Delia Hasch

INFN
Frascati

recent results from HERMES

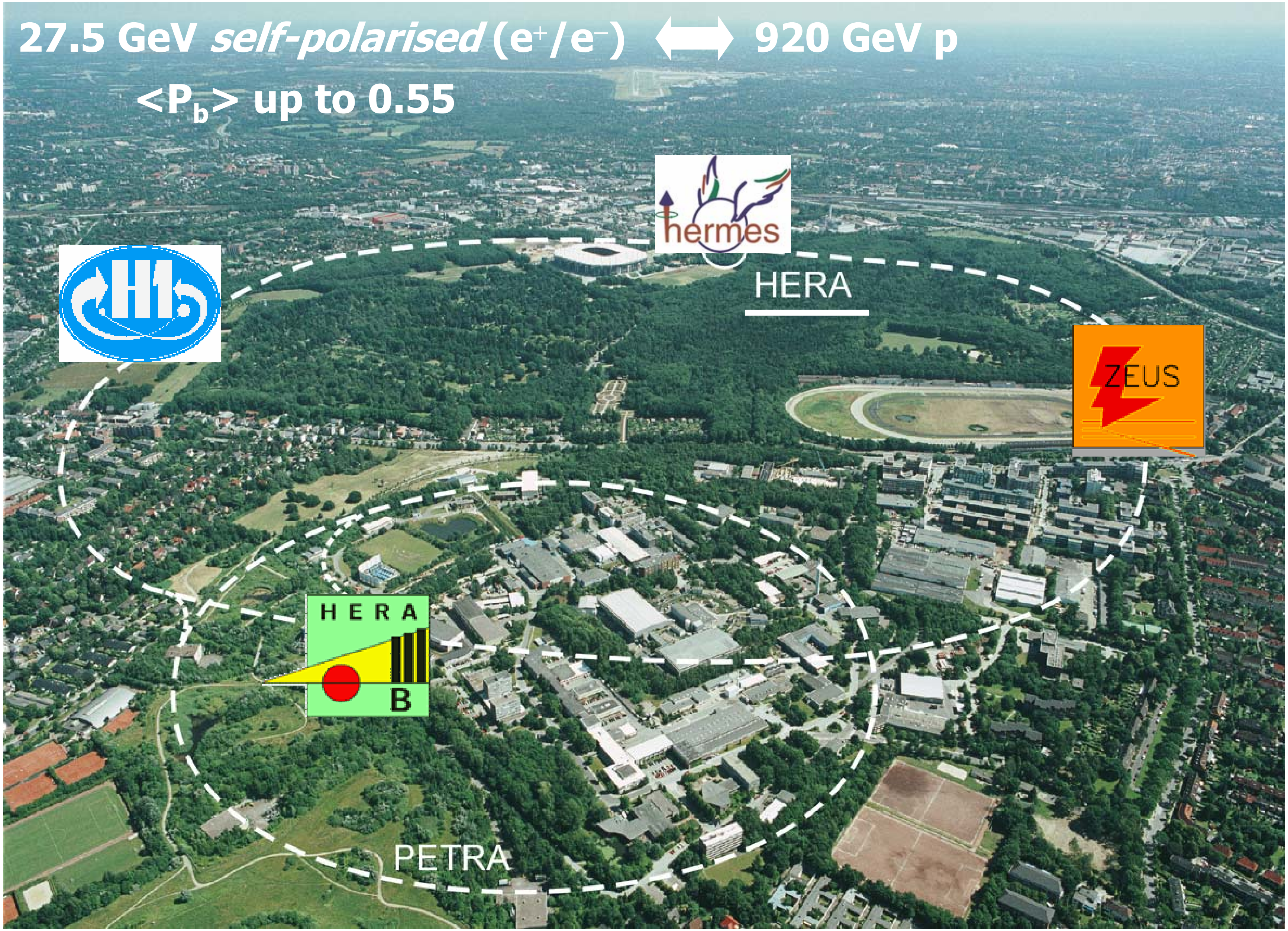
hermes

RBRC workshop on “Progress in high pT Physics at RHIC”, BNL, USA, March 17-19 2010

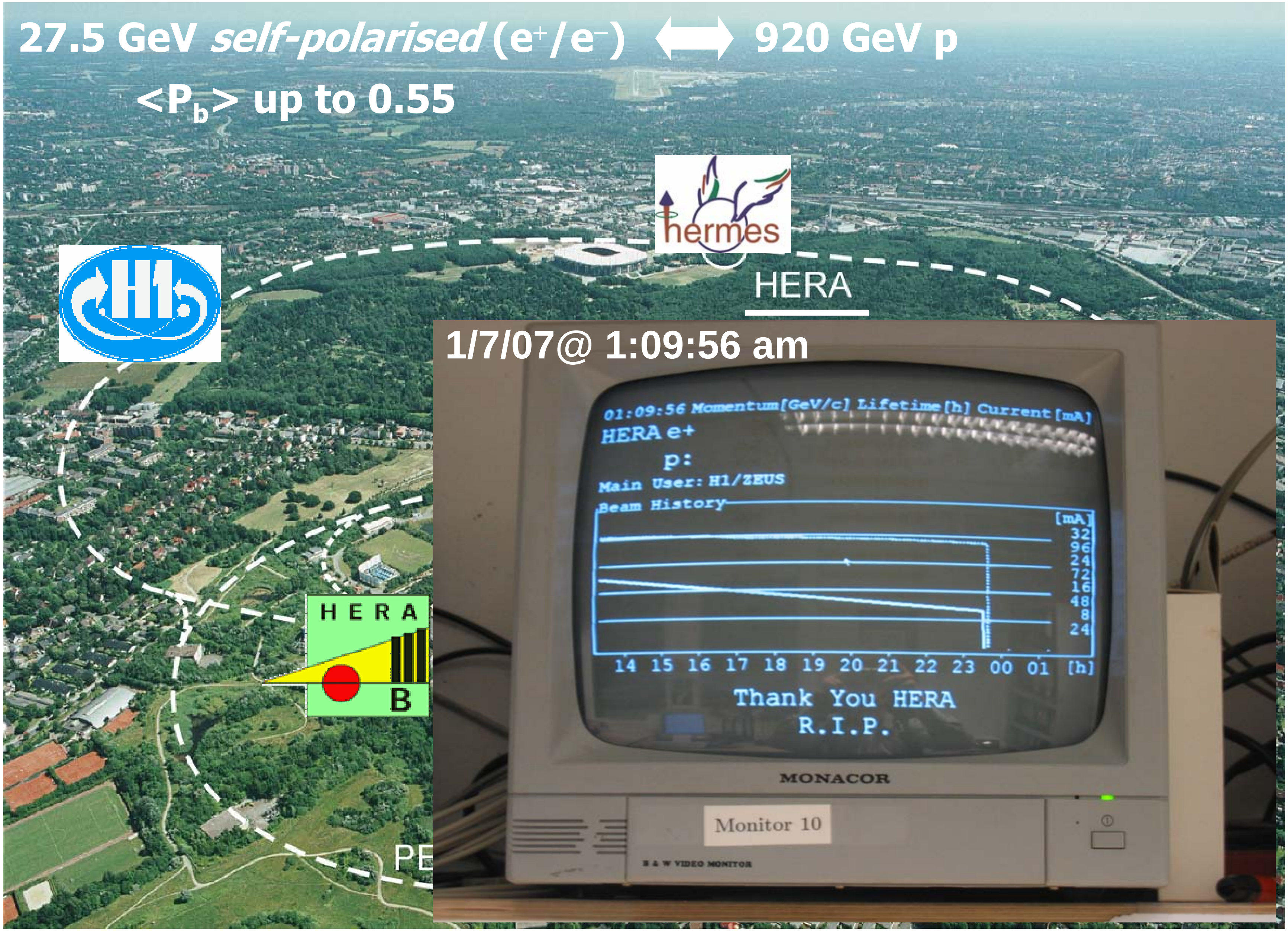
HERMES @HERA: a reminder

27.5 GeV *self-polarised* (e^+/e^-) ⟷ 920 GeV p

$\langle P_b \rangle$ up to 0.55



HERMES @HERA: a reminder



27.5 GeV *self-polarised* (e^+/e^-) ↔ 920 GeV p

$\langle P_b \rangle$ up to 0.55

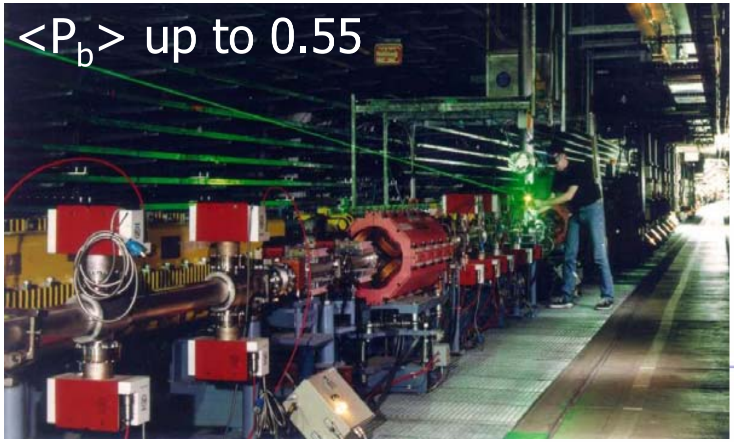
1/7/07@ 1:09:56 am

```
01:09:56 Momentum[GeV/c] Lifetime[h] Current[mA]
HERA e+
     p:
Main User: H1/ZEUS
Beam History
```

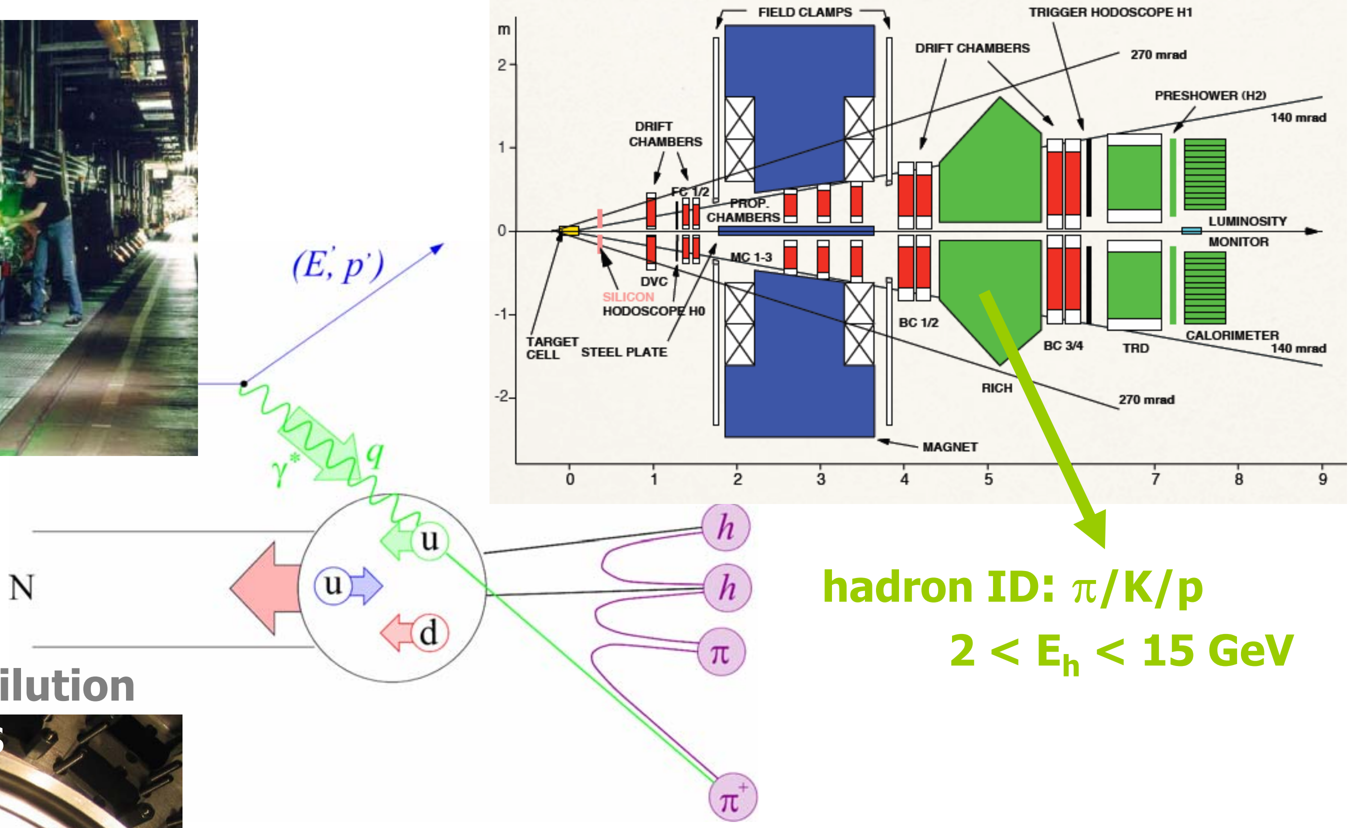
Thank You HERA
R.I.P.

HERMES @HERA: a reminder

27.5 GeV $(e^+/e^-)\rightarrow$



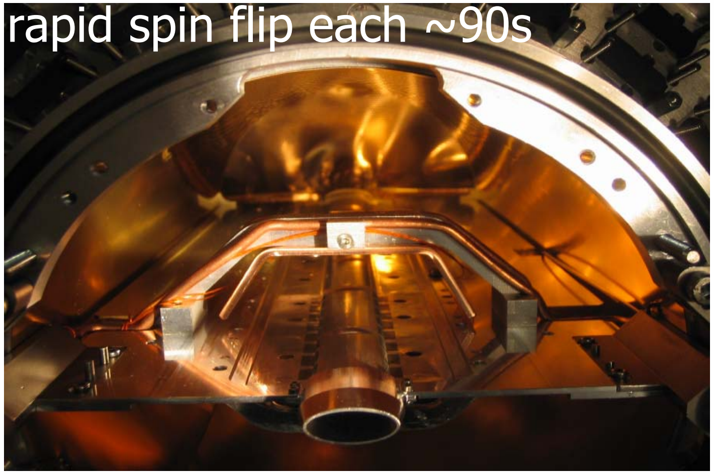
$\langle P_b \rangle$ up to 0.55



hadron ID: π/K/p

$2 < E_h < 15$ GeV

storage cell target: no dilution



rapid spin flip each ~90s

$\vec{H}$ $\langle|P_t|\rangle \sim 0.85$

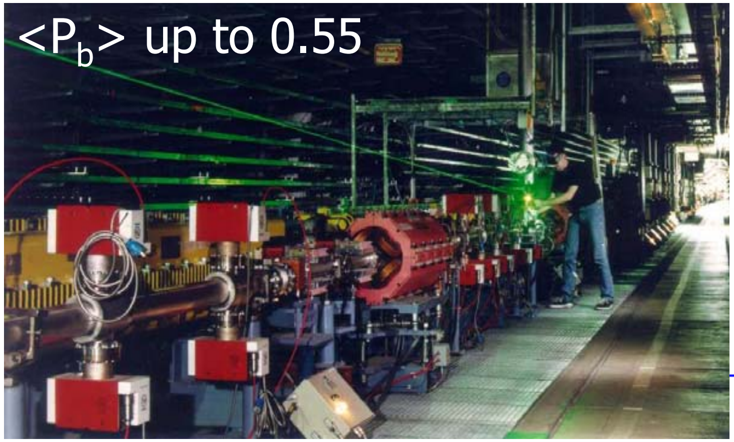
$\vec{D}$ $\langle|P_t|\rangle \sim 0.84$

$H^{\uparrow}$ $\langle|P_t|\rangle \sim 0.74$

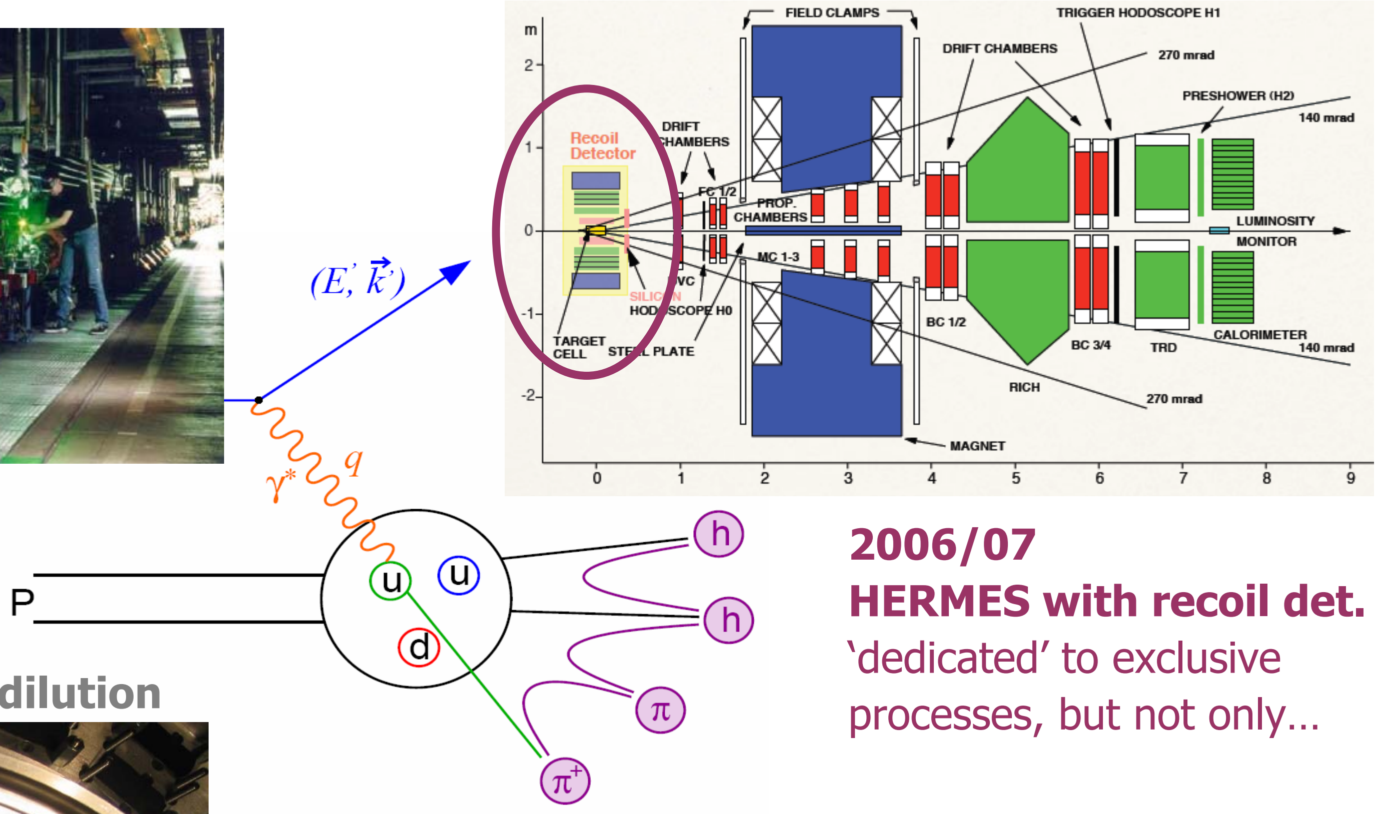
unpol: H, D, He, Ne, N, Kr, Xe

HERMES @HERA: a reminder

27.5 GeV (e^+/e^-)$\longrightarrow$



$<P_b>$ up to 0.55

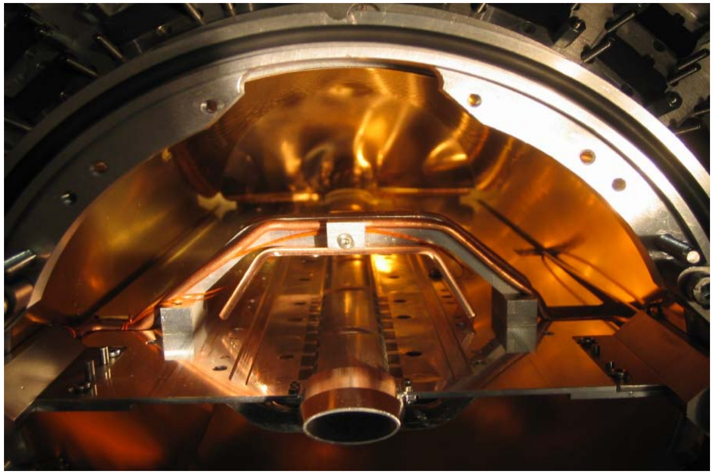


2006/07

HERMES with recoil det.

