Experimental results on TMDs, Facilities and Experiments (I)

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INFN TRIESTE

Followed by Measurements and Results (II) (Andrea Bressan)

Facilities and experiments (I), OVERVIEW

- Introduction
- From DIS to SIDIS
- SIDIS-dedicated Experiments:
  - HERMES (fix target at the HERA collider, DESY)
  - COMPASS (fix target at the CERN muon-beam)
  - JLAB
- Take-away messages

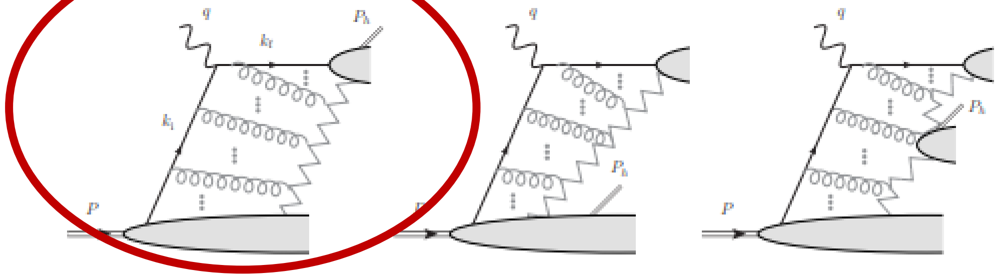
TMD, how to measure ?

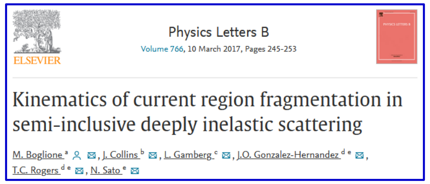
Needed for the experimental approaches:
- SIDIS
- Access to the high Q^2 domain

TMD distributions (Transverse-Momentum–Dependent distributions)

- **How do we access TMDs ?**
  - **Via SIDIS** (Semi-Inclusive Deep Inelastic Scattering)
    - In the experimental data TMDs are convoluted with fragmentation functions
    - Different levels of complexity in extracting TMD information according to the kinematic regions

Current region | Target region | Central region




Physics Letters B
Volume 766, 10 March 2017, Pages 245-253

Kinematics of current region fragmentation in semi-inclusive deeply inelastic scattering

M. Boglione, J. Collins, L. Gamberg, J.O. Gonzalez-Hernandez, T.C. Rogers, N. Sato

Reminders

$$Q^2 = -q^2 = -(l-l')^2; \qquad x_{bj} = \frac{Q^2}{2P\cdot q};$$

$$z_h = \frac{P\cdot P_h}{P\cdot q} = 2x_{bj}\frac{P\cdot P_h}{Q^2}; \qquad P_{hT},$$

$$\Lambda_{\overline{MS}} = 332 \pm 17\ \mathrm{MeV}$$

- Focus on current fragmentation region, where a factorization picture with fragmentation functions is appropriate for TMD studies: present status of the experimental data largely related to this region: large Q^2 ($Q^2 >> \Lambda^2_{QCD}$), at fixed x_{bj}, with large enough z_h, and with small P_{hT}.

Measuring TMDs, what is needed?

Messages related to the experimental approaches:
- Polarized leptons and nucleons
- Particle identification
- Fine control of the systematics !

A famous scheme : the 8 leading-twist (twist-two) quark TMDs

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1 \; h_{1T}^\perp$

Nucleon polarization

SIDIS measurements:
single hadron or **di-hadron detection**

Single-spin asymmetries, on transversally polarized target: the transversity (h_1), the Sivers function ($f_{1T}^\perp$), the pretzelosity function ($h_{1T}^\perp$)

Double spin asymmetries (polarized lepton beams !), on longitudinally/transversally polarized target: helicity (g_1) and worm-gear TMDs ($g_{1T}^\perp$, $h_1^\perp$, $h_{1L}^\perp$)

The access to all TMDs, apart f_1, is via **asymmetry measurements**, where the cross-section asymmetries are convoluted with instrumental parameters (like polarization dilution) resulting in extremely small measured asymmetries and with potential false asymmetries from instrumental effects.

One more parameter to explore: flavor-dependence of TMDs by identifying the hadrons in the final state

Facilities and experiments (I), OVERVIEW

- Introduction

- From DIS to SIDIS
  - With focus on spin-effect measurements:
    facilities and beams

- SIDIS-dedicated Experiments:

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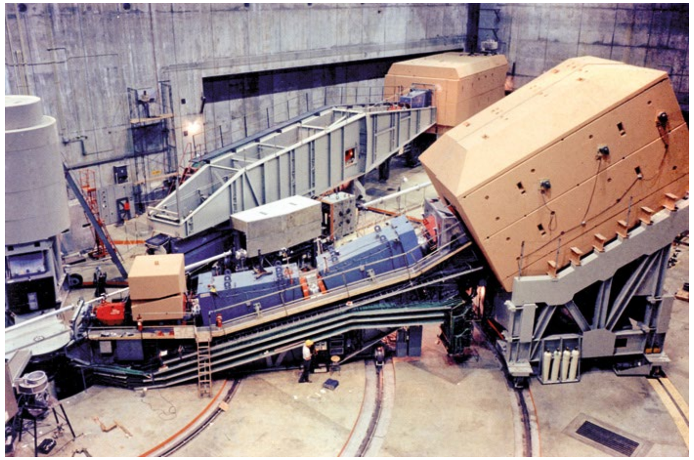
- Take-away messages

Facilities and Experiments , from DIS to SIDIS

DIS @ SLAC

Where everything started in the 60's @ Stanford Linear Accelerator Center(SLAC)



20 GeV e-beam:

The first observation of partons

VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

HIGH-ENERGY INELASTIC e-p SCATTERING AT 6° AND 10° *

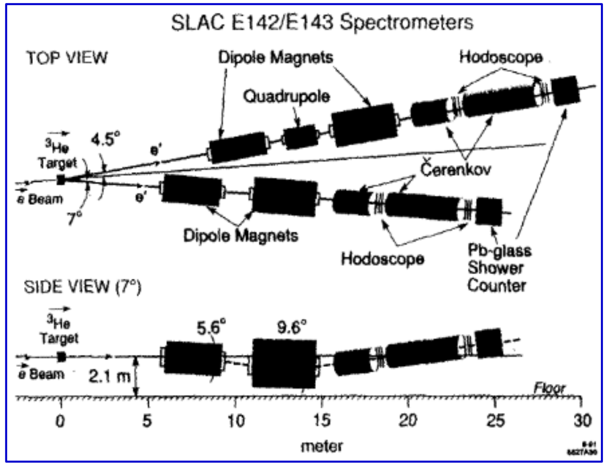
E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, G. Miller, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

M. Breidenbach, J. I. Friedman, G. C. Hartmann,† and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,‡
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 19 August 1969)

At SLAC in the 90's

- **increasing energy (up to 50 GeV)**
- **adding polarization:**
  - **beam (polarization reversed at each burst)**
  - **polarized gaseous (^{3}He) and solid state targets (NH_3, ND_3)**
- **experiments**
  - **E142 (29.2 GeV, ^{3}He)**
  - **E143 (29.2 GeV, H, D)**
  - **E154 (48.3 GeV, ^{3}He)**



Pros:

- **The high intensity of the e-beams for precision measurements**
- **The very frequent reversal of the beam polarization helps in keeping the systematic effects under control**
- **Beam monochromaticity** (ΔE ~ 0.1-1 %) and **fine optics** (spot size: 1-2 mm)

Cons:

- **The beam energy and the fix angle small acceptance spectrometers does not allow to explore the small-x domain**
- **No possible evolution toward SIDIS because of small-acceptance spectrometers**

Facilities and Experiments , from DIS to SIDIS

Polarized Beam at SLAC

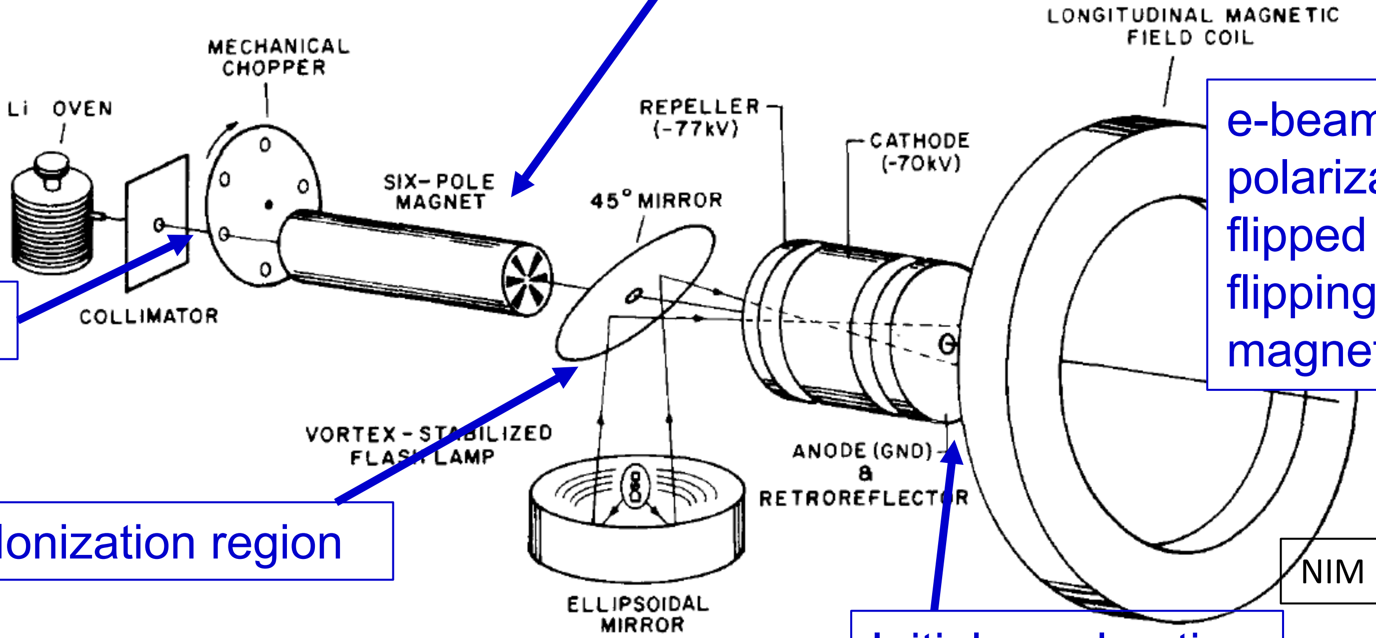
first polarized electron source for an accelerator

PEGGY : polarized electron source for the Stanford two-mile electron linear accelerator

- based upon photoionization of a state-selected ^{6}Li atomic beam
- pulsed beam of electrons with a maximum intensity of 2.6×10^{9} electrons per pulse
- **polarization of 85% after acceleration** !
- a pulse length of 1.6 μs
- a repetition rate of 180 Hz
- polarization reversal time ≤ 1 s

- 2 polarimeters:
  - at 70 keV by Mott scattering:
  left-right scattering asymmetry
  In scattering of transversally pol.ed e off heavy nuclei
  - at GeV energies
  by Møllerer scattering:
  e-e double spin asymmetry, polarized e target in a thin ferromagnetic foil magnetized to saturation and inclined to provide a large longitudinal polarization

Atoms in the $M_j = +½$ ground state are selected by deflection in the strong inhomogeneous field of a sextupole magnet



Li gas

Ionization region

e-beam polarization is flipped by flipping the magnetic field

Initial acceleration

NIM 163 (1979) 29

Later, an GaAs-based source used al SLAC

Facilities and Experiments , from DIS to SIDIS

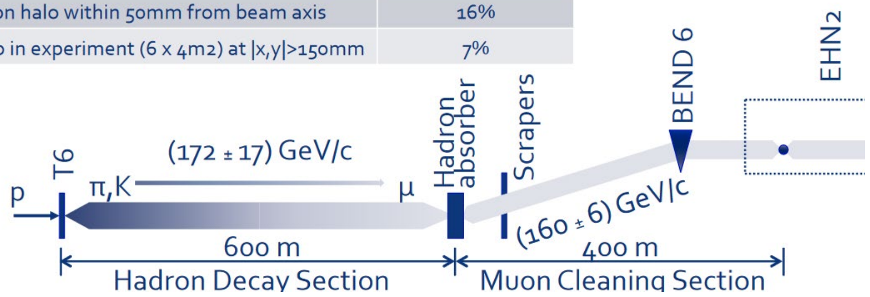
The high-energy μ-beam @ CERN

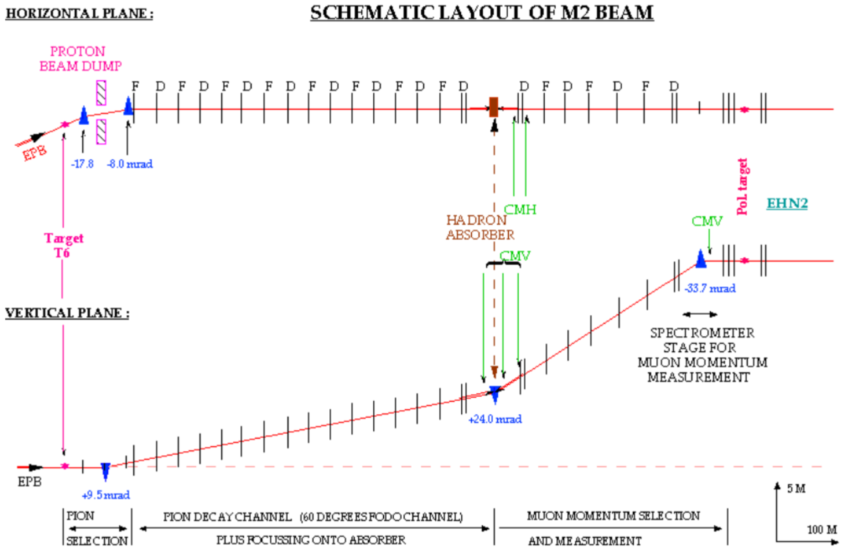
A great tool: the SPS μ-beam

Beam Parameters for COMPASS	Measured
Beam momentum p_{μ}/p_{π}	160 / 172 GeV/c
Proton flux on T6 per SPS cycle	$1.5\ 10^{13}$
Muon flux at COMPASS per SPS cycle	$2.5\ 10^{8}$
Beam polarisation	-80% ± 4%
Spot size at COMPASS target ($\sigma_x \times \sigma_y$)	8mm x 8mm
Divergence at COMPASS target ($\sigma_{dx} \times \sigma_{dy}$)	0.4mrad x 0.8mrad
Muon halo within 50mm from beam axis	16%
Halo in experiment (6 x 4m2) at |x,y|>150mm	7%

Beam intensity:
~ 2 orders of magnitude lower last century

M2

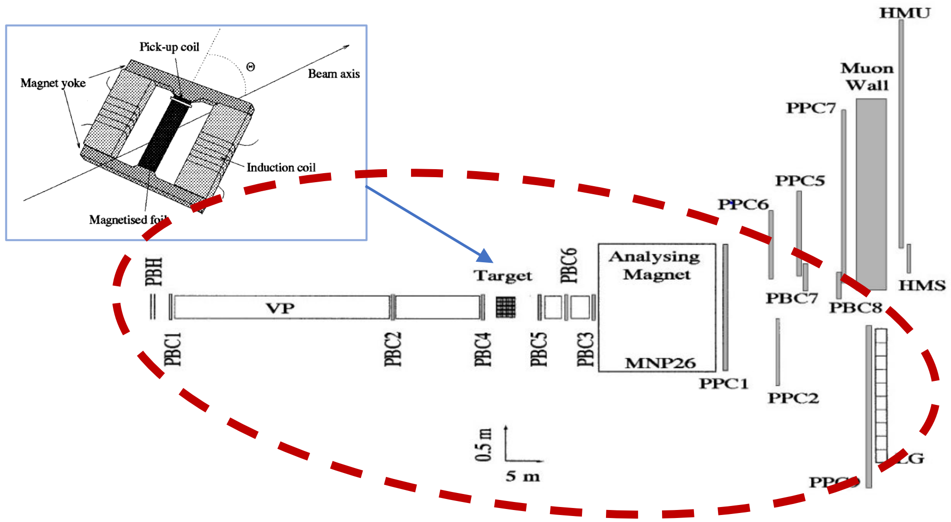




The beam is polarized: due to the parity violating nature of the weak decay $\pi \rightarrow \mu\nu$.

Beam polarization from simulation studies and then (SMC experiment) with two polarimeter measurements

1. From the energy spectrum of positrons in mu decay $\mu^{+} \rightarrow e^{+} \nu_e \bar{\nu}_{\mu}$.
2. From the asymmetry in the elastic scattering off polarized electrons



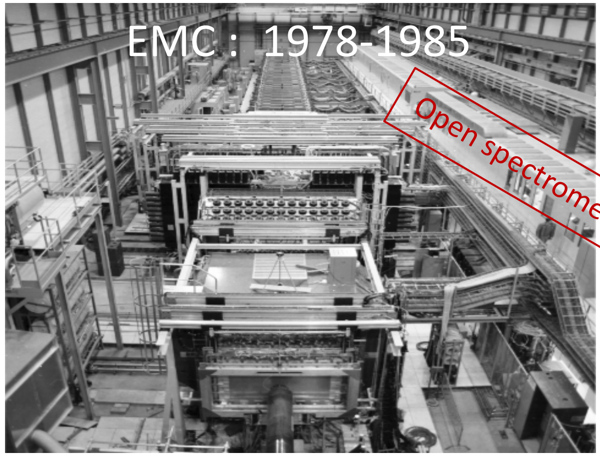
$\langle E_{\rm beam} \rangle$ (GeV)	$P_{\mu}^{\mu-e}$	$P_{\mu}^{\rm decay}$	P_{μ}
99.4	-0.80 ± 0.04		-0.80 ± 0.04
187.4	-0.797 ± 0.016	-0.806 ± 0.029 [10]	-0.799 ± 0.015

Euro

Facilities and Experiments , from DIS to SIDIS

Using high-energy μ-beams

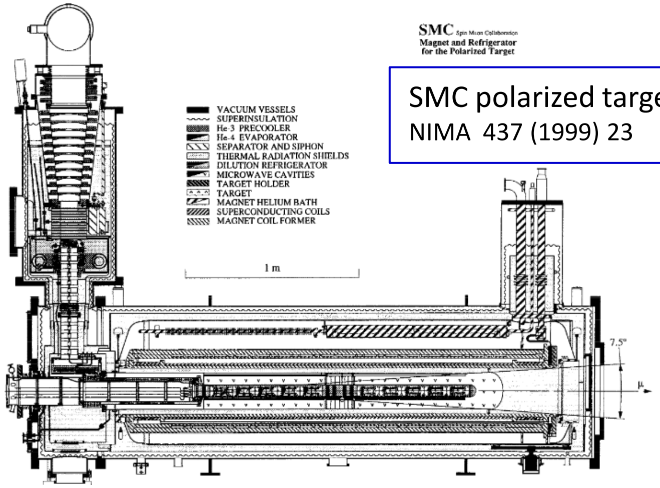
- Toroidal spectrometer
- Multiple targets to increase the luminosity



Open spectrometer !

then evolved in
- NMC: 1986 – 1989
- SMC: 1994 - 1998

Spin studies already initiated with EMC, enriched with SMC fully dedicated to spin



SMC polarized target, NIMA 437 (1999) 23

μ-beams and open spectrometers

Pros:
- **High energy (up to 250 GeV) → access to high Q^2 and small x**
- **Open spectrometer (EMC, NMC, SMC) → also supporting small x investigation and making possible a natural evolution to SIDIS → COMPASS**

Cons:
- **Beam intensity (before COMPASS), muon halo, beam chromaticity and optics**

Facilities and Experiments , from DIS to SIDIS

μ-beams Chromaticity and optics

NIM A 577 (2007) 455

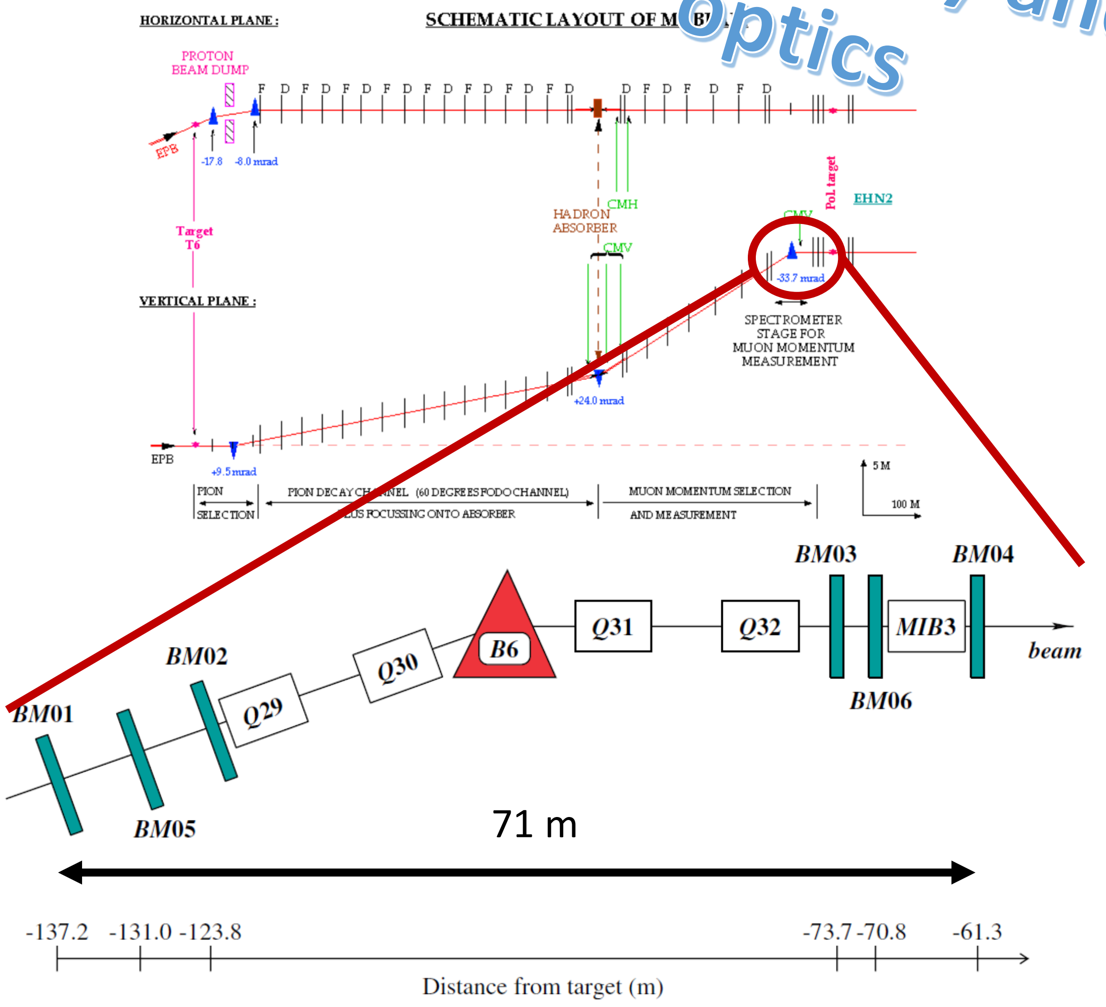
μ-beam chromaticity

Beam : Δp/p = 3% - 5% RMS

→ Measure the momentum of each beam particle : Δp/p < 1%

Beam size at the target:

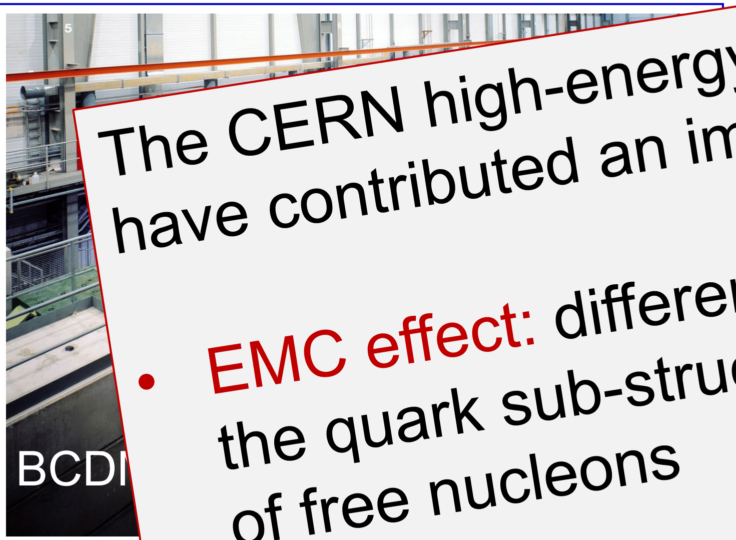
Spot size at COMPASS target ($\sigma_x \times \sigma_y$)	$8 \times 8\,\mathrm{mm}^2$
Divergence at COMPASS target ($\sigma_x \times \sigma_y$)	$0.4 \times 0.8\,\mathrm{mrad}$
Muon halo within 15 cm from beam axis	16%
Halo in experiment ($3.2 \times 2.5\,\mathrm{m}^2$) at	7%



Facilities and Experiments , from DIS to

Usi…

…nergy



The CERN high-energy muon beam and the open spectrometer detectors have contributed an important portion of what we know about QCD:

- **EMC effect:** different scattering rates off D and Fe ←→first evidence that the quark sub-structure of nucleons bound in nuclei is different from that of free nucleons
- **Proton spin-crisis:** evidence that only a small portion of the N spin is carried by quarks and that the strange quark see is polarized
- **Proving the Bjorken sum rule**: the SR relates the N spin structure functions to the nucleon axial charge (stated in 1966, experimentally confirmed in 1993 !)

