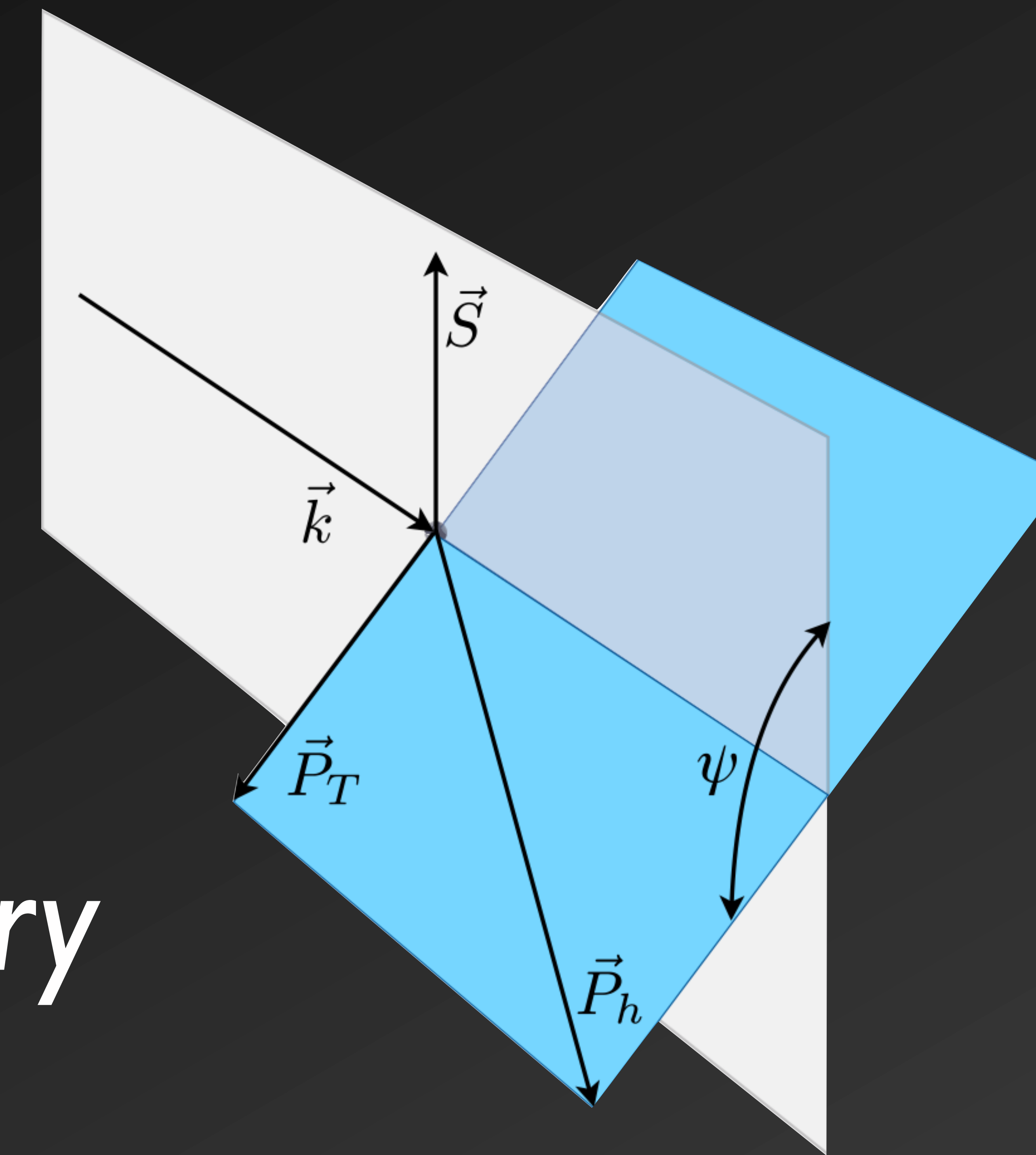
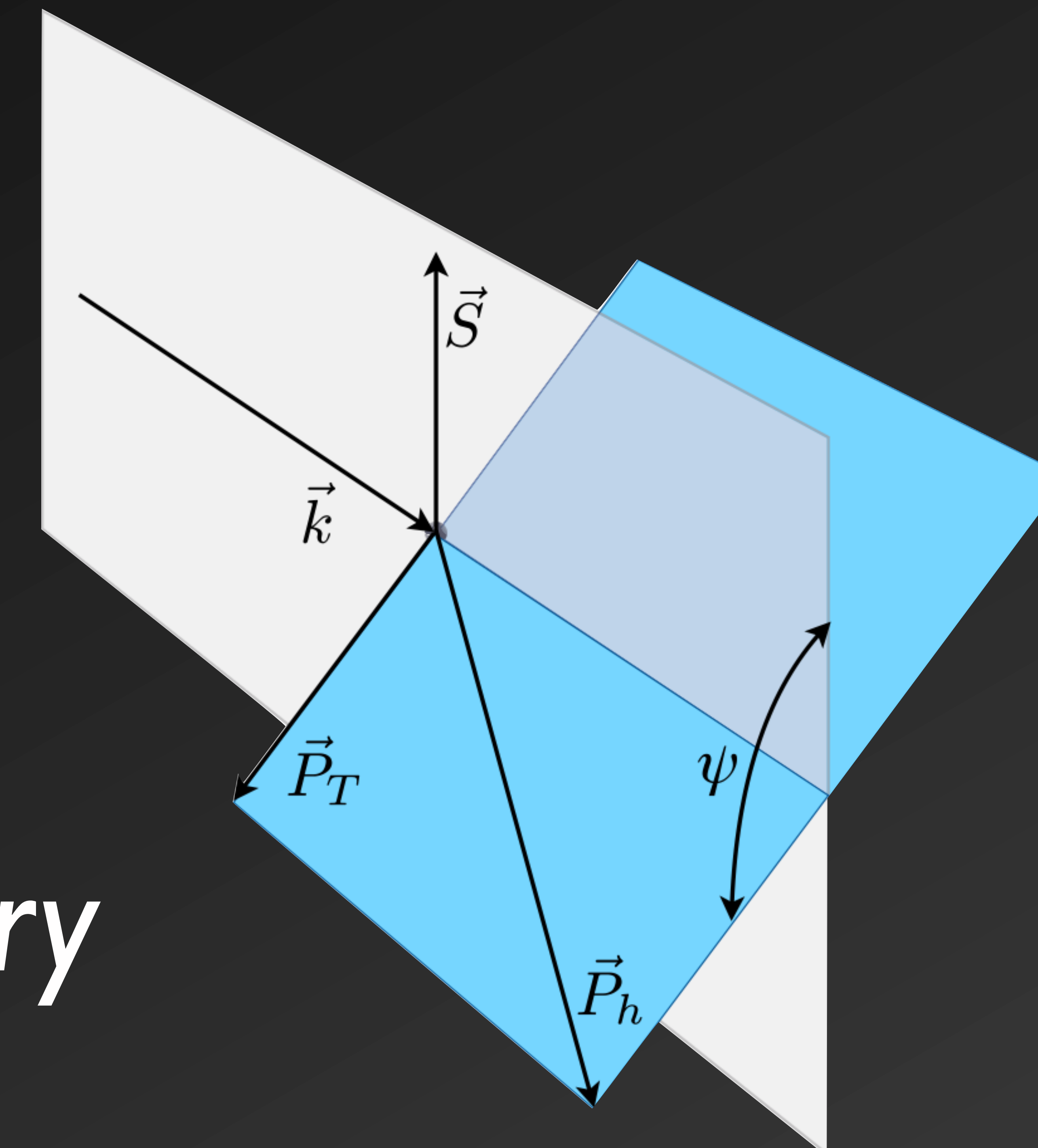


Transverse target single-spin asymmetry (SSA) in inclusive electroproduction of charged pions and kaons [1].

A. Rostomyan, G. Schnell [for the HERMES Collaboration]

[1] HERMES Collaboration, Phys. Lett. B 728 (2014) 183

hermes



Transverse target single-spin asymmetry (SSA) in inclusive electroproduction of charged pions and kaons [1].

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… and many recycled slides from A. Martínez de la Ossa

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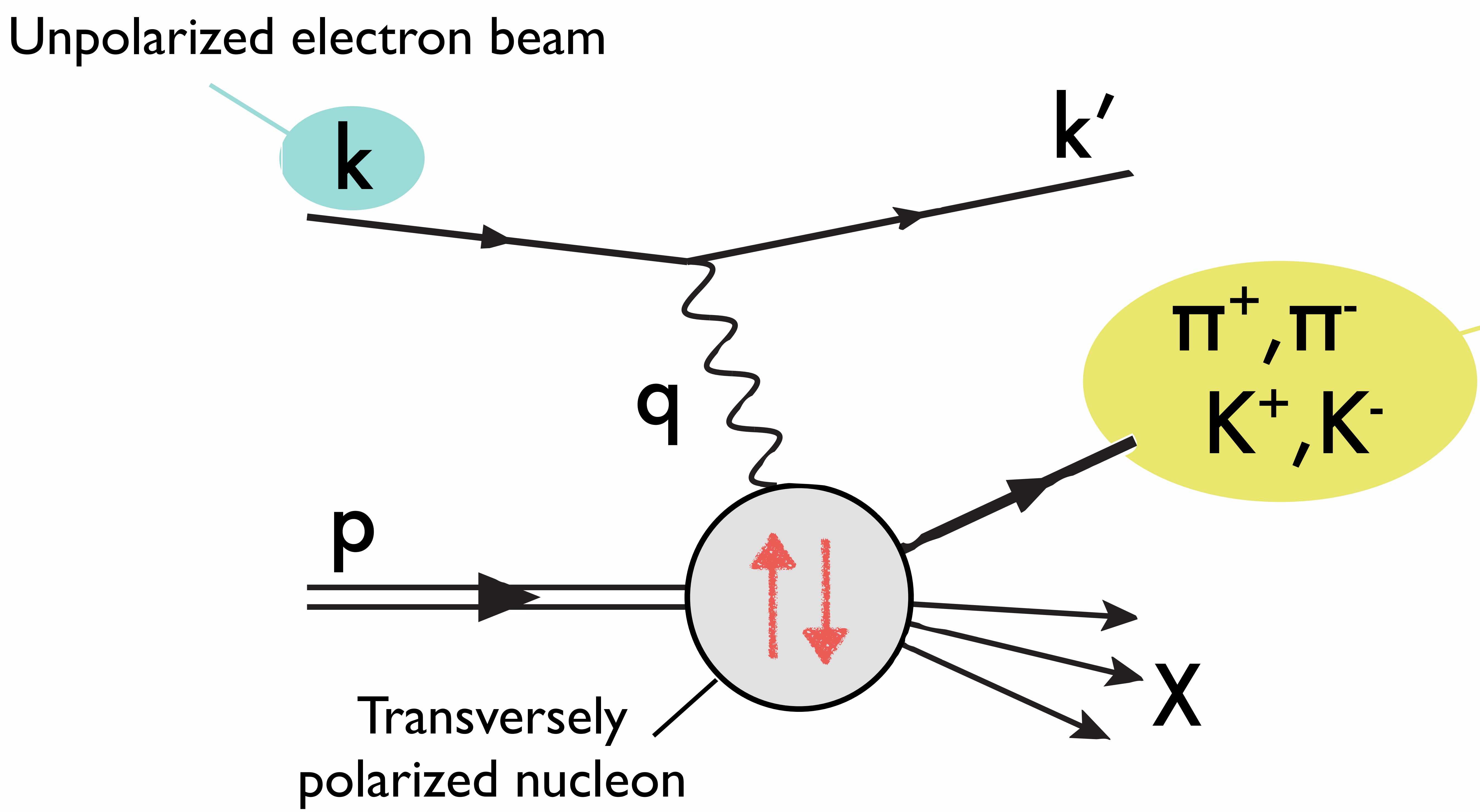
hermes

Outline

- >> Introduction
  - ★ Inclusive electro-production of pions and kaons
  - ★ Transverse single-spin asymmetries
- >> The Measurement
  - ★ The HERMES experiment
  - ★ Yields and kinematics
  - ★ Extraction of amplitudes
- >> The Asymmetries
  - ★ 1-dimensional projections
  - ★ 2-dimensional binning
  - ★ Subsample asymmetries
- >> Summary and Outlook

Inclusive electro-production

of charged π's and K's off a transversely polarized nucleon



$$lN^{\uparrow} \rightarrow hX$$

Only one of these mesons is measured in the final state

Spin-dependent cross section

$$d\sigma_{UT} \propto \vec{S}_T \cdot (\hat{P}_h \times \hat{k})$$

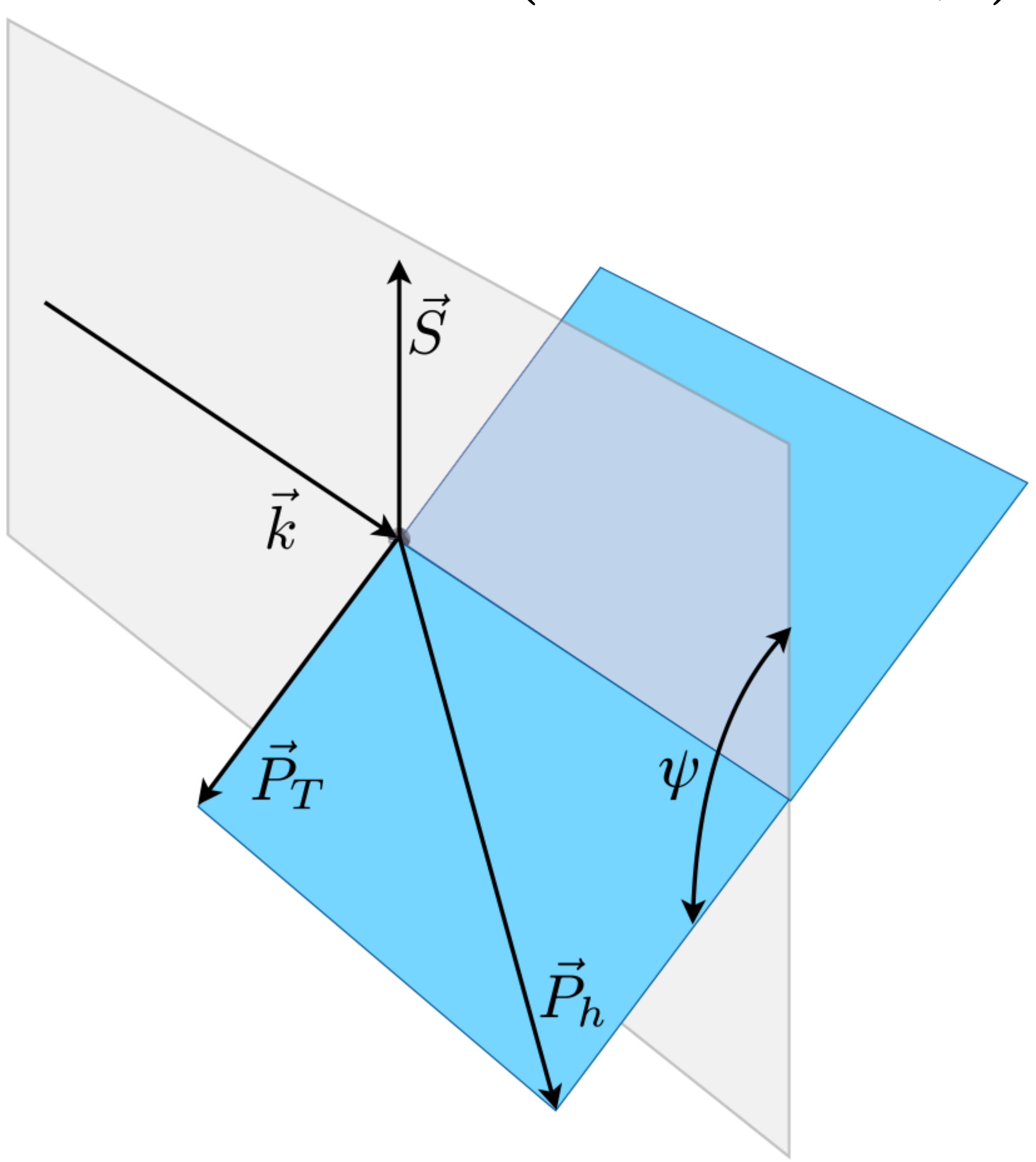
Transverse single-spin asymmetry (SSA)

with respect to the polarization axis of the nucleon

Azimuthal asymmetry (fully differential)

$$A(x_F, P_T, \psi) = \frac{d\sigma_{UT}(x_F, P_T, \psi)}{d\sigma_{UU}(x_F, P_T)} = A_{UT}^{\sin\psi}(x_F, P_T)\, S_T \sin\psi$$

asymmetry (Fourier) amplitude



Independent variables:

$$\{x_F, P_T, \psi\}$$

Feynman-x

$$x_F = 2P_z^{CM}/\sqrt{s}$$

Ratio of the longitudinal hadron momentum P_L along the **beam** direction to its maximum possible value

