Overview of recent HERMES results

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on behalf of the HERMES collaboration

ENPC09

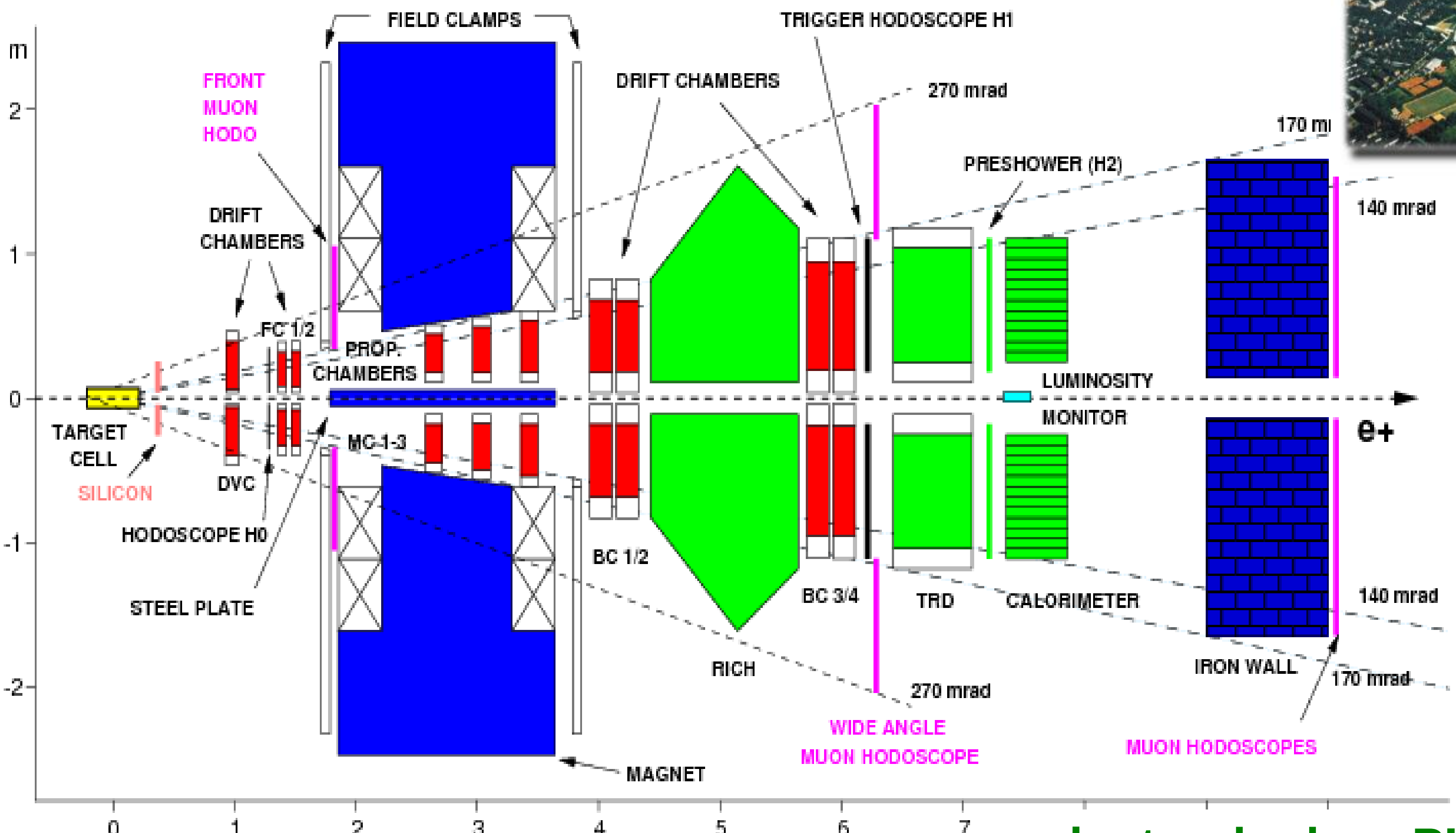
Overview

- strange quark distributions
- transverse structure of the nucleon

  - transverse momentum dependent distributions

  - transverse position:
    generalized parton distributions and
    deeply virtual Compton scattering

HERMES: HERA MEASUREMENT of SPIN



data taking from 1995 until June, 30 2007

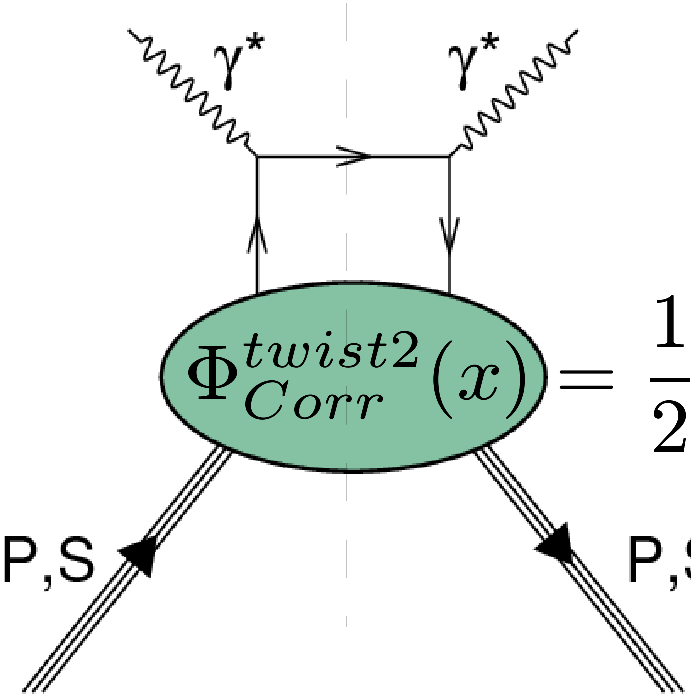
lepton-hadron PID efficiency:~98%
hadron PID: RICH 2-15 GeV/c

<u>Beam</u>
longitudinally pol.
e^+ & e^-
E= 27.6 GeV

<u>Gaseous internal target</u>
longitudinally pol. H,D,He
transversely pol. H
unpol. H,D,Ne,Kr,..

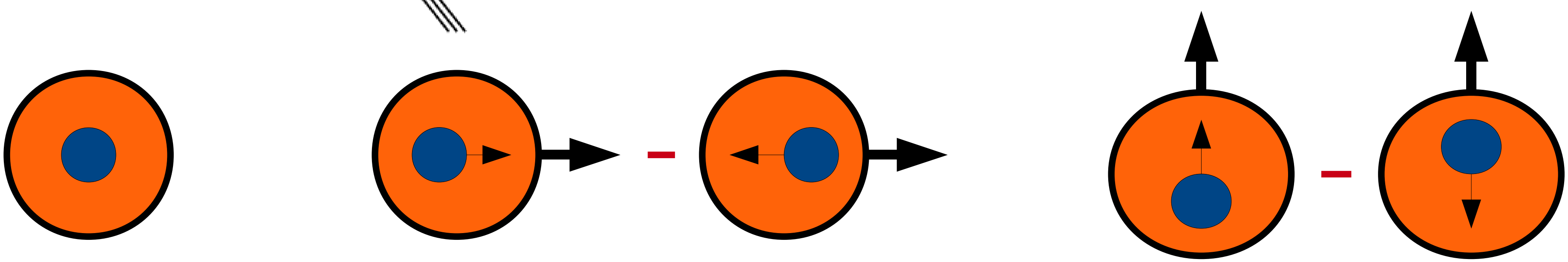
$\delta E\gamma/E\gamma \cong 5\%$
$\delta P/P < 2\%$
$\Delta\theta < 1$mrad

Probing the nucleon in DIS



$$\Phi^{twist2}_{Corr}(x) = \frac{1}{2}\{q(x) + S_L \Delta q(x)\gamma_5 + \delta q(x)\gamma_5\gamma^1 S_T\}n^+$$

x=longitudinal momentum fraction of quark



$q(x)$

unpolarized nucleon
unpolarized quark

(also $f_1(x)$)

$\Delta q(x)$

longitudinally polarized nucleon
longitudinally polarized quark

(also $g_{1L}(x)$)

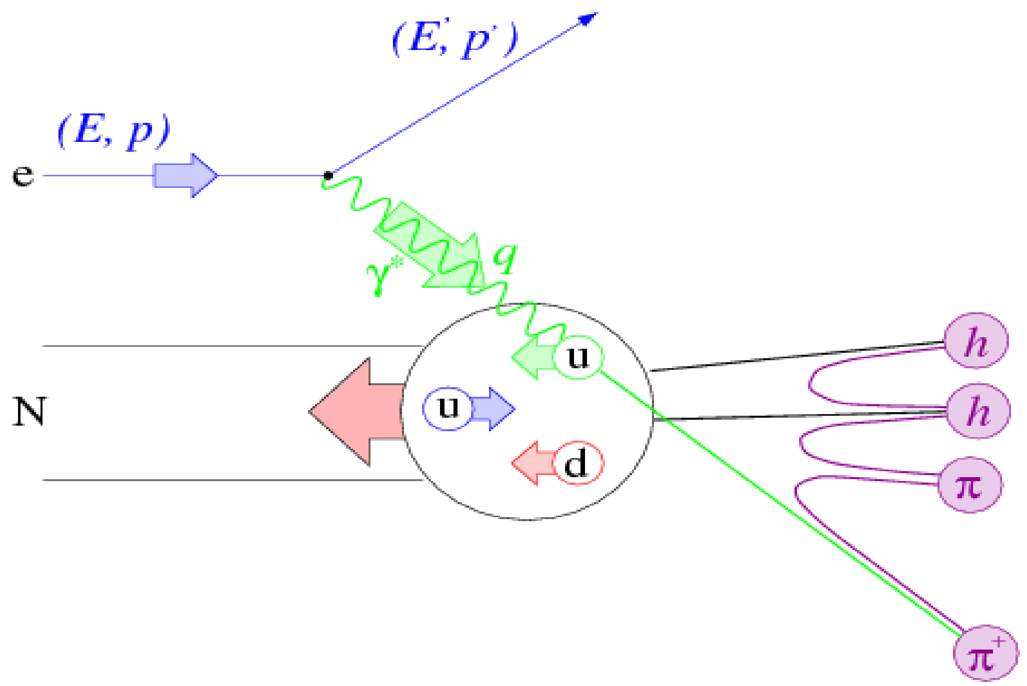
$\delta q(x)$

transversely polarized nucleon
transversely polarized quark

(also $h_{1T}(x)$)

How to access flavored quark distributions

Semi-inclusive deep-inelastic scattering (SIDIS)



$$Q^2 = -q^2$$
$$\nu \overset{lab}{=} E - E'$$
$$y \overset{lab}{=} \frac{\nu}{E}$$
$$x \overset{lab}{=} \frac{Q^2}{2M\nu}$$
$$z \overset{lab}{=} \frac{E_h}{\nu}$$

$$\sigma^{ep\to eh} = \sum_q DF^{p\to q}(x) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z)$$

Distribution Function (DF): distribution of quarks in nucleon
Fragmentation Function (FF): fragmentation of struck quark into final-state hadron

Strange quark distributions

Extraction of the strange quark distribution

- leading order extraction in α_s
- charged kaon production on (longitudinally pol.) deuteron:

$$e + d \to K^{\pm} + X$$

- strange quarks carry no isospin $\longrightarrow$ $s_p(x)=s_n(x)$
  $\Delta s_p(x)=\Delta s_n(x)$
- isoscalar target & $K^{+}+K^{-}$ $\longrightarrow$ FF without isospin dependence
- hypothesis: isospin symmetry between p and n
  charge-conjugation invariance of FF

A. Airapetian et al., Phys. Lett. B **666,** 446-450 (2008)

Kaon multiplicities

$$\frac{d^2N^K(x)}{d^2N^{DIS}(x)} = \frac{Q(x)\int_{0.2}^{0.8}\mathcal{D}_Q^K(z)dz + S(x)\int_{0.2}^{0.8}\mathcal{D}_S^K(z)dz}{5Q(x)+2S(x)}$$

$$Q(x) \equiv u(x) + \bar{u}(x) + d(x) + \bar{d}(x)$$

$$S(x) \equiv s(x) + \bar{s}(x)$$

$$\mathcal{D}_Q^K(z) \equiv 4D_u^K(z) + D_d^K(z)$$

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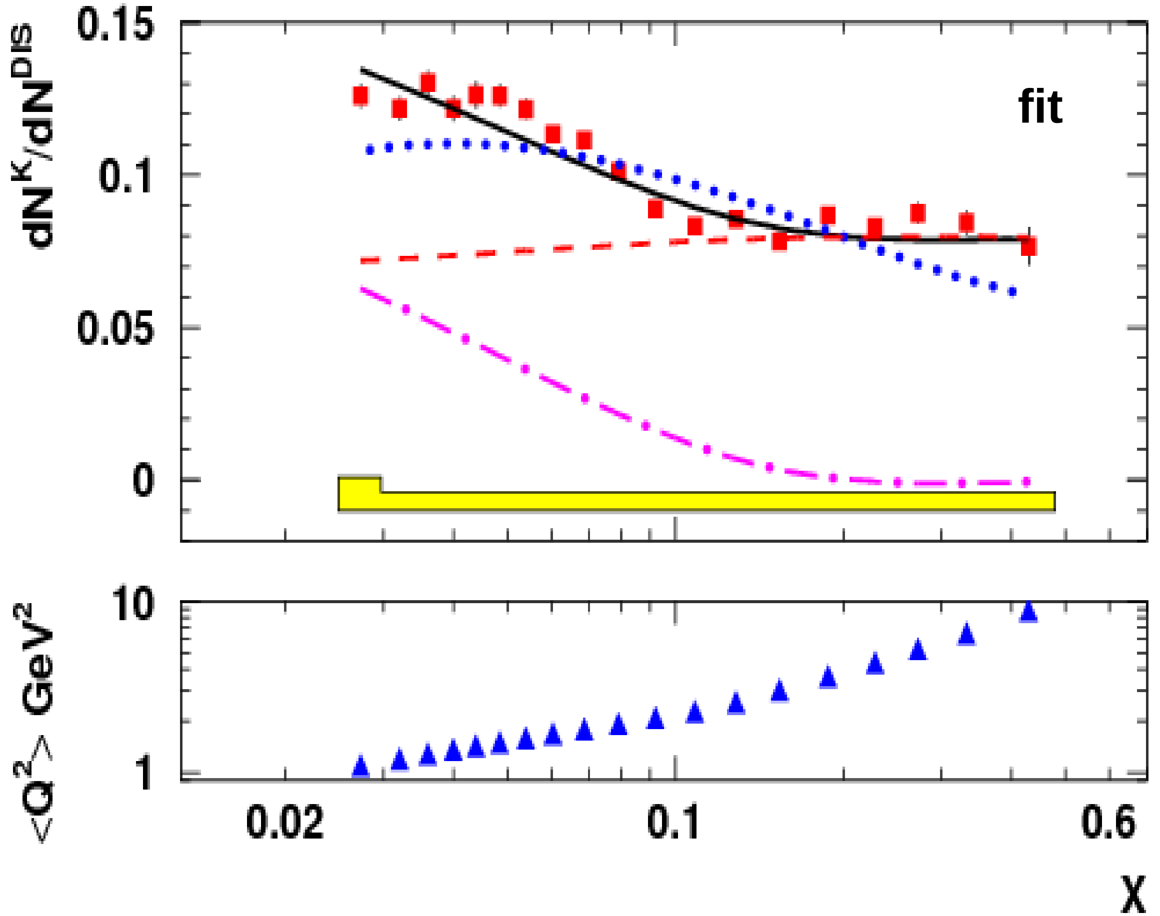

