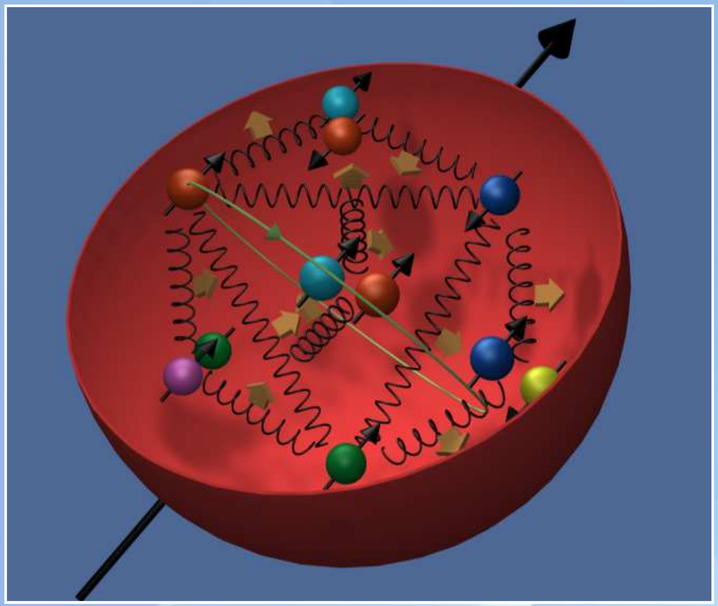
The Spin Structure of the Nucleon



Experimental Prerequisites

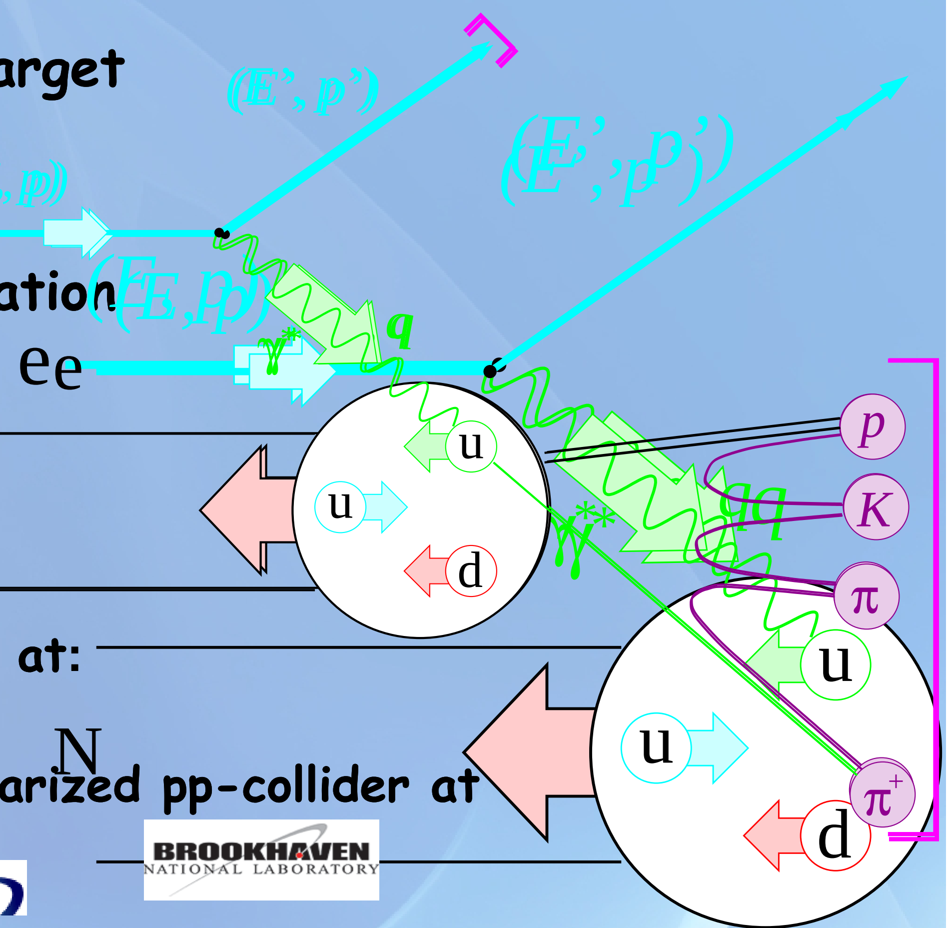
- longitudinally polarized lepton beam
- longitudinally polarized nuclear target
- large geometrical acceptance
  - small angles
    limited by synchrotron radiation
  - big angles
    limited by money
- good particle identification

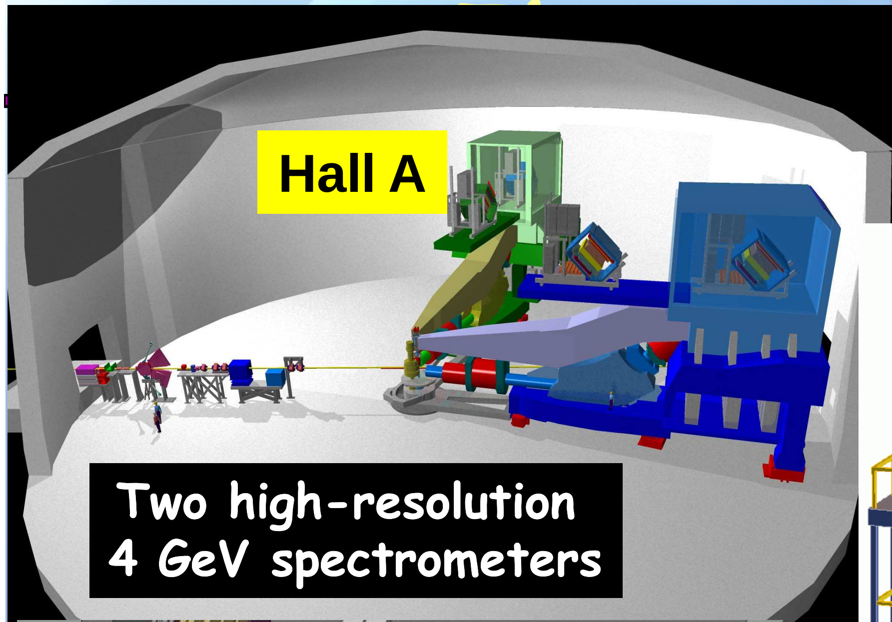
So far only **"fixed target"** experiments at:

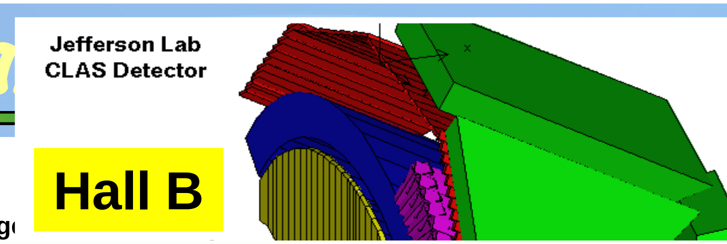
CERN, SLAC, DESY, Jefferson Lab

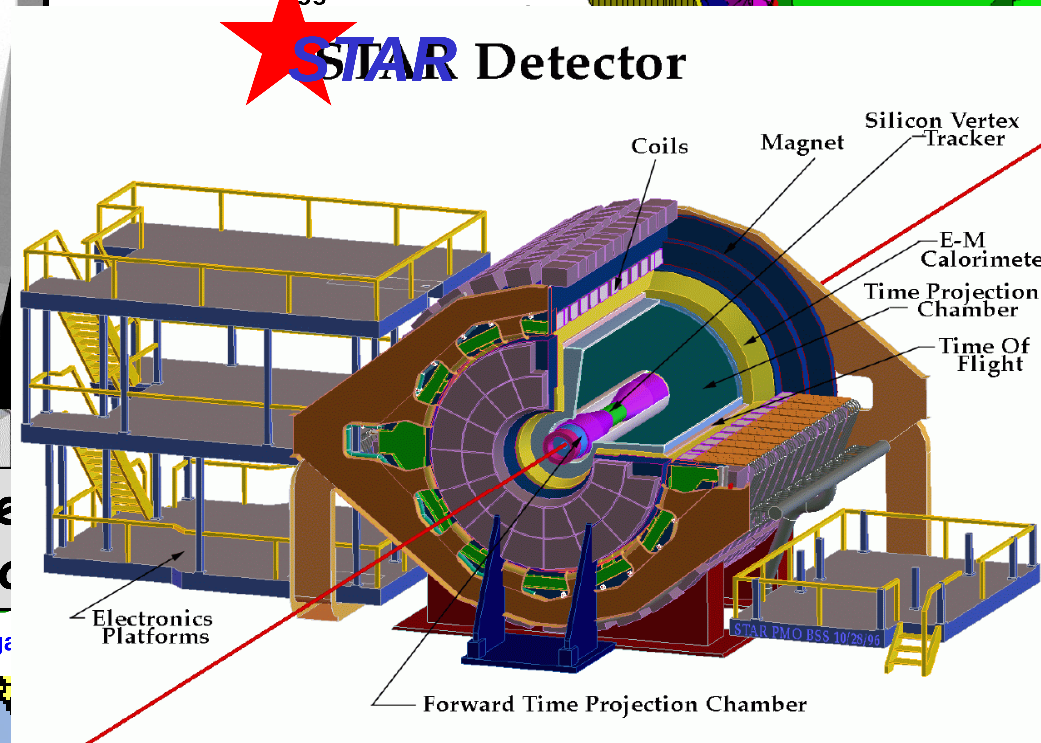
and polarized pp-collider at

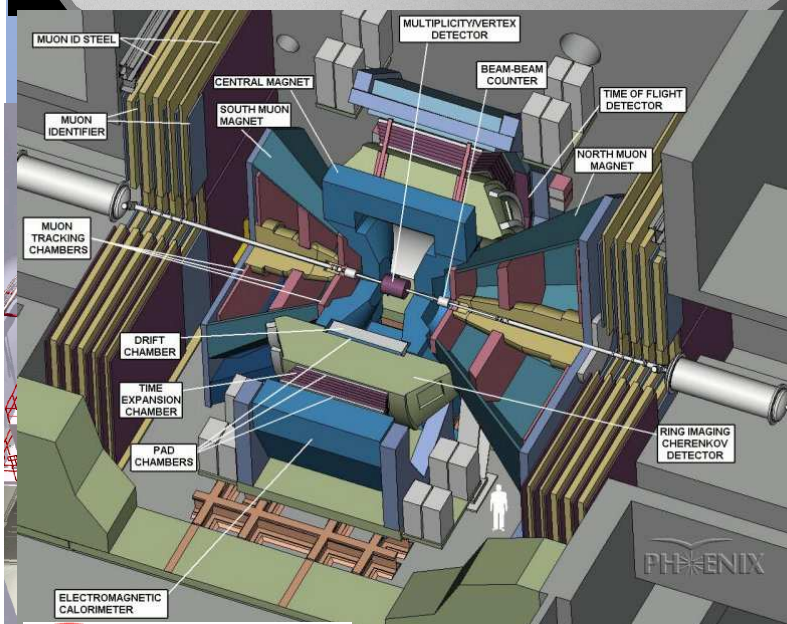
BROOKHAVEN NATIONAL LABORATORY







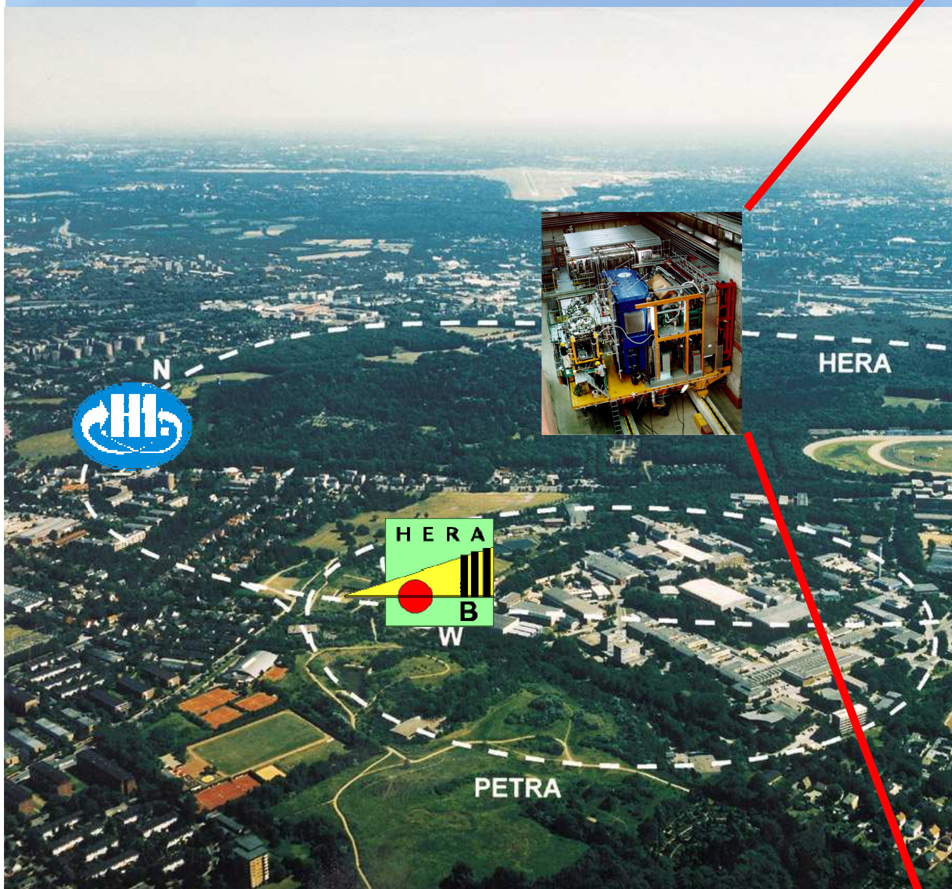


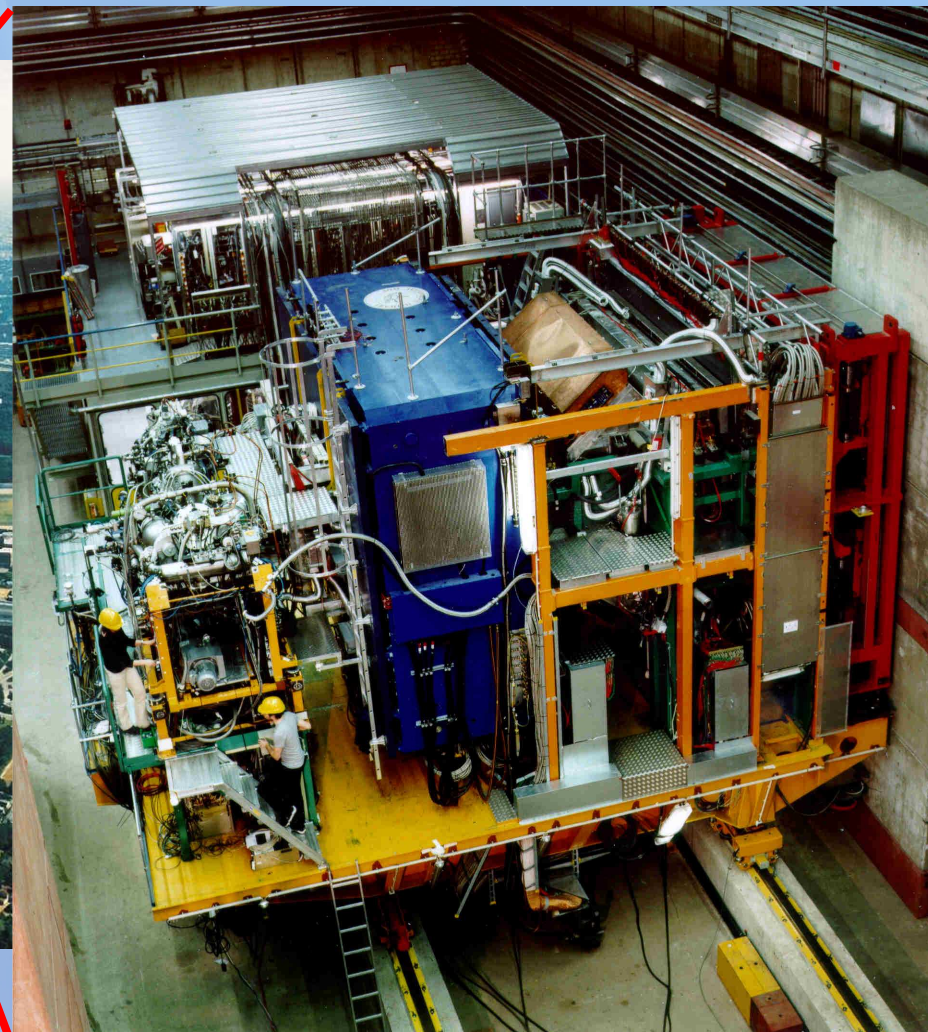


ion experiments

Beams: 250 GeV pp; <60>% polarization
Lumi: 1.2 $10^{31}cm^{-2}s^{-1}$

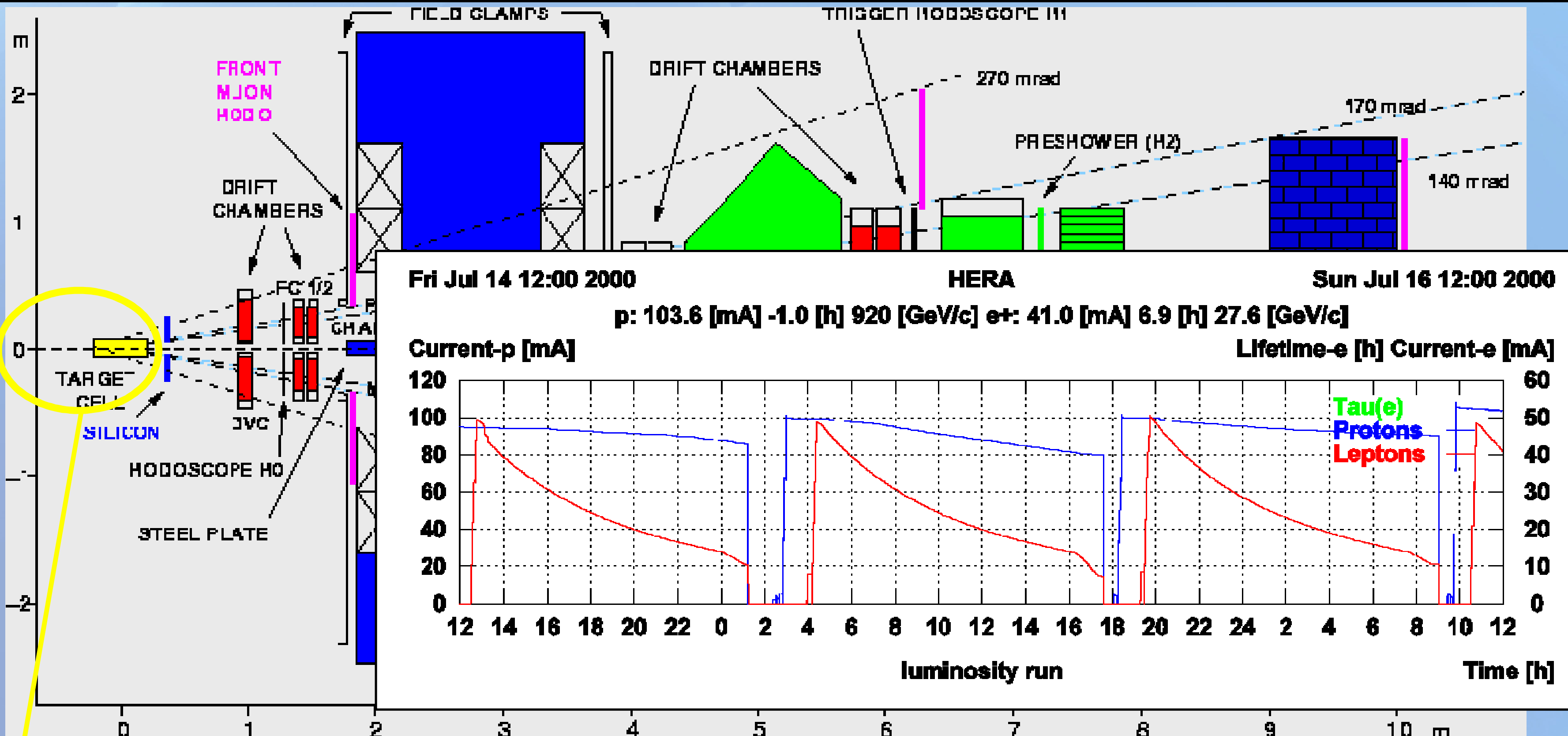
HERA @ DESY





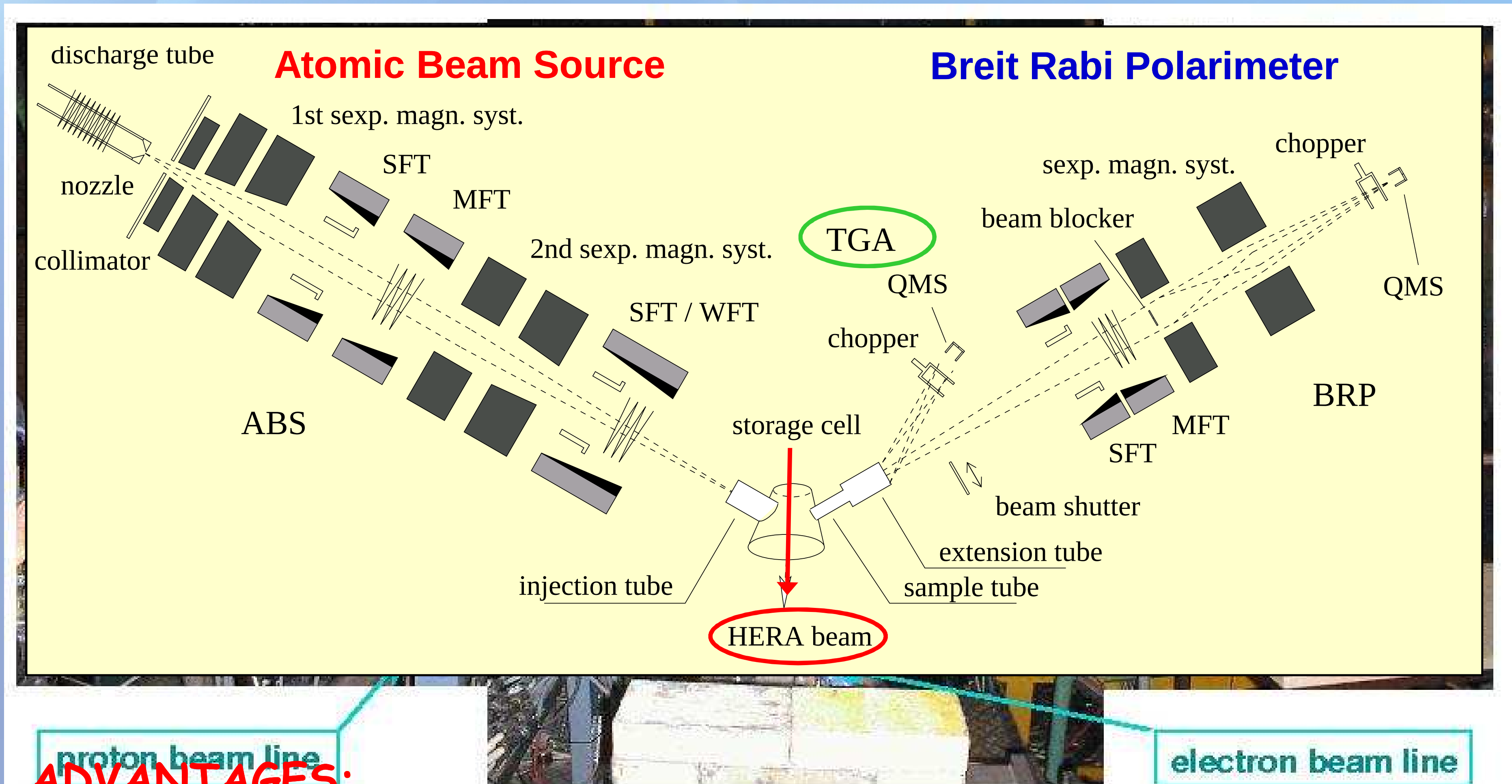
HERA: e^+/e^- (27GeV) - proton (920 GeV) collider

The HERMES Spectrometer



Internal Gas Target: $\vec{He}$, $\vec{H}$, $\vec{D}$, $H\uparrow$ unpol: H_2,D_2,He,N_2,Ne,Kr,Xe

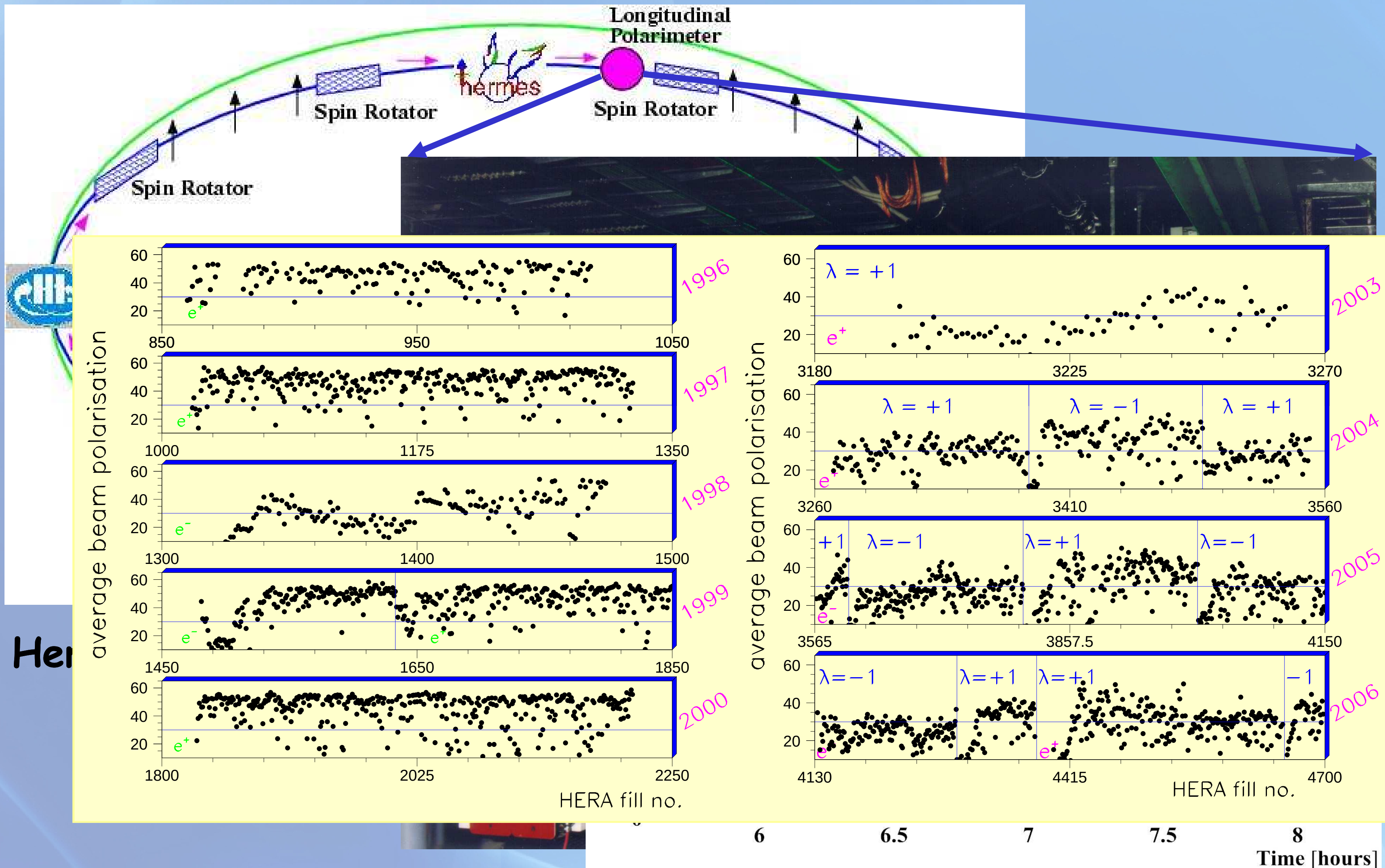
The HERMES polarized gas target



ADVANTAGES:

- no dilution; all the material is polarized
- no radiation damage
- rapid inversion of polarization direction every 90s in less than 0.5s

The HERA Polarimeters



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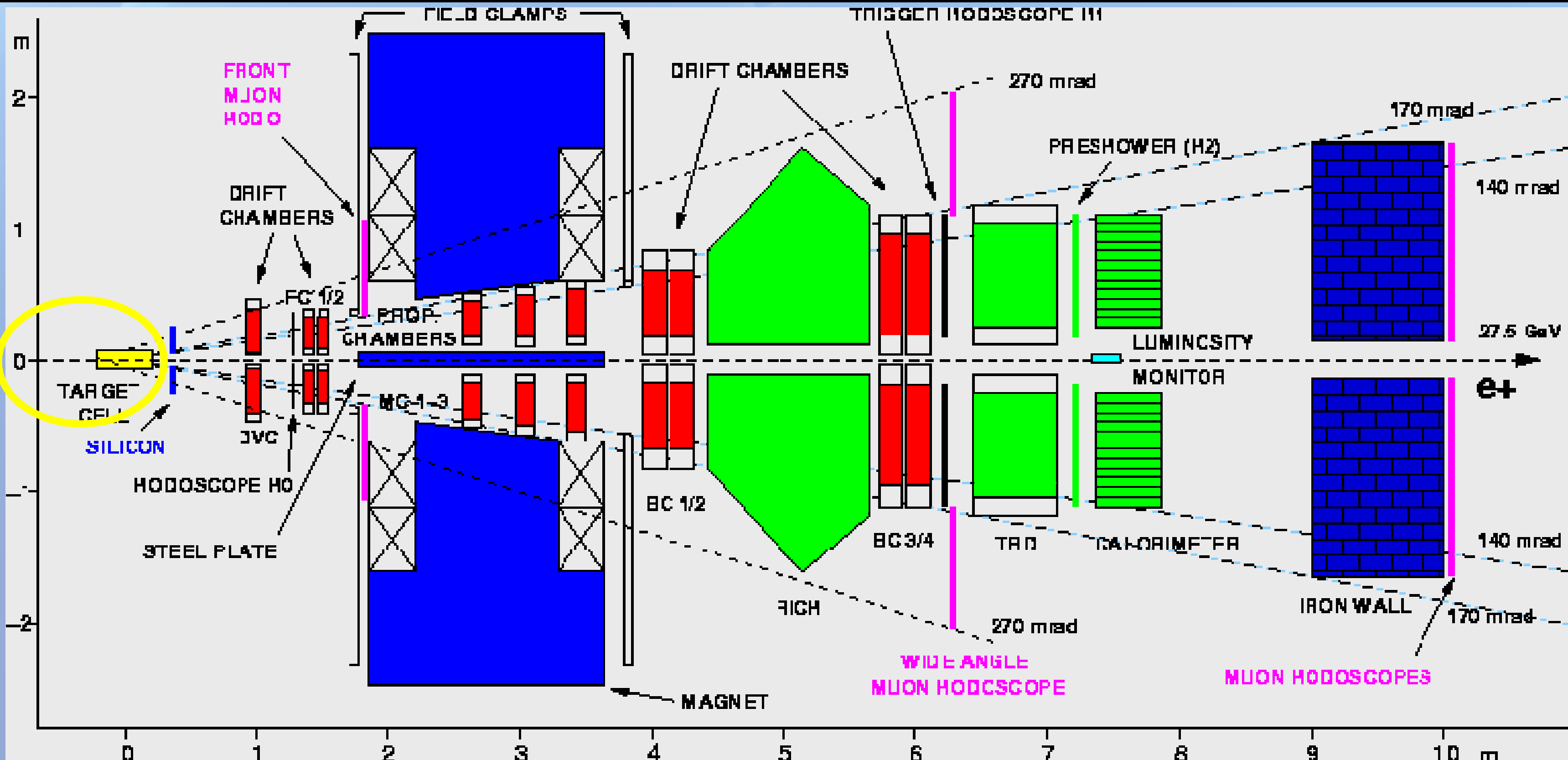


