Delia Hasch

INFN Frascati

Transverse spin effects

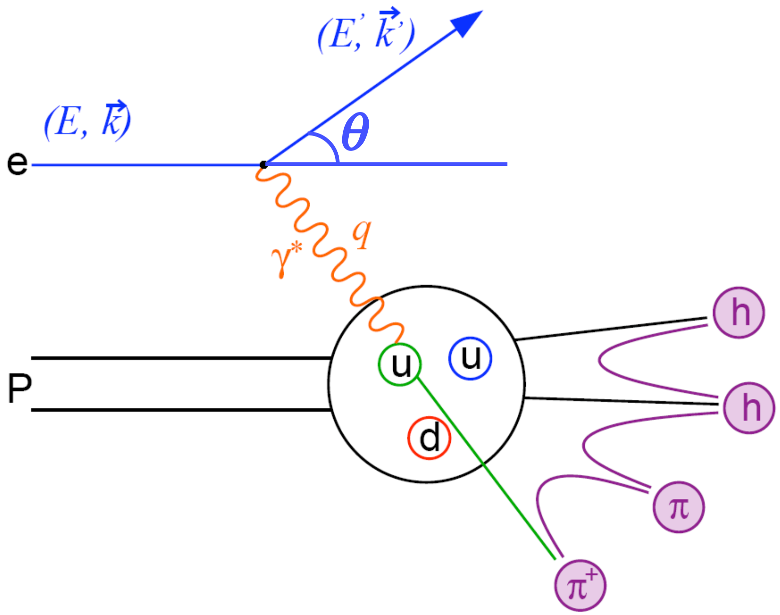
EINN "Electromagnetic Interactions with Nucleons and Nuclei", Milos, Sept 11-15, 2007

outline

- a brief introduction to transversity & friends;
  why do we care for transverse spin effects ?
- a short and incomplete history;
  what is the origin of single-spin asymmetries ?
- milestone results;
  single-spin asymmetries and not only …
- theory meets experiment;
  what did we learn so far ?

longitudinal structure of nucleon

studied for 40 years by hard scattering experiments, in particular *deep-inelastic scattering (**DIS**)*



$$Q^2 = -q^2 \overset{\text{lab}}{=} 2EE'(1\text{-}\cos\theta)$$

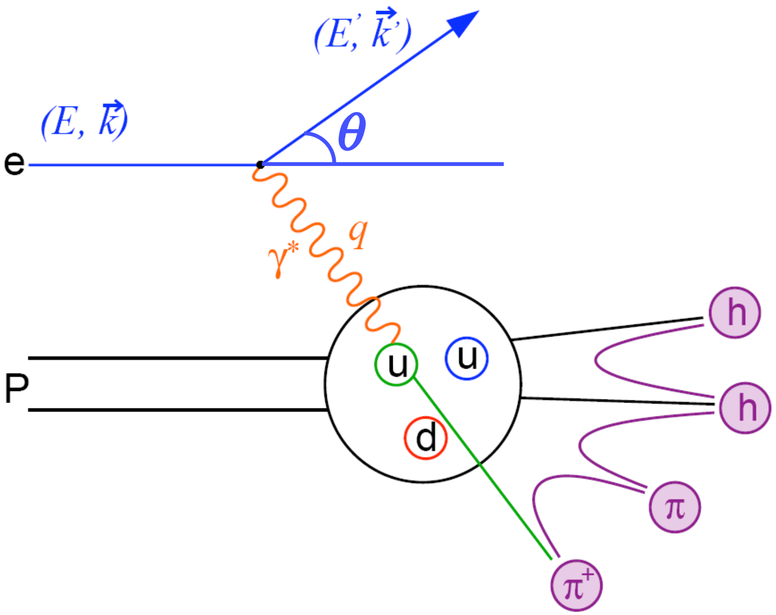
$$x \overset{\text{lab}}{=} \frac{Q^2}{2M\pounds}, \quad x \in [0,1] \qquad \pounds \overset{\text{lab}}{=} E - E'$$

- "deep" [redacted] high resolution: [redacted]
- "inelastic" [redacted]

longitudinal structure of nucleon

studied for 40 years by hard scattering, in particular by

*deep-inelastic scattering (**DIS**)*



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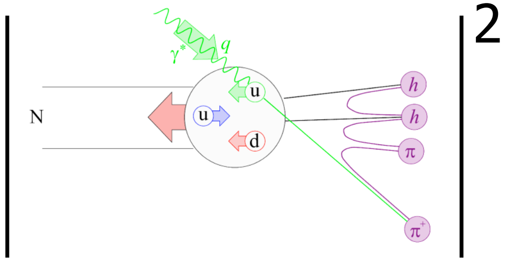
$$z \overset{\text{lab}}{=} \frac{E_h}{\pounds}, \qquad z \in [0,1]$$

[redacted]

the nucleon quark structure

$$\Phi^{\mathrm{Tw2}}_{\mathrm{Corr}}(x) = \frac{1}{2}\left\{ q(x) + \mathrm{S_L}\,\Delta q(x)\,{}'\,{}_5 + \delta q(x)\,{}'\,{}_5\,{}'\,{}^1\mathrm{S_T} \right\} n^+$$

optical theorem:



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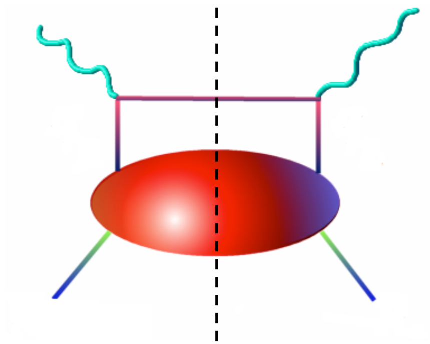
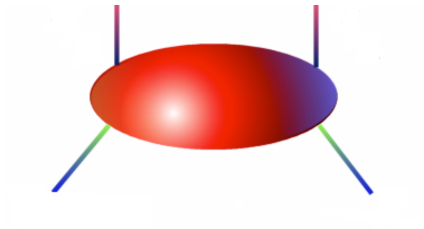
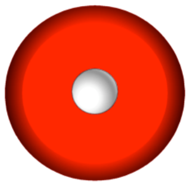




quark-quark correlator

the nucleon quark structure

$$\Phi^{\mathrm{Tw2}}_{\mathrm{Corr}}(x) = \frac{1}{2}\left\{ q(x) + \mathrm{S_L}\Delta q(x)'\,_5 + \delta q(x)'\,_5{}'\,{}^1\mathrm{S_T} \right\} n^+$$

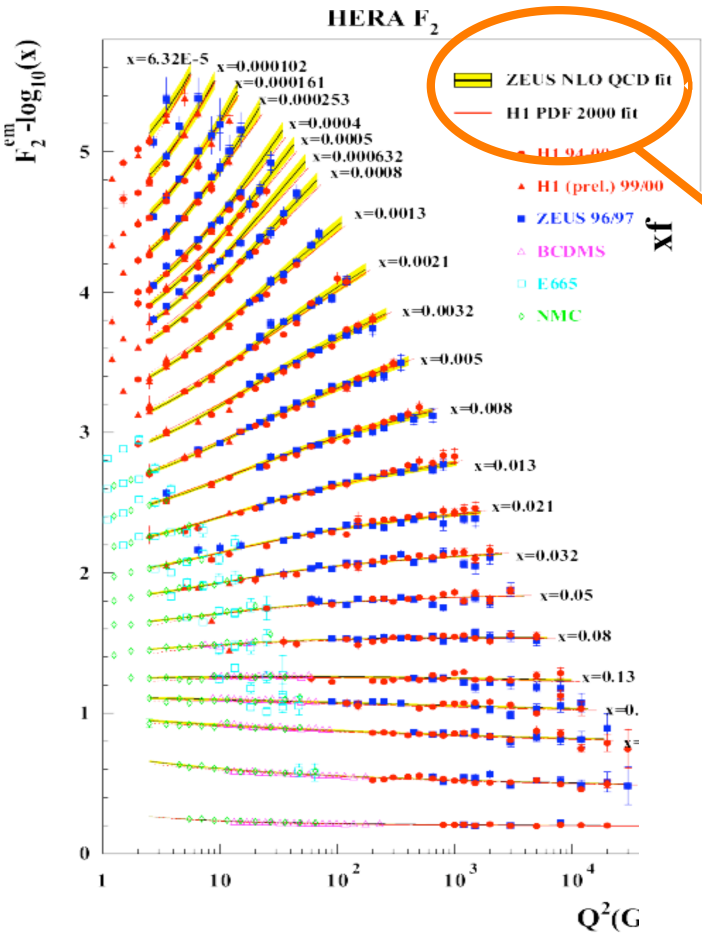
$q =$ 

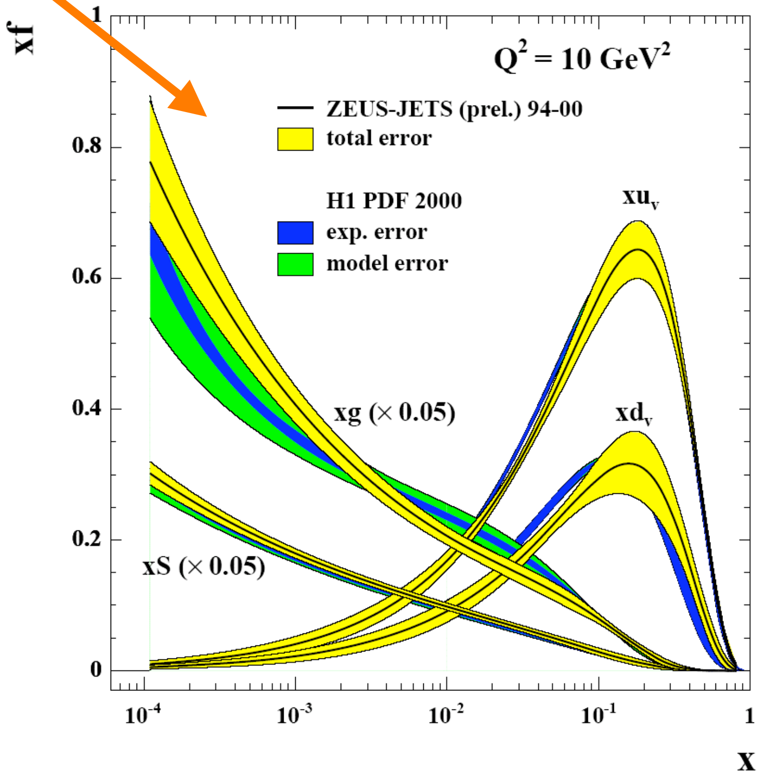
unpolarised quarks
and nucleons

$q(x)$ spin averaged

→vector charge

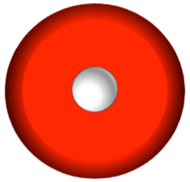
well known





the nucleon quark structure

$$\Phi^{\mathrm{Tw2}}_{\mathrm{Corr}}(x) = \frac{1}{2}\left\{q(x) + \mathrm{S_L}\,\Delta q(x)\,{}'\,{}_5 + \delta q(x)\,{}'\,{}_5\,{}'\,{}^1\mathrm{S_T}\right\}n^+$$

$q =$ 

unpolarised quarks and nucleons

q(x) spin averaged

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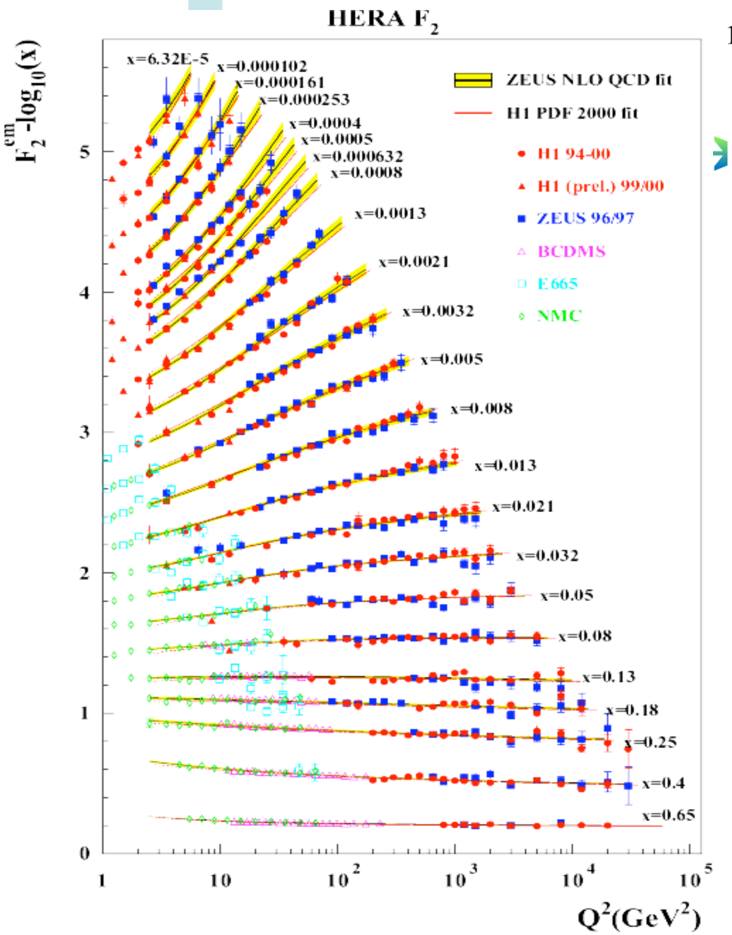
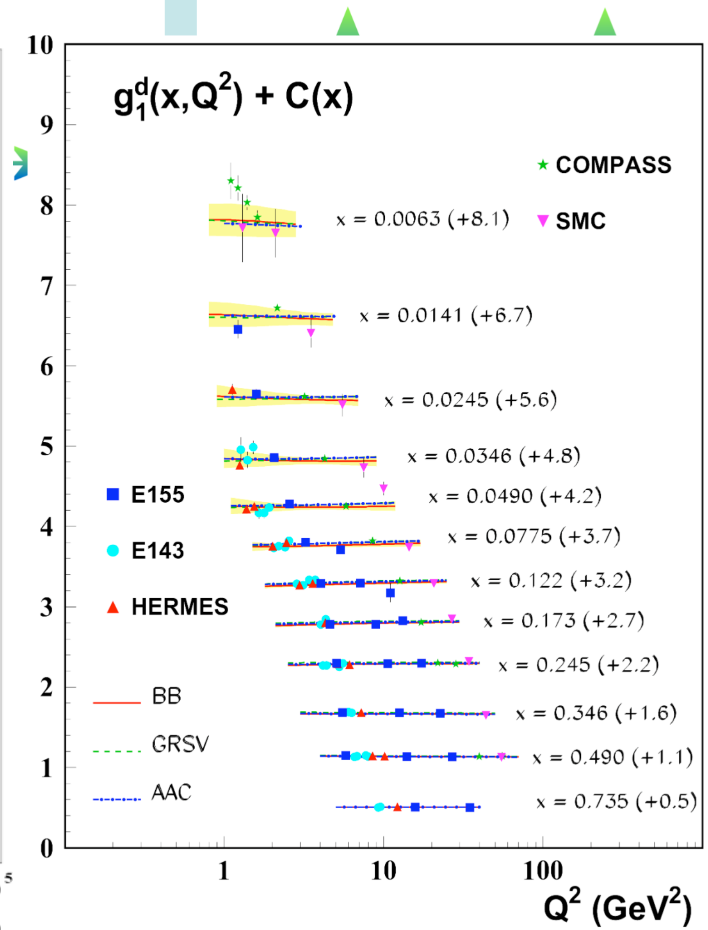


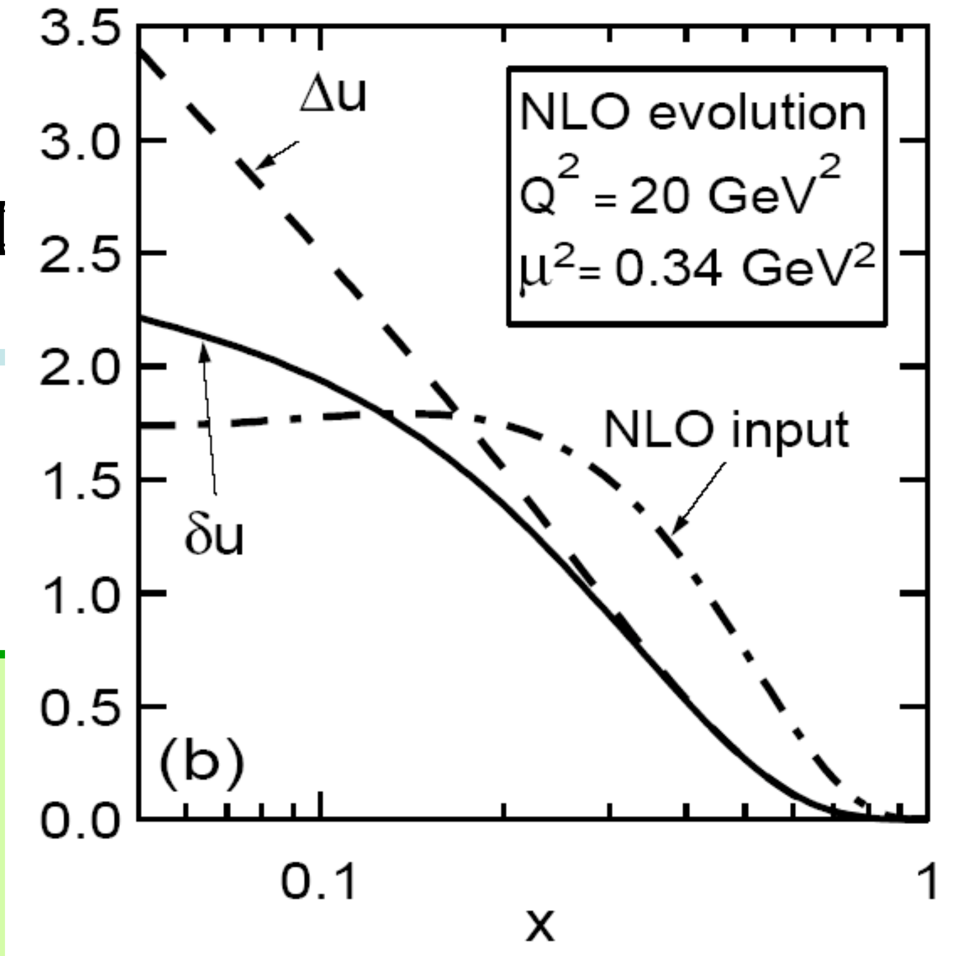


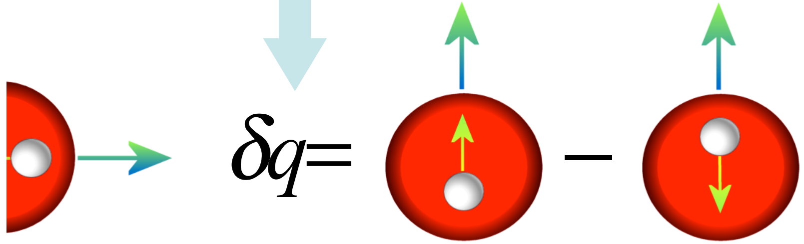
k structure

$)'_5 + \delta q(x)'_5\,'\,{}^1S_T\}n^+$

q

q





transversely polarised quarks and nucleons

δq(x): *helicity flip*

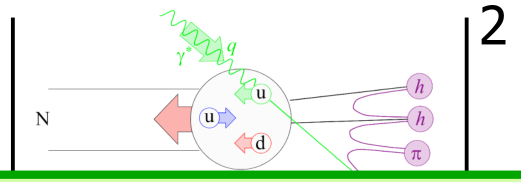
→tensor charge

first glimpse !

