First Transverse Target Data from HERMES

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- *The Collins and Sivers Effects*
- A_{UT} *Data Analysis and First Results*
- *Some Interpretation ...*

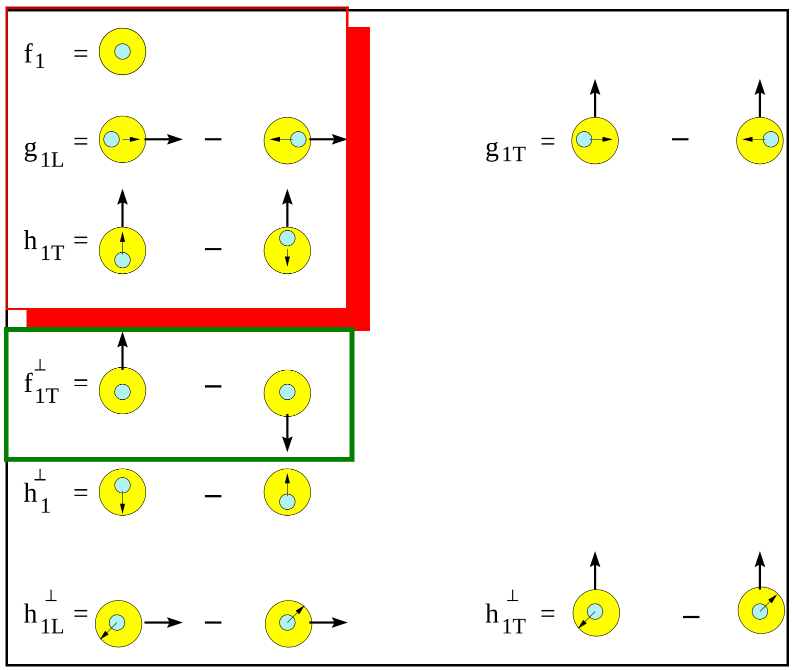
Thanks to superb analysis crew!

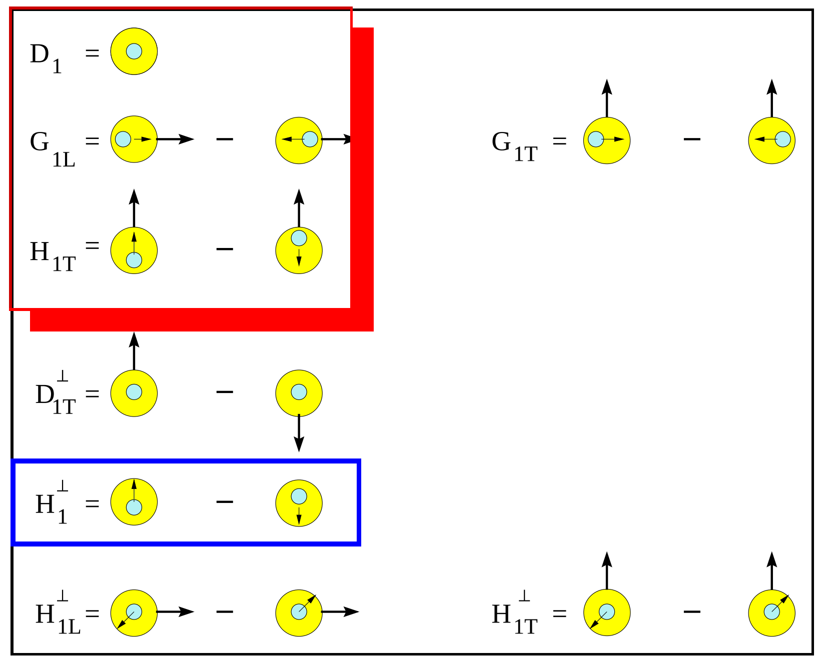
Gunar Schnell (Tokyo)
Ralf Seidl * (Erlangen)
Ulrike Elschenbroich (Gent)

* ***Thank you for use of slides from CIPANP!***

$k_\perp$ *dependent DFs or FFs*

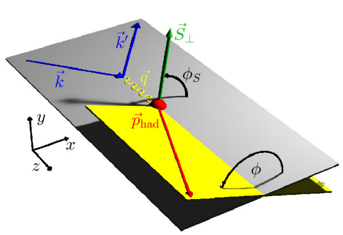
$$\sigma^{eH\to ehX} = \sum_q f^{H\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to h}$$





- survive $k_\perp$ integration
- T-even and T-odd functions
- chiral-even and chiral-odd functions

- Sivers function
- Collins function



E704: Sivers or Collins?

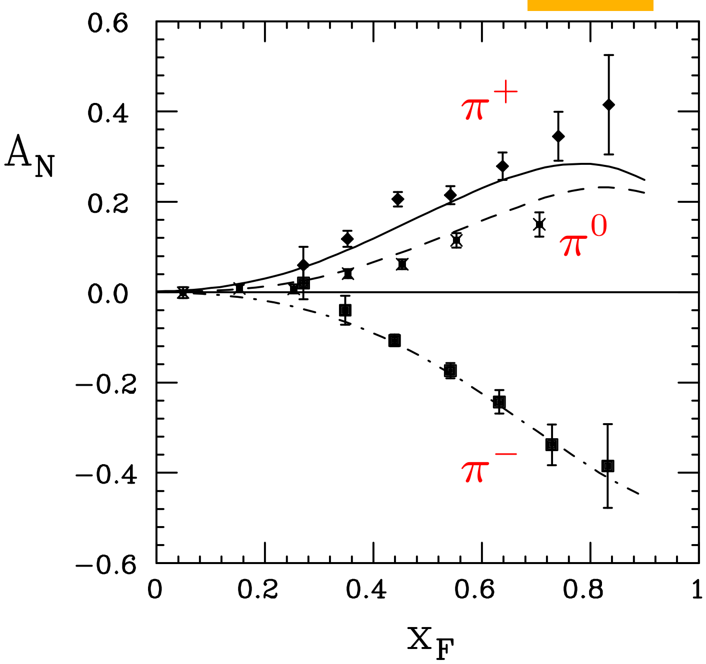
The E704 single-spin asymmetry could be due to ...

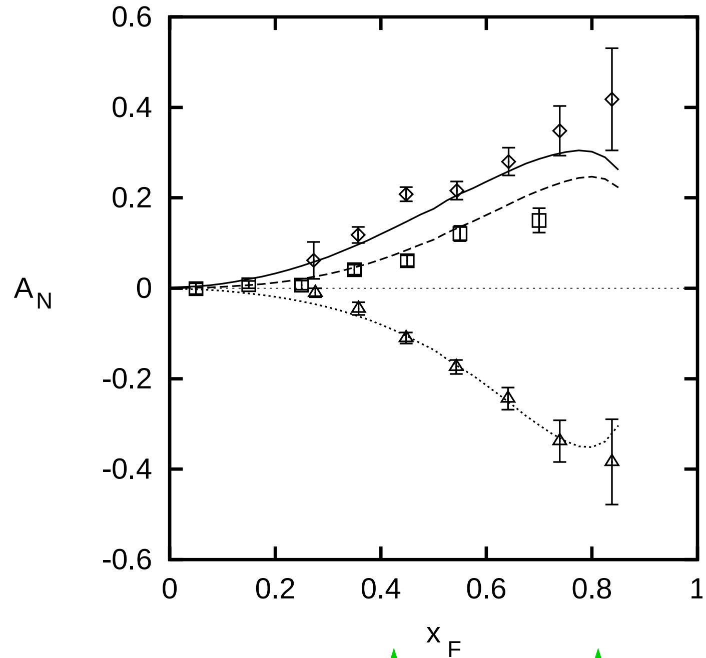
Sivers Effect

T-odd **dist$^{\underline{n}}$ function** $f_{1T}^{\perp}$

Collins Effect

T-odd **frag$^{\underline{n}}$ function** $H_1^{\perp}$

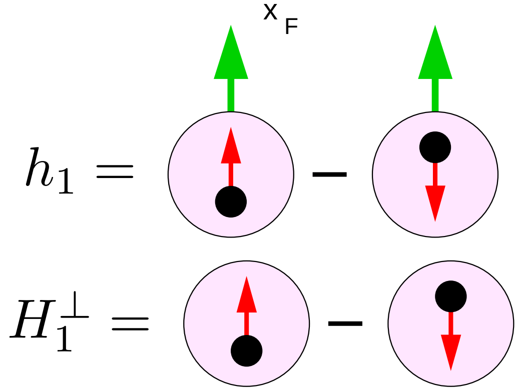




Collins Effect

$$A_N \sim h_1(x)\, H_1^{\perp}(z)$$

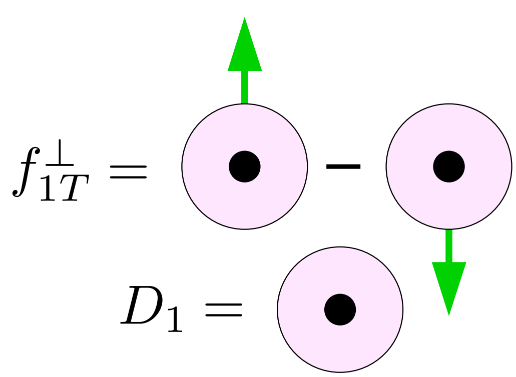
$\Rightarrow$ access to ***transversity!***



Sivers Effect

$$A_N \sim f_{1T}^{\perp}(x)\, D_1^{\perp}(z)$$

$\Rightarrow$ access to ***T-odd dist$^{\underline{n}}$ func***



QCD T-invariant : T-odd DF or FF → ***interference***

E704: T-odd Frag$^{\underline{n}}$ or Dist$^{\underline{n}}$ Function?

Transversity * Collins Fragmentation Func

Helicity distributions

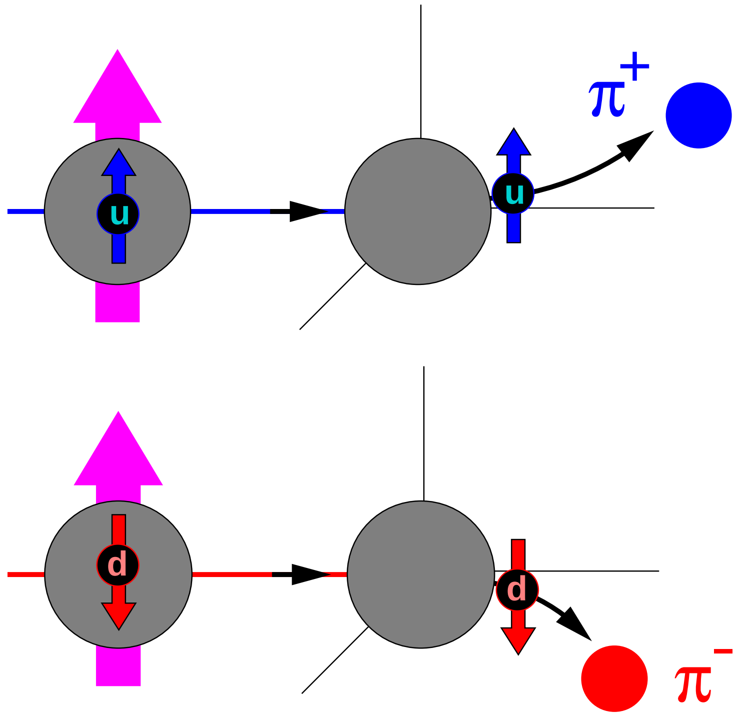
$\Delta u > 0, \qquad \Delta d < 0$

⋮

Transverse dist$^{\underline{n}}$s

$\delta u > 0, \qquad \delta d < 0$?