Transverse single-spin asymmetry (SSA)

with respect to the polarization axis of the nucleon

Azimuthal asymmetry (fully differential)

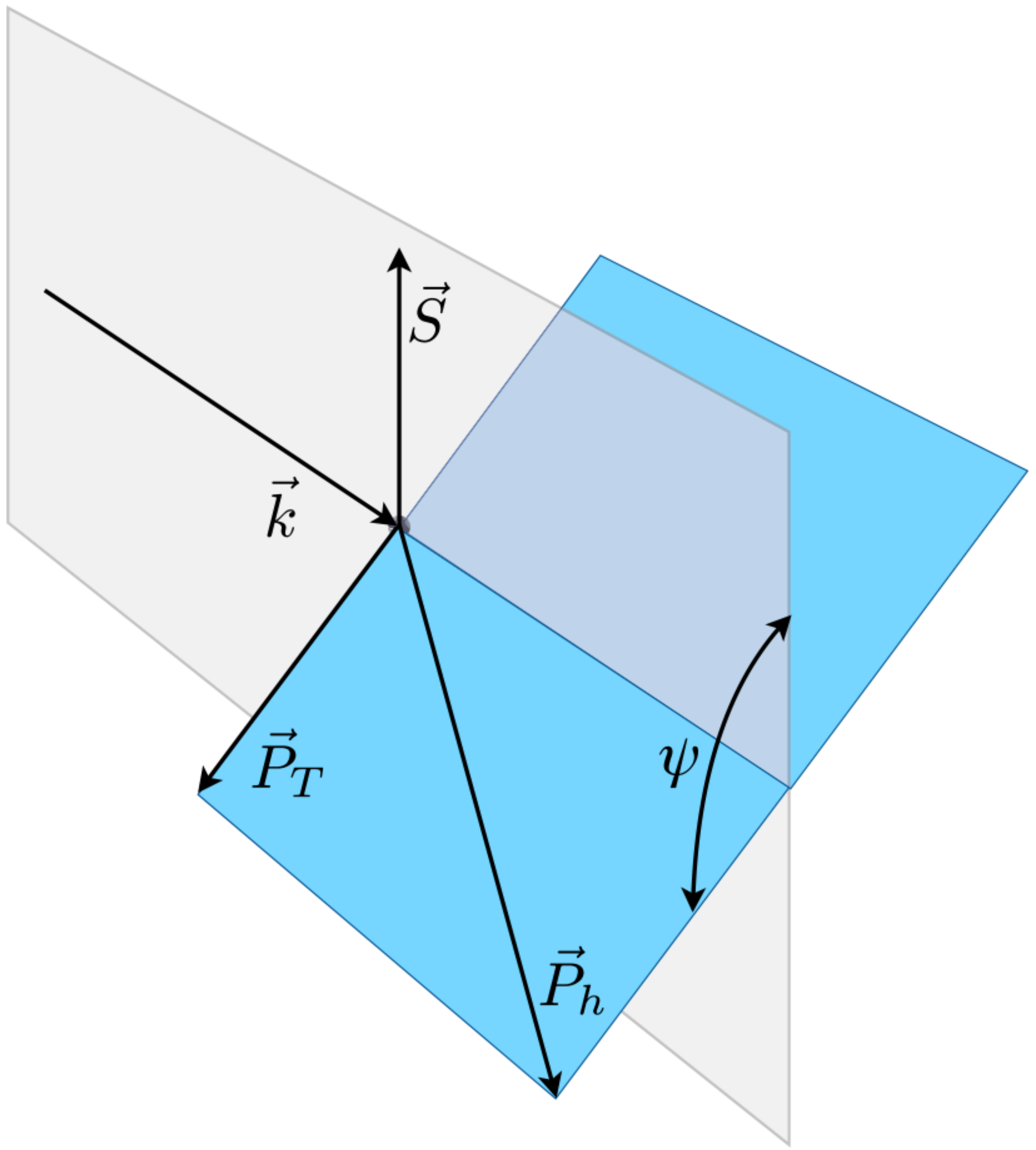
$$A(x_F, P_T, \psi) = \frac{d\sigma_{UT}(x_F, P_T, \psi)}{d\sigma_{UU}(x_F, P_T)} = A_{UT}^{\sin\psi}(x_F, P_T)\, S_T \sin\psi$$

asymmetry (Fourier) amplitude

↕

left-right asymmetry (in beam direction)

$$A_N(x_F, P_T) = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$
$$= -\frac{2}{\pi} A_{UT}^{sin\psi}(x_F, P_T)$$



Independent variables:

$$\{x_F, P_T, \psi\}$$

Feynman-x

$$x_F = 2P_z^{CM}/\sqrt{s}$$

Ratio of the longitudinal hadron momentum P_L along the **beam** direction to its maximum possible value

Motivation

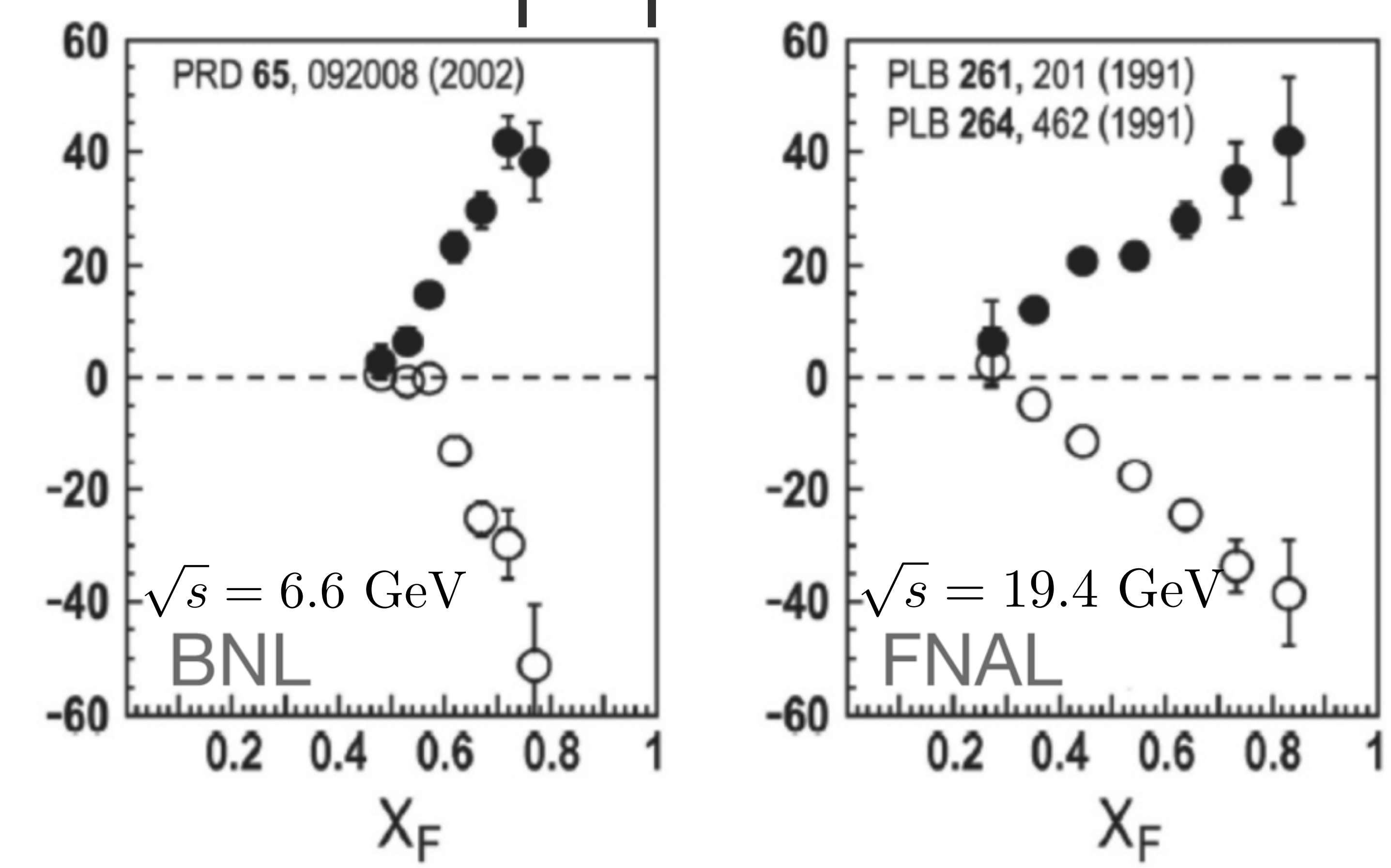
>> **Experimental**:

- ★ Large values of A_N were observed in $p^{\uparrow}p \rightarrow hX$ reactions, but never measured in $lN^{\uparrow} \rightarrow hX$.
- ★ Measurement of **Sivers**[2] and **Collins**[3] effects in semi-inclusive DIS: $lN^{\uparrow} \rightarrow l'hX$.
- ★ High-statistics data set on $lN^{\uparrow} \rightarrow hX$ at HERMES.
- ★ Involves detecting only one hadron in final state.

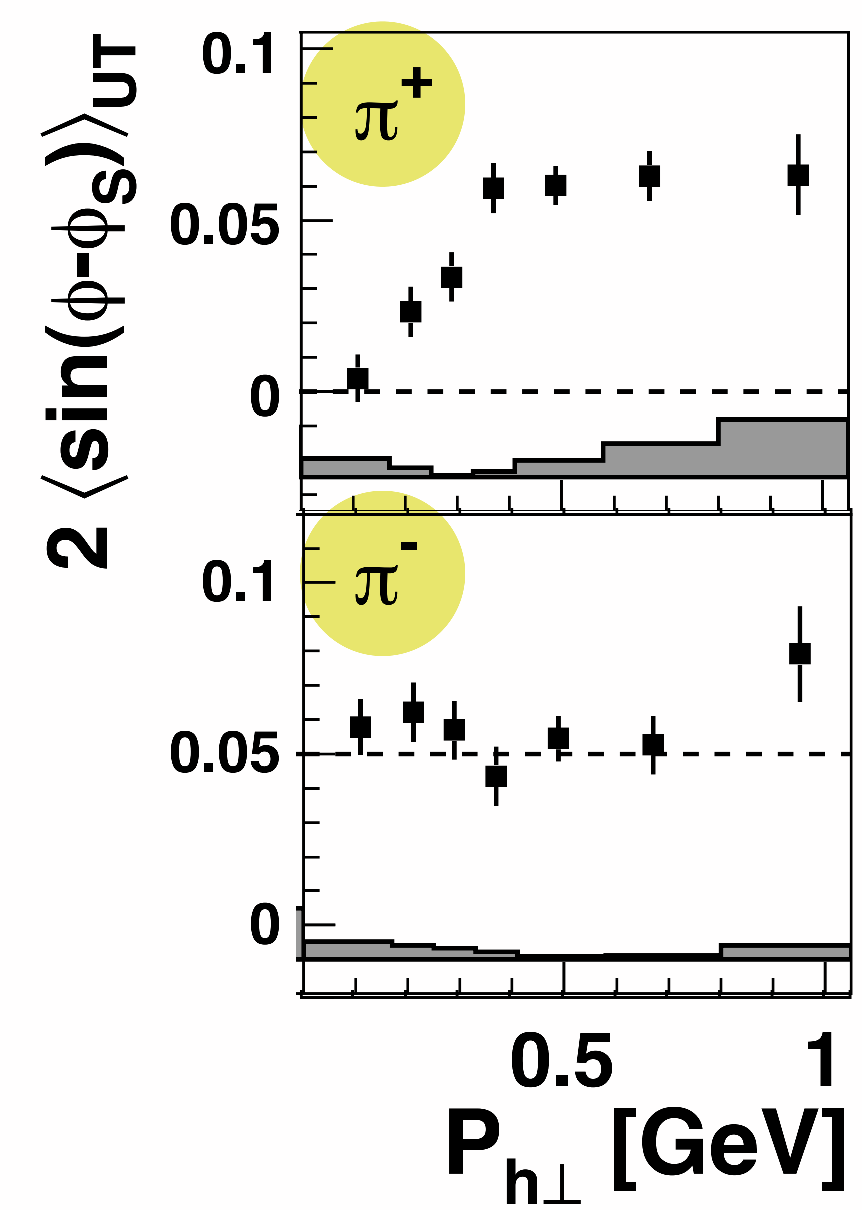
>> **Theoretical:** Two existing approaches:

- ★ TMD's and fragmentations functions[4] ($Q^2 \gg \Lambda_{QCD}^2$). Sivers and Collins effects.
- ★ Twist-3 parton correlation functions[5] ($P_T \gg \Lambda_{QCD}$).

