ASI SYMMETRIES AND SPIN

(SPIN-Praha-2010)

Prague, July 18 - July 24, 2010

AZIMUTHAL ASYMMETRIES of CHARGED HADRONS in SIDIS off LONGITUDINALLY POLARIZED DEUTERON at COMPASS

A.V. Efremov JINR, Dubna.

On behalf of the COMPASS Collaboration.

OUTLINE

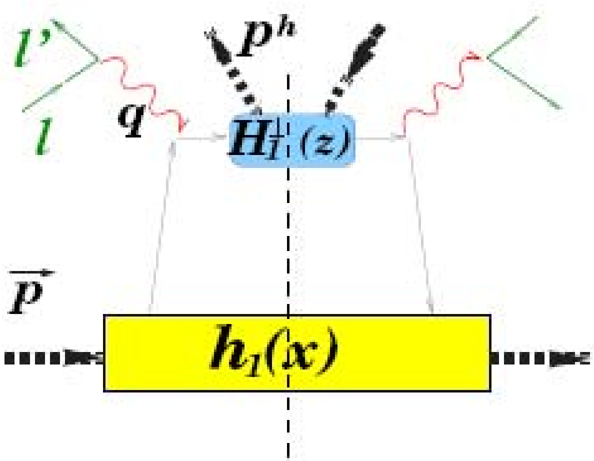
1. Introduction: Theoretical framework & Motivation
2. Method of analysis
3. Data selection
4. Results
5. Conclusions and prospects

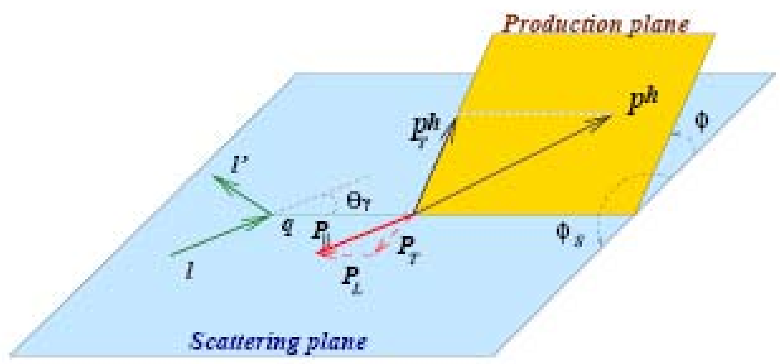
Supported by the RFFI-CERN grant 08-02-91013

INTRODUCTION (1)

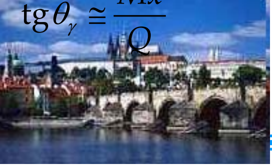
Hadron azimuthal distributions are sources of information on PDFs and PFFs, characterizing longitudinal and transverse nucleon spin structure , e.g.:

$$d\sigma_h / d\phi \sim h_1(x) \otimes H_1^{\perp}(z) \cdot \sin\phi + \ldots \qquad \ell + \bar{N} \to \ell' + X + h$$





A number of PDF's and PFF's enter in total SIDIS cross section



INTRODUCTION (2)

The cross section and asymmetry of SIDIS:

$$d\sigma = d\sigma_{00} + P_\mu d\sigma_{L0} + P_L\left(d\sigma_{0L} + P_\mu d\sigma_{LL}\right) + |P_T|\left(d\sigma_{0T} + P_\mu d\sigma_{LT}\right),$$

$$a(\phi) = \frac{d\sigma^{\leftrightarrow\Rightarrow} - d\sigma^{\leftarrow\Leftarrow}}{|P_L|(d\sigma^{\leftrightarrow\Rightarrow} + d\sigma^{\leftarrow\Leftarrow})} = -\frac{d\sigma_{0L} + P_\mu d\sigma_{LL} - \tan\theta_\gamma (d\sigma_{0T} + P_\mu d\sigma_{LT})}{d\sigma_{00} + P_\mu d\sigma_{L0}}$$

where contributions to σ_{ij} (i=beam, j= target polarizations) from each quark and antiquark (up to the order of (M/Q)) have forms:

worm-gear-1 — Twist 3

$$d\sigma_{0L} \propto \in x h_{1L}^{\perp}(x) \otimes H_1^{\perp}(z)\sin(2\phi) + \sqrt{2\in(1-\in)}\frac{M}{Q}x^2\left[h_L(x)\otimes H_1^{\perp}(z) + f_L^{\perp}(x)\otimes D_1(z)\right]\sin(\phi),$$

helicity — Twist 3

$$d\sigma_{LL} \propto \sqrt{1-\in^2}\; x g_{1L}(x)\otimes D_1(z) + \sqrt{2\in(1-\in)}\frac{M}{Q}x^2\left[g_L^{\perp}(x)\otimes D_1(z) + e_L(x)\otimes H_1^{\perp}(z)\right]\cos(\phi),$$

transversity — pretzelosity — Sivers

$$d\sigma_{0T} \propto \in[x h_1(x)\otimes H_1^{\perp}(z)\sin(\phi+\phi_S) + x h_{1T}^{\perp}(x)\otimes H_1^{\perp}(z)\sin(3\phi-\phi_S)$$
$$- x f_{1T}^{\perp}(x)\otimes D_1(z)\sin(\phi-\phi_S)]$$

Mulders&Tangerman
Boer&Mulders
Bucchetta et al.

$\otimes$=convolution in k_T

worm-gear-2

$$d\sigma_{LT} \propto \sqrt{1-\in^2}\; x g_{1T}(x)\otimes D_1(z)\cos(\phi-\phi_S).$$

ϕ_S = 0 for L-target

$$\mathrm{tg}\,\theta_\gamma \simeq \frac{M}{Q}x$$

INTRODUCTION (3)

Summary:

– $a(\phi)$ expected to be small, $\leq 1\%$.

