Recent results from HERMES

Charlotte Van Hulse, on behalf of the HERMES collaboration
University of the Basque Country – UPV/EHU

Outline

- the HERMES experiment
- the proton in 3D: Generalized parton distributions
- Single-helicity asymmetries in DVCS

  - complete data set, through missing mass reconstruction

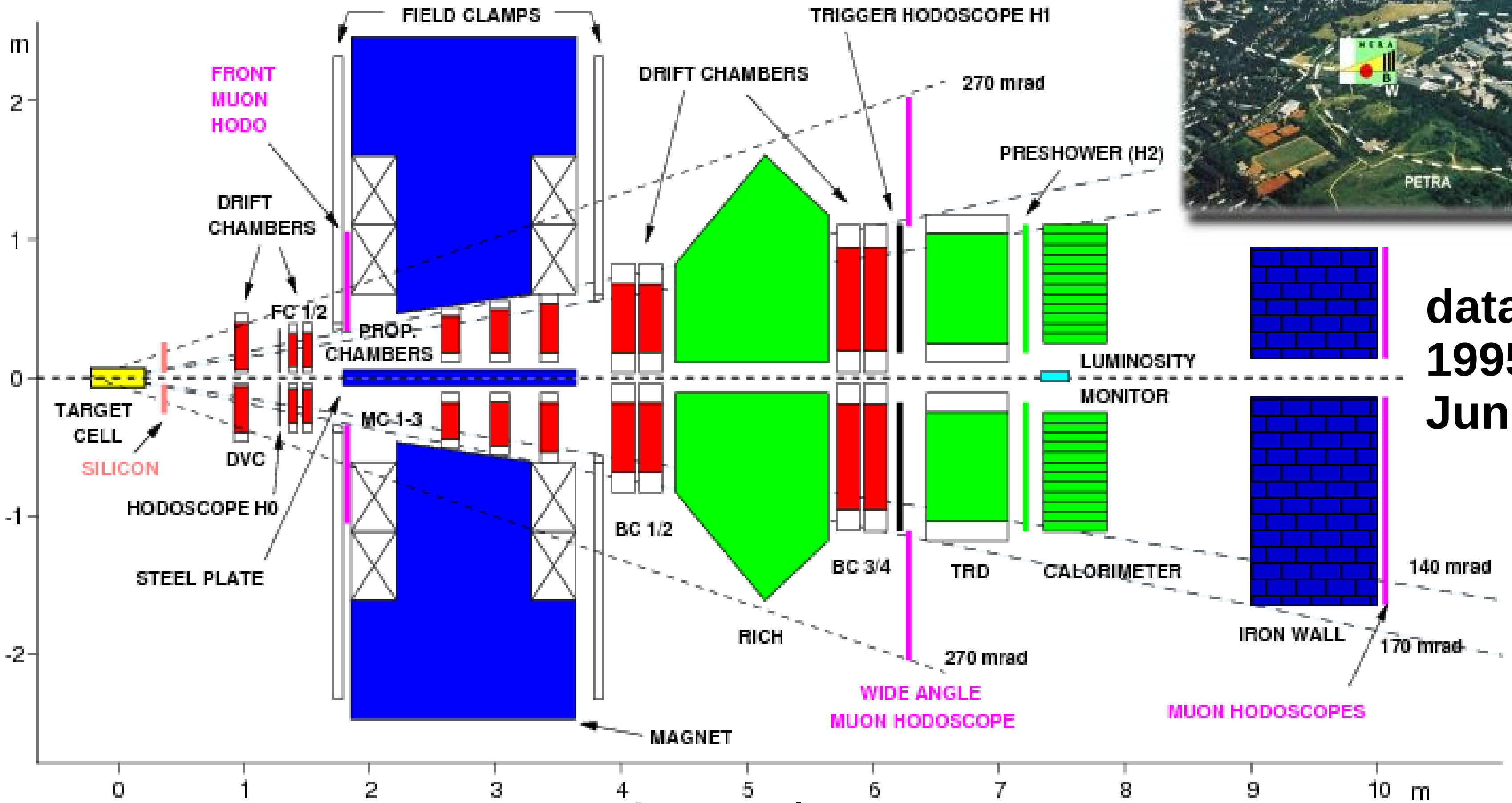
  - kinematically complete event reconstruction
- the proton in 3D: transverse-momentum-dependent parton distributions
- single-spin asymmetries in SIDIS off transversely polarized protons

  - Sivers distribution function

  - transversity and Collins fragmentation function
- spin-independent non-collinear cross section

  - Boer-Mulders-Collins amplitude

HERMES: HERA MEasurement of Spin



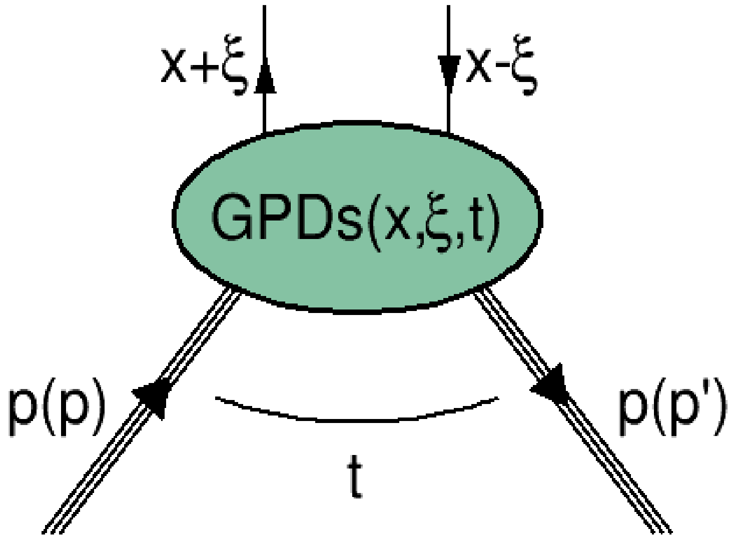
data taking from 1995 until June, 30 2007

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

<u>Gaseous internal target</u>
transversely pol. H (~75%)
unpol. H,D,He,Ne,Kr,Xe
longitudinally pol. H,D,He (~85%)

- **lepton-hadron PID: high efficiency (>98%) & low contamination (<1%)**
- **hadron PID: RICH 2-15 GeV**

Generalized Parton Distributions (GPDs)



- x=average longitudinal momentum fraction
- 2ξ=average longitudinal momentum transfer
- t= squared momentum transfer to nucleon

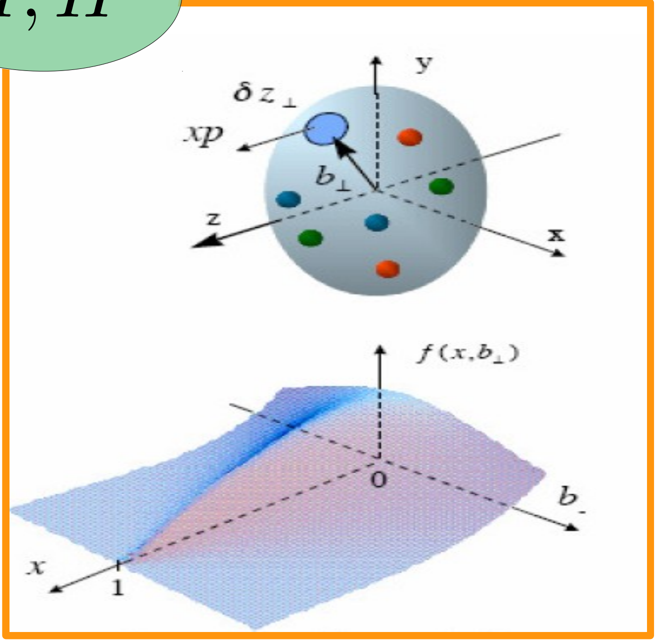
Four quark helicity-conserving GPDs at twist-2

$\mathrm{H}^q(x,\xi,t)$	$E^q(x,\xi,t)$	spin independent
$\widetilde{H}^q(x,\xi,t)$	$\widetilde{E}^q(x,\xi,t)$	spin dependent
proton helicity non-flip	proton helicity flip	

Generalized Parton Distributions (GPDs)

$H, \tilde{H}$

unpolarized nucleon



helicity-(in)dependent probability distribution of quarks as a function of their longitudinal fractional momentum and transverse position

M. Burkardt, Phys. Rev. D **62** (2000) 071503

Generalized Parton Distributions (GPDs)

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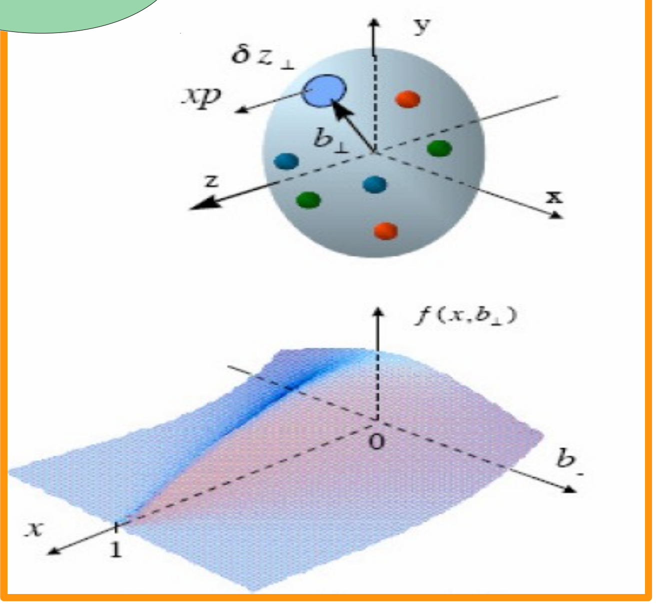
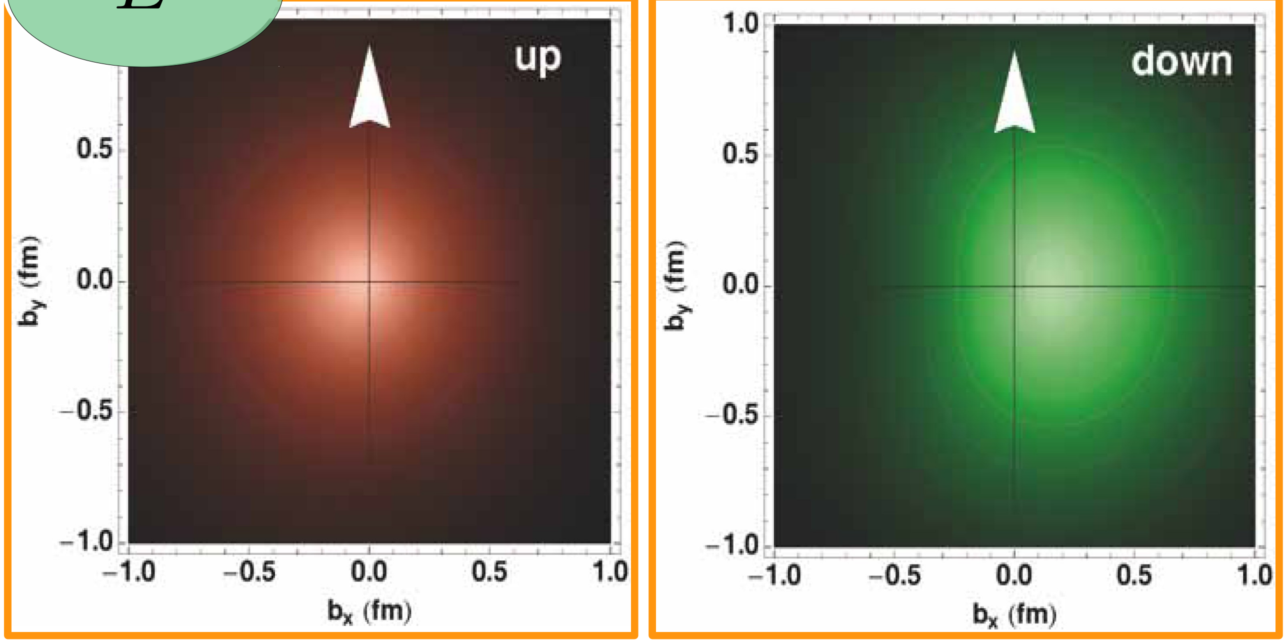


E transversely polarized nucleon



pictures taken from A. Bacchetta and M. Contalbrigo, Il Nuovo Saggiatore **28** (2012) 1-2

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distortion of quark probability distribution compared to unpolarized nucleon

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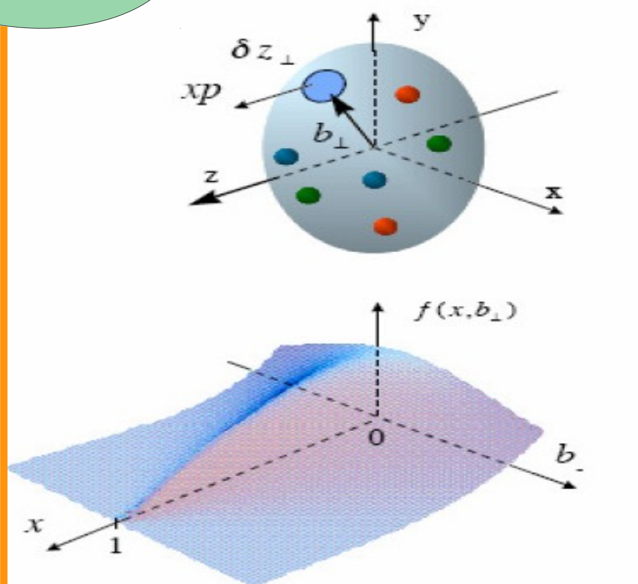

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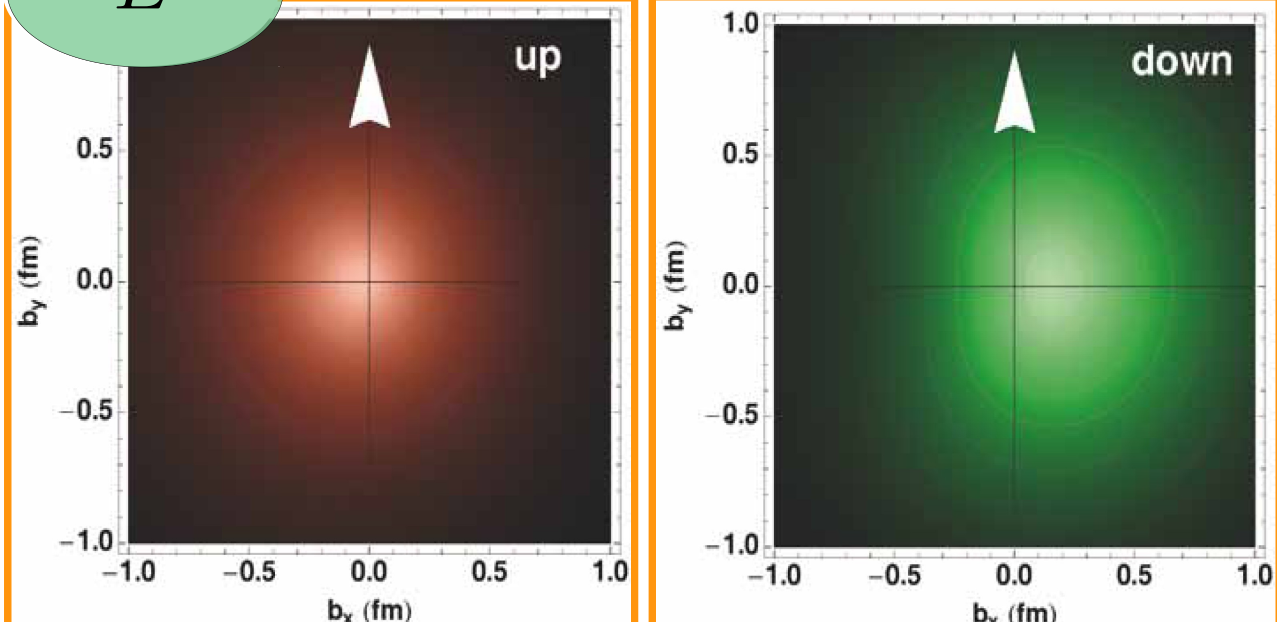

