AZIMUTHAL ASYMMETRIES IN SEMI-INCLUSIVE PRODUCTION OF HADRONS ON THE LONGITUDINALLY POLARIZED DEUTERIUM TARGET

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OUTLINE

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

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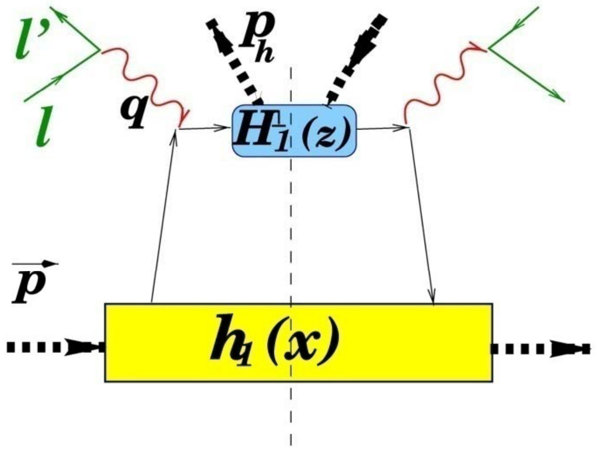
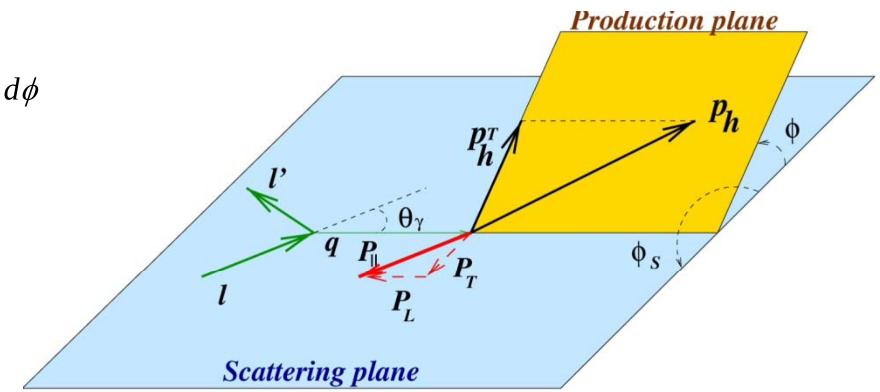
INTRODUCTION (1)

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

$$d\sigma_h / d\phi \sim h_1(x) \oplus H_1^{\perp}(z)$$

$$\ell + \overline{N} \rightarrow \ell' + X + h$$





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

INTRODUCTION (2)

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

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

$$A_L(\phi) = \frac{d\sigma^{\rightarrow\Rightarrow} - d\sigma^{\rightarrow\Leftarrow}}{d\sigma^{\rightarrow\Rightarrow} + d\sigma^{\rightarrow\Leftarrow}} \sim P_L\left(d\sigma_{0L} + P_\mu d\sigma_{LL}\right) + P_L \sin(\theta_\gamma)(d\sigma_{0T} + P_\mu d\sigma_{LT}),$$

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

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

helicity | Twist 3

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

transversity

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

Sivers

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

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

Mulders&Tangerman
Boer&Mulders
Bucchetta et al.

$\otimes$=convolution in k_T

, ϕ_S = 0 for L-target

INTRODUCTION (3)

Summary:

–Quark transverse spin effects contribute to the asymmetries $A_L(\phi)$ in hadron production from longitudinally polarized target.

–Asymmetries modulations should be seen in $A_L(\phi)$.