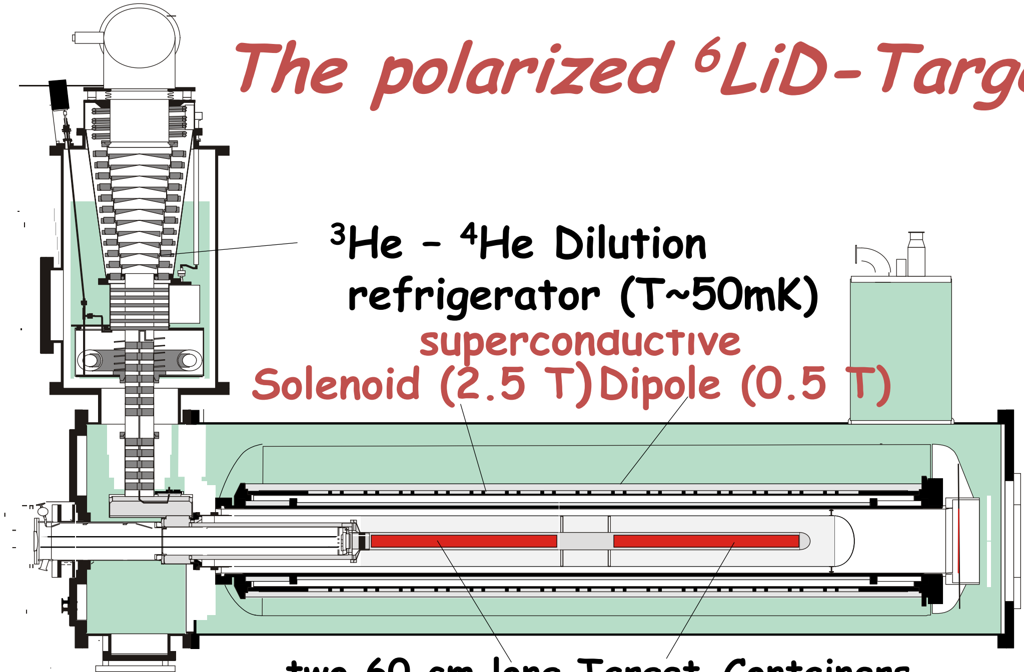
– Methods of analysis should be adequate.

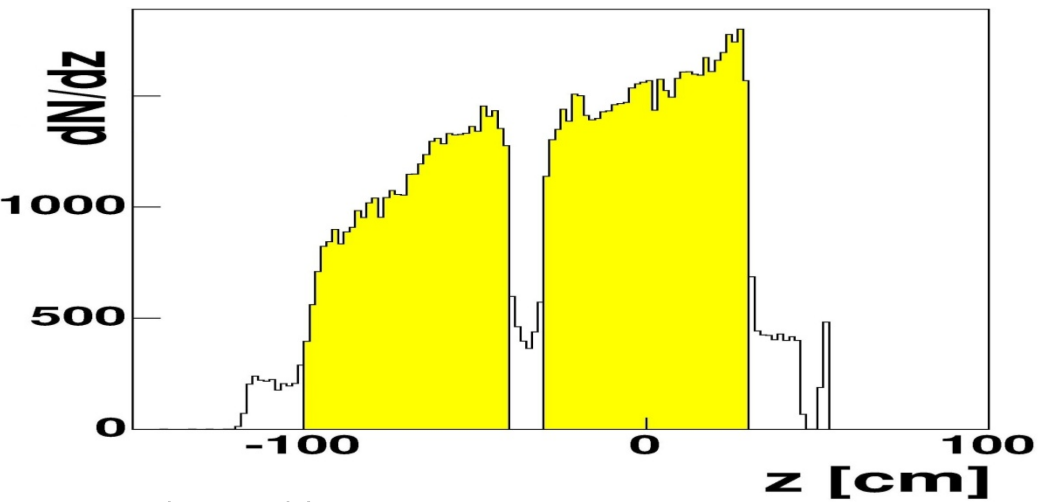
–Several asymmetry modulations should be seen in $a(\phi)$.

–Aims: search for $a(\phi)$, its possible sin(2ϕ), sin(ϕ) (Sivers + Transversity), sin(3ϕ) (Pretzelosity) and cos(ϕ) modulations and $\boldsymbol{x}$, $\boldsymbol{z}$ and $\boldsymbol{p_h^T}$ dependence of corresponding amplitudes.

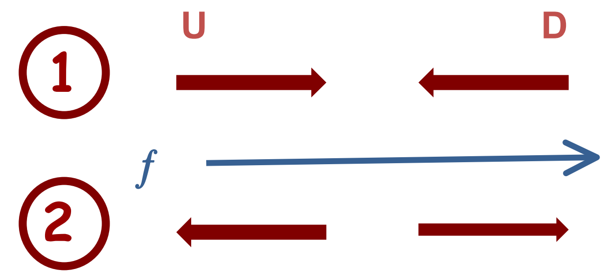
METHOD OF ANALYSIS (1)

The polarized ^6LiD-Target



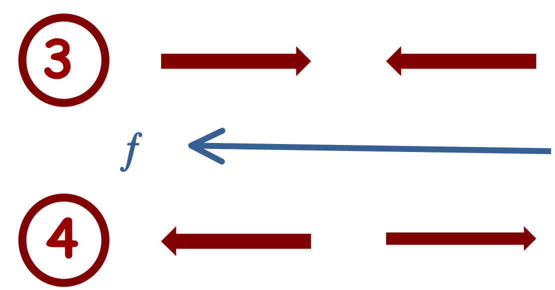


4 target polarizations:



reversed every 8 hours

After few weeks



reversed every 8 hours

Polarization: ~ 50%

METHODS OF ANALYSIS: (2)

$$R_f(\varphi)=\frac{N^U_{+f}(\varphi)}{N^D_{-f}(\varphi)}\times\frac{N^D_{+f}(\varphi)}{N^U_{-f}(\varphi)}=\frac{\cancel{C^U_f(\varphi)}\cancel{L^U_{+f}}\sigma_+(\varphi)}{\cancel{C^D_f(\varphi)}\cancel{L^D_{-f}}\sigma_-(\varphi)}\times\frac{\cancel{C^D_f(\varphi)}\cancel{L^D_{+f}}\sigma_+(\varphi)}{\cancel{C^U_f(\varphi)}\cancel{L^U_{-f}}\sigma_-(\varphi)}=\frac{\sigma_+(\varphi)^2}{\sigma_-(\varphi)^2},$$

