Highlights of HERMES

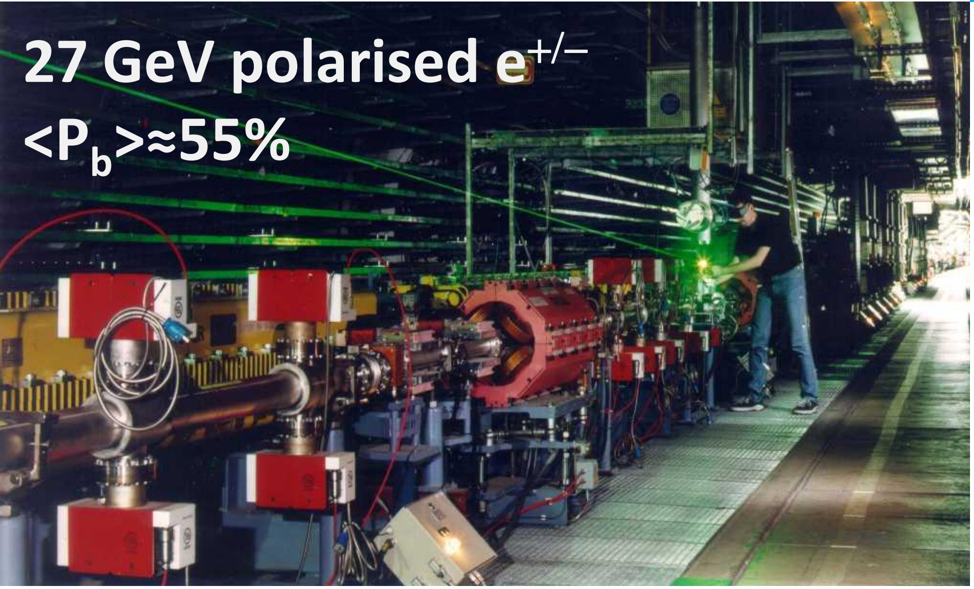
The 21st International Symposium on Spin Physics
October 20-24, 2014, Beijing, China

Ami Rostomyan
(for the HERMES collaboration)

Parallel sessions:

H. Marukyan:	Parallel-IV: S6
H. Marukyan:	Parallel-V: S6
G. Karyan:	Parallel-VI: S2
A. Rostomyan:	Parallel-VII: S3
G. Karyan:	Parallel-VII: S4

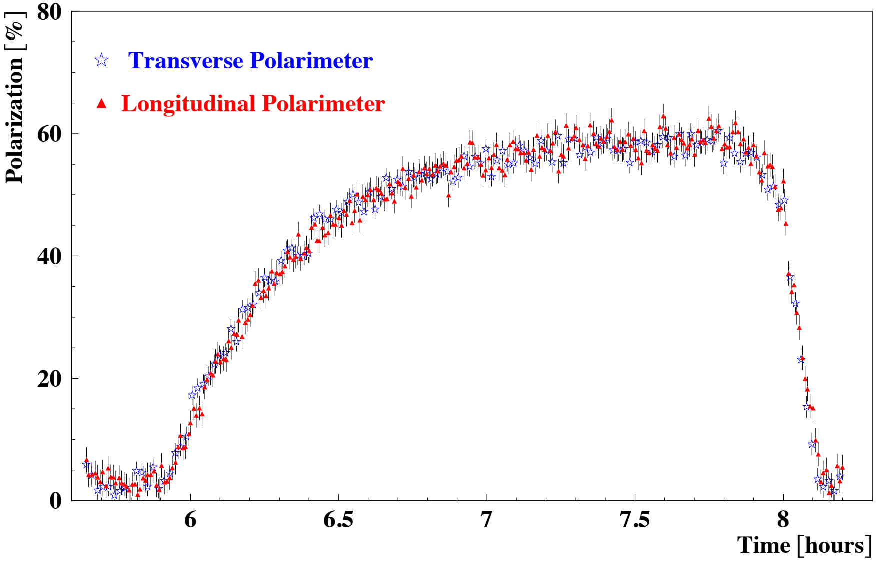
The HERMES experiment (1995-2007)



27 GeV polarised $e^{+/-}$

$\langle P_b \rangle \approx 55\%$

self-polarised e^+/e^-



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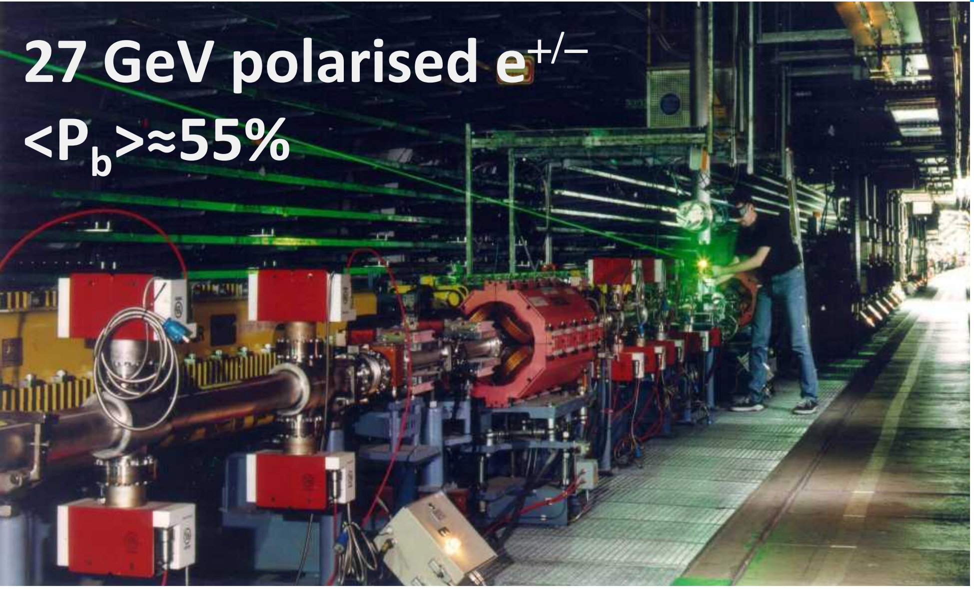