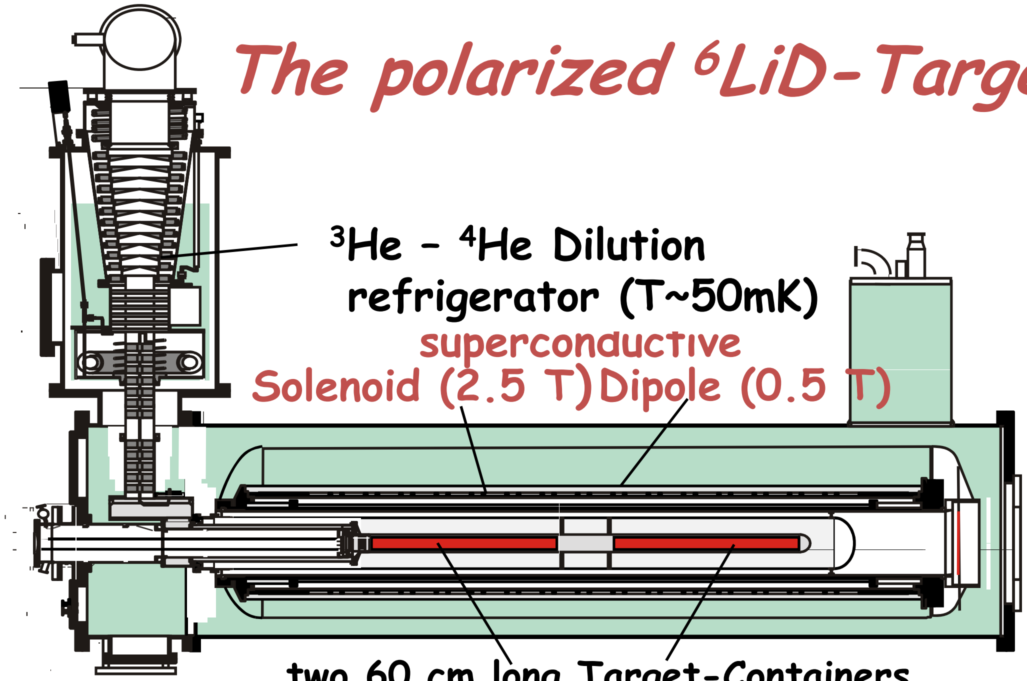
–Aims: search for $A_L(\phi)$, its possible $\sin(\phi)$ (Sivers + Transversity), $\sin(2\phi)$, $\sin(3\phi)$ (Pretzelosity) and $\cos(\phi)$ (Twist 3) modulations and x, z, p_h^T -dependence of corresponding amplitudes.

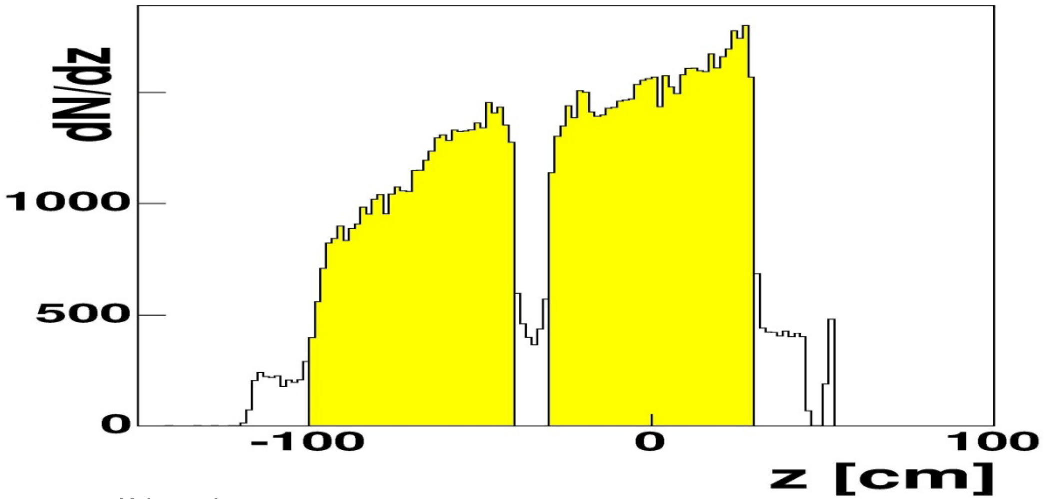
– $A_L(\phi)$ expected to be small, $\leq 1\%$.

– Methods of analysis should be adequate.

The single ratio method, SRM (1)

The polarized ^6LiD-Target





D target

4 possible spin combinations:

① → ←

② ← →

reversed every 8 hours

or:

③ ↑ ↓

④ ↓ ↑

reversed once a week

Polarization: ~ 50%

SRM (2)

Usually the ϕ- asymmetry is defined as

$$A(\phi)=\frac{\dfrac{dN_+(\phi)}{L_+d\phi}-\dfrac{dN_-(\phi)}{L_-d\phi}}{\dfrac{N_+}{L_+}\langle P_-\rangle+\dfrac{N_-}{L_-}\langle P_+\rangle},$$

$\pm$ - are the target polarizations

where

$$\frac{dN_\pm(\phi)}{d\phi}=CL_\pm\left[\frac{d\sigma_{00}}{d\phi}+P_\mu\frac{d\sigma_{L0}}{d\phi}\pm P_\pm\cos(\theta_\gamma)\left(\frac{d\sigma_{0L}}{d\phi}+P_\mu\frac{d\sigma_{LL}}{d\phi}\right)+P_\pm\sin(\theta_\gamma)\left(\frac{d\sigma_{0T}}{d\phi}+P_\mu\frac{d\sigma_{LT}}{d\phi}\right)\right]$$

$$=CL_\pm\left[(B_0+B_1\cos(\phi)+B_2\sin(\phi)+...)\pm P_\pm(A_0+A_1\sin(\phi)+A_2\sin(2\phi)+...)\right],$$

$$N_\pm=\int_{-\pi}^{\pi}d\phi\frac{dN_\pm(\phi)}{d\phi},$$

C is an acceptance (assumed to be ϕ-independent), $L_\pm$ is a luminosity and $\langle P_\pm\rangle$ are average products of target polarization and dilution factors.

