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Rencontres du Viet Nam

14th Workshop on Elastic and Diffractive Scattering
(EDS Blois Workshop)

Frontiers of QCD: From Puzzles to Discoveries

December 15-21, 2011
Qui Nhon, Vietnam

Spin Structure of the Nucleon Studied at HERMES

Y. Miyachi, Yamagata University

for the hermes collaboration

Contents

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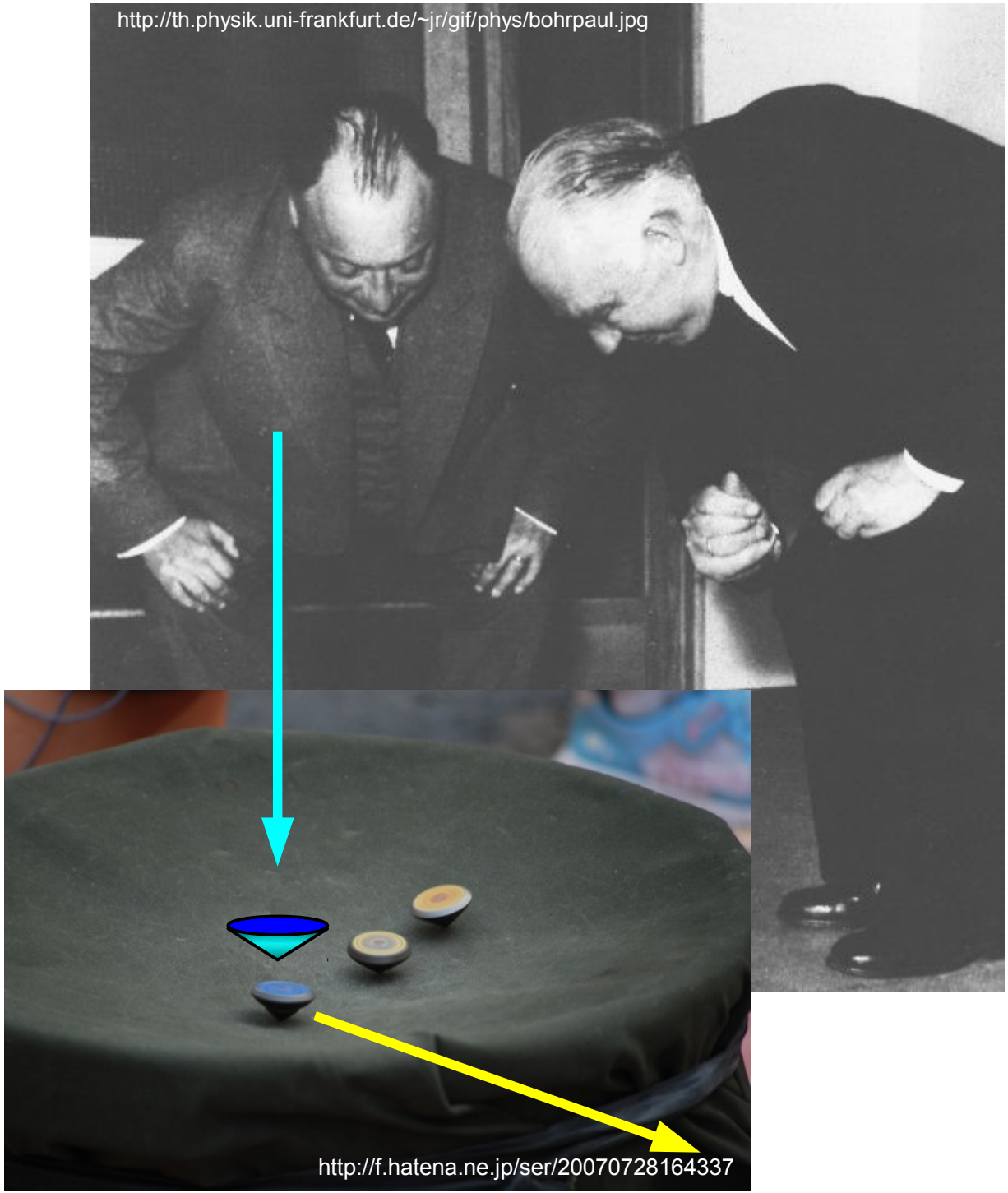
- How to study the “spin” structure of the proton?
- HERMES experiment
- Spin structure of the proton studied at HERMES
  - Semi-inclusive measurements of DIS
    - Quark helicity distributions
    - Transverse momentum dependent PDF
  - Hard-exclusive production and Generalized Parton Distribution
    - Deeply Virtual Compton Scattering
- Summary

In Japan,

we have a game with tops,

called “be-goma”.



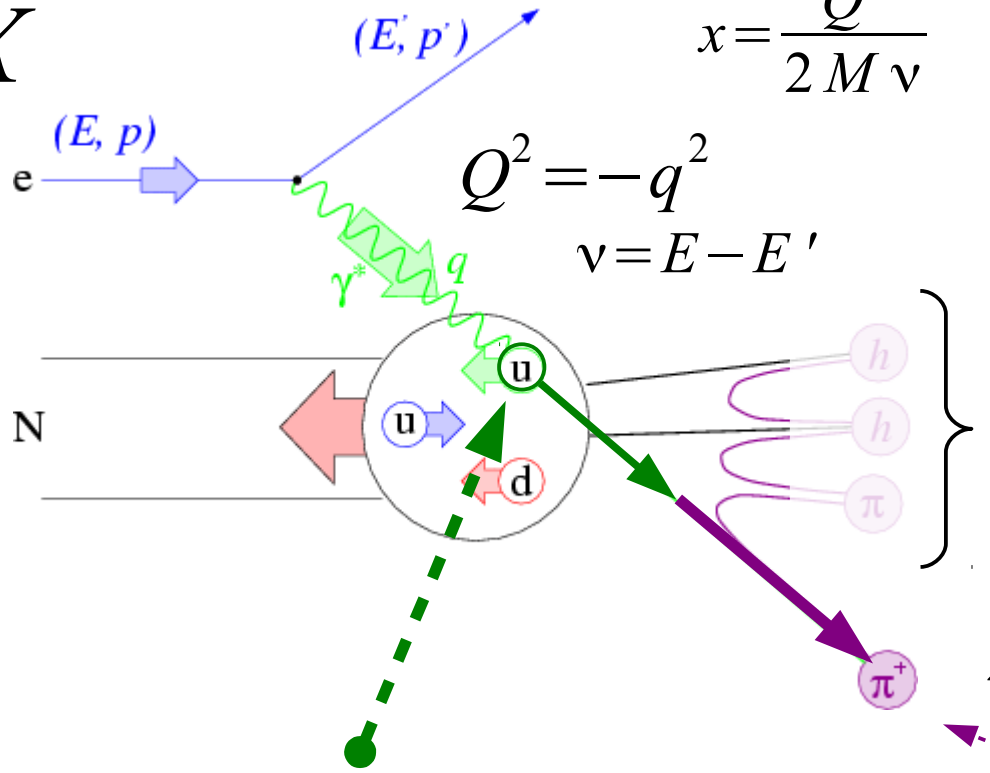
Try to kick the enemy's tops out.

To probe the elements,
let's hit with this top!

Now it becomes possible

Semi-inclusive measurement of DIS

$$e\,N \to e'\,h\,X$$



$$x = \frac{Q^2}{2\,M\,\nu}$$

$$Q^2 = -q^2$$

$$\nu = E - E'$$

$$z = \frac{E_h}{\nu}$$

$$\sigma^{eN \to e'hX} = \sum_q f^{N \to q} \otimes \hat{\sigma}^{eq \to e'q} \otimes F^{q \to h}$$

Parton Distribution Function

$$f\left(x, Q^2\right)$$

Fragmentation Function

$$F\left(z, Q^2\right)$$

HERMES experiment

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Targets: Unpolarized H, D, nuclei

Longitudinally polarized H, D (P ~ 85 %)

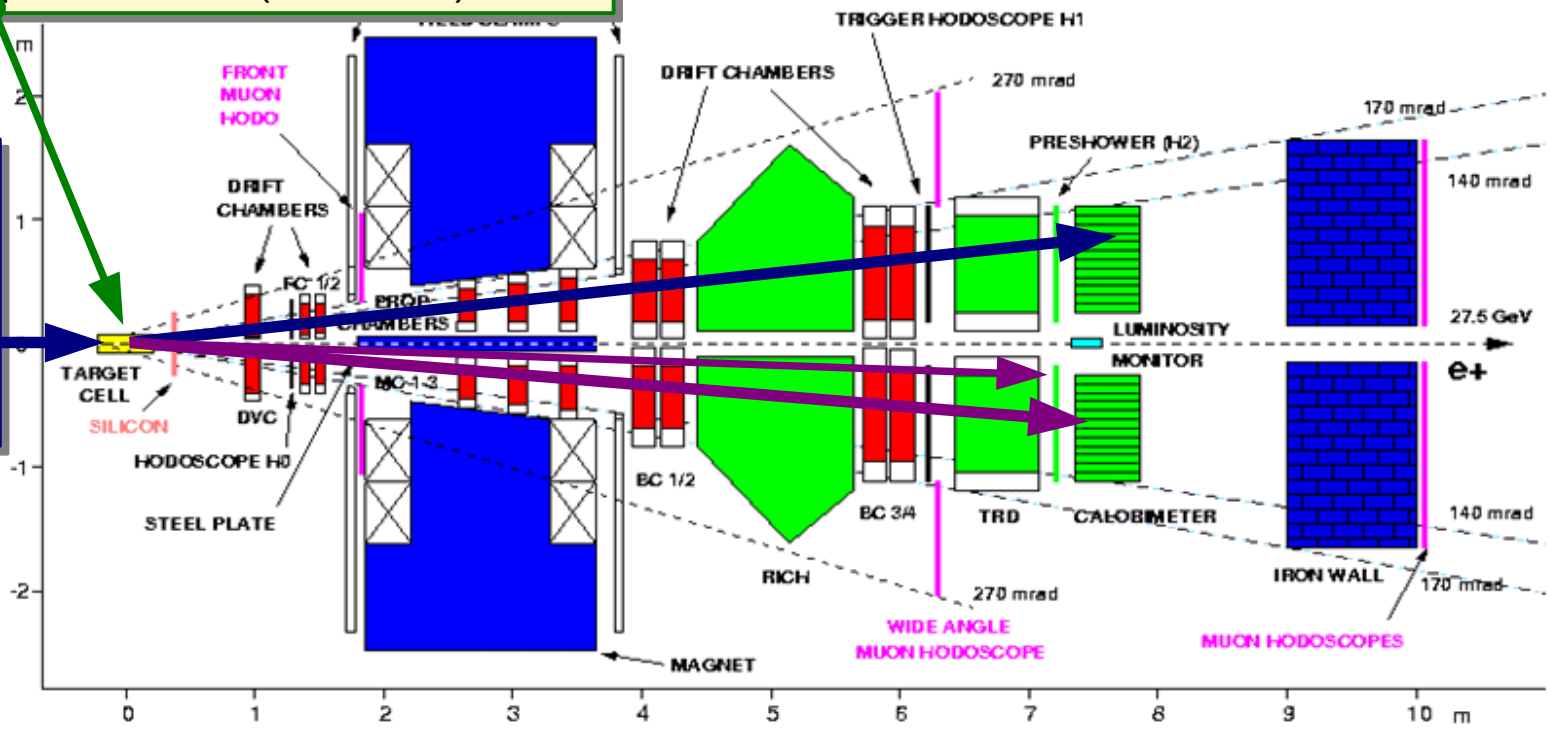
Transversely polarized H (P ~ 75%)

