9° European Research Conference on Electromagnetic Interactions with Nucleon and Nuclei

DiHadron analysis at CLAS
($e\,p \rightarrow e\,\pi^{+}\pi^{-}X$)

Silvia Pisano

Laboratori Nazionali di Fisica Nucleare di Frascati
& Università degli Studi di Roma «Tor Vergata»

Paphos, Cyprus
November 3°, 2011.

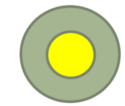
INFN
Istituto Nazionale di Fisica Nucleare

Jefferson Lab

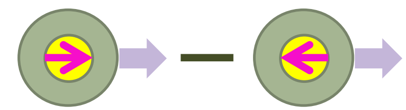
Introduction

At the leading order (twist)[1], three Parton Distribution Functions (PDF) exhaust the description of quarks inside the nucleon:

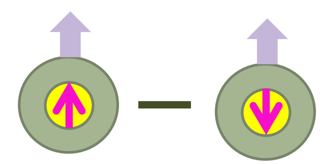
- $f_1^q(x)$: number density of an unpolarized quark in an unpolarized nucleon
  - ***known with high accuracy***



- $g_1^q(x)$: number density of longitudinally polarized quark in a longitudinally polarized nucleon
  - ***less well known (but there are measurements: see, e.g., Hermes data for 5 different quark flavours*)***



- $h_1^q(x)$: number density of transversely polarized quarks in a transversely polarized nucleon
  - ***<u>the transversity is the only missing ingredient to complete the leading-twist picture of the nucleon.</u>***



The cleanest approach to access the three PDFs is ***Deep Inelastic Scattering (DIS)***, but transversity does not appear in its cross-section:

$$\frac{d\sigma}{dxdyd\phi_S} = \frac{\alpha^2}{sx(1-\varepsilon)} \sum_q e_q^2 \left[f_1^q(x) + \lambda_e S_L \sqrt{1-\varepsilon^2}\, g_1^q(x) \right]$$

$f_1^q(x)$ and $g_1^q(x)$ are present, but $h_1^q(x)$ is not

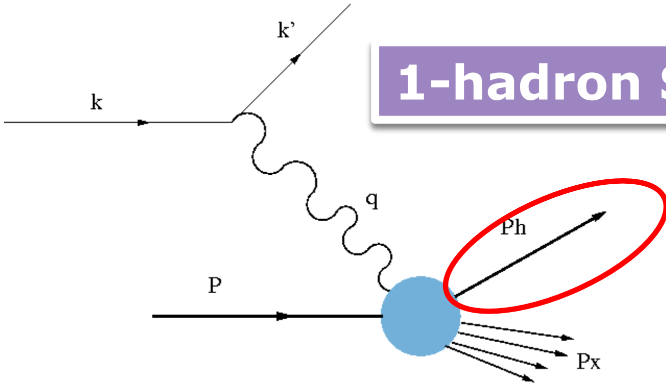
[1] *Twist refers to the order in M/Q at which the distribution function contributes to the cross-section. See Jaffe, hep-ph/9602236.*

**A. Airapetian et al. PRD 71, 012003 (2005)*

Semi-Inclusive Deep Inelastic Scattering

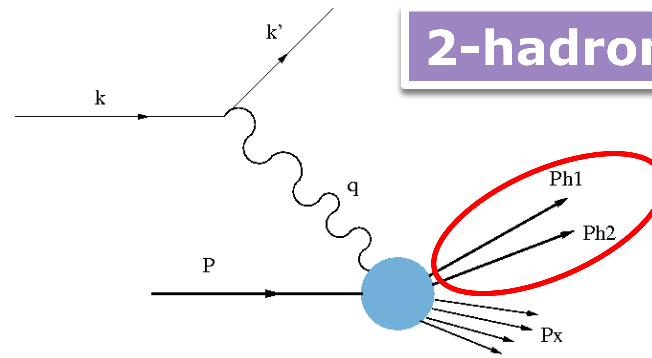
Since transversity does not appear in DIS, its experimental investigation relies on a different kind of processes, *i.e.* processes where a hadron appear *both* in the inital **and in the final state**.

1-hadron SIDIS



$$l(k) + N(P) \rightarrow l'(k') + X(P_X) + h(P_h)$$

2-hadron SIDIS

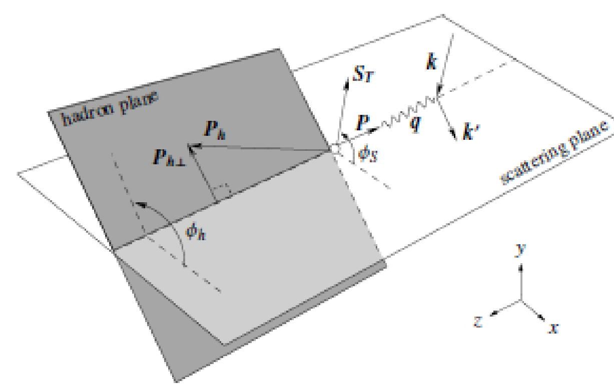


$$l(k) + N(P) \rightarrow l'(k') + X(P_X) + h_1(P_{h_1}) + h_2(P_{h_2})$$

With these processes, it is possible to access the quark transverse polarization:

- by extracting the asymmetry in the distribution of $P_{h\perp}$ of the final hadron
- by measuring the polarization of a transversely polarized final hadron (as the hyperon Λ^0)

Observable quantities



DiHadron processes

A specific example of SIDIS process is the dihadron semi-inlcusive production, that has the general form

$$e\,p \to e'\,h^+\,h^-\,X$$

- As a Semi-Inclusive Deep Inelastic (SIDIS) process, it allows to access transversity $h_1^q(x)$
- With respect to the single-hadron production, it provides an easier access to $h_1^q(x)$

  - $h_1^q(x)$ appears in the single-hadron cross section in a convolution integral

$$\frac{d^6\sigma}{d\ldots} \approx \ldots \Im\left[\frac{k_T \cdot \hat{P}_{h\perp}}{m_P} h_1^q H_1^{\perp q}\right]$$

  - ...while it appears in a direct product in the two-hadron cross section

$$\frac{d^7\sigma}{d\ldots} \approx \ldots h_1^q(x) H_1^{\angle q}$$

The extraction of the Beam-Spin Asymmetry allows to access the structure function

$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{M_h}\, x\, e^q(x)\, H_1^{\sphericalangle q}\big(z,\cos\theta,M_h\big) + \frac{1}{z}\, f_1^q(x)\, \widetilde{G}^{\sphericalangle q}\big(z,\cos\theta,M_h\big)\right]$$

The extraction of the PDF is possible since the interference fragmentation function has been recently extracted from Belle measurement*

Silvia Pisano – LNF
EINN 2011

*** BELLE Collaboration, A. Vossen et al., PRL (2011), 1104.2425.***

Analysis procedure

We will focus on the channel $\boldsymbol{e\,p \rightarrow e'\,\pi^{+}\,\pi^{-}\,X}$. The analysis procedure goes through the following steps:

$$e\,p \rightarrow e'\,\pi^{+}\,\pi^{-}\,X$$

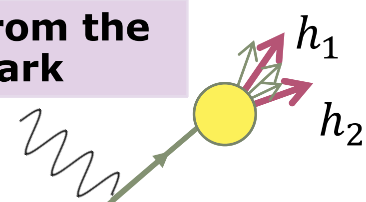
Identification of the events where these three particles appear

Particle Identification

Detection of the final state particles with CLAS

Event selection

Specific kinematic configurations are selected	**Selection of pions from the fragmenting quark**



- **DIS events**
- **Current Fragmentation Region pions**

Extraction of the Asymmetry

Extraction of the moments of the BSA	**Moment kinematic dependence**

$$A_{U/T/L} = \frac{\sigma^{+} - \sigma^{-}}{\sigma^{+} + \sigma^{-}}$$

$$A_{LU}{}^{\sin(\varphi)}(m_{\pi^{+}\pi^{-}}, z, x_B)$$

$$\sin(\Phi_{h,R} \pm \Phi_S) \times h(x) \times FF$$

modulation — *Distribution function* — *Fragmentation function*

Cebaf Large-Acceptance Spectrometer

INFN Istituto Nazionale di Fisica Nucleare

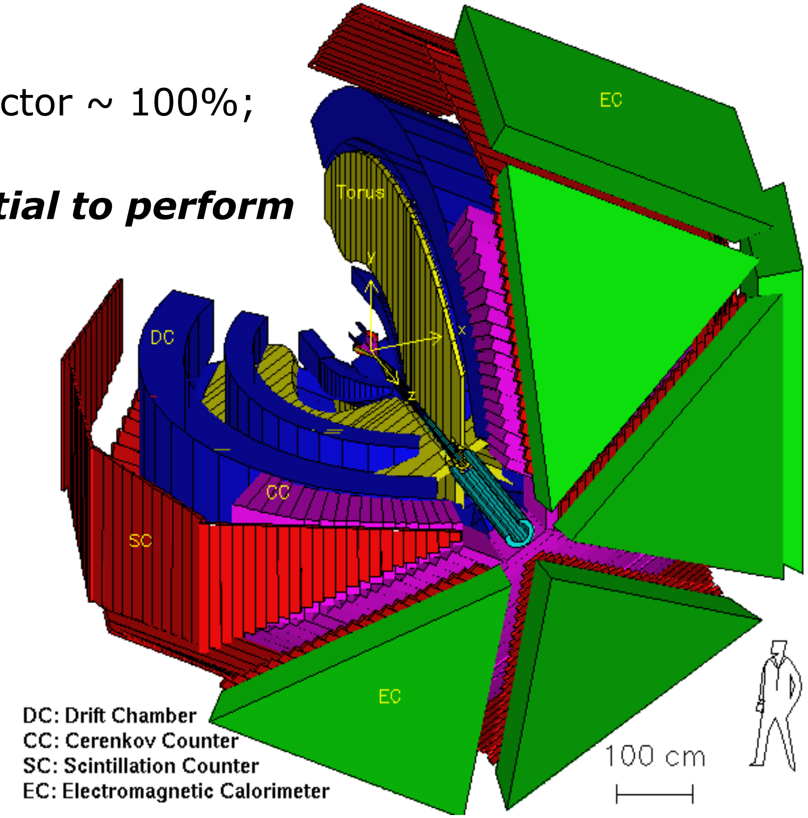
The ***Cebaf Large-Acceptance Spectrometer* (CLAS)** is installed in the Hall-B of the Thomas Jefferson National Accelerator Facility (Newport News, VA, USA). It is a natural enviroment to perform SIDIS measurements.

The CEBAF, indeed:

- provides a continous electron beam with a duty factor ~ 100%;
- has a good energy resolution ($\frac{\sigma_E}{E} \sim 10^{-5}$);
- and the beam has a polarization ~ 85% → ***essential to perform BSA measurements***

The CLAS detector is provided with:

- Toroidal magnetic field (6 supercondicting coils)
- Drift chambers (argon/CO_2 Gas, 35000 cells)
- Time-of-flight scintillators
- Electromagnetic calorimeters
- Cherenkov counters (e/π separation)



Its features allow the following performances:
- **Nearly 4π acceptance**
- **Large kinematical coverage**
- **Detection of charged and neutral particles**

Jefferson Lab

Data set & Particle Identification

This analysis is focused on the process

$$e\,p \rightarrow e'\,\pi^+\,\pi^-\,X$$

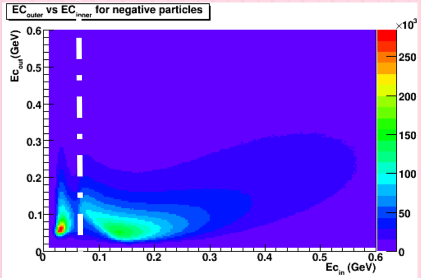
21 fb^{-1} from the e1f data set are used

- Longitudinally polarized electron beam with average polarization of 75 %
- Target: unpolarized liquid hydrogen
- Beam energy: 5.5 GeV
- Torus magnet reduced to 60% of full current to maximize acceptance of charged pions.

