E12-09-009: Spin-orbit correlations in Kaon electroproduction

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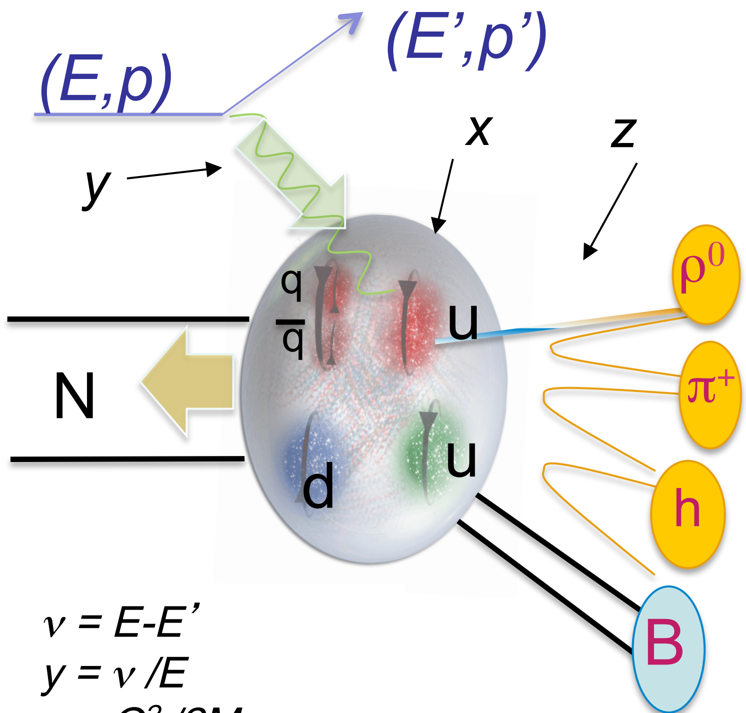
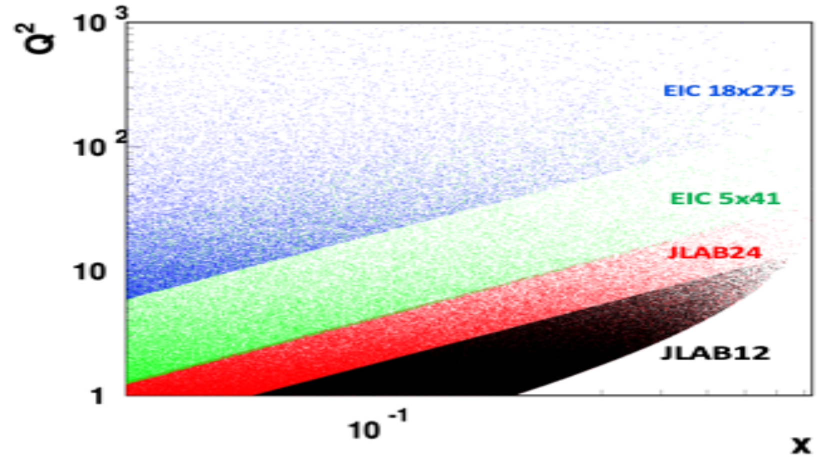
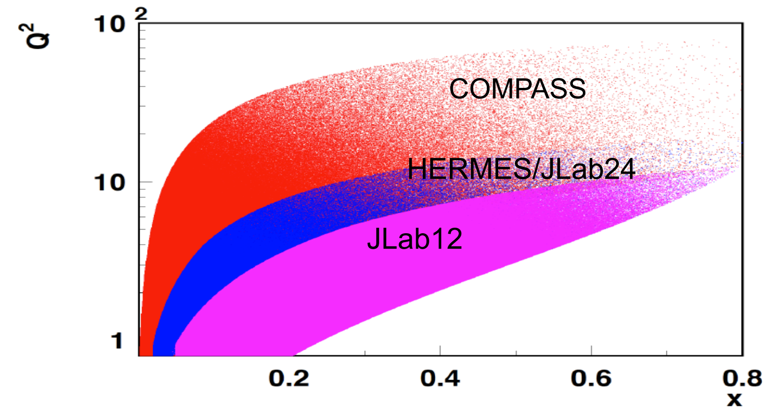
- Introduction
- CLAS12 approved experiments requiring kaon identification
- Kaons in SIDIS
- Medium effects (pions vs kaons)
- Kaons in hard exclusive processes
- Summary

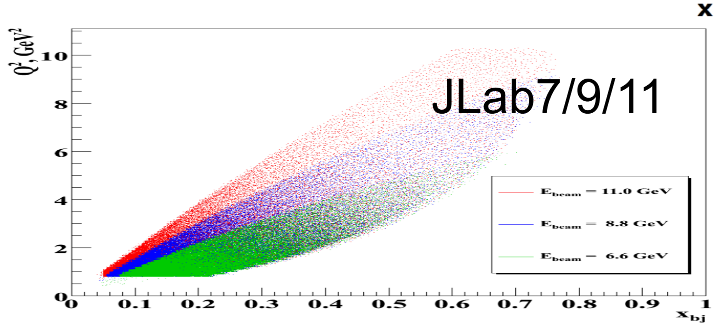
SIDIS kinematical coverage and observables



$\nu = E\text{-}E'$
$y = \nu / E$
$x = Q^2 / 2M\nu$
$z = E_h / \nu$



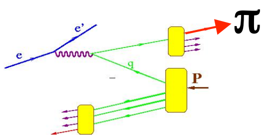




$$\sigma = F_{UU} + P_t F_{UL}^{\sin\phi} \sin 2\phi + P_b F_{LU}^{\sin\phi} \sin\phi \ldots$$

Studies of azimuthal modulations give access to underlying 3D partonic distributions

P_b, P_t:
- U unpolarized
- L long.polarized
- T trans.polarized



SIDIS at CLAS12

CLAS12

E12-06-112: π^+,π^-,π^0
E12-09-008: K^+, K^-, K^0

E12-07-107: π^+,π^-,π^0
E12-09-009: K^+, K^-, K^0

C12-11-111: π^+,π^-,π^0
K^+, K^-

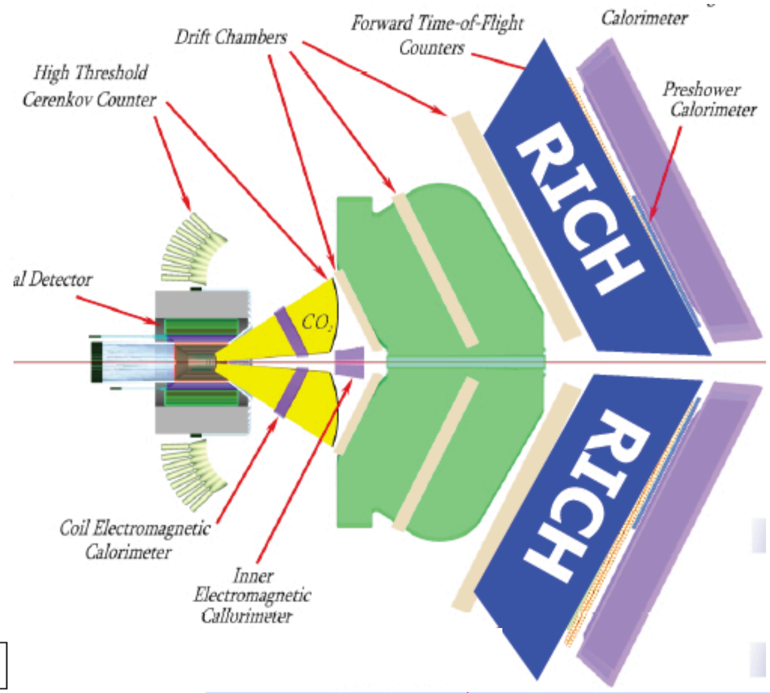
H_2, NH_3, HD

Proton

Quark spin polarization

Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



CLAS12

E09-008: π^+,π^-,π^0
K^+, K^-, K^0

E07-107: π^+,π^-,π^0
E09-009: K^+, K^-, K^0

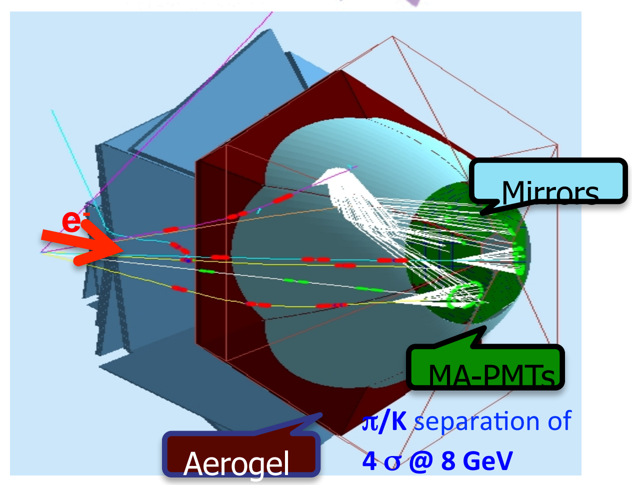
D_2, ND_3

D_2

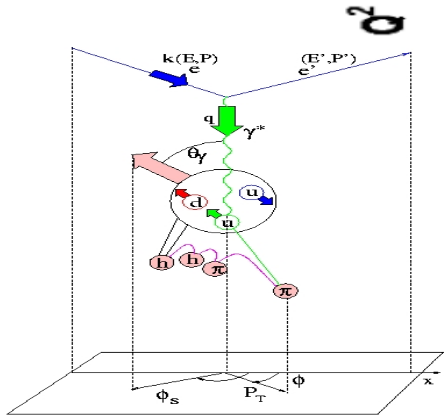
Quark spin polarization

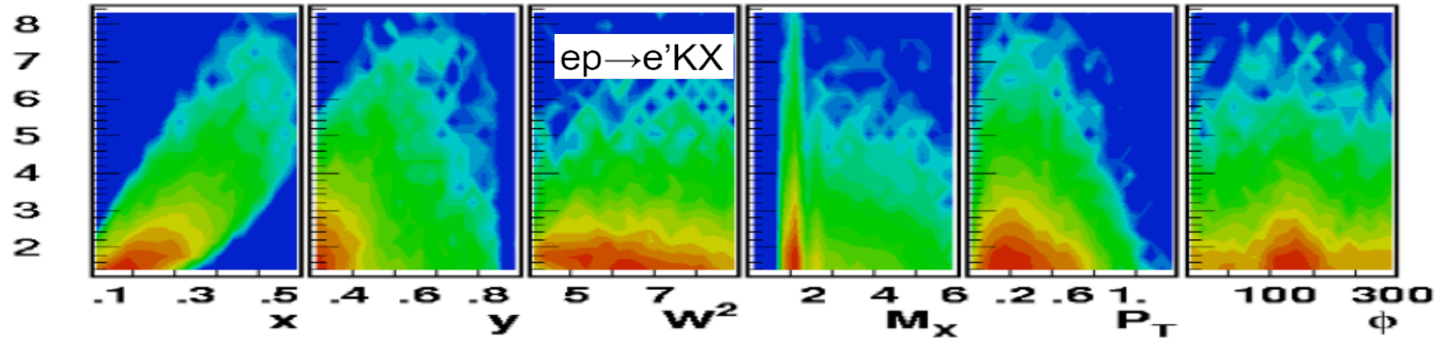
Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



CLAS12: Kinematical coverage





$\nu\ \ = E\text{-}E'$

$Q^2=(k\text{-}k')^2$

$y = \nu / E$

$x = Q^2 / 2M\nu$

$z = E_h / \nu$

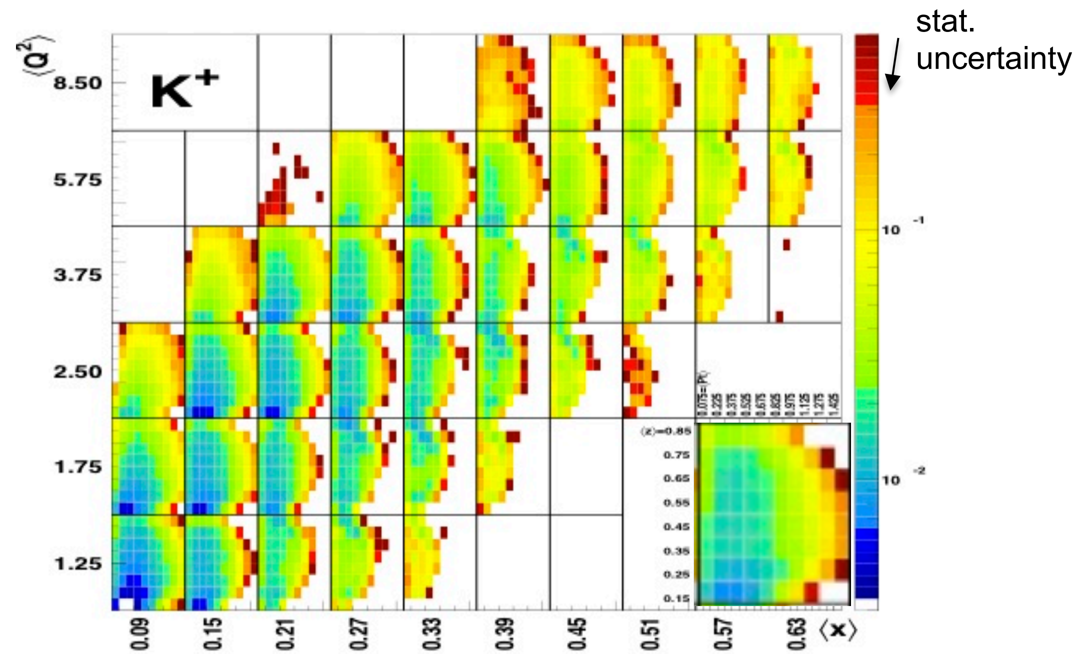
SIDIS kinematics defined

Q^2>1GeV^2

W^2>4 GeV^2

y<0.85

M_X>2GeV



Complete coverage in 5 dimensions (including ϕ) is important for studies of spin-azimuthal asymmetries in SIDIS

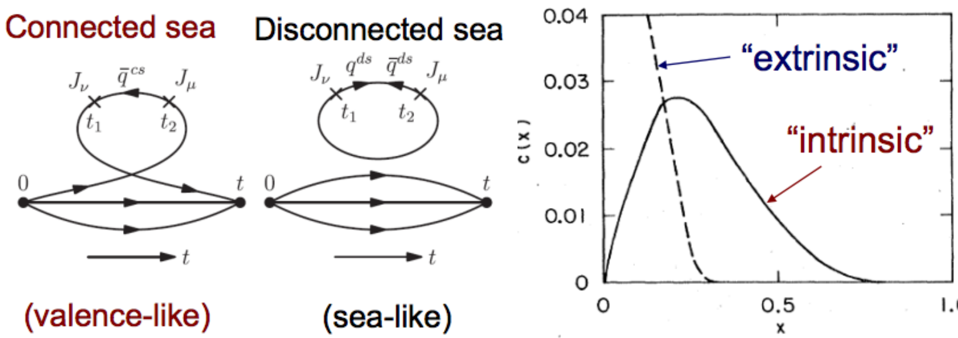
Non perturbative sea

$$P_{5q}^2 \sim 1/m_Q^2$$

$$|p\rangle = P_{3q}\,|uud\rangle + P_{5q}\,|uudQ\bar{Q}\rangle + \cdots\cdots$$

J.-C. Peng

PRL **109**, 252002 (2012)



"Intrinsic sea" and "extrinsic sea" are expected to have different x-distributions

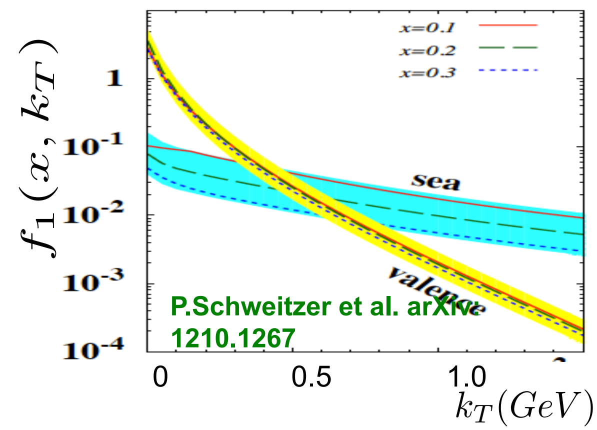
- Intrinsic sea is "valence-like" and is more abundant at larger x
- Extrinsic sea is more abundant at smaller x

Important to identify kinematics, where the non-perturbative effects dominate!!!

