The Transversity-Council of Trent, 2004

An attempt to summarize of a workshop "fantastico"!

My apologies in advance to the speakers whose ***superb*** talks and contributions I will be unable to cover

N.C.R. Makins, UIUC

High-Speed Progress in this Field!

My personal timeline of acquired jargon ...

1999: HERMES AUL data at DIS99

transversity

Collins function

2000

The Mulders Bible

= kT-dep & T-odd functions

2001: Zeuthen workshop

SSA history: E704,

hyperon polarization

2002: QCDN'02 Ferrara

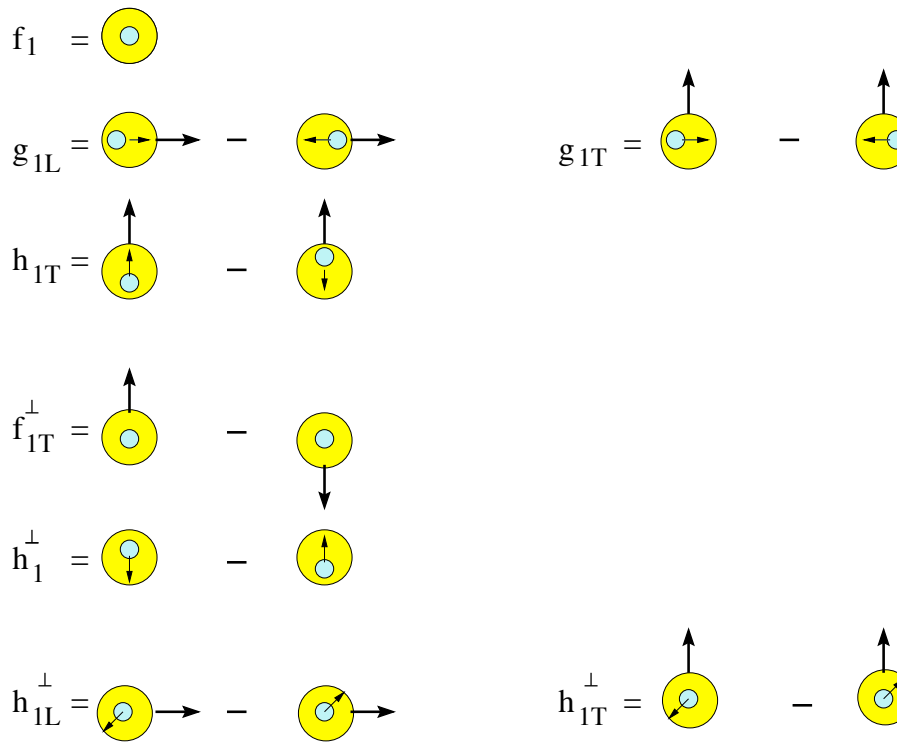
Sivers function

... which is **not** in DIS

2003: Urbana mini-workshop

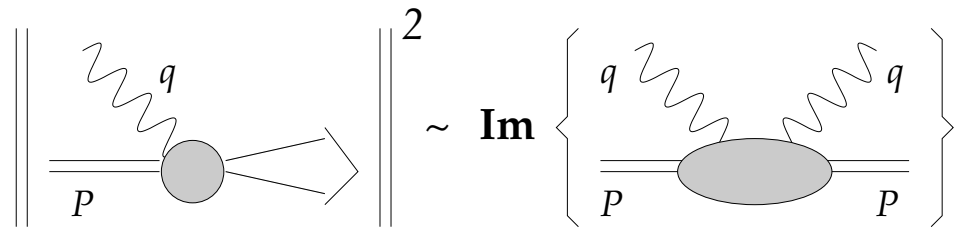
gauge links

... now Sivers function **is** in DIS !

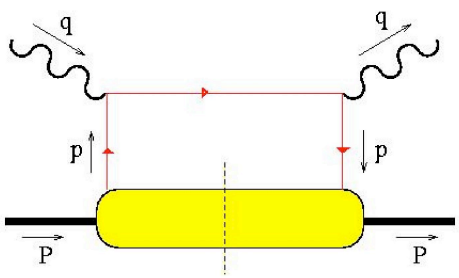


The Leading-Twist Sivers Function: Can it Exist in DIS?

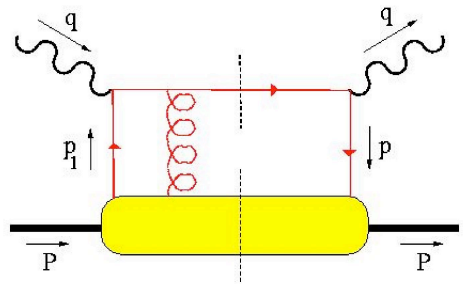
A T-odd function like $f_{1T}^{\perp}$ ***must*** arise from ***interference*** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?



Brodsky, Hwang, & Schmidt 2002



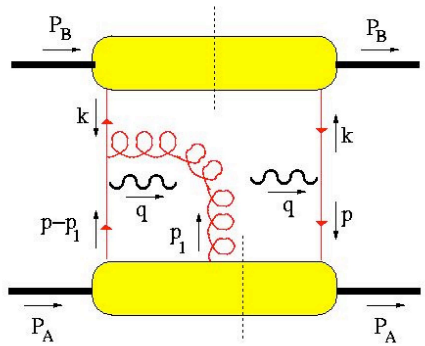
can interfere with



and produce a T-odd effect! (also need $L_z \neq 0$)

It looks like higher-twist ... but no , these are soft gluons = "gauge links" required for color gauge invariance

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



e.g. Drell-Yan

Trento 2004: New data!

(sorry, only hall with a logo!)

- **Universality** questions: are the new kT-dependent functions *process-dependent* or not?
- The **new data**: do we have a *qualitative* understanding?
- **Modelling**: toward a *quantitative* understanding
- Other avenues: **GPD's and Lattice QCD**

Universality Questions

Are the kT-dependent distribution and fragmentation functions process-dependent?

✔ 2003: **kT-weighted moments** of the **distribution functions** are universal to within a sign: e.g. $f_{1T}^{\perp(1)}\Big|_{DIS} = -\,f_{1T}^{\perp(1)}\Big|_{DY}$

⇒ depends on spacelike vs timelike probe

❶ Is the **kT-dependence** of these DF's also universal?

❷ What about the kT-dependent **fragmentation** functions?

❸ Can the universality relations be extended from the big 3 processes (e+e-, DIS, Drell-Yan) to more complex processes, e.g. "**E704 effect**"?

Universality, with k_T-dependence pdfs, etc

- Precise gauge invariant defn. of pdf and frag fn. needs Wilson lines

$$\text{Pdf} = \text{FT of } \langle p,s|\ \overline{\psi}(y)\, W(y \text{ to } \infty)^\dagger\ \Gamma\ W(0 \text{ to } \infty)\, \psi(0)\ |p,s\rangle$$

- Sivers function is coefficient of $\mathbf{s}_T \wedge \mathbf{k}_T$
- Time-reversal argument (insert $1 = AA^\dagger$ factors, with $A = TP$)

$$\begin{aligned}\text{Pdf} &= \text{FT of } \langle p,-s|\ \overline{\psi}(-y)\, W(-y \text{ to } -\infty)^\dagger\ \Gamma\ W(0 \text{ to } -\infty)\, \psi(0)\ |p,-s\rangle^* \\ &= \text{FT of } \langle p,-s|\ \overline{\psi}(0)\, W(0 \text{ to } -\infty)^\dagger\ W(-y \text{ to } -\infty)\, \psi(-y)\ |p,-s\rangle\end{aligned}$$

- $\Longrightarrow$ Without Wilson line: Sivers $=-$ Sivers
- But with Wilson lines (QCD)

> Sivers, WL to future $=-$Sivers, WL to past

A theorem of rare elegance in this complex field!

Universality Answers at Trento04!

❶ Is the **kT-dependence** of these DF's also universal (to within a sign)?

✔ ***YES! (J. Collins, D. Sivers)***

❷ What about the kT-dependent **fragmentation functions**?

✔ ***YES! (A. Metz)***

- More complex problem than for the distribution functions, but fortunate cancellations give the same e.g. Collins fragmentation function in DIS and e+e- annihilation ... and without a sign change
- Expect that this can be shown to all orders in pQCD

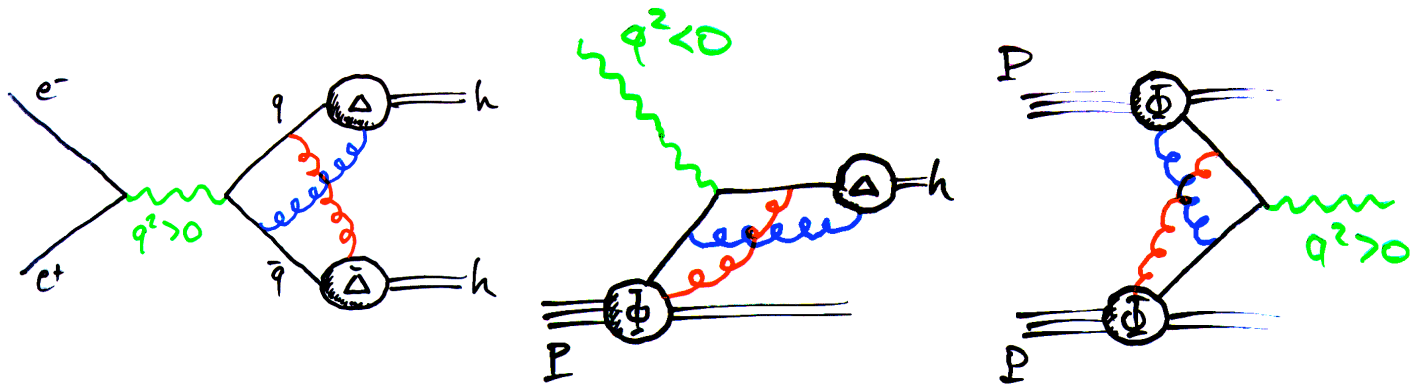
❸ Can the universality relations be extended from the big 3 processes (e+e-, DIS, Drell-Yan) to more complex processes, e.g. "**E704 effect**"?

✘ ***Probably, but not yet proved ... (A. Metz, J. Collins, P. Mulders)***

Universality of k_T-dependent Functions

These proceses have similar gauge-link topology:

e^+e^- Annihilation **SIDIS** **Drell-Yan**



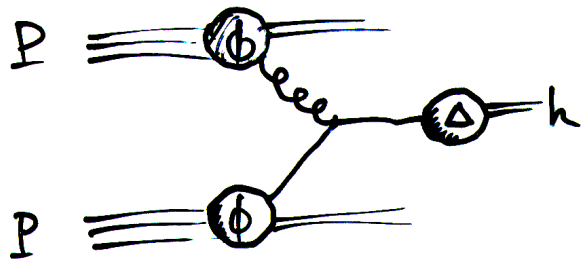
Expectation: T-odd functions will change sign between spacelike (SIDIS) and time-like (e^+e^- and DY) processes

BELLE e^+e^- Experiment

M. Grosse-Perdekamp

- Analysis of ***Collins function*** from high-statistics BELLE data in progress!
- Critical for providing ***normalization point*** for SIDIS and pp data $\sim h_1\, H_1^\perp$

Universality of E704 / RHIC $p^\uparrow p \to \pi X$ not yet clear ...



3 "soft blobs" ... gauge-link topology more complex

A. Kotzinian, M. Anselmino

Are these the same Sivers/Collins functions as in DIS ... ?

SSA

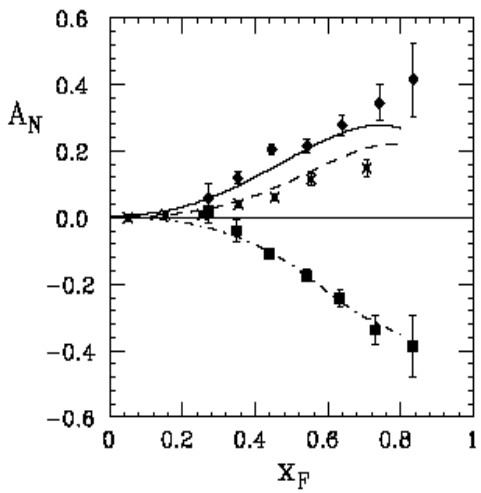
$$p^{\uparrow} + p \to \pi + X$$

Idea: consider spacelike/timelike nature of individual subprocesses in pp → πX ... work ongoing

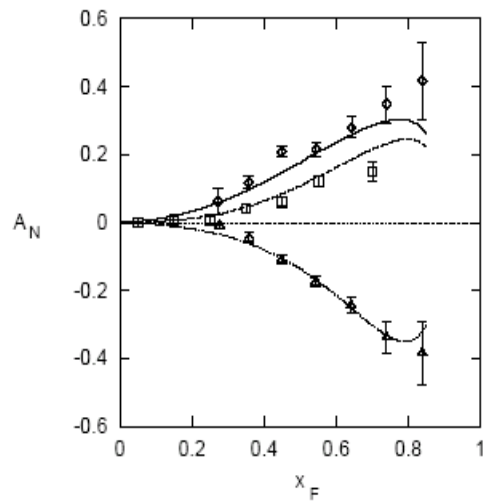
Analyzing power: $$A_N \equiv \frac{d\sigma^{\uparrow}(\boldsymbol{p}_T) - d\sigma^{\downarrow}(\boldsymbol{p}_T)}{d\sigma^{\uparrow}(\boldsymbol{p}_T) + d\sigma^{\downarrow}(\boldsymbol{p}_T)}$$

