Transverse target Single-Spin Asymmetry (SSA) in inclusive electroproduction of charged pions and kaons [1].

Deutsches Elektronen-Synchrotron (DESY)

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

Outline

>> Introduction

- ★ Inclusive electro-production of pions and kaons.
- ★ Transverse Single-Spin Asymmetry.

>> The measurement

- ★ The HERMES experiment.
- ★ Event selection.
- ★ Yields and kinematics.
- ★ Extraction of the amplitudes.

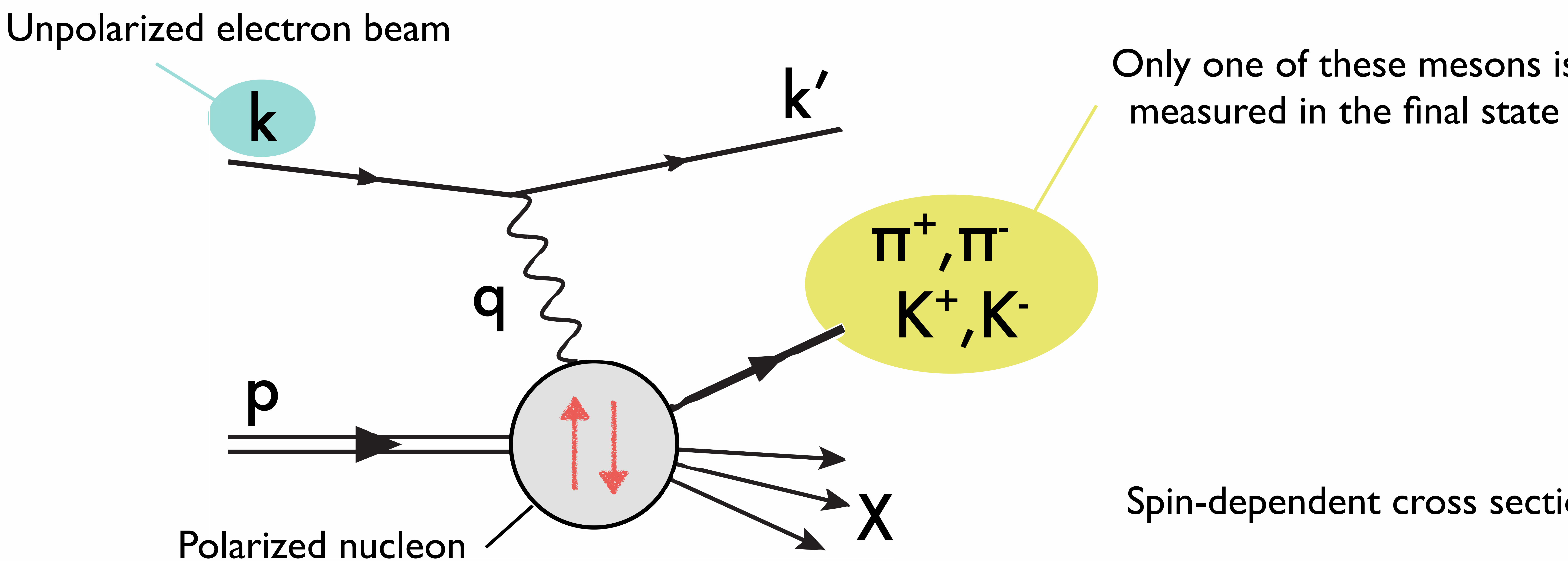
>> The Asymmetries

- ★ 1-dimensional projections.
- ★ 2-dimensional binning.
- ★ Systematics.
- ★ Categorized Asymmetries

>> Summary and Outlook

Inclusive Electro-production

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



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

Spin-dependent cross section

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

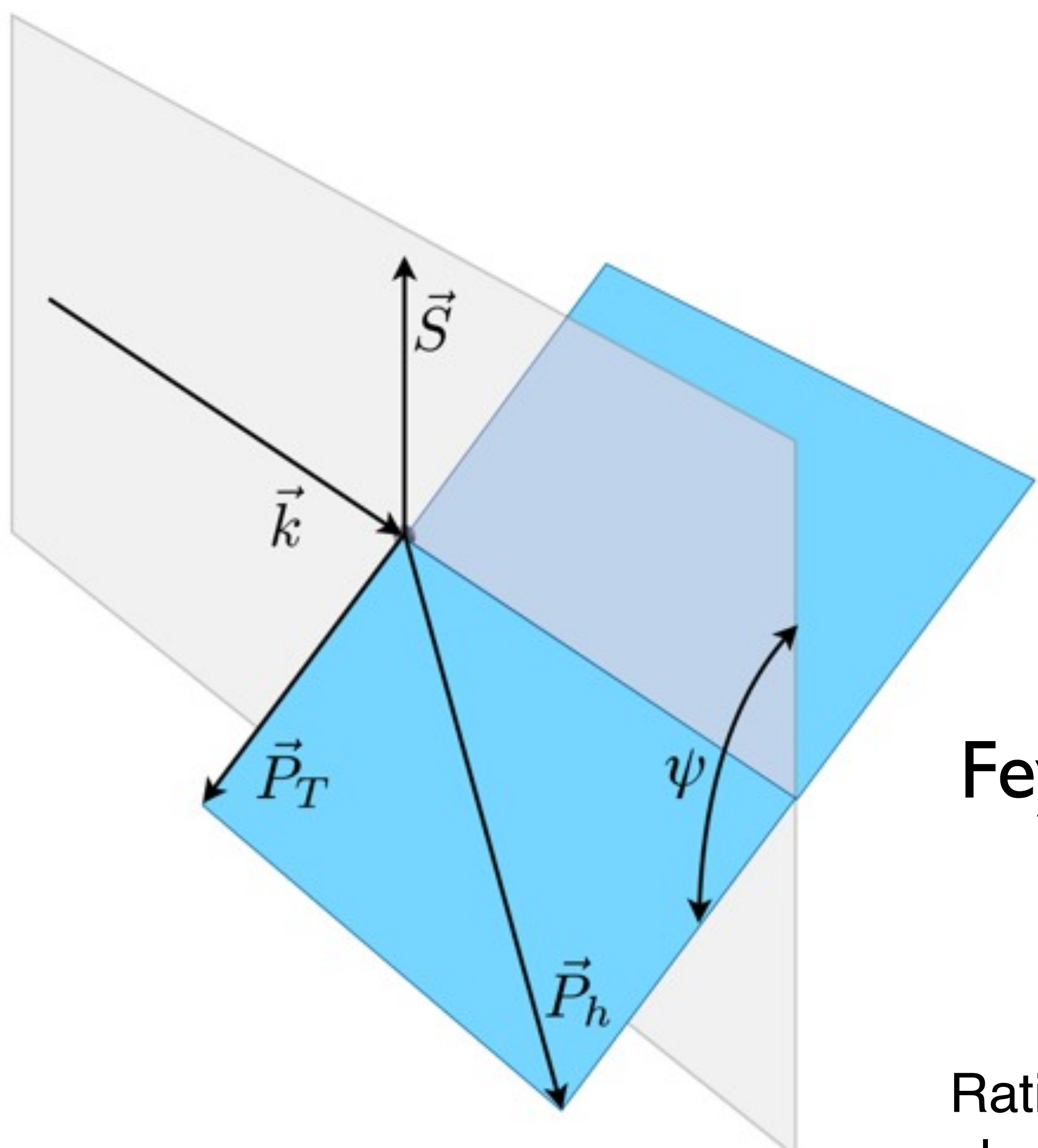
Transverse Single-Spin Asymmetry (SSA)

