The Transverse Spin Structure of the Nucleon

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JEFFERSON LAB

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Lessons Scheme

LECTURES 1 & 2

- Introduction
- Deep Inelastic Scattering and 1D parton distribution functions
- From 1D to 3D nucleon structure: Transverse Momentum Dependent (TMD) parton distribution functions
- TMD Measurements @ Jlab in Hall B

LECTURES 3 & 4

- Data analysis
- Monte Carlo simulations
- Asymmetries extraction
- TMDs extraction

LECTURE 5

- Where are we? What's next

Physics Reactions & Observables

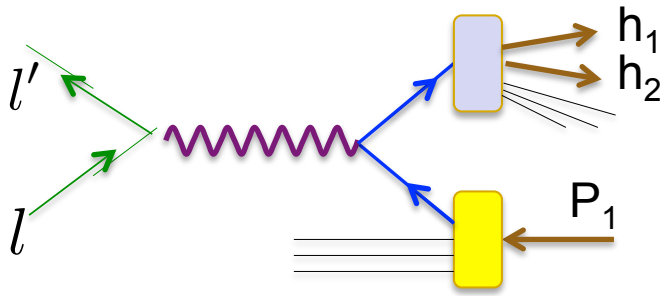
HOW ?
to access the quark transverse momentum

HARD PROCESSES

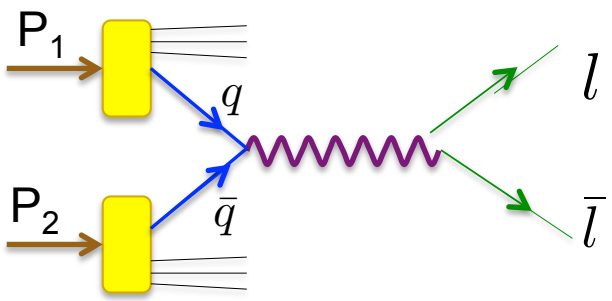
Observables

SPIN AZIMUTHAL ASYMMETRIES
due to correlations of spin of quark/nucleon and transverse momentum of quarks
(Spin-orbit correlations)

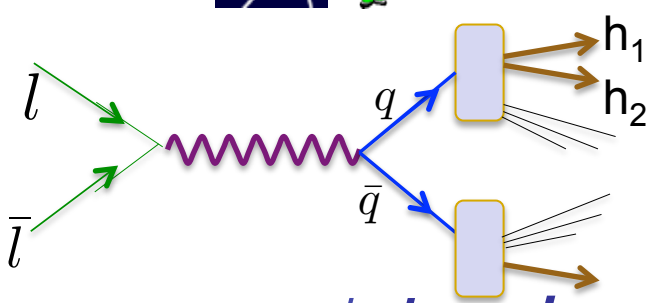
Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

hard scattering

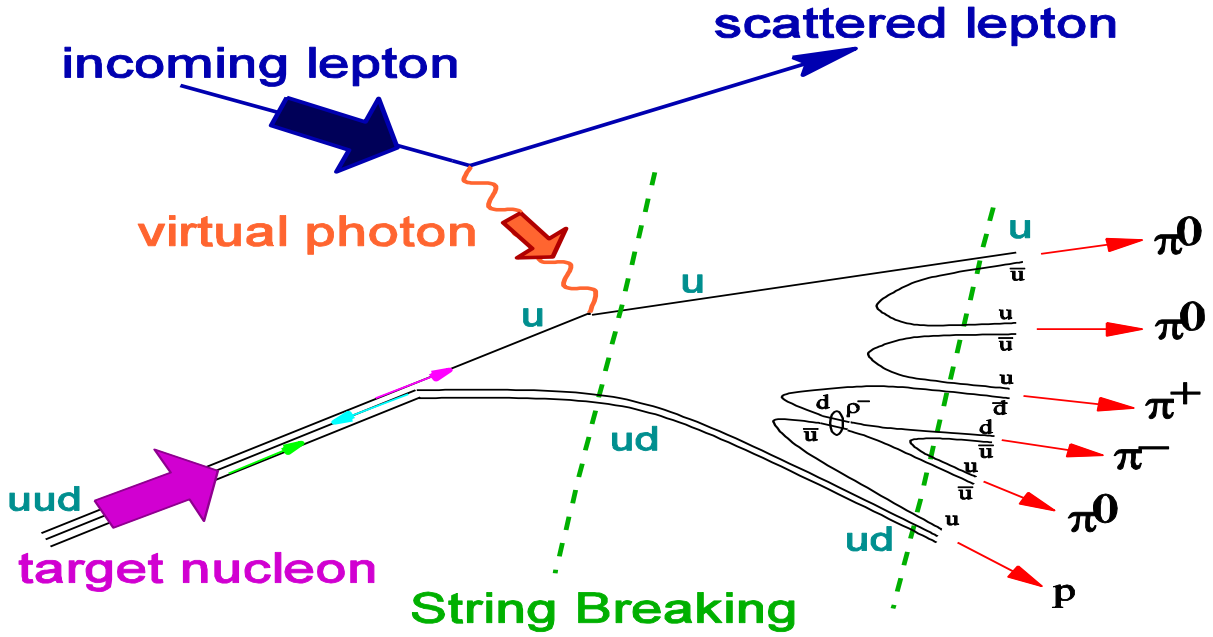
+

Partonic Fragmentation

Partonic Distributions

- Factorization proved
- Universality defined
- Evolution known

Single particle production in hard scattering

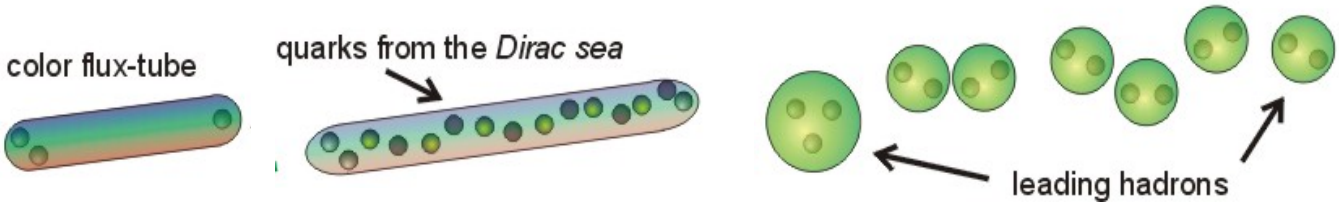


High probability to detect leading hadron in the forward detector

- Before

- After Target remnant quark

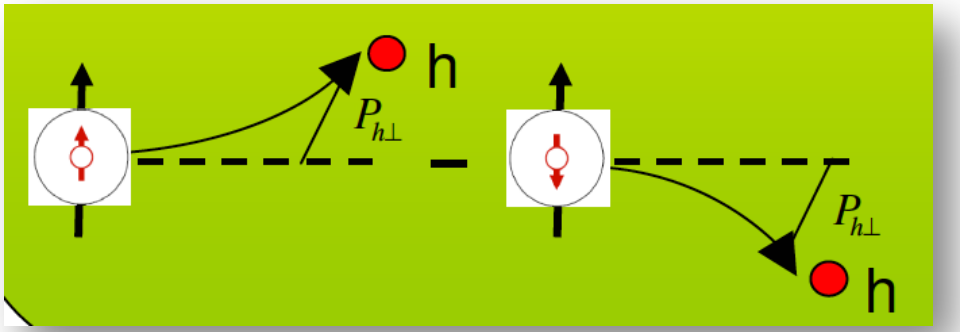
- Example: valence struck quark



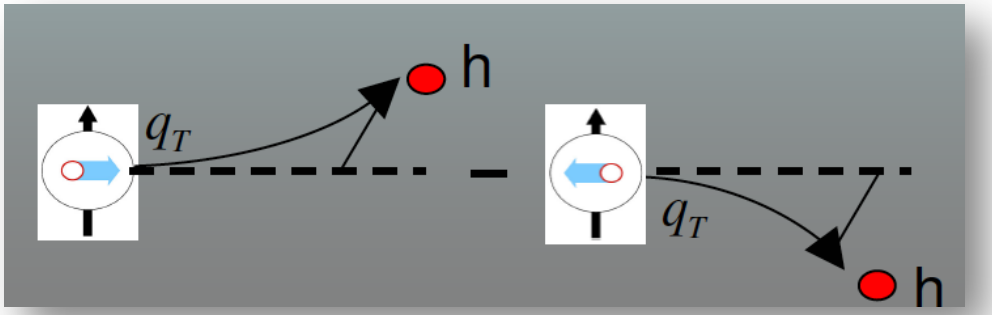
Mechanisms for SSA

Two fundamental QCD mechanisms have been identified to generate SSA: Collins & Sivers

Collins (fragmentation):
correlation between parton transverse polarization and transverse momentum of the produced hadron

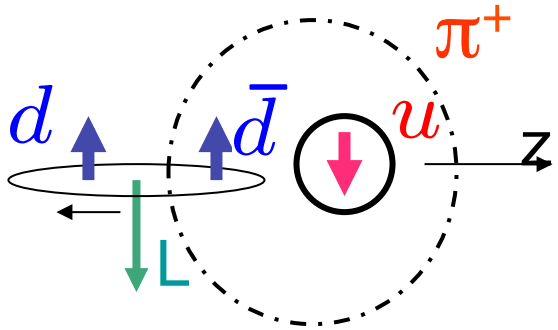


Sivers (distribution):
correlation between parton transverse momentum and nucleon transverse polarization. Requires orbital angular momentum