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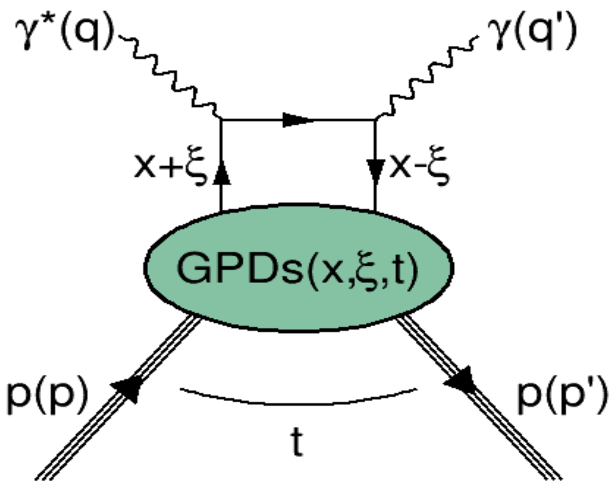
$$J^q = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} dx x [H^q(x, \xi, t) + E^q(x, \xi, t)]$$

quark orbital angular momentum

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

Deeply virtual Compton scattering

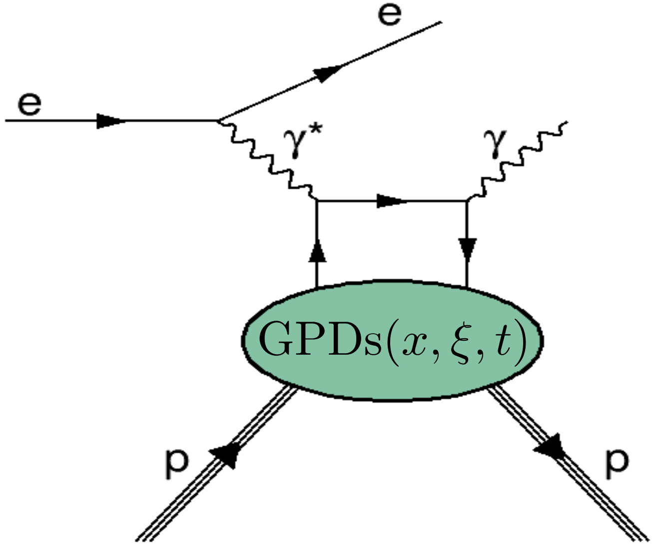


$$Q^2 \equiv -q^2$$

$$x_B \equiv \frac{Q^2}{2pq}$$

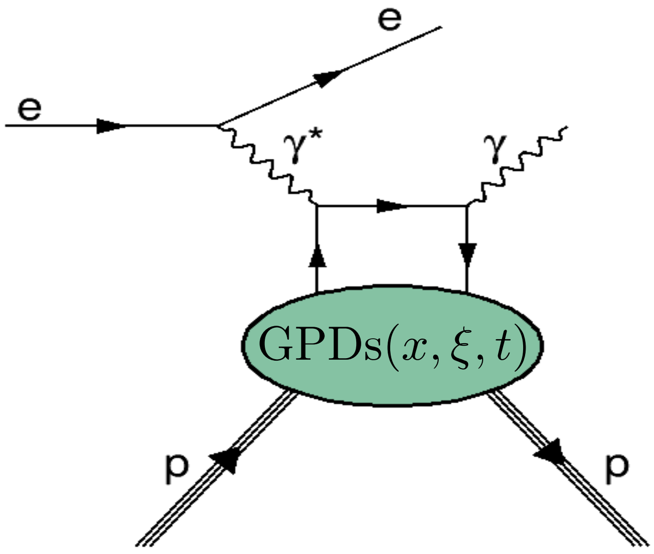
$$\xi \approx \frac{x_B}{2 - x_B}$$

Exclusive lepto-production of real photons

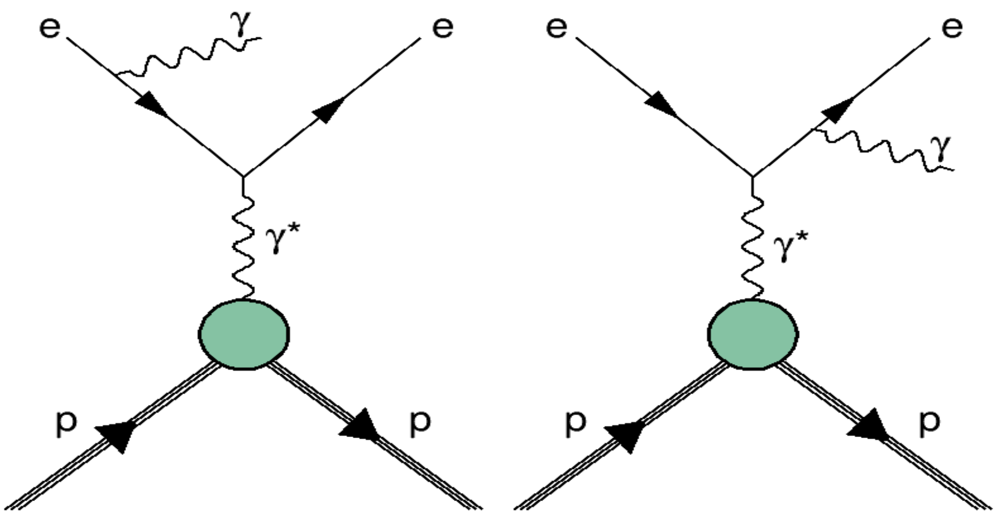


DVCS

Exclusive lepto-production of real photons



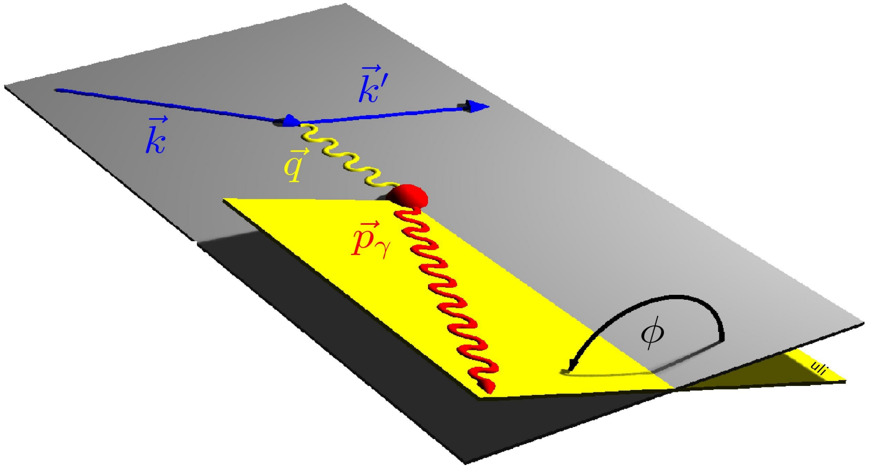
DVCS



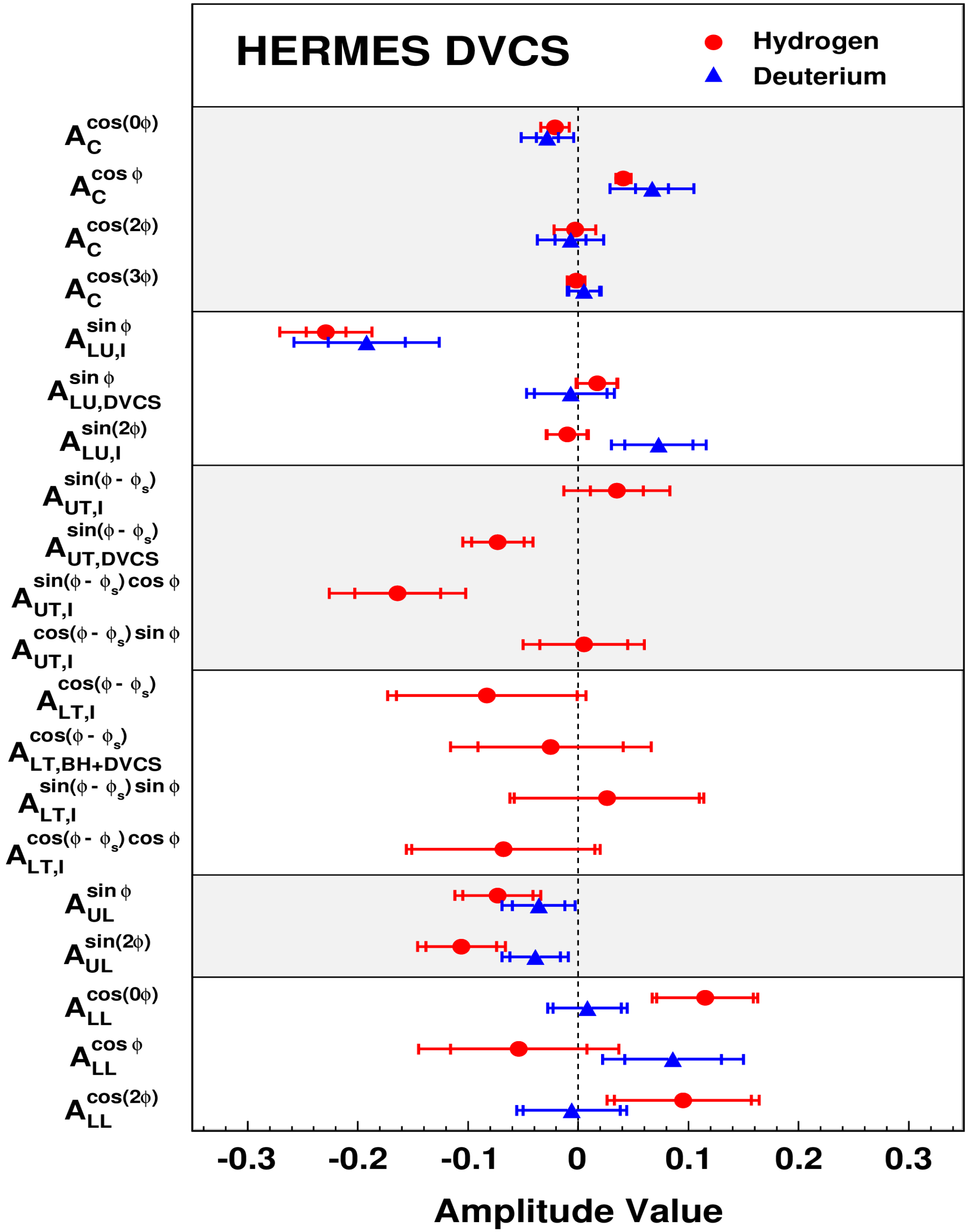
Bethe-Heitler

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

- $|\tau_{BH}|$: calculable (form factors)
- $|\tau_{BH}| \gg |\tau_{DVCS}|$ at HERMES
- interference term:
  through azimuthal asymmetries



DVCS at HERMES



beam-charge asymmetry
JHEP **07** (2012) 32
Nucl. Phys. B 829 (2010) 1

beam-helicity asymmetry
JEHP **07** (2012) 32
Nucl. Phys. B 829 (2010) 1

GPD H

transverse target-spin asymmetry
JHEP **06** (2008) 066

GPD E

double spin (LT) asymmetry
Phys. Lett. B **704** (2011) 15

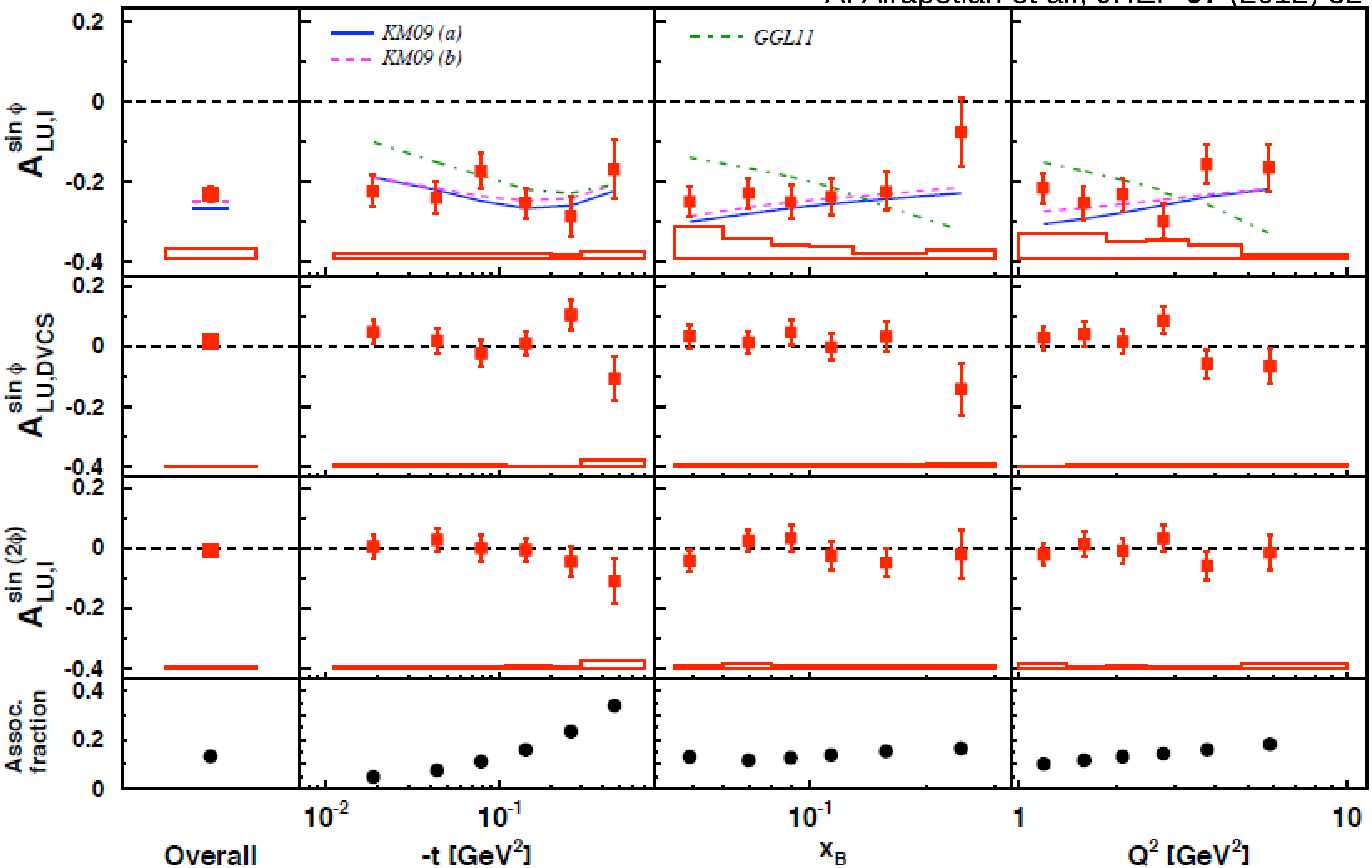
longitudinal target-spin asymmetry
JHEP **06** (2010) 019
Nucl. Phys. B 842 (2011) 265

double spin (LL) asymmetry
JHEP **06** (2010) 019
Nucl. Phys. B 842 (2011) 265

GPD $\tilde{H}$

Charged-separated beam-helicity asymmetry

A. Airapetian et al., JHEP **07** (2012) 32

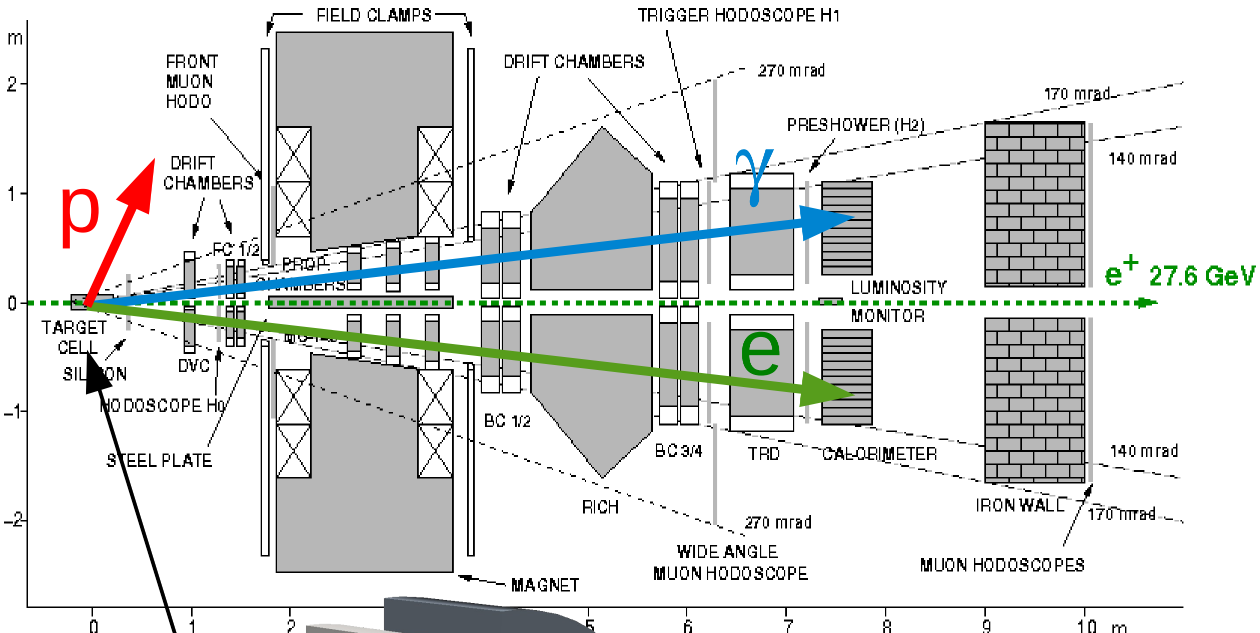


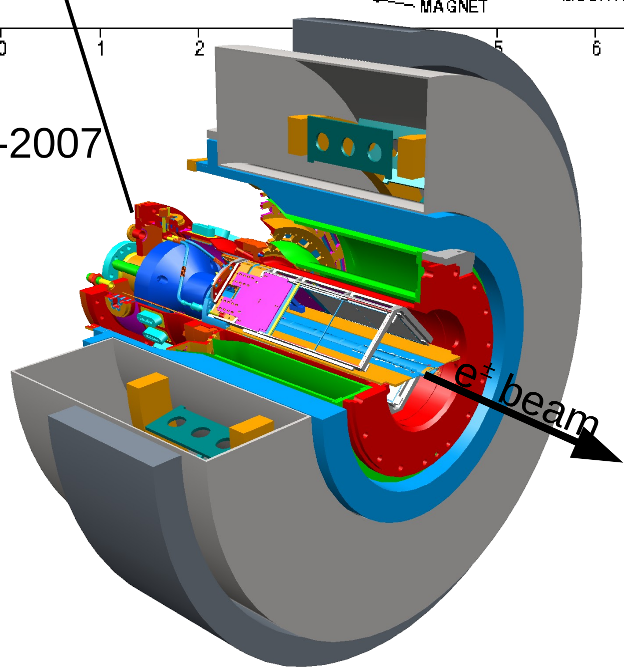
KM09: Nucl. Phys. B **841** (2010) 1:
fit to HERMES, ZEUS, H1 data
Fit to HERMES, ZEUS, H1, Jefferson Lab data

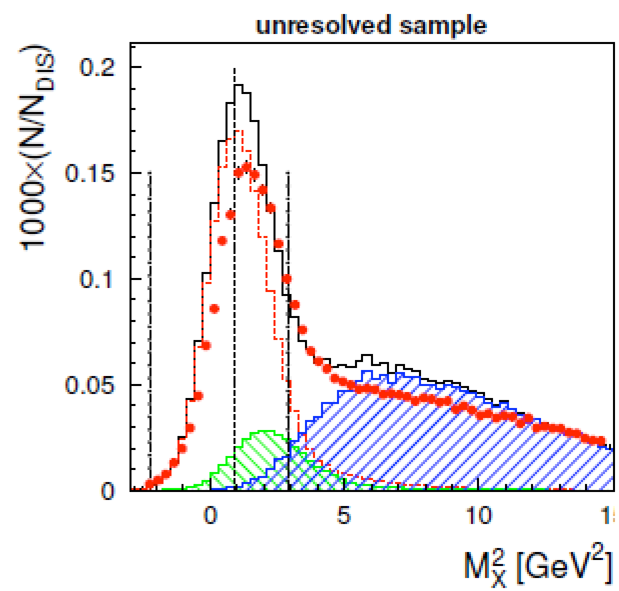
GGL11:Phys. Rev. D **84** (2011) 034007

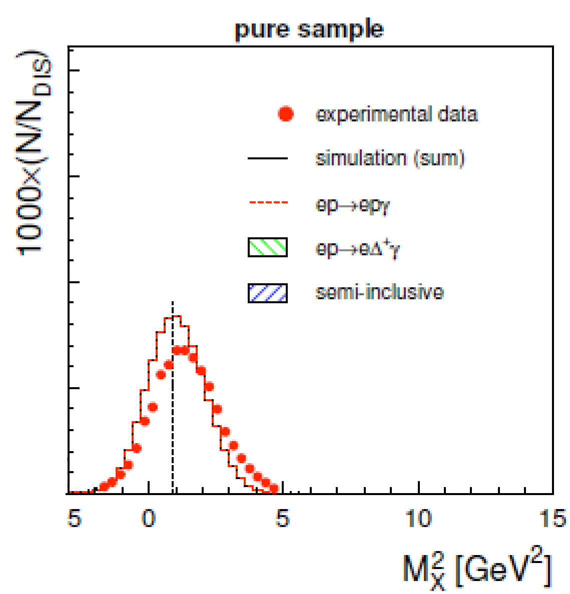
- data collected from 1996-2007 (74% of data from 2006-2007)
- additional 3.2% scale uncertainty from beam polarization