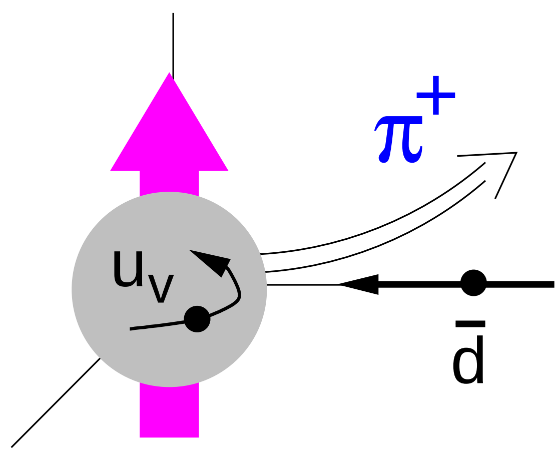
probably ...



Model of Meng, Chou, & Yang

Valence quarks = relativistic Dirac p'cles in central potential

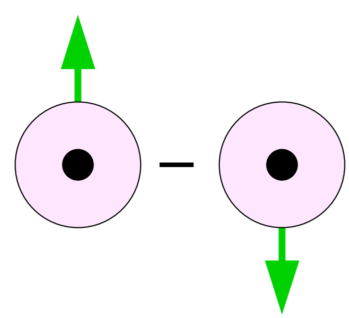
- relativistic quarks in eigenstates of J ... shared between L and S
- symmetrized wavefunction $\rightarrow \Delta u = +4/3, \Delta d = -1/3$
- forward π^+ produced from orbiting u_v quark at front surface of beam



Sivers Idea

Consider dependence of parton densities on ***intrinsic k_T*** == ***quark orbital motion***

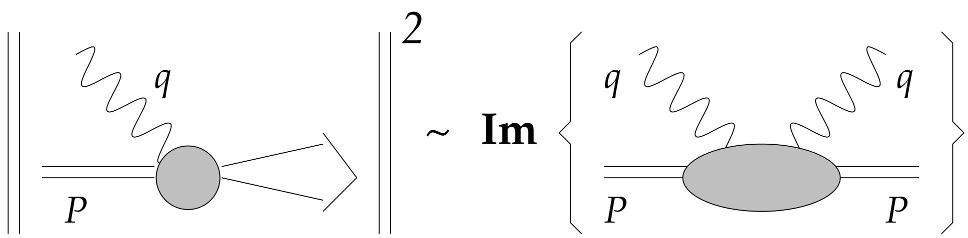
$f_{1T}^{\perp}(x_a, \mathbf{k}_{Ta})$ =



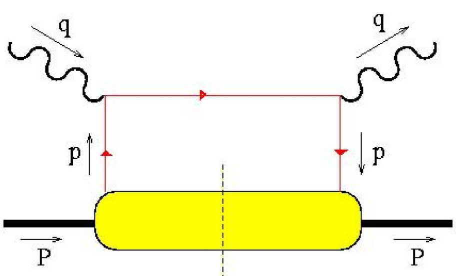
The Leading-Twist Sivers Function

Can it exist in DIS?

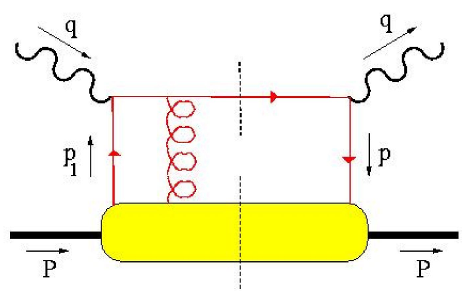
A T-odd function like $f_{1T}^{\perp}$ ***must*** arise from ***interference*** ...
but a distribution function is just a forward scattering amplitude,
how can it contain an interference?



Brodsky, Hwang, & Schmidt 2002



can interferere
with

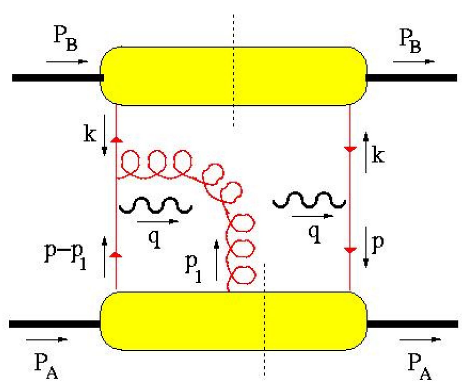


and produce a T-odd effect!
(***also requires*** $L_z \neq 0$ ... so does $F_2(q)$ form factor)

It looks higher-twist, but it's not ...
these are soft gluons

Such soft-gluon reinteractions
with the soft wavefunction are
final (or initial) state interactions ...
and may be ***process dependent*** !

new ***universality issues*** ...

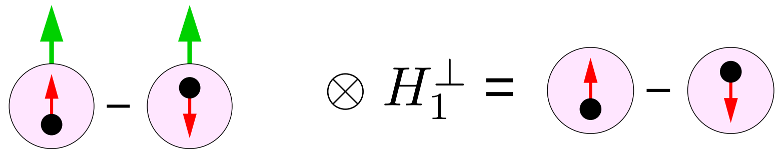


e.g. Drell-Yan

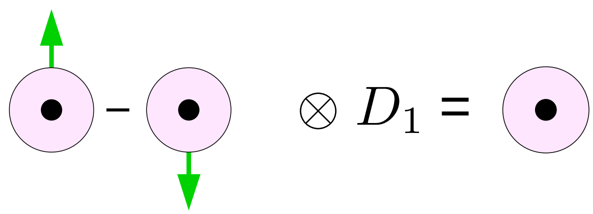
T-odd Distribution vs Fragmentation Function

SIDIS xsec $d\sigma_{\mathrm{UT}}$ with *transverse target* polarization has ***two*** similar terms:

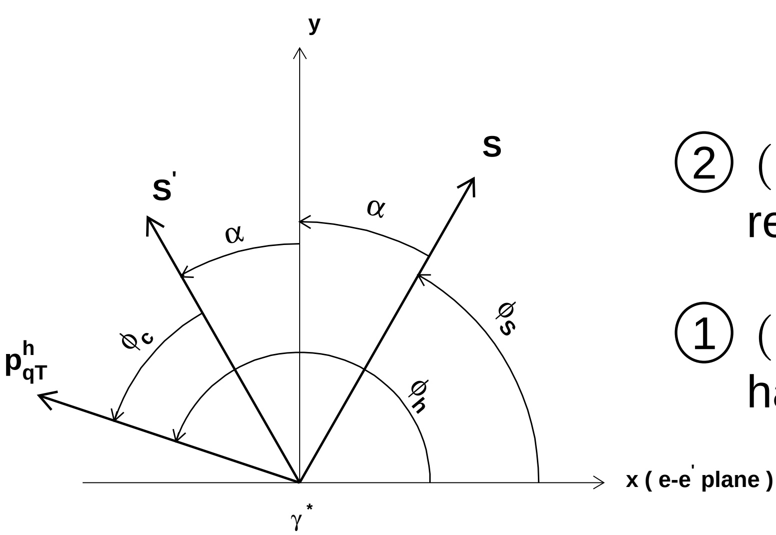
① $\sin(\phi_h^l + \phi_S^l)$ $\otimes h_1 =$ ... $\otimes H_1^{\perp} =$ ...



② $\sin(\phi_h^l - \phi_S^l)$ $\otimes f_{1T}^{\perp} =$ ... $\otimes D_1 =$ ...



seperate Sivers and Collins mechanisms



② $(\phi_h^l - \phi_S^l)$ = angle of hadron relative to **initial** quark spin

① $(\phi_h^l + \phi_S^l) = \pi + (\phi_h^l - \phi_S^{l'})$ = hadron relative to **final** quark spin

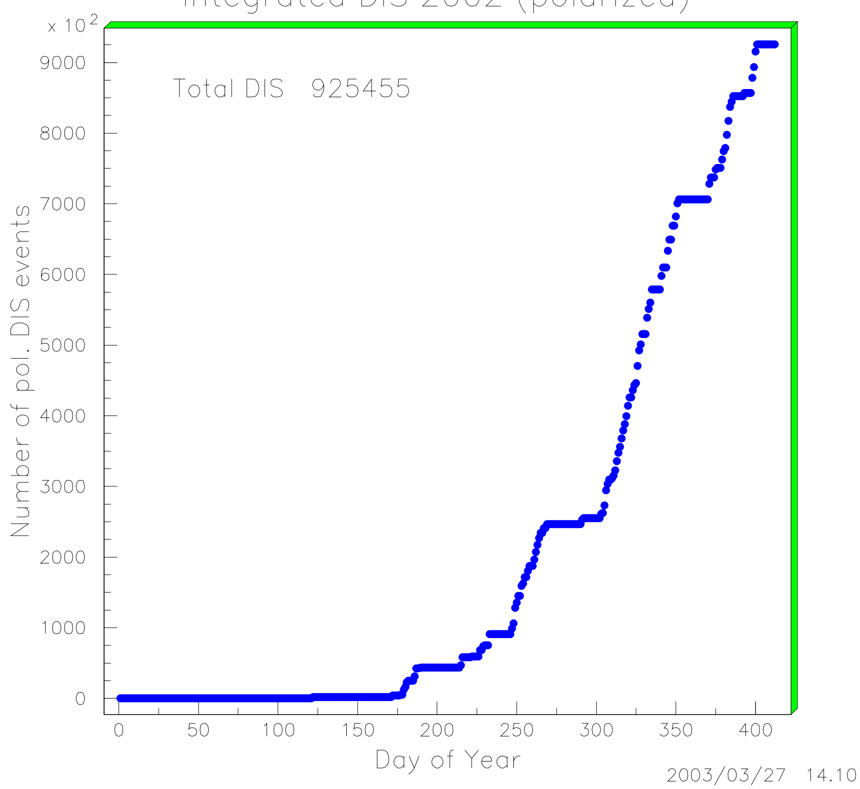
Cannot distinguish in:

- **longitudinal-target case** ...
  $\rightarrow$ transverse component has $\phi_S^l = 0$.
- **inclusive π production** , e.g. $p^{\uparrow}p \rightarrow \pi X$
  $\rightarrow$ jet axis not known

Data Collection 2002-2003 and Cuts

Transverse Hydrogen target installed in 2001

not so much lumi collected ...

