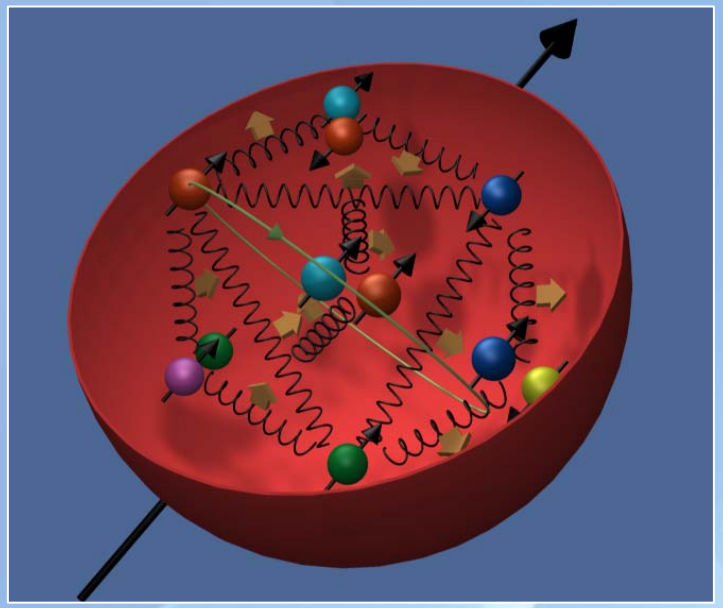
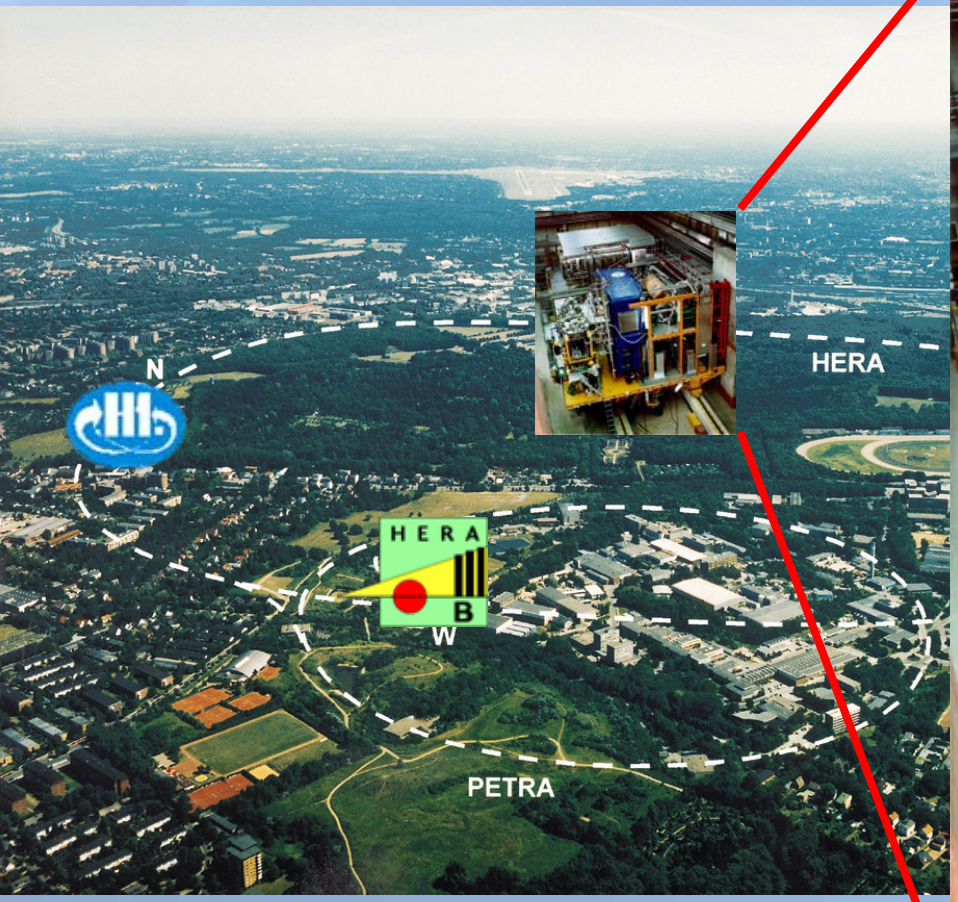
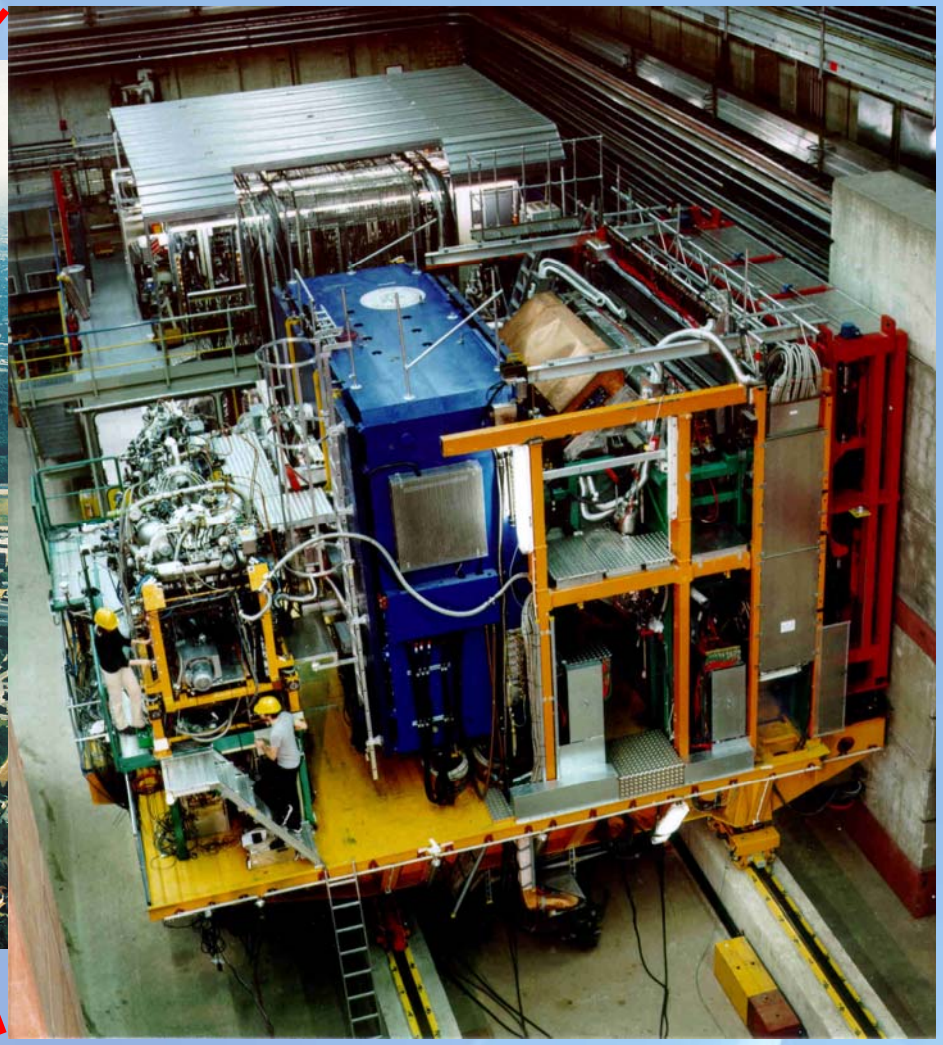
The Spin Structure of the Nucleon
Highlights from HERMES

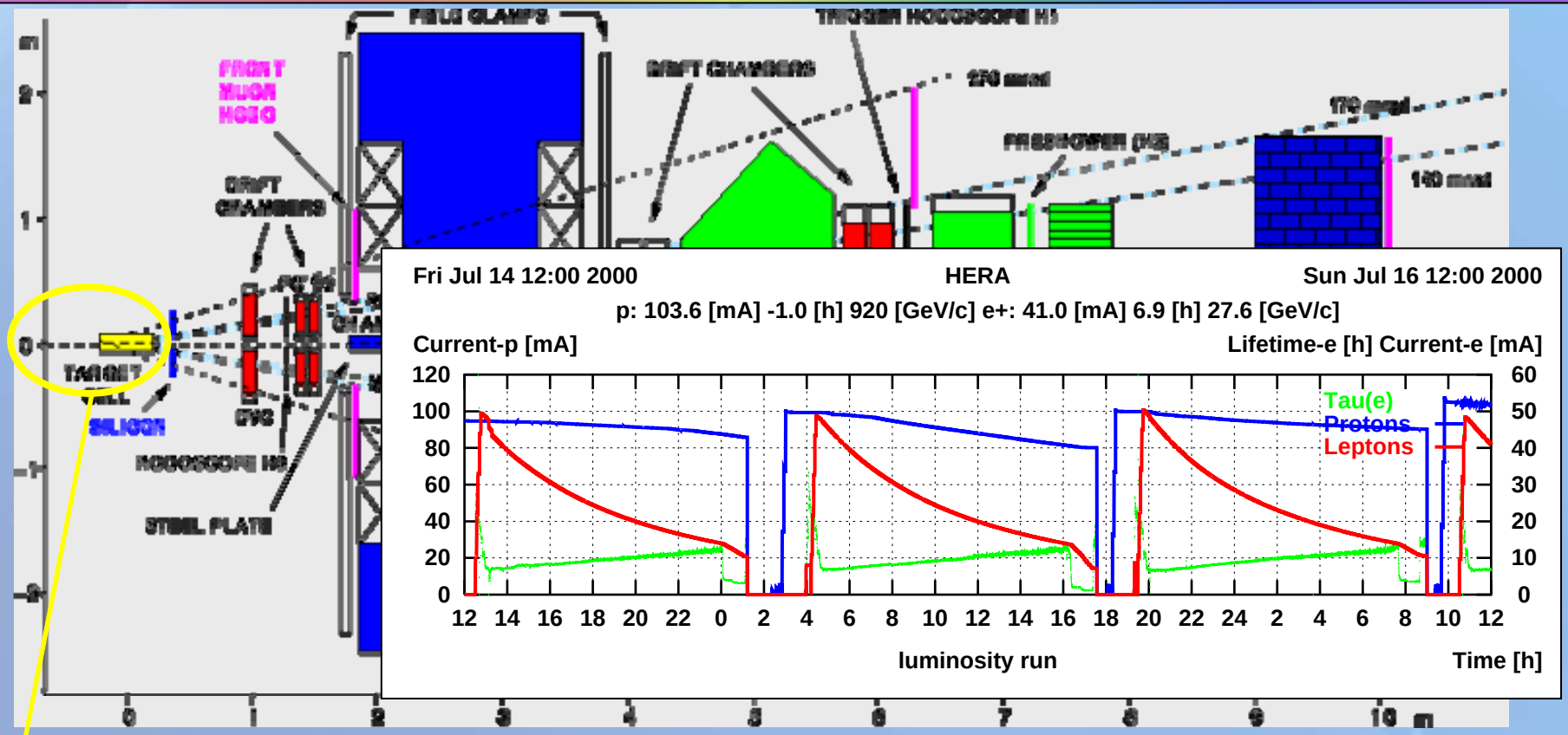






HERA: e^+/e^- (27GeV) - proton (920 GeV) collider

The HERMES Spectrometer



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

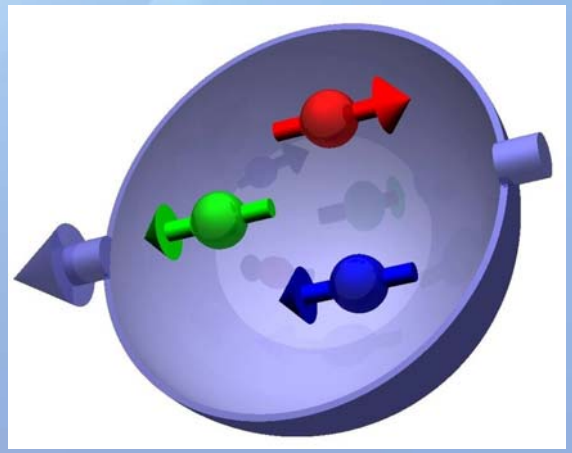
Particle ID: TRD, Preshower, Calorimeter

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

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

News on the spin structure of the nucleon



Naïve parton model

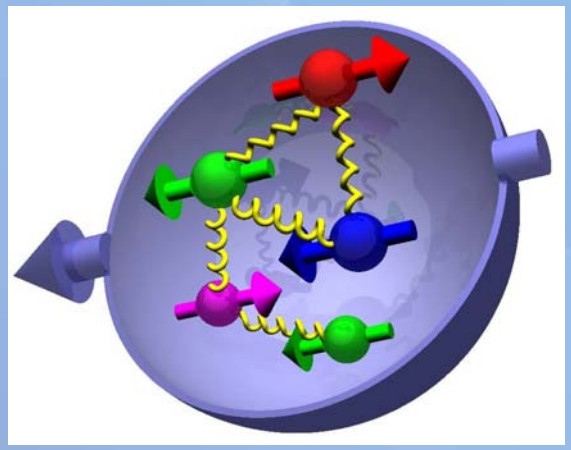
$$\Delta u_v = \tfrac{4}{3} \quad \Delta d_v = -\tfrac{1}{3}$$

BUT

1989 EMC measured

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

⟹ Spin Puzzle

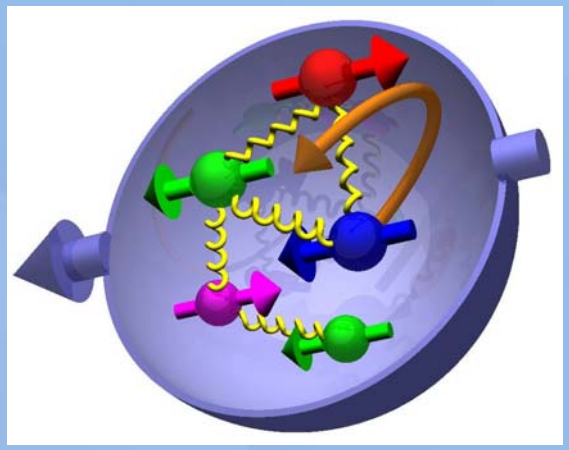


Unpolarised structure fct.

Gluons are important !

⟹ ΔG

⟹ Sea quarks Δq_s



Full description of J_q and J_g

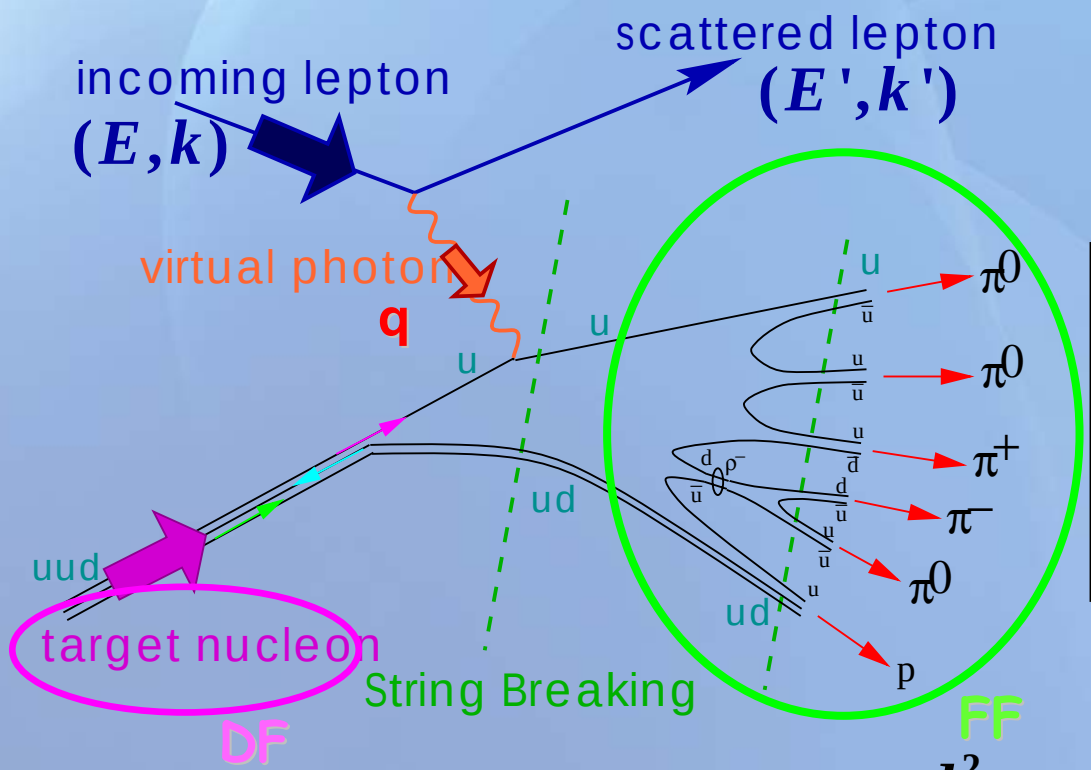
needs

orbital angular momentum

$$\frac{11}{22} = \frac{11}{22}\left(\frac{1}{2}(\Delta u_v + \Delta d_v) + \Delta u_s + \Delta d_s + \Delta s_s\right) + L_q + \Delta G + L_g$$

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

Deep Inelastic Scattering



Important kinematic variables:

$$Q^2 = -q^2 = -(k-k')^2$$

$$\nu = E - E'$$

$$x = \frac{Q^2}{2M\nu} \qquad z = \frac{E_h}{\nu}$$

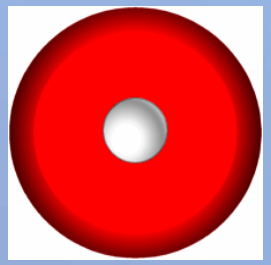
cross section: $$\frac{d^2\sigma}{d\Omega dE'} \sim L_{\mu\nu} W^{\mu\nu}$$

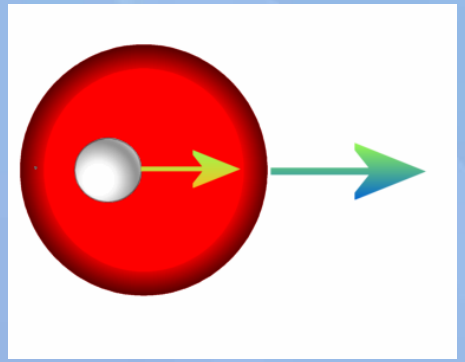
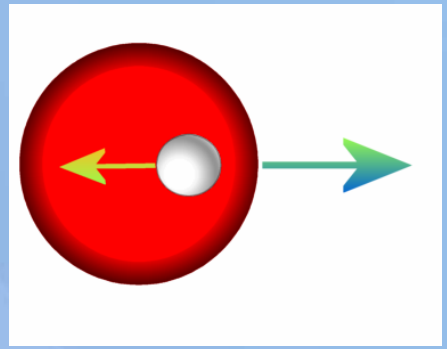
$$W^{\mu\nu} = -g^{\mu\nu} F_1 - \frac{p^\mu p^\nu}{\nu} F_2 + \frac{i}{\nu}\varepsilon^{\mu\nu\lambda\sigma} q^\lambda s^\sigma g_1 + \frac{i}{\nu^2}\varepsilon^{\mu\nu\lambda\sigma} q^\lambda (p\cdot q s^\sigma - s\cdot q p^\sigma) g_2$$