'dedicated' to exclusive processes, but not only…

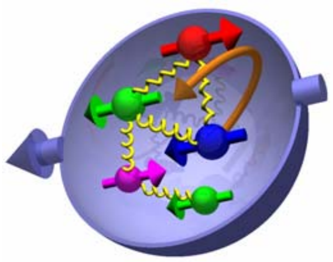
storage cell target: no dilution



unpol: H, D

→ **huge satistics**

the quest for the spin of the nucleon



$$\frac{1}{2} = \frac{1}{2} \sum_q \Delta\Sigma + \Delta G + L_q + L_g$$

- inclusive DIS from longitudinally polarised D target: [PRD75(2007)]

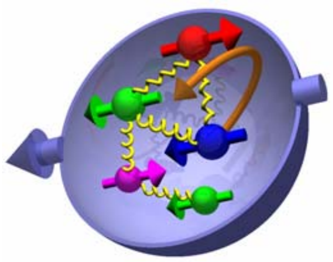
$$\Delta\Sigma = 0.330 \pm 0.025^{(\text{exp.})} \pm 0.011^{(\text{theory})} \pm 0.028^{(\text{evol.})}$$

SIDIS A_{LL} → flavour decomposition

- high pT hadron production: [arXiv:1002.3921, submitted to JHEP]

$$\Delta g / g \,|_{x=0.22} = 0.049 \pm 0.034^{(\text{stat})} \pm 0.010^{(\text{sys-exp})} \,{}^{+0.126}_{-0.099}{}^{(\text{sys-model})}$$

the quest for the spin of the nucleon



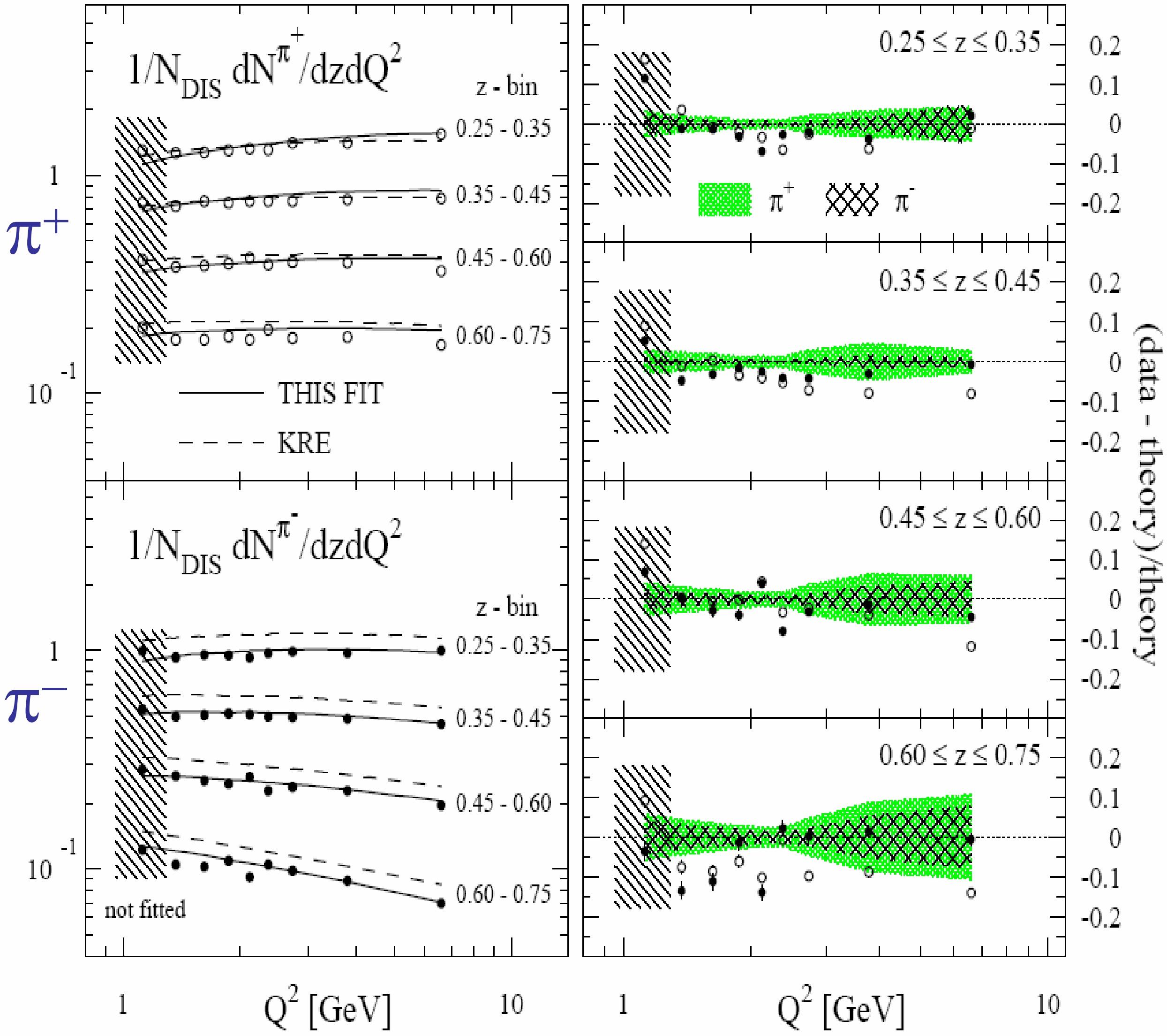
$$\frac{1}{2} = \frac{1}{2} \sum_q \underset{\substack{\uparrow \\ \sim 30\%}}{\Delta\Sigma} + \underset{\substack{\uparrow \\ \approx \text{zero}}}{\Delta G} + L_q + L_g$$

outline:

- longitudinal momentum & spin structure: role of strange quarks
- transverse spin phenomena & TMDs:
  - effects in inclusive processes
  - transversity & friends: spin-orbit correlations
  - intrinsic transverse momentum effects
- exclusive processes & GPDs: nucleon tomography
- nuclear effects

hadron production

preliminary



no SIDIS xsection

measurements → π, K

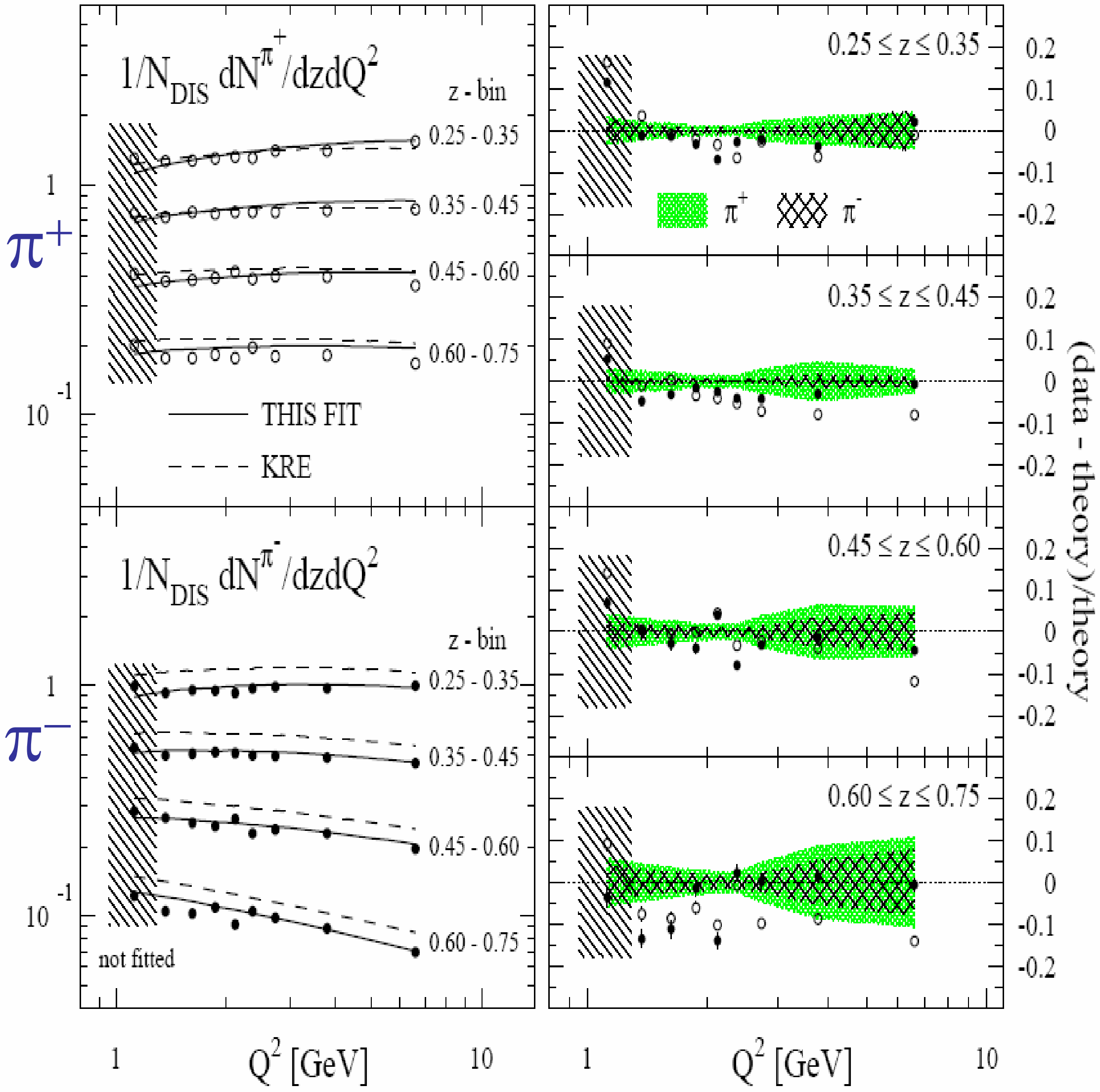
multiplicities compared to theory:

DSS: *FF* from combined NLO analysis of single-inclusive hadron production in e^+e^-, pp and SIDIS

[deFlorian,Sassot,Stratmann PRD75,76(2007)]

hadron production

preliminary



no SIDIS xsection

measurements → π, K *multiplicities* compared to theory

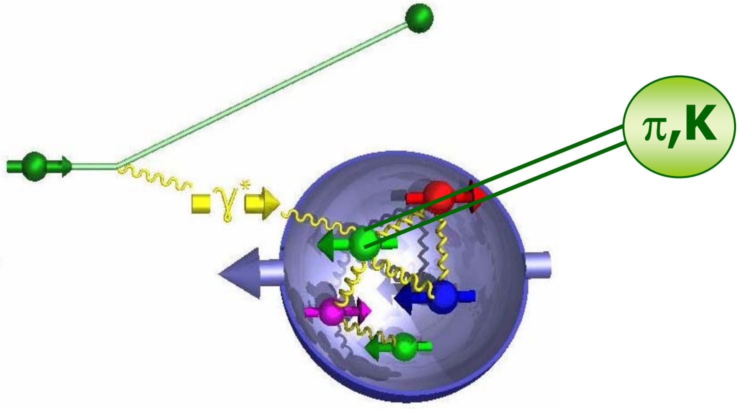
outlook:

→ publication in preparation ($\pi^{+/-/0}$, $K^{+/-}$):

- ~2 x more data
- 2D binning (x,z), (z,pT)

→ ~ 6 x more data on tape from last 1.5a running with unpolarised 'high density' H, D targets

longitudinal momentum
&
spin structure



strange quark distributions

→ use isoscalar probe + target: $S^p(x) = S^n(x)$; $S(x) = s(x) + \overline{s}(x)$

→ ingrediants: $K^+ + K^-$ multiplicities, $A_{1,d}^{K^+ + K^-}(x, z, Q^2)$, $A_{1,d}(x, Q^2)$

→ strange *FF* : $\int_{0.2}^{0.8} dz\, D_S^K(z) = 1.27 \pm 0.13$ [DSS, PRD75(2007)]

→ **LO extraction of** $S(x)$ & $\Delta S(x)$ **with only assumptions:**

- isospin symmetry between proton and neutron
- charge conjugation invariance in fragmentation

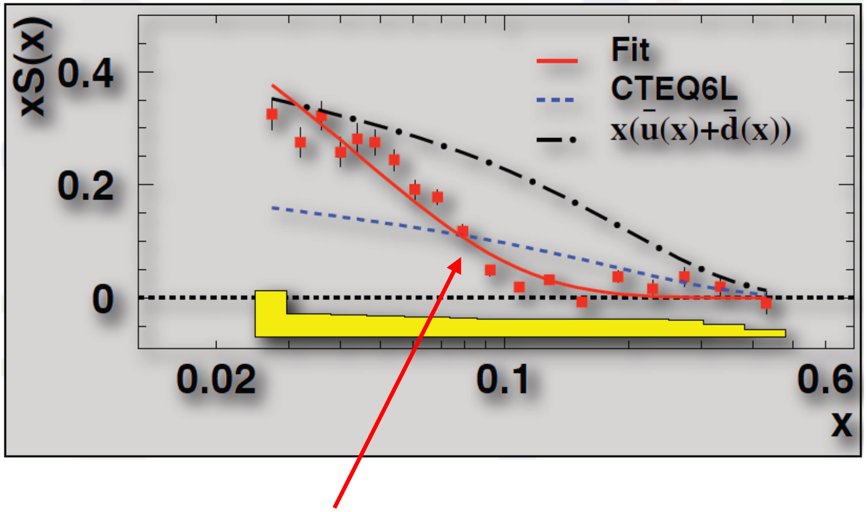
strange quark distributions

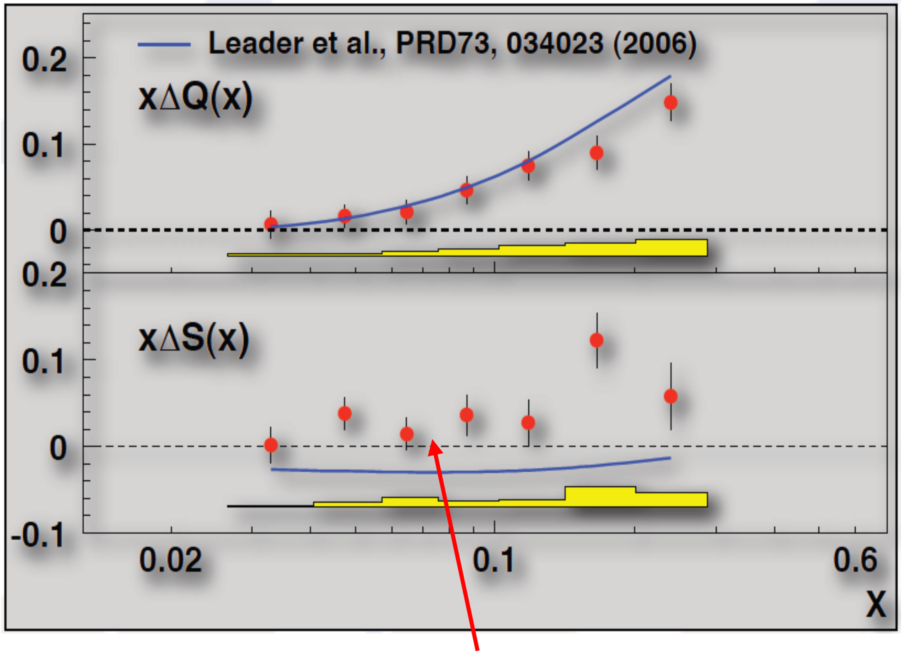
→ use isoscalar probe + target: $S^p(x) = S^n(x)$; $S(x) = s(x) + \bar{s}(x)$

→ ingrediants: $K^+ + K^-$ multiplicities, $A_{1,d}^{K^+ + K^-}(x, z, Q^2)$, $A_{1,d}(x, Q^2)$

→ strange *FF*: $\int_{0.2}^{0.8} dz\, D_S^K(z) = 1.27 \pm 0.13$ [DSS, PRD75(2007)]

hermes **LO extraction** [PLB666(2008)]





S(x) NOT average of an

isoscalar non-strange see

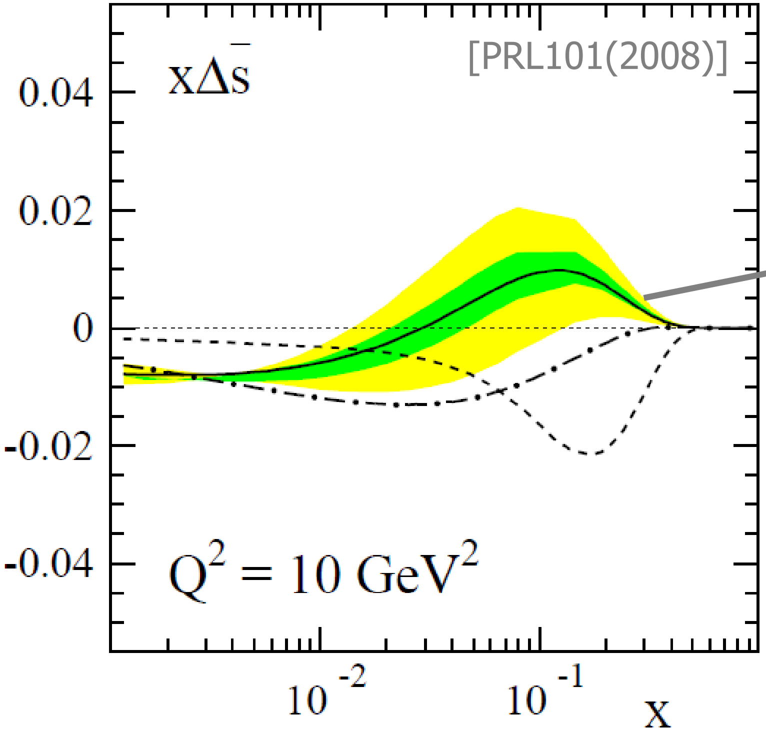
ΔS(x) ≈ zero/ slightly positive in contrast
to inclusive DIS analyses

strange quark distributions

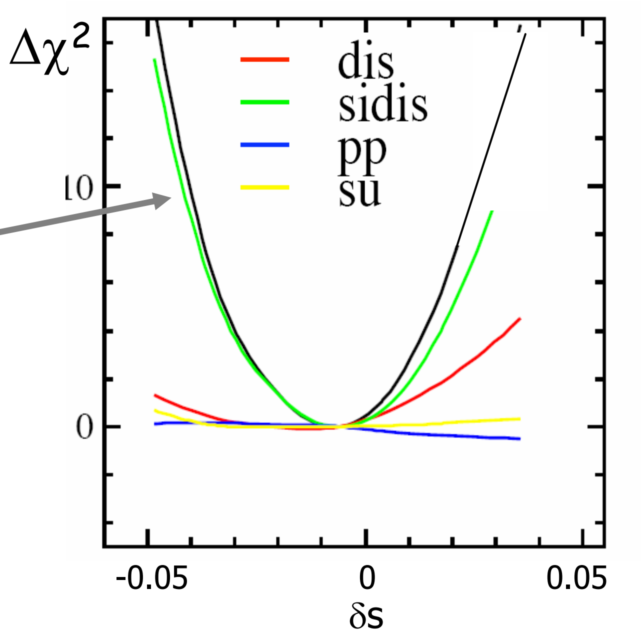
→ use isoscalar probe + target: $S^p(x) = S^n(x)$; $S(x) = s(x) + \bar{s}(x)$

→ ingrediants: $K^+ + K^-$ multiplicities, $A_{1,d}^{K^+ + K^-}(x, z, Q^2)$, $A_{1,d}(x, Q^2)$

DSSV – NLO fit result:



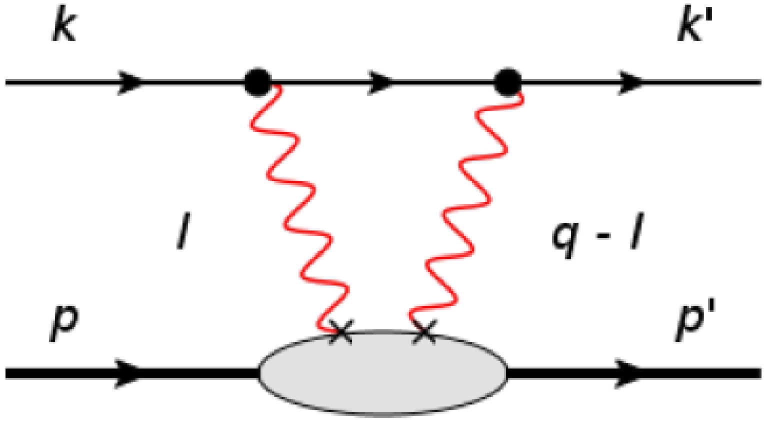
striking impact of SIDIS data



transverse spin phenomena

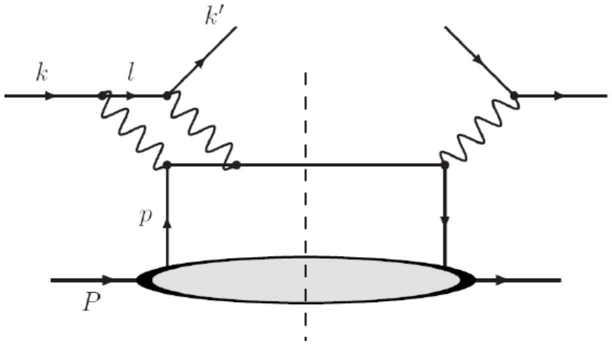
[courtesy of A. Bacchetta]

transverse effects in *inclusive* DIS



two-photon exchange

- candidate to explain discrepancy in form-factor measurements



- interference between 1γ & 2γ exchange leads to SSA in *inclusive* DIS off transversely polarised target

$$\sigma_{UT} \propto \vec{S} \cdot (\vec{k} \times \vec{k}')$$

[Metz,Schlegel,Goeke PLB643(2006)]

