Measurement of Transversity+friend in SIDIS

Delia Hasch

INFN Frascati

RHIC – Spin physics seminar

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outline

Introduction

→ Transversity+friends : Theory see Mauro's talk yesterday!

case: SIDIS

Experiments:

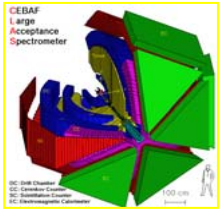
Details of extraction:

→ acceptance effects

→ VM contributions

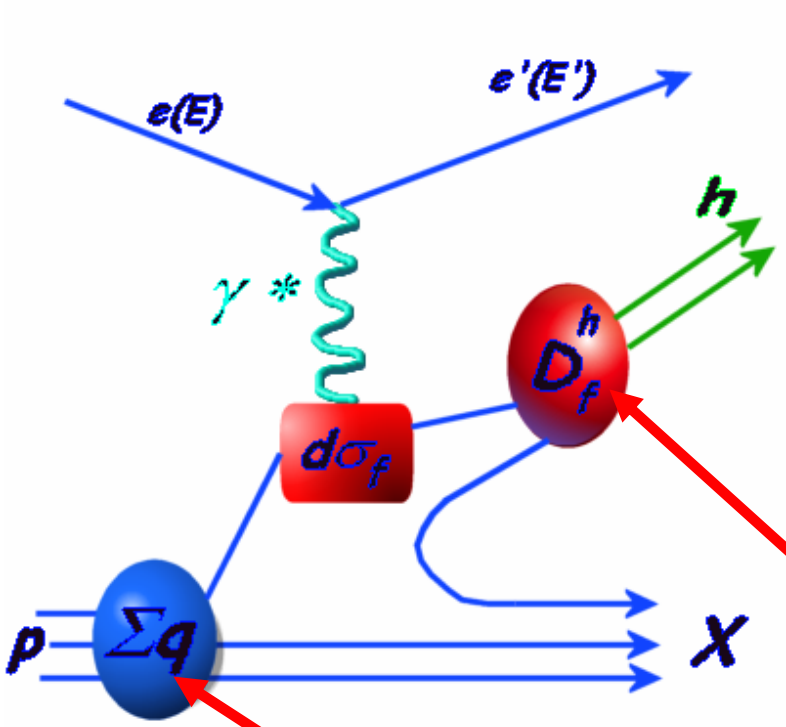
→ DF extraction

CLAS



,Hall A

polarised semi-inclusive DIS



$$e^{(\rightarrow)}\, p^{(\uparrow,\rightarrow)} \rightarrow e'\, h\, X$$

Q^2 ...hard scale

probability that struck quark of flavour *f* fragments into hadron of type *h* with energy fraction z

distribution function

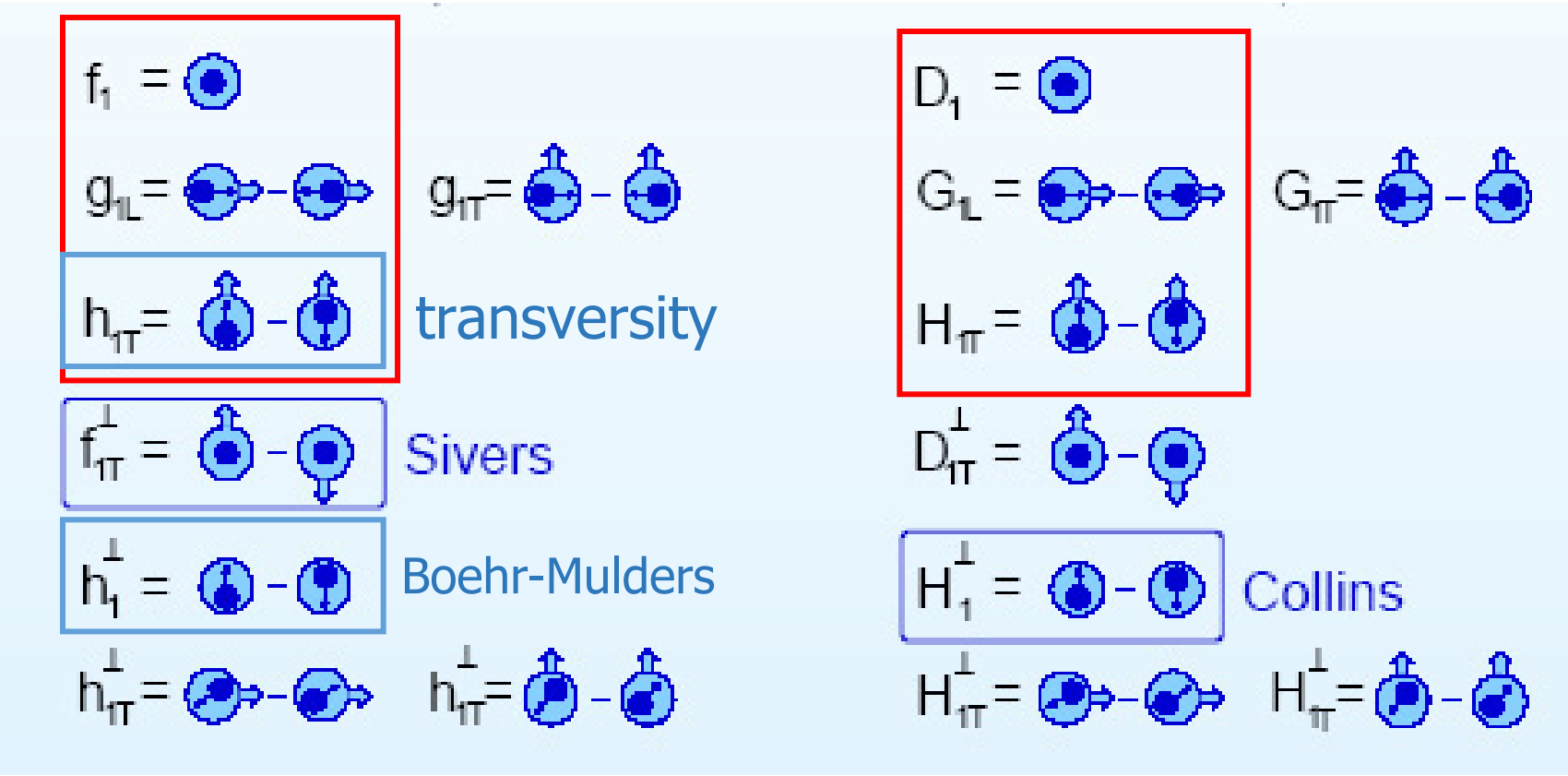
fragmentation function

$$d\sigma^{h}(z) \propto \sum_f q_f^{H\rightarrow q}(x) \otimes d\sigma_f^{q\rightarrow q} \otimes D_f^{q\rightarrow h}(z)$$

, $z=E_h/\nu$

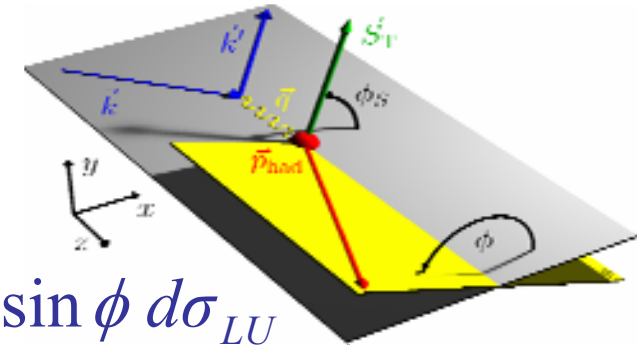
generalised (unintegrated) DF+FF

at leading twist: 8 functions:



functions surviving on integration over transverse momentum

sidis cross section



$$d\sigma = d\sigma_{UU} + \cos 2\phi\, d\sigma_{UU} + \frac{1}{Q}\cos\phi\, d\sigma_{UU} + \lambda \frac{1}{Q}\sin\phi\, d\sigma_{LU}$$

f_1 $\quad h_1^{\perp} \otimes H_1^{\perp}$ $\quad e \otimes H_1^{\perp} + \ldots$

$$+ S_L\left[\sin 2\phi\, d\sigma_{UL} + \frac{1}{Q}\sin\phi\, d\sigma_{UL}\right] + \lambda S_L\left[d\sigma_{LL} + \frac{1}{Q}\cos\phi\, d\sigma_{LL}\right]$$

$h_{1L}^{\perp} \otimes H_1^{\perp}$ $\quad h_L \otimes H_1^{\perp}$ $\quad g_1$

$$+ S_T\left[\sin(\phi+\phi_S)d\sigma_{UT} + \sin(\phi-\phi_S)d\sigma_{UT} + \sin(3\phi-\phi_S)d\sigma_{UT} + \frac{1}{Q}\ldots\right]$$

$h_1 \otimes H_1^{\perp}$ $\quad f_{1T}^{\perp} \otimes D_1$

$$+ \lambda S_T\left[\cos(\phi-\phi_S) + \frac{1}{Q}\ldots\right] + \ldots.$$

σ_{LT}

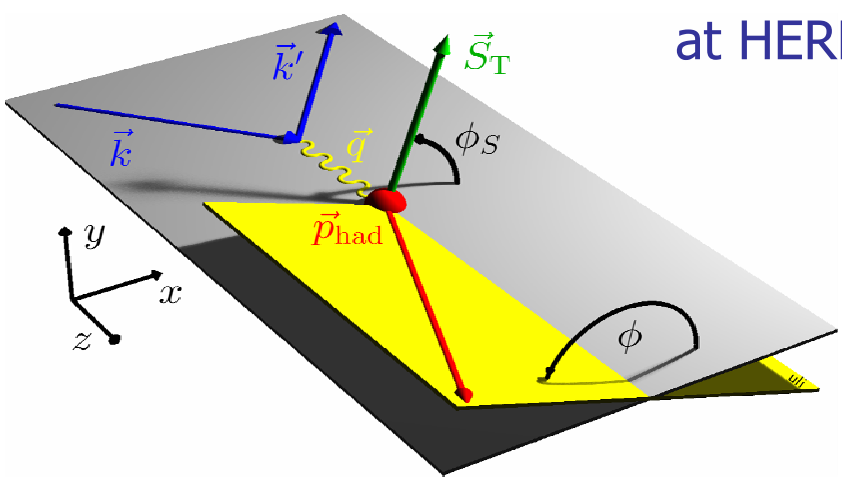
beam $\quad$ target polarisation

mixing of azimuthal moments

experiment: target polarisation w.r.t. beam direction (l)
theory: polarisation w.r.t. virtual photon direction (q)

[Diehl, Sapeter EPJC41(2005)]

$$\begin{pmatrix} \langle \sin\phi \rangle^{l}_{UL} \\ \langle \sin(\phi-\phi_S) \rangle^{l}_{UT} \\ \langle \sin(\phi+\phi_S) \rangle^{l}_{UT} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\ \frac{1}{2}\sin\theta_{\gamma^*} & \cos\theta_{\gamma^*} & 0 \\ \frac{1}{2}\sin\theta_{\gamma^*} & 0 & \cos\theta_{\gamma^*} \end{pmatrix} \begin{pmatrix} \langle \sin\phi \rangle^{q}_{UL} \\ \langle \sin(\phi-\phi_S) \rangle^{q}_{UT} \\ \langle \sin(\phi+\phi_S) \rangle^{q}_{UT} \end{pmatrix}$$



at HERMES energies: $\cos\theta_{\gamma^*} \cong 1$, $\sin\theta_{\gamma^*}$ up to 15%

mixing of azimuthal moments

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at HERMES energies: $\cos\theta_{\gamma*} \cong 1$, $\sin\theta_{\gamma*}$ up to 15%

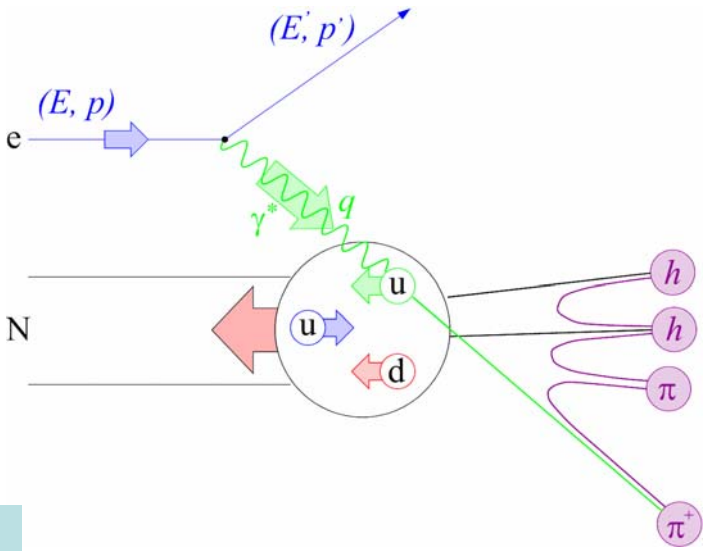
$$\langle \sin(\phi\pm\phi_S) \rangle^{q}_{UT} \simeq \langle \sin(\phi\pm\phi_S) \rangle^{l}_{UT} - \frac{1}{2}\underbrace{\sin\theta_{\gamma^*}\left(\langle \sin\phi \rangle^{l}_{UL}\right)}_{\text{max. 0.4\% absolute}} + \underbrace{\tan\theta_{\gamma^*}\langle \sin(\phi\mp\phi_S) \rangle^{l}_{UT}}_{\text{max. 1\% relative}}$$

prerequisites

HERMES:
27.5 GeV $\vec{e}^{+/-}$

Compass:
100-190 GeV $\vec{\mu}^{+}$

Jlab: HallA,B
up to 6 GeV $\vec{e}^{-}$



→ good hadron identification

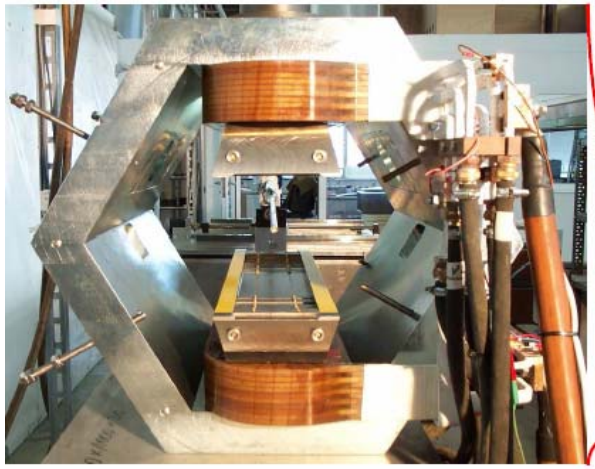
HERMES: $\vec{d}$, $\vec{p}\uparrow$

Compass: $\vec{d}\uparrow$, $\vec{p}\uparrow$

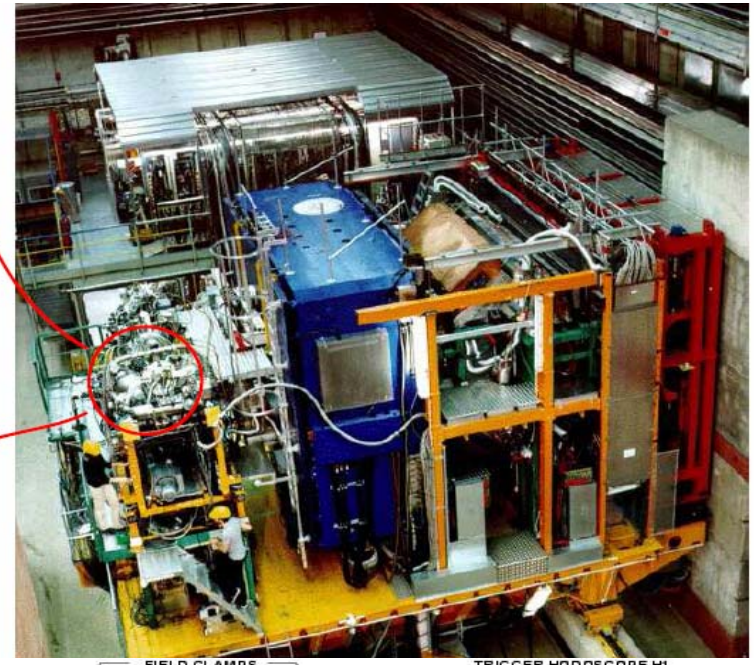
Hall A,B: $\vec{p}$, $n\uparrow$

→ full phi coverage!!