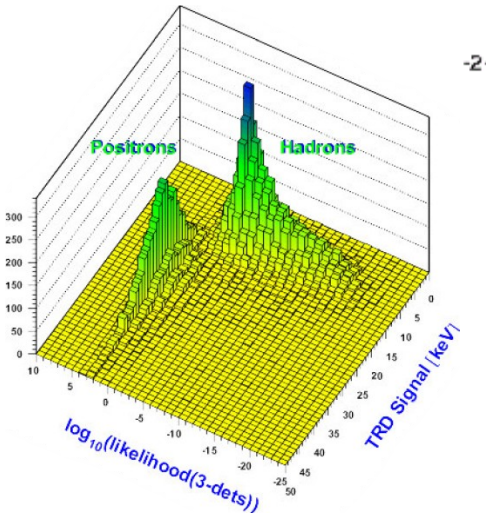
$$e + N \rightarrow e' + h + X$$

HERA: 27.6 GeV

polarized

electron/positron





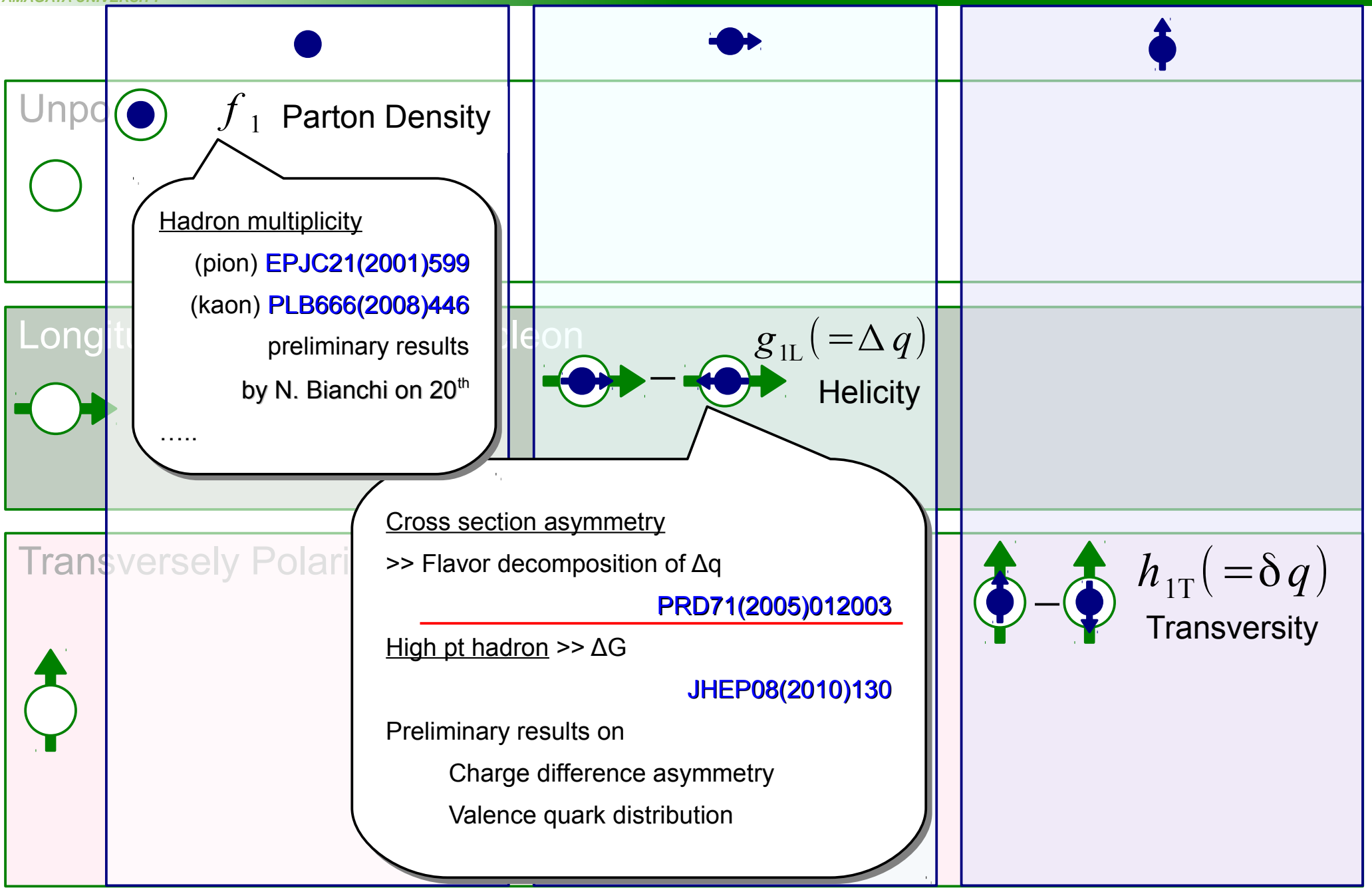
Reconstruction: Δp/p < 2%, Δθ<0.6 mrad

Lepton selection efficiency: > 99%

with hadron contamination < 1%

Hadron ID with RICH: π, K, p in 2 < p < 15 GeV/c

Parton distribution functions



Quark helicity distributions

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PRD71(2005)012003

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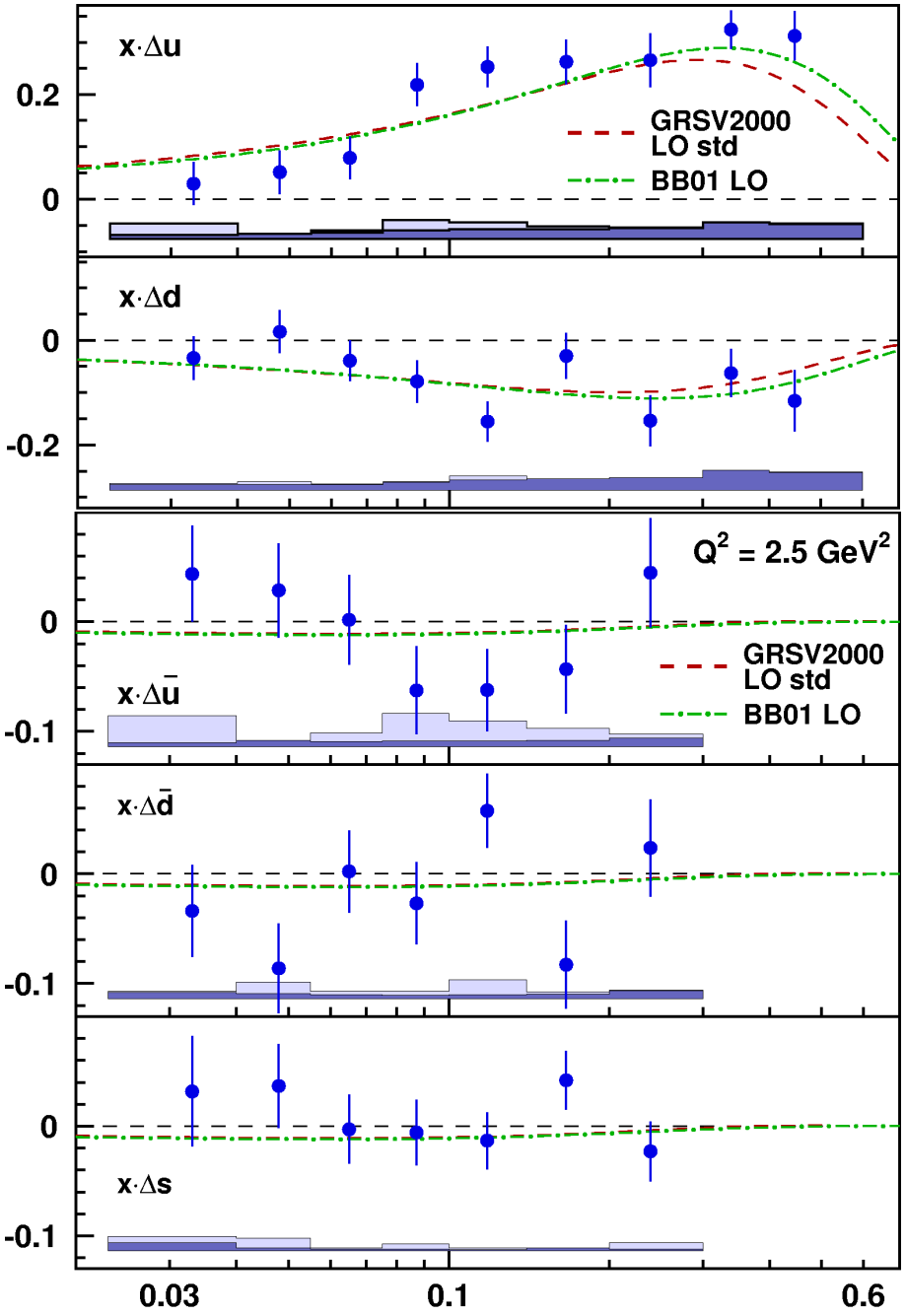


TABLE VIII. First and second moments of various helicity distributions in the measured range at a scale of $Q_0^2 = 2.5\ \mathrm{GeV}^2$.

$0.023 < x < 0.6$	Moments in measured range
Δu	$0.601 \pm 0.039 \pm 0.049$
$\Delta \bar{u}$	$-0.002 \pm 0.036 \pm 0.023$
Δd	$-0.226 \pm 0.039 \pm 0.050$
$\Delta \bar{d}$	$-0.054 \pm 0.033 \pm 0.011$
Δs	$0.028 \pm 0.033 \pm 0.009$

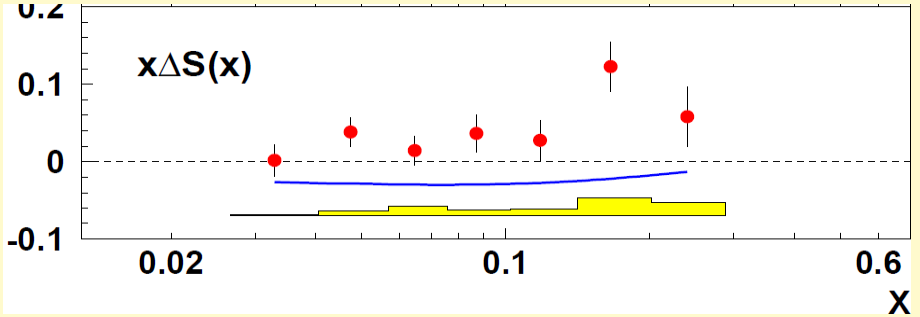
Inclusive measurements **PRD75(2007)012007**

$$\Delta s + \Delta \bar{s} = -0.085 \pm 0.013 \pm 0.008 \pm 0.009$$

$$\Delta \Sigma = 0.330 \pm 0.025 \pm 0.011 \pm 0.028$$

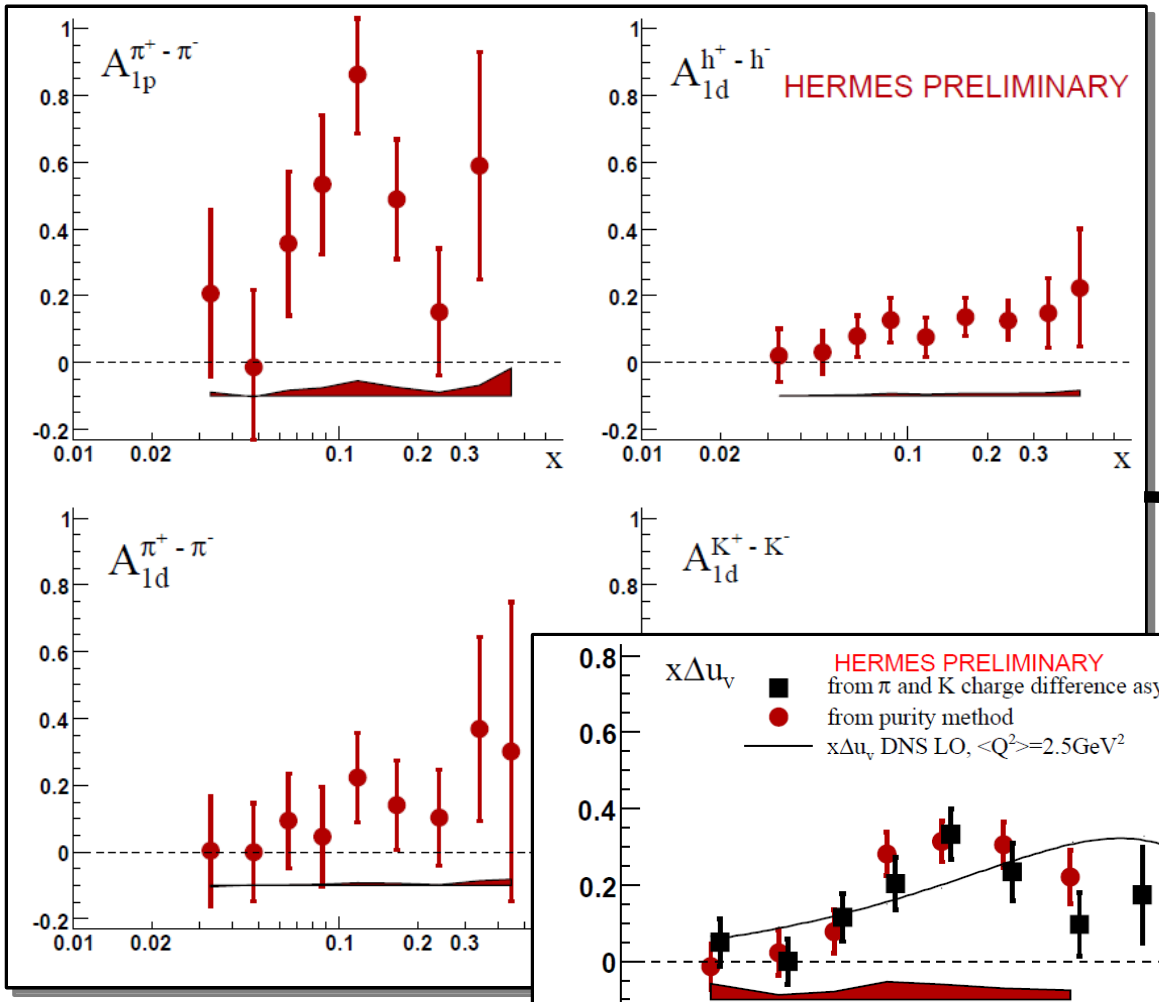
$\Delta\Sigma$	$0.347 \pm 0.024 \pm 0.066$
Δq_3	$0.880 \pm 0.045 \pm 0.107$
Δq_8	$0.262 \pm 0.078 \pm 0.045$

