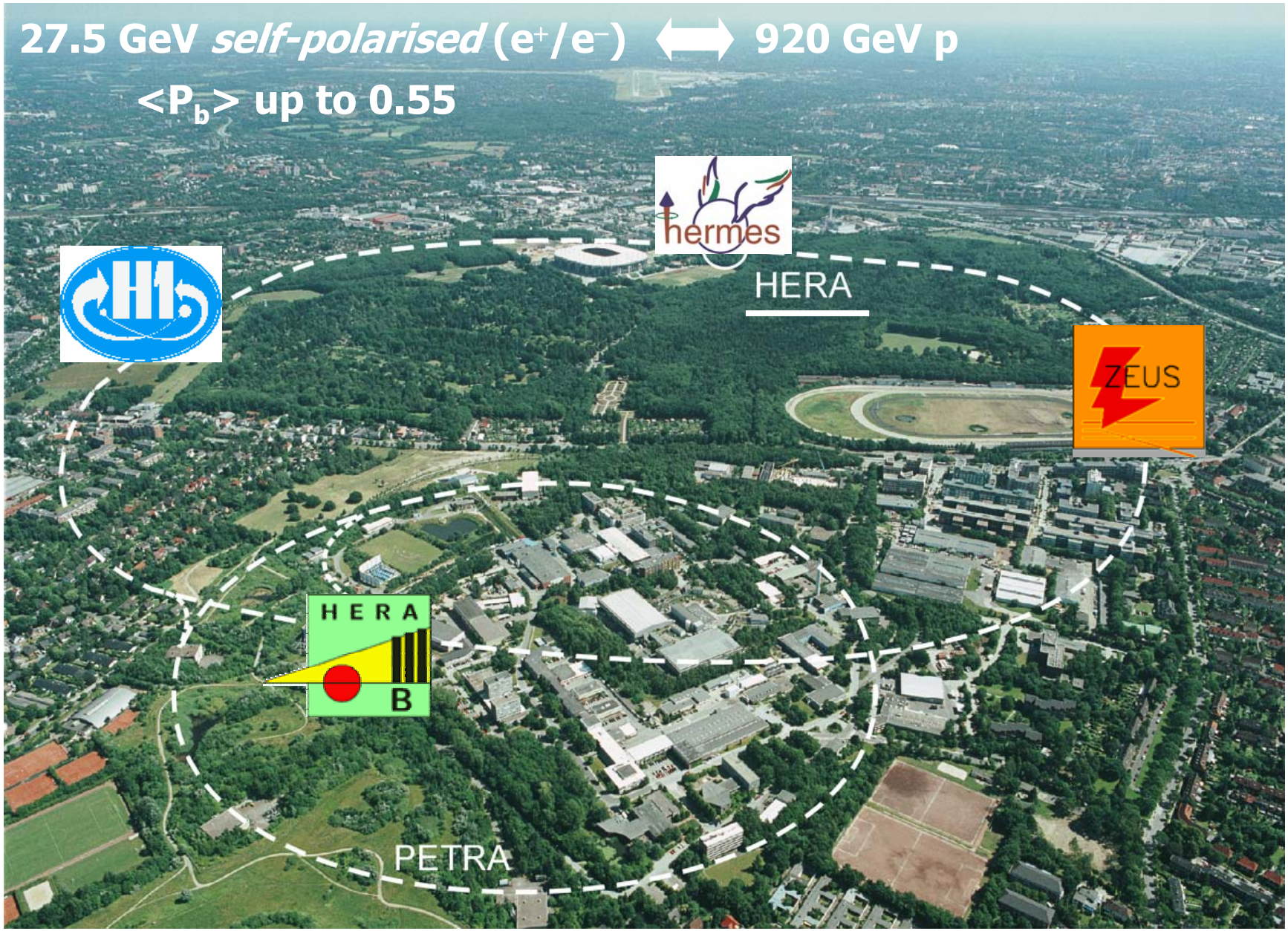
Delia Hasch

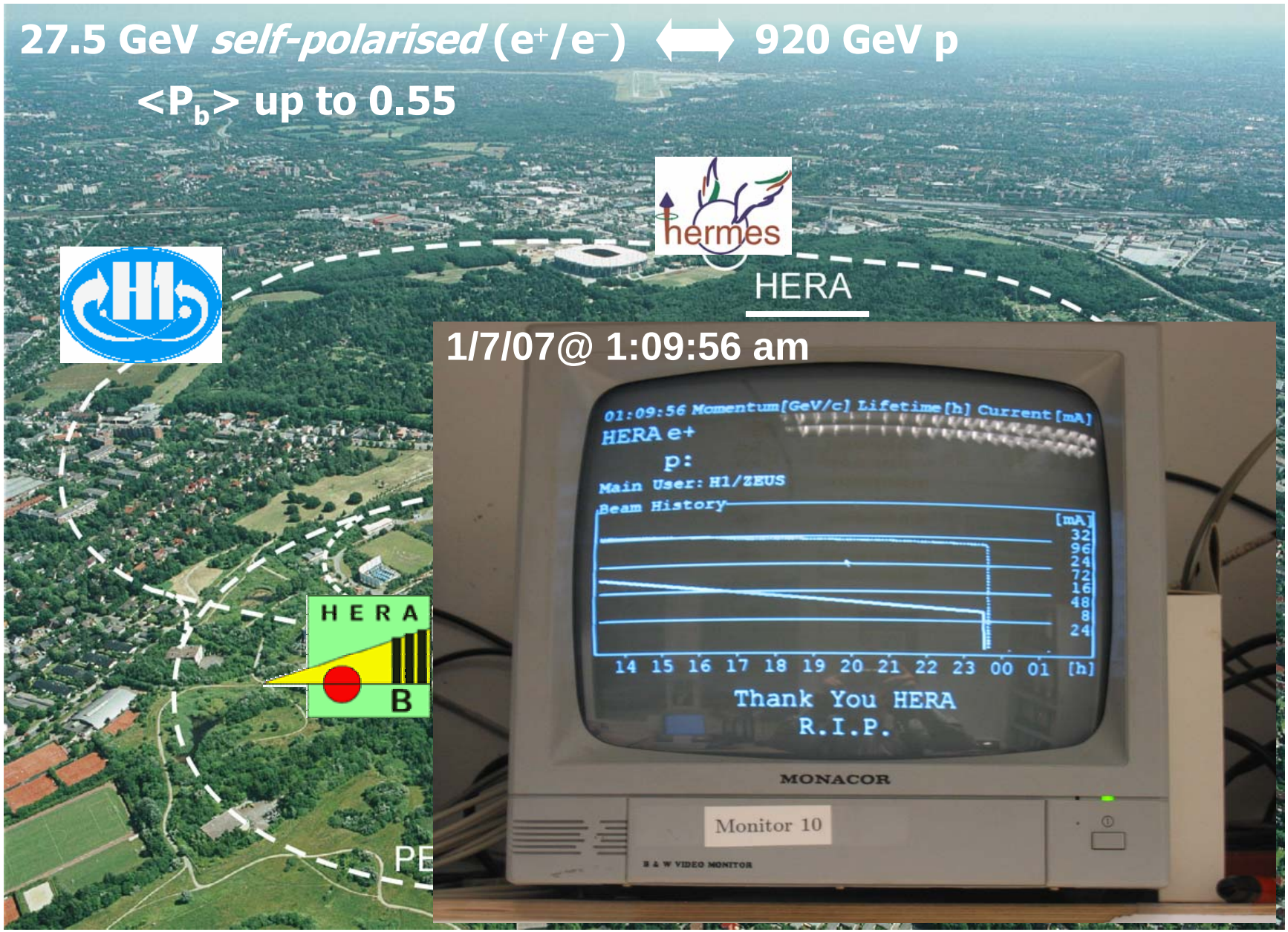
recent results from HERMES

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

HERMES @HERA: a reminder

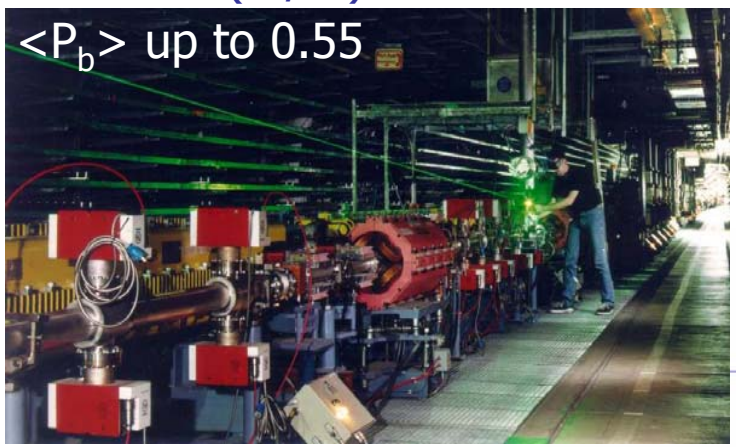


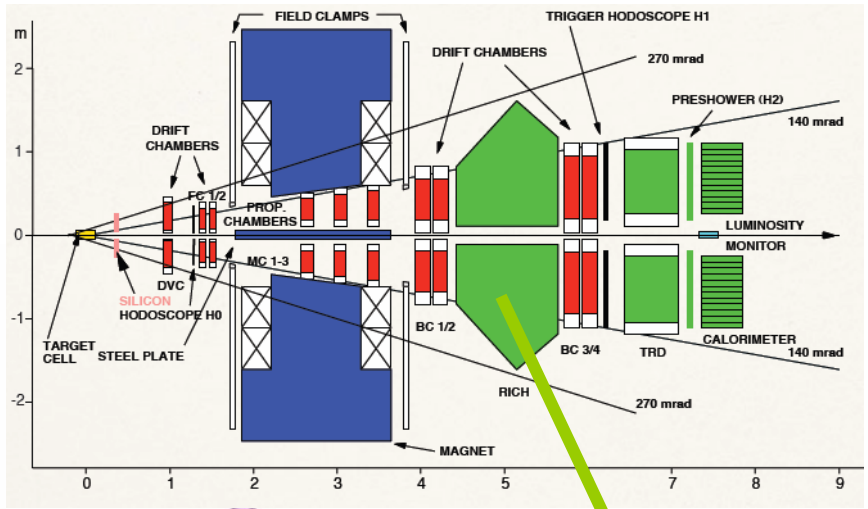
HERMES @HERA: a reminder

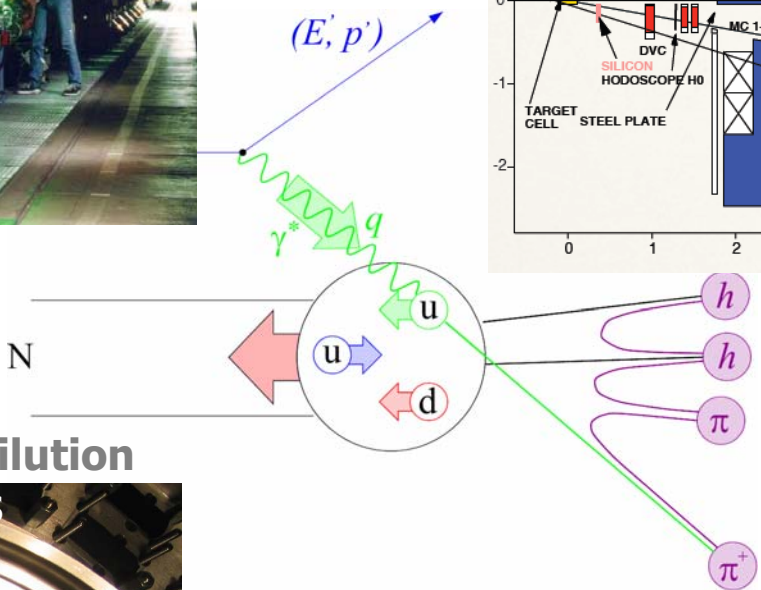


HERMES @HERA: a reminder

27.5 GeV (e^+/e^-) →



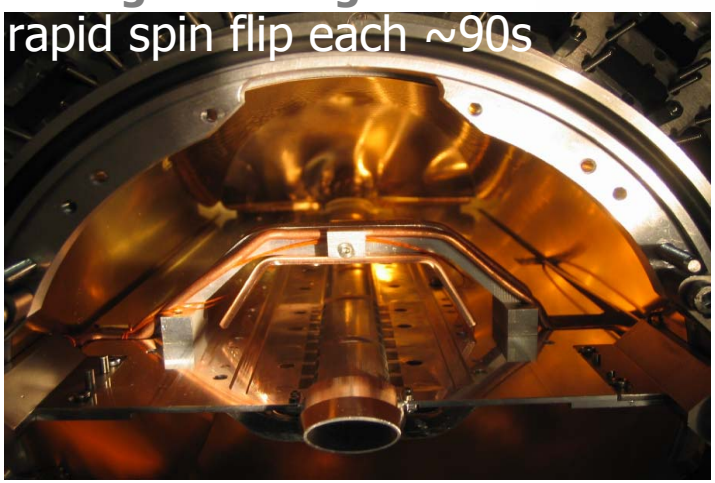




hadron ID: π/K/p

$2 < E_h < 15$ GeV

storage cell target: no dilution



H → $\langle|P_t|\rangle \sim 0.85$

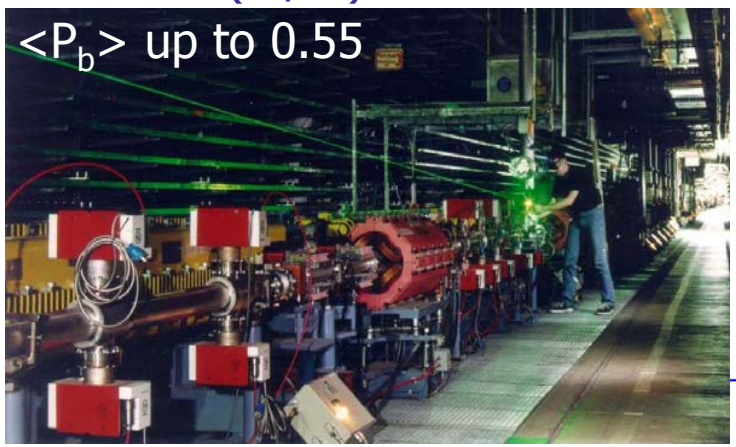
D → $\langle|P_t|\rangle \sim 0.84$

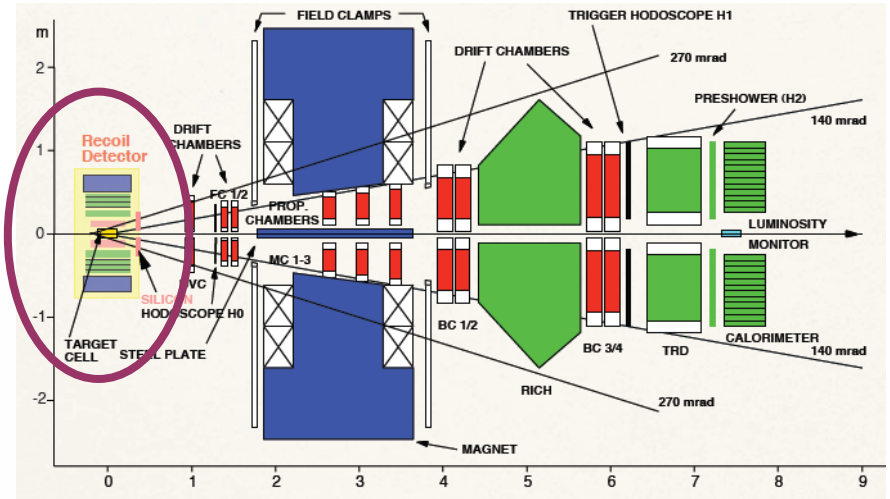
H ↑ $\langle|P_t|\rangle \sim 0.74$

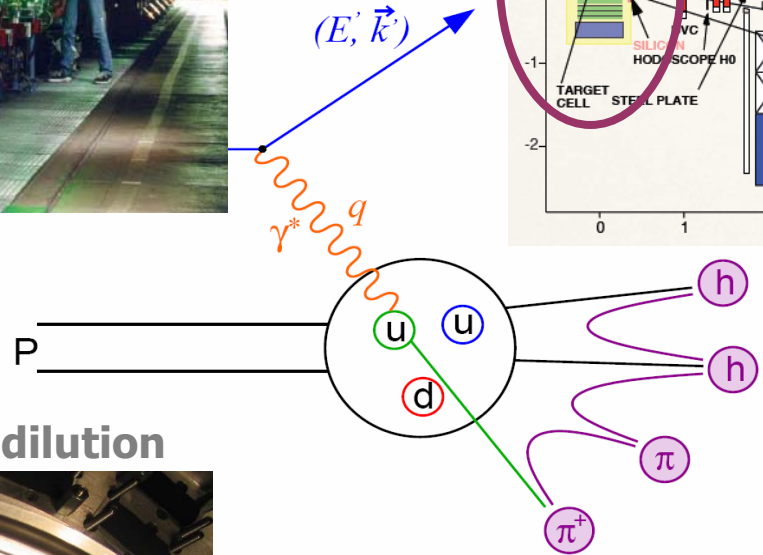
unpol: H, D, He, Ne, N, Kr, Xe

HERMES @HERA: a reminder

27.5 GeV (e^+/e^-) →

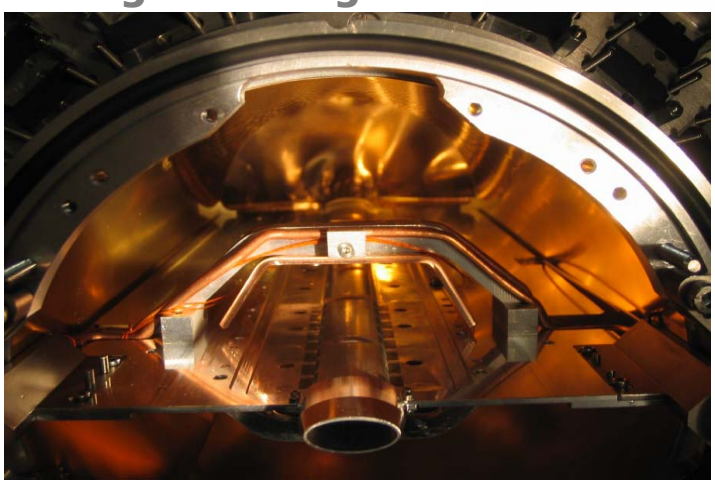






2006/07
HERMES with recoil det.
'dedicated' to exclusive processes, but not only…

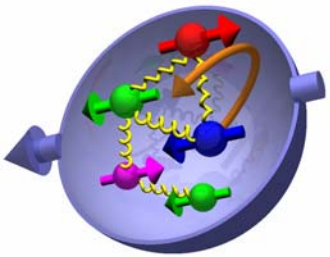
storage cell target: no dilution



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)]

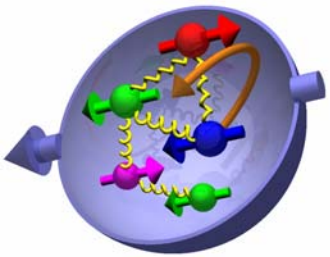
  $$\Delta\Sigma = 0.330 \pm 0.025^{(\text{exp.})} \pm 0.011^{(\text{theory})} \pm 0.028^{(\text{evol.})}$$