Analysis by Anselmino *et al,* E704

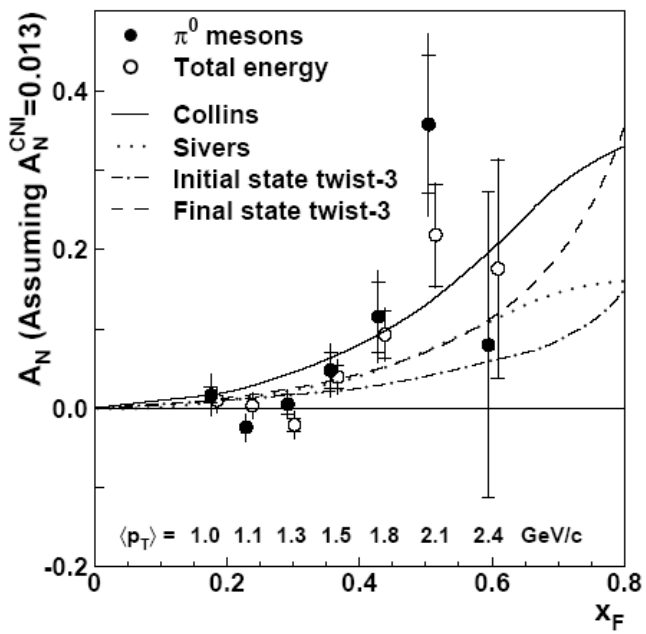
Only Sivers effect



Only Collins effect



STAR



The New Data

❶ **A_{UT} Sivers** moments from HERMES

➡ isolate Sivers distribution function

❷ **A_{UT} Collins** moments from HERMES & COMPASS

➡ isolate transversity & Collins fragmentation function

❸ **"E704 effect"** at forward- and mid-rapidity from STAR & PHENIX

➡ sensitive to transversity, Collins, & Sivers at very-hard scales

❹ **A_{LU}** from CLAS

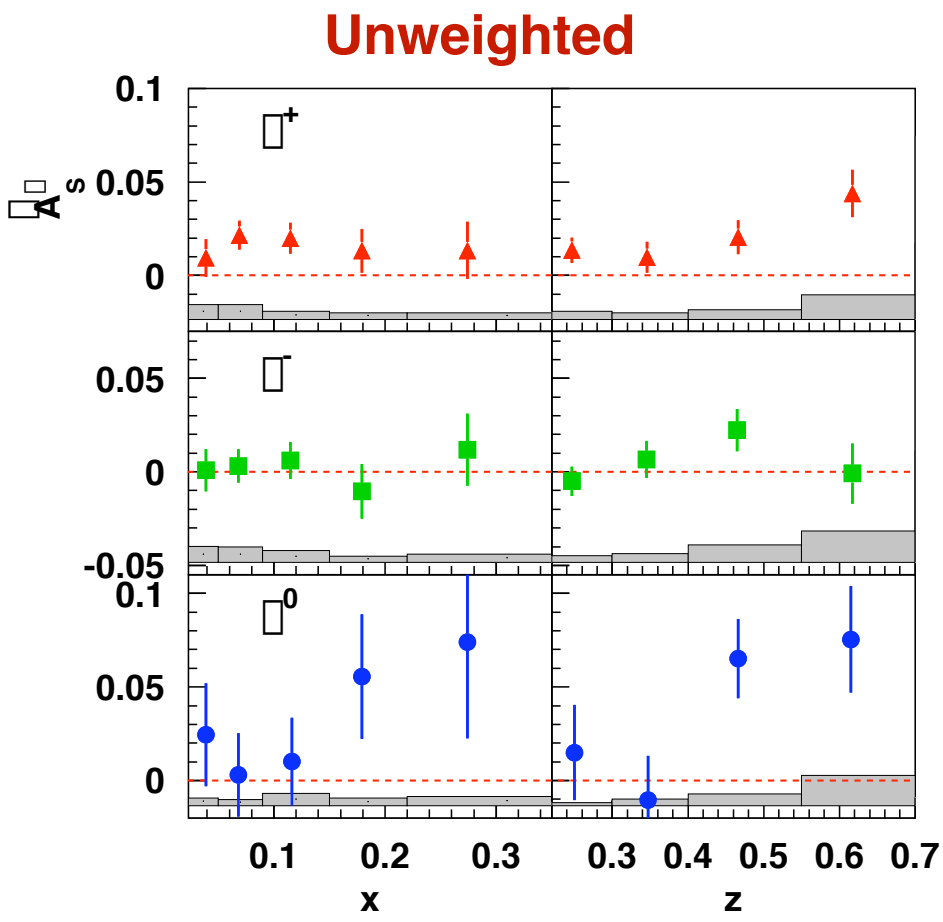
➡ new higher-twist functions

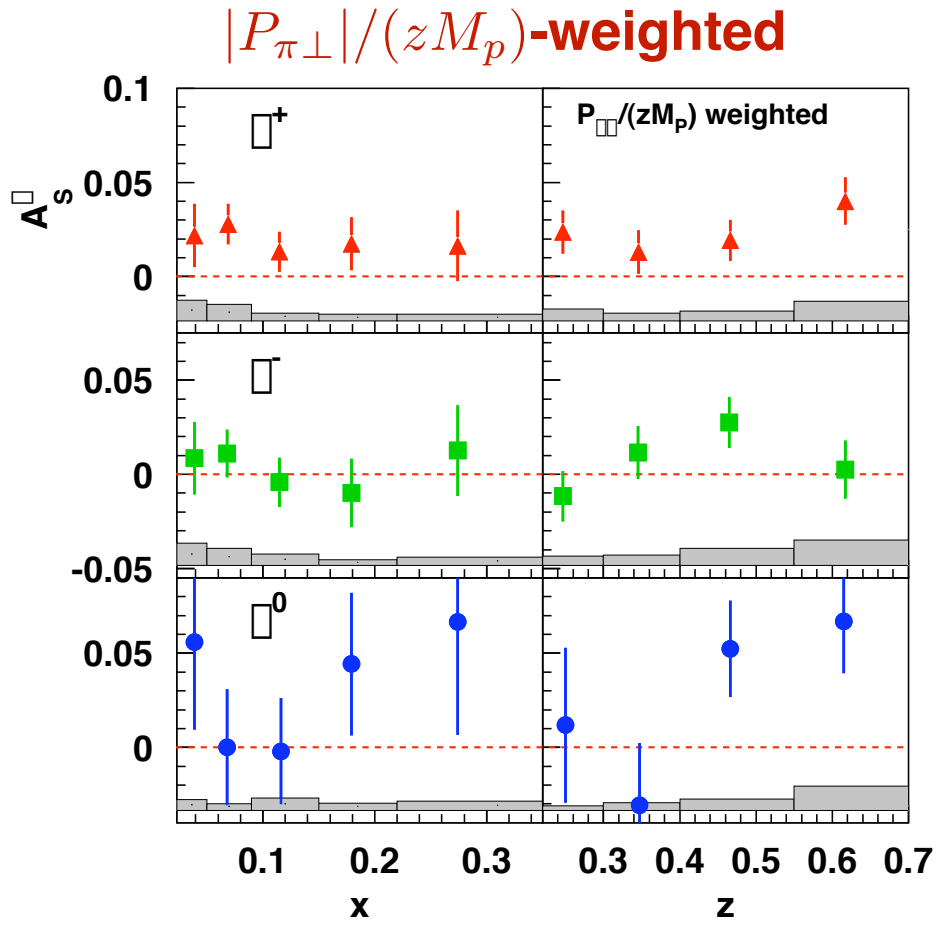
❺ **Interference Fragmentation Function** from HERMES

➡ first glimpse of a promising transversity-avenue at RHIC

A. Miller

The Sivers asymmetries

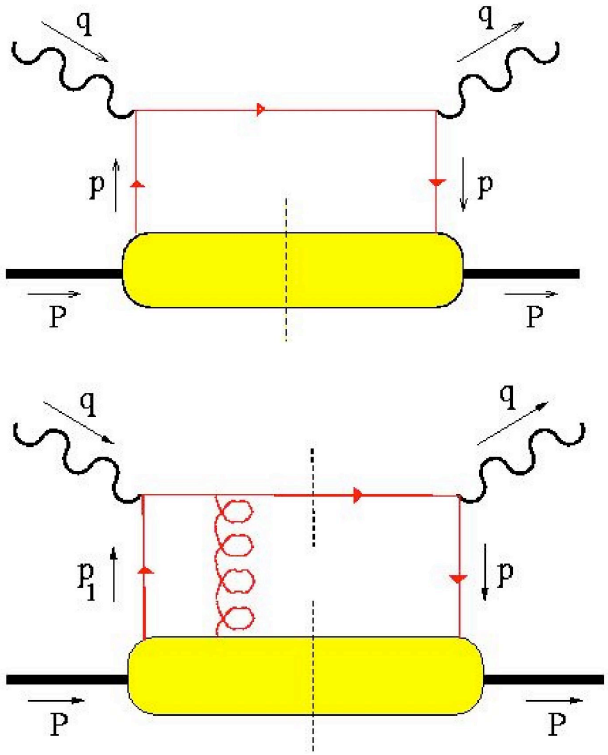




- **The π^+ Asymmetries appear to be positive and nonzero**
  (averaged: +4σ from 0)
- Little kinematic dependence is visible
- Little difference is seen between weighted and unweighted asymmetries

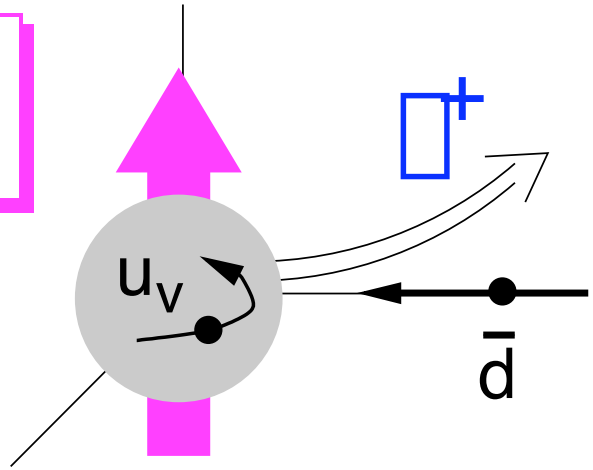
Understanding the Sivers Asymmetry

Rigorous Field Theory



"Cartoons"

Model of Meng, Chou, Yang



Forward π^+ produced from orbiting u_v quark by recombination at ***front surface*** of beam

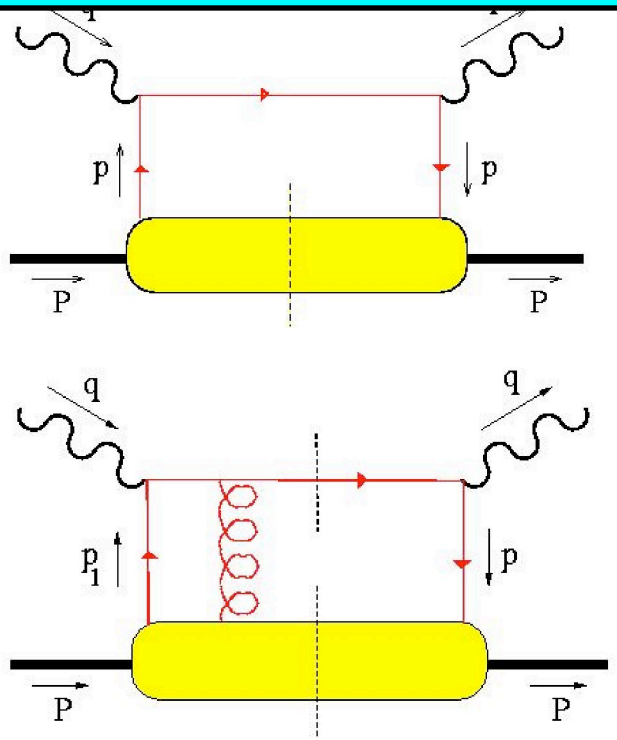
Requires:

- ***rescattering*** via gauge link
- interference between L=0 and L=1 states ⇒ ***orbital angular momentum*** needed

D. Sivers: this "***shadowing***" arises naturally from parton / jet energy loss as it traverses nucleon

Understanding the Sivers Asymmetry

Heisenberg Picture



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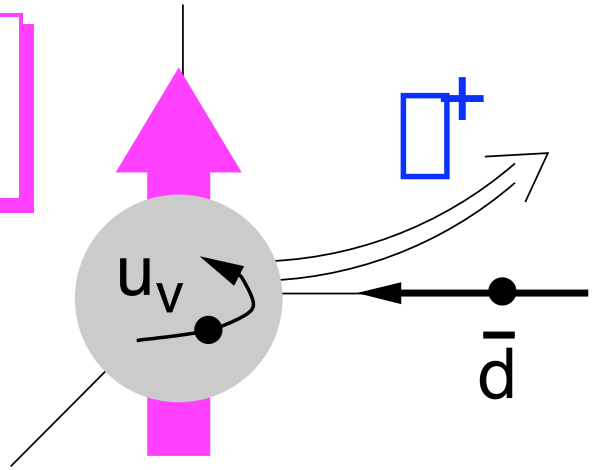
Schroedinger Picture

Model of Meng, Chou, Yang



Forward π^+ produced from orbiting u_v quark by recombination at ***front surface*** of beam

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So what is the sign of L?

My mangled-version of a lunch-time insight from M. Burkhardt

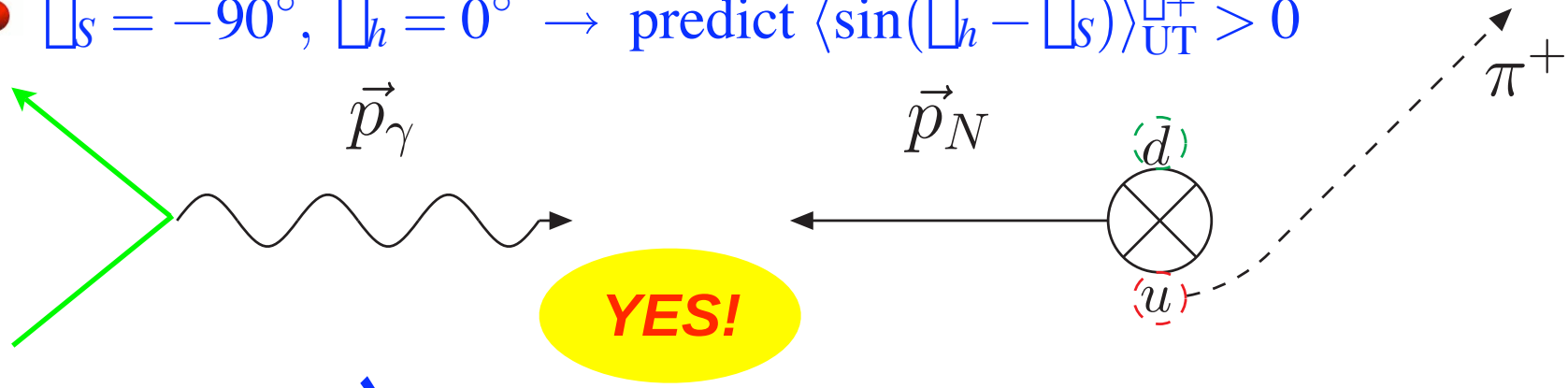
- Consitituent quark model (CQM) says Δu = +4/3, Δd = –1/3
- CQM does a great job of explaining the proton anomalous magnetic moment, via $\mu_p \sim \sum_q e_q/m_q \Box q$
- ... but we know that the quarks are not as highly polarized as in the CQM
- Missing piece must come from $\sum_q e_q L_q$ and must be positive
- Therefore L_u must be positive!