Kinematic Range: 0.02 < x < 0.8 at $Q^2 > 1$ GeV^2 and W > 2 GeV

Reconstruction: $\Delta p/p < 2\%$, $\Delta\theta < 1$ mrad

Internal Gas Target: unpol: H_2,D_2,He,N,Ne,Kr, Xe $\overrightarrow{He}$, $\overrightarrow{H}$, $\overrightarrow{D}$, H$\uparrow$

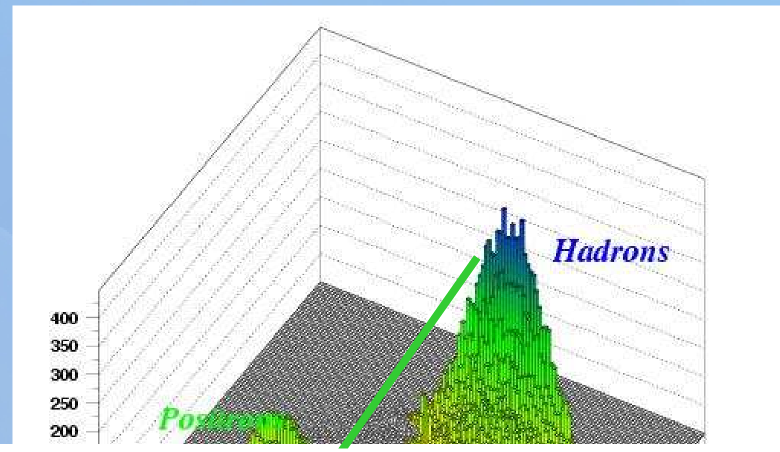
Particle ID: TRD, Preshower, Calorimeter

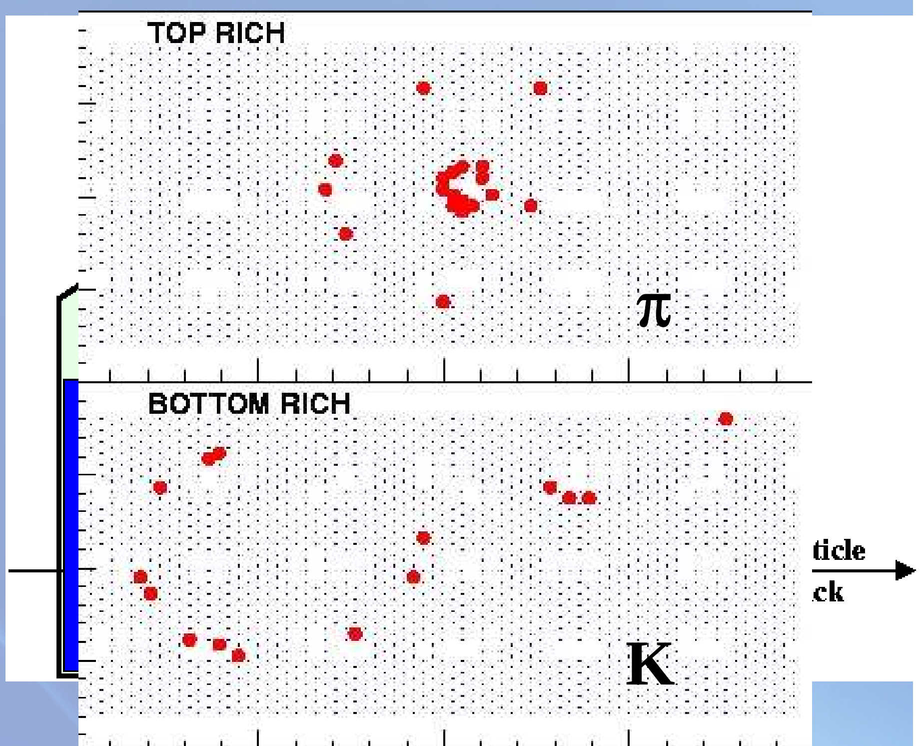
$\mapsto$1997: Cherenkov, 1998$\mapsto$: RICH + Muon-ID

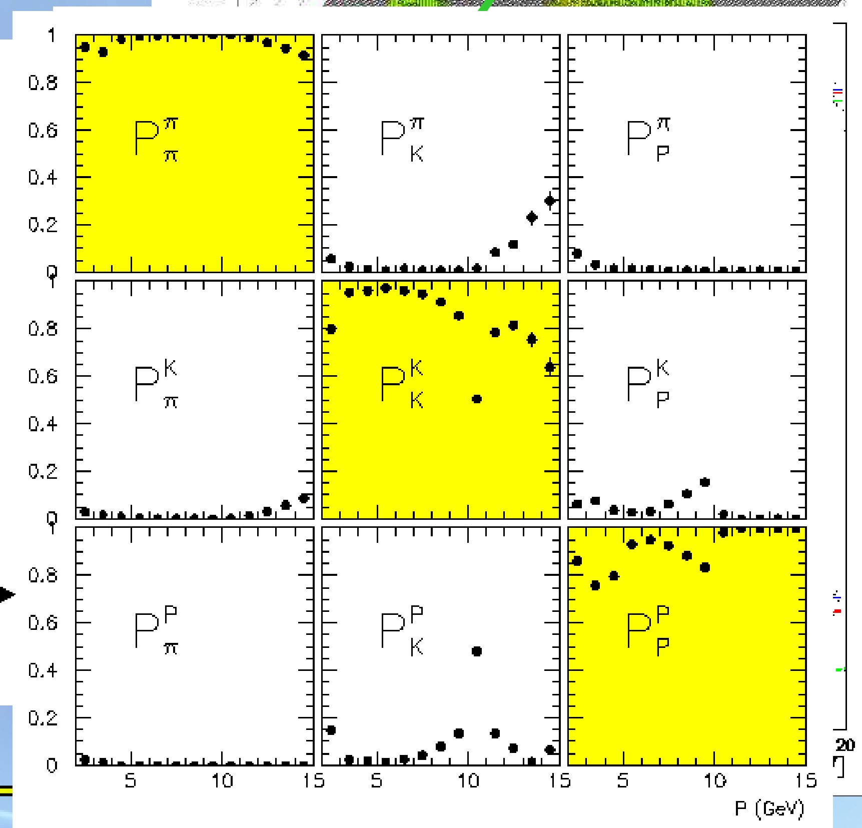
Which Hadron (π,K,p) is Which

hadron/positron separation
combining signals from:
TRD, calorimeter, preshower

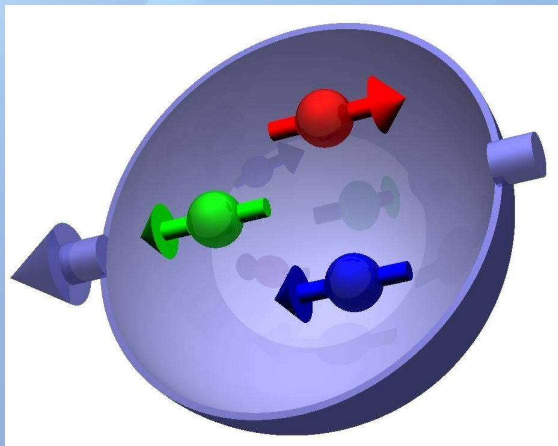
hadron separation
Dual radiator RICH for π, K, p







News on the spin structure of the nucleon



Naïve parton model

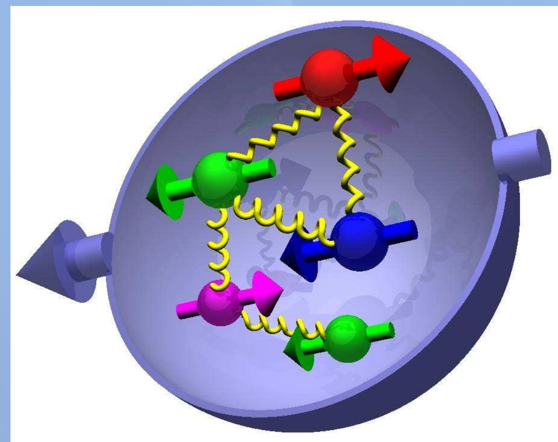
$$\Delta u_v = \tfrac{4}{3} \quad \Delta d_v = -\tfrac{1}{3}$$

BUT

1989 EMC measured

$\Sigma = 0.120 \pm 0.094 \pm 0.138$

⇒ Spin Puzzle

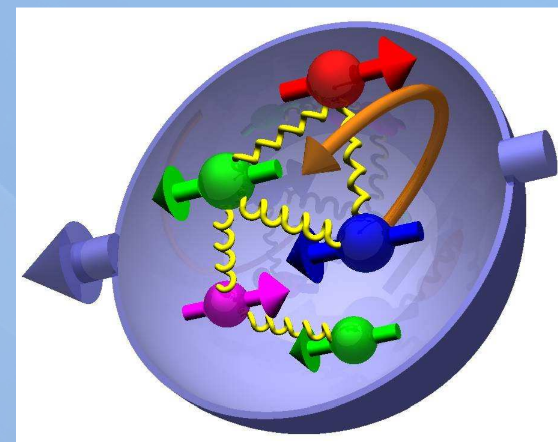


Unpolarised structure fct.

Gluons are important !

⇒ ΔG

⇒ Sea quarks Δq_s



Full description of J_q and J_g

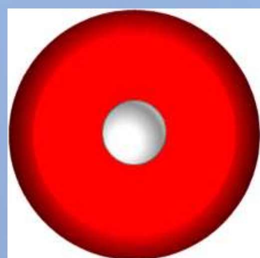
needs

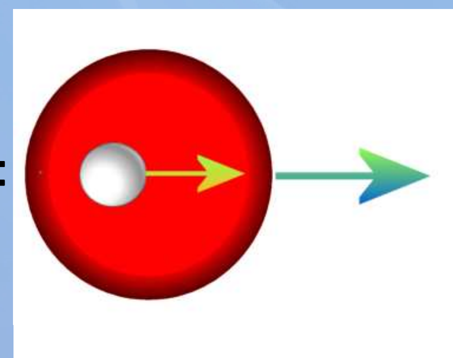
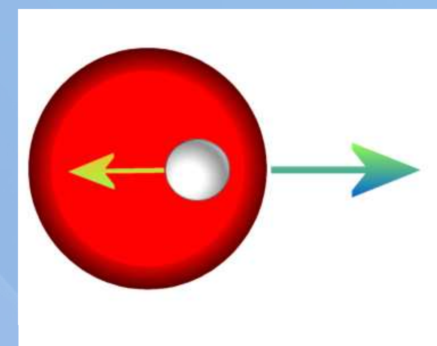
orbital angular momentum

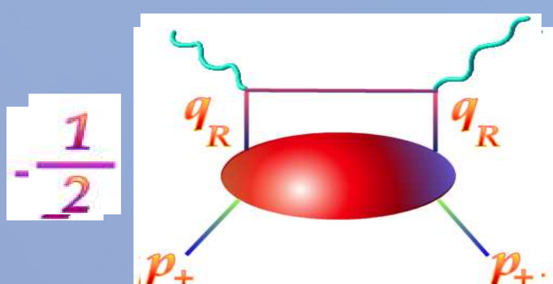
$$\frac{1}{2} = \frac{1}{2}\underbrace{(\Delta u_v + \Delta d_v + \underbrace{\Delta q_s}_{(\Delta u_s + \Delta d_s + \Delta \bar{u} + \Delta \bar{d} + \Delta s + \Delta \bar{s})})}_{\Delta\Sigma} + L_q + \Delta G + L_g$$

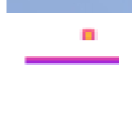
The quark content of the nucleon

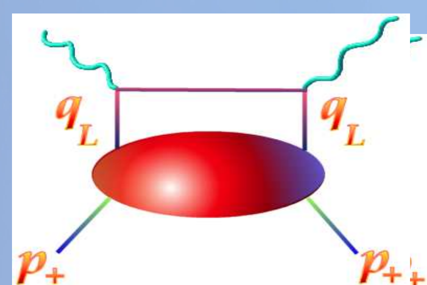
$$\Phi^{Tw2}_{Corr}(x) = \frac{1}{2}\left\{ \boxed{f_1(x)} + S_L \boxed{g_1(x)}\gamma_5 + h_1(x)\gamma_5\gamma^1 S_T \right\} n^+$$

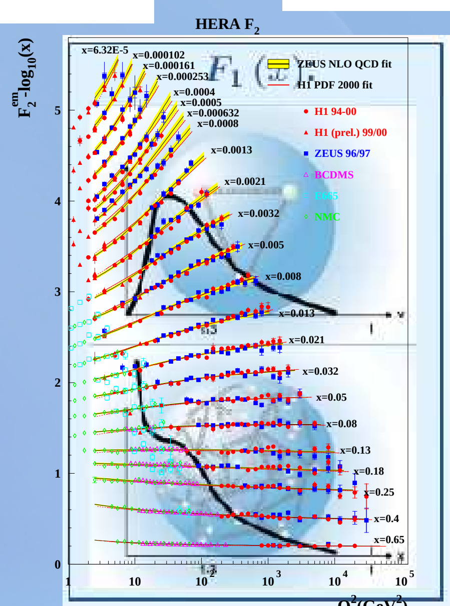
$f_1 =$ 

$g_{1L} =$  $-$ 

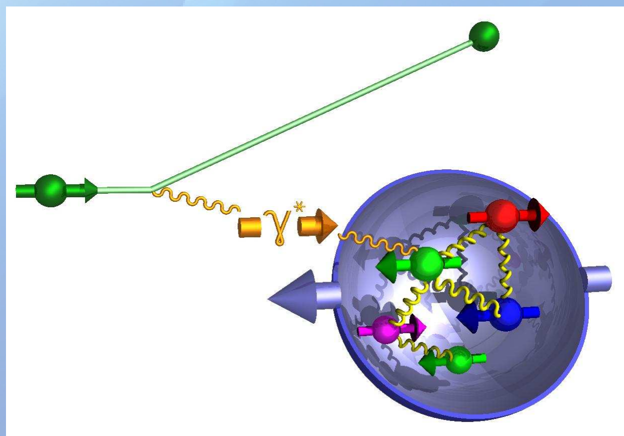




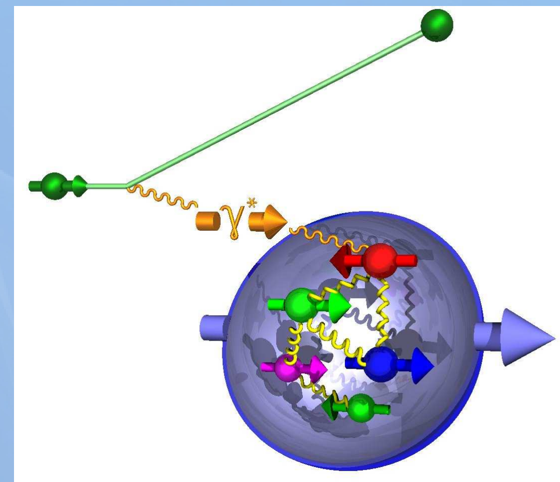




How to measure Quark Polarizations



$$\vec{S}_{\gamma^*} + \vec{S}_N = 1/2$$
$$\vec{S}_N = \vec{S}_q$$
$$\sigma_{1/2} \sim q^+(x)$$



$$\vec{S}_{\gamma^*} + \vec{S}_N = 3/2$$
$$\vec{S}_N = -\vec{S}_q$$
$$\sigma_{3/2} \sim q^-(x)$$

- Virtual photon γ^* can only couple to quarks of opposite helicity
- Select $q^+(x)$ or $q^-(x)$ by changing the orientation of target nucleon spin or helicity of incident lepton beam

$$\Delta q = q^+ - q^-$$

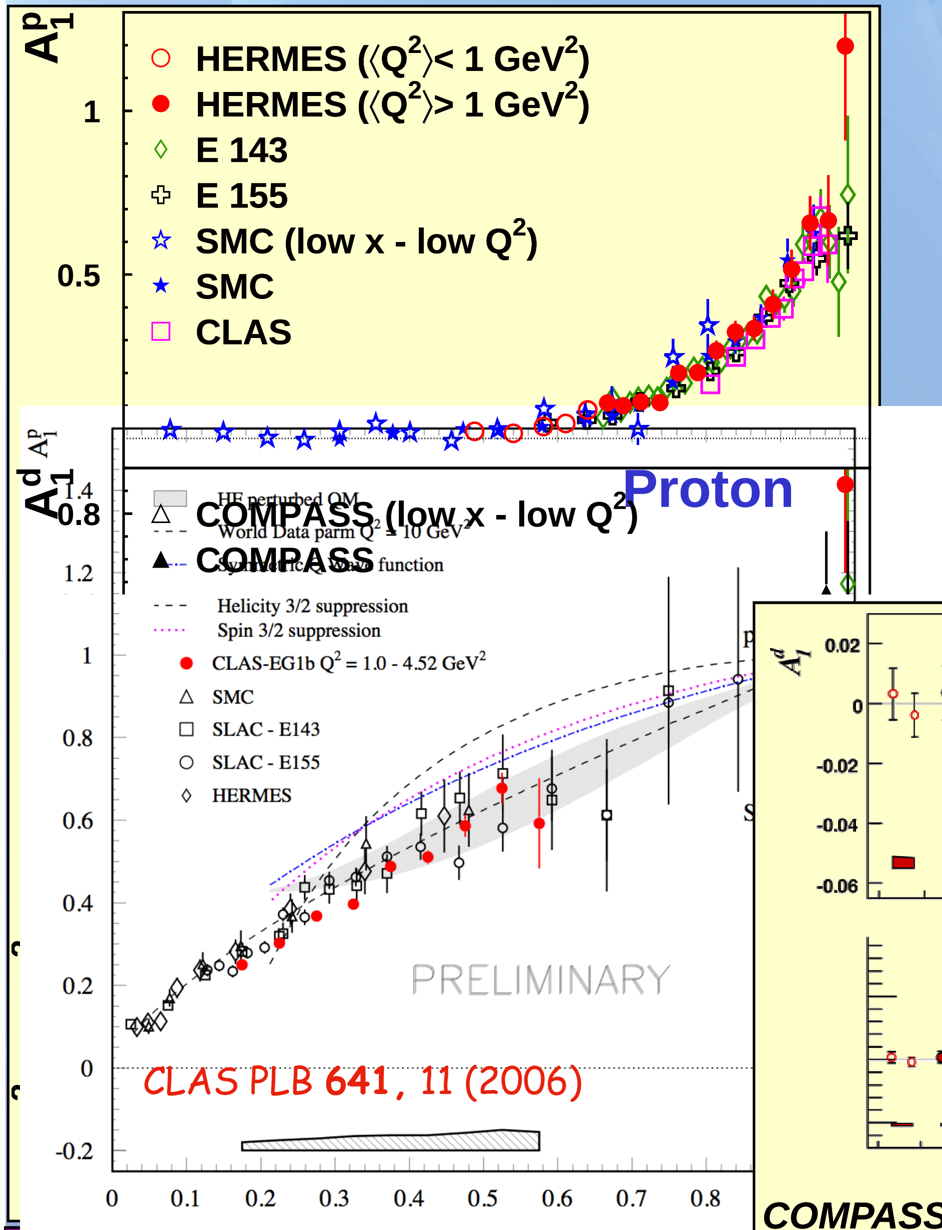
Asymmetry definition:

$$A_{\parallel}^{e',h} \sim \frac{\sigma_{1/2}^{e',h} - \sigma_{3/2}^{e',h}}{\sigma_{1/2}^{e',h} + \sigma_{3/2}^{e',h}} \qquad A_{\parallel}^{e'h} = \frac{1}{\langle P_B P_T \rangle} \frac{N_{e',h}^{\rightleftarrows} L^{\rightrightarrows} - N_{e',h}^{\rightrightarrows} L^{\rightleftarrows}}{N_{e',h}^{\rightleftarrows} L^{\rightrightarrows} + N_{e'h}^{\rightrightarrows} L^{\rightleftarrows}}$$

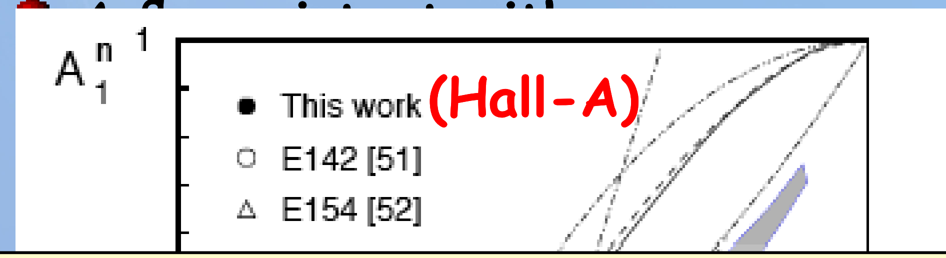
inclusive DIS: only e' info used

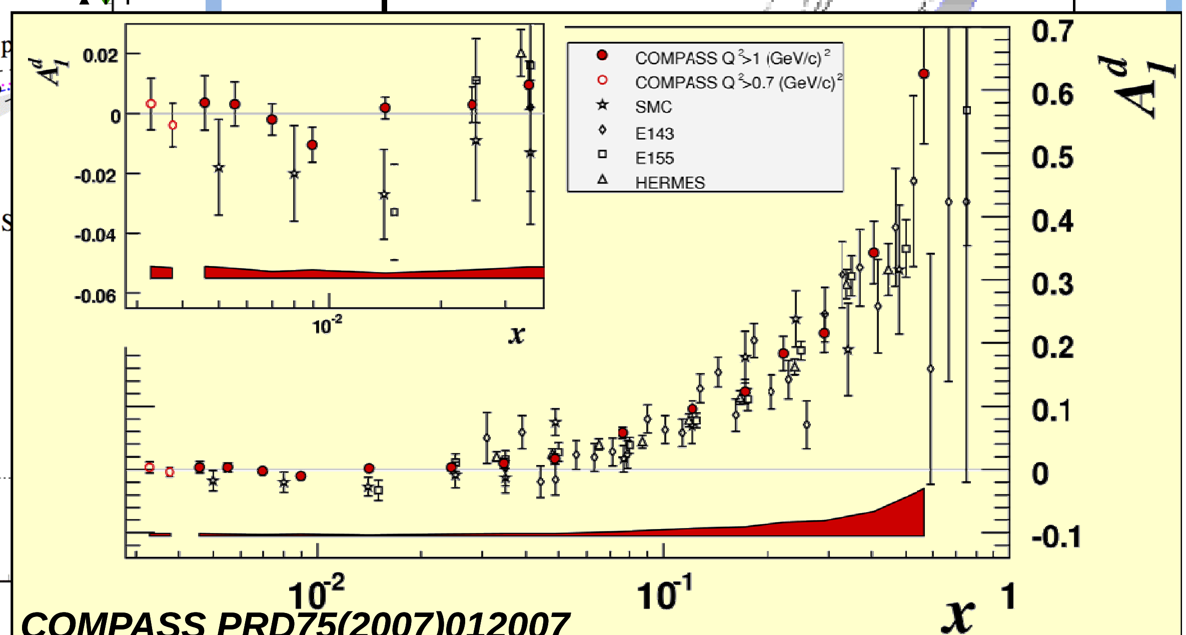
semi-inclusive DIS: e'+h info used

World data on inclusive DIS



- New data from COMPASS, HERMES & JLab very precise
- high x-behaviour consistent with A→1 with x→1





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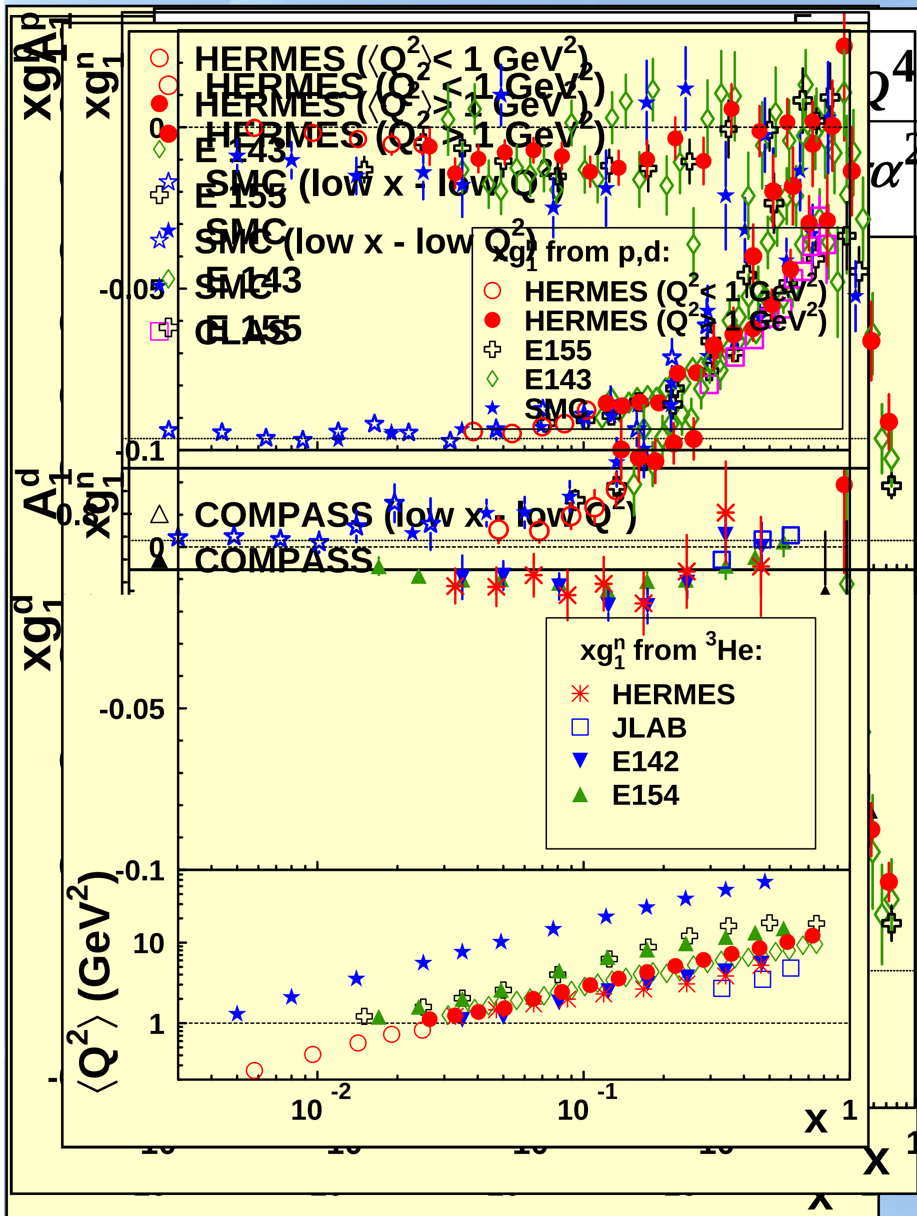


$$\ldots\frac{Q^4}{\ldots\alpha^2 y}\frac{d^2\sigma_{unpol}}{dxdQ^2}\left[A_{\parallel}(x,Q^2)+\frac{y}{2}\gamma^2 g_2(x,Q^2)\right]$$

Combine p and d to get n:

$$g_1^d = \frac{1}{2}(g_1^p + g_1^n)(1-\frac{3}{2}w_D)$$

or ^{3}He

$$g_1^{He^3} \approx P_n g_1^n + 2P_p g_1^p$$

- What can we learn on the PDFs

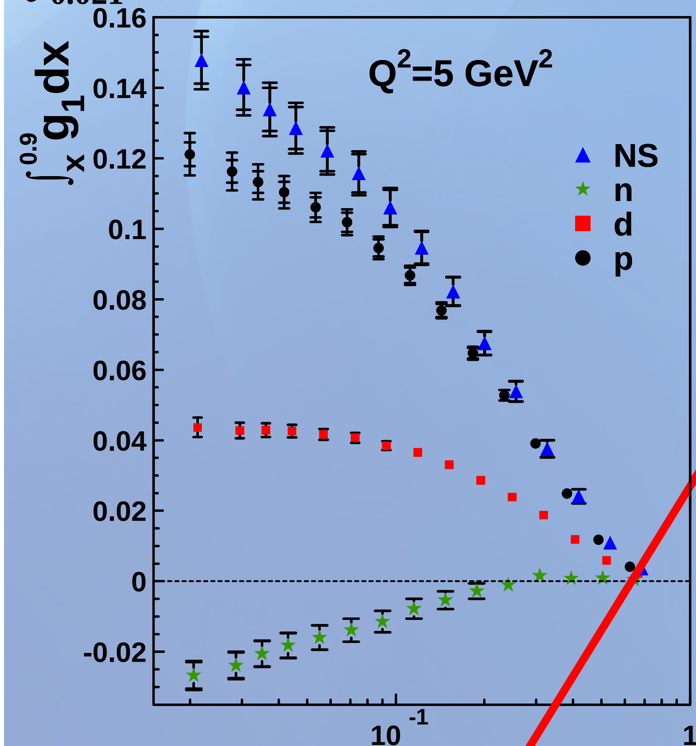
$$g_1 \sim \left\langle e^2 \right\rangle [\Delta C_\Sigma \otimes \Delta\Sigma + \Delta C_G \otimes \Delta G + \Delta C_{NS} \otimes \Delta q_{NS}^{p,n}]$$

$$\overset{\text{LO-QCD}}{=} \frac{1}{2}\left\langle e^2 \right\rangle \left[\Delta\Sigma + \Delta q_{NS}^{p,n}\right]$$