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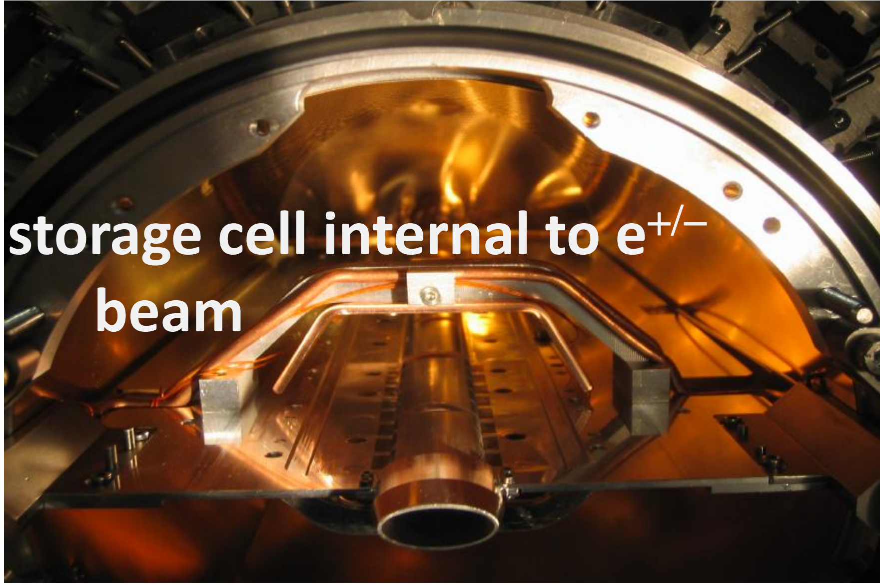
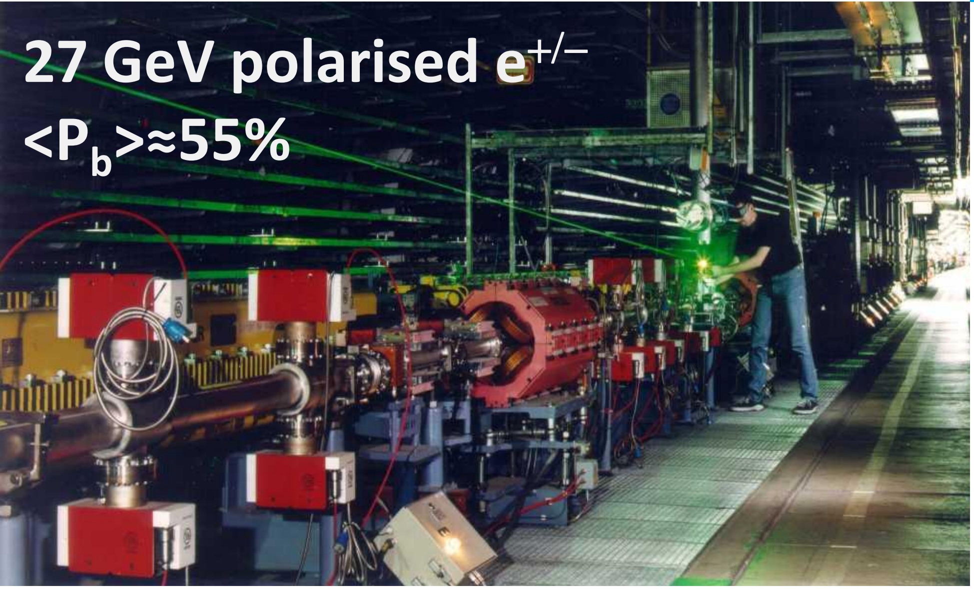


storage cell internal to $e^{+/-}$ beam

pure gas targets

- longitudinal target polarisation: **H, D, ^{3}He**
- transverse target polarisation: **H**
- unpolarised targets: **H, D, ^{4}He, ^{14}N, ^{20}Ne, ^{84}Kr, ^{131}Xe**
- unpolarised targets with recoil detector: **H, D**

The HERMES experiment (1995-2007)