where

$N^t_{pf}(\varphi)$ **is a number of events,**

$t = U$ **or D for Upper or Down cell,**

$p = +$ **or – polarization (along or opposite to the beam),**

$f = +$ **or – solenoid field direction (along or opposite to beam),**

$C^t_f(\varphi)$ **target acceptance factor (source of false asymmetries),**

$L^t_{pf}=\Phi^t_{pf}n^t$ **product of beam flux and target density,**

σ_p **spin dependent cross sections.**

$L^t_{\pm f}$ **and** $C^t_f(\varphi)$ **cancel if beam crosses both cells and if one combines periods with the same *f*.**

$$R_f(\varphi)=\frac{\left(1+P^U_{+f}a_f(\varphi)\right)\left(1+P^D_{+f}a_f(\varphi)\right)}{\left(1-P^D_{-f}a_f(\varphi)\right)\left(1-P^U_{-f}a_f(\varphi)\right)},$$

$$a_f(\varphi)\simeq\frac{R_f(\varphi)-1}{P^U_{+f}+P^D_{+f}+P^U_{-f}+P^D_{-f}}$$

$$a_+(\varphi)\approx a_-(\varphi)$$

$$a(\varphi)=a_+(\varphi)\oplus a_-(\varphi)\rightarrow\text{final results}$$

METHODS OF ANALYSIS: (3)

Summary:

– the DR method has been tested using a part of data,

– possible ϕ-dependent false asymmetries, connected with the acceptance, are canceled,

– the DR method can be used for studies of small modulations of ϕ- asymmetries, of order 0.2% or smaller, the analysis of the full set of COMPASS L-data is in progress, first the data of 2002-2004 from deuterium, presented in this talk.

DATA SELECTION (1)

AIM: TO HAVE A CLEAN SAMPLE OF HADRONS

(1) Selection of "GOOD EVENTS" out of preselected sample of events with $Q^2 > 1$ GeV^2 and $y > 0.1$ (=167.5 M from 2002, 2003, 2004 data taking)

EXCLUDED EVENTS:

- originated from bad spills,
- with a number of rec.prim.vertex >1,
- χ^2/NDF>2,
- *Z* vertex outside the fiducial volume U or D- cell,
- 140 GeV >E(muon)> 180 GeV,
- invariant mass W < 5 GeV,
- y > 0.9.

= 58% of initial sample

DATA SELECTION (2)

(2) Selection of "GOOD TRACKS" from "GOOD EVENTS".

Total number of tracks from "GOOD EVENTS" = 290 M

Excluded tracks:

- **identified as muons,**
- **with z-variable >1,**
- **with p_T^h <0.1 GeV ---------→ "GOOD TRACKS" = 157 M**

(3) Selection of "GOOD HADRONS" from "GOOD TRACKS".

Each track should:

- **hit one of the hadron calorimeters HCAL1 or HCAL2,**
- **have an associated energy cluster E_{hcal1}>5 GeV or E_{hcal2} > 7 GeV,**
- **energy cluster coordinates compatible with the track coordinates,**
- **energy cluster compatible with the momentum of the track →**

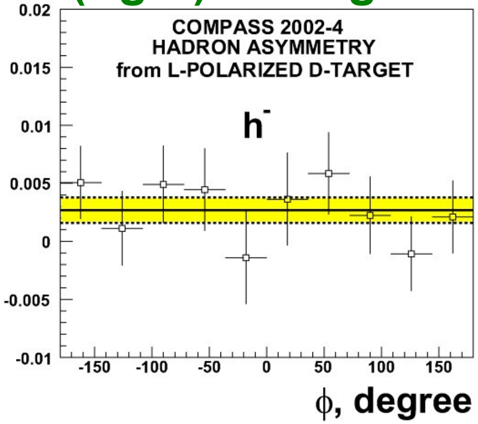
"GOOD HADRONS" = 53 M (25 M h^- + 28 M h^+)

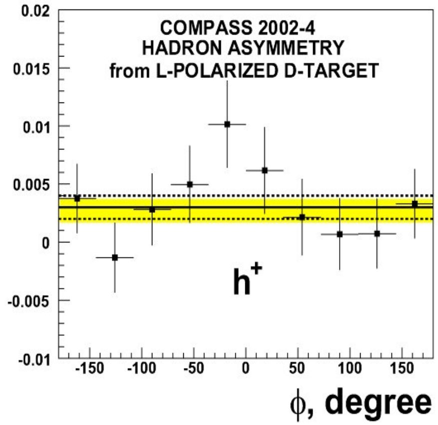
(4) Each "GOOD HADRON" enters in considerations of asymmetries in restricted region

$$x = 0.004 - 0.7, \;\; z = 0.2 - 0.9, \; p_T^h = 0.1 - 1 \text{ GeV/c}$$

RESULTS (1)

The weighted sum of azimuthal asymmetries $a(\phi)=a_+(\phi) \otimes a_-(\phi)$ for h^- (left) and h^+ (right) averaged over all kinematical variables :





Fit parameters $\times 10^4$	h^-	h^+	h^-	h^+
a^{const}	23 ± 17	40 ± 15	23 ± 16	35 ± 15
$a^{\sin\phi}$	15 ± 23	-30 ± 21	–	–
$a^{\sin 2\phi}$	30 ± 23	-24 ± 21	–	–
$a^{\sin 3\phi}$	40 ± 24	-10 ± 21	–	–
$a^{\cos\phi}$	-4 ± 24	38 ± 22	–	–
$\chi^2/\text{n.d.f.}$	6.1/5	1.0/5	10.4/9	7.0/9