The "intrinsic" sea for lighter quarks have larger probabilities!

$$P_5^{uud d\bar{d}} = 0.240;\ P_5^{uud u\bar{u}} = 0.122;\ P_5^{uud s\bar{s}} = 0.024$$

$\bar{d} - \bar{u}$ has no contribution from extrinsic sea ($g \to \bar{q}q$) and is sensitive to "intrinsic sea" only

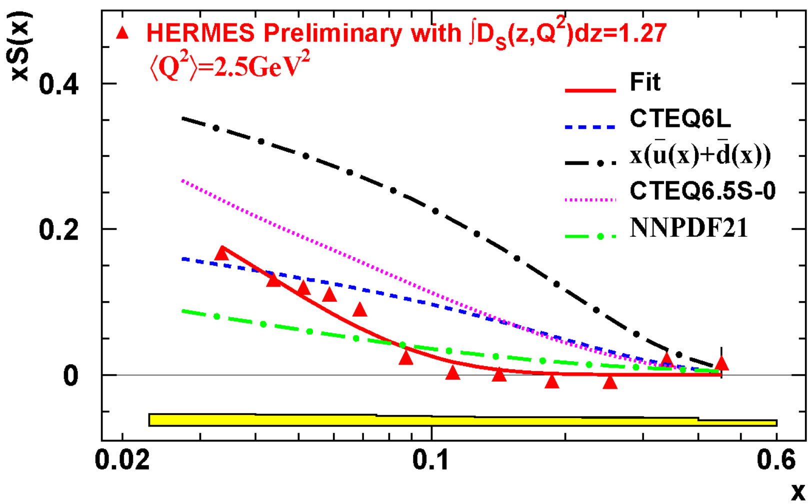


Also very different k_T-distributions

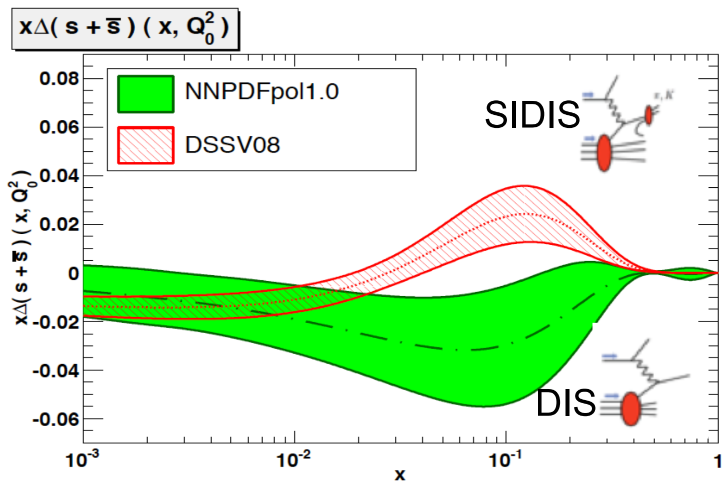
Strangenes in SIDIS

Use Kaon multiplicities from deuteron to access strange distributions

$$\int_{z_{min}}^{z_{max}} M^{K^+ + K^-}(x,z)dz = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)}{5Q(x)+2S(x)}$$



- SIDIS analysis depends on s->K fragmentation function
- The shape of S(x) from HERMES makes extraction of intrinsic strangeness very challenging.



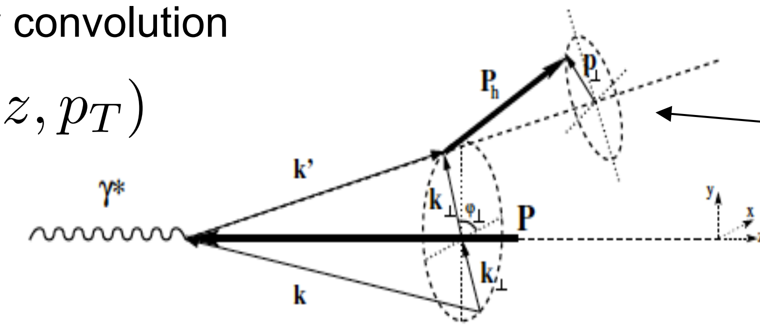
Polarized strangeness is practically unknown, even sign is not defined.

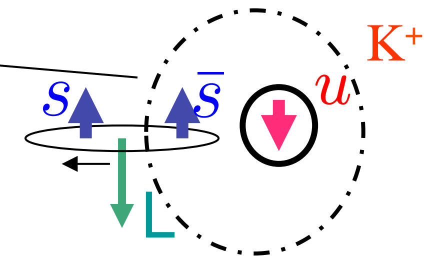
N/q	U	L	T
U	f_1		
L		g_1	
T			h_1

Flavor dependence of transverse momentum

SIDIS x-section defined by convolution

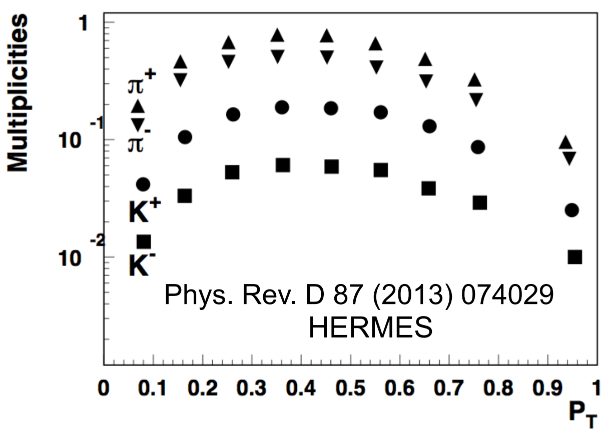
$$f_1^q(x, k_T) \otimes D_1^{q\to h}(z, p_T)$$

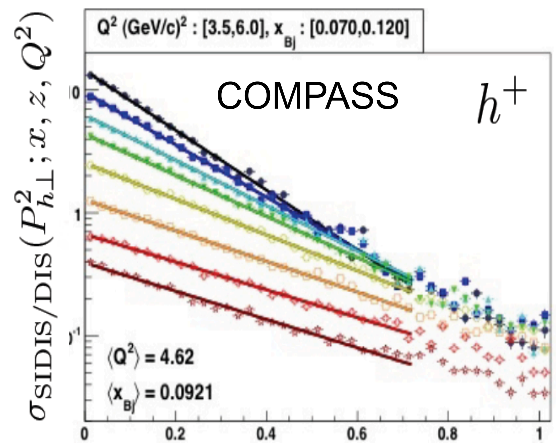


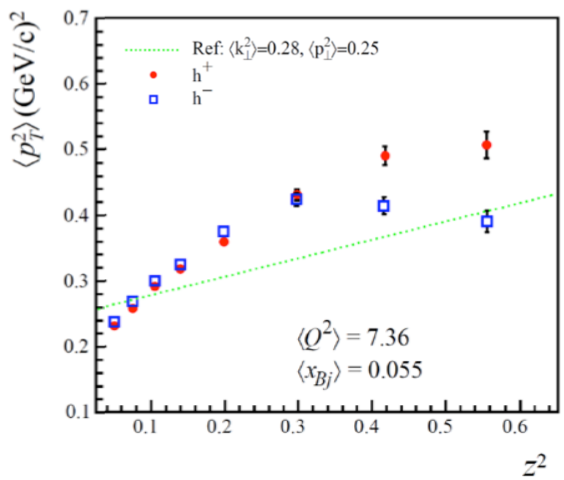


Disentanglement of z and P_{hT} : provides access to the transverse intrinsic quark k_T and fragmentation p_T,

$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$



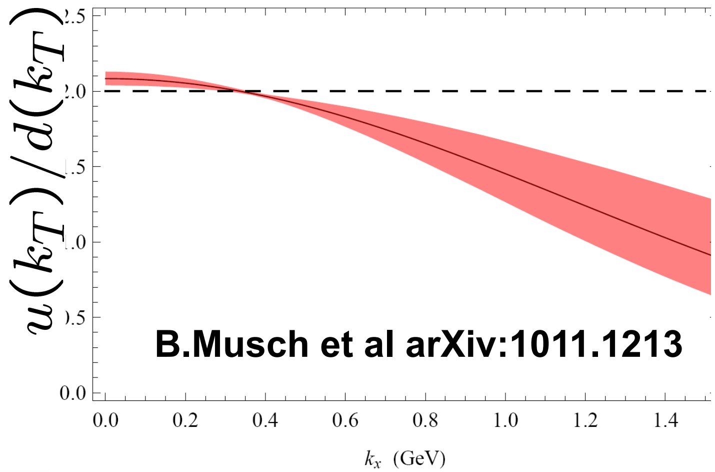


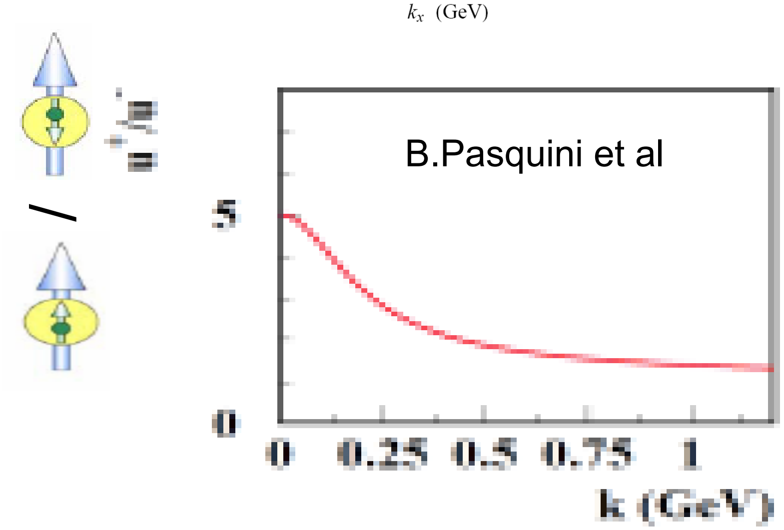


Multiplicities deviate from simple Gaussian distributions already at small P_T
Data indicating flavor dependence of widths of partonic distributions

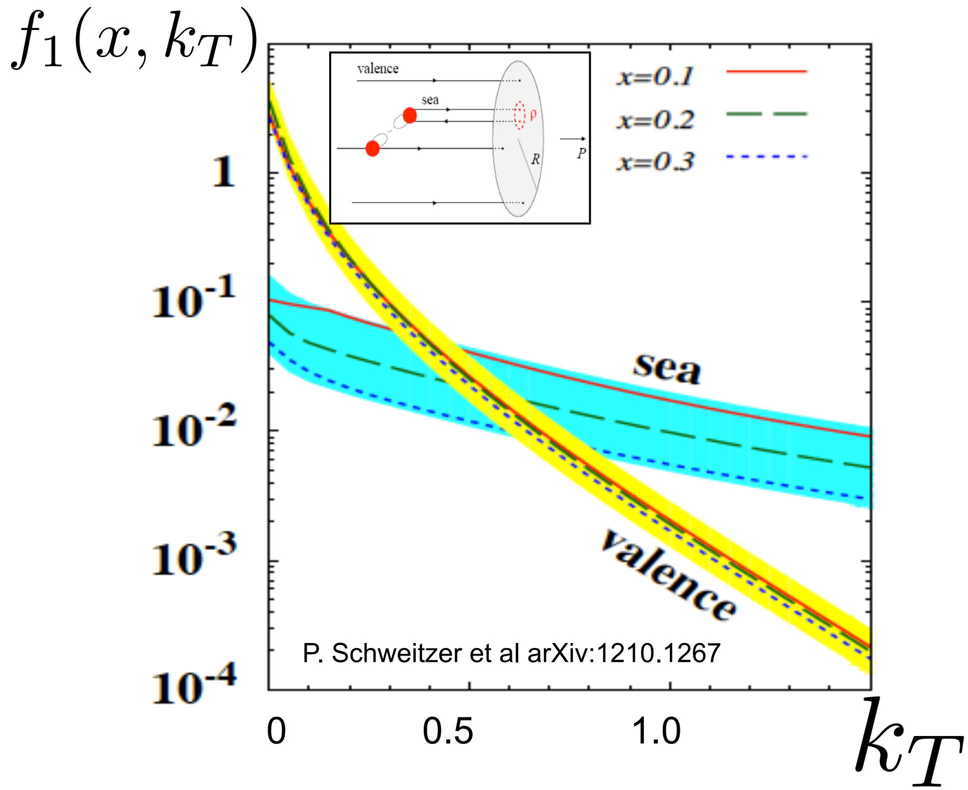
Precision studies of transverse momentum dependence of distribution and fragmentation functions are crucial for future SIDIS program at Jlab

