Spin Experiments

Technological challenges and selected physics highlights

Klaus Rith

University of Erlangen-Nürnberg & DESY

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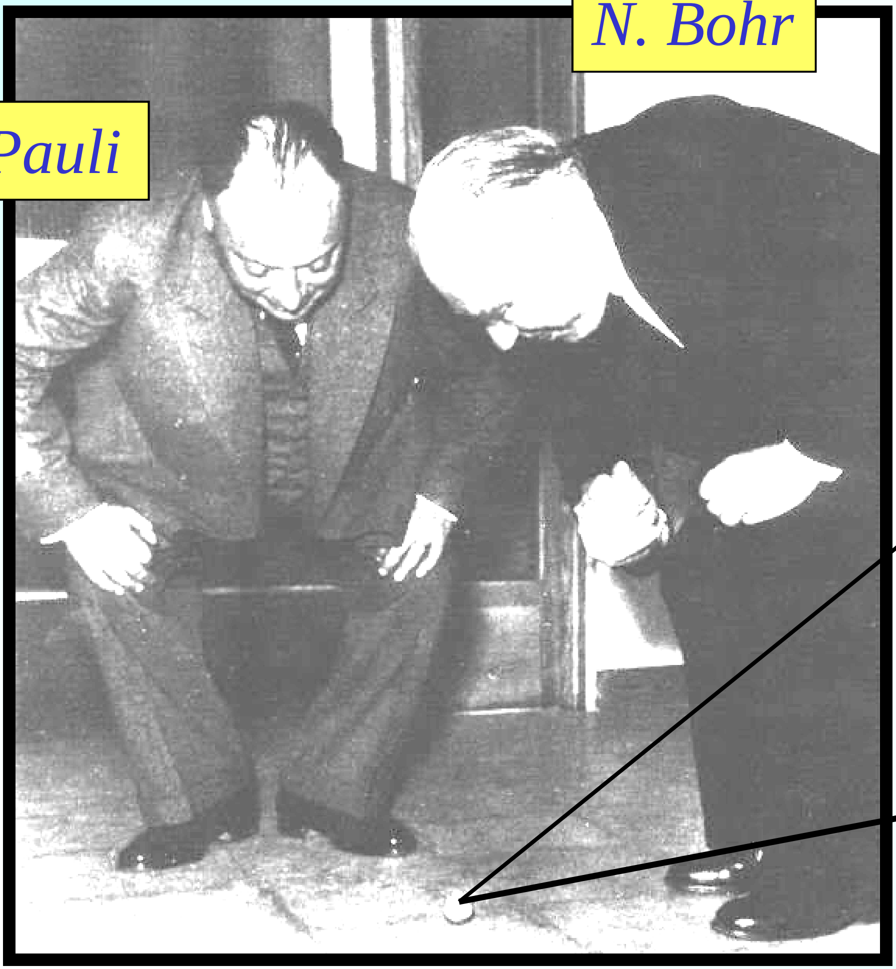
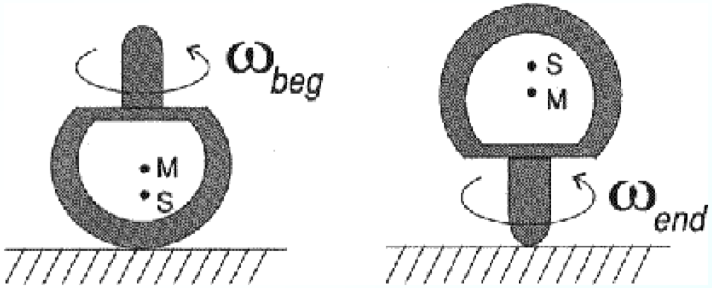
Spin experiments

W. Pauli

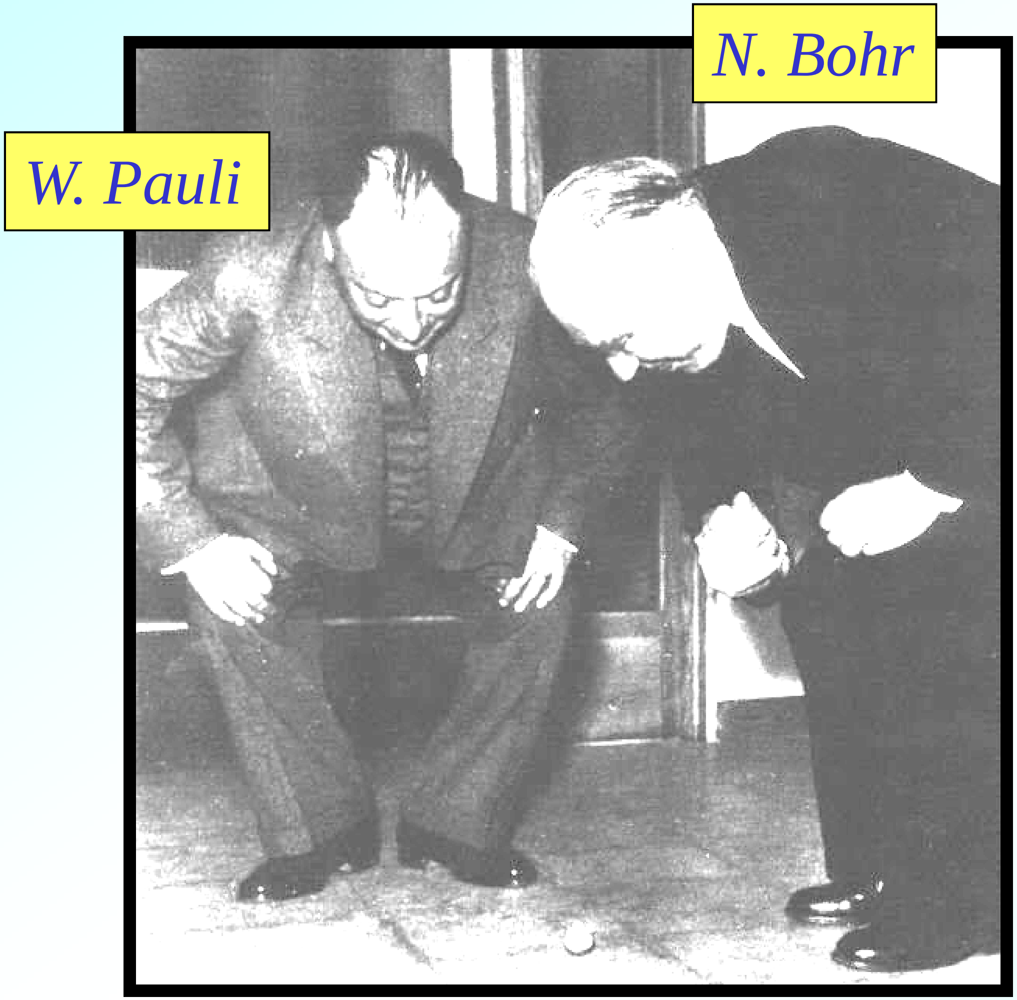
N. Bohr



University of Lund, 31.5.1951



Spin experiments



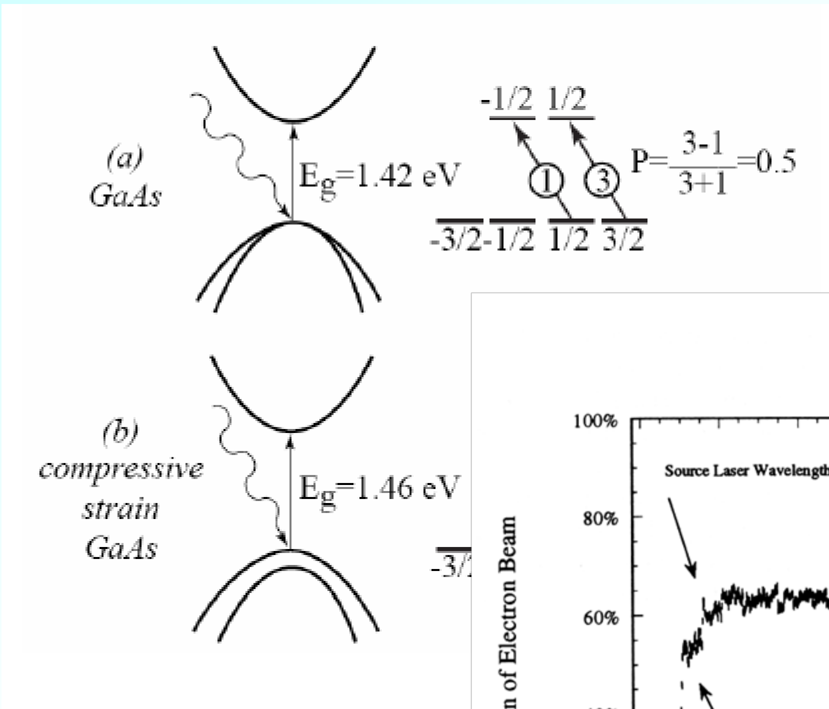
- are fascinating
- enhance small signals
- provide new observables
- often generate surprises

Prerequisites - Technological achievements

- strained GaAs polarized e^--sources with $p_e \geq 0.8$
- longitudinal polarization of 27.6 GeV stored e^-/e^+ beam with $p_e \cong 0.6$ – spin rotators
- internal storage cell polarized $\vec{H}$, $\vec{D}$, $^3\vec{He}$ gas targets with no dilution (f=1), $p_T^{H,D} \geq 0.8$
- large polarized kryogenic targets ($N\vec{H}_3$, $N\vec{D}_3$, $\vec{L}i\vec{D}$)
- polarized stored proton beams (presently up to 100 GeV) with $p_p \cong 0.6$ – Siberian snakes
- Fast and precise polarimeters
- Challenges: - polarized positron sources (for ILC) → J. Clarke
  - polarized antiprotons with $p_{\bar{B}} \geq 0.2$ → E. Steffens

Strained GaAs polarized e-sources

Early ´90s @SLAC: Overcome GaAs limit of p_e= 0.5 bv strained GaAs



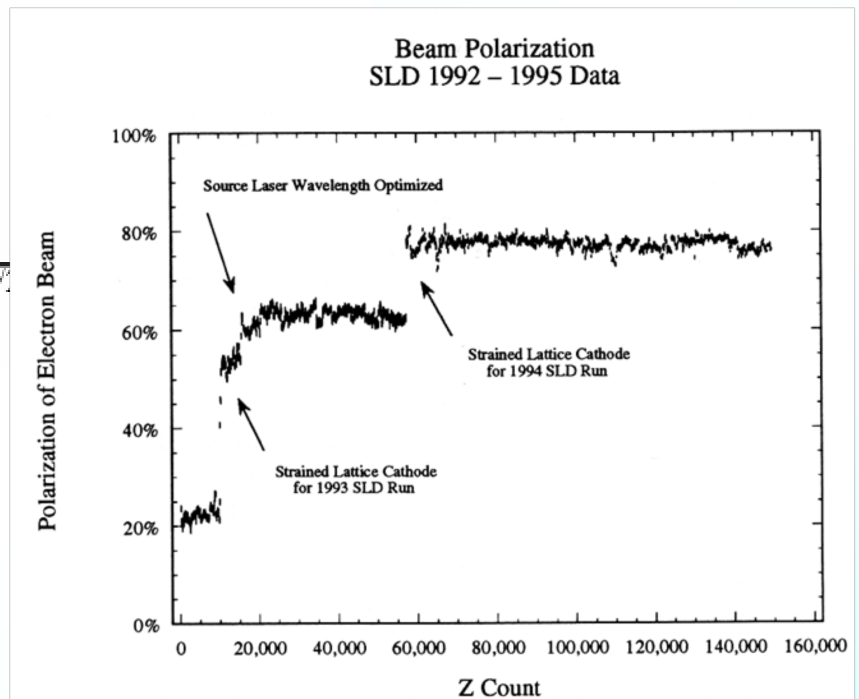


Figure 2: SLC beam polarization history.

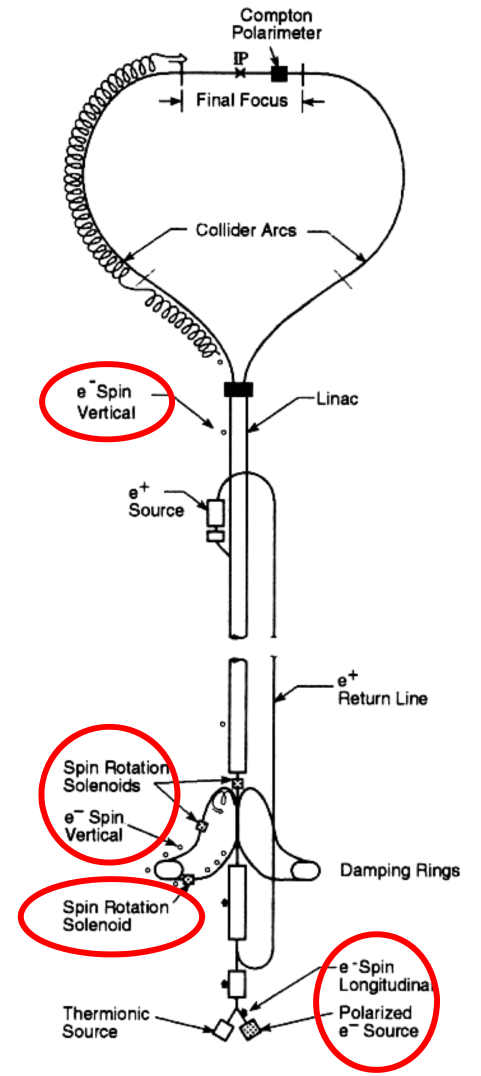


Figure 1: Polarization in the SLC layout

Highlight 1

A^f_{LR} from SLD

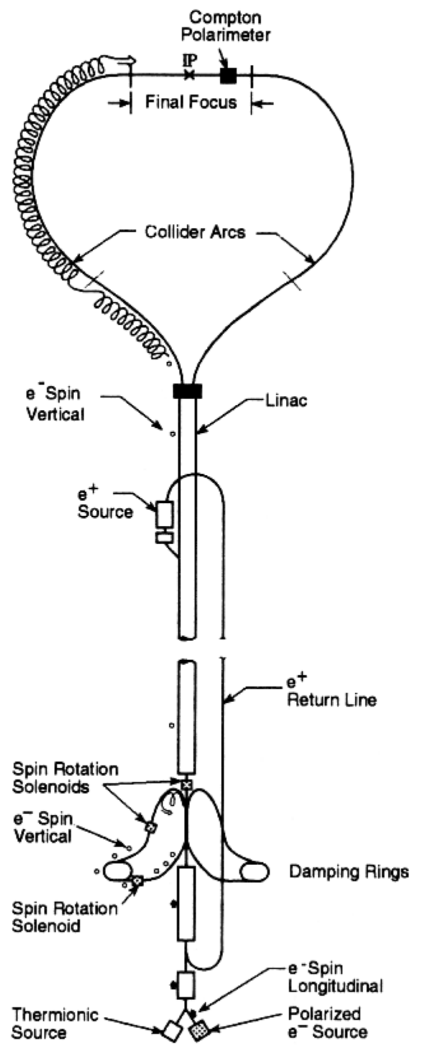


Figure 1: Polarization in the SLC layout

SLD achievements:

Unique data on

$$A^f_{LR} = \frac{g^2_{L,f} - g^2_{R,f}}{g^2_{L,f} + g^2_{R,f}} = \frac{2g_{V,f}/g_{A,f}}{1 + g^2_{V,f}/g^2_{A,f}}$$

$$g_{V,e-}/g_{A,e-} = 1 - 4 \sin^2 \Theta_{W,f}$$

Statistically most precise single determination of $\sin^2 \Theta_W$

$$\sin^2\Theta_W(M_Z) = 0.23098 \pm 0.00026$$

Strained GaAs polarized e-sources

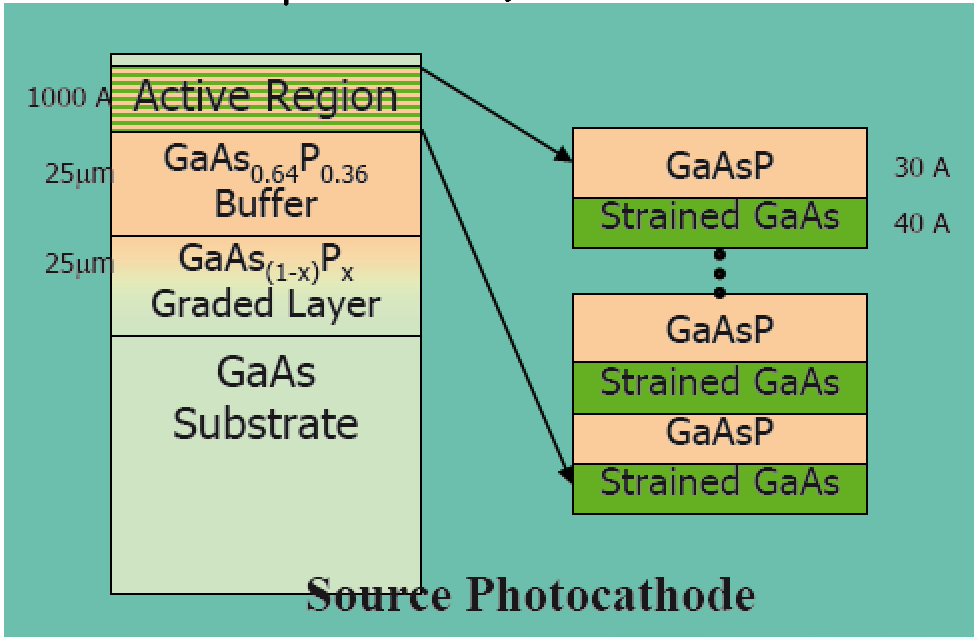
Now ‚standard equipment' at all electron facilities:

(AMPS, BATES), ELSA, JLAB, MAMI, JPARC,........

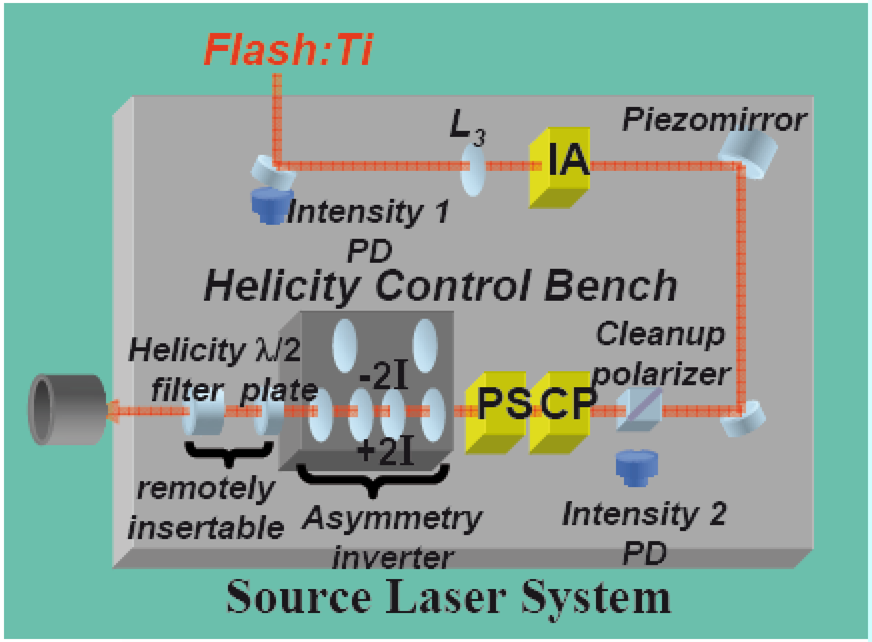
Example: SLAC E158 –Run 3

Sophisticated surface structure to overcome charge limit and achieve high polarisation (gradient-doped strained superlattice)

Precise control of beam helicity at source



Source Photocathode



Source Laser System

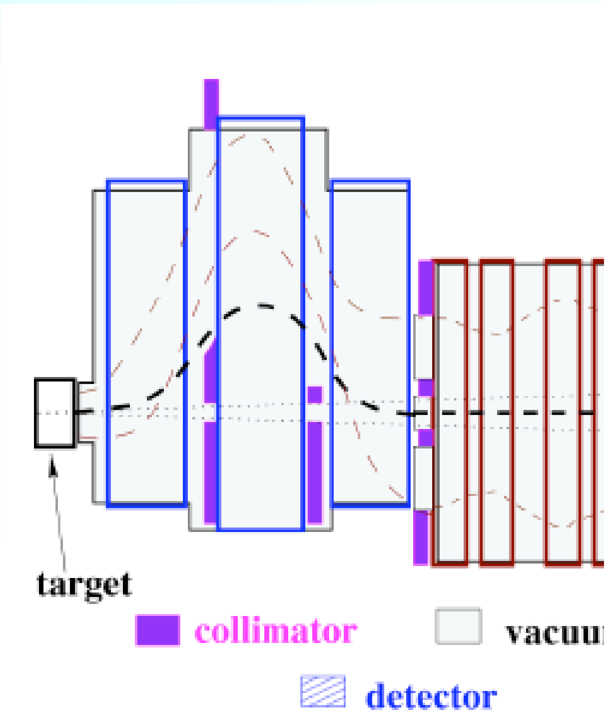
E158 – PV in Møller-scattering

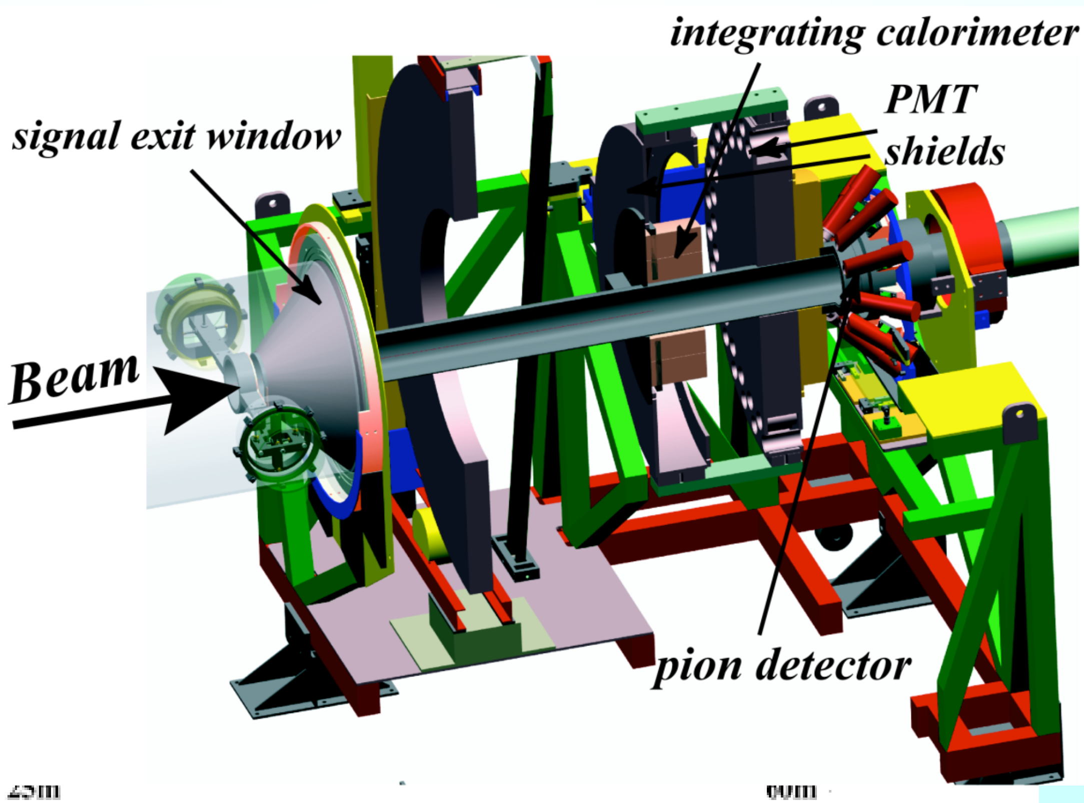
First PV experiment in $\vec{e}^-_{L,R}\, e^- \rightarrow e^-\, e^-$

End of SLAC fixed target programme

$P_e = 0.89 \pm 0.04$, $E_{beam} = 45$ & 48 GeV (spinrotation by extra π due to g-2)

$E' \approx 13\text{-}24$ GeV, $Q^2 \approx 0.026$ GeV^2



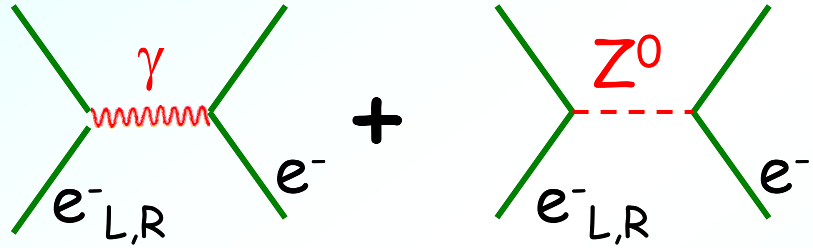


Challenge: Control of beam-helicity related systematic errors

Highlight 2

E158 – PV in Møller-scattering

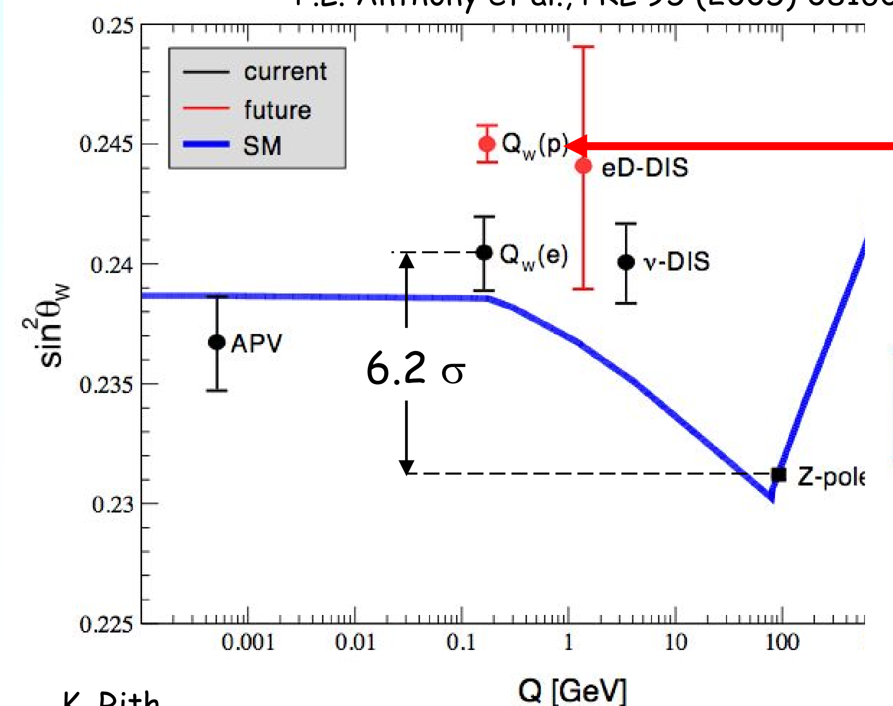
Electroweak interference:

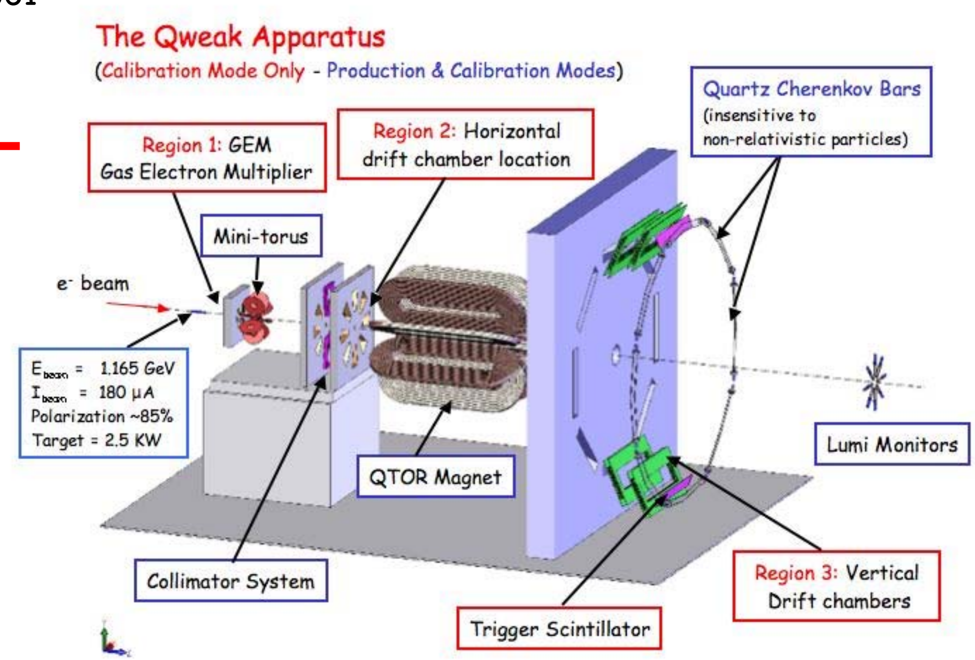


$$A_{PV} = -\mathcal{A}(Q^2,y)[1-4\sin^2\Theta_W^{eff}(Q)] = [-1.31\pm0.14\ (stat)\pm0.10\ (sys)]10^{-7}$$

$$\sin^2\Theta_W^{eff}(Q) = 0.2397\pm0.0010\pm0.008$$

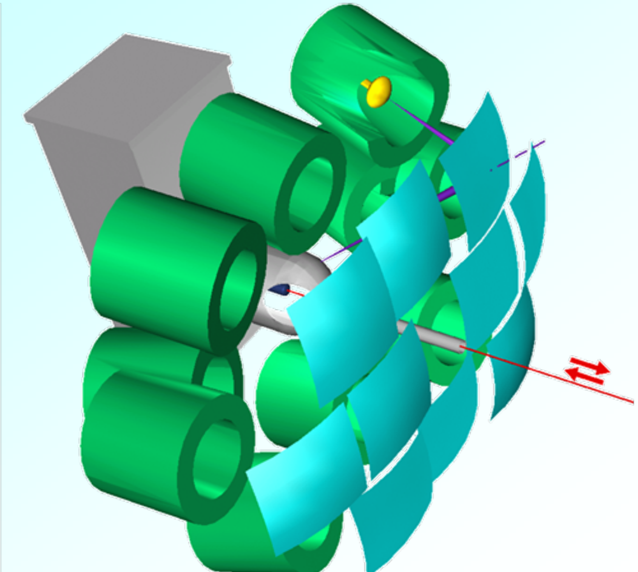
P.L. Anthony et al., PRL 95 (2005) 081601



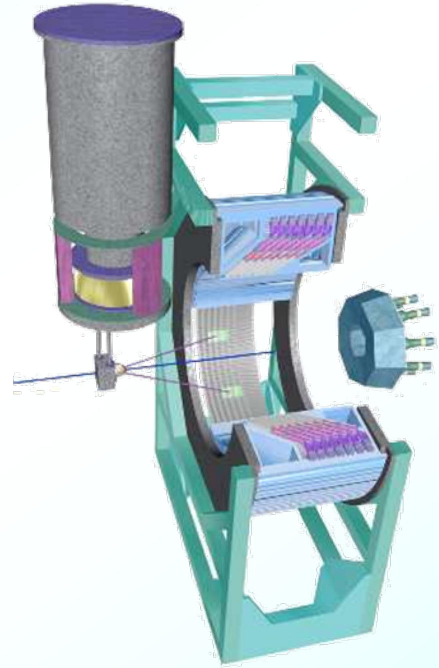


PV in $\vec{e}N \to eN$

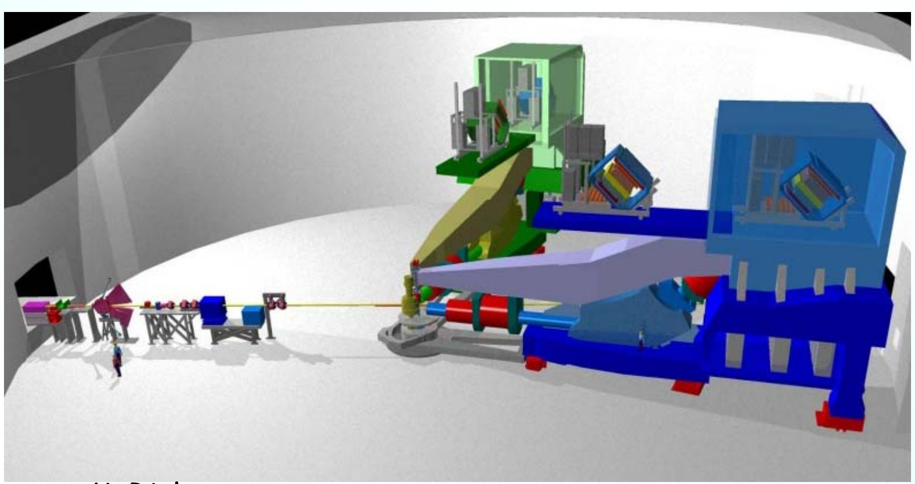
SAMPLE/BATES



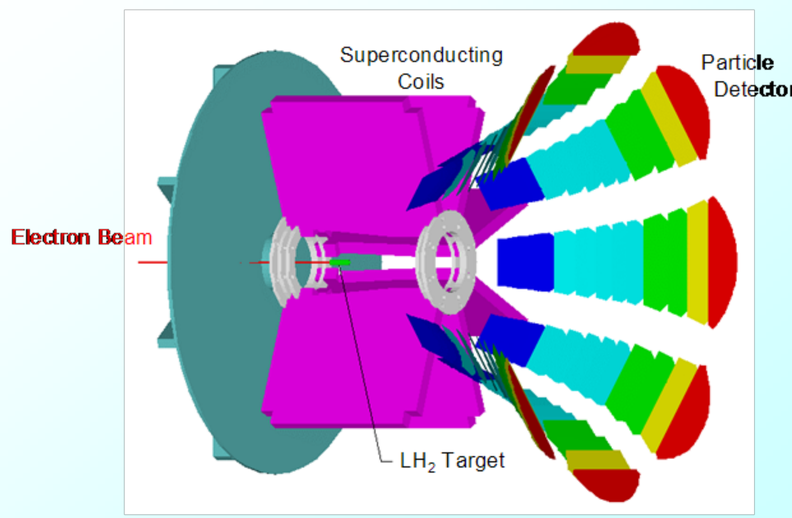
A4/MAMI



HAPPEX/JLAB



G0/JLAB

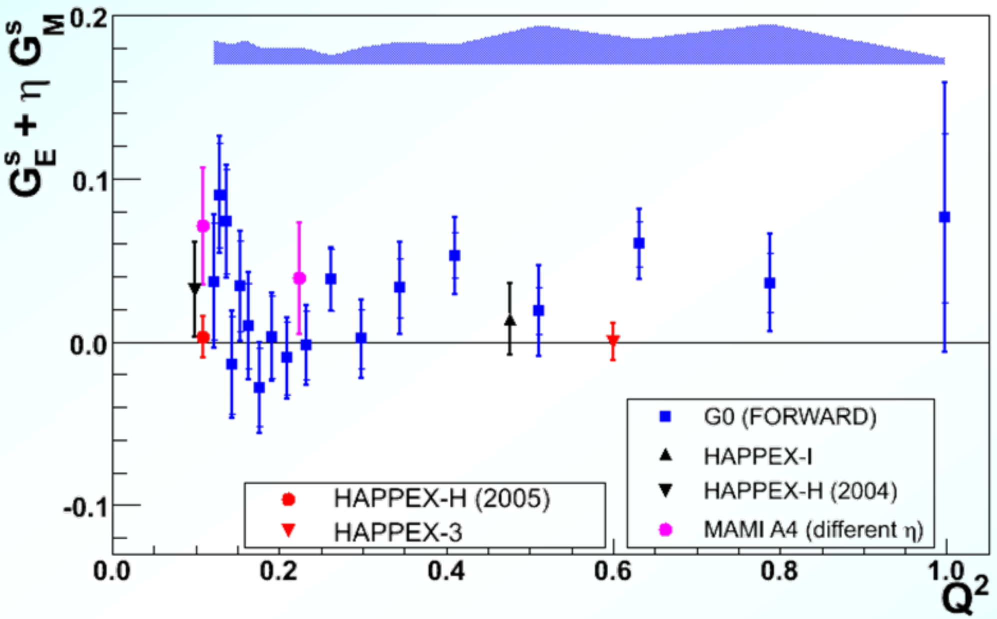


Highlight 3

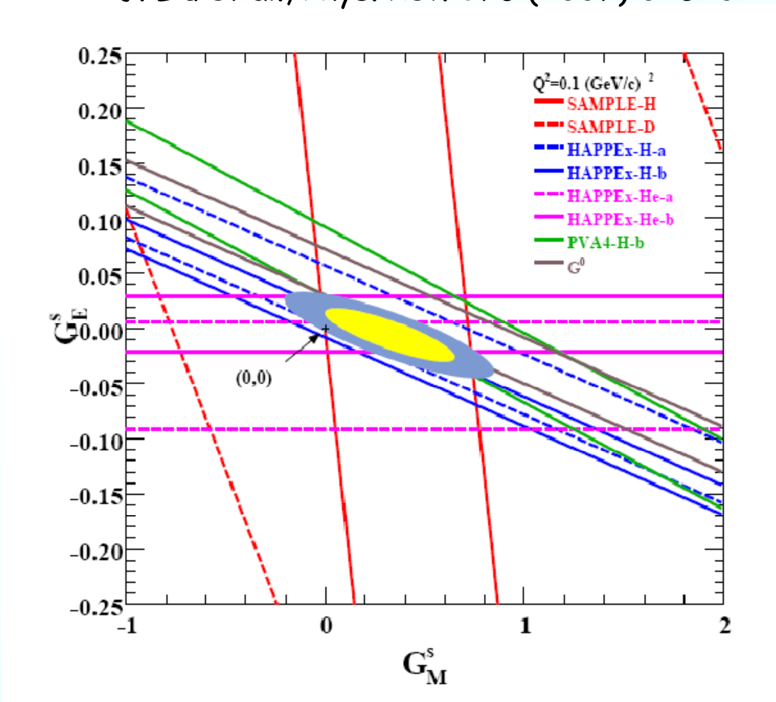
Nucleon Strange Form Factors

Very small asymmetries: $O(10^{-6})$

D.S. Armstrong et al., PRL 95 (2005) 092001



J. Liu et al., Phys. Rev. C76 (2007) 025202



Highlight 4

Precise determination of G_E^n

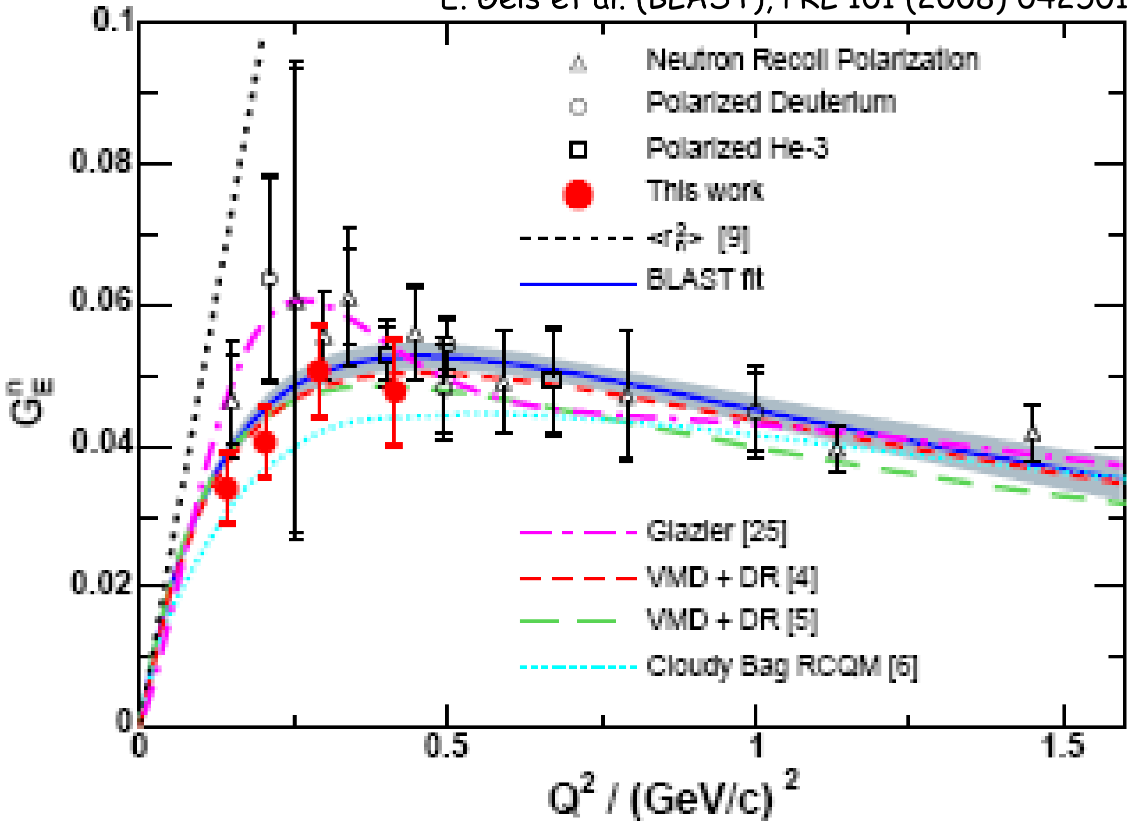
Tool: double-polarization experiments

$\vec{D}(\vec{e},e'n)$ with polarized $\vec{D}$ target

$^2D(\vec{e},e'\vec{n})$ with LD_2 target and n recoil polarimeter

$^3\vec{He}(\vec{e},e'n)$ with polarized $^3\vec{He}$ target

E. Geis et al. (BLAST), PRL 101 (2008) 042501

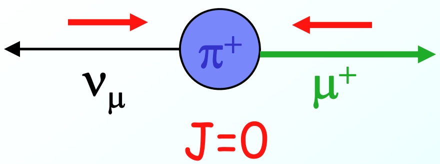


Polarized muon beam – EMC, SMC, COMPASS

- **Myon beam**: 100 - 200 GeV

  $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$

- Advantage: 'Natural' beam polarization:



- Disadvantage: low beam currents – $I \approx 1$ pA

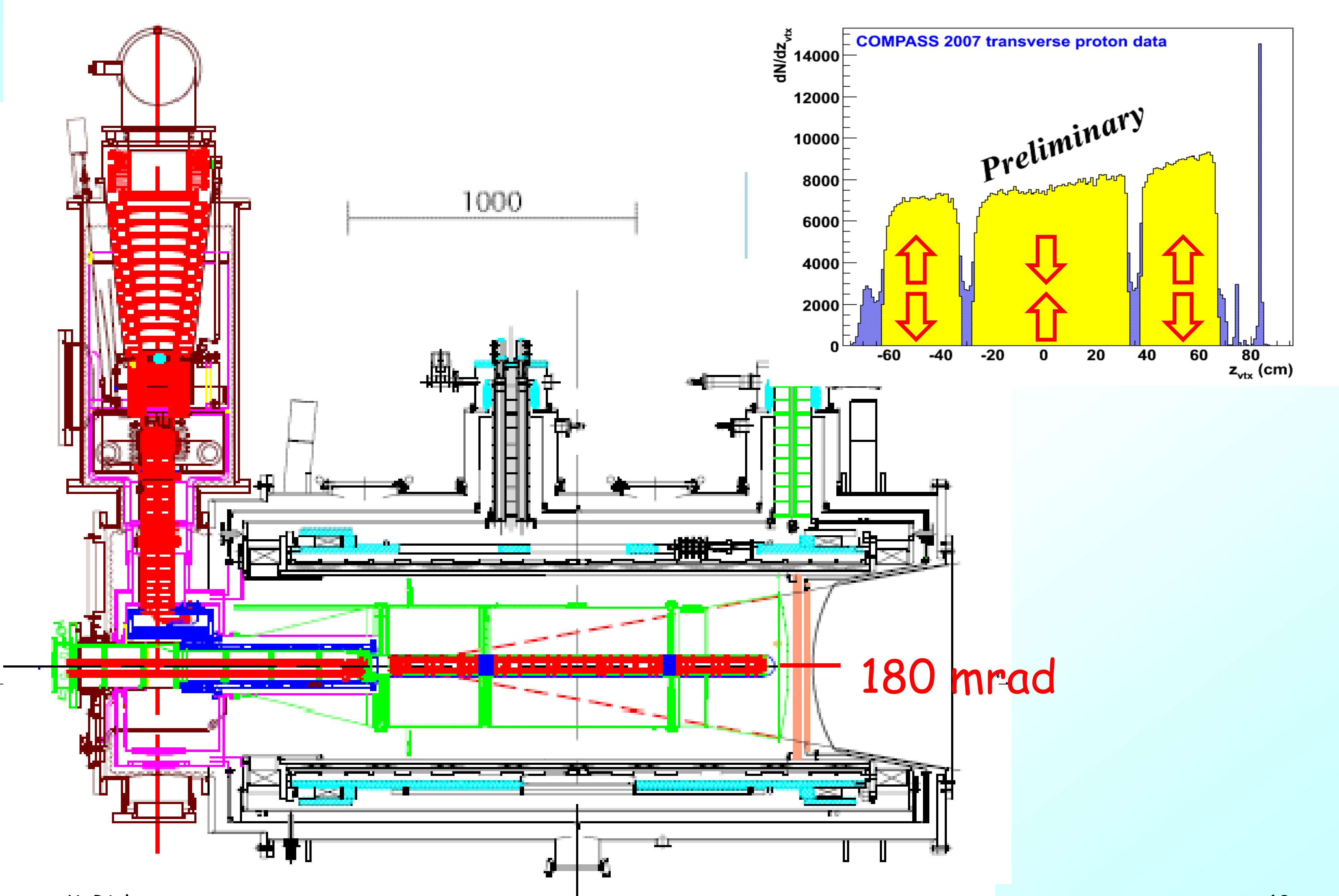
- Require high-mass polarized target, $N \approx 10^{24}$ nucleons/cm^2

  $N\vec{H}_3$ ($f \approx 3/17$) , $N\vec{D}_3$ ($f \approx 6/20$), $\vec{Li}\vec{D}$ ($f \approx 4/8$),……

  f = fraction of polarizable nucleons

→ W. Meyer

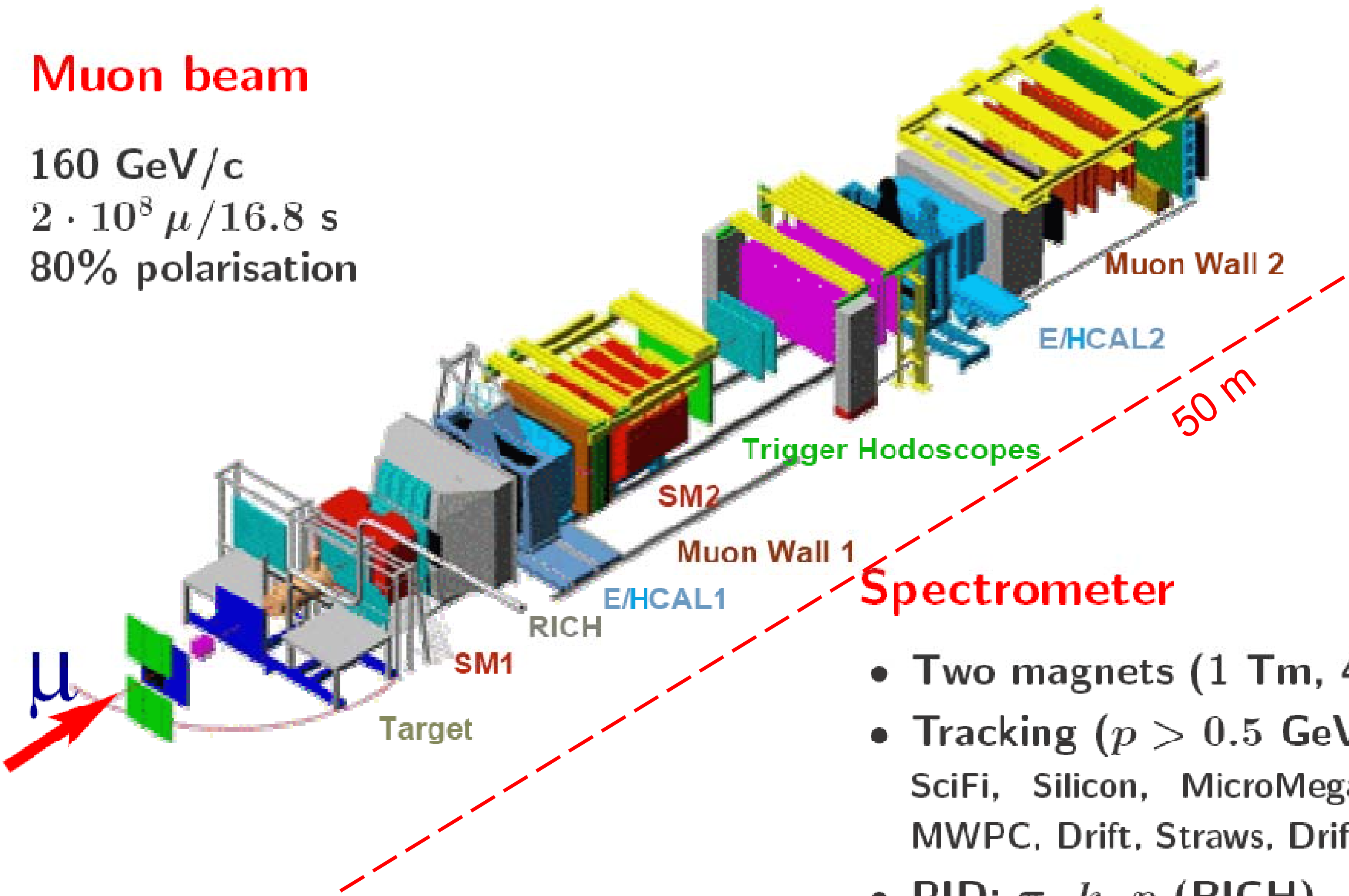
Polarized target - COMPASS



COMPASS spectrometer

Muon beam

160 GeV/c
$2 \cdot 10^8\ \mu/16.8$ s
80% polarisation



Spectrometer

- Two magnets (1 Tm, 4.5 Tm)
- Tracking ($p > 0.5$ GeV/c):
  SciFi, Silicon, MicroMega, GEM, MWPC, Drift, Straws, Driftubes
- PID: π, k, p (RICH)
  above 2, 9, 18 GeV/c
- ECAL, HCAL, muon filter

Polarized $e^{\pm}$ beam in storage ring– LEP, HERA

- Mechanism: Spin flip by emission of synchrotron radiation

  $\approx 1 / 10^{10} - 10^{11}$ emissions (Sokolov-Ternov)

- Degree of polarization: depends critically on machine energy and magnet alignement

- Example: LEP – $m_Z = 91.1874 \pm 0{,}0021$ GeV

  Beam energy dominant error of 1.7 MeV
  Measurement by resonant depolarization of transversely polarized beam

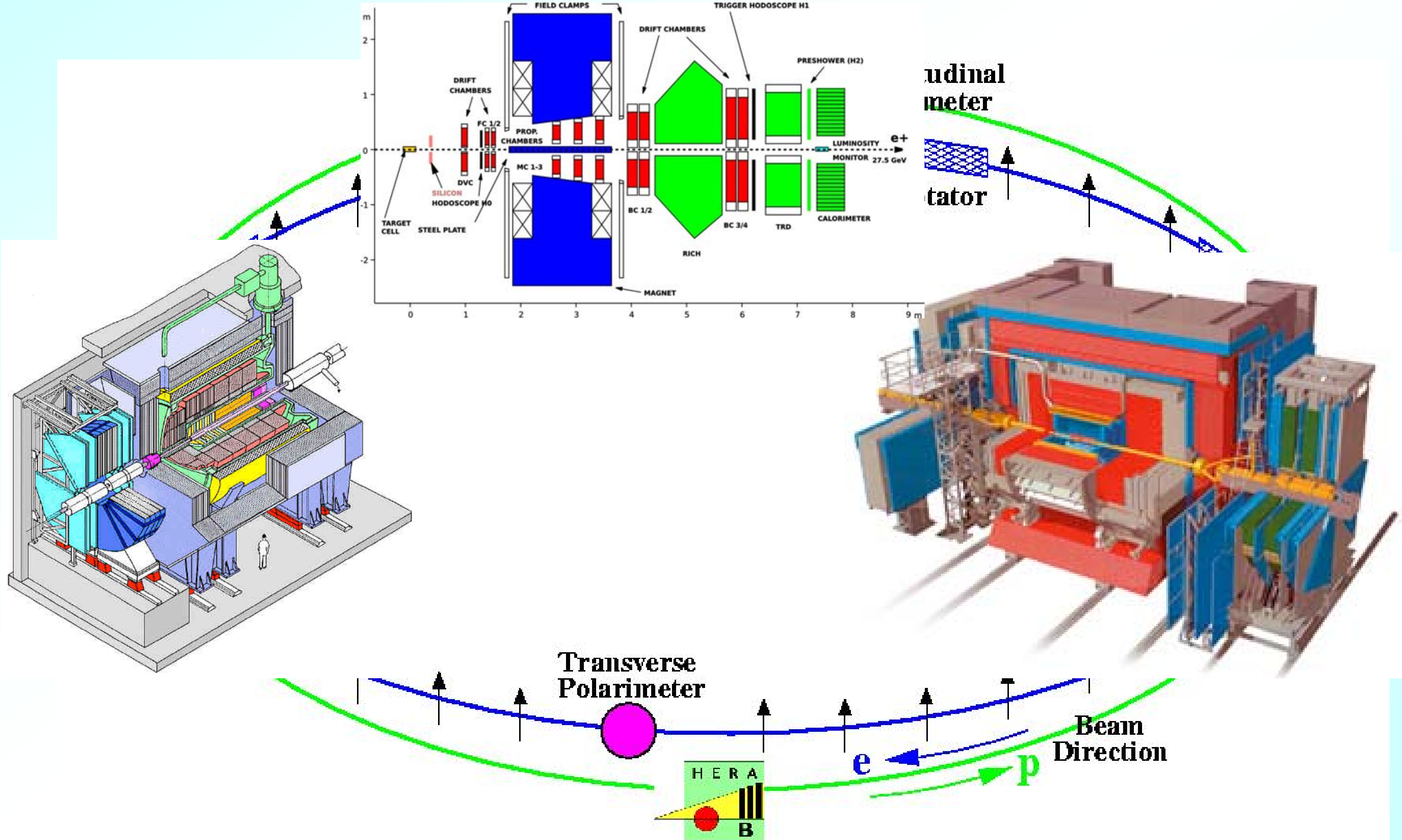
  Influence of tide, TGV leaving airport station etc.