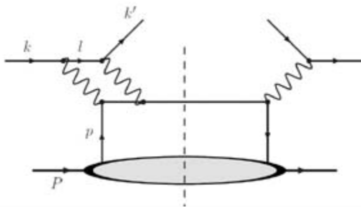
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{2}{\pi} A_{UT}^{\sin\phi_S}$$

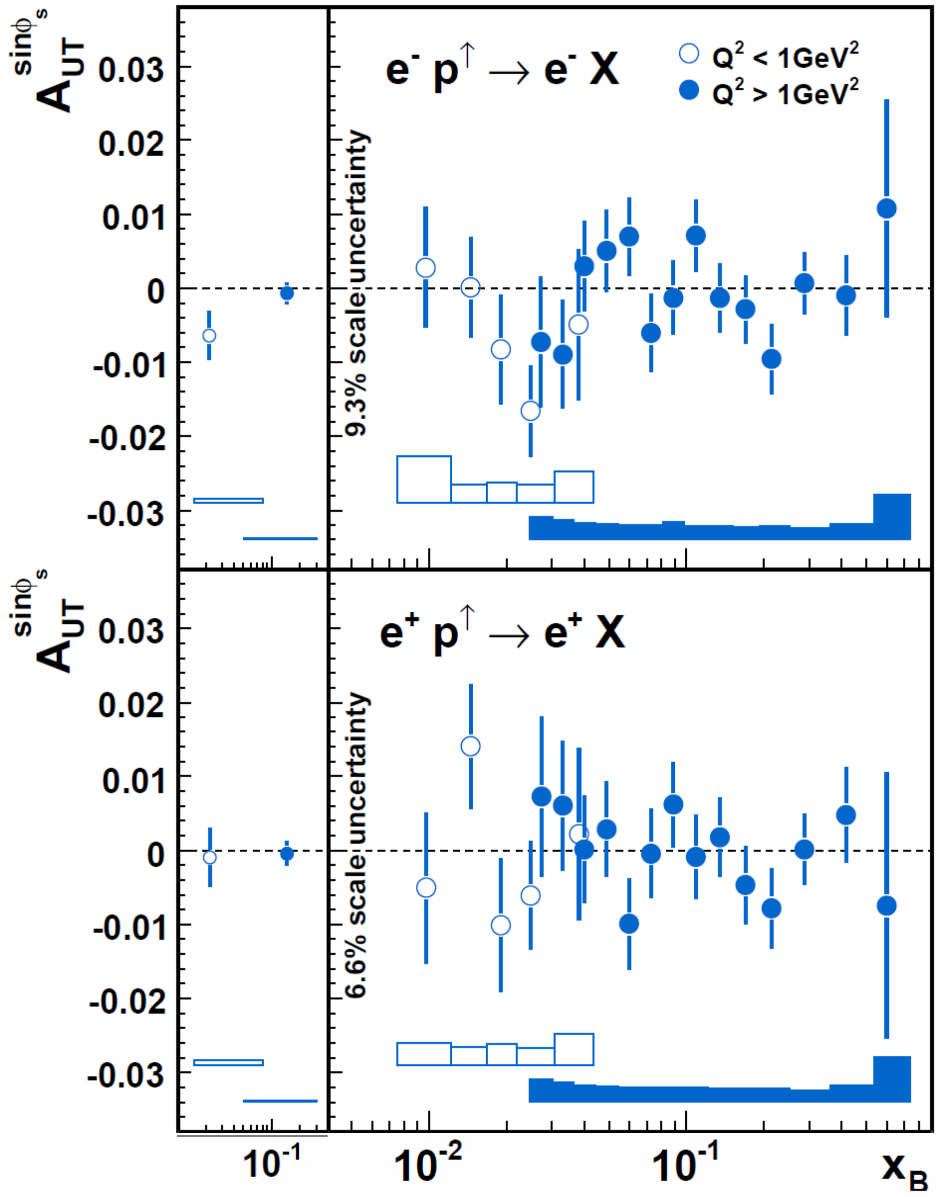
estimated size: O(10^{-4} – 10^{-2})

$$A_{UT}(x, Q^2, \phi_S) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- sensitive to beam charge due to odd number of e.m. couplings to beam

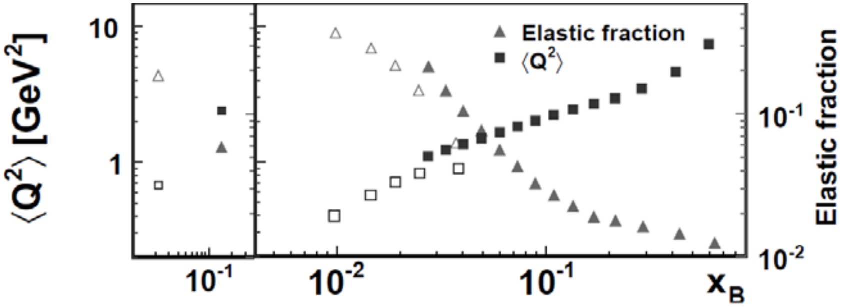
any sign of 2γ exchange ?

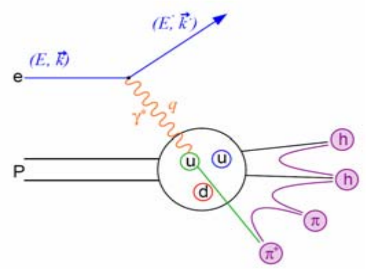




[PLB682(2010)]

→ no evidence of 2γ exchange within experimental uncertainty of 10^{-3}





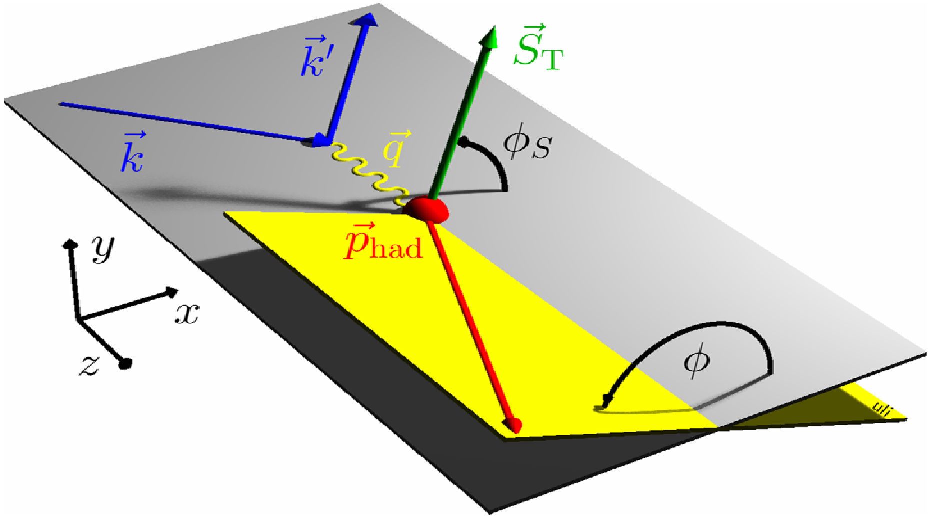
SIDIS cross section

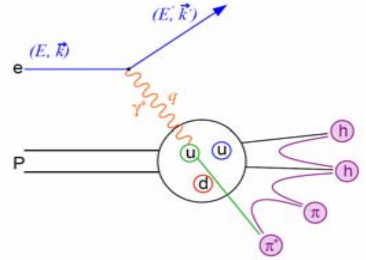
$$\sigma^{h}_{XY} \propto \sum_f \hat{\sigma}_{part} \otimes pdf(x, k_T) \otimes frag^{q,g\to h}(z, p_T)$$

σ_{XY}

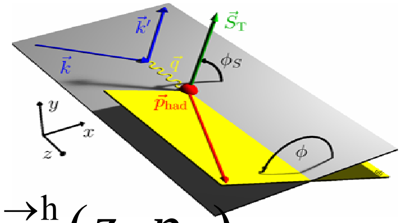
beam: target:

λ S_L ,S_T





SIDIS cross section



$$\sigma_{\mathrm{XY}}^{\mathrm{h}} \propto \sum_f \hat{\sigma}_{part} \otimes pdf(x, k_T) \otimes frag^{\mathrm{q,g\to h}}(z, p_T)$$

8 leading-twist terms

$$d\sigma = \boxed{d\sigma_{UU}^{0} + \cos 2\phi\, d\sigma_{UU}^{1}} + \frac{1}{Q}\cos\phi\, d\sigma_{UU}^{2} + \lambda_e \frac{1}{Q}\sin\phi\, d\sigma_{LU}^{3}$$

$$+ S_L\left\{\boxed{\sin 2\phi\, d\sigma_{UL}^{4}} + \frac{1}{Q}\sin\phi\, d\sigma_{UL}^{5} + \lambda_e\left[\boxed{d\sigma_{LL}^{6}} + \frac{1}{Q}\cos\phi\, d\sigma_{LL}^{7}\right]\right\}$$

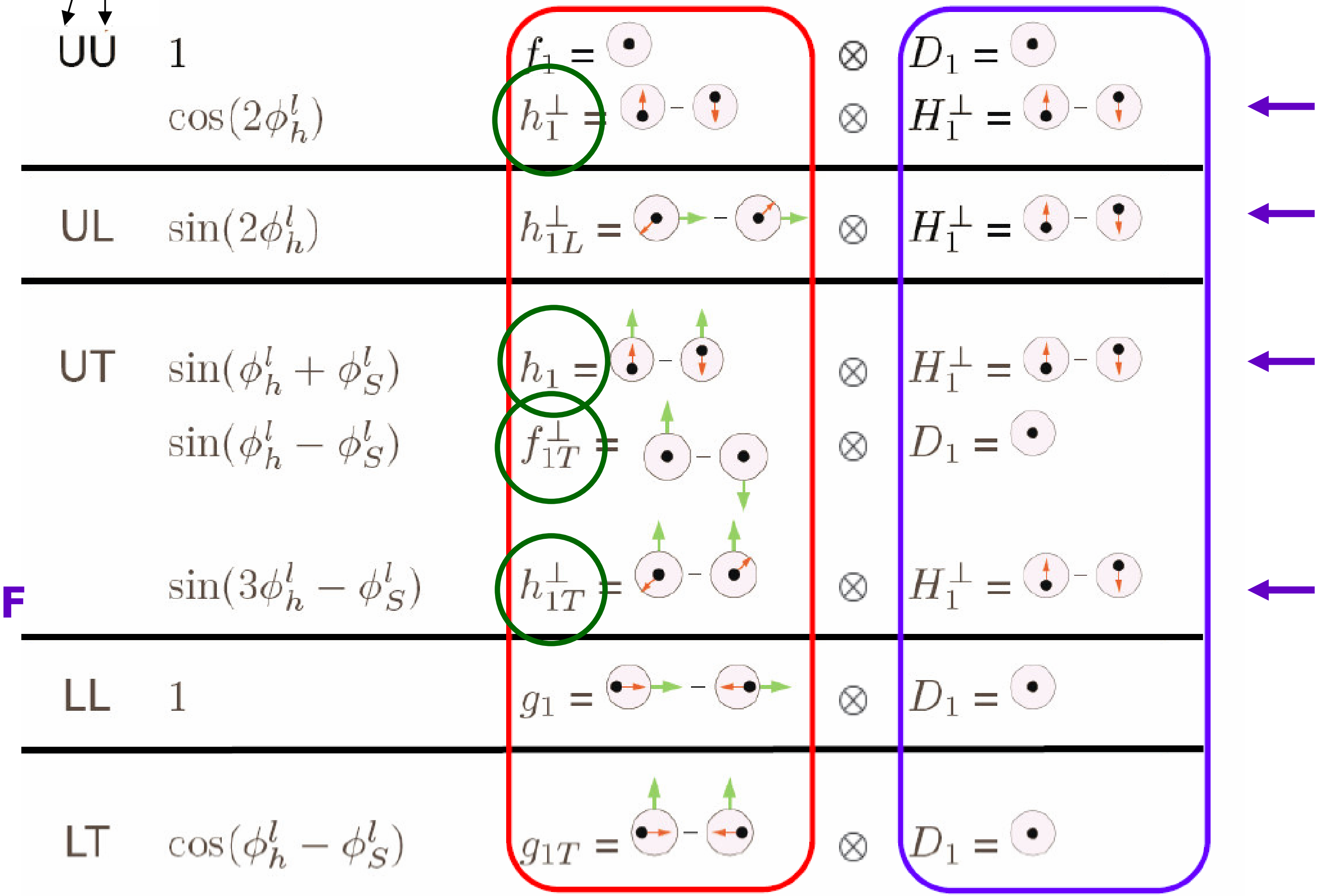
$$+ S_T\left\{\boxed{\sin(\phi-\phi_S)\ d\sigma_{UT}^{8} + \sin(\phi+\phi_S)\ d\sigma_{UT}^{9} + \sin(3\phi-\phi_S)\ d\sigma_{UT}^{10}}\right.$$

$$+ \frac{1}{Q}\sin(2\phi-\phi_S)\ d\sigma_{UT}^{11} + \frac{1}{Q}\sin\phi_S\, d\sigma_{UT}^{12}$$

$$\left. + \lambda_e\left[\boxed{\cos(\phi-\phi_S)\ d\sigma_{LT}^{13}} + \frac{1}{Q}\cos\phi_S\, d\sigma_{LT}^{14} + \frac{1}{Q}\cos(2\phi-\phi_S) d\sigma_{LT}^{15}\right]\right\}$$

leading-tw distribution functions

$$\sigma^{h}_{XY} \propto \sum_f \hat{\sigma}_{part} \otimes pdf\,(x, k_T) \otimes frag^{q,g\to h}(z, p_T)$$



UU	1	$f_1 =$	$\otimes$	$D_1 =$
	$\cos(2\phi_h^l)$	$h_1^\perp =$	$\otimes$	$H_1^\perp =$
UL	$\sin(2\phi_h^l)$	$h_{1L}^\perp =$	$\otimes$	$H_1^\perp =$
UT	$\sin(\phi_h^l + \phi_S^l)$	$h_1 =$	$\otimes$	$H_1^\perp =$
	$\sin(\phi_h^l - \phi_S^l)$	$f_{1T}^\perp =$	$\otimes$	$D_1 =$
	$\sin(3\phi_h^l - \phi_S^l)$	$h_{1T}^\perp =$	$\otimes$	$H_1^\perp =$
LL	1	$g_1 =$	$\otimes$	$D_1 =$
LT	$\cos(\phi_h^l - \phi_S^l)$	$g_{1T} =$	$\otimes$	$D_1 =$

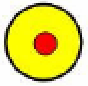
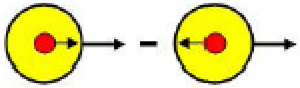
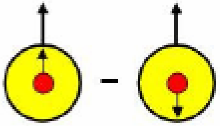
on the menu today

chiral-odd pdf & Collins FF

'Amsterdam notation'

leading-tw distribution functions

@leading twist, integrated over pT:

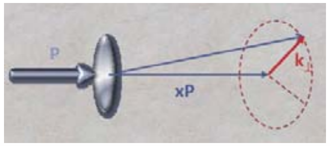
		quark		
		U	**L**	**T**
nucleon	**U**	f_1 		
	L		g_1 	
	T			h_1 

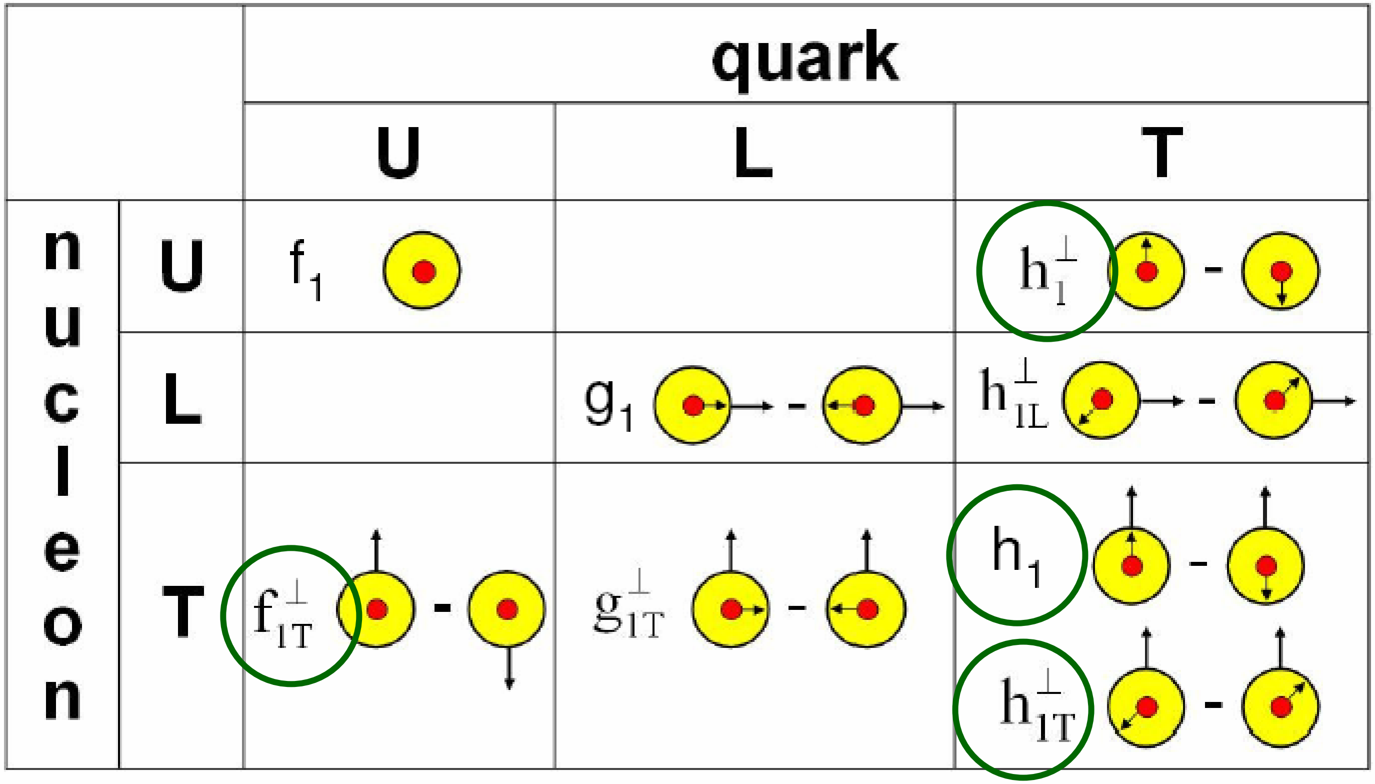
'transversity'

leading-tw distribution functions

@leading twist, no pT integration:

→ spin-orbit correlations





		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

'Boer-Mulders'

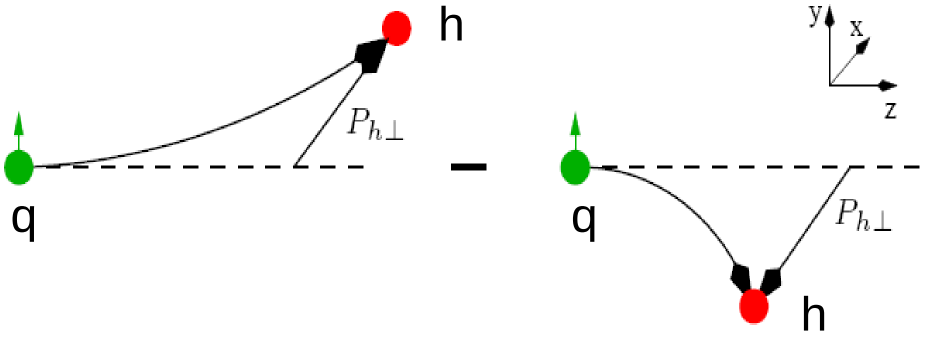
'transversity'

'pretzelosity'

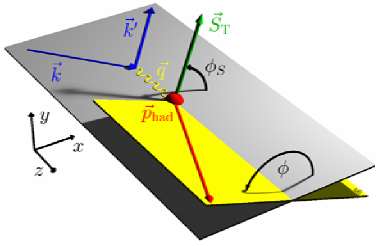
'Sivers'

transversity

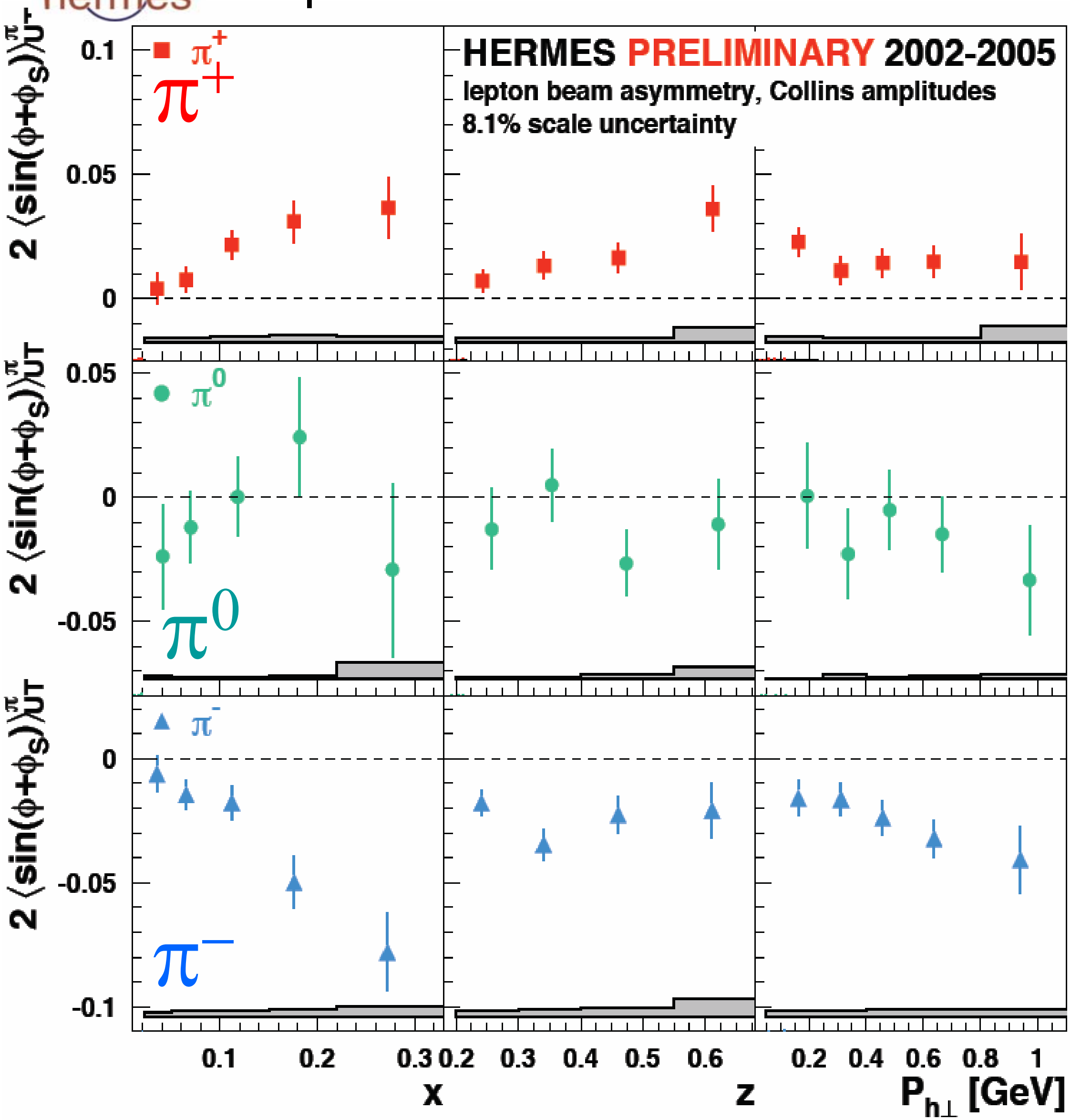
via ***Collins*** fragmentation fct.



