Probing Strangeness in Hard Processes

Laboratori Nazionali di Frascati
November 11-13, 2013

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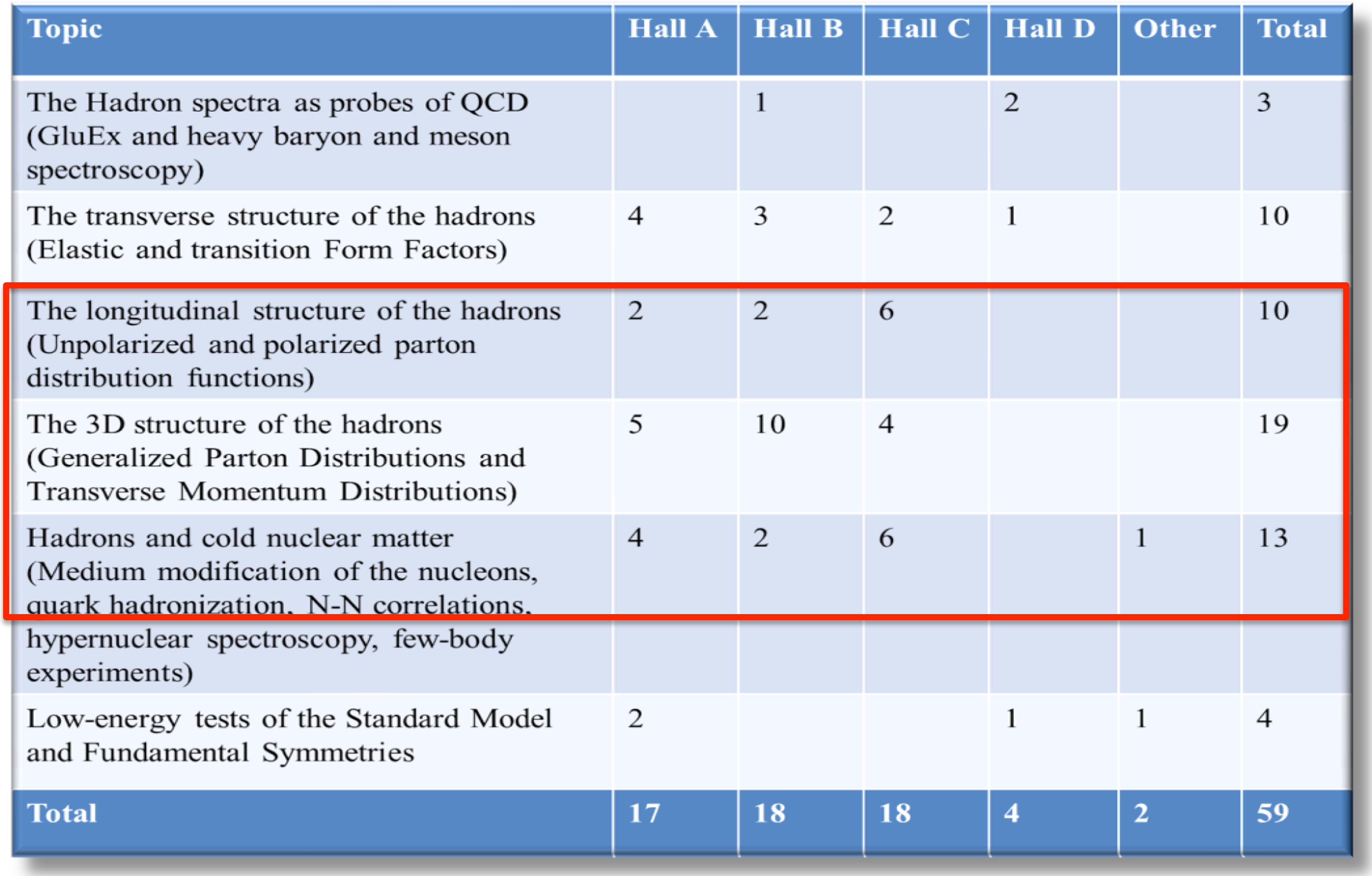
- Collinear PDFs
- 3D structure TMDs
- Multidimensional analysis
- Dihadrons
- 3D structure GPDs and OAM
- Kaons in Medium
- Conclusions

12 GeV Approved Experiments by Physics Topics



Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD (GluEx and heavy baryon and meson spectroscopy)		1		2		3
The transverse structure of the hadrons (Elastic and transition Form Factors)	4	3	2	1		10
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	2	6			10
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	10	4			19
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	4	2	6		1	13
Low-energy tests of the Standard Model and Fundamental Symmetries	2			1	1	4
Total	**17**	**18**	**18**	**4**	**2**	**59**

Nucleon structure

1D-ists

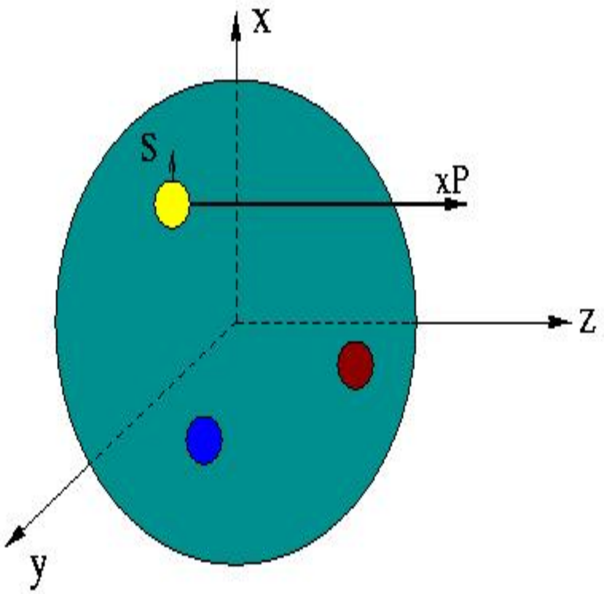
$f_1(x), g_1(x) \quad D_1(z)$

N/q	U	L
U	$\mathbf{f_1}$	
L		$\mathbf{g_1}$

3D-ists

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

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



quark polarization

nucleon polarization

N/q	U	L	T
U	$\mathbf{f_1}$		e
L		g_1	h_L
T		g_T	$\mathbf{h_1}$

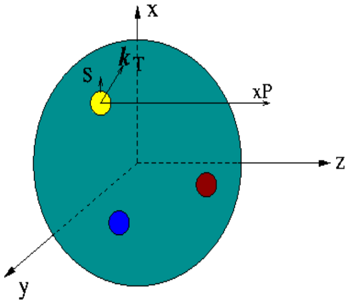
Quark polarized in the x-direction right after scattering feels a force in the y-direction

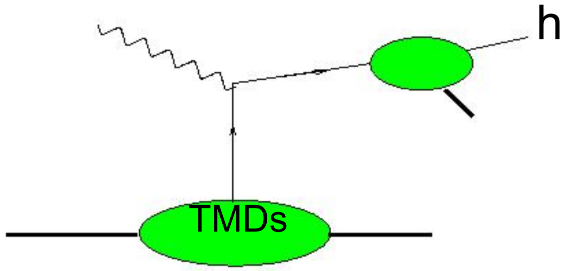
Burkardt (2008)

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

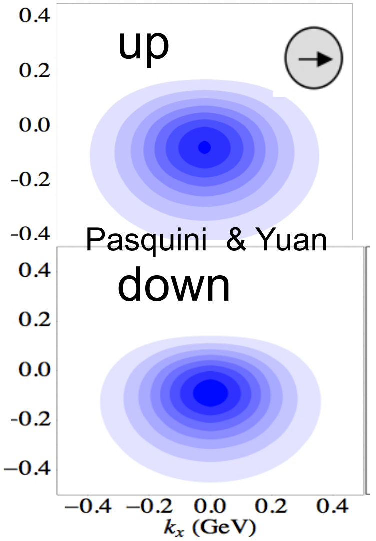
3D structure of the nucleon

Semi-Inclusive processes and transverse momentum distributions

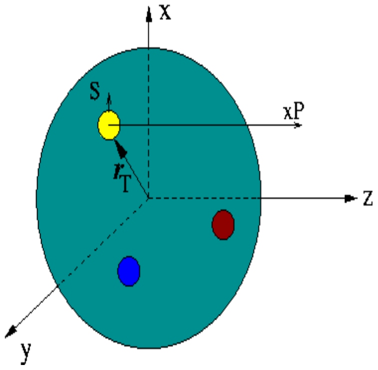


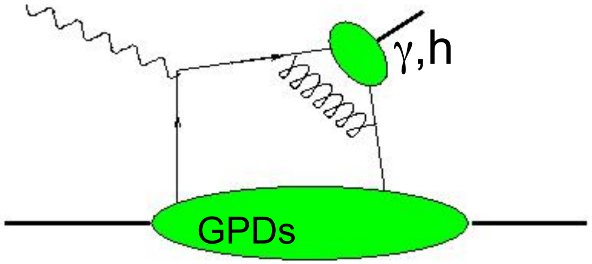


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

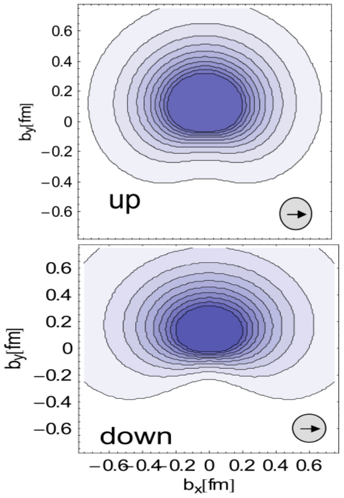


Hard exclusive processes and spatial distributions of partons





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



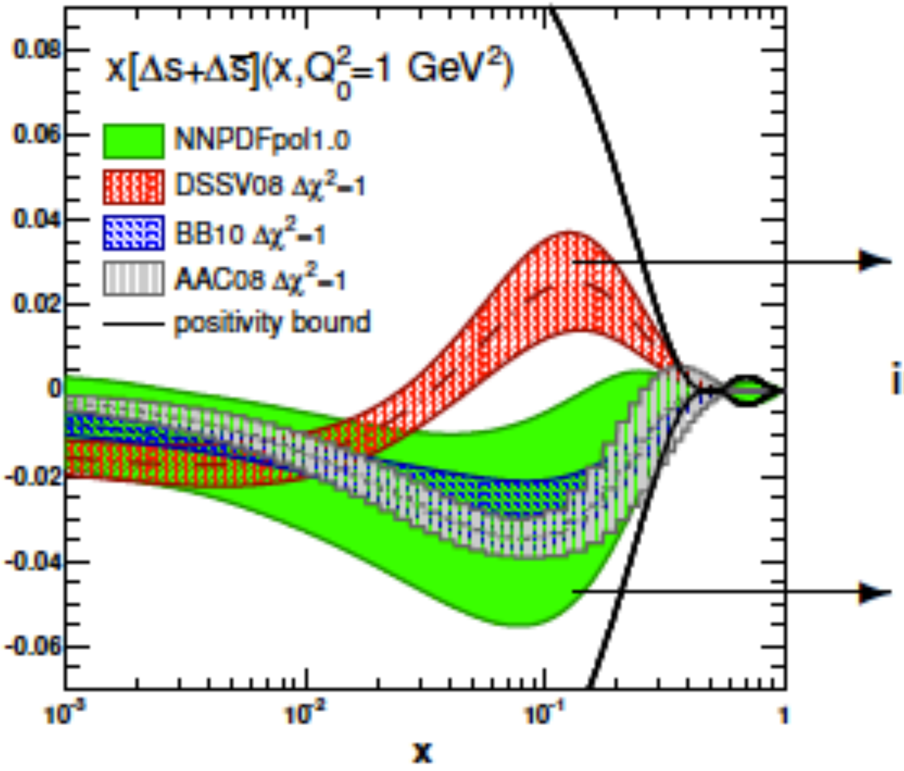
(QCDSF)

Wide kinematic coverage of large acceptance detectors allows studies of exclusive (GPDs) and semi-inclusive (TMDs) processes providing complementary information on transverse structure of nucleon

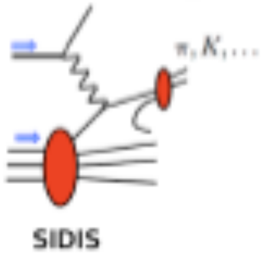
Polarized Strangeness from NNPDFpol1.0

☞ E. Nocera

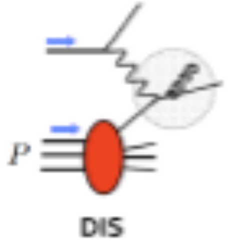
N/q	U	L
U	f_1	
L		g_1



directly from SIDIS Kaon data



indirectly from DIS scaling violations

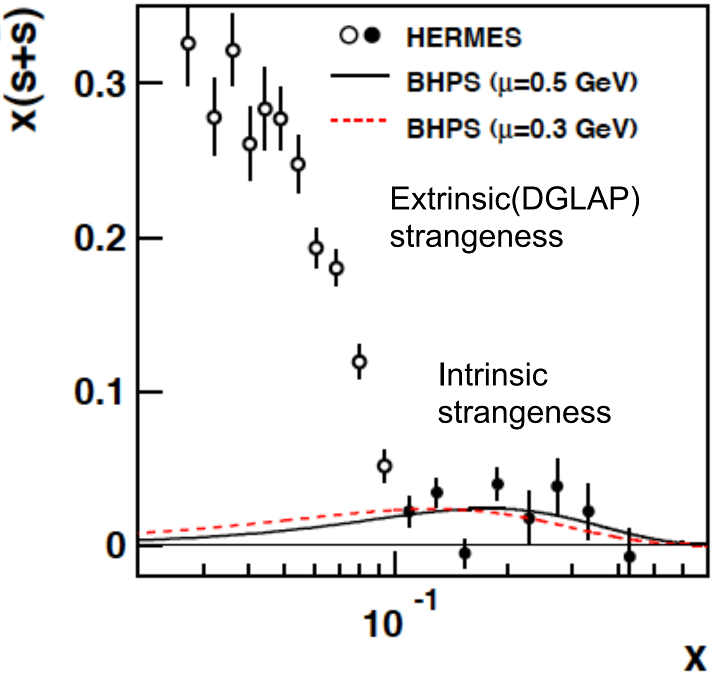


Polarized strangeness is practically unknown, even sign is not defined
SIDIS analysis depends on s->K fragmentation function

Strangeness from SIDIS on Deuteron

two components of the nucleon sea?

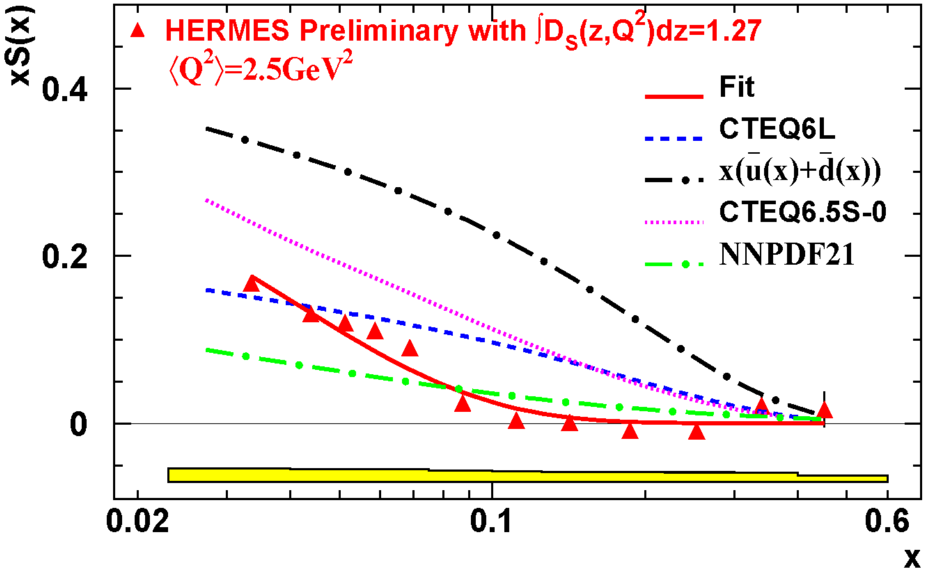
J.C. Peng



$$\frac{dN^{K^\pm}}{dN^{DIS}} = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_s^K(z)dz}{5Q(x)+2S(x)}$$

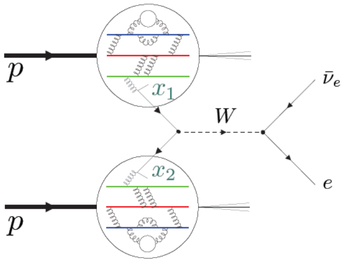
Strange parton distribution S(x) - revised

K. Rith



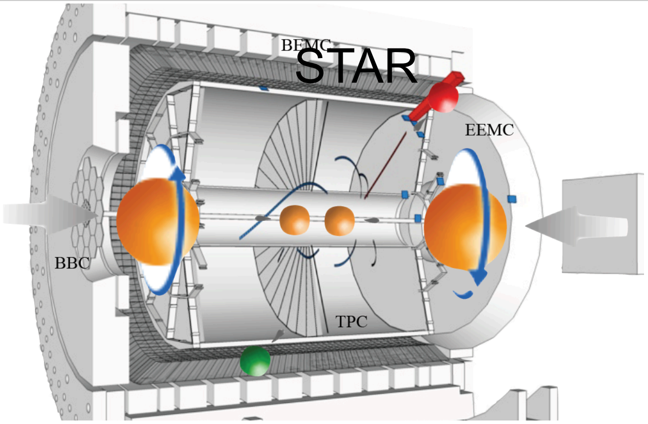
- S(x) is consistent with recent predictions of the NNPDF.
- The shape of S(x) makes extraction of intrinsic strangeness very challenging.