  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



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

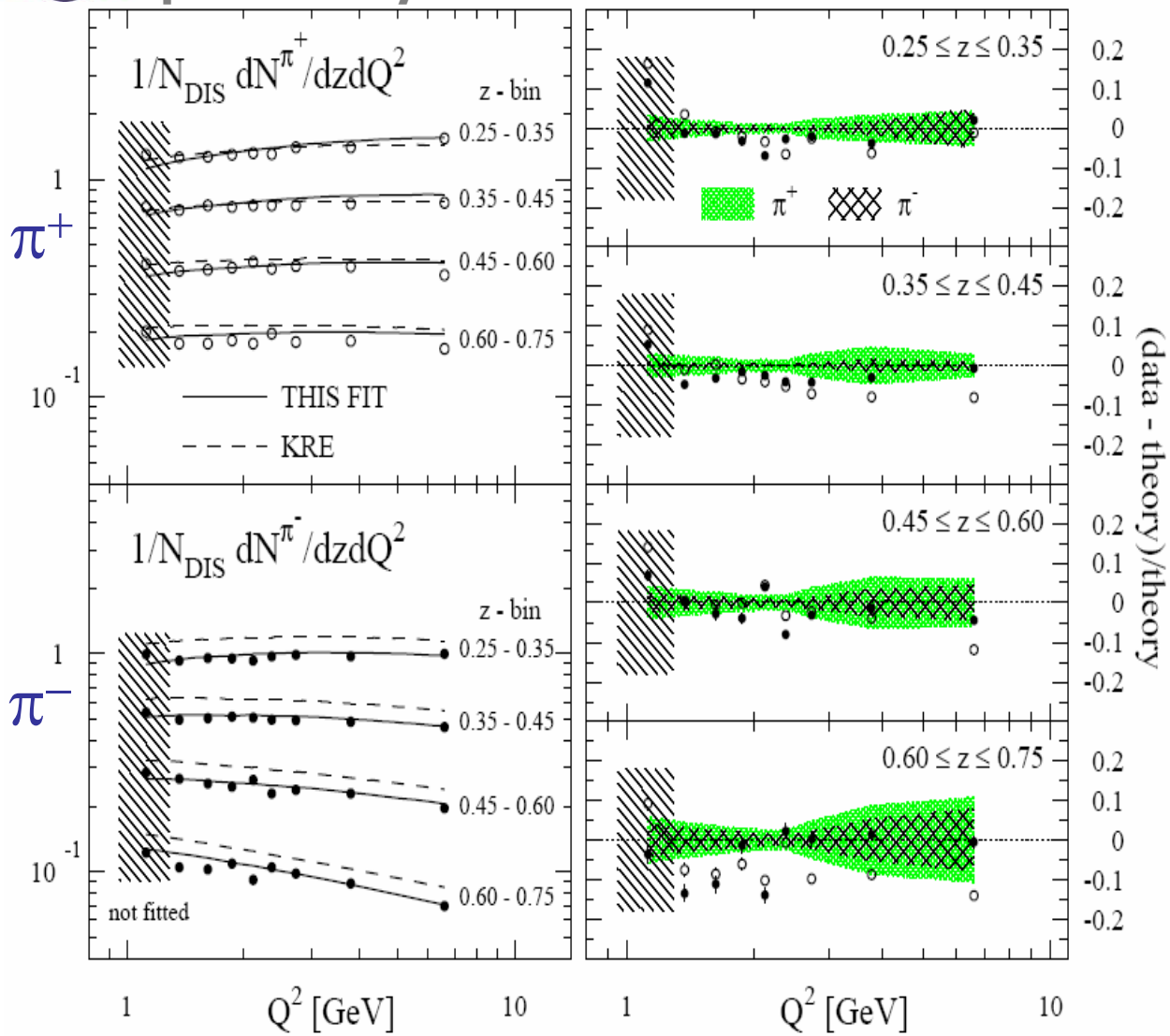
~30% ≈zero

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

hermes **preliminary**



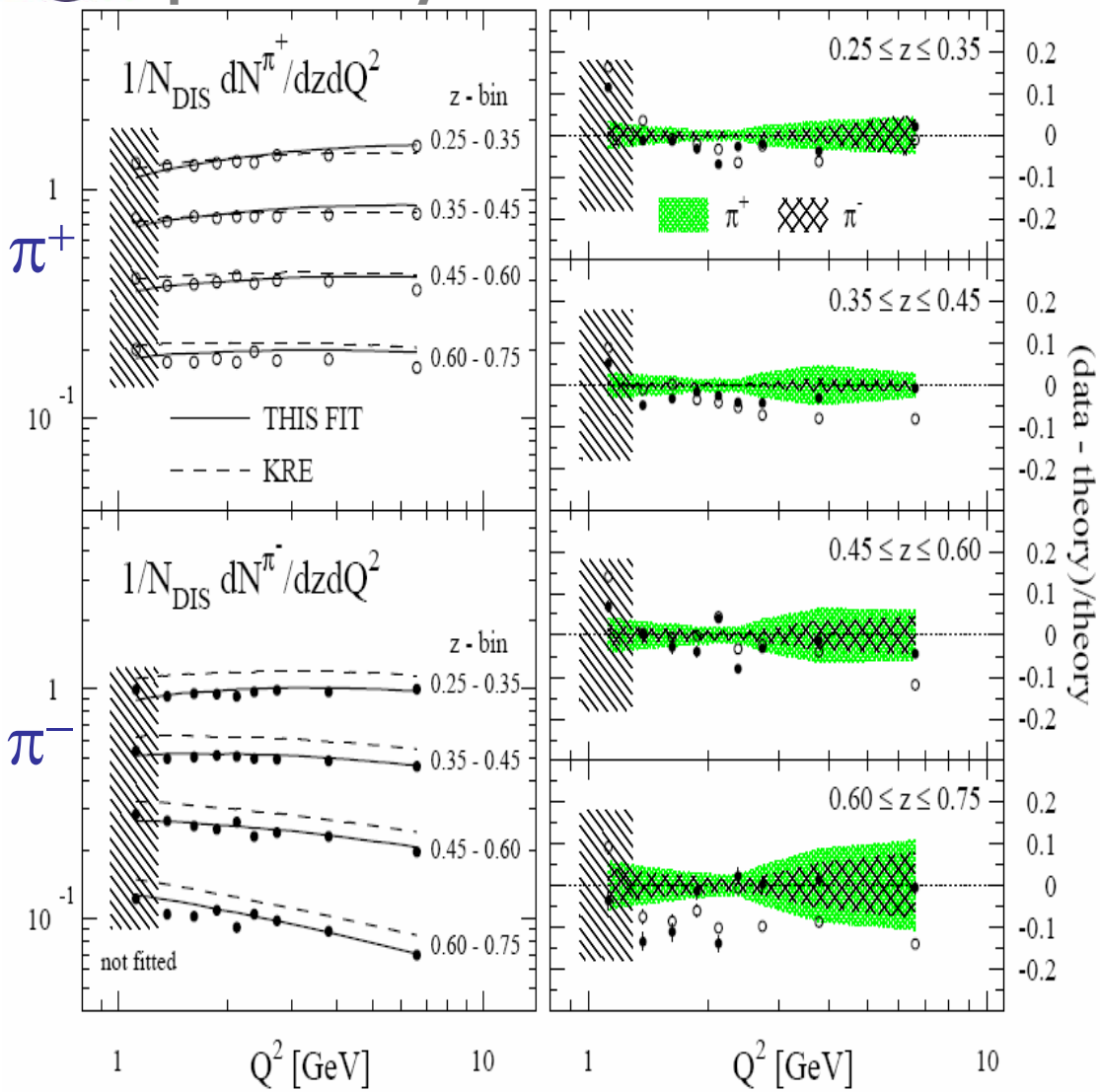
no SIDIS xsection measurements → π, K *multiplicities* compared to theory:

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

hermes **preliminary**



no SIDIS xsection measurements → π, K *multiplicities* compared to theory

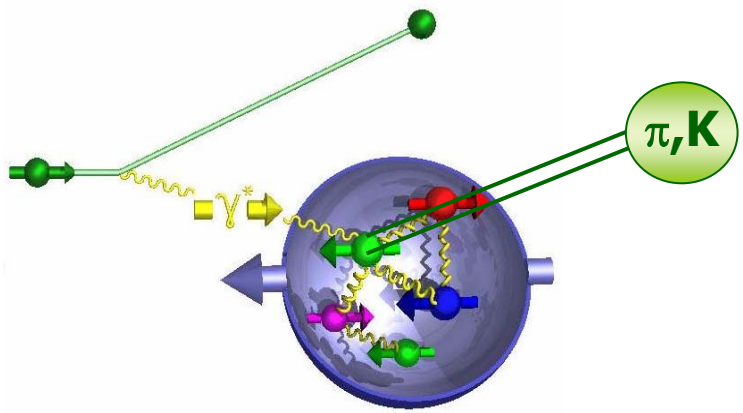
outlook:

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

→ 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)]

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

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

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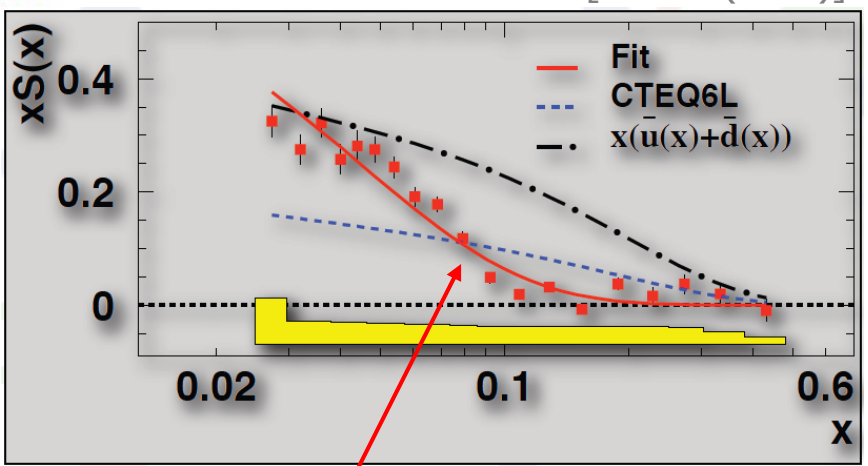
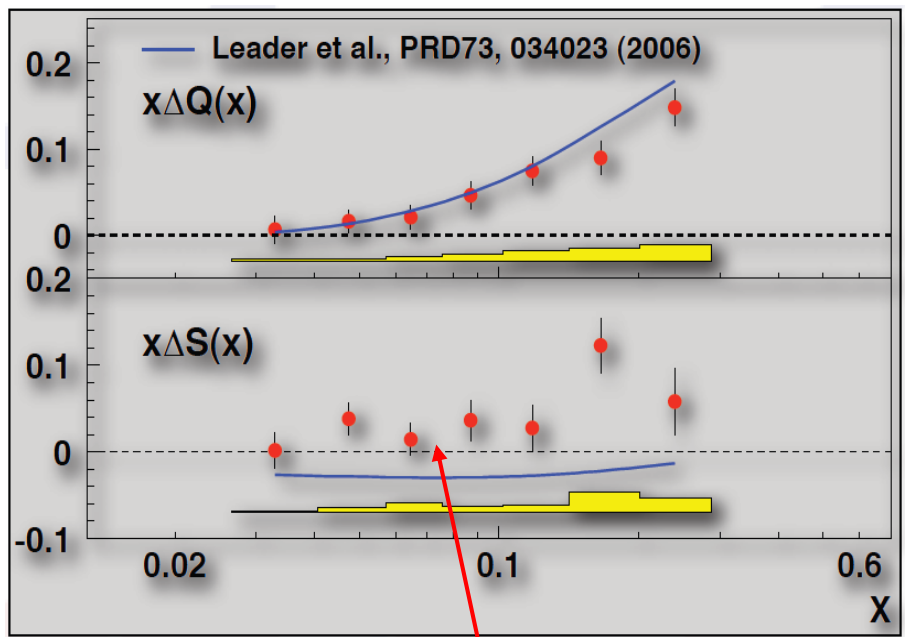
hermes **LO extraction** [PLB666(2008)]



S(x) NOT average of an isoscalar non-strange see



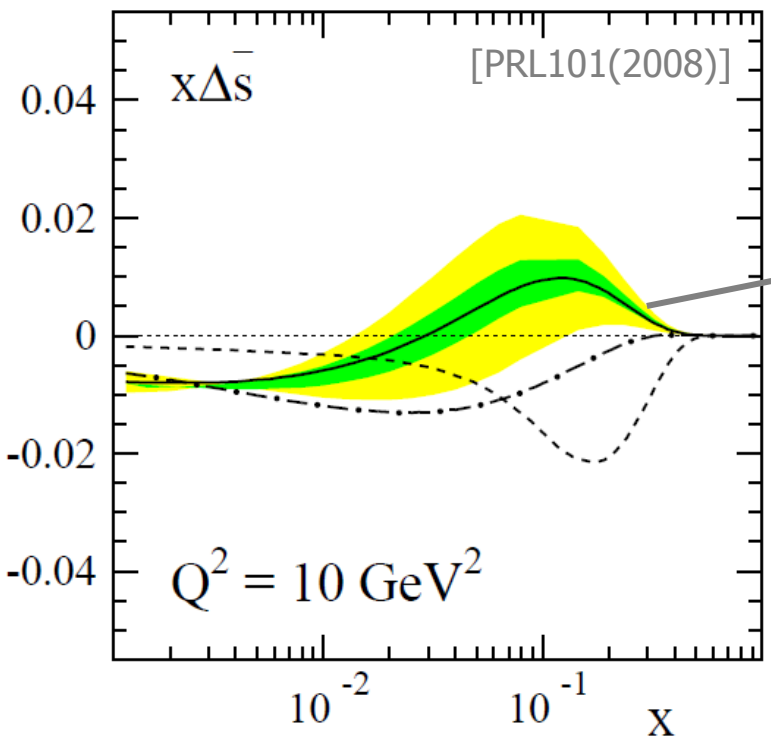
ΔS(x) ≈ zero/ slightly positive in contrast to inclusive DIS analyses

strange quark distributions

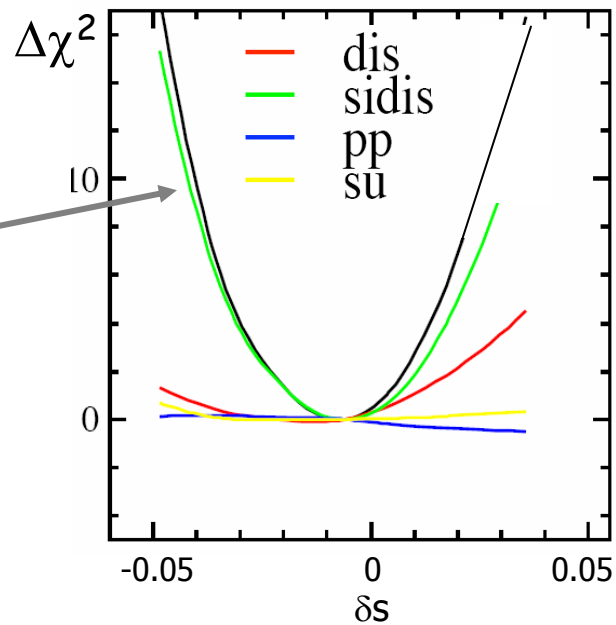
→ use isoscalar probe + target: $S^p(x) = S^n(x)$; $S(x) = s(x) + \bar{s}(x)$

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

DSSV – NLO fit result:

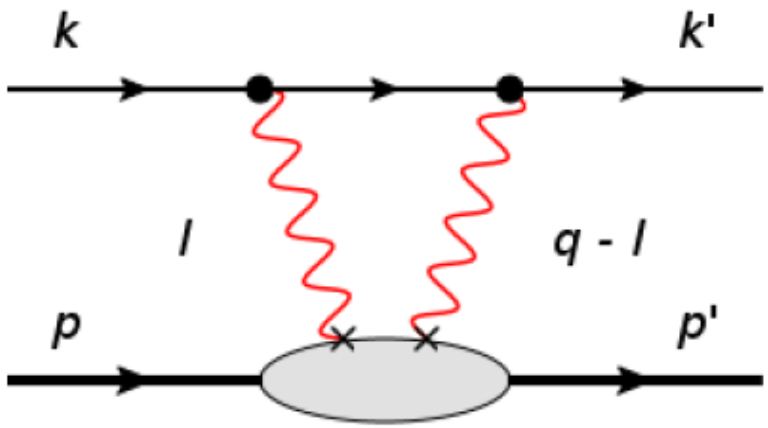


striking impact of SIDIS data



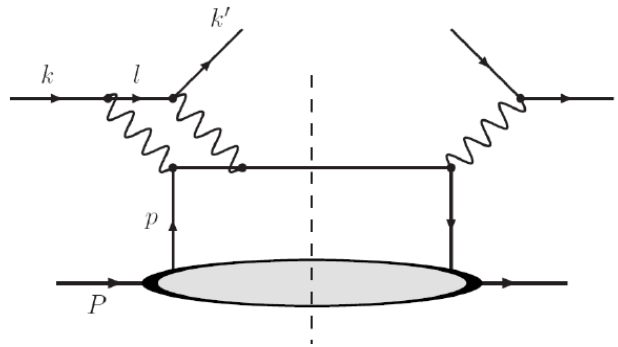
transverse spin phenomena

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)]

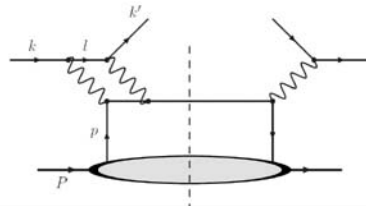
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{2}{\pi} A_{UT}^{\sin\phi_S}$$

estimated size: O(10^{-4} – 10^{-2})

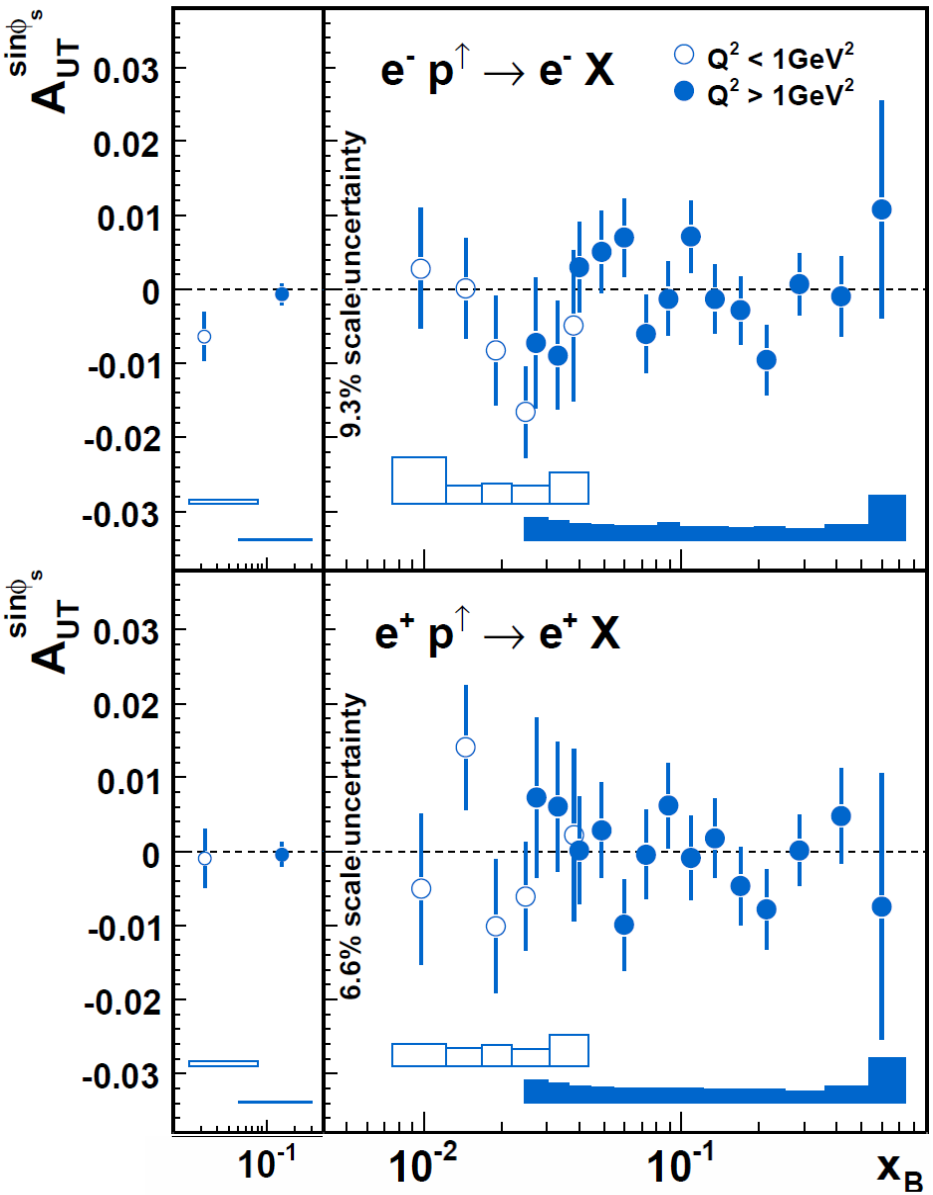
$$A_{UT}(x, Q^2, \phi_S) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

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

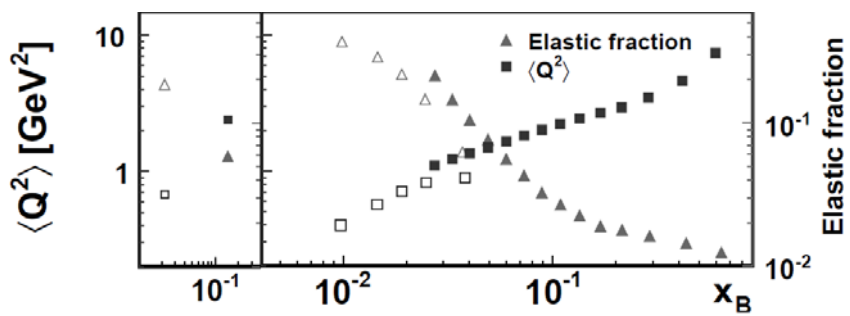
any sign of 2γ exchange ?