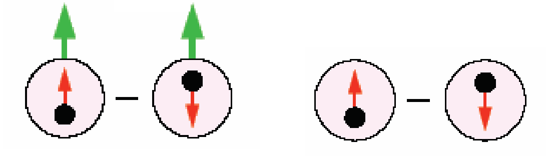
Collins amplitudes



$ep^{\uparrow} \rightarrow \pi X$



$$\delta q(x, k_T) \otimes H_1^{\perp q}(z, p_T)$$



distinctive pattern:

- 🟥 π^+ positive
- ● π^0 ≈zero
- ▲ π^- negative

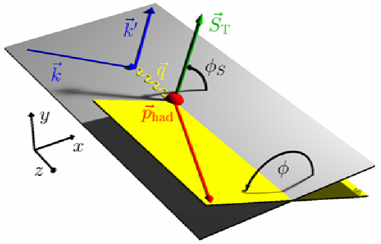
isospin relation for π triplet fulfilled

approximation:

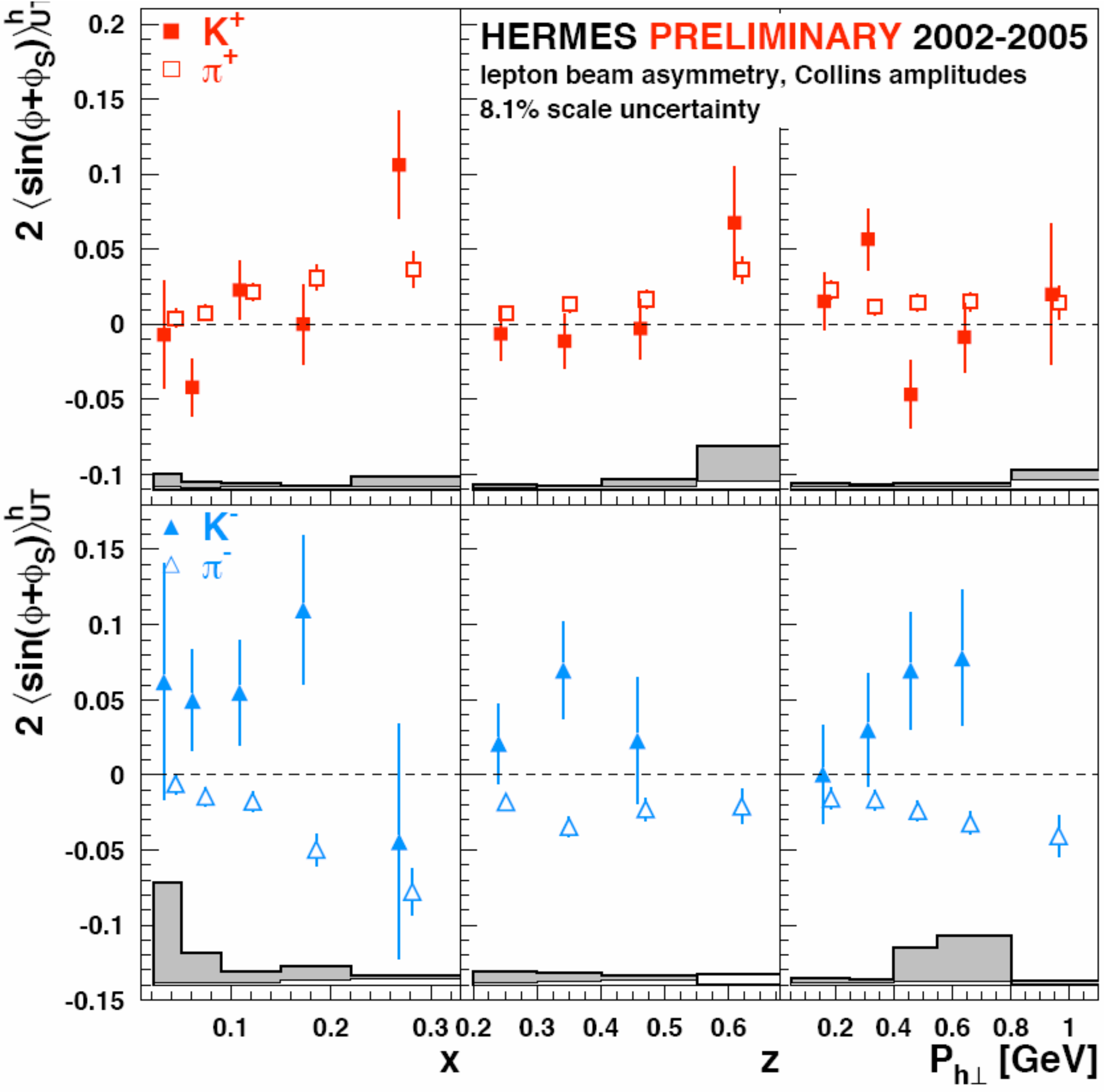
u-quark dominance

$$H_1^{\perp,\text{disfav}} \boxed{\approx -} H_1^{\perp,\text{fav}}$$

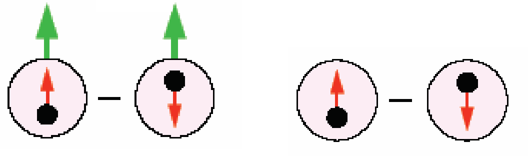
Collins amplitudes



$ep^{\uparrow} \rightarrow K\,X$



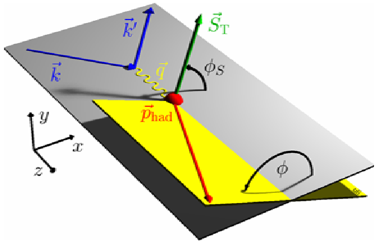
$$\delta q(x.k_T) \otimes H_1^{\perp q}(z, p_T)$$



K⁺ amplitudes consistent with π⁺ amplitudes as expected from u-quark dominance

K⁻ of opposite sign from π⁻ (K⁻ is *all-sea* object)

Collins amplitudes
-- extras: 2D binning --



kinematic dependencies often don’t factorise

→ bin in as many independent variables as possible:

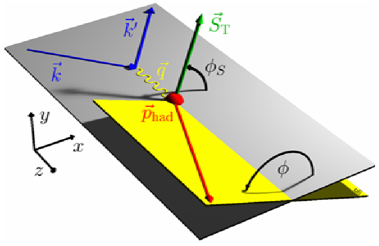
z @`fixed’ x

$P_{h\perp}$ @`fixed’ z

x @`fixed’ z

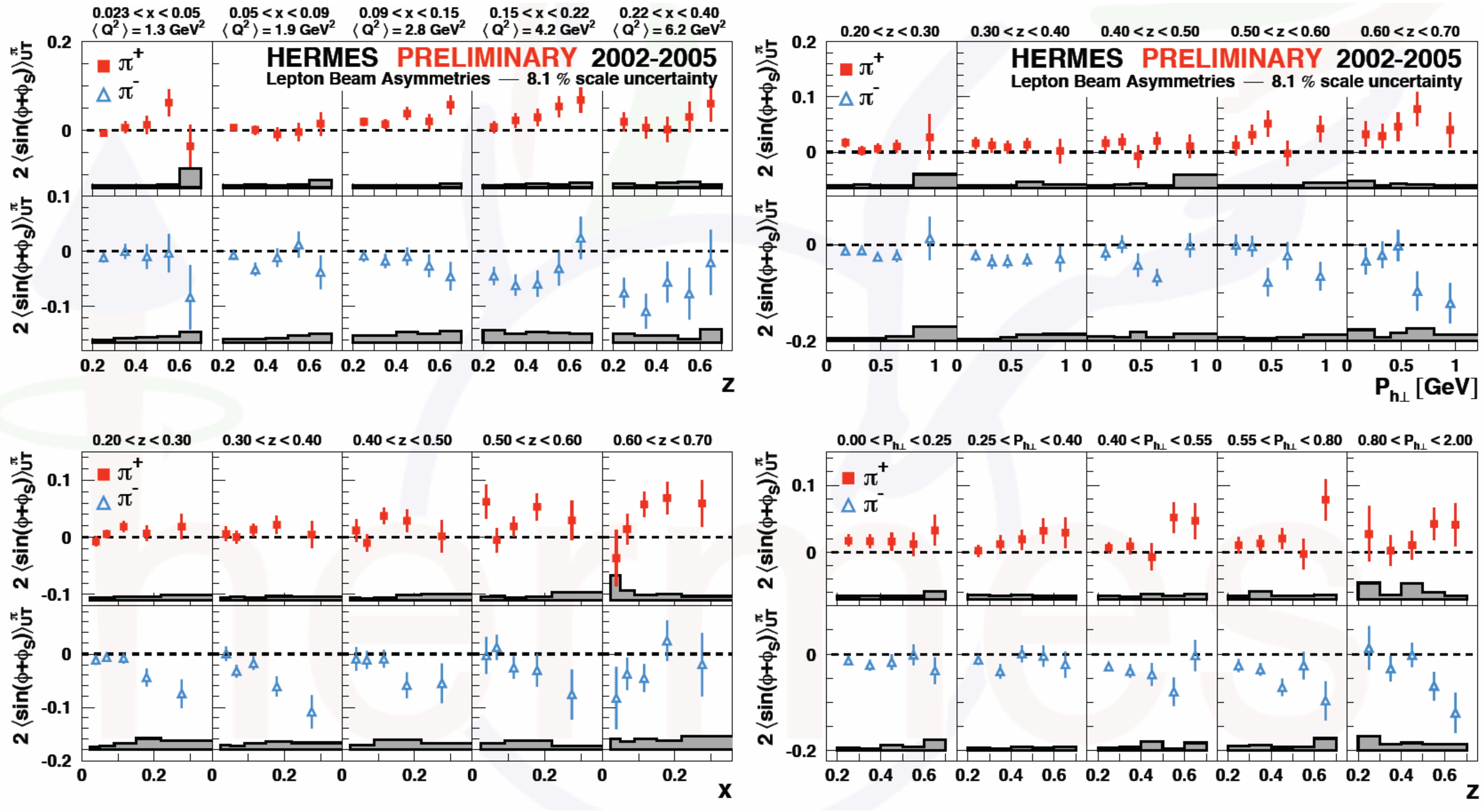
z @`fixed’ $P_{h\perp}$

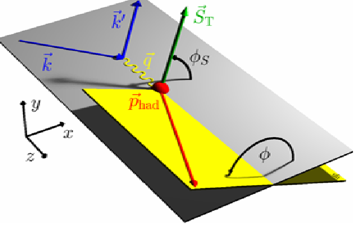
Collins amplitudes
-- extras: 2D binning --



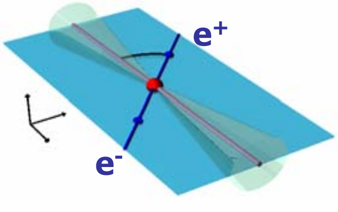
kinematic dependencies often don't factorise

→ bin in as many independent variables as possible:

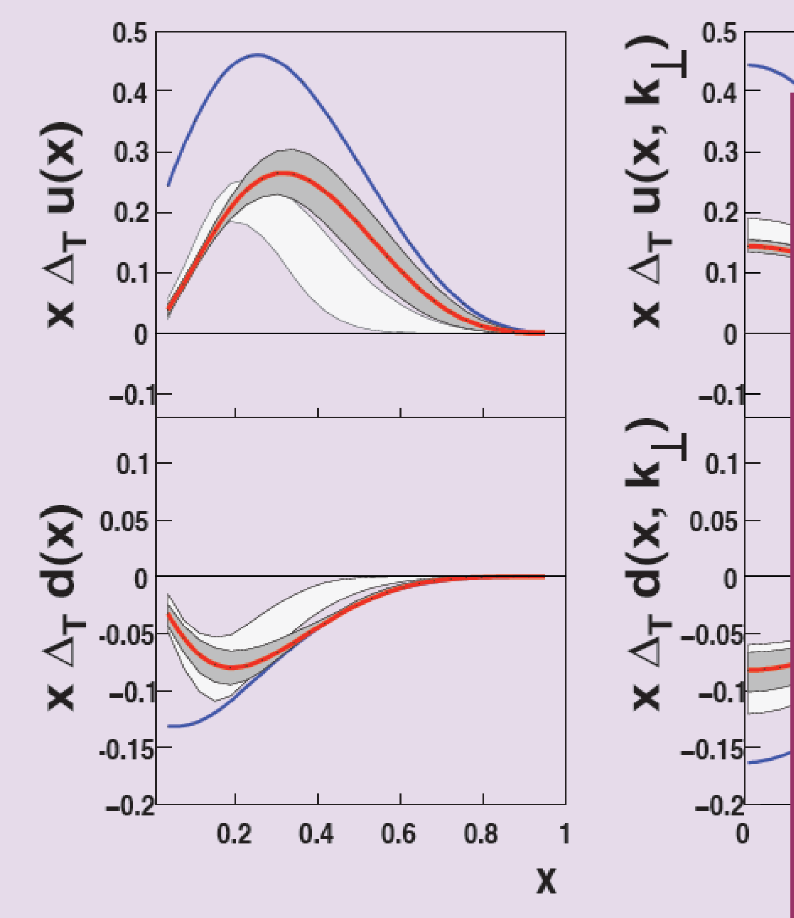


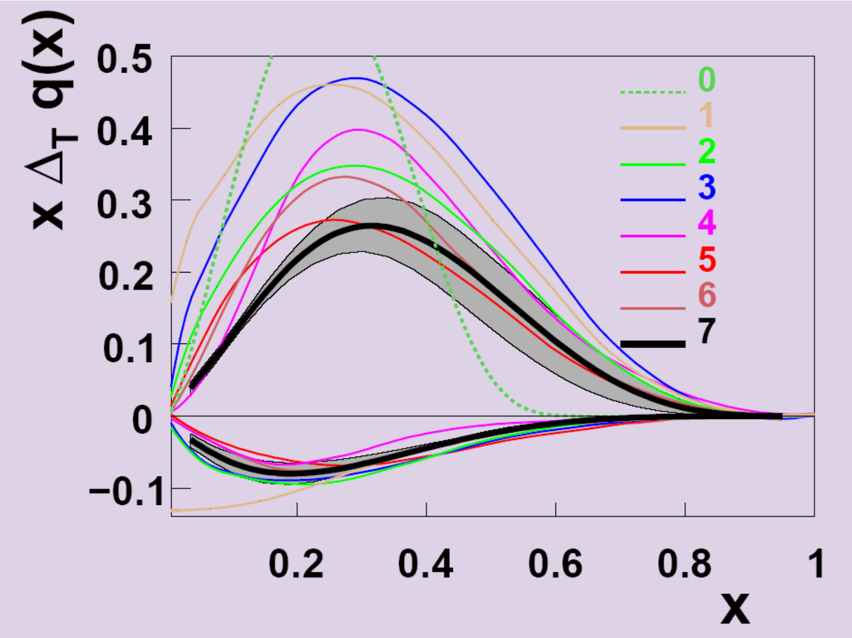


transversity & *Collins* FF



[Anselmino etal. PRD75(2007); update: 2009]

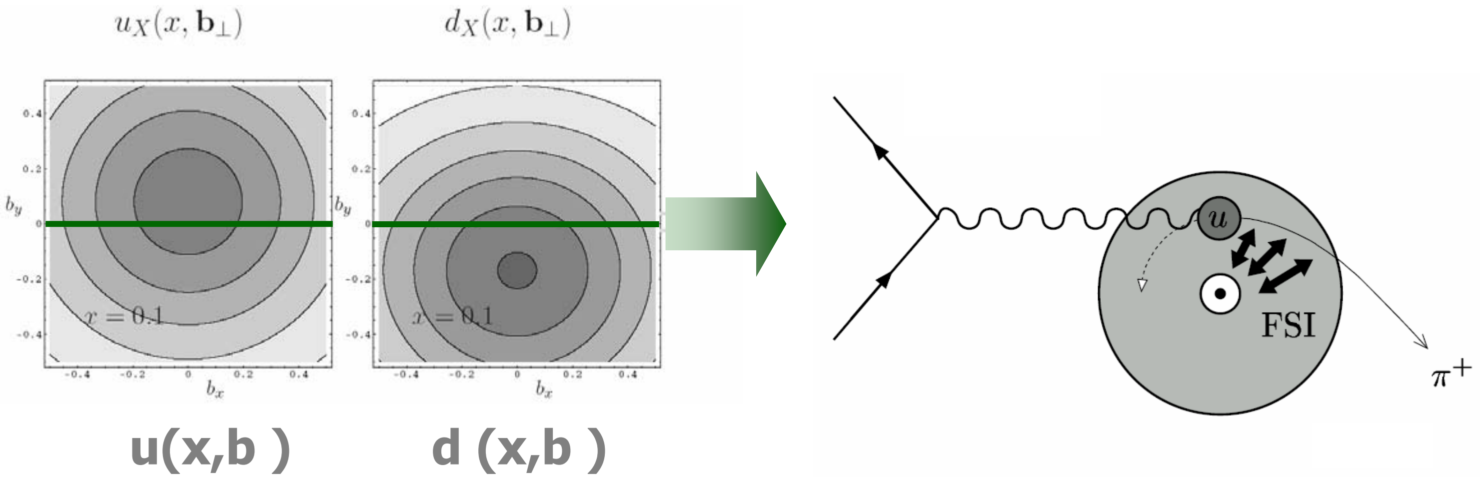




consistent flavour pattern

spin-orbit correlations

Sivers function:

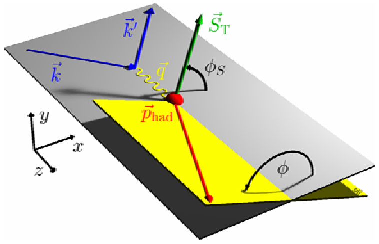


u(x,b) **d (x,b)**

[Matthias Burkardt]

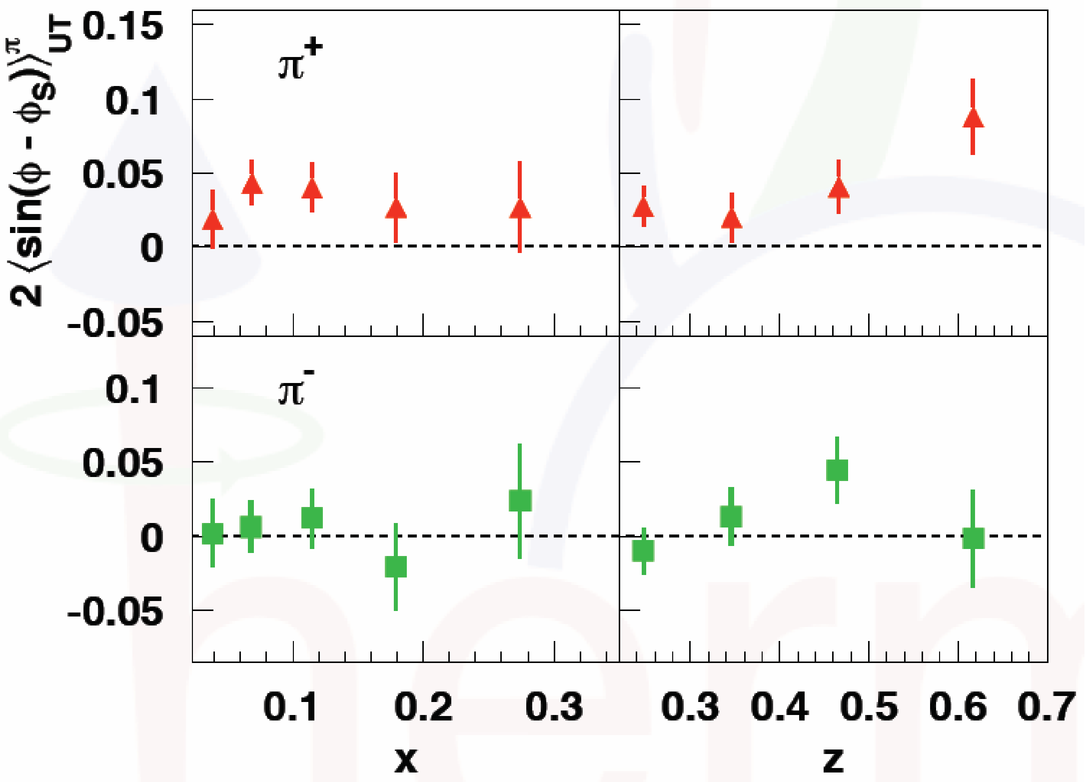
a non-zero Sivers fct. requires non-zero orbital angular momentum !