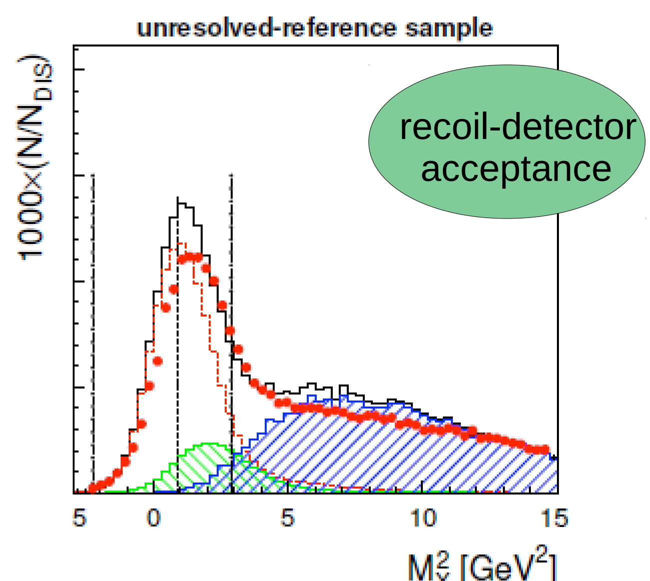
DVCS event selection





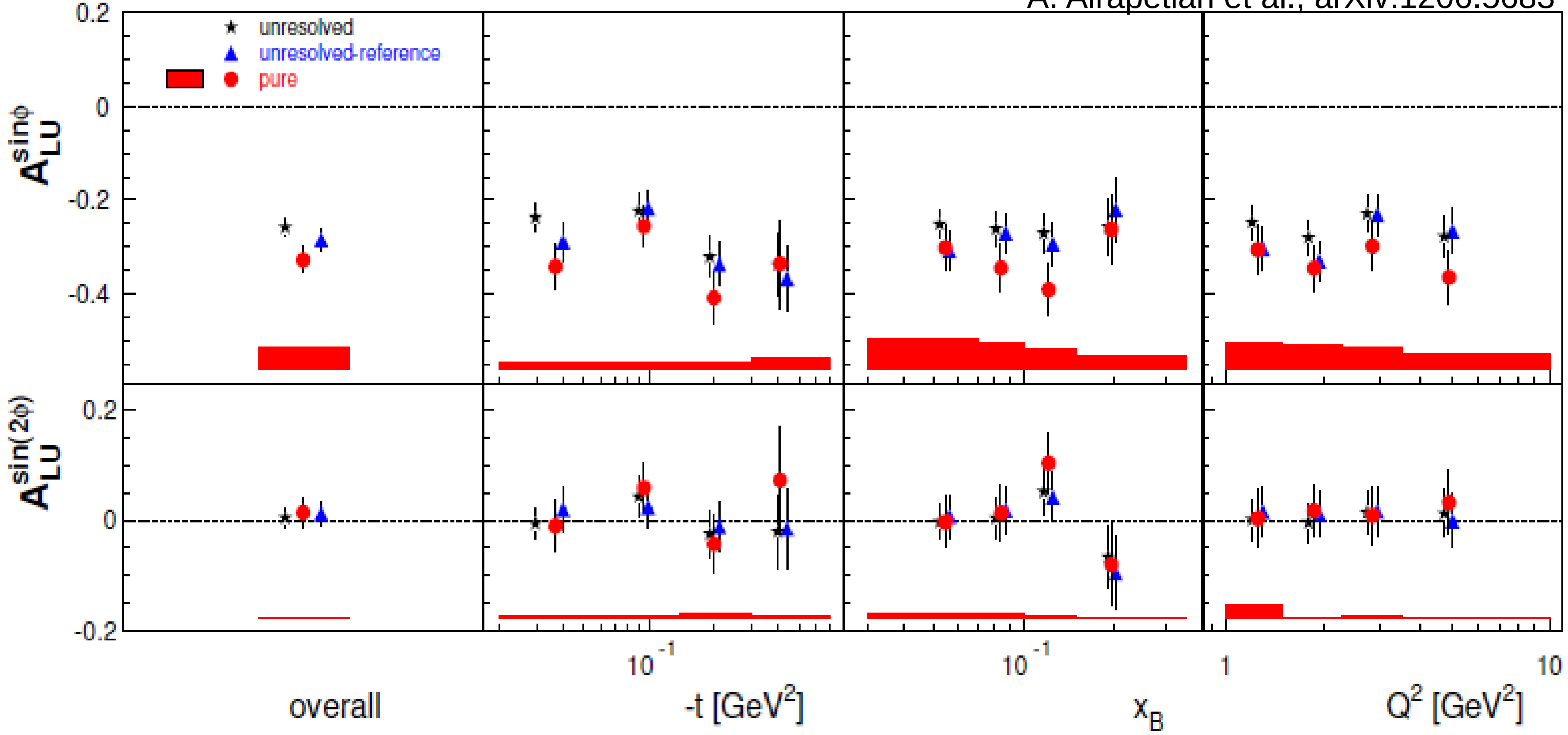






Beam-helicity asymmetry

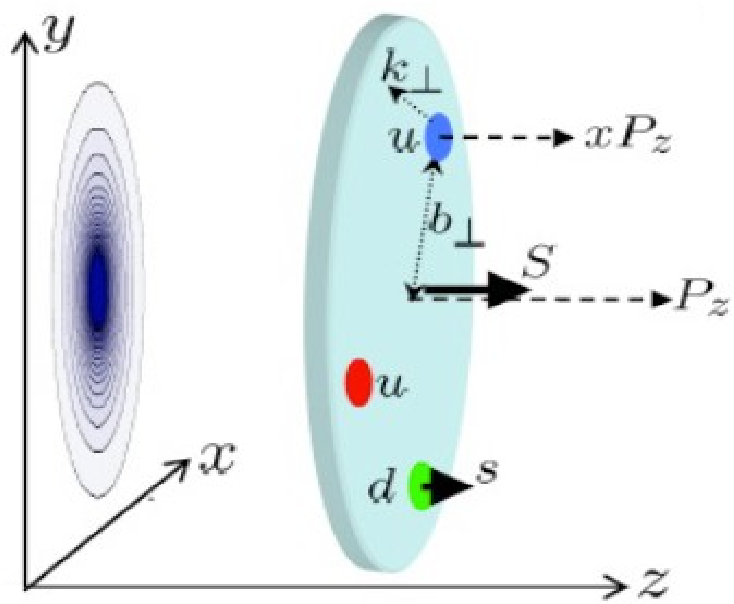
A. Airapetian et al., arXiv:1206.5683



- additional 1.96 % scale uncertainty from beam polarization

Generalized parton distributions

$$\int d^2\vec{k}_T\, W(x,\vec{k}_T,\vec{b_\perp}) = \text{GPDs}\ (x,\xi,t)$$



$$W(x, \vec{k}_T, \vec{b_\perp})$$

Generalized parton distributions

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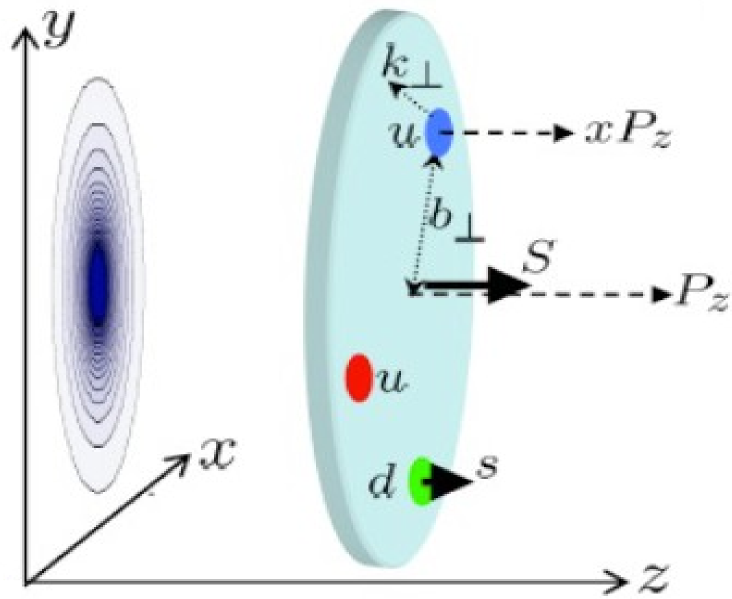


$$W(x, \vec{k}_T, \vec{b_\perp})$$

Generalized parton distributions

$$\int d^2\vec{k}_T\, W(x, \vec{k}_T, \vec{b_\perp}) = \text{GPDs } (x, \xi, t)$$

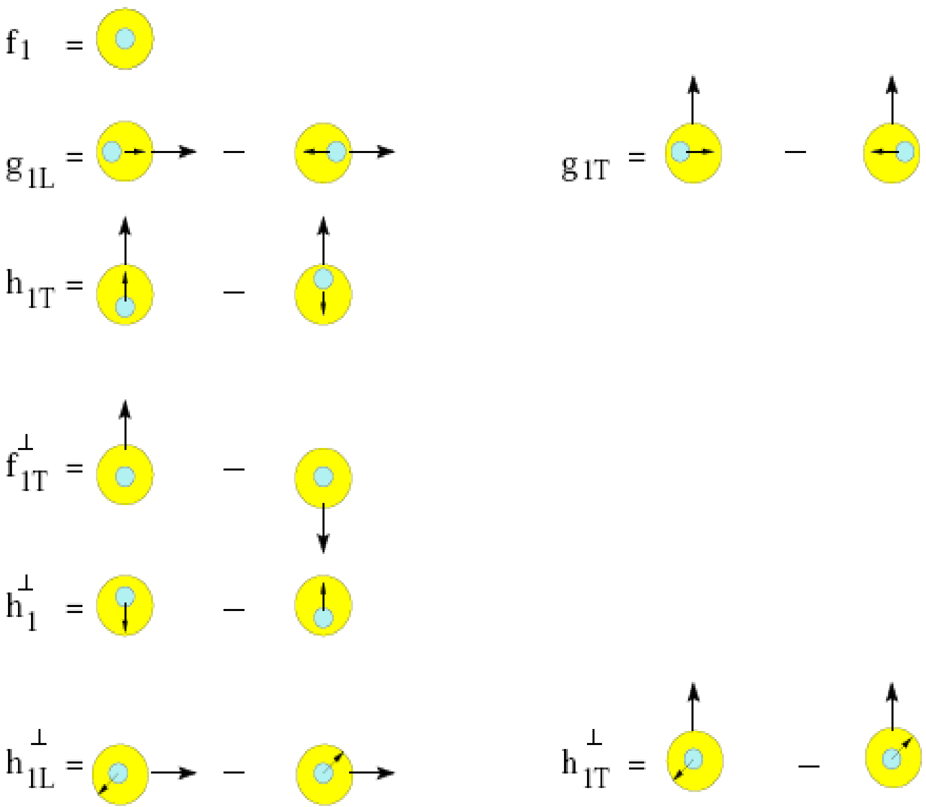
Transverse-momentum-dependent parton distribution functions

$$\int d^2\vec{b_\perp}\, W(x, \vec{k}_T, \vec{b_\perp}) = \text{TMD PDFs } (x, \vec{k}_T)$$

Transverse momentum dependent distributions (TMDs)

Distribution functions

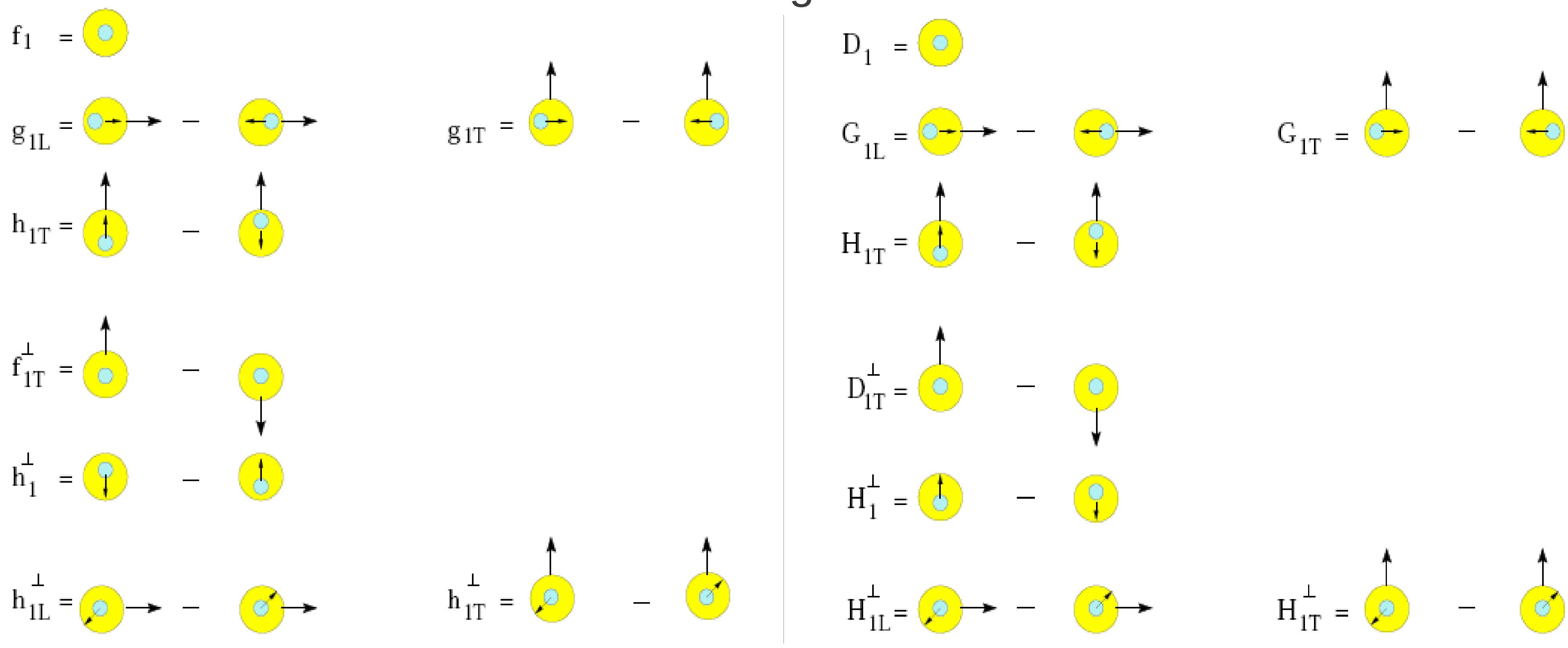
leading twist



Transverse momentum dependent distributions (TMDs)

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

Distribution functions | leading twist | Fragmentation functions



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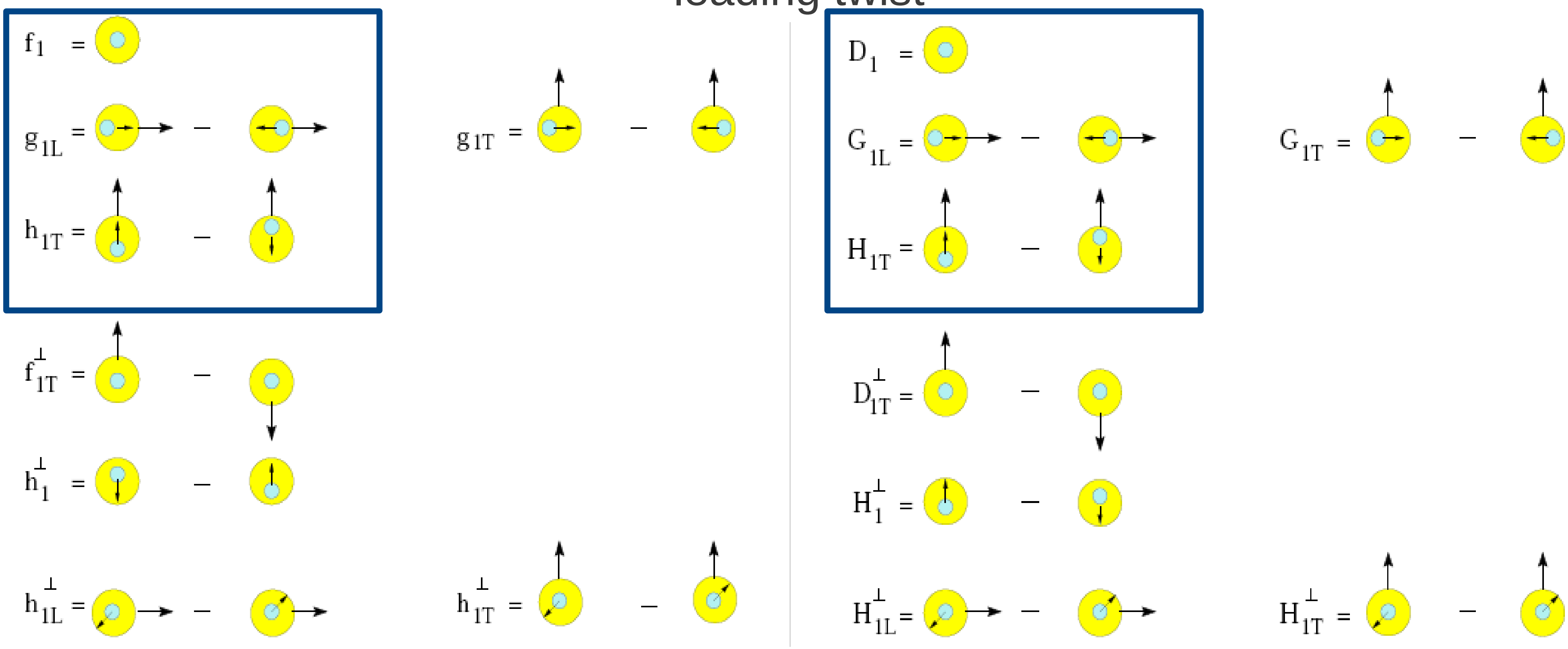
<u>Distribution functions</u>   leading twist   <u>Fragmentation functions</u>