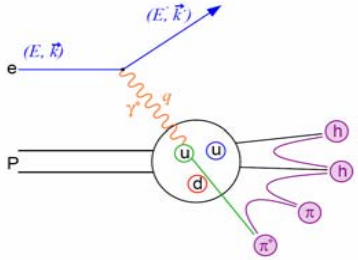


[PLB682(2010)]



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



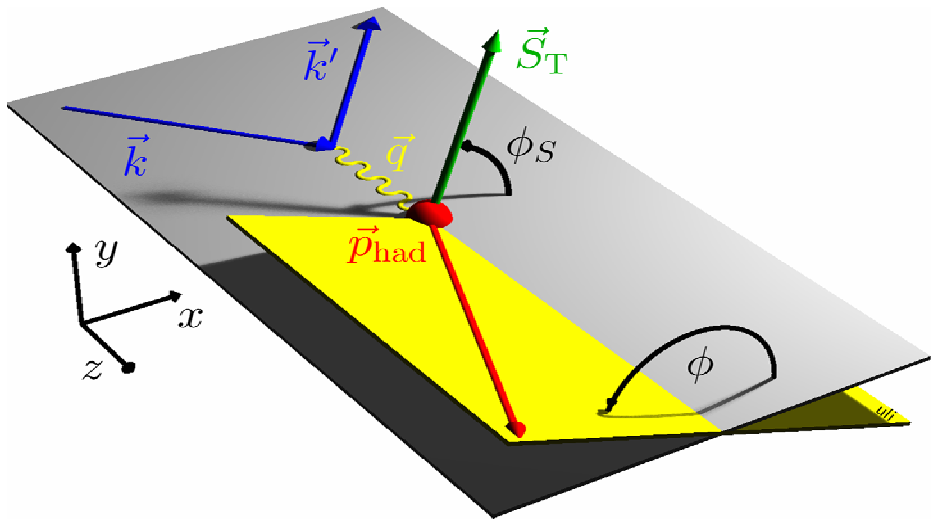


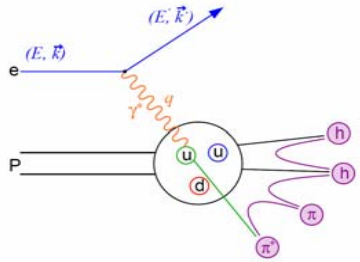
SIDIS cross section

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

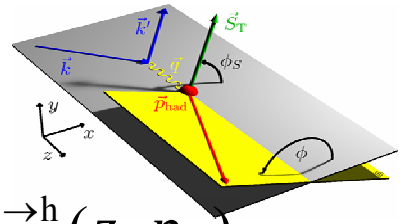
σ_{XY}

beam: λ target: S_L ,S_T





SIDIS cross section



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

8 leading-twist terms

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

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

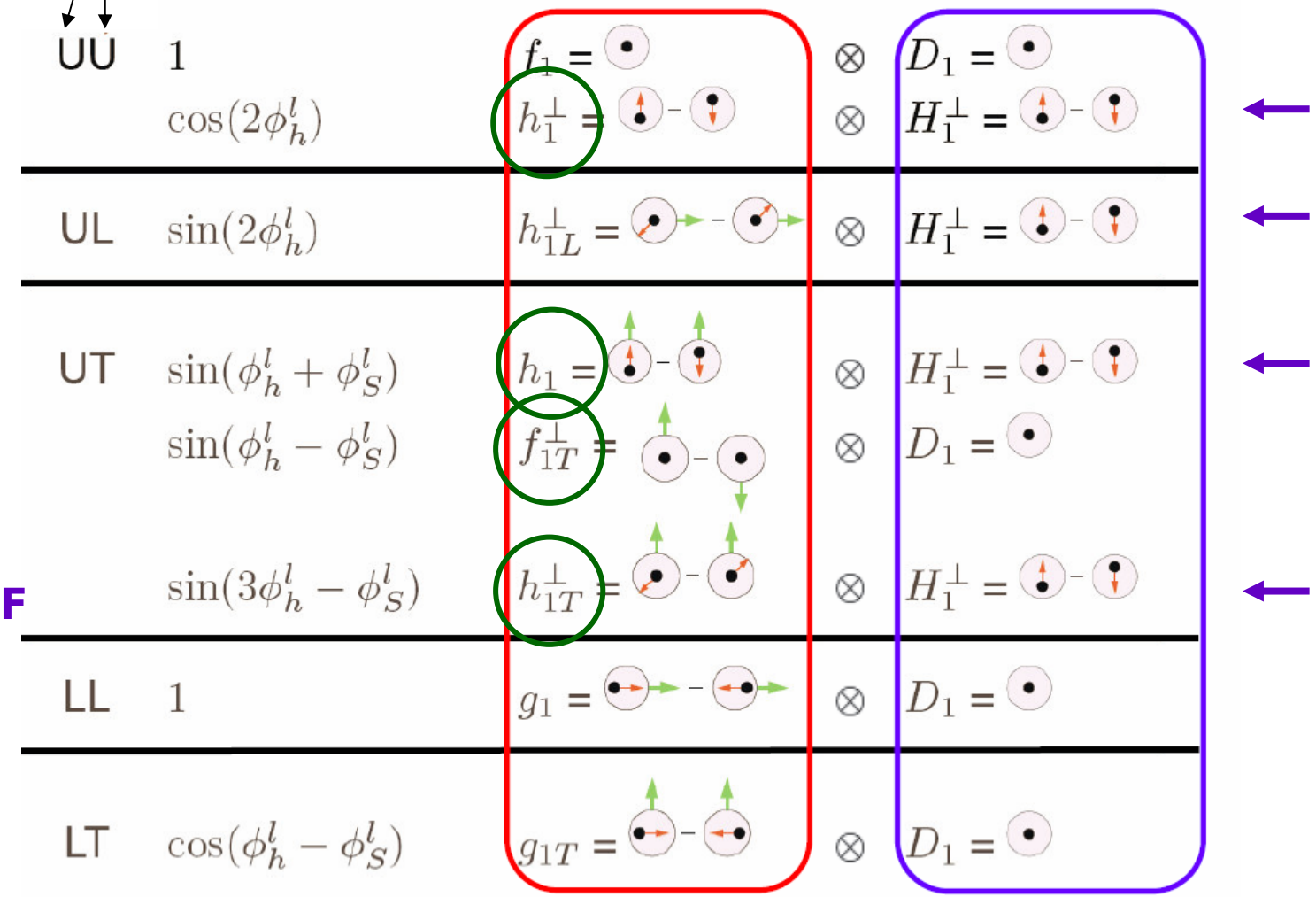
$$+ S_T\left\{\boxed{\sin(\phi-\phi_S)\ d\sigma^8_{UT} + \sin(\phi+\phi_S)\ d\sigma^9_{UT} + \sin(3\phi-\phi_S)\ d\sigma^{10}_{UT}}\right.$$

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

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

leading-tw distribution functions

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



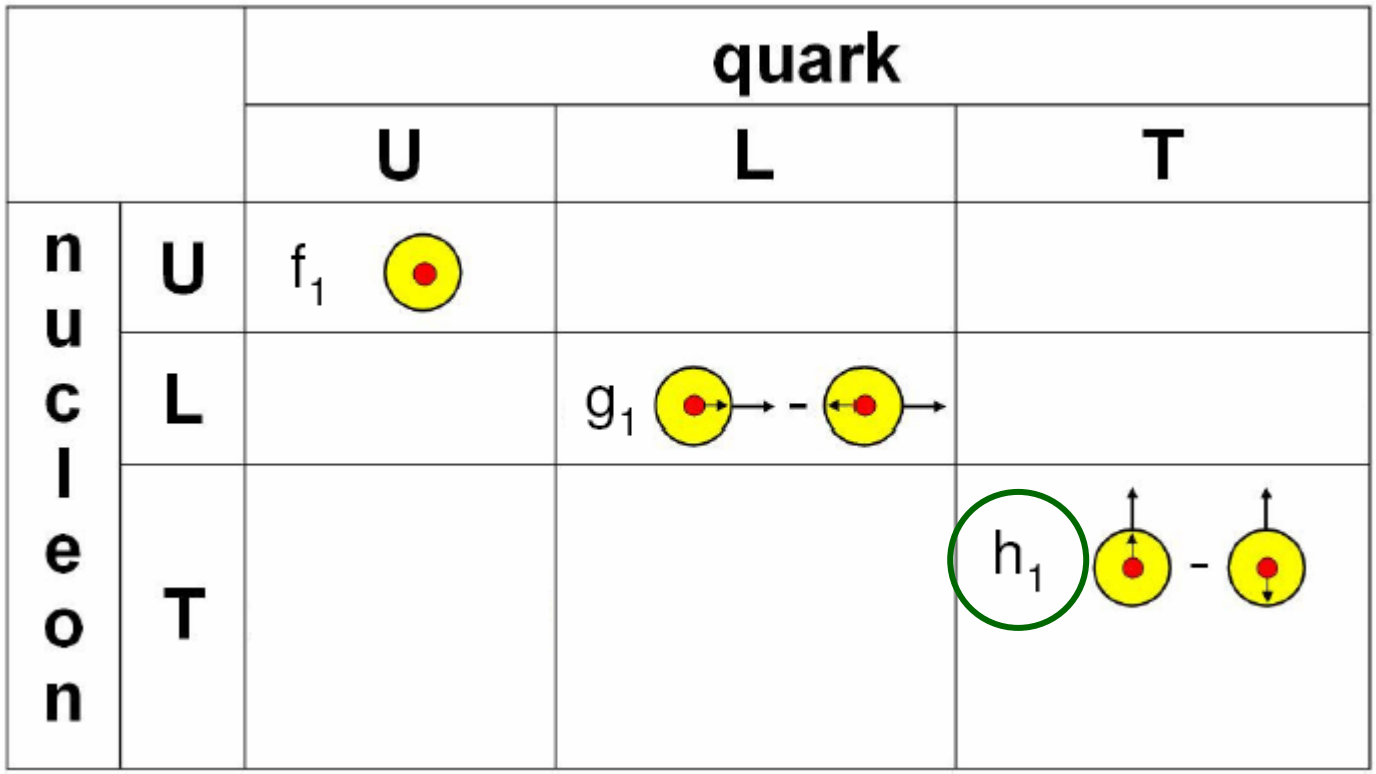
on the menu today

chiral-odd pdf & Collins FF

'Amsterdam notation'

leading-tw distribution functions

@leading twist, integrated over pT:

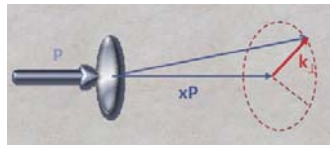


'transversity'

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'

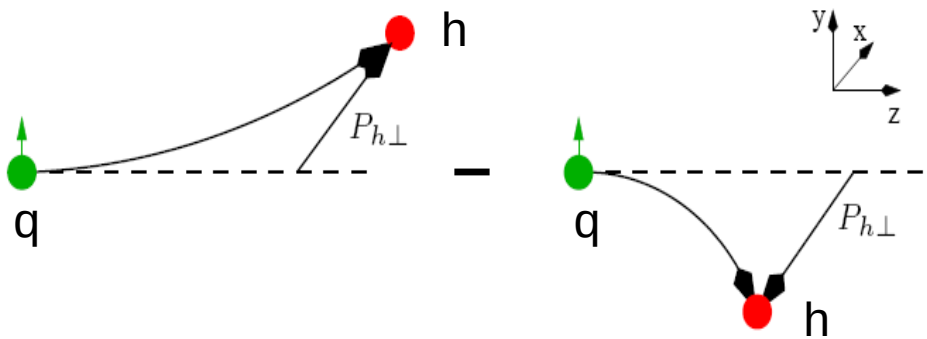
'transversity'

'pretzelosity'

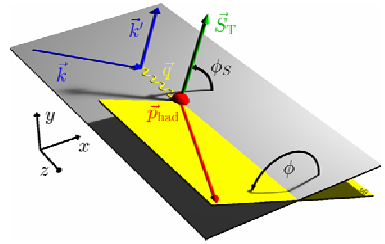
'Sivers'

transversity

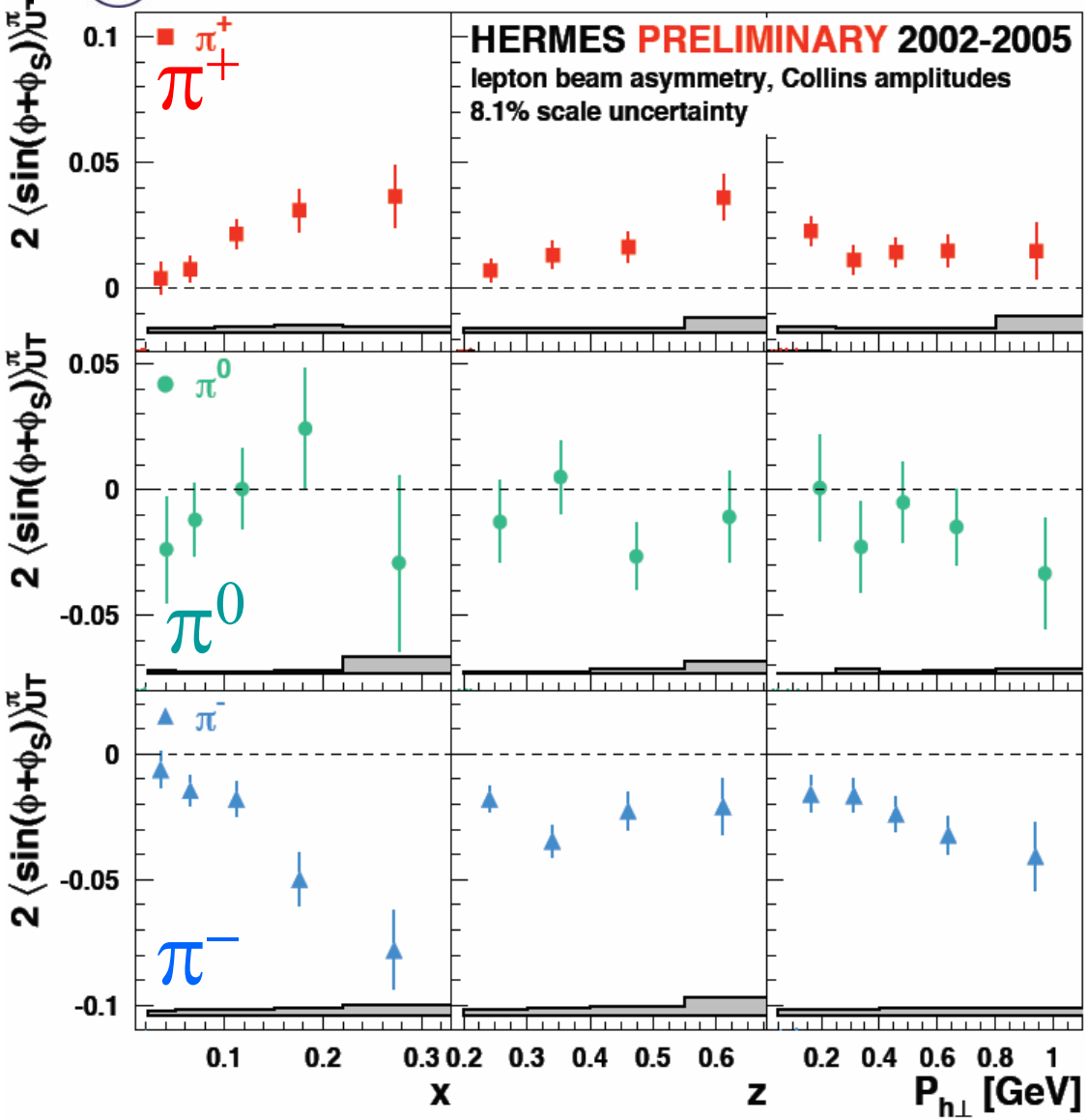
via ***Collins*** fragmentation fct.



