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AZIMUTHAL ASYMMETRIES IN PRODUCTION OF CHARGED HADRONS BY HIGH ENERGY MUONS ON POLARIZED DEUTERIUM TARGETS AT COMPASS

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On behalf of the COMPASS Collaboration.

OUTLINE

1. **Introduction: theoretical summary & motivations.**
2. **Method of the analysis.**
3. **Data selection.**
4. **Results.**
5. **Conclusions and prospects.**
6. **Back up slides.**

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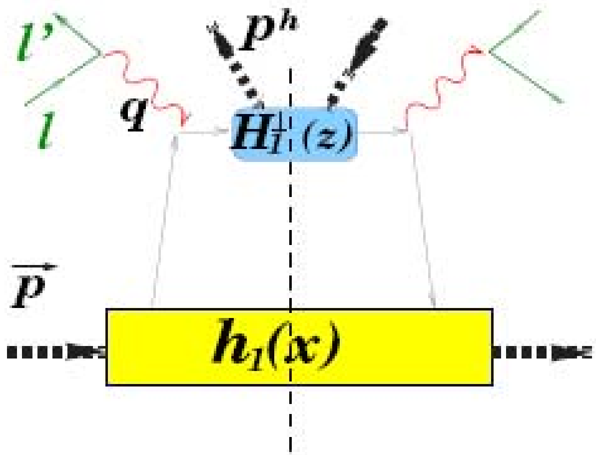
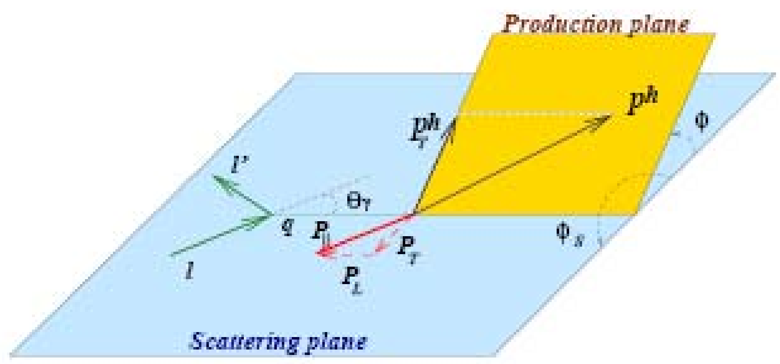
INTRODUCTION (1)

The azimuthal distributions of hadrons in SIDIS of leptons on T-and L-targets are sources of information on new PDFs and PFFs, characterizing the longitudinal and transverse spin structure of nucleons, e.g.:

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





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

INTRODUCTION (2)

The cross section and asymmetry of the h production in SIDIS:

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

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

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

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

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

Sivers

$$-x f_{1T}^{\perp}(x)\otimes D_1(z)\sin(\phi-\phi_S)]$$

Mulders&Tangerman
Boer&Mulders
Bucchetta et al.

$\otimes$=convolution in k_T

ϕ_S = 0 for L-target

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

INTRODUCTION (3)

Summary:

–~~Quark~~ t- and ℓ- spin effects contribute to the asymmetries *a(ϕ)* in hadron production from longitudinally polarized target.

–Several ~~asymmetry~~ modulations ~~should be seen~~ in *a(ϕ)*.

–~~Aims: search for *a(ϕ)*, its~~ possible sin(ϕ) (Sivers + Transversity), sin(2ϕ) , sin(3ϕ) (Pretzelosity) and cos(ϕ) (Twist 3) modulations ~~and~~