Fit function :

$$a(\phi) = a^{const} + a^{\sin\phi}\sin(\phi) + a^{\sin 2\phi}\sin(2\phi) + a^{\sin 3\phi}\sin(3\phi) + a^{\cos\phi}\cos(\phi) \ \text{ or } \ a(\phi) = a^{const}$$

—Within a stat. precision of about 1-1.5σ, ϕ-dependent amplitudes are compatible with zero; fits by constants: OK,

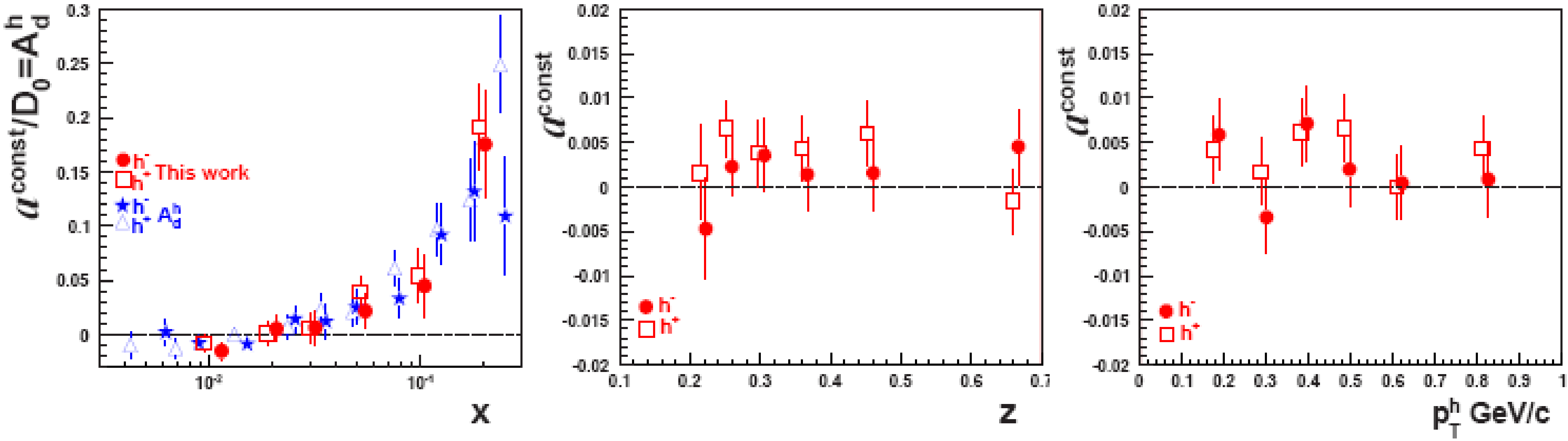
—Parameters a^{const} are different from zero and about equal for *h^+* and *h^-*

REMIND: $a^{const} \propto d\sigma_{LL} \propto g_{1L}(x) \otimes D_1(z)$, where g_{1L} is helicity PDF convoluted with non-polarized PFF. For isoscalar D-target it expected to be weakly dependent on the hadron charge.

—Qualitatively (to be confimed by higher statistics) $a^{\sin\phi}$, $a^{\sin 2\phi}$ and $a^{\sin 3\phi}$ have opposite signes for *h^- and h^+* predicted by quark models of nucleon due to WW-relation between $h_{1L}^\perp$ and h_1 and relation $h_{1T}^\perp h_1 = -1/2[h_{1L}^\perp]^2$).

RESULTS (2)

Dependence of the parameter a^{const} for h^+ and h^- on kinematical variables:



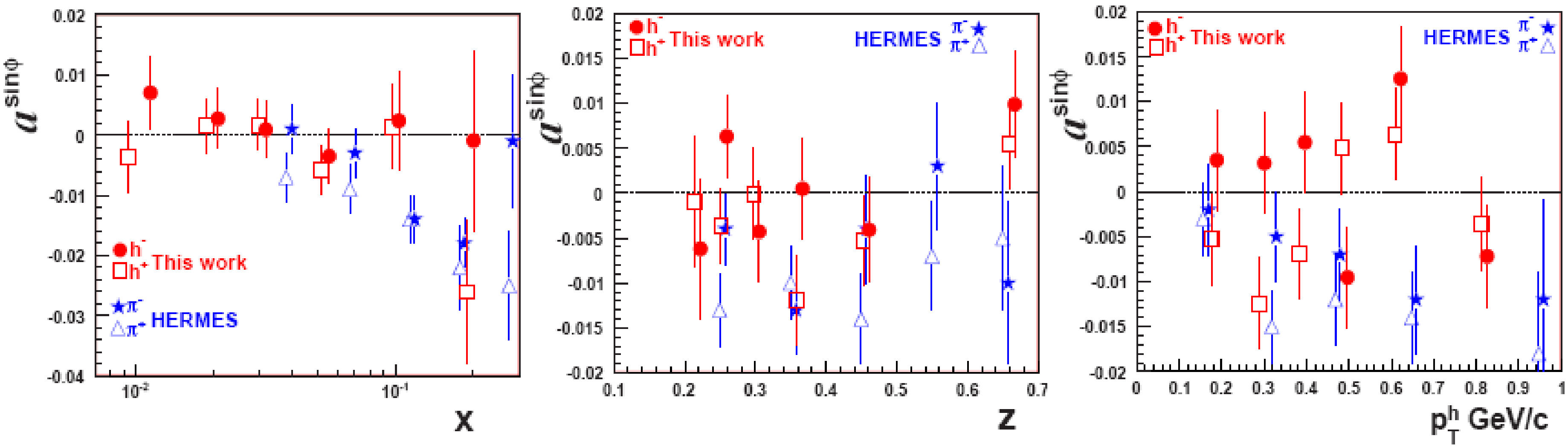
— $a^{const}(x)/D_0(x) \equiv A_d^h(x)$ (*D_0* is a virtual photon depolarization factor) is in agreement with COMPASS published data (PLB660(2008)458),

— $a^{const}(z, p_T^h)$ for h^- and for h^+: small and flat.

—Statistical errors are shown, systematic ones are estimated to be smaller: global systematic multuplicative errors are smaller than 6%.