For COMPASS two cells target:

$$A_{UD}(\phi)=\frac{\left(\dfrac{dN_+^U(\phi)}{L_+^U d\phi}-\dfrac{dN_-^D(\phi)}{L_-^D d\phi}\right)+\left(\dfrac{dN_+^D(\phi)}{L_+^D d\phi}-\dfrac{dN_-^U(\phi)}{L_-^U d\phi}\right)}{\left(\dfrac{N_+^U}{L_+^U}\langle P_-^U\rangle+\dfrac{N_-^D}{L_-^D}\langle P_+^D\rangle\right)+\left(\dfrac{N_+^D}{L_+^D}\langle P_-^D\rangle+\dfrac{N_-^U}{L_-^U}\langle P_+^U\rangle\right)}$$

$$A_U(\phi)\approx A_D(\phi)$$

$$A_{UD}(\phi)\approx\frac{1}{2}\left(A_U(\phi)+A_D(\phi)\right)$$

SRM (3)

The SRM method has been tested using a part of the COMPASS data of 2002, standard COMPASS selection cuts.

Results on asymmetries: $A_f(\phi)$, *f* is a direction of the target solenoid magnetic field, f=+ or -:

- different for f_+ and f_-, i.e. $A(\phi)$ distributions depend on the initial f

-different for U and D cells: $A_U(\phi) \neq A_D(\phi)$,

$\Downarrow$

Large false asymmetries,

larger than physics ones $\Rightarrow$ **SRM can not be used for searches of small asymmetries**

METHODS OF ANALYSIS: THE MODIFIED DOUBLE RATIO METHOD, (MDR) (1)

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

where

$N^t_{pf}(\phi)$ 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),

$C^t_f(\phi)$ 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 $C^t_f(\phi)$ cancel if beam crosses both cells and if one combines periods with the same *f*.

$$R_+(\phi) = \frac{dN^U_{+,+}(\phi)/d\phi}{dN^D_{-,+}(\phi)/d\phi} \cdot \frac{dN^D_{+,+}(\phi)/d\phi}{dN^U_{-,+}(\phi)/d\phi}; \qquad R_-(\phi) = \frac{dN^U_{+,-}(\phi)/d\phi}{dN^D_{-,-}(\phi)/d\phi} \cdot \frac{dN^D_{+,-}(\phi)/d\phi}{dN^U_{-,-}(\phi) d\phi}$$

MDR (2)

Configuration 1

	Up	Down
H(*f*)	→	→
Beam	→	→
S(p)	→	←
$N^{t}_{p,f}$:	$N^{U}_{+,+}$	$N^{D}_{-,+}$
C^{t}_{f} :	C^{U}_{+}	C^{D}_{+}

Configuration 2

	Up	Down
H(*f*)	→	→
Beam	→	→
S(p)	←	→
$N^{t}_{p,f}$:	$N^{U}_{-,+}$	$N^{D}_{-,+}$
C^{t}_{f} :	C^{U}_{+}	C^{D}_{+}

R_f :

$$R_{+} \sim \frac{C^{U}_{+}}{C^{D}_{+}} \cdot \frac{C^{D}_{+}}{C^{U}_{+}} \sim 1$$

$$R_f(\phi) = \frac{\left(1 + P^{U}_{+,f}\, a_f(\phi)\right)\left(1 + P^{D}_{+,f}\, a_f(\phi)\right)}{\left(1 - P^{D}_{-,f}\, a_f(\phi)\right)\left(1 - P^{U}_{-,f}\, a_f(\phi)\right)},$$

$$a_f(\phi) \approx \frac{R_f(\phi) - 1}{P^{U}_{+,f} + P^{D}_{+,f} + P^{u}_{-,f} + P^{D}_{-,f}}$$

$$a(\phi) = \frac{\left(a_0 + a_1 \sin(\phi) + a_2 \sin(2\phi) + \ldots\right)}{\left(1 + b_1 \sin(\phi) + b_2 \cos(\phi) + b_3 \sin(\phi) + \ldots\right)} \qquad a_i = A_i / B_0, b_i = B_i / B_0,$$

$$\cong a_0 + a_1 \sin(\phi) + a_2 \sin(2\phi) + a_3 \sin(3\phi) + a_4 \cos(\phi) \ldots + \mathrm{O}(a_i b_j).$$

$$a_{+}(\phi) \approx a_{-}(f),$$

free of false (multiplicative) asymmetries connected with the field.