$p^{\uparrow}p \rightarrow hX$

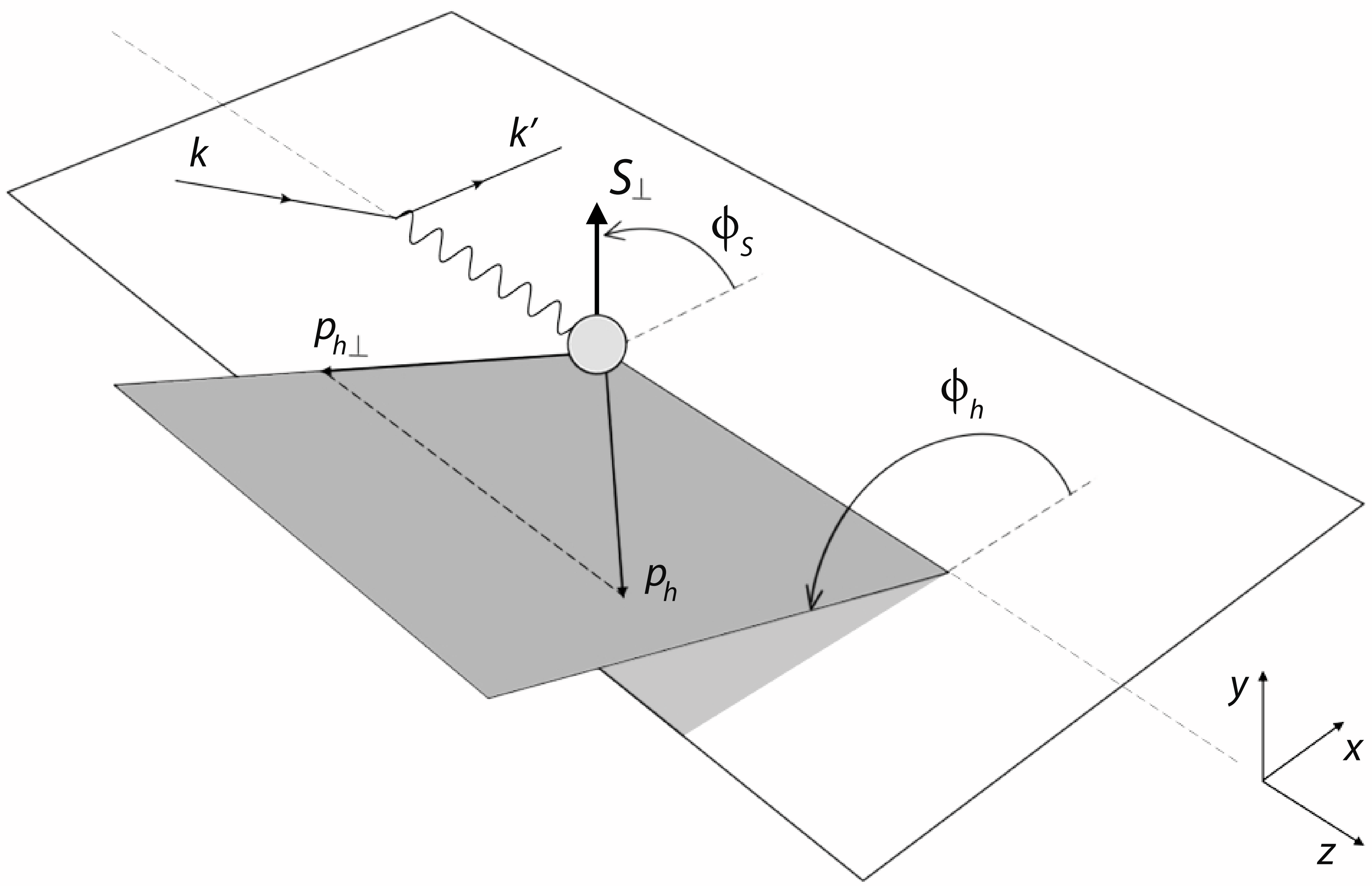


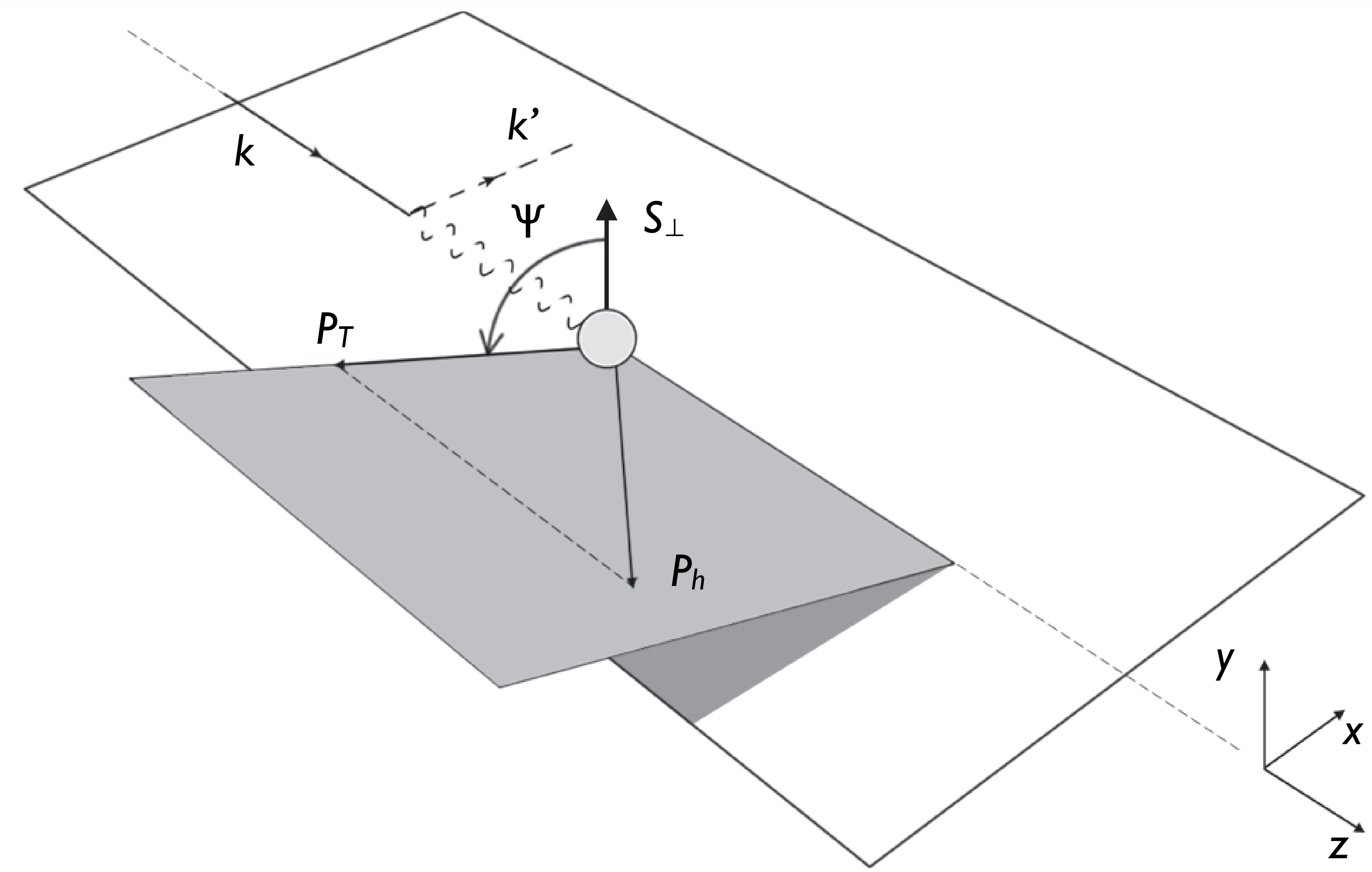
SIVERS



[2] Phys. Rev. Lett. 103, 152002 (2009).
[3] Phys. Lett. B 693 (2010) 11-16.
[4] Phys. Lett. B 362 (1995) 164–172.
[5] Phys. Rev. D 59 (1999) 014004.

Similarity between Sivers and inclusive SSA





semi-inclusive DIS

inclusive hadron production

SIVERS

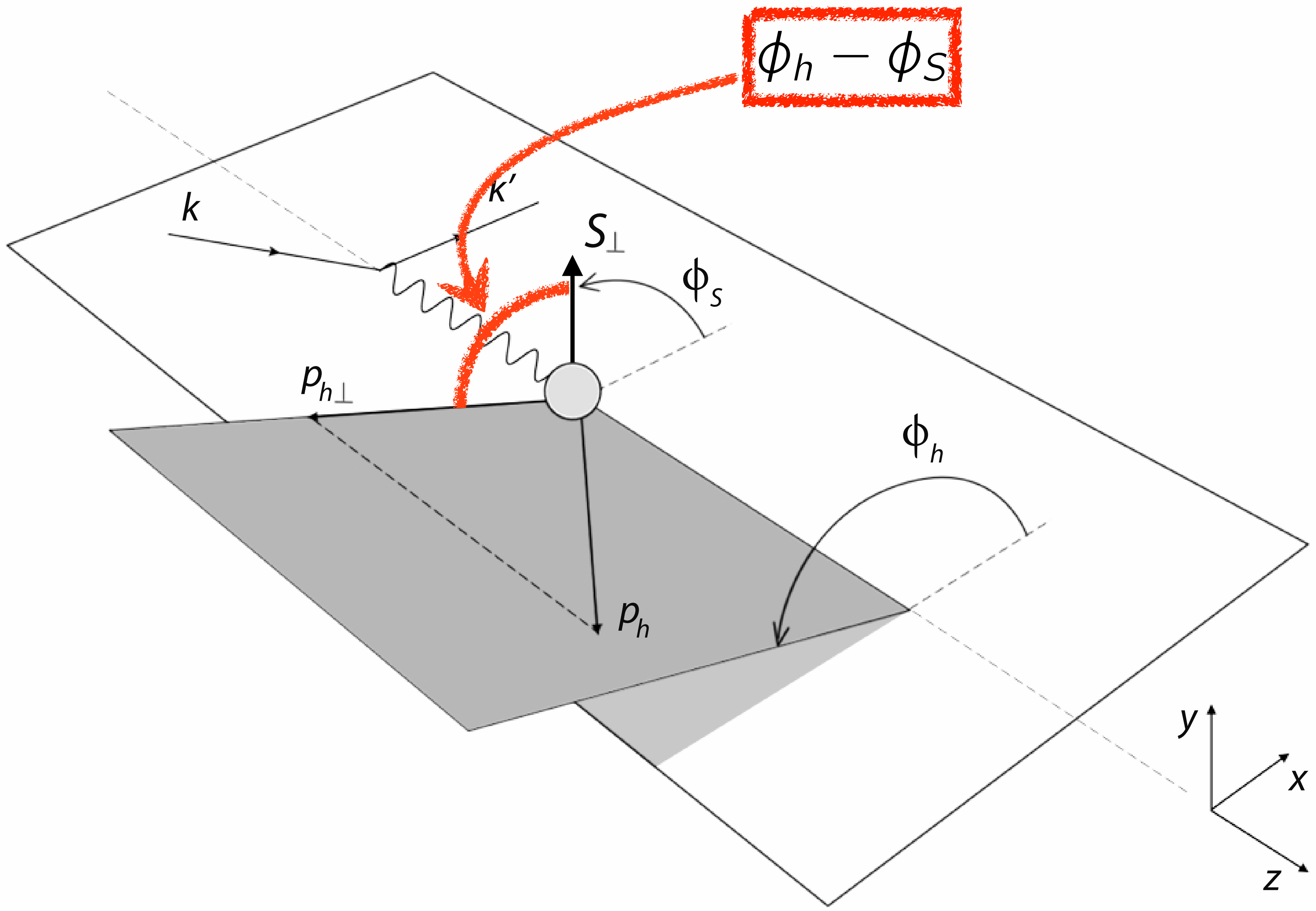
$$d\sigma_{UT}^{ep\to ehX} \sim |\mathbf{S}_\perp| \left[\sin(\phi_h - \phi_S)\, f_{1T}^\perp \otimes D_1 + \sin(\phi_h + \phi_S)\, h_1 \otimes H_1^\perp + \ldots \right]$$

COLLINS

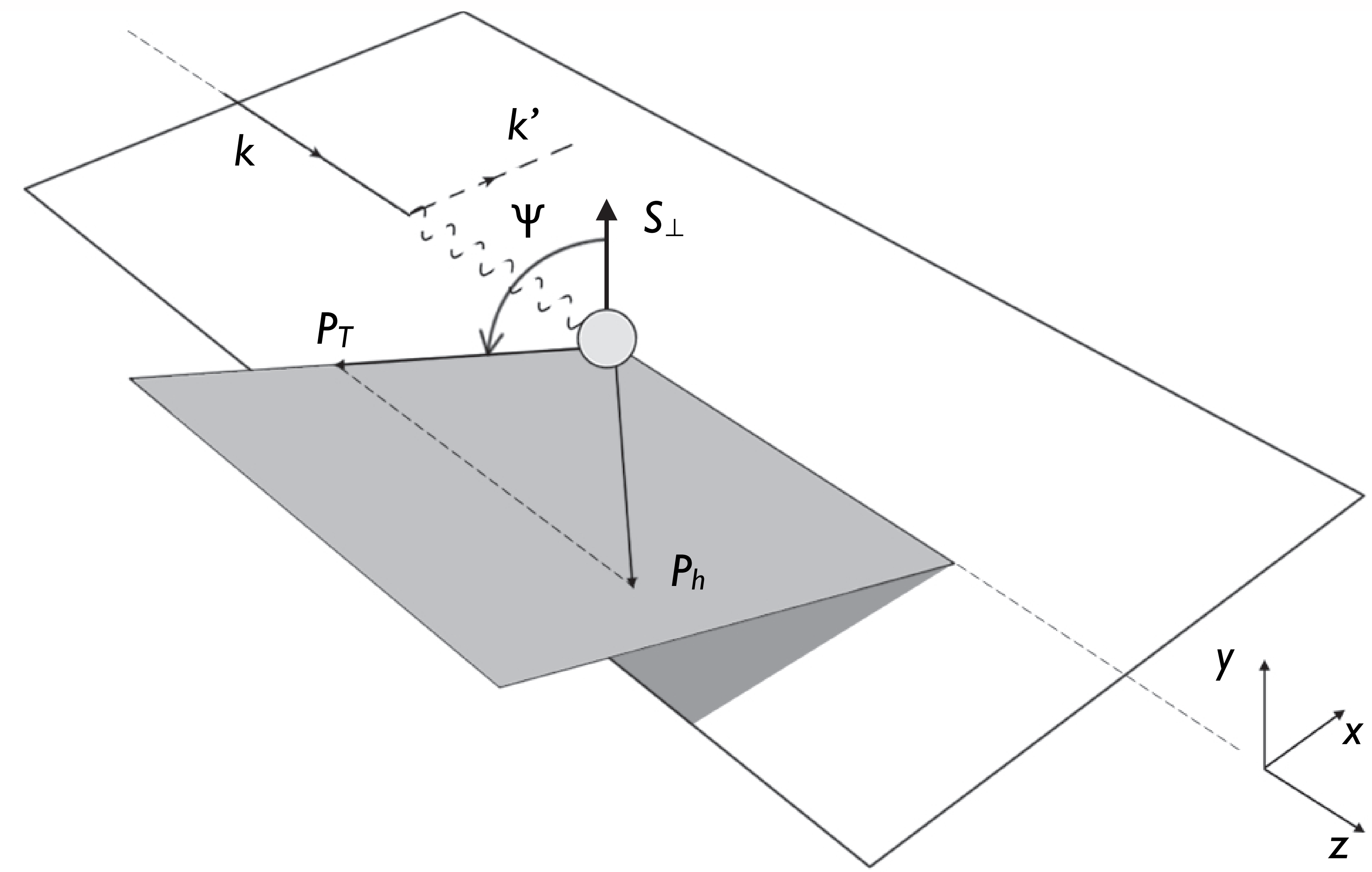
$$d\sigma_{UT}^{ep\to hX} \propto A_{UT}^{\sin\psi}\, S_T \sin\psi$$