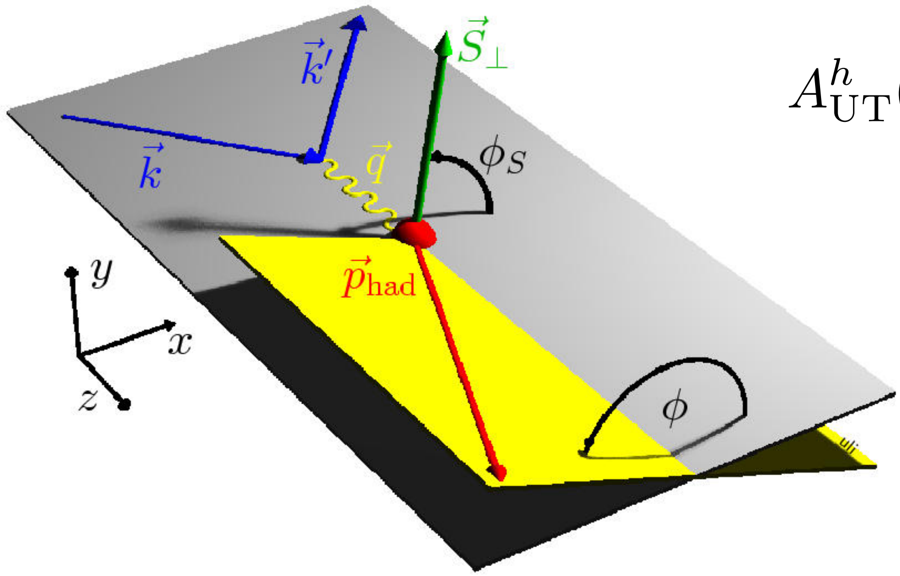


SIDIS cuts

- $0.1 \leq y < 0.85$
- $0.023 < x < 0.4$
- $Q^2 > 1\mathrm{GeV}^2$
- $W^2 > 10\mathrm{GeV}^2$
- $0.2 < z < 0.7$
  (avoid exclusive region)
- 0.02 rad $< \theta_{\gamma,\pi}$

year	target gas	spin orientiation	# pol. DIS
96-97	hydrogen	L	2.4 M
98-00	deuterium	L	9.1 M ☺
02-03	hydrogen	T	0.7 M ☹

Definition of Angles and Asymmetries



$$A^h_{\rm UT}(\phi,\phi_S) = \frac{1}{|P_T|}\frac{N_h^\uparrow(\phi,\phi_S) - N_h^\downarrow(\phi,\phi_S)}{N_h^\uparrow(\phi,\phi_S) + N_h^\downarrow(\phi,\phi_S)}$$

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

➡ fit amplitudes ***simultaneously***

(prevents mixing of effects by acceptance)

Weighted moments

$$A_{\rm UT}^{\rm Collins,wt} = \frac{2\langle\frac{Q_T}{M_\pi}\sin(\phi+\phi_S)\rangle_{\rm UT}}{\langle 1\rangle_{\rm UU}} = |S_T|\frac{\sum_q e_q^2\, \mathbf{h_1^q}\,\mathbf{H_1^{\perp(1),q\to h}}}{\sum_q e_q^2\, f_1^q\, D_1^{q\to h}}\,\frac{1-y}{1-y+y^2/2}$$

$$A_{\rm UT}^{\rm Sivers,wt} = \frac{2\langle\frac{Q_T}{M_\pi}\sin(\phi-\phi_S)\rangle_{\rm UT}}{\langle 1\rangle_{\rm UU}} = |S_T|\frac{\sum_q e_q^2\, \mathbf{f_{1T}^{\perp,q}}\,\mathbf{D_1^{q\to h}}}{\sum_q e_q^2\, f_1^q\, D_1^{q\to h}}$$

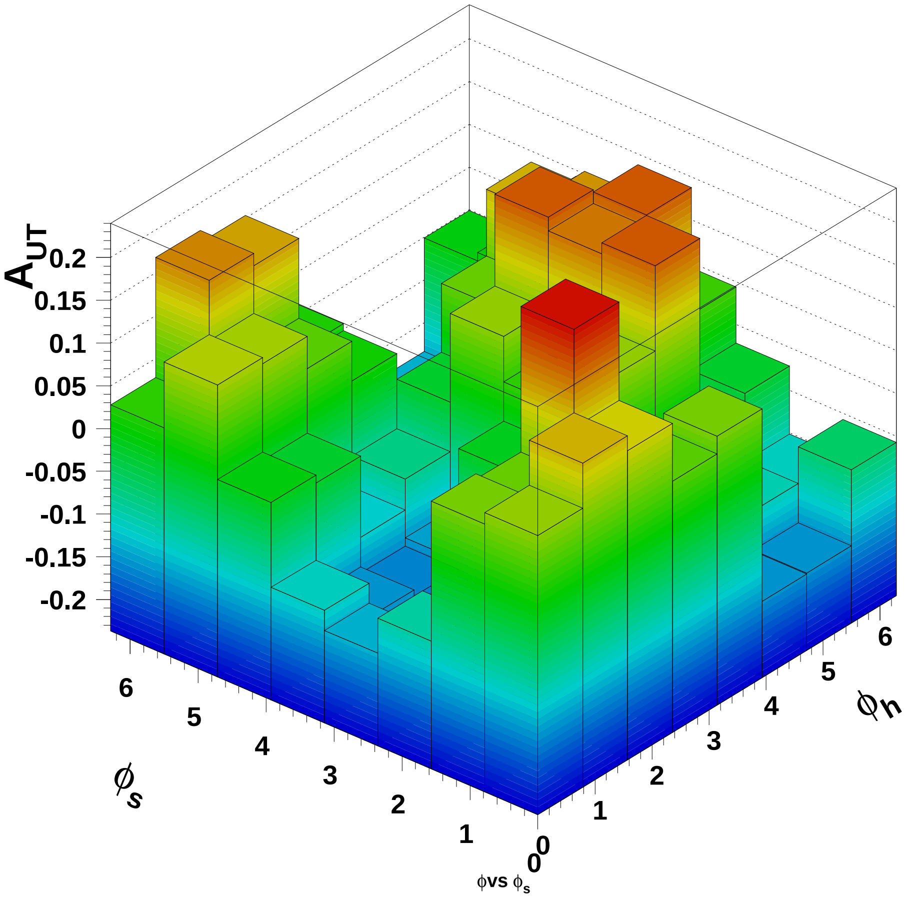
Unweighted moments

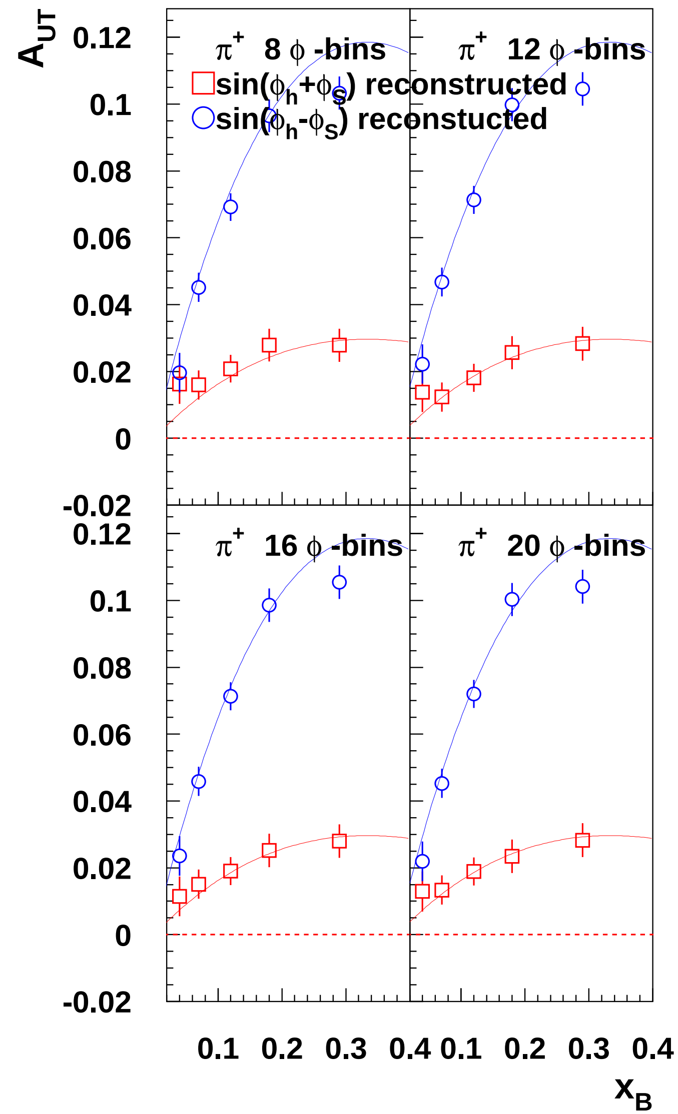
$$A_{\rm UT}^{\rm Collins} = \frac{2\langle\sin(\phi+\phi_S)\rangle_{\rm UT}}{\langle 1\rangle_{\rm UU}} \sim A_{\rm UT}^{\rm Collins,wt}\cdot\frac{M_\pi z}{2\langle P_{\pi\perp}\rangle}$$

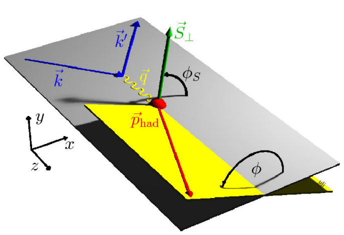
$$A_{\rm UT}^{\rm Sivers} = \frac{2\langle\sin(\phi-\phi_S)\rangle_{\rm UT}}{\langle 1\rangle_{\rm UU}} \sim A_{\rm UT}^{\rm Sivers,wt}\cdot\frac{M z}{2\langle P_{\pi\perp}\rangle}$$

(in Gaussian ansatz)