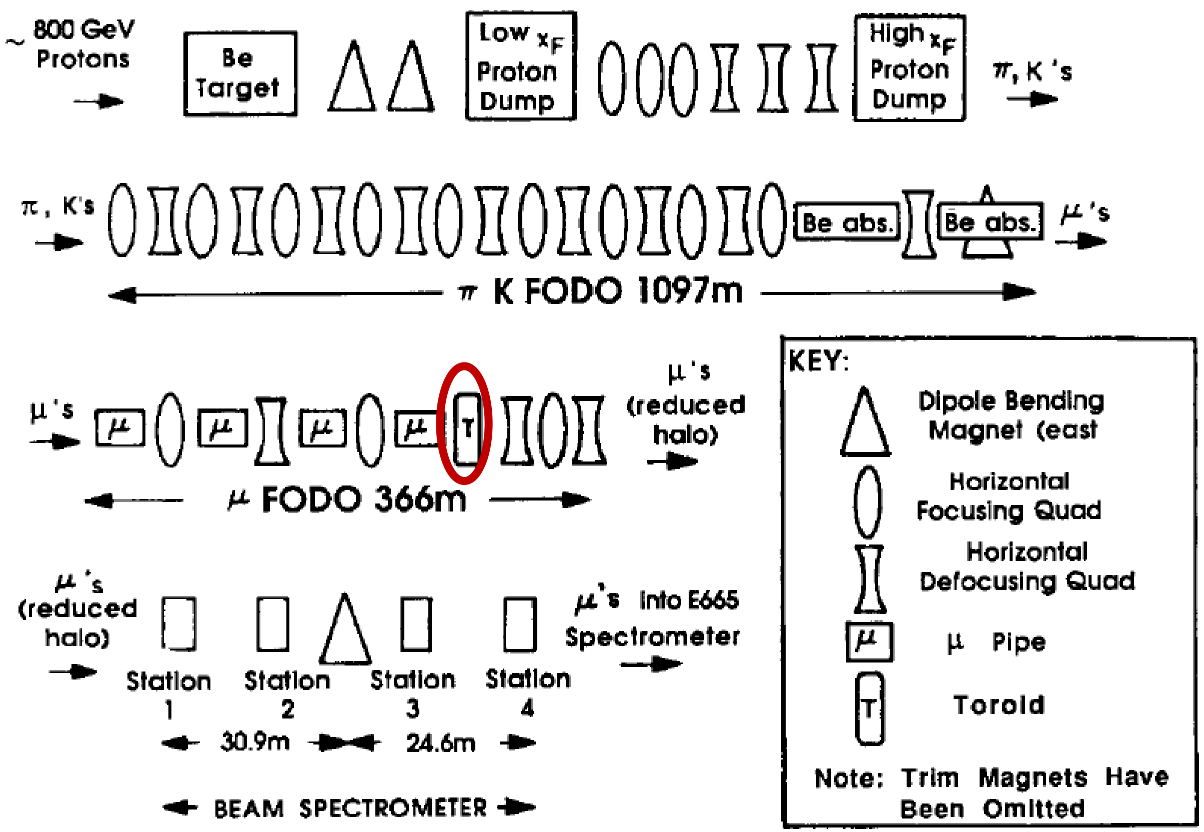
…am intensity (before COMPASS), muon halo, beam optics

Facilities and Experiments , from DIS to SIDIS

Using high-energy μ-beams

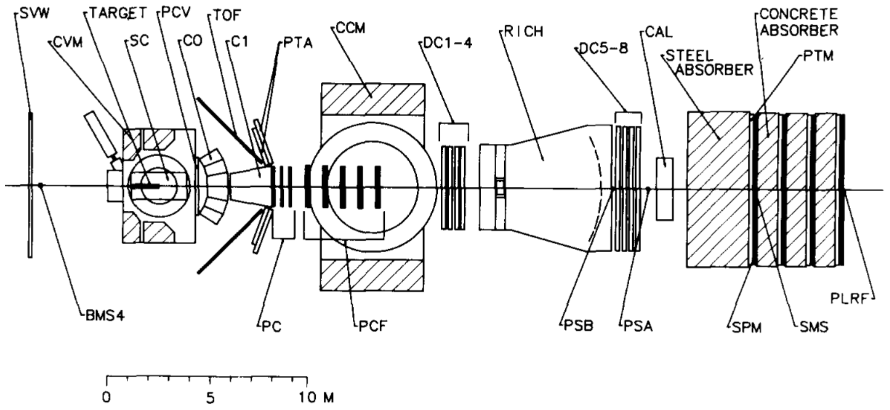
NIM A291 (1990) 533

μ-beam line using an extracted p-beam from the TEVATRON fix target operation



FNAL E665 :
1987-1992

- Secondary μ-beam at Tevatron fix-target, E up to 500 GeV
- Open spectrometer



To remark:

- First time that an extended PID system (ToF, 2 threshold Č, a gaseous RICH) in included in a DIS setup ↔ exclusive vector meson production as part of the physics program

Facilities and Experiments , from DIS to SIDIS

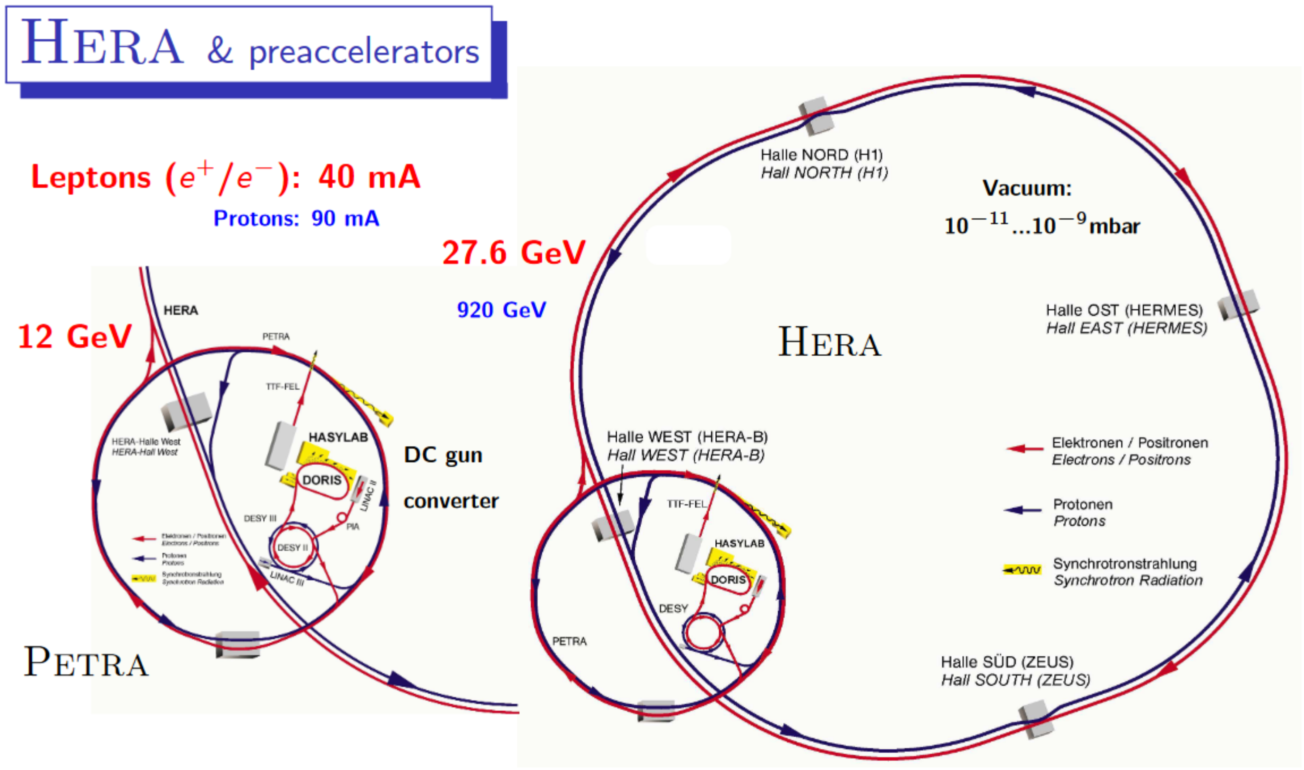
BCDMS

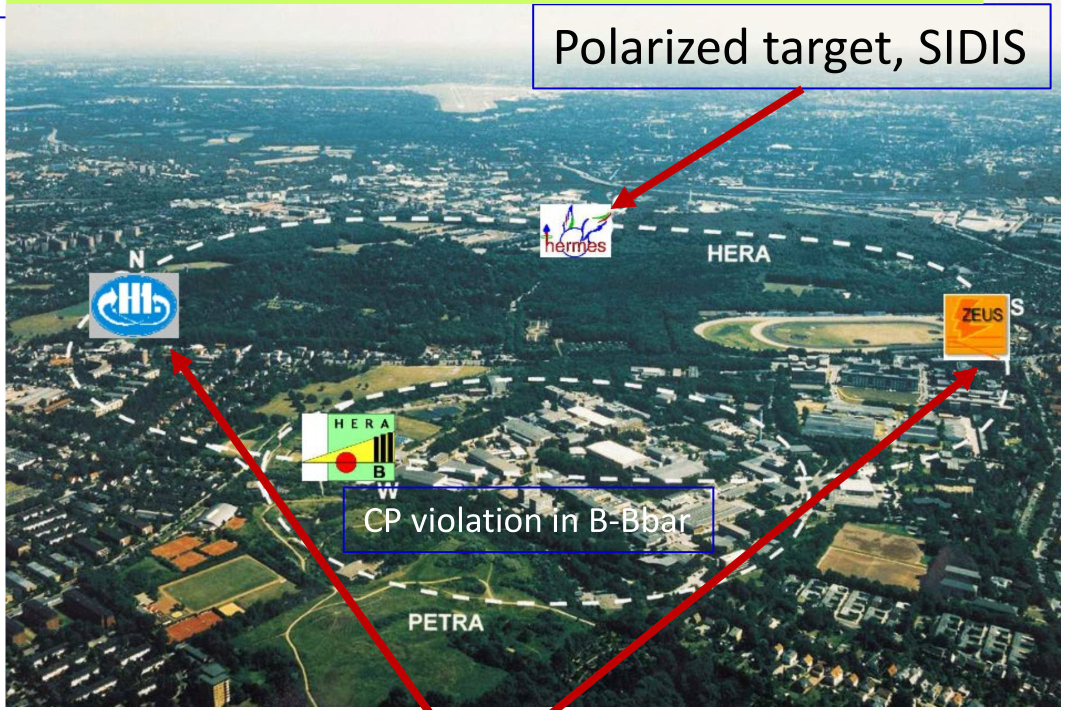
HERA (**H**adron-**E**lectron **R**ing **A**ccelerator) at DESY (Hamburg, D)

- 1992-2007
  - HERA I (till 2000)
  - HERA II (from 2001) with increased luminosity (x 4.7)
- The first and, so far, unique e-p collider

A collider for DIS studies

- Collisions of 27.5 GeV polarized electrons(positrons) on 920 GeV protons
- Bunch crossing every 96 ns
- Luminosity 10^{31} cm^{-2} sec^{-1}





Polarized target, SIDIS

DIS studies at the highest energies
- Access to a wide kinematic domain

Facilities and Experiments , from DIS to SIDIS

A collider for DIS studies

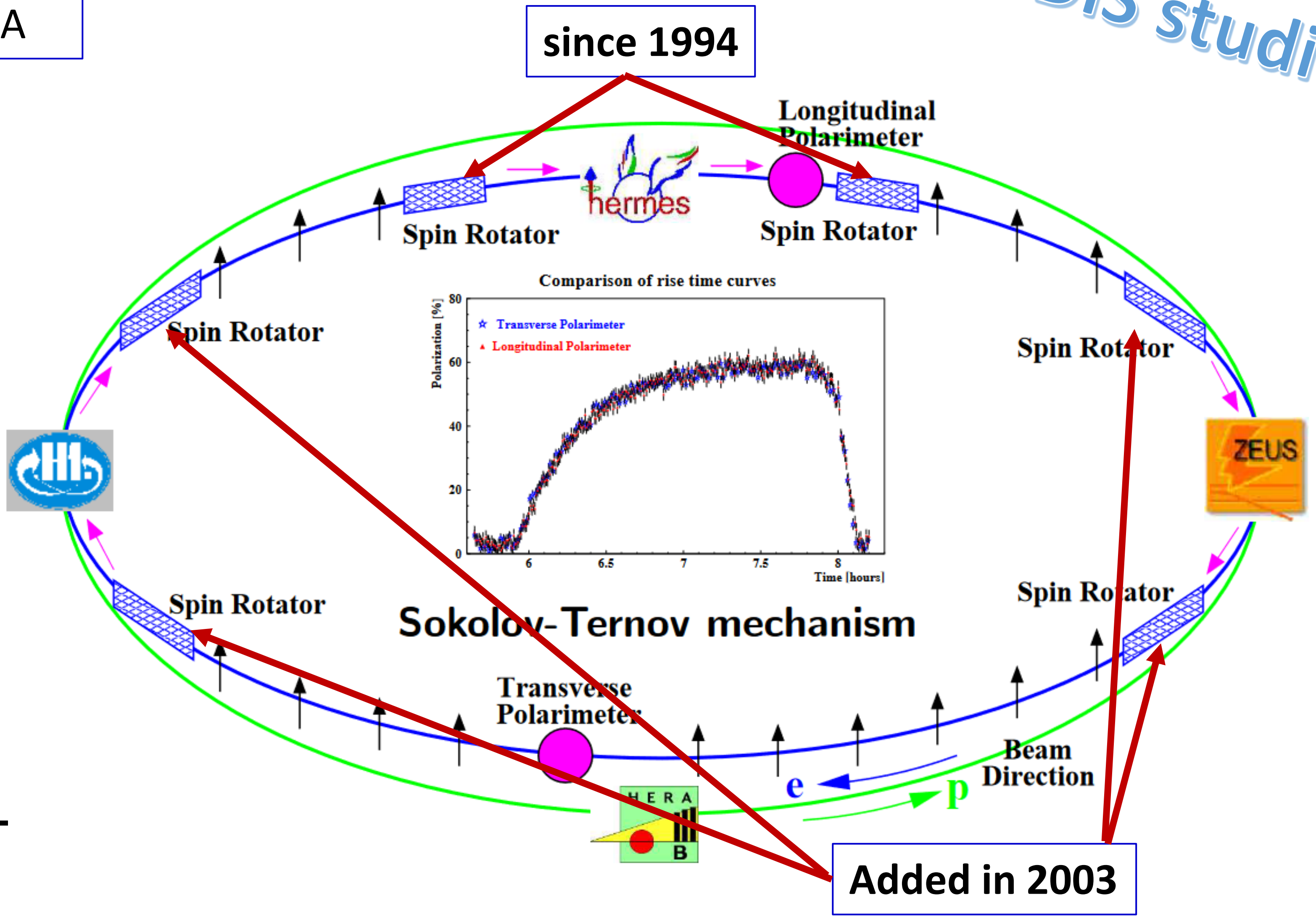
BCDMS

Lepton beam **polarization** at HERA

The **Sokolov–Ternov effect** is the self-polarization of relativistic electrons or positrons moving at high energy in a magnetic field. The self-polarization occurs through the emission of spin-flip synchrotron radiation.

The magnetic field creates an asymmetry in the spin-flip rates:

e+ (e−) align parallel (anti-parallel) to H



Facilities and Experiments , from DIS to SIDIS

e-beam polarimeters at HERA

BCDMS

Lepton beam **polarimetry** at HERA

1994 - Lpol: 1000 γ x BX measuring the **energy asymmetry** in crystal calorimeter (COMPTON scattering). Single γ for calibration.

NIM A 479 (2002) 334

1996 - Tpol: single photon mode measuring **space asymmetry** with sampling calorimeter.

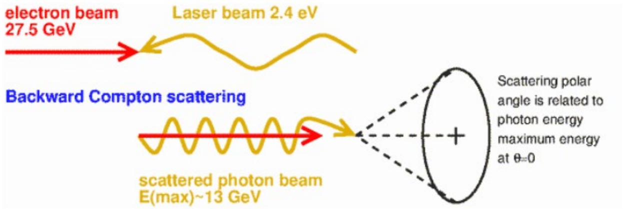
NIM A329 (1993) 79

2006 - Fabry-Perot Lpol: increase the statistical precision thanks to the addition of the cavity

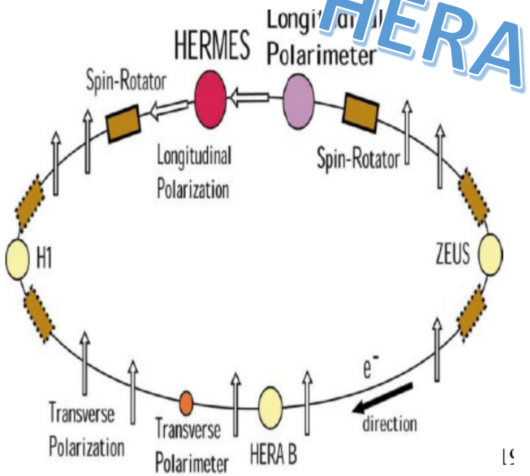
JINST 5 (2010) P06005

$$\frac{d\sigma}{dE_\gamma} = \frac{d\sigma_0}{dE_\gamma}\left[1 - P_\lambda P_e A_z(E_\gamma)\right]$$

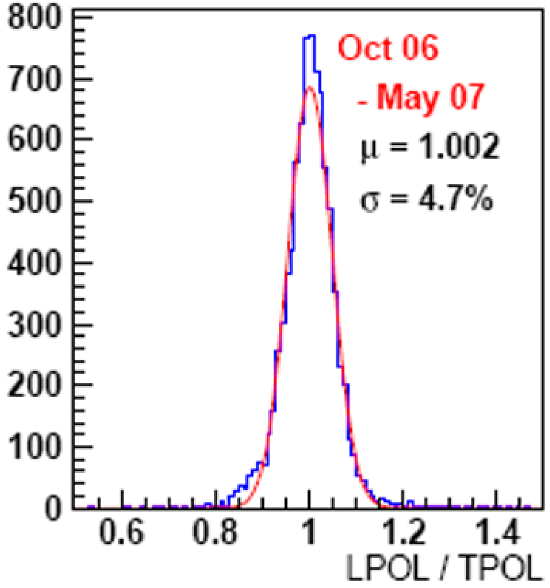
- Make use of backward Compton scattering off a laser beam



- Laser helicity is flipped regularly
- Polarization is proportional to the difference between cross section data with opposite laser helicity



Measure electron polarization to few % with the Compton polarimeter



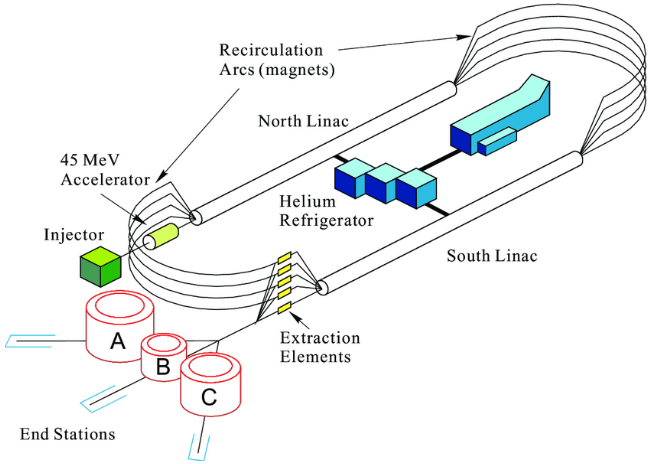
Facilities and Experiments , from DIS to SIDIS

BCDMS

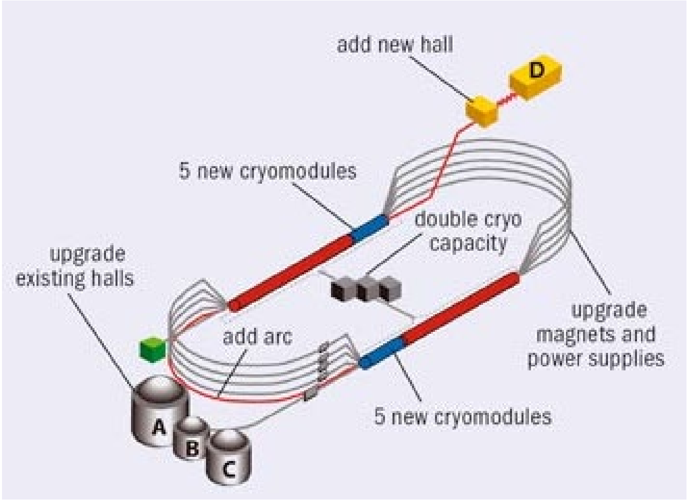
Intense e-beam

CEBAF (Continuous Electron Beam Accelerator Facility) at Jefferson Lab

- The 6 GeV accelerator
  - 0.6-6 GeV electrons
  - 3 experimental halls (Hall-A, -B and C)
  - Almost continuous beams, ~ 100% duty cycle
  - Years: 1995 – 2012



- The 12 GeV electrons
  - Up to 12 GeV
  - Upgrade of the 3 experimental Halls
  - Addition of a 4th Hall (Hall-D) dedicated to photoproduction experiments
  - Years: from 2014, from 2017 with upgraded Halls



Facilities and Experiments , from DIS to SIDIS

BCDMS

CEBAF
Polarized e-beam

Polarized e-beams at CEBAF

A series of 3 sources

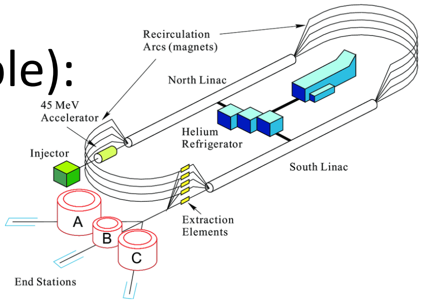
- GaAs treated to have a negative electron affinity (NEA) as e-source
  - photoemission using monochromatic circularly polarized laser light
  - Making photocathode life-time longer by improving vacuum and photocathode preparation

	First photoinjector	Second photoinjector	Third photoinjector
Date	Feb. 1995–Jan. 1998	Feb. 1998–June 1999	July 1999 to present
Charge lifetime (C)	<10	~100	200
Charge density lifetime (C/cm^2)	~10^4	~10^5	2×10^5
Polarization	~35%	70%–75%	>80%

ACCELERATORS AND BEAMS **10**, 023501 (2007)

Managing beam polarization in the accelerator

- At CEBAF, net spin precession only in the horizontal plane (any spin orientation possible):
  - no net vertical bend between the injector and the experimental hall beam lines
  - no energy difference between pairs of equal and opposite vertical bends
- negligible loss of polarization between the injector and the experimental halls