in respect to the polarization axis of the nucleon

Azimuthal asymmetry

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

Asymmetry 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

Left-Right Asymmetry

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

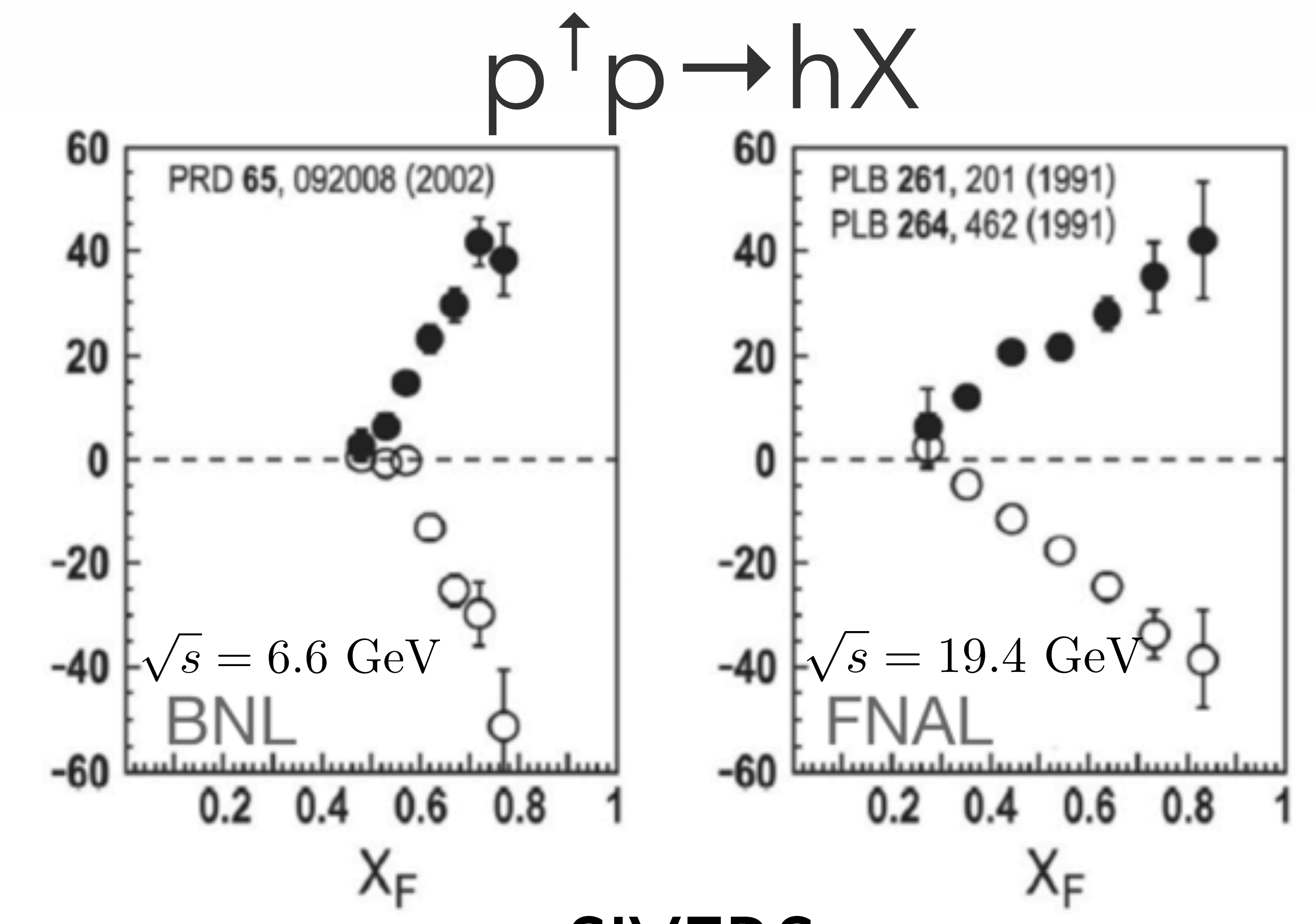
Motivation

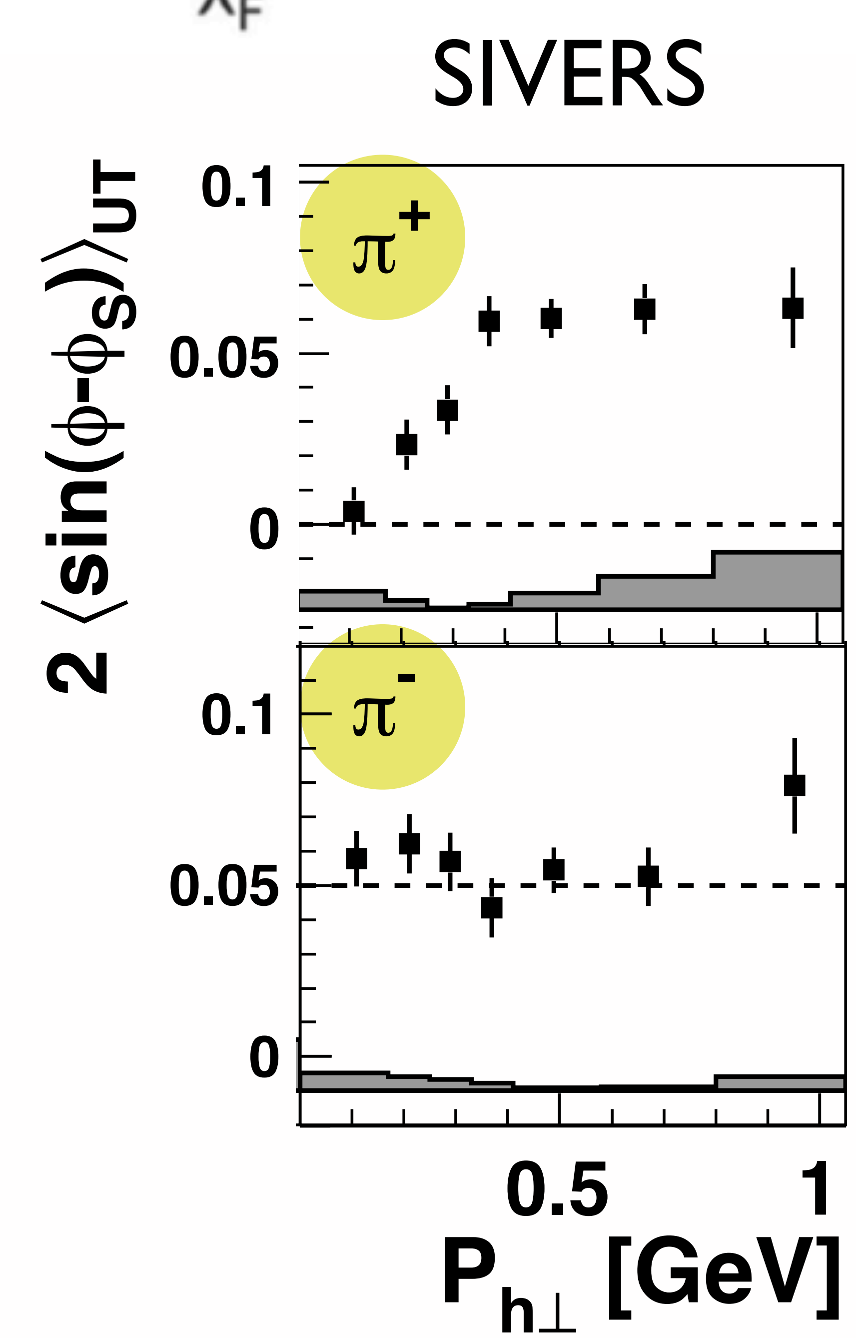
>> **Experimental**:

- ★ 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 on SIDIS: $lN^{\uparrow} \rightarrow l'hX$.
- ★ Lots of $lN^{\uparrow} \rightarrow hX$ data in HERMES!
- ★ Involves only one hadron.

>> **Theoretical puzzle.** Two existing approaches:

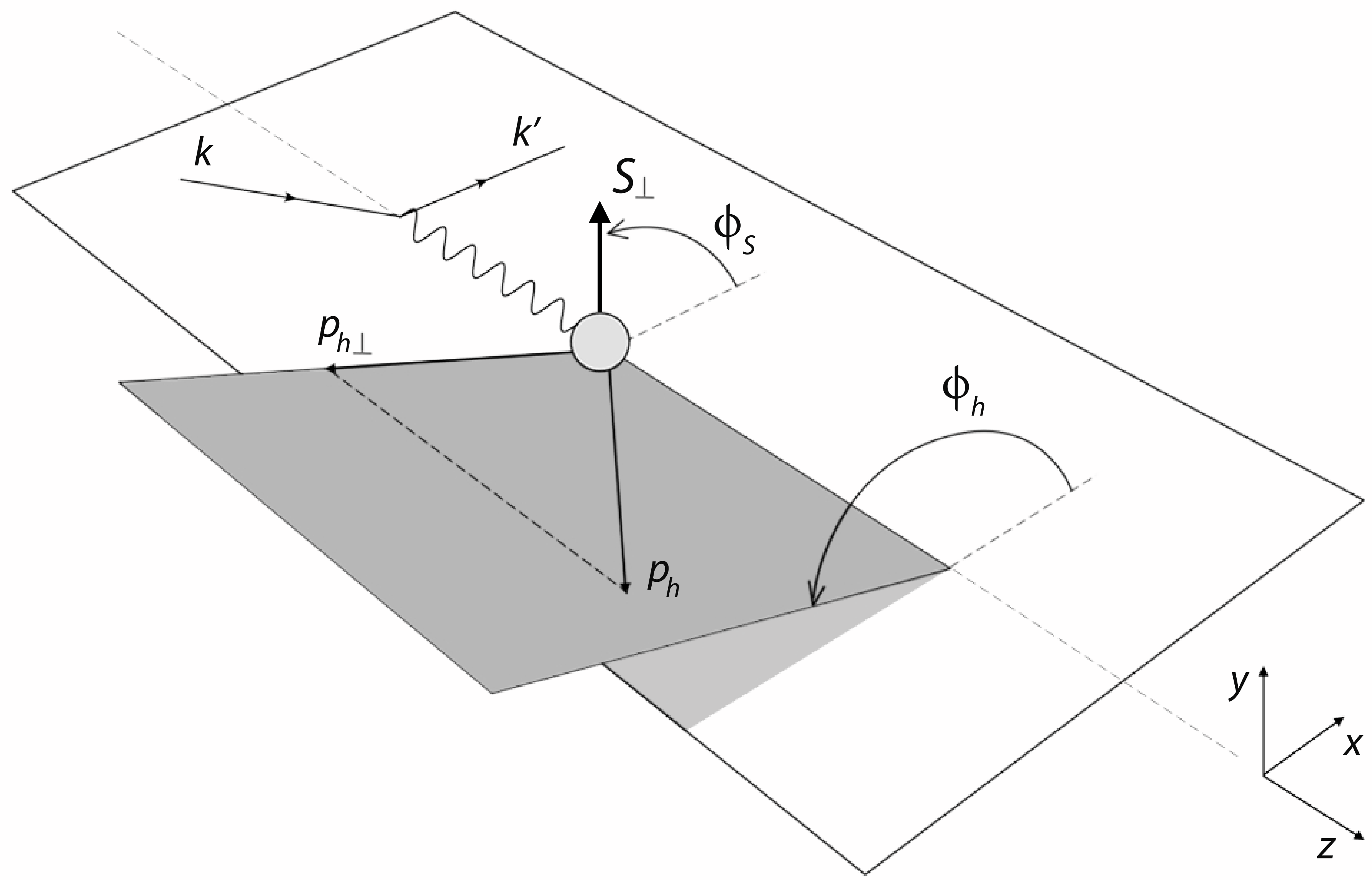
- ★ TMD's and fragmentations functions[4] ($Q^2 \gg \Lambda_{QCD}^2$). Sivers and Collins effects.
- ★ Twist-3 parton correlation functions[5] ($P_T \gg \Lambda_{QCD}$).

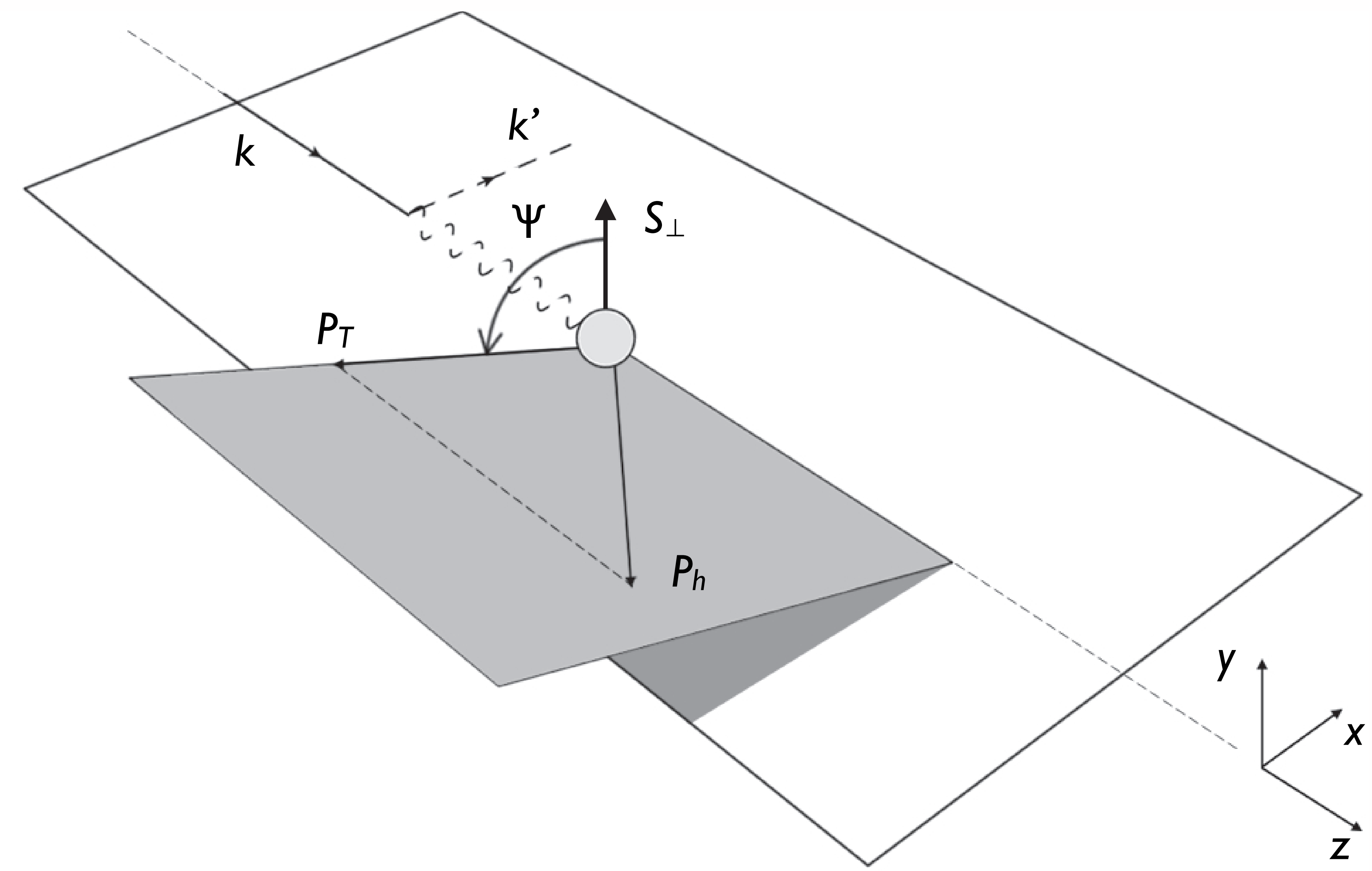




[2] Phys. Rev. Lett. 103, 152002 (2009).
[3] Phys. Lett. B 693 (2010) 11-16.
[4] Phys. Lett. B 362 (1995) 164–172.
[5] Phys. Rev. D 59 (1999) 014004.