From charged kaon asymmetry **PLB666(2008)446**

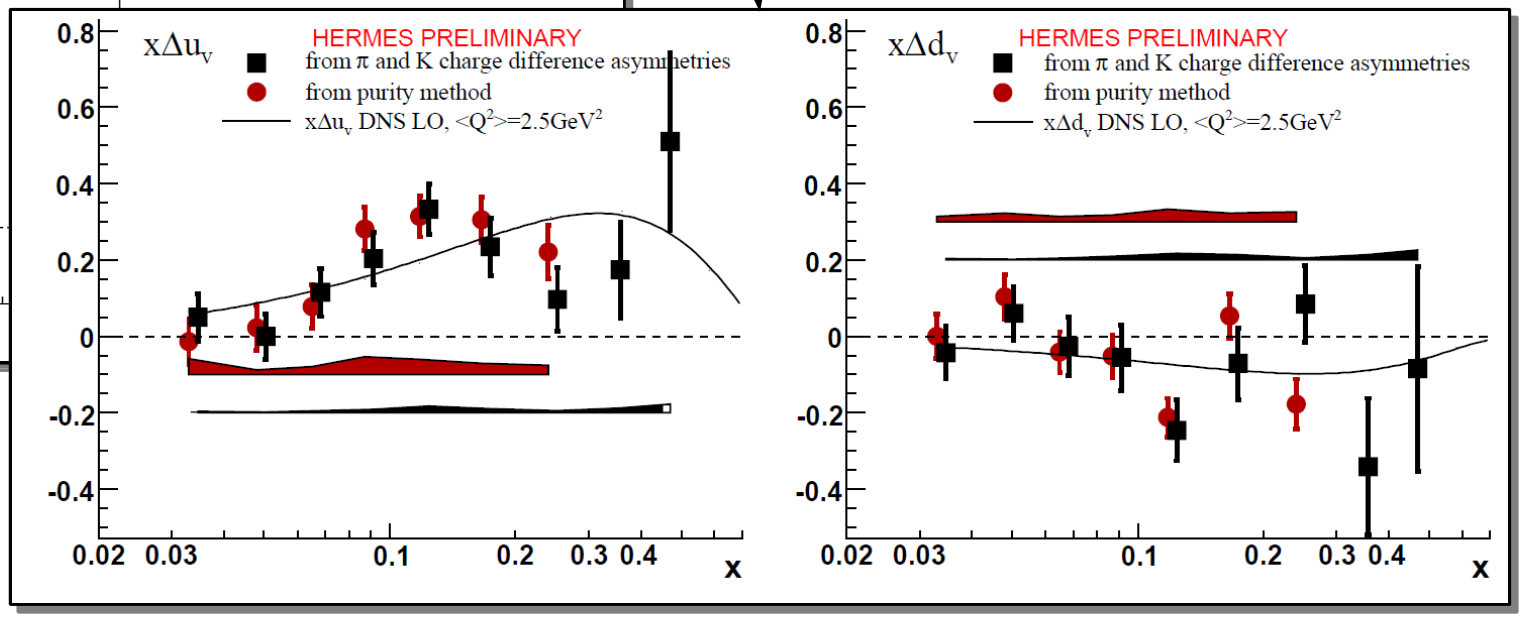


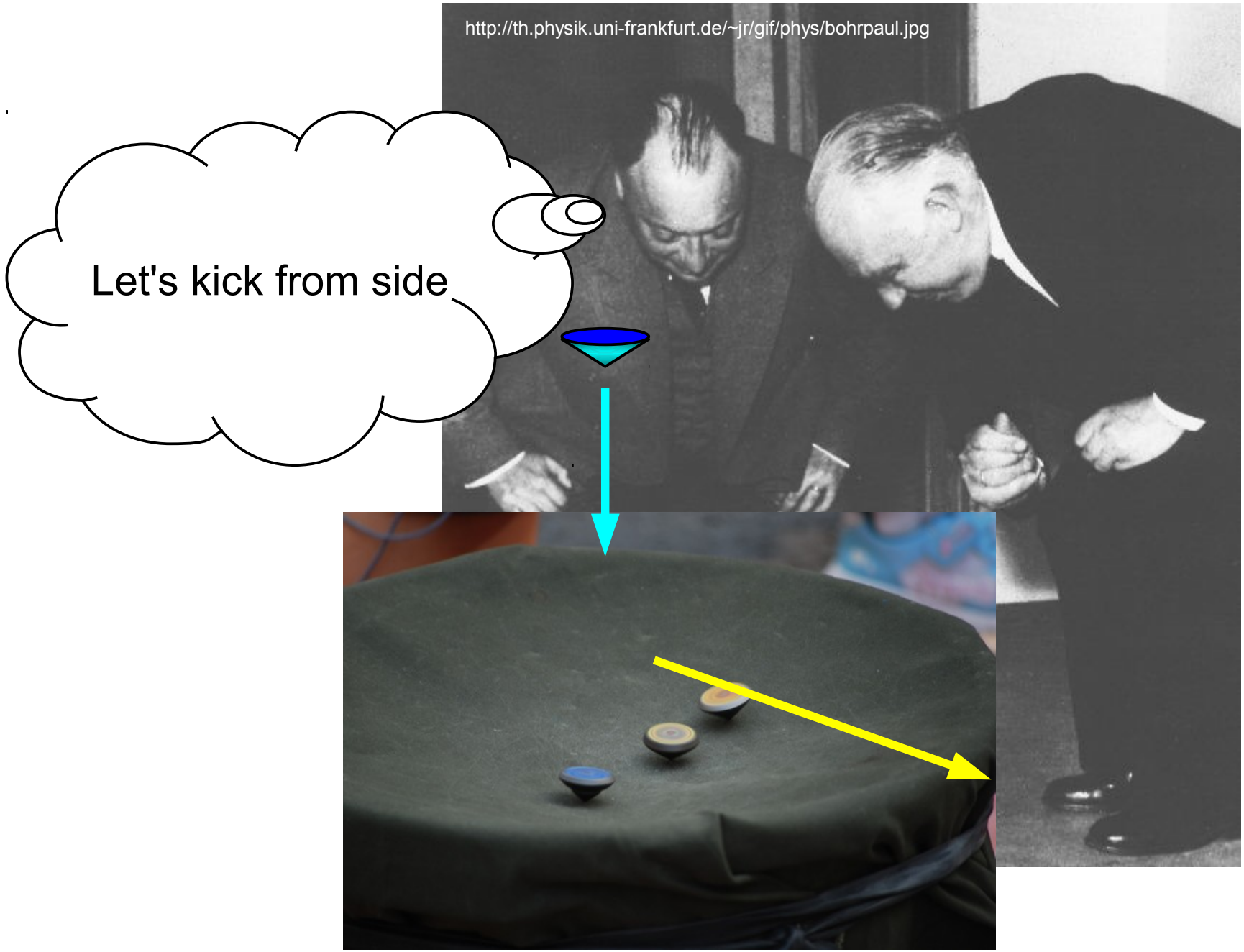
$$\Delta s + \Delta \bar{s} = 0.037 \pm 0.019 \pm 0.027$$

Difference asym. & valence quark

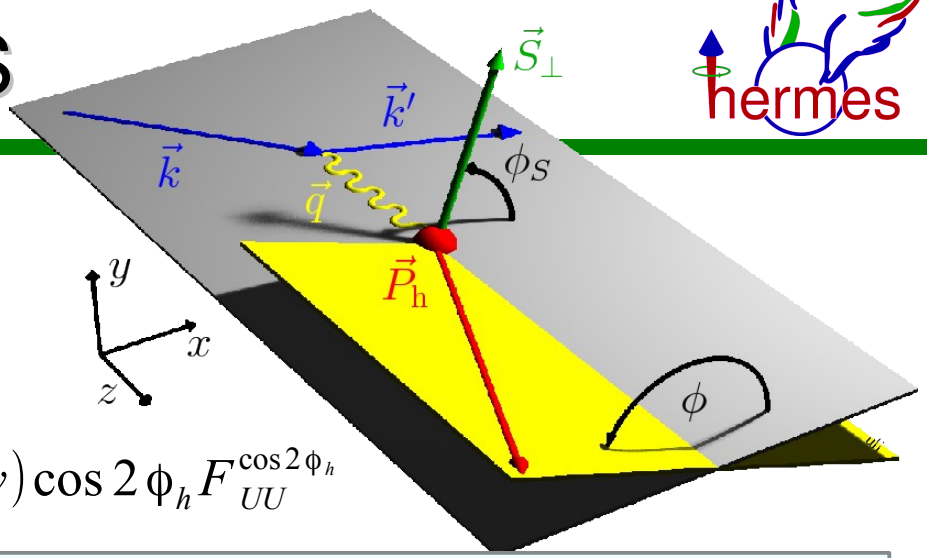


$$\begin{cases} A_{1p}^{\pi^+ - \pi^-} = \dfrac{\Delta 4u_v - \Delta d_v}{4u_v - d_v} \\ A_{1d}^{\pi^+ - \pi^-} = \dfrac{\Delta u_v - \Delta d_v}{u_v - d_v} \end{cases}$$




http://th.physik.uni-frankfurt.de/~jr/gif/phys/bohrpaul.jpg
Let's kick from side

Azimuthal angles in SIDIS



$$e + N \to e' + h + X$$

$$d\sigma \propto$$

$$\frac{1+(1-y)^2}{2} F_{UU} + (2-y)\sqrt{1-y}\cos\phi_h F_{UU}^{\cos\phi_h} + (1-y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}$$

$$+ S_L \left[(1-y)\sin 2\phi_h F_{UL}^{\sin 2\phi_h} + (2-y)\sqrt{1-y}\sin\phi_h F_{UL}^{\sin\phi_h} \right]$$

$$+ S_L P_z^l \left[\frac{1-(1-y)^2}{2} F_{LL} + y\sqrt{1-y}\cos\phi_h F_{LL}^{\cos\phi_h} \right]$$

$$+ S_T \left[\frac{1+(1-y)^2}{2} \sin(\phi_h - \phi_S) F_{UT}^{\sin(\phi_h-\phi_S)} \right.$$
$$+ (1-y)\left(\sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)} \right)$$
$$\left. + (2-y)\sqrt{1-y}\left(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi - \phi_S) F_{UT}^{\sin(2\phi-\phi_S)} \right) \right]$$

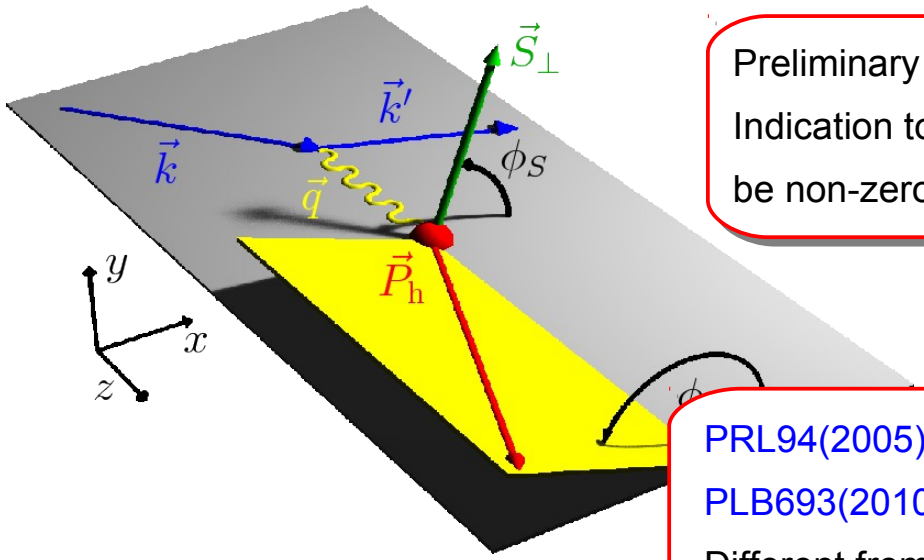
$$+ S_T P_z^l \left[\frac{1-(1-y)^2}{2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + y\sqrt{1-y}\left(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi - \phi_S) F_{LT}^{\cos(2\phi-\phi_S)} \right) \right]$$

Leading-twist Transverse Momentum Dependent PDF

Unpo

Long

Transversely Polarized Nucleon



Preliminary results
Indication to
be non-zero

$h_1^\perp$ Boer-Mulders

$h_1^\perp \otimes H_1^\perp \sim \cos 2\phi$

$h_{1L}^\perp$ Mulders-Kotzinian

$h_{1L}^\perp \otimes H_1^\perp \sim \sin 2\phi$

PRL94(2005)012002
PLB693(2010)11
Different from zero

$f_{1T}^\perp$ Sivers

PRL94(2005)012002
PRL103(2009)152002
Different from zero

$f_{1T}^\perp \otimes D_1 \sim \sin(\phi - \phi_S)$

g_{1T} Worm-gear

$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$

$h_{1T}(=\delta q)$ Transversity

$h_{1T} \otimes H_1^\perp \sim \sin(\phi + \phi_S)$

$h_{1T}^\perp$ Pretzelosity

$h_{1T}^\perp \otimes H_1^\perp \sim \sin(3\phi - \phi_S)$

Sivers & Collins amplitudes

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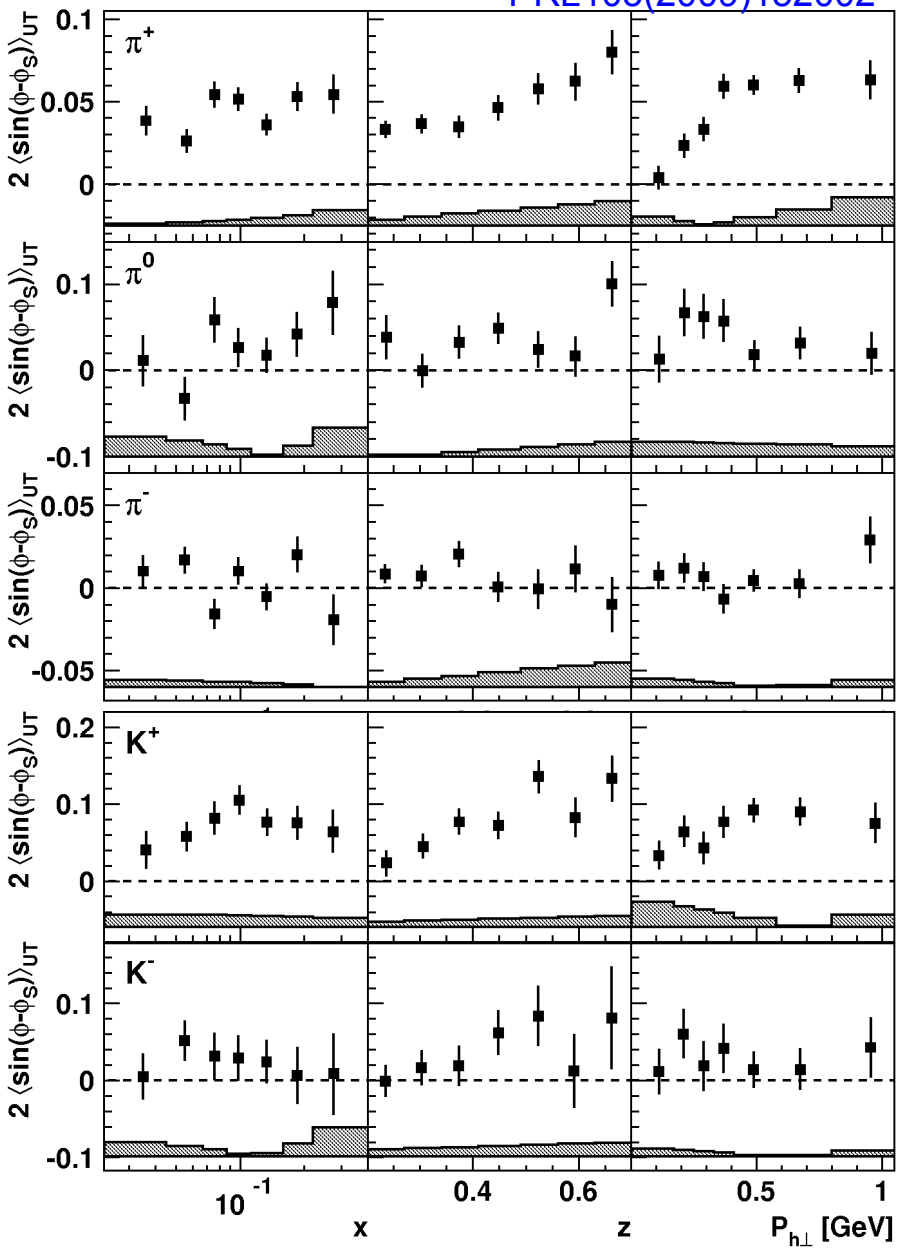
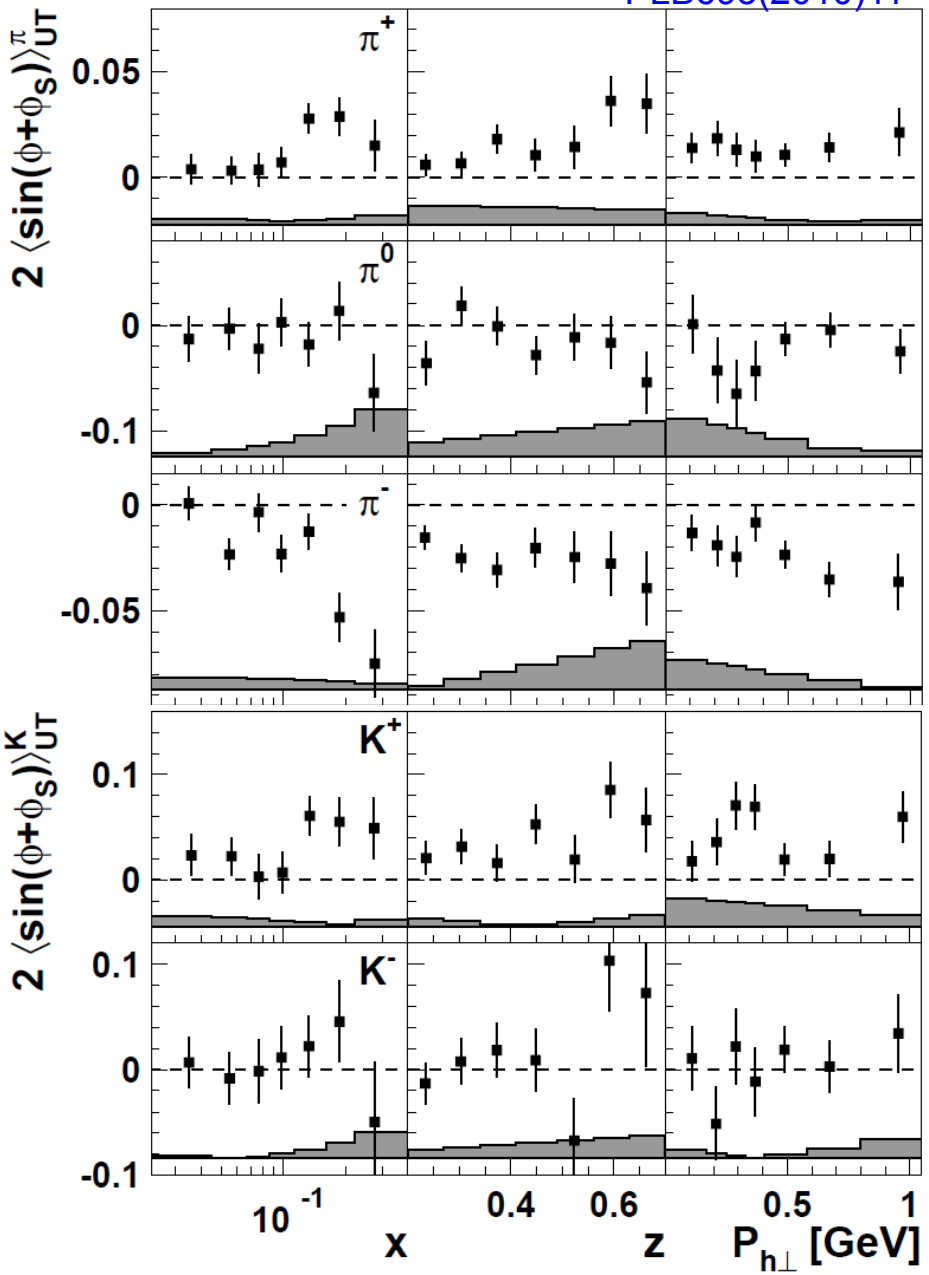
$f_{1T}^{\perp} \otimes D_1 \sim \sin(\phi - \phi_S)$