Numerous model calculations give $L_u > 0$ ***and*** $L_d < 0$
i.e. quark angular momentum shared between spin and L

Quark Correlations $\longleftrightarrow$ SSA

M. Burkhardt

- $\phi_S = -90°,\ \phi_h = 0° \ \rightarrow$ predict $\langle \sin(\phi_h - \phi_S) \rangle^{\uparrow +}_{\rm UT} > 0$



- u, d distrib[illegible] $\perp$ polarized proton have left-right asymmetry in $\perp$ positi[illegible]e (T-even!); sign determined by κ_u & κ_d
- attra[illegible]SI deflects active quark towards the center of m[illegible]um

Bellissima!

↪ [illegible]onverts [illegible] of leading quark i[illegible]o right-left

- compare: co[illegible] trically
- ↪ "chromodyna[illegible]
- naturally lea[illegible] L_q and sign of SSA

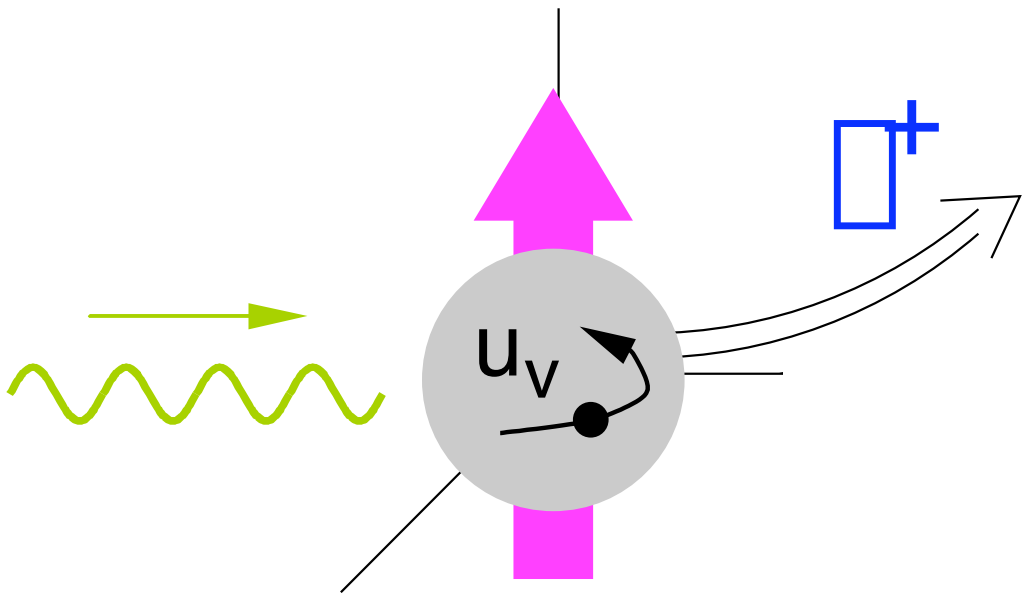
Rigorous derivation of our ***phenomenological picture*** of the Sivers function, and its connection to orbital angular momentum

What about "shadowing" mechanism?

D. Sivers

Parton energy loss considerations suggest quenching of jets from "near" surface of target

➡ quarks from "far" surface should dominate

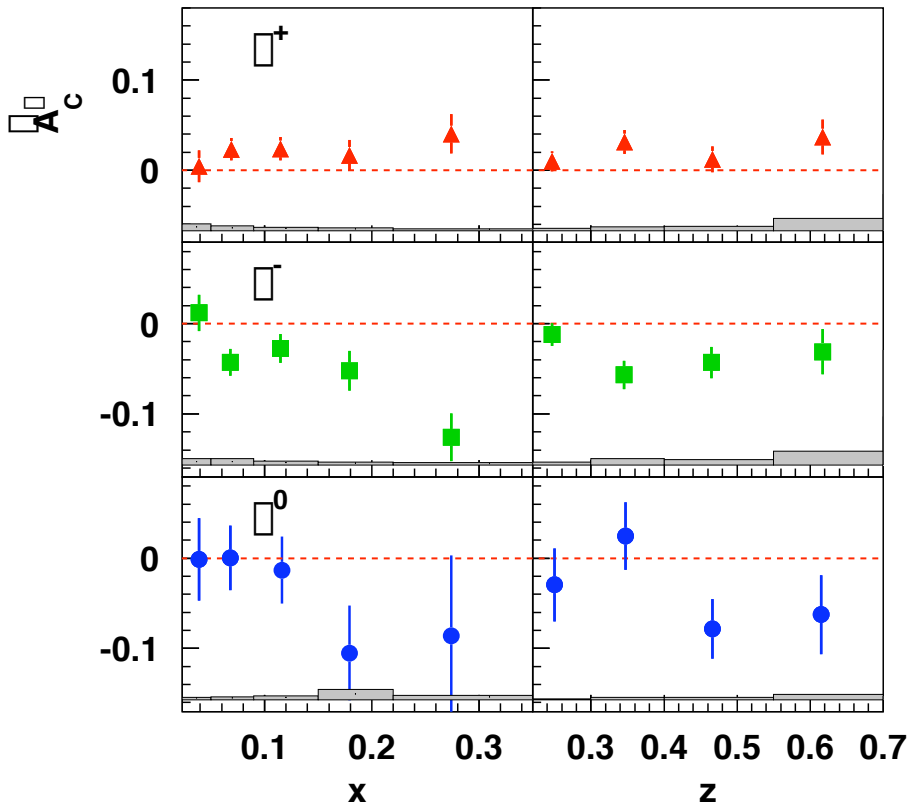


$$\phi_S = +90^\circ,\ \phi_h = 0^\circ \ \rightarrow\ \text{predict}\ \langle \sin(\phi_h - \phi_S) \rangle^{\pi^+}_{\text{UT}} < 0$$

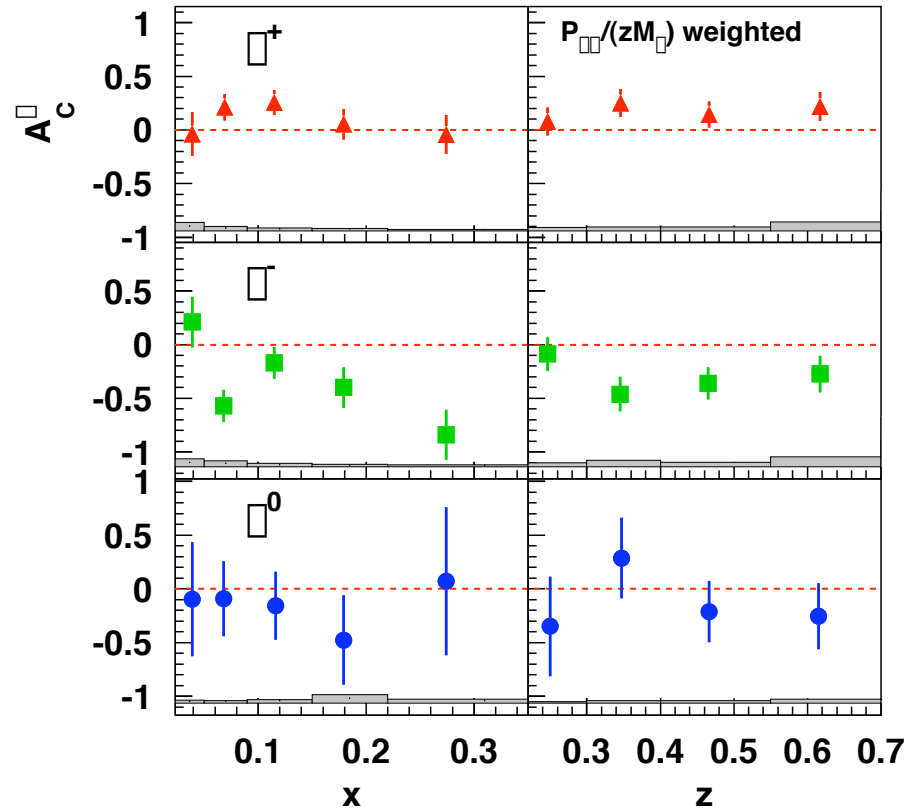
✗ Opposite sign to data ... hmm ...

The Collins virtual-photon asymmetries

Unweighted



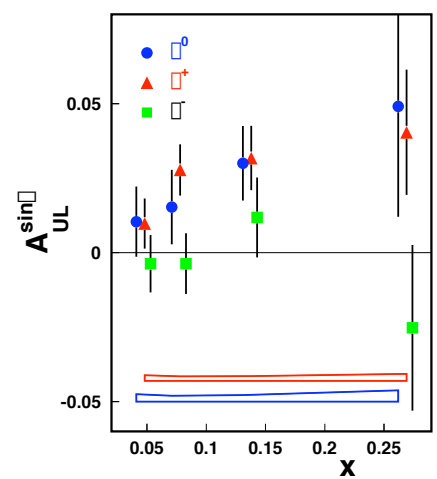
$|P_{\pi\perp}|/(zM_\pi)$-weighted



In view of up quark dominance of both π^+ and π^-, and existing longitudinal single-spin asymmetries $\Rightarrow\Rightarrow$

How can the negative π^- asymmetry be at least similar in magnitude to π^+?

Unweighted asymmetries depend little on z, contrary to expectations.

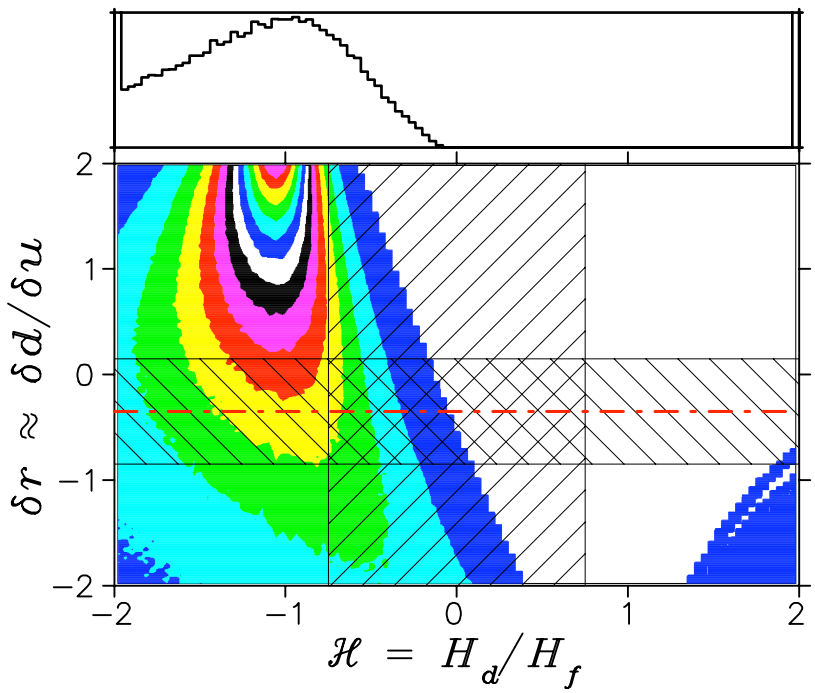


Plug in the acceptance-averaged data

- Have two constraints in three unknowns: δr, $\mathcal{H}$ and $\mathcal{K}$.
- Take ratios of equations:
  $\Rightarrow$ eliminate the "messy" unknown $\mathcal{K}$
- Relate these two unknowns:

$$\delta r \equiv \frac{\delta d + 4\delta\bar{u}}{\delta u + \frac{1}{4}\delta\bar{d}}$$

$$\mathcal{H} \equiv \frac{H_{dis}}{H_{fav}}$$



- Sample Gaussian distributions in three asymmetries, taking all combinations
  $\Rightarrow$ set of trajectories in δr versus $\mathcal{H}$.
- Plot density of trajectories: $\Rightarrow \Rightarrow$
- Hatched bands are arbitrary guesses of previously plausible ranges

- Horizontal red line is prediction of chiral quark soliton model:
  Wakamatsu, Phys. Lett. B509 (2001) 59; Schweitzer et al., *Phys. Rev. D 64 (2001) 034013*

The disfavoured Collins function is opposite in sign and probably substantial

Unfortunately, this relationship doesn't constrain transversity.

Plug in the acceptance-averaged data

- Have two constraints in three unknowns: δr, $\mathcal{H}$ and $\mathcal{K}$.
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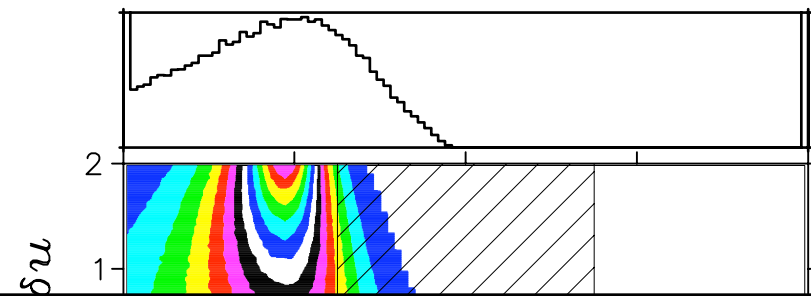
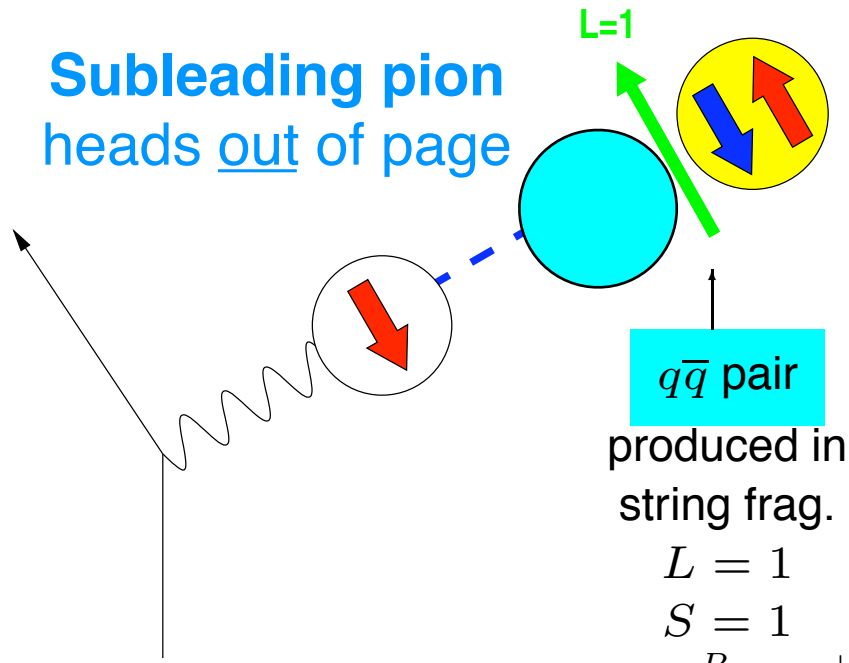


Artru model

based on Lund-string fragmentation picture



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previously plausible ranges

The disfavoured Collins function is opposite in sign and probably substantial

Unfortunately, this relationship doesn't constrain transversity.

