a puzzle...

mathematician

theoretical physicist

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engineer

experimental physicist

experiment

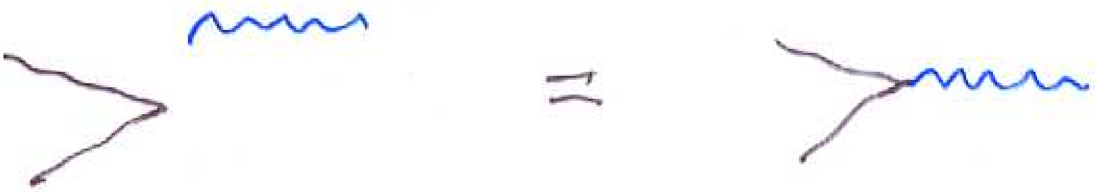
theory

10 Sept. 2005
Como Transversity
G. Bunce

Where we've been

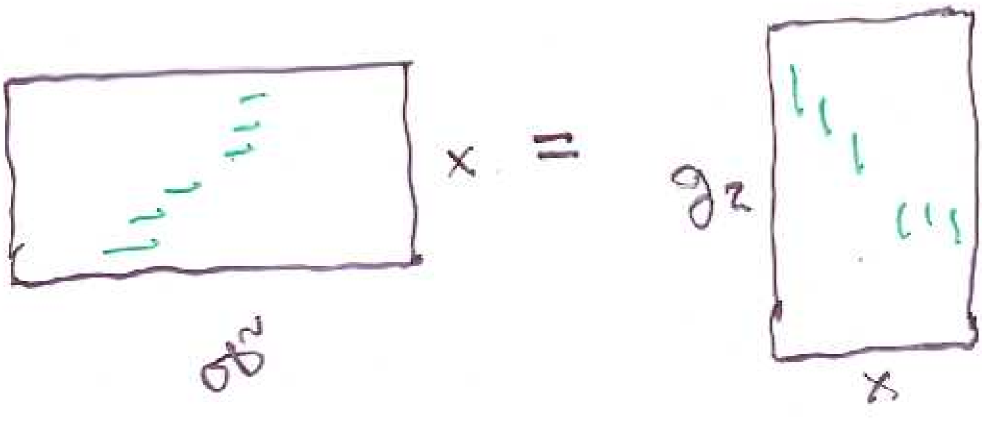
A few definitions...

Powerpoint → **Transparencies**



$$H_1^{\square} = H_1^{\Delta}$$

$$N_L - R N_R \quad N_L + R N_R = \frac{N_L - R N_R}{N_L + R N_R} \quad (= A_N)$$



p + Be → Λ + X
at 300 GeV

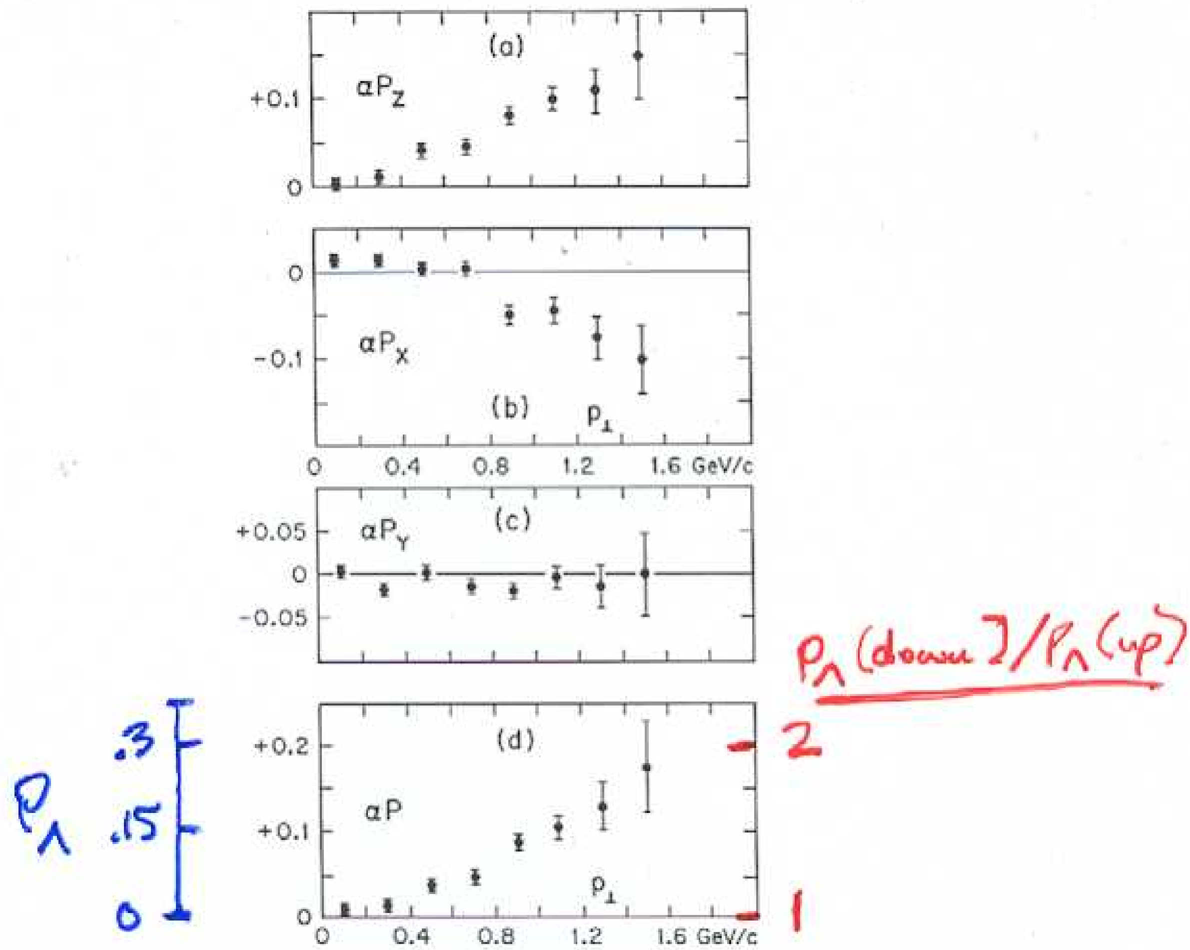
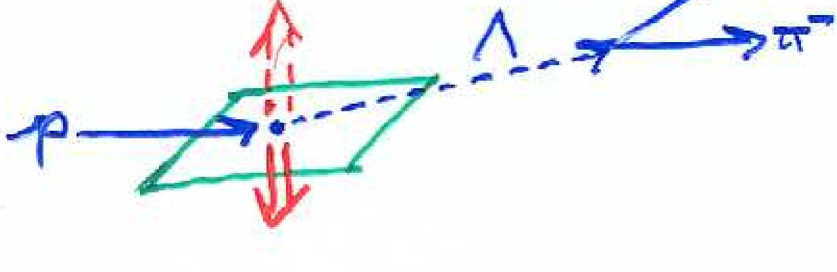


FIG. 3. Three components and magnitude of the $\Lambda^0 \to p+\pi^-$ asymmetry as a function of Λ^0 transverse momentum.



let's start with 30 years ago...

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not pQCD! $p_T \approx 1.5$ GeV/c!

$p\,p \rightarrow \Lambda^{\Uparrow} X$,

$P_\Lambda \cong 0.25$ for $p_T = 1.5$ to $\underline{\underline{4}}$ GeV/c

(fixed x_F, large)

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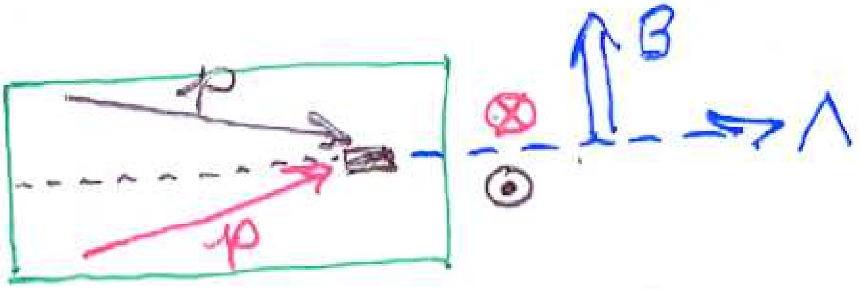
an experimentalist's view:

Such a large polarization must come from something simple.

also: a beautiful effect!

the discovery of P_Λ was not an accident...

- we rebuilt the proton beam line to have a vertical production plane



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the discovery of the spin "crisis" in 1989 was not an accident...