MDR (3)

SUMMARY:

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

– possible ϕ-dependent false asymmetries, connected with the target solenoid magnetic field, are canceled,

– the MDR 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_h^T <0.1 GeV -----------→ "GOOD TRACKS" = 157 M

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

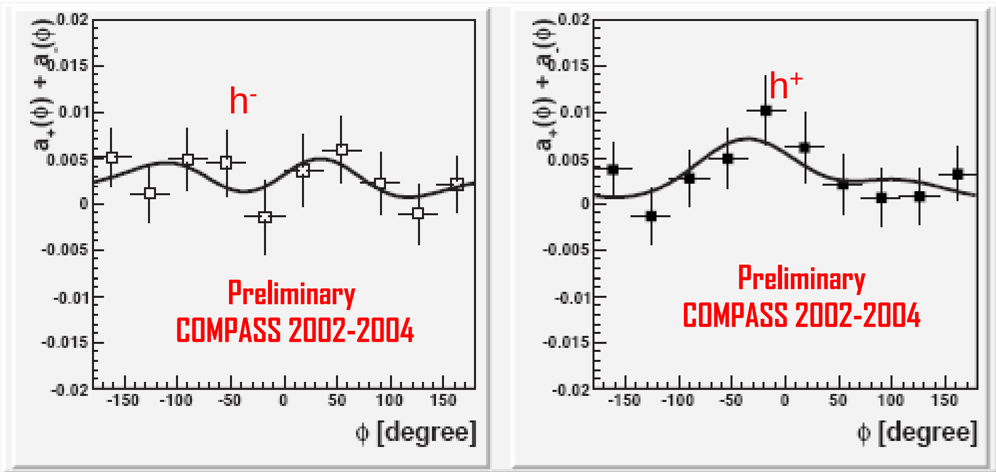
Each track should:

- 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

RESULTS (1)

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



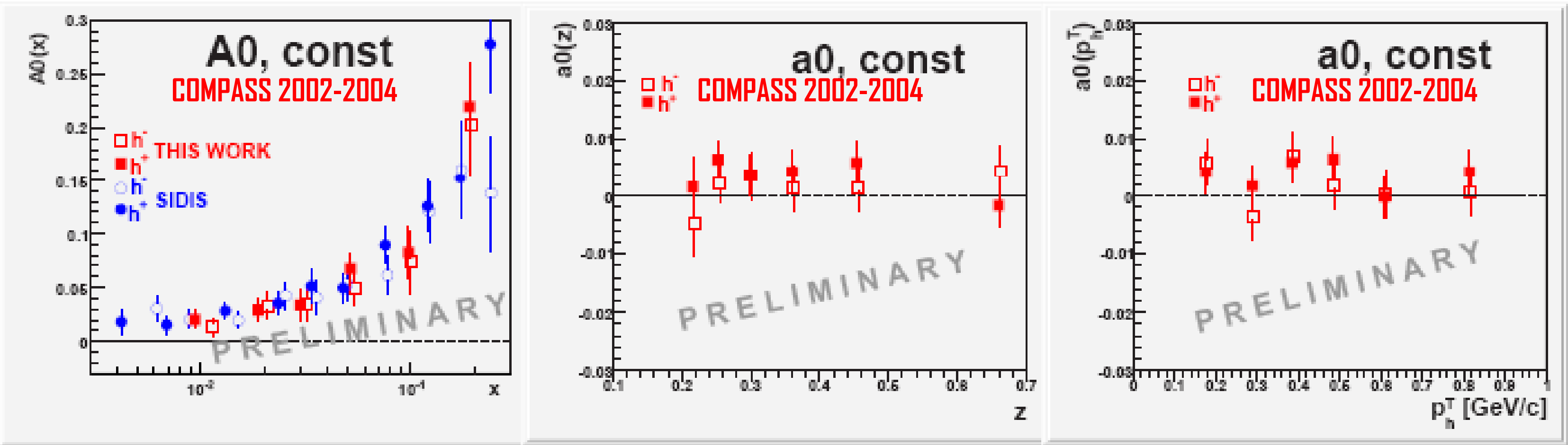
where solid lines are fit functions $a_+ + a_- = a_0 + a_1 \sin(\phi) + a_2 \sin(2\phi) + a_3 \sin(3\phi) + a_4 \cos(\phi)$.