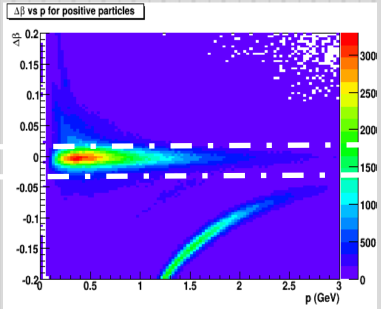
Standard PID cut to identify the particle in the finale state:

$$e\,p \rightarrow e'\,\pi^+\,\pi^-\,X$$

- $p_e > 0.8\ GeV$
- $n_{phe} > 25$
- $ec_{InnEn} > 0.06\ GeV$
- $0.2 < \frac{E_{Tot}}{p} < 0.36\ GeV$
- $\pm 4\ cm$ from the vertex



- Cuts complementary to the electron ones
- $\Delta\beta < 0.02$

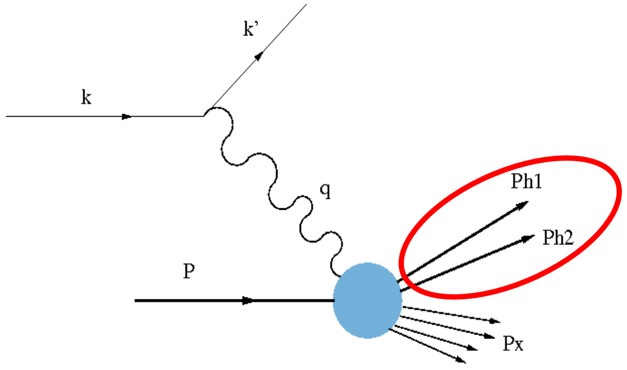


Silvia Pisano – LNF

Jefferson Lab

DiHadron sample selection

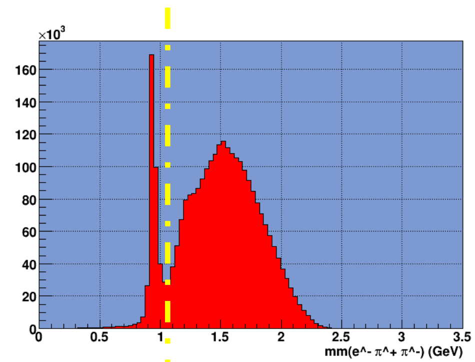
- The events with at least one π^+ and one π^- are selected
- In the case of more than one $\pi^\pm$, the various combinations are considered
- DIS cuts are applied: W > 2 GeV && $Q^2 > 1$ GeV^2
  - W > 2 GeV removes the resonance region
  - $Q^2 > 1$ GeV^2 to be in deep inelastic region



- Missing mass cut in order to remove exclusive events
  - The missing mass mm_X of the system $e^- \pi^+ \pi^-$ is defined as the invariant mass of the following 4-Vector:

$$P_X(e^-,\pi^+,\pi^-) = (P_{tar} + P_{beam}) - (P_{e^-} + P_{\pi^+} + P_{\pi^-})$$

  - The cut $mm_X > 1.05$ *GeV* removes the proton peak, *i.e.* the exclusive electro-production of two pions



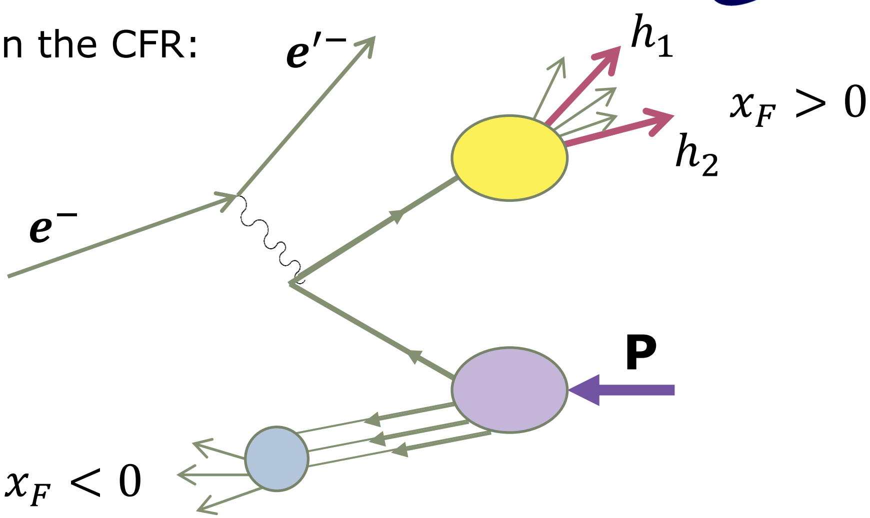
- After these cuts, only the events where the pions lie in the CFR are selected (next slide).

Silvia Pisano – LNF

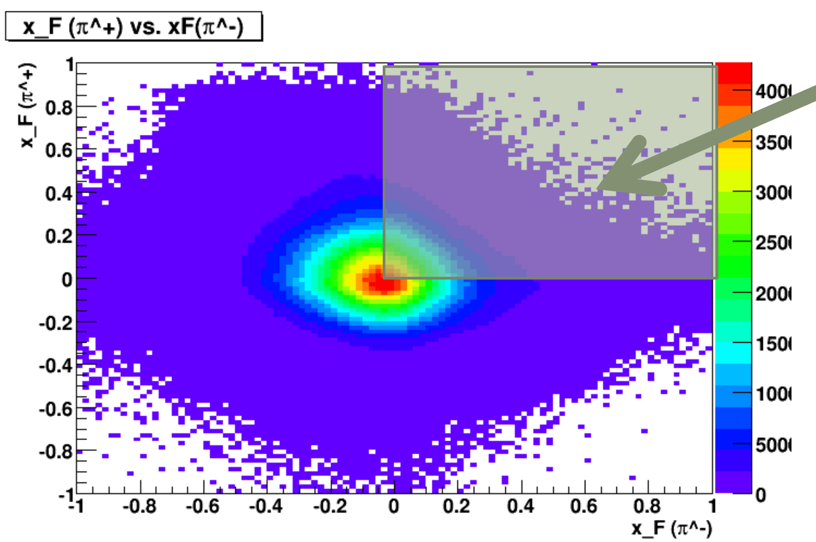
Current Fragmentation Region

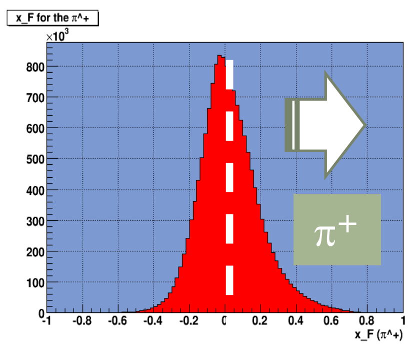
The variable x_F is considered to select hadrons in the CFR:

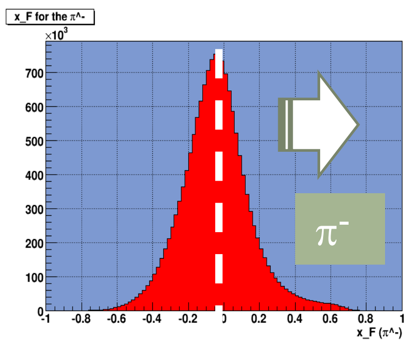
$$x_F(\pi^{\pm}) = \frac{2p_{\parallel}}{W} > 0$$



where W is the γ^*-p centre-of-mass energy and $p_{||}$ is the longitudinal component of the pion momentum (evaluated in the γ^*-p centre-of-mass).





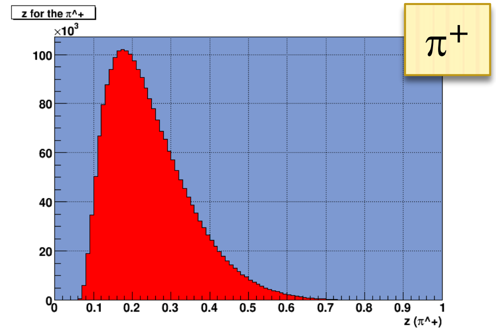


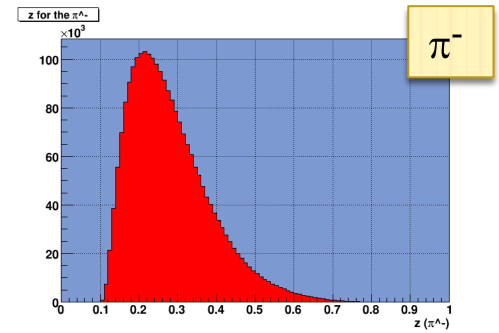
Silvia Pisano – LNF

Z definition & distribution(s)

The dimensionless variable ***z*** represents the fraction of the virtual-photon energy transferred to the hadron:

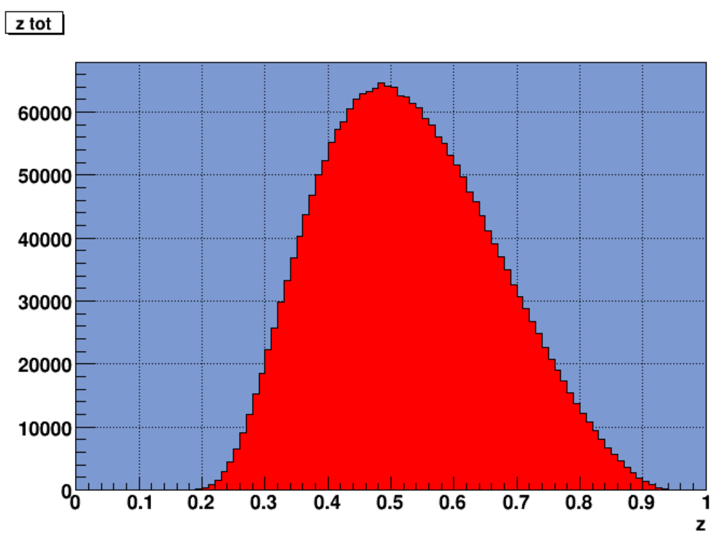
$$z \equiv \frac{P \cdot P_h}{P \cdot q} \stackrel{LAB}{=} \frac{E_h}{E - E'} = \frac{E_h}{\nu}$$