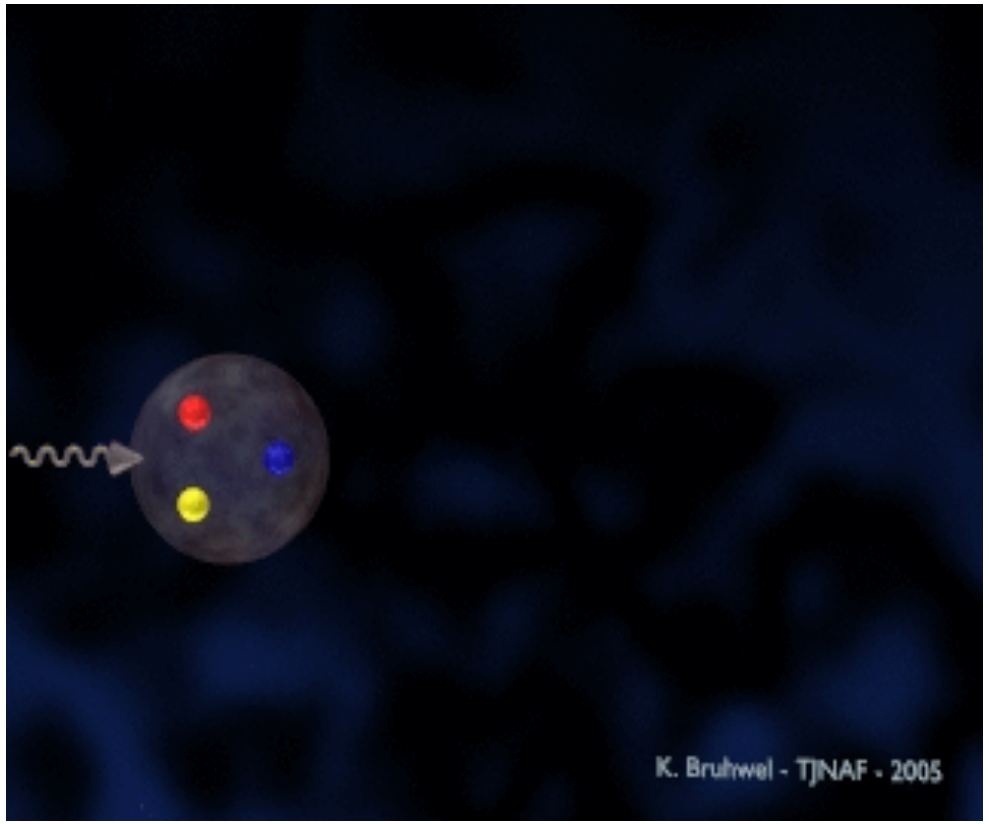


Collins Mechanisms for SSA

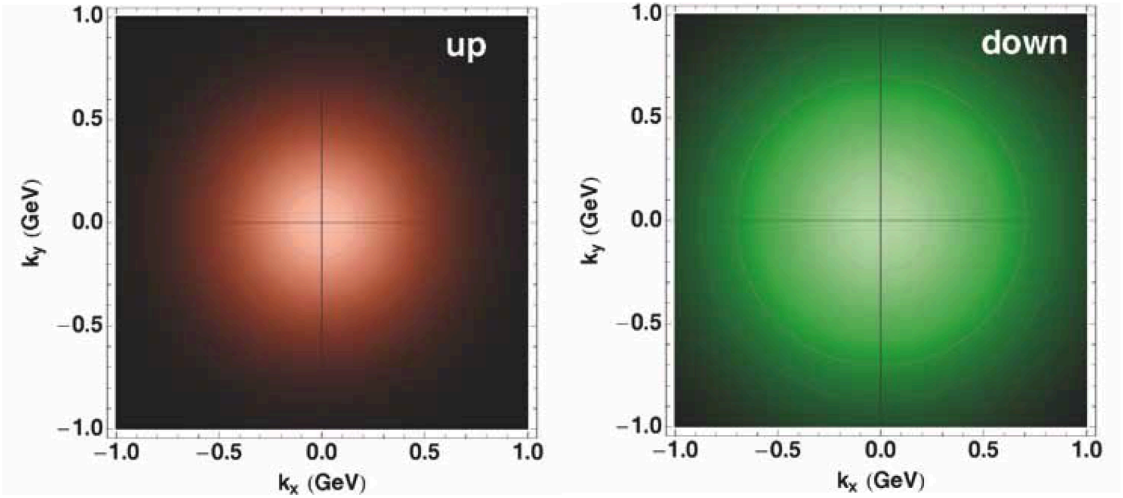
- **Collins asymmetries** are generated in the **hadronization** process of transversely polarized quarks.
- It implies a correlation between the **transverse polarization** of the quark and the **transverse momentum** of the unpolarized hadron it fragments into

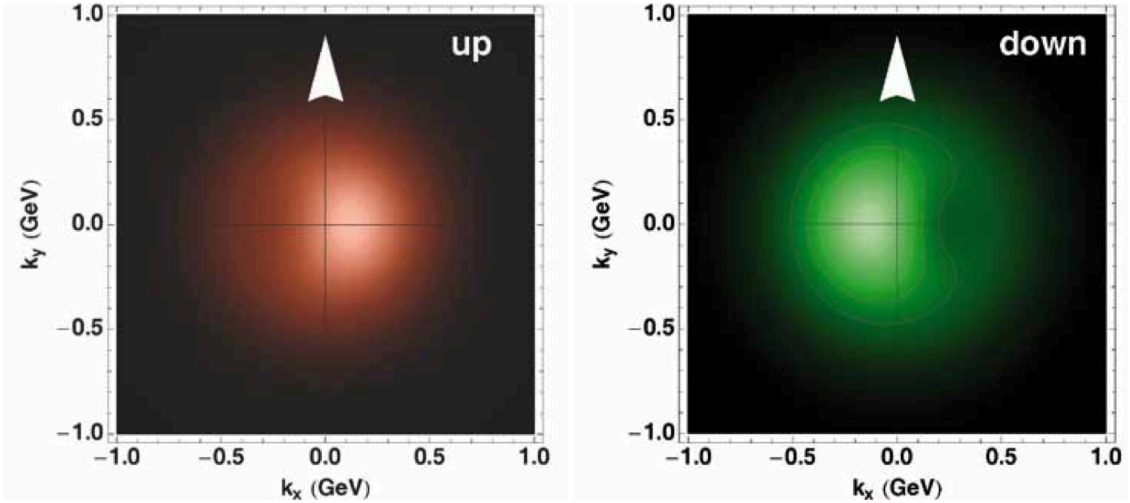


- Behind the leading quark u a string forms.
- The string breaks through the formation of the qqbar pair. The qqbar pair has the vacuum q.n. $J=0^+ \rightarrow L=1$ $S=1$ with L and S in the opposite direction and in the case of fragmentation into π (spin 0) L is in the same direction as the spin of the leading quark.
- The qbar that merges with the fragmenting quark retain some of that transverse orbital angular mom., causing it to move in a preferred direction.
- The pion inherits the transverse momentum carried by the antiquark.



Sivers Mechanisms for SSA

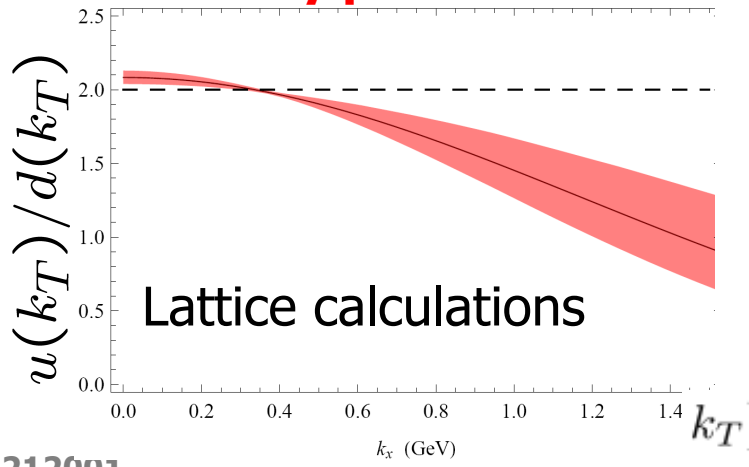




The transverse-momentum distribution may be different for quarks of different flavors. In an upolarized proton there are some indications (from exp data and lattice calculations) that the up-quarks are closer to the center than the down-quarks. [PLB, 665 (2008) 20 - PRD 83 (2011) 094507]

$$f_1(x,k_T^2) - f_{1T}^{\perp}(x,k_T^2)\frac{(\hat{P}\times\vec{k}_T)\vec{S}_T}{M}$$

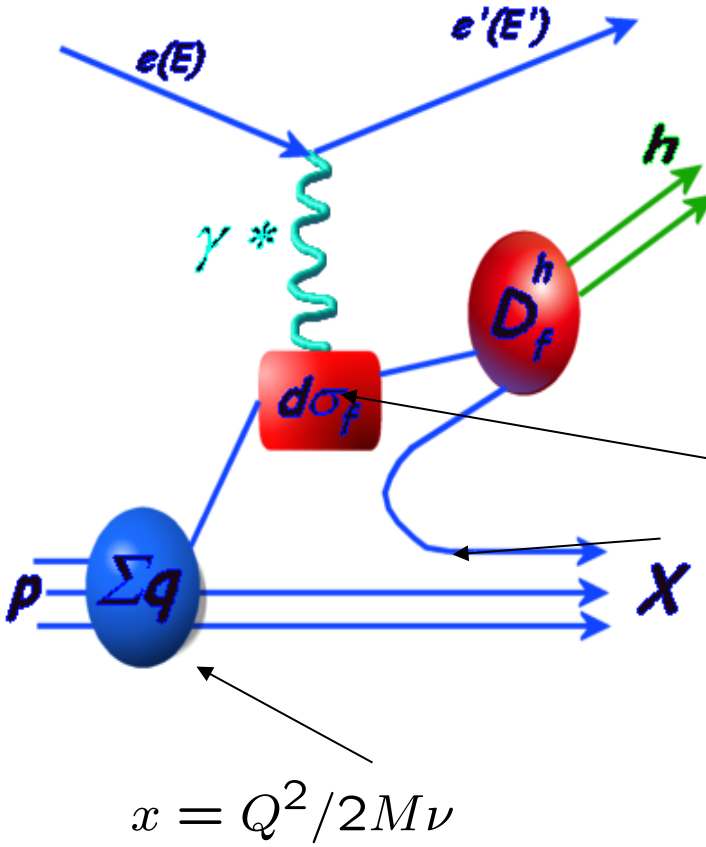
Sivers Asymmetry: generated in the **distribution** function of **unpolarized** quarks in **transversely polarized** nucleon



Images elaborated from real data: EPJA (2009) 89 – PRL107 (2011) 212001

Semi-Inclusive DIS

$ep \to e'hX$ $\quad d\sigma^h \propto \sum q_f(x) \otimes \mathrm{d}\sigma_f(y) \otimes D_f^{q\to h}(z)$



$z = E_h/\nu$

$y = \nu/E$ **Hard scattering**

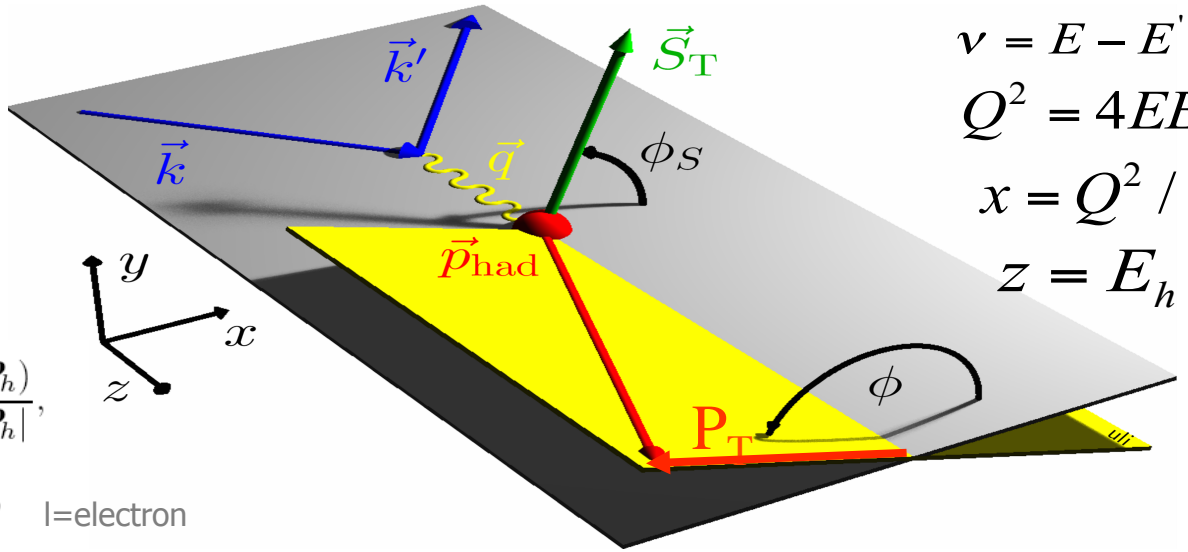
$x = Q^2/2M\nu$

Parton-Hadron transition by **fragmentation function** $D^{\pi^+(\pi^-)}(z)$: probability for a **u**-quark to produce a $\pi^+(\pi^-)$ with momentum fraction ***z***

Hadron-Parton transition by **distribution function** $q_f = f_1^u(x)$: probability to find a **u**-quark with a momentum fraction ***x***

SIDIS Kinematical Plane & Cross Section

Trento Conventions
Phys.Rev. D70, 117504 (2004)



$$\nu = E - E'$$
$$Q^2 = 4EE' \sin(\theta/2)$$
$$x = Q^2 / 2M\nu$$
$$z = E_h / \nu$$

$$\cos\phi_h = \frac{(\hat{q}\times l)}{|\hat{q}\times l|}\cdot\frac{(\hat{q}\times P_h)}{|\hat{q}\times P_h|},$$
$$\sin\phi_h = \frac{(l\times P_h)\cdot\hat{q}}{|\hat{q}\times l||\hat{q}\times P_h|},$$

l=electron

The possible contributions to the **cross section** of deep-inelastic scattering in a **semi-inclusive measurement** arise from the various combinations in the scattering of unpolarised (U) or longitudinally polarised (L) leptons off unpolarised, longitudinally or transversely polarised (T) nucleons:

$$\sigma = \sigma_{UU} + \lambda_l\sigma_{LU} + S_L\sigma_{UL} + \lambda_l S_L\sigma_{LL} + S_T\sigma_{UT} + \lambda_l S_T\sigma_{LT}$$

Beam polarization

Target polarization

S_L, S_T = Longitudinal/Transverse polarization

SIDIS Cross Section

- SIDIS differential cross section studied including the dependence on the azimuthal angles ϕ_h and ϕ_S.
- In OPE approximation: cross section decomposed in a model independent way into 18 **structure function F** related to the various **azimuthal modulations**

$$\mathbf{F = F(x, Q^2, z, |P_{h,\perp}|)}$$

$$\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&\quad + S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&\quad + S_T\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}$$

arXiv:hep-ph/0611265

α	fine structure constant
ϕ_S	Azimuthal angle of the target spin
ϕ_h	Azimuthal angle between the scattering plane and the hadronic plane
S_L	Transverse target pol.
S_T	Longitudinal target pol.
λ_ε	Beam polarization
$P_{h\perp}$	Transverse hadron momentum

SIDIS Cross Section @ Leading Twist

- The contributions to deep-inelastic scattering are commonly classified by twist (t), a quantum number, denoting the order in M/Q at which an effect arises. Dominant contributions are labelled as twist-two, t = 2, higher twist contributions, t > 2, are suppressed by $(M/Q)^{t-2}$.

