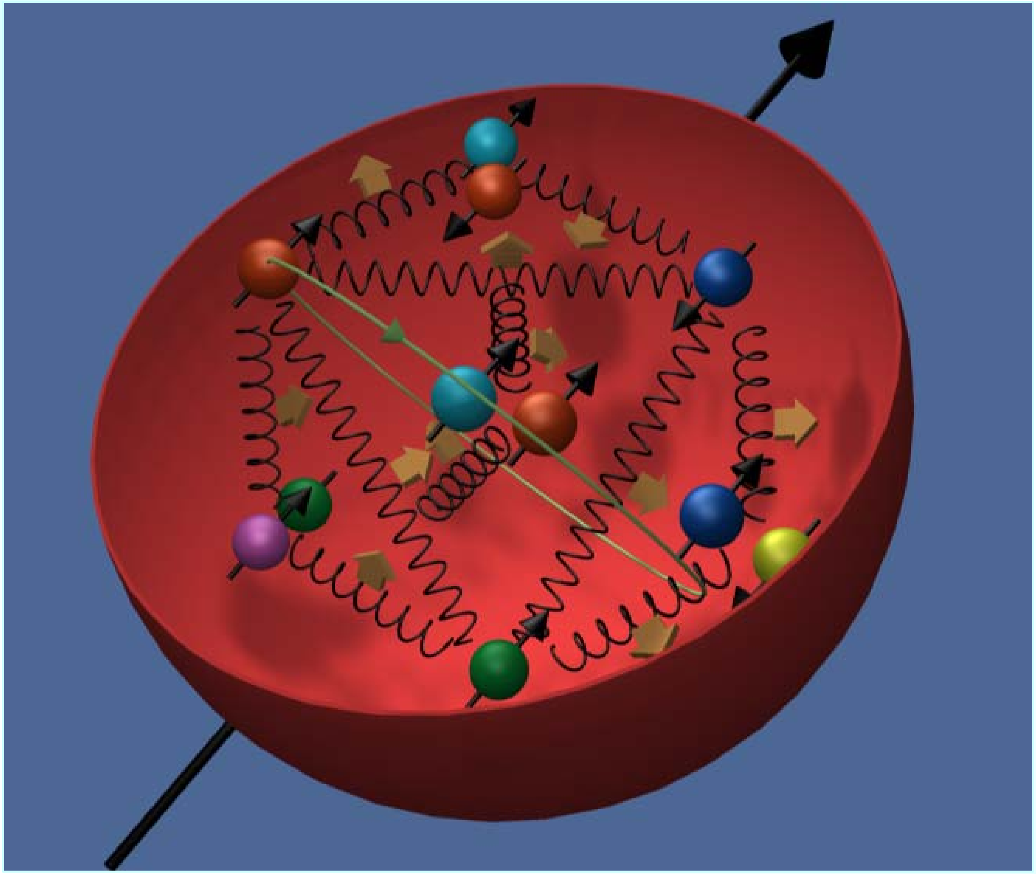
Selected spin physics results from COMPASS, HERMES and RHIC

K. Rith, CIPANP06, 2.6.2006



$s_z = \frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q + (\Delta G + L_g)$

COMPASS

hermes

BRAHMS

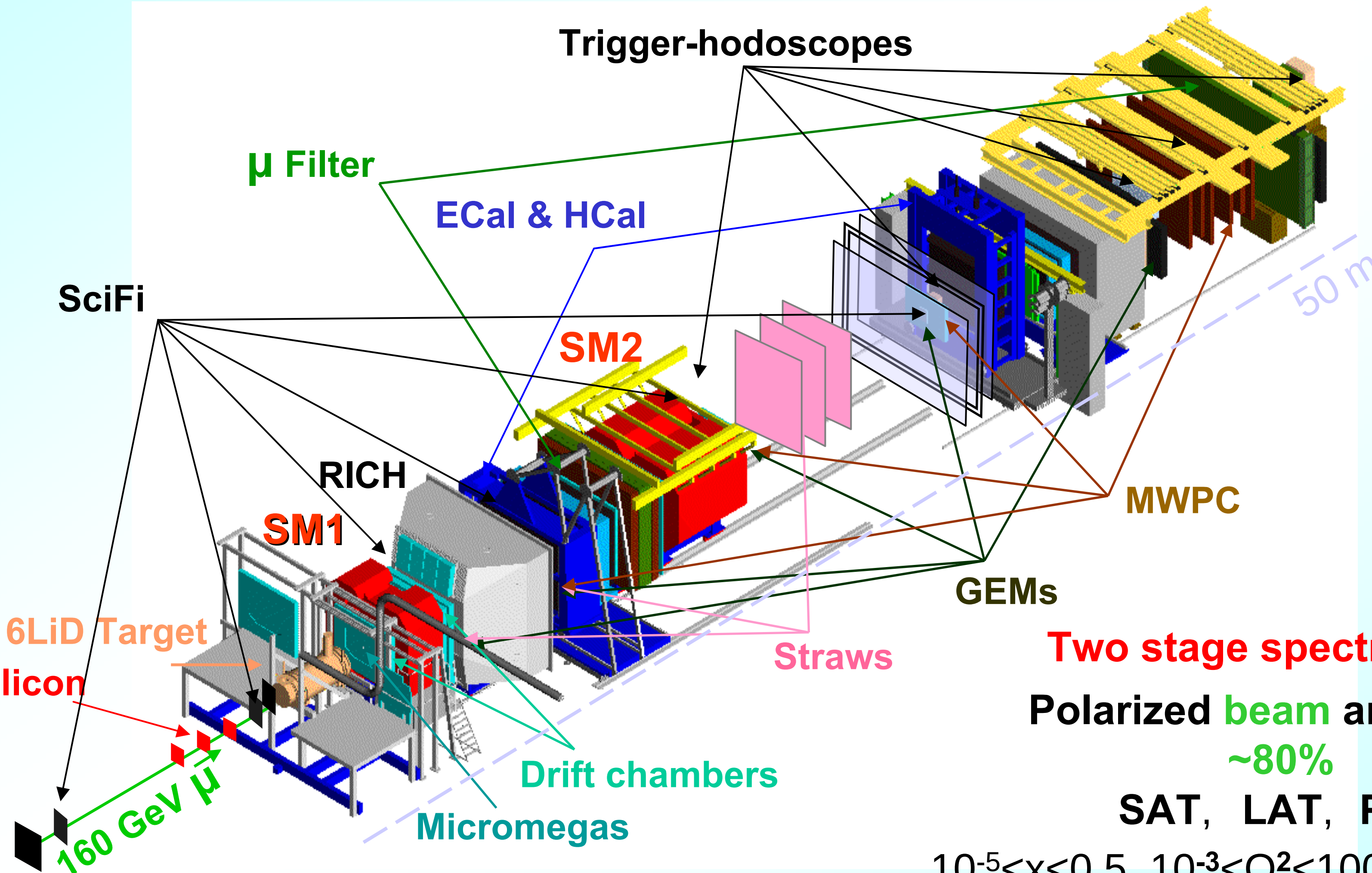
PHENIX

STAR

Outline

- The Experiments
- Inclusive Asymmetries
- Quark helicity distributions
- Gluon helicity distribution
- (Exclusive processes → GPDs) ➡ M. Garcon
- Transverse spin physics
  - Transversity – Collins fragmentation function
  - Sivers distribution function
  - A_N in pp collisions
- Conclusions

COMPASS



Two stage spectrometer

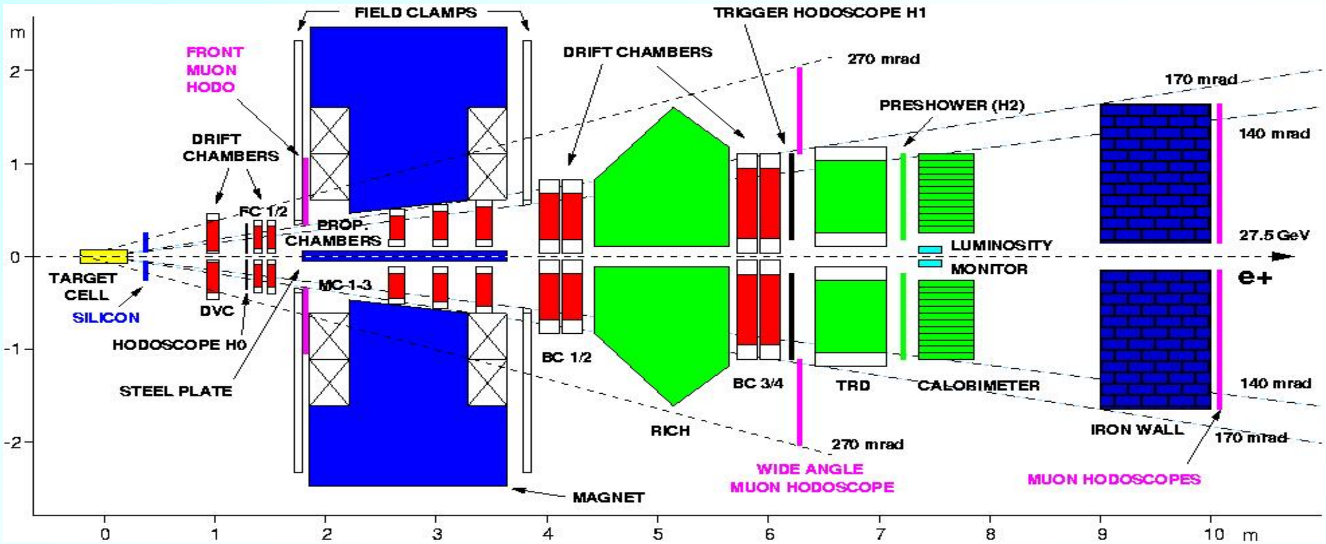
Polarized beam and target

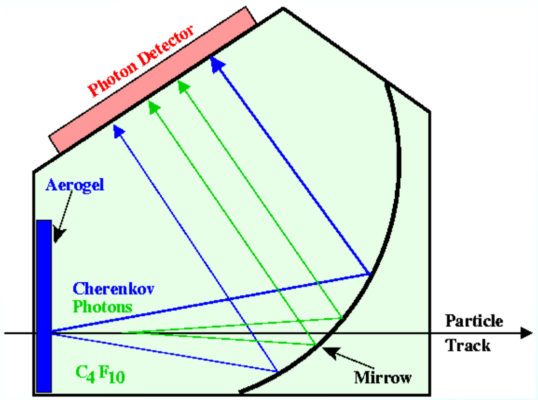
~80% ≥50%

SAT, LAT, PID

$10^{-5} < x < 0.5$, $10^{-3} < Q^2 < 100\ (\mathrm{GeV}/c)^2$

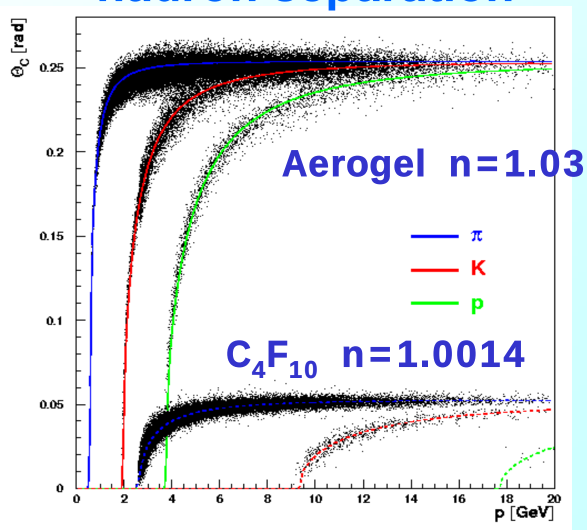
HERMES



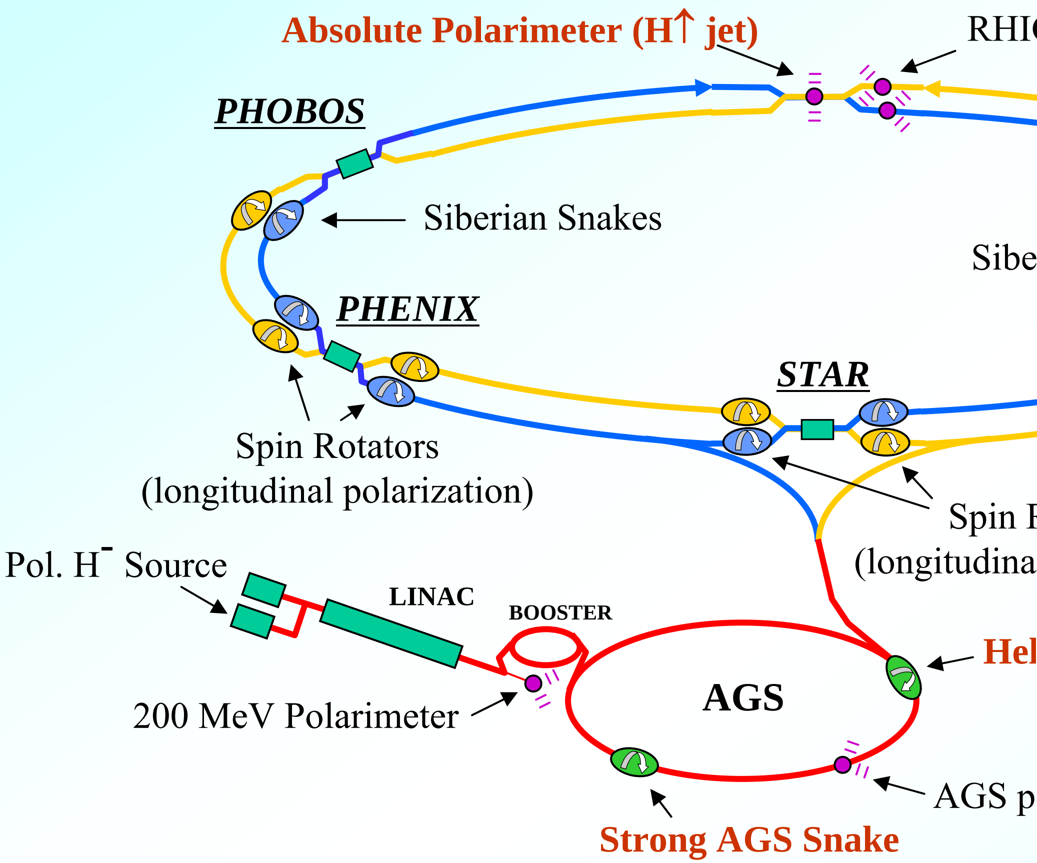


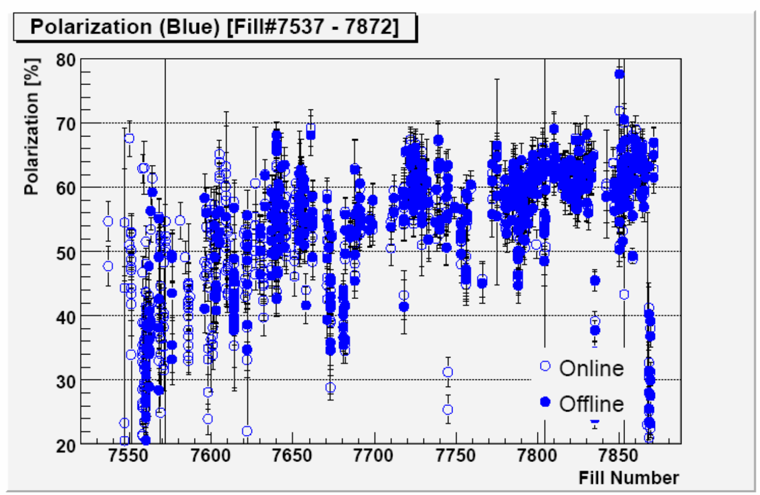
- HERA e+/e- beam of 27.6 GeV
- Polarized internal gas target (H, D, ^{3}He)
- kinematics: $0.02<x<0.6$, $1.0<Q^2<15$ GeV^2
- tracking: $\delta p/p \sim 2\%$, $\delta\Theta<0.6$ mrad, 40-220 mrad
- PID: Calorimeter, Preshower, TRD, RICH

hadron separation



RHIC-Polarized Collider



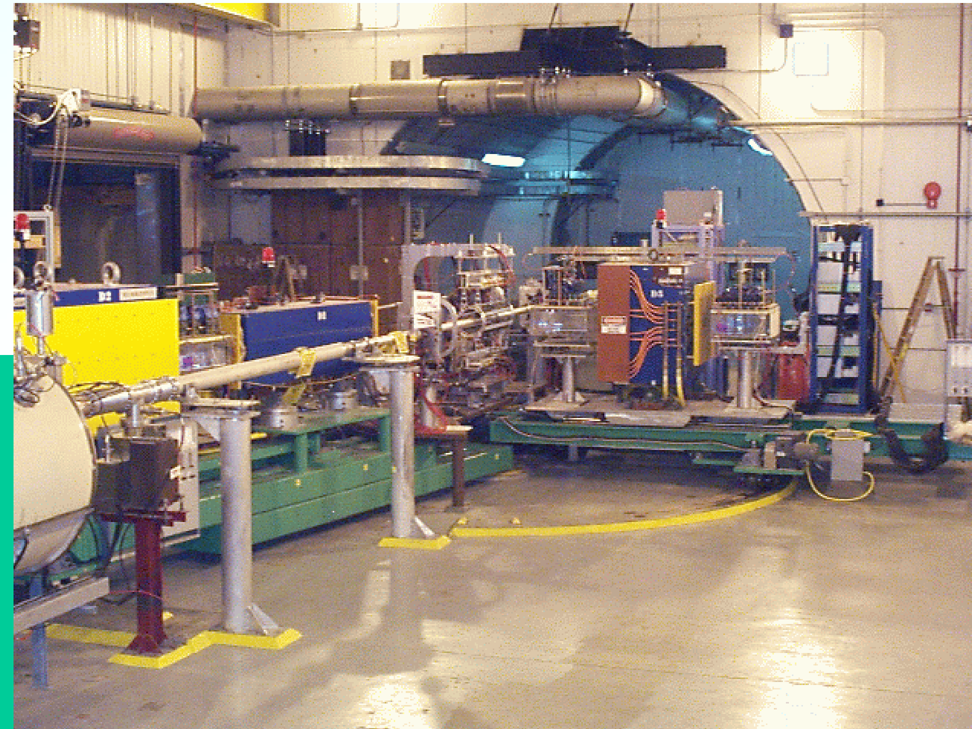


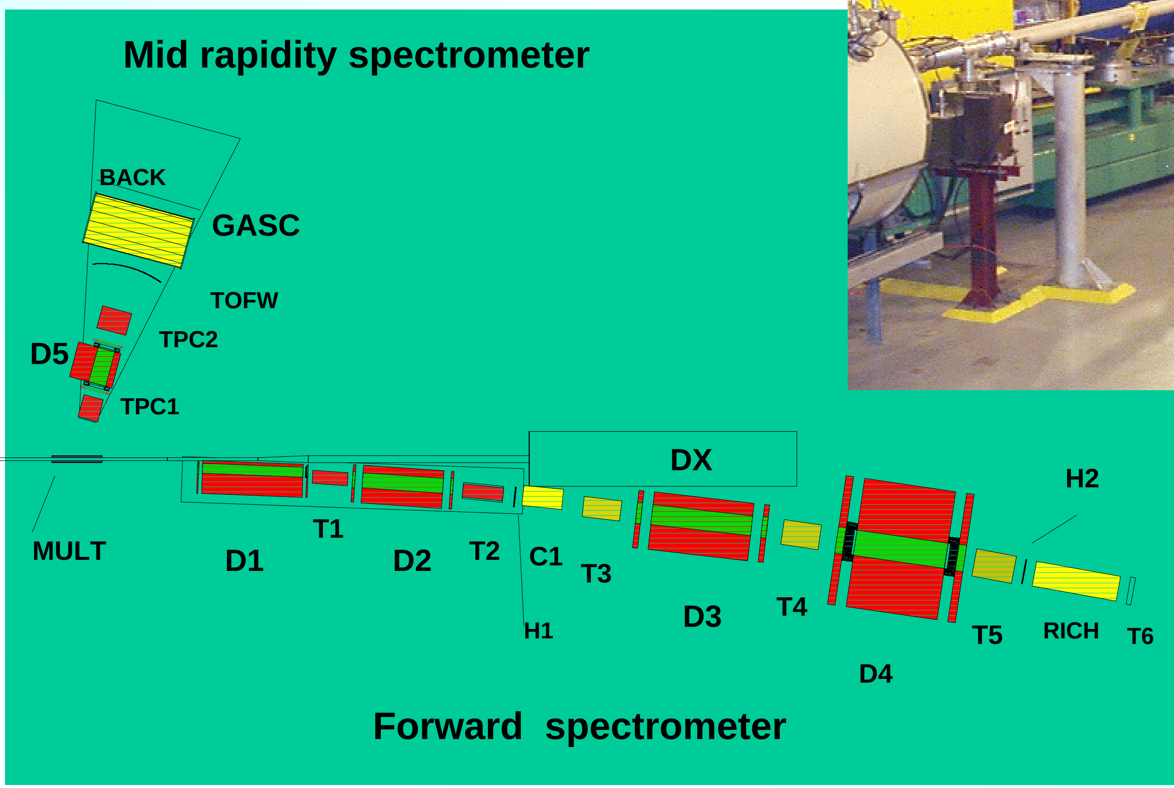
2006: 1 MHz collision rate; P~0.6

Congratulations!!!