Sign of the Collins Effect: does the Artru Model get it right?

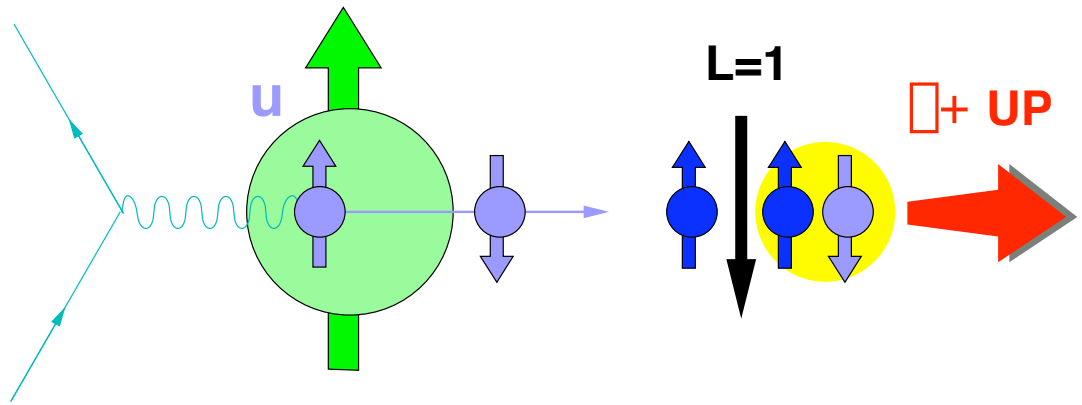
Observation: $\langle \sin(\phi_h^l + \phi_S^l) \rangle_{UT}^{\pi^+} > 0$ (and opposite for pi–)

Assuming that $h_1^u > 0$ ***and*** $h_1^d < 0$ ***...***

For $\phi_S^l = 0$

$\phi_h^l = \pi/2$ is preferred ...

✔



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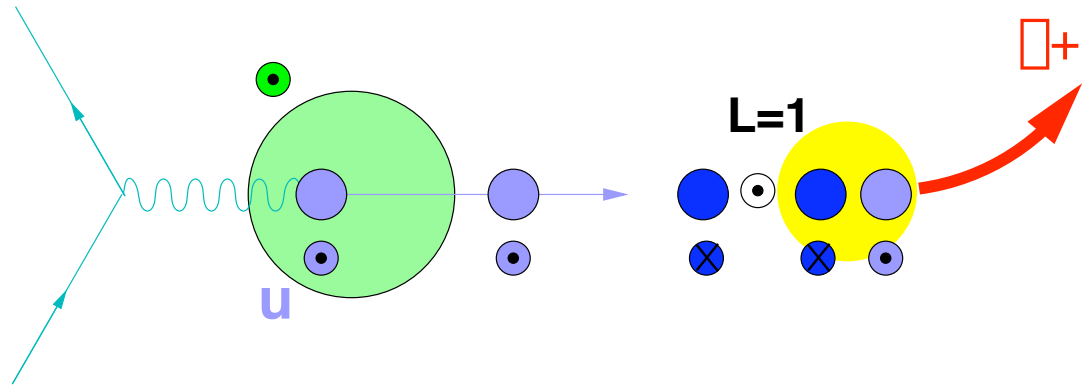
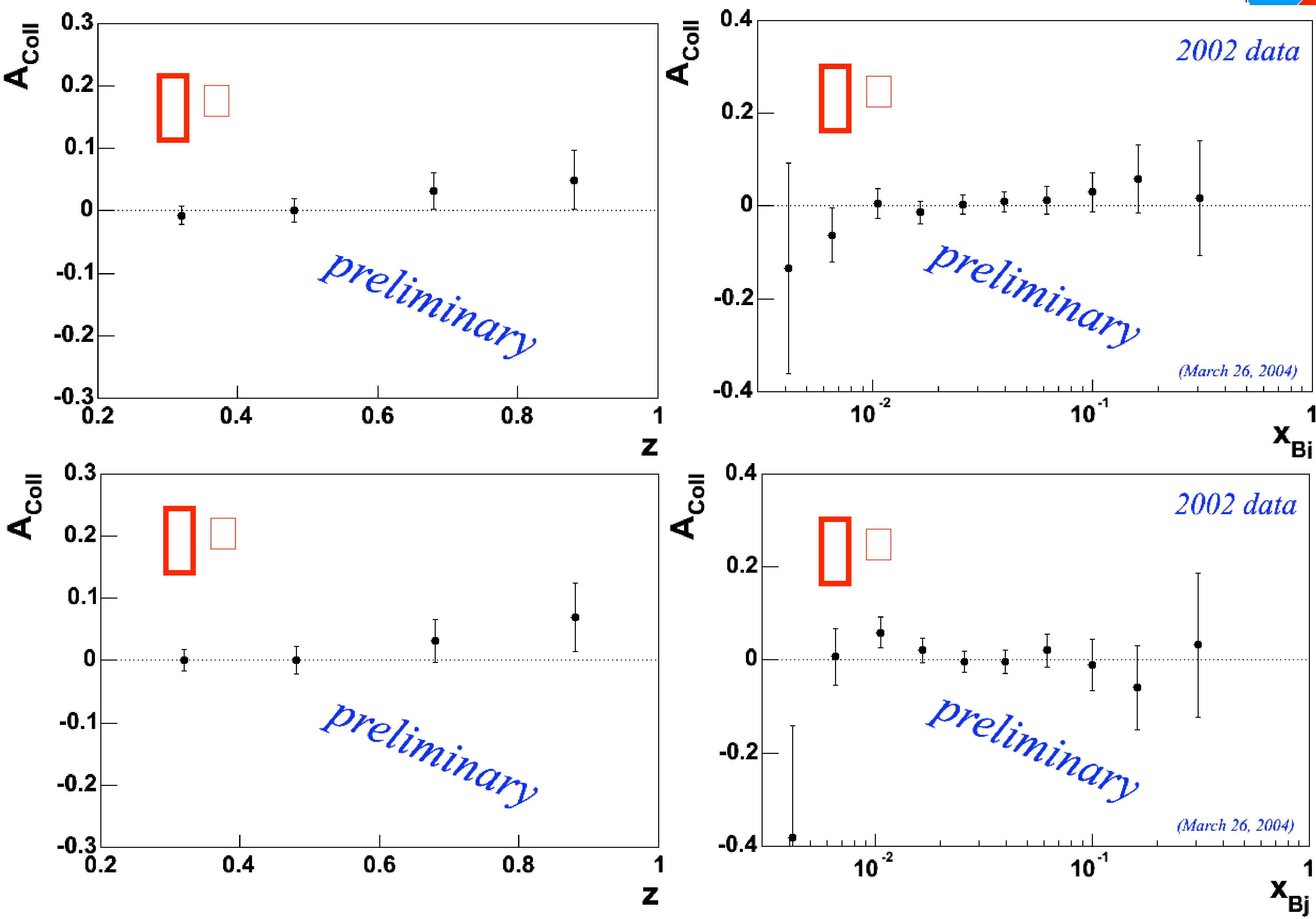


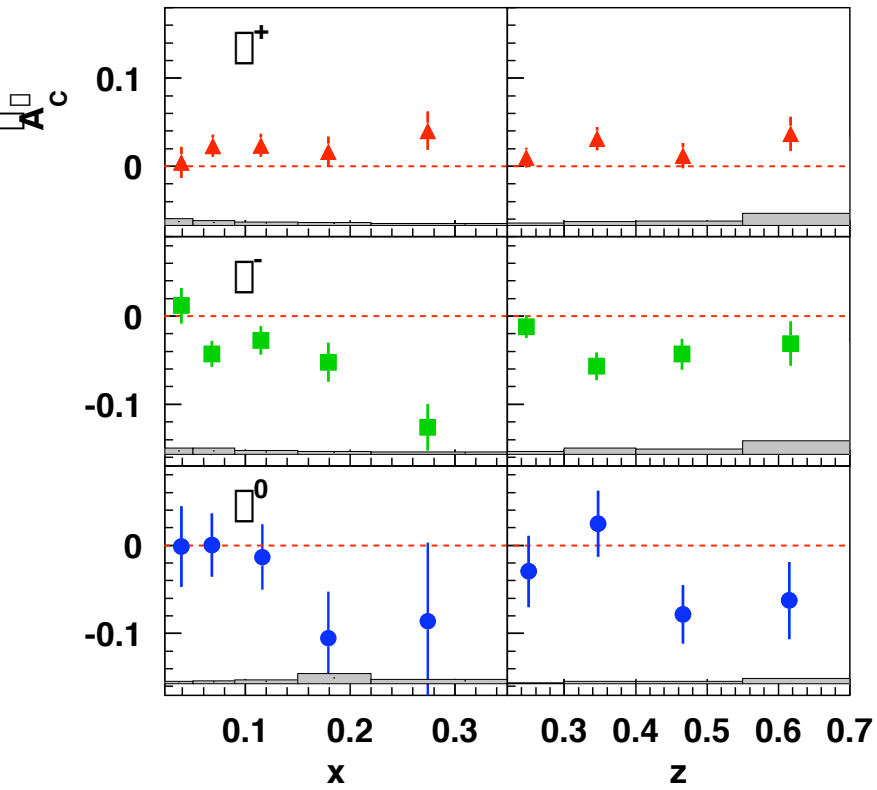
It actually works !!? Wow ...

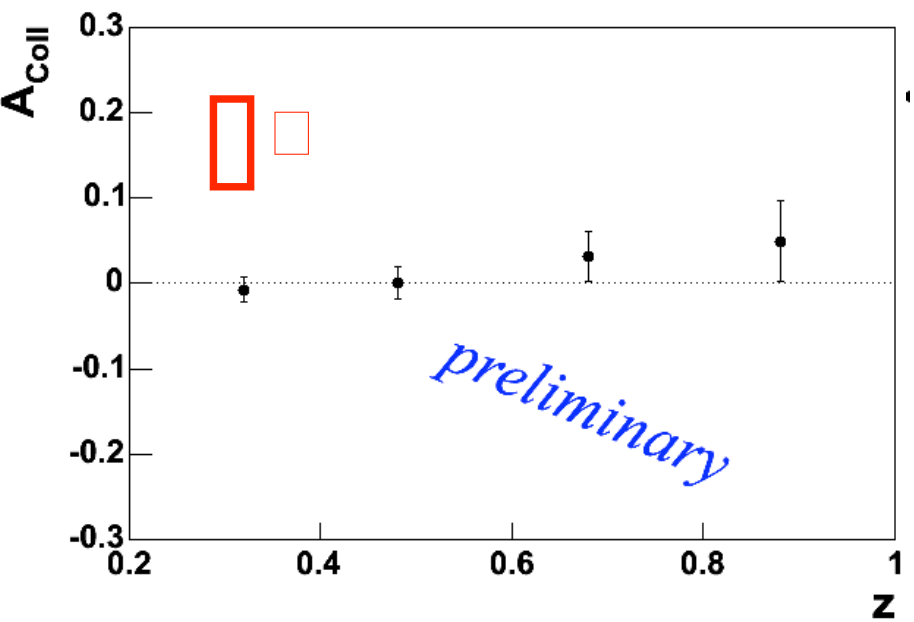
R. Joosten

COMPASS

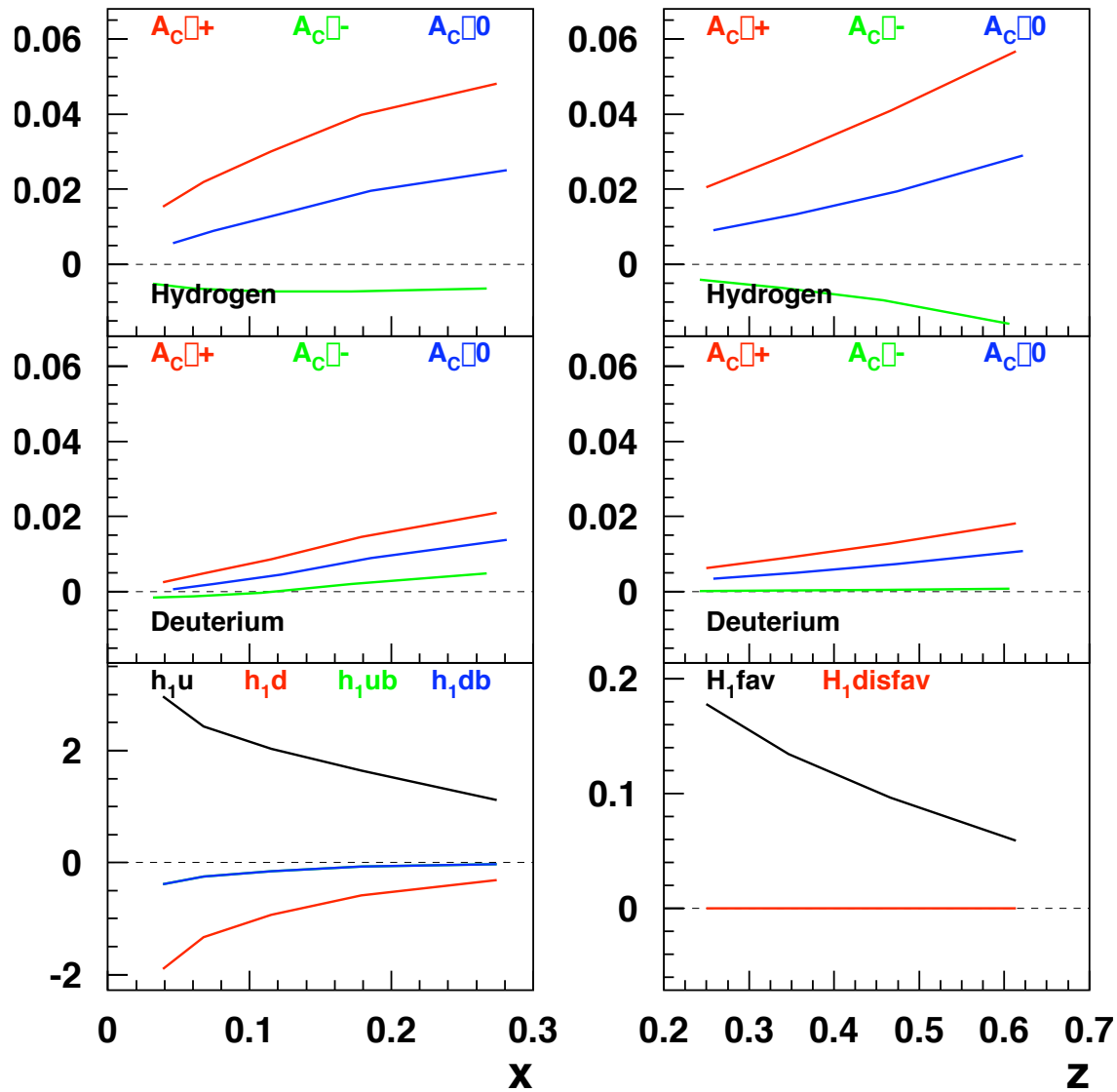


A quick model calculation ...