Flavor and spin dependence of k_T–distributions





•k_T-distributions of TMDs depend on flavor and spin

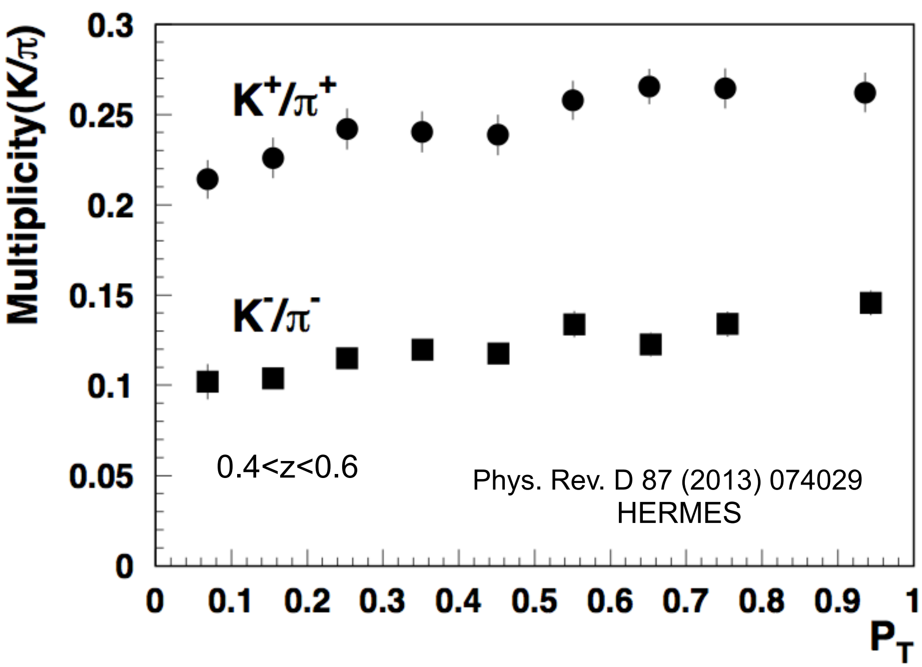


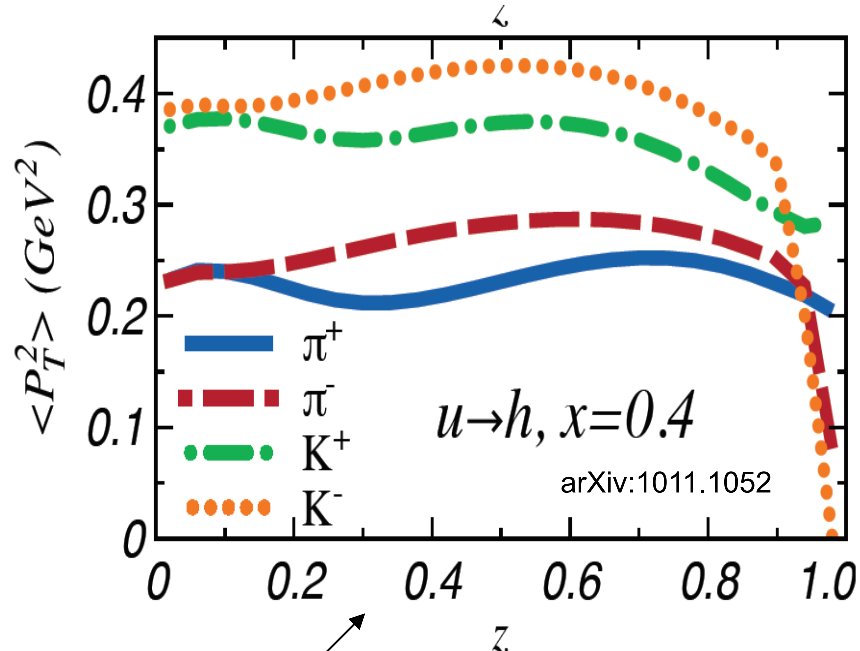
Nucleons 3D structure is complex, with weight of different type of partons changing with k_T
Final states, with different sensitivity to different parton types will be critical to separate contributions

Hadronization effects

$$f_1^q(x, k_T) \otimes D_1^{q \to h}(z, p_T) \quad \begin{matrix} D_1^{u \to \pi^+}(z, p_T) \\ D_1^{u \to K^+}(z, p_T) \end{matrix}$$

•Widths of fragmentation functions are flavor dependent. (H. Matevosyan, A. W. Thomas & W. Bentz)





Assuming u-quark dominance the increase with P_T of the fraction of kaons in the final hadron sample is consistent with wider $D_1^{u\to K}$

Study of kaon multiplicities in SIDIS is crucial for understanding of spin-orbit effects in hadronization

Projections for Kotzinian-Mulders SSA

$$\sigma^{\pi+}_{KM}(p) = 4h^{\perp u}_{1L} H_1^{\perp(1/2)fav} + h^{\perp d}_{1L} H_1^{\perp(1/2)unfav}$$
$$\sigma^{\pi-}_{KM}(p) = 4h^{\perp u}_{1L} H_1^{\perp(1/2)unfav} + h^{\perp d}_{1L} H_1^{\perp(1/2)fav}$$
$$\sigma^{\pi 0}_{KM}(p) = 4(h^{\perp u}_{1L} + h^{\perp d}_{1L})(H_1^{\perp(1/2)unfav} + H_1^{\perp(1/2)fav})$$
$$\sigma^{K+}_{KM}(p) = 4h^{\perp u}_{1L} H_1^{\perp(1/2)u/K^+} + h^{\perp d}_{1L} H_1^{\perp(1/2)d/K^+} + h^{\perp \bar{s}}_{1L} H_1^{\perp(1/2)\bar{s}/K^+}$$
$$\sigma^{K-}_{KM}(p) = 4h^{\perp u}_{1L} H_1^{\perp(1/2)u/K^-} + h^{\perp d}_{1L} H_1^{\perp(1/2)d/K^-} + h^{\perp s}_{1L} H_1^{\perp(1/2)s/K^-} + 4h^{\perp \bar{u}}_{1L} H_1^{\perp(1/2)\bar{u}/K}$$
$$\sigma^{\pi+}_{KM}(n) = 4h^{\perp d}_{1L} H_1^{\perp(1/2)fav} + h^{\perp u}_{1L} H_1^{\perp(1/2)unfav}$$
$$\sigma^{\pi-}_{KM}(n) = 4h^{\perp d}_{1L} H_1^{\perp(1/2)unfav} + h^{\perp u}_{1L} H_1^{\perp(1/2)fav}$$
$$\sigma^{\pi 0}_{KM}(n) = (4h^{\perp d}_{1L} + h^{\perp u}_{1})(h_{1L}^{\perp(1/2)unfav} + H_1^{\perp(1/2)fav})$$
$$\sigma^{K+}_{KM}(n) = 4h^{\perp d}_{1L} H_1^{\perp(1/2)u/K^+} + h^{\perp u}_{1L} H_1^{\perp(1/2)d/K^+} + h^{\perp \bar{s}}_{1L} H_1^{\perp(1/2)\bar{s}/K^+}$$
$$\sigma^{K-}_{KM}(n) = 4h^{\perp d}_{1L} H_1^{\perp(1/2)u/K^-} + h^{\perp u}_{1L} H_1^{\perp(1/2)d/K^-} + h^{\perp s}_{1L} H_1^{\perp(1/2)s/K^-} + h^{\perp \bar{u}}_{1L} H_1^{\perp(1/2)\bar{u}/K^-}$$

$$A^{p/(\pi^+-\pi^-)}(x,y,z) = 2\frac{B(y)}{A(y)} \frac{\left(4\,h^{u_v} - h^{d_v}\right) H_1^{\perp(1)\mathrm{f}}}{\left(4\,f_1^{u_v} - f_1^{d_v}\right)\left(D_1^{\mathrm{f}} - D_1^{\mathrm{d}}\right)},$$
$$A^{n/(\pi^+-\pi^-)}(x,y,z) = 2\frac{B(y)}{A(y)} \frac{\left(4\,h^{d_v} - h^{u_v}\right) H_1^{\perp(1)\mathrm{f}}}{\left(4\,f_1^{d_v} - f_1^{u_v}\right)\left(D_1^{\mathrm{f}} - D_1^{\mathrm{d}}\right)},$$
$$A^{p/(K^+-K^-)}(x,y,z) = 2\frac{B(y)}{A(y)} \frac{4\,h^{u_v}\,H_1^{\perp(1)\mathrm{fd}} - h^{s_v}\,H_1^{\perp(1)\mathrm{f}'}}{4\,f_1^{u_v}\left(D_1^{\mathrm{fd}} - D_1^{\mathrm{dd}}\right) + f_1^{s_v}\left(D_1^{\mathrm{d}'} - D_1^{\mathrm{f}'}\right)},$$
$$A^{n/(K^+-K^-)}(x,y,z) = 2\frac{B(y)}{A(y)} \frac{4\,h^{d_v}\,H_1^{\perp(1)\mathrm{fd}} - h^{s_v}\,H_1^{\perp(1)\mathrm{f}'}}{4\,f_1^{d_v}\left(D_1^{\mathrm{fd}} - D_1^{\mathrm{dd}}\right) + f_1^{s_v}\left(D_1^{\mathrm{d}'} - D_1^{\mathrm{f}'}\right)}.$$

Assuming that the transverse spin of the sea quarks in longitudinally polarized nucleon is negligible →

$$A_{UL}^{K+} \propto \frac{4h_{1L}^{\perp(1)u}(x)}{4u(x) + \bar{d}(x)} \frac{H_1^{\perp u \to K^+}(z, P_\perp)}{D_1^{u \to K^+}(z, P_\perp)}$$

Study of kaon multiplicities in SIDIS is crucial for understanding of spin-orbit effects in hadronization

Spin-orbit correlations: kaons vs pions

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

D_1 Initial state asymmetries

$H_1^\perp$ Final state asymmetries

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

$$K^-\{s\bar{u}\} \quad \pi^-\{d\bar{u}\}$$

$D^{u\to\pi^+}$, $D^{u\to K^+}$ — u-quark present (favored fragmentation)

$D_1^{u\to\pi^-}$, $D_1^{u\to K^-}$ — u-quark not present (unfavored fragmentation)

azimuthal moments/asymmetries contain in the denominator the unpolarized x-section → Expect similar effects for all favored (and unfavored) azimuthal moments/ asymmetries for unpolarized and longitudinally polarized quarks (D_1)

Hermes/Belle measurements for pions indicate

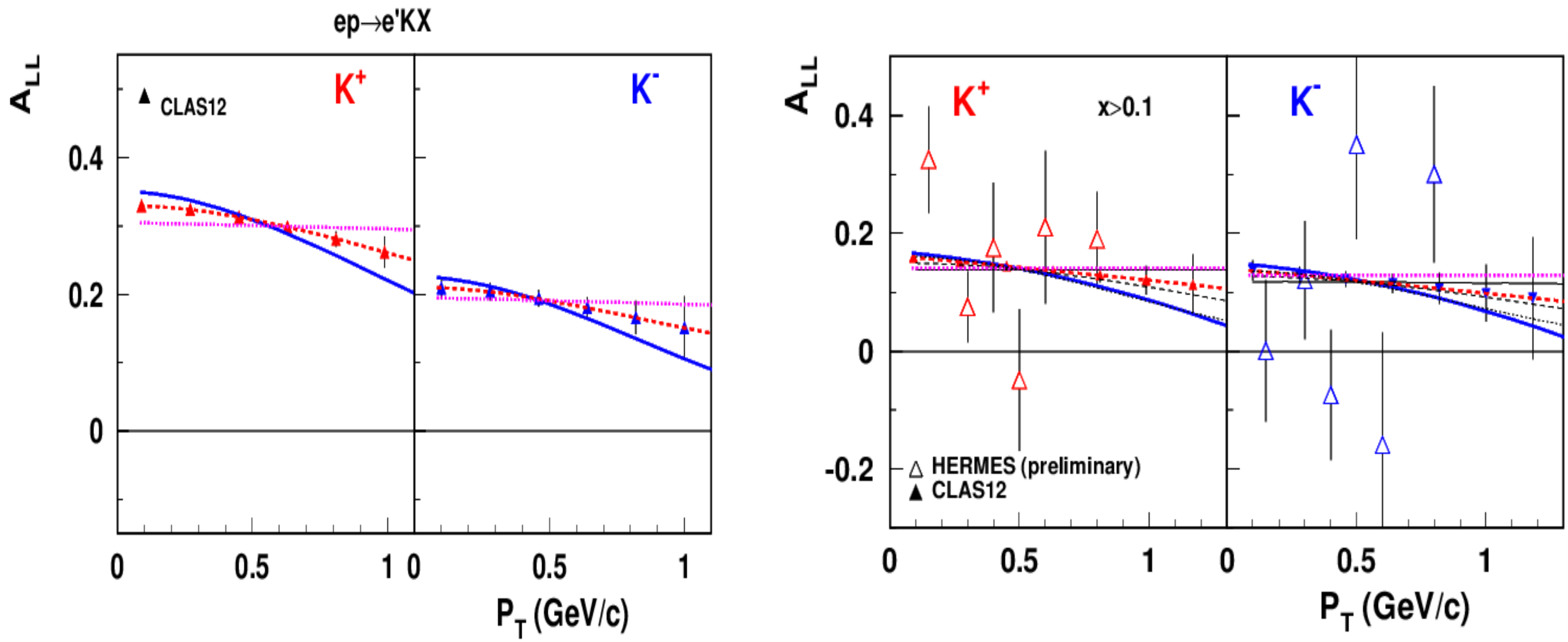
$$H_1^{\perp fav} \approx -H_1^{\perp unfav}$$

→ Expect opposite sign for azimuthal moments/ asymmetries of favored unfavored hadrons for transversely polarized quarks (H_1)

- Spin-azimuthal asymmetries bigger for K^+ compared to π^+
- Spin-azimuthal asymmetries for K^- vs K^+ do not follow the trend of π^- vs π^+ (“Kaon puzzle”)

Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with Longitudinally Polarized Hydrogen and Deuterium Targets (E12-09-009)