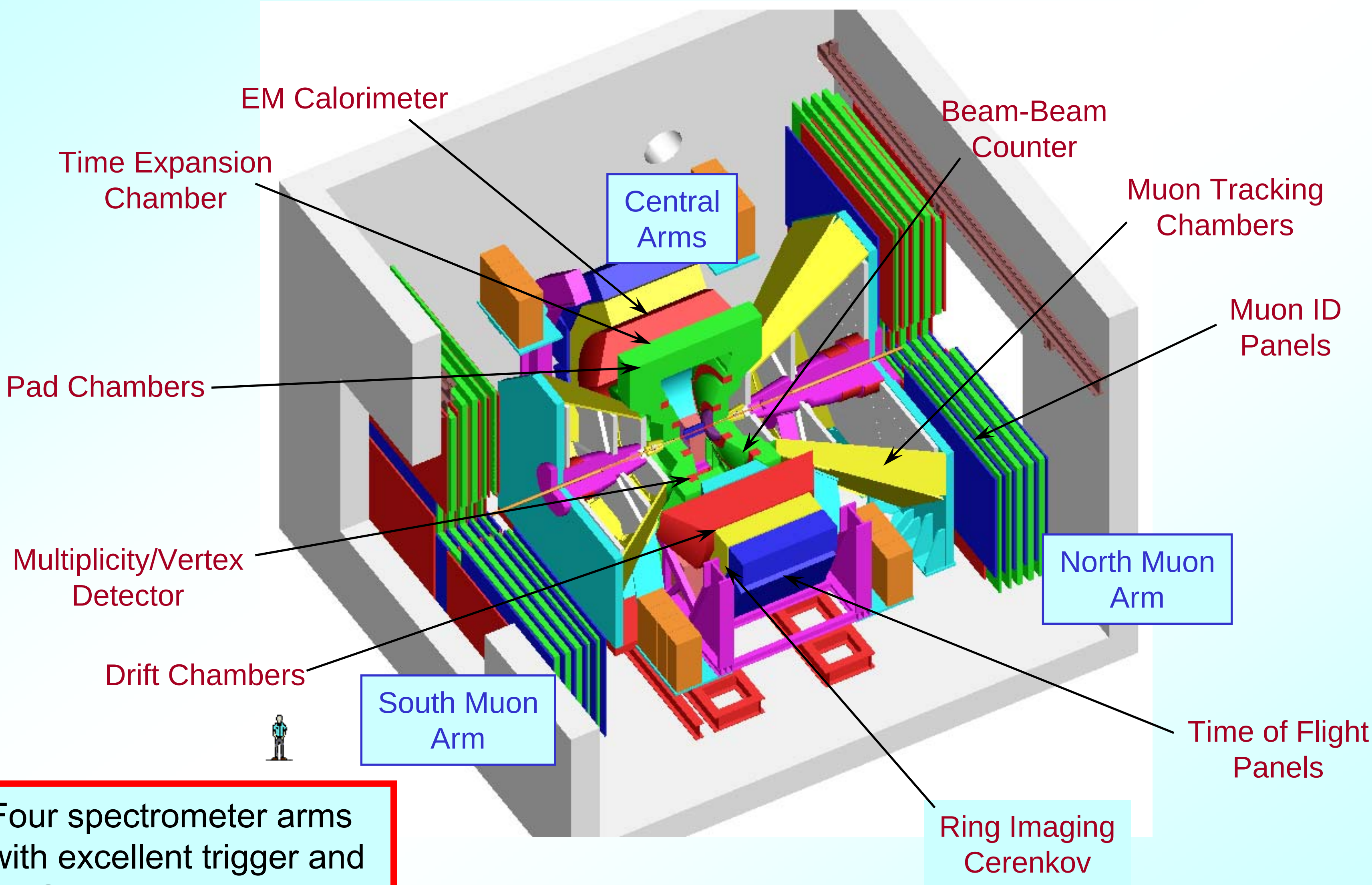
BRAHMS

100% transverse spin!
Two spectrometer arms with good particle ID at high momenta



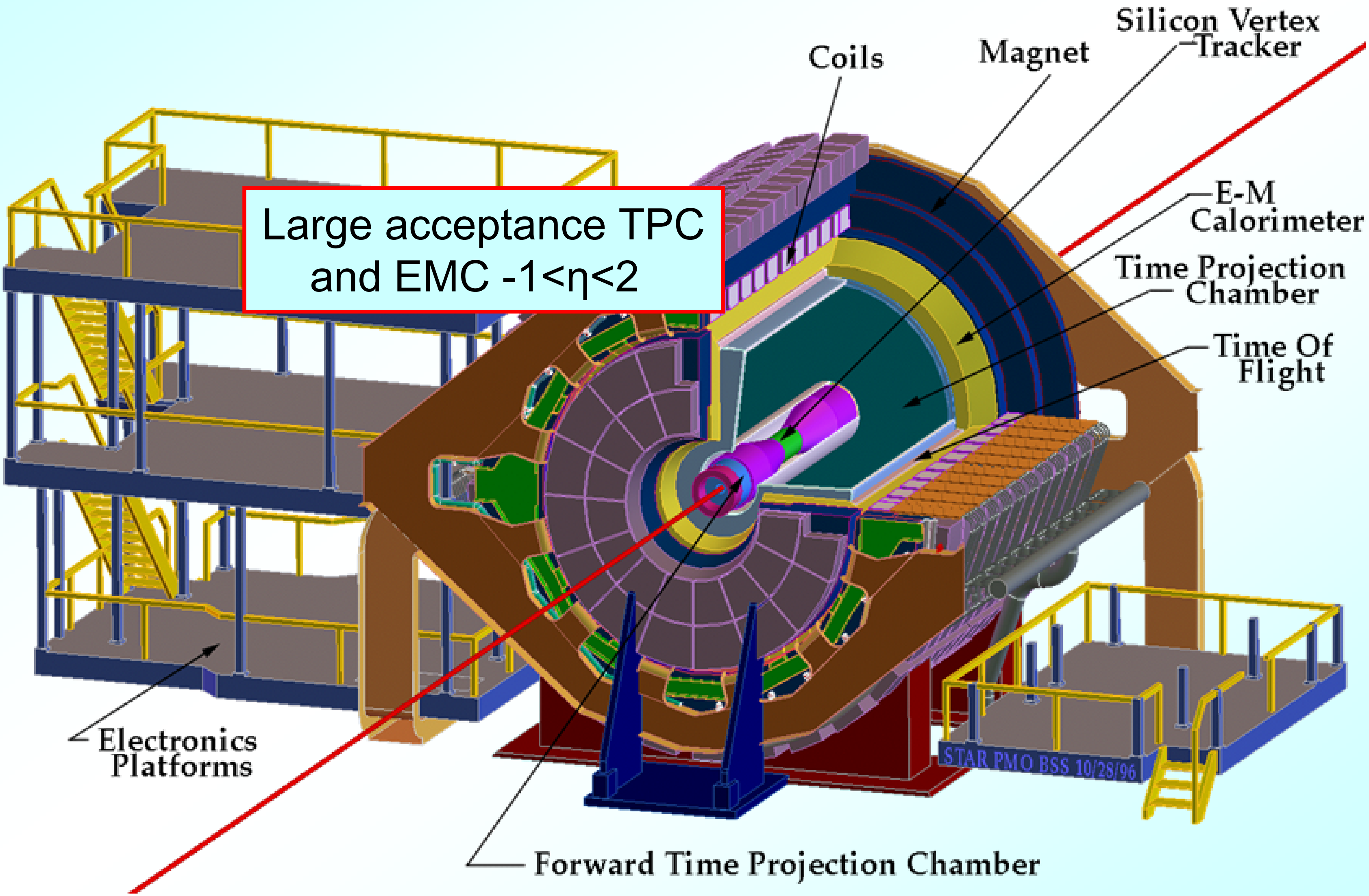


PHENIX

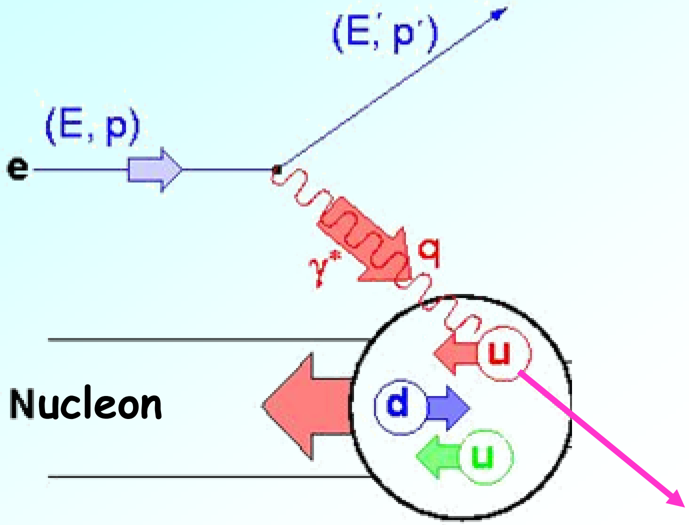


Four spectrometer arms with excellent trigger and DAQ capabilities.

Large acceptance TPC and EMC -1<η<2



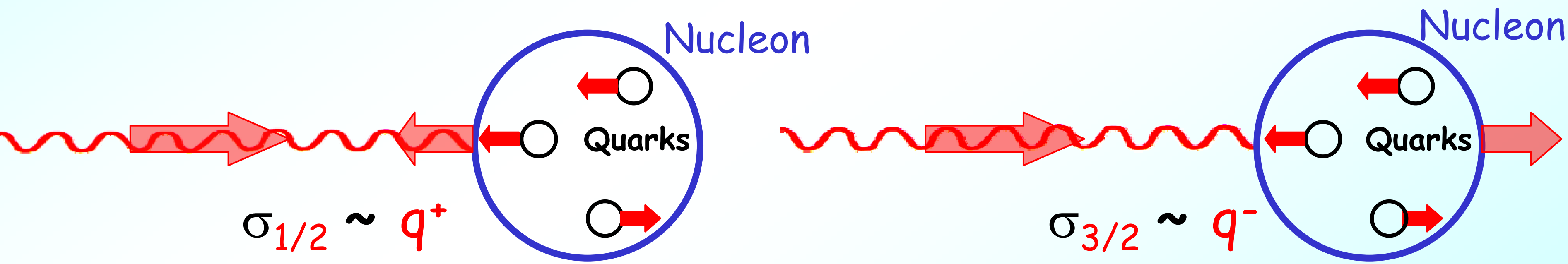
Spin-dependent DIS



$\nu = E - E'$

$Q^2 = -q^2$

$x = Q^2/(2M\nu)$ = fraction of nucleon's momentum carried by struck quark



$\sigma_{1/2} \sim q^+$ $\sigma_{3/2} \sim q^-$

Helicity DF: $\Delta q(x) := q^+(x) - q^-(x)$

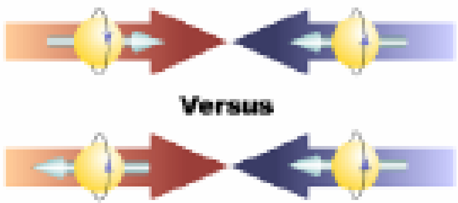
Asymmetry: $A_1 = \dfrac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \cong \dfrac{g_1}{F_1}$

$$g_1(x) := \tfrac{1}{2} \sum_q z_q^2 \, \Delta q(x)$$

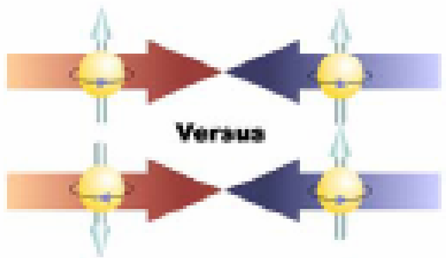
$$F_1(x) := \tfrac{1}{2} \sum_q z_q^2 \, q(x)$$

Asymmetries in polarized pp collisions

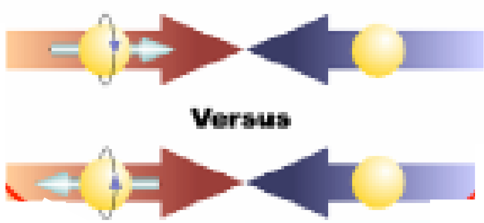
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



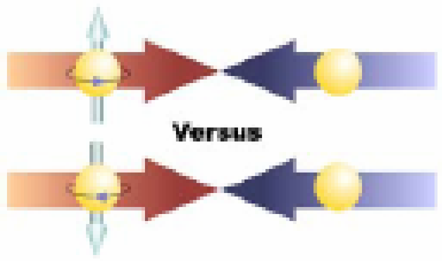
$$A_{TT} = \frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}$$



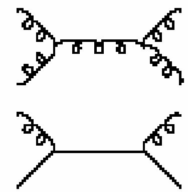
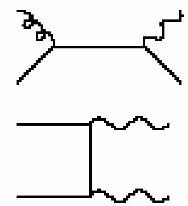
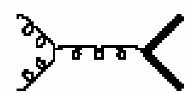
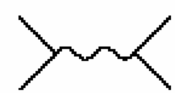
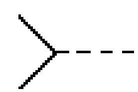
$$A_{L} = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)}$$



$$A_{T} = \frac{\sigma(\uparrow)-\sigma(\downarrow)}{\sigma(\uparrow)+\sigma(\downarrow)}$$



Parton helicity distributions from polarized pp

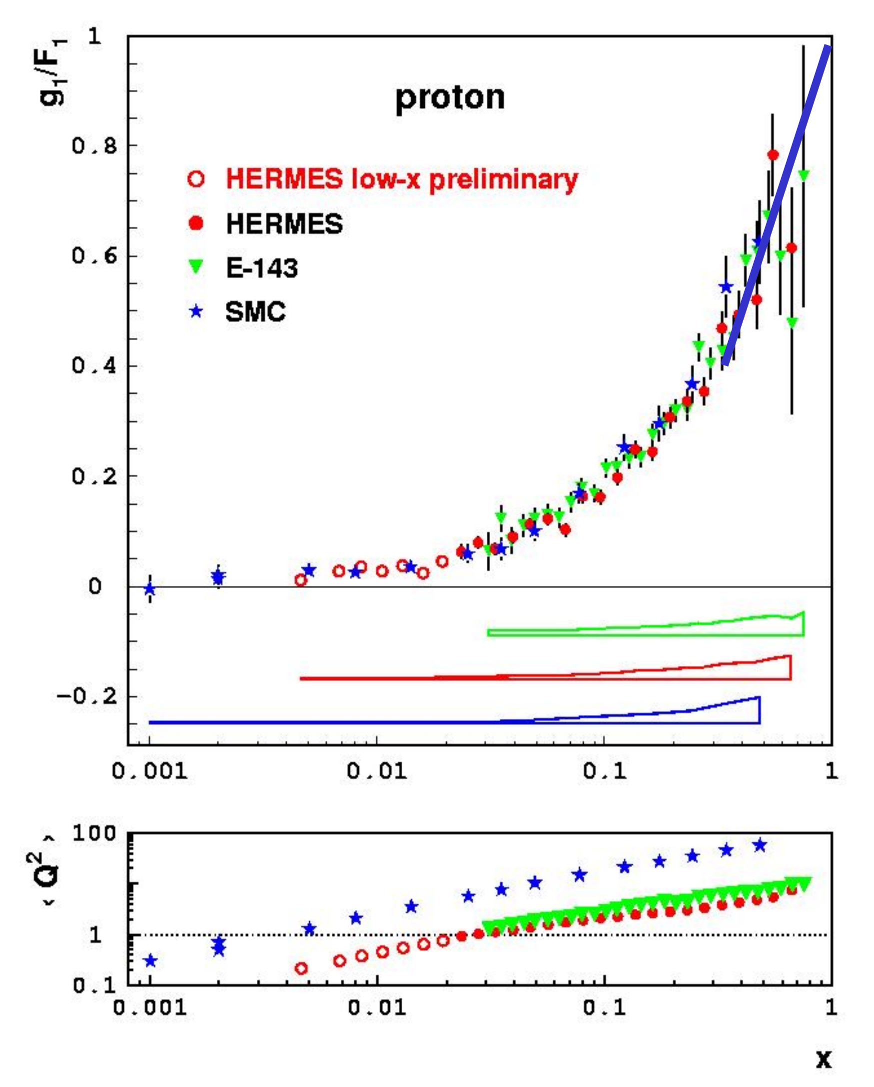
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan)	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm,\ q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	

Δg

Δq

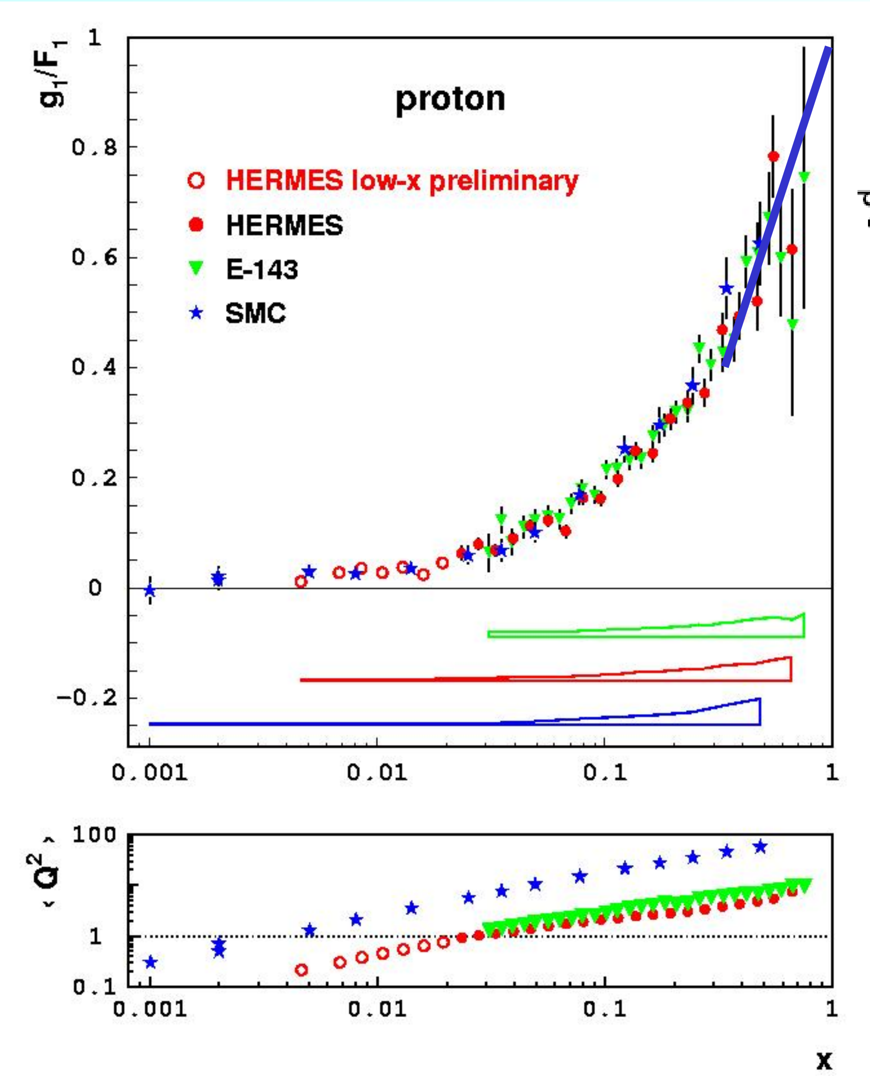
Inclusive asymmetries in DIS

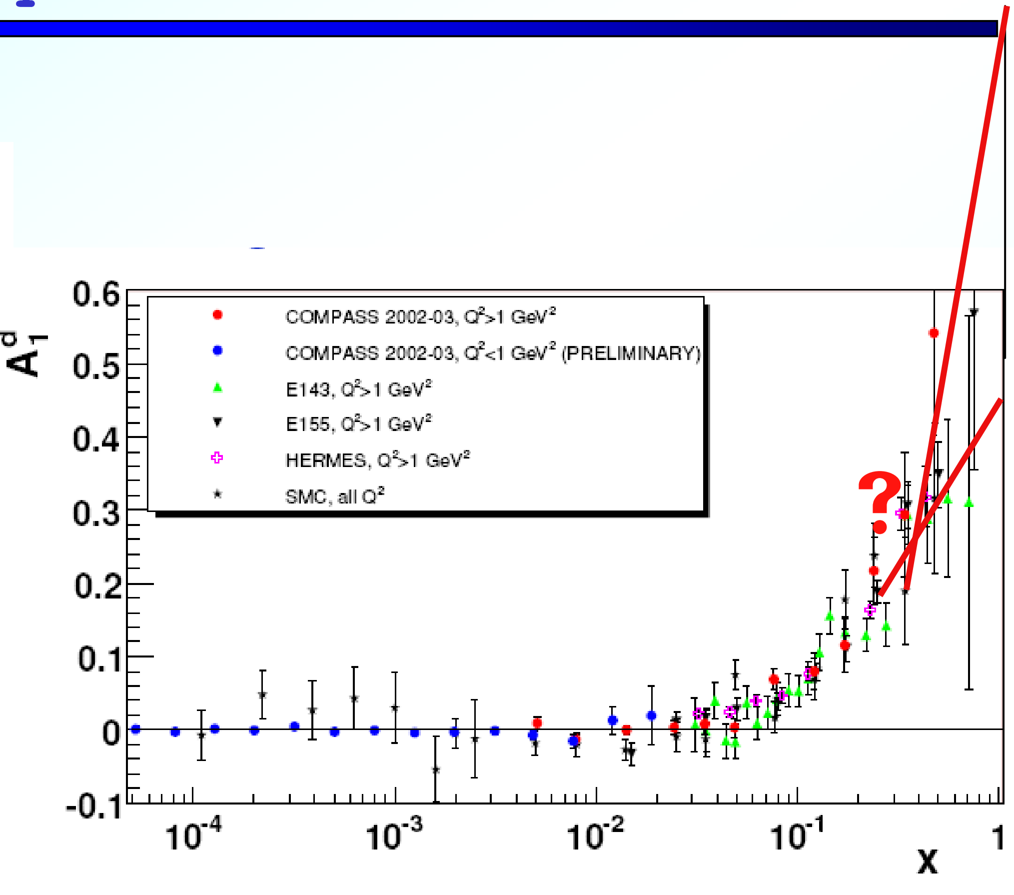
$A_1 \cong g_1/F_1$ - Proton



- g_1^p/F_1^p well known for $x \searrow 10^{-3}$
- Excellent agreement between all experiments
- g_1^p/F_1^p (within errors) ‚independent' of Q^2, accuracy still insufficient to confirm Q2 dependence predicted by QCD
- $\langle Q^2 \rangle = f(x)$
- Extrapolation to $x \to 0$ for $Q^2 = Q_0^2$?
- $g_1^p/F_1^p \to 1$ for $x \to 1$

