Latest results on transverse momentum dependent distribution functions

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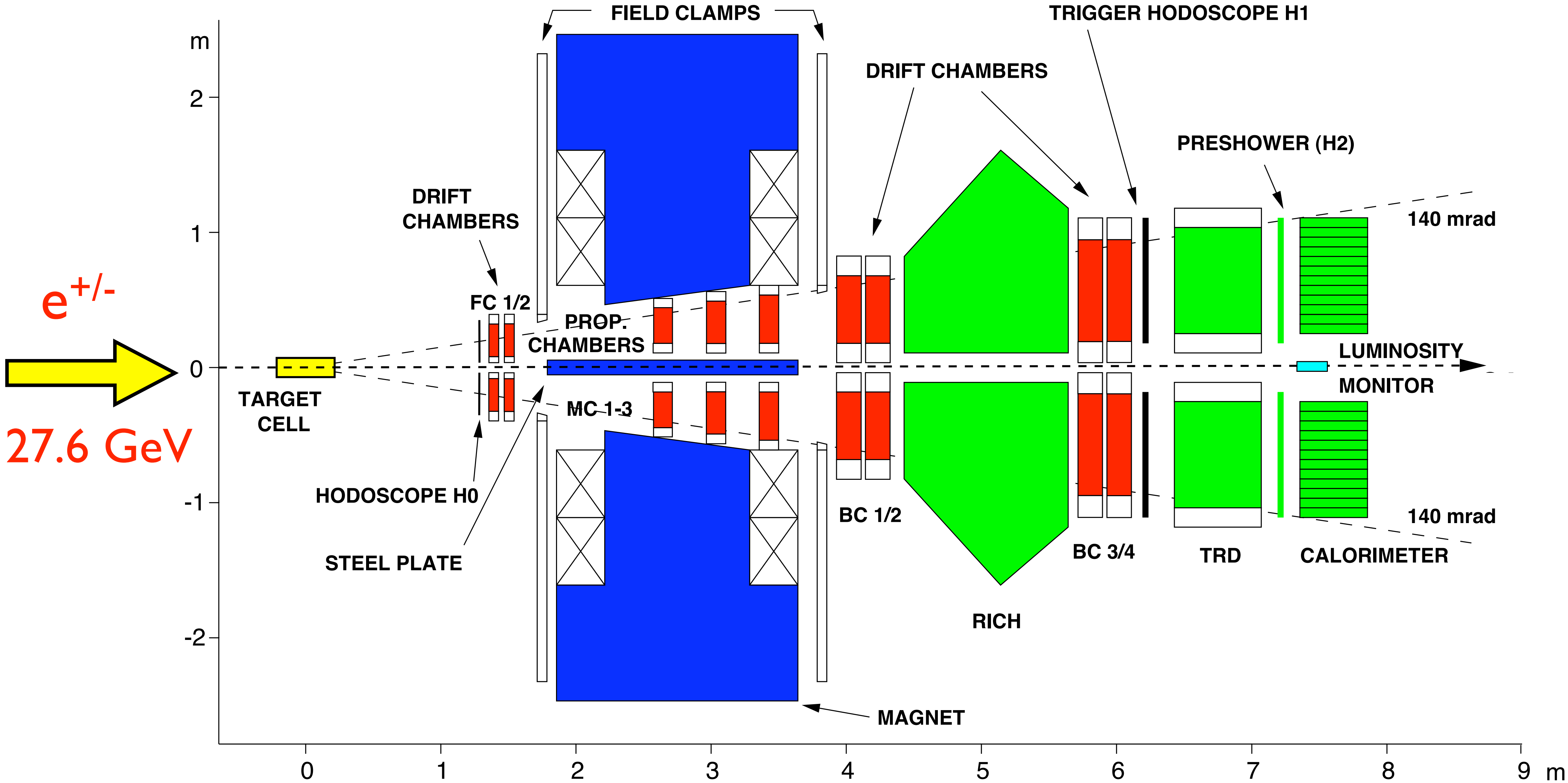
for the hermes collaboration

- HERMES overview
- Transverse single-spin asymmetries in semi-inclusive DIS
  - Collins effect (final results: Phys. Lett. B 693 (2010) 10-16)
  - Sivers effect (final results: PRL 103 (2009) 152002)
- Transverse target single-spin asymmetries in inclusive hadron production in DIS (new preliminary results)

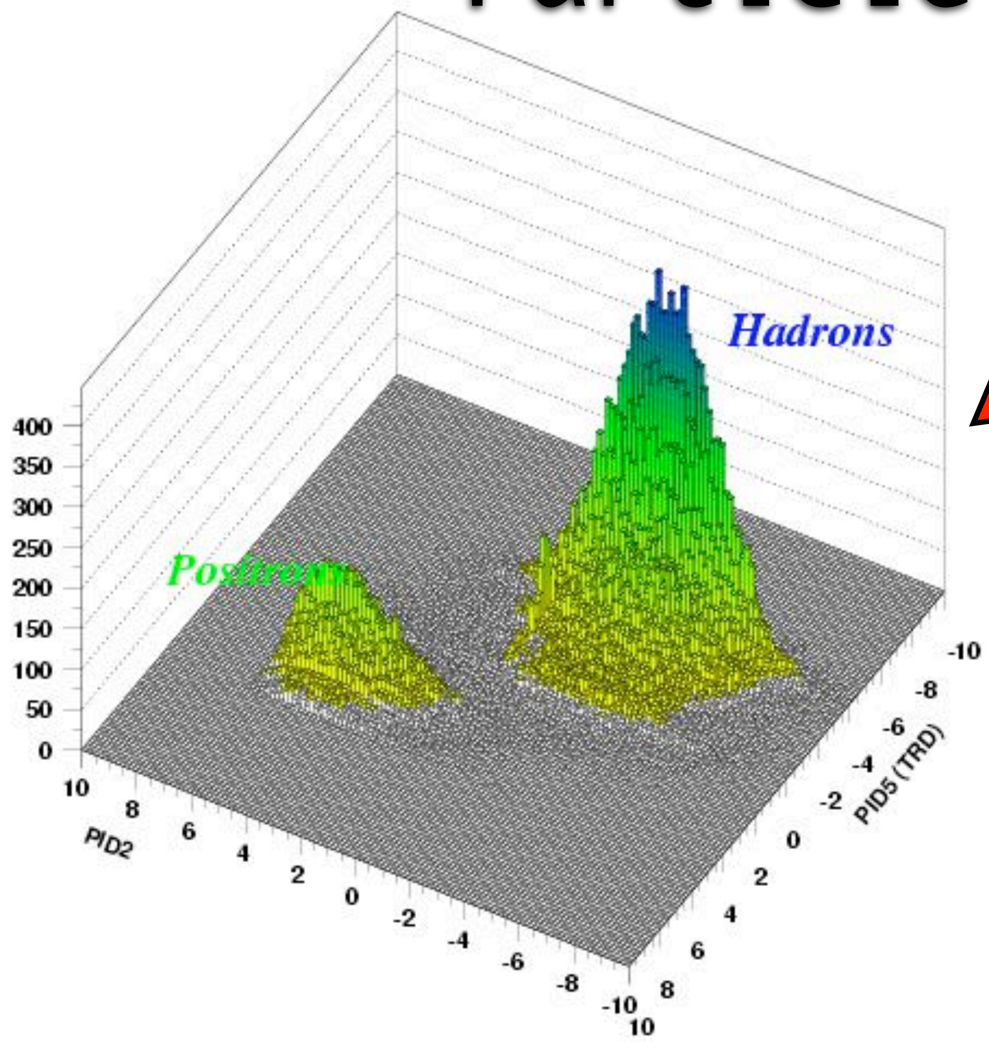
HERMES Spectrometer



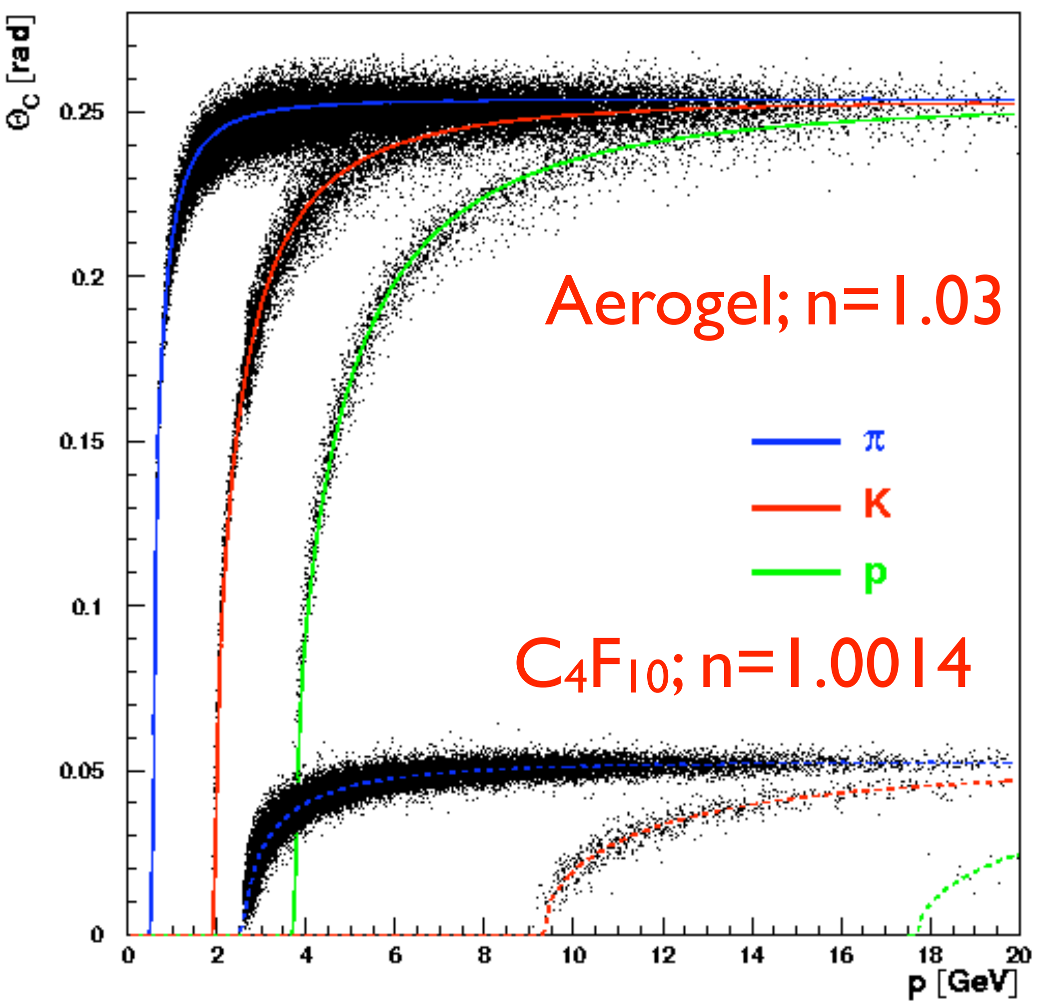
- forward acceptance spectrometer: 40 mrad $\leq \Theta \leq$ 220 mrad
- kinematic coverage: $0.02 \leq x_{Bj} \leq 0.8$ for $Q^2 > 1$ GeV^2 and $W > 2$ GeV
- tracking: $\delta P/P$ = 0.7% - 2.5%, $\delta\Theta \leq$ 1 mrad
- PID: TRD, Preshower, Calorimeter, RICH