- no gluon analog for spin-1/2 nucleon
  →<u>different Q^2 evolution than Δq</u>
- sensitive to *valence* quark polarisation
- only known way to obtain tensor charge

peculiarities of transversity

optical theorem:



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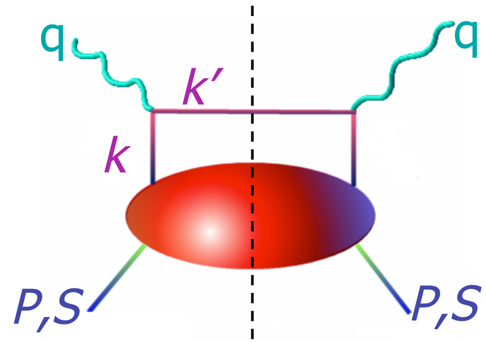
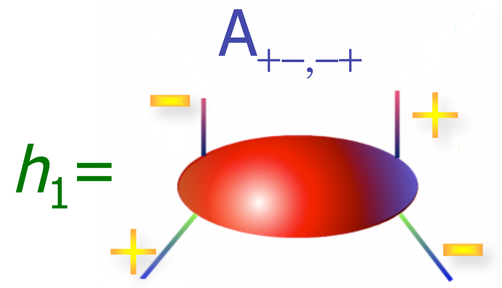


(quark: λ and nucleon: Λ helicities)



helicity-flip amplitude

chiral-odd

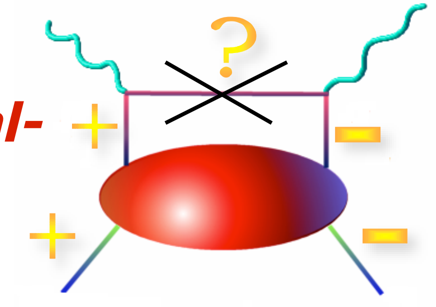
Peculiarities of h_1

- probes relativistic nature of quarks
  → otherwise $h_1 = g_1$
- no gluon analog for spin-1/2 nucleon
  → different Q^2 evolution than g_1
- sensitive to *valence* quark polarisation
- first moment of h_1 : tensor charge
  (large from lattice QCD)
- angluar momentum sum rule
  for transversity: [illegible]

peculiarity of transversity

- *transversity* flips helicity of both quark and nucleon

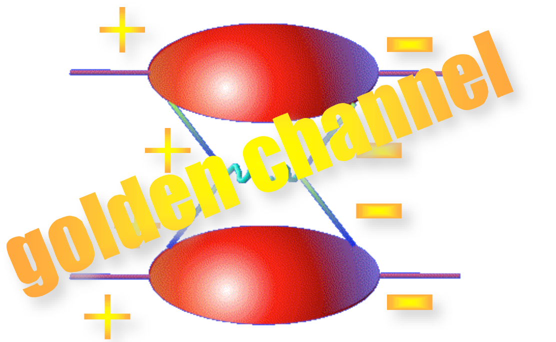
chiral-odd



DIS: [redacted]

needs

chiral-odd partner

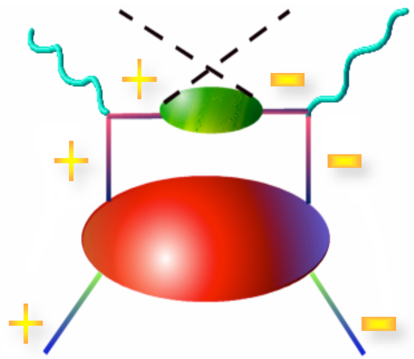


Drell-Yan: [redacted]

hadron production:

Chiral-odd **fragmenation funtion → *Collins*** *FF* : [redacted]

[redacted]

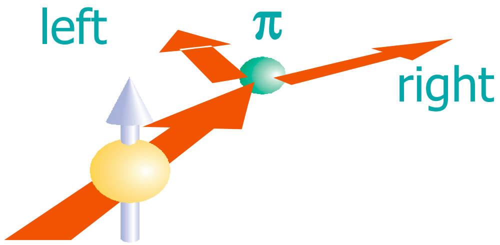


[redacted], …

→ leads to single-spin asymmetries:

a brief and incomplete history

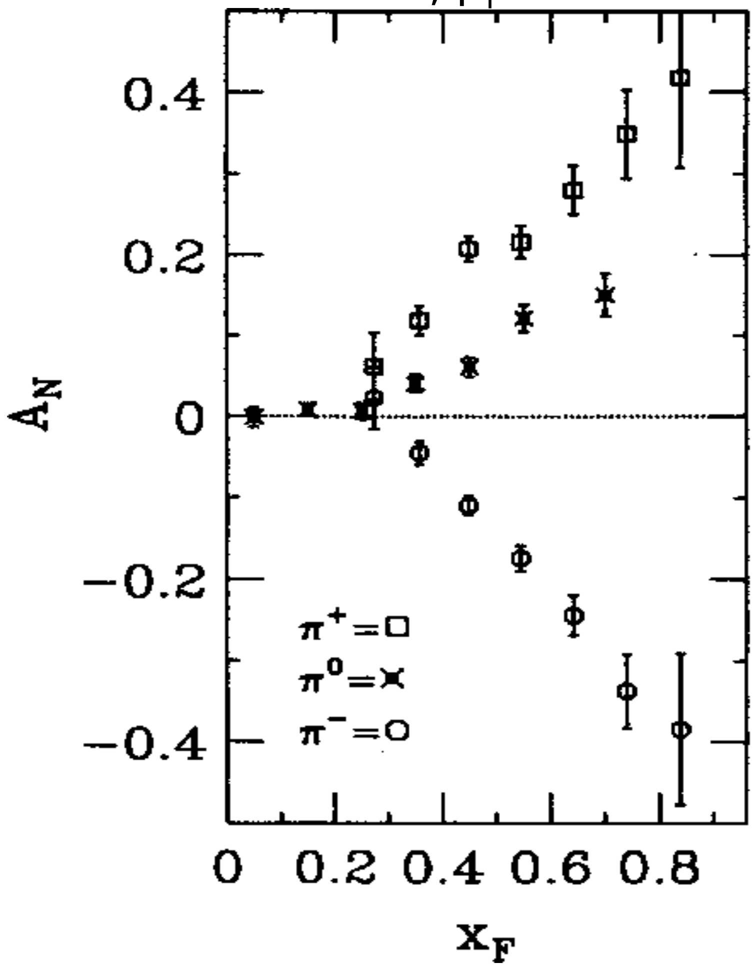
transverse single-spin asymmetry: [redacted]



$$A_N = \frac{N^{\downarrow} - N^{\uparrow}}{N^{\downarrow} + N^{\uparrow}} = \frac{L-R}{L+R}$$

FERMILab: E-704 (1991)

$\sqrt{s}$=20 GeV, p_T=0.5-2.0 GeV



expectation from theory:

$$A_N \propto \text{Im}(NF^*)$$

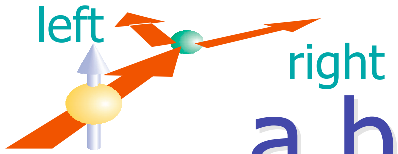
N… non-*helicity*-flip amplitude

F… is *helicity*-flip amplitude

gauge theory: $F \to 0$

as $m_q \to 0$

⇒ $A_N \sim m_q/p_T \sim 0.001$ at p_T=2 GeV



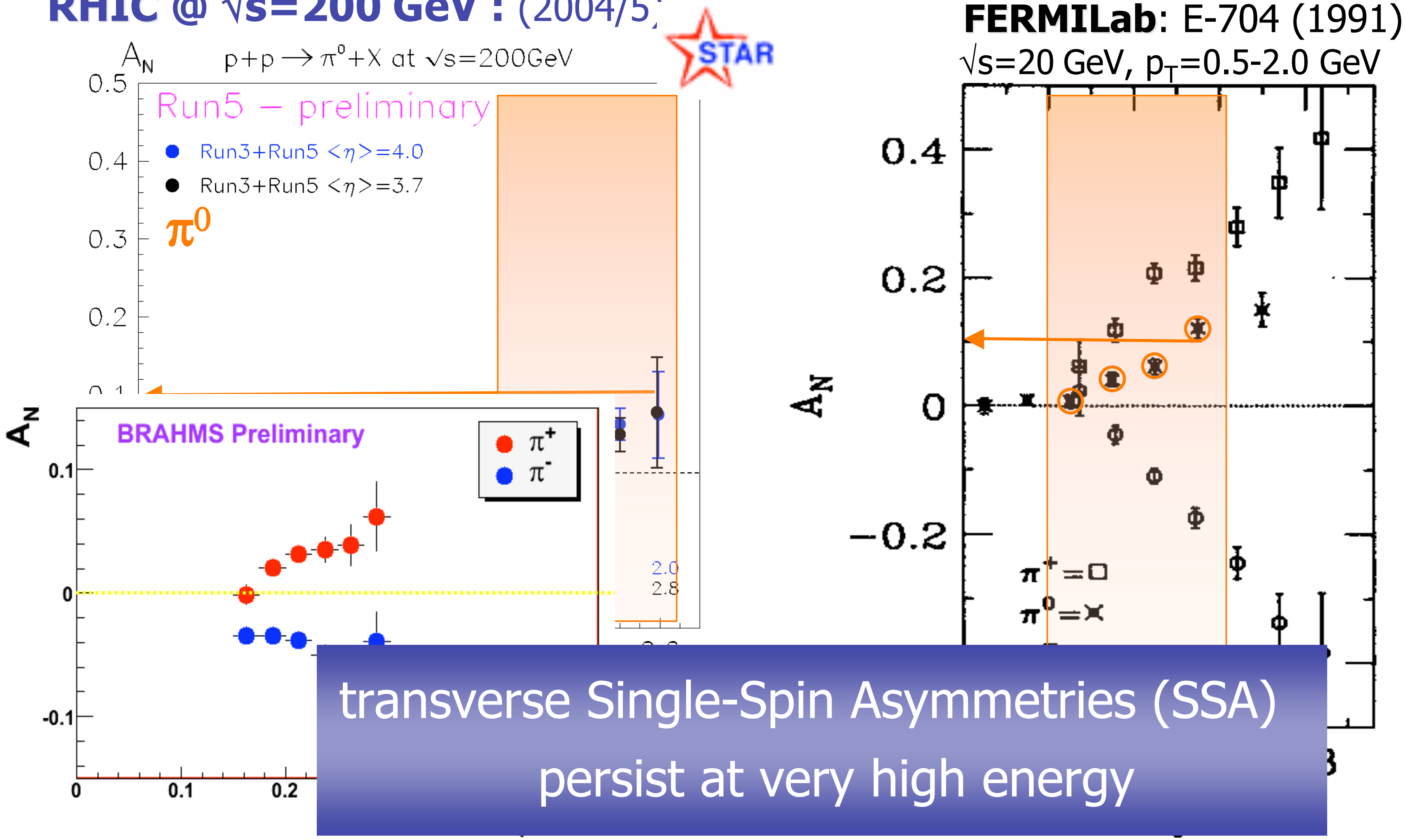
a brief and incomplete history

transverse single-spin asymmetries: [redacted]

RHIC @ √s=200 GeV : (2004/5)

FERMILab: E-704 (1991)

√s=20 GeV, p_T=0.5-2.0 GeV



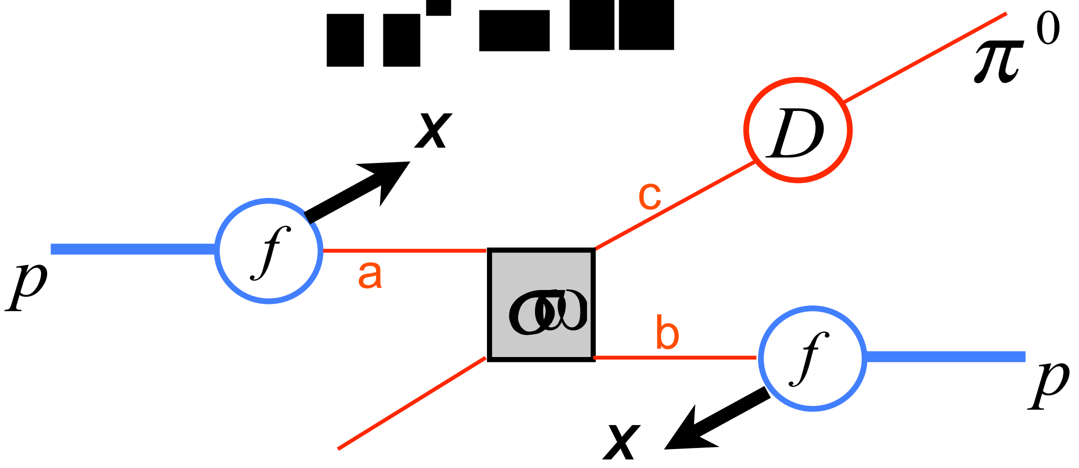
transverse Single-Spin Asymmetries (SSA)

persist at very high energy

how to explain the transverse SSA?

(as in DIS) **factorisation theorem for:**

[redacted]



$$d\sigma = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{f_{a/p}(x_a) \otimes f_{b/p}(x_b)}_{\text{PDF}} \otimes d\hat{\sigma}^{ab\to cd} \otimes \underbrace{D_{\pi/c}(z)}_{\text{FF}}$$

$d\hat{\sigma}^{ab\to cd}$: pQCD elementary interactions

[redacted]

how to explain the transverse SSA?

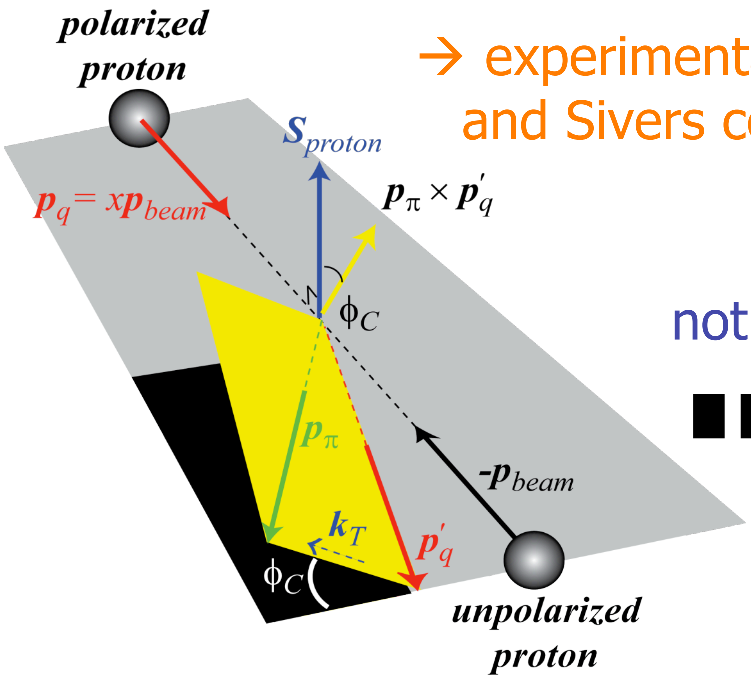
[redacted]

I: Collins mechanism

requires transverse quark polarisation (*transversity*) and spin-depedent fragmentation

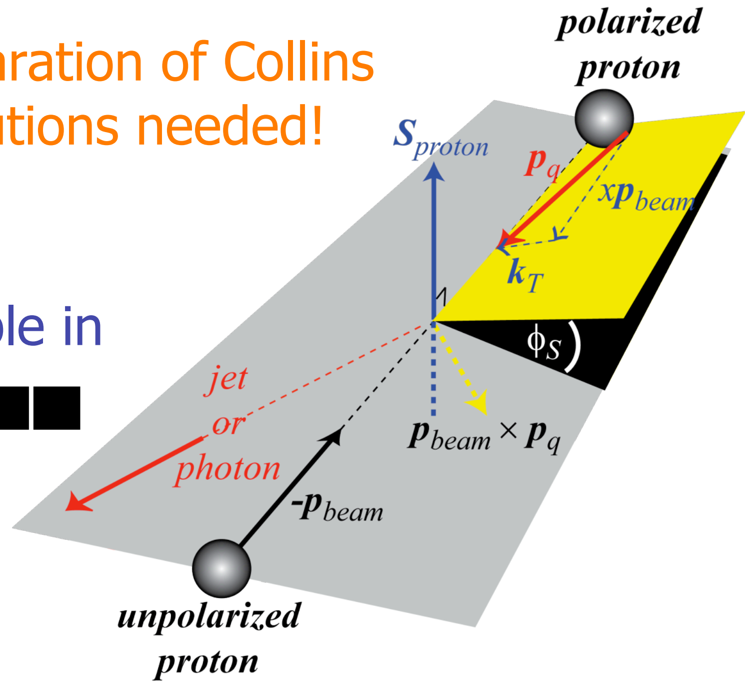
II: Sivers mechanism

requires spin-correlated transverse momentum in the proton (*orbital motion*)



→ experimental separation of Collins and Sivers contributions needed!

not possible in [redacted]



III: Qui-Stermann/Koike mechanism: initial/final state multiparton correlations twist-3 pQCD

back to lepton-hadron scattering (DIS)!

- no initial state interaction
- k_T-dependent factorisation proven
- Collins and Sivers mechanism can be disentangled !!!
  (using transversely polarised targets)

polarised DIS^h cross section

σ_{UU}

beam: λ target: S_L, S_T

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

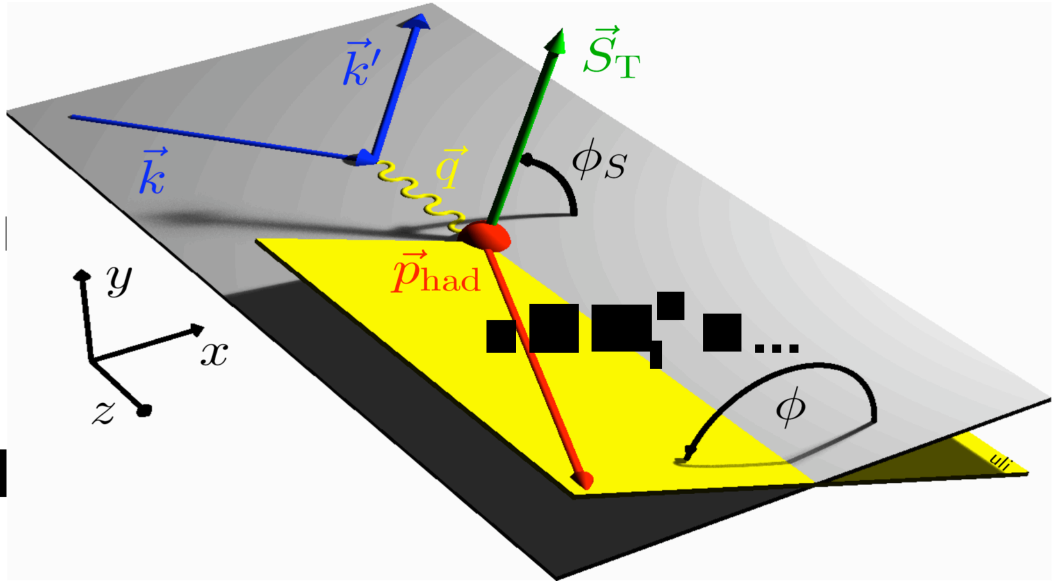
polarised DIS^h cross section

[redacted]

[redacted]

q

[redacted]



[redacted]

Δq

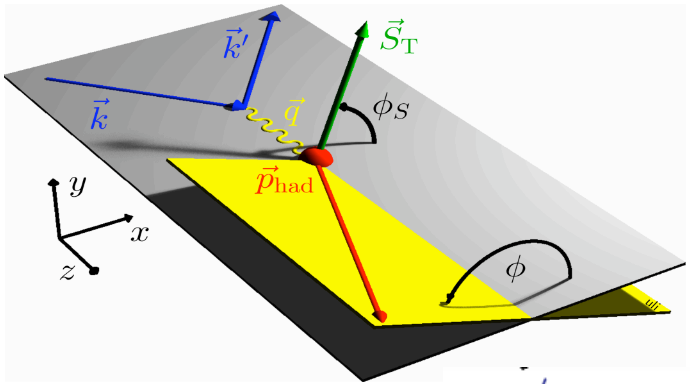
[redacted]

transversity

(Collins effect)

DIS^h with *transversely* polarised targets but not only...

transverse single-spin asymmetries



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

$$\approx 2\langle\sin(\phi+\phi_S)\rangle_{UT}^{h}\sin(\phi+\phi_S) + 2\langle\sin(\phi-\phi_S)\rangle_{UT}^{h}\sin(\phi-\phi_S) + \cdots$$

[redacted]

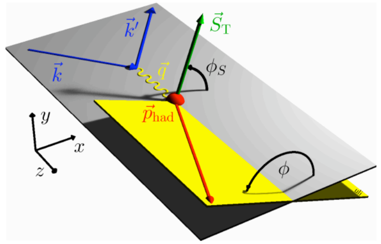
[redacted]

Collins moment

Sivers moment

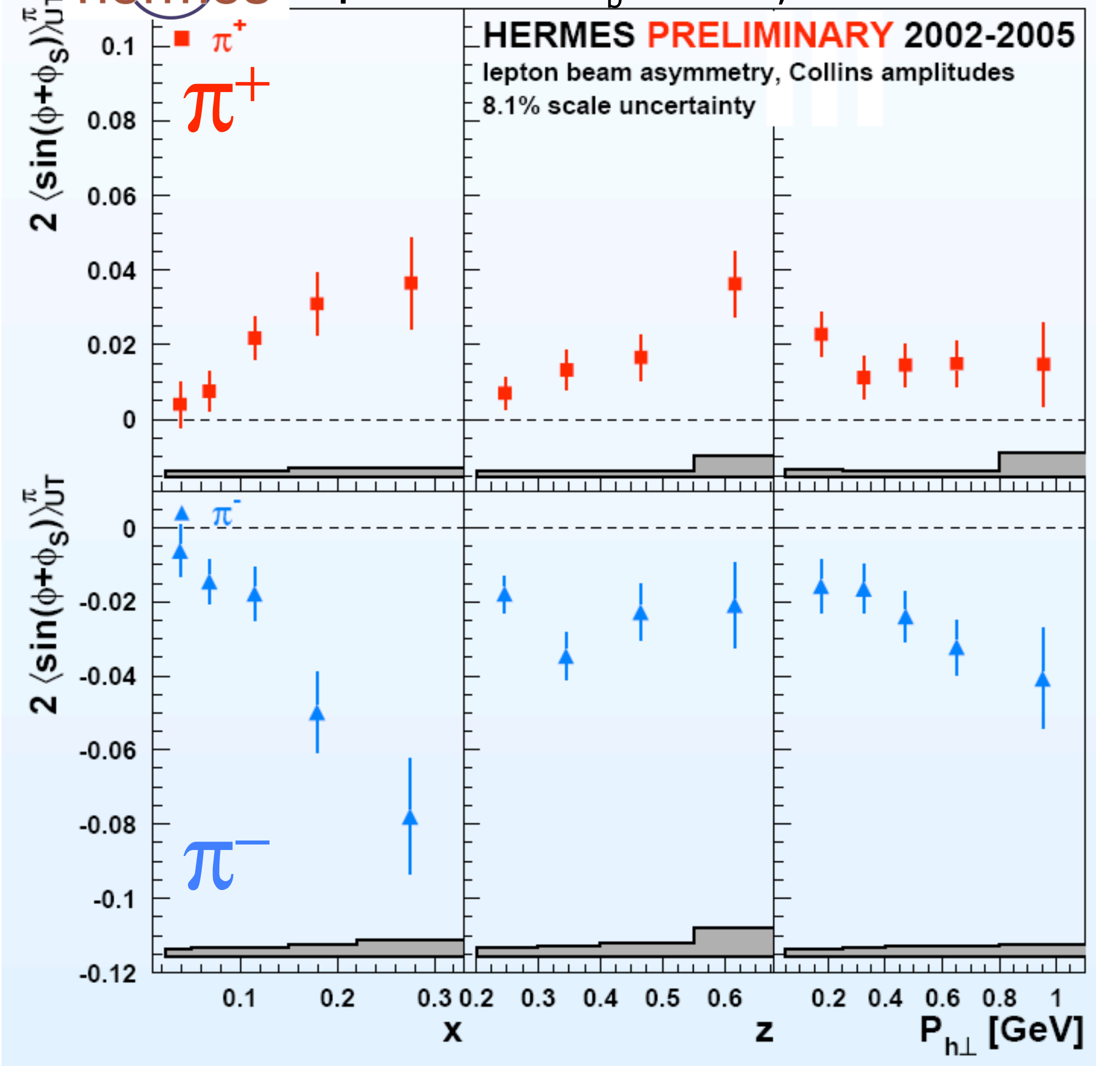
[redacted]

