Longitudinal double-spin asymmetreis in SIDIS studied at HERMES

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For the hermes collaboration

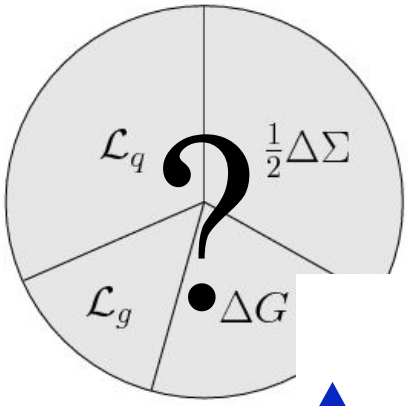
"Longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering of electrons and positrons by protons and deuterons", Phys. Rev. D 99 (2019) 112001

Contents

- Spin structure of the proton
- Semi-inclusive measurement of Deep Inelastic Scattering
- HERMES experiment
- Longitudinal double spin asymmetry
  - x, z, and $P_{h\perp}$ dependence
  - 3D results (x, z, $P_{h\perp}$)
  - Charge difference asymmetry
  - Azimuthal modulation, $\cos\phi$
- Summary

Spin structure of the proton studied with a fixed target

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_q + \mathcal{L}_g$$



1980

EMC, "Spin Crisis"

1st generation

1990

Inclusive DIS ⇒ ΔΣ~0.3, **ΔG**

2nd generation

Semi-Inclusive DIS ⇒ **Spin-Flavor structure**

Transverse This talk zed target ⇒ **TMD**

Open Charm, high pt ⇒ **ΔG**

Exclusive process ⇒ **GPD**

3rd generation

Polarized Drell-Yan

4th generation?

collider exp.

Pacific Spin

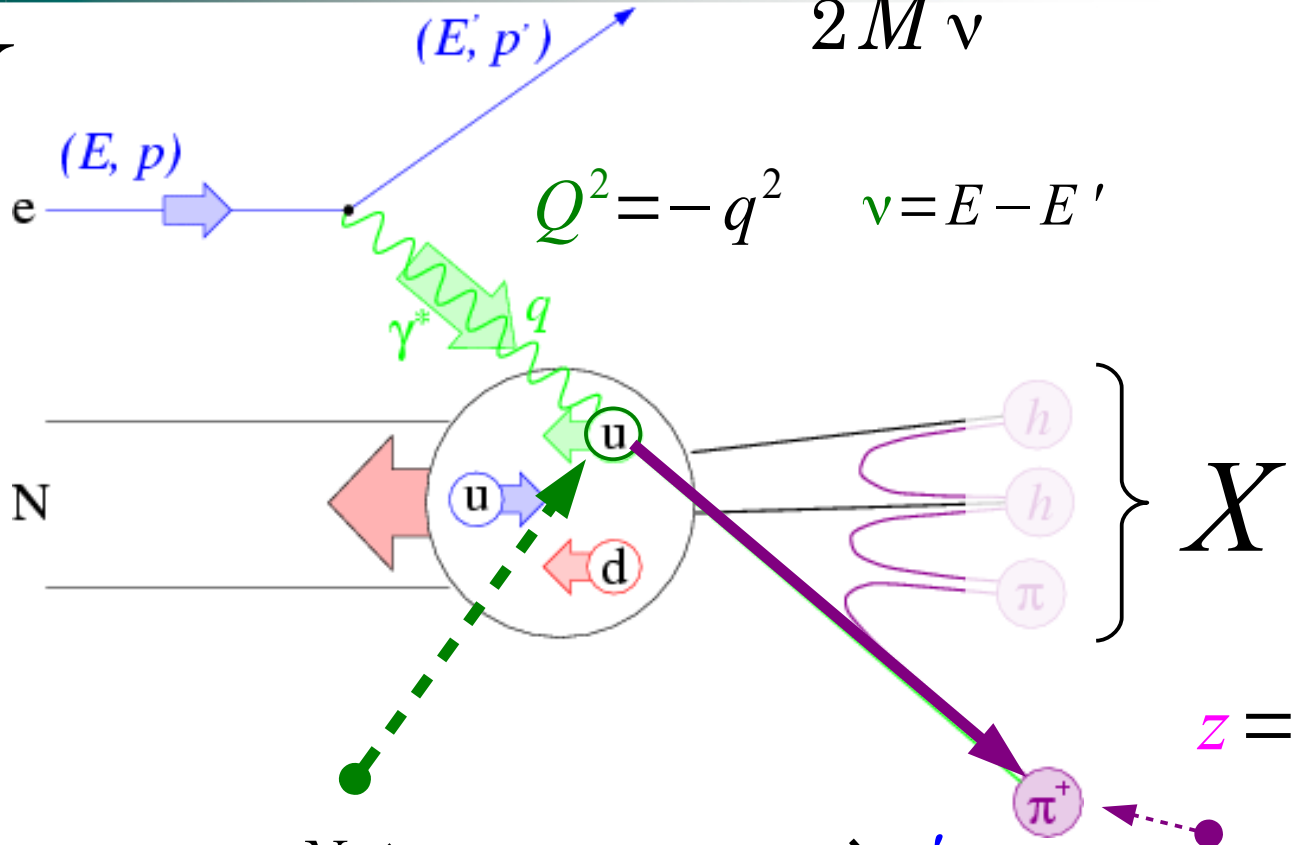
1996	Kobe
1999	Wako
2000	
2001	Beijing
2003	Washington
2005	Tokyo
2007	Vangouver
2009	Yamagata
2010	
2011	Cairns
2013	Ji'nan
2015	Taipei
2019	**Miyazaki**

2020

Semi-inclusive measurement of Deep Inelastic Scattering

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

$$eN \rightarrow e'hX$$



$$Q^2 = -q^2 \qquad \nu = E - E'$$

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

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

Parton Distribution Function $f(x, Q^2)$	Fragmentation Function $F(z, Q^2)$

Parton Distribution Functions

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Unpolarized Nucleon

f_1 Parton Density

$h_1^{\perp}$ Boer-Mulders

Longitudinally Polarized Nucleon

$g_{1L}(=\Delta q)$ Helicity

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

Transversely Polarized Nucleon

$f_{1T}^{\perp}$ Sivers

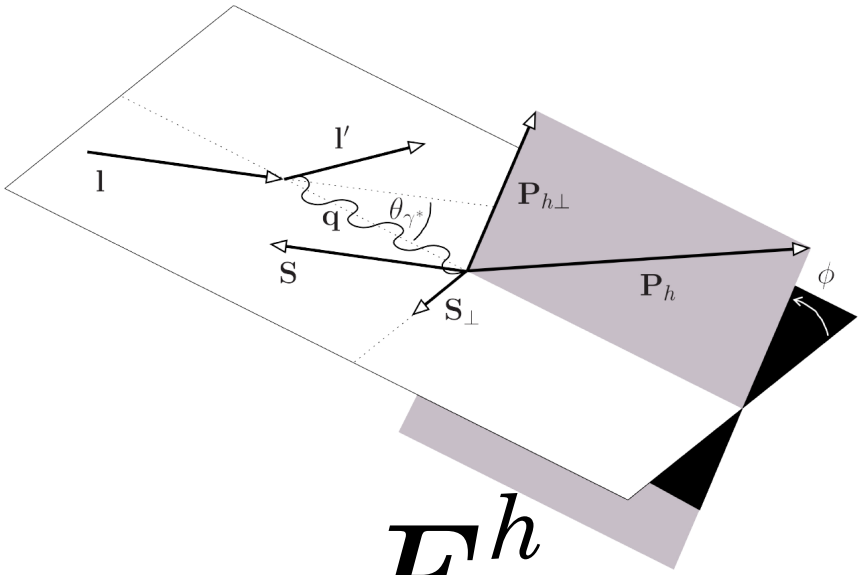
g_{1T} Worm-gear

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

$h_{1T}^{\perp}$ Pretzelosity

Semi-Inclusive DIS cross section
in the one-photon-exchange approximation

※transverse nucleon polarization neglected



$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1-\epsilon^2}\,F_{LL}^h$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}$$

F^h_{LL} beam L L target

$$F_{LL}^h \propto \sum_q e_q^2 \left[\, g_{1L}^q(x,p_T^2) \otimes_{\mathcal{W}_1} D_1^{q\to h}(z,k_T^2) \,\right]$$

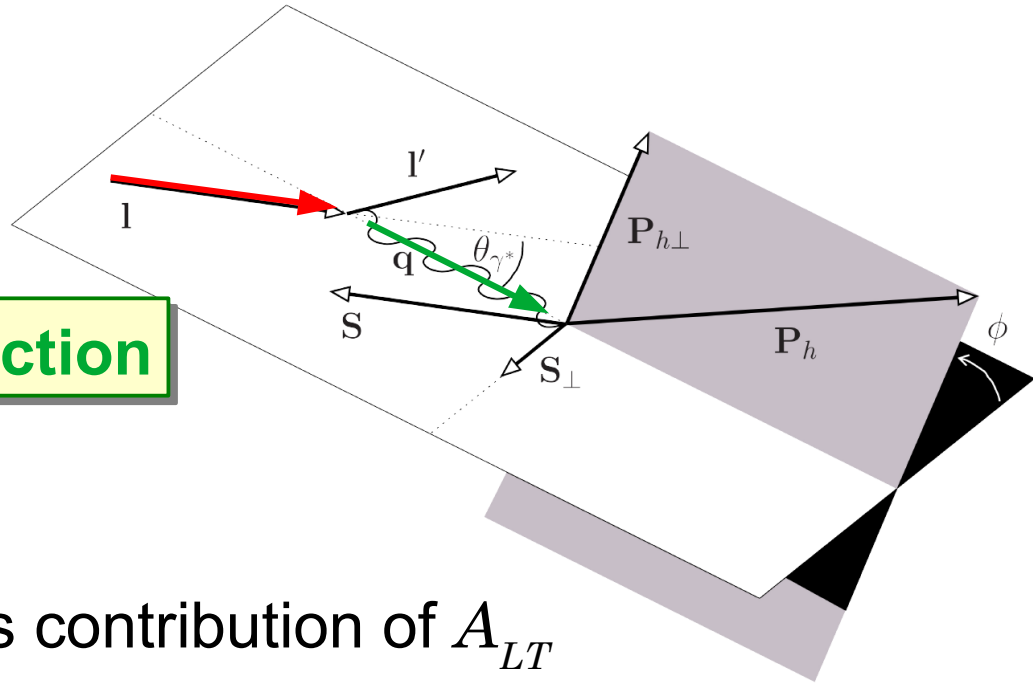
Longitudinal double spin asymmetry

$$A_{LL}^h \equiv \frac{\sigma_{+-}^h - \sigma_{++}^h + \sigma_{-+}^h - \sigma_{--}^h}{\sigma_{+-}^h + \sigma_{++}^h + \sigma_{-+}^h + \sigma_{--}^h}$$