e.g. HERMES

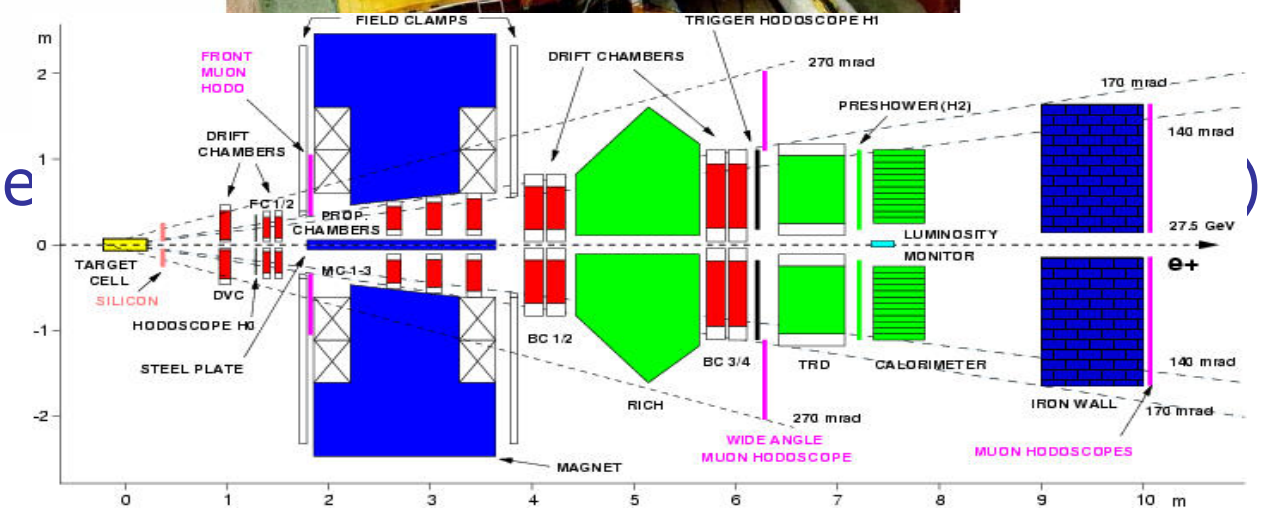


0.3T transverse holding field



→forward spectrome)

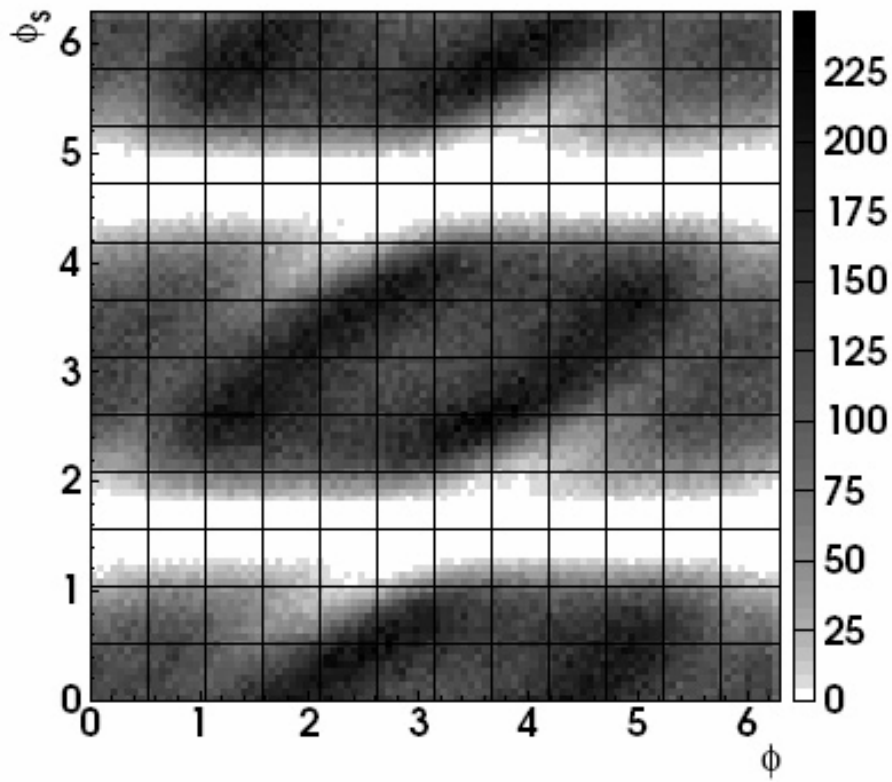
→split in two halfs

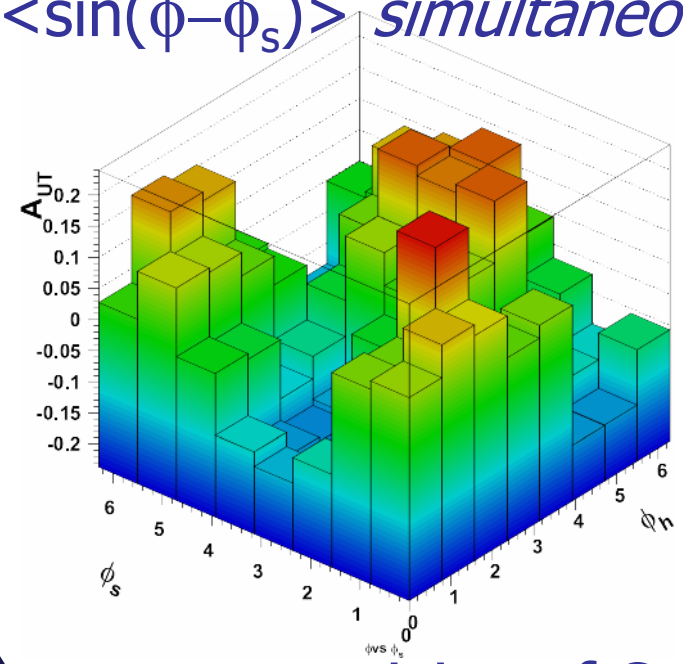


acceptance coverage in ϕ and ϕ_s

→ good acceptance in ϕ and ϕ_s, though not perfect

→ fit amplitudes $<\sin(\phi+\phi_s)>$ and $<\sin(\phi-\phi_s)>$ *simultaneously*





prevents mixing of Collins + Sivers via acceptance!

extraction method: MC tests

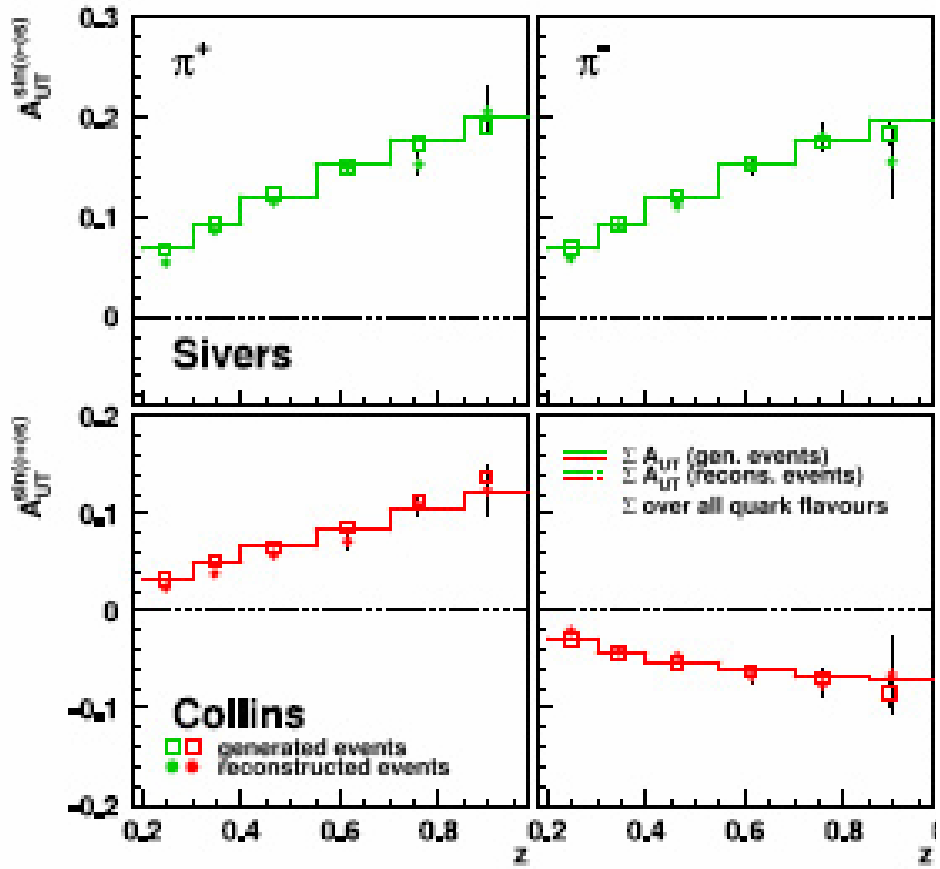
→ generate Collins + Sivers asymmetries (gaussian ansatz in p_T^2)

→ analyse MC like data…

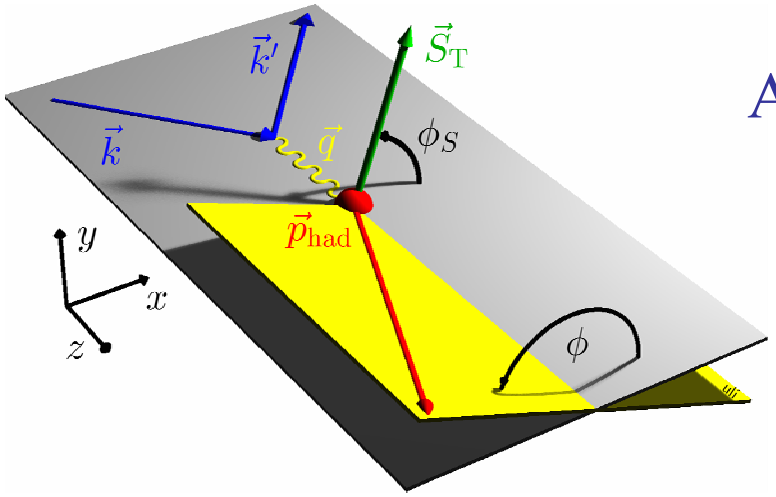
➡

extraction method robust to effects of:

- → acceptance+detector smearing
- → QED radiative effects
- → target holding field
- → Collins-Sivers cross contaminations



asymmetries and moments



$$A_{UT}^{h}(\phi,\phi_S) = \frac{1}{|S_T|}\frac{N_h^{\uparrow}(\phi,\phi_S) - N_h^{\downarrow}(\phi,\phi_S)}{N_h^{\uparrow}(\phi,\phi_S) + N_h^{\downarrow}(\phi,\phi_S)} =$$

$$= A_{UT}^{\text{Collins}}\sin(\phi+\phi_S) + A_{UT}^{\text{Sivers}}\sin(\phi-\phi_S)$$

$$+ A_{UT}\sin(2\phi-\phi_S) + A_{UT}\sin(\phi_S) + C$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2 \cdot I\left[\frac{k_T P_{h\perp}}{M_h} h_1^q(x,p_T^2)\cdot H_1^{\perp q}(z,k_T^2)\right]$$

$$+\sin(\phi-\phi_S)\sum_q e_q^2 \cdot I\left[\frac{p_T P_{h\perp}}{M} f_{1T}^{\perp q}(x,p_T^2)\cdot D_1^q(z,k_T^2)\right]$$

$I[\ldots]$ → convolution integral over initial (p_T) and final (k_T) quark transverse momenta

solving the convolution integral

weighted asymmetries:

$$A_{UT}^{h}(\phi,\phi_S) = \frac{1}{|S_T|}\frac{\sum_{i=1}^{N\uparrow} P_{h\perp,i} - \sum_{i=1}^{N\downarrow} P_{h\perp,i}}{N_h^{\uparrow} + N_h^{\downarrow}}$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2\, h_1^q(x)\, z\, H_1^{\perp(1),q}(z)$$

$$+\sin(\phi-\phi_S)\sum_q e_q^2\, f_{1T}^{\perp(1),q}(x)\, z\, D_1^q(z)$$

$$A_{UT}^{h}(\phi,\phi_S) = M_h\, A_{UT}^{Collins}\sin(\phi+\phi_S) + M_p\, A_{UT}^{Sivers}\sin(\phi-\phi_S) + \ldots$$

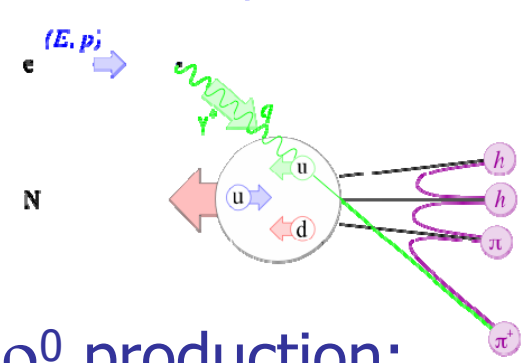
→ acceptance effects not yet under control ☹