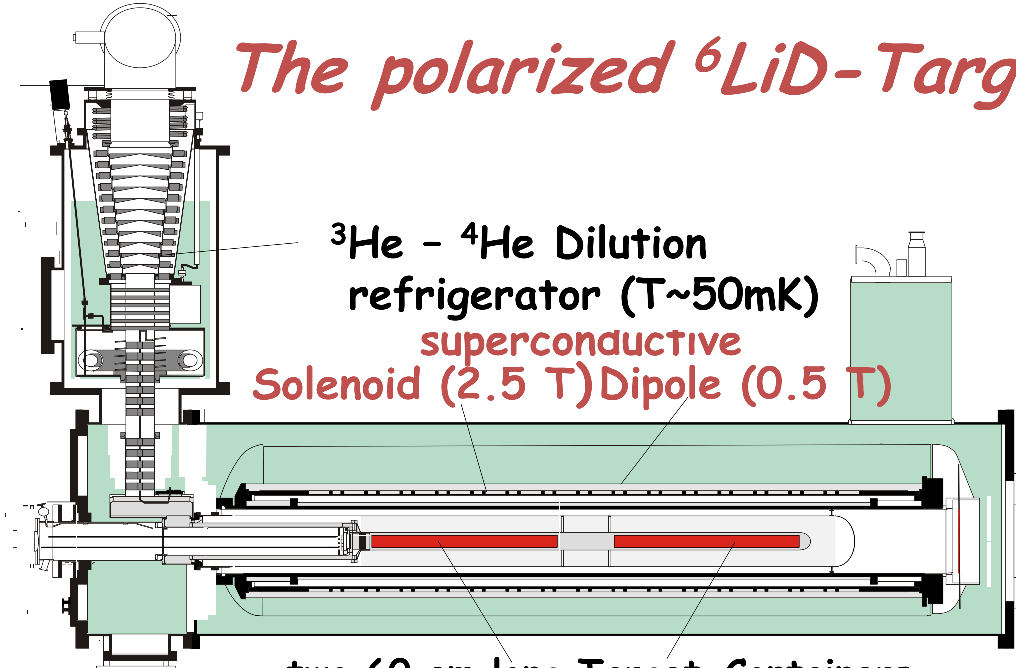
x, z, p_h^T ~~-dependence of corresponding amplitudes.~~

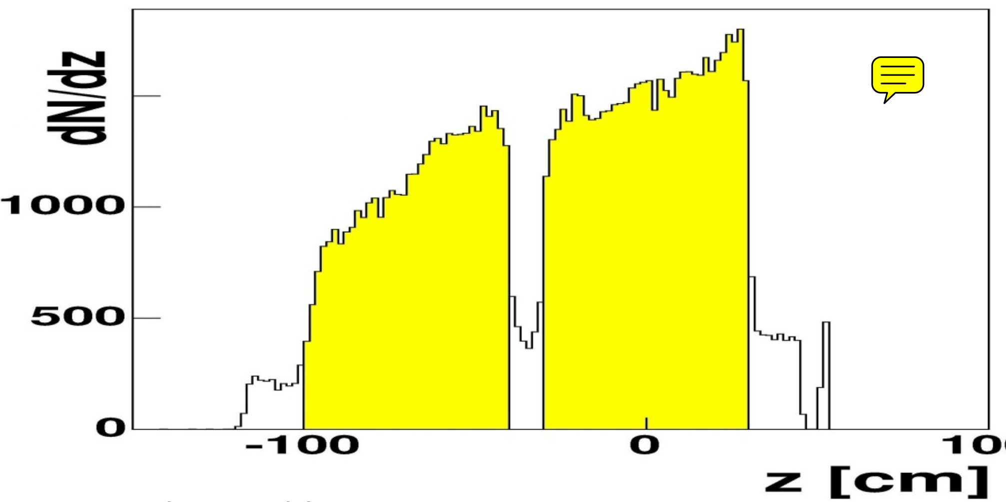
– *a(ϕ)* expected to be small, ≤1%.

– Methods of analysis should be adequate.

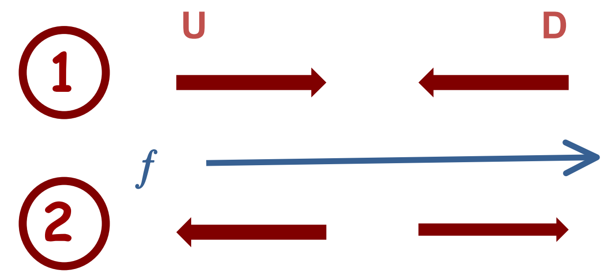
METHOD OF ANALYSIS (1)

The polarized ^{6}LiD-Target



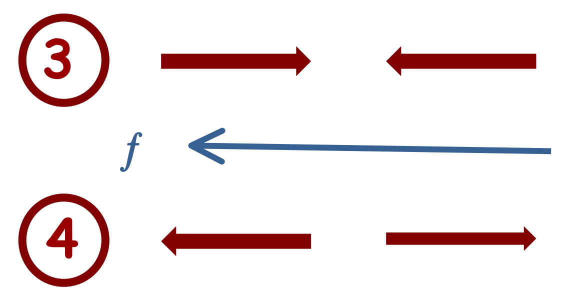


4 target polarizations:



reversed every 8 hours

After few weeks



reversed every 8 hours

Polarization: ~ 50%

METHODS OF ANALYSIS: (2)

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

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*.**

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

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

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

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

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 IDENTITYED 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 →