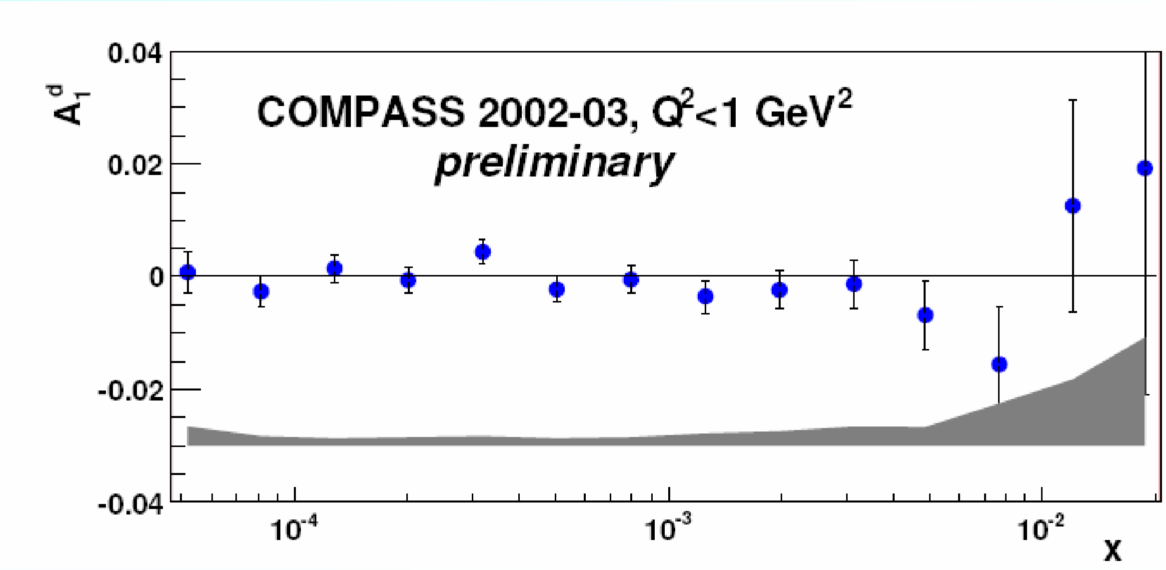
$A_1 \cong g_1/F_1$ - Proton and Deuteron

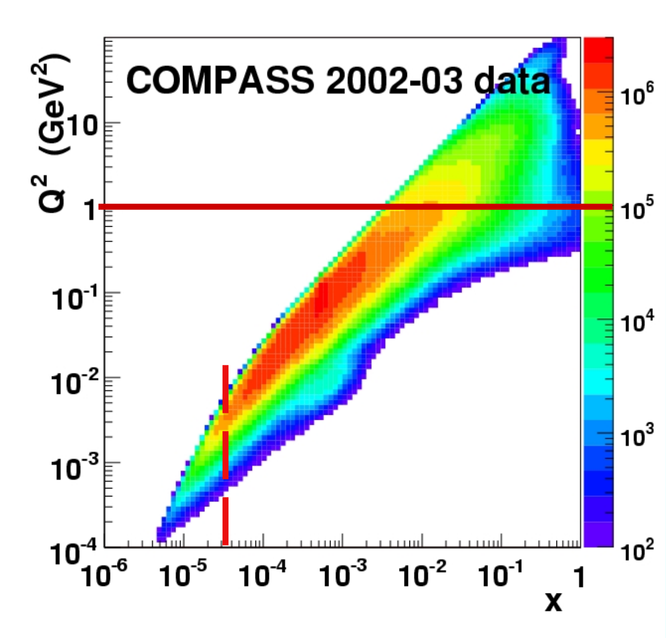


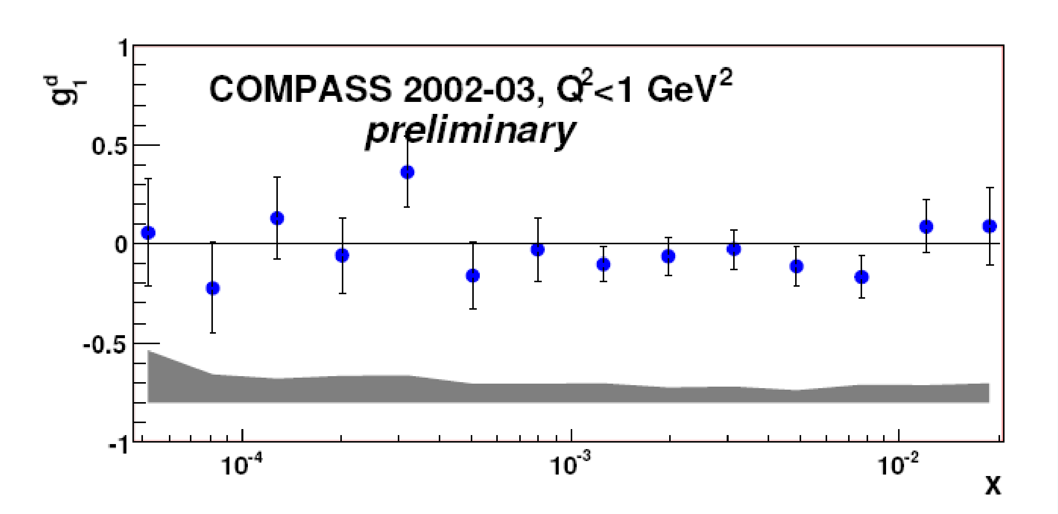


- A_1^d vanishes below x = 0.05
- $A_1^d \to ?$ for $x \to 1$
- High x: JLAB-12 GeV

A_1^d and g_1^d at low x and Q^2







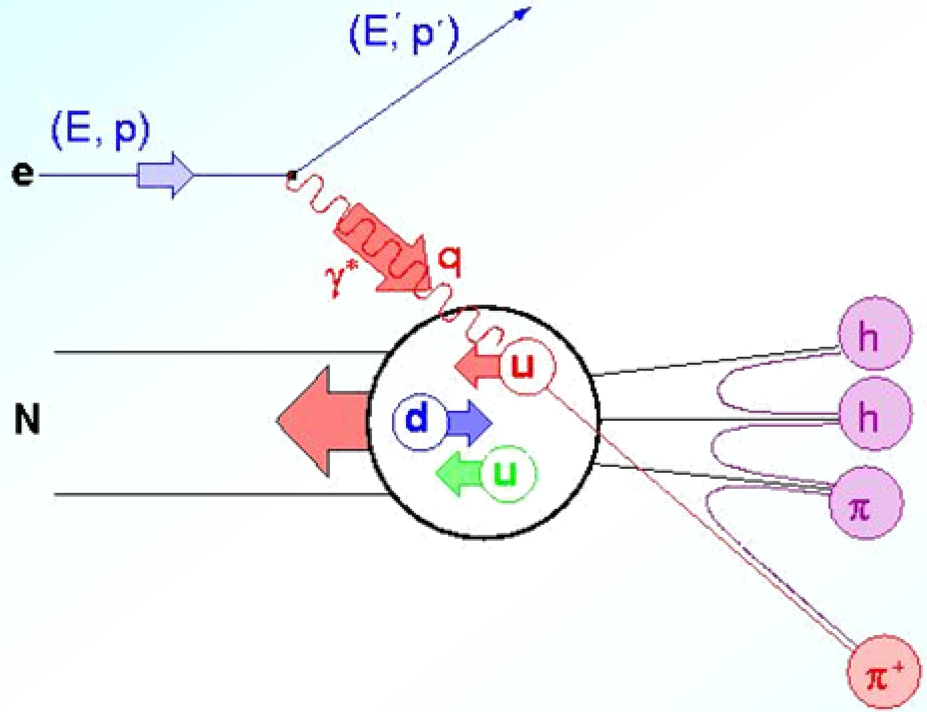
- A_1^d compatible with 0 at low x
- g_1^d compatible with 0 at low x and very low Q^2

But:

- What is the interpretation of g_1^d at these low values of Q^2?

Quark helicity distributions

Quark helicity distributions from SIDIS



$\nu = E - E'$

$z = E_h/\nu$

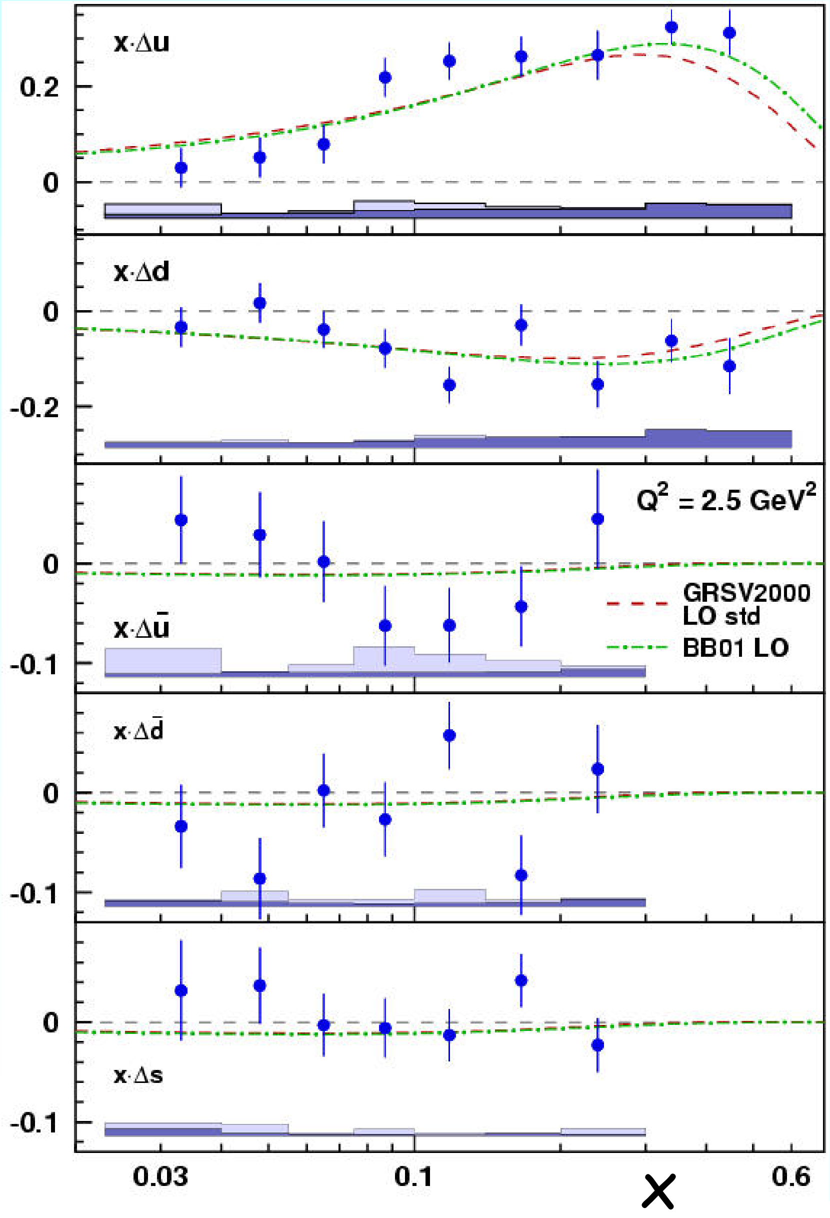
Leading hadron originates with large probability from struck quark

$D(z)$:= Fragmentation function (FF)

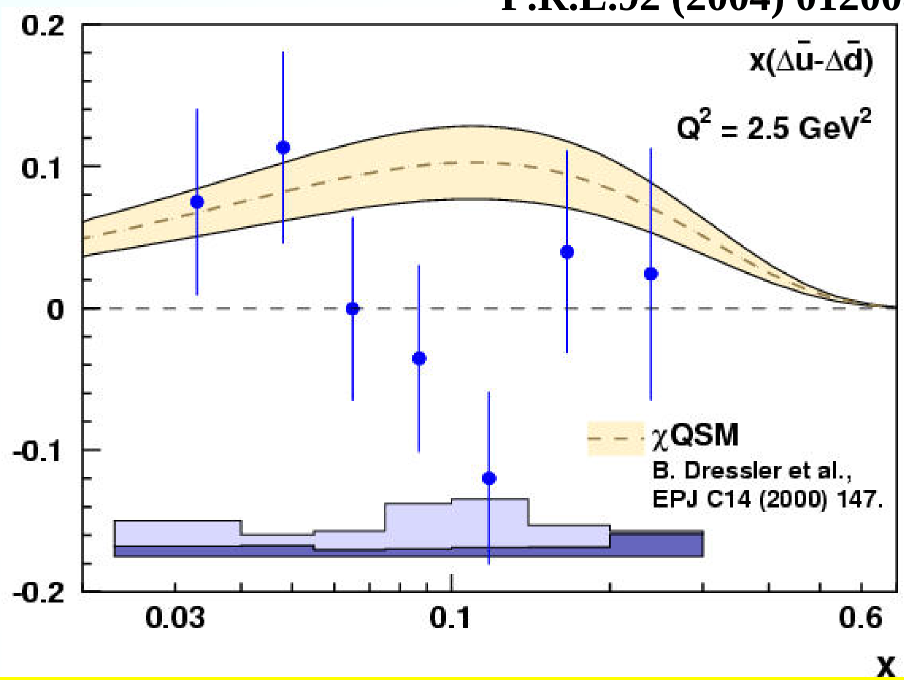
$q(x), \Delta q(x)$:= Distribution functions (DF)

Measure hadron asymmetries $A_1^h(x,z) = \frac{\sum_q z_q^2 \Delta q(x)\ D_q^h(z)}{\sum_q z_q^2\ q(x)\ D_q^h(z)}$

Extracted quark helicity distributions



P.R.L.92 (2004) 012005



In measured range (0,023 – 0.6):

$\int \Delta u(x)\, dx = +0.601 \pm 0.063$

$\int \Delta d(x)\, dx = -0.226 \pm 0.063$

$\int \Delta \bar{u}(x)\, dx = -0.002 \pm 0.043$

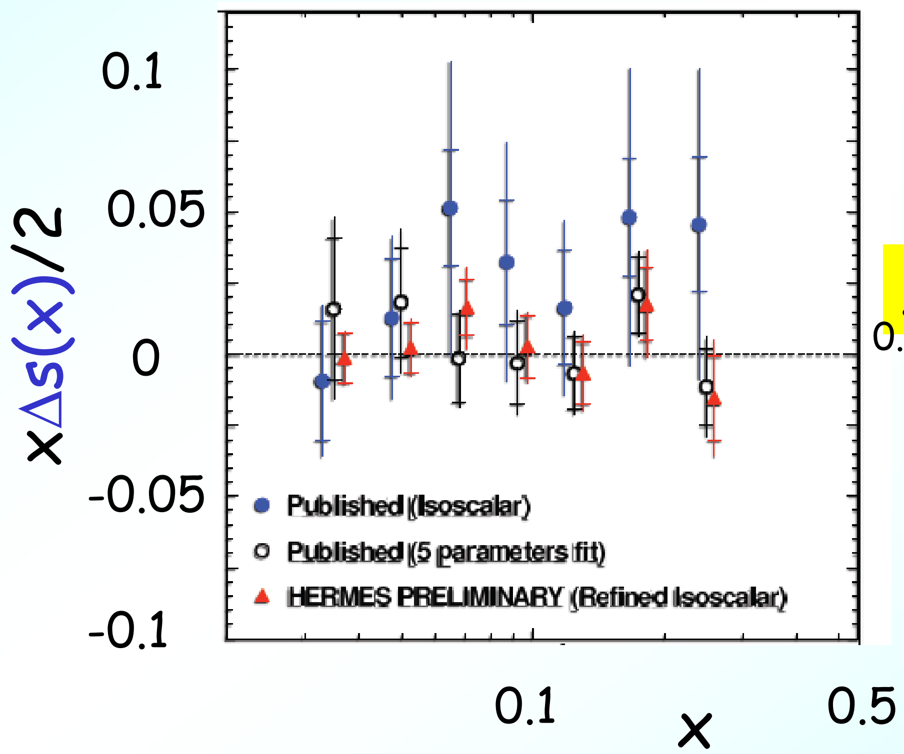
$\int \Delta \bar{d}(x)\, dx = -0.054 \pm 0.035$

$\int \Delta \bar{s}(x)\, dx = +0.028 \pm 0.034$

$\Delta s(x)$ from Kaon asymmetries

Inputs:

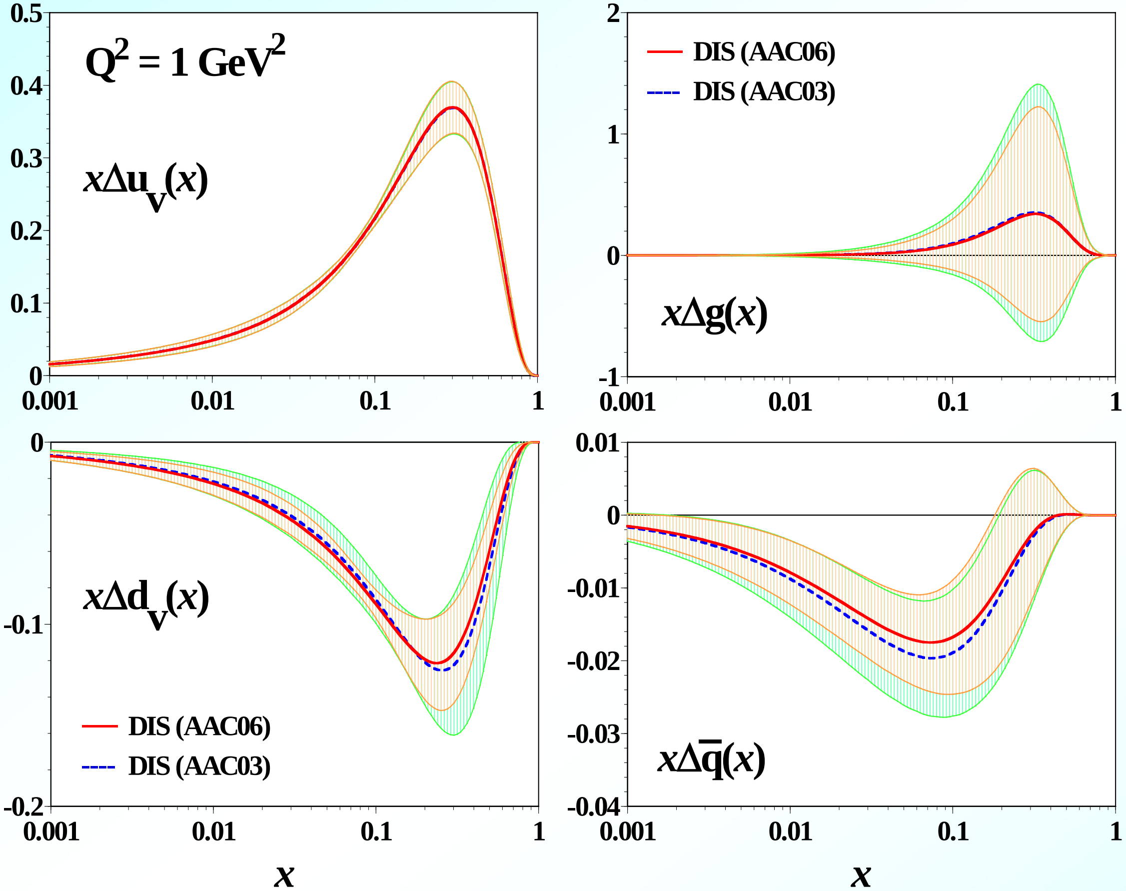
- Multiplicities for K+ and K- with deuteron target
- Inclusive deuteron symmetry A_1^d
- Asymmetries for K+ and K- from deuteron: A_1^{K+} , A_1^{K-}



$$\int_{0.02}^{1} \Delta s(x)dx = 0.006 \pm 0.029 \pm 0.007$$

NLO QCD ($\overline{MS}$) fits

Typical example: AAC06, hep-ph/0603213



- <u>Assumptions:</u>

  Helicity distribution of sea quarks flavour symmetric

  Δu_v and Δd_v constraint by F and D (SU(3) symmetry)

- <u>Results</u> for $Q_0^2 = 1\ GeV^2$:

  $\Delta\Sigma = 0.25 \pm 0.10$

  $\Delta G = 0.47 \pm 1.08$

  ΔG undetermined by only DIS

- <u>Note:</u> From g_1^d

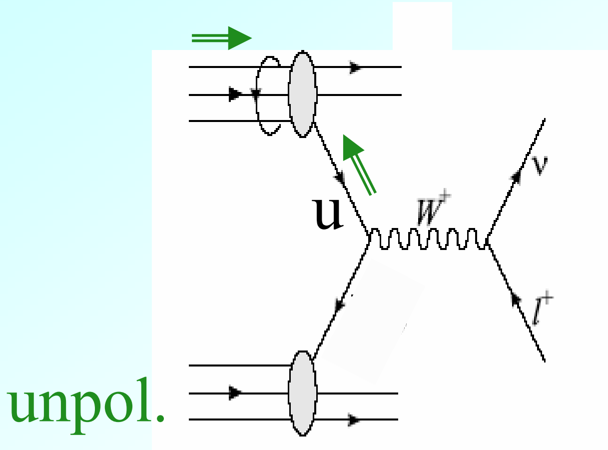
  $\Delta\Sigma(0.01<x<1)_{exp} \cong 0.35 \pm 0.03$

  From NLO fits

  $\Delta\Sigma(0<x<0.01)_{fit} \cong -0.13 \pm 0.11$

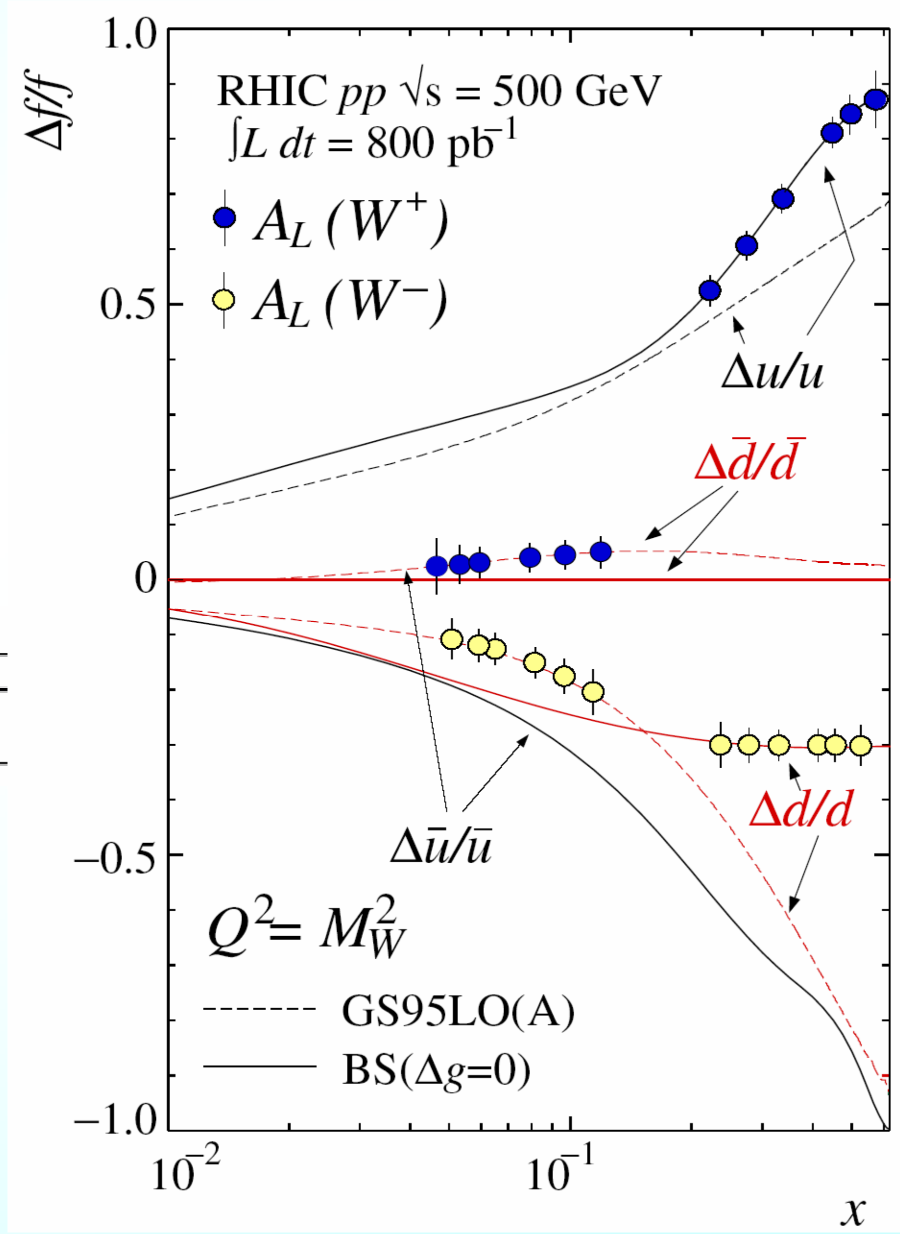
Low-x data urgently needed ➡ e-RHIC

Δq-Δq̄ at RHIC via W production



$$\Delta d + \bar{u} \rightarrow W^-$$
$$\Delta \bar{u} + d \rightarrow W^-$$
$$\Delta \bar{d} + u \rightarrow W^+$$
$$\Delta u + \bar{d} \rightarrow W^+$$

$$\mathbf{A_L} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

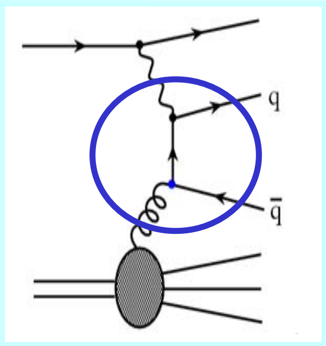


Expected start: 2009

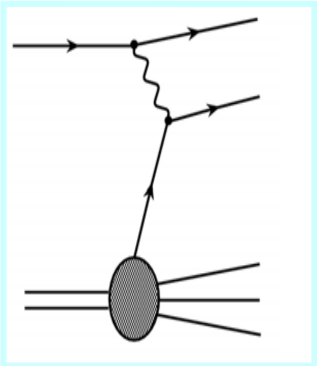
The Gluon helicity distribution

ΔG/G from high p_T hadron pairs

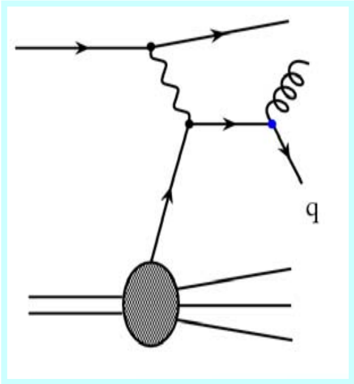
$$A_{||} = R_{PGF} \times a_{LL}^{PGF} \times \frac{\Delta G}{G} + A_{Bkg}$$



Photon
Gluon
Fusion

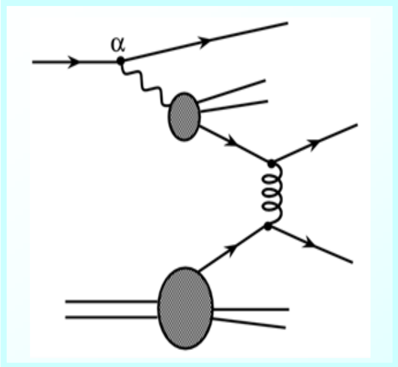


Leading
Order



QCD
compton

+



Resolved γ
$Q^2 < 1\ (GeV/c)^2$

a_{LL} : calculable partonic asymmetries
R_{PGF} : Monte Carlo is required to calculate R_{PGF}

From A. Magnon

$\Delta G/G$ from high p_T hadron pairs

Two high p_T hadrons, $p_T > 0.7$ GeV/c, $\Sigma p_T^2 > 2.5$ (Gev/c)2

- $Q^2 < 1$ (GeV/c)^2 analysis - large statistics (PL B612 (2005) 154)
  - perturbative QCD scale from Σp_T^2
  - **PHYTIA MC** used to evaluate physical Bkg, low p_T, resolved γ,
- $Q^2 > 1$ (GeV/c)^2 analysis - lower statistics
  - perturbative QCD scale from Q^2,
  - **LEPTO MC** used to evaluate Bkg, better controlled

Different data sets and analysis. Independent results

From A. Magnon

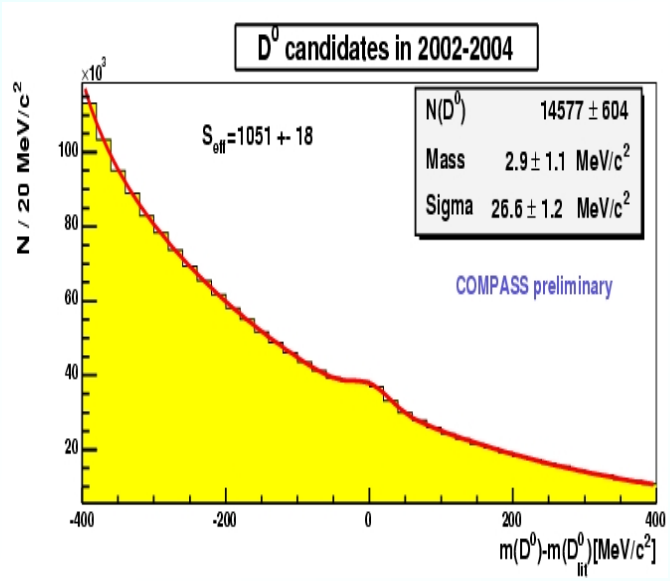
ΔG/G from open charm

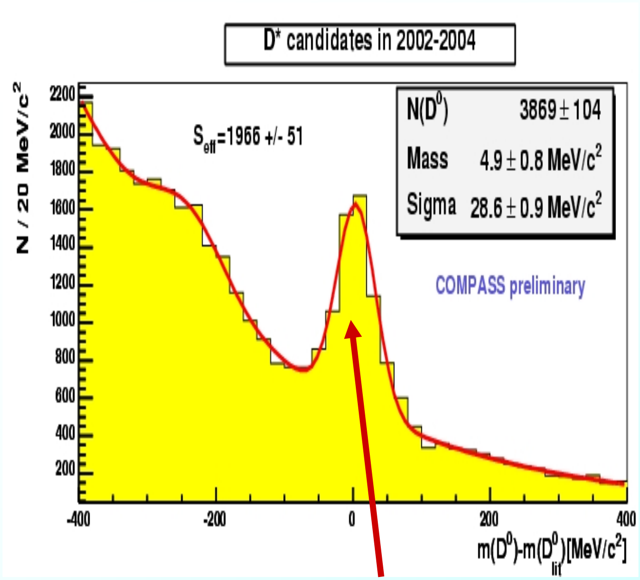
$$D^0 \rightarrow K + \pi$$

untagged

$$D^* \rightarrow D^0 + \pi_s \rightarrow K + \pi + \pi$$

tagged

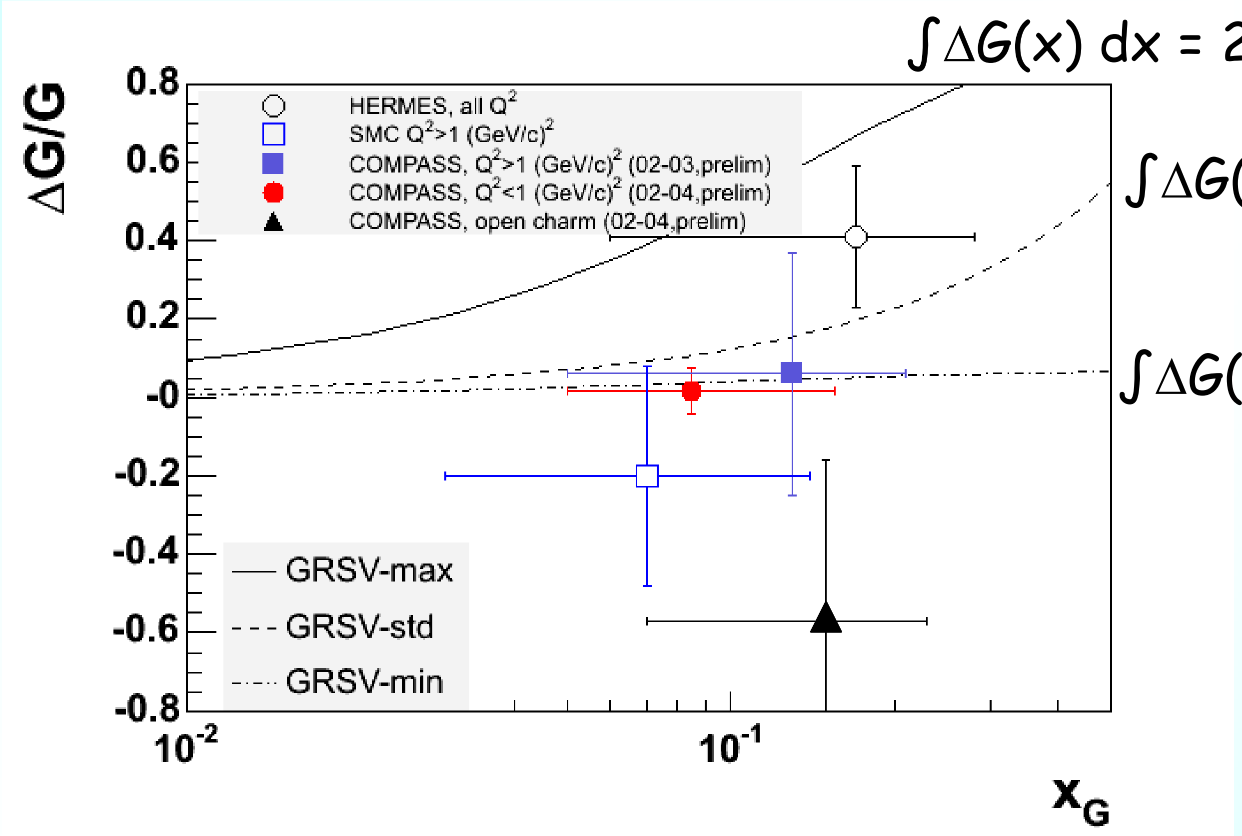




We have now estimate for σ (nb)

From A. Magnon

$\Delta G/G$ from high p_T hadron pairs and open charm



High p_T hadron pairs, $Q^2 > 1$ GeV^2: $\Delta G/G = 0.06 \pm 0.31$ (stat) ± 0.06 (syst) $\langle x_g \rangle \sim 0.13$

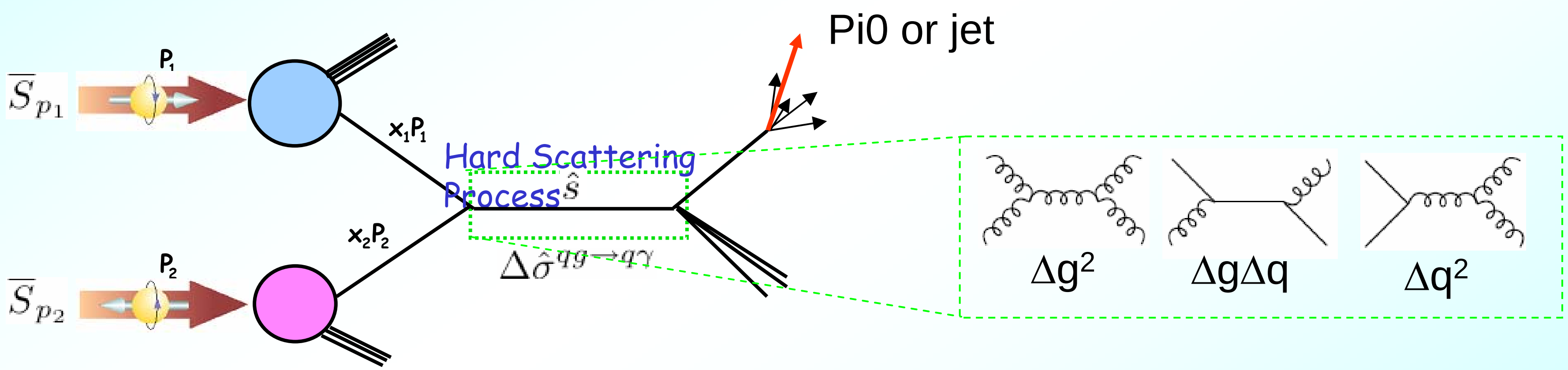
High p_T hadron pairs, $Q^2 < 1$ GeV^2: $\Delta G/G = 0.016 \pm 0.058$ (stat) ± 0.055 (syst) $\langle x_g \rangle \sim 0.085$

Open charm: $\Delta G/G = -0.57 \pm 0.41$ $\langle x_g \rangle \sim 0.15$

$\Delta G/G$ ($x_g \approx 0.1$) is small

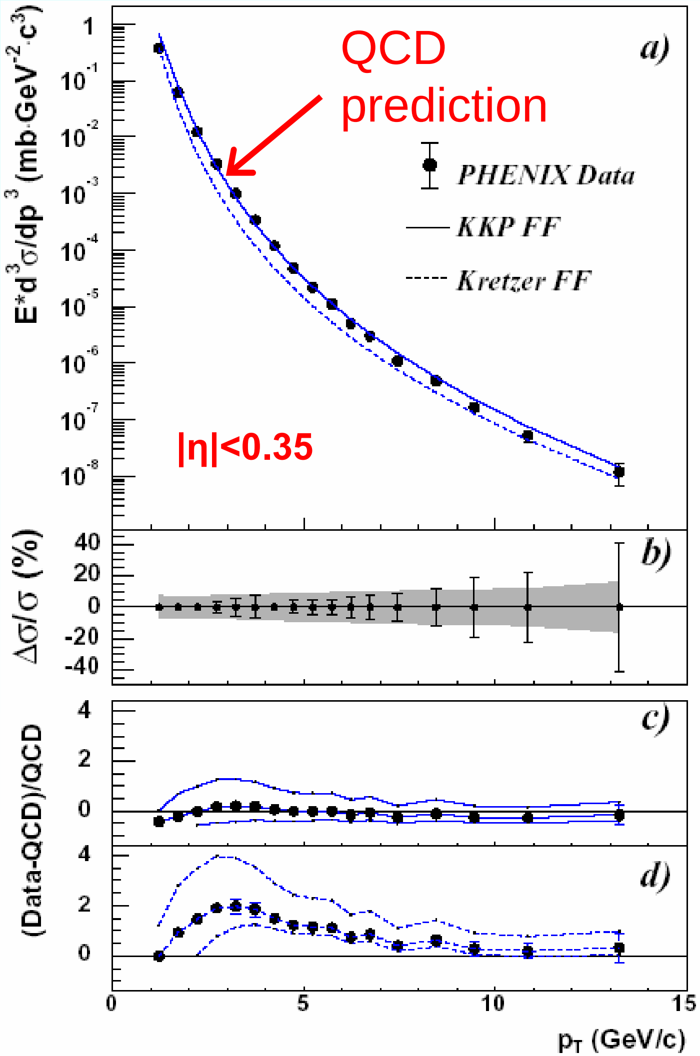
ΔG/G from polarized pp collisions

How to measure Δg:



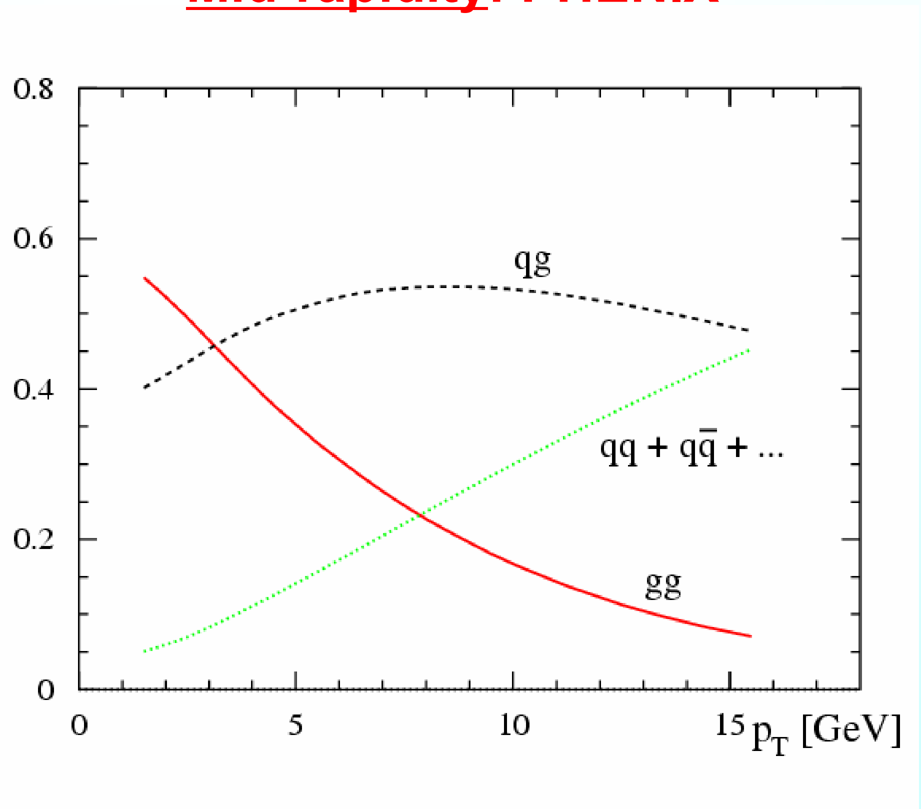
$$A_{LL}^{\pi^0} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \sim a_{gg} * \Delta g^2 + b_{gq} * \Delta g + c_{qq}$$

$pp \rightarrow \pi^0 X$

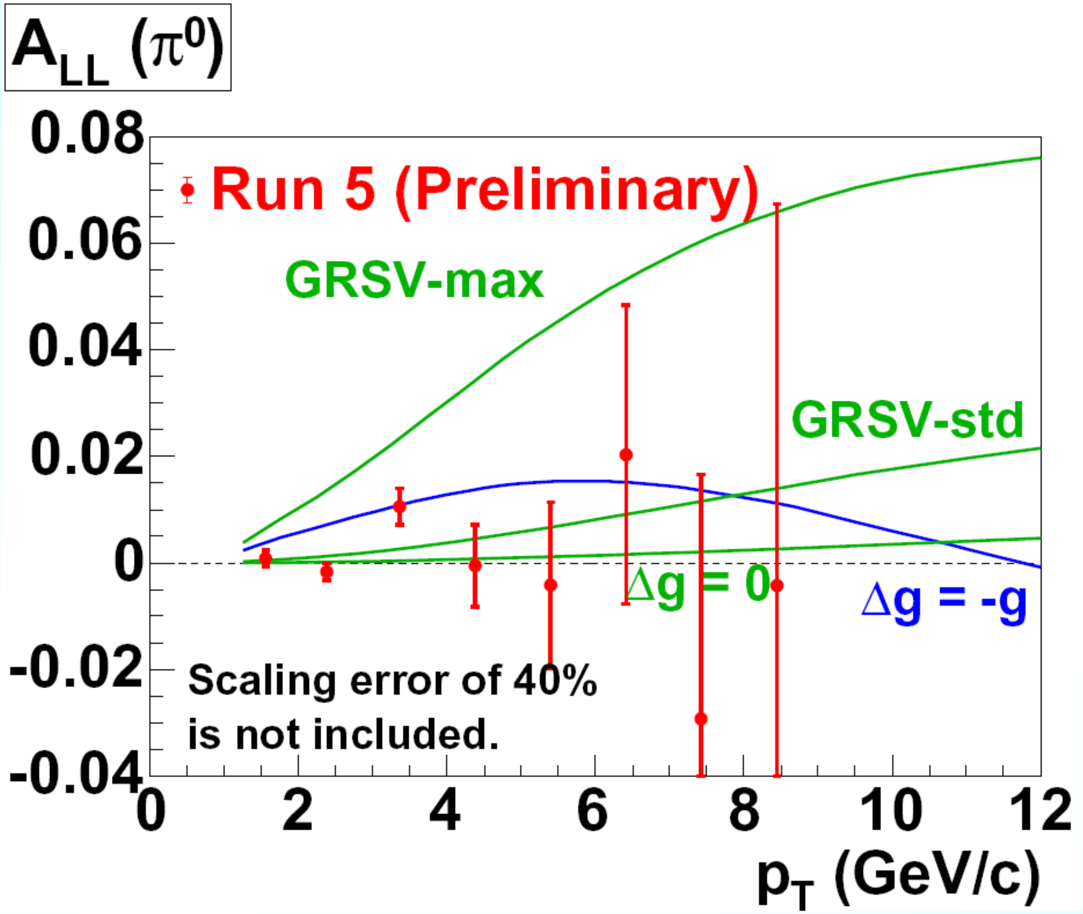


PRL **91**, 241803 (2003)

Mid-rapidity: PHENIX



ΔG from $A_{LL}(\pi^0)$



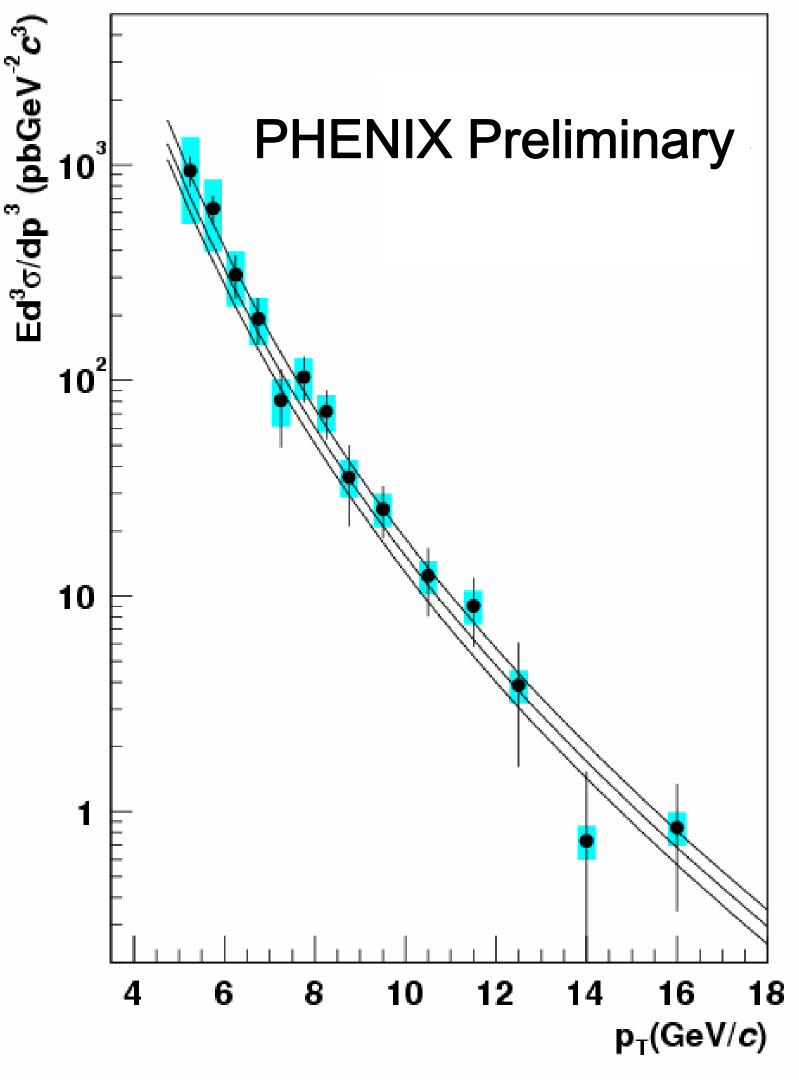
Theory model	C.L. (%)
GRSV-std	21.7-17.1
*GRSV-max (Δg=g)	0.0-0.0
*GRSV Δg=0	16.7-18.4
*GRSV Δg=−g	0.7-0.0

GRSV: M. Glück, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. D 53 (1996) 4775.

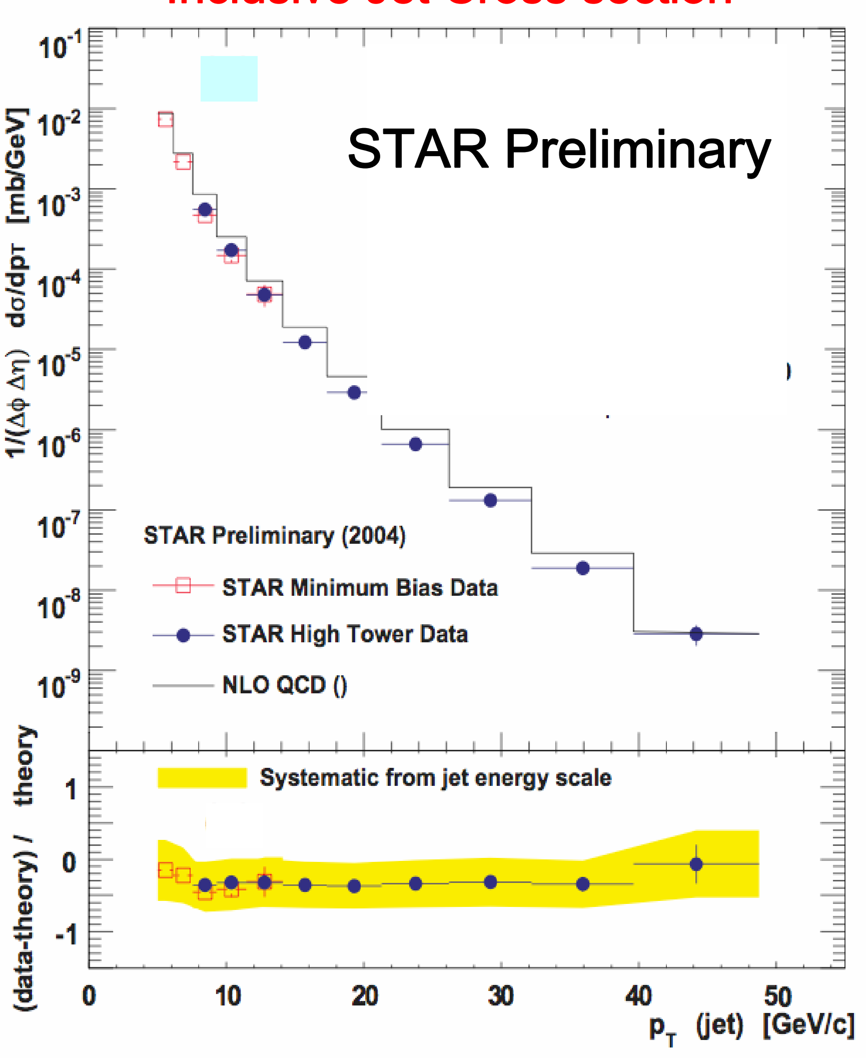
* At input scale: Q^2 = .4 Gev

pp → γ +X, pp → jet +X

Direct Photon Cross section

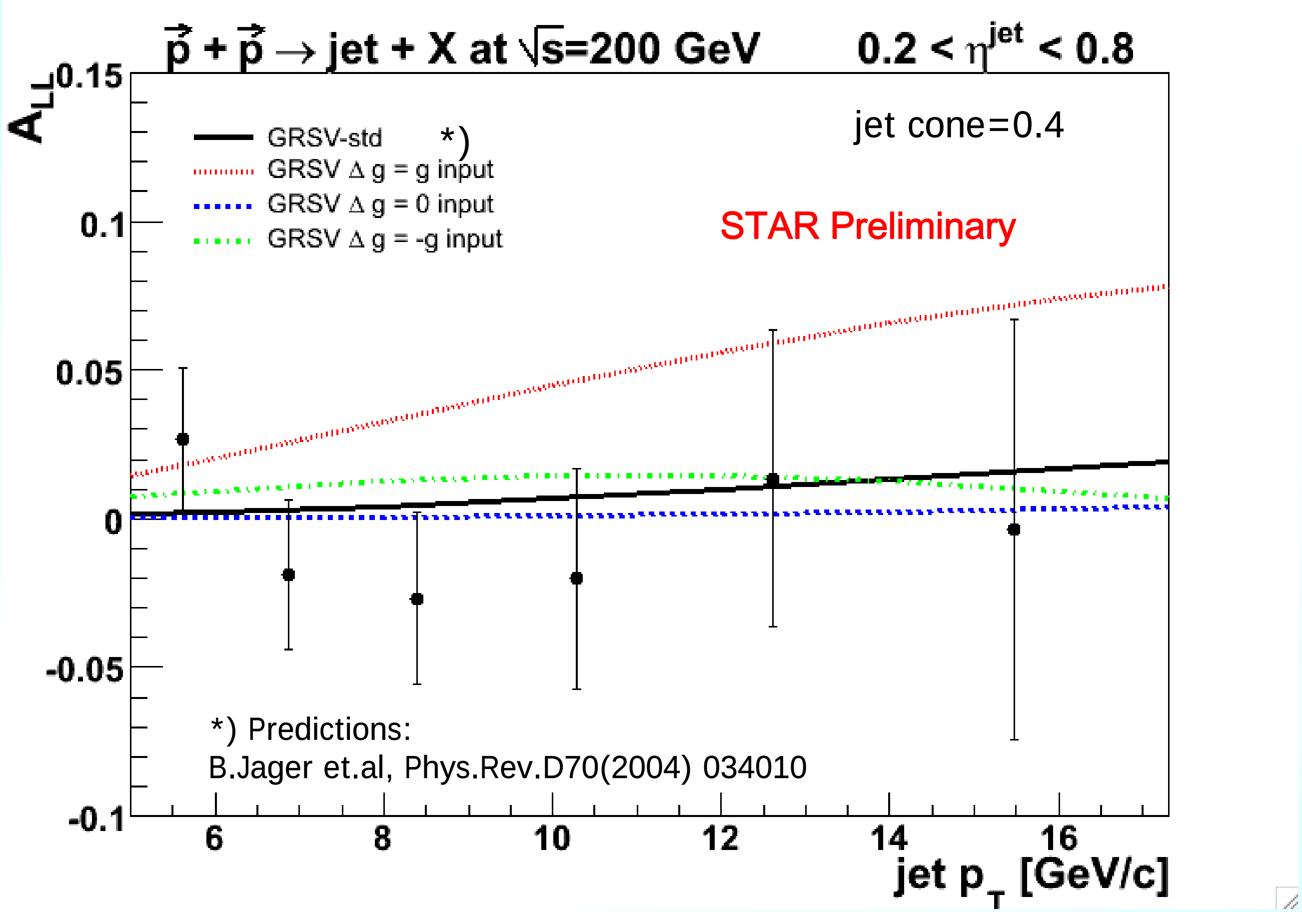


Inclusive Jet Cross section



STAR

ΔG from A_{LL}(jet)

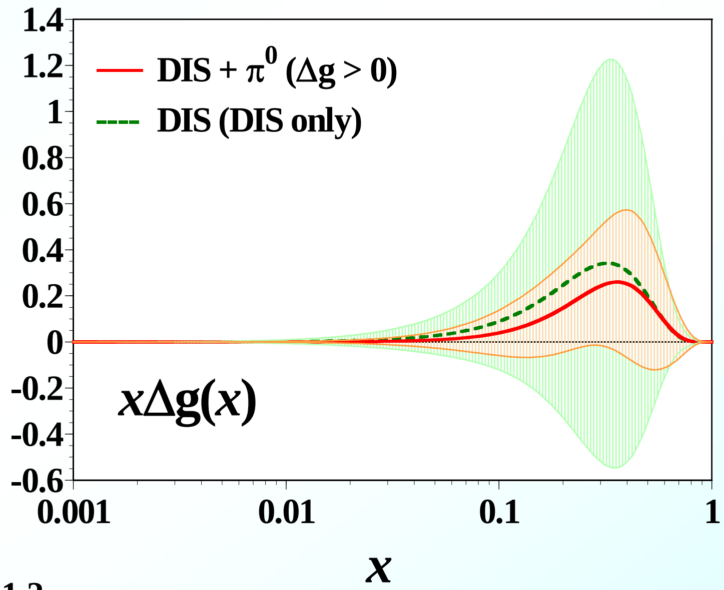


- Results limited by statistical precision
- Total systematic uncertainty ~0.01 (STAR) + beam pol. (RHIC)
- GRSV-max gluon polarization scenario disfavored

NLO QCD (MS) fits, DIS + π^0

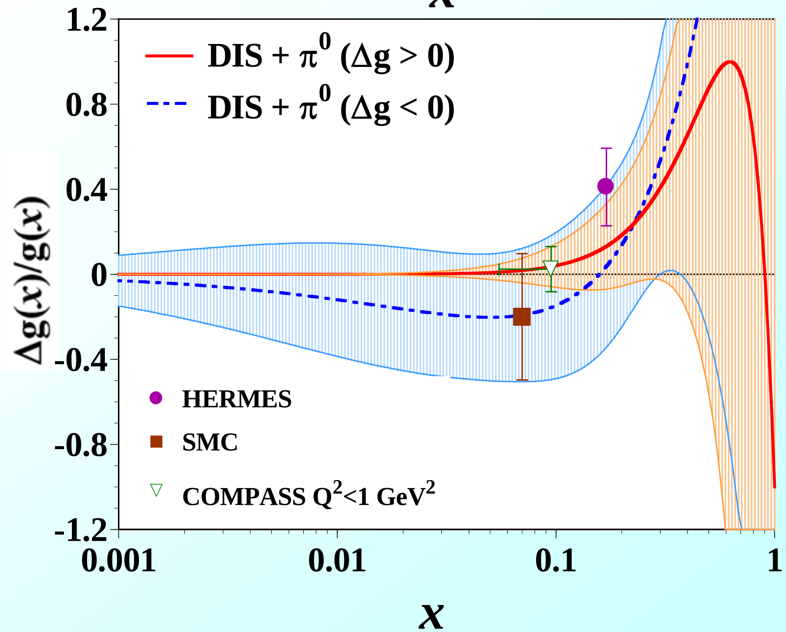
AAC06, hep-ph/0603213

- Significant reduction of ΔG uncertainty
  - $\Delta G = 0.31 \pm 0.32$ (DIS+p^0)
  - $\Delta G = 0.47 \pm 1.08$ (DIS only)



- Sign problem : gg dominates
  Similar χ^2 for ($\Delta G(x)$ >0) and ($\Delta G(x)$<0)

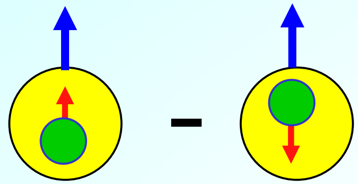
- Consistent results for partial 1st moment(0.1<x<1)
  - $\Delta G(x)$>0: 0.30 ± 0.30
  - $\Delta G(x)$<0: 0.32 ± 0.42



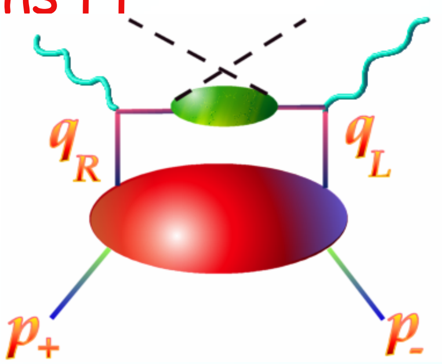
Transverse Spin physics

Transversity DF $\delta q(x)$ and Sivers DF $f_{1T}^{\perp q}(p_T^2)$

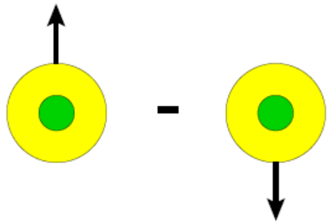
- $\delta q(x,Q^2)$



- DF of transv. polarized quarks in a transv. polarized nucleon
- 3rd leading twist DF. As important as $q(x)$ and $\Delta q(x)$
- δq is chiral-odd: not accessible in DIS
- Need 2nd chiral-odd object Collins FF