Compass: hep-ex/0609038
Hermes: hep-ex/0609039

HERMES: Integrals

$$\int_{0.021}^{0.9} dx g_1^d = 0.0436 \pm 0.0012(stat) \pm 0.0018(syst) \pm 0.0008(par) \pm 0.0026(evol)$$



Saturation in deuteron integral is assumed

- use only deuterium

$$a_0 = \frac{1}{\Delta C_S}\left[\frac{9\Gamma_1^d}{(1-\frac{3}{2}w_D)} - \frac{1}{4}a_8 \Delta C_{NS}\right]$$

From hyperon beta decay
a_8=0.586±0.031

From neutron beta decay
a_3=1.269±0.003

$$\Delta u + \Delta\bar{u} = \frac{1}{6}[2a_0 + a_8 + 3a_3]$$

$$\Delta d + \Delta\bar{d} = \frac{1}{6}[2a_0 + a_8 - 3a_3]$$

$$\Delta s + \Delta\bar{s} = \frac{1}{3}[a_0 - a_8]$$

	central value	uncertainties theor.	exp.	evol.
a_0	0.330	0.011	0.025	0.028
$\Delta u + \Delta\bar{u}$	0.842	0.004	0.008	0.009
$\Delta d + \Delta\bar{d}$	-0.427	0.004	0.008	0.009
$\Delta s + \Delta\bar{s}$	-0.085	0.013	0.008	0.009

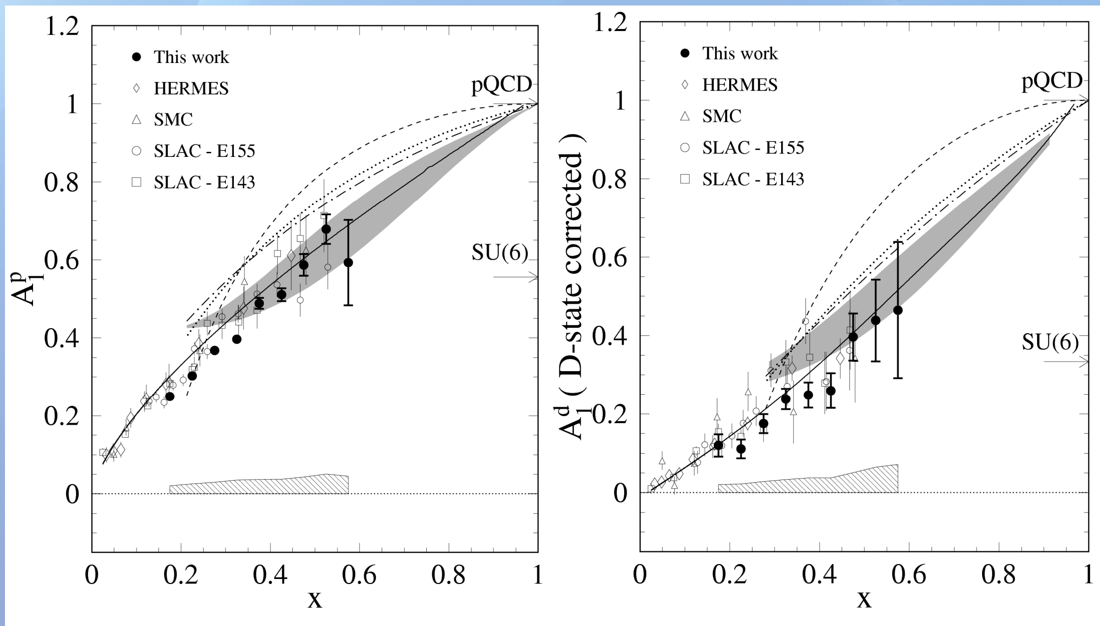
Q^2=5 GeV², NNLO in $\overline{MS}$ scheme

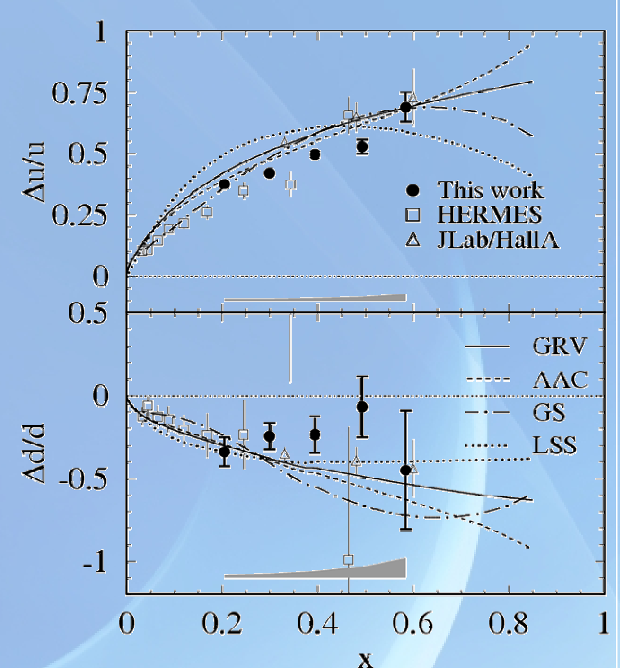
- COMPASS:

$$a_0 = 0.33 \pm 0.03 \pm 0.05$$

$$\Delta s + \Delta\bar{s} = -0.08 \pm 0.01 \pm 0.02$$

CLAS: Δq



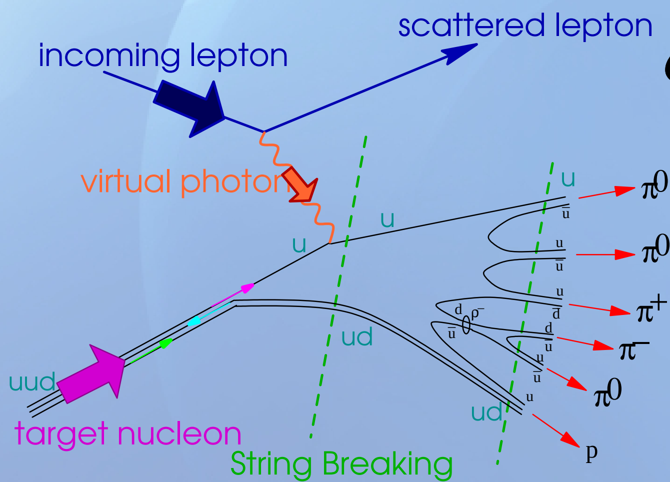


- **Using:**

$$\frac{\Delta u}{u} \approx \frac{5g_1^p - 2g_1^d/(1-1.5w_D)}{5F_1^p - 2F_1^d}$$

$$\frac{\Delta d}{d} \approx \frac{8g_1^d/(1-1.5w_D) - 5g_1^p}{8F_1^d - 5F_1^p}$$

Polarised quark distributions



Correlation between detected hadron and struck q_f

⟹ **"Flavor – Separation"**

Inclusive DIS:

$$\Delta\Sigma = (\Delta u + \Delta d + \Delta \bar{u} + \Delta \bar{d} + \Delta s + \Delta \bar{s})$$

Semi-inclusive DIS:

$$(\Delta u, \Delta d, \Delta \bar{u}, \Delta \bar{d}, \Delta s, \Delta \bar{s})$$

In LO-QCD:

$$A_1^h(x,Q^2,z) = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} \sim C \sum_q \frac{e_q^2 q(x,Q^2) D_q^h(z,Q^2)}{\sum_{q'} e_{q'}^2 q'(x,Q^2) D_{q'}^h(z,Q^2)} \frac{\Delta q(x,Q^2)}{q(x,Q^2)}$$

COMPASS: Valence PDFs

$$A^{+/-} = \frac{(\sigma^{\rightleftarrows}_{h^+} - \sigma^{\rightleftarrows}_{h^-}) - (\sigma^{\rightrightarrows}_{h^+} - \sigma^{\rightrightarrows}_{h^-})}{(\sigma^{\rightleftarrows}_{h^+} - \sigma^{\rightleftarrows}_{h^-}) + (\sigma^{\rightrightarrows}_{h^+} - \sigma^{\rightrightarrows}_{h^-})}$$

- **For LO:**

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

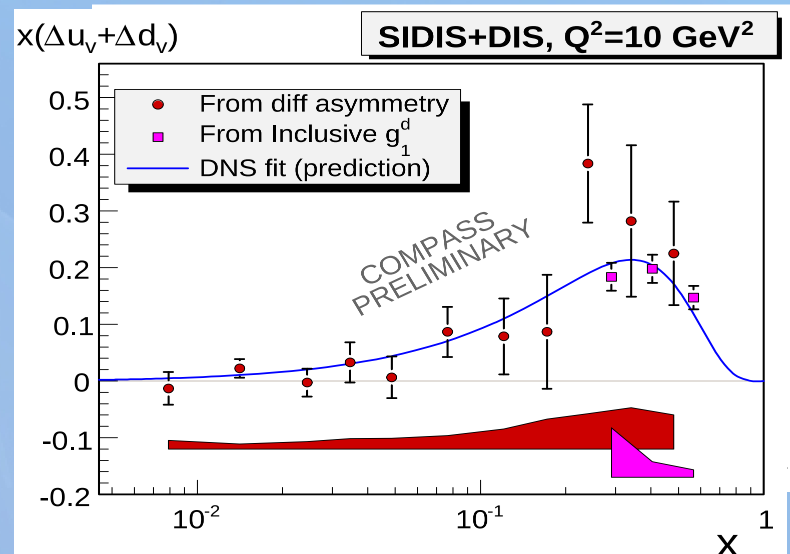
- **Assuming:**

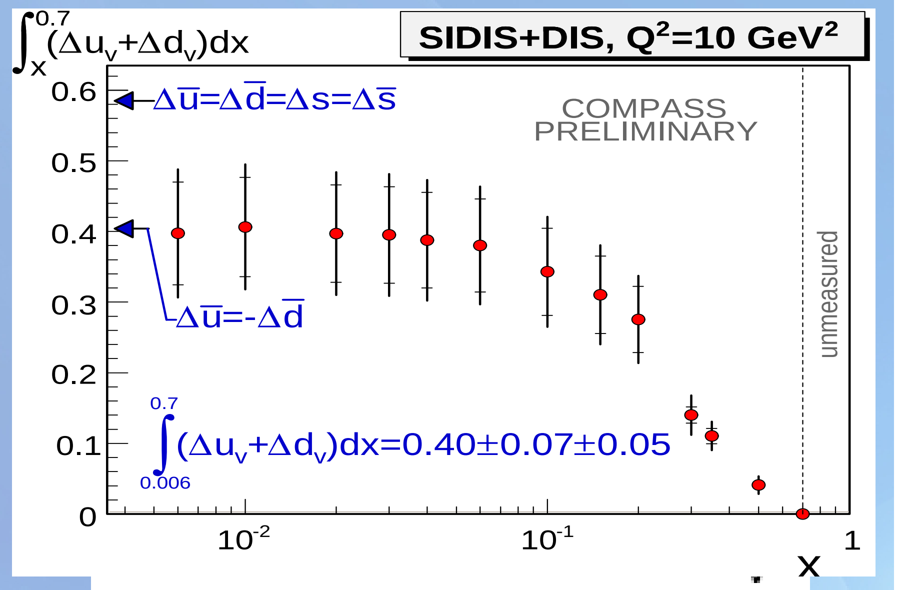
$$\Gamma_1^N = \frac{1}{9}\left(a_0 + \frac{1}{4}a_8\right)$$

$$\Gamma_v = \int_0^1 (\Delta u_v(x) + \Delta d_v(x))dx$$

$$\Delta\bar{u} + \Delta\bar{d} = 3\Gamma_1^N - \frac{1}{2}\Gamma_v + \frac{1}{12}a_8$$

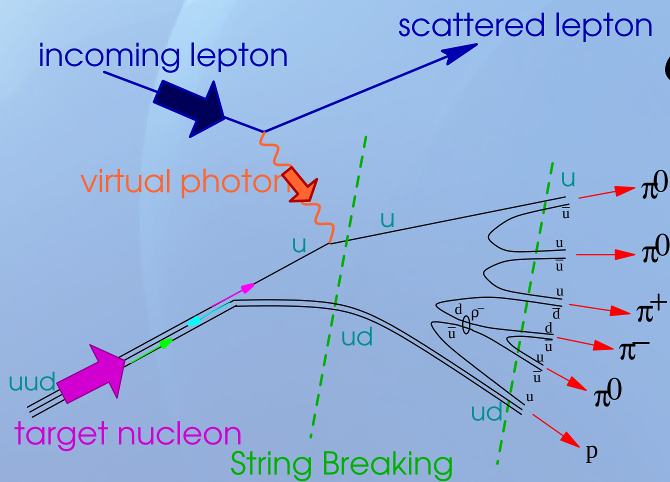
$$= (\Delta s + \Delta\bar{s}) + \frac{1}{2}(a_8 - \Gamma_v)$$





➡ Γ_v is $2.5\sigma_{stat}$ away from flavor symmetric sea scenario

Polarised quark distributions



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$P_q^h(x,Q^2,z) \Longleftarrow$ MC

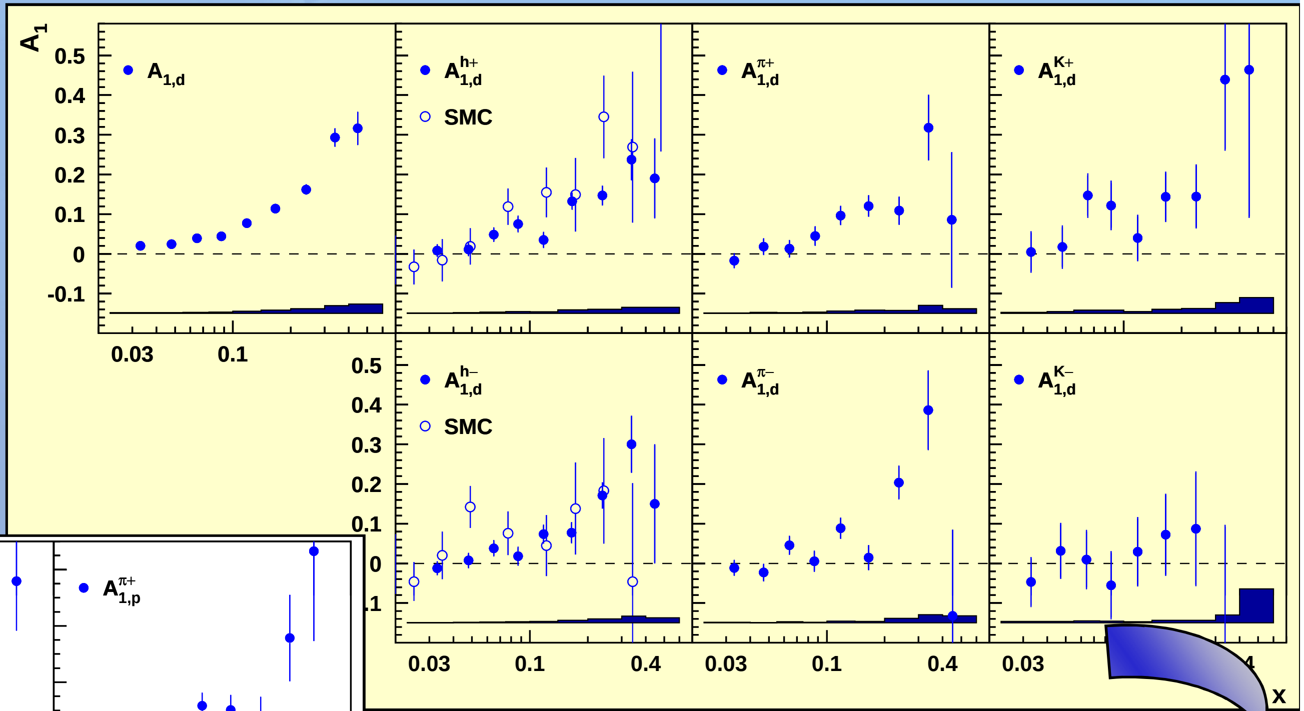
Extract Δq by solving:

$$\boxed{\vec{A} = P\vec{Q}}$$

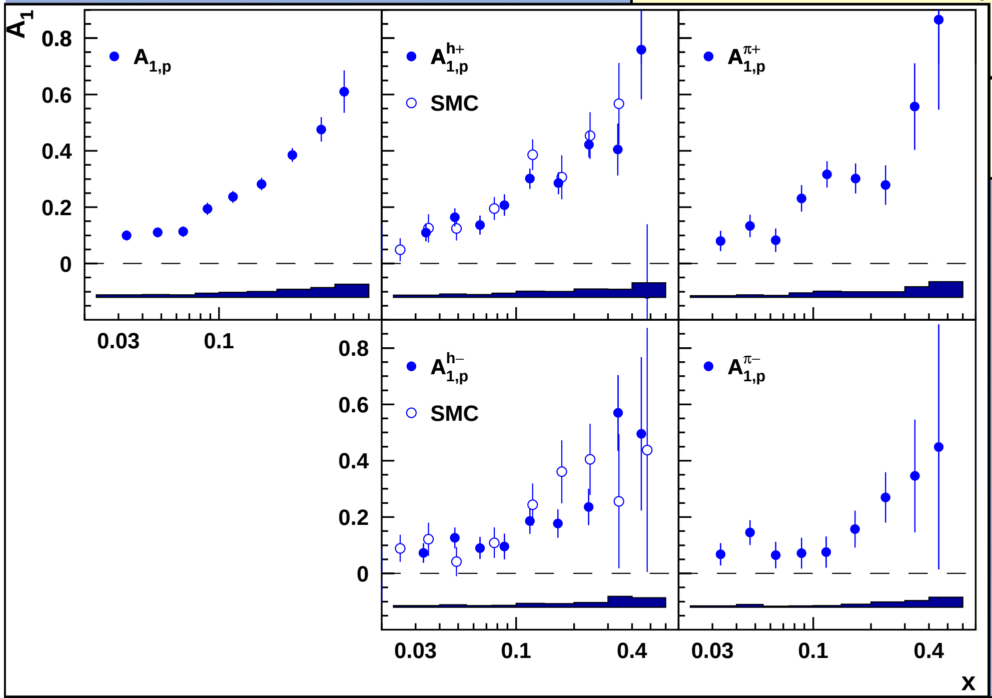
$$\vec{A} = (A_{1,p}(x), A_{1,p}^{\pi\pm}(x), A_{1,d}(x), A_{1,d}^{\pi\pm}(x), A_{1,d}^{K\pm}(x)) \qquad \vec{Q} = (\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta\bar{u}}{\bar{u}}, \frac{\Delta\bar{d}}{\bar{d}}, \frac{\Delta s}{s}, \frac{\Delta\bar{s}}{\bar{s}})$$

Measured Asymmetries

Deuterium



Proton

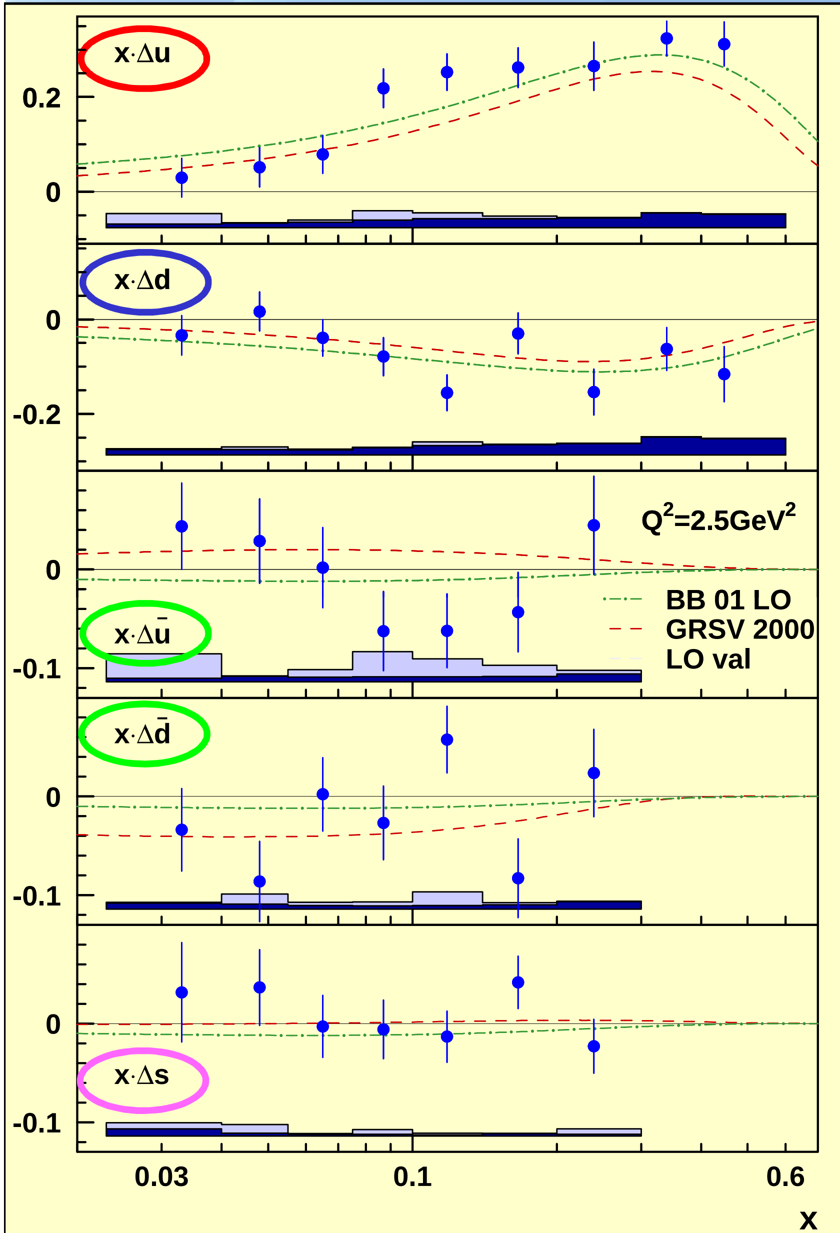


$$A_1^{K^-} \sim 0 \Rightarrow K^- = (\bar{u}s)$$

- statistics sufficient for 5 parameter fit

$$\vec{Q} = \left(\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta \bar{d}}{\bar{d}}, \frac{\Delta s}{s}, \frac{\Delta \bar{s}}{\bar{s}} = 0\right)$$

Polarized Quark Densities



- First complete separation of pol. PDFs without assumption on sea polarization
- $\Delta u(x) > 0$ $\Delta d(x) < 0$

→ good agreement with NLO QCD
→ Polarised parallel to proton spin

- $\Delta\bar{u}(x)$, $\Delta\bar{d}(x)$ ~ 0
- No indication for $\Delta s(x)$ < 0
- In measured range (0.023 – 0.6)

$$\int \Delta\bar{u} = -0.002 \pm 0.043$$

$$\int \Delta\bar{d} = -0.054 \pm 0.035$$

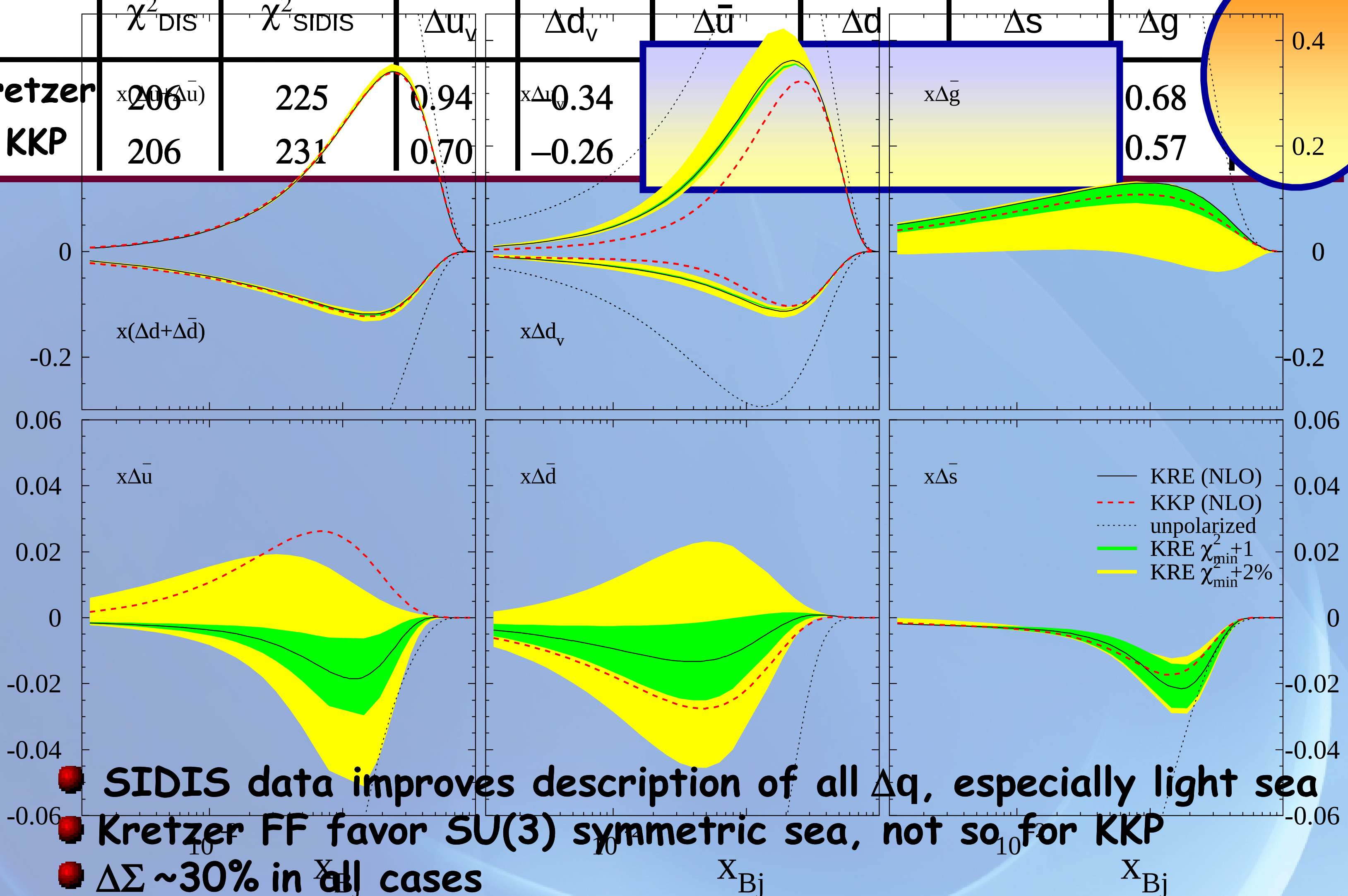
$$\int \Delta s = +0.028 \pm 0.034$$

NLO FIT to DIS & SIDIS Data

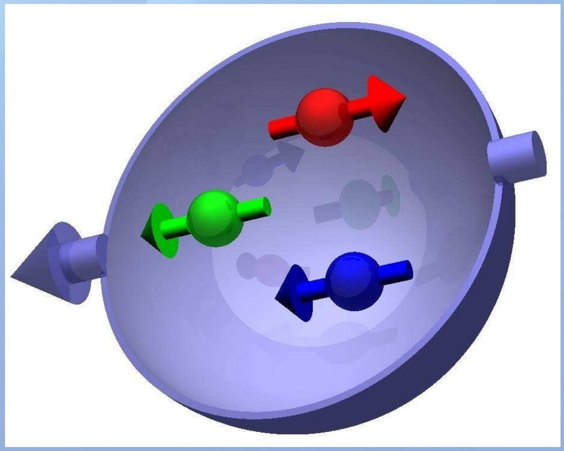
D. De Florian et al. hep-ph/0504155

NLO @ Q^2=10 GeV^2

	χ^2_{DIS}	χ^2_{SIDIS}	Δu_v	Δd_v	$\Delta\bar{u}$	$\Delta\bar{d}$	Δs	Δg	
Kretzer	206	225	0.94	–0.34				0.68	
KKP	206	231	0.70	–0.26				0.57	



- SIDIS data improves description of all Δq, especially light sea
- Kretzer FF favor SU(3) symmetric sea, not so for KKP
- $\Delta\Sigma$ ~30% in all cases



Naïve parton model

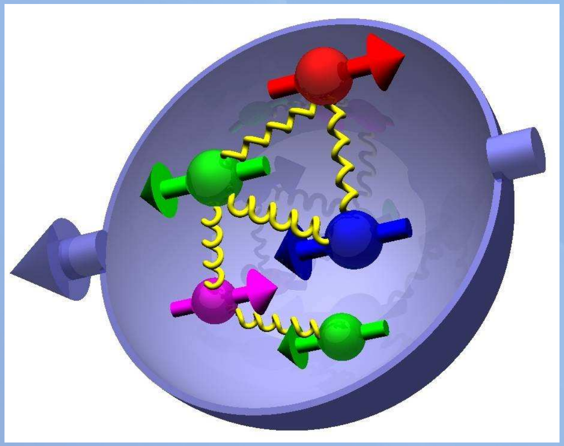
$\Delta u_v = \frac{4}{3} \quad \Delta d_v = -\frac{1}{3}$

BUT

1989 EMC measured

$\Sigma = 0.120 \pm 0.094 \pm 0.138$

⟹ Spin Puzzle



Unpolarised structure fct.

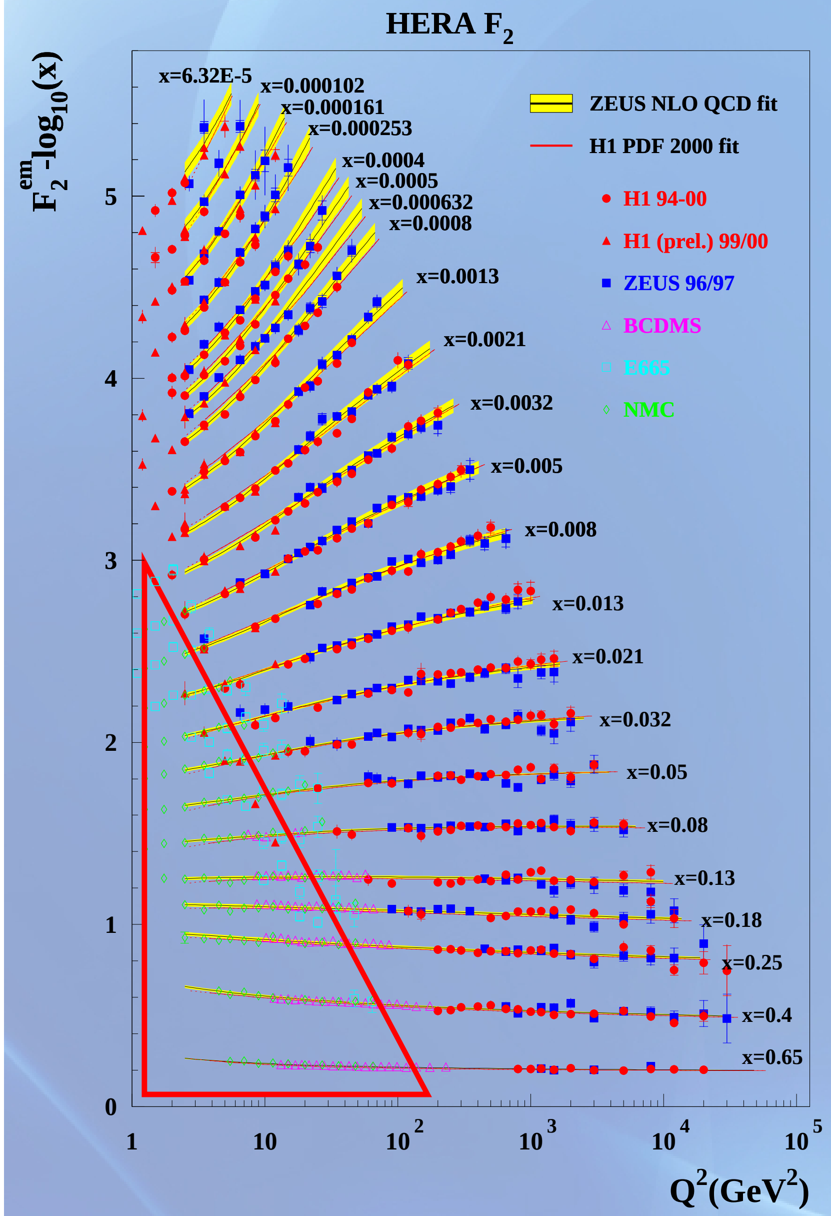
Gluons are important !