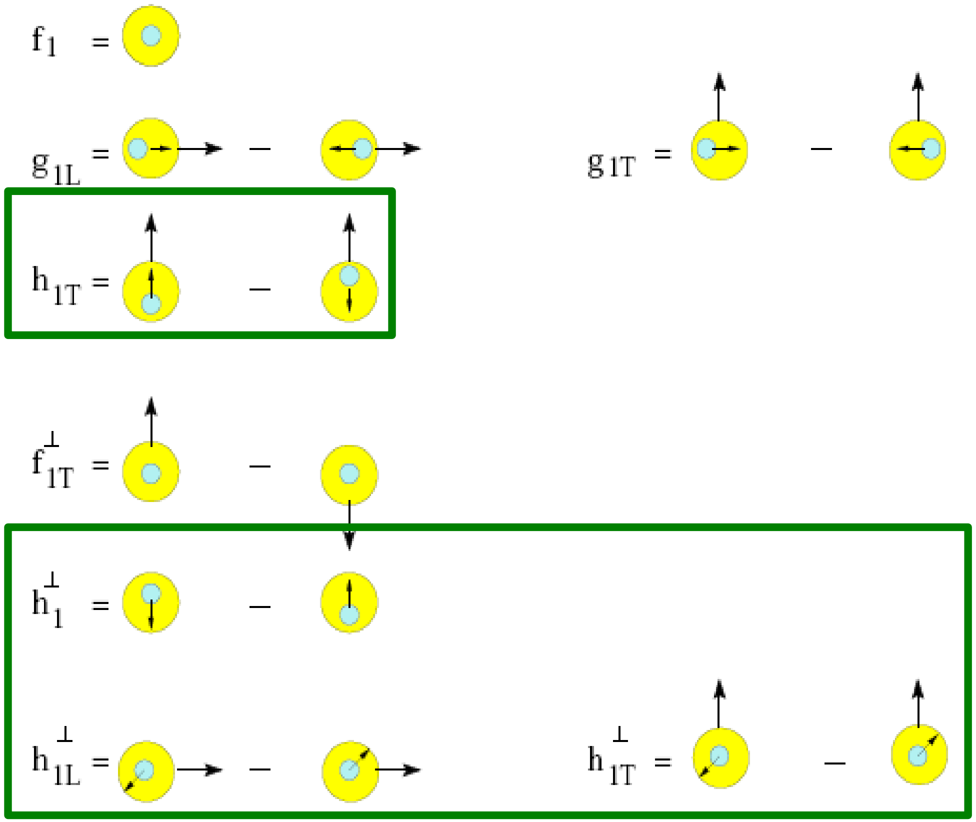
only distributions that survive integration over transverse momentum

Transverse momentum dependent distributions (TMDs)

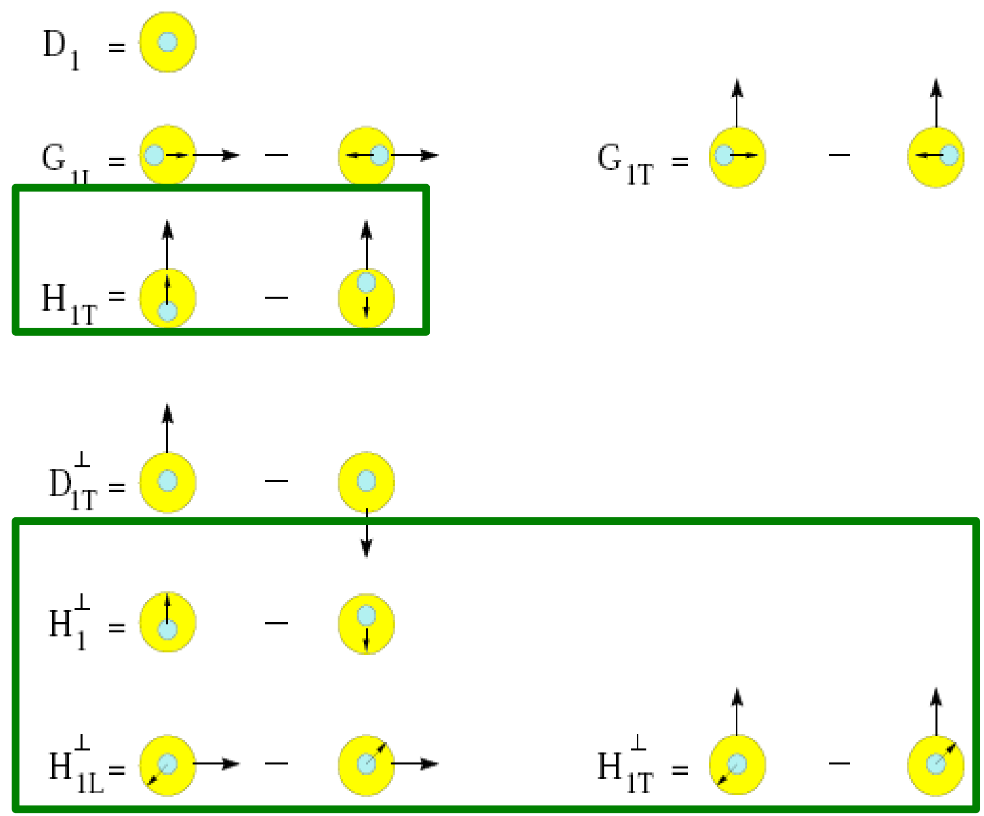
$$\sigma^{ep\to eh} = \sum_q \mathcal{I}[DF^{p\to q}(x,k_T^2)\,\sigma^{eq\to eq}\,FF^{q\to h}(z,p_T^2)]$$

leading twist

Distribution functions



Fragmentation functions



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

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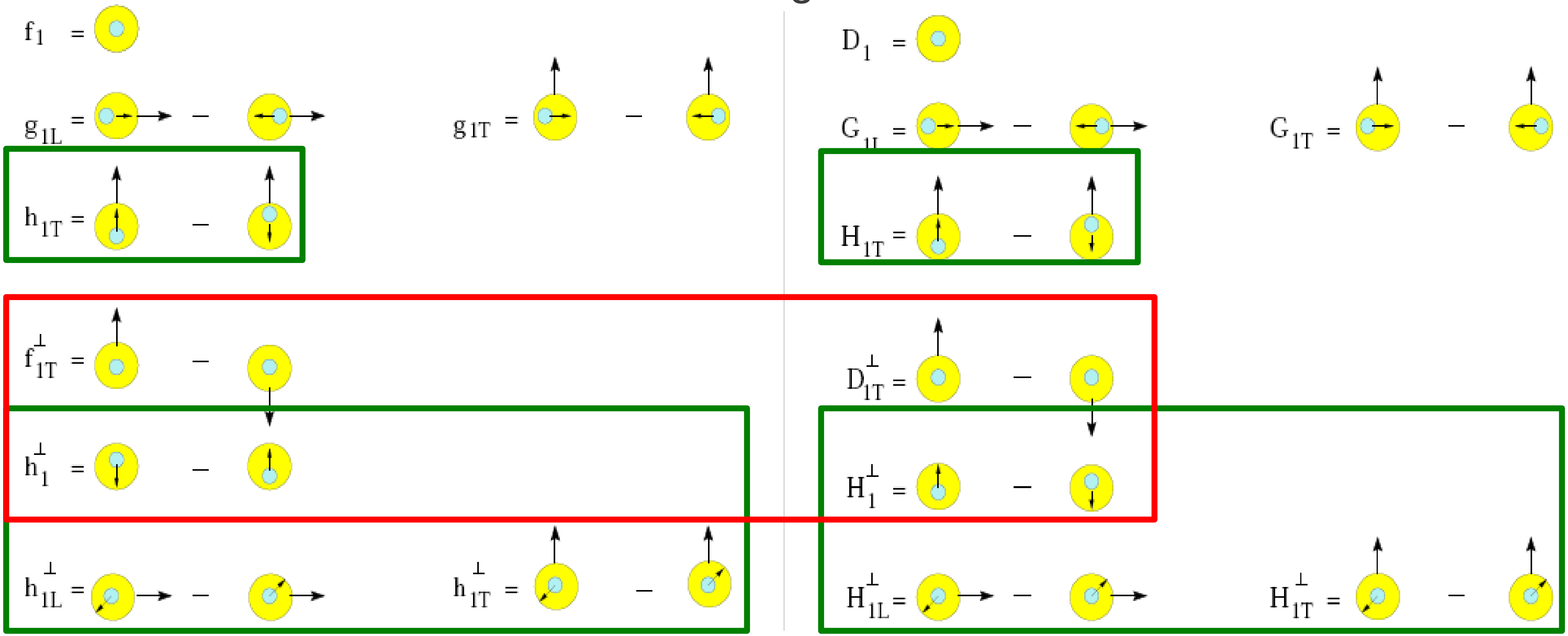
$$\sigma^{ep\to eh} = \sum_q \mathcal{I}[DF^{p\to q}(x,k_T^2)\,\sigma^{eq\to eq}\,FF^{q\to h}(z,p_T^2)]$$

Distribution functions | leading twist | Fragmentation functions



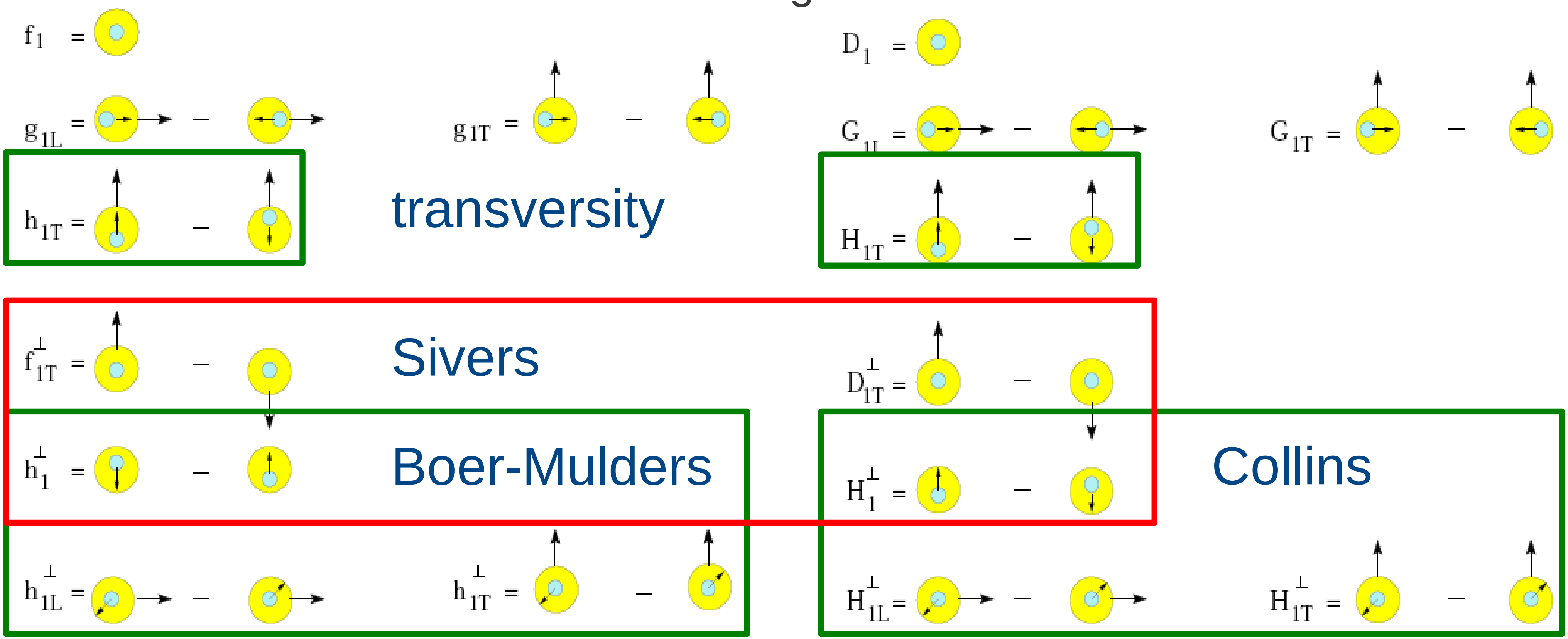
Chiral odd: involve helicity flip of transversally polarized quark
appear in pairs in cross section

T-odd: appear in pairs in spin-independent x-section & double-spin asymmetries
single in single-spin asymmetries

Transverse momentum dependent distributions (TMDs)

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

Distribution functions | leading twist | Fragmentation functions



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
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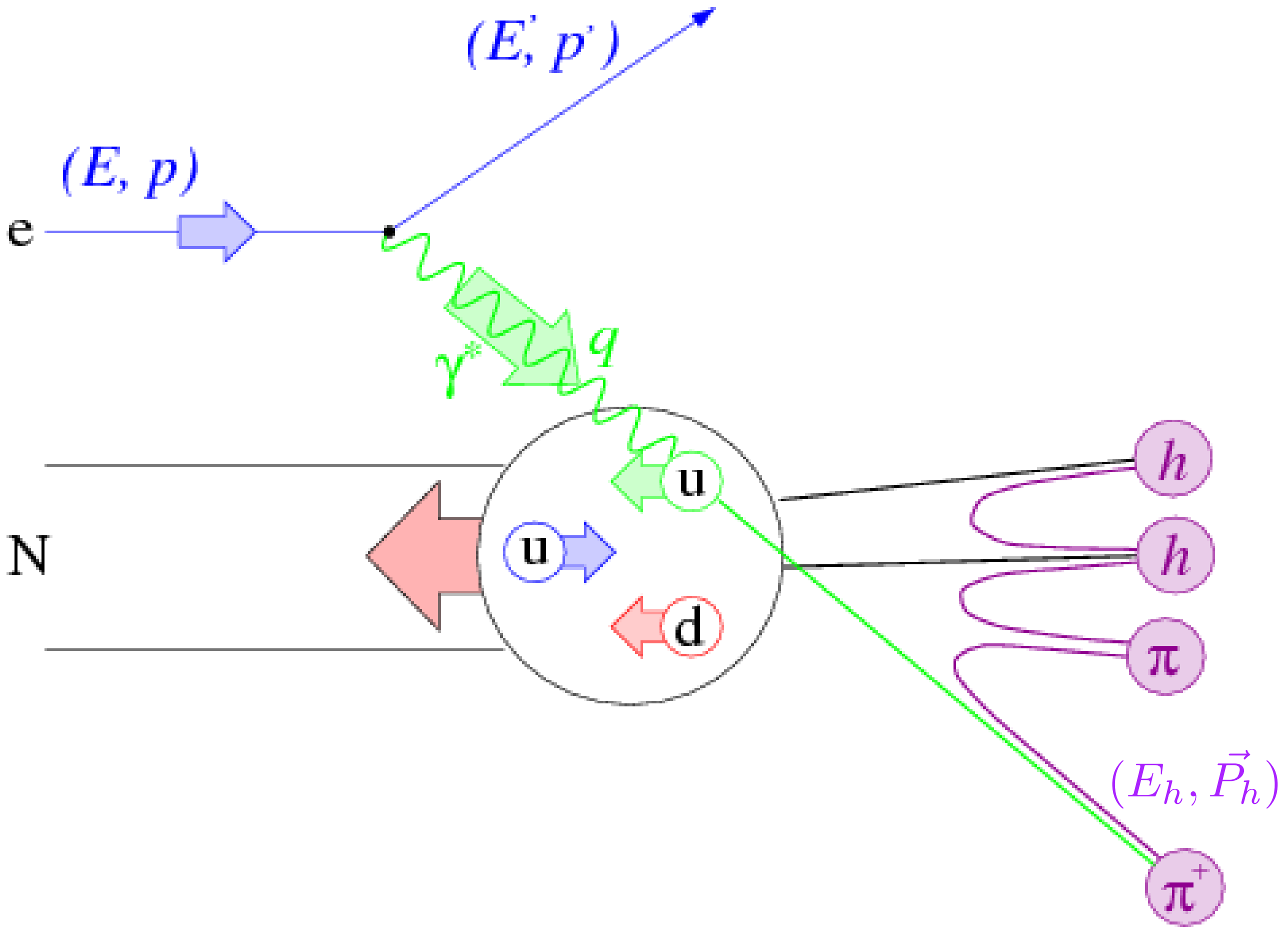
Semi-inclusive deep-inelastic scattering



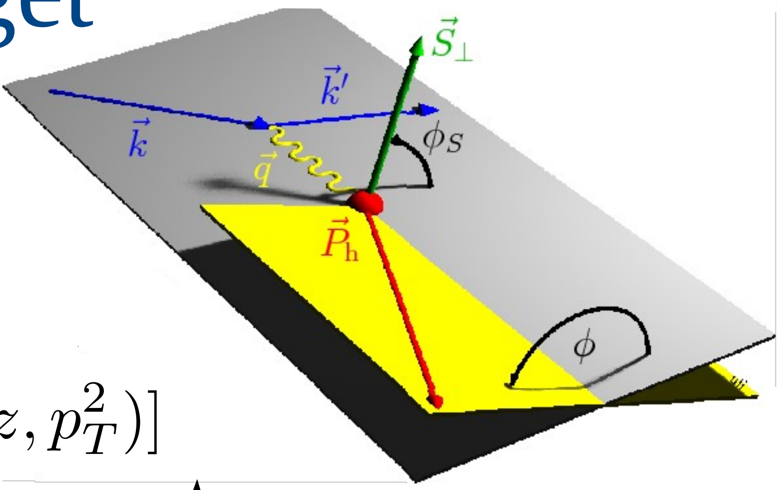
$$Q^2 = -q^2$$

$$y \overset{lab}{=} \frac{\nu}{E}$$

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

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

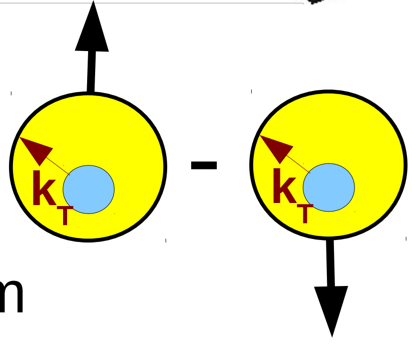
Single-spin asymmetry on transversely polarized target



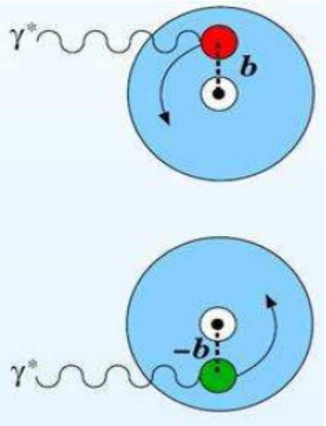
$$A_{UT} = \frac{1}{\langle|S_T|\rangle} \frac{N^{\uparrow}(\phi,\phi_S) - N^{\downarrow}(\phi,\phi_S)}{N^{\uparrow}(\phi,\phi_S) + N^{\downarrow}(\phi,\phi_S)}$$