➡ *gaussian ansatz* (model dependent)

interpretative uncertainty from exclusive VM

wanted: SIDIS process

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

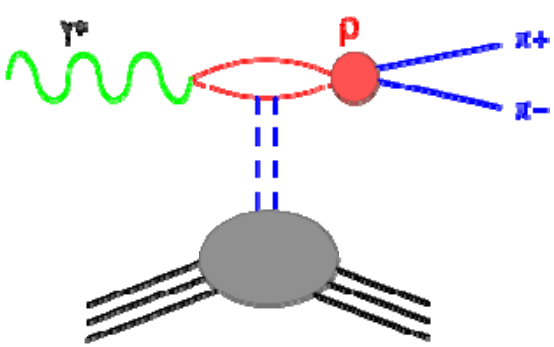


exclusive ρ^0 production:

different physics…

$$e\,p^{\uparrow} \rightarrow e'\rho^0 p$$

$$\hookrightarrow \pi^+\pi^-$$



one of the π escapes…

interpretative uncertainty from exclusive VM

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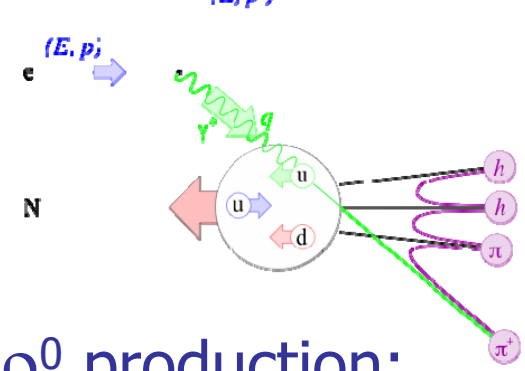

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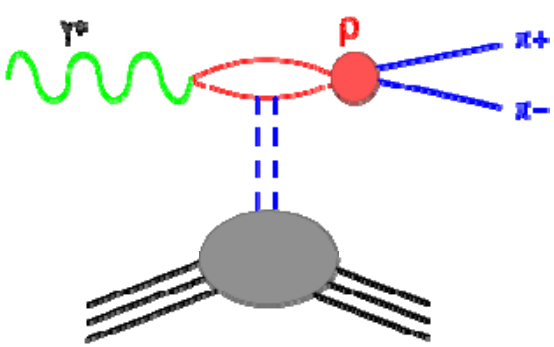
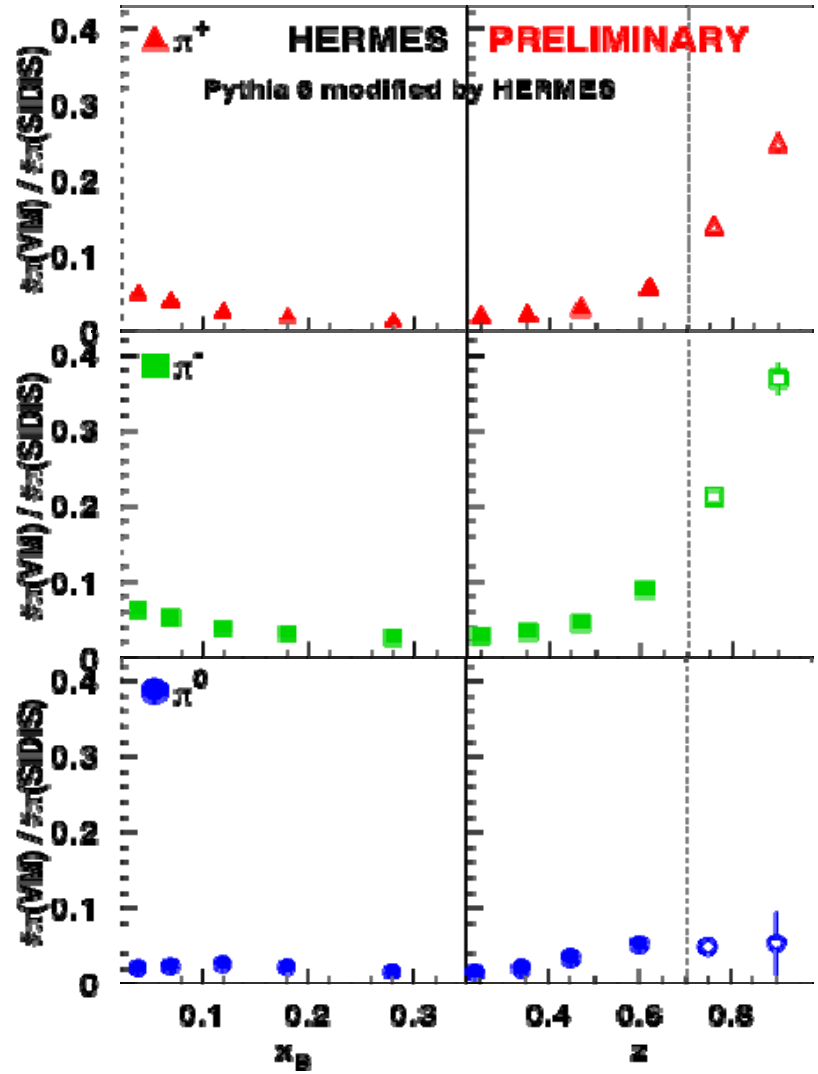




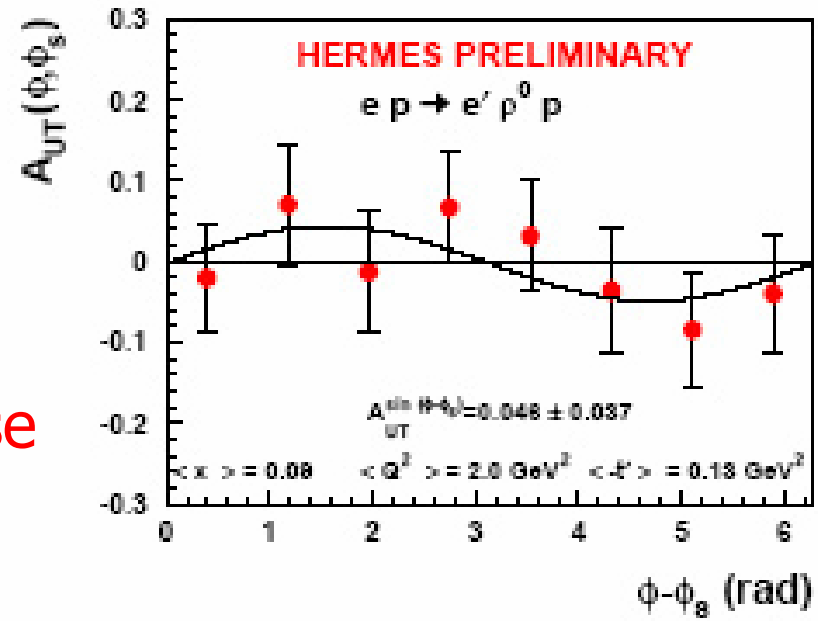
interpretative uncertainty from exclusive VM

→ transfer coefficients

from MC

→ decay angular distributions

spin density matrix for transverse target *NEEDED*



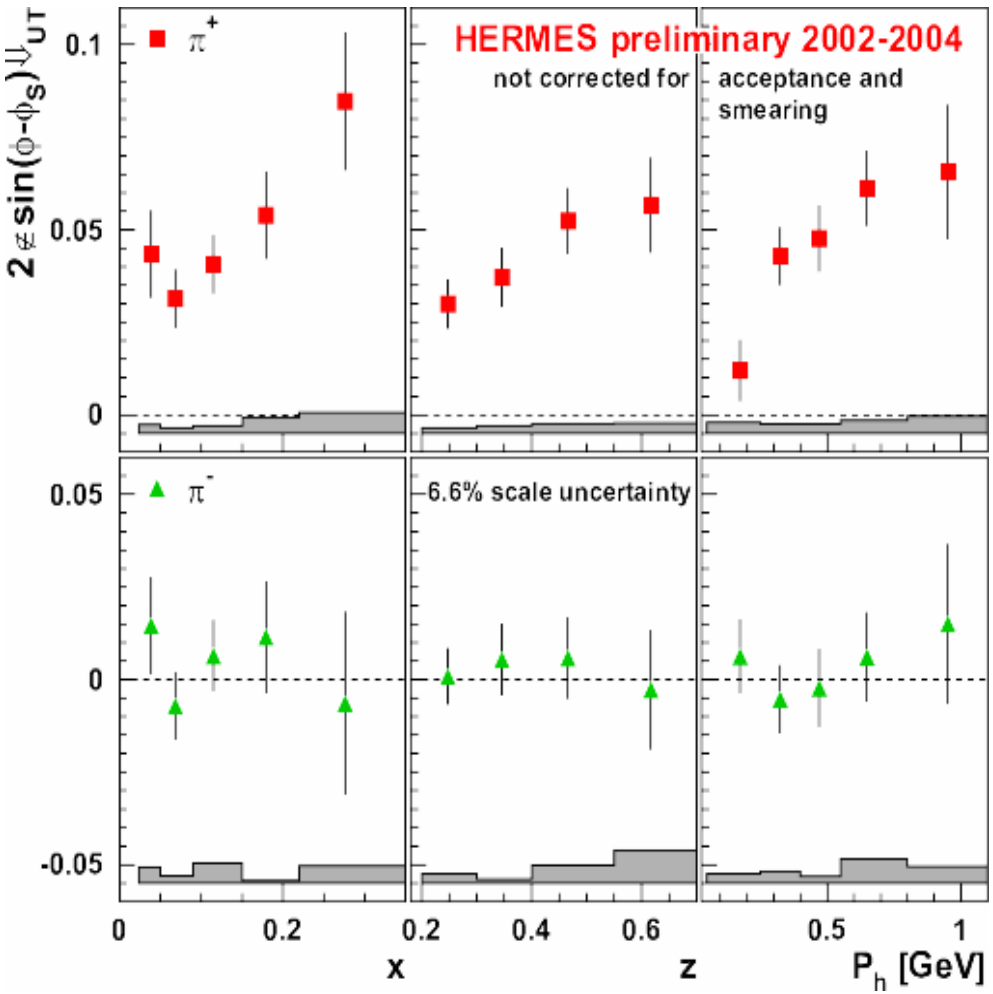
a CHECK:

→ difference ($\pi^+ - \pi^-$) asymmetries significantly *non-zero!*

however: NO agreement if processes should be excluded…

Sivers asymmetries 2002-2004

$$A_{siv}(\phi-\phi_S) \propto f_{1T}^{\perp}(x) D_1(z)$$



- significantly positive π^+ asymmetry

→ requires non-zero orbital angular momentum

→ first hint of naïve T-odd DF from DIS

→ test of universality:

$$f_{1T}^{\perp}(x)_{DIS} = -f_{1T}^{\perp}(x)_{DY}$$

- D_1 known → Sivers DF can be extracted

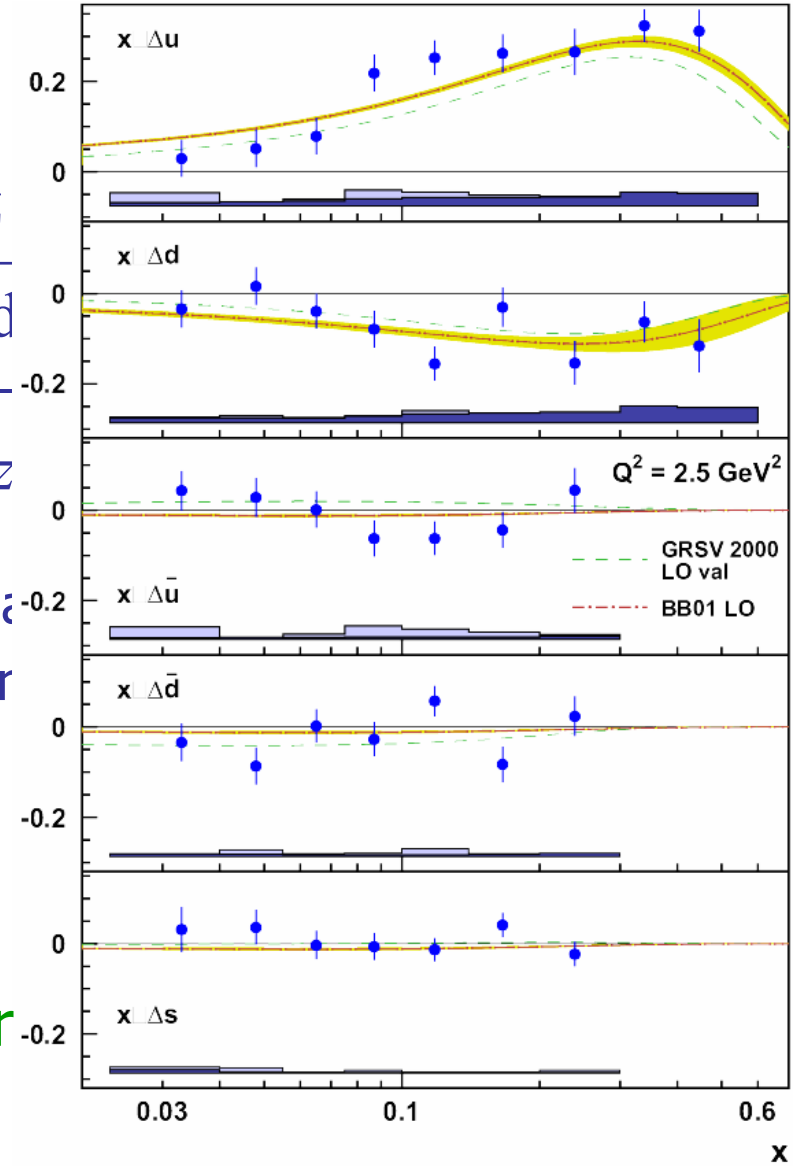
extracting quark distributions

purity formalism:

$$A_{UT}^{\sin(\phi-\phi_S)} \approx \sum_q \frac{e_q^2\, q\ (x) \int dz}{\underbrace{\sum_{q'} e_{q'}^2 q'(x) \int d}_{P_q^h(x,z}}$$

... from a

hadron r



e.g.: extraction of quark helicity distributions: first *direct* 5-flavour separation