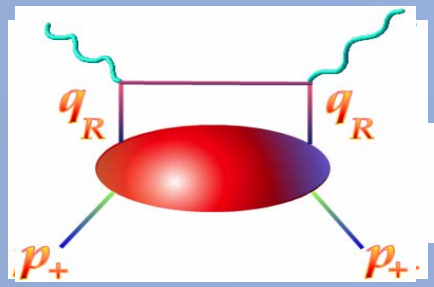
$$\underbrace{-r_{\mu\nu} b_1 + \frac{1}{6}(s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) b_2 + \frac{1}{2}(s_{\mu\nu} - u_{\mu\nu}) b_3 + \frac{1}{2}(s_{\mu\nu} - t_{\mu\nu}) b_4}_{\text{Spin 1}}$$

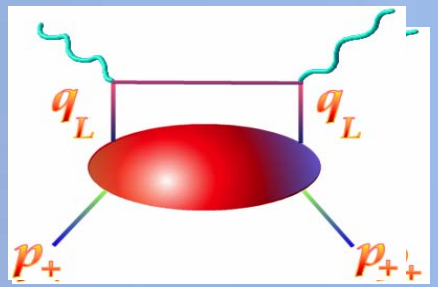
The quark content of the nucleon

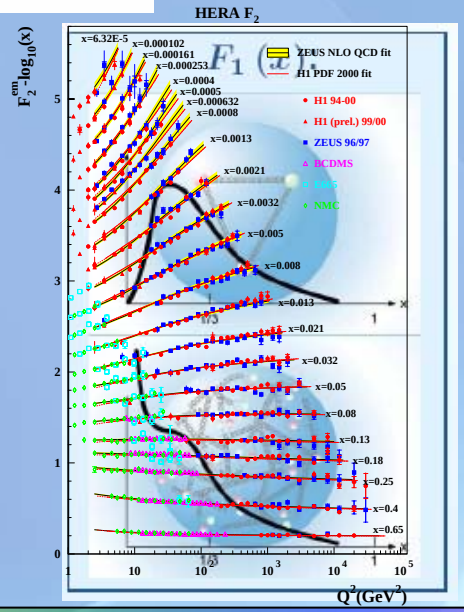
$$\Phi^{Tw2}_{Corr}(x) = \frac{1}{2}\left\{ f_1(x) + S_L g_1(x)\gamma_5 + h_1(x)\gamma_5\gamma^1 S_T \right\} n^+$$

$f_1 =$ 

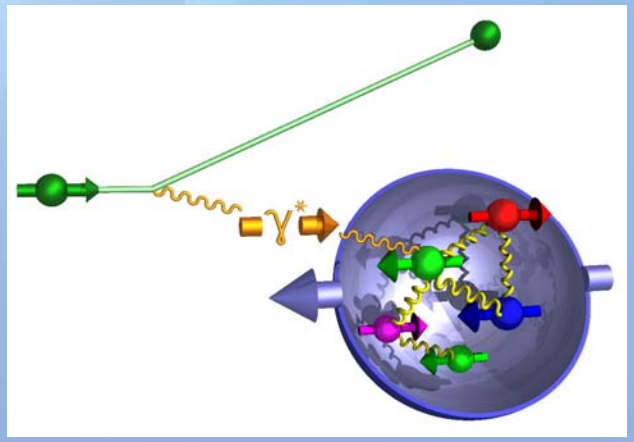
$g_{1L} =$  $-$ 

$\frac{1}{2}$ 

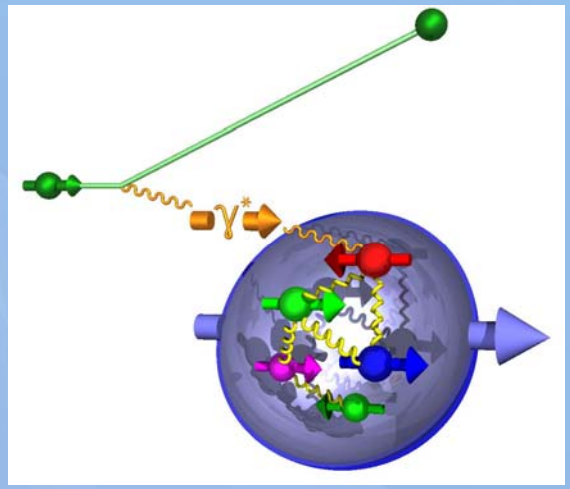
$-$ 



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

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

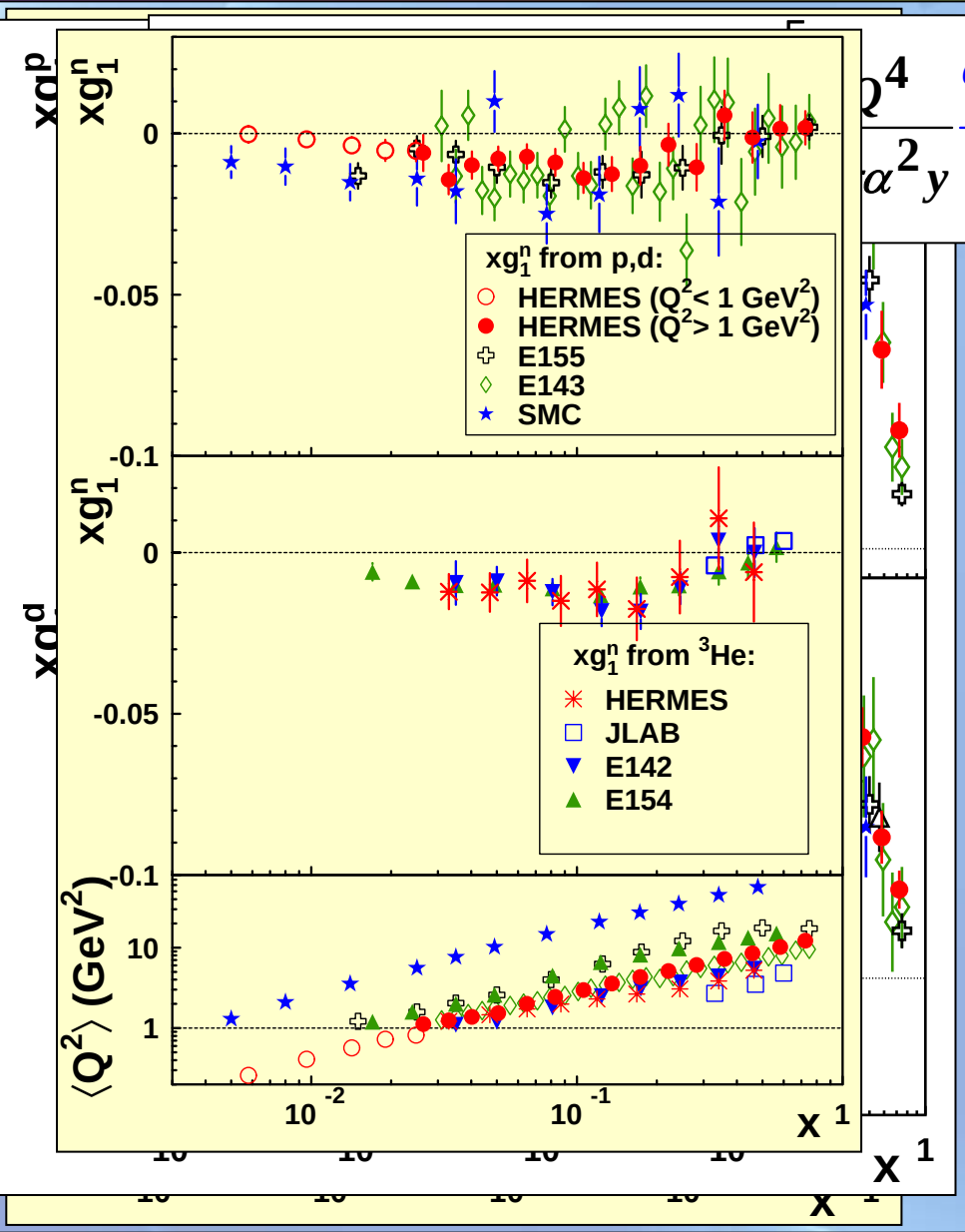
Asymmetry definition:

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

inclusive DIS: only e' info used

semi-inclusive DIS: e'+h info used

World data on inclusive DIS



$$\frac{d^2\sigma_{unpol}}{dxdQ^2} \quad A_{\square}(x,Q^2) + \frac{y}{2}\gamma^2 g_2(x,Q^2)$$

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

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

➡ What can we learn on the PDFs

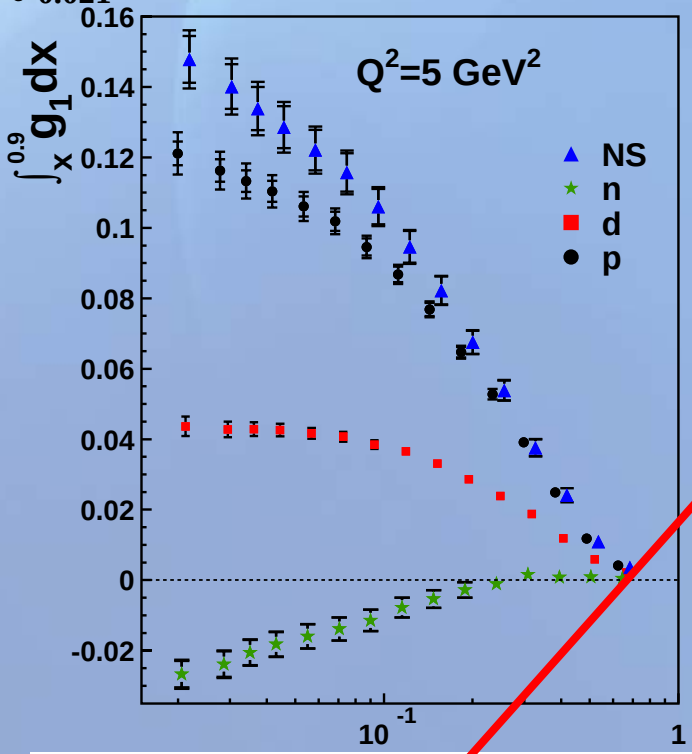
$$g_1 \sim \langle e^2 \rangle [\Delta C_\Sigma \otimes \Delta\Sigma + \Delta C_G \otimes \Delta G + \Delta C_{NS} \otimes \Delta q_{NS}^{p,n}]$$

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

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

HERMES: Integrals

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



	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 GeV^2, NNLO in $\overline{MS}$ scheme

Saturation in deuteron integral is assumed

➡ use only deuterium

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

from hyperon beta decay (a_8=0.586±0.031)

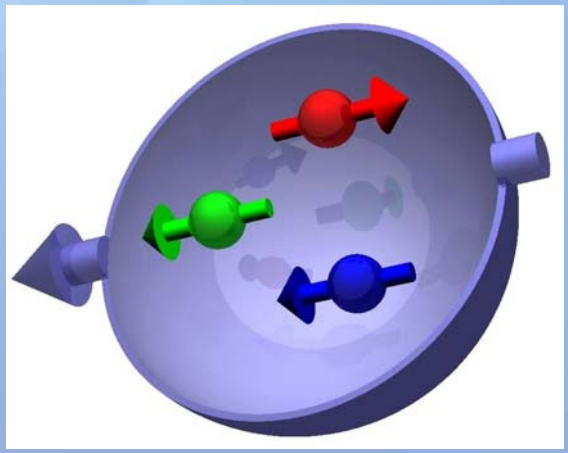
$$\Delta u + \Delta\bar{u} = \frac{1}{6}[2a_0 + a_8 + 3a_3]$$

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

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

From neutron beta decay a_3=1.269±0.003

The Gluon Polarization



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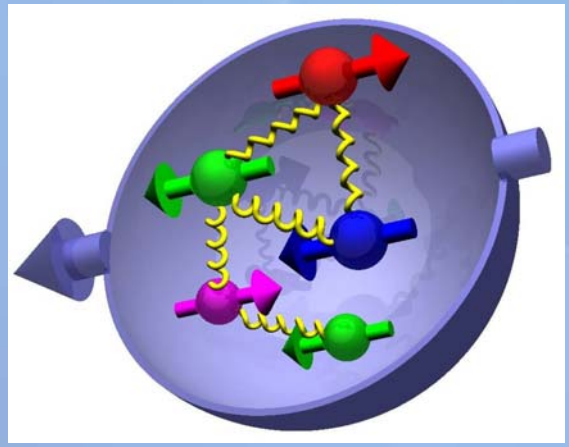


Unpolarised structure fct.

Gluons are important !

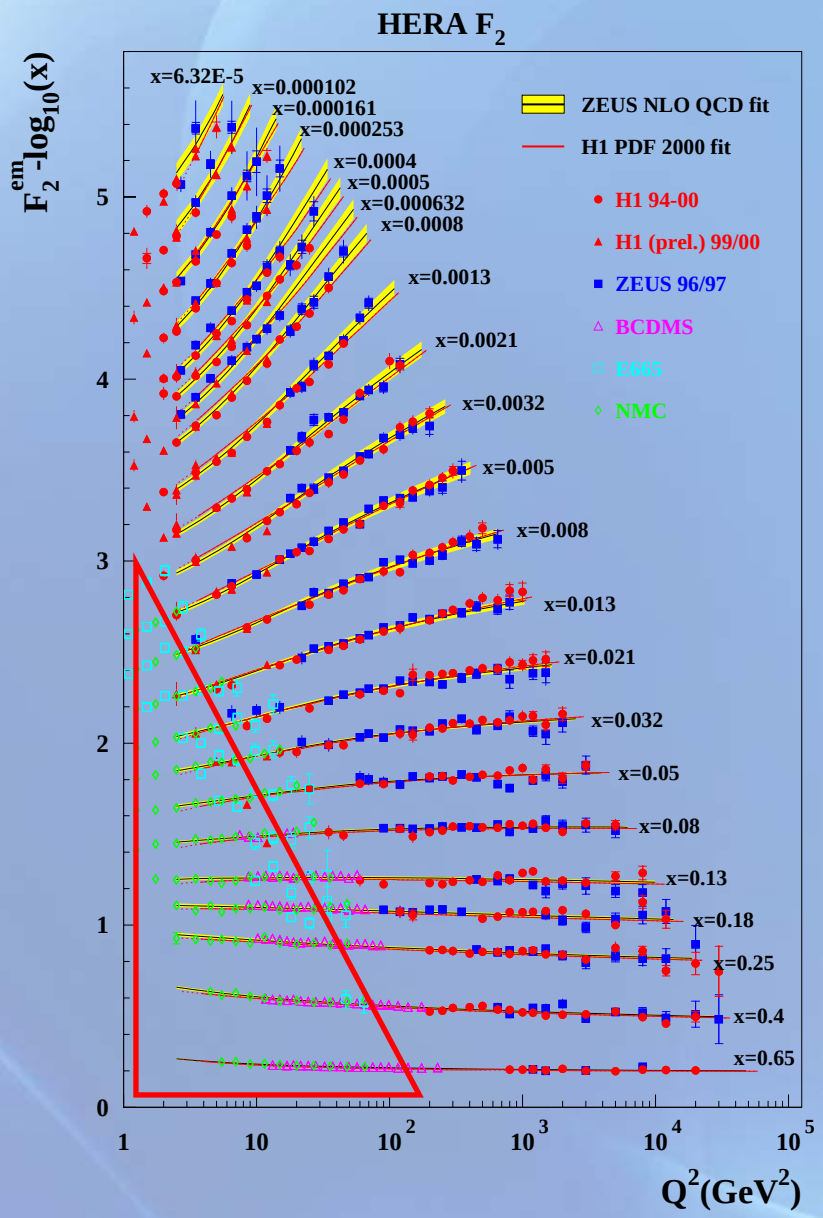
⟹ ΔG

⟹ Sea quarks Δq_s

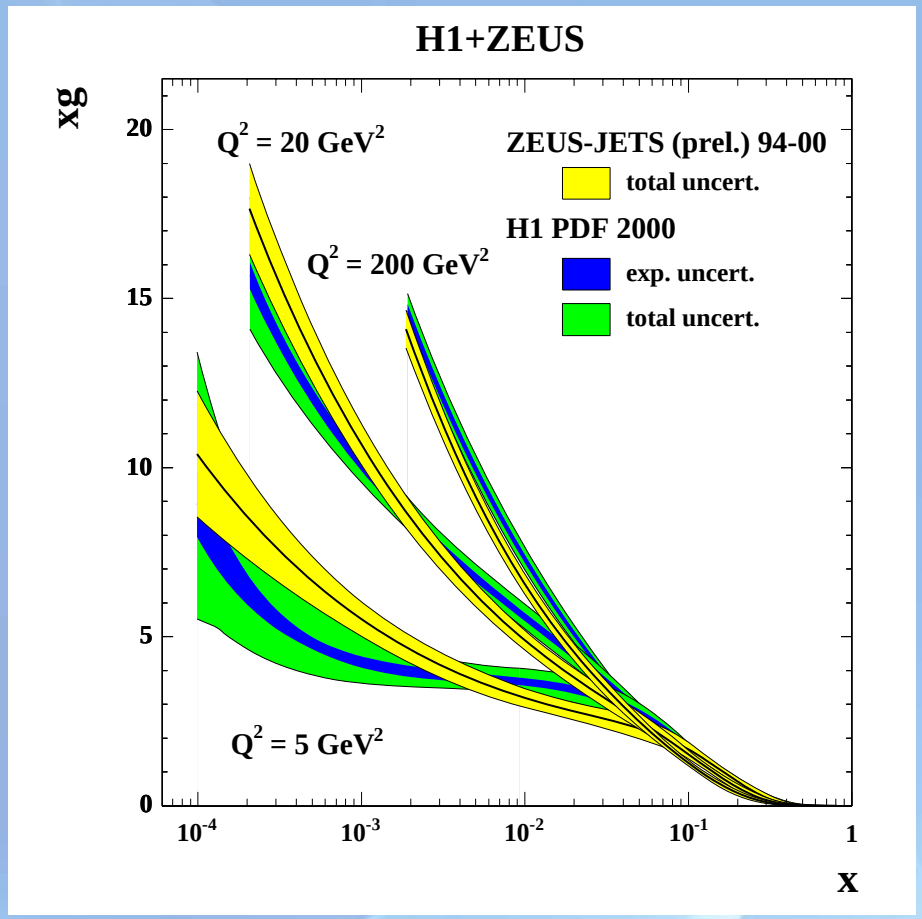
$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v + \Delta q_s) + \Delta G$$