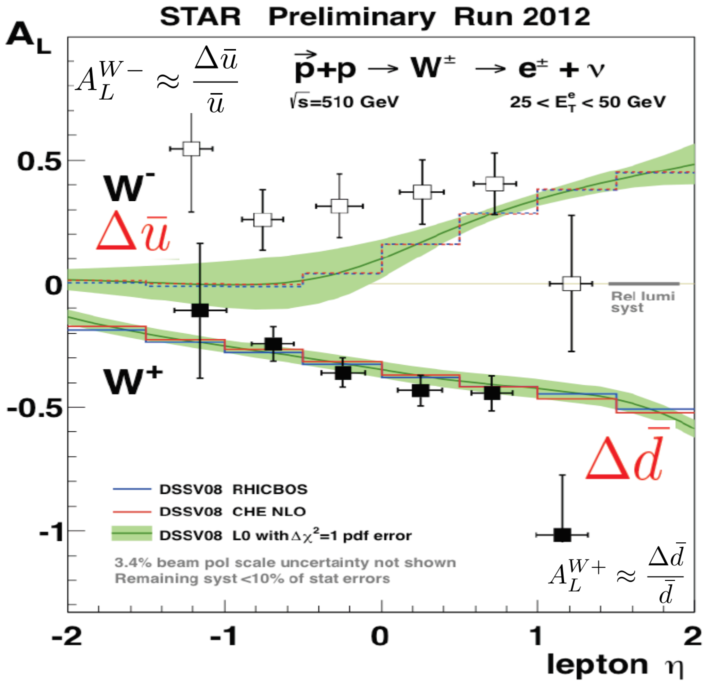
Sea polarization

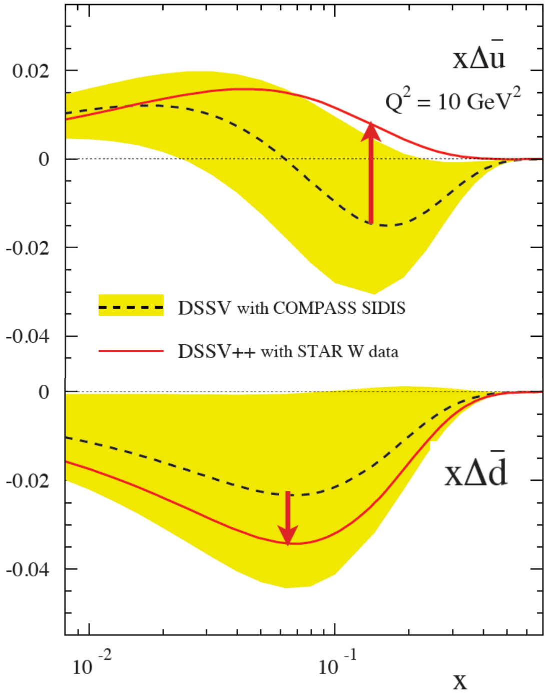


$$\vec{p}+p \rightarrow W^{\pm}+X \rightarrow l^{\pm}+X$$

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{1}{P}\frac{N_+ - RN_-}{N_+ + RN_-}$$

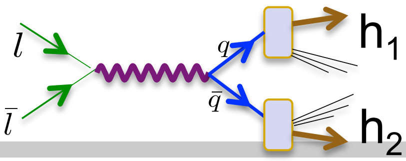






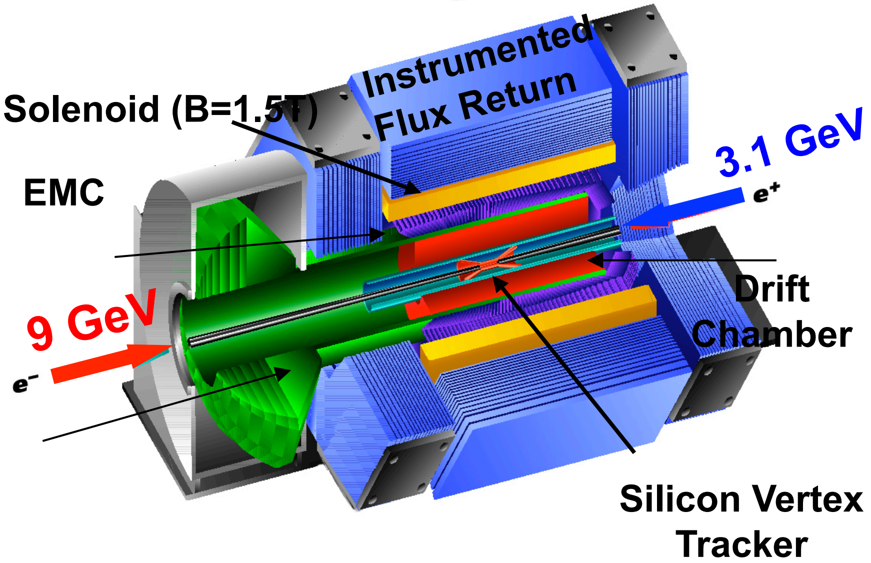
New fit points towards rather sizable

$\Delta\bar{u}(x) - \Delta\bar{d}(x)$

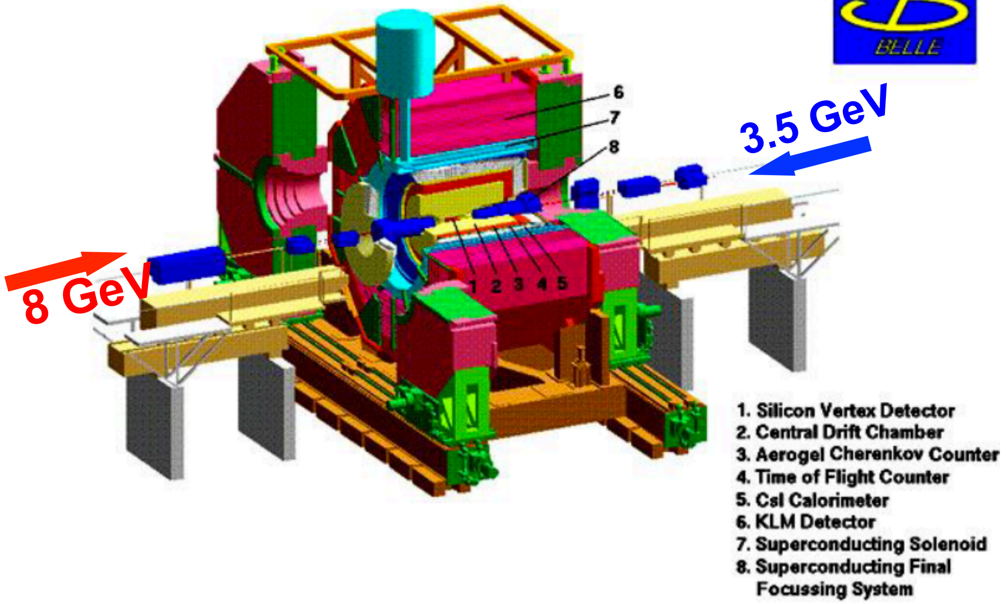


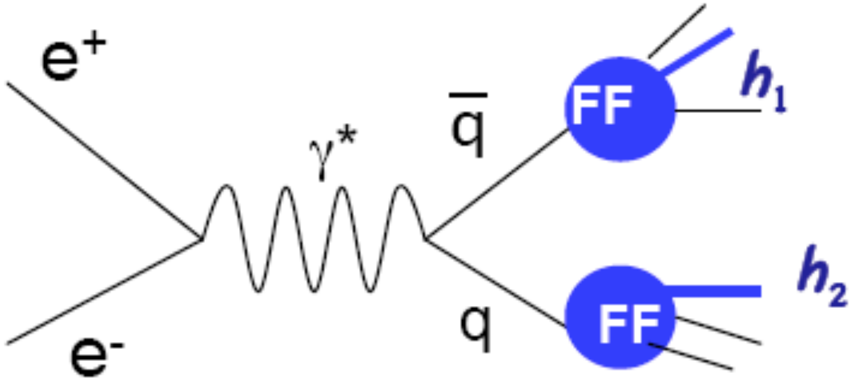
e+ e- and fragmentation functions

BaBar detector I. Garzia



BELLE Detector F. Giordano





Precision measurements of **formation of hadrons** from **quarks/anti-quarks** resulting from the annihilation of electron-positron pairs colliding at high energy.

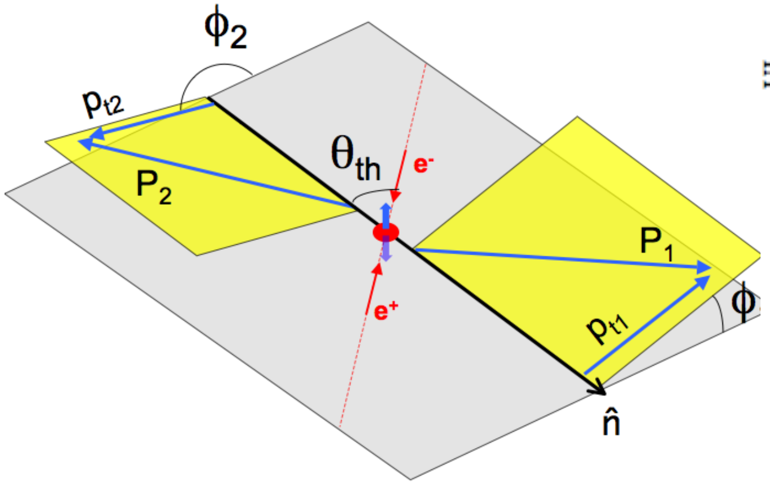
$$A \propto H_{1\perp}(z_1) \otimes H_{1\perp}(z_2)$$

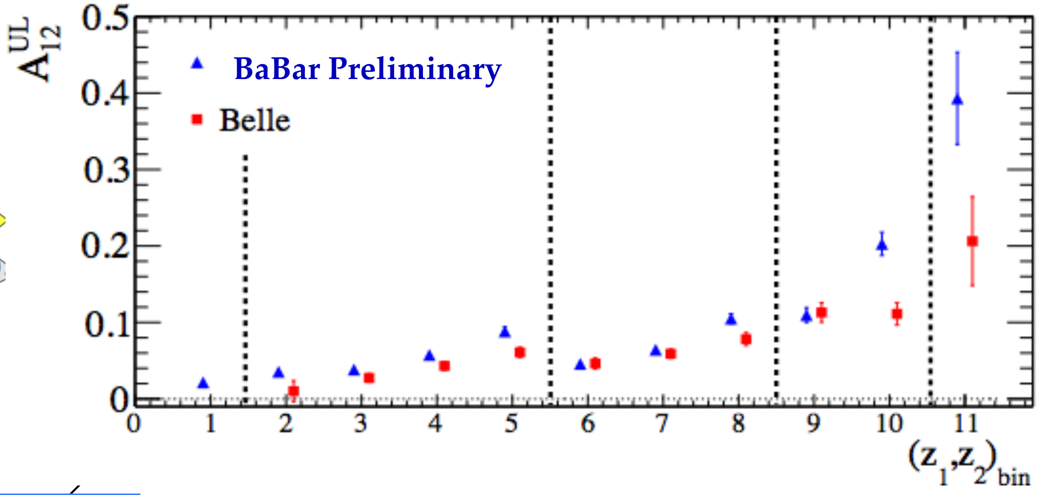
Measurements of the Collins function

"Standard" unpolarized FF

I. Garzia

$$D_1^{q\uparrow}(z,\mathbf{P}_\perp;s_q)=D_1^q(z,P_\perp)+\frac{P_\perp}{zM_h}\boxed{H_1^{\perp q}(z,P_\perp)\,\mathbf{s}_q\cdot(\mathbf{k}_q\times\mathbf{P}_\perp)}$$





$$\boxed{\sigma\sim1+\frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}}\cos(\phi_1+\phi_2)\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}}$$

BaBar (0.15<z<0.9) **Belle (0.2<z<1)**

$\int\mathcal{L}$~468 fb^{-1} **$\int\mathcal{L}$~547 fb^{-1}**

Significant Collins effect measured at Belle and confirmed by BaBar

In progress: Collins function for Kaons and pT-dependences of FFs

Spin-orbit correlations: kaons vs pions

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

D_1 $H_1^\perp$

Initial state asymmetries

Final state asymmetries

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

$$\left.\begin{matrix} D^{u\to\pi^+} \\ D^{u\to K^+} \end{matrix}\right\}$$

u-quark present
(favored fragmentation)

$$\left.\begin{matrix} D_1^{u\to\pi^-} \\ D_1^{u\to K^-} \end{matrix}\right\}$$

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)

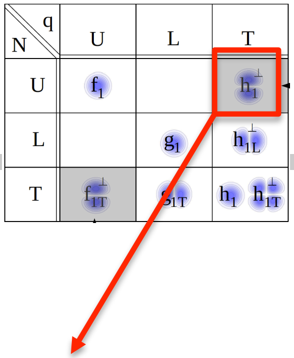
Hermes/Belle measurements for pions indicate

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

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

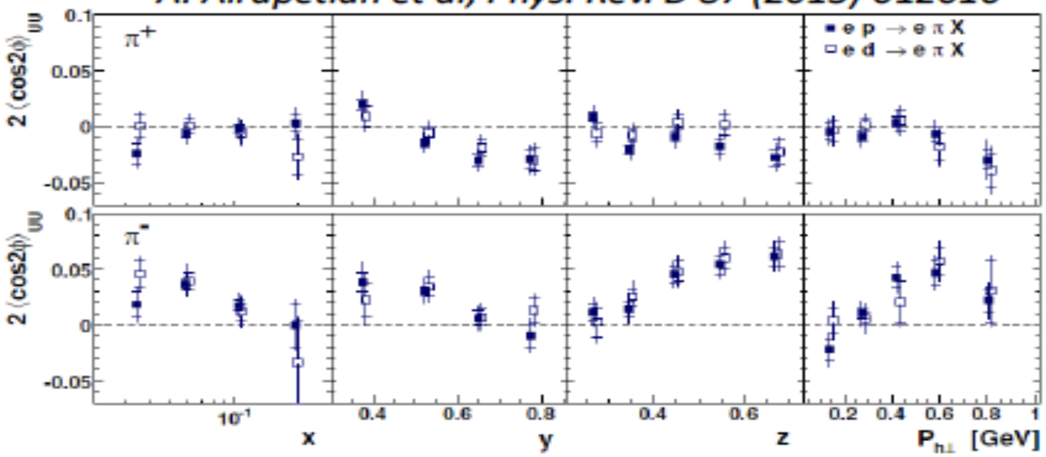
- Spin-azimuthal asymmetries bigger for K^+ compared to π^+
- Spin-azimuthal asymmetries for K^- vs K^+ do not follow the trend of π^- vs π^+ ("Kaon puzzle")