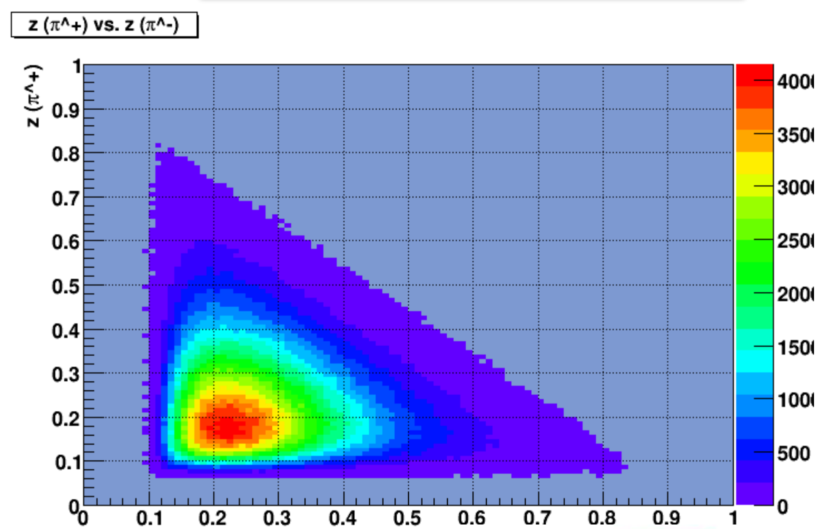




In this analysis, z indicates the sum of the zs of the two pions

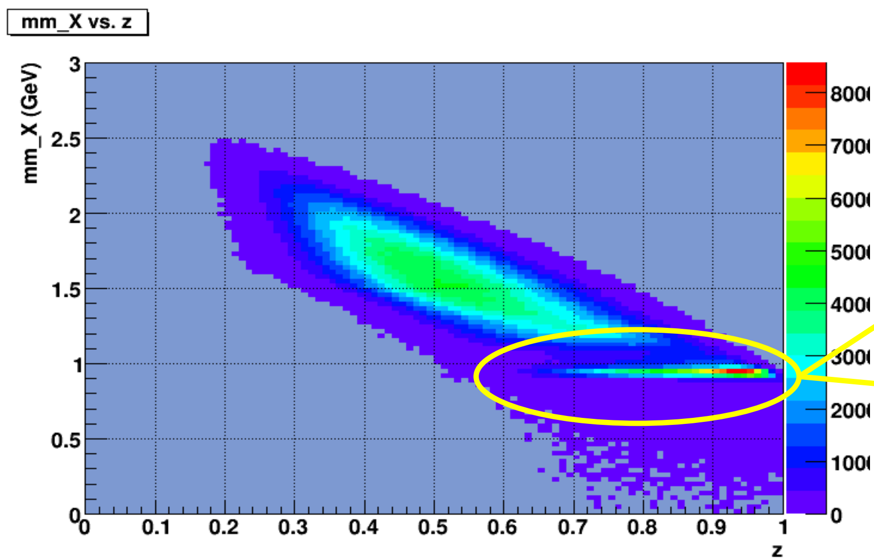
$$z_{TOT} = z_{\pi^+} + z_{\pi^-}$$

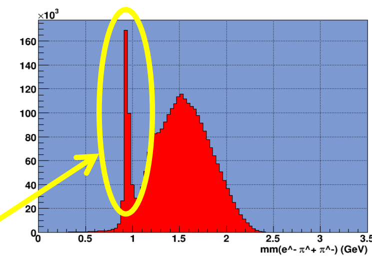


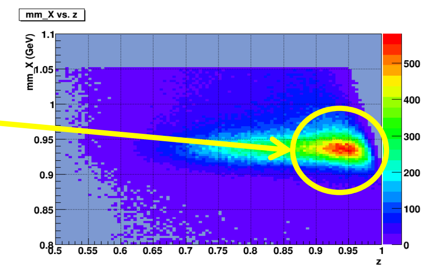


Exclusive contribution in z

The two-pion exclusive electro-production events lie in the high-z region (z > 0.7):

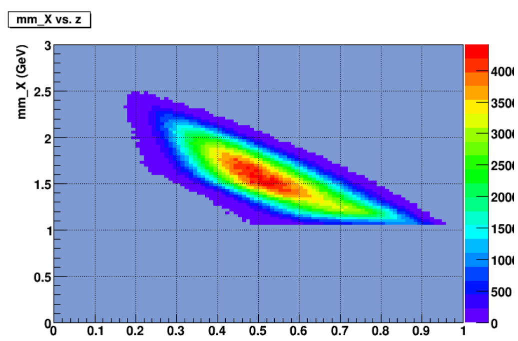


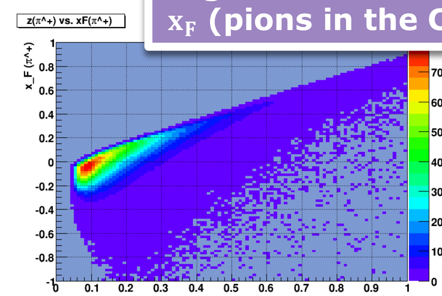




Higher z means higher x_F (pions in the CFR)

The cut on the missing mass mmX > 1.05 GeV removes this contribution





Extraction of the Beam Spin Asymmetry

Beam-Spin Asymmetry (BSA) is defined as

$$A_{LU} = \frac{1}{P_{beam}} \frac{N^+ - N^-}{N^+ + N^-}$$

where

- P_{beam} is the beam polarization
- N^+ is the number of dihadron events corresponding to a positive beam-helicity
- N^- is the number of dihadron events corresponding to a negative beam-helicity

Fitting function

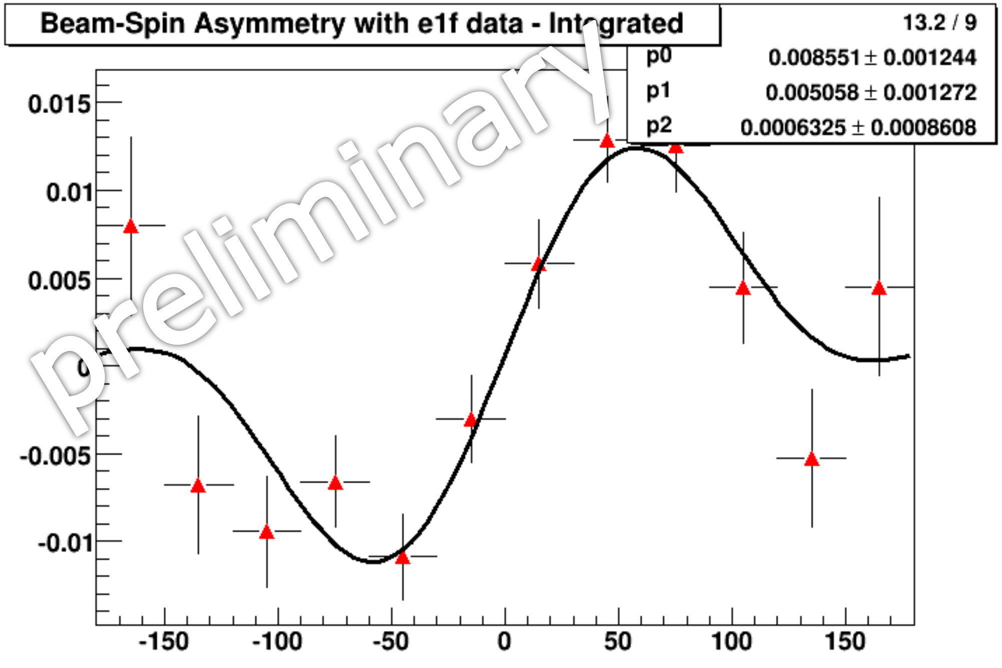
$$p^0 \sin\varphi + p^1 \sin 2\varphi + p^2$$

Sin(Φ) moment → 0.0086 ± 0.0012

Sin(2Φ) moment → 0.0050 ± 0.0013

Constant term compatible with zero

BSA integrated on the full data sample

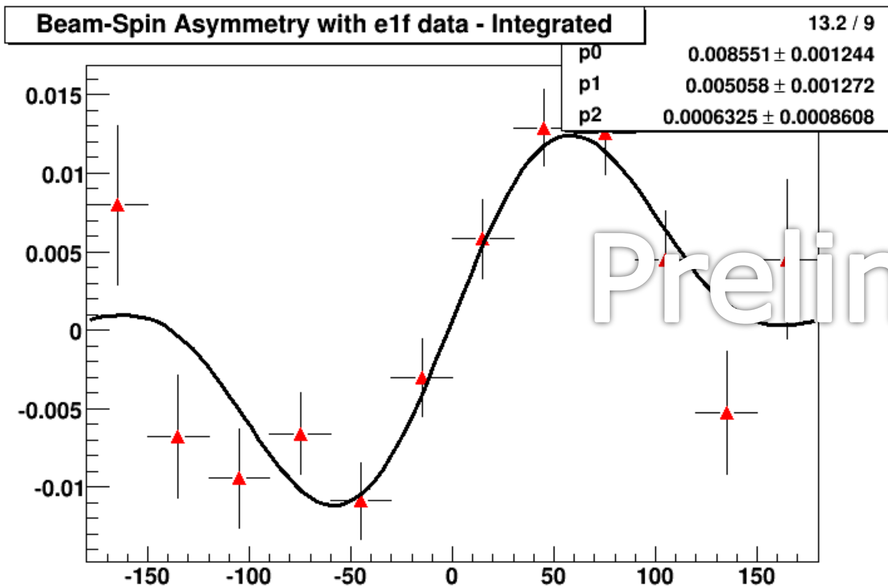


Silvia Pisano – LNF
EINN 2011

Dependence on x_F

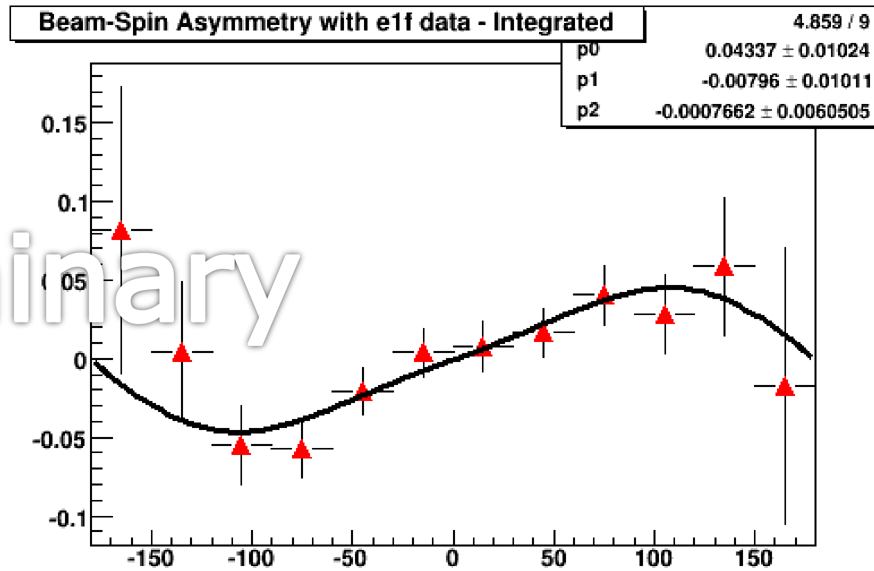
BSA increases as a function of x_F

$x_{F\pi^\pm} > 0$



Sin(Φ) moment → 0.0086 ± 0.0012

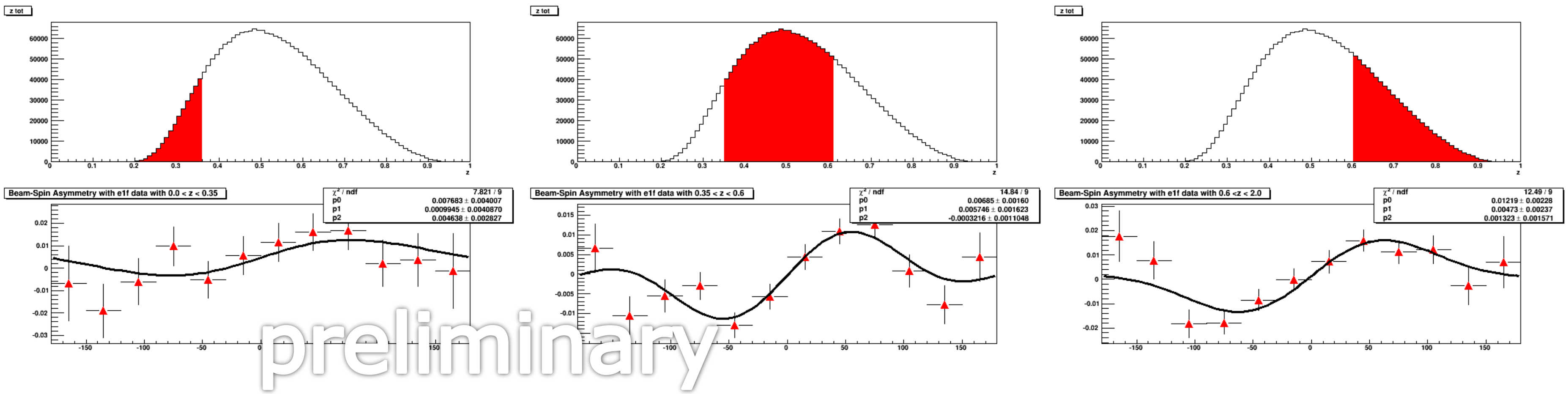
$x_{F\pi^\pm} > 0.2$



Sin(Φ) moment → 0.043 ± 0.010

Preliminary

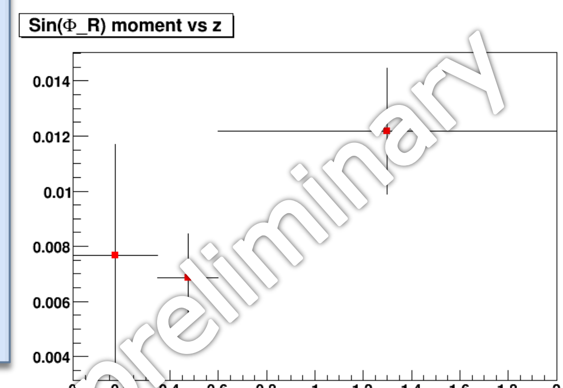
BSA dependence on z



Sin(ϕ) moments obtained by the fit

<z>	sin(Phi)	sin(2Phi)	offset	χ^2	N($\pi^+\pi^-$)
0.175	0.0077 +-0.0040	0.0010 +-0.0041	0.0046 +-0.0028	7.8/9	219629
0.475	0.0069 +-0.0016	0.0057 +-0.0016	-0.0003 +-0.0011	15/9	1.43798e+06
1.3	0.0122 +-0.0023	0.0047 +-0.0024	0.0013 +-0.0016	12/9	711138

