Report from hermes

Contalbrigo Marco
INFN Ferrara

DESY PRC 71 – Open session
April 28, 2011 DESY Hamburg

Inclusive Measurements

DIS cross-section and F_2

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha_{em}^2}{Q^4}\frac{\mathrm{F}_2(x,Q^2)}{x}\left[1 - y - \frac{Q^2}{4E^2} + \frac{y^2 + Q^2/E^2}{2\left(1+\mathrm{R}(x,Q^2)\right)}\right]$$

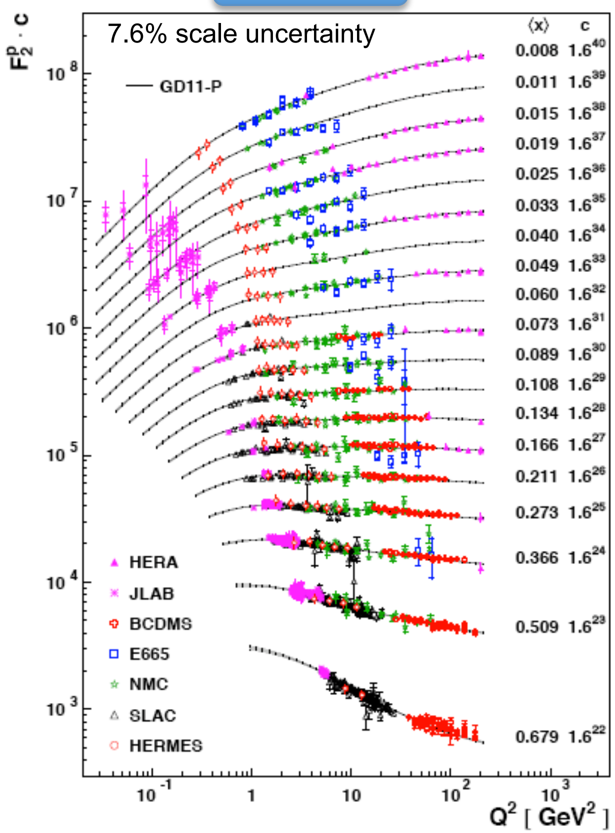
Exploring perturbative to non perturbative regime in an un-measured x-Q^2 region
$0.006 < x < 0.9$ $\quad$ $0.1\ \mathrm{GeV}^2 < Q^2 < 20\ \mathrm{GeV}^2$

From global fit GD11: HERMES relative normalization ~ 2% for P and D and < 0.5% for the ratio

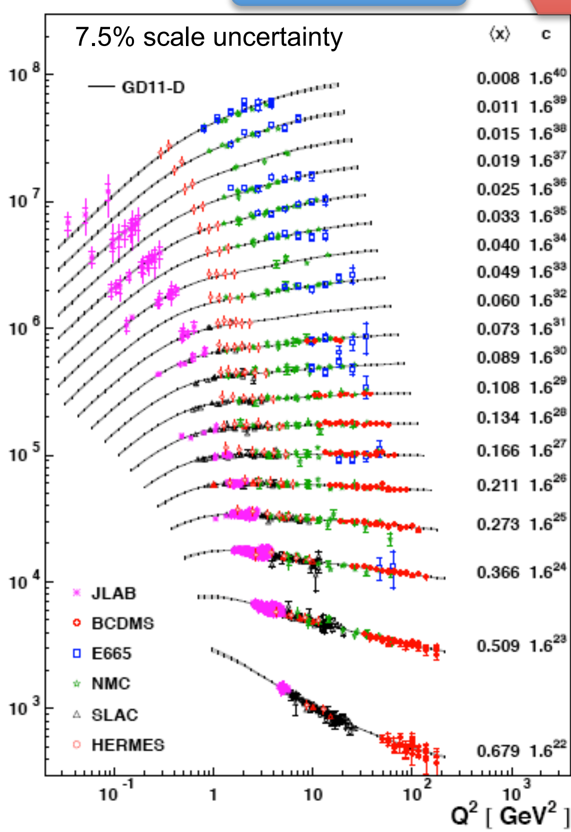
normalization	value
HERMES	0.996
NMC	0.999
BCDMS	1.010
SLAC	1.003
JLAB	1.000
EMC	0.995

JHEP (submitted)

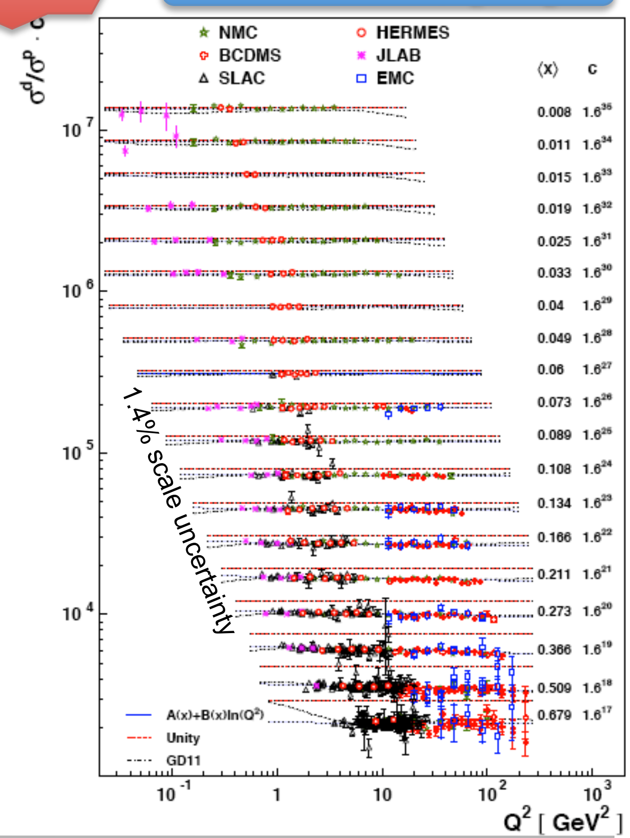
Proton



Deuteron



Ratio σ^d/σ^p (F_2^n/F_2^p)

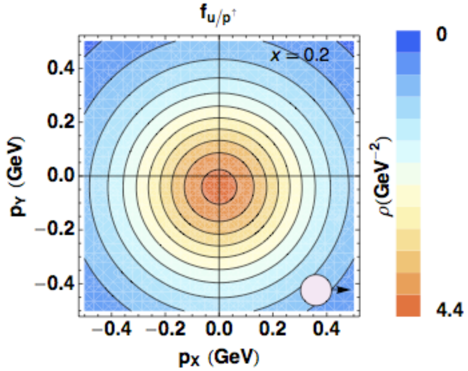


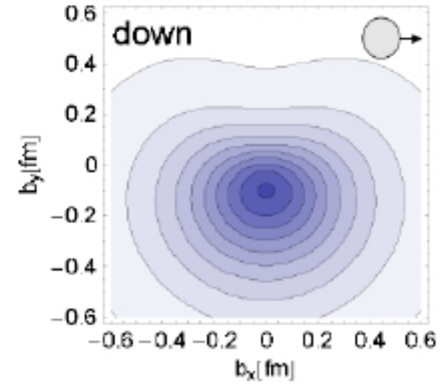
Semi-Inclusive & Exclusive

Quantum phase-space distributions of quarks

$W_p^q(x,k_T,r)$ "Mother" Wigner distributions

Probability to find a quark q in a nucleon P with a certain polarization in a position r & momentum k





d^3r

d^2k_T (FT)

TMD PDFs: $f_p^u(x,k_T)$,…

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

GPDs: $H_p^u(x,\xi,t)$, …

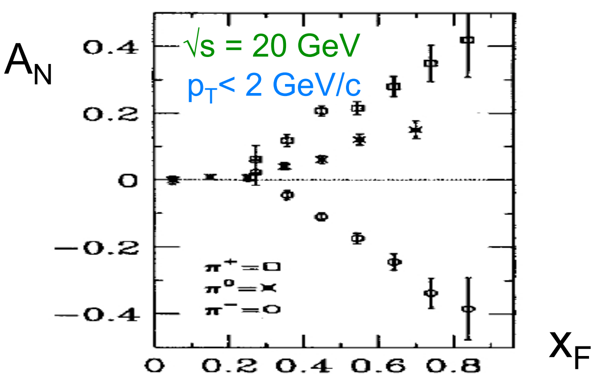
Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

d^2k_T

$\xi=0, t=0$

PDFs $f_p^u(x)$,…

May explain SSA



May solve
proton spin puzzle

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

Semi-Inclusive Measurements

Leading Twist TMDs

Quark polarisation

Nucleon polarisation

	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ - *Boer Mulders*
L		g_1 - *Helicity*	$h_{1L}^\perp$ - *Worm-gear*
T	$f_{1T}^\perp$ - *Sivers*	$g_{1T}^\perp$ - *Worm-gear*	h_1 - *Transversity* $h_{1T}^\perp$ - *Pretzelosity*

Indication to be not-zero !
Preliminary result

Consistent with zero
PLB 562 (2003) 182
PRL 84 (2000) 4047

Different from zero !
PRL 94 (2005) 012002
PLB 693 (2010) 11

Consistent with zero
Preliminary result

Different from zero !
PRL 94 (2005) 012002
PRL 103 (2009) 152002

HERMES has access to all of them through specific azimuthal modulations (ϕ, ϕ_S) of the cross-section thanks to the polarized beam and target

Leading Twist TMDs

quark polarisation

nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$

Diagonal elements:

Survive transverse momentum integration
(A collinear analysis is possible)

Multidimensional approach to investigate factorization and transverse momentum dependence

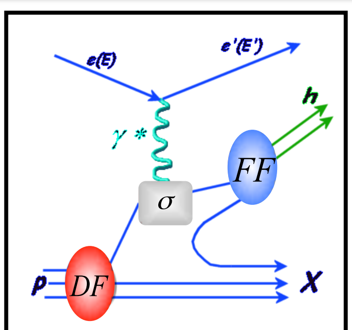
Off-diagonal elements:

Interference between wave functions with different angular momenta: contains information about parton orbital angular motion and spin-orbit effects

$f_1 \otimes D_1$

$g_{1L} \otimes D_1$

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \overset{Leading}{\underset{Twist}{\propto}} \left\{F_{UU,T} + \varepsilon\cos 2\phi\, F_{UU}^{\cos 2\phi}\right\} + S_\parallel \lambda_e \left\{\sqrt{1-\varepsilon^2}\, F_{LL}\right\} +$$



$$+\left|S_\perp\right| \lambda_e \left\{\sqrt{1-\varepsilon^2}\cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)}\right\} + \ldots$$

$g_{1T}^\perp \otimes D_1$

Charged-hadron multiplicities

LO interpretation:

$$\sigma_{UU} \propto f_1 \otimes D_1$$

$$M_N^h = \frac{1}{N_N^{DIS}(Q^2)}\frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\; f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\; f_{1q}(x,Q^2)}$$

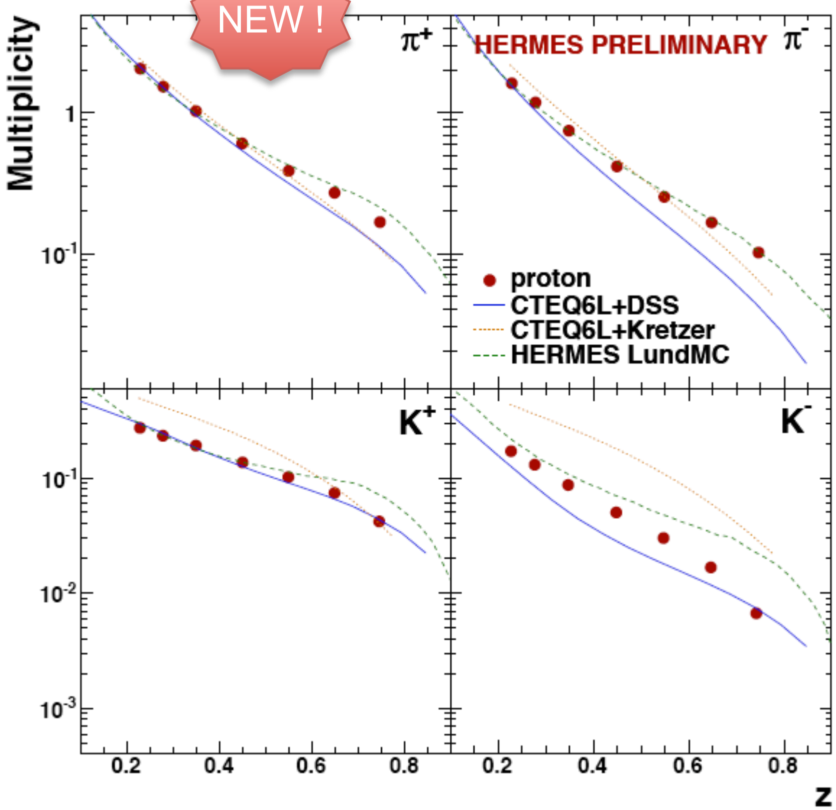
Disagreement for negative hadrons
SIDIS data important to constrain fragmentation into kaons

Proton-deuteron asymmetry:

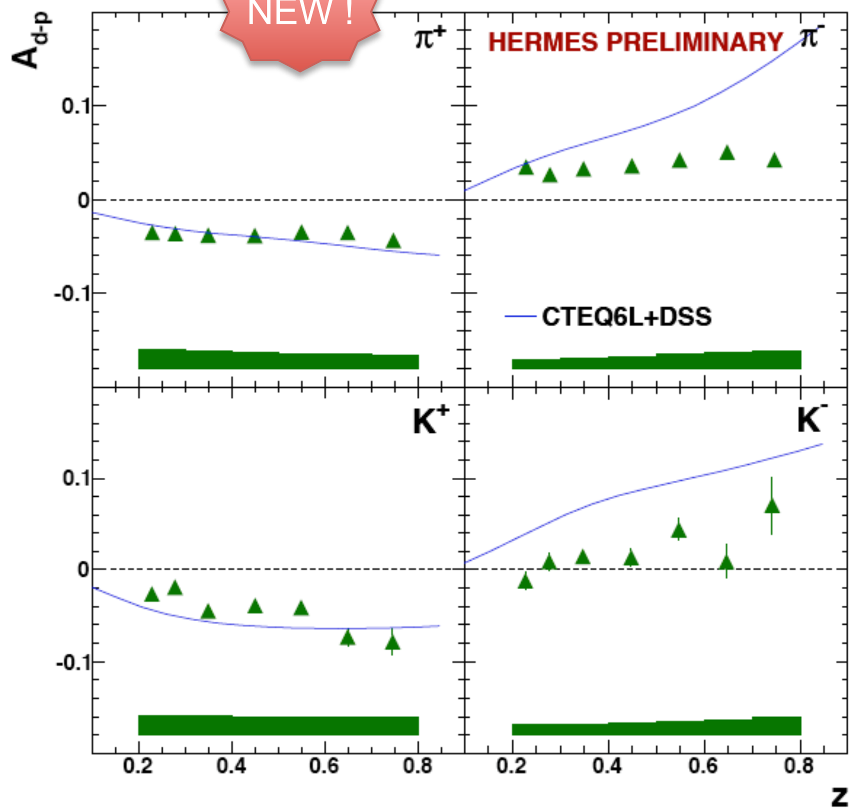
$$A_{d-p}^h \equiv \frac{M_d^h - M_p^h}{M_d^h + M_p^h}$$

Reflects different flavor content
Correlated systematics cancels

NEW !