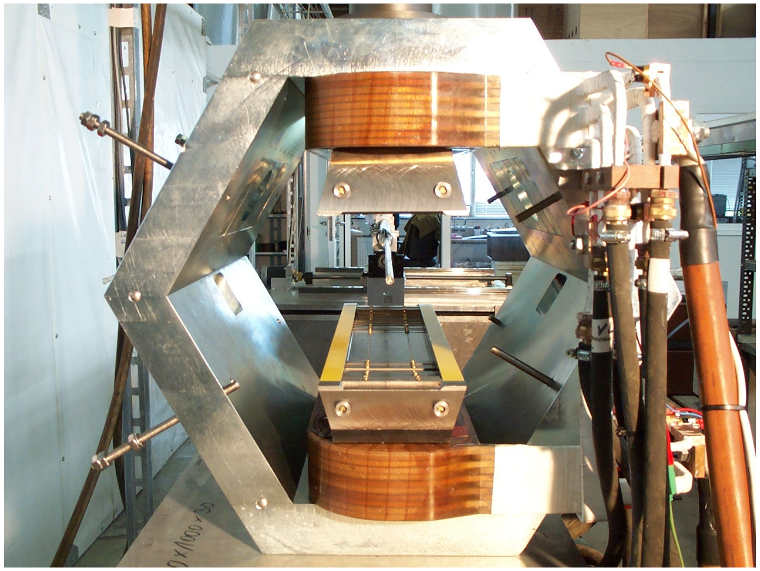
MC: reconstruction of moments

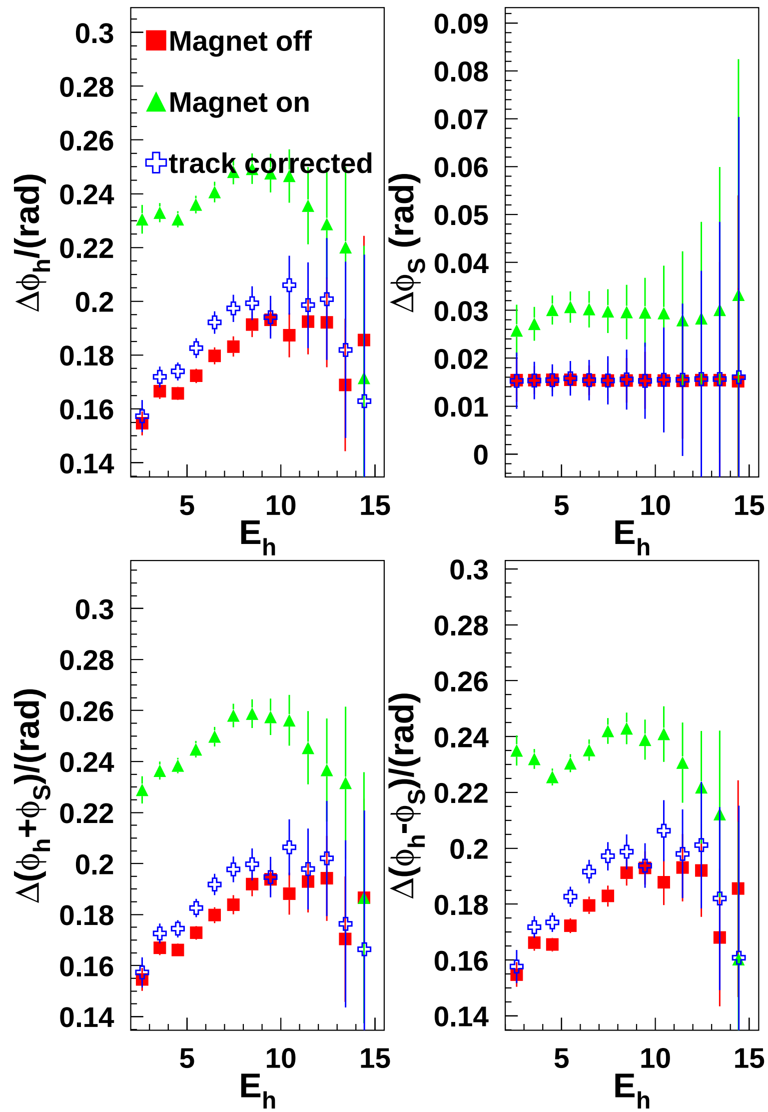




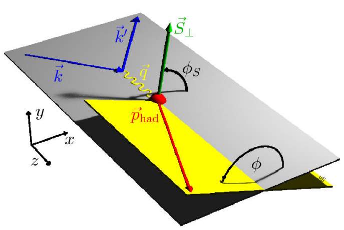


MC-studies: resolutions



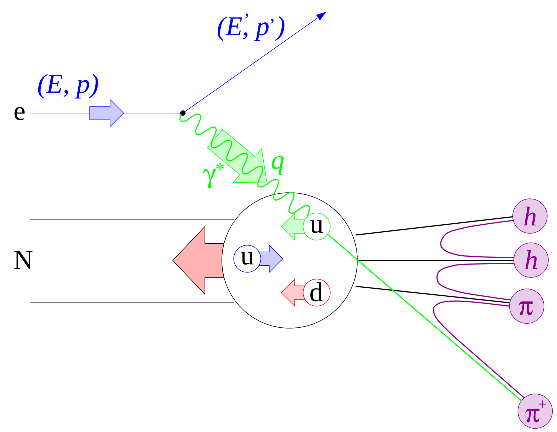


and <u>many</u> more systematic checks by Ralf, Uli, & Gunar!

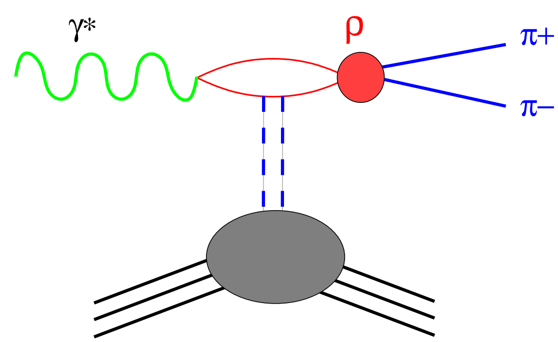


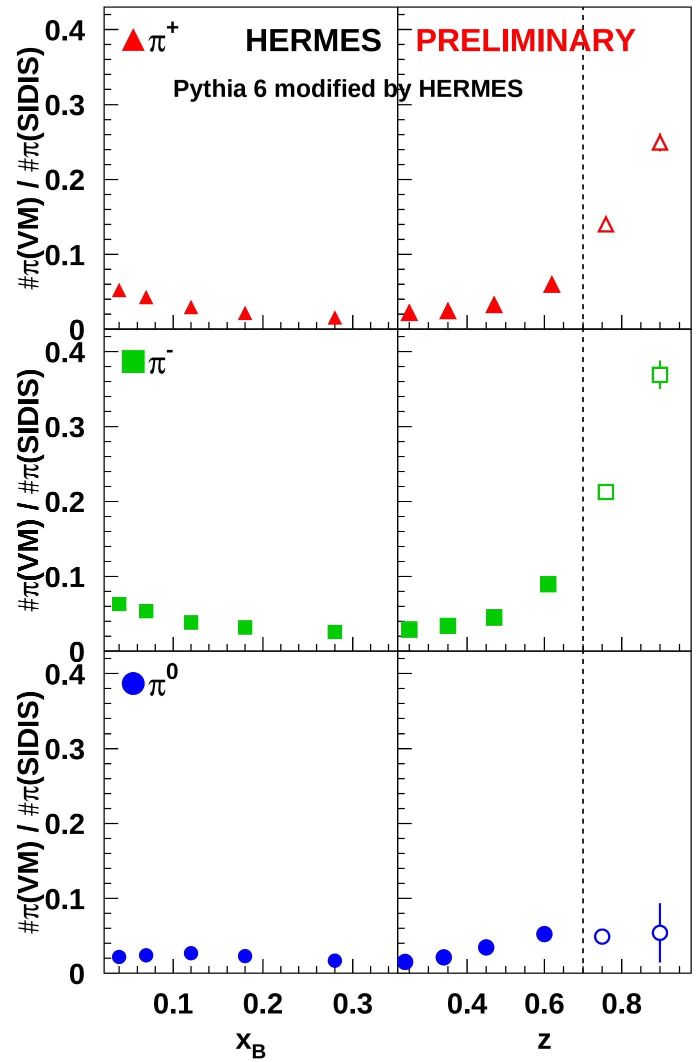
Uncertainty from Diffractive VM Contribution

Desired process: SIDIS $ep \rightarrow \pi^+ X$



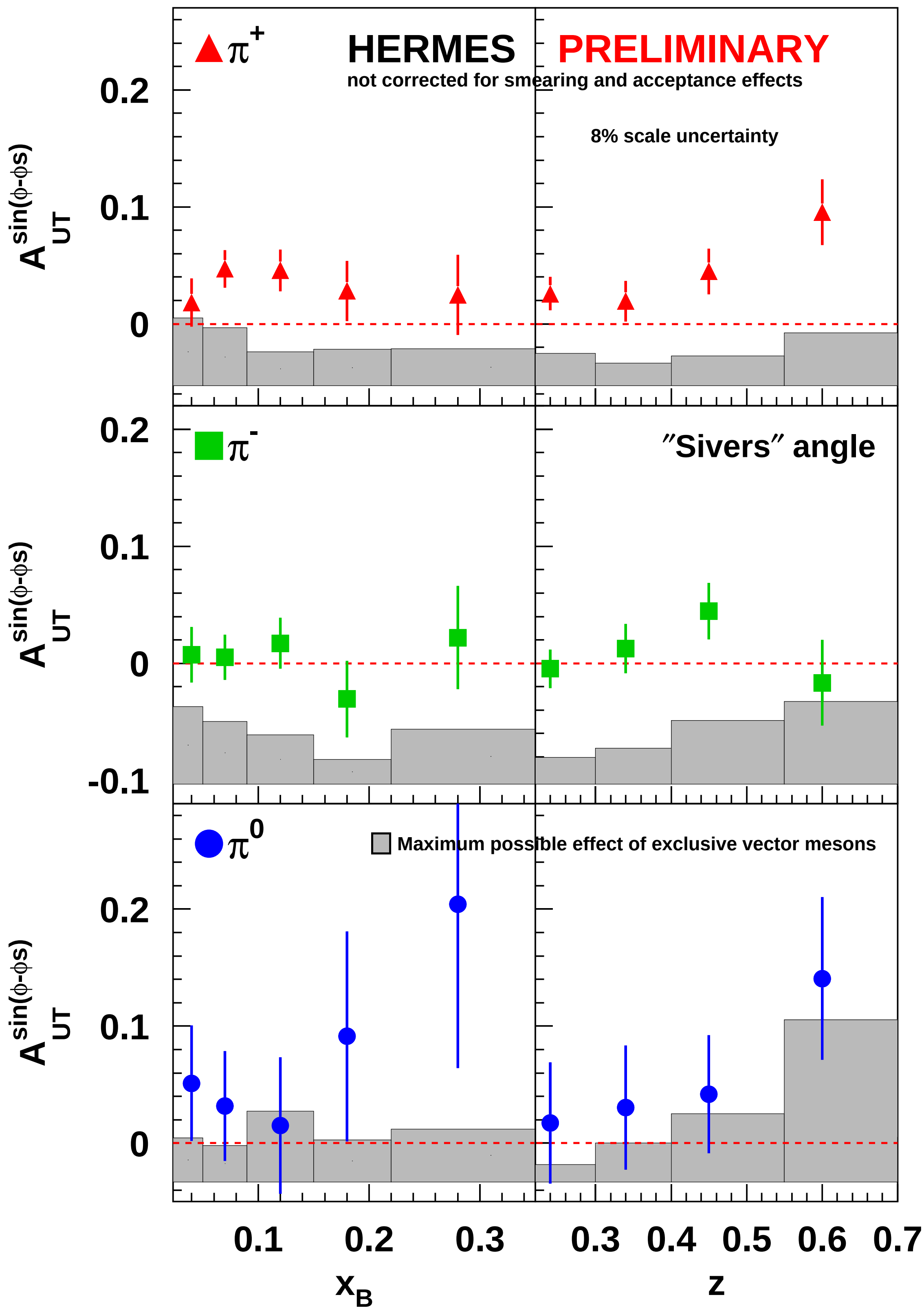
Diffractive ρ^0 production: different physics