Dependence of the sin(ϕ) moment on the *z* bin



Summary&Conclusions

A preliminary DiHadron analysis@CLAS has been presented

DiHadron processes are a powerful tool to access transversity

- Easier access with respect to single-hadron SIDIS
- Access to higher-twist pdfs

A non-zero A_{LU} is observed with 6 GeV CLAS data

- $\pi^+ \pi^-$ channel analyzed
- Sin(ϕ) moment appear to be the dominant contribution
- A BSA dependence on z and other kinematical variables can be appreciated already at 6 GeV
- 1-D binning so far

Improvements ongoing

- Analysis on MC
- Study of acceptance effects
- Check on the possibility of a multi-D binning
- Analysis of other two-pion channels ($\pi^+\pi^0$) with different CLAS data sets

Thank you!

backup

Definitions

DiHadron variables

Vectors

$$P_h = P_{\pi^+} + P_{\pi^-}$$

$$R = \frac{1}{2}\left(P_{\pi^+} - P_{\pi^-}\right)$$

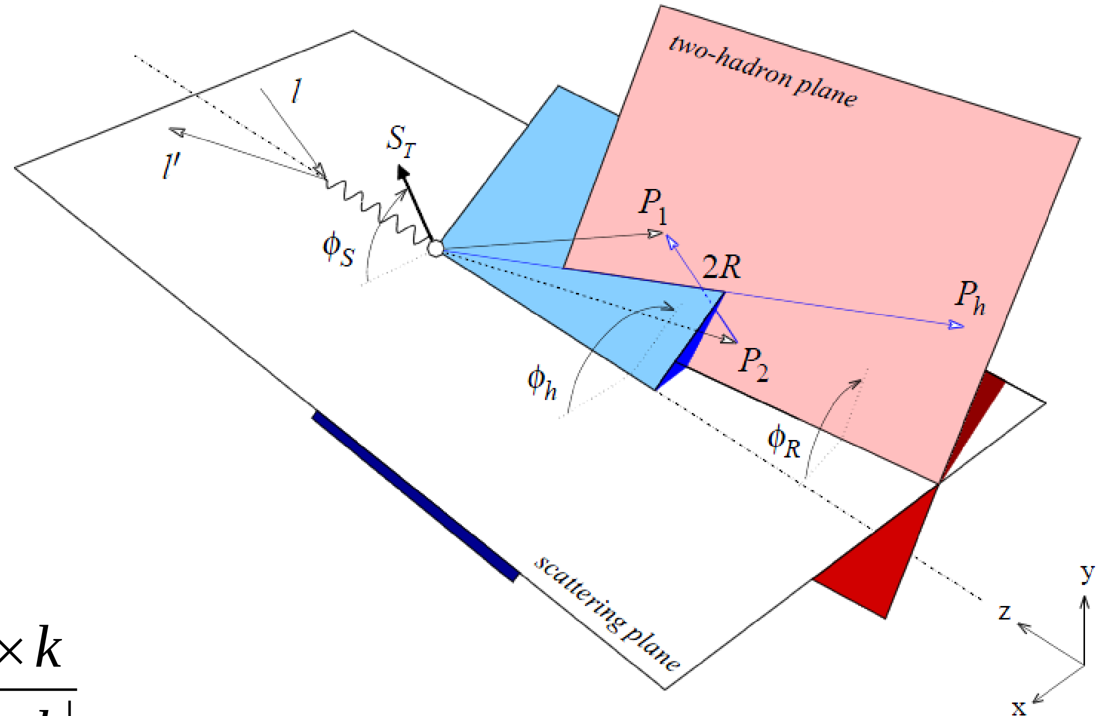
$$R_T \equiv R - \left(R \cdot \hat{P}_h\right)\hat{P}_h$$

Planes

$$\hat{n}_{had} = \frac{P_h \times q}{\left|P_h \times q\right|} \qquad \hat{n}_{lept} = \frac{q \times k}{\left|q \times k\right|}$$

Sign

$$sign = \frac{\hat{n}_{lept} \cdot P_h}{\left|\hat{n}_{lept} \cdot P_h\right|}$$



$$\hat{n}_{lept} \cdot \hat{n}_{had} = \cos(\varphi_h)$$

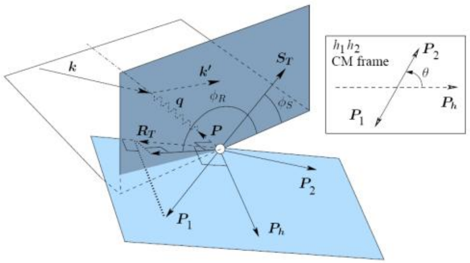
$$\varphi_h = sign\, \arccos(\hat{n}_{lept} \cdot \hat{n}_{had})$$

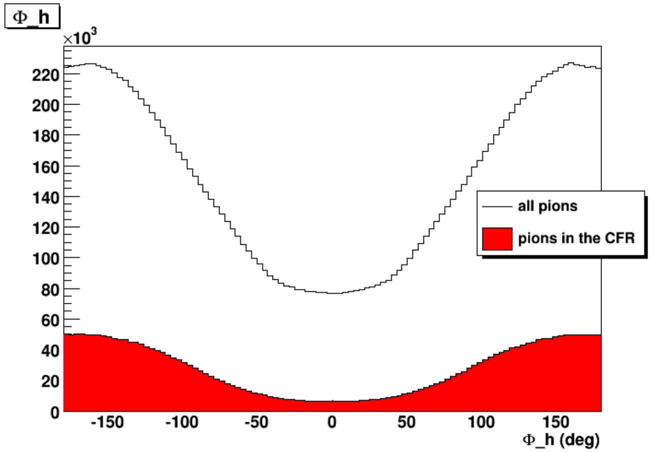
Angle definition & distributions

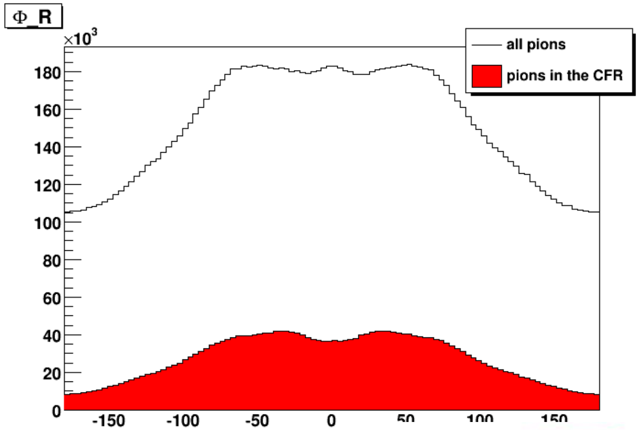
Definition adopted in this analysis for Φ_R&Φ_h:

$$\phi_h = \frac{\boldsymbol{q}\times\boldsymbol{k}\cdot\boldsymbol{P}_h}{|\boldsymbol{q}\times\boldsymbol{k}\cdot\boldsymbol{P}_h|}\cos^{-1}\frac{\boldsymbol{q}\times\boldsymbol{k}\cdot\boldsymbol{q}\times\boldsymbol{P}_h}{|\boldsymbol{q}\times\boldsymbol{k}||\boldsymbol{q}\times\boldsymbol{P}_h|} \qquad \phi_R = \frac{\boldsymbol{q}\times\boldsymbol{k}\cdot\boldsymbol{R}_T}{|\boldsymbol{q}\times\boldsymbol{k}\cdot\boldsymbol{R}_T|}\cos^{-1}\frac{\boldsymbol{q}\times\boldsymbol{k}\cdot\boldsymbol{q}\times\boldsymbol{R}_T}{|\boldsymbol{q}\times\boldsymbol{k}||\boldsymbol{q}\times\boldsymbol{R}_T|}$$

- q is the virtual photon 4-Vector
- k is the incoming electron 4-Vector
- P_h is the sum of the two pion 4-Vectors
- R_T is the component of R orthogonal to P_h
- All these 4-Vectors are evaluated in the ***γ*-p centre-of-mass frame***







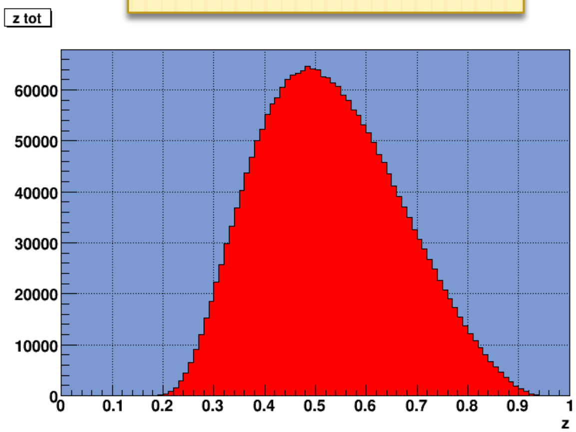
Binning in $m(\pi^+ \pi^-)$, z, x_B

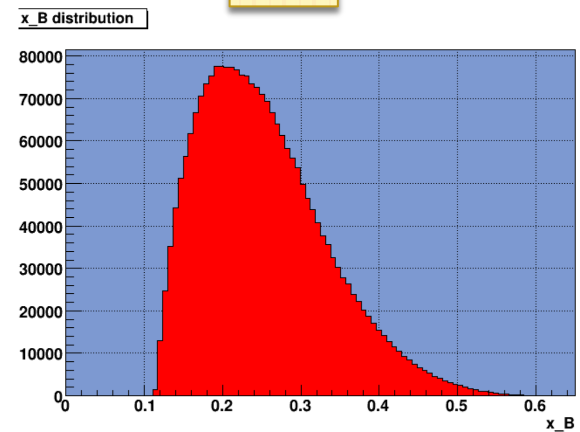
BSAs will be binned in these three variables:

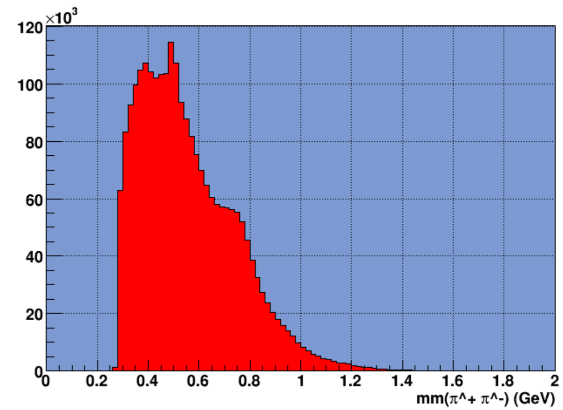
$z_{TOT} = z_{\pi^+} + z_{\pi^-}$

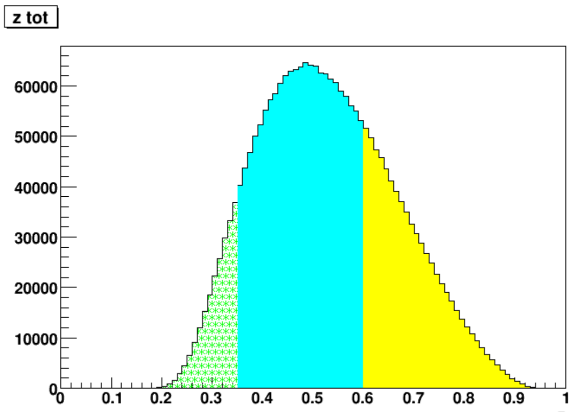
x_B

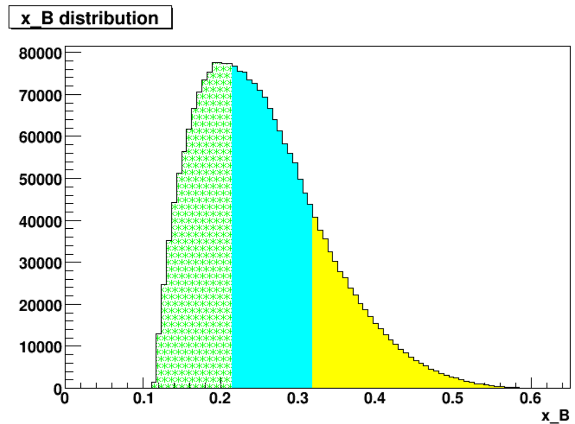
$m(\pi^+\pi^-)$

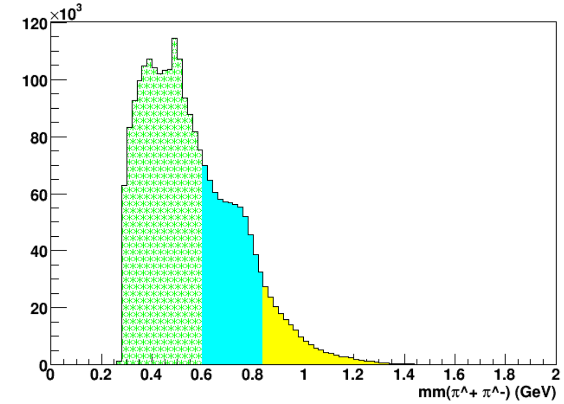












Other analyses @CLAS

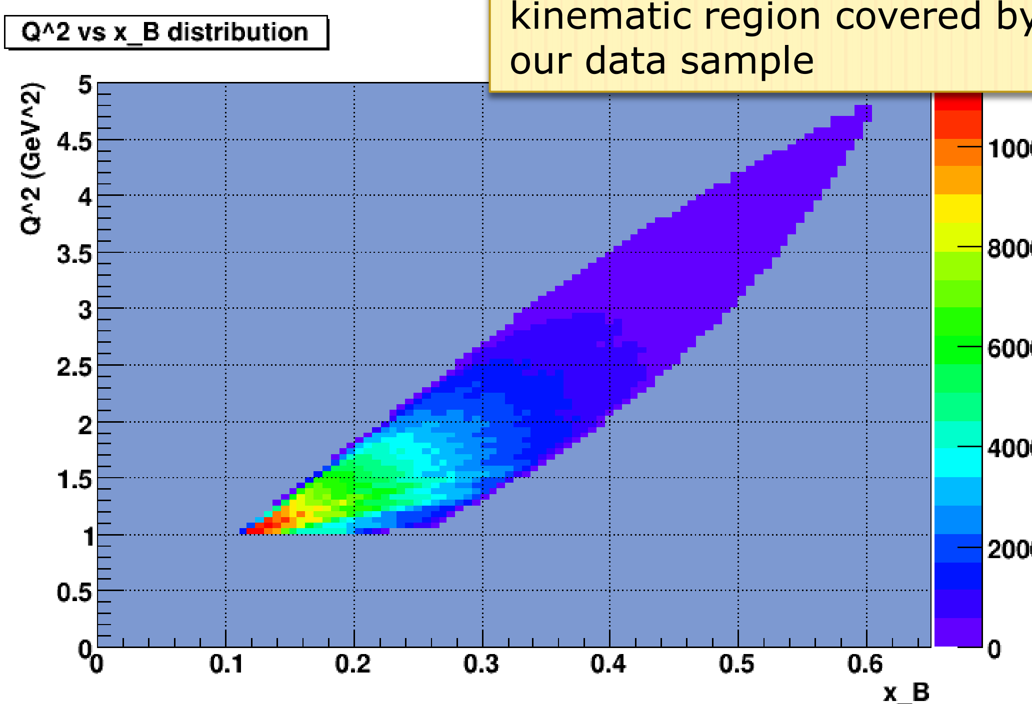
Further details on the analysis

Counting the pairs

In our 21 fb^{-1} data set, we have

- 1.52×10^7 DIS events with two charged pions ($\pi^+ \pi^-$)
- 2.76×10^6 DIS events with two charged pions in the CFR
- 2.37×10^6 DIS events with two pions in the CFR, semi-inclusively produced

kinematic region covered by our data sample



Total number of $\pi^+ \pi^-$ pairs in the e1f data set: **2.37×10^6**

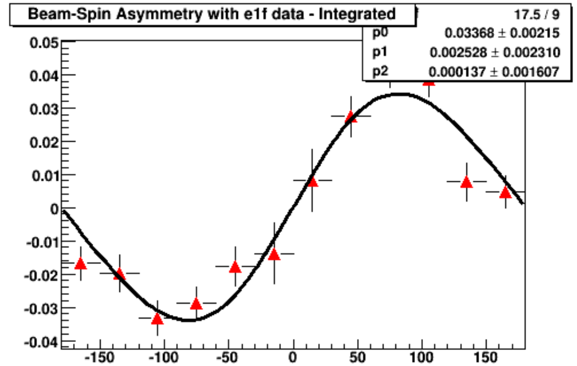
Silvia Pisano – LNF
CLAS Collaboration Meeting

Single hadron asymmetry (π^+)

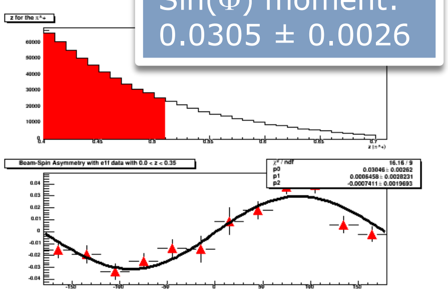
The single-hadron ($\boldsymbol{\pi}^+$) BSA is evaluated in the two-hadron sample

- The integrated BSA shows a Sin(Φ) moment ~ 0.0337 ± 0.0021

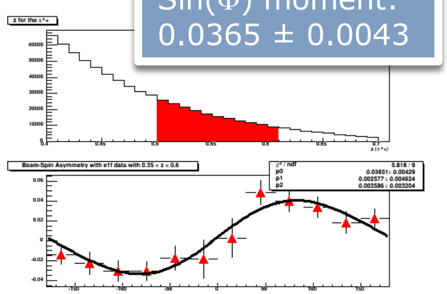
- BUT there is a strong dependence on z (Sin(Φ) moment increases with z)



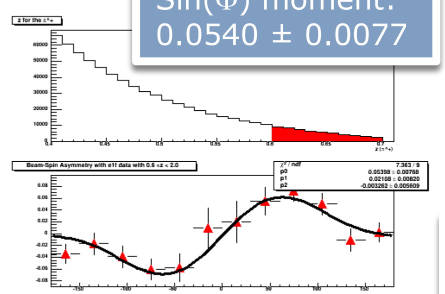
Sin(Φ) moment: 0.0305 ± 0.0026

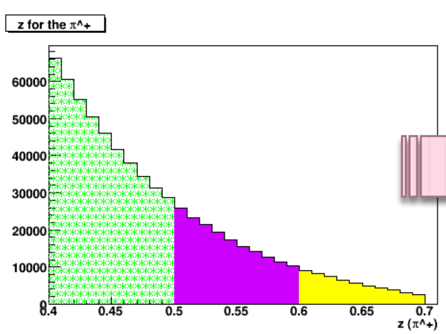


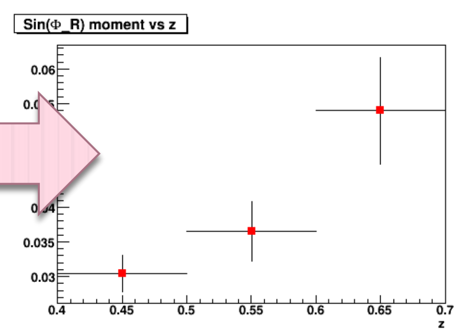
Sin(Φ) moment: 0.0365 ± 0.0043



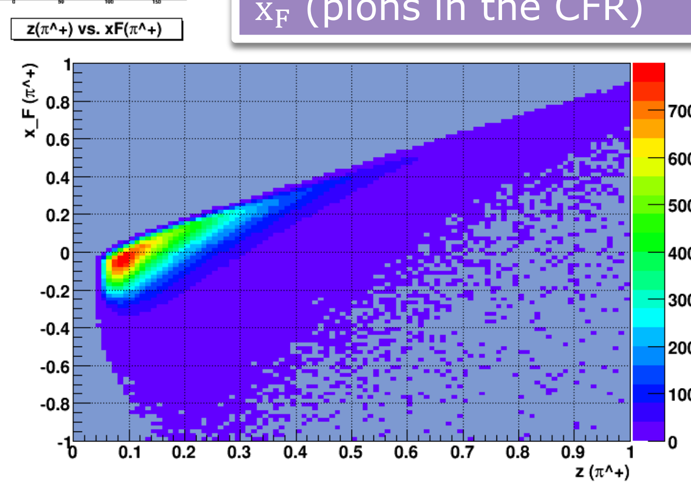
Sin(Φ) moment: 0.0540 ± 0.0077







Higher z means higher x_F (pions in the CFR)



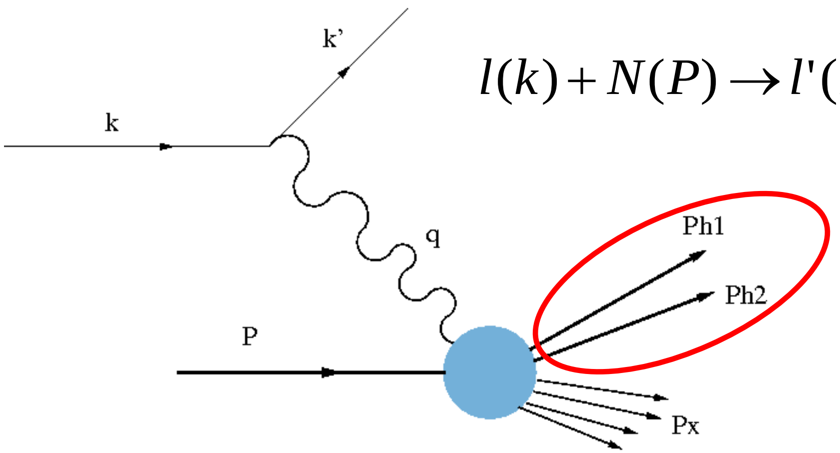
Silvia Pisano – LNF
CLAS Collaboration Meeting