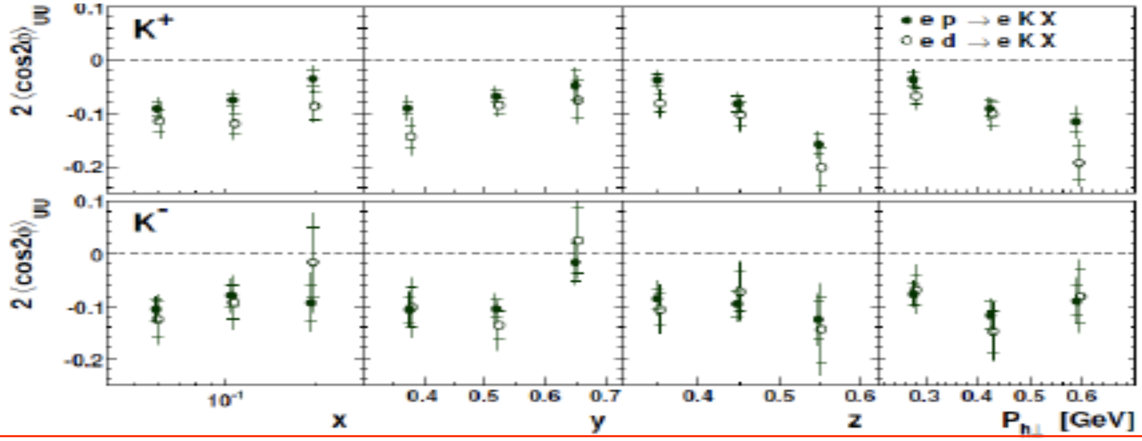
Boer-Mulders effect: kaons vs pions



L. Pappalardo

A. Airapetian et al, Phys. Rev. D 87 (2013) 012010





$$h_1^\perp H_1^\perp$$

$$u - dominance$$

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

$$\Big\downarrow$$

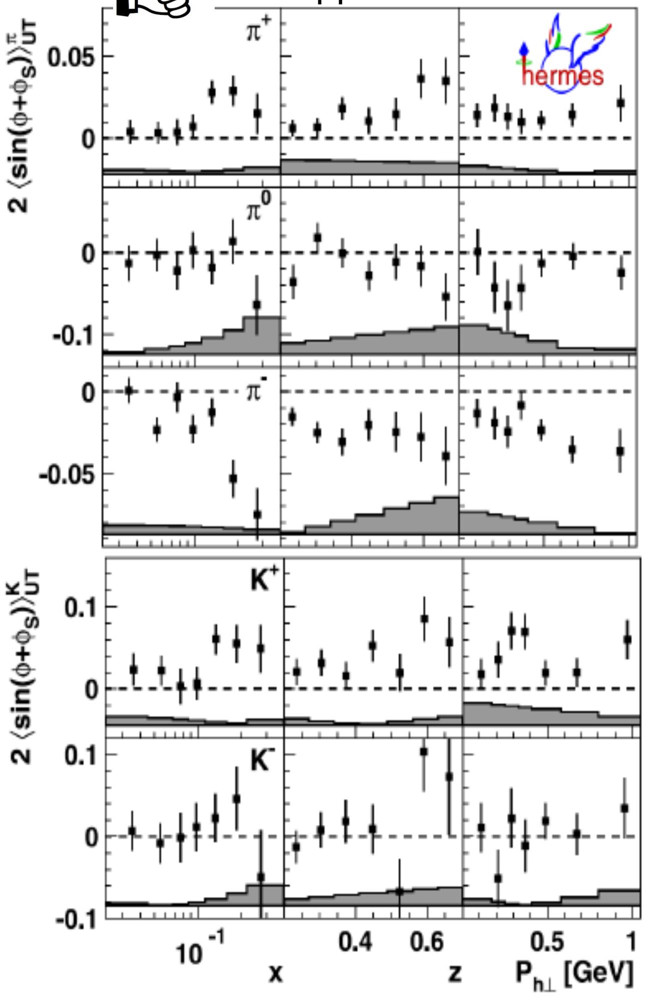
$$\frac{H_1^{\perp,u\to K^+}}{D_1^{u\to K^+}} > \frac{H_1^{\perp,u\to\pi^+}}{D_1^{u\to\pi^+}}$$

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

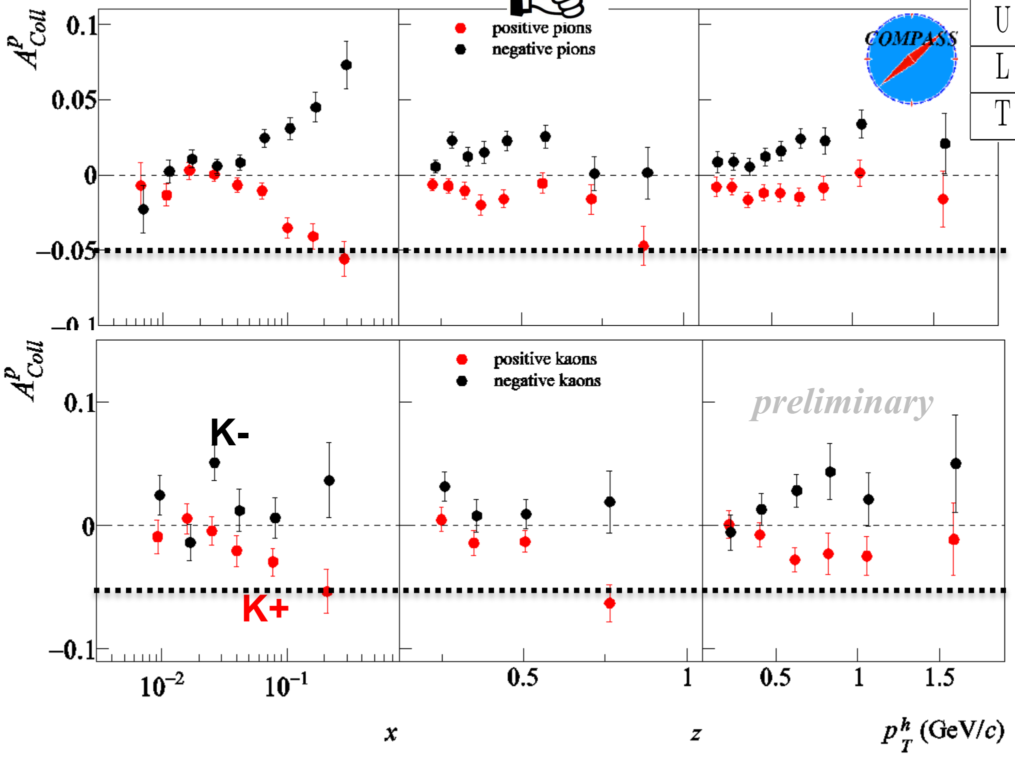
Independent, high precision measurement at large x is crucial

Collins asymmetry: kaons vs pions

L. Pappalardo



A. Martin



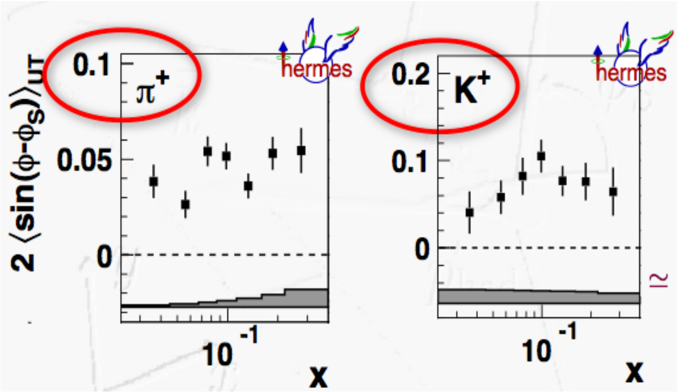
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

$$h_1 H_1^\perp$$

- 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

Sivers asymmetry: kaons vs pions



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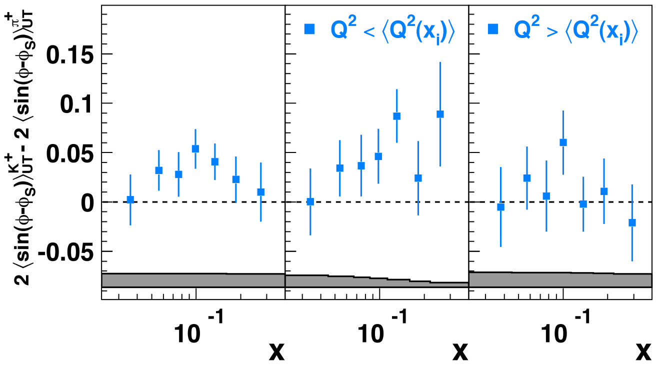
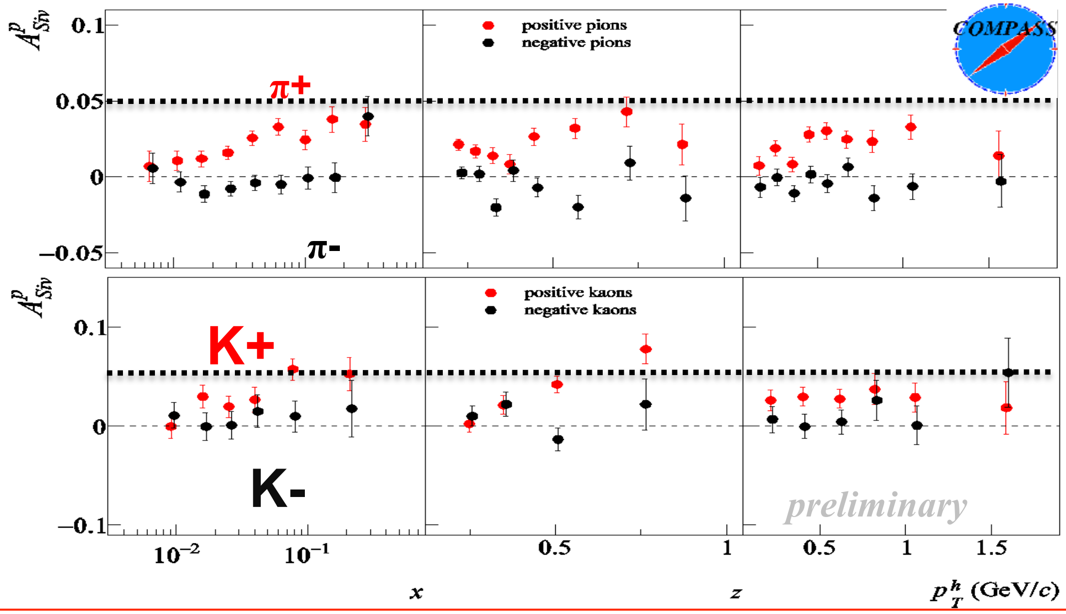


$$A_{UT}^{Siv} = A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{f_{1T}^{\perp u}(x,k_T)\otimes_W D_1^{u\to h}(z,p_T)}{f_1^u(x,k_T)\otimes D_1^{u\to h}(z,p_T)}$$

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



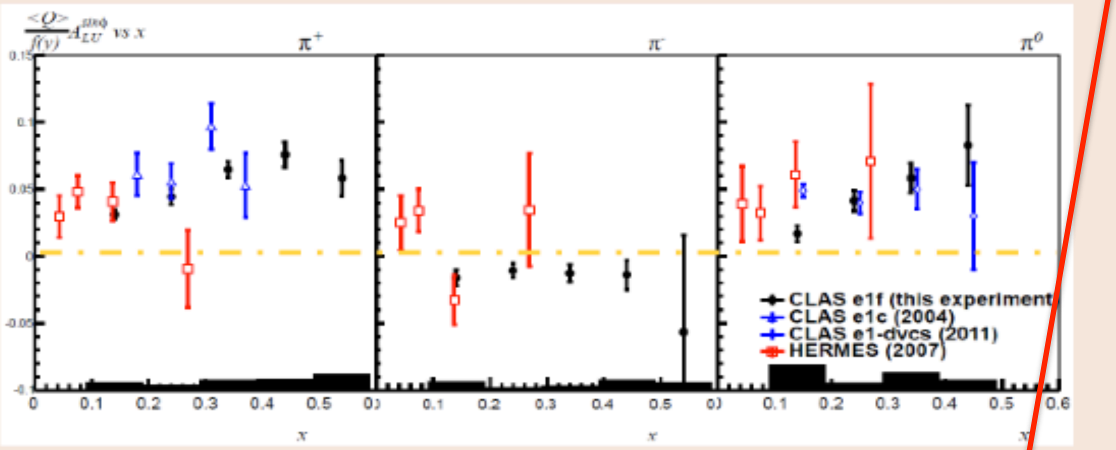
- K+ at large x has larger Sivers SSA which may come from orbital effects in hadronization (higher twist effects)
- K- and π- consistent with 0 indicating contributions from different flavors cancel.

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

☞ S. Pisano

Beam SSA: comparing pions

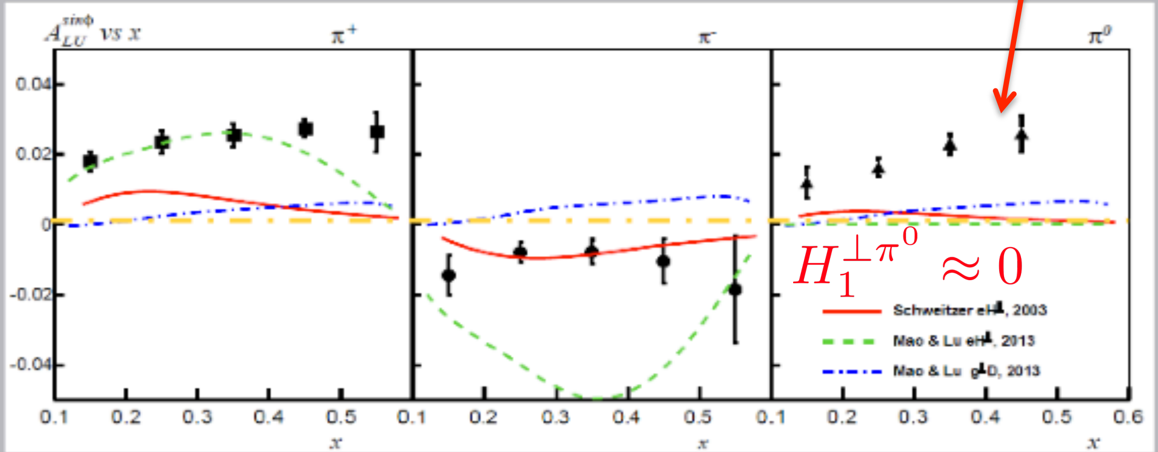
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(\boxed{xe\,H_1^{\perp}} + \frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(\boxed{xg^{\perp}D_1} + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$



HERMES, A. Airapatian et al., Phys. Lett. B648, 164 (2007), hep-ex/0612059

Comparison with previous measurements (evolution-weighted).