- Vernon Hughes developed a polarized electron source from the late 1950s (PEGGY)

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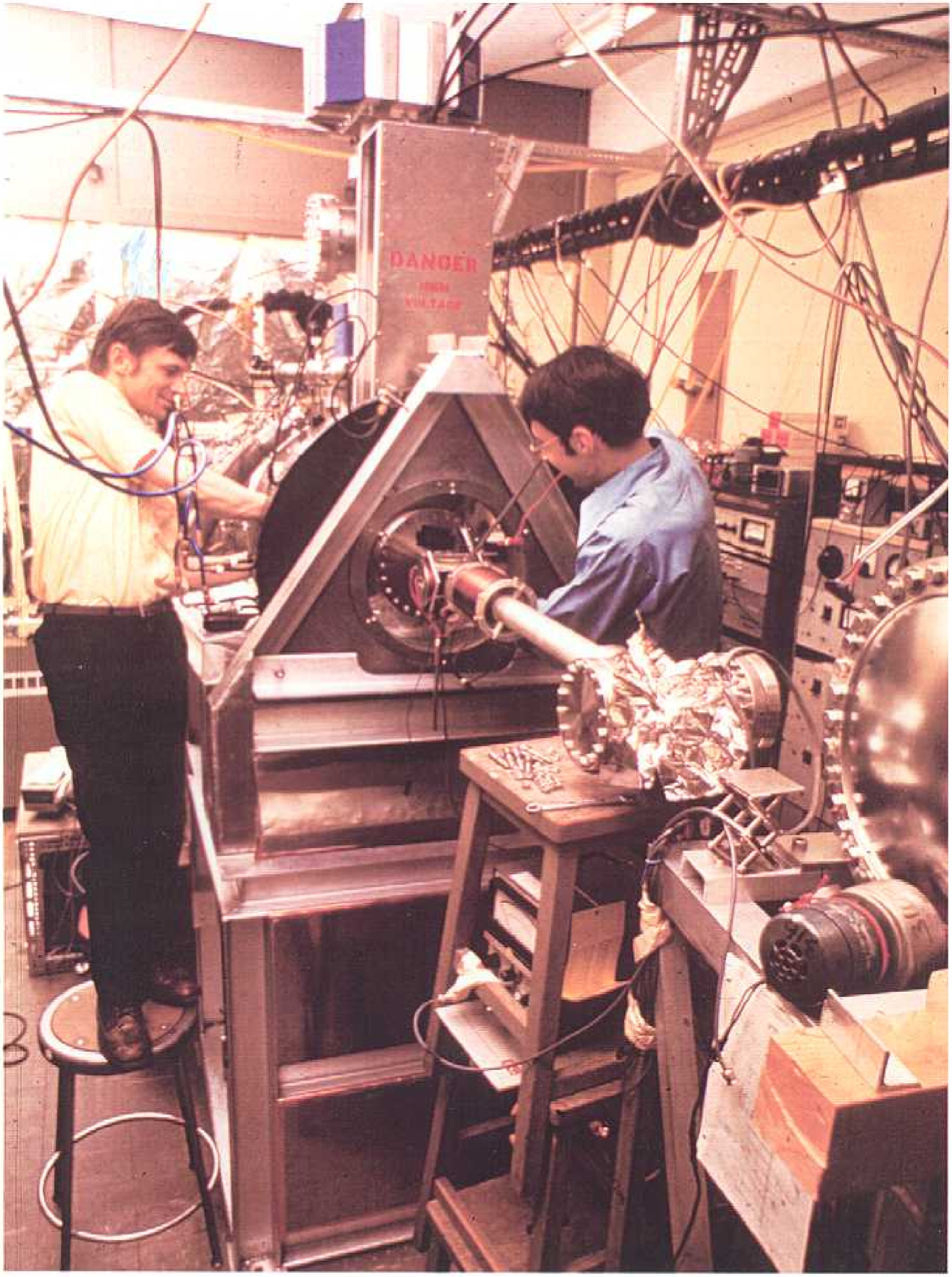
and both discoveries (and the SSAs etc.) were driven by curiousity


DANGER

pp elastic scattering

~1976

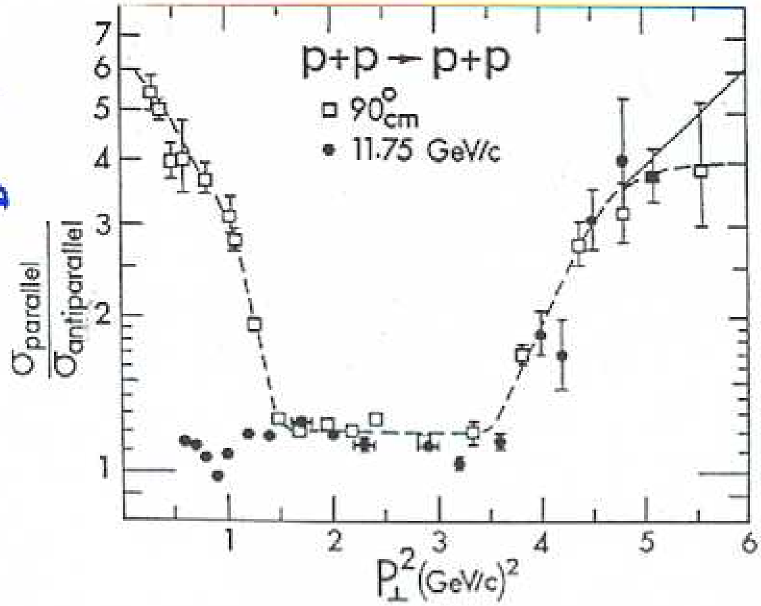


Fig. 3. Ratio of spin-parallel to spin-antiparallel p-p elastic cross-sections plotted against $P_\perp^2$ for fixed energy and fixed angle experiments.

N_{left}/N_{Right}

$p^{\Uparrow} + p \to \pi + X$ at 200 GeV

$A_N = \frac{1}{P_{beam}} \frac{N_{left} - N_{Right}}{\text{sum}}$

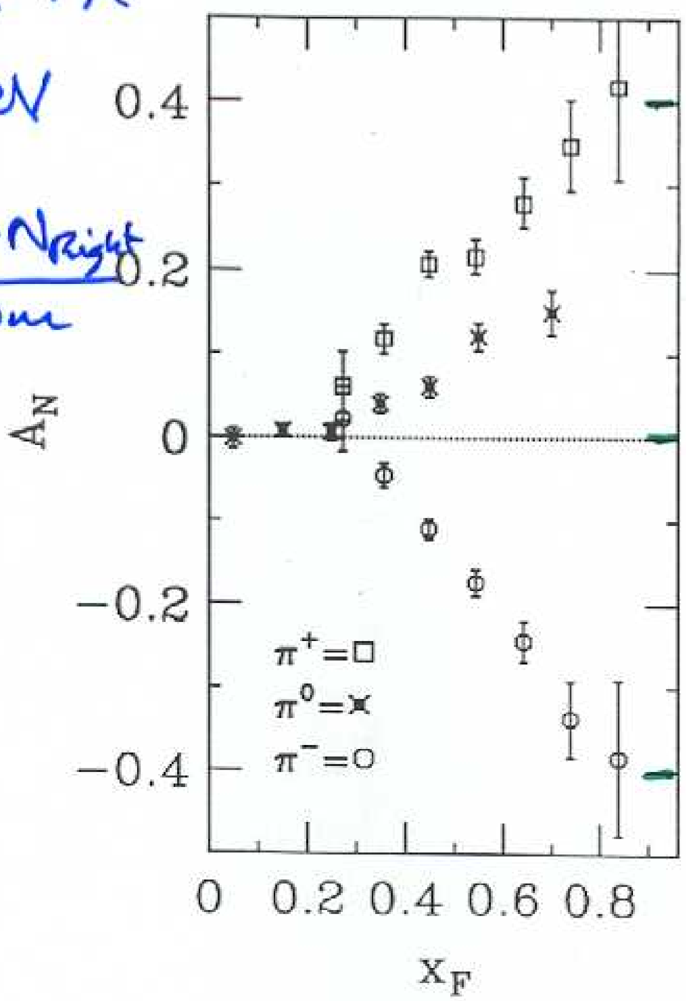
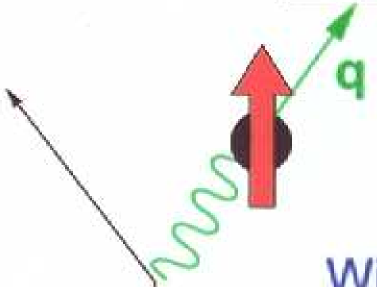


Fig. 4. A_N versus x_F for π^+, π^- and π^0 data.