- $f_{1T}^{\perp q}(p_T^2)$



- DF of unpolarised quark with transv. momentum p_T in a transv. polarised nucleon.
- Non-zero Sivers DF requires non-vanishing orbital angular momentum in nucleon WF
- Chiral-even & naïve T-odd

Azimuthal angular asymmetries in SIDIS

$$A_{\mathrm{UT}}(\phi,\phi_S) = \frac{1}{S_\perp}\frac{N^\uparrow(\phi,\phi_S) - N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S) + N^\downarrow(\phi,\phi_S)}$$

U: unpol. beam

T: transv. pol. Target

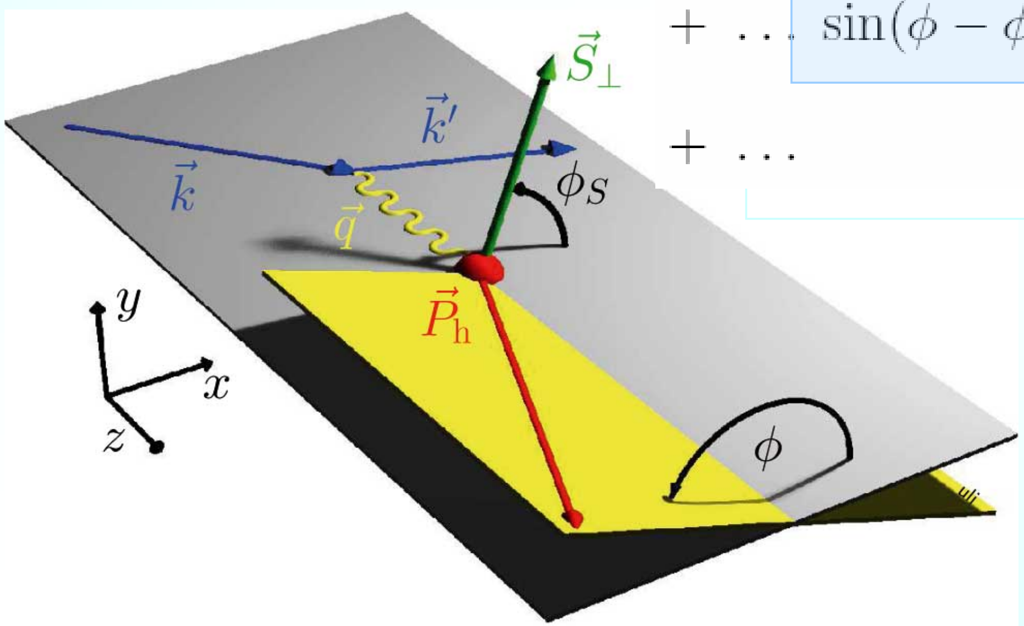
Collins

$$A_{\mathrm{UT}}(\phi,\phi_S) \sim \ldots \sin(\phi+\phi_S)\frac{\sum_q e_q^2\,\mathcal{I}\left[\ldots\delta q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, q(x)\cdot D_1^q(z)}$$

$$+\ \ldots \sin(\phi-\phi_S)\frac{\sum_q e_q^2\,\mathcal{I}\left[\ldots f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, q(x)\cdot D_1^q(z)}$$

$$+\ \ldots$$

Sivers

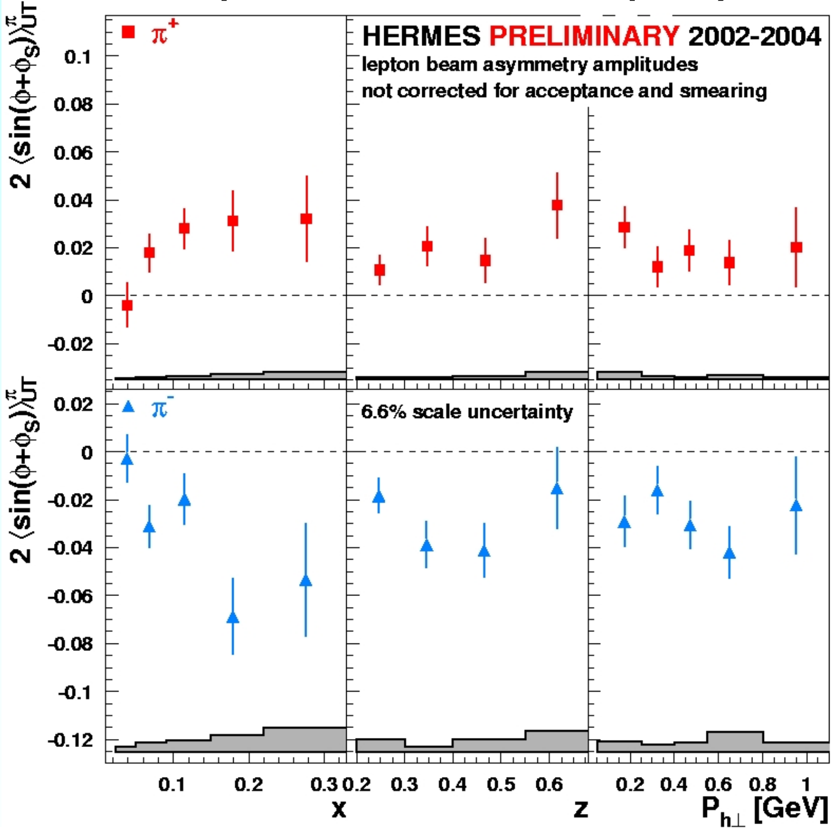


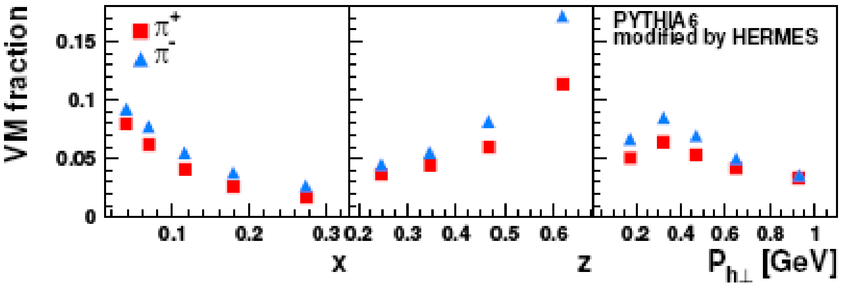
$\mathcal{I}[\ldots]$: convolution integral over quark transverse momenta $\vec{p}_T$ and $\vec{k}_T$

Collins amplitudes for $\pi^{+/-}$ (proton)

$$A_{UT}^{\sin(\phi+\phi_S)} \sim \delta q(x) \cdot H_1^{\perp(1/2)}(z)$$

also: A. Airapetian et al, P. R. L. 94 (2005) 012002





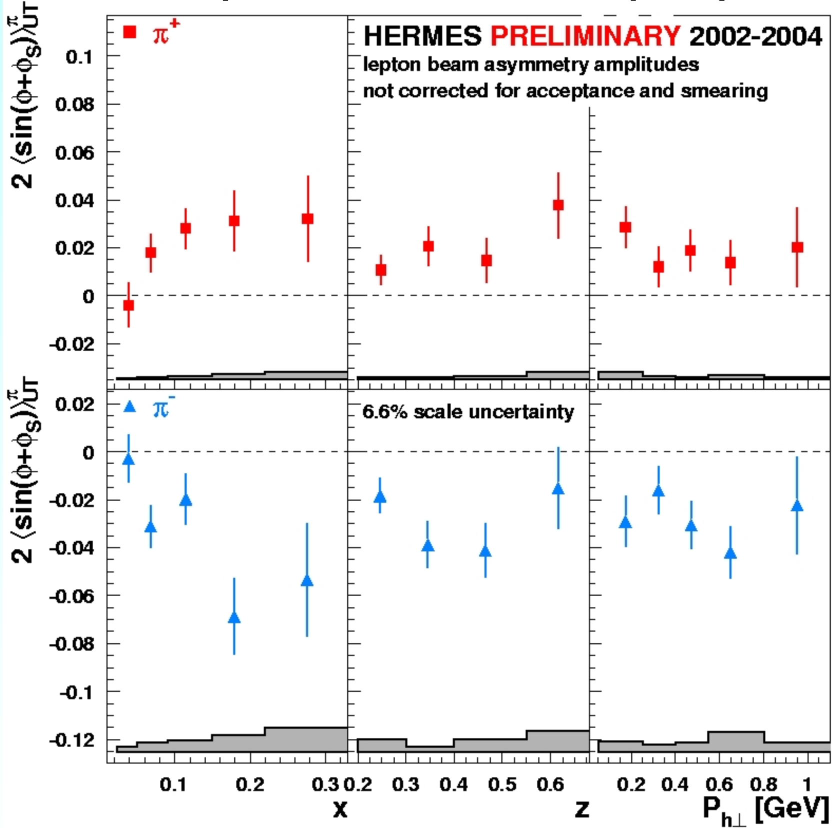
- Non-zero Collins effect
- Both Collins FF and transversity DF sizeable
- Surprisingly large π^- asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation, i.e. $u \rightarrow \pi^-$

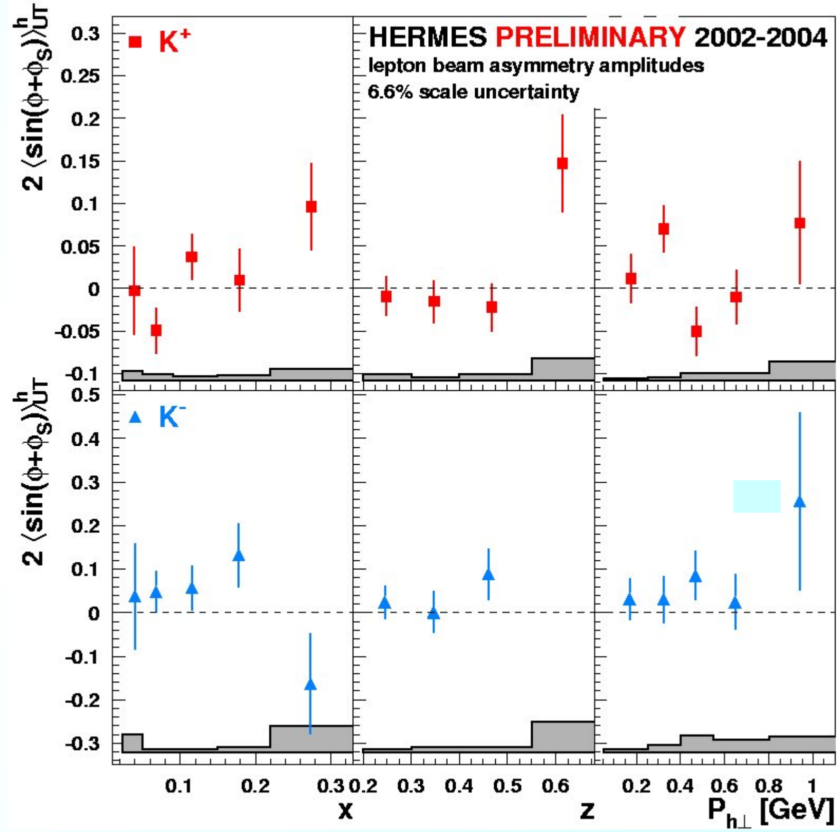
  $H_{1,disf} \approx - H_{1,fav}$
- Substantial contribution to pion sample from exclusively produced vector mesons (PYTHIA)

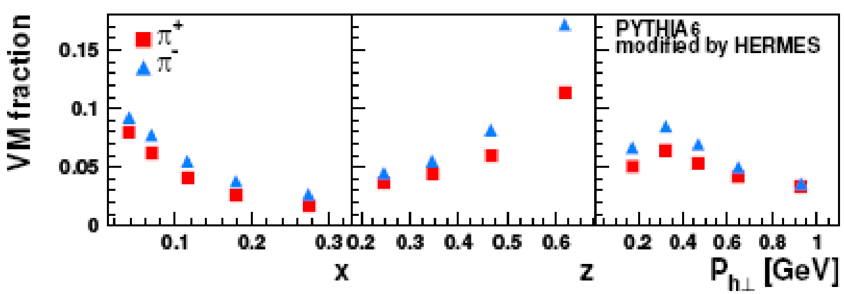
Collins amplitudes for $\pi^{+/-}$ and $K^{+/-}$

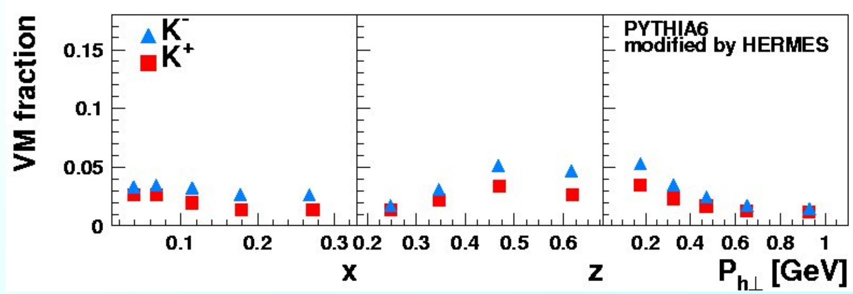
$$A_{UT}^{\sin(\phi+\phi_S)} \sim \delta q(x)\cdot H_1^{\perp(1/2)}(z)$$

also: A. Airapetian et al, P. R. L. 94 (2005) 012002



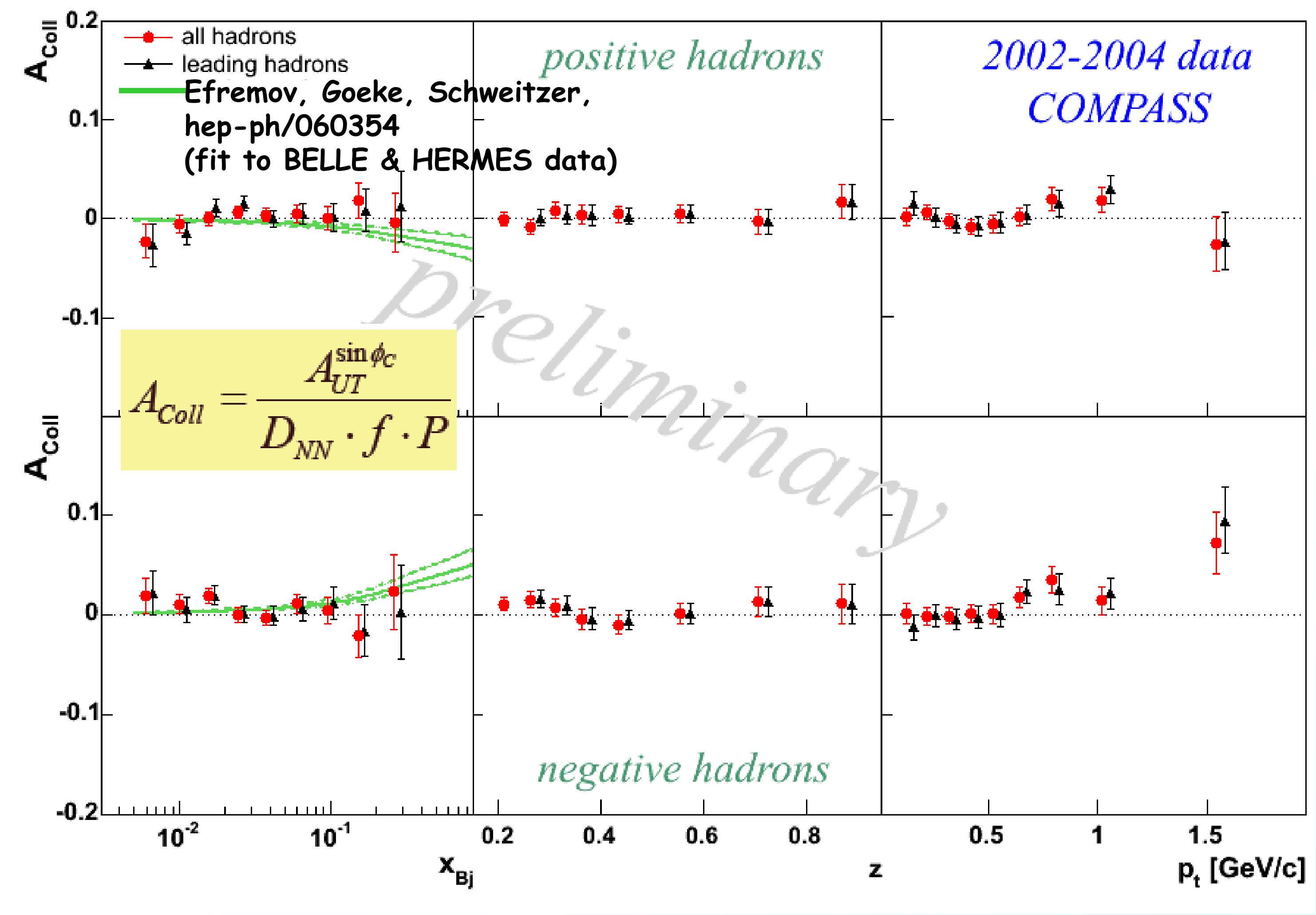






Collins Asymmetries – D target

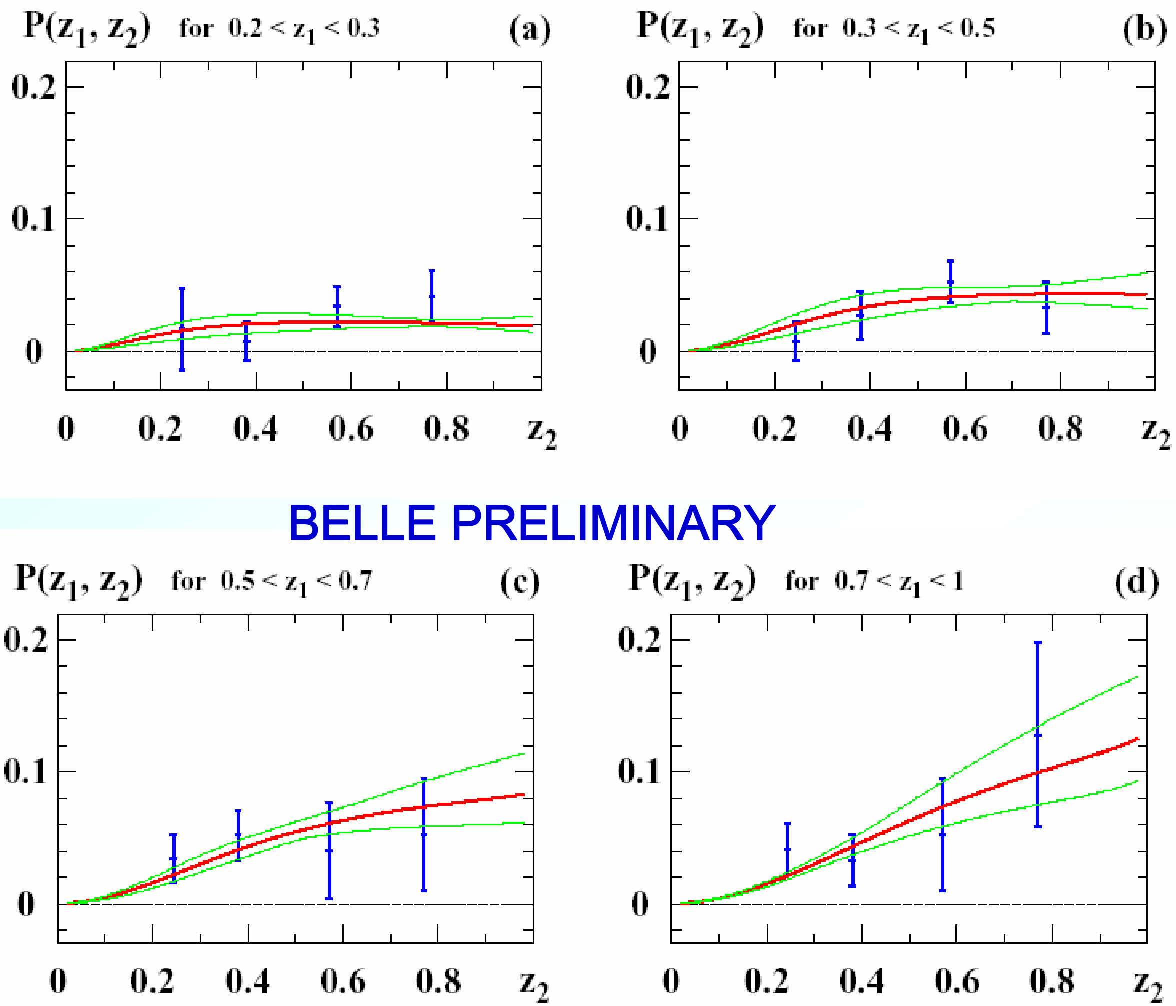
Note: different convention : $\phi_{Coll} = \phi + \phi_S - \pi$ *also: V. Yu. Alexakhin et al, PRL 94 (2005) 202002*

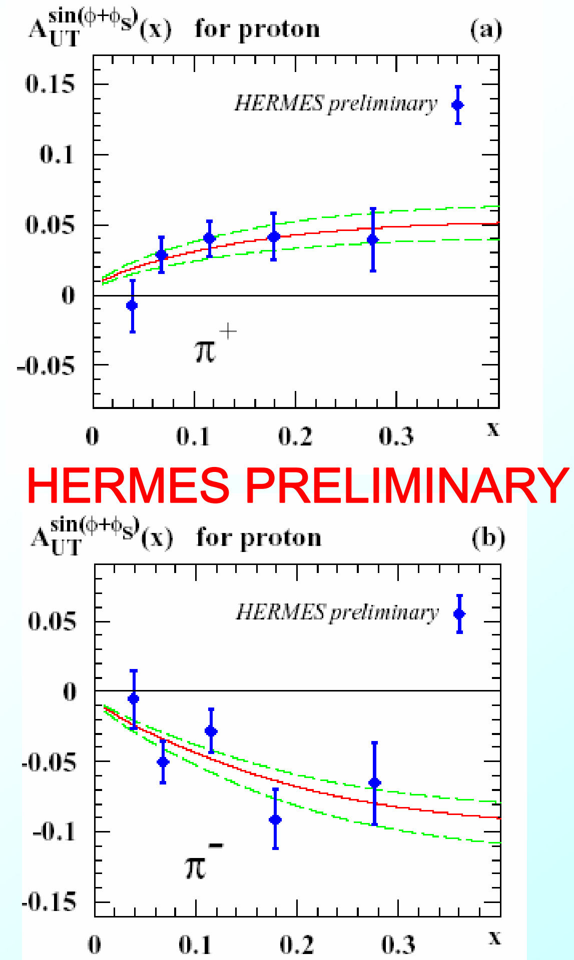


Consistent with zero. Cancellation due to deuteron target?