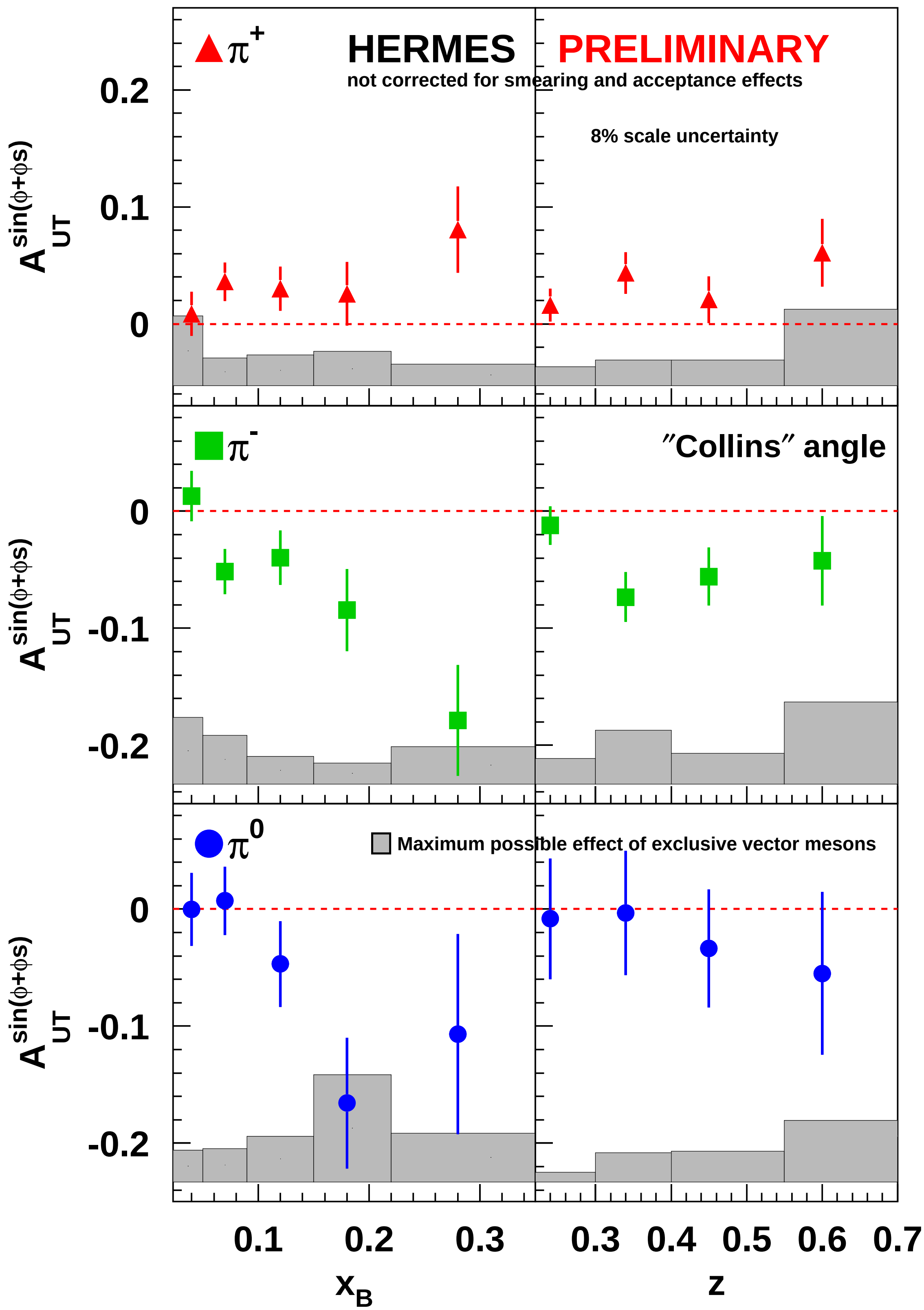
***Conservative approach:* calculate systematic error for full range of possible diffractive ρ asymmetries: $A_{UT}^{Collins,\rho}$ and $A_{UT}^{Sivers,\rho} = \pm 1$**

Unweighted Sivers Moments $A_{UT}^{\sin(\phi-\phi_S)}$



asym's small, but Sivers $\langle A^{\pi^+} \rangle$ is 3σ away from zero

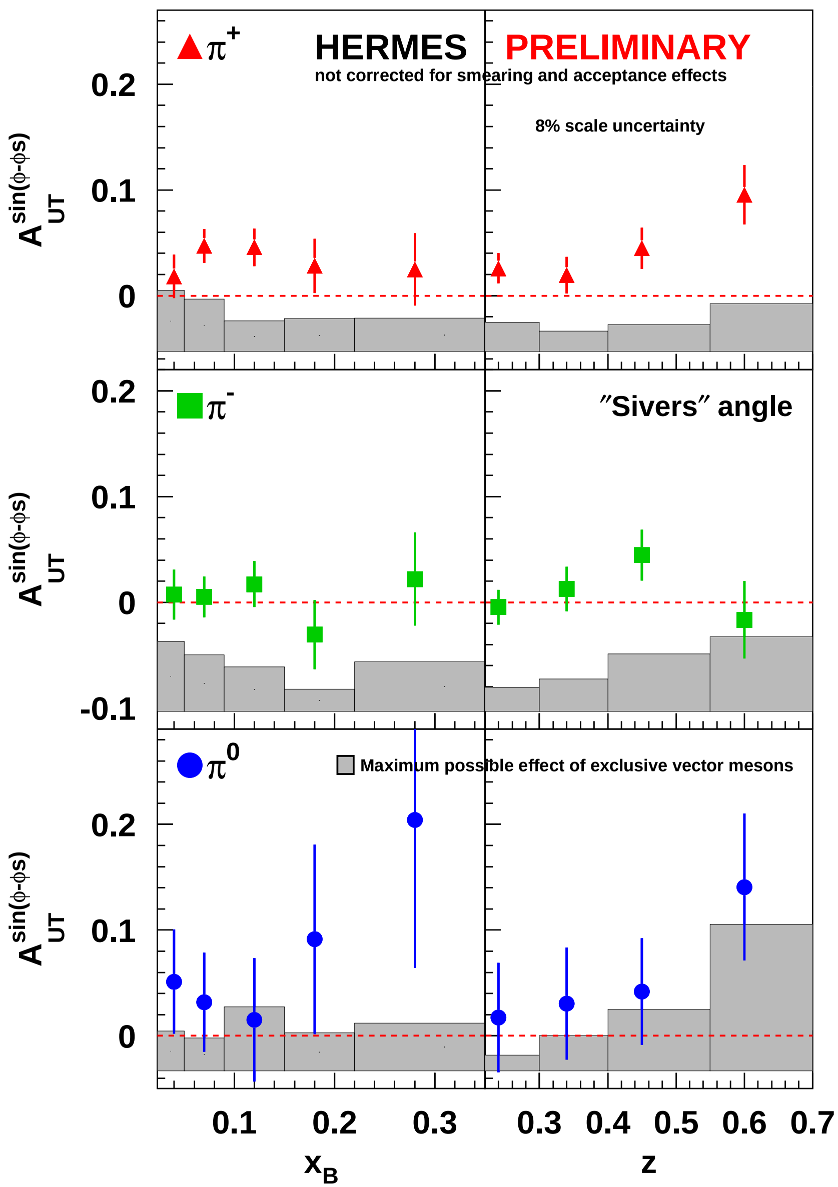
Unweighted Collins Moments $A_{UT}^{\sin(\phi+\phi_S)}$



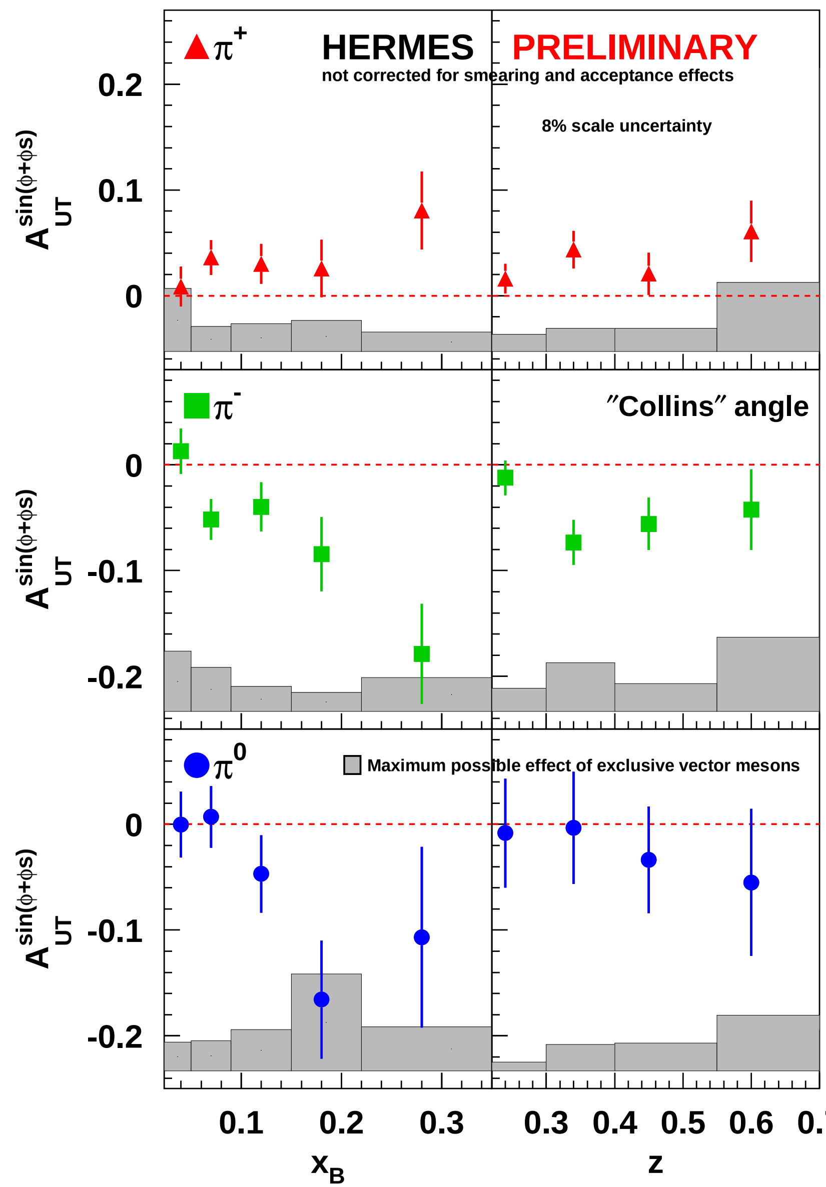
$\Rightarrow$ A^{π^+} ***small, but*** ***large negative π^0 and π^- asym's***