Sivers amplitudes

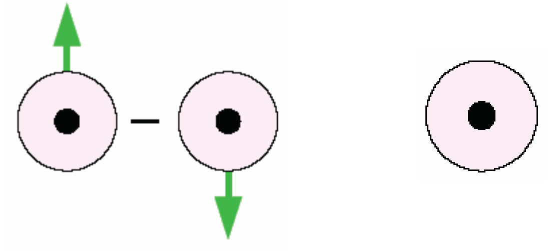


ep↑→ h X

[PRL94(2005)]

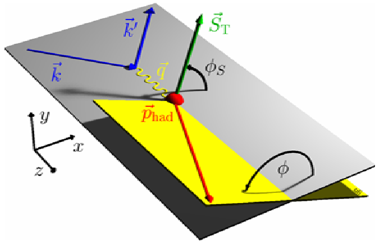


$$f_{1T}^{\perp q}(x,k_T) \otimes D_1^q(z,p_T)$$



- first observation of T-odd Sivers effect in SIDIS
- u quark dominance suggests sizable u quark orbital motion

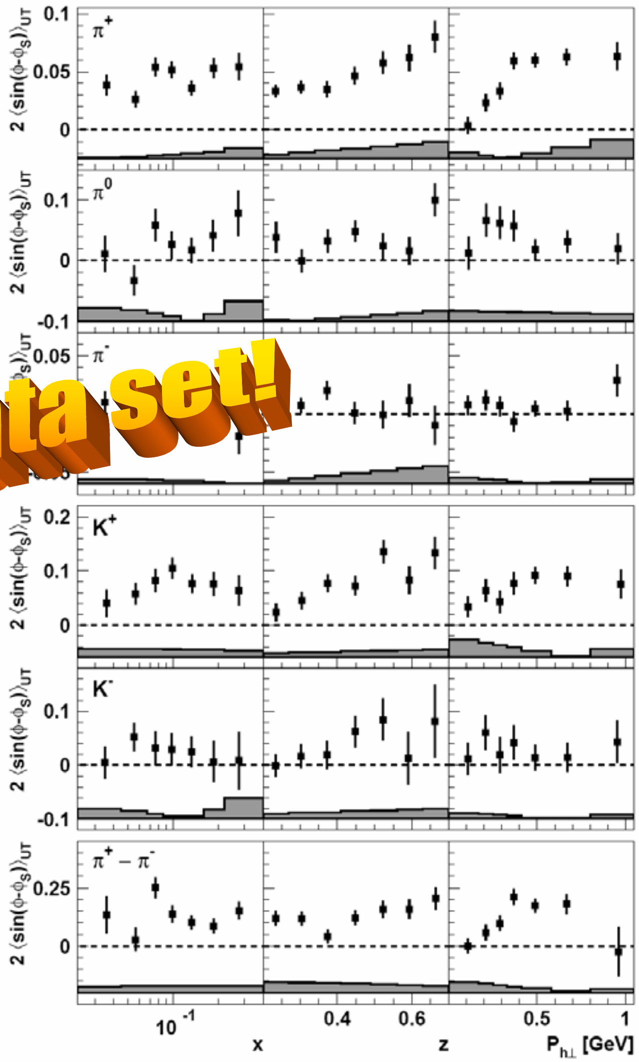
Sivers amplitudes



hermes

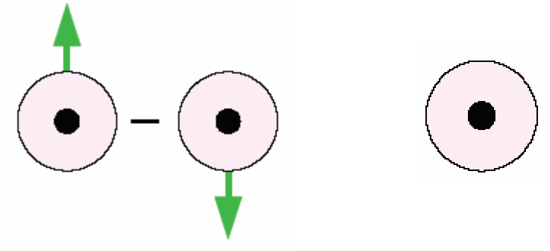
$ep^{\uparrow} \rightarrow h\ X$

[PRL103(2009)]



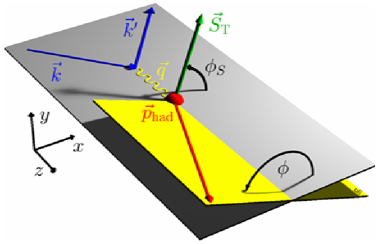
final data set!

$$f_{1T}^{\perp q}(x,k_T) \otimes D_1^q(z,p_T)$$

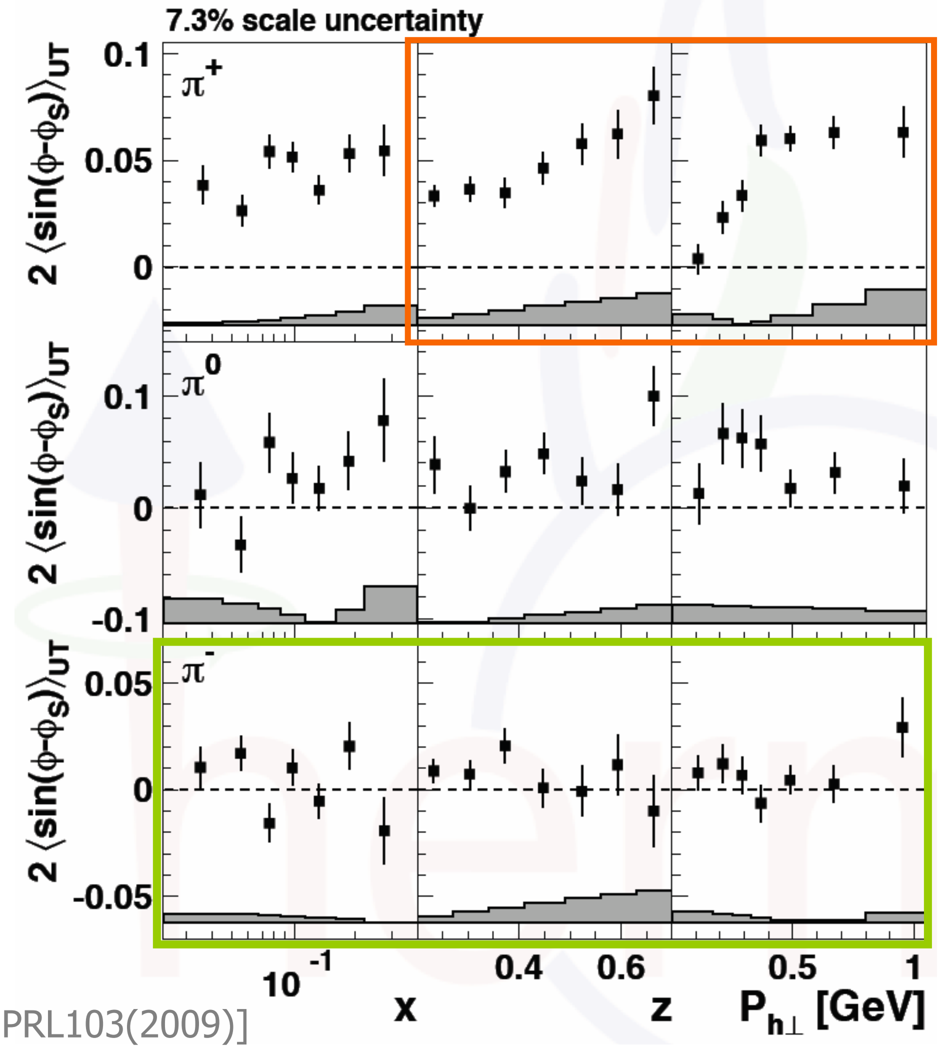


- first observation of T-odd Sivers effect in SIDIS
- u quark dominance suggests sizable u quark orbital motion

Sivers amplitudes for π



$$f_{1T}^{\perp q}(x,k_T) \otimes D_1^q(z,p_T)$$



[PRL103(2009)]

- clear rise with z

  rise at low $P_{h\perp}$
  plateau at high $P_{h\perp}$

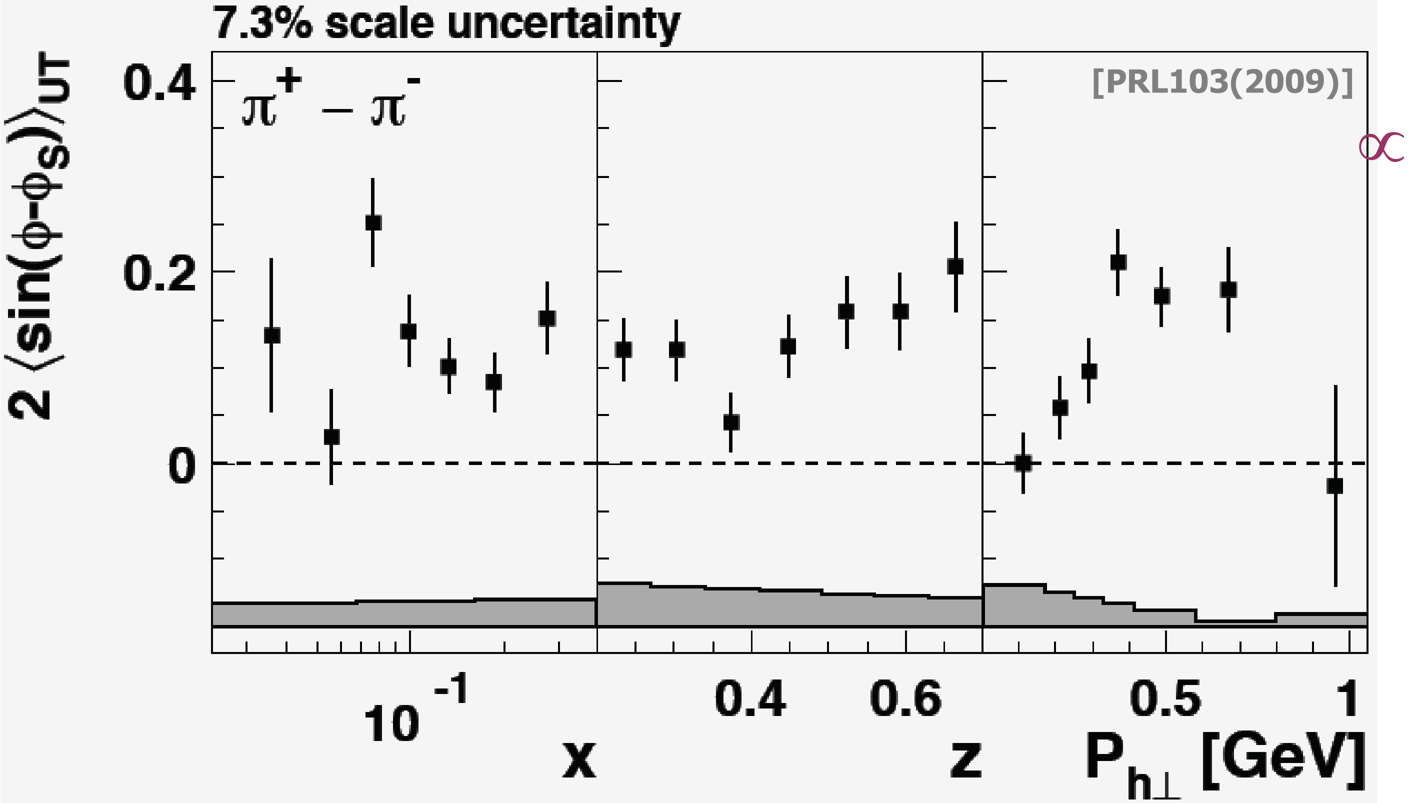
- cancellation for π^- :

  u and d quark Sivers DF of opposite sign

Sivers distribution for valence quarks

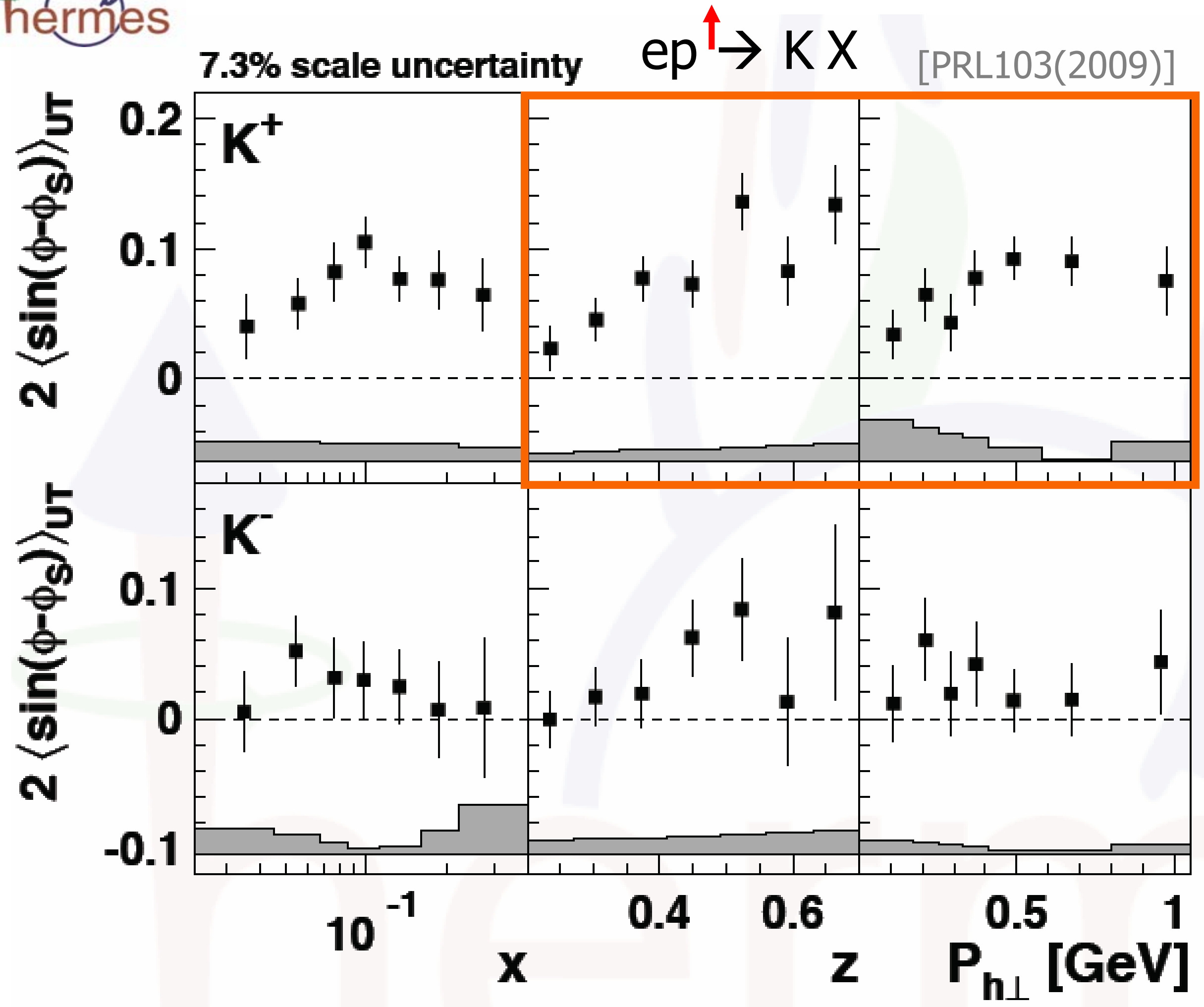
transverse SSA of pion cross section difference:

$$A_{UT}^{\pi^+-\pi^-} = \frac{1}{\langle|S_T|\rangle} \frac{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}$$



$$\propto \frac{4 f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4 f_1^{u_v} - f_1^{d_v}}$$

Sivers: kaon amplitudes



[PRL103(2009)]

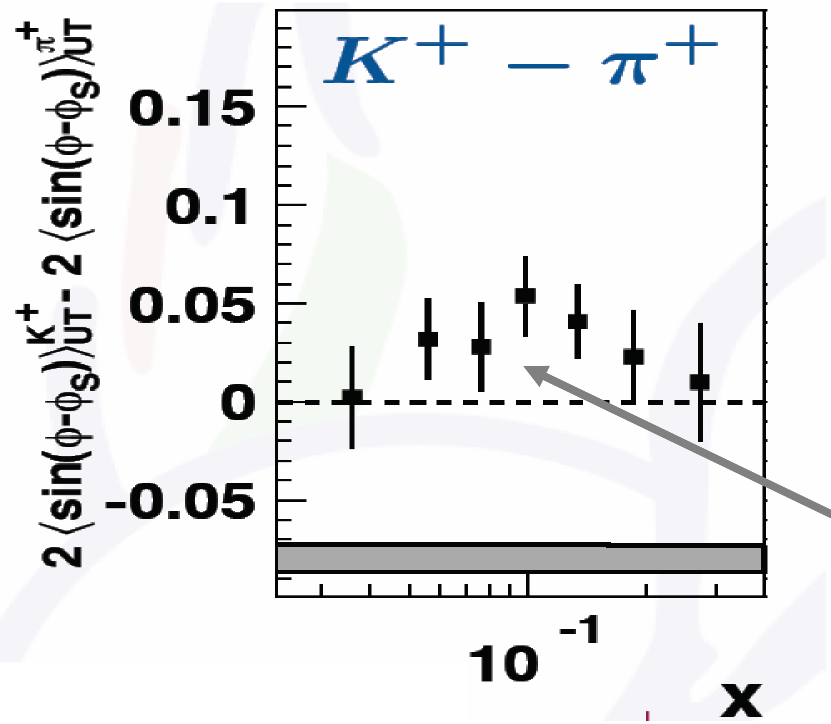
🟧 clear rise with z

rise at low $P_{h\perp}$

plateau at high $P_{h\perp}$

🟦 slightly positive

Sivers: the kaon riddle



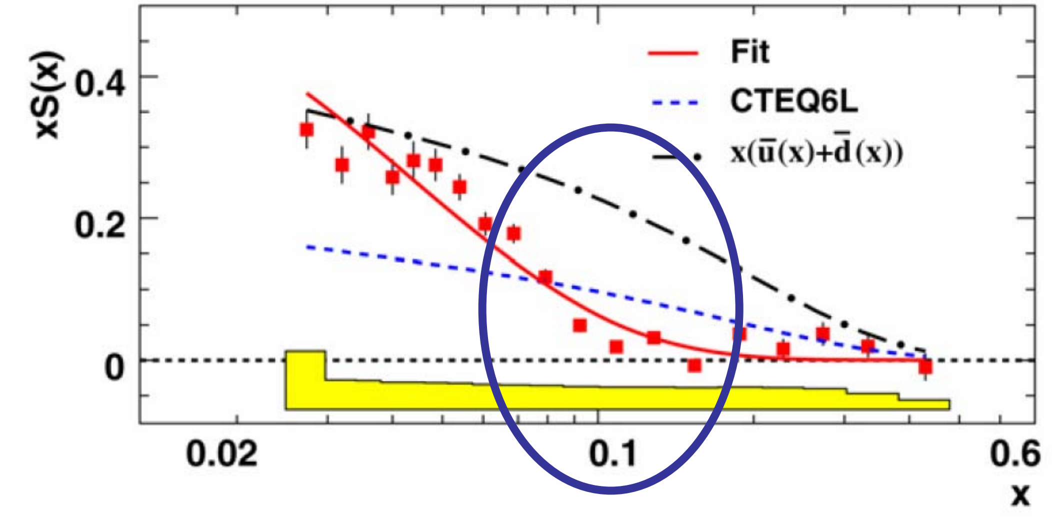
π^+ / K^+ production dominated by scattering off u-quarks