10/14/2011

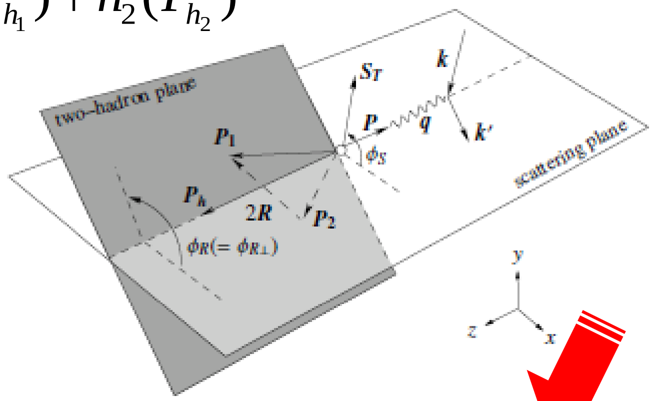
Details on the detectors

Two-hadron SIDIS

In the case of two-hadron semi-inclusive production



$$l(k)+N(P)\rightarrow l'(k')+X(P_X)+h_1(P_{h_1})+h_2(P_{h_2})$$



$$\frac{d^7\sigma}{d\ldots}=\frac{2\alpha^2}{4\pi sxy^2}\sum_q e_q^2 A(y) f_1^q(x) D_1^q+\lambda_e S_L C(y) g_1^q(x) D_1^q - B(y) S_T \ldots \sin(\phi_R+\phi_S) h_1^q(x) H_1^{\angle q}$$

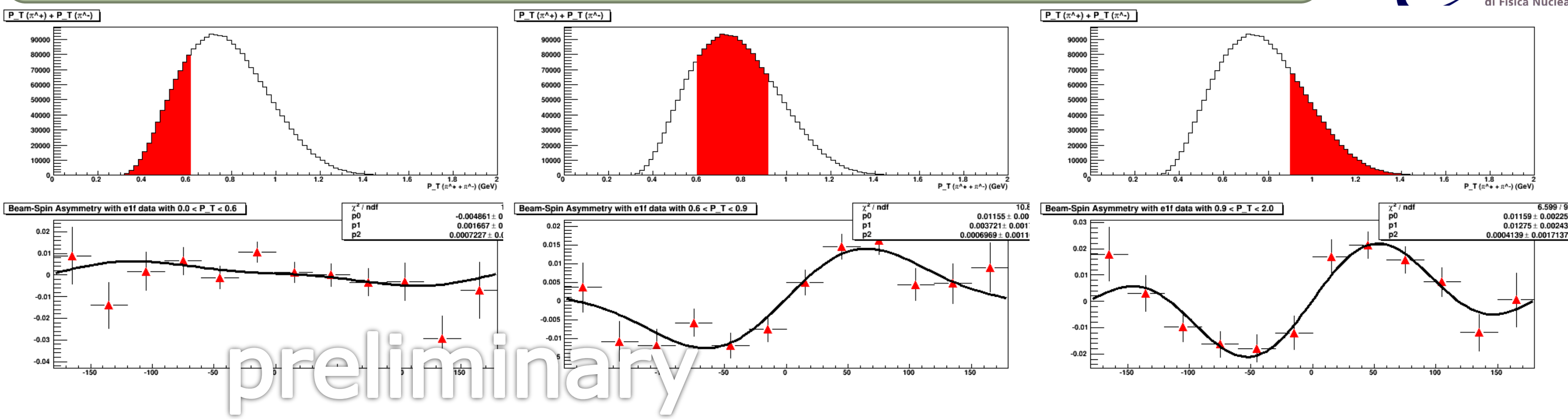
$$\boxed{A_{U/T/L}=\frac{\sigma^+-\sigma^-}{\sigma^++\sigma^-}}$$

$$\sin(\Phi_{h,R}\pm\Phi_S)\times h(x)\times FF$$

modulation **transversity** **Fragmentation function**

Further BSA dependences

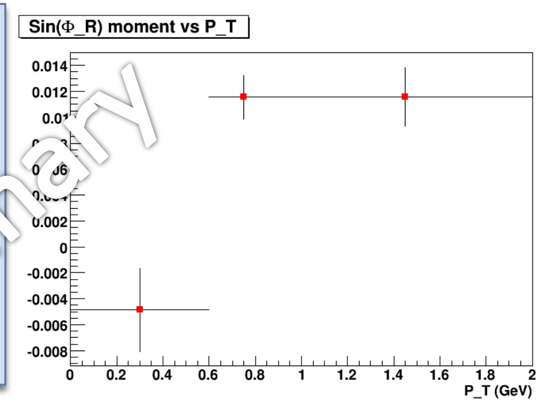
BSA dependence on P_T



Sin(ϕ) moments obtained by the fit

Dependence of the sin(ϕ) moment on the P_T bin

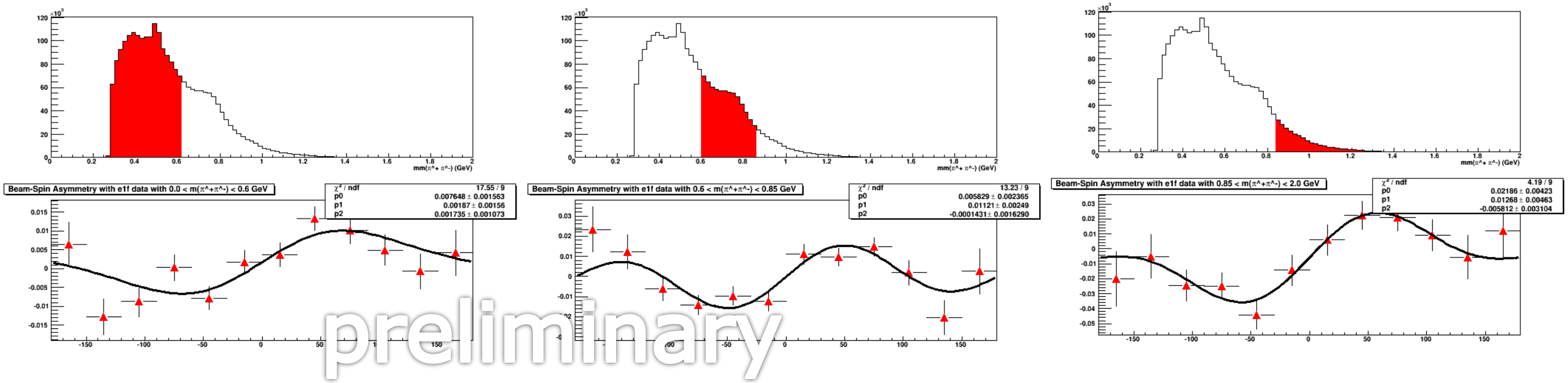
<pt>	*sin(Phi)*	*sin(2Phi)*	*offset*	*χ^2*	*N(π⁺π⁻)*
0.3	*-0.0049 +-0.0032*	*0.0017 +-0.0032*	*0.0007 +-0.0019*	*15/9*	*479597*
0.75	*0.0116 +-0.0017*	*0.0037 +-0.0017*	*0.0007 +-0.0012*	*11/9*	*1.29141e+06*
1.45	*0.0116 +-0.0022*	*0.0128 +-0.0024*	*0.0004 +-0.0017*	*6.6/9*	*59773[illegible]*



Silvia Pisano – LNF
CLAS Collaboration Meeting

10/14/2011

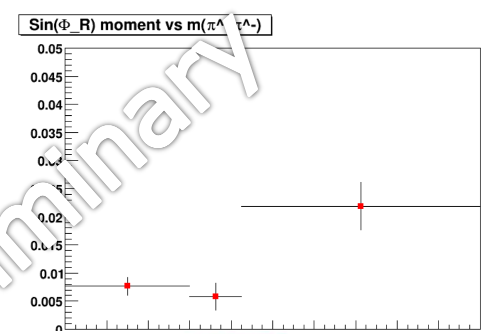
BSA dependence on m($\pi^+ \pi^-$)



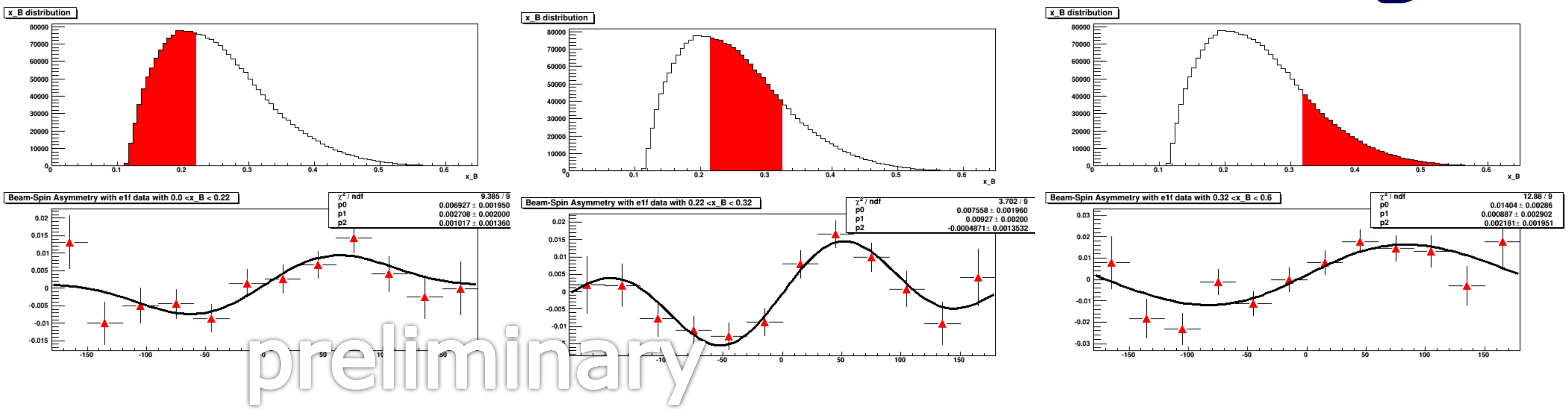
Sin(ϕ) moments obtained by the fit

<m>	sin(Phi)	sin(2Phi)	offset	χ^2	N($\pi^+\pi^-$)
0.3	0.0076 +-0.0016	0.0019 +-0.0016	0.0017 +-0.0011	18/9	1.52504e+06
0.725	0.0058 +-0.0024	0.0112 +-0.0025	-0.0001 +-0.0016	13/9	661410
1.425	0.0219 +-0.0042	0.0127 +-0.0046	-0.0058 +-0.0031	4.2/9	182302

Dependence of the sin(ϕ) moment on the *m* bin



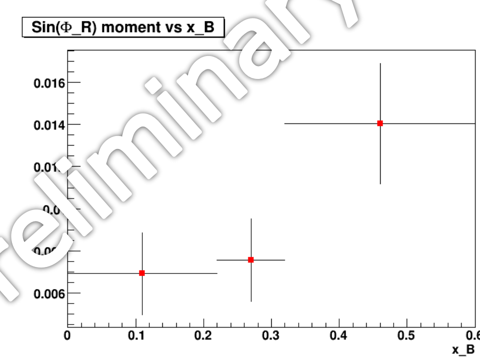
BSA dependence on x_B



Sin(ϕ) moments obtained by the fit

<xb>	sin(Phi)	sin(2Phi)	offset	χ^2	$N(\pi^+\pi^-)$
0.11	0.0069 +-0.0019	0.0027 +-0.0020	0.0010 +-0.0014	9.4/9	949154
0.27	0.0076 +-0.0020	0.0093 +-0.0020	-0.0005 +-0.0014	3.7/9	958586
0.46	0.0140 +-0.0029	0.0009 +-0.0029	0.0022 +-0.0020	13/9	461010