⟹ ΔG

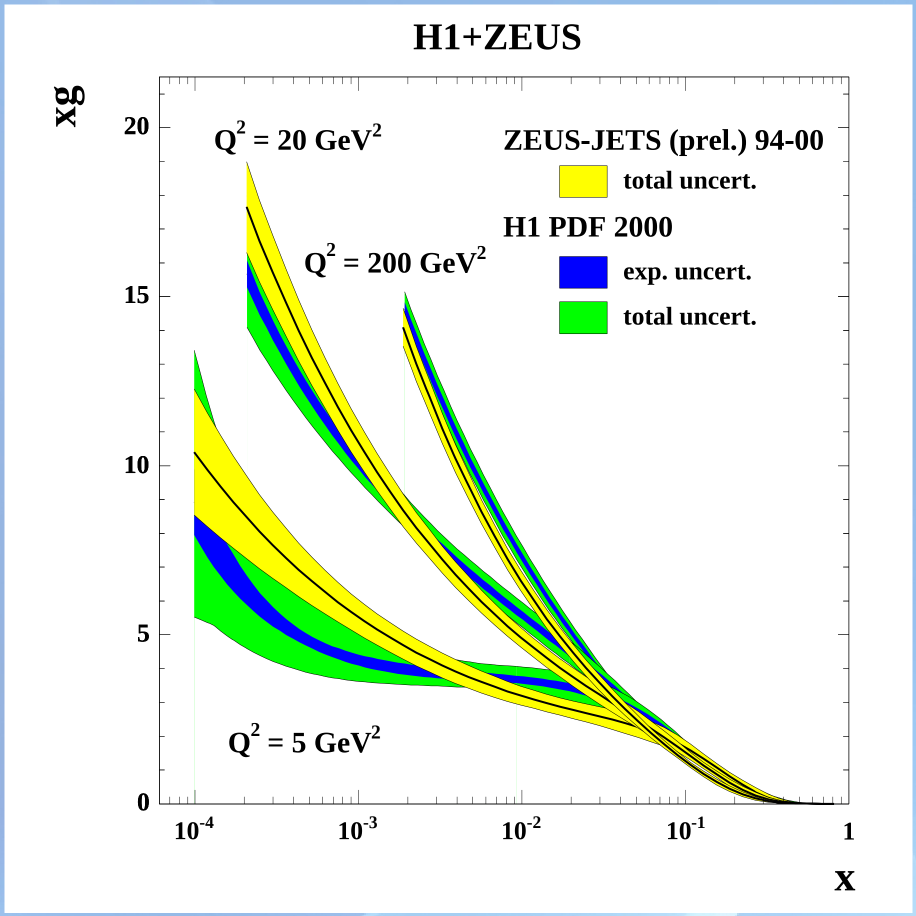
⟹ Sea quarks Δq_s

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v + \underbrace{\Delta q_s}_{(\Delta u_s + \Delta d_s + \Delta \bar{u} + \Delta \bar{d} + \Delta s + \Delta \bar{s})}) + \Delta G$$

Unpolarized Gluon Distribution

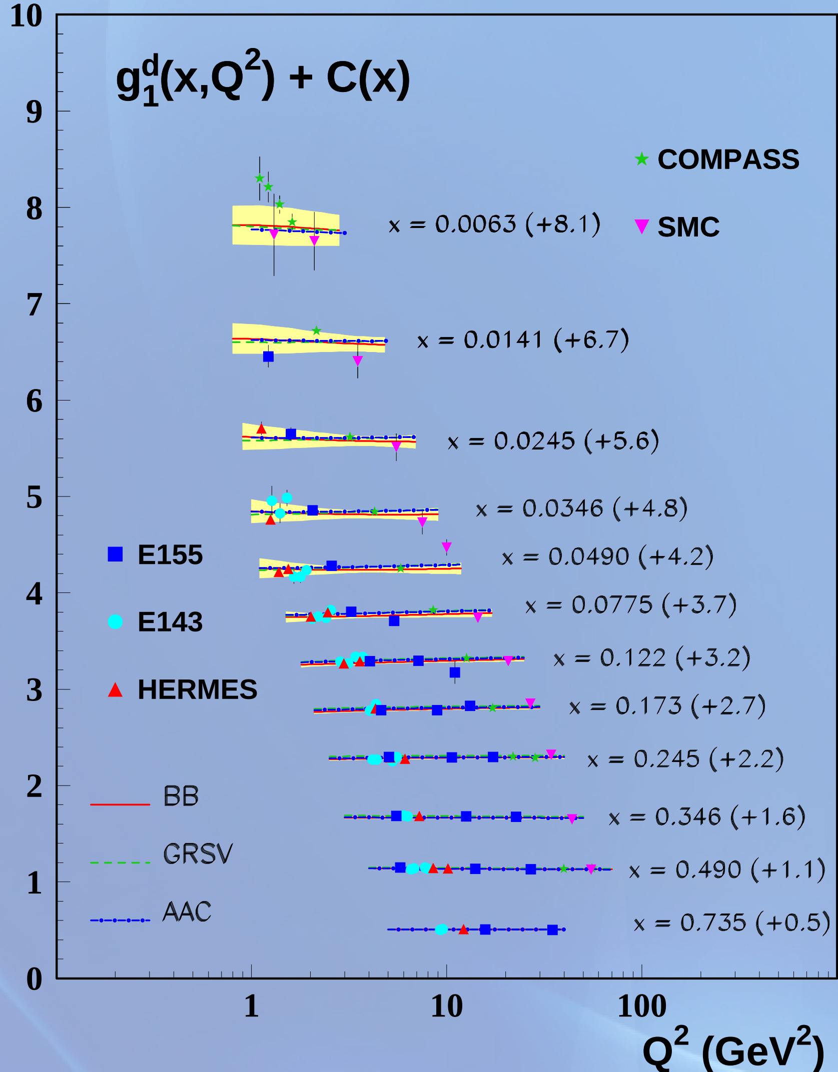


- big Q^2-x lever arm
  - ➡ very accurate G(x)

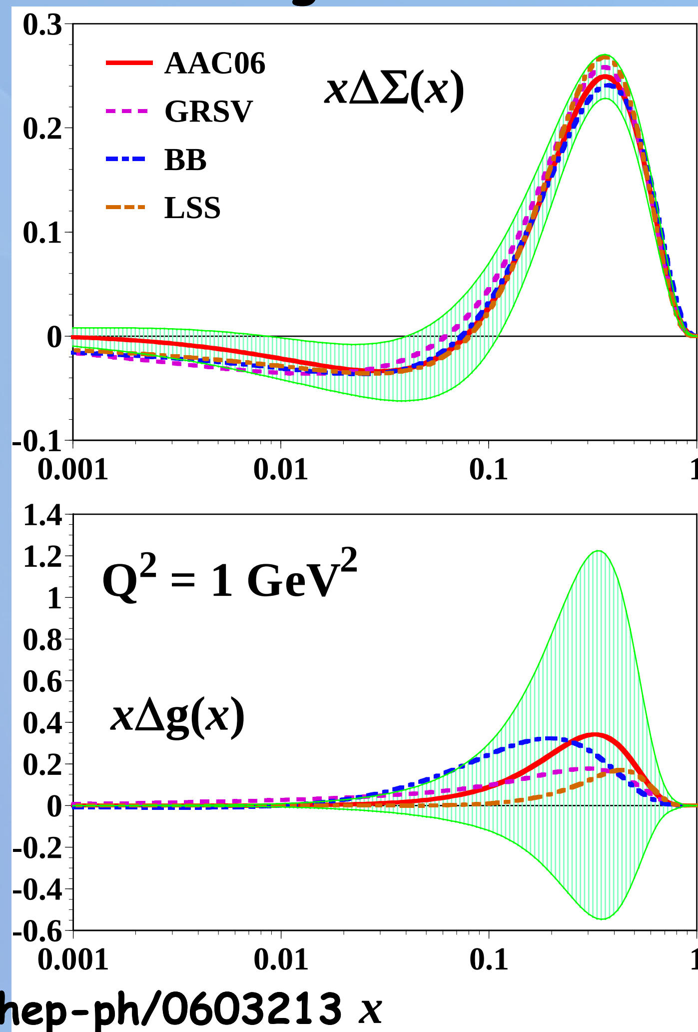


How to measure ΔG

- Indirect from scaling violation

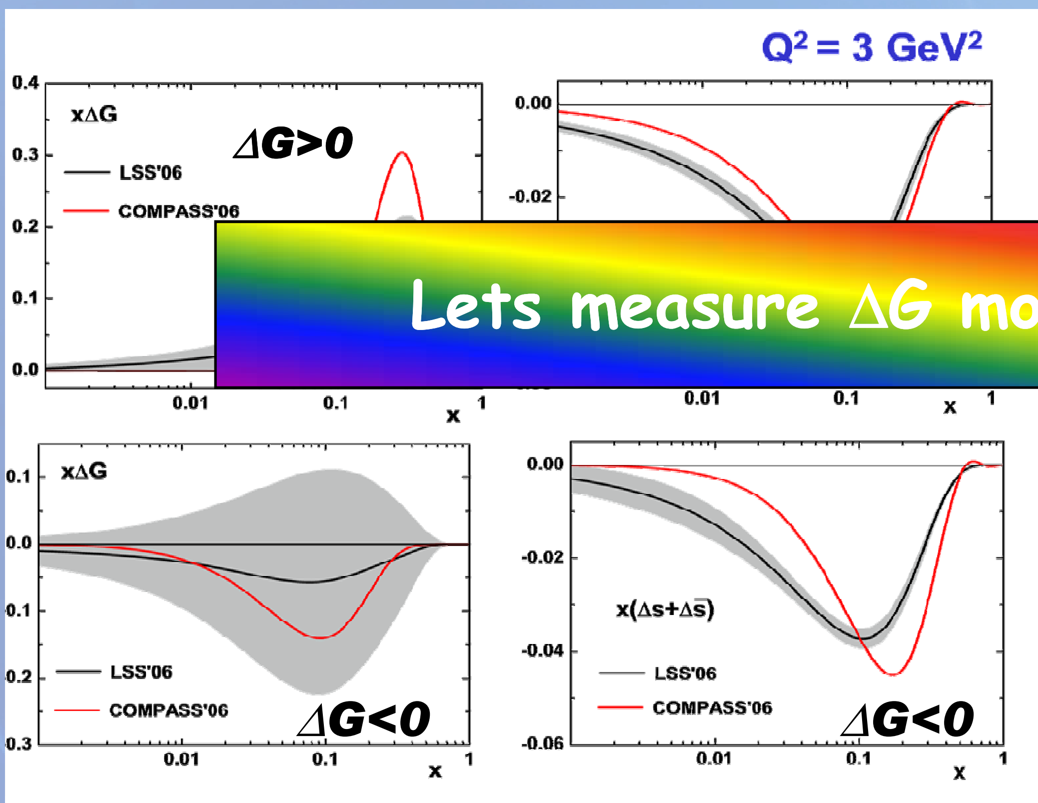


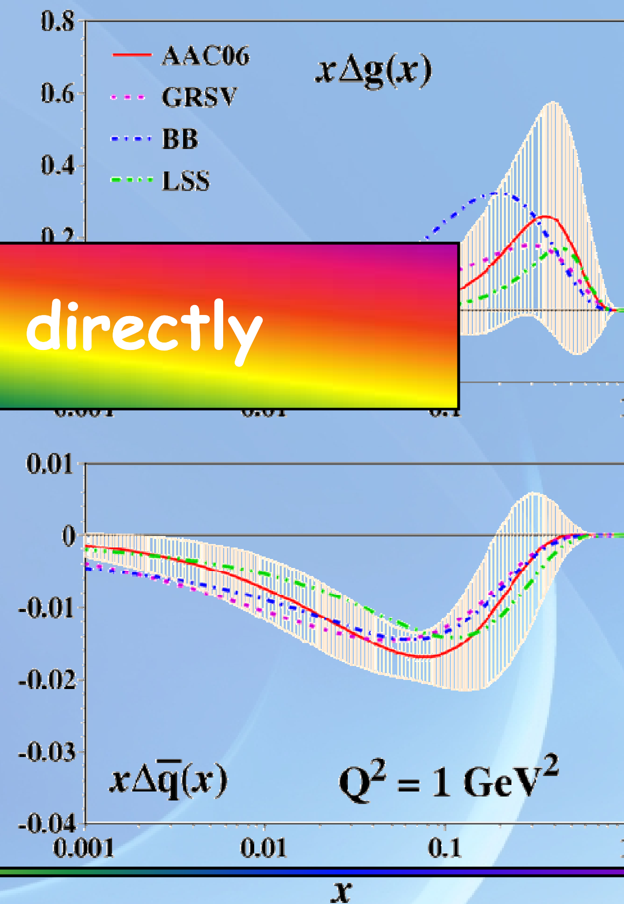
- fixed target experiments
  - small Q^2-x lever arm
  - even sign of ΔG unknown



Several more fits

- using mainly only inclusive data or a combination of inclusive and some semi-inclusive data
- Results for ΔG still completely all over the place
- Need a consistent approach for fit and uncertainty determination with all world data taken into account





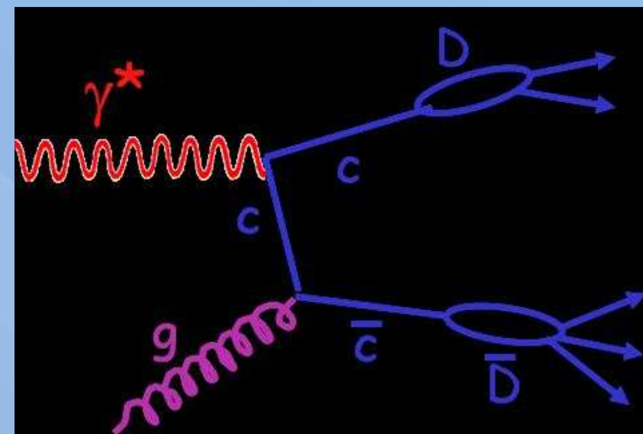
Lets measure ΔG more directly

Idea: Direct measurement of ΔG

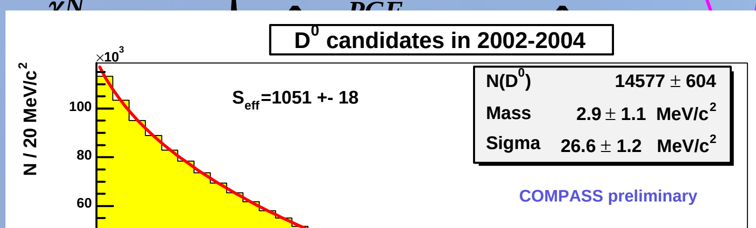
⟹ Isolate the photon gluon fusion process (PGF)

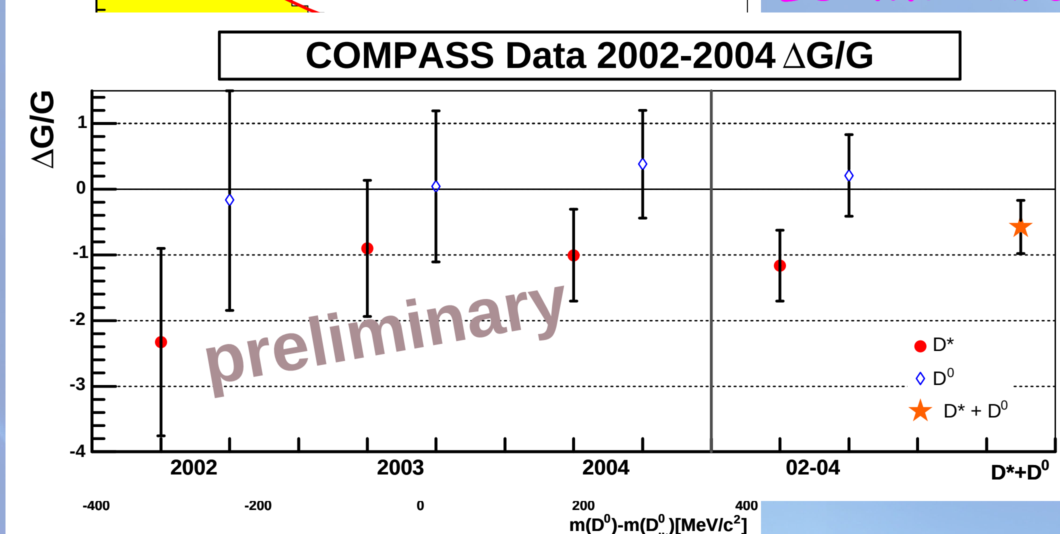
- Open Charm production
  - Reaction: $\gamma^* p \to \bar{D}^0 + D^0 + X$
  - $c\bar{c} \Rightarrow$ reconstruct D^*, D^0

$$A^{PGF}_{\gamma N} = \frac{\int d\hat{s}\,\Delta\sigma^{PGF}\,\Delta G(x_g,\hat{s})}{\int \ldots} \approx \left\langle a_{LL}^{PGF} \right\rangle \frac{\Delta G}{G}$$



LO-MC: Aroma

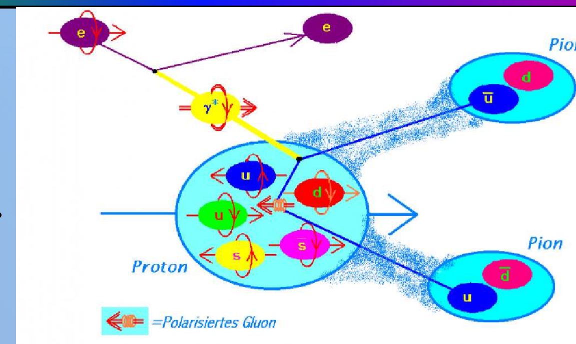




$$\left\langle \frac{\Delta G}{G} \right\rangle = -0.57 \pm 0.41(\text{stat.}) \pm 0.17$$

$x_G \approx 0.15$ $\quad \mu^2 = 13 GeV^2$

Idea: Direct measurement of ΔG



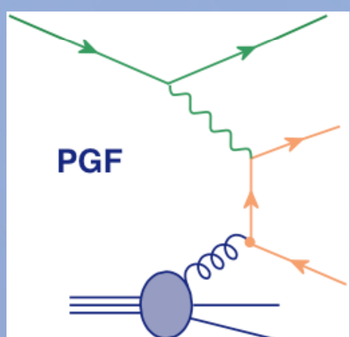
⟹ Isolate the photon gluon fusion process

- detection of hadronic final states with high p_T
  - high p_T pairs of hadrons
  - single high p_T hadrons
- Several possible contributions to the measured asymmetry
- MC needed to determine R and a_{LL}

$h^\pm h^\pm$

$\langle Q^2 \rangle > 1$ less sub-processes contributing ☺

$\langle Q^2 \rangle < 0.1$ more sub-processes contributing ☹



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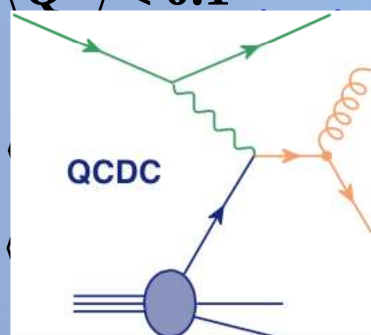

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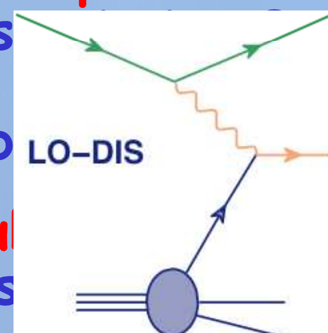
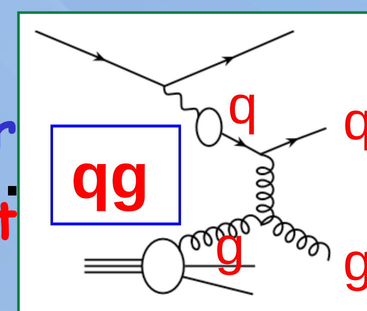


+ ..



Important at Q2<0.1

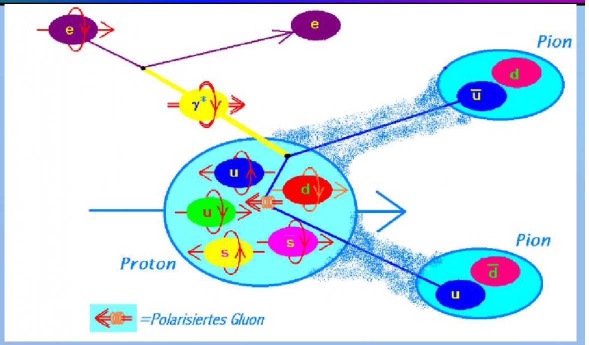
$$A_\parallel^{meas}(p_t) = \sum_i f_i A_\parallel^i = f_{Bg} A_\parallel^{Bg} + f_{Sig} A_\parallel^{Sig}; \qquad f_i = \frac{\sigma_i}{\sigma_{tot}}$$

$$\left\langle \frac{\Delta G}{G} \right\rangle = \frac{1}{f_{Sig} \langle \hat{a} \rangle} [A_\parallel^{meas} - f_{Bg} A_\parallel^{Bg}]$$

Idea: Direct measurement of ΔG

⟹ Isolate the photon gluon fusion process

- detection of hadronic final states with high p_T
  - high p_T pairs of hadrons
  - single high p_T hadrons



- Several possible contributions to the measured asymmetry
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h±h±

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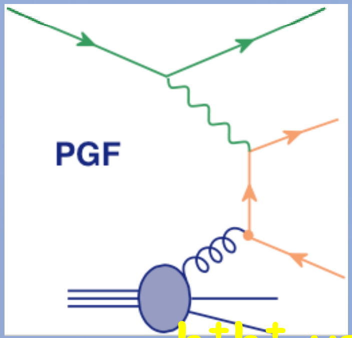

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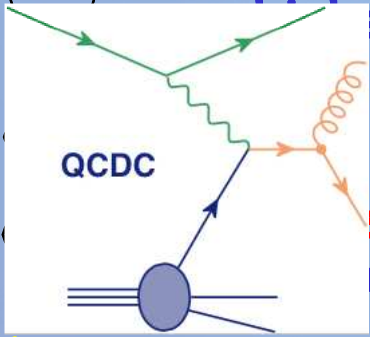

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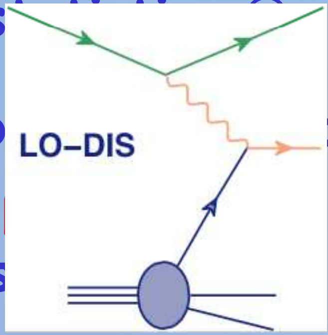

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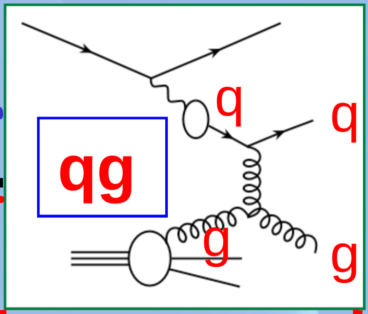


Important at Q2<0.1

h±h± vs. h±:

h±: more inclusive → pQCD NLO calculations (easier) possible

$$A_{\parallel}^{meas}(p_i) = \sum_i f_i A_{\parallel}^{i} = f_{Bg} A_{\parallel}^{Bg} + f_{Sig} A_{\parallel}^{Sig}; \quad f_i = \frac{\sigma_i}{\sigma_{tot}}$$

$$\left\langle \frac{\Delta G}{G} \right\rangle = \frac{1}{f_{Sig} \langle \hat{a} \rangle} [A_{\parallel}^{meas} - f_{Bg} A_{\parallel}^{Bg}]$$

COMPASS Results

- Channel: $h^\pm h^\pm$
- Cuts: $Q^2 > 1$ GeV^2

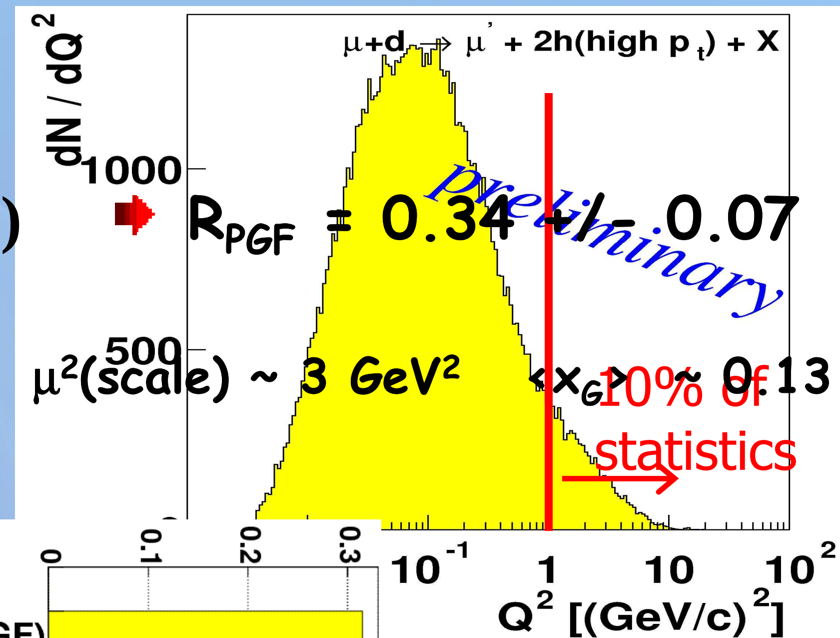
$p_T^1, p_T^2 > 0.7 GeV$, $p_{T1}^2 + p_{T2}^2 > 2.5 GeV^2$