- At leading twist the SIDIS differential cross section depends on **8 Structure Functions**:

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\,\frac{y}{2\,(1-\varepsilon)}$$

$$\times\Big\{F_{UU,T} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + S_L\,\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}$$

$$+ S_L\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL} + |\boldsymbol{S}_T|\Big[\sin(\phi_h-\phi_S)\,F_{UT,T}^{\sin(\phi_h-\phi_S)}$$

$$+ \varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$

$$+ |\boldsymbol{S}_T|\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\Big]\Big\},$$

$$F(x, Q^2, z, |\mathbf{P_{h,\perp}}|)$$

Different ϕ modulation for different TMDs contributions

SIDIS Cross Section @ Leading Twist

$$\epsilon = \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}y^2\gamma^2} \qquad \gamma = \frac{2Mx}{Q}$$

Take into account the dependence of the longitudinal and transverse polarisation of the virtual photon.
ε = ratio of the longitudinal to the transverse photon flux, which is determined by the kinematics of the lepton:

For small transverse hadron momentum, $P^2_{h\perp} \ll Q^2$, the structure functions can be interpreted in terms of a **convolution** over the intrinsic transverse momenta $k_\perp$ and $p_\perp$ **of quark distribution and fragmentation functions factorization proved!**

$$d\sigma^{lp\to lhX} = \sum_q f_q(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{lq\to lq}(y, \boldsymbol{k}_\perp; Q^2) \otimes D_q^h(z, \boldsymbol{p}_\perp; Q^2)$$

(N.B. In this formula $k_T \equiv k_\perp$)

Two scales:

- $P_{h\perp} \sim \Lambda_{QCD}$ ➔ Non perturbative regime! $P_{h\perp}$ is generated from partons inside of hadrons. Transverse momenta of partons: a transparent explanation for SSA
- Q large ➔ Hard process

From Structure Functions to Parton Distribution Functions (I)

The formulation of the cross section arises from a contraction of the leptonic ($L_{\mu\nu}$) and hadronic ($W^{\mu\nu}$) tensors

$$\frac{d\sigma}{dx_B dy d\psi dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2 y}{8zQ^4} L^{\mu\nu} 2MW_{\mu\nu}$$

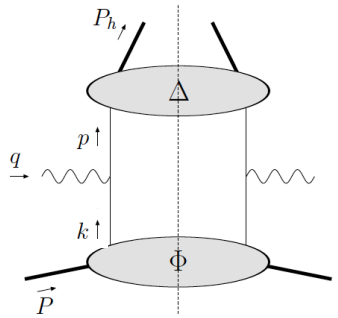
- The hadronic tensor is defined as:

$J^\mu(\xi)$ = e.m. current divided by the elementary charge

$$2MW^{\mu\nu} = \frac{1}{(2\pi)^3} \sum_X \int \frac{d^3\boldsymbol{P}_X}{2P_X^0} \, \delta^{(4)}\left(q + P - P_X - P_h\right) \langle P|J^\mu(0)|h, X\rangle\langle h, X|J^\nu(0)|P\rangle$$

Sum over the polarizations of all hadrons in the final state

- Calculations limited to the leading term in the 1/Q expansion of the cross section



$$2MW^{\mu\nu} = 2z \sum_a e_a^2 \int d^2\boldsymbol{k}_T \, d^2\boldsymbol{p}_T \, \delta^2(\boldsymbol{k}_T + \boldsymbol{q}_T - \boldsymbol{p}_T) \; \mathrm{Tr}\left\{\Phi^a(x, k_T)\gamma^\mu \Delta^a(z, p_T)\gamma^\nu\right\},$$

Sum over the quark and antiquark flavors a

fractional charge of the struck quark or antiquark

Correlation functions for quark distributions & fragmentation

Distribution functions with k_T

Ralston & SoperNP B 152 (1979) 109
Tangerman & Mulders PR D 51 (1995) 3357

Selection via specific probing operators

Calculations in light cone coordinate

DISTRIBUTION FUNCTIONS IN $\Phi(x, k_T)$

$$\frac{1}{2}\mathrm{Tr}\left[\Phi\gamma^+\right] = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3} e^{ip\cdot\xi} \langle P,S|\bar{\psi}(0)\gamma^+\psi_i(\xi)|P,S\rangle\Big|_{\xi^+=0}$$

$$= f_1(x,k_T^2) - f_{1T}^{\perp}(x,k_T^2)\frac{(\hat{P}\times\vec{k}_T)\vec{S}_T}{M}$$

$$\frac{1}{2}\mathrm{Tr}\left[\Phi\gamma^+\gamma_5\right] = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3} e^{ip\cdot\xi} \langle P,S|\bar{\psi}(0)\gamma^+\gamma_5\psi_i(\xi)|P,S\rangle\Big|_{\xi^+=0}$$

$$= \vec{S}_L g_{1L}(x,k_T^2) + g_{1T}(x,k_T^2)\frac{(\vec{k}_T\vec{S}_T)}{M}$$

$$\frac{1}{2}\mathrm{Tr}\left[\Phi\gamma^+\gamma^\alpha\gamma_5\right] = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3} e^{ip\cdot\xi} \langle P,S|\bar{\psi}(0)\gamma^+\gamma^\alpha\gamma_5\psi_i(\xi)|P,S\rangle\Big|_{\xi^+=0}$$

$$= \vec{S}_T h_{1T}(x,k_T^2) + ih_1^{\perp}(x,k_T^2)\frac{\vec{k}_T}{M}$$

$$+\vec{S}_L h_{1L}^{\perp}(x,k_T^2)\frac{\vec{k}_T}{M} + h_{1T}^{\perp}(x,k_T^2)\frac{(\vec{k}_T\vec{S}_T)}{M}\frac{\vec{k}_T}{M}$$

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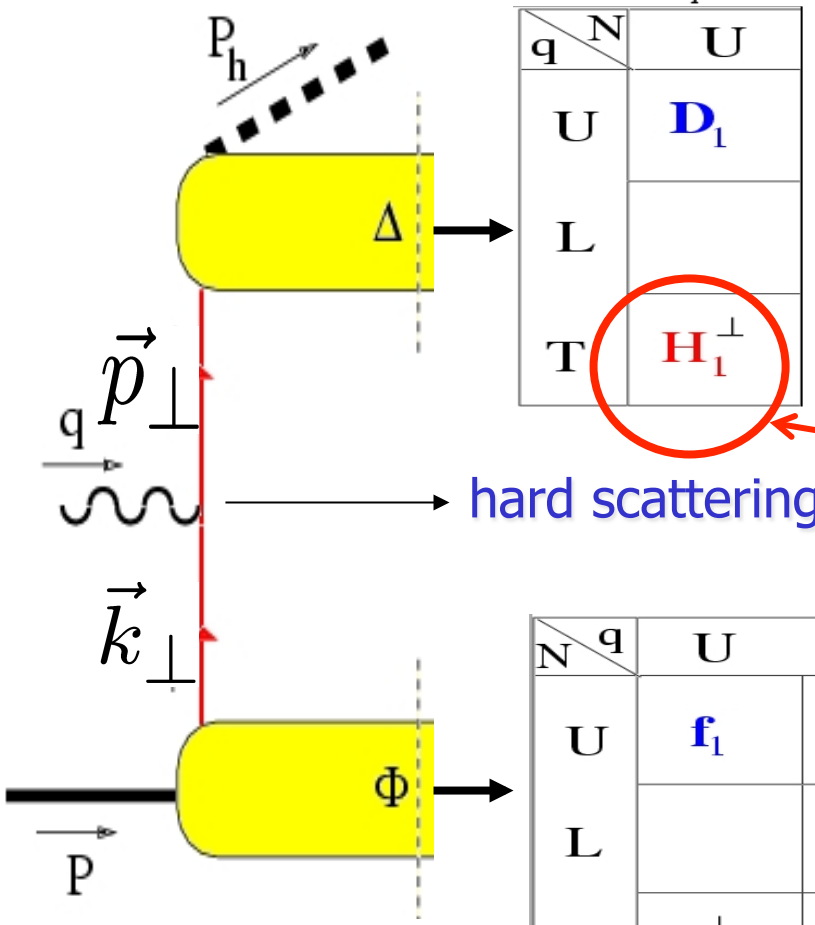
TMDs at Leading Twist

$$\sigma^{eH\to ehX} = \sum_q f^{H\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to\pi}$$



q \ N	U
U	D_1
L	
T	$H_1^\perp$

Transverse momentum dependent FRAGMENTATION functions

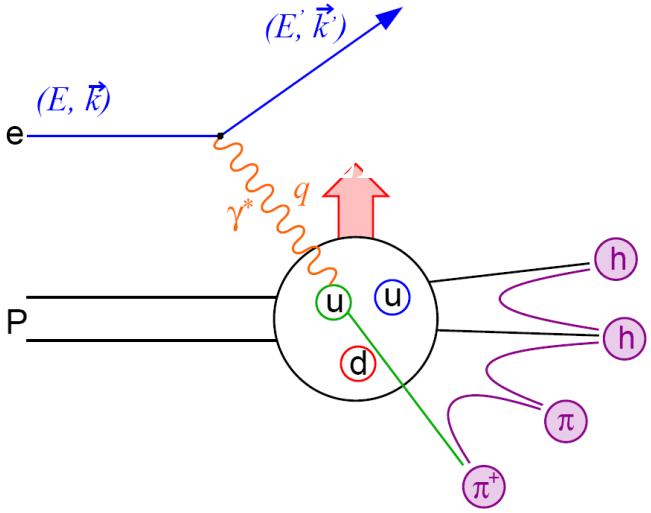
hard scattering

Collins function describes the fragmentation of a tranversely polarized quark into an unpolarized hadron

