeV/c, $1\cdot10^{3}$ *e*/s)

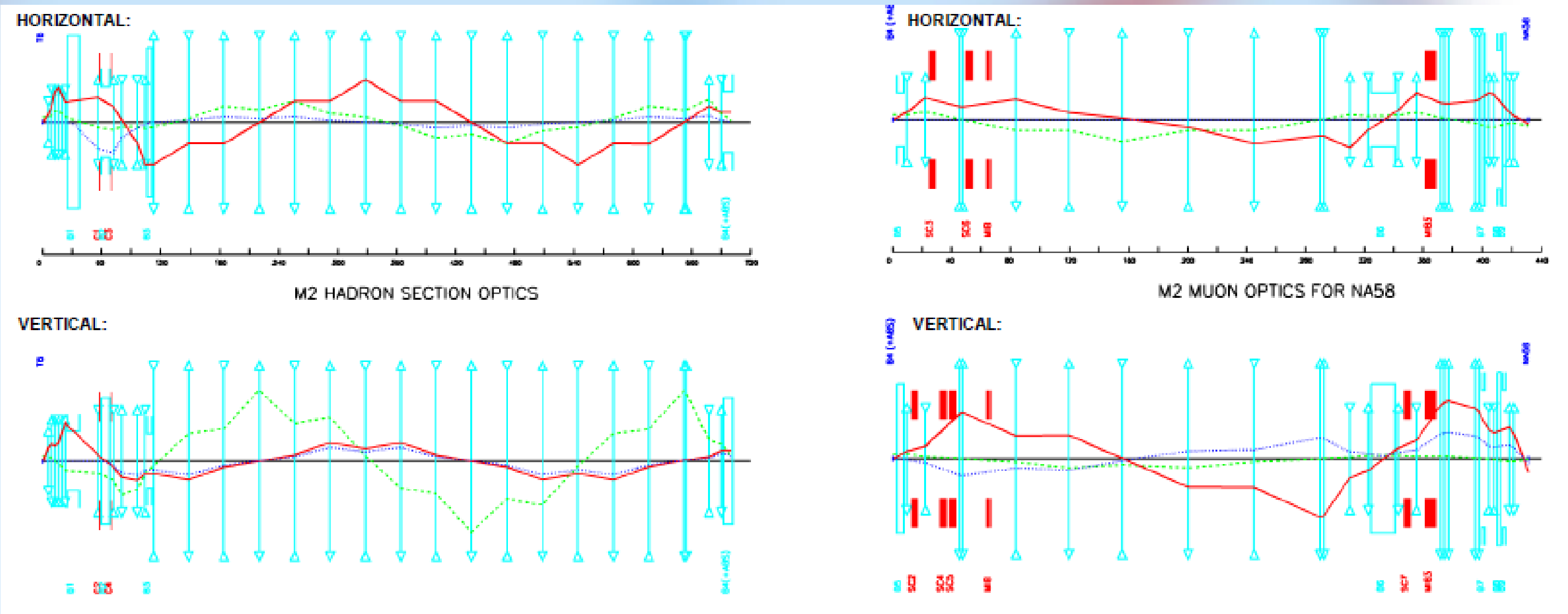
Beam optics

Hadron beam

Muon beam

horizontal

vertical



Alternating sequence of focussing and defocussing quadrupole magnets. When a quadrupole is focussing in the horizontal plane, it is defocussing in the vertical plane (and vice versa).

Making the beam

- ~1.1 km long beamline from SPS to the experiment
  Normal conducting quadrupoles to focus,
  and dipoles to guide the beam from the SPS to COMPASS
- SPS 400 GeV protons interact with a primary target (500 mm long beryllium) creating mainly pions and kaons
- About 10% of these pions and kaons decay along a 700m long line producing muons
- A ~10 m long beryllium absorber filters the rest of the beam and only muons are left
- The muon beam is naturally polarized due to parity violation in the weak decay of the spinless pion

Some facts

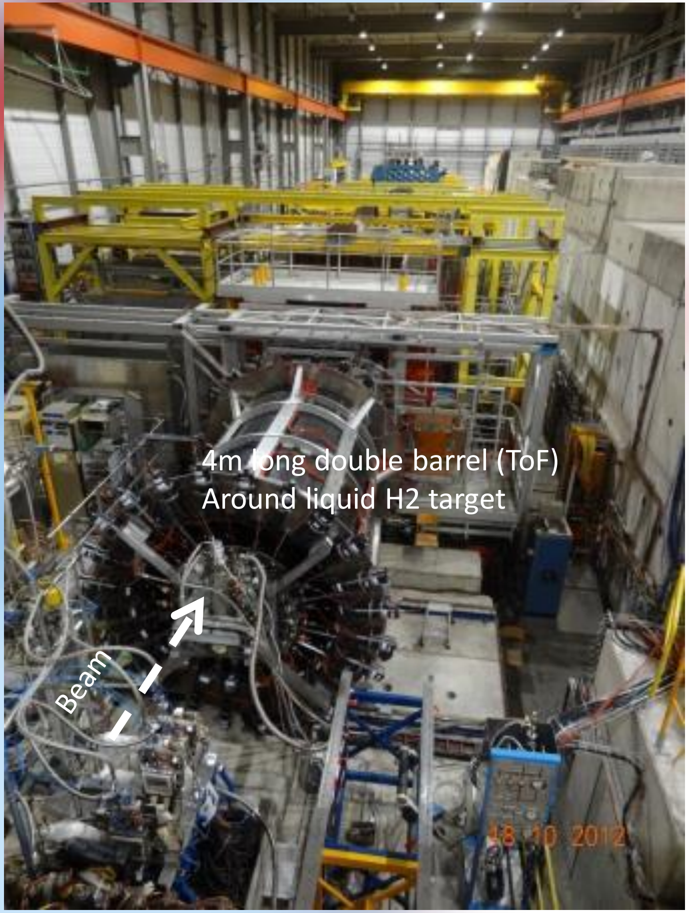
- Quadrupole magnets: about 10 tons, 150V, 750A, 113kW
- Dipoles magnets: about 25 tons, bend the beam up with an angle smaller than 2 degrees
- The ionisation chamber monitors beam intensity. Capacitive plates measure induced charge.
- The primary beam from the SPS has an energy of 1.6 MJ/spill

The target area

Different targets are used depending on the physics goals:

- Solid materials (carbon, copper or lead)
- Liquid hydrogen
- Polarized target (^{6}LiD or NH_3)

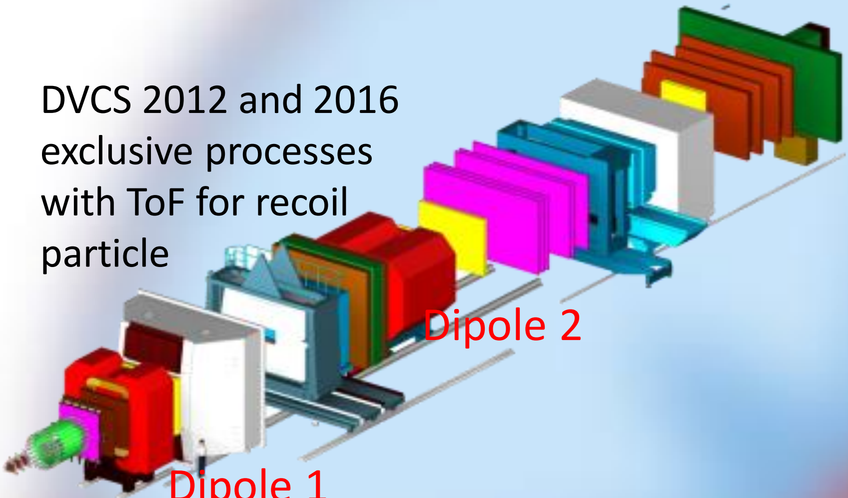
Plateform for 2m long superconducting solenoid for polarized target



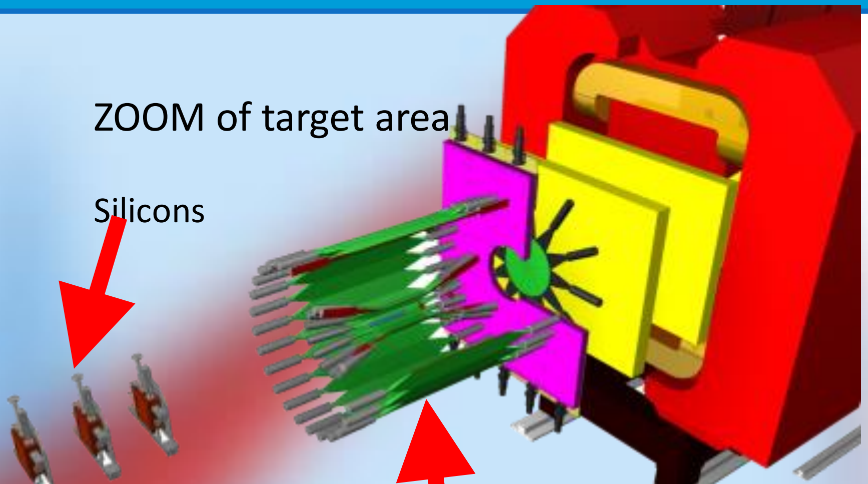
4m long double barrel (ToF) Around liquid H2 target

Flexible target area

DVCS 2012 and 2016
exclusive processes
with ToF for recoil
particle



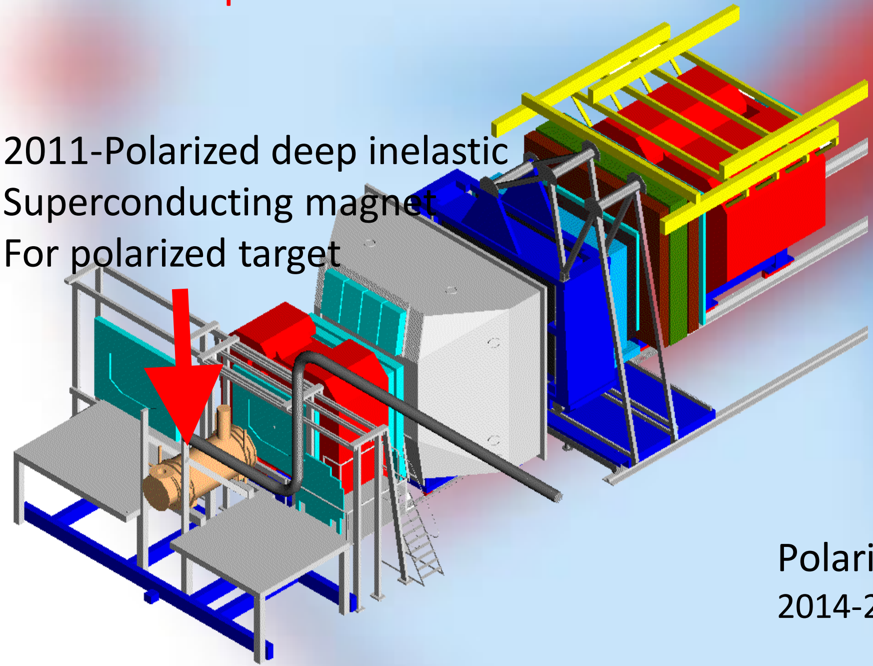
ZOOM of target area



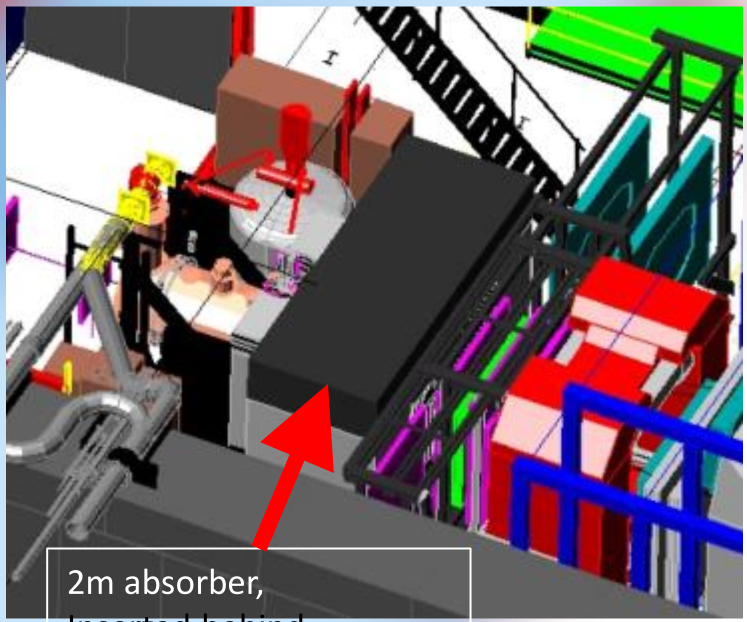
Silicons

ToF double barrel: Recoil Proton Detector

2011-Polarized deep inelastic
Superconducting magnet
For polarized target



Polarized Drell-Yan
2014-2015



2m absorber,
Inserted behind
polarized target magnet

Liquid hydrogen target

The hydrogen target contains about 5 l of liquid at a temperature of about 20K. When the target is warmed up to room temperature, five 1000 l tanks are needed to store the hydrogen gas.