$x_F > 0.1$ $z > 0.1$

$m(h_1, h_2) > 1.5$ GeV

$$\frac{A_\parallel}{D} = -0.015 \pm 0.080(stat) \pm 0.013(syst)$$

$$\frac{\Delta g}{g} = 0.06 \pm 0.31(stat) \pm 0.06(syst)$$

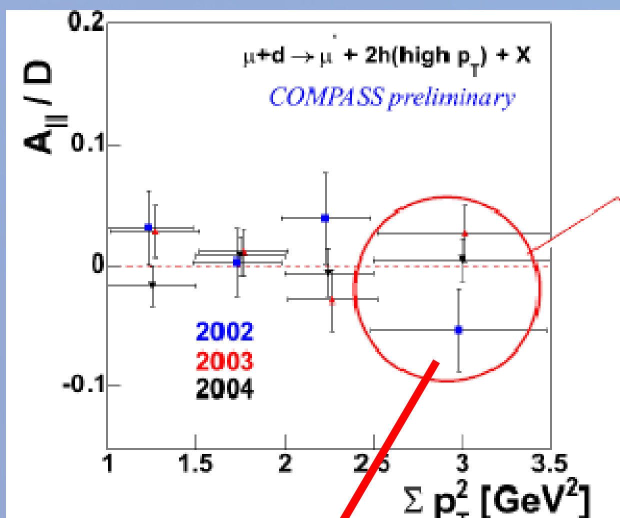


$R_{PGF} = 0.34 +/- 0.07$

μ^2(scale) ~ 3 GeV^2 $\langle x_G \rangle$ ~ 0.13

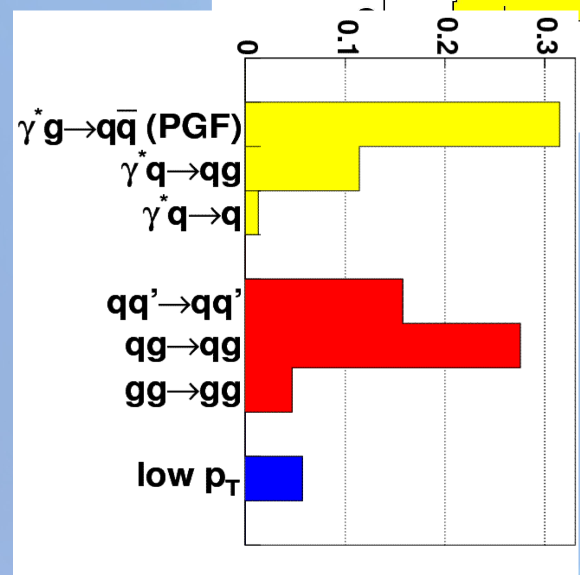
10% of statistics

$Q^2 < 1$ GeV^2



used for $\Delta g/g$ extraction

&

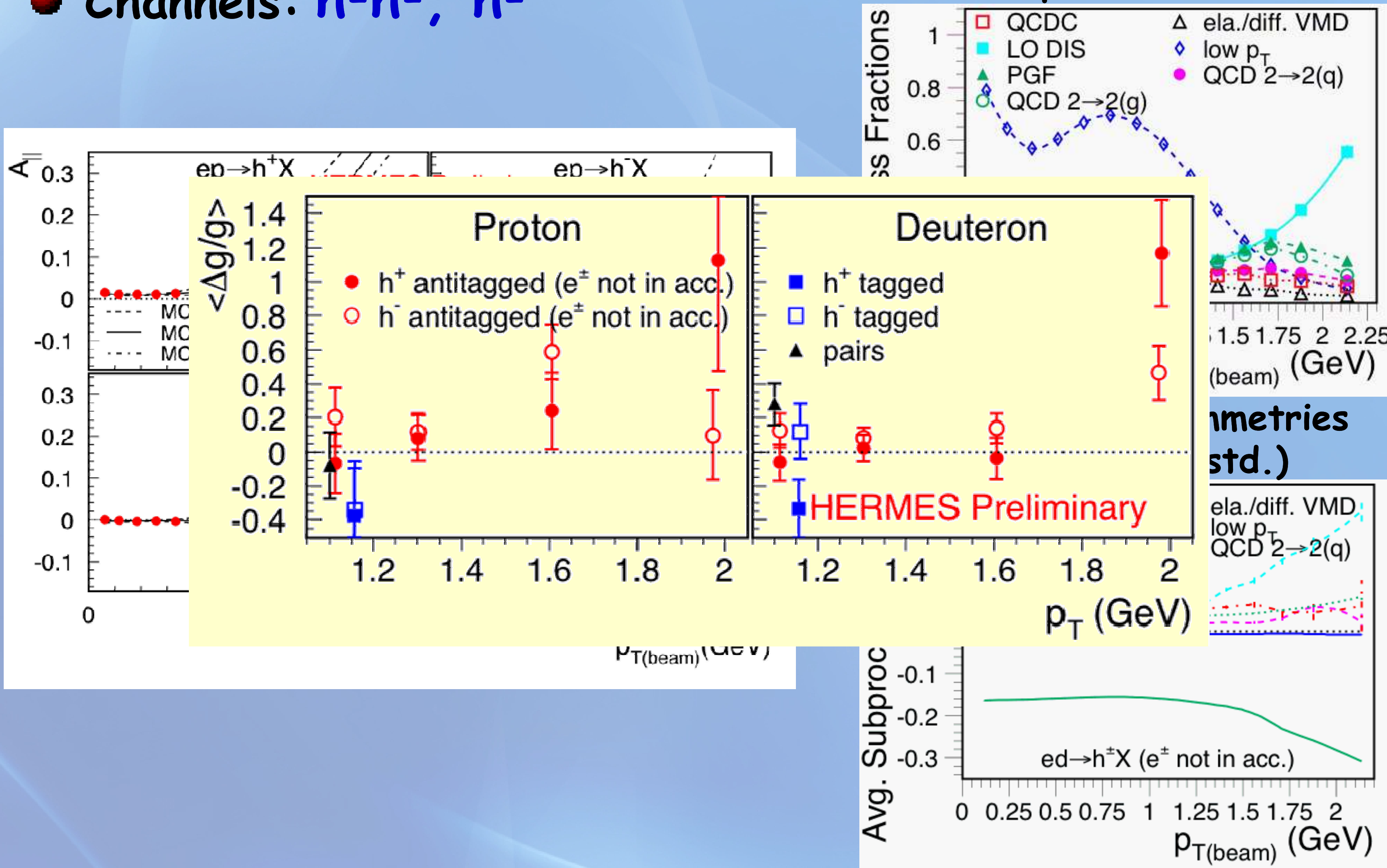


$\Delta g/g = 0.016 \pm 0.058(stat.) \pm 0.055(syst.)$

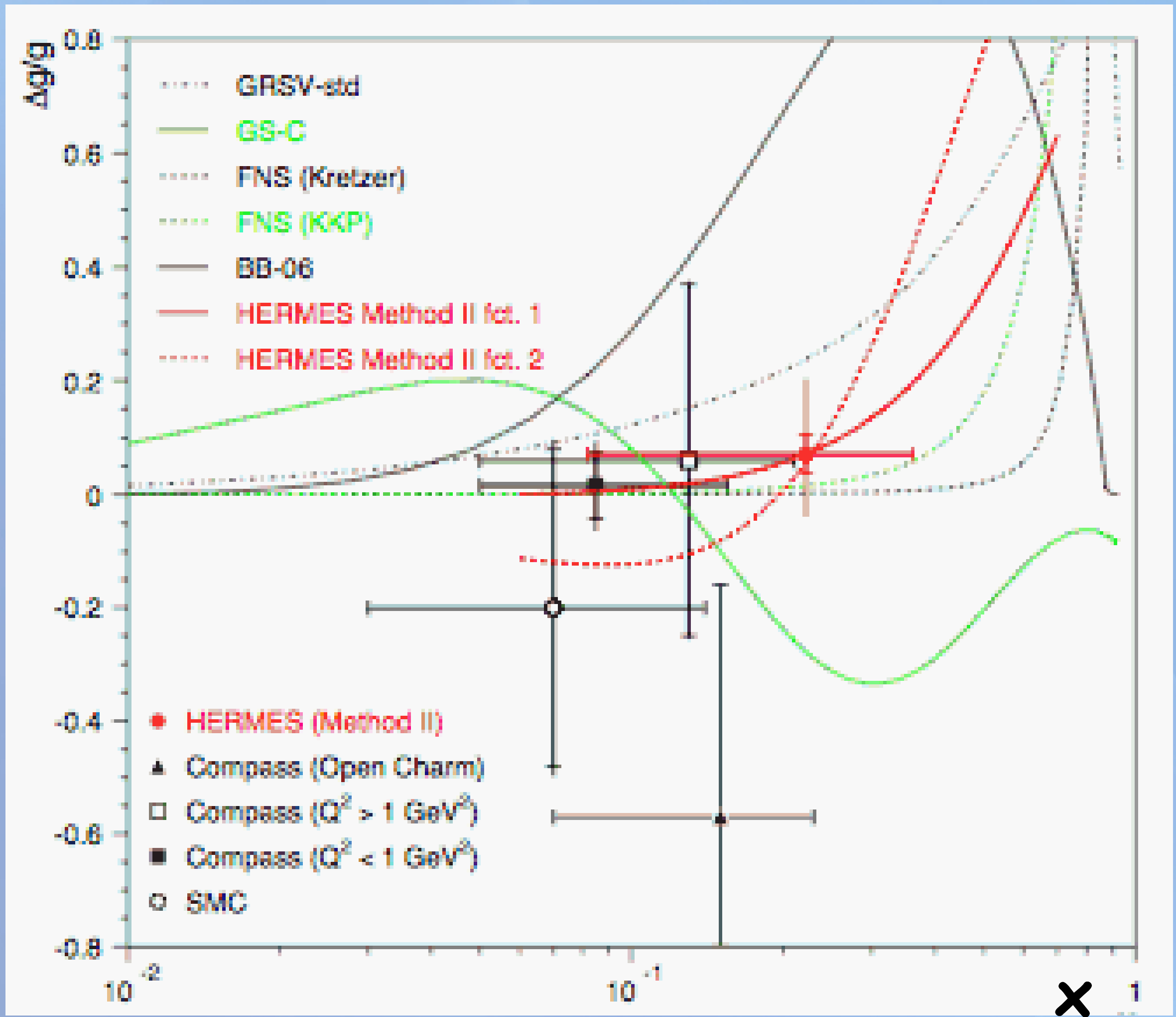
$\langle x_g \rangle = 0.085^{+0.07}_{-0.035}$ $\mu^2 = 3.0 GeV^2$

- **Channels:** $h^{\pm}h^{\pm}$, $h^{\pm}$

Subprocess Fractions

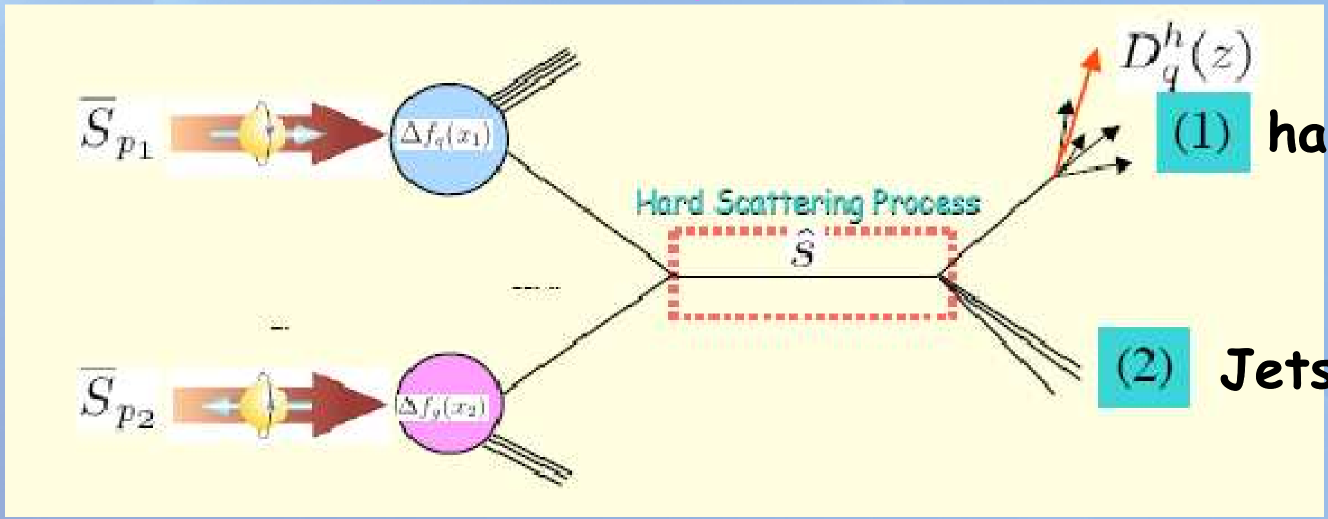


World Data on $\Delta G/G$



Long way to go till $\Delta g(x)$

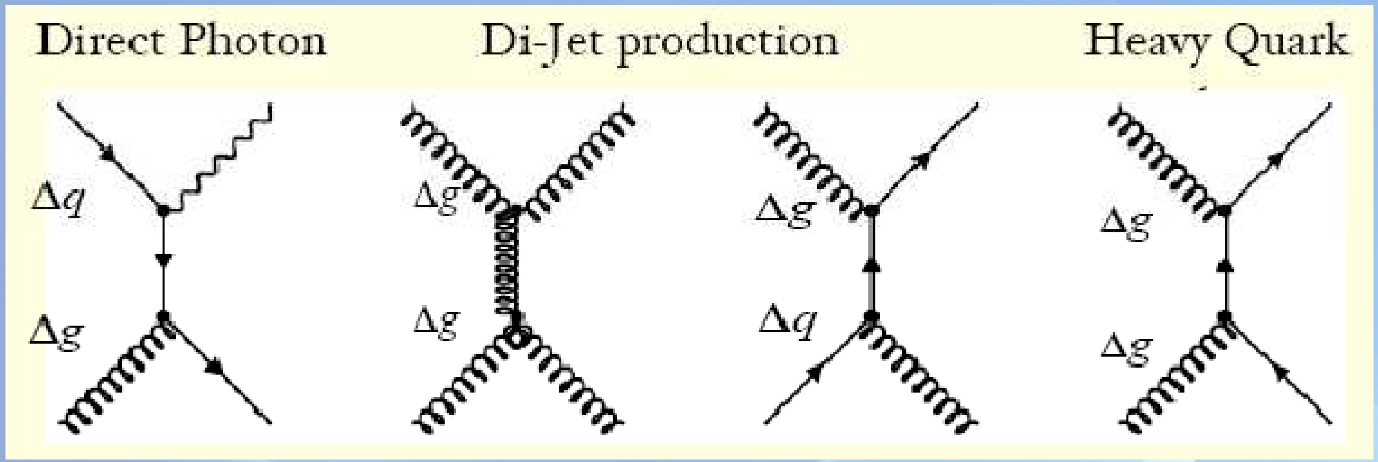
Reaction mechanism:



(1) hadronic final states

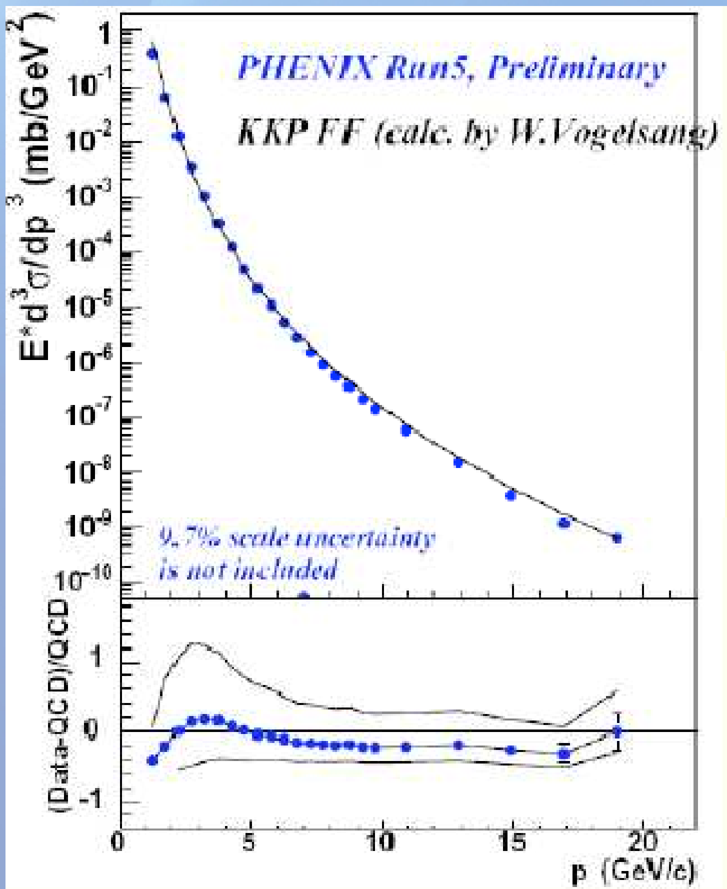
(2) Jets

Hard sub processes:

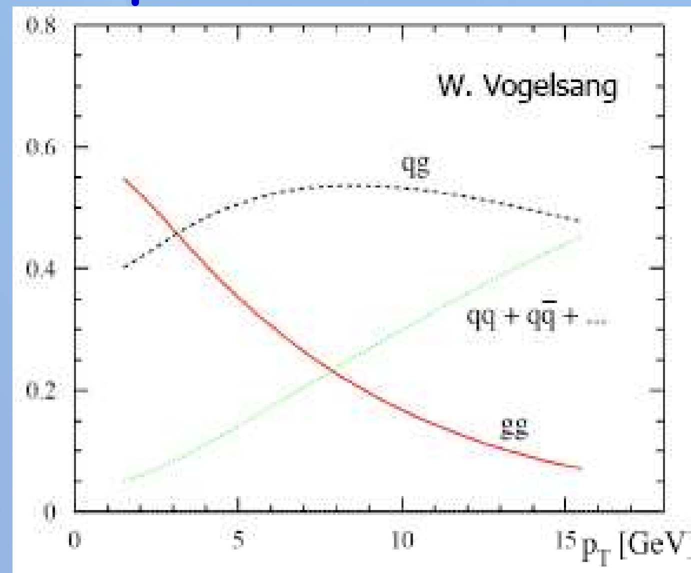


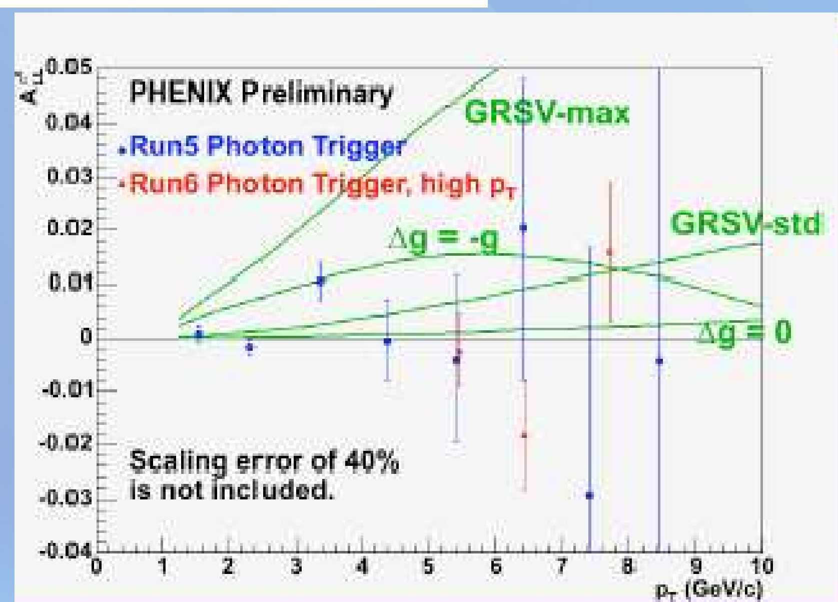
π^0 Production

unpolarized cross section:



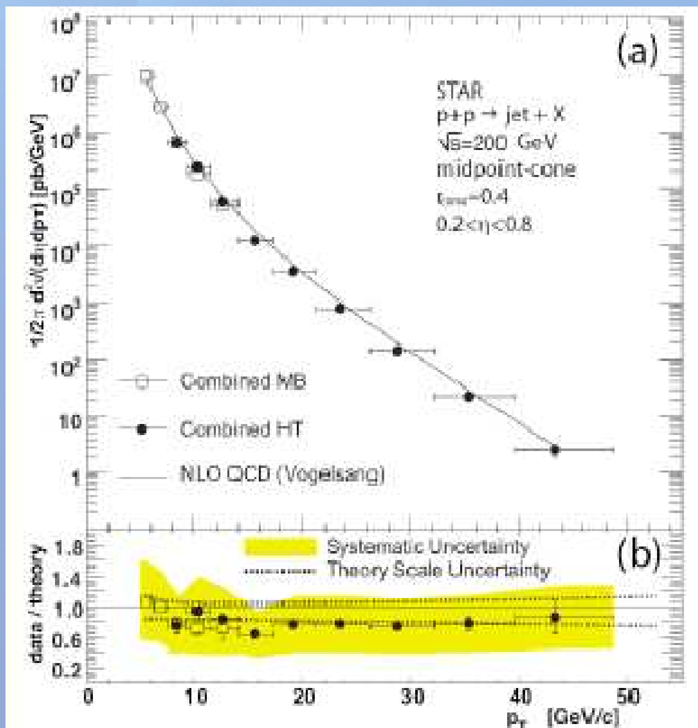
sub processes:



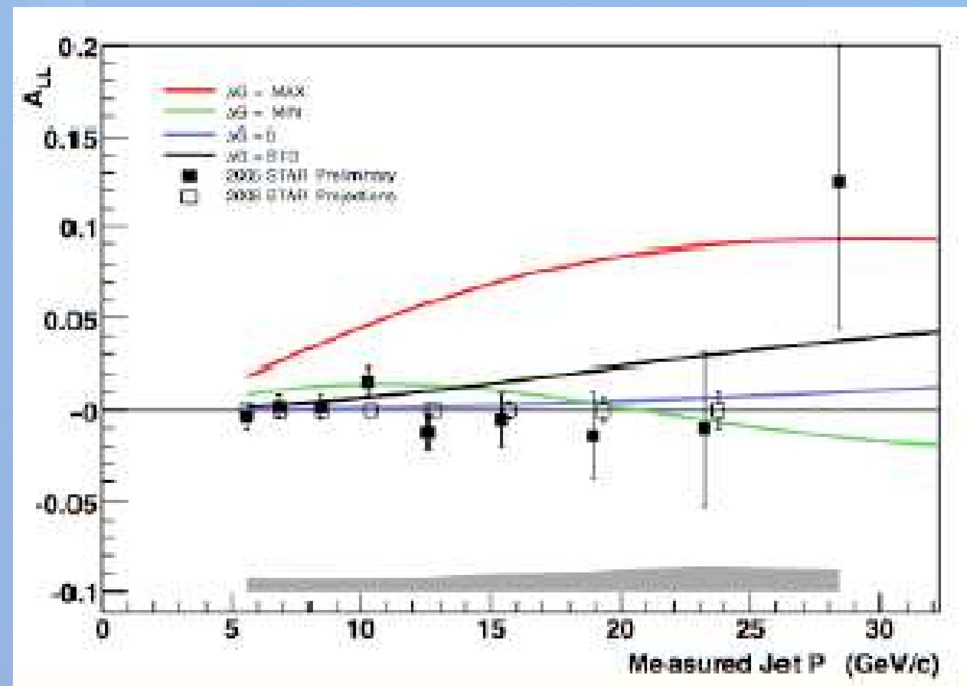


- good agreement with NLO pQCD

unpolarized cross section:

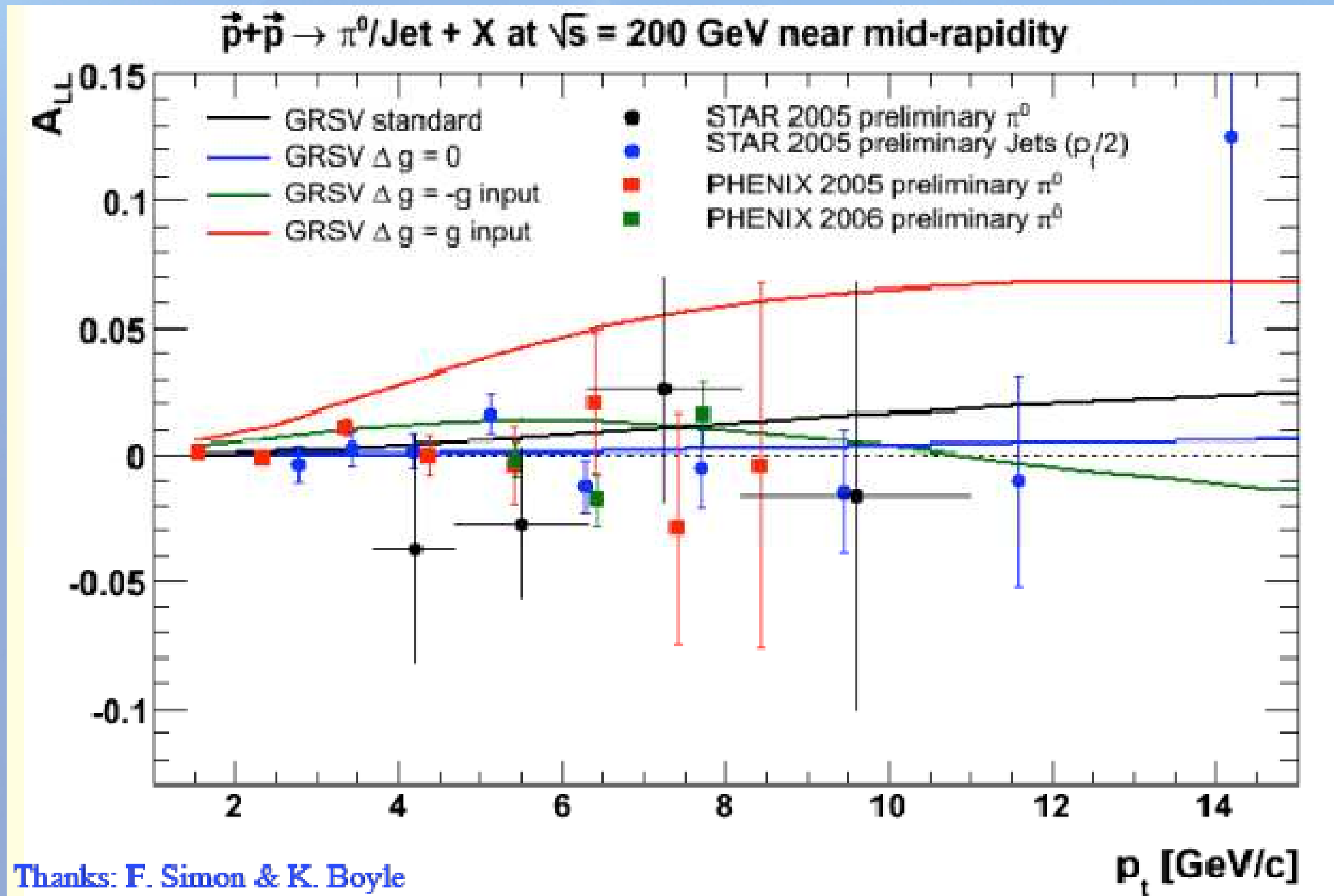


Asymmetry:



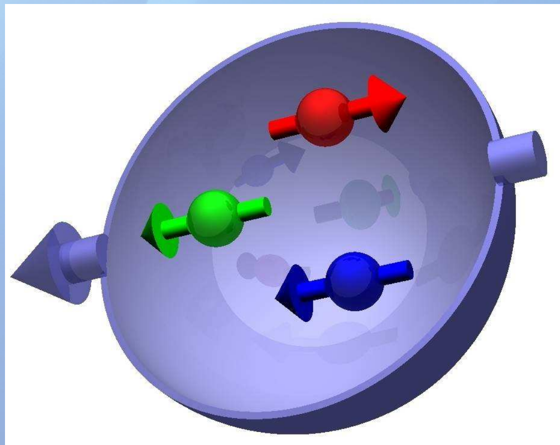
- good agreement with NLO pQCD
- ΔG seems small

RHIC RESULTS



maybe the way is a bit shorter till $\Delta g(x)$

Quark Orbital Angular Momentum



Naïve parton model

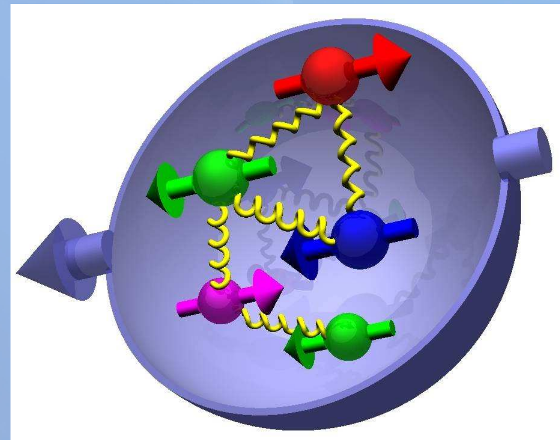
$$\Delta u_v = \tfrac{4}{3} \quad \Delta d_v = -\tfrac{1}{3}$$

BUT

1989 EMC measured

$\Sigma = 0.120 \pm 0.094 \pm 0.138$

⇒ Spin Puzzle

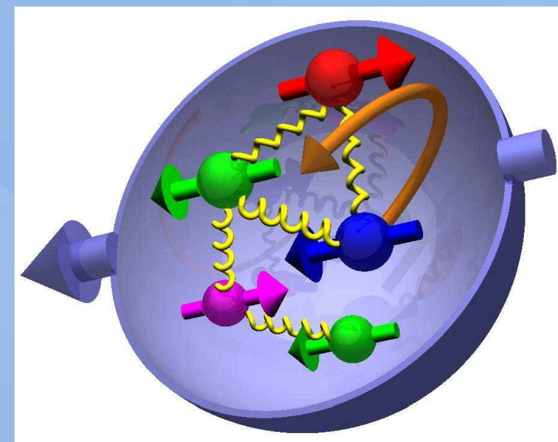


Unpolarised structure fct.

Gluons are important !

⇒ ΔG

⇒ Sea quarks Δq_s

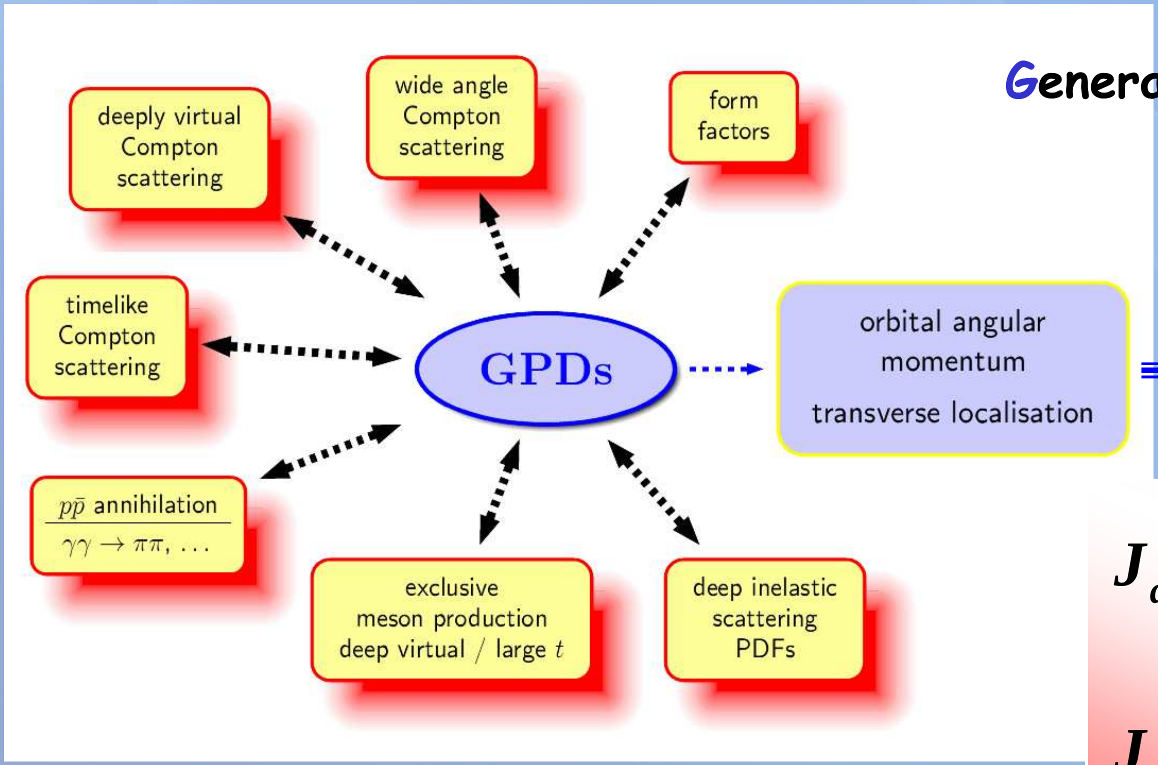


Full description of J_q and J_g
needs
orbital angular momentum

$$\frac{1}{2} = \frac{1}{2}\underbrace{(\Delta u_v + \Delta d_v + \Delta q_s)}_{\Delta\Sigma} + L_q + \Delta G + L_g$$

$$\Delta q_s = (\Delta u_s + \Delta d_s + \Delta\bar{u} + \Delta\bar{d} + \Delta s + \Delta\bar{s})$$

Study of hard **exclusive processes** leads to a new class of PDFs



Generalized **P**arton **D**istributions

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q$$

⟹ possible access to orbital angular momentum

$$J_q = \frac{1}{2}\left(\int_{-1}^{1} x dx \left(H^q + E^q\right)\right)_{t\to 0}$$

$$J_q = \frac{1}{2}\Delta\Sigma + L_q$$

from DIS: HERMES ~0.3

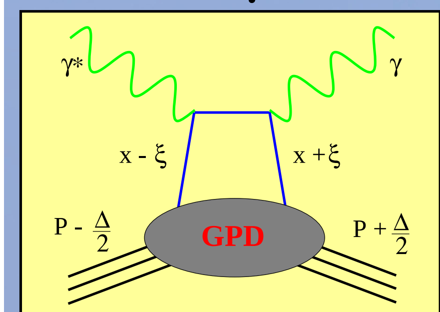
exclusive: all products of the reation are detected

⟹ missing energy (ΔE) and missing Mass (M_x) = 0

What does GPDs charaterize?