Collins asymmetries



[illegible]

$ep^{\uparrow} \rightarrow \pi X$ E_b=27GeV,   √s~7 GeV



first time: *transversity* & *Collins FF* are **non-zero!**

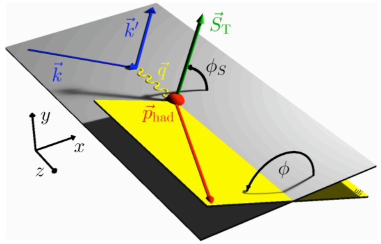
- π^+ asymmetries positive – no surprise: u-quark dominance and expect $\delta q>0$ since $\Delta q>0$

- large negative π^- asymmetries – **ARE** a surprise: suggests the *disfavoured CollinsFF* being large and with oposite sign:

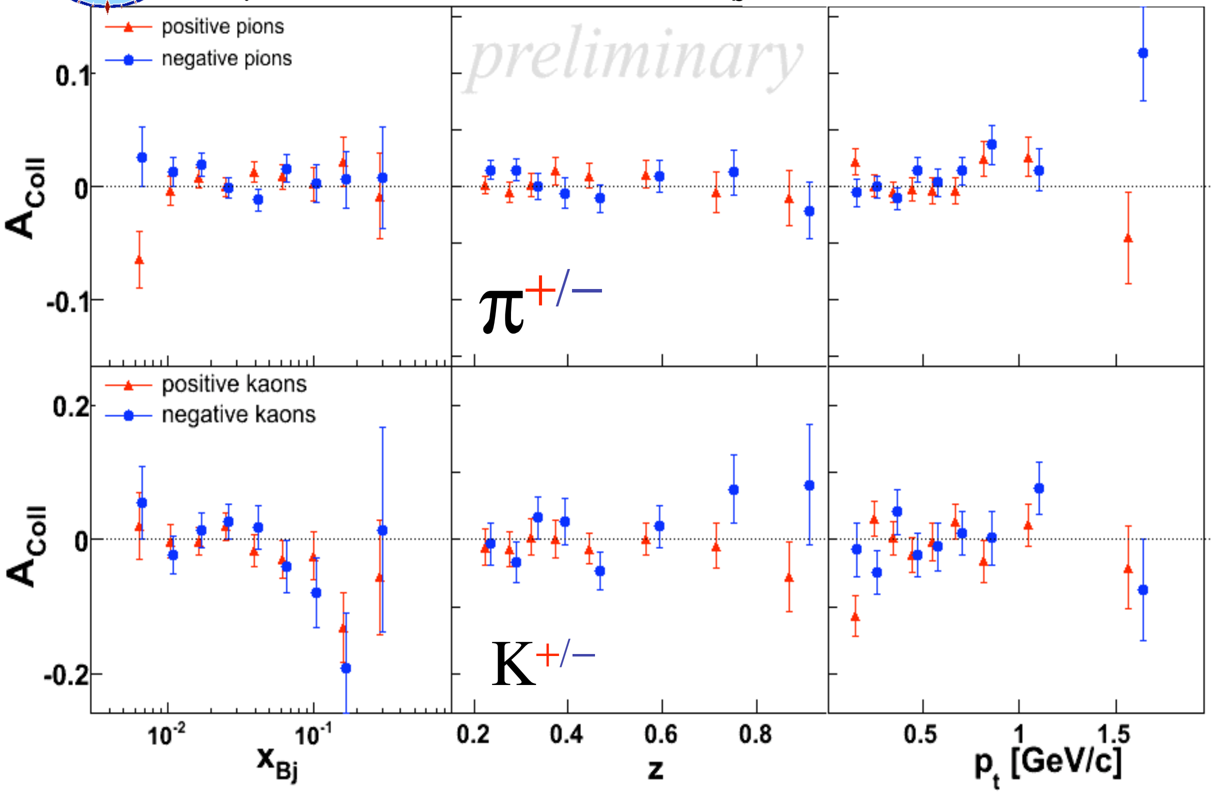
[illegible]

Collins asymmetries

[redacted]



μd↑ → π(K) X E_b=190 GeV, √s~30 GeV

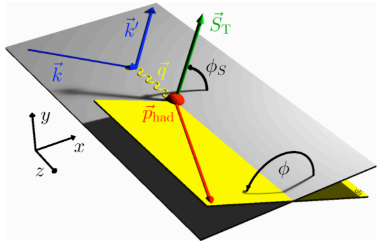


- all asymmtries consistent with **zero**
- deuteron target:

  [redacted]

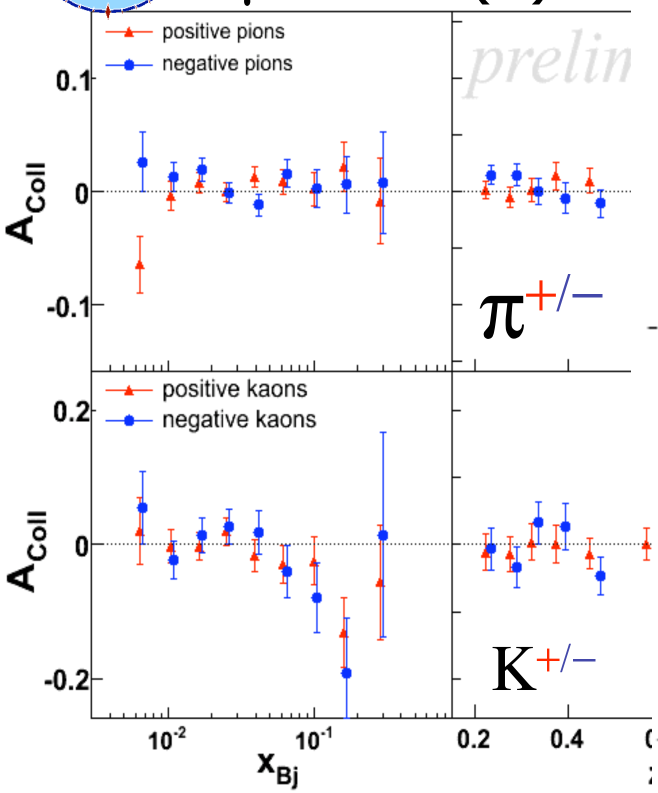
see talk by A. Vossen

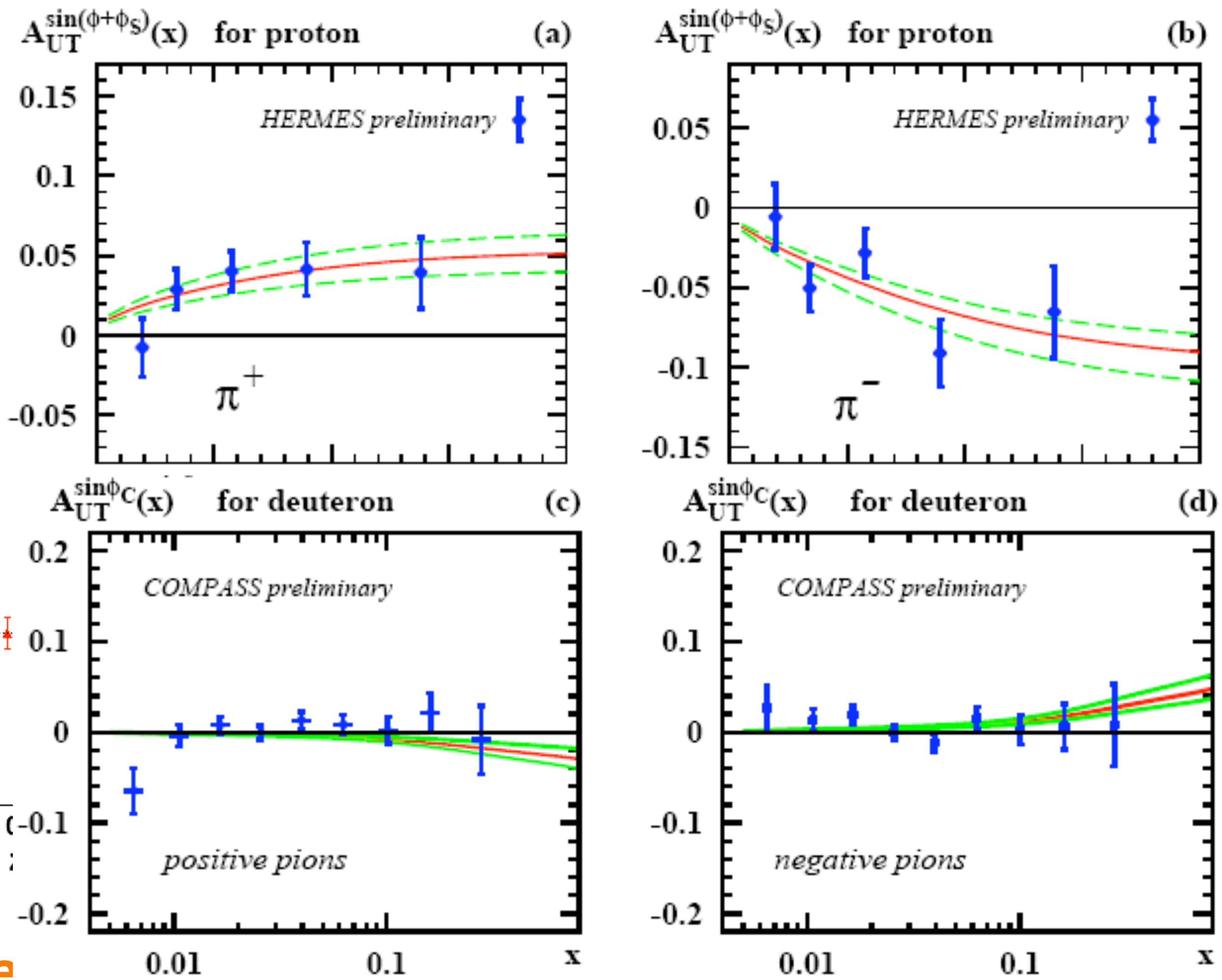
Collins asymmetries



COMPASS

$\mu d^{\uparrow} \rightarrow \pi(K)\ X$

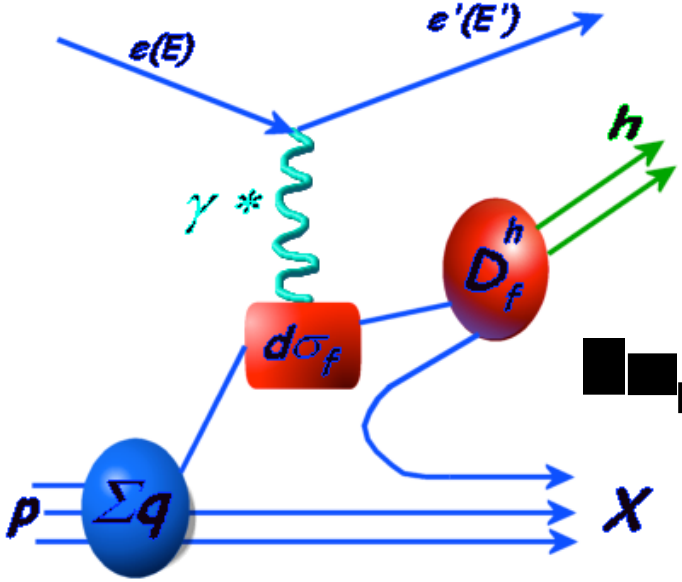




Efremov et. al / Anse

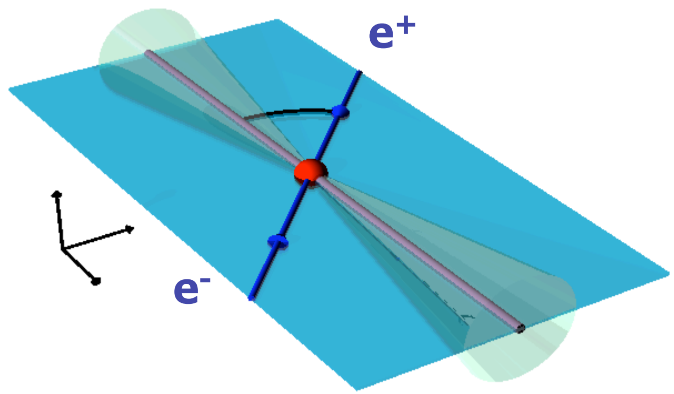
HERMES and COMPASS data **are consistent** !

extracting *transversity*



[illegible]

spin-dependent fragmentation function → e^+e^-

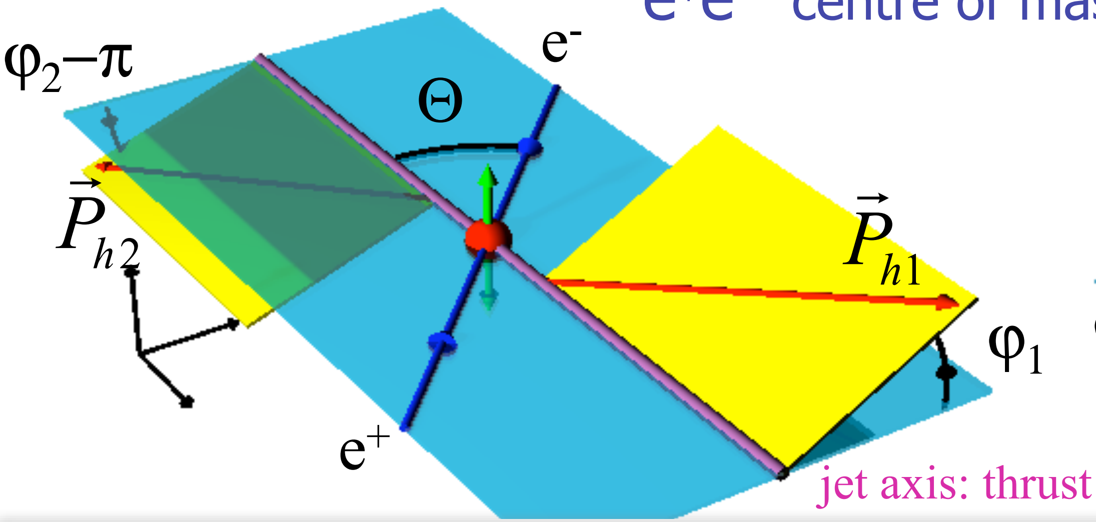


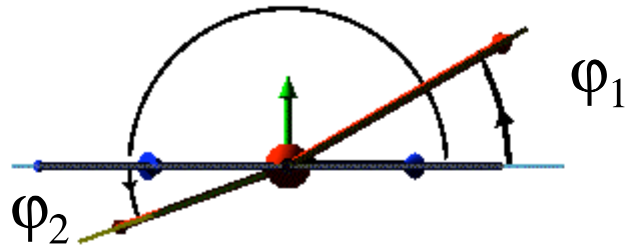
[illegible]

Collins fragmentation in e^+e^-

$\sqrt{s} \sim 10.52$ GeV

e^+e^- centre of mass frame:





2-hadron inclusive *transverse momentum dependent* cross section:

$$\frac{d\sigma\left(e^+e^- \to h_1 h_2 X\right)}{d\Omega dz_1 dz_2 d^2 q_T} = \cdots B(y)\cos(\varphi_1 + \varphi_2) H_1^{\perp}(z_1) \overline{H}_1^{\perp}(z_2)$$

$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

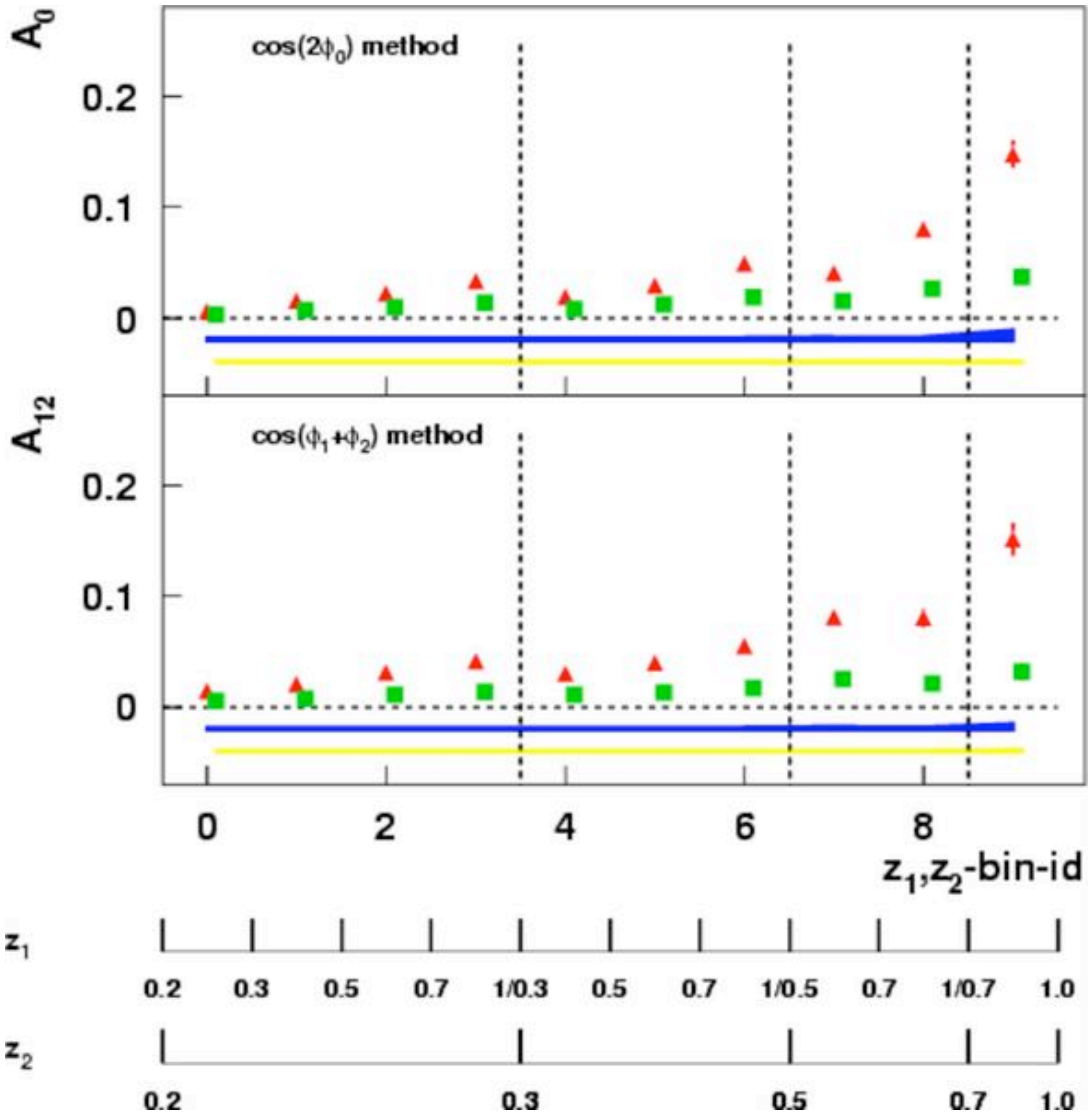
net (anti) alignment of transverse quark spins

Collins fragmentation in e^+e^-

$\sqrt{s}\sim 10.52$ GeV

$e^+e^- \rightarrow \pi\pi X$

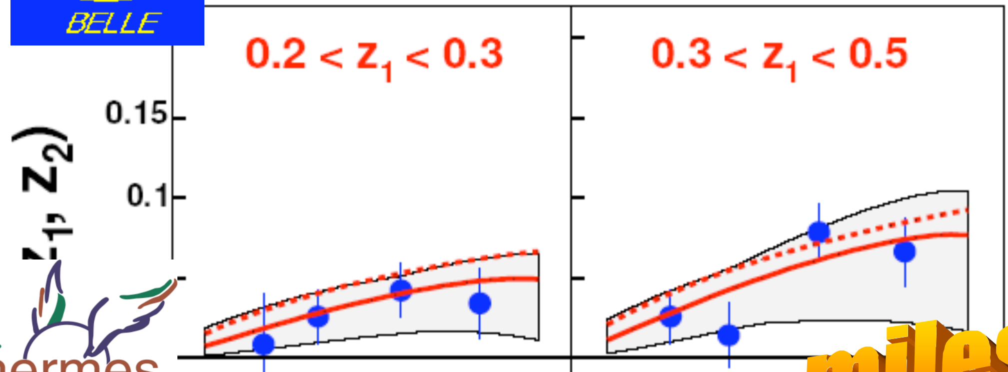
($547\ fb^{-1}$)



first glimpse of transversity

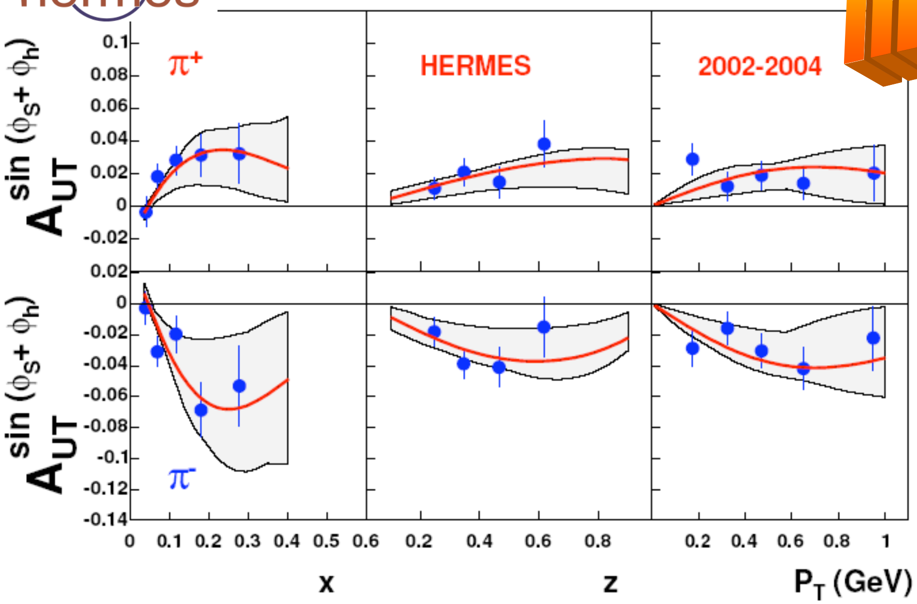
global, simultaneous fit:

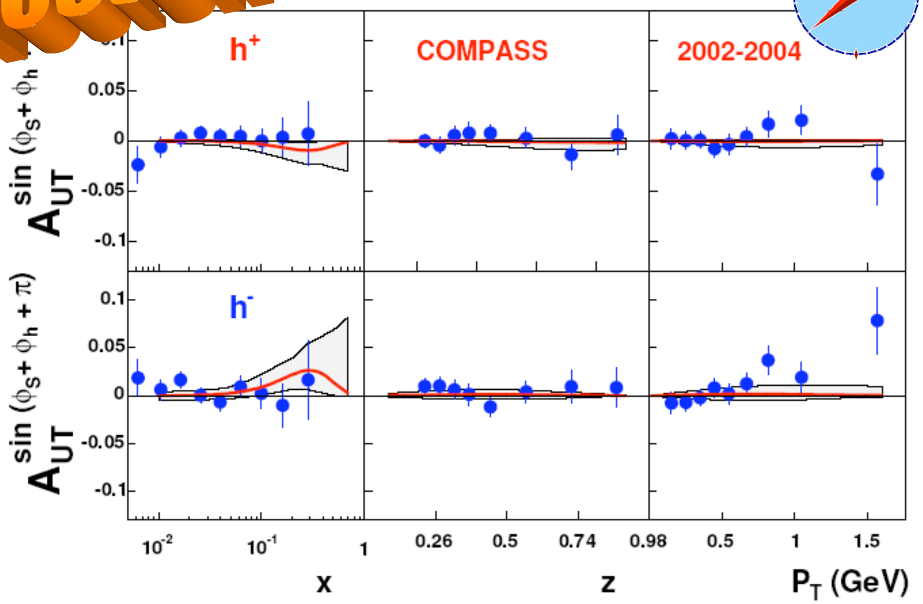
[Anselmino et al. PRD75(2007)]



Collins
fragmentation function

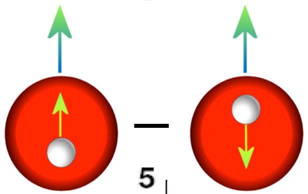
milestones!