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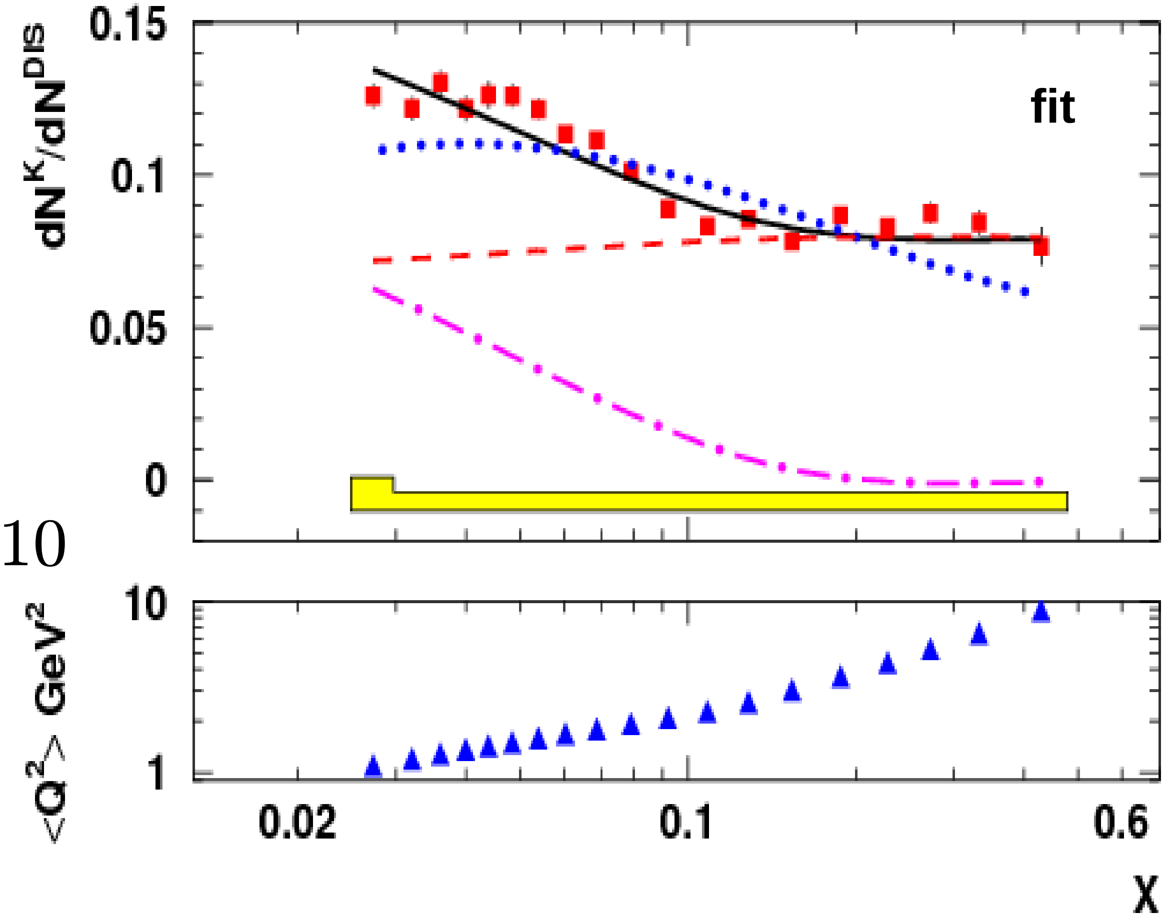
S(x)=0 for x>0.15
Q(x) from CTEQ6L

$$\int_{0.2}^{0.8}\mathcal{D}_Q^K(z)dz = 0.398 \pm 0.010$$



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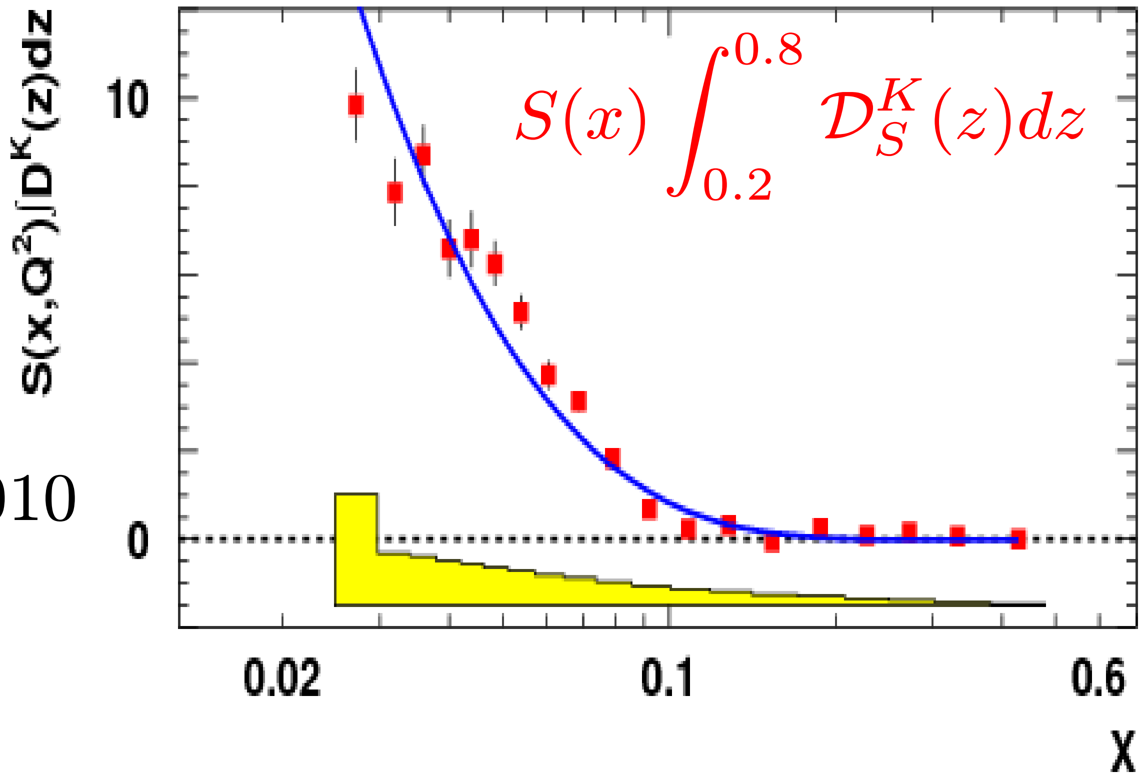
$$\int_{0.2}^{0.8}\mathcal{D}_Q^K(z)dz = 0.398 \pm 0.010$$

neglecting 2S(x)

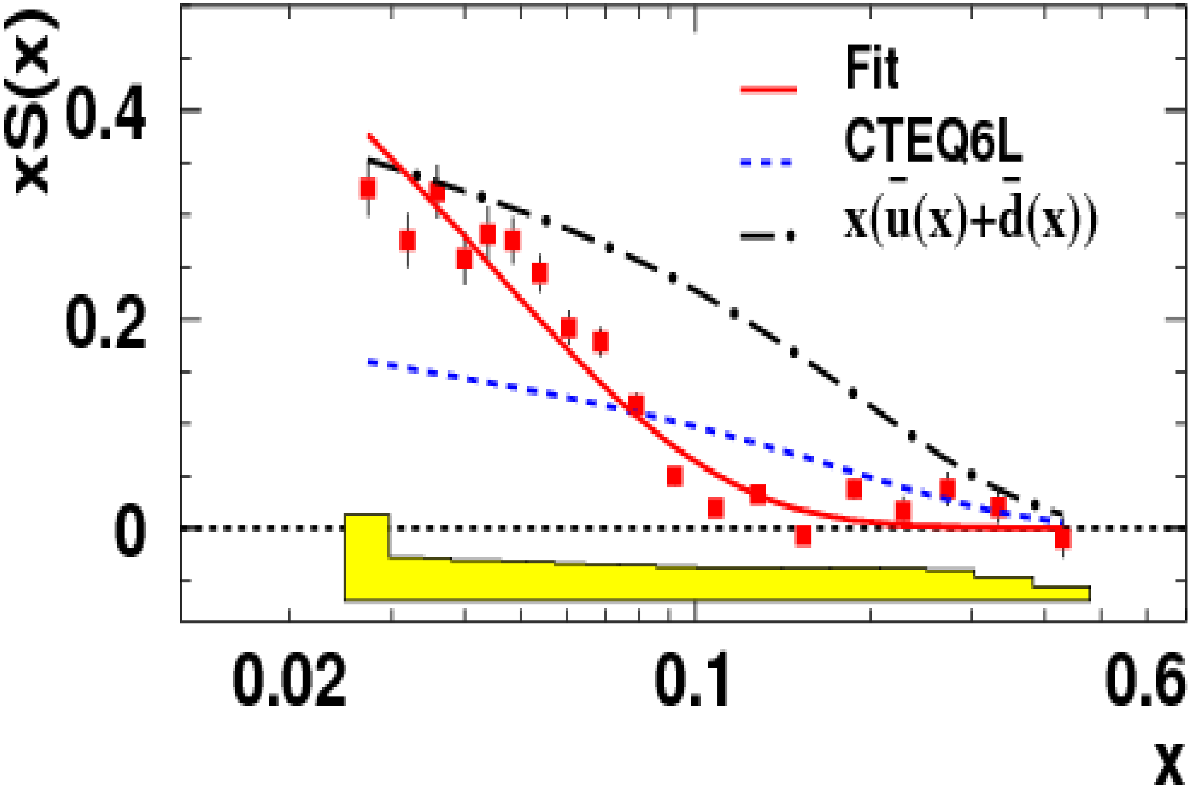
$$S(x)\int_{0.2}^{0.8}\mathcal{D}_S^K(z)dz$$



Spin-independent strange quark distribution

- evolution of data to Q^2=2.5 GeV^2 (CTEQ6L)
- $\int_{0.2}^{0.8} \mathcal{D}_S^K(z)dz = 1.27 \pm 0.13$

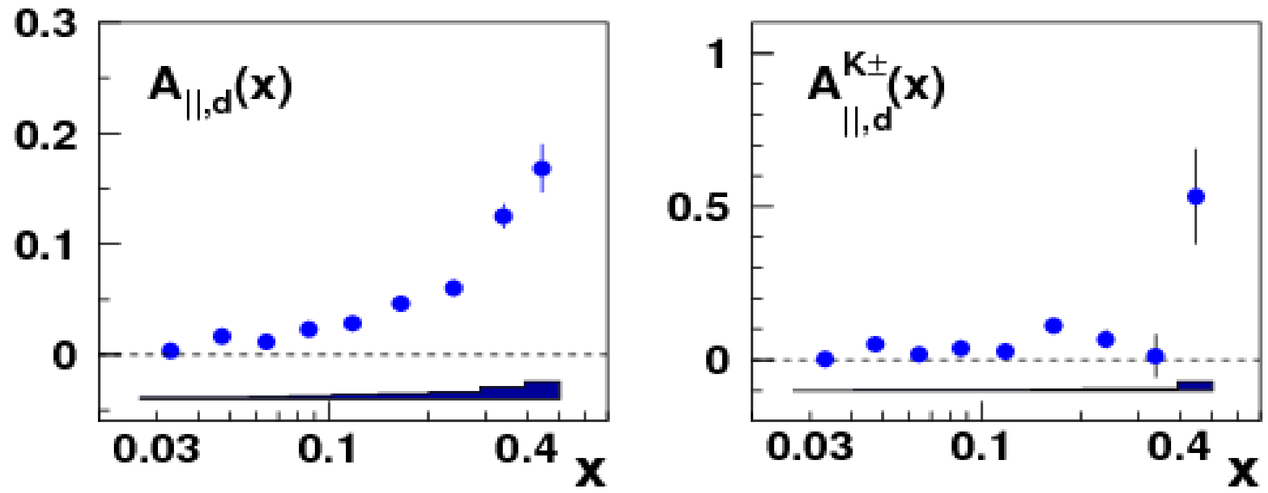
D. de Florian et al., PRD75, 114010



- discrepancy with CTEQ6L
- S(x) not an average of isoscalar non-strange sea S(x) towards lower x-values