Particle Identification

excellent lepton/hadron separation



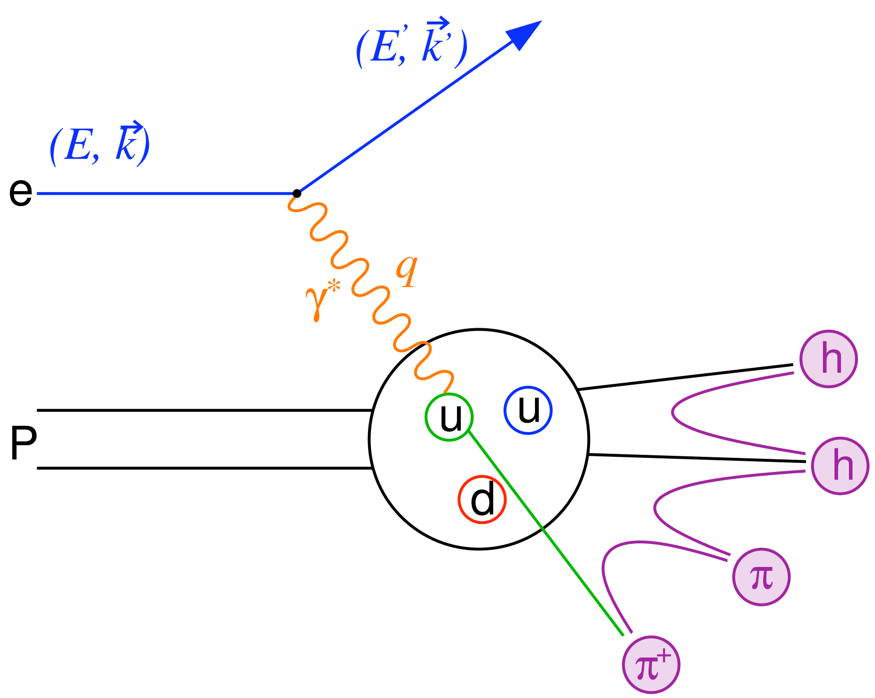
RICH: two radiators allow hadron separation between 2-15 GeV



Transverse target single-spin asymmetries in semi-inclusive DIS

DIS: probing the nucleon structure

e$^{+,-}$ @ 27.6 GeV (HERA)



$$Q^2 = -q^2 = -(k-k')^2$$
$$\nu \stackrel{lab}{=} E - E'$$
$$x = \frac{Q^2}{2M\nu}$$
$$z \stackrel{lab}{=} \frac{E_{had}}{\nu}$$

Target:
H: <P_{trans}>~72.5±5.3%

Cross section contains Distribution Functions and Fragmentation Functions:

$$\sigma^{ep\rightarrow ehX} \sim \sum_q \mathrm{DF}^{p\rightarrow q} \otimes \sigma^{eq\rightarrow eq} \otimes \mathrm{FF}^{q\rightarrow h}$$

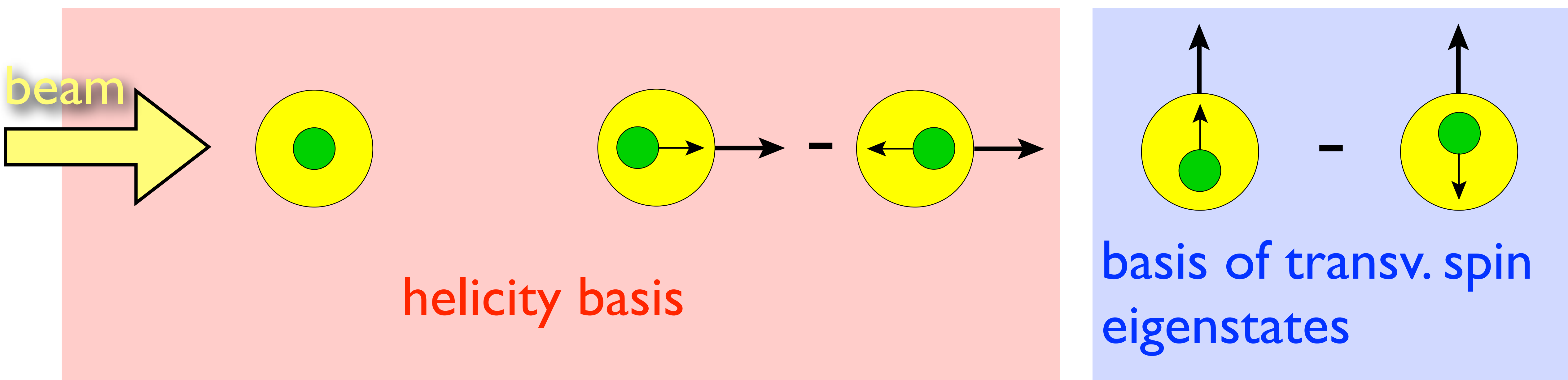
DF: distribution of quarks in the nucleon
FF: fragmentation of (struck) quark into hadronic final state

Distribution functions

Leading twist:

3 DFs survive integration over transverse quark momenta

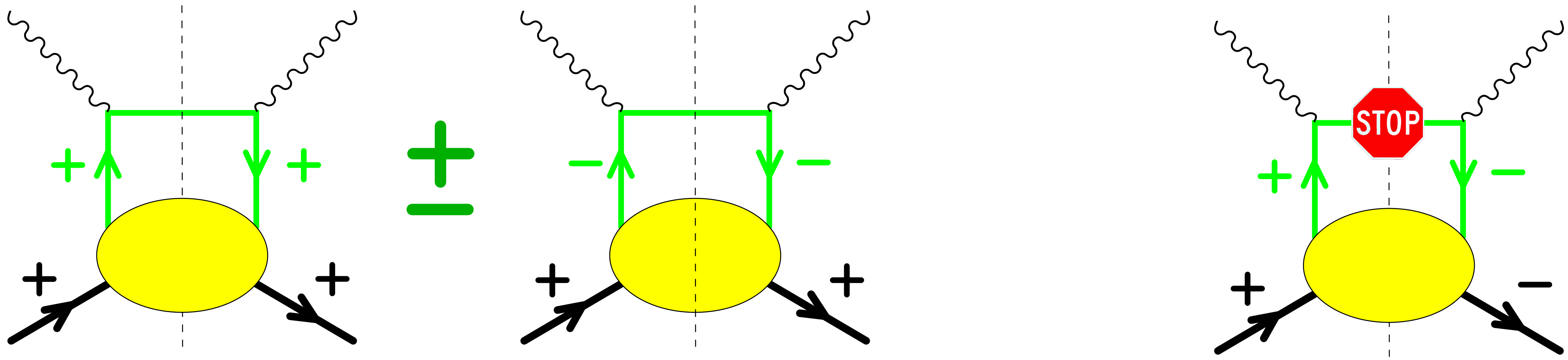
momentum distribution	**helicity distribution**	**transversity distribution**
$q(x)$	$\Delta q(x)$	$\delta q(x)$



all three DFs needed for complete description of the nucleon!

Transversity δq

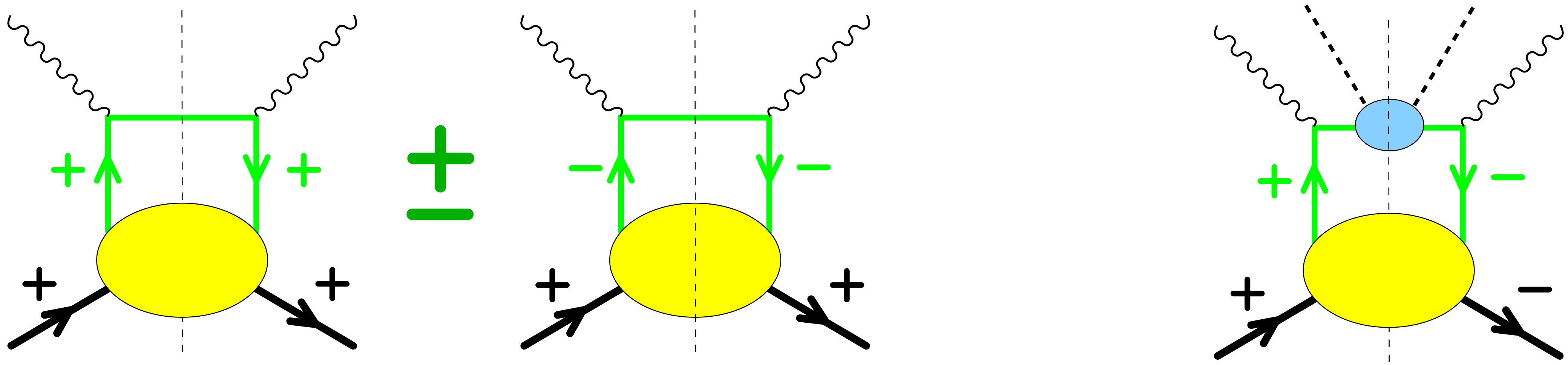
- δq: helicity-flip of the quark ⇒chiral-odd



$+ \Rightarrow q(x)$ $\quad - \Rightarrow \Delta q(x)$ $\quad \delta q(x)$

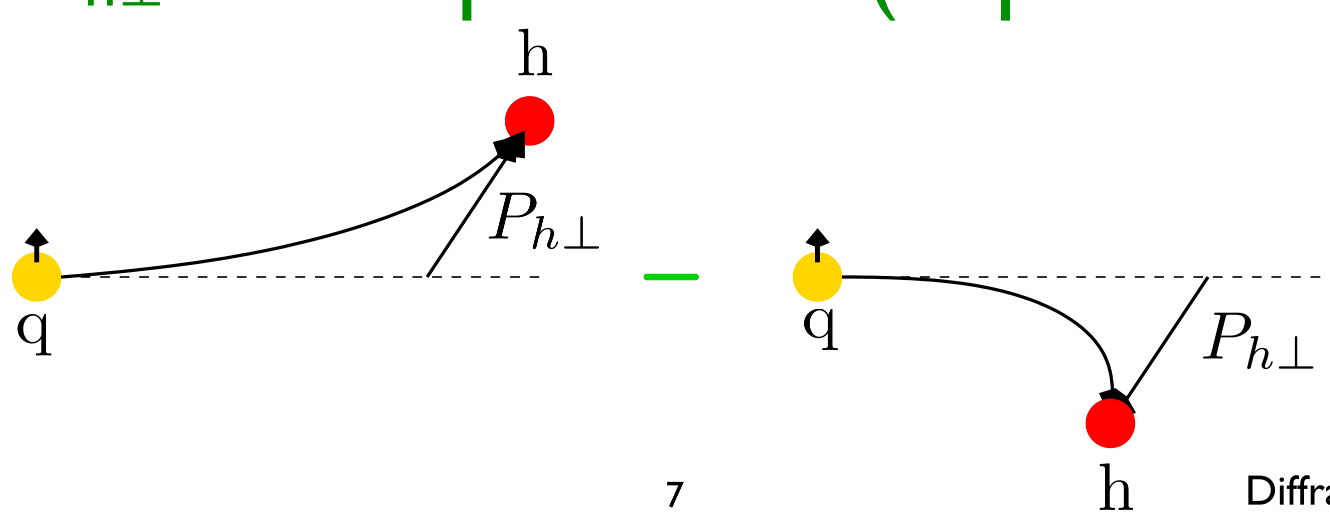
Transversity δq

- δq: helicity-flip of the quark ⇒chiral-odd



$+ \Rightarrow q(x)$ $\quad - \Rightarrow \Delta q(x)$ $\quad \delta q(x)$

- Collins-FF $H_1^\perp$ describes correlation between transverse polarisation of fragmenting quark and the transverse momentum $P_{h\perp}$ of the produced (unpolarised) hadron