Facilities and experiments (I), OVERVIEW

- Introduction

- From DIS to SIDIS
  - With focus on spin-effect measurements: polarized targets

- SIDIS-dedicated Experiments:

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- Take-away messages

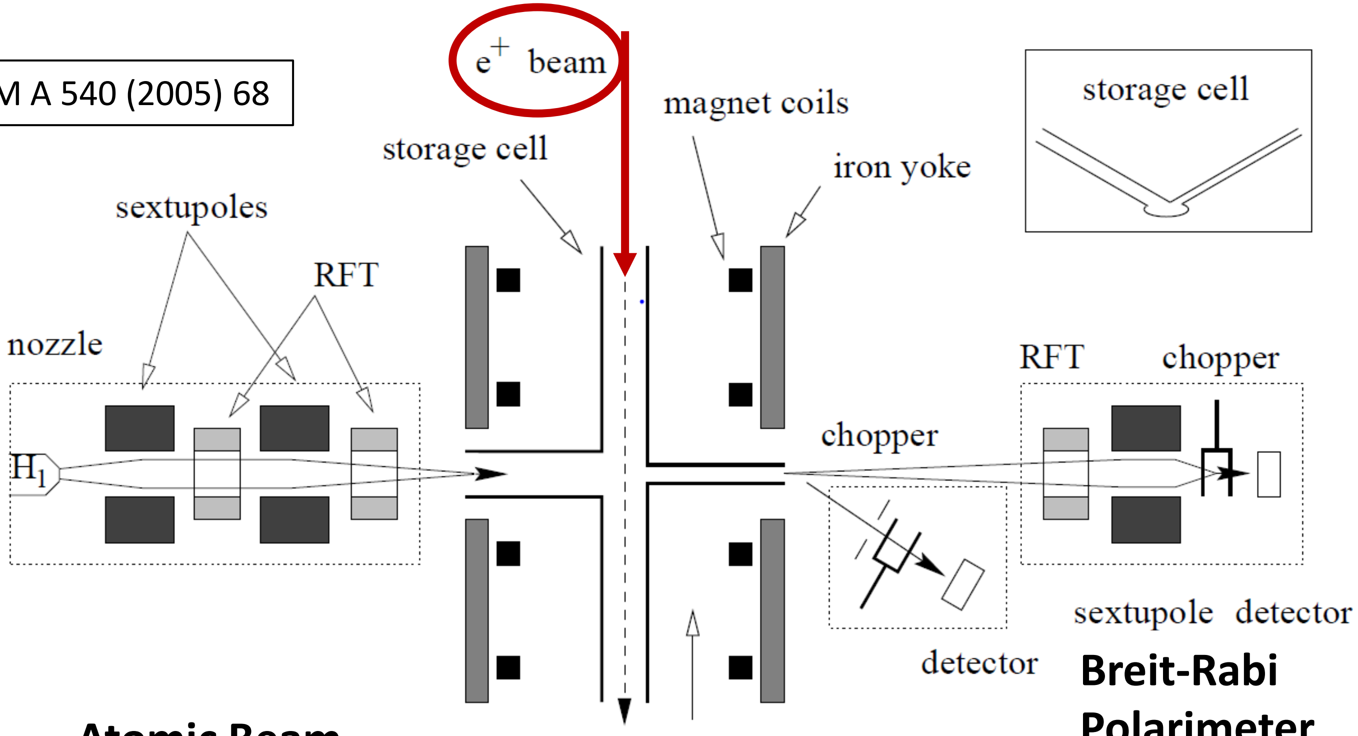
Facilities and Experiments , from DIS to SIDIS

HERMES: Fixed target at HERA

BCDMS

The HERA polarized lepton beam scattering off a gaseous polarized jet target

NIM A 540 (2005) 68



Atomic Beam Source

target chamber

- evacuated by two turbo-molecular pumps
- pressure is typically 10^{-7}mbar

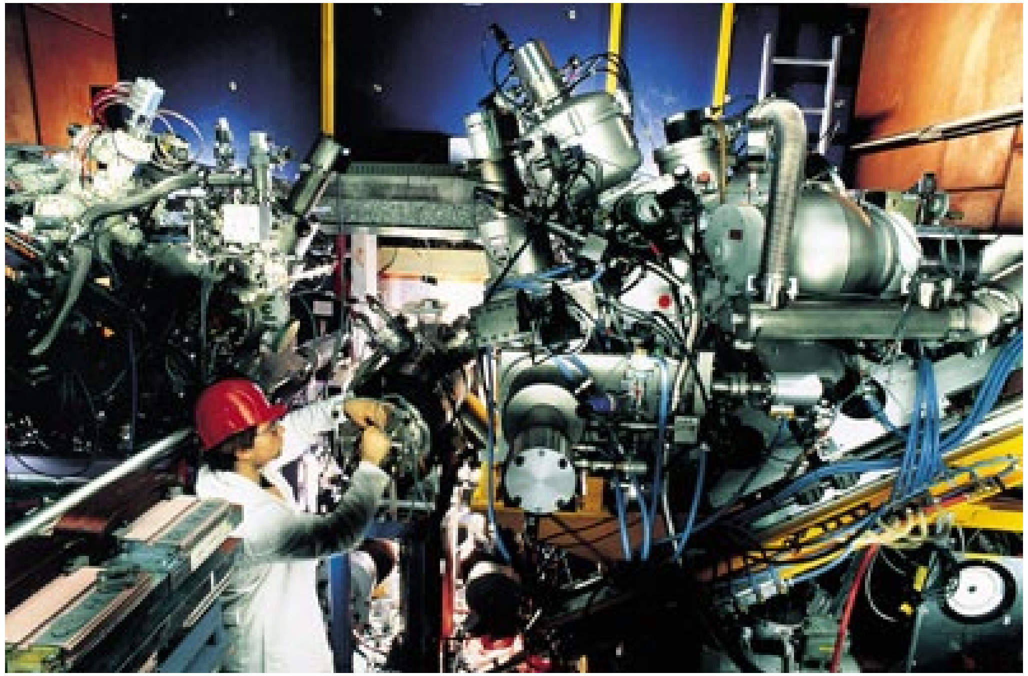
Target Gas Analyzer (relative atomic and molecular content of the gas)

Breit-Rabi Polarimeter

relative populations of the hyperfine states of H, D inducing rf transitions

A magnet surrounding the storage cell provides a holding field defining the polarization axis

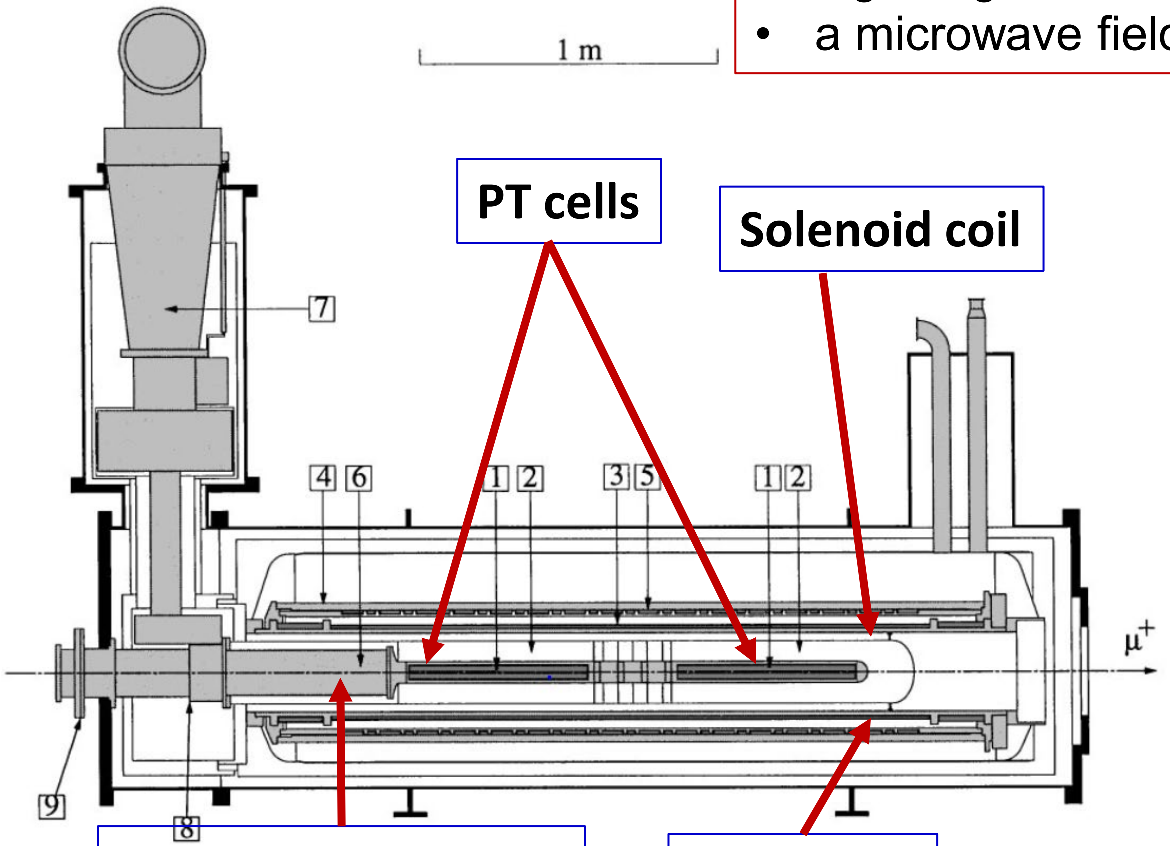
- Longitudinal polarized ^{3}He up to 1996
- Longitudinal polarization up to 2000 (H, D)
- Transverse polarization from 2002 (H)



Facilities and Experiments , from DIS to SIDIS

Solid state polarized targets

SMC polarized target,
NIMA 437 (1999) 23



Method : dynamic nuclear polarization (DNP)

- T < 1 K
- using a homogeneous magnetic field to polarize paramagnetic spins to a high degree
- a microwave field to transfer the polarization to the nuclear spins

Relevant parameters of the SMC polarized target

- 2 cells with opposite polarization, 65 cm each, 30 cm gap, 5 cm Ø
- Superconducting solenoid, 2.5 T, microwave sources at 70 GHz
- Coil superposed on the solenoid coil to produce a dipole transversal field of 0.5 T for
    - fast polarization reversal
    - transverse polarization (~50 mK to reduce relation time at 0.5 T)
- Dilution refrigerator
- nuclear magnetic resonance (NMR) system with 10 coils was designed for polarization measurement in the two target cells

Facilities and Experiments , from DIS to SIDIS

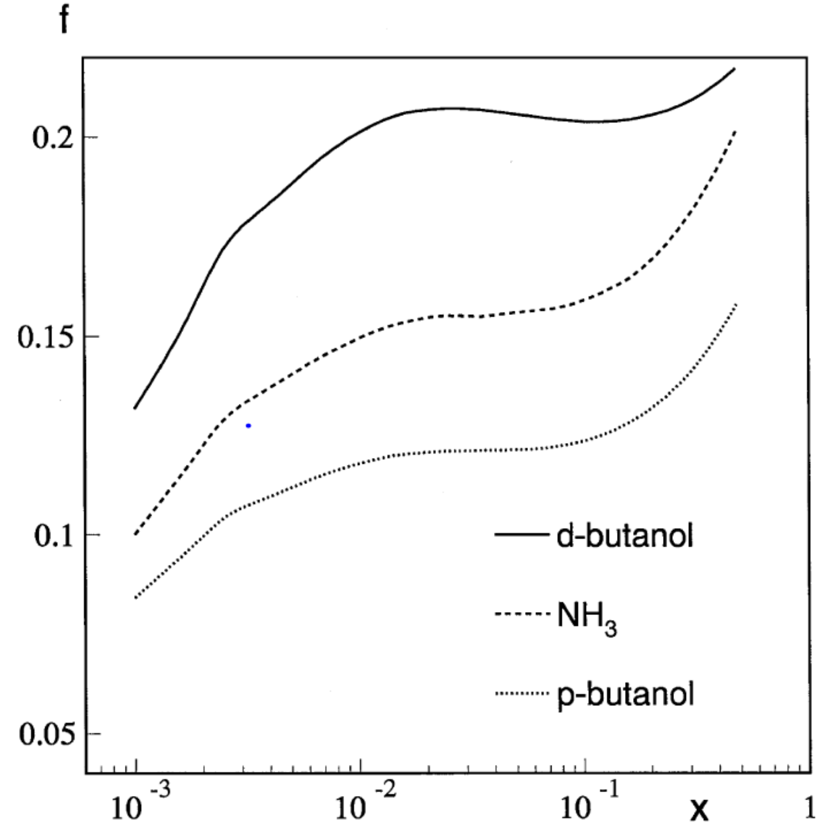
Solid state polarized targets

Target materials
- un-paired electron spins with a density in the range of 10^{19} – $10^{20}/cm^3$ are needed, obtained by
  - Chemical doping
  - Irradiation to produce free radicals
- Examples of PT target material (from SMC experience)
  - p↑: butanol (C_4H_9OH) with a paramagnetic complex
  - p↑: irradiated ammonia (NH_3)
  - n↑: deuterated butanol (C_4D_9OD) with a paramagnetic complex

Material	P_{av} (%)	$\Delta P_{av}/P_{av}$ (%)	$\tau_{0.7}$ (h)
Butanol	86	3.2	1.5
d-Butanol	51	2.0	2.5
Ammonia	89	2.7	3.5

Dilution factor f

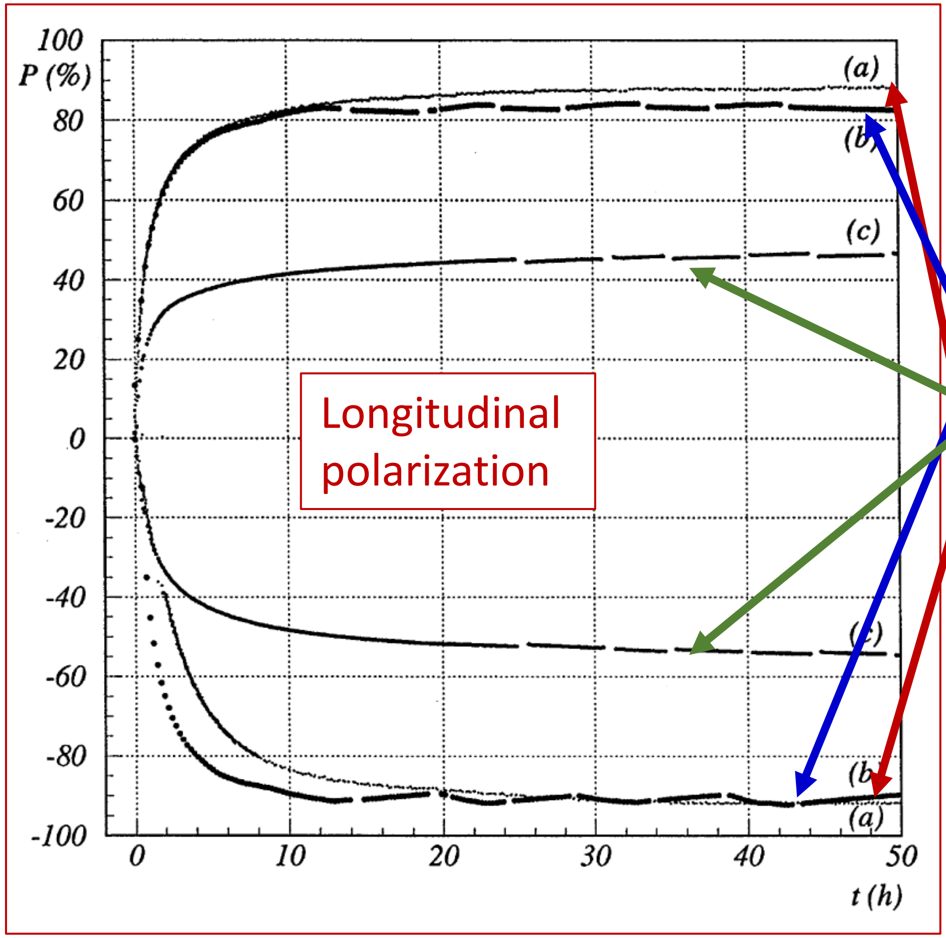
$$f = \left(1 + \sum_A \frac{n_A \cdot \sigma_A}{n_{p(d)} \cdot \sigma_{p(d)}}\right)^{-1}$$



Facilities and Experiments , from DIS to SIDIS

Solid state polarized targets

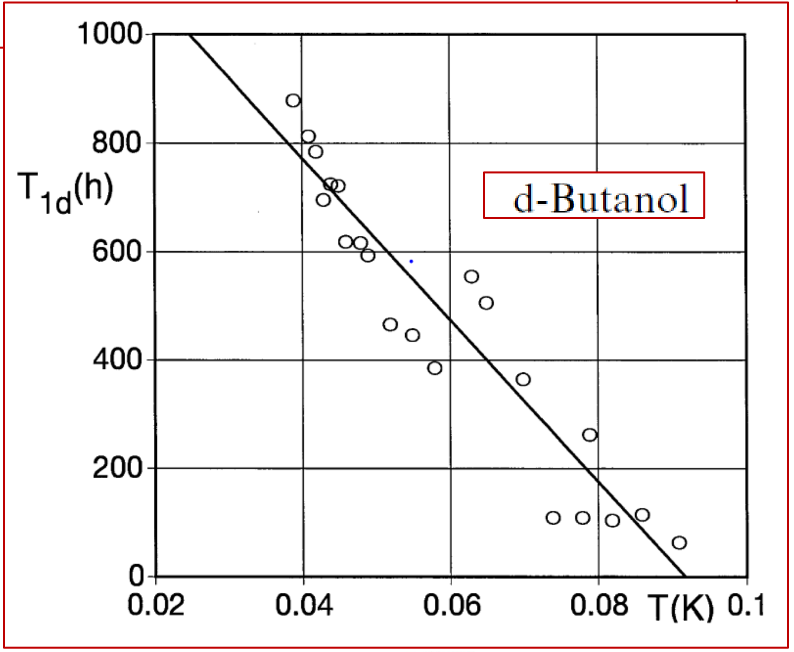
Polarized target in operation at the experiments
(still from SMC example)



Transverse polarization (frozen spin mode)

Relaxation times function of magnetic field intensity and temperature; at 50 mK and 0.5 T :

- Butanol : 1000 h
- D-butanol : 600 h
- Ammonia : 500 h



Polarized targets for TMD studies with fix target experiments

Where ?	experiment	lepton beam	polarized nucleon	also transversal polarization	target type	target material	reference	notes
CERN	EMC	μ	p		solid state	NH_3		
	SMC		p	Y		C_4H_9OH	NIM A 437 (1999) 23	
						NH_3		
			n			C_4D_9OD		
	COMPASS		p	Y		NH_3	NIM A 1025 (2022) 166069	
			n			^6LiD	NIM A 498 (2003) 101	
SLAC	E143	e	p	Y	solid state	NH_3	NIM A 356 (1995) 9	
			n			ND_3		
	E142		p		gaseous	^3He	NIM A 356 (1995) 148	
	E154		p				NIM a 402 (1998) 247	
DESY	HERMES		p		gaseous	^3He	NIM A 419 (1998) 16	internal jet target
				Y		H	NIM A 540 (2005) 68,	
			n			D	NIM A 536 (2005) 244	
Jlab	Hall C		p		gaseous	^3He		
	Hall A		p	Y	solid state	NH_3	NIM A 427 (1999) 440	"UVa polarized target", also used in Hall C, foreseen also for SOLID
			n			ND_3		
	Hall B - CLAS, CLAS12		p	Y	solid state	NH_3	NIM A 684 (2012) 27	"FROST", frozen spin mode, not polarized in situ, also ^6LiH and ^6LiD
			n		solid state	ND_3		
			p, n	Y	solid state	HD	NIM A 815 (2016) 31	"HDice", frozen spin mode

SOLID STATE PTs

- μ–beams impose LONG (> 1 m) solid-state PT to preserve luminosity
  - polarization reversal requiring ~ 1h every ~1w → 2(3) cells with opposite pol.
  - Important dilution factors
  - No vertex detector
- e-beams can operate with SHORT (some cm) solid state PTs
- Frozen-spin operation
  - Target transverse polarization
  - Non in situ polarization: less demanding services at the experimental target

GASEOUS PTs

- e-beams can operate with gaseous PTs preserving luminosity thanks to the beam intensities
  - Low target density
  - Frequent polarization reversal
  - Limited dilution factor for H, D atomic gasses (molecular content at the ~20% level)

Facilities and experiments (I), OVERVIEW

- Introduction
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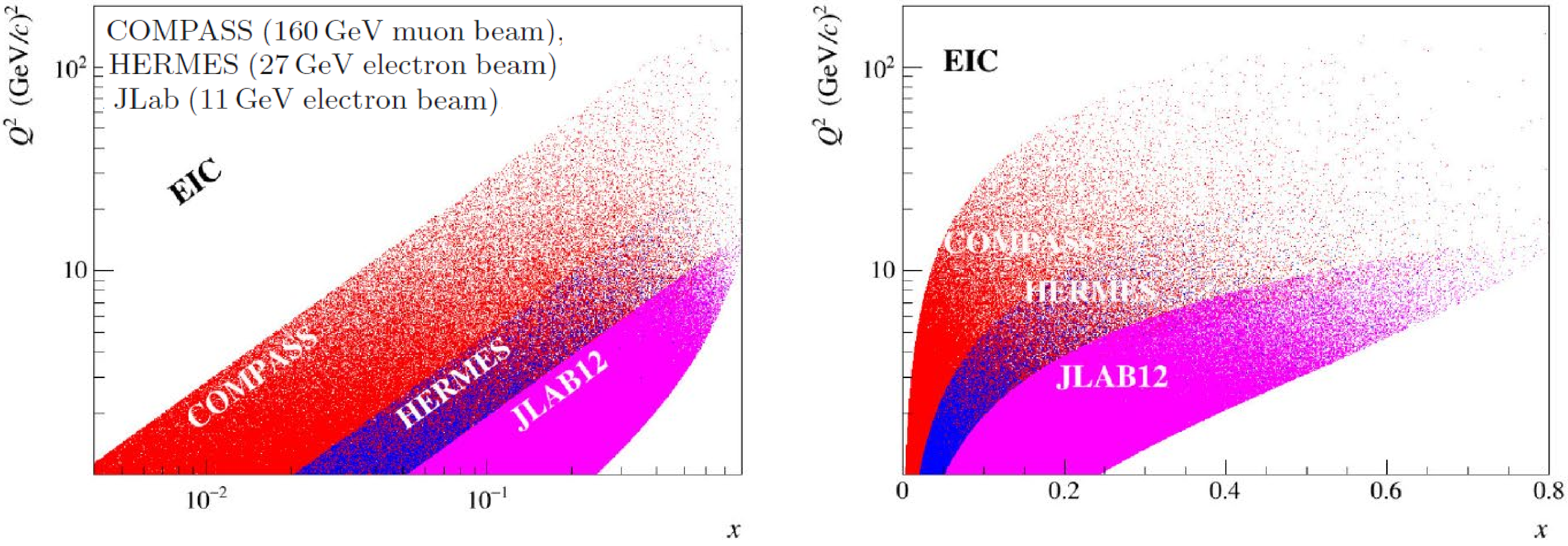
    - JLAB (fix target at CEBAF)
- Take-away messages

KINEMATIC COVERAGE

Studying TMD distributions means exploring them in a wide kinematic range

- Facilities and experiments can give access to portions of the kinematic domain of interest, typically presented in the (x, Q^2) plane; the different experimental efforts, therefore, globally offer a powerful strategy based on **complementarity**