Double spin asymmetry from longitudinally polarized deuterons

$$A_{\parallel}^{(h)} = \frac{\sigma^{\overleftarrow{\Leftarrow},(h)} - \sigma^{\overrightarrow{\Rightarrow},(h)}}{\sigma^{\overleftarrow{\Leftarrow},(h)} + \sigma^{\overrightarrow{\Rightarrow},(h)}}$$



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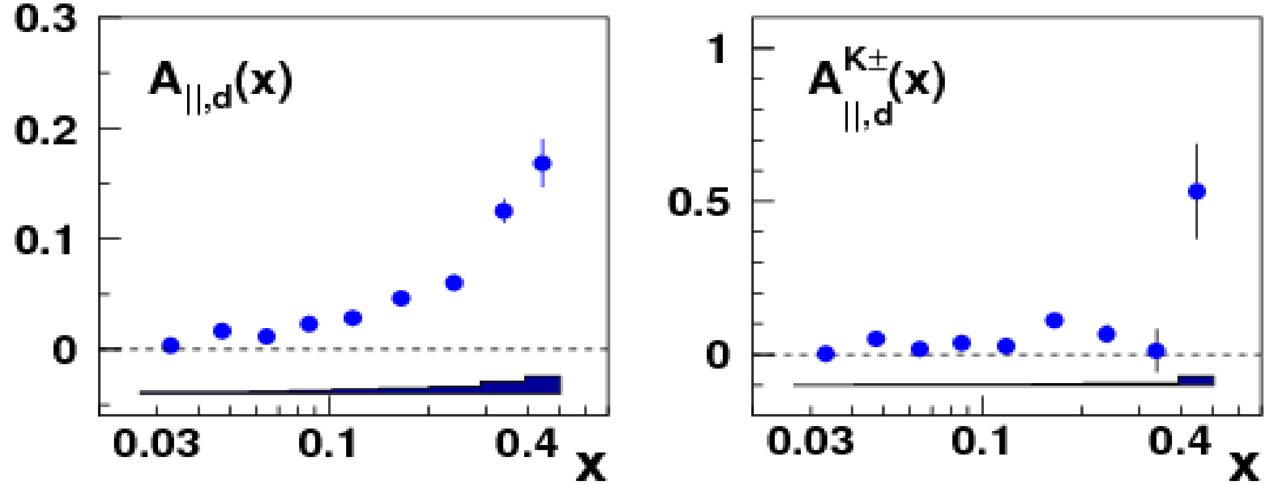


$$A_{\parallel,d}(x)\frac{d^2N^{DIS}(x)}{dxdQ^2} = \mathcal{K}_{\mathcal{LL}}(x,Q^2)\left[5\Delta Q(x) + 2\Delta S(x)\right]$$

$$A_{\parallel,d}^{K^{\pm}}(x)\frac{d^2N^{K}(x)}{dxdQ^2} =$$

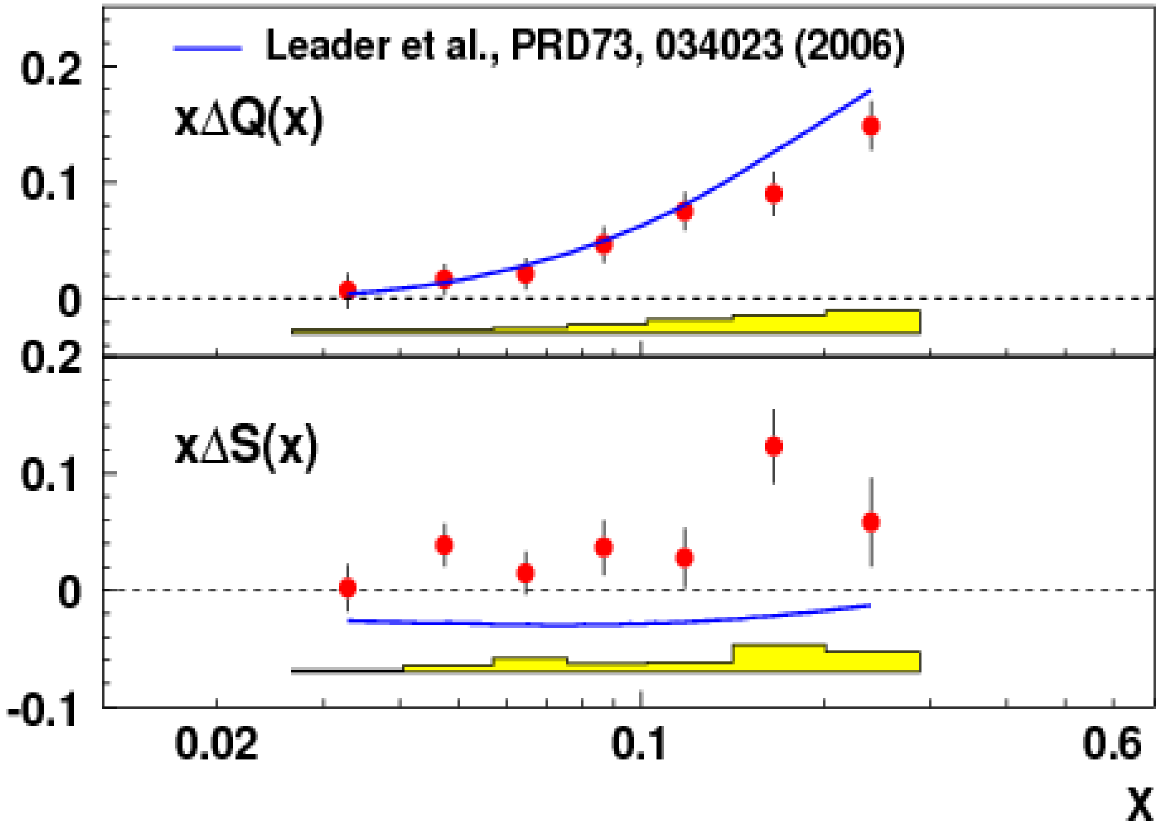
$$\mathcal{K}_{\mathcal{LL}}(x,Q^2)\left[\Delta Q(x)\int_{0.2}^{0.8}\mathcal{D}_Q^K(z)dz + \Delta S(x)\int_{0.2}^{0.8}\mathcal{D}_S^K(z)dz\right]$$

$$\Delta Q(x) \equiv \Delta u(x) + \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{d}(x)$$

$$\Delta S(x) \equiv \Delta s(x) + \Delta\bar{s}(x)$$

$\int_{0.2}^{0.8}\mathcal{D}_Q^K(z)dz, \int_{0.2}^{0.8}\mathcal{D}_S^K(z)dz$ from S(x) extraction

Helicity distribution @ Q^2=2.5 GeV^2



- ΔQ and ΔS in agreement with previous HERMES results

- $\Delta q_8 = \int [\Delta Q(x) - 2\Delta S(x)]\, dx$ for x: 0.02 → 0.6

  = 0.285 ± 0.046(stat.) ± 0.057(sys.)

  ≠

  Δq_8 from hyperon decay, assuming SU(3) symmetry (x: 0 → 1)

  = 0.586 ±0.031

SU(3) symmetry violation ⟺ large contribution from x<0.02 region

Transverse structure of the nucleon

Transverse structure of the nucleon

transverse momentum
dependent distributions

Transverse structure of the nucleon

transverse momentum dependent distributions

transverse position: generalized parton distributions

Transverse momentum dependent distributions (TMDs)

$$\sigma^{ep\rightarrow eh} = \sum_q \mathcal{I}[DF^{p\rightarrow q}(x, k_T^2) \otimes \sigma^{eq\rightarrow eq} \otimes FF^{q\rightarrow h}(z, p_T^2)]$$

k_T/p_T = transverse momentum of struck/fragmenting quark

$\mathcal{I}[...]$ = convolution integral over k_T and p_T

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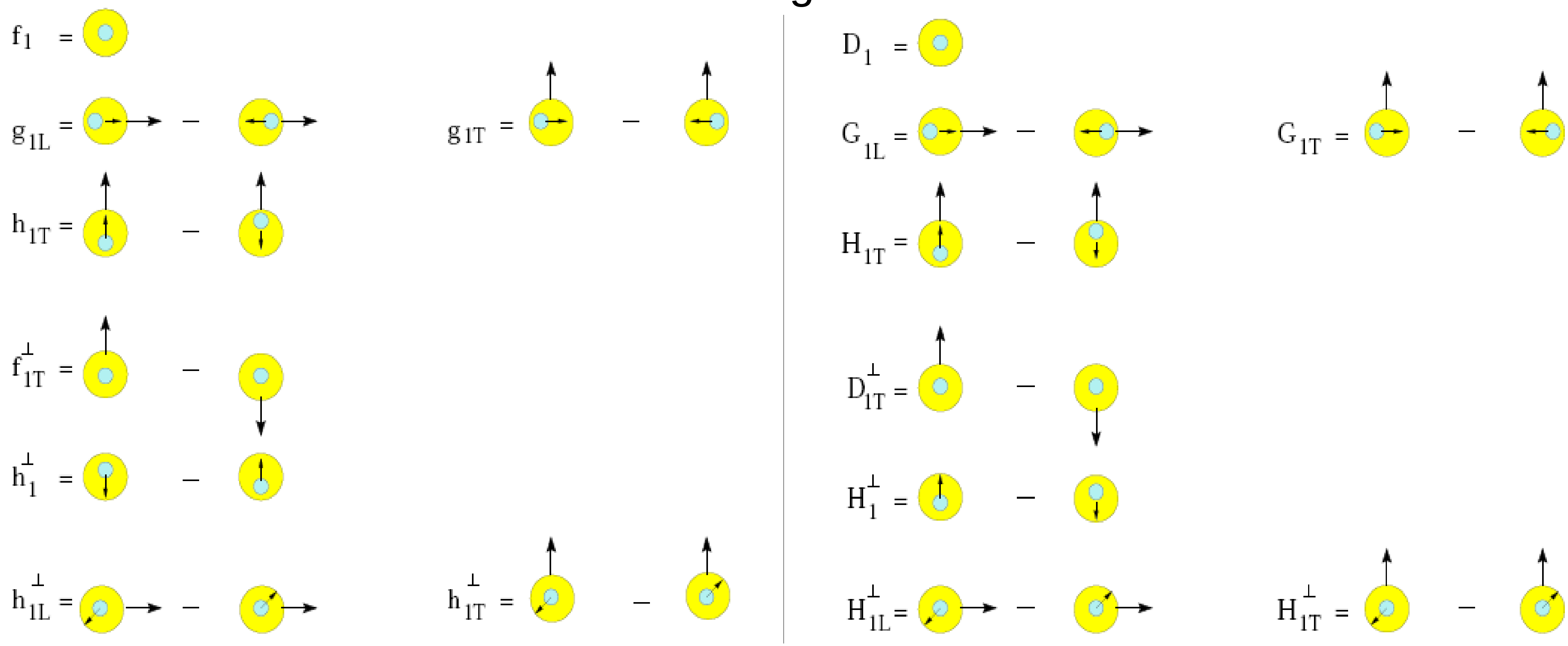
Distribution functions leading twist Fragmentation functions



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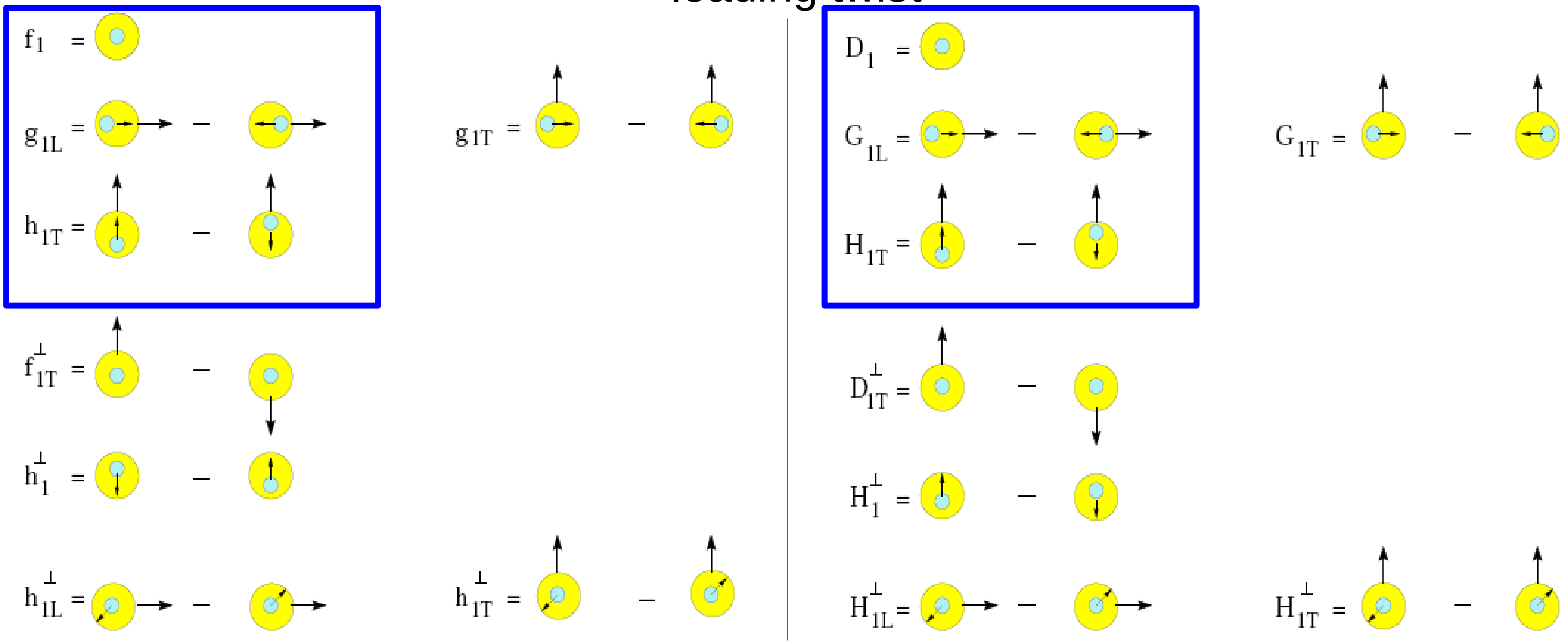
Distribution functions — leading twist — Fragmentation functions