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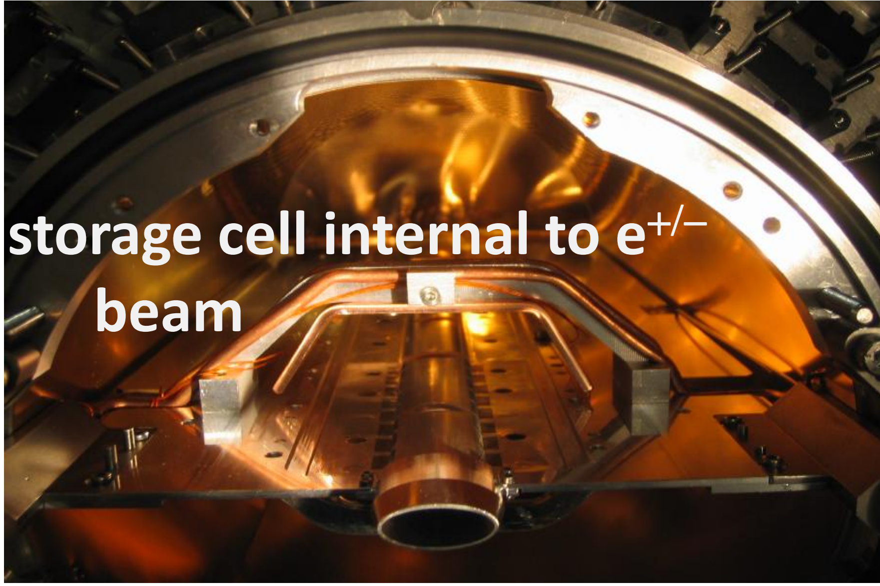
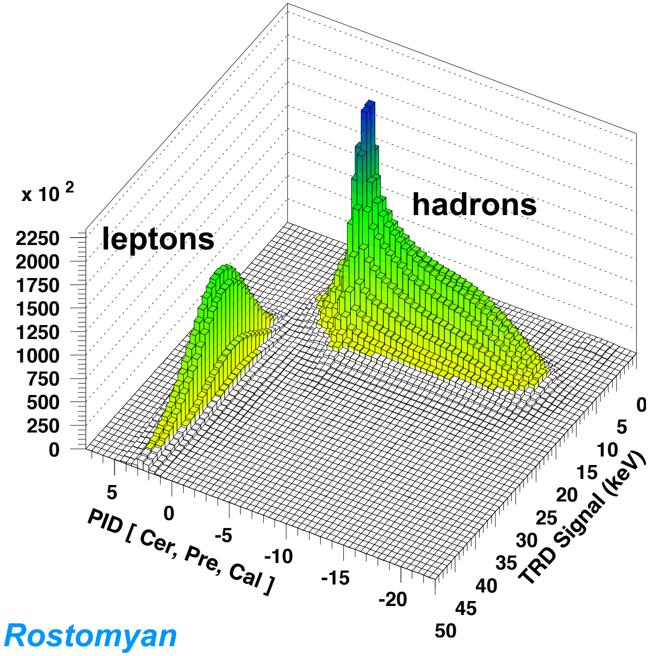
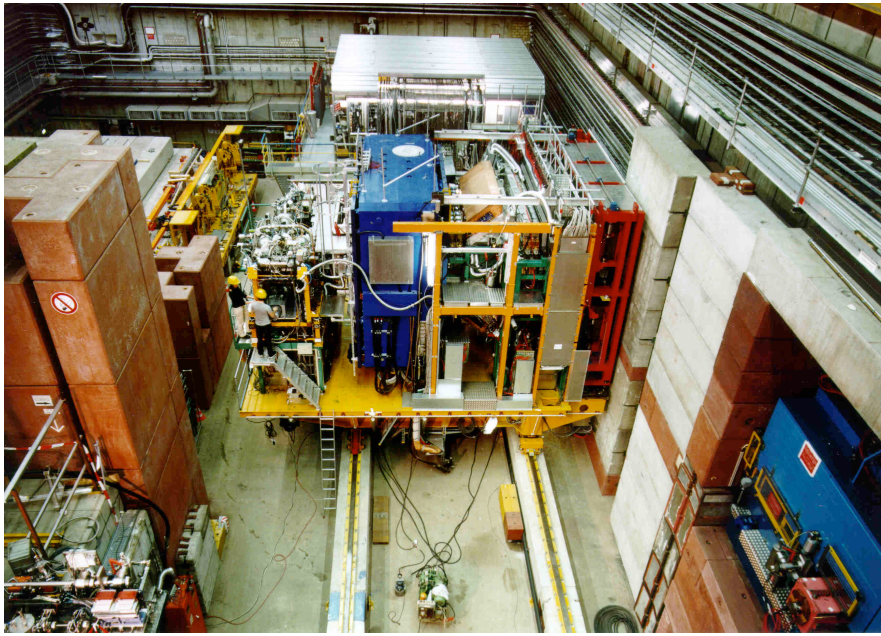


storage cell internal to $e^{+/-}$ beam

excellent lepton/hadron separation





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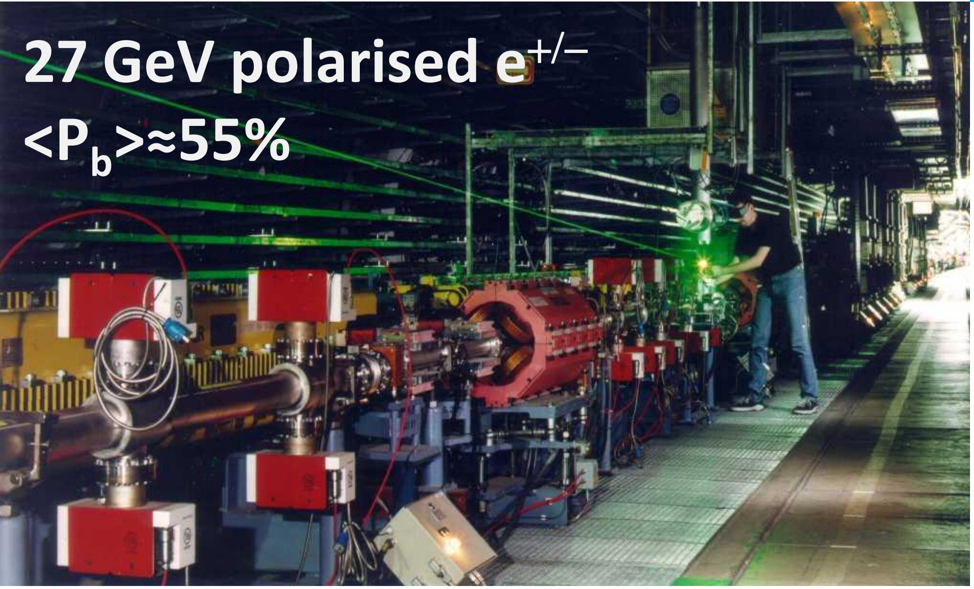