Eur. Phys. J. A (2016) **52**: 150

Facilities and experiments (I), OVERVIEW

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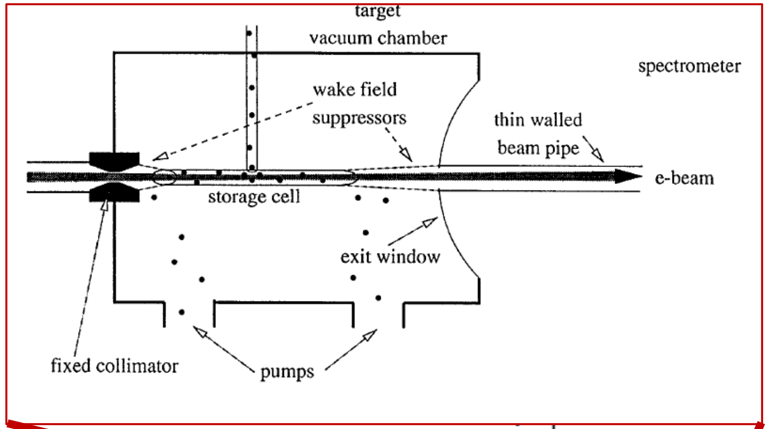
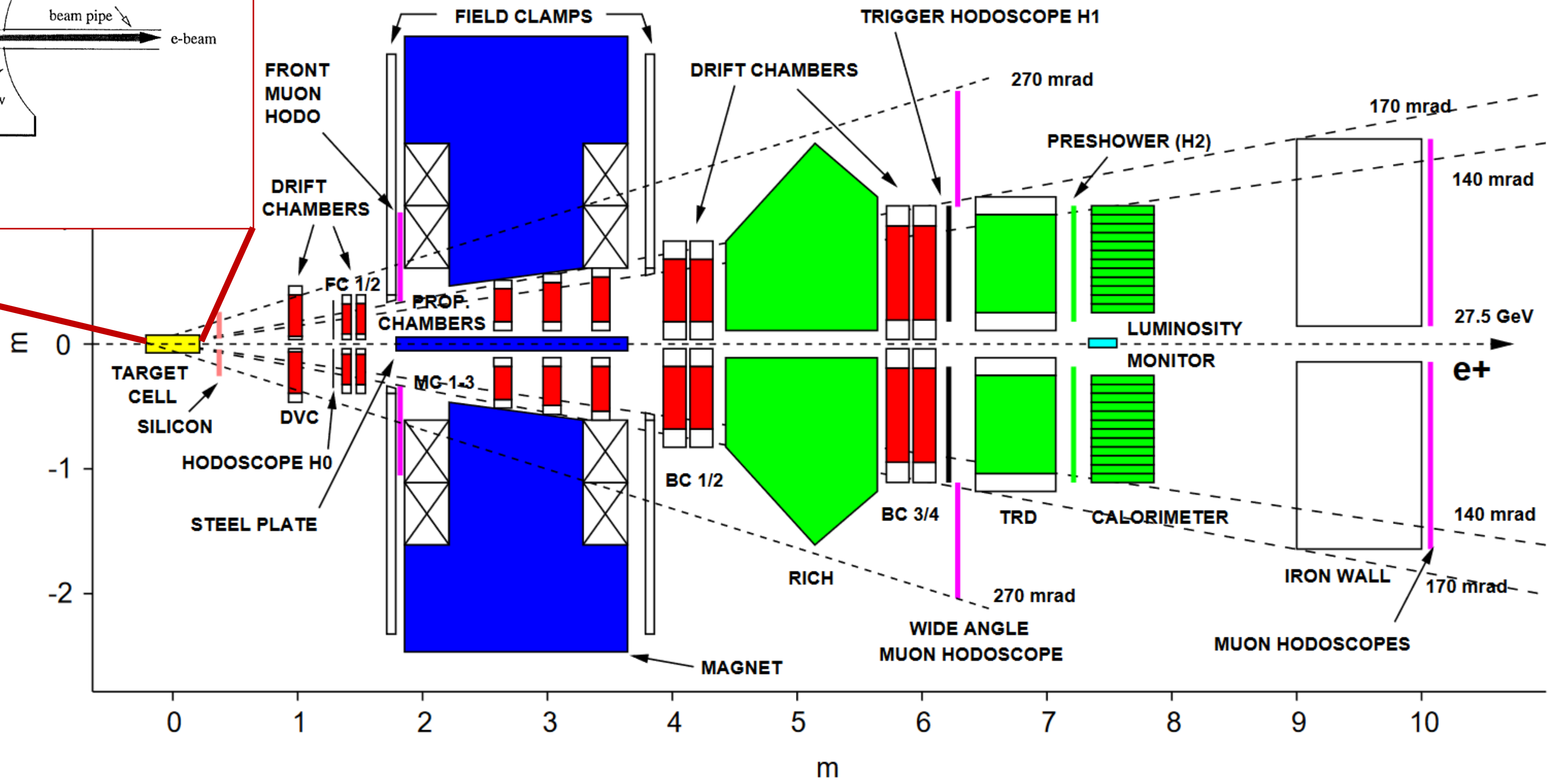
SIDIS-dedicated Experiments: HERMES

BCDMS

The HERA polarized lepton beam scattering off a gaseous polarized jet target (also non polarized targets used)

NIM A 417 (1998) 230





Angular acceptance:

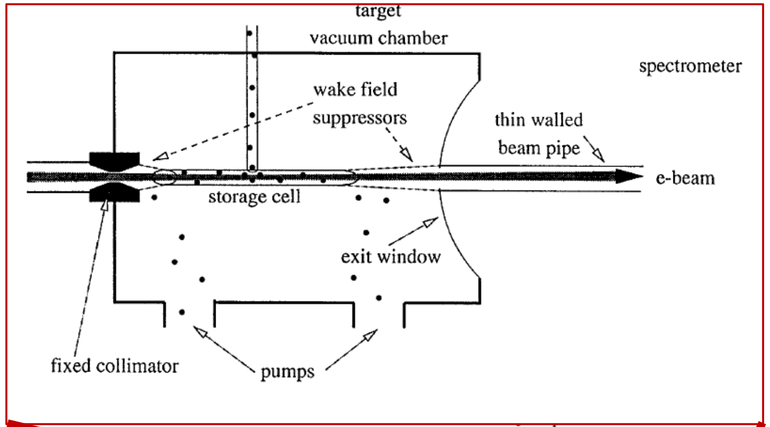
H: +/- 140 mrad
V: +/- (40-170 mrad)

Scattering angle:
40-220 mrad
(not 2 π at all angles)

SIDIS-dedicated Experiments: HERMES

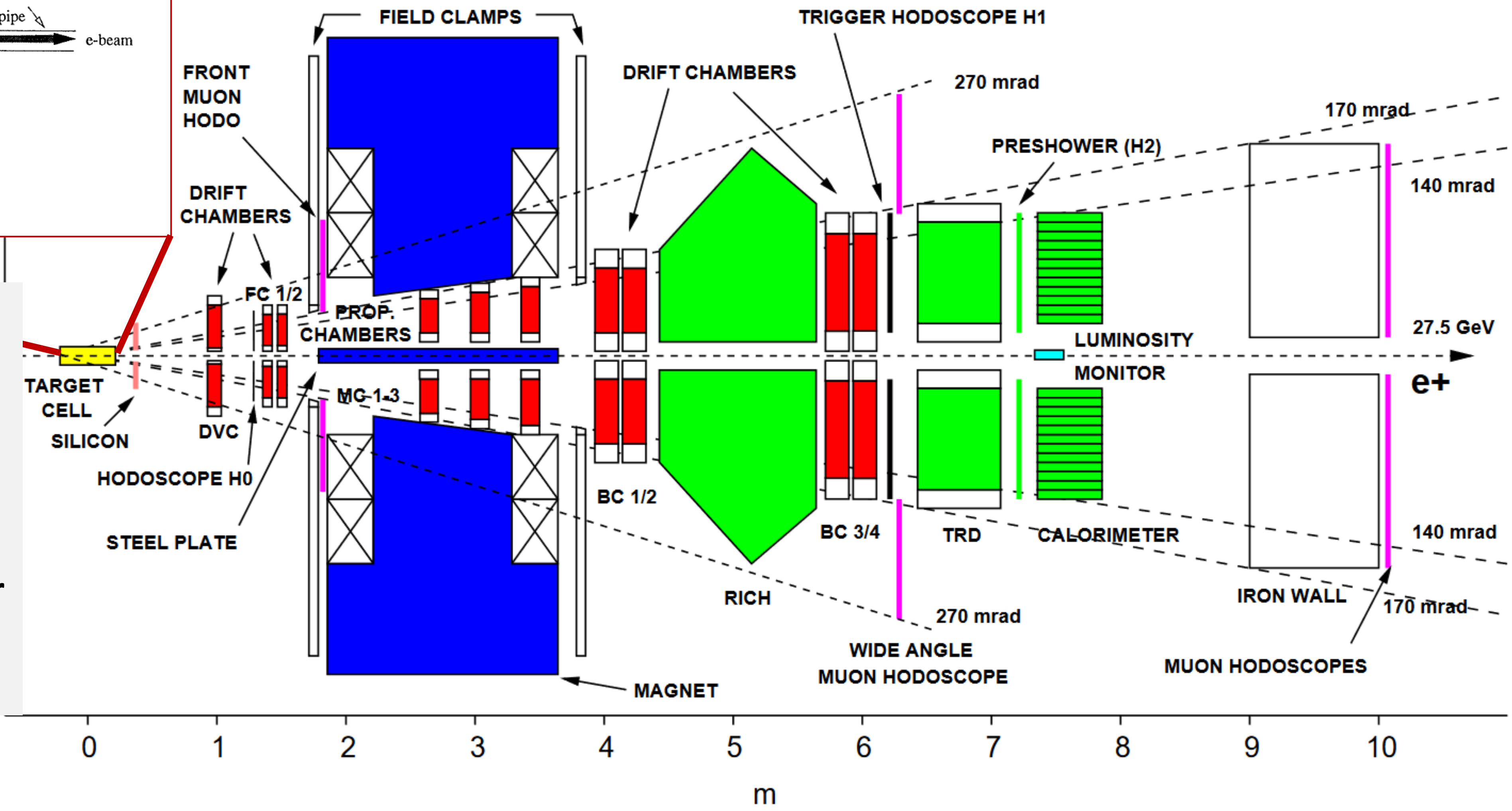
BCDMS

The HERA polarized lepton beam scattering off a gaseous polarized jet target (also non polarized targets used)



Main components:

- Trigger hodoscopes
- Spectrometer magnet
- Tracking (a variety of gaseous detectors
- EMcal with pre-shower
- An extended PID system



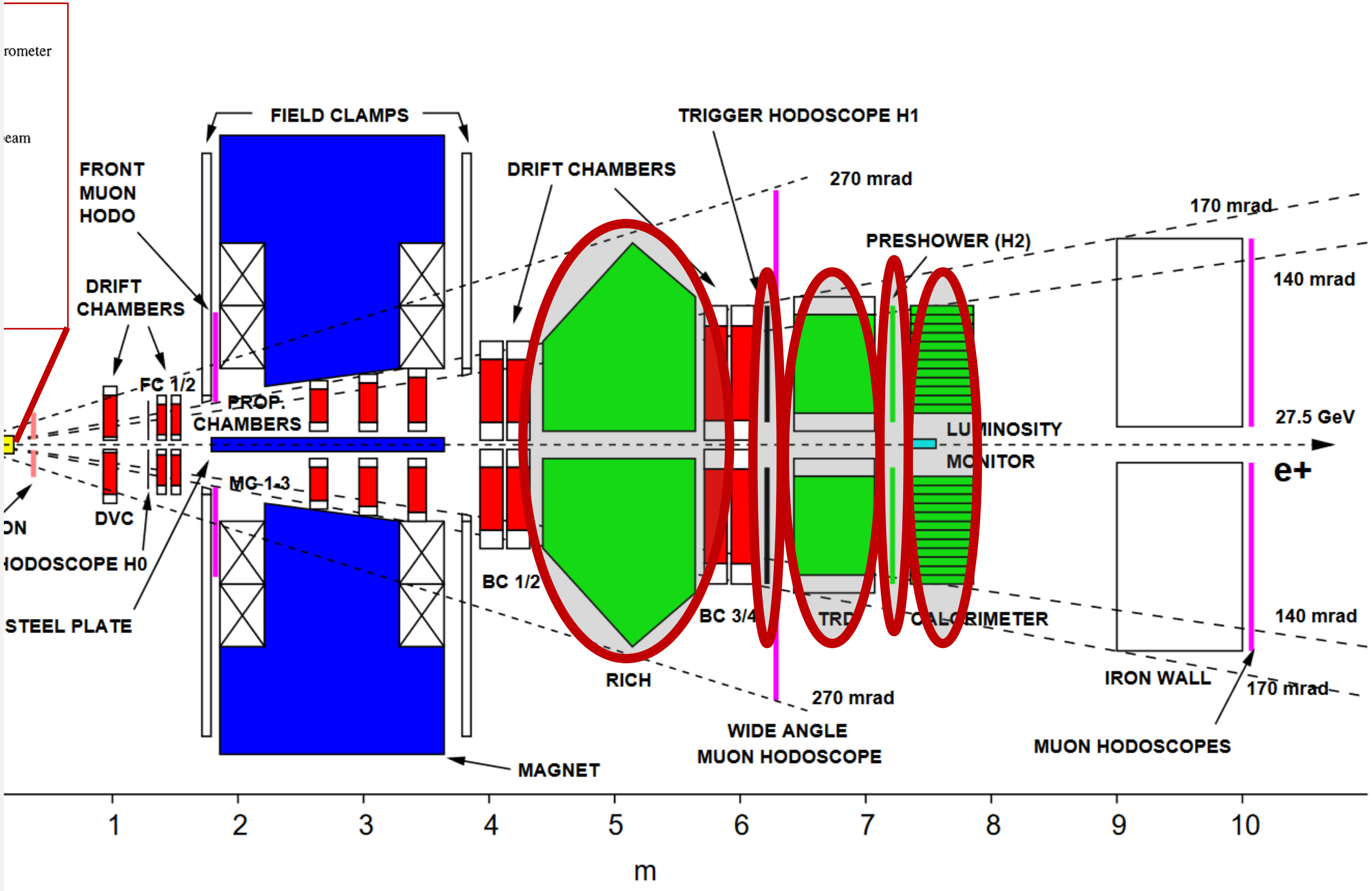
SIDIS-dedicated Experiments: HERMES

BCDMS

The HERA polarized lepton beam scattering off a gaseous polarized jet target (also non polarized targets used)

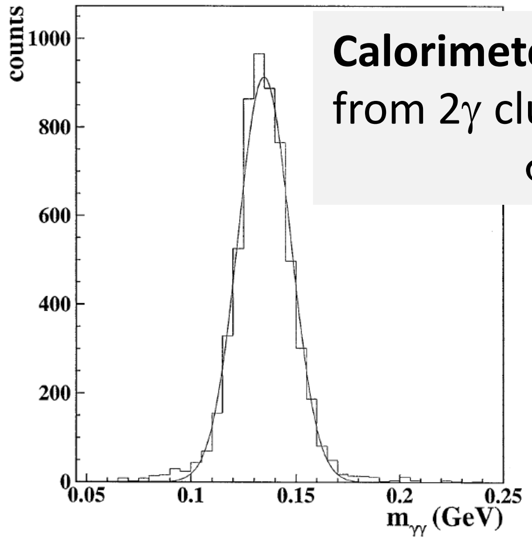
PID system:

- **EMcal** by lead glass (also used in trigger)
- **Pre-shower**, 2 X_0 lead followed by scint. Hodoscope (also used in trigger)
- **ToF** hodoscope H1
- **TRD (Transition Radiation Detector**) for momenta >5 GeV/c; 6 identical modules with radiator and MWPCs are sensors (making use of both TR and dE/dx in the Xe/CH_4)
- **Cherenkov threshold**; after 1998 **RICH**



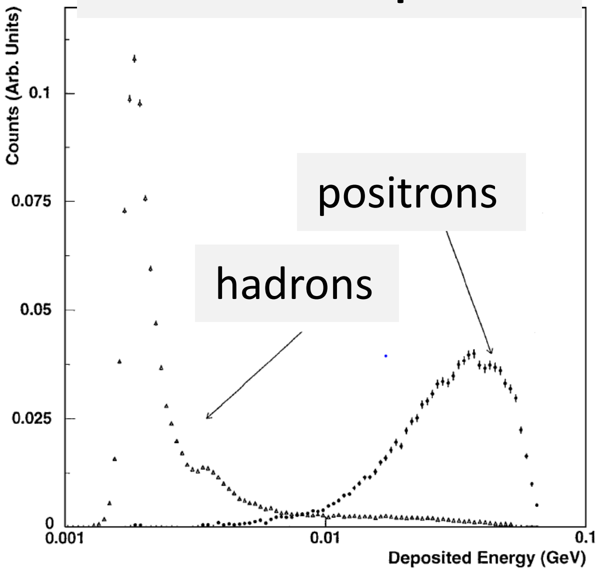
SIDIS-dedicated Experiments: HERMES

HERMES PID system, a hint about performance



Calorimeter: π^0 mass reconstructed from 2γ cluster events
σ = (12.5+/- 0.2)MeV

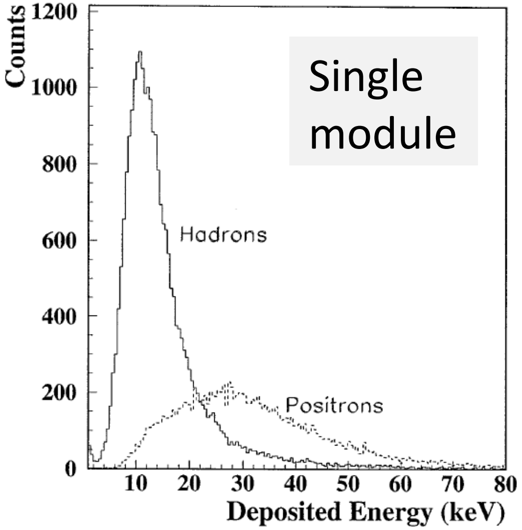
Pre-shower response



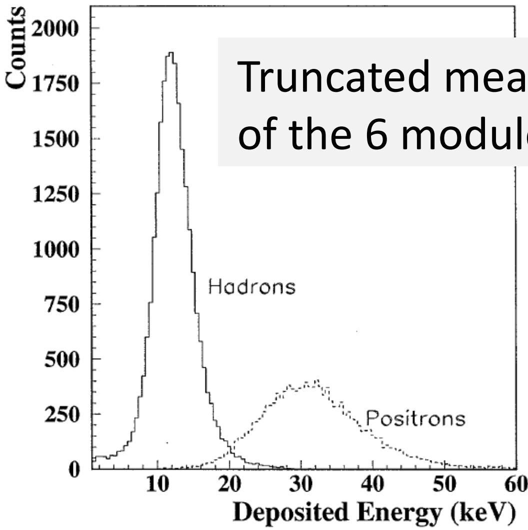
positrons

hadrons

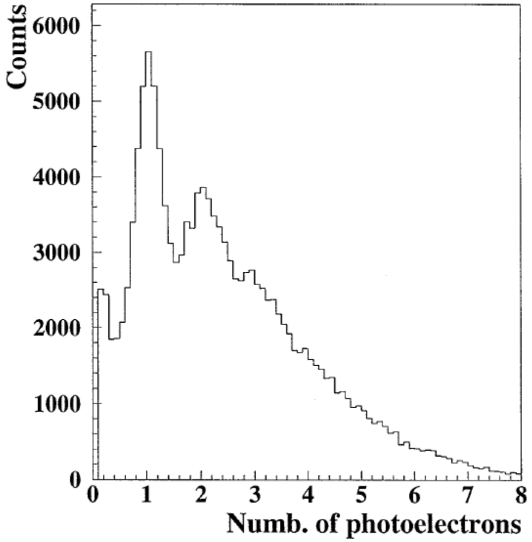
TDR



Single module



Truncated mean of the 6 modules



Threshold Cherenkov

Here with N_2

- π–threshold at 5.6 GeV
- On average, ~3 detected photoelectrons

Also used with N_2-C_4F_{10} mixture to lower the threshold

SIDIS-dedicated Experiments: HERMES

HERMES PID system, a hint about performance

- **e/h separation at trigger level (factor ~10 h rejection)**
- **e/h separation in data analysis (factor ~ 10^4)**
- **hPID identification (enhanced with the RICH) for <u>SIDIS studies</u>**

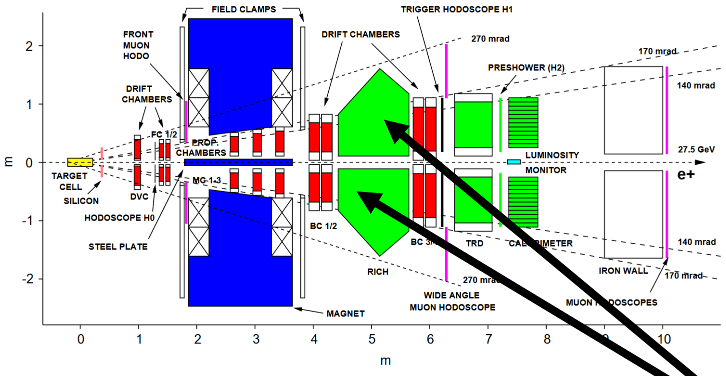
h:e production up to 400:1

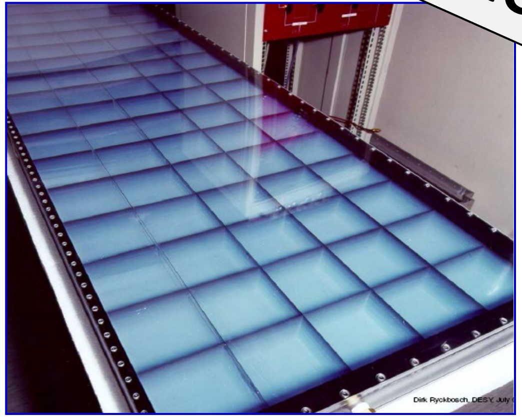
x-bin	e^+ eff. (%)	h^+ cont. (%)
0.023–0.04	97.77	1.18
0.04–0.055	98.38	0.81
0.055–0.075	98.78	0.55
0.075–0.1	99.21	0.37
0.1–0.14	99.44	0.22
0.14–0.2	99.64	0.16
0.2–0.3	99.71	0.16
0.3–0.4	99.72	0.16
0.4–0.6	99.72	0.11

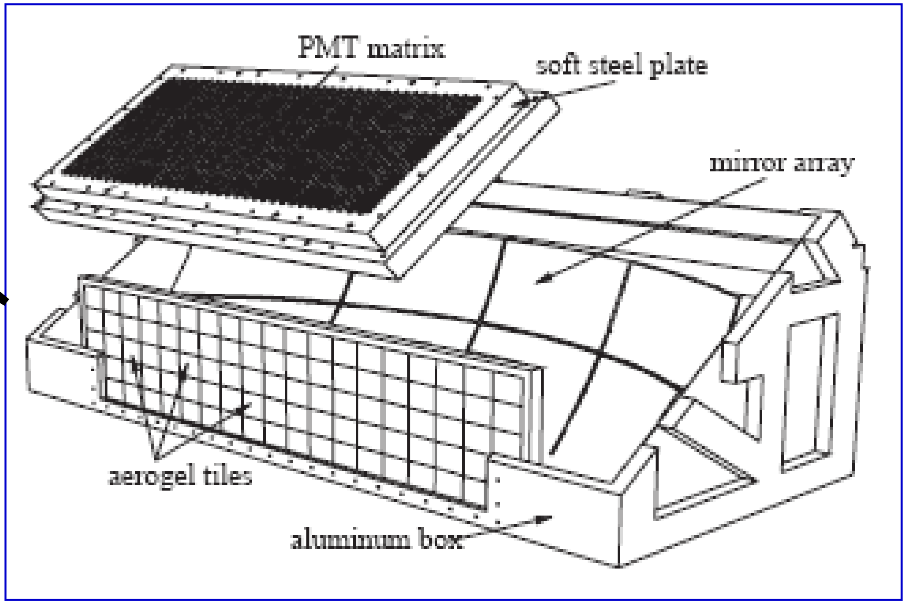
SIDIS-dedicated Experiments: HERMES

HERMES RICH

- Dual radiator configuration (following DELPHI barrel RICH)
- First RICH using aerogel, second radiator: C_4F_{10}
- HERMES: 2 identical RICH counters