NEW !



Charged-hadron multiplicities

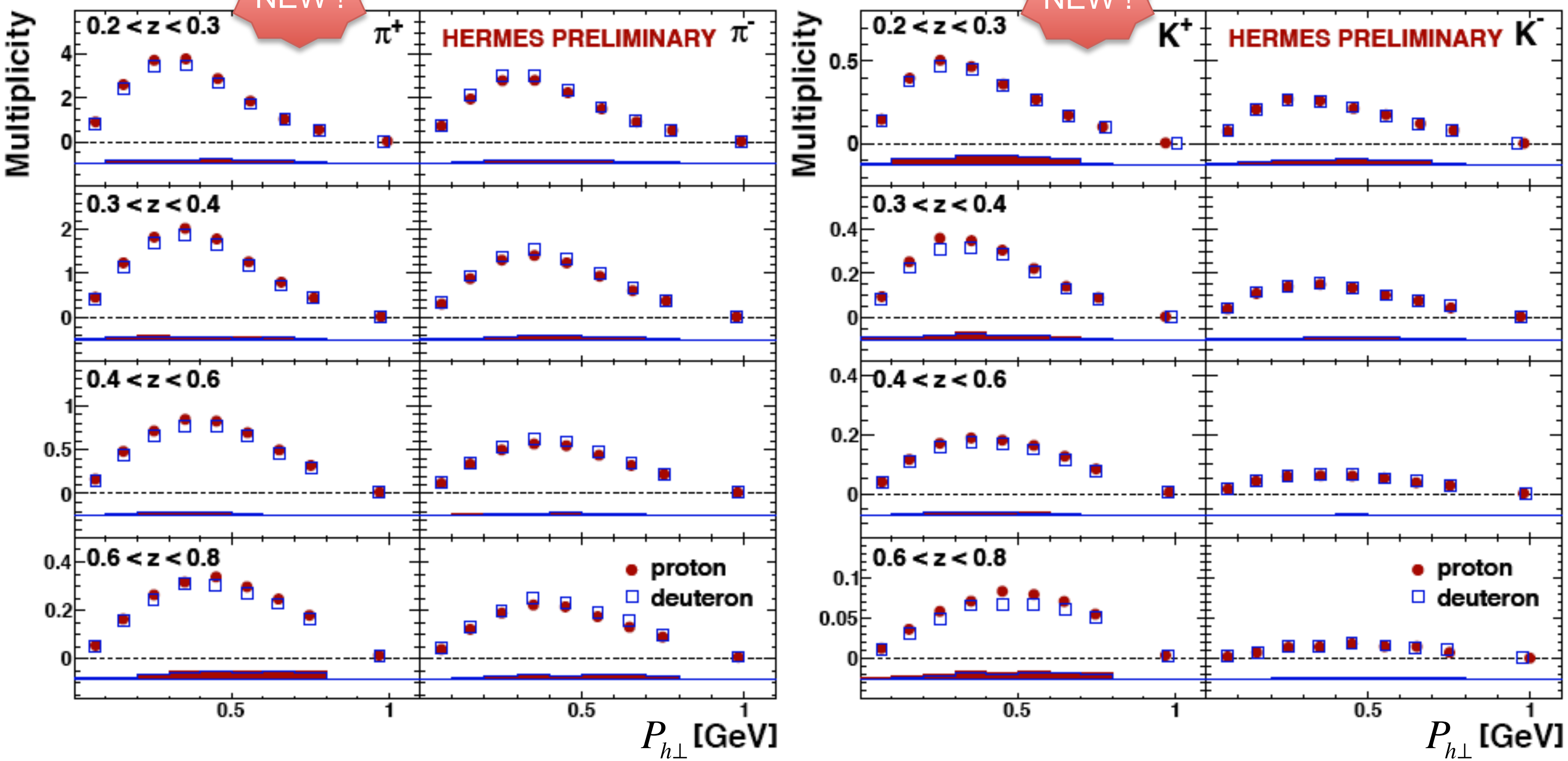
- Disentanglement of z and $P_{h\perp}$
- Access to the transverse intrinsic quark p_T and fragmentation k_T

$$\sigma_{UU} \propto f_1 \otimes D_1$$

$$\langle P_{h\perp}^2 \rangle = z^2 \langle p_T^2 \rangle + \langle k_T^2 \rangle$$

NEW !

NEW !

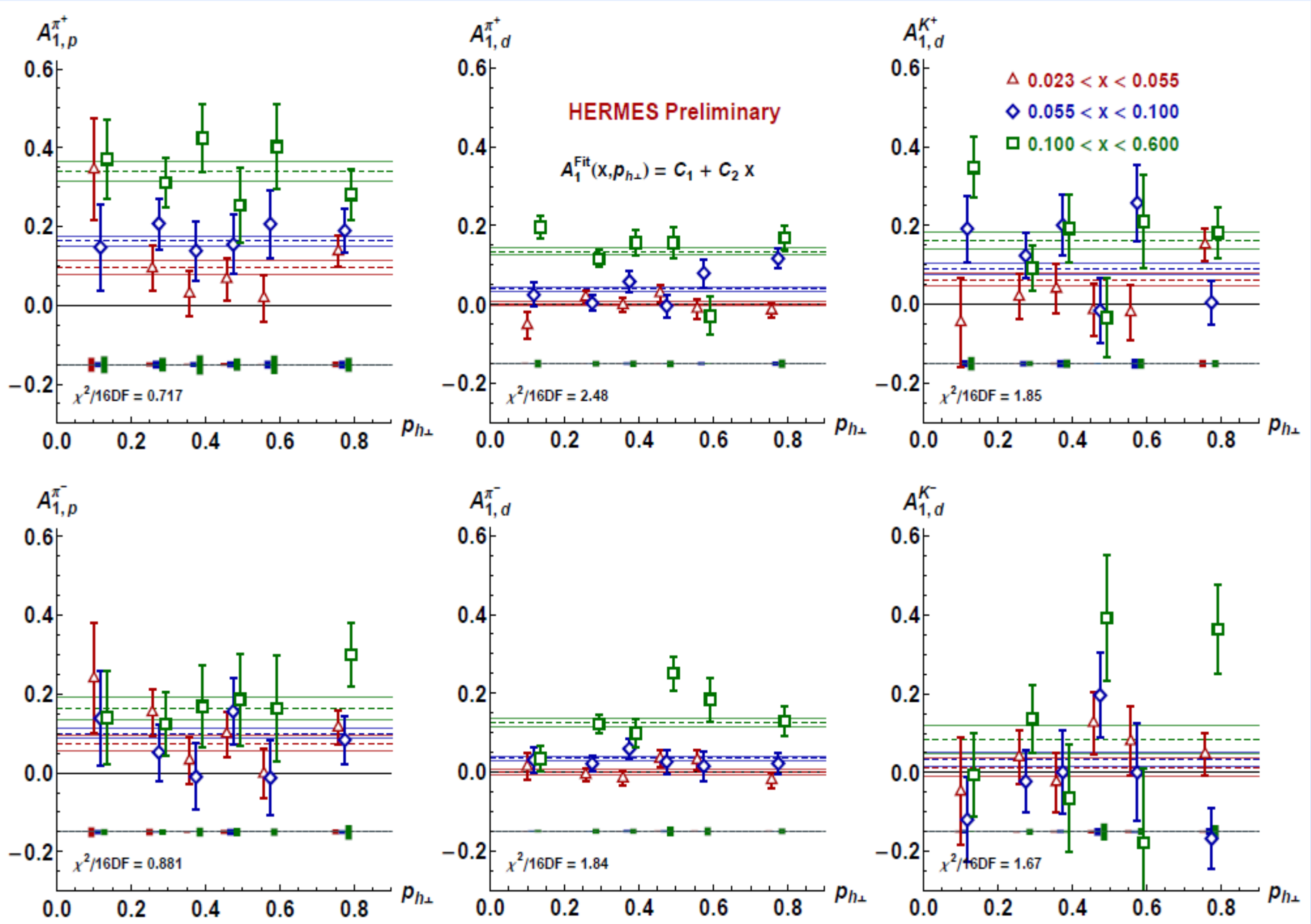


A_1 double-spin asymmetry

Refined studies extending the standard approach published *in Phys. Rev. Lett. 92 (2004) 012005*

$$\sigma_{LL} \propto g_{1L} \otimes D_1$$

$A_1(x, P_{h\perp})$ 2D - dependence



Sensitive to differences in transverse momentum dependence of g_1 and f_1

No significant $P_{h\perp}$ dependence observed

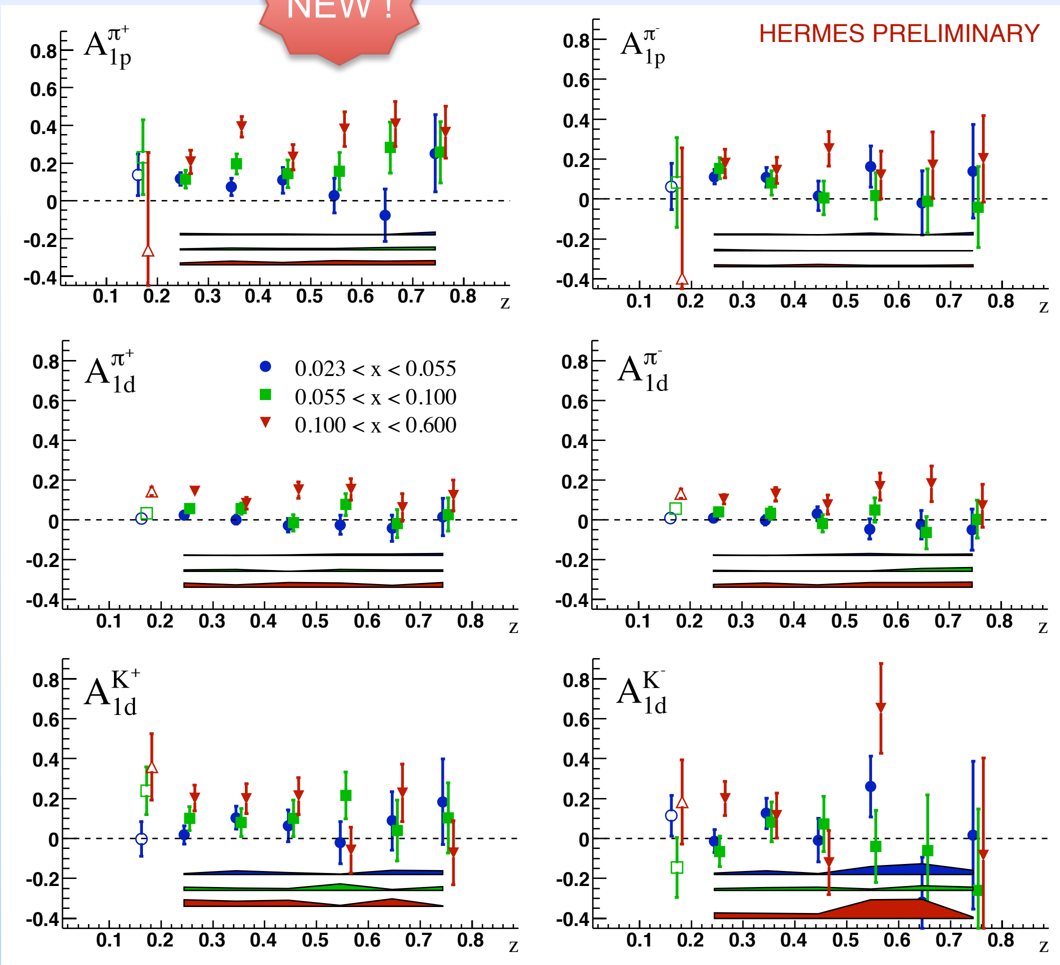
A_1 double-spin asymmetry

Refined studies extending the standard approach published *in Phys. Rev. Lett. 92 (2004) 012005*

$$\sigma_{LL} \propto g_{1L} \otimes D_1$$

$A_1(x, z)$ 2D - dependence

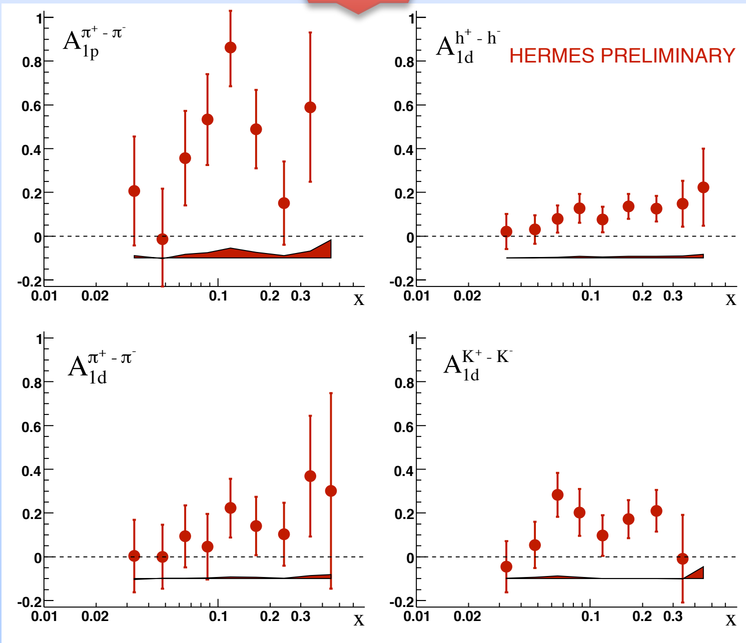
NEW !