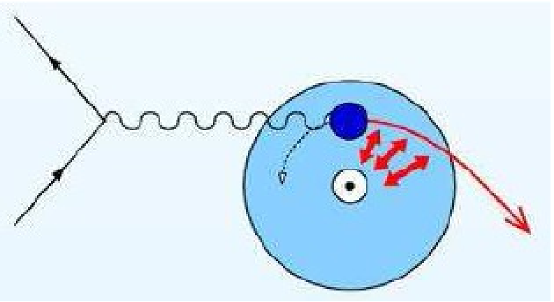
$$\sim \sin(\phi - \phi_S) \sum_q e_q \mathcal{I}[\frac{\vec{k}_T.\hat{P}_{h\perp}}{M_h} f_{1T}^{\perp,q}(x,k_T^2) D_1^q(z,p_T^2)]$$

$f_{1T}^{\perp,q}(x,k_T^2)$: Sivers distribution function



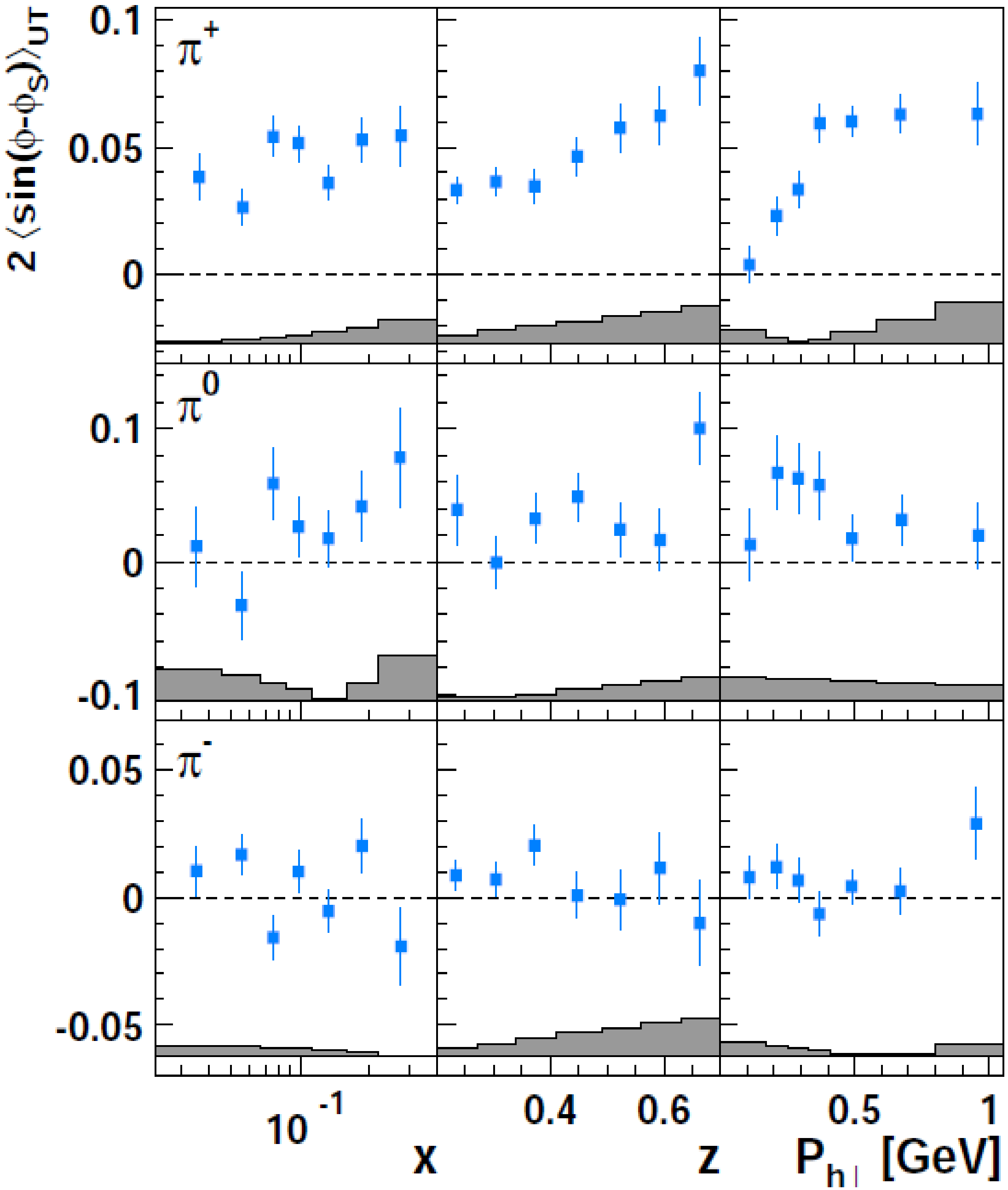
- requires non-zero quark orbital angular momentum
- naïve-T-odd
- FSI ⟶ left-right (azimuthal) asymmetry in direction of outgoing hadron





Sivers amplitudes for pions

A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002



- π^+
  - significantly positive
    → non-zero orbital angular momentum!
  - clear rise with z
  - rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
  - amplitude dominated by u-quark scattering:

$$\approx -\frac{\mathcal{I}[f_{1T}^{\perp,u}(x,k_T^2)D_1^{u\to\pi^+}(z,p_T^2)]}{\mathcal{I}[f_1^u(x,k_T^2)D_1^{u\to\pi^+}(z,p_T^2)]}$$

→ $f_{1T}^{\perp,u}(x,k_T^2) < 0$

- π^-
  - consistent with zero
  - u- and d- quark cancellation
  - $f_{1T}^{\perp,d}(x,k_T^2) > 0$
- π^0
  - slightly positive
  - isospin symmetry fulfilled

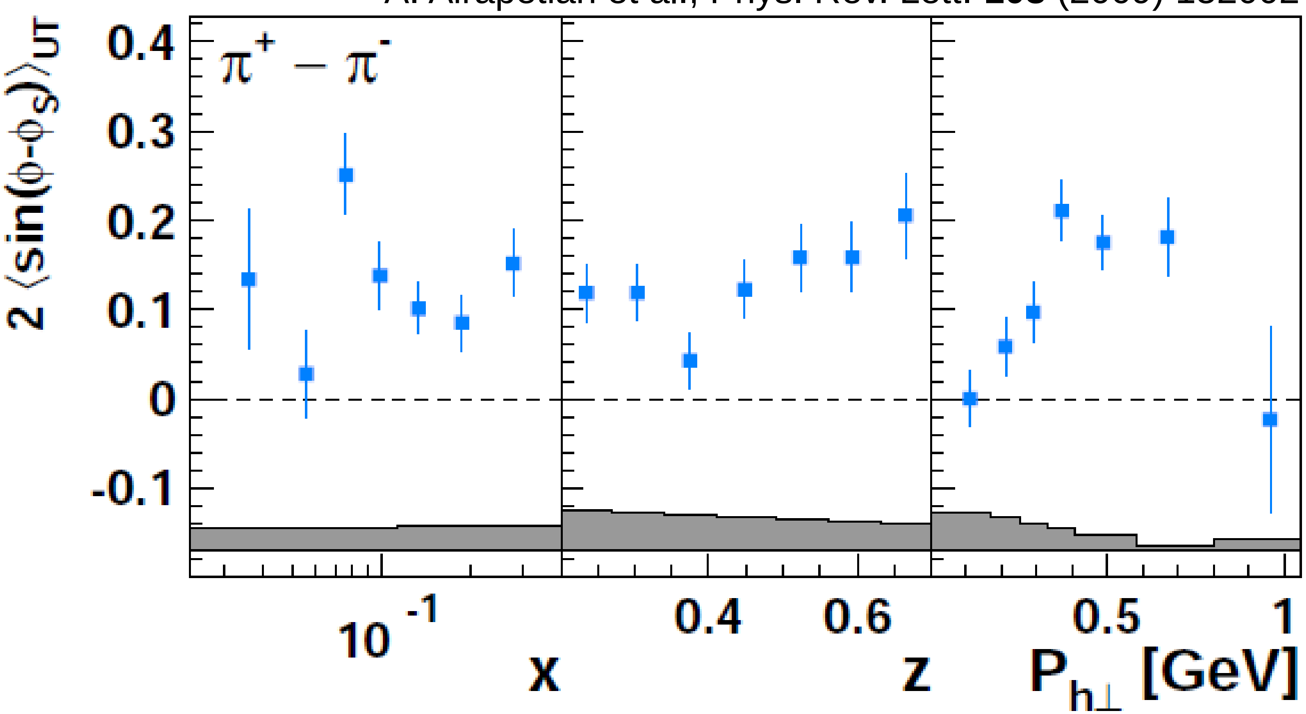
Sivers distribution for valence quarks

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

→ suppressed exclusive VM (ρ^0) contribution

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

A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002

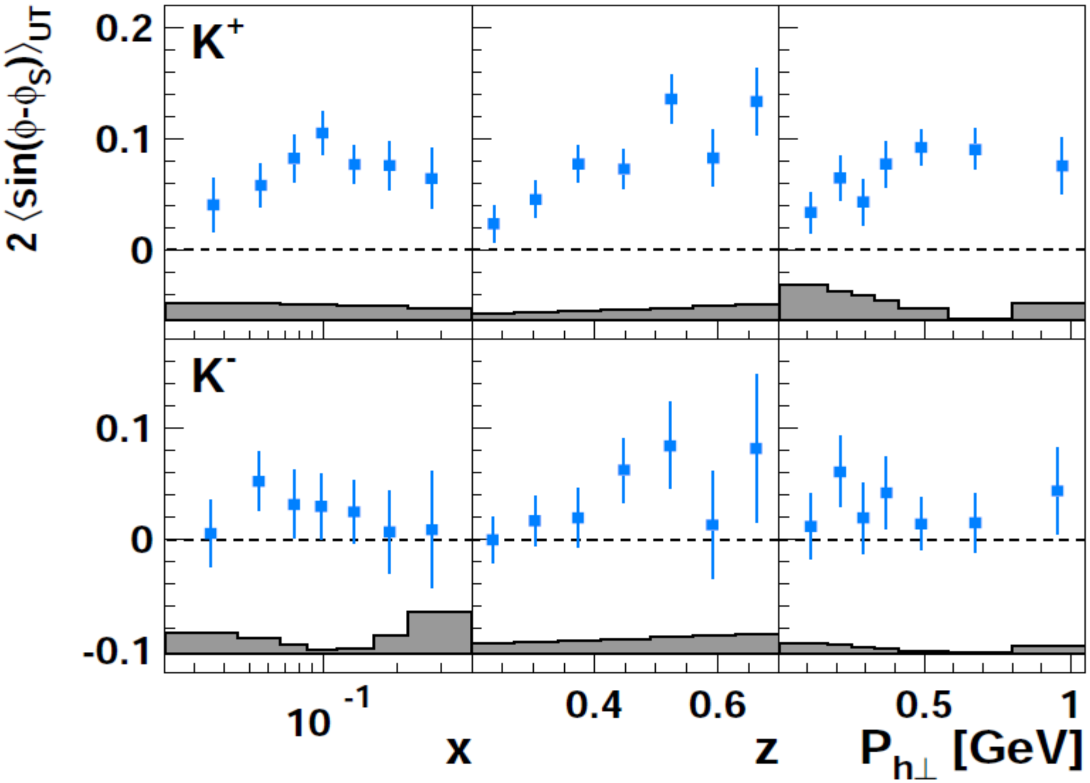


- Sivers distribution for d-valence >> u-valence

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

Sivers amplitudes for kaons

A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002

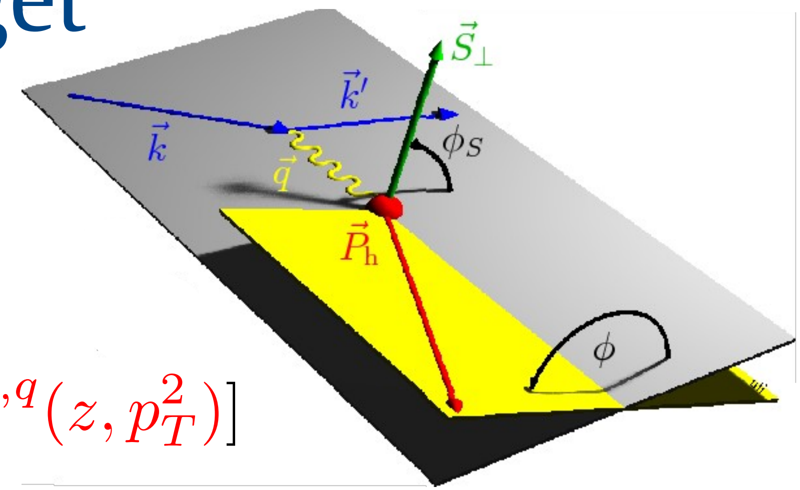


- K^+
  - significantly positive
  - clear rise with z
  - rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
  - larger than π^+

non-trivial role of sea quarks?

- K^-
  - slightly positive

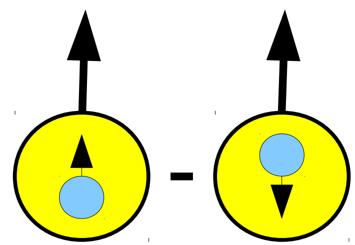
Single-spin asymmetry on transversely polarize target



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

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

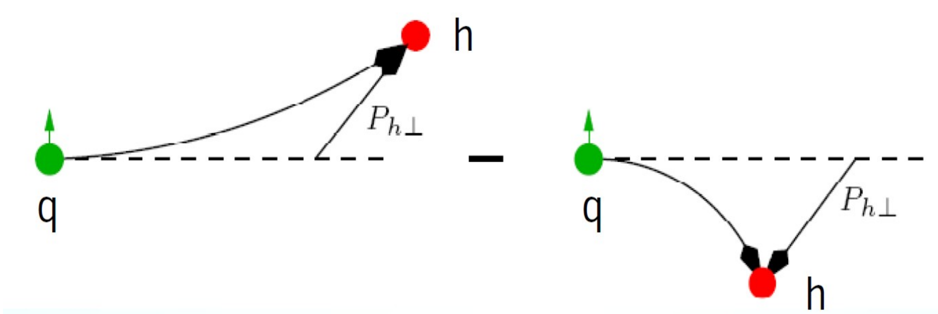
$h_{1T}^q(x, k_T^2)$: transversity



- chiral odd

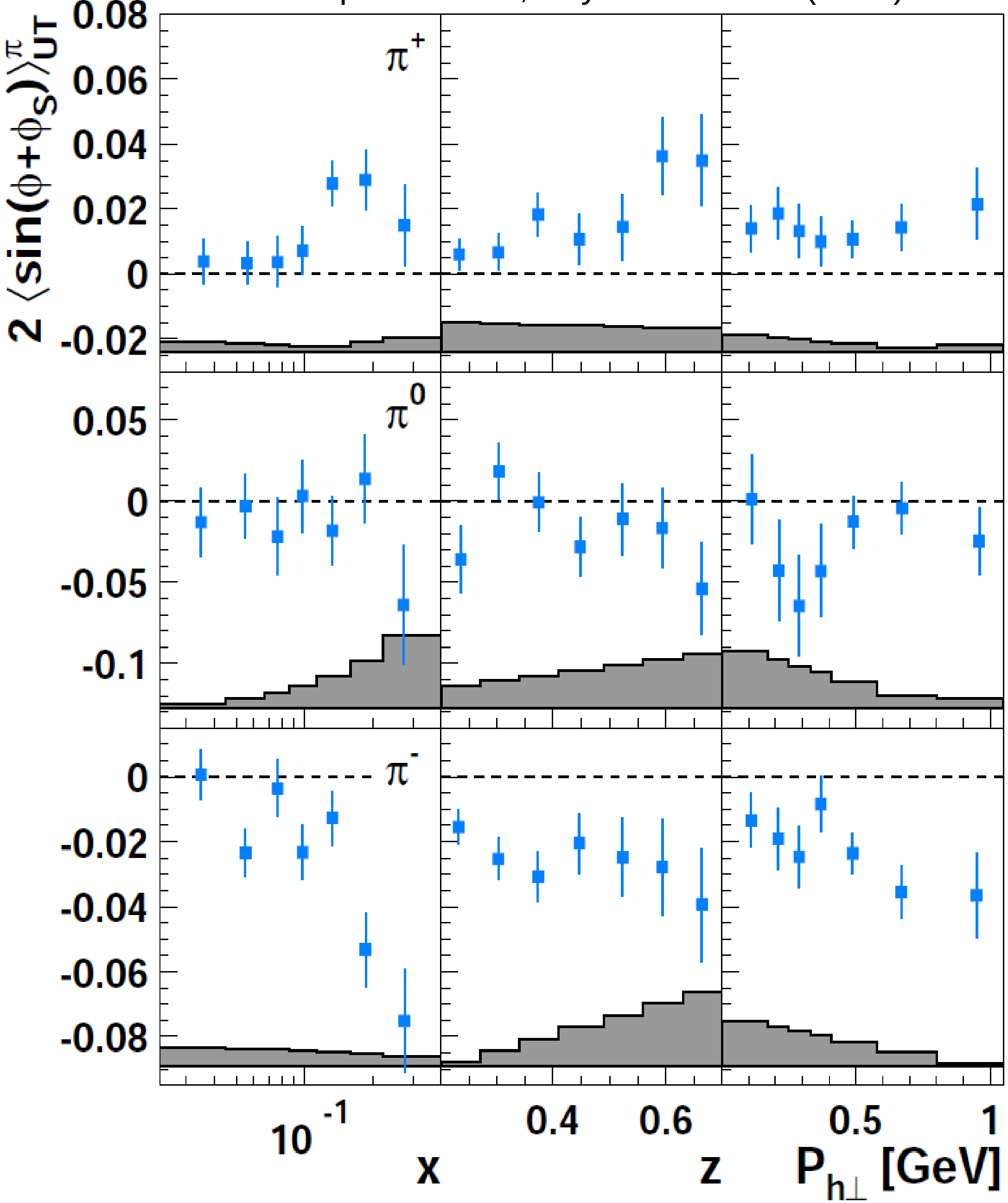
$H_1^{\perp,q}(z, p_T^2)$: Collins fragmentation function