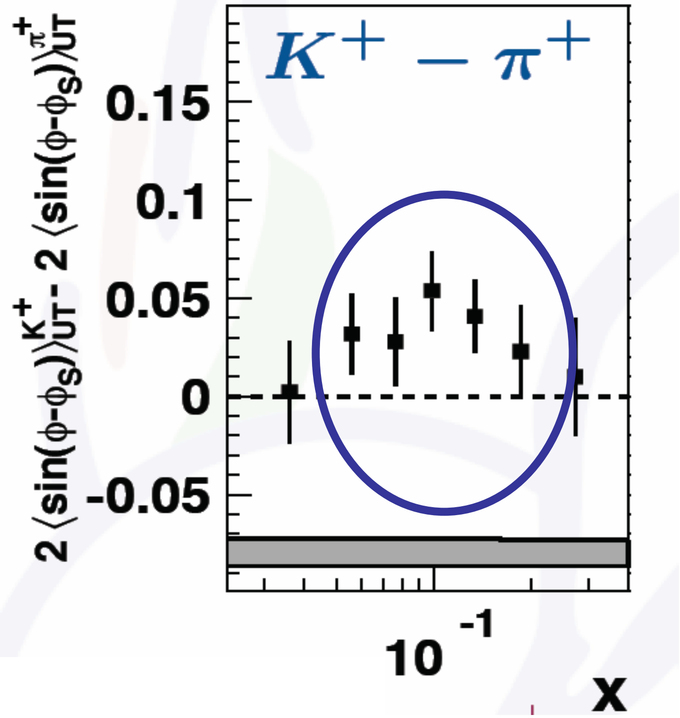
difference non-zero @90% confidence level

- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ → ***non-trival role of sea quarks***
- convolution integral in numerator depends on p_T dependence of FF
- differences in dependences on kinematics integrated over

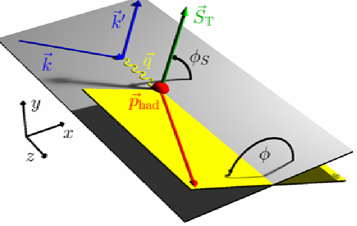
role of sea quarks

strange sea pdf



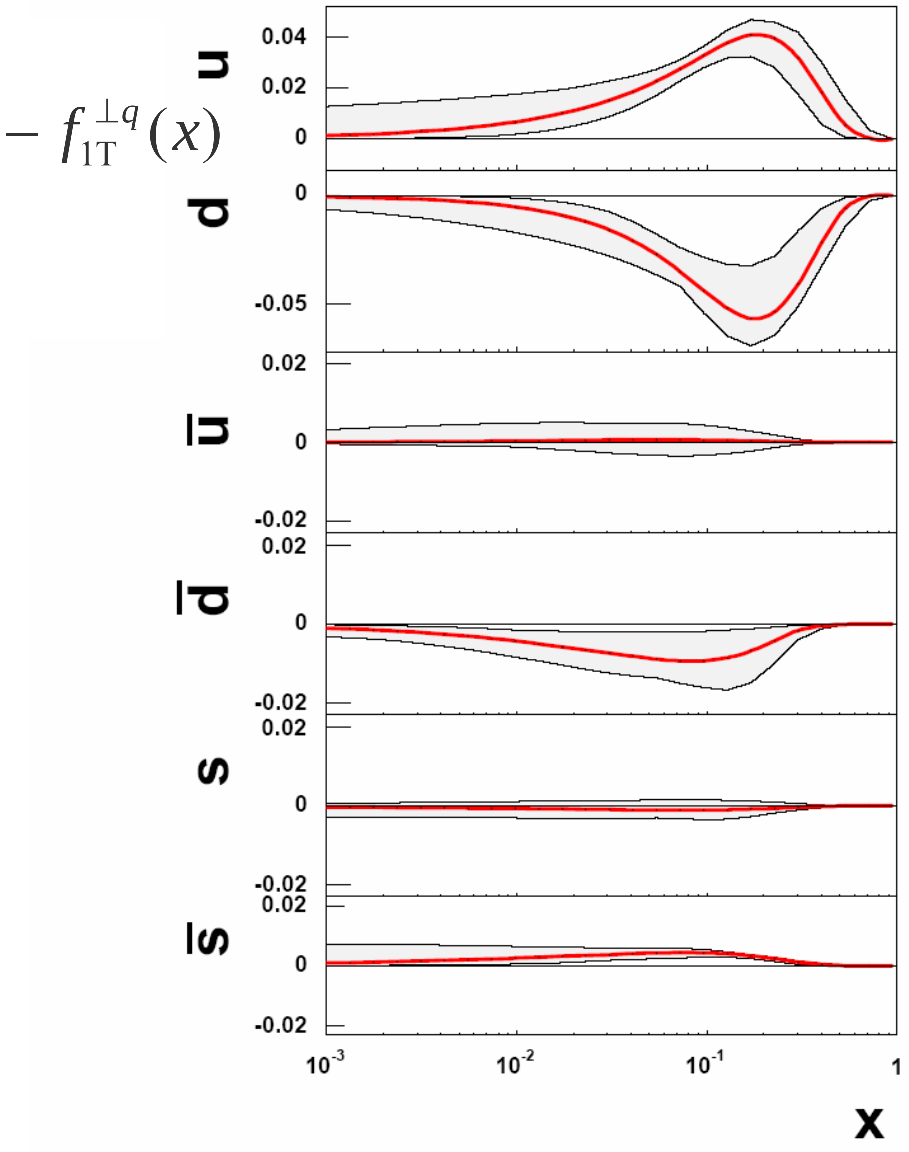


→ differences biggest in region where strange sea is most different from light sea

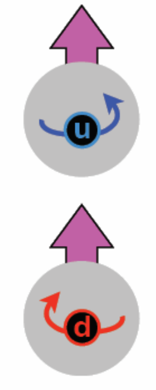


Sivers function

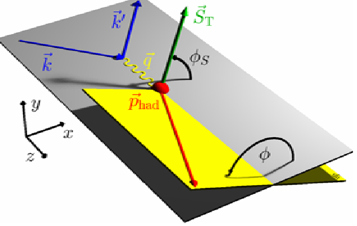
[Anselmino et al., EPJA(2009),89]



combined analysis:



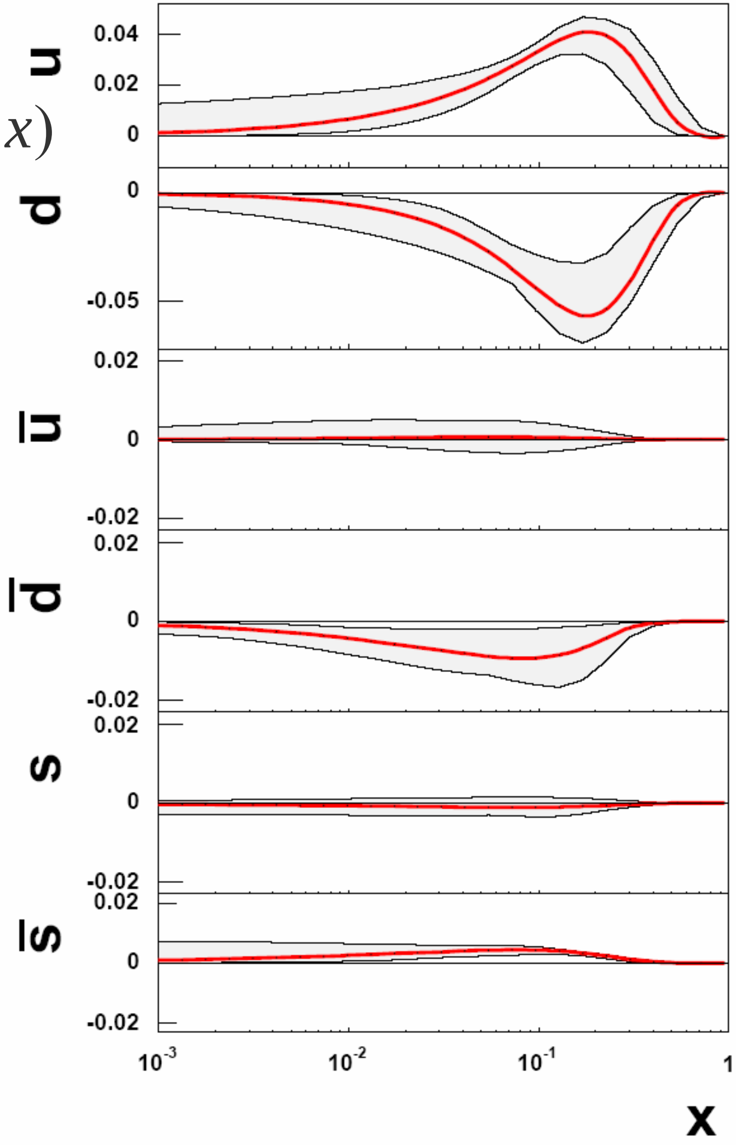
anti-quark
L≠0 favoured



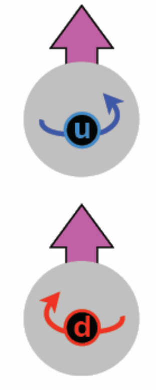
Sivers function

[Anselmino et al., EPJA(2009),89]

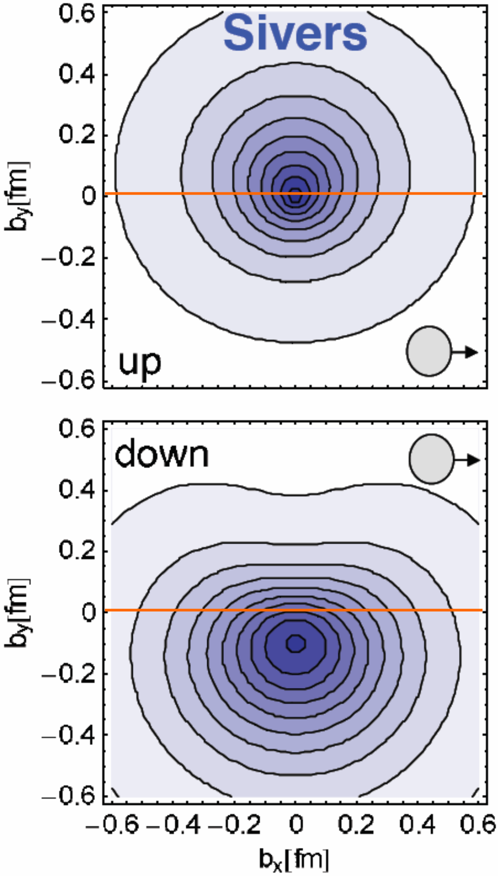
$-f_{1T}^{\perp q}(x)$



combined analysis:



lattice [Haegeler et al.]

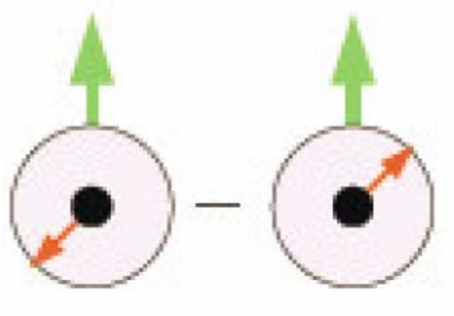


$L_u>0$

$L_d<0$

the shape of the nucleon

‘pretzelosity’



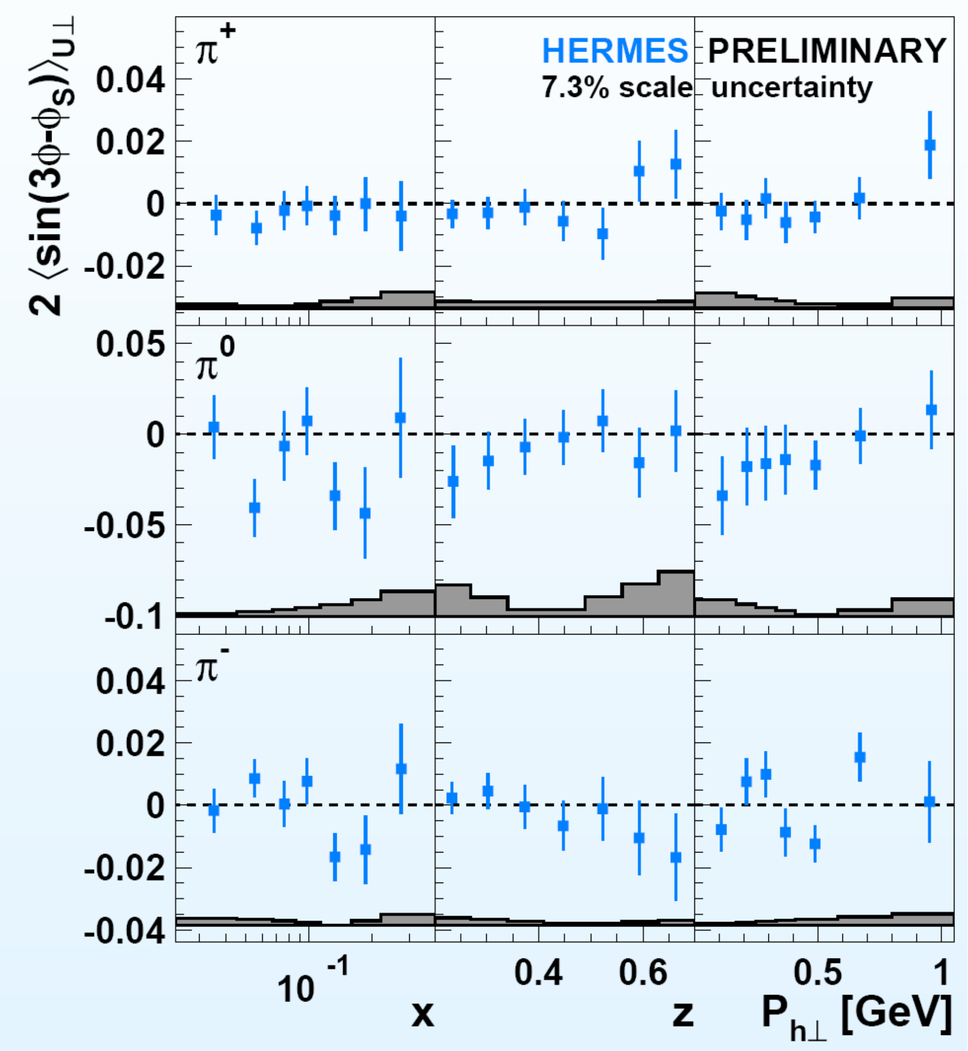
$$h_{1T}^{\perp} \otimes H_{1T}^{\perp}$$

$$g_1(x) - h_1(x) = h_{1T}^{\perp(1)}(x)$$ [model dependent]

pretzelosity: measure for relativistic effects

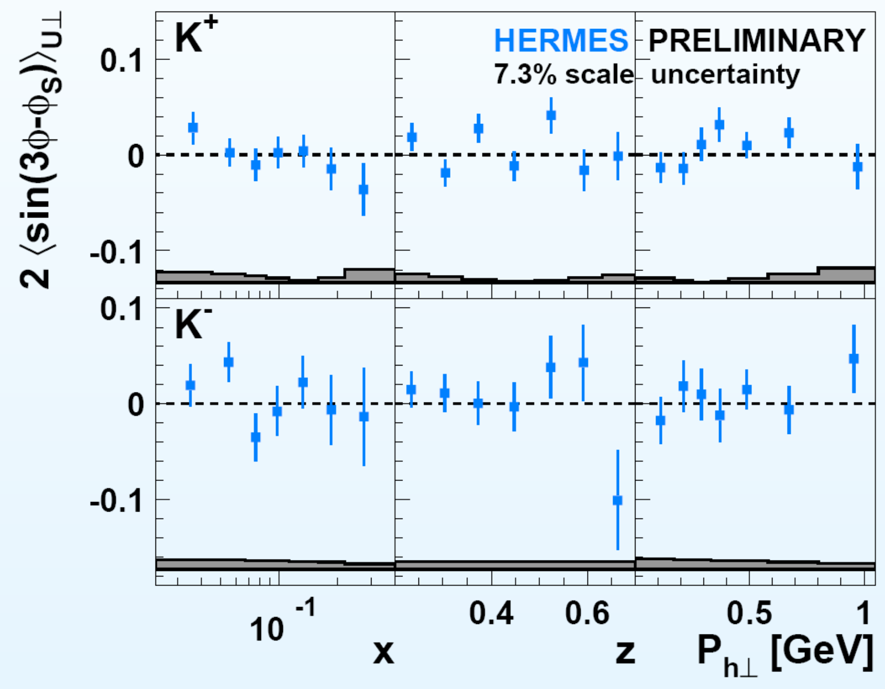
the shape of the nucleon

‘pretzelosity’

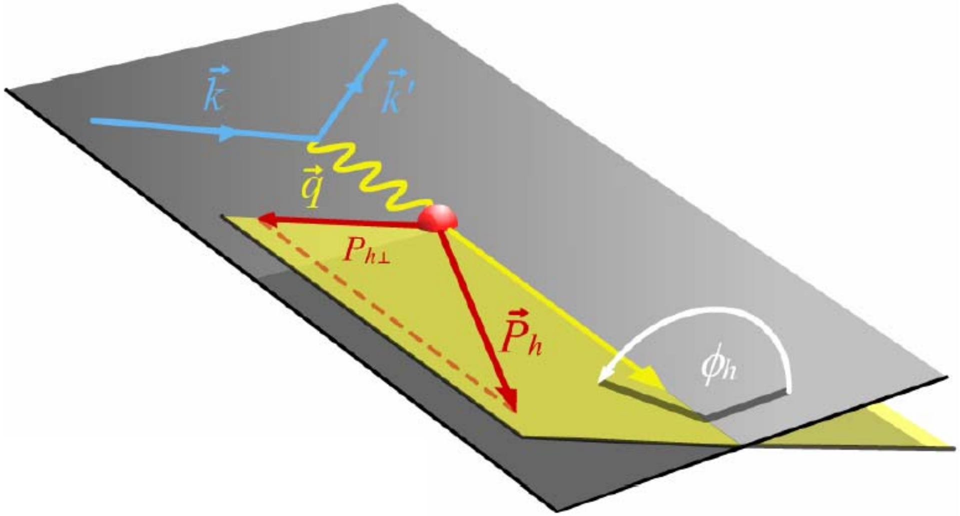


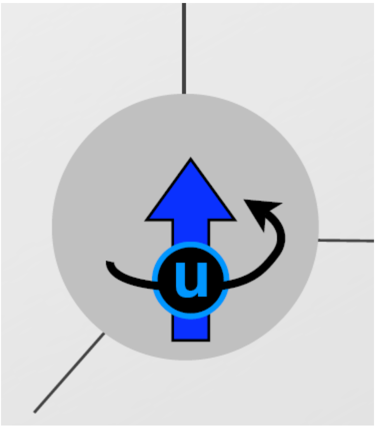
- expected to scale as $(P_{h\perp})^3$

→ suppressed wrt. Collins & Sivers



transverse spin effects the unpolarised cross section





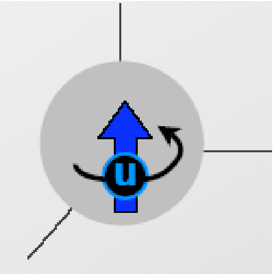
$$h_1^{\perp}(x, k_T)$$

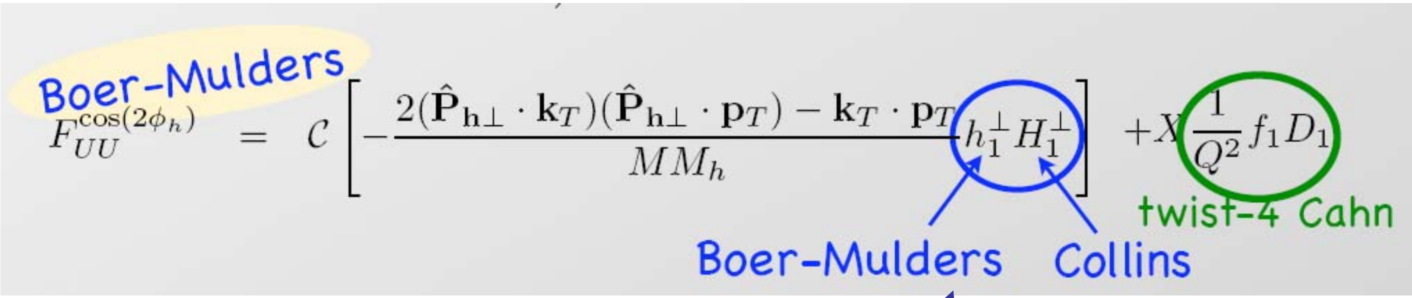
spin-orbit effect (Boer-Mulders DF):

correlation between quark transverse motion and transverse spin

unpolarised cross section

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





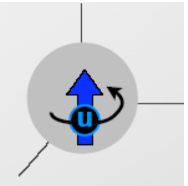
Boer-Mulders

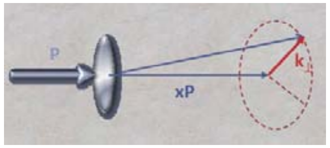
$$F_{UU}^{\cos(2\phi_h)} = \mathcal{C}\left[-\frac{2(\hat{\mathbf{P}}_{\mathbf{h}\perp}\cdot\mathbf{k}_T)(\hat{\mathbf{P}}_{\mathbf{h}\perp}\cdot\mathbf{p}_T) - \mathbf{k}_T\cdot\mathbf{p}_T}{M M_h} h_1^\perp H_1^\perp\right] + X\frac{1}{Q^2} f_1 D_1$$