RESULTS (3)

Dependence of the parameter $a^{\sin\varphi}$ for h⁺ and h⁻ on kinematic variables:



— $a^{\sin\varphi}(x)$ are less pronounced than the HERMES ones [Phys.Lett. B562 (203)182],

— $a^{\sin\varphi}(z, p_T^h)$ is flat and do not confirm the HERMES trends.

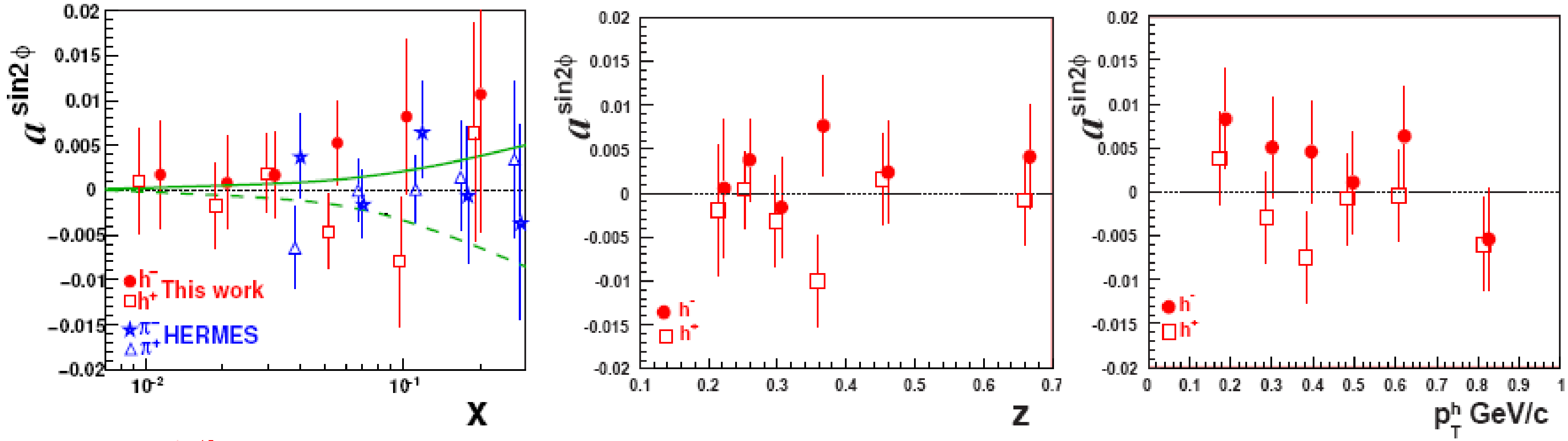
REMIND: $a^{\sin\phi} \propto -d\sigma_{0L} + \tan\theta_\gamma d\sigma_{0T} \propto -\frac{M}{Q} x\left(\left(h_L(x) - h_1(x)\right) \otimes H_1^\perp(z) + \left(f_L^\perp(x) + f_{1T}^\perp\right) \otimes D_1(z)\right)$

where $h_L(x)$ and $f_L^\perp(x)$ are pure twis-3 PDF.

NOTE: HERMES data are for identified π^+ and π^- and at smaller $\langle Q^2 \rangle$.

RESULTS (4)

Dependence of the parameter $a^{\sin 2\varphi}$ for h^+ and h^- on kinematic variables:



— $a^{\sin 2\varphi}(x)$ are small and in general agree with HERMES and theoretical predictions by H.Avakian et al., Phys.Rev. D77 (2008) 014023,

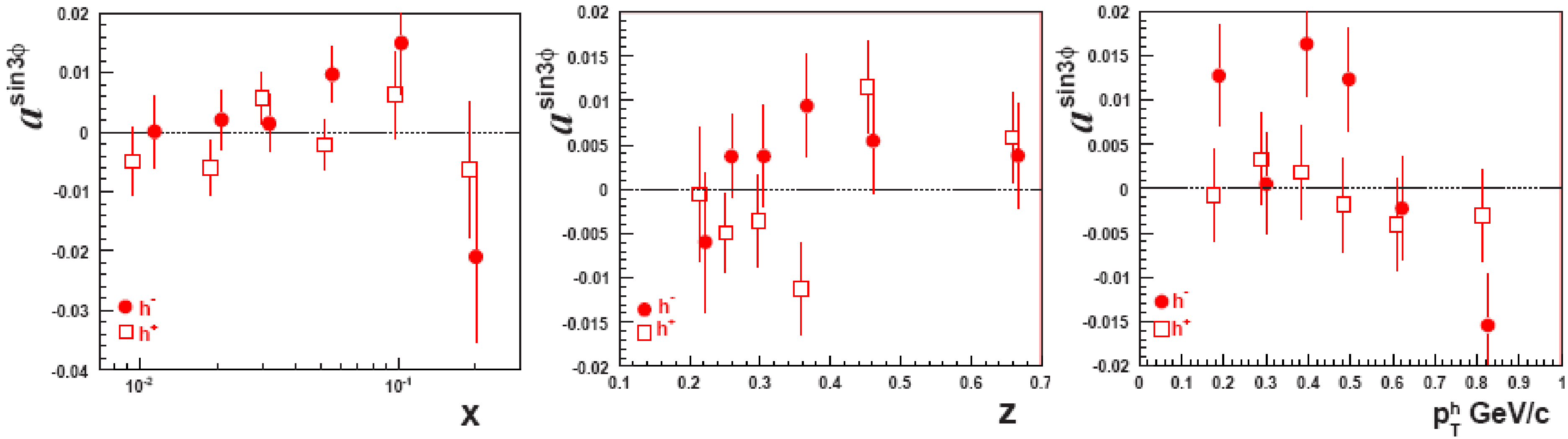
— $a^{\sin 2\varphi}(z, p_T^h)$ - no other data.