Azimuthal Asymmetries

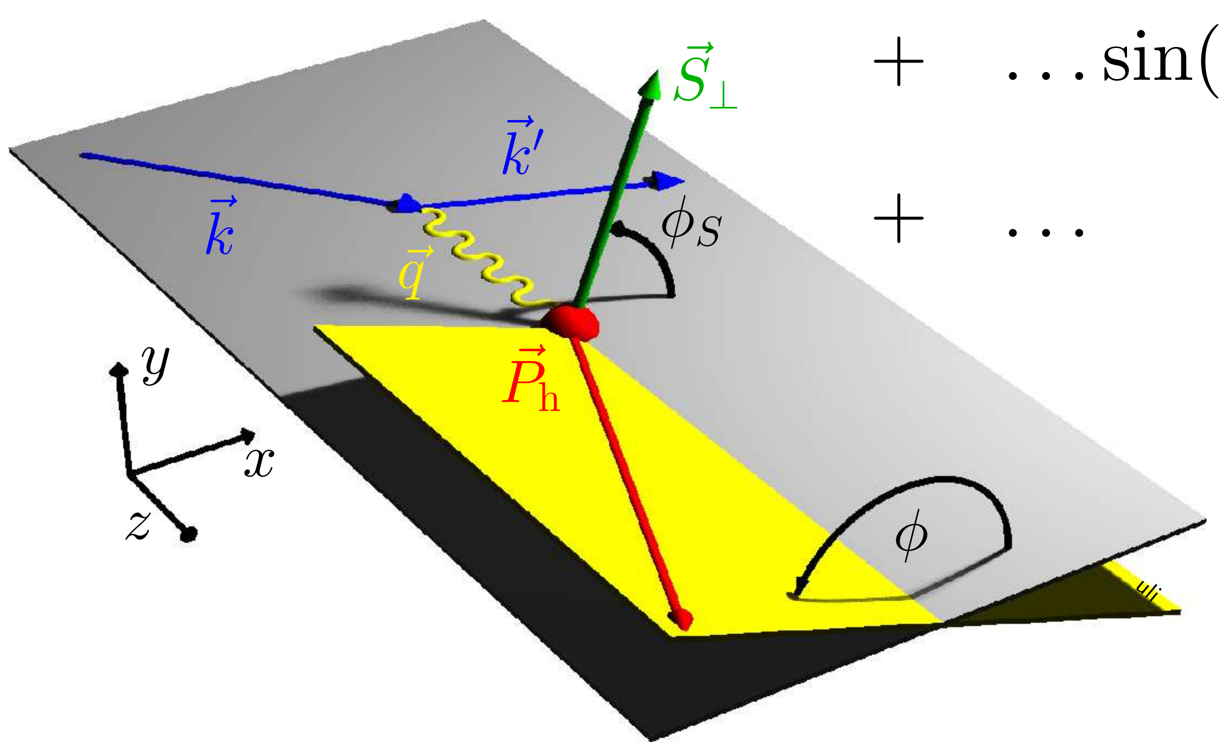
Measurement of cross-section asymmetries depending on the azimuthal angles Φ and Φ_S

$$A_{UT}(\phi,\phi_S,\ldots) = \frac{1}{S_\perp}\frac{\sigma^{\Uparrow}-\sigma^{\Downarrow}}{\sigma^{\Uparrow}+\sigma^{\Downarrow}}$$

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

$$+ \ldots\sin(\phi-\phi_S)\frac{\sum_q e_q^2\,\mathcal{I}\left[\ldots f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, q(x)\cdot D_1^q(z)}$$

$$+ \ldots$$



$\mathcal{I}[\ldots]$ convolution integral over initial (p_T) and final (k_T) quark transverse momenta

Azimuthal Asymmetries

Measurement of cross-section asymmetries depending on the azimuthal angles Φ and Φ_S

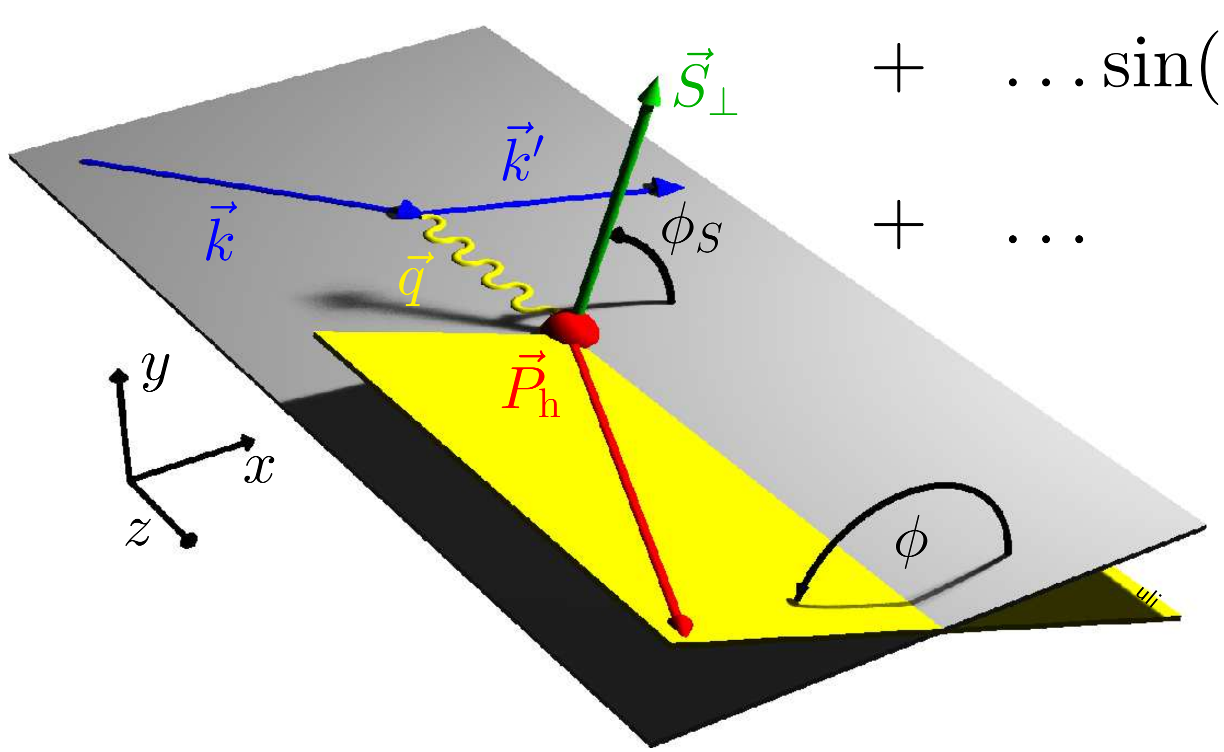
$$A_{UT}(\phi, \phi_S, \ldots) = \frac{1}{S_\perp} \frac{\sigma^{\Uparrow} - \sigma^{\Downarrow}}{\sigma^{\Uparrow} + \sigma^{\Downarrow}}$$

Collins Amplitude

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

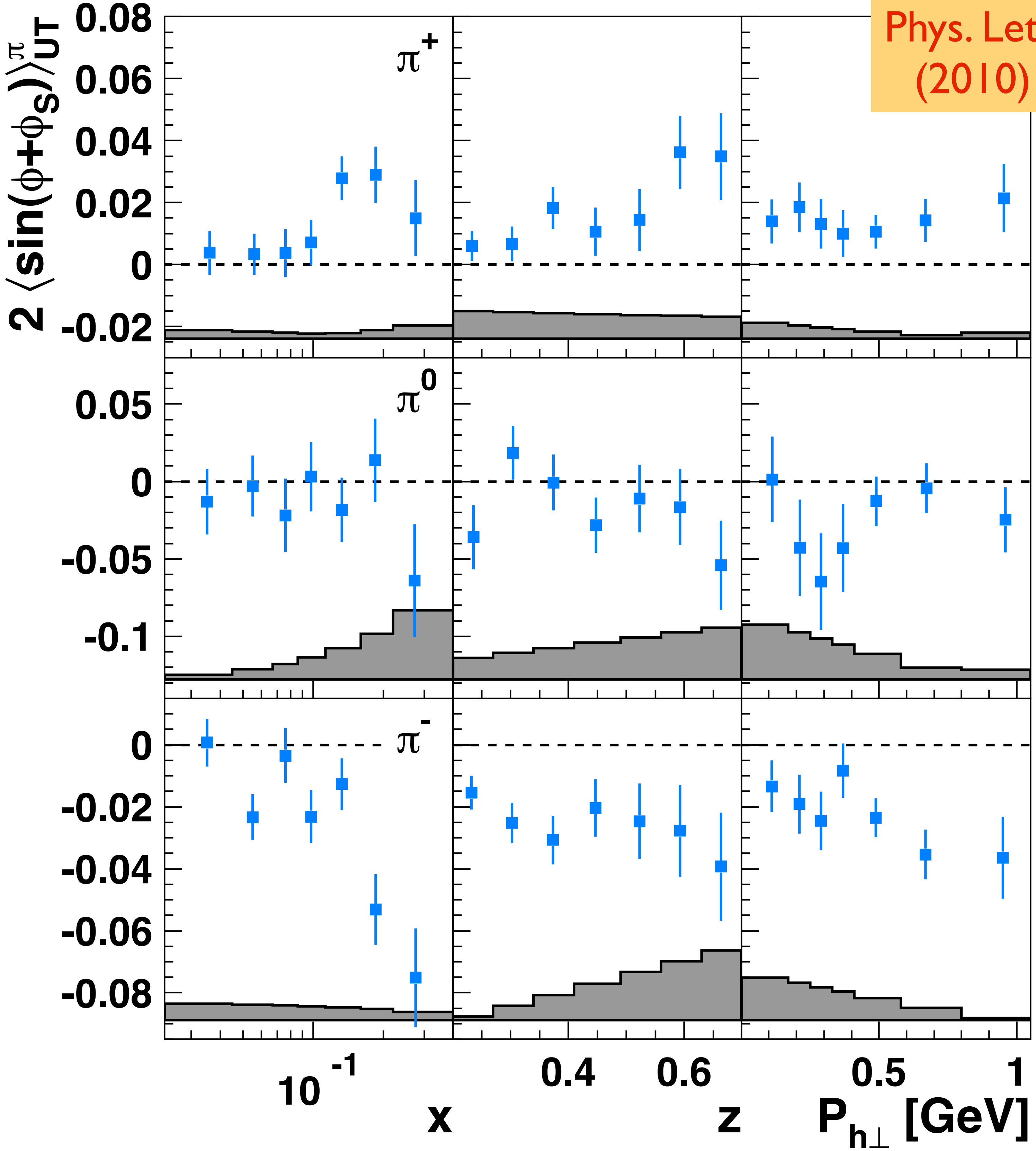
$$+ \ldots \sin(\phi - \phi_S) \frac{\sum_q e_q^2 \, \mathcal{I}\left[\ldots f_{1T}^{\perp q}(x, \vec{p}_T^{\,2}) \cdot D_1^q(z, \vec{k}_T^{\,2})\right]}{\sum_q e_q^2 \, q(x) \cdot D_1^q(z)}$$

$$+ \ldots$$



$\mathcal{I}[\ldots]$ convolution integral over initial (p_T) and final (k_T) quark transverse momenta