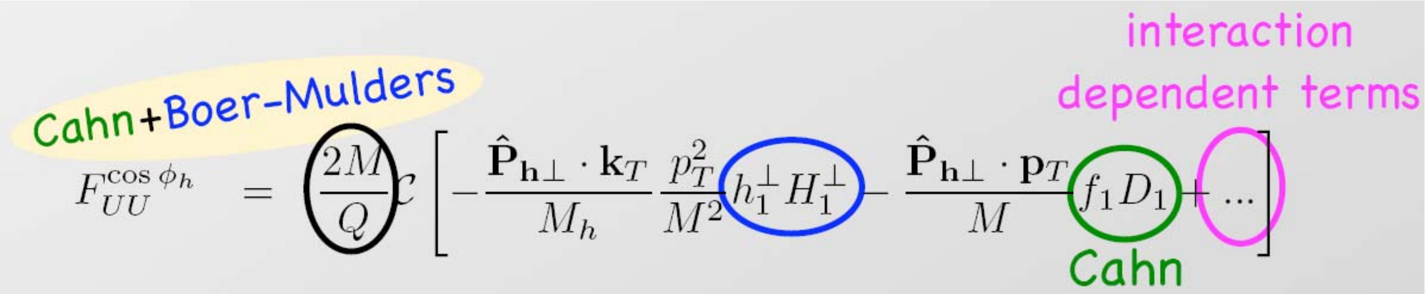
twist-4 Cahn

Boer-Mulders Collins

spin-orbit correlations







interaction dependent terms

Cahn+Boer-Mulders

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{\mathbf{h}\perp}\cdot\mathbf{k}_T}{M_h}\frac{p_T^2}{M^2} h_1^\perp H_1^\perp - \frac{\hat{\mathbf{P}}_{\mathbf{h}\perp}\cdot\mathbf{p}_T}{M} f_1 D_1 + \ldots\right]$$

Cahn

access to intrinsic quark transverse momentum

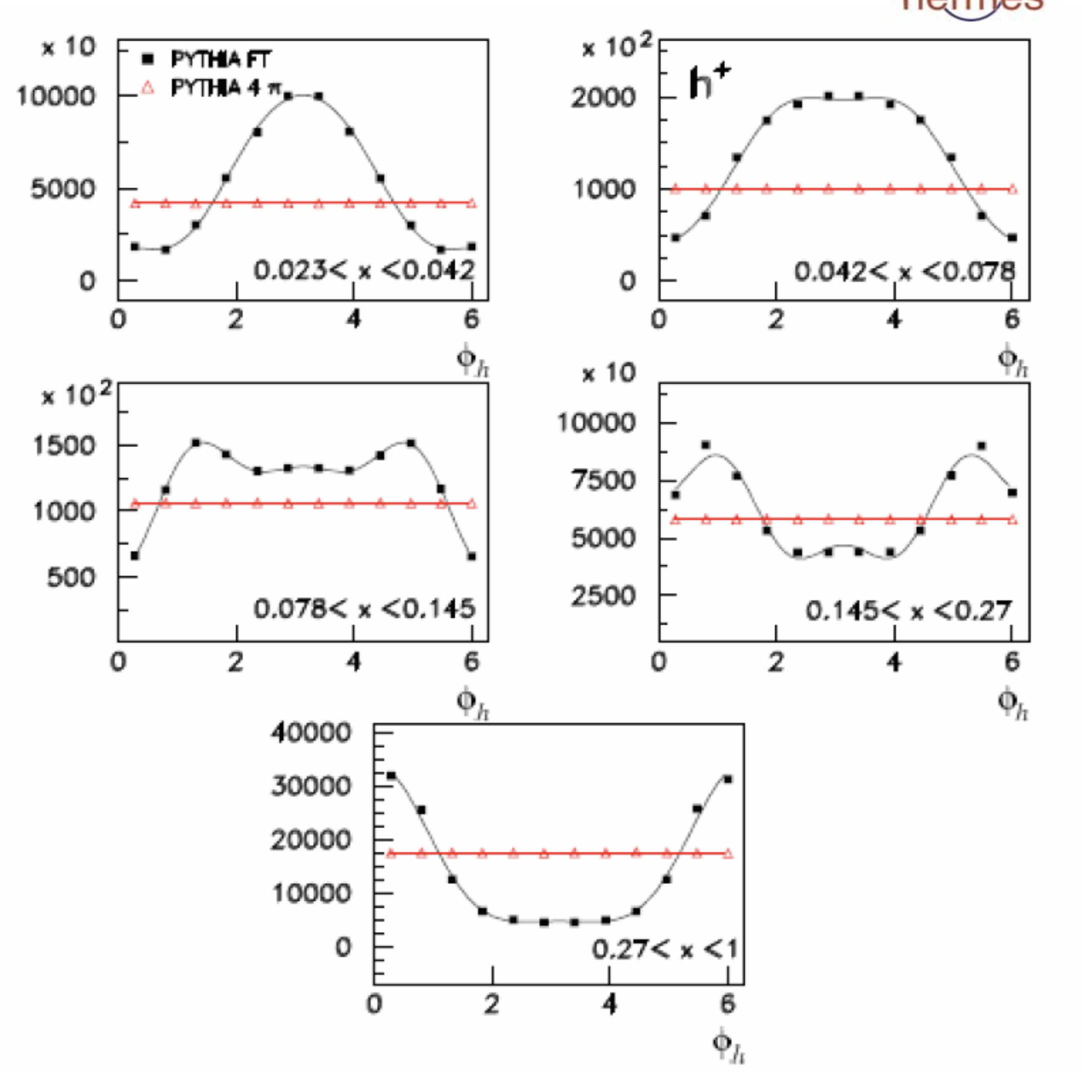
analysis challenge

Monte Carlo:

●–●–●–●–●–●–●–●–●–● **generated in 4π**

●–●–●–●–●–●–●–●–●–● **measured inside acceptance**

→ acceptance and radiative effects generate cos(nϕ) moments



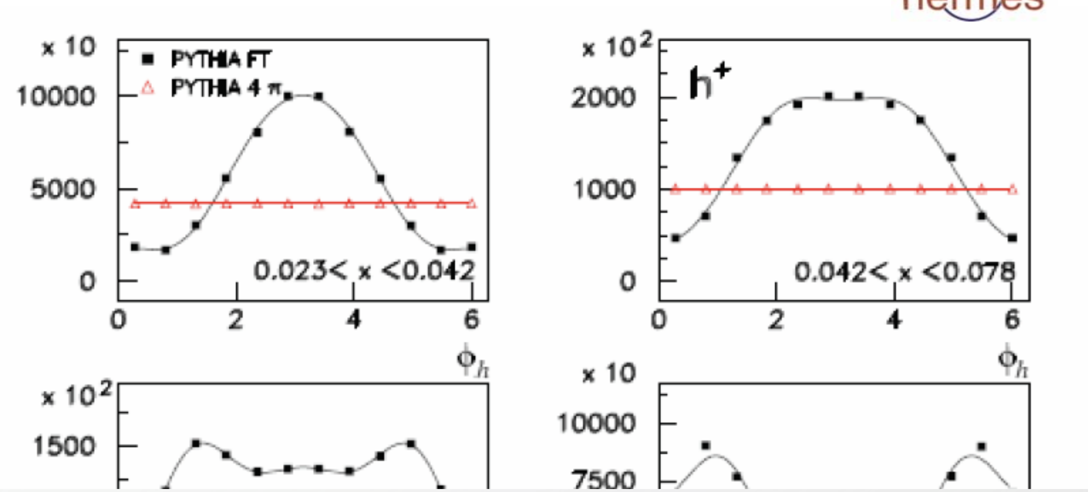
analysis challenge

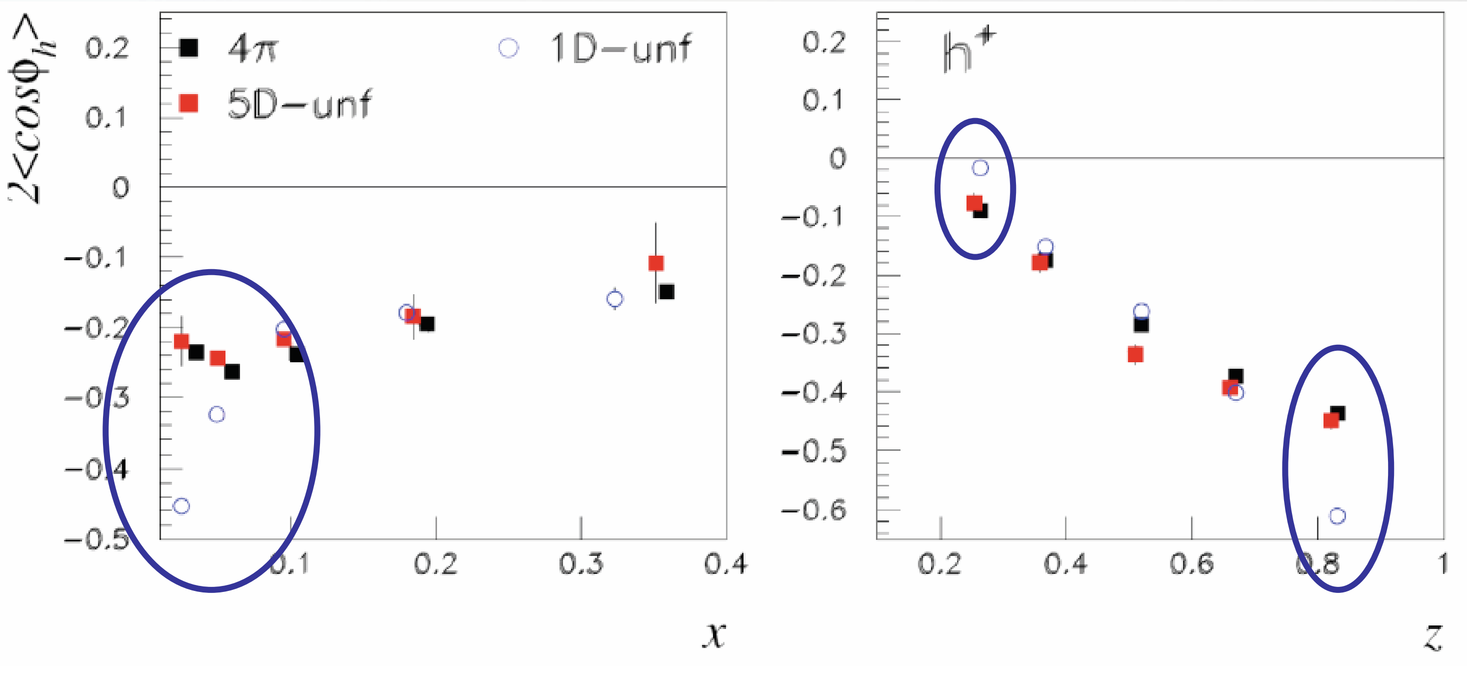
Monte Carlo:

●–●–●–●–●–●–●–●–●–● **generated in 4π**

●–●–●–●–●–●–●–●–●–● **measured inside acceptance**

→ acceptance and radiative effects generate cos(nϕ) moments





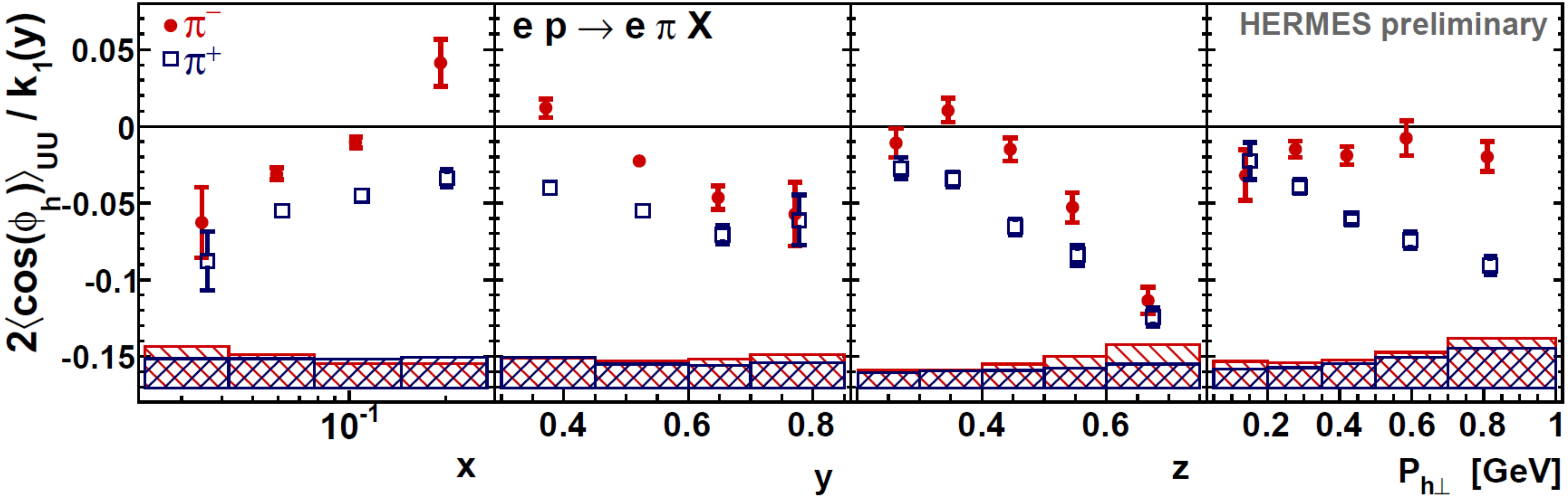
■ Cahn model in 4π

■ unfolded in 5-D

○ unfolded in 1-D
→ *inacurate* !!

<cosϕ>: intrinsic quark transverse momentum

- very similar result for deuterium

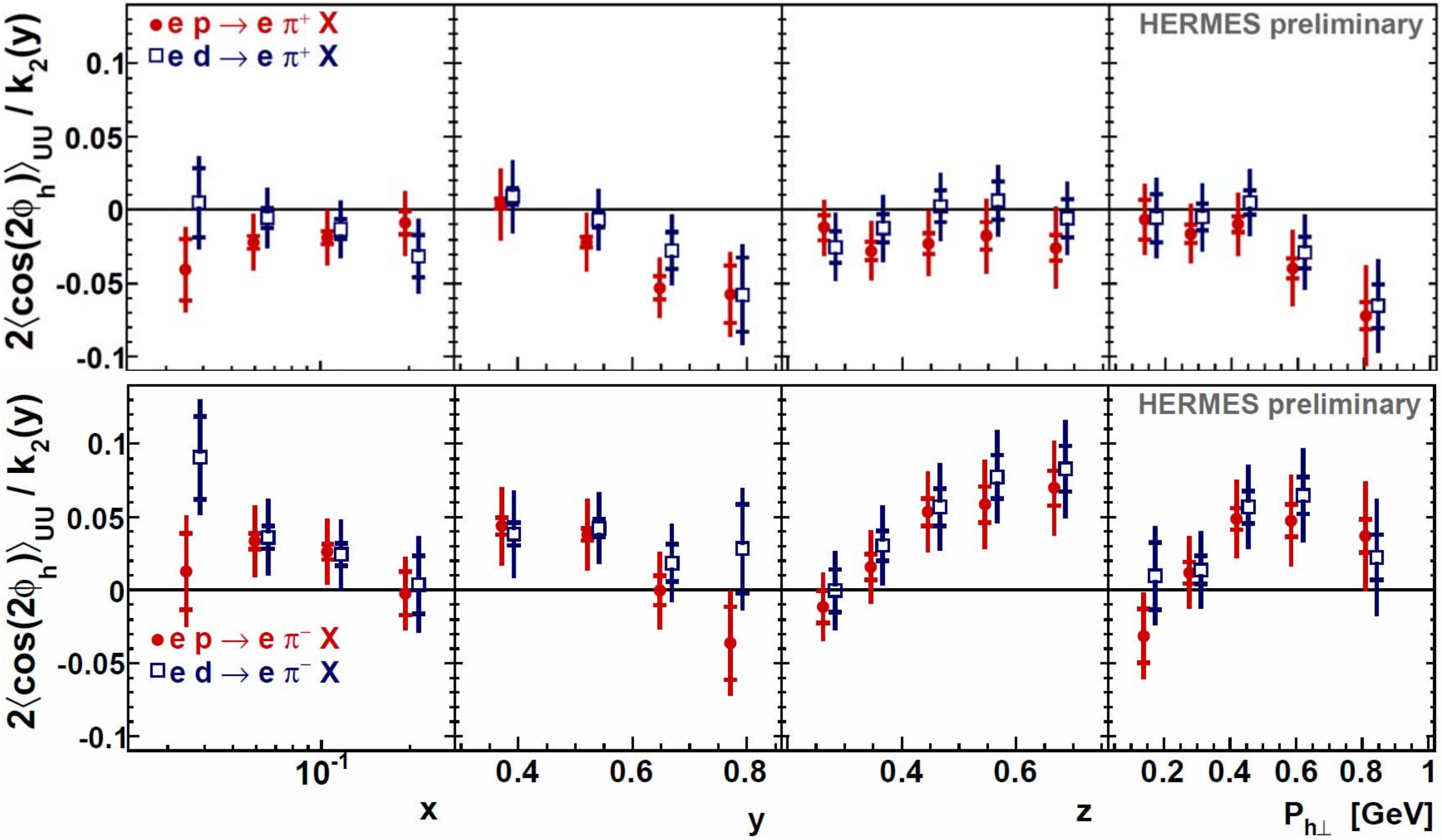


→ different effects for different pion charges … **unexpected** for Cahn effect!

- Boer-Mulders term important ?
- $<k_T>$ flavour dependent ?

<cos2ϕ>: spin-orbit correlations

$$h_1^{\perp}(x,k_T)\otimes H_1^{\perp}(z,p_T)$$



deuterium ≈ hydrogen values → B-M must have *same sign* for u & d

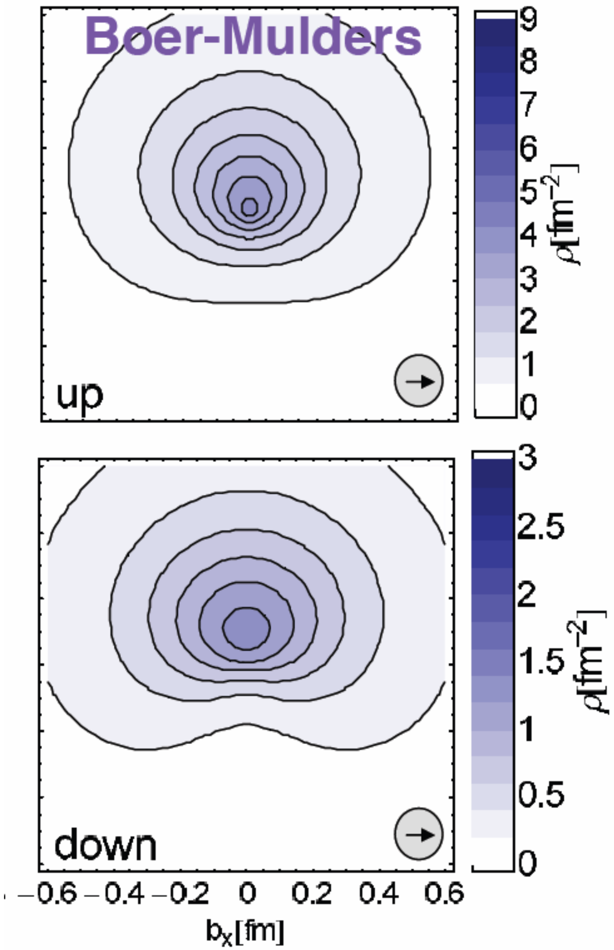
<cos2ϕ>: spin-orbit correlations

$$h_1^{\perp}(x,k_T)\otimes H_1^{\perp}(z,p_T)$$

models: same sign for u & d Boer-Mulders fct.