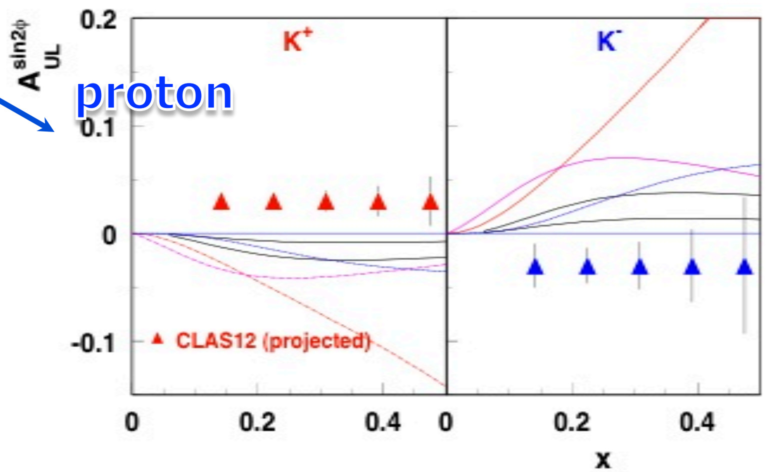
$$A_{LL}(x,z,P_{h\perp}) = A_{LL}(x,z)\,\frac{\langle P_{h\perp}^{2,\mathrm{unp}}\rangle}{\langle P_{h\perp}^{2,\mathrm{pol}}\rangle}\,\exp\left(P_{h\perp}^2/\langle P_{h\perp}^{2,\mathrm{unp}}\rangle - P_{h\perp}^2/\langle P_{h\perp}^{2,\mathrm{pol}}\rangle\right)$$

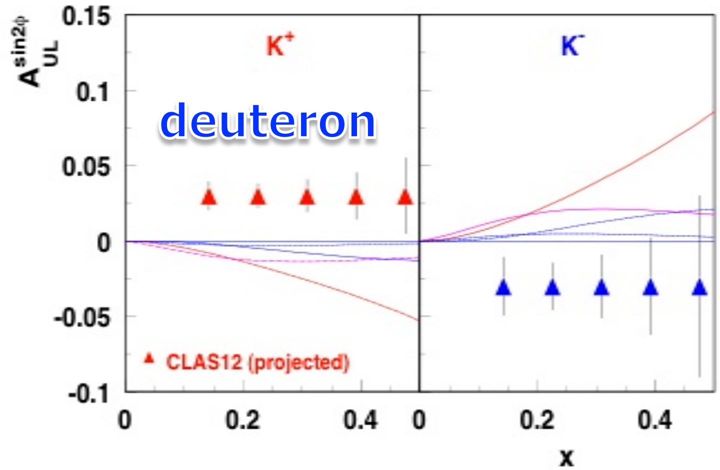


The double spin asymmetry **A**LL for the NH**3**-target (left) and ND**3**-target (right) as a function of the transverse momentum of hadrons, **P**T , averaged in the 0:4 **< z <** 0:7 range. Curves are calculated using different **k**T widths for helicity distributions.

Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with Longitudinally Polarized Hydrogen and Deuterium Targets (E12-09-009)

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	$h_1\ h_{1T}^{\perp}$





E_e = 11GeV, Long. Pol. NH3 (P=85%) & ND3 (P=40%), **Lumi**= ~ 10^{35} $cm^{-2}s^{-1}$

-non trivial transverse distributions of the sea quarks in the nucleon
-peculiar behaviour of the fragmentation mechanism in the presence of s quark

identification of Kaons in a wide range of x,Q^2 and P_T is crucial for these studies

E12-09-009 will provide a complementary information on transversely polarized quarks in the longitudinally polarized nucleon and measure the Collins fragmentation of Kaons

Medium modifications of partonic distributions

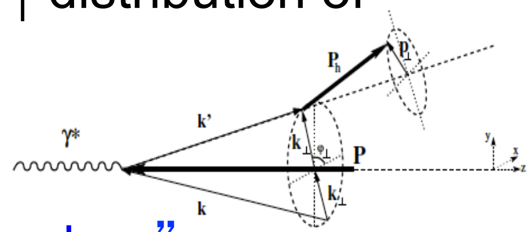
In terms of the QCD, there are several contributions to P_T distribution of hadrons produced in semi-inclusive DIS:

•primordial transverse momentum,

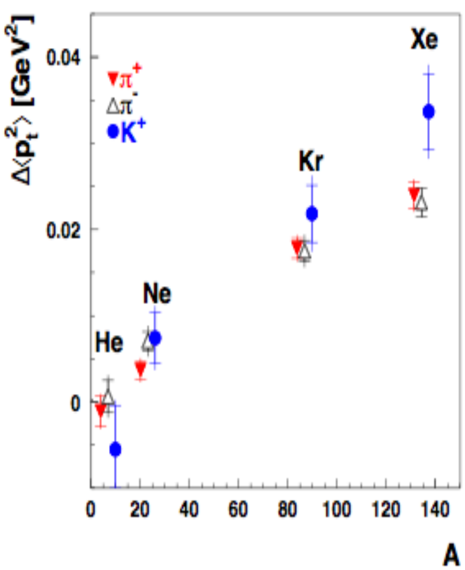
•gluon radiation of the struck quark,

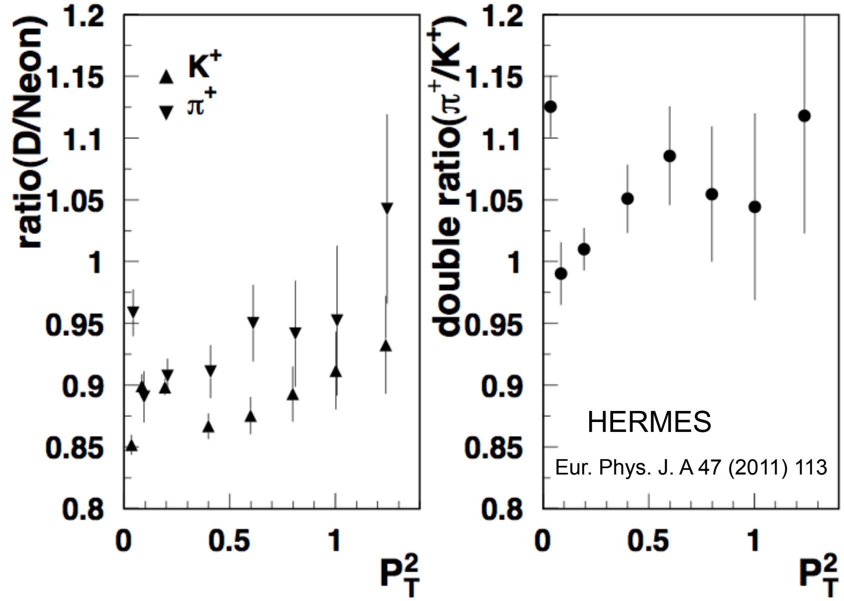
•the formation and soft multiple interactions of the "pre-hadron"

•the interaction of the formed hadrons with the surrounding hadronic medium



In simple parton model with gaussian distributions

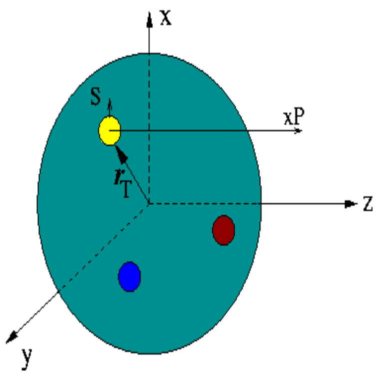




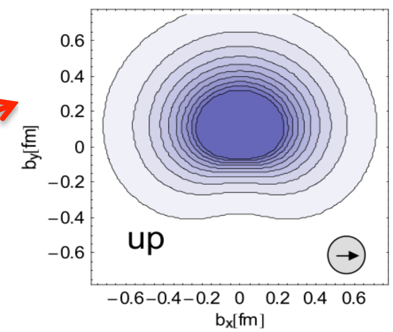
Difference in ratios of K^+/π^+ in SIDIS will provide direct information on medium modification of hadronization

3D structure of the nucleon: GPDs

Hard exclusive processes and spatial distributions of partons

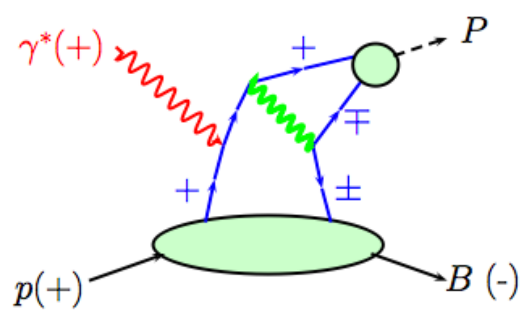


	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$



Lattice (QCDSF)

ep➔e' p(Kπ^0)

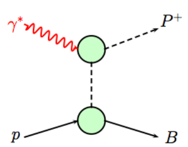


Within the handbag approach based on factorization in hard parton subprocesses and soft generalized parton distributions (GPDs) the K x-sections are dominated by transversely polarized photons (like π^0)

Hard exclusive pion and kaon production provides a unique possibility to study the chiral-odd GPDs describing spatial distributions of transversely polarized quarks.