Polarized target

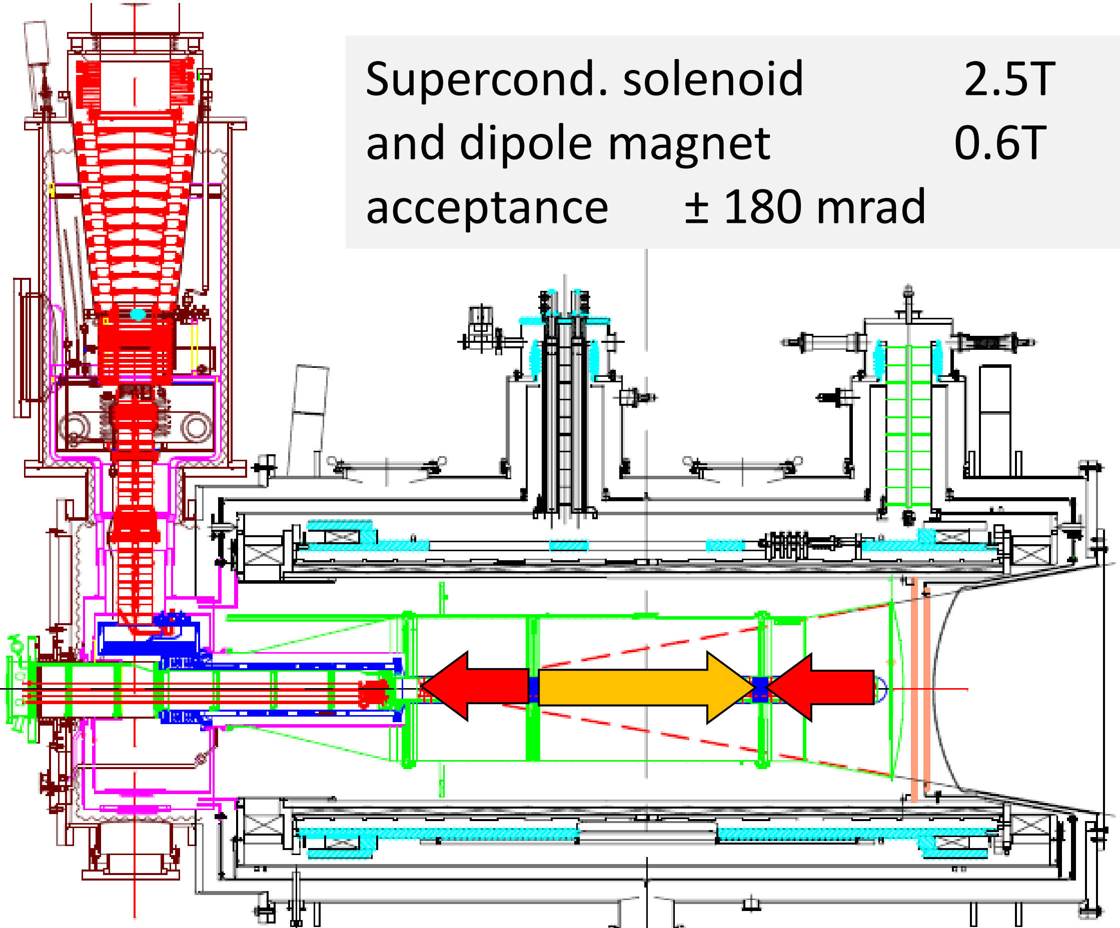
- 1.2 m long, 40 mm diameter, 5-6 l
- Temperature ~50mK with a record of 30 mK
- ^{6}LiD, deuterated lithium – deuterium acts as target
- NH_3 ammonia – hydrogen acts as target
- Polarization is obtained by Dynamic Nuclear Polarization
- Three things are needed: high magnetic field to align the spins, a very low temperature to reduce thermal energy and microwaves to transfer spin from the electrons to the nucleons
- A 2.5 T solenoid field is applied by a superconducting magnet with a 10^{-4} homogeneity over the target volume

Polarized target system

^{3}He – ^{4}He dilution
refrigerator (T~50mK)

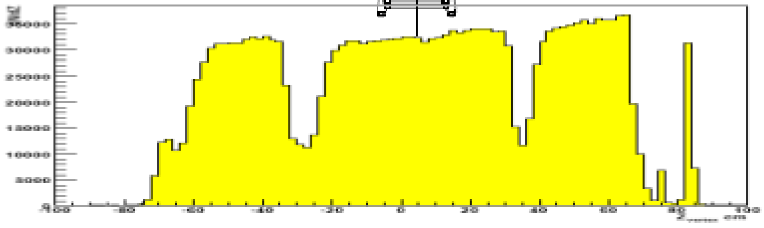
^{6}LiD/NH$_3$ (d/p)
50/90% polarization
40/16% dilution factor