PRL103(2009)152002

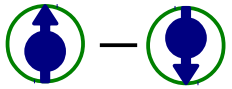


$h_{1T} \otimes H_1^{\perp} \sim \sin(\phi + \phi_S)$

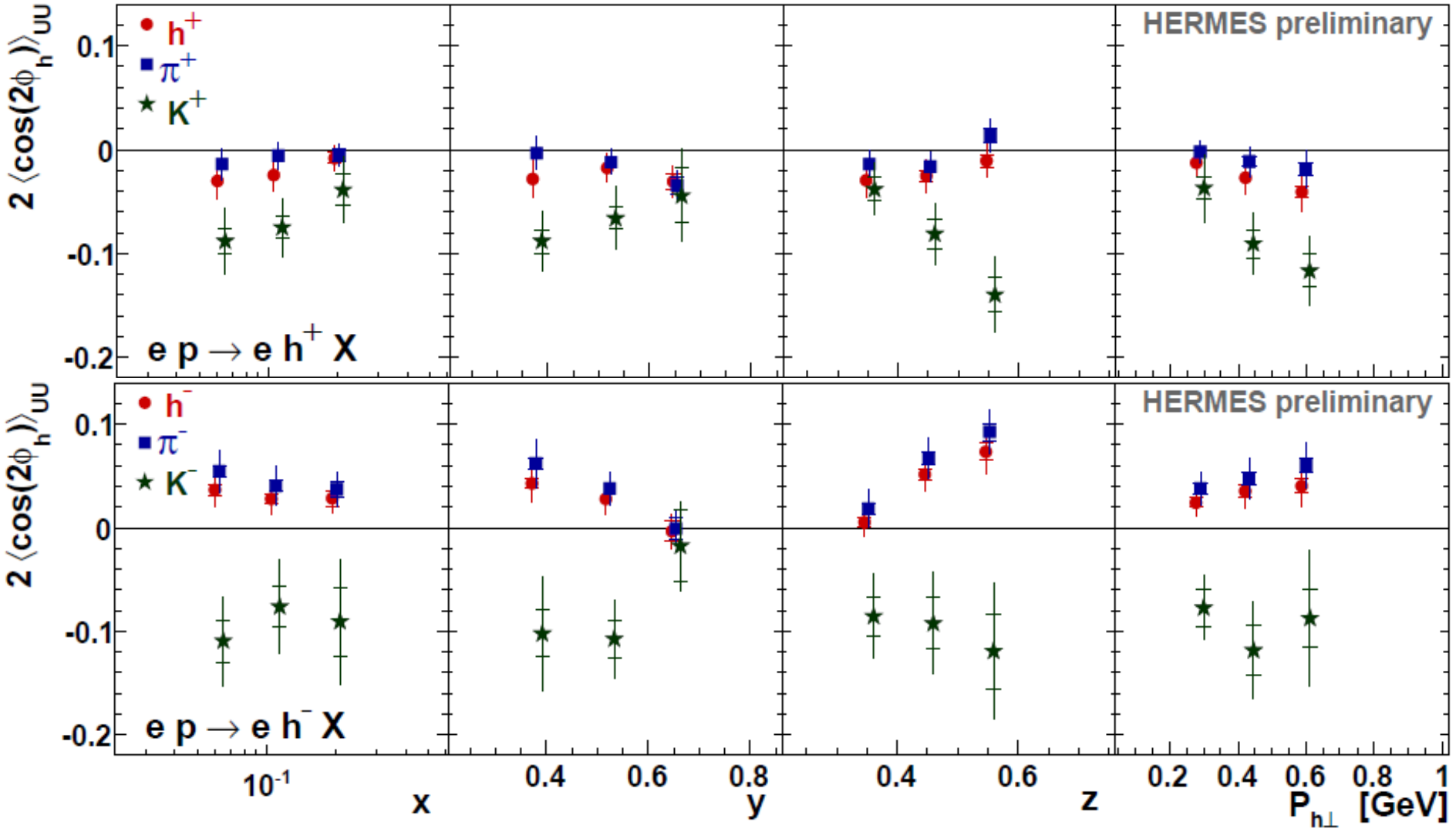
PLB693(2010)11



Boer-Mulders amplitude



$$h_1^{\perp} \otimes H_1^{\perp} \sim \cos 2\phi$$



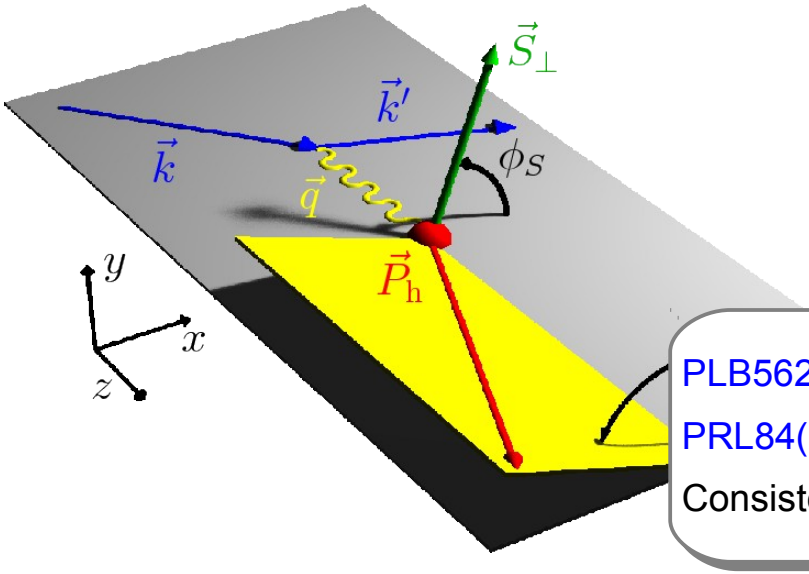
Leading-twist

Transverse Momentum Dependent PDF

Unpo

Long

Transversely Polarized Nucleon



$h_1^\perp$ Boer-Mulders

$h_1^\perp \otimes H_1^\perp \sim \cos 2\phi$

PLB562(2003)182

PRL84(2000)4047

Consistent with zero

$h_{1L}^\perp$ Mulders-Kotzinian

$h_{1L}^\perp \otimes H_1^\perp \sim \sin 2\phi$

$f_{1T}^\perp$ Sivers

Preliminary results

small

$f_{1T}^\perp \otimes D_1 \sim \sin(\phi - \phi_S)$

g_{1T} Worm-gear

Preliminary results

Consistent with zero

$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$

$h_{1T}(=\delta q)$ Transversity

$h_{1T} \otimes H_1^\perp \sim \sin(\phi + \phi_S)$

$h_{1T}^\perp$ Pretzelosity

$h_{1T}^\perp \otimes H_1^\perp \sim \sin(3\phi - \phi_S)$

Leading-twist

Transverse Momentum Dependent PDF

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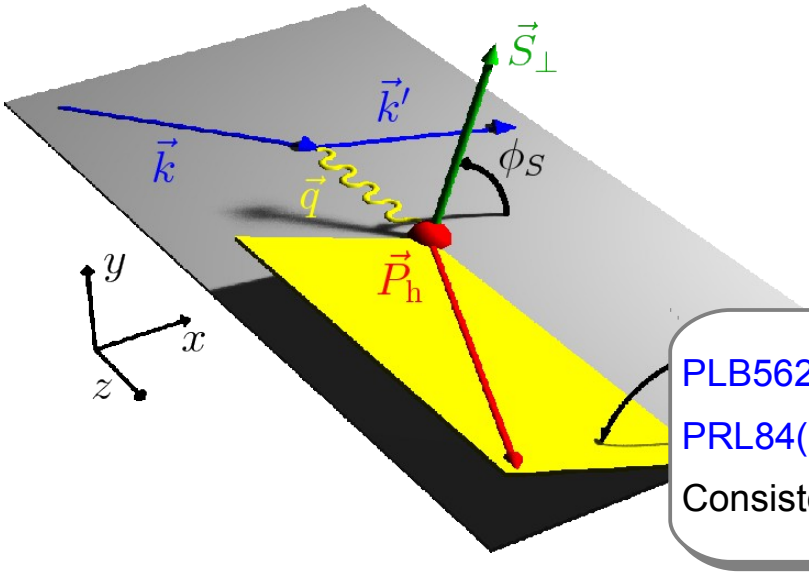
Transversely Polarized Nucleon



$h_1^\perp$ Boer-Mulders

$h_1^\perp \otimes H_1^\perp \sim \cos 2\phi$

$h_{1L}^\perp$ Mulders-Kotzinian

PLB562(2003)182

PRL84(2000)4047

Consistent with zero

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Preliminary results

small

$f_{1T}^\perp \otimes D_1 \sim \sin(\phi - \phi_S)$

g_{1T} Worm-gear

Preliminary results

Consistent with zero

$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$

$h_{1T}(=\delta q)$ Transversity

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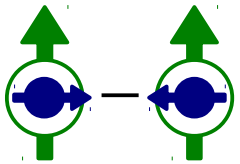
$h_{1T}^\perp \otimes H_1^\perp \sim \sin(3\phi - \phi_S)$