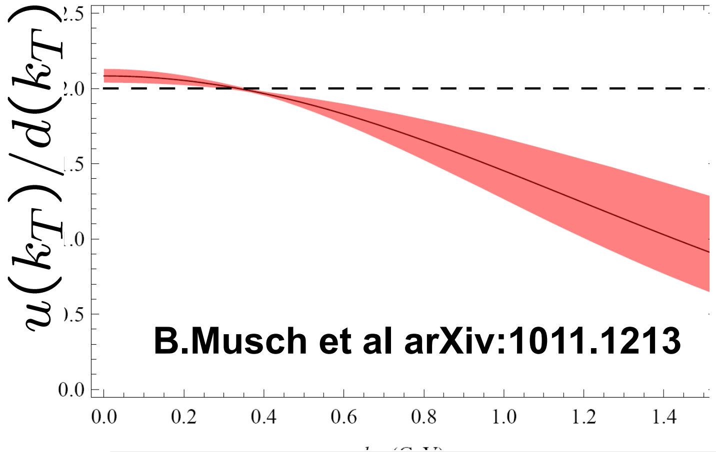
1. It is the first π^- A_{LU} measured by CLAS.
2. First measurement with sufficient precision to determine the sign of $A_{LU}^{\sin\varphi}$



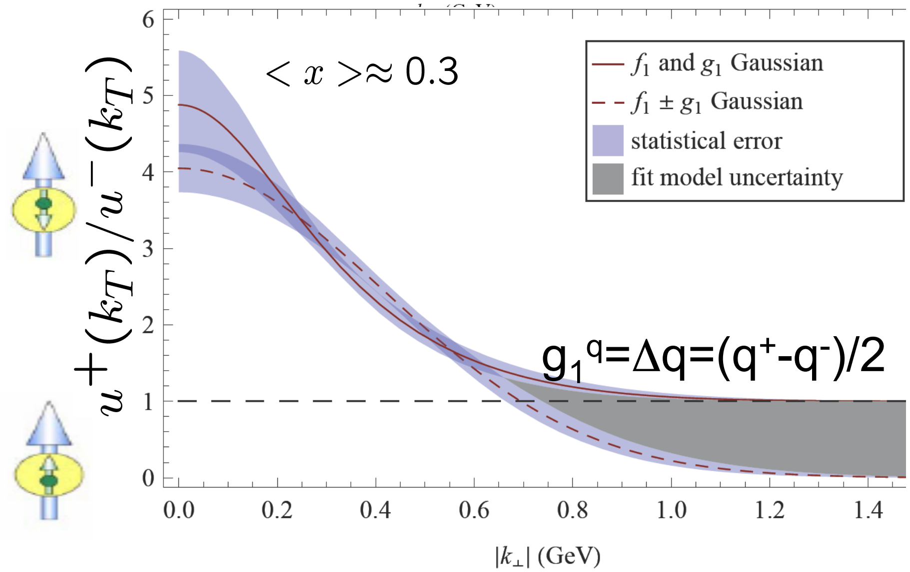
$H_1^{\perp\pi^0} \approx 0$

Each model curve shows the convolution of one TMD with one fragmentation function. The curves shown display $e(x) \otimes H_1^{\perp}$ or $g_1(x) \otimes D_1$

Flavor and spin dependence of k_T–distributions

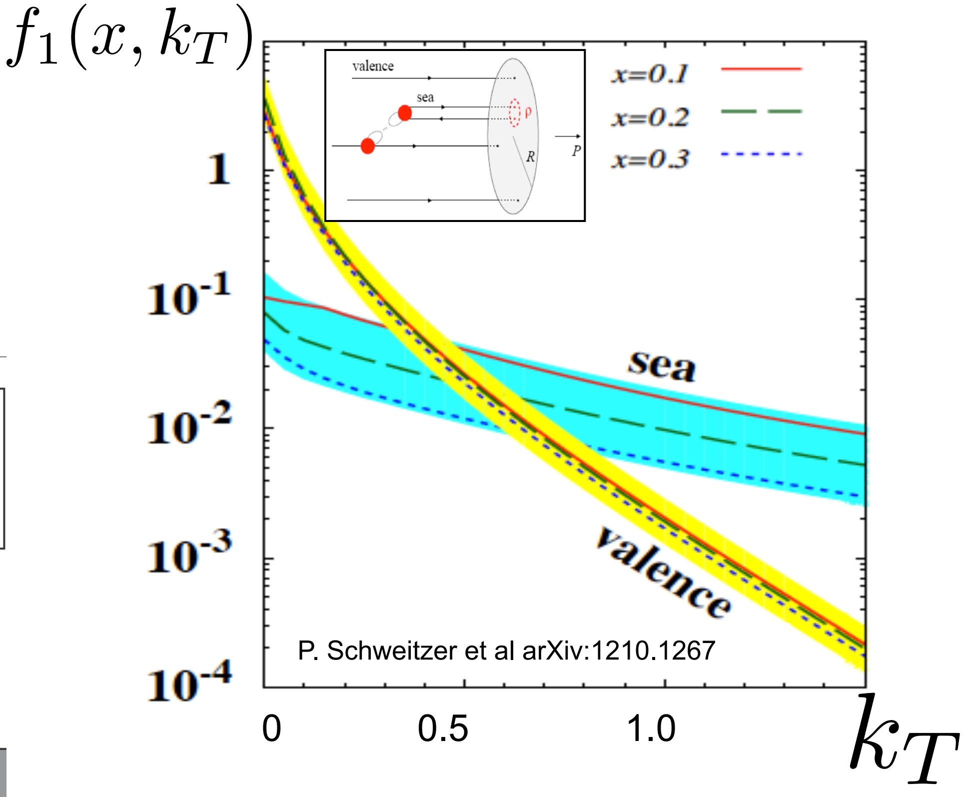


B.Musch et al arXiv:1011.1213



$g_1^q = \Delta q = (q^+ - q^-)/2$

- k_T-distributions of TMDs depend on flavor and spin



P. Schweitzer et al arXiv:1210.1267

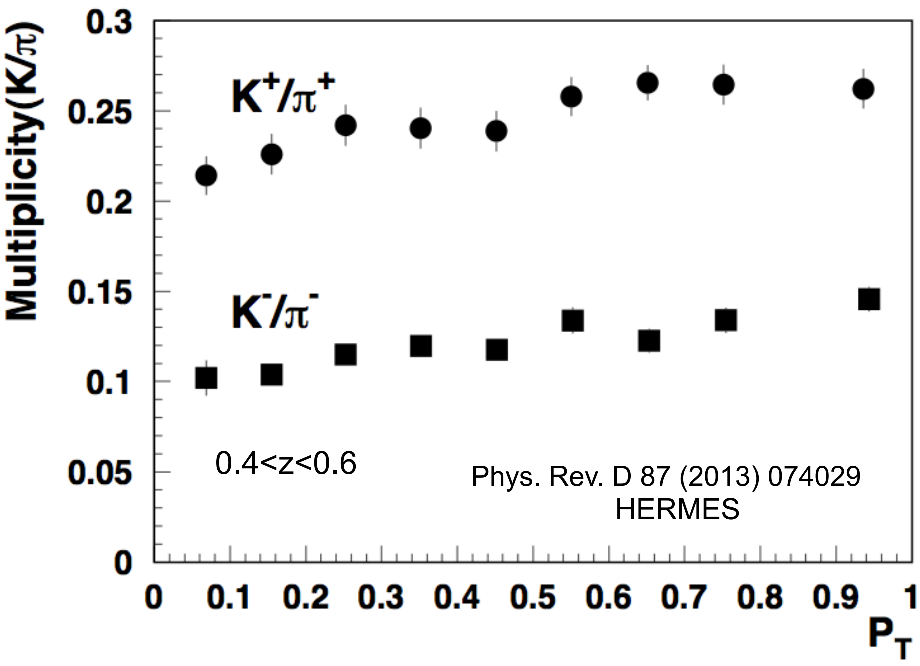
Nucleons 3D structure is complex, with weight of different type of partons changing with k_T
Final states, with different sensitivity to different parton types will be critical to separate contributions

Hadronization effects

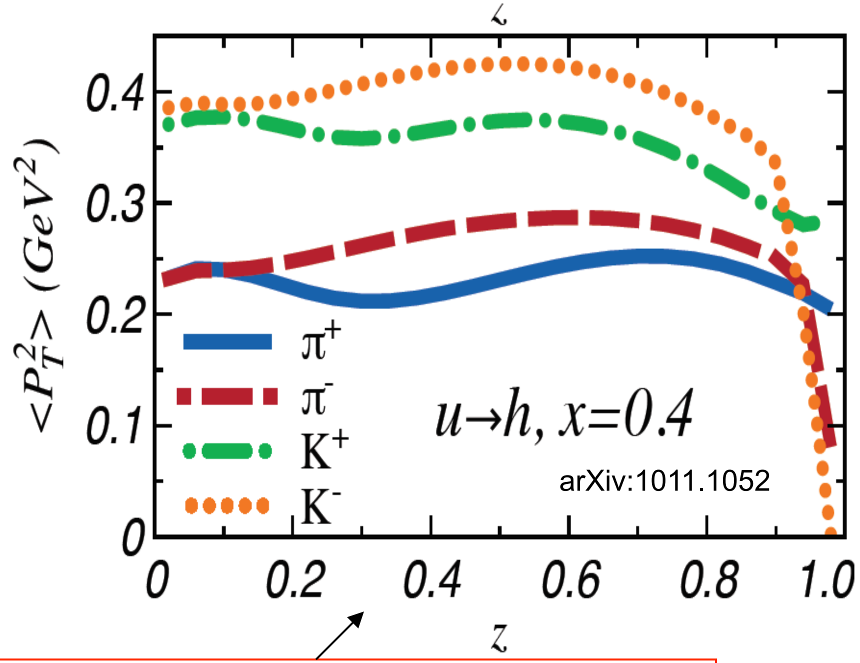
$$f_1^q(x,k_T)\otimes D_1^{q\to h}(z,p_T)$$

$$D_1^{u\to\pi^+}(z,p_T)$$
$$D_1^{u\to K^+}(z,p_T)$$

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



Phys. Rev. D 87 (2013) 074029
HERMES



arXiv:1011.1052

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

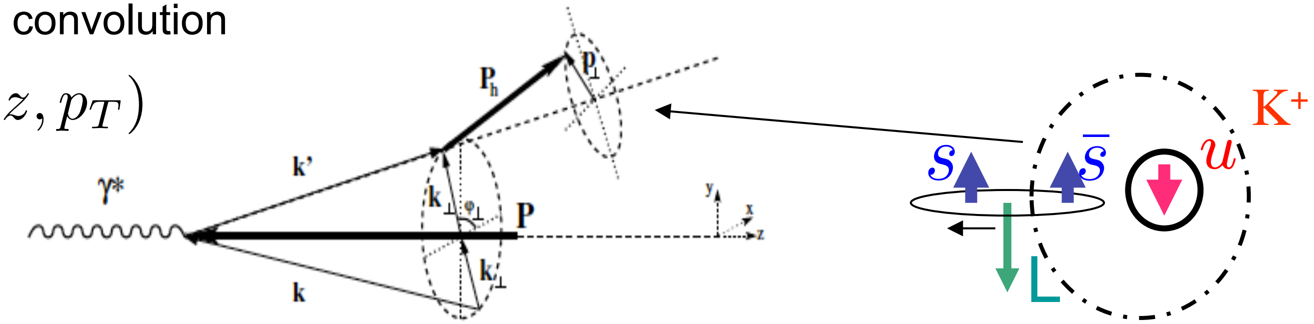
Study of kaon multiplicities in SIDIS is crucial for understanding of spin-orbit effects in hadronization

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

Flavor dependence of transverse momentum

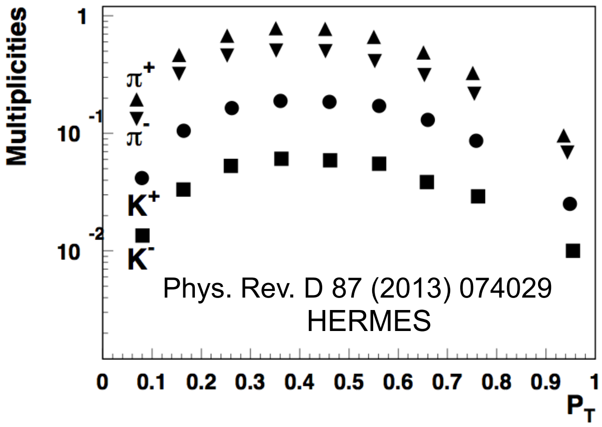
SIDIS x-section defined by convolution

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



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

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



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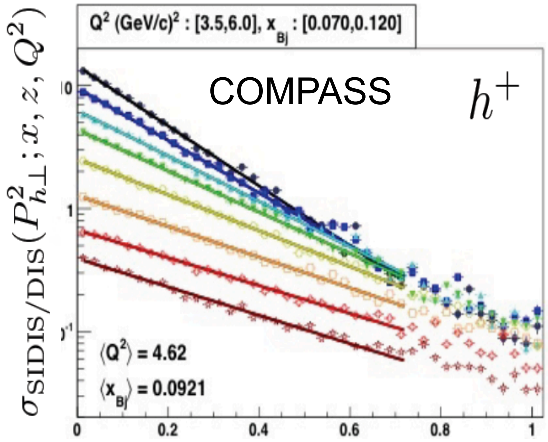
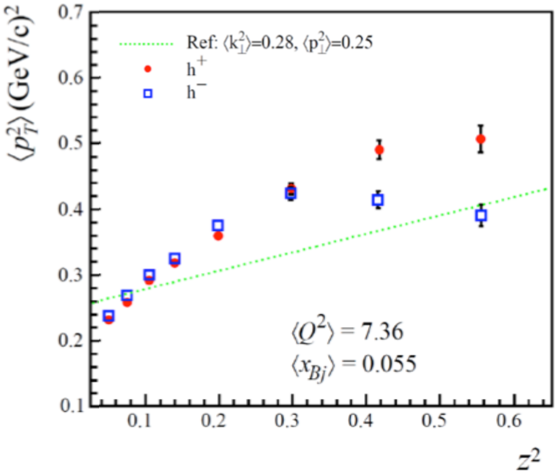
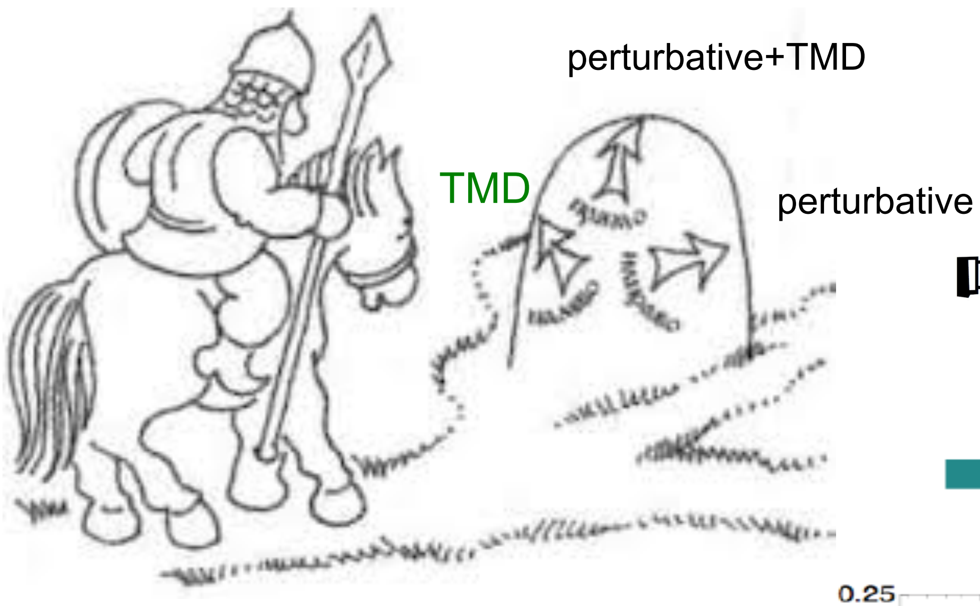




Multiplicities deviate from simple Gaussian distributions already at small P_T
Data indicating flavor dependence of widths of partonic distributions

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

Extraction of TMDs: f_1



$$\sigma \propto \frac{1}{\pi\langle P_T^2\rangle} e^{-P_T^2/\langle P_T^2\rangle}$$

$$\langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle.$$

☞ J. Gonzalez Hernandez

π only, z dependence

$<p_\perp^2> \to A\,(1-z)^B z^C$

- HERMES and COMPASS data do not seem to be compatible.