Collins Amplitudes for Pions



Phys. Lett. B 693 (2010) 10-16

$$A_C \propto \delta q \otimes H_1^{\perp}$$

- positive amplitudes for π^+
- large negative π^- amplitude

$$u \rightarrow \pi^+ \quad \Rightarrow \quad H_1^{\perp,\mathrm{fav}}$$

$$u \rightarrow \pi^- \quad \Rightarrow \quad H_1^{\perp,\mathrm{unfav}}$$

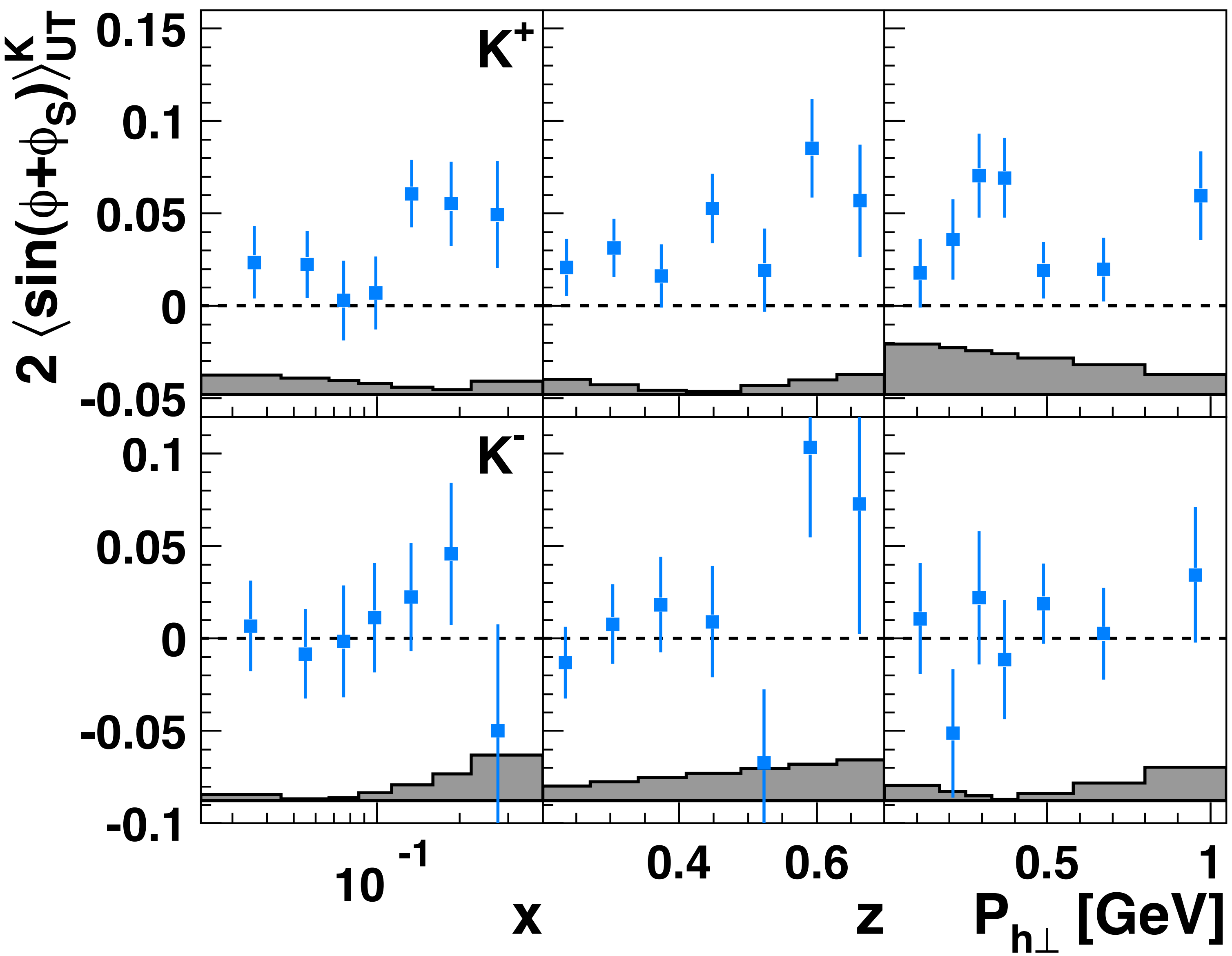
$$\Rightarrow \quad H_1^{\perp,\mathrm{fav}} \approx -H_1^{\perp,\mathrm{unfav}}$$

- π^0 consistent with zero (isospin symmetry)
- information from another process on Collins FF (BELLE) allows extraction of δq (eg. Anselmino et. al. Phys.Rev.D75:054032,2007)

Collins Amplitudes for Kaons

$$A_C \propto \delta q \otimes H_1^{\perp}$$

Phys. Lett. B 693 (2010) 10-16



- Collins amplitudes for K^+ larger than for π^+
- Collins fragmentation function for kaons unknown
- Collins amplitudes for K^- consistent with zero
- Sea quark transversity expected to be small

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Collins Amplitude

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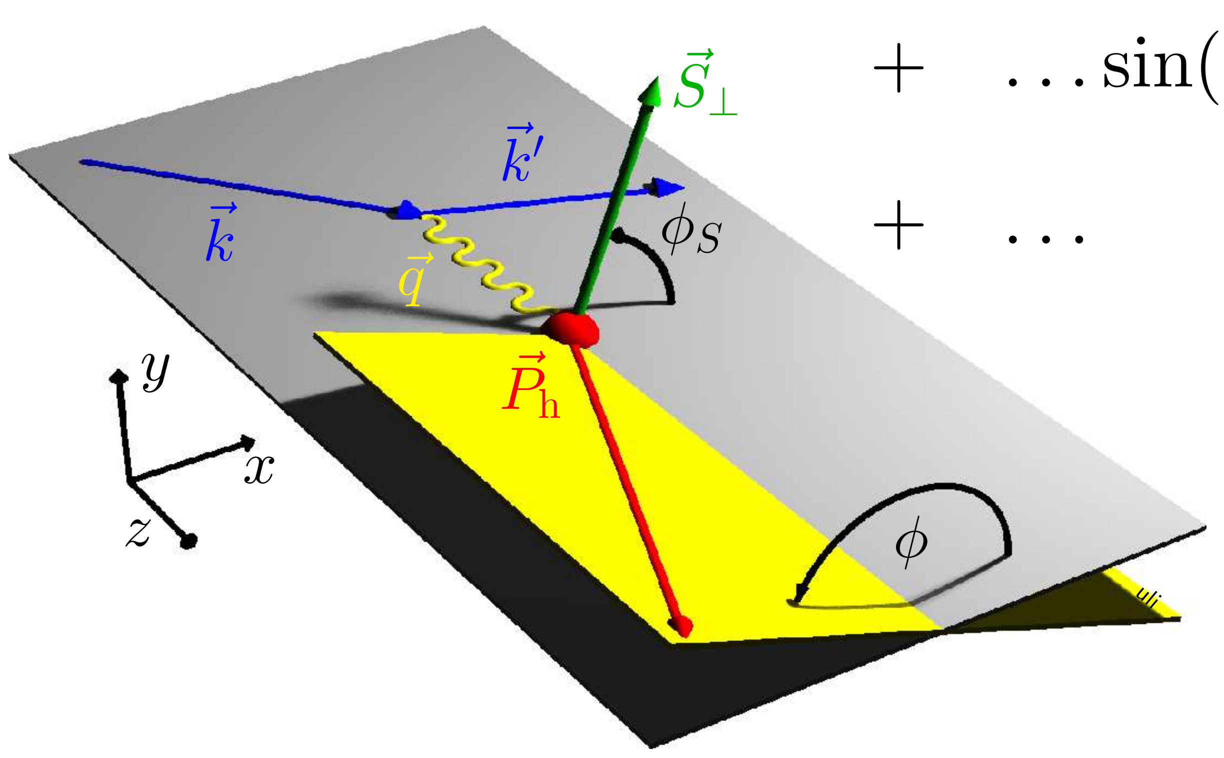
$$+ \ldots \sin(\phi-\phi_S)\frac{\sum_q e_q^2\,\mathcal{I}\left[\ldots f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, q(x)\cdot D_1^q(z)}$$

$$+ \ldots$$



$\mathcal{I}[\ldots]$ convolution integral over initial (p_T) and final (k_T) quark transverse momenta

Azimuthal Asymmetries

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Collins Amplitude

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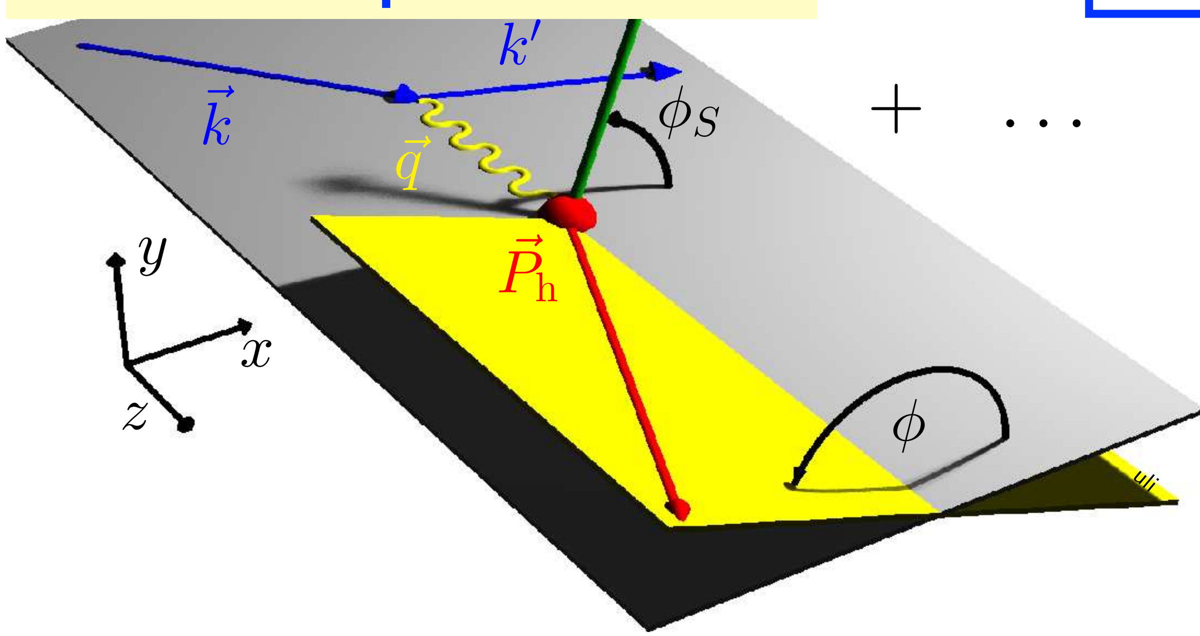
Sivers Amplitude

$$+ \ldots \sin(\phi - \phi_S) \frac{\sum_q e_q^2 \, \mathcal{I}\left[\ldots f_{1T}^{\perp q}(x, \vec{p}_T^{\,2}) \cdot D_1^q(z, \vec{k}_T^{\,2})\right]}{\sum_q e_q^2 \, q(x) \cdot D_1^q(z)}$$