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

Unpolarized Gluon Distribution

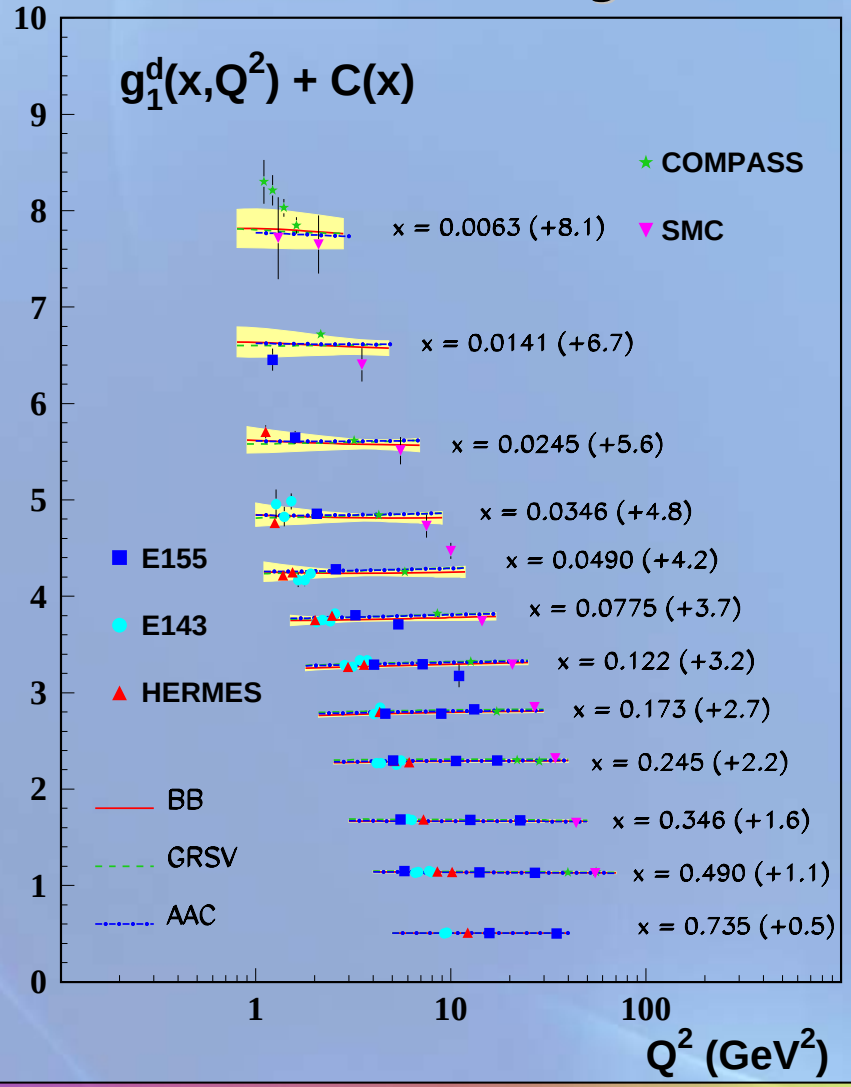


- big Q^2-x lever arm
  - very accurate G(x)

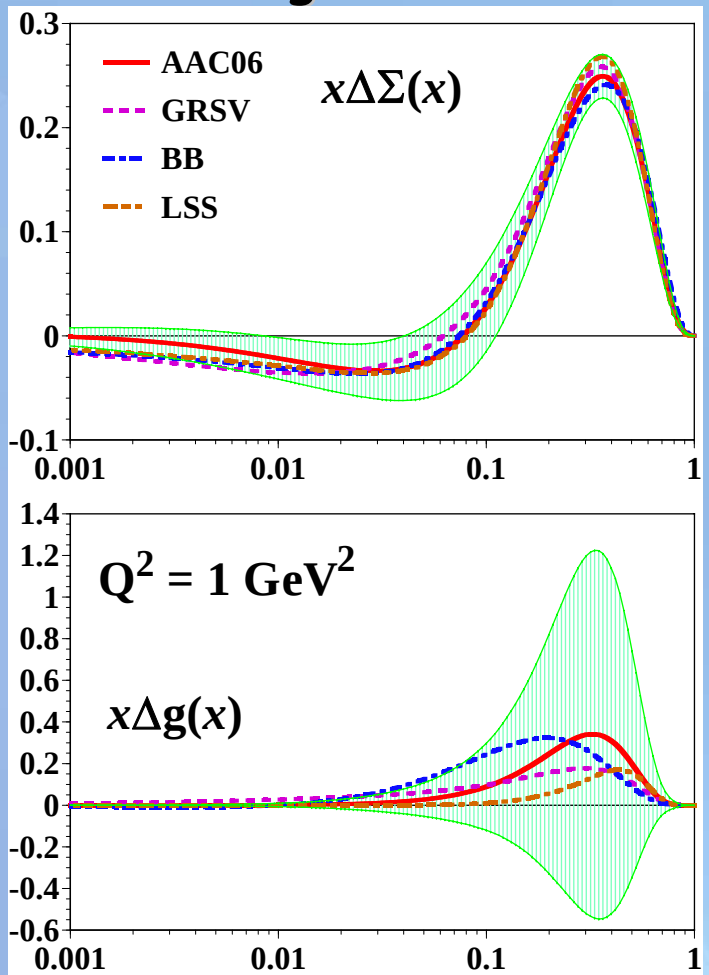


How to measure ΔG

- Indirect from scaling violation



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

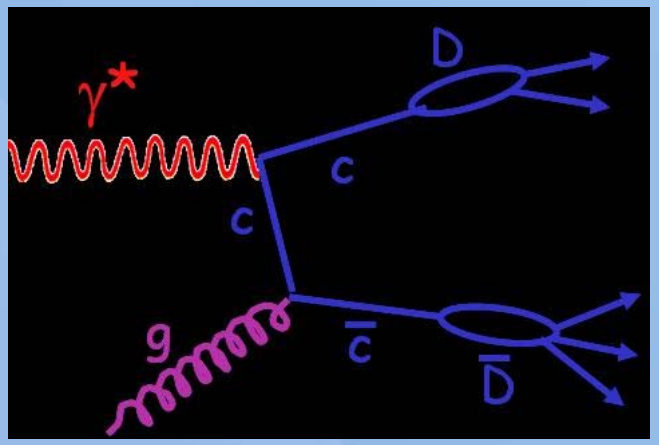


hep-ph/0603213 x

Idea: Direct measurement of ΔG

⟹ Isolate the photon gluon fusion process (PGF)

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



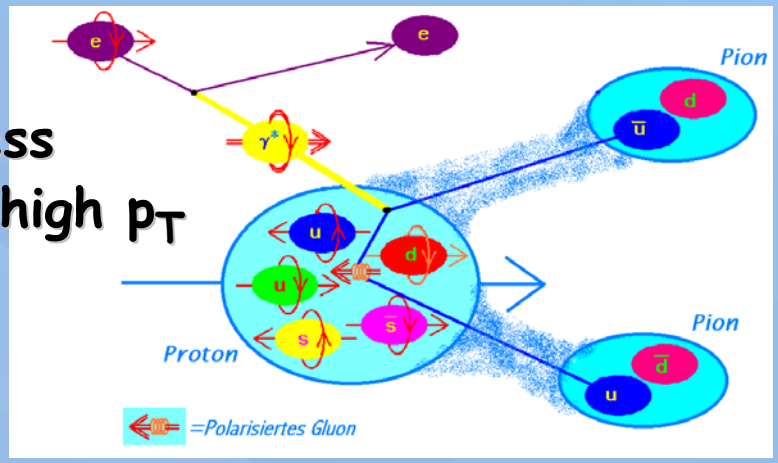
$$A_{\gamma N}^{PGF} = \frac{\int d\hat{s}\,\Delta\sigma^{PGF}\,\Delta G(x_g,\hat{s})}{\int d\hat{s}\,\sigma^{PGF}\,G(x_g,\hat{s})} \approx \left\langle a_{LL}^{PGF} \right\rangle \frac{\Delta G}{G}$$

LO-MC: Aroma

HERMES sqrt(s) to low for reasonable statistics

The golden channels

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

$h^\pm h^\pm$

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

$\langle Q^2 \rangle < 0.1$ 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

The Method

- 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

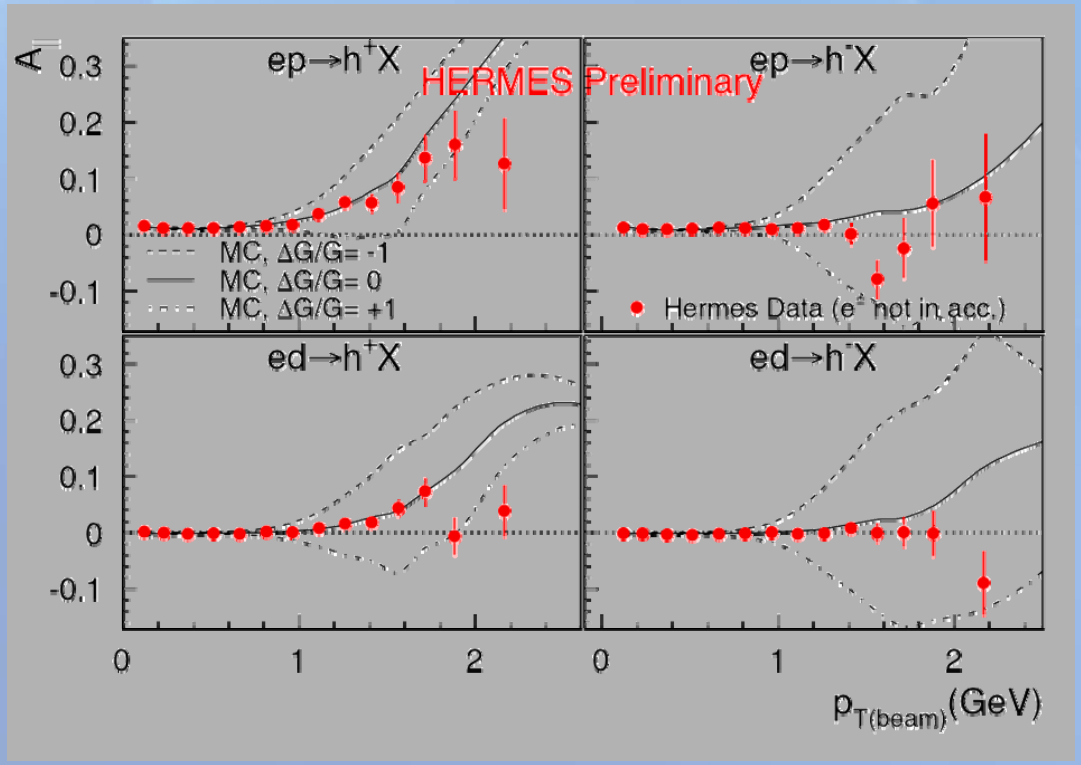
$$A_{\parallel}^{Sig}(p_t) = \langle \hat{a}_{Sig} \rangle \left\langle \frac{\Delta G}{G} \right\rangle; \qquad \hat{a}_{Sig}:$$ Asymmetry of the hard sub-process

  - Background: all other sub-processes

- The gluon polarization is then:

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

From Measurements …



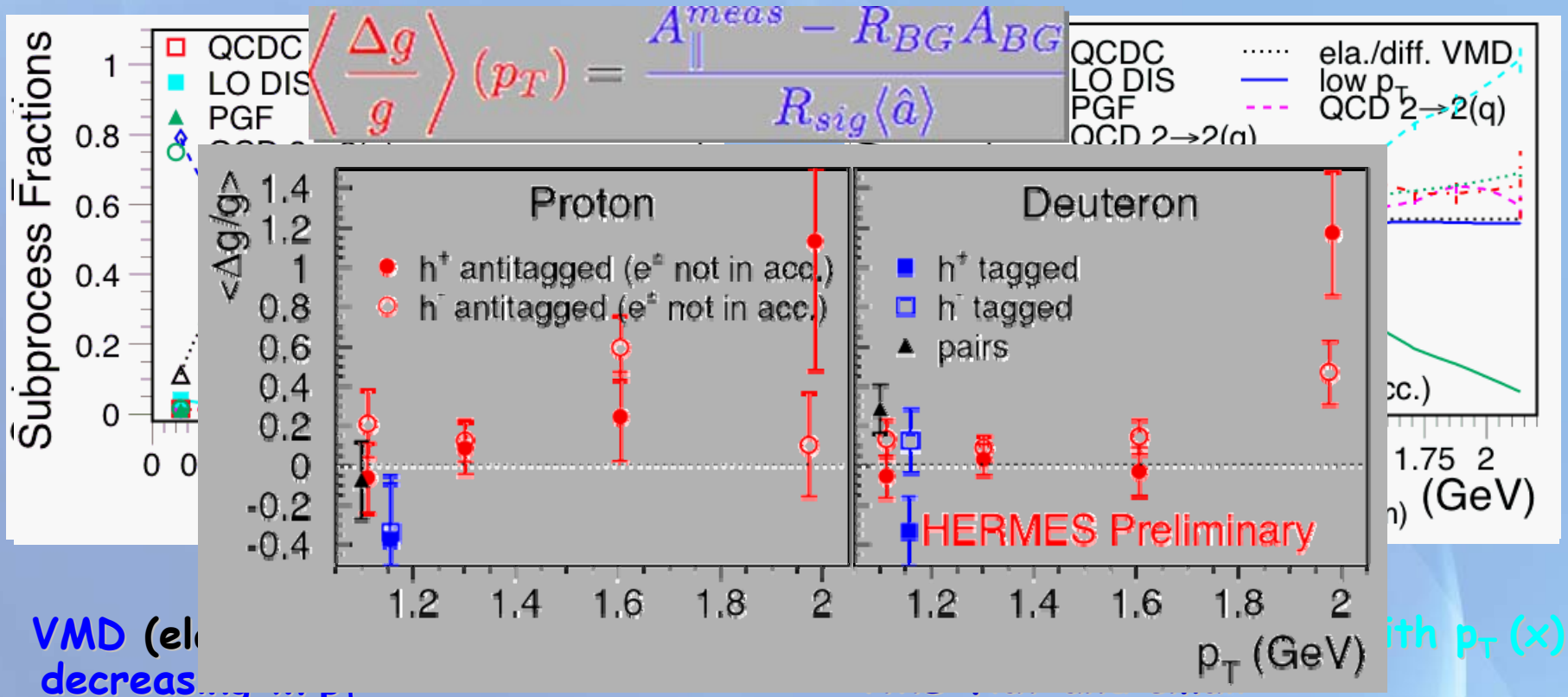
- "Antitagged" data:
  - Scattered lepton not in the acceptance
  - p_T measured w/respect to beam axis
- Curves from MC+asymmetry model using
  - $\Delta g/g(x)=0$: central
  - $\Delta g/g(x)=-1$: upper
  - $\Delta g/g(x)=+1$: lower

The $\Delta g/g=0$ asymmetry is due to quarks only!
Gluons contribute to the cross section (asymmetry) above $p_T \approx 1$ GeV

Fractions and Asymmetries

Subprocess Fraction

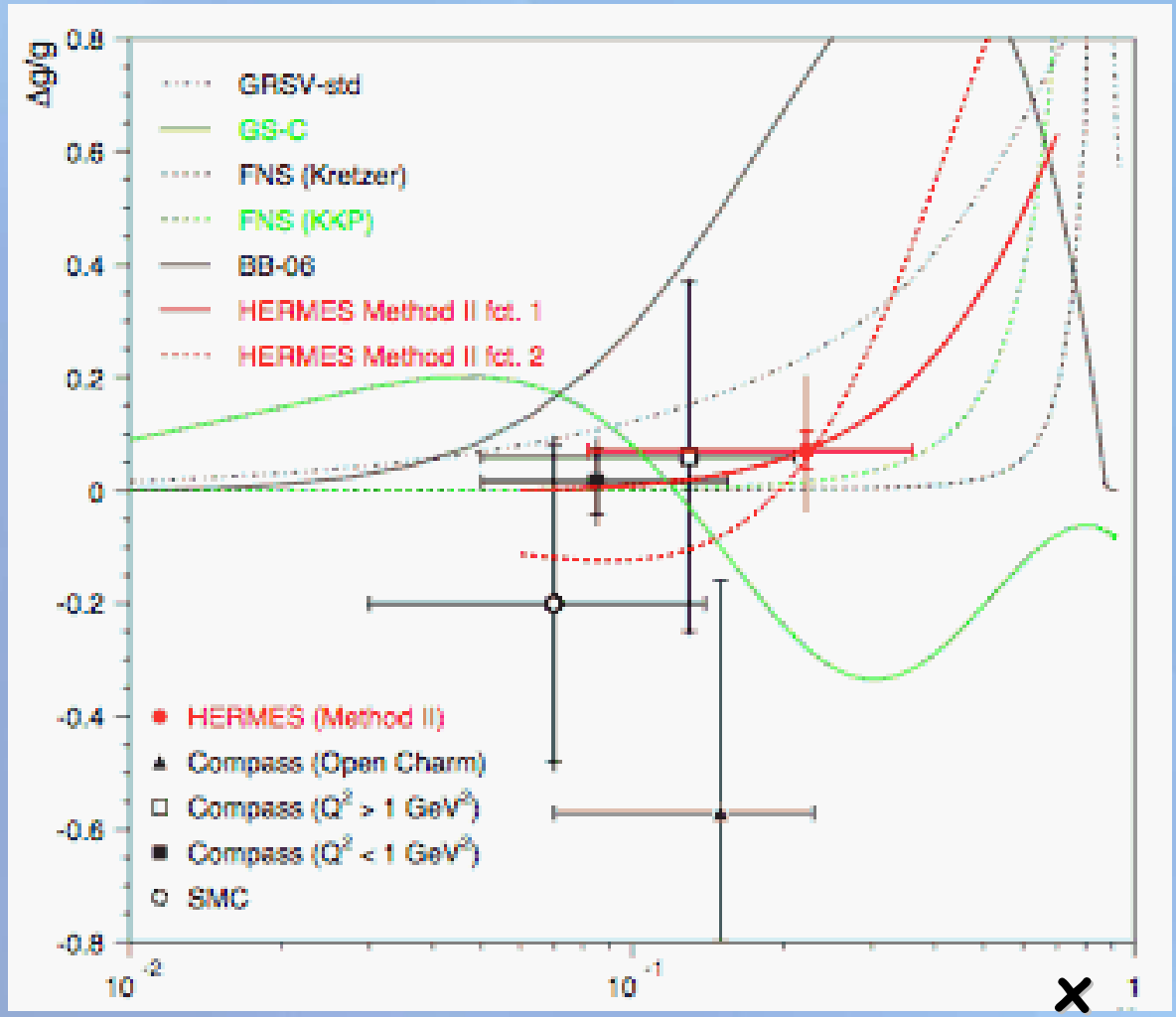
Subprocess Asymmetries (using GRSV std.)