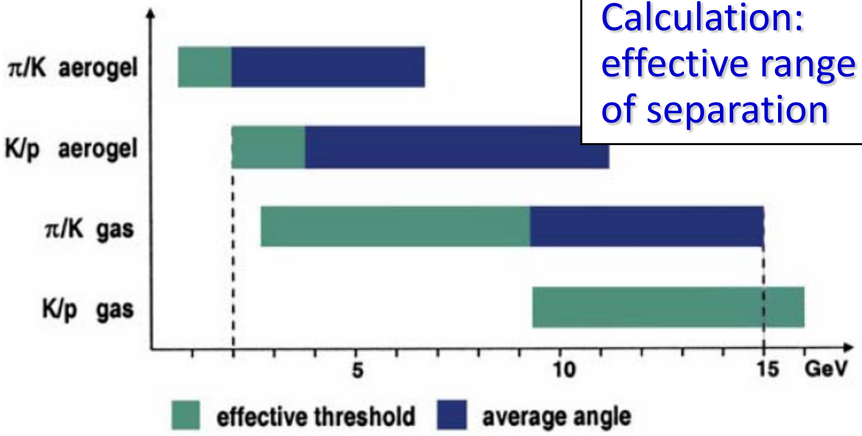


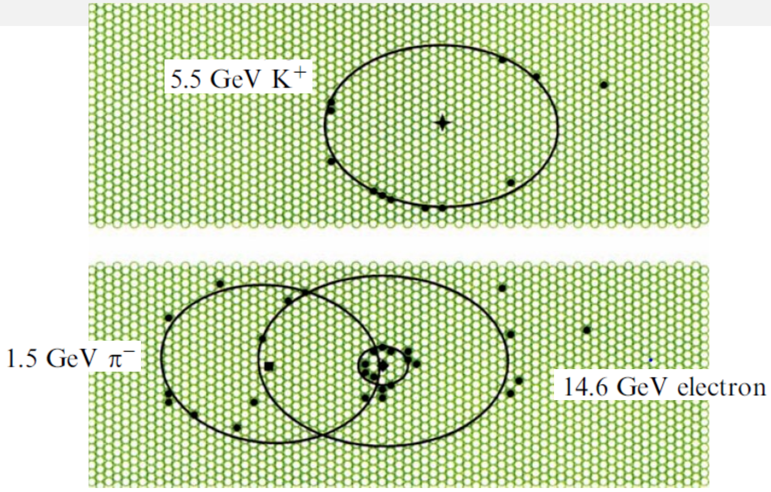


SIDIS-dedicated Experiments: HERMES

HERMES RICH

Calculation: effective range of separation



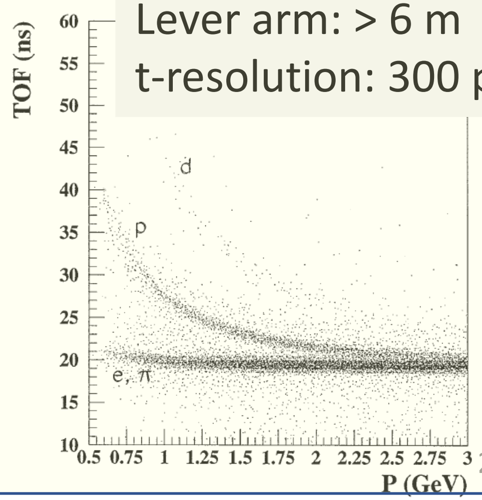


NIM A 479 (2002) 511

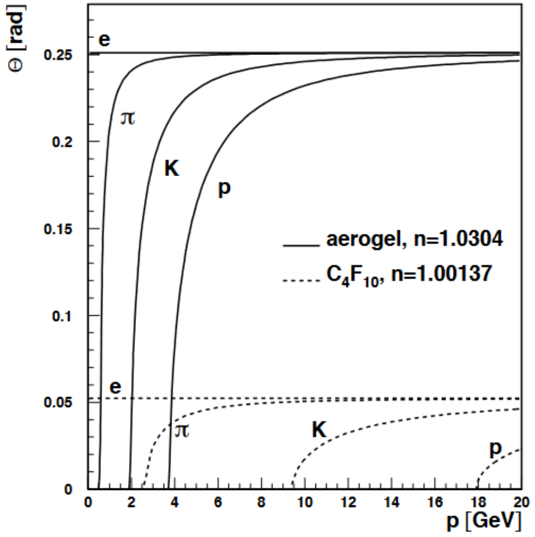
RICH complemented by ToF

Lever arm: > 6 m

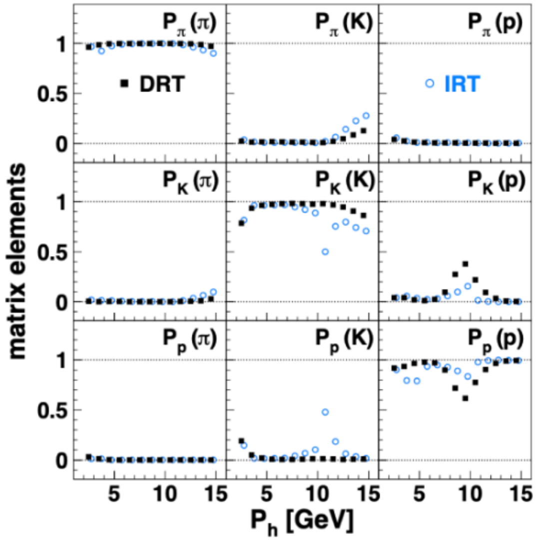
t-resolution: 300 ps



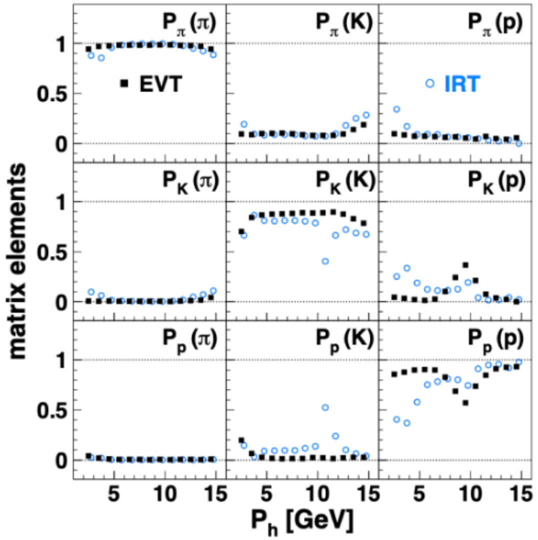
M. Diefenthaler, May 26, 2023 (internal ePIC meeting)



One hadron track in RICH half
(58% of all SIDIS events):



More than one track
(42% of all SIDIS event):



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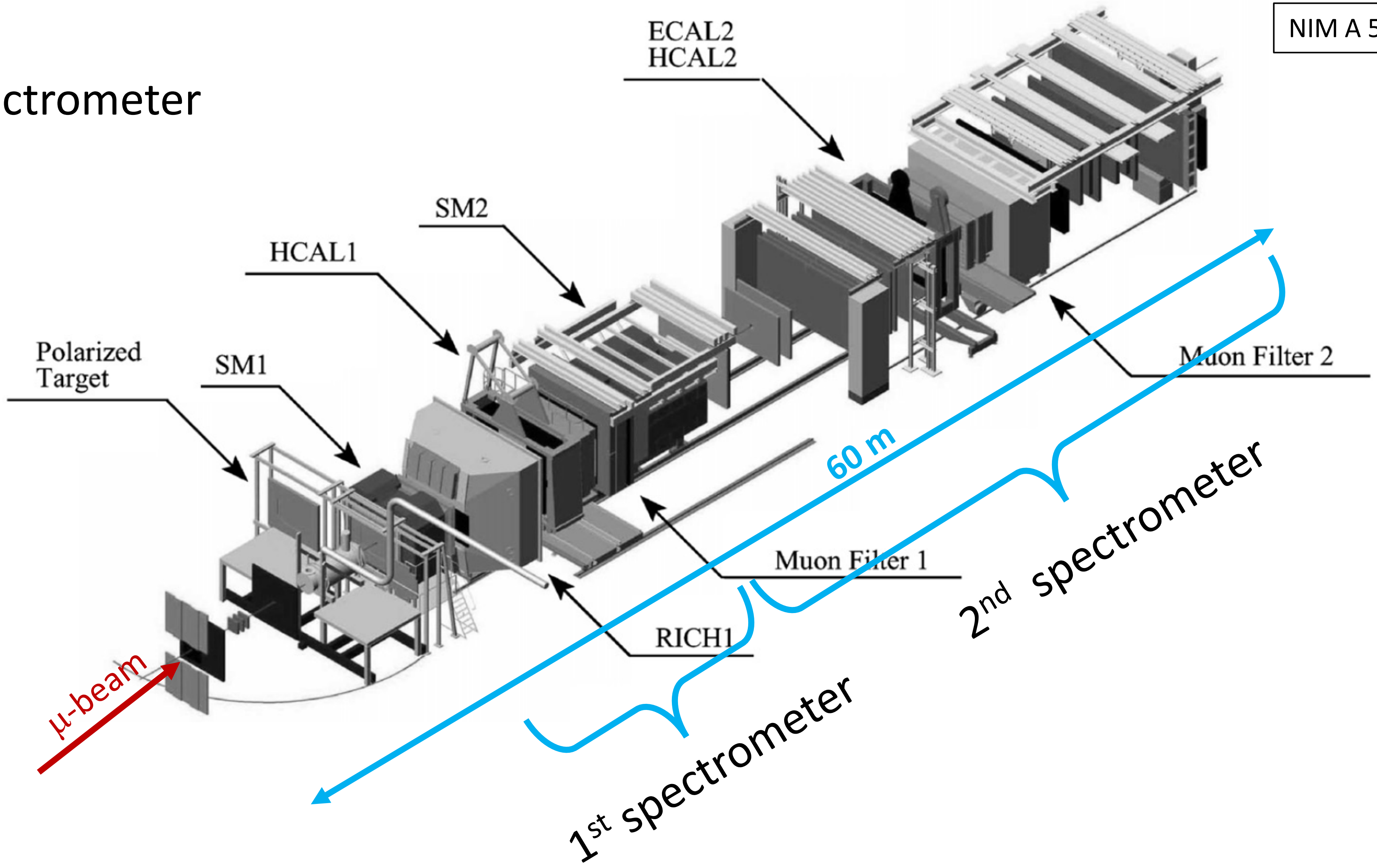
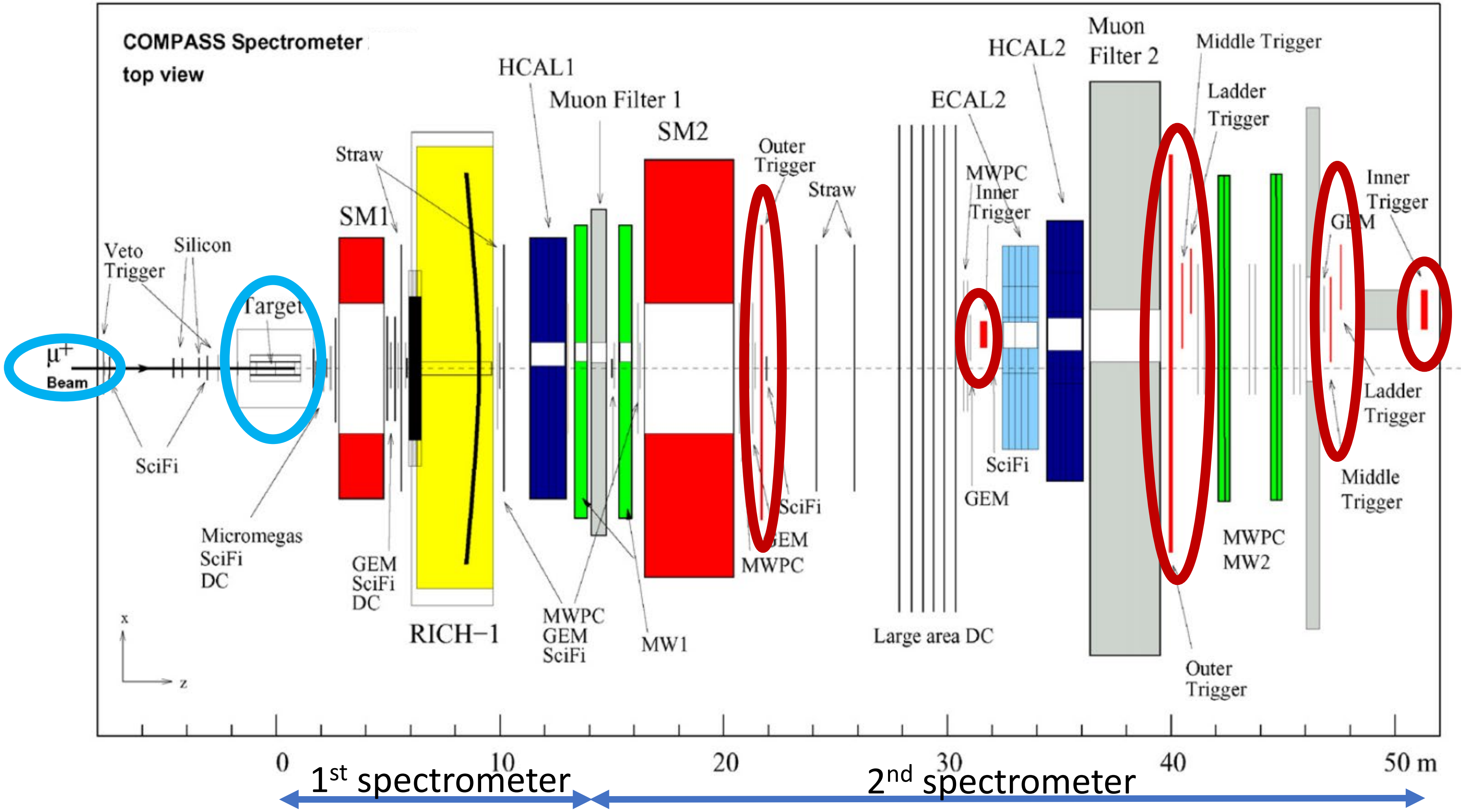
SIDIS-dedicated Experiments: COMPASS

NIM A 577 (2007) 455

2-stage spectrometer



SIDIS-dedicated Experiments: COMPASS



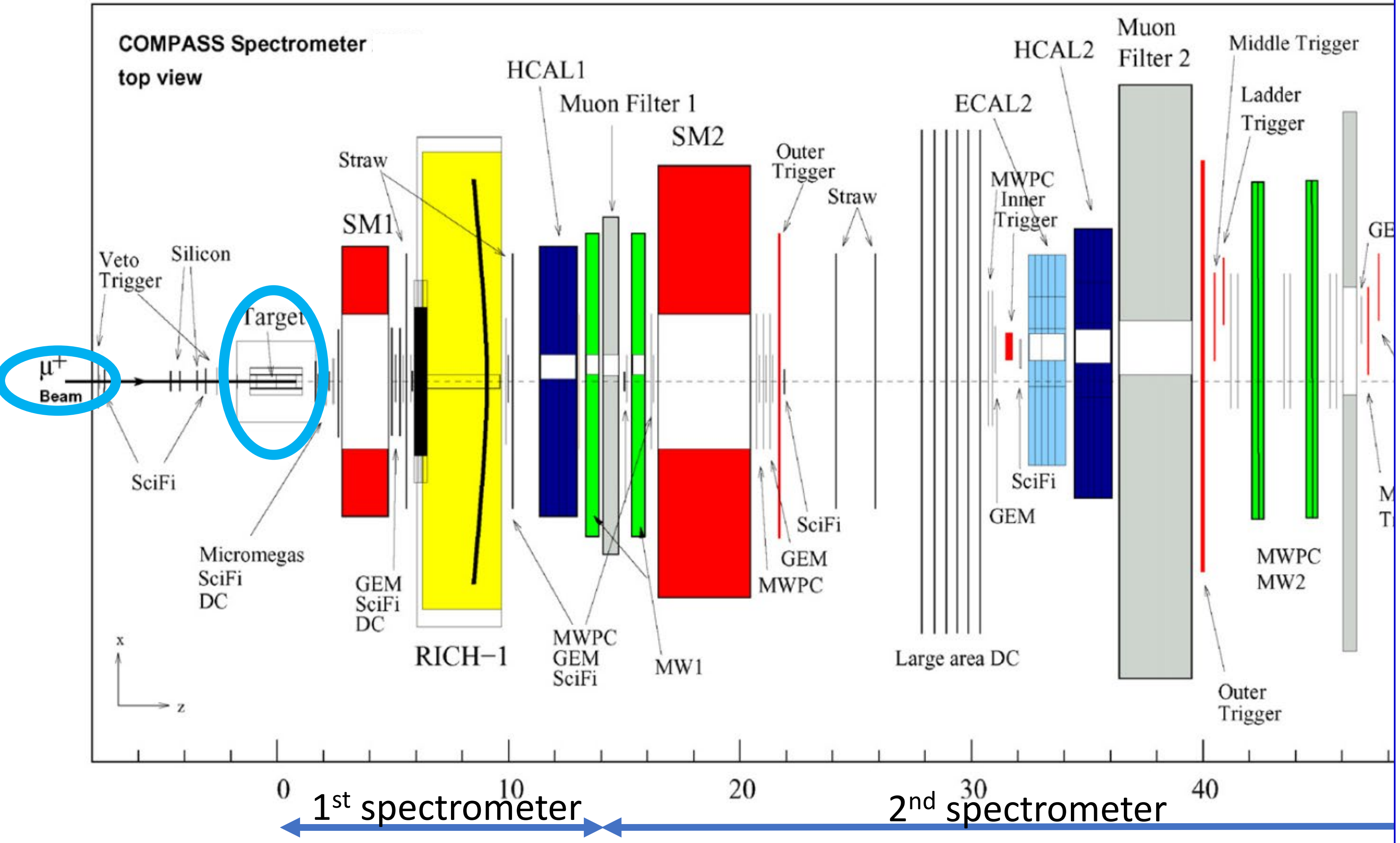
HODOSCOPES & TRIGGER

Scintillating counter hodoscopes, main components of the trigger

Veto counters by scintillator counters (beam halo !)

A stand-alone **calorimetric trigger** covers the high Q^2 range where the scattered muon does not reach the trigger hodoscopes.

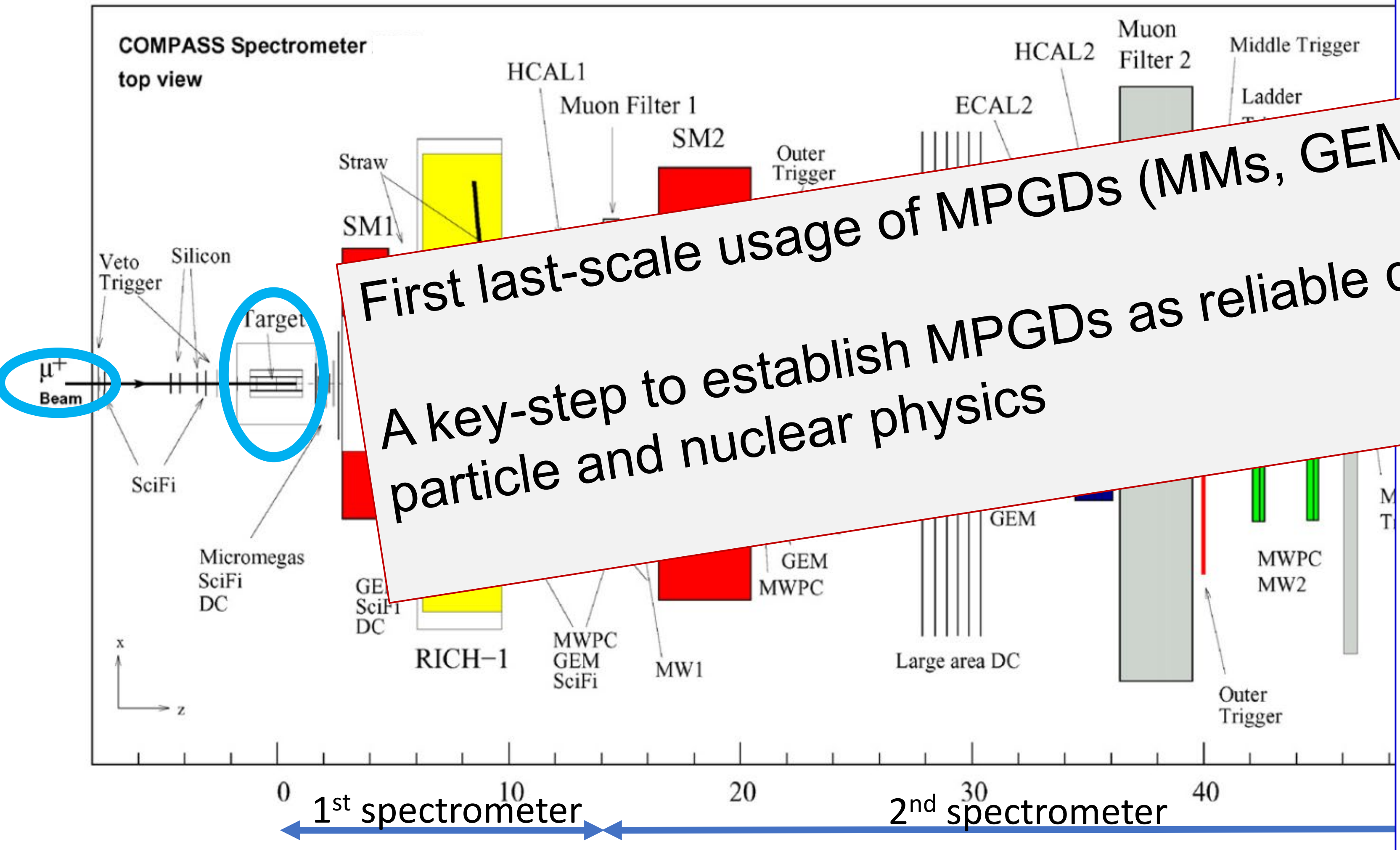
SIDIS-dedicated Experiments: COMPASS



trackers

- *Grouped according to the area to cover and the rates to handles*
- *No vertex detector compatible with the large-size solid-state polarized target*
- **VSATs**
  - Si microstrips
  - SciFi's
- **SATs**
  - MicroMegas (12 trackers, 40x 40 cm^2)
  - GEMs (22 trackers, 31x 31 cm^2)
- **LATs**
  - Drift Chambers
  - Straw tubes
  - MWPCs
  - Large area Drift Chambers

SIDIS-dedicated Experiments: COMPASS



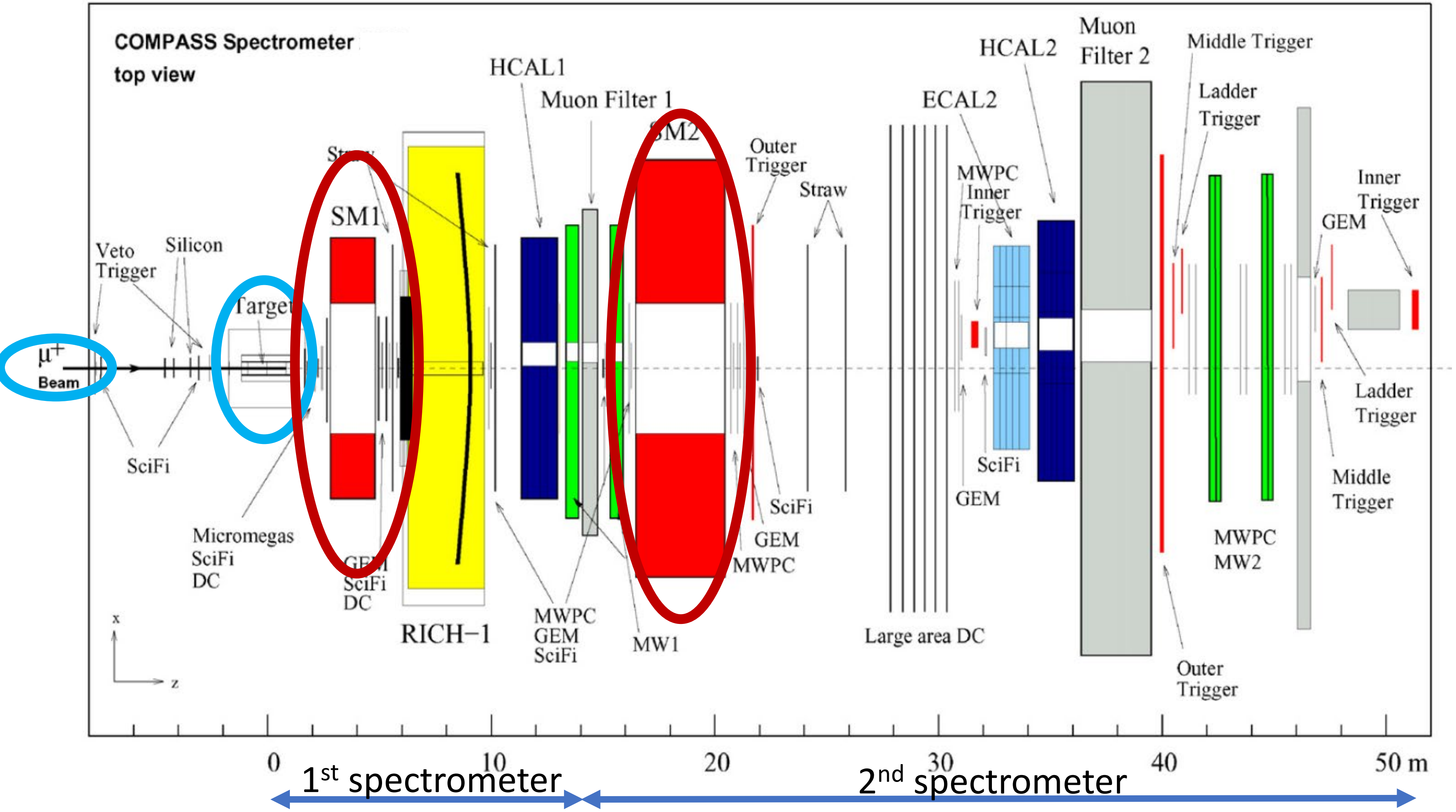
First last-scale usage of MPGDs (MMs, GEMs)