—Within a stat. precision of about 0.15%, parameters a_1-a_4 are compatible with zero; fits by constants: Chsq/DF=4.8/9(h^-) and 8.0/9(h^+),
—parameters a_0 are different from zero and about equal for h^+ and h^-.

REMIND: $a_0 \propto d\sigma_{LL} \propto x g_{1L}(x) \oplus D_1(z)$, where g_{1L} is a helicity PDF of L-polarized quarks in L-polarized target

RESULTS (2)

Dependence of the AA parameter a_0 for h^+ and h^- on kinematical variables:



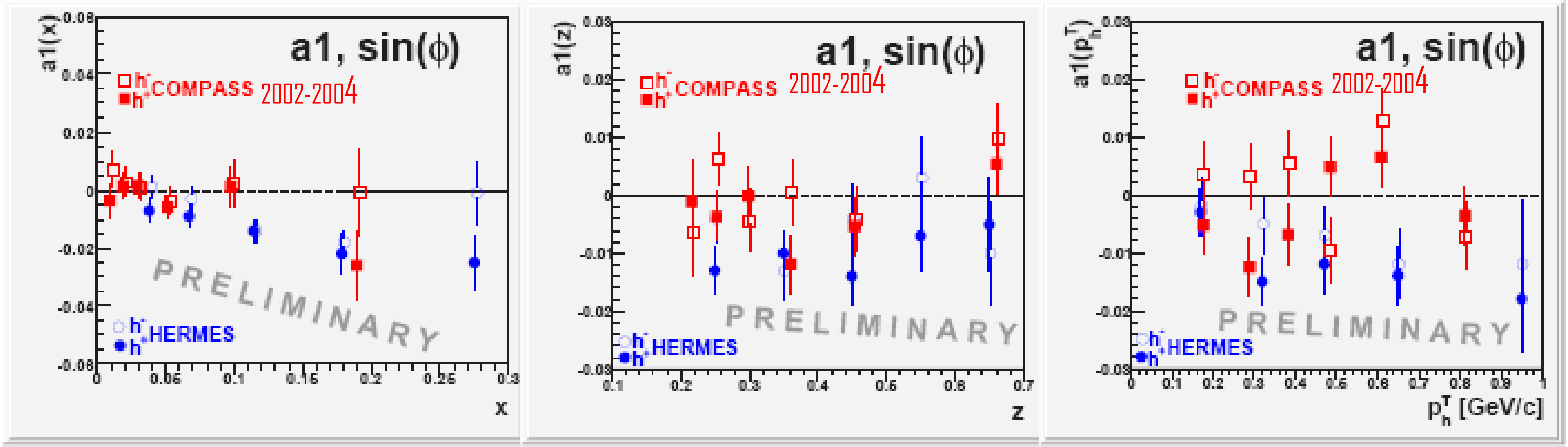
— $A_0(x) = a_0(x)/D_0 \equiv A_d^h$ (D_0 is a virtual photon depolarization factor) is in agreement with COMPASS published data (PLB660(2008)458),

— $a_0(z, p_h^T)$ for h^- and for h^+: small and flat.

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

RESULTS (3)

Dependence of the AA parameter a_1 for h^+ and h^- on kinematic variables:



— $a_1(x)$ are less pronounced than the HERMES ones,

— $a_1(p_h^T)$ is flat and do not confirm the HERMES trends.