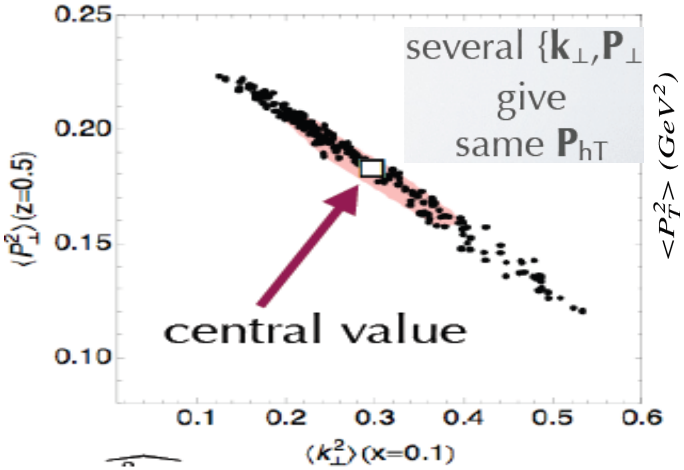
☞ M.Radici

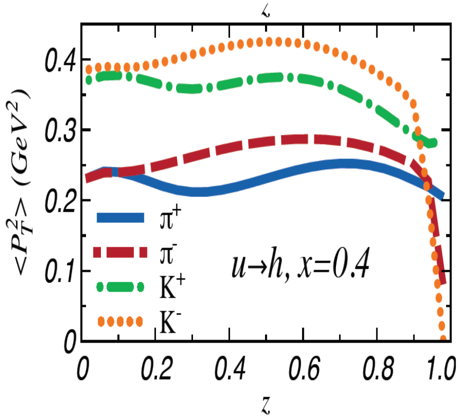
x-dependent width

$$\langle k_{\perp,q}^2\rangle(x) = \langle \widehat{k_{\perp,q}^2}\rangle \, \frac{(1-x)^\alpha \, x^\sigma}{(1-\hat{x})^\alpha \, \hat{x}^\sigma}$$

z-dependent width

$$\langle P_{\perp,q\to h}^2\rangle(z) = \langle \widehat{P_{\perp,q\to h}^2}\rangle \, \frac{(z^\beta+\delta)\,(1-z)^\gamma}{(\hat{z}^\beta+\delta)\,(1-\hat{z})^\gamma}$$





"q→π favored" width < "unfavored" & "q→K favored"

☞ S.Melis

Extraction of TMDs: Sivers/Transversity

➢Gaussian parametrization of the unpolarized PDF & FF:

- $f_{q/p}(x,k_\perp) = f_{q/p}(x)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$
- $D_{h/q}(z,p_\perp) = D_{h/q}(z)\,\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$

[*] $\langle k_\perp^2\rangle = 0.25\ \mathrm{GeV}^2 \qquad \langle p_\perp^2\rangle = 0.20\ \mathrm{GeV}^2$

➢Parametrization of Transversity function:

✎ $$\Delta_T q(x,k_\perp) = \frac{1}{2}\mathcal{N}_q^T(x)\,[\underbrace{f_{q/p}(x)}_{\text{Unpolarized PDF}} + \underbrace{\Delta q(x)}_{\text{Helicity PDF}}]\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_T}}{\pi\langle k_\perp^2\rangle_T}$$

$$\boxed{\mathcal{N}_q^T(x) = N_q^T\,x^{\alpha_q}(1-x)^{\beta_q}\,\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\,\beta_q^{\beta_q}}}$$

Sivers parameterization

$$\Delta^N\widehat{f}_{q/p^\uparrow}(x,k_\perp;Q_0) = 2\mathcal{N}_q(x)h(k_\perp)\widehat{f}_{q/p}(x,k_\perp;Q_0)$$

$$\mathcal{N}_q(x) = N_q\,x^{\alpha_q}(1-x)^{\beta_q}\,\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\,\beta_q^{\beta_q}}$$

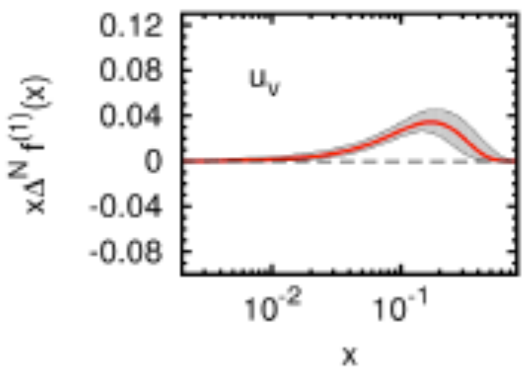
$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M_1}\,e^{-k_\perp^2/M_1^2}$$

$$\widehat{f}_{q/p}(x,k_\perp;Q_0) = f_{q/p}(x,Q_0)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle},$$

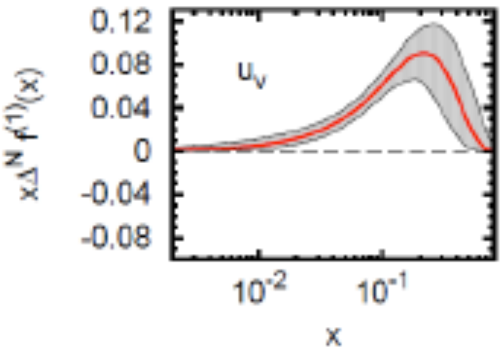
$$\widehat{D}_{h/q}(z,p_\perp;Q_0) = D_{h/q}(z,Q_0)\,\frac{1}{\pi\langle p_\perp^2\rangle}\,e^{-p_\perp^2/\langle p_\perp^2\rangle}$$

Many parameters, but shapes not too flexible.

DGLAP evolution



TMD evolution



➢Sea quark Sivers functions need more precise SIDIS data and/or Drell-Yan data.

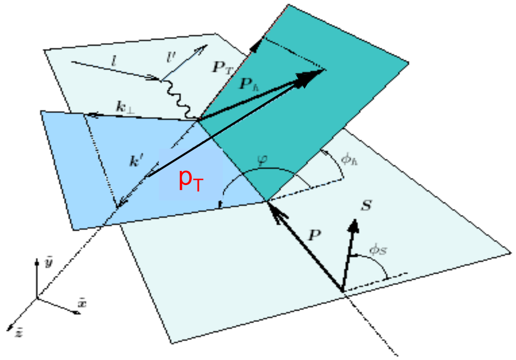
➢There are indications supporting TMD evolution in SIDIS

☞ L.Gamberg/D. Boer

TMD extraction with Bessel weighting

$$F_{UU}^{\pi^+}(P_T) \propto \sum e_q^2 H \times f_1^q(x, k_T, ..) \otimes D_1^{q\to\pi^+}(z, p_T, ..)S$$

$$F_{UU,T} = x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T|\, J_0(|\boldsymbol{b}_T|\,|\boldsymbol{P}_{h\perp}|)\ \tilde{f}_1(x, z^2\boldsymbol{b}_T^2)\ \tilde{D}_1(z, \boldsymbol{b}_T^2)$$



↓

$$\tilde{f}(x, b_T^2) \equiv \int d^2p_T\, e^{i\boldsymbol{b}_T\cdot\boldsymbol{p}_T}\ f(x, p_T^2) = 2\pi \int d|\boldsymbol{p}_T||\boldsymbol{p}_T|\ J_0(|\boldsymbol{b}_T||\boldsymbol{p}_T|)\ f(x, p_T^2)$$

$$\tilde{F}_{UU}^{\pi^+}(b_T) \propto \sum e_q^2 H \times \tilde{f}_1^q(x, b_T, ..) \times \tilde{D}_1^{q\to\pi^+}(z, b_T, ..)$$

Experimental procedure requires sum over all events → $\tilde{\sigma}^{\pm}(b_T) \simeq S^{\pm} = \sum_{i=1}^{N^{\pm}} J_0(b_T P_{hT,i})$

- the formalism in **b$_T$-space** avoids convolutions
- provides a model independent way to study kinematical dependences of TMD
- allows direct comparison with lattice

M.Aghasyan

Simulation of TMDs

Collins,Rogers,Staśto:PRD77,085009,2009

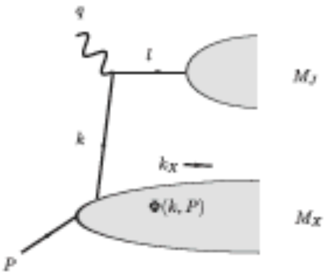
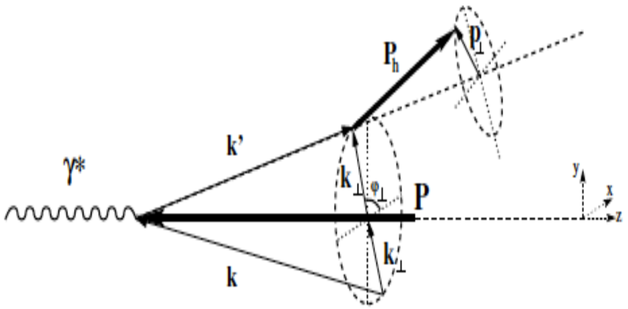


FIG. 2. The amplitude for γ^*p scattering into two jets with fixed masses.

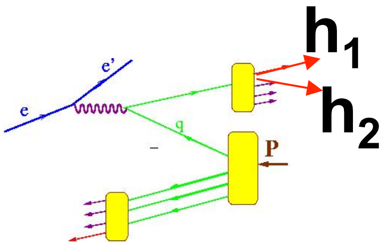
- The kinematics of the initial and final states must be kept exact.
- The sums over physical final states must be kept explicit.
- To avoid making kinematical approximations in the initial and final states, the factors need to be function of all components of parton four-momentum.
- The hard-scattering matrix element should appear as <u>on-shell</u> parton matrix element in the final factorization formula.

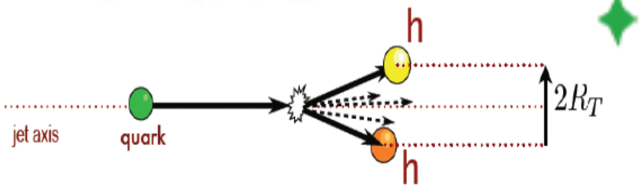


It is not enough to describe things, we need MC to test extraction procedures !

Dihadron production

☞ A.Courtoy

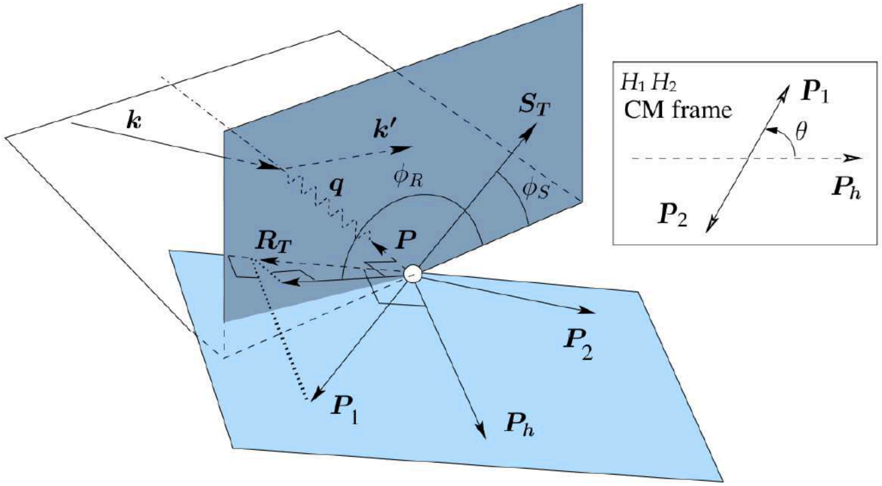




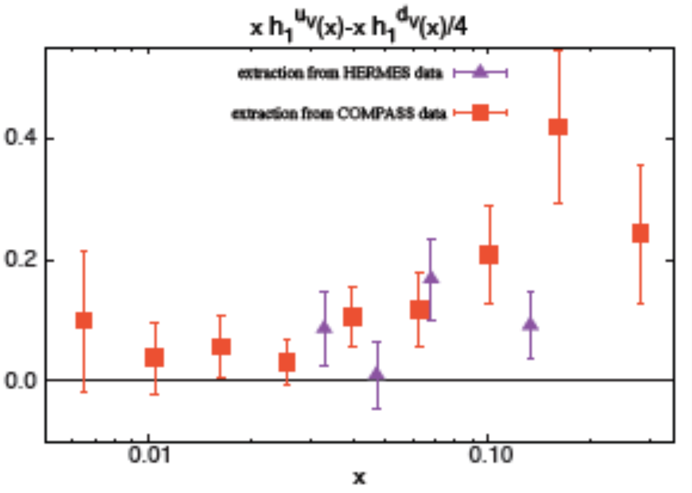
DiFF

$$\boxed{D_1^{q\to h_1,h_2}(z_1,z_2,R_T^2)}$$

$$A_{UT} \sim \sin(\phi_{R\perp}+\phi_S)\sin\theta h_1 H_1^{\sphericalangle}$$



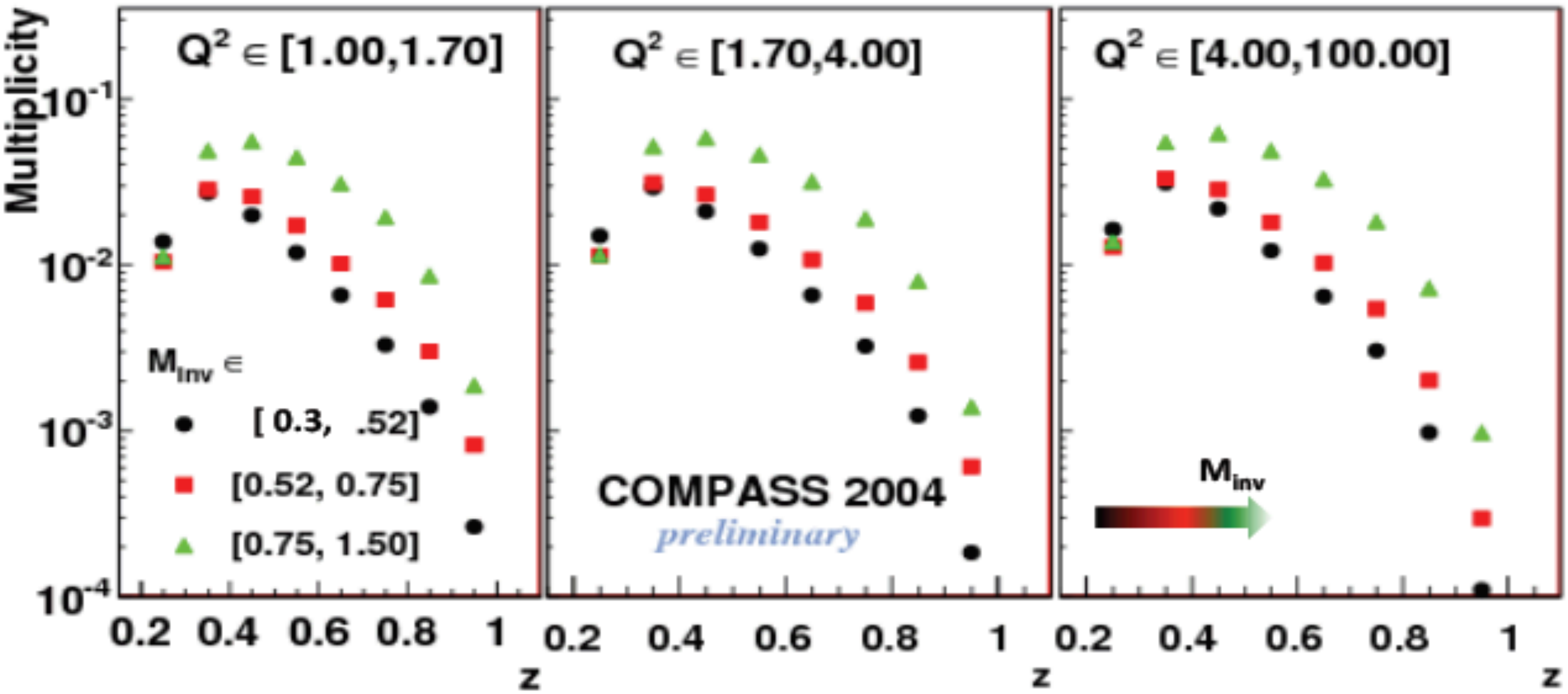
Dihadron productions offers exciting possibility to access transversity distribution as we deal with the product of functions instead of convolution