Similarity between Sivers and inclusive SSA





semi-inclusive DIS

SIVERS

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

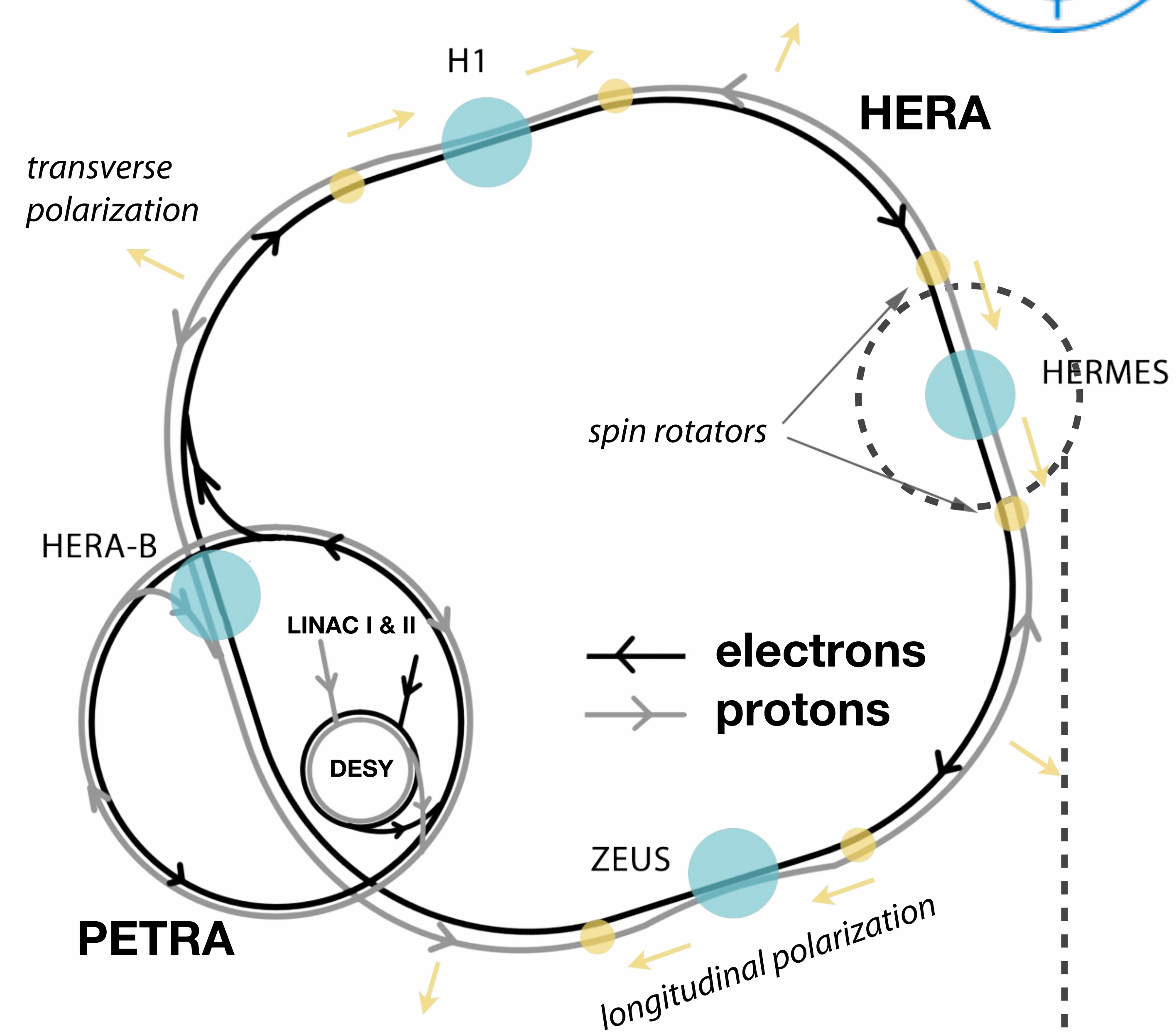
COLLINS

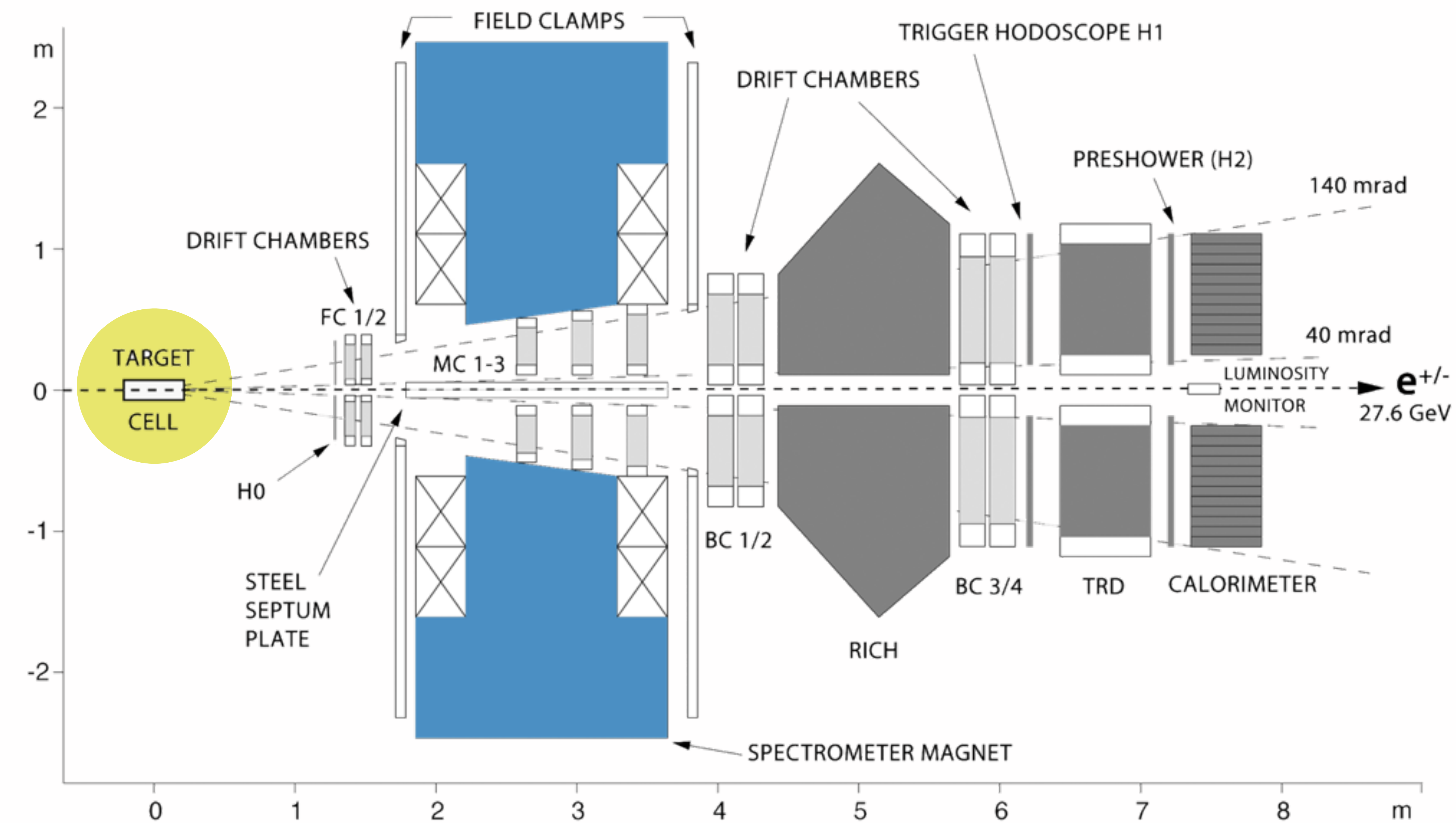
Inclusive hadron production

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

Inclusive SSA amplitude

HERA accelerator at DESY





★ Lepton e^+/e^- beam at 27.6 GeV.

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

Event Selection

- Integrated luminosity ~ **146 pb^{-1}**.
- Selected 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 the calorimeter:
  - ~100 % efficient for electrons.
  - Finite efficiency for single hadrons calculated as a function of h-type, momentum and detector position.
  - Event-wise determination of average efficiencies.
- Current polarization degree of the target $\langle S_\perp \rangle = 0.713 \pm 0.063$

For every track/event:

PID weight

$$w_{id} = P^{-1}(\mathrm{id}^{\mathrm{true}}|\mathrm{id}^{\mathrm{tag}})$$

Event weight (trig. eff.)