only distributions that survive integration over transverse momentum

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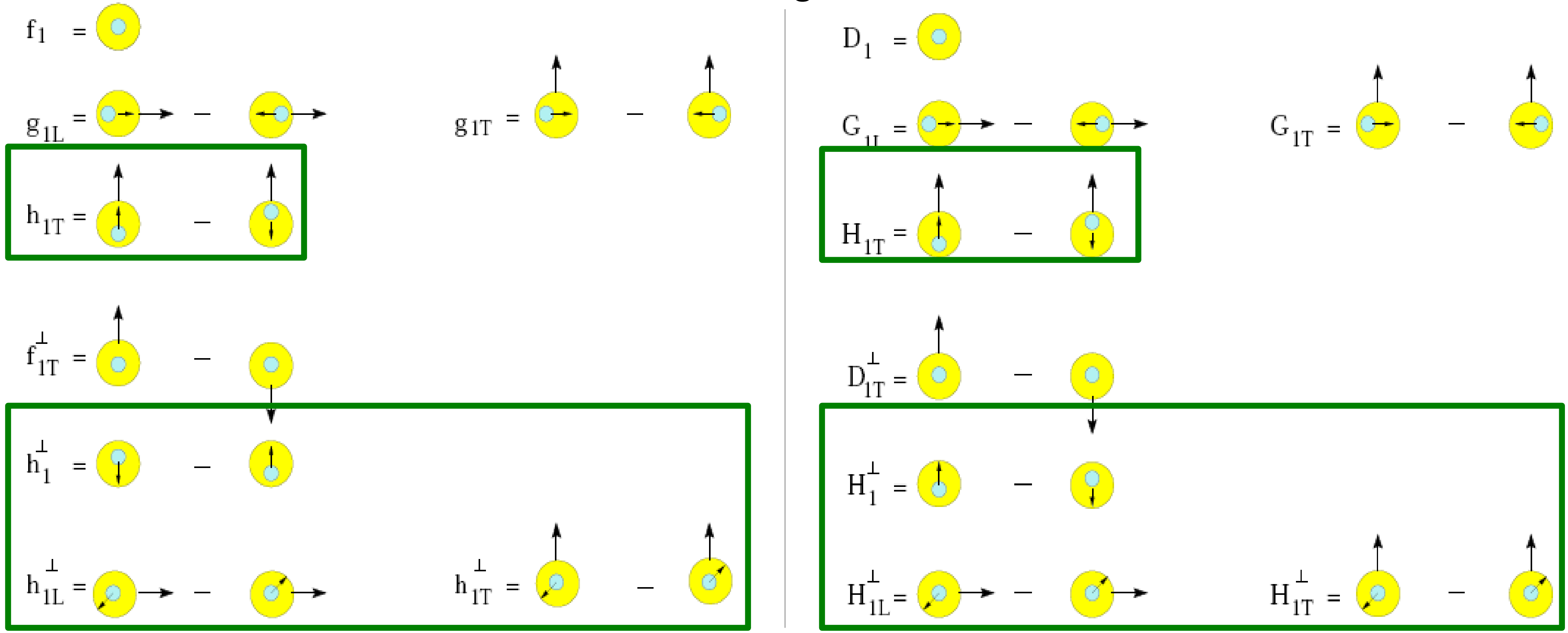

Chiral odd: involve helicity flip of quark
appear in pairs in cross section

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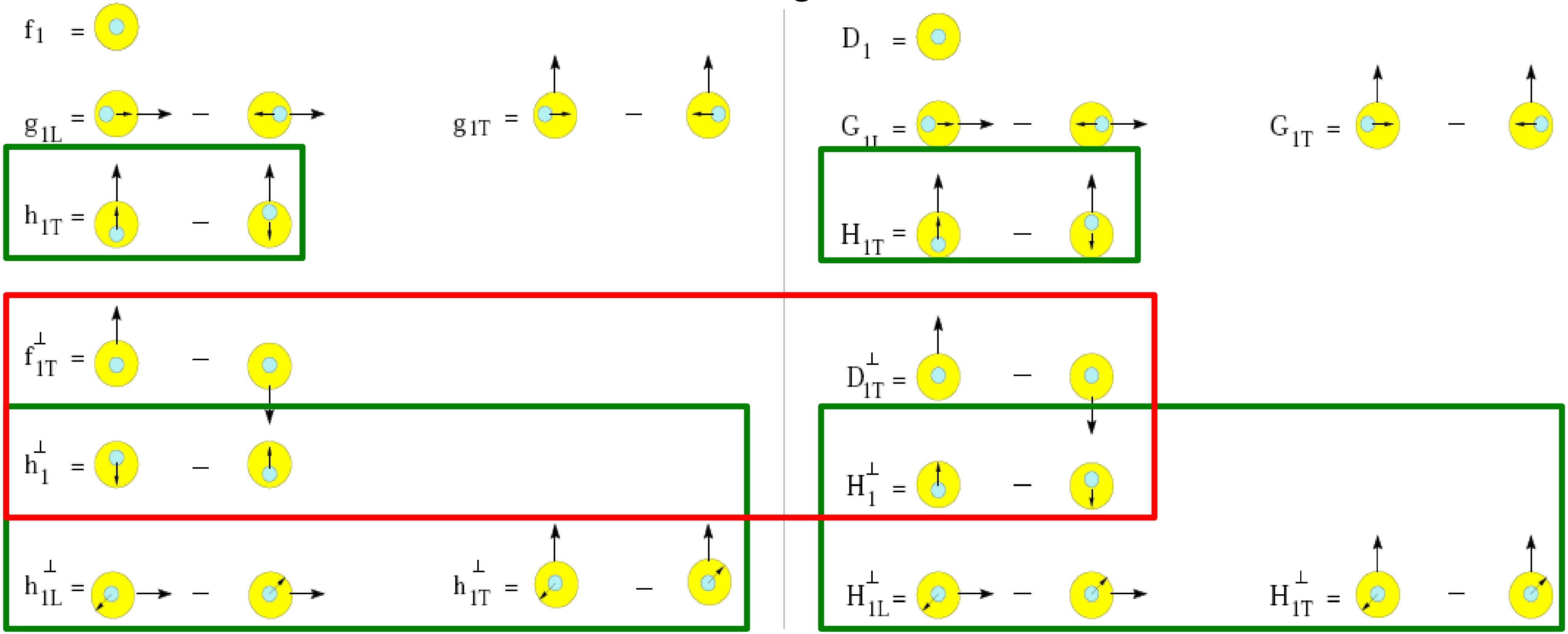

Chiral odd: involve helicity flip of transversally polarized quark
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T-odd : appear in pairs in spin-independent x-section & double spin asymmetries
single in Single Spin Asymmetries (SSAs)

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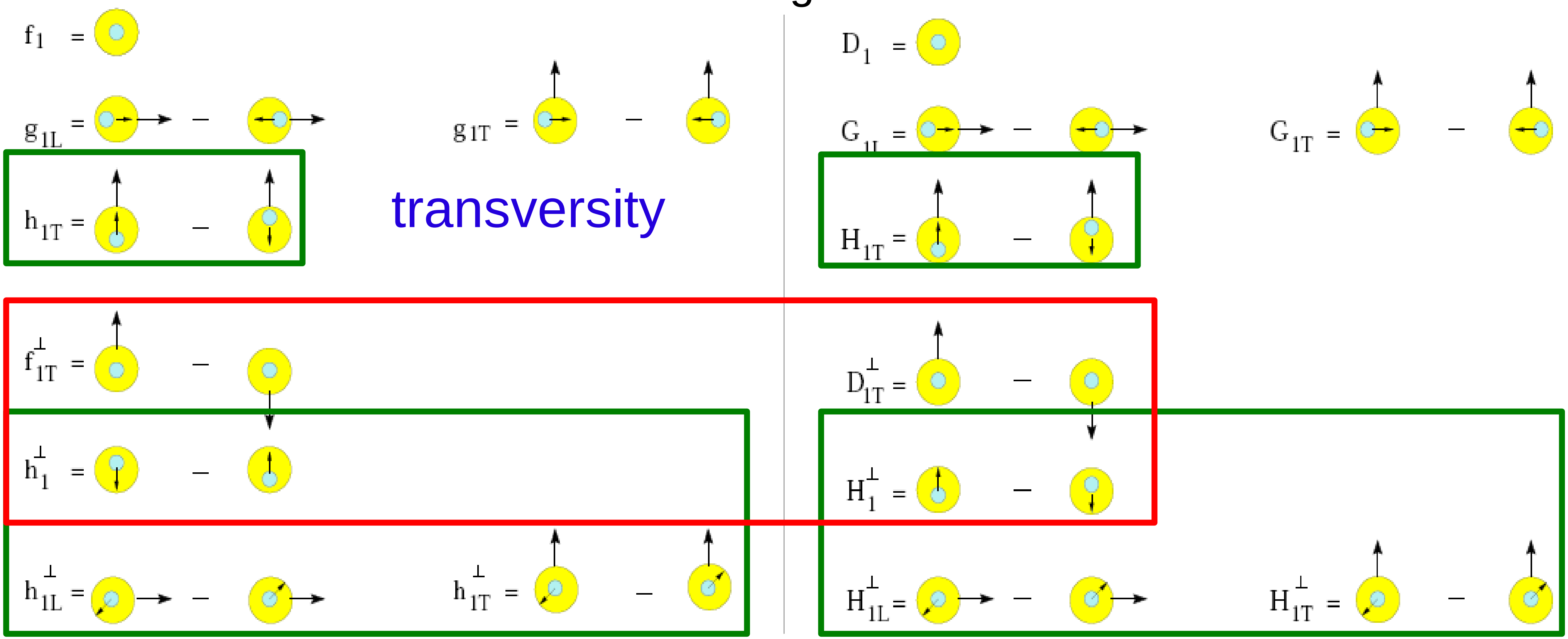

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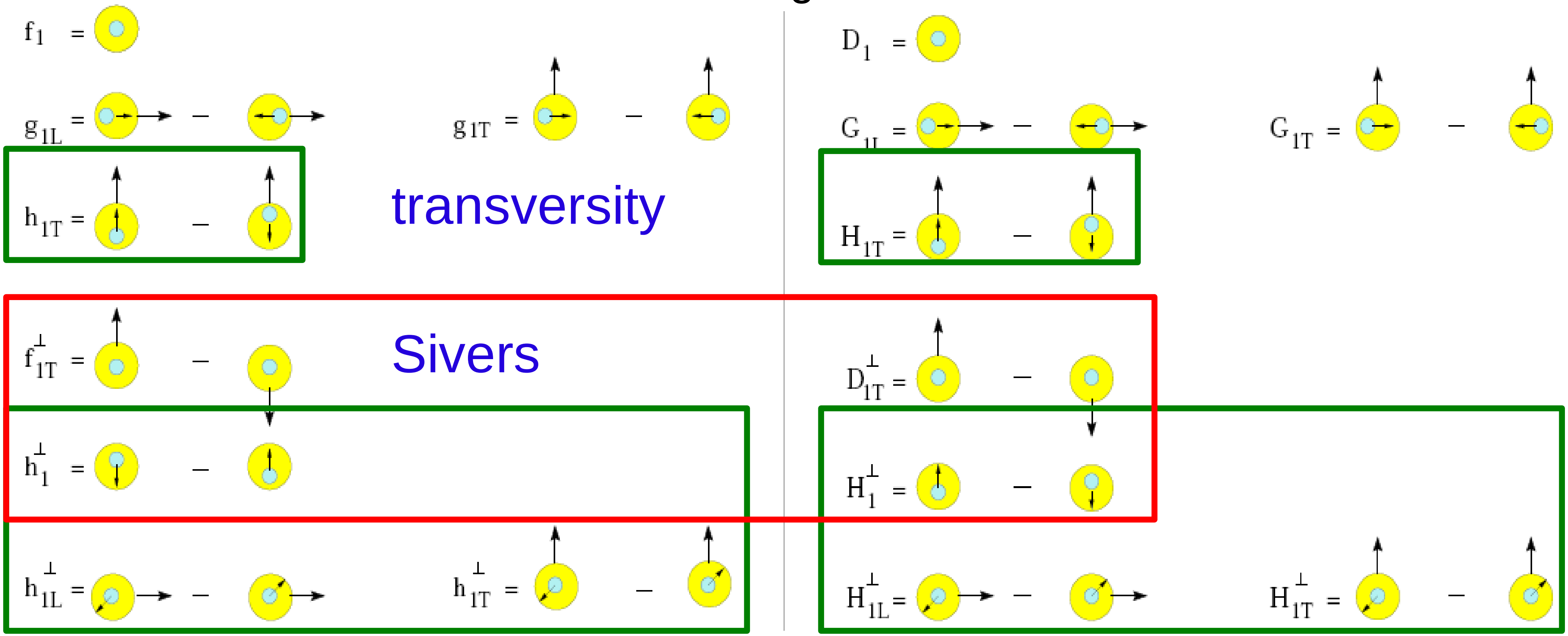