inclusive SSA amplitude

Similarity between Sivers and inclusive SSA



semi-inclusive DIS



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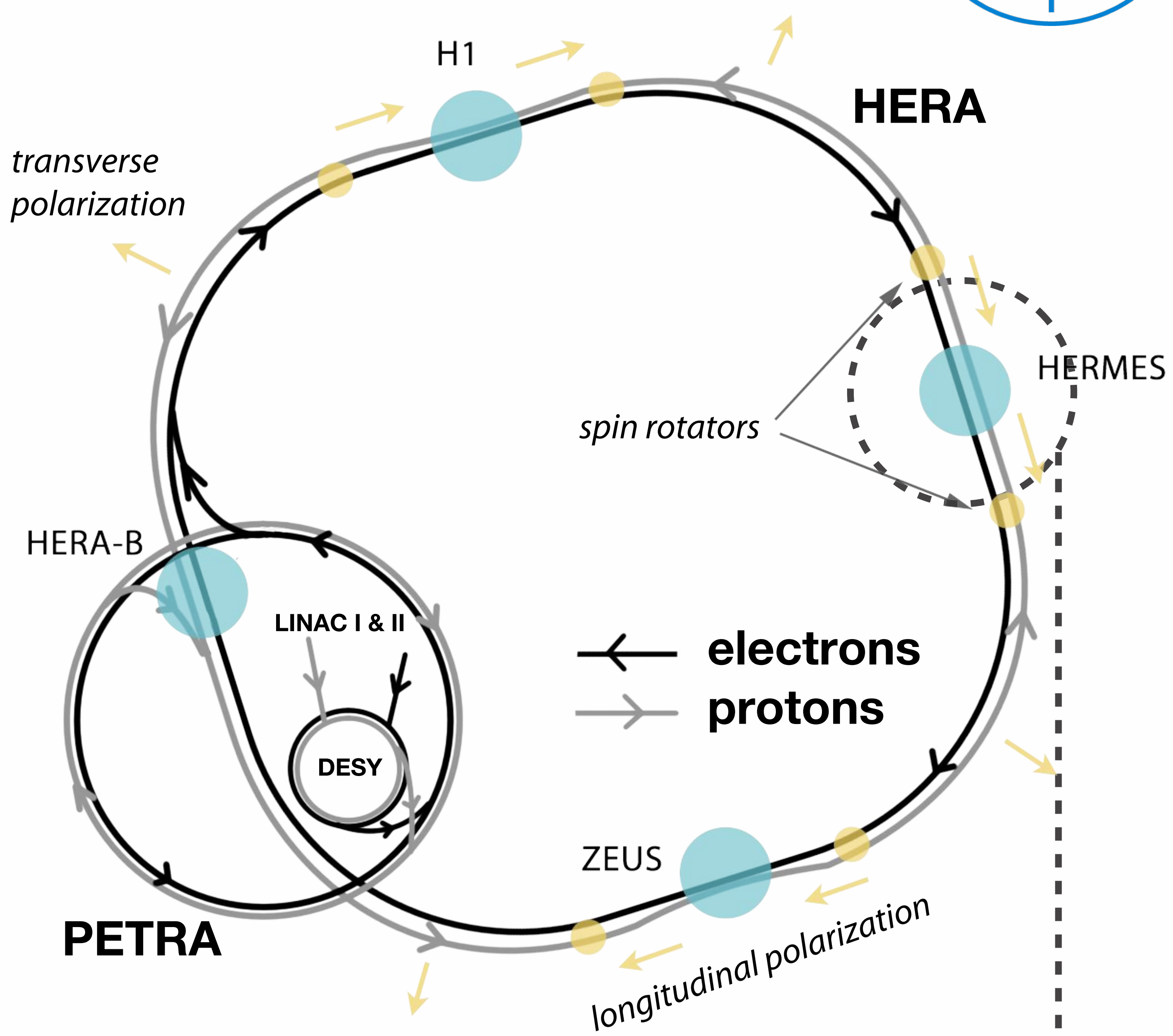
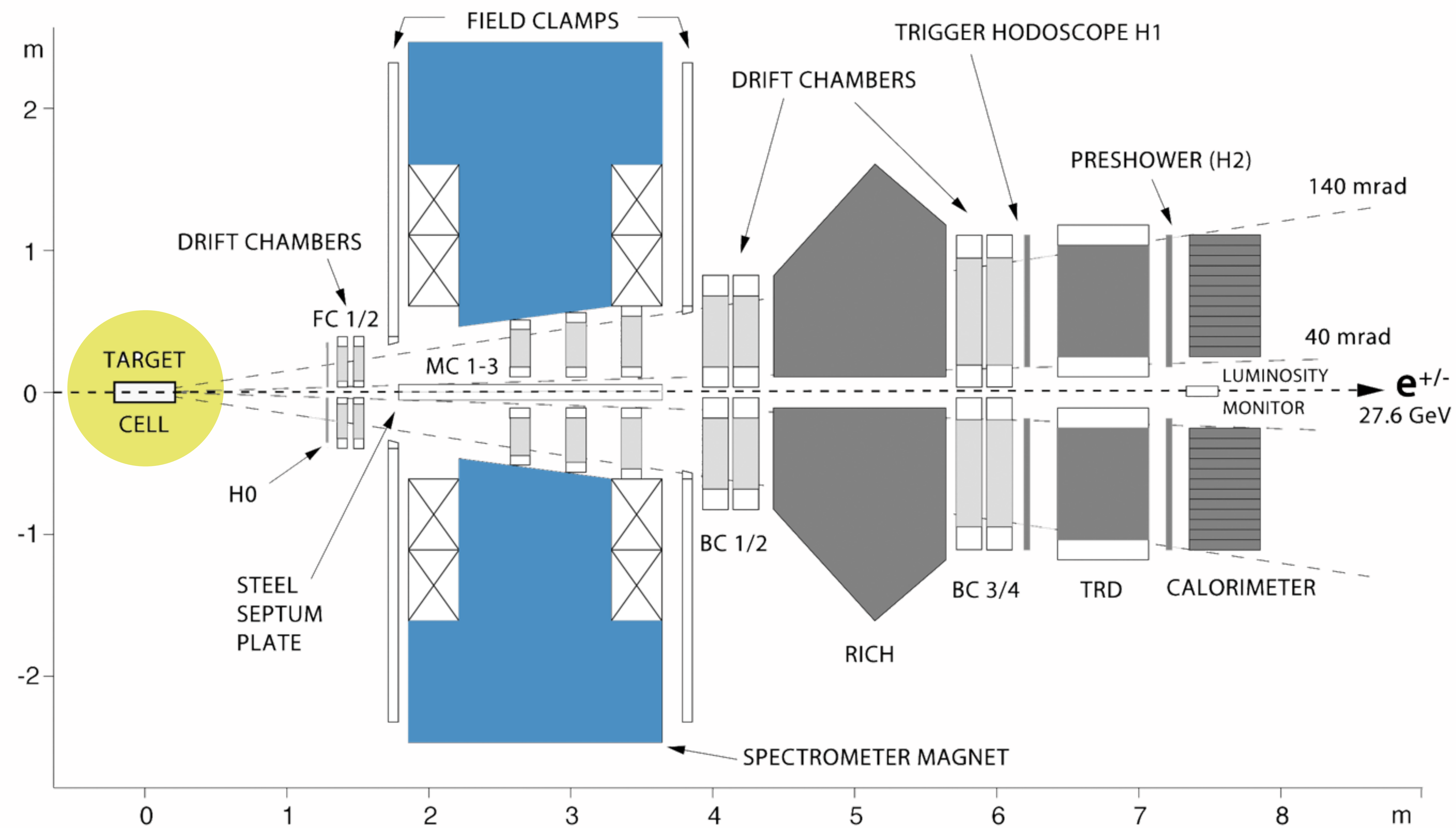
COLLINS

$$d\sigma_{UT}^{ep\to hX} \propto A_{UT}^{\sin\psi} S_T \sin\psi$$

inclusive SSA amplitude

HERA accelerator at DESY





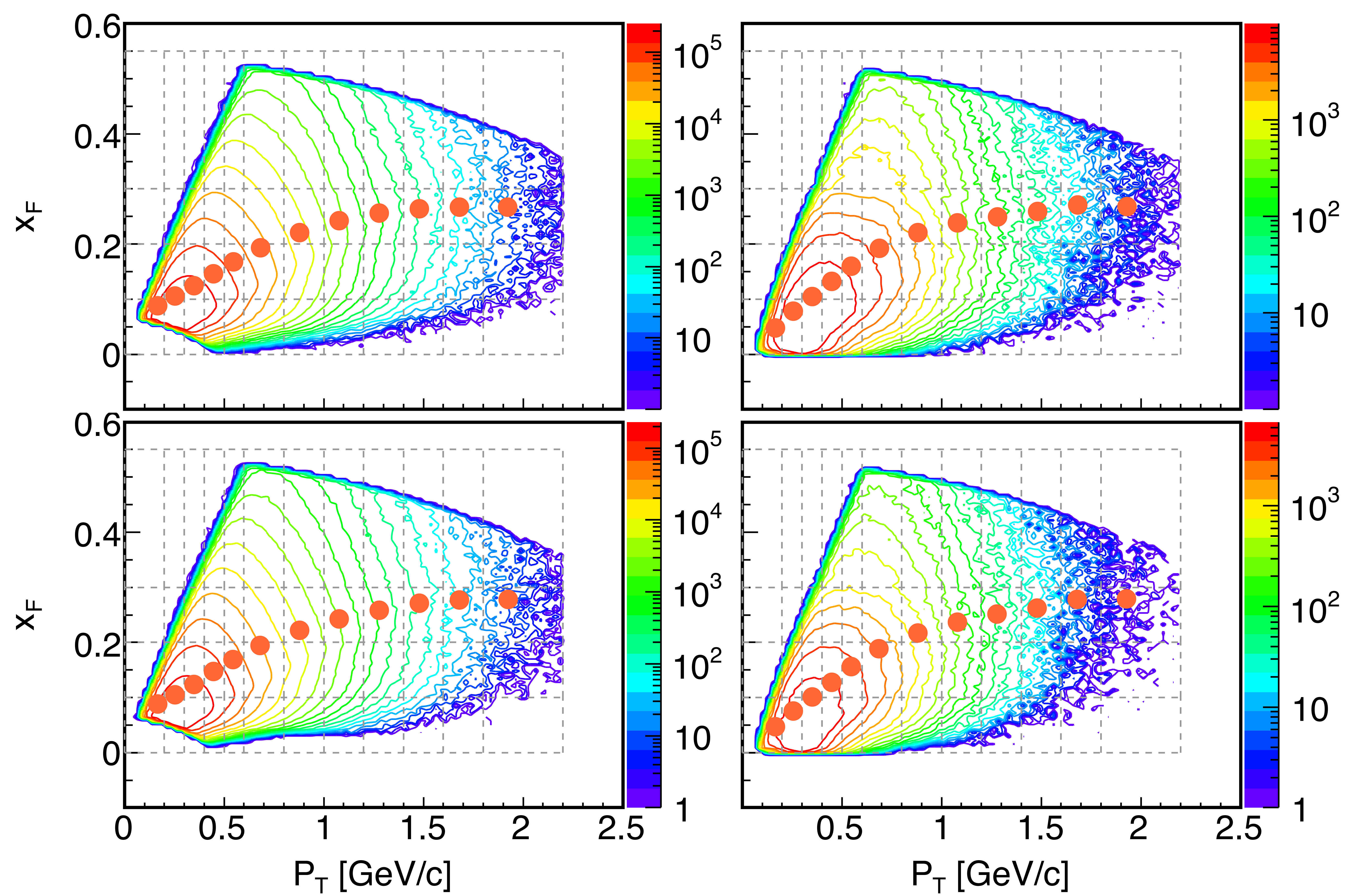
★ Lepton e^+/e^- beam of 27.6 GeV.

★ Transversely polarized pure H target.
Polarization state reversed every 1-3 min.

Kinematics and yields

π^+ 172 M

π^- 142 M

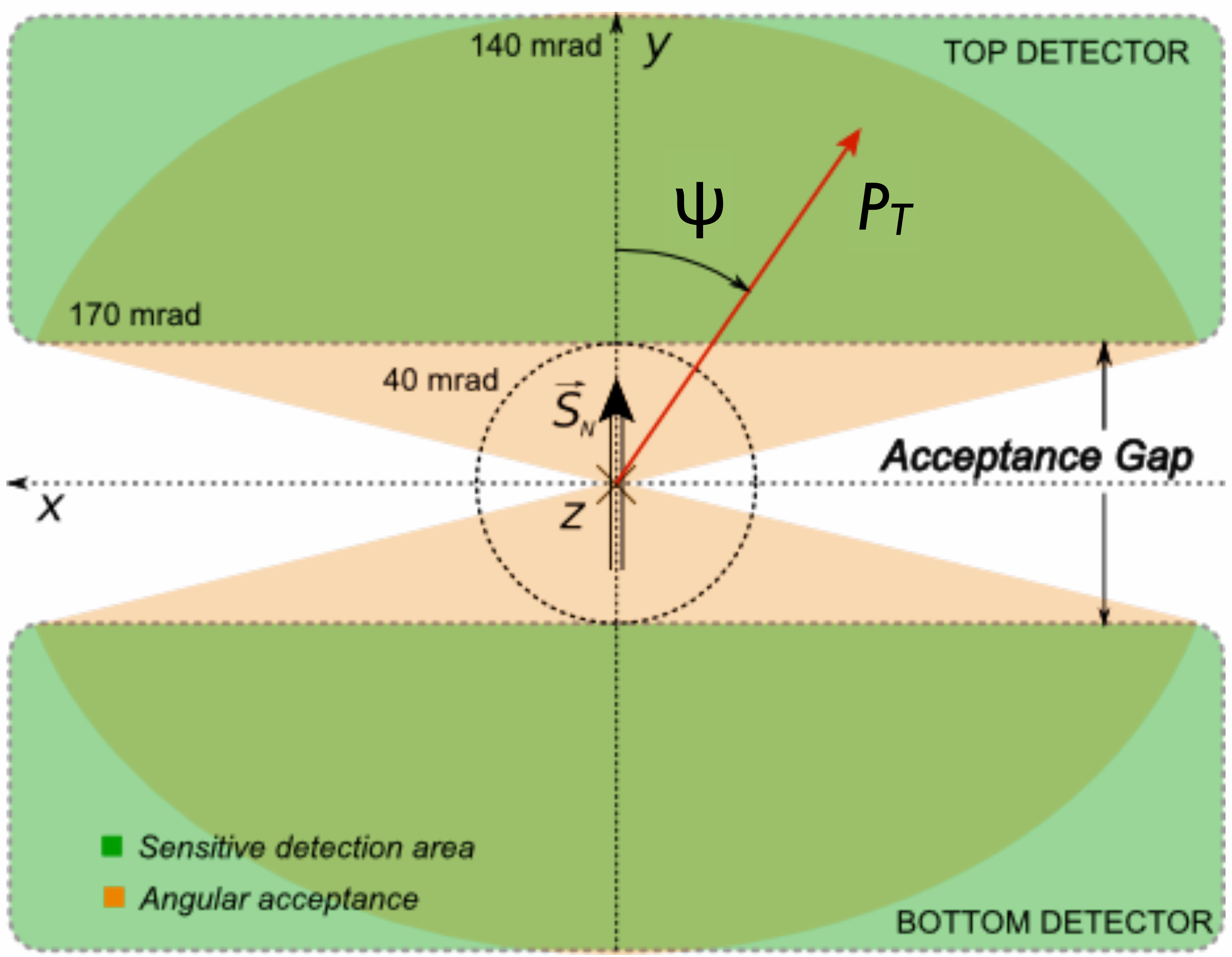


K^+ 14.5 M

K^- 7.3 M

Extraction of asymmetry amplitudes

Maximum likelihood fit



Detection efficiencies and acceptance effects cancel in the unbinned maximum-likelihood fit.