- VMD (el… decreas… with p_T
- DIS increasing with p_T
- QCDC/QCD2->2(q) increasing with p_T
- Signal processes are PGF and QCD2->2(g) (resolved photon)

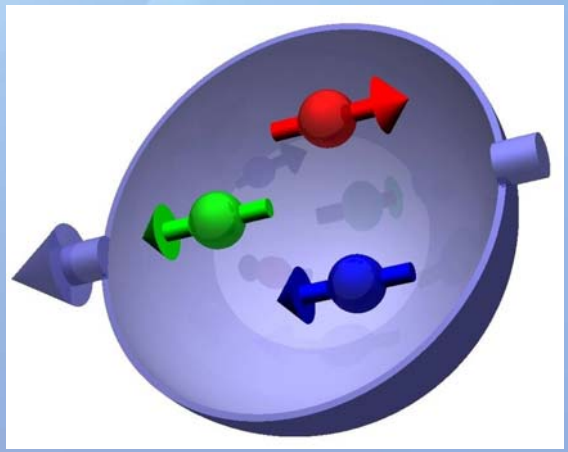
- …ith p_T (x)
- QCDC/QCD2->2, flat and small Important for background asymmetry
- |PGF| increasing with p_T - negative QCD2->2(g) opposite to PGF, small

World Data on ΔG/G



Long way to go till Δg(x)

Quark Orbital Angular Momentum



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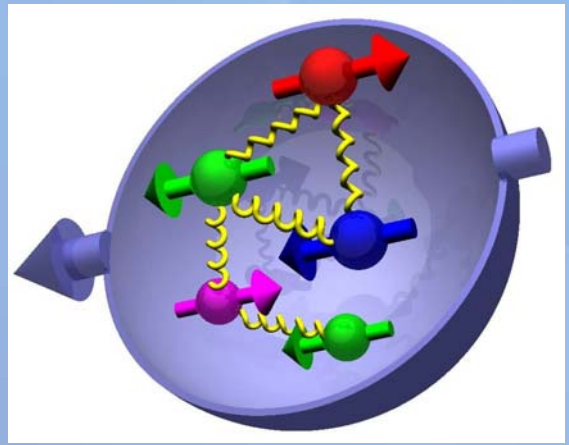

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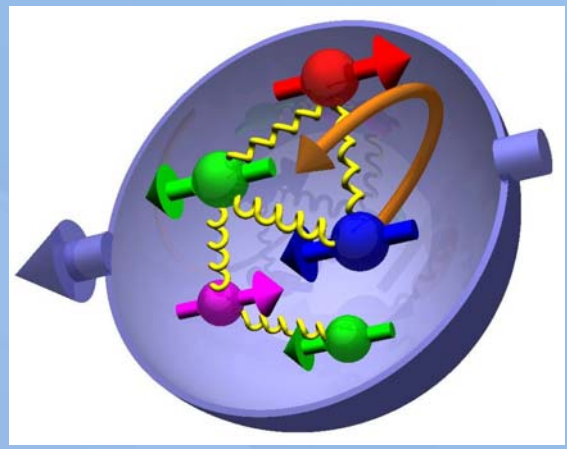

Full description of J_q and J_g

needs

orbital angular momentum

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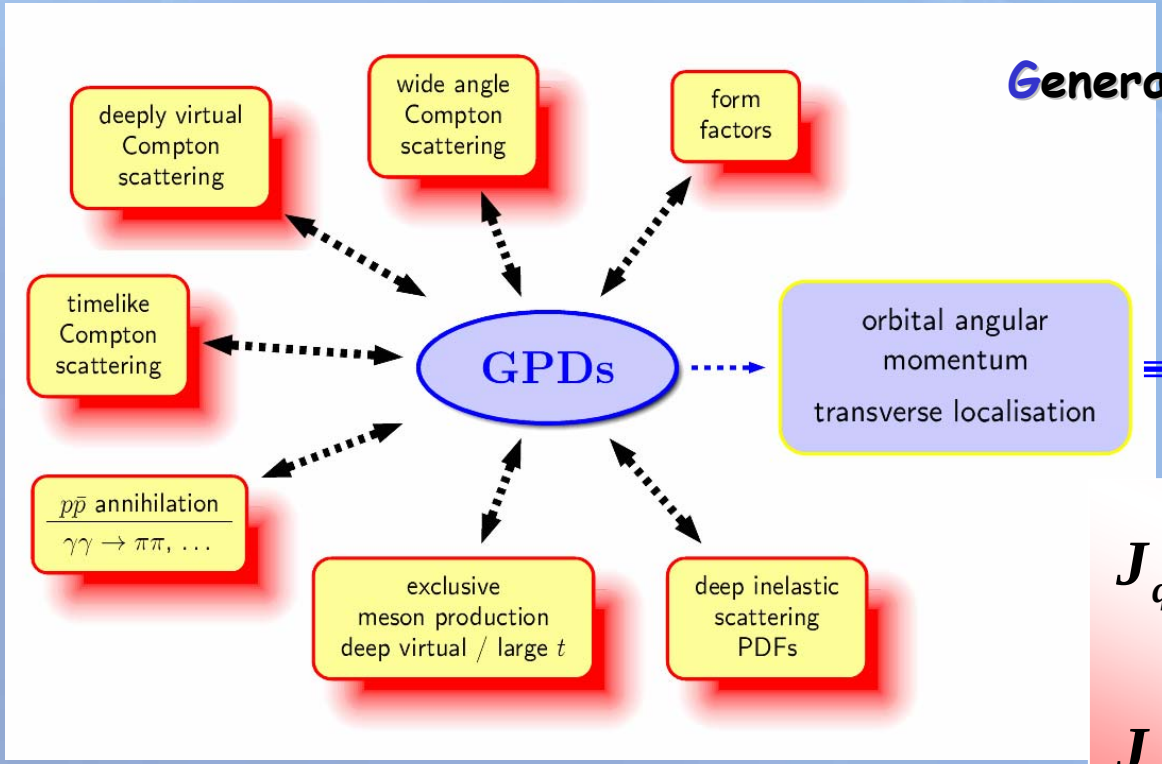
$\Delta\Sigma$

The Hunt for L_q

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



Generalized Parton Distributions

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

⟹ 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

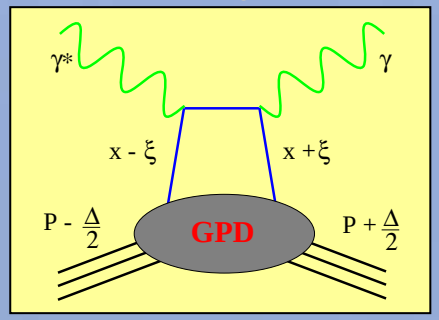
exclusive: all products of the reaction are detected

⟹ 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

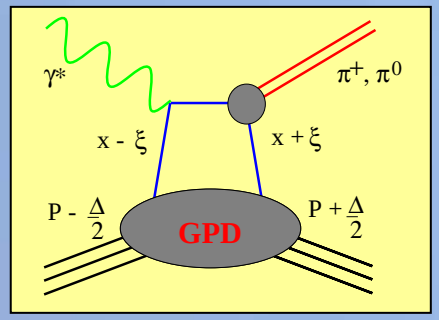
quantum numbers of final state ⟹ select different GPD



DVCS

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

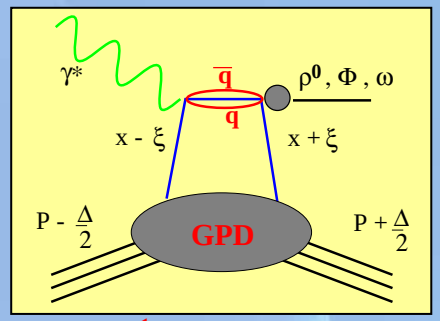
A_C, A_{LU}, A_{UT}, A_{UL}



pseudo-scaler mesons

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

$A_{UT}, \sigma_{\pi+}$

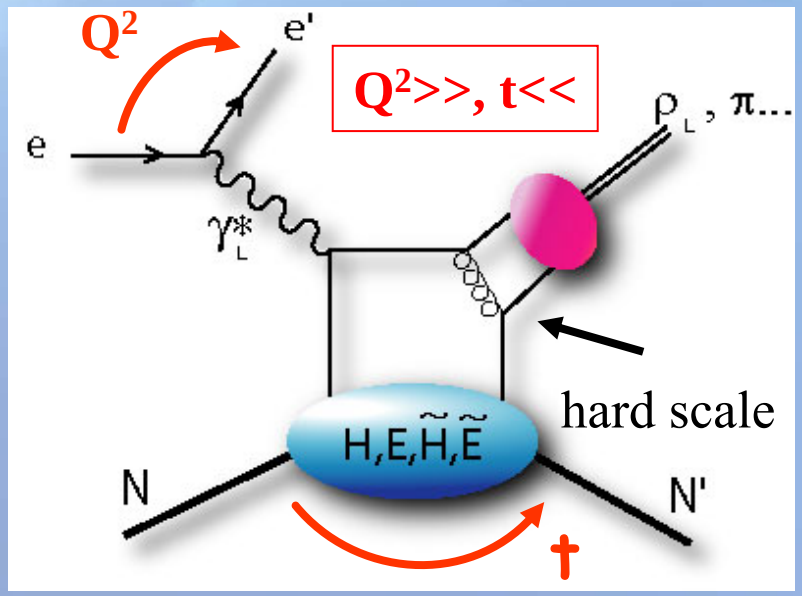


vector mesons

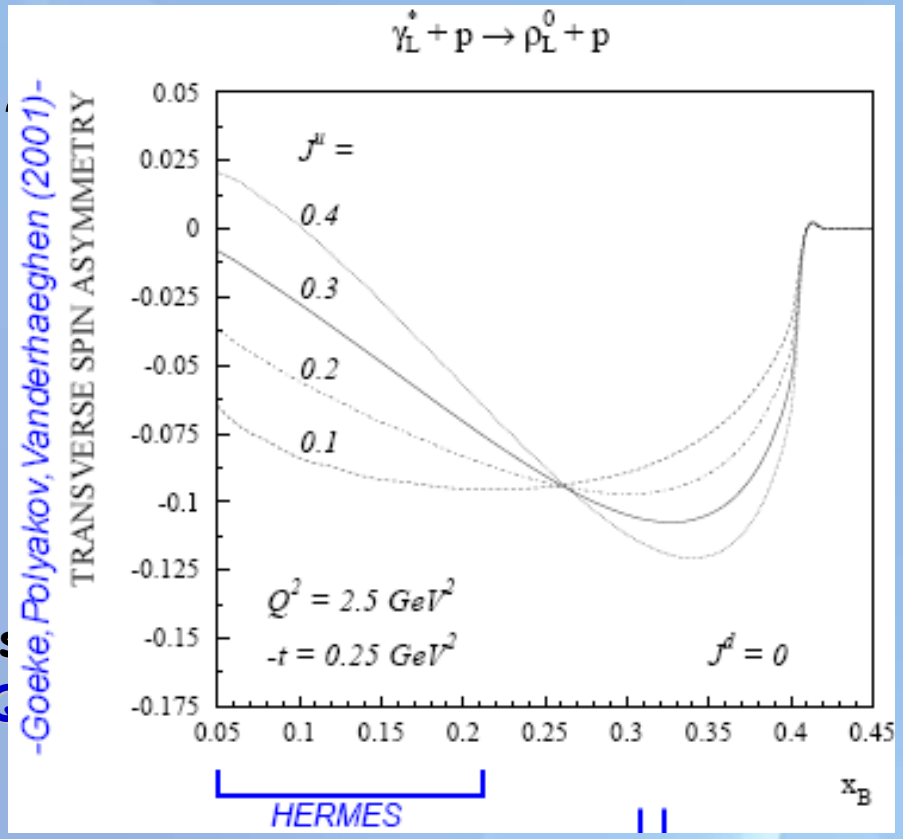
$\underbrace{H^q, E^q}$

$A_{UT}, \sigma_{\rho,\Phi,\omega}$

Exclusive ρ production



- **Meson production:** wave function: additional information/uncertainty



- **Meson production:**
  factorization for longitudinal photons
  σ_T suppressed by $1/Q^2 \rightarrow$ at large Q

$$A_{UT} = -\frac{\pi}{2} A_{theo}$$

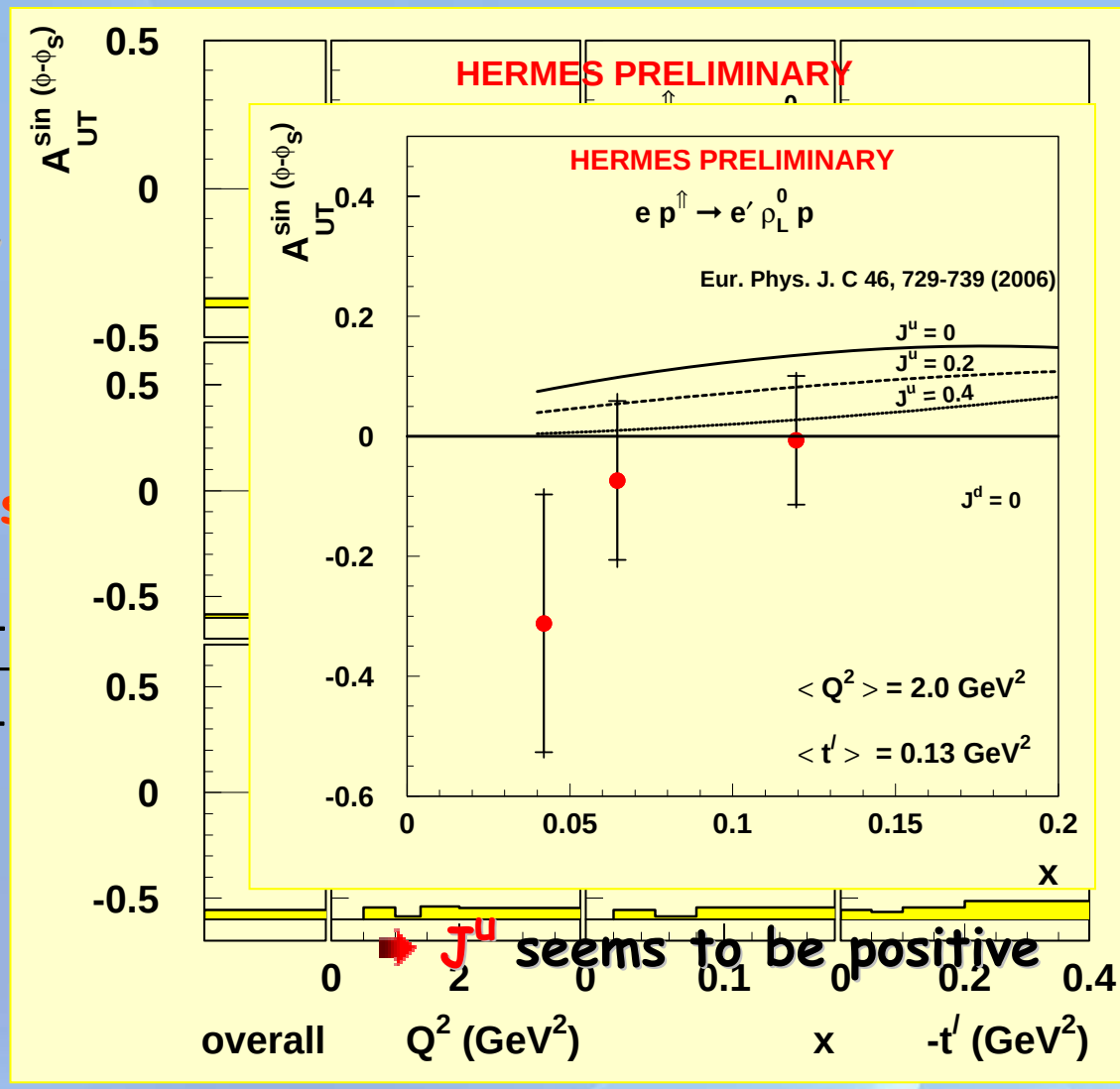
A_{UT} - Exclusive ρ

$$e + p^{\Uparrow} \rightarrow e + p + \rho$$

- exclusivity ensured by ΔE
  - background estimated by
- reconstruct ρ^0 from h^+h^-
- Transverse Target Spin As

$$A_{UT}(\Phi - \Phi_s) = \frac{1}{|P_T|} \frac{N^{\Uparrow} -}{N^{\Uparrow} +}$$