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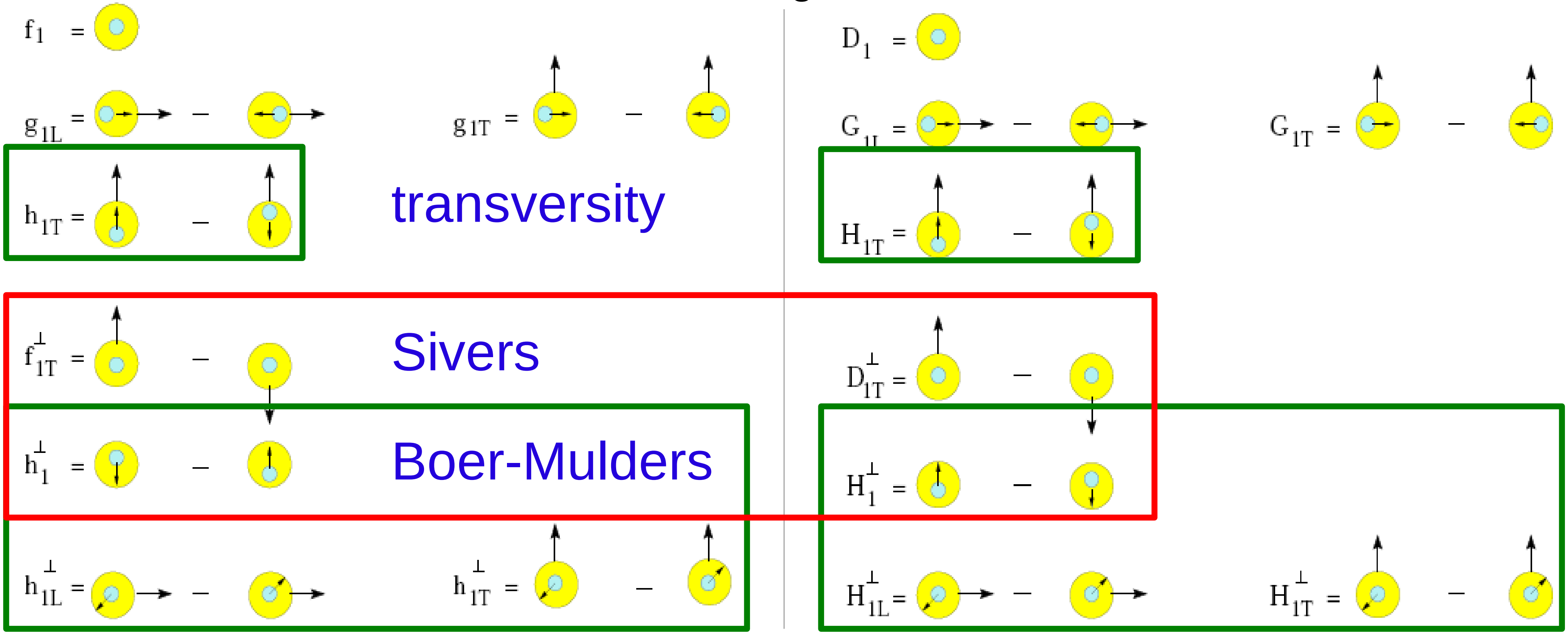

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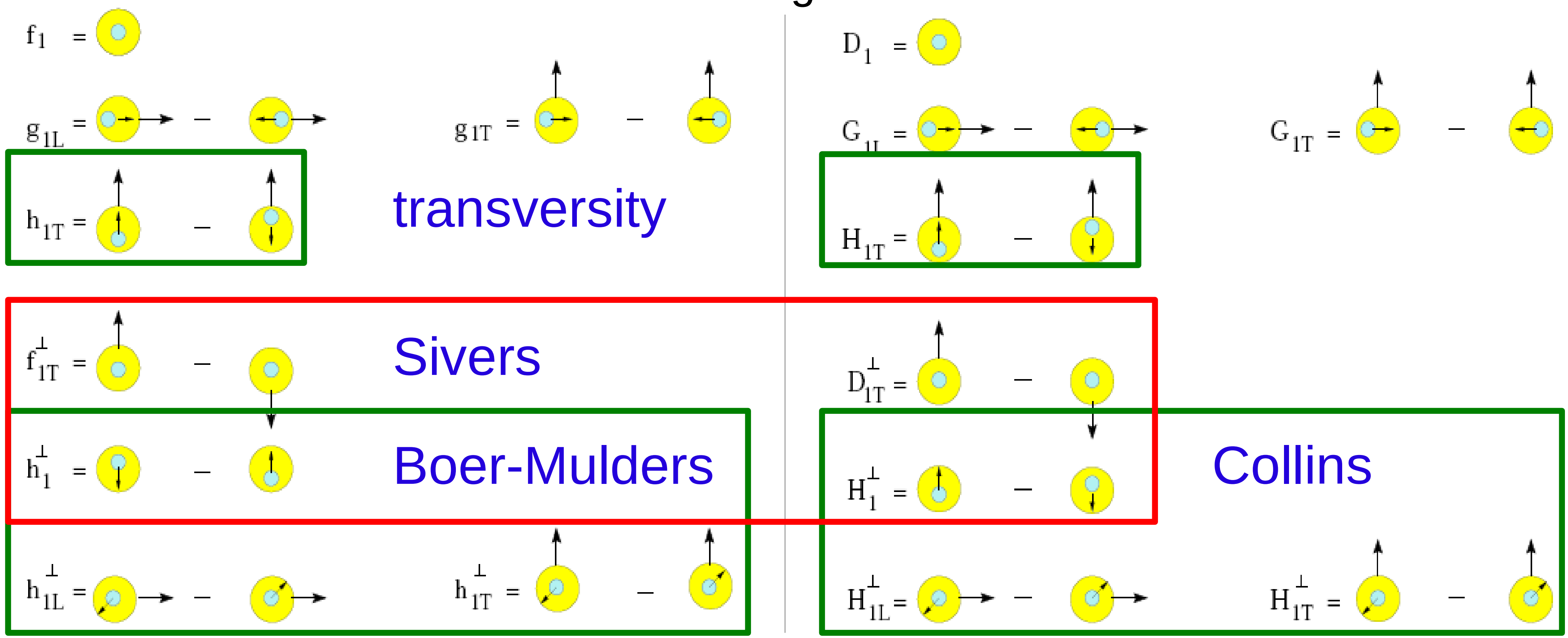

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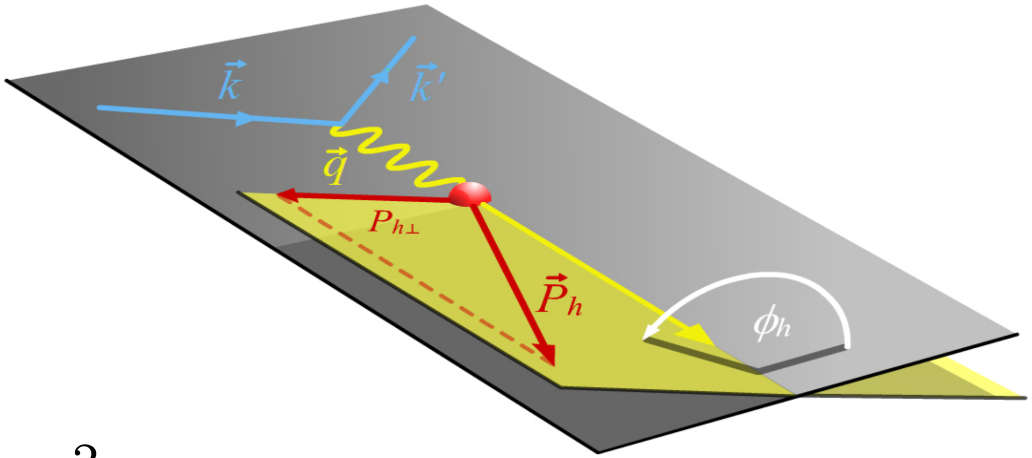
Spin-independent SIDIS cross section

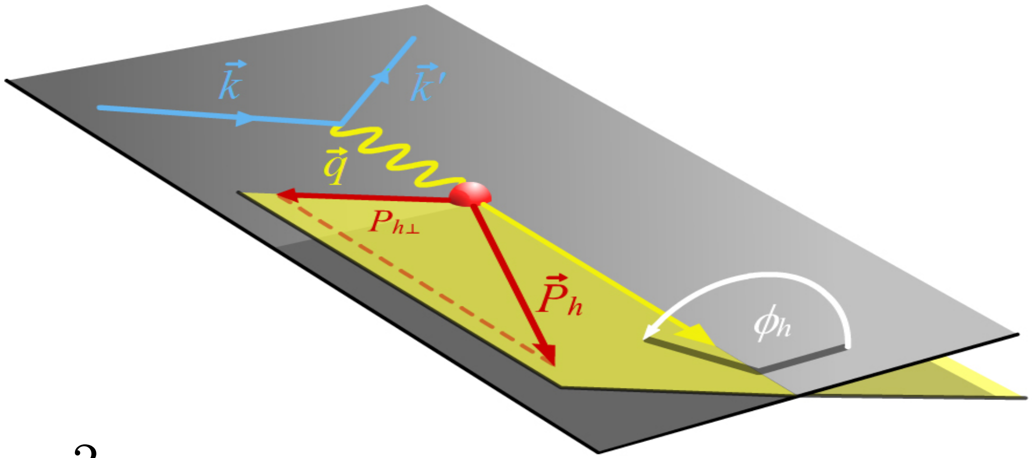


Non-collinear cross section

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi_h} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\{A(y)F_{UU,T} + B(y)F_{UU,L}$$
$$+C(y)\cos\phi_h F_{UU}^{\cos\phi_h} + B(y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\}$$

$$\gamma = \frac{2Mx}{Q},\ \ F = F(x, Q, z, \vec{P_{h\perp}})$$

Spin-independent SIDIS cross section



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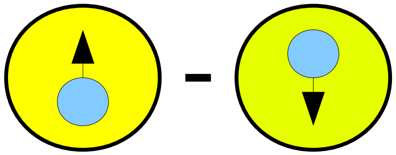
leading twist term

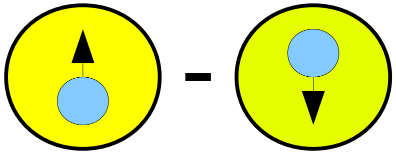
$$\gamma = \frac{2Mx}{Q},\;\; F = F(x, Q, z, \vec{P_{h\perp}})$$

$$F_{UU}^{\cos 2\phi_h} = \mathcal{I}\left[-\frac{2(\hat{P}_{h\perp}.\vec{k}_T)(\hat{P}_{h\perp}.\vec{p}_T) - \vec{k}_T.\vec{p}_T}{M_h M} h_1^\perp H_1^\perp\right]$$

$h_1^\perp$ = Boer-Mulders distribution function



$H_1^\perp$ = Collins fragmentation function



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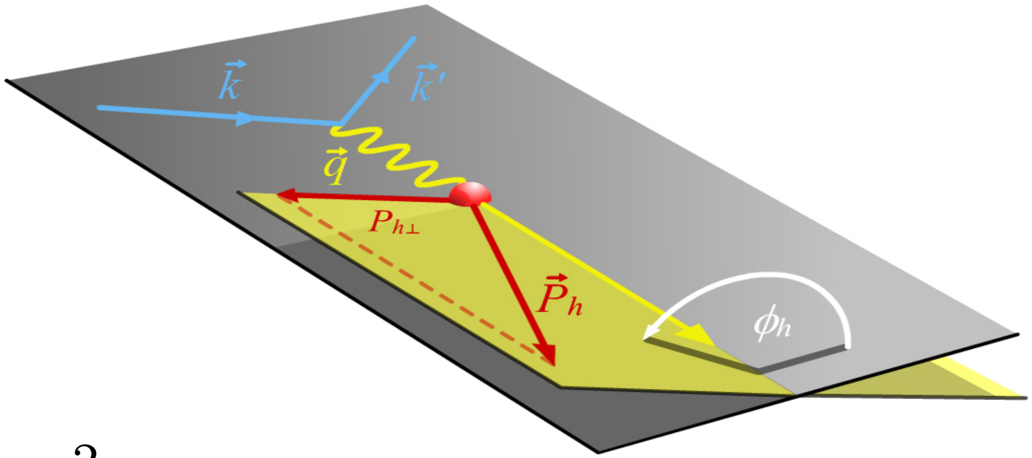

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sub-leading twist term

$$\gamma = \frac{2Mx}{Q},\ \ F = F(x, Q, z, \vec{P_{h\perp}})$$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{I}\left[-\frac{\hat{P}_{h\perp}.\vec{k}_T}{M} f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{p}_T}{M_h}\frac{k_T^2}{M^2} h_1^\perp H_1^\perp + \ldots\right]$$

Cahn effect

quark-gluon-quark correlations

Extraction of the cosine moments

$$\langle \cos(n\phi_h) \rangle \stackrel{th.}{=} \frac{\int d\phi_h \cos(n\phi_h) \sigma_{UU}(x, y, z, P_{h\perp}^2, \phi_h)}{\int d\phi_h \sigma_{UU}(x, y, z, P_{h\perp}^2, \phi_h)}$$

$$\updownarrow$$

$$\langle \cos(n\phi_h) \rangle \stackrel{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h) \epsilon_{acc}(\phi_h) \epsilon_{rad}(\phi_h) \sigma_{UU}(x, y, z, P_{h\perp}^2, \phi_h)}{\int d\phi_h \epsilon_{acc}(\phi_h) \epsilon_{rad}(\phi_h) \sigma_{UU}(x, y, z, P_{h\perp}^2, \phi_h)}$$

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Extraction is challenging!