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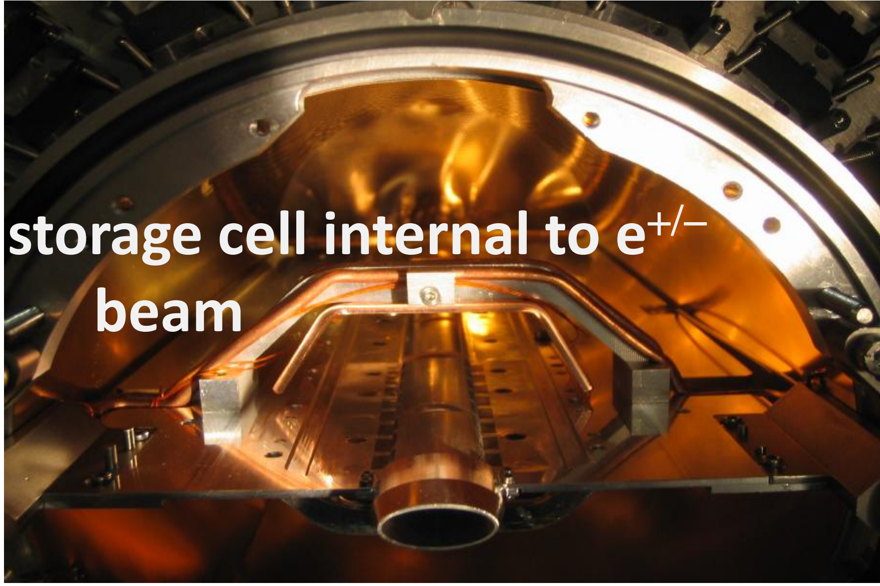
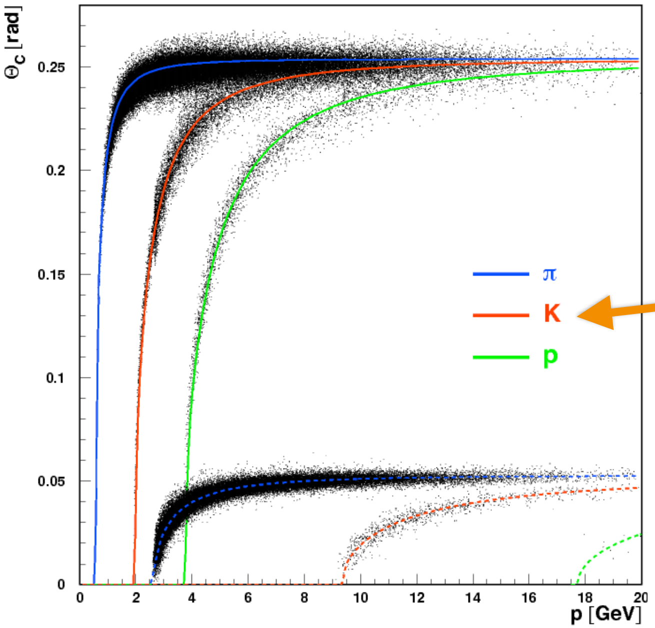
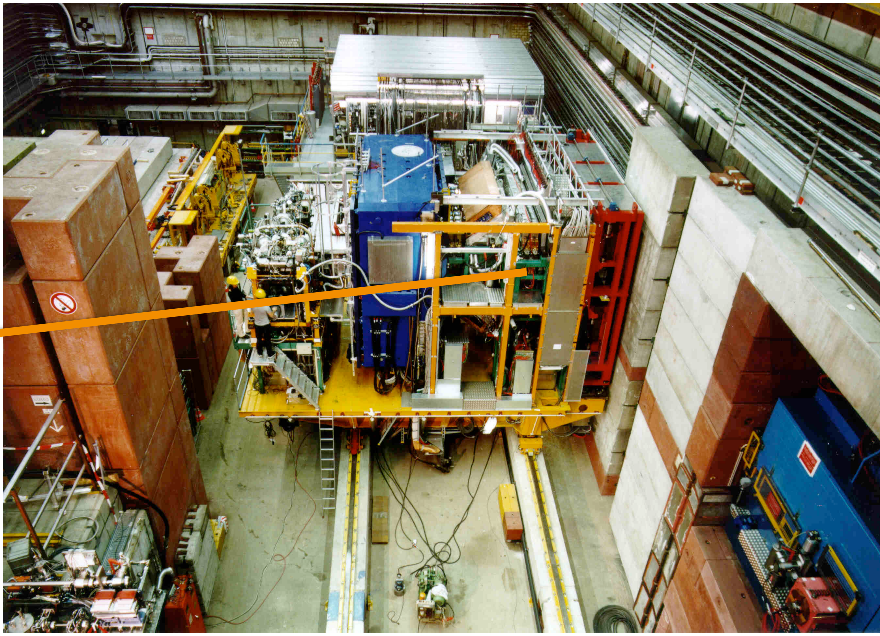