- chiral odd
- naïve-T-odd



Collins amplitudes for pions

A. Airapetian et al., Phys. Lett. B**693** (2010) 11-16



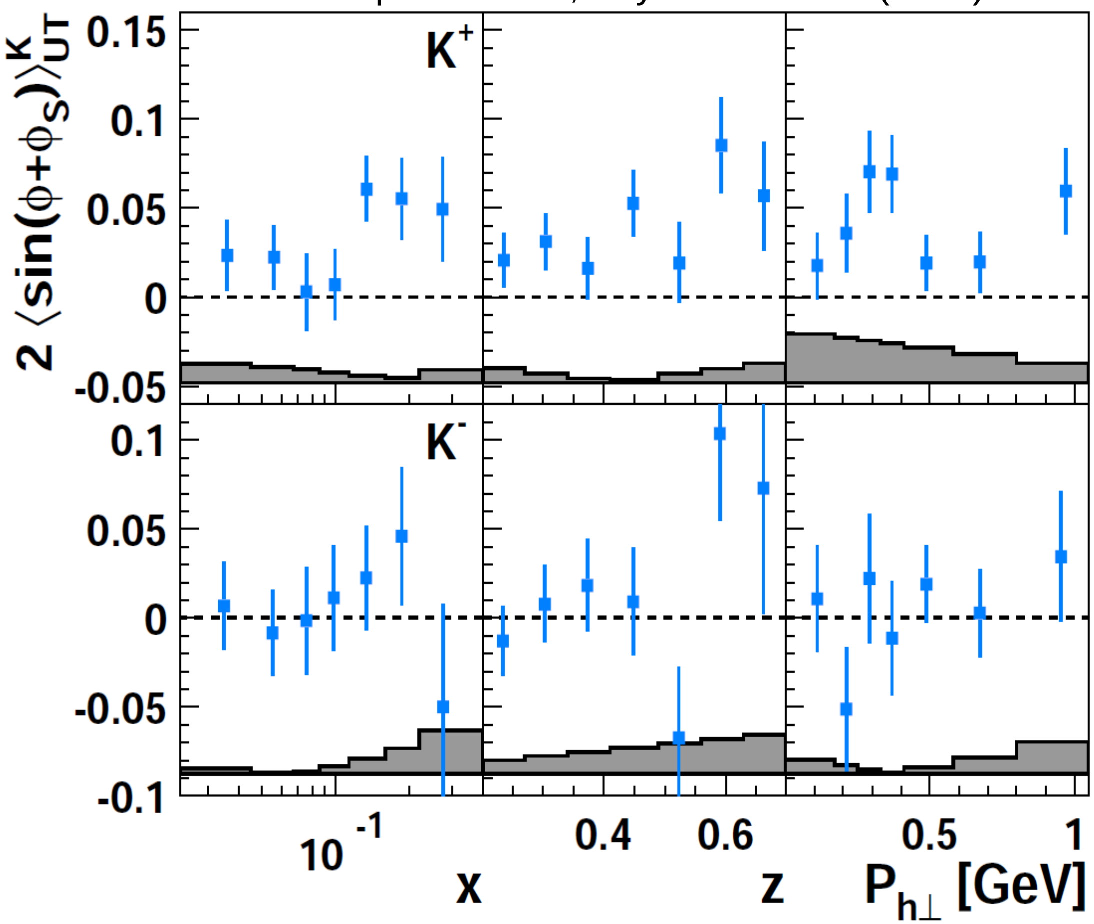
- $\pi^{\pm}$ increasing with z and x_B
- positive for π^+
- large & negative for π^-

$$H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$$

- isospin symmetry fulfilled

Collins amplitudes for kaons

A. Airapetian et al., Phys. Lett. B**693** (2010) 11-16

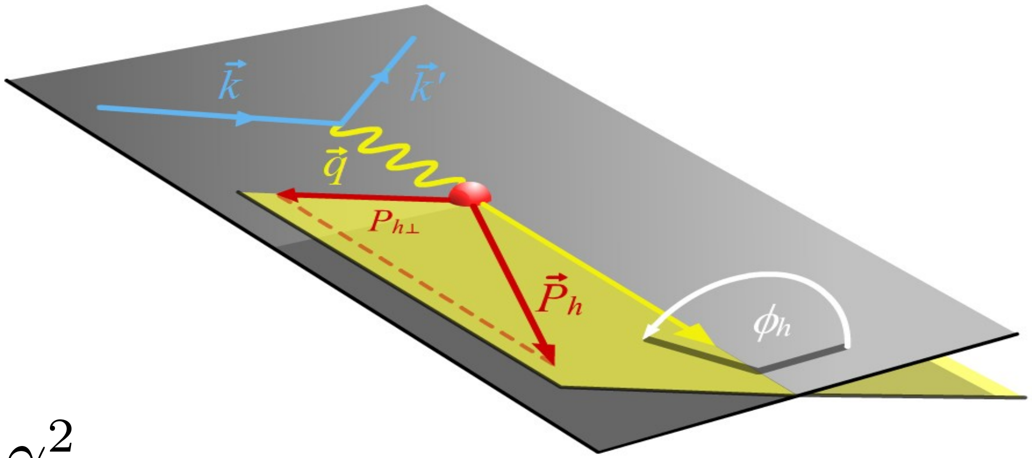


- K^+: increasing with z and x_B
- positive for K^+ & larger than for π^+
  - role of s-quark
  - u-dominance $\xrightarrow{?}$

$$H_1^{\perp,u\to K^+} > H_1^{\perp,u\to\pi^+}$$

- $K^- \approx 0$, ≠ from π^-
  K^- is pure sea object:
  sea-quark transversity expected to be small

Spin-independent semi-inclusive DIS cross section



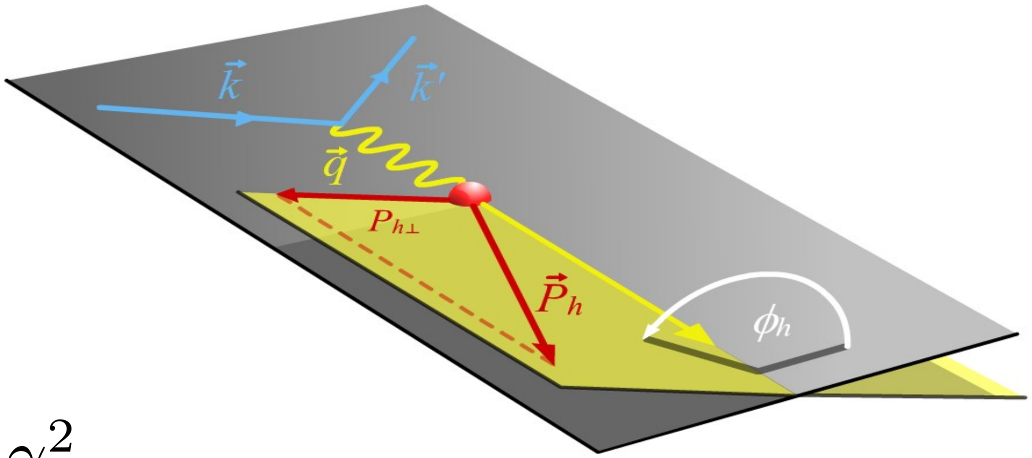
non-collinear cross section

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

$$+C(y)\cos\phi_h F_{UU}^{\cos\phi_h} + B(y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\}$$

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

Spin-independent semi-inclusive DIS cross section



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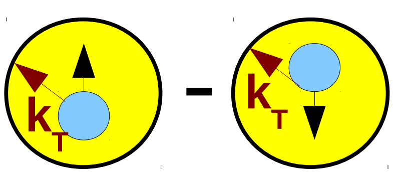
$$\gamma = \frac{2Mx}{Q},\quad F = F(x, Q, z, \vec{P}_{h\perp})$$

leading twist

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



Boer-Mulders DF

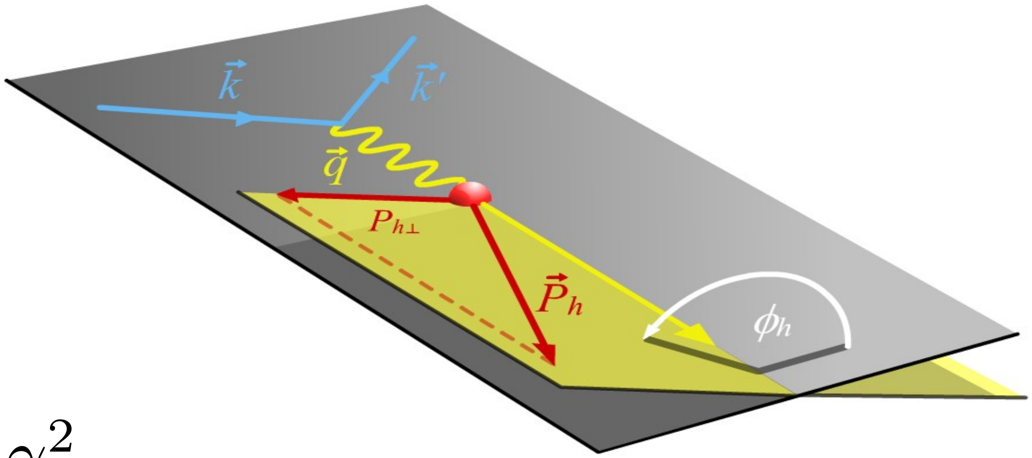
- chiral odd
- naïve-T-odd

↔

Collins FF

- chiral odd
- naïve-T-odd

Spin-independent semi-inclusive DIS cross section



non-collinear cross section

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

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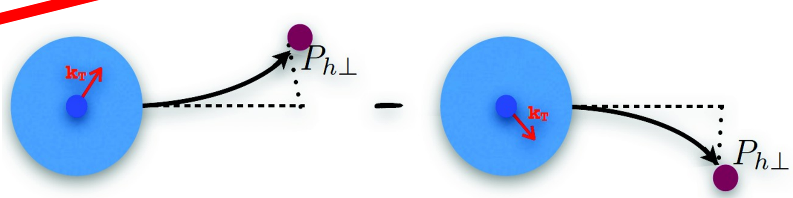
$$\gamma = \frac{2Mx}{Q},\quad F = F(x, Q, z, \vec{P_{h\perp}})$$

sub-leading twist

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

Cahn effect



quark-gluon-quark correlations

Extraction of the cosine moments

$$\langle \cos(n\phi_h) \rangle \stackrel{th.}{=} \frac{\int d\phi_h \cos(n\phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \sigma_{UU}(\omega, \phi_h)}$$

$$\omega = (x, y, z, P_{h\perp}^2)$$

↕

$$\langle \cos(n\phi_h) \rangle \stackrel{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h) \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}$$

extraction is challenging!

azimuthal modulations also possible due to

- detector geometrical acceptance
- higher-order QED effects

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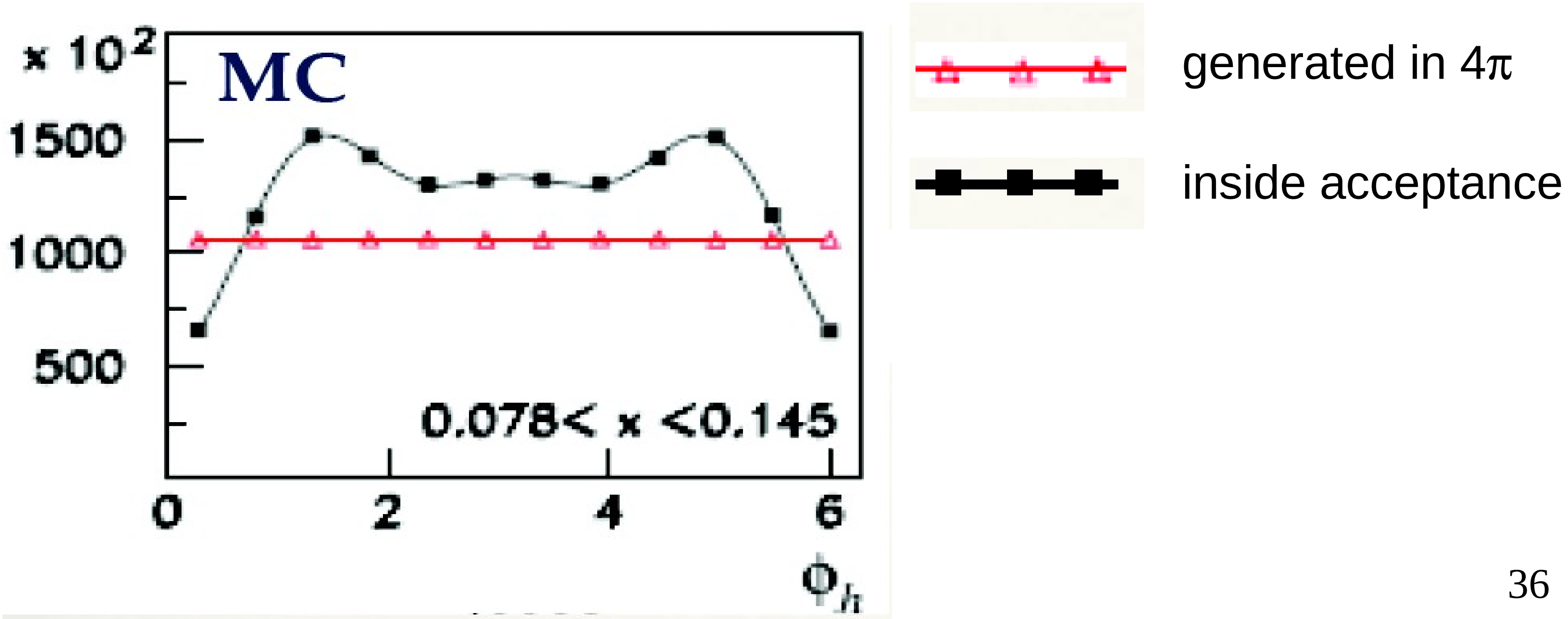

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fully differential analysis needed

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

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$$\langle \cos(n\phi_h) \rangle \overset{th.}{=} \frac{\int d\phi_h \cos(n\phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \sigma_{UU}(\omega, \phi_h)}$$

$$\omega = (x, y, z, P^2_{h\perp})$$

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extraction is challenging!
azimuthal modulations also possible due to
- detector geometrical acceptance
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unfolding

fully differential analysis needed
unfolding procedure with 400 x 12 bins

$$\langle \cos(n\phi_h) \rangle \Big|_{\text{bin i}} \approx \frac{\int d\phi_h \cos(n\phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \sigma_{UU}(\omega, \phi_h)} \Bigg|_{\text{bin i}}$$

BINNING
400 kinematic bins x 12 ϕ-bins

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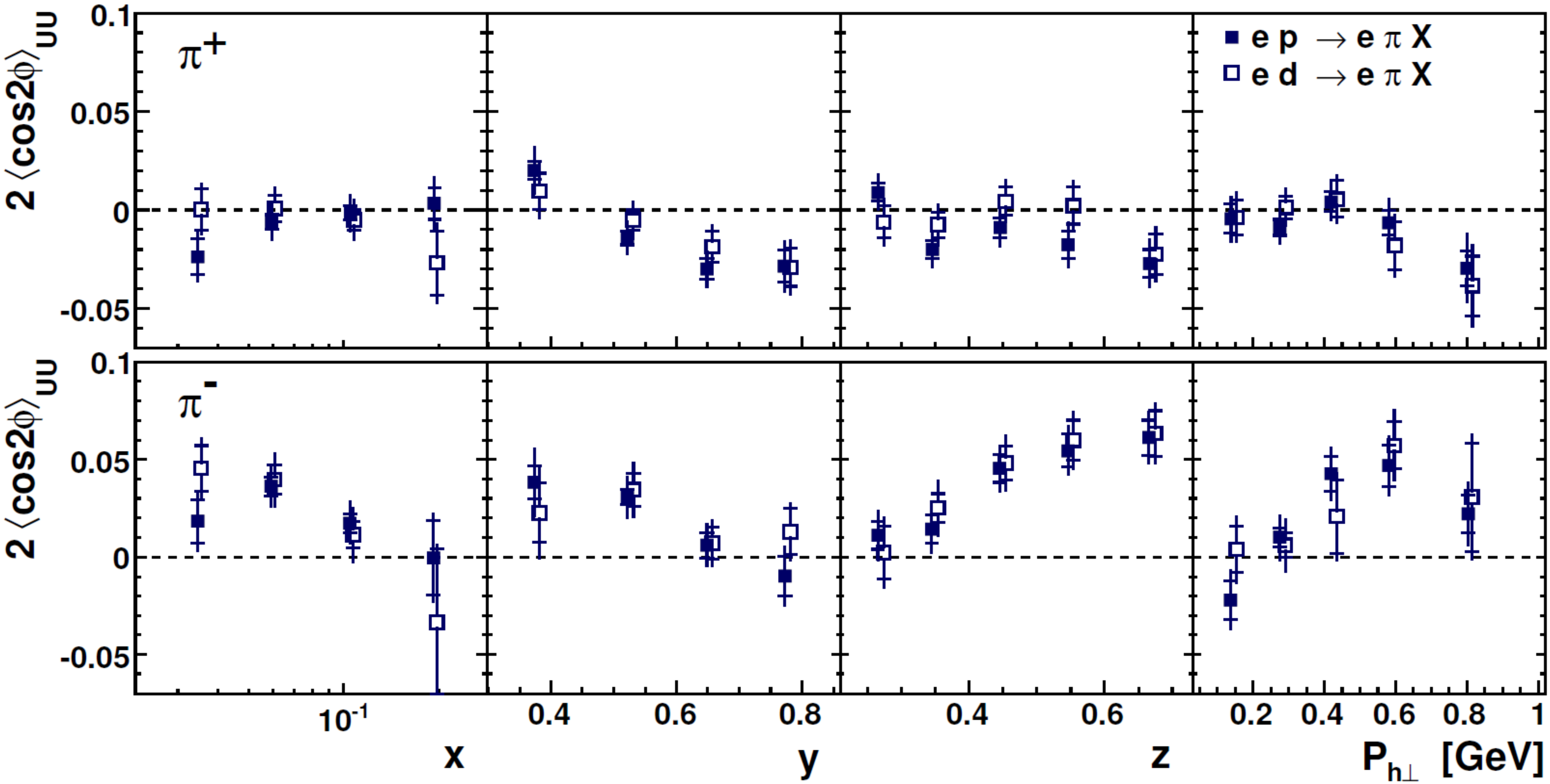
Results for <cos 2ϕ_h>: pions

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

A. Airapetian et al., arXiv:1204.4161



- H-D comparison: $h_1^{\perp,u} \approx h_1^{\perp,d}$
- π^- > 0 ◄──► $\pi^+ \leqslant$ 0: $H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$