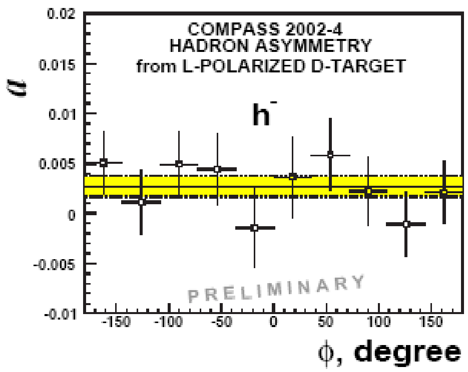
"GOOD HADRONS" = 53 M (25 M h^- + 28 M h^+)

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

$$x = 0.004 – 0.7, \quad z = 0.2 – 0.9, \qquad p_T^h = 0.1 - 1.0 \, \mathrm{GeV}/c$$

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 :



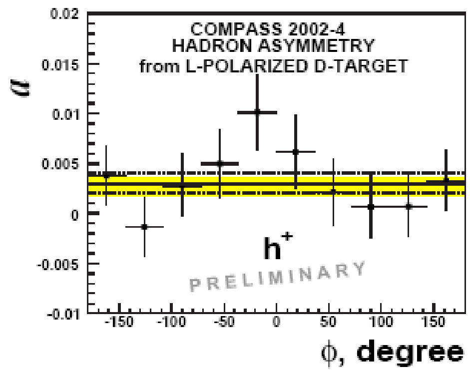


Table 1. The fit parameters of $a(\phi)$-distributions in units of 10^{-4}.

	h^-	h^+	h^-	h^+
a^{const}	23 ± 11	35 ± 11	27 ± 11	30 ± 11
$a^{\sin\phi}$	-1 ± 16	-13 ± 15	0	0
$a^{\sin 2\phi}$	20 ± 16	-15 ± 15	0	0
$a^{\sin 3\phi}$	6 ± 16	3 ± 15	0	0
$a^{\cos\phi}$	10 ± 16	24 ± 15	0	0
$\chi^2/n.d.f.$	3.42/5	5.18/5	4.82/9	8.03/9

Fit function :

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

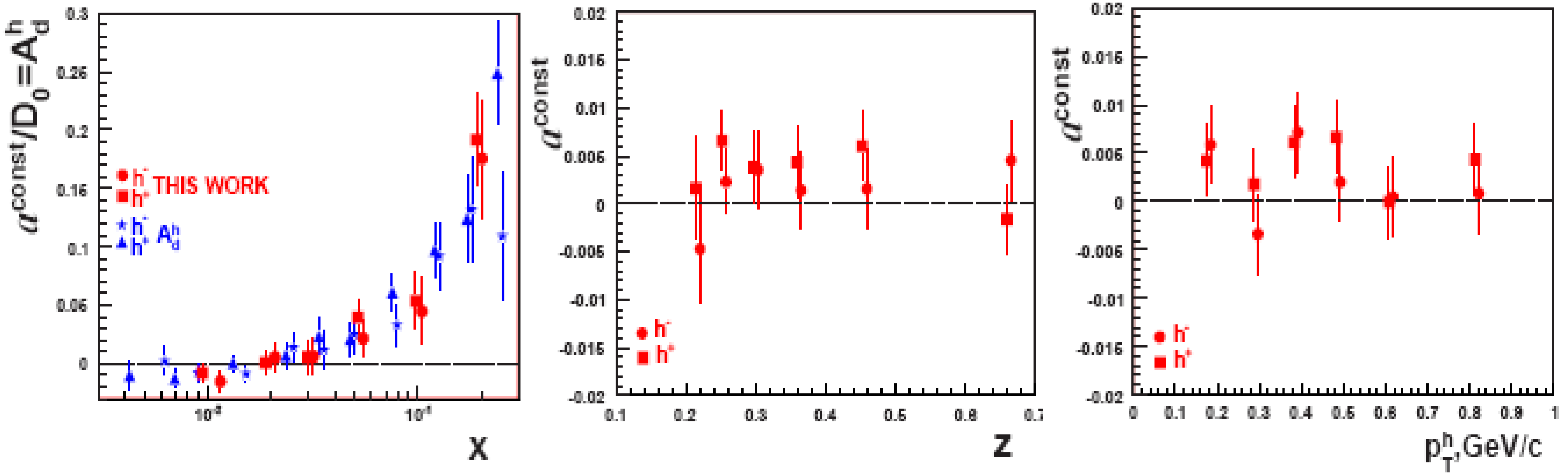
—Within a stat. precision of about 0.15%, ϕ-dependent amplitudes are compatible with zero; fits by constants: OK,