REMIND: $a^{\sin 2\varphi} \propto d\sigma_{0L} \propto x h_{1L}^{\perp}(x) \otimes H_1^{\perp}(z)$, where $h_{1L}^{\perp}$ is a PDF not seen yet. It is linked with the transversity PDF h_1 by a relation of the Wandzura-Wilczek type.

$$h_{1L}^{\perp(1)}(x) \approx -x^2 \int_x^1 \frac{dy}{y^2} h_1(y)$$

RESULTS (5)

Dependence of the parameter $a^{\sin 3\varphi}$ for h^{+} and h^{-} on kinematic variables:

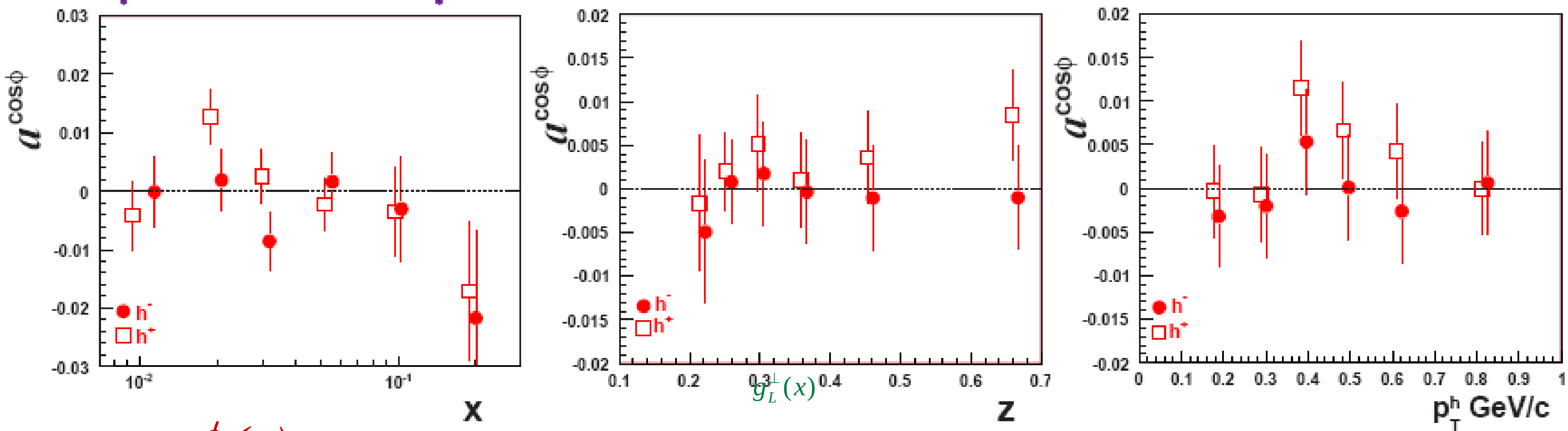


– $a^{\sin 3\varphi}(x)$ are small, compatible with zero. But some peculiarities: points for h^{-} are mostly positive whill these for h^{+} are mostly negative as for the COMPASS results for the amplitude of the $\sin(3\phi - \phi_S)$ modulation extracted form the data with transversally polarized D-target.

REMIND: $a^{\sin 3\varphi} \propto d\sigma_{0T} \propto x h_{1T}^{\perp} \otimes H_1^{\perp}(z)$, where $h_{1T}^{\perp}$ is pretzelosity PDF additionally suppressed by $\tan(\theta_\gamma) \sim \dfrac{M}{Q}$.

RESULTS (6)

Dependence of the parameter $a^{\cos\varphi}$ for h^+ and h^- on kinematic variables:



$-a^{\cos\phi}(x)$ increasing with x in absolute value,

- $a^{\cos\phi}(z)$ and $a^{\cos\phi}(p^h{}_T)$ small, flat and consistent with zero,

- studied for the first time.

Remind:

$$a^{\cos\phi} \propto -d\sigma_{LL} + \tan\theta_\gamma d\sigma_{LT} \propto \frac{M}{Q} x\left(\left(g_L^\perp(x) - g_{1T}(x)\right) \otimes D_1(z) + e_L(x) \otimes H_1^\perp(z)\right)$$

$g_L^\perp(x)$ is pure twist-3 PDF (analog to Cahn effect in unpolarized SIDIS)

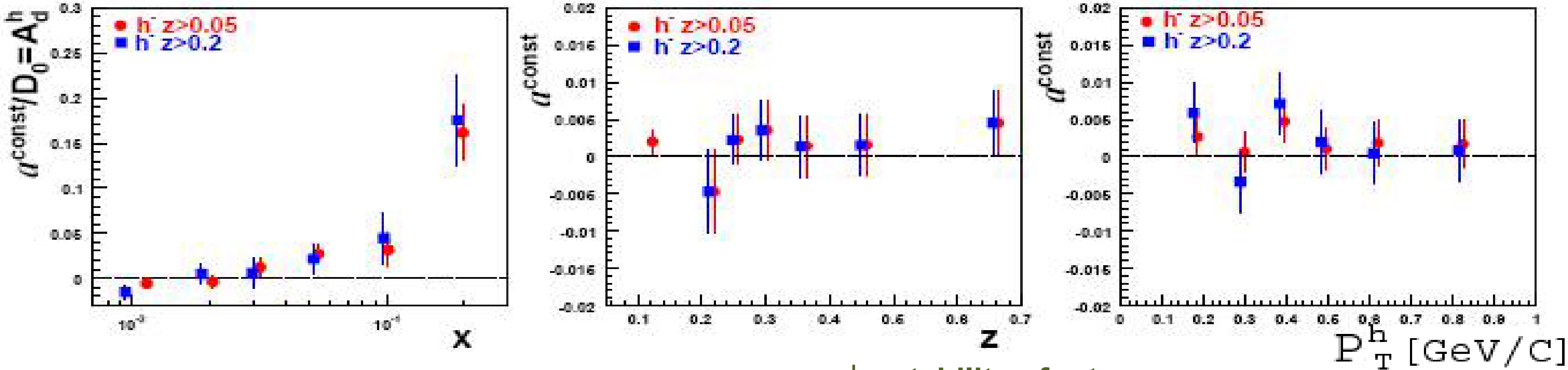
CONCLUSIONS & PROSPECTS (1)