Results for <cos 2ϕ_h>: kaons

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

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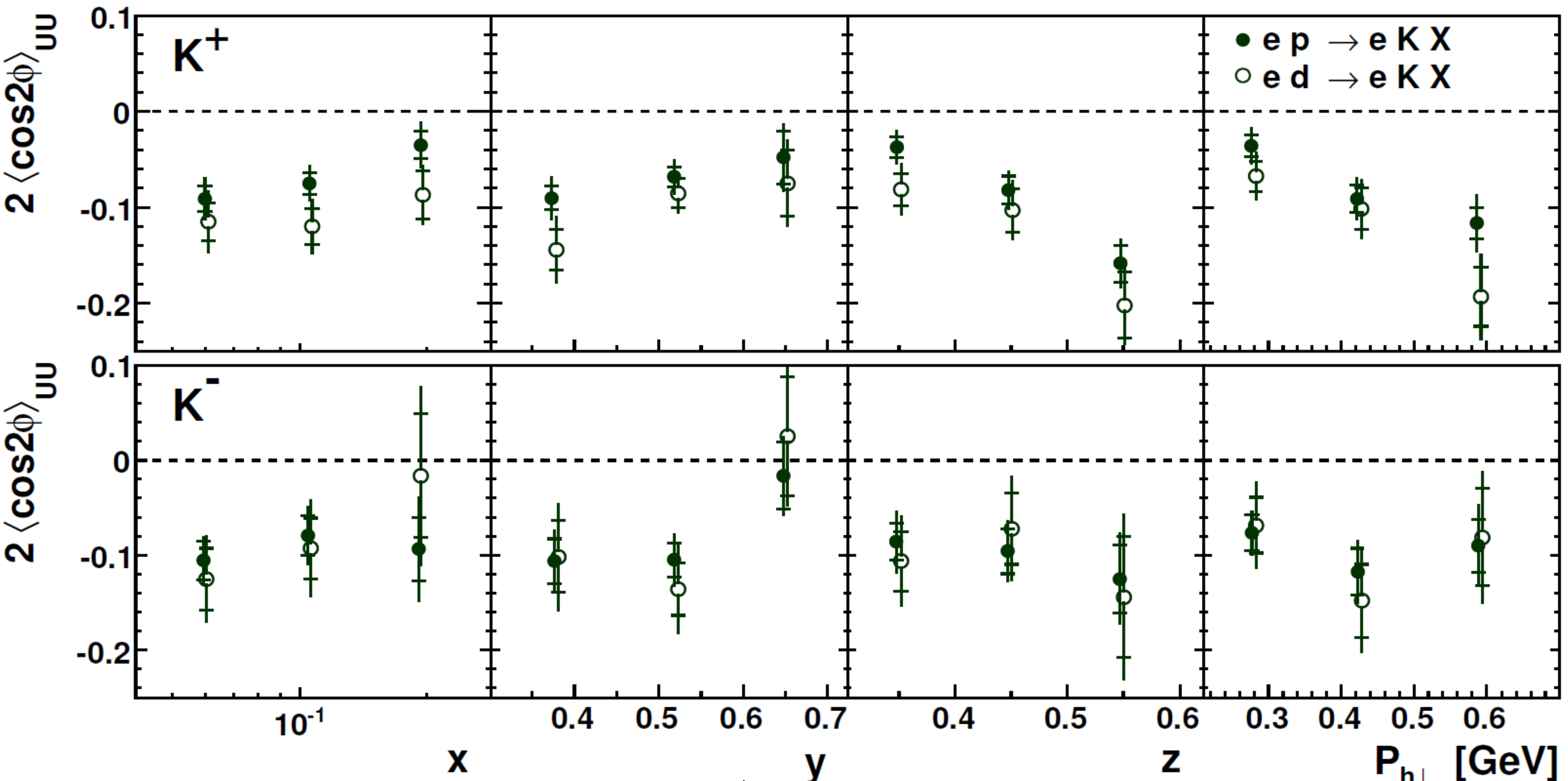
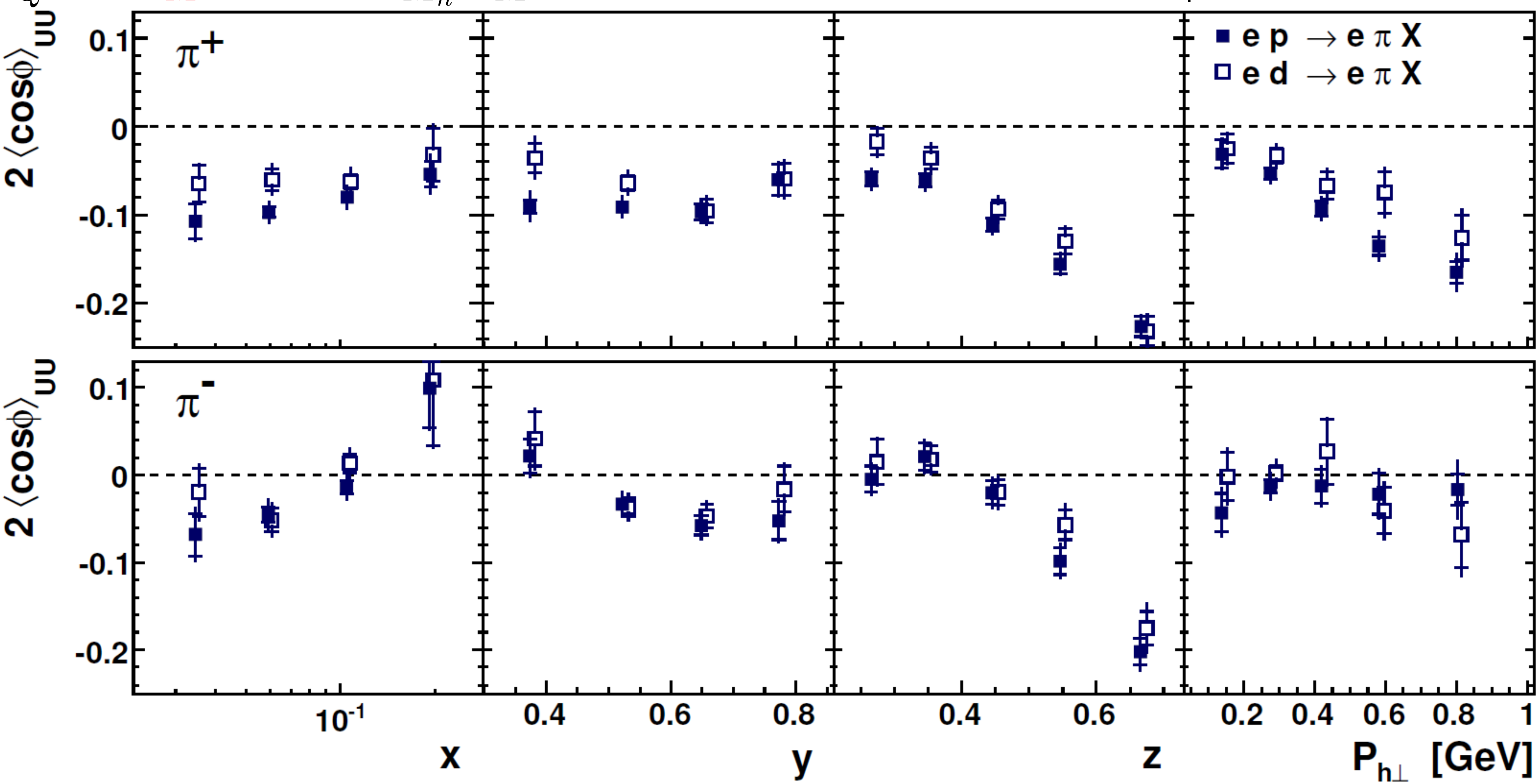


- $K^+<0$: - Artru model: sign $H_1^{\perp,u\to K^+}$ = sign $H_1^{\perp,u\to\pi^+}$
- $K^- \simeq K^+$: - u-dominance $\xrightarrow{?}$ $H_1^{\perp,u\to K^+} \approx H_1^{\perp,u\to K^-}$
  - role of sea-quarks

Results for <cos ϕ_h>: pions

$$\frac{2M}{Q}\mathcal{I}[-\frac{\hat{P}_{h\perp}.\vec{k}_T}{M}f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{p}_T}{M_h}\frac{k_T^2}{M^2}h_1^{\perp}H_1^{\perp} + ...]$$

A. Airapetian et al., arXiv:1204.4161

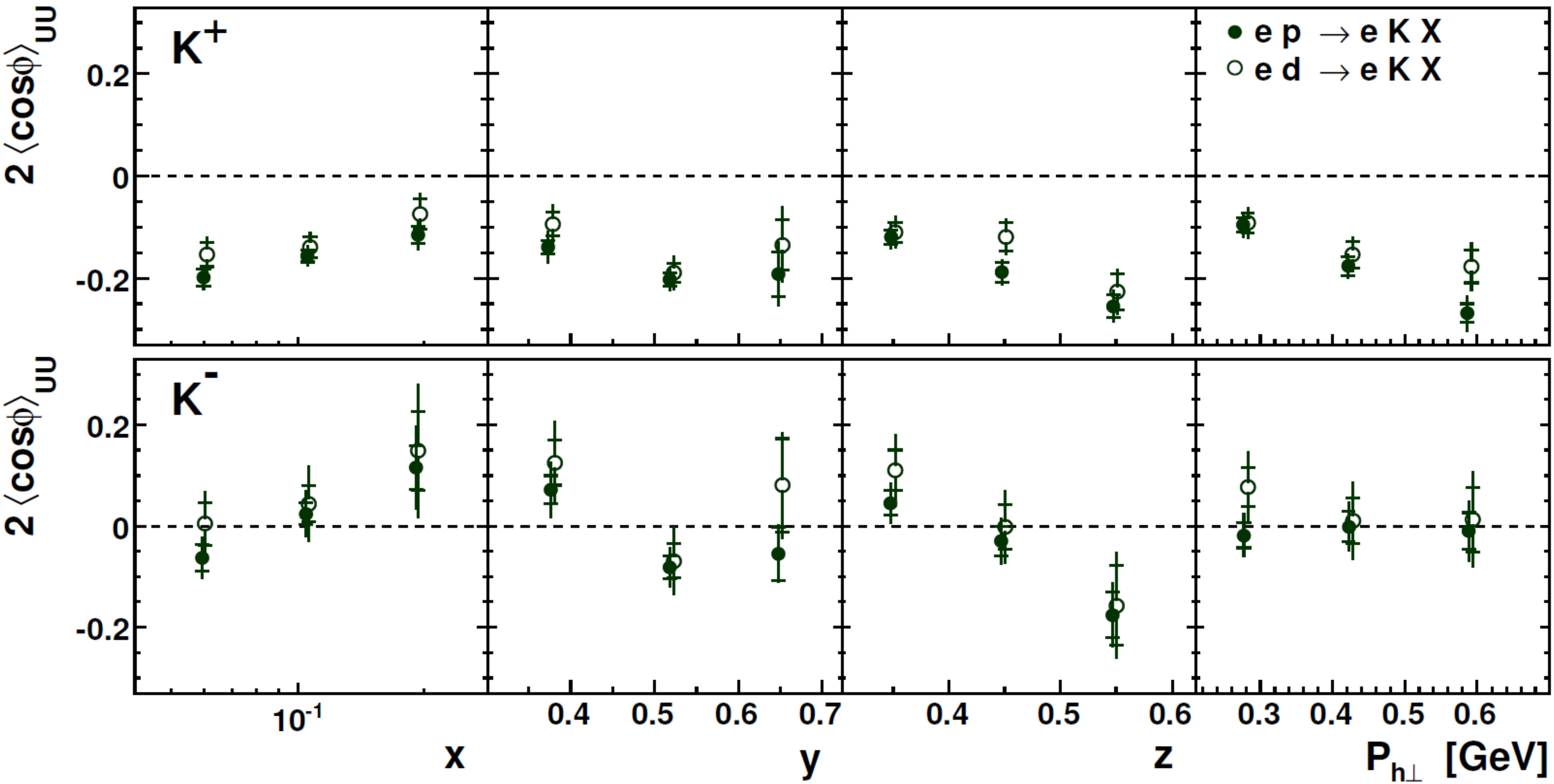


- H-D comparison: weak flavor dependence
- magnitude increases with z
- π^+: magnitude increases with $P_{h\perp}$

Results for <cos ϕ_h>: kaons

$$\frac{2M}{Q}\mathcal{I}[-\frac{\hat{P}_{h\perp}.\vec{k}_T}{M}f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{p}_T}{M_h}\frac{k_T^2}{M^2}h_1^{\perp}H_1^{\perp} + ...]$$

A. Airapetian et al., arXiv:1204.4161



- $K^+<0$, larger in magnitude than π^+
- $K^- \simeq 0$

Summary

- DVCS beam-helicity asymmetries:

  - complete data set: large increase in statistics

  - complete event reconstruction: negligible background

- significant Sivers amplitudes for π^+ and K^+ (role of sea quarks)

  non-zero orbital angular momentum

- significant Collins amplitudes for $\pi^\pm$ and K^+

  access to transversity and Collins fragmentation function

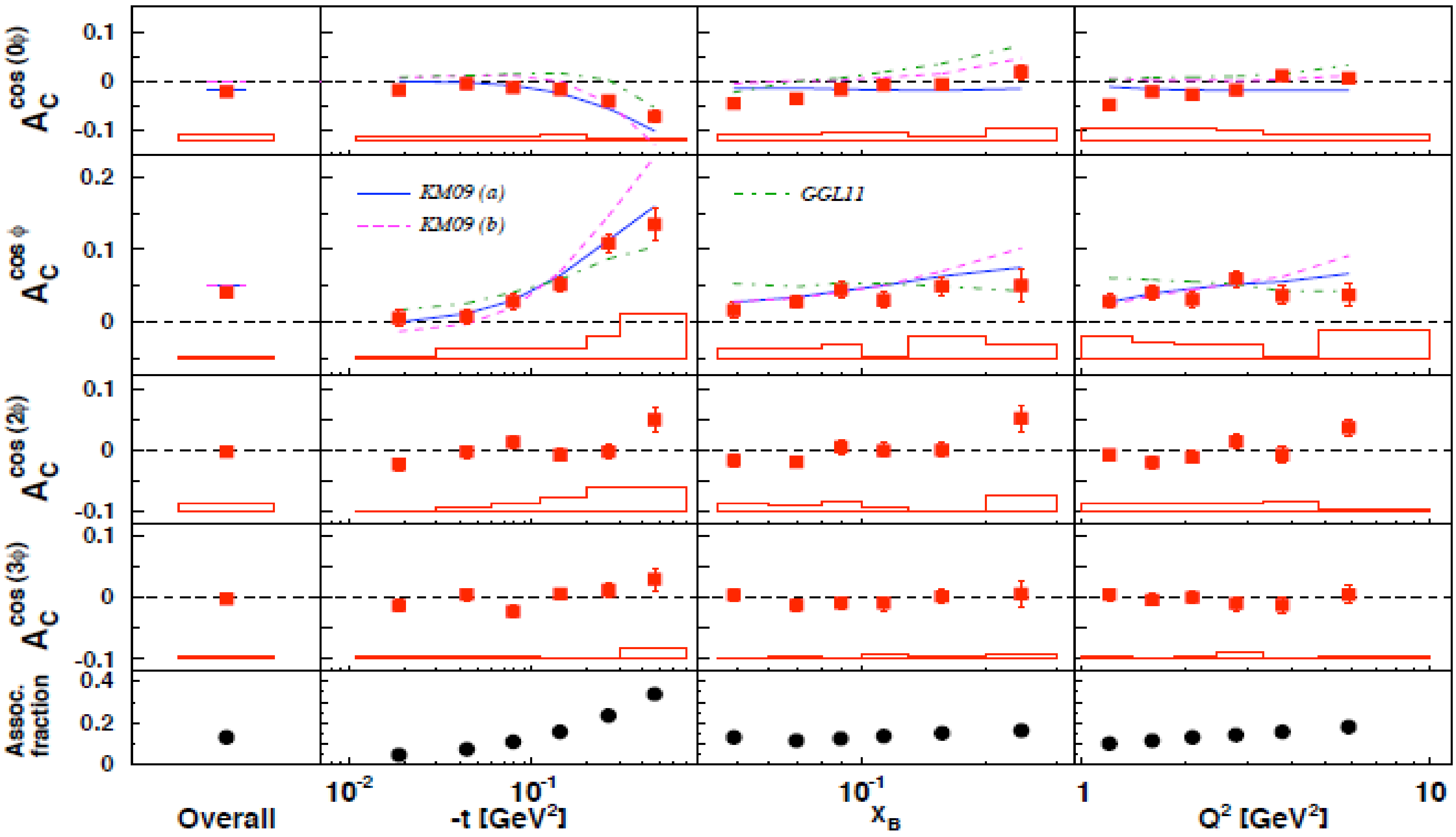
- Spin-independent non-collinear cross section:

  - evidence for non-zero Boer-Mulders distribution function and Collins fragmentation function

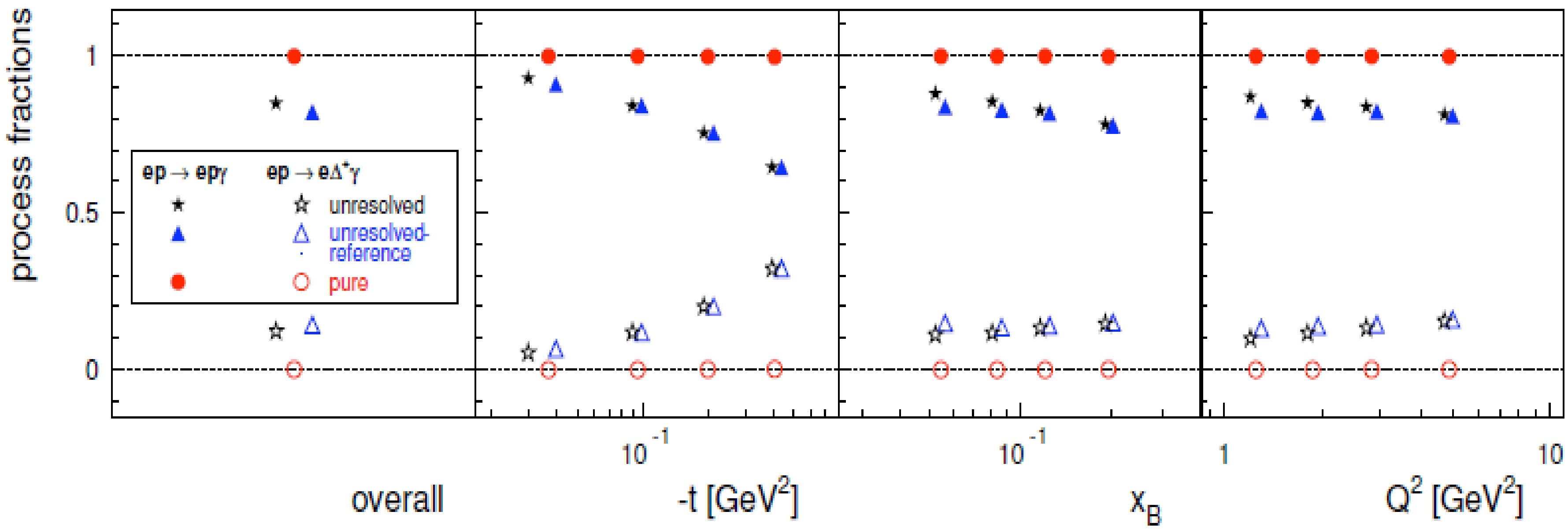
  - through Cahn effect constraint on quark intrinsic momentum and spin-independent transverse-momentum fragmentation functions