Double spin asymmetries in SIDIS

$$A_{LL}^{h} \equiv \frac{\sigma_{+-}^{h} - \sigma_{++}^{h} + \sigma_{-+}^{h} - \sigma_{--}^{h}}{\sigma_{+-}^{h} + \sigma_{++}^{h} + \sigma_{-+}^{h} + \sigma_{--}^{h}}$$

along **virtual photon direction**



along **beam direction**

$A_{\parallel}$ includes contribution of A_{LT}

A_1^h virtual-photon-nucleon asymmetry

$$A_1^h = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} = \frac{1}{D(1+\eta\gamma)} A_{\parallel}^h$$

$$D = \frac{1-(1-y)\epsilon}{1+\epsilon R}$$

$$\eta = \frac{\epsilon\gamma y}{1-(1-y)\epsilon}$$

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

Targets: Unpolarized H, D, nuclei

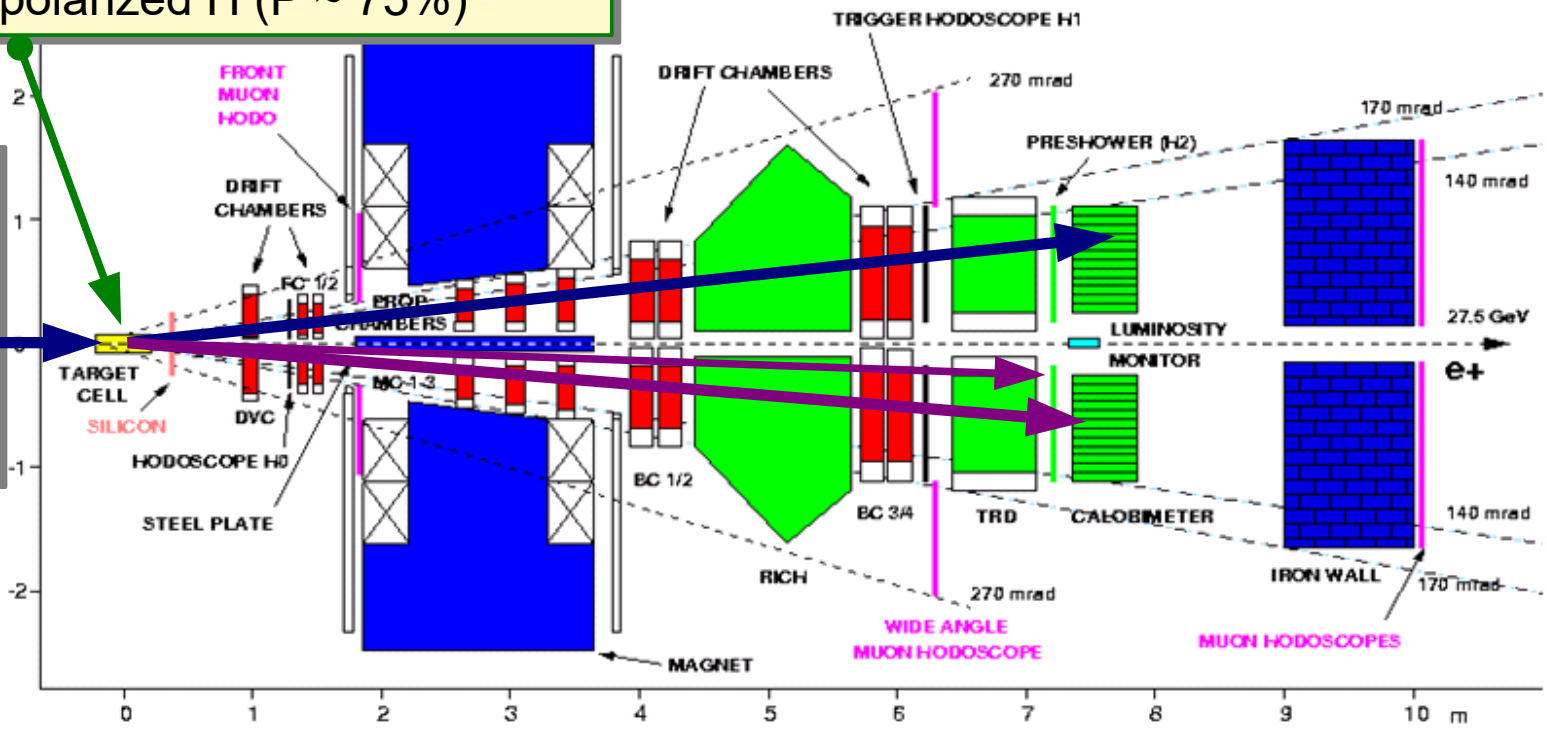
Longitudinally polarized H, D (P ~ 85 %)

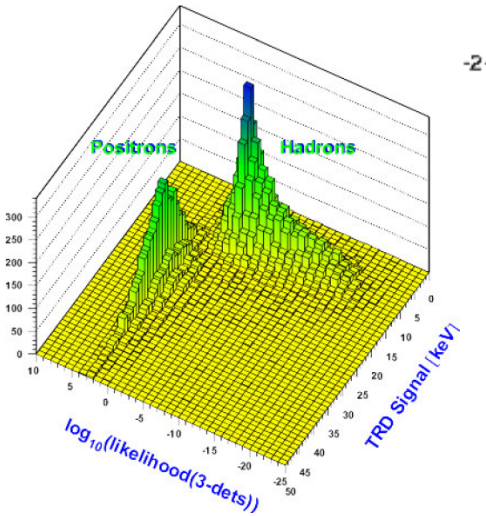
Transversely polarized H (P ~ 75%)

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

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

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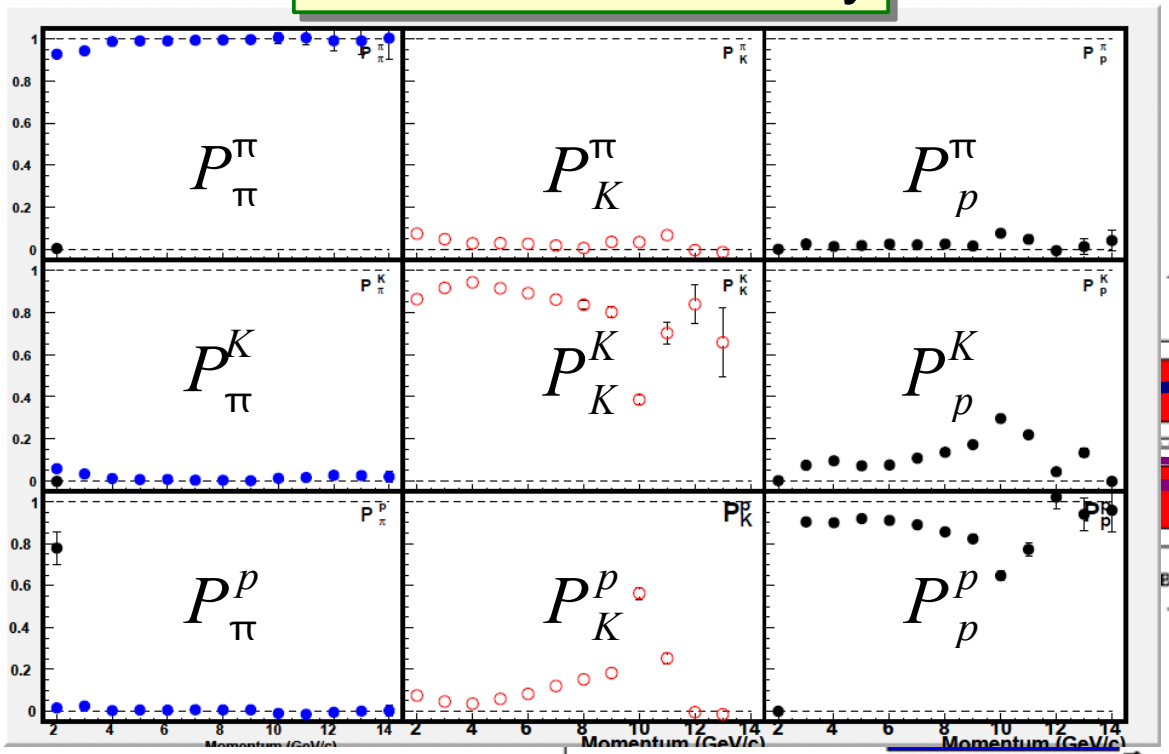
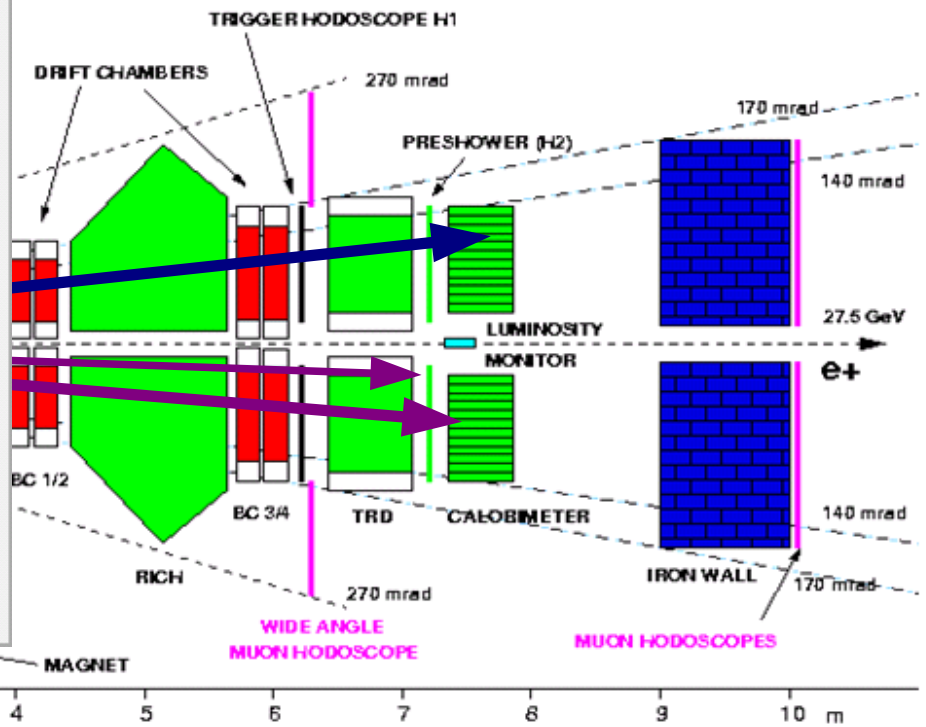
RICH PID efficiency





Reconstruction: $\Delta p/p < 2\%$, $\Delta\theta < 0.6$ mrad

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

A_1^h from HERMES

"*Flavor Decomposition of the Polarized Quark Distributions in the Nucleon from Inclusive and Semi-Inclusive Deep-inelastic Scattering*", Phys. Lett. B464 (**1999**) 123-134