- Longitudinal polarization: requires spin rotators

- Polarization measurement: Compton backscattering of circularly polarized laser light

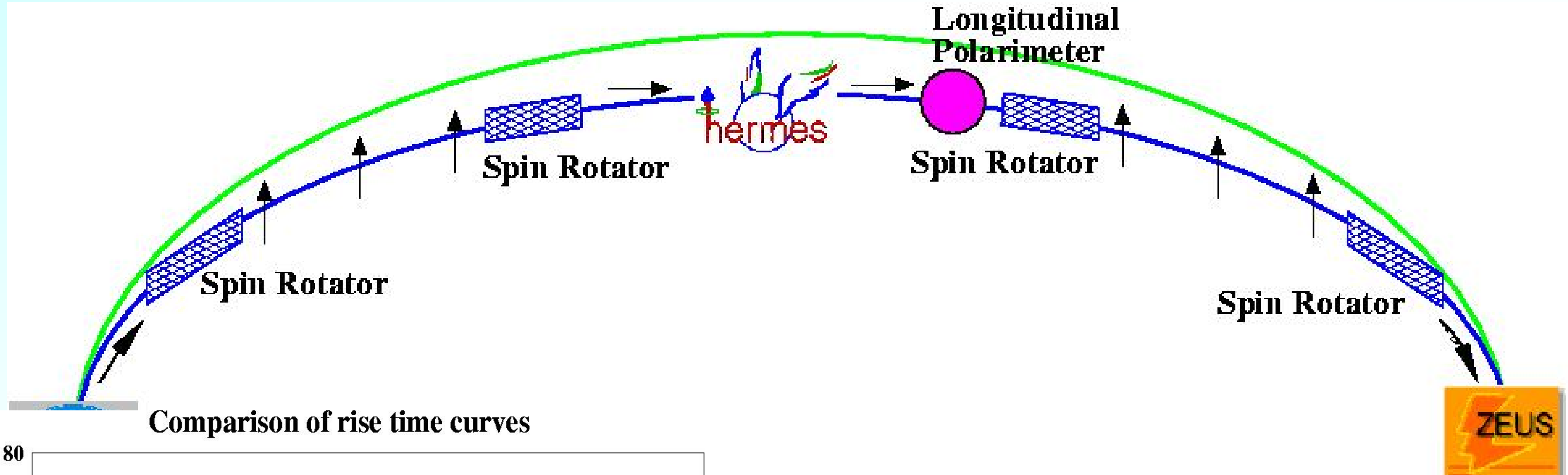
Polarized e$^{\pm}$ beam in HERA

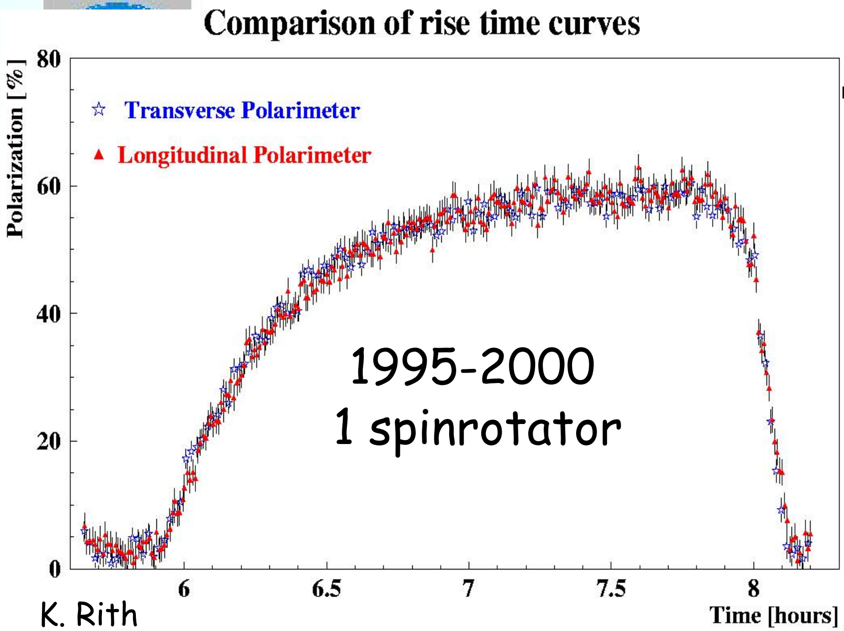
e$^{\pm}$ beam: E = 27.6 GeV, I_e < 50 mA

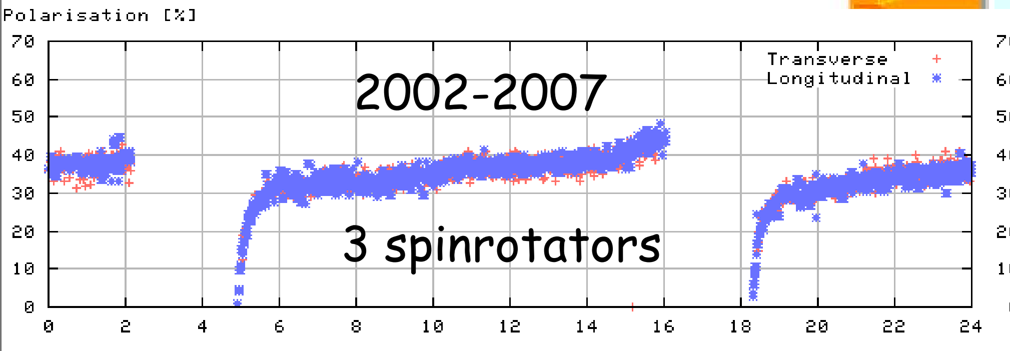


Polarized e± beam in HERA

e± beam: E = 27.6 GeV, I_e < 50 mA





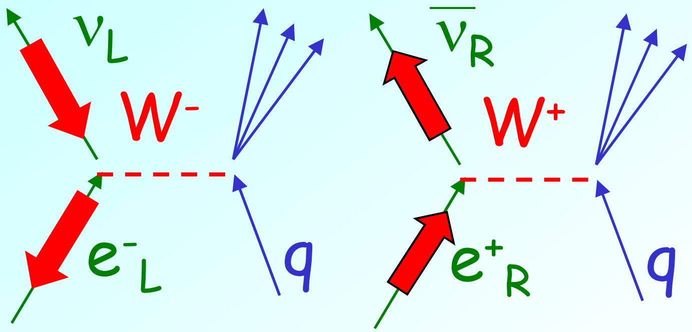


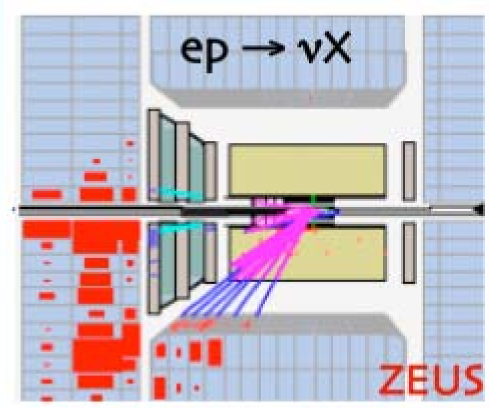
After ´high -luminosity upgrade': depolarization by beam-beam interactions

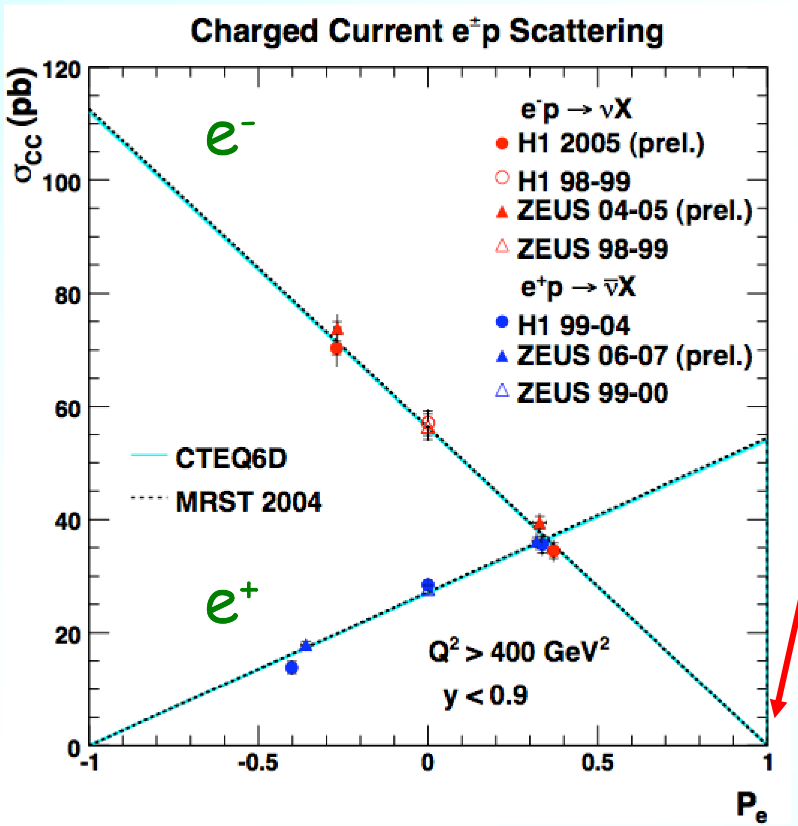
K. Rith

Highlight 5

Total polarized CC cross section

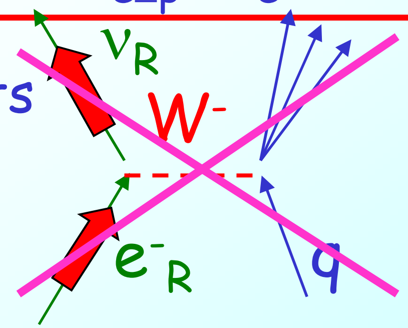






$$\sigma^{CC}_{e\pm p}(P_e) = (1 \pm P_e)\sigma^{CC}_{e\pm p}(P_e{=}0)$$

No sign of r.h currents

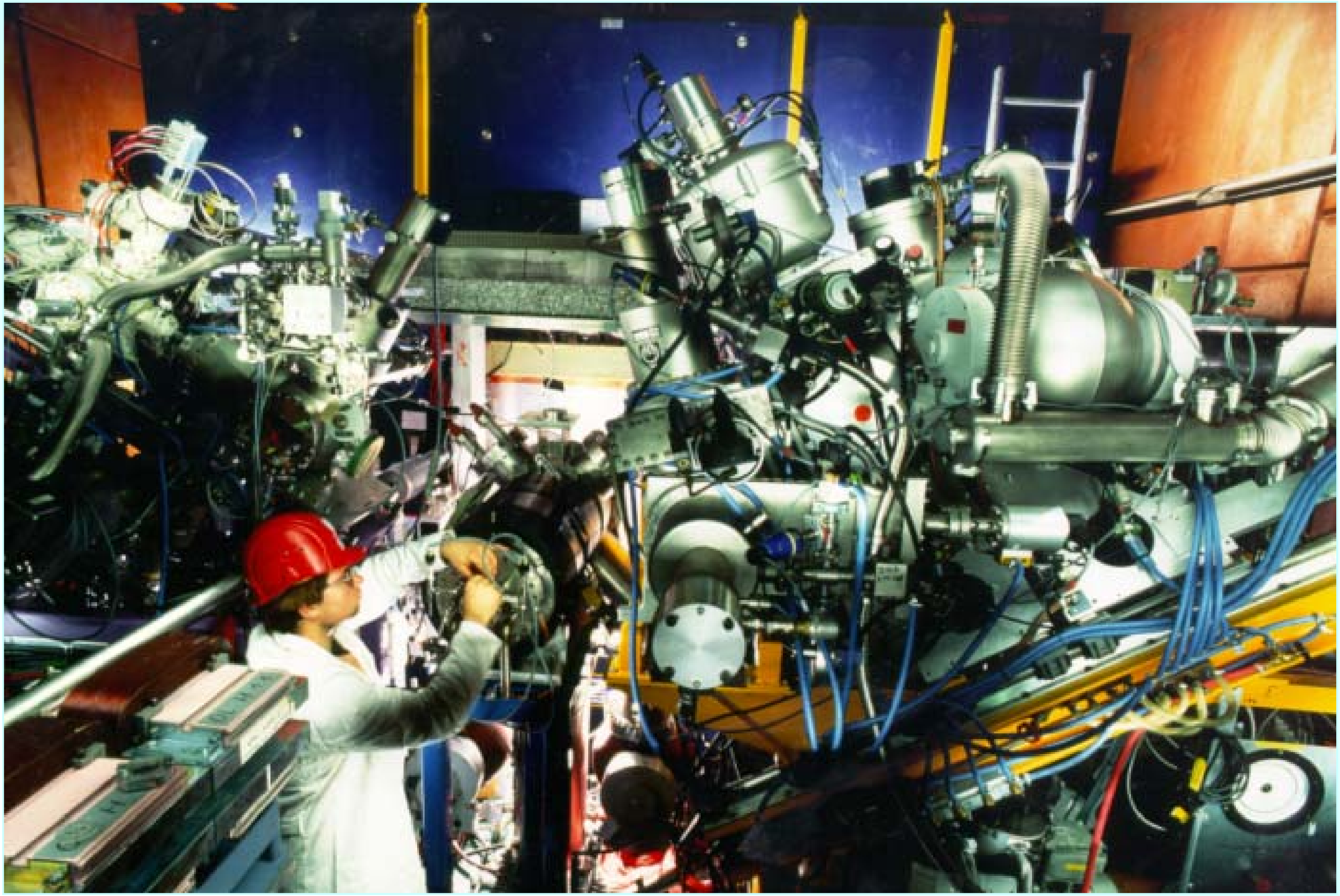


Chiral structure of SM confirmed

Convert to 90% CL on heavy W_R:

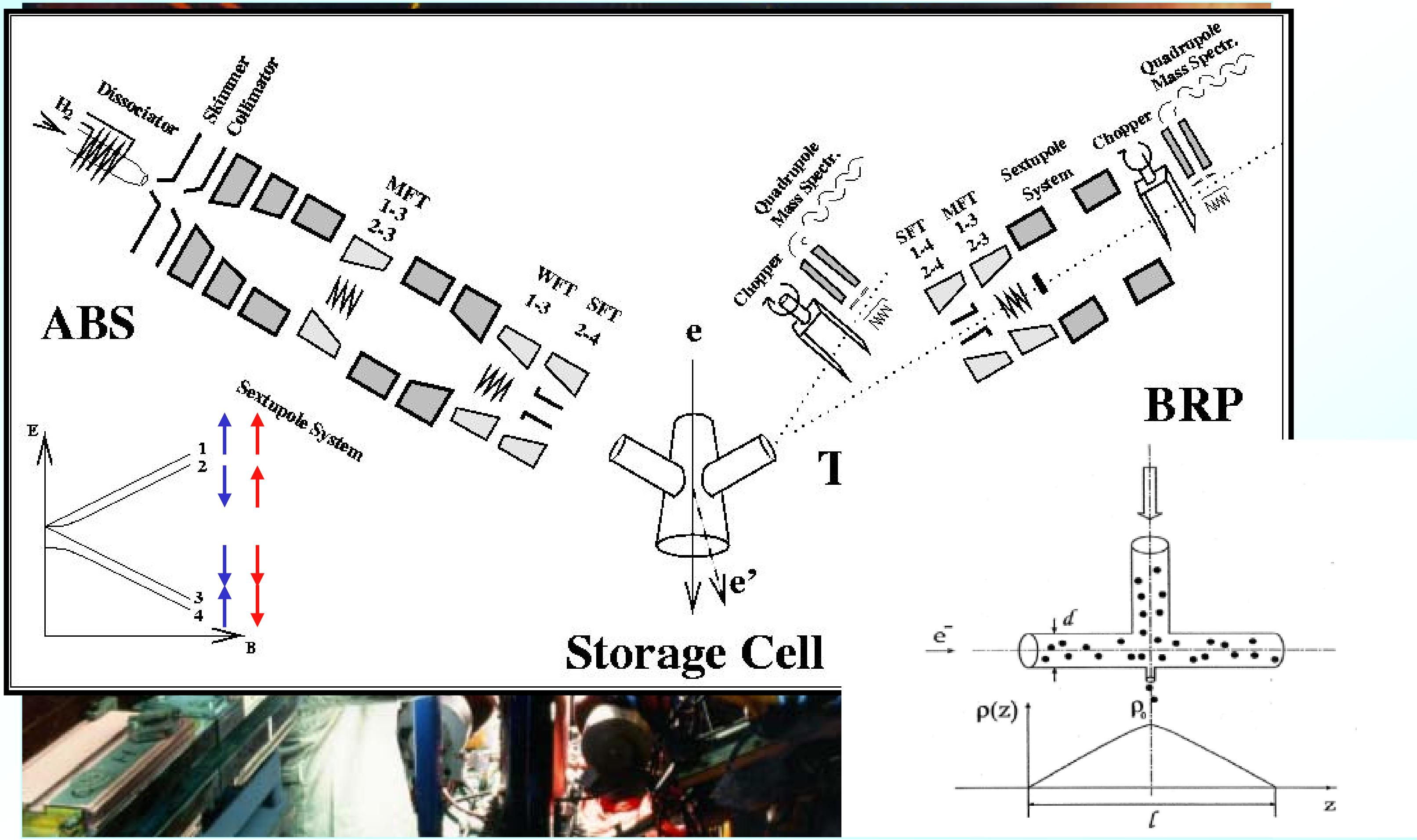
$m_{W,R}$ > 208 GeV (H1)

Internal polarized storage-cell gas targets



hermes

Internal polarized storage-cell gas targets



Principle: Stern-Gerlach separation of HF-states + RF-transitions

Target polarisation: $P_T \approx 0.85$, Dilution factor: f=1

Ideal for storage rings: IUCF, COSY, BATES..