Azimuthal modulations also possible due to

- detector geometrical acceptance
- higher-order QED effects

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↕

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fully differential analysis needed
unfolding procedure with 400 x 12 bins *

BINNING 400 kinematic bins x 12 ϕ -bins							
Variable	Bin limits						#
x	0.023	0.042	0.078	0.145	0.27	1	5
y	0.3	0.45	0.6	0.7	0.85		4
z	0.2	0.3	0.45	0.6	0.75	1	5
P_{hT}	0.05	0.2	0.35	0.5	0.75		4

(*)see F. Giordano,
Proceedings of Transversity 2008 Workshop,
May 28-31 2008, Ferrara, Italy,
to be published by World Scientific

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z	0.2	0.3	0.45	0.6	0.75	1	5
P_{hT}	0.05	0.2	0.35	0.5	0.75		4

$$\langle \cos(n\phi_h)\rangle\Big|_{\text{bin } i} \approx \left.\frac{\int d\phi_h \cos(n\phi_h)\sigma_{UU}(x,y,z,P_{h\perp}^2,\phi_h)}{\int d\phi_h \sigma_{UU}(x,y,z,P_{h\perp}^2,\phi_h)}\right|_{\text{bin } i}$$

(*)see F. Giordano,
Proceedings of Transversity 2008 Workshop,
May 28-31 2008, Ferrara, Italy,
to be published by World Scientific

Extraction of the cosine moments

$$\langle\cos(n\phi_h)\rangle \overset{th.}{=} \frac{\int d\phi_h \cos(n\phi_h)\sigma_{UU}(x,y,z,P_{h\perp}^2,\phi_h)}{\int d\phi_h \sigma_{UU}(x,y,z,P_{h\perp}^2,\phi_h)}$$

↕

$$\langle\cos(n\phi_h)\rangle \overset{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h)\epsilon_{acc}(\phi_h)\epsilon_{ra}\ldots_{UU}(x,y,z,P_{h\perp}^2,\phi_h)}{\int d\phi_h \epsilon_{acc}(\phi_h)\epsilon_{ra}\ldots_{UU}(x,y,z,P_{h\perp}^2,\phi_h)}$$

more on unfolding, see F. Giordano (HK81)

Extraction is challenging!
Azimuthal modulations also pos… due to
- detector geometrical accep…e
- higher-order QED effe…

fully differential an…s needed
unfolding proc…e with 400 x 12 bins *

BINNING …inematic bins x 12 ϕ -bins							
Variable	Bin limits						#
x	0.023	0.042	0.078	0.145	0.27	1	5
y	0.3	0.45	0.6	0.7	0.85		4
z	0.2	0.3	0.45	0.6	0.75	1	5
P_{hT}	0.05	0.2	0.35	0.5	0.75		4

unfolding

$$\langle\cos(n\phi_h)\rangle\Big|_{\text{bin i}} \approx \frac{\int d\phi_h \cos(n\phi_h)\sigma_{UU}(x,y,z,P_{h\perp}^2,\phi_h)}{\int d\phi_h \sigma_{UU}(x,y,z,P_{h\perp}^2,\phi_h)}\Bigg|_{\text{bin i}}$$

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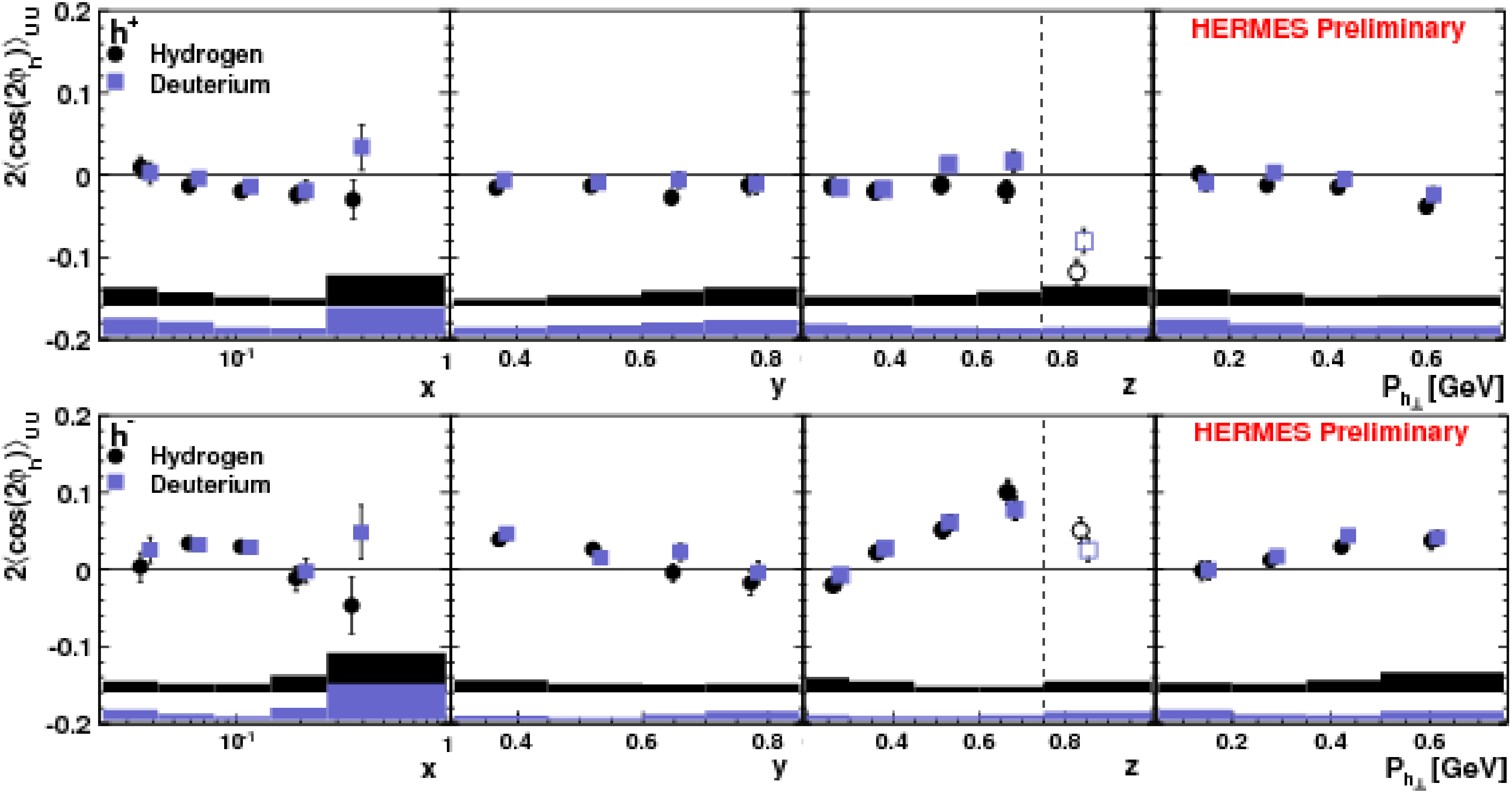
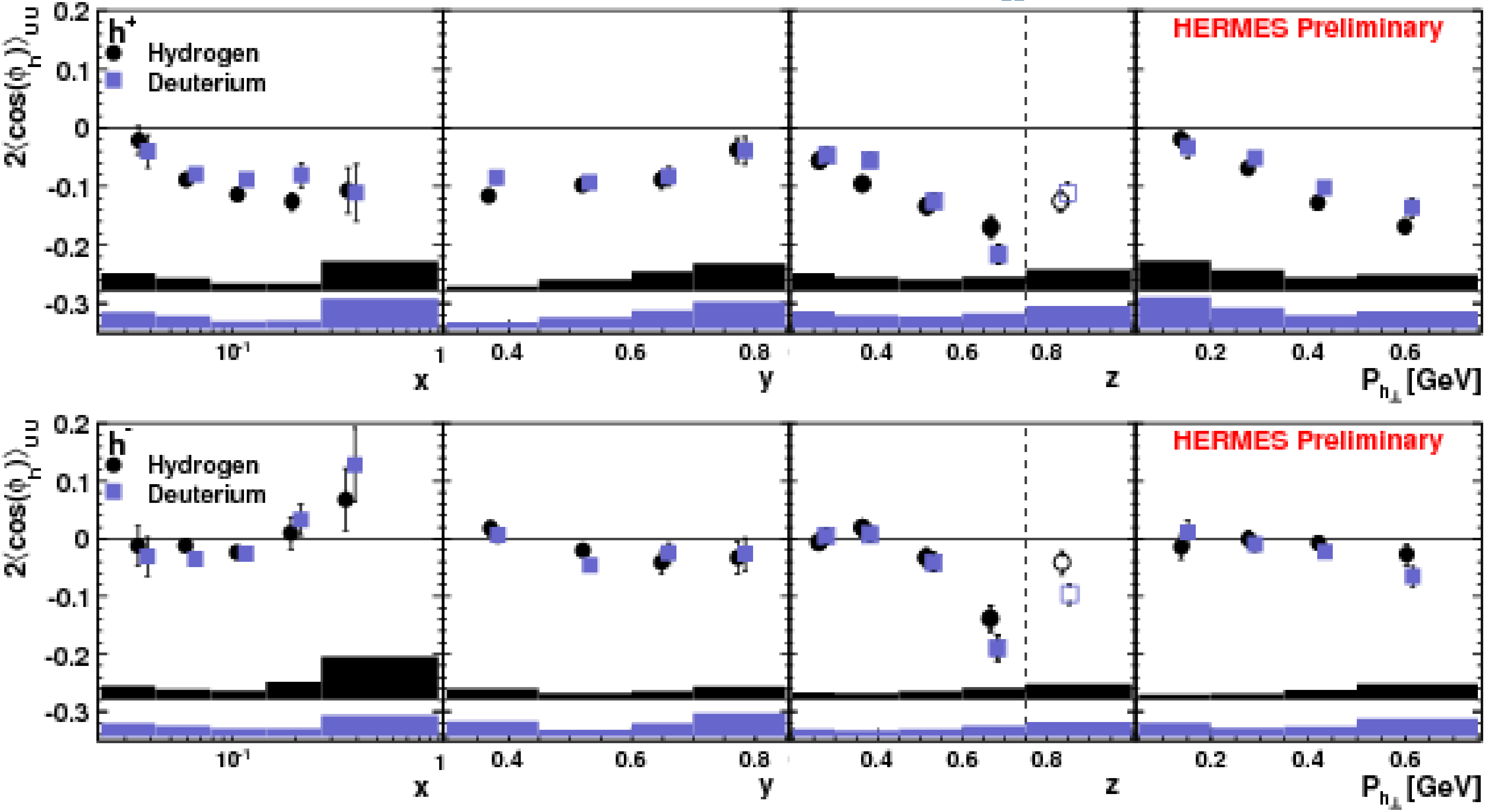
Results for <cos $2\phi_h$>



- evidence for transversely polarized quarks in unpolarized nucleon!
- h^+ and h^-: opposite sign in agreement with models

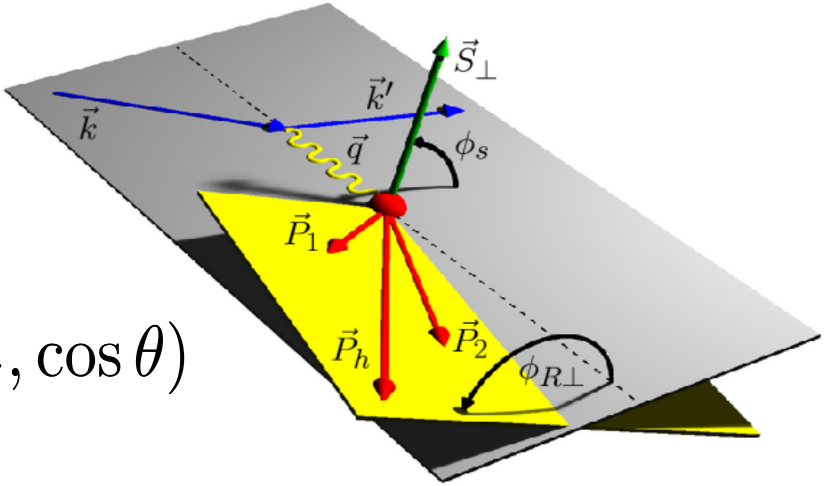
Results for <cos ϕ_h>



- predictions for Cahn effect: negative for h^+ and h^-
- → also other effects have to be taken into account

Single Spin Asymmetries

$$A_{UT} = \frac{1}{\langle |S_T| \rangle} \frac{N^{\uparrow}(\phi, \phi_S) - N^{\downarrow}(\phi, \phi_S)}{N^{\uparrow}(\phi, \phi_S) + N^{\downarrow}(\phi, \phi_S)}$$



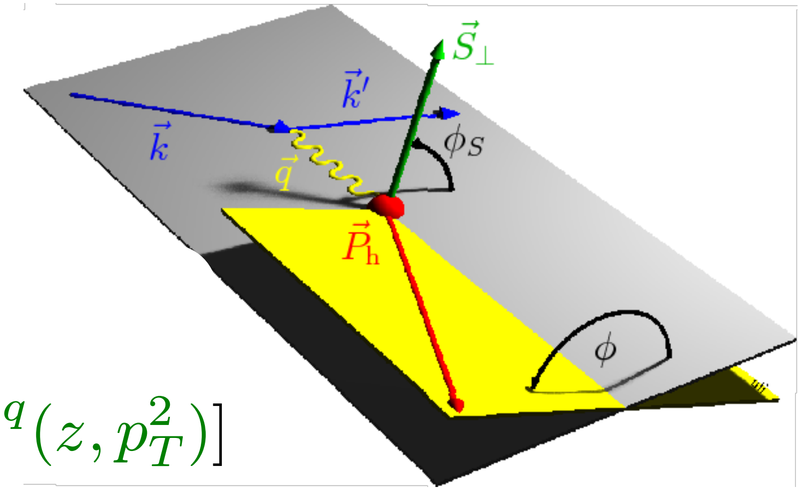
2-hadron production

$$\sim \sin(\phi_{R\perp} + \phi_S) \sum_q e_q^2 h_{1T}^q(x) H_1^{\measuredangle,q}(z, M_{\pi\pi}, \cos\theta)$$

h_{1T}: transversity

$H_1^{\perp}$: Collins fragmentation function

$f_{1T}^{\perp}$: Sivers distribution function



1-hadron production

$$\sim \sin(\phi + \phi_S) \sum_q e_q \mathcal{I}[\frac{\vec{p}_T.\hat{P}_{h\perp}}{M_h} h_{1T}^q(x, k_T^2) \otimes H_1^{\perp,q}(z, p_T^2)]$$

$$+ \sin(\phi - \phi_S) \sum_q e_q \mathcal{I}[\frac{\vec{k}_T.\hat{P}_{h\perp}}{M_h} f_{1T}^{\perp,q}(x, k_T^2) \otimes D_1^q(z, p_T^2)]$$