With charge conjugation symmetry in fragmentation $D_q^{h^+} = D_{\bar{q}}^{h^-}$

$$A_{1d}^{h^+-h^-}(x) = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}(x)$$

NEW !



Leading Twist TMDs

quark polarisation

nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$

Diagonal elements:

Survive transverse momentum integration
(A collinear analysis is possible)

Multidimensional approach to investigate factorization and transverse momentum dependence

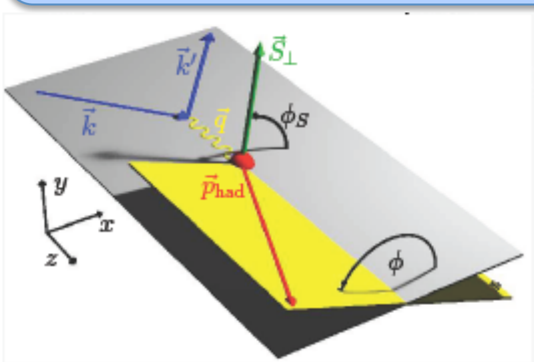
Off-diagonal elements:

Interference between wave functions with different angular momenta: contains information about parton orbital angular motion and spin-orbit effects

$f_1 \otimes D_1$

$g_{1L} \otimes D_1$

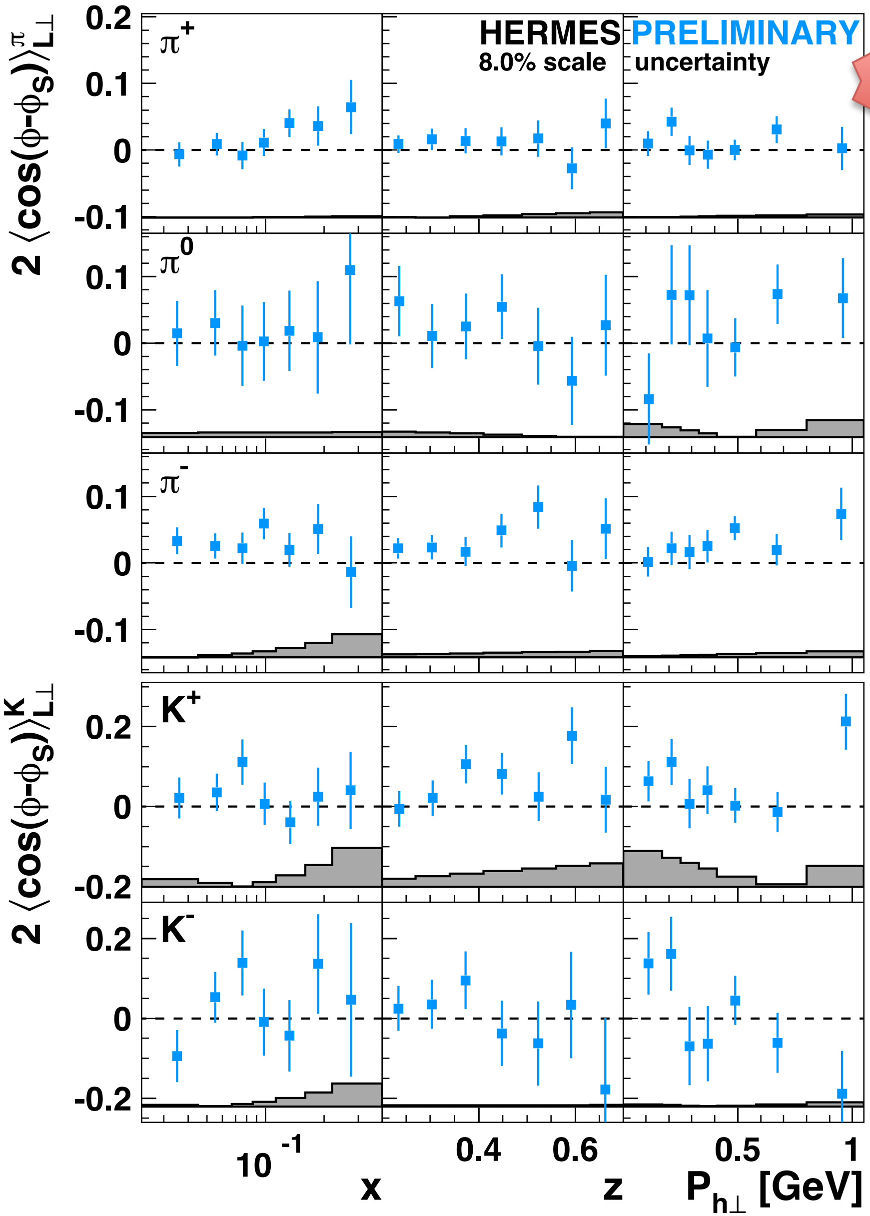
$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \underset{Twist}{\overset{Leading}{\propto}} \left\{F_{UU,T} + \varepsilon\cos 2\phi\, F_{UU}^{\cos 2\phi}\right\} + S_\parallel \lambda_e \left\{\sqrt{1-\varepsilon^2}\, F_{LL}\right\} +$$



$$+\left|S_\perp\right| \lambda_e \left\{\sqrt{1-\varepsilon^2}\cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)}\right\} + \ldots$$

$g_{1T}^\perp \otimes D_1$

New TMD measurement



NEW !

$$\sigma_{LT}^{\cos(\phi-\phi_S)} \propto g_{1T}^{\perp} \otimes D_1$$

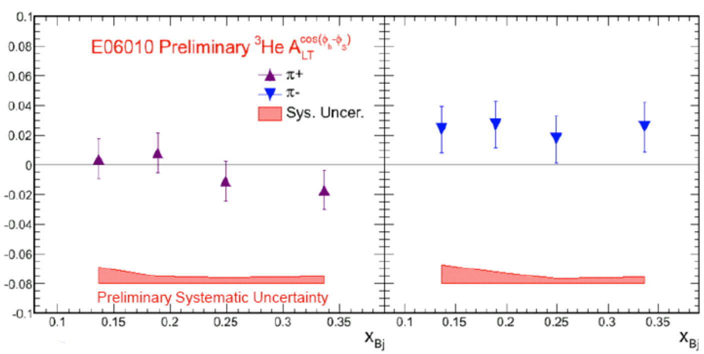
Worm-gear function: longitudinally polarized quarks in a transversely polarized nucleon

Related to parton orbital motion: requires interference between wave functions with OAM difference by 1 unit

$$g_{1T}^{\perp} = -h_{1L}^{\perp}$$ (supported by many models)

$$g_{1T}^{\perp}(x) \overset{WW-type}{\approx} x\int_0^1 \frac{dy}{y} g_1(y)$$ (Wandzura-Wilczek type approximation)

Jlab (Hall-A) result on ^{3}He



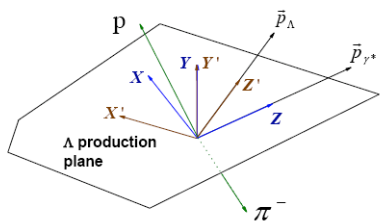
Anti-Lambda longitudinal spin trasfer

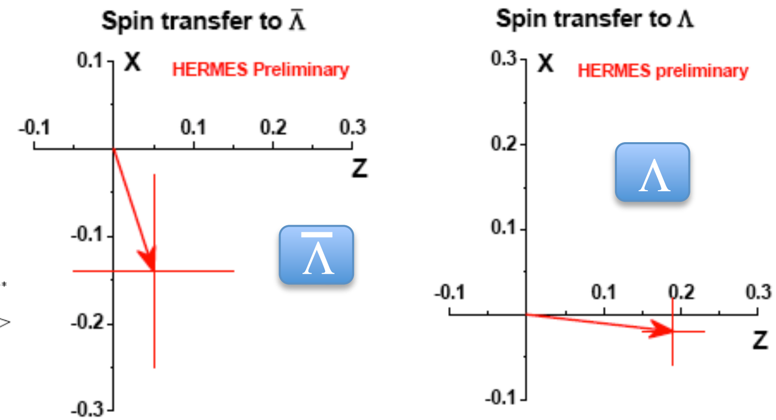
$$\vec{\gamma}^* N \rightarrow \vec{\bar{\Lambda}} X$$

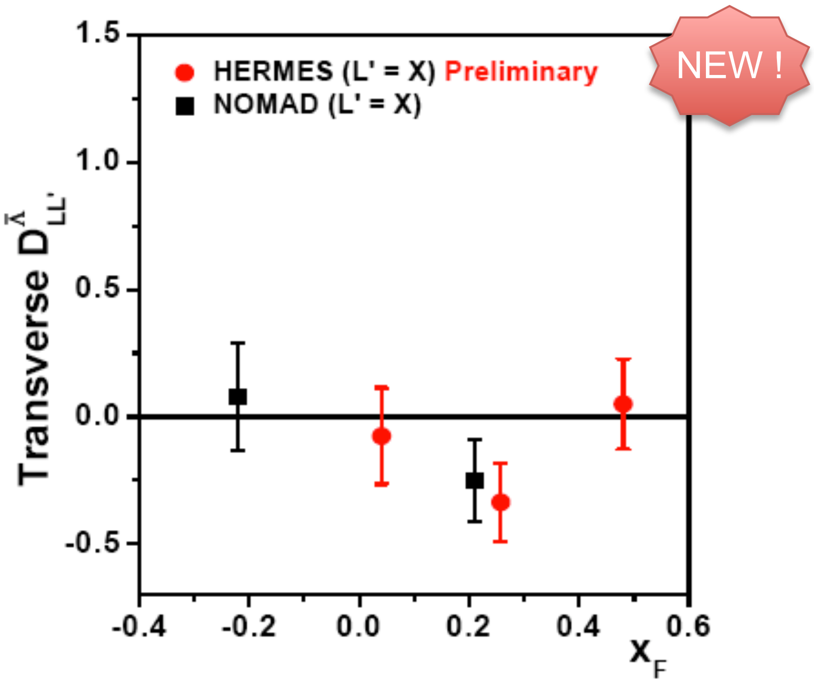
$$\sigma_{LL} \propto f_1 \otimes G_{1L}$$

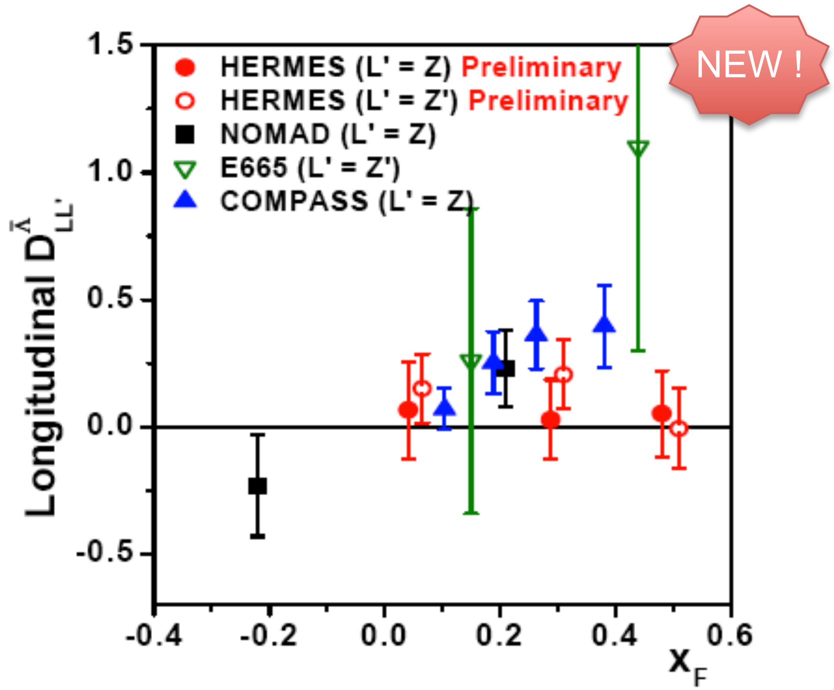
Parity violating decay : proton preferentially emitted along anti-Lambda spin $\alpha_{\bar{\Lambda}} = -0.642 \pm 0.013$

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}\left(1 + \alpha_{\bar{\Lambda}} P_B \sum_{i=x,y,z} D_{Li}^{\Lambda} \cos\theta_i\right)$$