1. Integrated over x , z and p_h^T, all ϕ -modulation are consistent with zero within errors, while ϕ - independent parts differ from zero and are almost equal for h^- and h^+.
2. In study of amplitudes over range $0.004<x<0.7$, $0.2<z<0.9$ and $0.1< p_h^T < 1$ GeV/c it was found:
   - the ϕ - independent parts $a^{const}(x)/D_0$ are in agreement with COMPASS data on $A_d^h(x)$, calculated by another method and using different cuts;
   - the amplitudes $a^{\sin\phi}(x, z, p_h^T)$ are small and in general compatible with the HERMES data, if one takes into account the difference in x, W and Q^2 between the two experiments;
   - other amplitudes are consistent with zero within statistical errors of about 0.5% (systematical errors are estimated to be much smaller).
3. Tests have shown that lower cut , $z>0.05$, gives identical results with smaller errors.
4. Data of 2006 from deuterium target will be added. Data of 2007 from hydrogen target will be interesting to compare with effects observed by COMPASS and HERMES on transversally polarized targets.

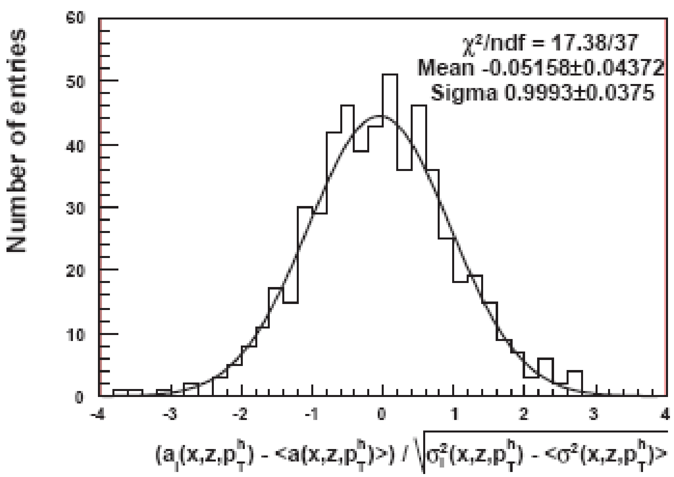
Thank you!

BACK UP SLIDES. STABILITY of RESULTS

Z – stability of results

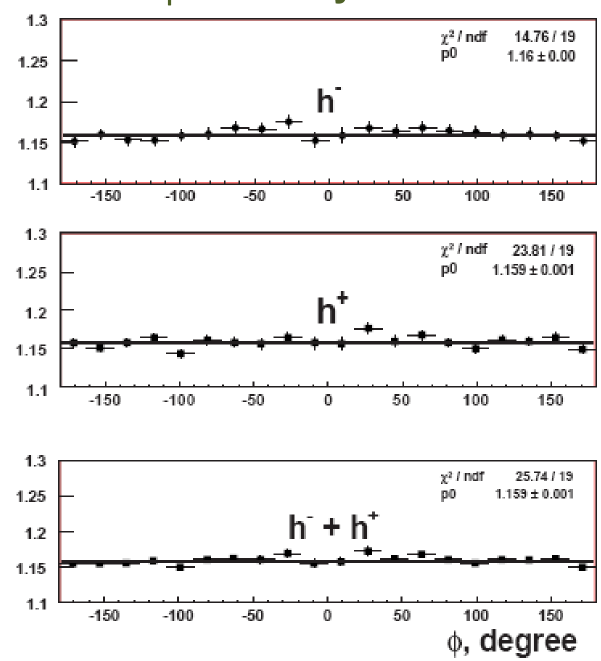


"Pulls" distribution for a_i



Expected: Mean = 0.
Sigma = 1.

ϕ - stability of rates



$$F = F_+ \oplus F_-$$

$$F_+ = \frac{N_{++}^u}{N_{++}^D} \cdot \frac{N_{-+}^D}{N_{-+}^U} = \frac{L_{++}^2}{L_{-+}^2}$$

$$F_1 = \frac{N_{+-}^U}{N_{+}^D} \cdot \frac{N_{--}^D}{N_{--}^U} = \frac{L_{+-}^2}{L_{--}^2}$$

BACK UP SLIDES. PDF & FF IN SIDIS.

$f_1(x) \equiv q(x)$ is the PDF of non-polarized quarks in a non-polarized target,

$g_{1L}(x) \equiv g_1(x) \equiv \Delta q(x)$ is the PDF of the longitudinally polarized quarks in the longitudinally polarized target (helicity PDF),

$g_{1T}(x)$ is the same as $g_1(x)$ but in the transversely polarized target,

$h_1(x)$ is the PDF of the transversely polarized quark with polarization parallel to that one of a transversely polarized target (so-called transversity PDF),

$h_{1L}^{\perp}(x)(h_{1T}^{\perp})$ is the PDF of the transversely polarized quark in direction of transverse momentum in longitudinally (transversely) polarized target (so-called pretzelosity PDF),

$h_1^{\perp}(x)$ is the PDF of the transversely polarized quark (perpendicular to transverse momentum) in the non-polairzed target (so-called Boer-Mulders PDF),

$f_{1T}^{\perp}(x)(f_{1L}^{\perp})$ is the PDF responsible for a left-right asymmetry in the distibution of the non-polarized quarks in the transversely (longitudinally) polarized target (so-called Sivers PDF),

$D_1(z)$ is the PFF of the non-polarized quark in the non-polarized or spinless produced hadron,

$H_1^{\perp}(z)$ is the PFF responsible for a left-right asymmetry in the fragmentation of a transversely polarized quark into a non-polarized or spinless produced hadron (so-called Collins PFF),

$e, e_L, g^{\perp}, g_L^{\perp}, h, h_L, f^{\perp}$ and $f_L^{\perp}$ are pure twist-3 terms entering the cross section with a factor M/Q and having no clear physical interpretation.