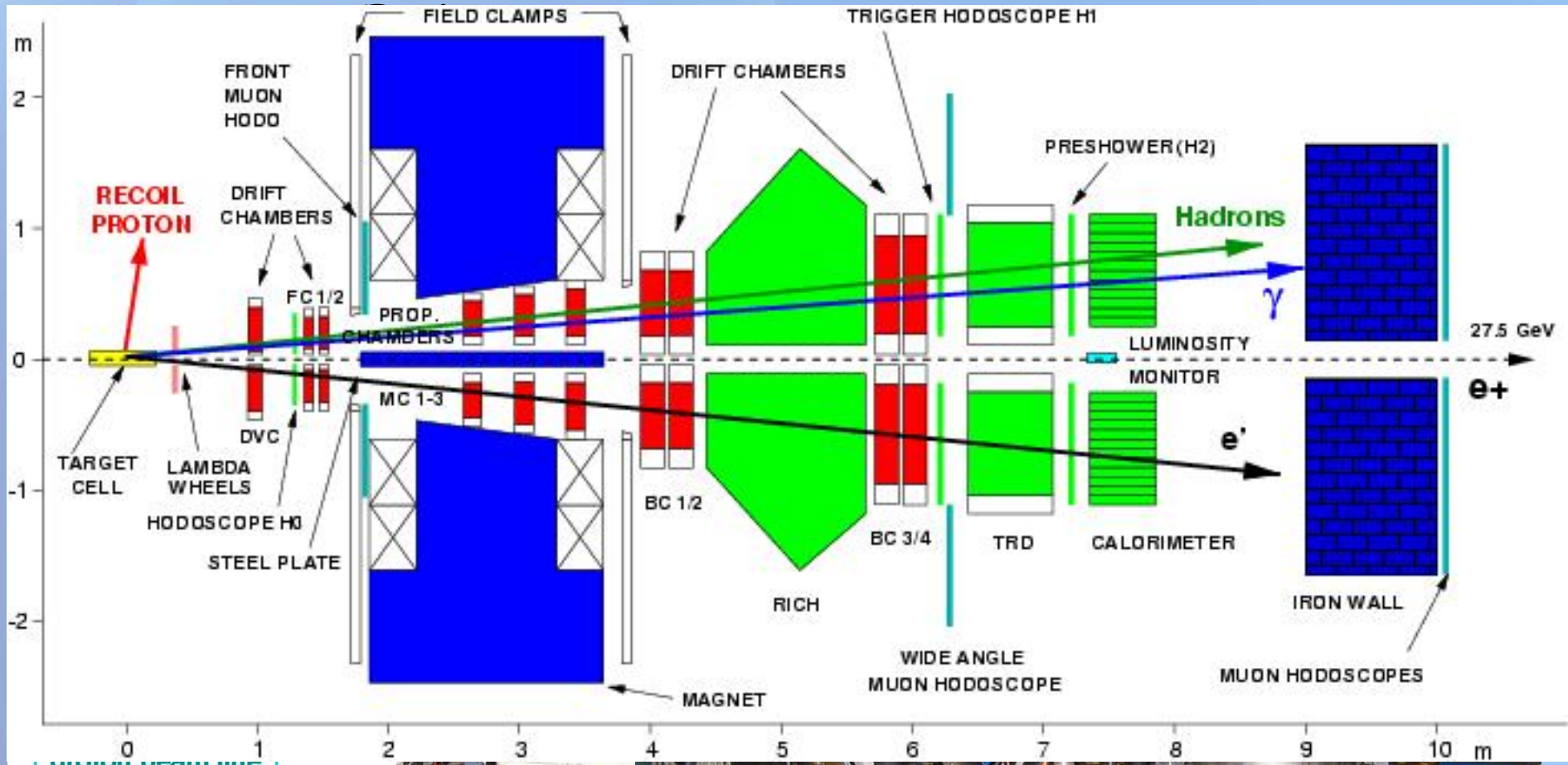
  - with L-T separation



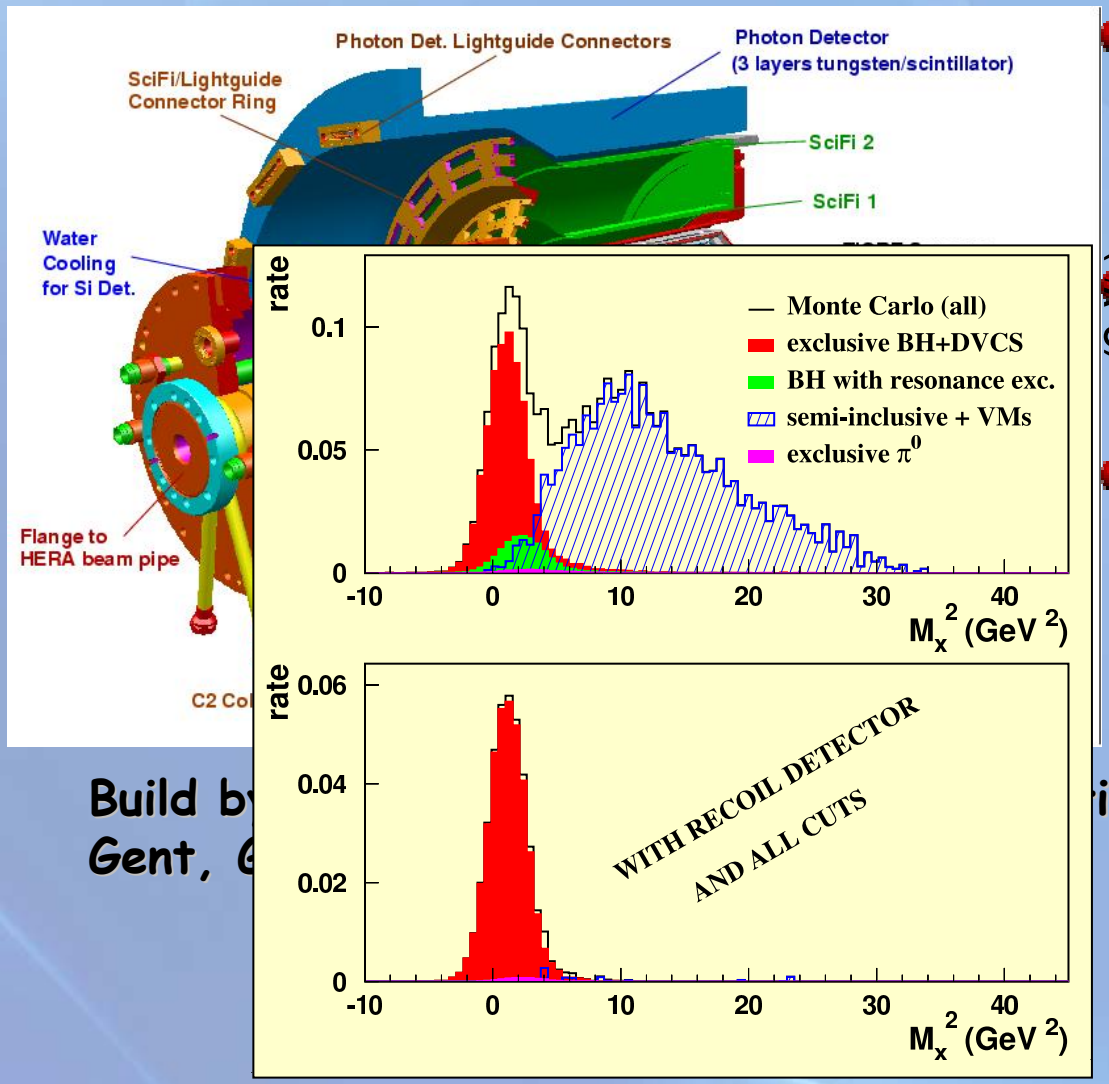
- J^u seems to be positive

The end of polarized targets at HERMES

DVCS exclusivity by missing mass M_x



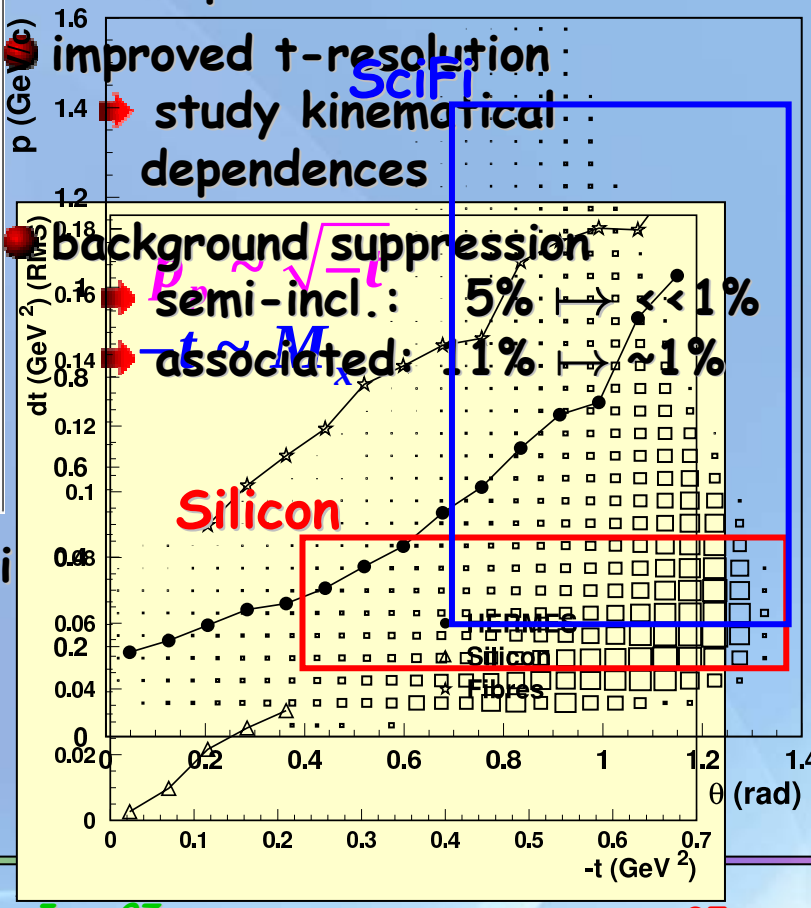
The HERMES Recoil Detector



- 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: 1% $\mapsto$ ~1%

$p_r \sim \sqrt{-t}$

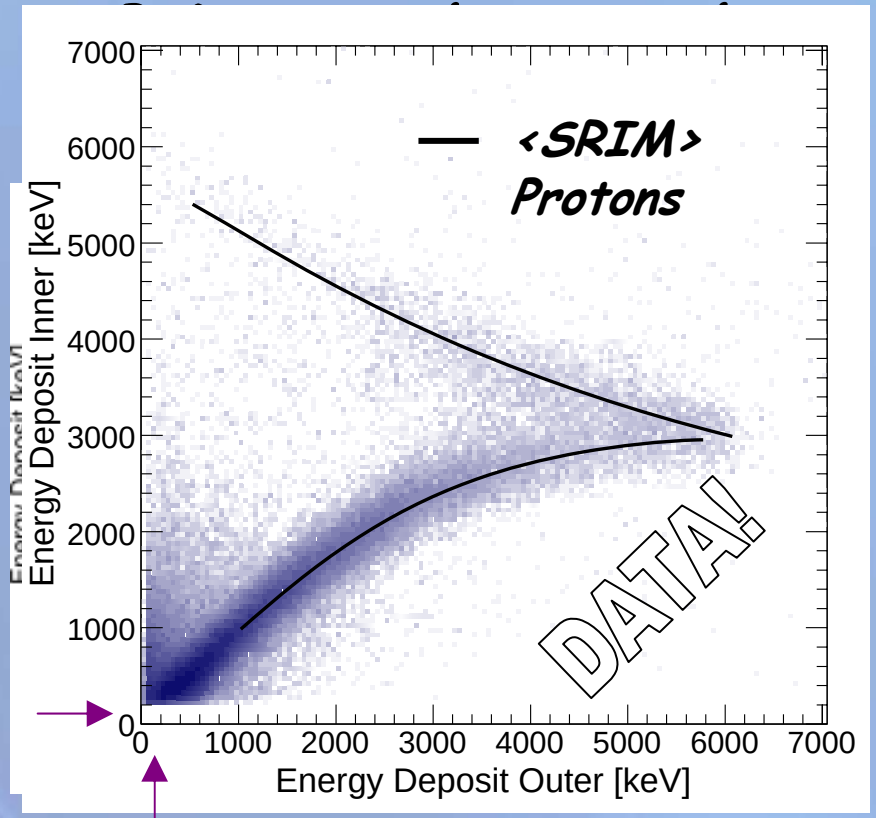
$-t \sim M_x^2$



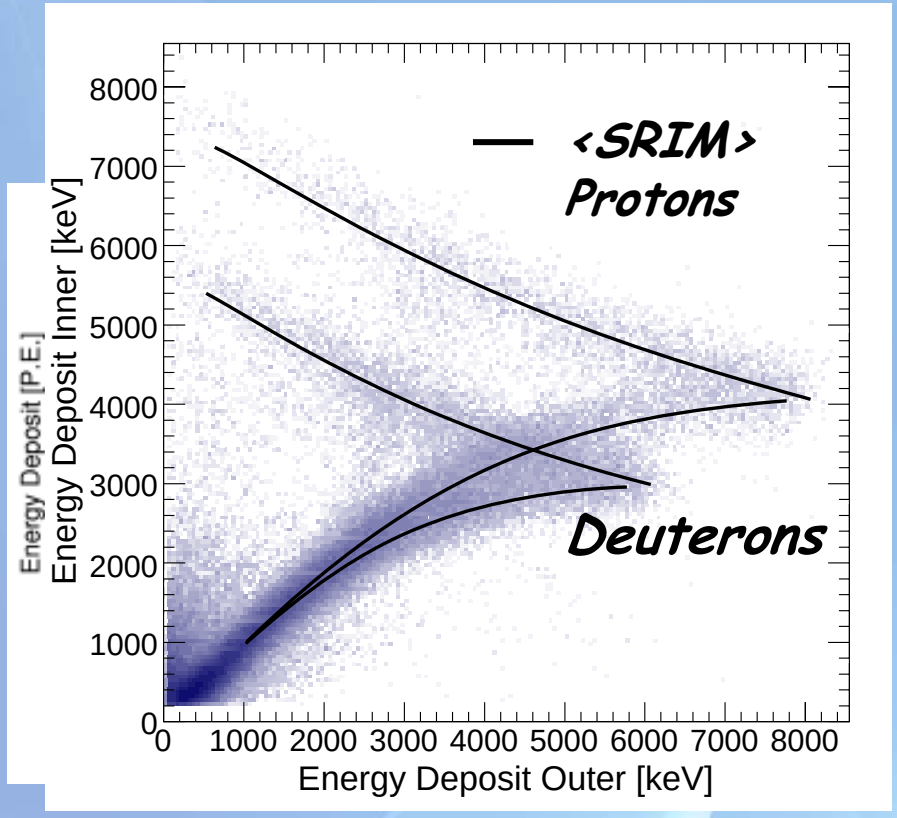
Build by
Gent, G

The HERMES Recoil Detector

- perfectly running since July 06
- alignment and first calibration done
- Recoil proton and deuteron seen in silicon

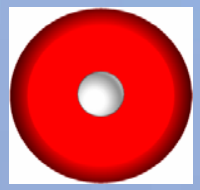


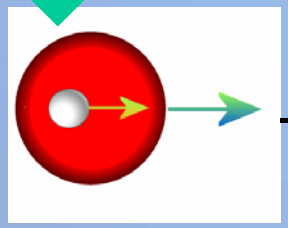
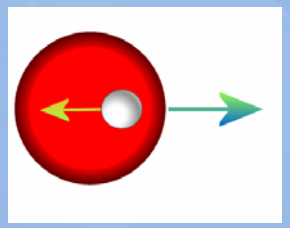
1MIP

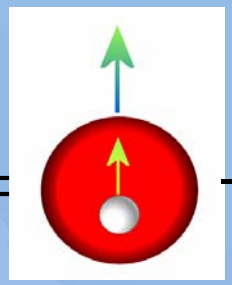
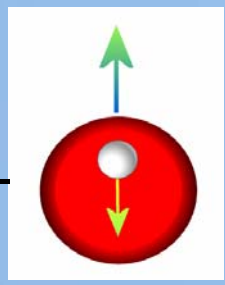


The 3rd Twist-2 structure function

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

$f_1^q =$ 

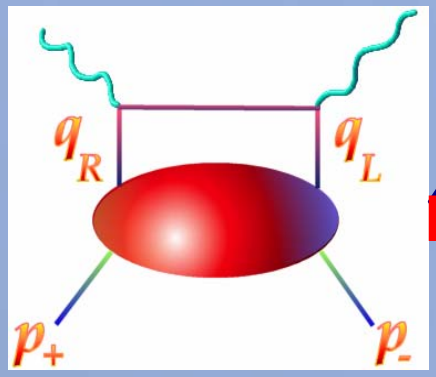
$g_1^q =$  $-$ 

$h_1^q =$  $-$ 

unpolarised quarks and nucleons	longitudinally polarized quarks and nucleons	transversely polarized quarks and nucleons
q(x): spin averaged	Δq(x): helicity difference	δq(x): *helicity flip*
→ vector charge	→ axial charge	→ tensor charge
well known	**known**	***measuring!***

Peculiarities of transversity

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



single helicity flip

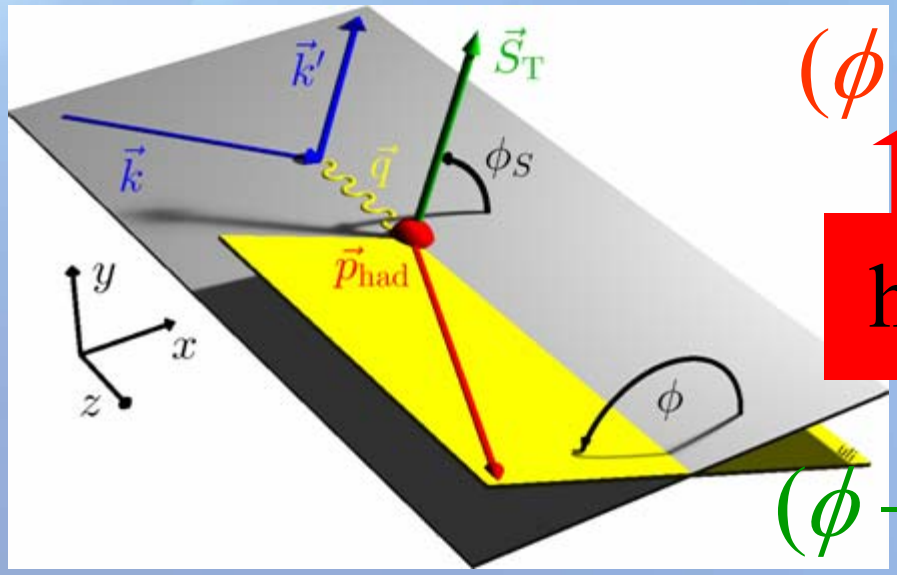
<u>relativistic nature of quark</u>:
in absence of relativistic effects $h_1(x)=g_1(x)$

<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)