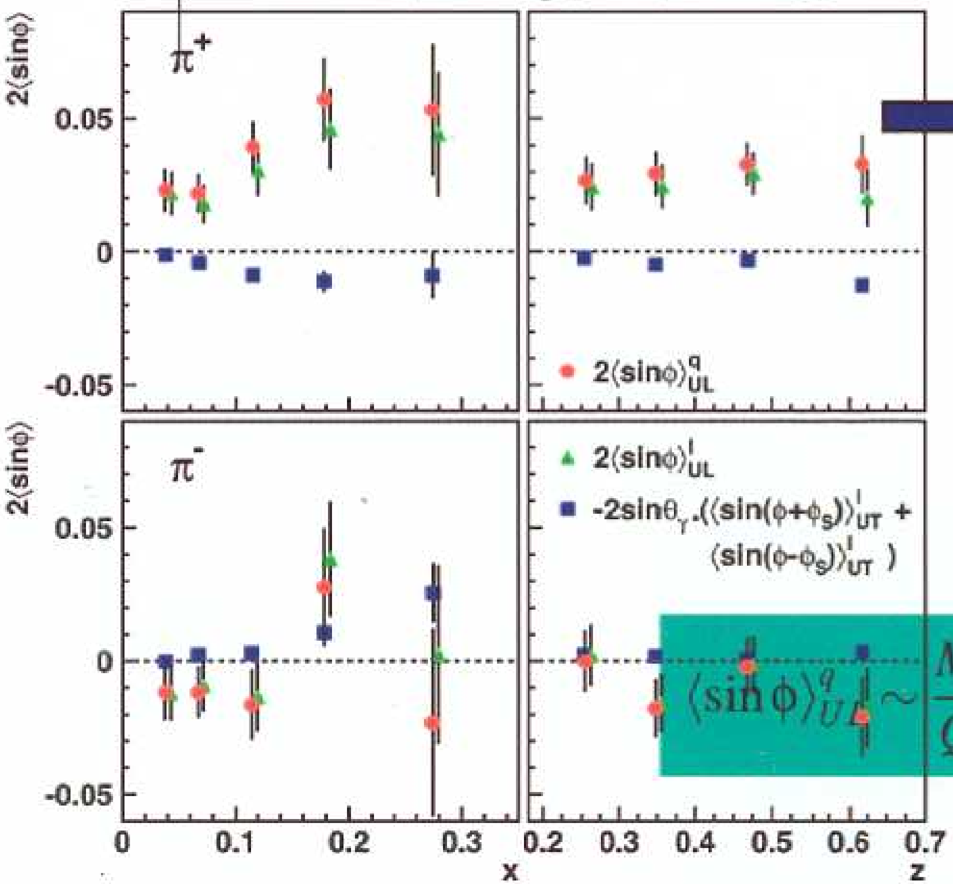
Revisiting the Longitudinal Target SSA's



Experiment: "longitudinal target" polarized // **lepton beam *l***
Theory: "longitudinal target" polarized // **virtual photon *q***

With both targets measured, can now extract pure *UL* moments

$$\langle\sin\phi\rangle^{q}_{UL} = \langle\sin\phi\rangle^{l}_{UL} + \sin\theta_{\gamma*}[\langle\sin(\phi+\phi_S)\rangle^{l}_{UT} + \langle\sin(\phi-\phi_S)\rangle^{l}_{UT}]$$



Correction is **small**: as anticipated earlier, A_{UL} ***is*** almost-entirely longitudinal (i.e. **twist-3**) in origin

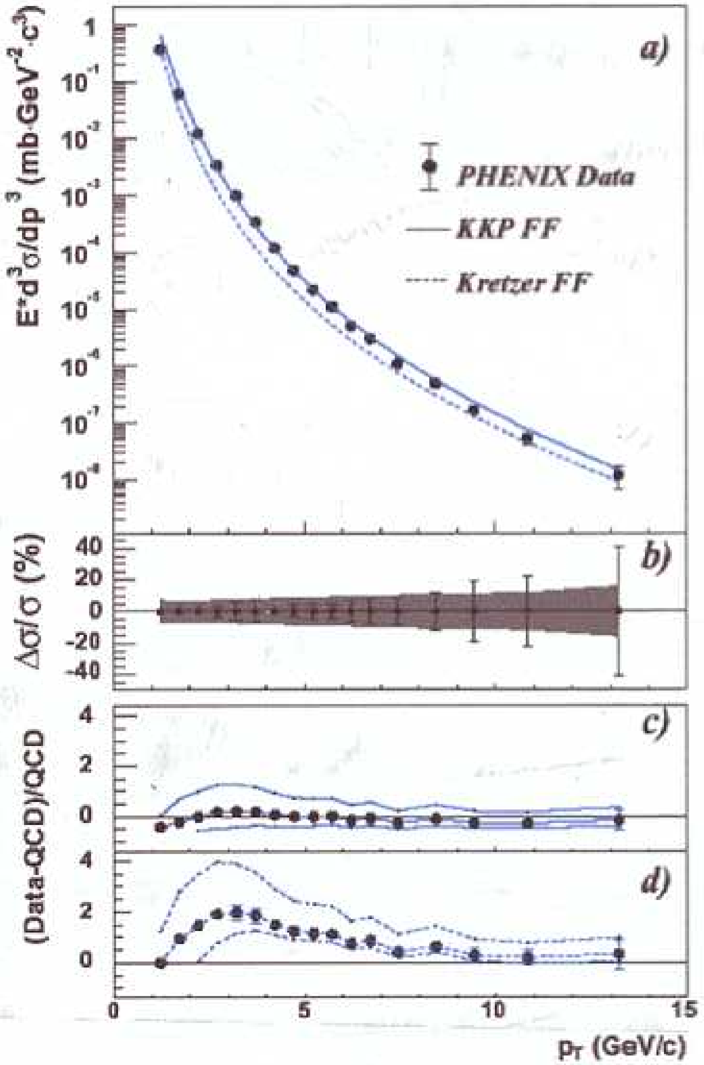
Recent, more complete theoretical analysis of **sub-leading** $A_{UL}(\Phi)$ includes contribution from **twist-3 Sivers function $f_L^{\perp}$**

$$\langle\sin\phi\rangle^{q}_{UL} \sim \frac{M}{Q}\,\frac{I[g_{1L}G^{\perp} \oplus h_L H_1^{\perp} \oplus h_{1L}^{\perp}\tilde{H} \oplus f_L^{\perp} D_1]}{f_1 D_1}$$

Theoretical revisit needed ...

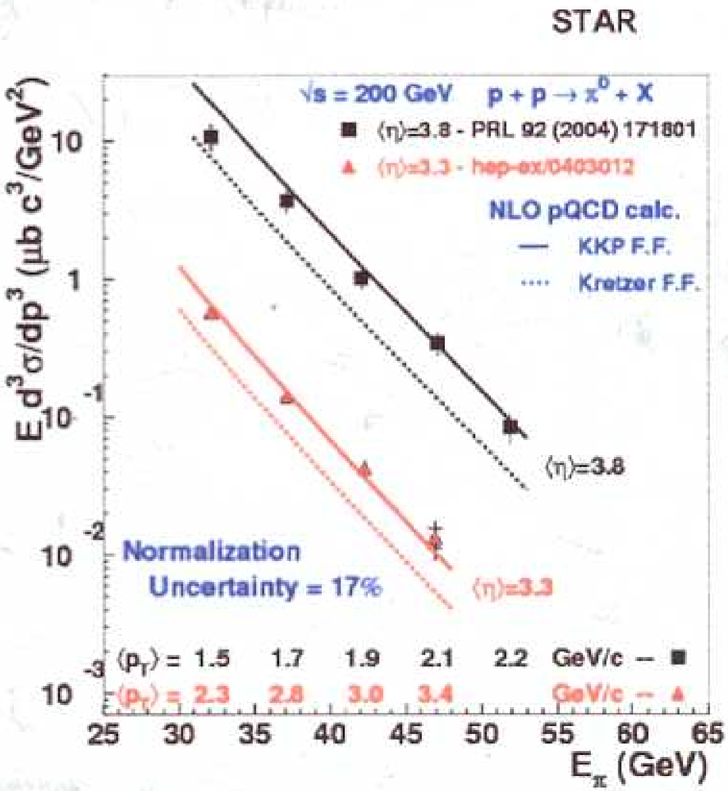
CW2-117-96

Cornerstone to the RHIC Spin program



Phys. Rev. Lett. **91**, 241803 (2003)