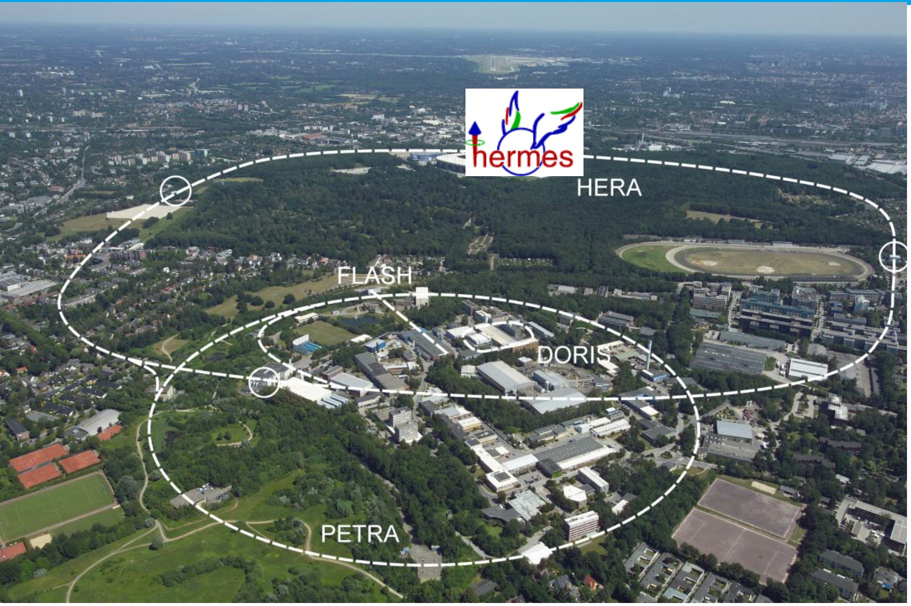
storage cell internal to $e^{+/-}$ beam

π / K / p separation over whole momentum range





spin and hadronisation



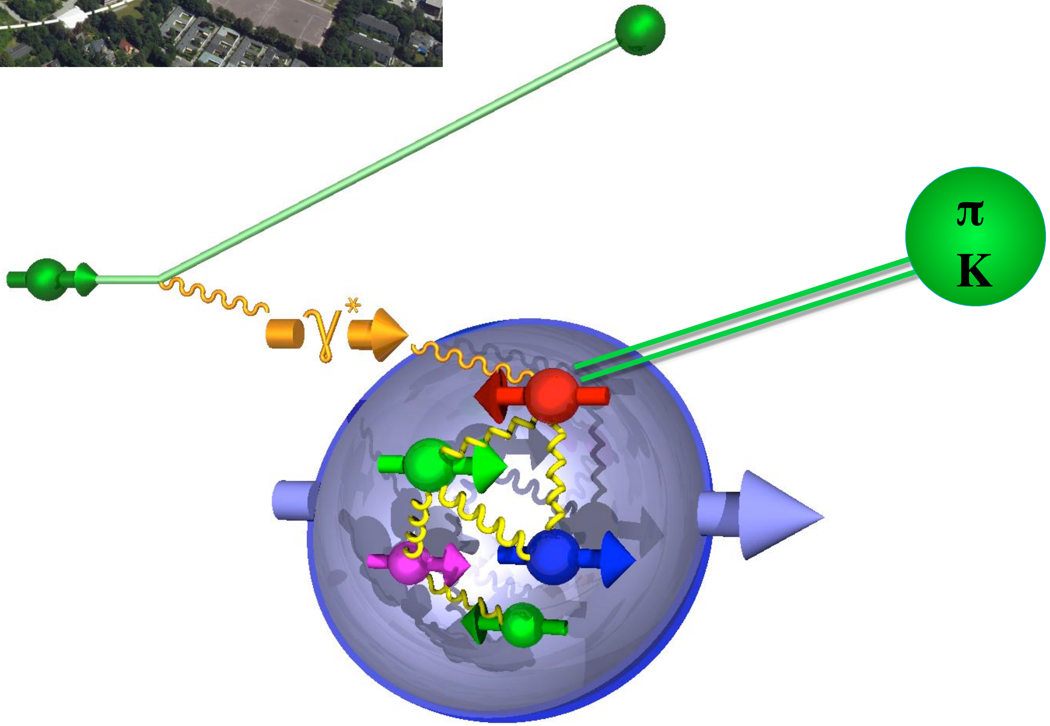
HERMES main research topics:

> origin of nucleon spin

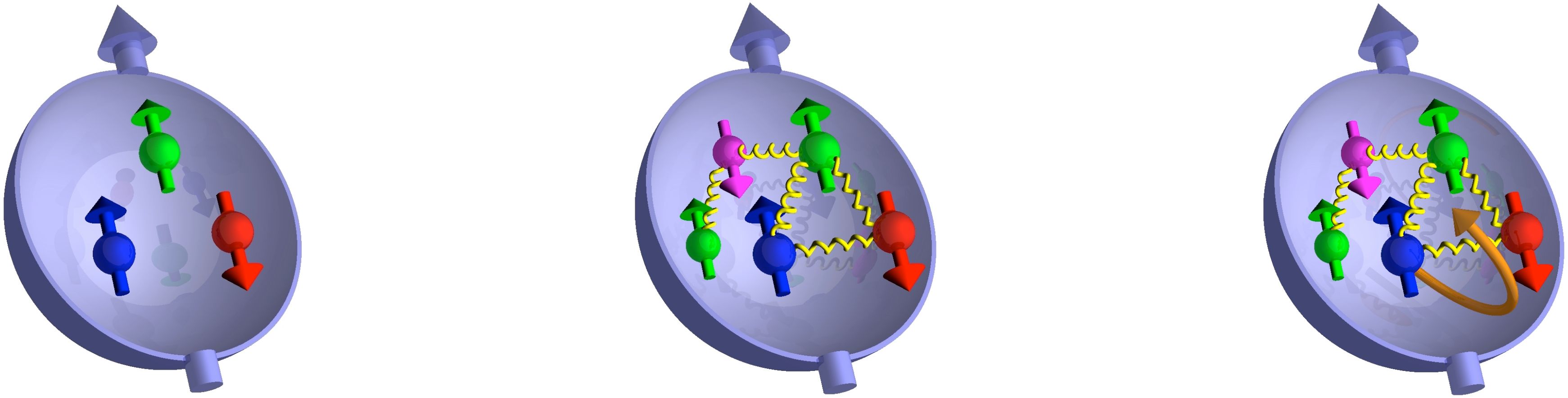
- longitudinal spin/momentum structure
- transverse spin/momentum structure

> hadronisation

- flavour separation of fragmentation functions



hunting for spin of proton



- **1980s - 1990s:**

  EMC (CERN),
  E130, E143, E155,
  E142, E154 (SLAC),
  SMC (CERN),
  HERMES (DESY)

  ➡ small quark spin contribution to proton spin

- **1990-2000s → future:**

  HERMES(DESY),
  COMPASS (CERN),
  RHIC-Spin (BNL)

  ➡ individual quark spin flavour decomposition

  ➡ surprisingly small gluon spin contribution ($0.05 < x_g < 0.2$)

  ➡ significant contributions of
    - gluons and/or sea quarks at low x
    - orbital angular momentum

- **nowadays → future:**

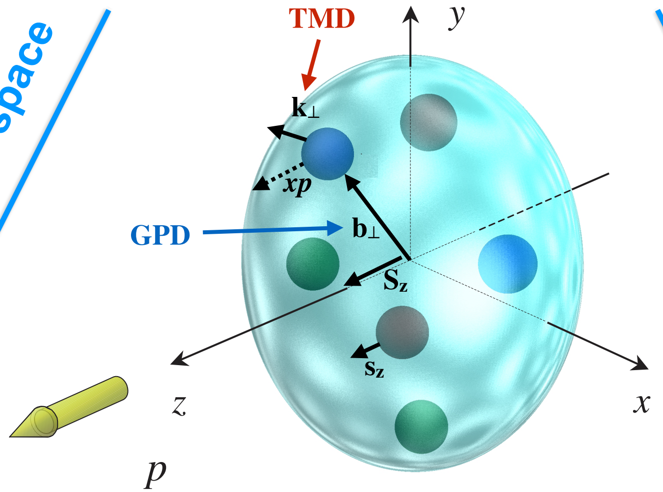
  HERMES(DESY),
  COMPASS (CERN),
  RHIC-Spin (BNL),
  JLab

  ➡ hunting for the spin of proton turned into hunting for the orbital angular momentum

nucleon tomography

$$W(x, k_\perp, b_\perp, \vec{S})$$

cannot be measured… but its projections in coordinate or momentum space

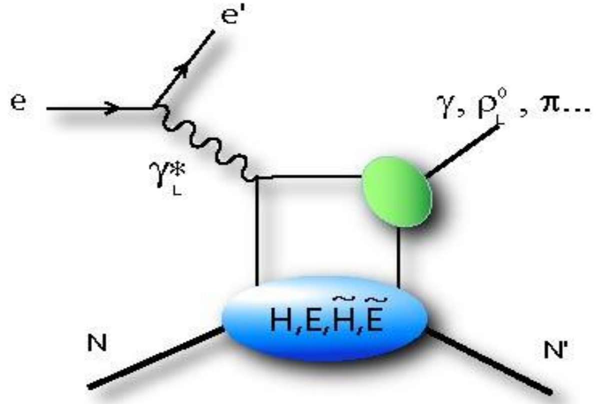


transfers coordinate space

GPDs

[generalised parton distributions]