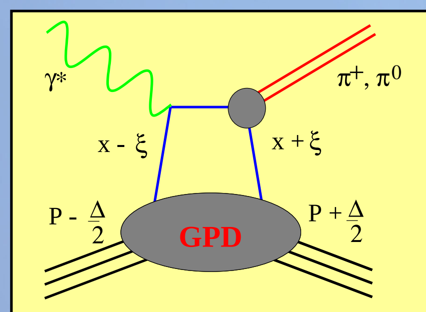
unpolarized	polarized	
$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$	conserve nucleon helicity $H^q(x,0,0)=q, \tilde{H}^q(x,0,0)=\Delta q$
$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$	flip nucleon helicity not accessible in DIS

quantum numbers of final state $\Longrightarrow$ select different GPD



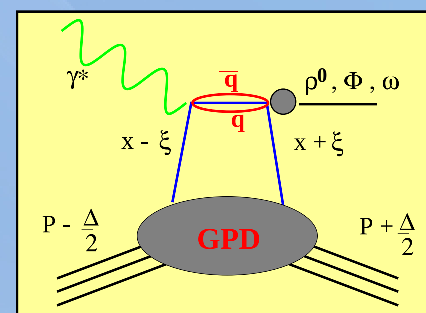
DVCS

$\underbrace{H^q}_{A_C, A_{LU},}$ $\underbrace{E^q}_{A_{UT},}$ $\underbrace{\tilde{H}^q}_{A_{UL}}$ $\tilde{E}^q$



pseudo-scaler mesons

$\underbrace{\tilde{H}^q, \tilde{E}^q}_{A_{UT}, \sigma_{\pi+}}$



vector mesons

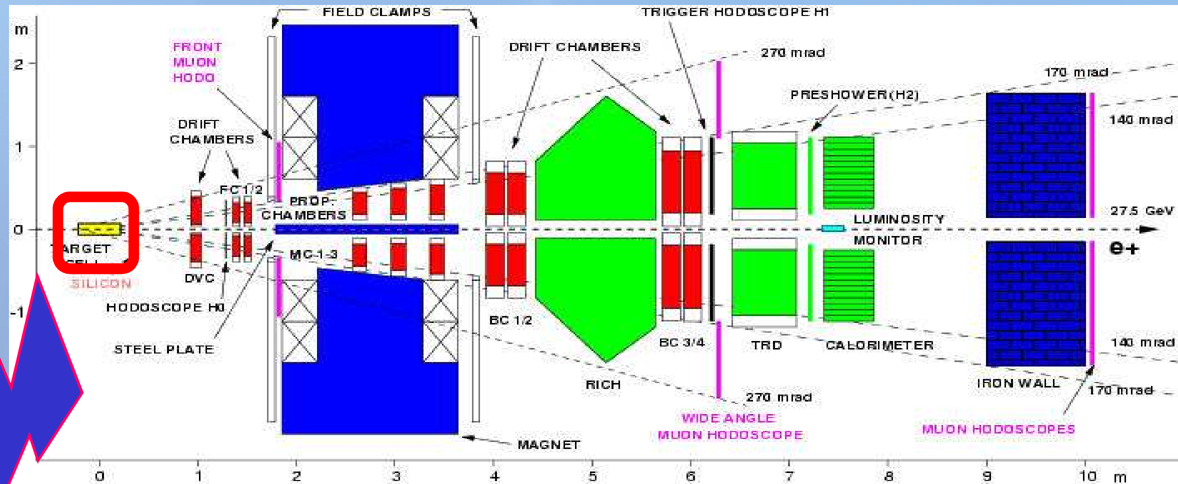
$\underbrace{H^q, E^q}_{A_{UT}, \sigma_{\rho,\Phi,\omega}}$

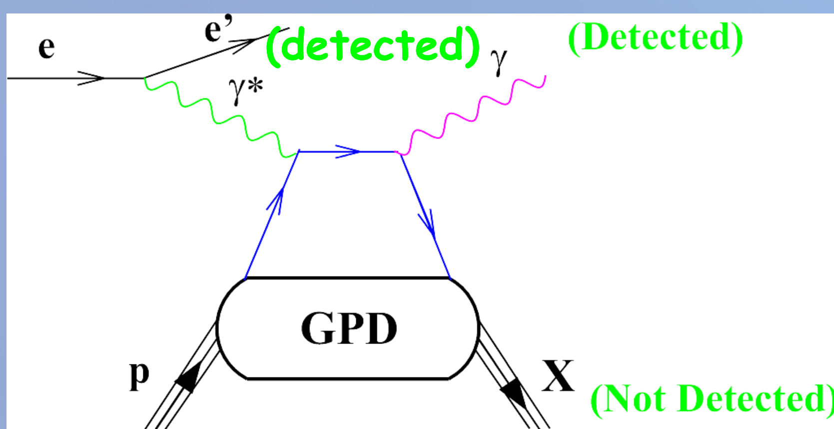
Exclusivity @ HERMES

e^+/e^-

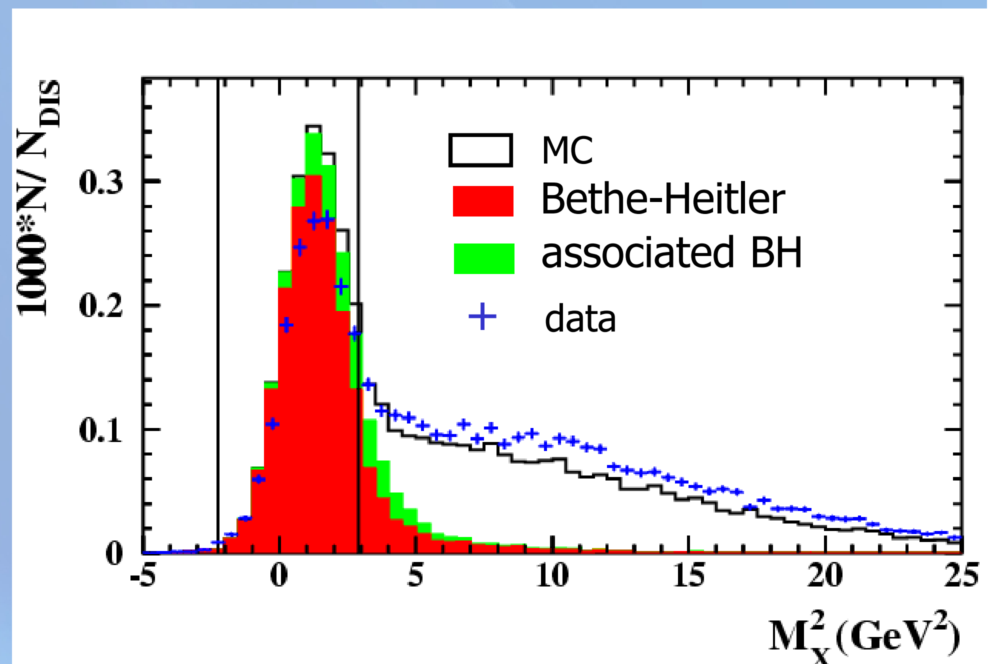
27.5 GeV

P_b=55%



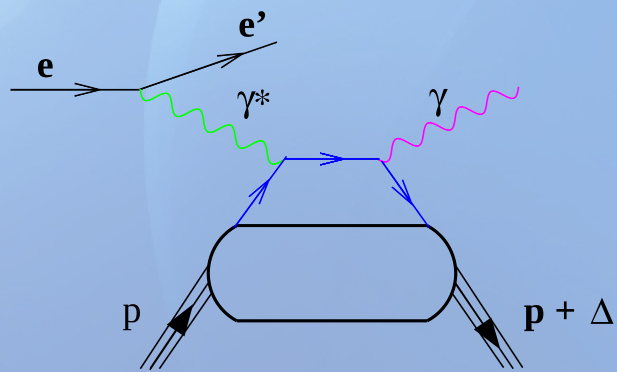


no recoil detection

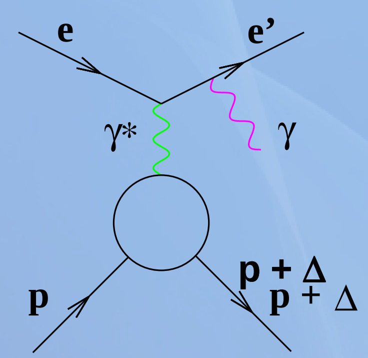


DVCS

two experimentally undistinguishable processes:



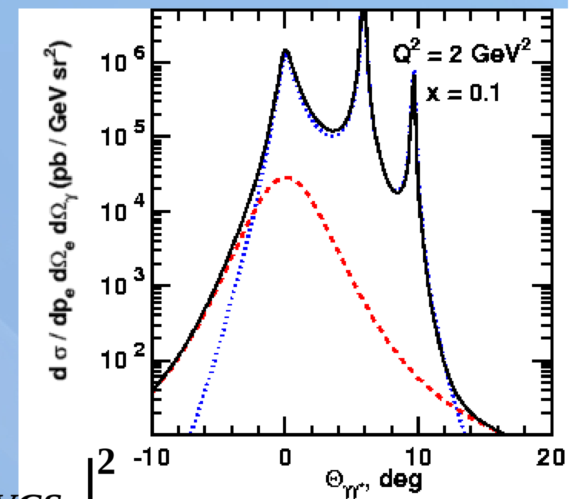
DVCS



Bethe-Heitler (BH)

HERMES / JLAB

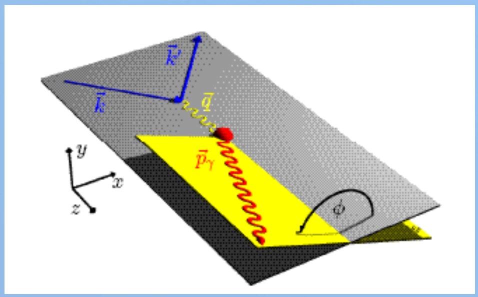
kinematics: BH >> DVCS



$$d\sigma \sim \left(\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH}\right) + |\tau_{BH}|^2 + |\tau_{DVCS}|^2$$

isolate BH-DVCS interference term $\Longrightarrow$ non-zero azimuthal asymmetries

$$d\sigma \sim \left(\tau^{*}_{BH}\tau_{DVCS} + \tau^{*}_{DVCS}\tau_{BH}\right) + |\tau_{BH}|^{2} + |\tau_{DVCS}|^{2}$$



→ different charges: e⁺ e⁻ *(only @HERA!)*:

$$\Delta\sigma_{C} \sim \cos\phi \cdot \mathrm{Re}\{\, H + \cancel{\xi\tilde{H}} + \ldots \}$$ ⟹ H

→ polarization observables:

$$\Delta\sigma_{LU} \sim \sin\phi \cdot \mathrm{Im}\{H + \cancel{\xi\tilde{H}} + \cancel{kE}\}$$ ⟹ H

$\Delta\sigma_{UT}$

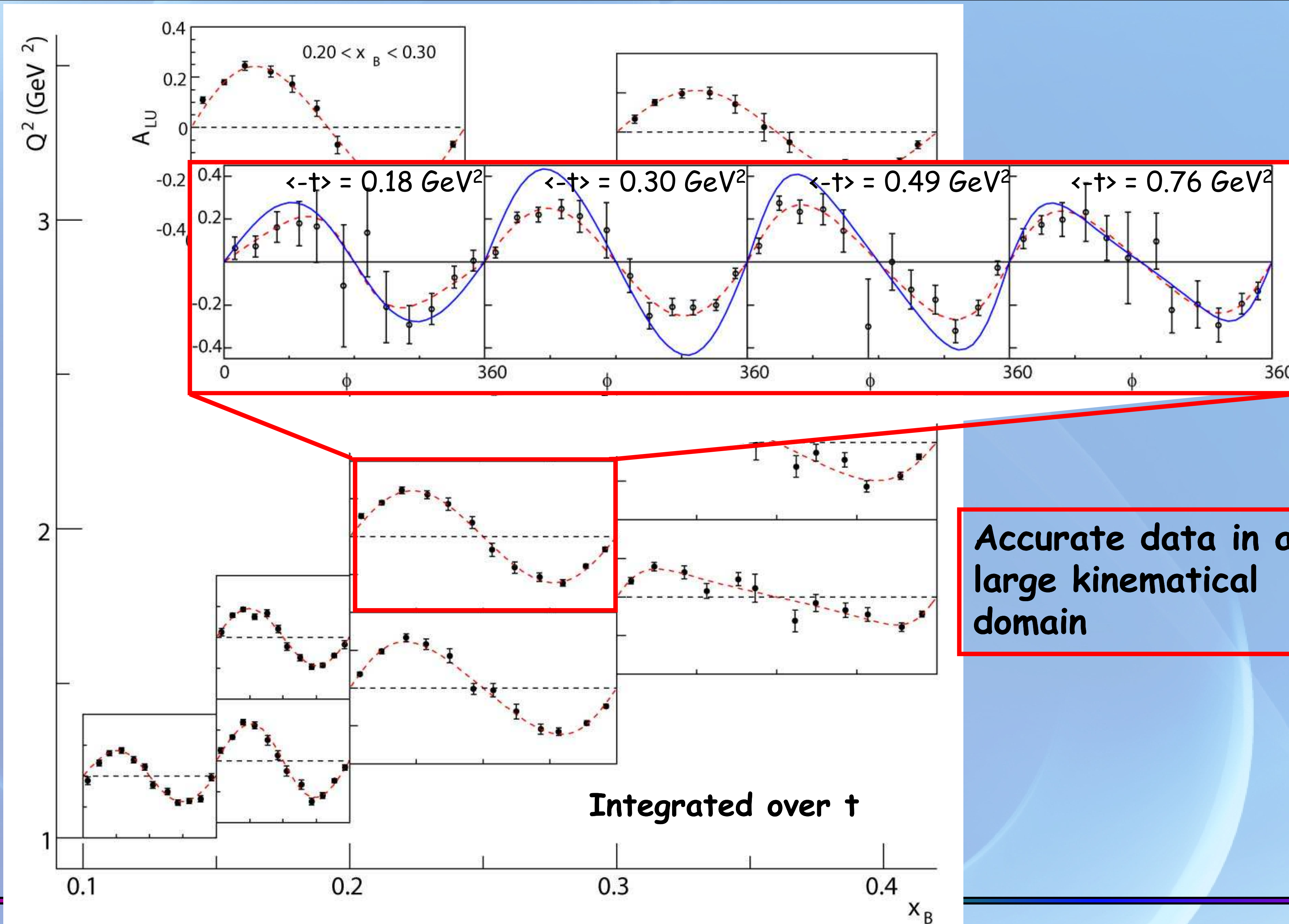
beam ~target

$$\Delta\sigma_{UL} \sim \sin\phi \cdot \mathrm{Im}\{\tilde{H} + \cancel{\xi H} + \ldots\}$$ ⟹ $\tilde{H}$

$$\Delta\sigma_{UT} \sim \sin\phi \cdot \mathrm{Im}\{k(H - E) + \cancel{\ldots}\}$$ ⟹ H, E

$\xi = x_B/(2-x_B), k = t/4M^2$

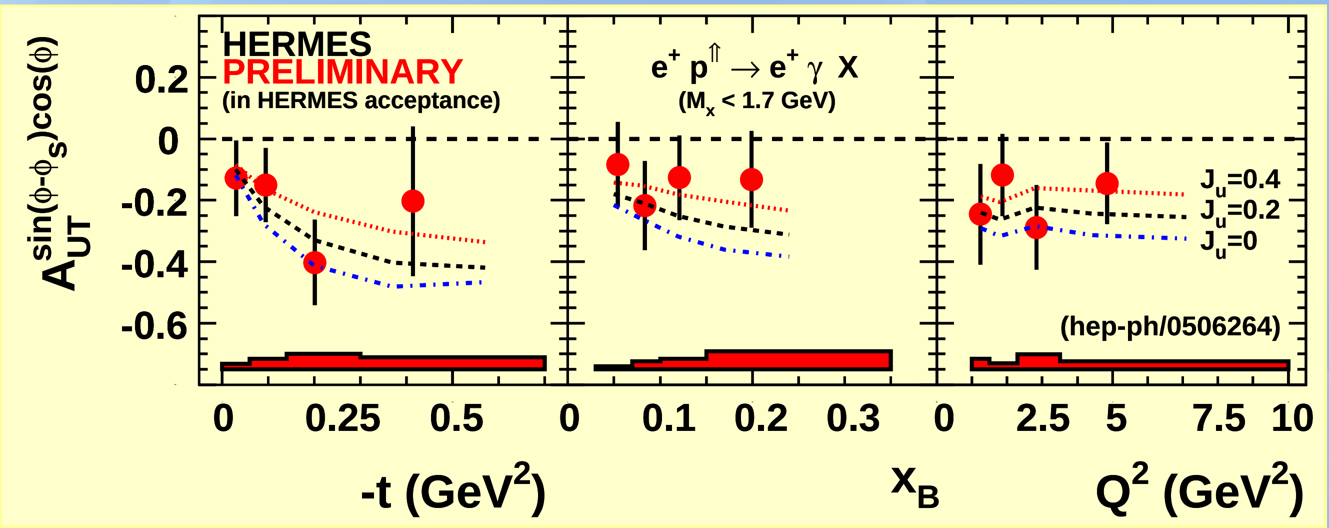
kinematically suppressed



Accurate data in a large kinematical domain

A way to E and J_u-J_d

Hermes DVCS-TTSA:



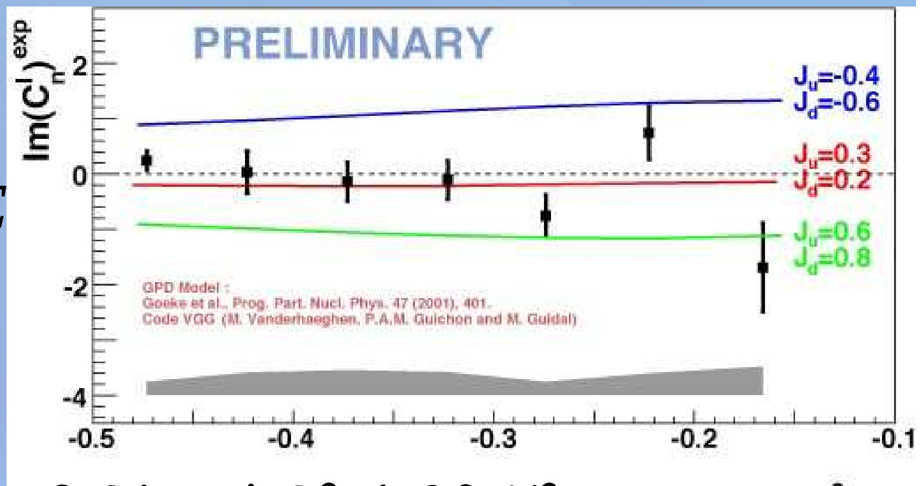
$$A_{UT}^{\sin(\phi-\phi_s)\cos(\phi)} \sim$$
$$\mathrm{Im}(F_2 H - F_1 E)$$

Hall A nDVCS-BSA:

- Neutron obtained combining deuterium and proton

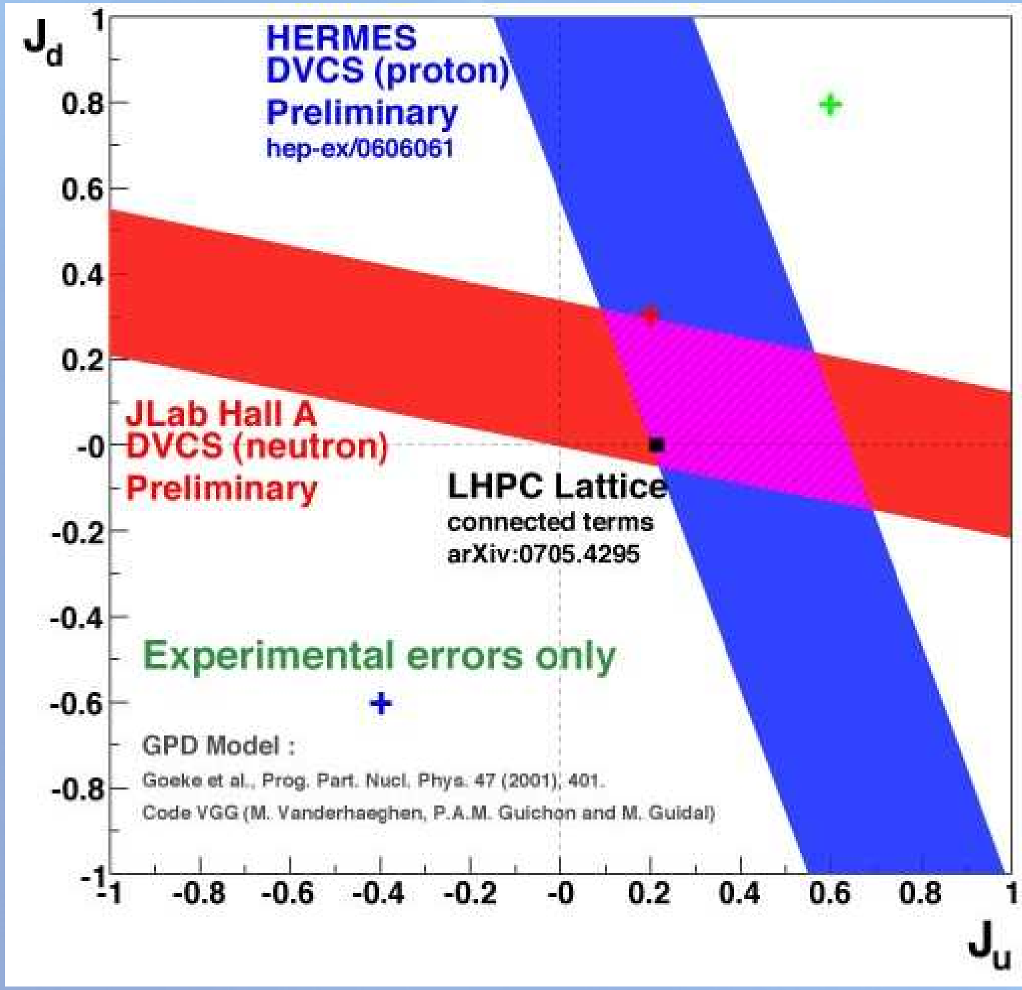
$$A_{LU} \sim F_1 H + x(F_1 + F_2)\tilde{H} - \frac{t}{4M^2} F_2 E$$

- F_1 small u & d cancel in $\tilde{H}$



x=0.36 and Q^2=1.9GeV²

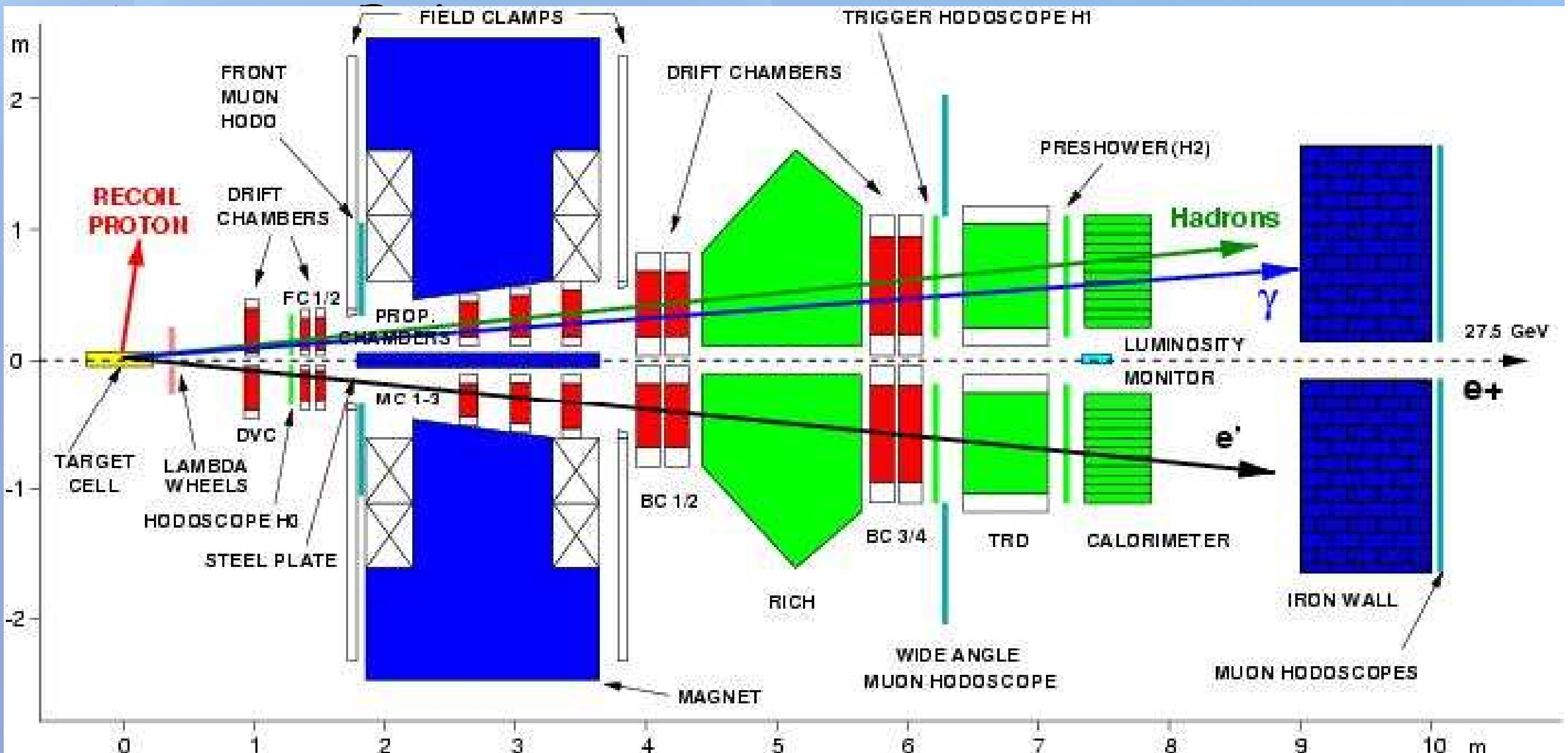
Can we constrain (J_u - J_d)

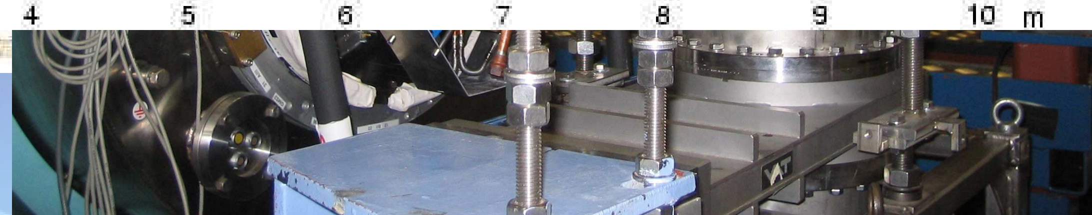


- first model dependent extraction of J_u - J_d possible
  VGG-Code: GPD-model: LO/Regge/D-term=0

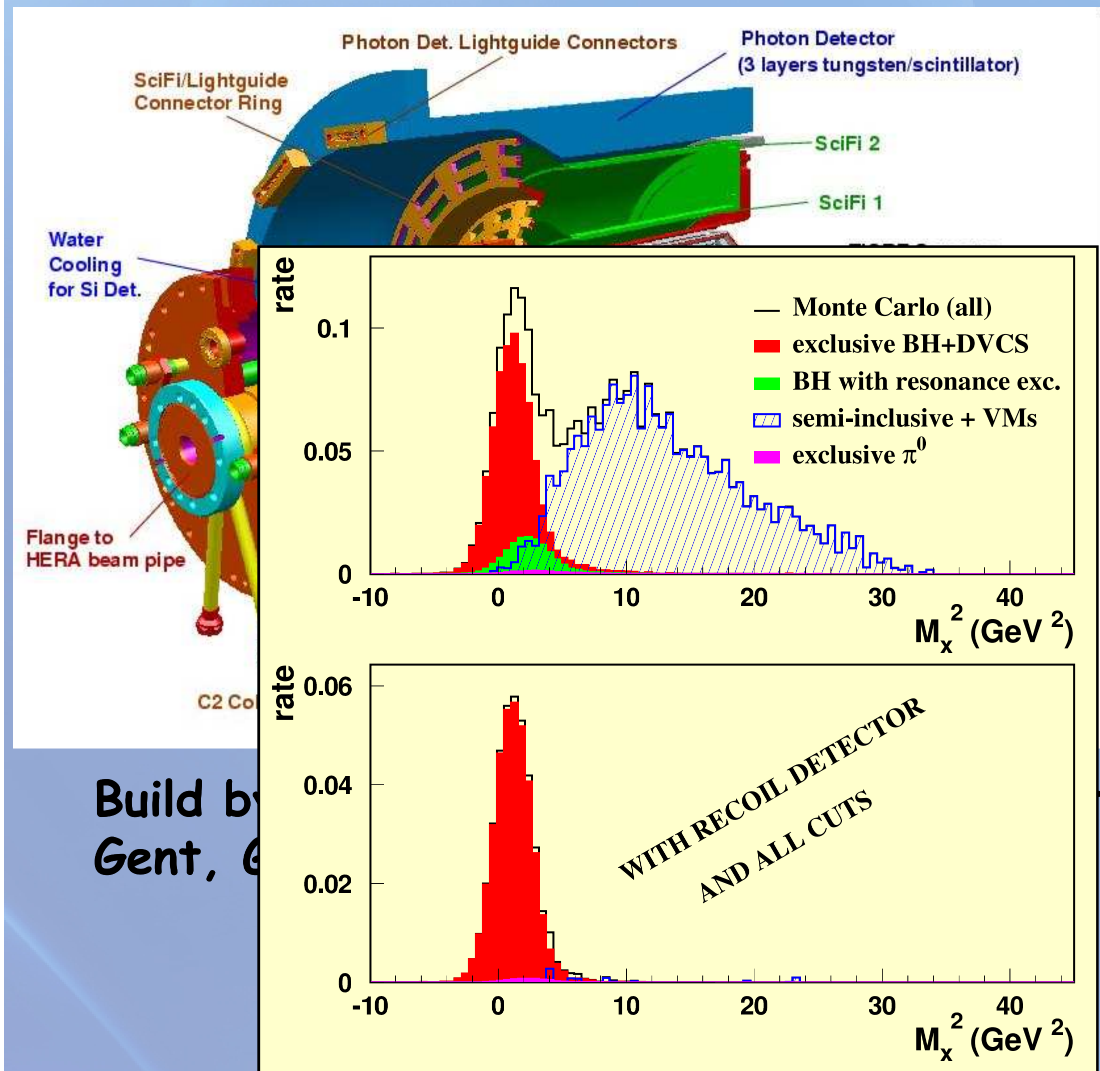
The end of polarized targets at HERMES

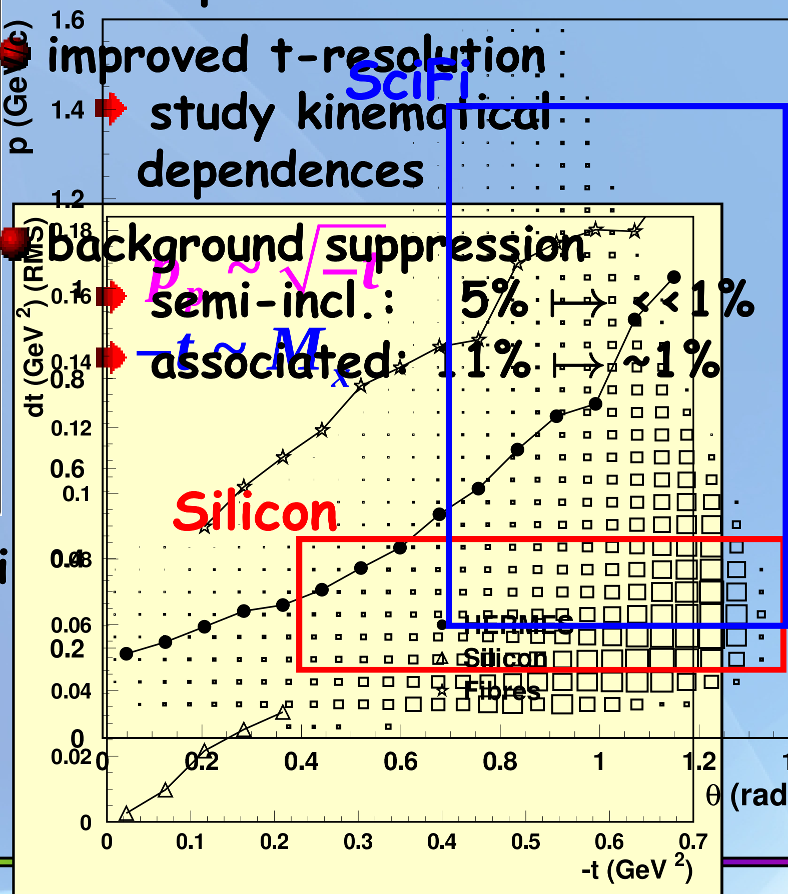
DVCS exclusivity by missing mass M_x





The HERMES Recoil Detector



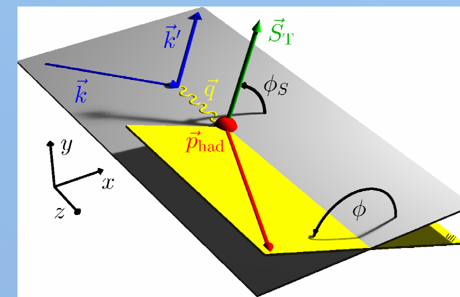


- detection of the recoiling proton
  - p; 135 -1200 MeV/c
  - 76% ϕ acceptance
  - π/p PID via dE/dx
- improved t-resolution
  - study kinematical dependences
- background suppression
  - semi-incl.: 5% $\mapsto$ << 1%
  - associated: 11% $\mapsto$ ~1%

Build by ...
Gent, G...