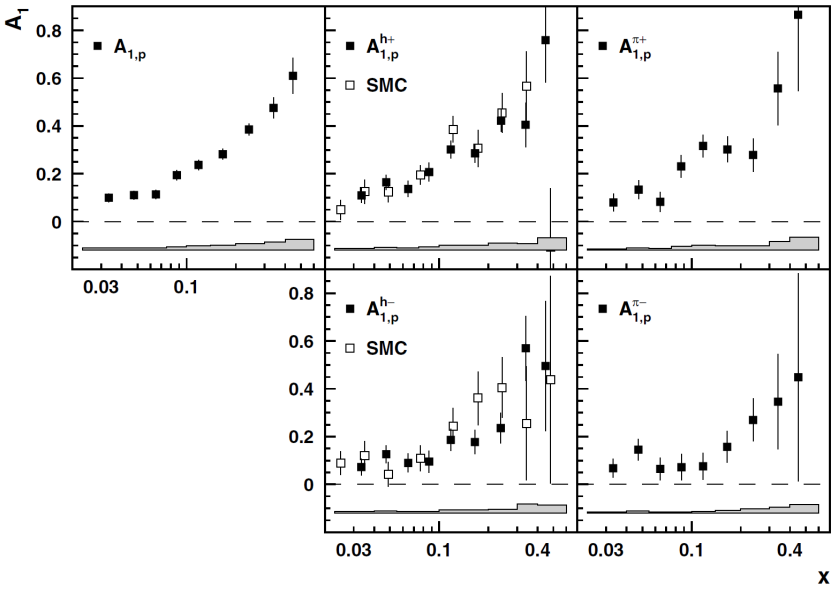
"*Flavor Decomposition of the Sea Quark Helicity Distributions in the Nucleon from Semi-inclusive Deep-inelastic Scattering*", Phys. Rev. Lett. 92 (**2004**) 012005

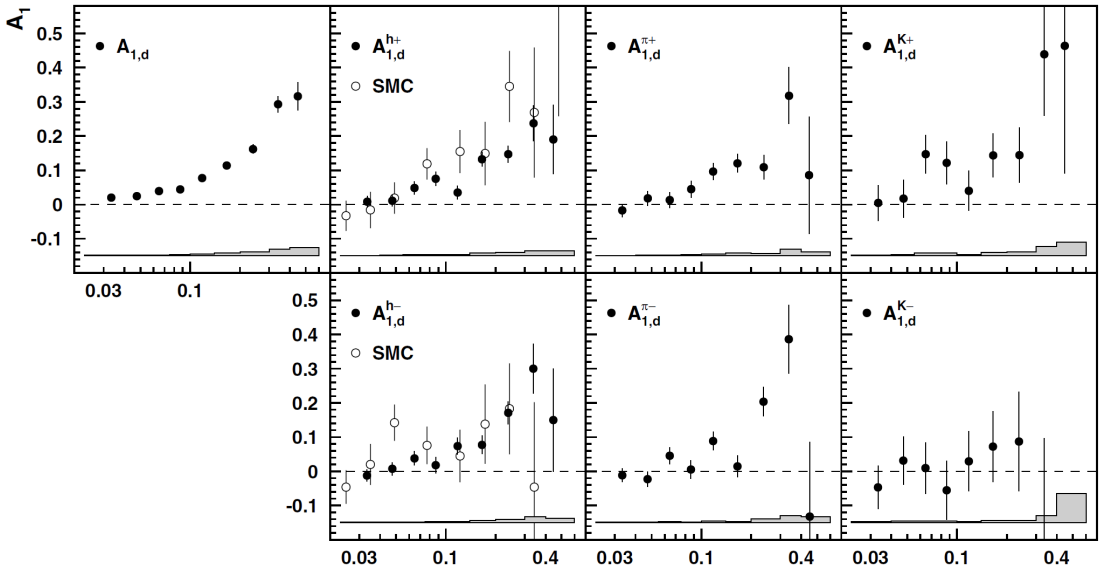
"***Quark Helicity Distributions in the Nucleon for up, down, and strange Quarks from Semi-inclusive Deep-inelastic Scattering***", Phys. Rev D 71 (**2005**) 012003

"*Measurement of Parton Distributions of Strange Quarks in the Nucleon from Charged-Kaon Production in Deep-Inelastic Scattering on the Deuteron*", Phys. Lett. B 666 (**2008**) 446

*"**Longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering of electrons and positrons by protons and deuterons***", Phys. Rev. D 99 (**2019**) 112001

Previous results: PRD71(2005)012003

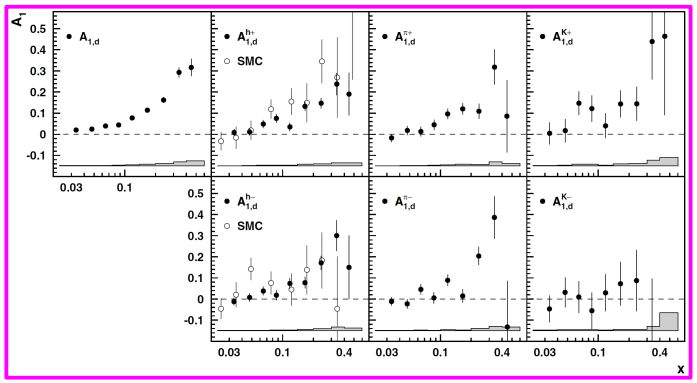




Year	Lepton beam charge	Average polarization	Fractional uncertainty
1996	e^+	52.8%	3.4%
1997	e^+	53.1%	3.4%
1998	e^-	52.1%	3.4%
1999	e^+	53.3%	1.8%
2000	e^+	53.3%	1.9%

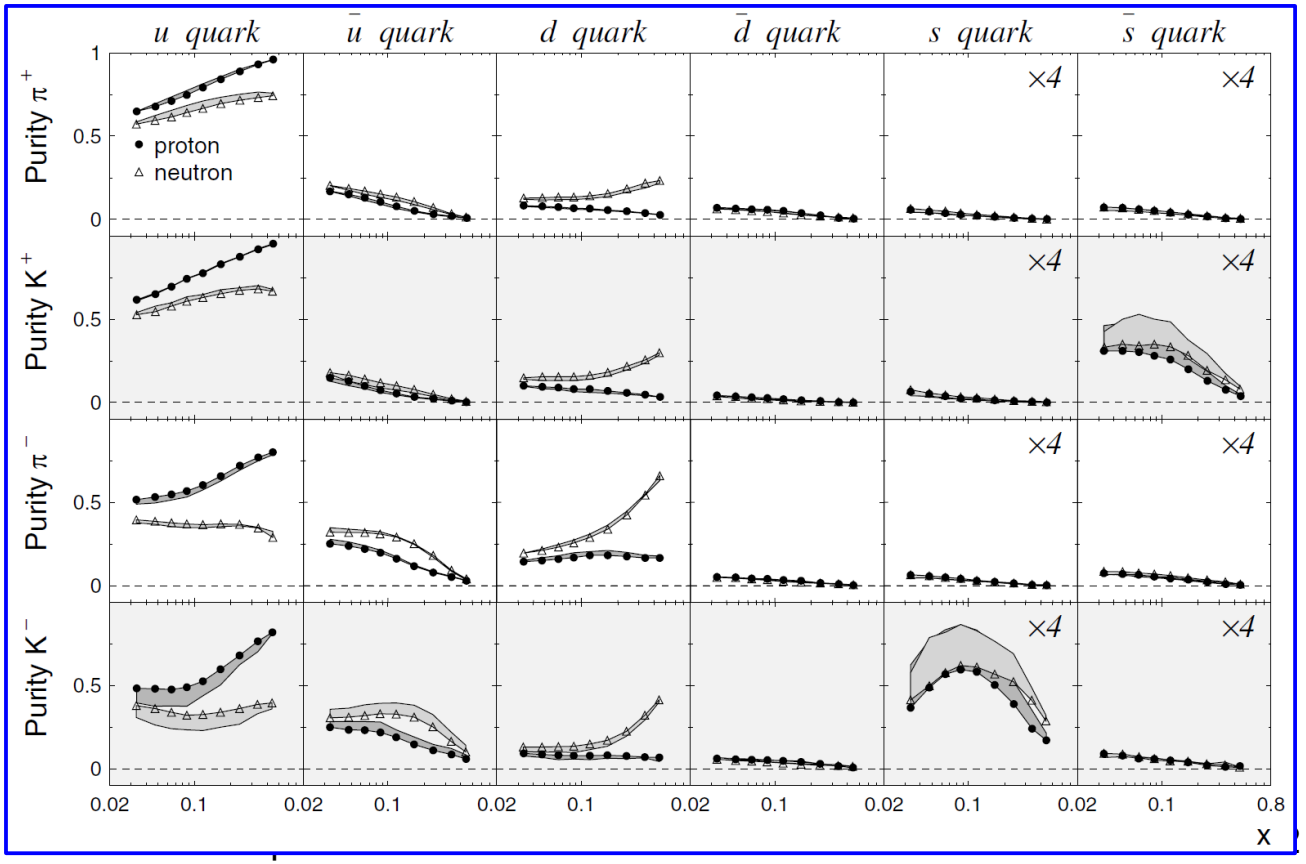
$$A_1^h = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h}$$