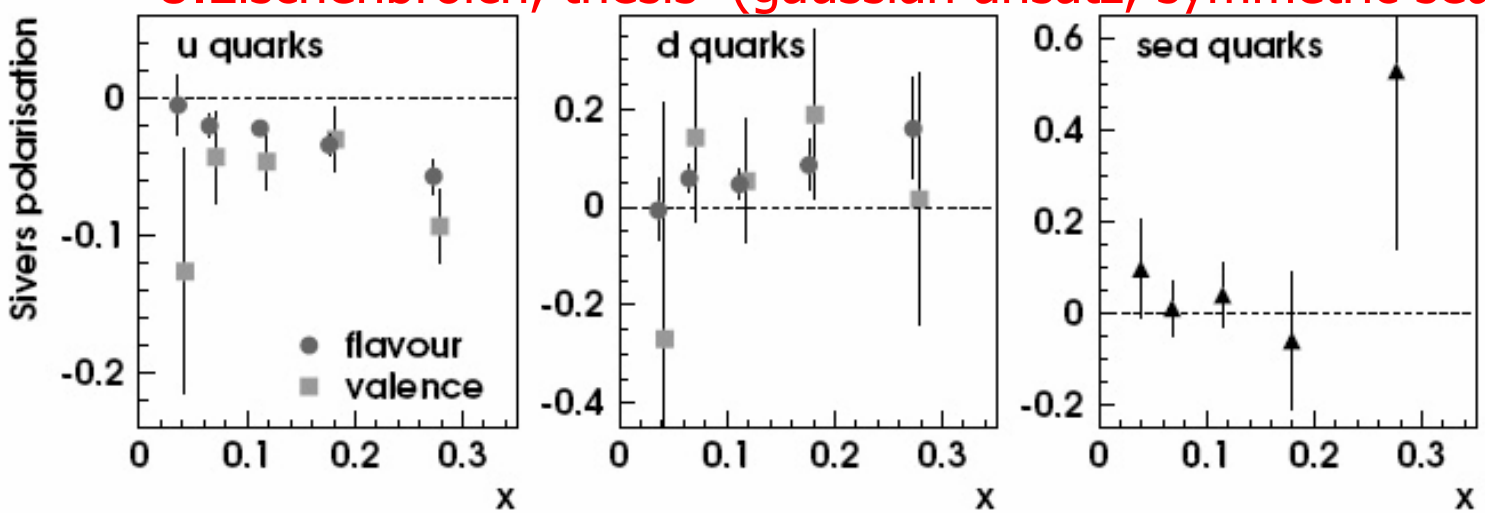
extracting quark distributions

purity formalism:

$$A_{UT}^{\sin(\phi-\phi_S)} \approx \sum_q \underbrace{\frac{e_q^2\, q(x) \int dz\, D_q^h(z)}{\sum_{q'} e_{q'}^2 q'(x) \int dz\, D_{q'}^h(z)}}_{P_q^h(x,z)} \cdot \frac{f_{1T}^{\perp(1),q}(x)}{q(x)}$$

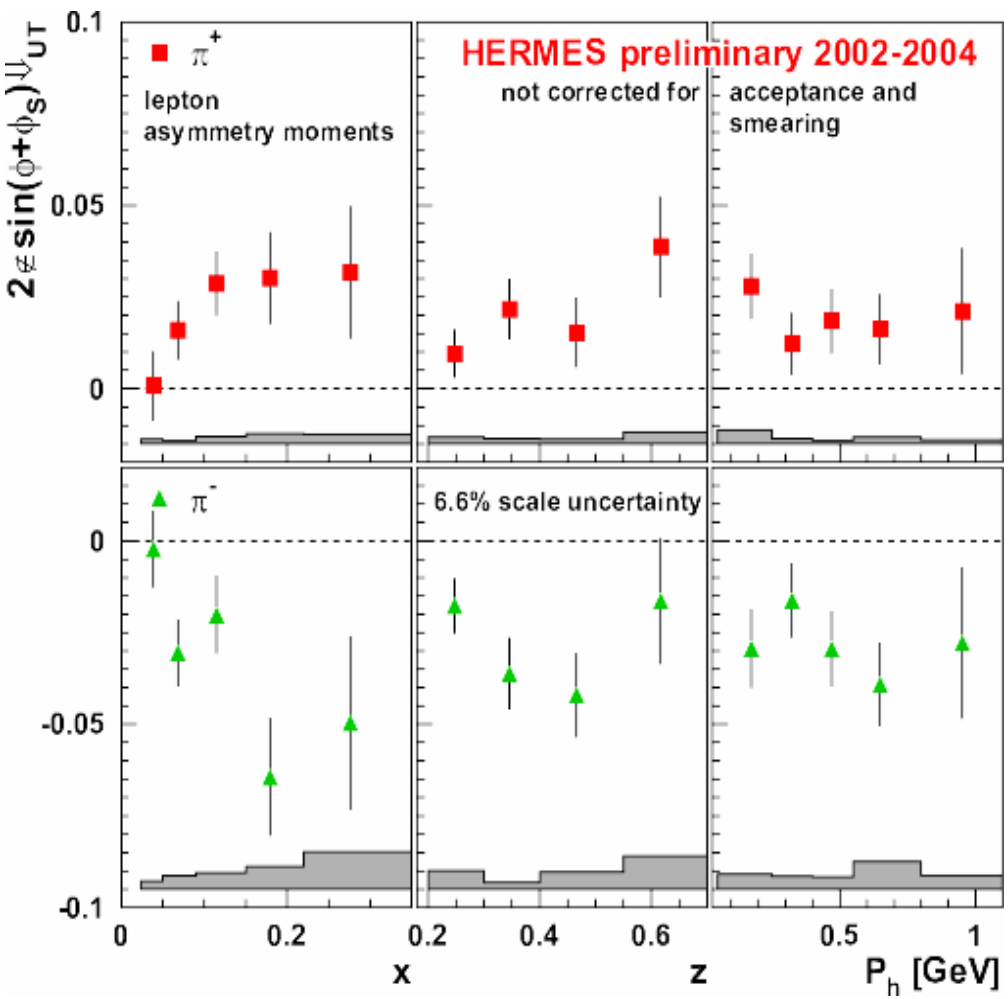
Sivers:

U.Elschenbroich, thesis (gaussian ansatz, symmetric sea)



Collins asymmetries 2002-2004

$$A_{\text{coll}}(\phi+\phi_S) \propto h_1(x)H_1^{\perp}(z)$$



- positive π^+ and negative π^- asymmetries ... as maybe expected:

  ($\Delta u>0 \rightarrow \delta u>0$
  $\Delta d<0 \rightarrow \delta d<0$)

- *unexpected large* π^-
  → role of *unfavoured* fragmentation function?

$$H_1^{\perp}(z)_{unfav.} \approx -H_1^{\perp}(z)_{fav.}$$

→ $H_1^{\perp}(z)$ *NEEDED!*

BELLE ☺

why are π^- Collins asymm. so large?

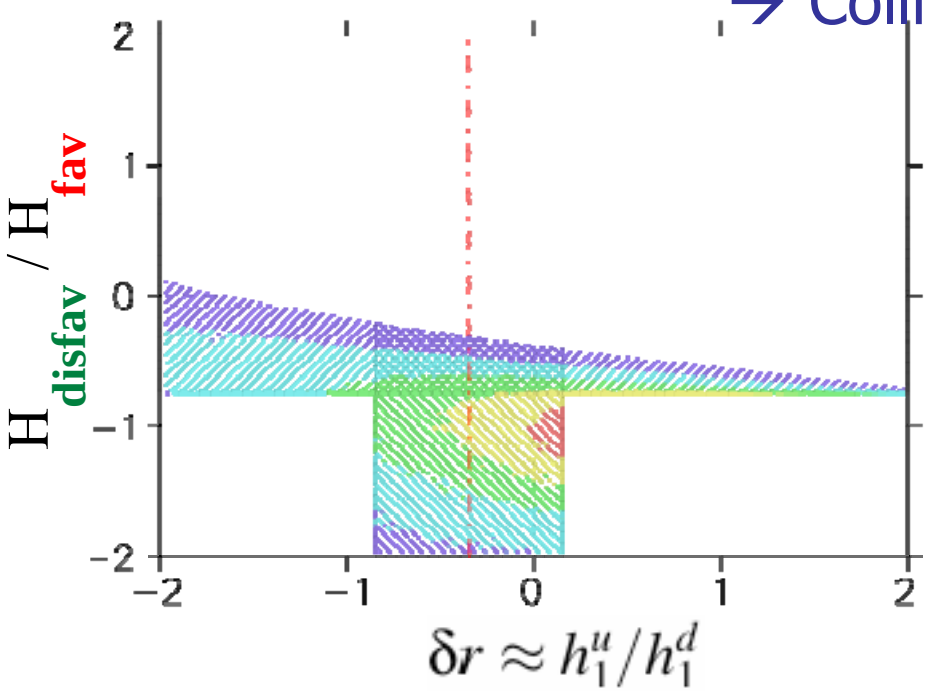
DIS on p target always dominated by *u-quark scattering*

→ $A_{\mathrm{Coll}}^{\pi+} \sim h_1^{\mathrm{u}} H_{1,\mathrm{favoured}}^{\perp}$ ... expected: positive

→ $A_{\mathrm{Coll}}^{\pi-} \sim h_1^{\mathrm{u}} H_{1,\mathrm{disfav}}^{\perp}$ ... expected: ~zero

minimal assumptions: → A_{UT} is leading twist

→ CollinsFF obeys *fav/disfav* symmetry



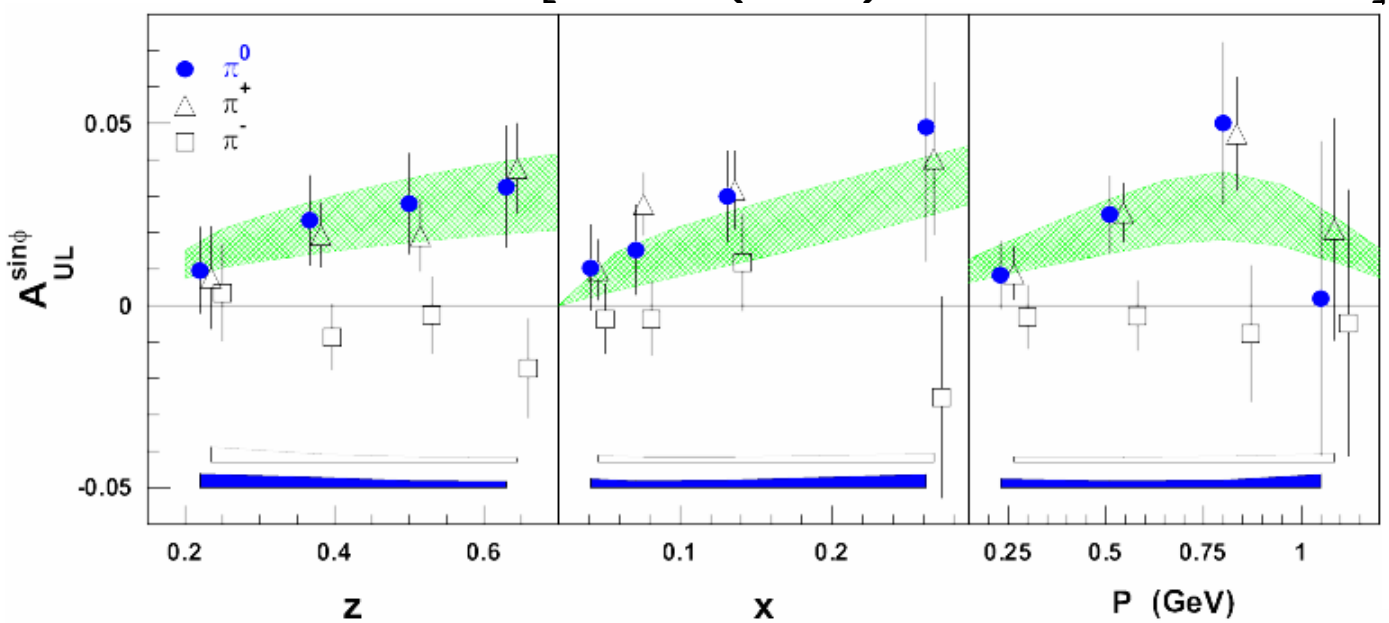
map out solution space:

$H_{\mathrm{disfav}} \approx - H_{\mathrm{fav}}$

revisiting the longitudinal target SSA

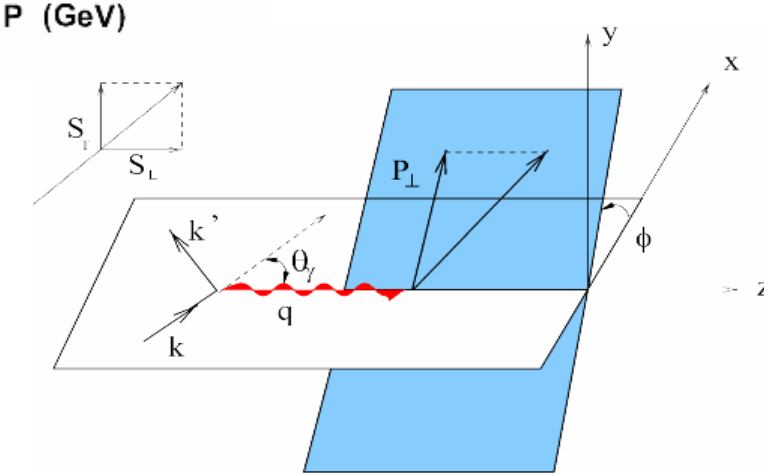
revisiting the longitudinal target SSA

[PRL 84 (2000) 4047 : 160 citations !]