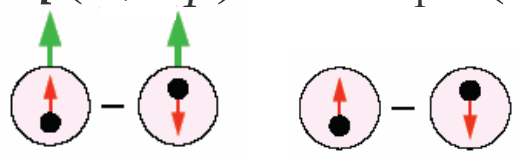
Collins amplitudes



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



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



distinctive pattern:

- π^+ positive
- π^0 ≈zero
- π^- negative

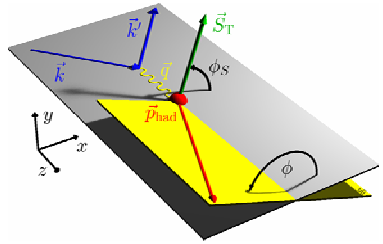
isospin relation for π triplet fulfilled

approximation:

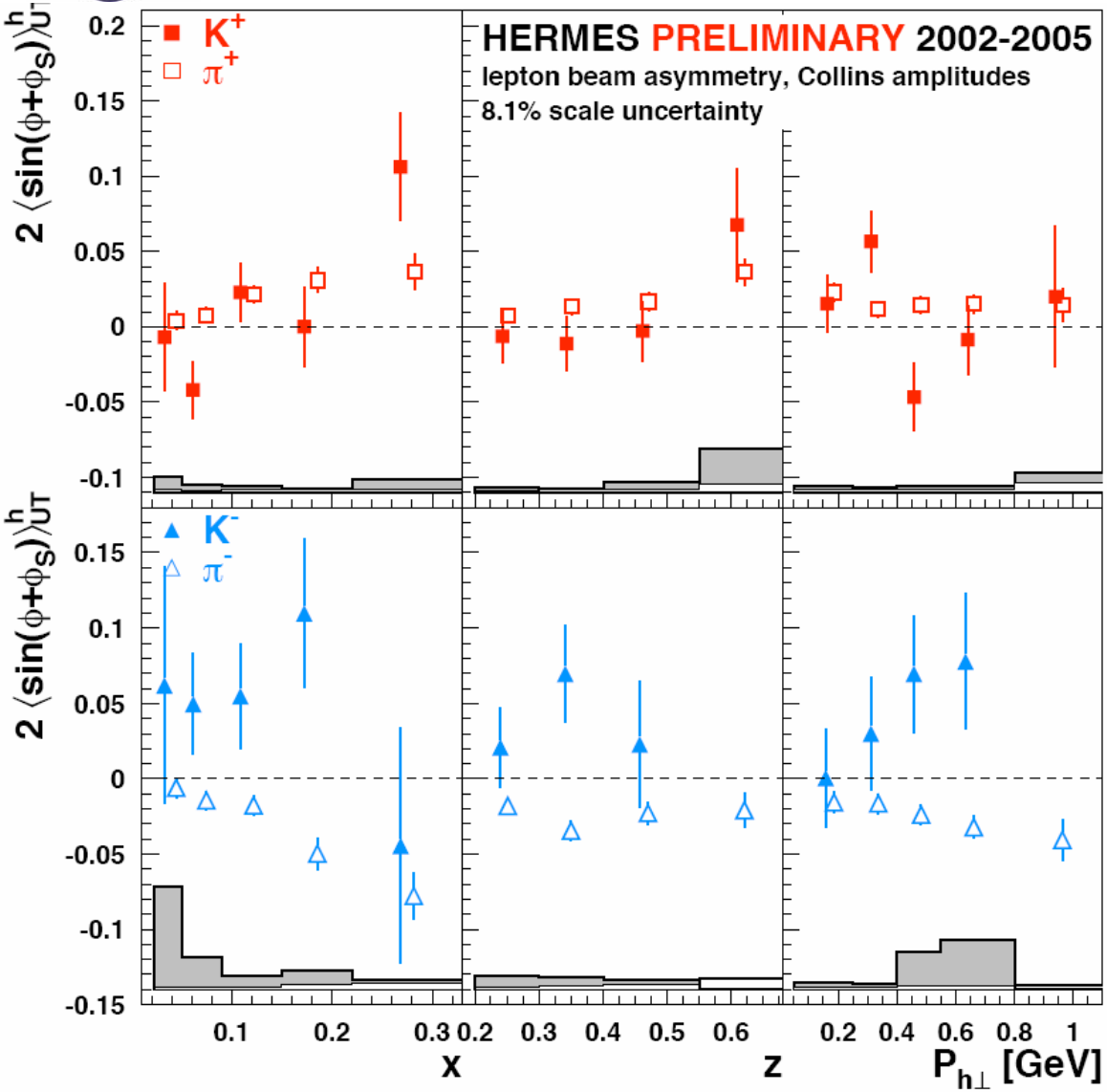
u-quark dominance

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

Collins amplitudes



ep↑ → K X

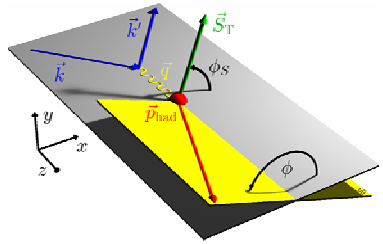


$$\delta q(x.k_T) \otimes H_1^{\perp q}(z, p_T)$$

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:

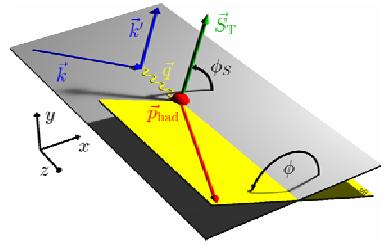
z @`fixed' x

$P_{h\perp}$ @`fixed' z

x @`fixed' z

z @`fixed' $P_{h\perp}$

Collins amplitudes
-- extras: 2D binning --



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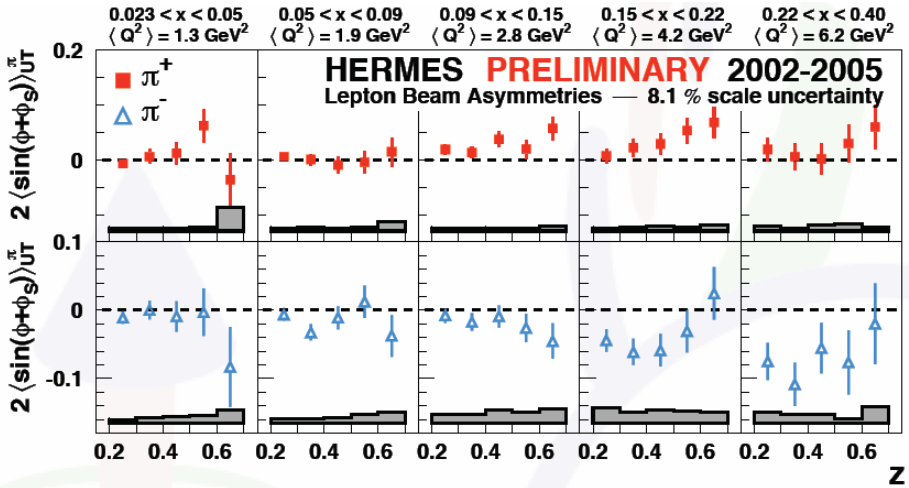
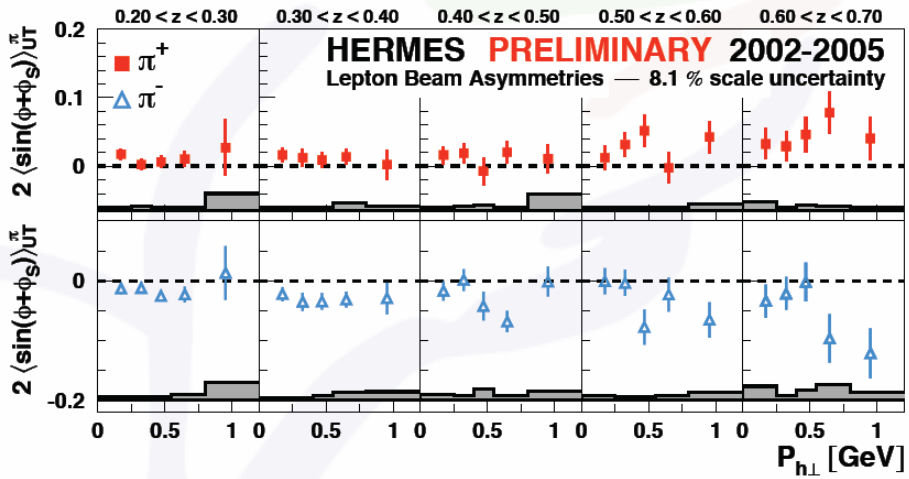
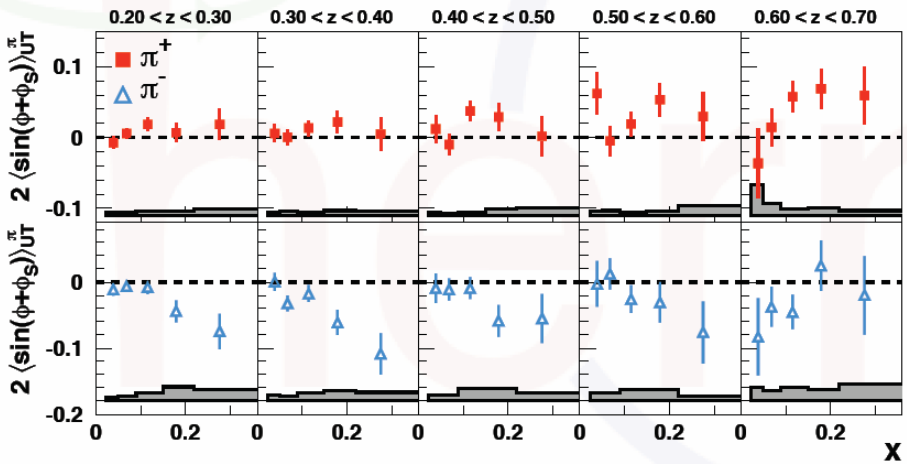
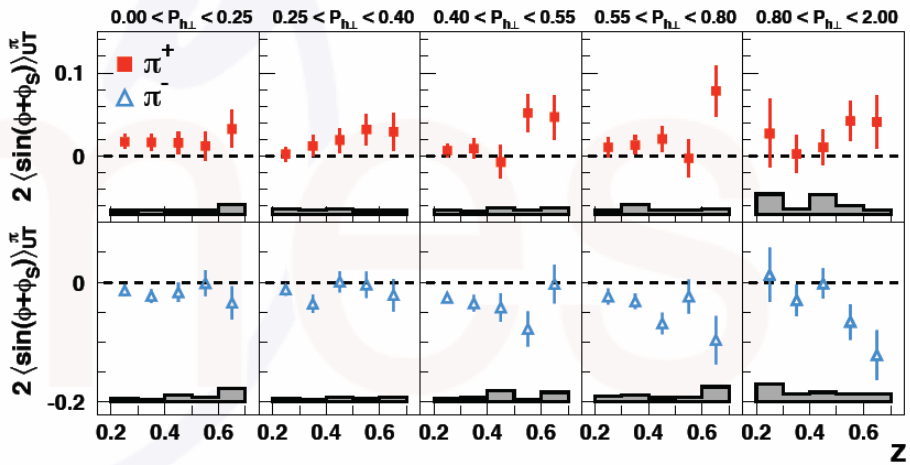
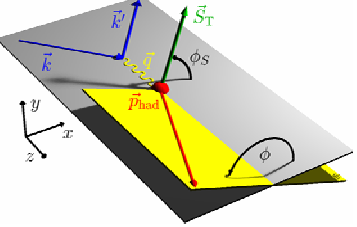


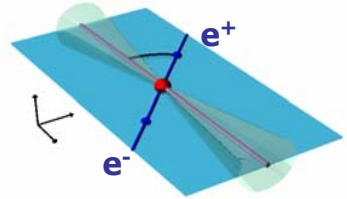




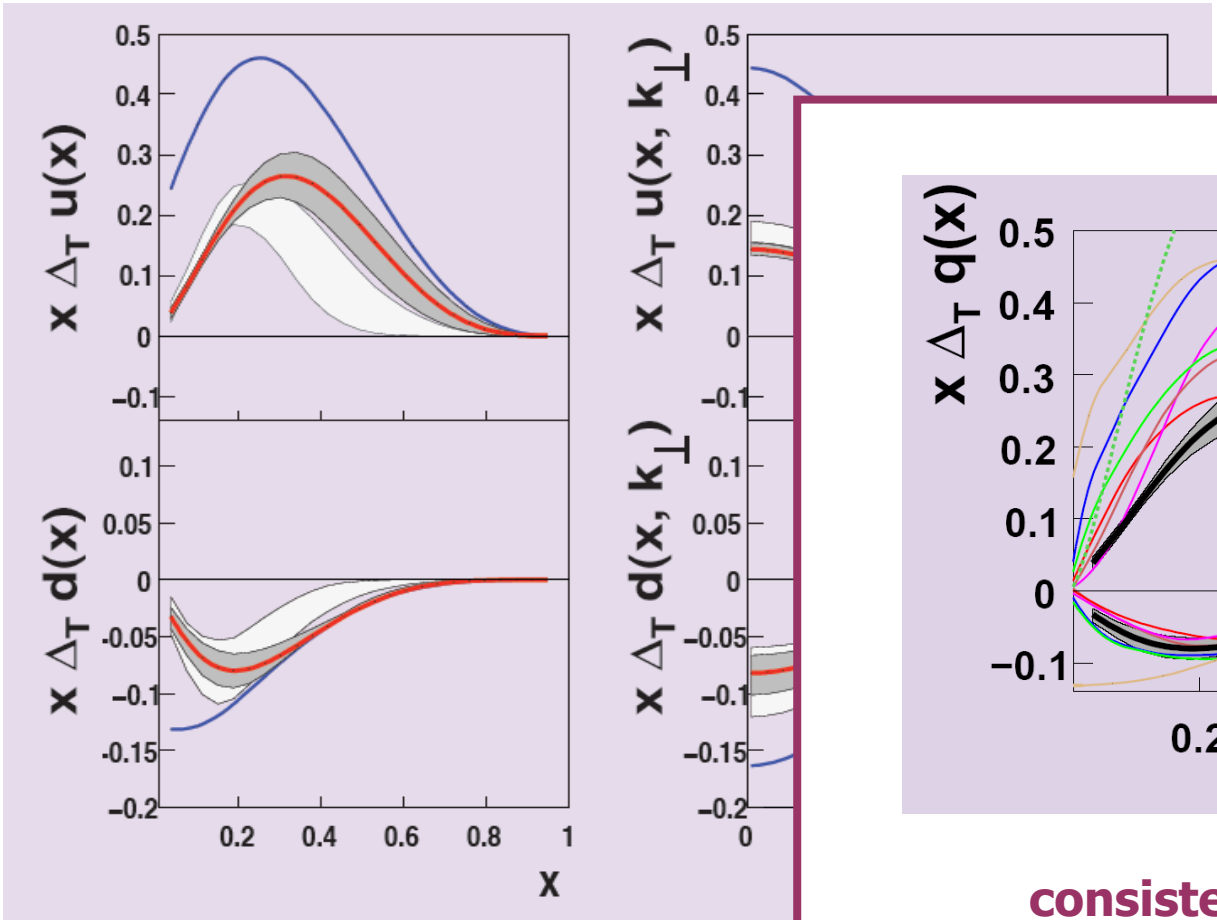


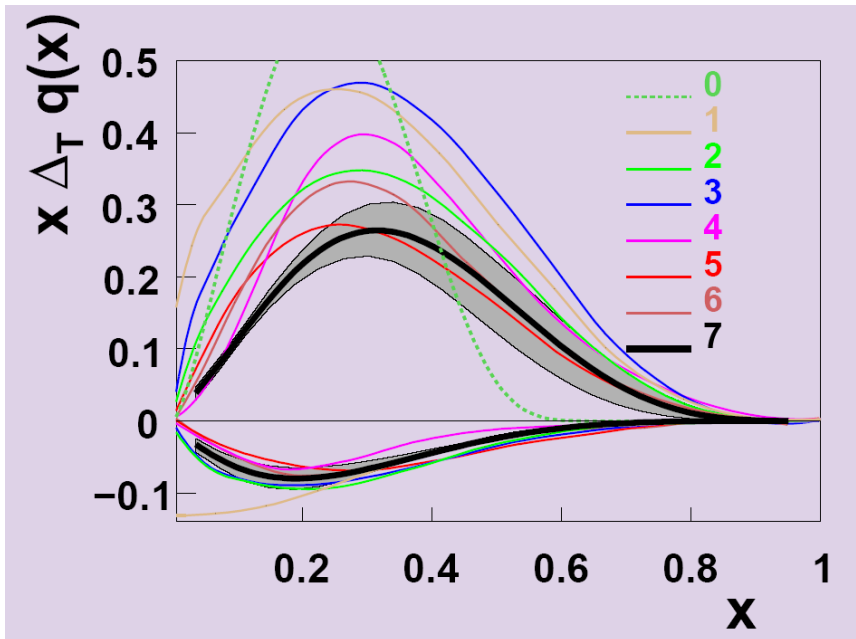


transversity & *Collins* FF



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

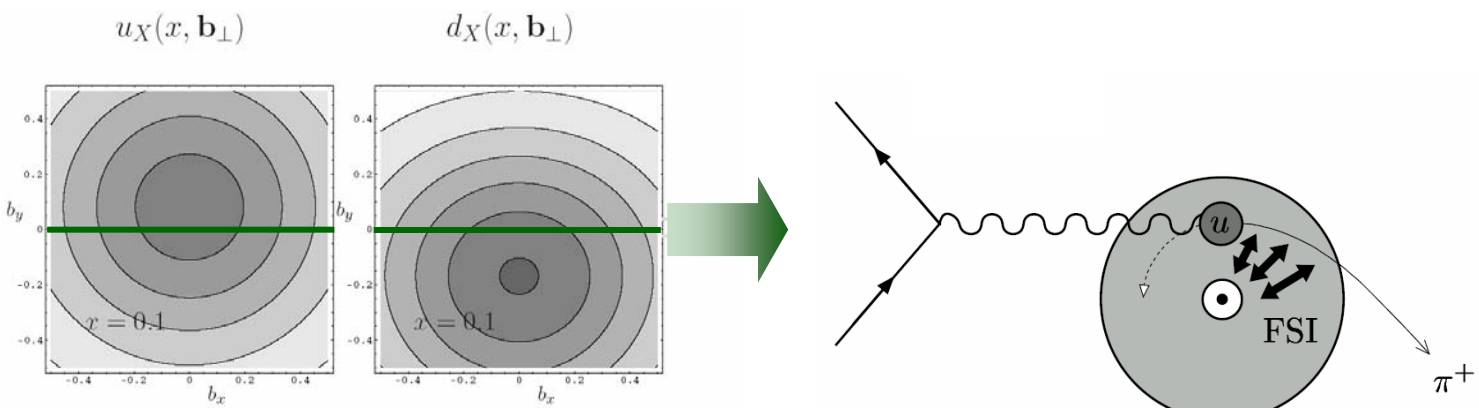




consistent flavour pattern

spin-orbit correlations

Sivers function:

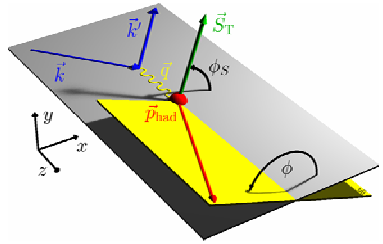


u(x,b) **d (x,b)**

[Matthias Burkardt]

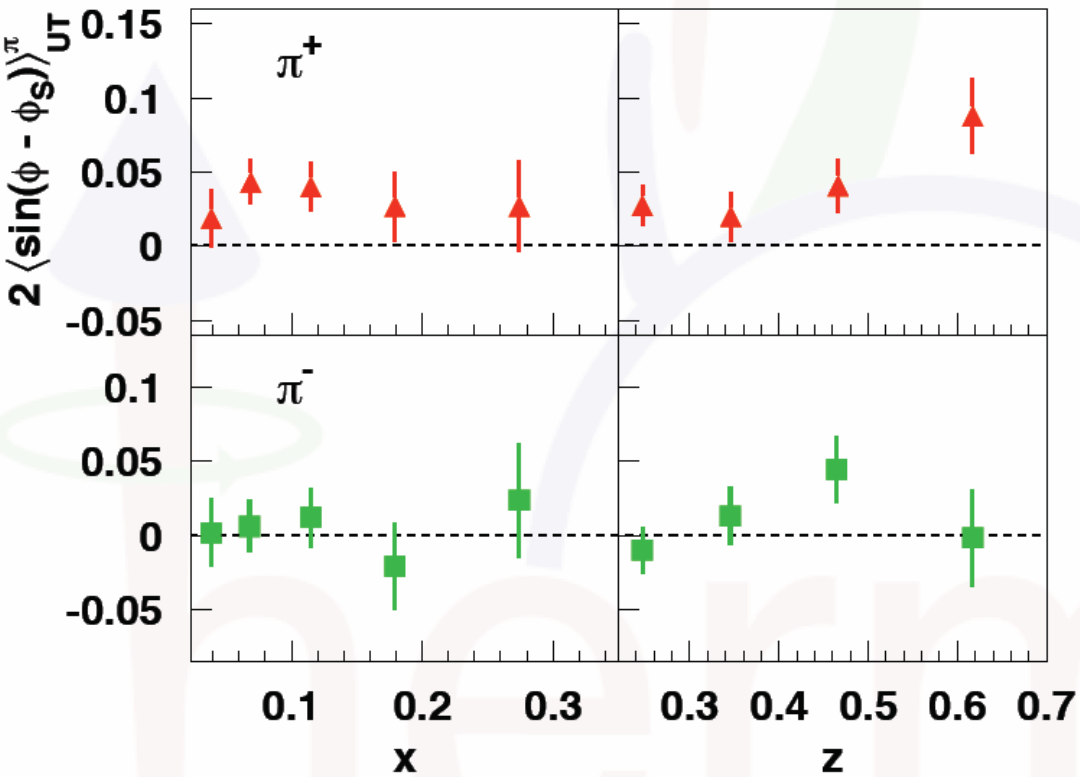
a non-zero Sivers fct. requires non-zero orbital angular momentum !