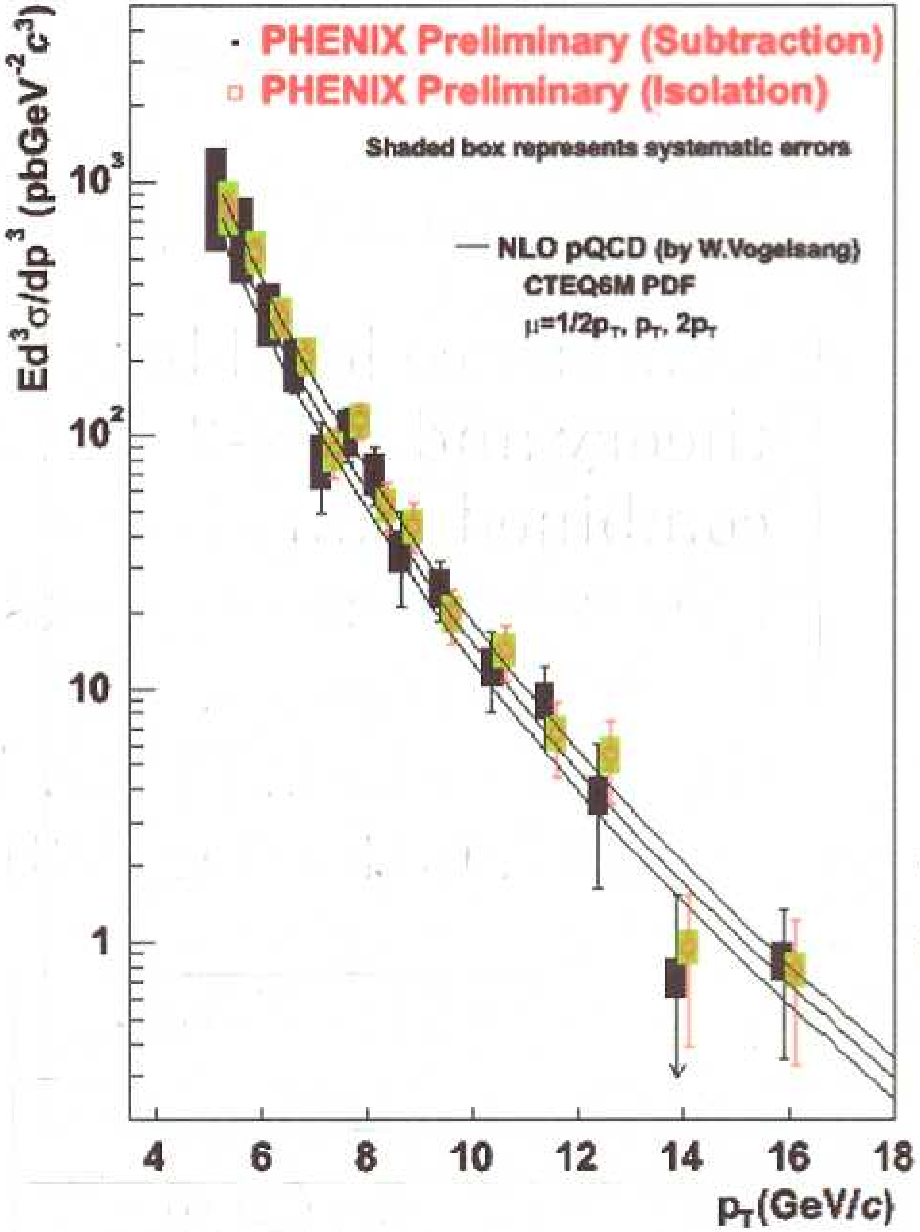
$pp \rightarrow \pi^0 X$



Phys. Rev. Lett. **92**, 171801(2004);
arXiv:nucl-ex/051026

$p + p \rightarrow \gamma + X$

Comparison to NLO pQCD calculation

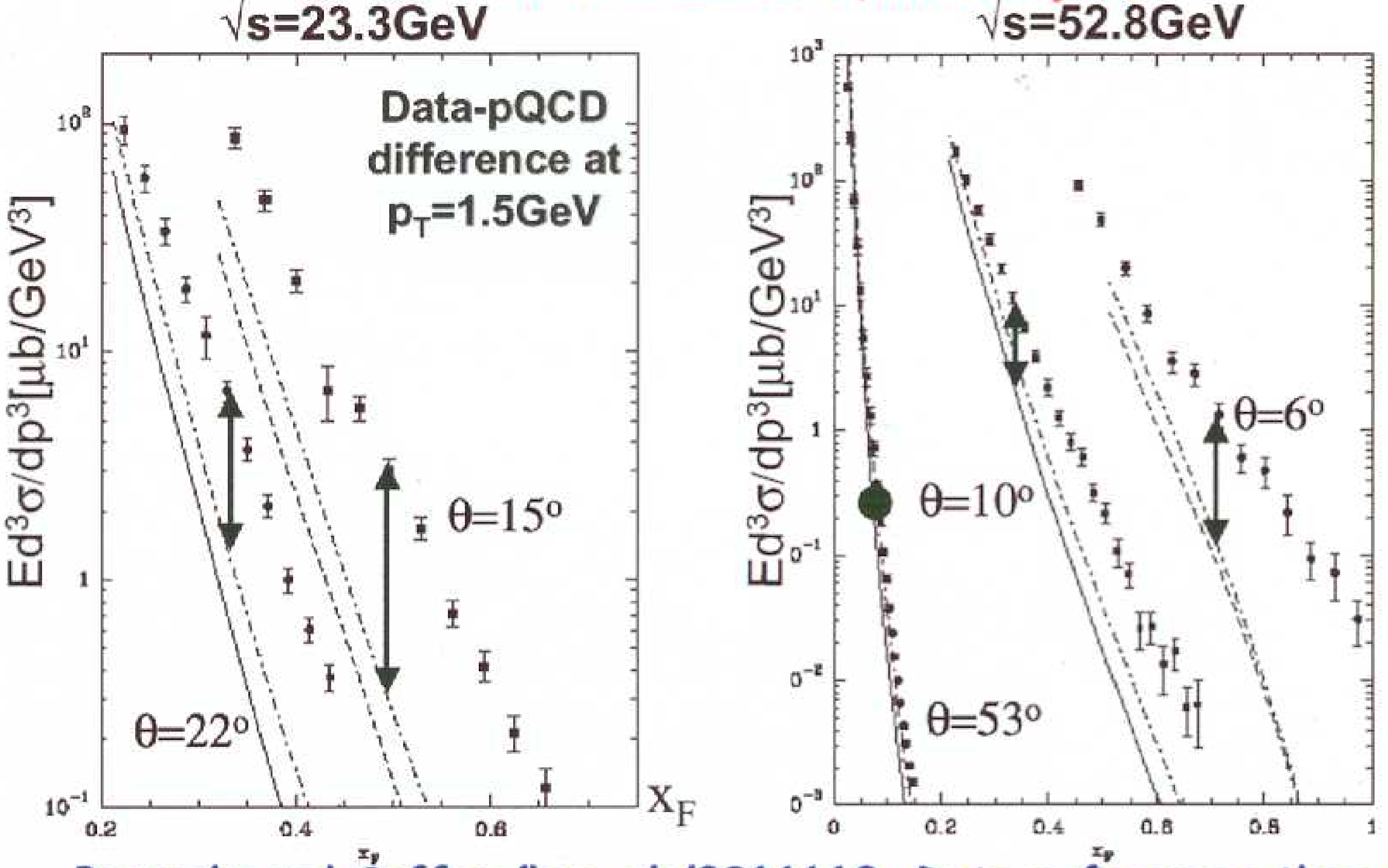


- NLO-pQCD calculation
  - Private communication with W.Vogelsang
  - CTEQ6M PDF.
  - direct photon + fragmentation photon
  - Set Renormalization scale and factorization scale pT/2,pT,2pT

The theory calculation shows a good agreement with our result.

But, do we understand forward π^0 production in p + p?

At $\sqrt{s}$ << 200 GeV, not really….