Results I: Unweighted Moments

"Sivers" Moments



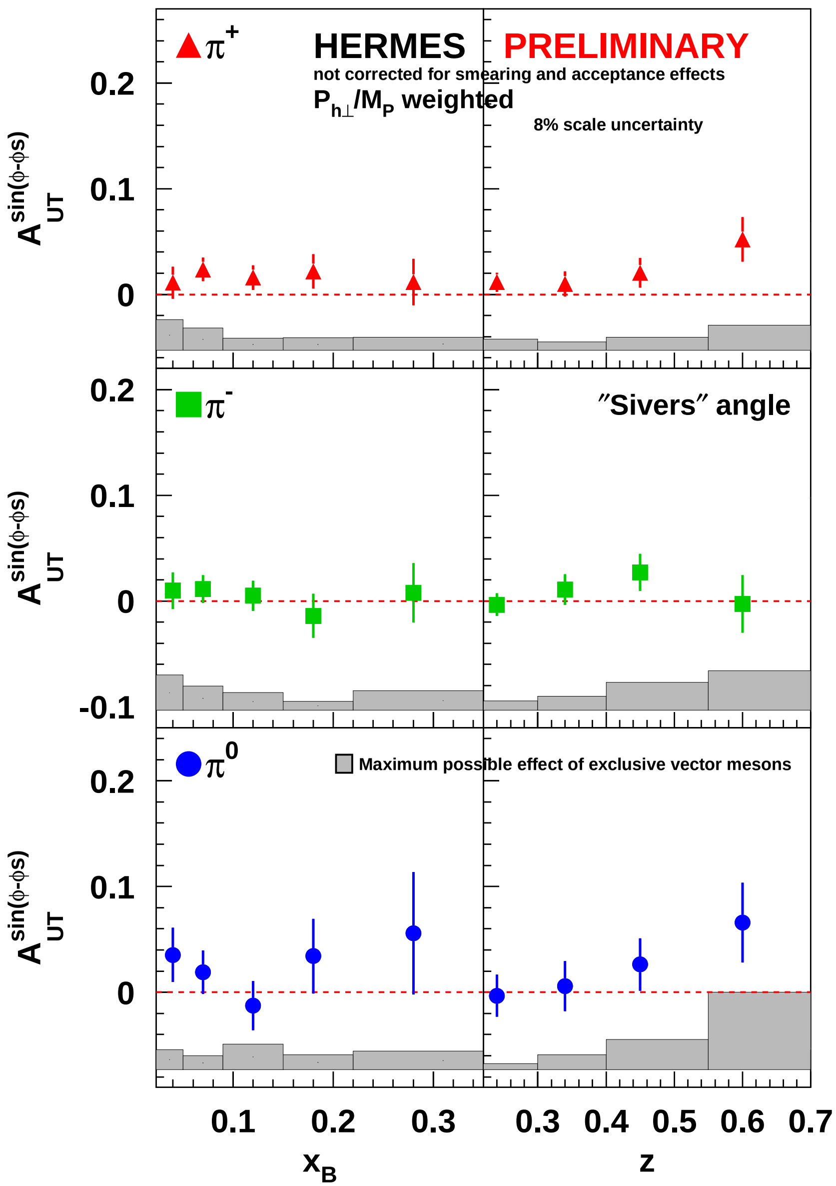
"Collins" Moments



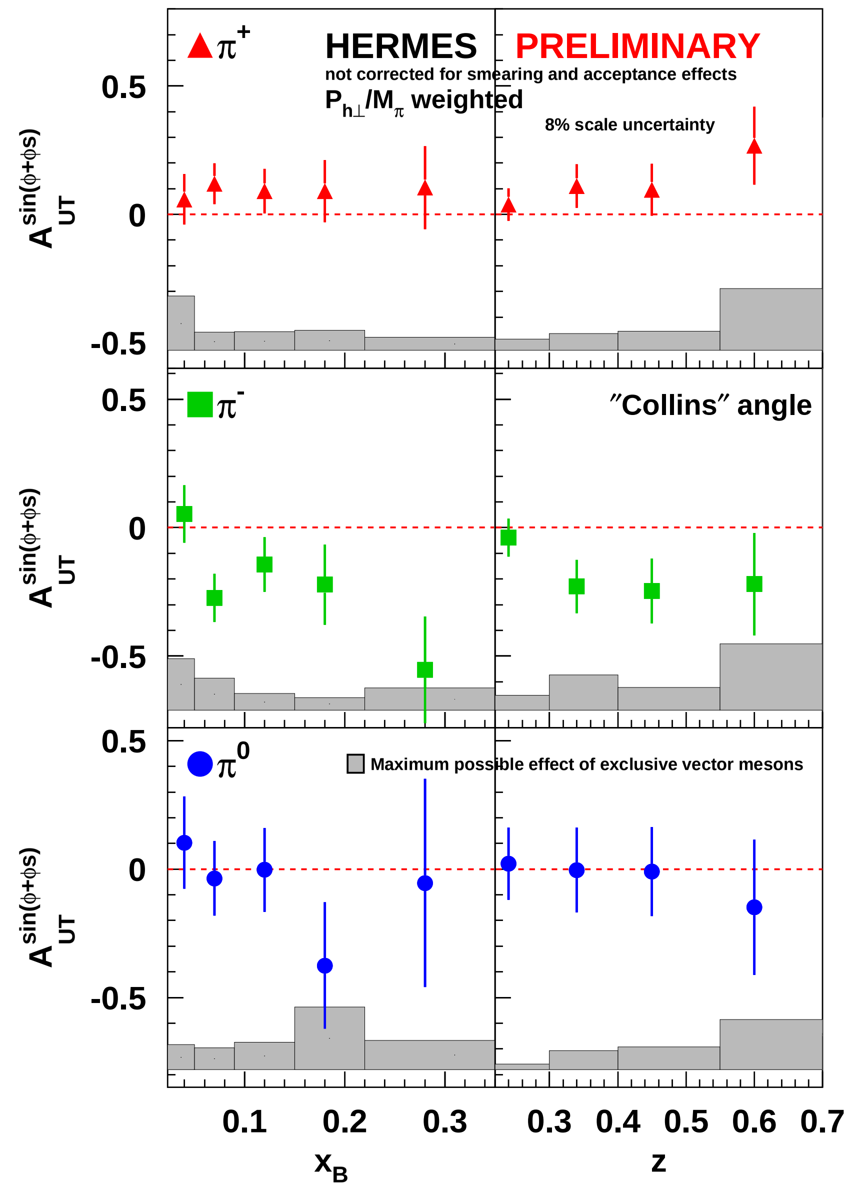
Sivers $\langle A^{\pi^+} \rangle$ ***3σ away from zero*** ... **Collins asym** ***large for π^0 and π^-***

Results II: p_T/M_π-weighted Moments

"Sivers" Moments



"Collins" Moments



(No correction yet for experimental acceptance in p_T)

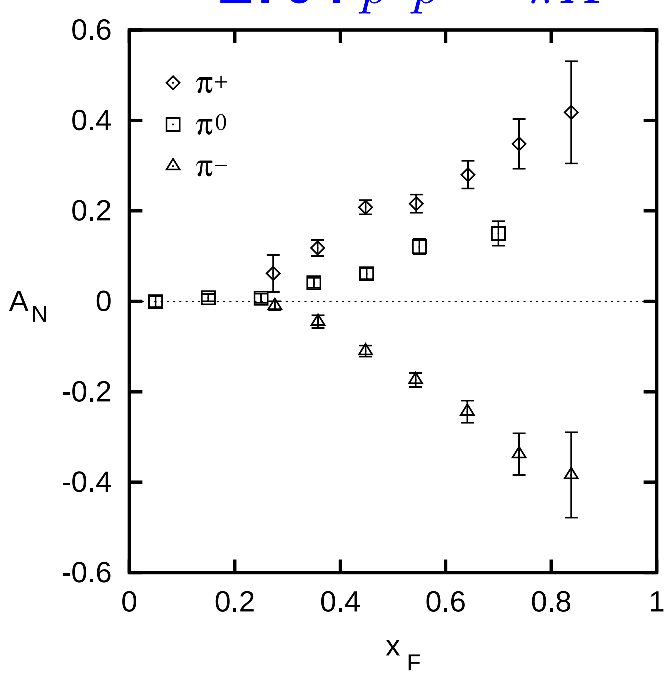
Interpretation of Collins Results

The Collins results for π^+, π^-, π^0 show an <u>unexpected</u> pattern ...