µ

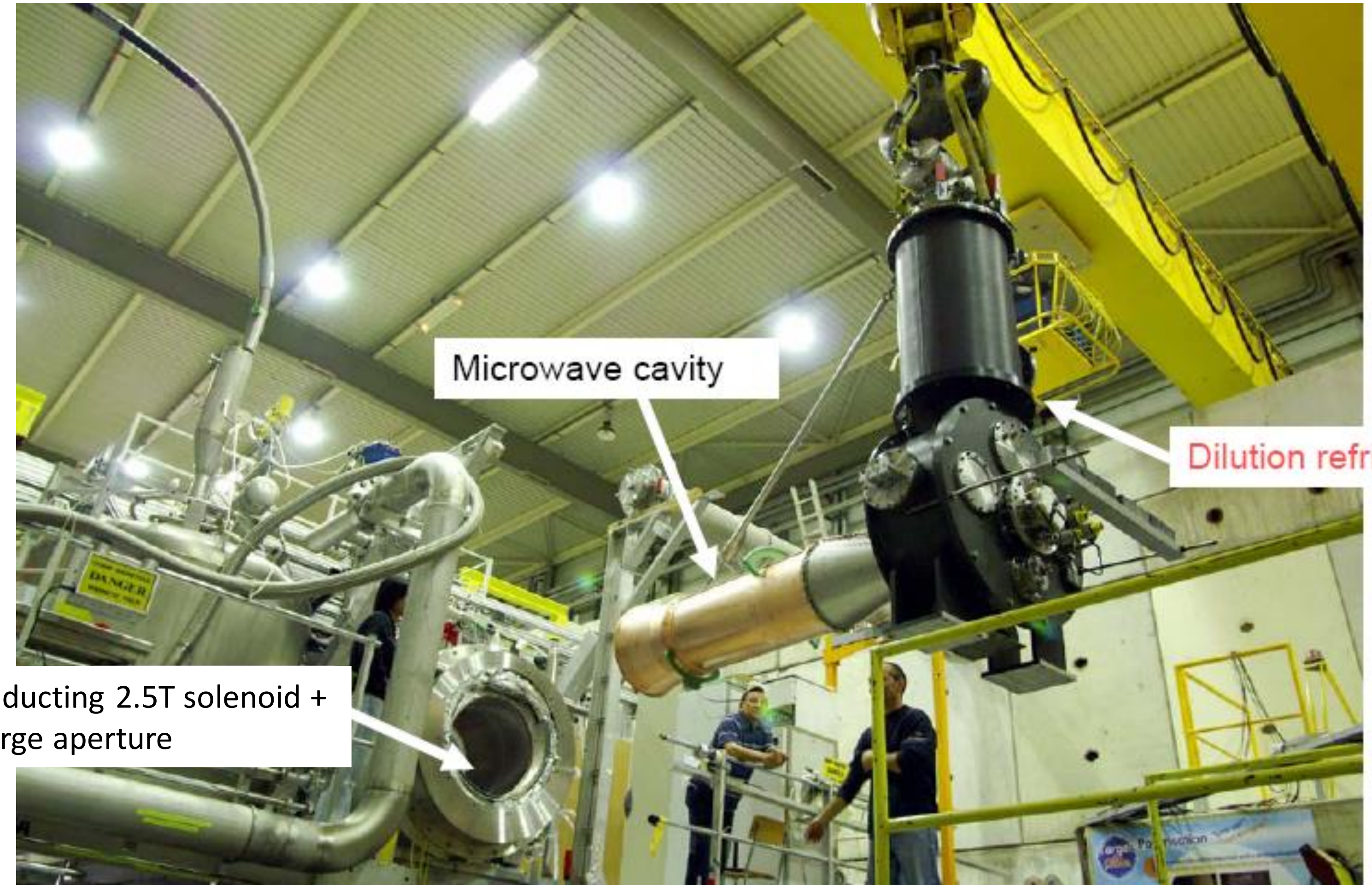


Supercond. solenoid 2.5T
and dipole magnet 0.6T
acceptance ± 180 mrad

Recontructed interaction vertices



Polarized target system

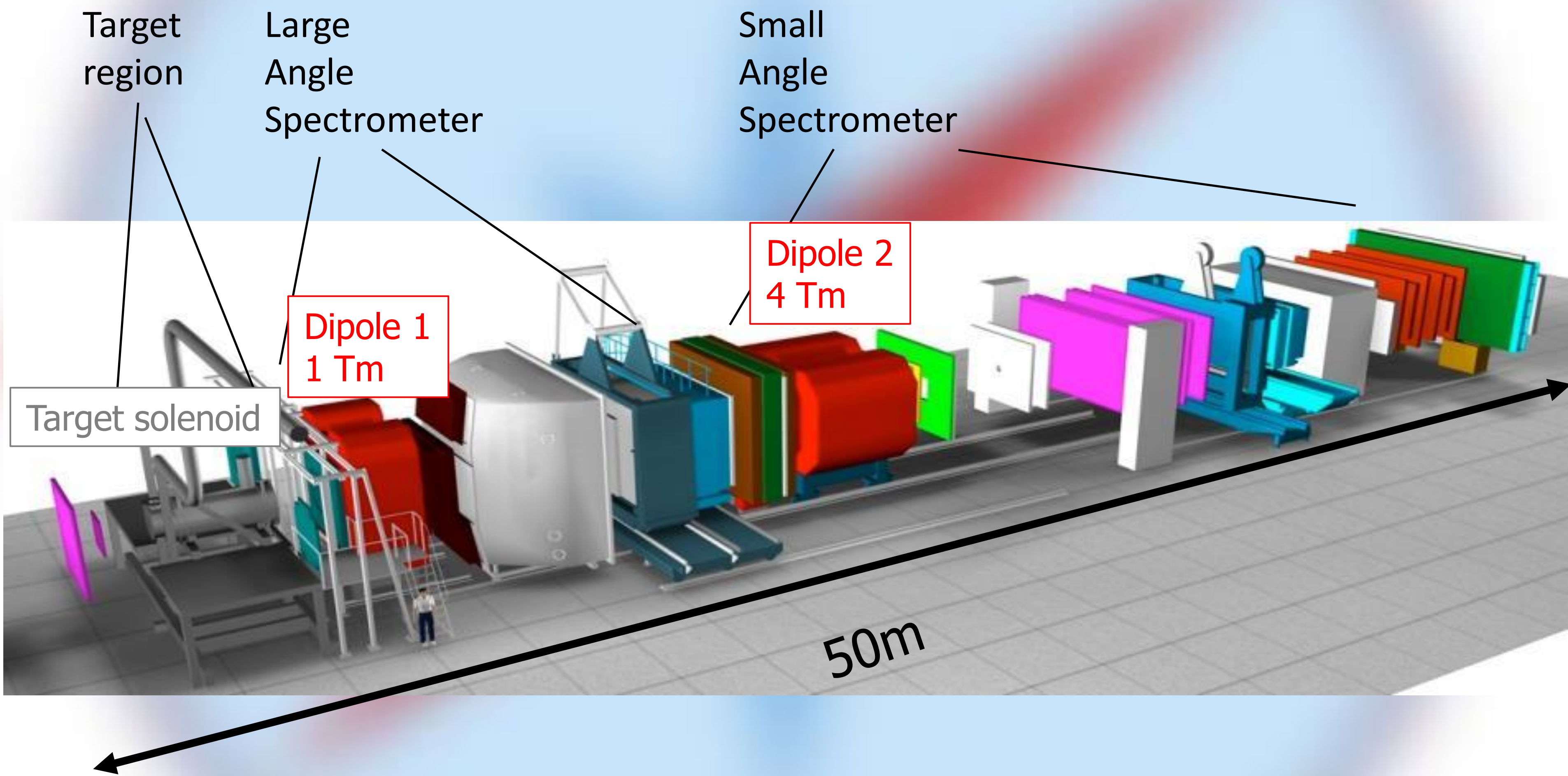


Microwave cavity

Dilution refrigerator

Superconducting 2.5T solenoid + dipole, large aperture

The COMPASS setup – Three main parts



Target region

Large Angle Spectrometer

Small Angle Spectrometer

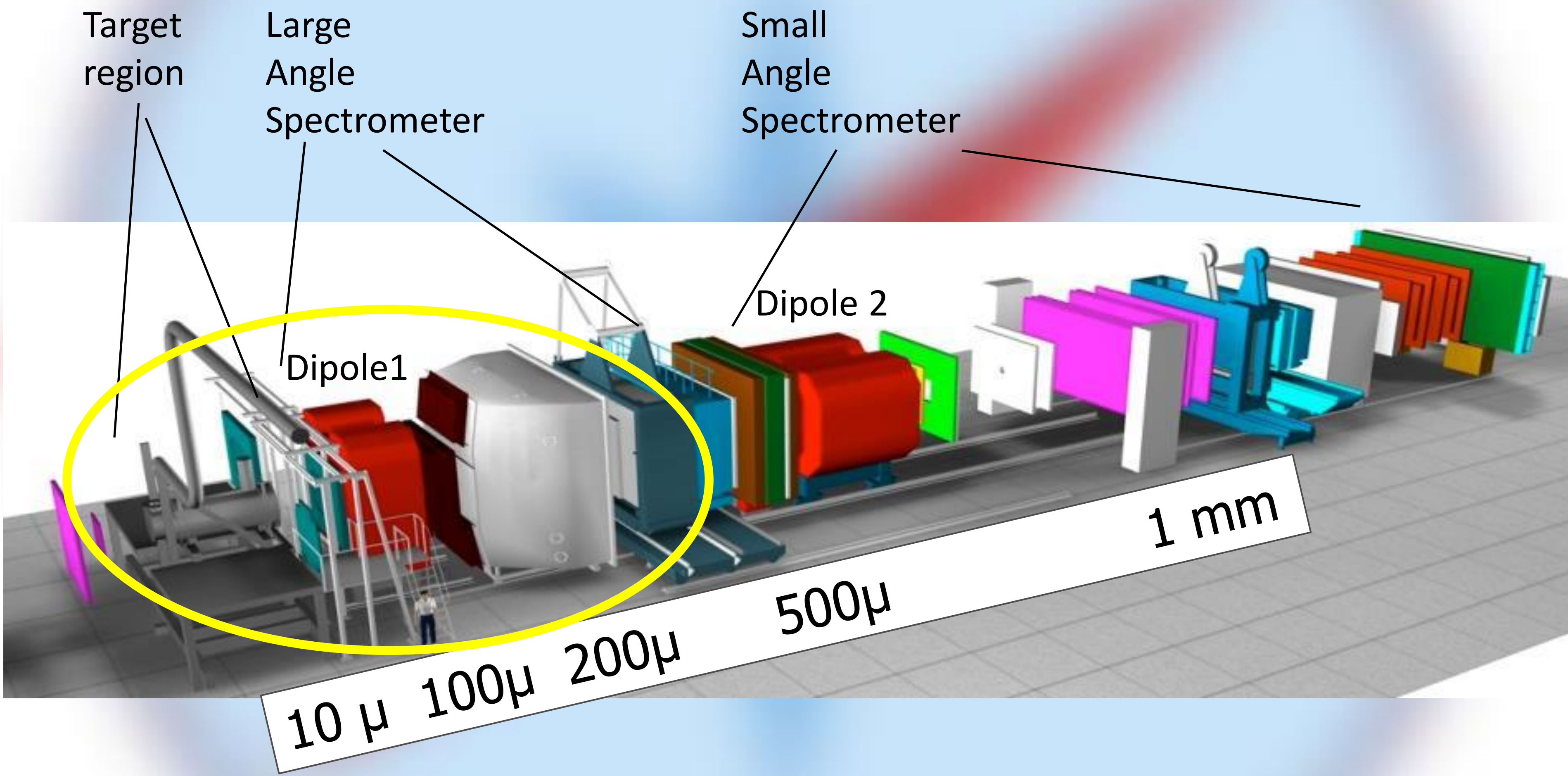
Dipole 1
1 Tm

Dipole 2
4 Tm

Target solenoid

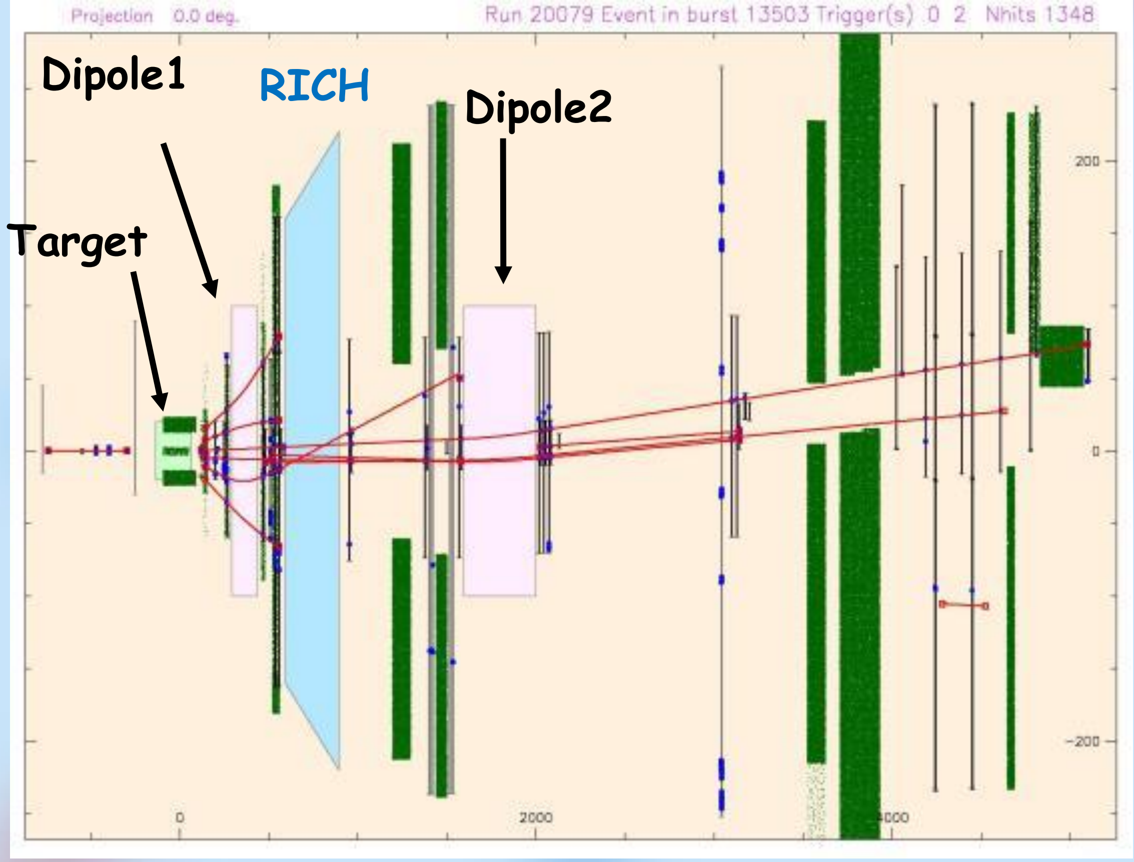
50m

The COMPASS setup – Space resolution



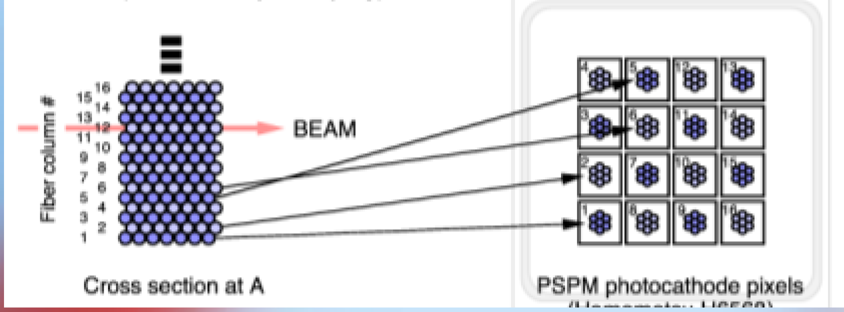
Space resolution is function of the distance to the target, and to the center of the beam

Online display

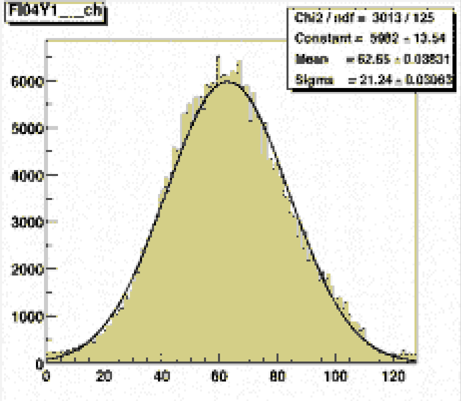


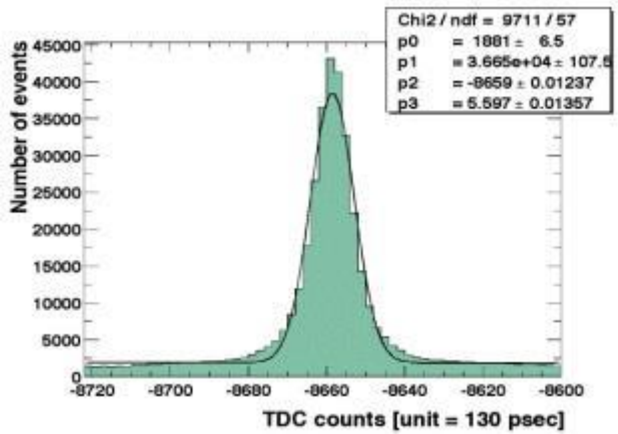
Scintillating Fibers

- Specifications
  - **9 stations**
  - **0.5, 0.75 and and 1.0 mm fibers**
  - **2668 channels**
  - 8-14 layers per projection



- Performances
  - **Time resolution: 350-400 ps**
  - **Spatial resolution: 130-210 µm**
  - Efficiency: 97-99%
  - High-rate capability



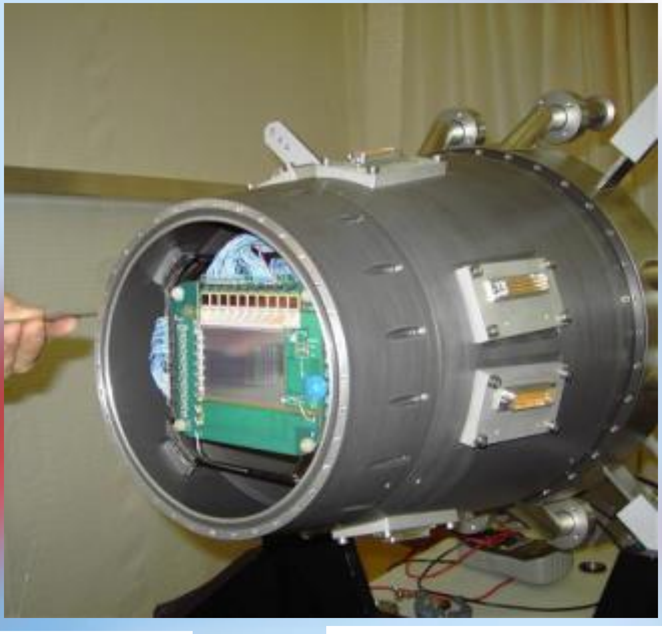


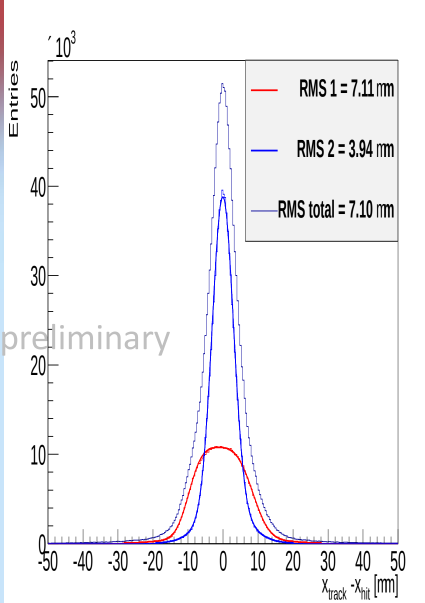
Very good time resolution, high-rate capability

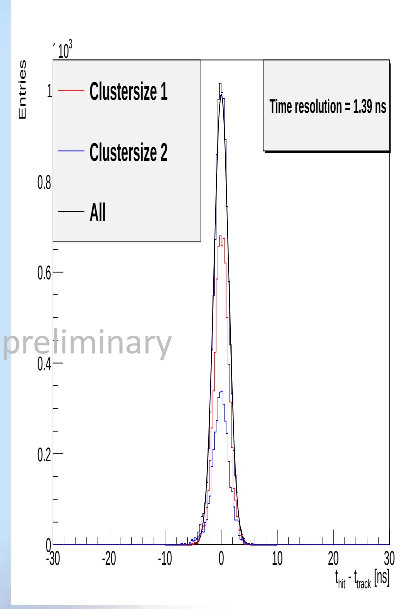
Silicons

- Specifications
  - 5x7 cm^2, 1280 and 1024 strips
  - 5 N-cooled stations
  - 52 µ and 55 µ pitch
  - 2 projections per detector
  - Designed for high fluencies
  - R/O: APV25 chip, 128 ch
- Performances
  - **Time resolution: 1.4 ns**
  - **Spatial resolution: 6 – 11 µm**

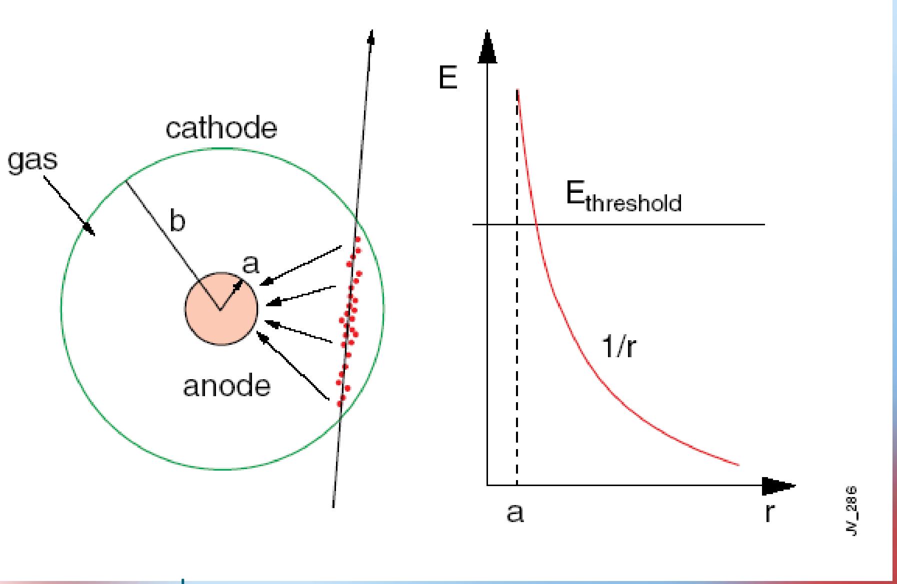
Very good spatial resolution







GASEOUS DETECTORS: Proportional Chamber



- A charged particle ionizes the gas, creating electron-ion pairs
- Electrons drift towards the anode wire.
- Close to the wire, electrical field is sufficiently high (above 10 kV/cm) for electrons to gain energy to ionize further and create an avalanche ⇒ exponential increase of number of electron-ion pairs.