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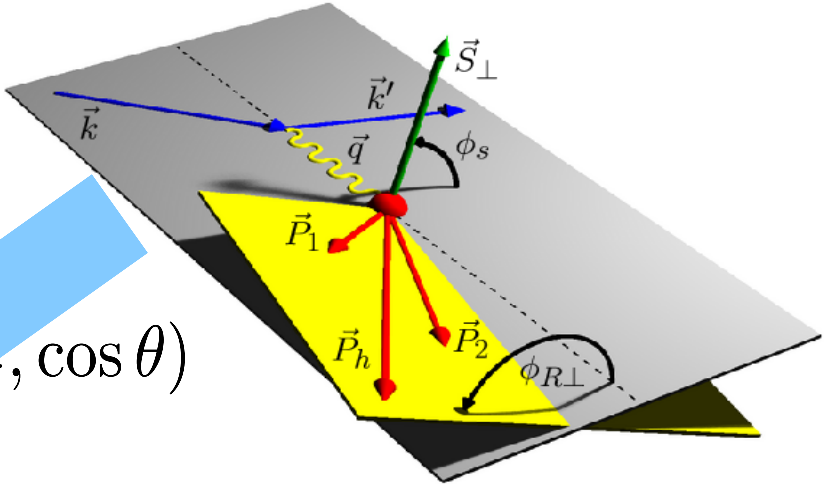

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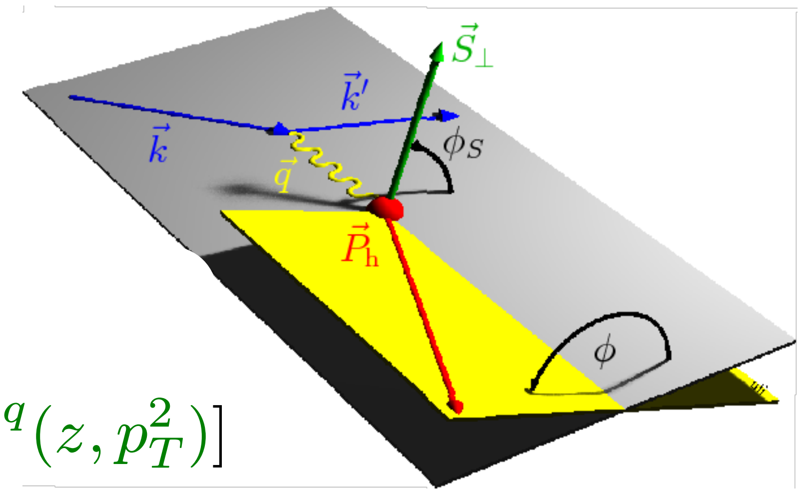
$$\sim \sin(\phi_{R\perp} + \phi_S) \sum_q e_q^2 h_{1T}^q(x) H_1^{\measuredangle,q}(z, M_{\pi\pi}, \cos\theta)$$

see talk by M. Diefenthaler

h_{1T}: transversity

$H_1^{\perp}$: Collins fragmentation function

$f_{1T}^{\perp}$: Sivers distribution function



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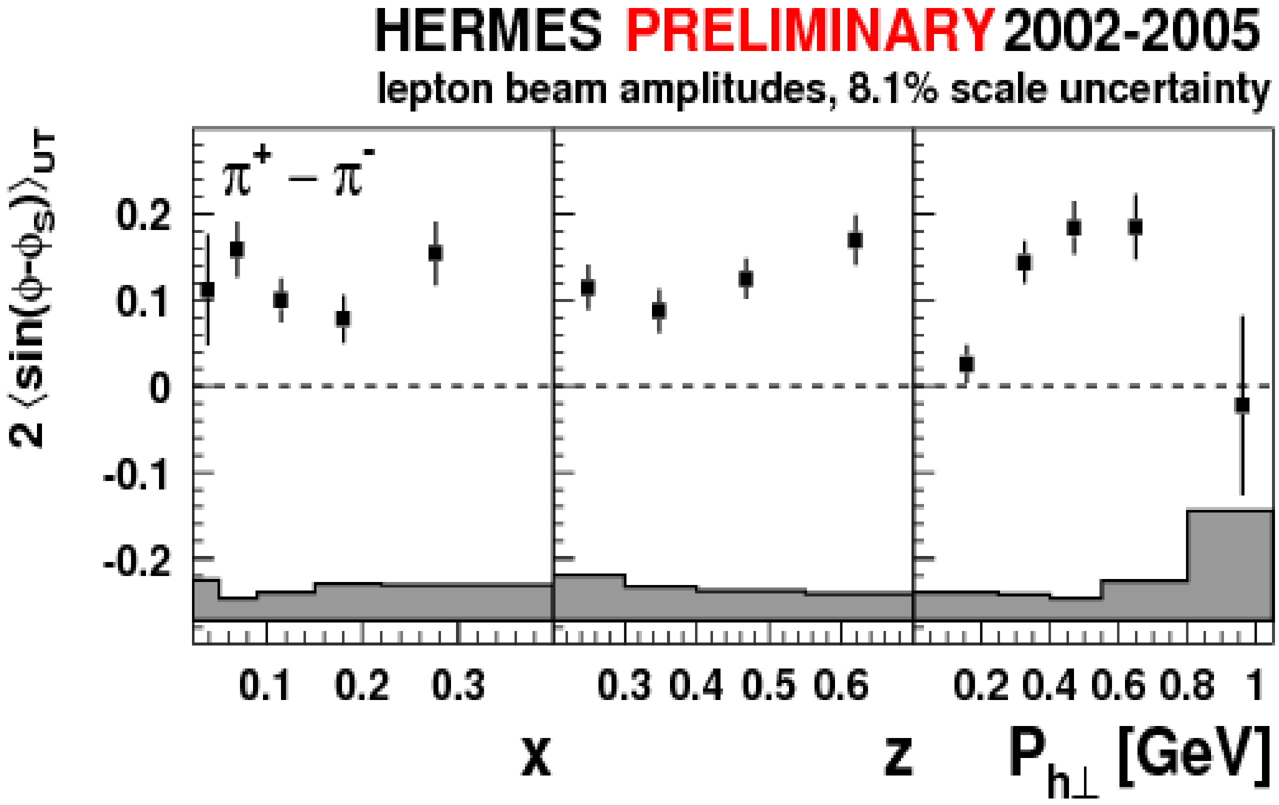
Sivers distribution for valence quarks

$$A_{UT}^{\pi^+-\pi^-} = \frac{1}{\langle|S_T|\rangle} \frac{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}$$

$$\longrightarrow \quad \langle\sin(\phi-\phi_S)\rangle_{UT}^{\pi^+-\pi^-} = -\frac{4f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4f_1^{u_v} - f_1^{d_v}}$$



- Sivers distribution for d-valence >> u-valence

or

- Sivers distribution for u-valence is large & <0 (more likely)

Generalized parton distributions
and
Deeply virtual Compton scattering

Spin decomposition of the nucleon

X. Ji, *Phys. Rev. Lett.* **78,** 610-613 (1997)

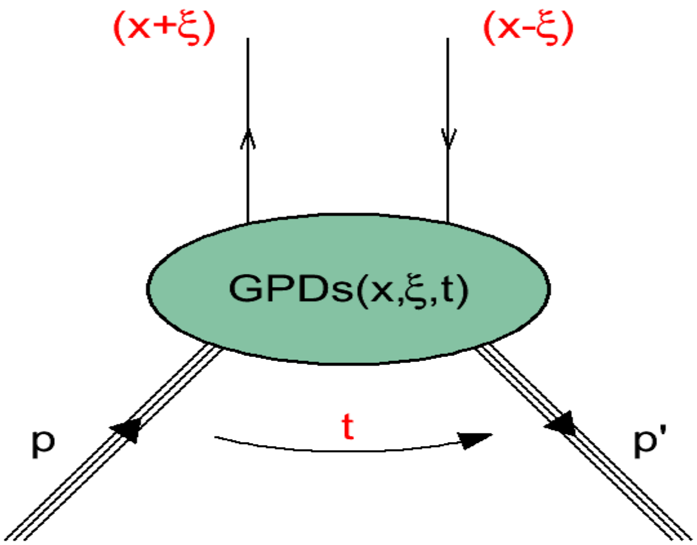
$$\frac{1}{2} = \sum_q J^q + J^g = \frac{1}{2}\Delta\Sigma + \sum_q L^q + J^g$$

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

→ possibility to access quark orbital angular momentum

Generalized Parton Distributions (GPDs)

- 4 twist-2 quark helicity conserving GPDs:
  $H^q, \tilde{H}^q, E^q, \tilde{E}^q$



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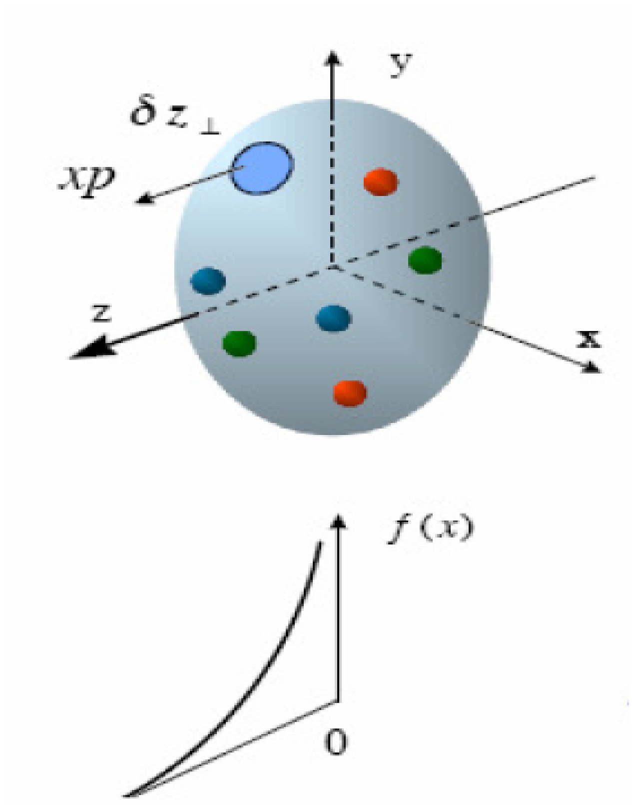
- forward limit → parton distribution functions

$$H^q(x,0,0) = q(x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x)$$



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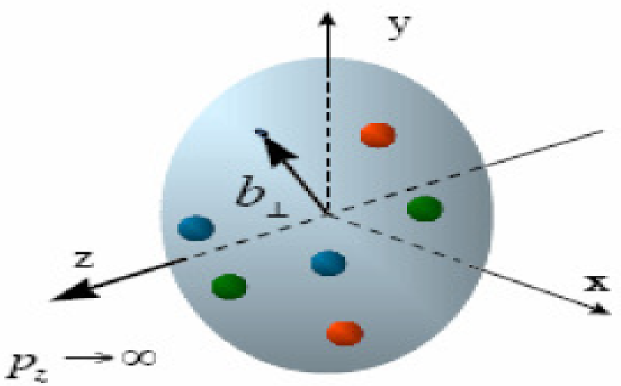
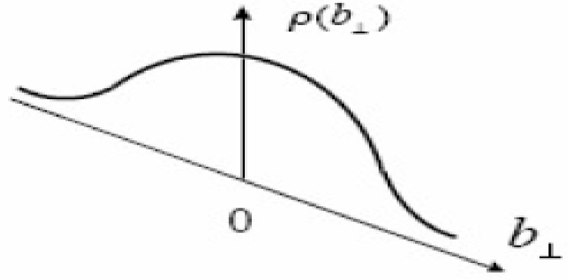
- moments → form factors

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

⋮





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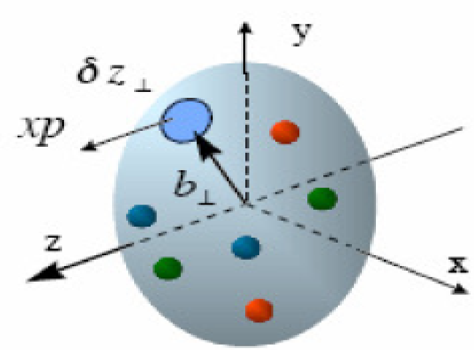

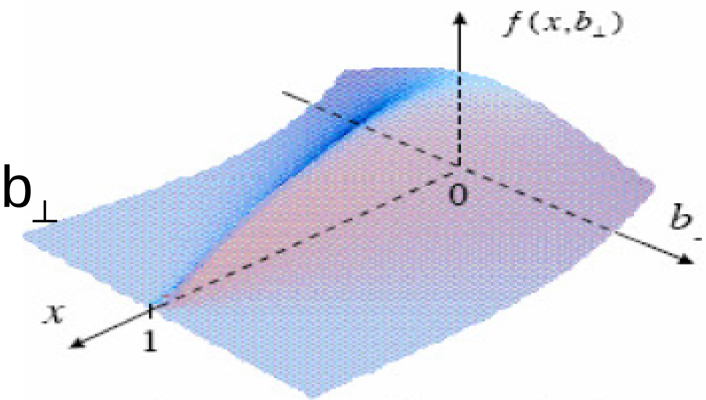

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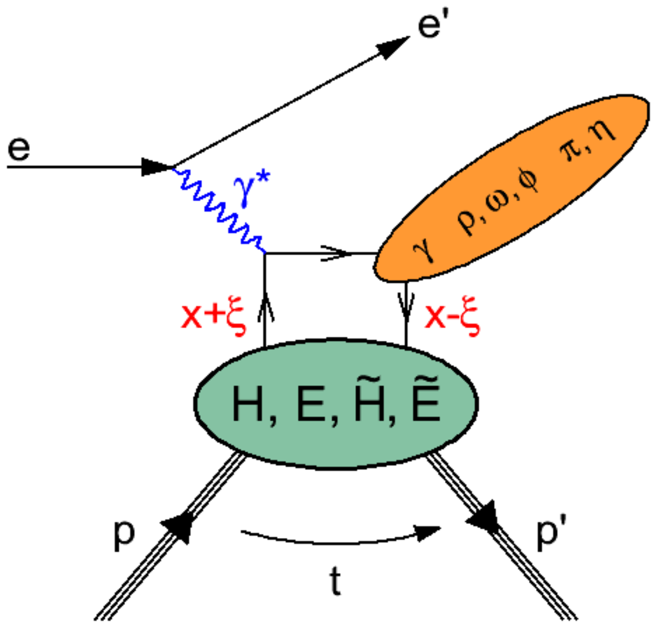
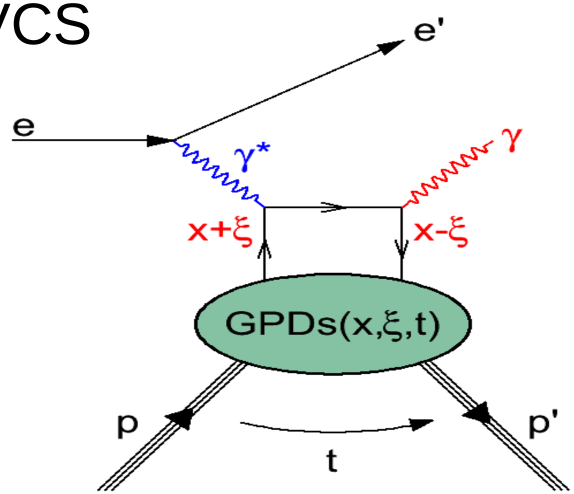
- forward limit → parton distribution functions
- moments → form factors
- probability to find quark with longitudinal momentum fraction x at transverse location $b_\perp$
- access via exclusive meson production and deeply virtual Compton scattering