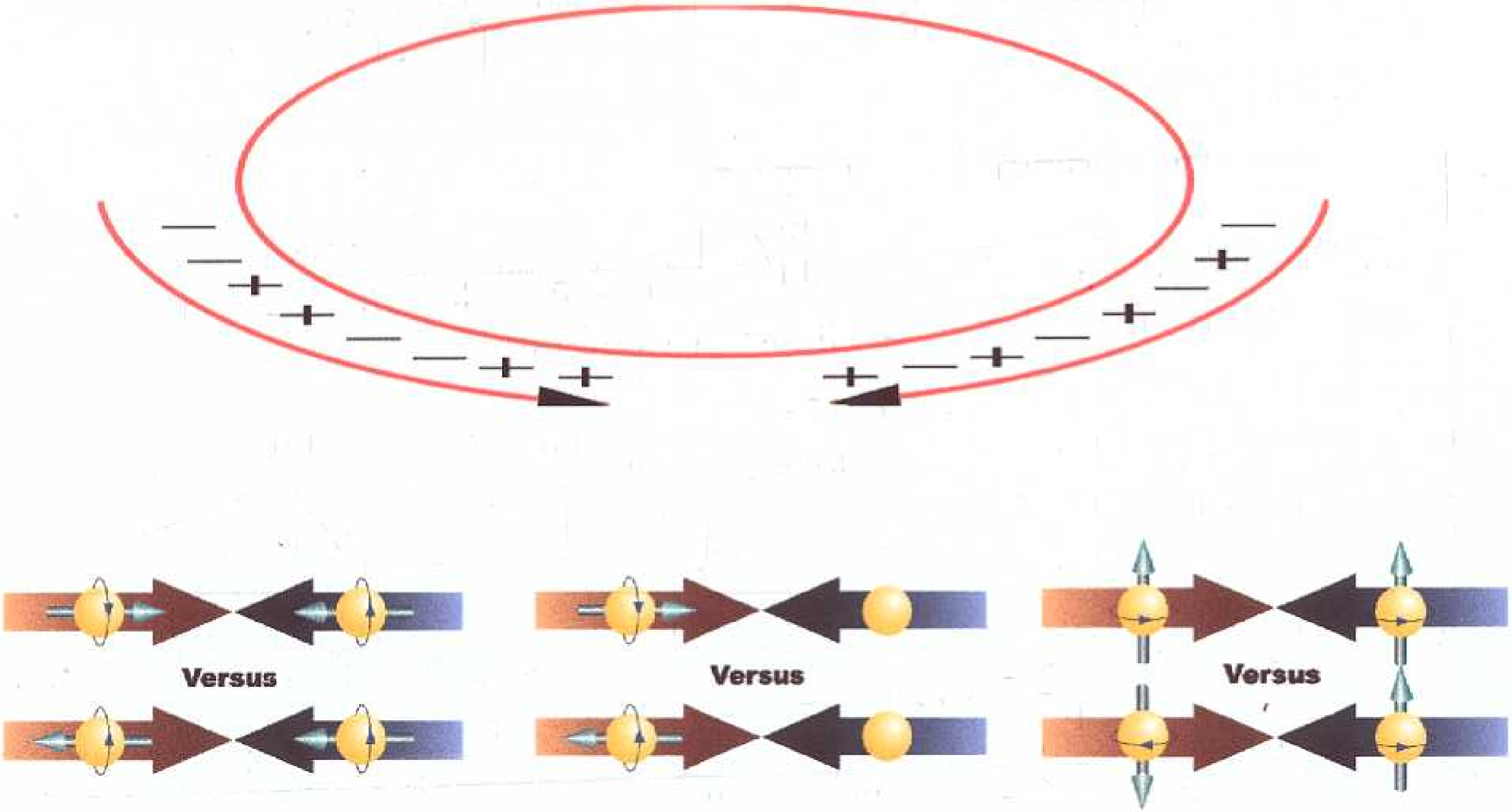
2 NLO collinear calculations with different scale: p_T and $p_T/2$

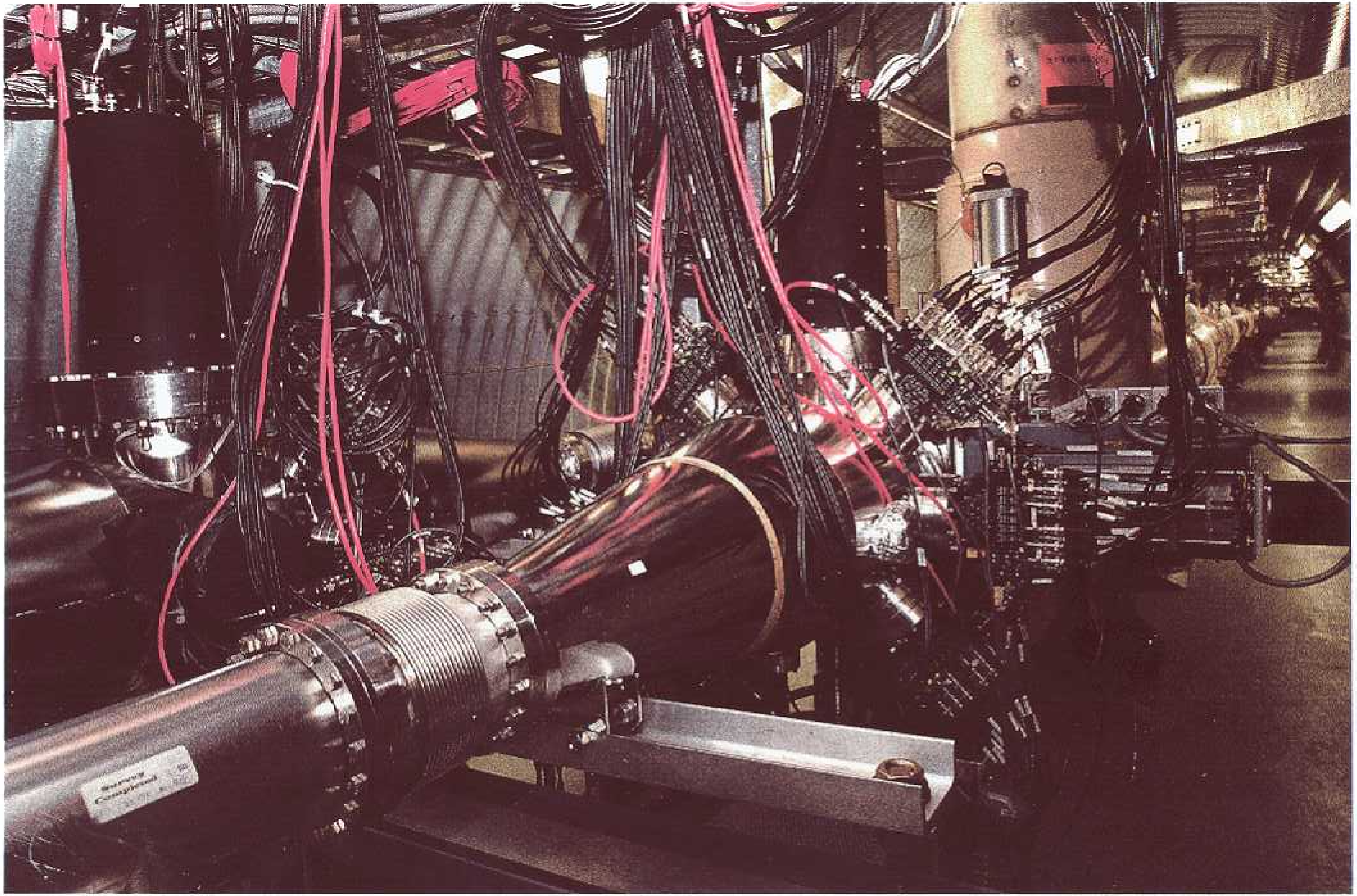
Bourrely and Šoffer (hep-ph/0311110, Data references therein): NLO pQCD calculations underpredict the data at low $\sqrt{s}$ from ISR

$\sigma_{data}/\sigma_{pQCD}$ appears to be function of θ, $\sqrt{s}$ in addition to p_T