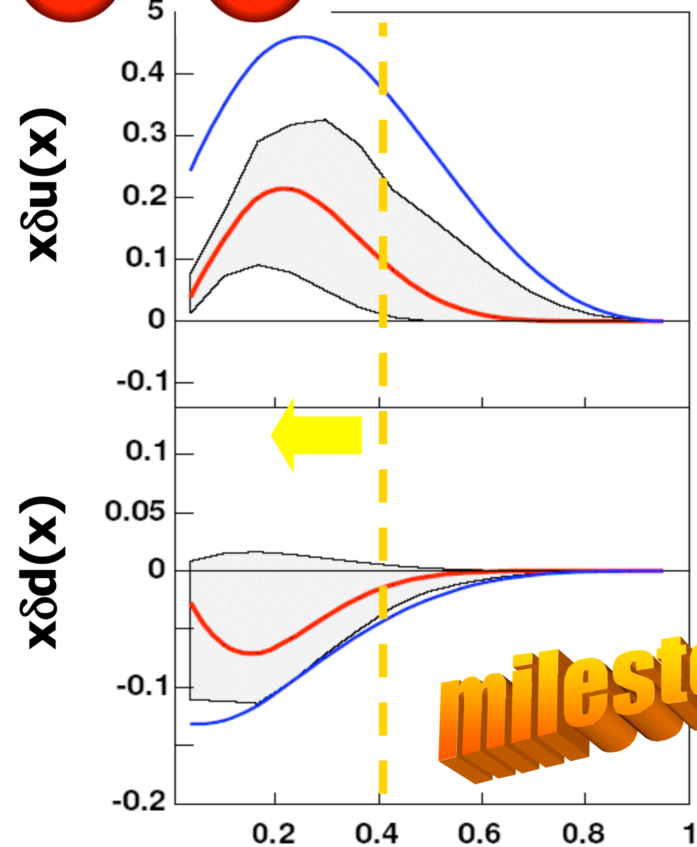




first glimpse of transversity

global, simultaneous fit:

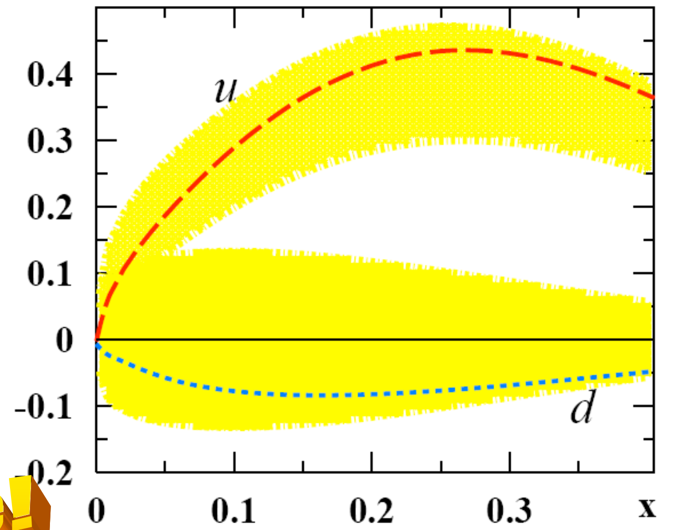
$\delta q =$ 



[Anselmino et al. PRD75(2007)]

compare to a model calculation:

$x\delta q(x)$ χQSM

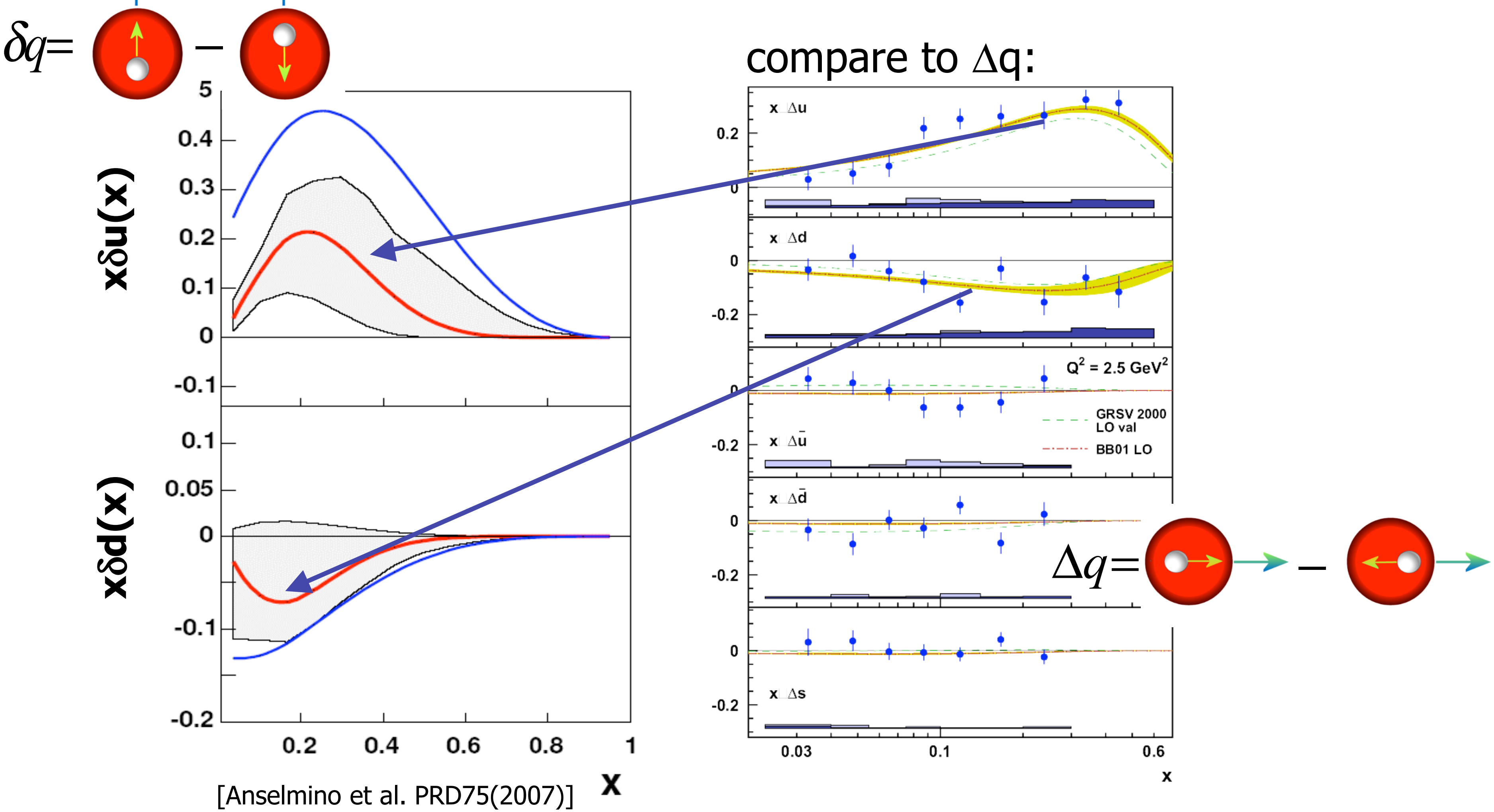


[Efremov,Goeke,Schweitzer PRD73(2006)]

milestone!

first glimpse of transversity

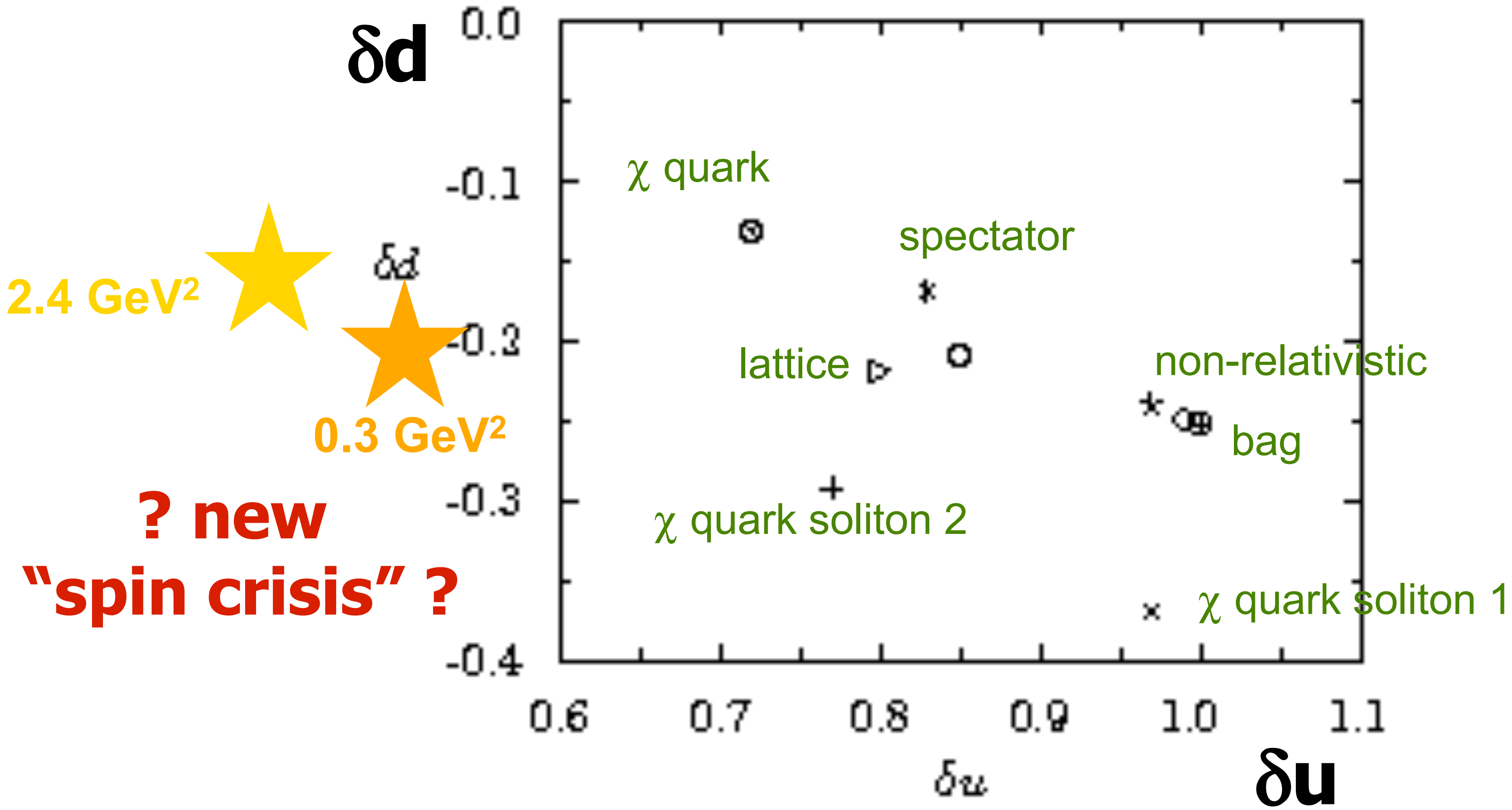
global, simultaneous fit:



[Anselmino et al. PRD75(2007)]

what about the tensor charge?

from theory and lattice: [Barone, Drago, Ratcliffe, PR 359 (2002)]



? new "spin crisis" ?

using Anselmino et al. parametrisation of δu and δd from DIS and e^+e^- data

[Wakamatsu, 0705.2917[hep-ph]]

!caution:
- model dependence
- extrapolations

more transverse spin effects:

spin-orbit correlations

Sivers function:

distribution of unpolarised quarks in a transversely polarised nucleon

Peculiarity of $f_{1T}^{\perp}$

- chiral-even, naïve *time reversal odd* (T-odd)
- related to parton orbital momentum
- violates naïve *universality* of PDF:

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

more transverse spin effects:

spin-orbit correlations

Sivers function:

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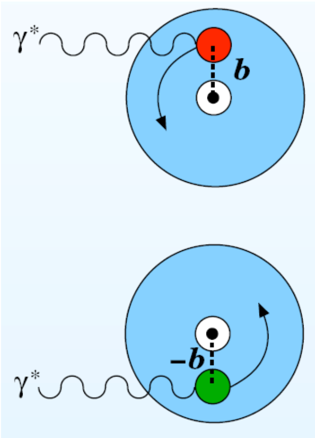
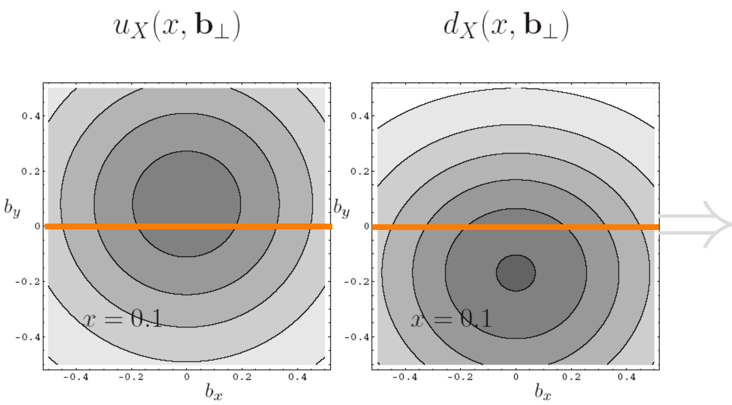
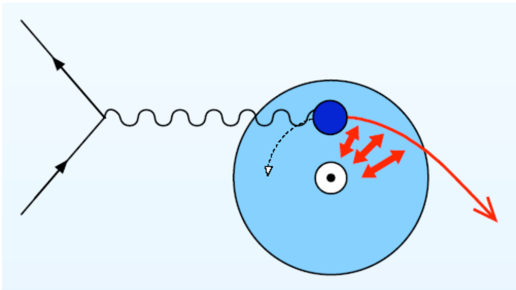
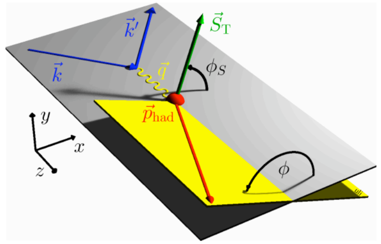




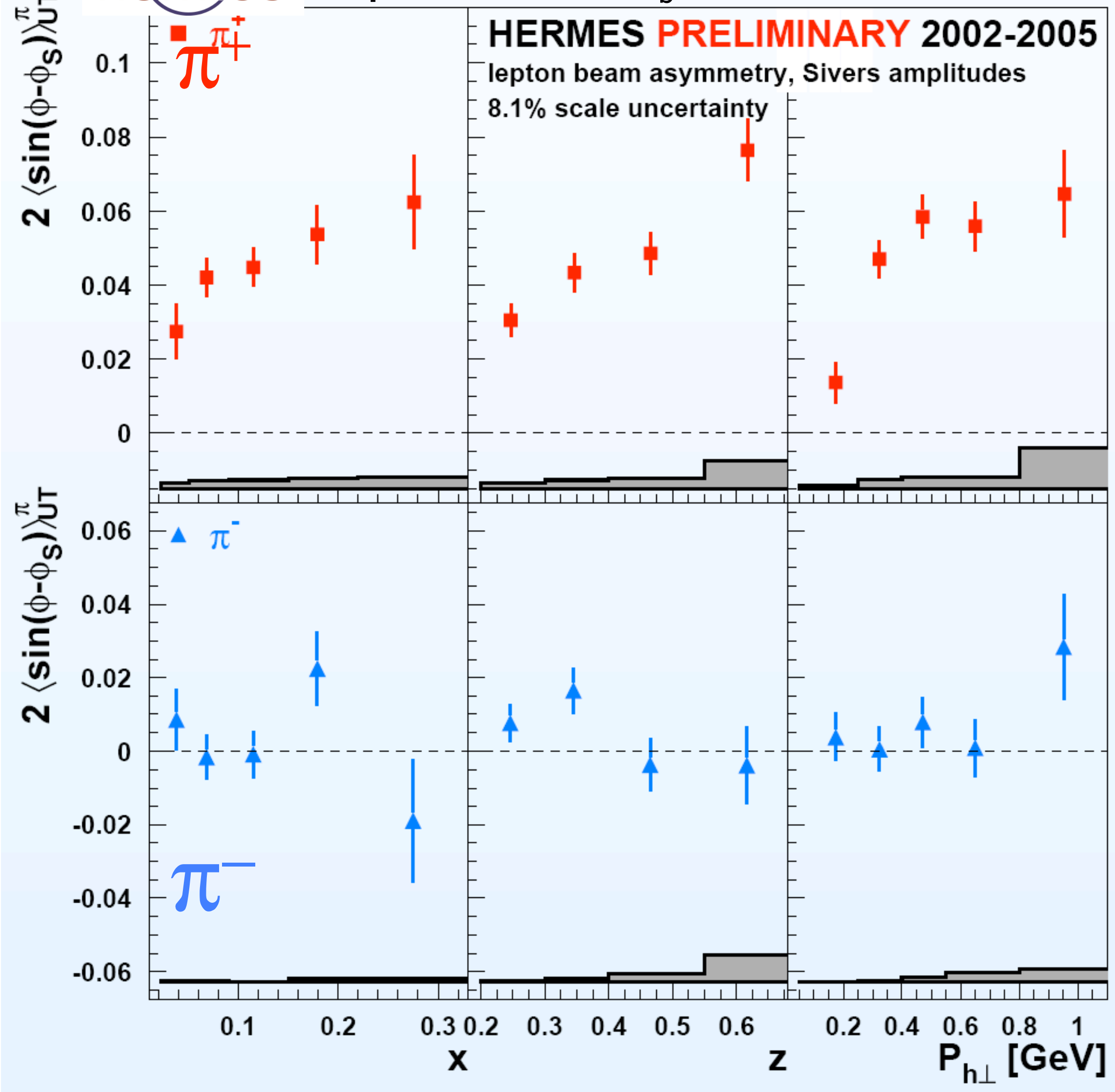


Sivers asymmetries



hermes

$ep^{\uparrow} \rightarrow \pi X$ E_b=27GeV, $\sqrt{s}$~7 GeV

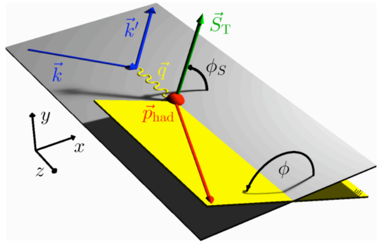


π^+ are subtantial and positive:

- first unambiguous evidence for a **non-zero T-odd** distribution function in DIS