—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 a helicity PDF of L-polarized quarks in L-polarized target convoluted with PFF of non-polarized quarks in non-polarized hadron. For isoscalar D-target it is expected to be weakly dependent on the hadron charge.***

RESULTS (2)

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



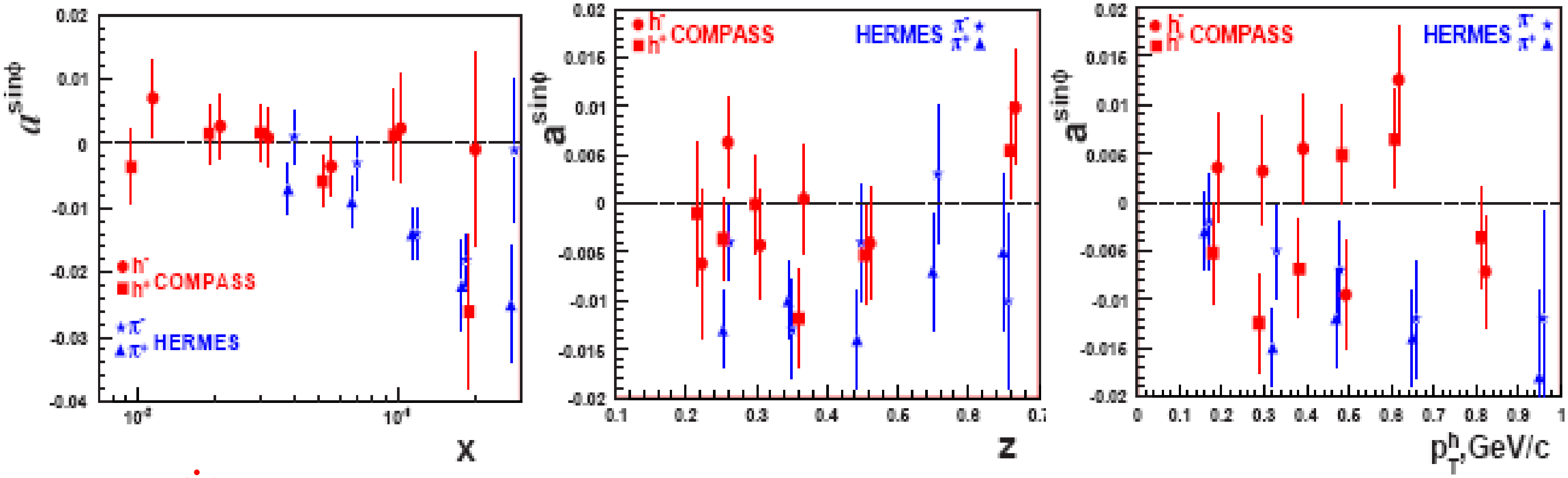
— $A_0(x) = a^{const}(x)/D_0(x) \equiv A_d^h(x)$ (**D_0 is a virtual photon depolarization factor) is in agreement with COMPASS published data (PLB660(2008)458),**

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

—Statistical errors are shown, systematic ones are estimated to be smaller: global systematic multiplicative 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.

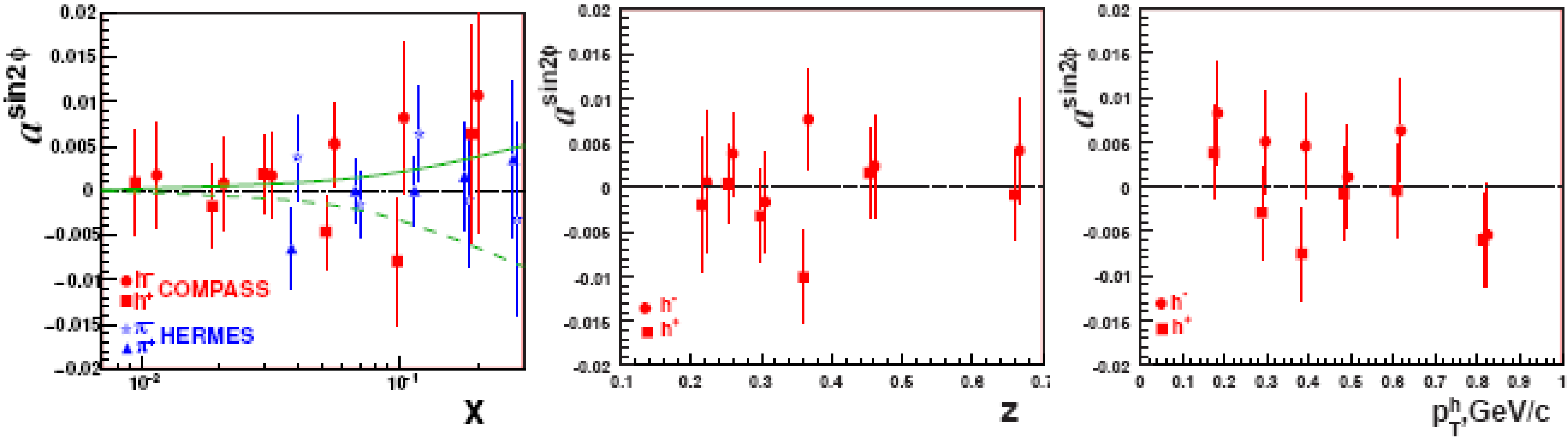
REMIND: $a^{\sin\varphi} \propto d\sigma_{0L} \propto \frac{M}{Q} x^2 \left(h_L(x) \otimes H_1^{\perp}(z) + f_L^{\perp}(x) \otimes D_1(z) \right)$