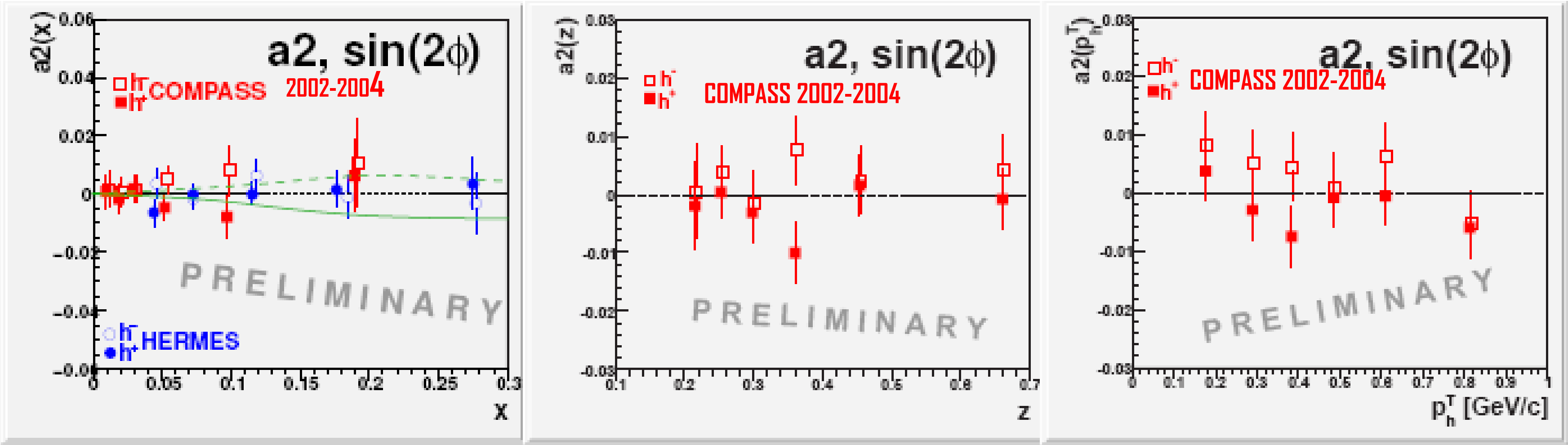
REMIND: $a_1 \propto d\sigma_d \propto \frac{M}{Q} x^2 \left(h_L(x) \oplus H_1^{\perp}(z) + f_L^{\perp}(x) \oplus D_1(z) \right)$

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

NOTE: HERMES data are for identified π^+ and π^- and smaller $<Q^2>$.

RESULTS (4)

Dependence of the AA parameter a_2 for h^+ and h^- on kinematic variables:



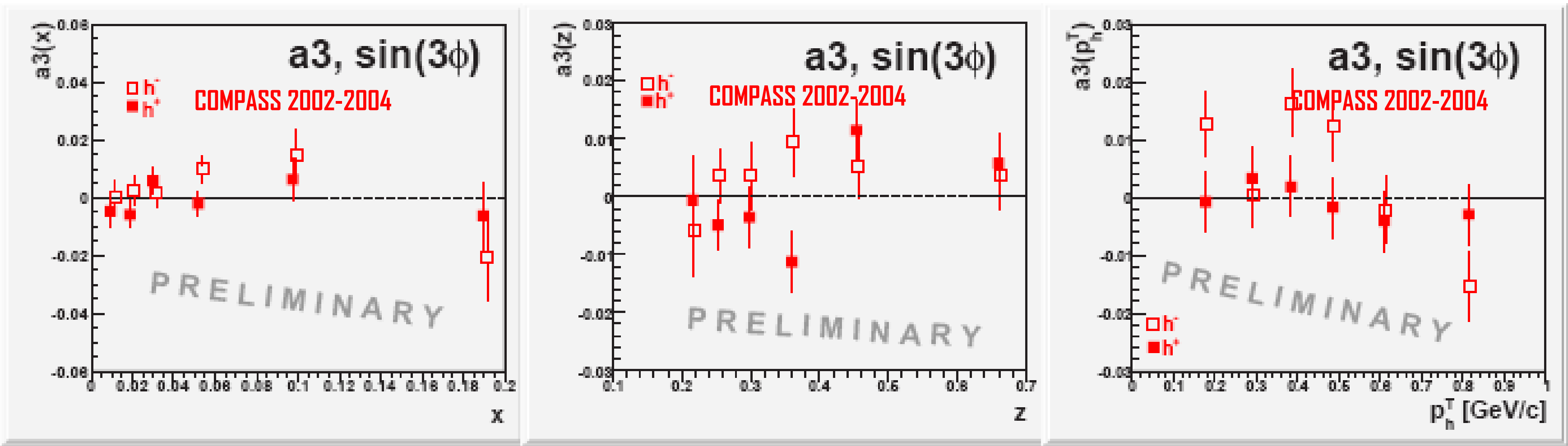
— $a_2(x)$ are small and in general agree with HERMES and theoretical predictions by H.Avakian et al., Phys.Rev. D77 (2008),

— $a_2\left(z, p_h^T\right)$ - no other data.

REMIND: $a_2 \propto d\sigma_{0L} \propto x h_{1L}^{\perp}(x) \oplus H_1^{\perp}(z)$, where $h_{1L}^{\perp}$ is a PDF not seen yet.