anode

e^-
primary electron

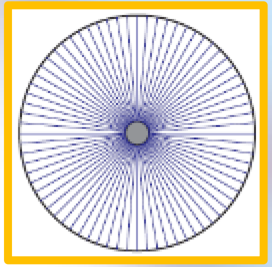
$$E(r)=\frac{CV_0}{2\pi\varepsilon_0}\cdot\frac{1}{r}$$

$$V(r)=\frac{CV_0}{2\pi\varepsilon_0}\cdot\ln\frac{r}{a}$$

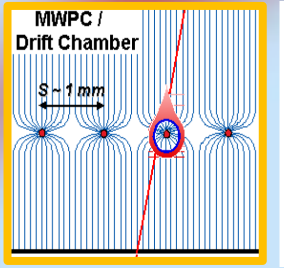
C – capacitance/unit length

$$C=\frac{2\pi\varepsilon_0}{\ln(b/a)}$$

Cylindrical geometry is not the only one able to generate strong electric field:

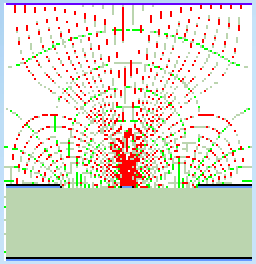


wire

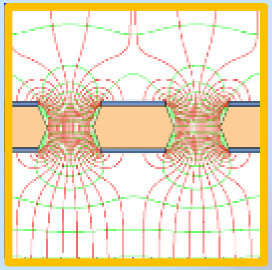


MWPC

parallel plate

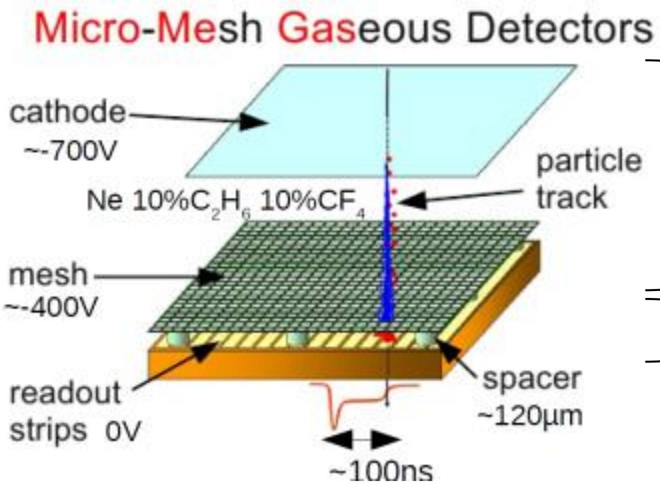


strip



hole

MicroPattern Gaseous Detectors (MPGD): Micromegas



ionisation region (300V in few mm):
low field, drift of e-

micromesh

amplification region (400V in ~100 µm):
high field electrical field: avalanche

- e$^-$/ion pairs are formed in the low field, ionisation region.
- e$^-$ avalanches created in the amplification region are collected on micro strips
- while ions created in the amplification region are collected by the micromesh; they drift within less than 100µm, i.e., less than 100 ns.

→ A very high rate detector : 1MHz/cm^2

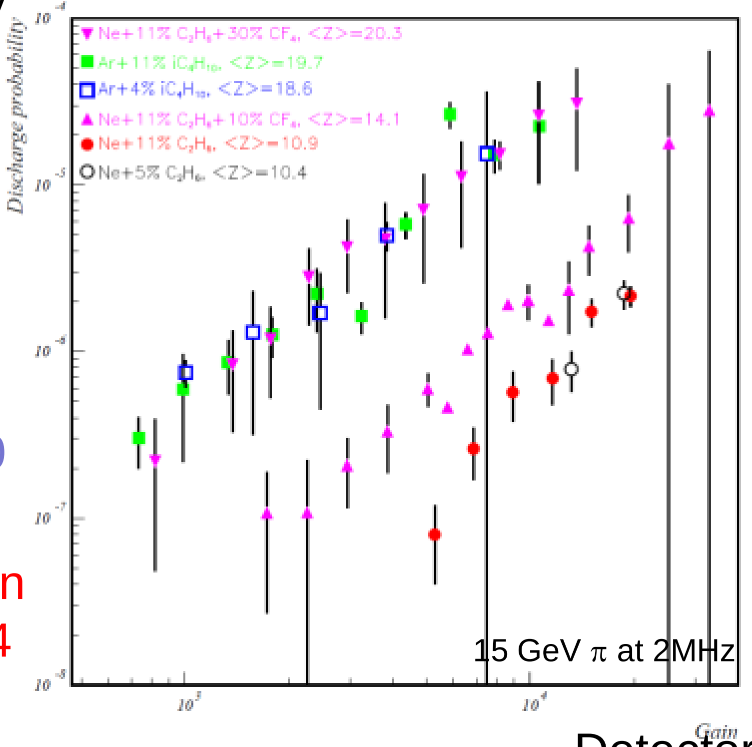
Other properties: **Low material budget**
Spatial resolution ~70 µm
Time resolution ~10 ns

Micromegas discharge probability

- Extensive studies on discharge rates and their possible reduction
- High dependence on **gain**
- **One of the findings was the relation with gas mixture mass**

  Gas mixtures: high **<Z>** give higher discharge rates

Discharge probability



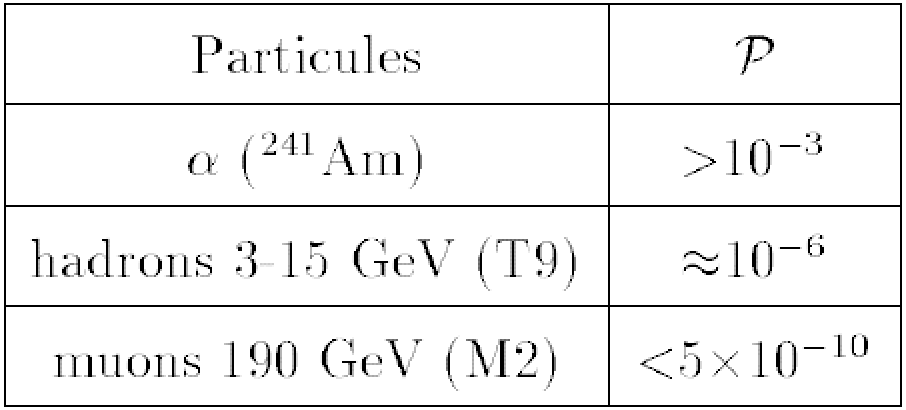
15 GeV π at 2MHz

Mixtures based on Argon <Z>~20

Mixtures based on Neon <Z>~10-14

Detector gain

Discharge probability and particle type

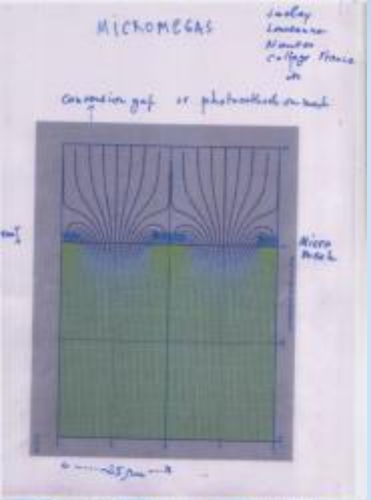


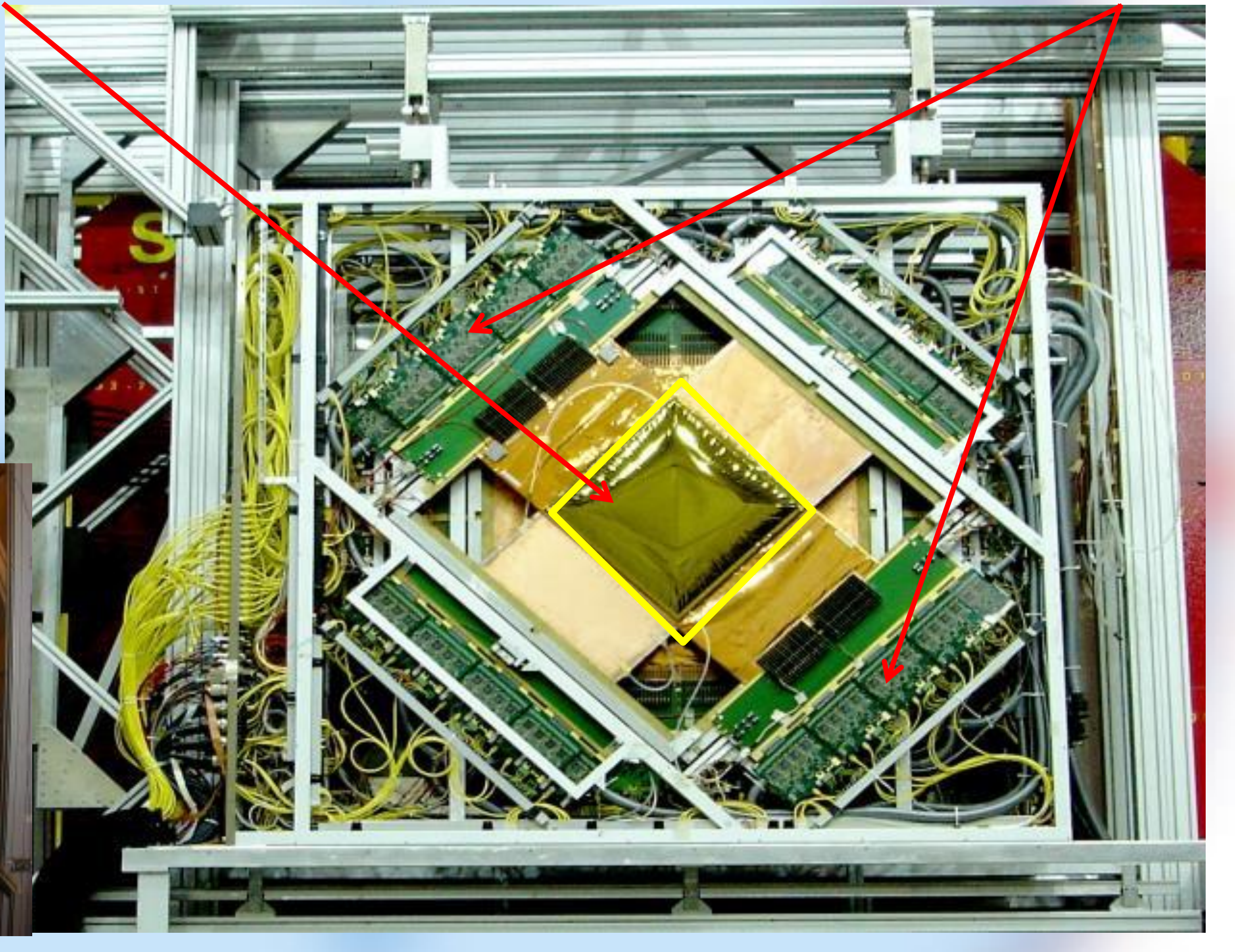
Particules	$\mathcal{P}$
α (^{241}Am)	$>10^{-3}$
hadrons 3-15 GeV (T9)	$\approx 10^{-6}$
muons 190 GeV (M2)	$<5\times 10^{-10}$

in Ne-C2H6-CF4, G=7000

- Highly ionising particles give higher discharge rates
- Rates differ by orders of magnitude

Micromegas in COMPASS





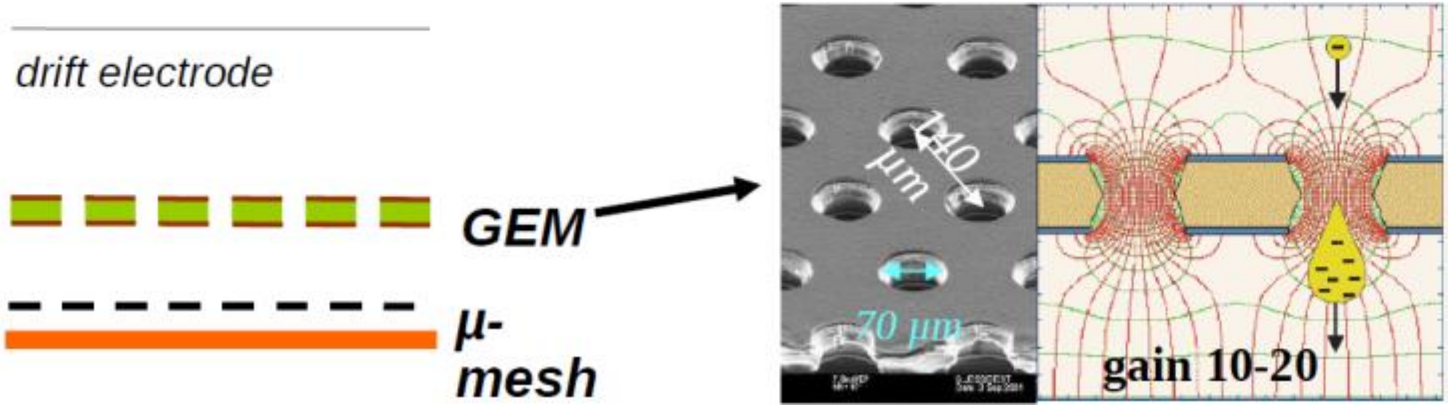
Detector 40x40 cm^2

Electronics

First Micromegas used in a High Energy Experiment

Hybrid ‘Micromegas+GEM’