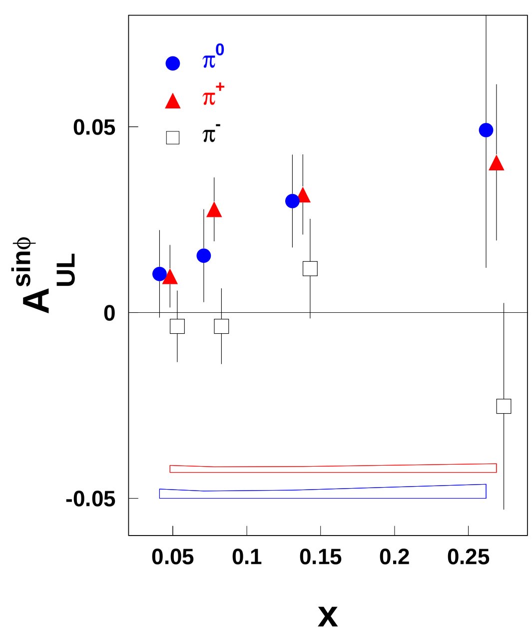
Expect<u>n</u>: ***u-quark dominance*** (esp. in DIS) and ***quark polarization*** $\Delta u > 0, \Delta d < 0$

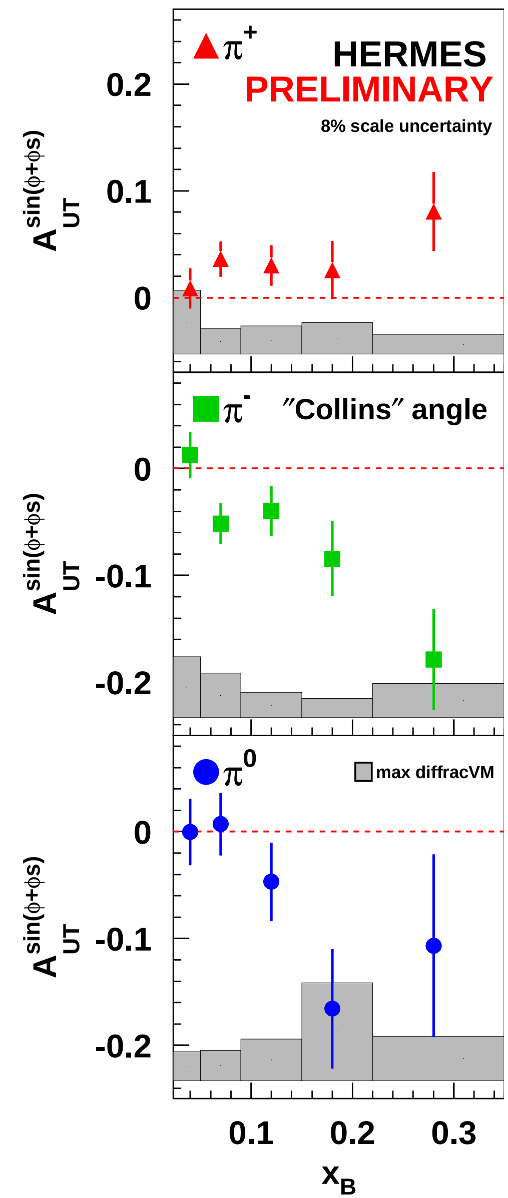
$\Rightarrow A^{\pi^+} \approx A^{\pi^0} > 0$ and $A^{\pi^-} \leq 0$ & smaller

E704 $p^\uparrow p \to \pi X$



$A_{\rm UL}$ **on proton**





New Data for $A_{\rm UT}^{\rm Collins}$ show

$A^{\pi^+} > 0$, but $A^{\pi^0} \approx A^{\pi^-} < 0$ and <u>larger</u> ...

Interpretation of Collins Results

Minimalist Assumptions

- $A_{\mathrm{UT}}^{\mathrm{Collins}}$ is ***leading twist***
- Collins FF obeys ***favoured / disfavoured*** symmetry:

$$H_{\mathrm{fav}} \equiv H_{1\perp}^{u\to\pi^+} = H_{1\perp}^{d\to\pi^-} = H_{1\perp}^{\overline{u}\to\pi^-} = H_{1\perp}^{\overline{d}\to\pi^+}$$
$$H_{\mathrm{dis}} \equiv H_{1\perp}^{u\to\pi^-} = H_{1\perp}^{d\to\pi^+} = H_{1\perp}^{\overline{u}\to\pi^+} = H_{1\perp}^{\overline{d}\to\pi^-}$$

$$\Rightarrow A^{\pi^+} = k\frac{(4\delta u + \delta\overline{d})H_{\mathrm{fav}} + (\delta d + 4\delta\overline{u})H_{\mathrm{dis}}}{(4u+\overline{d})D_{\mathrm{fav}} + (d+4\overline{u})D_{\mathrm{dis}}}, \qquad A^{\pi^-} = k\frac{\cdots}{\cdots}, \quad \mathrm{etc}$$

Consider Asym Ratios $\alpha^- \equiv A^{\pi^-}/A^{\pi^+}$, $\alpha^0 \equiv A^{\pi 0}/A^{\pi^+}$

$$r \equiv \frac{d+4\overline{u}}{u+\overline{d}/4} \qquad \eta \equiv \frac{D_{\mathrm{dis}}}{D_{\mathrm{fav}}} \qquad \Rightarrow \qquad \alpha^- = \left(\frac{4\eta_H + \delta r}{4\eta + r}\right)\left(\frac{4+r\eta}{4+\delta r\eta_H}\right)$$

$$\delta r \equiv \frac{\delta d + 4\delta\overline{u}}{\delta u + \delta\overline{d}/4} \quad \eta_H \equiv \frac{H_{\mathrm{dis}}}{H_{\mathrm{fav}}} \qquad \alpha^0 = \frac{(4+\delta r)(1+\eta_H)}{(4+r)(1+\eta)}\left(\frac{4+r\eta}{4+\delta r\eta_H}\right)$$

$\Rightarrow$ Constraint Equ$\underline{\text{n}}$ involving ***<u>only unpolarized</u>*** q'ties

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

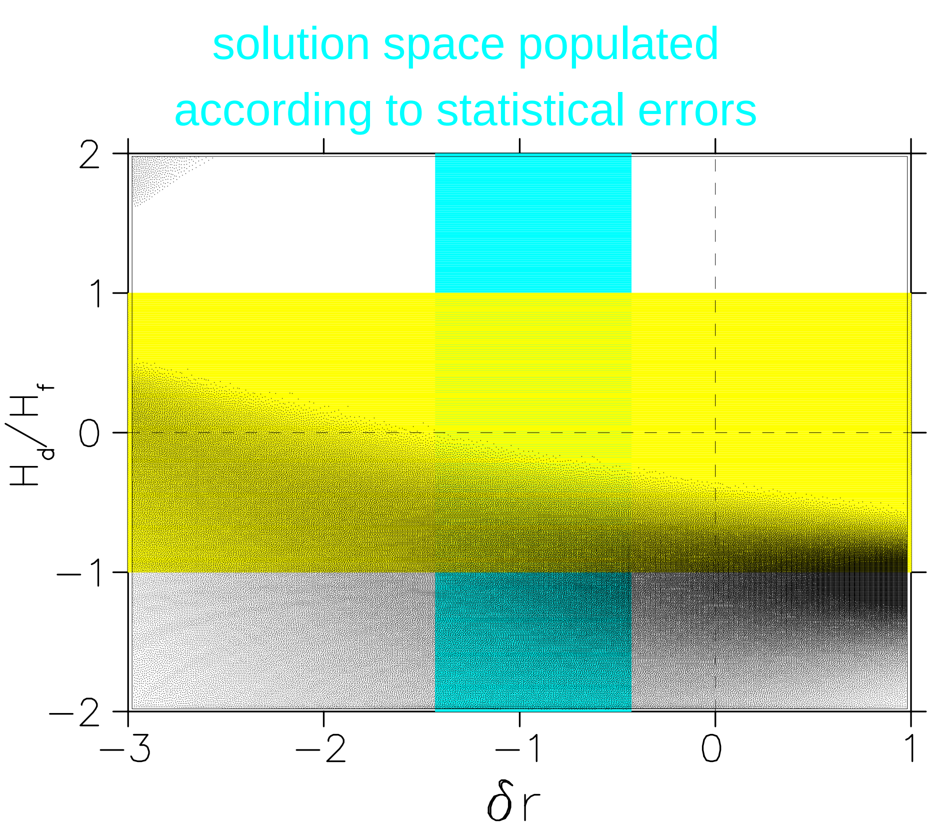
$\Rightarrow$ Solution Space in η_H vs δr can be determined:

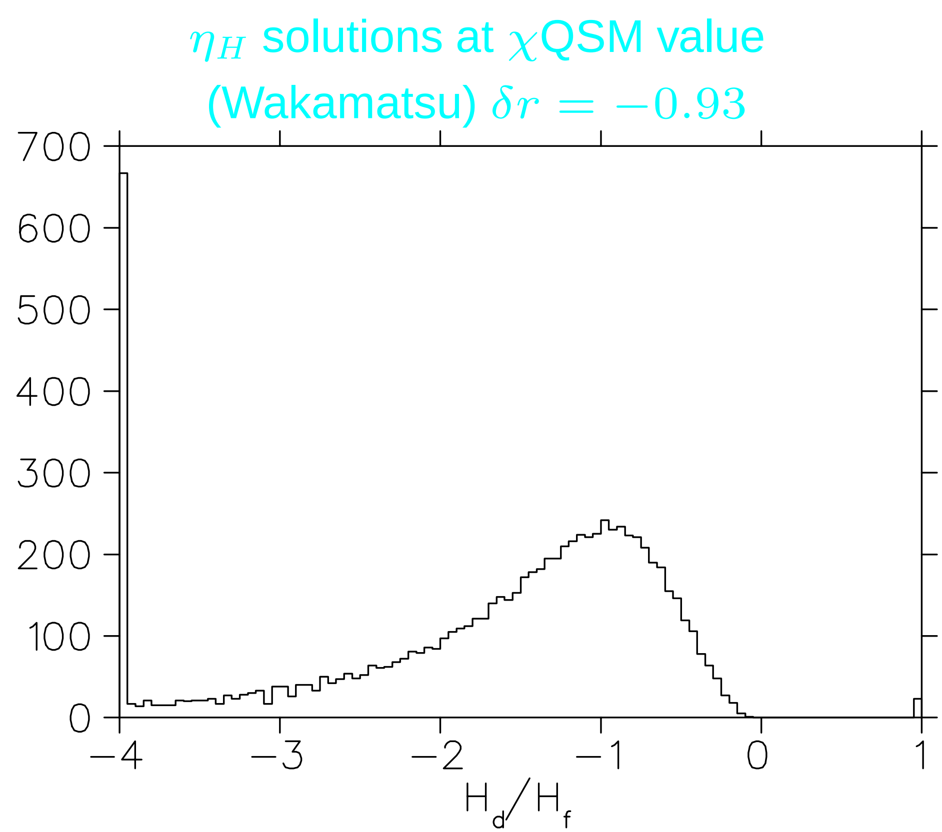
$$\eta_H = \frac{\delta r - 4(\alpha^- C)}{(\alpha^- C)\delta r - 4} \qquad \text{and} \qquad \eta_H = \frac{\delta r - 4(\alpha^0(1+C) - 1)}{(\alpha^0(1+C)-1)\delta r - 4}$$

Interpretation of Collins Results

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 $\eta_H = H_{\rm dis}/H_{\rm fav}$