A key-step to establish MPGDs as reliable detectors for particle and nuclear physics

trackers

- *Grouped according to the area to cover and the rates to handles*
- *No ve... r compatible with ... -state polarized*
  - MicroMegas (12 trackers, 40x 40 cm^2)
  - GEMs (22 trackers, 31x 31 cm^2)
- **LATs**
  - Drift Chambers
  - Straw tubes
  - MWPCs
  - Large area Drift Chambers

SIDIS-dedicated Experiments: COMPASS



Particle momentum from trackers and analyzing magnets →

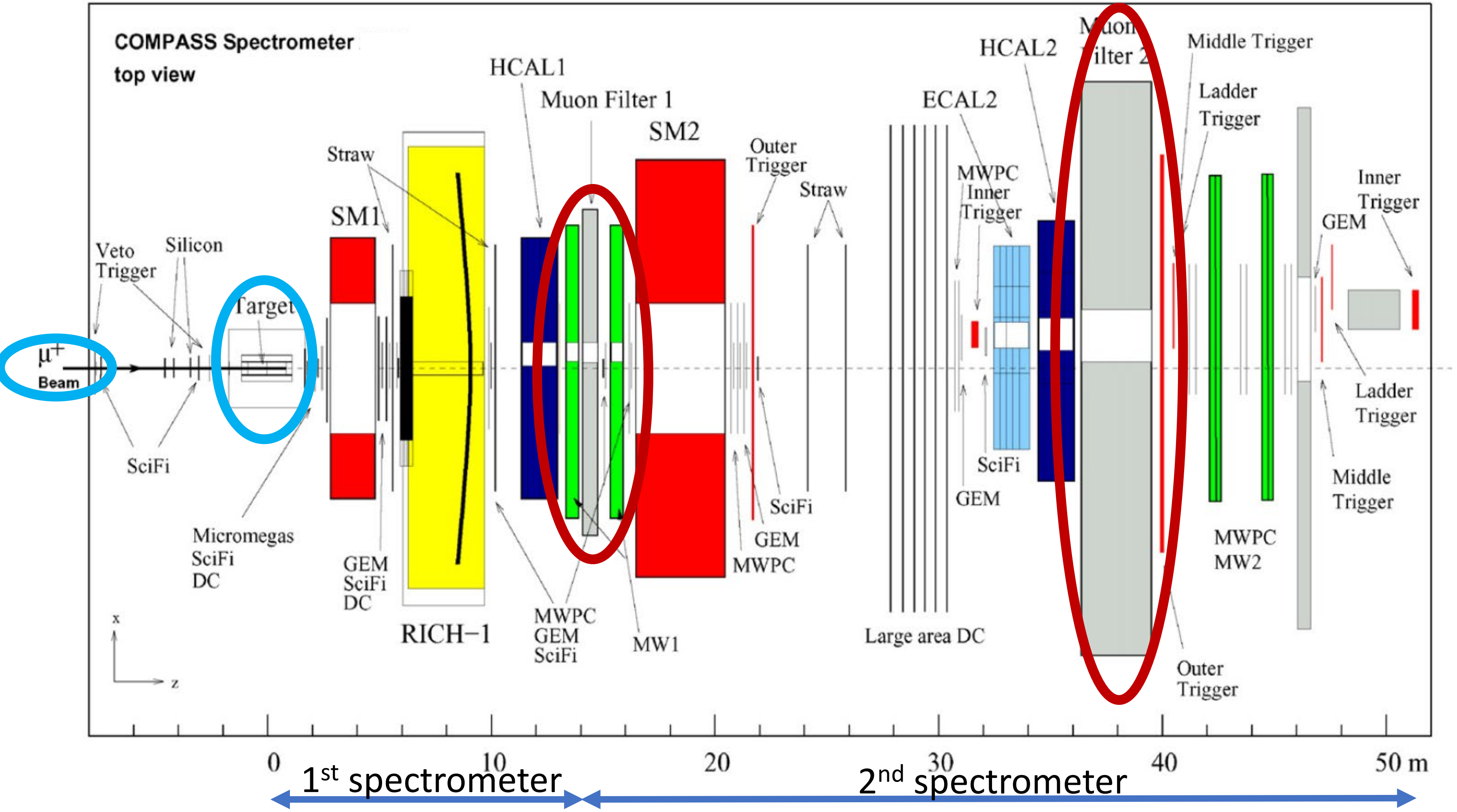
1st spectrometer

- SM1: 1 Tm
- $\sigma_p/p = 1.2\ \%$ $(p > 2\ \text{GeV/c})$

2nd spectrometer

- SM2: 4.4 Tm
- $\sigma_p/p = 0.5\ \%$ $(p > 5\ \text{GeV/c})$

SIDIS-dedicated Experiments: COMPASS

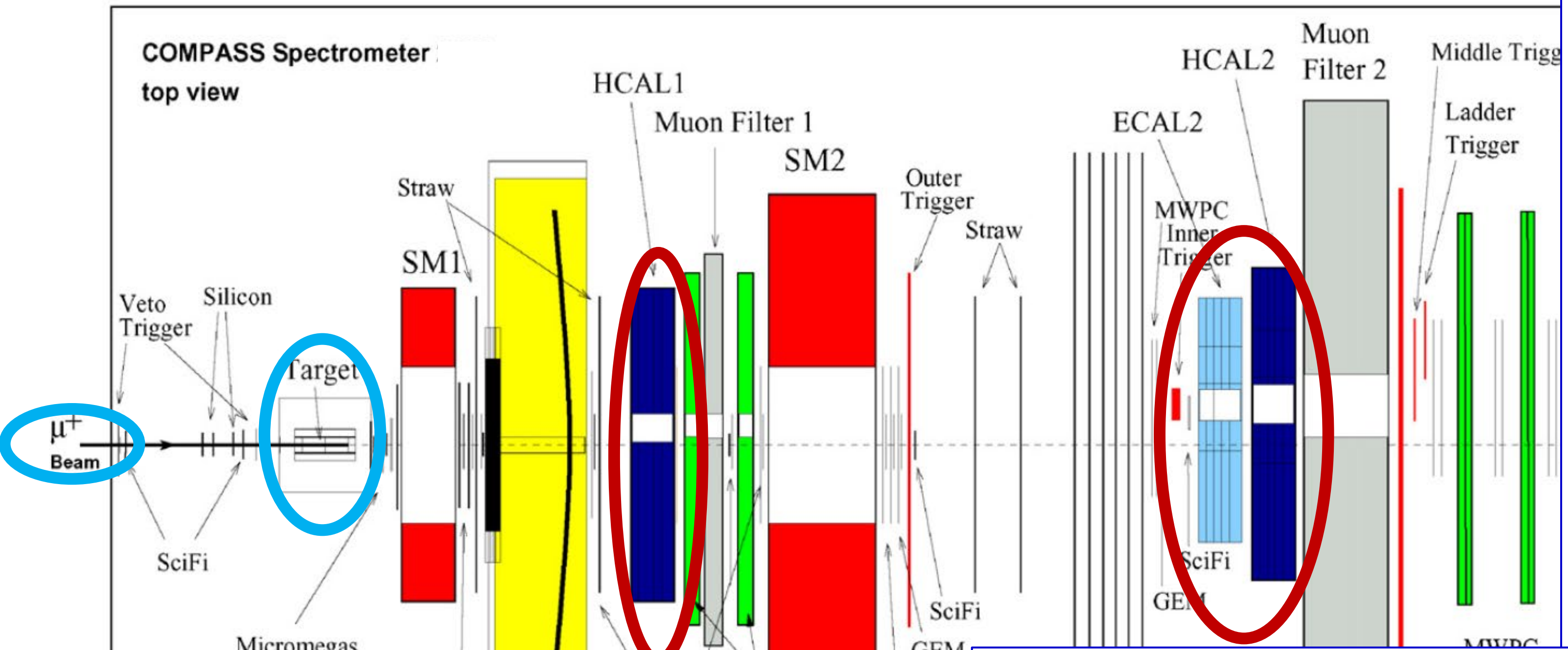


PID – 1

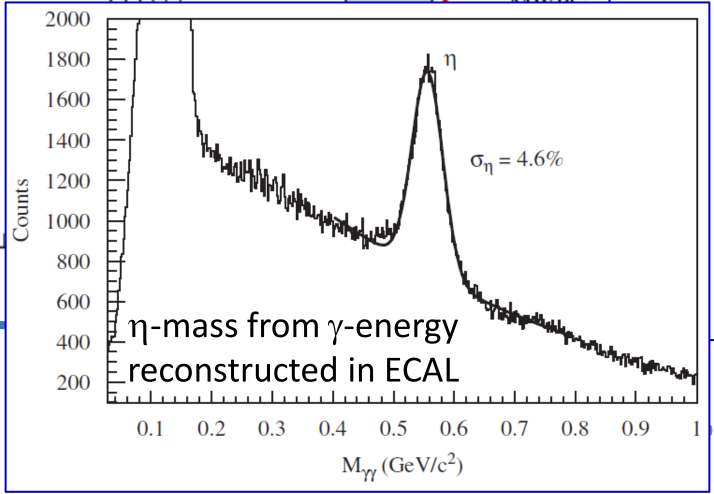
μ identification

- By **muon filters**: muon when the particle trajectory continues after an absorber thick enough to stop the incoming h
  - 1st absorber: **Fe wall (60 cm thick)**; central hole: 1.4 x $0.9 m^2$
  - 2nd absorber: **concrete wall (2.4 m thick)**

SIDIS-dedicated Experiments: COMPASS



1st spectrometer



PID – 2

CALORIMTERS

- **HCAL1, HCAL2 –** sampling hadron calorimeters (Fe, scintillating plates)
  - Measure h energy, contribute in muon identification;

    $\sigma(E)/E = (59.4 \pm 2.9)\%/\sqrt{E} \oplus (7.6 \pm 0.4)\%$

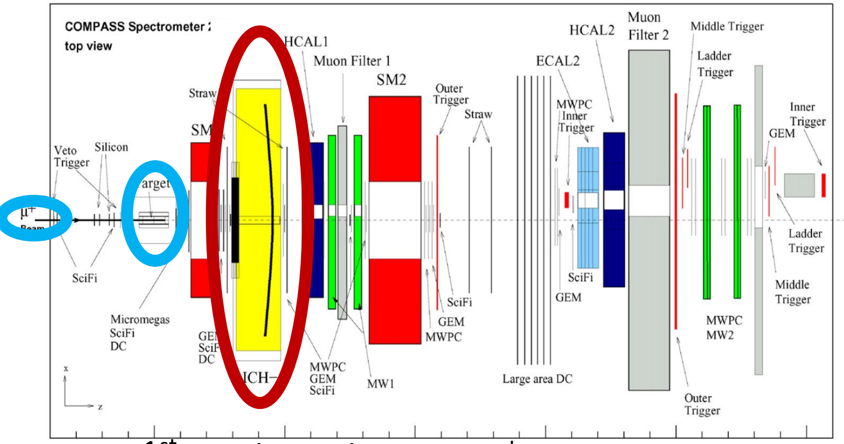
    $\sigma(E)/E = (66/\sqrt{E} \oplus 5)\%$
  - e/π response: 1.2 +/- 0.1
- **ECAL2 –** homogeneous electromagnetic by lead glass (different block size from center to periphery)
  - Measure the energy of the electromagnetic showers

    $\sigma(E)/E = 5.5\%/\sqrt{E} \oplus 1.5\%$

    $\sigma(x) = 6\,\mathrm{mm}/\sqrt{E} \oplus 0.5\,\mathrm{mm}$

SIDIS-dedicated Experiments: COMPASS

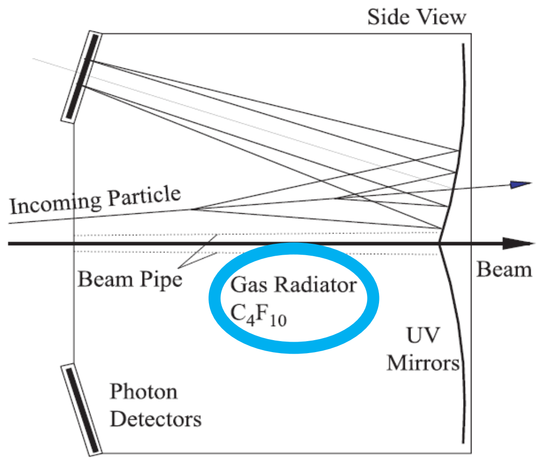
NIM A 970 (2020) 163768

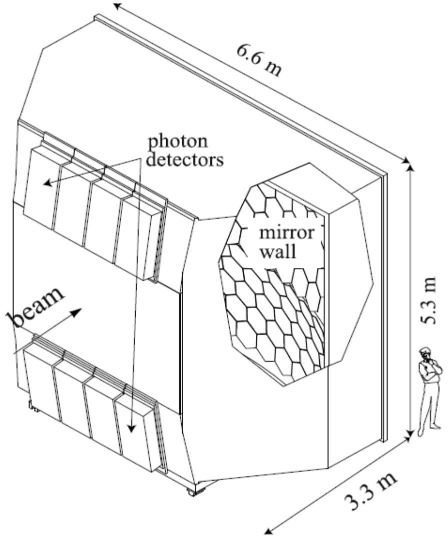


1^{st} spectrometer 2^{nd} spectrometer

PID – 3

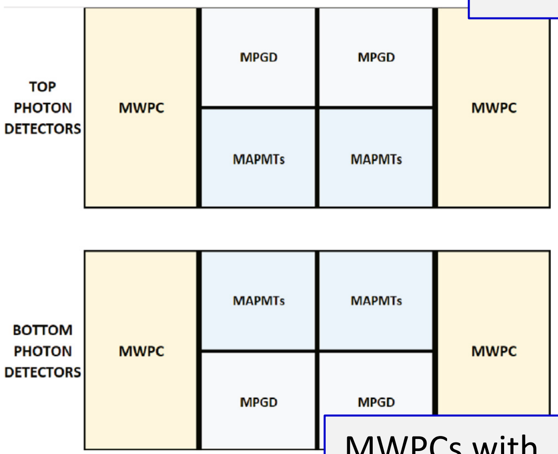
COMPASS RICH

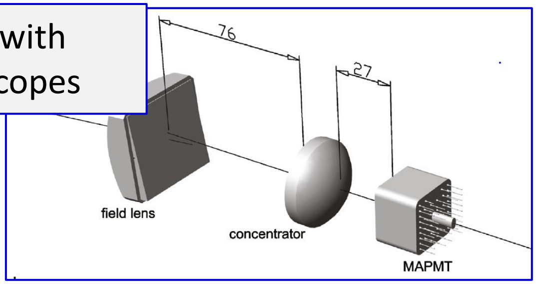




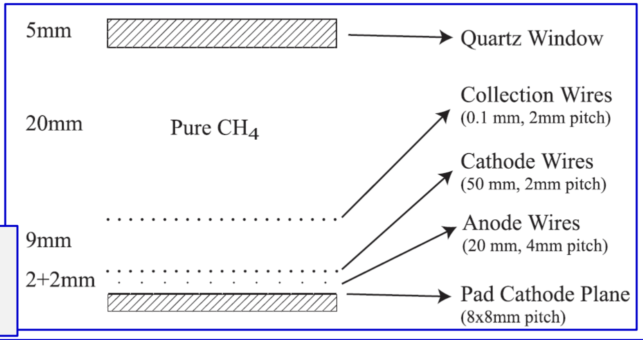
Photon detectors

MAPMTS with lens telescopes

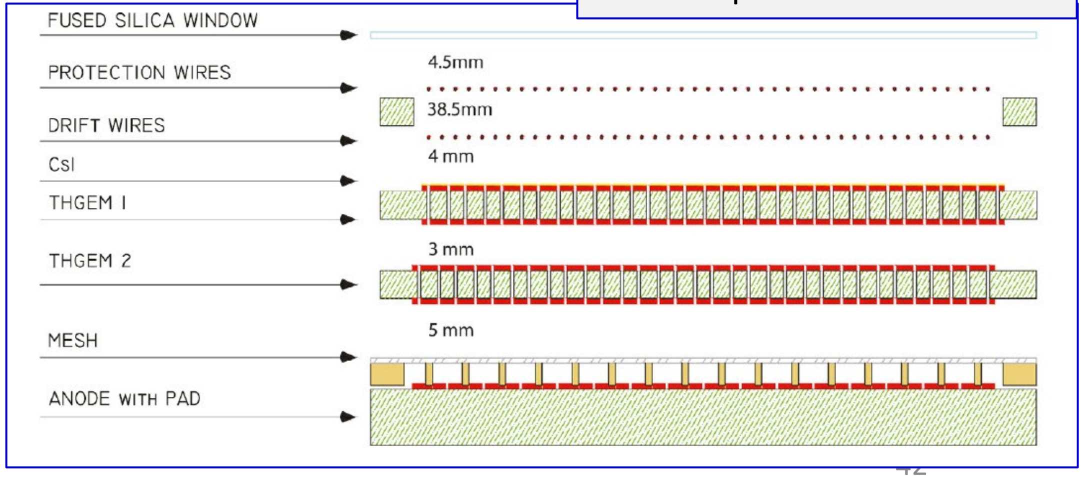




MWPCs with CsI photocathode

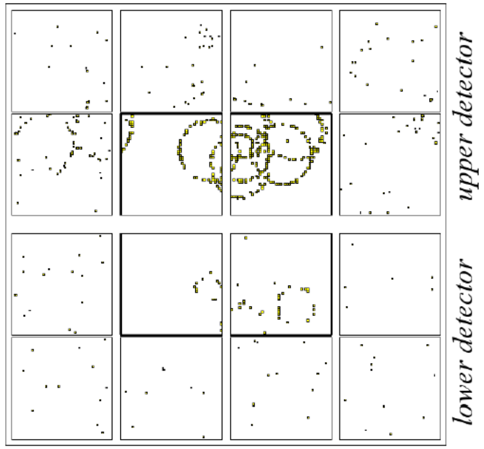


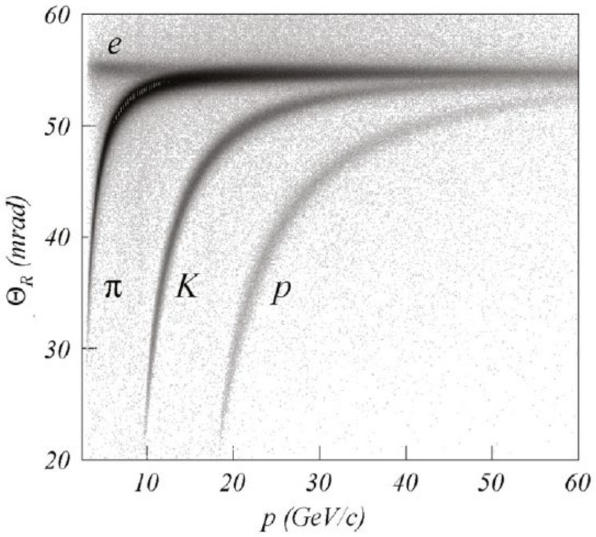
Hybrid MPGDs (THGEM, MM) With CsI photocathode

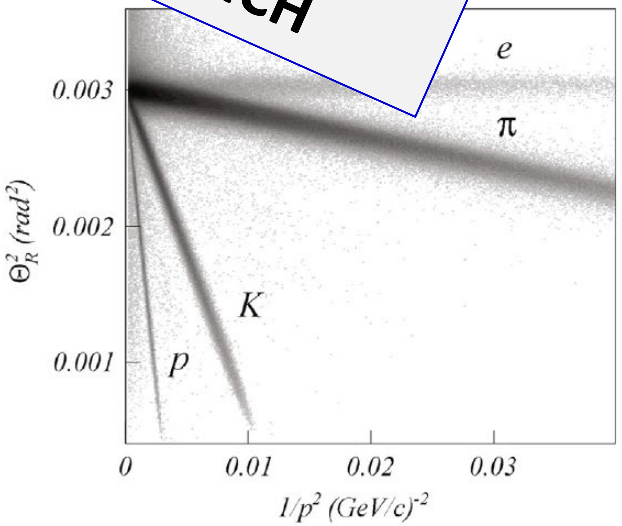


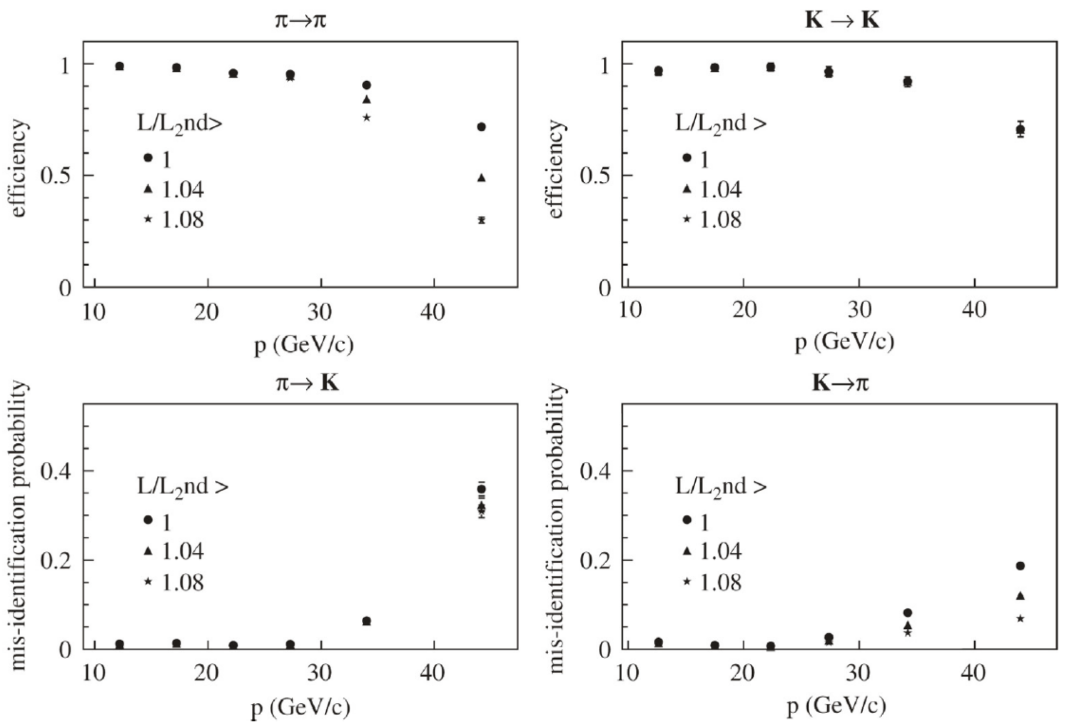
SIDIS-dedicated Experiments: COMPASS

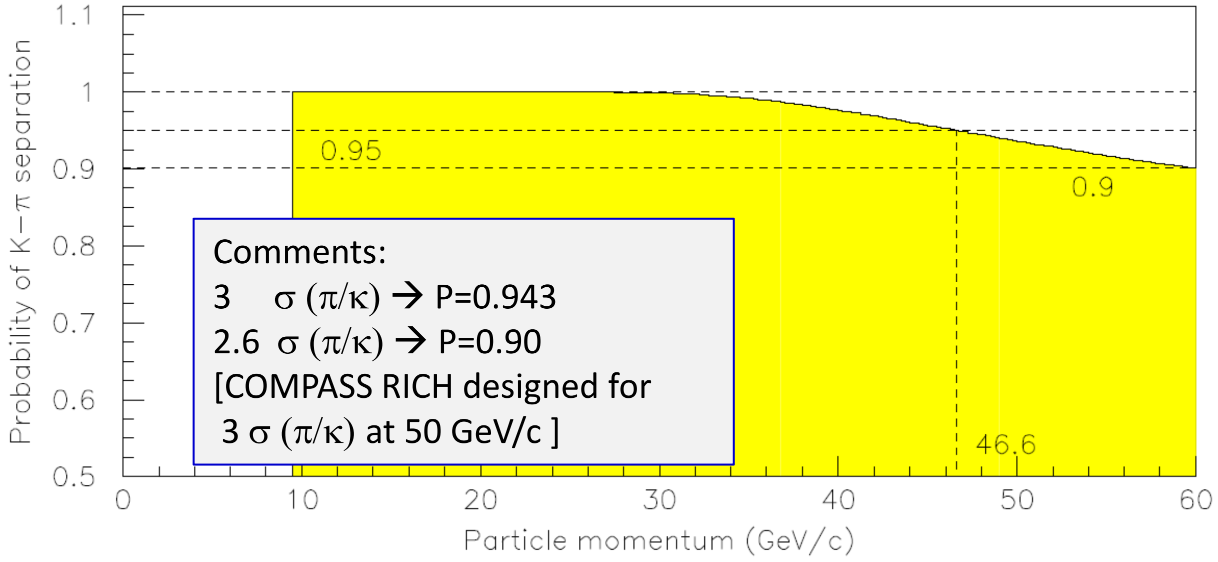
COMPASS RICH











Comments:
3 σ (π/κ) → P=0.943
2.6 σ (π/κ) → P=0.90
[COMPASS RICH designed for
3 σ (π/κ) at 50 GeV/c]