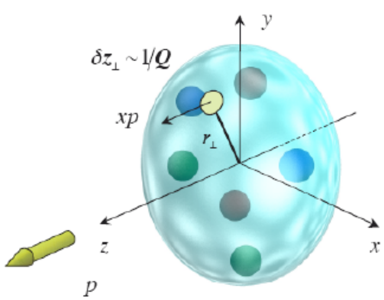


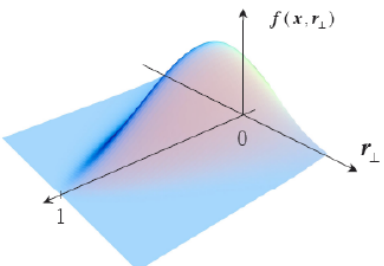


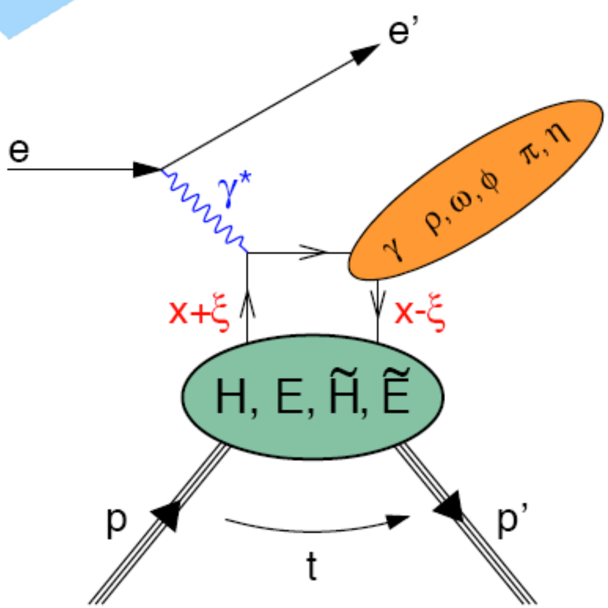


Exclusive Measurements

Generalized parton distributions







Encompass parton distributions and form factors

longitudinal momentum and transverse spatial position correlated information

Access OAM $L_q = J_q - ½\Delta\Sigma$ via Ji sum rule

$$J_q = \lim_{t \to 0} \int_{-1}^{1} dx\, x\left[H_q(x,\xi,t) + E_q(x,\xi,t)\right]$$

- Sensitivity of different final states to different GPDs
- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$
- $H, \tilde{H}$ conserve nucleon helicity, $E, \tilde{E}$ involve nucleon helicity flip
- DVCS (γ) → $H, E, \tilde{H}, \tilde{E}$
- Vector mesons (ρ, ω, ϕ) → H, E
- Pseudoscalar mesons (π, η) → $\tilde{H}, \tilde{E}$

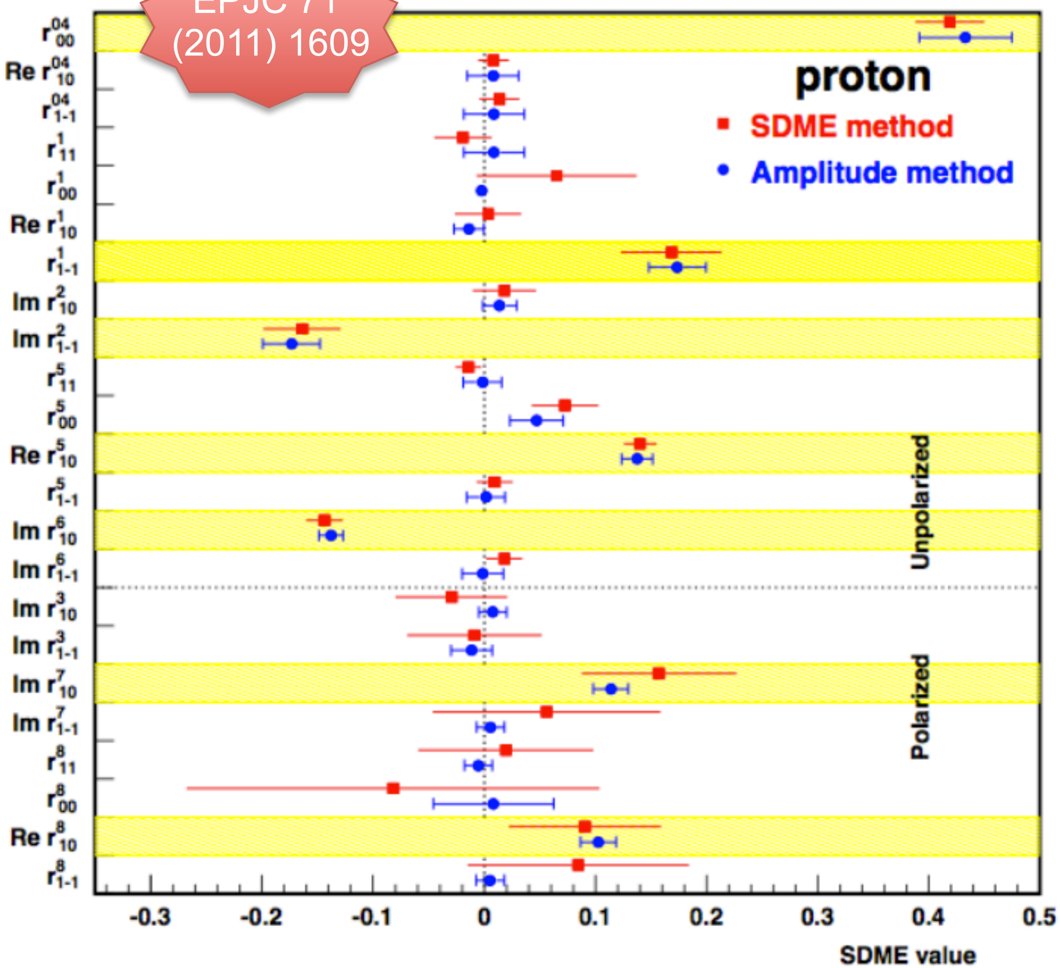
Hard Exclusive ρ^0 Meson Production

Meson SDMEs
EPJC 62 (2009) 659-694

Photon SDMEs

$$r^{\eta}_{\lambda_V \mu_V} = \frac{1}{2N} \sum_{\lambda_\gamma \mu_\gamma \lambda'_N \lambda_N} F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \Sigma^{\eta}_{\lambda_\gamma \mu_\gamma} F^{*}_{\mu_V \lambda'_N \mu_\gamma \lambda_N}$$

EPJC 71 (2011) 1609



Helicity Amplitudes

$$F_{\lambda_V \lambda_\gamma} = T_{\lambda_V \lambda_\gamma} + U_{\lambda_V \lambda_\gamma}$$

They form a basis for the SDMEs

Re-derived SDMEs consistent with published ones
[A. Airapetian et al. EPJC 62 (2009) 659)]

Enhanced sensitivity for polarized SDMEs

Helicity amplitudes are the fundamental quantities to be compared with theory

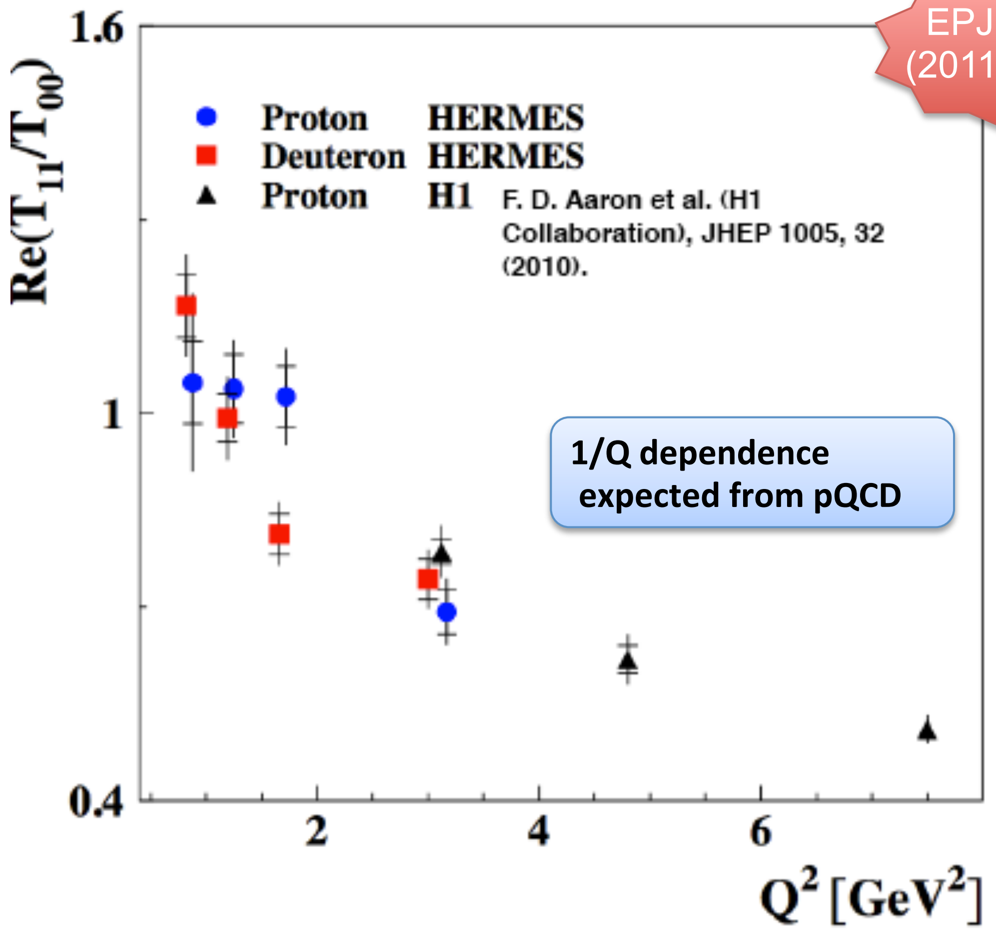
Hard Exclusive Meson Production

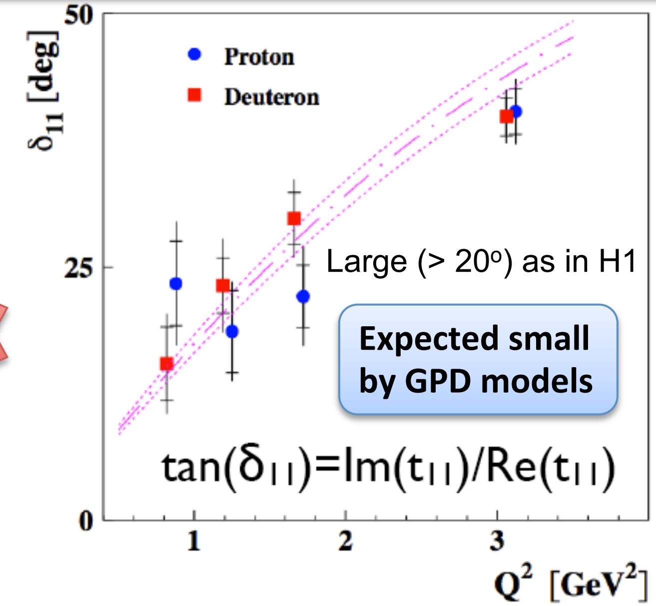
Hierarchy predicted by theory, confirmed by HERMES

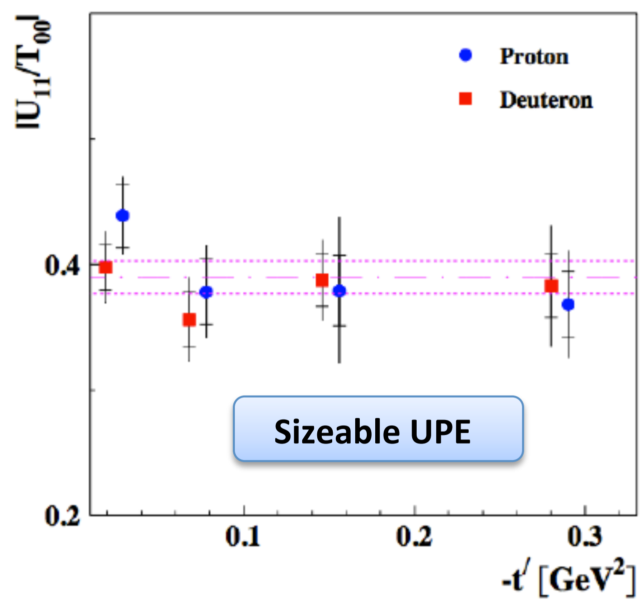
$|T_{00}|^2 \approx |T_{11}|^2 >> |U_{11}|^2 > |T_{01}|^2 >> |T_{10}|^2 \ldots$

D. Yu. Ivanov and R. Kirschner, Phys. Rev. D 58, 114026 (1998)

EPJC 71 (2011) 1609





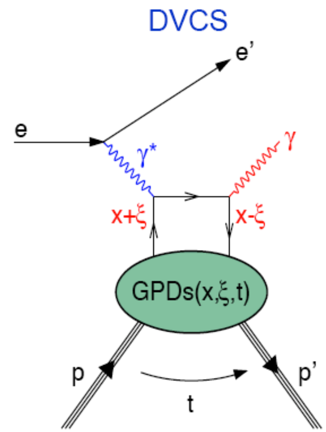


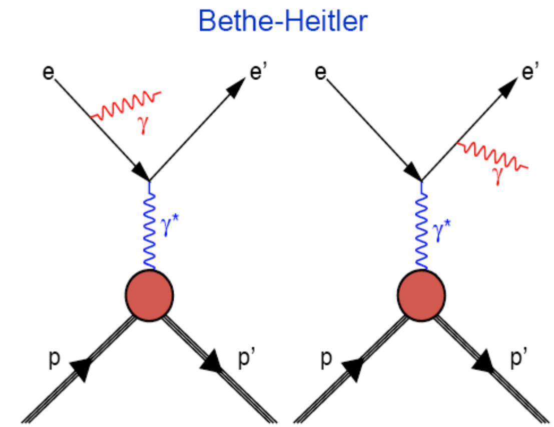
Deeply Virtual Compton scattering

Theoretically cleanest way to access GPDs

@ HERMES:

Large BH amplitude enhances DVCS signal via interference





Complete set of beam helicity, beam charge, target polarization asymmetries

DVCS A_{LT} Azimuthal Asymmetry

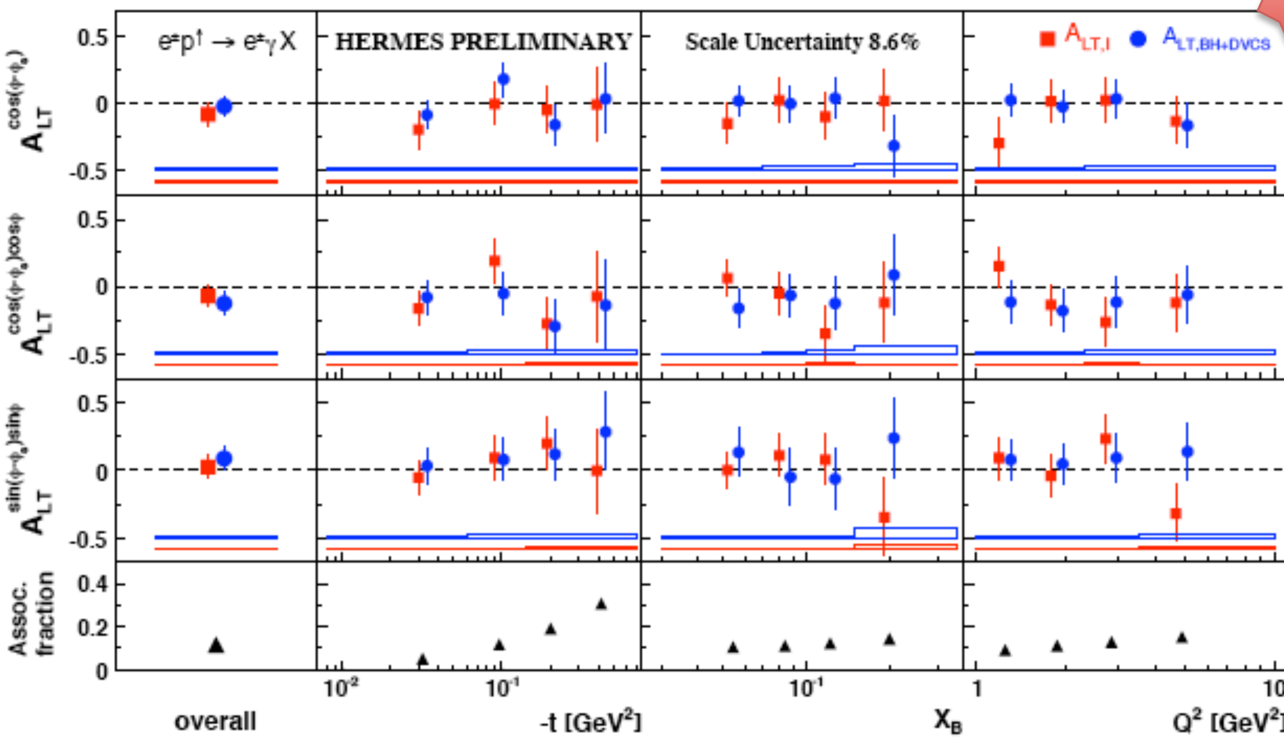
Beam charge

Beam polarization

Target polarization

$$\langle \mathcal{N}(e_\ell, P_l, S_t, \phi, \phi_S)\rangle \propto \sigma_{UU}(\phi)[1+\ldots+P_l S_t \mathcal{A}_{LT}^{BH+DVCS} + e_\ell P_l S_t \mathcal{A}_{LT}^{I}]$$

NEW !



$$\propto A_{LT}^{\cos(\phi-\phi_S)\cos(\phi)}$$

$$\propto \begin{array}{l} \mathcal{R}e\left[F_2\tilde{\mathcal{H}} - (F_1+\xi F_2)\tilde{\mathcal{E}}\right] \\ \mathcal{R}e\left[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* - \xi(\tilde{\mathcal{H}}\tilde{\mathcal{E}}^* - \tilde{\mathcal{E}}\tilde{\mathcal{H}}^*)\right] \end{array}$$

$$\propto \begin{array}{l} \mathcal{R}e\left[F_2\mathcal{H} - F_1\mathcal{E}\right] \\ \mathcal{R}e\left[-\tilde{\mathcal{H}}\mathcal{E}^* - \tilde{\mathcal{H}}^*\mathcal{E} + \xi(\mathcal{H}\tilde{\mathcal{E}}^* + \tilde{\mathcal{E}}\mathcal{H}^*)\right] \end{array}$$

Sensitive to the GPDs entering the Ji sum rule

Consistent with zero

Sensitivity to J_u is suppressed by kinematic factors

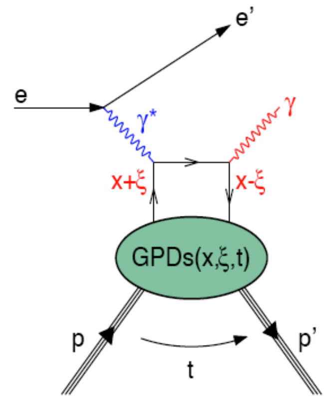
Deeply virtual Compton scattering

Theoretically cleanest
way to access GPDs

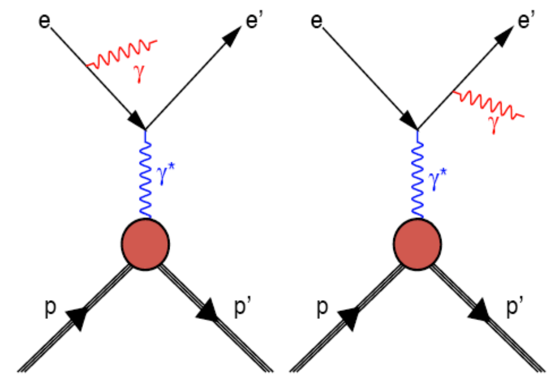
@ HERMES:

Large BH amplitude enhances
DVCS signal via interference

DVCS

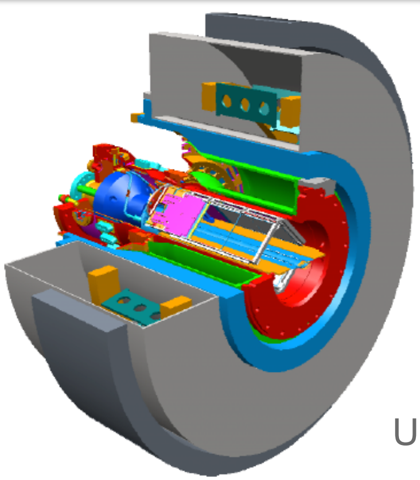


Bethe-Heitler



Complete set of beam helicity, beam charge, target polarization asymmetries

Recoil detector to tag exclusivity



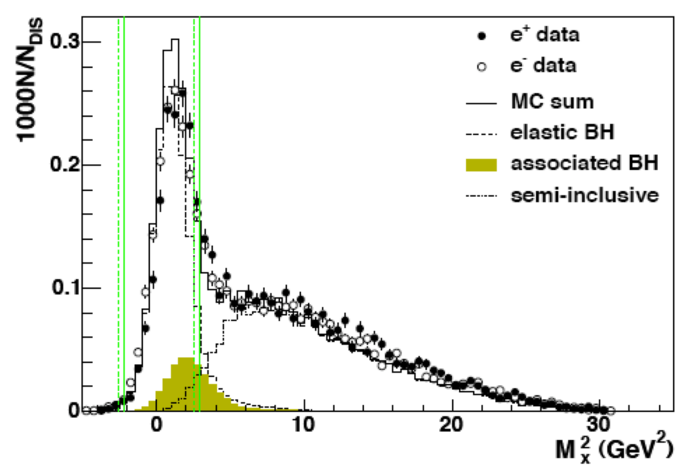
1T SC Solenoid

Photon Detector

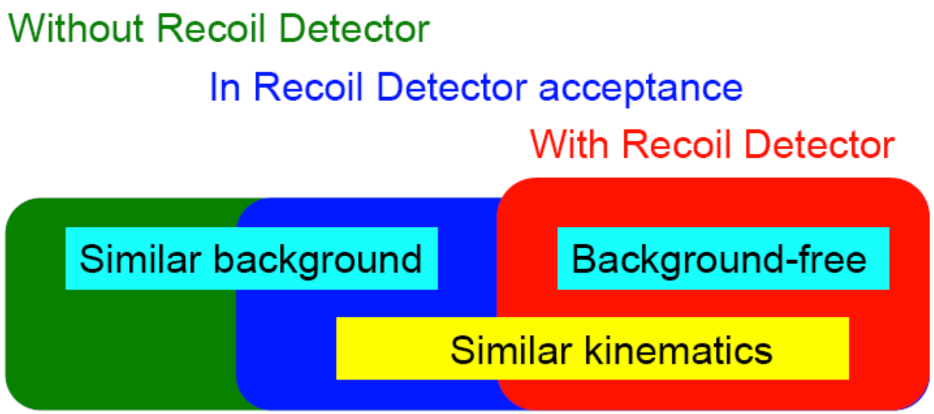
Scintillating Fiber Tracker

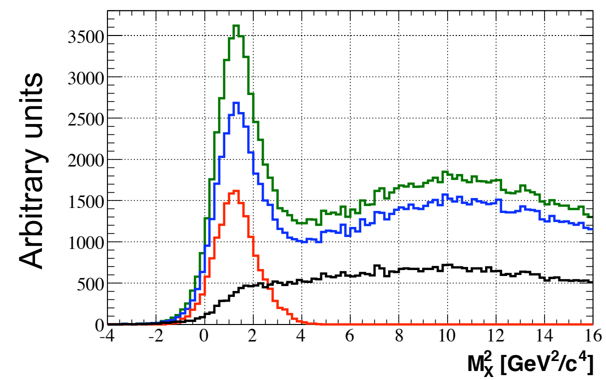
Silicon Strip Detector

Unpolarized H and D targets

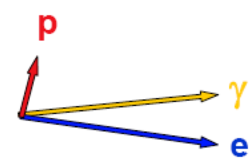


The recoil detector

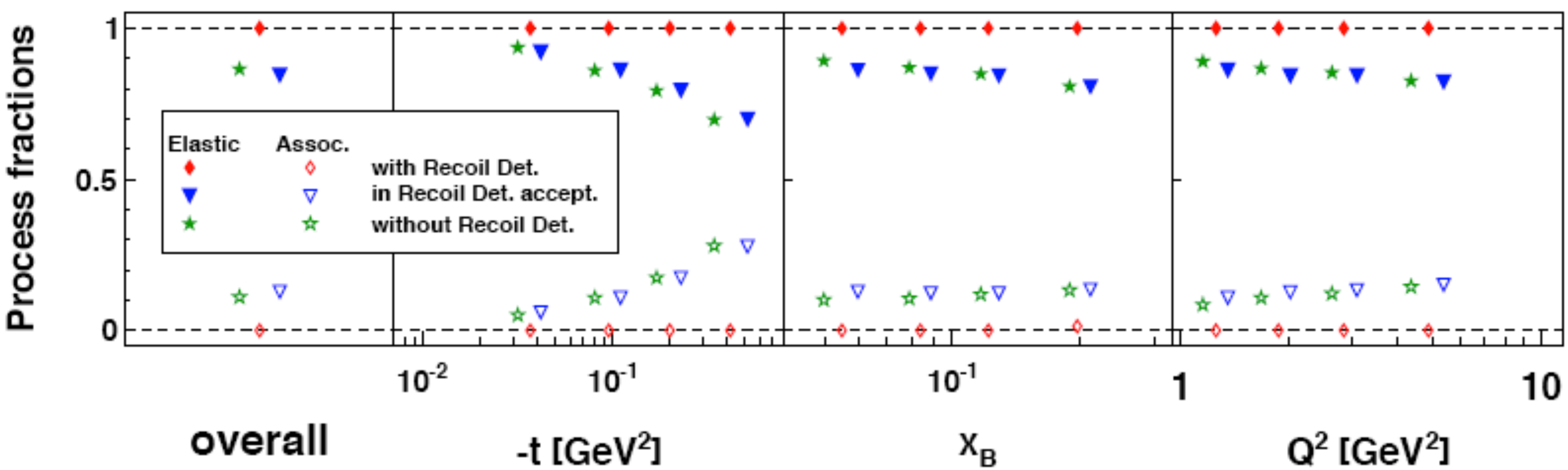




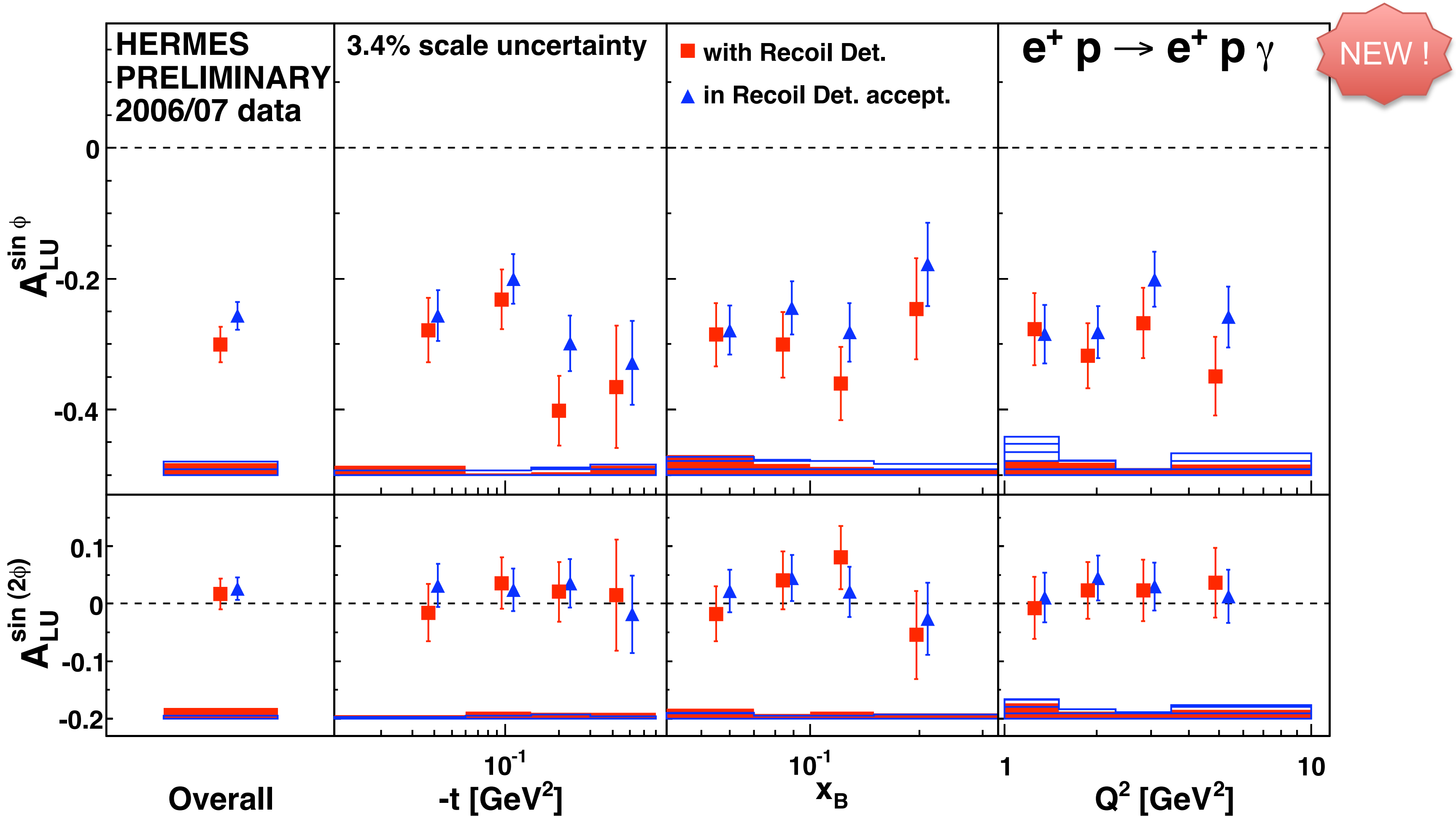
Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation



- No requirement for Recoil
- Charged recoil track in acceptance
- Kinematic fit probability > 1 %
- Kinematic fit probability < 1 %



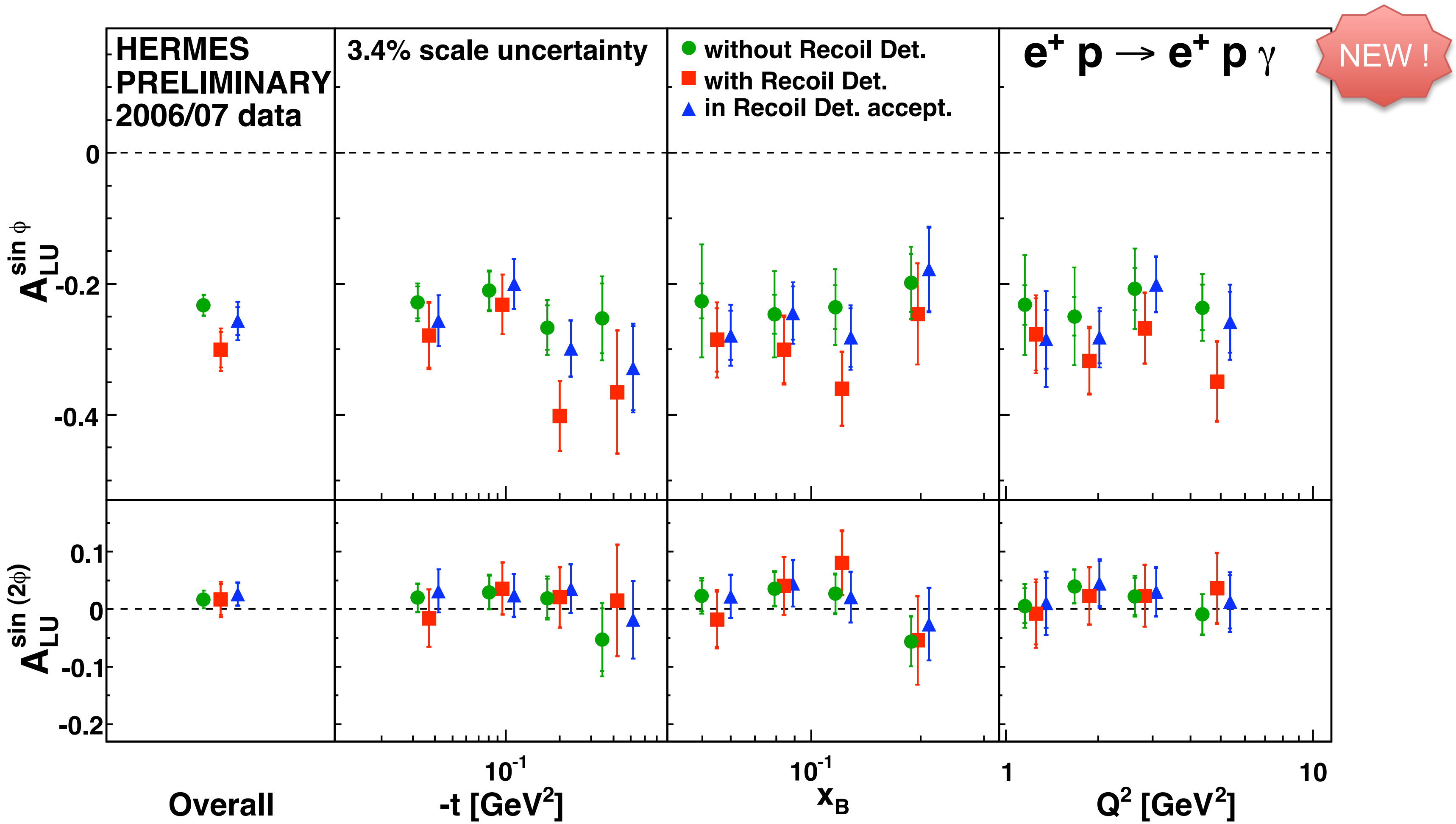
Pure elastic DVCS



Within the present level of precision, the signal is stable with respect background subtraction

Indication that the leading amplitude for pure elastic process (background < 0.1%)
is slightly larger in magnitude than the one for not-resolved elastic+associated processes

Recoil vs Traditional DVCS



DVCS analysis based on Recoil and/or Forward detector spans slightly different phase space

With recoil information (overconstrained kinematics) the systematics is better under control

Extraction of asymmetry amplitudes for associated processes is a subject of ongoing dedicated analysis

Summary

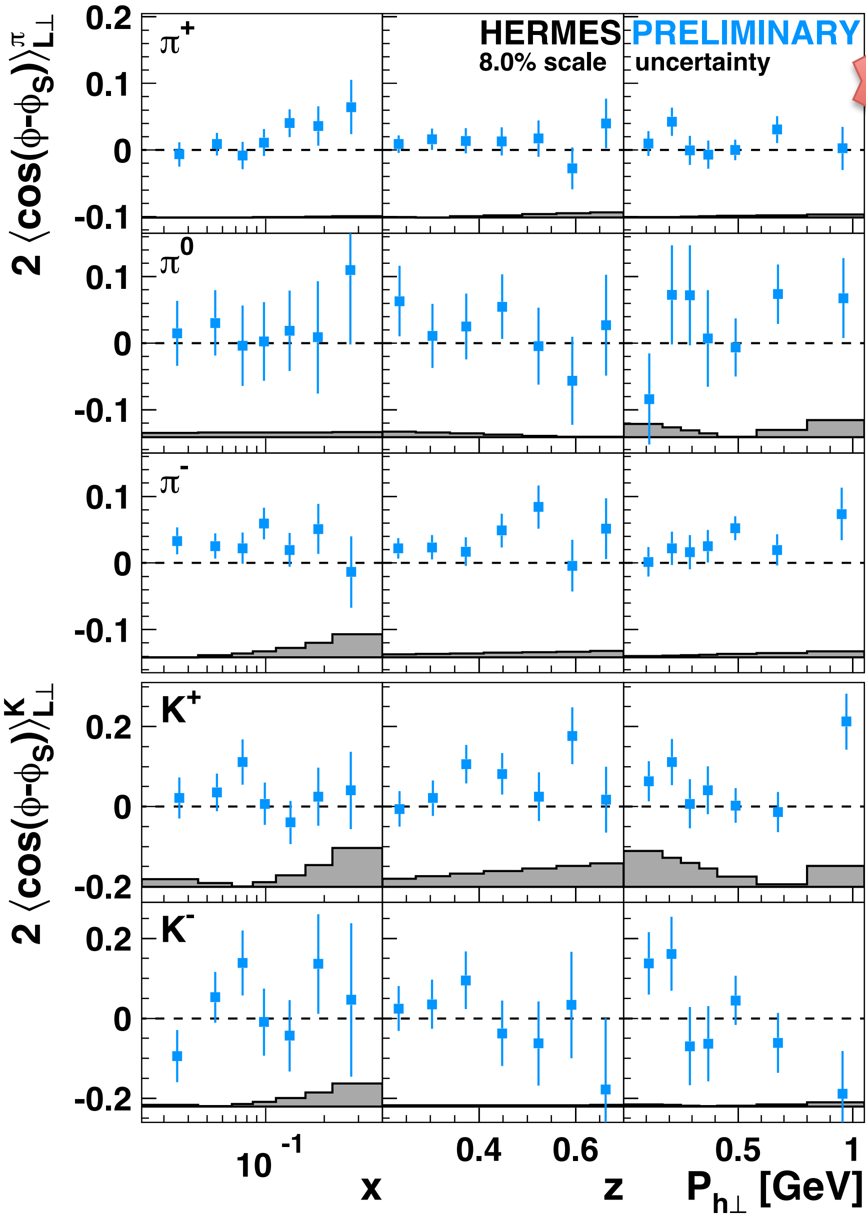
- 2011 started with:
  - 6 new preliminary results
  - 1 published, 2 submitted papers
  - 8 papers in circulation of the collaboration
  - 7 papers in advanced drafting stage
  - 9 talks at DIS (7 in spin session)
- New preliminary results cover all areas of physics studied at HERMES
- First released physics result based on Recoil Detector:
  DVCS background-free beam helicity amplitude

  Major Achievement

- Collaboration still actively working to accomplish the broad physics program

Spares

New TMD measurement



NEW !

$$\sigma_{LT}^{\cos(\phi-\phi_S)} \propto g_{1T}^{\perp} \otimes D_1$$

Worm-gear function: longitudinally polarized quarks in a transversely polarized nucleon

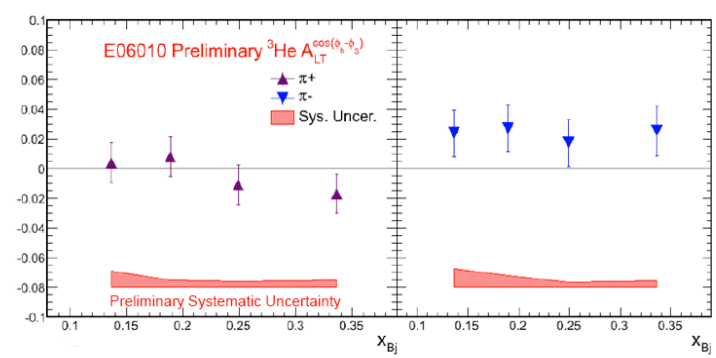
Related to parton orbital motion: requires interference between wave functions with OAM difference by 1 unit

Many models support simple relations

$$g_{1T}^{q} = -h_{1L}^{\perp q}$$ (supported by Lattice QCD and first data)

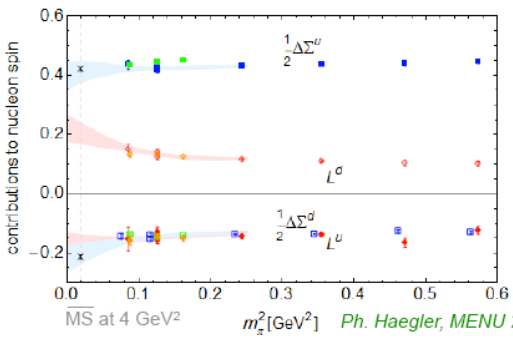
$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} g_1^q(y)$$ (Wandura-Wilczek type approximation)

Jlab (Hall-A) result on ^{3}He



Open issues: test field for QCD

Proton spin budget: role of partonic orbital motion?