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:



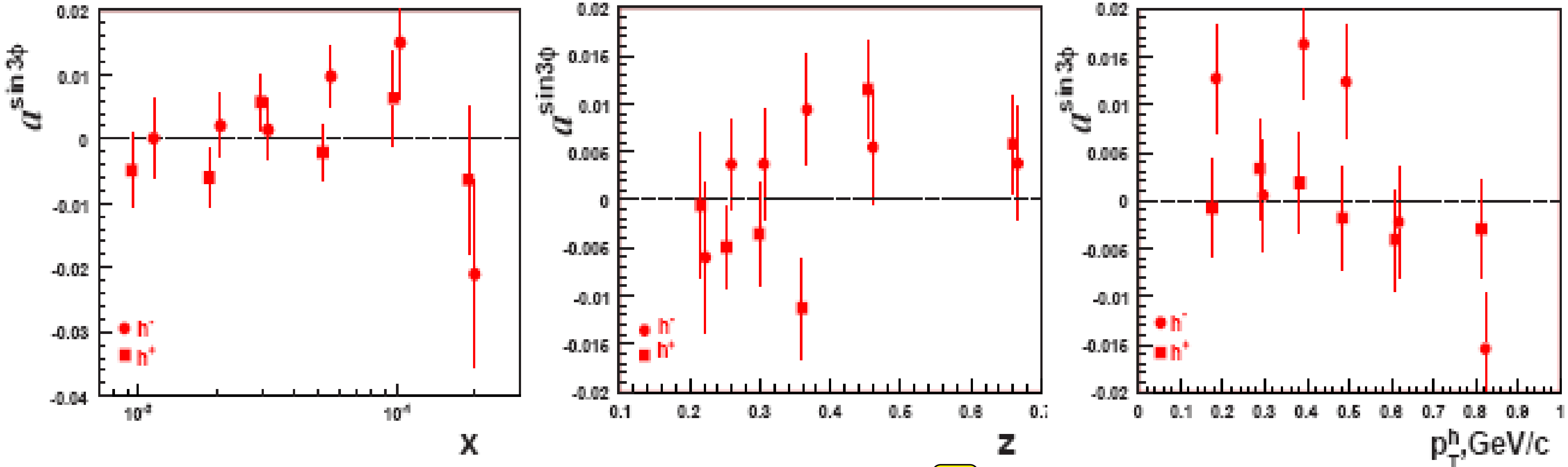
— $a^{\sin 2\varphi}(x)$ are small and in general agree with HERMES and theoretical predictions by H.Avakian et al., Phys.Rev. D77 (2008) 014023,

— $a^{\sin 2\varphi}(z, p_T^h)$ - 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.