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

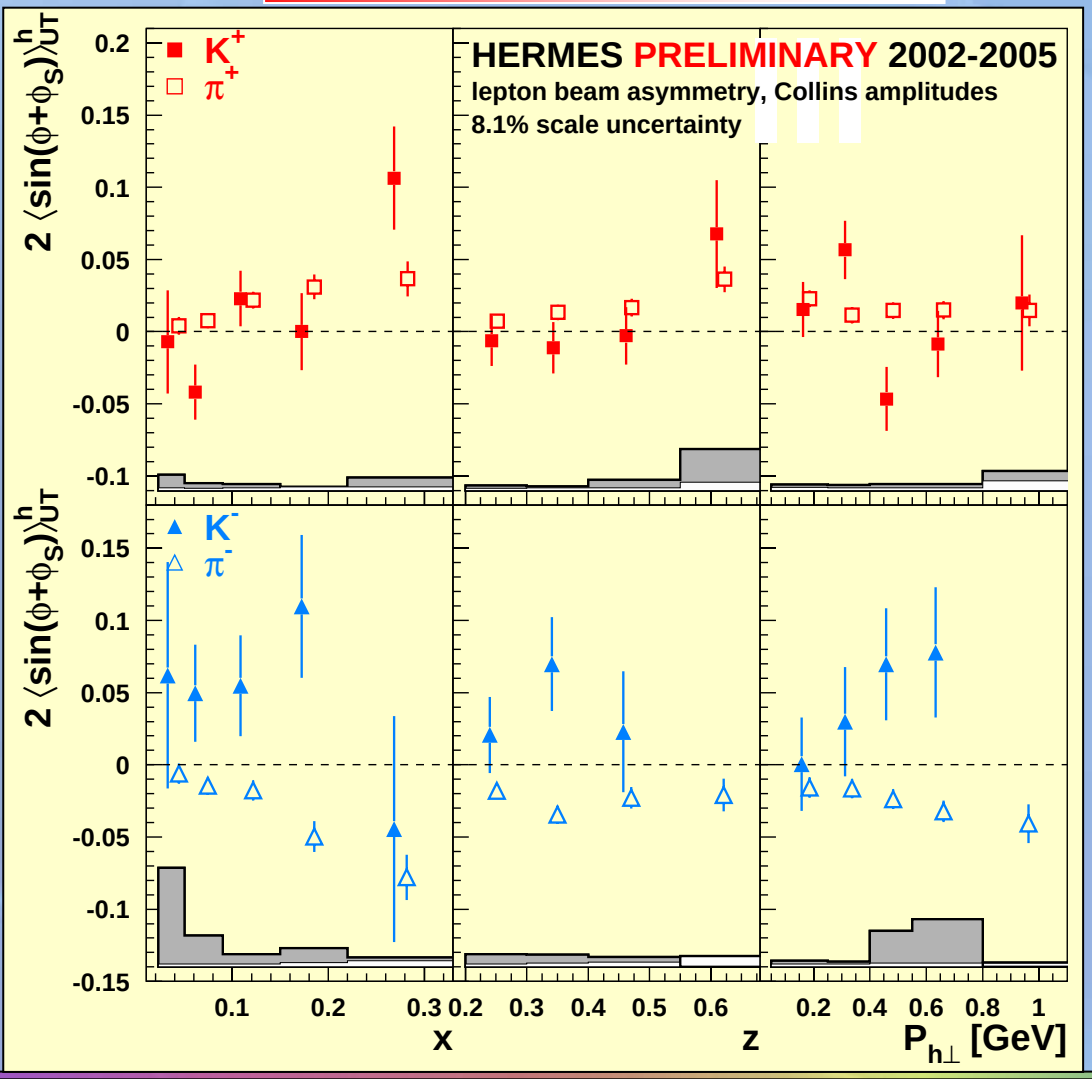
related to parton orbital momentum

violates naïve universality of PDF

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

Collins moments

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

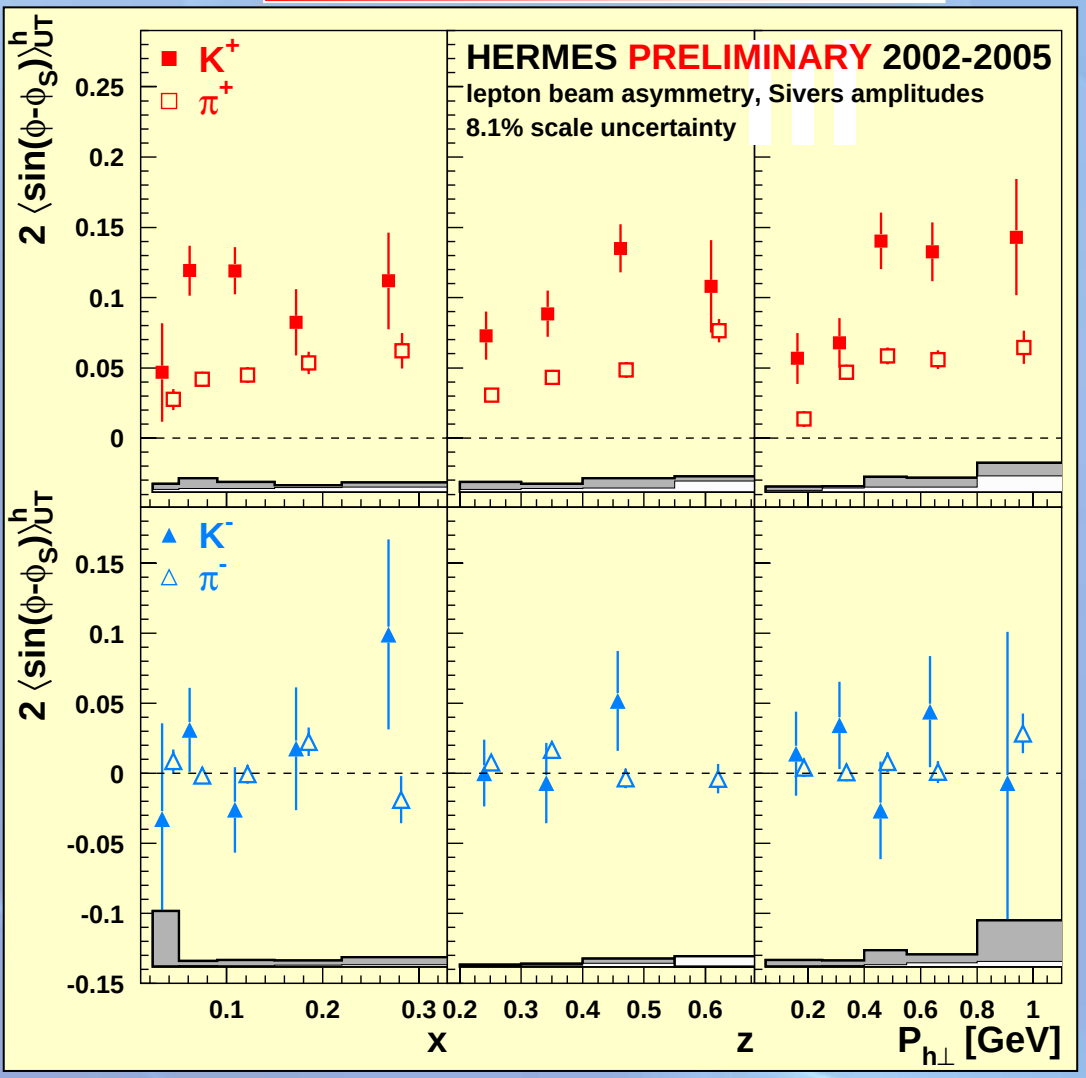


- Collins moment:
  $\pi^+ > 0$ $\pi^- < 0$
- π^- unexpected large
  - role of unfavoured FF
    $H_{fav} = - H_{unfav}$
- $K^+ > 0$ $K^- > 0$
  K^+ and π^+ consistent with u-quark dominance
- K^- and π^-
  complicated sea quark contr
- Collins moments:

π^+: 0.01374 ± 0.0028
π^0: -0.01158 ± 0.0078
π^-: -0.02260 ± 0.0033
K^+: 0.00229 ± 0.0101
K^-: 0.04336 ± 0.0189

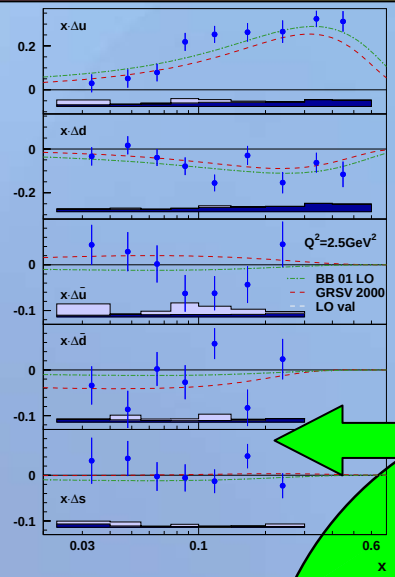
Sivers moments

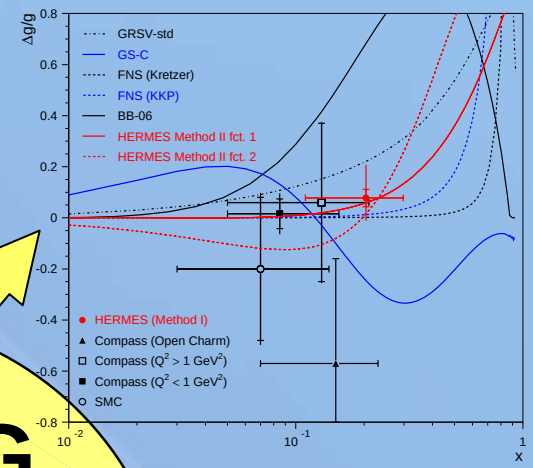
$$A_{Sivers} \propto f_{1T}^{\perp}(x) D_1(z)$$

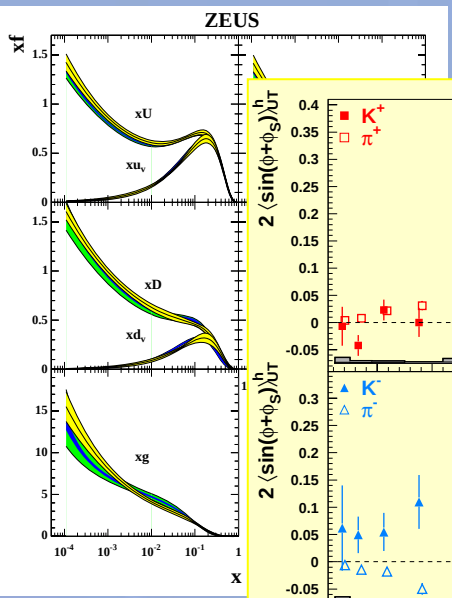


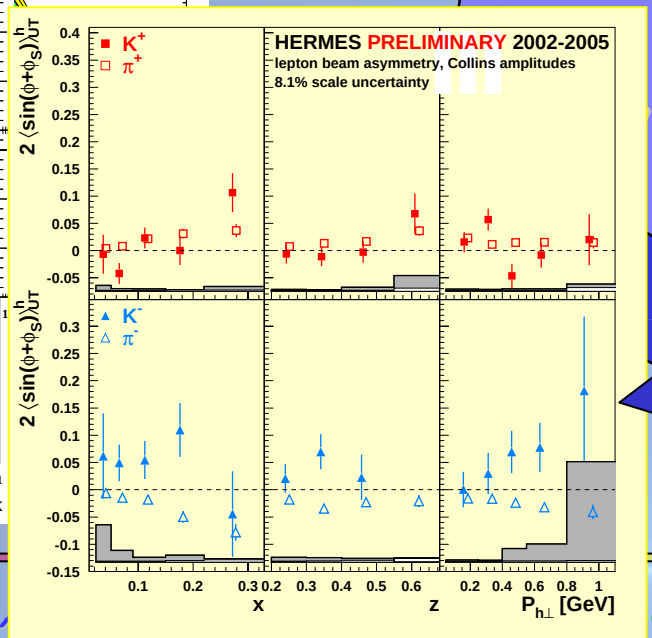
- Sivers moment:
  $\pi^+ > 0$ $\pi^- \sim 0$
- $K^+ > 0$ $K^- \sim 0$
  $K^+ > \pi^+$
  - sea quarks important
- Sivers moments:
  π^+: 0.04343 ± 0.0027
  π^0: 0.02892 ± 0.0078
  π^-: 0.00579 ± 0.0033
  K^+: 0.10009 ± 0.0093
  K^-: 0.01081 ± 0.0165
- non-zero orbital angular momentum in p-wave fct.
  - L_q ??
- opposite sign $f_{1T}^{\perp}$ in DIS and Drell-Yan

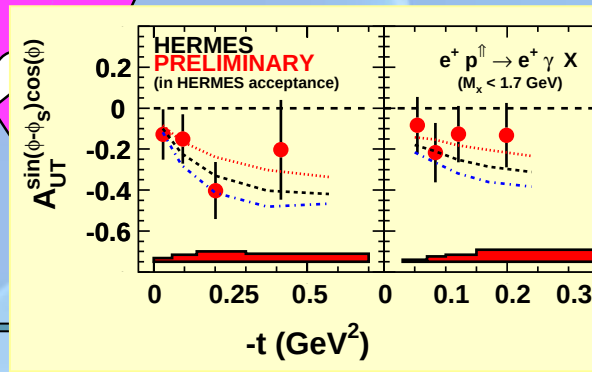
Summary and Outlook



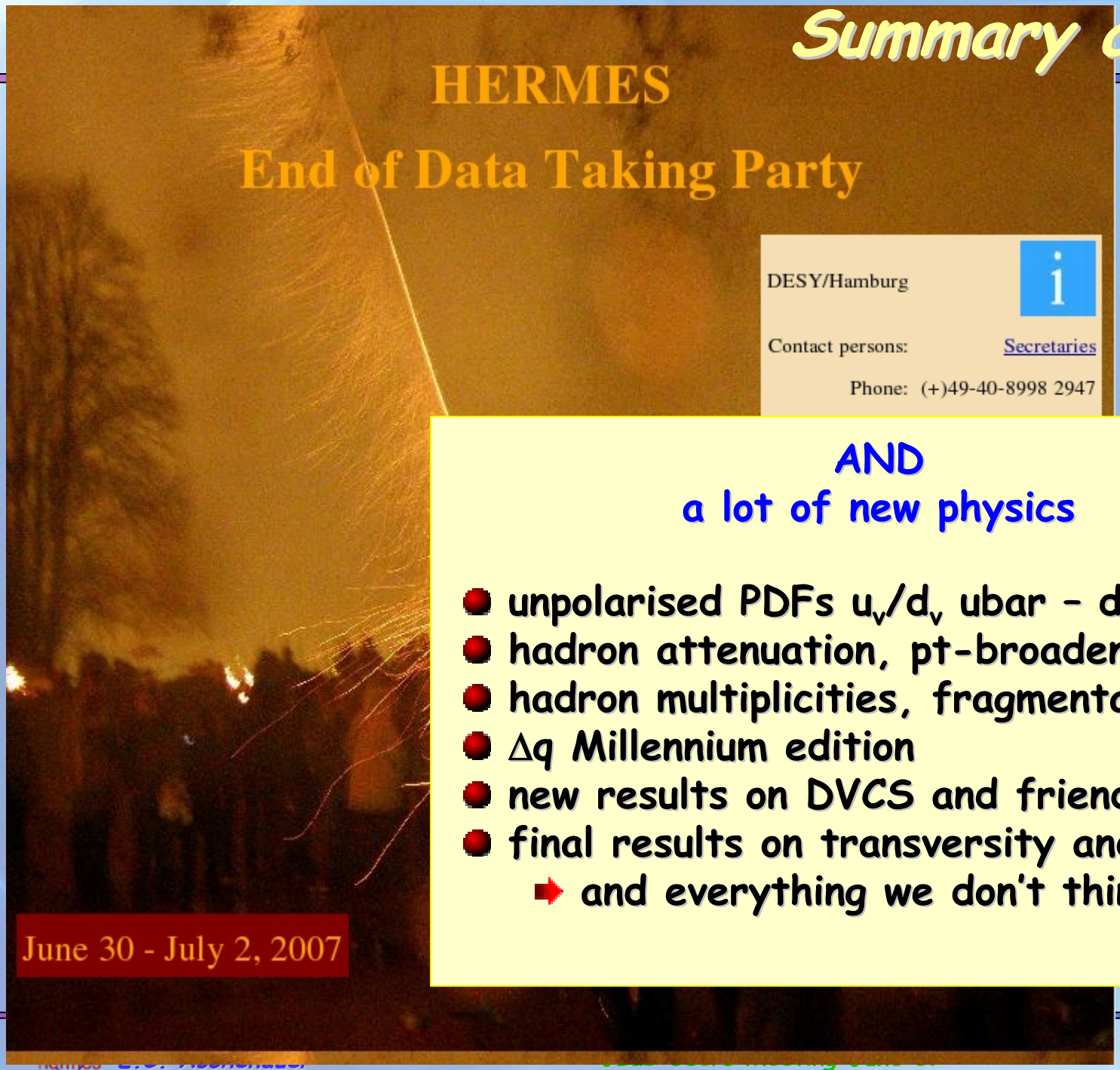








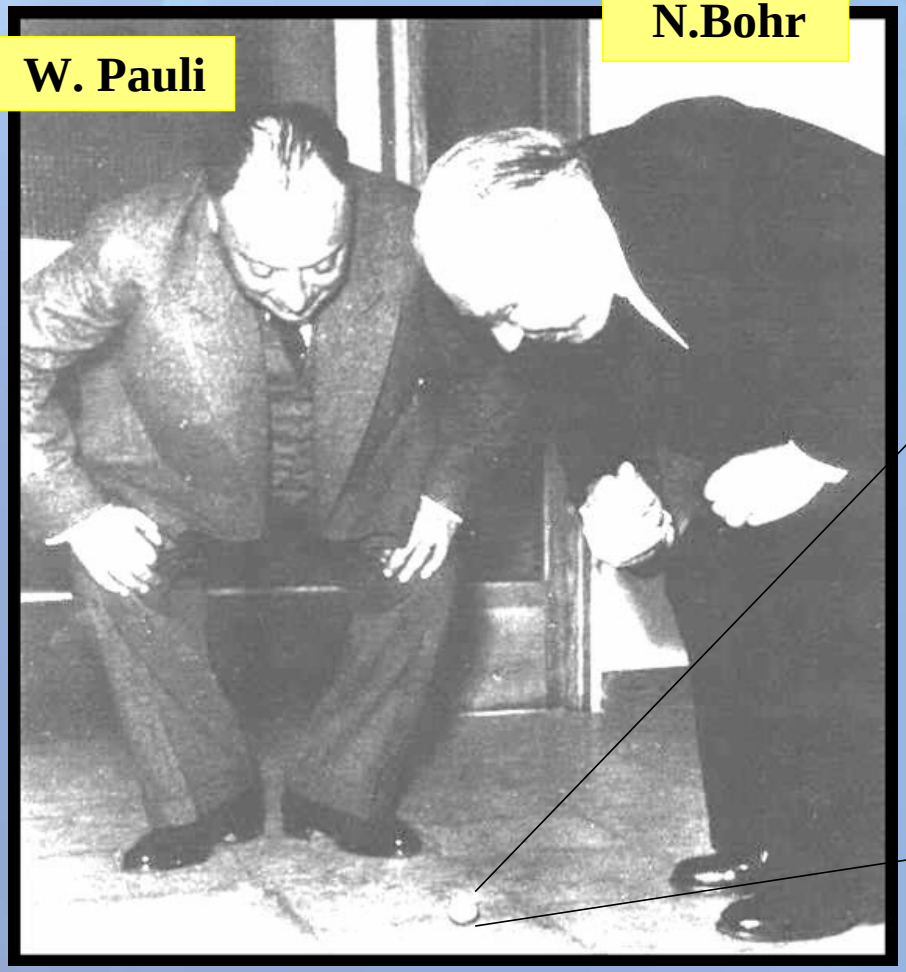
Summary and Outlook

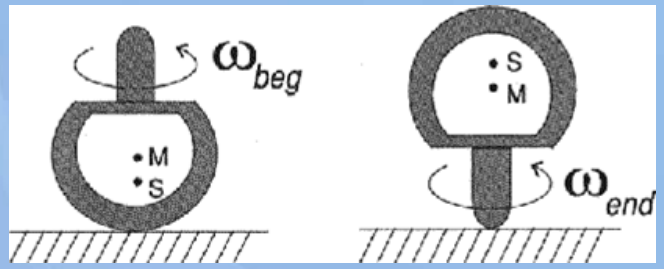


AND
a lot of new physics

- unpolarised PDFs u_v/d_v ubar – dbar, F_2
- hadron attenuation, pt-broadening
- hadron multiplicities, fragmentation fcts.
- Δq Millennium edition
- new results on DVCS and friends
- final results on transversity and friends
  - and everything we don't think about yet