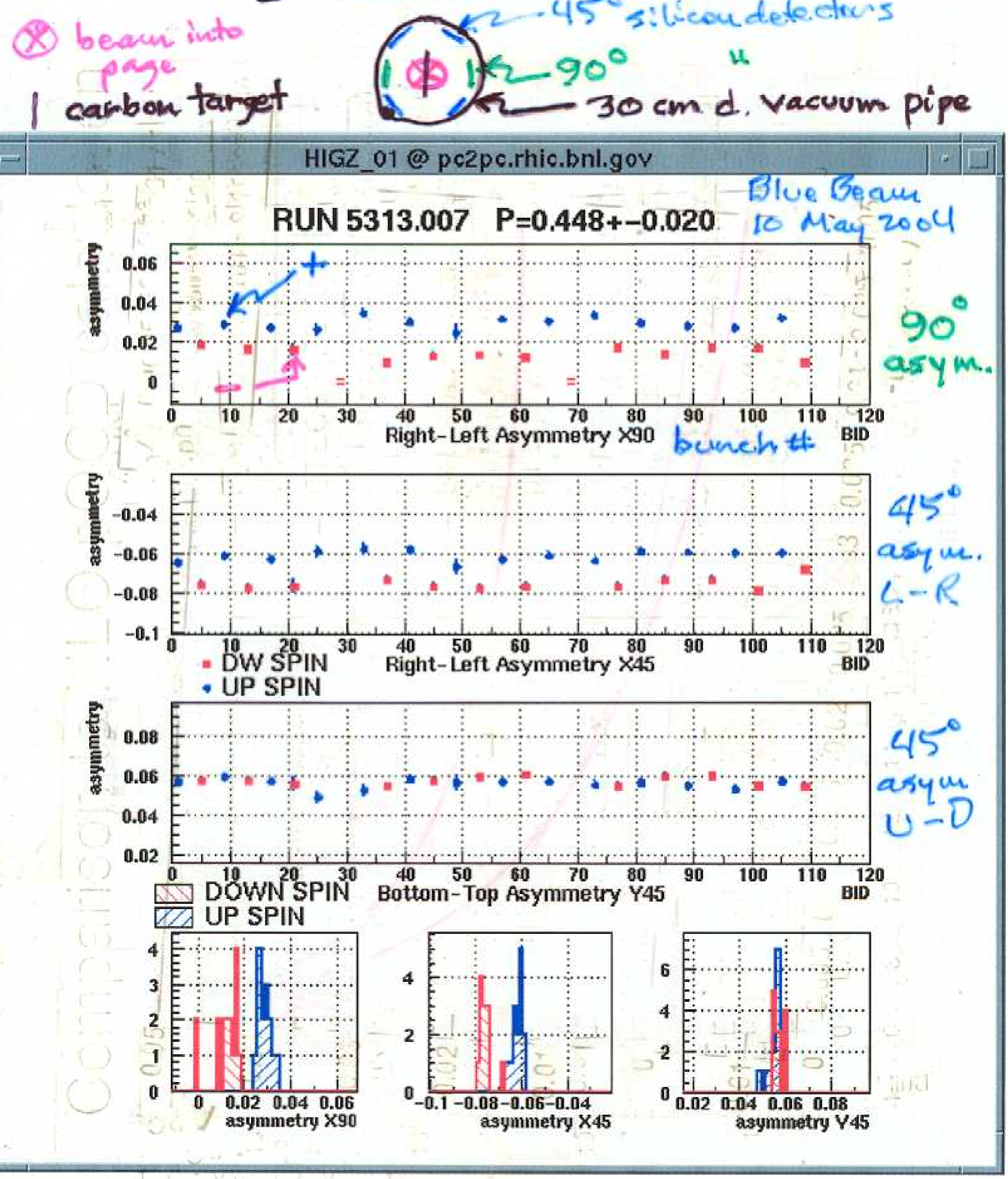
Siberian Snake for AGS: 5% × 180°
-2004

Exquisite Control of Systematics





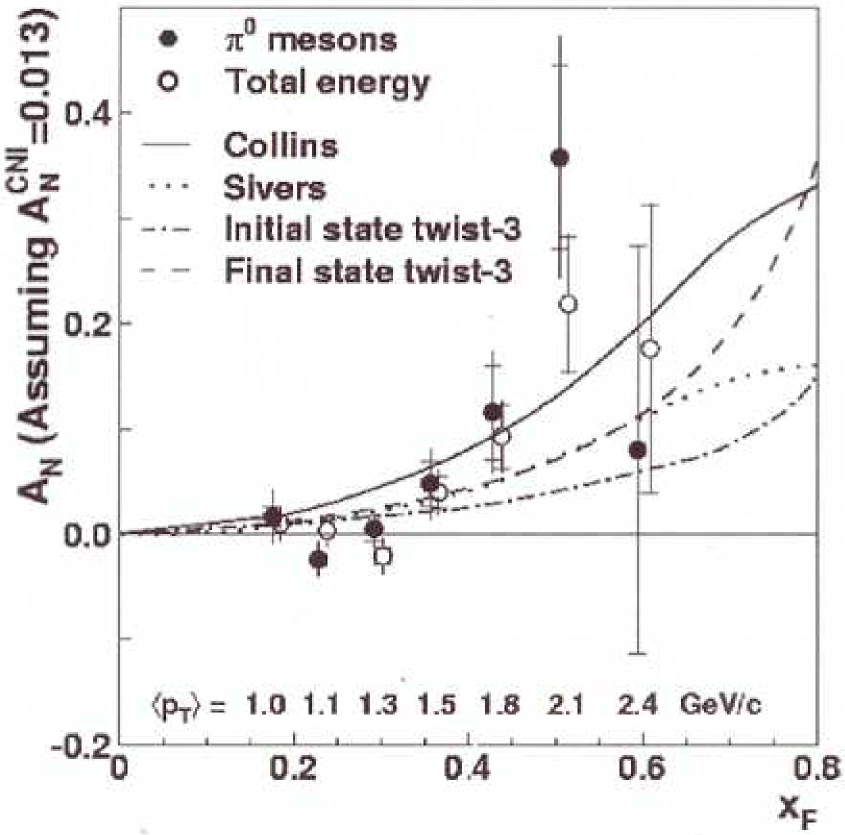
RHIC CNI Polarimeters



First A_N Measurement at STAR

prototype FPD results

STAR collaboration
Phys. Rev. Lett. **92** (2004) 171801



$\sqrt{s}$=200 GeV, <η> = 3.8

Similar to result from E704 experiment ($\sqrt{s}$=20 GeV, 0.5 < p_T < 2.0 GeV/c)

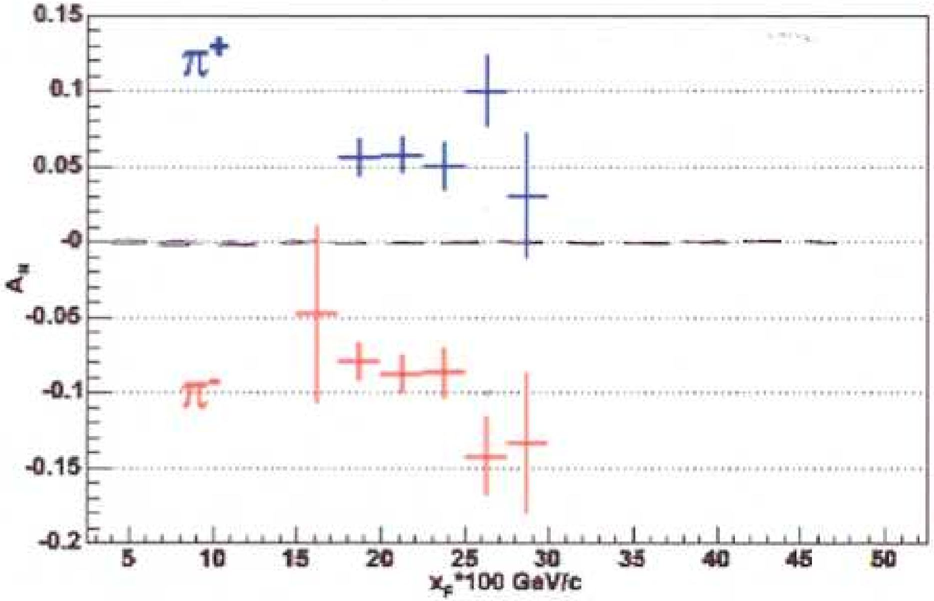
Can be described by several models available as predictions:

- Sivers: spin and $k_\perp$ correlation in parton distribution functions (initial state)
- Collins: spin and $k_\perp$ correlation in fragmentation function (final state)
- Qiu and Sterman (initial state) / Koike (final state): twist-3 pQCD calculations, multi-parton correlations

BRAHMS: 2004 Data $p^{\uparrow}p \to \pi^{\pm}X$

Comparing An for π^+ and π^-

Polarization was ~42% for π^+ measurements and ~38% for π^-.
Systematic scale error on P ~ 20-30%. Will improve final final analysis of CNI and Gas Jet data.