RESULTS (5)

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

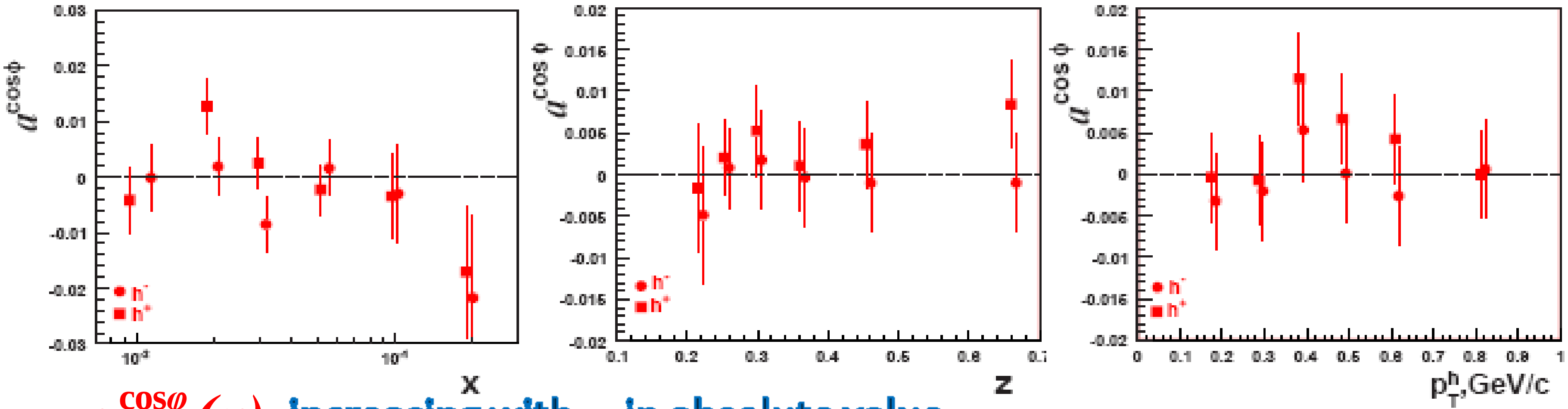


– $a^{\sin 3\varphi}(x)$ are small, compatible with zero. But some peculiarities: points for h$^-$ are mostly positive whill these for h$^+$ are mostly negative as for the COMPASS results ~~for the amplitude~~ of the sin(3ϕ- ϕ$_S$) modulation extracted form the data with transversally polarized D-target.

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:



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

— $a^{\cos\varphi}(z)$ and $a^{\cos\varphi}\left(p_T^h\right)$ small, flat and consistent with zero,

— are studied for the first time.

REMIND: $a^{\cos\phi} \propto d\sigma_{LL} \propto \frac{M}{Q} x^2 \left(g_L^{\perp}(x) \otimes D_1(z)_4 + \ldots\right)$, where $g_L^{\perp}$ is a pure twist-3 PDF (analog to the Cahn effect in unpolarized SIDIS).

CONCLUSIONS & PROSPECTS (1)

1. The azimuthal asymmetries $a(\phi)$ in the SIDIS ~~(Q^2>1 GeV^2, y>0.1)~~ production of negative ~~(h^-)~~ and positive ~~(h^+)~~ hadrons by 160 GeV muons on the longitudinally polarized deuterium target, have been studied with COMPASS data collected in 2002-2004.
2. After integration over *x* , *z* and p_T^h variables, all ϕ -modulation amplitudes of $a(\phi)$ are consistent with zero within errors, while ϕ - independent parts of the $a(\phi)$ differ from zero and are almost equal for h^- and h^+.
3. In the study of the amplitudes over the range 0.0004<*x*<0.7, 0.2<*z*<0.9 and 0.1< p_T^h < 1 GeV/c it was found:
   - the ϕ - independent parts of the $a(\phi)$, $a^{const}(x)/D_0$, where D_0 *is a virtual photon depolarization factor, are in agreement with the COMPASS published data on* A_d^h *, calculated by another method and using different cuts;*
   - *the amplitudes* $a^{\sin\phi}(x,z,p_T^h)$ *are small and in general compatible with the HERMES data, if one takes into account the difference in x and Q^2 between the two experiments. One can also note, that in the HERMES experiment the asymmetries are calculated for identified leading pions, while in this analysis every hadron is included in the asymmetry evaluation;*
   - the amplitudes $a^{\sin2\phi}$, $a^{\sin3\phi}$ and $a^{\cos\phi}$ are consistent with zero within statistical errors of about 0.5% ~~(only statistical errors are shown in the plots while systematical errors are estimated to be much smaller).~~