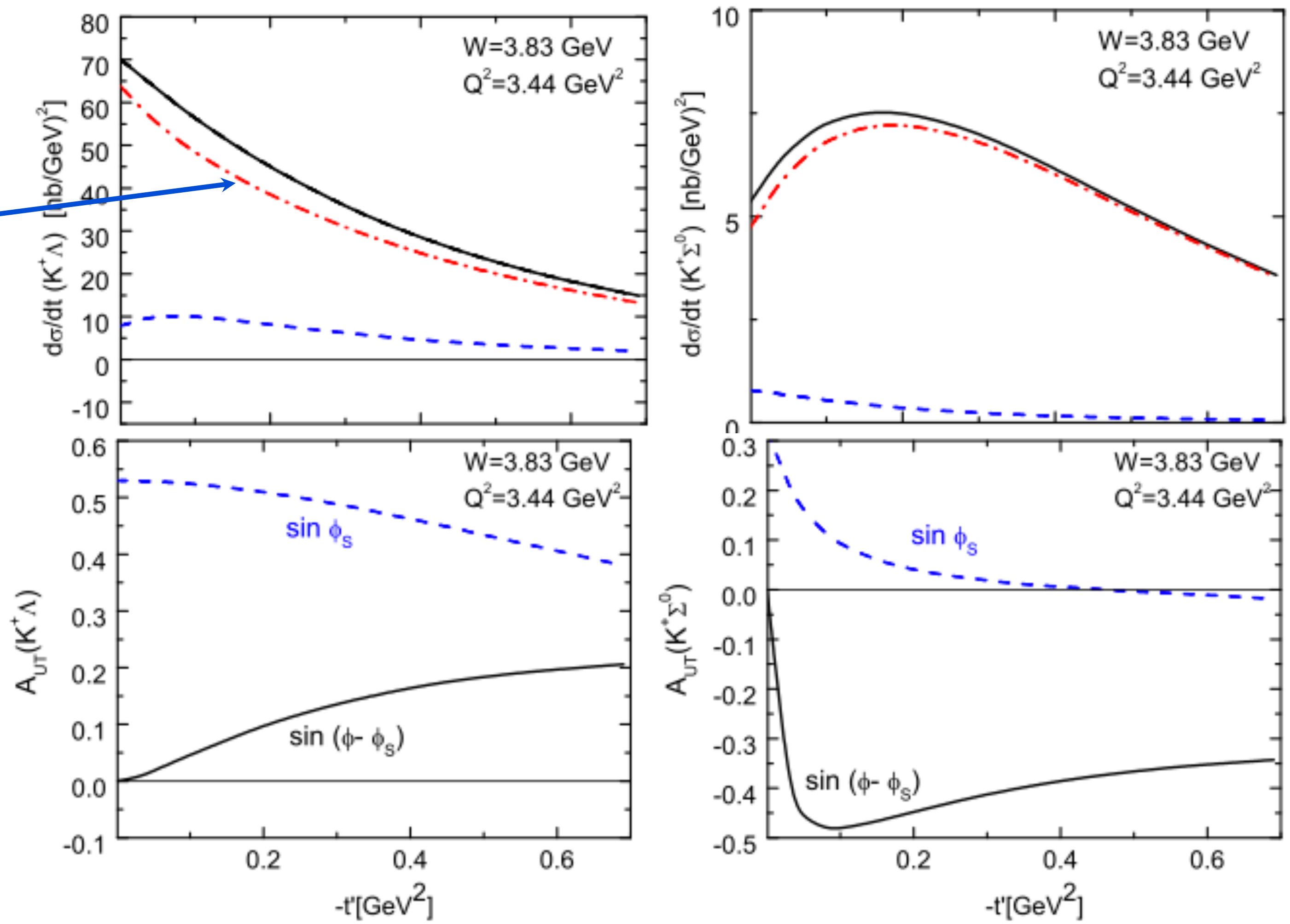
Exclusive kaon production

Unlike π+ the K+ x-section is totally dominated by the transverse photon



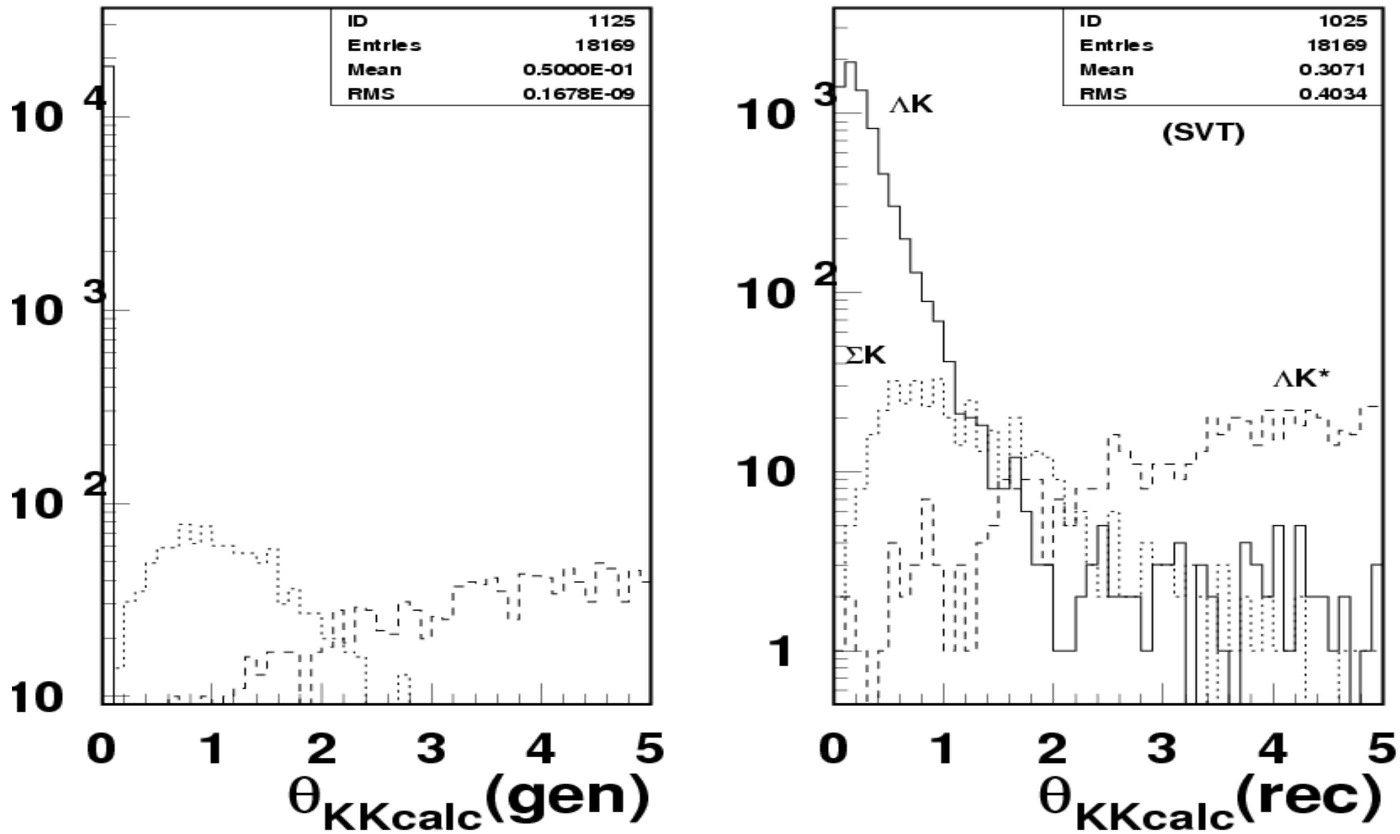
pole contribution negligible

KΣ asymmetries are predicted to be large and with opposite sign to KΛ



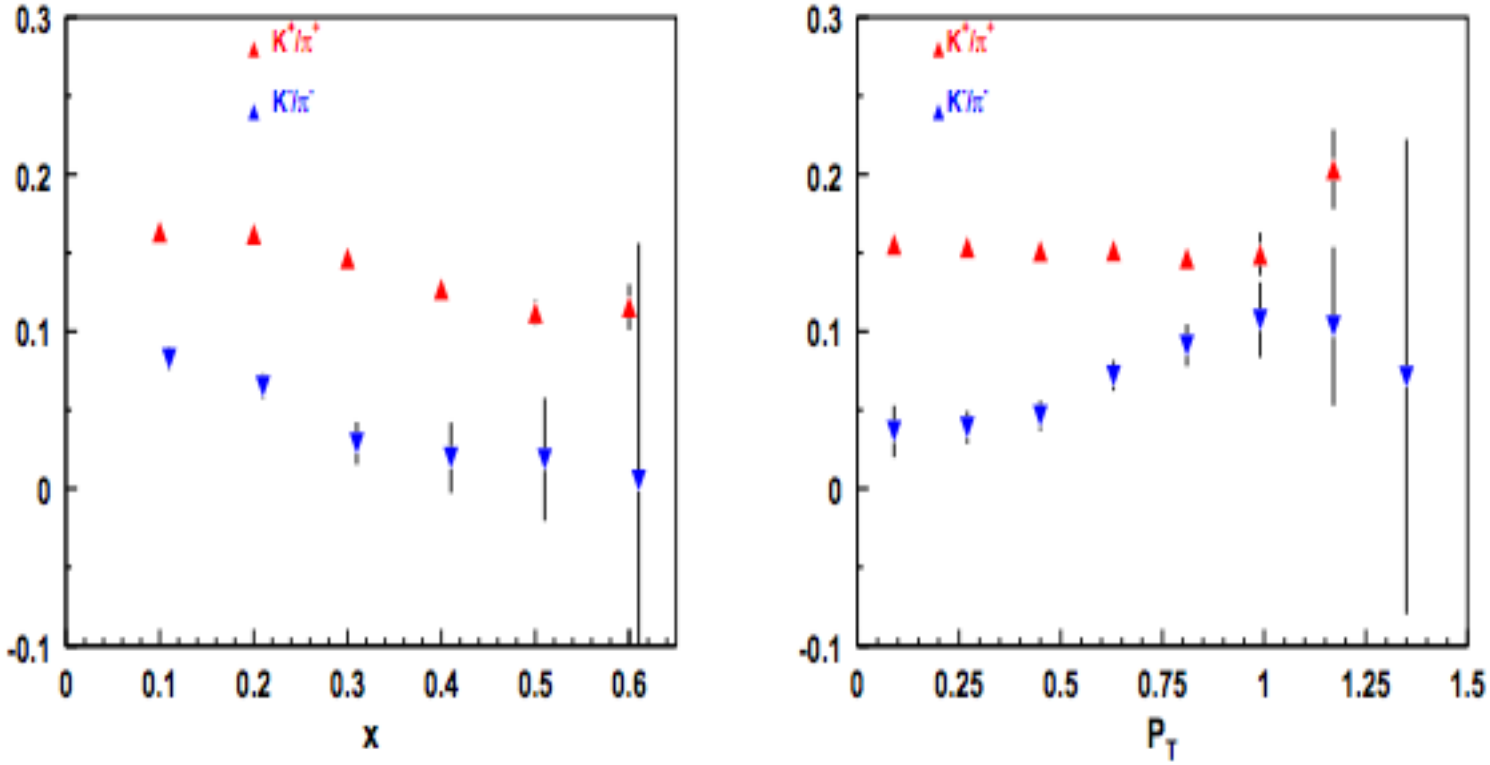
Cross sections and asymmetries in exclusive production of KΛ and KΣ provide access to different combinations of chiral-odd GPDs (Goloskokov&Kroll arXiv:1106.4897)

K/K* and Λ/Σ separation



Detection of K+ is crucial for separation of different final states (Λ,Σ,K*)

Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with Longitudinally Polarized Hydrogen and Deuterium Targets (E12-09-009)



PEPSI-Lepto predictions for x-dependence (left) and PT -dependence of kaon pion ratios.

Summary

•Correlations of spin and transverse momentum of partons are important in understanding of the nucleon structure in terms of partonic degrees of freedom of QCD.

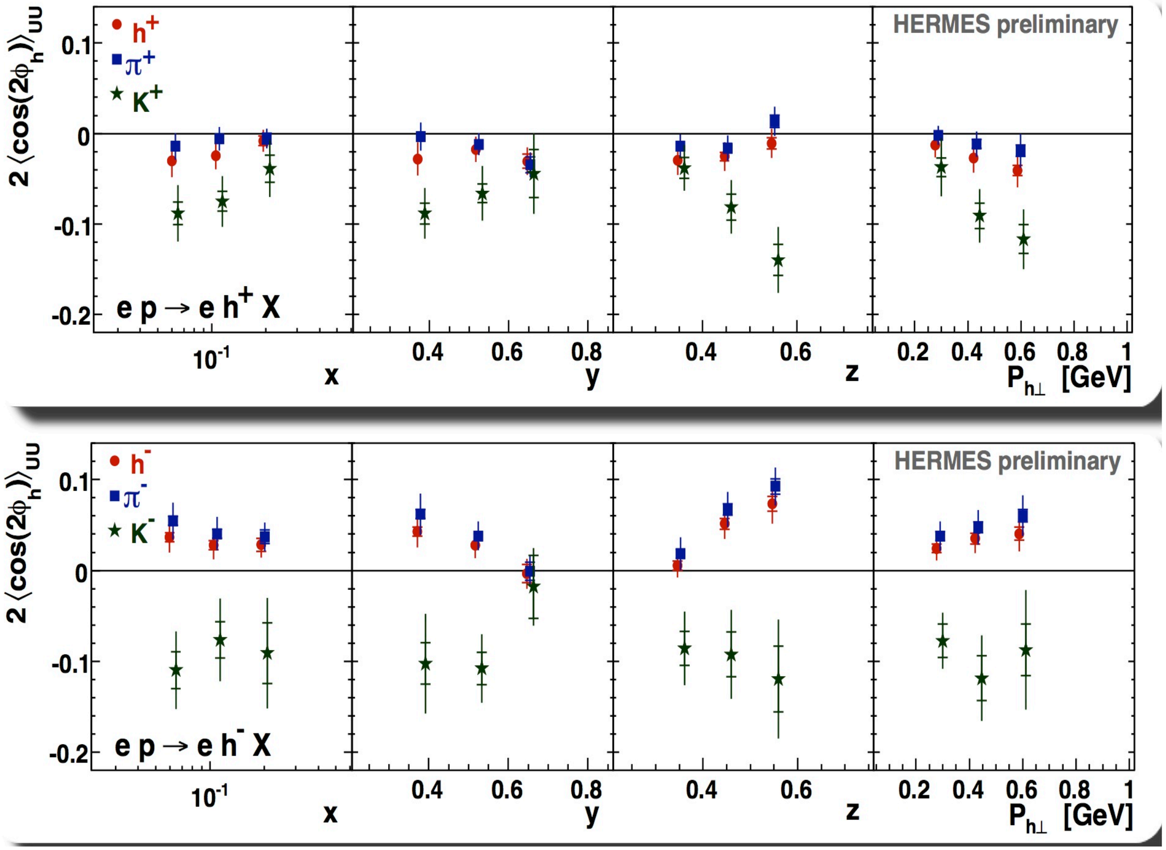
•Existing measurements with Kaons indicate significant effects related to spin-orbit correlations in hadronization of strange quarks, making Kaon separation in a wide range of x,Q^2 and P_T, crucial.

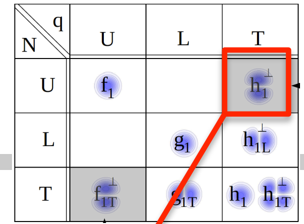
•Identification of Kaons will significantly enhance CLAS12 capabilities to study exclusive processes involving kaons, spectroscopy,….

Measurements with Kaons in semi-inclusive and hard-exclusive processes will be crucial in understanding the underlying dynamics behind spin orbit correlations in hard processes and accomplish the CLAS12 program of studies of the 3D structure of the nucleon

- Support Slides

Boer-Muders effect: kaons vs pions





$h_1^\perp H_1^\perp$

$u-dominance$

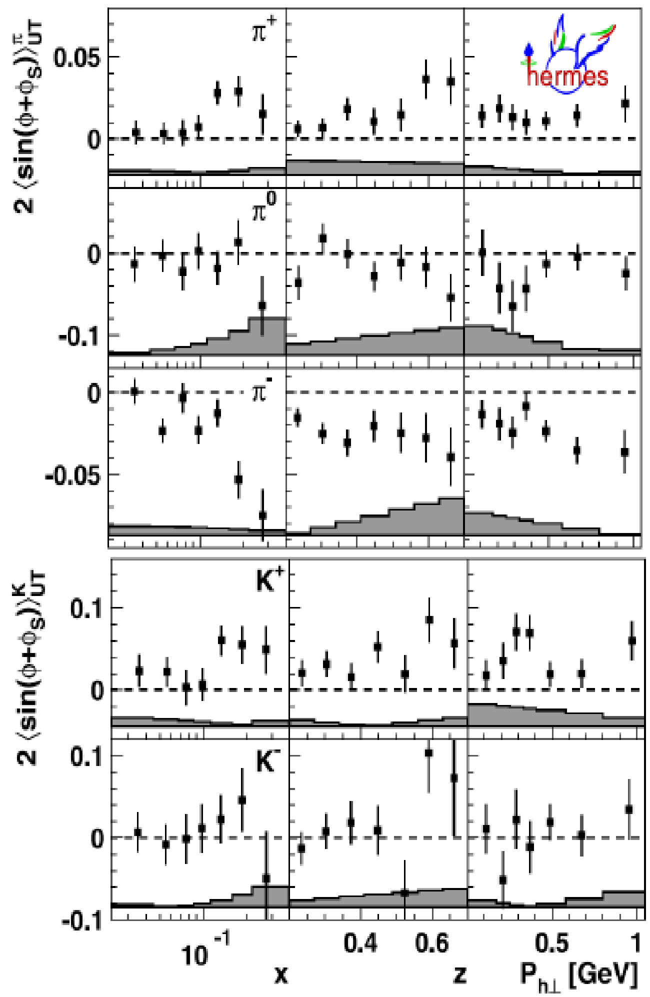
$K^+\{u\bar{s}\}$ $\pi^+\{u\bar{d}\}$

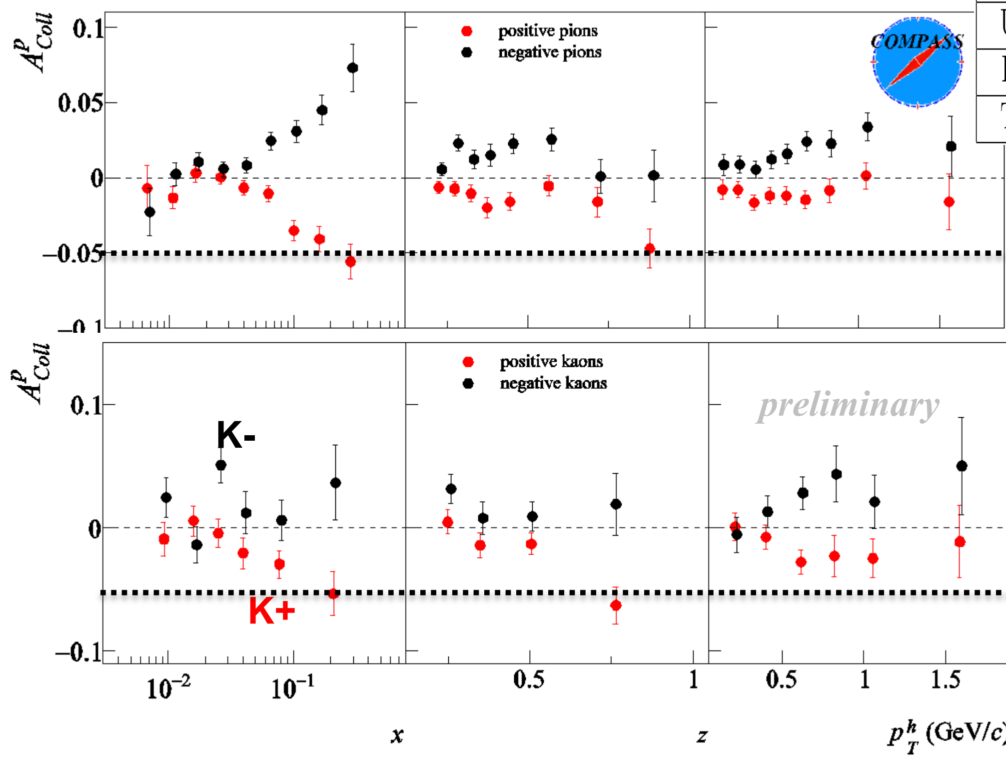
$$\frac{H_1^{\perp,u\to K^+}}{D_1^{u\to K^+}} > \frac{H_1^{\perp,u\to \pi^+}}{D_1^{u\to \pi^+}}$$