Sivers amplitudes

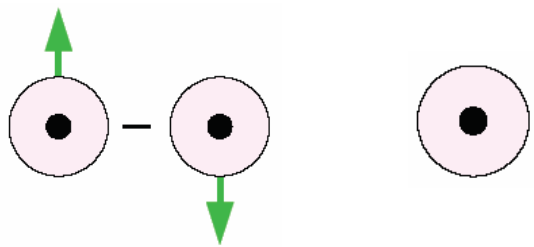


ep↑→ h X

[PRL94(2005)]

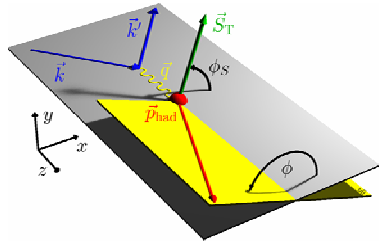


$$f_{1T}^{\perp q}(x, k_T) \otimes D_1^q(z, p_T)$$



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

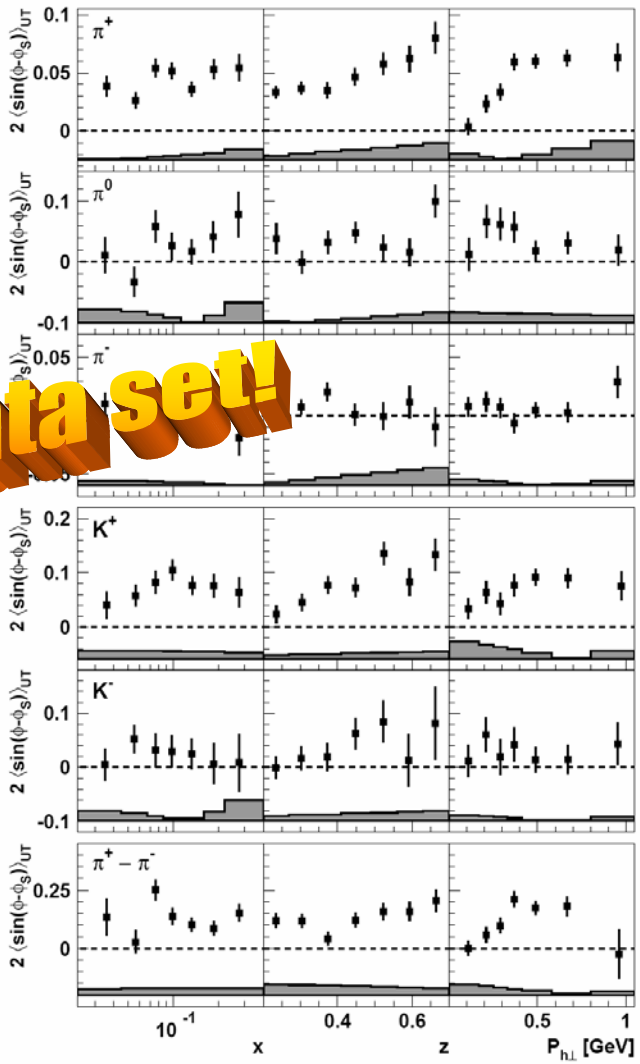
Sivers amplitudes



hermes

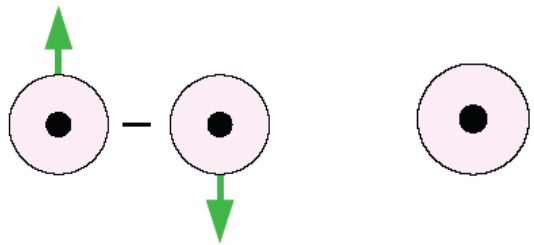
$ep^{\uparrow} \rightarrow h\,X$

[PRL103(2009)]



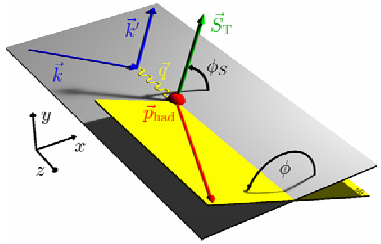
final data set!

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

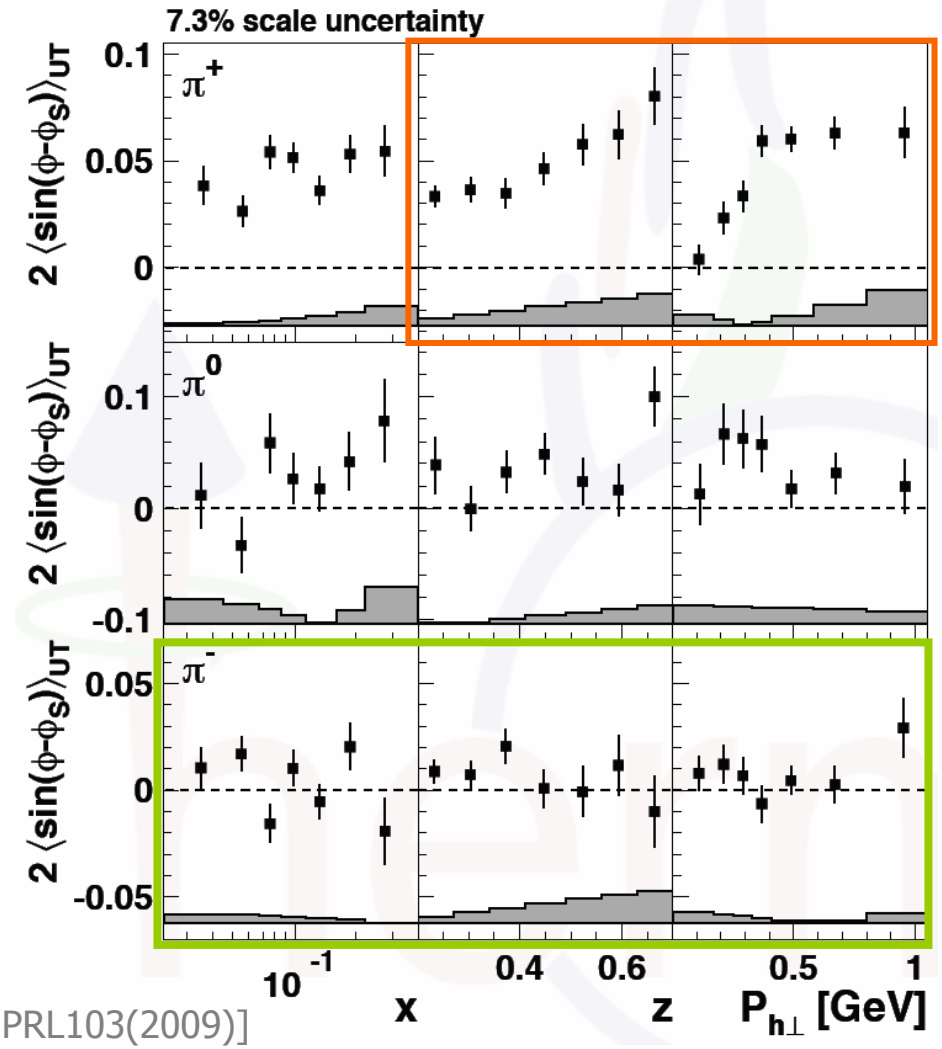


- first observation of T-odd Sivers effect in SIDIS
- u quark dominance suggests sizable u quark orbital motion

Sivers amplitudes for π



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



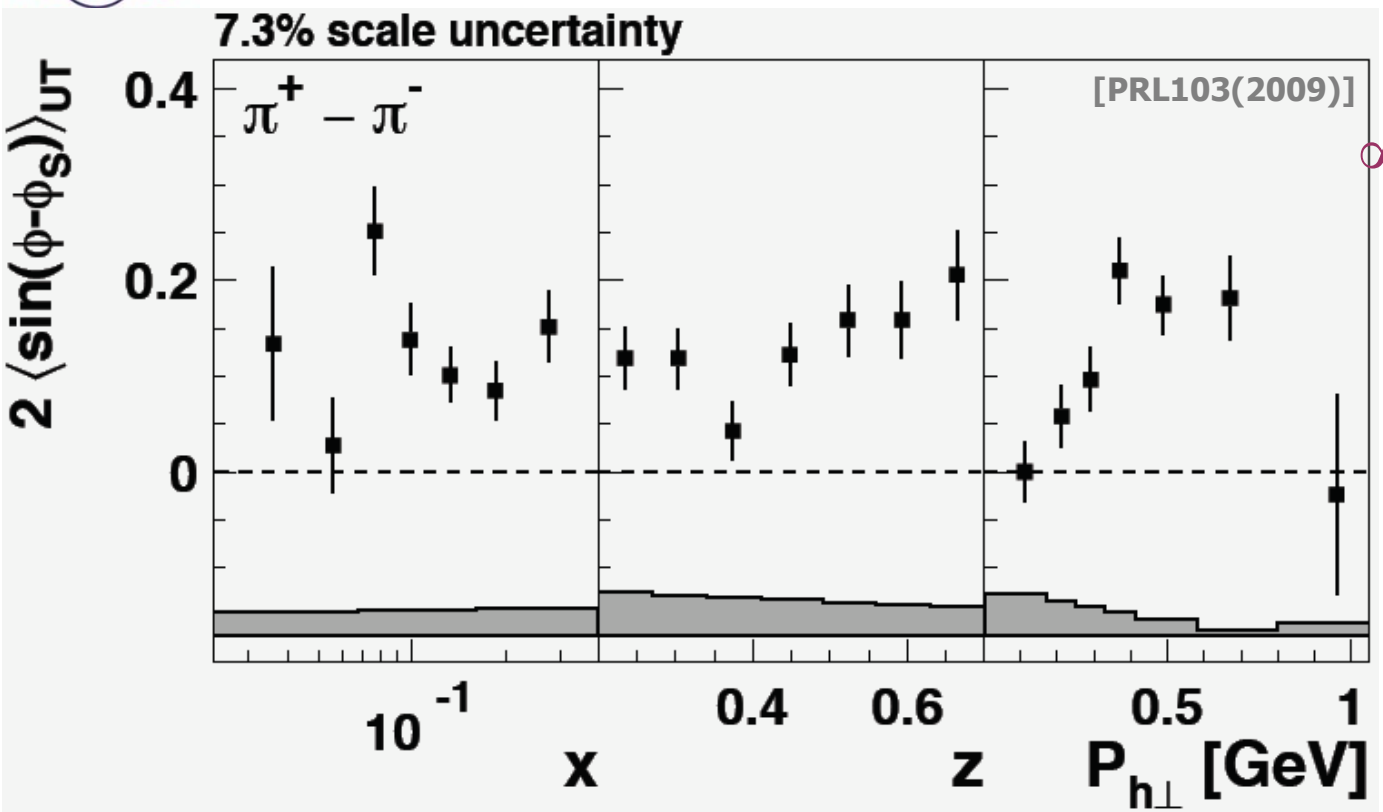
- clear rise with z
  - rise at low $P_{h\perp}$
  - plateau at high $P_{h\perp}$
- cancellation for π^- :
  - u and d quark Sivers DF of opposite sign

[PRL103(2009)]

Sivers distribution for valence quarks

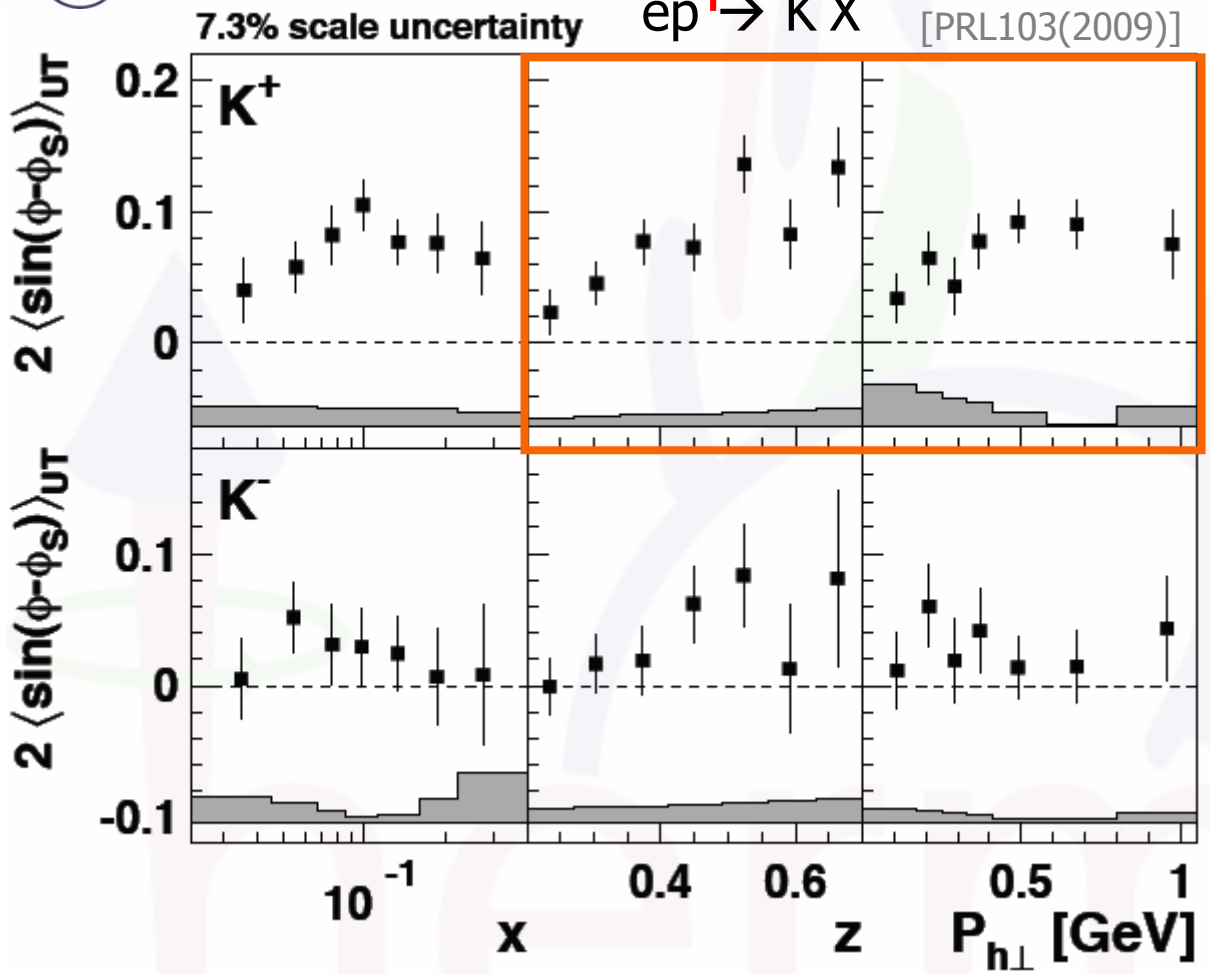
transverse SSA of pion cross section difference:

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



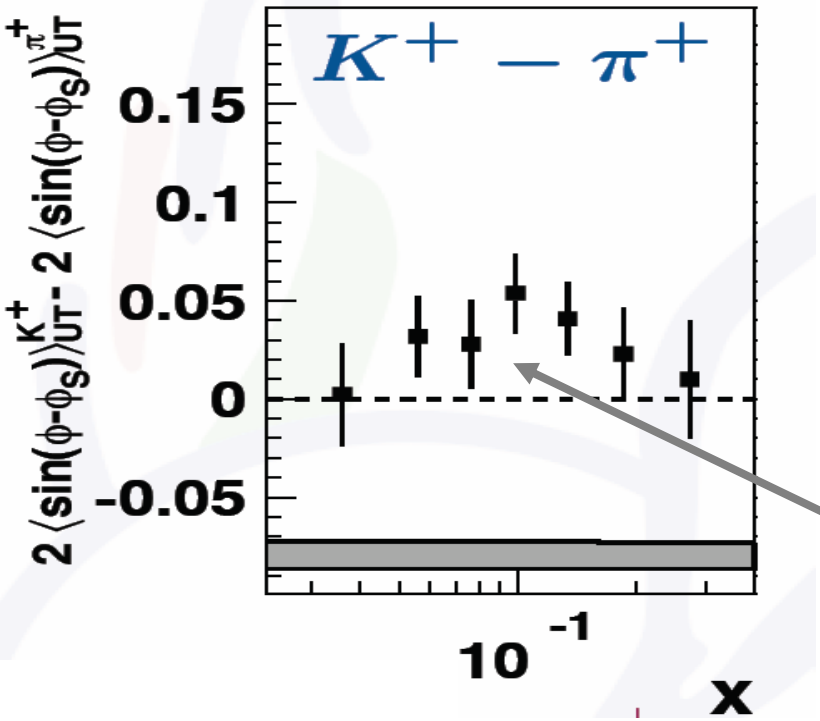
$$\propto \frac{4 f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4 f_1^{u_v} - f_1^{d_v}}$$

Sivers: kaon amplitudes



- clear rise with z
  - rise at low $P_{h\perp}$
  - plateau at high $P_{h\perp}$
- slightly positive