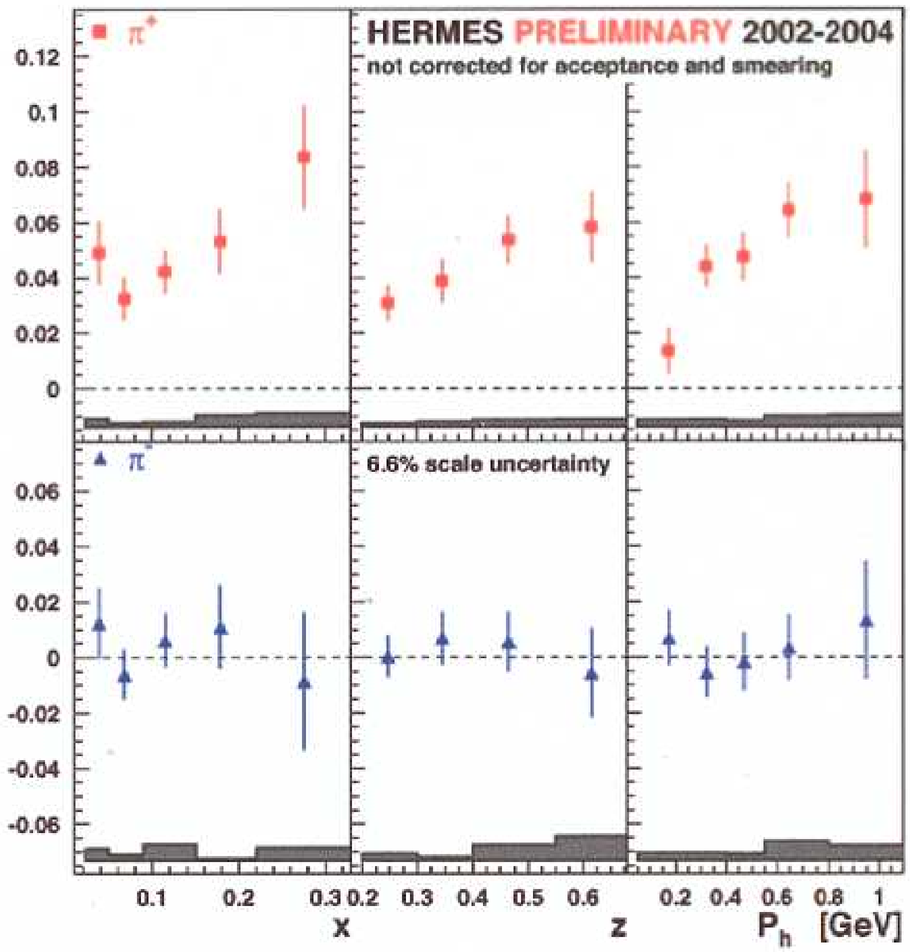
A_N = +0.05 +- 0.005 +- [0.015] in $0.17 < x_F < 0.32$

A_N = -0.08 +- 0.005 +- [0.02] in $0.17 < x_F < 0.32$

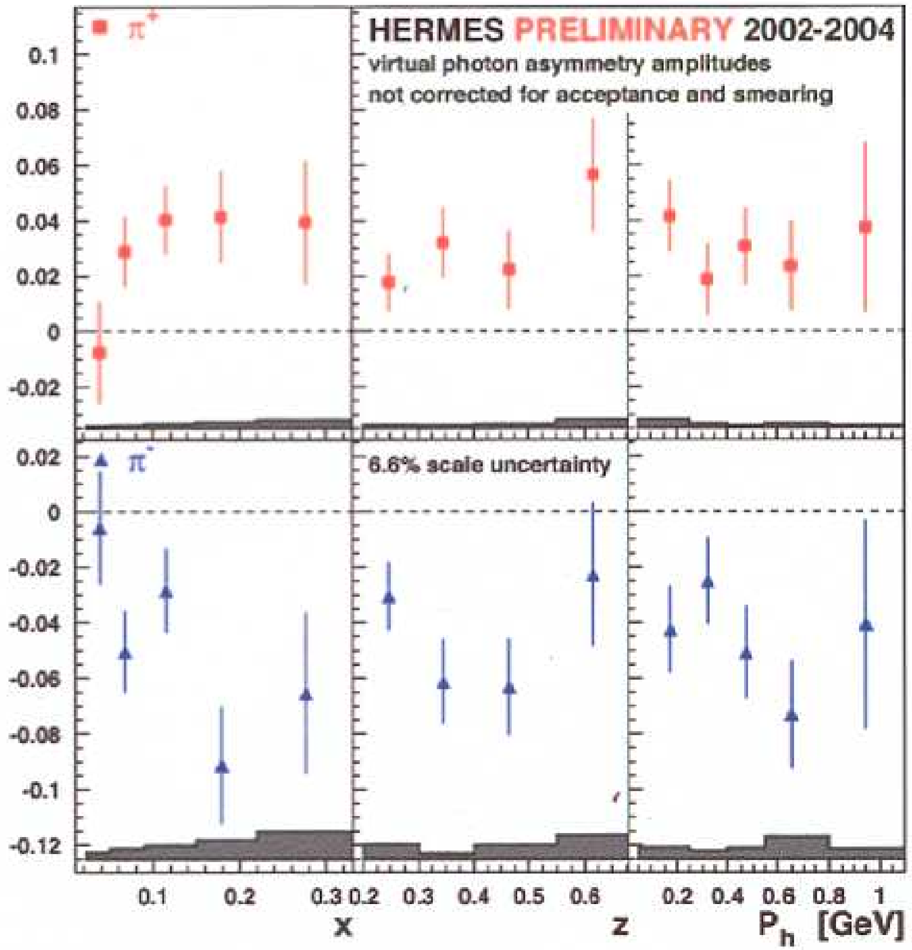
From Fleming Videbaek

New Results from 2002–2004: H$^{\uparrow}$ Target

Sivers Moments for π^+ π^-



Collins Moments for π^+ π^-

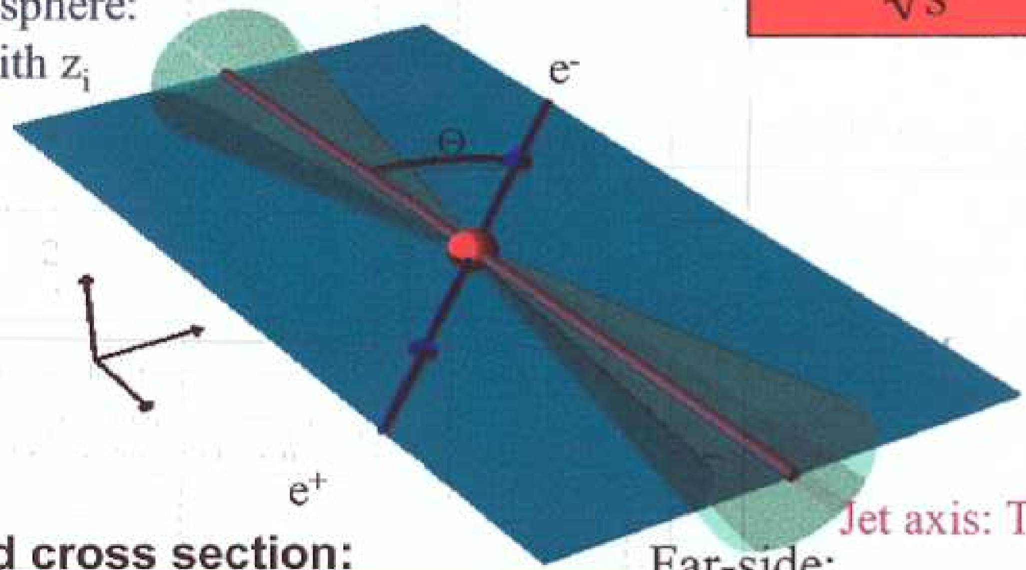


RBRC at Belle: quark analyzing power

e^+e^- CMS frame:

$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\ GeV$$

Near-side Hemisphere:
h_i, $i=1,N_n$ with z_i



$\langle N_{h+,-} \rangle = 6.4$

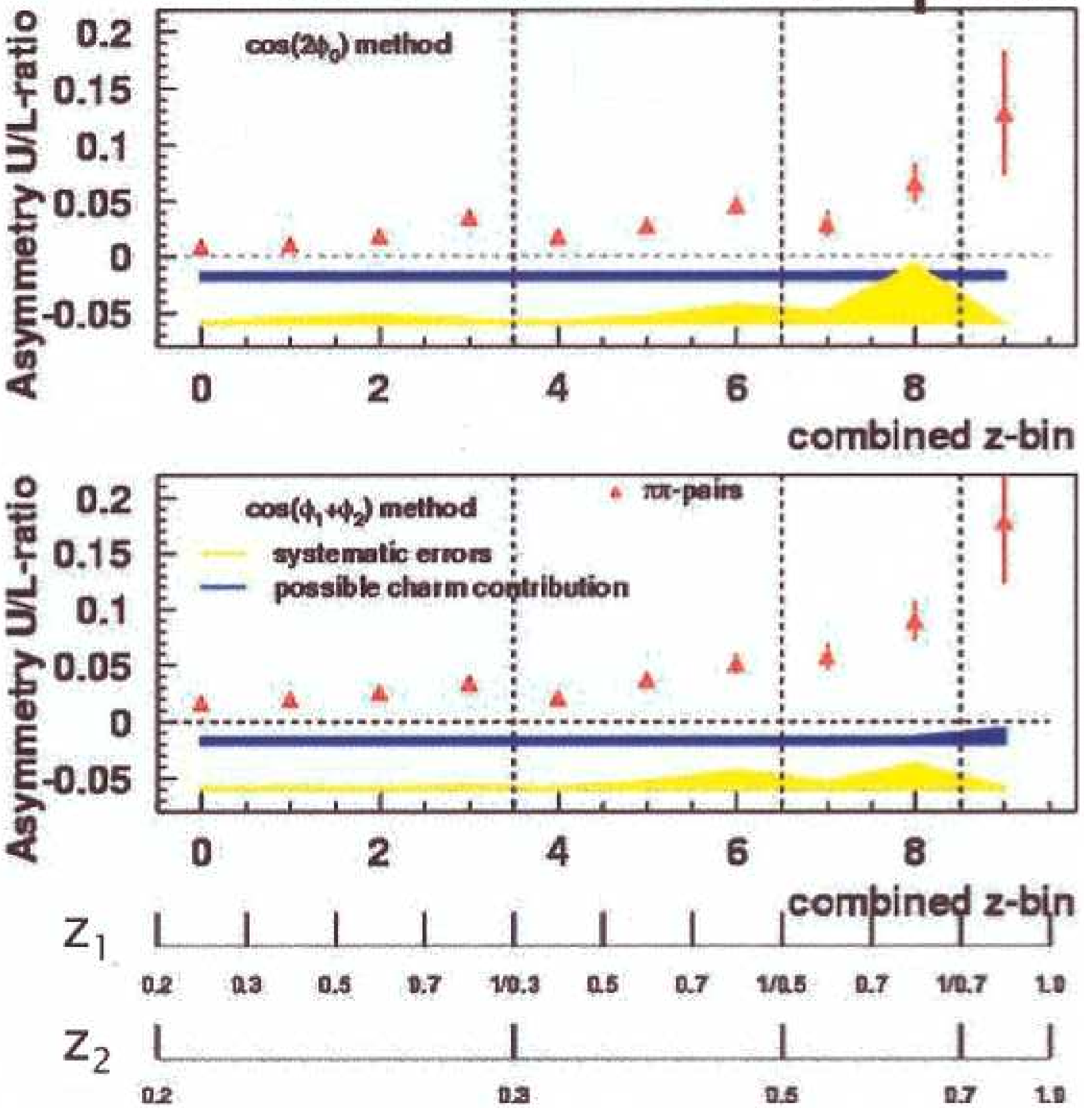
Far-side:
h_j, $j=1,N_f$ with z_j

Spin averaged cross section:

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1) \overline{D}_1(z_2)$$

$$A(y) = \left(\frac{1}{2} - y + y^2\right) \overset{(cm)}{=} \frac{1}{4}\left(1 + \cos^2\Theta\right)$$

Results for π-pairs for $30fb^{-1}$



Ralf Seidl (RBRC) at DIS05, Madison, Wisc. April 05

Quark fragmentation has very large analyzing power!

What have we learned?

Cross sections:

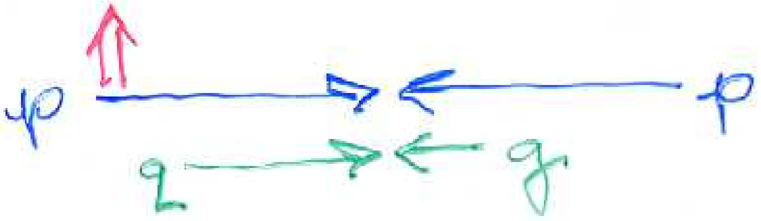
- $\sqrt{s} = 200$ $pp \to \pi^0 X$, $\eta = 0$, $\eta = 4$
  - → described by pQCD (NLO)
    - down to $p_T \cong 1.5$ GeV/c (!)
- $\sqrt{s} < 50$ → not
  - → but k_T → does
  - →  → may

  } crucial to exploit fixed target!

  - also: asymmetry K factors <u>can</u> be small

Asymmetries:

- $\sqrt{s} = 200$ $p\Uparrow p \to \pi X$
  - → A_N <u>large</u> in forward region
  - ⇒ in pQCD region there are <u>large</u> asymmetries.
    - → this statement has been a long time in coming!



} forward π^0 production

- can be from H-C or Sivers
- for quark
- $\langle z_{\pi^0} \rangle \simeq 0.8 \Rightarrow \pi^0 = \text{jet} \Rightarrow$ Sivers
- prediction that H-C must be small (Mungia)

- BRAHMS observes mirror (π^+, π^-) A_N (like E704 at $\sqrt{s} = 20$)

$\Rightarrow$ are the fixed target asymmetries also from hard scattering?!

$\Rightarrow$ implication for fixed target SIDIS

- SIDIS
  - large q Sivers for π^+, p⇑ tgt
  - zero " for π^-, p⇑ tgt
  - zero " for π^+, π^-, d⇑ tgt

    $\Rightarrow$ large q Sivers for u, d

    $\Rightarrow$ cancellations for p⇑ π^-, d⇑ $\pi^\pm$

- large (transv. × H-C), both $\pi^{\pm}$, $p^{\Uparrow}$
- zero " " , $d^{\Uparrow}$

⇒ transversity large!

⇒ $q^{\Uparrow} \rightarrow \pi(\phi)$ large! (A_{H-C})

$e^+e^- \rightarrow q\bar{q}$

- A_{H-C}(jet 1) × A_{H-C}(jet 2) ≈ .05

⇒ $A_{H-C} \approx 20\%$!

- still preliminary but SIDIS $p^{\Uparrow}$ result!

So...

- gluon Sivers small ($x \sim .1$, $x \sim 10^{-2}$, 10^{-3})
- quark Sivers large
- transversity large
- Heppelmann-Collins large
- some <u>are</u> and all <u>may</u> be in hard scattering domain

and where we're going

Where to? Experiment:

planned –

- revisit large fixed target asymmetries and polarizations and spin transfer!
- COMPASS with $p^{\Uparrow}$
- SIDIS π^0 ; $2\times$ statistics
- k_T using 2 jets (2 hadrons) at RHIC
- ($W^{\pm}$ (A_{N}) with transverse P at RHIC)
- P_{Λ} at COMPASS, Hermes, RHIC
- large forward e-m spectrometer at STAR
- interference frag. at COMPASS, Hermes

"Future" –

- we now know that these spin signals are <u>large</u>!

→ exploit the e^+e^- data!

→ exploit PID and luminosity available at fixed target

→ $p^{\Uparrow}\overset{(-)}{p}{}^{\Uparrow}$ → Drell-Yan → transversity

$p^{\Uparrow}p$ → D-Y
↳ Sivers

→ $e \longrightarrow \; \longleftarrow\!\!\Uparrow\!\! - \, p$

The "gold standard": $q^{\Uparrow} \to h(\phi)$

The "gold mine":

$$\pi(\phi) \longleftarrow \bullet \longrightarrow K, \Lambda(\phi)$$

$$K, \overset{(-)}{\Lambda}(\phi) \longleftarrow \bullet \longrightarrow K, \Lambda(\phi)$$

$$\pi(\phi) \longleftarrow \bullet \longrightarrow \Lambda^{\Uparrow}$$

$$K, \overset{(-)}{\Lambda}(\phi) \longleftarrow \bullet \longrightarrow \Lambda^{\Uparrow}$$

$$\overset{(-)}{\Lambda}(\phi) \longleftarrow \bullet \longrightarrow \Lambda^{\Uparrow}$$

$$\Lambda \longleftarrow \bullet \longrightarrow \Xi$$

$u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, $b\bar{b}$

π, K, φ, Λ, Ξ, ρ, ...

unpolarized FF, polarized

...

Where to? Theory

- L   GPDs; L ⇄ Sivers
- models → QCD
  - pQCD and lattice
  - how to exploit new field of fragmentation analyzing power?!
    $q^{\Uparrow} \rightarrow h(\phi)$ is bare QCD!
- connections between Sivers and Heppelmann-Collins and Transversity?
- huge spin effects cannot have complicated origins!

Toward understanding this structure!

Spin is one of the most fundamental concepts in physics, deeply rooted in Poincare invariance and hence in the structure of space-time itself. All elementary particles we know today carry spin, among them the particles that are subject to the strong interactions, the spin ½ quarks and the spin 1 gluons. Spin, therefore, plays a central role also in our theory of the strong interactions, QCD, and to understand spin phenomena in QCD will help to understand QCD itself. — from RHIC Spin Report spin.riken.bnl.gov/rsc/

To contribute to this understanding is the primary goal of the spin physics program at RHIC.