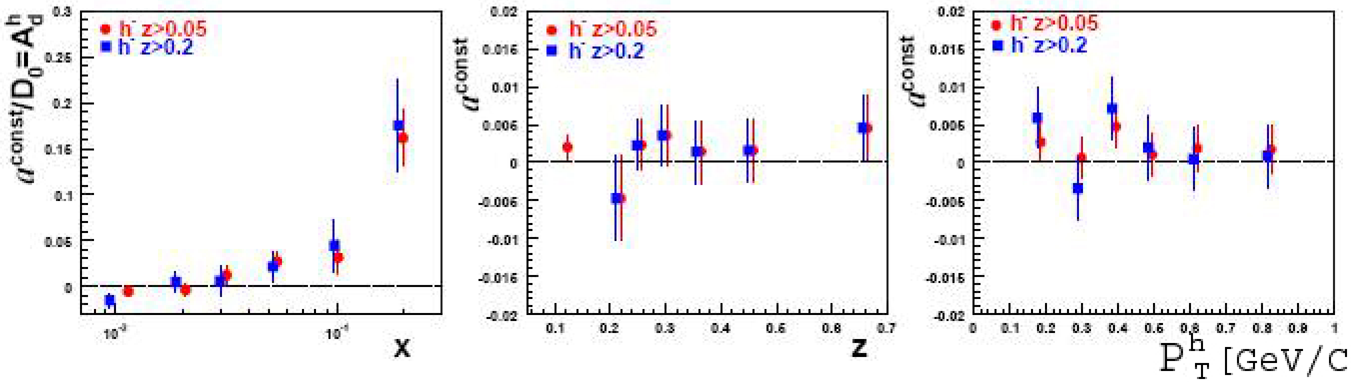
CONCLUSIONS & PROSPECTS (2)

4. The results of this analysis are obtained with restriction z>0.2 of the energy fraction of the hadron in order to assure that it comes from the current fragmentation region. This request removes almost one half of statistics. The tests have shown that with a lower cut , z>0.05 , the results are identical.
5. These data will be useful to constrain models for PDFs. The present general description of the SIDIS cross-section involves a considerable number PDFs depending on the longitudinal or transversal components of the nucleon spin. Probably, not all of them are on the same footing. Hopefully our data will help to assess which PDFs are important in the description of the nucleon structure .

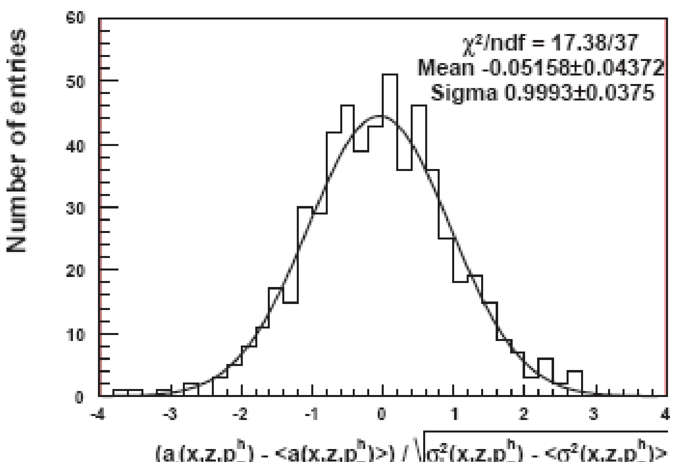
6.The samples used in the present analysis account only for a part of the COMPASS data. New data of 2006 from the deuterium target will be added. These data will increase the statistics by about a factor of 2. New data of 2007 from the hydrogen target will be interesting in comparison with the effects already observed by the COMPASS and HERMES on the transversally polarized targets.

BACK UP SLIDES. STABILITY of RESULTS

Z – stabilitv of results



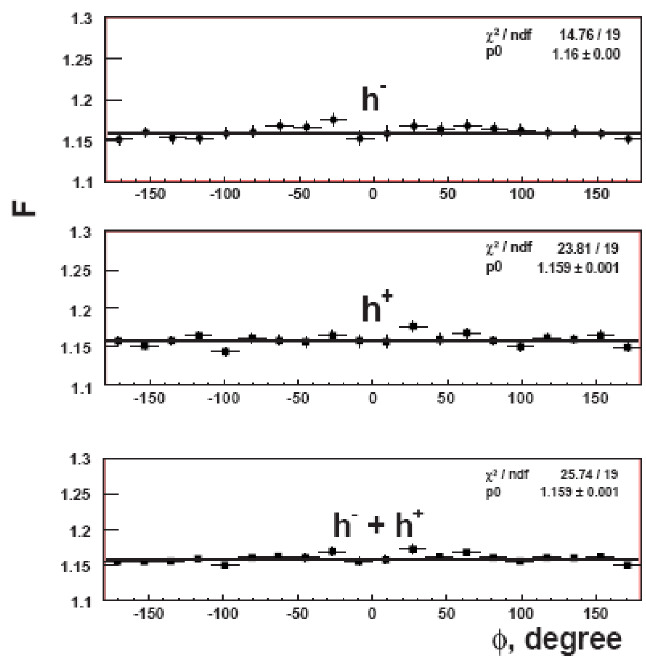
"Pulls" distribution for a_i



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),

$e, e_L, g^{\perp}, g_L^{\perp}, h, h_L, f^{\perp}$ $f_L^{\perp}$ and are pure twist-3 trms 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(ϕ)