Backup

Beam-charge asymmetry



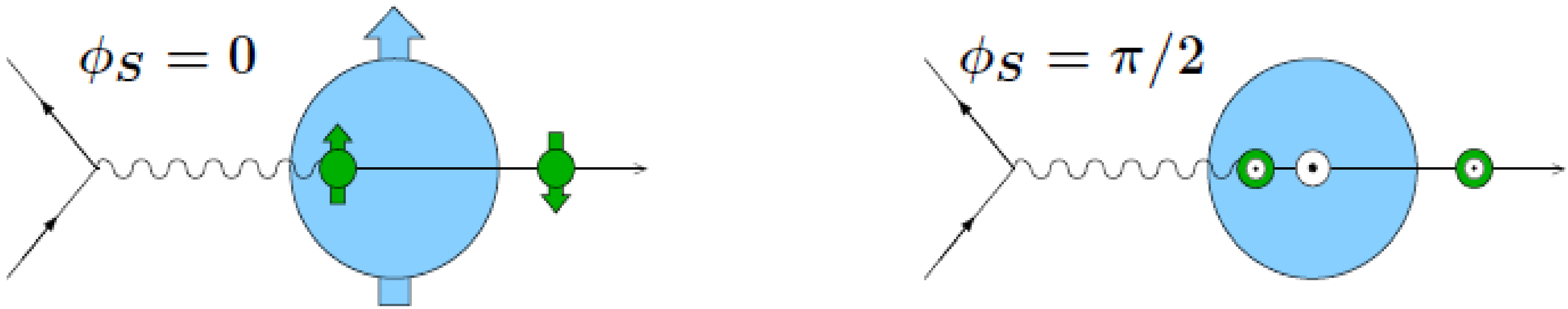
DVCS sample purity



Collins fragmentation function: Artru model

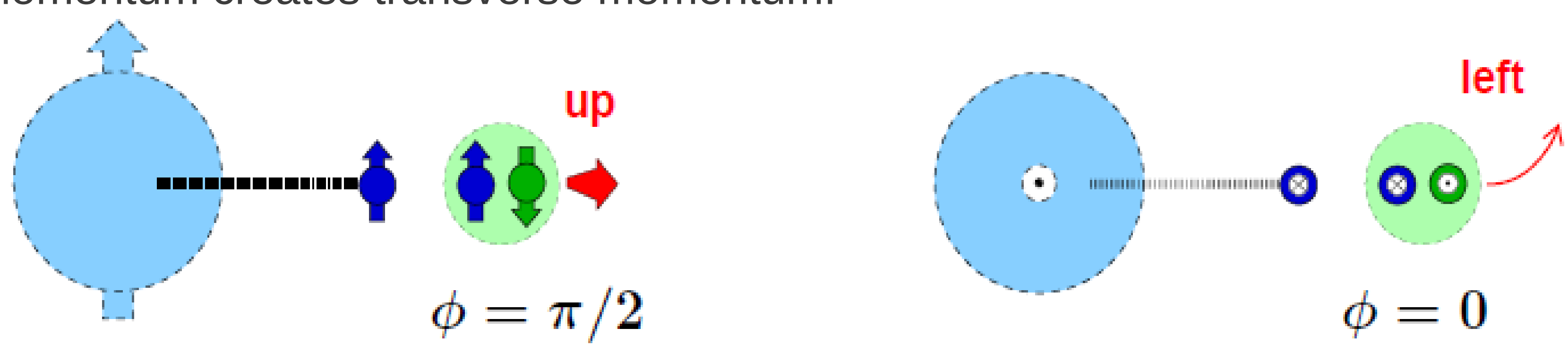
X. Artru et al. , Z. Phys. C**73** (1997) 527

polarisation component in lepton scattering plane reversed by photoabsorption:



string break, quark-antiquark pair with vacuum numbers:

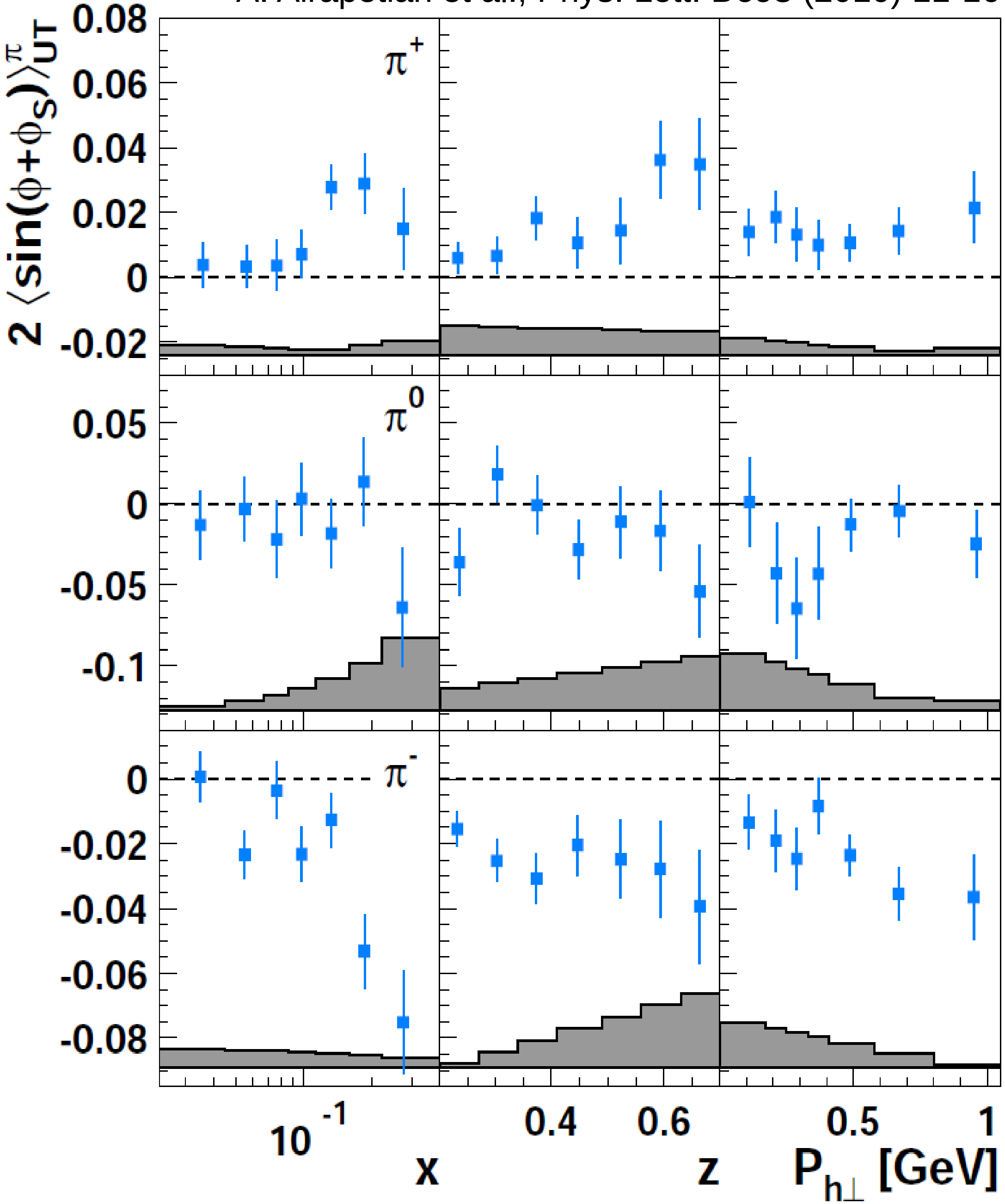
orbital angular momentum creates transverse momentum:



courtesy from U. Elschenbroich

Collins amplitudes for pions

A. Airapetian et al., Phys. Lett. B**693** (2010) 11-16

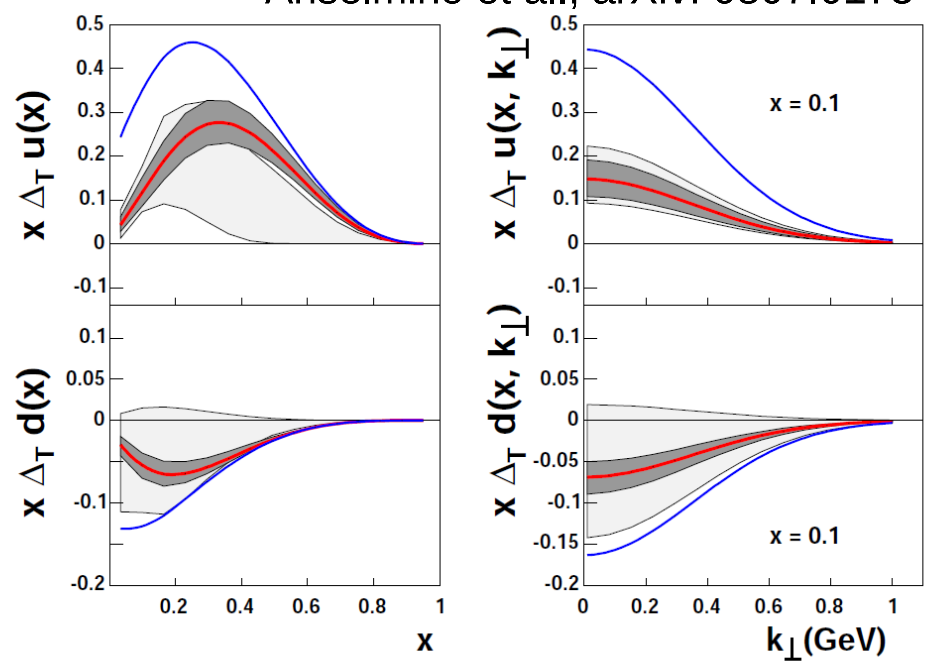


- $\pi^\pm$ increasing with z
- positive for π^+
- large & negative for π^-

$$H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$$

- isospin symmetry fulfilled
- data from BELLE, COMPASS & HERMES ⟶ extraction of h^q_{1T}

Anselmino et al., arXiv: 0807.0173



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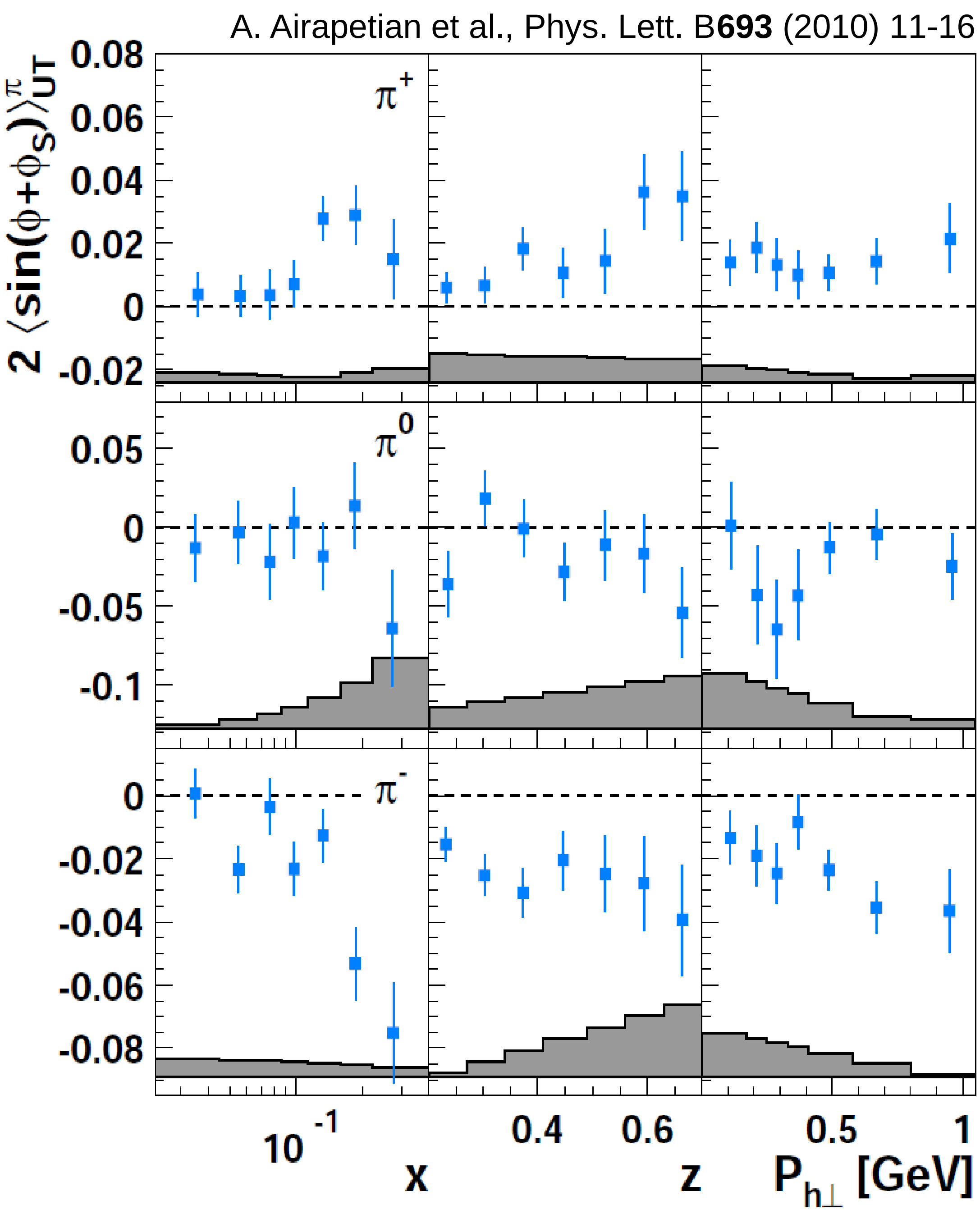

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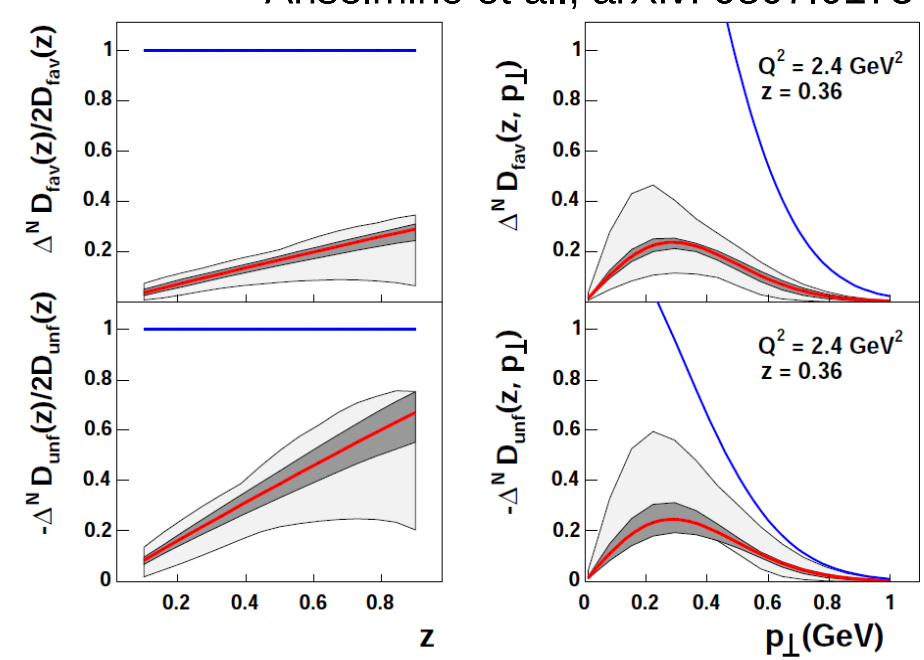
Anselmino et al., arXiv: 0807.0173

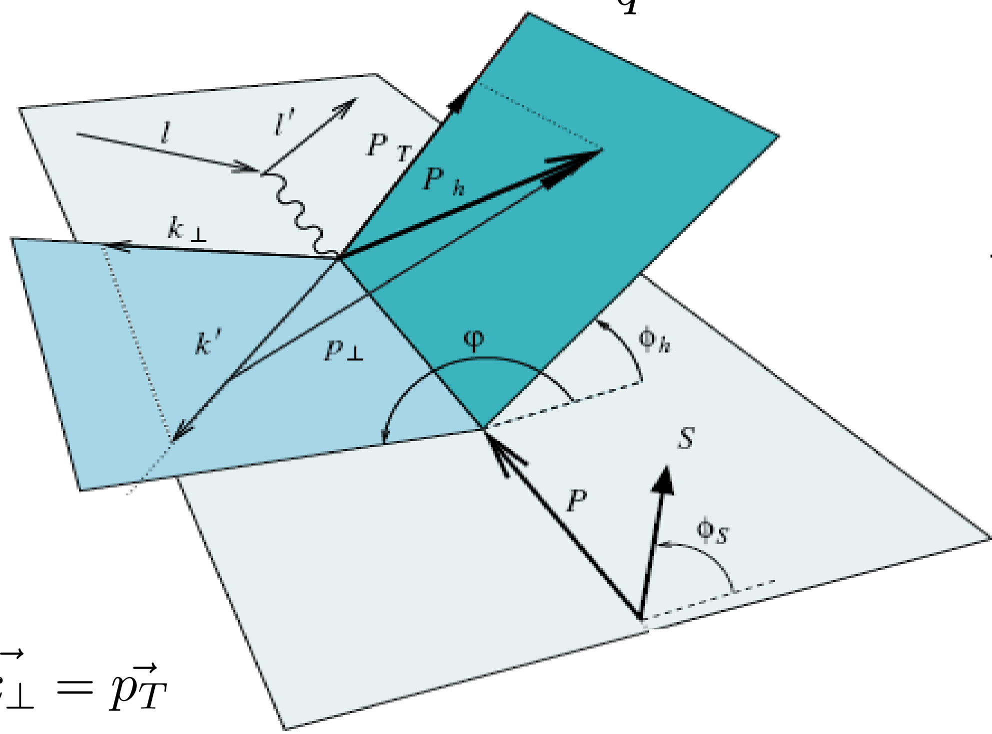


Cahn effect

R. N. Cahn, Phys. Lett. B78:269, 1978
Phys. Rev. D40: 3107, 1989

M. Anselmino et al., Phys. Rev. D71:074006, 2005

$$\frac{d\sigma}{dx\,dQ^2\,dz\,dP_{h\perp}^2} \sim \sum_q \int d^2p_T\, f_1^q(x,p_T)\, \frac{d\hat{\sigma}^{lq\to lq}}{dQ^2}\, D_1^q(z,p_\perp)....$$



$\vec{k_\perp} = \vec{p_T}$

$$\frac{2\pi\alpha^2}{x^2 s^2}\,\frac{\hat{s}^2+\hat{u}^2}{Q^4} \sim \vec{l}.\vec{p}_T \sim \cos\varphi$$

and

$$\vec{P}_{h\perp} \simeq z\vec{p}_T + \vec{k}_T$$

after integration over p_T azimuthal dependence remains, reflected in $\cos\phi_h$