RESULTS (5)

Dependence of the AA parameter a_3 for h^+ and h^- on kinematic variables:

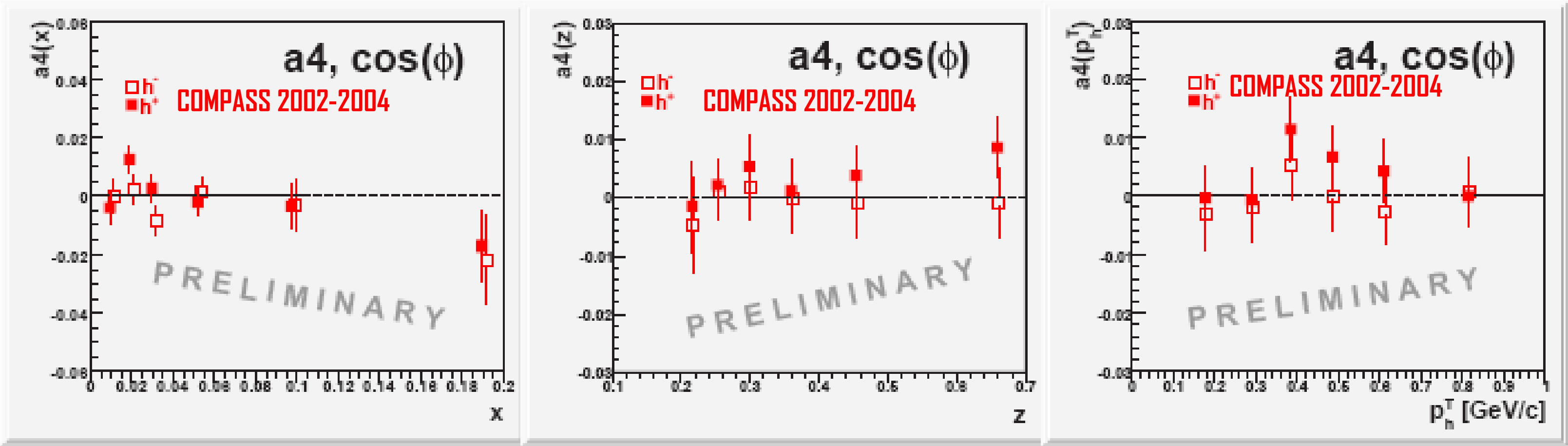


— a_3 are small, compatible with zero.

REMIND: $a_3 \propto d\sigma_{0T} \propto x h_{1T}^{\perp} \oplus H_1^{\perp}(z)$, where $h_{1T}^{\perp}$ is pretzelosity PDF ,additionally suppressed by $\sin\theta_\gamma \sim \frac{M}{Q}$.

RESULTS (6)

Dependence of the AA parameter a_4 for h^+ and h^- on kinematic variables:



— $a_4(x)$ increasing with x in absolute value,

— $a_4(z)$ and $a_4\left(p_h^T\right)$ small, flat and consistent with zero,

—$a_4(x, z, p_h)$ are studied for the first time.

REMIND: $a_4 \propto d\sigma_{LL} \propto \frac{M}{Q} x^2 \left(g_L^{\perp}(x) \oplus D_1(z)_4 + \ldots\right)$, where $g_L^{\perp}$ is a pure twist-3 PDF (analog to the Cahn effect in unpolarized SIDIS).

RESULTS (1)-(6) DO NOT DEPEND ON Z-CUT (0.05 or 0.2).

CONCLUSIONS & PROSPECTS (1)

1. The azimuthal asymmetries (AA) in the h^- and h^+ production on L-polarized target are observed and parameterized with sin (ϕ), sin (2ϕ), sin (3ϕ) and cos(ϕ). For the AA integrated over-all-kinematical-variables , these amplitudes are consistent with zero within errors.

2. The behaviour of the AA parameters are studied in the available region of kinematical variables which have shown that:
   - the constant term of the AA parameterization, $A_0(x)$, is in good agreement with the COMPASS data on $A_d^{h\pm}$;
   - the values of the sin (ϕ) parameter $a_1(x, z, p_h^T)$ are small and in general do not contradict to the HERMES data, if one takes into account the difference in Q^2 between the two experiments;
   - the values of the sin (2ϕ) parameter $a_2(x, z, p_h^T)$, sin (3ϕ) parameter $a_3(x, z, p_h^T)$ and cos(ϕ) parameter $a_4(x, z, p_h^T)$ are consistent with zero.

THE REPORTED DATA ARE PRELIMINARY.

NEW DATA of 2006 on D and
NEW DATA of 2007 on H ,
obtained with 3-cells target (smaller systematics) will be added

BACK UP SLIDES (1)

PDF & FF APPEARING 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 trms entering the cross section with a factor M/Q and having no clear physical interpretation.