→ interpreted in terms of arising from transv. Component

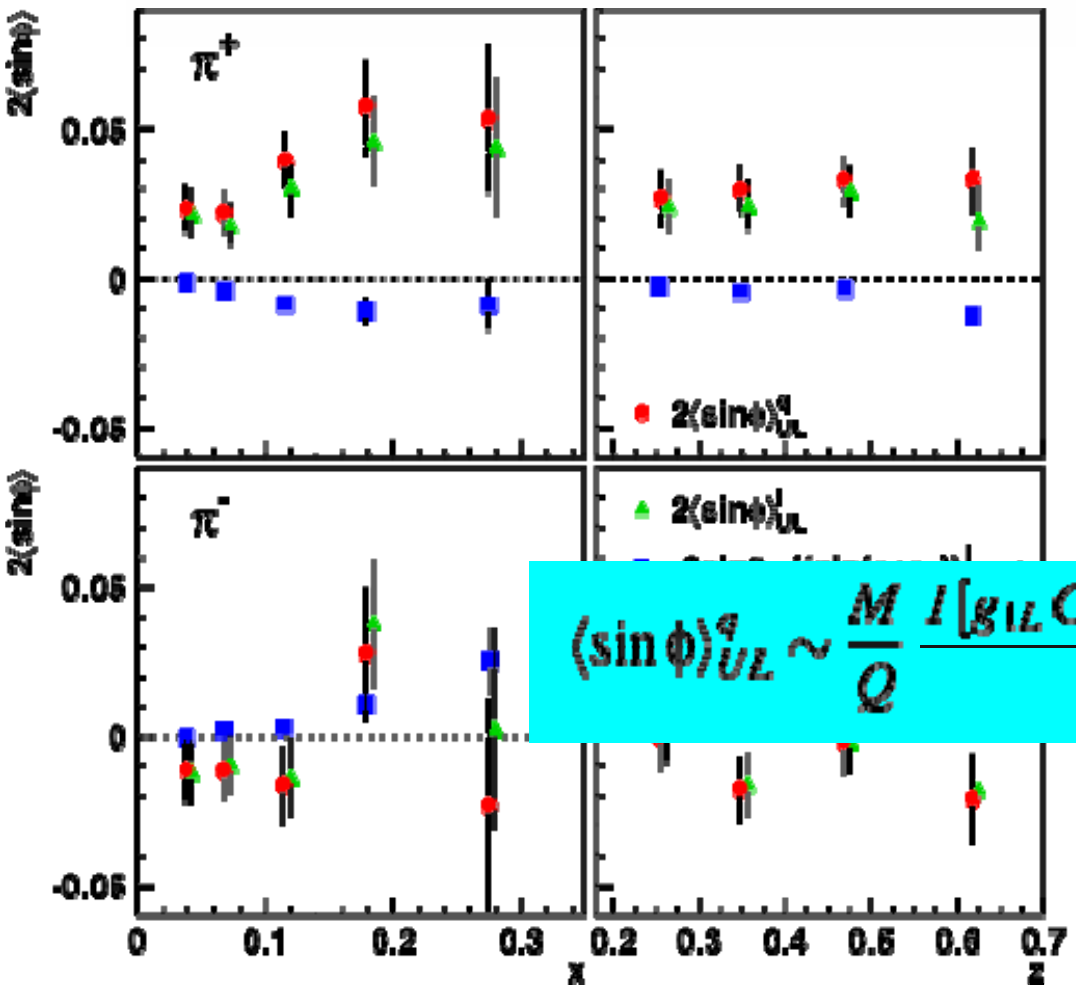
(tw-3 contributions essentially neglected)



→ subtract A_{UT} part from A_{UL} to obtain pure A_{UL} moments:

revisiting the longitudinal target SSA

$$\left\langle \sin\phi \right\rangle^{q}_{UL} = \left\langle \sin\phi \right\rangle^{l}_{UL} + \sin\theta_{\gamma^*}\left(\left\langle \sin(\phi+\phi_S) \right\rangle^{l}_{UT} + \left\langle \sin(\phi-\phi_S) \right\rangle^{l}_{UT} \right)$$



→ A_{UL} is almost-entirely longitudinal (i.e. tw-3)

→ recent, more complete theoret. analysis:

$$\langle \sin\phi \rangle^{q}_{UL} \sim \frac{M}{Q} \frac{l\left[g_{1L} G^{\perp} \oplus h_L H_1^{\perp} \oplus h_{1L}^{\perp} \tilde{H} \oplus f_L^{\perp} D_1\right]}{f_1 D_1}$$

...theoretical revisit needed!

2hadron asymmetries

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

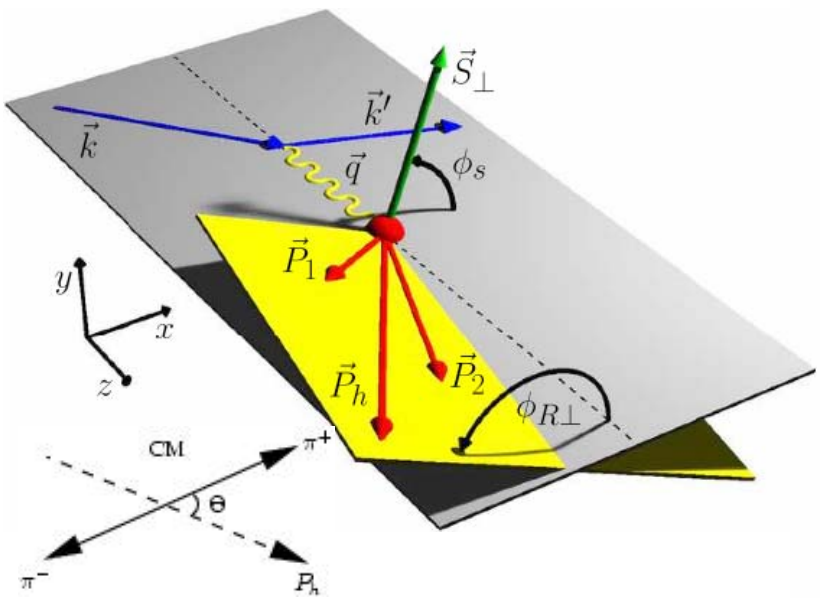
interference fragmentation function

interference arises from different partial waves of $\pi^+\pi^-$ system

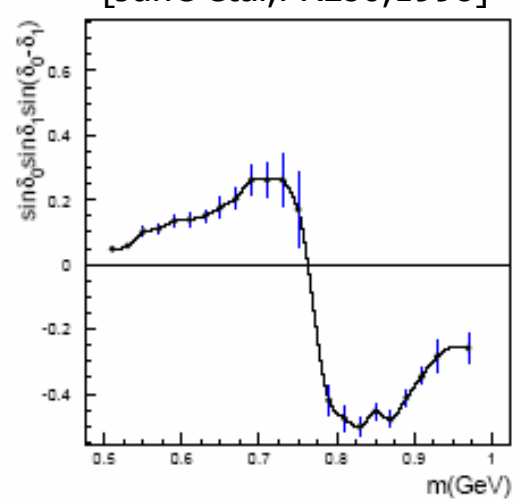
→!collinear factorisation! ← relativ. momentum: $R=(P_{\pi+}+P_{\pi-})/2$

can have transv. component even when integrating over P_T of the pair

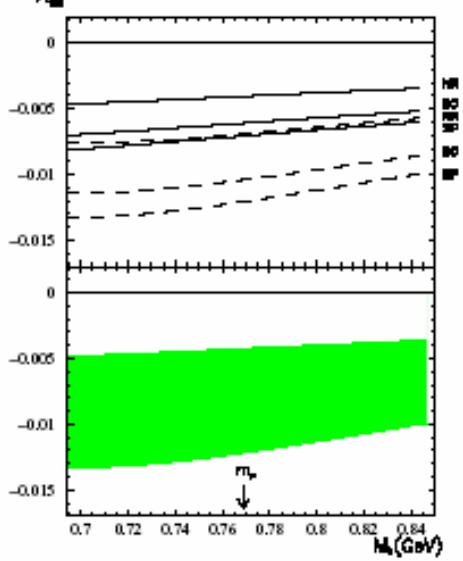
$$A_{UT}^{\sin(\phi_R-\phi_S)\sin\theta} \propto h_1(x)H_1^{\perp\sphericalangle}(z)$$



[Jaffe etal,PRL80,1998]

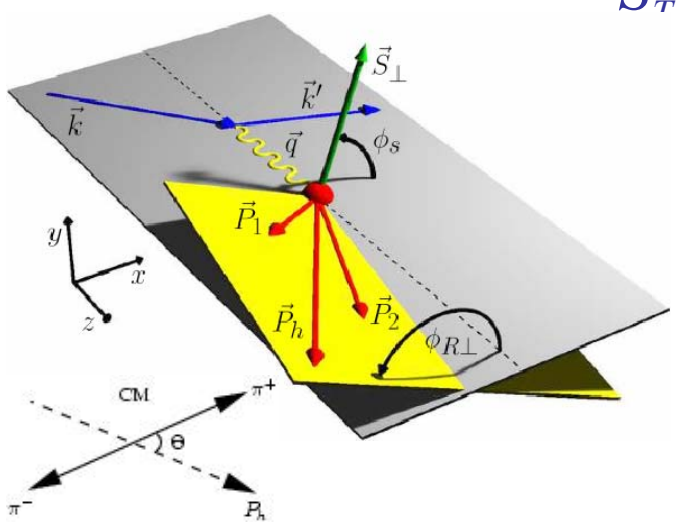


[Radici etal,PRD65,2002]



interference fragmentation function

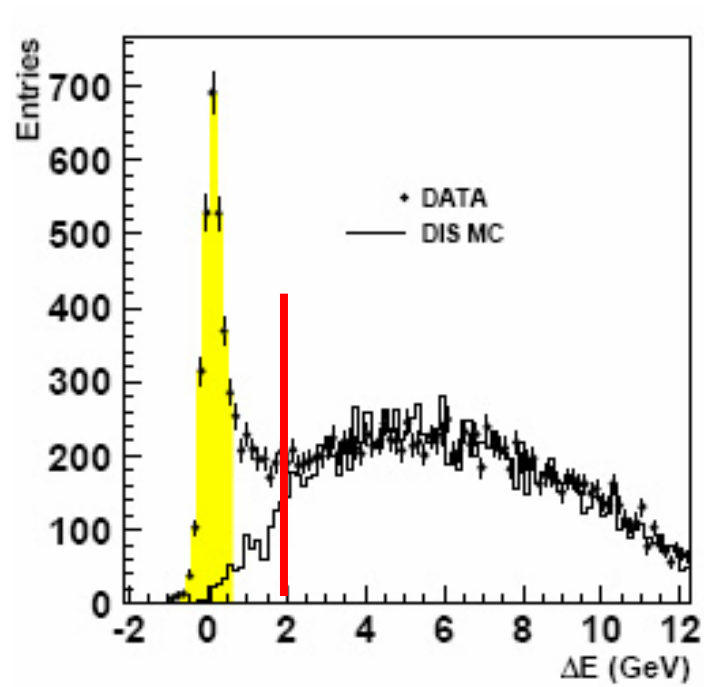
$$A_{UT}(\phi_{R\perp},\phi_S,\theta) = \frac{1}{S_T}\frac{N^{\uparrow}(\phi_{R\perp},\phi_S,\theta)/N^{\uparrow}_{\mathrm{DIS}} - N^{\downarrow}(\phi_{R\perp},\phi_S,\theta)/N^{\downarrow}_{\mathrm{DIS}}}{N^{\uparrow}(\phi_{R\perp},\phi_S,\theta)/N^{\uparrow}_{\mathrm{DIS}} + N^{\downarrow}(\phi_{R\perp},\phi_S,\theta)/N^{\downarrow}_{\mathrm{DIS}}}$$



$$= A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}\sin(\phi_{R\perp}+\phi_S)\sin\theta$$

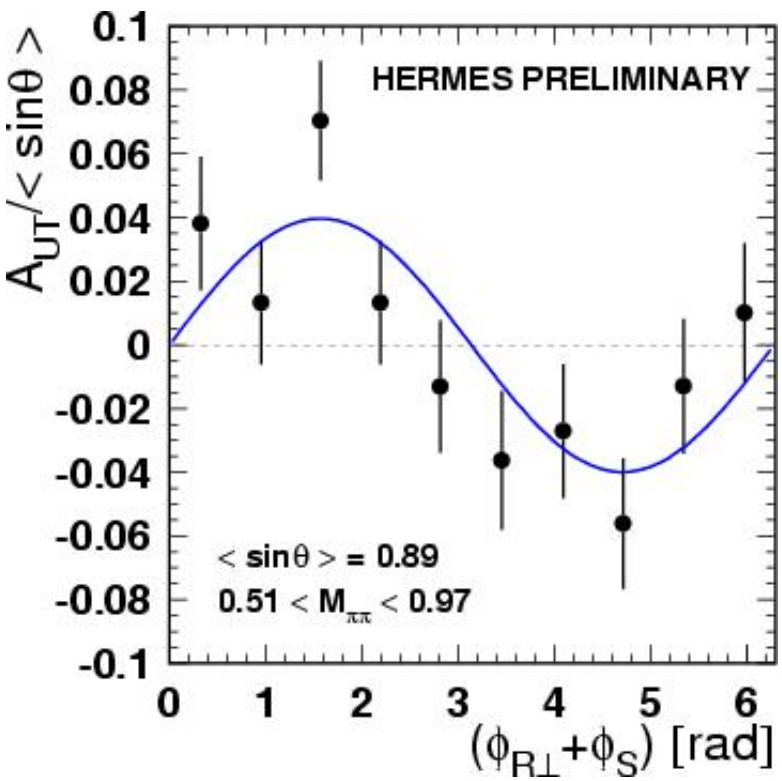
→ for >2 hadrons: all combinations

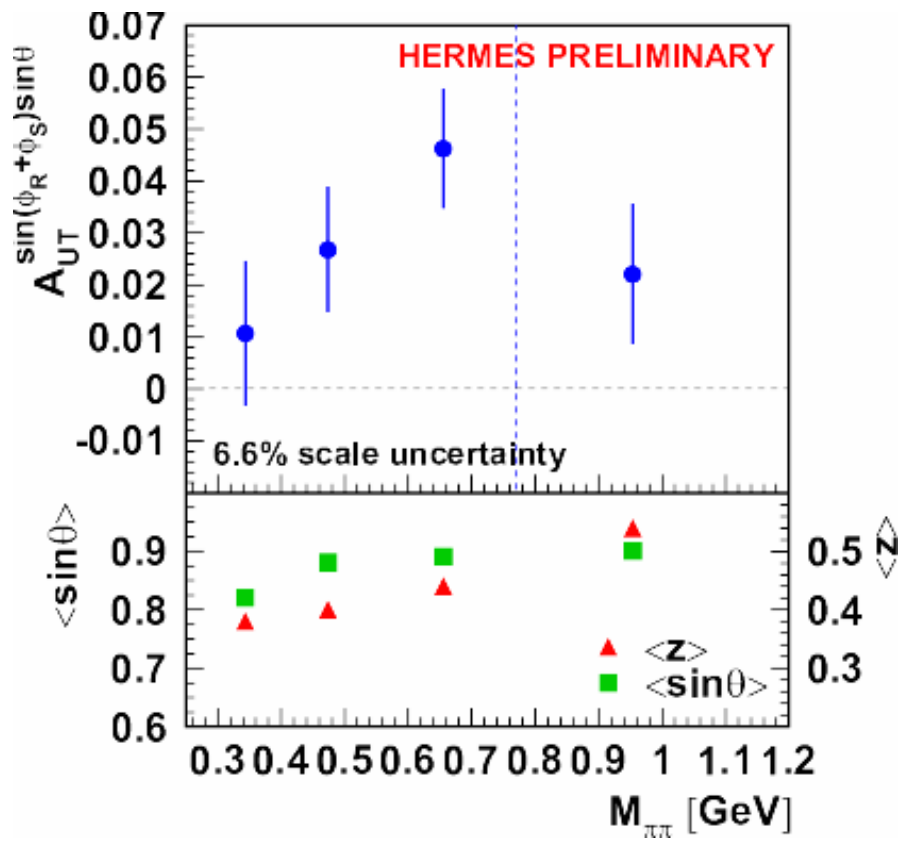
→ excl. ρ0 excluded



interference fragmentation function

$$A_{UT} = A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} \sin(\phi_{R\perp} + \phi_S)\sin\theta$$