Effect much bigger for Kaons than for pions
Sign of K- is the same as for K+ (sign $H_1^{\perp\, fav}$ / $H_1^{\perp\, unfav}$ for π and K inconsistent)

Independent, high precision measurement at large x is crucial

Collins asymmetry: kaons vs pions





N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

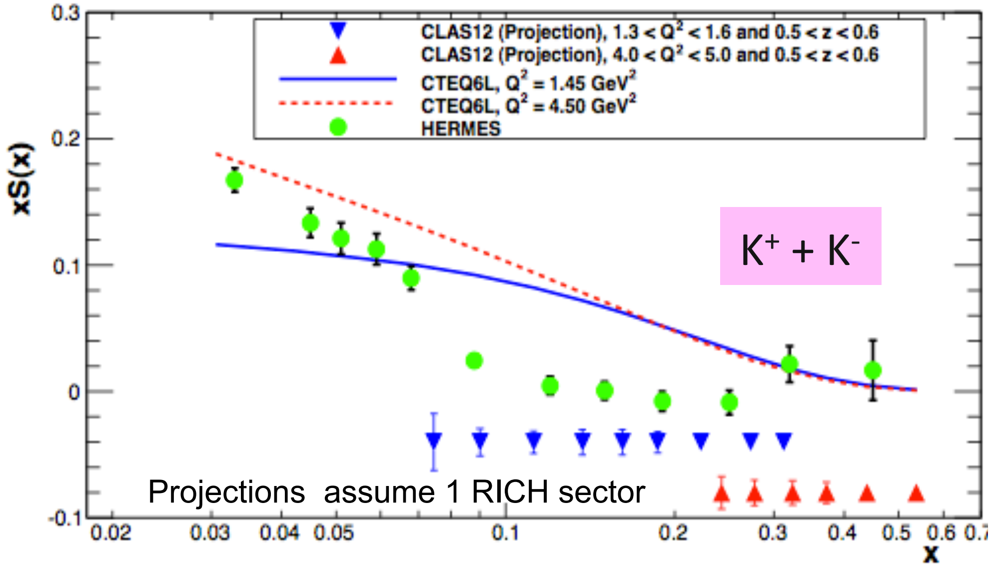
$h_1 H_1^\perp$

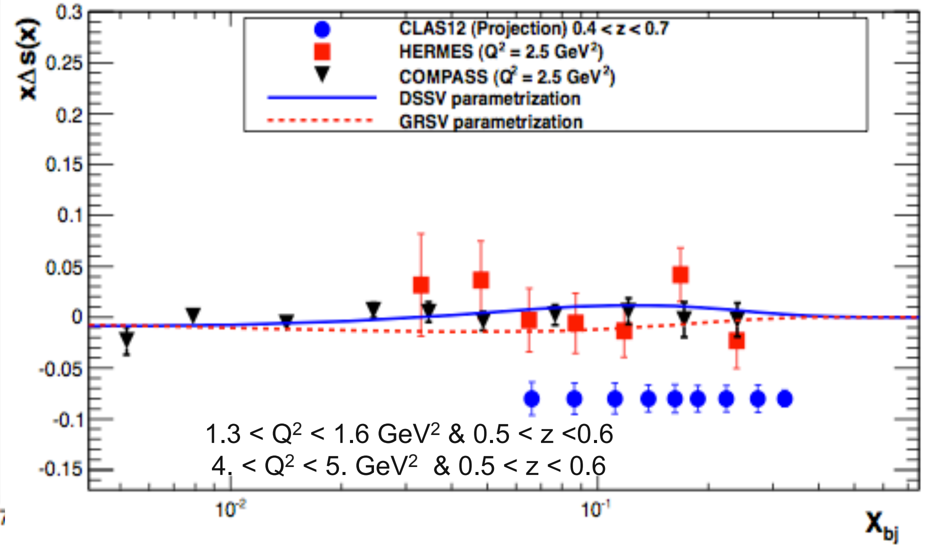
- K+ at large x has larger Collins asymmetry (HERMES COMPASS)
- K- seem to have opposite to π- sign(HERMES/ BRAHMS(pp->hX) and the same at COMPASS

Independent, high precision measurement at large x is crucial

Strange Sea Momentum and Spin Dependent Distributions E12-09-007

measurements require a good charged kaon identification for the whole momentum range





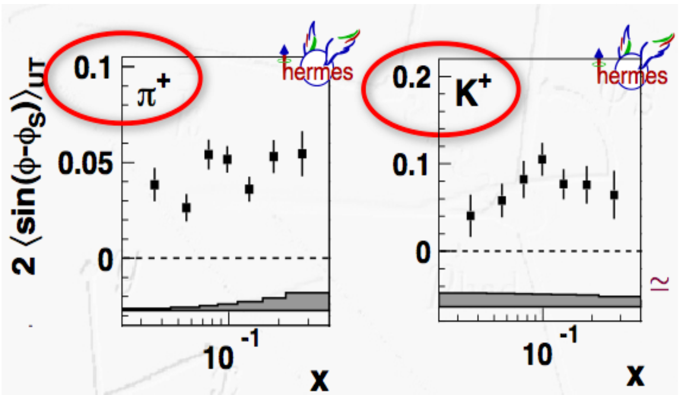
High precision measurement of the shape of the strange parton distribution functions and check the ansatz that they are average of the two light sea quark distributions (unpol deuteron).

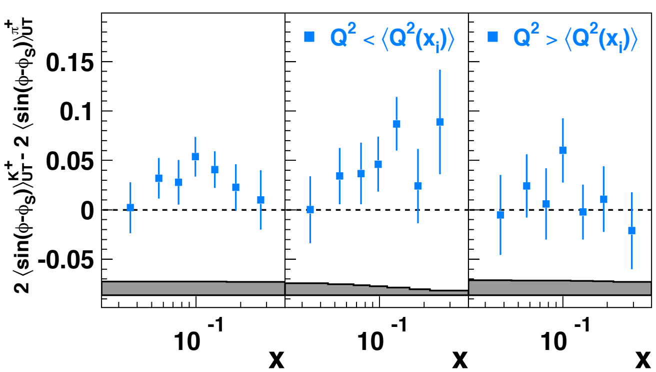
Two methods to access the strange quark polarization.

1. isoscalar method (only polarized deuterium is used)
2. flavor decomposition method (the information on both hydrogen and deuterium targets used)

E12-09-007 experiment allow studies of x-dependence of strange sea distributions in wide range of kinematics, using multidimensional binning.

Sivers asymmetry: kaons vs pions

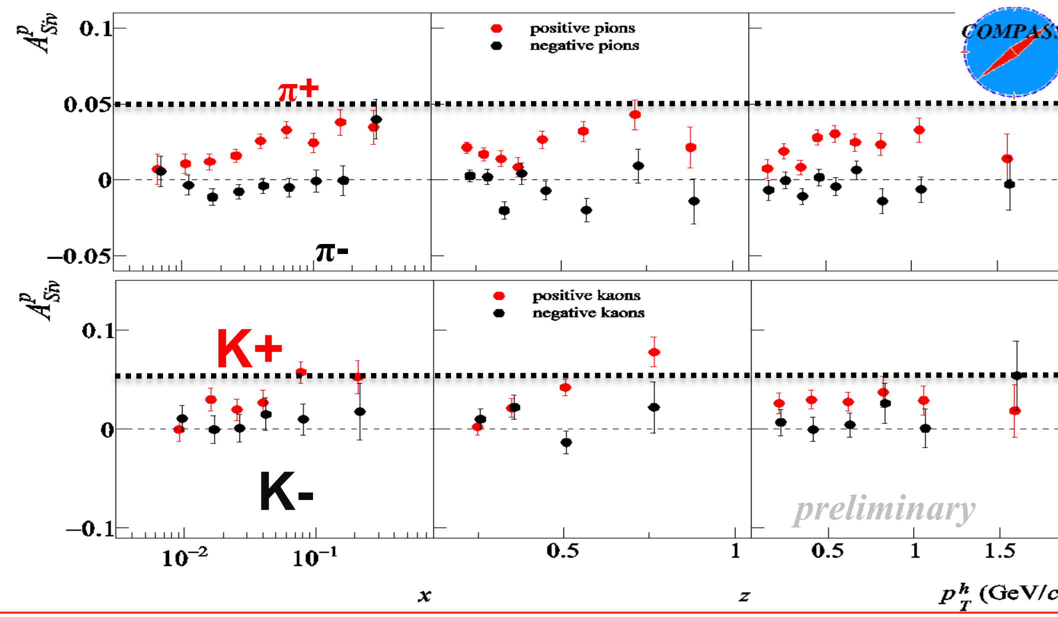




$$A_{UT}^{Siv} = A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{f_{1T}^{\perp u}(x,k_T) \otimes_W D_1^{u\to h}(z,p_T)}{f_1^u(x,k_T) \otimes D_1^{u\to h}(z,p_T)}$$

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1 $h_{1T}^{\perp}$

combined 2007 – 2010 results

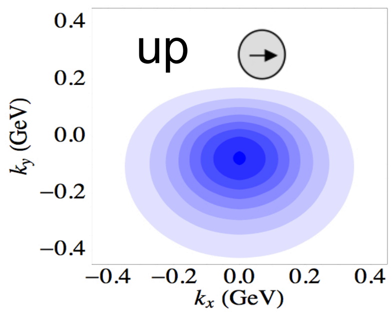


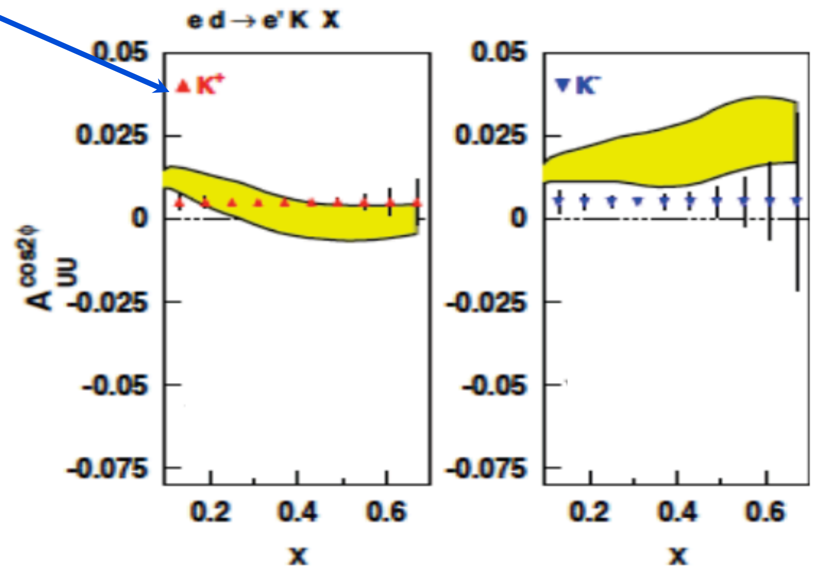
- K+ at large x has larger Sivers SSA which may come from orbital effects in hadronization (higher twist effects)
- K- and π- consistent with 0 indicating contributions from different flavors cancel.

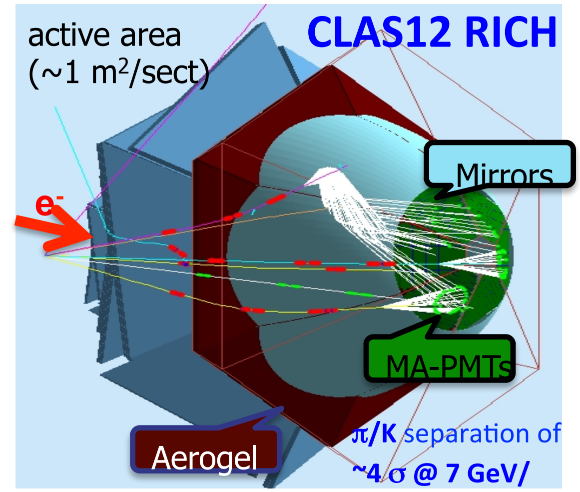
Independent, high precision measurement in a wide Q^2 range is crucial

Spin-Orbit Correlations in Kaon Electroproduction in DIS with Unpolarized Hydrogen and Deuterium Targets (E12-11-111)