$$\langle \epsilon \rangle = 1 - \prod_{event} (1 - \epsilon_w)$$

or 1 if a detected lepton

Final weight

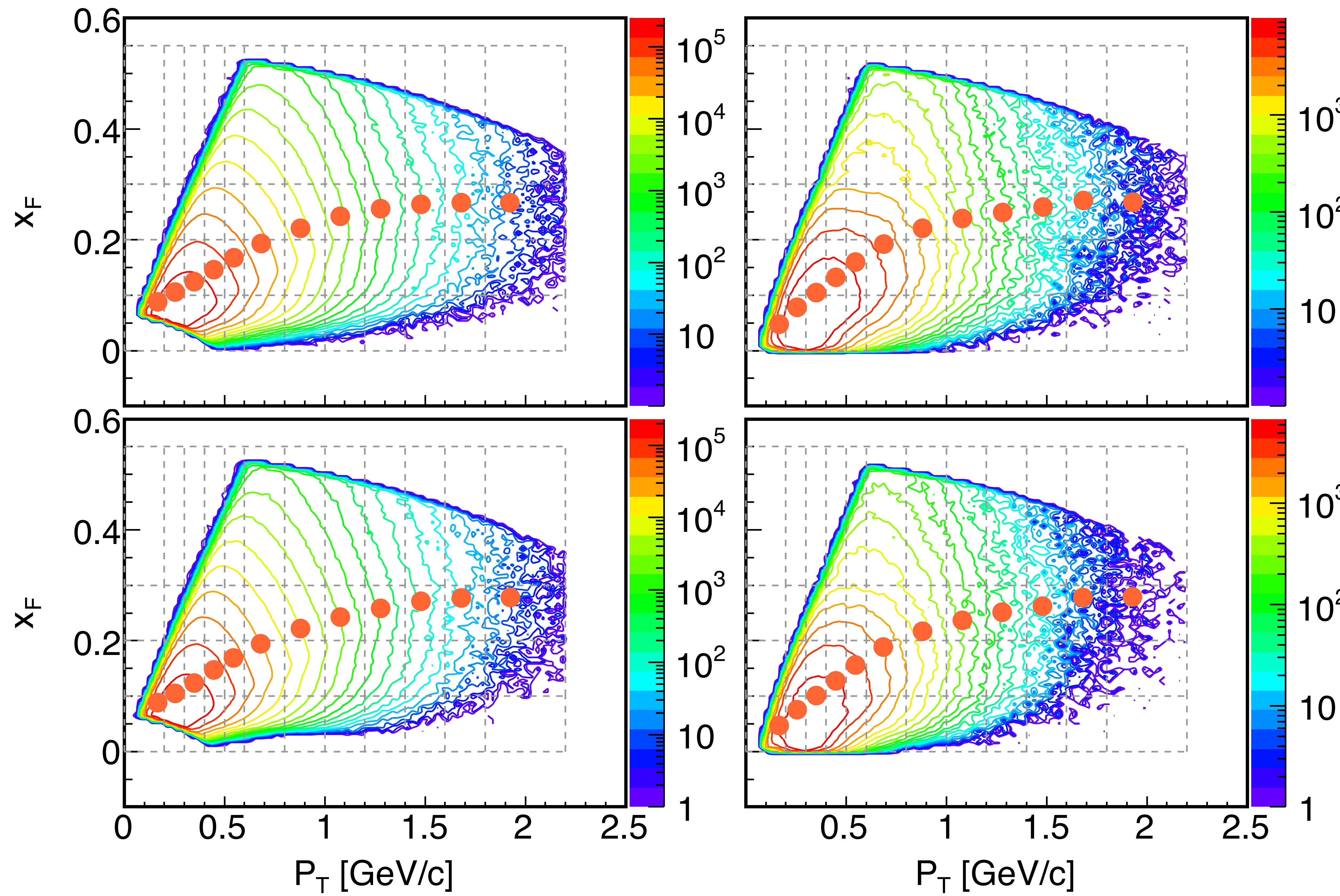
$$W_{event} = \frac{w_{id}}{\langle \epsilon \rangle}$$

Kinematics and Yields

Corrected by trig. eff.

π^+ 172 M

π^- 142 M

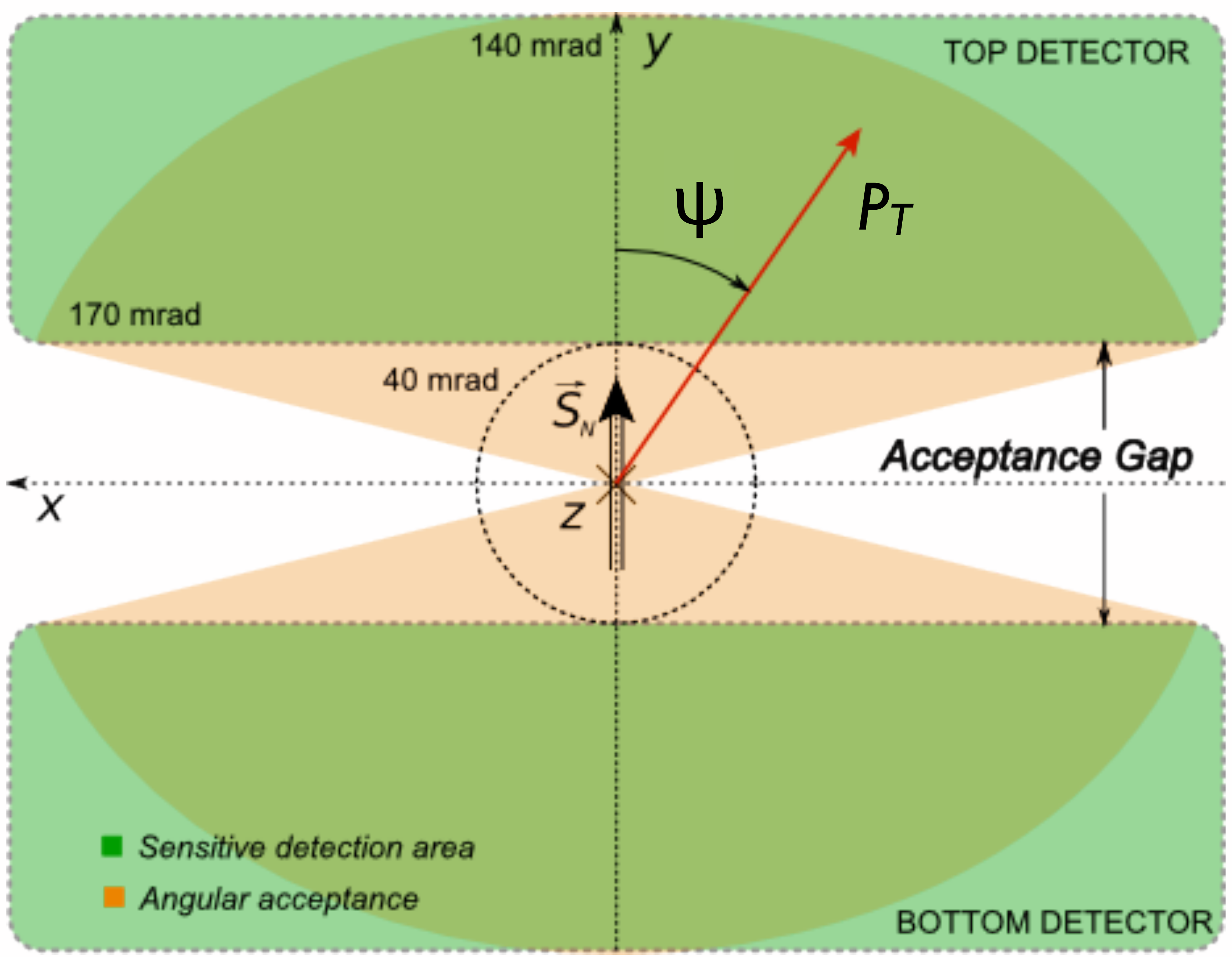


K^+ 14.5 M

K^- 7.3 M

Extraction of the Asymmetry Amplitude

Maximum likelihood fit



Detection efficiencies and acceptance effects cancels in the max. 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 max. likelihood fit to the differential cross section.

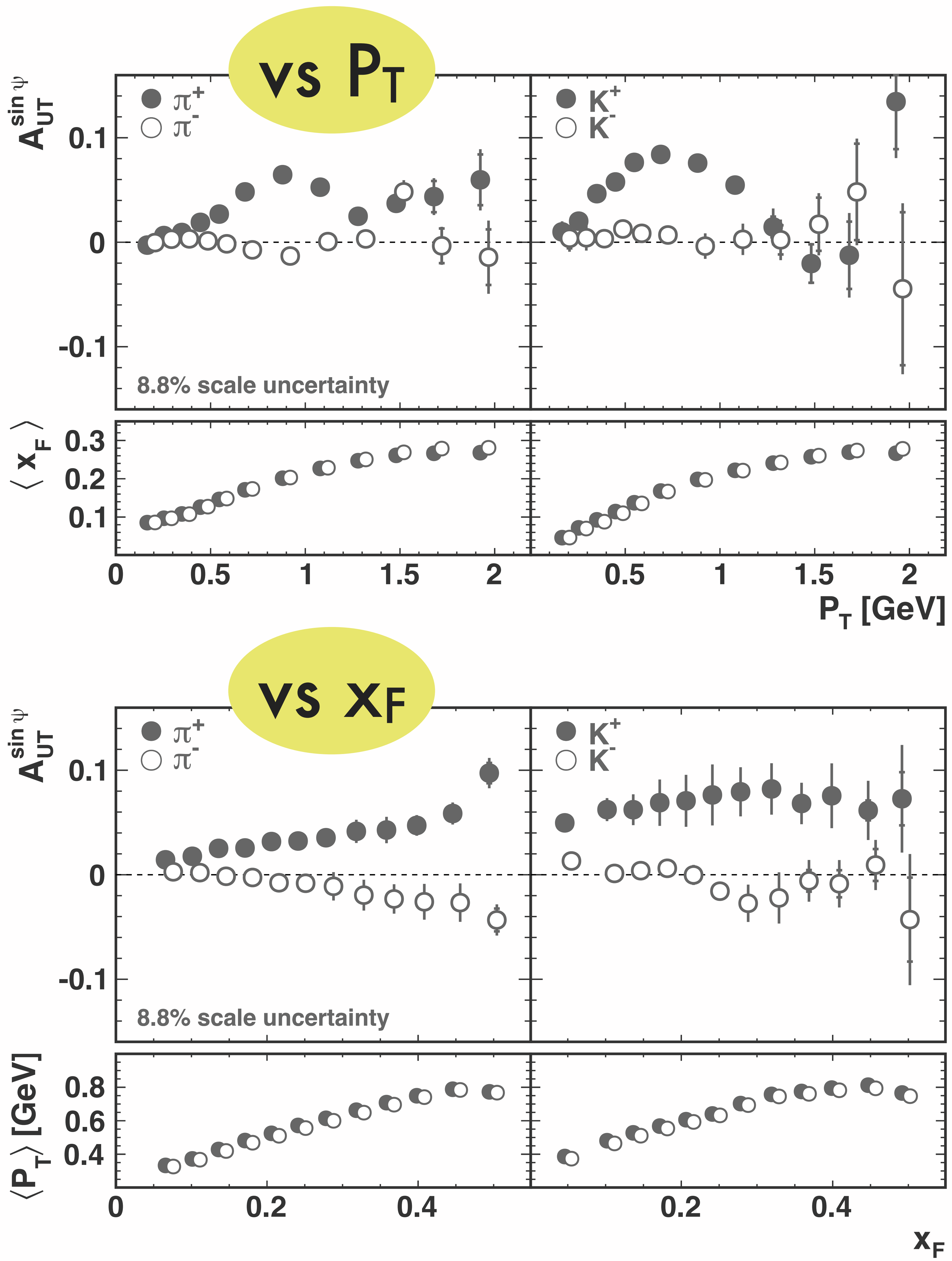
$$\mathcal{L} = \prod_i^N \left(\frac{1 + S_{T,i}\left[A_0 + A_{UT}^{\sin\psi} \sin\psi_i\right]}{L_i^{\uparrow\downarrow}} \right)^{W_i}$$