0.040±0.009 (stat) ±0.003 (sys)

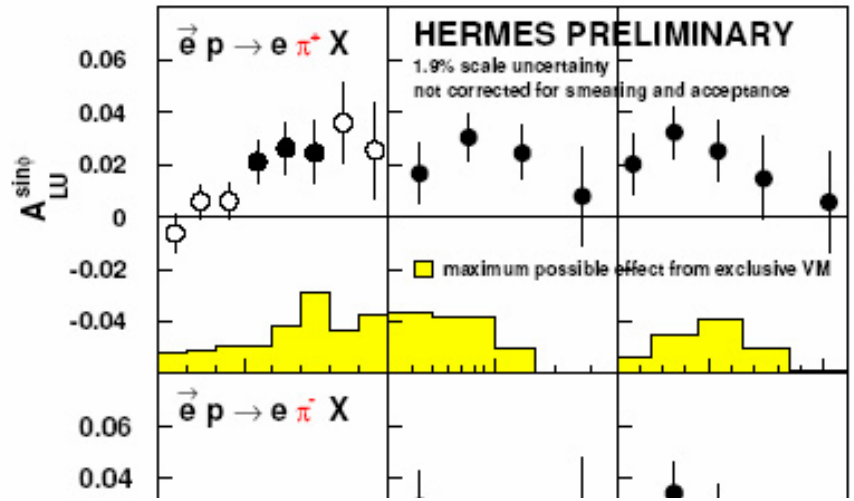
→ positive moments for all invariant mass bins

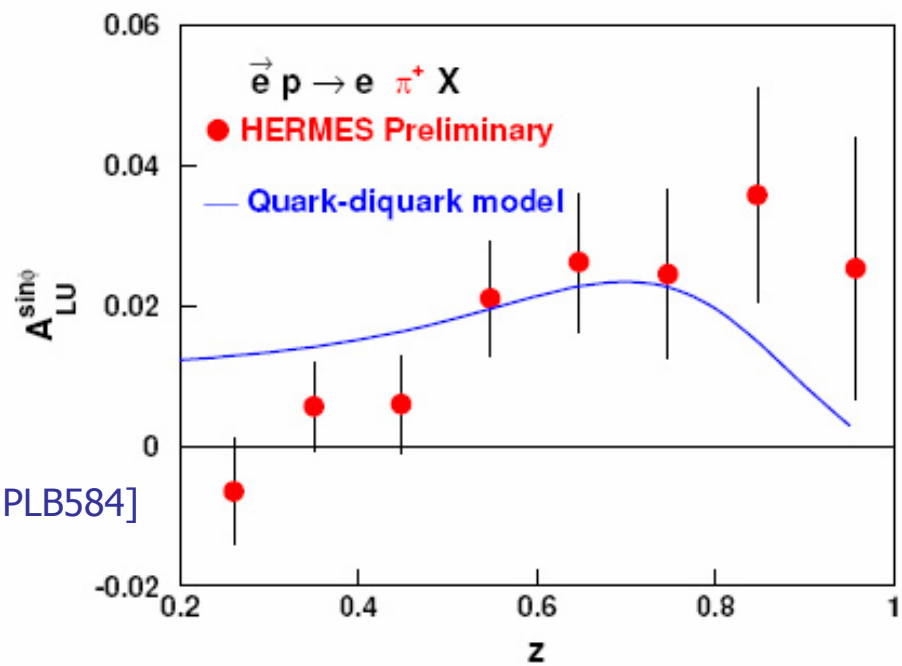
single beam-spin asymmetry

$$A_{LU}^{h}(\phi) = \frac{1}{|P_b|}\frac{N_h^{\uparrow}(\phi) - N_h^{\downarrow}(\phi)}{N_h^{\uparrow}(\phi) + N_h^{\downarrow}(\phi)}$$

$$\propto \lambda_e \sin(\phi)\ y\sqrt{1-y}\ \frac{M}{Q}\sum_q e_q^2\, x^2$$

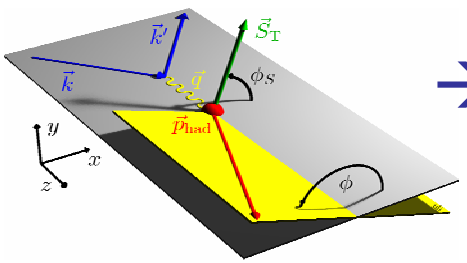
$$\cdot\left[e^q(x)H_1^{\perp q}(z) + h_1^{\perp q}(x)E^q(z)\right]$$





→ QdQ-model prediction of z-dependence [Gamberg,Hwang,Oganessyan,PLB584]

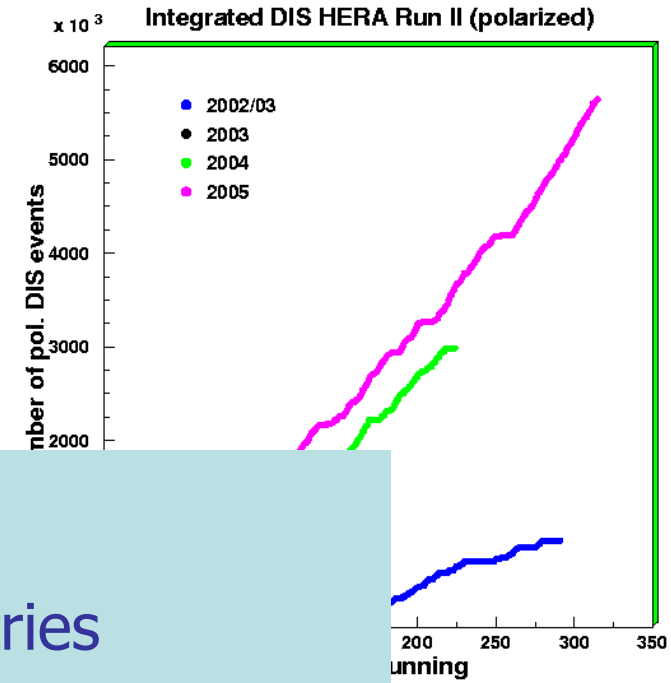
HERMES future →2007



→ till Nov2005: p ↑

transversity+friends

exclusive A_{UT} (DVCS, ρ^0, π^+)

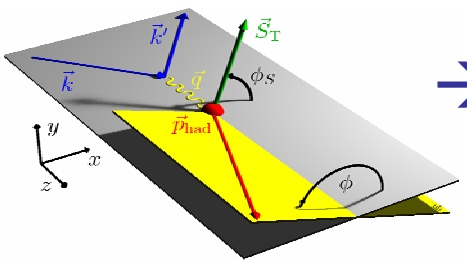


transversity+friends from 02-05 data:

- → 2D binning for single pion asymmetries
- → charged kaon asymmetries
- → working on weighted asymmetries
- → cosϕ and cos2ϕ moments
- → Sivers extraction (purity formalism)

… waiting Belle data for Collins*FF*

HERMES future →2007

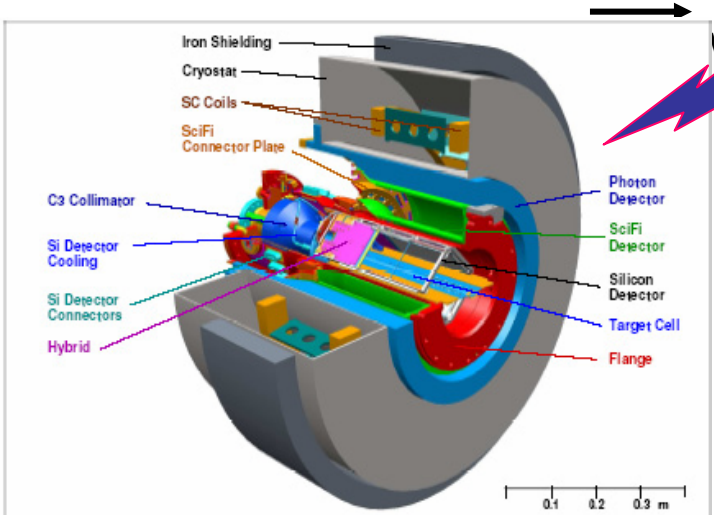


→ till Nov2005: p ↑

transversity+friends

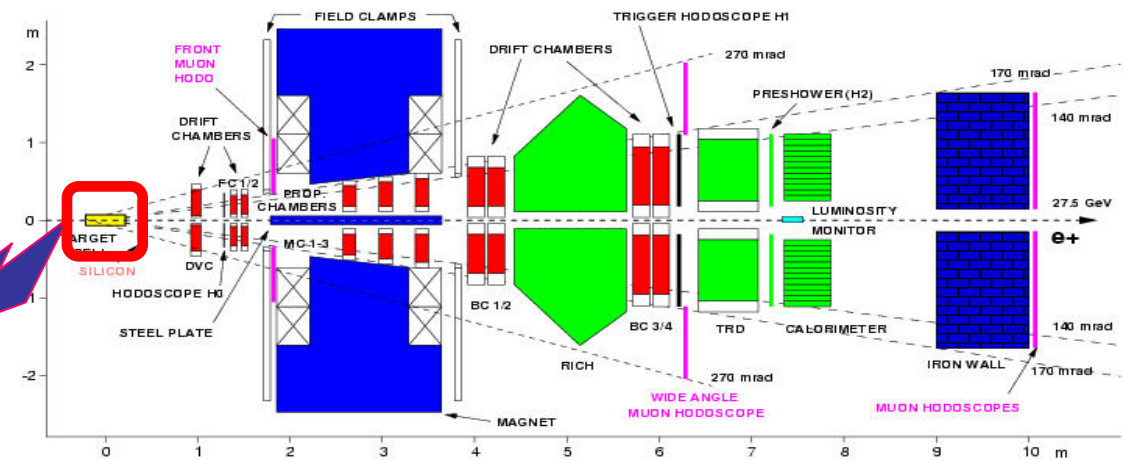
exclusive A_{UT} (DVCS, ρ^0, π^+)

→ 2006-07:



e^+/e^- →

γ



dedicated measurements of hard exclusive processes with *recoil*

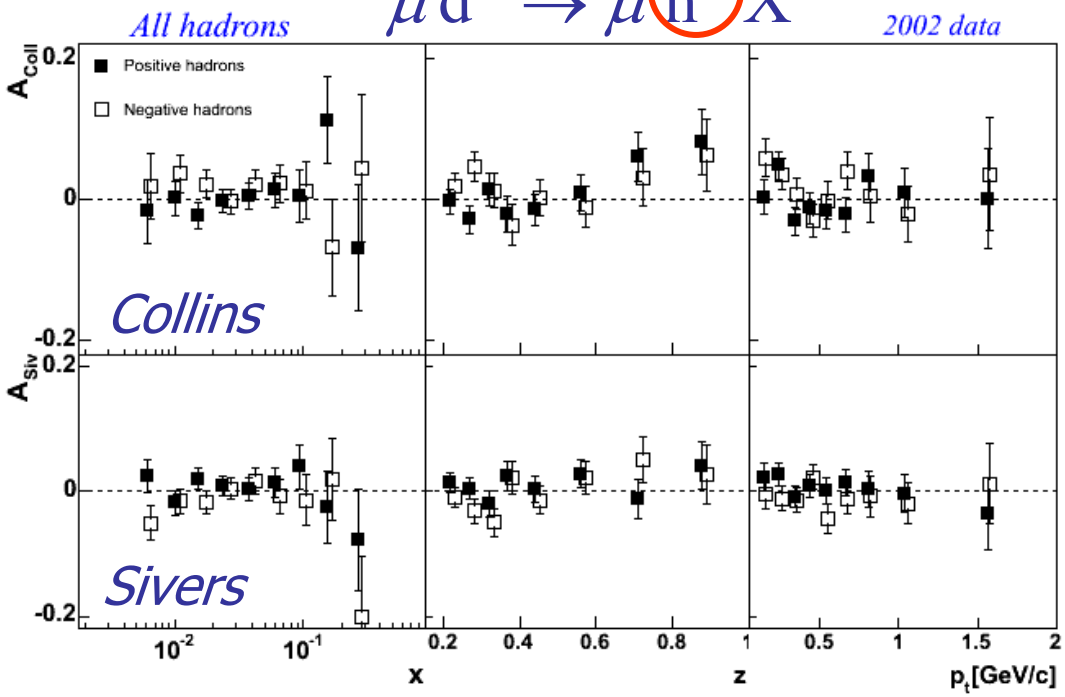
transversity+friends

@COMPASS

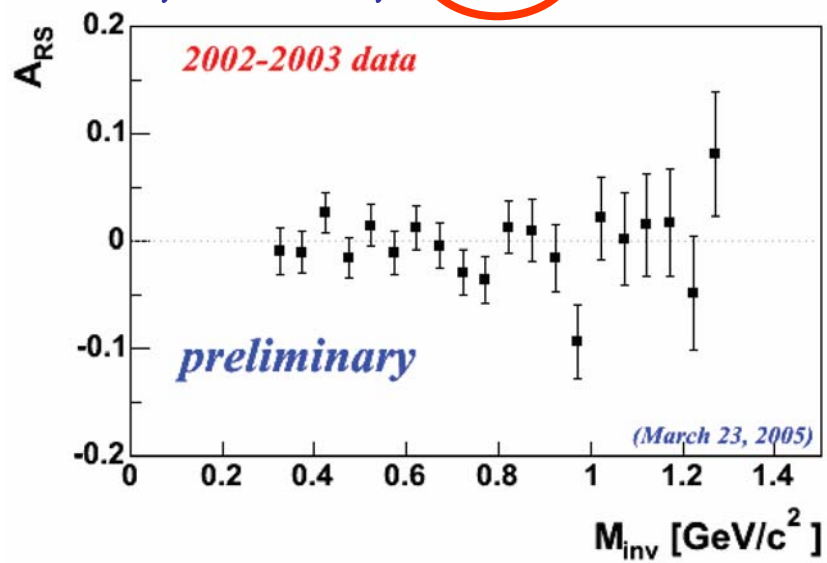
@JLAB

TMDs @COMPASS

$\mu d^{\uparrow} \rightarrow \mu h^{\pm} X$



$\mu d^{\uparrow} \rightarrow \mu h^{+} h^{-} X$



→ all asymmetries compatible with zero

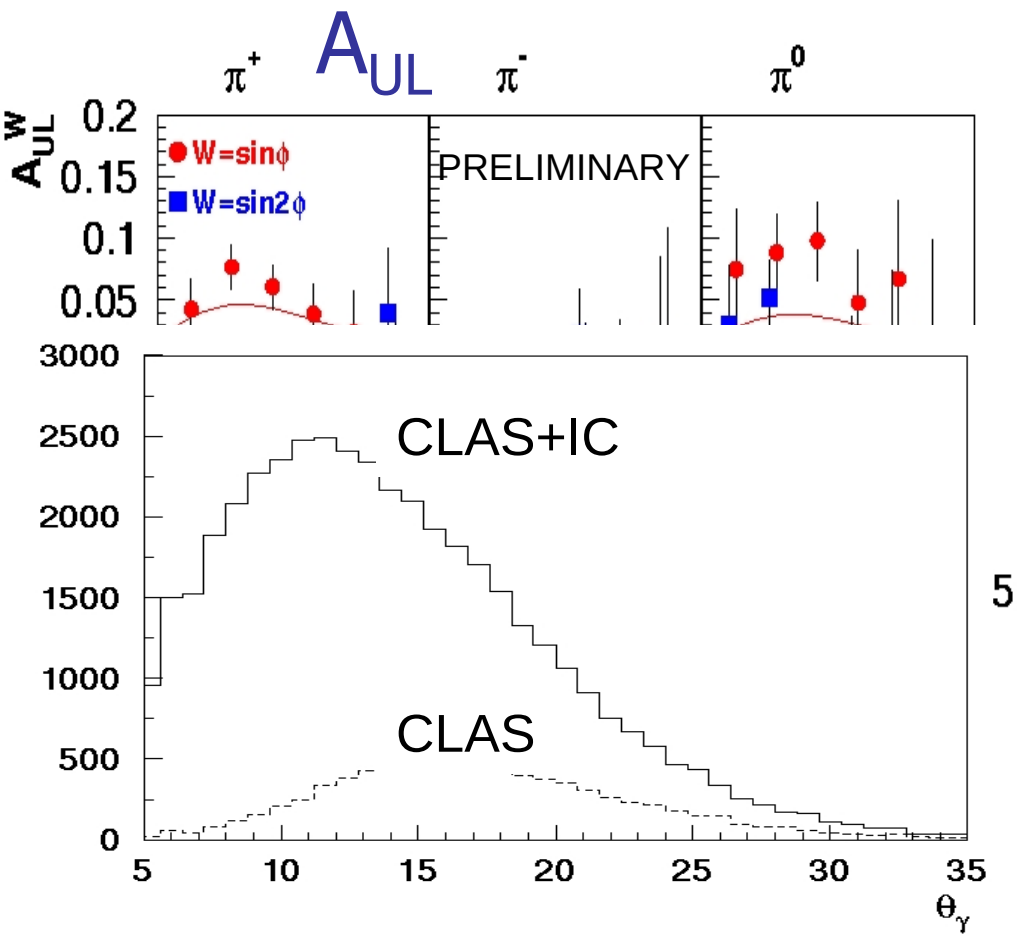
→ proton target in 2006: 30 days $NH_3^{\uparrow}$

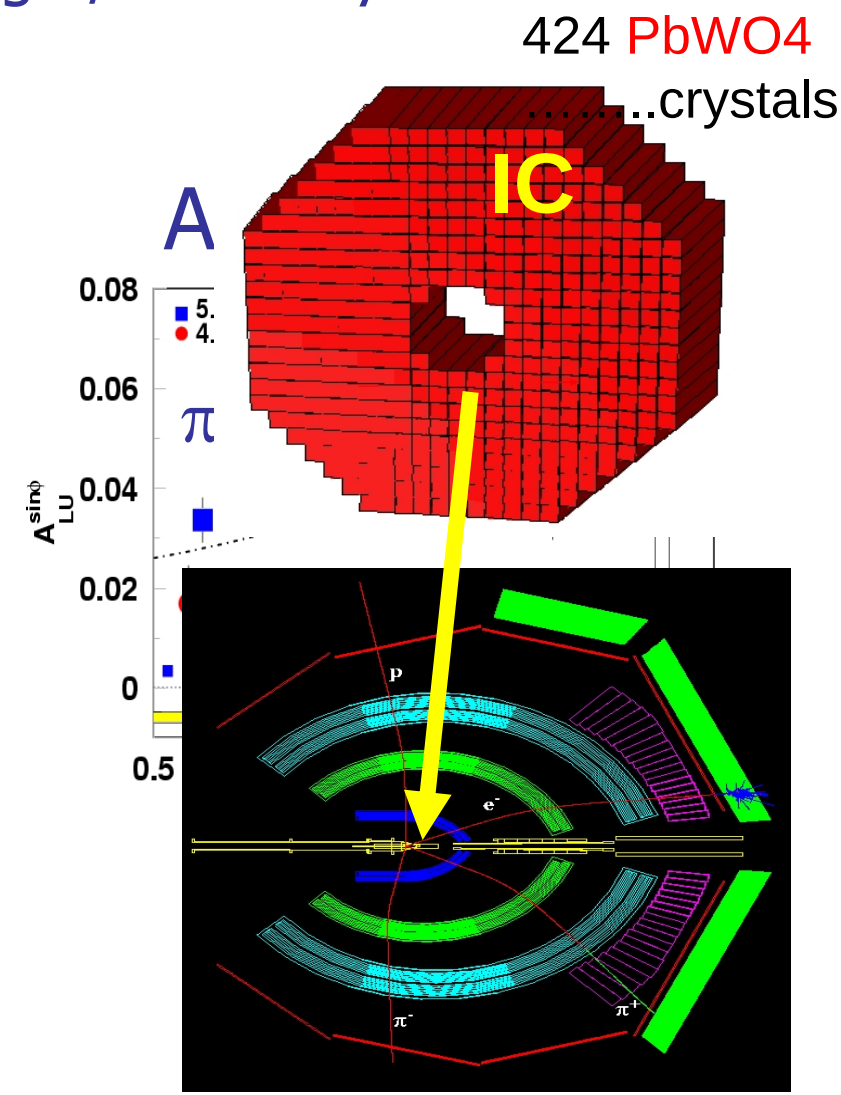
→ 2007/08 priority of hadron program

TMDs @JLab (6 GeV)

→ *longitudinal* target/beam asymmetries from

CLAS:

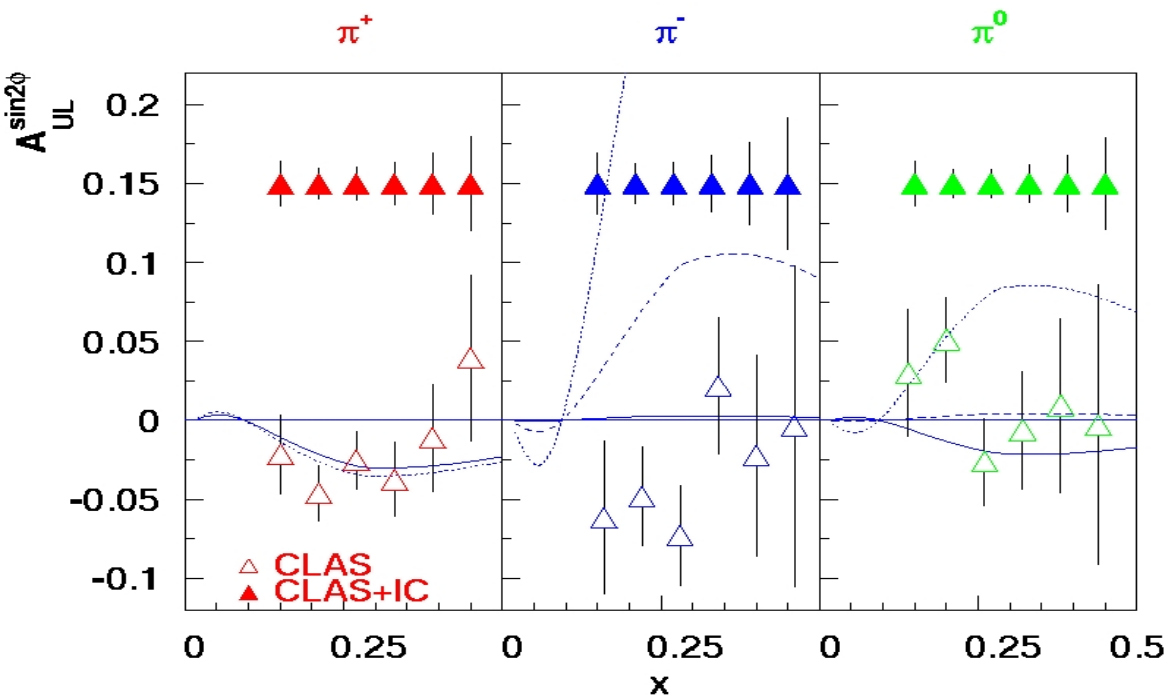




TMDs @JLab (6 GeV)

→ *longitudinal* target/beam asymmetries from

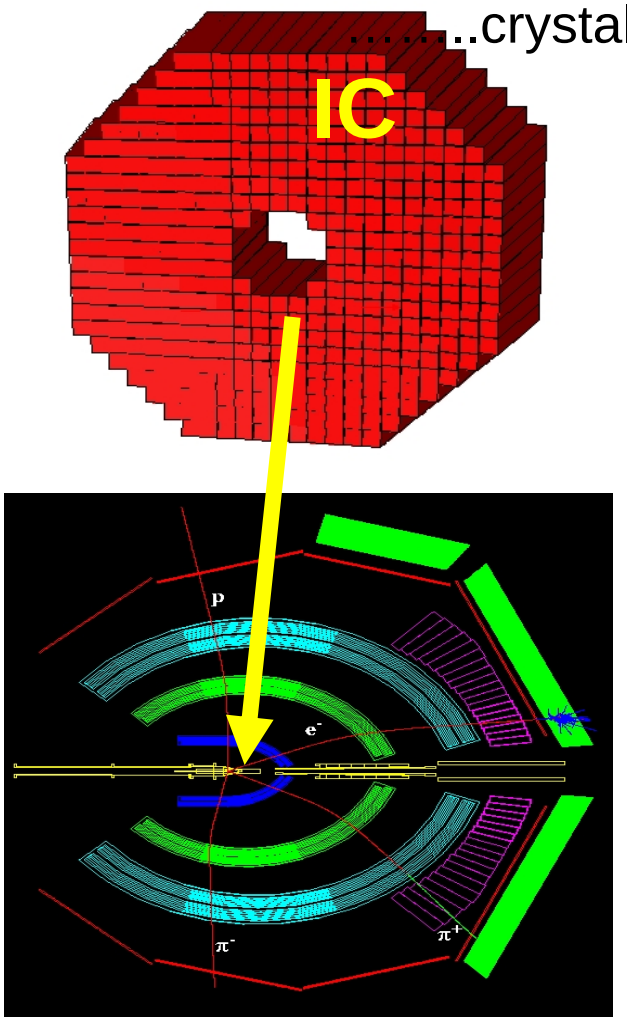
CLAS:



$$A_{UL}^{\sin 2\phi} \propto h_{1L}^{\perp} H_1^{\perp}$$

→ Mulders

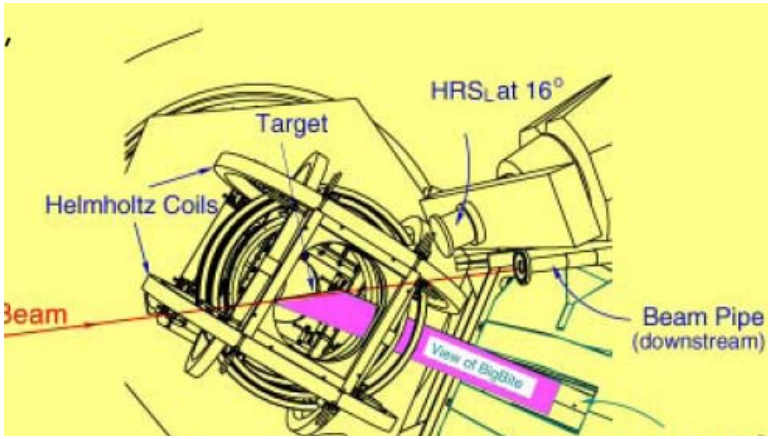
424 PbWO4 ..crystals



TMDs @JLab (6 GeV)

→ transverse target polarisation:

approved proposal @Hall-A
with ^{3}He → neutron

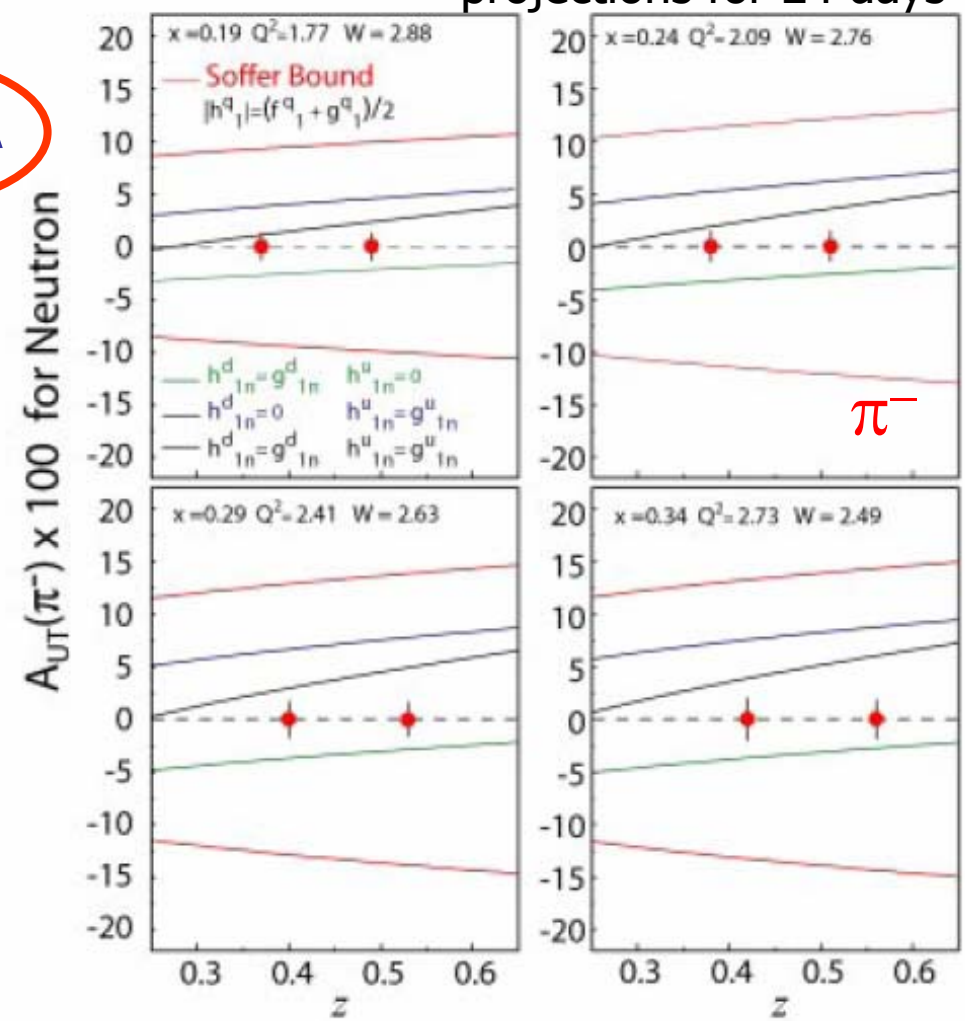


☺ valence region

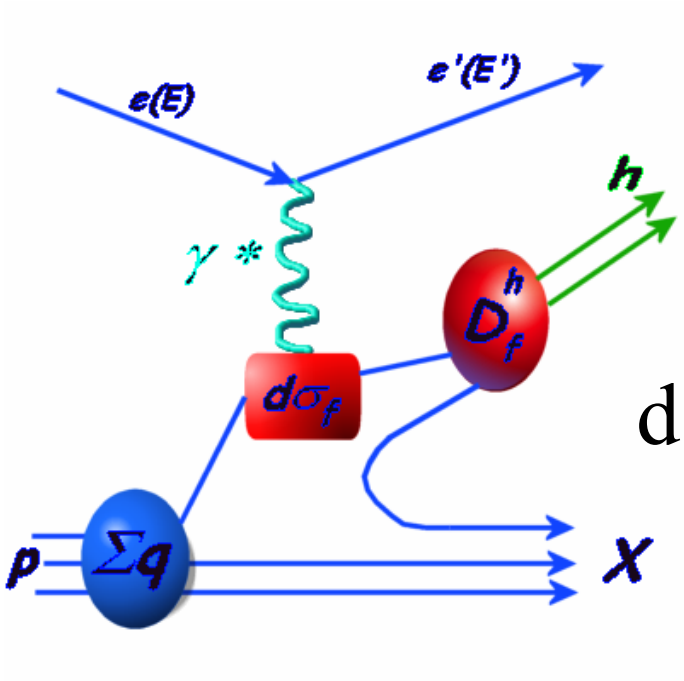
😐 small z-range

☹ limited ϕ acceptance

projections for 24 days



fragmentation in sidis

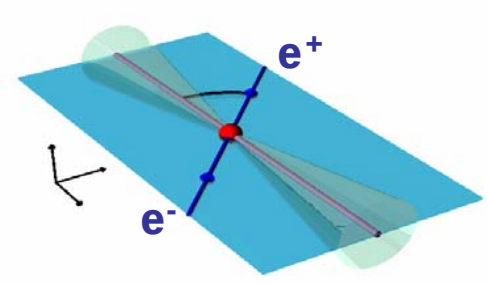


$$\mathrm{d}\sigma^{\mathrm{h}}(z) \propto \sum_f q_f(x) \otimes d\sigma_f \otimes D_f^h(z)$$

fragmentation function

→

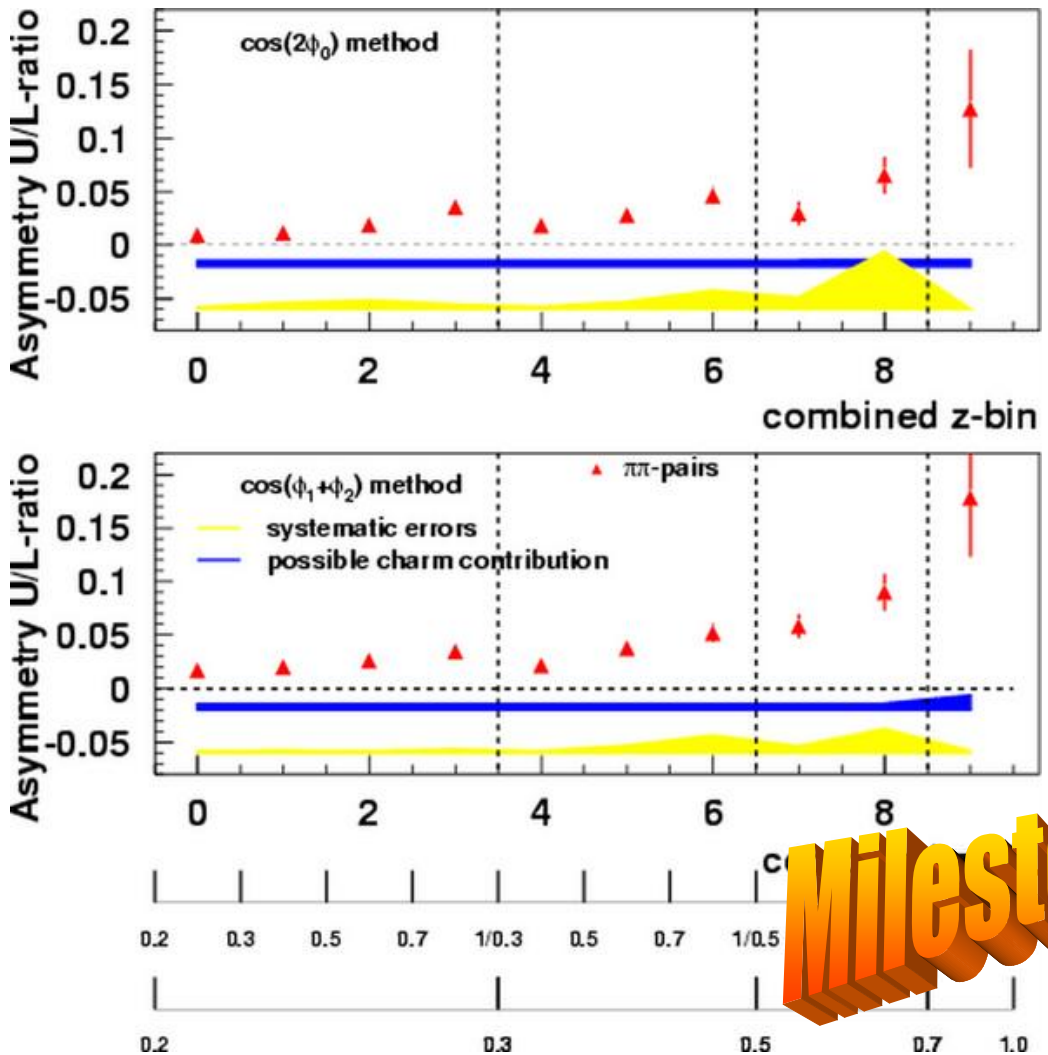
e^+e^-



FF from e^+e^-

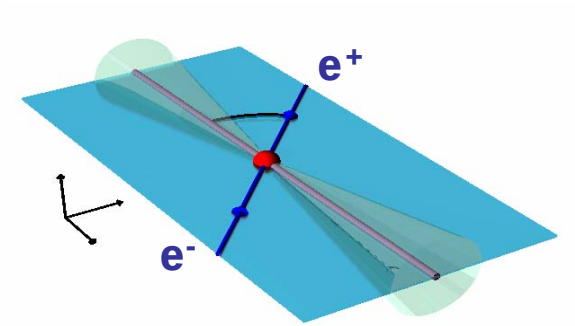
→ add π^0:
favoured/unfavoured

→ extension to *IFF*
straight forward



Milestone!

current facilities:
near+mid term future



→ Collins/2hadron *FF* with high accuracy

BELLE

PHENIX STAR BRAHMS

hermes COMPASS JLAB @6GeV

first extraction of TMDs feasible

very near future:

√ Sivers function from HERMES

√ transversity from HERMES+BELLE

√ Mulders function from CLAS+BELLE

Backup slides

Statistics: 02-04 : ~70 pb-1

05 ~150 pb-1

Interpretation: Minimal Assumptions

- $A_{UT}^{Collins}$ is ***leading twist***
- Collins FF obeys ***favored / disfav*** symmetry:

$$H_{fav} = H_{1\perp}^{u/\pi^+} - H_{1\perp}^{d/\pi^+} - H_{1\perp}^{\bar{u}/\pi^+} - H_{1\perp}^{\bar{d}/\pi^+}$$
$$H_{disf} = H_{1\perp}^{u/\pi^-} - H_{1\perp}^{d/\pi^-} - H_{1\perp}^{\bar{u}/\pi^-} - H_{1\perp}^{\bar{d}/\pi^-}$$

$$\rightarrow A^{\pi^+} \sim k\frac{(4\delta u + \delta\bar{d})H_{fav} + (\delta d + 4\delta\bar{u})H_{disf}}{(4u + \bar{d})D_{fav} + (d + 4\bar{u})D_{disf}}$$

Some definitions

$$r \equiv \frac{d - 4u}{u - \bar{d}/4} \qquad \eta \equiv \frac{D_{disf}}{D_{fav}}$$

$$\delta r \equiv \frac{\delta d - 4\delta\bar{u}}{\delta u - \delta\bar{d}/4} \qquad \eta_H \equiv \frac{H_{disf}}{H_{fav}}$$

Consider Asymmetry Ratios

$$\alpha^- = \frac{A^{\pi^-}}{A^{\pi^+}} - \left(\frac{4\eta_H + \delta r}{4\eta + r}\right)\left(\frac{4 + r\eta}{4 + \delta r\eta_H}\right), \quad \alpha^0 = \frac{A^{\pi^0}}{A^{\pi^+}} - \frac{(4 + \delta r)(1 + \eta_H)}{(4 + r)(1 + \eta)}\left(\frac{4 + r\eta}{4 + \delta r\eta_H}\right)$$

⇒ **Leads to Constraint Equ^n** involving ***only unpolarized*** quantities

$$\alpha^- C = \alpha^0(1 - C) - 1 \qquad \text{where} \qquad C \equiv \frac{4\eta - r}{4 - \eta r}$$

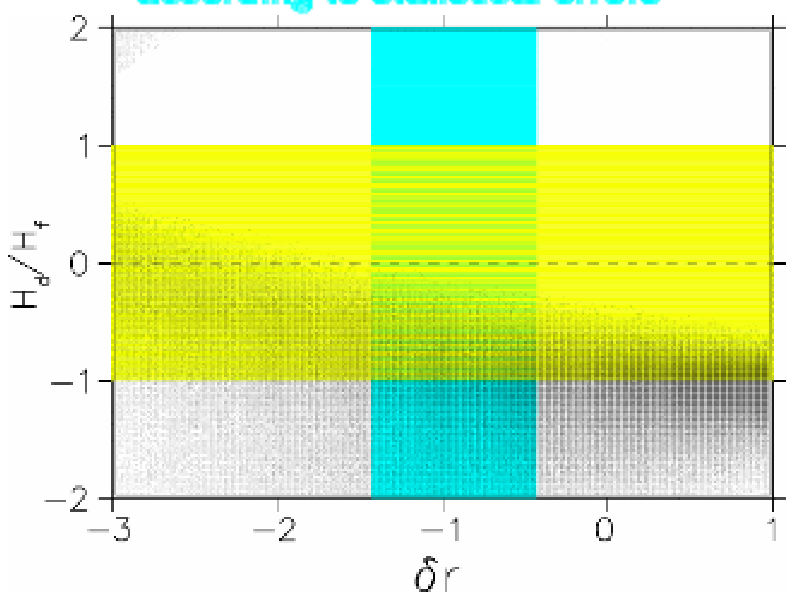
⇒ **Solution Space** in η_H vs δr can be determined:

$$\eta_H = \frac{\delta r - 4(\alpha^- C)}{(\alpha^- C)\delta r - 4} \quad \text{and} \quad \eta_H = \frac{\delta r - 4(\alpha^0(1 - C) - 1)}{(\alpha^0(1 - C) - 1)\delta r - 4}$$

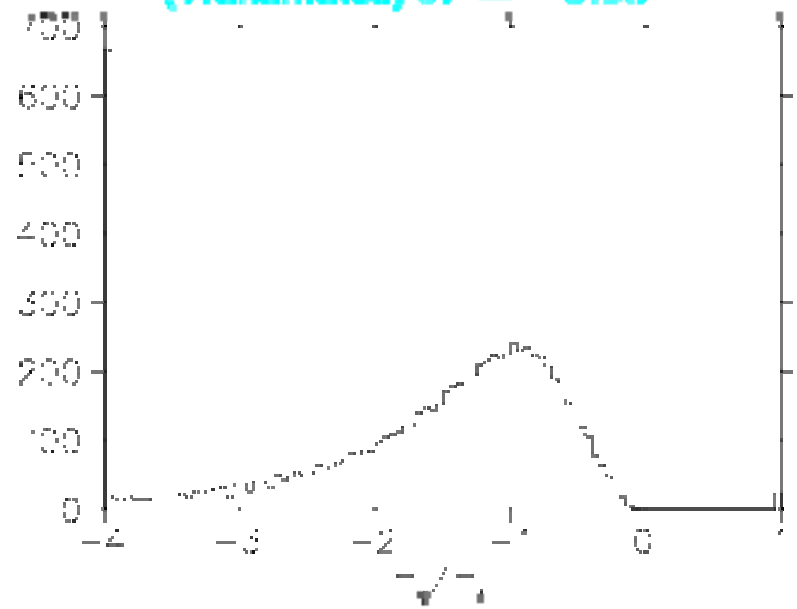
① **Constraint equation:** well satisified by both weighted and unweighted asymmetries (within 1σ statistical) ➡ no problem with internal consistency

② **Solution space** for $\delta r \approx \delta d/\delta u$ vs $\eta_{fl} = H_{\rm dis}/H_{\rm fav}$

solution space populated according to statistical errors



η_{fl} solutions at χQSM value (Wakamatsu) $\delta r = -0.03$



Neglecting possible diffractive contamination, there seems to be a pronounced indication that $H_{\rm fav} \approx -H_{\rm dis}$

Summary

pp →

A_N for inclusive hadrons,
di-jets → Sivers
A_T in jets: → Collins *FF*
→ *IFF*

A_{TT} inclusive jets, DY

STAR, PHENIX, Brahms
PAX

SIDIS →

$\mathbf{A_{UT}}$, A_{LT}, A_{UL}, A_{LU}, A_{UU}
for single and double hadrons

Λ production, VM

HERMES, Compass, JLab@6GeV
JLab@12GeV, *EIC*

e^+e^- → Collins*FF* , I*FF*
BELLE

factorisation
universality

TMDs