In every kinematic bin $\{x_F, P_T\}$:

$$d\sigma(\psi) = d\sigma_{UU}\left[1 + S_T A_{UT}^{\sin\psi} \sin\psi\right]$$

The amplitudes are extracted from data by a maximum-likelihood fit to the differential cross section.

$$\mathcal{L} = \prod_i^N \left(\frac{1 + S_{T,i}\left[A_0 + A_{UT}^{\sin\psi} \sin\psi_i\right]}{L_i^{\uparrow\downarrow}} \right)^{W_i}$$

Polarization degree: $S_{T,i}$

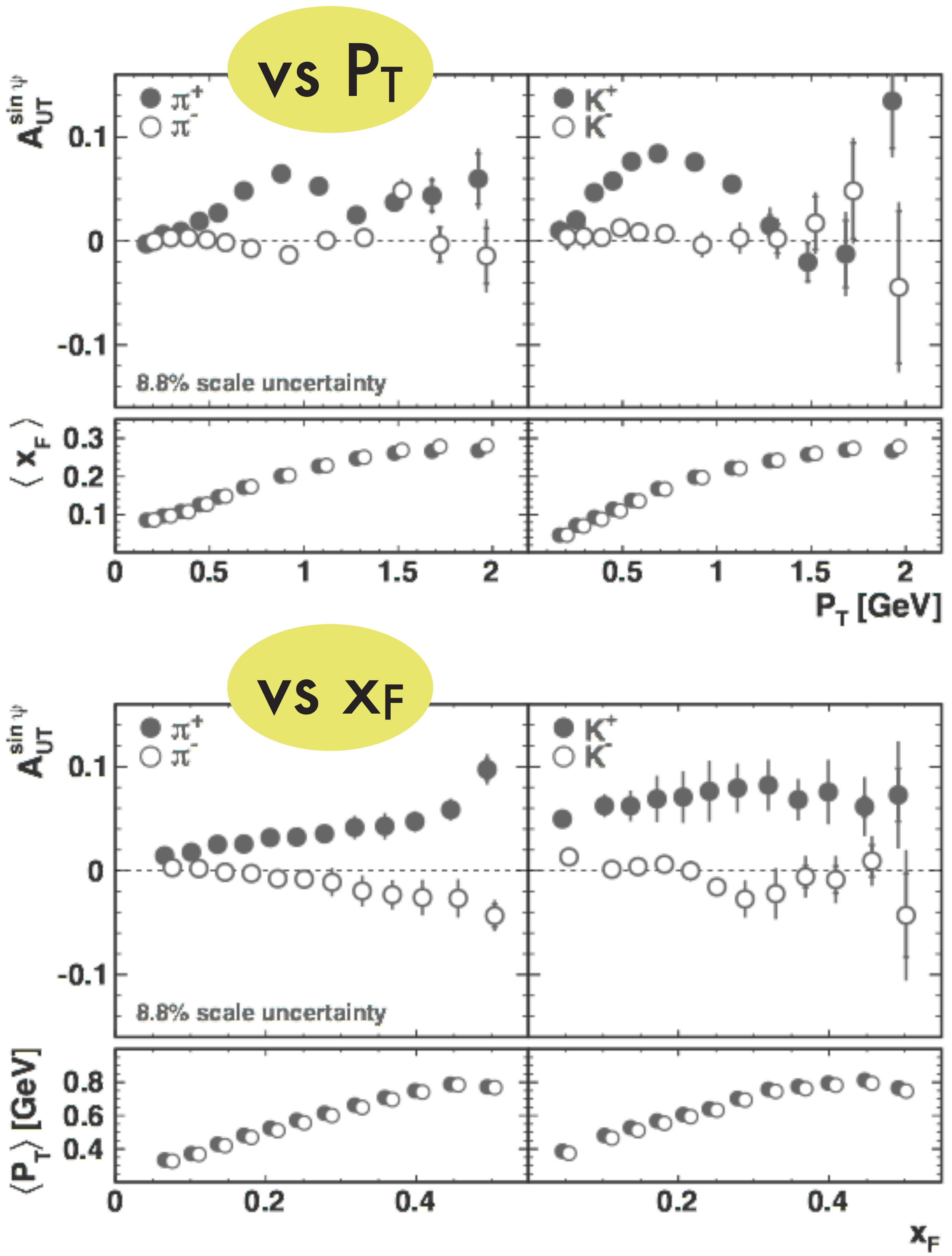
Asymmetry amplitude: $A_{UT}^{\sin\psi}$

Relative luminosity: $L_i^{\uparrow\downarrow}$

Event weight W_i ←
- >> Particle weight
- >> Trigger efficiency

Inclusive SSA (1D)

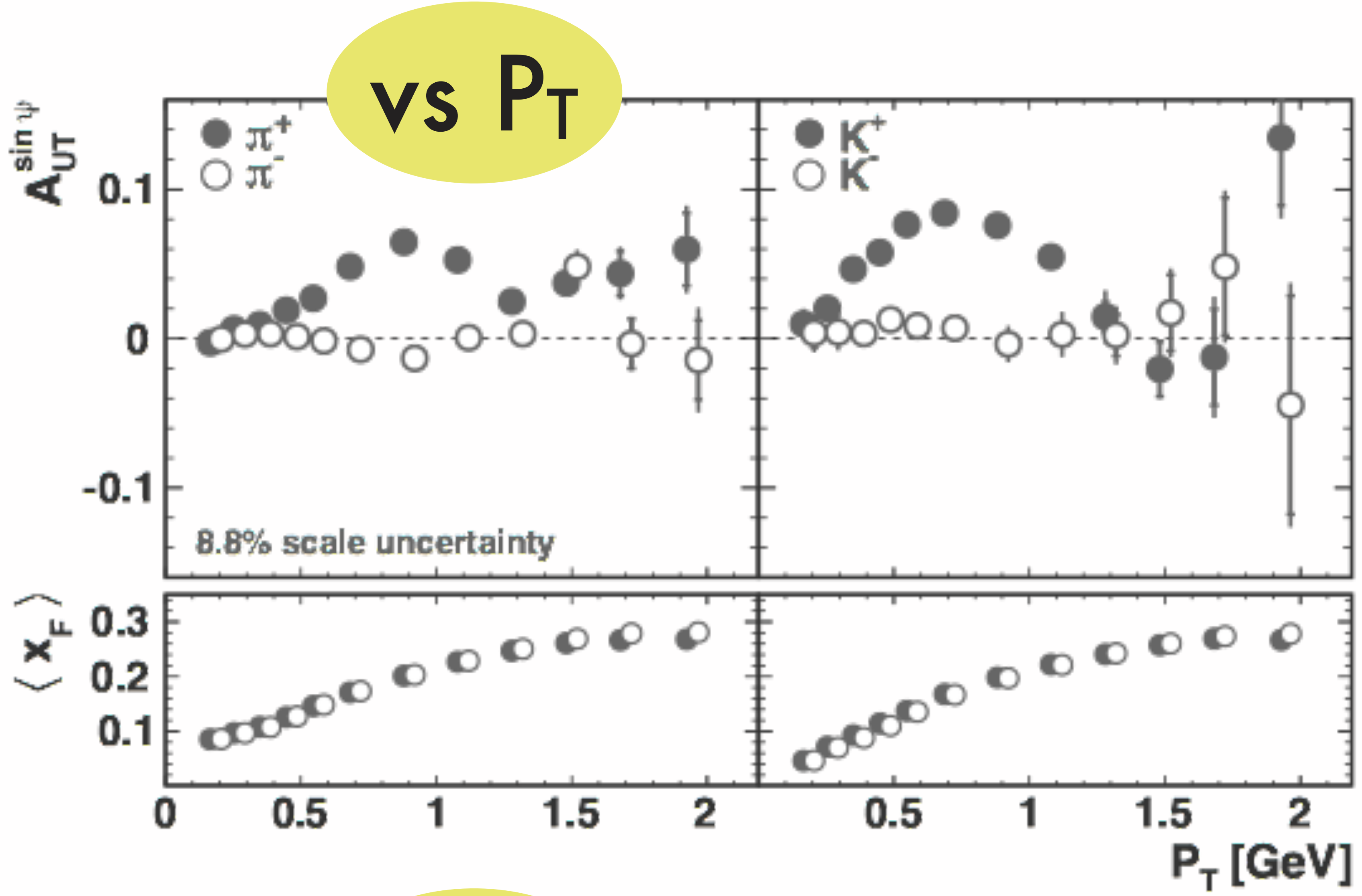
… as a function of P_T and x_F separately

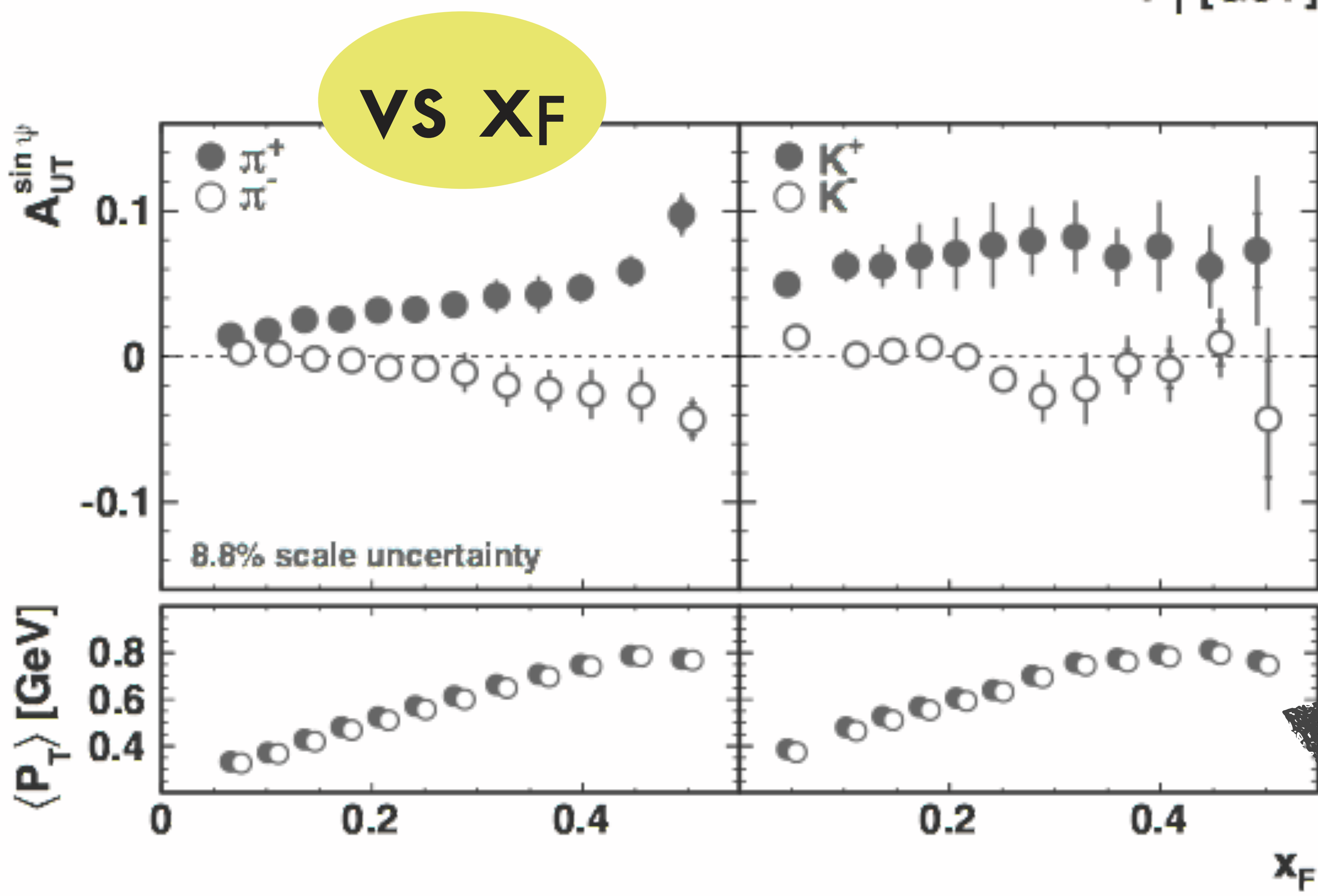


- ★ The asymmetry amplitudes are **positive** for π^+ and $\mathbf{K^+}$ and compatible with **zero** for π^- and $\mathbf{K^-}$.
- ★ A clear two-fold structure in P_T.
  - >> The amplitudes increase with P_T up to ~0.6 (~0.9) at P_T~0.8 GeV for π^+($\mathbf{K^+}$). From this point on, the tendency is inverted.
  - >> For π^+ there is a hint of another rise at high P_T, while for $\mathbf{K^+}$ it seems to remain vanishing.
- ★ The amplitudes vs. x_F increase (decrease) nearly linearly for π^+(π^-).
- ★ For $\mathbf{K^+}$($\mathbf{K^-}$) are about constant around 0.7 (0.0).

Inclusive SSA (1D)

… as a function of P_T and x_F separately





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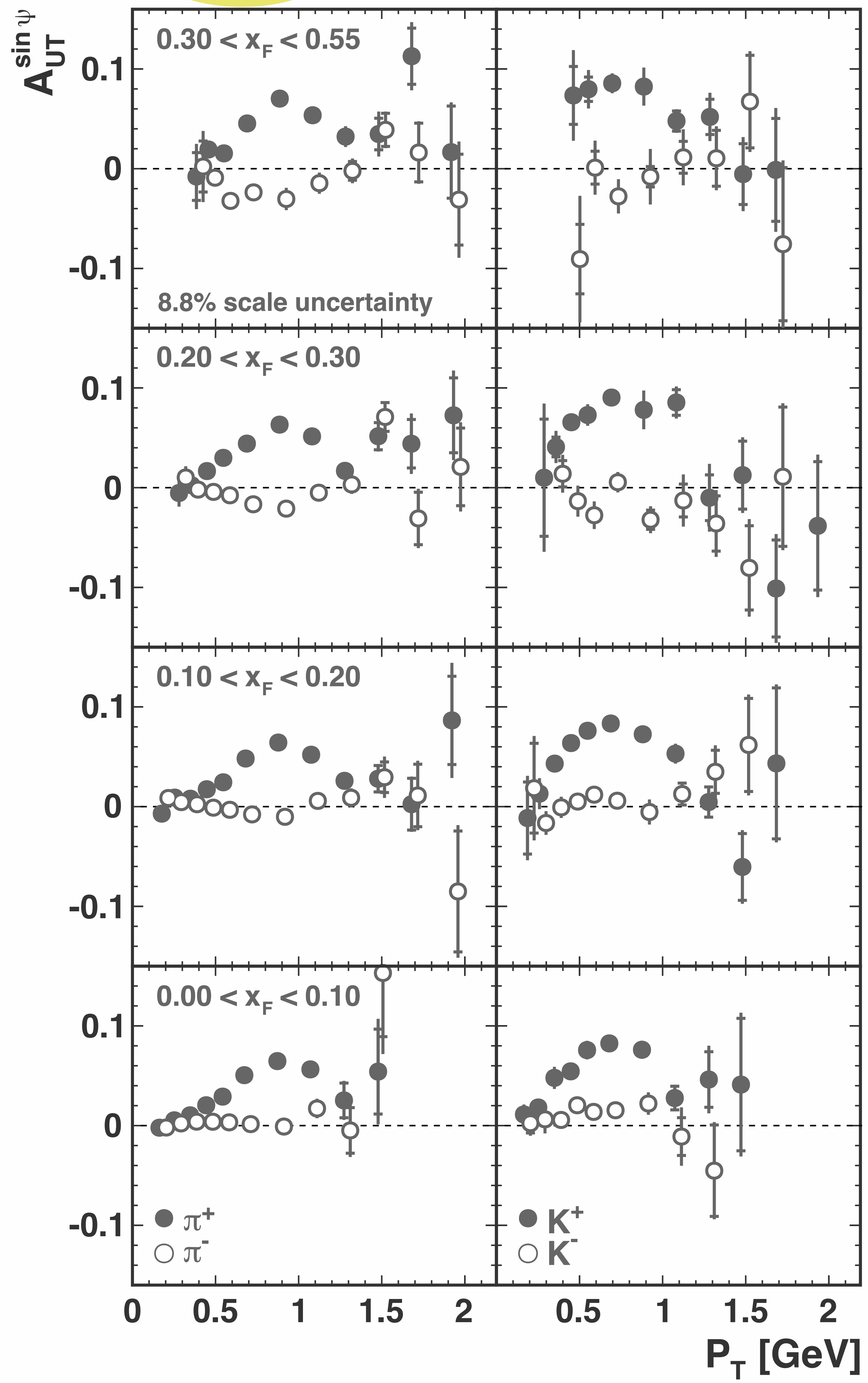
  - >> For π^+ there is a hint of another rise at high P_T, while for $\mathbf{K^+}$ it seems to remain vanishing.
- ★ The amplitudes vs. x_F increase (decrease) nearly linearly for π^+(π^-).
- ★ For $\mathbf{K^+}$($\mathbf{K^-}$) are about constant around 0.7 (0.0).