Sivers: the kaon riddle

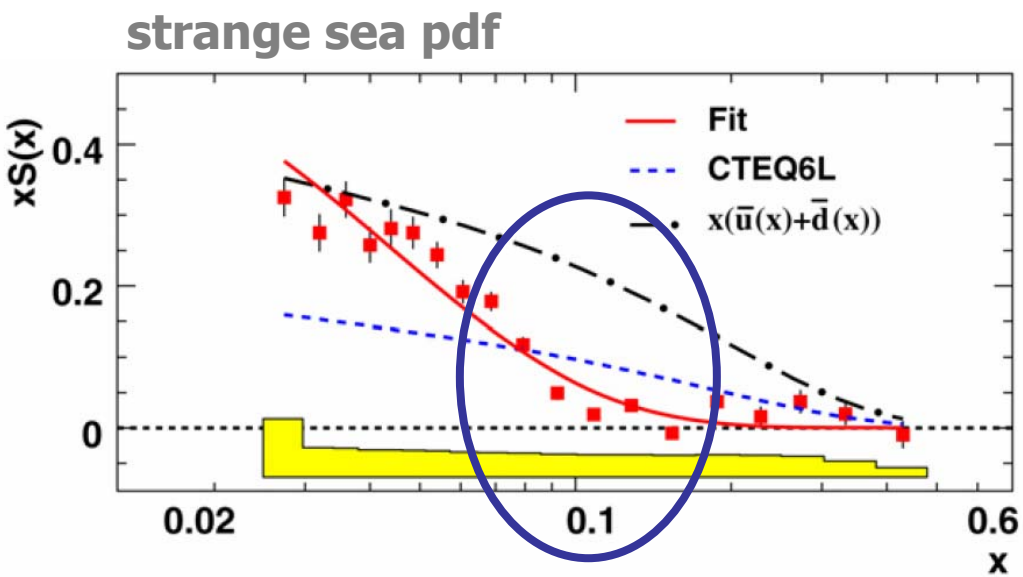


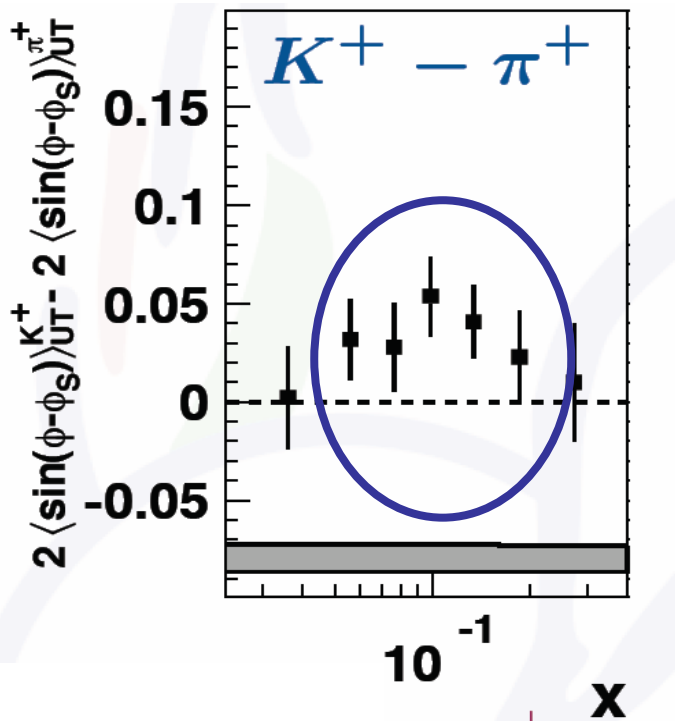
π^+ / K^+ production dominated by scattering off u-quarks

difference non-zero @90% confidence level

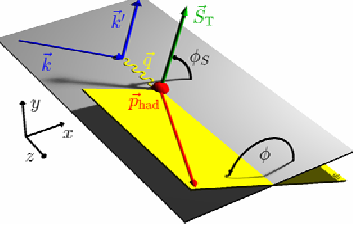
- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ → ***non-trival role of sea quarks***
- convolution integral in numerator depends on p_T dependence of FF
- differences in dependences on kinematics integrated over

role of sea quarks





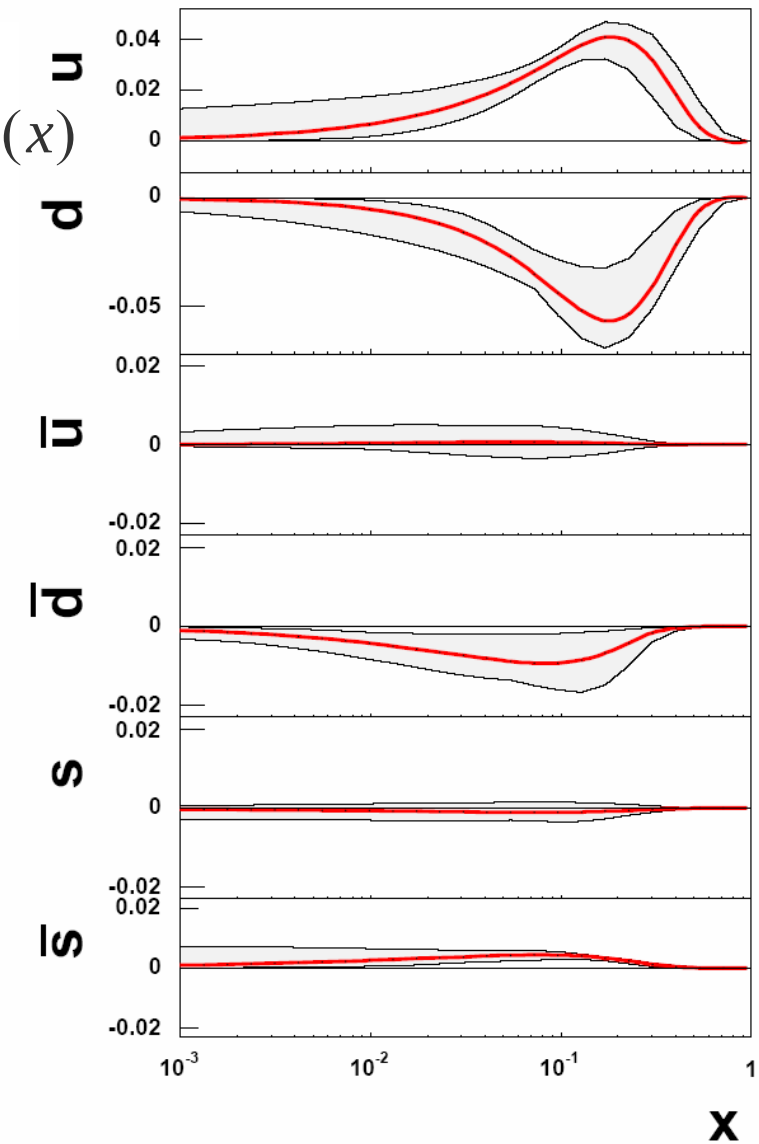
→ differences biggest in region where strange sea is most different from light sea



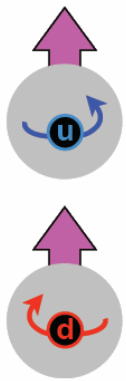
Sivers function

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

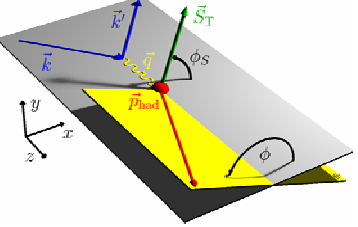
$-f_{1T}^{\perp q}(x)$



combined analysis: hermes COMPASS



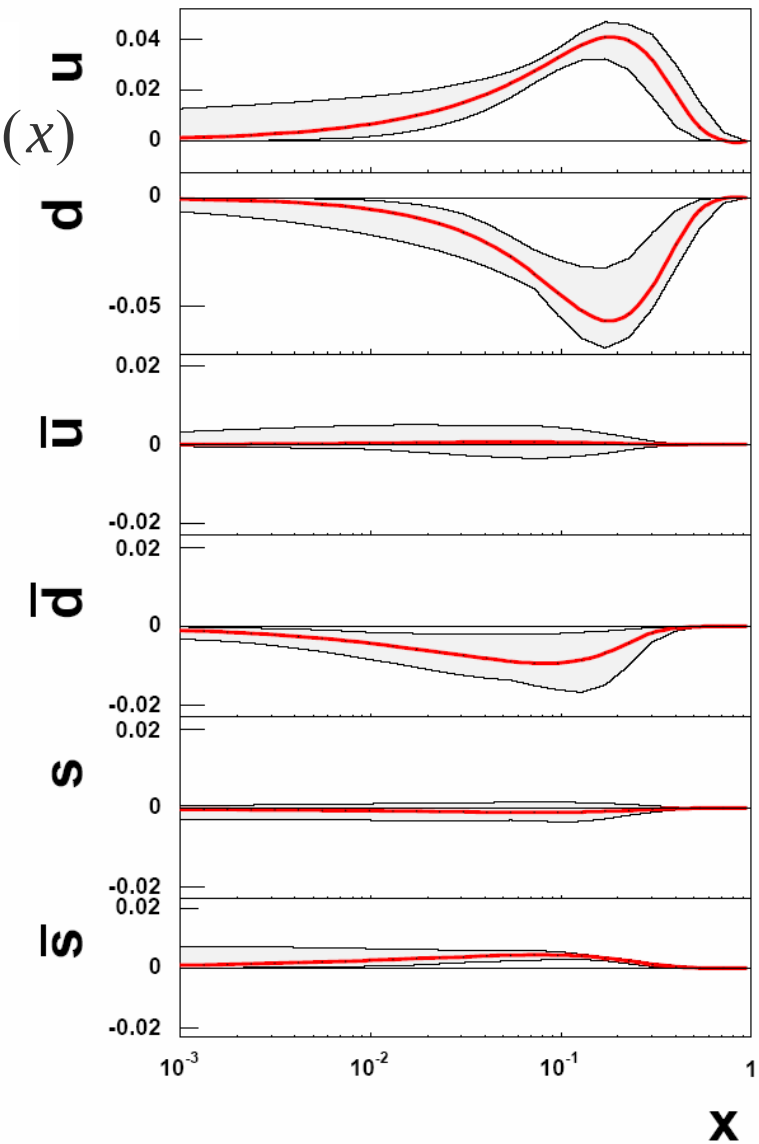
anti-quark
L≠0 favoured



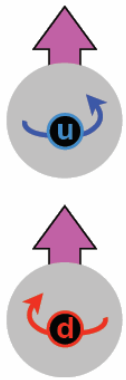
Sivers function

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

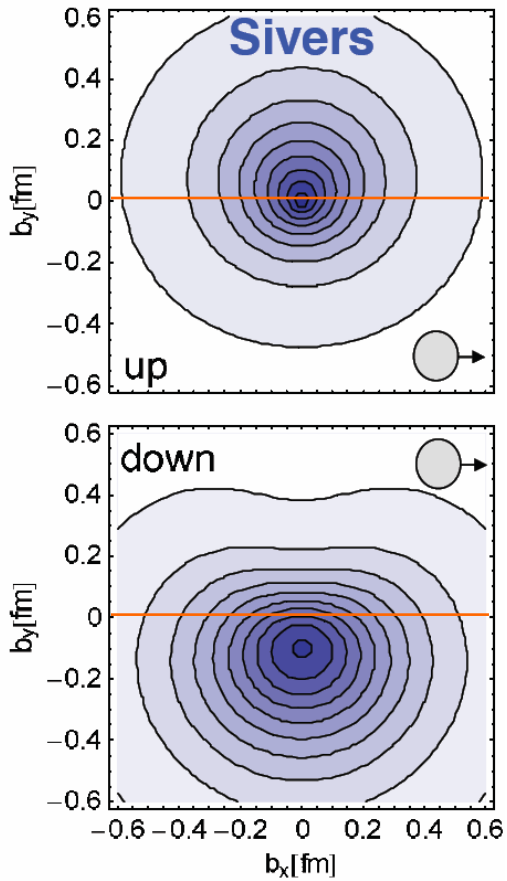
$-f_{1T}^{\perp q}(x)$



combined analysis: hermes COMPASS



lattice [Haegeler et al.]

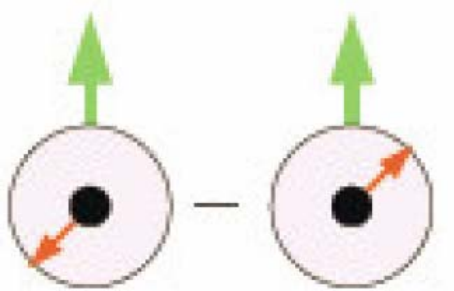


$L_u > 0$

$L_d < 0$

the shape of the nucleon

'pretzelosity'



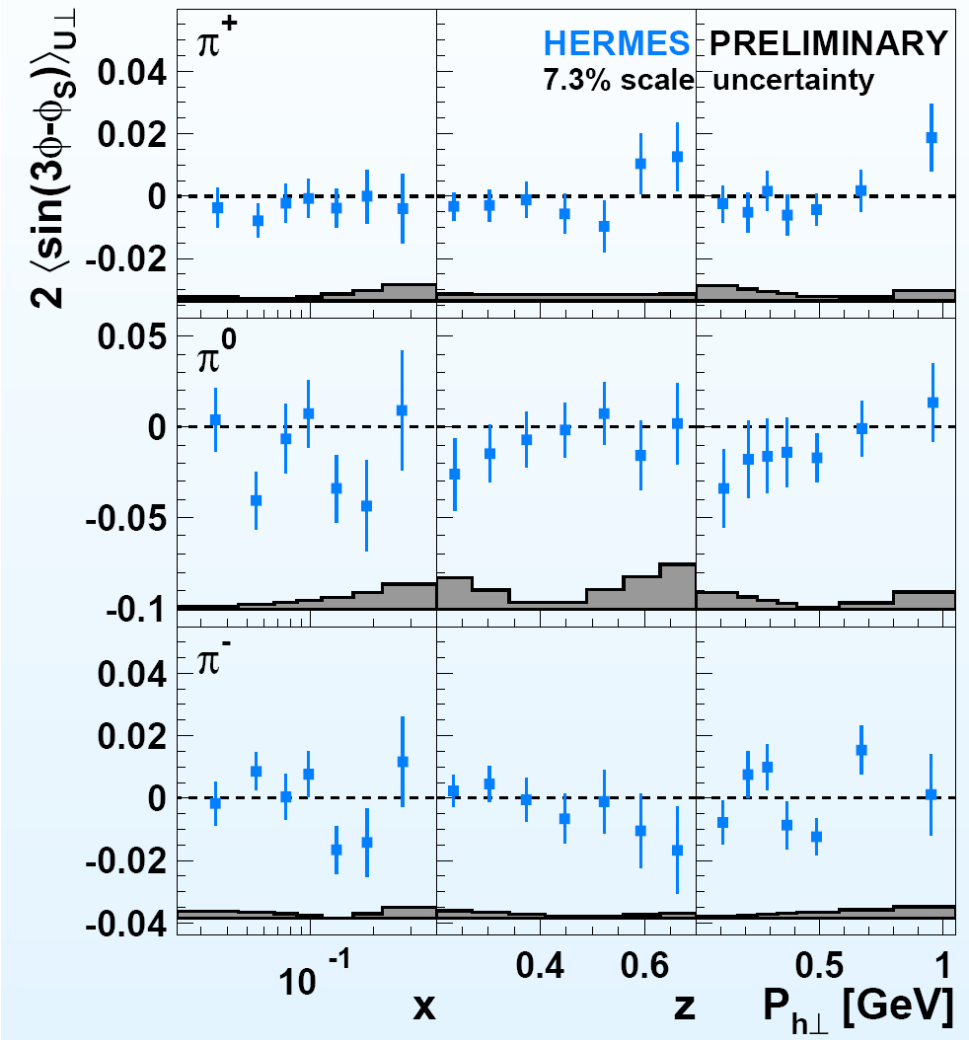
$$h_{1\mathrm{T}}^{\perp} \otimes H_{1\mathrm{T}}^{\perp}$$

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

pretzelosity: measure for relativistic effects

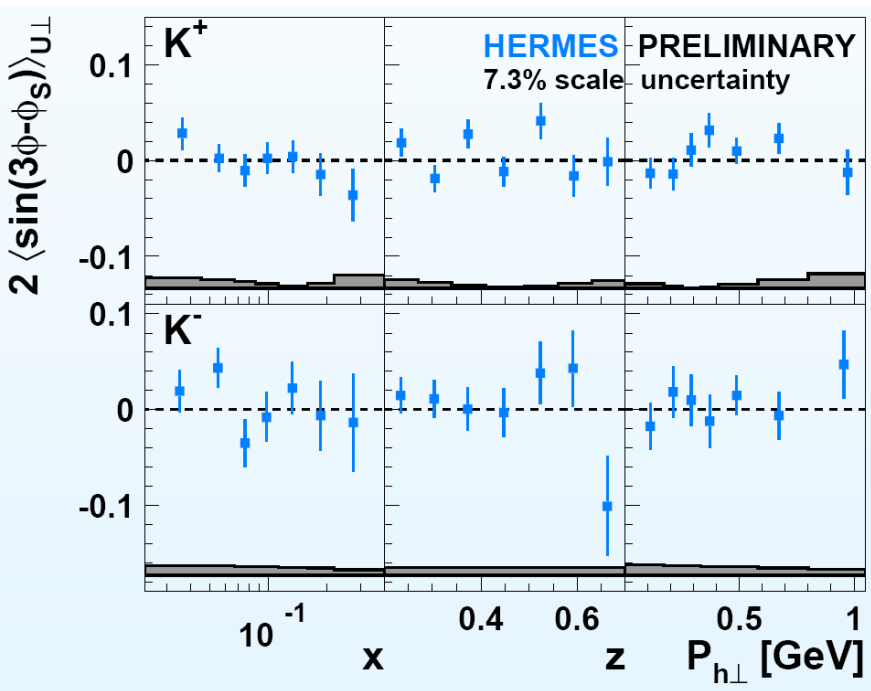
the shape of the nucleon

'pretzelosity'

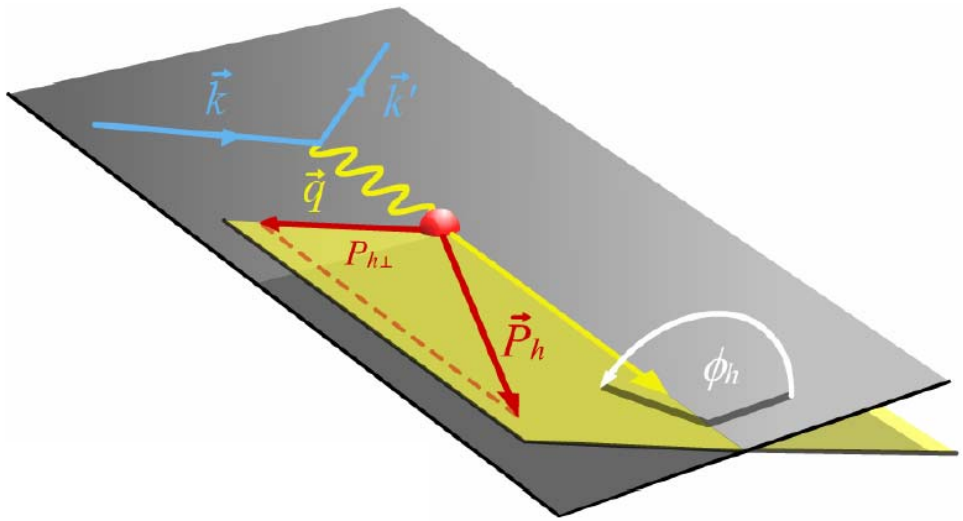


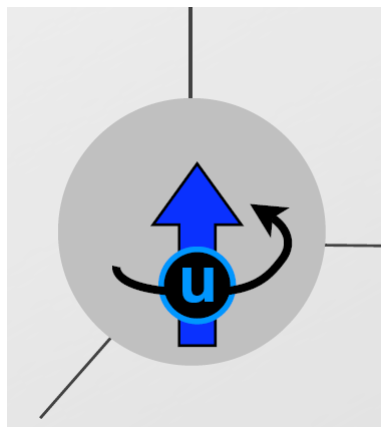
- expected to scale as $(P_{h\perp})^3$

→ suppressed wrt. Collins & Sivers



transverse spin effects the unpolarised cross section





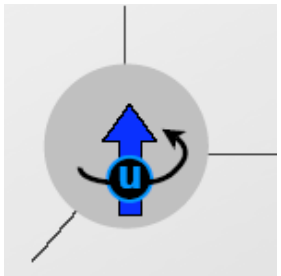
$h_1^{\perp}(x, k_T)$

spin-orbit effect (Boer-Mulders DF):