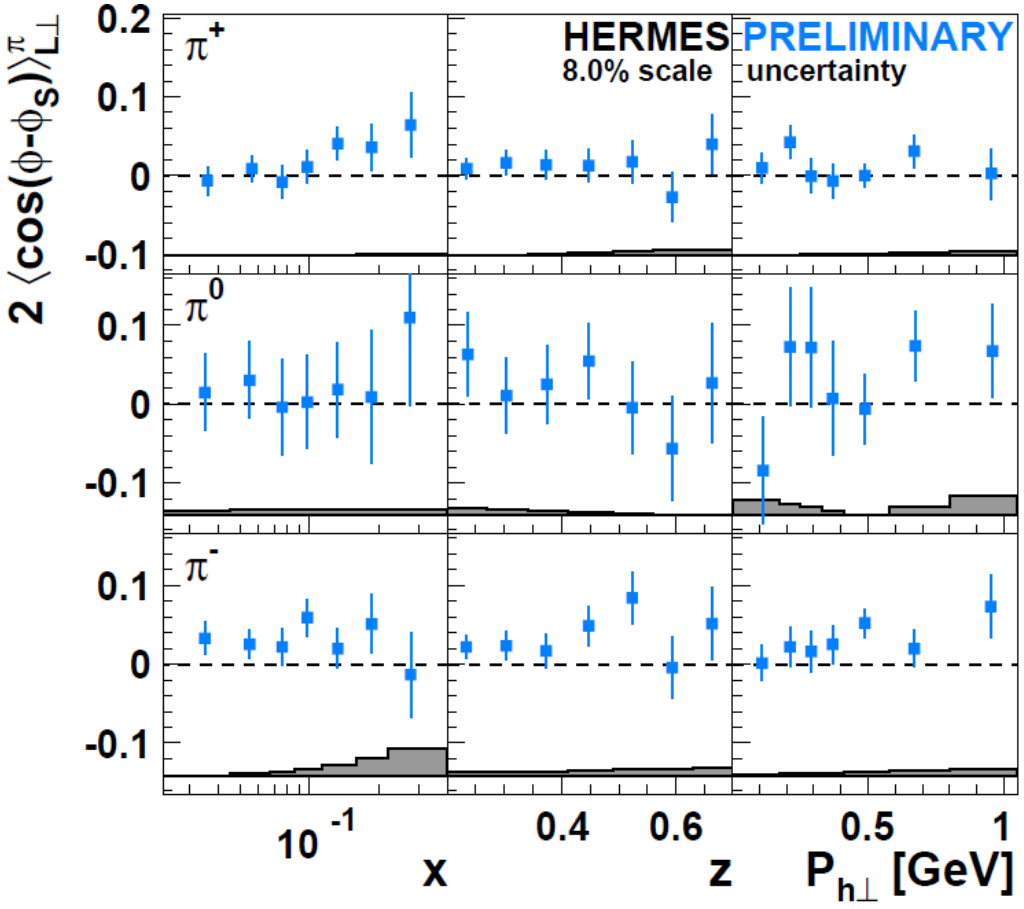
Worm-gear amplitude

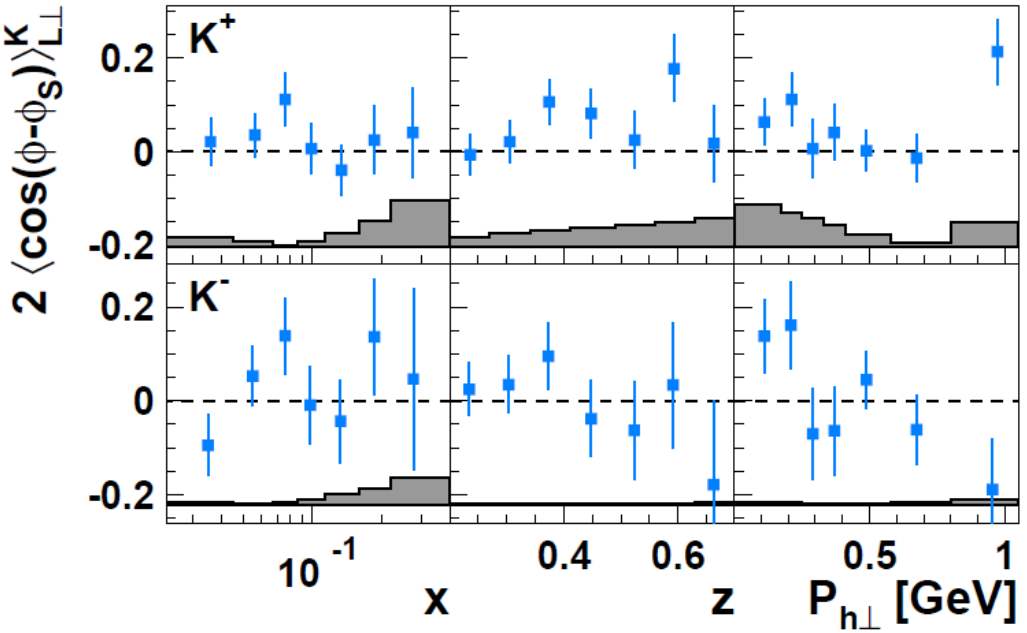


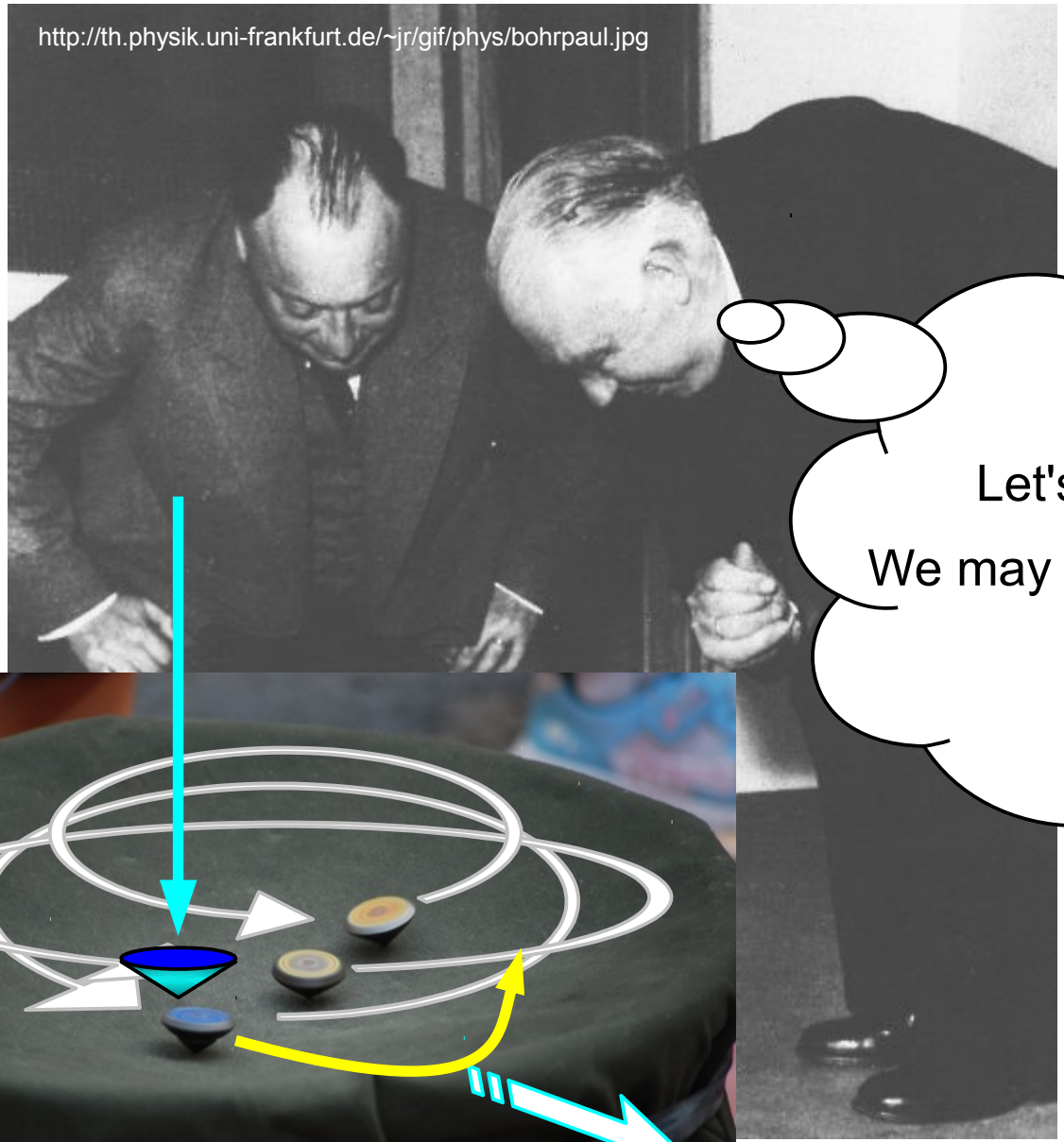
g_{1T}

Worm-gear

$$g_{1T} \otimes D_1 \sim \cos\left(\phi - \phi_S\right)$$







Let's keep it inside, then.

We may access the orbital motion.

Hard Exclusive Production and GPD

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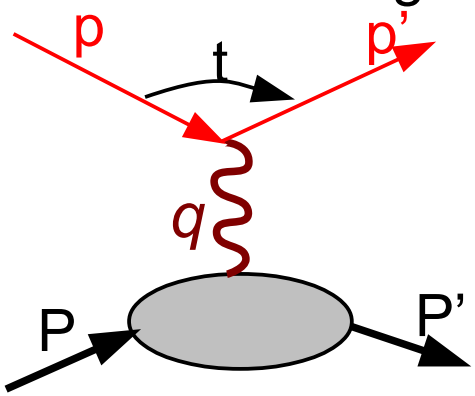
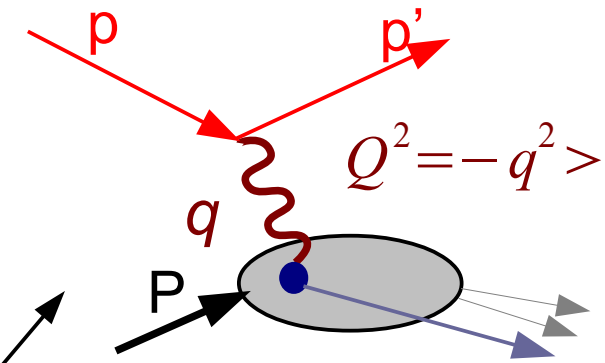
Elastic scattering



Form Factor: F(t), G(t)

$\int_{-1}^{1} dx$

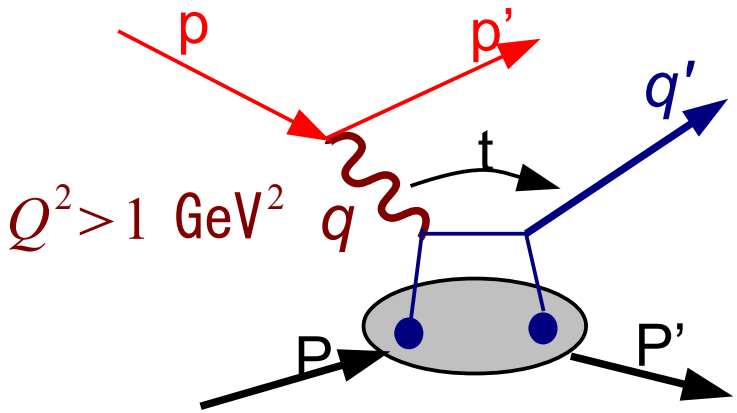
Deep Inelastic Scattering



Forward limit

Parton distribution: **q(x), Δq(x)**

Hard Exclusive Production:



$$e + N \rightarrow e' + N' + \{\gamma,\ \rho,\ \pi, \ldots\}$$

Generalized Parton Distribution:

$$\boldsymbol{H},\ \boldsymbol{E},\ \tilde{\boldsymbol{H}},\ \tilde{\boldsymbol{E}}$$

$$J_q = \frac{1}{2}\int_{-1}^{1} dx\, x\,[H^q(x,\xi,t\rightarrow 0) + E^q(x,\xi,t\rightarrow 0)]$$

Deeply Virtual Compton Scattering

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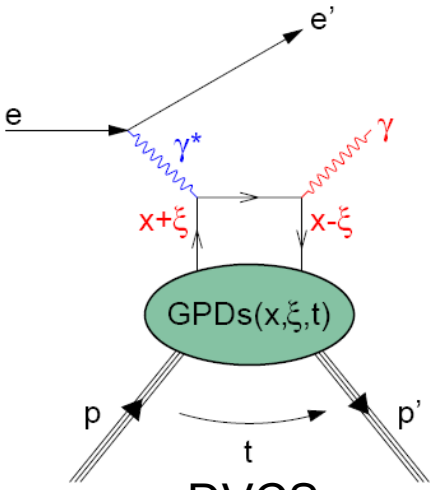
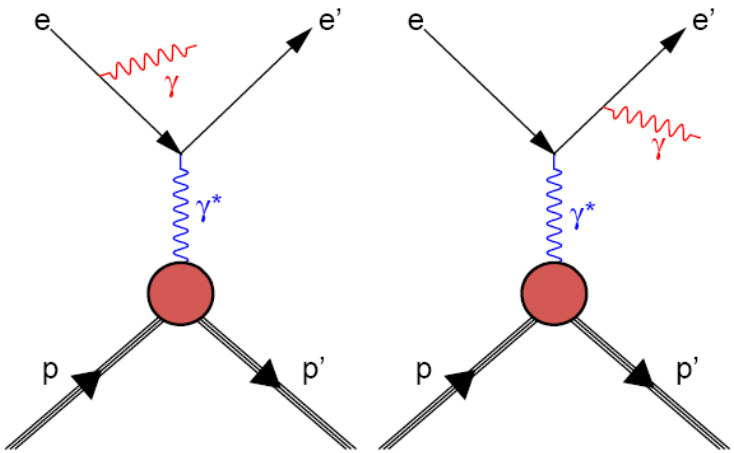
$$e + N \rightarrow e' + N + \gamma$$

$$\sigma_{DVCS} \ll \sigma_{BH}$$

@HERMES



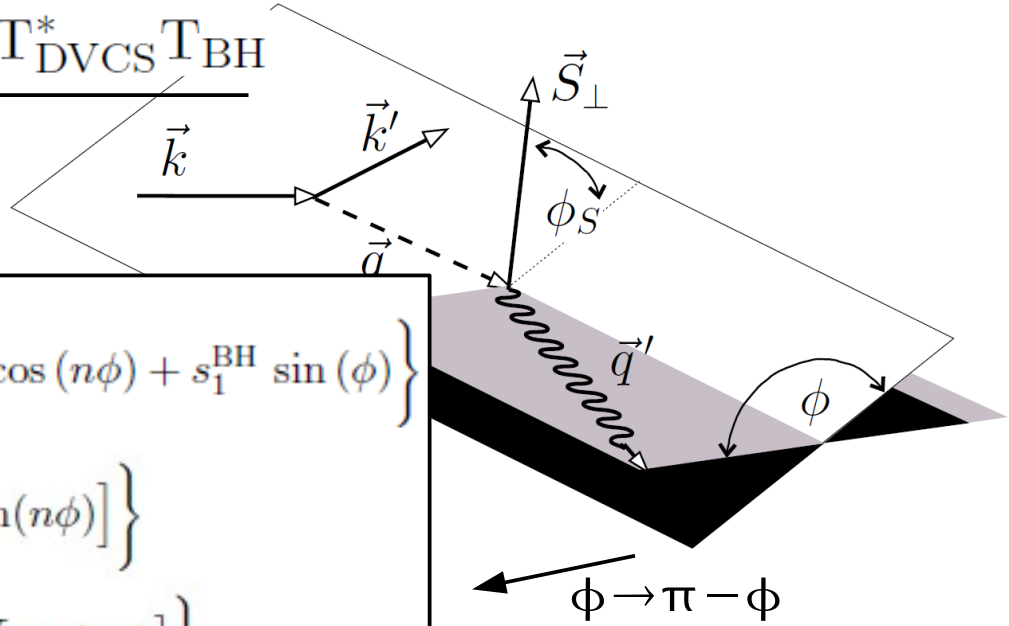
DVCS



Bethe-Heitler (BH)

$$|T|^2 = |T_{DVCS}|^2 + |T_{BH}|^2 + T_{DVCS} T^*_{BH} + T^*_{DVCS} T_{BH}$$

$$= I$$



$$|\mathcal{T}_{BH}|^2 = \frac{e^6}{x_B^2 y^2 (1+\epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} \cos(n\phi) + s_1^{BH} \sin(\phi) \right\}$$

$$|\mathcal{T}_{DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{DVCS} + \sum_{n=1}^{2} \left[c_n^{DVCS} \cos(n\phi) + s_n^{DVCS} \sin(n\phi) \right] \right\}$$

$$\mathcal{I} = \frac{\pm e^6}{x_B y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\}$$