Dihadron production

☞ N. Makke

First measurements in M_{inv}, $z=z_1+z_2$, Q^2 bins



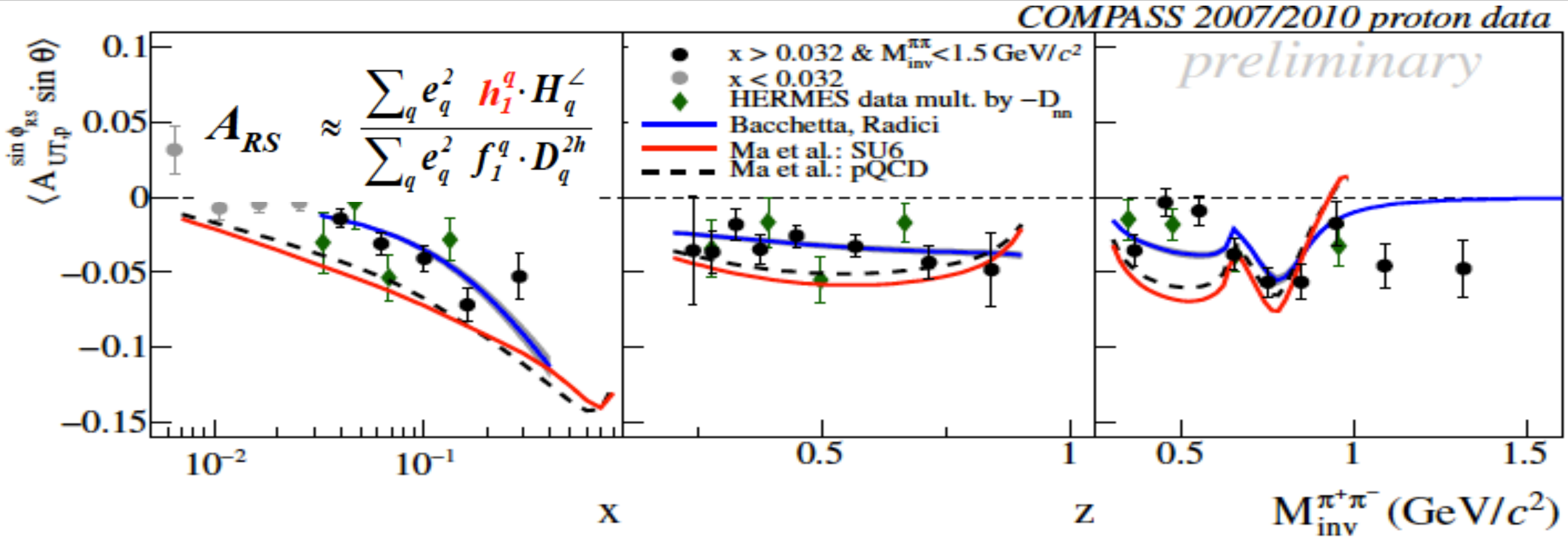
Significant M_{inv} and $z=z_1+z_2$ dependences (as expected)

Trend and shape reproduced by LEPTO (no parametrizations yet exist)

- First measurement of unidentified hadron pair multiplicities for the perspective of extracting Dihadron fragmentation functions

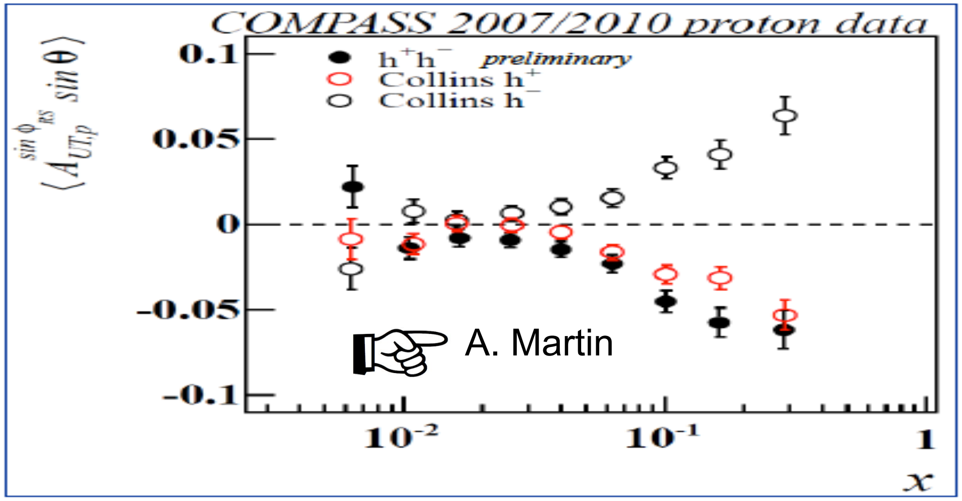
Dihadron production

☞ C. Braun



$$A_{RS} \approx \frac{\sum_q e_q^2 \; h_1^q \cdot H_q^{\angle}}{\sum_q e_q^2 \; f_1^q \cdot D_q^{2h}}$$

$$A_{Coll} \approx \frac{\sum_q e_q^2 \; h_1^q \otimes H_1^{\perp q}}{\sum_q e_q^2 \; f_1^q \otimes D_q}$$



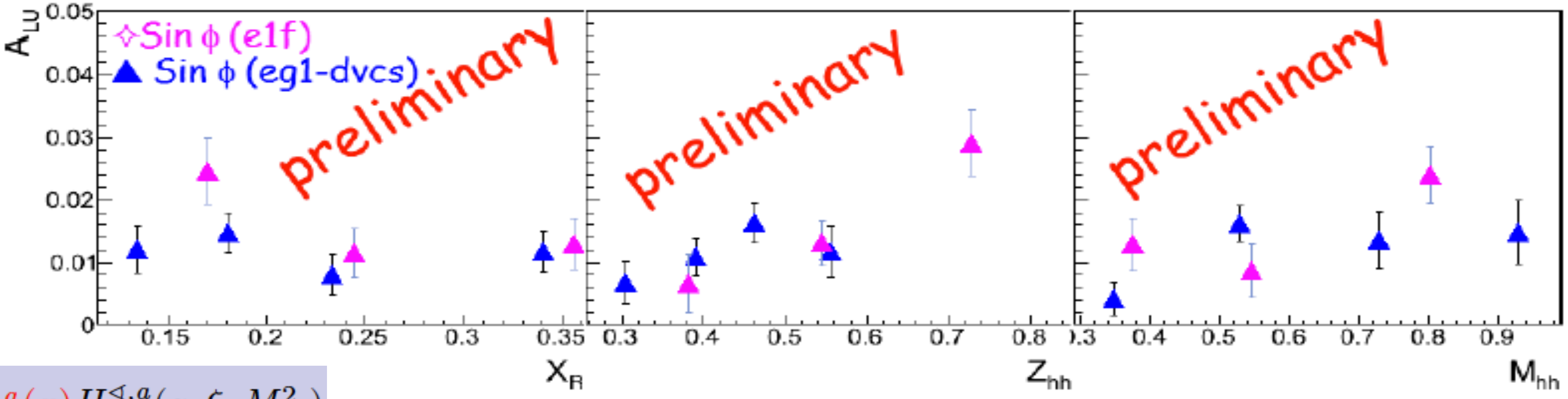
☞ A. Martin

Dihadron production

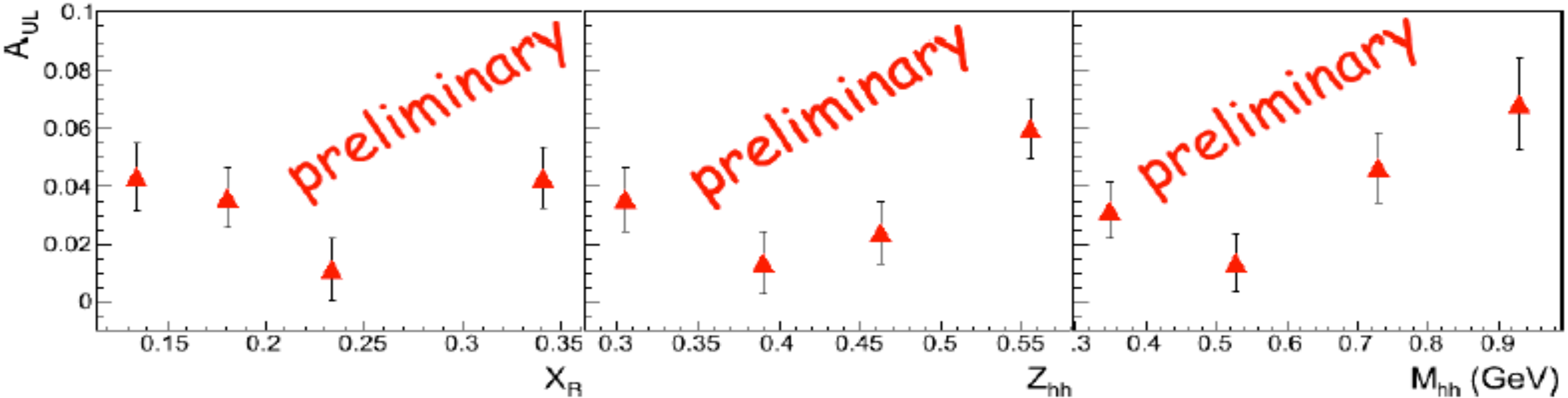
☞ C. Braun

JLab ▶ $\pi^+\pi^-$ dihadron asymmetries A_{LU} A_{UL}

$e^a(x) H_1^{\sphericalangle,a}(z,\xi,M_{hh}^2)$

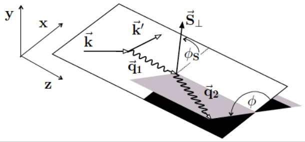


$h_L^a(x) H_1^{\sphericalangle,a}(z,\xi,M_{hh}^2)$



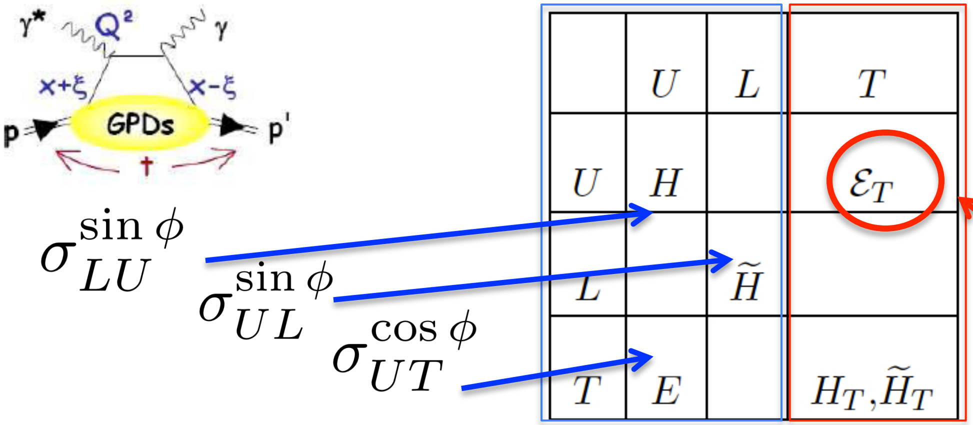
$\hookrightarrow$ Sizeable asymmetry amplitudes

$\hookrightarrow$ Very small statistical uncertainties



3D structure: GPDs

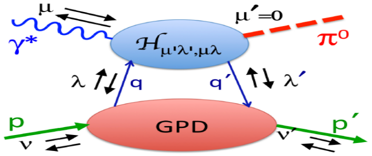
☞ S. Goloskokov

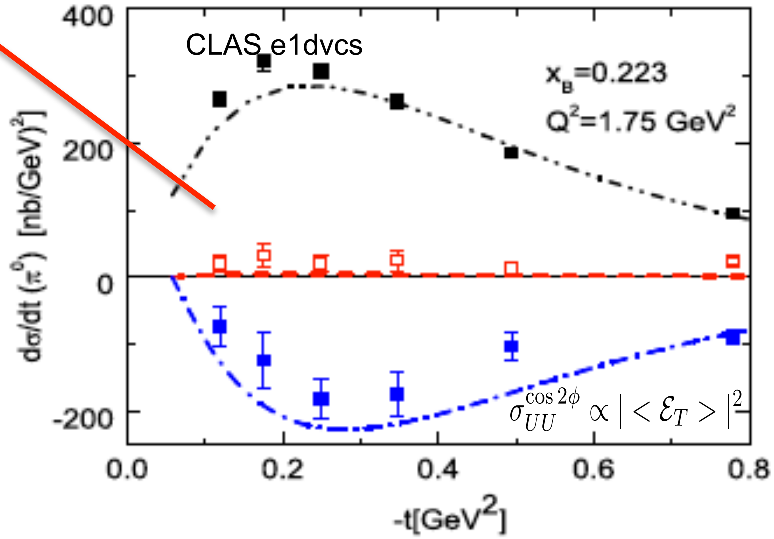


$\sigma_{LU}^{\sin\phi}$ $\sigma_{UL}^{\sin\phi}$ $\sigma_{UT}^{\cos\phi}$

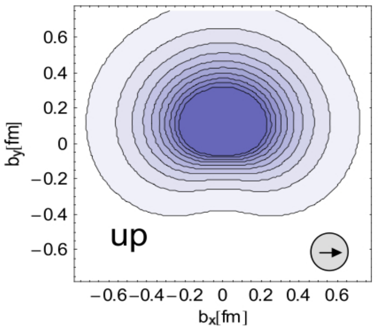
	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$

ep➔e’ pπ^0





Asymmetries measured at HERMES & JLAB
More measurements at JLab, Compass, RHIC



Lattice (QCDSF)

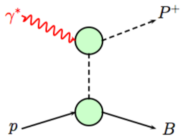
Transverse photon dominates the x-section for exclusive π^0 production

Spin-azimuthal asymmetries in hard exclusive production of photons and pions give access to underlying GPDs