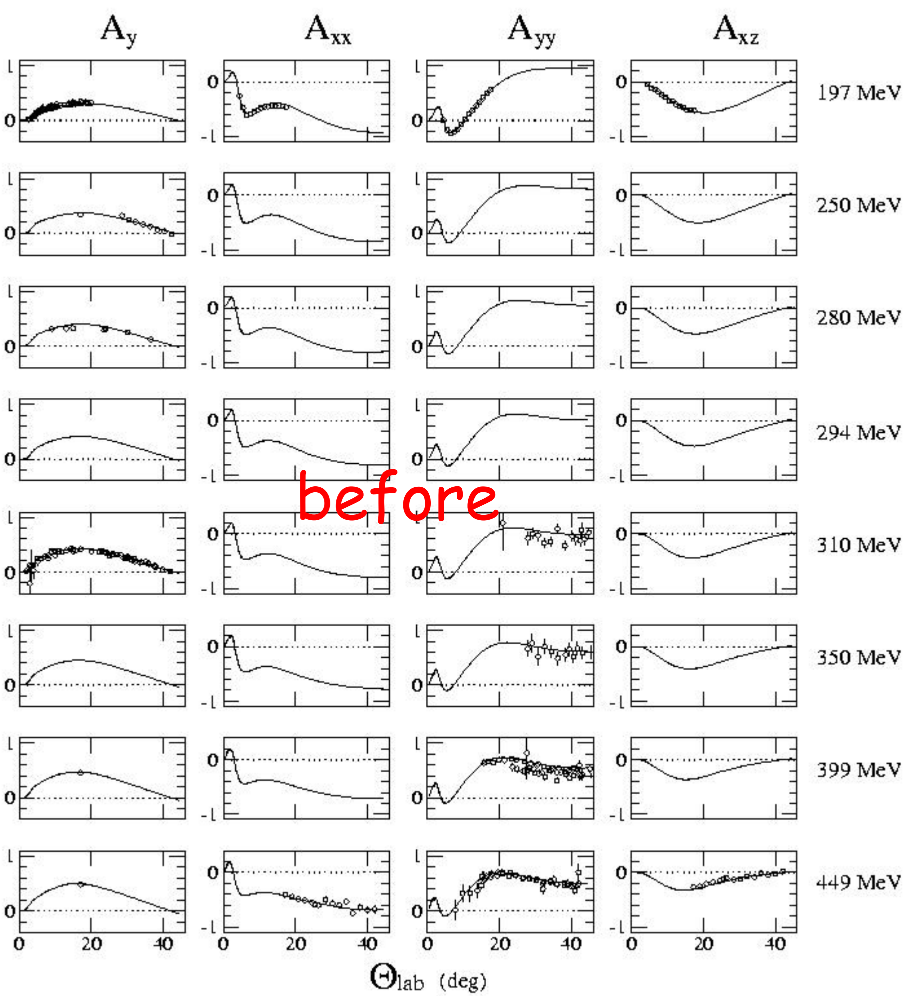
Highlight 6

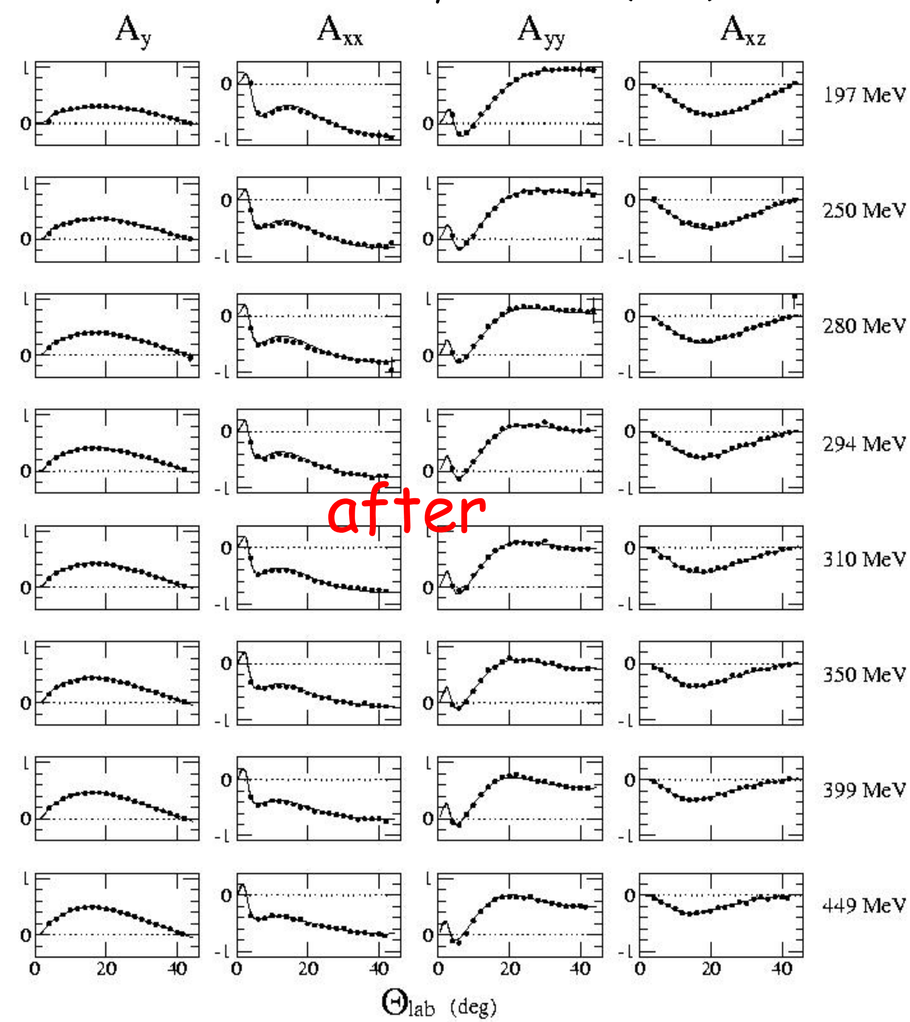
Asymmetries in polarized pp scattering

Example: PINTEX at IUCF: $\vec{p}\,\vec{p} \to p\,p$

Precise measurement of spin correlation parameters

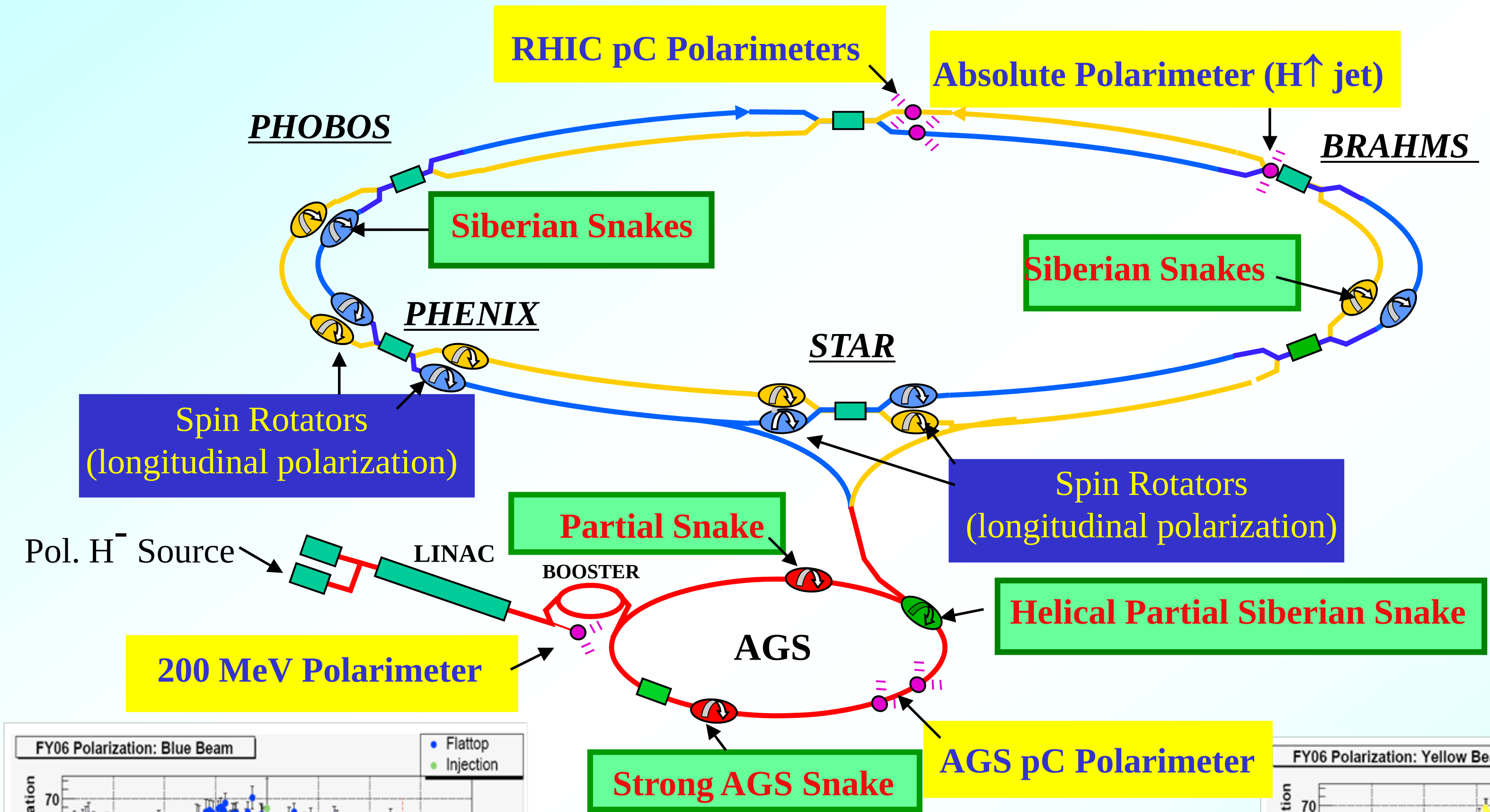
F. Rathmann et al., Phys. Rev. C58 (1998) 658

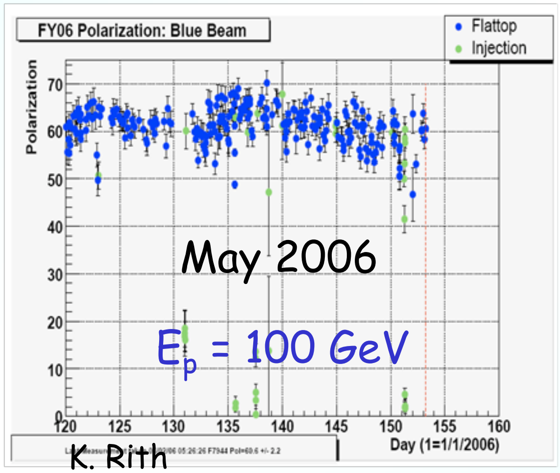




Test and improvement of NN potential models

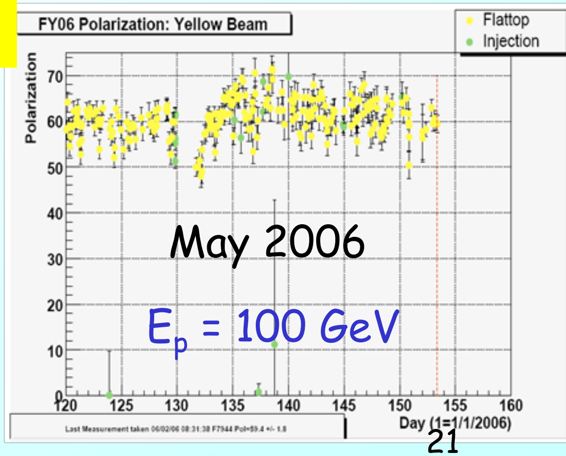
Polarized proton collider - RHIC



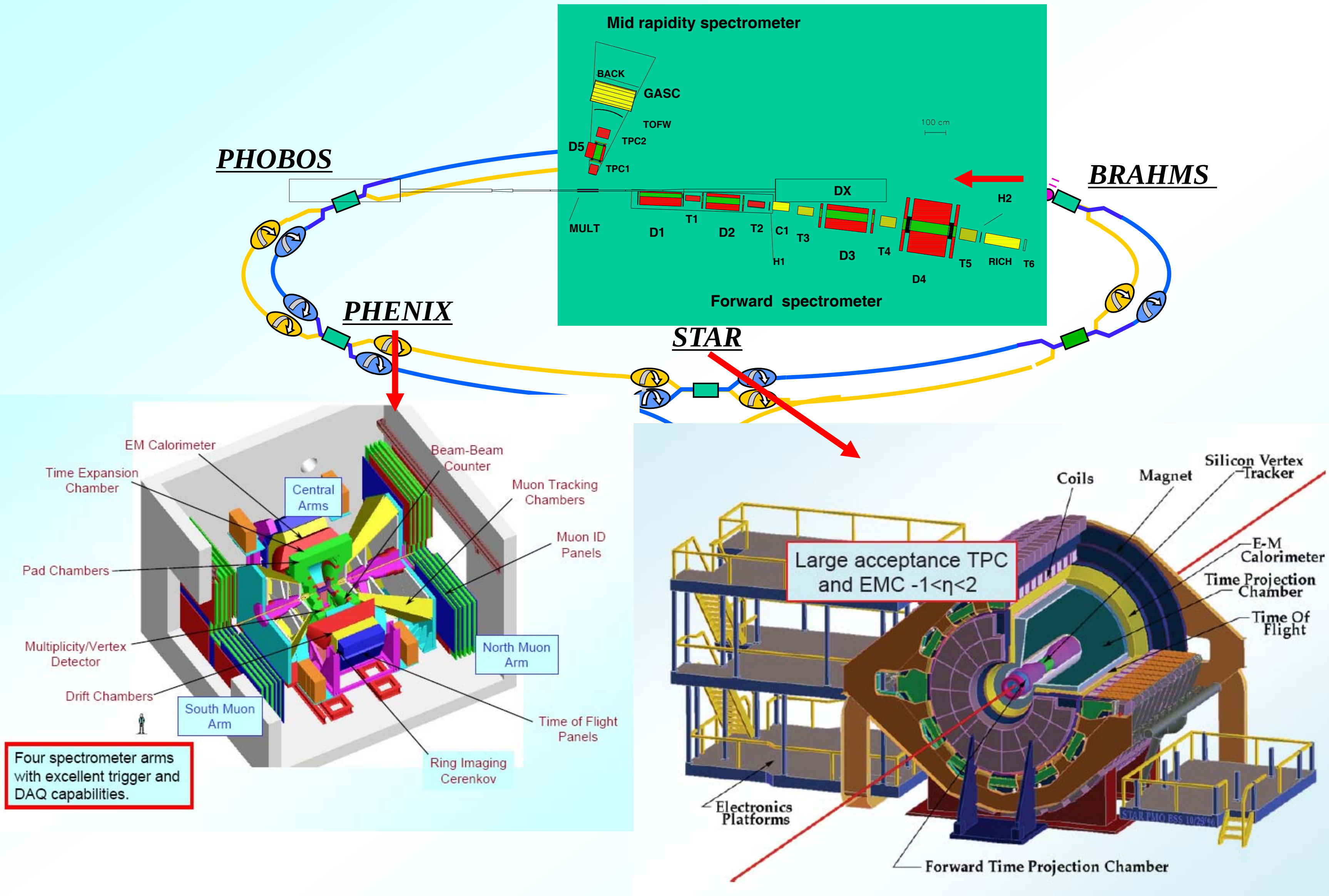


Masterpiece of accelerator physics

→ T. Roser

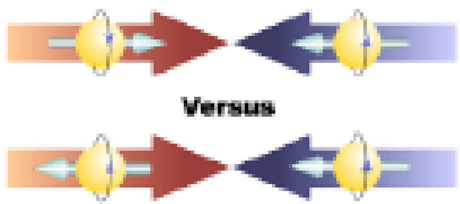


Polarized proton collider - RHIC

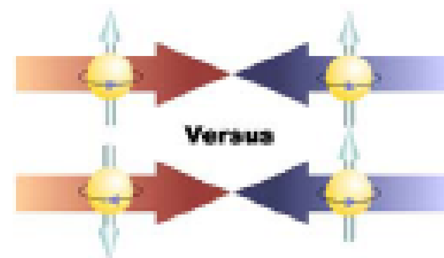


Asymmetries in polarized pp collisions

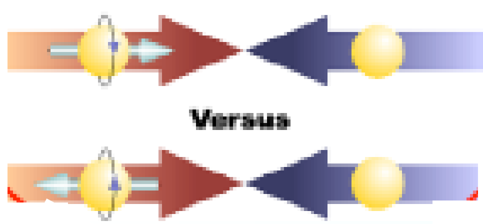
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



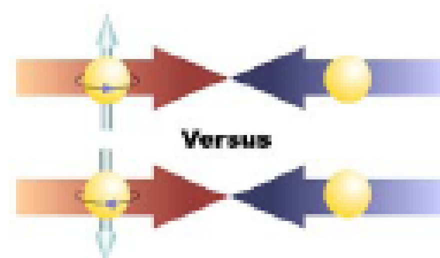
$$A_{TT} = \frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}$$



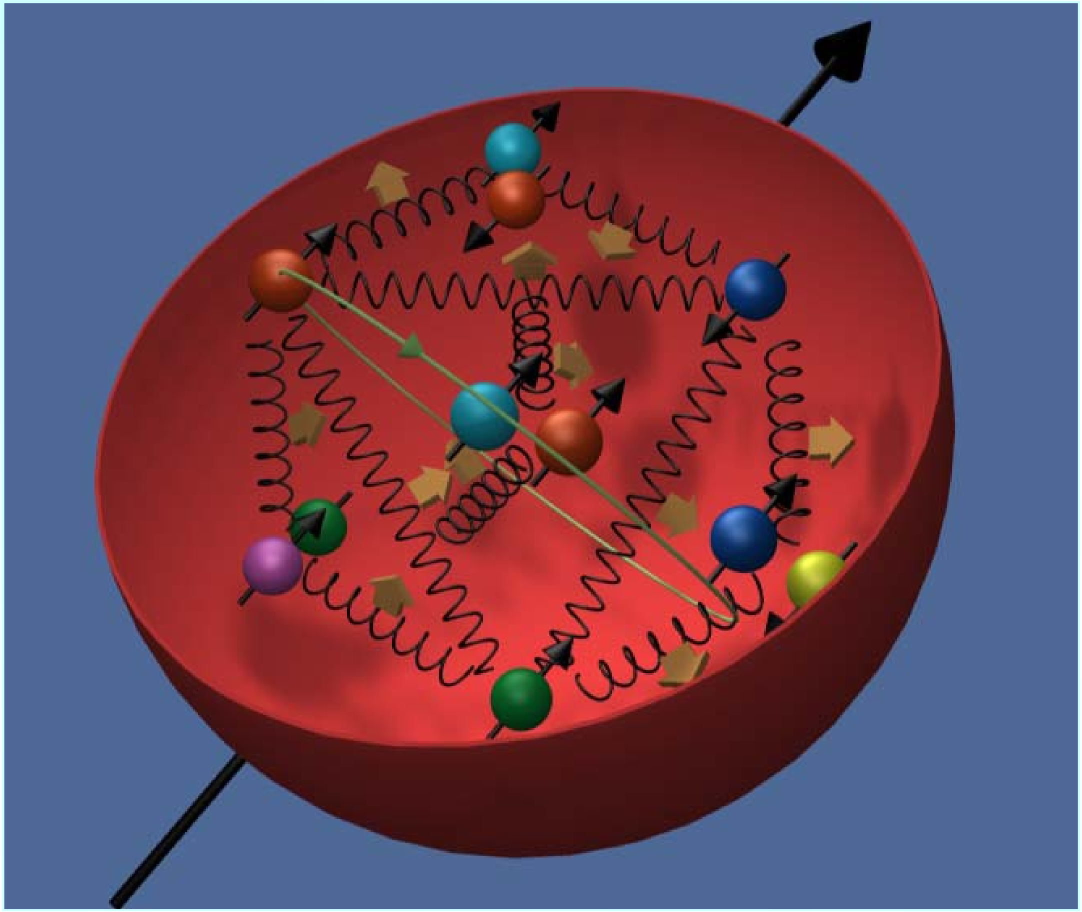
$$A_{L} = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)}$$



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



Nucleon Spin



$$\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma \text{ (Quark spins)}$$

$$+ \Delta G \text{ (Gluon spins)}$$

$$+ L_q + L_g$$

(Orbital angular momenta)

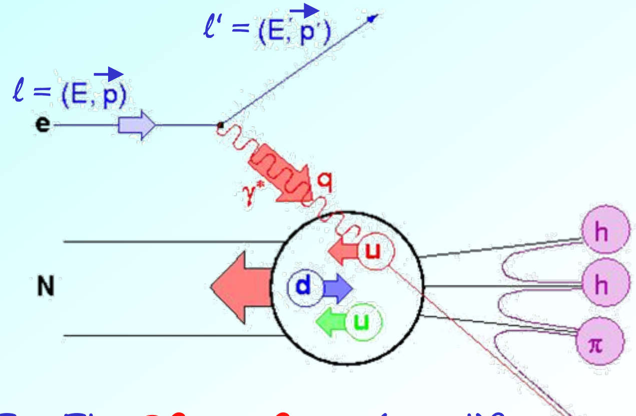
EMC (1987):

$\Delta\Sigma$ = 0,12 ±0,09±0,14

K. Slifer

Nucleon Spin - Tools

Polarised DIS

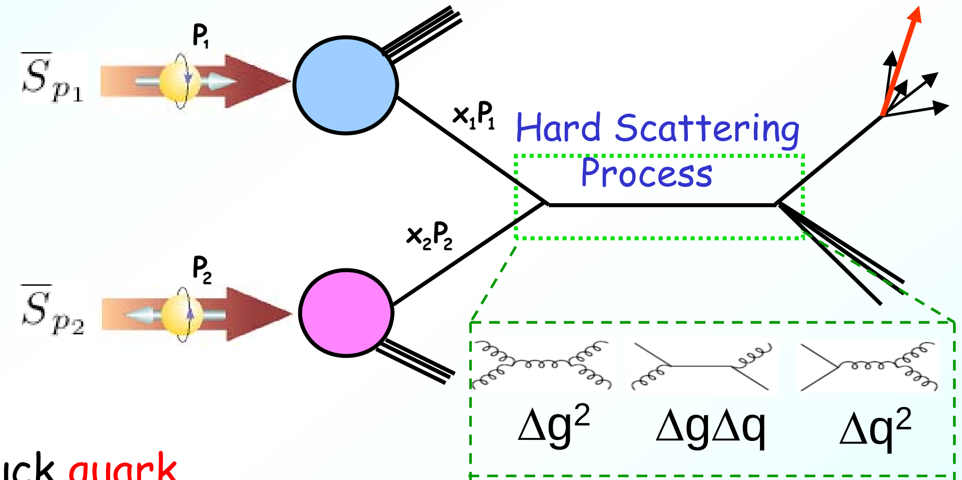


ν = E - E', $Q^2 = -q^2 = -(\ell - \ell')^2$

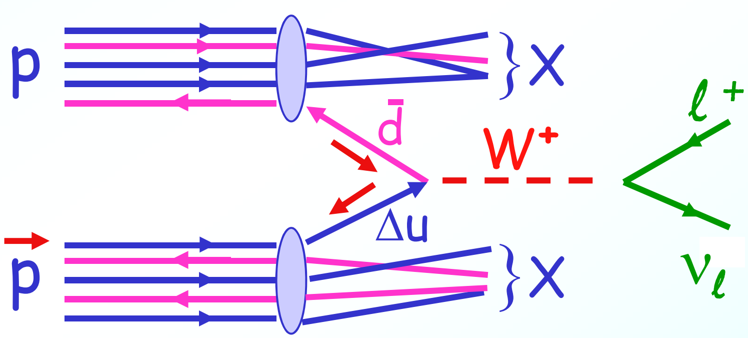
$x = Q^2/(2M\nu)$ = fraction of nucleon's longitudinal momentum carried by struck quark

q(x) = quark number density

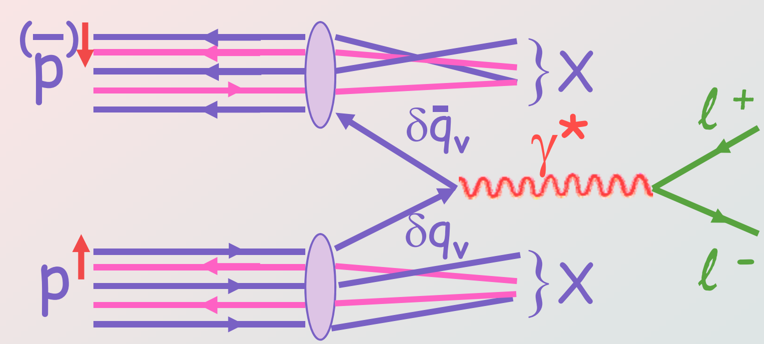
π° or jet production in $\vec{p}\vec{p}$



W± -production

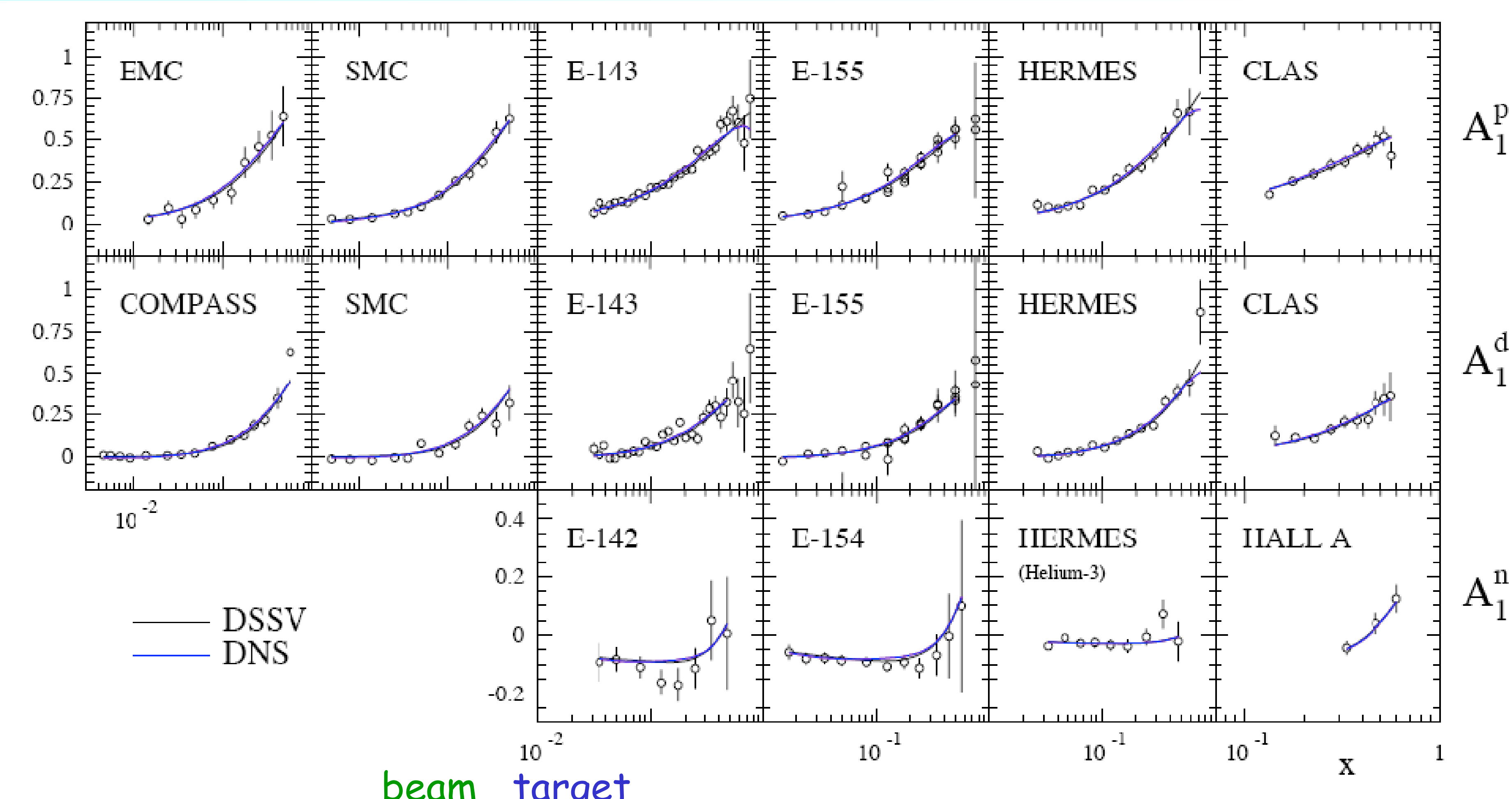


Drell-Yan



Highlight 7

Asymmetries in polarized DIS



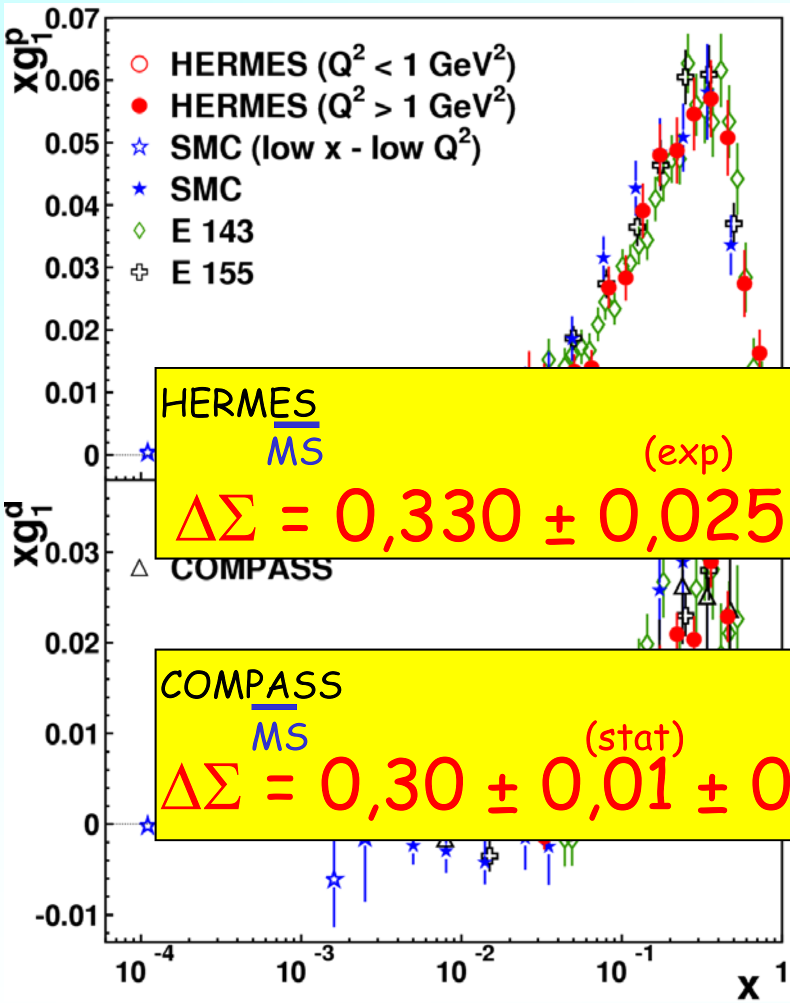
From W. Vogelsang

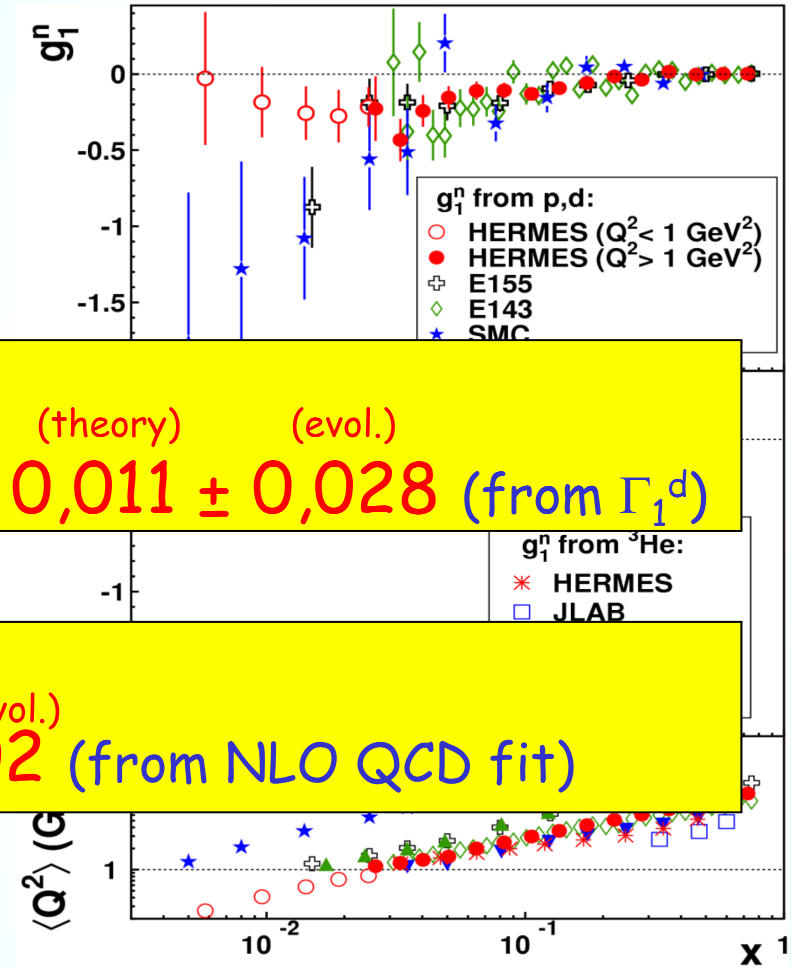
beam target

$$A_1(x) \cong \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} \overset{L.O.}{\cong} \frac{\sum_q e_q^2 \Delta q(x)}{\sum_q e_q^2 q(x)} = \frac{g_1(x)}{F_1(x)}$$

Highlight 7

$g_1(x)$, $\Delta\Sigma$





HERMES

$\overline{MS}$ (exp) (theory) (evol.)