A.V. Belitsky, D. M¨uller and A. Kirchner, NPB 629 (2002) 323

Measurement of exclusive production at

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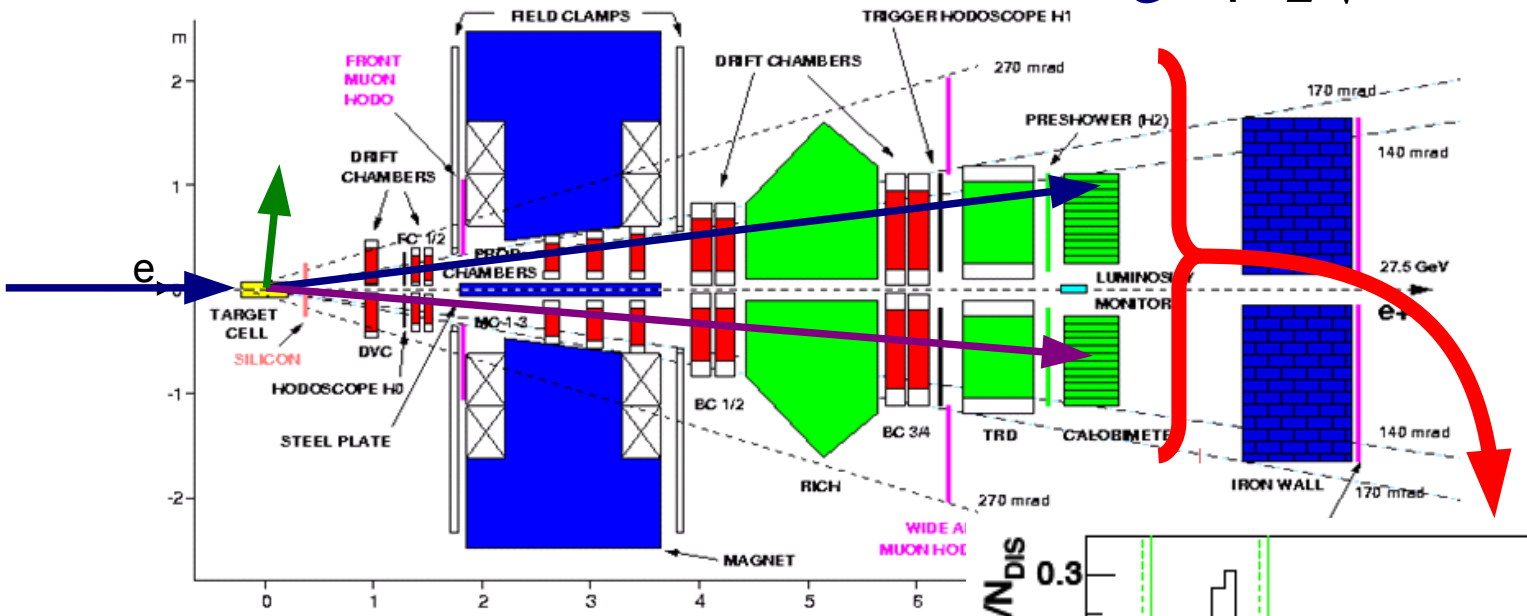
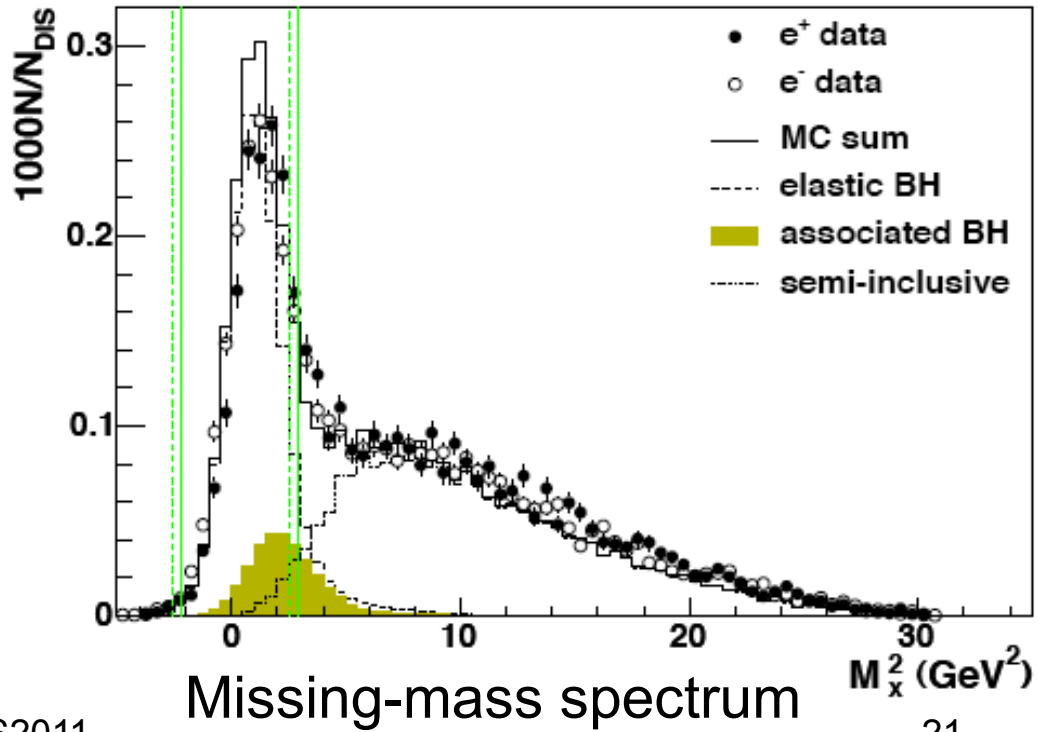
$$e + N \rightarrow e' + N + \gamma$$





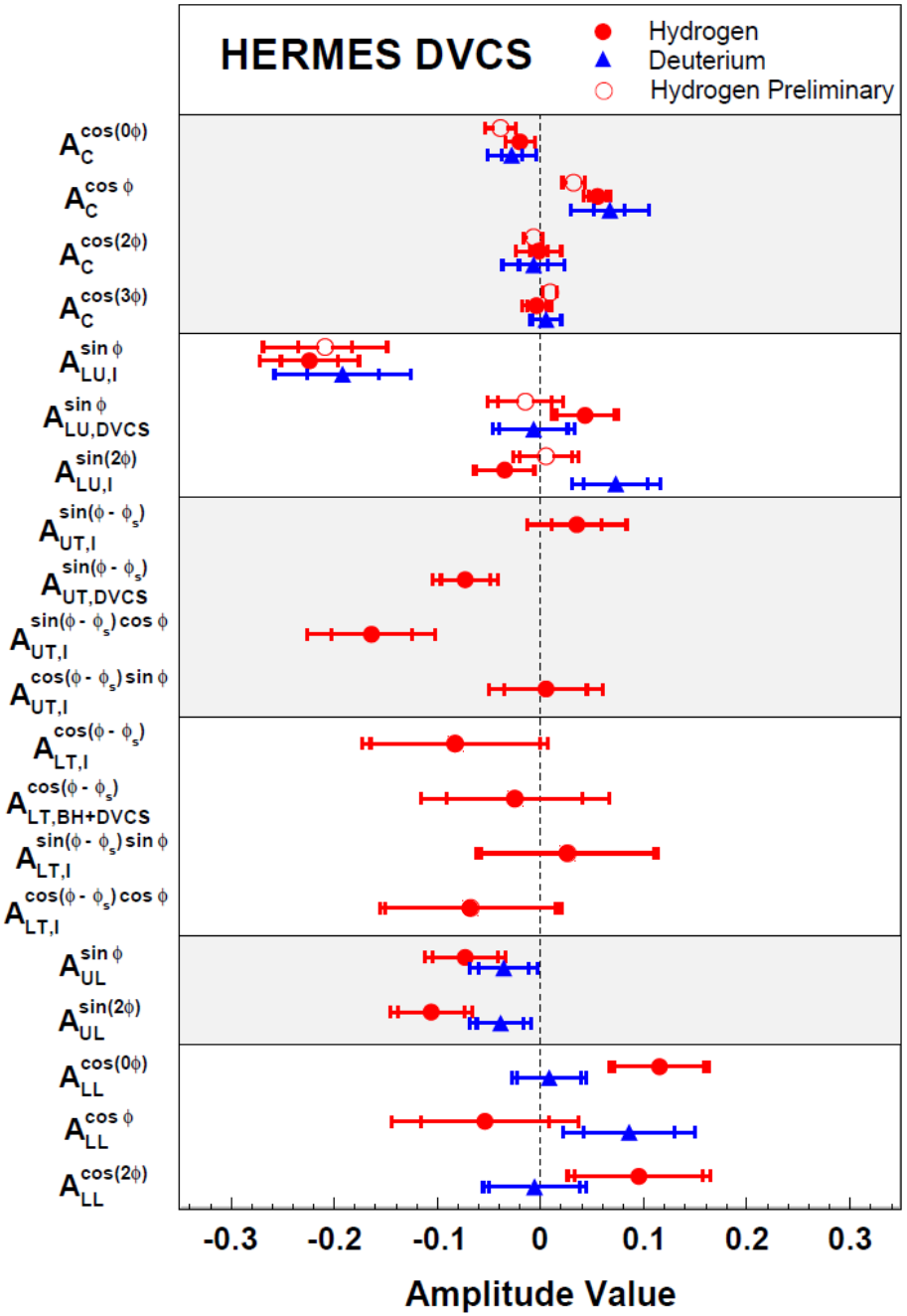
Missing-mass spectrum

1996 ~ 2005:

No detector for the recoil proton

Cut on missing-mass spectrum

DVCS amplitudes measured at HERMES



DVCS asymmetries:

Beam Charge	JHEP11(2009)083 NPB829(2010)1
Beam Helicity	→ GPD H
Transverse Target Spin → GPD E	JHEP06(2008)066
Transverse Double Spin (LT) → GPD $\tilde{H}$	PLB704(2011)53
Longitudinal Target / Double Spin → GPD $\tilde{H}$	JHEP06(2010)019 NPB842(2011)265