P_T and x_F are strongly correlated!

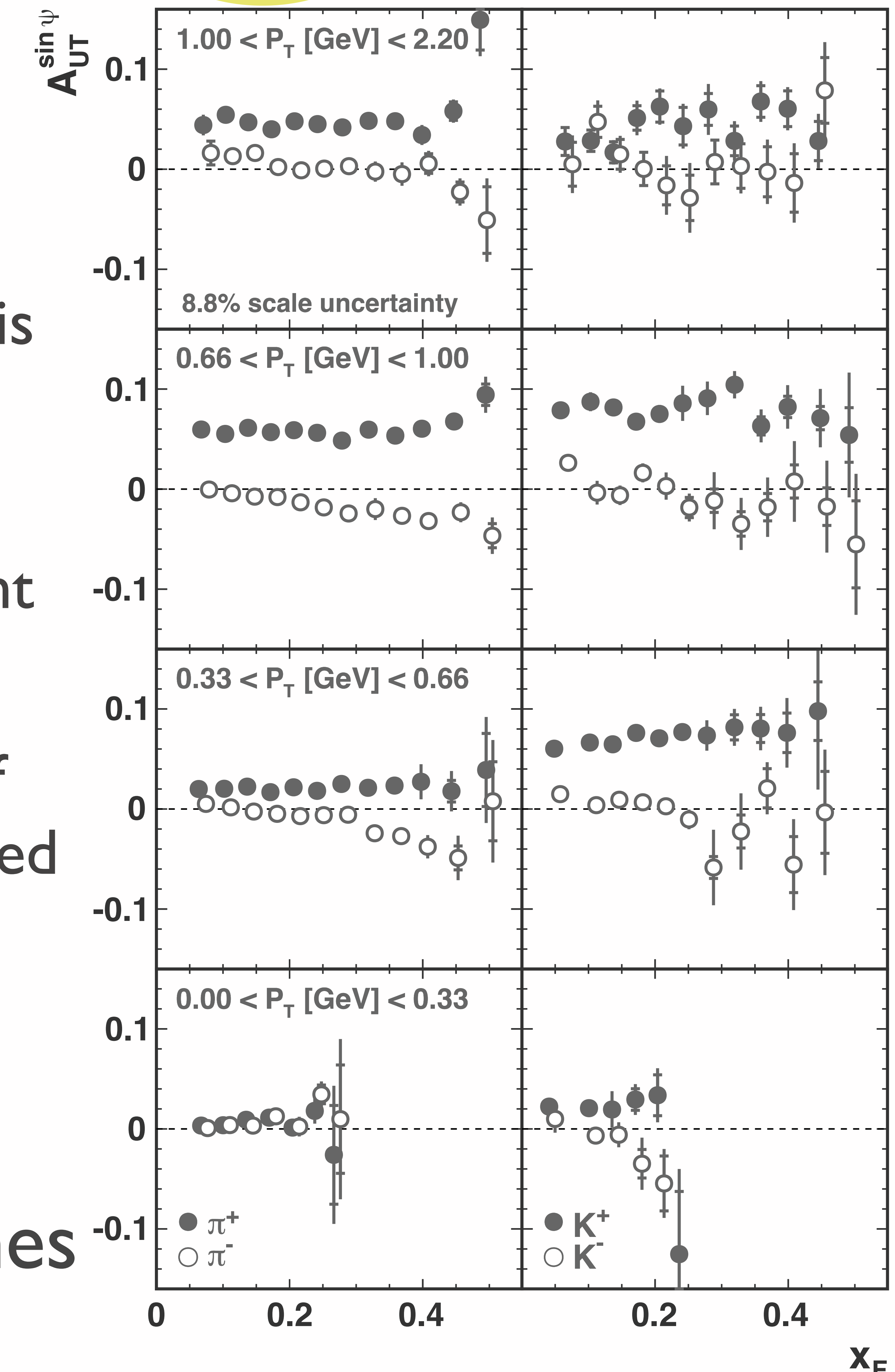
Inclusive SSA (2D)

… as a function of P_T and x_F simultaneously

vs P_T in x_F bins



vs x_F in P_T bins



π^+: Similar dependence on P_T as in 1D; no dependence on x_F.
➡The observed 1D x_F dependence is a reflection of the underlying dependence on P_T.

π^-: Like in the 1D case, there is a slight linear decrease with x_F.

K^+ and **K^-**: The dependence on x_F of the kaon amplitudes is less pronounced in 2D, with a slight tendency towards an increase (decrease) with x_F for positive (negative) kaons.

➡ most of the structure comes from P_T dependence

Event categories

Inclusive sample:

Comprises several subsamples, related to different production channels. These subsamples contribute differently to the measured SSA, and can be differentiated by electron tagging and kinematic constraints on DIS variables:

$$A_{UT}^{\sin\psi} = \sum_{i}^{samples} f_i A_{UT,i}^{\sin\psi}$$

Anti-tagged (~98%):

The undetected lepton in most cases had a small scattering angle and remained within the beam pipe. **Photoproduction** regime ($Q^2 \approx 0$).

Tagged (semi-inclusive):

The scattered lepton is detected.

DIS events:

(Q^2>1 GeV^2, W^2>10 GeV^2, 0.023<x<0.4, 0.1 < y < 0.95)

Non-DIS events (e.g., low Q^2)

mid-z (0.2<z<0.7):

Identical selection as in Sivers and Collins measurements at HERMES.

low-z (z<0.2)

high-z (z>0.7):

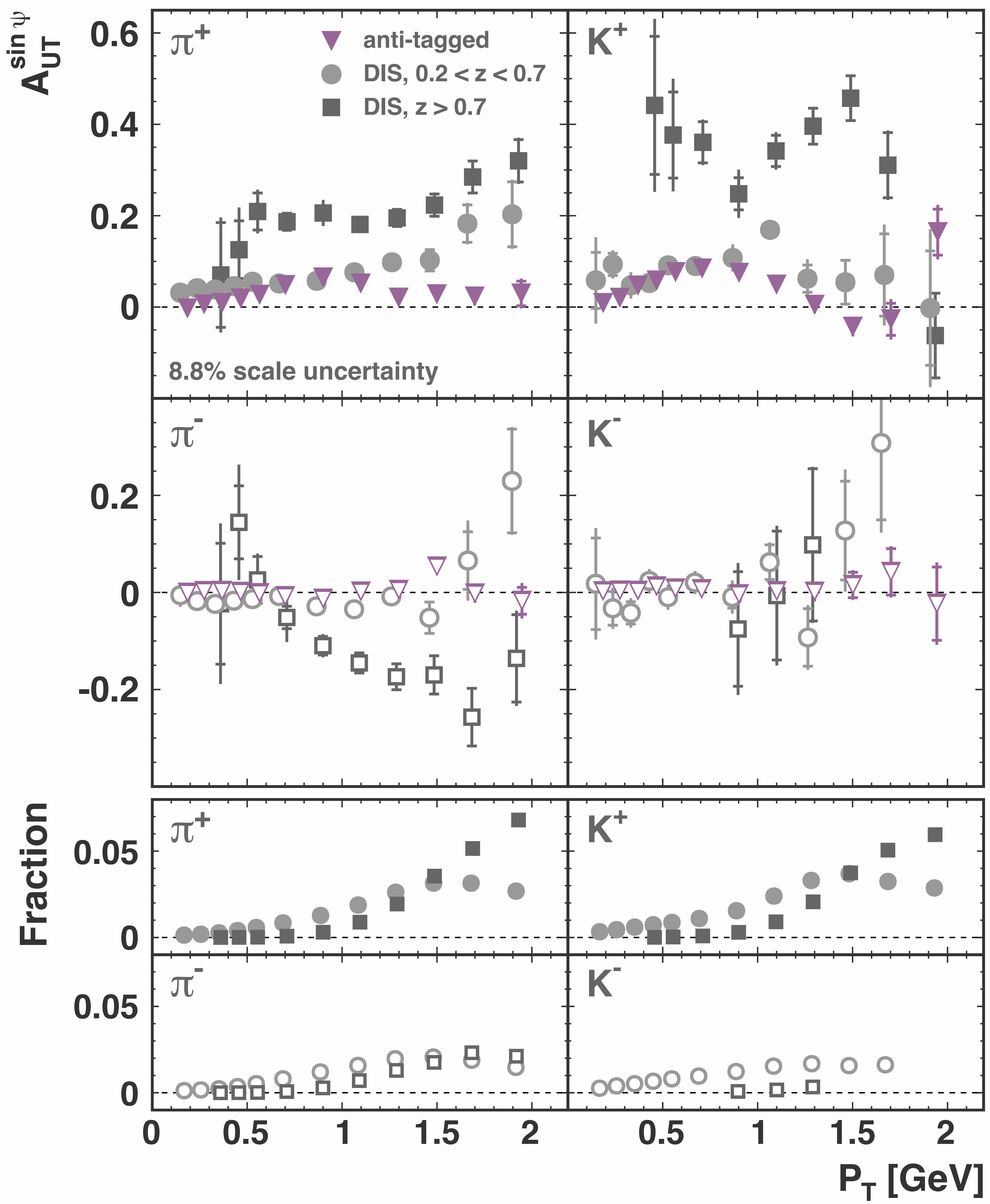
Hadrons in this region might have more pronounced correlation with struck quark.

$$z \equiv \frac{P \cdot P_h}{P \cdot q} \overset{lab}{=} \frac{E_h}{\nu}$$

fractional virtual-photon energy carried by the hadron

SSA for subsamples

... as a function of P_T



Anti-tagged ("photoproduction")

★ Inclusive asymmetries dominated by quasi-real photoproduction.

★ Rather similar behavior as overall inclusive asymmetries (largest subsample)

DIS, mid-z (0.2<z<0.7)

★ Q^2 is large scale. Factorization in terms of TMD PDFs and FFs expected to hold.

★ π^+ asymmetries keep rising with P_T.

★ Sivers effect is expected to have large contribution.

DIS, high-z (z>0.7)

★ Large asymmetries for π^+, π^-, and K^+.

★ Dominance of struck quark (u and d) in hadron production at high z.

At high P_T contribution from DIS becomes sizable.

Transverse target single-spin asymmetry in inclusive electroproduction of charged pions and kaons.[1]

[1] HERMES Collaboration, Phys. Lett. B 728 (2014) 183

Summary and Outlook

- >> Transverse azimuthal SSA measured in inclusive electro-production of pions and kaons.
- >> Two-dimensional extraction by binning simultaneously in x_F and P_T :
  - ★ For π^+, the asymmetry is independent of x_F.
  - ★ For π^-, and less for K^- (K^+), the asymmetry amplitudes decrease (increase) with x_F.
- >> As a function of P_T, the amplitudes are positive for positive mesons.
  - ★ Two-fold structure at low and high P_T.
- >> Inclusive sample dominated by photoproduction:
  - ★ Description in terms of higher-twist effects: predicts a vanishing A_{UT} with $1/P_T$.
- >> At high-P_T, sizable contribution from semi-inclusive DIS.
  - ★ Possibly description in terms of TMD Sivers distribution function: Non-vanishing A_{UT} at high P_T.
- >> For DIS at high-z, large asymmetry amplitudes have been found.
  - ★ Large asymmetries also for negative pions.
  - ★ Effects from favored fragmentation of the struck quark dominate.

Backup Slides

$$d\sigma_{UT}^{ep\to ehX} \sim |\mathbf{S}_\perp| \left[\sin(\phi_h - \phi_S)\, f_{1T}^\perp \otimes D_1 + \sin(\phi_h + \phi_S)\, h_1 \otimes H_1^\perp + \ldots \right]$$

SIVERS ($f_{1T}^\perp$)

COLLINS ($H_1^\perp$)

SIVERS (1990)

An asymmetric distribution of unpolarized quarks inside a transversely polarized proton leads to an asymmetric distribution of the outgoing hadrons

$$\mathbf{S} \cdot (\hat{\mathbf{P}} \times \hat{\mathbf{k}}_\perp)$$

This happens via a correlation between the spin of the proton, its momentum and the (intrinsic) transverse momentum of the quarks.

COLLINS (1993)

Spin transfer from a transversely polarized quark, fragmenting to an unpolarized hadron should lead to a transverse SSA

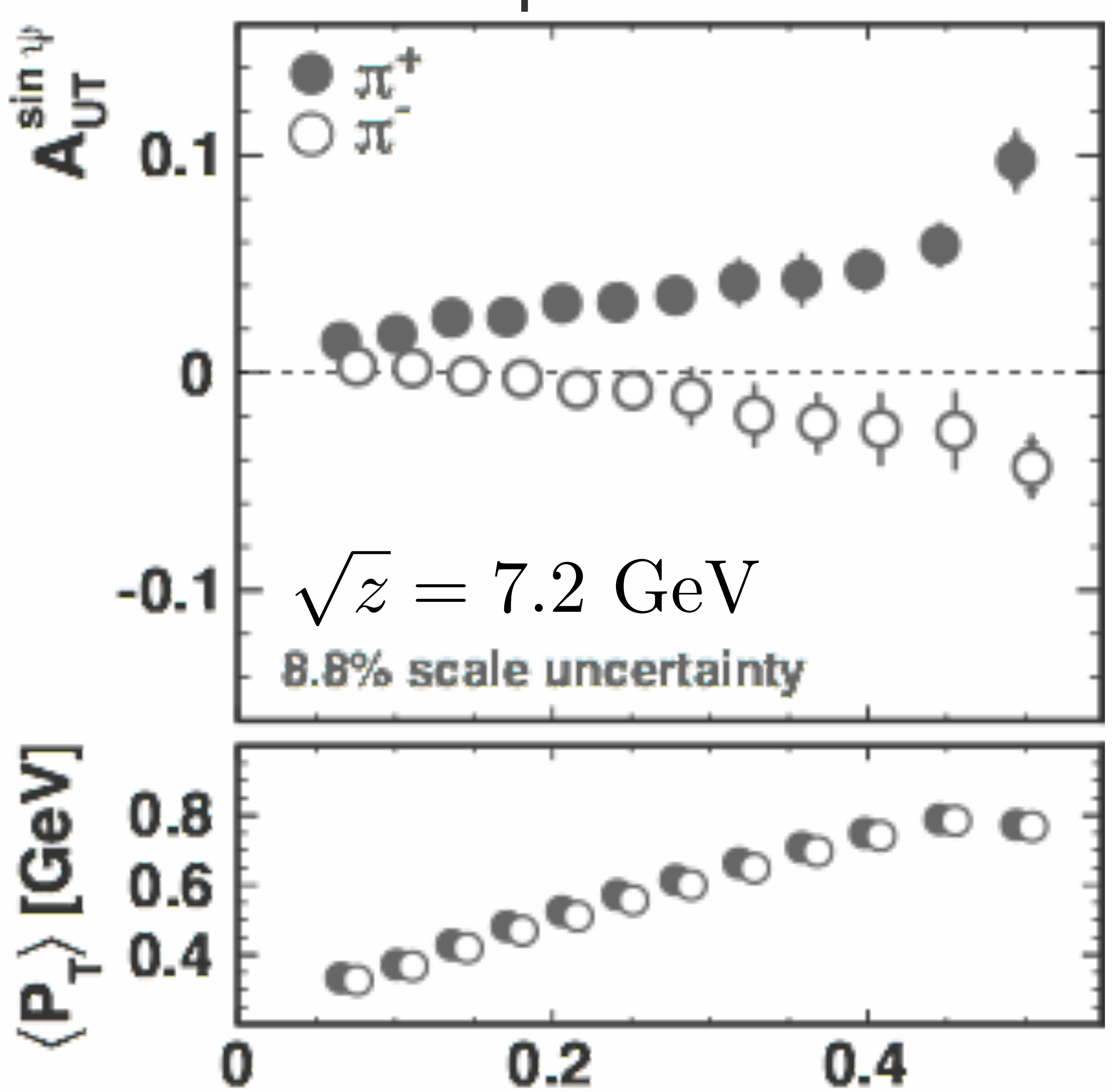
$$(\hat{\mathbf{p}}_q \times \hat{\mathbf{p}}_{h\perp}) \cdot \mathbf{s}_q$$