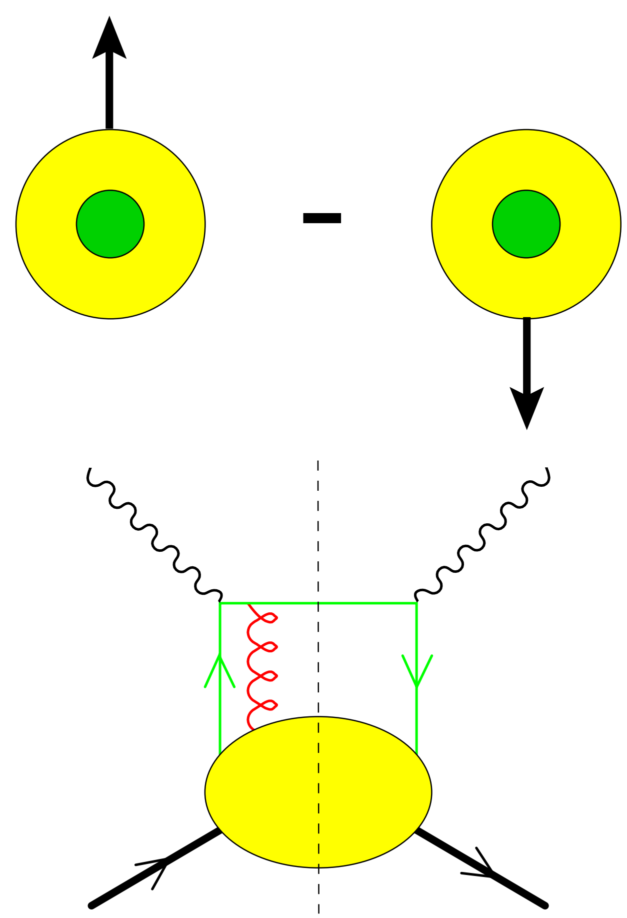
$$+ \ldots$$



$\mathcal{I}[\ldots]$ convolution integral over initial (p_T) and final (k_T) quark transverse momenta

Sivers function

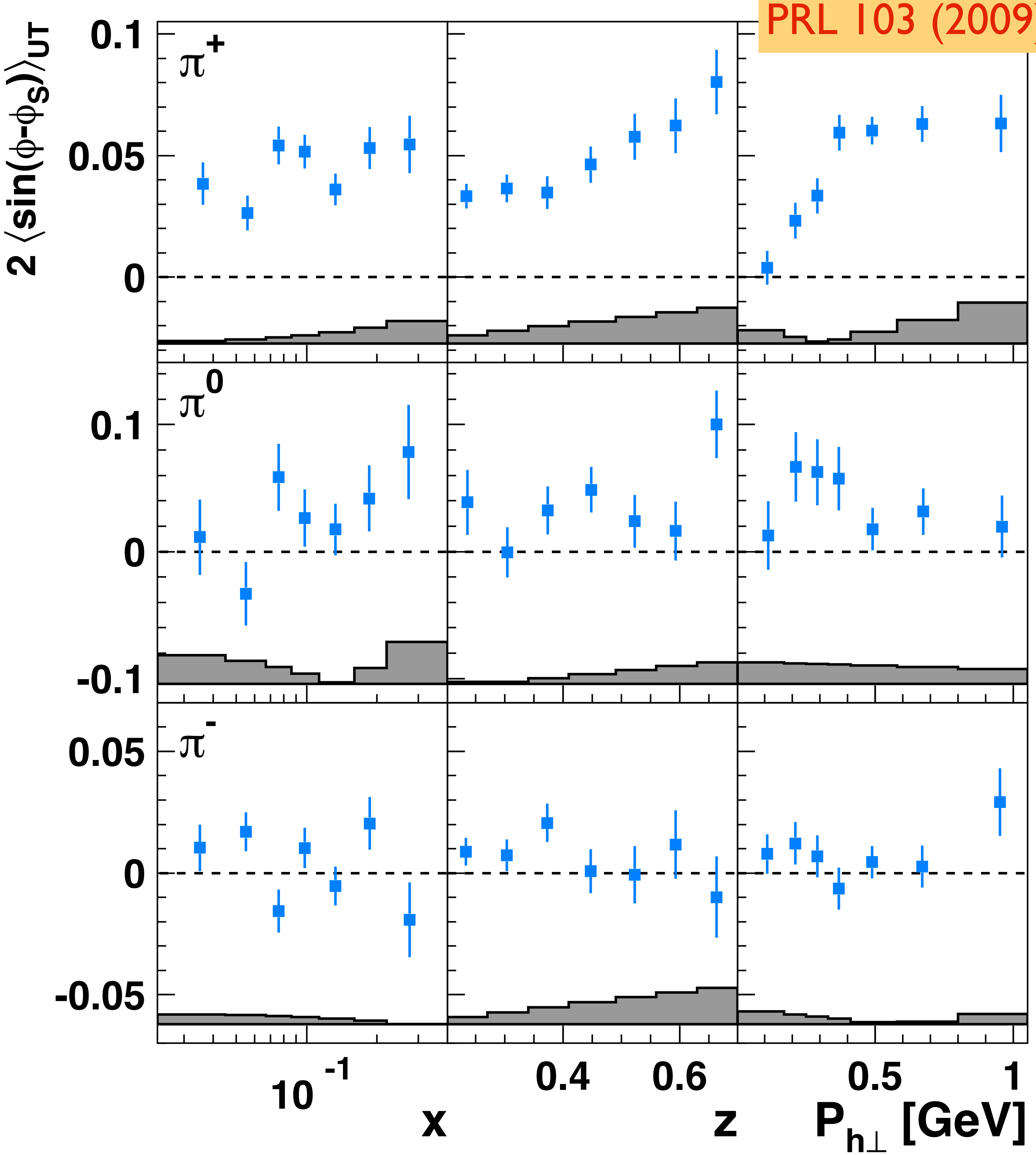
- describes correlation between intrinsic transverse quark momentum (p_T) and transverse nucleon spin
- chiral-even function
- T-odd functions allowed due to final state interactions (FSI):
  quark rescattering via a soft gluon
- non-zero Sivers function requires non-vanishing orbital angular momentum in the nucleon wave function
  (can contribute to nucleon spin!)



Sivers Amplitudes for Pions

PRL 103 (2009) 152002

$$A_S \propto f_{1T}^{\perp} \otimes D_1^q$$

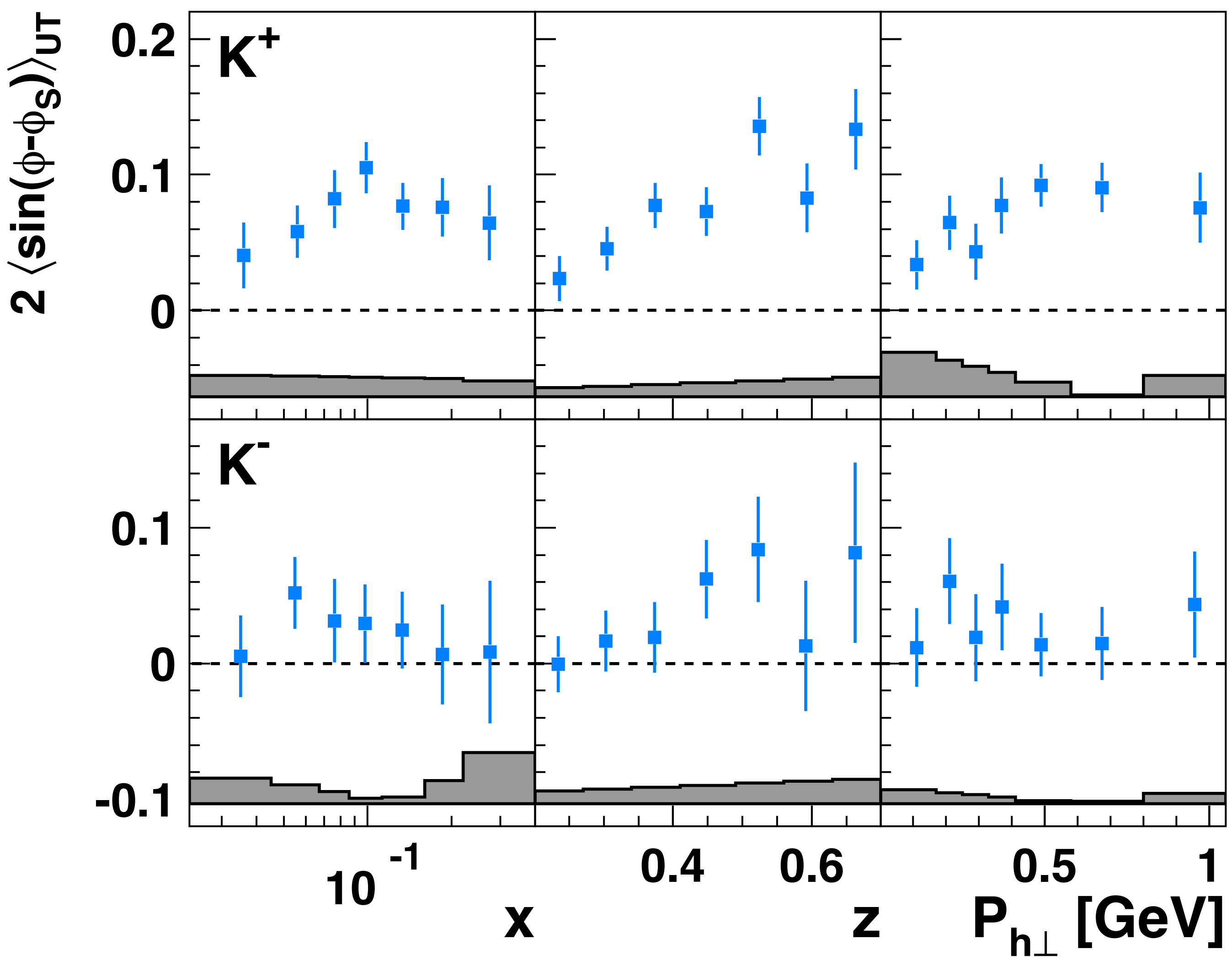


- significantly positive for π^+
- rise with low $p_{h\perp}$, plateau at high $p_{h\perp}$
- implies non-zero orbital angular momentum of quarks
- slightly positive for π^-
- isospin symmetry of π mesons fulfilled