Access to L_q in semi-inclusive scattering

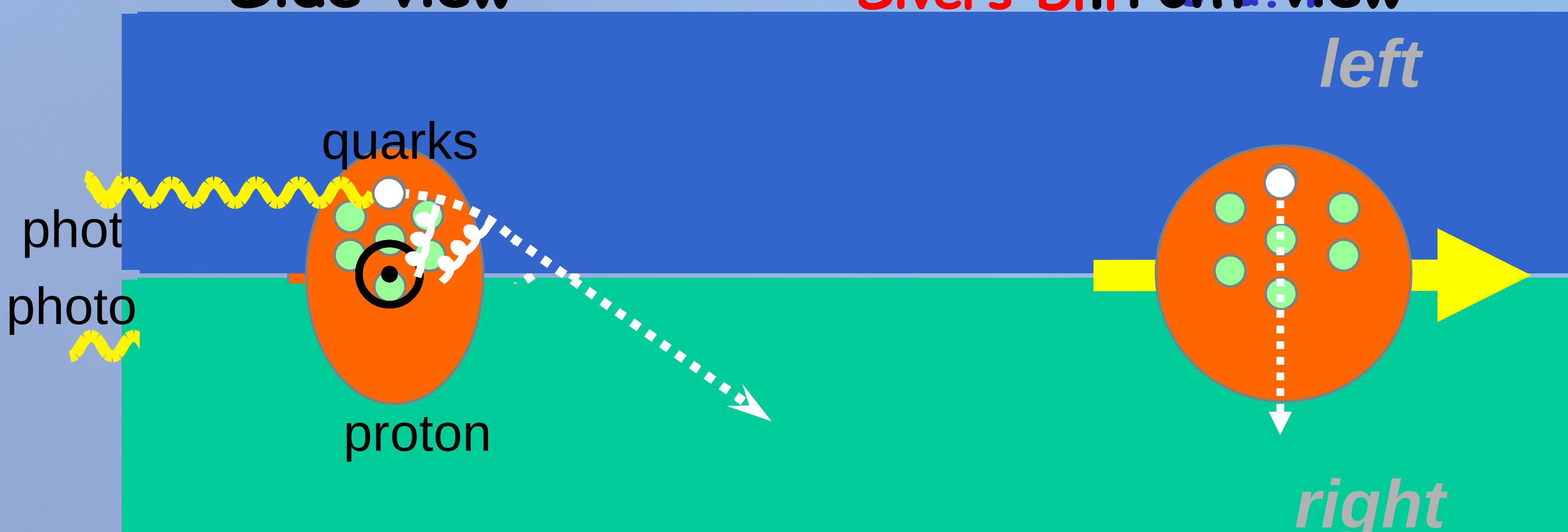
- New structure function accessible with SSA



$$F_{UU,T}^{\sin(\phi_h-\phi_s)}(x,z,P_{h\perp}^2) = \mathcal{C}\left[-\frac{\hat{h}\cdot p_T}{M} f_{1T}^{\perp} D_1\right]$$

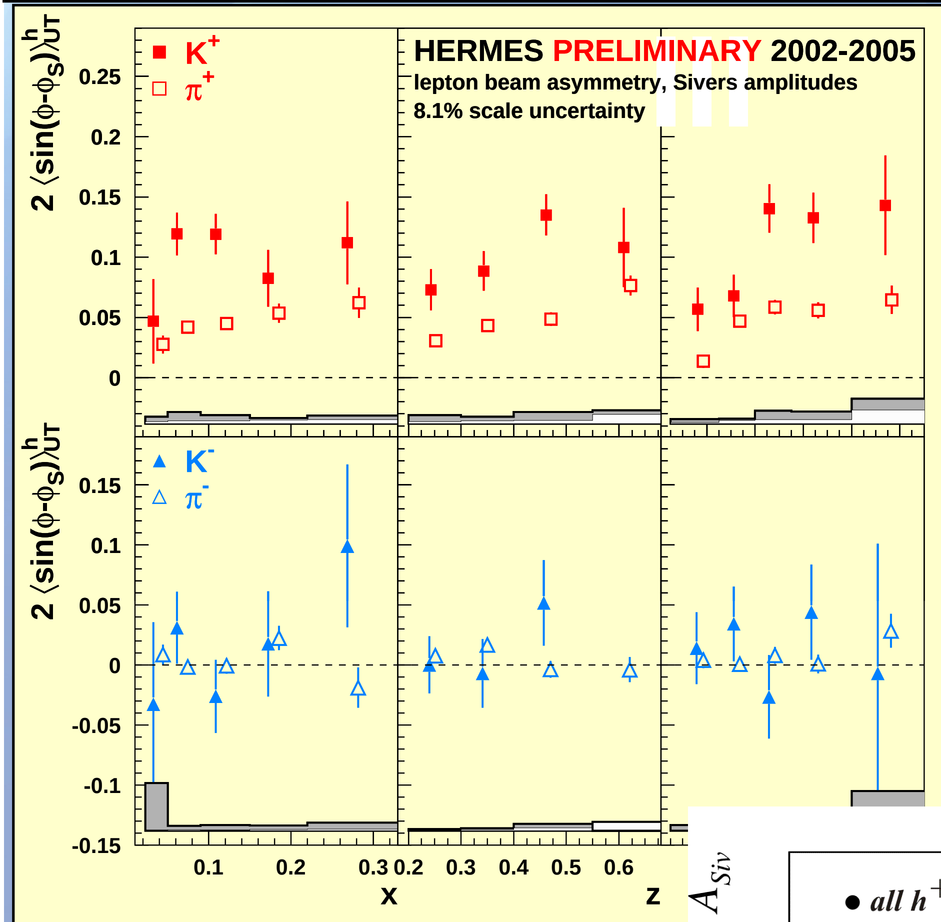
Sivers DF std. FF

Side view Front view



- NOTE: QCD tells us that the FSI has to be attractive, since quarks and antiquarks form a color nonsinglet state
- The presence of spin can distort the distribution of quarks in transverse space (orbital angular momentum of quarks is required)
- A distortion in the distribution of quarks in transverse space can give rise to a nonzero Sivers function

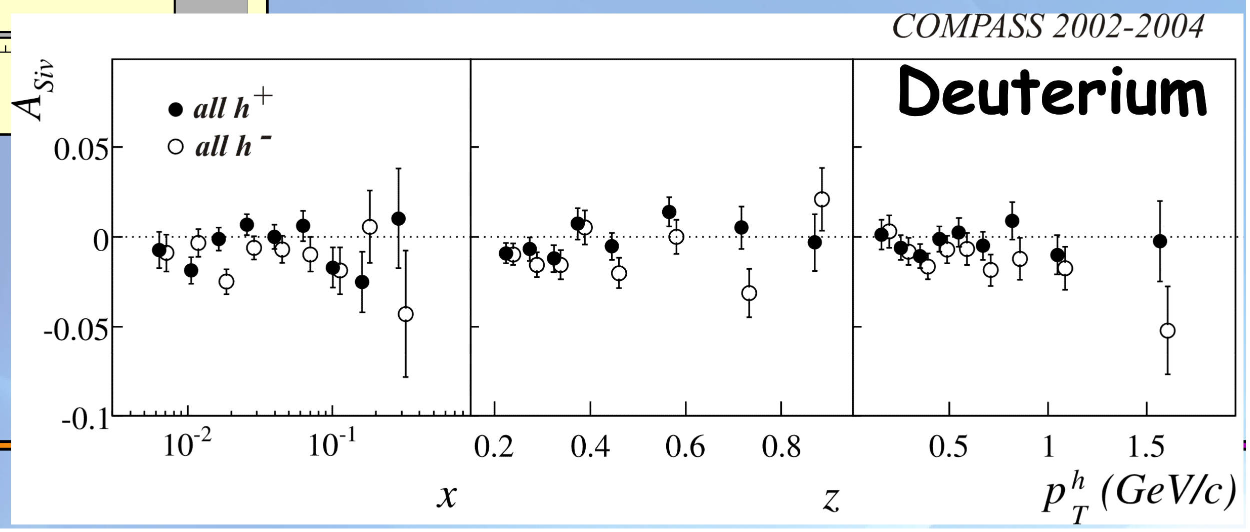
HERMES & COMPASS Measurements



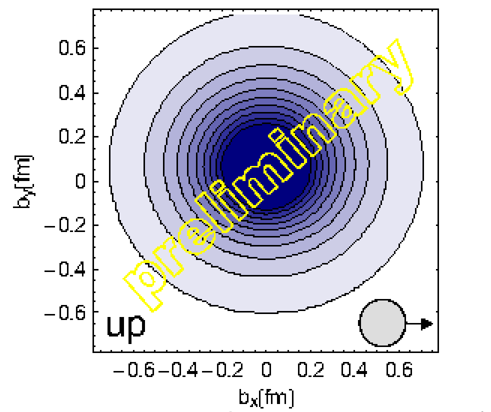
Proton

$$A_{Sivers} \propto f_{1T}^{\perp}(x) D_1(z)$$

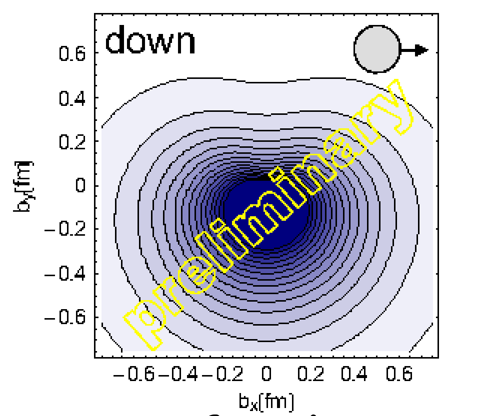
- Proton:
- Sivers moment:
  $\pi^+ > 0$ $\pi^- \sim 0$
- $K^+ > 0$ $K^- \sim 0$
  $K^+ > \pi^+$
  - sea quarks important
- Deuterium ~ 0
  - u and d quark cancel



Lattice QCD: Sivers



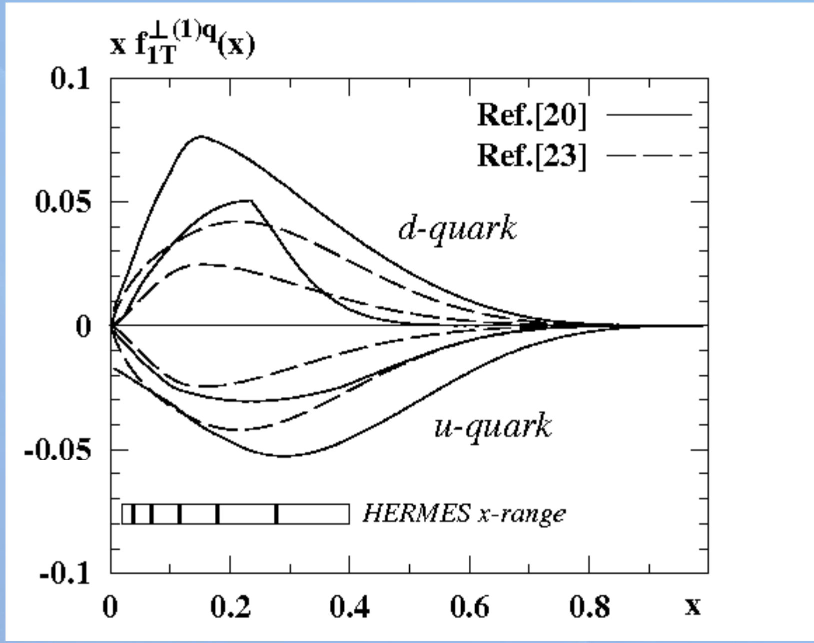
negative for up quarks



positive for down quarks

QCDSF/UKQCD Collab. (hep-ph/05110032)

Pheno. analysis from data:



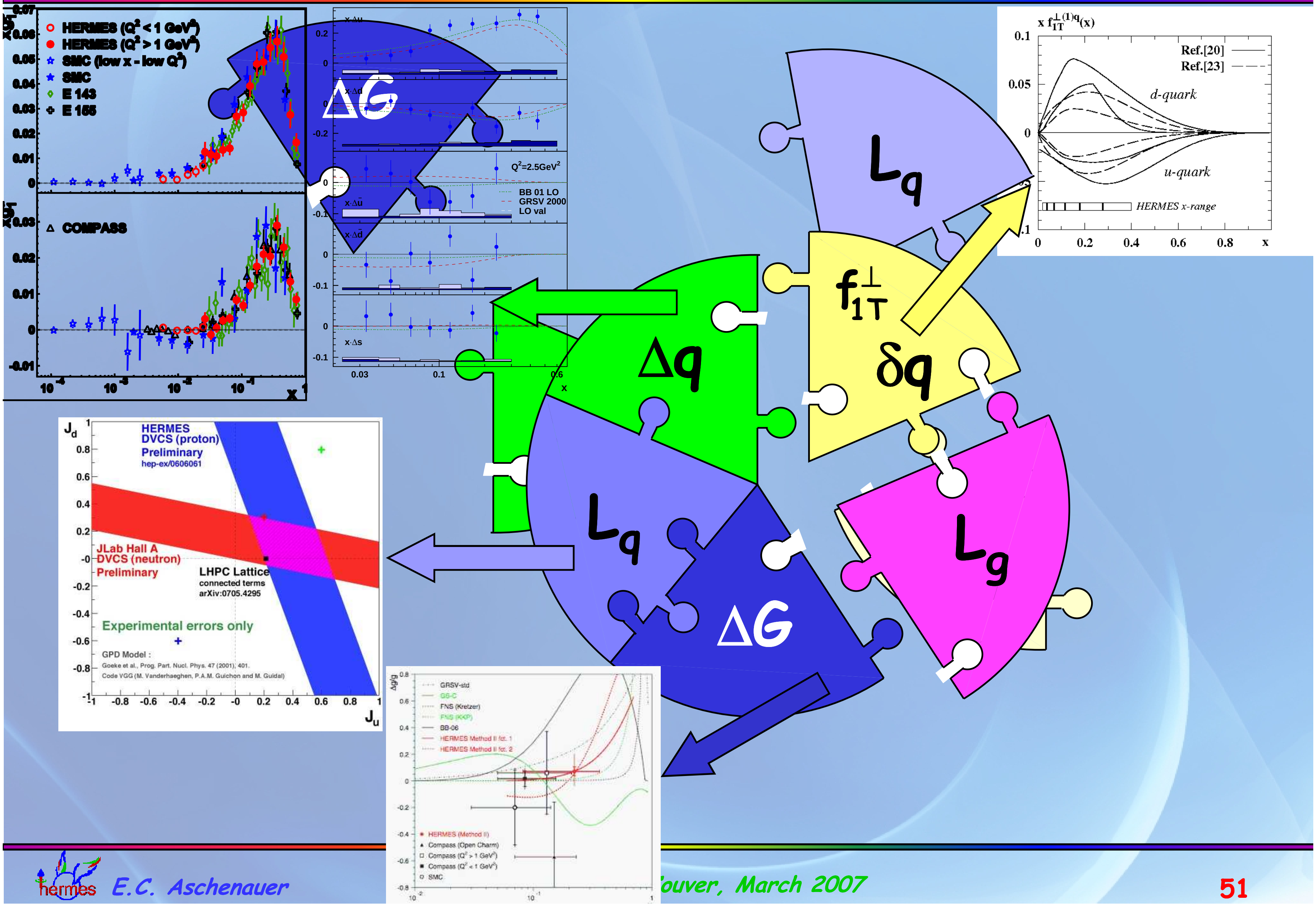
Anselmino et al., hep-ph/0511017

[20] Anselmino et al., PRD72 (05)

[21] Vogelsang, Yuan, PRD72 (05)

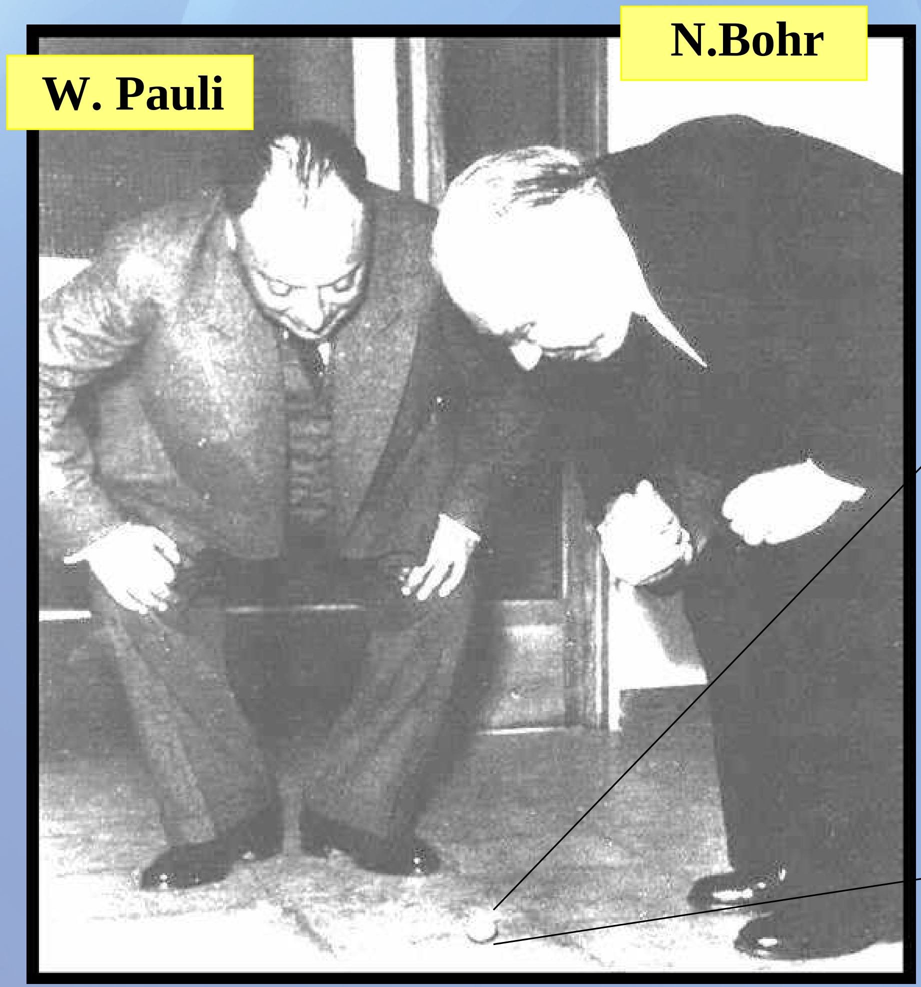
[23] Collins et al., hep-ph/0510342

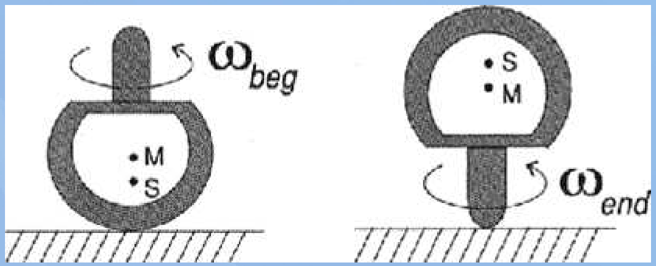
Summary



HERMES (Q^2 < 1 GeV^2)
HERMES (Q^2 > 1 GeV^2)
SMC (low x - low Q^2)
SMC
E 143
E 155
COMPASS
ΔG
Q^2=2.5GeV^2
BB 01 LO
GRSV 2000
LO val
Δq
L_q
$f_{1T}^{\perp}$
δq
L_g
$x f_{1T}^{\perp(1)q}(x)$
Ref.[20]
Ref.[23]
d-quark
u-quark
HERMES x-range
HERMES
DVCS (proton)
Preliminary
hep-ex/0606061
JLab Hall A
DVCS (neutron)
Preliminary
LHPC Lattice
connected terms
arXiv:0705.4295
Experimental errors only
GPD Model :
Goeke et al., Prog. Part. Nucl. Phys. 47 (2001), 401.
Code VGG (M. Vanderhaeghen, P.A.M. Guichon and M. Guidal)
J_d
J_u
GRSV-std
FNS (Kretzer)
BB-06
HERMES Method II fct. 1
HERMES Method II fct. 2
HERMES (Method II)
Compass (Open Charm)
SMC

Spin is fascinating





Thank you for your attention

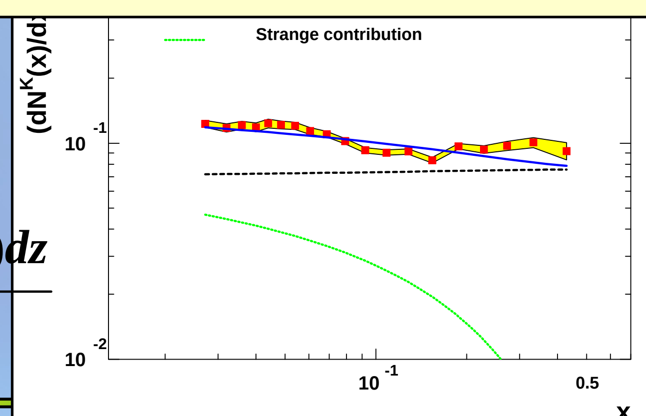
BACKUP SLIDES

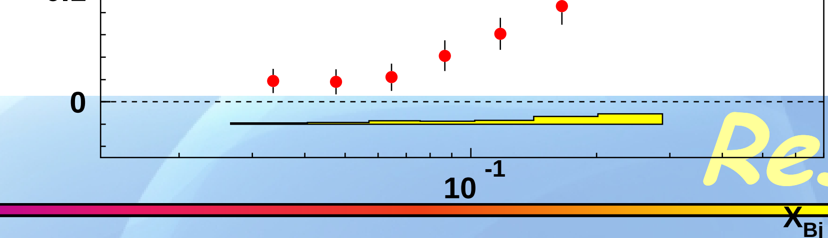
Results for ΔQ and ΔS

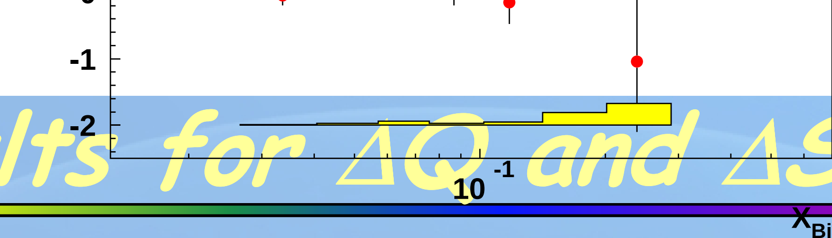
- Need a longitudinal polarized deuterium target
  - strange quark sea in proton and neutron identical
  - fragmentation simplifies
- All needed information can be extracted from HERMES data alone
  - inclusive $A_{1,d}(x,Q^2)$ and kaon $A^K_{1,d}(x,Q^2)$ double spin asym.
  - Kaon multiplicities
- Only assumptions used:
  - isospin symmetry between proton and neutron
  - charge-conjugation invariance in fragmentation

$\int D_{strange}(z)dz = 2\int D(z)_s \ldots dz$

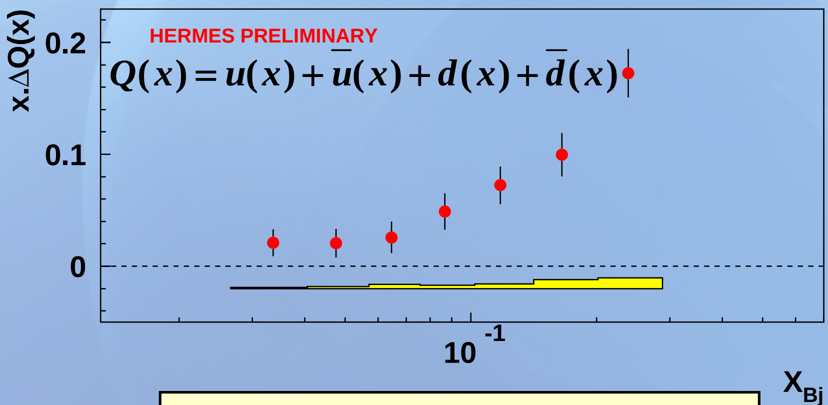
	This Work	Kretzer	KKP
$\int D^K_{nstrg}(z)dz$	0.41±0.02	1.103	1.111
$\int D^K_{strg}(z)dz$	1.41±0.29	0.783	0.296

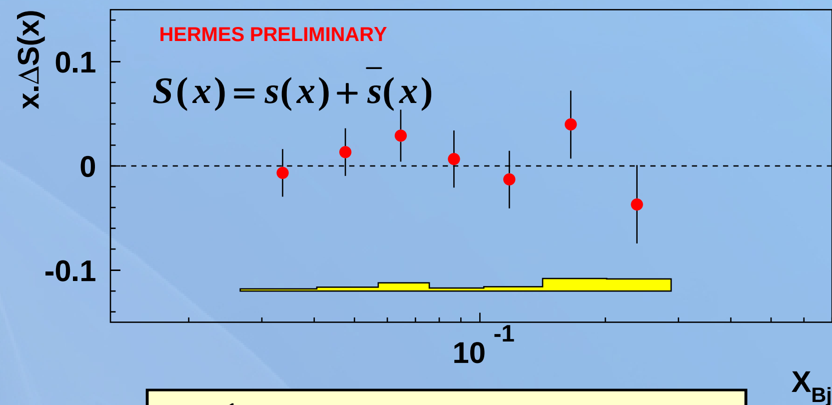






Results for ΔQ and ΔS

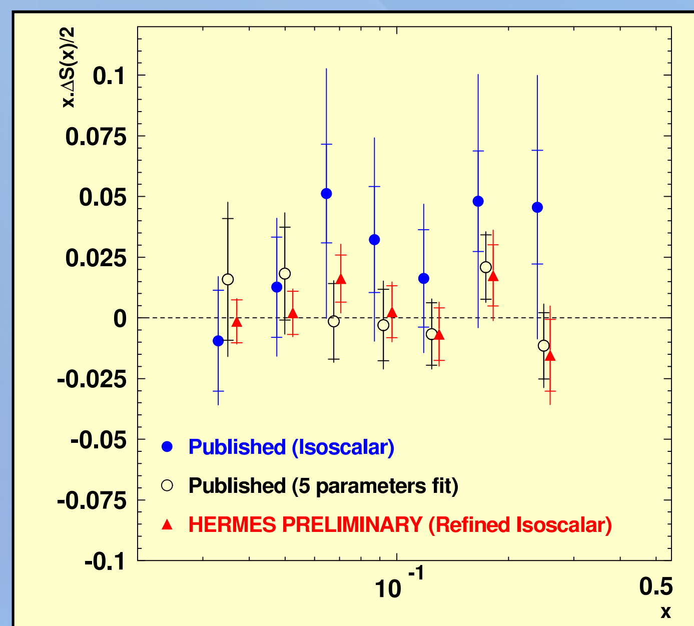




$$\int_{0.02}^{1} \Delta Q = 0.286 \pm 0.026 \pm 0.011$$

$$\int_{0.02}^{1} \Delta S = 0.006 \pm 0.029 \pm 0.007$$

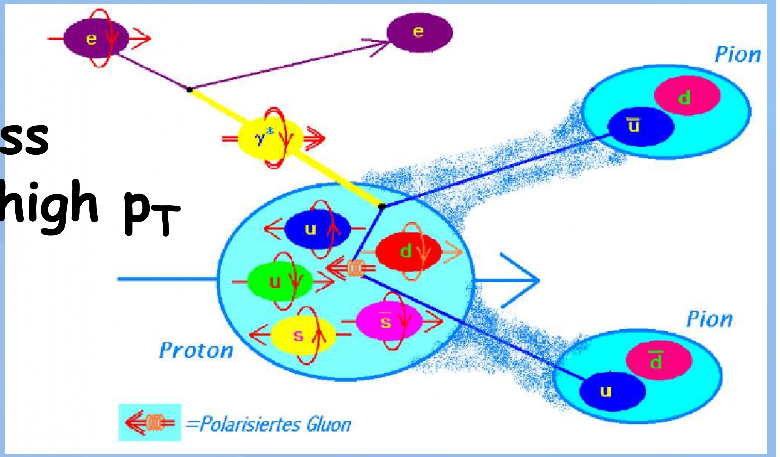
- Earlier HERMES conclusions of unpolarized strange sea confirmed
  - ➧ factor 2 smaller error bars
- Errors very sensitive to FF input