Previous results: PRD71(2005)012003

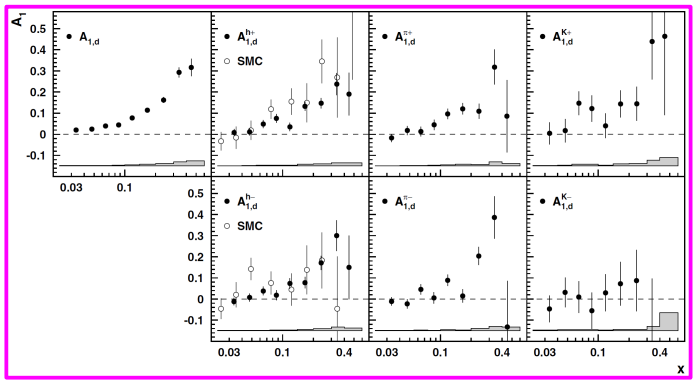


$$A_{1N}^{h} = P \cdot \frac{\Delta q}{q}$$

Estimated using MC tuned to the HERMES data

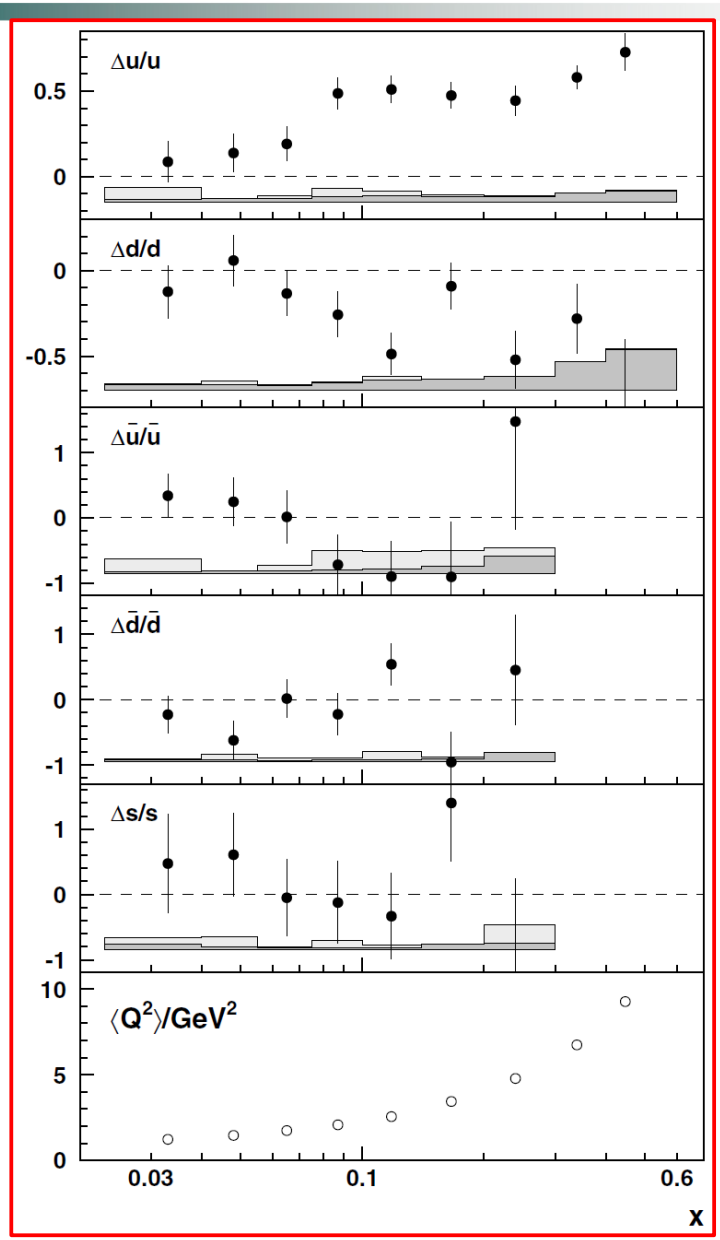


Previous results: PRD71(2005)012003



$$A_{1N}^{h} = P \cdot \frac{\Delta q}{q}$$

$$\Rightarrow \quad \frac{\Delta q}{q} = P^{-1} A_{1N}^{h}$$



	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	$0.028 \pm 0.033 \pm 0.009$
$\Delta u + \Delta \bar{u}$	$0.599 \pm 0.022 \pm 0.065$
$\Delta d + \Delta \bar{d}$	$-0.280 \pm 0.026 \pm 0.057$
Δu_v	$0.603 \pm 0.071 \pm 0.040$
Δd_v	$-0.172 \pm 0.068 \pm 0.045$
$\Delta \bar{u} - \Delta \bar{d}$	$0.048 \pm 0.057 \pm 0.028$
$\Delta \Sigma$	$0.347 \pm 0.024 \pm 0.066$
Δq_3	$0.880 \pm 0.045 \pm 0.107$
Δq_8	$0.262 \pm 0.078 \pm 0.045$
$\Delta^{(2)} u$	$0.142 \pm 0.009 \pm 0.011$
$\Delta^{(2)} \bar{u}$	$-0.001 \pm 0.005 \pm 0.002$
$\Delta^{(2)} d$	$-0.049 \pm 0.010 \pm 0.013$
$\Delta^{(2)} \bar{d}$	$-0.003 \pm 0.004 \pm 0.001$
$\Delta^{(2)} s$	$0.001 \pm 0.003 \pm 0.001$
$\Delta^{(2)} u_v$	$0.144 \pm 0.013 \pm 0.011$
$\Delta^{(2)} d_v$	$-0.047 \pm 0.012 \pm 0.012$

Analysis update from PRD71(2005)012003

- Lower hadron momentum cut for the deuteron target
  - 4 GeV/c ⇒ 2 GeV/c, (※ 4 GeV/c for proton w/o RICH)
- Make $A_{\parallel}^{h}$ available (w/ A_{1}^{h})
  - R in SIDIS still to be measured

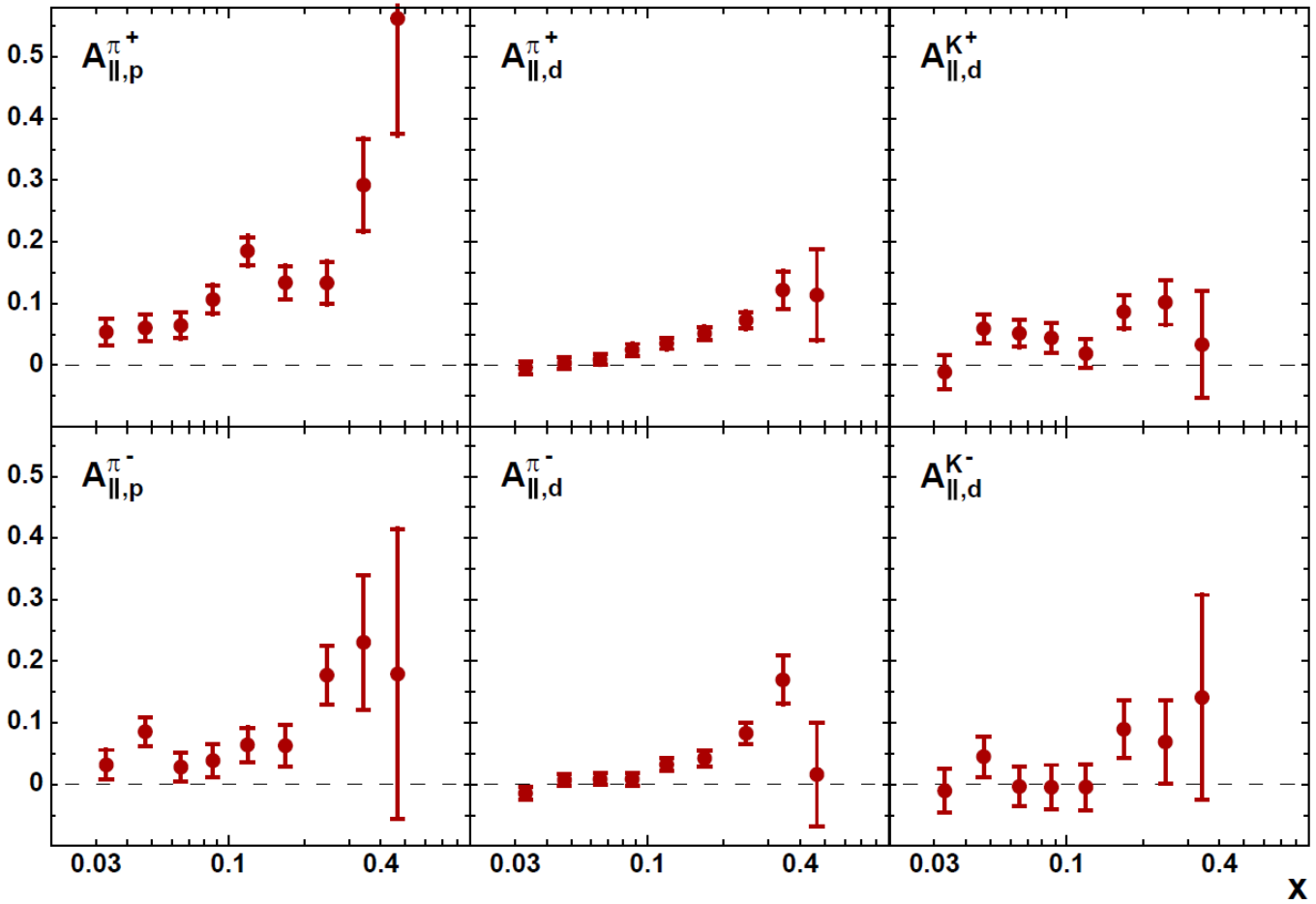
$$D = \frac{1-(1-y)\epsilon}{1+\epsilon R}$$

- D-state correction for deuteron on asymmetry level
- Better azimuthal asymmetry correction
  - Correction factor extracted using MC, in which data-driven model for azimuthal modulations (PRD87(2013)012010) are implemented
- Multi-dimensional (x, z, $P_{h\perp}$) dependences
- Charge difference asymmetry extraction
- Extract twist-3 cosine modulations

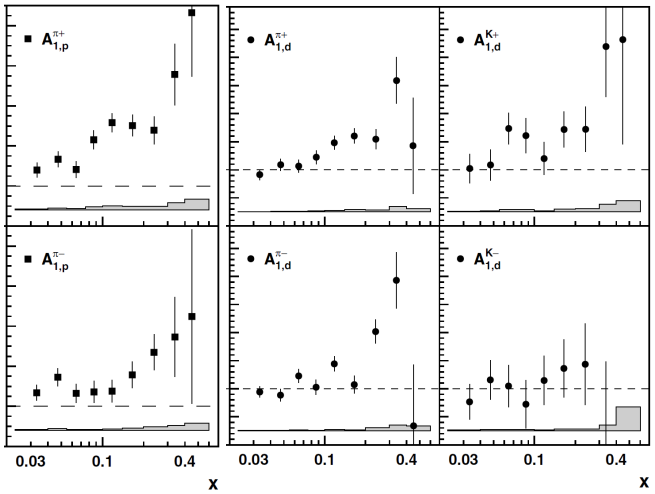
New Resutls (PRD71(2005)012003)

- Longitudinal double spin asymmetry
  - x-dependence
  - z-dependence
  - $P_{h\perp}$ dependence
  - $(x, z, P_{h\perp})$ dependence
  - Charge difference asymmetry
  - Azimuthal modulation: cosϕ