Assuming disfavored Collins FF = 0 ...



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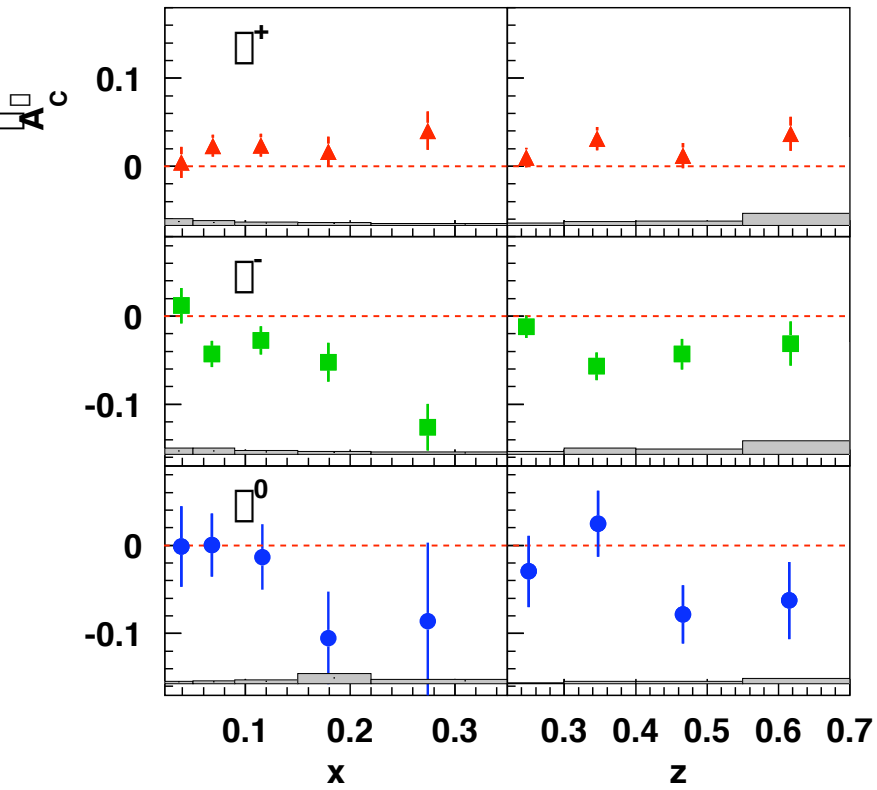
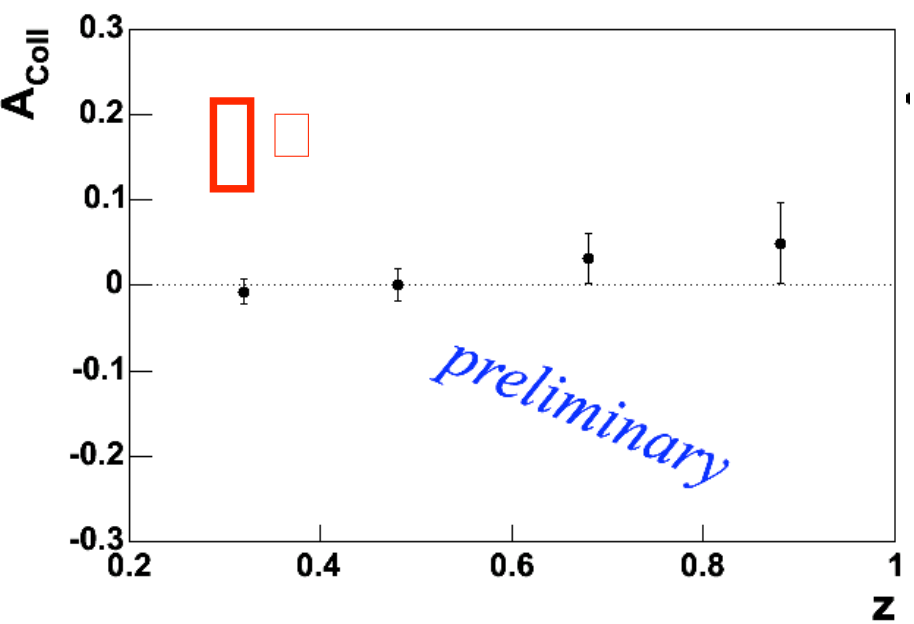
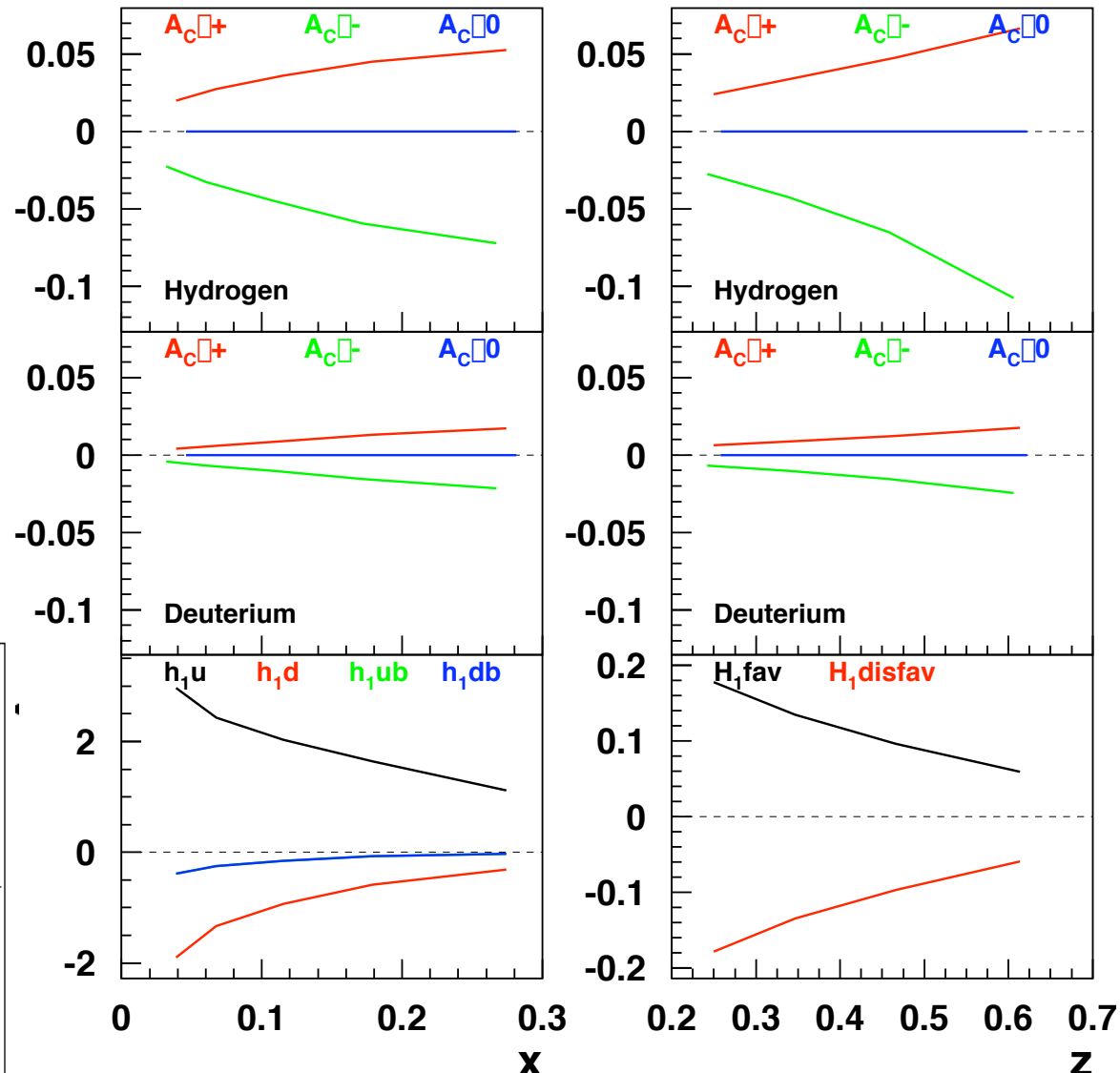
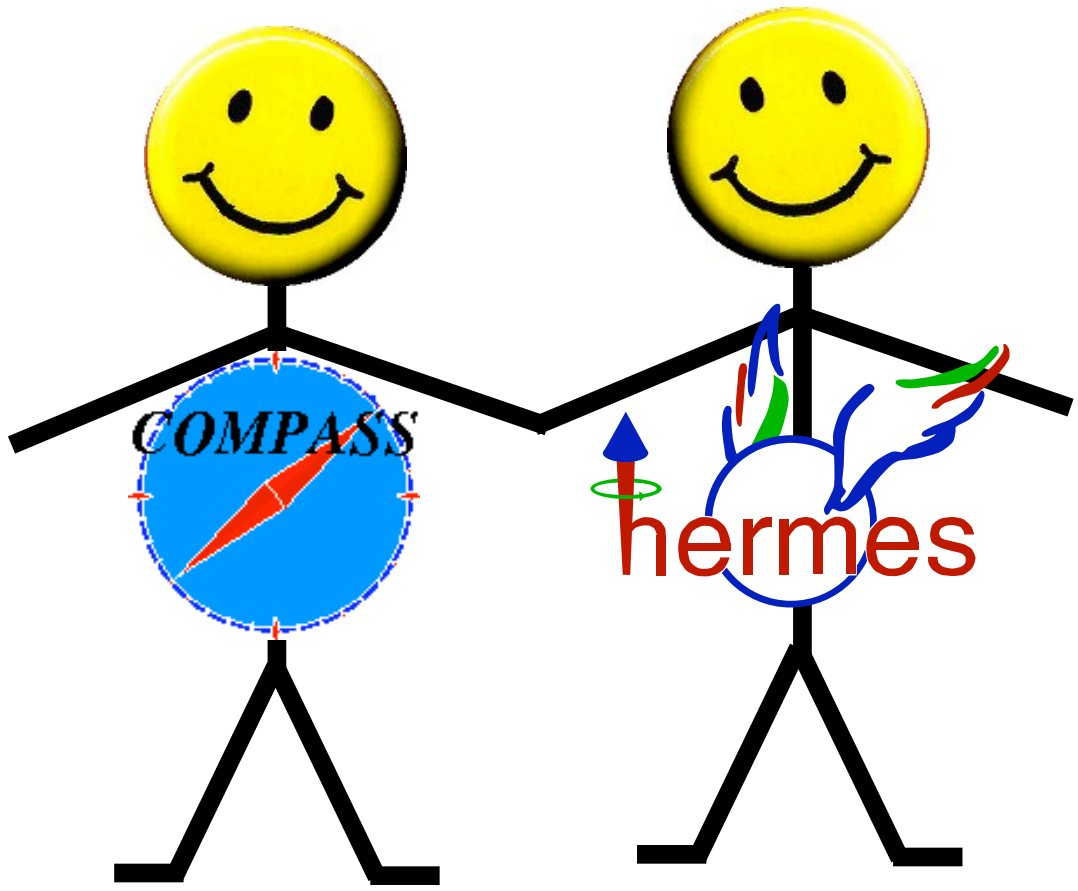




Assuming H(disfav) = -H(fav) ...