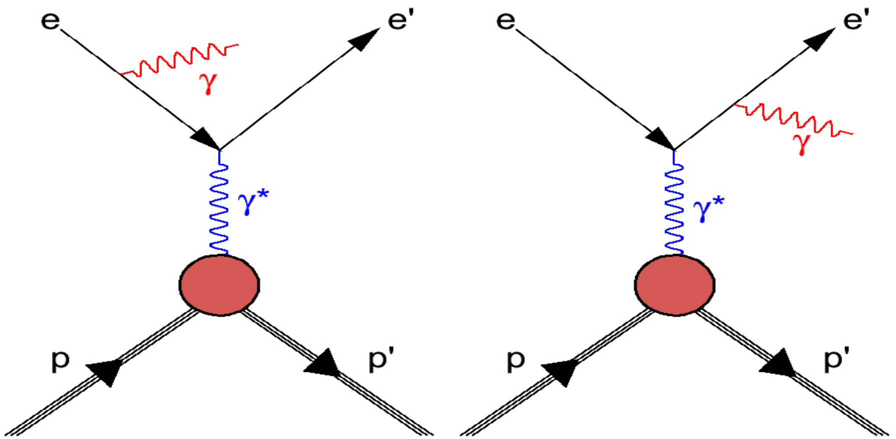


Deeply virtual Compton scattering

DVCS



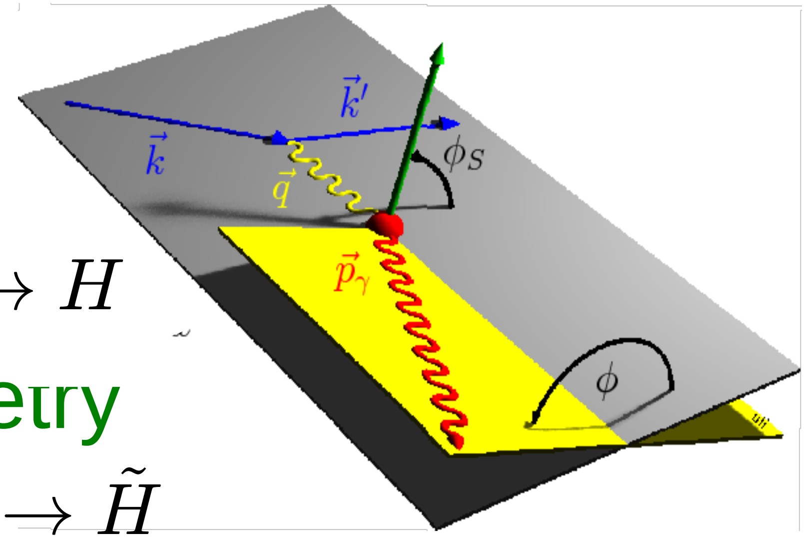
Bethe-Heitler



$$d\sigma \sim |T_{DVCS}|^2 + |T_{BH}|^2 + \underbrace{T_{BH}T^*_{DVCS} + T^*_{BH}T_{DVCS}}_{\textbf{interference term}}$$

- theoretically cleanest process to access GPDS
- DVCS and BH: indistinguishable ⟶ interference
- $T_{BH} >> T_{DVCS}$
- T_{BH}: calculable (form factors)
- access interference term by measuring azimuthal asymmetries

Azimuthal asymmetries



- Beam-spin asymmetry

$$d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \backsim \Im[F_1\mathcal{H}]\sin\phi \rightarrow H$$

- Longitudinal target-spin asymmetry

$$d\sigma(\overrightarrow{P},\phi) - d\sigma(\overleftarrow{P},\phi) \backsim \Im[F_1\tilde{\mathcal{H}}]\sin\phi \rightarrow \tilde{H}$$

- Beam-charge asymmetry

$$d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \backsim \Re[F_1\mathcal{H}]\cos\phi \rightarrow H$$

- Transverse target-spin asymmetry

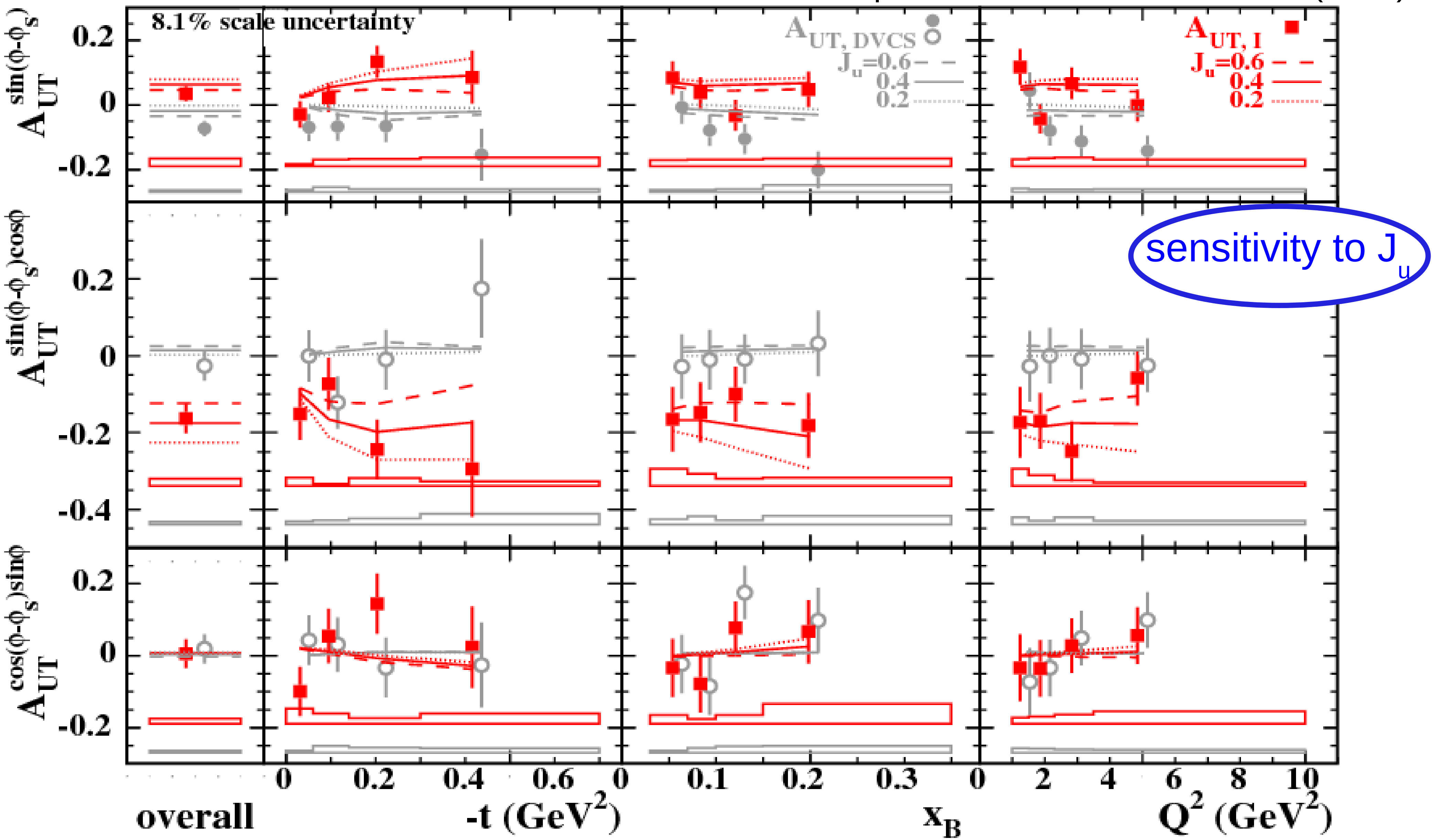
$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \sim$$
$$\Im[F_2\mathcal{H} - F_1\mathcal{E}]\sin(\phi-\phi_S)\cos\phi$$
$$\Im[F_2\tilde{\mathcal{H}} - F_1\xi\tilde{\mathcal{E}}]\cos(\phi-\phi_S)\sin\phi$$

⇨ only access to E!

$\mathcal{H},\mathcal{E},\tilde{\mathcal{H}},\tilde{\mathcal{E}}$: Compton form factors

Transverse target-spin asymmetry

A. Airapetian et al., JHEP **0806**, 066 (2008)



VGG model: Phys. Rev. D60, 094017 (1999)
Prog. Part. Nucl. Phys. 47, 401 (2001)

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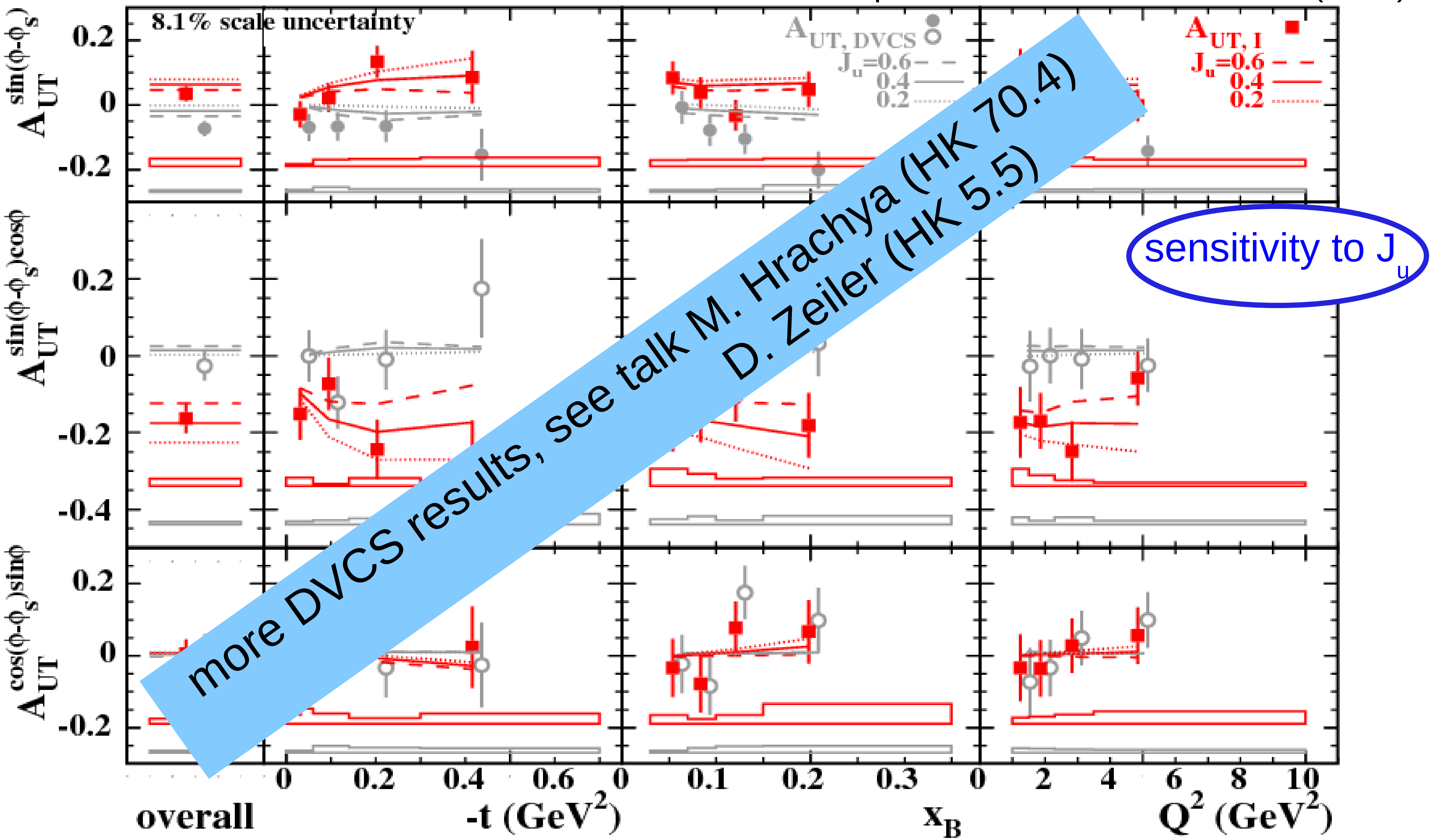

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Summary

- strange quark distributions

  - SU(3) symmetry appears to be violated

  - S(x) much softer than light isoscalar

  - $\Delta S(x)$ consistent with 0

- accounting for transverse momentum of parton →

  azimuthal dependence of unpolarized cross-section

  Boer-Mulders effect: non zero!

- Sivers distribution for valence quarks:

  likely, large and negative for u_v

- generalized parton distributions →
  access to quark orbital angular momentum:

  transverse target-spin asymmetry sensitive to J_u