Results: x-dependence

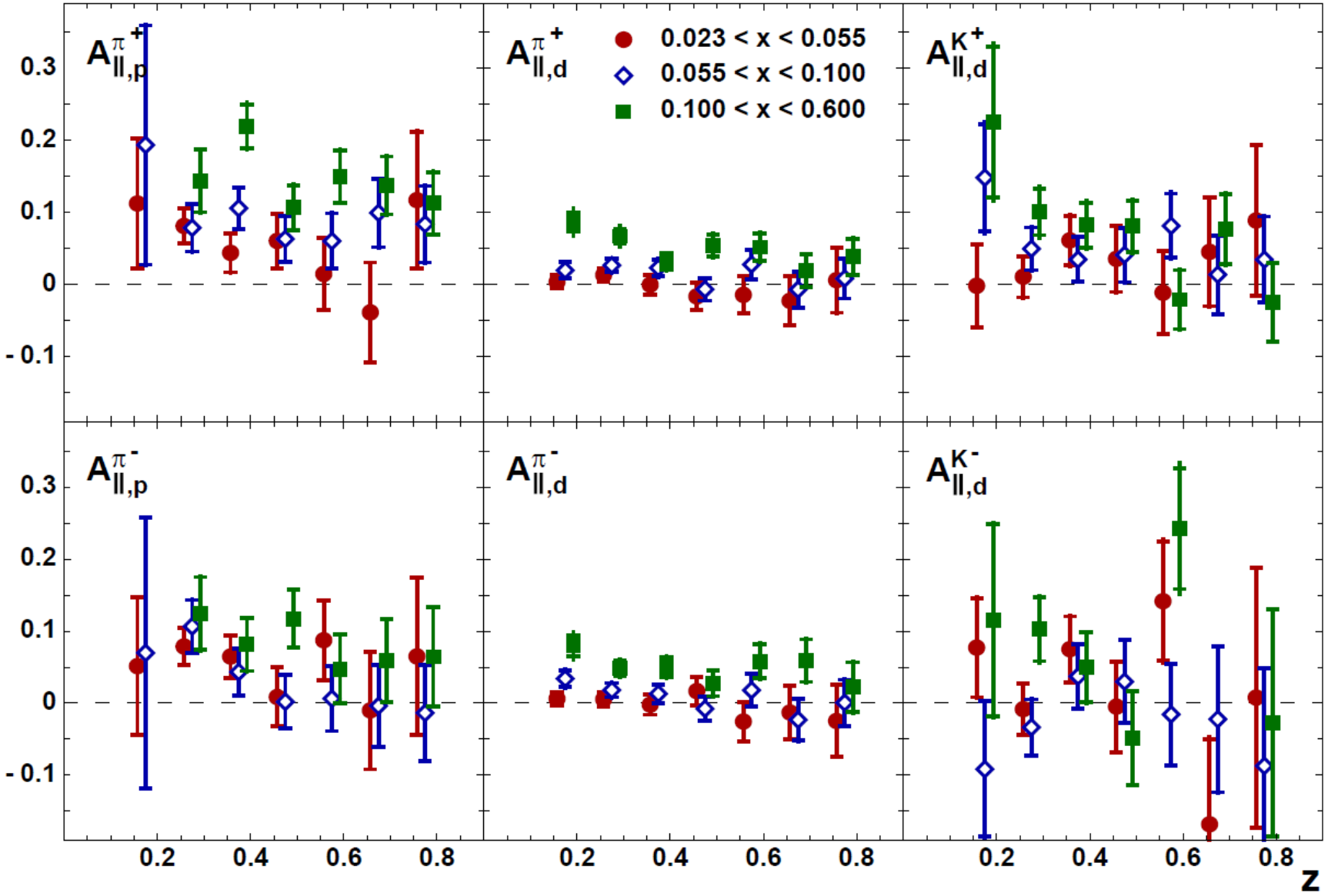


Consistent with PRD71(2005)012003

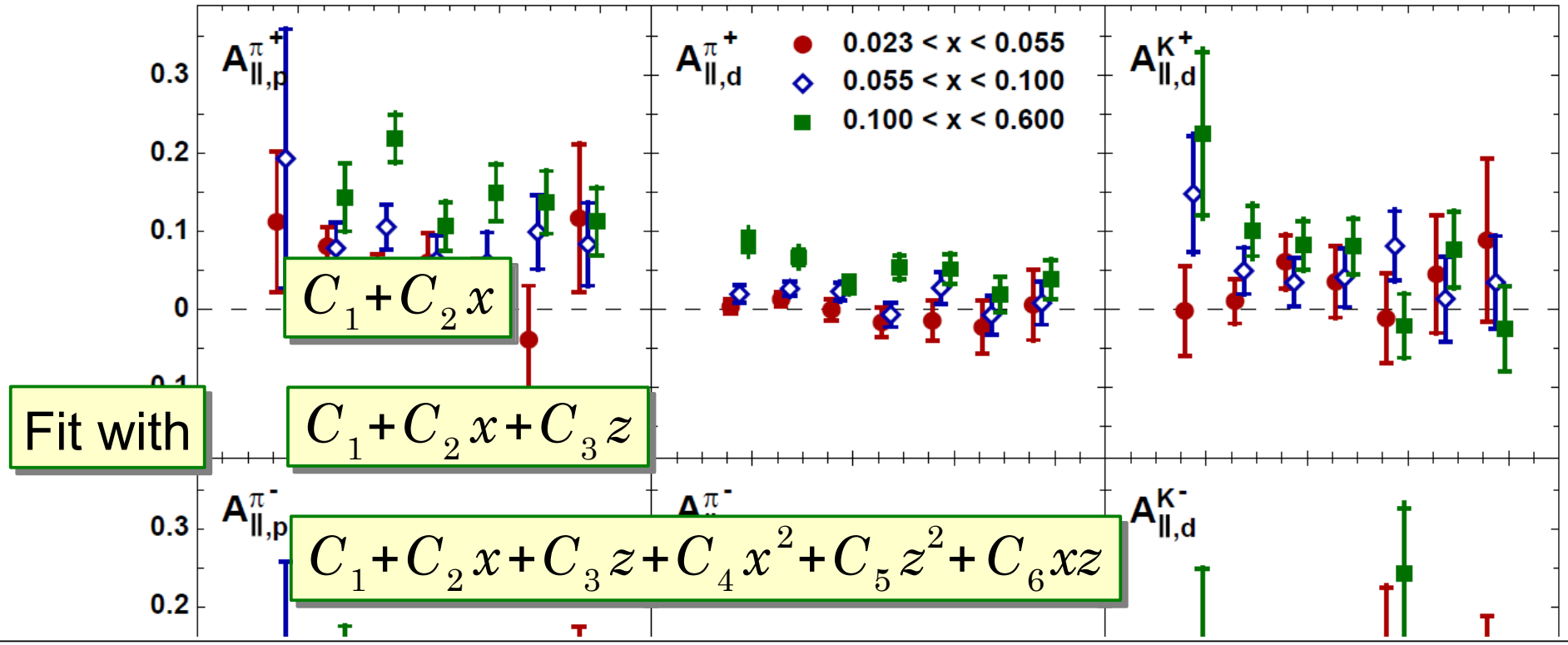


Results: z-dependence

No strong z dependence



Results: z-dependence



Fit with

$C_1 + C_2 x$

$C_1 + C_2 x + C_3 z$

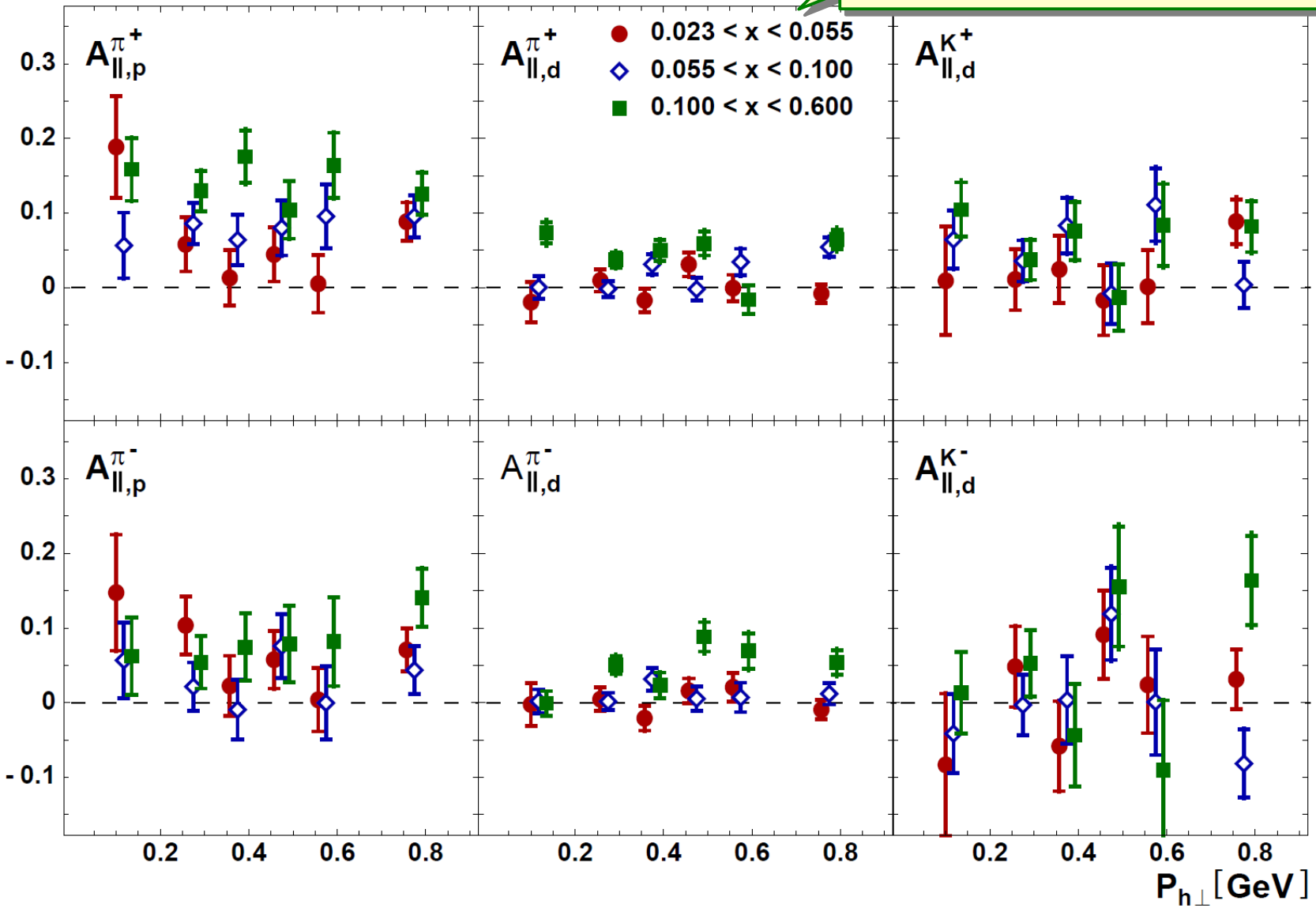
$C_1 + C_2 x + C_3 z + C_4 x^2 + C_5 z^2 + C_6 xz$

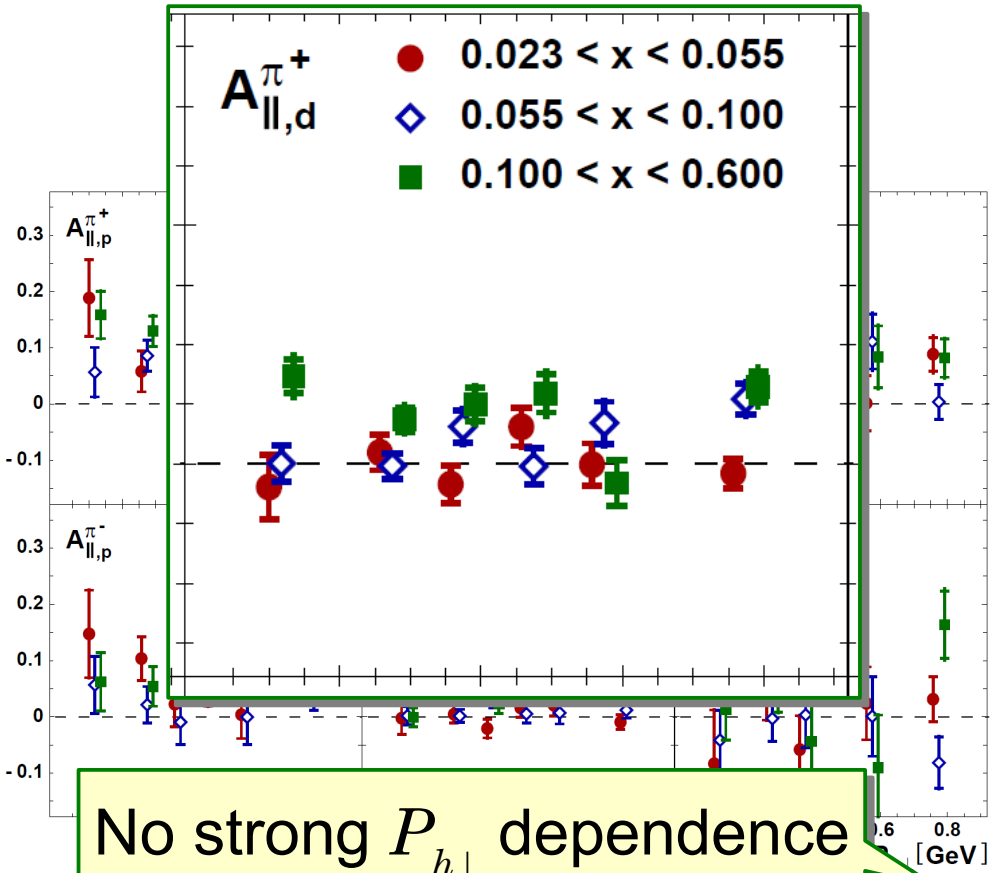
	$A_{1,p}^{\pi^+}$	$A_{1,p}^{\pi^-}$	$A_{1,d}^{\pi^+}$	$A_{1,d}^{\pi^-}$	$A_{1,d}^{K^+}$	$A_{1,d}^{K^-}$
$\chi^2_{C_1^h + C_2^h x}$ $(NDF=16)$	12.6	10.0	13.4	9.1	10.7	26.0
$\chi^2_{C_1^h + C_2^h x + C_3^h z}$ $(NDF=15)$	12.2	6.3	7.2	7.2	10.1	24.8
$\chi^2_{C_1^h + C_2^h x + C_3^h z + C_4^h x^2 + C_5^h z^2 + C_6^h xz}$ $(NDF=12)$	10.3	4.5	5.5	4.8	5.8	16.1