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

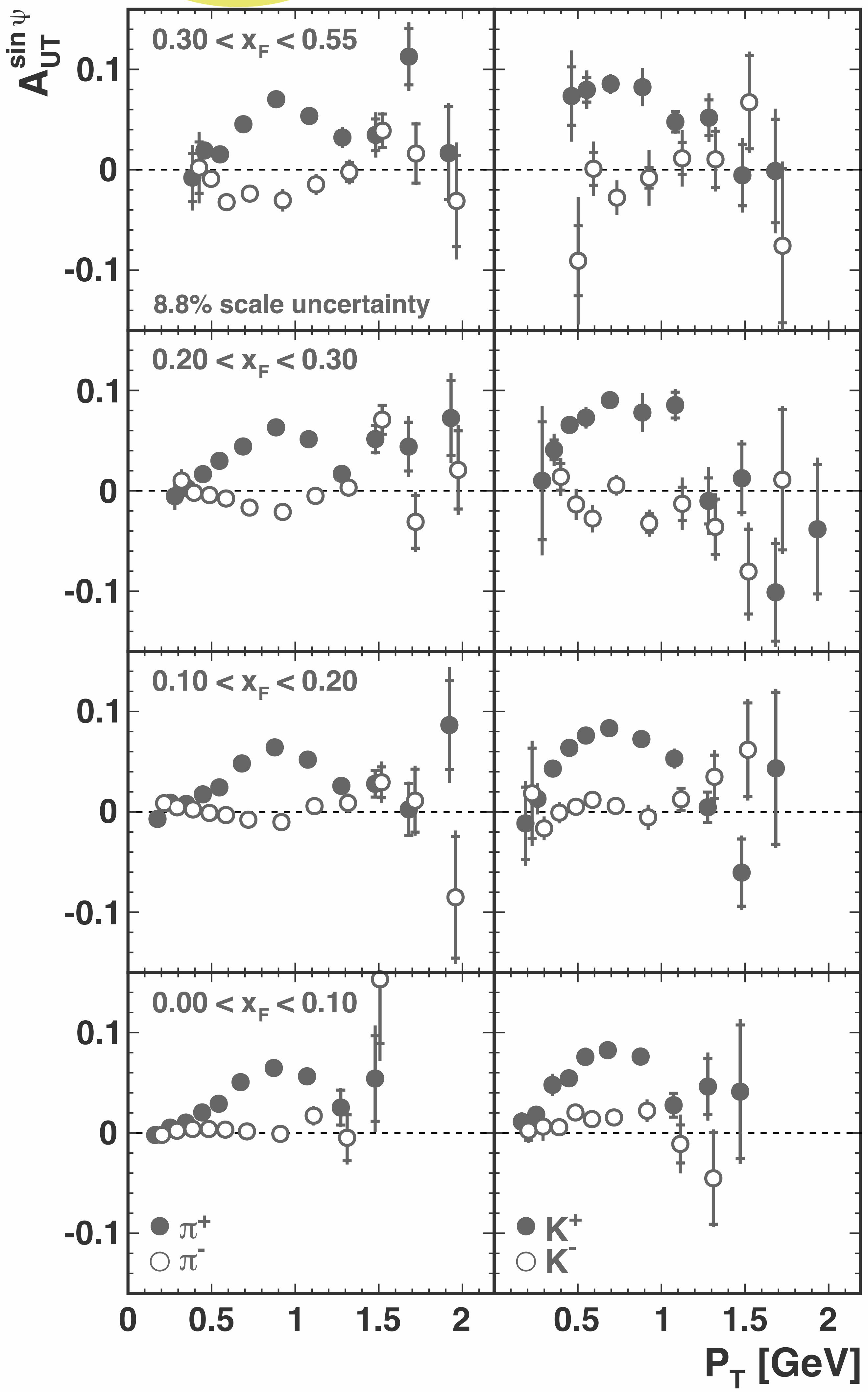
- ★ *The asymmetry amplitudes are **positive** for π^+ and K^+ and compatible with **zero** for π^- and K^-.*
- ★ *A clear two-fold structure in P_T.*
  - >> *The amplitudes increase with P_T up to ~0.6 (~0.9) at P_T~0.8 GeV for π^+(K^+). For this point on, the tendency is inverted.*
  - >> *For π^+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

P_T and x_F are strongly correlated.

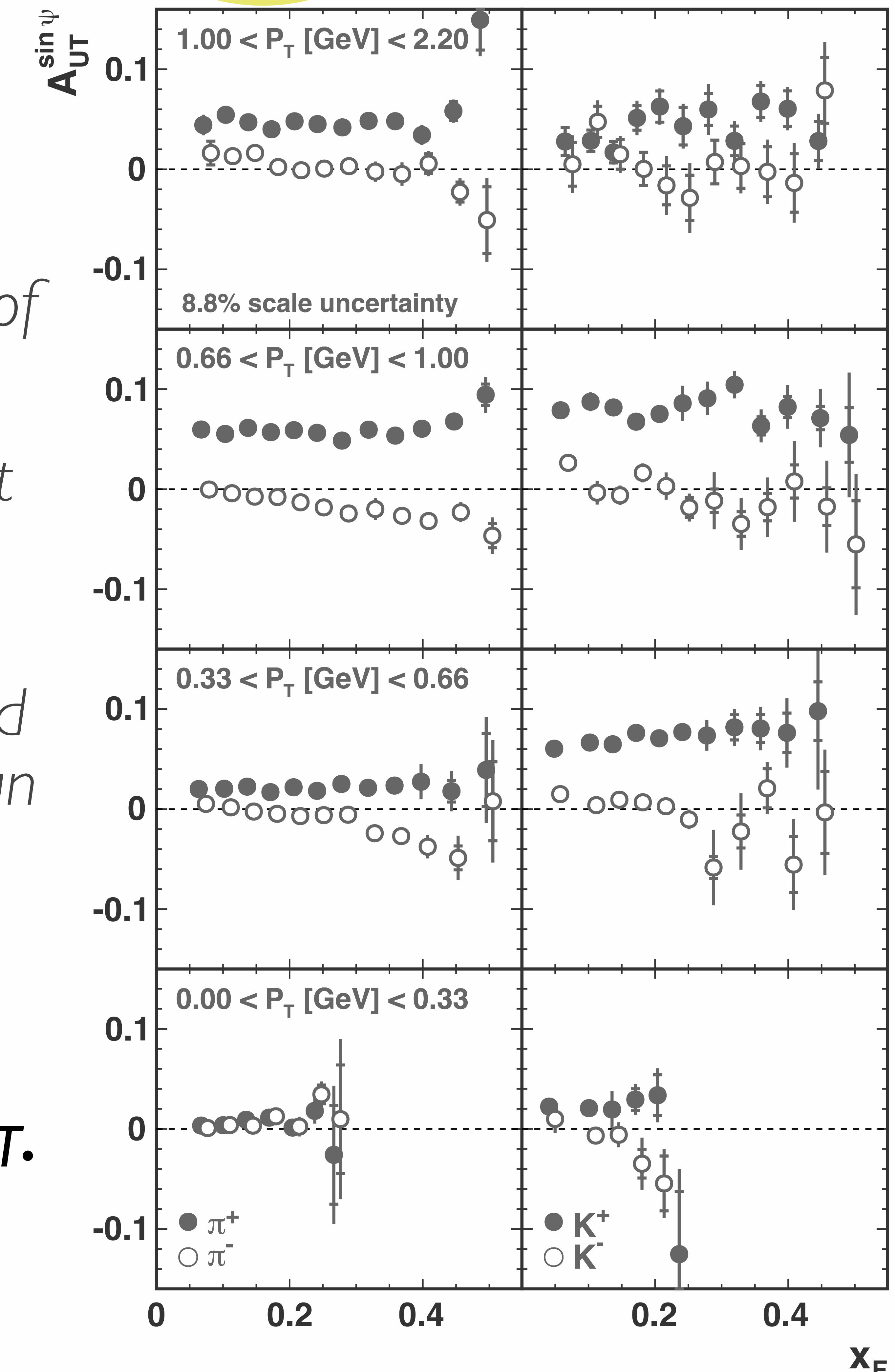
Inclusive SSA (2D)

...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. No dependence on x_F.
The 1D x_F dependence is a reflection of the underlying dependence on P_T.

π^-: Like in the 1D case, there is a slight decreasing linear tendency 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 is on P_T.

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 $A_{UT,MC}^{\sin\psi}$

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 or Semi-inclusive:

The scattered lepton is detected.

DIS events:

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

mid-z (0.2<z<0.7):

Identical to the SIDIS in Sivers and Collins measurements at HERMES.

$$\langle Q^2 \rangle \lesssim \langle P_T^2 \rangle$$

low-z (z<0.2)

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

fractional virtual-photon energy carried by the hadron

high-z (z>0.7):

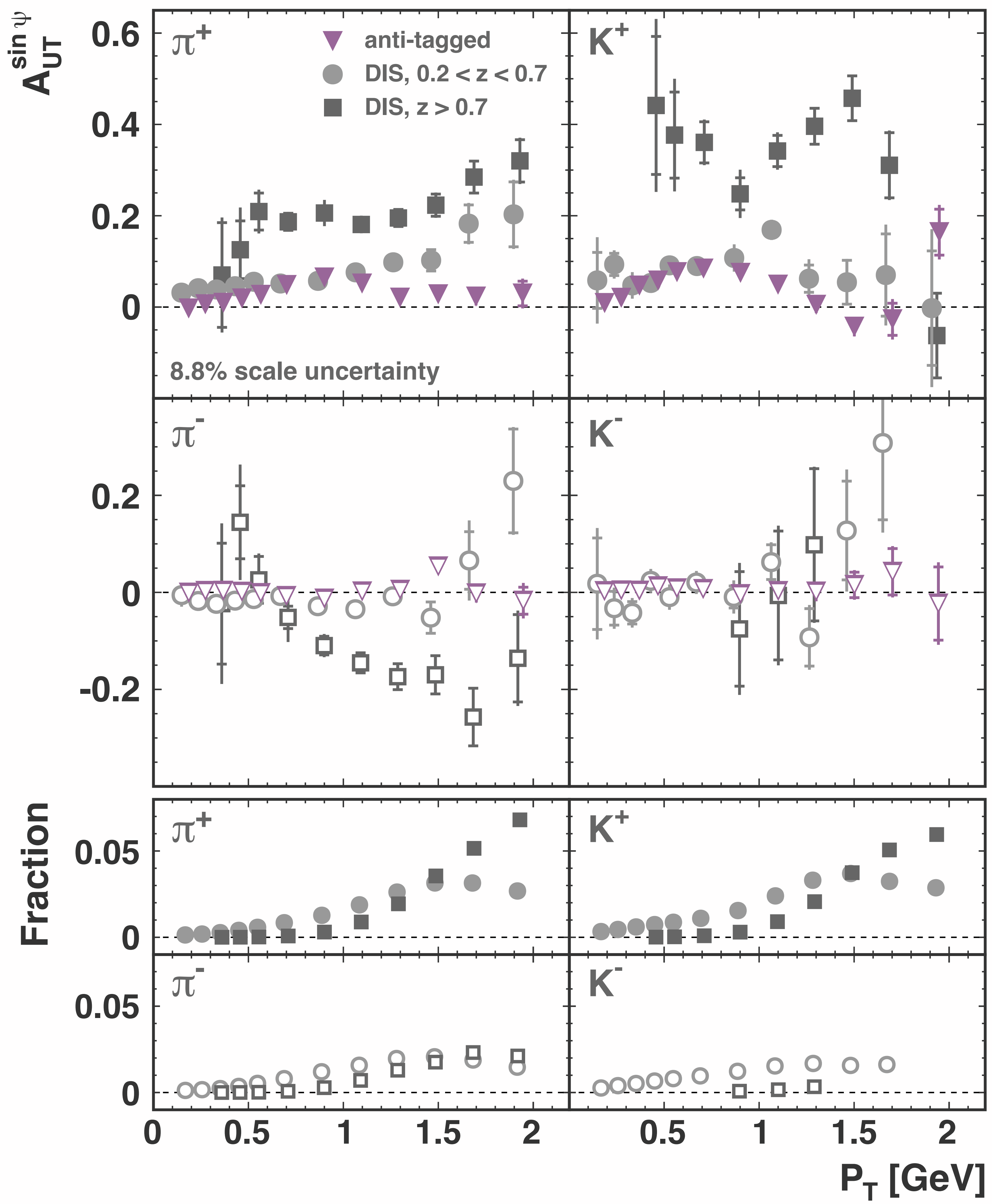
Hadrons in this region might be produced in exclusive reactions.