Insert a GEM foil to realize a preamplification



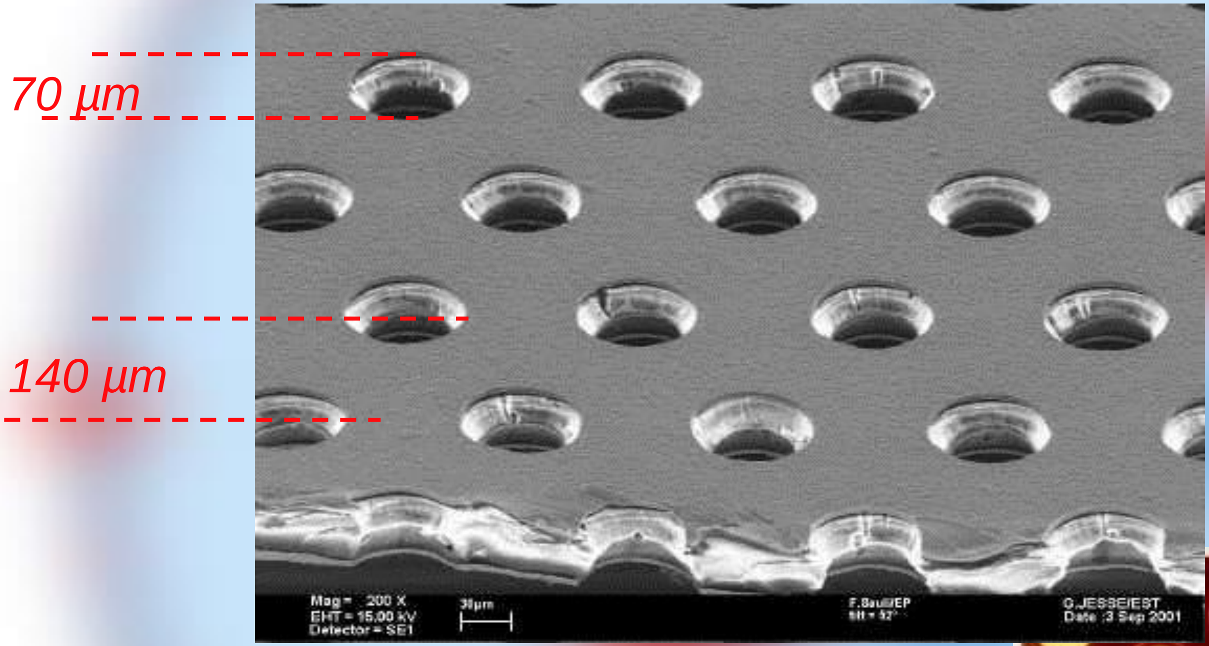
No more discharges: operating in highly ionizing environment

12 detectors inserted in the spectrometer 2015

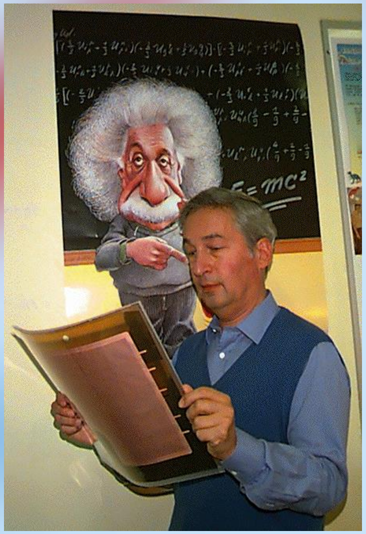
MPGD: GEM-Gas Electron Multiplier

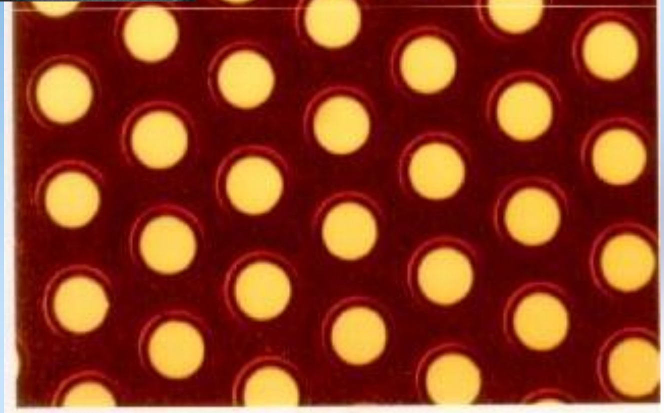
Thin metal-coated polymer foil pierced by a high density of holes (50-100/mm^2)

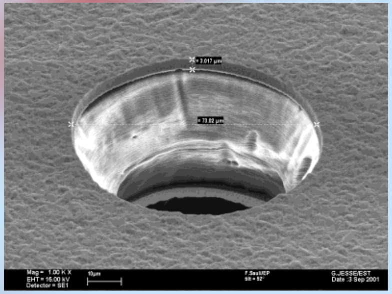
Typical geometry: 5 μm Cu on 50 μm Kapton, 70 μm holes at 140 μm pitch



F. Sauli, Nucl. Instrum. Methods A386(1997)531

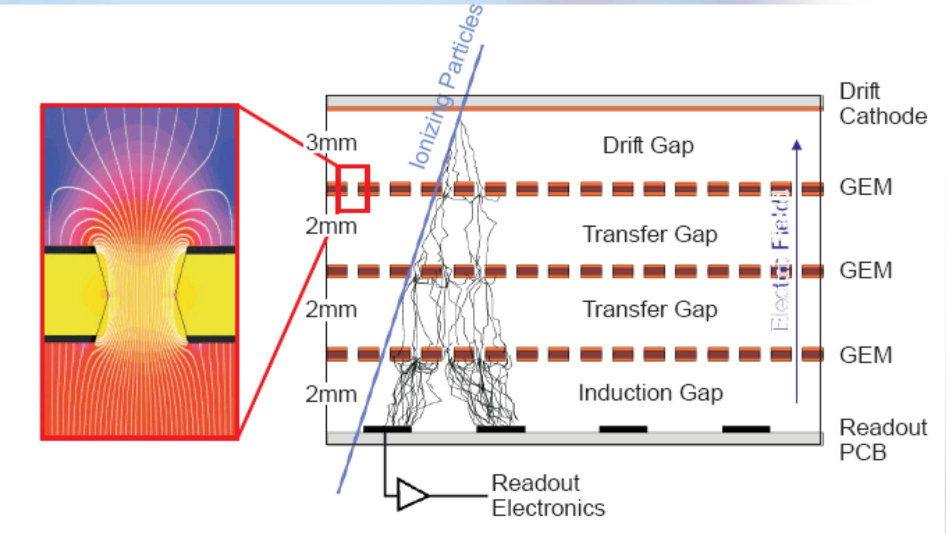


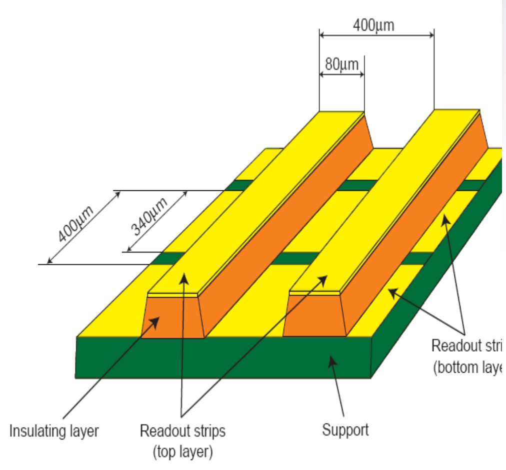




GEM detectors

- Specifications
  - 3 GEM stages
  - Active area: 31x31 cm^2
  - Dead area diameter: 5 cm
  - Minimal material budget
  - 11 stations (22 planes)
  - Two sets of 768 perpendicular strips
  - 400 µ pitch X and Y





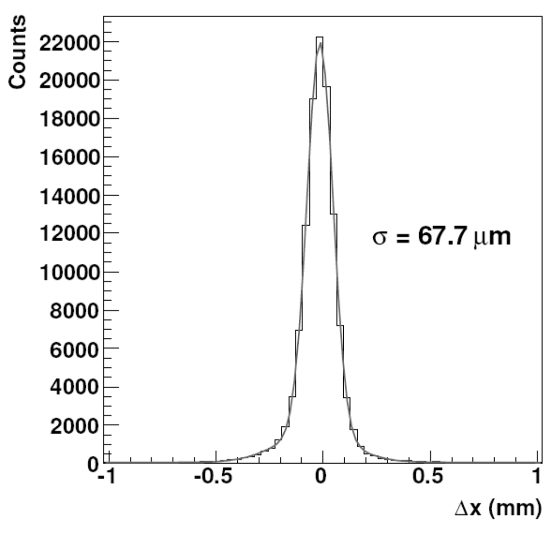
- Specific features
  - 2-dim read-out
  - Very large integration
    - APV chip = 128 ch

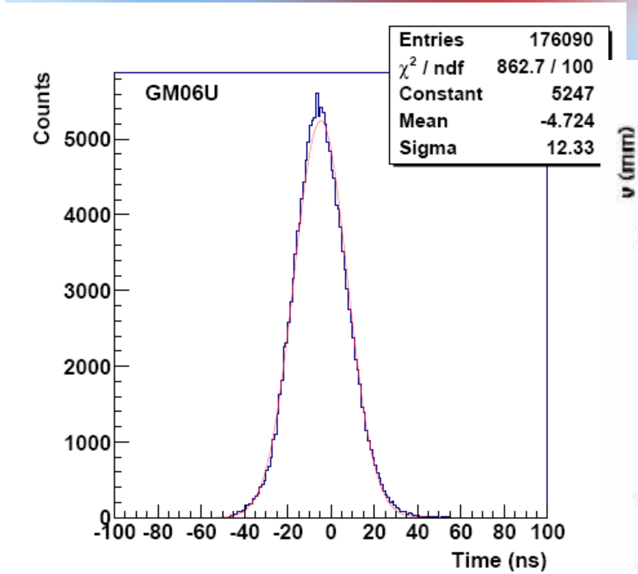
GEM detectors: performances

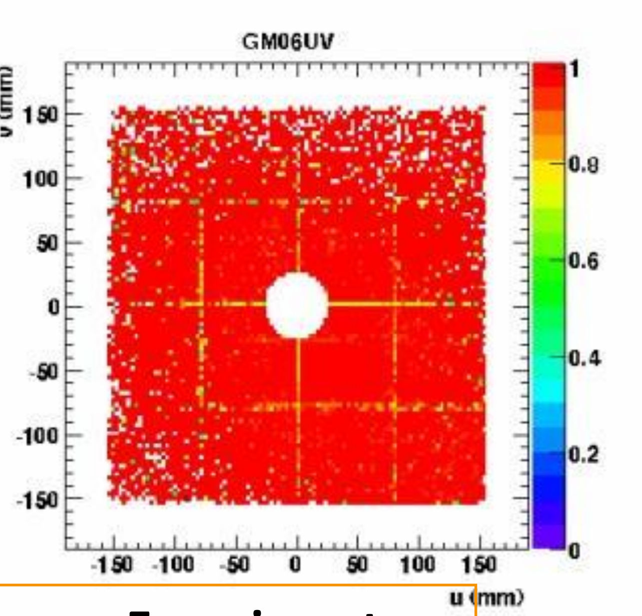
Space resolution: 68 µ

Time resolution: 12 ns

Efficiency: > 97%



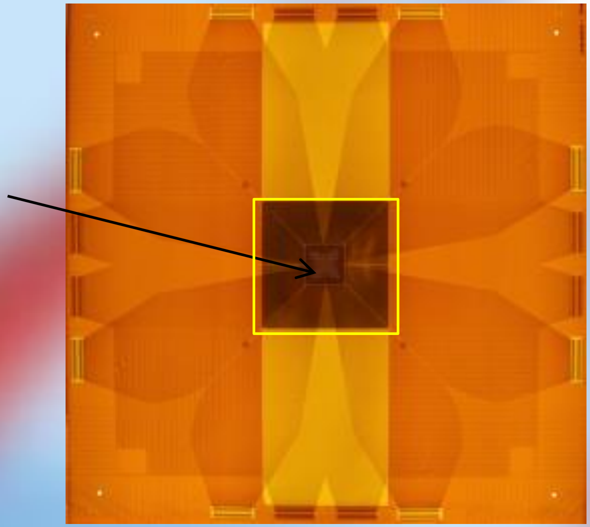


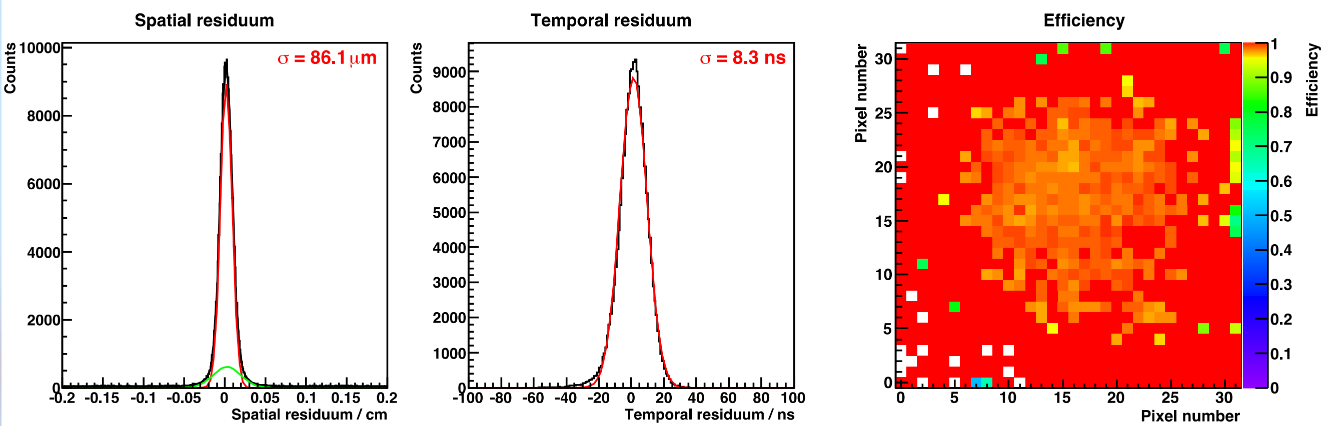


First GEM detectors used in a High Energy Experiment

Very Small Angle Trackers - PixelGEMs

- Specifications
  - Active size: 100x100 mm^2
  - Strip: 2 x 512, pitch=400 µ
  - Pixel area: 32x32 mm^2
  - Pixel size: 1 mm^2
  - APV chip R/O, 128 ch.
- Performances