Idea: Direct measurement of ΔG

⟹ Isolate the photon gluon fusion process

- detection of hadronic final states with high p_T
  - high p_T pairs of hadrons
  - single high p_T hadrons



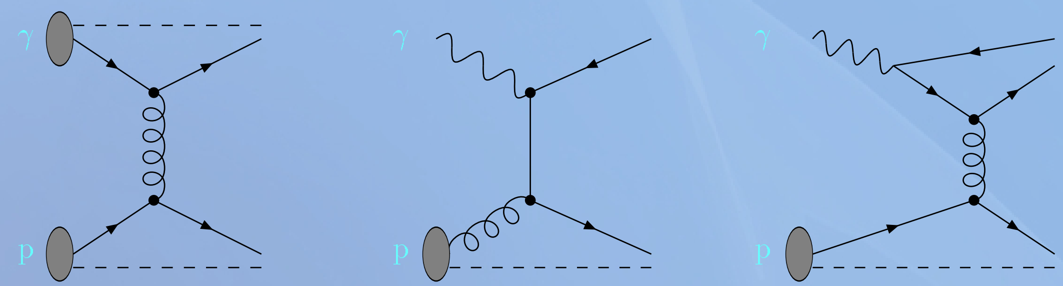
	COMPASS	HERMES	
$h^\pm h^\pm$	$\langle Q^2 \rangle > 1$	---	less sub-processes contributing ☺
	$\langle Q^2 \rangle < 1$	$\langle Q^2 \rangle < 0.1$	more sub-processes contributing ☹ higher statistics ☺
$h^\pm$	---	$\langle Q^2 \rangle > 0.1$	less sub-processes contributing ☺
	---	$\langle Q^2 \rangle < 0.1$	more sub-processes contributing ☹ higher statistics ☺

$h^\pm h^\pm$ vs. $h^\pm$:

$h^\pm$ more inclusive → pQCD NLO calculations (easier) possible

- **Model:** Mix processes with different photon characteristics

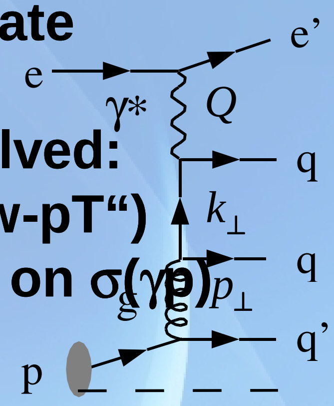
VMD	direct	anomalous photon



a) b) c)

„Soft“ VMD: Elastic, diffractive, non-diffractive („minimum bias“, „low-p_T“) processes Hard VMD: QCD 2→2 processes	QCD-Compton PGF (=„resolved“) LO DIS (virtual photon)	Splitting of $\gamma\to qq$ QCD 2→2 processes

- Small Q^2: VMD+anomalous (=„resolved“) photon dominate
- Large Q^2: LO DIS dominates
- Choice of hard process according to hardest scale involved:
- If all scales are too small „soft“ VMD (diffractive or „low-pT“)
- The „resolved“ part is modeled to match the world data on $\sigma(\gamma p)$



- Measured asymmetry is an incoherent superposition of different sub-process asymmetries:

$$A_{\parallel}^{meas}(p_t) = \sum_i f_i A_{\parallel}^{i} = f_{Bg} A_{\parallel}^{Bg} + f_{Sig} A_{\parallel}^{Sig}; \qquad f_i = \frac{\sigma_i}{\sigma_{tot}}$$

  - Signal: Gluon of the nucleon in the initial state

$$A_{\parallel}^{Sig}(p_t) = \left\langle \hat{a}_{Sig} \right\rangle \left\langle \frac{\Delta G}{G} \right\rangle; \qquad \hat{a}_{Sig}: \text{Asymmetry of the hard sub-process}$$

  - Background: all other sub-processes

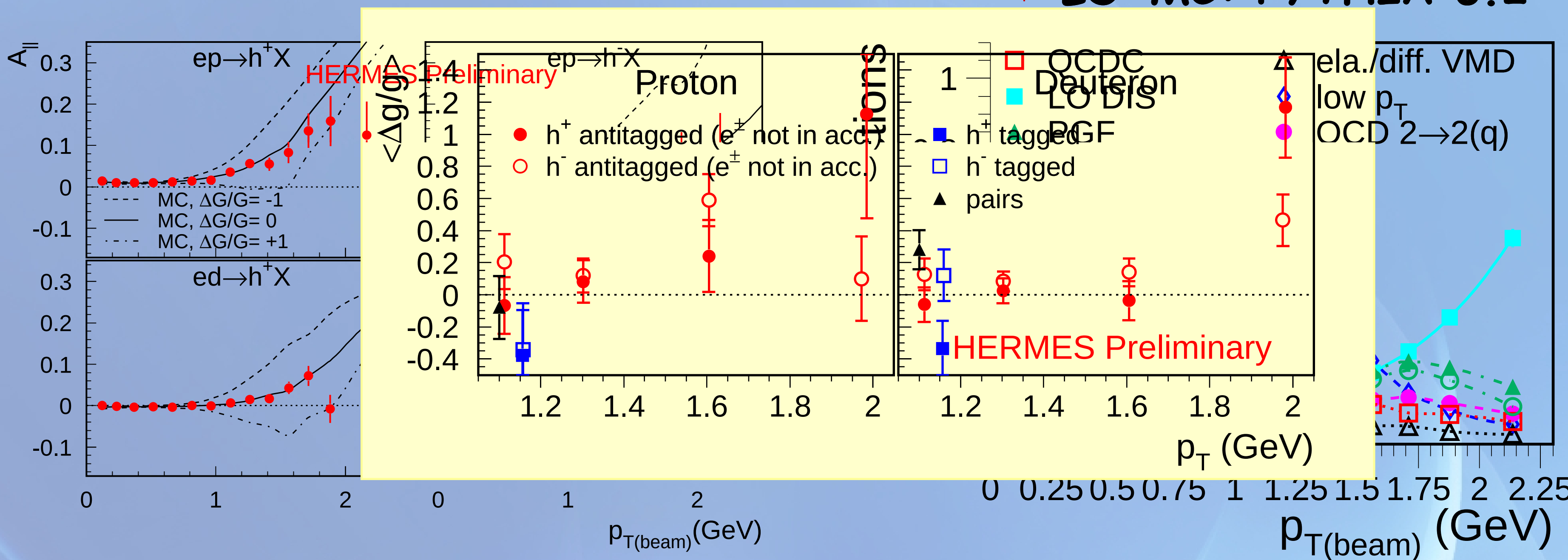
- The gluon polarization is then:

$$\left\langle \frac{\Delta G}{G} \right\rangle = \frac{1}{f_{Sig} \left\langle \hat{a} \right\rangle} [A_{\parallel}^{meas} - f_{Bg} A_{\parallel}^{Bg}]$$

- **Channels:**
  - $h^{\pm}$ with $Q^2 < 0.1 GeV^2$; $p_T > 1 GeV$
  - $h^{\pm}$ with $Q^2 > 0.1 GeV^2$; $p_T > 1 GeV$
  - $h^{\pm}h^{\pm}$ with $Q^2 < 0.1 GeV^2$;

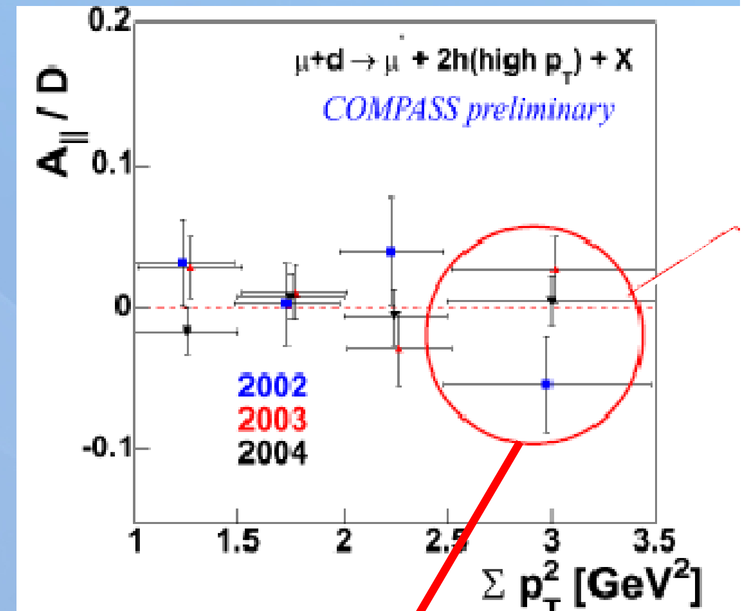
    $p_T^1, p_T^2 > 0.5 GeV \quad p_{T,1}^2 + p_{T,2}^2 > 2.0 GeV^2$

- **Considered sub-processes:**
  - LO-MC: PYTHIA 6.2

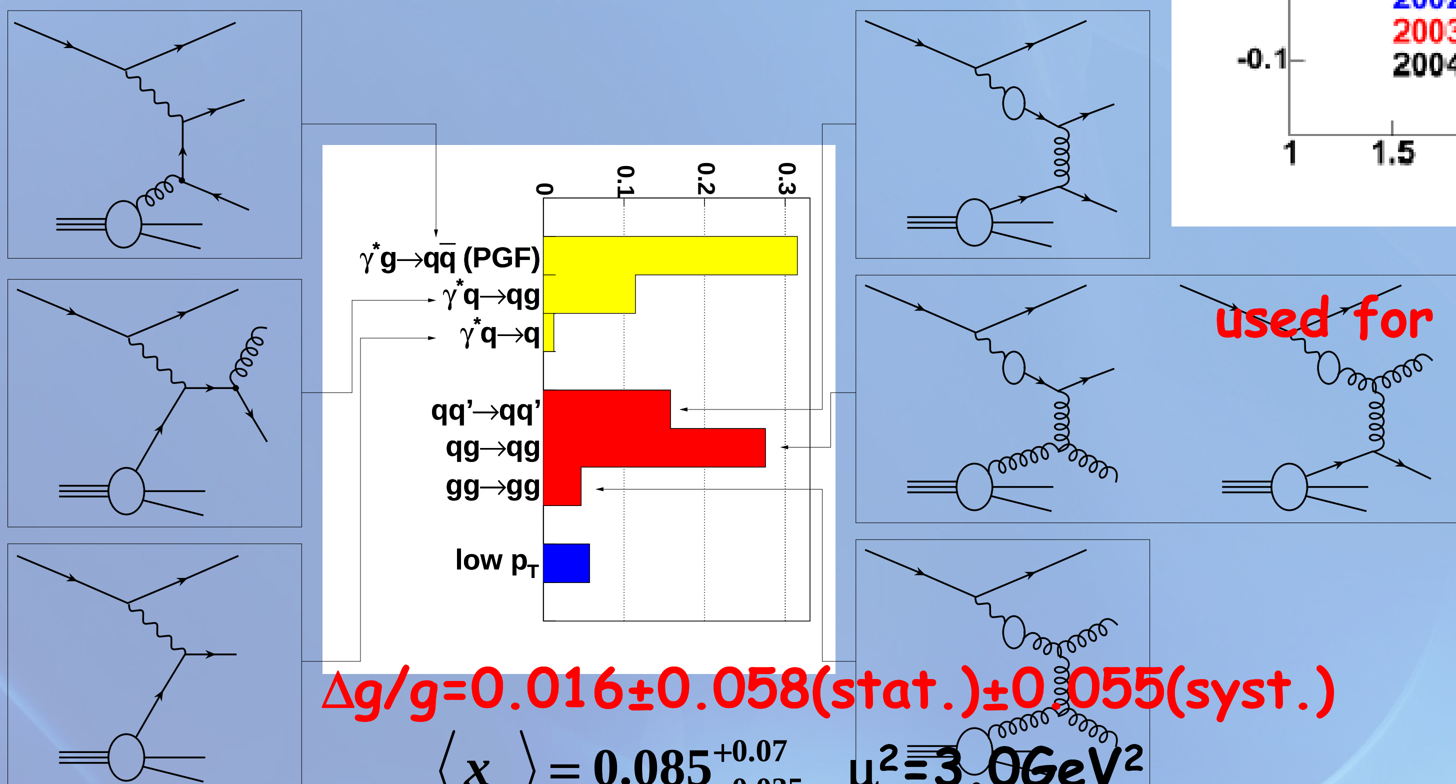


COMPASS Results

- Channel: $h^{\pm}h^{\pm}$ with $Q^2 < 1GeV^2$
- Cuts:
  $p_T^1, p_T^2 > 0.7GeV \quad p_{T,1}^2 + p_{T,2}^2 > 2.5GeV^2$
- Considered sub-processes:
  - LO-MC: PYTHIA 6.2



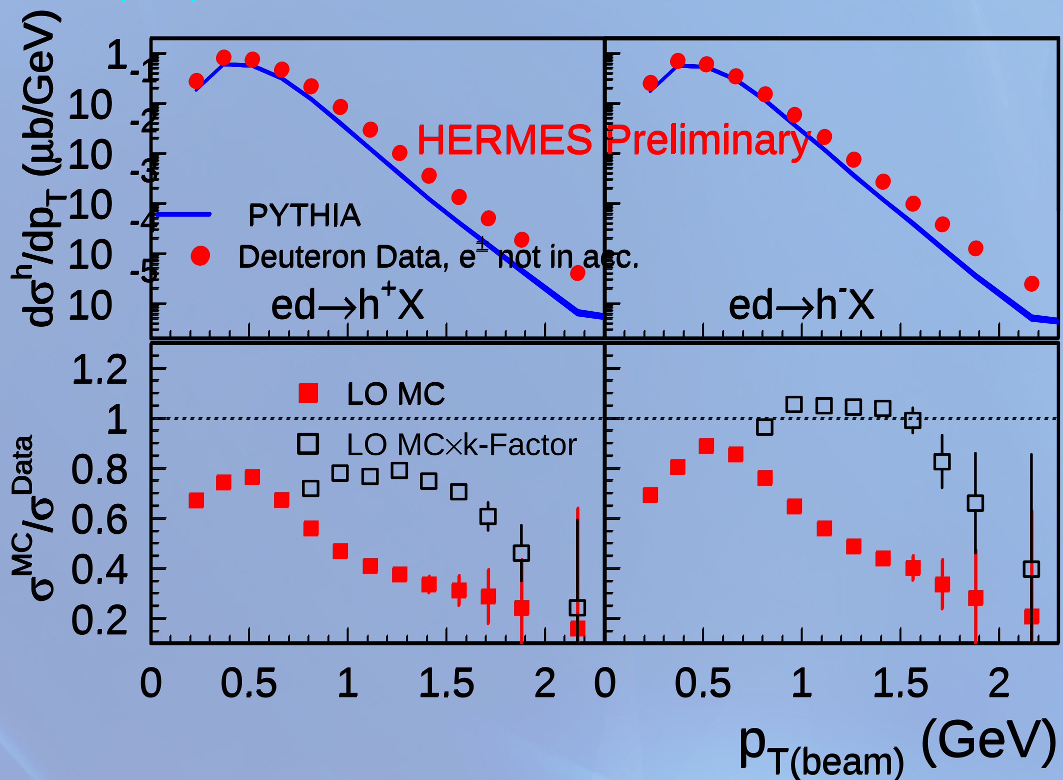
used for Δg/g extraction

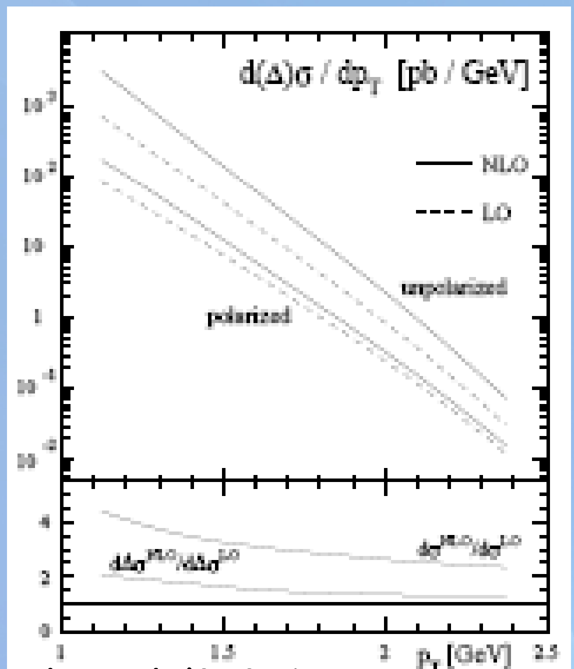


$\Delta g/g = 0.016 \pm 0.058(stat.) \pm 0.055(syst.)$

$\left\langle x_g \right\rangle = 0.085^{+0.07}_{-0.035} \quad \mu^2 = 3.0 GeV^2$

- **HERMES cross section:**
  k_T, p_T standard values:
  $\langle k_T^{p,\gamma} \rangle = 0.40 GeV$ $\langle p_T^{frag} \rangle = 0.40 GeV$
  - M.Anselmino et al. Phys. Rev. D71,074006
    $\langle k_t^2 \rangle = 0.25 GeV^2 \pm 20\%$ $\langle p_t^2 \rangle = 0.20 GeV^2 \pm 20\%$



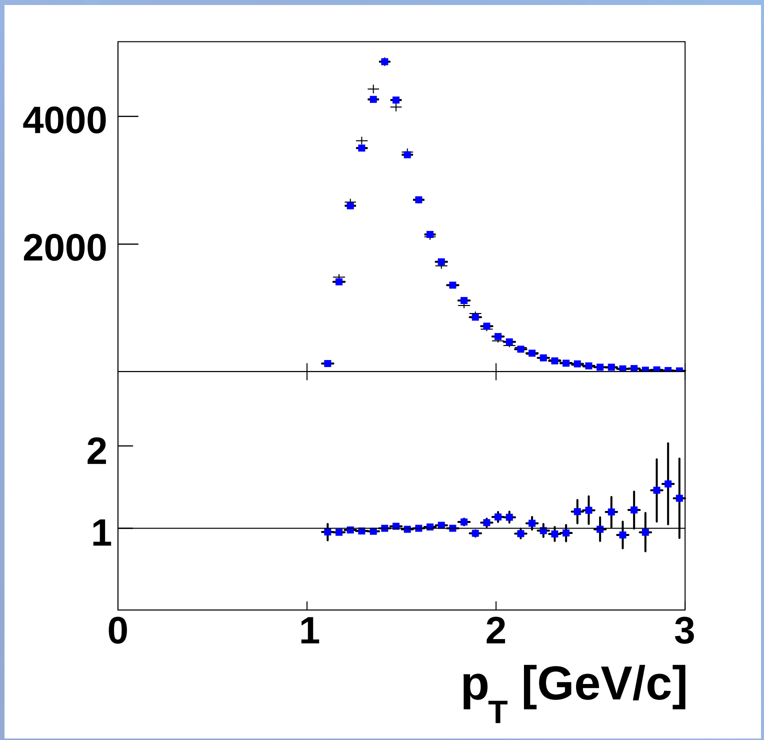


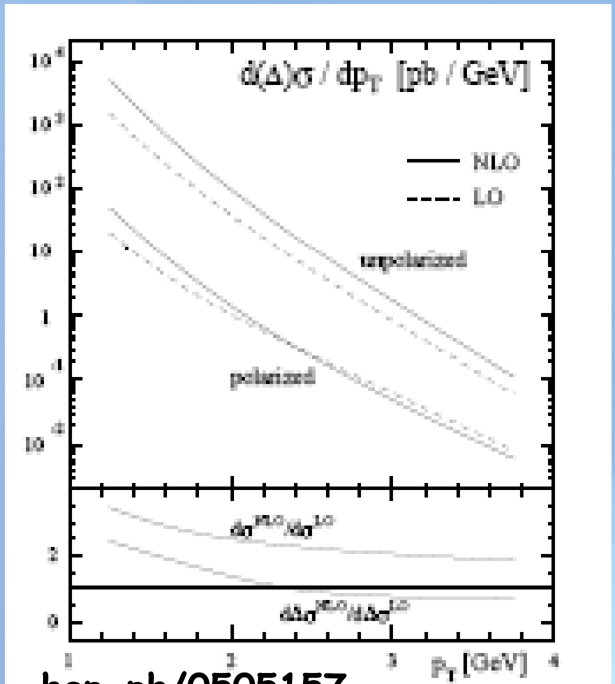
hep-ph/0505157

- **COMPASS standard values:**

$\langle k_T^{\gamma} \rangle = 0.50 GeV$ $\langle k_T^{p} \rangle = 1.00 GeV$

$\langle p_T^{frag} \rangle = 0.36 GeV$

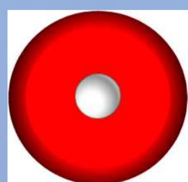


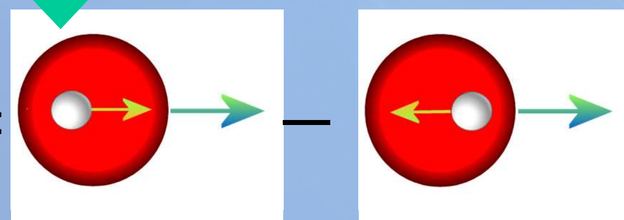


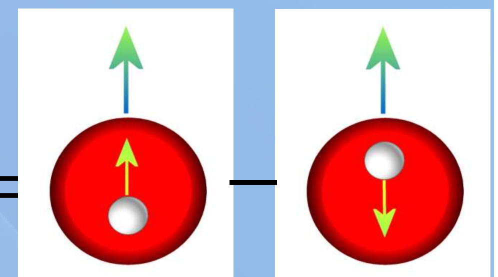
hep-ph/0505157

The 3rd Twist-2 structure function

$$\Phi^{\mathrm{Tw2}}_{\mathrm{Corr}}(x) = \frac{1}{2}\left\{ \boxed{f_1(x)} + S_L\, \boxed{g_1(x)}\gamma_5 + \boxed{h_1(x)}\gamma_5\gamma^1 S_T \right\} n^+$$

$f_1^q =$ 

$g_1^q =$ 

$h_1^q =$ 

unpolarised quarks and nucleons

q(x): spin averaged

→ vector charge

well known

longitudinally polarized quarks and nucleons

Δq(x): helicity difference

→ axial charge

known

transversely polarized quarks and nucleons

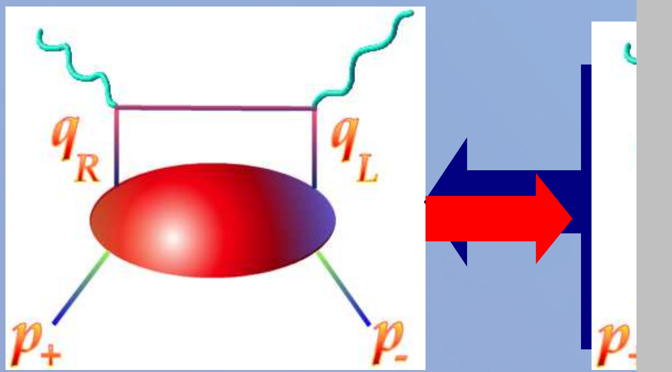
δq(x): *helicity flip*

→ tensor charge

measuring!

Peculiarities of transversity

$$\Phi^{\mathrm{Tw2}}_{\mathrm{Corr}}(x) = \frac{1}{2}\left\{ f_1(x) + S_L\, g_1(x)\gamma_5 + \boxed{h_1(x)}\gamma_5\gamma^1 S_T \right\} n^+$$



single helicity flip

<u>relativistic nature of quark</u>:
in absence of relativistic effects $h_1(x)=g_1(x)$

<u>Q^2 –evolution</u>: unlike for $g_1^p(x)$,
the gluon doesn't mix with quark in $h_1^p(x)$
(no gluon analog for spin-½ nucleon)

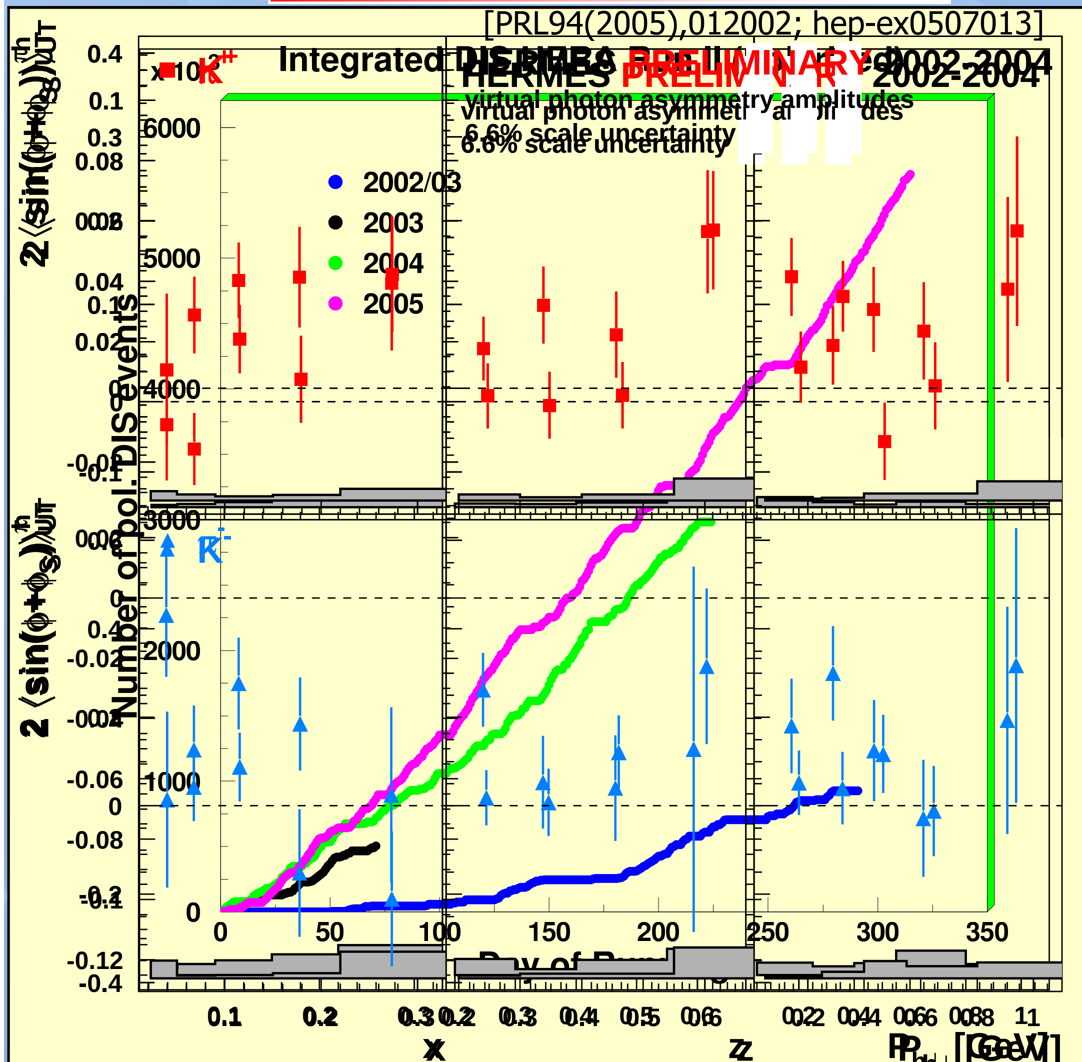
sensitive to the <u>valence quark polarisation</u>
q and $\bar{q}$ have opposite sign.

<u>tensor charge:</u> first moment of h_1
(large from lattice QCD)

Collins moments

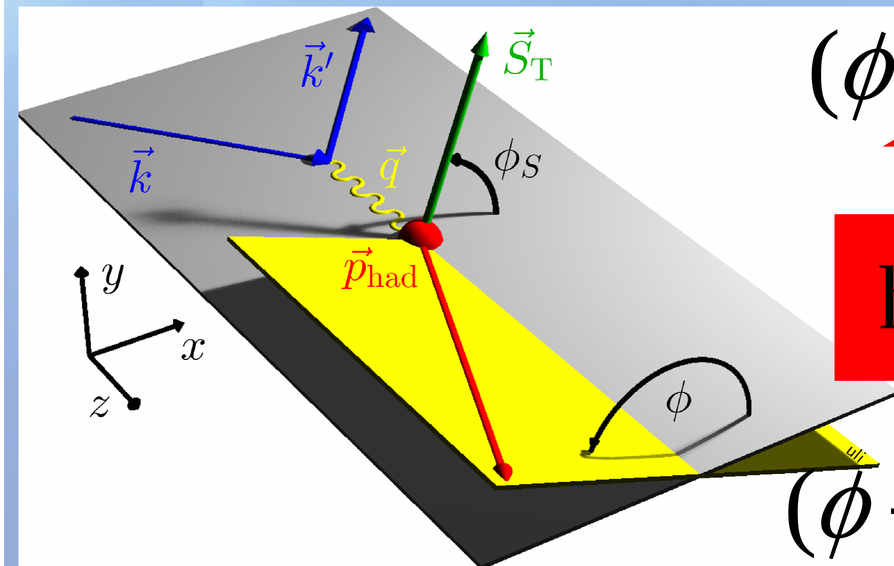
$$A_{coll} \propto h_1(x) H_1^{\perp}(z)$$

[PRL94(2005),012002; hep-ex0507013]



- **Collins moment:**
  $\pi^+ > 0$ $\pi^- < 0$
- **π^- unexpected large**
  ⇒ role of unfavoured FF
- **first data for Collins FF $H_1^{\perp}(z)$ available from Belle**
  ⇒ extraction of h_1 from Hermes asymmetries
- **$K^+ > 0$ $K^- > 0$**
  K^+ in agreement with π^+
- **2005 data:**
  ⇒ 2 dimensional binning disentangle x (PDF) and z (FF) dependence

Azimuthal angles and asymmetries



$(\phi + \phi_S)$ **angle of hadron relative to *final* quark spin (Collins)**

$h_1 \otimes H_1^{\perp}$ **(Collins)**

$(\phi - \phi_S)$ **angle of hadron relative to *initial* quark spin (Sivers)**

(Sivers) $f_{1T}^{\perp} \otimes D_1$

peculiarity of $f^{\perp}_{1T}$

chiral-even naïve T-odd DF

related to parton orbital momentum

violates naïve universality of PDF
⟹ different sign of $f^{\perp}_{1T}$ in DY