Dependence of the sin(ϕ) moment on the x_B bin

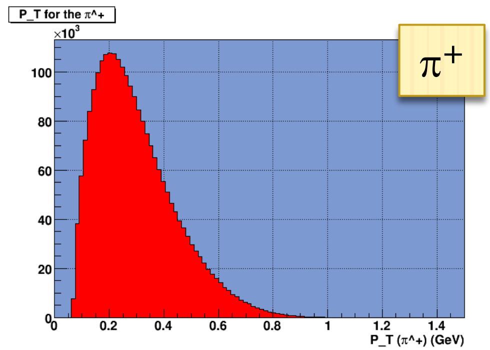


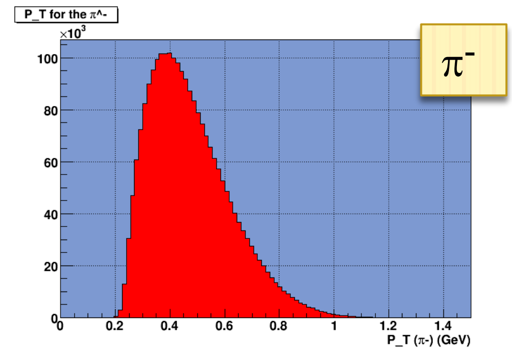
Kinematics

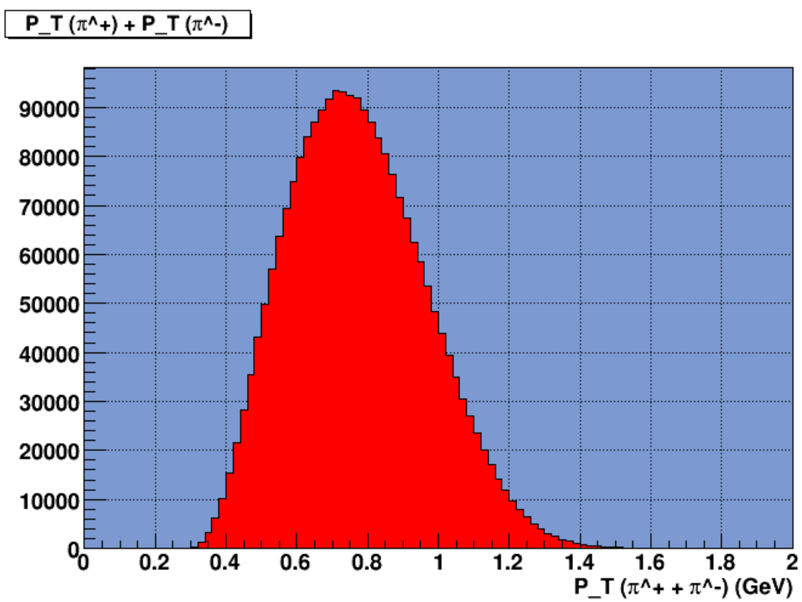
P_T definition & distribtion

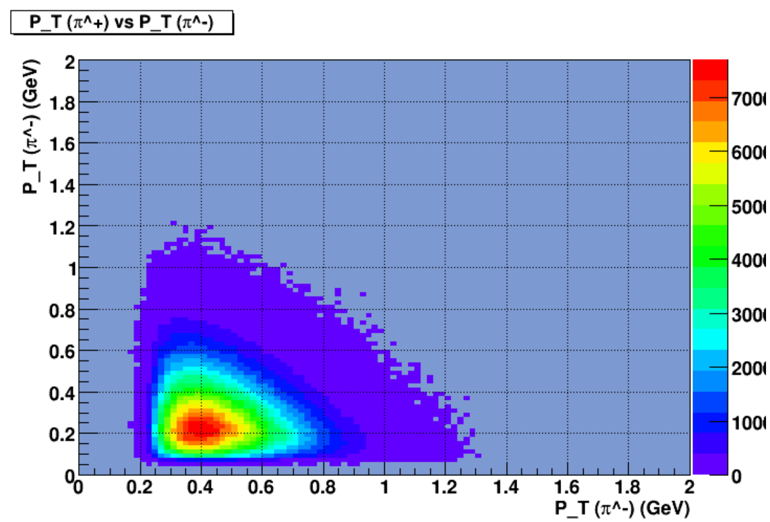
The variable P_T represents the component of P_h perpendicular to the virtual-photon direction. P_T is given by:

$$P_T = P_{T\pi^+} + P_{T\pi^-}$$

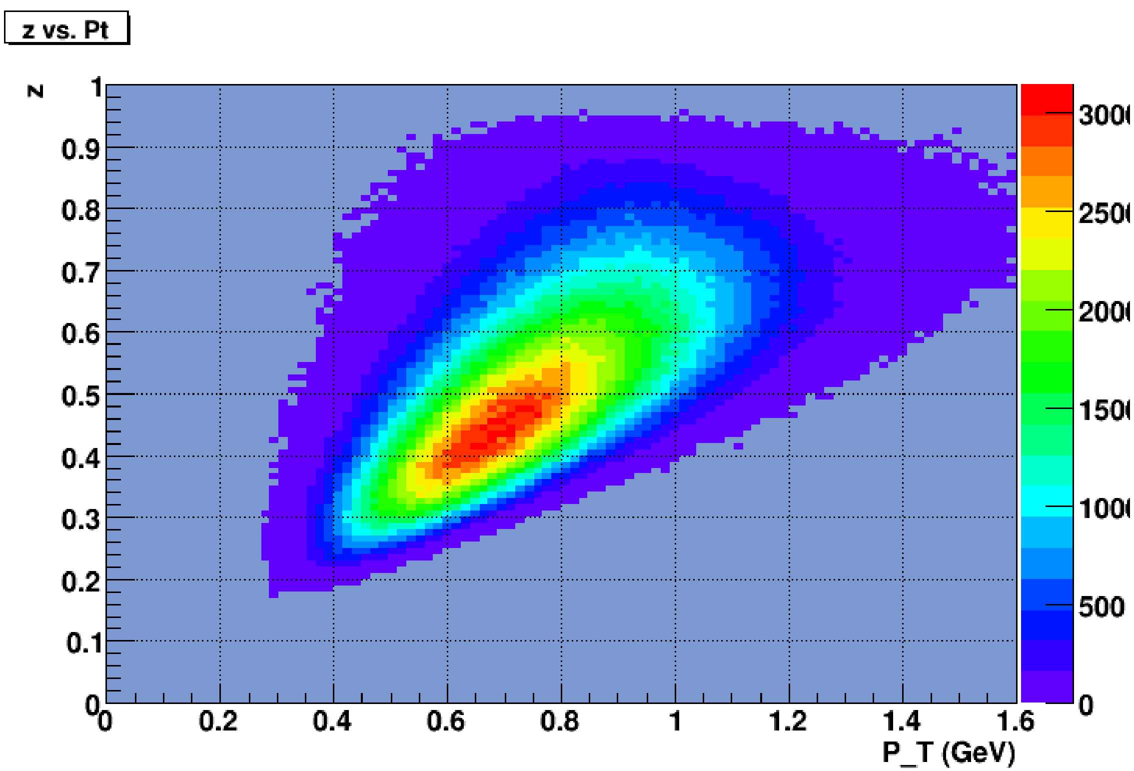


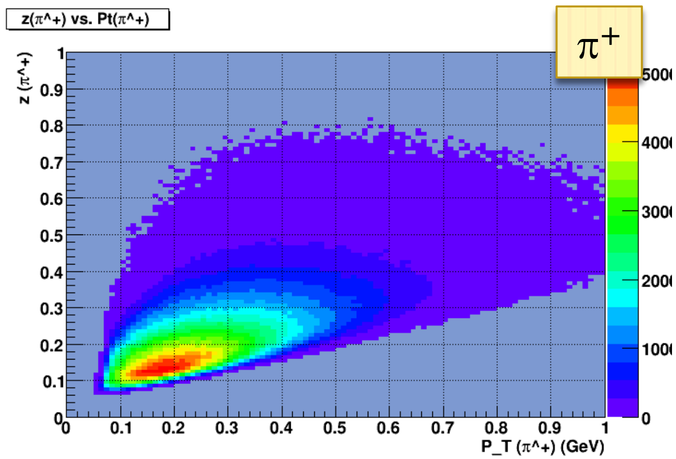


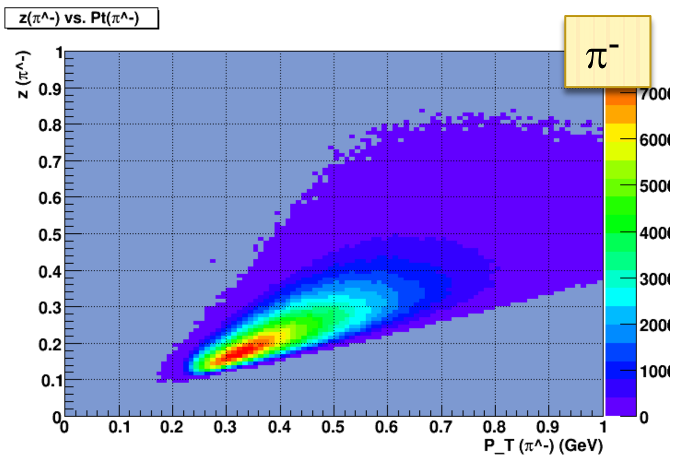




Kinematics: z *vs* P_T







Useful formulas

SIDIS cross section

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_R\,dM_h^2\,d\cos\theta} =$$

$$\frac{\alpha^2}{xy\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_R\,F_{UU}^{\cos\phi_R}$$

$$+\,\varepsilon\cos(2\phi_R)\,F_{UU}^{\cos 2\phi_R}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_R\,F_{LU}^{\sin\phi_R}$$

$$+\,S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_R\,F_{UL}^{\sin\phi_R}+\varepsilon\sin(2\phi_R)\,F_{UL}^{\sin 2\phi_R}\right]$$

$$+\,S_L\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_R\,F_{LL}^{\cos\phi_R}\right]$$

$$+\,|\boldsymbol{S}_T|\Big[\sin(\phi_R-\phi_S)\left(F_{UT,T}^{\sin(\phi_R-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_R-\phi_S)}\right)$$

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

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_R-\phi_S)\,F_{UT}^{\sin(2\phi_R-\phi_S)}\Big]$$

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

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_R-\phi_S)\,F_{LT}^{\cos(2\phi_R-\phi_S)}\Big]\Big\},$$

Structure Functions in the limit $M_h \ll Q^2$

$$F_{UU,T} = x f_1^q(x)\, D_1^q\big(z, \cos\theta, M_h\big),$$

$$F_{UU,L} = 0,$$

$$F_{UU}^{\cos\phi_R} = -x \frac{|\boldsymbol{R}| \sin\theta}{Q} \frac{1}{z} f_1^q(x)\, \widetilde{D}^{\sphericalangle q}\big(z, \cos\theta, M_h\big),$$

$$F_{UU}^{\cos 2\phi_R} = 0,$$

$$F_{LU}^{\sin\phi_R} = -x \frac{|\boldsymbol{R}| \sin\theta}{Q} \left[\frac{M}{M_h} x\, e^q(x)\, H_1^{\sphericalangle q}\big(z, \cos\theta, M_h\big) + \frac{1}{z} f_1^q(x)\, \widetilde{G}^{\sphericalangle q}\big(z, \cos\theta, M_h\big) \right],$$

$$F_{UL}^{\sin\phi_R} = -x \frac{|\boldsymbol{R}| \sin\theta}{Q} \left[\frac{M}{M_h} x\, h_L^q(x)\, H_1^{\sphericalangle q}\big(z, \cos\theta, M_h\big) + \frac{1}{z} g_1^q(x)\, \widetilde{G}^{\sphericalangle q}\big(z, \cos\theta, M_h\big) \right],$$

$$F_{UL}^{\sin 2\phi_R} = 0,$$

$$F_{LL} = x g_1^q(x)\, D_1^q\big(z, \cos\theta, M_h\big),$$

$$F_{LL}^{\cos\phi_R} = -x \frac{|\boldsymbol{R}| \sin\theta}{Q} \frac{1}{z} g_1^q(x)\, \widetilde{D}^{\sphericalangle q}\big(z, \cos\theta, M_h\big),$$