BACK UP SLIDES (2)

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

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

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:

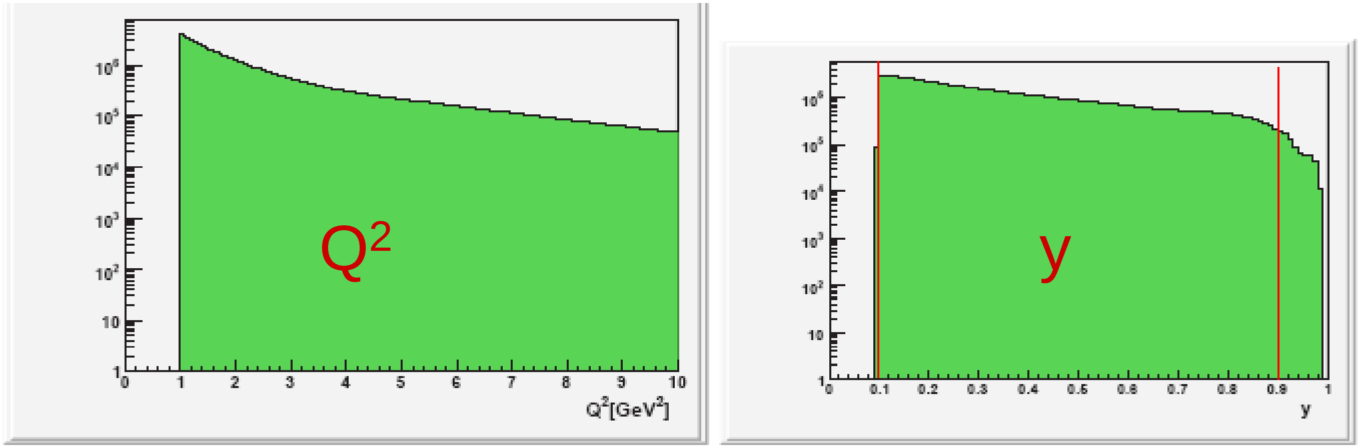
spin of the target	$\vec{S}$,	with a fraction	p_s	physics asym.
spin of the muon	$\vec{\mu}$,	"	p_μ	
target magnetic field	$\vec{H}$,	"	p_H	false asym., due to incomplete knowledge of $\vec{H}$ and/or misalignments
product	$(\vec{H} \times \vec{\mu})$,	"	$p_{H\mu}$	
product	$(\vec{H} \times \vec{S})$,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

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

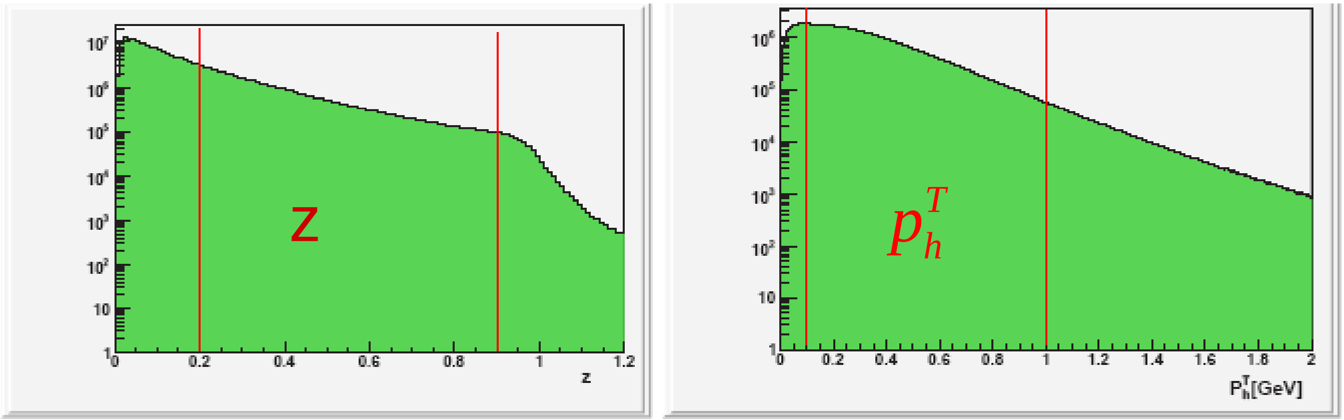
- directions of the field,
- track extrapolations,
- sign of particles.

} different for U and D cells.

BACK UP SLIDES (3)



The distributions of events, passed all data selection cuts, vs. Q^2 (left) and vs. y (right). Cuts are shown by red lines.



The distributions of identified good charged hadrons vs. z (left) and vs. p_h^T (right).

BACK UP SLIDES (4)

x bins	z bins	p_h^T 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