BACK UP SLIDES.FALSE ASYM.

Sources of false asymmetries are identified using a simplified expression for $A(\phi)$

$$A(\phi) \approx \frac{dN_+(\phi)}{N_+ d\phi} - \frac{dN_-(\phi)}{N_- d\phi} \approx p_0 + p_1 \sin(\phi) + p_2 \sin(2\phi) + p_3 \sin(3\phi) + p_4 \cos(\phi) + \ldots$$
$$\approx p_0 + p_1 \sin(\phi).$$

Remind, that $\phi = \arccos\left(\frac{(\vec\ell\times\vec\ell')\cdot(\vec q\times\vec p_h)}{|\vec\ell\times\vec\ell'||\vec q\times\vec p_h|}\right)\cdot \mathrm{sign}\left[\vec p_h\cdot(\vec\ell\times\vec\ell')\right].$

Sin(ϕ) appears from the vector product $(\vec\ell\times\vec p_h)$, which is pseudo-vector.
But it could appear only being multiplied by another pseudo-vector:

spin of the target $\vec S$, with a fraction p_s
spin of the muon $\vec\mu$, " p_μ
— physics asym.

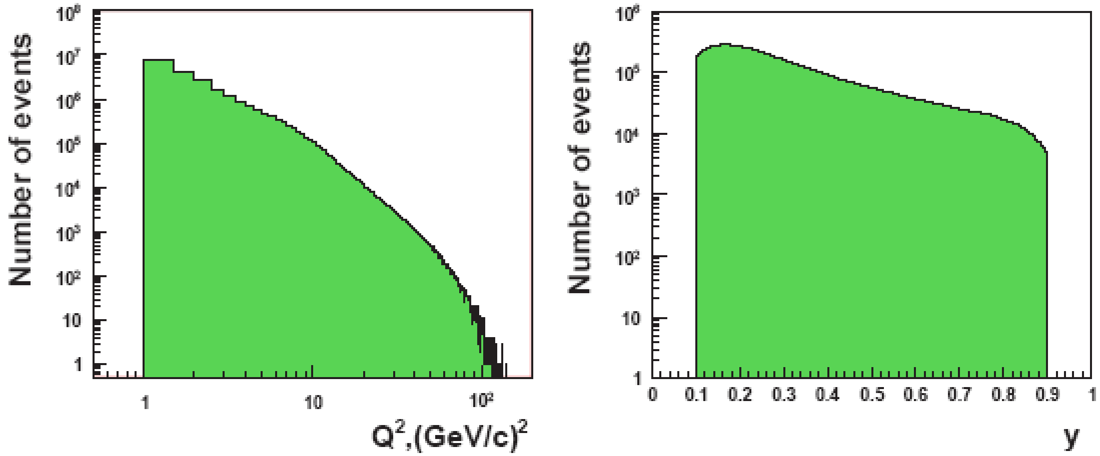
target magnetic field $\vec H$, " p_H
product $(\vec H\times\vec\mu)$, " $p_{H\mu}$
product $(\vec H\times\vec S)$, " p_{HS}
— false asym., due to incomplete knowledge of $\vec H$ and/or misalignments

So, $p_1 \sim p_s + p_\mu + p_{H\mu} + p_{HS} + p_H$,where false asim depend on:

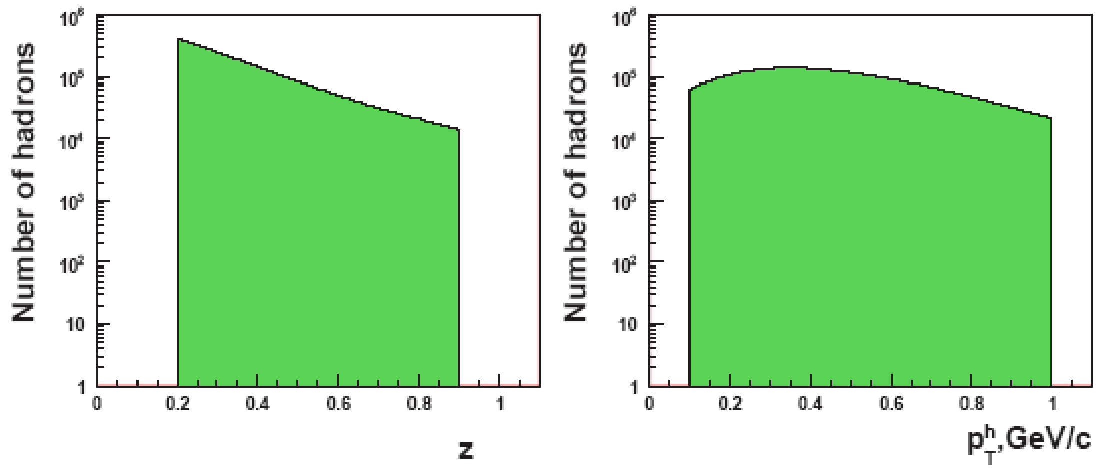
- directions of the field,
- track extrapolations,
- sign of particles.

— different for U and D cells.

BACK UP SLIDES.KINEMATICS



The distribution of events, passed all data selection cuts, vs. Q^2 (left) and vs. y(right).



The distribution of identified good charged hadrons vs. z (left) and vs. p_T^h (right).

BACK UP SLIDES.BINNING

x bins	z bins	p_T^h bins (GeV)
	0.05(0.120)0.200	
0.004(0.010)0.012	0.200(0.216)0.234	0.100(0.177)0.239
0.012(0.020)0.022	0.234(0.253)0.275	0.239(0.289)0.337
0.022(0.031)0.035	0.275(0.299)0.327	0.337(0.385)0.433
0.035(0.053)0.076	0.327(0.361)0.400	0.433(0.485)0.542
0.076(0.098)0.132	0.400(0.455)0.523	0.542(0.610)0.689
0.132(0.190)0.700	0.523(0.661)0.900	0.689(0.814)1.000

The size of each bin is optimized to have ≥ 1 M of events
The first z bin (0.05 – 0.2) has been used for tests only