LO-QCD Analysis of HERMES and BELLE Results

(Efremov, Goeke, Schweitzer, hep-ph/0603054)





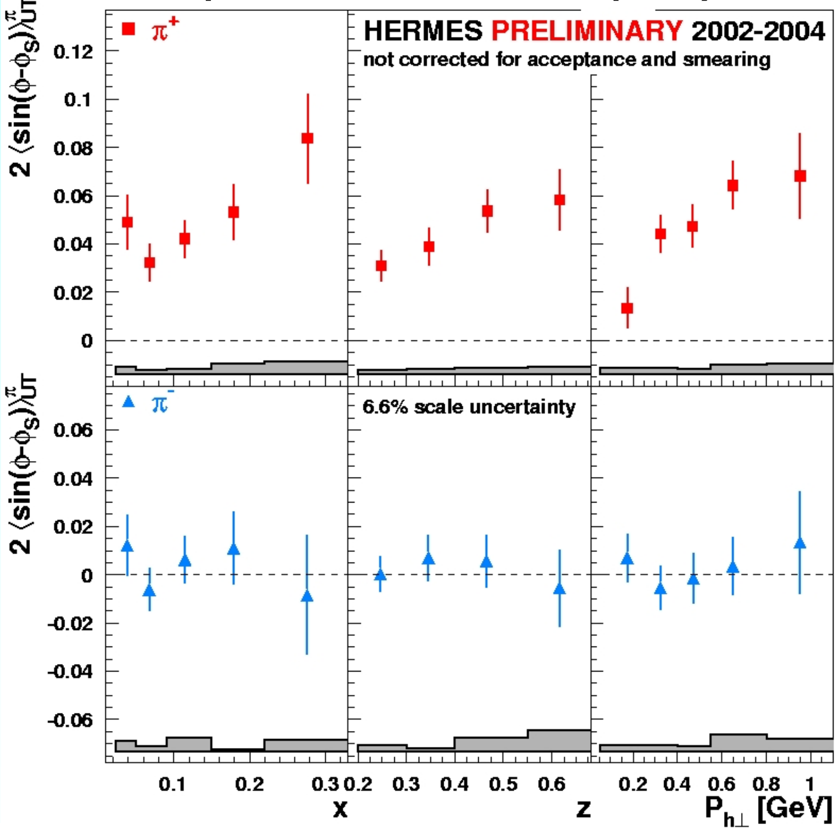
Combined fit to Hermes asymmetries (Transversity x Collins-FF) and Belle asymmetries (Collins-FF^2) ➔ Excellent agreement!

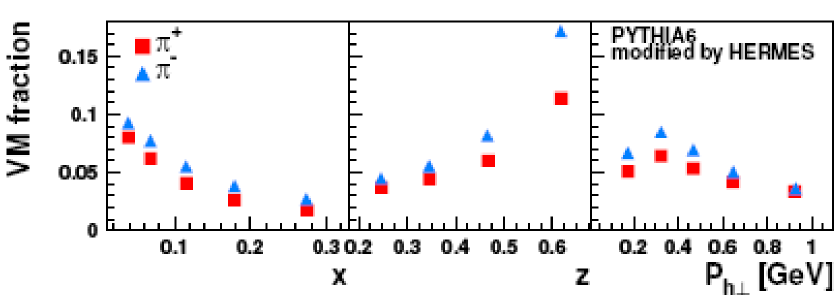
From M. Grosse Perdekamp, DIS06

Sivers amplitudes for $\pi^{+/-}$ (2002-2004)

$$A_{UT}^{\sin(\phi-\phi_S)} \sim f_{1T}^{\perp(1/2)}(x) \cdot D_1(z)$$

also: A. Airapetian et al, P. R. L. 94 (2005) 012002





- π^+ asymmetry significantly different from zero and positive

→ First hint of naive T-odd DF from DIS

→ orbital angular momentum L_z^q

But: Contribution of L_z^q to nucleon spin unclear

- π^- asymmetry consistent with zero

- Substantial contribution to pion sample from exclusively produced vector mesons (PYTHIA)

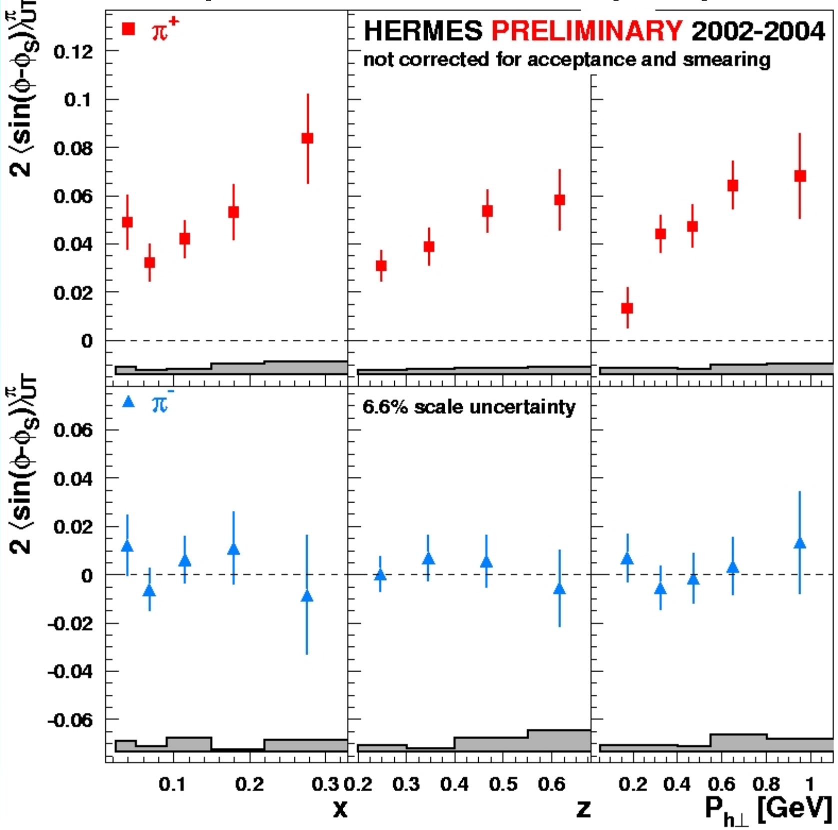
Sivers amplitudes for $\pi^{+/-}$ and $K^{+/-}$

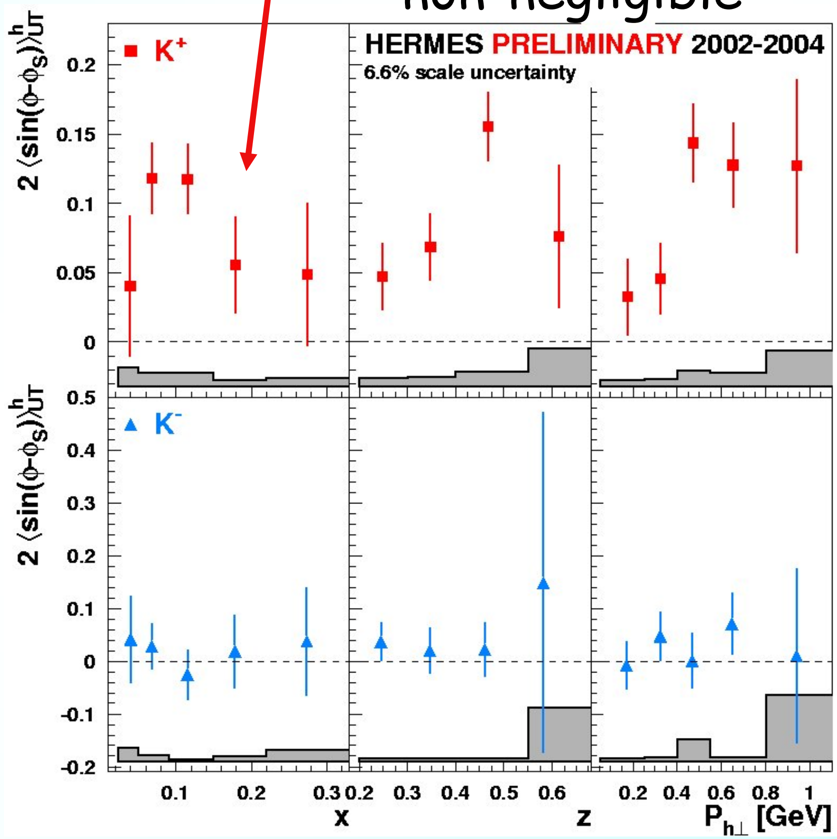
$$A_{UT}^{\sin(\phi-\phi_S)} \sim f_{1T}^{\perp(1/2)}(x)\cdot D_1(z)$$

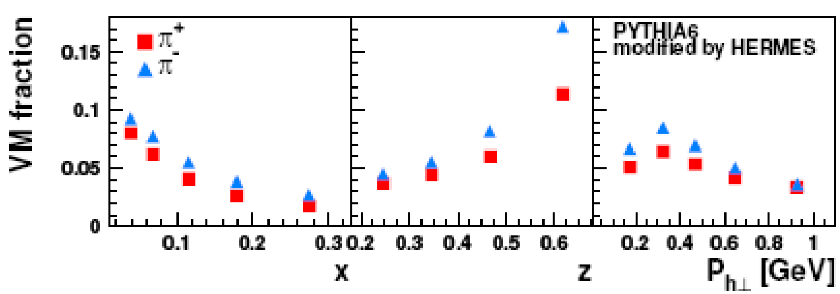
also: A. Airapetian et al, P. R. L. 94 (2005) 012002

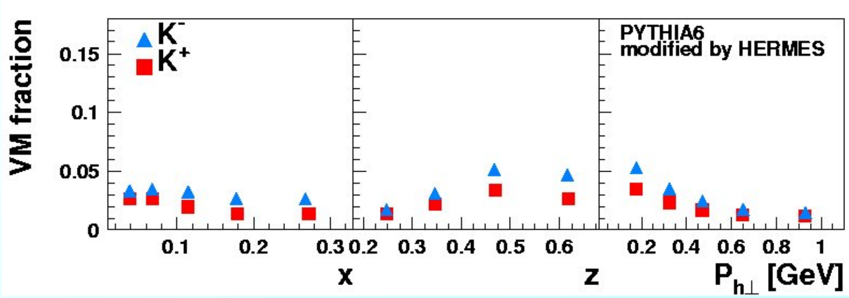
large!

Sea contribution non-negligible



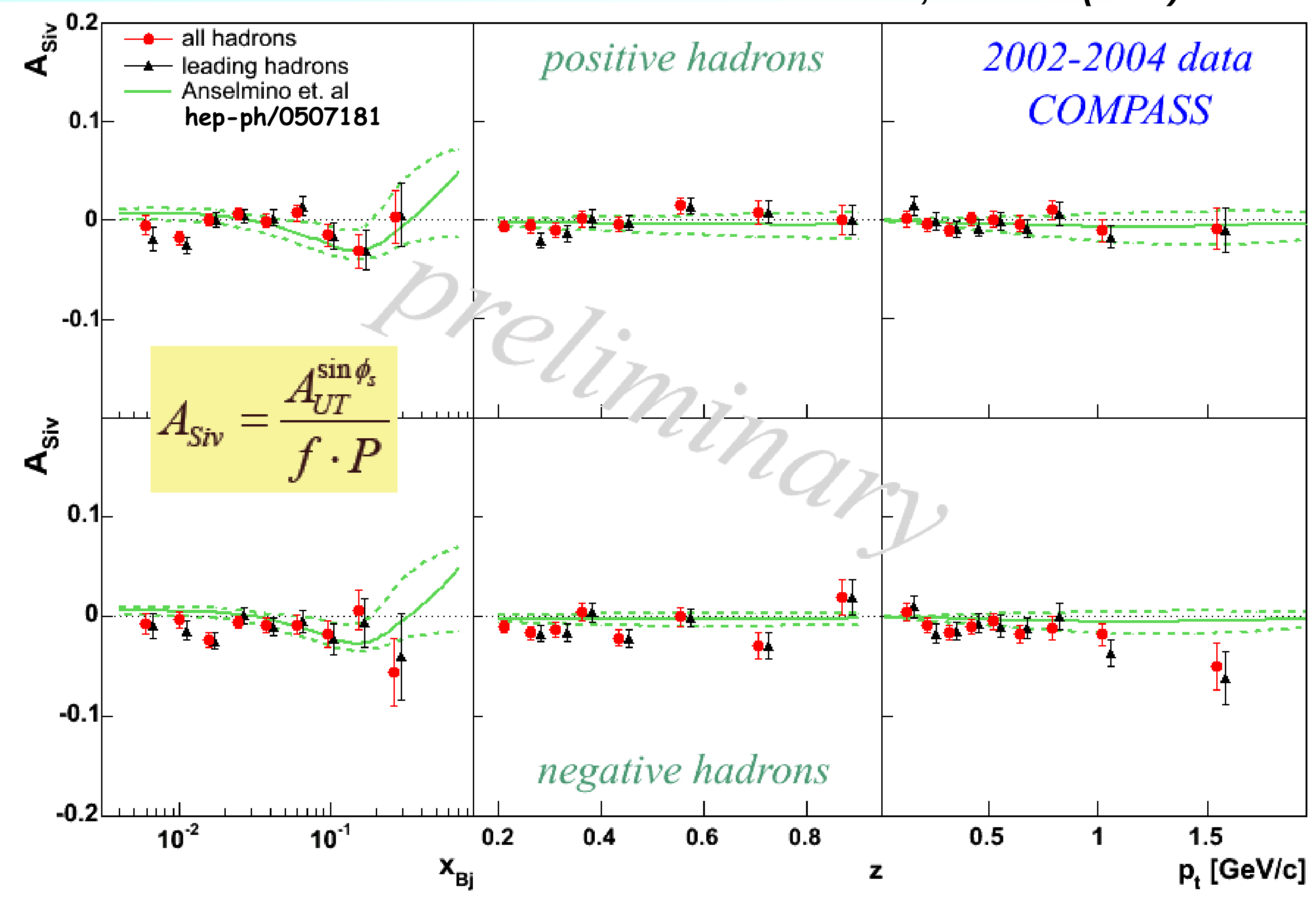






Sivers Asymmetry – D target

also: V. Yu. Alexakhin et al, P R L 94 (2005) 202002



Consistent with zero. Cancellation due to deuteron target?

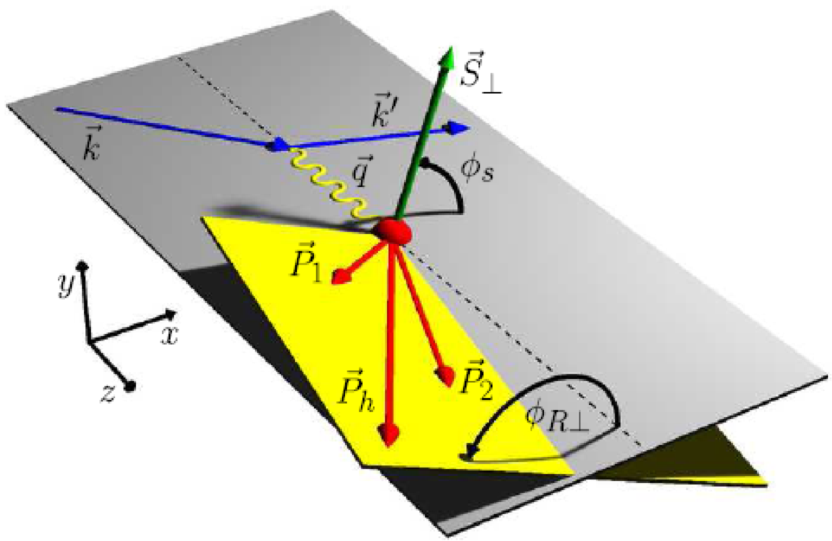
Two-pion Asymmetries – H target

Detection of two final state pions with opposite charge:

$$A_{\rm UT}(\phi_{R\perp},\phi_S) \quad \sim \quad \ldots \sin(\phi_{R\perp}+\phi_S)\,\frac{\sum_q e_q^2\,\delta q(x)\cdot H_1^{\sphericalangle q}(z,M_{\pi\pi}^2)}{\sum_q e_q^2\,q(x)\cdot D_1^q(z,M_{\pi\pi}^2)}$$

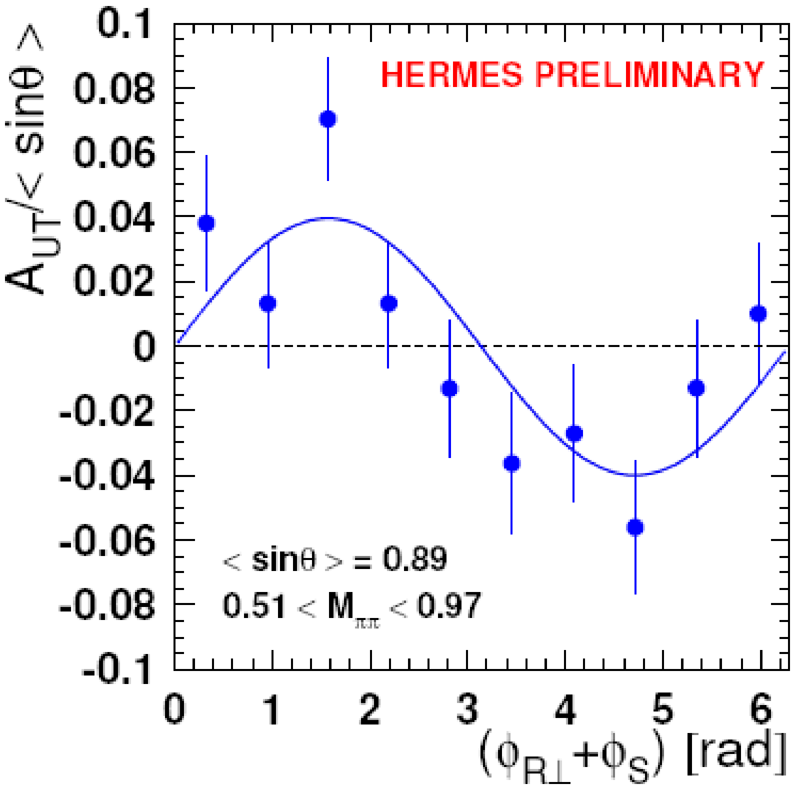
$$+\ldots$$

$H_1^{\sphericalangle}(z,M_{\pi\pi}^2)$, $D_1(z,M_{\pi\pi}^2)$: two pion fragmentation functions