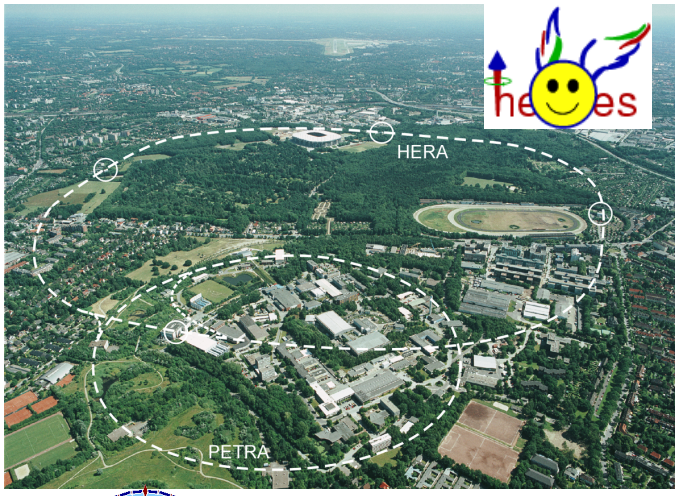
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

Transverse momentum dependent DISTRIBUTION functions

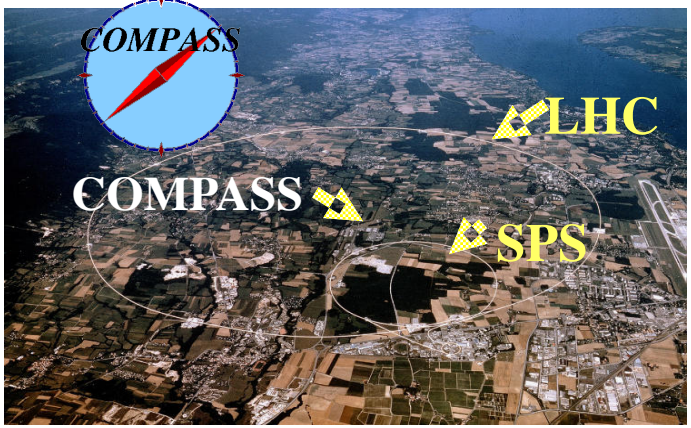
Main Players in the game



27 GeV $e^{+/-}$



190 GeV μ

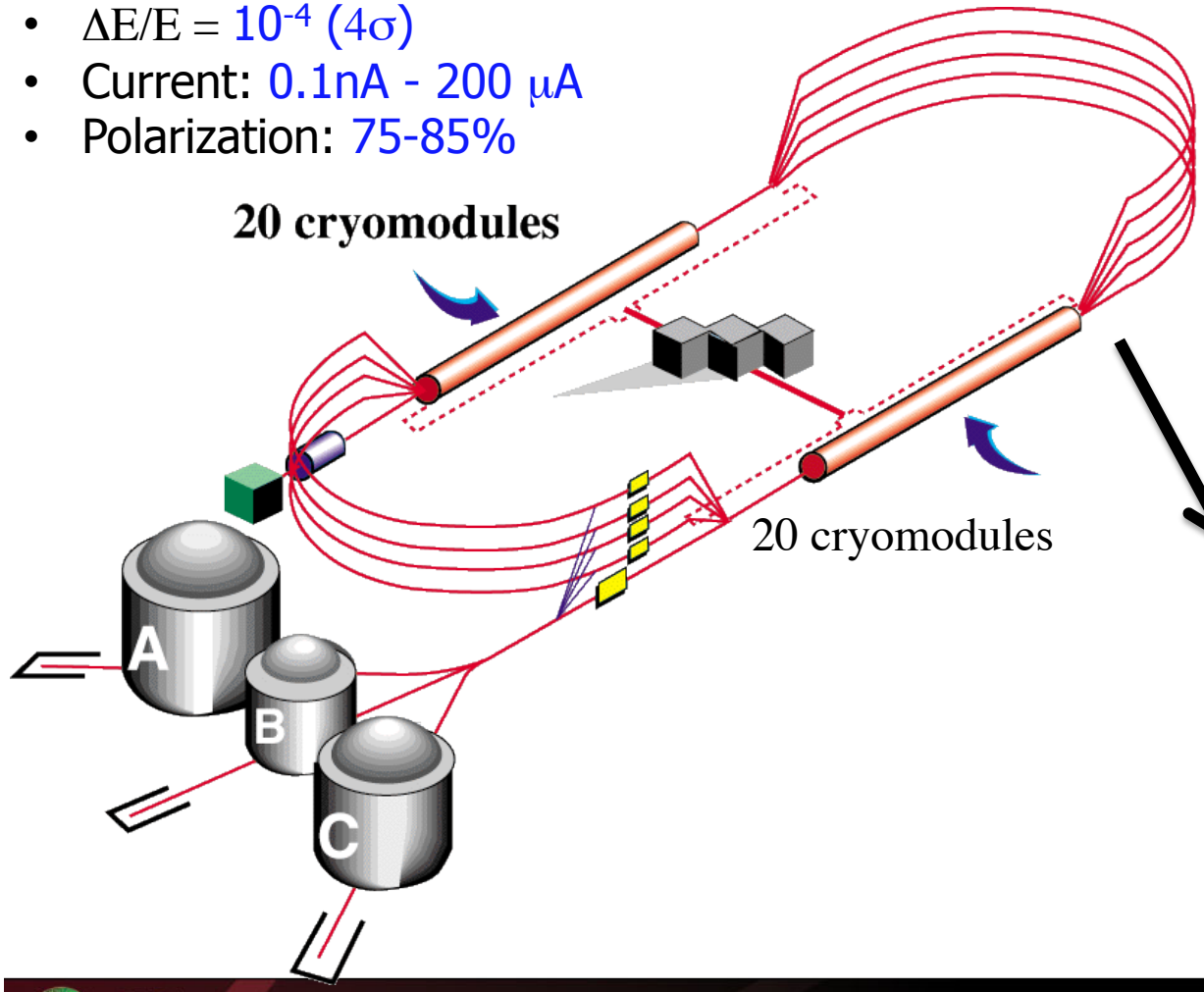


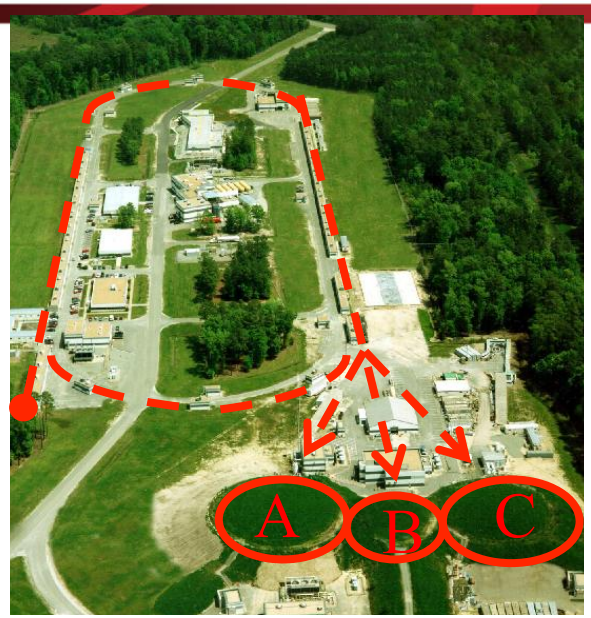
≈6 GeV e^{-}

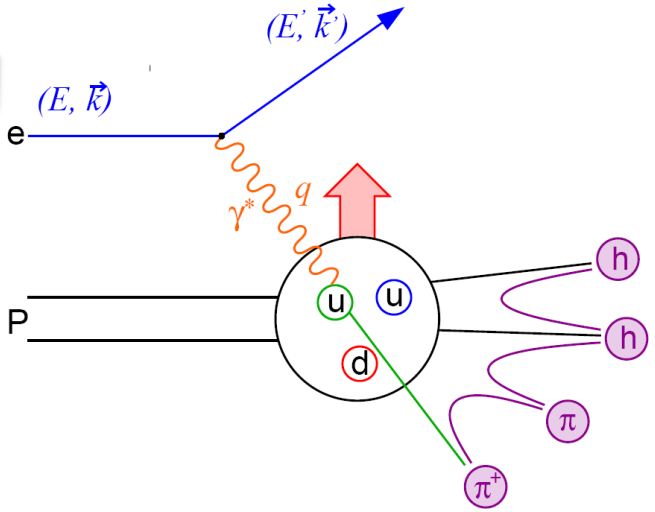
Hall A
Hall B
Hall C

Experimental Tools

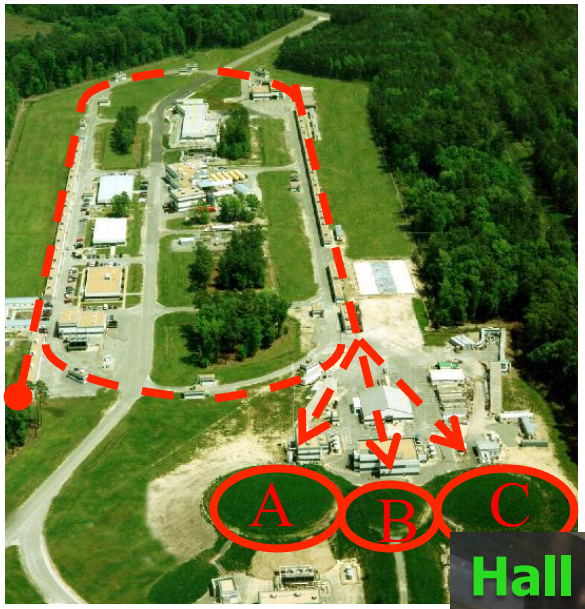
- First large high-power **CW recirculating e-linac** (based on SRF technology)
- Energy: 0.8 - 5.7 GeV → $(10 > \lambda > 0.1$ fm)
- $\Delta E/E = 10^{-4}$ (4σ)
- Current: 0.1nA - 200 μA
- Polarization: 75-85%







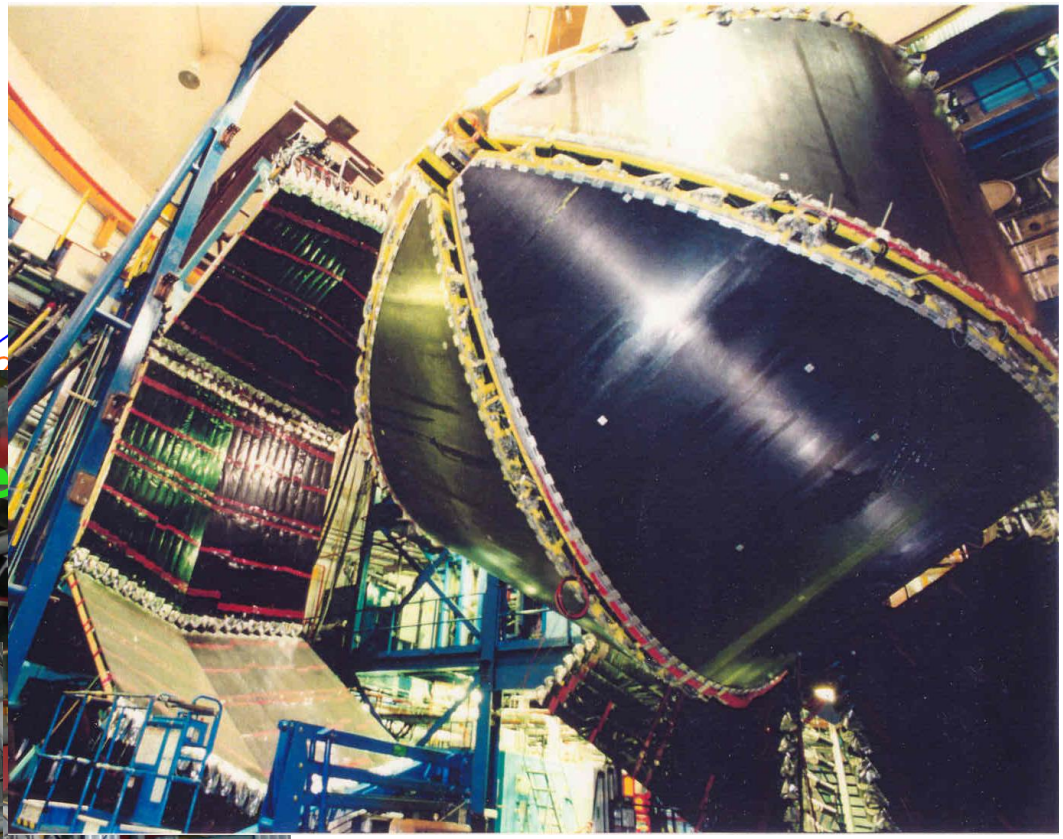
Experimental Tools



$(E, \vec{k})$

e

Hall B - CLAS detector



Hall A
Polarized ^{3}He

Hall A
Polarized ^{3}He Target

Hall B
Polarized H/D Ta

Hall B
Polarized H/D Target

Pol. NH_3, ND_3 targets
$\langle P_H \rangle$ =0.8, $\langle P_D \rangle$=0.3
Longitudinal polarization