Spin is fascinating





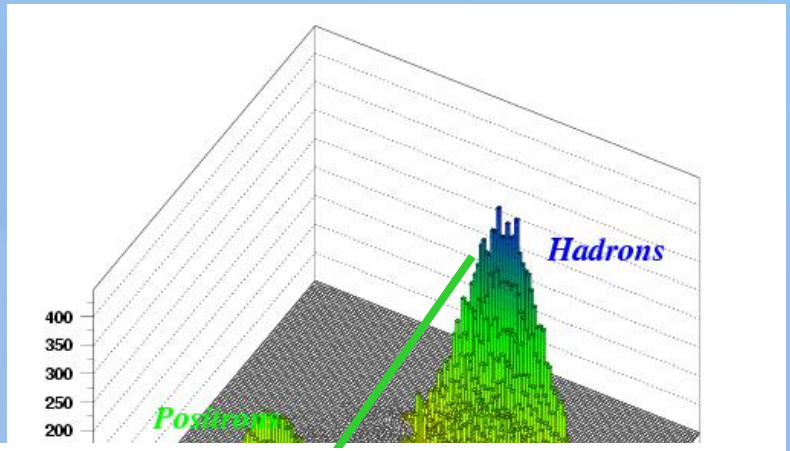
Thank you for your attention

BACKUP

Which Hadron (π,K,p) is Which

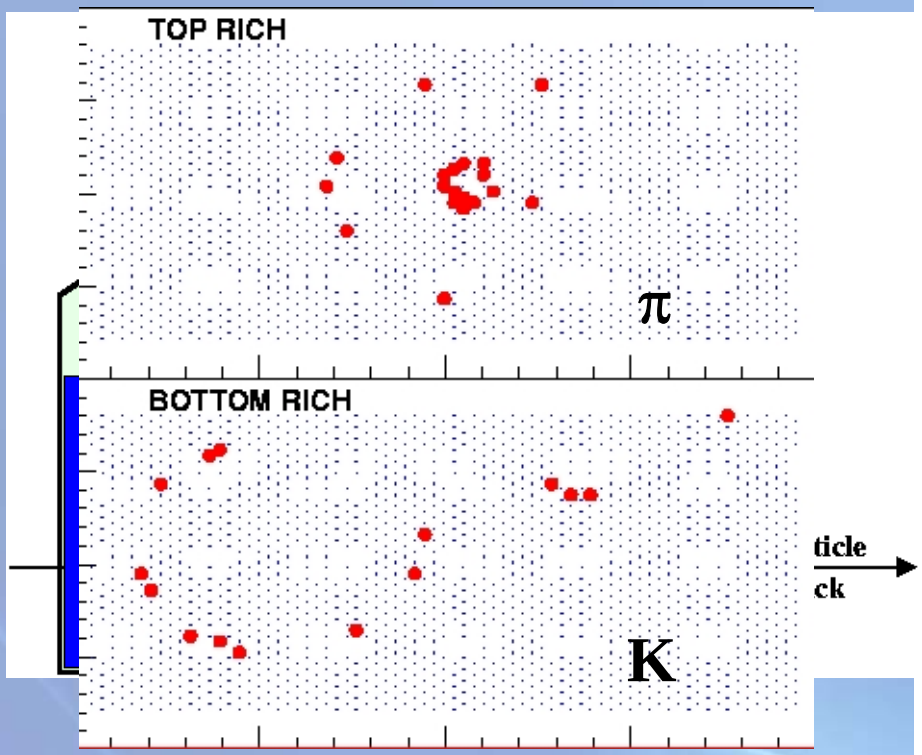
hadron/positron separation

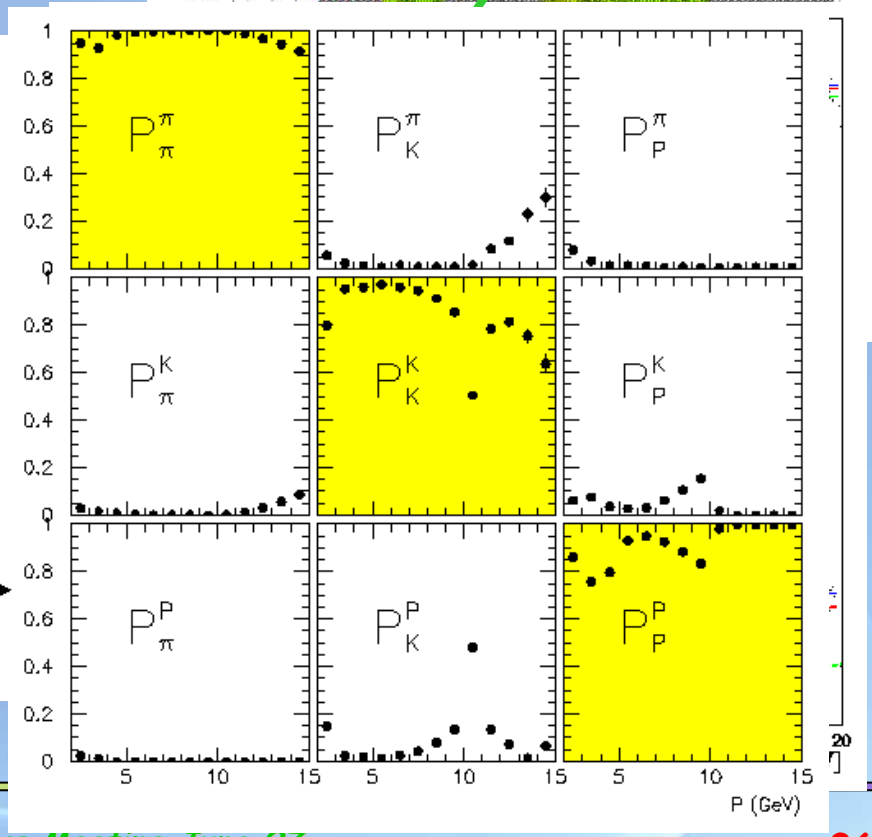
combining signals from:
TRD, calorimeter, preshower



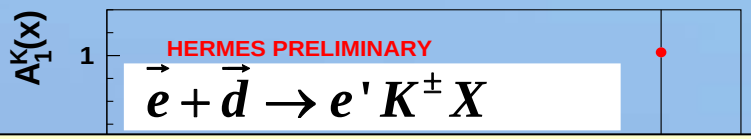
hadron separation

Dual radiator RICH for π, K, p





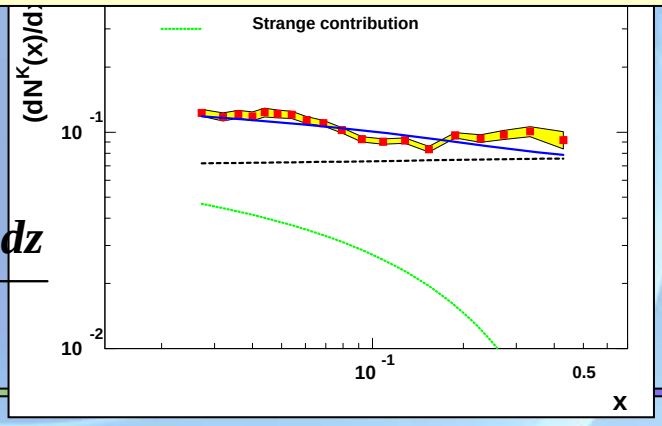
Results for ΔQ and ΔS



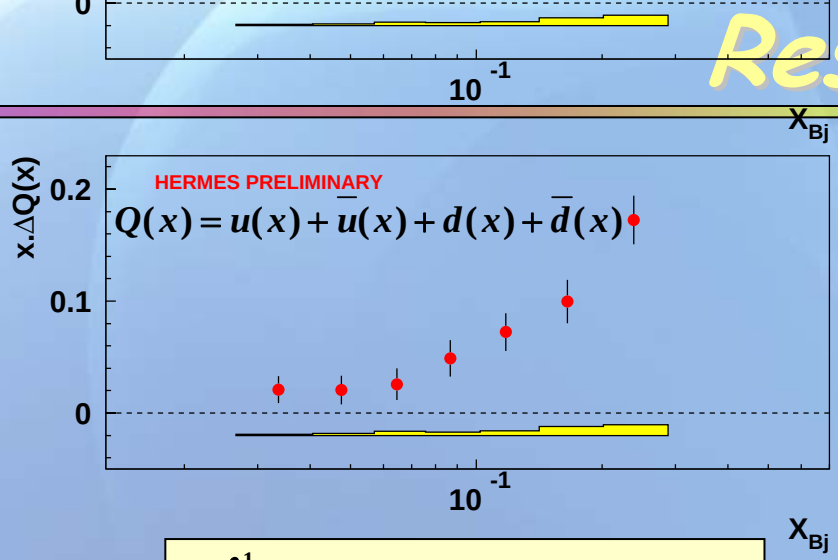
- Need a longitudinal polarized deuterium target
  - strange quark sea in proton and neutron identical
  - fragmentation simplifies
- All needed information can be extracted from HERMES data alone
  - inclusive $A_{1,d}(x,Q^2)$ and kaon $A^K_{1,d}(x,Q^2)$ double spin asym.
  - Kaon multiplicities
- Only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

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

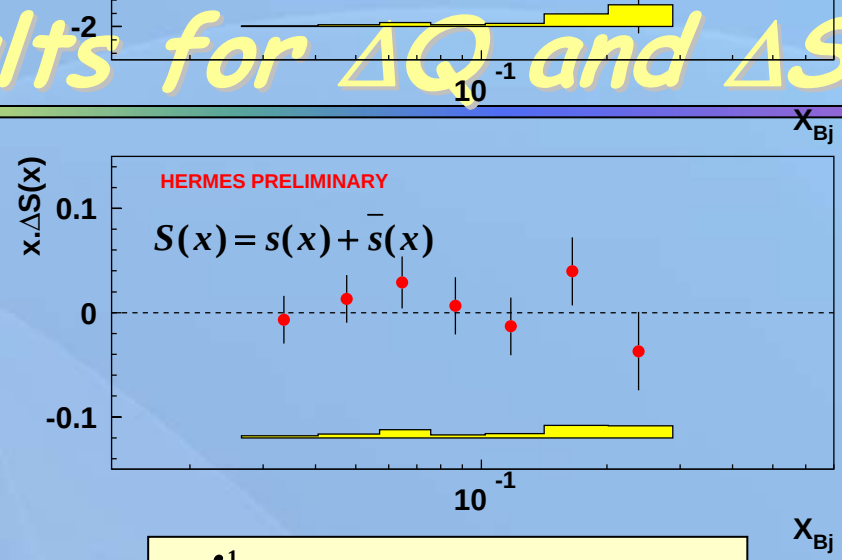
	This Work	Kretzer	KKP
$\int D^K_{nstrg}(z)dz$	0.41±0.02	1.103	1.111
$\int D^K_{strg}(z)dz$	1.41±0.29	0.783	0.296



Results for ΔQ and ΔS

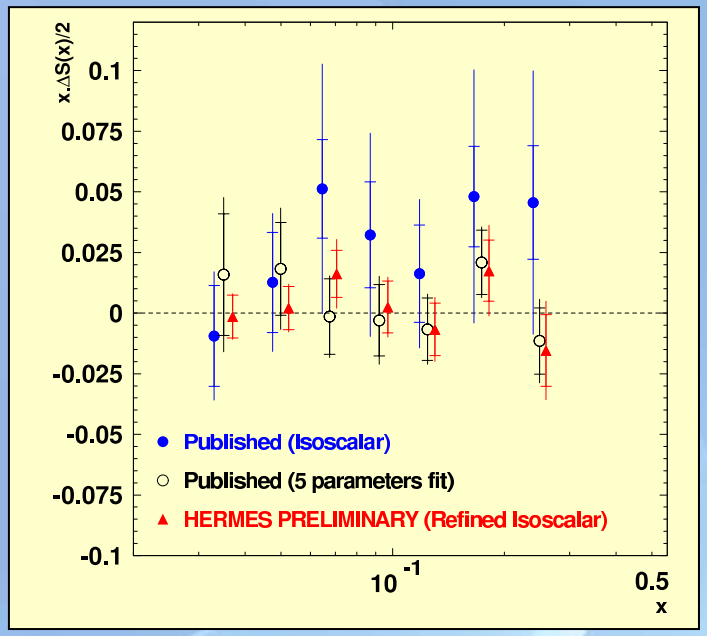


$$\int_{0.02}^{1} \Delta Q = 0.286 \pm 0.026 \pm 0.011$$



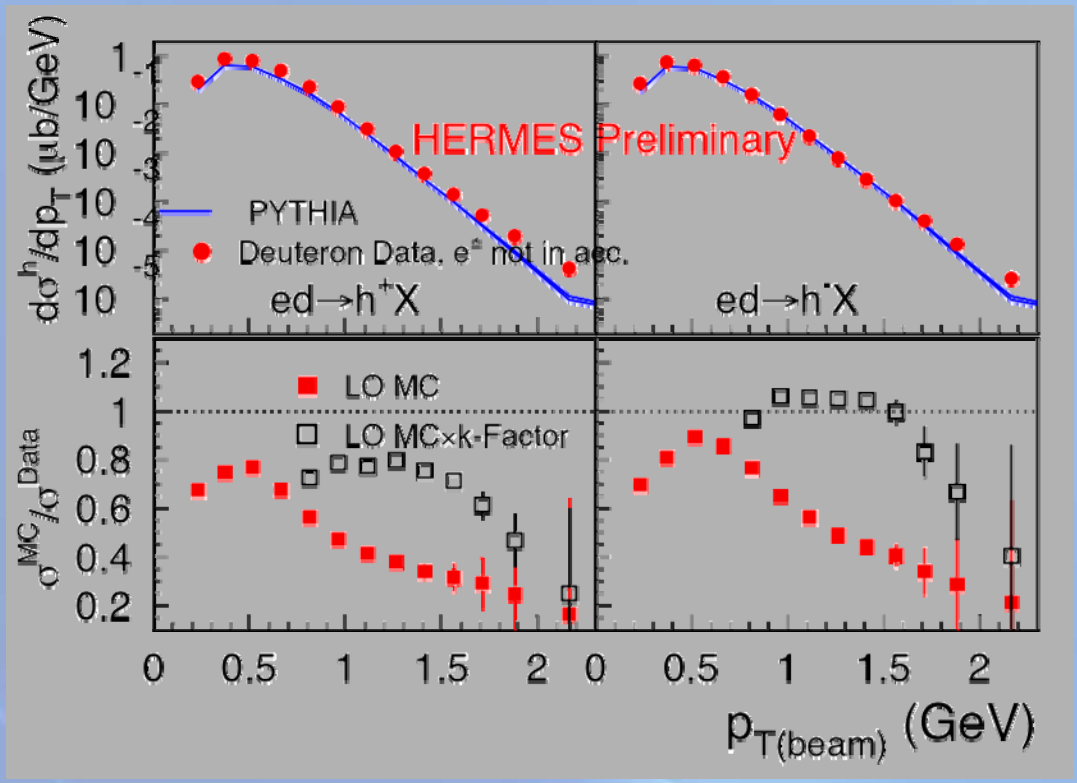
$$\int_{0.02}^{1} \Delta S = 0.006 \pm 0.029 \pm 0.007$$

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

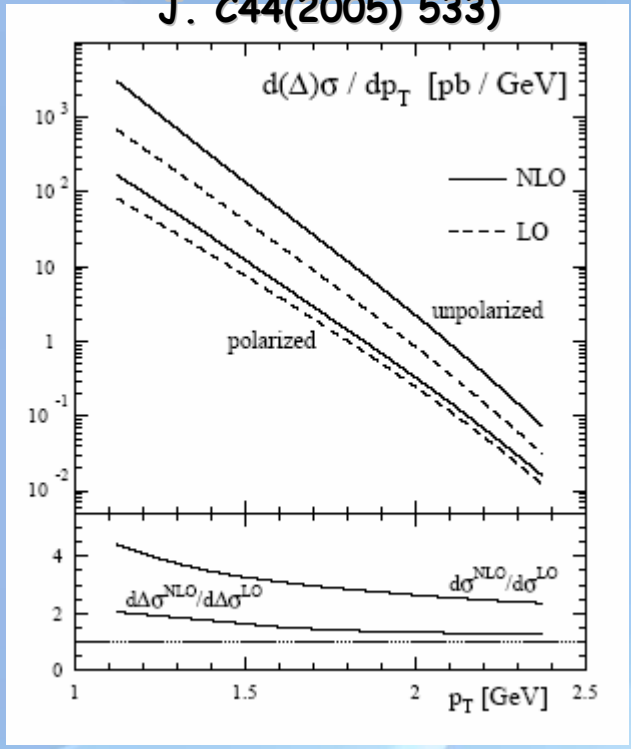


Cross Section Data-MC

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



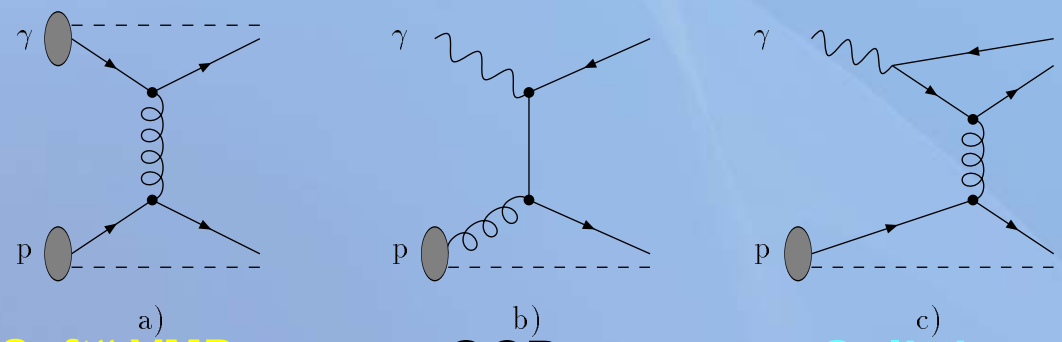
Polarized and unpol. cross sections and k factors (B. Jäger et. al., Eur.Phys. J. C44(2005) 533)



The Model in PYTHIA-6

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

VMD | direct | anomalous photon



„Soft“ VMD: Elastic, diffractive, non-diffractive („minimum bias“, „low-p_T“) processes

Hard VMD: QCD 2→2 processes

QCD-Compton

BGF

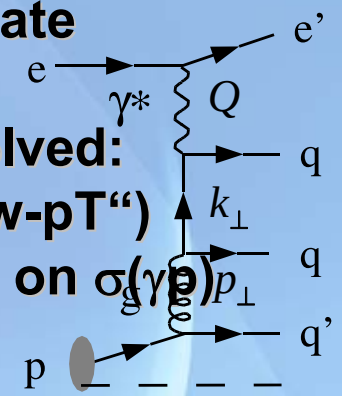
LO DIS

(according to hardest scale involved: „soft“)

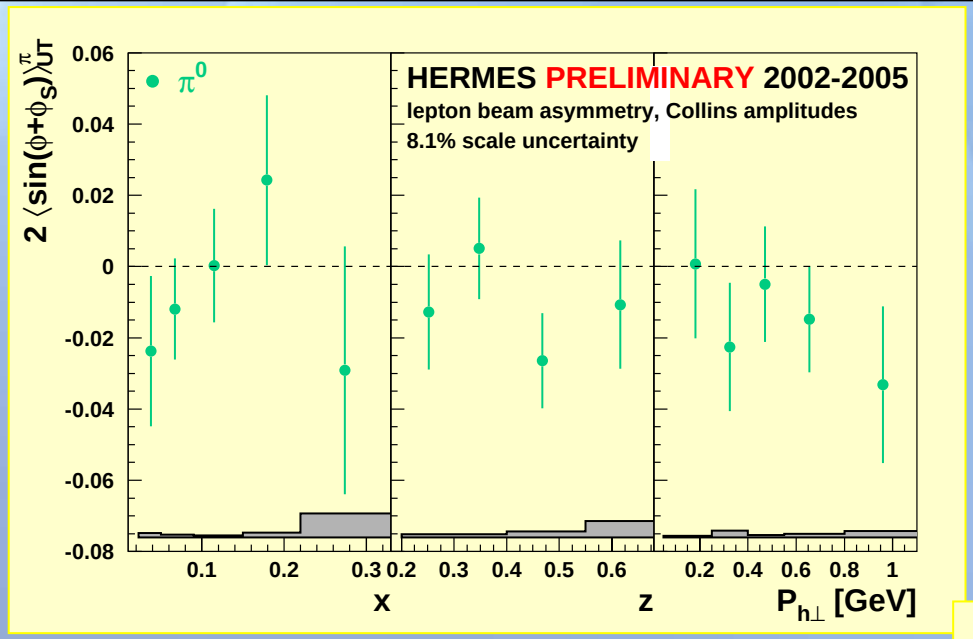
Splitting of $\gamma \to qq$

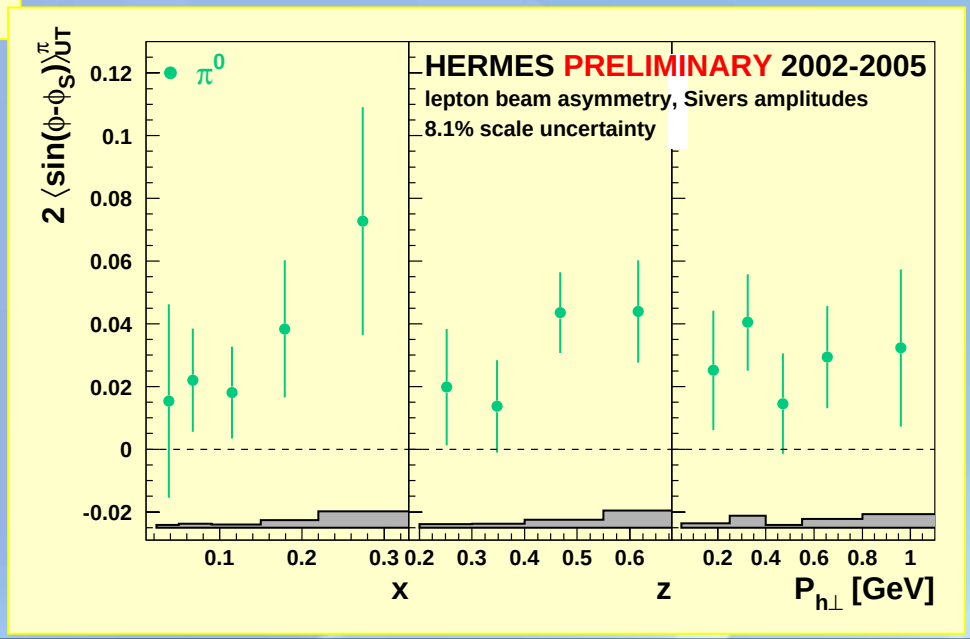
QCD 2→2 photon-dominate processes

- 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 $\sigma(\gamma p)$

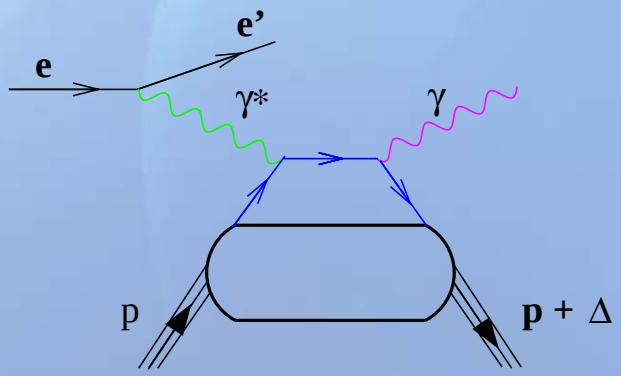


Transverity and Sivers π^0

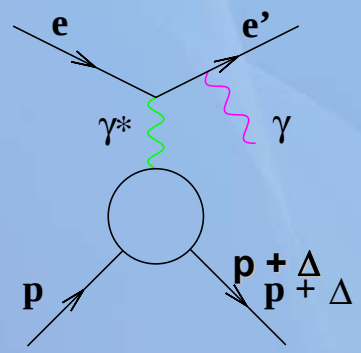




two experimentally undistinguishable processes:

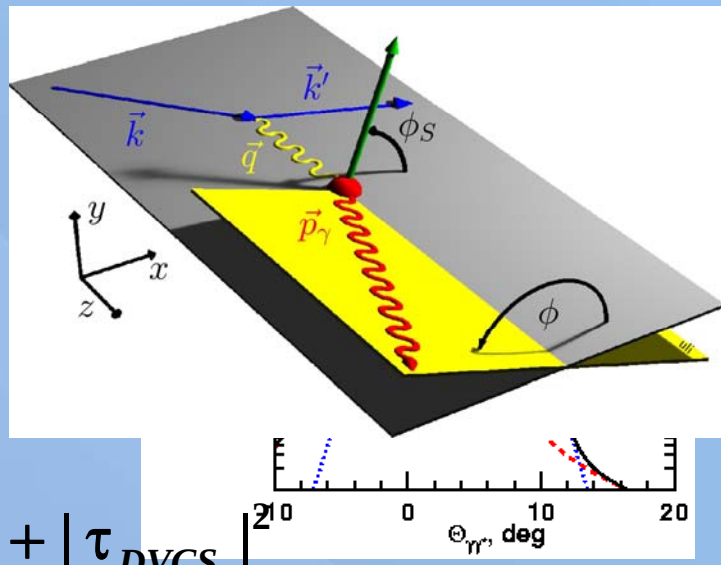


DVCS



Bethe-Heitler (BH)

HERMES kinematics:



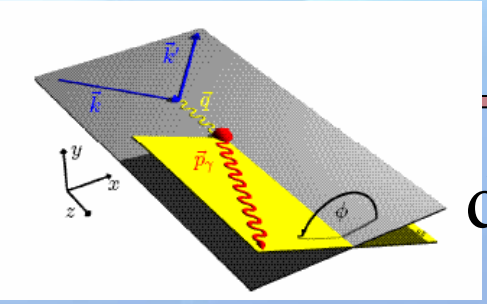
$$d\sigma \sim \left(\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH}\right) + |\tau_{BH}|^2 + |\tau_{DVCS}|^2$$

isolate BH-DVCS interference term ⟹ non-zero azimuthal asymmetries

transverse target spin asymmetry:

$$d\sigma_{p\Uparrow} - d\sigma_{p\Downarrow} \sim \underbrace{\mathrm{Im}(F_2 H - F_1 E)}_{A_{UT}^{\sin(\phi-\phi_s)\cos(\phi)}} \sin(\phi-\phi_s)\cos(\phi) + \underbrace{\mathrm{Im}(F_2 \tilde{H} - F_1 \xi \tilde{E})}_{A_{UT}^{\cos(\phi-\phi_s)\sin(\phi)}} \cos(\phi-\phi_s)\sin(\phi)$$

DVCS ASYMMETRIES



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

$I \sim \Delta\sigma$

→ different charges: $e^+ e^-$ *(only @HERA!)*:

$\Delta\sigma_C \sim \cos\phi \cdot \mathrm{Re}\{ \mathbf{H} + \xi\tilde{\mathbf{H}} + \ldots \}$ ⇒ H ←

→polarization observables:

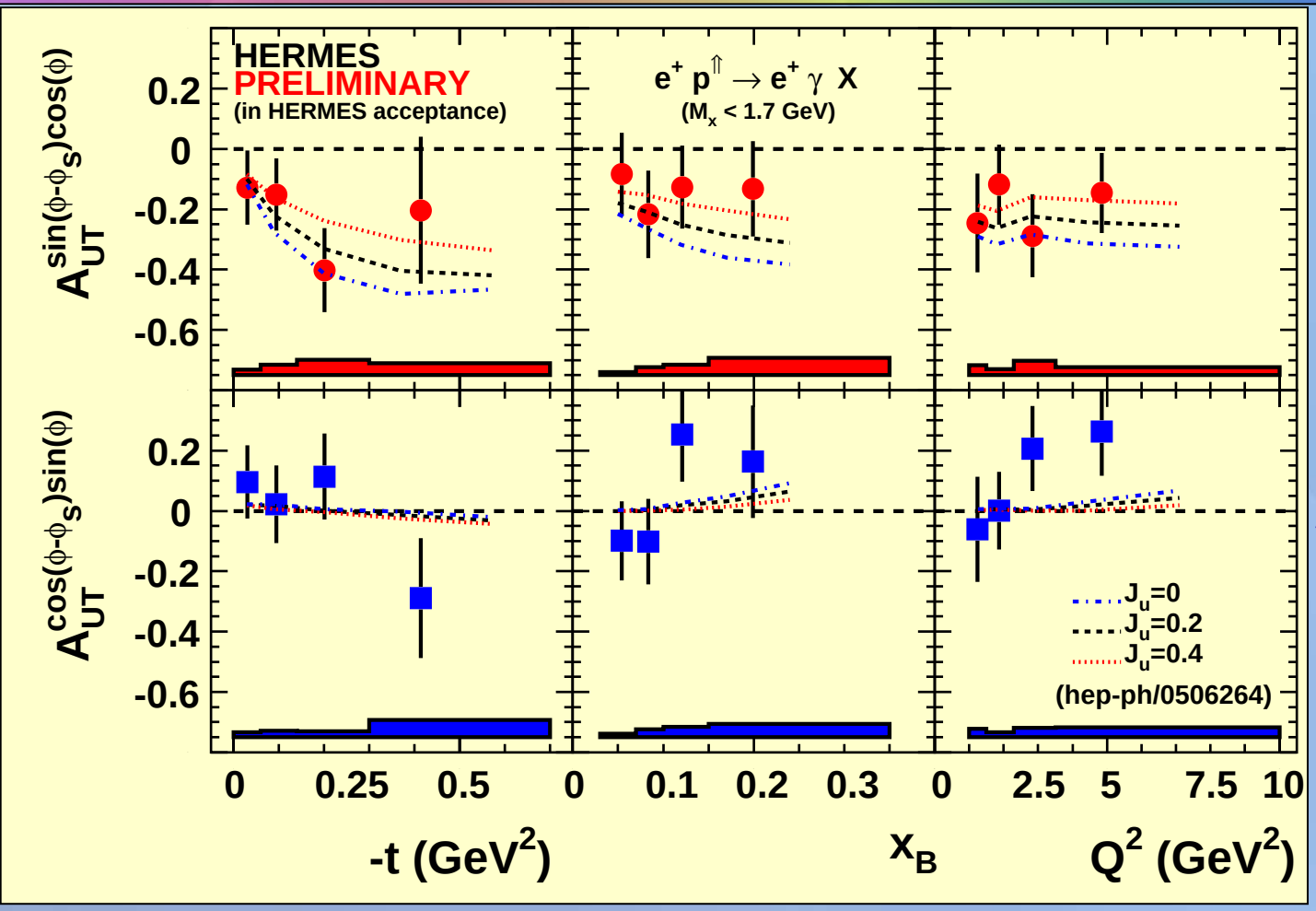
$\Delta\sigma_{LU} \sim \sin\phi \cdot \mathrm{Im}\{\mathbf{H} + \xi\tilde{\mathbf{H}} + k\mathbf{E}\}$ ⇒ $\Delta\sigma_{UH}$

$\Delta\sigma_{UL} \sim \sin\phi \cdot \mathrm{Im}\{\tilde{\mathbf{H}} + \xi\mathbf{H} + \ldots\}$ ⇒ beam $\tilde{H}$, target H ←

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

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

DVCS-TTSA



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

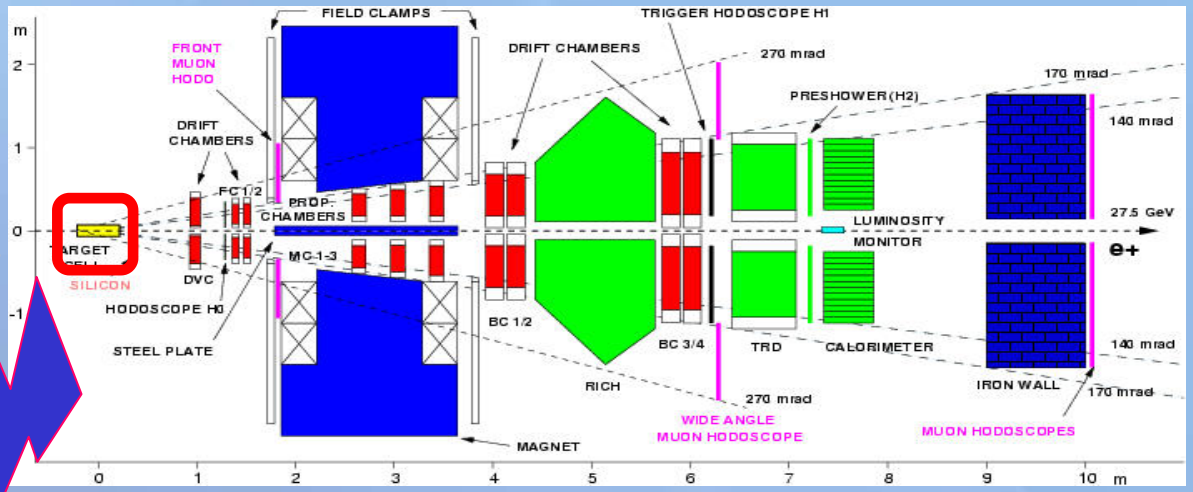
$$A_{UT}^{\cos(\phi-\phi_s)\sin(\phi)} \sim \mathrm{Im}(F_2 \tilde{H} - F_1 \xi \tilde{E})$$

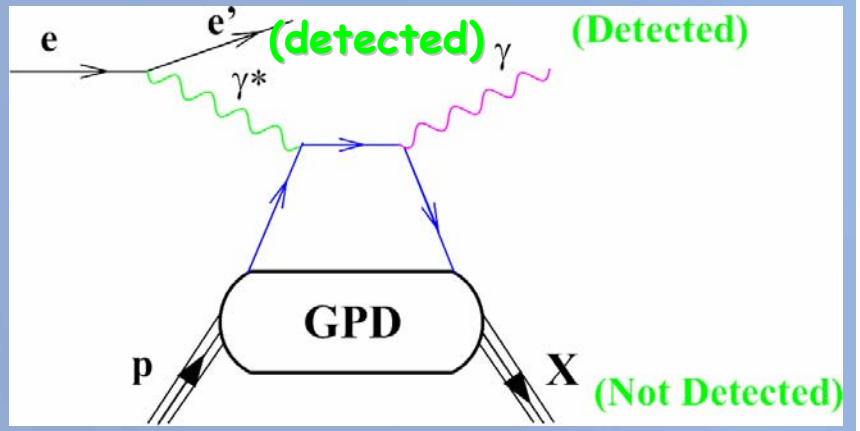
- first model dependent extraction of J_u possible
  Code: VGG
  J_d assumed to be zero

Exclusivity @ HERMES

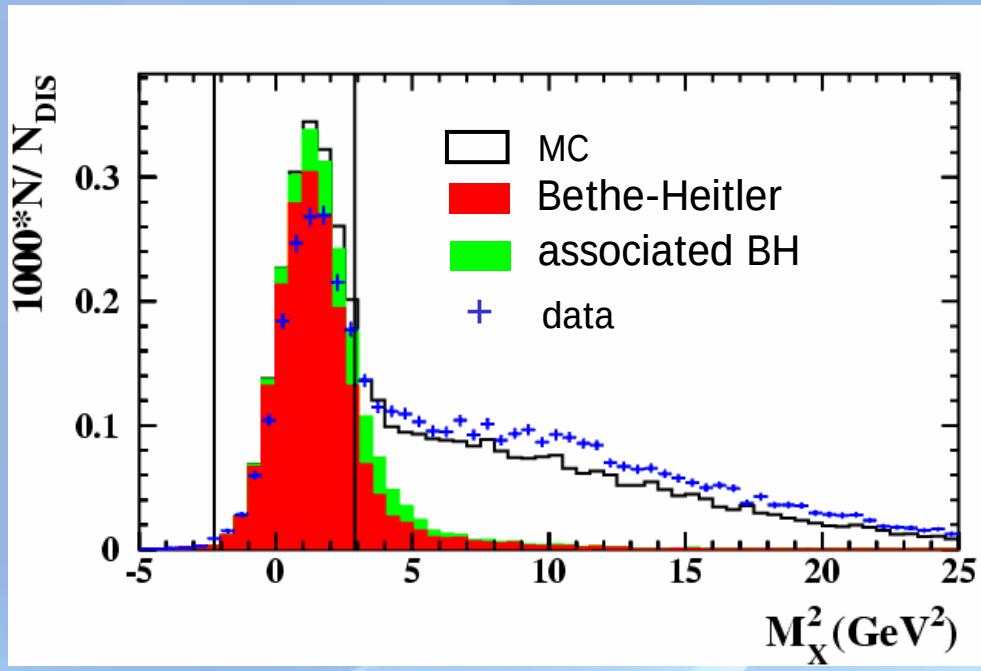
e^+/e^- → 27.5 GeV

P_b=55%

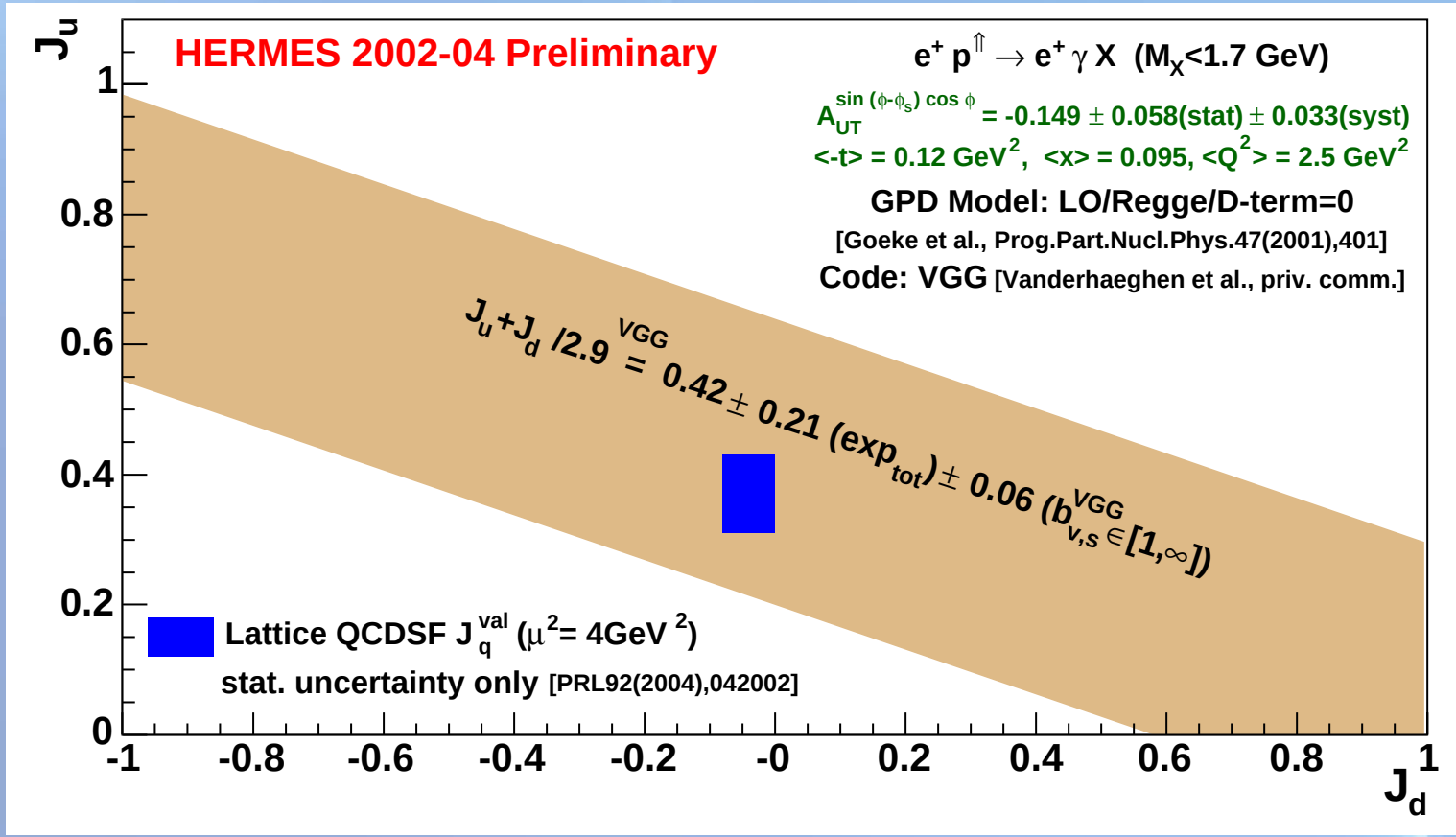




no recoil detection



Can we constrain (J_u+J_d)



- same statistics with electron beam on tape
  ⟹ independent data set to constrain (J_u+J_d)