$$\langle Q^2 \rangle < \langle P_T^2 \rangle$$

Non-DIS events

Categorized SSA

.. as a function of P_T



Anti-tagged *(photoproduction)*

★ *Inclusive asymmetries dominated by quasi-real photoproduction: they go like $1/P_T$.*

★ *At high P_T contribution from DIS becomes sizable.*

DIS, mid-z *(SIDIS)*

★ *Q^2 is the largest scale. TMD's and frag. functions holds. Non-vanishing asymmetries at high P_T.*

★ *Sivers effect is expected to be the main contribution.*

DIS, high-z *(Exclusive)*

★ *Large asymmetries in π^+, π^- and K^+.*

★ *Exclusive production of ρ mesons in π^+ and π^- channels can be substantial.*

★ *Dominance of the struck quark d in π^- production at high z.*

Transverse target Single-Spin Asymmetry (SSA) in inclusive electroproduction of charged pions and kaons.

Summary and Outlook

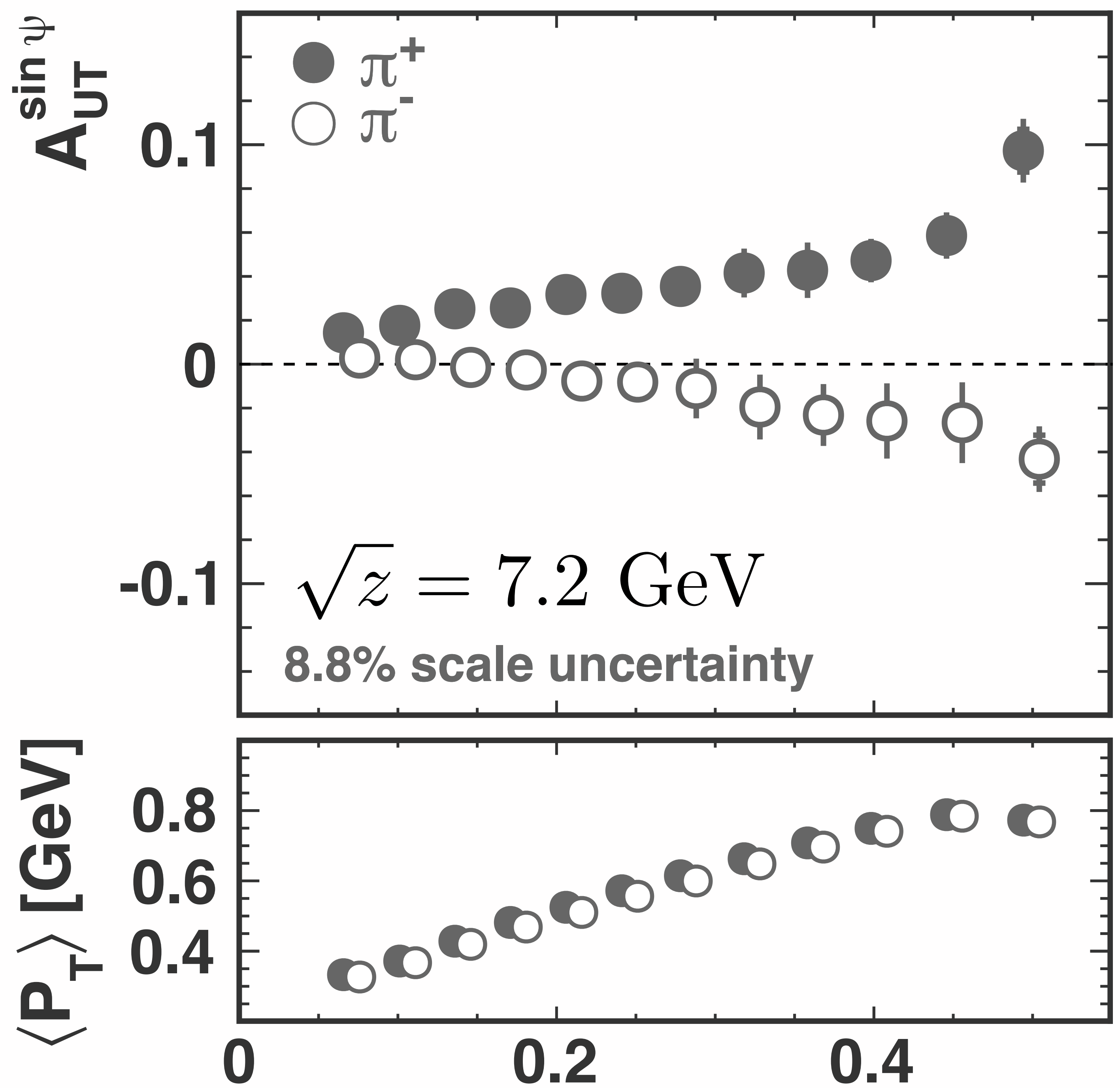
- >> Transverse azimuthal SSA measured in inclusive electroproduction of pions and kaons.
- >> Two-dimensional extraction by binning simultaneously in x_F and P_T :
  - ★ For π^+, the asymmetry is independent of x_F.
  - ★ For π^-, and less for K^- (K^+), the asymmetry amplitudes decrease (increase) 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-PT, sizable contribution from SIDIS processes.
  - ★ 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.
  - ★ Substantial contribution from exclusive processes.
  - ★ Effect from favored fragmentation of the struck quark dominate.