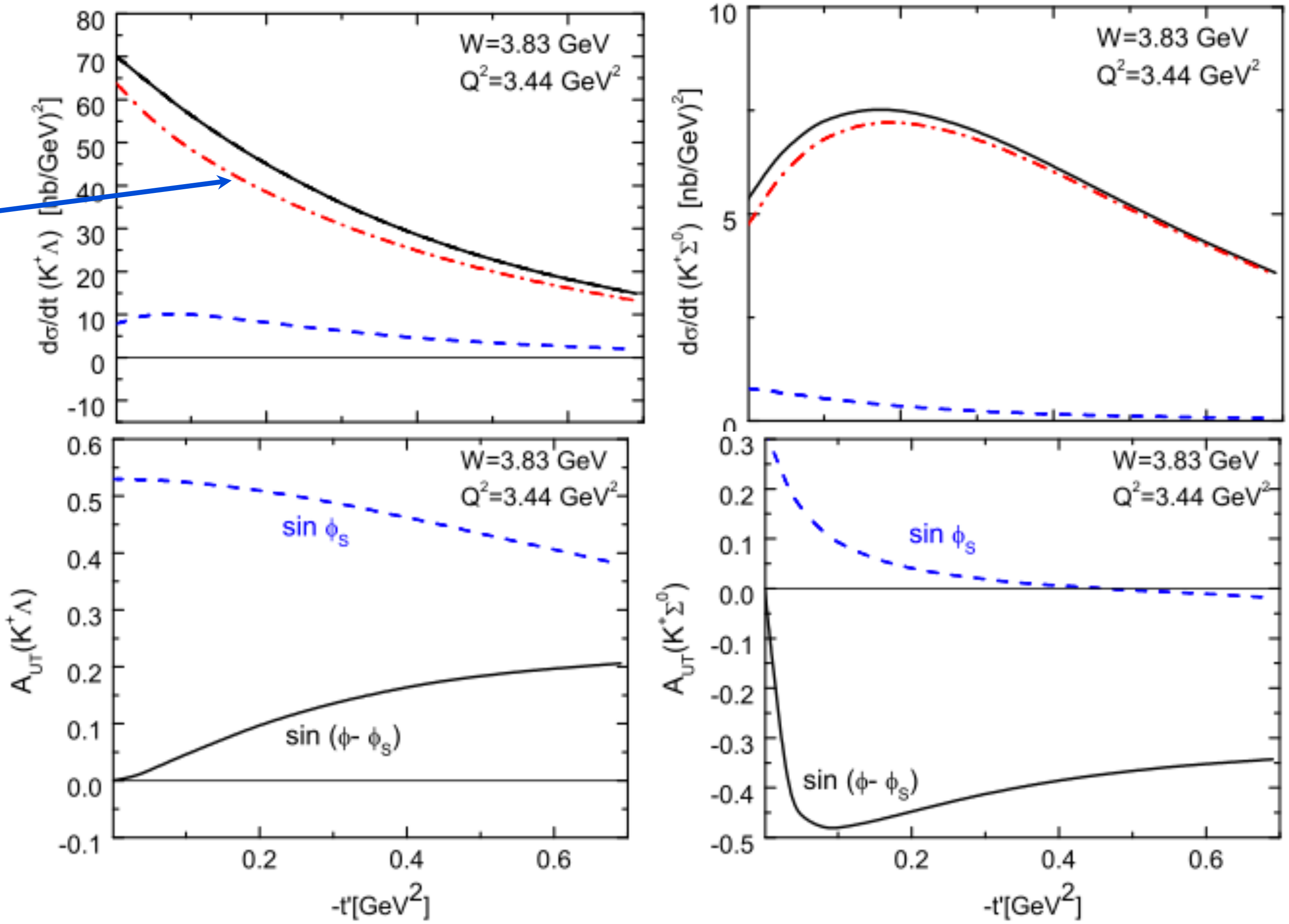
Exclusive kaon production

S.Goloskokov

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

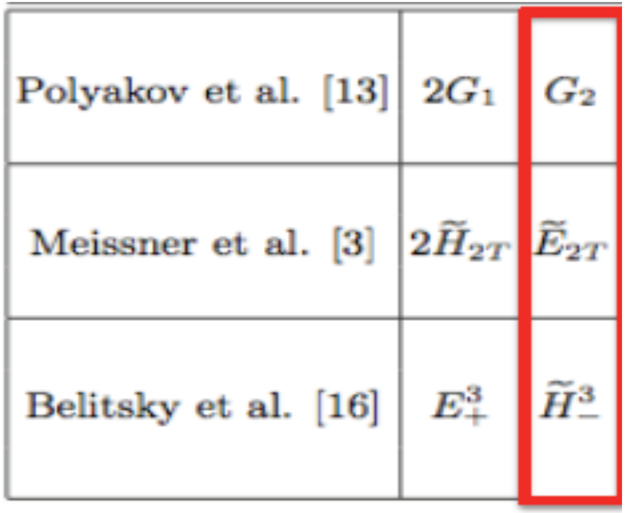
☞S. Liuti

Observing quarks orbital angular momentum

OAM can be defined through a sum rule similar to Ji's at tw 2

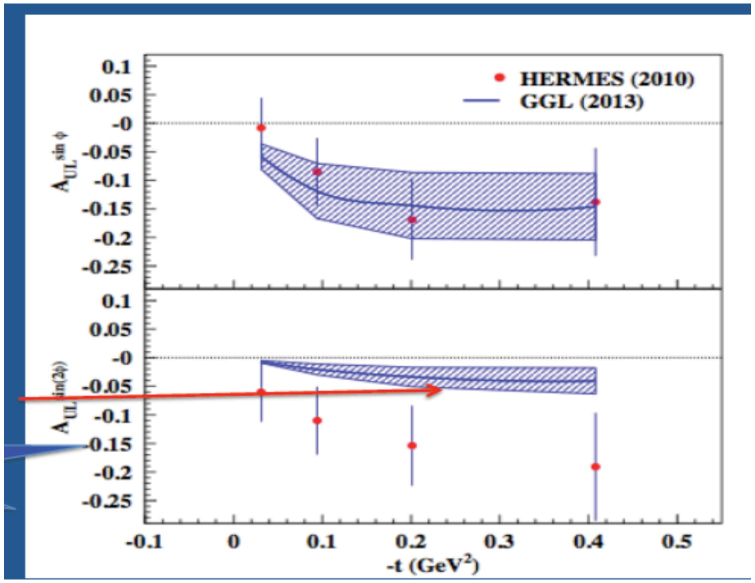
$$\underset{\displaystyle\downarrow\;-L_q}{\int dx\, xG_2} = \underset{\displaystyle\downarrow\;-J_q}{-\frac{1}{2}\int dx\, x(H+E)} + \underset{\displaystyle\downarrow\;S_q}{\frac{1}{2}\int dx\, \tilde{H}}$$

Polyakov et al. (2000)
Hatta (2011)



Polyakov et al. [13]	$2G_1$	$\boxed{G_2}$
Meissner et al. [3]	$2\tilde{H}_{2T}$	$\boxed{\tilde{E}_{2T}}$
Belitsky et al. [16]	E_+^3	$\boxed{\tilde{H}_-^3}$

$$A_{UL,L} = \frac{N_{s_z=+} - N_{s_z=-}}{N_{s_z=+} + N_{s_z=-}} = \frac{\sqrt{2\epsilon(\epsilon+1)}\,\sin\phi F_{UL}^{\sin\phi}}{F_{UU,T} + \epsilon F_{UU,L}} + \frac{\epsilon \sin 2\phi \boxed{F_{UL}^{\sin 2\phi}}}{F_{UU,T} + \epsilon F_{UU,L}}$$

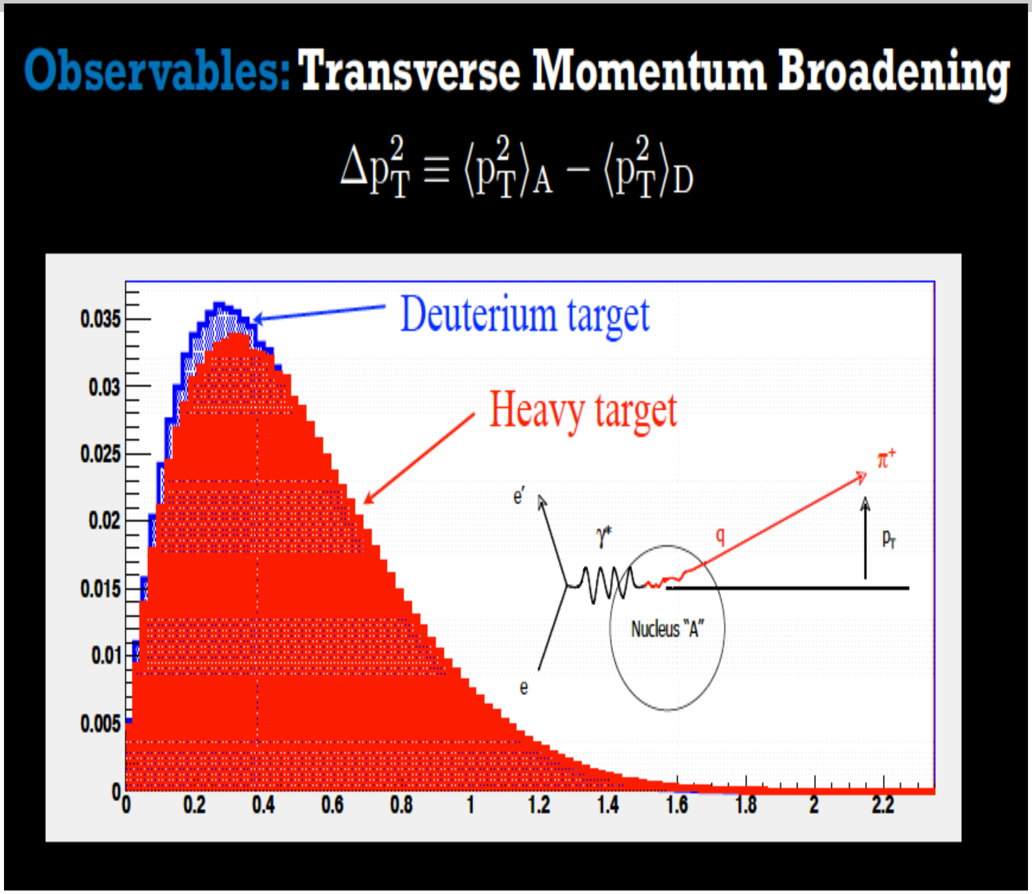


WW, small ξ

The sin2ϕ moment of the SSA A_{UL} for DVCS may be sensitive to the Higher Twist GPD G2!

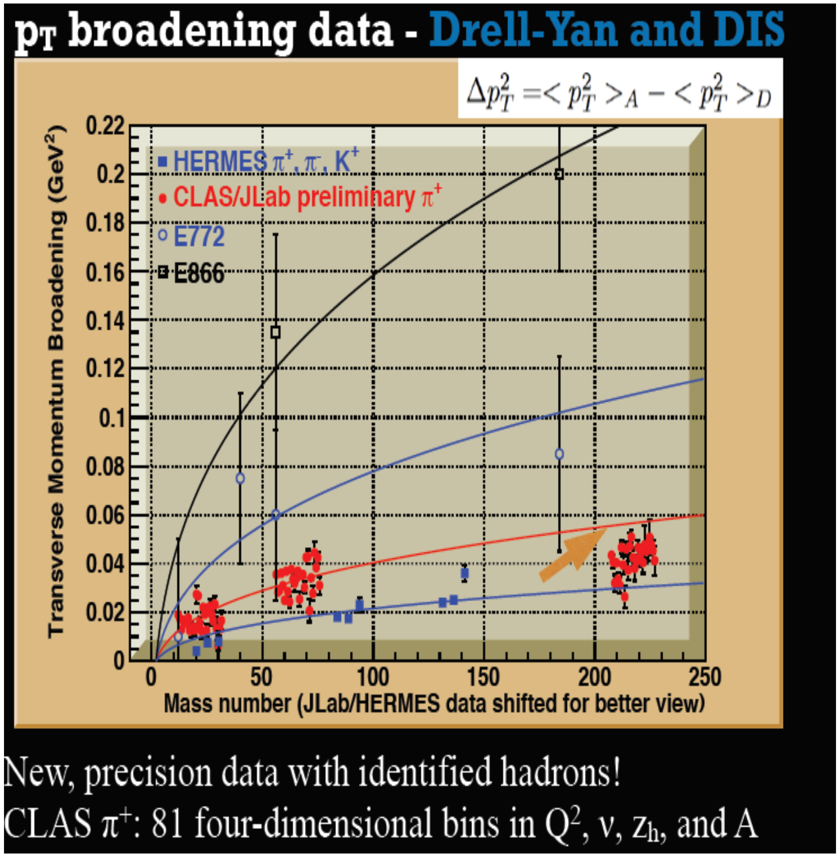
PT-broadening

☞W. Brooks



Observables: Transverse Momentum Broadening

$$\Delta p_T^2 \equiv \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$



p_T broadening data - Drell-Yan and DIS

$$\Delta p_T^2 = <p_T^2>_A - <p_T^2>_D$$

New, precision data with identified hadrons!

CLAS π^+: 81 four-dimensional bins in Q^2, ν, z_h, and A

☞ D. Boer

$$f_1^{(1)} \equiv \int d^2k_T \frac{k_T^2}{2M^2} f_1(x, k_T)$$

$$\frac{\langle p_T^2 \rangle}{2M^2} = f_1^{(1)}(x)$$

Medium modified TMDs

$$\boxed{f_1^p / g_1^p(x, k_T) \longrightarrow f_1^A / g_1^A(x, k_T)}$$

☞ D. Boer

P_T-broadening and Bessel weighting

$$\frac{\langle p_T^2\rangle}{2M^2} = f_1^{(1)}(x)$$

p_T-broadening

p_T broadening involves a p_T^2 weighting, which theoretically yields divergent quantities, hence usually it is defined as a (finite) difference: $\Delta p_T^2 \equiv \langle p_T^2\rangle_A - \langle p_T^2\rangle_p$

An alternative is to consider Bessel weighting:

$$\tilde{f}_1^{(1)q/A}(x, \boldsymbol{b}_T^2) - \tilde{f}_1^{(1)q/p}(x, \boldsymbol{b}_T^2) \overset{\boldsymbol{b}_T^2 \to 0}{\longrightarrow} \Delta p_T^2 \equiv \langle p_T^2\rangle_A - \langle p_T^2\rangle_p$$

Converges very slowly, but Δp_T^2 also converges very slowly to 'true' value as function of (experimental or theoretical) cut-off on p_T

A study of the link (in)dependence of p_T-broadening would be interesting

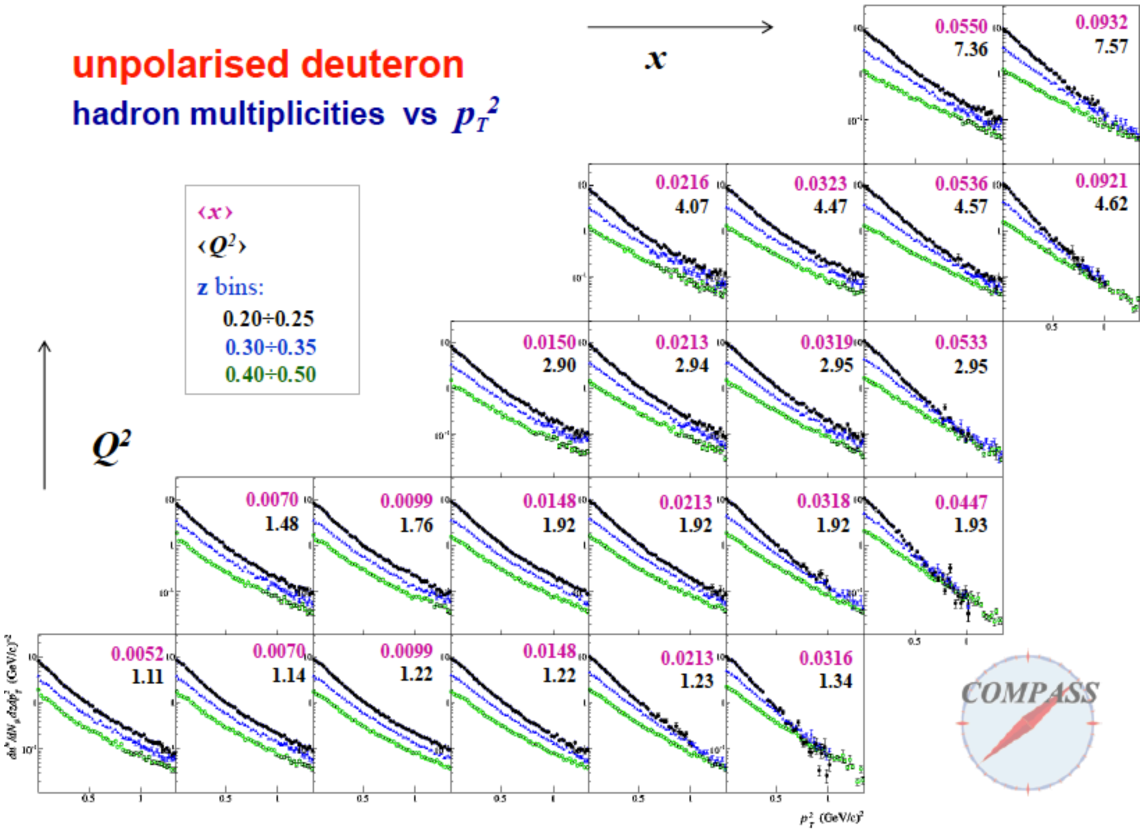
$$\tilde{f}_1^{(1)q/A[\mathcal{U}]}(x, \boldsymbol{b}_T^2) - \tilde{f}_1^{(1)q/p[\mathcal{U}]}(x, \boldsymbol{b}_T^2) \overset{\boldsymbol{b}_T^2 \to 0}{\longrightarrow} \Delta p_T^{2\,[\mathcal{U}]} \equiv \langle p_T^2\rangle_A^{[\mathcal{U}]} - \langle p_T^2\rangle_p^{[\mathcal{U}]}$$

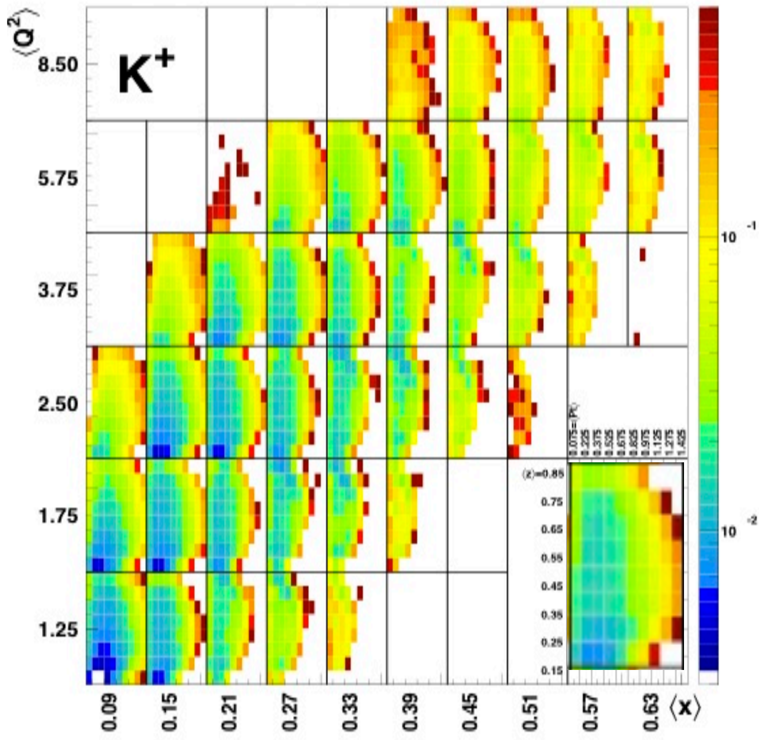
A well-defined ratio can also be formed, but as b_T gets smaller the interesting information about the A versus p difference is lost, $(\infty+\Delta)/\infty$:

$$R_\Delta \equiv \frac{\tilde{f}_1^{(1)q/A}(x, \boldsymbol{b}_T^2)}{\tilde{f}_1^{(1)q/p}(x, \boldsymbol{b}_T^2)} \overset{\boldsymbol{b}_T^2 \to 0}{\longrightarrow} 1$$

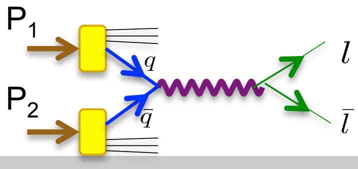
A. Martin / M. Contalbrigo

Going Multidimensional



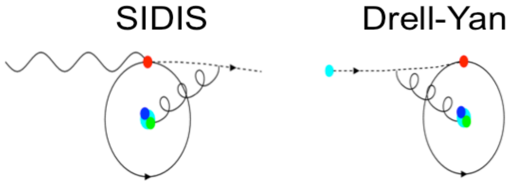


How we store and visualize the multidimensional data?