- no assumptions for $\vec{p}_T$ and $\vec{k}_T$ distributions necessary
- completely independent from single pion analysis

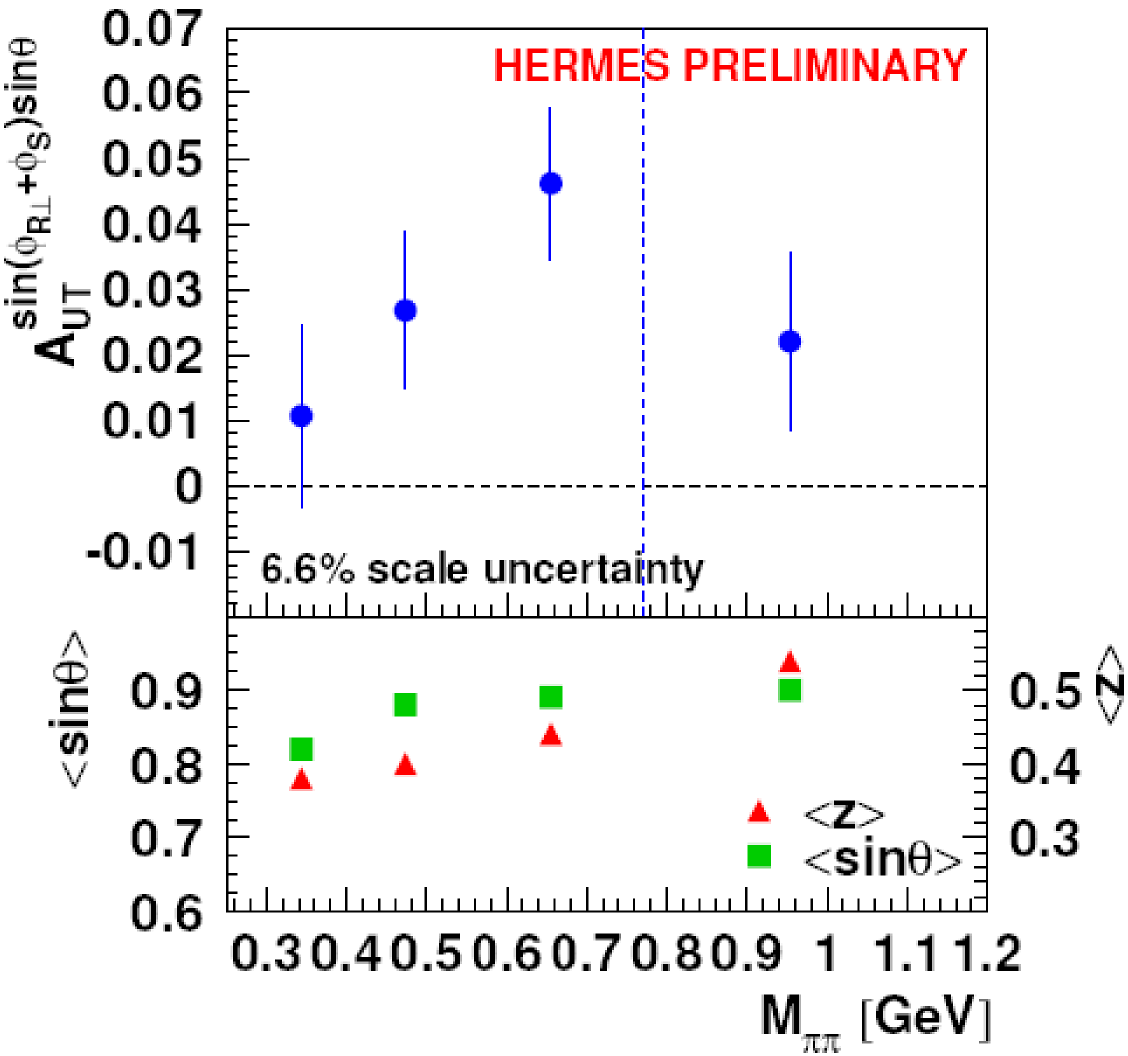
Two-pion Asymmetries – H target



- hadrons assumed to be pions
- fit $A_{UT}(\phi_{R\perp}+\phi_S)/\langle \sin\theta \rangle$ with $p_1 + p_2 \sin(\phi_{R\perp}+\phi_S)$
- significant $\sin(\phi_{R\perp}+\phi_S)$ behaviour!
- extract $A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$ from $A_{UT}(\phi_{R\perp}, \phi_S, \theta)$ by three dimensional fit

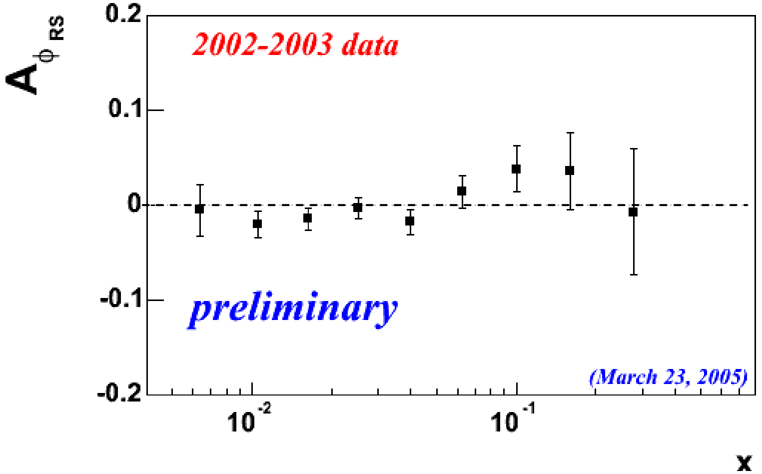
$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$ = 0.040 $\pm$ 0.009 (stat) $\pm$ 0.003 (syst)

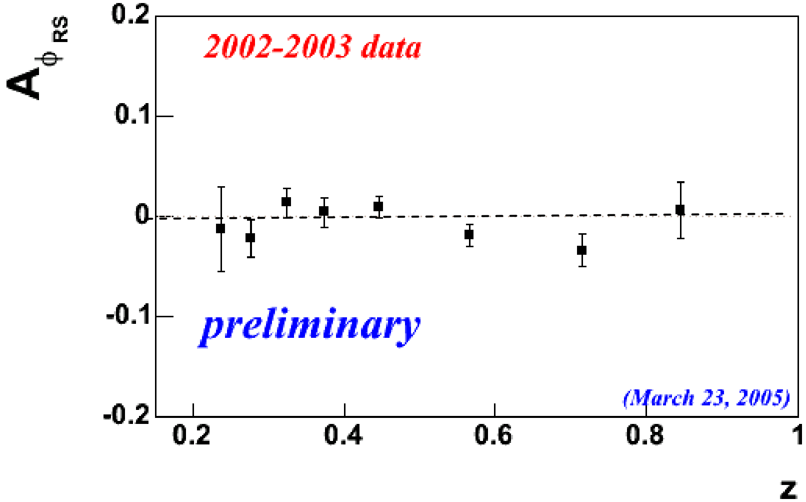
Two-pion Asymmetries – H target

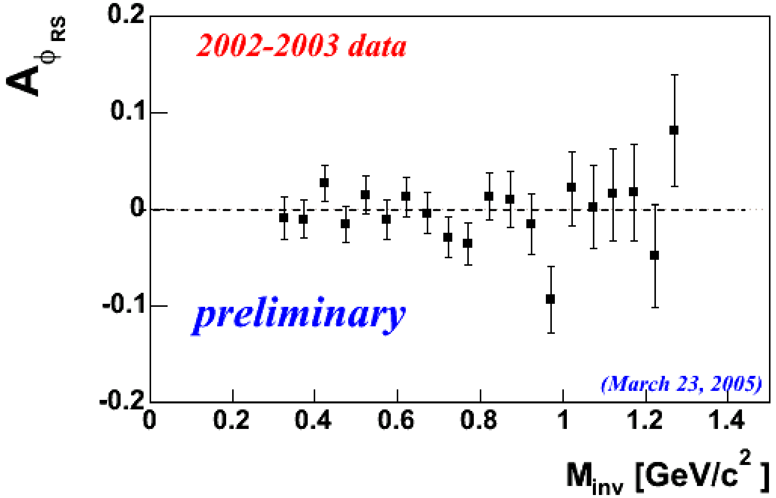


- positive asymmetry amplitudes in all bins
- no sign change at m_{ρ^0}!
- significant result for $A_{\mathrm{UT}}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$
  ➔ non-zero IFF!

Two-hadron Asymmetries – D target



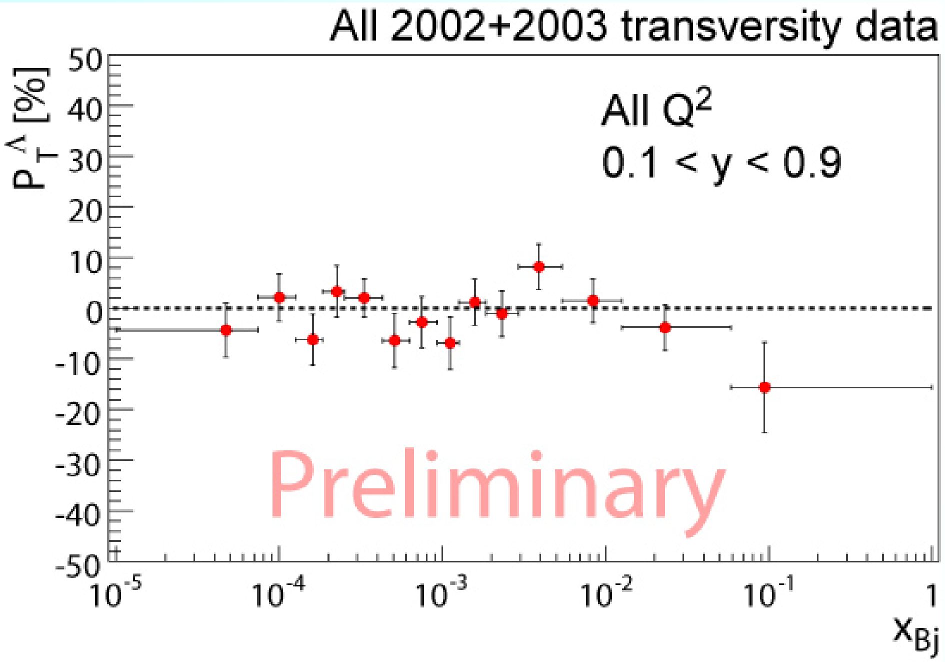


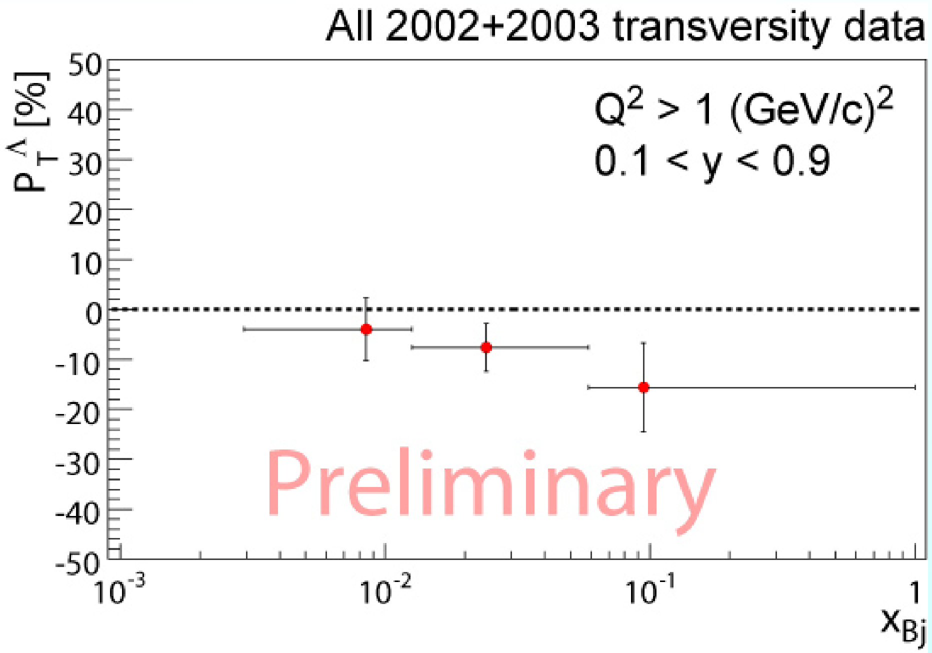


- Asymmetries compatible with zero
- Results from 2004 data analysis about to be released. **Event sample has doubled**

Transversity from transverse Λ polarisation

$$P_T^\Lambda = f\, P_T\, D \frac{\sum_q e_q^2 \times \Delta_T q \times \Delta D_q^\Lambda}{\sum_q e_q^2 \times q \times D_q^\Lambda}$$



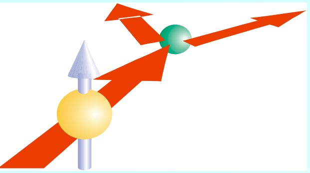


Negative trend for Q^2 > 1 GeV^2, but deviation from zero not significant

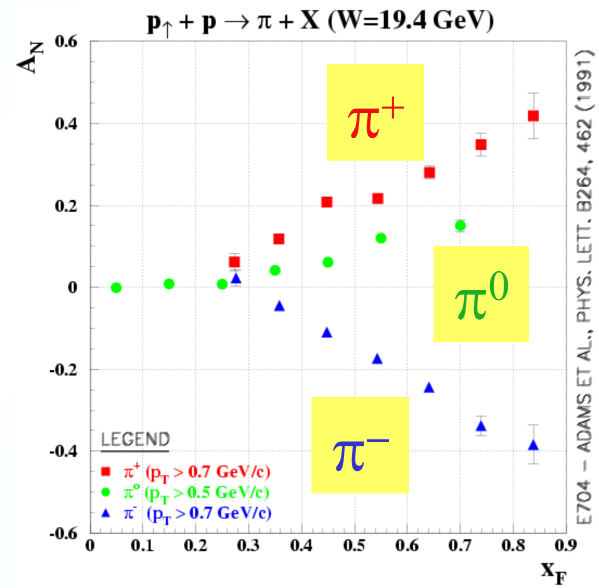
Statistics will double with 2004 data

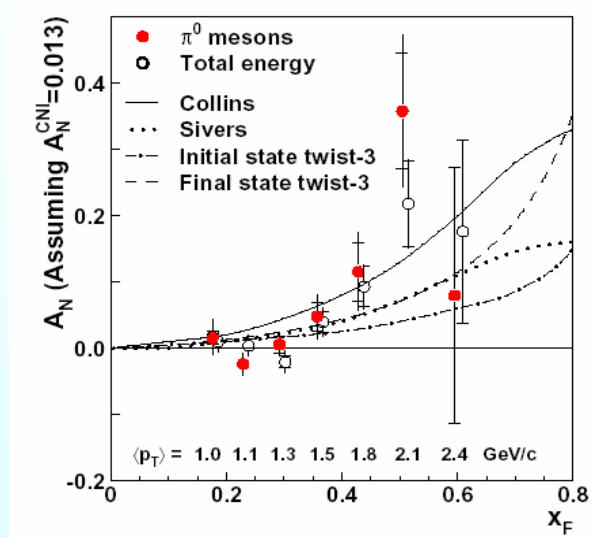
But: HERMES data for quasi-real photoproduction from unpolarized and longt. polarized target: $p_T^\Lambda \sim +5\%$

Single transverse Spin Asymmetry A_N in pp

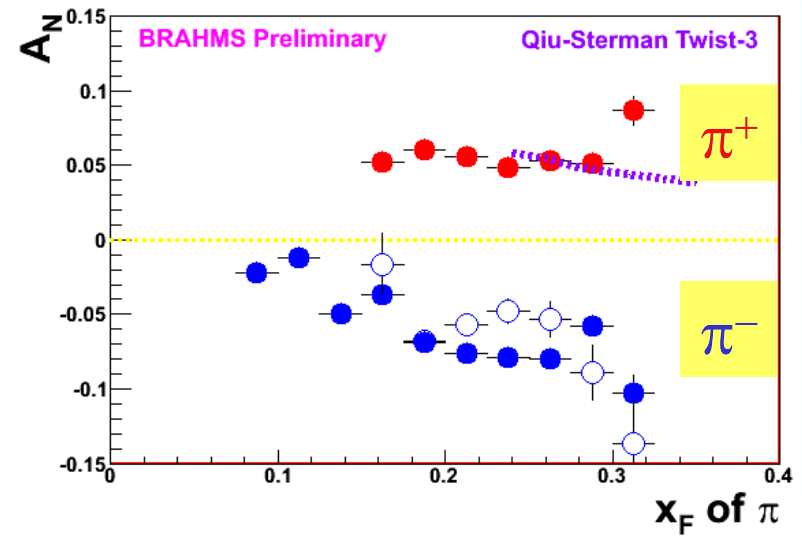


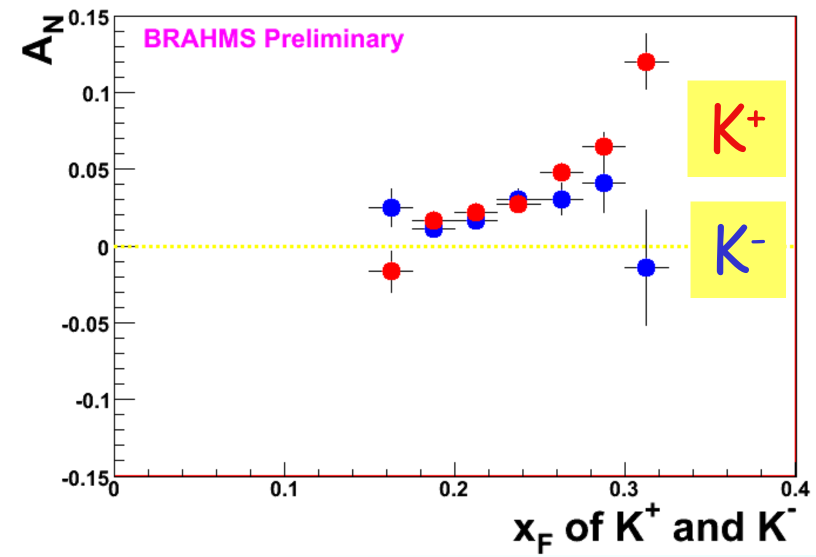
- Large A_N has been observed at forward rapidities in hadronic reactions: E704 and STAR
- Possible origins:
  - Collins FF
  - Sivers DF
  - Twist-3
  - Combinations of above
- Possible connection to orbital angular momentum L ?
- For consistent partonic description: Need flavor dependent $A_N(E, x_F, p_T)$

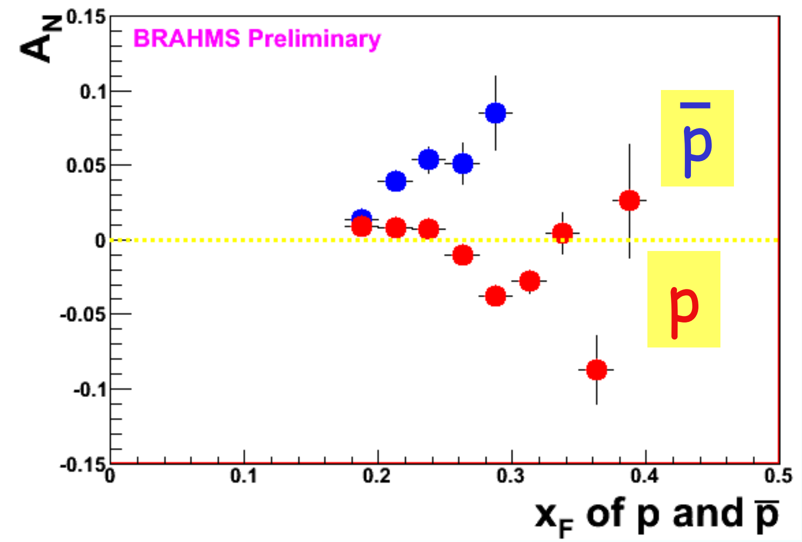




A_N for identified hadrons







- $A_N(\pi^+)$ positive ~ $A_N(\pi^-)$ negative
- $A_N(K^+)$ ~ $A_N(K^-)$ positive (in disagreement with expectation from valence quark fragmentation)
- $A_N(p)$ ~ 0, $A_N(\bar{p})$ positive
- More theoretical input needed

Conclusions

- Plenty of new data from COMPASS, HERMES, RHIC improve our understanding of nucleon spin structure

- Gluon and sea quark polarisations small. Further improvements expected soon, especially from RHIC

- First results on transverse spin physics (Transversity DF, Collins FF, Sivers DF, A_N) very promising

Stay tuned …
New exiting results will come soon!

Special thanks to G. Bunce and A. Magnon