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

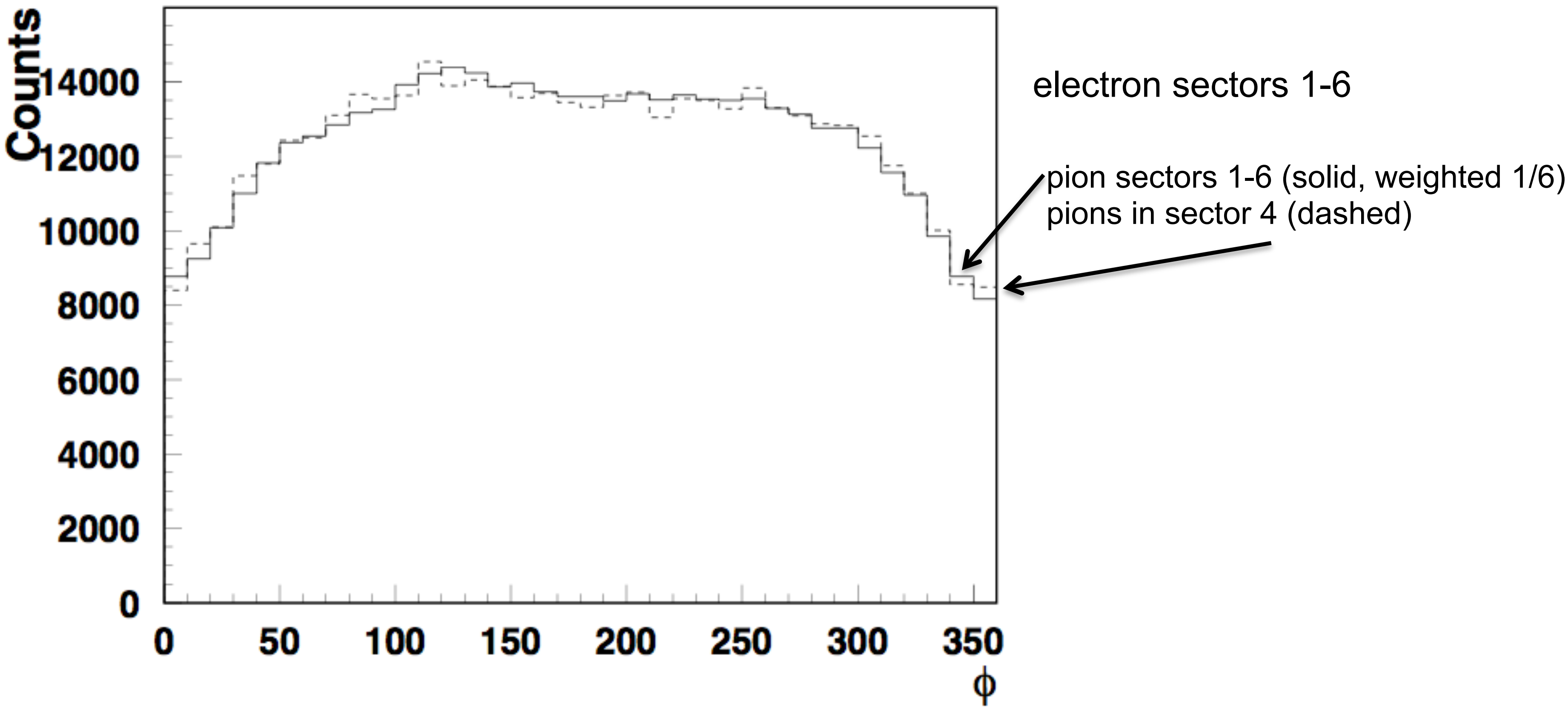






Measurement of Boer-Mulders asymmetry in kaon SIDIS providing complementary information on Boer-Mulders function and the Collins fragmentation functions for kaons can shed light on the "kaon puzzle", and on the structure of the nucleon in general

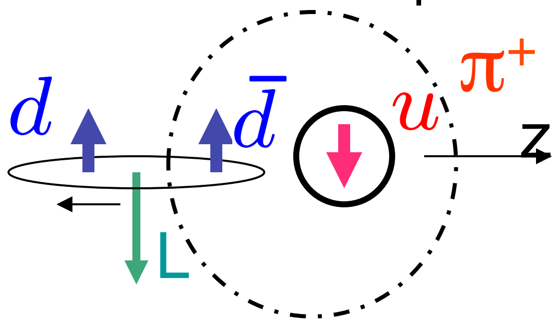
Acceptance with a single sector



Identification of kaons in a single sector provides full coverage in CM azimuthal angle

Collins effect

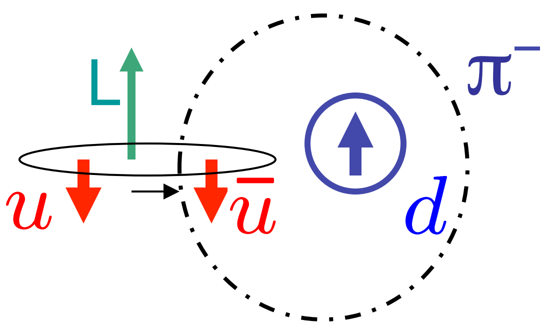
Simple string fragmentation (Artru model)



Leading pion out of page ($\bar{d}$ - direction)

$$h_1 H_1^{\perp u\rightarrow\pi^+}$$

d kicked in the opposite to the leading pion(into the page)



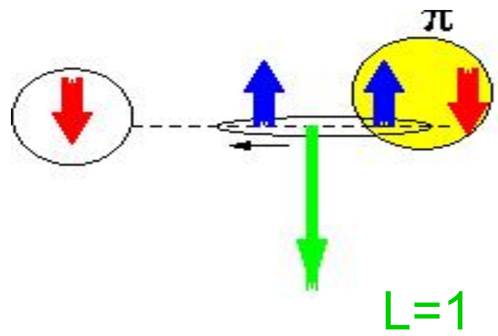
Sub-leading pion opposite to leading (double kick into the page)

$$H_1^{\perp u\rightarrow\pi^-} > H_1^{\perp u\rightarrow\pi^+}$$

If unfavored Collins fragmentation dominates measured π- vs π+, why K- vs K+ is different?

Collins effect

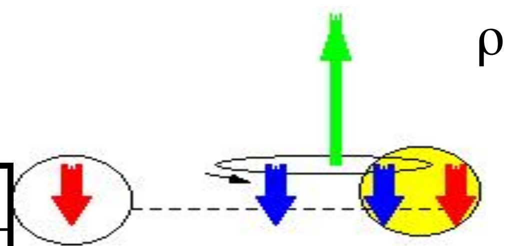
Simple string fragmentation
(Artru model)



Sub-leading pion opposite to leading (into page)

$$h_1 H_1^{\perp u \to \pi^+}$$

ρ production may produce an opposite sign A_{UT}



Leading ρ opposite to leading π(into page)

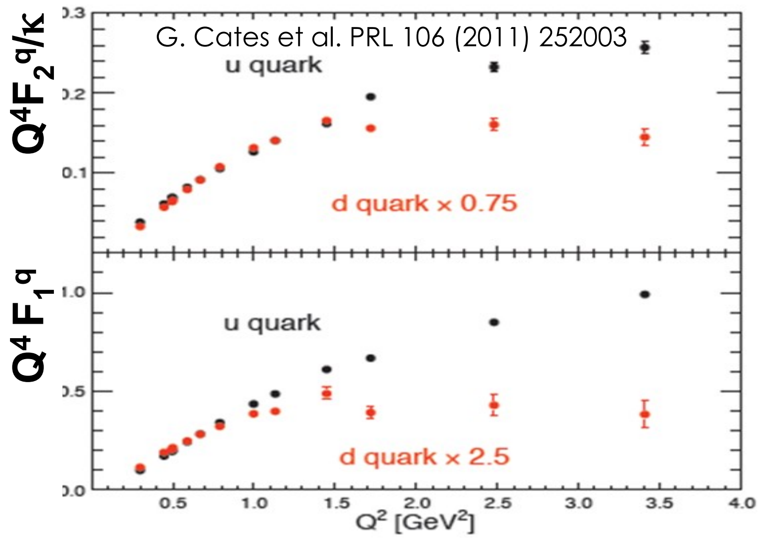
Fraction of ρ in eπX	% left from eπX asm
40%	~50%
60%	~20%
75%	0

$$H_1^{\perp u \to \rho} \sim -\frac{1}{3} H_1^{\perp u \to \pi}$$

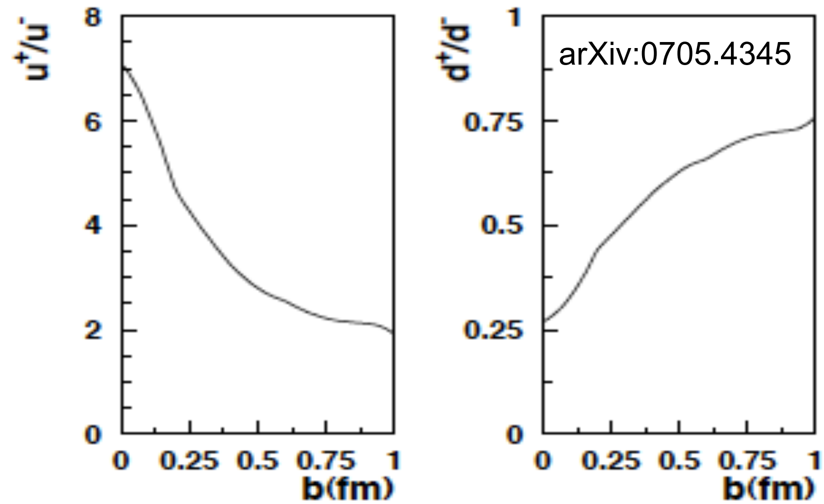
hep-ph/9606390

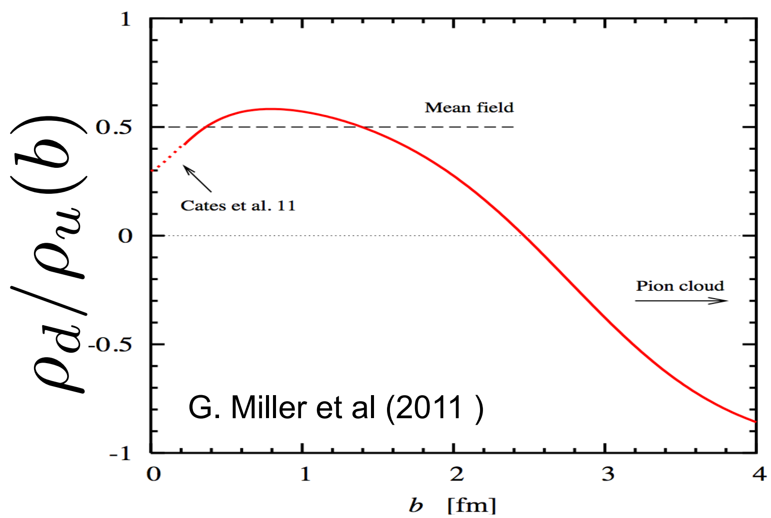
Fraction of direct kaons significantly higher than the fraction of direct pions.

Flavor and spin dependence of spatial distributions



B.Pasquini et al

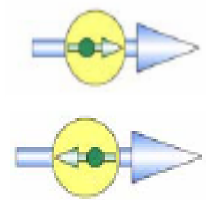




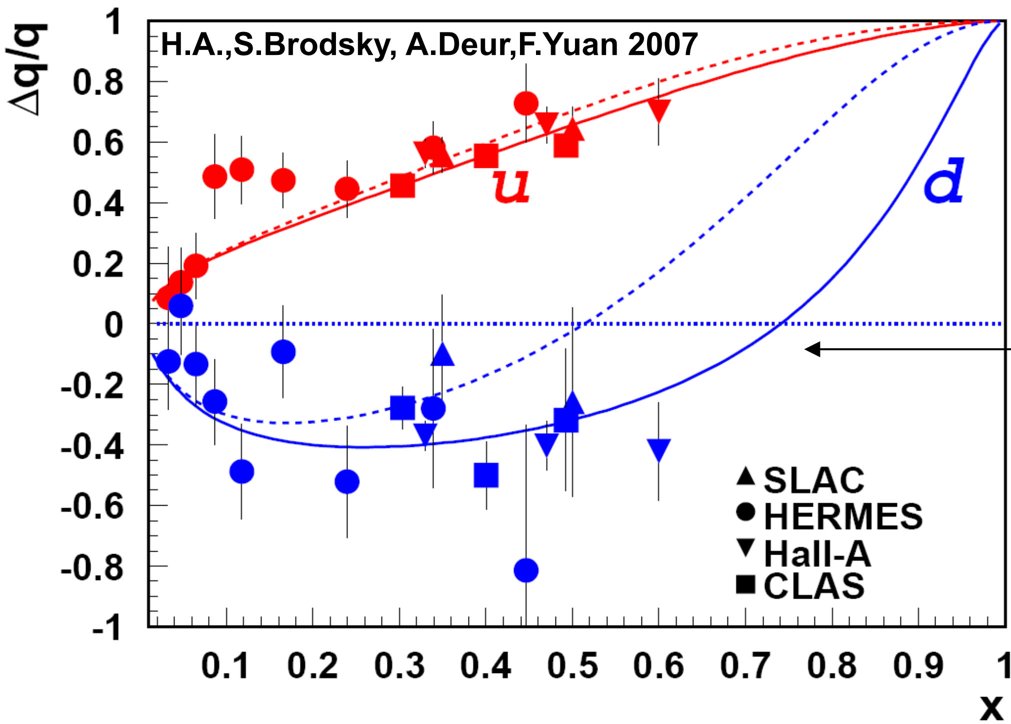
space distributions depend on flavor and spin (modify in medium)