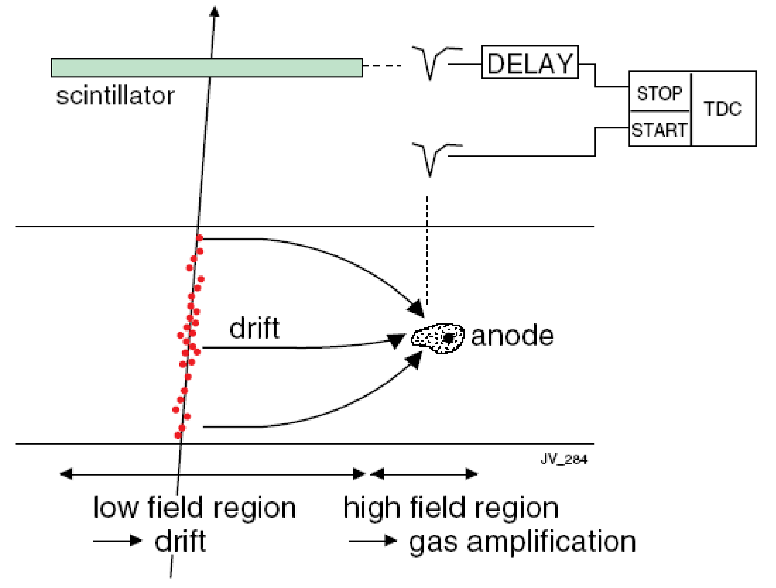




Good space resolution, minimized material along the beam

Drift Chambers

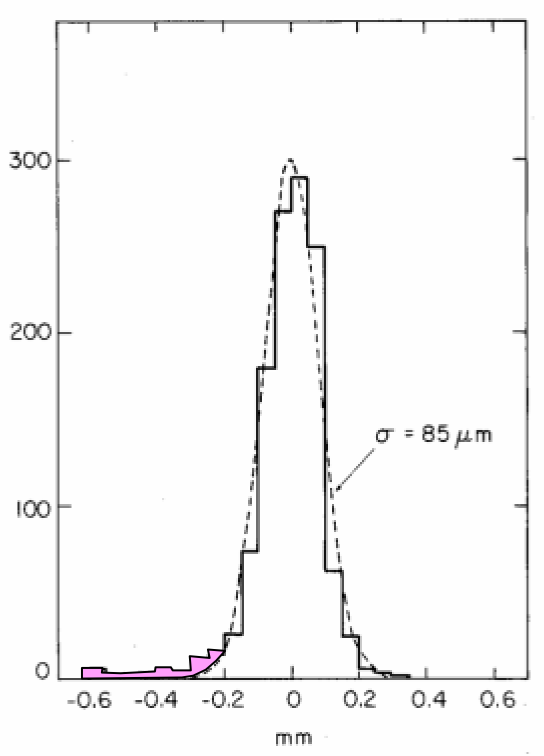
Spatial information obtained by measuring time of drift of electrons



Measure arrival time of electrons at sense wire relative to a time t_0.
Need a trigger (bunch crossing or scintillator).
Drift velocity independent from E.

$$s = \int_{t_{start}}^{t_{stop}} v_D dt$$

F. Sauli, NIM 156(1978)147

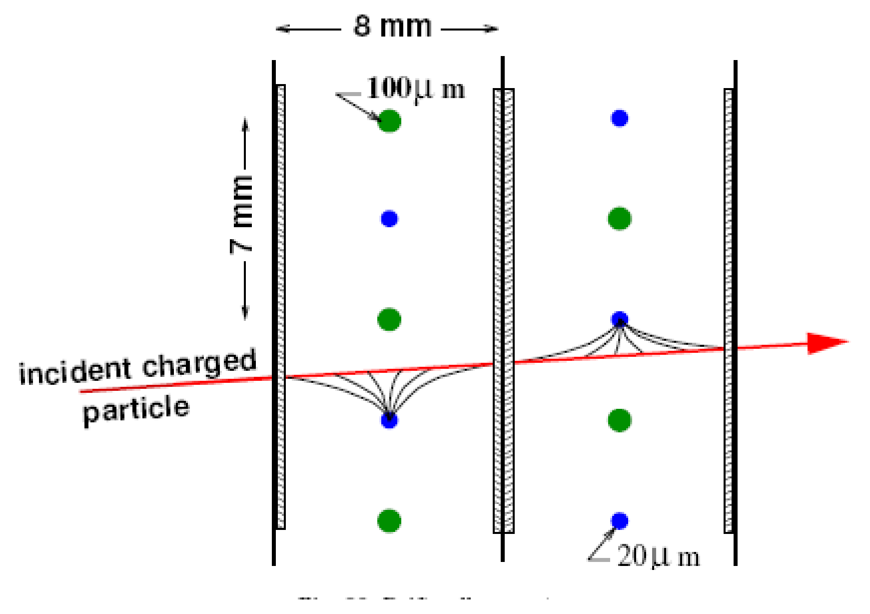


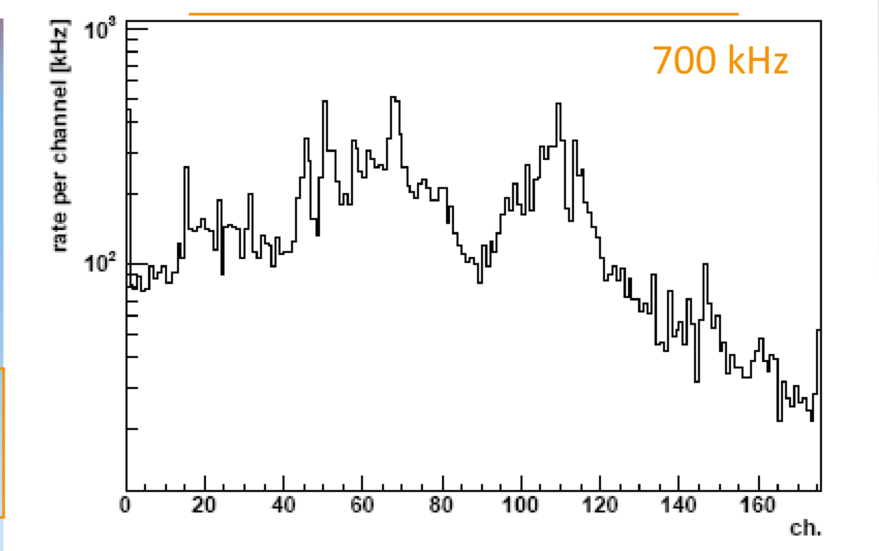
Advantages: smaller number of electronics channels.

Resolution determined by diffusion, primary ionization statistics, path fluctuations and electronics.

Large Angle Trackers – Drift Chambers

- Specifications
  - Sensitive area: 180x127 cm^2
  - 3 stations (8 planes/station)
  - Dead area diameter: 30 cm
  - Drift cell: 7mm(pitch) x8 mm^2
- Performances
  - Efficiency: > 97%
  - Space resolution: 170 µ
- Specific features
  - Located near high magnetic field
    - (up to 0.3 T)
  - Operate in a high-rate environment



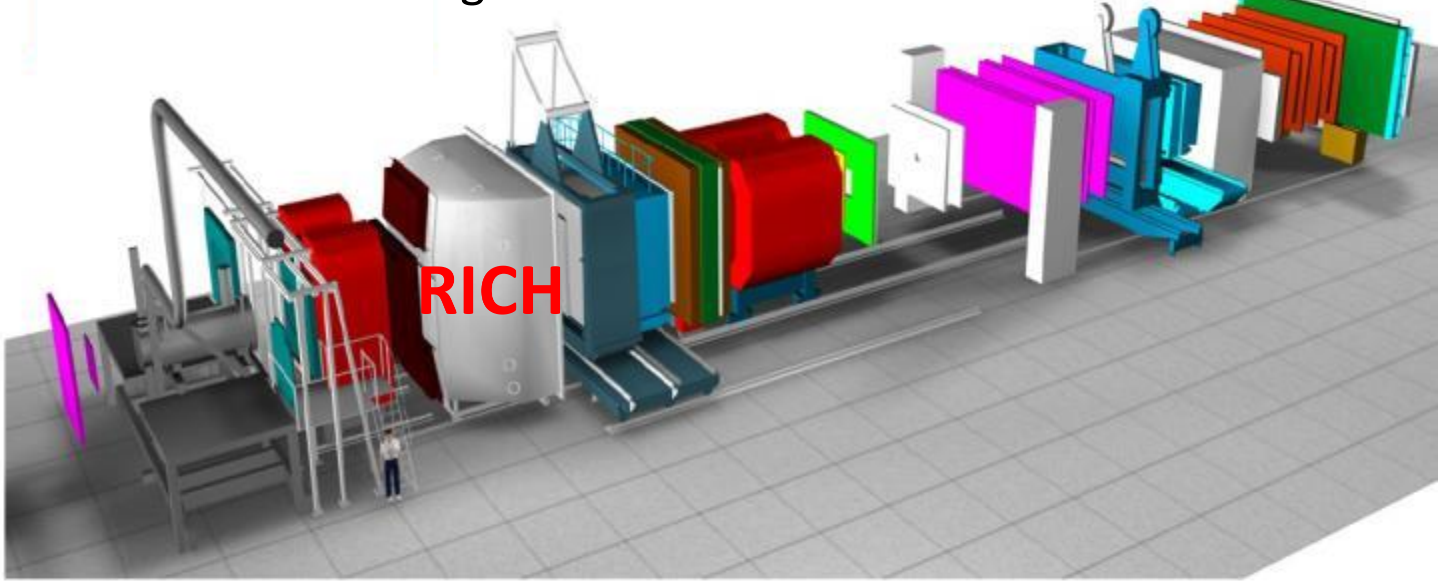


Large areas. Very high-rate capability - up to 700 kHz/ch!

RING IMAGING CHERENKOV: RICH

Used to discriminate between various particles : π, K, p…
by measuring their velocity

Based on the Cerenkov effect
Emission of Cerenkov light in a medium chosen for its refractive index **n**



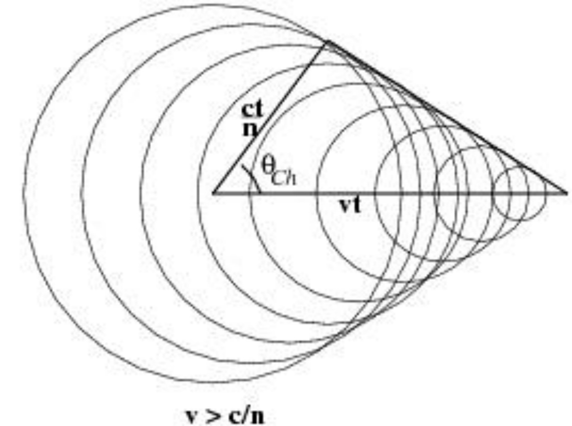
Light emitted above a certain momentum threshold
Here: large volume of gas C4F10