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

$$\approx p_0 + p_1 \sin(\phi).$$

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

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:

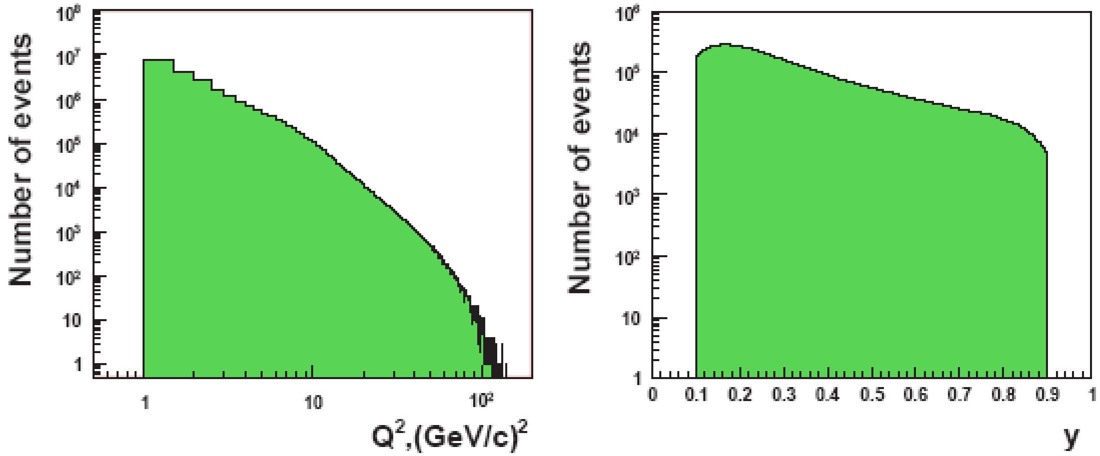
spin of the target	$\vec{S}$,	with a fraction	p_s	physics asym.
spin of the muon	$\vec{\mu}$,	"	p_μ	
target magnetic field	$\vec{H}$,	"	p_H	false asym., due to incomplete knowledge of $\vec{H}$ and/or misalignments
product	$(\vec{H} \times \vec{\mu})$,	"	$p_{H\mu}$	
product	$(\vec{H} \times \vec{S})$,	"	p_{HS}	

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

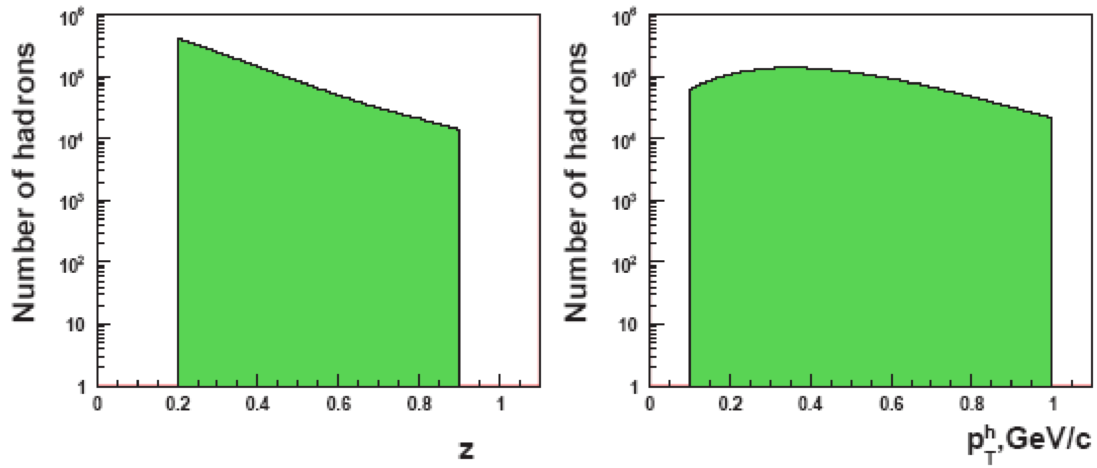
- directions of the field,
- track extrapolations,
- sign of particles.

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