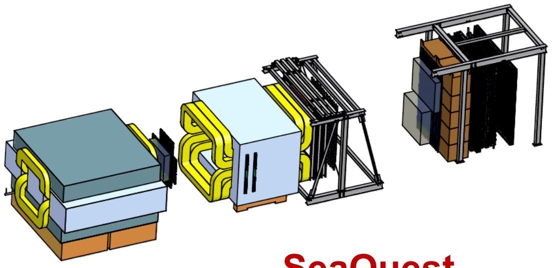


Drell-Yan

a test of QCD

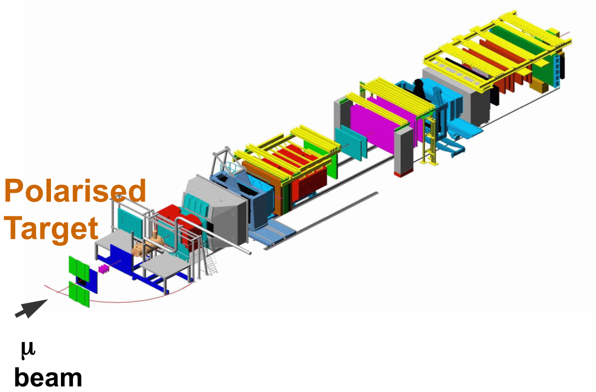


$$f_{1T}^{\perp q}(SIDIS) = -f_{1T}^{\perp q}(DY)$$



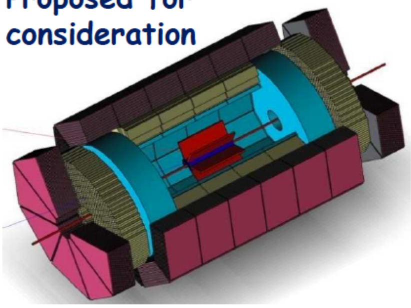
SeaQuest Spectrometer

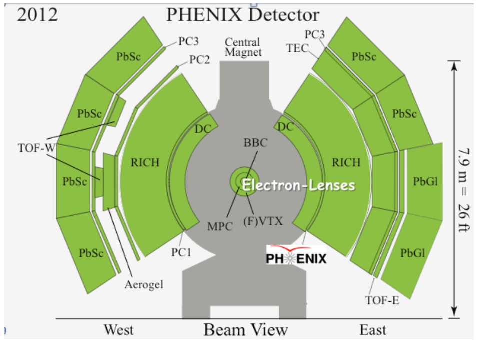
Low Drell-Yan cross section requires a high intensity beams



Nuclotron based Ion Collider fAcility

Proposed for consideration





Clean probe to study hadron structure:

- ➡ convolution of parton distributions
- ➡ no QCD final state effects
- ➡ no fragmentation process

Conclusions

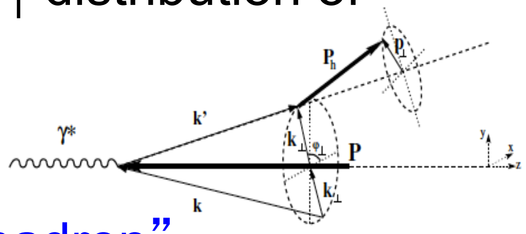
Measurements with Kaons in semi-inclusive and hard-exclusive processes will be crucial in understanding the underlying dynamics behind spin orbit correlations in hard processes and accomplish the studies of the 3D structure of the nucleons and nuclei

1D+3D+medium ⟶ 3D PDFs in nucleons and nuclei

- Support Slides

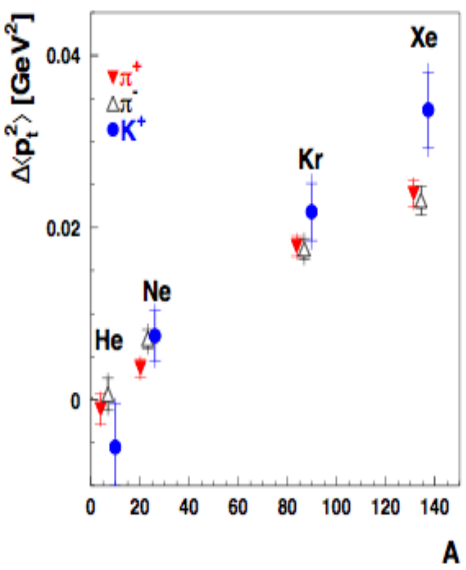
Medium modifications of partonic distributions

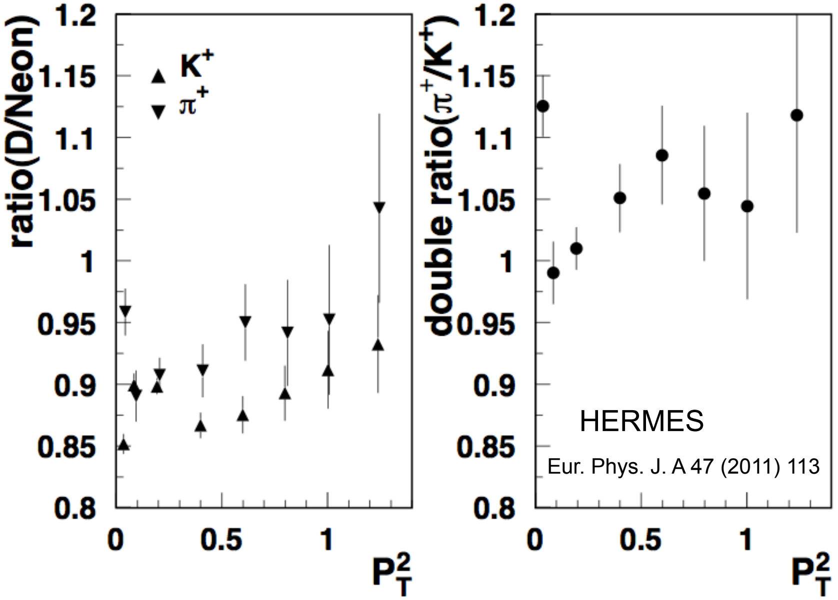
In terms of the QCD, there are several contributions to P_T distribution of hadrons produced in semi-inclusive DIS:



- •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





HERMES

Eur. Phys. J. A 47 (2011) 113

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

The sum rule including the OAM

Ji's quark and gluon kinetic angular momentum can be expressed in terms of twist-2 GPDs.

$$J^{q,g} = \frac{1}{2}\int \mathrm{d}x\, x\,[H^{q,g}(x,0,0) + E^{q,g}(x,0,0)] \qquad L_z^q = J_z^q - \frac{\Delta q}{2}, \qquad L_z^g = J_z^g - \Delta g.$$

the **z**-component of the quark kinetic OAM is related to a pure twist-3 GPD (Polyakov et al)

$$L_z^q = -\int \mathrm{d}x\, x\, G_2^q(x,0,0).$$

The genuine spin sum rule in the quark sector is therefore given by

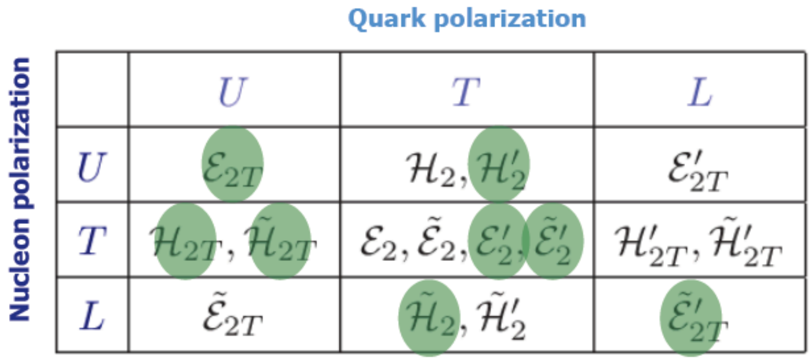
$$\int \mathrm{d}x \left\{ x\,[H^q(x,0,0) + E^q(x,0,0) + 2G_2^q(x,0,0)] - \tilde{H}^q(x,0,0) \right\} = 0,$$

C.Lorce, B. Pasquini arXiv:1208.3065

$$-\int \mathrm{d}x\, x\, \tilde{E}_{2T}(x,0,0) = L_z^q + 2S_z^q.$$

$$\int \mathrm{d}x \left[x \left(H + E + 2\tilde{E}_{2T} \right) + \tilde{H} \right] = 0.$$

describes the vector distribution of quarks inside a longitudinally polarized target ->related to the **z** -component of angular momentum.



Quark polarization

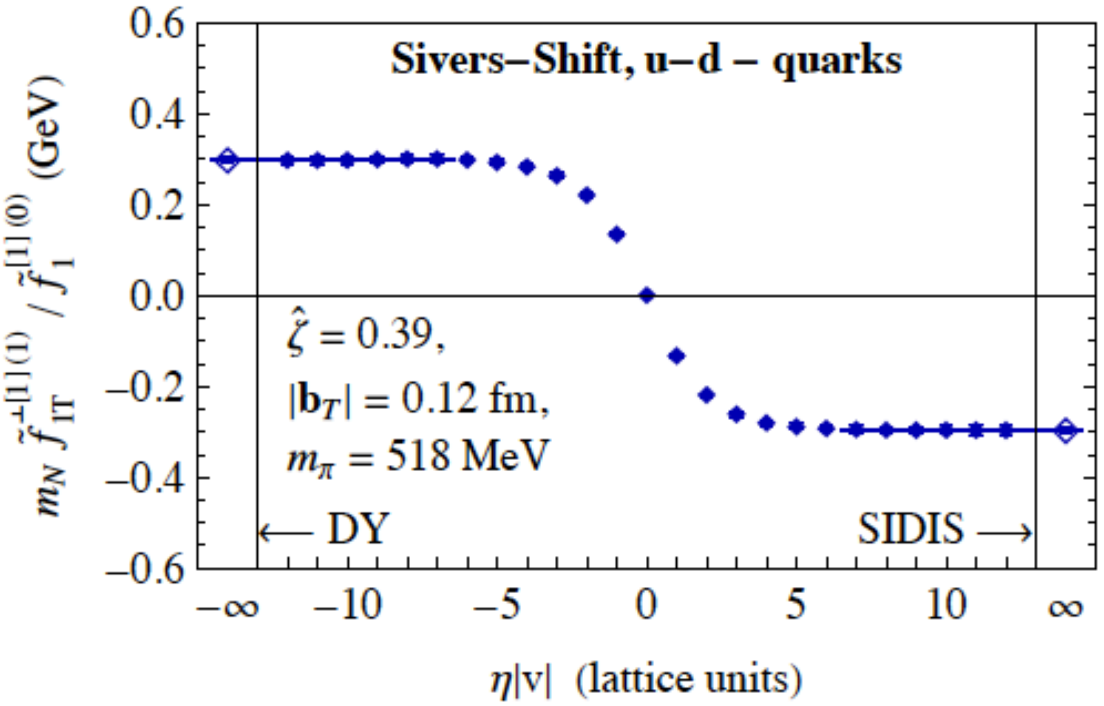
Nucleon polarization

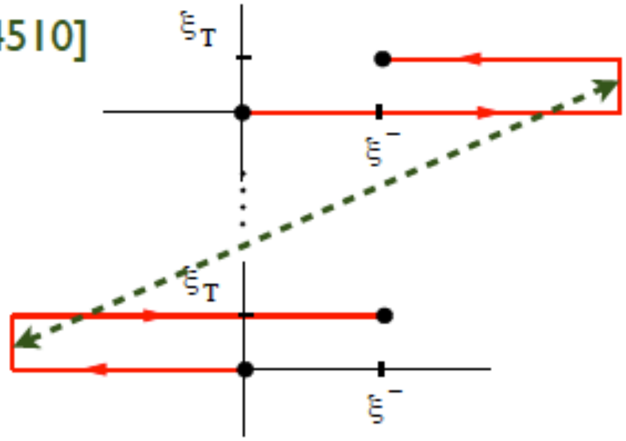
	U	T	L
U	🟩 $\mathcal{E}_{2T}$	$\mathcal{H}_2$, 🟩 $\mathcal{H}_2'$	$\mathcal{E}_{2T}'$
T	🟩 $\mathcal{H}_{2T}$, 🟩 $\tilde{\mathcal{H}}_{2T}$	$\mathcal{E}_2, \tilde{\mathcal{E}}_2$, 🟩 $\mathcal{E}_2'$, 🟩 $\tilde{\mathcal{E}}_2'$	$\mathcal{H}_{2T}', \tilde{\mathcal{H}}_{2T}'$
L	$\tilde{\mathcal{E}}_{2T}$	🟩 $\tilde{\mathcal{H}}_2$, $\tilde{\mathcal{H}}_2'$	🟩 $\tilde{\mathcal{E}}_{2T}'$

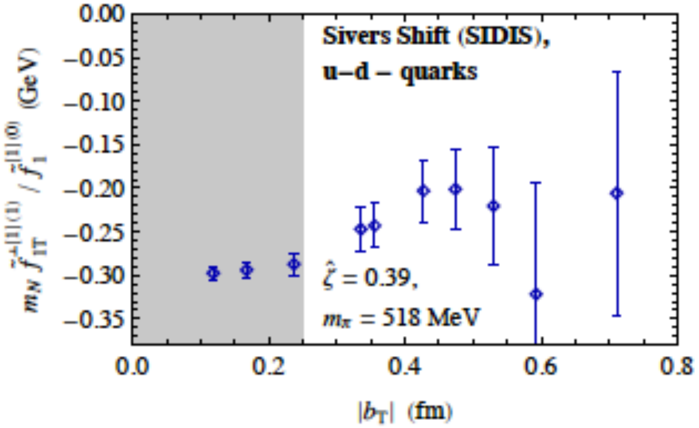
🟩 ξ **-odd**

Sivers function on the lattice

[Musch, Hägler, Engelhardt, Negele & Schäfer, PRD 85 (2012) 094510]







The first `first-principle' demonstration in QCD that the Sivers function is nonzero
It clearly corroborates the sign change relation!

$$f_{1T}^{\perp[\mathrm{SIDIS}]} = -f_{1T}^{\perp[\mathrm{DY}]}$$

compatible with fits and models:
up Sivers ($f_{1T}^{\perp}$) of SIDIS < 0 and down Sivers of SIDIS > 0 and smaller