Miscellaneous

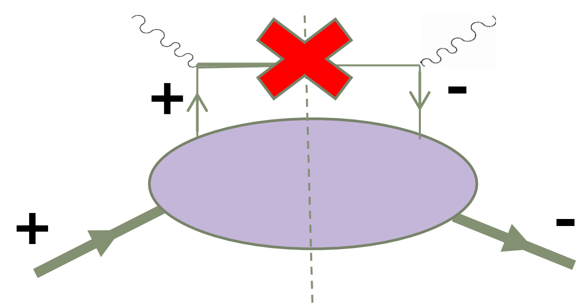
Odd-chiral nature of transversity

Helicity basis $|+\rangle, |-\rangle$

Transverse Spin basis $|\uparrow\rangle, |\downarrow\rangle$

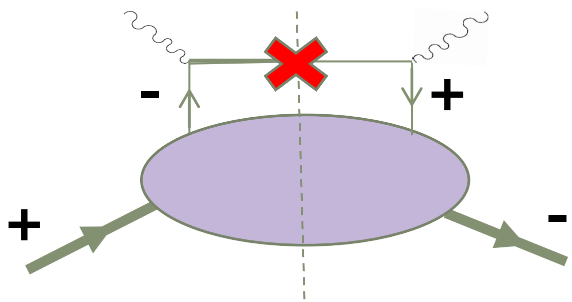
Tranversity in Helicity basis

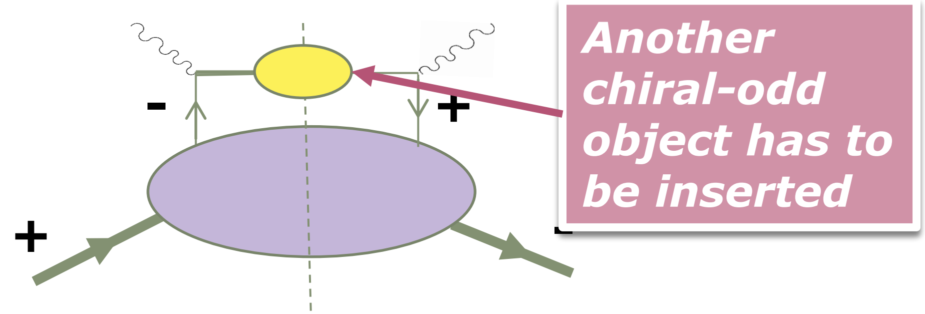
$$|\uparrow,\downarrow\rangle = \frac{1}{\sqrt{2}}(|+\rangle \pm i\,|-\rangle)$$



Chirality

As a chiral-odd object, transverse polarization of quarks cannot be probed through the cleanest hard process, the DIS.

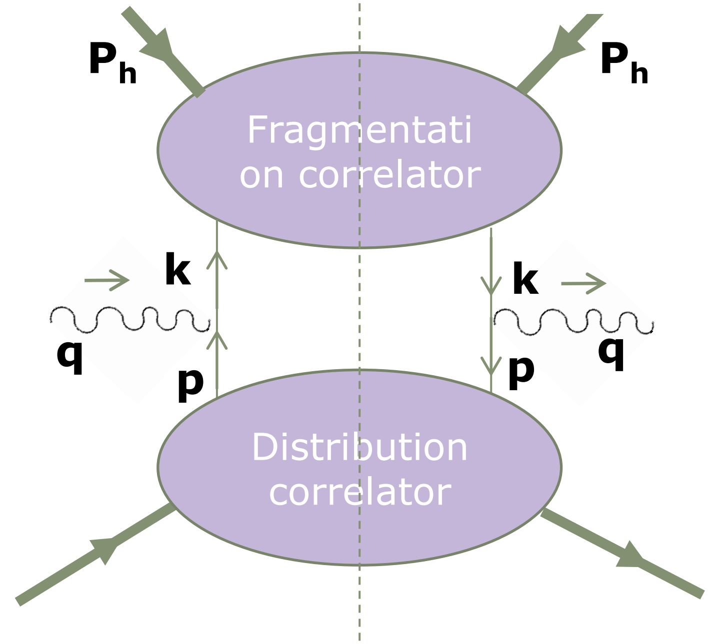




SIDIS cross section

Two new variables are introduced:

- $P_{h\perp}$, the transverse momentum of the final hadron
- z, the fraction of the virtual photon energy transferred to the final hadron



In the case of the SIDIS cross section, the hadronic tensor contains now even the Fragmentation Correlator Δ:

$$2MW^{\mu\nu}(q,P,S,P_h) = 2z\Im\left[Tr\left(\Phi(x,p_T,S)\gamma^{\mu}\Delta(z,k_T)\gamma^{\nu}\right)\right]$$

p_T/k_T: tranverse momentum dependence of the quark/fragmentation process

P_h: tranverse momentum dependence of the final hadron

Tranverse Momentum Distributions

If the quarks inside the nucleon are perfectly collinear, the three pdfs $f_1^q(x)$, $g_1^q(x)$, $h_1^q(x)$ complete the information about the internal hadron dynamics:

$$\Phi(x) = \frac{1}{2}\left\{ f_1 \not{n}_+ + S_L g_1 \gamma_5 \not{n}_+ + h_1 \frac{[\not{S}_T, \not{n}_+]\gamma_5}{2} \right\}$$

If, instead, we allow the presence of a finite quark tranverse momentum p_T, the number of functions increases up to eight:

$$\Phi(x, p_T) = \frac{1}{2}\left\{ f_1 \not{n}_+ - f_{1T}^{\perp} \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M} \not{n}_+ + S_L g_{1L} \gamma_5 \not{n}_+ - g_{1T} \frac{p_T \cdot S_T}{M} \gamma_5 \not{n}_+ \right.$$
$$+ h_{1T} \frac{[\not{S}_T, \not{n}_+]\gamma_5}{2} + S_L h_{1L}^{\perp} \frac{[\not{p}_T, \not{n}_+]\gamma_5}{2M}$$
$$\left. - h_{1T}^{\perp} \frac{p_T \cdot S_T}{M} \frac{[\not{p}_T, \not{n}_+]\gamma_5}{2M} + i\, h_1^{\perp} \frac{[\not{p}_T, \not{n}_+]}{2M} \right\}$$

$$f_1^q(x, p_T) \to f_1^q(x)$$
$$g_{1L}^q(x, p_T) \to g_1^q(x)$$
$$h_{1T}^q(x, p_T) \to h_1^q(x)$$

Accessing the moments of σ

In the most general, non collinear case, the hadron is described in terms of 8 TMD. To access them, we have to isolate their specific modulation in the cross-section:

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}$

$$\sin(\Phi_{h,R} \pm \Phi_S) \times TMD \times FF$$

modulation

Tranverse Momentum Distribution

Fragmentation function

To this end, the following asymmetry is introduced:

$$A_{U/T/L} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

The method of extracting asymmetries has two big advantages:

- Many systematic uncertainties cancel because they appear in the same way in the numerator and denominator
- It is not needed to measure absolute cross sections.

where refers to the various polarization states. The asymmetry selects the terms in the cross section proportional to the chosen distribution functions.

DiHadron Structure Functions

$$F_{UU,T} = x f_1^q(x)\, D_1^q\big(z, \cos\theta, M_h\big),$$

$$F_{UU}^{\cos\phi_R} = -x \frac{|\boldsymbol{R}|\sin\theta}{Q}\, \frac{1}{z}\, f_1^q(x)\ , \widetilde{D}^{\sphericalangle\, q}\big(z, \cos\theta, M_h\big),$$

$$\boxed{F_{LU}^{\sin\phi_R} = -x \frac{|\boldsymbol{R}|\sin\theta}{Q} \left[\frac{M}{M_h}\, x\, e^q(x)\, H_1^{\sphericalangle\, q}\big(z, \cos\theta, M_h\big) + \frac{1}{z}\, f_1^q(x)\, \widetilde{G}^{\sphericalangle\, q}\big(z, \cos\theta, M_h\big) \right],}$$

$$F_{UL}^{\sin\phi_R} = -x \frac{|\boldsymbol{R}|\sin\theta}{Q} \left[\frac{M}{M_h}\, x\, h_L^q(x)\, H_1^{\sphericalangle\, q}\big(z, \cos\theta, M_h\big) + \frac{1}{z}\, g_1^q(x)\, \widetilde{G}^{\sphericalangle\, q}\big(z, \cos\theta, M_h\big) \right],$$

$$F_{LL} = x g_1^q(x)\, D_1^q\big(z, \cos\theta, M_h\big),$$

$$F_{LL}^{\cos\phi_R} = -x \frac{|\boldsymbol{R}|\sin\theta}{Q}\, \frac{1}{z}\, g_1^q(x)\, \widetilde{D}^{\sphericalangle\, q}\big(z, \cos\theta, M_h\big).$$

$$F_{UT}^{\sin(\phi_R+\phi_S)} = x \frac{|\boldsymbol{R}|\sin\theta}{M_h}\, h_1(x)\, H_1^{\sphericalangle}\big(z, \cos\theta, M_h^2\big),$$

$$F_{UT}^{\sin\phi_S} = x \frac{M_h}{Q} \left[h_1(x) \left(\frac{1}{z}\, \widetilde{H}\big(z, \cos\theta, M_h^2\big) + \frac{|\boldsymbol{R}|\sin\theta^2}{M_h^2}\, H_1^{\sphericalangle\, o\,(1)}\big(z, \cos\theta, M_h^2\big) \right) \right],$$

$$F_{LT}^{\cos\phi_R} = \frac{M_h}{Q} \left[-\frac{M}{M_h}\, x\, g_T(x)\, D_1\big(z, \cos\theta, M_h^2\big) - \frac{1}{z}\, h_1(x)\, \widetilde{E}\big(z, \cos\theta, M_h^2\big) \right]$$

Silvia Pisano – LNF
CLAS Collaboration Meeting

DiHadron *vs.* Single-Hadron

Single-hadron

$$A_{DIS}(x,z,P_{h\perp}^2) = -\langle C_y \rangle \frac{\sum_q e_q^2\, h_1^q(x,p_T^2) \otimes_C H_{1,q}^{\perp}(z,k_T^2)}{\sum_q e_q^2\, f_1^q(x,p_T^2) \otimes D_{1,q}(z,k_T^2)}$$

Dihadron

$$A_{DIS}(x,z,M_h^2) = -\langle C_y \rangle \frac{\sum_q e_q^2\, h_1^q(x)\, \frac{|\boldsymbol{R}|}{M_h} H_{1,q}^{\sphericalangle}(z,M_h^2)}{\sum_q e_q^2\, f_1^q(x)\, D_{1,q}(z,M_h^2)}$$

Asymmetries & Structure Functions

The relevant spin asymmetries can be built as ratios of structure functions. For the longitudinal polarization of the beam or of the target, alternatively, *i.e.* on the LU and UL combinations, one can define the following asymmetries

$$A_{LU}^{\sin\phi_R \sin\theta}(x,y,z,M_h,Q) = \frac{1}{\lambda_e}\frac{\frac{8}{\pi}\int d\phi_R\, d\cos\theta\ \sin\phi_R\,(d\sigma^+ - d\sigma^-)}{\int d\phi_R\, d\cos\theta\,(d\sigma^+ + d\sigma^-)} = \frac{\frac{4}{\pi}\sqrt{2\,\varepsilon(1-\varepsilon)}\int d\cos\theta\, F_{LU}^{\sin\phi_R}}{\int d\cos\theta\ (F_{UU,T} + \epsilon F_{UU,L})}$$

$$A_{UL}^{\sin\phi_R \sin\theta}(x,y,z,M_h,Q) = \frac{1}{S_L}\frac{\frac{8}{\pi}\int d\phi_R\, d\cos\theta\ \sin\phi_R\,(d\sigma^+ - d\sigma^-)}{\int d\phi_R\, d\cos\theta\,(d\sigma^+ + d\sigma^-)} = \frac{\frac{4}{\pi}\sqrt{2\,\varepsilon(1+\varepsilon)}\int d\cos\theta\, F_{UL}^{\sin\phi_R}}{\int d\cos\theta\ (F_{UU,T} + \epsilon F_{UU,L})}$$

CLAS kinematics *vs.* other experiments