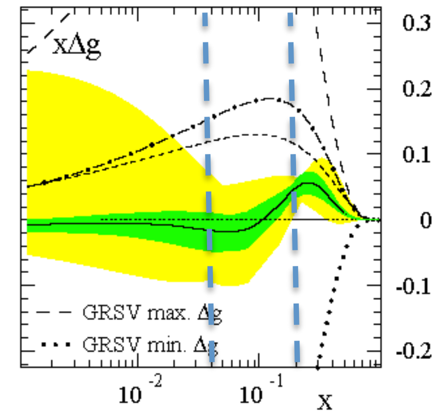
Ph. Haegler, MENU 2010

$\Delta\Sigma$=0.33±0.03
from DIS & Lattice

ΔG small at 0.02<x<0.3
from DIS and pp scattering

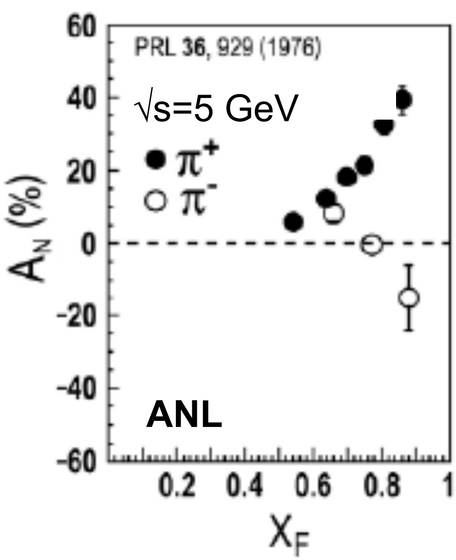
$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

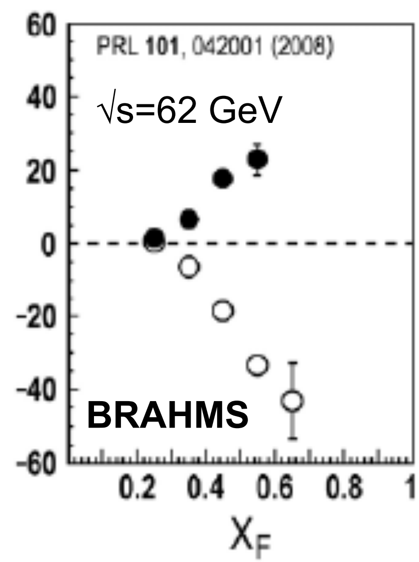
DSS, PRL101 (2008) 072001



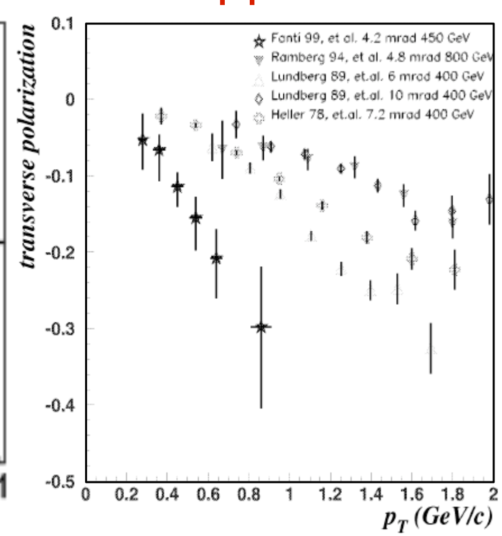
Single spin asymmetries: BIG (?!) although suppressed as m_q/Q^2 in pQCD

$p^{\uparrow}p \rightarrow \pi X$



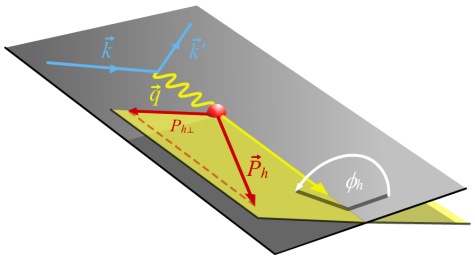


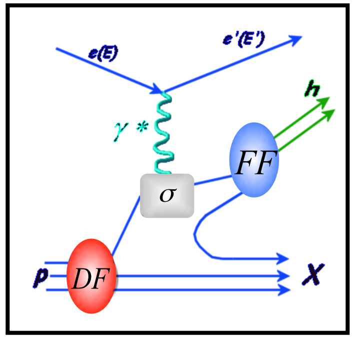
$pp \rightarrow \Lambda^{\uparrow} X$



Cahn effect

Intrinsic k_T quark distribution



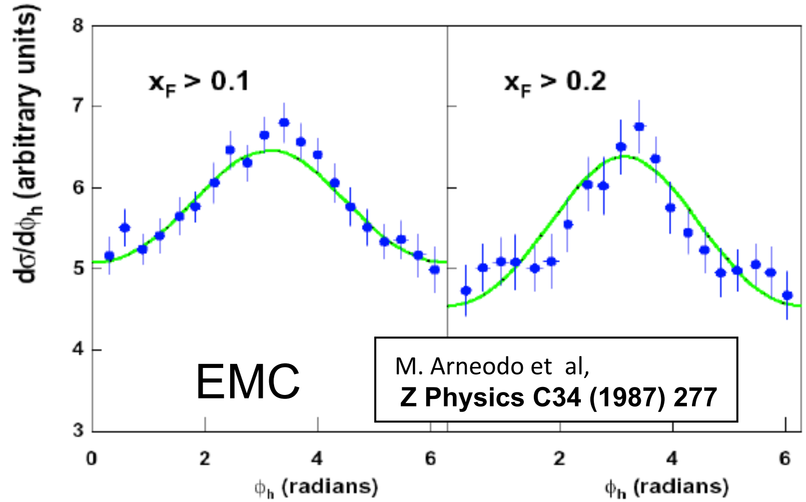


SIDIS:
ep ⟶ e'hX

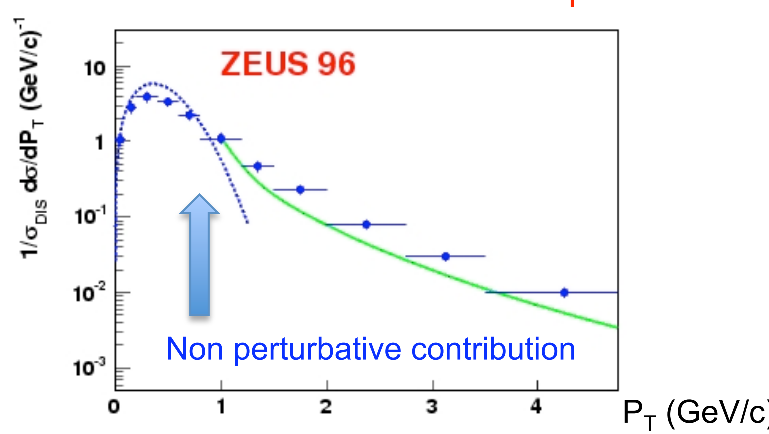
$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + \ldots \right] / Q$$

Distribution Functions (DF)			
N/q	U	L	T
U	f_1 *number density*		$h_1^\perp$ - *Boer-Mulders*

Fragmentation Functions (FF)			
N/q	U	L	T
U	D_1 *unpolarized*		$H_1^\perp$ - *Collins*



Predicted since 1978 by Cahn
Non-zero intrinsic k_T !!

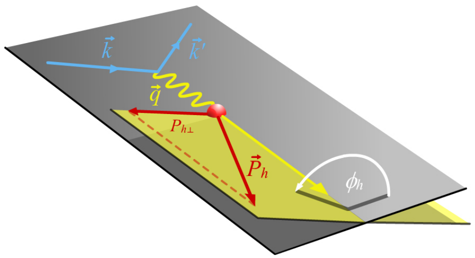


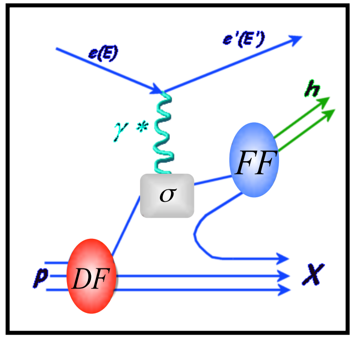
Boer-Mulders effect

Partonic spin-orbit effect

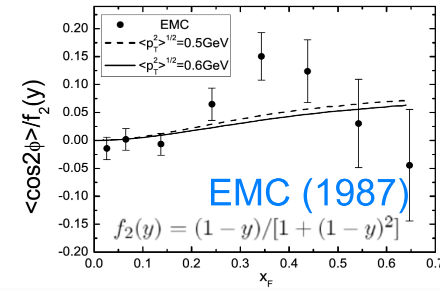
$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + \ldots \right] / Q$$

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$





SIDIS:
ep → e'hX
Sparse data before 2008



Distribution Functions (DF)

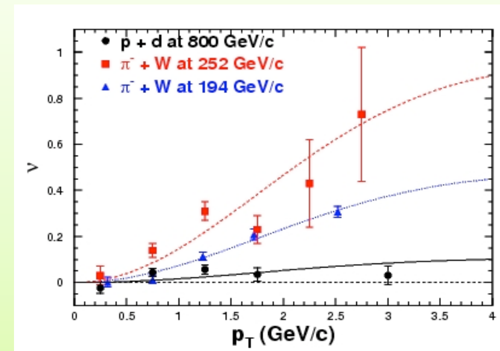
N/q	U	L	T
U	f_1 *number density*		$h_1^{\perp}$ - *Boer-Mulders*

Fragmentation Functions (FF)

N/q	U	L	T
U	D_1 *unpolarized*		$H_1^{\perp}$ - *Collins*

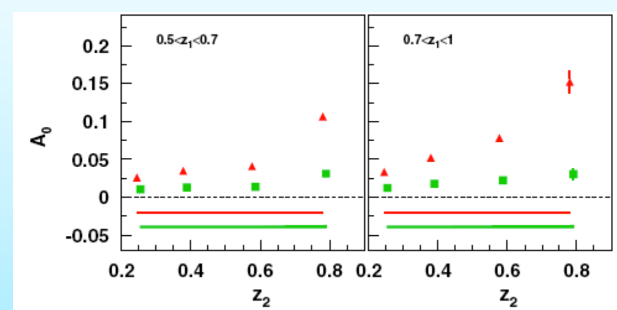
Drell-Yan
hp → μμX

$$\sigma_{UU}^{\cos 2\phi} \propto h_1^{\perp} h_1^{\perp}$$



e+e- machines
ee → ππX

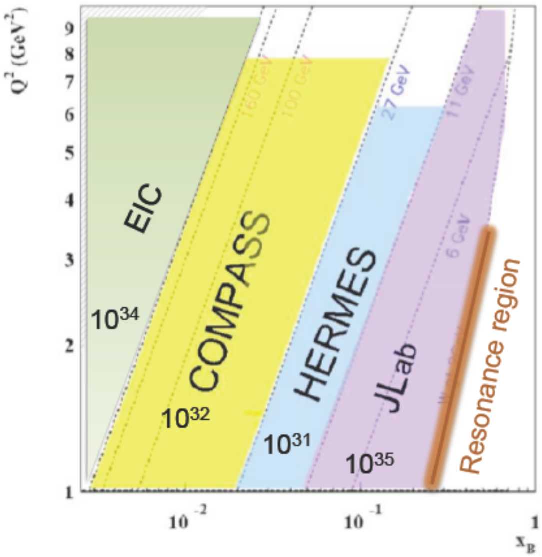
$$A_0^{\cos 2\phi_0} \propto H_1^{\perp} H_1^{\perp}$$



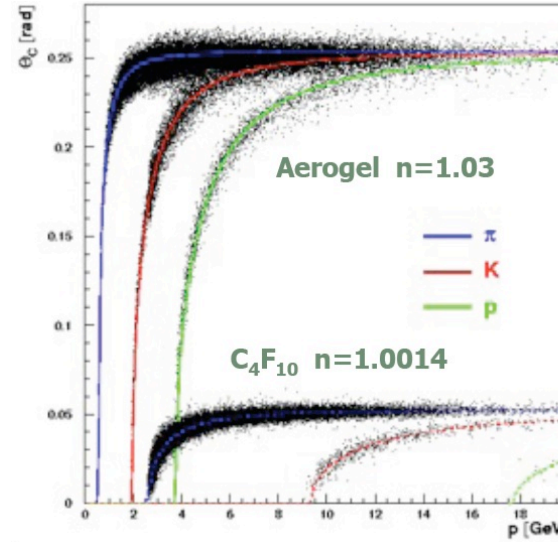
The experiment

27.6 GeV e+/e- HERA beam

Access to valence and sea



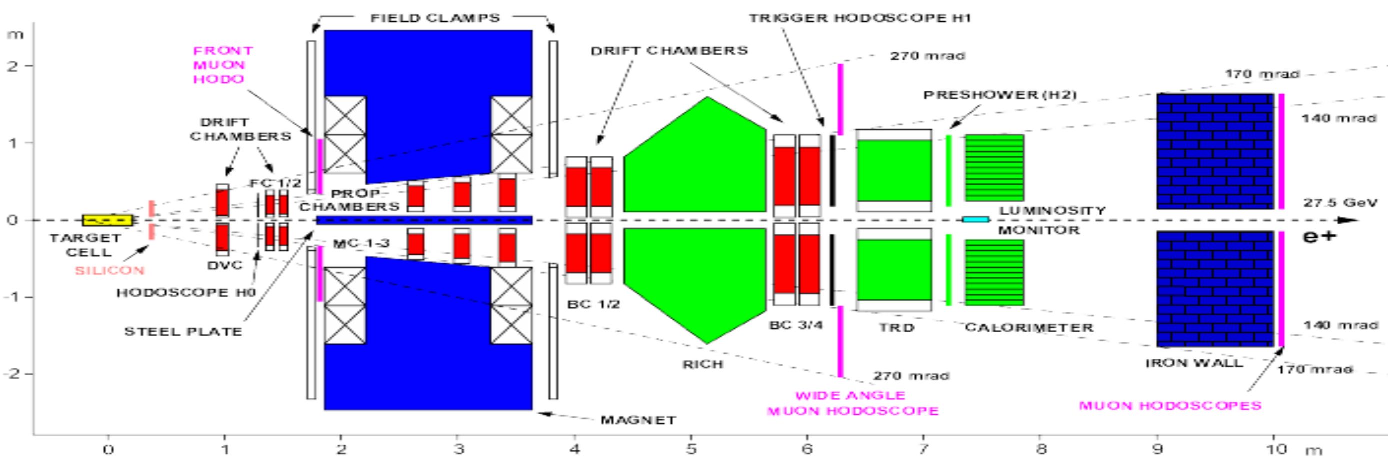
Electron and Hadron ID



Data taking: 95-07

Internal gaseous target
(no nuclear effects)