$\langle P \rangle$ =0.55-0.60
Long. & Transv. polarization

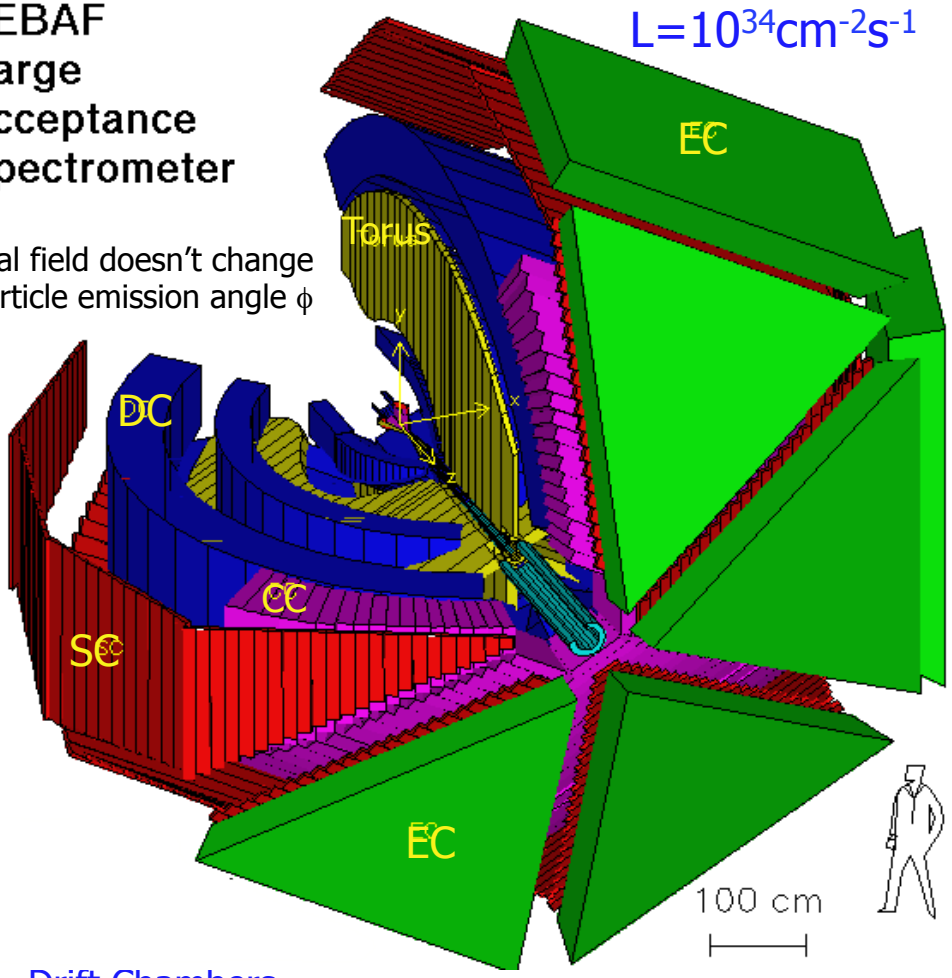
sverse polarization

The CLAS Detector

CEBAF
Large
Acceptance
Spectrometer

$L=10^{34}cm^{-2}s^{-1}$

Toroidal field doesn't change the particle emission angle ϕ

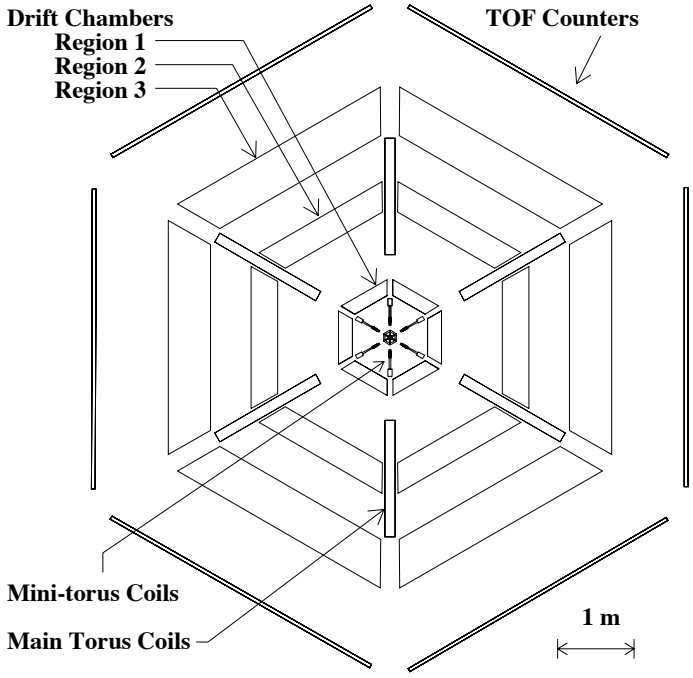


DC= Drift Chambers
CC= Cherenkov Detector
SC= Time-of-Flight detector
EC= Electromagnetic Calorimeter

Large Acceptance Detector:

$8^o<\theta<140^o$

$\Rightarrow$ideal for detecting multi-particles final state



Basic Tools for Particle Identification (PID)

PID: methods based on the momentum measurement **p** and another kinematical variable (β or γ)

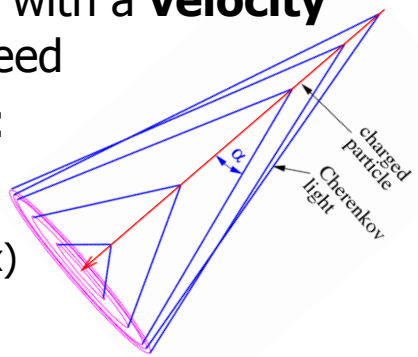
$$p=\gamma m_0 \beta c$$

Cerenkov Detectors

Based on Čerenkov effect: a cone of light is produced when a particle traverses a medium with a **velocity** greater than the speed of light in that medium:

$v = \beta c > c/n$,

(n being the refractive index)

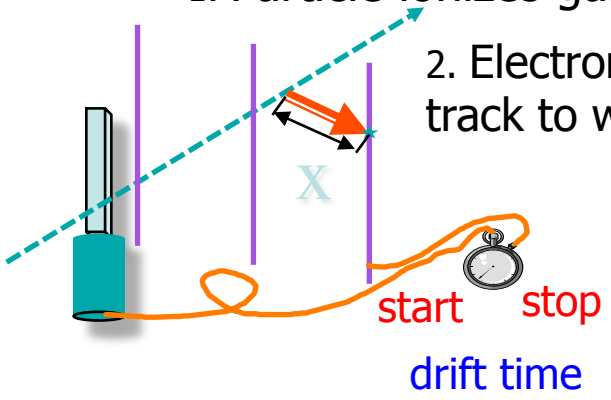


Calorimeter

If we stop a particle in a scintillator (or other suitable material, es. Liquid Argon), then the amount of light detected provides a measure of the total **energy** that the particle had

Drift Chamber (Tracking)

1. Particle ionizes gas.



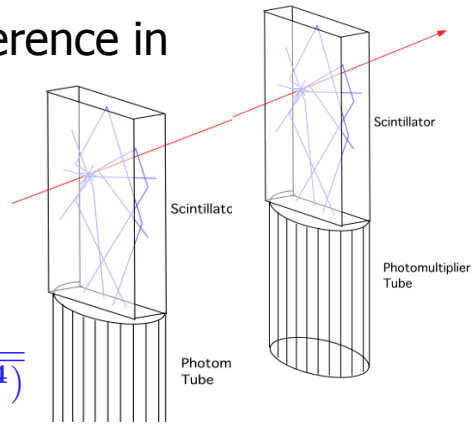
2. Electrons drift from track to wire

3. Measure the drift time and get x (**position**)

Time-of-Flight (TOF)

Knowing the separation of the scintillators and measuring the difference in arrival time of the signals gives us the **particle speed**

$$\frac{L}{\Delta t} = \beta c = c\frac{p}{\sqrt{(p^2 + m^2c^4)}}$$



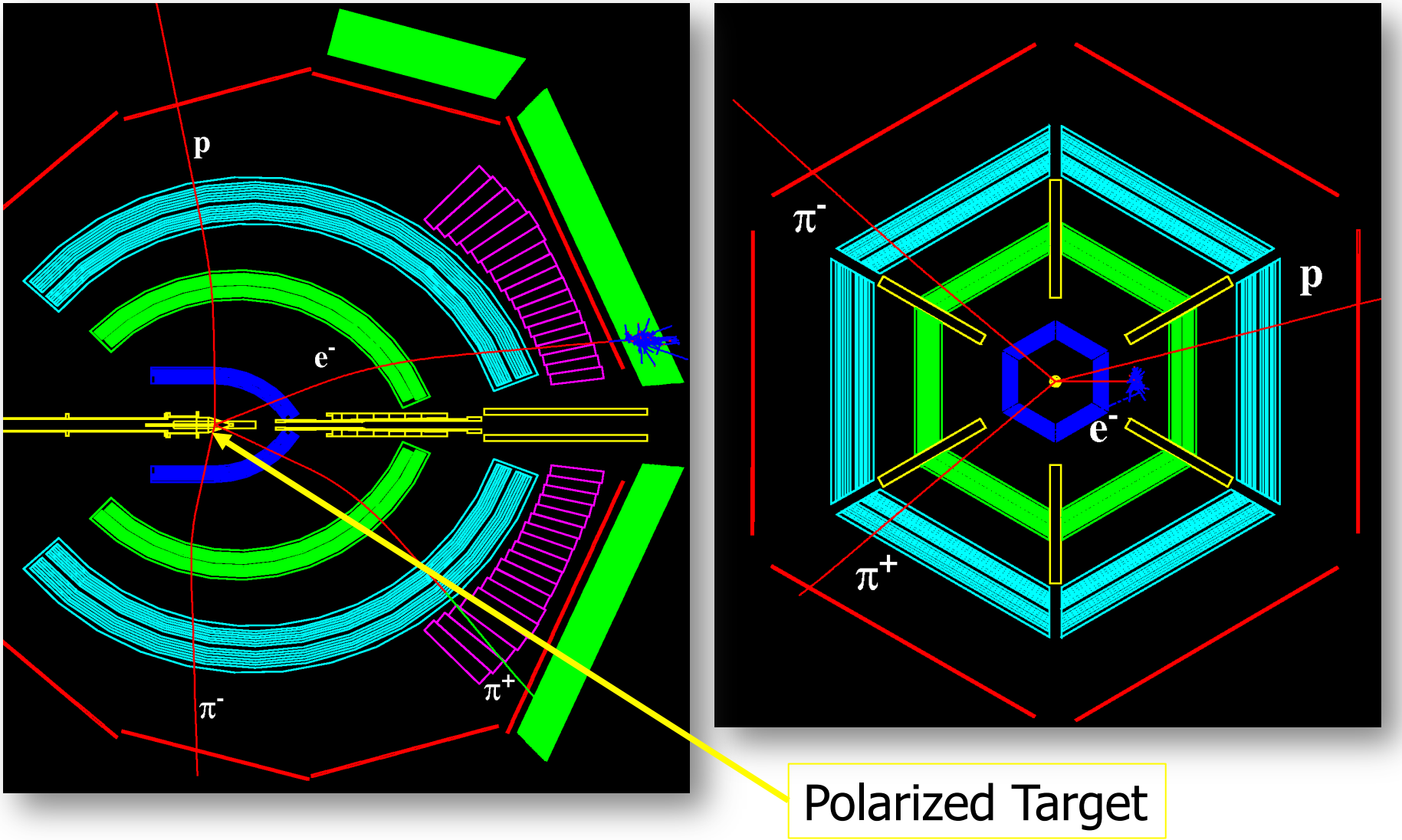
k_T-effects with longitudinally polarized target