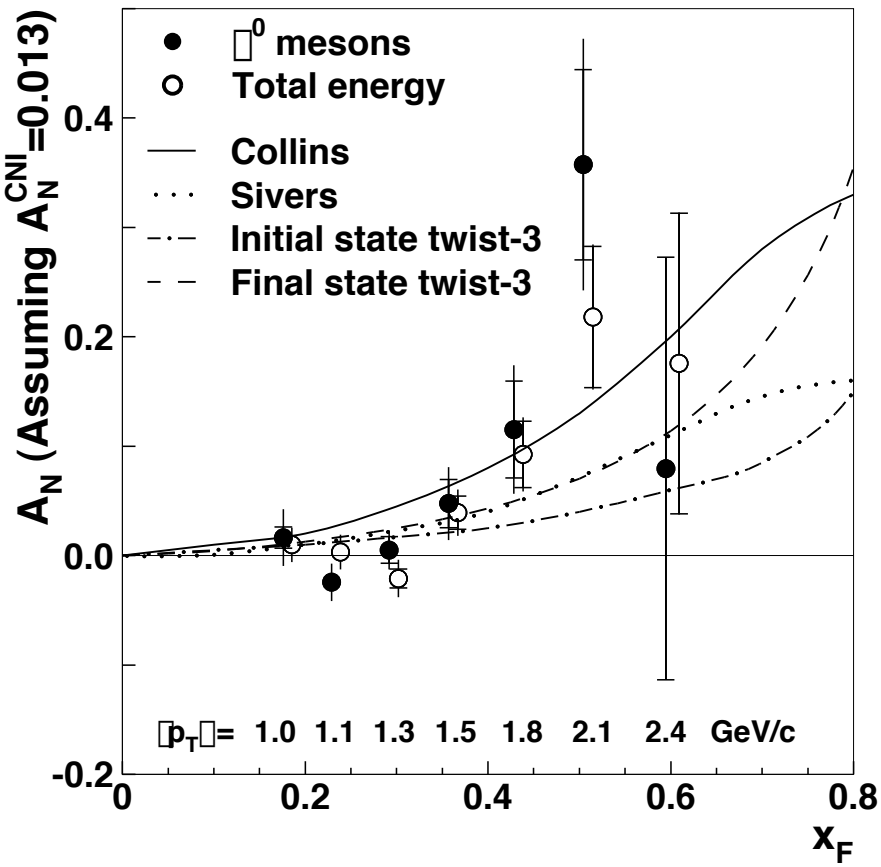



COMPASS
hermes

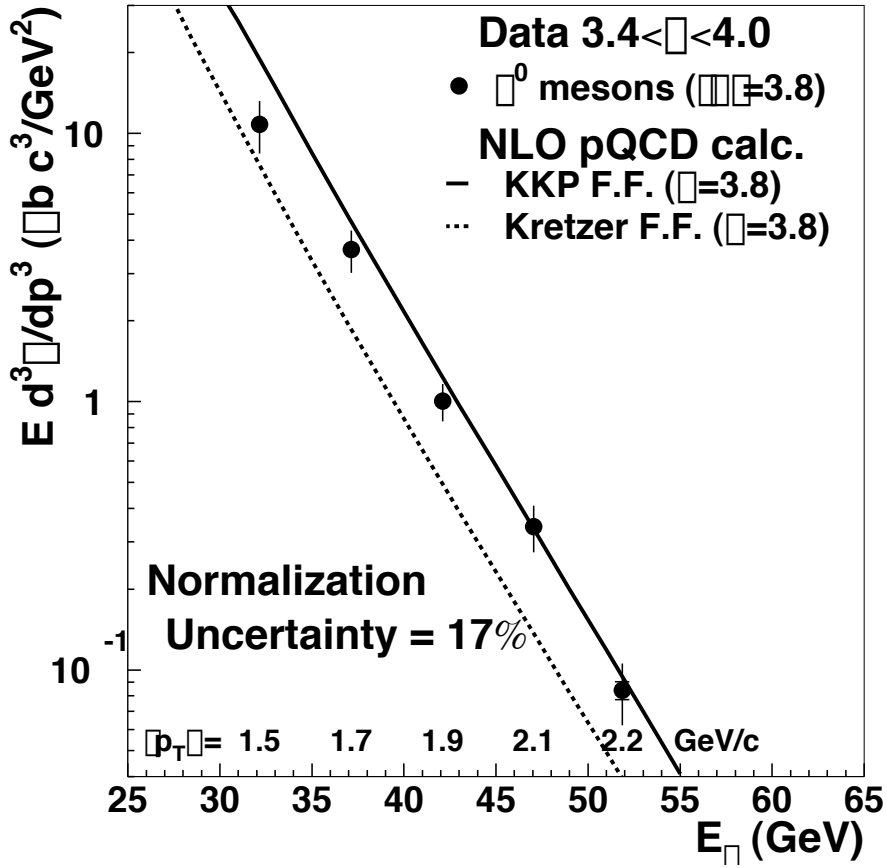
Results from STAR: $A_N^{\pi^0}$ at forward rapidity

Was E704 at a hard-enough scale for reliable pQCD analysis?
well RHIC certainly is!

Clear evidence of analyzing power

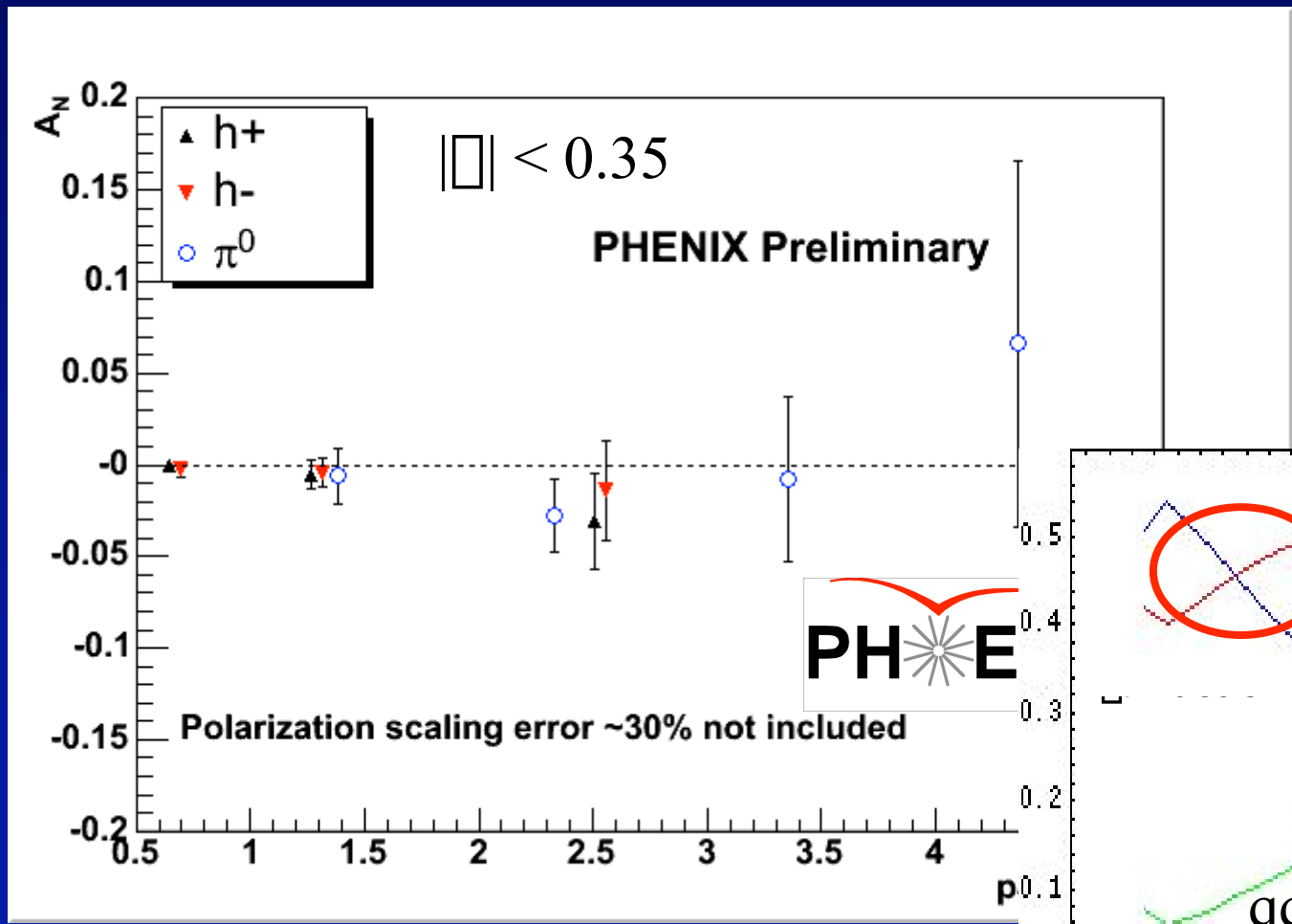


Xsec well-described by pQCD

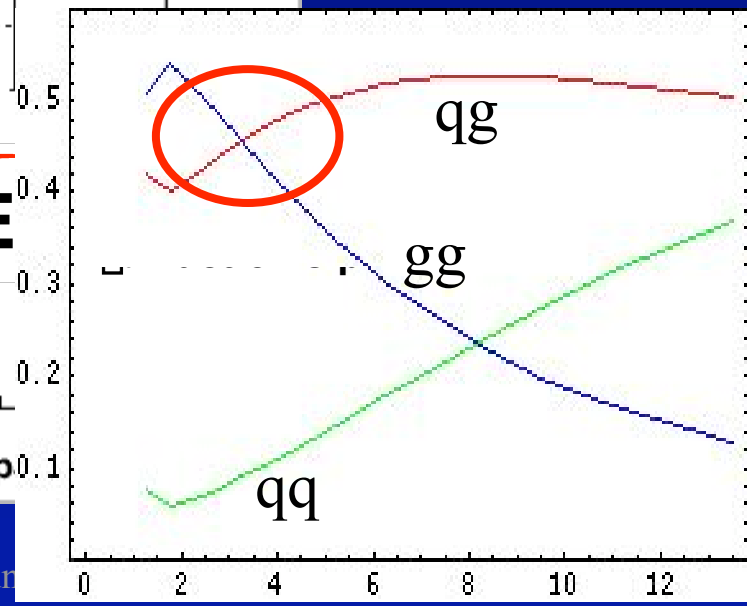


Asymmetry shows similar **rise with x_F** as observed at E704

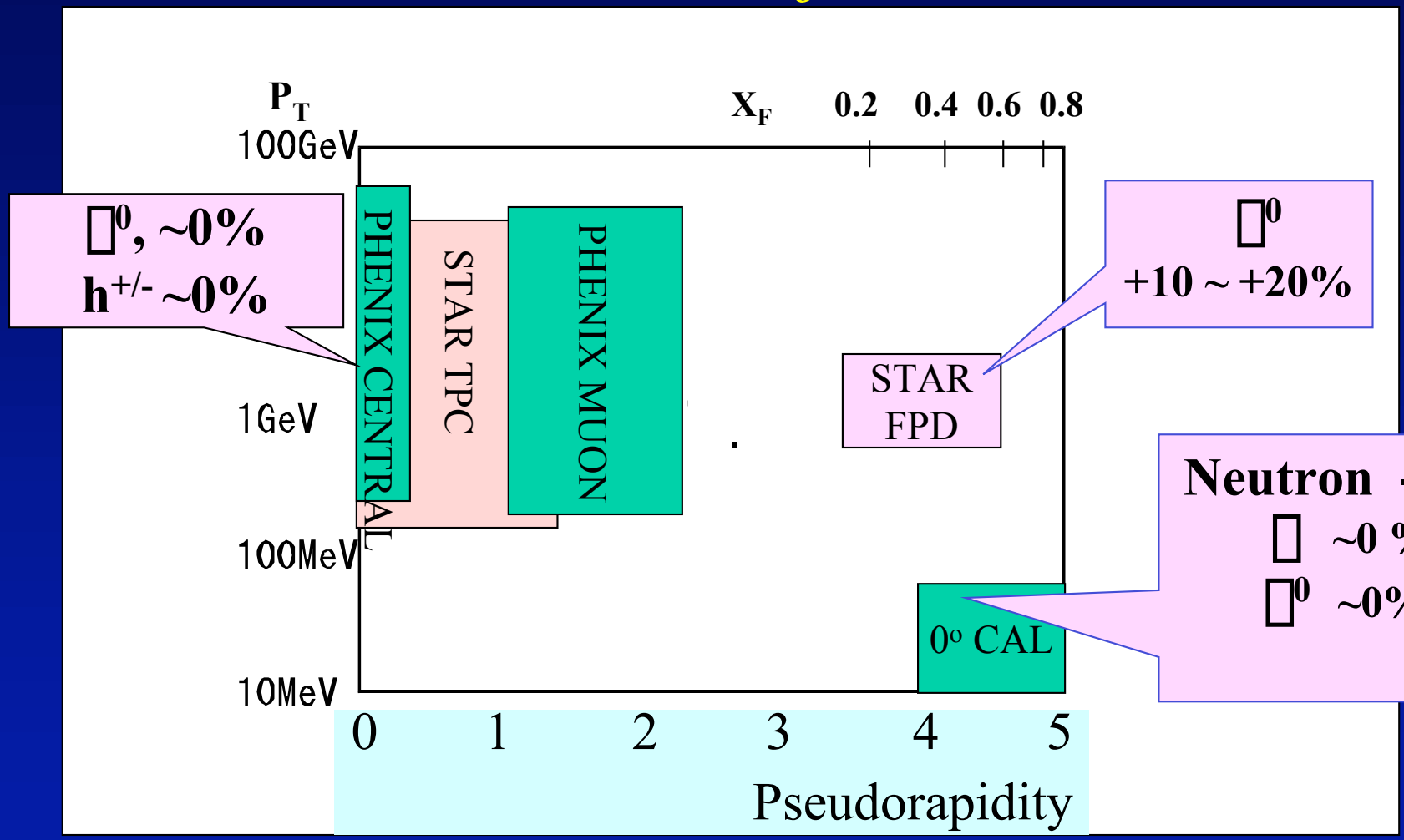
A_N of Neutral Pions and Non-Identified Charged Hadrons at Midrapidity



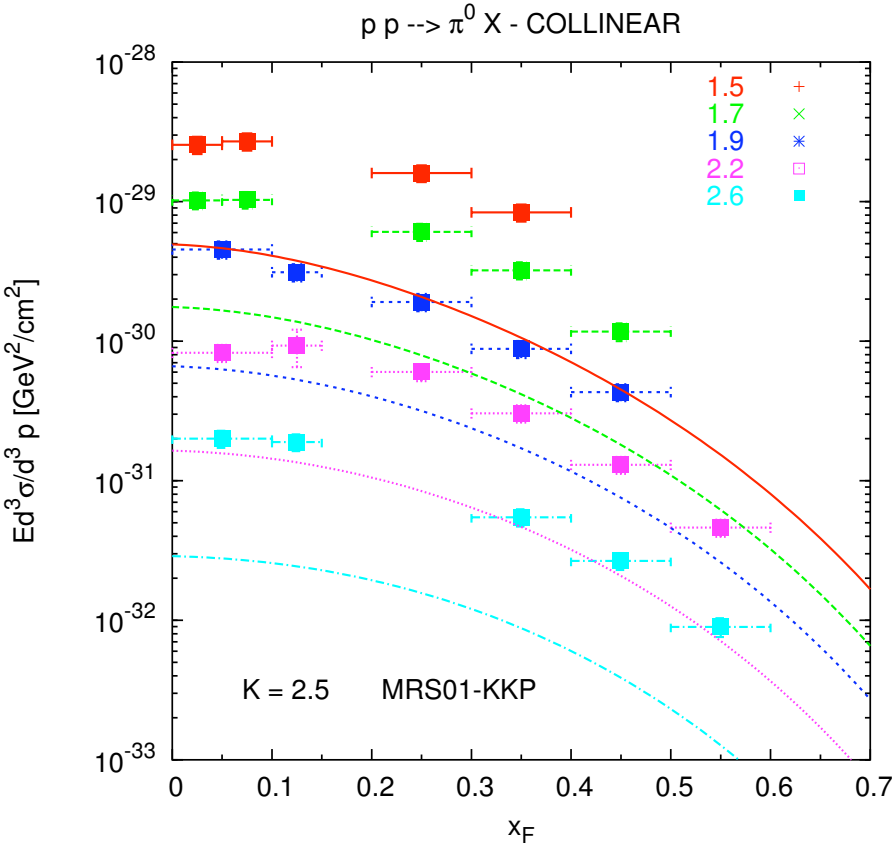
A_N for both charged hadrons and neutral pions consistent with zero.