Exclusive production with Recoil Detector

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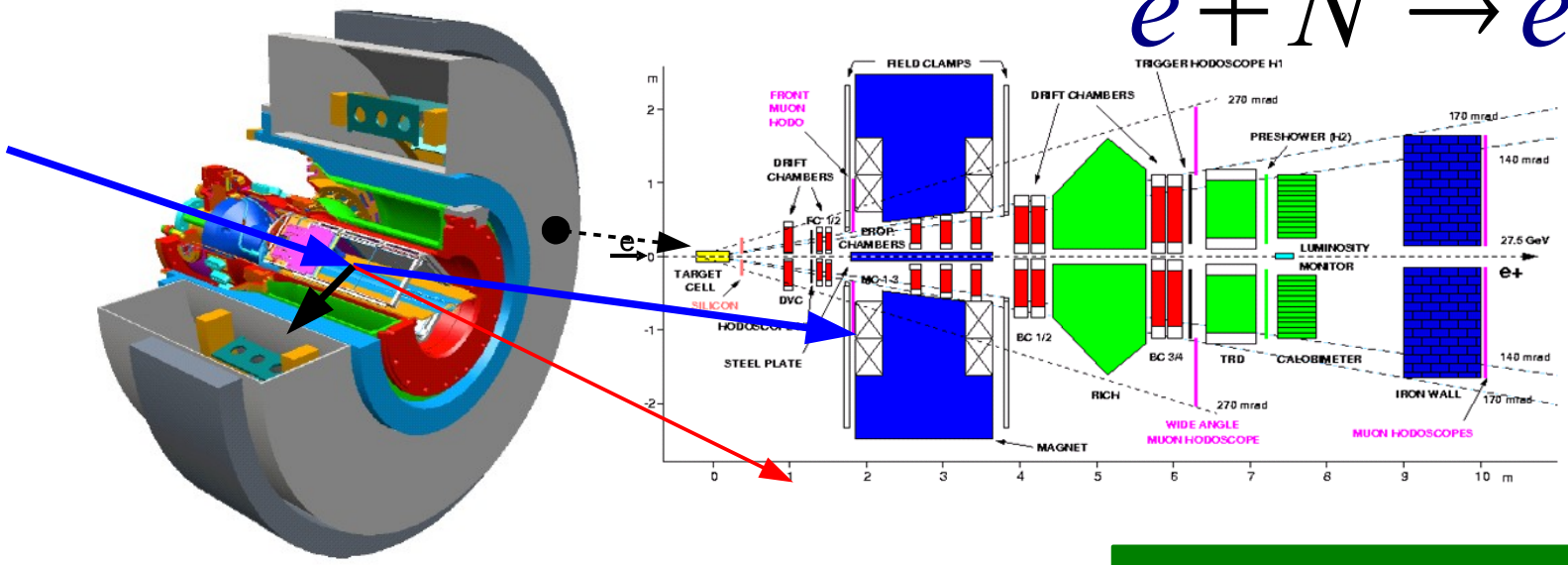
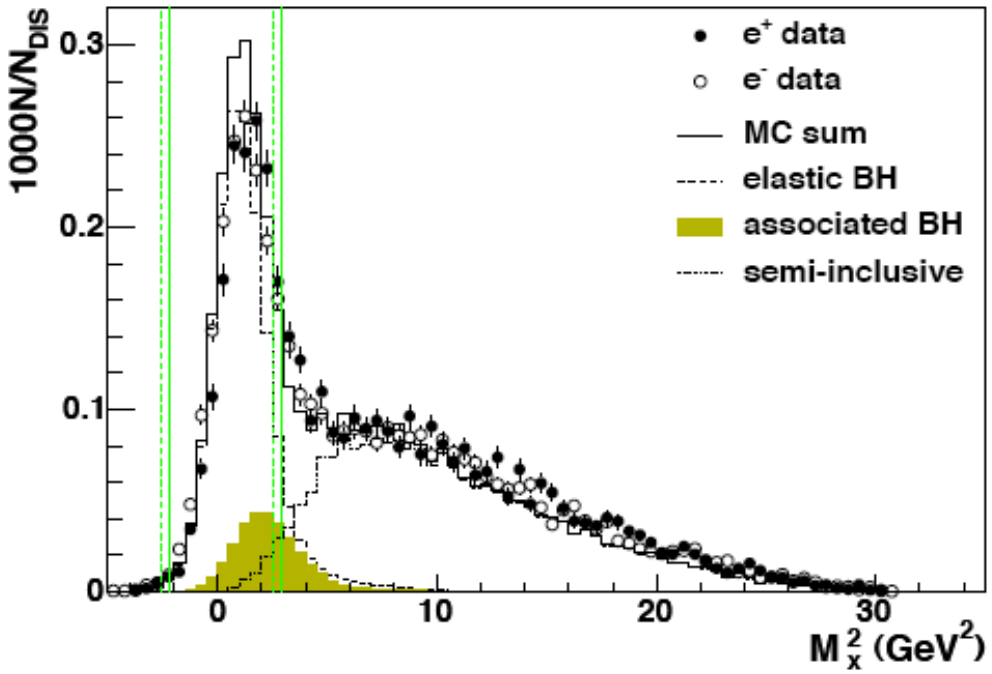
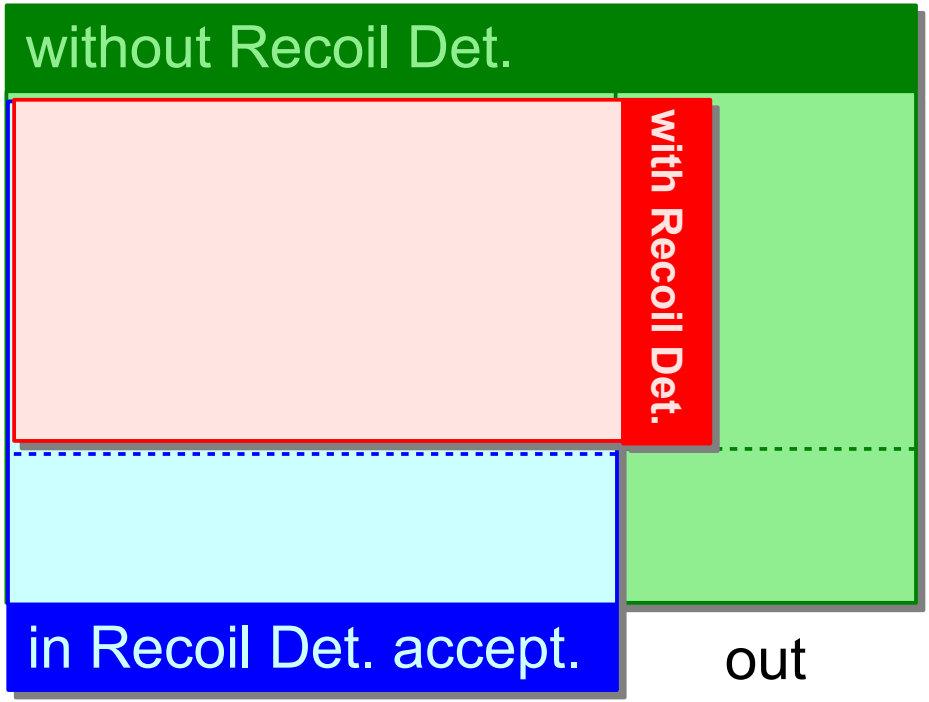
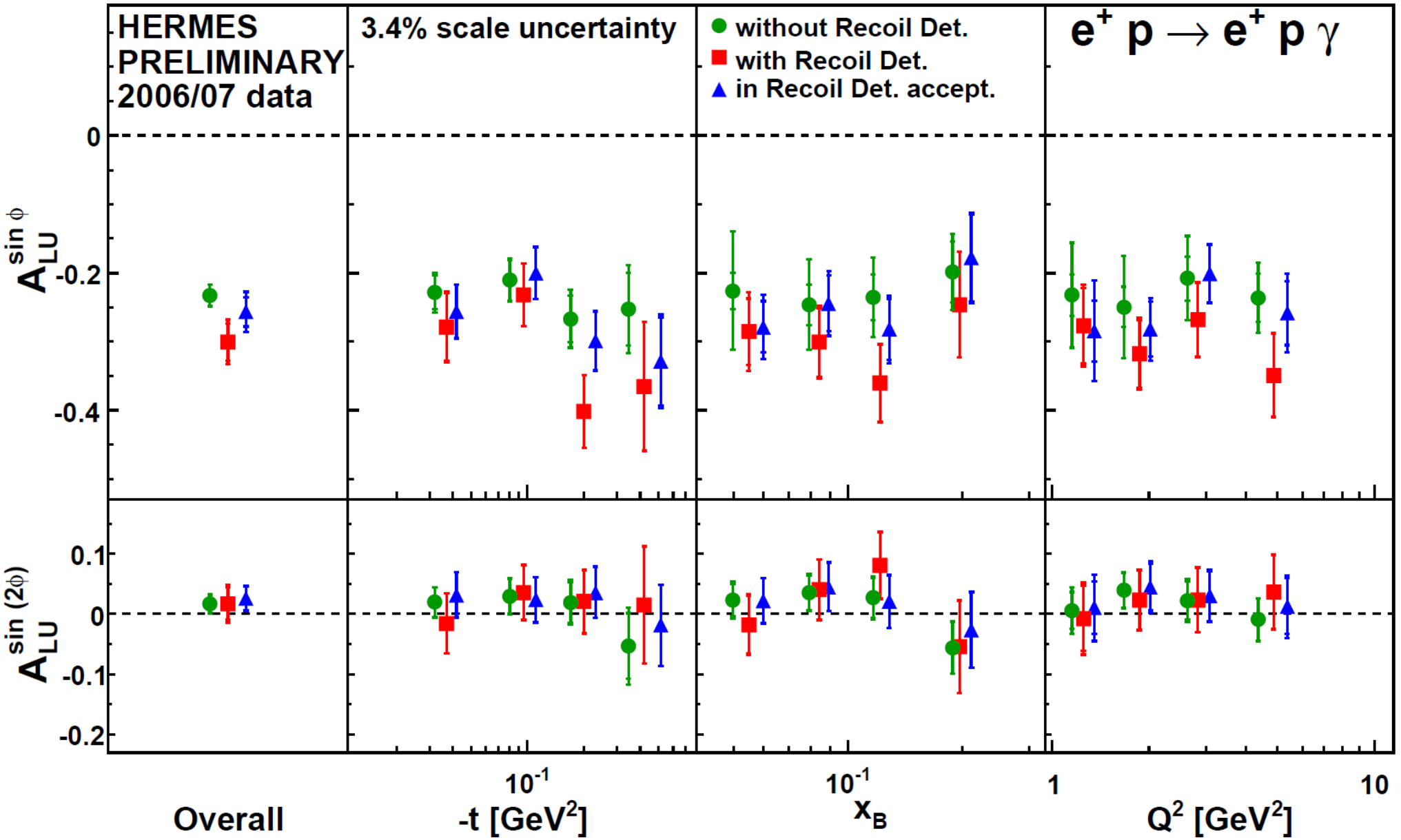
$$e + N \rightarrow e' + N + \gamma$$







DVCS amplitudes with Recoil Detector at



Summary

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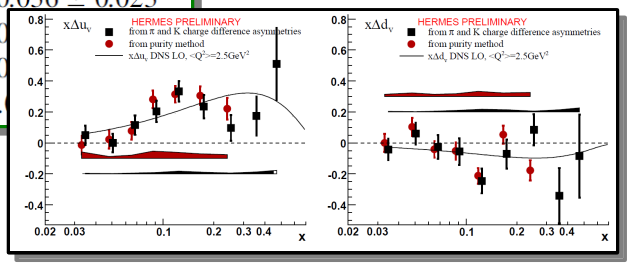
HERMES has studied the spin structure of the nucleon.

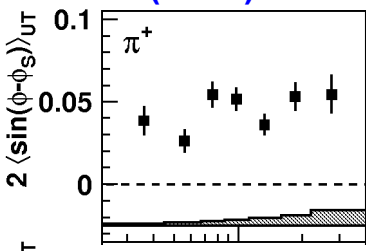
Inclusive DIS: $\Delta\Sigma = 0.330 \pm 0.025 \pm 0.011 \pm 0.028$ PRD75(2007)012007

Semi-inclusively: PRD71(2005)012003

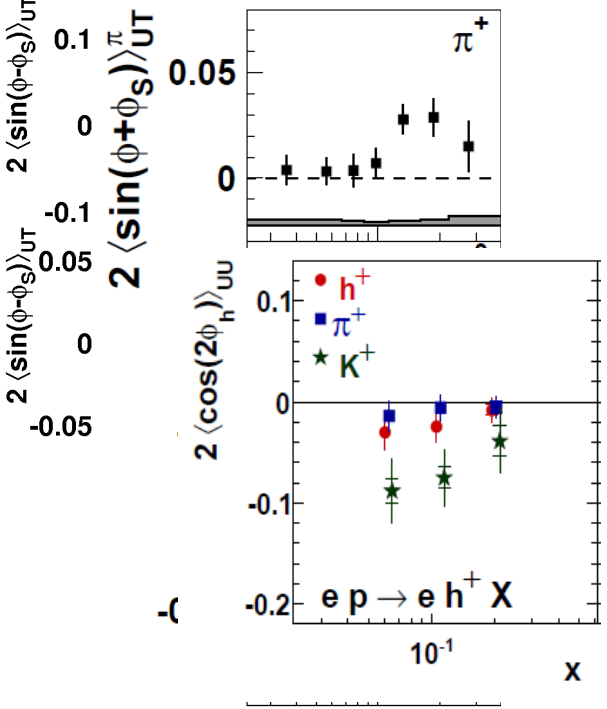
Δu	$0.601 \pm 0.039 \pm 0.049$
$\Delta \bar{u}$	$-0.002 \pm 0.036 \pm 0.023$
Δd	-0.226 ± 0
$\Delta \bar{d}$	-0.054 ± 0
Δs	$0.028 \pm 0.$