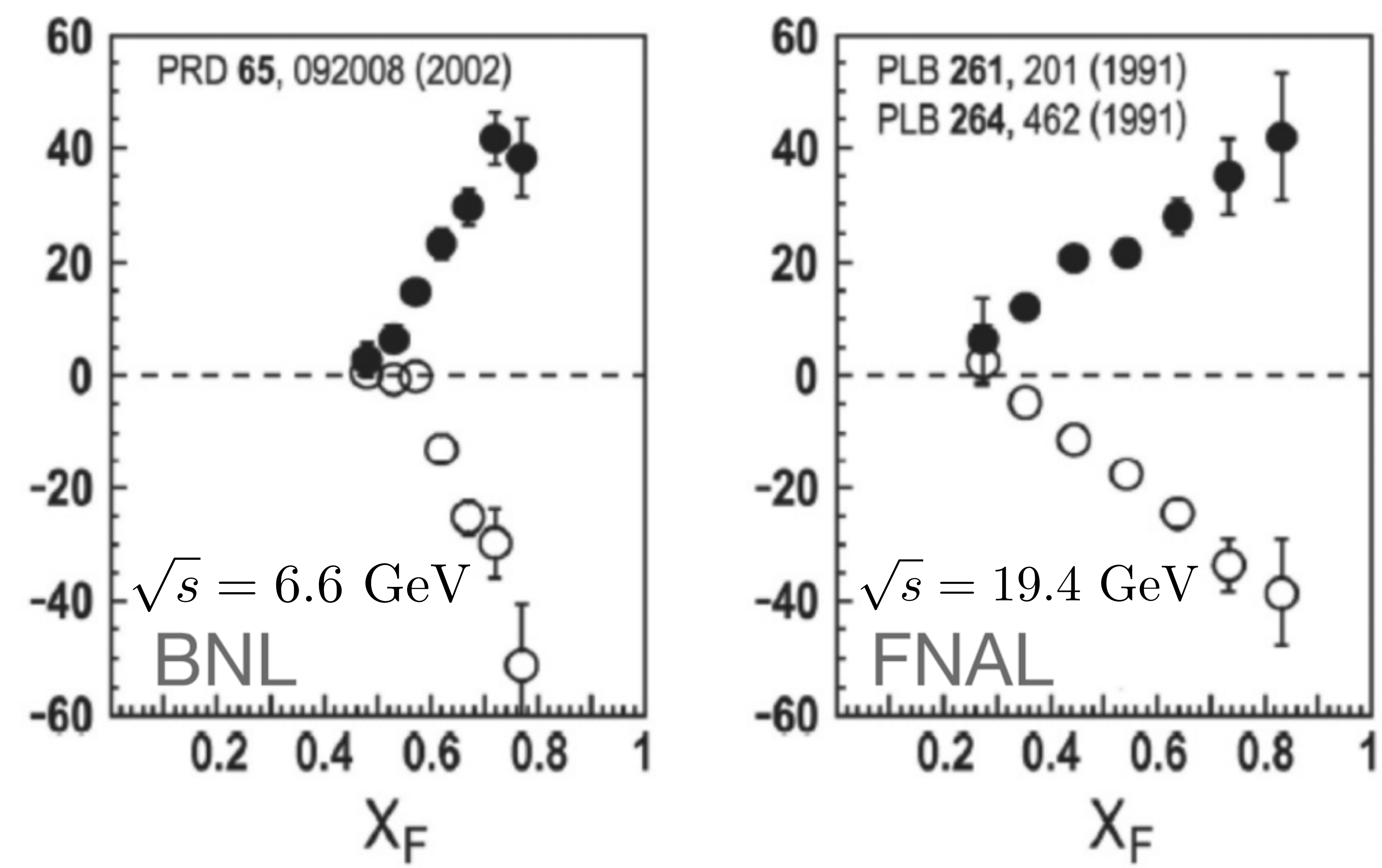
This happens via a correlation between the spin of the fragmenting quark, its momentum and the transverse momentum of the produced hadron.

Comparison

with A_N in hadron-hadron collisions

$lp^{\uparrow} \rightarrow hX$ $\quad$ $p^{\uparrow}p \rightarrow hX$

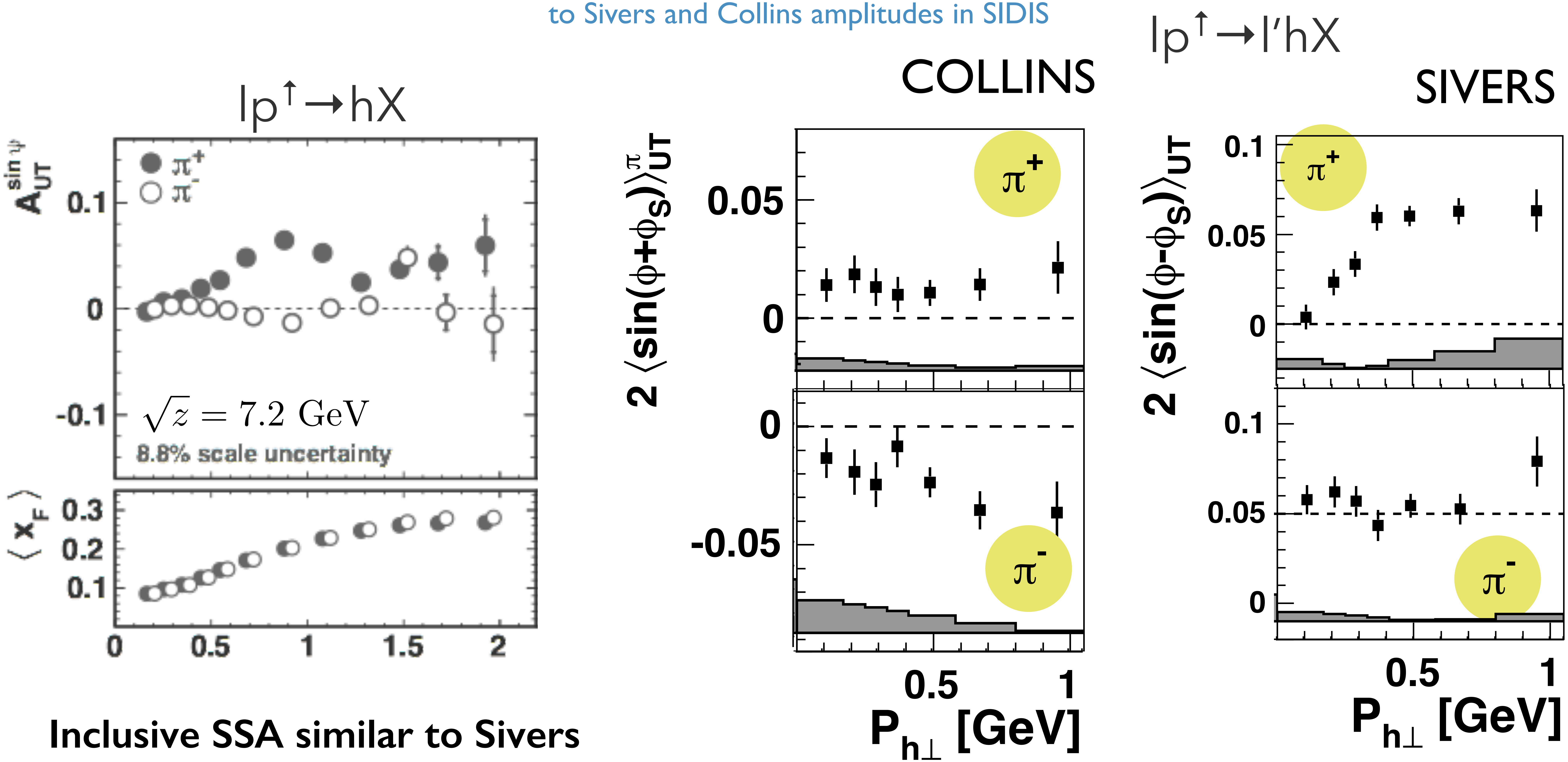




Smaller size, but similar behavior.

Comparison

to Sivers and Collins amplitudes in SIDIS

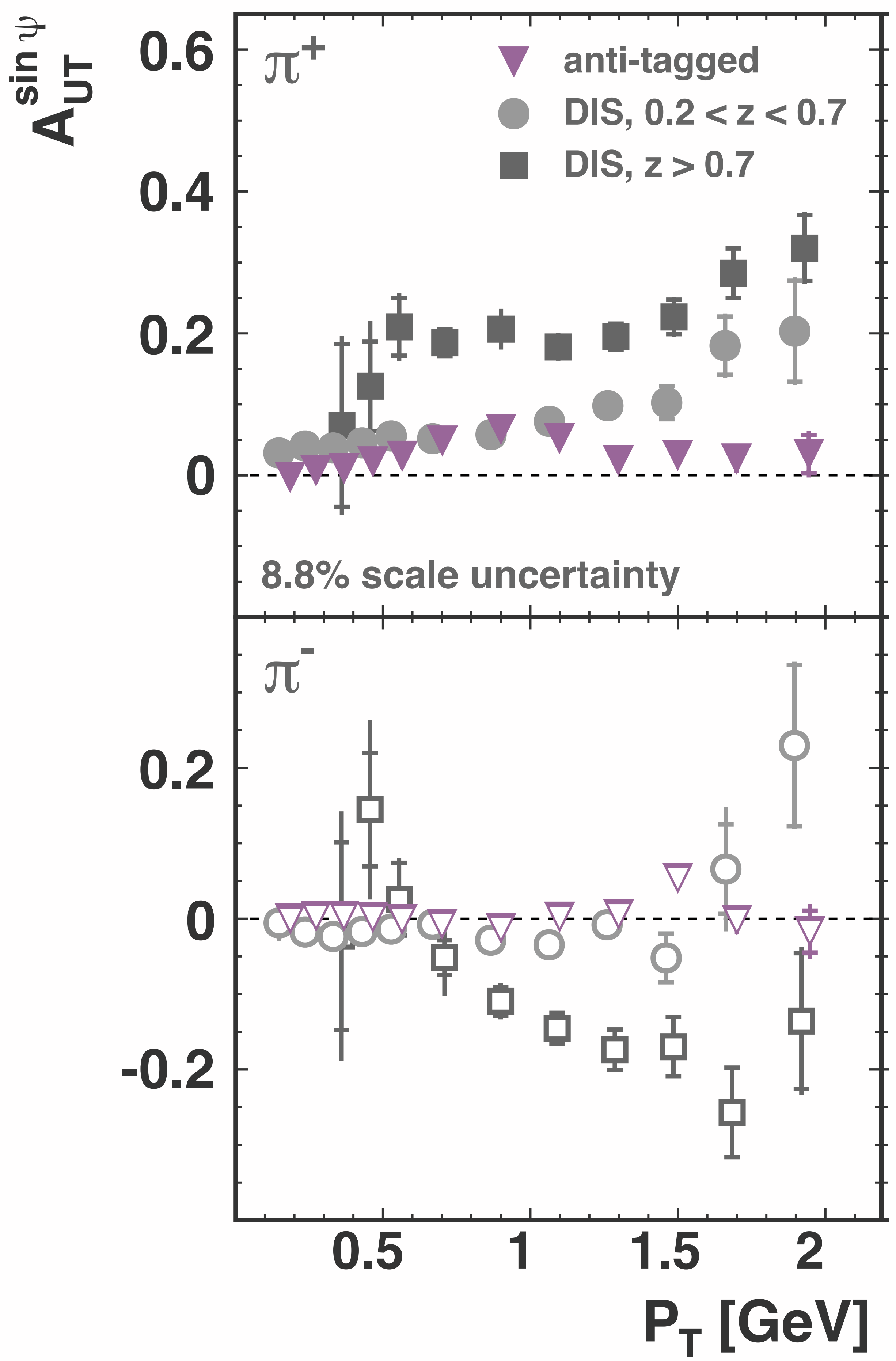


Inclusive SSA similar to Sivers

Comparison

to Sivers and Collins amplitudes in SIDIS

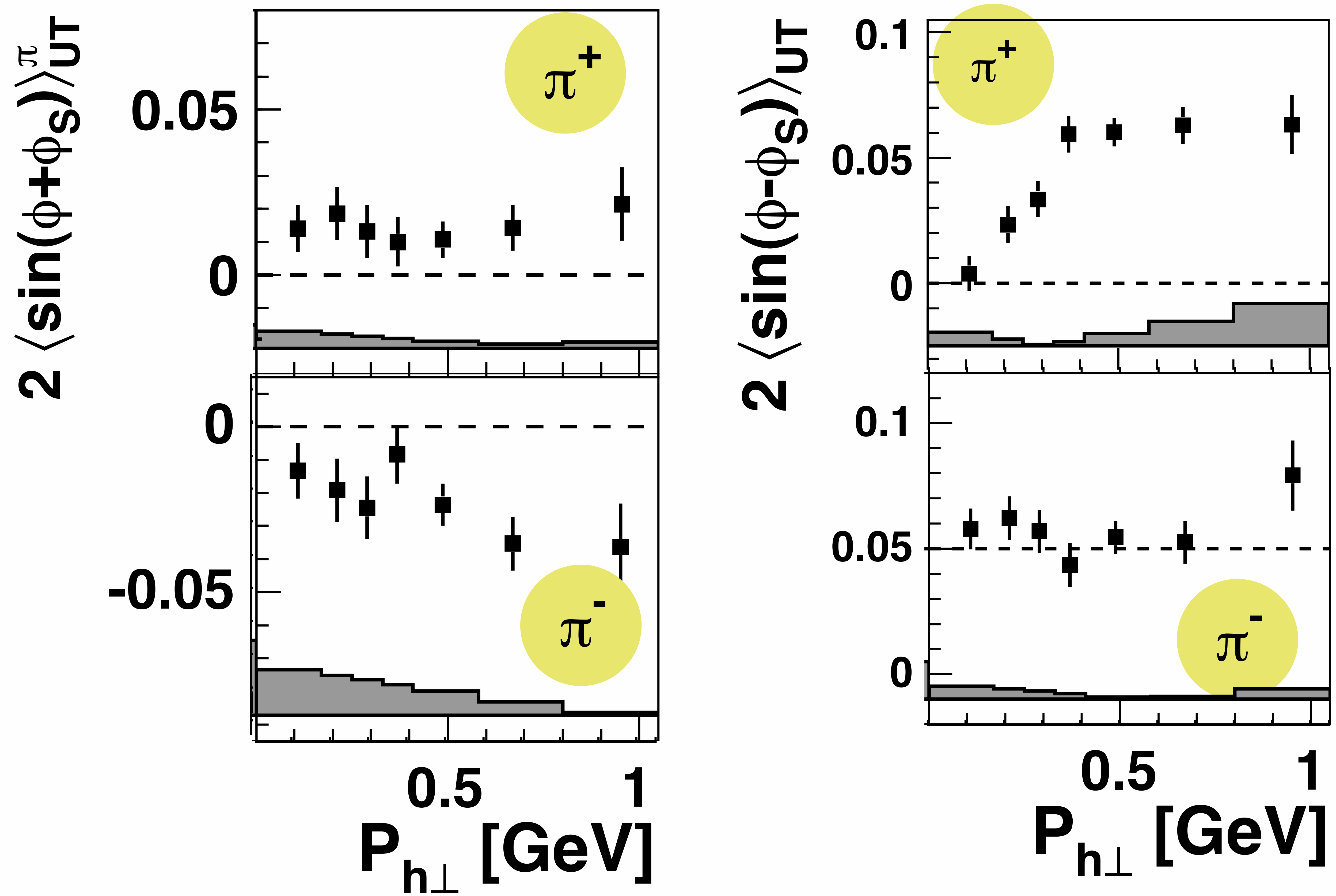
$lp^{\uparrow} \rightarrow hX$



$lp^{\uparrow} \rightarrow l'hX$

COLLINS

SIVERS



Event selection

- ★ Events with at least 1 hadron track in acceptance. (<0.1% lepton contamination)
- ★ Hadrons selected in **2-15 GeV** energy range
  - >> further PID using a dual-radiator ring-imaging Cherenkov detector (RICH): RICH unfolding
- ★ Trigger by signal coincidence of different sub-detectors and energy deposition (>1.4 GeV) in electro-magnetic calorimeter:
  - >> ~100 % efficient for electrons
  - >> finite efficiency for single hadrons calculated as a function of hadron type, momentum, and detector position
  - >> event-wise determination of (and correction for) trigger efficiency
- ★ Average polarization degree of target: $\langle S_\perp \rangle = 0.713 \pm 0.063$