Velocity determination

The Cherenkov Effect

A charged particle travelling in a dielectric medium faster than light in that medium, emits a cone of light with an opening

$$\cos(\theta) = \frac{1}{n\beta}$$



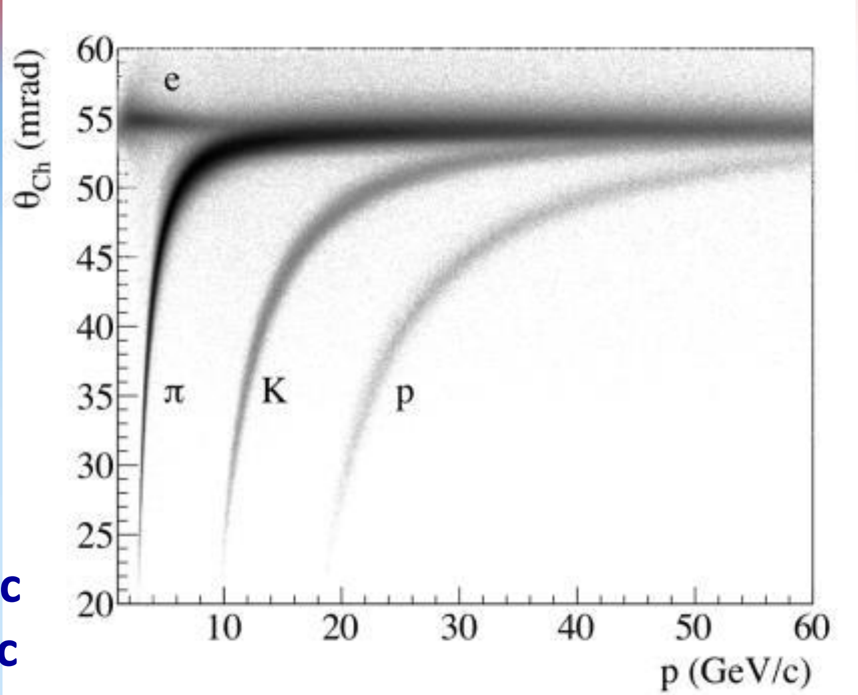
$$v > \frac{c}{n}$$

- Measure opening angle θ

→ determine **v** =βc

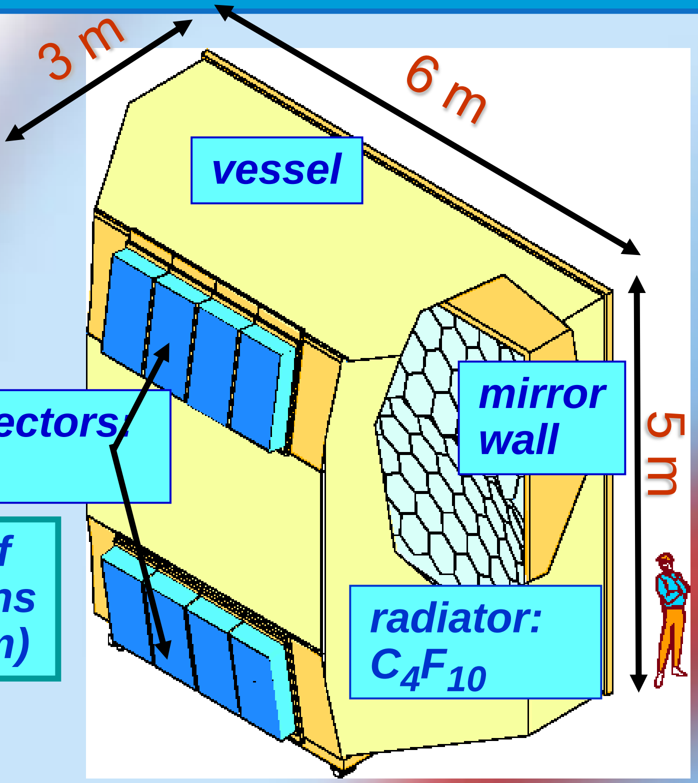
- Knowing momentum ***p*** (spectrometer),

→ obtain particle mass **M**



threshold: π ~2 GeV/c
K ~ 10 GeV/c
p ~ 18 GeV/c

COMPASS RICH detector



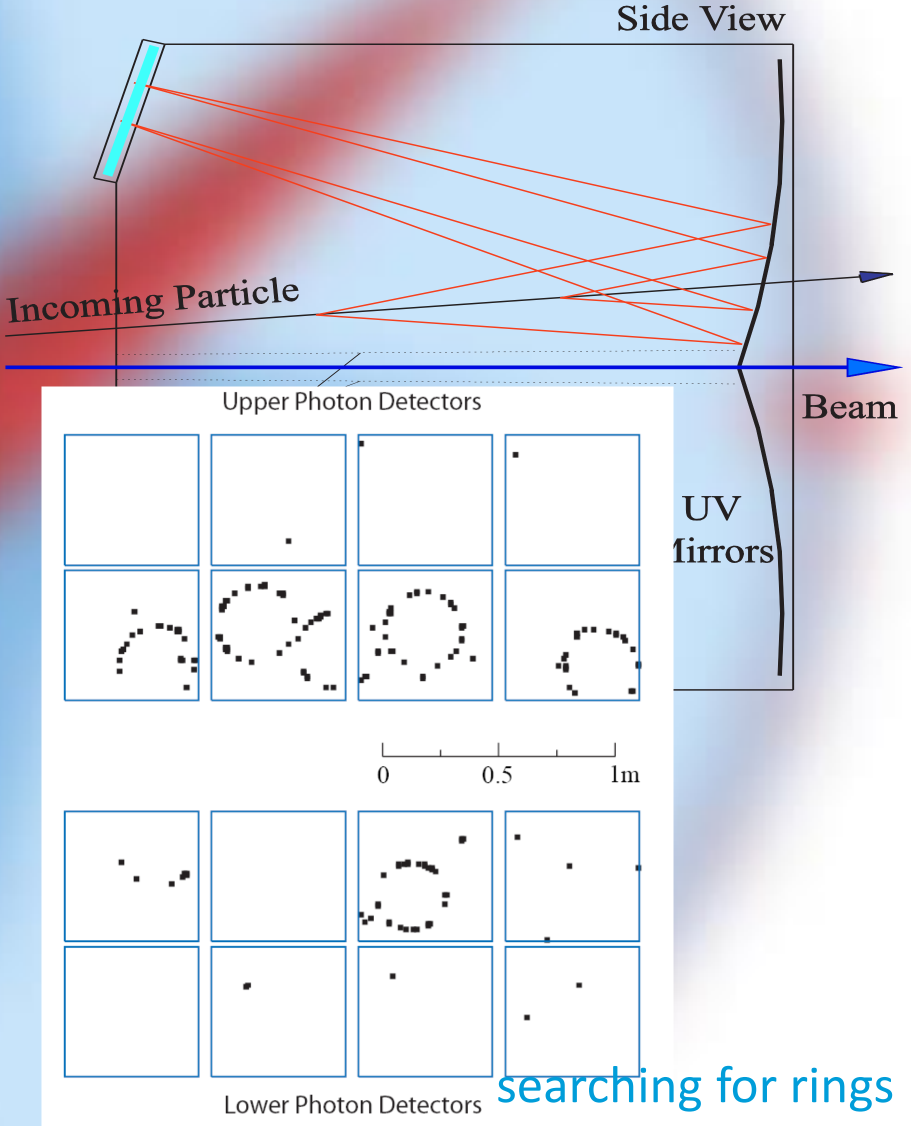
vessel

mirror wall

radiator: C_4F_{10}

Photon detectors: CsI MWPC

detection of VUV photons (165-200 nm)



searching for rings

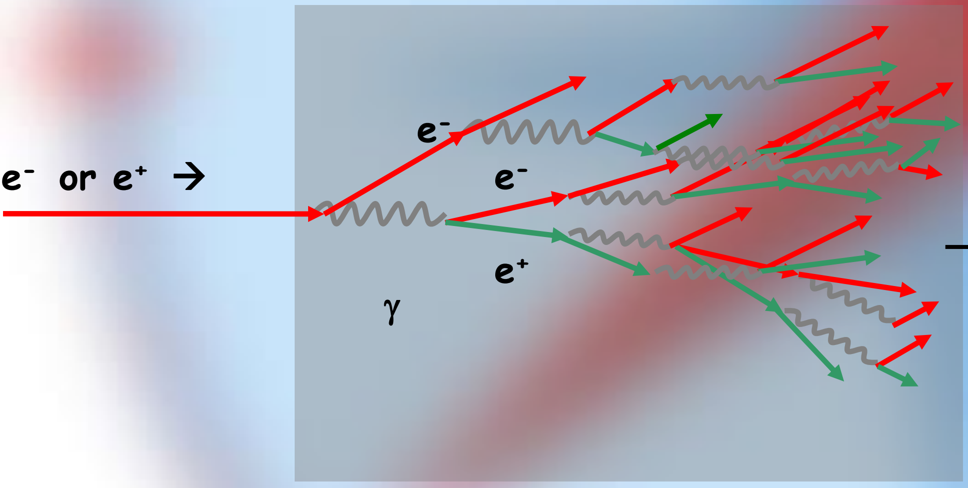
CALORIMETER: ENERGY DETERMINATION

Electromagnetic calorimeter

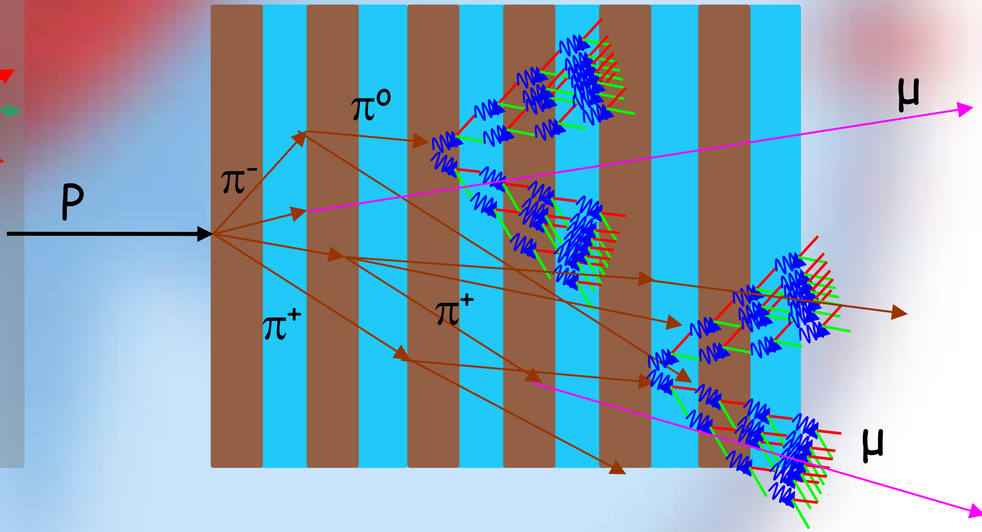
Hadronic calorimeter

Measure energy of electrons, positrons, gammas

Protons, pions & kaons initiate hadronic cascades.



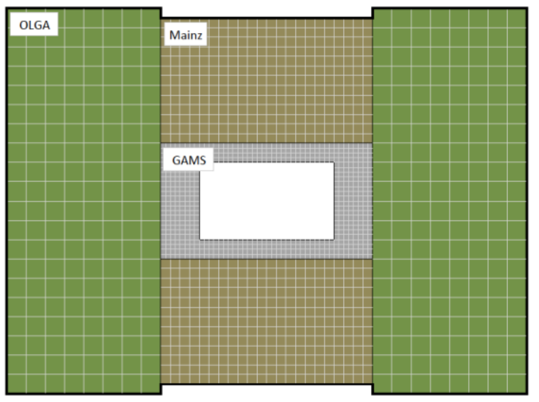
massive material (lead glass)



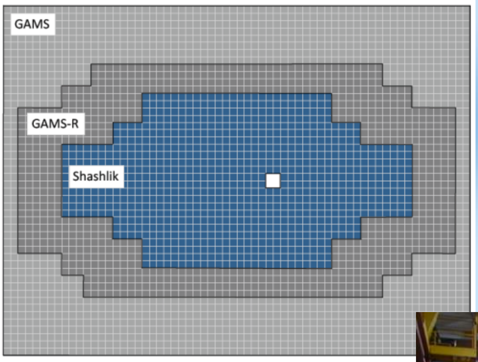
Sandwich lead-scintillator

Electromagnetic calorimeters (x2)

- ECAL1
  - 1500 channels
  - Pb0 modules (3 dimensions)
    - 18-20 X_0
  - Energy range: 0.2-60 GeV

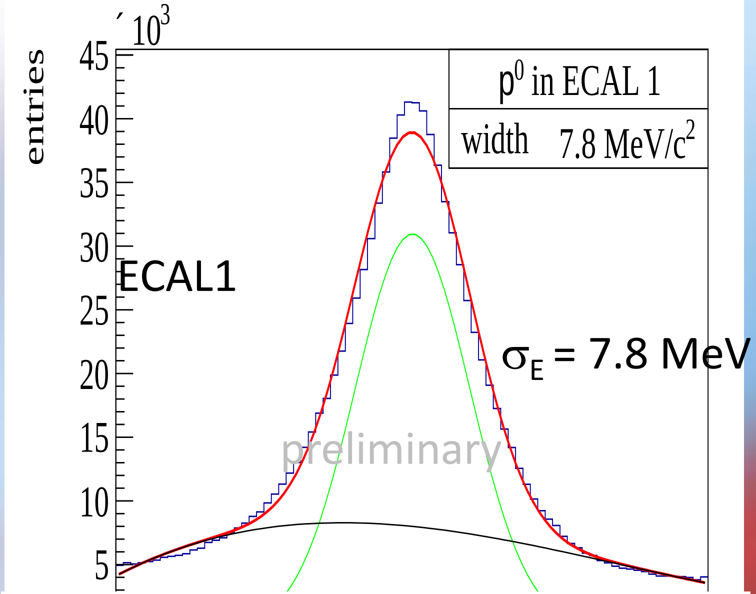


- ECAL2
  - 2180 Pb0 type modules
  - 888 “Shashlik” type (Pb/Scint)
    - (radiation hardness)
  - Energy range: 1-200 GeV