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

$$\vec{e}\,\vec{p} \rightarrow e'\,\pi\,X$$

Correlation between the transverse momentum and transverse spin of quarks in longitudinally polarized proton

Scattering $\vec{e}$ $\vec{p}$



Charged Particle Identification

- **Tracks measured in the Drift Chambers**

$$\rho = \frac{p}{qB} \rightarrow p = qB\rho$$

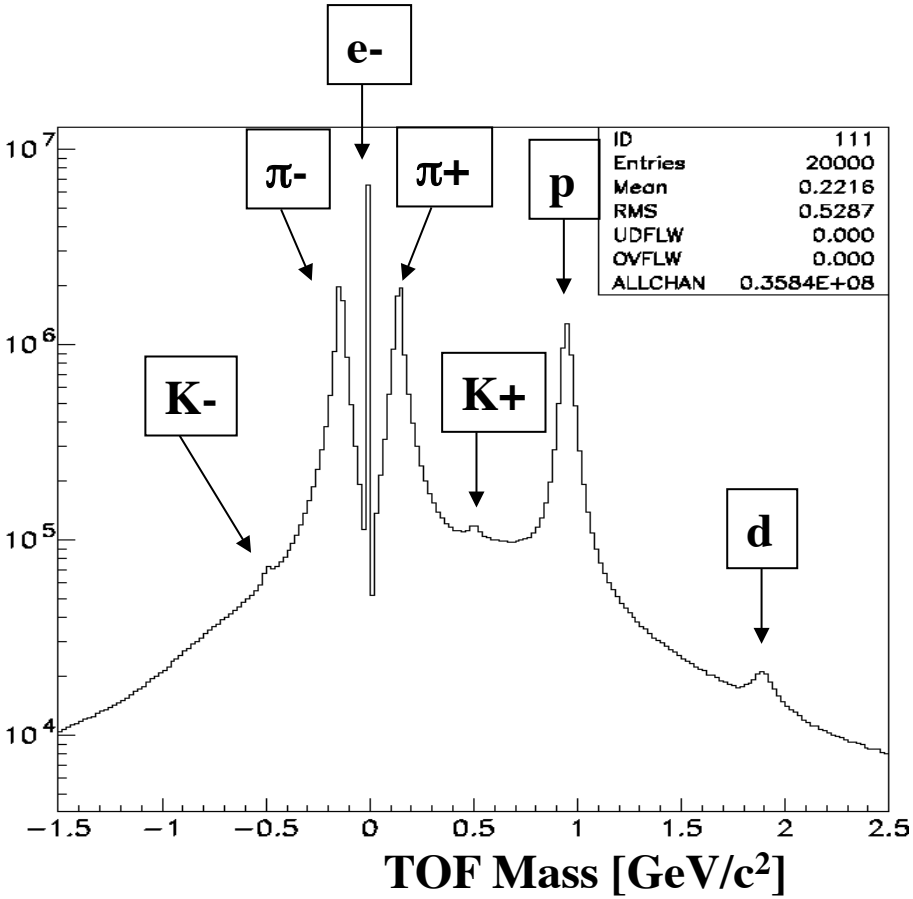
B known; ρ measured in DC

- **β measured with TOF**

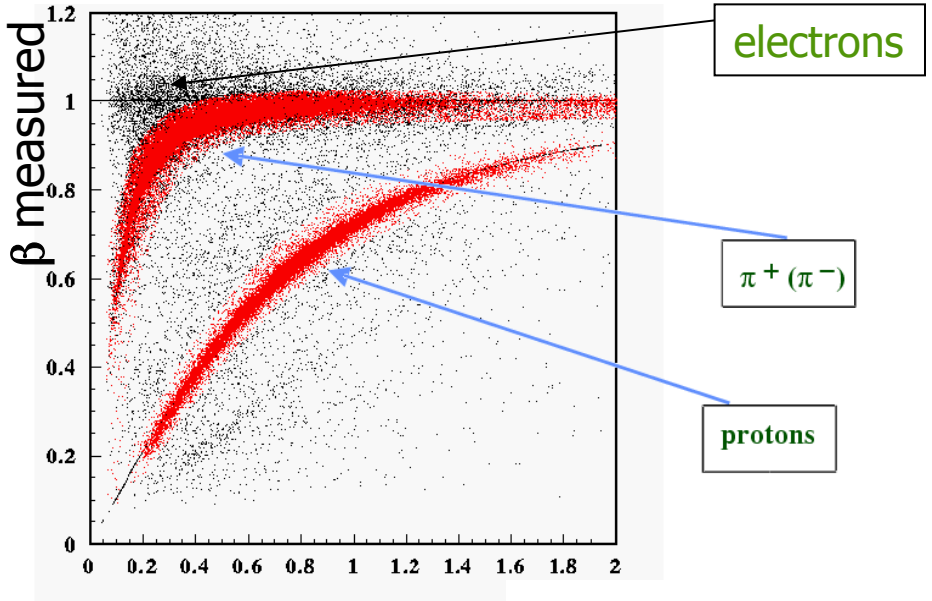
$$\beta = \frac{L}{c\Delta t}$$

L = path length from target to TOF scintillator
Δt= time of flight

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \rightarrow \mathbf{M = \frac{p}{\beta\gamma}}$$

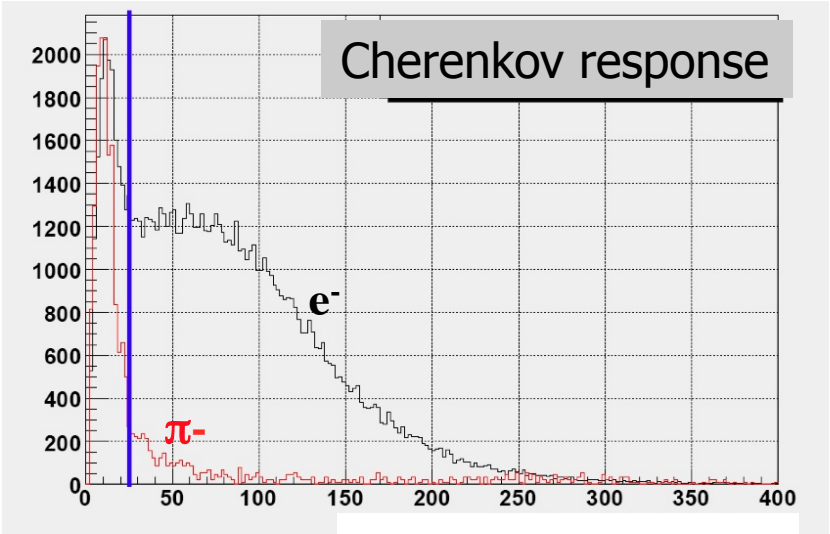


e/π Rejection with Cherenkov



β=p/E

At energies ~ GeV it is difficult to separate e^- / π^- using only TOF and path length → we need information from the Cherenkov and the electromagnetic calorimeter. In fact, hadron interaction in the scintillator is very different from e^- interaction.



Particles emit Cherenkov light only when their velocity is :

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

in CLAS n=1.0013 (C_4F_{10})
→ P_π >2.7 GeV/c

Number of emitted γ is:

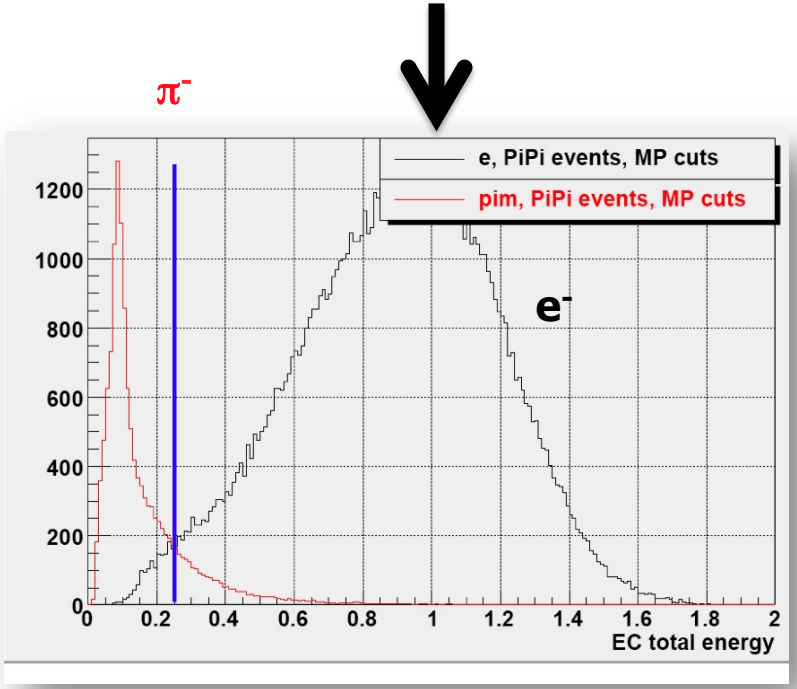
$$\frac{dN_\gamma^2}{d\lambda dL} \propto sin^2_{\theta_C}(\lambda)$$

The angle of emission increases with β

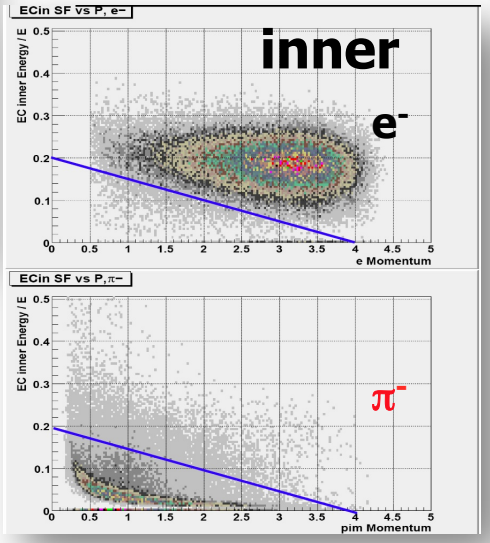
→ **Min p.e.=2 for e^-**

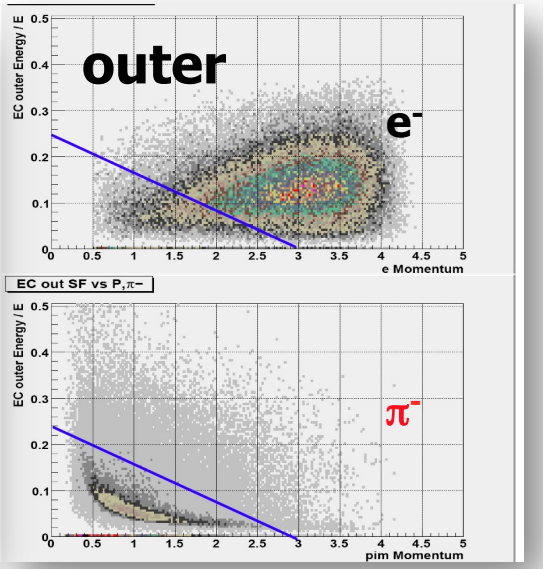
e/π Rejection with e.m. Calorimeter

The e- /π - rejection in the calorimeter e.m. is based on the fact that most of the incident pions lose energy only for ionization (and therefore a small fraction of their total energy) thus they can be rejected placing a suitable threshold in the released energy.