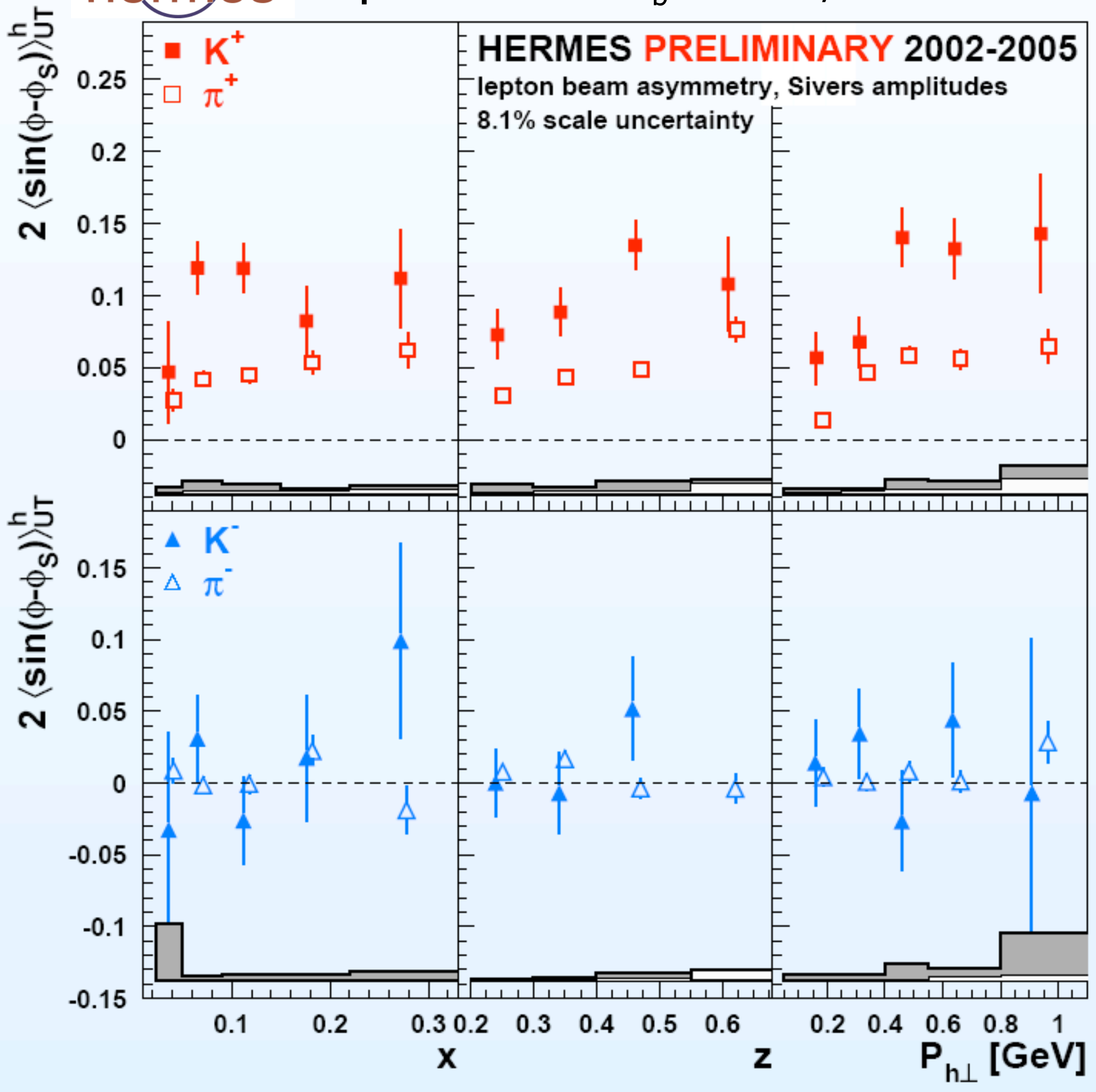
- a signature for quark orbital angular momentum !

Sivers asymmetries



hermes

$ep^{\uparrow} \rightarrow KX$ E_b=27GeV, $\sqrt{s}$~7 GeV



[redacted]

- SURPRISE:

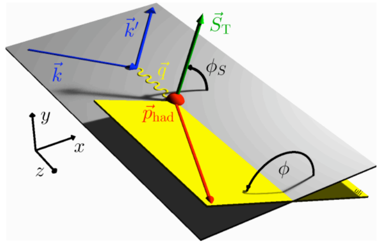
K^+ amplitude 2.3±0.3 times larger than for π^+

→ conflicts with usual expectations based on u-quark dominance

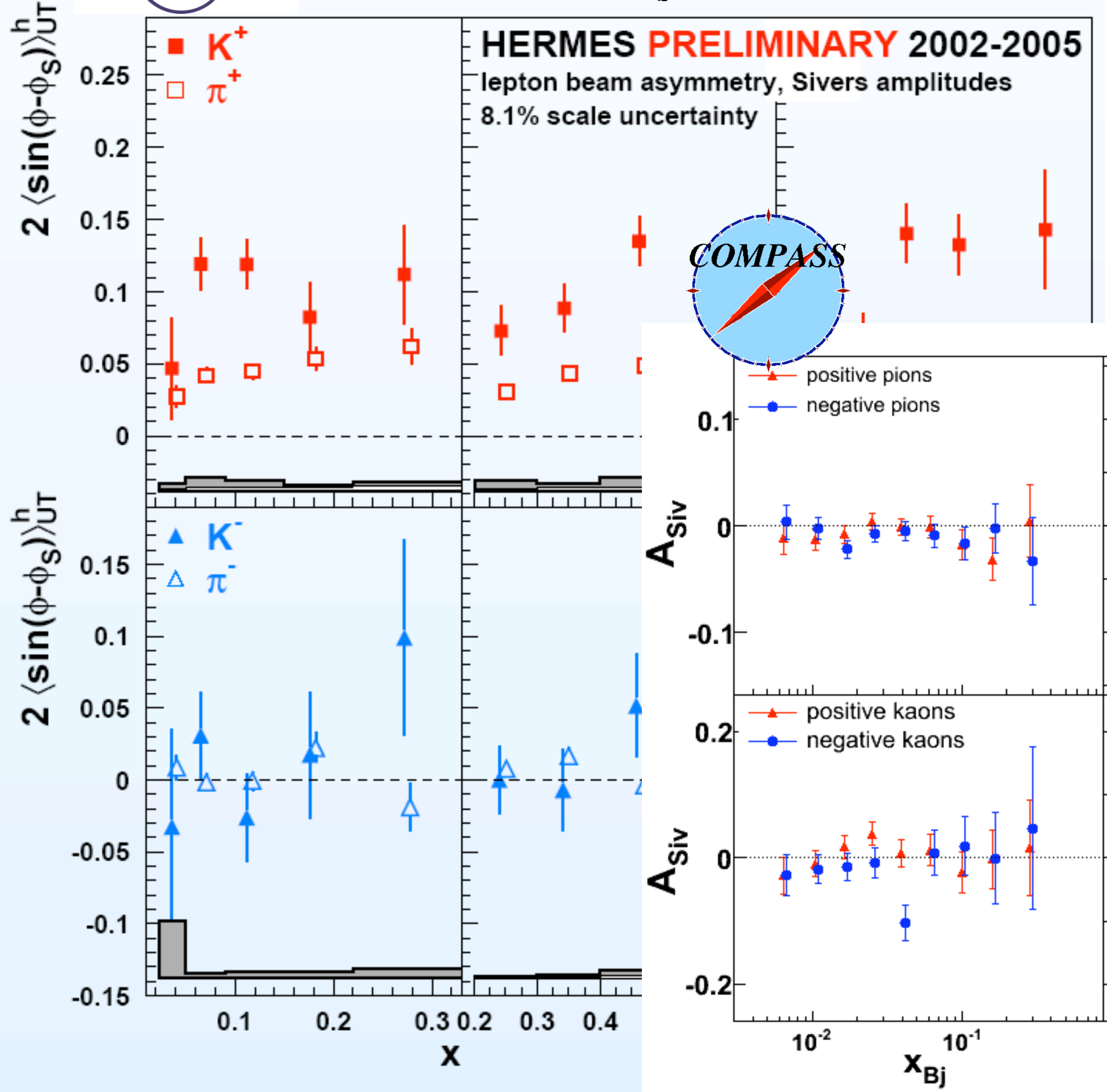
→ suggests substantial magnitude of the Sivers fct. for sea quarks

$$K^+ = |u\bar{s}\rangle \qquad \pi^+ = |u\bar{d}\rangle$$

Sivers asymmetries

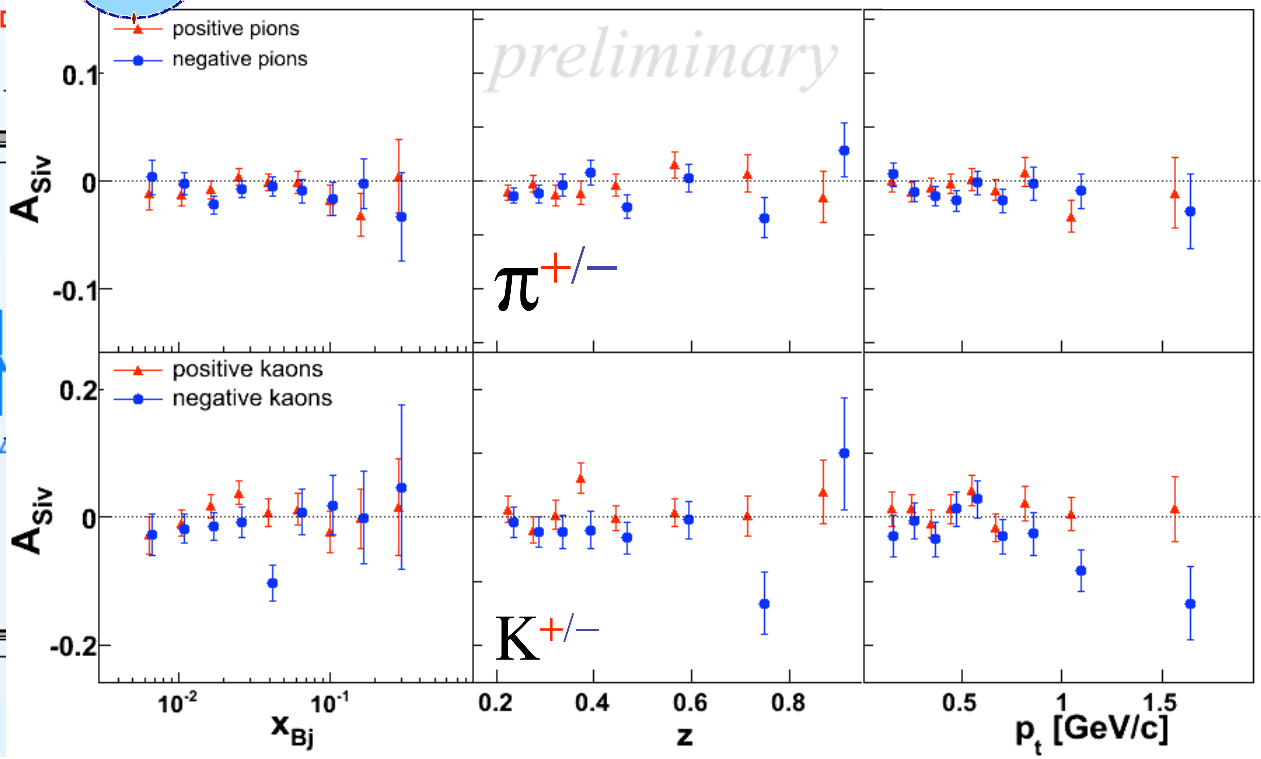


$ep^{\uparrow} \rightarrow KX$ E_b=27GeV, $\sqrt{s}$~7 GeV

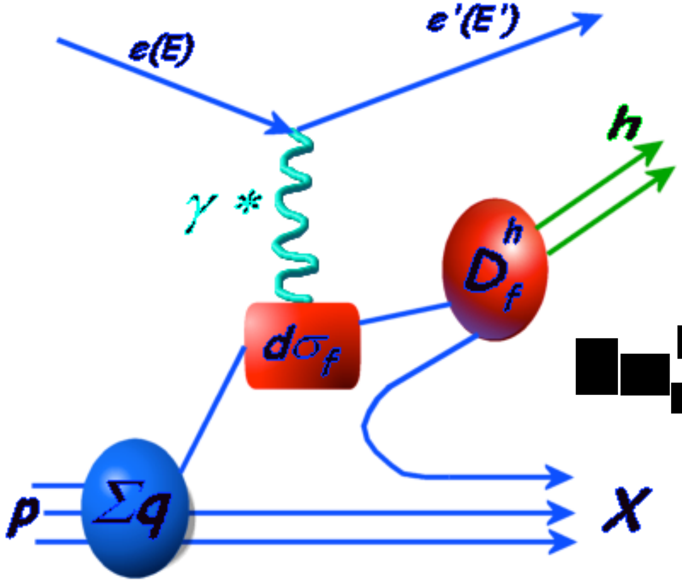


- deuteron target:

E_b=190 GeV, $\sqrt{s}$~30 GeV



extracting the *Sivers* function



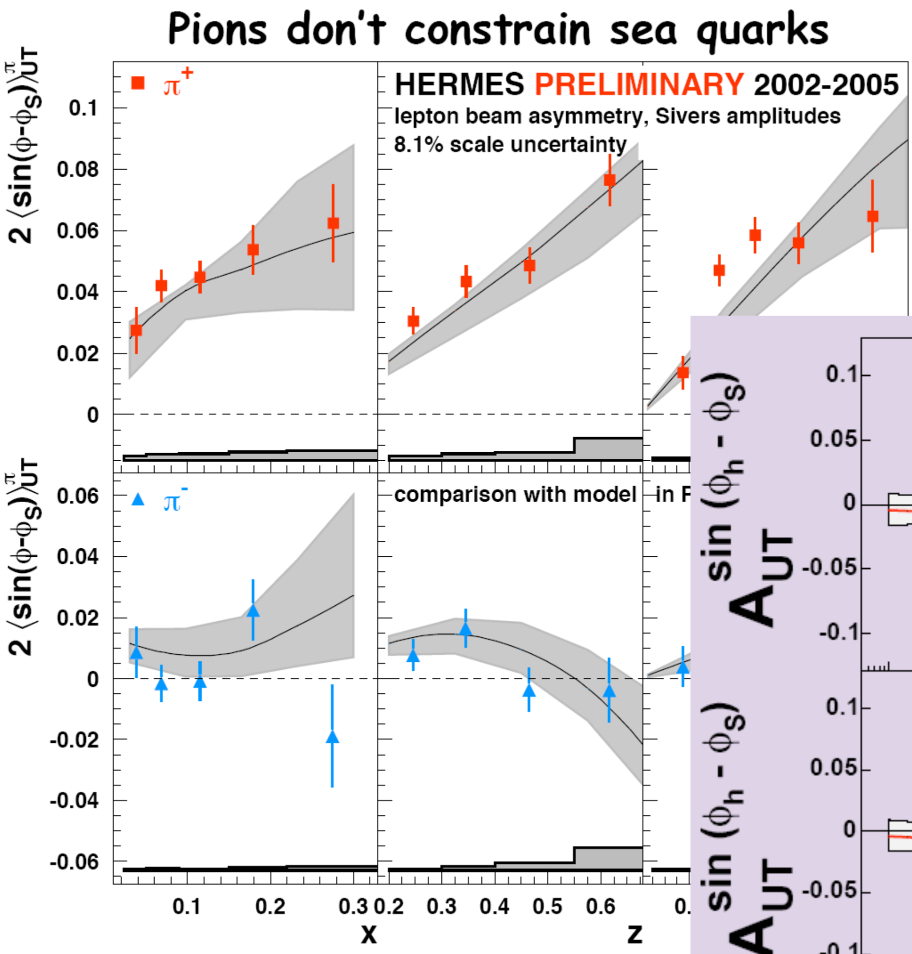
[redacted]

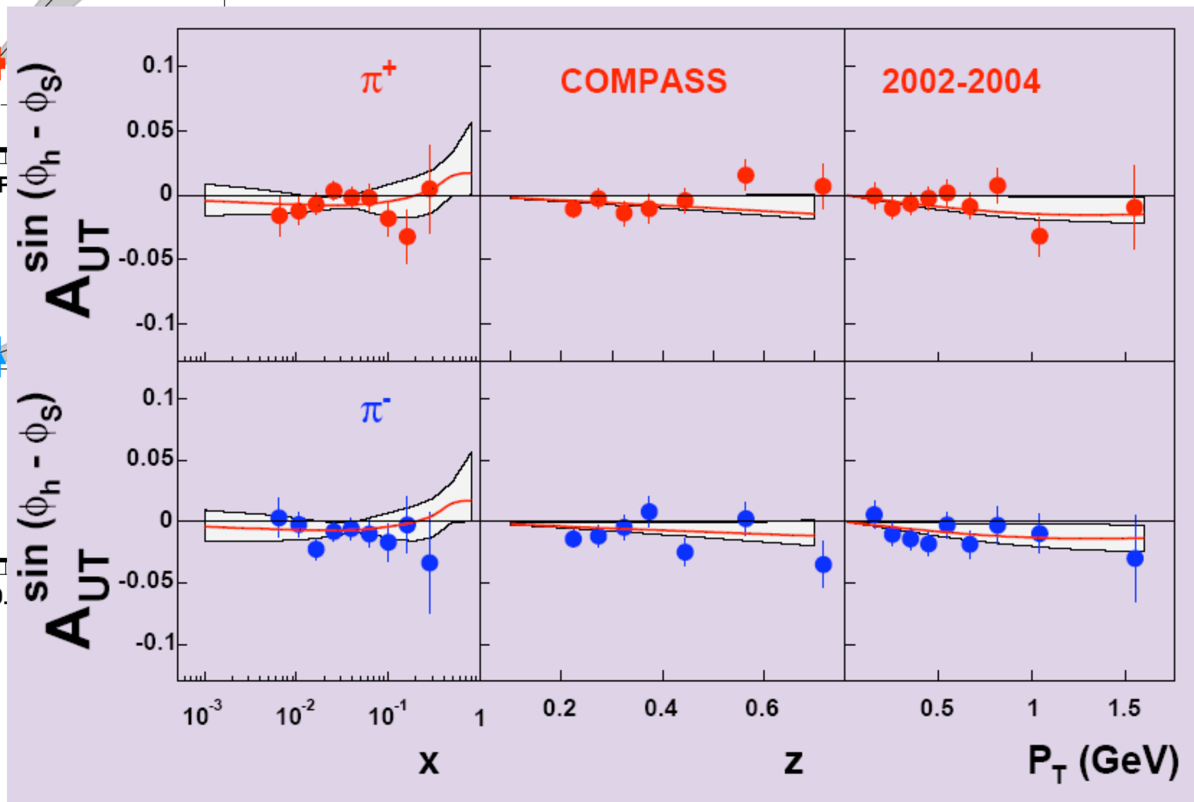
fragmentation function → e^+e^-

use "standard" parametrisations of unpolarised fragmentation functions

a fit of HERMES+COMPASS pion data

[Anselmino et al. PRD72(2005)]

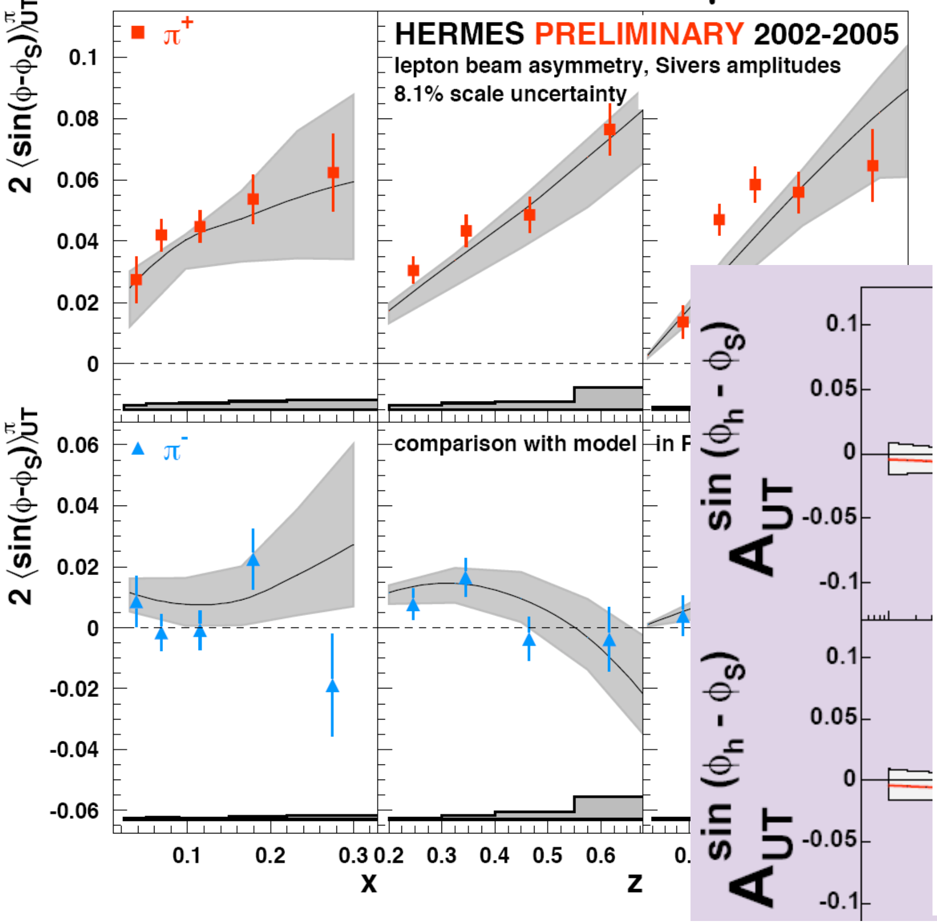




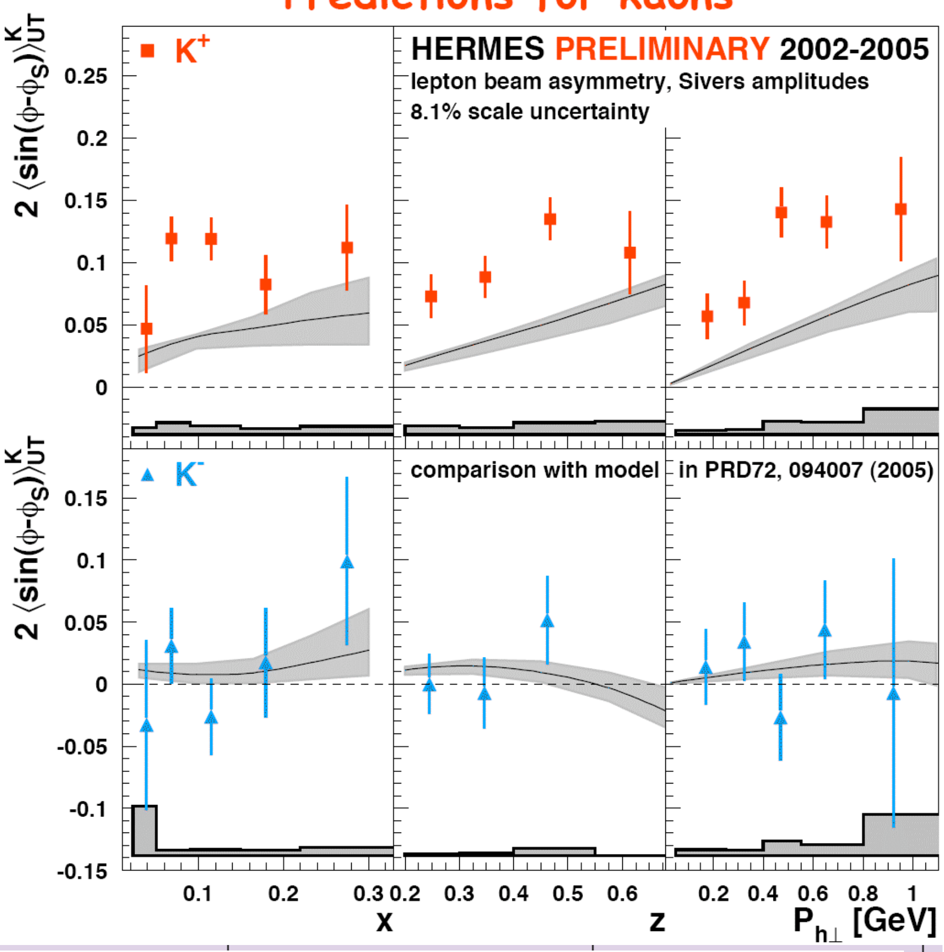
a fit of HERMES+COMPASS pion data

[Anselmino et al. PRD72(2005)]