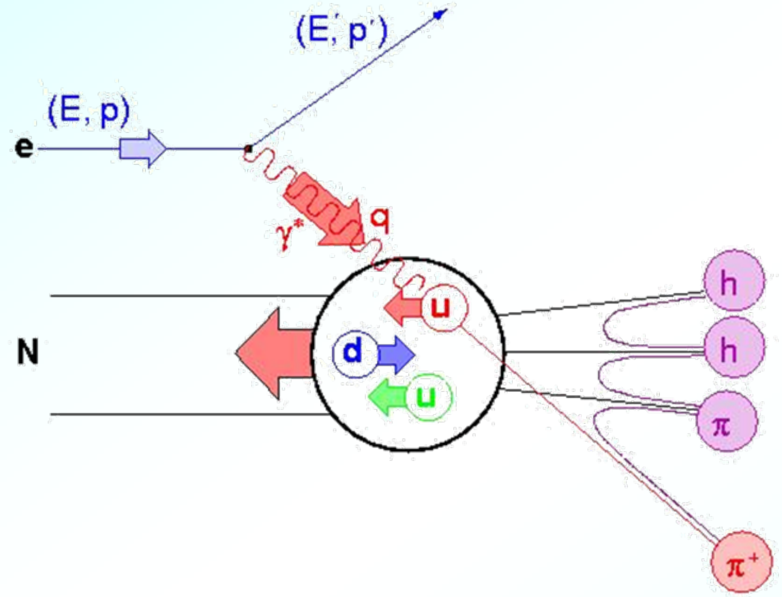
$\Delta\Sigma = 0{,}330 \pm 0{,}025 \pm 0{,}011 \pm 0{,}028$ (from Γ_1^d)

COMPASS

$\overline{MS}$ (stat) (evol.)

$\Delta\Sigma = 0{,}30 \pm 0{,}01 \pm 0{,}02$ (from NLO QCD fit)

Quark helicity distributions from SIDIS



Leading hadron originates with large probability from struck quark

$D_q^h(z)$:= Fragmentation function (FF)

$z = E_h/\nu$

Measure hadron asymmetries

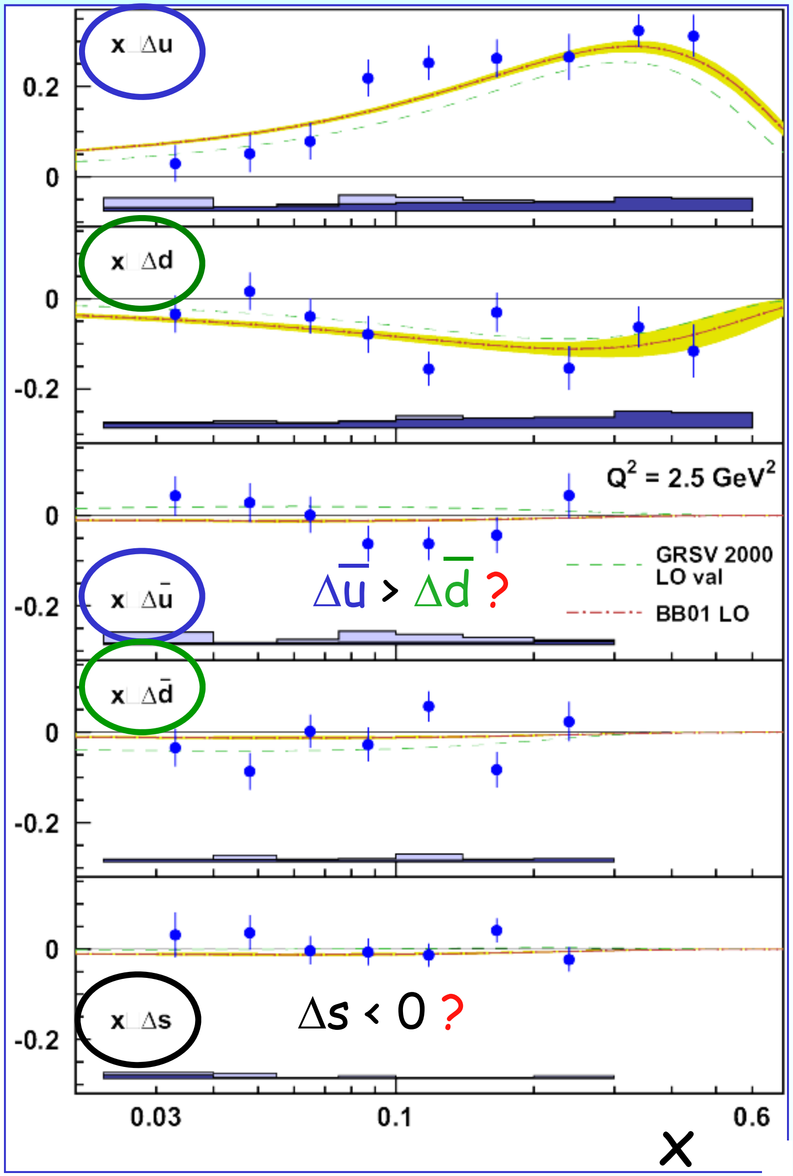
$$A_1^h(x,z) = \frac{\sum_q z_q^2 \Delta q(x) D_q^h(z)}{\sum_q z_q^2 q(x) D_q^h(z)}$$

Targets: $\vec{H}$, $\vec{D}$; h = $\pi^\pm$, $K^\pm$, p

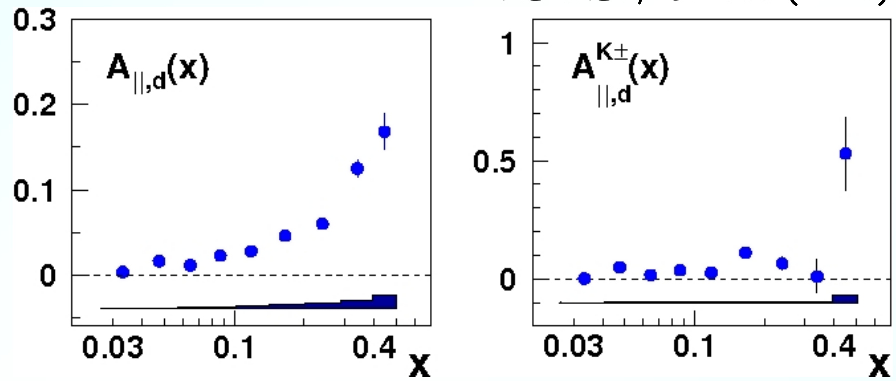
Highlight 8

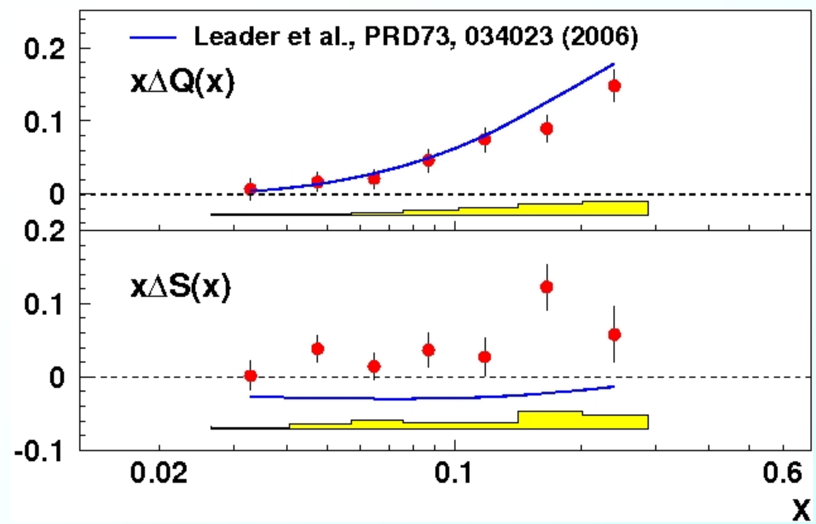
Quark helicity distributions

HERMES, PRL 92 (2004) 012005, PRD 71 (2005) 012003



HERMES, PLB 666 (2008)





$\Delta S = 0.037 \pm 0.019(\text{stat.}) \pm 0.027(\text{syst.})$

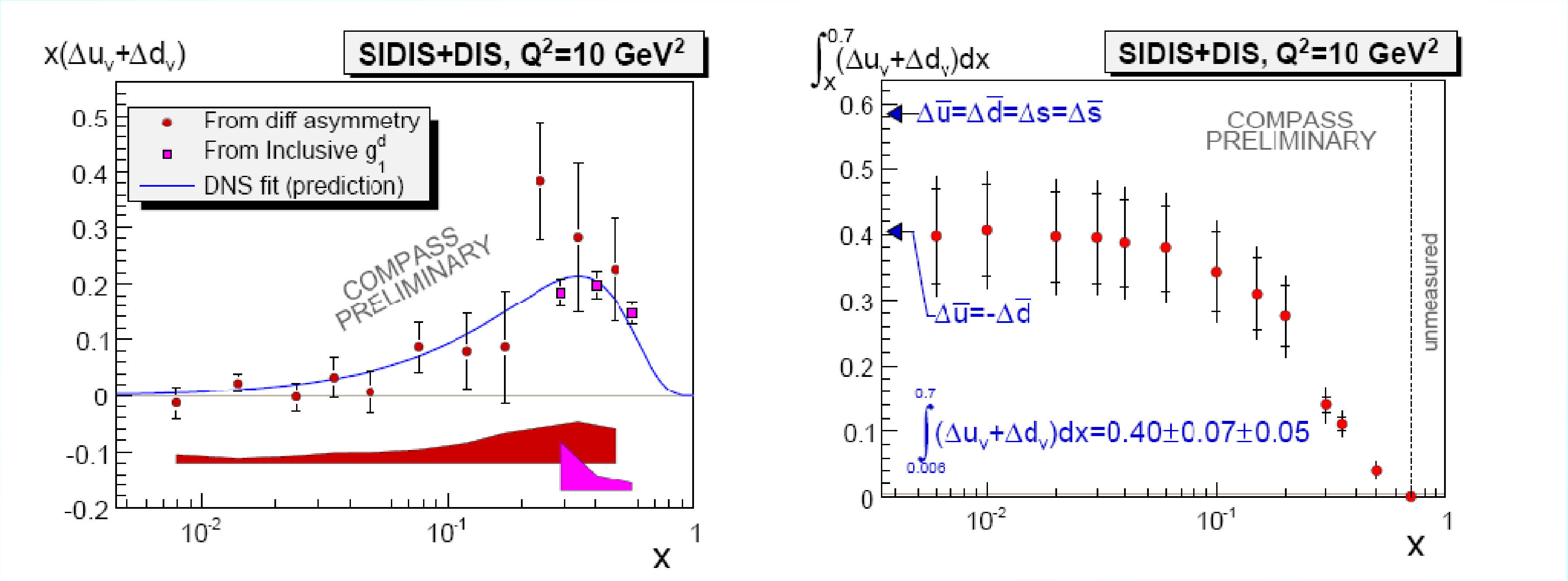
(inclusive data and SU(3):
$\Delta S = -0.085 \pm 0.013(\text{stat.}) \pm 0.012(\text{syst.})$)

Highlight 8

Valence-quark helicity distributions

$$A_d^{\pi^+-\pi^-}(x) \overset{L.O.}{=} A_d^{K^+-K^-}(x) \overset{L.O.}{=} \frac{\Delta u_v(x)+\Delta d_v(x)}{u_v(x)+d_v(x)}$$

COMPASS, PLB 660 (2008) 458



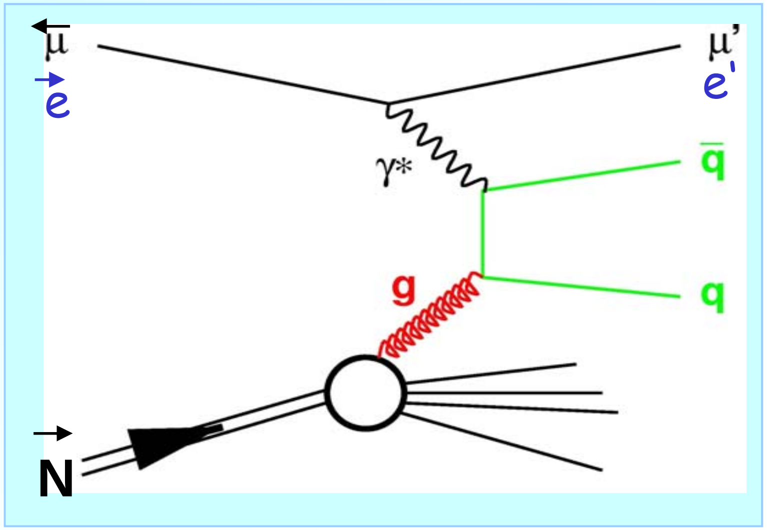
$$\Delta\bar{u} + \Delta\bar{d} = 3\Gamma_1^N - \tfrac{1}{2}\Gamma_1^V + a_8/12$$

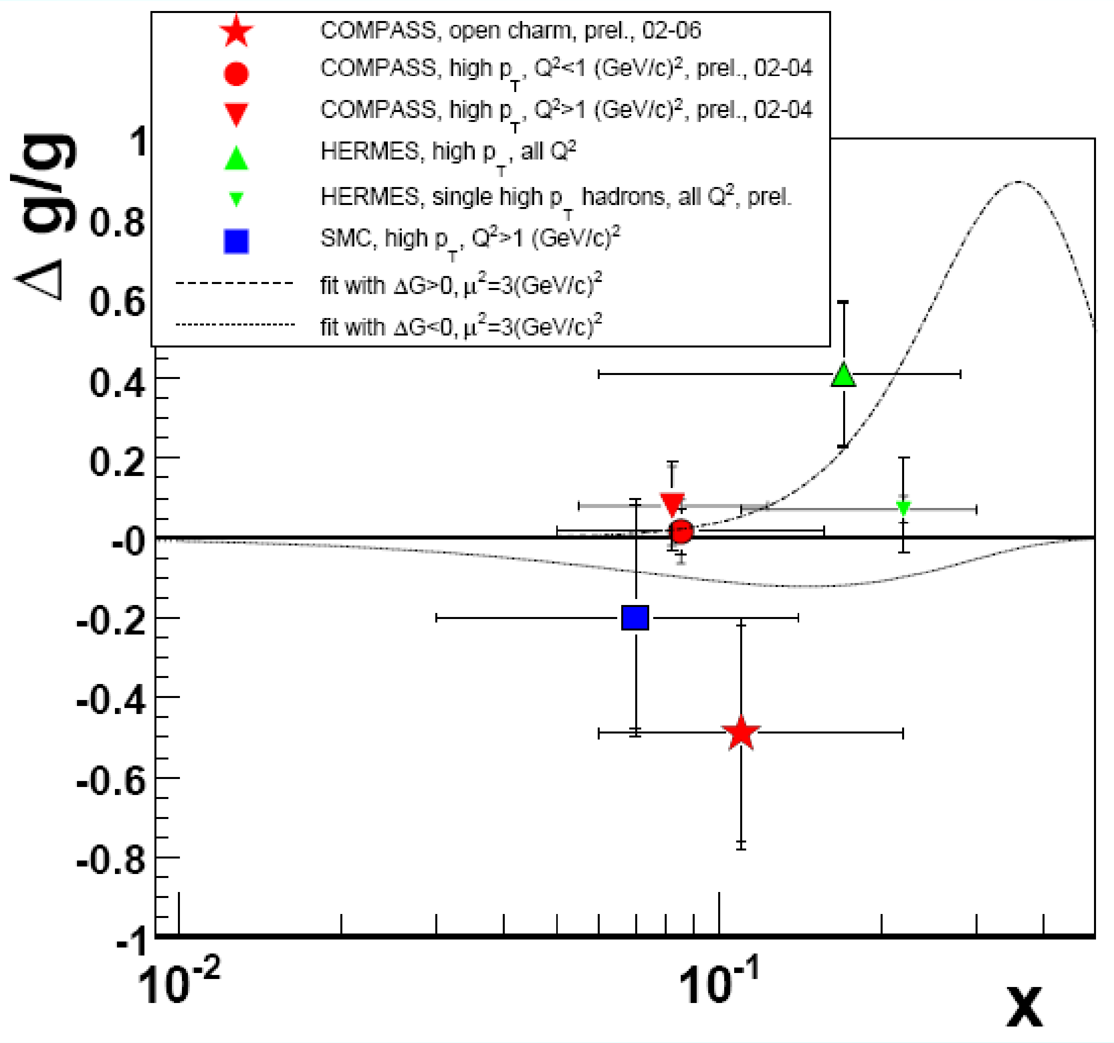
Flavor asymmetric polarized sea ($\Delta\bar{u} = -\Delta\bar{d}$) favoured

Highlight 9

Gluon helicity distribution

Photon-gluon fusion





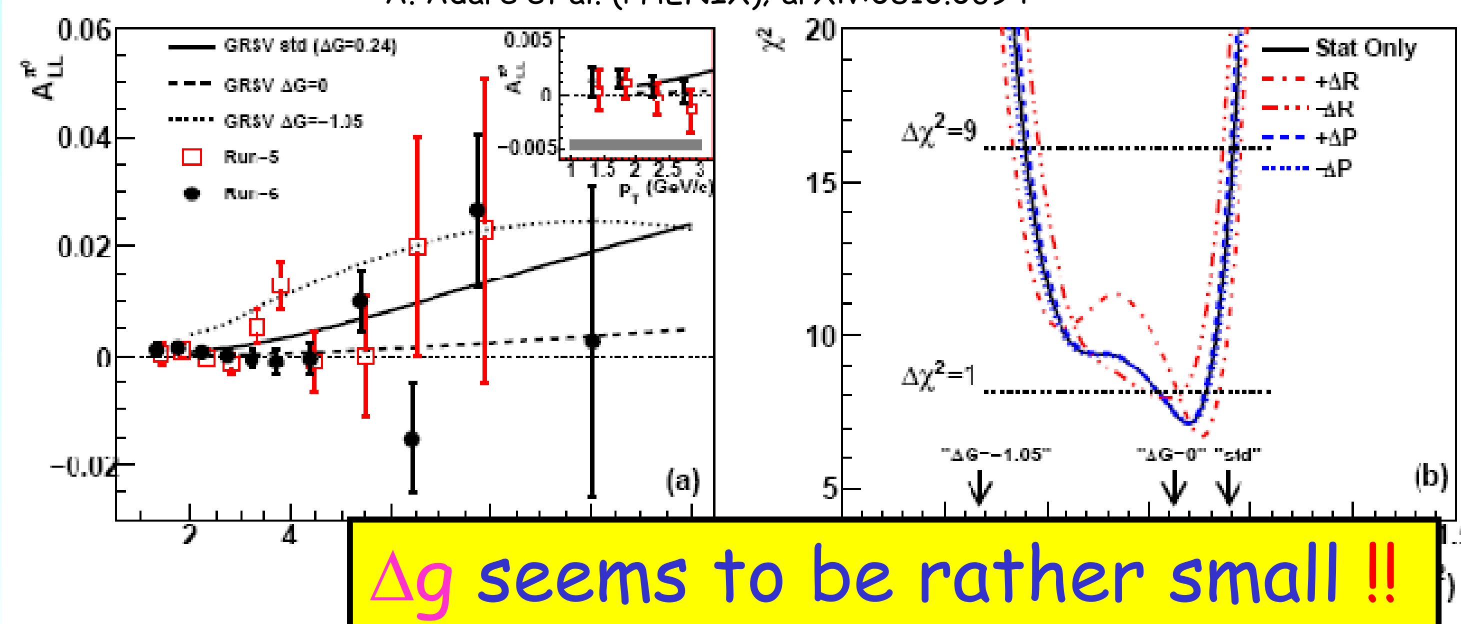
L.O. analyses

E. Rondio

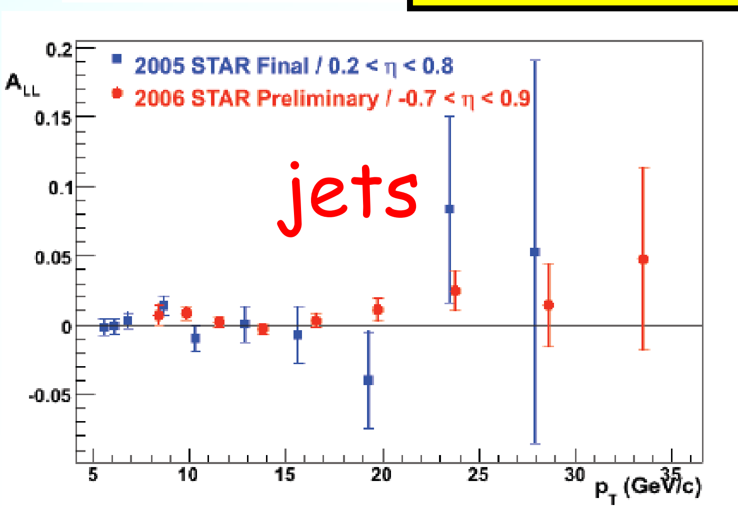
Highlight 9

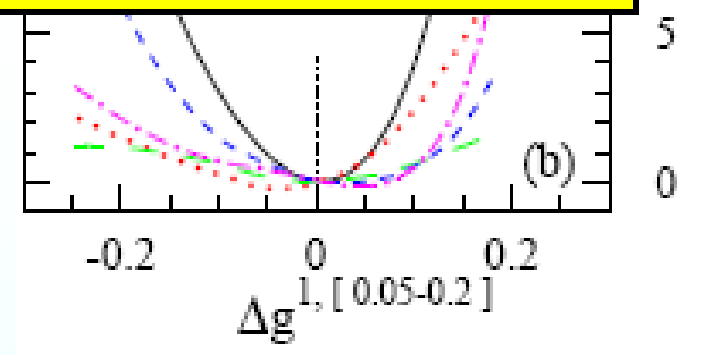
ΔG from $\vec{p}\vec{p} \rightarrow \pi^0$ (jet) X

A. Adare et al. (PHENIX); arXiv:0810.0694



Δg seems to be rather small !!





NLO analysis (without data from previous slide)

Spin budget

- <u>Origin of nucleon spin still unclear:</u>

  Where do the missing 65% come from?
  X. Ji: ‚Dark Spin'

- Is there a substantial contribution of Δg and/or $\Delta\bar{q}$ at very low x?

  ➡ EIC

- What is the contribution of orbital angular momenta

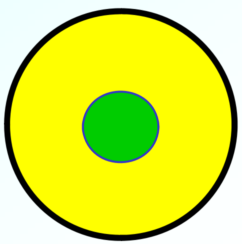
  L_q, L_g ???