No strong z dependence

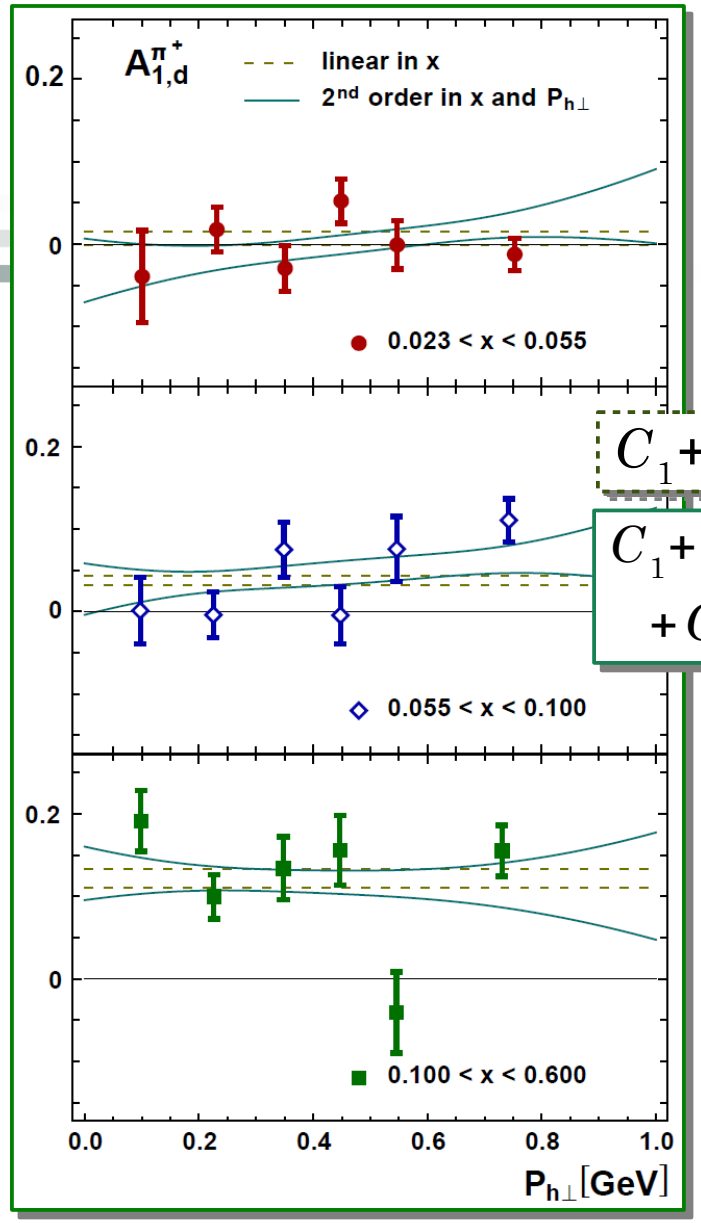
Results: $P_{h\perp}$-depdence

No strong $P_{h\perp}$ dependence





No strong $P_{h\perp}$ dependence

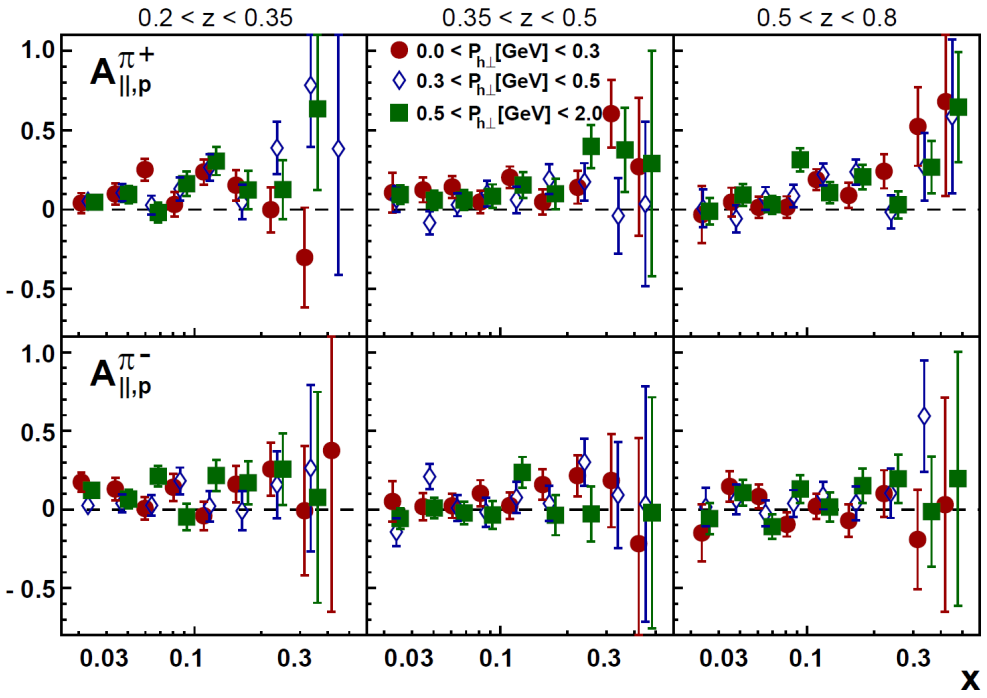


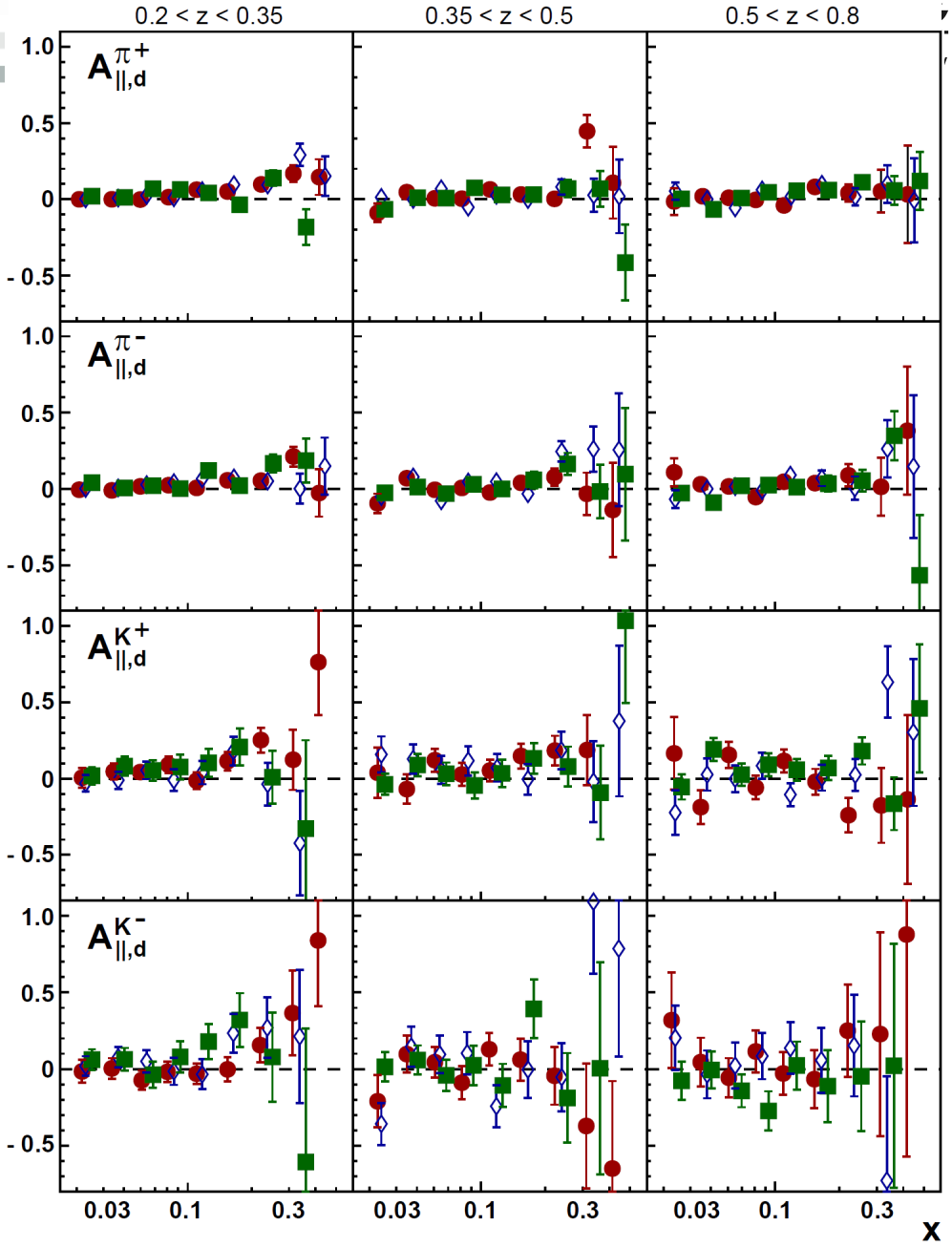
$$C_1 + C_2 x$$

$$C_1 + C_2 x + C_3 P_{h\perp} + C_4 x^2 + C_5 P_{h\perp}^2$$

	$A_{1,p}^{\pi^+}$	$A_{1,p}^{\pi^-}$	$A_{1,d}^{\pi^+}$	$A_{1,d}^{\pi^-}$	$A_{1,d}^{K^+}$	$A_{1,d}^{K^-}$
$\chi^{2\ (NDF=16)}_{C_1^h+C_2^h x}$	12.7	14.0	33.7	22.9	16.0	24.4
$\chi^{2\ (NDF=15)}_{C_1^h+C_2^h x+C_3^h P_{h\perp}}$	12.7	13.9	31.9	20.6	16.0	23.6
$\chi^{2\ (NDF=12)}_{C_1^h+C_2^h x+C_3^h P_{h\perp}+C_4^h x^2+C_5^h P_{h\perp}^2+C_6^h x P_{h\perp}}$	8.5	5.1	29.7	12.0	12.2	18.7