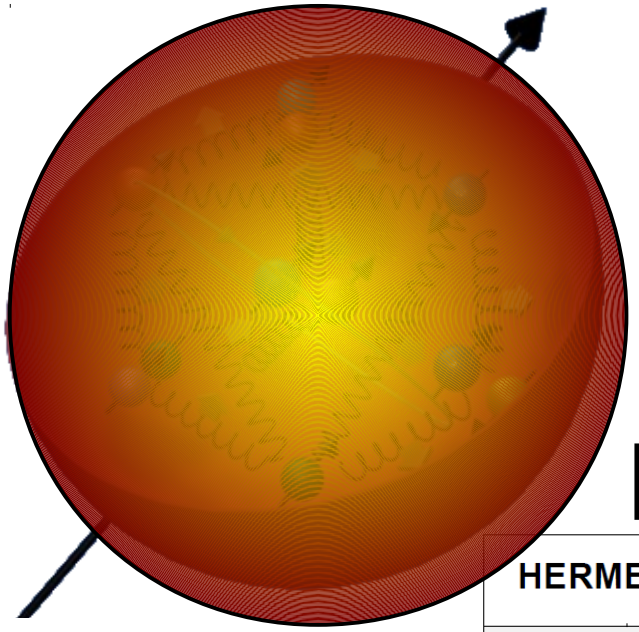


PRL103(2009)152002



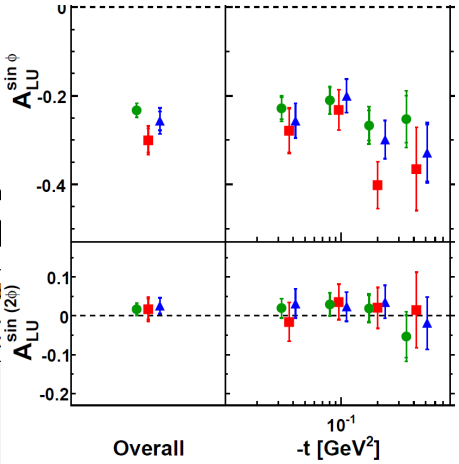
PLB693(2010)11

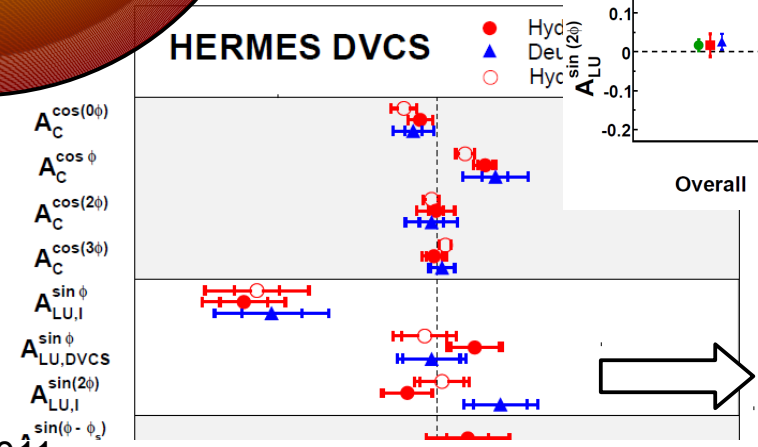




DVCS

With recoil detector



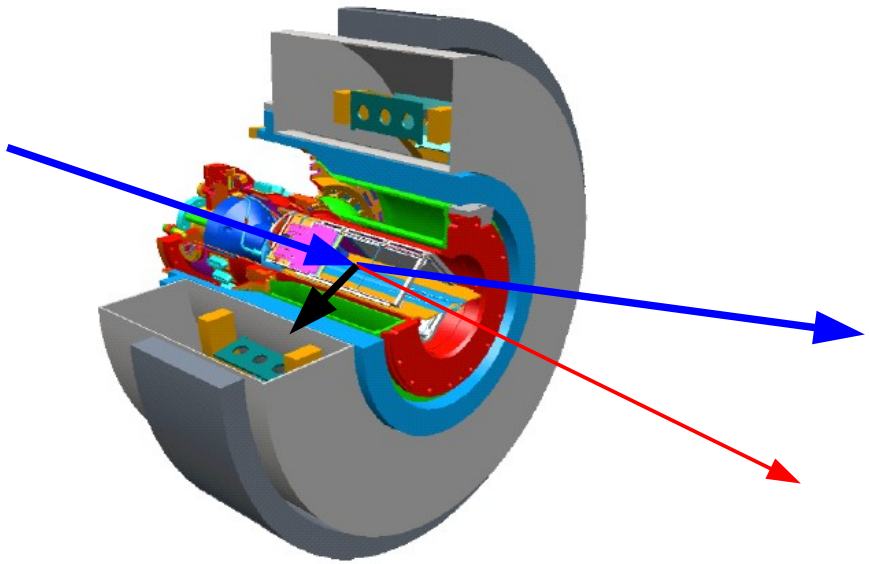


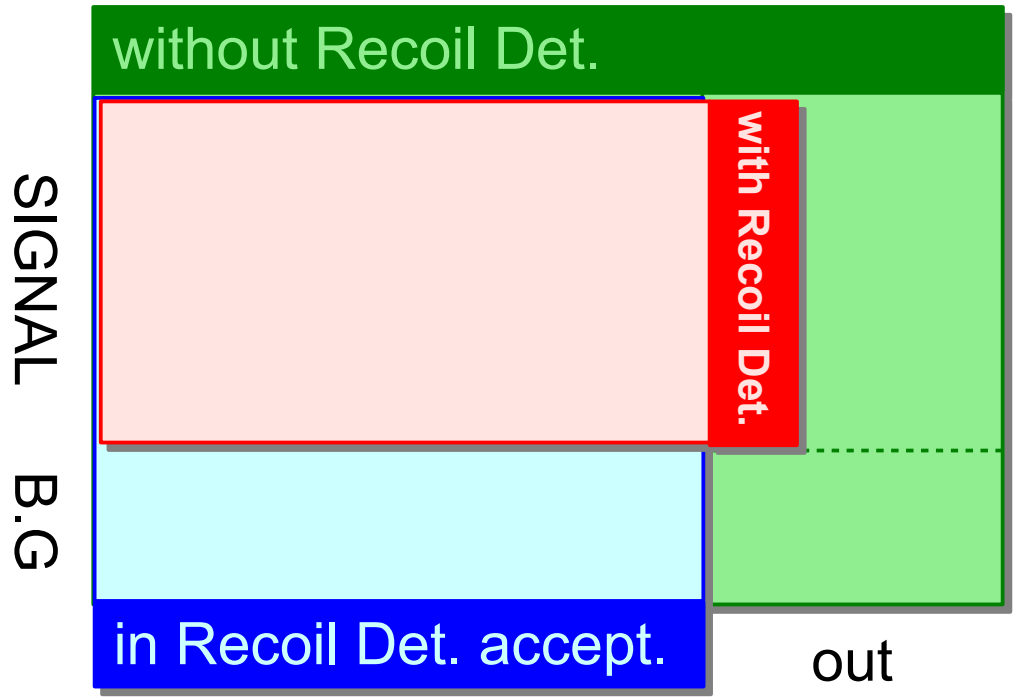
TMDs

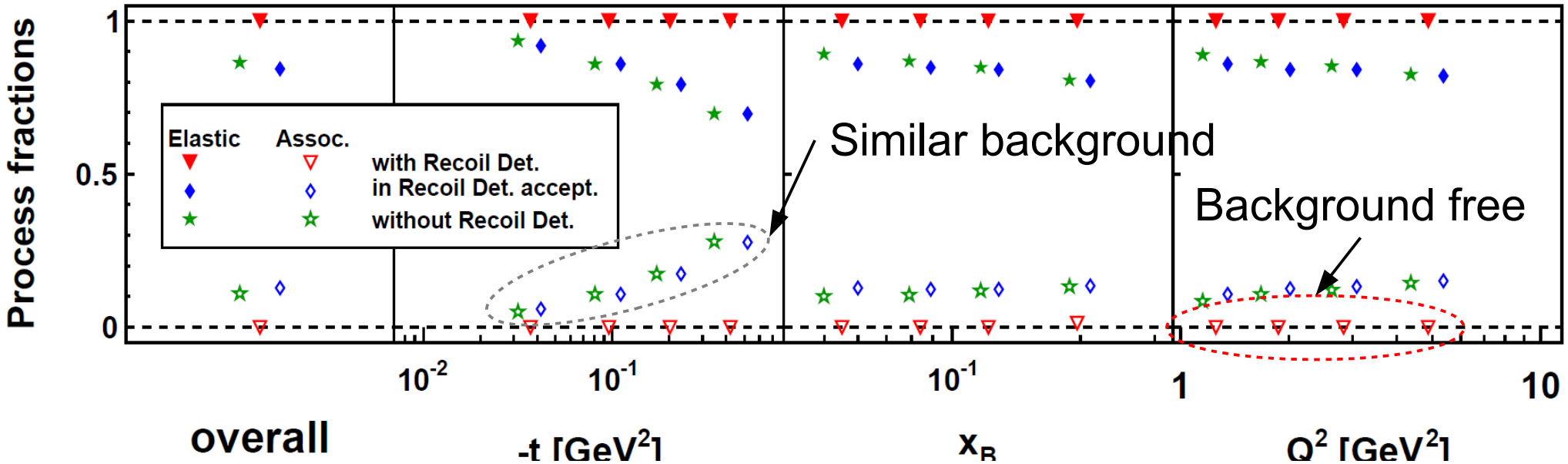
GPDs

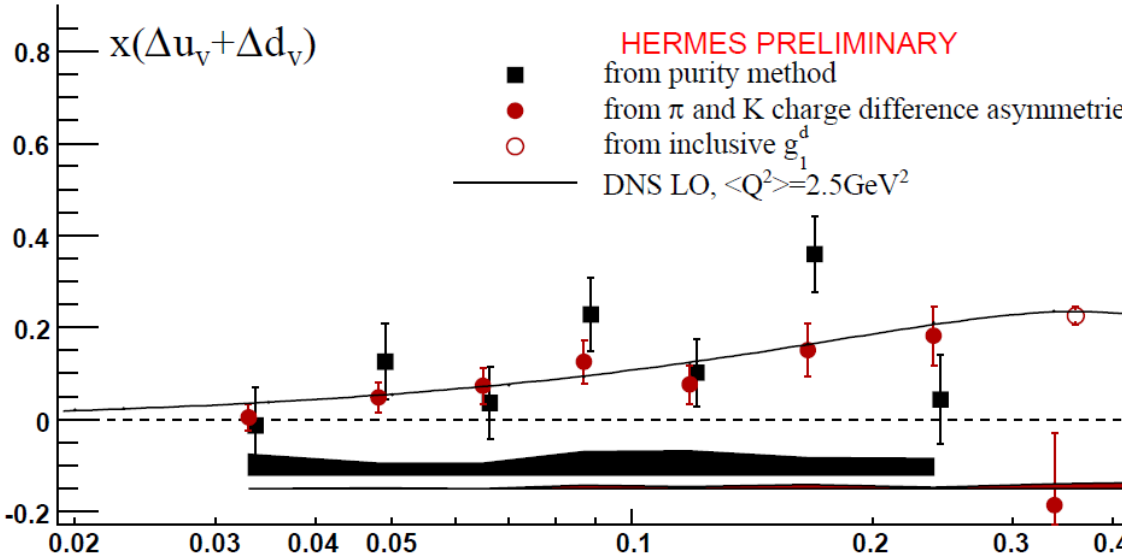
END

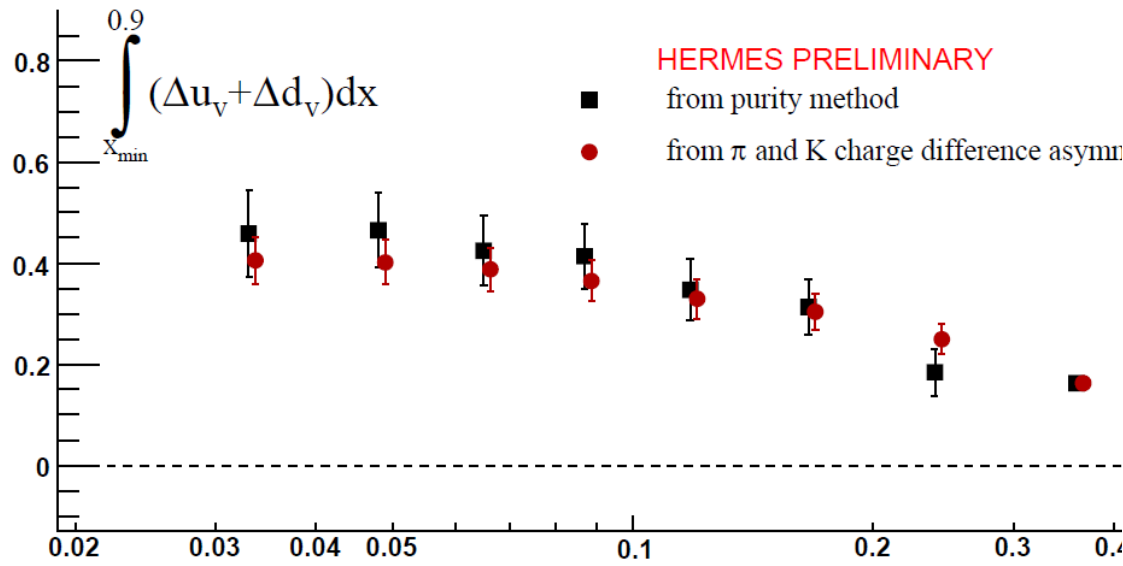
Exclusive events with Recoil








x(Δu_v+Δd_v)
HERMES PRELIMINARY
from purity method
from π and K charge difference asymmetrie
from inclusive g_1^d
DNS LO, <Q^2>=2.5GeV^2
0.8
0.6
0.4
0.2
0
-0.2
0.02
0.03
0.04
0.05
0.1
0.2
0.3


0.9
∫ (Δu_v+Δd_v)dx
x_min
HERMES PRELIMINARY
from purity method
from π and K charge difference asymm
0.8
0.6
0.4
0.2
0
0.02
0.03
0.04
0.05
0.1
0.2
0.3

Exclusivity with Recoil Detector

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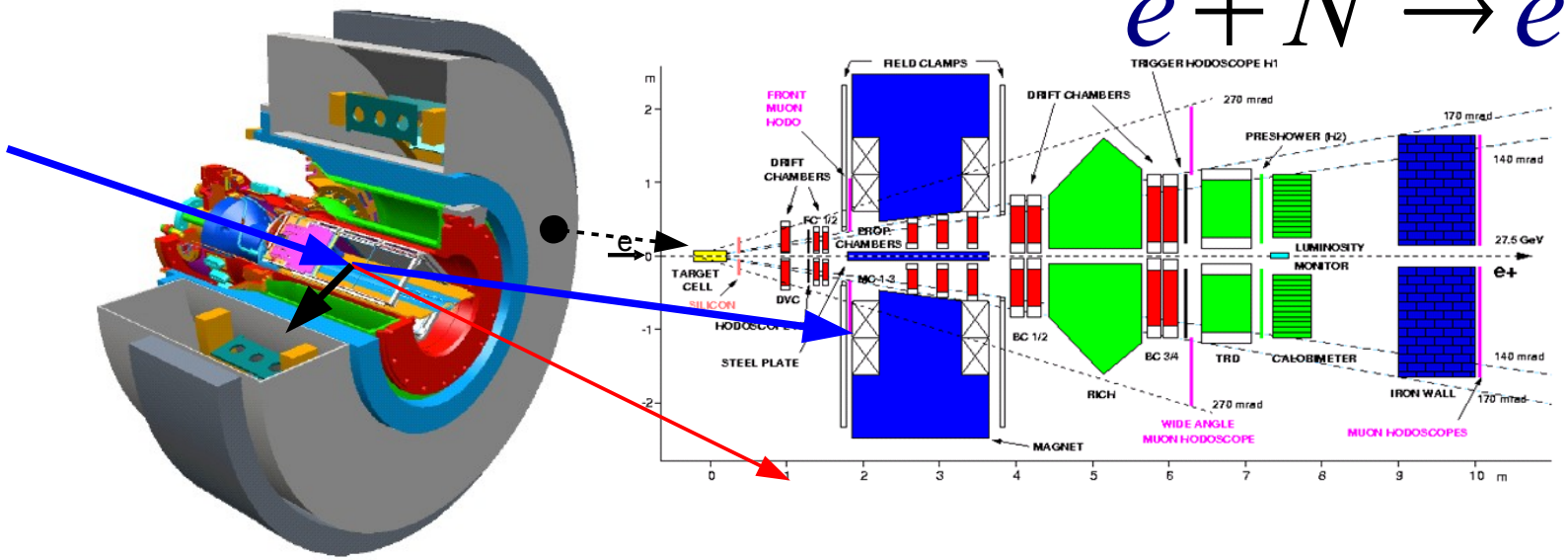
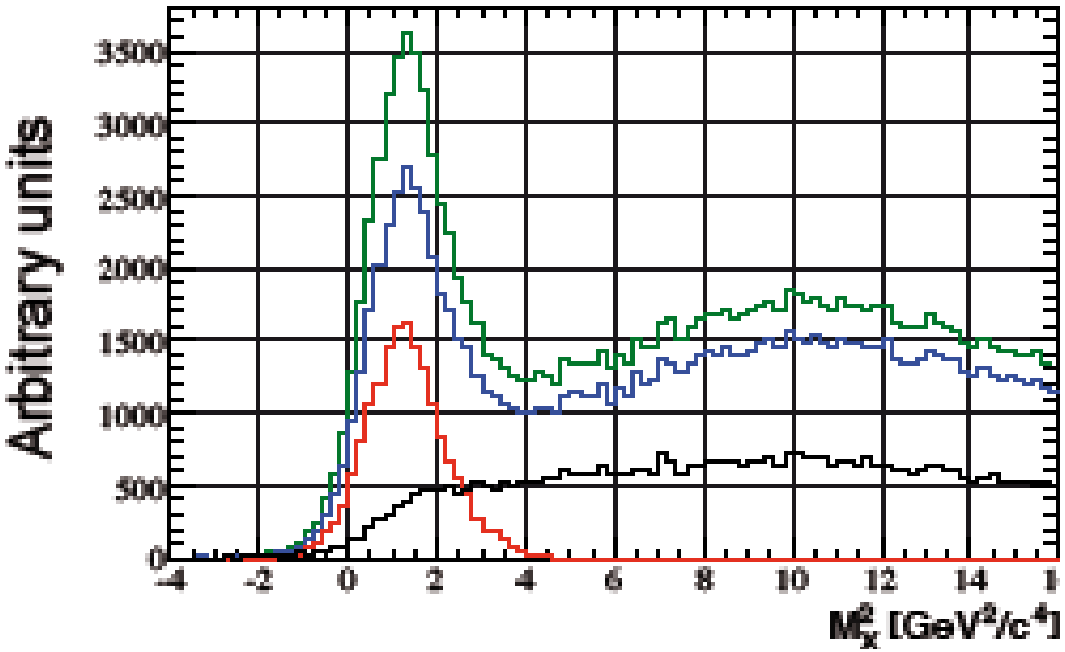
hermes

$$e + N \rightarrow e' + N + \gamma$$





No requirement for Recoil

Charged recoil track in acceptance

Kinematic fit probability > 1%

Kinematic fit probability < 1%