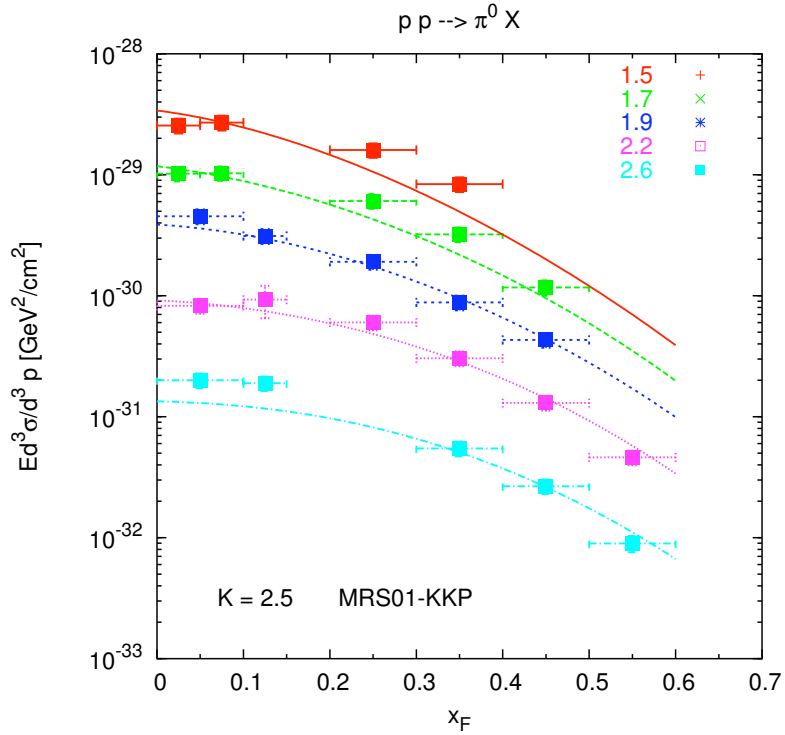


Single-spin asymmetries seen at RHIC so far…



Cross-section at E704: pQCD works?



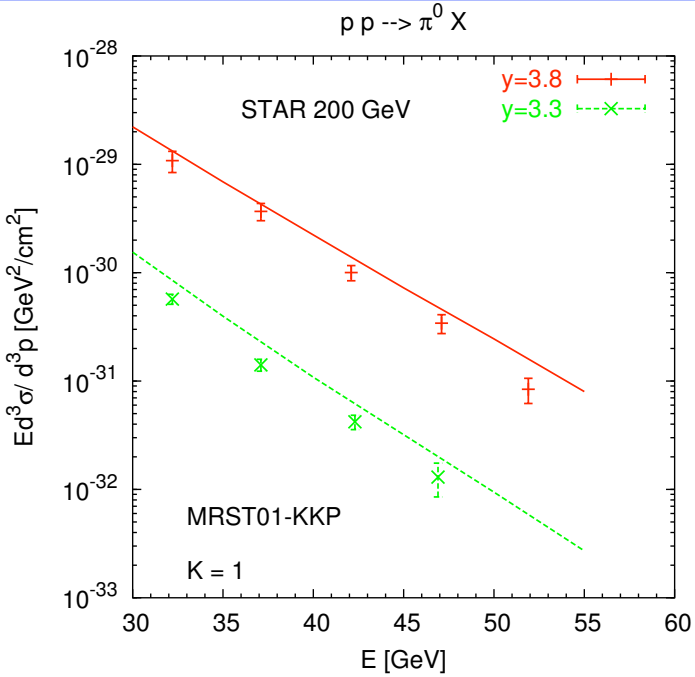


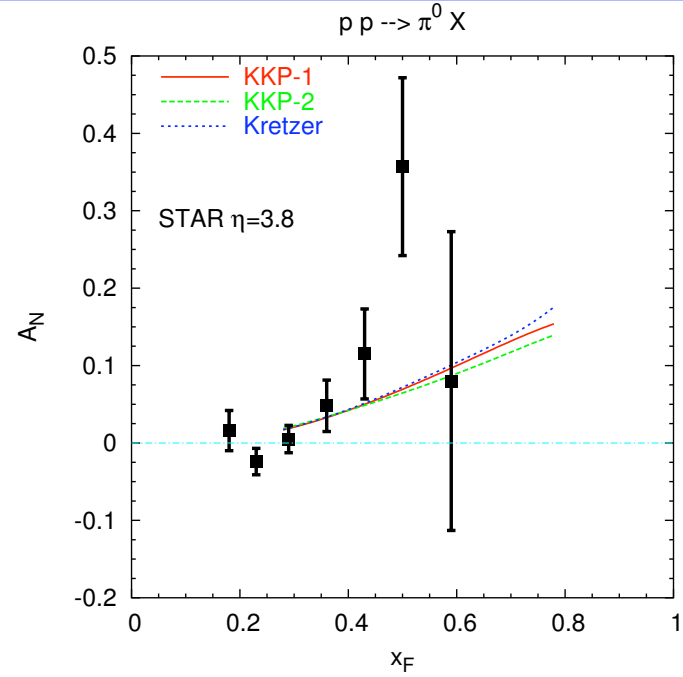
Estimates of π^0 invariant cross sections **in collinear pQCD** at E vs. x_F for different p_T values. Distribution function set: MRST01 fragment. function sets: KKP. Data are from Donaldson *et al.* [BN

Estimates of π^0 invariant cross sections at E= 200 GeV vs. x_F for different p_T values. Distribution function set: MRST01; fragmentation function sets: KKP. Data are from Donaldson *et al.* [BNL] PLB 73 (1978).

including kT induces slight overestimate of xsec at STAR ...

but Sivers-only fit to E704 AN also works for STAR





Estimates of unpolarized cross sections at $\sqrt{s}$ = 200 GeV vs. x_F at fixed rapidity η= 3.8. Distribution function set: MRST01; fragmentation function set: KKP. Data are from Adams, *et al.* (STAR), PRL 92, (2004).

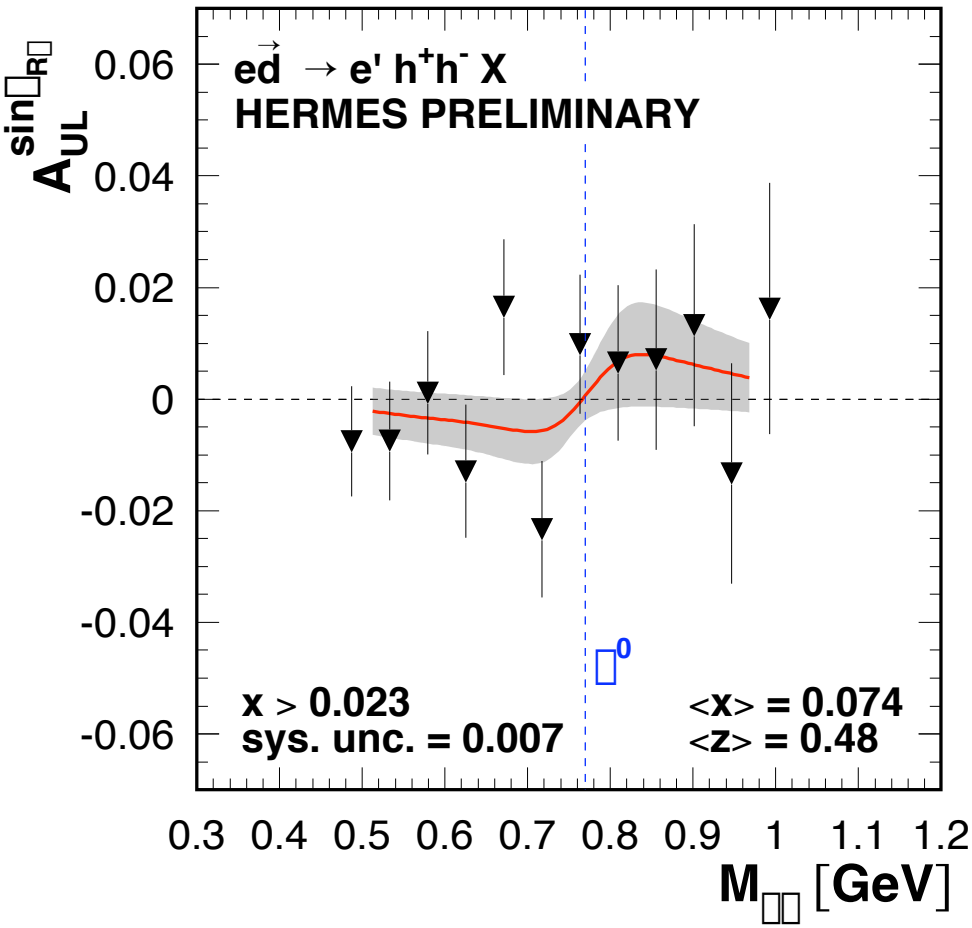
Estimates for A_N (Sivers effect) at

funct. sets. Data are from Adams, *et al.* (STAR), PRL 92, (2004).

new calculation: Collins contribution to AN appears to be very small

U. d'Alesio

comparison to model prediction



$$c_1 = \quad 0.040 \pm 0.036$$
$$c_2 = -0.001 \pm 0.004$$

- hint of a sign change at the ρ^0 mass

$$g(M^2_{\pi\pi}) \simeq c_1 \mathcal{P}(M^2_{\pi\pi}) + c_2$$

P. van der Nat

h_1

Can we understand the old A_{UL} data from HERMES & CLAS?

A. Kotzinian

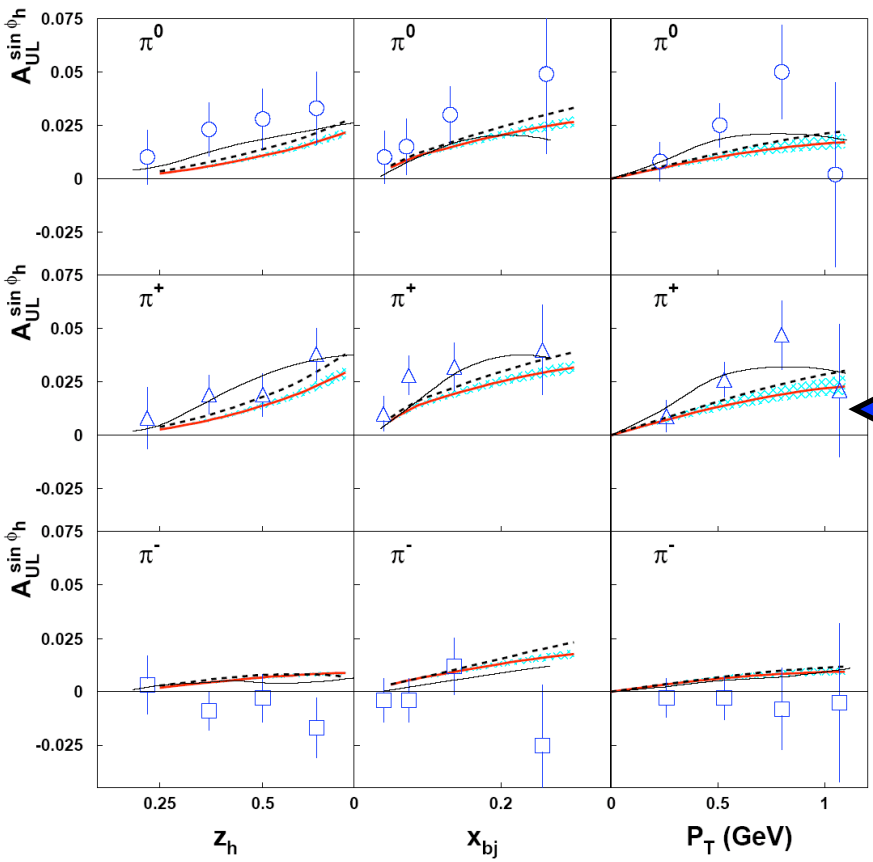


Figure 8: Hermes data on $A_{UL}^{\sin(\phi_h)}$. The bold solid red line corresponds to kinematics up to $\mathcal{O}(k_\perp^2/Q^2)$ terms, the dashed line up to $\mathcal{O}(k_\perp/Q)$ terms, the thin solid line corresponds to calculation with the use of event generator.

Many **Collins-only** models & fits were able to explain the data ... but assuming ***no Sivers*** and ***disfavoured Collins FF = zero*** ... now what?

New: **Sivers-only** fit
Not inconsistent with E704
Sivers-only fits because of very different x range

(Do twist-3 "Sivers-type" terms also need to be considered?)

Figure 9: Hermes data on $A_{UL}^{\sin(\phi_h)}$ on deuterium target. The bold solid red line corresponds to kinematics up to $\mathcal{O}(k_\perp^2/Q^2)$ terms, the dashed line up to $\mathcal{O}(k_\perp/Q)$ terms, the thin [illegible] generator.