Results: $A^{h}_{\parallel,N}(x, z, P_{h\perp})$





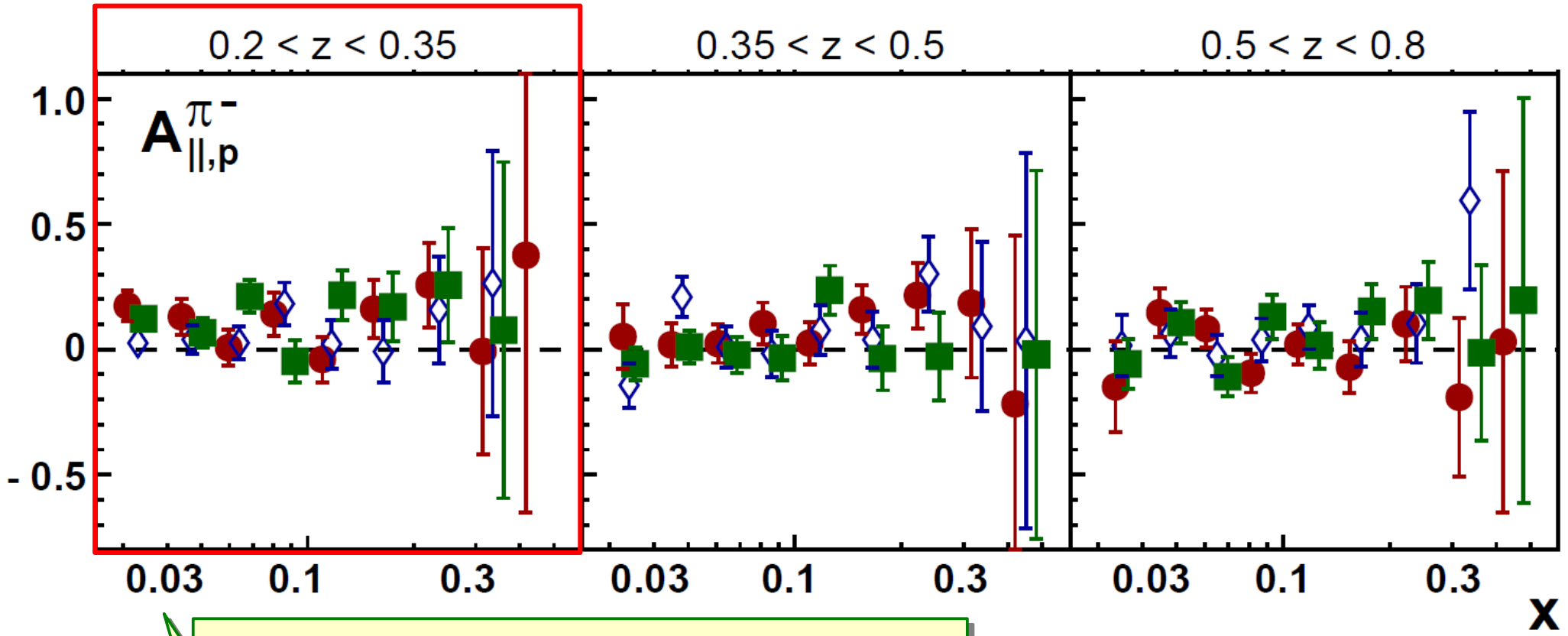
0.0 GeV $< P_{h\perp} <$ 0.3 GeV

0.3 GeV $< P_{h\perp} <$ 0.5 GeV

0.5 GeV $< P_{h\perp} <$ 2.0 GeV

the most complete, unintegrated, longitudinally polarized double-spin dataset

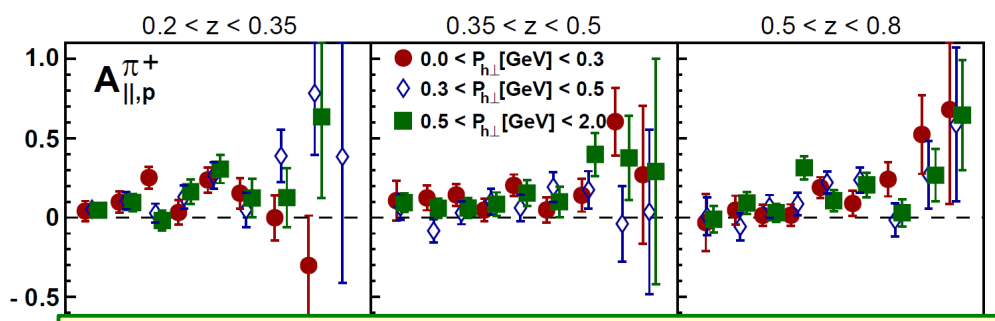
Results: $A^{h}_{\parallel,N}(x, z, P_{h\perp})$

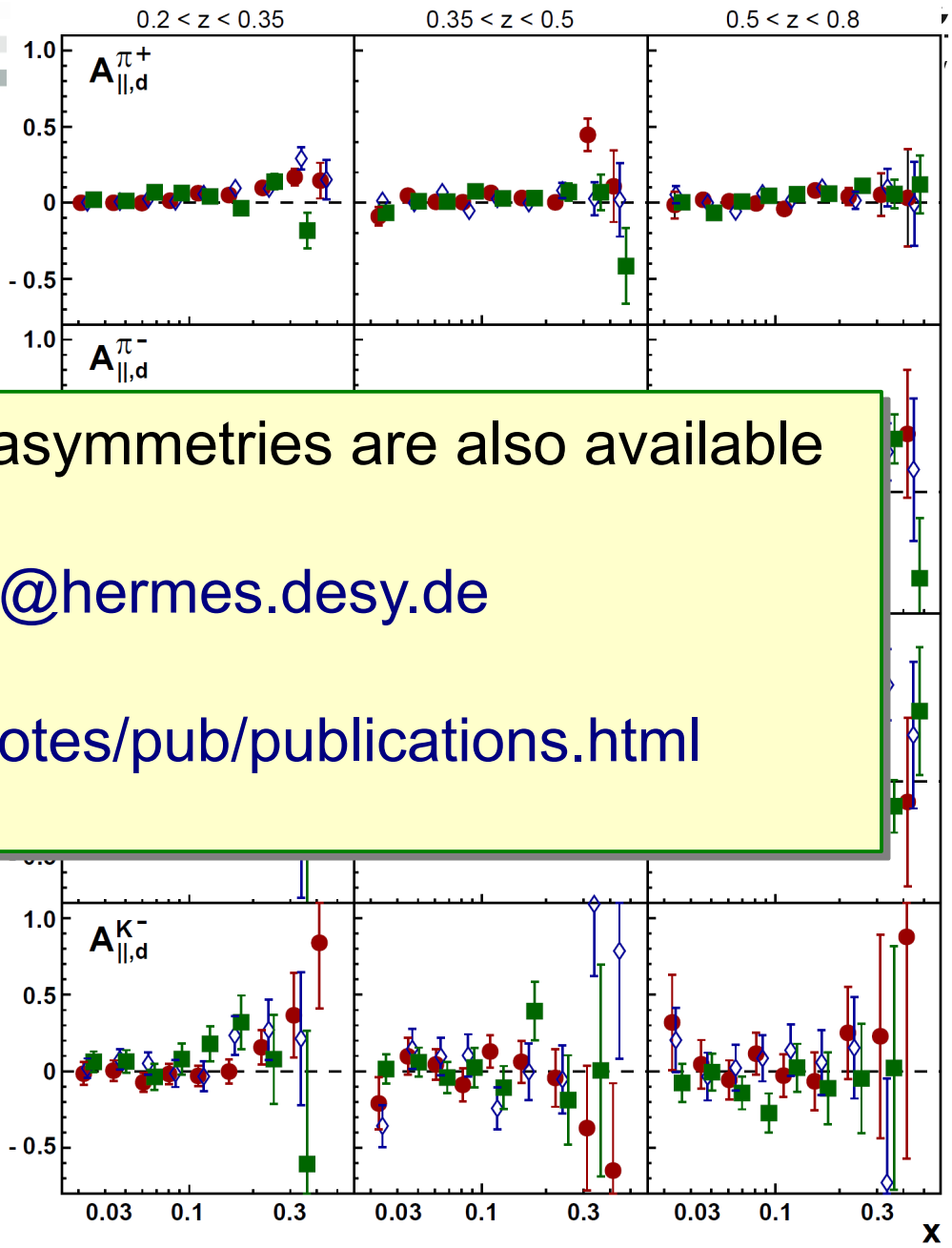


Possible contribution from **Δu>0** through dis-favored fragmentation process.

- ● $0.0\ \text{GeV} < P_{h\perp} < 0.3\ \text{GeV}$
- ◇ $0.3\ \text{GeV} < P_{h\perp} < 0.5\ \text{GeV}$
- ■ $0.5\ \text{GeV} < P_{h\perp} < 2.0\ \text{GeV}$

Results: $A^{h}_{\parallel,N}(x, z, P_{h\perp})$





Statistical covariant matrix, other asymmetries are also available

mail-to: management@hermes.desy.de

http://www-hermes.desy.de/notes/pub/publications.html

◇ $0.3\ \text{GeV} < P_{h\perp} < 0.5\ \text{GeV}$

■ $0.5\ \text{GeV} < P_{h\perp} < 2.0\ \text{GeV}$

the most complete, unintegrated, longitudinally polarized double-spin dataset

Charge difference asymmetry

$$A_1^{h^+-h^-}(x) \equiv \frac{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) - \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) + \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}$$

At **L**eading **O**rder and **L**eading **T**wist

proton

FFs disappeared

deuteron

$$A_{1,p}^{h^+-h^-} \overset{\text{LO LT}}{=} \frac{4g_1^{u_v} - g_1^{d_v}}{4f_1^{u_v} - f_1^{d_v}} \qquad A_{1,d}^{h^+-h^-} \overset{\text{LO LT}}{=} \frac{g_1^{u_v} + g_1^{d_v}}{f_1^{u_v} + f_1^{d_v}}$$