Backup Slides

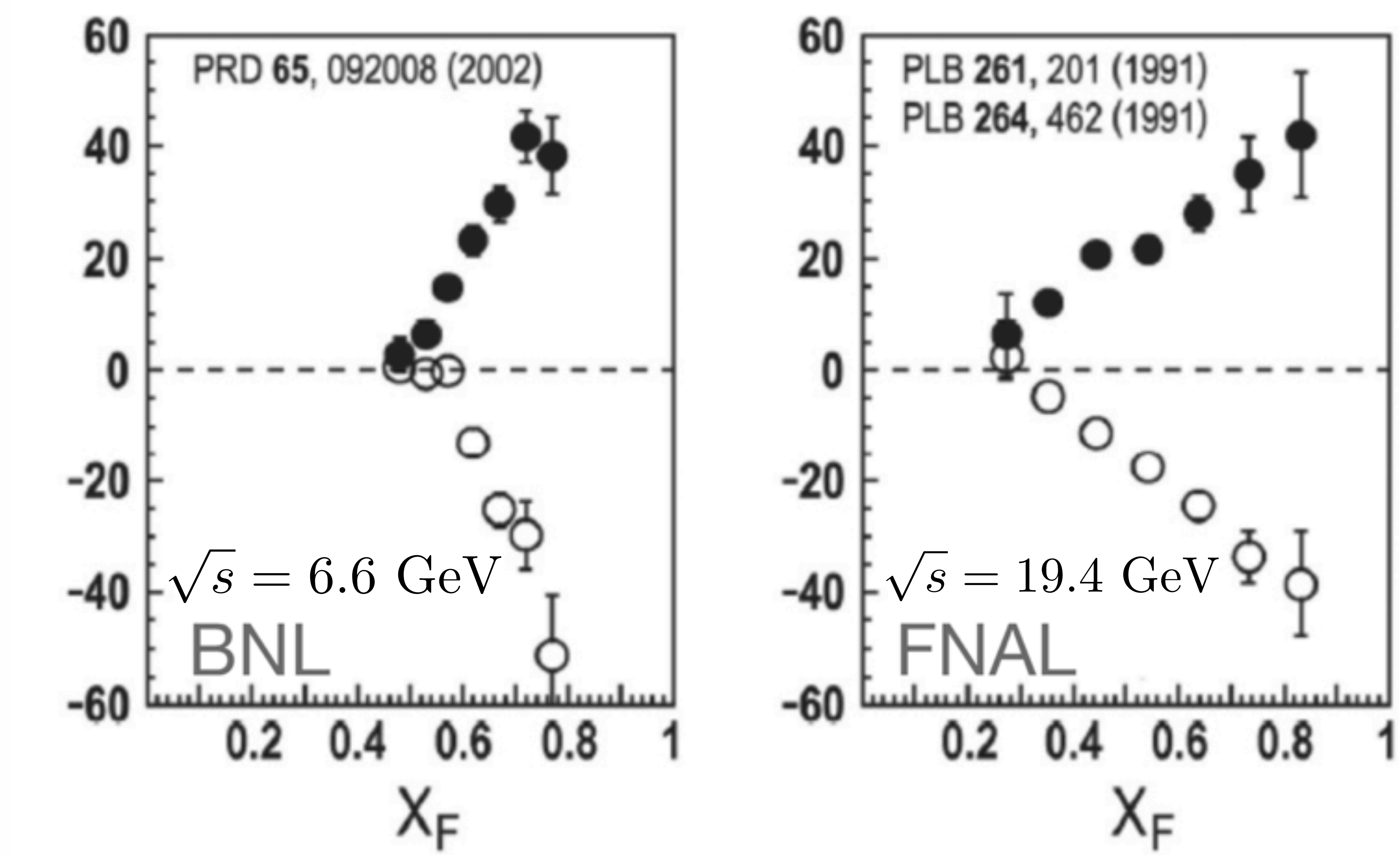
Comparison

to A_N in hadron-hadron collisions

$lp^{\uparrow} \rightarrow hX$



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

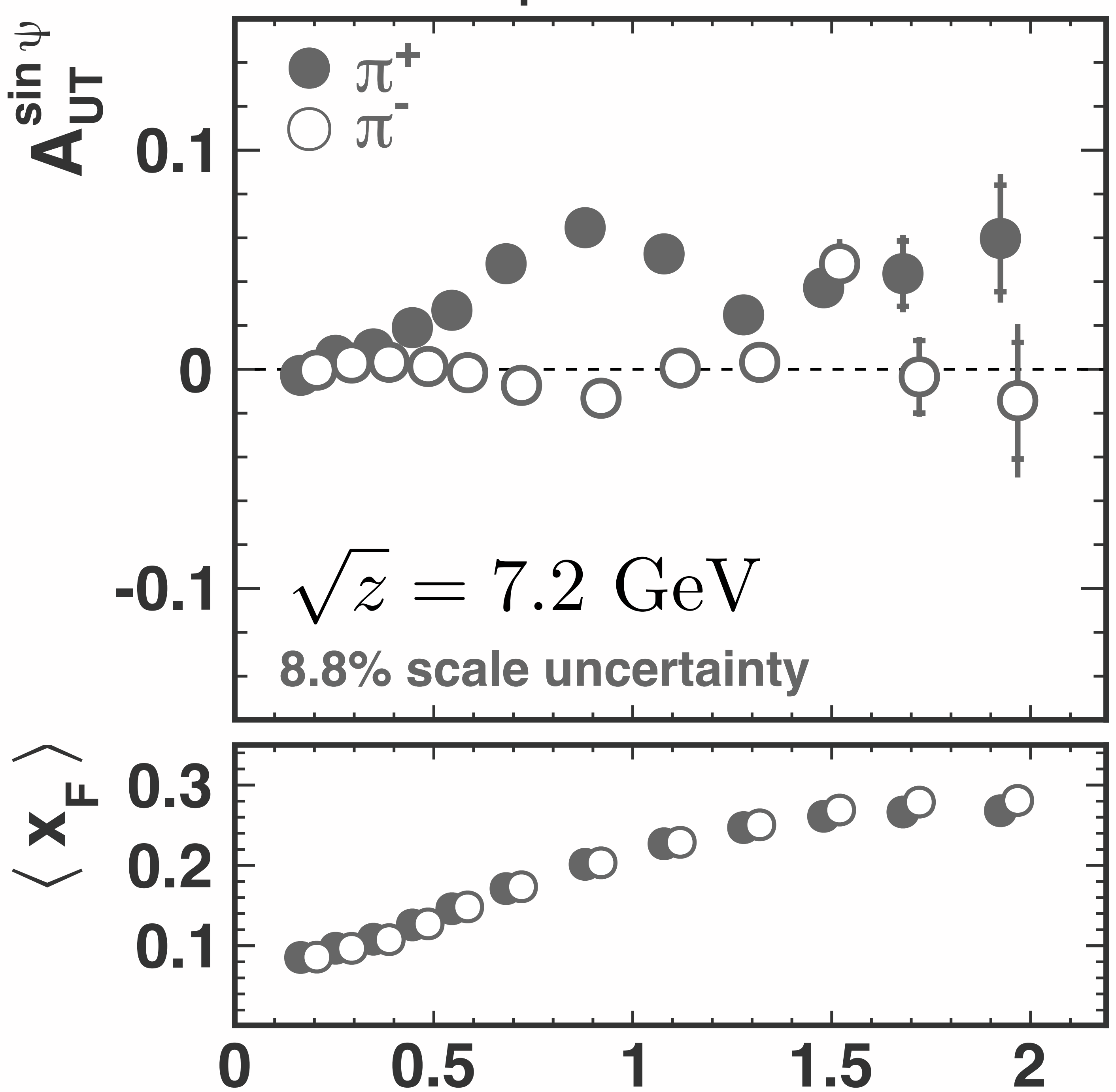


Smaller size, but similar evolution.