New global analysis is in progress

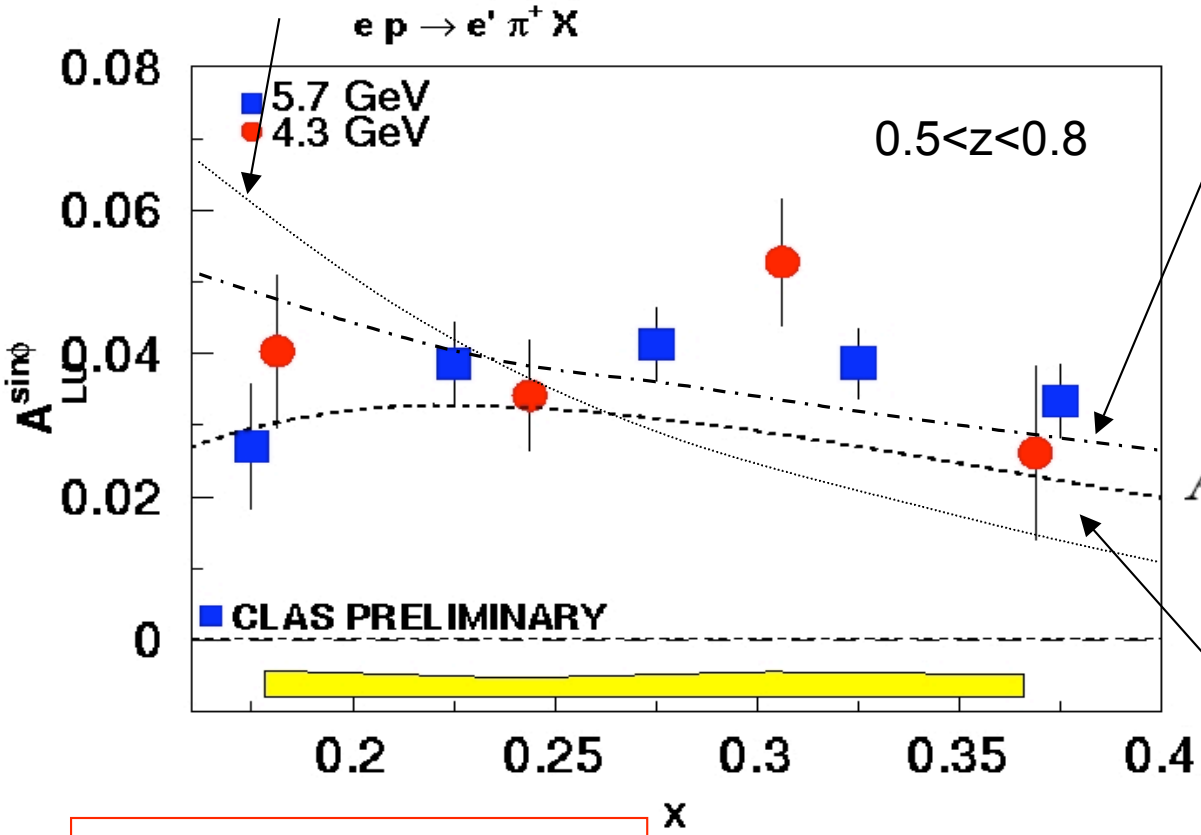
A_{LU} x-dependence: CLAS @ 4.3 and 5.7 GeV

$$A_{LU}^{AC} \propto g^{\perp(1)}(x) D_1(z)$$

Photon Sivers Effect Afanasev & Carlson, Metz & Schlegel

$$A_{LU}^{Sivers} \propto h_1^{\perp(1)}(x) E(z)$$

Beam SSA analyzed in terms of the Sivers effect by F.Yuan using h_1– from MIT bag model



$$A_{LU}^{Collins} \propto e(x) H_1^{\perp(1)}(z)$$

Beam SSA analyzed in terms of the Collins effect by Schweitzer et al. using e(x) from QSM

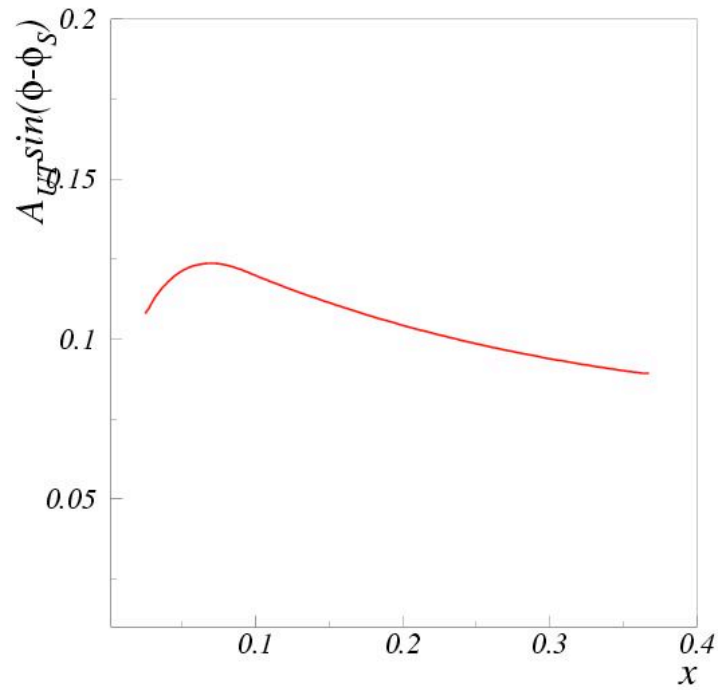
4.3 GeV and 5.7 GeV data consistent

Modelling the T-odd dist and frag functions

Numerous groups now calculating these functions via the Brodsky-Hwang-Schmidt gauge-link

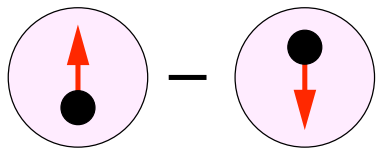
T-Odd Distribution Functions

e.g. ***Gamberg, Goldstein***: calculate $f_{1T}^{\perp}$ and $h_1^{\perp}$ via 1-gluon exchange in quark-diquark spectator model



... and ***many*** other groups & models ...

Note: don't forget the "other" T-odd DF ...

$h_1^{\perp} =$  (Sokolov-Ternov PDF?)

- Already observed in old Drell-Yan data! (now reinterpreted)
- Also accessible in SIDIS: $\langle \cos(2\square) \rangle_{UU}$ ... but very difficult experimentallly due to QED radiation and acceptance effects

Extracting the Sivers functions

A similar analysis proceeds with one fewer unknown

(no spin-dependent fragmentation)

$\Rightarrow$ the system can be solved for first x-moments of the Sivers functions:

$$f_{1T}^{\perp(1)u} + \frac{1}{4} f_{1T}^{\perp(1)\bar{d}} = -0.044 \pm 0.016\,(\text{stat})$$

$$f_{1T}^{\perp(1)d} + 4 f_{1T}^{\perp(1)\bar{u}} = 0.074 \pm 0.066(\text{stat})$$

Theoretical predictions have been made by:

Gamberg et al., *Phys. Rev. D 67 (2003) 071504:* $f_{1T}^{\perp(1)u} =$ Comment from audience?

Spectator model with quark & scalar diquark, 1-gluon exchange, Gaussian form factors

Yuan, Phys. Lett. B575 (2003) 45: $f_{1T}^{\perp(1)u} = -0.01$ (correct sign!) $f_{1T}^{\perp(1)d} = +0.003$

MIT bag model with one gluon exchange from gauge link

Bacchetta et al., *Phys. Lett. B578 (2004) 109:* $f_{1T}^{\perp(1)u} = 0.037$ (wrong sign) $f_{1T}^{\perp(1)d} = -0.011$

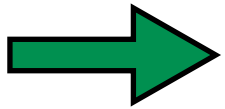
Spectator model: quark plus scalar and axial-vector diquarks, dipole form factors

Modelling the T-odd dist and frag functions

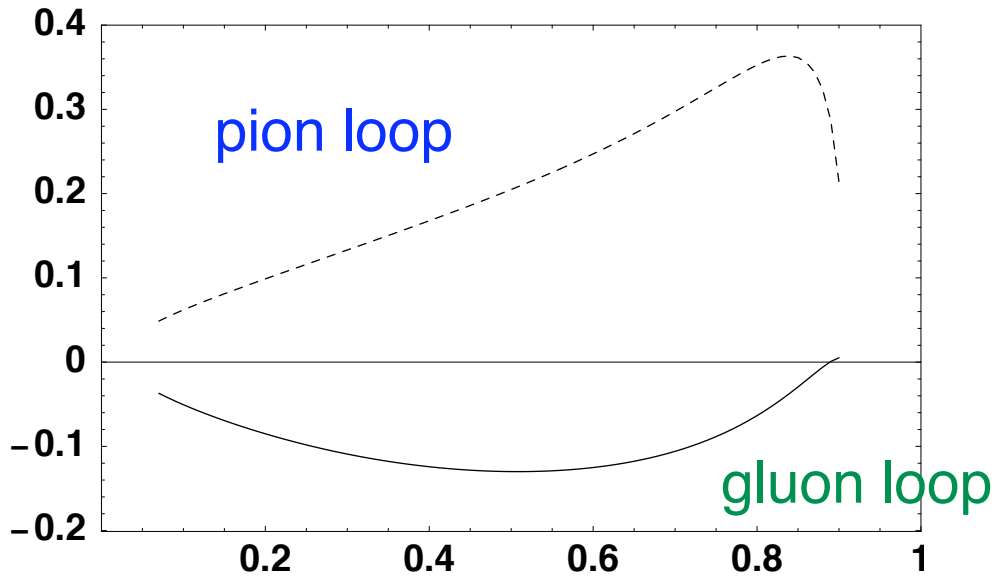
T-Odd Fragmentation Functions

again, many groups calculating

e.g. Metz et al: Collins FF via 1-gluon and 1-pion exchange in Georgi-Manohar model



$H_1^{\perp(1/2)}(z)/D_1(z)$



- unlike in distribution-function case, get non-zero result even *without* the gauge link
- pion- and gluon-loop contributions of opposite sign ...
- disfavored FF could be calculated, but would be higher-order in chiral PT: emission of two pions from quark line instead of one

*General modelling issue: How good an approximation is **one-gluon** exchange?*

A. Metz: "We cannot (yet) model the Collins FF reliably enough to use it to extract h1"

GPD's and Lattice QCD

M. Diehl: Generalized Parton Distributions & Transversi

(please!)

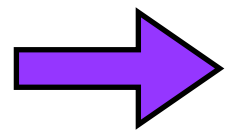
- We thought there were 4 GPD's: $H, \tilde{H}, E, \tilde{E}(x, \Delta, t)$
- But now there are 8 GPD's: $H_T, \tilde{H}_T, E_T, \tilde{E}_T(x, \Delta, t)$
- New GPD H_T gives transversity in forward limit $\Delta \to 0,\ t \to 0$
  ... but if you go off-forward, gluons can contribute! (via L)

Important point: GPD's and kT-dependent PDF's
give ***complementary information***

GPD's = distribution of partons in transverse space
TMD PDF's = distribution of partons in transverse momentum

P. Haegler: Lattice Calculations of GPD's

The raison-d'etre of next-generation facilities like EIC will be to bring non-perturbative QCD into a new era of precision (like QED)



must be matched by precision-theory = **lattice QCD**

Results for the generalized transversity H_T

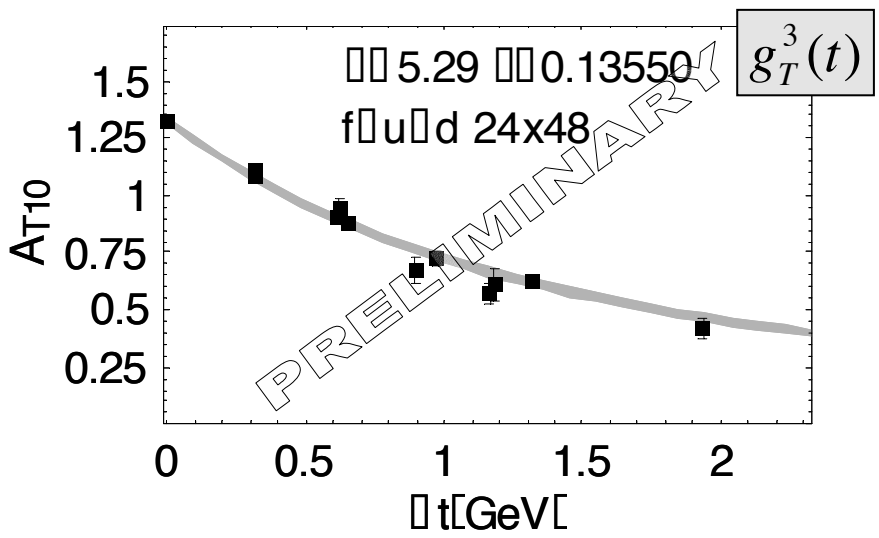
P. Haegler

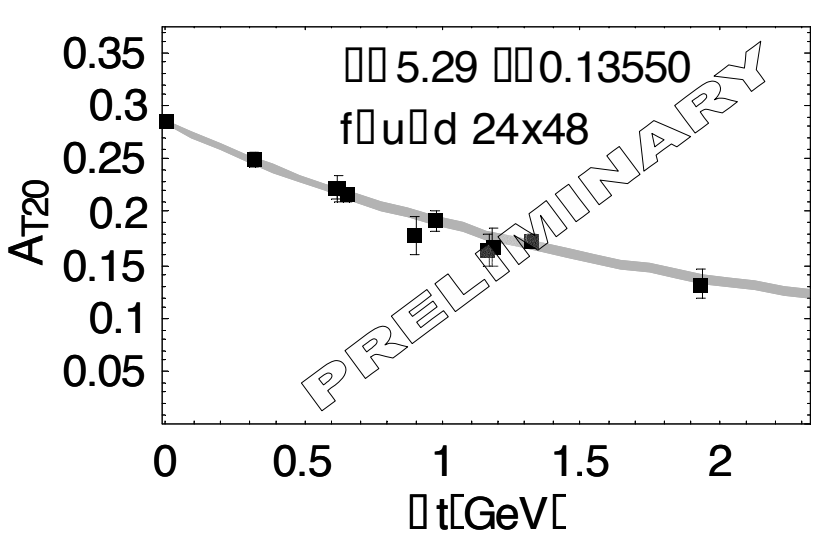
concentrate on up-down in order to cancel disconnected pieces

dipole - fit $GFF(t) = \frac{a}{\left(1 - t/m_D^2\right)^2}$

$$\int_{-1}^{1} dx\, x^0 H_T(x,0,t=0) = \int_{-1}^{1} dx\, H_q(x) = A_{T10}(0)$$

$$\int_{-1}^{1} dx\, x^1 H_T(x,0,t=0) = \int_{-1}^{1} dx\, x H_q(x) = A_{T20}(0)$$





dipole mass: 1.678 ± 0.032 GeV

normalization (t = 0): 1.332 ± 0.013

dipole mass: 2.105 ± 0.039 GeV

normalization (t = 0): 0.2852 ± 0.0023

non-perturbative renormalization lattice → $\overline{MS}$ will come soon

Conclusions & Outlook

- Trento2004 featured a splendid ***theoretical synthesis*** of field-theoretic analysis (rigour) and phenomenological thinking (intuition)
- ***New data*** from DESY, CERN, JLAB directly related to kT-dependent structures within the proton are already teaching us new things about ***non-perturbative QCD***
- ***Understanding*** of the new results is proceeding at a rapid rate, but much work is still required ⇒ ***global analysis***
- The new data are just the ***first trickle*** of a ***great wealth*** of upcoming information on transversity and the new kT-dependent distribution / fragmentation functions

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See you all at QCD-N'06!
Frascati, June 12-16, 2006

Warmest thanks to all the organizers for the superb organization and stimulating agenda!