Sivers Amplitudes for Kaons

PRL 103 (2009) 152002

$$A_S \propto f_{1T}^{\perp} \otimes D_1^q$$



- significantly positive for K^+
- implies non-zero orbital angular momentum of quarks
- slightly positive for K^-
- K^+ amplitude larger than π^+ amplitude

⇒ sea quark contribution to Sivers mechanism may be important

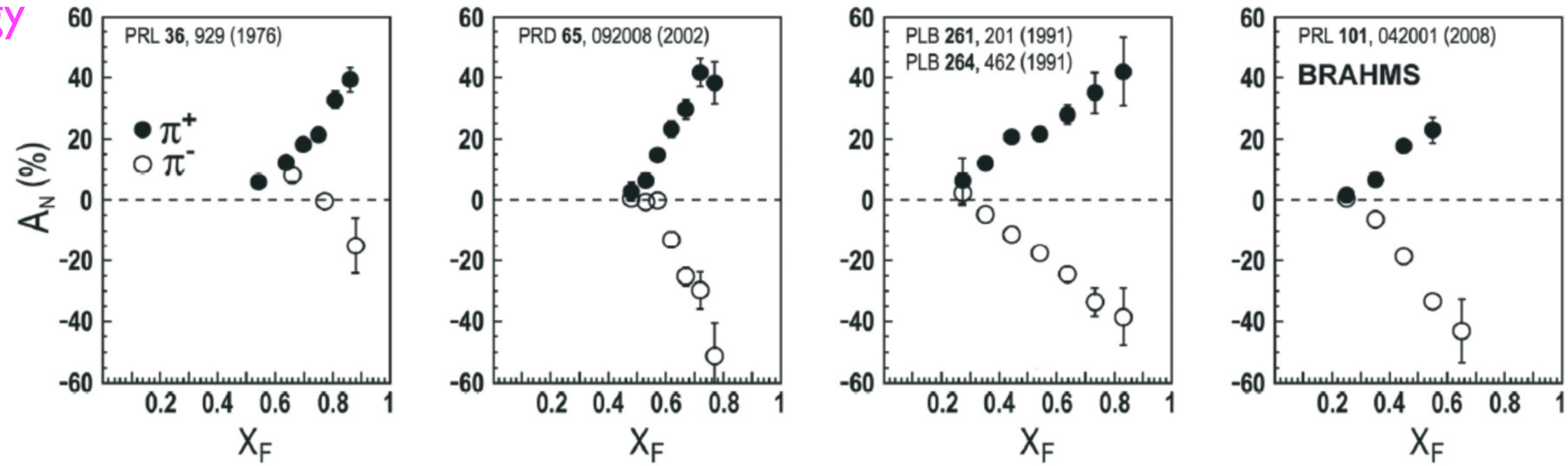
$$\pi^+ = |u\bar{d}\rangle \quad K^+ = |u\bar{s}\rangle$$

Transverse target single-spin asymmetries in inclusive hadron production in DIS

Transverse single-spin asymmetry of inclusive hadrons (I)

- reminder: clear non-zero left-right asymmetry A_N measured in inclusive pion production in $p^{\uparrow}p$ collisions:

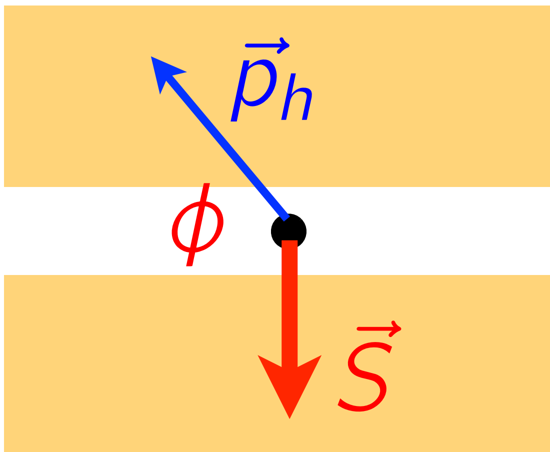
center-of-mass energy: 4.9 GeV, 6.6 GeV, 19.4 GeV, 62.4 GeV



1976 | 2002 | 1991 | 2008

- two models for two approaches:
  - TMD approach: both Sivers and Collins can contribute
  - collinear (high-p_T) approach: Sivers-like and Collins-like

Transverse single-spin asymmetry of inclusive hadrons (II)

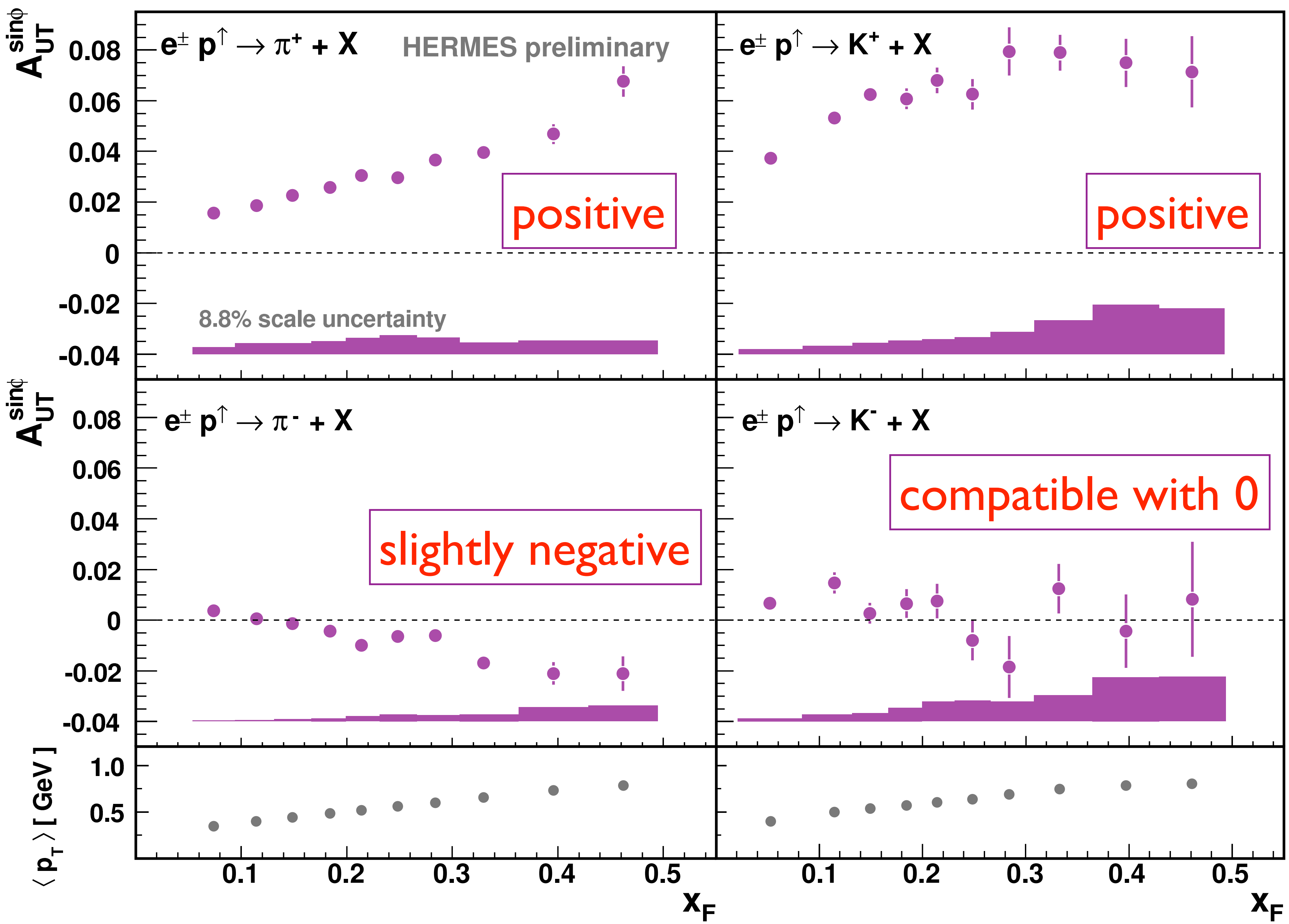


- so far: all available data from $p^{\uparrow}p$ collisions
- HERMES data:
  - first data on leptoproduction $lp^{\uparrow}$ (scattered lepton not detected ⇒ quasi-real photoproduction)
  - high statistics (~100 Million hadrons)
  - complimentary to $p^{\uparrow}p$, cleaner channel (one p quark field)
  - target spin S reversed every 90s (cancelation of systematic effects)