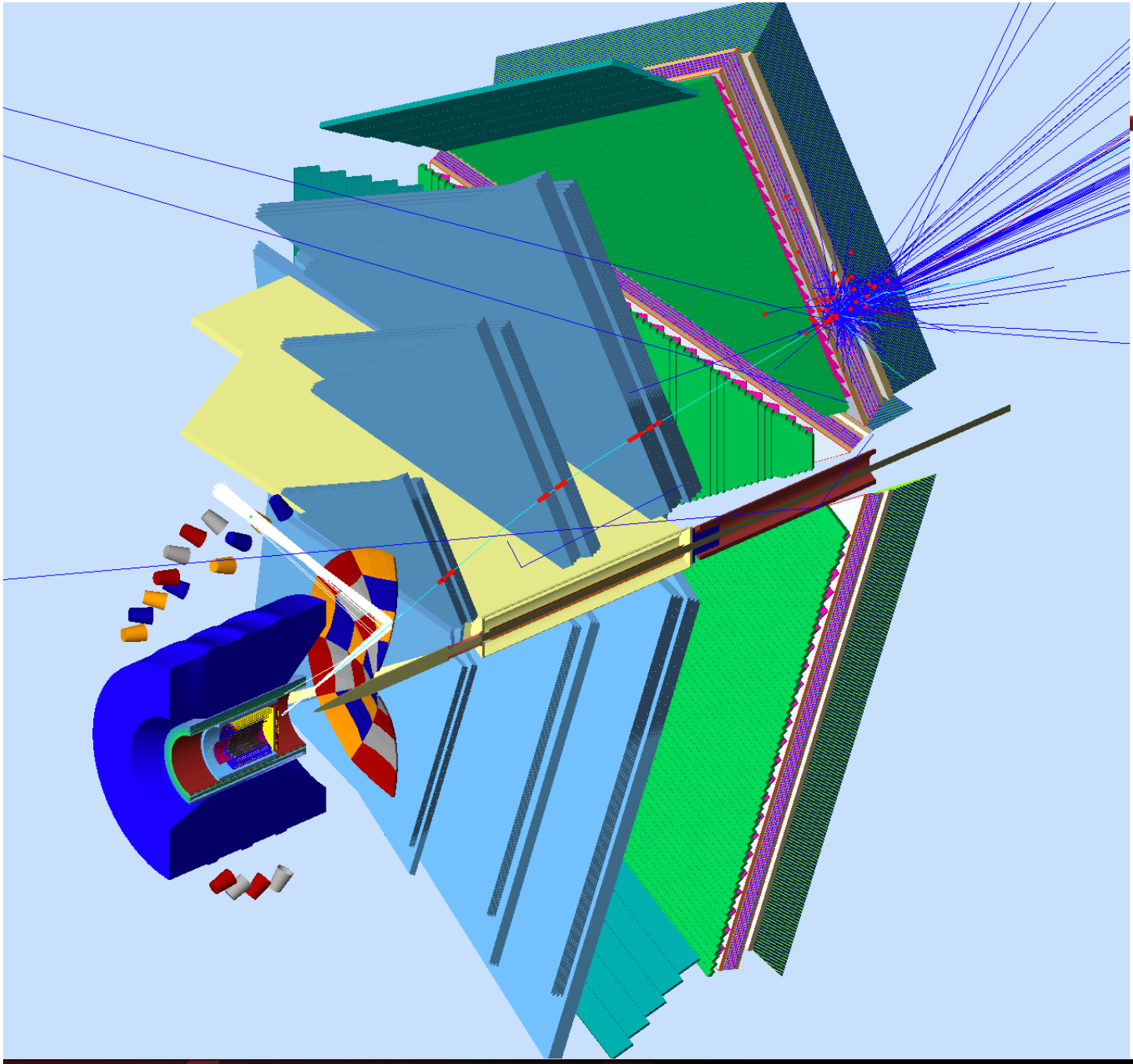
- To improve the e- / π - rejection a comparative analysis of the energy deposited in the inner and outer part of the calorimeter is used.
- The π- deposite uniformly their energy in the inner and outer part of the calorimeter while this is not the case for e-





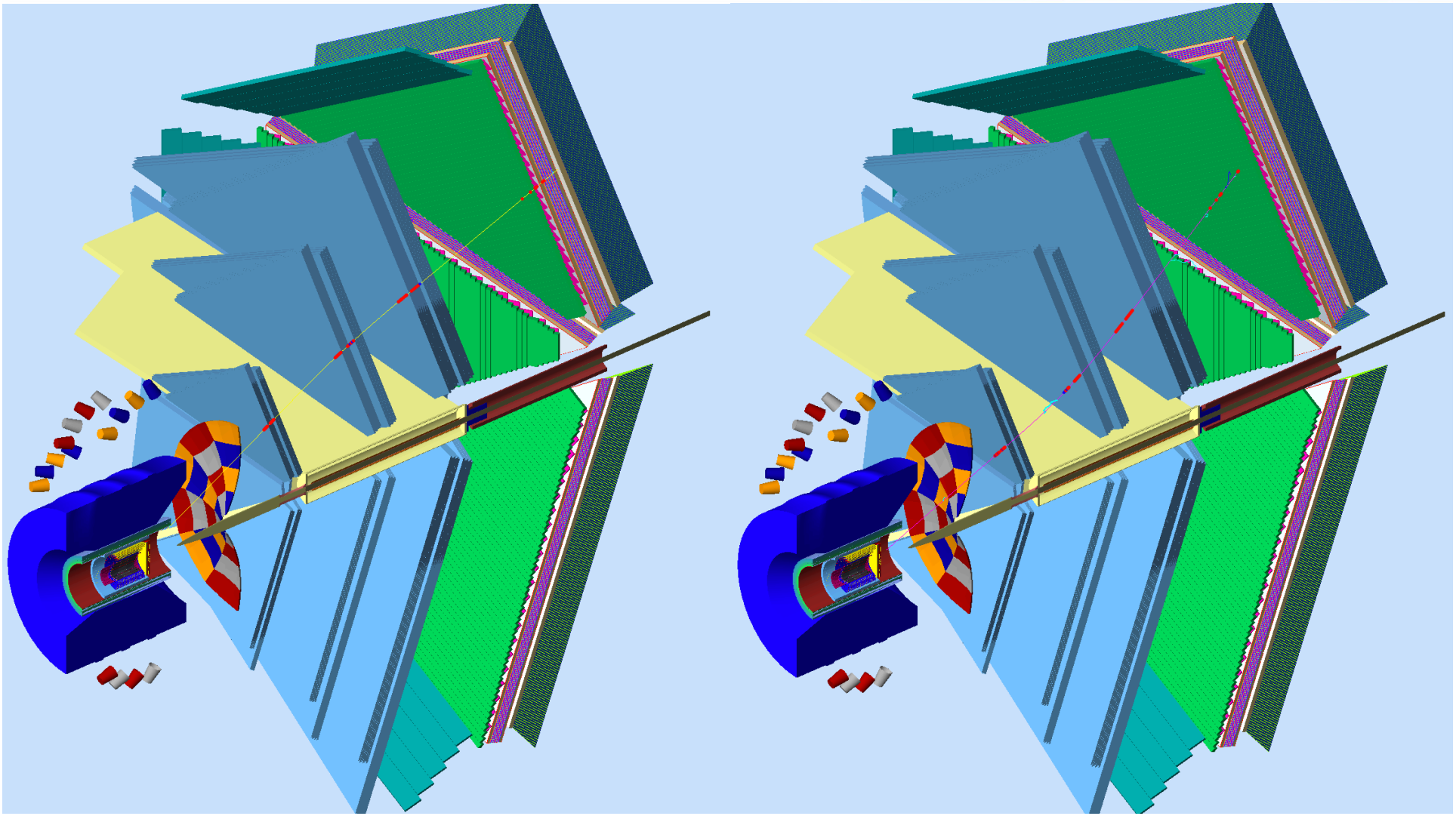
Sampling fraction≅0.3

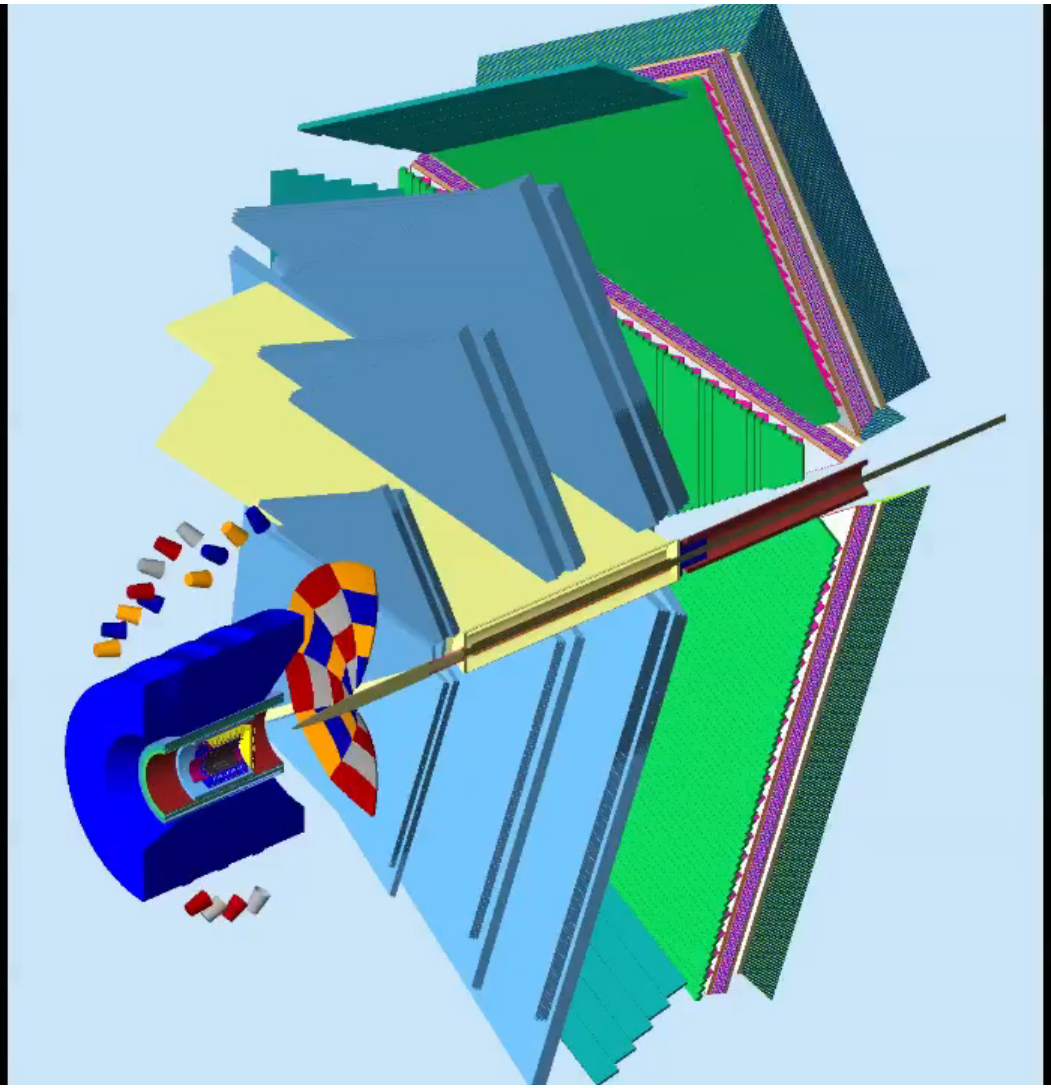
(fraction of the deposited energy deposited in the active medium- and then detectable- with respect to the total energy lost)