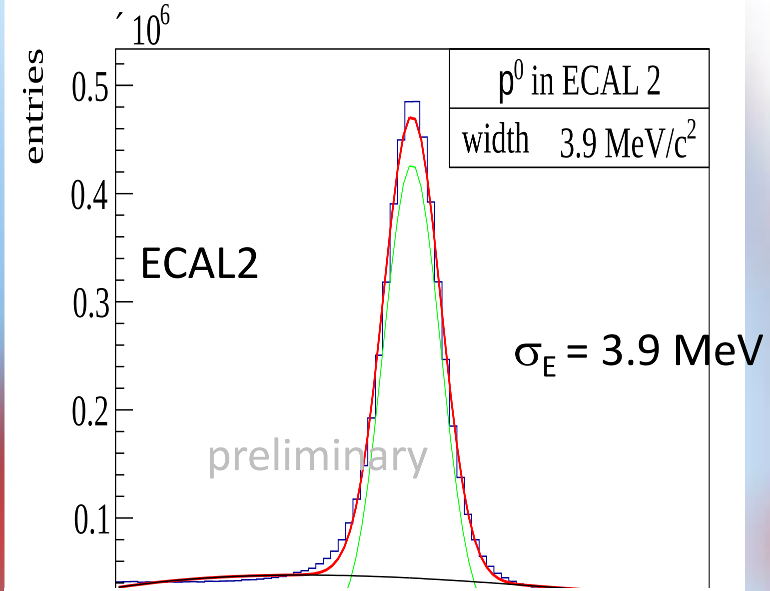


Detect photons and electrons

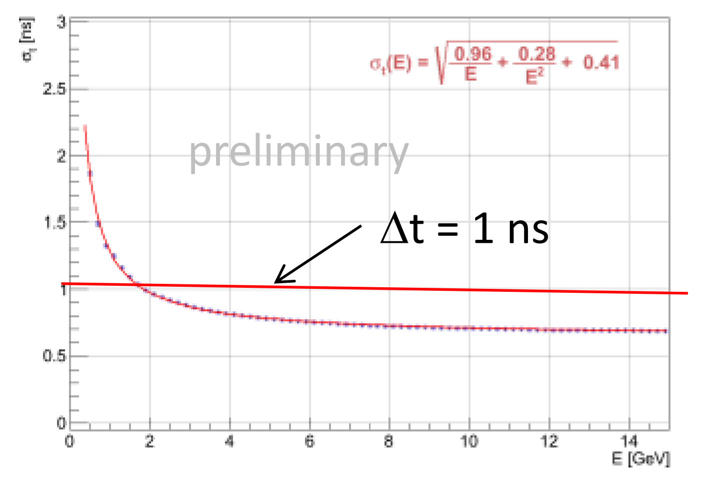
ECAL performances



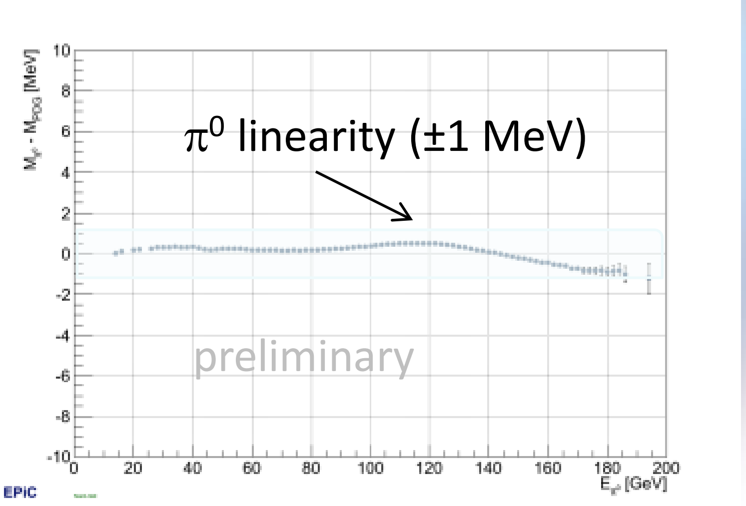
σ_E = 7.8 MeV



σ_E = 3.9 MeV



Δt = 1 ns



π^0 linearity (±1 MeV)

Good time resolution, reasonable energy resolution

Hadron calorimeter

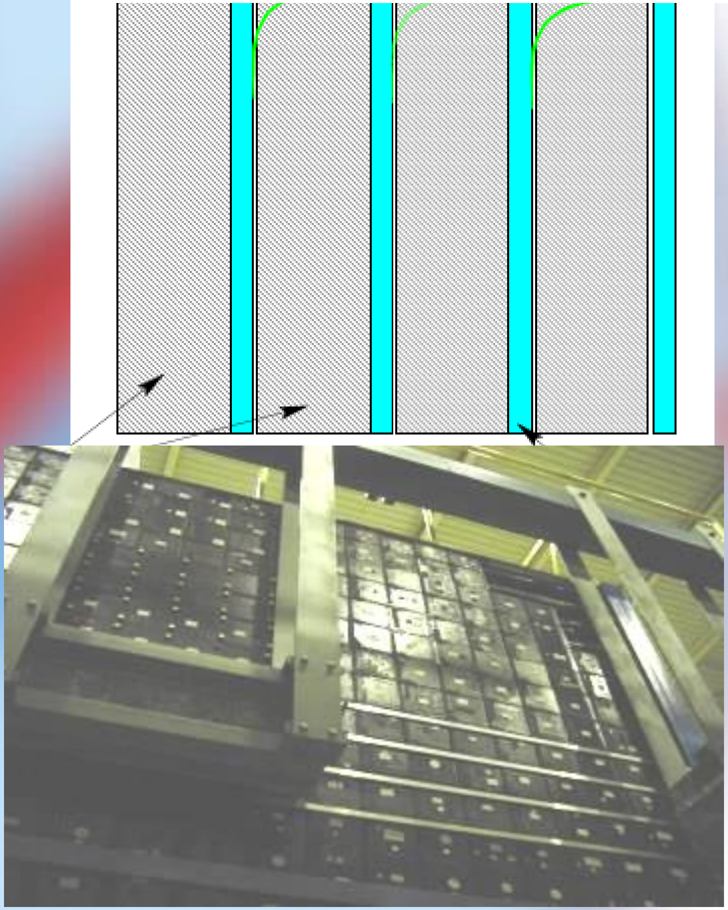
- Hadron calorimeters (x2)
  - HCAL1: 480 channels (20x28)
    - Each block: 15x15 cm^2

$$\frac{\sigma}{E} = \frac{59\%}{\sqrt{E}} \oplus 7.6\%$$

  - HCAL2: 216 ch (22x10)
    - Each block: 20x20 cm^2

$$\frac{\sigma}{E} = \frac{65\%}{\sqrt{E}} \oplus 4.6\%$$

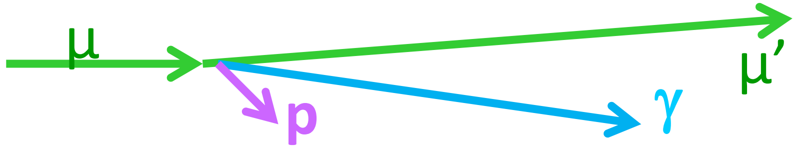
Fe-Scintillator sandwich (x40)

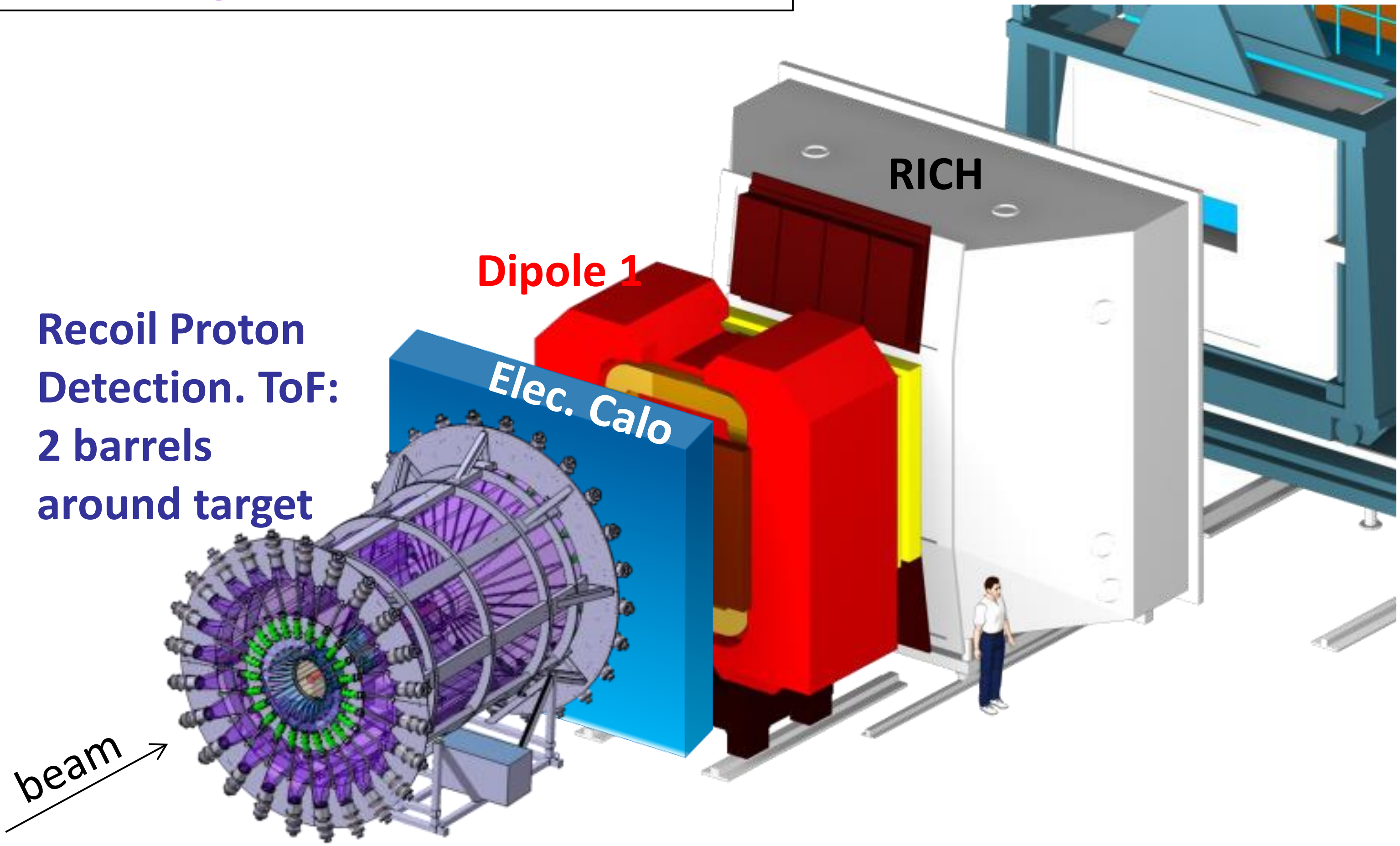


Detect hadrons = maximize INTERACTION length

Recoil Proton Detection and Time of Flight

DVCS : μ p → μ' p γ

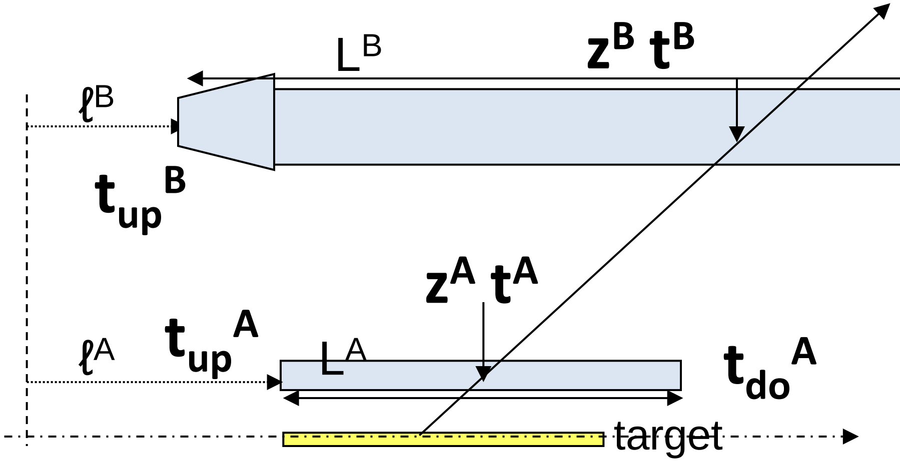


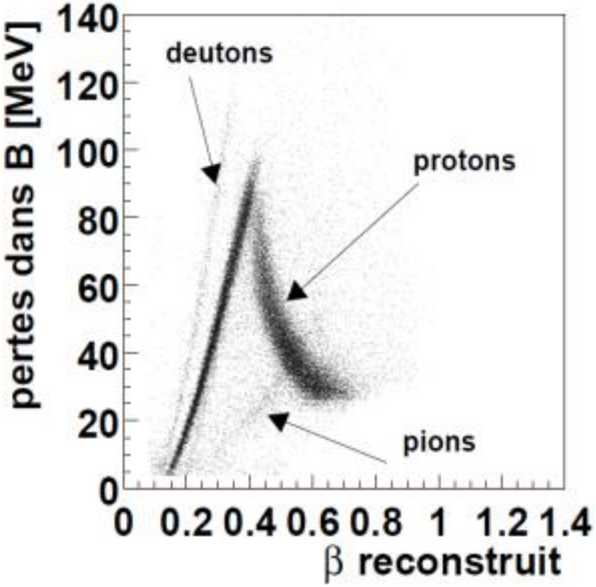


Recoil Proton Detection. ToF: 2 barrels around target

Recoil Proton Detection and Time of Flight

Two concentric barrels of scintillators





Measure 4 times : t_{do}^A , t_{up}^A , t_{do}^B , t_{up}^B
and corresponding amplitudes

➔ reconstruct positions and energy
➔ $\beta = L_{AB}/ToF$

Time resolution : **200 ps** in 4m long outer barrel, **350ps** in inner
Position resolution: **2-3 cm**
Momentum range **270 MeV – 2 GeV**

End of the visit