Transversity $\delta q(x)$

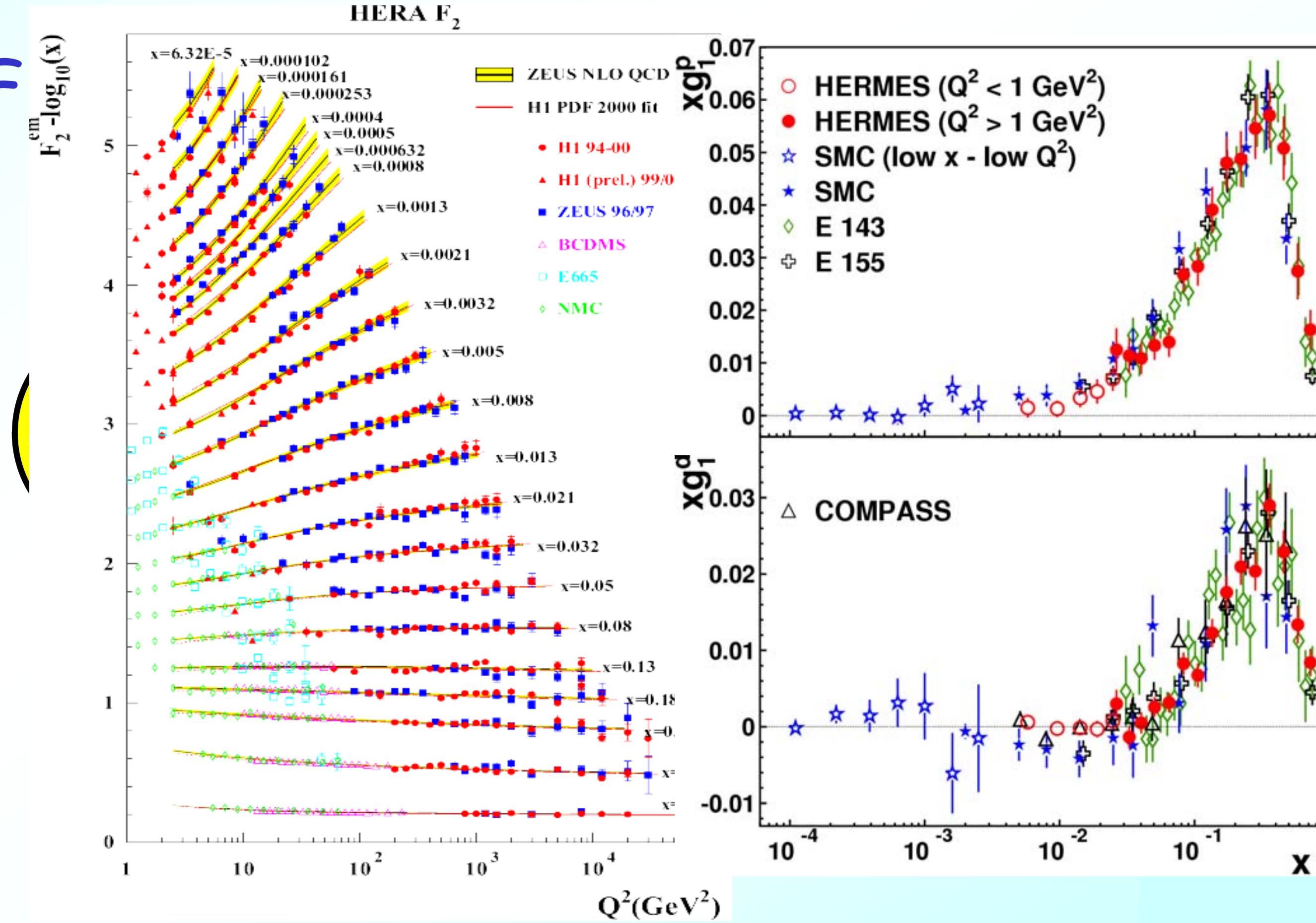
For a complete description of momentum and spin distribution of the nucleon at leading-twist: 3 distribution functions (DF)

Unpolarised DF

$q(x)$

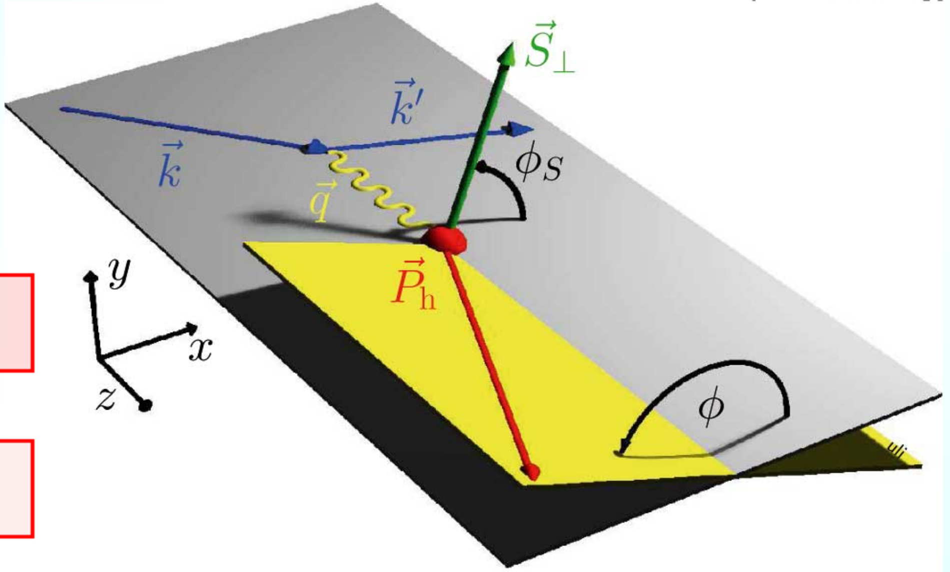


well known



Azimuthal angular distributions

Amplitude has 2 components:



Transversity DF

$2\langle\sin(\phi + \phi_S)\rangle^h_{UT} \sim \delta q(x) \otimes H_1^{\perp q}(z)$

Collins Fragmentation Function

U: unpol. e±-beam

T: transv. pol. Target

$z = E_h/\nu$

⊗: conv. integral over $\mathbf{p}_T$ and $\mathbf{K}_T$

Unpolarised FF

$2\langle\sin(\phi - \phi_S)\rangle^h_{UT} \sim f_{1T}^{\perp q}(x) \otimes D_1^q(z)$

Sivers DF

(Requires non-vanishing orbital angular momenta L_q of quarks)

→ N. Makins, M. Anselmino

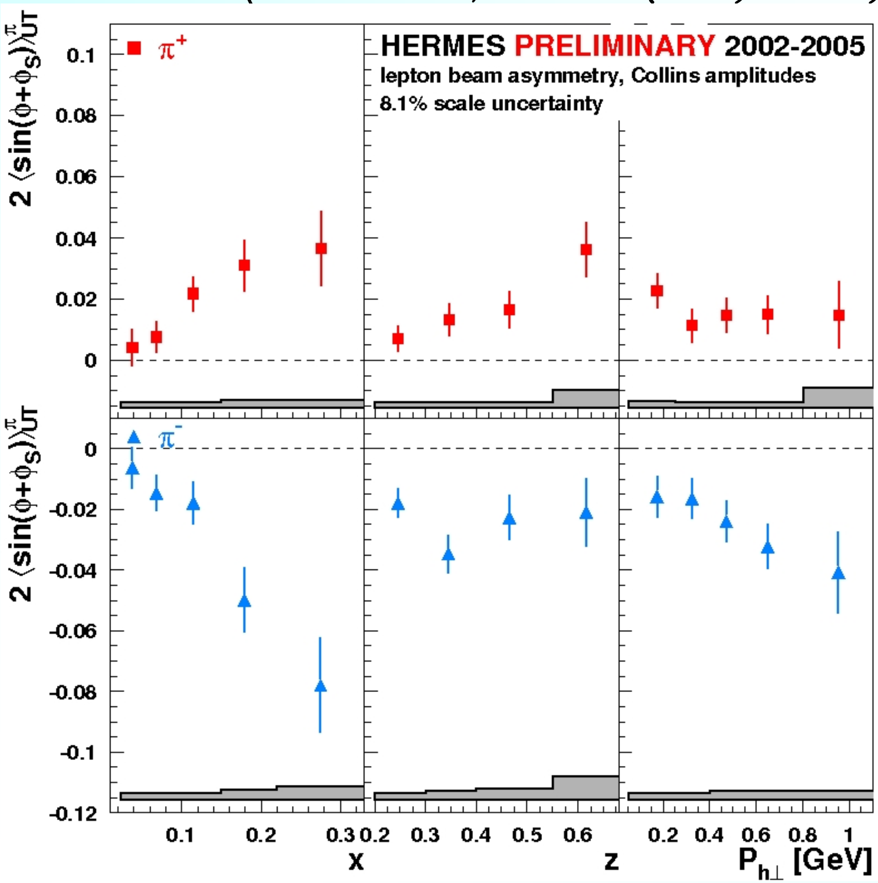
Highlight 10

Collins amplitudes (proton)

$$2\langle\sin(\phi + \phi_S)\rangle^h_{UT} \sim \delta q(x) \otimes H_1^{\perp q}(z)$$

M. Diefenthaler @ DIS07, hep-ex 0707.0222

(also HERMES, P. R. L. 94 (2005) 012002)



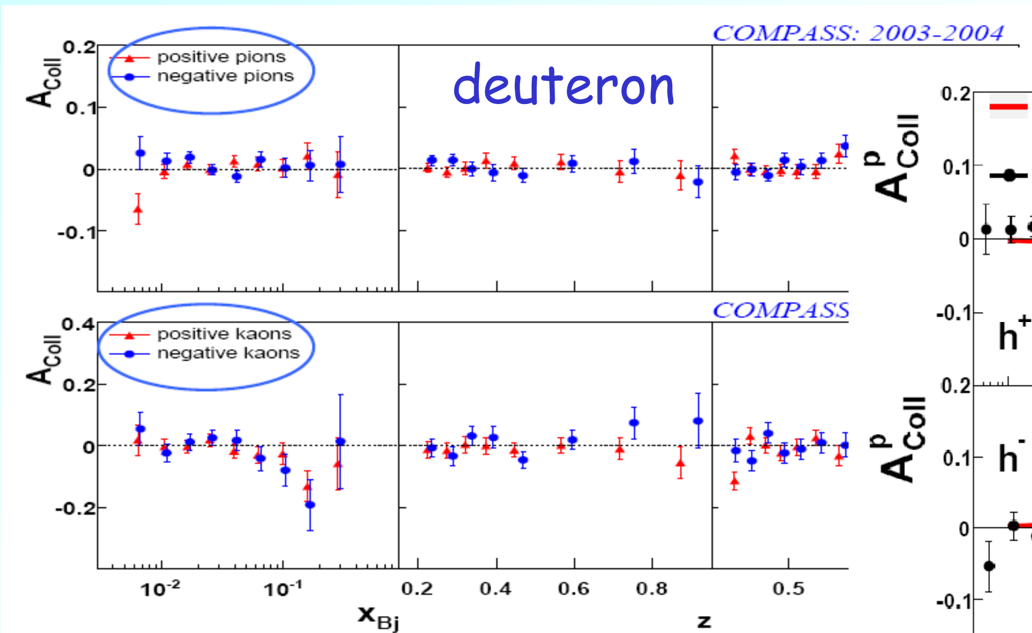
- First measurement of non-zero Collins effect
- Both Collins fragmentation function and transversity distribution function are sizeable
- Surprisingly large π^- asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation, i.e. $u \rightarrow \pi^-$

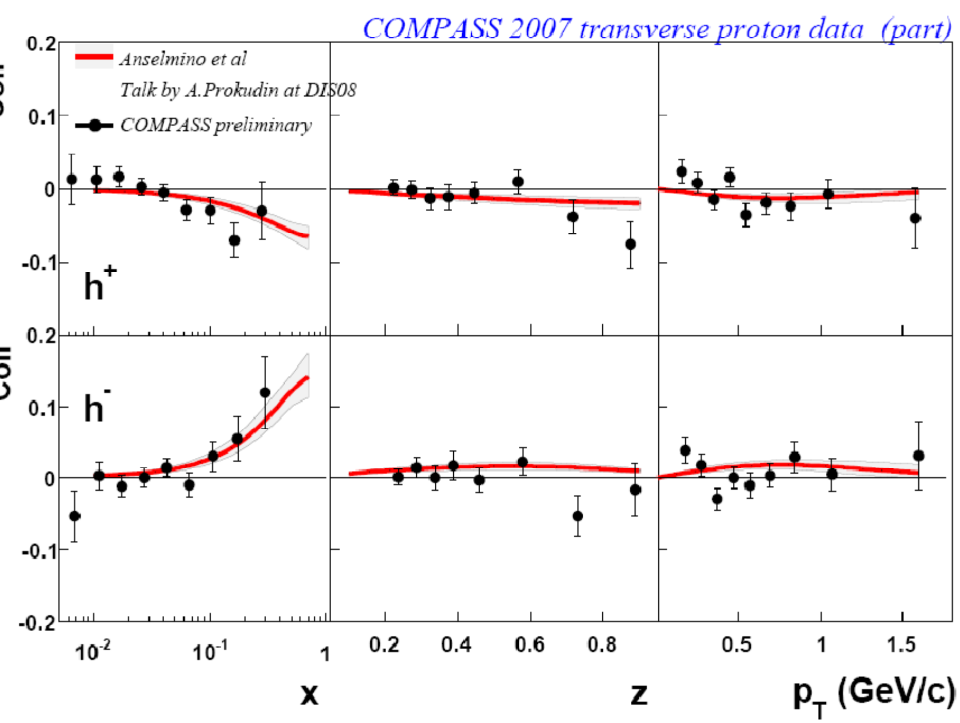
$$H_{1,disf} \approx - H_{1,fav}$$

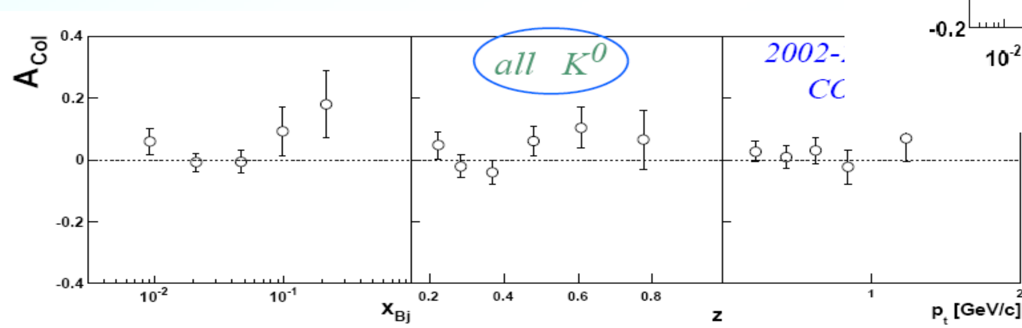
Highlight 10

Collins amplitudes (d +p)

COMPASS, hep-ex/0802.2160







Different from zero,
Compatible with HERMES

Compatible with zero
information about δd

N. Makins, M. Anselmino

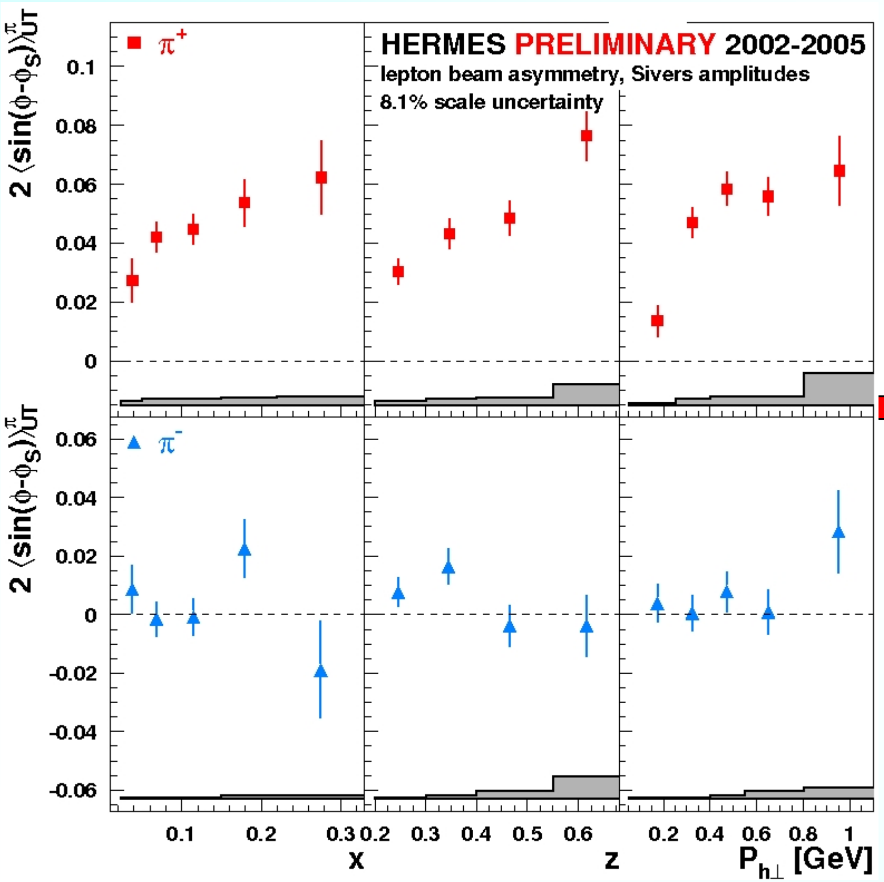
Highlight 11

Sivers amplitudes (p)

$$2\langle \sin(\phi - \phi_S)\rangle^h_{UT} \sim f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

M. Diefenthaler @ DIS07, hep-ex 0706.2242

(also HERMES, P. R. L. 94 (2005) 012002)



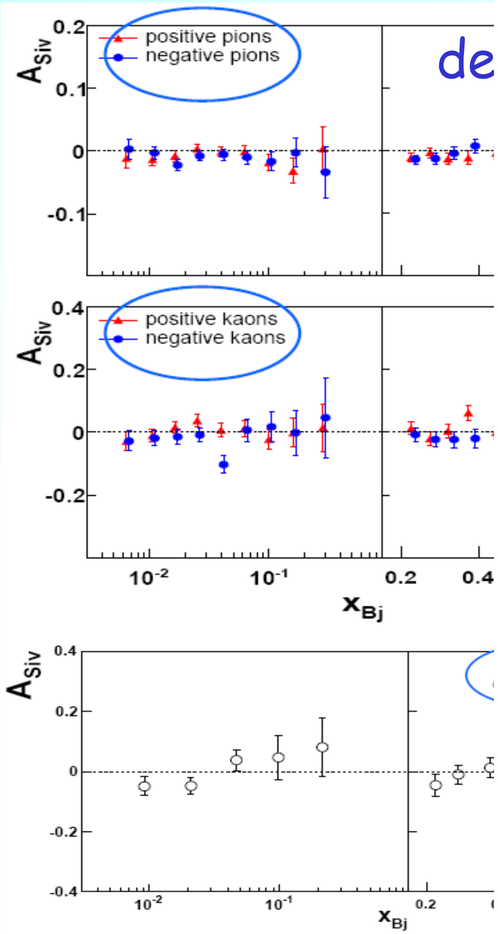
- First observation of non-zero Sivers distribution function in DIS

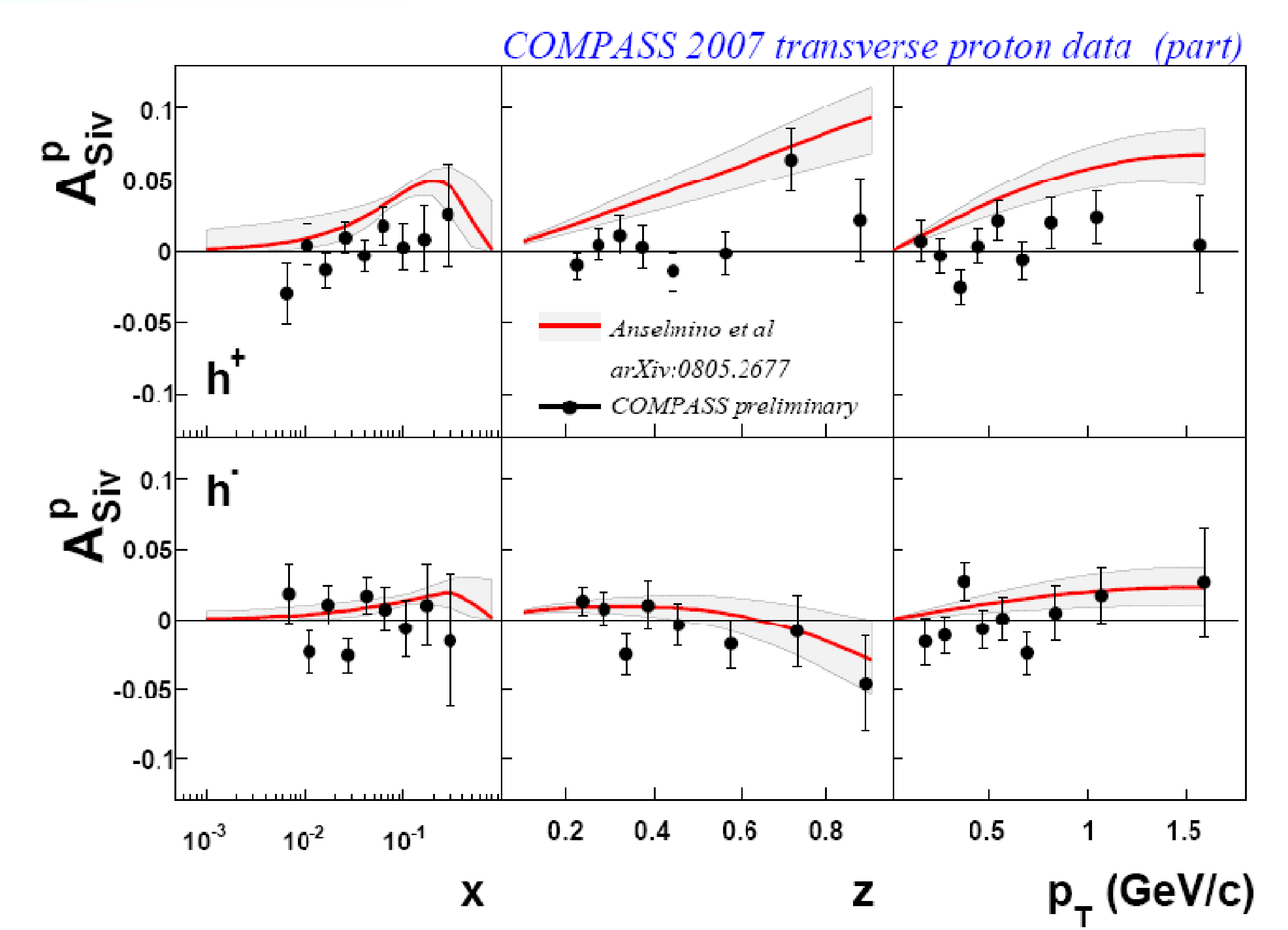
→ Experimental evidence for orbital angular momentum L_q of quarks

But: Quantitative contribution of L_q to nucleon spin still unclear

Sivers ampl. (d +p)

COMPASS, hep-ex/0802.2160

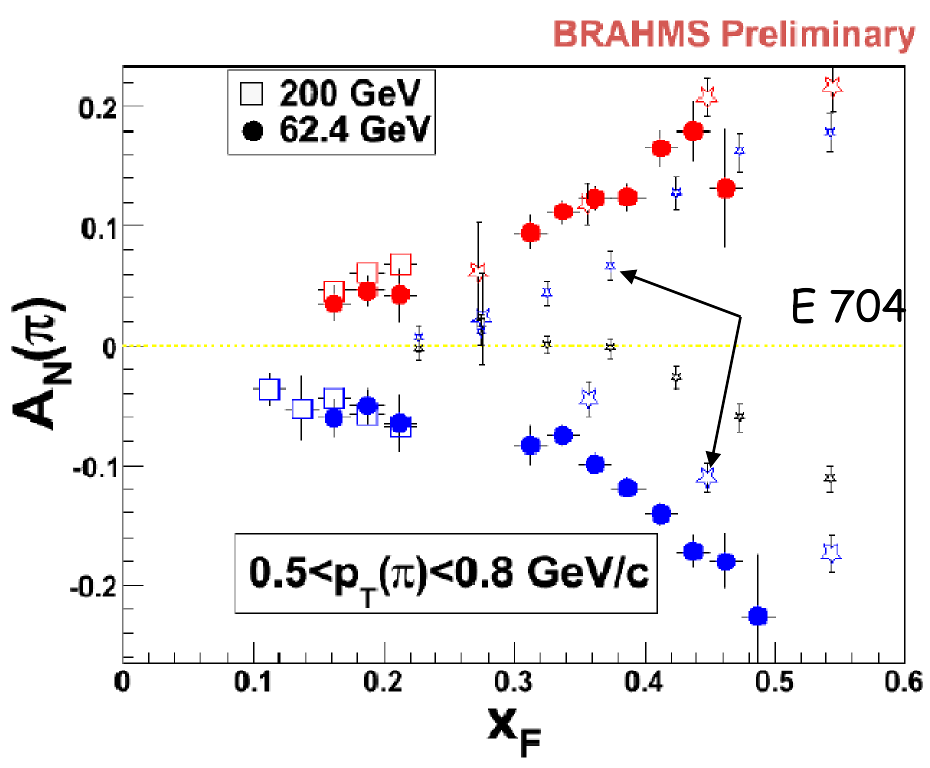


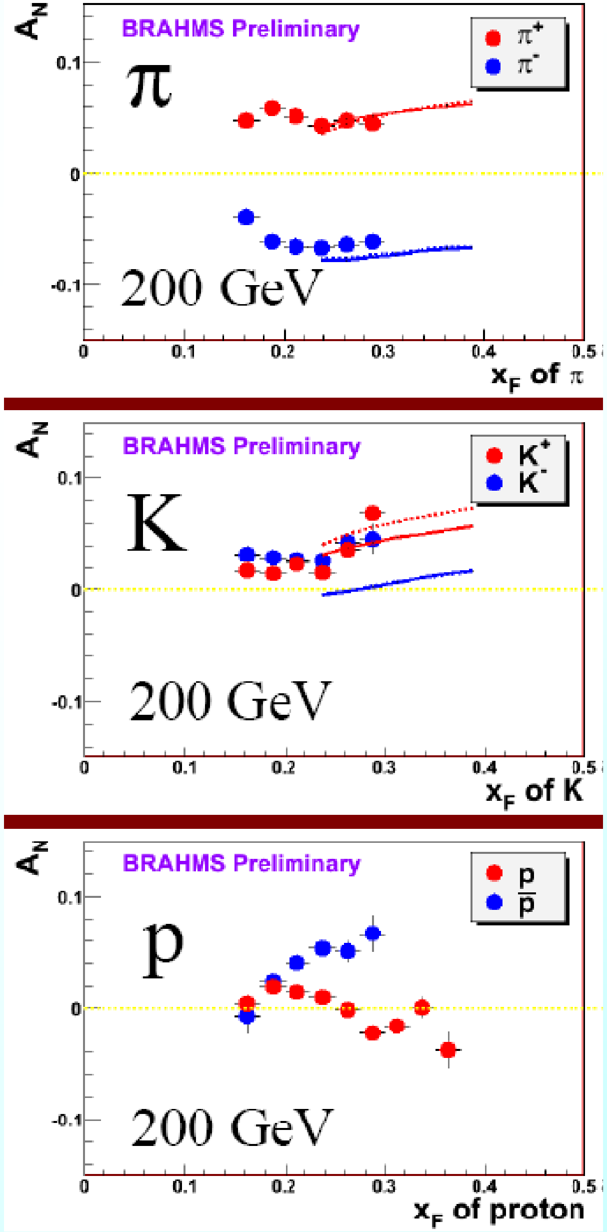


Compatible with zero

Still compatible with zero

A_N for identified hadrons in $p^{\uparrow}p$





Possible origins:

Collins FF, Sivers DF, Twist-3

Combinations of above

Important data for test of theoretical models

Future

δq and $f_{1T}^{\perp}$ in $\bar{p}^{\uparrow}p^{\uparrow}$ Drell-Yan

- δq is chiral-odd. Its measurement requires another chiral-odd object!