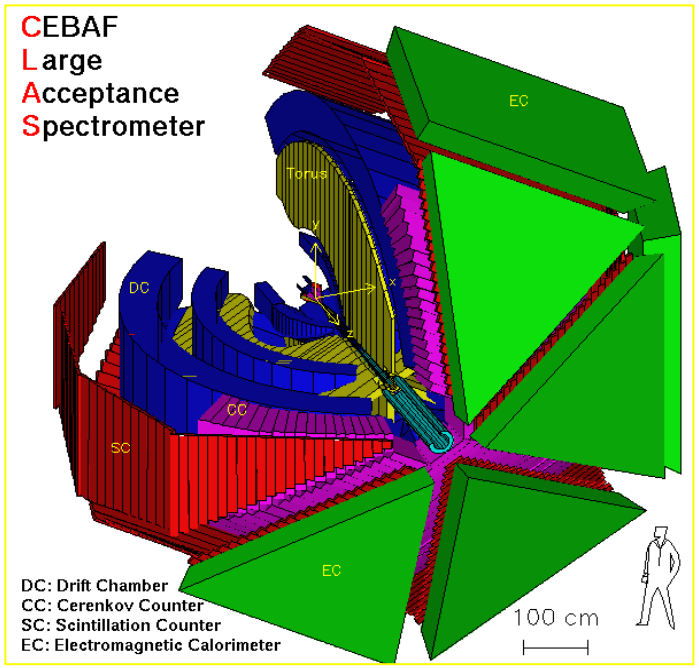
e^-

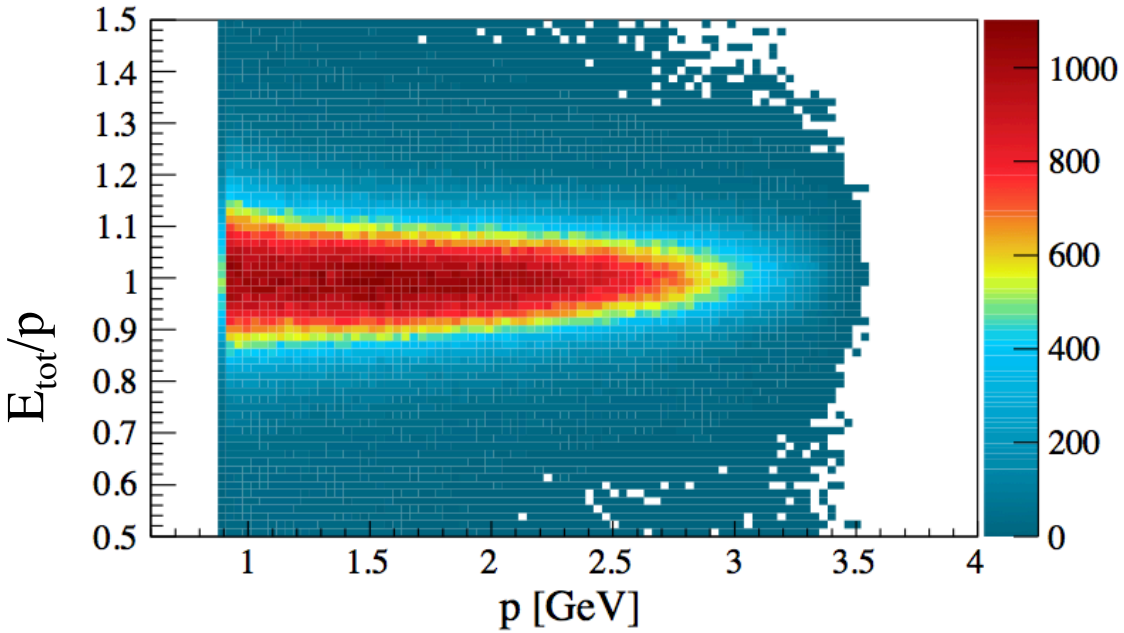
π^-/π^+





e/π Rejection: e.m. Calorimeter + Cherenkov

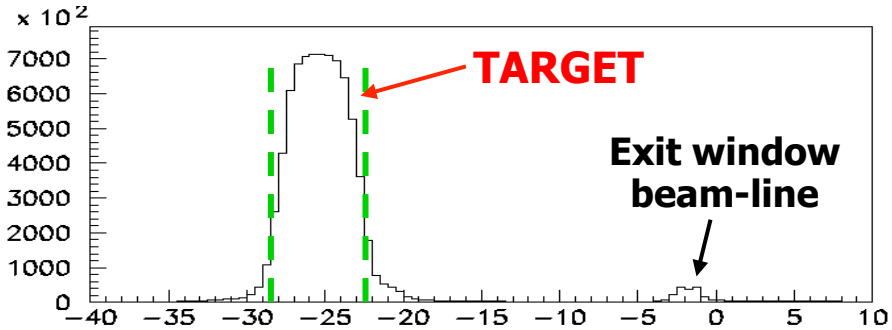


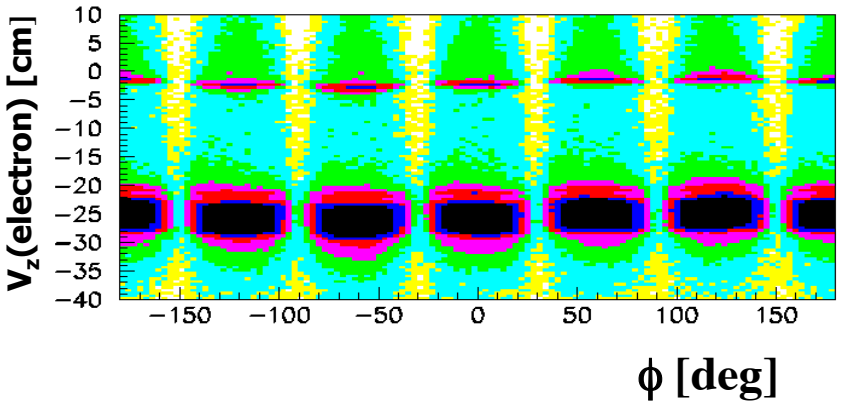


Combined cuts on Cherenkov and the e.m. calorimeter select correctly the electron

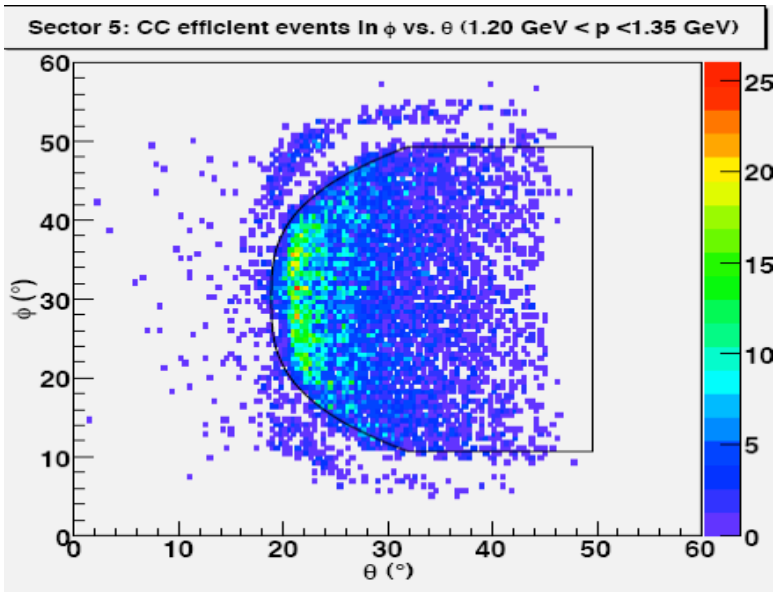
Fiducial Region

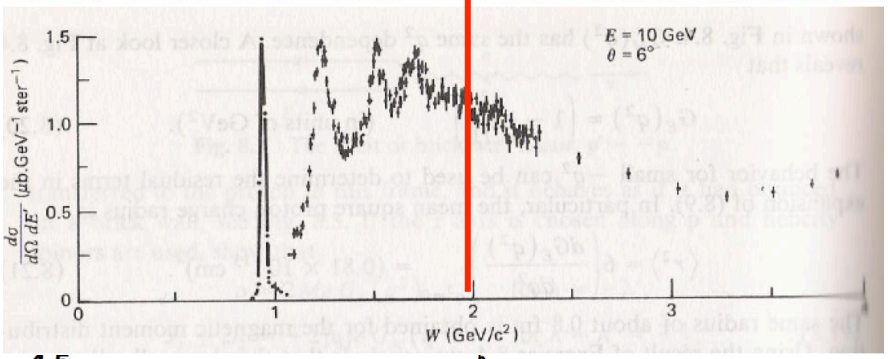
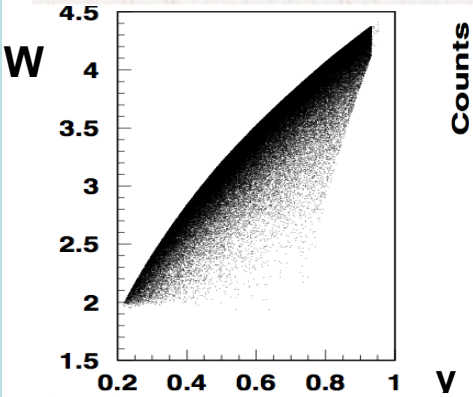
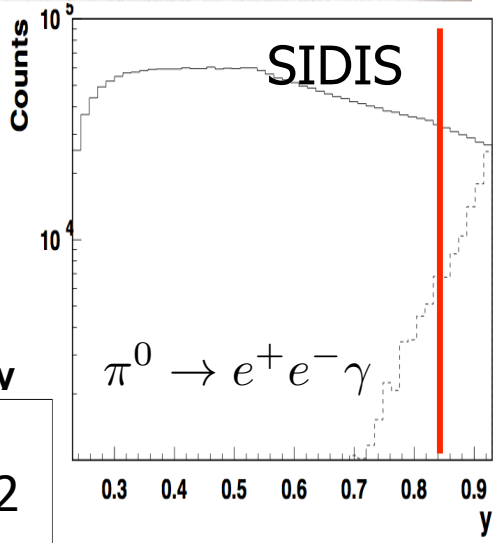
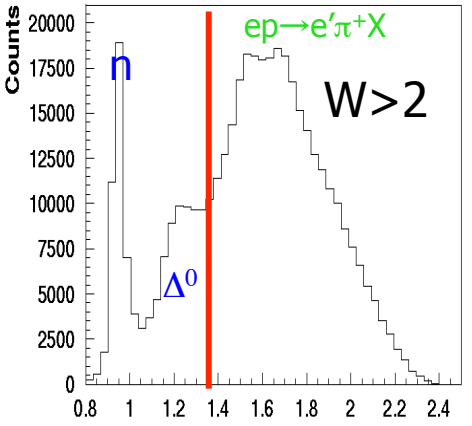
- A z-coordinate cut of the electron vertex is made to select events that are created in the target





- Momentum dependent fiducial cuts on ϑ and ϕ are made for electrons and charged pions to constrain the data to a region in CLAS that can be accurately recreated by simulation



Kinematical Cuts for SIDIS events

Q^2 (GeV^2)	**> 1**	Virtuality	Hard process
W^2 (GeV^2)	**> 4**	Inv. mass squared of the final state	Removes resonance region contributions
z	**> 0.4** **< 0.7**	Fraction of the γ^* energy carried by the detected hadron	Excludes events in the target fragmentation region (lower limit) and the exclusive region (upper limit)
y	**< 0.85**	Fraction of the electron energy carried by the γ^*	Removes region of low energy e^- coming mainly from π^0 decay
M_x^2 (GeV^2)	**> 2**	invariant mass of the residual system after detection of $e'\pi$	Remove exclusive $\pi\Delta$, πn