$$A_{UT}(x, Q^2, \phi) \cong A_{UT}^{\sin\phi}(x, Q^2) \sin(\phi)$$

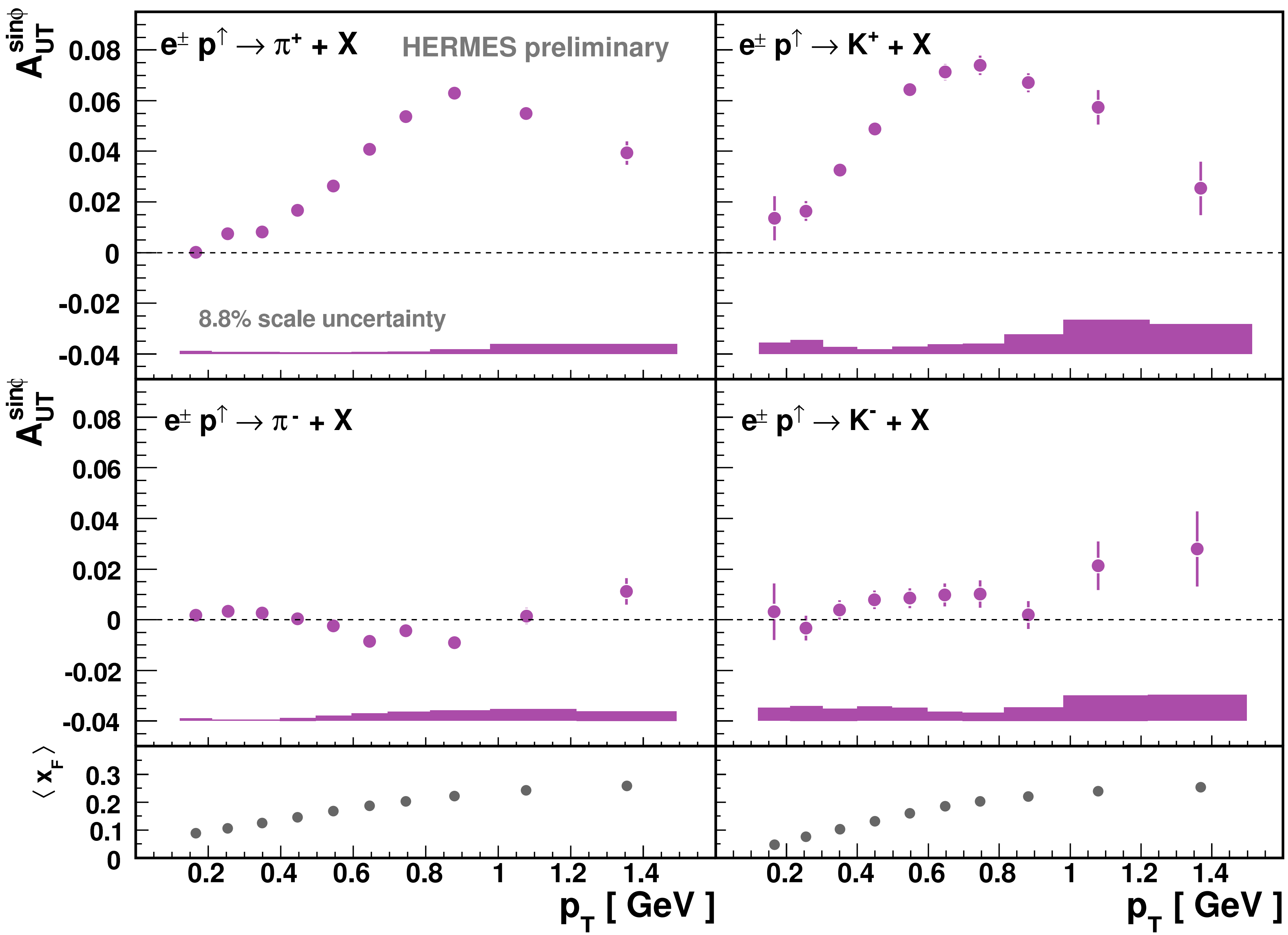
- prediction: $A_{UT} \rightarrow 0$ for high p_T and for $p_T \rightarrow 0$

A_{UT} of incl hadrons vs x_F



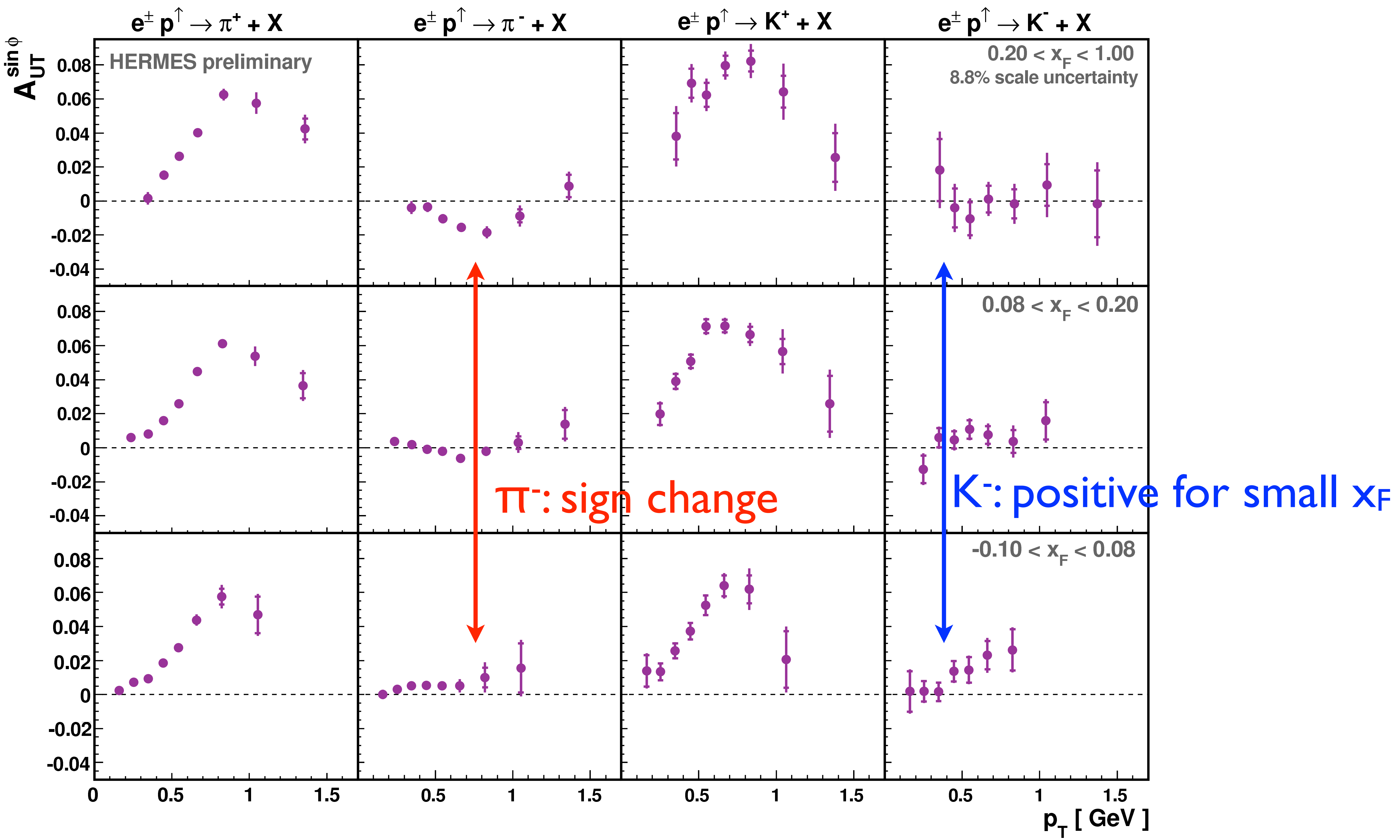
- π: similar to $p^{\uparrow}p$
- K:
  $p^{\uparrow}p$ (Brahms): K^+ and K^- same size and same sign

A_{UT} of incl hadrons vs p_T

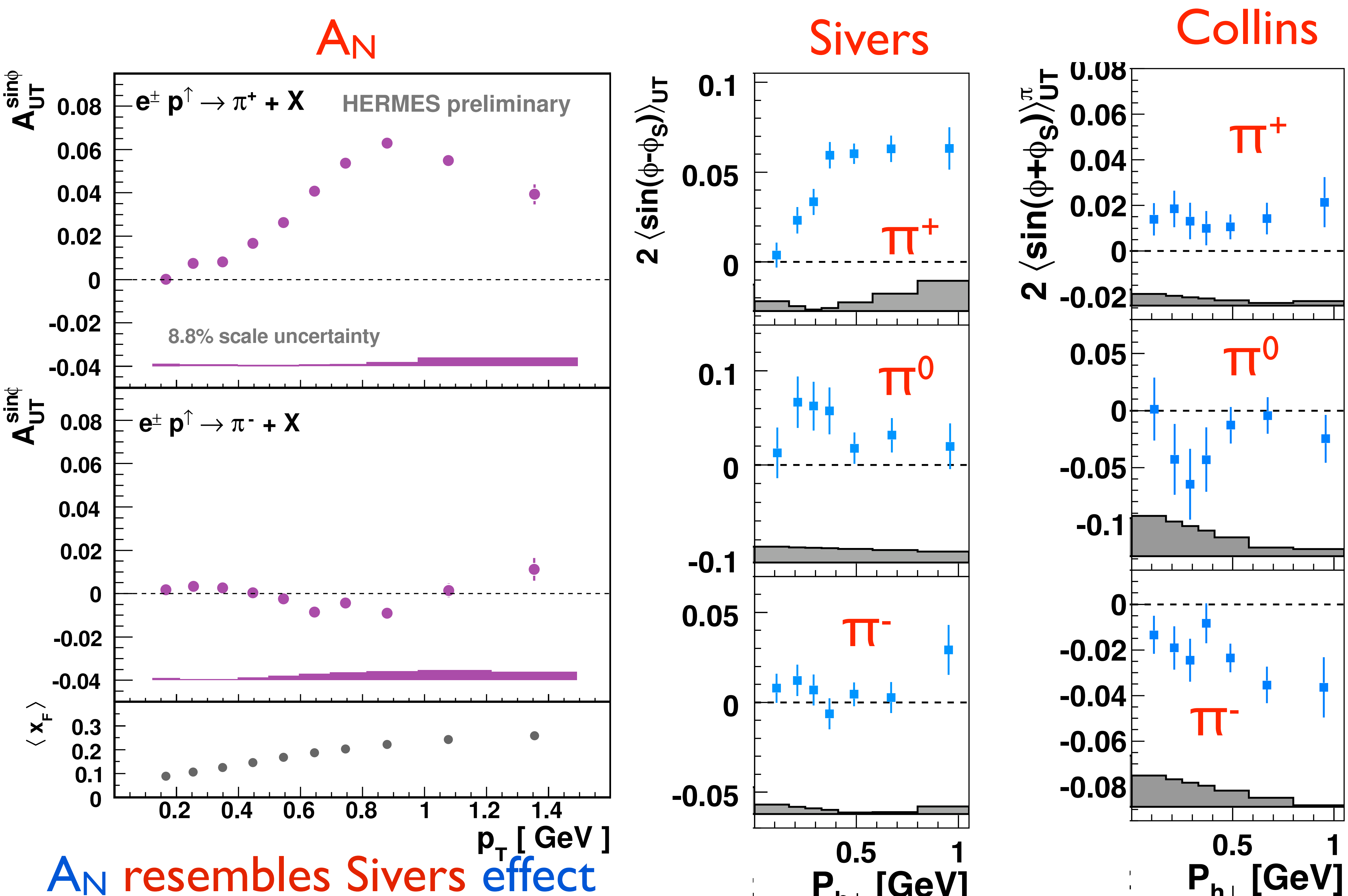


- positive for π^+ and K^+
- small/zero for negative hadrons
- decrease at high p_T

A_{UT} of incl hadrons: 2D



A_{UT} of incl pions vs p_t



AN resembles Sivers effect

as predicted in M.Anselmino et al., PRD 81(2010) 034007

Conclusions

- final results on Collins amplitudes published
  - significant Collins amplitudes for charged pions and K^+