  Semi-Inclusive DIS: Collins fragmentation function.
  (Requires additional input e.g. from BELLE)

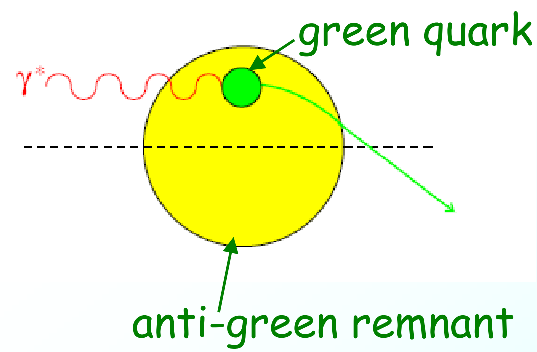
  $\bar{p}^{\uparrow}p^{\uparrow}$ Drell-Yan: Combination of δq_v and $\delta \bar{q}_v$ → E. Steffens

- QCD prediction: $f_{1T}^{\perp}(x)_{SIDIS} = - f_{1T}^{\perp}(x)_{DY}$

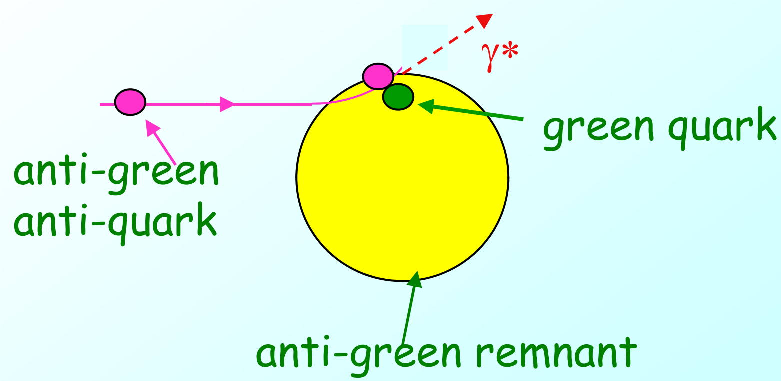
$\gamma^* q \rightarrow q$

$q\bar{q} \rightarrow \gamma^* \rightarrow \ell^+ \ell^-$

lensing effect



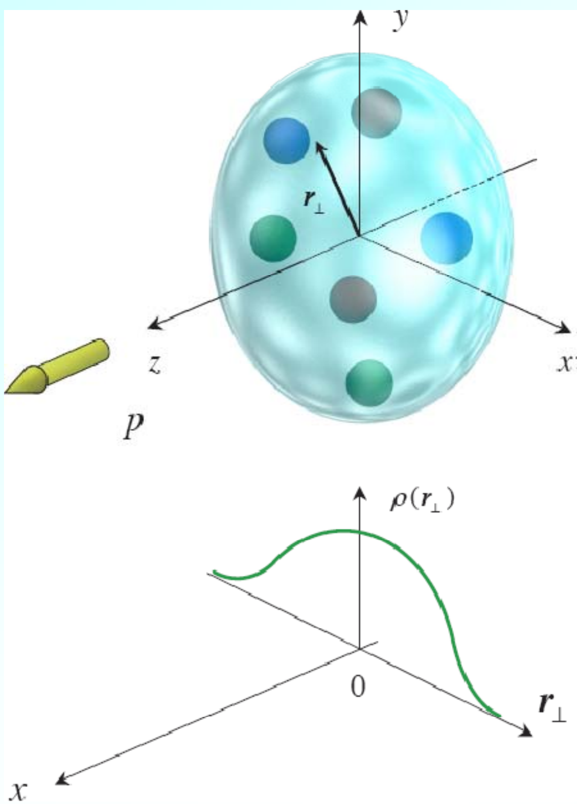
anti-lensing



Determination of L_q - GPDs

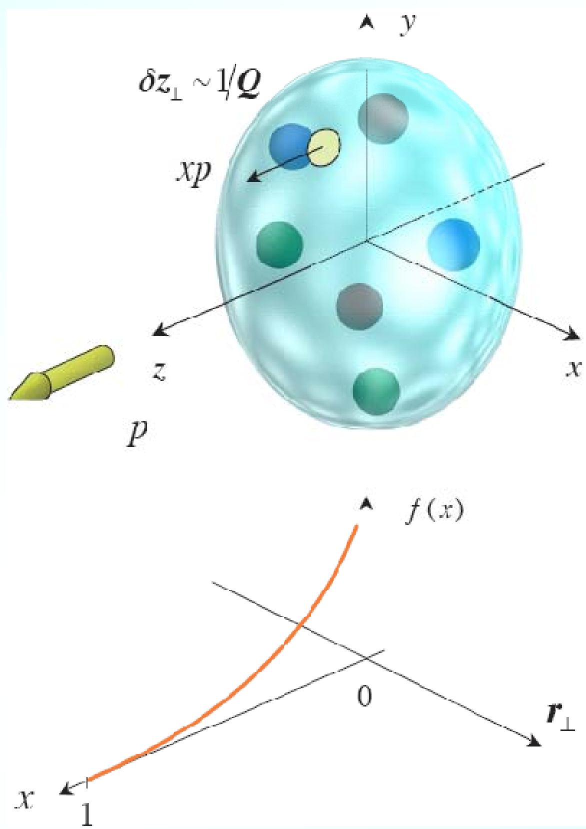
Tool: Generalised Parton Distributions

Formfactors:



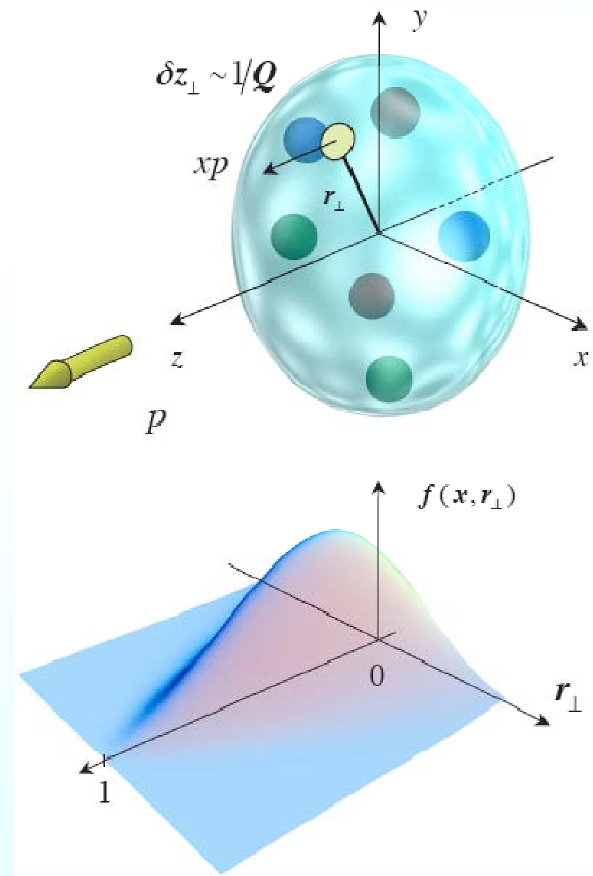
Fouriertransform of e.g. a radial charge distribution

PDFs:



Number density of quarks with longitudinal momentum fraction x

GPDs:



Generalised description in 2+ 1 dimensions

C. Weiss

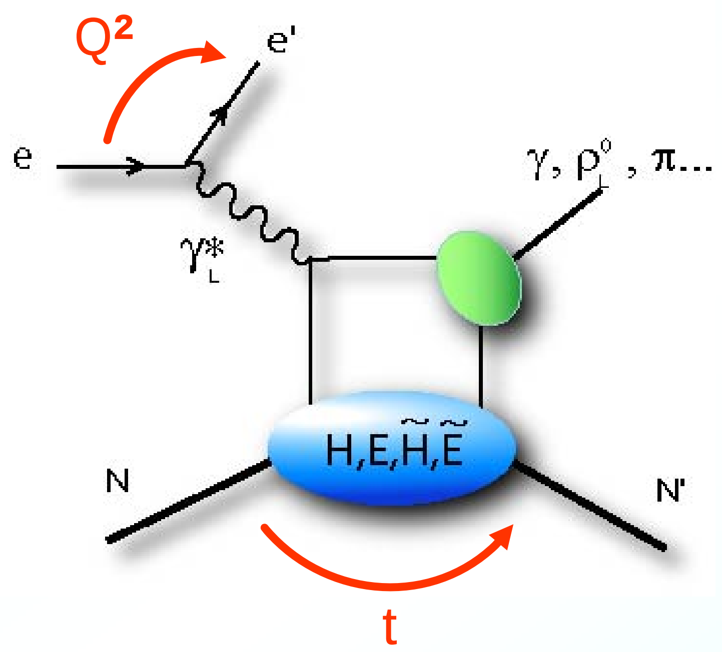
Determination of L_q

Ji relation:

$$J_q = 1/2\Delta\Sigma + L_q = \lim_{t \to 0} \int_{-1}^{1} dx\ x\ [H(x,\zeta,t) + E(x,\zeta,t)]$$

$H(x,\zeta,t)$, $E(x,\zeta,t)$: Generalised Parton Distributions (GPDs)

Access: *exclusive processes*



Final state sensitive to different GPDs

Vector mesons (ρ, ω, ϕ) H, E

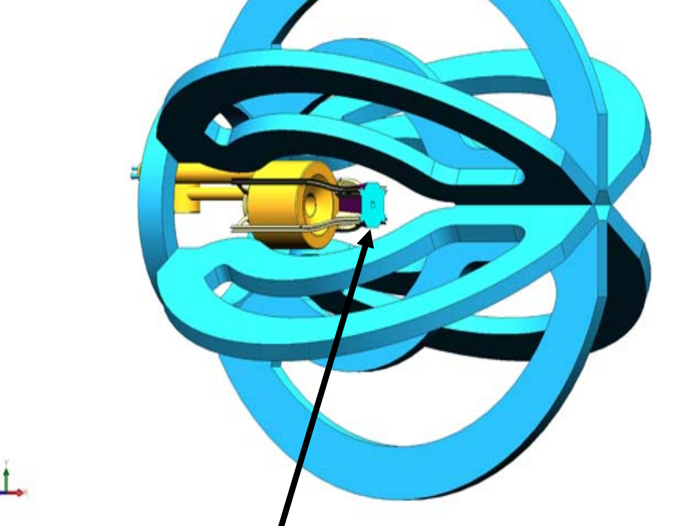
Pseudoscalar mesons(π,η) $\tilde{H}$, $\tilde{E}$

DVCS (γ) H, E, $\tilde{H}$, $\tilde{E}$

→ E. Voutier

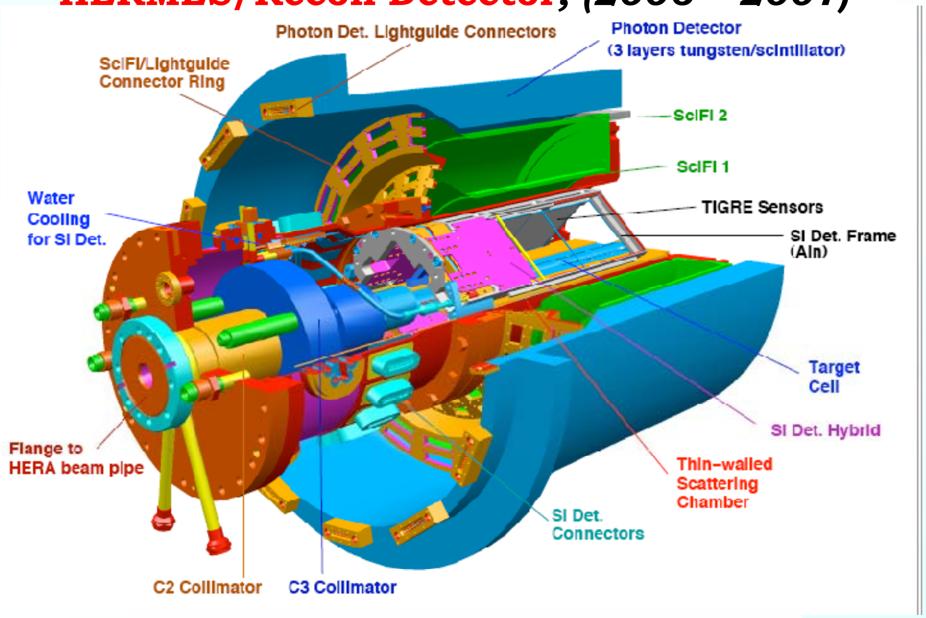
Hard exclusive processes - L_q

*Calorimeter and superconducting magnet within **CLAS** torus*

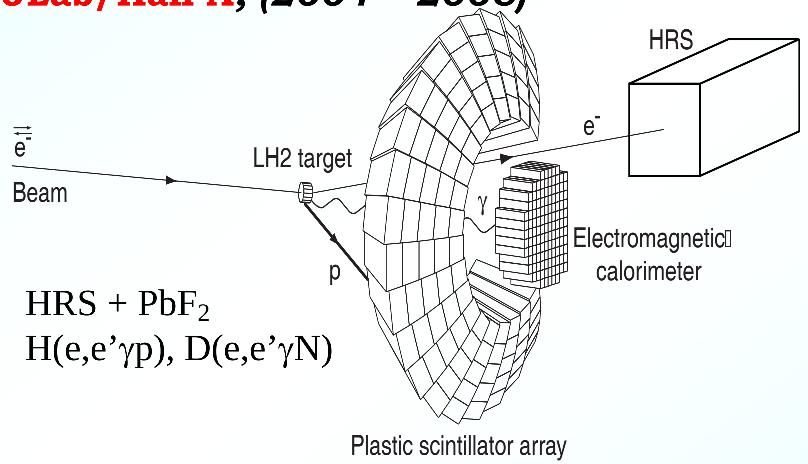


dedicated calorimeter (424 PbWO4 crystals) detect photons from 5º

HERMES/Recoil Detector, *(2006 – 2007)*

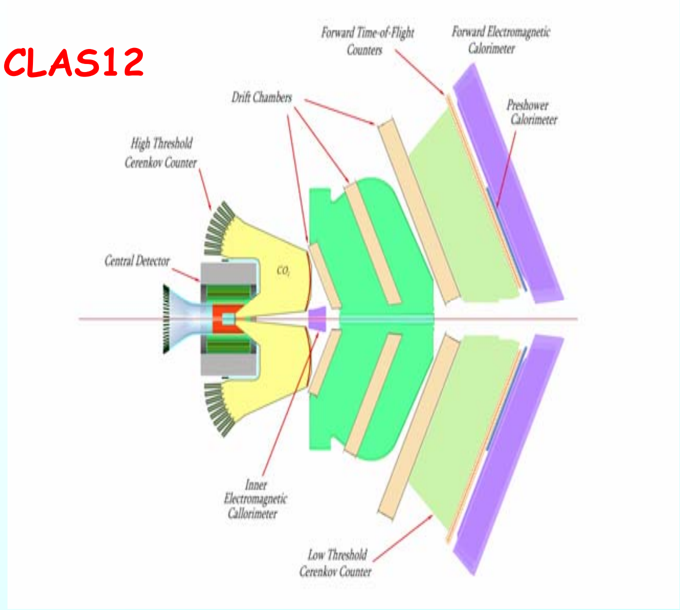


JLab/Hall A, *(2004 – 2005)*



HRS + PbF_2
H(e,e’γp), D(e,e’γN)

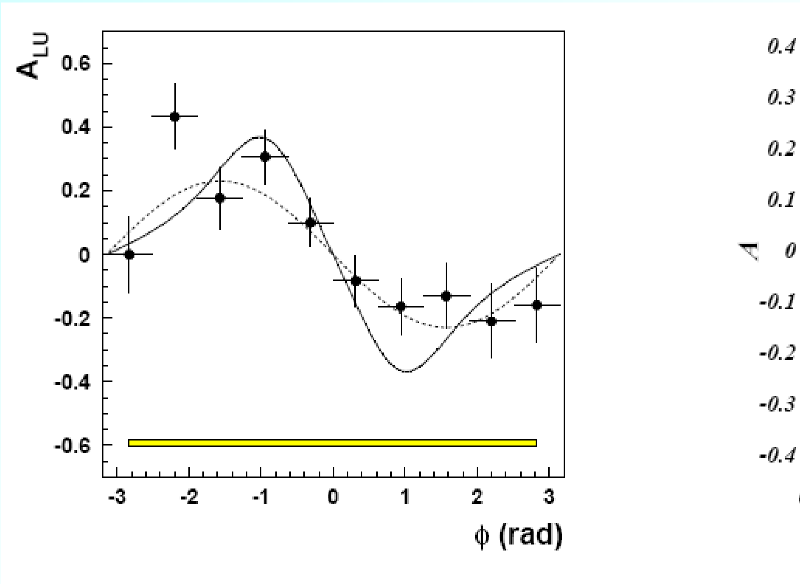
CLAS12



Azimuthal asymmetries

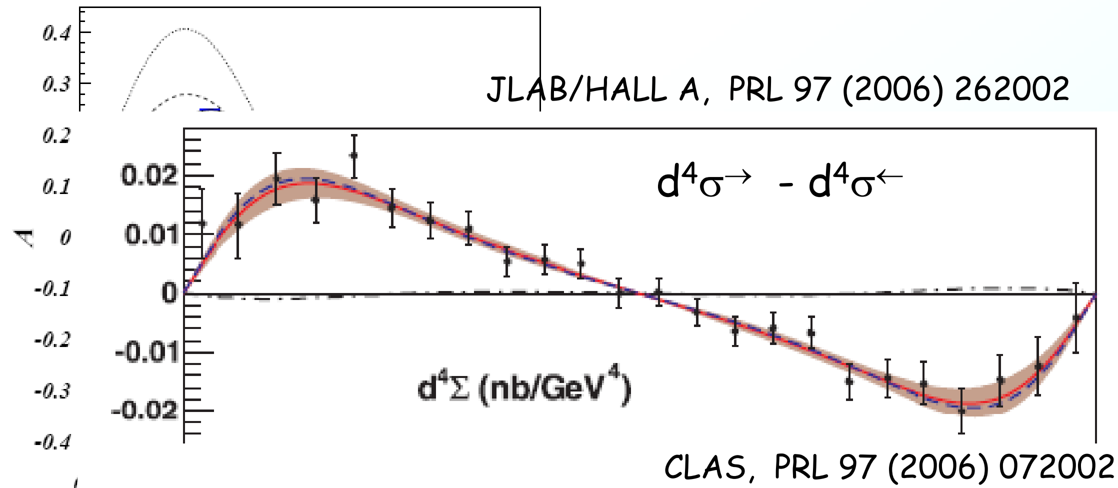
DVCS: Beam-spin asymmetry

HERMES, PRL 87 (2001) 182001



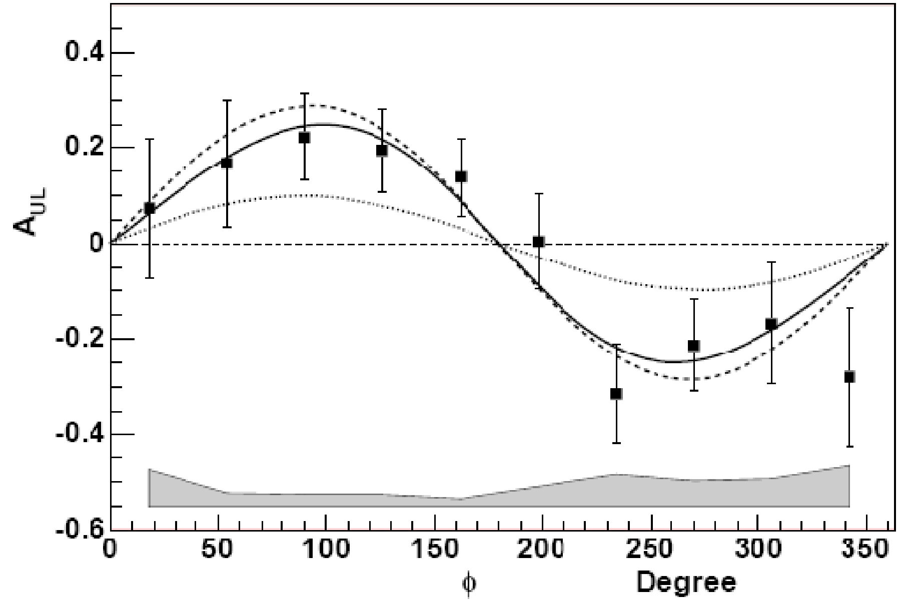
CLAS, PRL 87 (2001) 182002

JLAB/HALL A, PRL 97 (2006) 262002



DVCS: Longitudinal target-spin asymmetry

CLAS, PRL 97 (2006) 072002



Highlight 13

Hard exclusive processes - L_q

Pioneer measurements

DVCS: Beam charge asymmetry

HERMES, JHEP 0806 (2008) 66

DVCS: Transv. target spin asymmetry (SA)

DVCS: Long. target SA

ρ^0: Transv. target SA

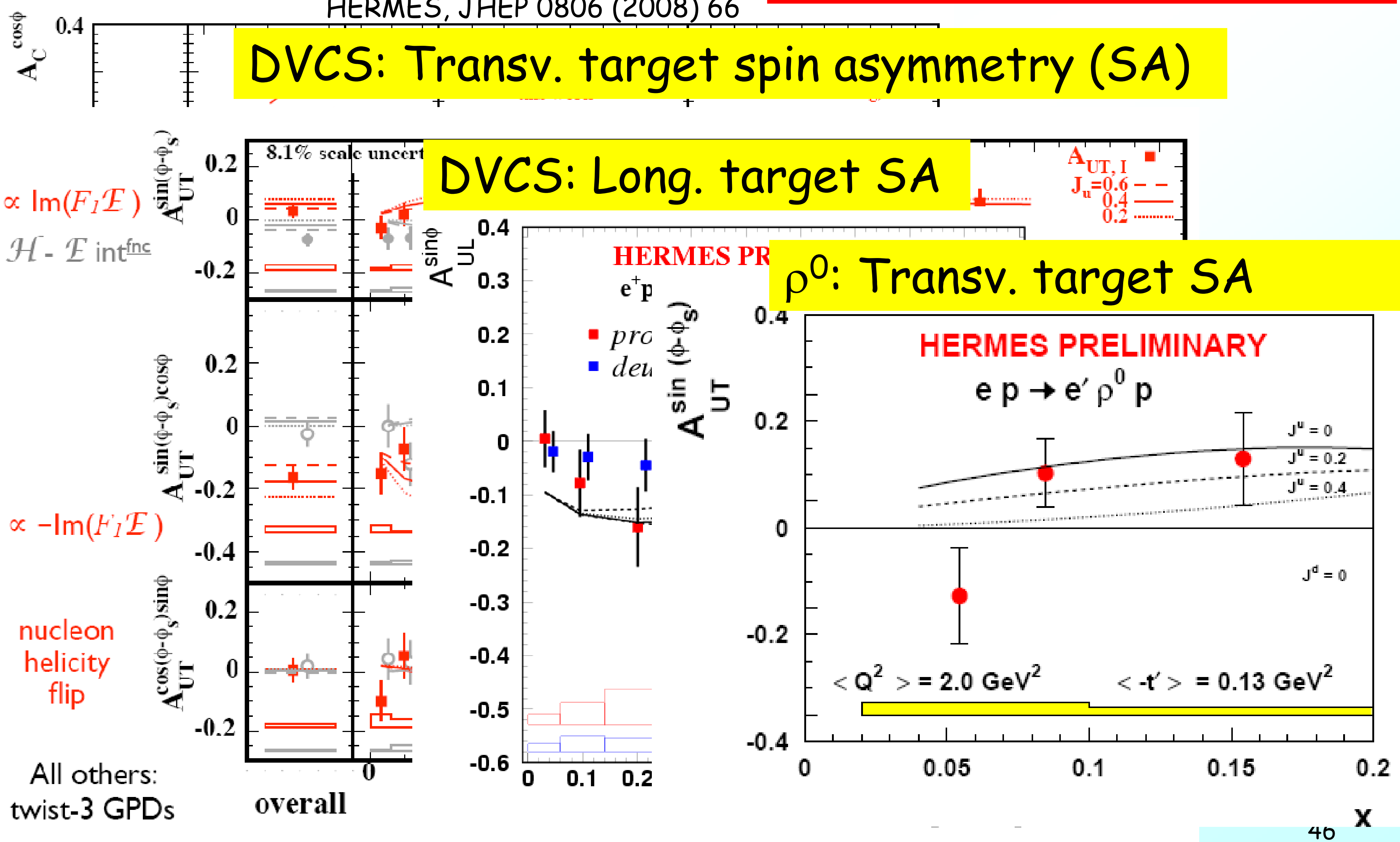
$\propto$ Im($F_1\mathcal{E}$)