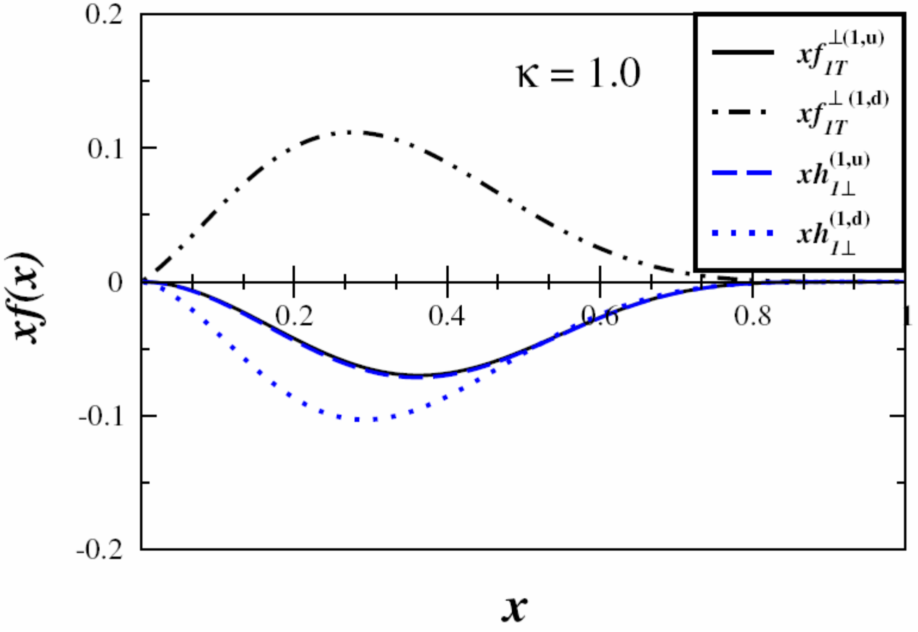
lattice:

[Hageler et.al. PRL98(2007)]



diquark spectator model:

[Gamberg et.al. PRD67(2003), (2007)]

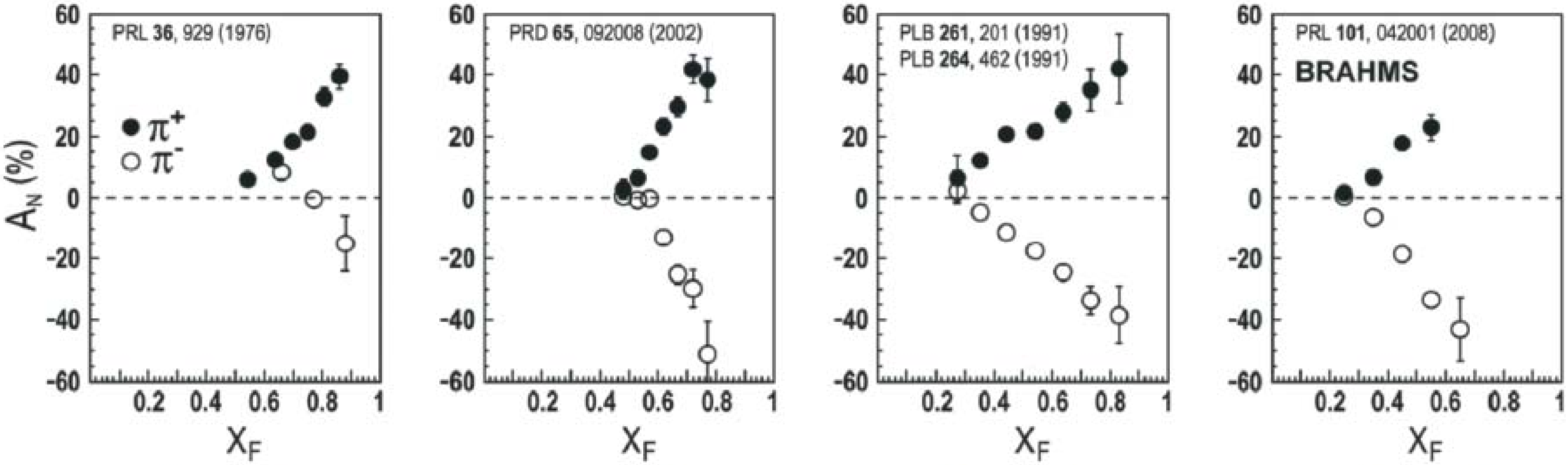


inclusive hadrons

$$p\,p^{\uparrow} \to h\,X$$

large transverse single-spin asymmetries @ center of mass energies:

4.9 GeV 6.6 GeV 19.4 GeV 62.4 GeV



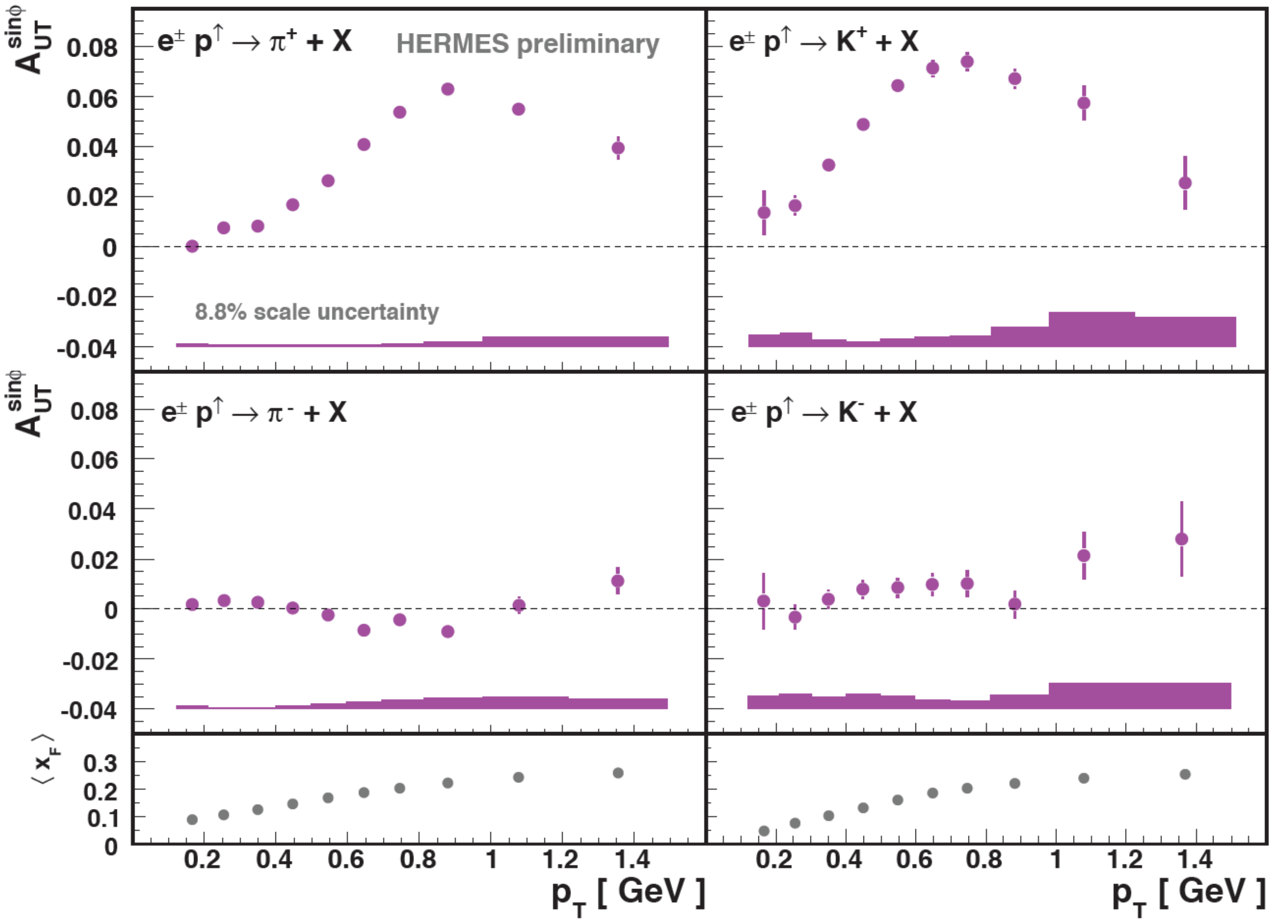
1976 2002 1991 2008

inclusive hadrons: $e\,p^{\uparrow} \rightarrow h\,X$

- scattered electron not detected (ignored) → Q2 ≈ 0 → huge statistics

P_T, x_F w.r.t. **beam direction**

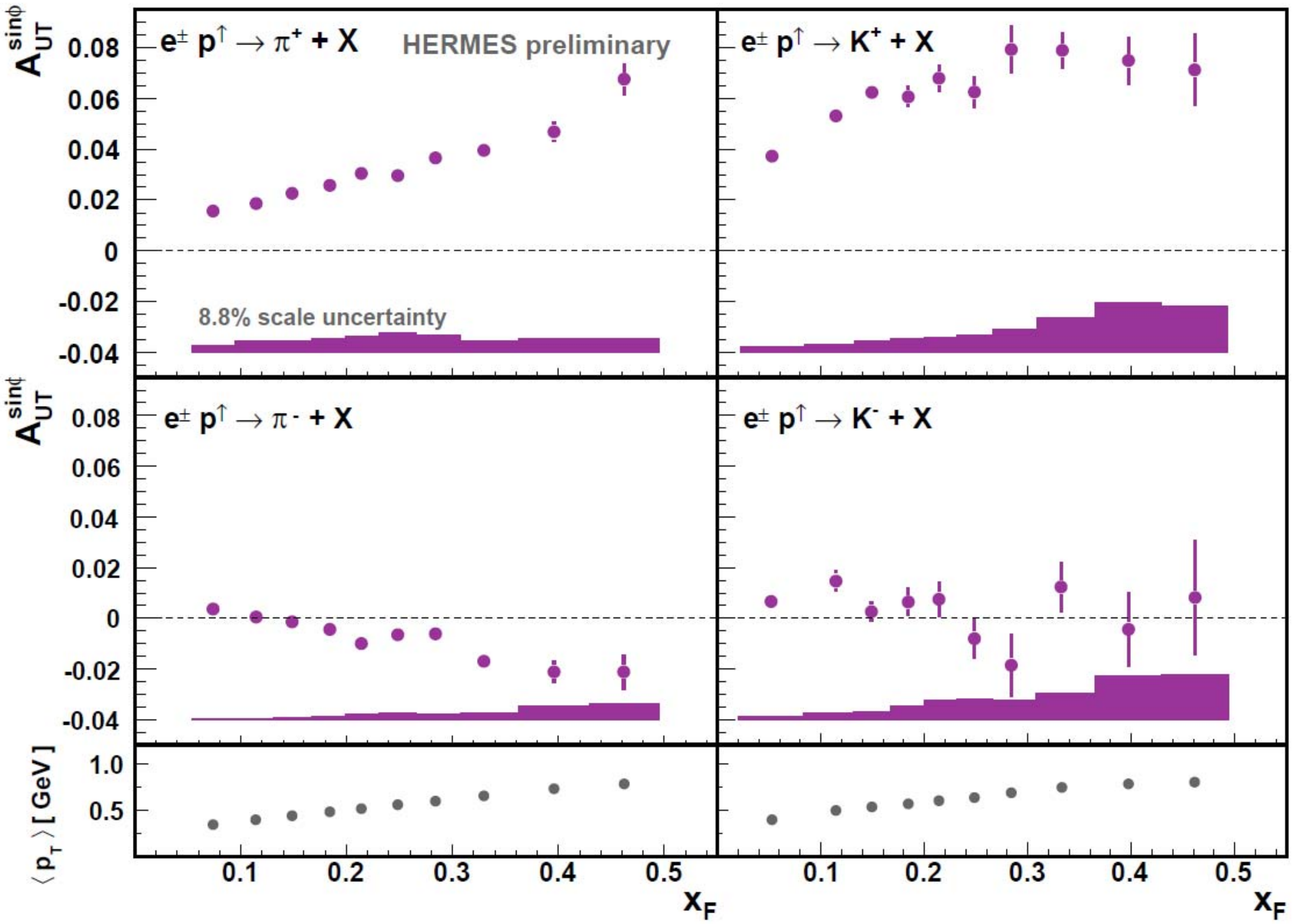
$$A_N = \frac{2}{\pi} A_{UT}^{\sin\varphi}$$



inclusive hadrons: $e\,p^{\uparrow} \rightarrow h\,X$

- scattered electron not detected (ignored) → Q2 ≈ 0 → huge statistics

  P_T, x_F w.r.t. **beam direction**



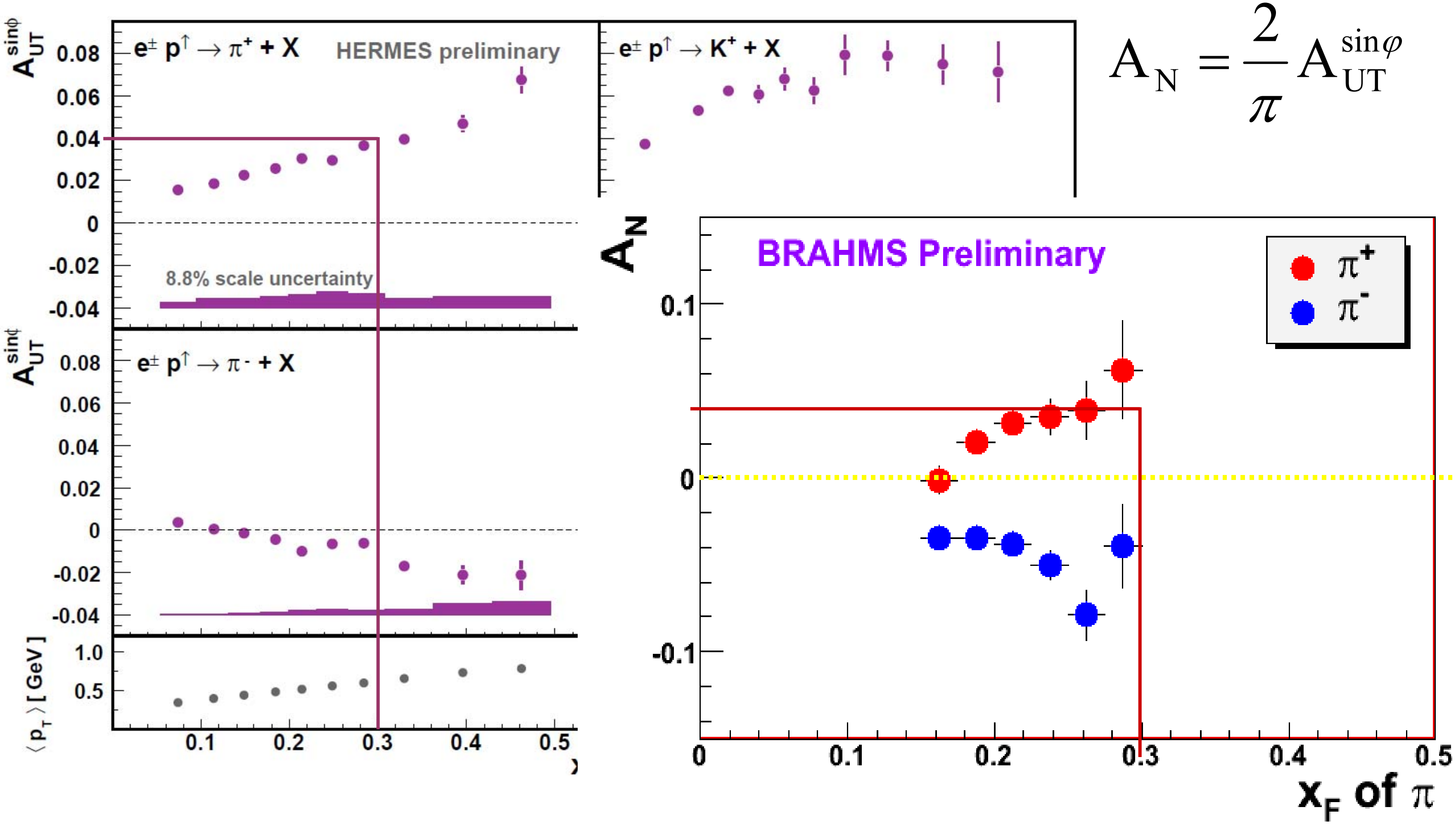
$$A_N = \frac{2}{\pi} A_{UT}^{\sin\varphi}$$

inclusive hadrons: $e\,p^{\uparrow} \rightarrow h\,X$

- scattered electron not detected (ignored) → Q2 ≈ 0 → huge statistics

  P_T, x_F w.r.t. **beam direction**

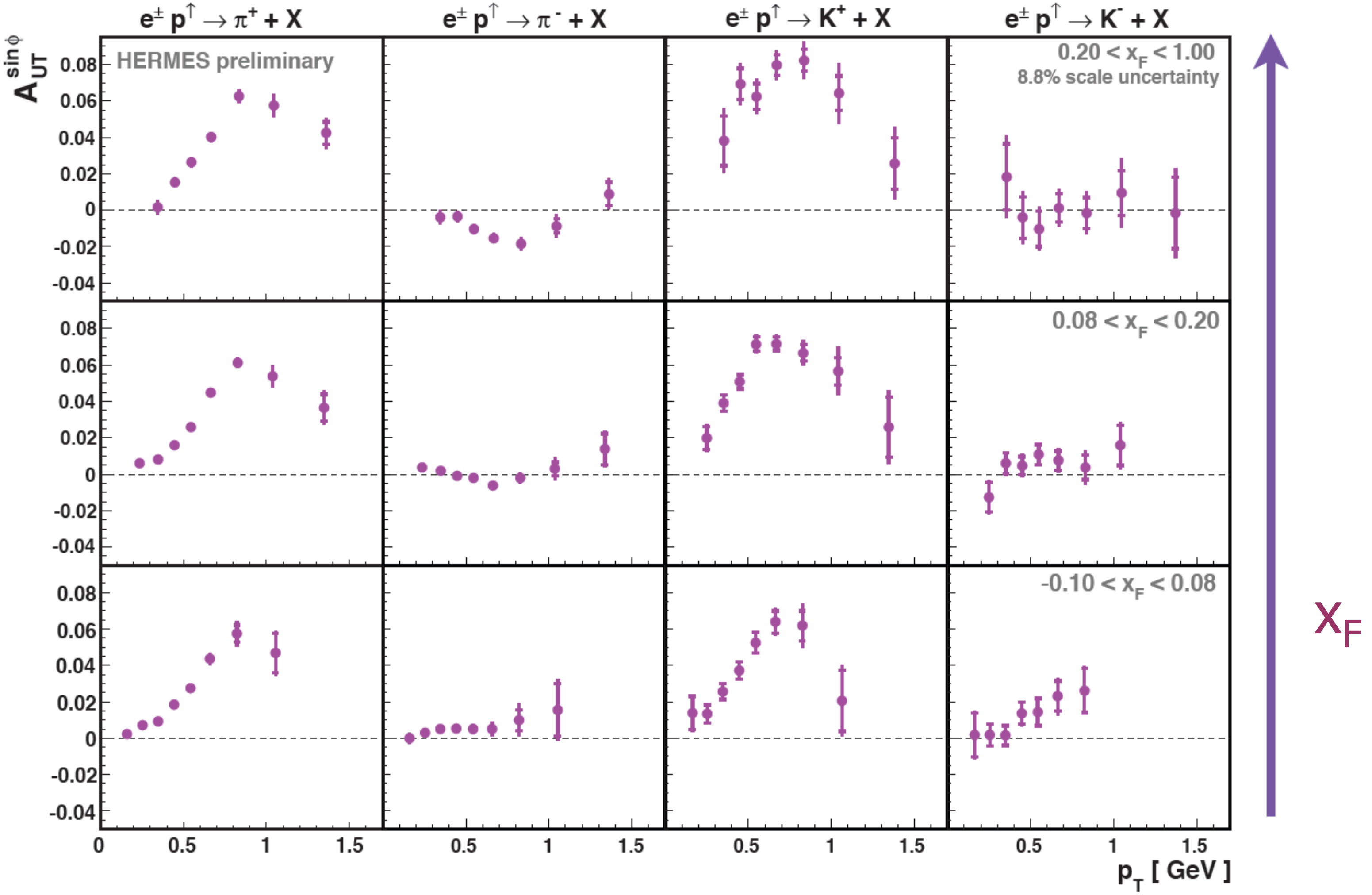
$$A_N = \frac{2}{\pi} A_{UT}^{\sin\varphi}$$



inclusive hadrons: $e\,p^{\uparrow} \rightarrow h\,X$

- scattered electron not detected (ignored) → Q2 ≈ 0 → huge statistics

P_T, x_F w.r.t. **beam direction**



conclusion & outlook

≈3 years after HERA shutdown many exciting results still to come:

longitudinal momentum & **spin distributions**; **fragmentation:**

publications in preparation:

- final SIDIS A_1 for pions, kaons, protons
- multiplicities for pions, kaons; factor ~6 more statistics to be analysed

transverse spin effects & **intrinsic k_T:**

publications in preparation:

- full set of A_{UT} & A_{LT} moments → new quality: p_T weighted asymmetries
- azimuthal asymmetries in unpolarised cross section

not discussed here: wealth of results from exclusive processes

→ **GPDs** & **nucleon tomography** : **complementary to TMDs**