Independent on h

Charge conjugation symmetry

Fragmentation

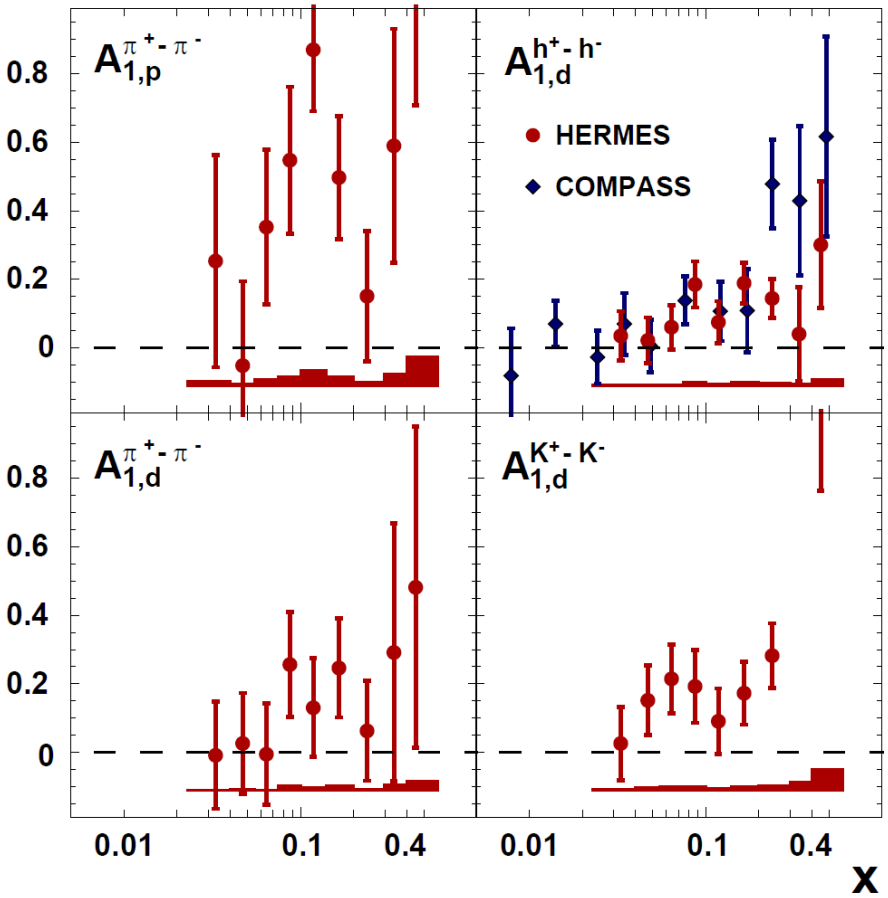
$$q \to h^+ = \bar{q} \to h^- \qquad q \to h^+ = \bar{q} \to h^-$$

$$u \to \pi^{\pm} = d \to \pi^{\mp}$$

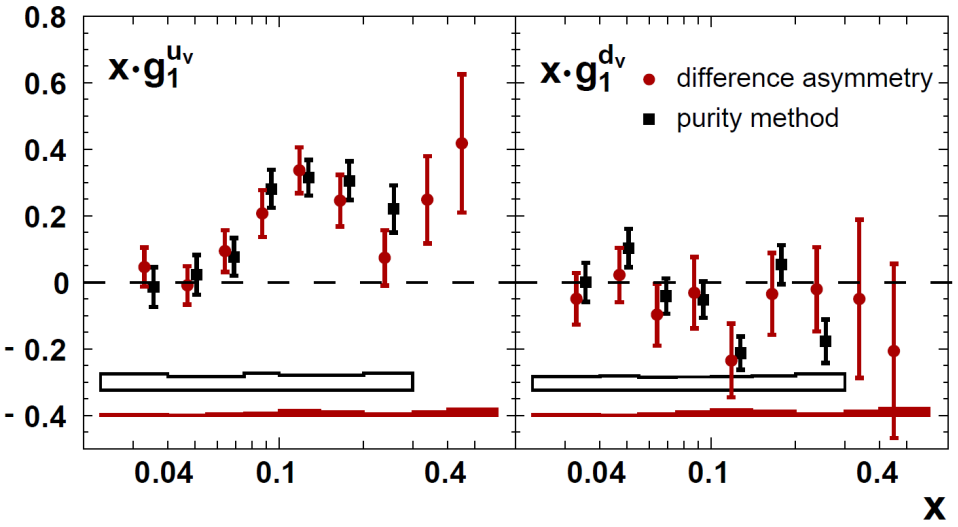
isospin symmetry

Charge difference asymmetry

$$A_1^{h^+-h^-}(x) \equiv \frac{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) - \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) + \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}$$



$$\begin{cases} A_{1,p}^{h^+-h^-} \overset{\text{LO LT}}{=} \dfrac{4g_1^{u_v} - g_1^{d_v}}{4f_1^{u_v} - f_1^{d_v}} \\ A_{1,d}^{h^+-h^-} \overset{\text{LO LT}}{=} \dfrac{g_1^{u_v} + g_1^{d_v}}{f_1^{u_v} + f_1^{d_v}} \end{cases}$$



Semi-Inclusive DIS cross section
in the one-photon-exchange approximation

※transverse nucleon polarization neglected

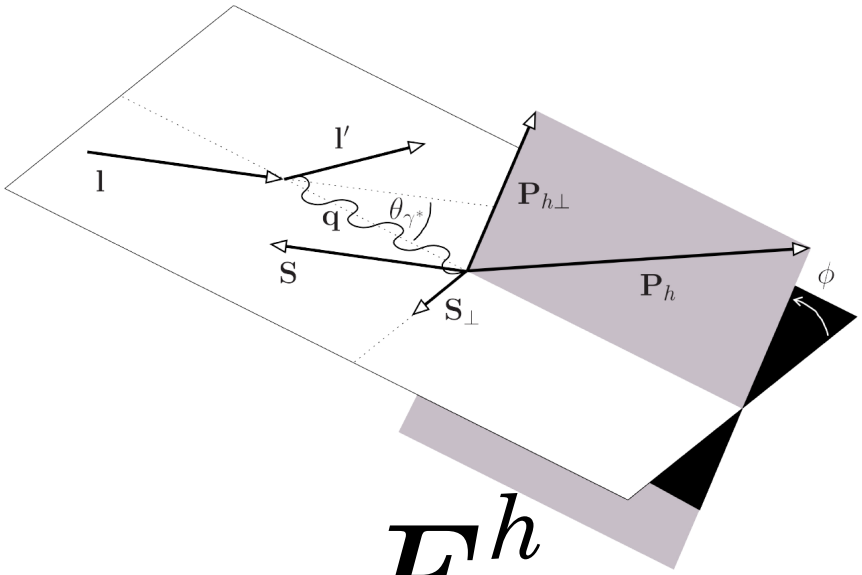
$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1-\epsilon^2}\,F_{LL}^h$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi \Big\}$$



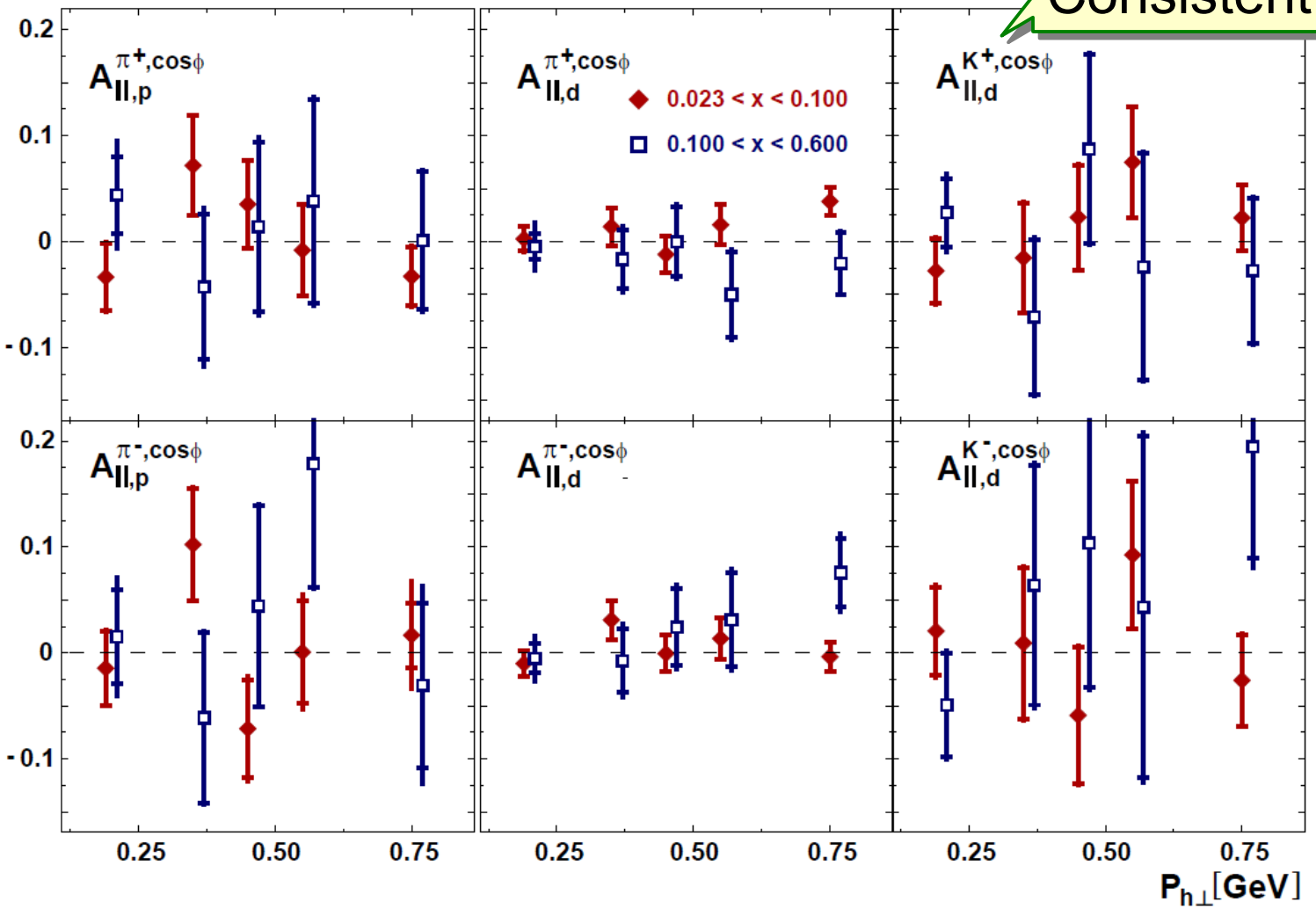
F_{LL}^h

beam L L target

These cosine modulations were extracted.

Azimuthal asymmetry: $A_{\parallel,N}^{h,\cos\phi}(x, P_{h\perp})$

Consistent with zero



$\cos 2\phi$ modulations were also found to be consistent with zero.

Summary

- Extracted longitudinal double-spin asymmetries in SIDIS using the full HERMES data set with updated analysis method
  - the most complete, unintegrated, longitudinally polarized double-spin dataset available
    - provide $A_{\parallel}$ in addition to virtual-photon-nucleon asymmetry A_1
    - no significant dependence on z and $P_{h\perp}$ in A_1 within precision of the measurements
  - hadron-charge difference asymmetries
    - in agreement with COMPASS
    - used for LO, leading-twist extraction of valence helicity PDFs
  - Zero consistent $\cos\phi$ moments of semi-inclusive double-spin asymmetry obtained