Orbital effects on PDFs

Brodsky,Burkardt&Schmidt



$$q^+ \sim (1-x)^3$$
$$q^- \sim (1-x)^5$$



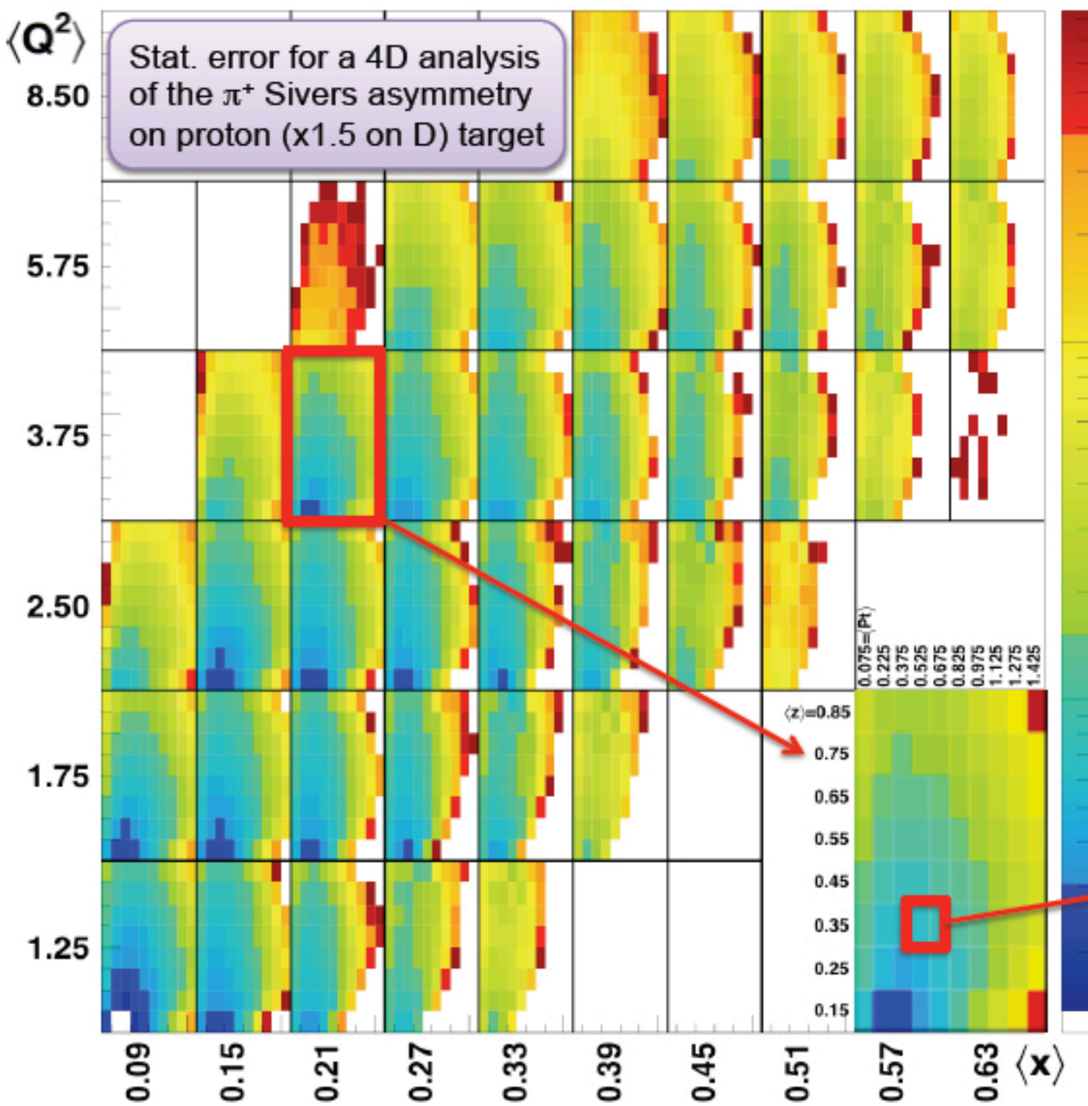
BBS/LSS no OAM

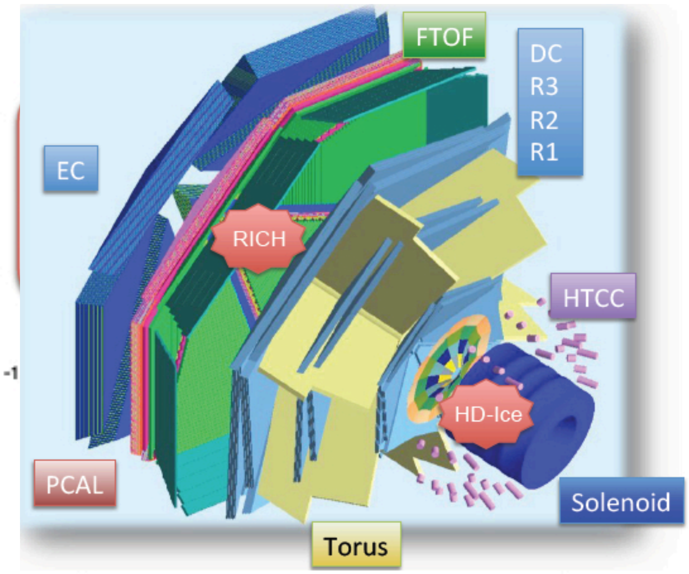
BBS/LSS with OAM

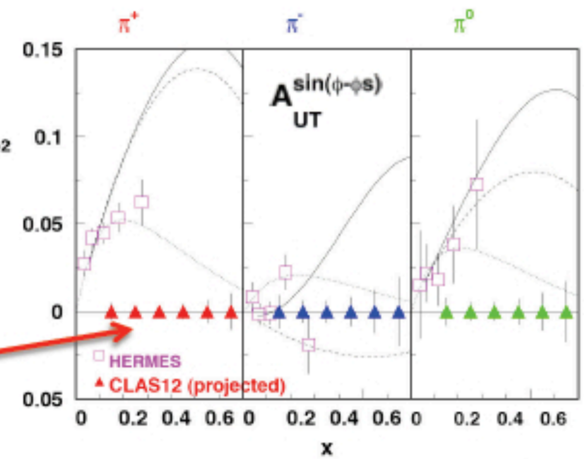
$$q^-_{L=1} \sim (1-x)^5 log^2(1-x)$$

Effect of the orbital motion on the x-dependence of PDFs may be significant!

CLAS12 A_{UT} with transverse proton target





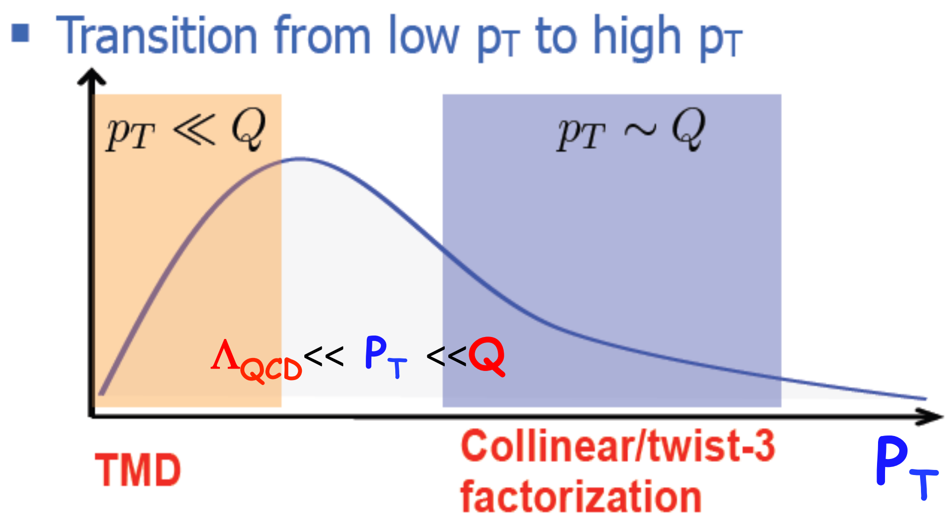


Curves from hep-ph/0507266 and hep-ph/0507181

From low P_T TMDs to high P_T collinear

Matching the angular integrated cross section at low P_T to fixed order pQCD collinear factorization calculations at high P_T

Transverse momentum dependent
$Q >> P_T >= \Lambda_{QCD}$



Collinear
$Q, P_T >> \Lambda_{QCD}$

Cahn effect $\rightarrow F_{UU}^{\cos\phi}$

Twist-3 Cahn — Leading Twist → P_T

Georgi Politzer

Collinear/ Twist-2

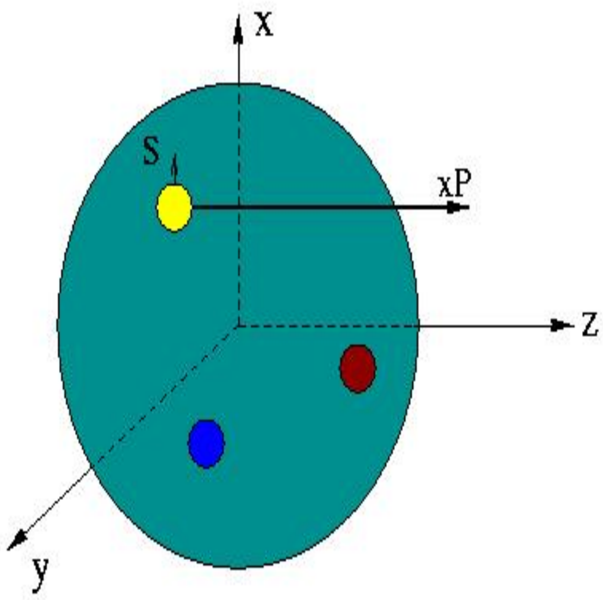
Sivers effect $\rightarrow F_{UT}^{\sin(\phi-\phi_S)}$

Twist-2 Sivers — Higher Twist → P_T

Efremov, Teryaev; Qiu, Sterman

Collinear/ twist-3

1D Structure of the Nucleon (+twist-3)



quark polarization

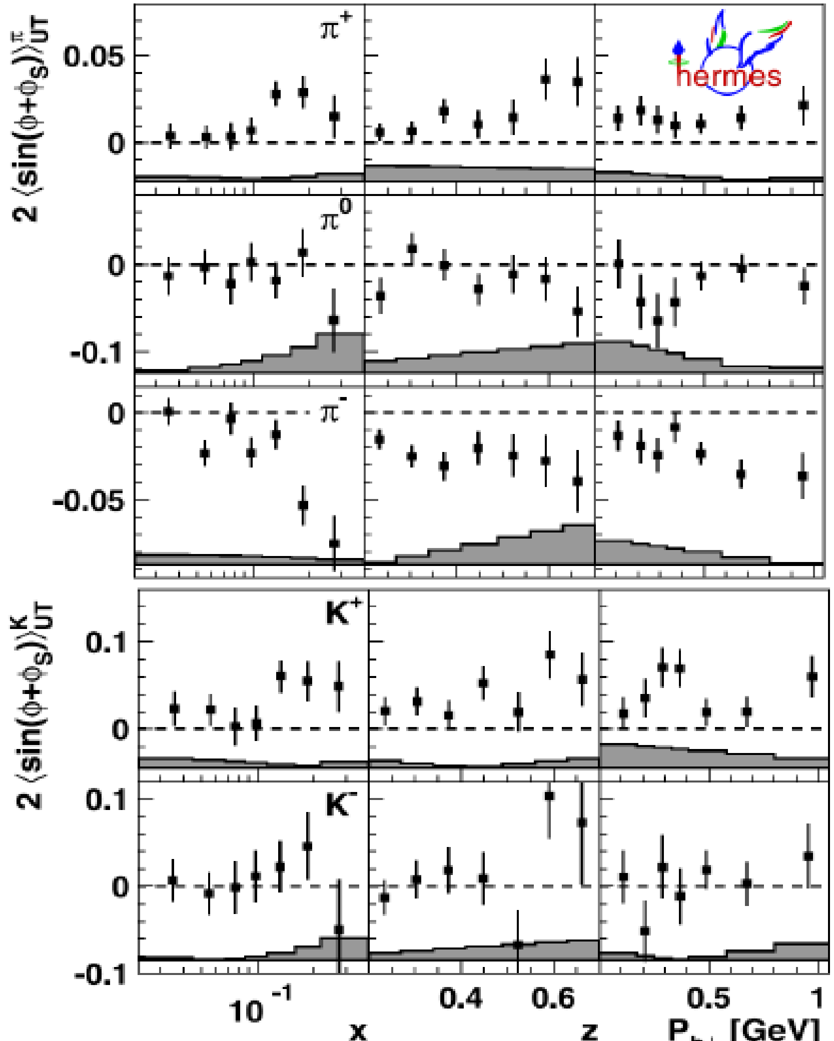
nucleon polarization

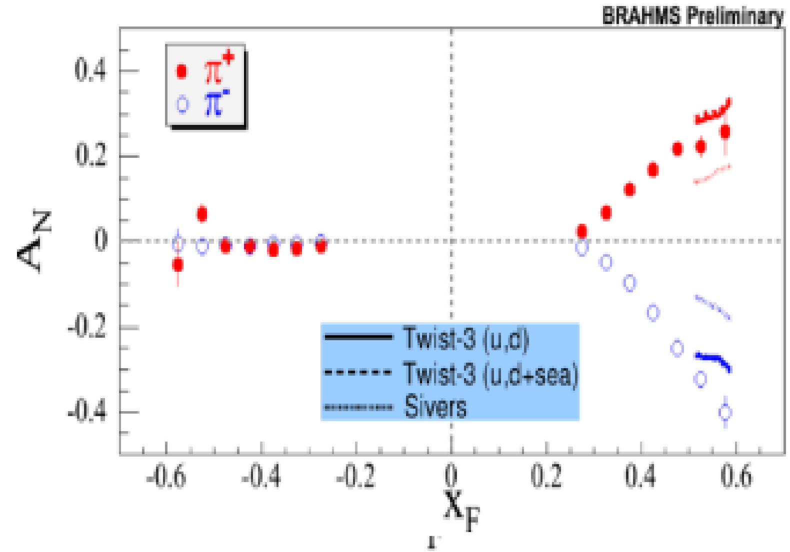
N/q	U	L	T
U	f_1		e
L		g_1	h_L
T		g_T	h_1

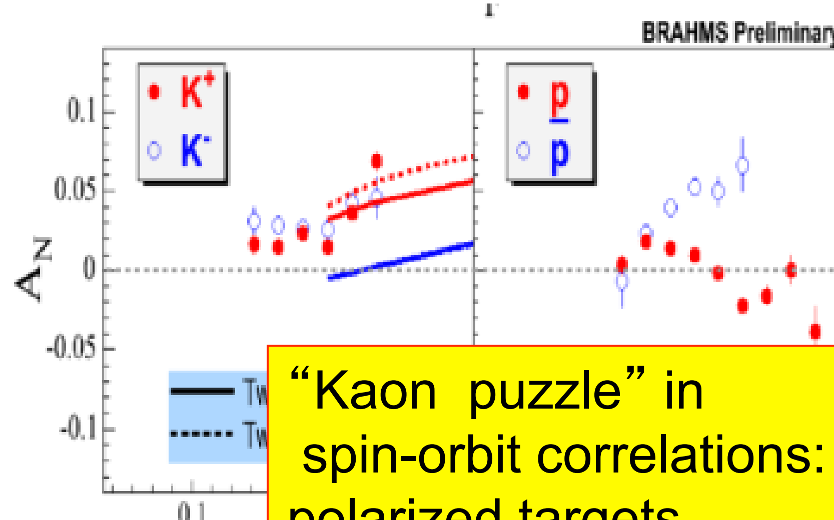
Quark polarized in the x-direction right after scattering feels a force in the y-direction
Burkardt (2008)

$$\sim \int_0^1 x^2 \bar{e}(x) dx$$

Collins asymmetry - proton







"Kaon puzzle" in spin-orbit correlations: polarized targets

Is there a link between HERMES and BRAHMS Kaon vs pion moments (K- has the same sign as K+ and pi+, comparable with K+)?