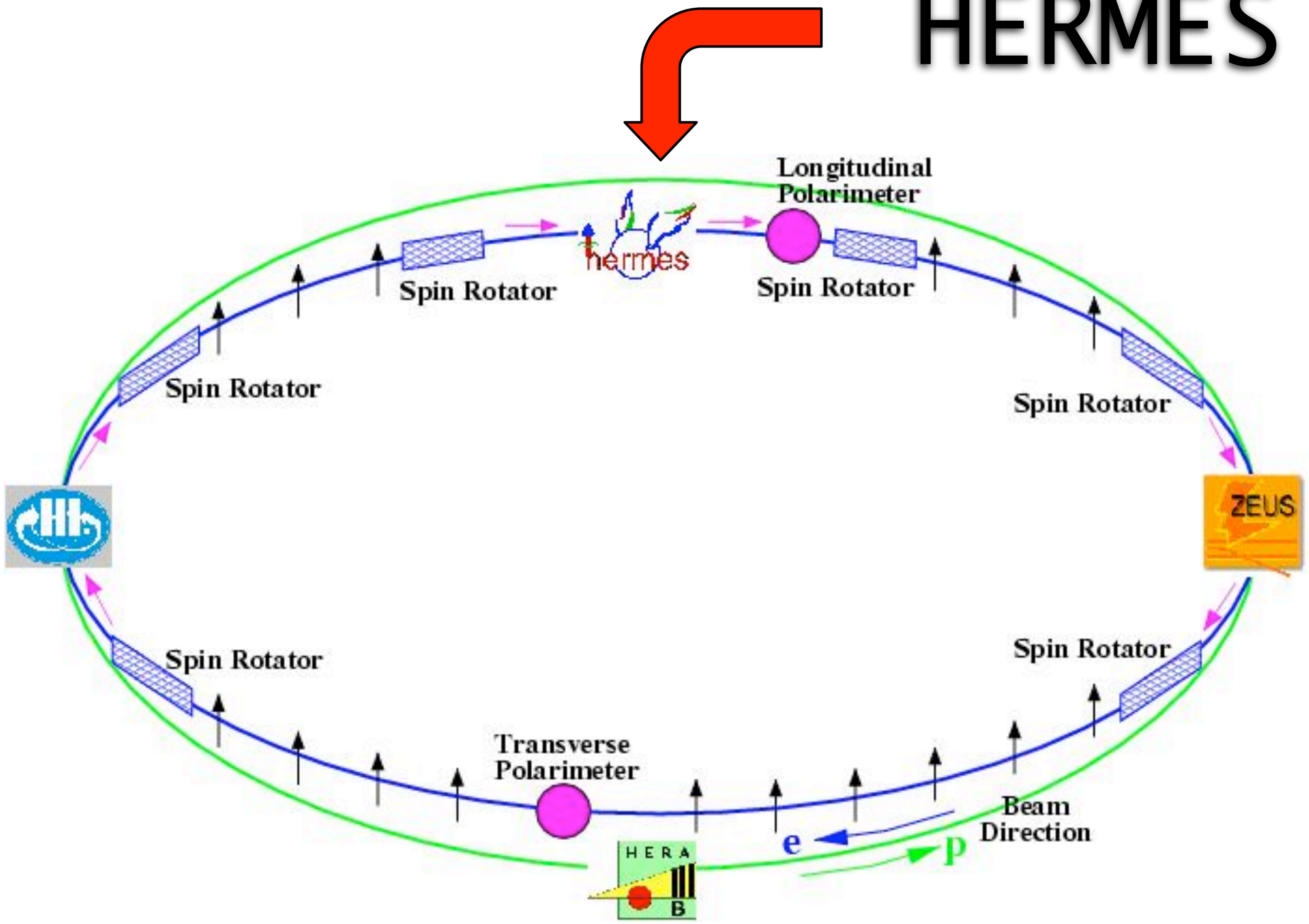
    ⇒ enables quantitative extraction of transversity distribution
- significant Sivers amplitudes for π^+ and K^+ mesons

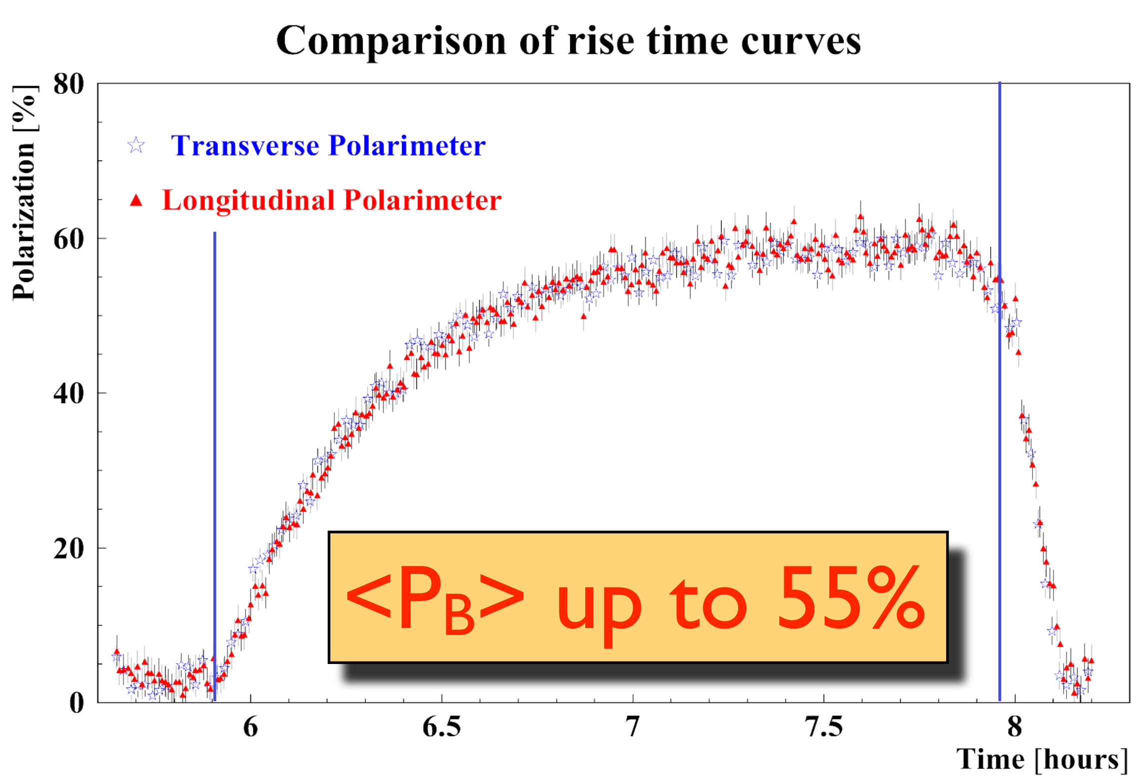
  ⇒ clear (and first) evidence of naive T-odd parton distribution

  ⇒ enables quantitative extraction of the Sivers function
- new preliminary results on transverse target single-spin asymmetries in inclusive hadron production
  - large asymmetry for π^+ and K^+
  - no good theoretical understanding yet of inclusive TTSA

Backup

HERMES @ HERA

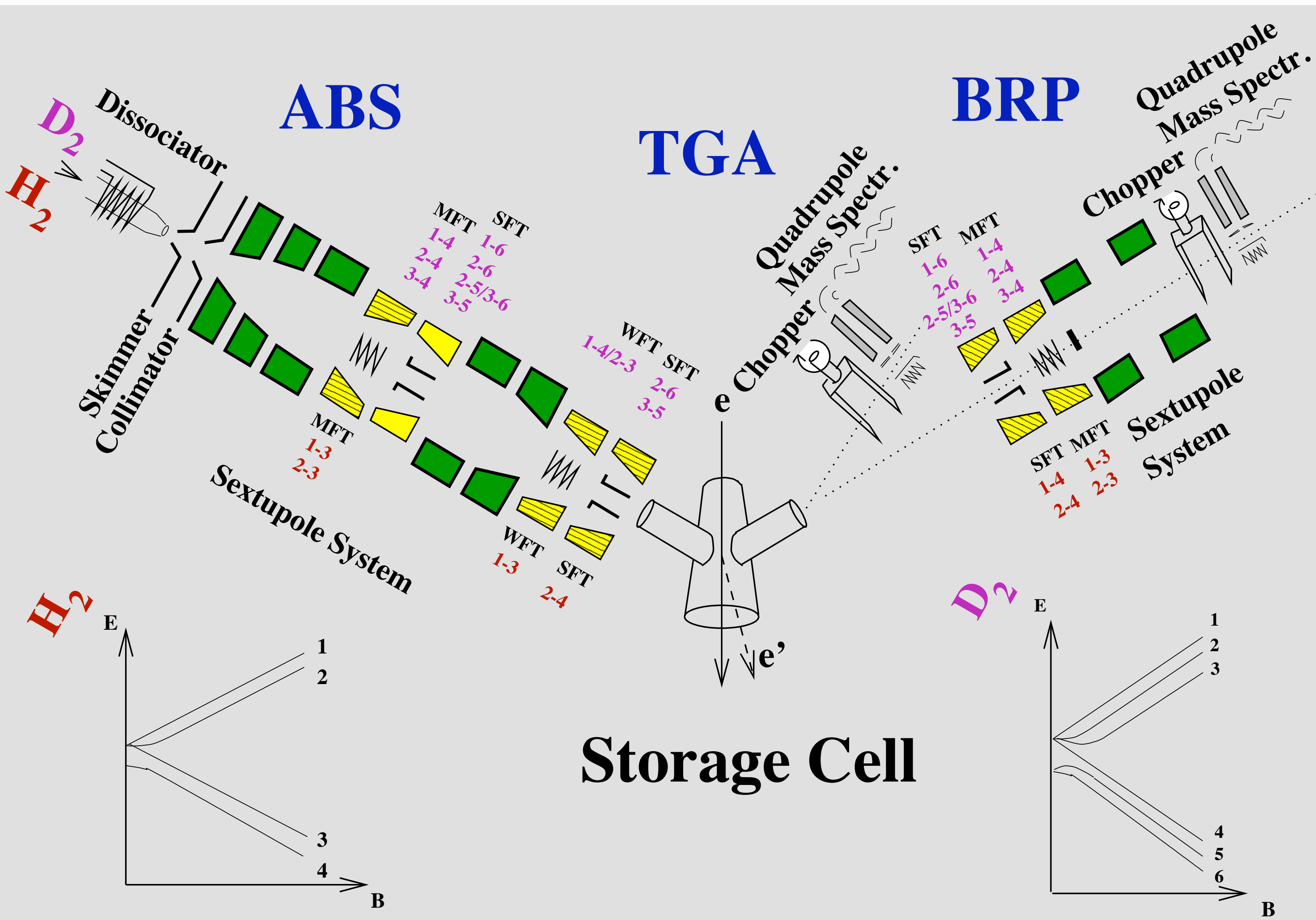




- Fixed target experiment
  - ➡ only using HERA lepton (e^+/e^-) beam
- HERA lepton beam self-polarizing
  - ➡ cross section asymmetry in synchrotron radiation emission leads to build-up of transverse polarization (Sokolov-Ternov effect)
- Spin-rotators ➡ longitudinal polarization at HERMES interaction region
- Beam polarization measured by two independent polarimeters

The HERMES Target

Gaseous target in storage cell aligned with lepton beam



Polarization:
longitudinal: ~85%
transversal: ~75%

Features:

- Pure target (no dilution)
- Unpolarized targets: variety of nuclear targets
  - H, D, He, Ne, Kr, ...
- Polarized targets:
  - Longitudinal pol. (<=2000) H, D, He
  - Transverse pol. (2002-2005) H
  - Rapid reversal of polarization direction within 0.5s (every 90s)