Pions don't constrain sea quarks



Predictions for kaons



kaon data suggest that sea quark contribution may be significant

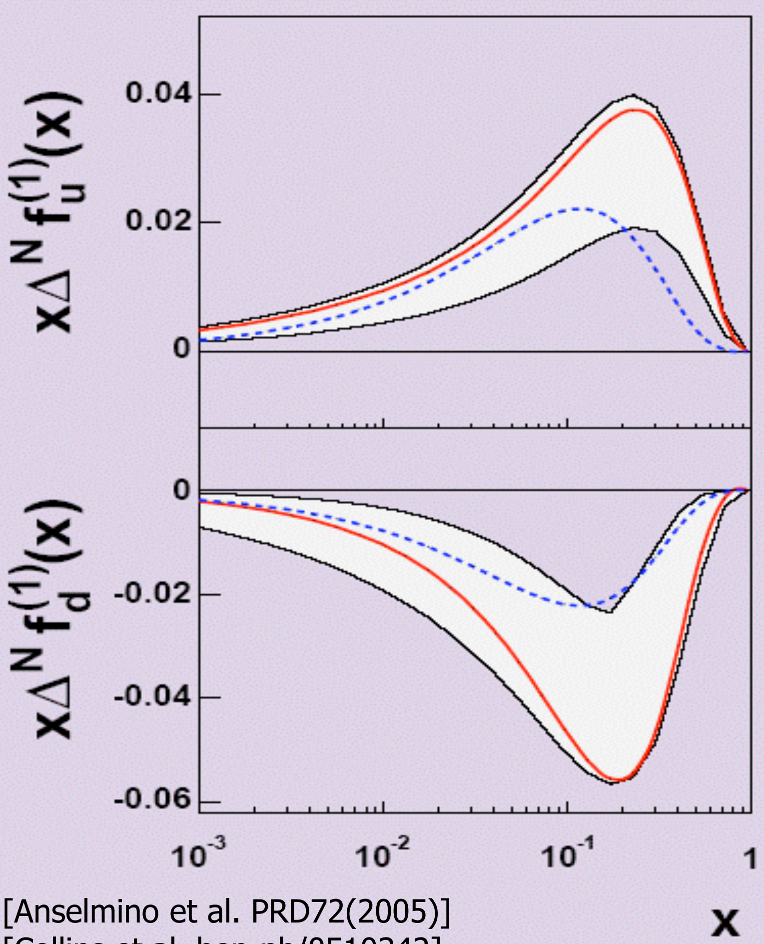
extracting the *Sivers* function

[redacted]

usual unpolarised fragmentation function

[redacted]

[...just notation]



[Anselmino et al. PRD72(2005)]
[Collins et al. hep-ph/0510342]

ToDo:

crucial test of pQCD:

[redacted]

Polarized Antiproton EXperiments

@FAIR (GSI)

conclusion: transversity & TMDs

transversity:

3rd basic quark distribution function (@leading twist)

first glimpse: road to an accurate extraction is still long, but exists!

TMDs: transverse momentum dependent distribution and fragmentation functions

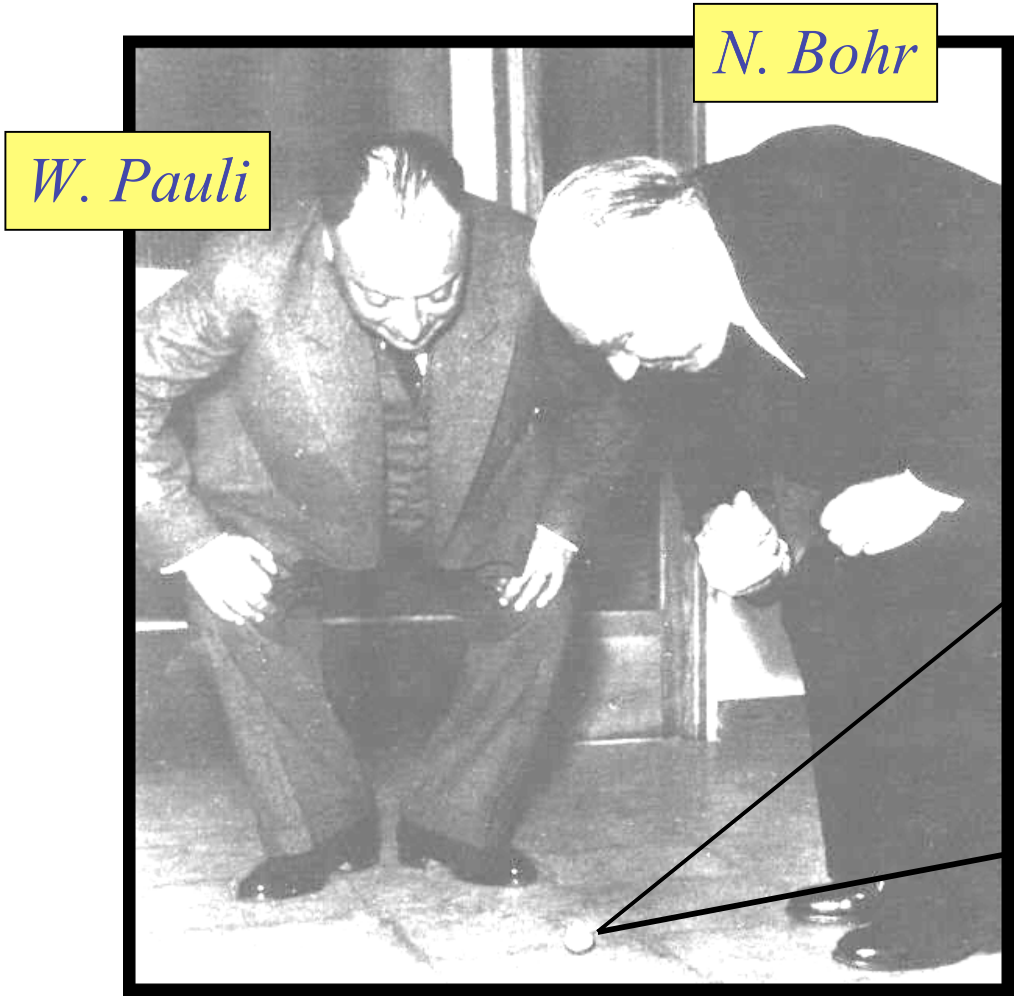
→ **Sivers pdf, Collins FF, ...many more friends**

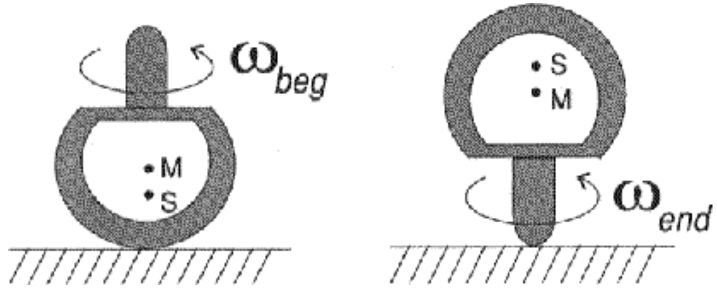
describe correlations of transverse momentum and spin
→ explore spin-orbit structure

key to construct a complete picture about the spin structure of the nucleon going ***beyond the collinear approximation***

fascinated by spin ?

"You think you understand something? Now add spin..." *-- R. Jaffe*

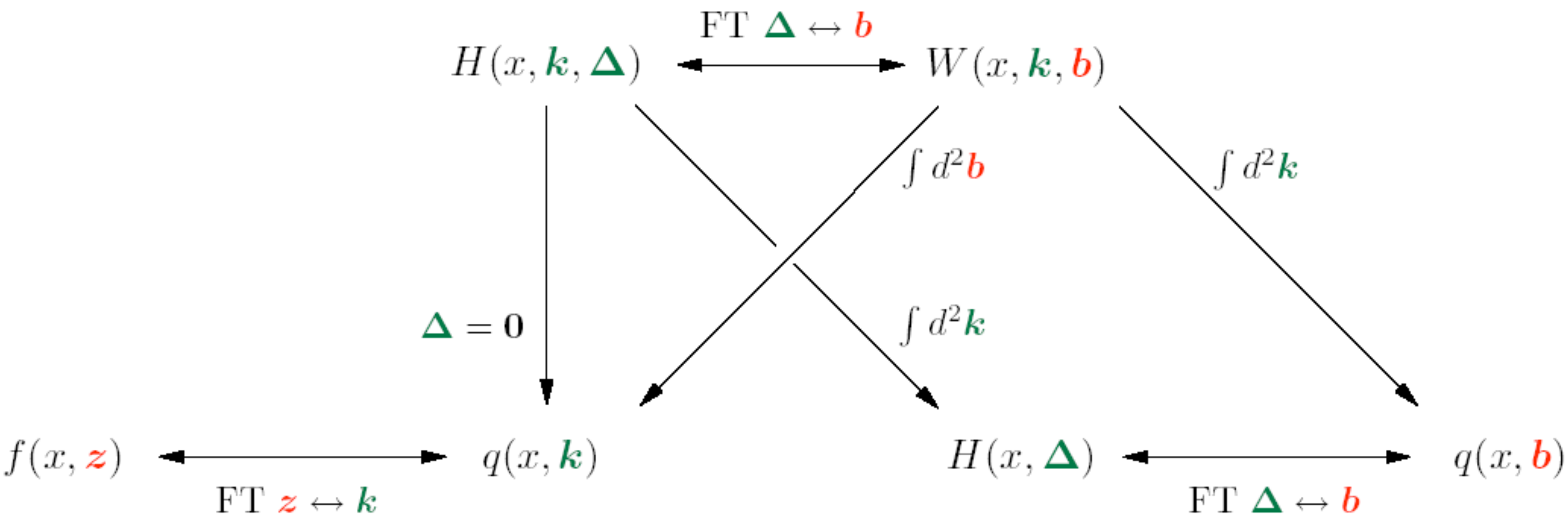




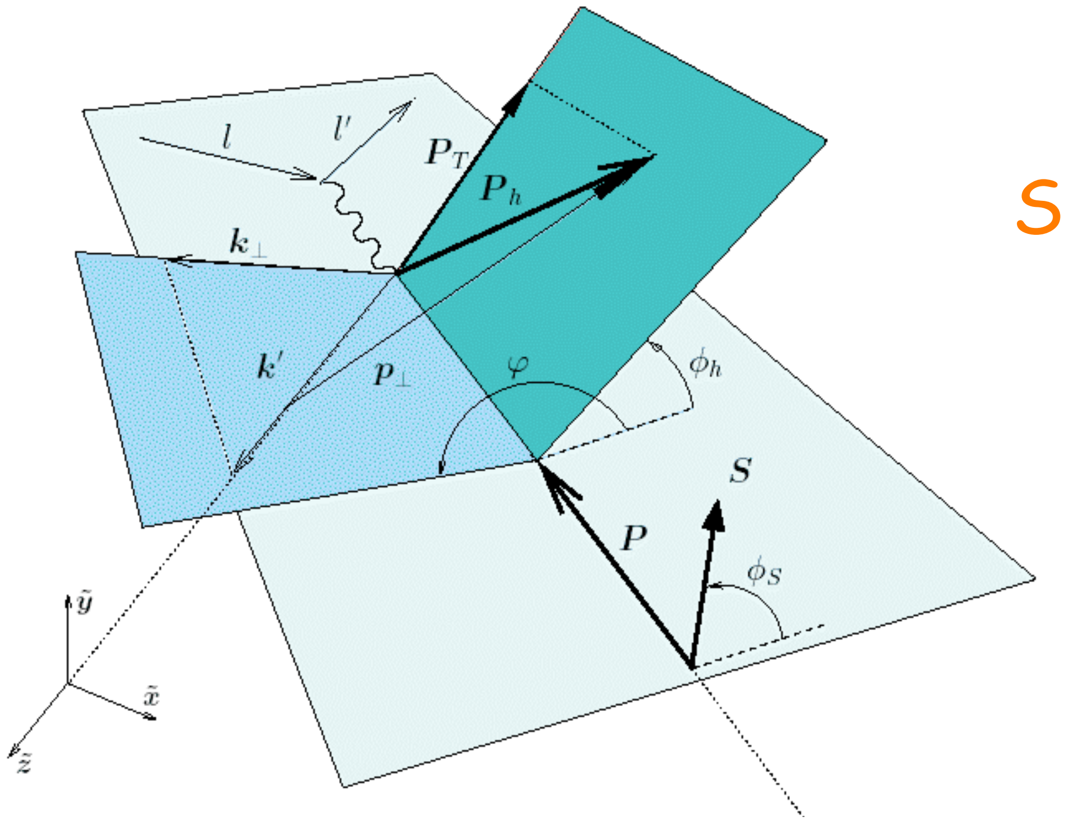
thank you !

BACKUP SLIDES

the mother of all functions



- densities $q(x, \boldsymbol{k})$ and $q(x, \boldsymbol{b})$ not connected by Fourier transf.
- but descend from same function
  e.g. represent $H(x, \boldsymbol{k}, \boldsymbol{\Delta})$ through wave functions $\psi(x_i, \boldsymbol{k}_i)$



SIDIS in parton model with intrinsic $k_\perp$

factorization holds at large Q^2, and $P_T \approx k_\perp \approx \Lambda_{QCD}$ Ji, Ma, Yuan

$$d\sigma^{lp\to lhX} = \sum_q f_q(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{lq\to lq}(y, \boldsymbol{k}_\perp; Q^2) \otimes D_q^h(z, \boldsymbol{p}_\perp; Q^2)$$

nucleon distribution functions

@leading twist, no pT integration:

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

→employ all possible polarisation observables:

A_{UT}, A_{UL}, A_{LU}, A_{LT} + unpol

Polarized SIDIS cross section, up to subleading order in 1/Q

$$
\begin{aligned}
d\sigma = {} & d\sigma_{UU}^{0} + \cos 2\phi_h \, d\sigma_{UU}^{1} + \frac{1}{Q}\cos\phi_h \, d\sigma_{UU}^{2} + \lambda_e \frac{1}{Q}\sin\phi_h \, d\sigma_{LU}^{3} \\
& + S_L \left\{ \sin 2\phi_h \, d\sigma_{UL}^{4} + \frac{1}{Q}\sin\phi_h \, d\sigma_{UL}^{5} + \lambda_e \left[d\sigma_{LL}^{6} + \frac{1}{Q}\cos\phi_h \, d\sigma_{LL}^{7} \right] \right\} \\
& + S_T \left\{ \sin(\phi_h - \phi_S) \, d\sigma_{UT}^{8} + \sin(\phi_h + \phi_S) \, d\sigma_{UT}^{9} + \sin(3\phi_h - \phi_S) \, d\sigma_{UT}^{10} \right. \\
& + \frac{1}{Q} \left[\sin(2\phi_h - \phi_S) \, d\sigma_{UT}^{11} + \sin\phi_S \, d\sigma_{UT}^{12} \right] \\
& \left. + \lambda_e \left[\cos(\phi_h - \phi_S) \, d\sigma_{LT}^{13} + \frac{1}{Q} \left(\cos\phi_S \, d\sigma_{LT}^{14} + \cos(2\phi_h - \phi_S) \, d\sigma_{LT}^{15} \right) \right] \right\}
\end{aligned}
$$

SIDISLAND

Kotzinian, **NP B441** (1995) 234

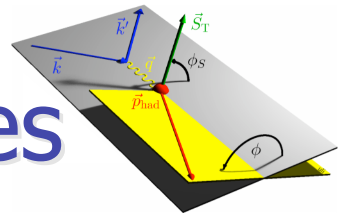
Mulders and Tangermann, **NP B461** (1996) 197

Boer and Mulders, **PR D57** (1998) 5780

Bacchetta et al., **PL B595** (2004) 309

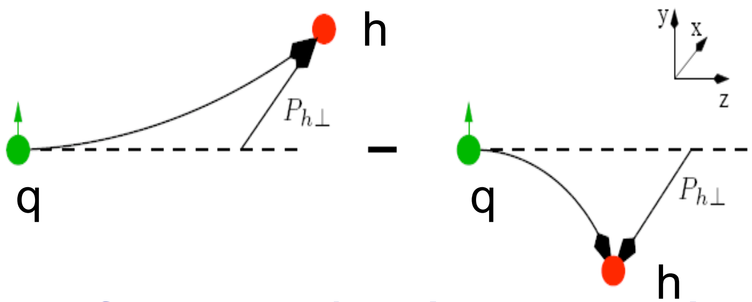
Bacchetta et al., **JHEP 0702** (2007) 093

azimuthal single-spin asymmetries



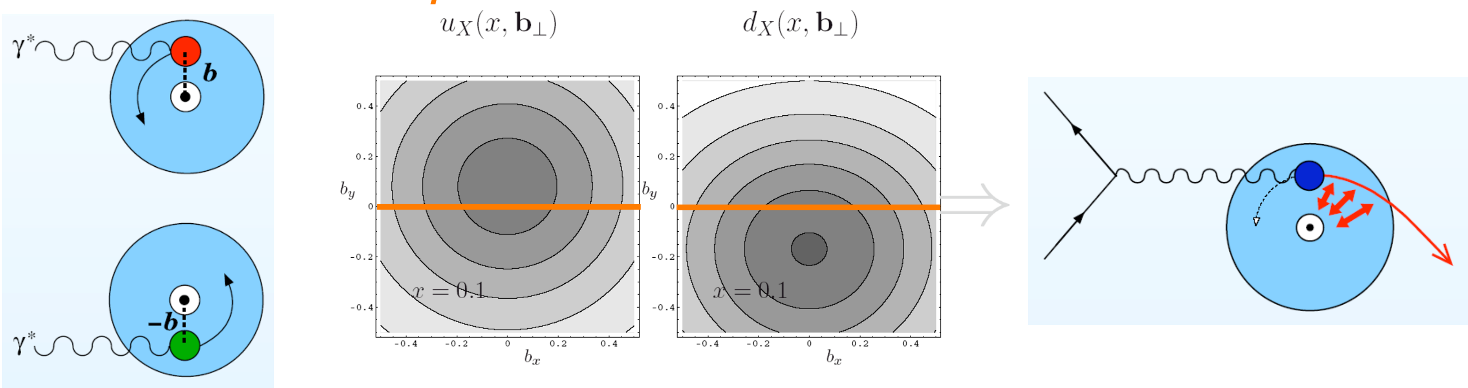
- ***Collins FF*** **$H_1^{\perp}(z,k_T^2)$** correlates *transverse spin* of fragmenting quark and *transverse momentum* $P_{h\perp}$ of produced hadron h

  → *left-right asymmetry* in the direction of the outgoing hadron

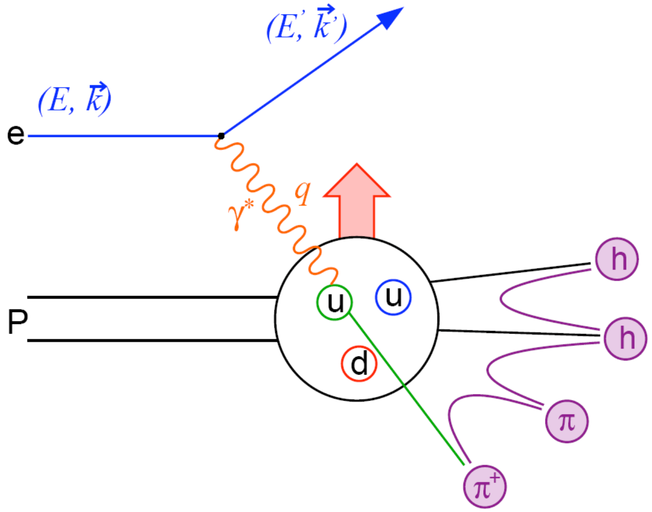


- other mechanism for azimuthal (single-spin) asymmetries:

  Sivers fct. : distribution of unpolarised quarks in a transversely polarised nucleon → describes *spin-orbit correlations*

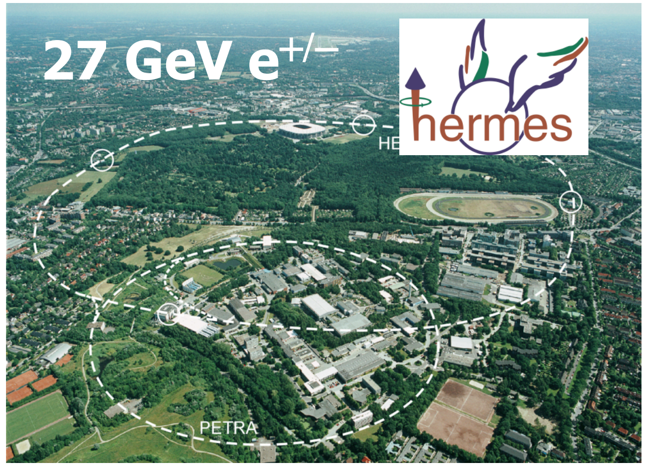


experimental prerequisites

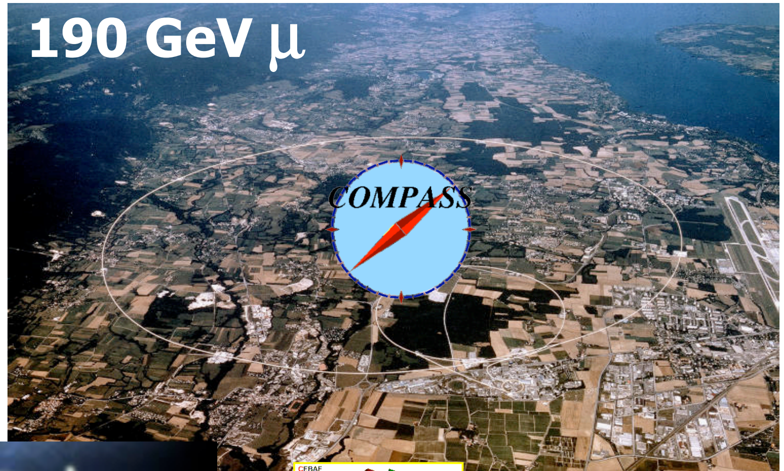


main players in the game:

A_{UL}, A_{LU}, A_{UT}
A_{LT}, $\cos 2\phi$



A_{UT}
A_{LT}, A_{UL}, A_{LU}, $\cos 2\phi$

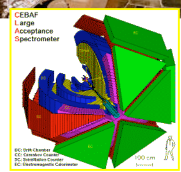


CLAS: A_{UL} , A_{LU} , $\cos 2\phi$
HallA: A_{UT}, A_{LT}

$\approx$6 GeV e^-

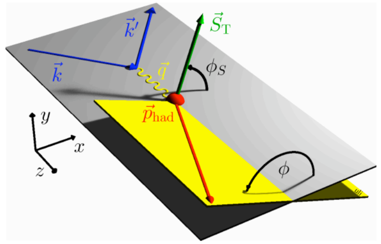
Jefferson Lab
Exploring the Nature of Matter

HALL A

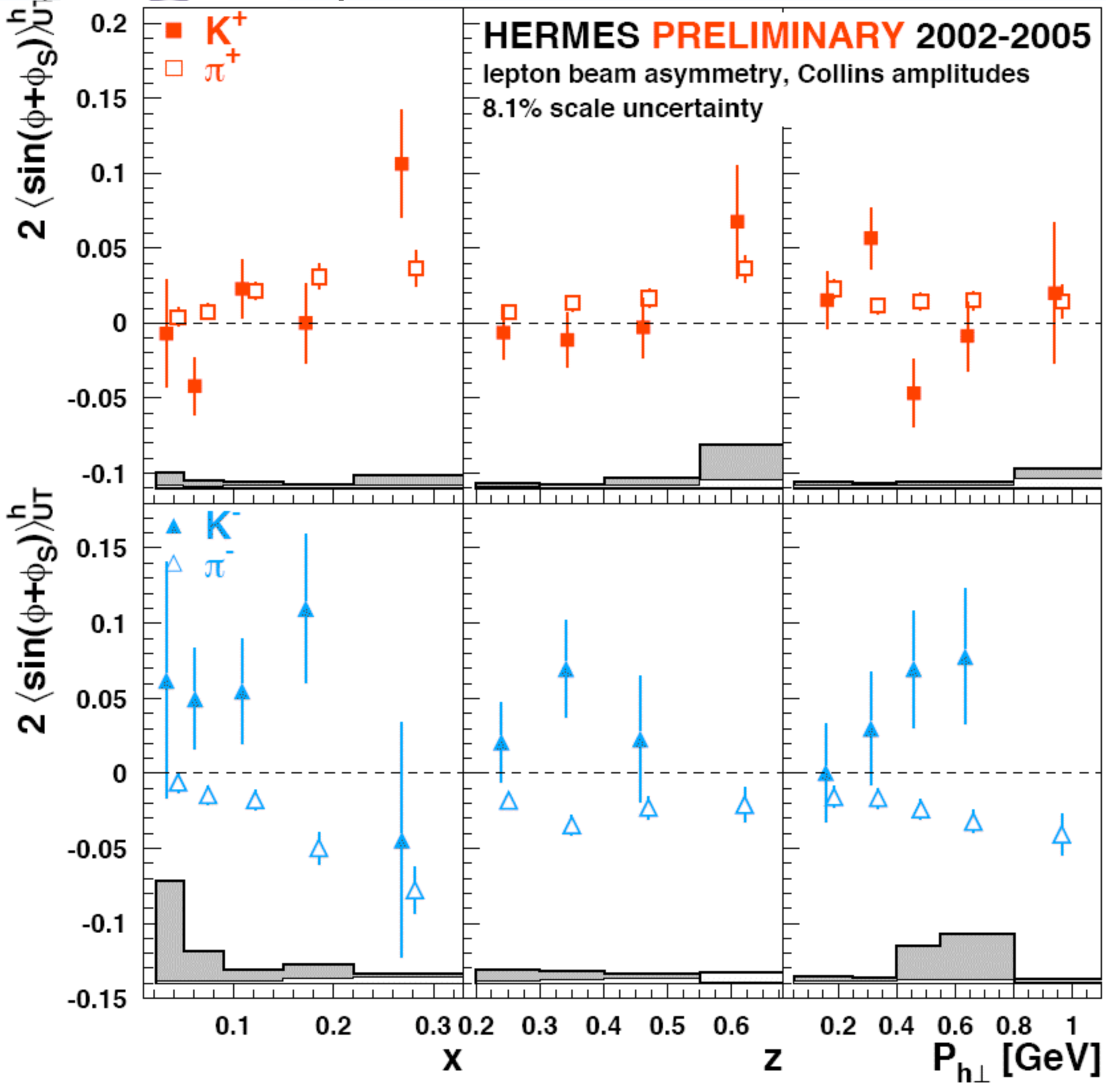


Collins asymmetries

[redacted]



hermes ep↑→ πX

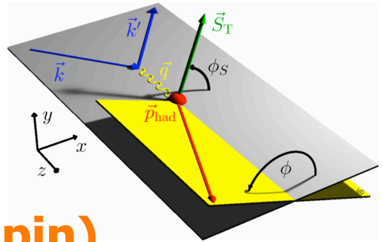


first time: *transversity* & *Collins FF* are **non-zero!**

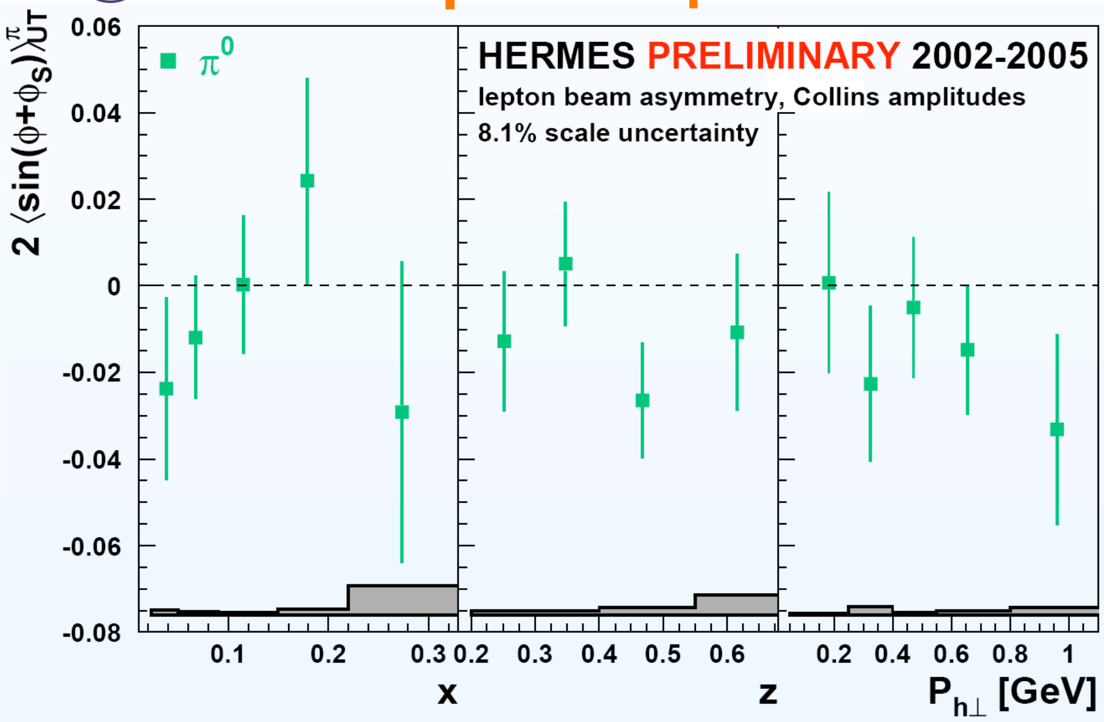
K^+ amplitudes consistent with π^+ amplitudes as expected from u-quark dominance

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

more Collins asymmetries



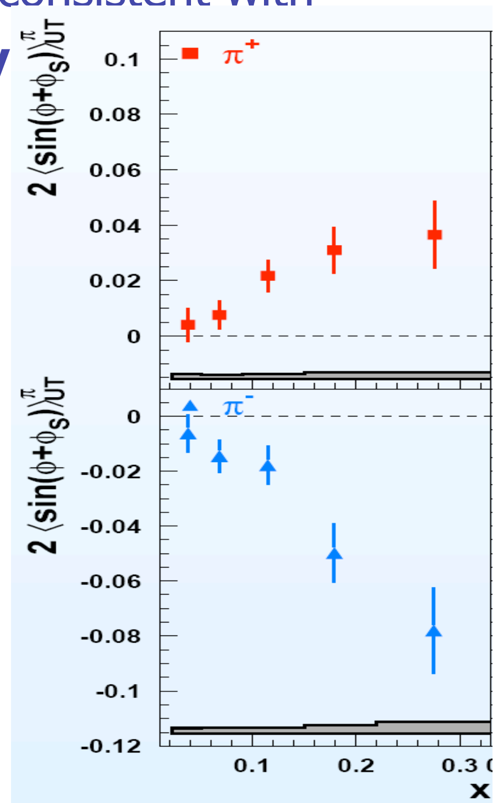
neutral pions: important 'control' asymmetry (isospin)



[redacted]

neutral pions:

results for the three pion charge states are consistent with **isospin sy**



- the isospin triplet of π-mesons is reflected in a relation for any SSA and DSA amplitudes in semi-inclusive DIS ($C = \sigma^{\pi^-}/\sigma^{\pi^+}$):

$$2\langle\sin(\phi\pm\phi_S)\rangle_{UT}^{\pi^+} + C\cdot 2\langle\sin(\phi\pm\phi_S)\rangle_{UT}^{\pi^-} - (1+C)\cdot 2\langle\sin(\phi\pm\phi_S)\rangle_{UT}^{\pi^0} = 0$$

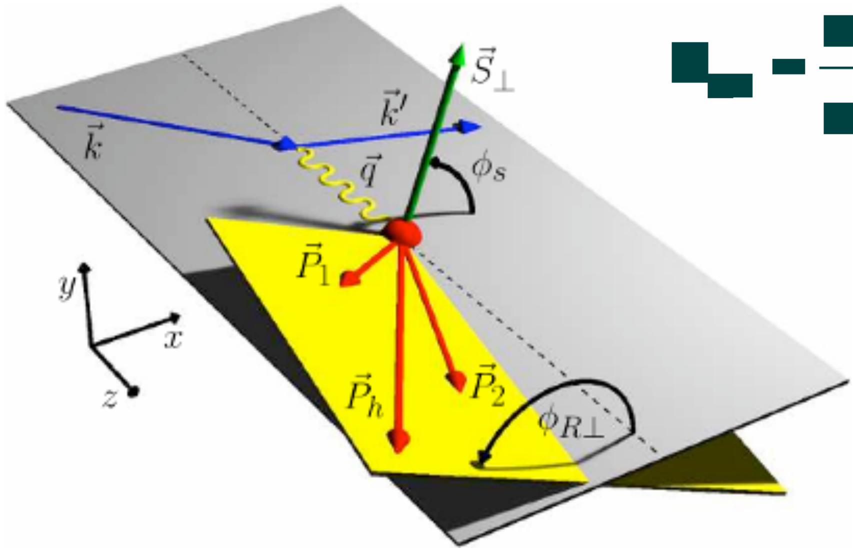
assuming isospin symmetry of the Collins fragmentation function

alternative probe for transversity:

2-hadrons

[redacted]

2-hadron asymmetries



[illegible]

[illegible]

interference fragmentation function
between pions in s-wave and p-wave

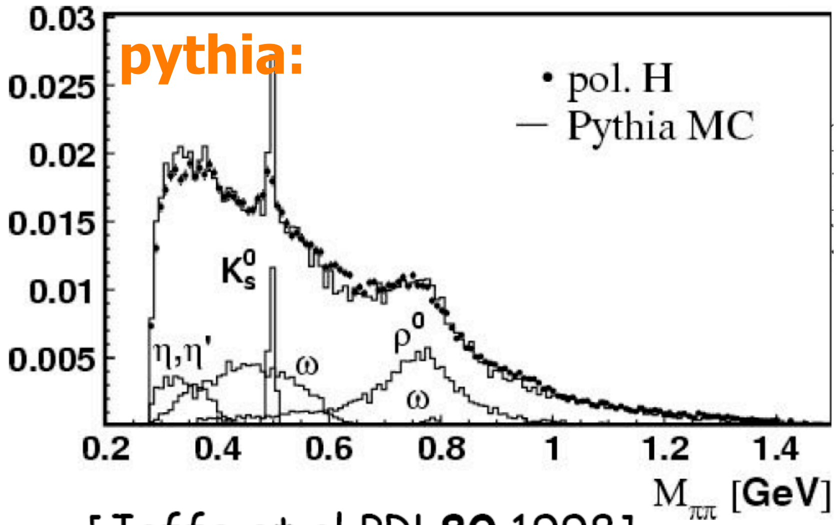
☺ advantages:

- *direct product* of transversity and fragmentation function (no convolution)
- easier to calculate Q^2 evolution

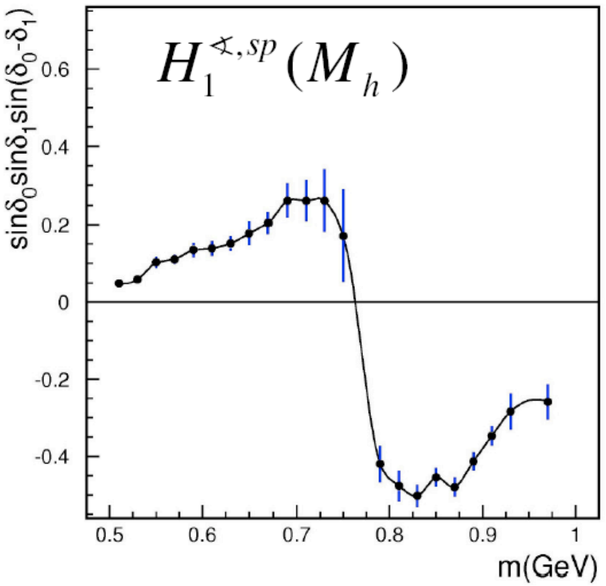
☹ disadvantages:

- less statistics
- cross section dependents on 9 variables → sensitive to detector acceptance effects

models for 2-hadron asymmetries

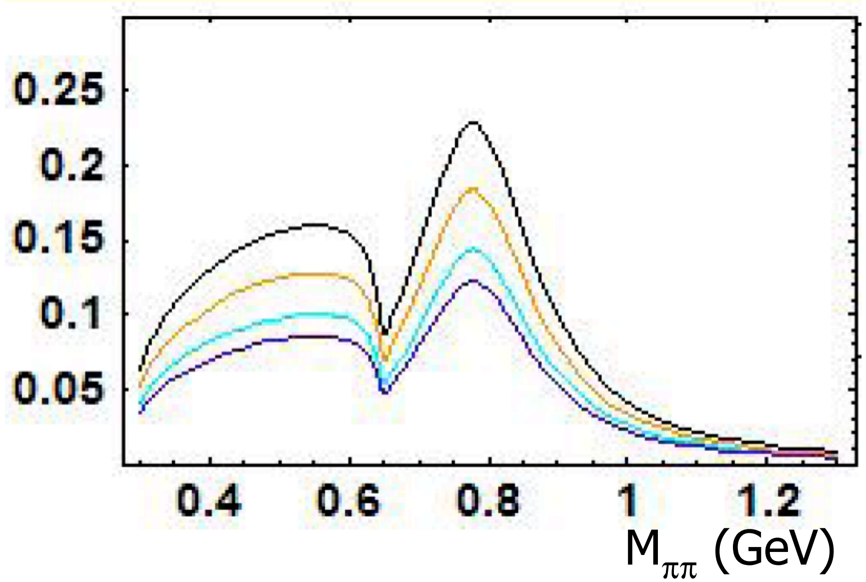


[Jaffe et al,PRL**80**,1998]

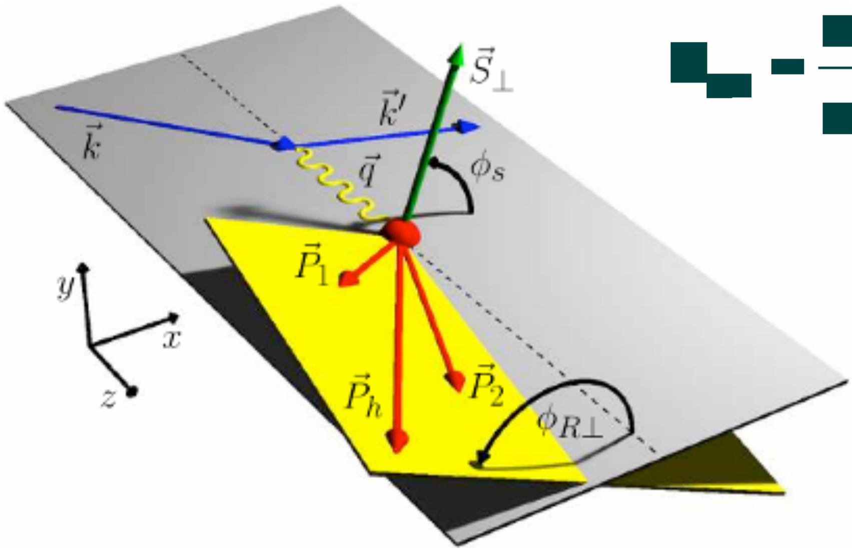


→model calculation for $H_1^{<|q}(z)$ combined with various models for $\delta q(x)$

[Bacchetta, Radici PRD74(2006)]

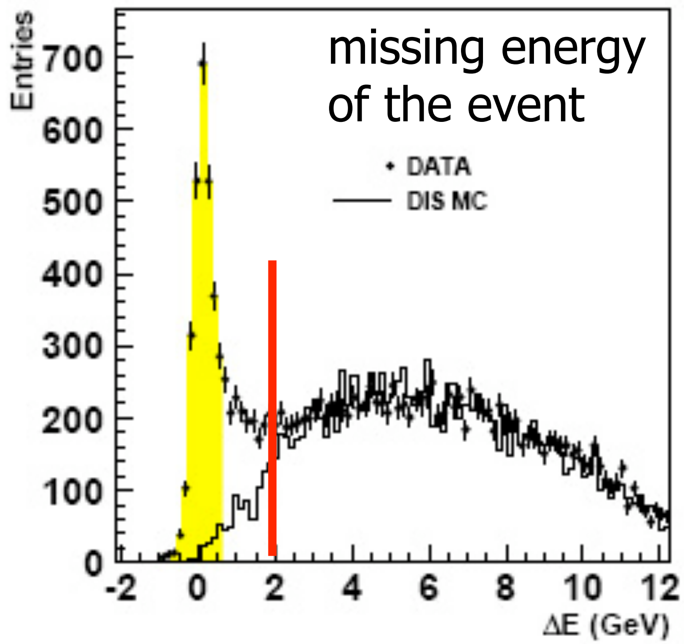


2-hadron asymmetries



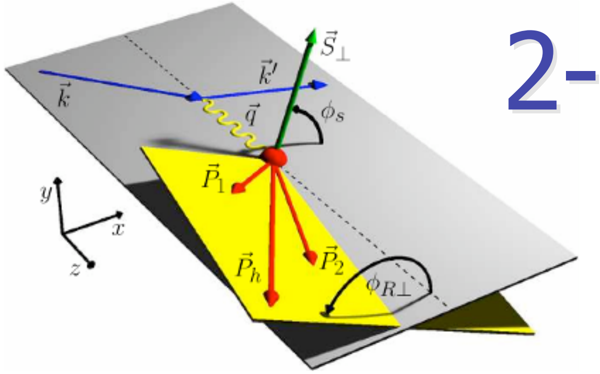
interference fragmentation function between pions in s-wave and p-wave