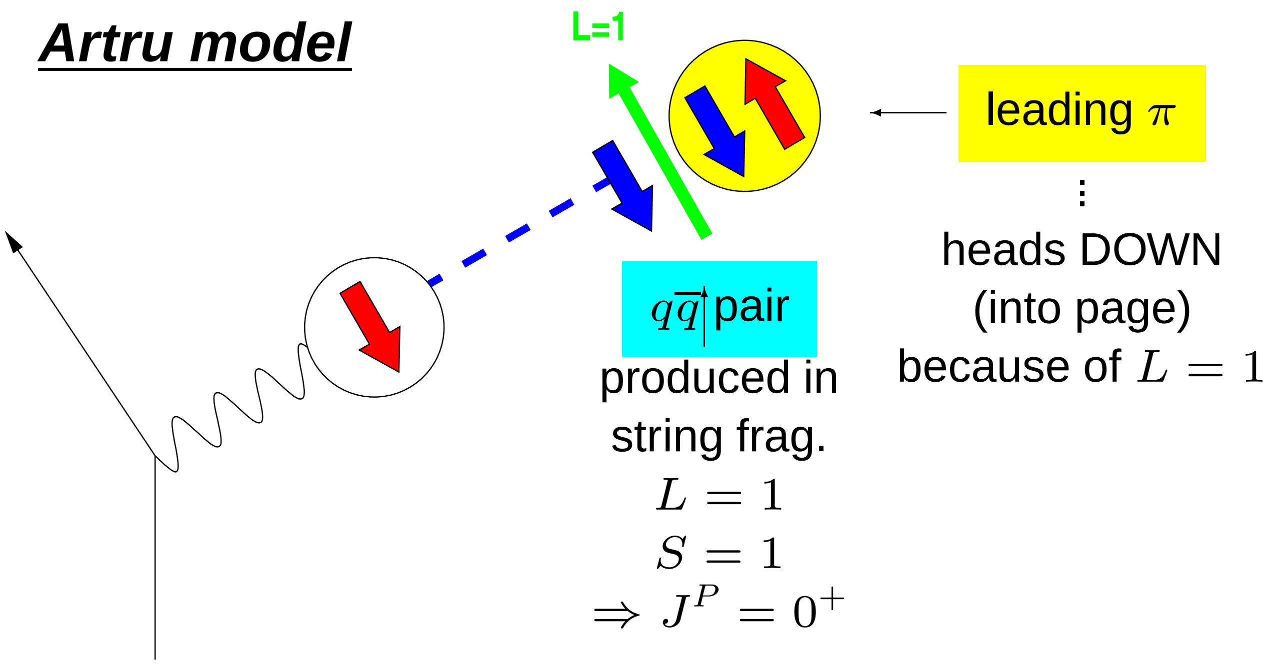




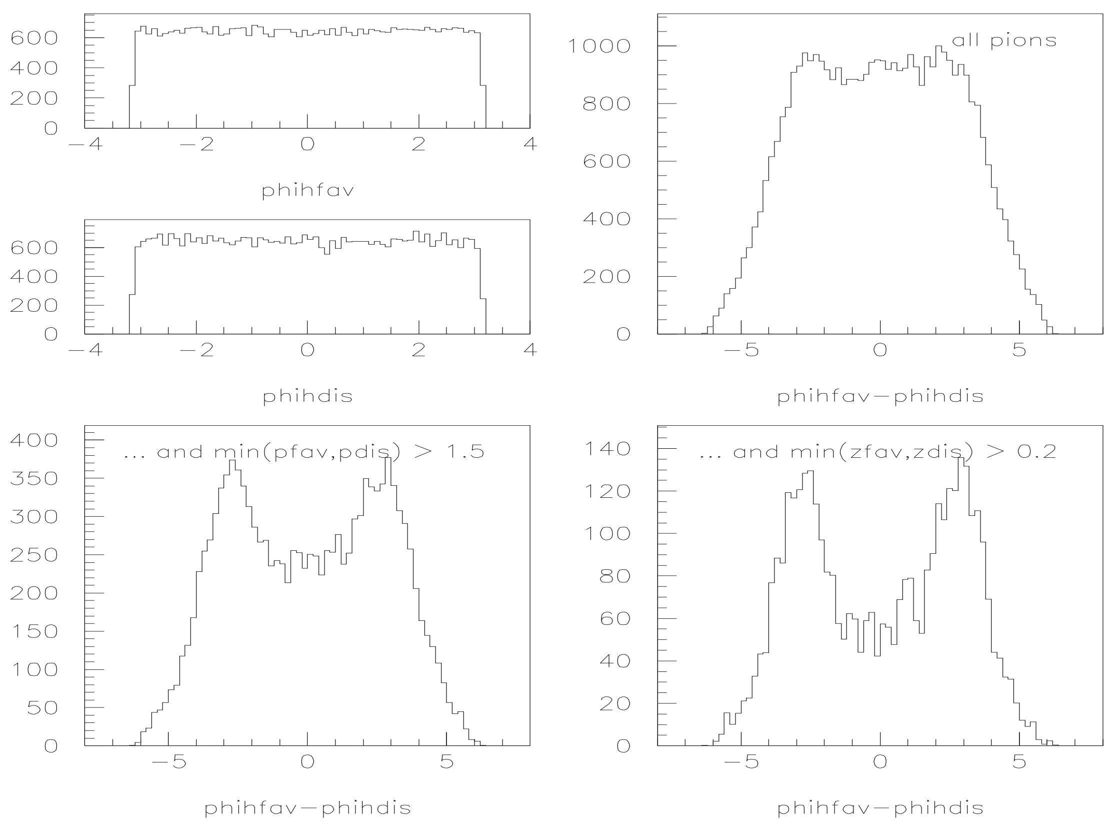
Neglecting possible diffractive contamination, there seems to be a pronounced indication that $H_{\rm fav} \approx -H_{\rm dis}$

Interpretation of Collins Results

Artru model



unpolarized Lund Monte Carlo result on
ϕ correlation between favoured and disfavoured pions ...



Perhaps $H_{\rm dis} \approx -H_{\rm fav}$ is not only reasonable, but likely ?

Extracting Distribution Functions

Further analysis using all measured asymmetries (not just ratios):

$$A_{UT}^{\mathrm{Collins,wt}}(x,z) = \frac{\sum_q e_q^2\, \mathbf{h_1^q(x)}\, \mathbf{H_1^{\perp(1),q\to h}(z)}}{\sum_q e_q^2\, f_1^q(x)\, D_1^{q\to h}(z)} \frac{1-y}{1-y+y^2/2}$$

$$A_{UT}^{\mathrm{Sivers,wt}}(x,z) = \frac{\sum_q e_q^2\, \mathbf{f_{1T}^{\perp,q}(x)}\, \mathbf{D_1^{q\to h}(z)}}{\sum_q e_q^2\, f_1^q(x)\, D_1^{q\to h}(z)}$$

- for ***transversity*** extraction, ***Collins FF*** must be determined
  - ⇒ need normalization point from ***another process***
  - ⇒ analysis of ***BELLE*** e^+e^- data eagerly awaited! (universality seems to be under control for SIDIS and e^+e^-)
- for ***Sivers*** extraction, everything is known to generate purities
- look forward to ***COMPASS*** data on ***deuterium*** target to help disentangle conrtibutions by flavour

Other Ways to Measure $h_1(x)$

① Interference Fragmentation Function to two pions

Analysis is in progress ...

② Higher Twist Fragmentation Function $\tilde{E}$

$$d\sigma_{\mathrm{LT}} \sim \cos(\phi_S^l) \left[\frac{Mx}{Q} \cdot g_T(x)\, D_1(z) + \frac{M_h}{zQ} \cdot \mathbf{h_1}(x)\, \tilde{E}(z) \right]$$

... calculation of Ji & Zhu suggests $\tilde{E}(z) = \frac{m_q}{M} z D_1(z) \approx \frac{1}{3} z D_1(z)$

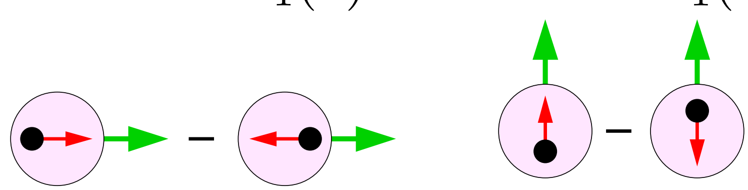
③ Final State Polariz$^{\underline{n}}$

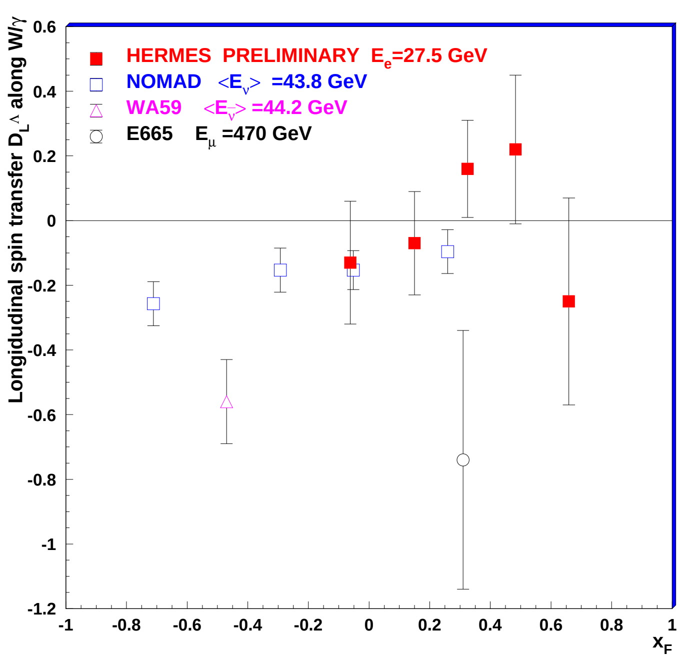
(spin transfer to Λ)

$$d\sigma_{\mathrm{UTT}} \sim \cos(\phi_S^l + \phi_{S_h}^l) \cdot \mathbf{h_1}(x)\, H_1(z)$$

Method requires significant ***spin transfer*** from ***quark to*** Λ in fragmentation process ...

longitudinal spin transfer: $G_1(z)$ *transverse spin transfer:* $H_1(z)$





⋮

But longitudinal spin-transfer results from HERMES 2000 data indicate **small** $G_1(z)$ ...

not too promising ☹

Conclusions

A_{UT} *asymmetries are small and statistics are still limited but ...*

- First observation of ***non-zero Sivers*** effect !
- ***Large*** ***Collins*** asymmetries measured for π^0**and** π^-
- Tentative conclusion: ***disfavoured*** Collins fragmentation function of ***opposite sign*** and similar magnitude to ***favoured*** function
- Contamination of asymmetries from ***diffractive vector meson*** production must be better constrained and understood
- ***More data*** eagerly anticipated ... !