Comparison

to Sivers and Collins amplitudes in SIDIS

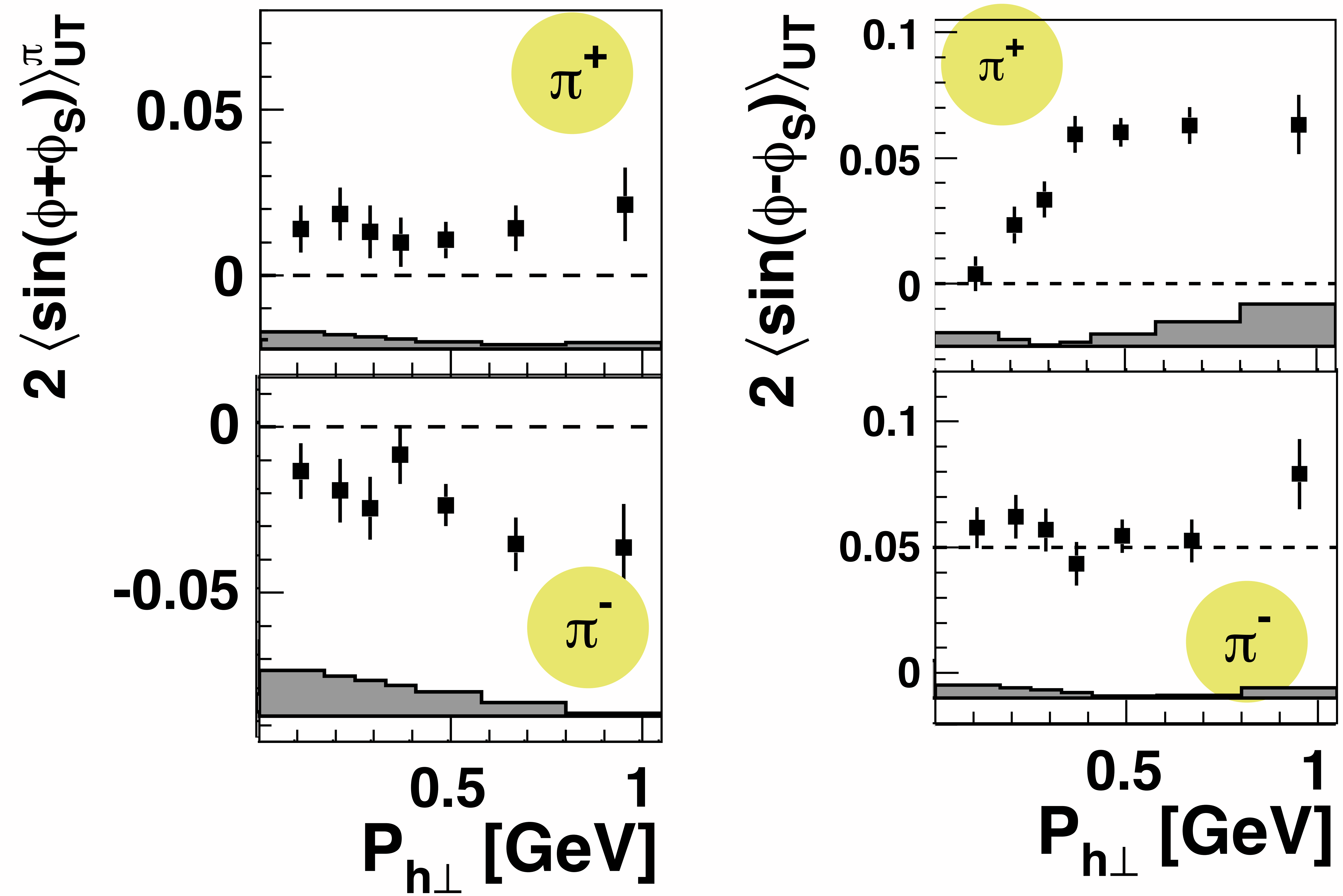
$lp^{\uparrow} \rightarrow hX$



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

COLLINS

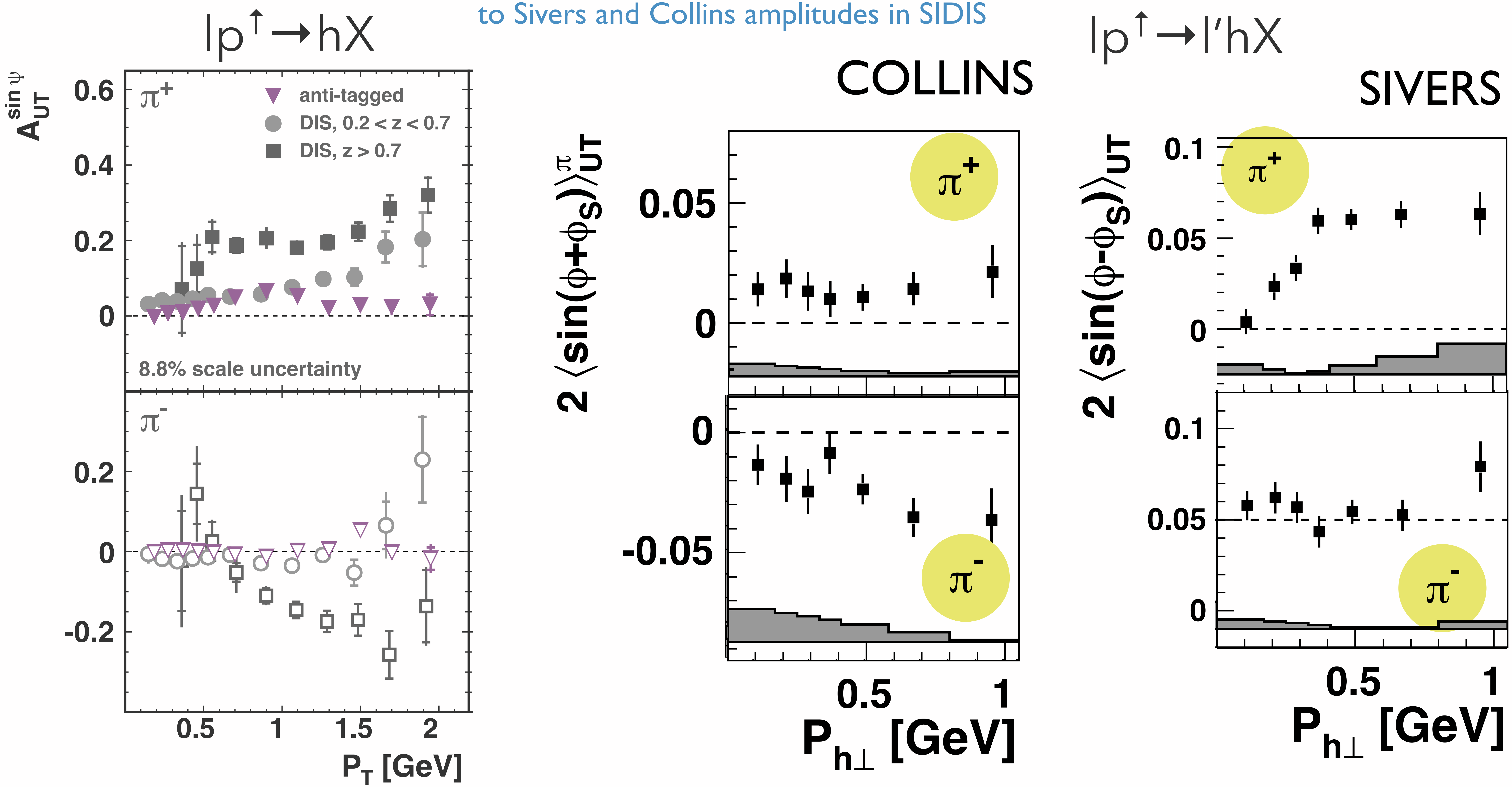
SIVERS

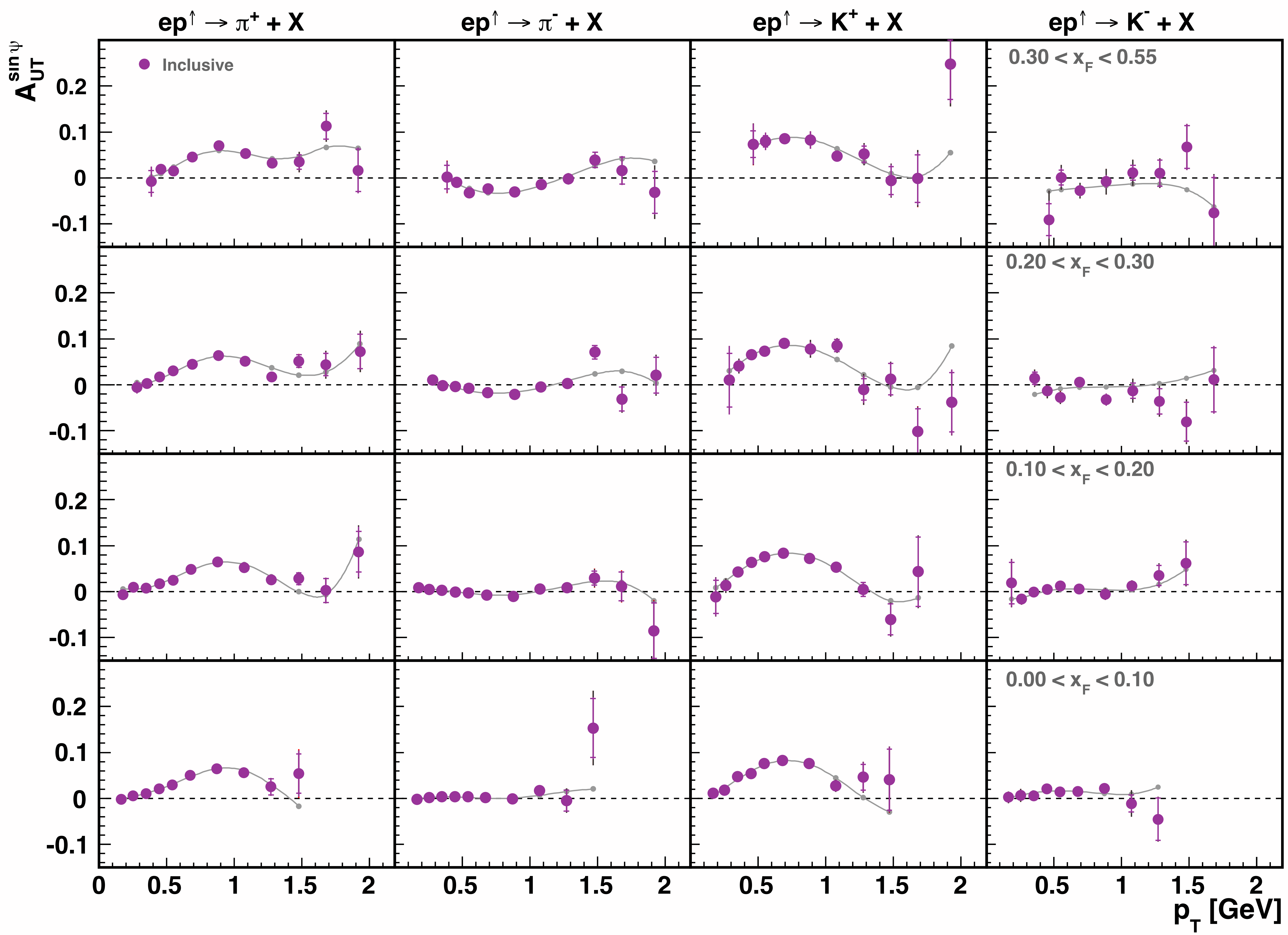


Inclusive SSA similar to Sivers.

Comparison

to Sivers and Collins amplitudes in SIDIS





A parametric model

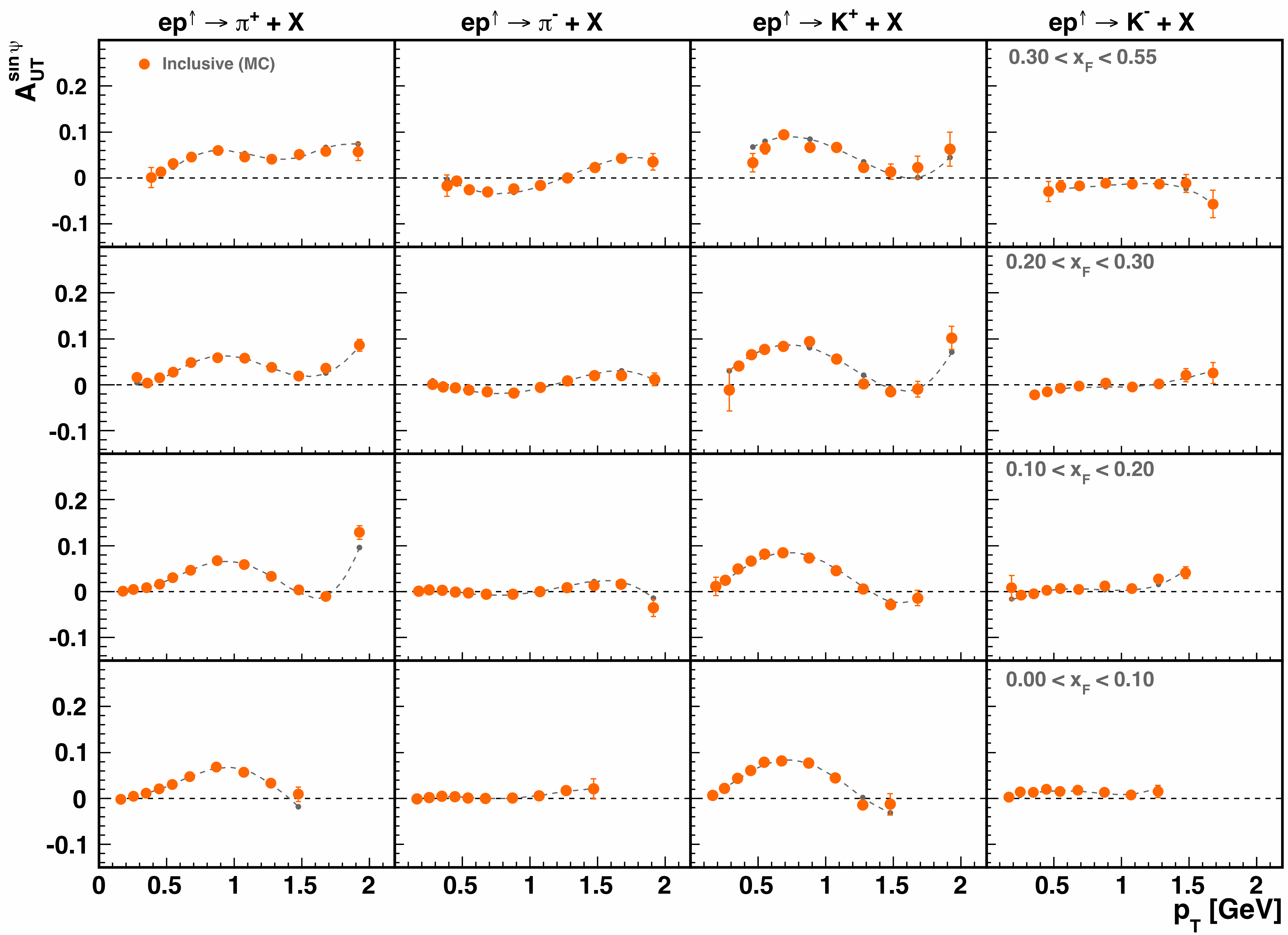
Fit to global data

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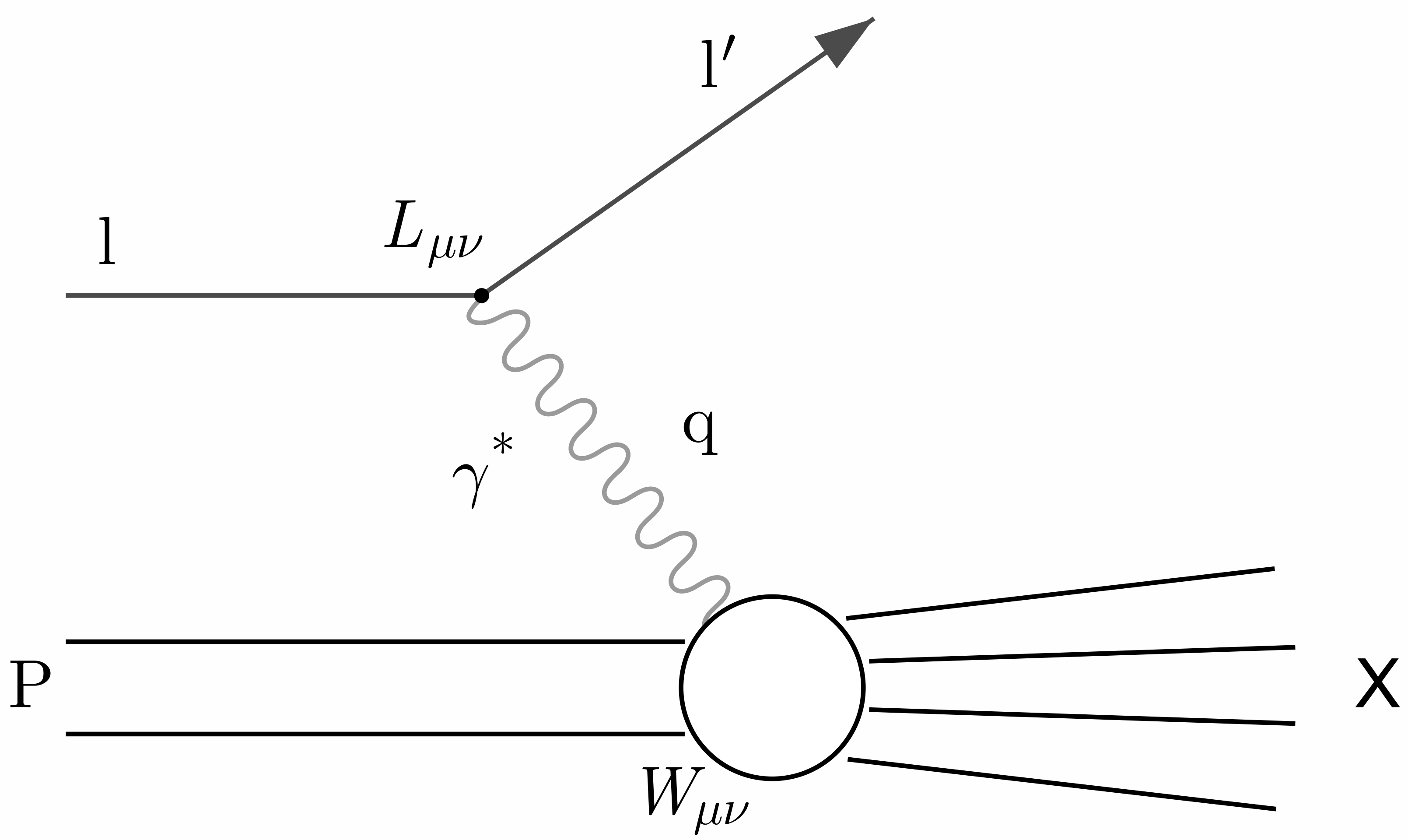
$$\hat{P}_T \equiv P_T - \langle P_T \rangle$$

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

DIS variables



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

SIVERS

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

COLLINS

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.