96-00 (H/D) Lpol + Upol
02-05 (H) Tpol + Upol
06-07 (H/D) Upol+Recoil



Unpolarized cross-section

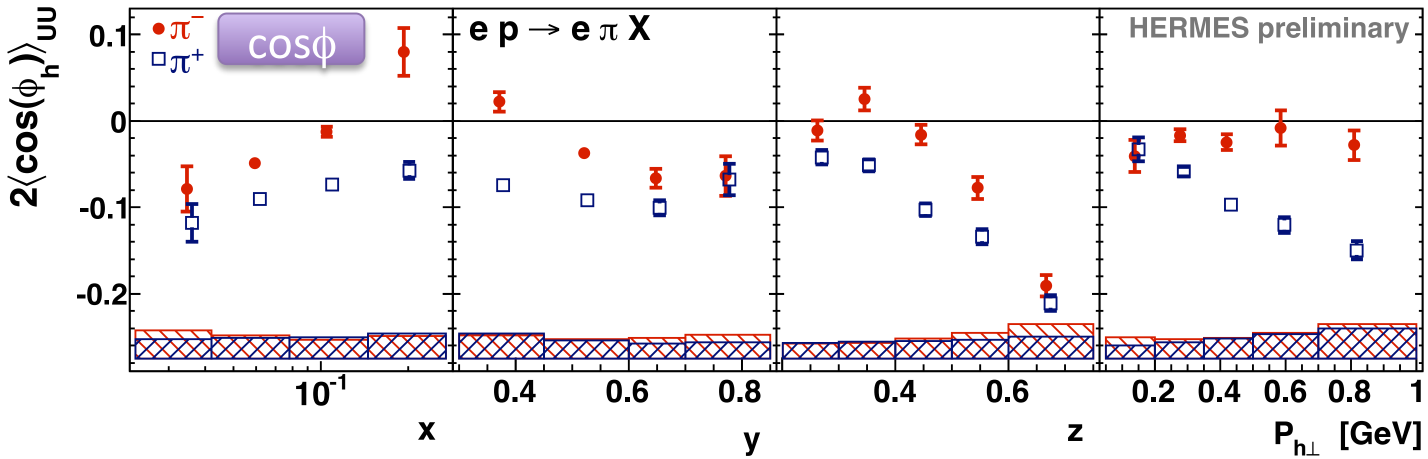
cosϕ large and negative !

$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + \ldots \right] / Q$$

Increasing with z and P_h

Large difference in hadron charge !

Larger in magnitude for π+



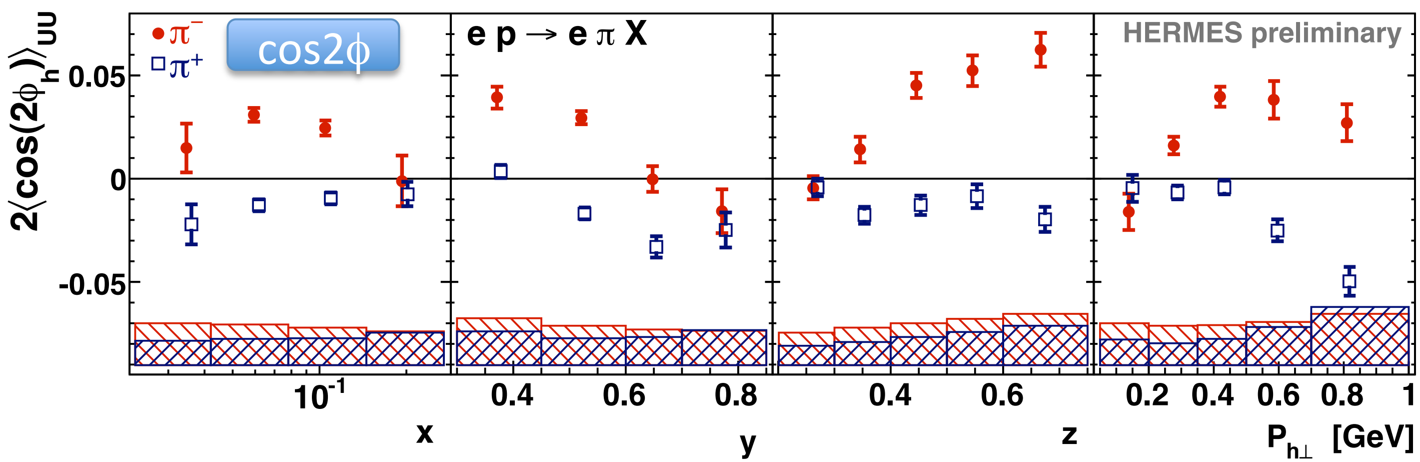
cos2ϕ non-zero !

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

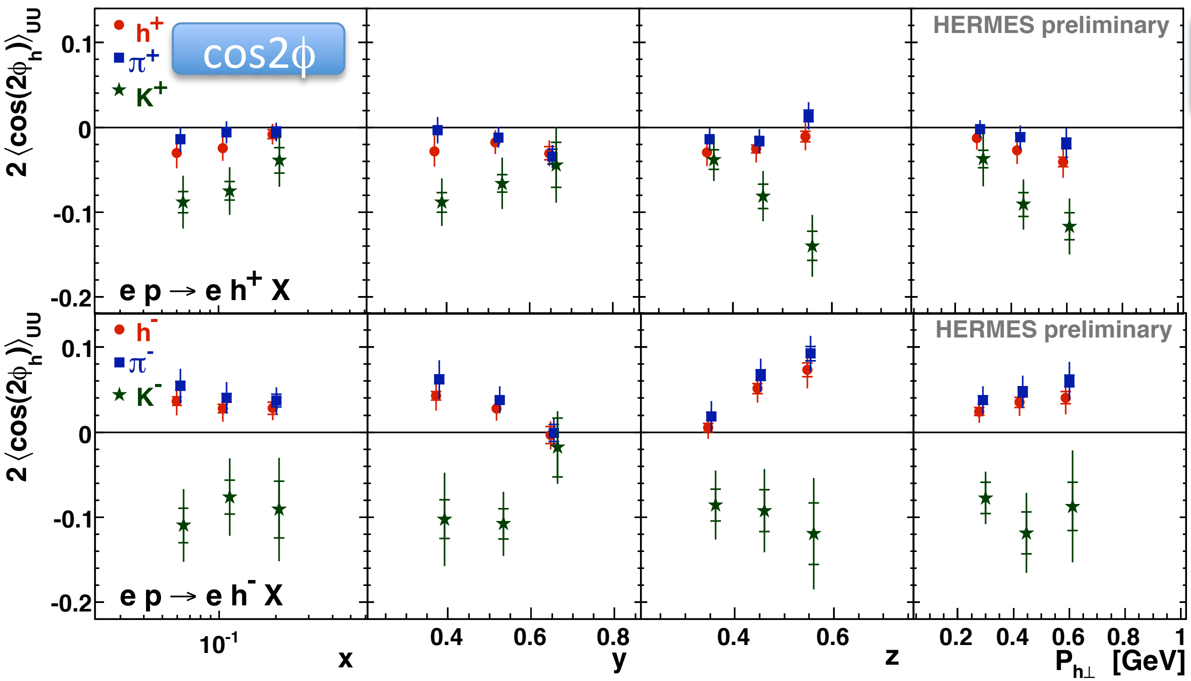
Difference in hadron charge !

Positive for π-

Negative for π+



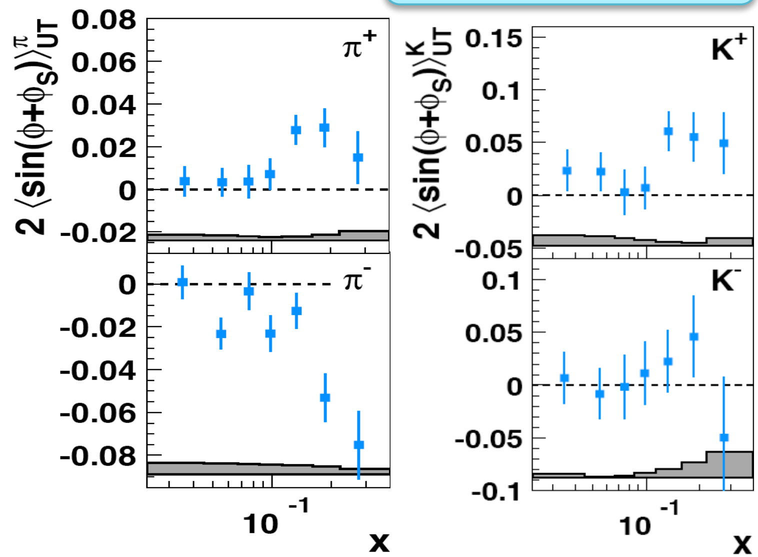
The kaon signal



$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

NEW !!

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^\perp$$



The kaon puzzle

Already found in A_{UT}: Collins+Transversity

Role of the sea in
distribution and fragmentation functions

Spares

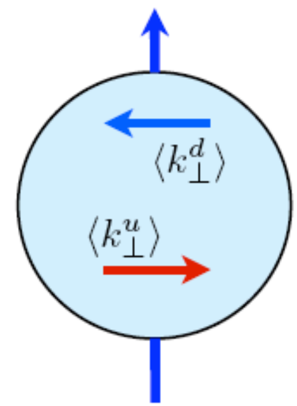
$$\boxed{\sum_a \int dx\, d^2\boldsymbol{k}_\perp\, \boldsymbol{k}_\perp\, f_{a/p^\uparrow}(x, \boldsymbol{k}_\perp) \equiv \sum_a \langle \boldsymbol{k}_\perp^a \rangle = 0}$$

M. Burkardt, PR **D69**, 091501 (2004)

$$\langle k_\perp^u \rangle + \langle k_\perp^d \rangle = -17^{+37}_{-55}\ (\mathrm{MeV}/c)$$

$$\left[\, \langle k_\perp^u \rangle = 96^{+60}_{-28} \qquad \langle k_\perp^d \rangle = -113^{+45}_{-51} \,\right]$$

$$\langle k_\perp^{\bar{u}} \rangle + \langle k_\perp^{\bar{d}} \rangle + \langle k_\perp^{s} \rangle + \langle k_\perp^{\bar{s}} \rangle = -14^{+43}_{-66}\ (\mathrm{MeV}/c)$$



Burkardt sum rule almost saturated by u and d quarks alone; little residual contribution from gluons

$$-10 \le \langle k_\perp^g \rangle \le 48\ (\mathrm{MeV}/c)$$

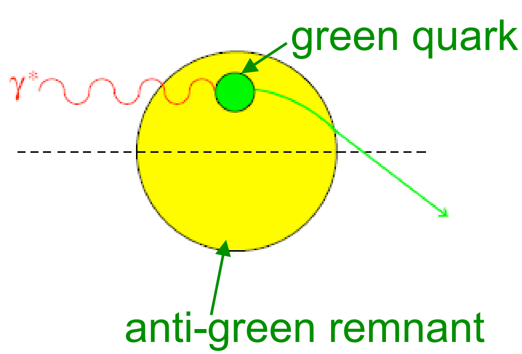
Spares

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

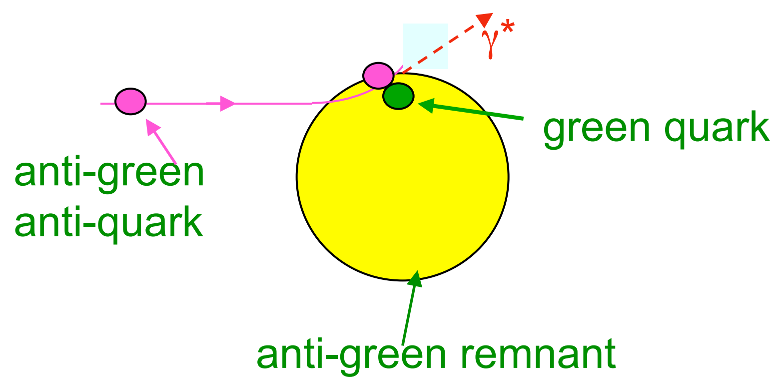
$\gamma^* q \rightarrow q$

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

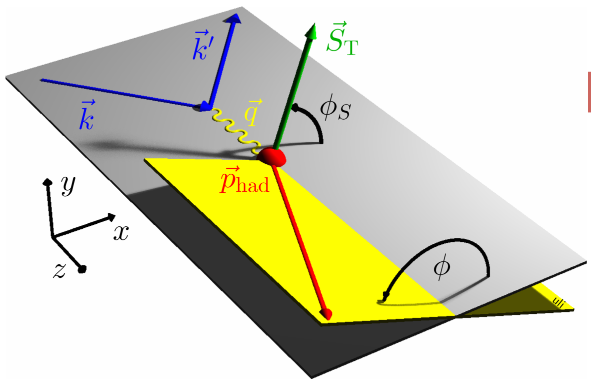
lensing effect



anti-lensing



Asymmetries and moments



[angle and moments definitions according to Trento conventions]

$$A^h_{UT}(\phi,\phi_S) = \frac{1}{|S_T|}\frac{N_h^{\uparrow}(\phi,\phi_S) - N_h^{\downarrow}(\phi,\phi_S)}{N_h^{\uparrow}(\phi,\phi_S) + N_h^{\downarrow}(\phi,\phi_S)} =$$

Collins moment

$$\propto \ldots \sin(\phi+\phi_S)\cdot \frac{\sum_q e_q^2\, I\left[\ldots h_1^q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, f_1(x)\cdot D_1^q(z)}$$