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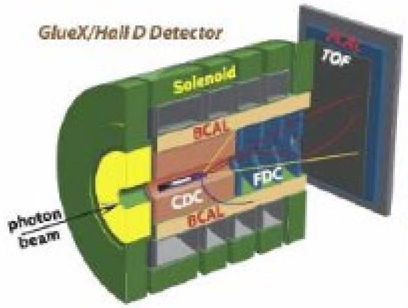
SIDIS-dedicated Experiments: **JLab**
experimental scope for the 12 GeV program

Eur. Phys. J. A **48**, 187 (2012)

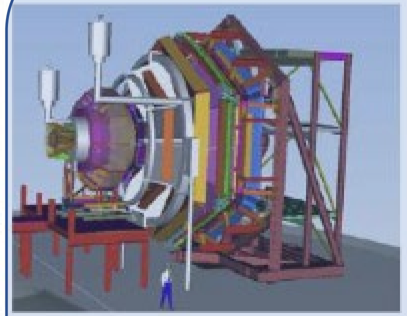
Topic	Hall A	Hall B	Hall C	Hall D	Total
The Hadron spectra as probes of QCD (*GlueX* and heavy baryon and meson spectroscopy)		1		1	**2**
The transverse structure of the hadrons (Elastic and transition Form Factors)	4	3	2		**9**
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	2	5		**9**
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	10	3		**18**
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	3	2	6		**11**
Low-energy tests of the Standard Model and Fundamental Symmetries	2			1	**3**
TOTAL	**16**	**18**	**16**	**2**	**52**

SIDIS-dedicated measurements included in the physics scope

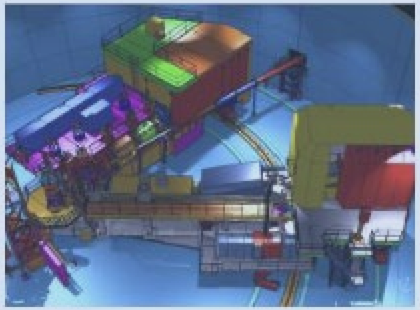
SIDIS-dedicated Experiments: **JLab**
experimental setup for the 12 GeV program



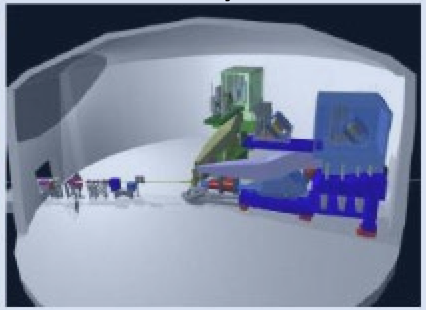
CLAS12



HRS & SHRS



SBB, *SOLID*

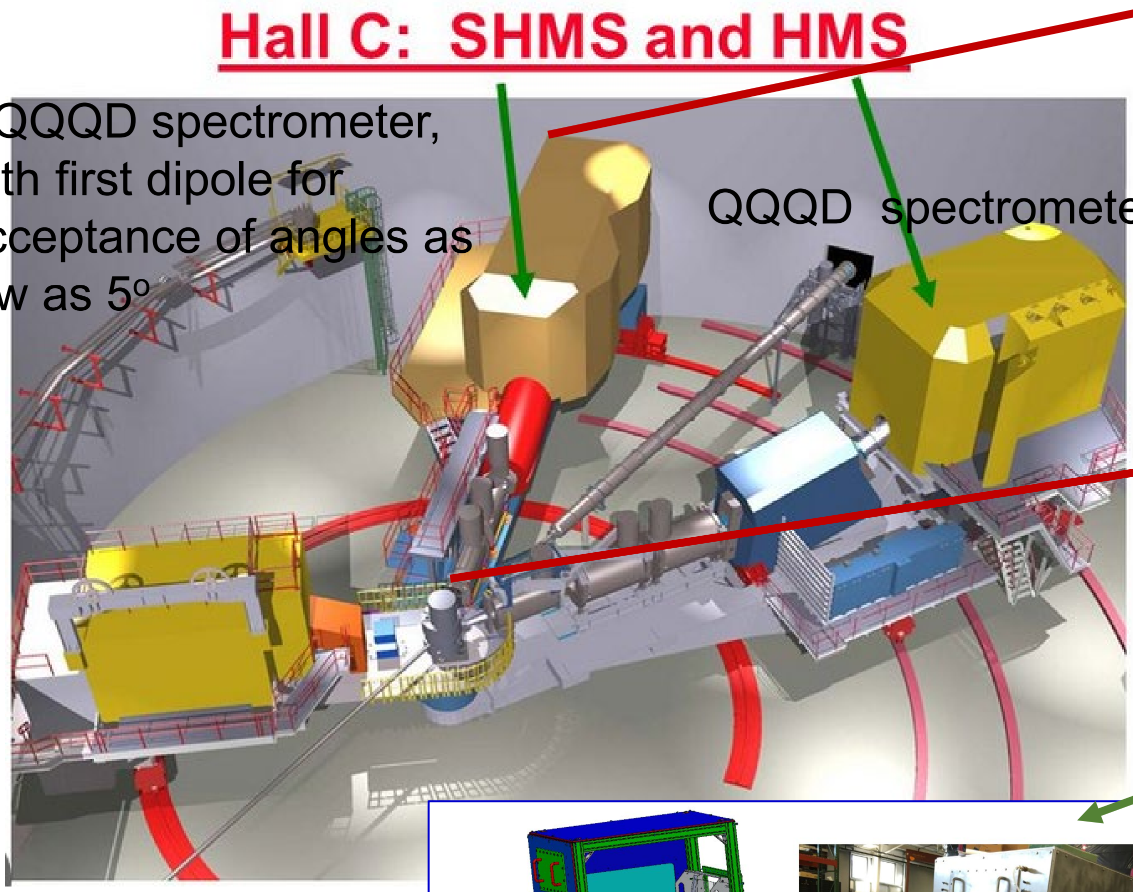


SIDIS-dedicated measurements included in the physics scope

Hall D	Hall B	Hall C	Hall A
Large acceptance	luminosity 10^{35}	energy reach	installation space
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction		luminosity up to 10^{38}	
particle ID			

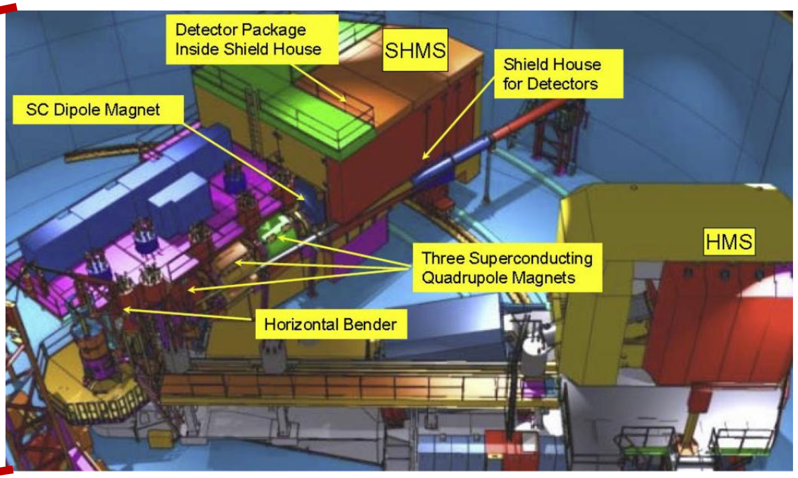
Eur. Phys. J. A **48**, 187 (2012)

SIDIS-dedicated Experiments: JLab HALL C - HMS and Super HMS



DQQQD spectrometer, with first dipole for acceptance of angles as low as 5º

QQQD spectrometer

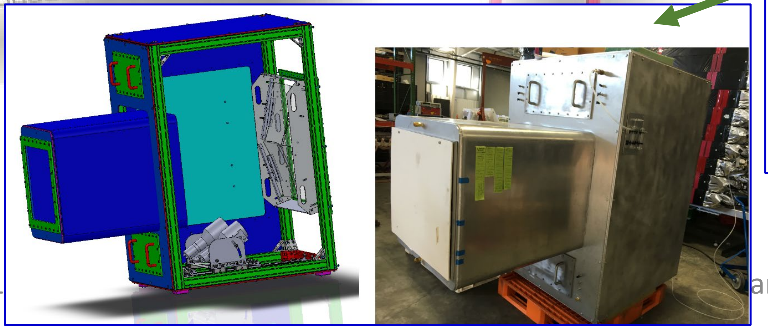


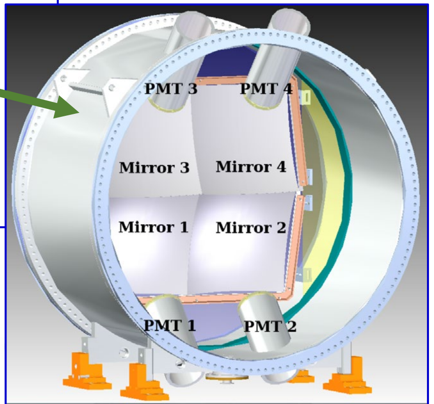
- Trackers
- Magnet for p analysis
- ECal with pre-shoer
- PID !

SHMS (5.5 to 40.0 degrees) pion background rate dominates the scattered electron rate by more than 1000:1

→

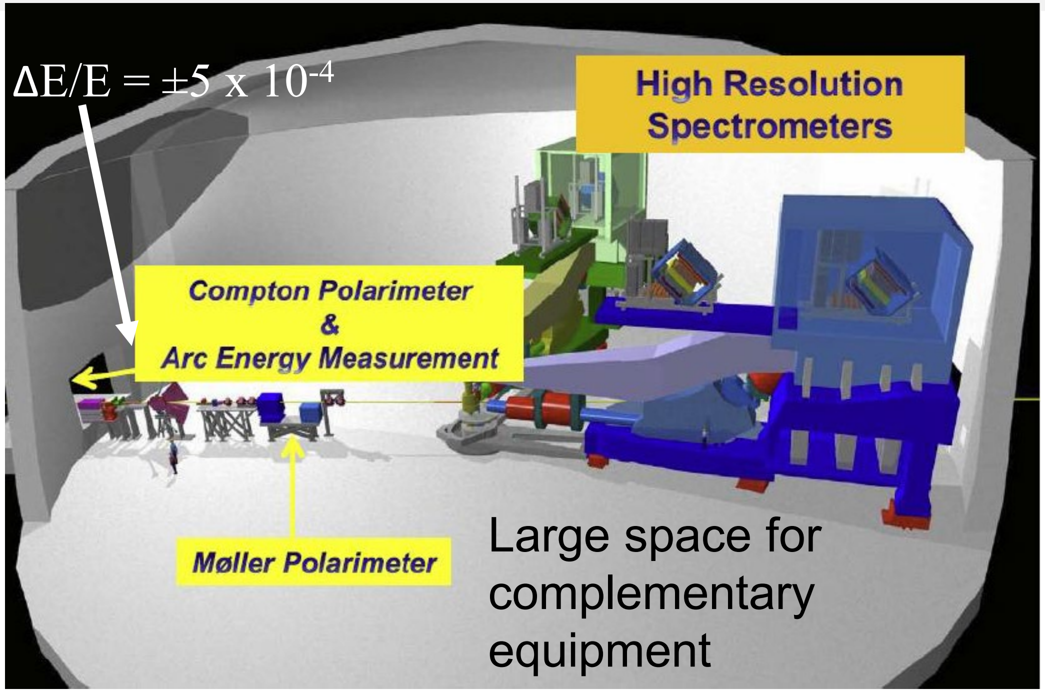
- Noble Gas Cherenkov Detector (Ne)
- Heavy Gas Cherenkov Detector (C_4F_8O)
- Aerogel Counter

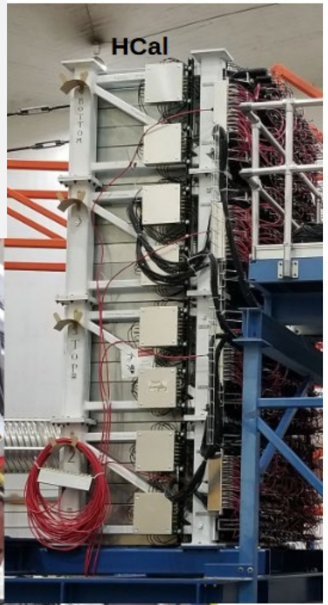




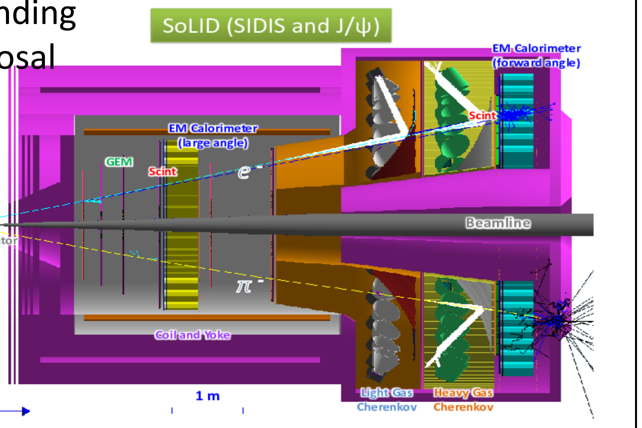
C4F8O

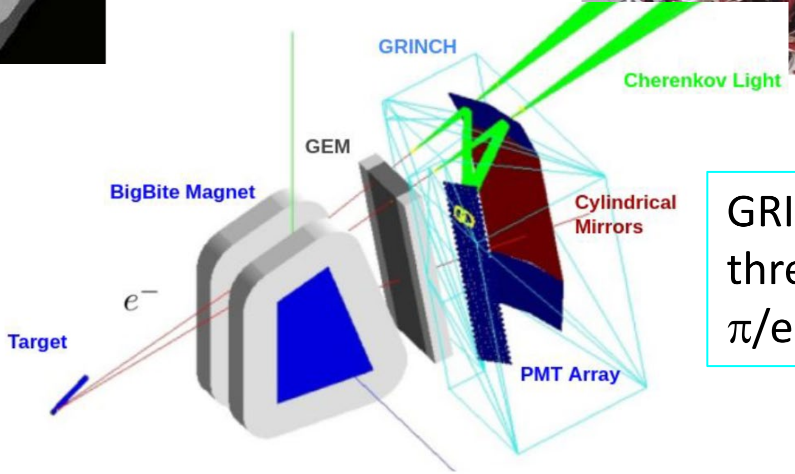
SIDIS-dedicated Experiments: JLab HALL A - BB and SBB, *SOLID*





A pending proposal

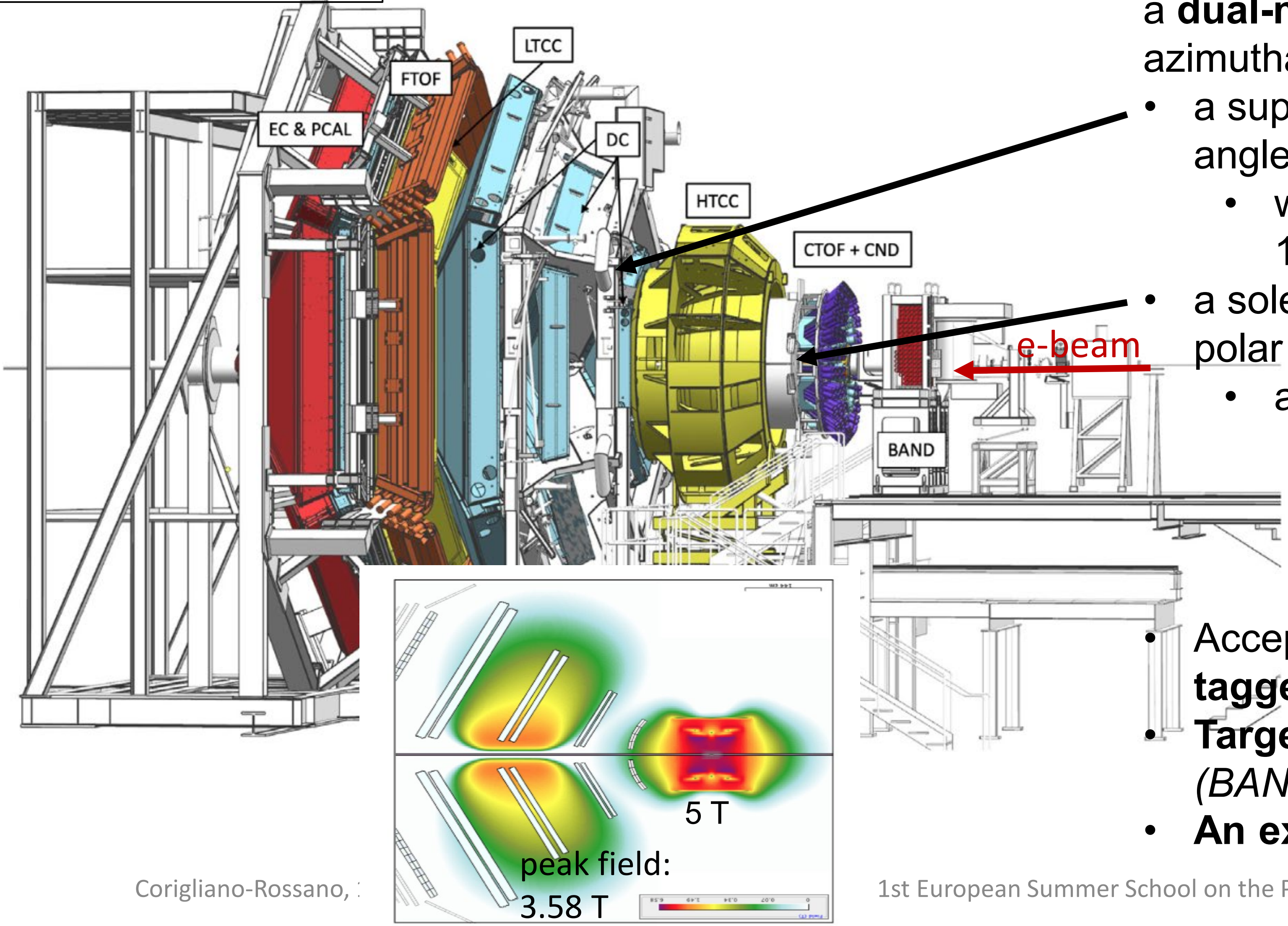




GRINCH - heavy gas Chereknov threshold detector (C_4F_8O) for π/e separation

SIDIS-dedicated Experiments: JLab
HALL B - CLAS12 (CEBAF Large Acceptance Spectrometer 12 GeV)

NIM A 959 (2020) 163419



a **dual-magnet** and detection systems with full azimuthal coverage

- a superconducting torus magnet the forward polar angle range **5º - 35º**
  - with a drift chamber system, p resolution < 1%
- a solenoid magnet and detector covering the polar angles from **35º to 125º**
  - a vertex tracker, p resolutions of <3%

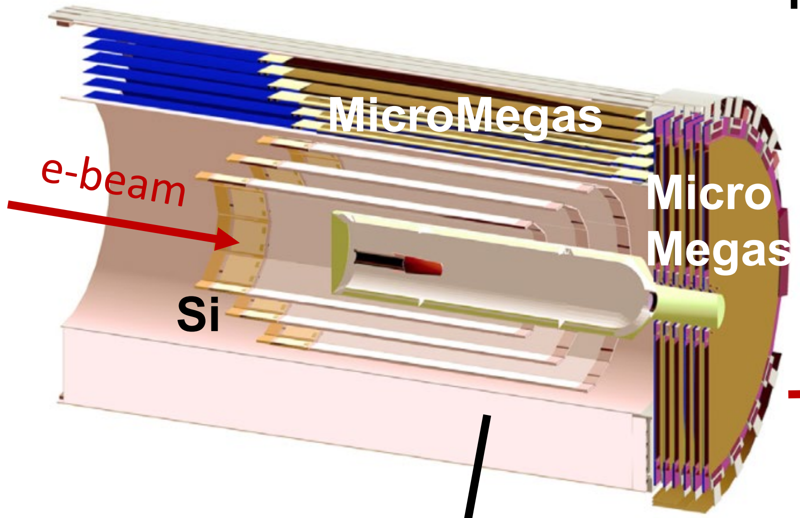
- Acceptance completed by a **forward e and γ tagger**: **2.5º – 4.5º**
- **Target fragments:** *Back angle neutron detector (BAND)*
- **An extended PID system**

SIDIS-dedicated Experiments: JLab
HALL B - CLAS12 (CEBAF Large Acceptance Spectrometer 12 GeV)

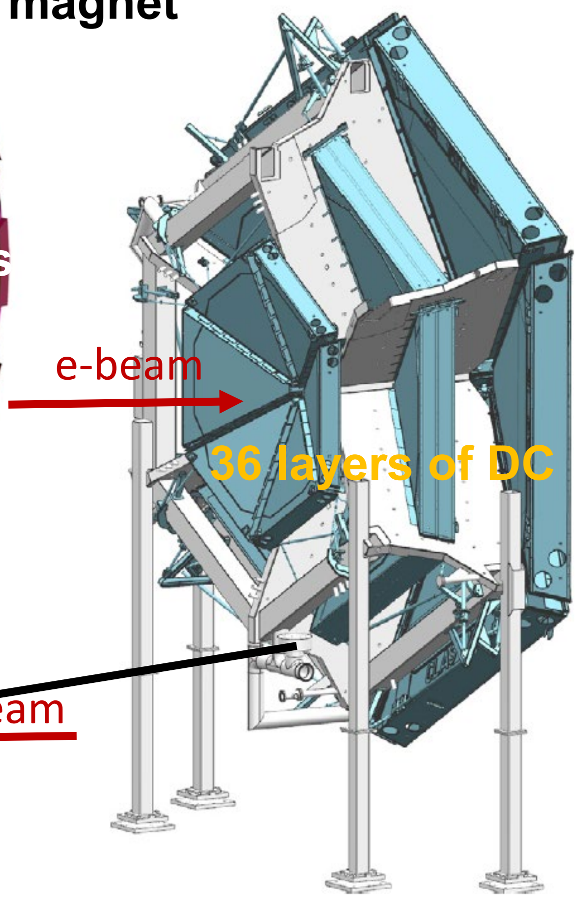
Tracking, calorimetry

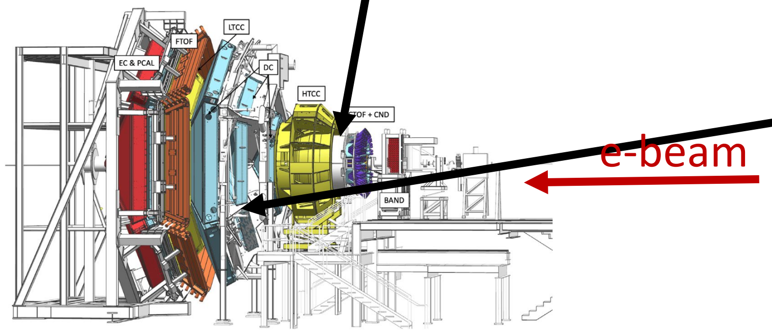
NIM A 959 (2020) 163425

Tracking in the solenoid



Tracking in Toroidal magnet

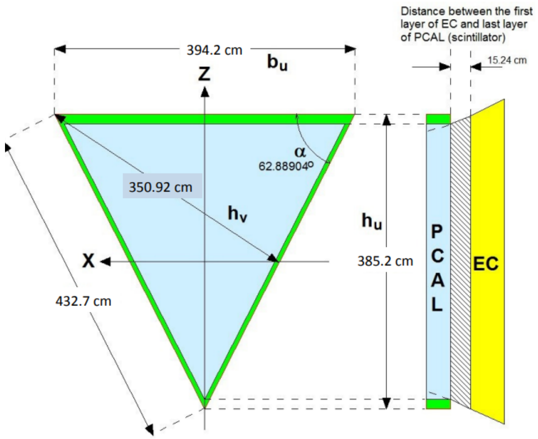


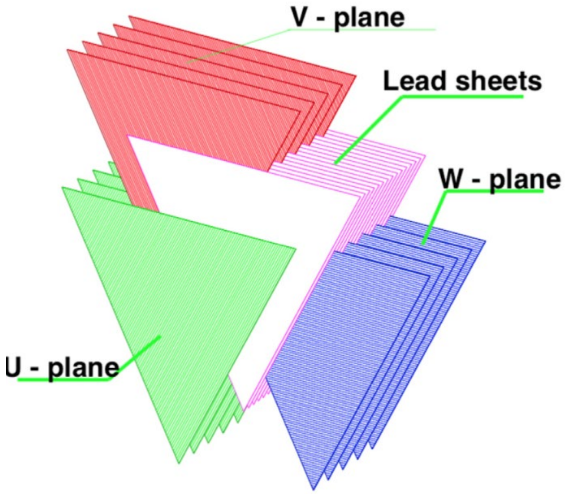


Electromagnetic calorimeter:
PCAL + EC
Sampling calorimetry with stereo read-out

Scope: identification and kinematical reconstruction of electrons, photons (e.g. from $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ decays), and neutrons.