- more than 2 hadrons → all combinations
- exclusive ρ^0 excluded

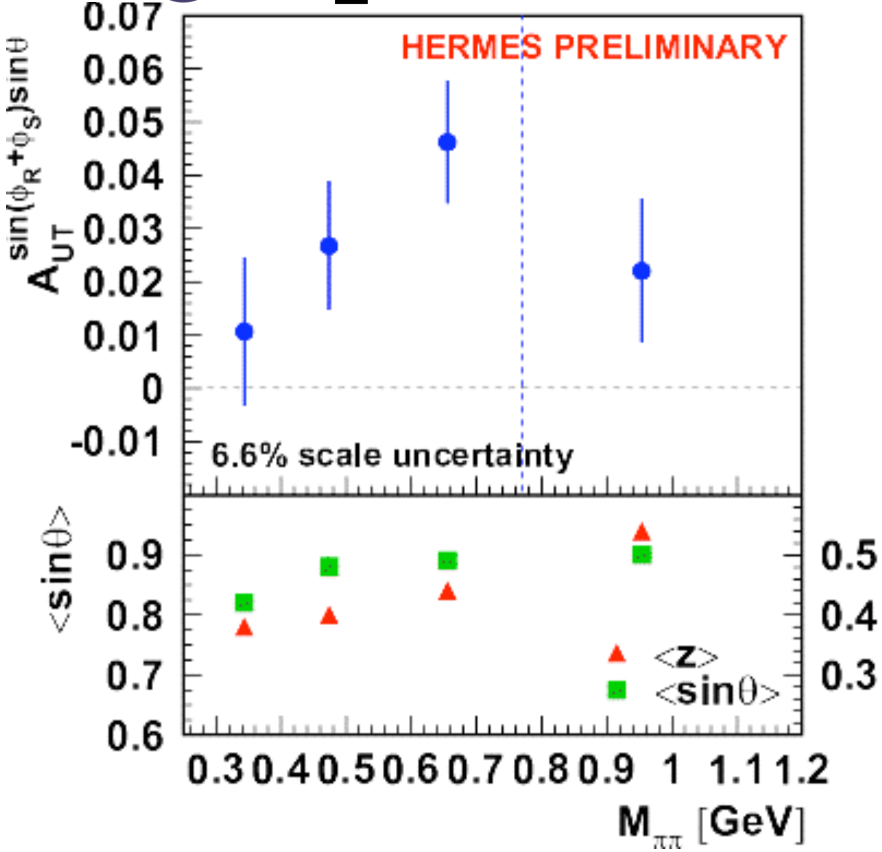


2-hadron asymmetries

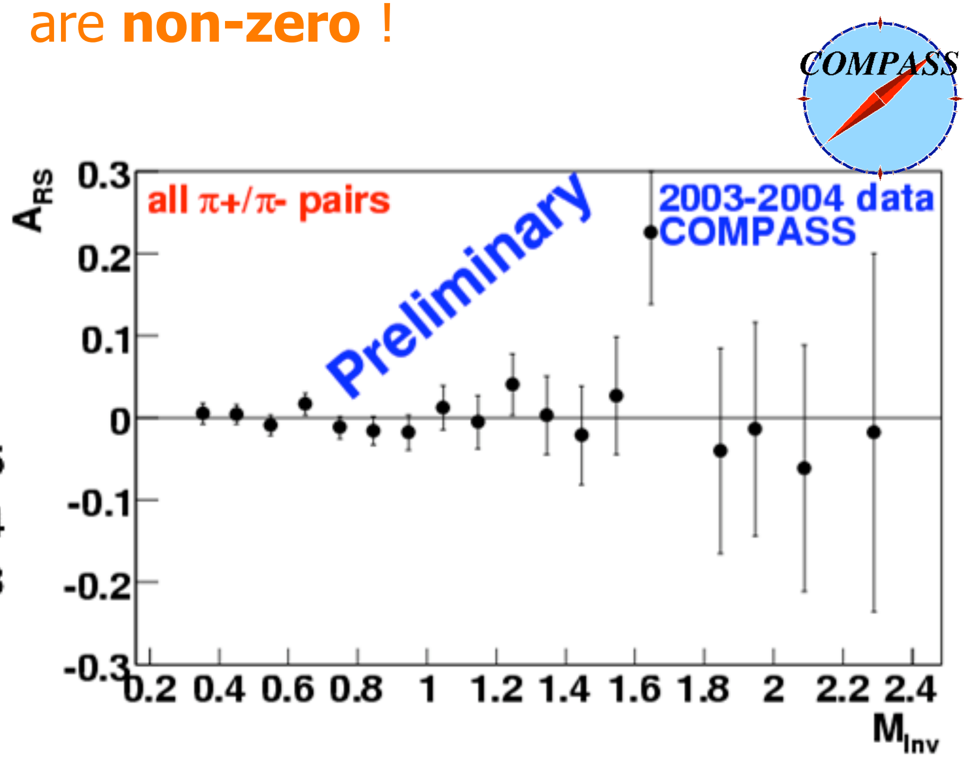
[redacted]



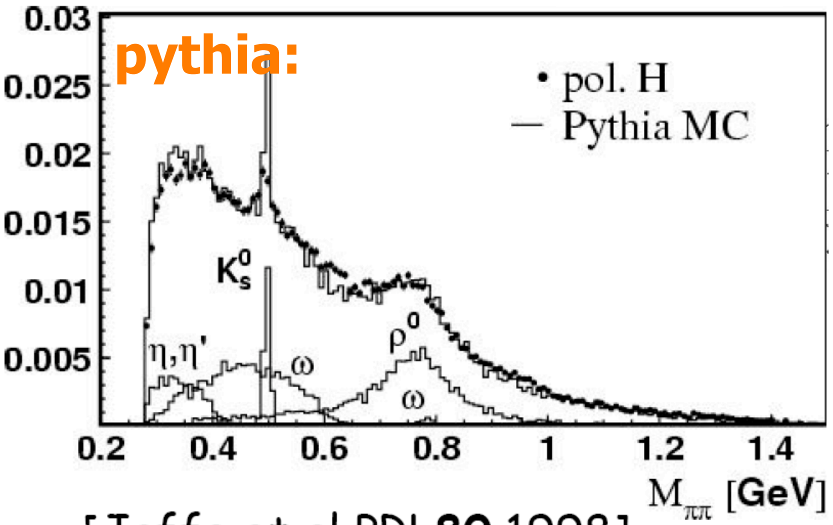
hermes [redacted]

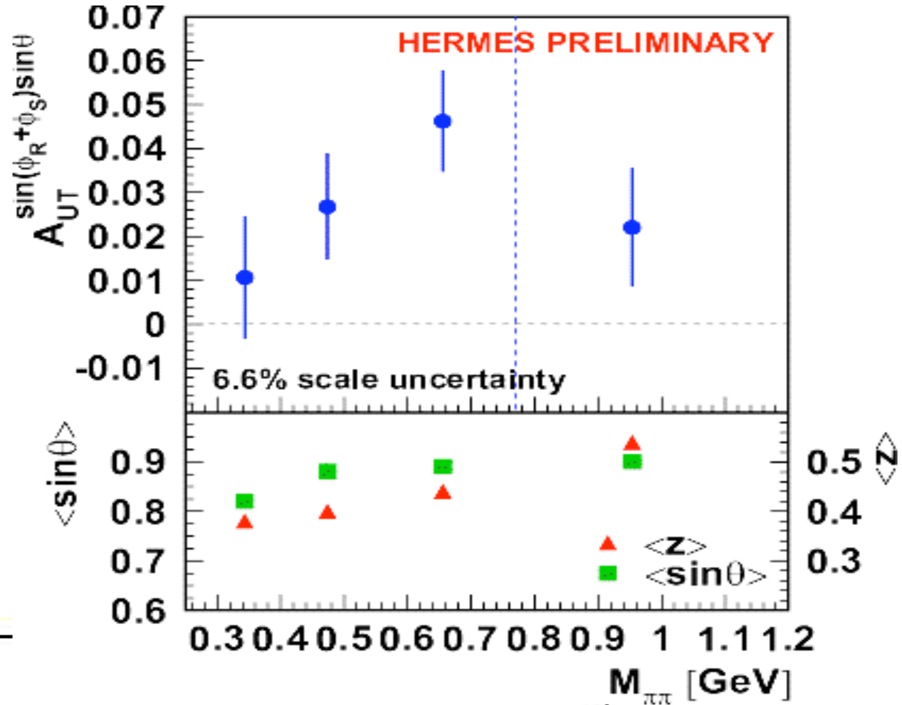


- BOTH: *transversity* and *interference fragmention function* are **non-zero** !

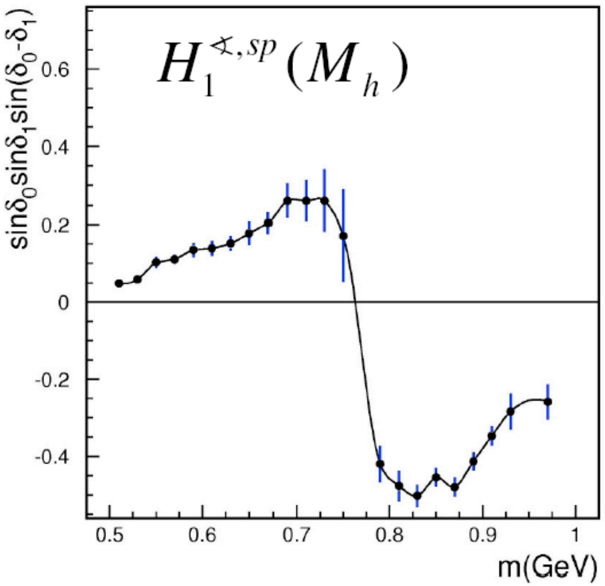


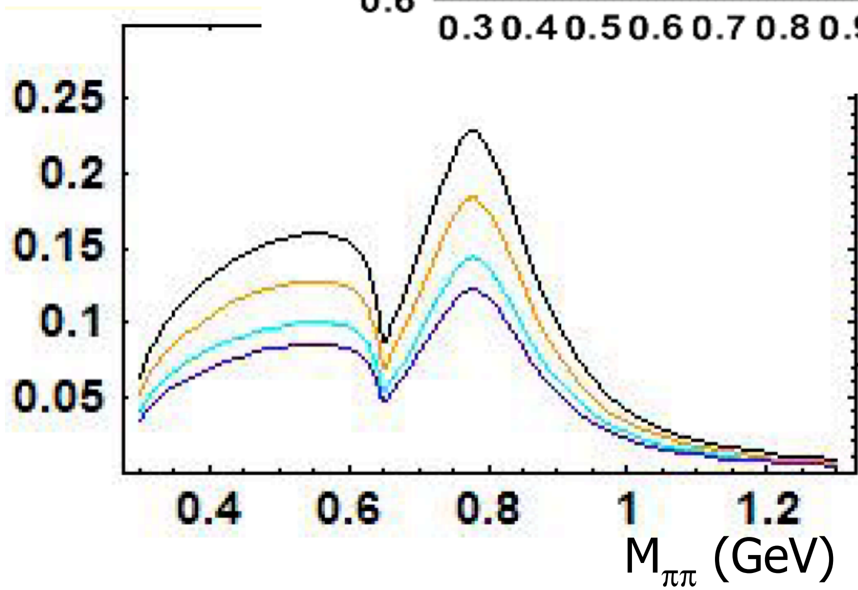
models for 2-hadron asymmetries





[Jaffe et al,PRL**80**,1998]





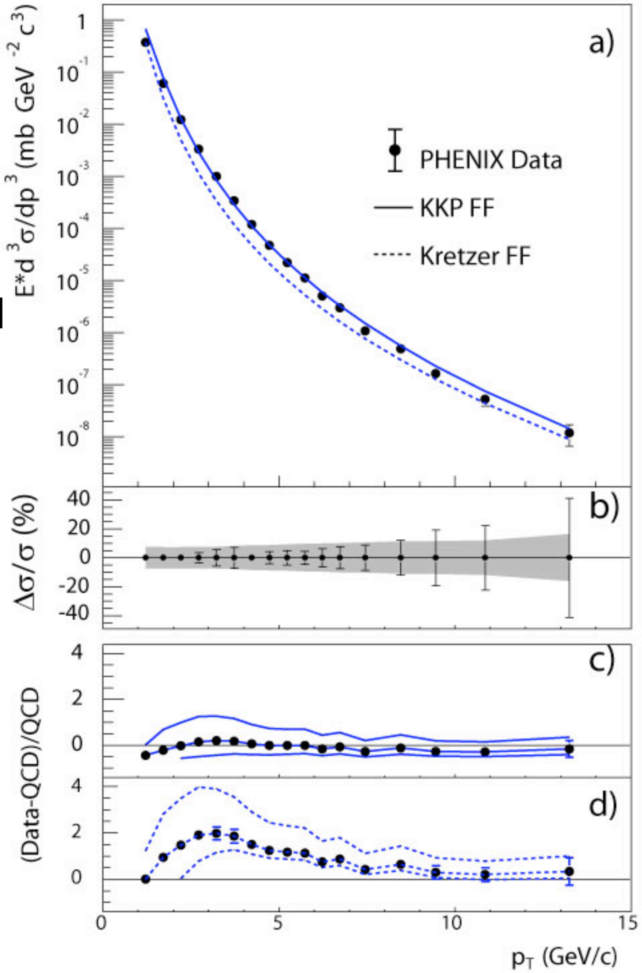
template

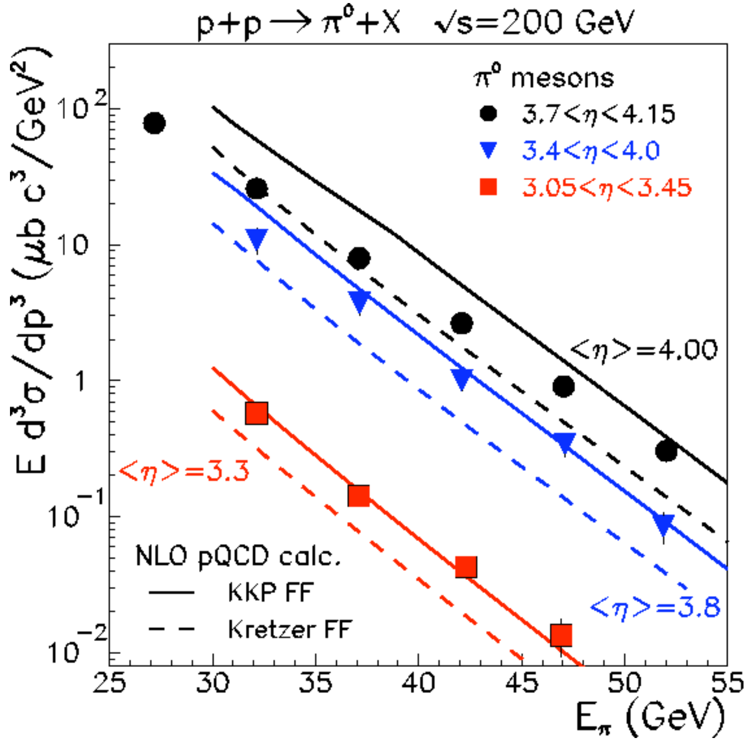
Hermes multiplicities ->FF (see andy’s talk)!

Does pQCD describe particle production at RHIC?

Compare cross sections measured for $p+p \rightarrow \pi^0 + X$ at $\sqrt{s}$=200 GeV to next-to-leading order pQCD calculations

S.S. Adler *et al.* (PHENIX), PRL **91** (2003) 241803





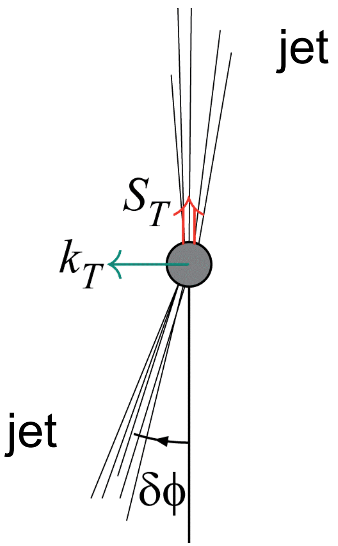
J. Adams *et al.* (STAR), PRL **92** (2004) 171801; and PRL **97** (2006) 152302

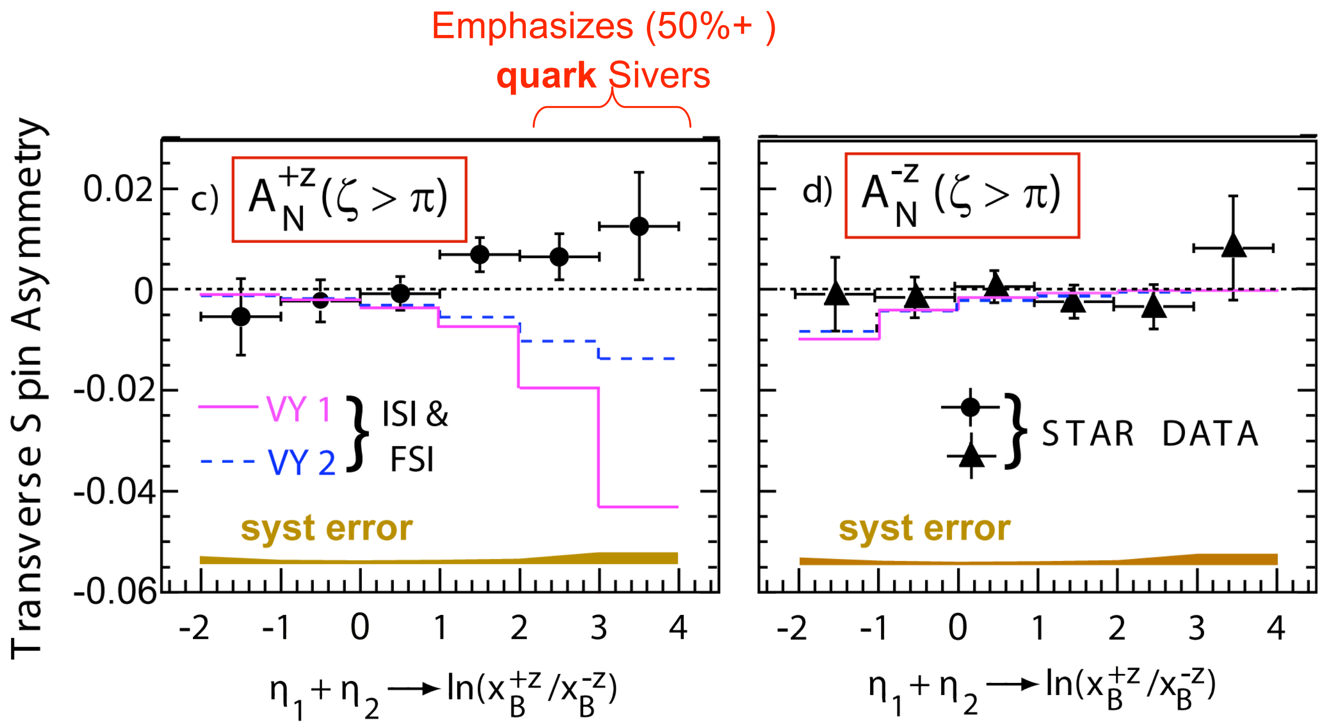
Cross sections agree with NLO pQCD down to p_T~2 GeV/c over a wide range, $0 < \eta < 3.8$, of pseudorapidity ($\eta = -\ln \tan \theta/2$) at $\sqrt{s}$ = 200 GeV.

STAR Results vs. Di-Jet Pseudorapidity Sum

Run-6 Result → measuring the Sivers function

VY 1, VY 2 are calculations by
Vogelsang & Yuan, PRD **72** (2005) 054028





A_N consistent with zero

⇒~order of magnitude smaller in pp → di-jets than in semi-inclusive DIS quark Sivers asymmetry!

STAR

arXiv:0705.4629v1,
submitted to PRL

Transverse spin program at RHIC is luminosity limited

Physics channel	Luminosity?
A_N	very good
A_N(back-to-back)	good
A_T (Collins FF)	limited
A_T (Interference FF)	limited
A_{TT} (Jets)	not studied
A_T (Drell Yan)	---
A_{TT}(Drell Yan)	---

RHIC by 2009 at 200 GeV

$\int L dt \sim 275 pb^{-1}$ delivered

$\int L dt \sim 100 pb^{-1}$ accepted (eg. PHENIX: vertex cut, trigger efficiencies, duty factor)

➔ $\int L dt \sim 25\ pb^{-1}$ transverse

Transverse Spin Physics at RHIC with Large ∫Ldt

Transversity : correlation between transverse proton spin and quark spin

$$A_{TT} \propto \delta q(x_1)\delta q(x_2)$$

Collins and Interference FF
∫Ldt > 30 pb^{-1}

Sivers : correlation between transverse proton spin and quark transverse momentum

$$A_T \propto q(x_1) \cdot \bar{f}_{1T}^{\perp q}(x_2, k_\perp^2) \cdot \frac{(\vec{P} \times \vec{k}_T) \cdot \vec{S}_P}{M}$$

A_T in Drell Yan
∫Ldt ~ 250 pb^{-1}

Boer/Mulders: correlation between transverse quark spin and quark transverse momentum

$$N(\phi) \propto h_1^{\perp q}(x_1, k_\perp^2) \cdot \frac{(\vec{P} \times \vec{k}_\perp) \cdot \vec{S}_q}{M} \cdot h_1^{\perp \bar{q}}(x_2, \bar{k}_\perp^2) \cdot \frac{(\vec{P} \times \vec{\bar{k}}_\perp) \cdot \vec{S}_{\bar{q}}}{M}$$

A(ϕ_0) Drell Yan
?, not studied