$\mathcal{H}$ - $\mathcal{E}$ int^fnc

$\propto$ −Im($F_1\mathcal{E}$)

nucleon helicity flip

All others: twist-3 GPDs

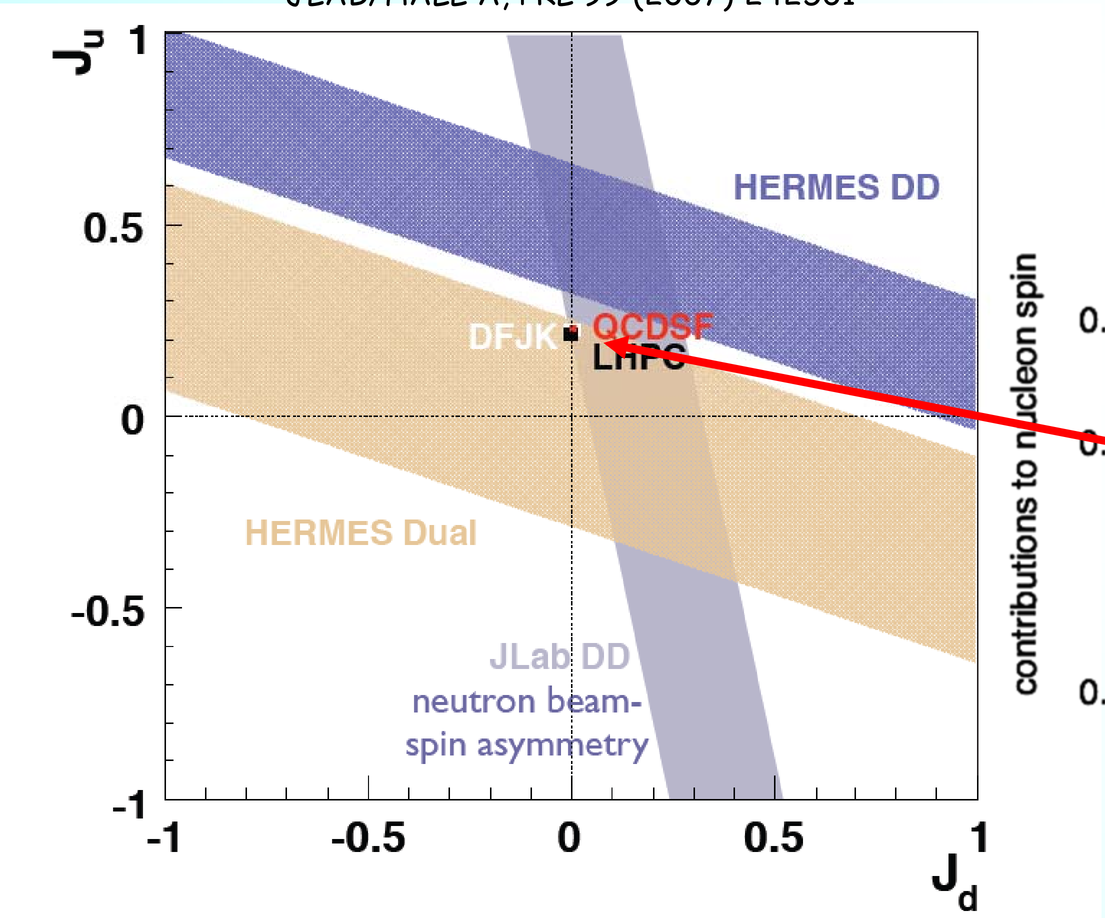


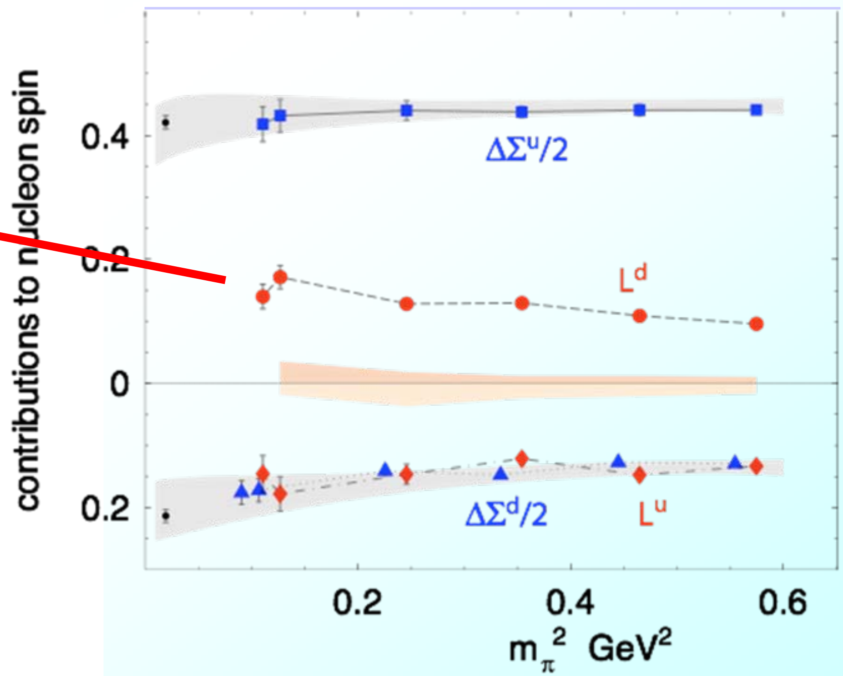
Highlight 13

Determination of J_q

First model dependent attempt:

HERMES, JHEP 06 (2008) 066;
JLAB/HALL A, PRL 99 (2007) 242501





Lattice: $L_d \approx -L_u \approx 0.2$!??

Conclusion

Spin physics is exciting

We are looking forward to see

plenty of new results

at this conference

and from the next generation of

high precision spin experiments

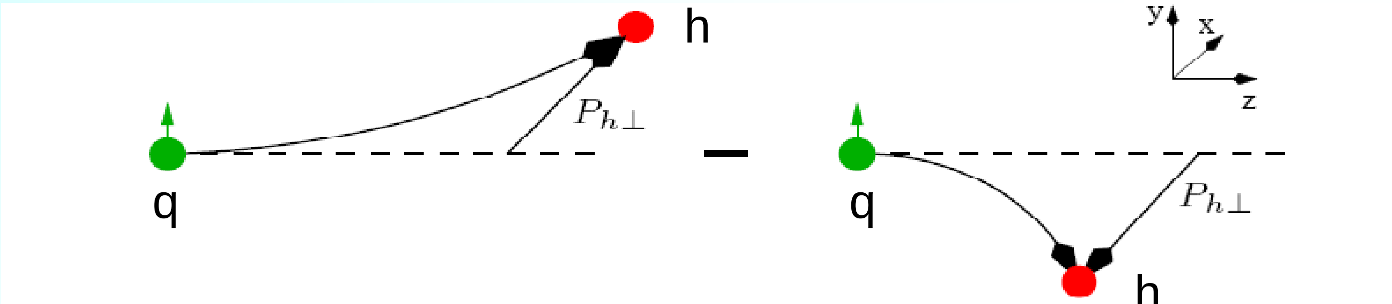
Backups

Azimuthal angular distributions

C O L L I N S

Transverse quark spin + spin-dependent fragmentation

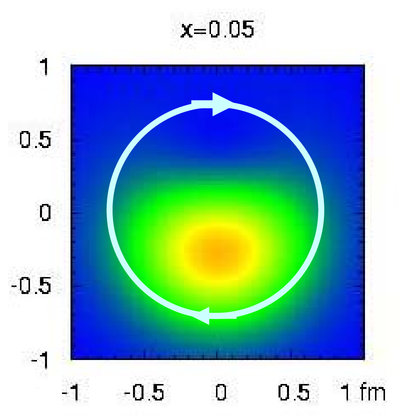
Azimuthal asymmetry ~ $\sin(\phi + \phi_S)^h$

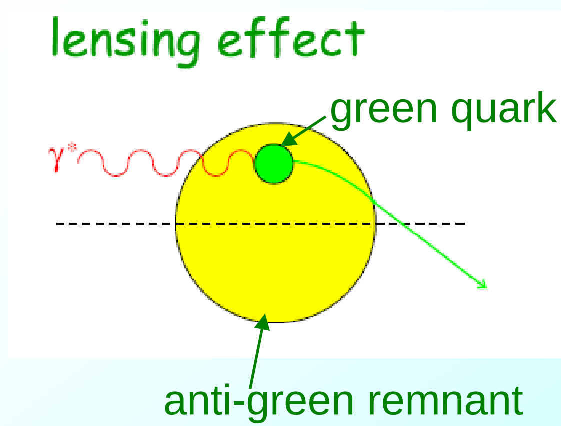


S I V E R S

Left-right distribution asymmetry (due to orbital angular momentum) + final state interaction

Azimuthal asymmetry ~ $\sin(\phi - \phi_S)^h$

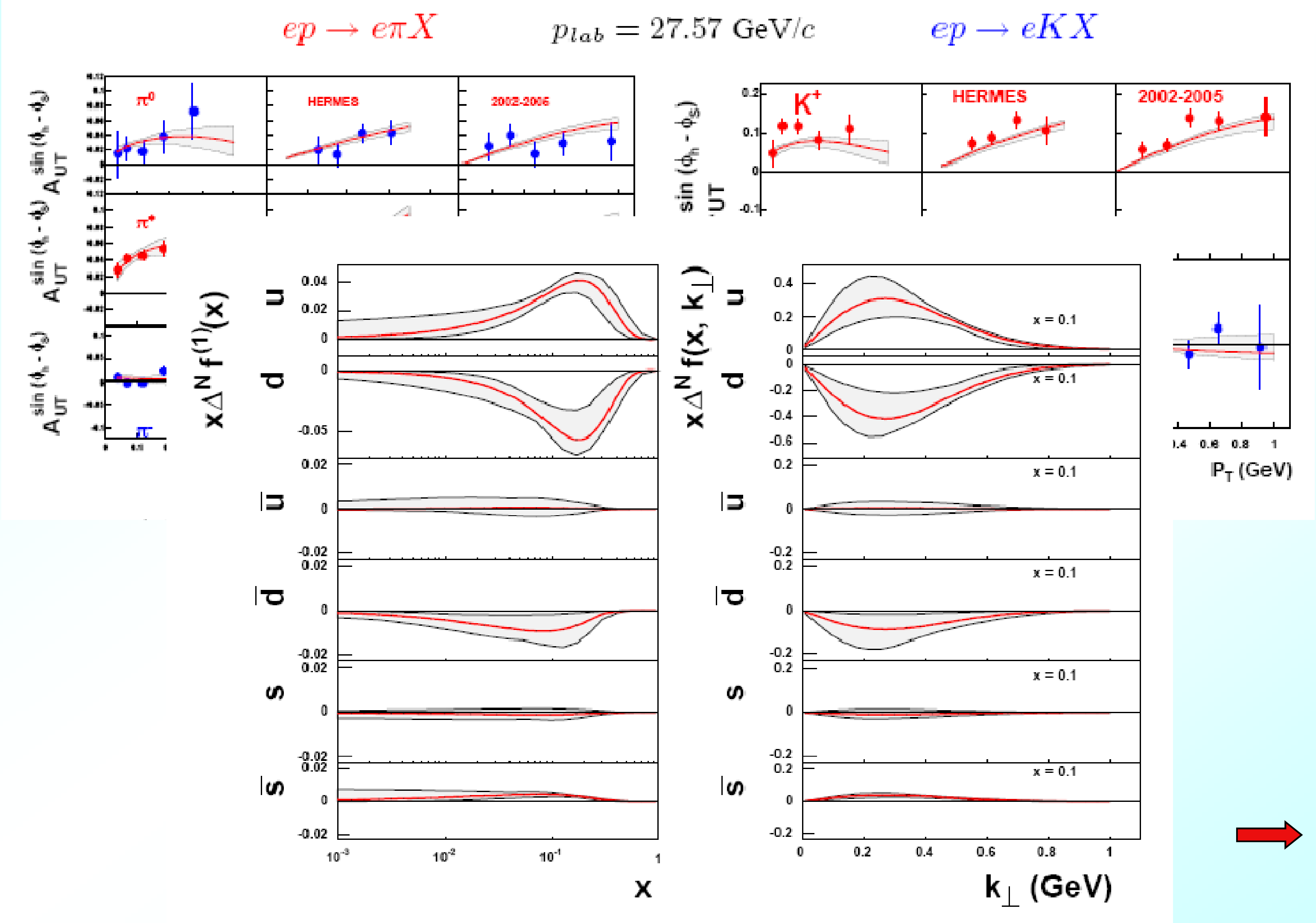




Highlight 10

Sivers distribution

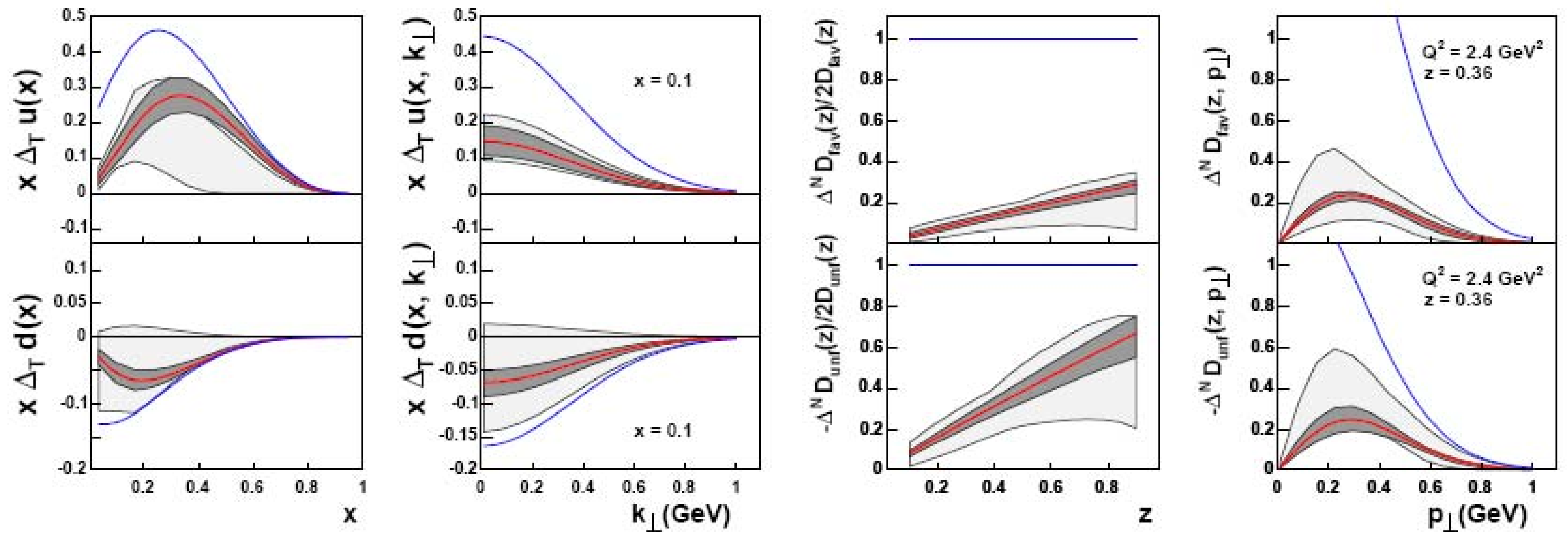
Fits of HERMES (p) and COMPASS (d) data
by Anselmino et al., arXiv: 0805.2677 and 0807.0166



Highlight 11

Collins FF and Transversity

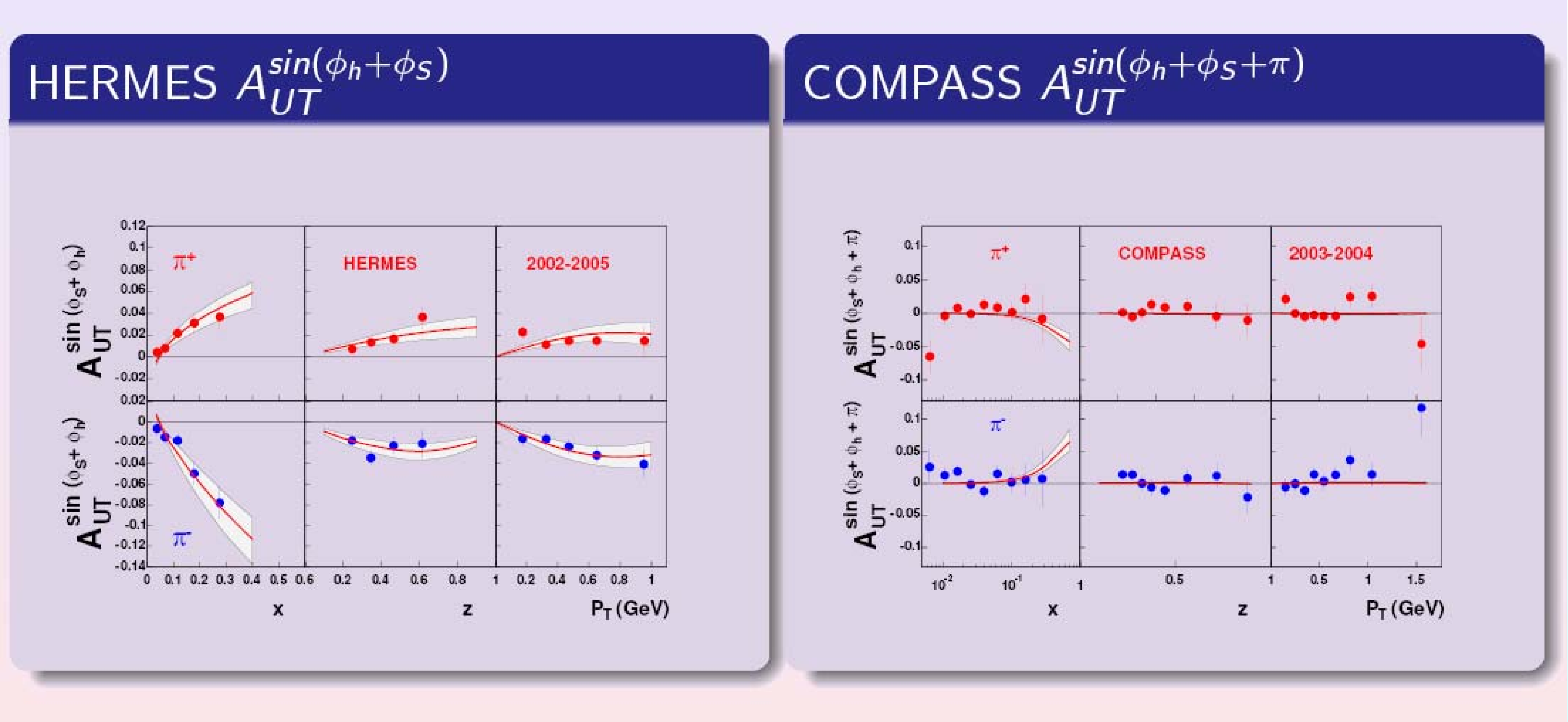
Fits of HERMES (p), COMPASS (d) and BELLE data
by Anselmino et al., arXiv:0807.0173



Highlight 11

Collins amplitudes

Fits of HERMES (p), COMPASS (d) and BELLE data by Anselmino et al. (from A. Prokudin @ DIS2008)



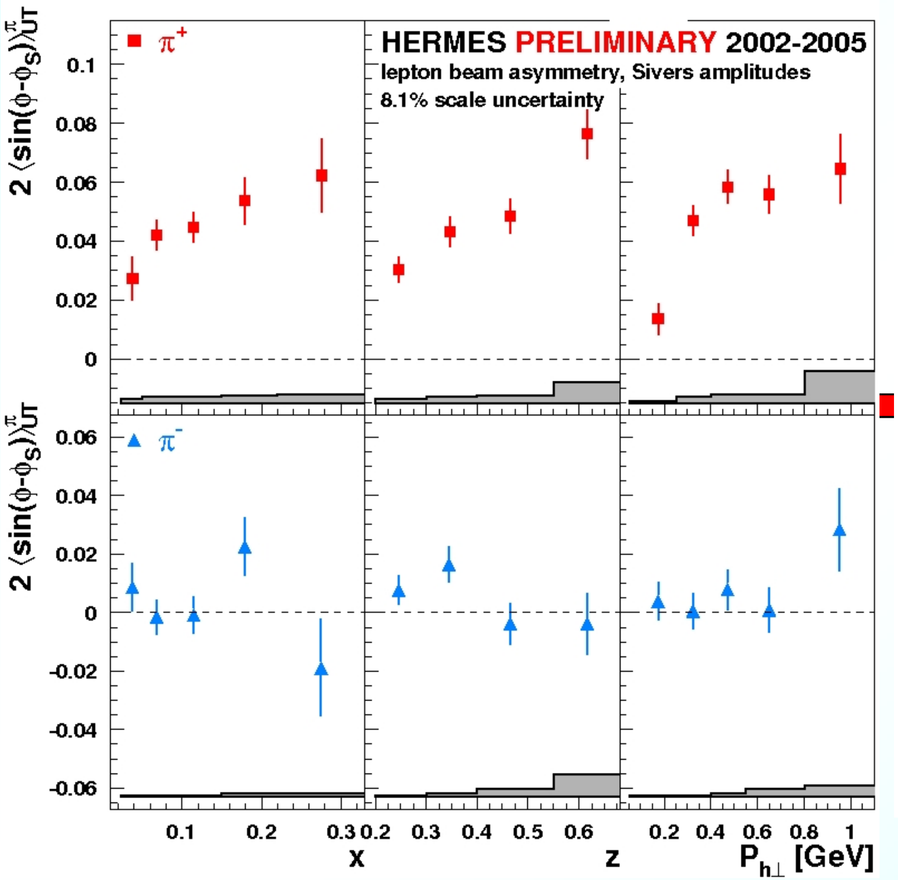
Highlight 10

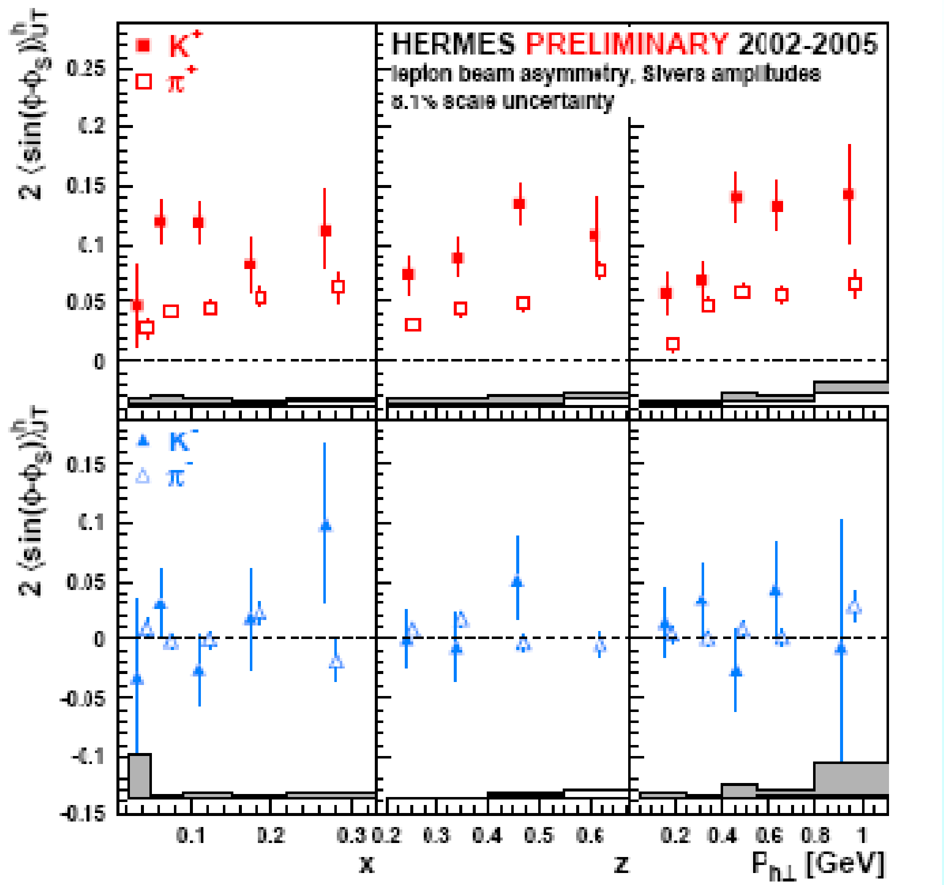
Sivers amplitudes (p)

$$2\langle\sin(\phi - \phi_S)\rangle^h_{UT} \sim f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

M. Diefenthaler @ DIS07, hep-ex 0706.2242

(also HERMES, P. R. L. 94 (2005) 012002)





Precise determination of G_E^n