1 of the 6 sectors



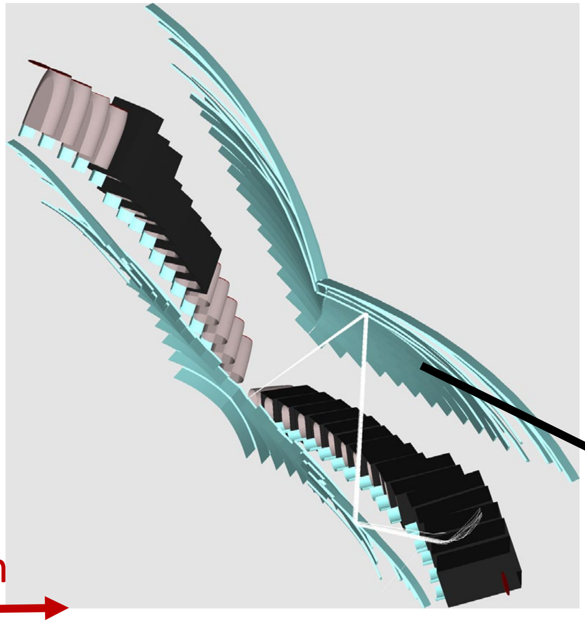


SIDIS-dedicated Experiments: JLab
HALL B - CLAS12 (CEBAF Large Acceptance Spectrometer 12 GeV)

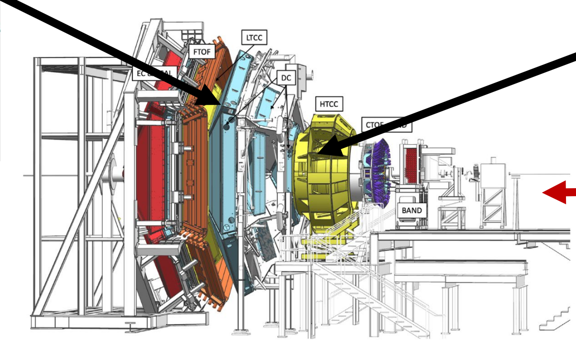
PID: e/h separation

LTCC: <u>threshold Cherenkov counter</u> (C_4F_{10}),
4 boxes, Acceptance: 5° - 35°, e/h separation up to 3.5 GeV

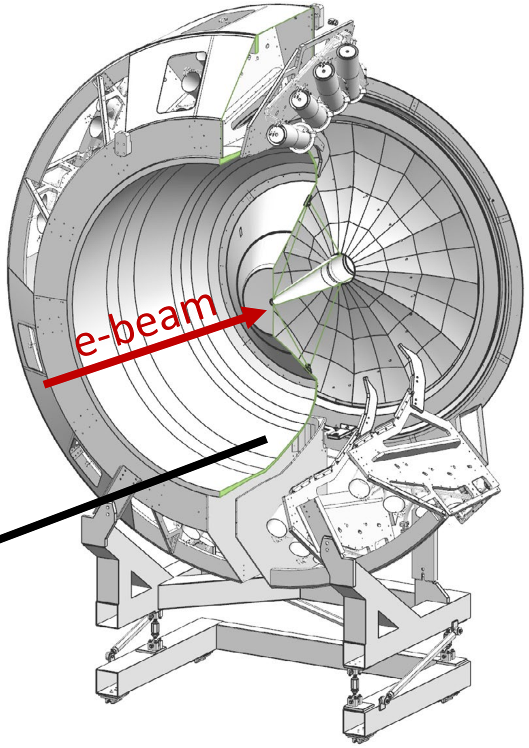
HTCC: <u>threshold Cherenkov counter</u> (CO_2),
Acceptance: 5° - 35°,
e/h separation up to 4.9 GeV



e-beam



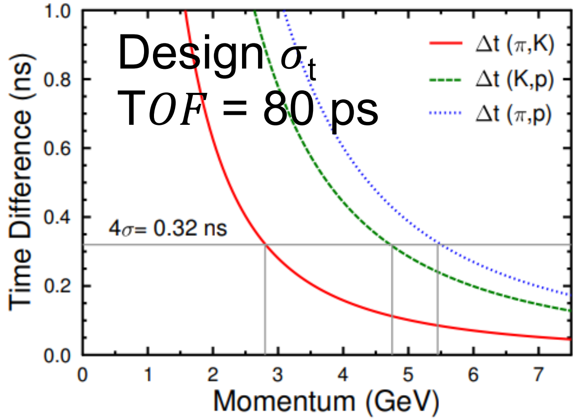
e-beam

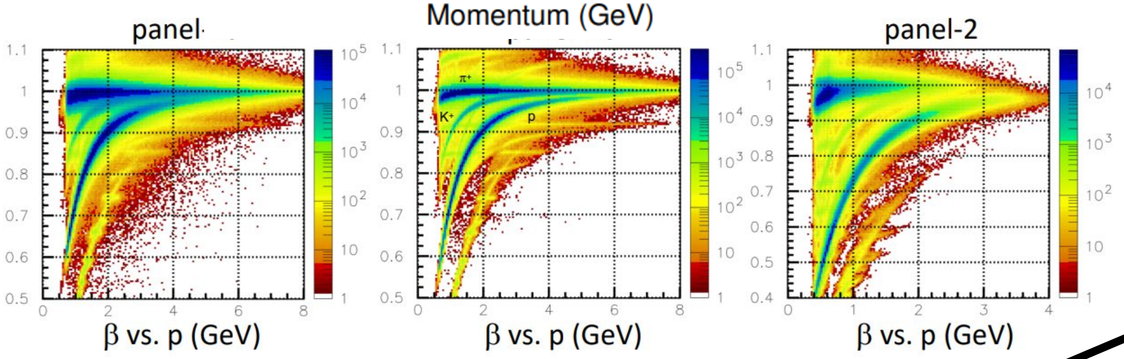


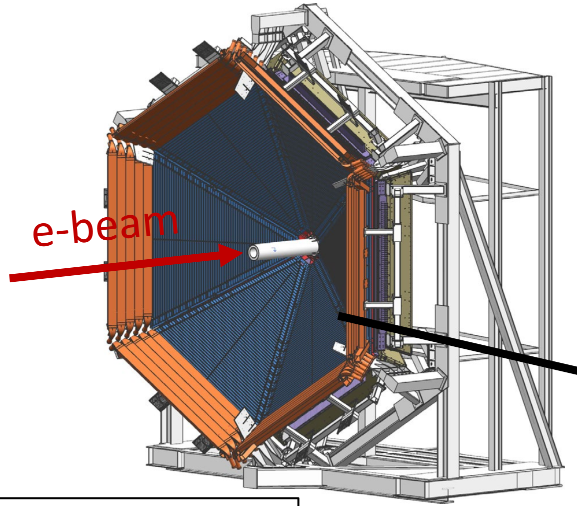
SIDIS-dedicated Experiments: JLab
HALL B - CLAS12 (CEBAF Large Acceptance Spectrometer 12 GeV)

PID: h identification (1/2)

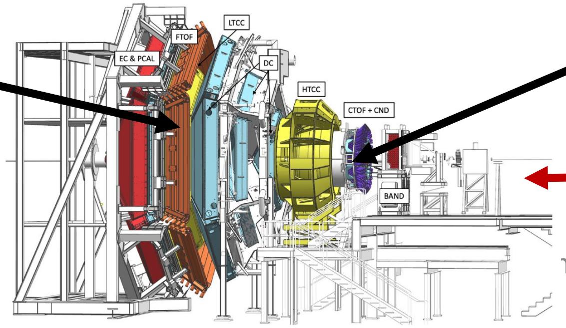
FToF by plastic scintillators with double-sided PMT readout
Acceptance: 5^o - 45^o,
3 arrays per sector with time resolution of
125 ps, 85 ps and 155 ps



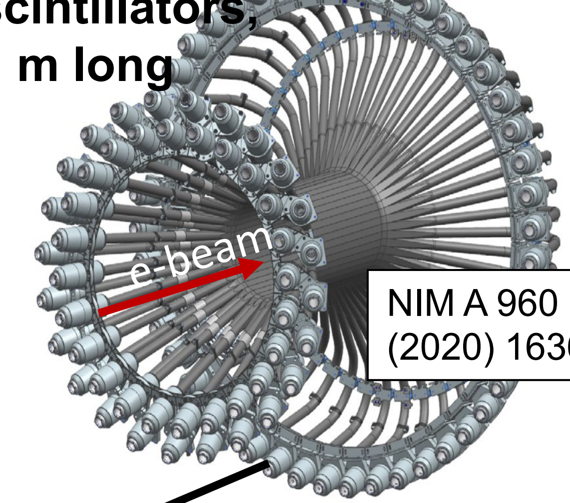




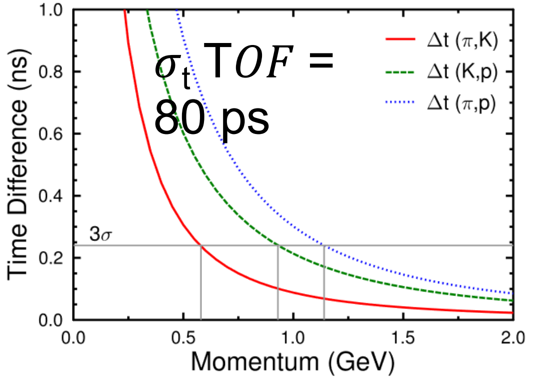
NIM A 960 (2020) 163629



CToF in the solenoid by plastic scintillators, 1 m long



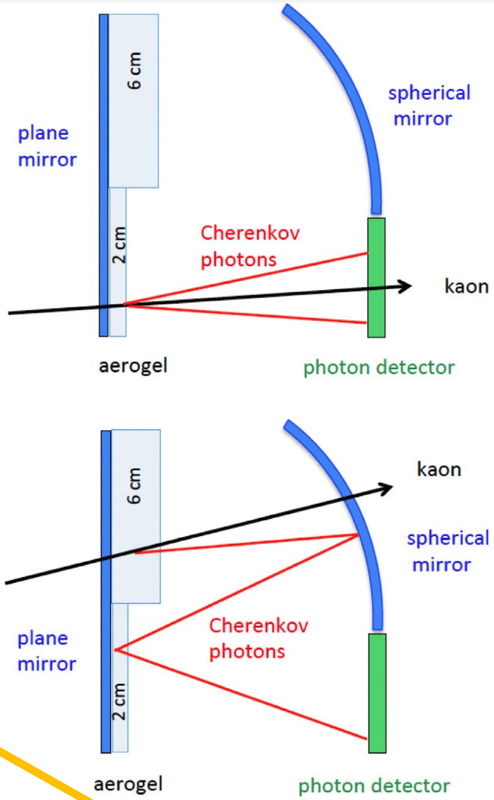
NIM A 960 (2020) 163626

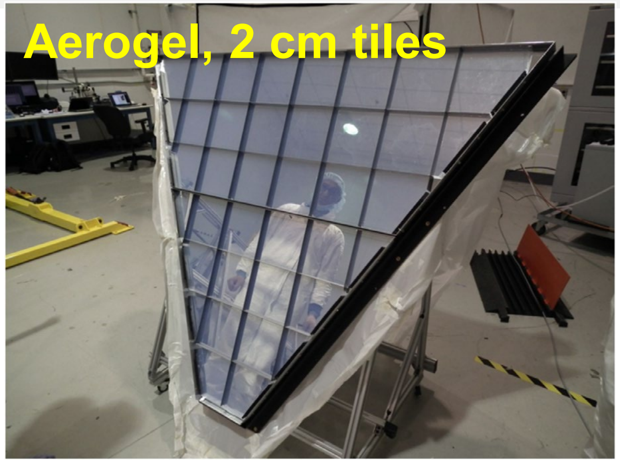


SIDIS-dedicated Experiments: JLab
HALL B - CLAS12 (CEBAF Large Acceptance Spectrometer 12 GeV)

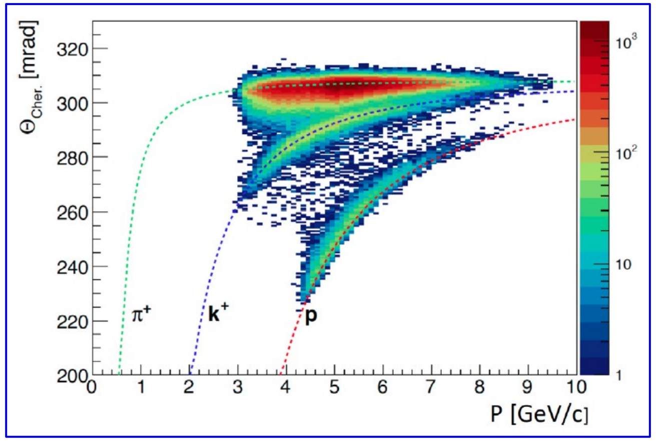
PID: h identification (2/2)

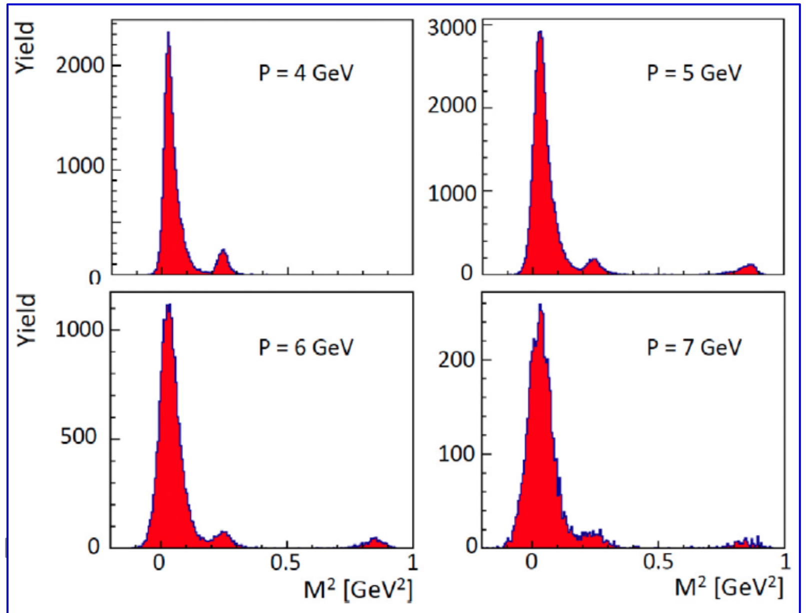
RICH
Aerogel, n = 1.05
MAPMTs

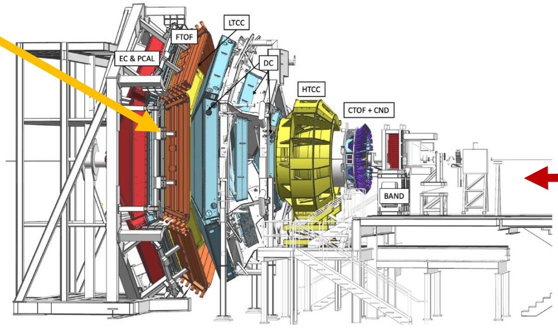




RICH response for h







e-beam

Facilities and experiments (I), OVERVIEW

- Introduction
- From DIS to SIDIS
- SIDIS-dedicated Experiments:
  - HERMES (fix target at the HERA collider, DESY)
  - COMPASS (fix target at the CERN muon-beam)
  - JLAB (fix target at CEBAF)
- Take-away messages

Take-away messages

- **TMD domain** is a composite and complex one: 8 independent structure functions
  - Important dedicated work ongoing (status of the result panorama in the following part)
- **What is needed ?**
  - **Facilities** making DIS and SIDIS measurement possible
    - Intense lepton beam, variety of the center of mass energies aiming at covering the whole kinematic domain of interest
    - Large acceptance detectors
  - **Polarization**: leptons and hadrons
  - **Identification of the scattered lepton**
  - **Hadron PID**: flavor-dependent TMDs
- **Technological progress** is key !
  - Beam energy and experiment luminosity
  - Polarized sources for the beams, polarimeters
  - Polarized targets (solid state and gaseous)
  - Detector coping with the challenges (intensity, resolution, PID)

Take-away messages

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When they tell you: it is only technology …
Recall them that technology progress of facilities and detectors is building-up the science !

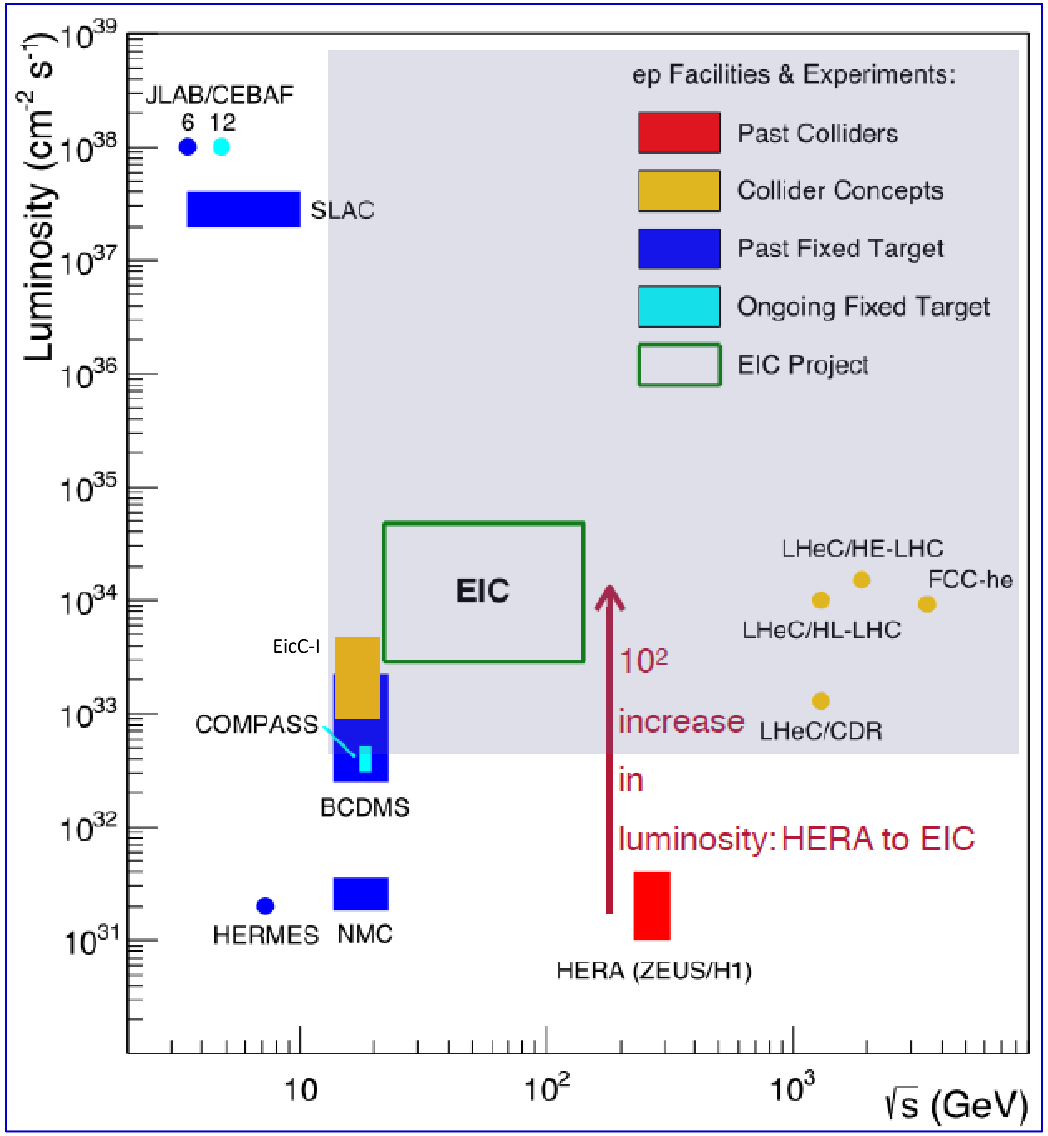
THANK YOU

BACKUP SLIDES

ENERGY & LUMINOSITY, past, present and future

PAST
&
PRESENT

FIXED TARGET, e BEAM				
SLAC	concluded	high $\mathscr{L}$	polarization	
CEBAF	active		polarization	
HERMES	concluded	limited $\mathscr{L}$	polarization	internal gas jet target
FIXED TARGET, HIGH ENERGY μ BEAM				
BCDMS	concluded	high $\mathscr{L}$		access to small x & large Q2 range
EMC	concluded	limited $\mathscr{L}$	polarization	
NMC	concluded			
SMC	concluded		polarization	
COMPASS	active	high $\mathscr{L}$	polarization	
COLLIDER ep				
HERA	concluded	limited $\mathscr{L}$		high energy, access to very small x & very large Q2 range



FUTURE:

Filling the high E - high $\mathscr{L}$ region:

- precision
- wide kinematic range, also access to high x-region