correlation between quark transverse motion and transverse spin

unpolarised cross section

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

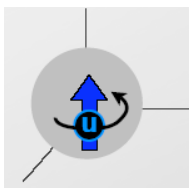


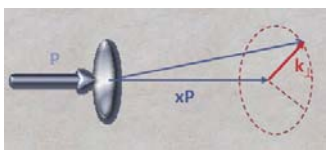
Boer-Mulders

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

Boer-Mulders Collins twist-4 Cahn

spin-orbit correlations





Cahn+Boer-Mulders

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

interaction dependent terms

Cahn

access to intrinsic quark transverse momentum

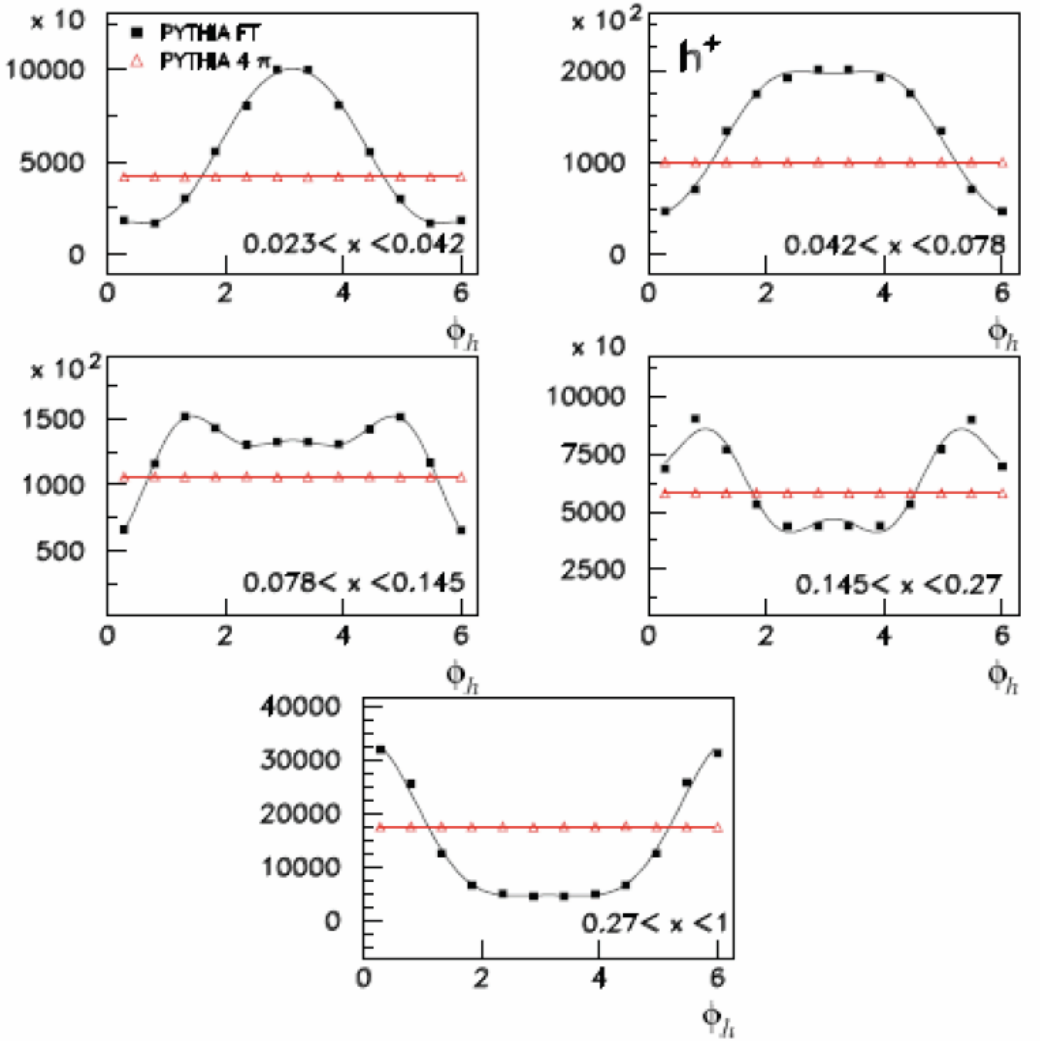
analysis challenge

Monte Carlo:

generated in 4π

measured inside acceptance

→ acceptance and radiative effects generate cos(nϕ) moments



analysis challenge

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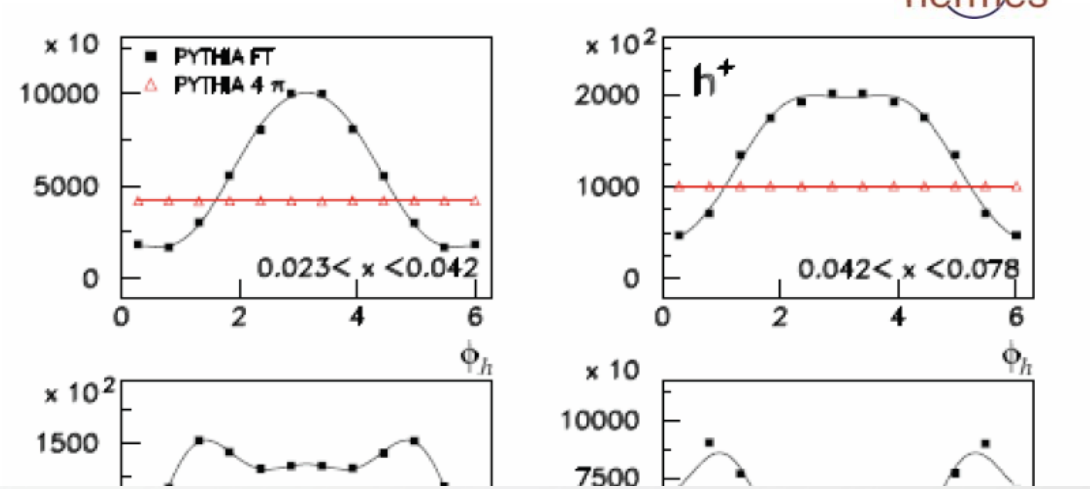
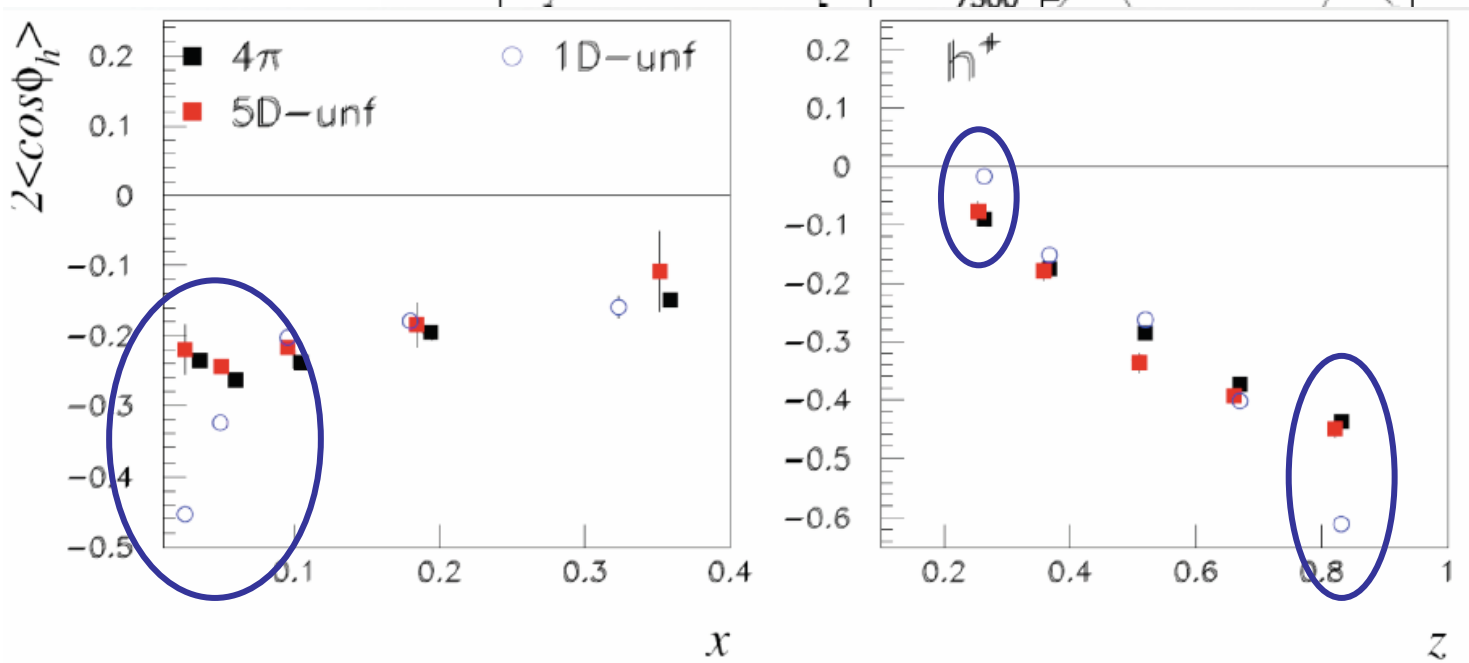
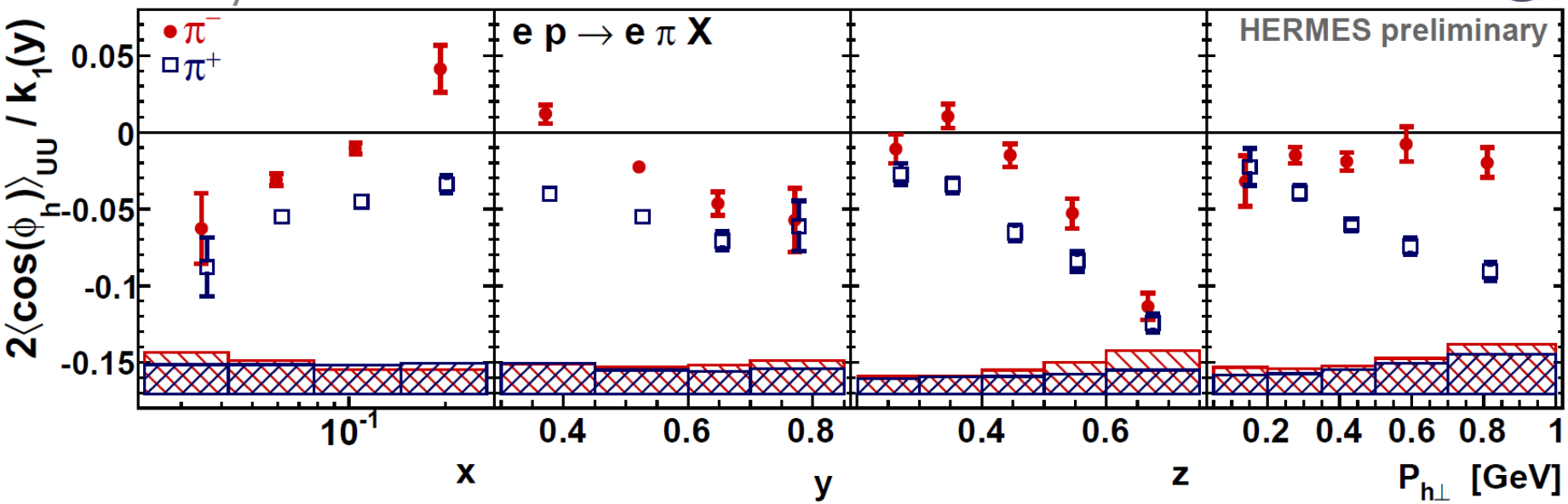


- Cahn model in 4π
- unfolded in 5-D
- unfolded in 1-D → *inacurate* !!



<cosϕ>: intrinsic quark transverse momentum

- very similar result for deuterium

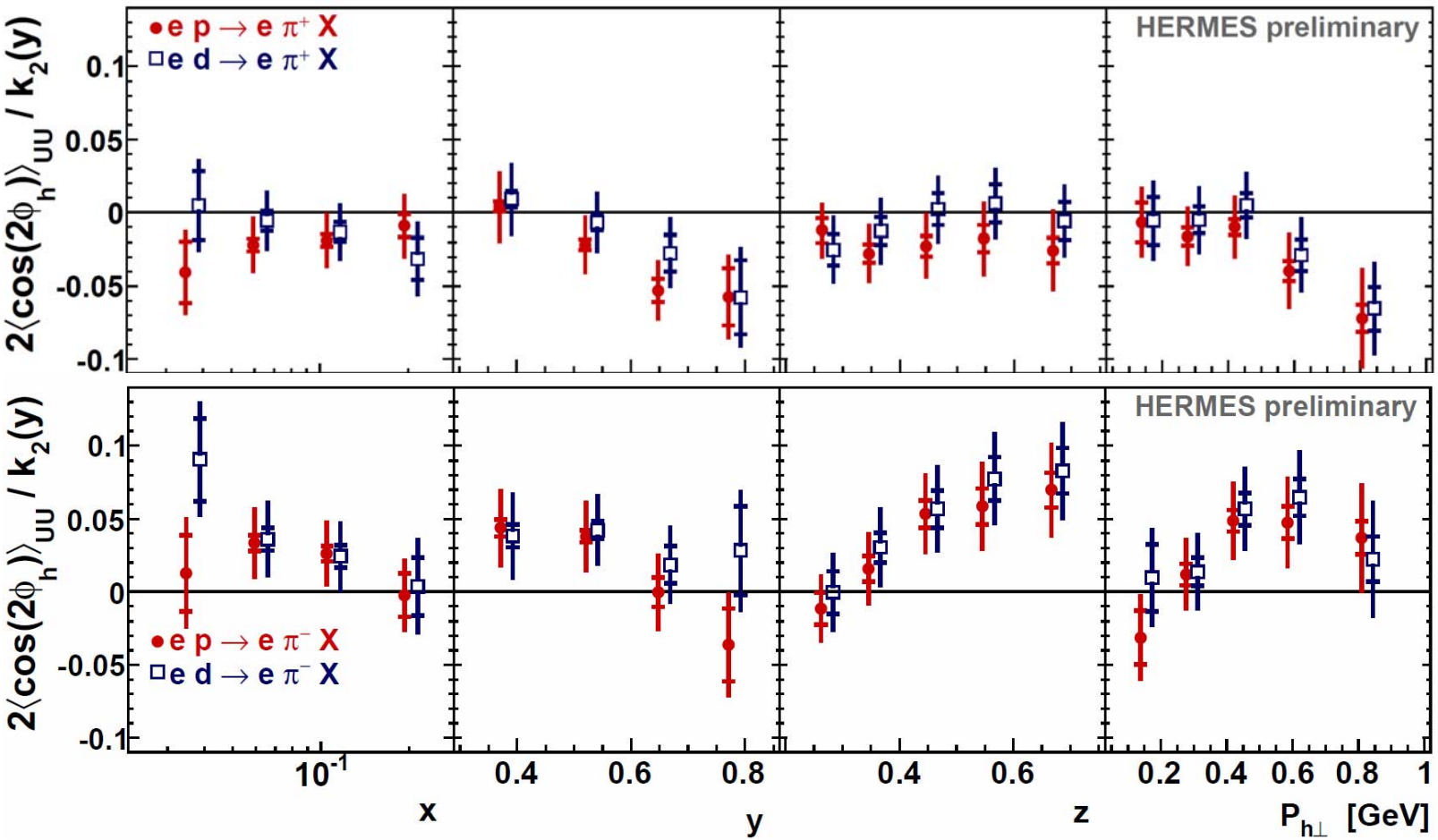


→ different effects for different pion charges … **unexpected** for Cahn effect!

- Boer-Mulders term important ?
- $\langle k_T \rangle$ 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

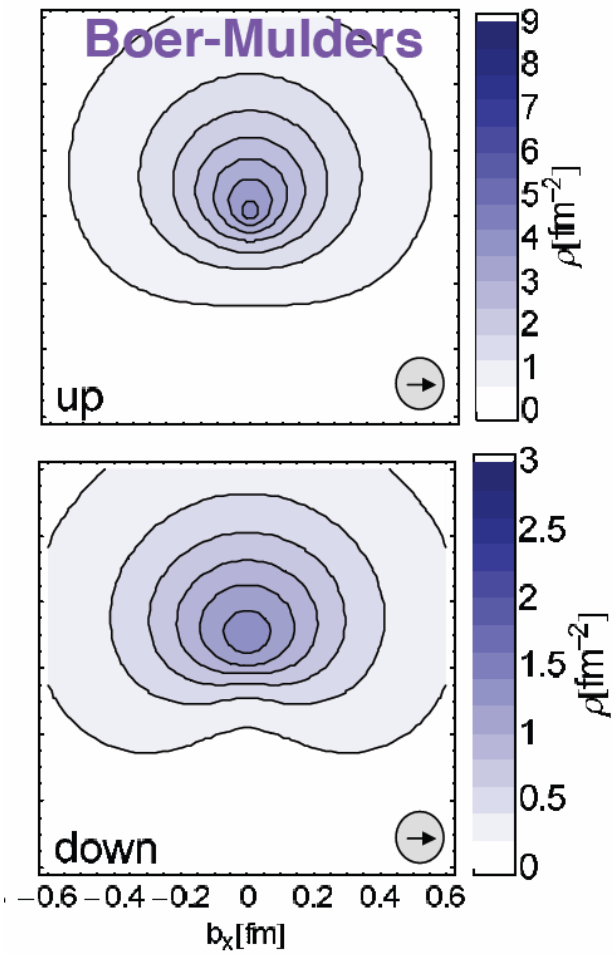
<cos2ϕ>: spin-orbit correlations

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

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

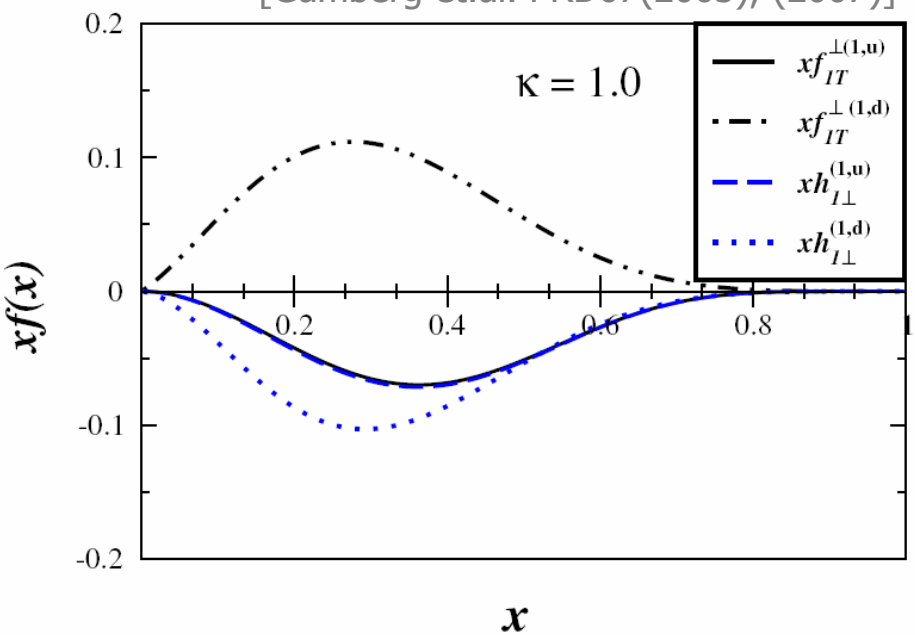
lattice:

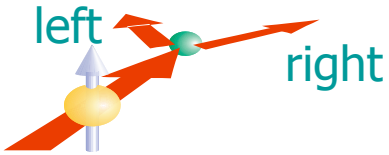
[Hageler et.al. PRL98(2007)]



diquark spectator model:

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



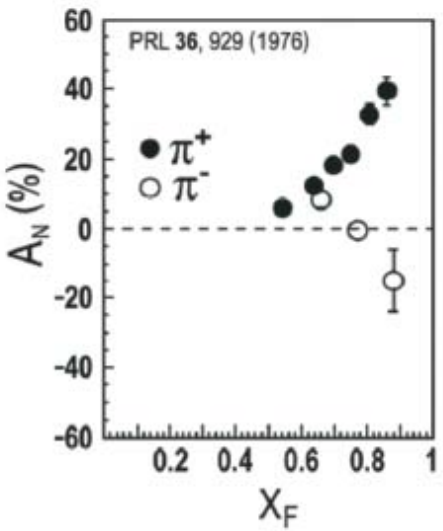


inclusive hadrons

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

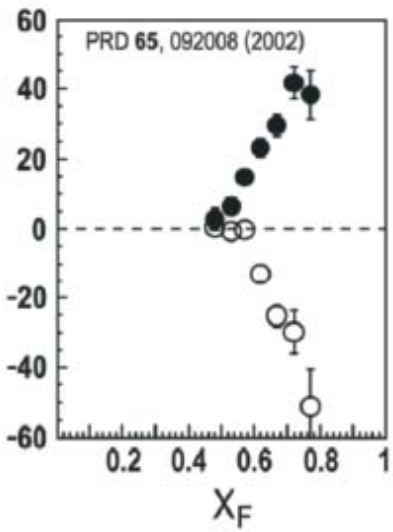
large transverse single-spin asymmetries @ center of mass energies:

4.9 GeV



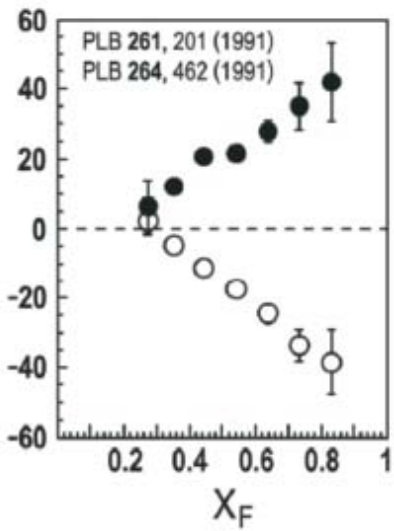
1976

6.6 GeV



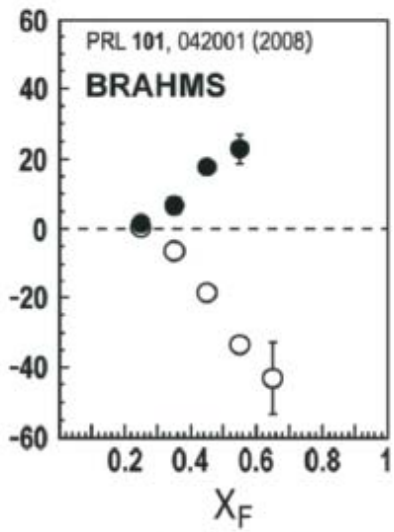
2002

19.4 GeV



1991

62.4 GeV

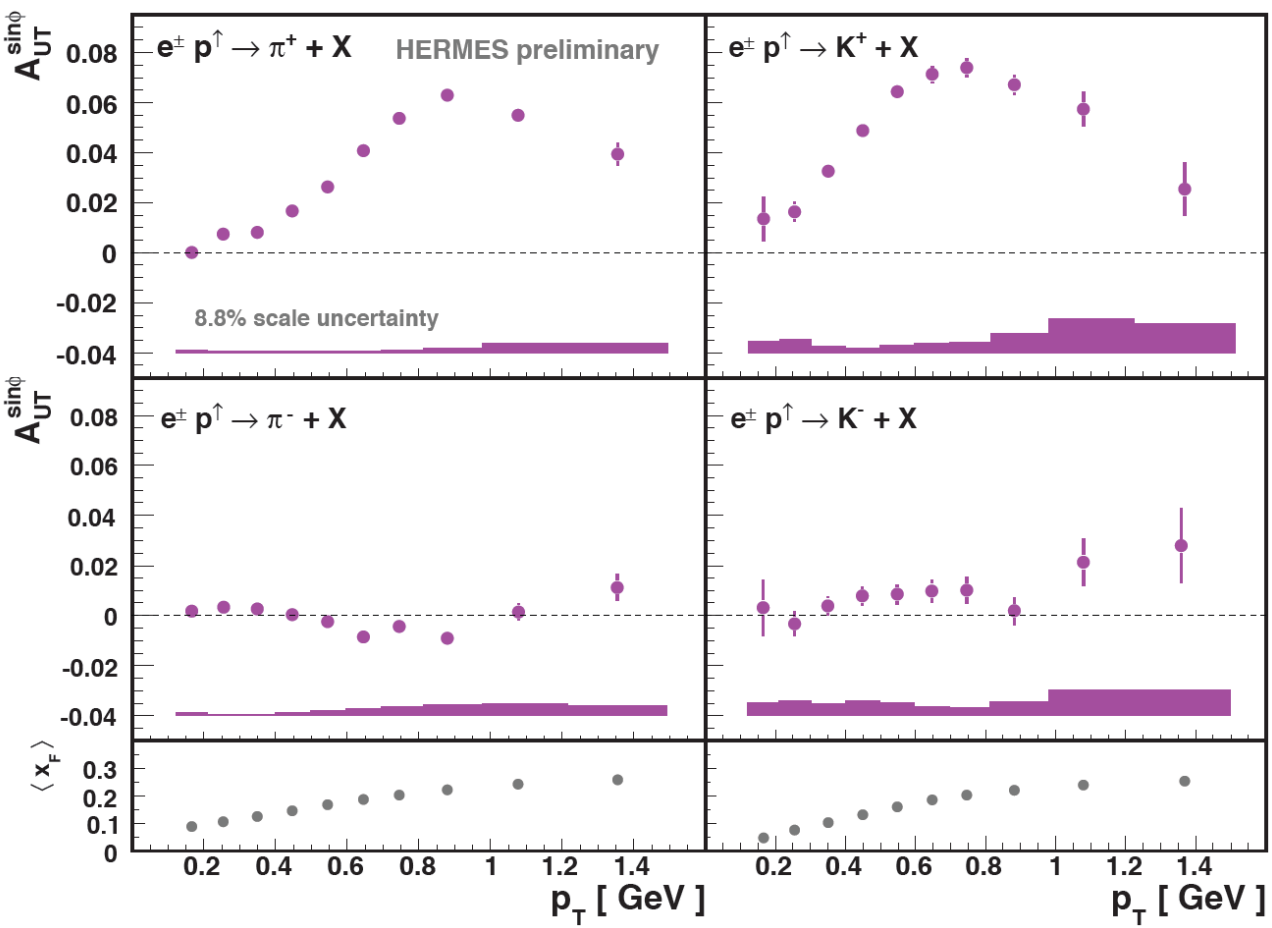


2008

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

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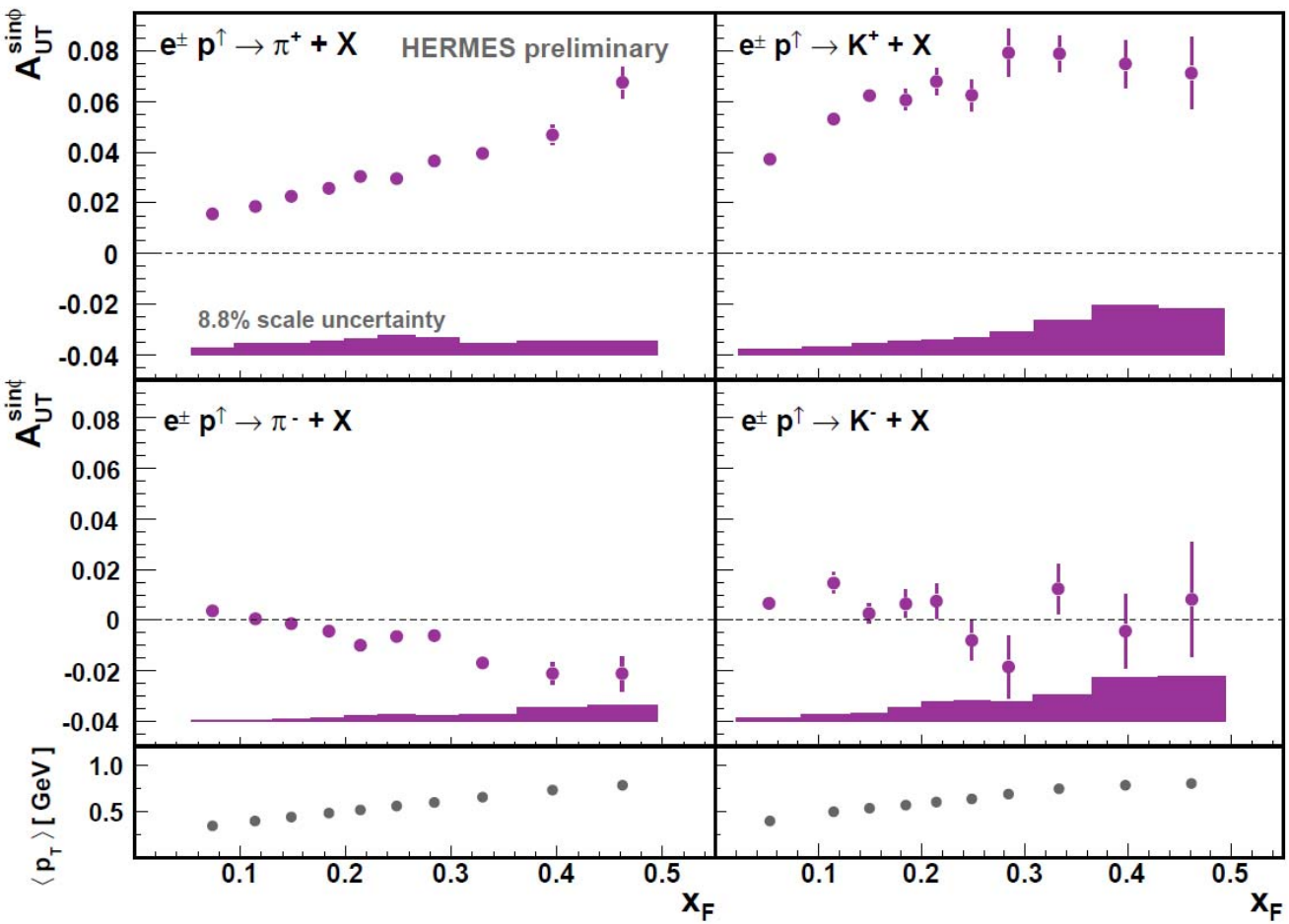

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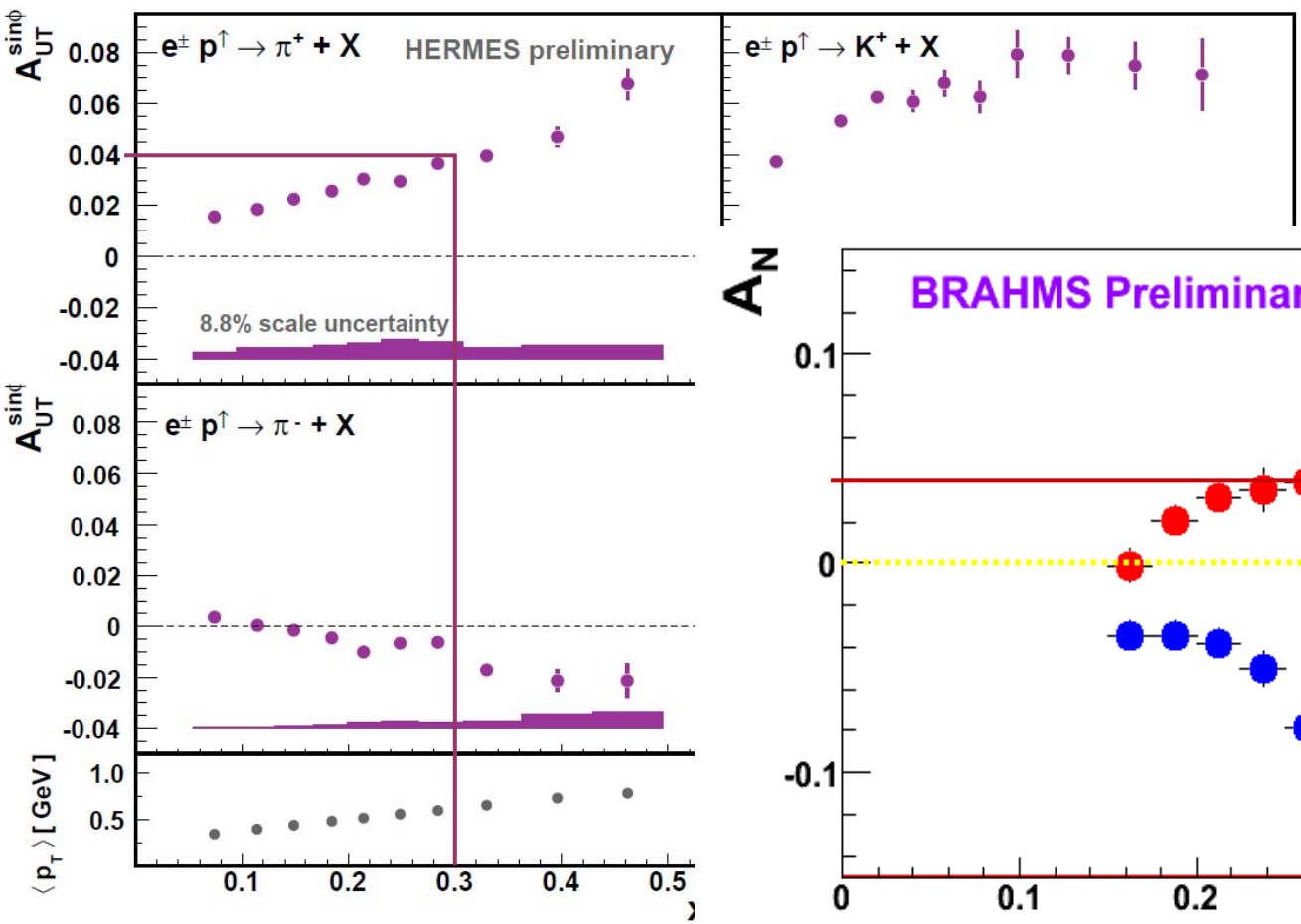

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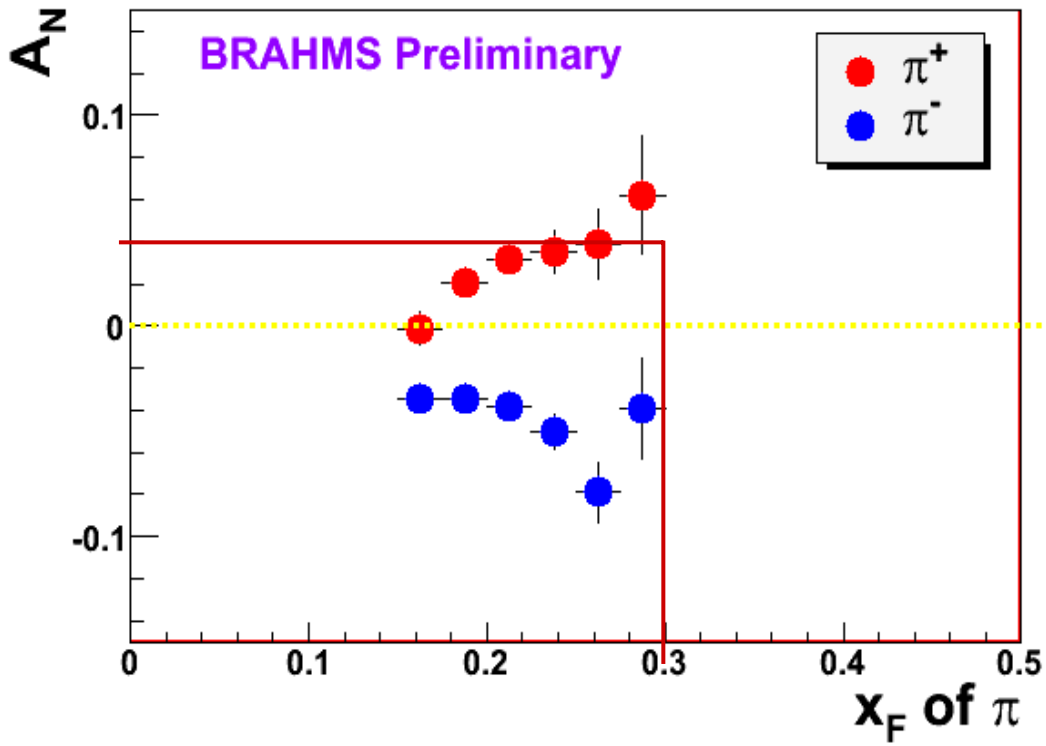

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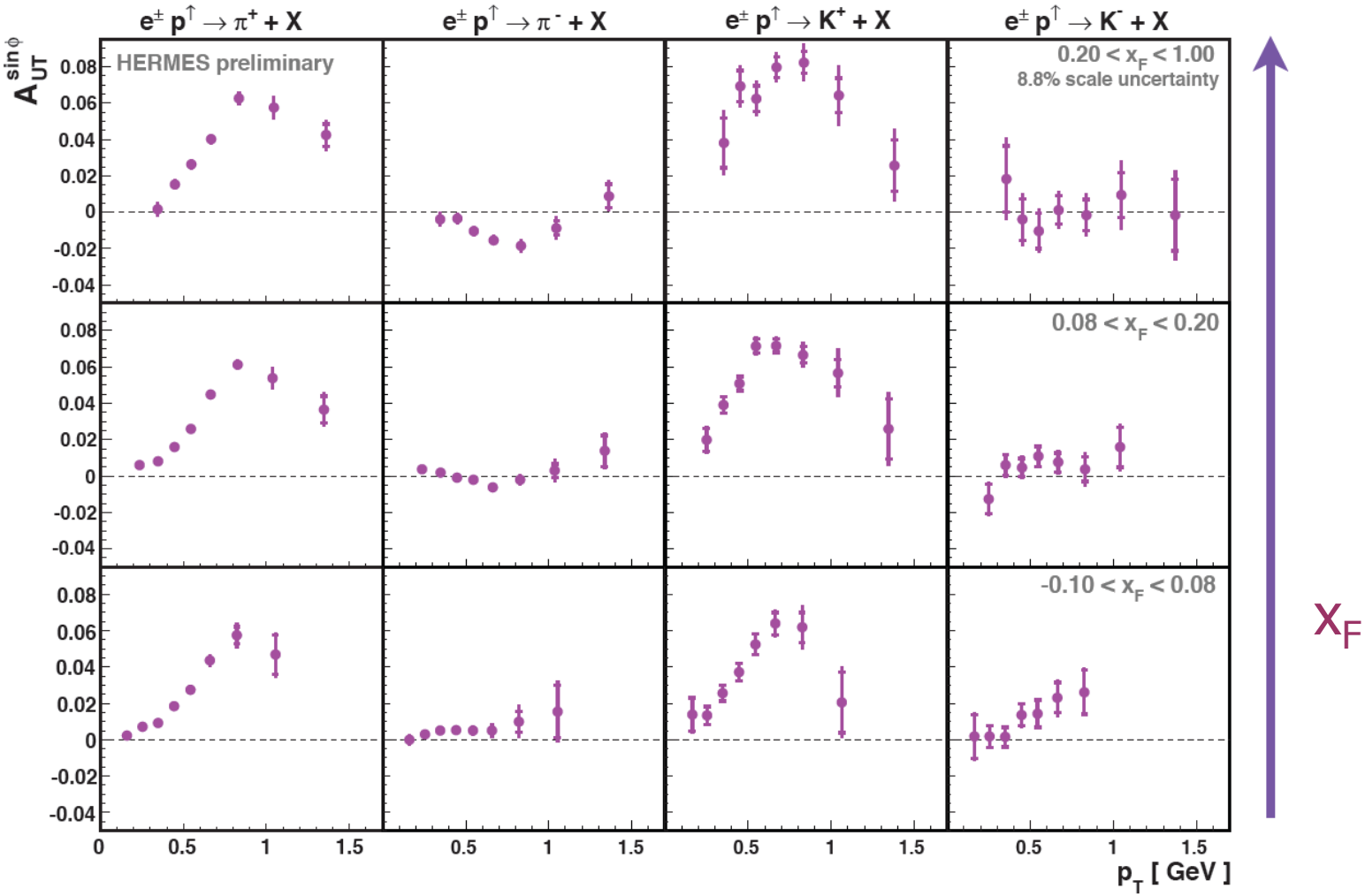

conclusion & outlook

≈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**

BACKUP SLIDES

Alternatively one can use the so-called $P_{h\perp}$-weighted moments (don't require any assumption on transverse momenta distributions)

$$\left\langle \frac{P_{h\perp}}{zM}\sin(\phi-\phi_S)\right\rangle_{UT}^{h} \equiv \frac{\int d\phi_S d^2\vec{P}_{h\perp}\sin(\phi-\phi_S)\frac{P_{h\perp}}{zM}d^6\sigma_{UT}}{\int d\phi_S d^2\vec{P}_{h\perp} d^6\sigma_{UU}}$$

P_{hT}-weighted Sivers moments (measured)

$$\propto -\left|\vec{S}_T\right|\sum_{q\bar{q}}\mathbf{P}_q^h(x,z)\,f_{1T}^{\perp(1)q}(x) \rightarrow \textbf{Sivers function}$$

$$\mathbf{P}_q^h(x,z) \equiv \frac{e_q^2 q(x) D_1^{q\rightarrow h}(z)}{\sum_{q'\bar{q}'} e_{q'}^2 q'(x) D_1^{q'\rightarrow h}(z)}$$

purities (based on known quantities)

Extraction above requires, in principle, a full integration over $P_{h\perp}$ (from 0 to ∞)

Due to the partial experimental coverage in $P_{h\perp}$ the evaluation of acceptance effects is of crucial importance.