Systematic uncertainties

- ★ *Misalignment of detectors/beam.*
- ★ *Hadron misidentification.*
- ★ *Angular and momentum resolution.*
- ★ *Secondary interactions:*
  Radiative corrections, M.S., decays, etc.
- ★ *Target polarization:*
  - >> *8.8% scale uncertainty.*
- ★ *Trigger efficiency correction:*
  - >> *Difference among two alternative methods.*
- ★ *Compatibility of data productions:*
  - >> *Negligible.*

All-in-one Monte Carlo approach:

High-statistics PYTHIA 6.2 +
Spin-dependent model (from fit to data).
$A_{UT}^{\sin\psi}(x_F, P_T)$

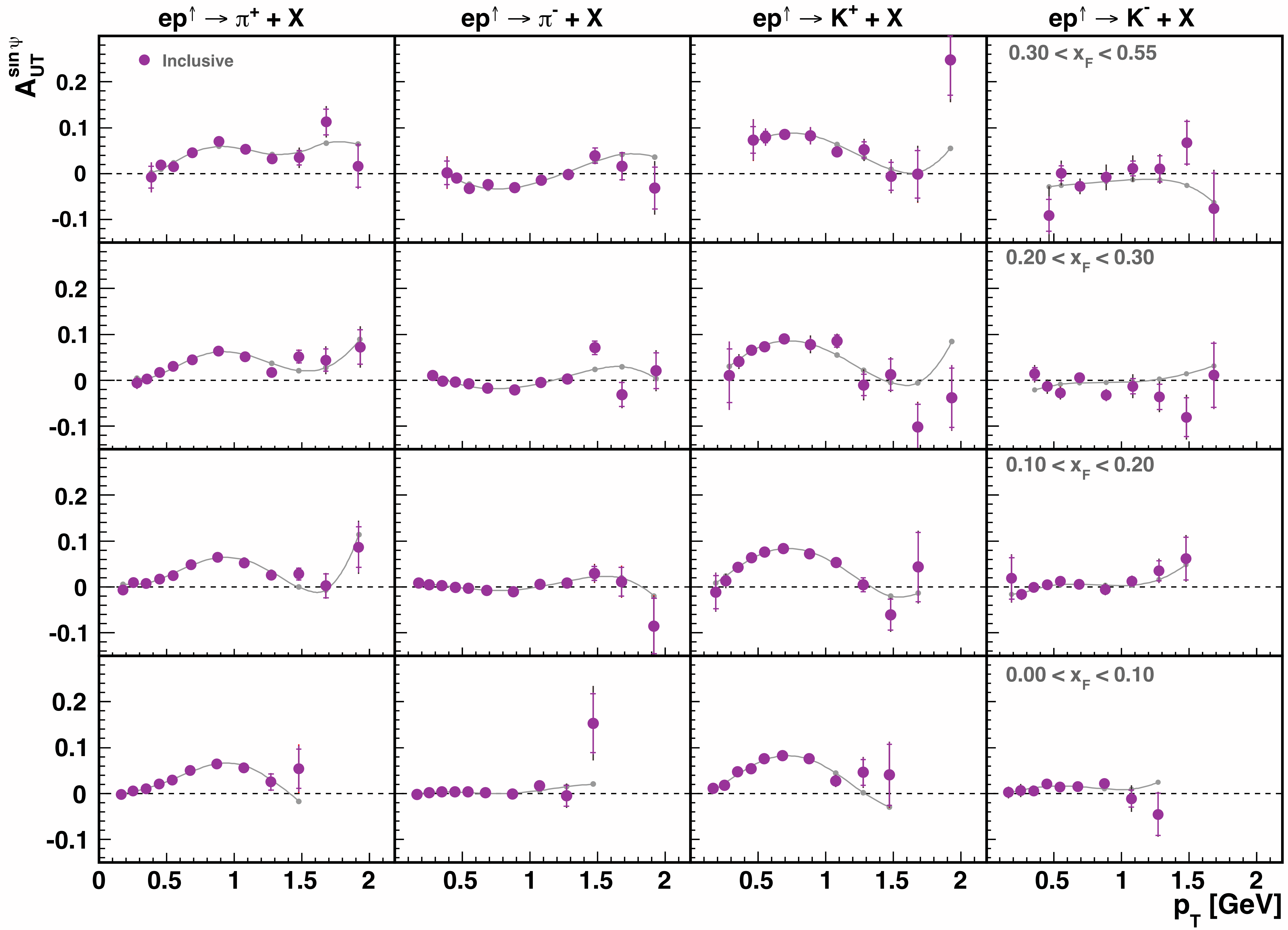
Full description of the detector

Extraction of the Asym. in every bin $A_{UT,MC}^{\sin\psi}$

The systematic uncertainty is taken then as the biggest of either:
(i) The deviation

$$|A_{UT,MC}^{\sin\psi} - A_{UT}^{\sin\psi}(\langle x_F \rangle, \langle P_T \rangle)|$$

(ii) The statistical error of $A_{UT,MC}^{\sin\psi}$



A parametric model

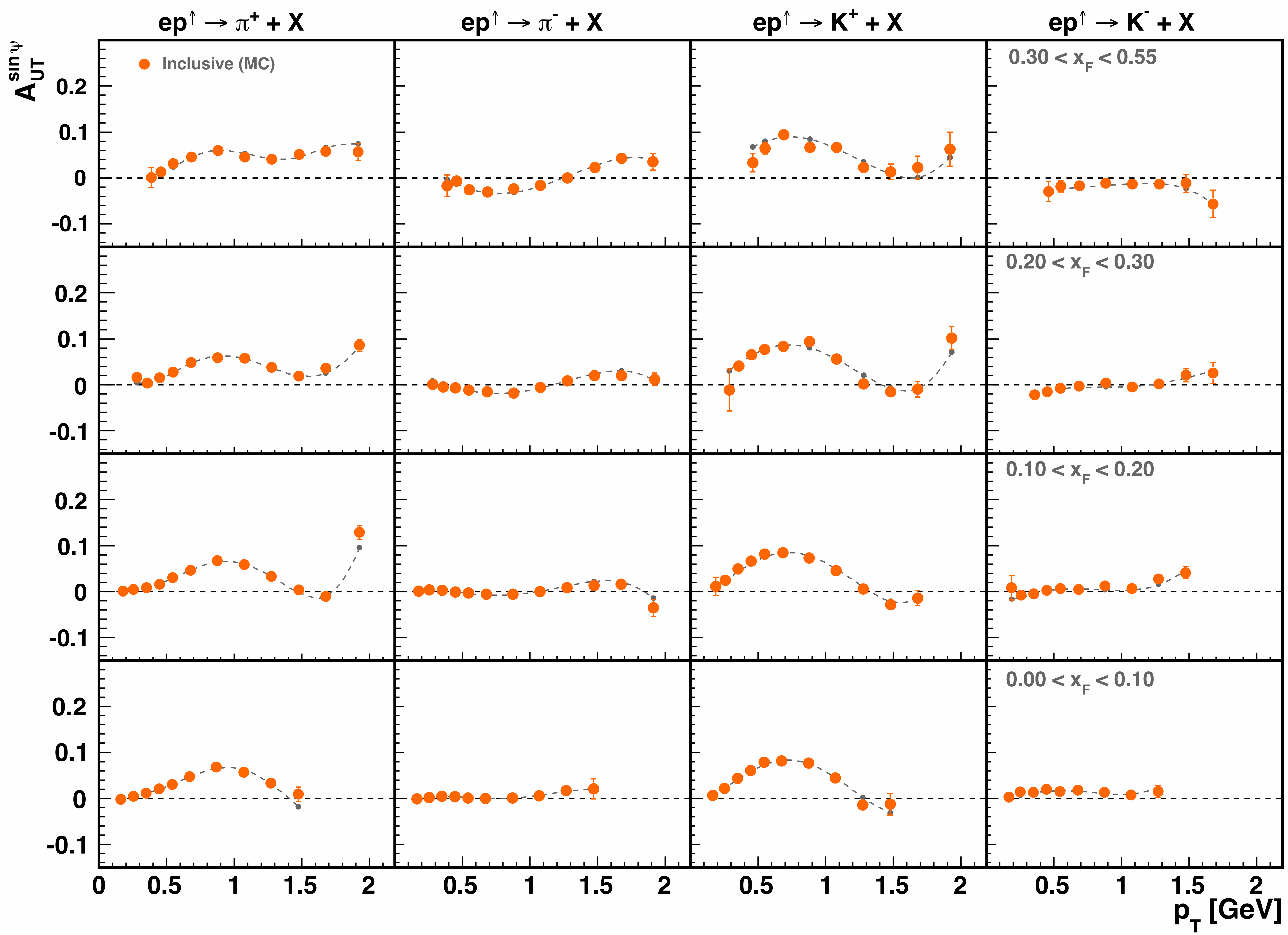
Fit to HERMES data

The functional form is a Taylor expansion in P_T (up to fifth order) and x_F (up to first order) around the average kinematics of the entire experimental data sample.

$$\mathcal{A}_{UT}^{\sin\psi} = \sum_{i=0}^{5} \hat{P}_T^i c_i + \hat{x}_F \sum_{i=0}^{5} \hat{P}_T^i d_i$$

$$\hat{P}_T \equiv P_T - \langle P_T \rangle$$

$$\hat{x}_F \equiv x_F - \langle P_T \rangle$$



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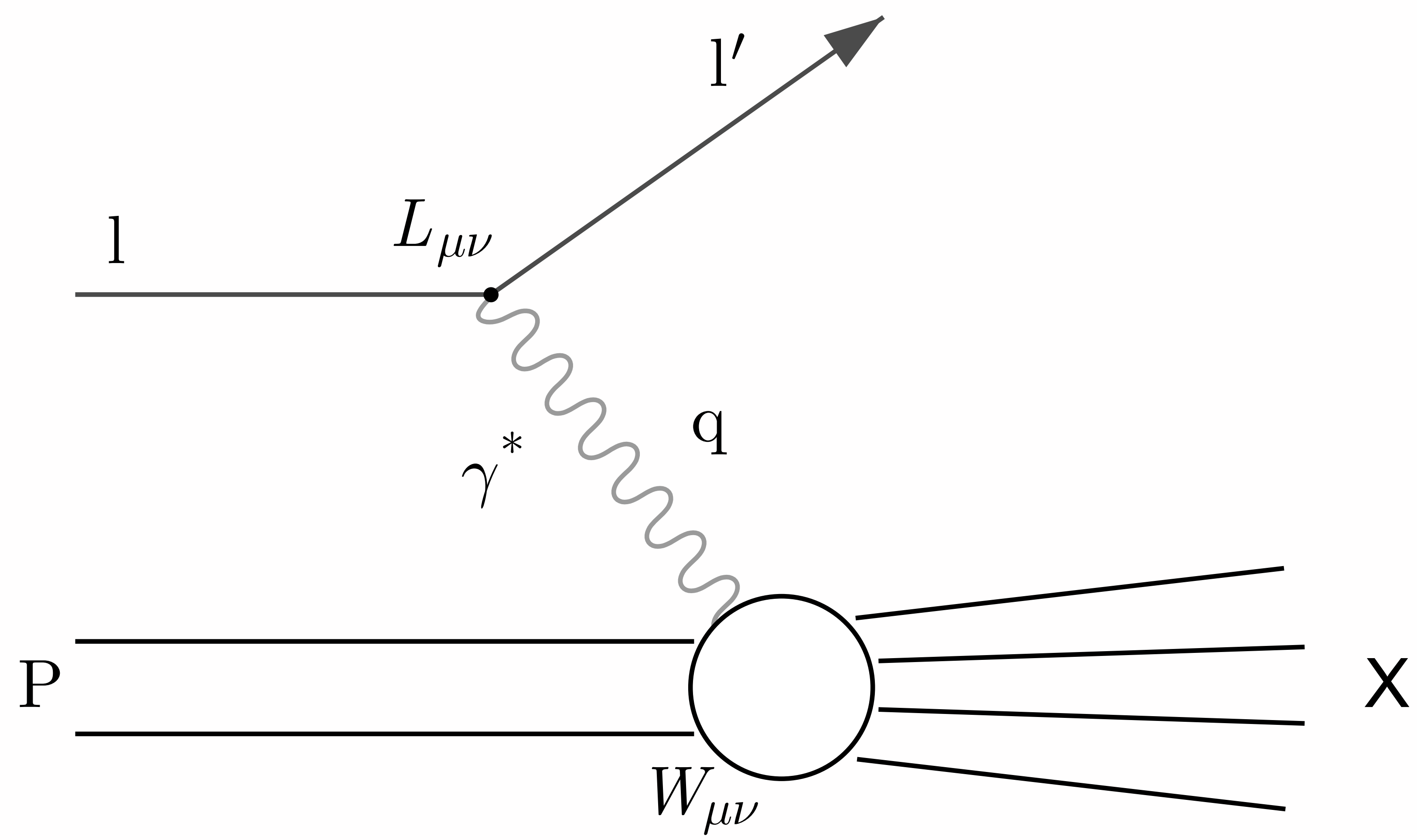
$$\hat{P}_T \equiv P_T - \langle P_T \rangle$$

$$\hat{x}_F \equiv x_F - \langle P_T \rangle$$

DIS variables



θ	polar scattering angle in the laboratory frame
$\mathbf{q} = \mathbf{l} - \mathbf{l}'$	four-momentum transfer to the target
$s = (\mathbf{P} + \mathbf{l})^2 \stackrel{\text{lab}}{\approx} M^2 + 2ME$	squared centre-of-mass energy
$\nu = \frac{\mathbf{P}\cdot\mathbf{q}}{M} \stackrel{\text{lab}}{=} E - E'$	energy transfer to the target
$y = \frac{\mathbf{P}\cdot\mathbf{q}}{\mathbf{P}\cdot\mathbf{l}} \stackrel{\text{lab}}{=} \frac{\nu}{E}$	fractional energy transfer to the target
$Q^2 = -\mathbf{q}^2 \stackrel{\text{lab}}{\approx} 4EE' \sin^2\frac{\theta}{2}$	squared invariant mass of the virtual photon
$W^2 = (\mathbf{P} + \mathbf{q})^2 \stackrel{\text{lab}}{=} M^2 + 2M\nu - Q^2$	squared mass of the final state
$x = \frac{Q^2}{2\mathbf{P}\cdot\mathbf{q}} \stackrel{\text{lab}}{=} \frac{Q^2}{2M\nu}$	Bjorken scaling variable