➡ **exclusive measurements**

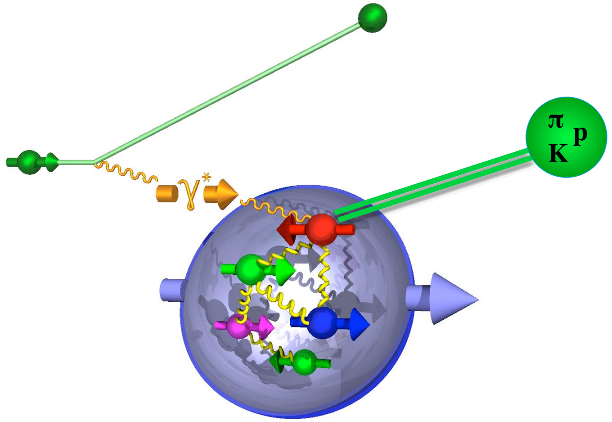


transfers momentum space

TMDs

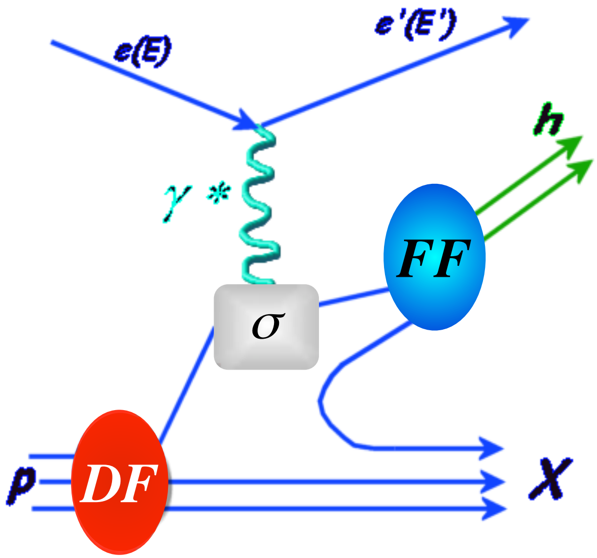
[transverse momentum dependent PDFs]

➡ **semi-inclusive measurements**



[... preferably with polarised beam and/or target ...]

semi-inclusive DIS



$$Q^2 = -q^2 = (k - k')$$

- 4-momentum squared of virtual photon

$$x = \frac{Q^2}{2P \cdot q}\,, \quad x \in [0,1]$$

- fraction of proton momentum carried by the struck quark

$$z = \frac{P \cdot P_h}{P \cdot q}\,, \quad z \in [0,1]$$

- energy fraction carried by the produced hadron

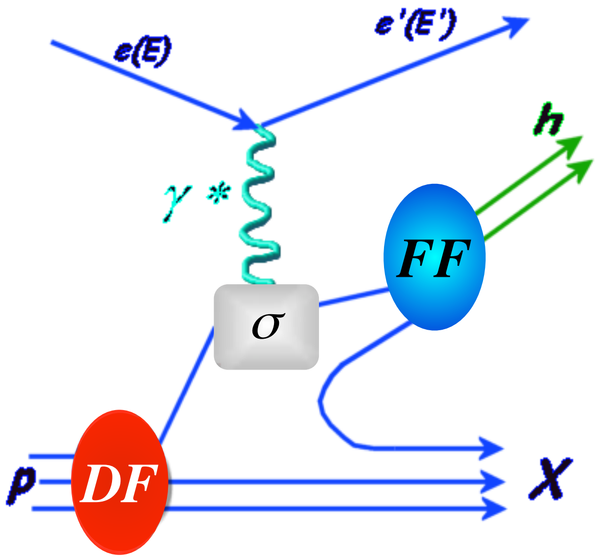
pQCD factorisation:

$$\sigma_{DIS} \propto \sum_f \hat{\sigma}_{part} \otimes DF(x) \otimes FF(z)$$

parameterise the nucleon structure

parameterise the conversion of a quark into a certain type of hadron

semi-inclusive DIS



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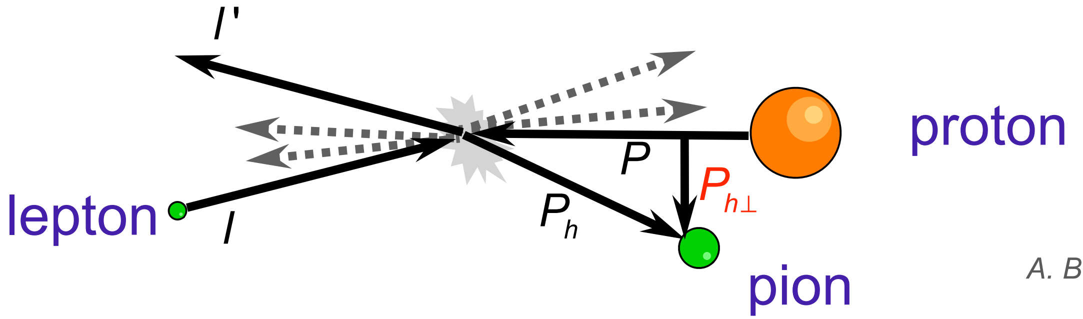
$$P_{h\perp}$$

- transverse momentum of hadron



A. Bacchetta

pQCD factorisation:

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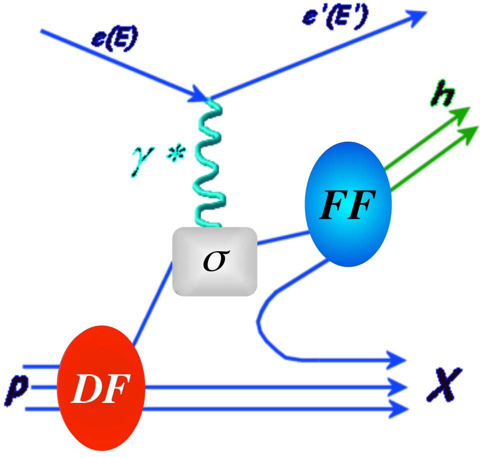
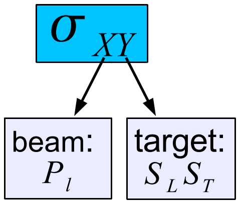
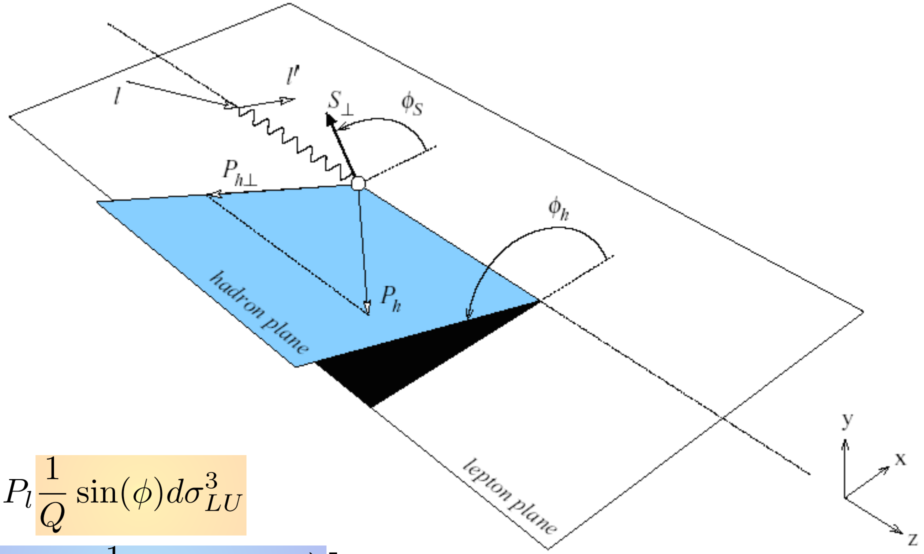
TMDs




σ_{XY}

beam: P_l

target: $S_L S_T$



$$
\begin{aligned}
d\sigma \;=\;& d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} \;+\; P_l\frac{1}{Q}\sin(\phi)d\sigma^3_{LU}\\
+\;& S_L\left[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} \;+\; P_l\left(d\sigma^6_{LL} + \frac{1}{Q}\cos(\phi)d\sigma^7_{LL}\right)\right]\\
+\;& S_T\left[\sin(\phi-\phi_s)d\sigma^8_{UT} + \sin(\phi+\phi_s)d\sigma^9_{UT} + \sin(3\phi-\phi_s)d\sigma^{10}_{UT} + \frac{1}{Q}\sin(2\phi-\phi_s)d\sigma^{11}_{UT} + \frac{1}{Q}\sin(\phi_s)d\sigma^{12}_{UT}\right.\\
&\left.\quad + \; P_l\left(\cos(\phi-\phi_s)d\sigma^{13}_{LT} + \frac{1}{Q}\cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi-\phi_s)d\sigma^{15}_{LT}\right)\right]
\end{aligned}
$$

DF		quark polarisation			
		U	L	T	
nucleon polarisation	U	f_1		$h_1^\perp$	
	L		g_1	$h_{1L}^\perp$	
	T	$f_{1T}^\perp$	g_{1T}	h_1	$h_{1T}^\perp$

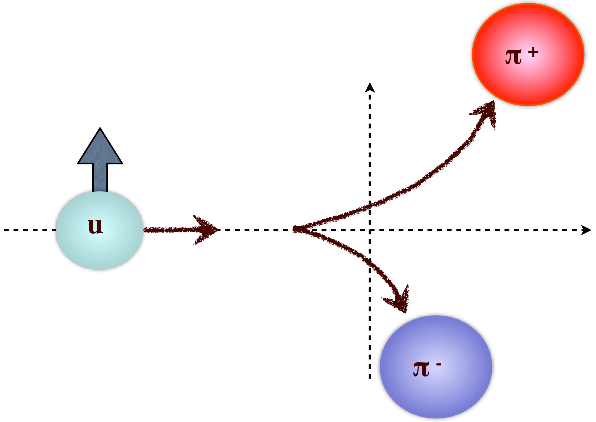
FF		quark polarisation	
		U	T
hadron polarisation	U	D_1	$H_1^\perp$

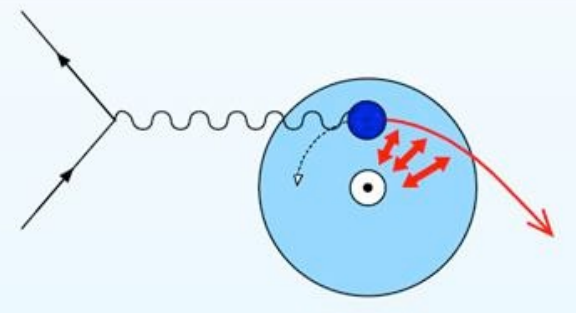
semi-inclusive measurements (probing TMDs)

hermes highlights

> **first demonstration of Sivers effect**

- ➡ *PRL 94 (2005) 012002*
- ➡ *PRL 103 (2009) 152002*





> correlation between the transverse ***momentum*** of the fragmenting quark and the transverse momentum of the produced unpolarised hadron

> correlation between the transverse ***spin*** of the fragmenting quark and the transverse momentum of the produced unpolarised hadron

> **first evidence for Collins effect**

- ➡ *PRL 94 (2005) 012002*
- ➡ *JHEP 06 (2008) 017*
- ➡ *PLB 693 (2010) 11]*

semi-inclusive measurements (probing TMDs)

hermes highlights

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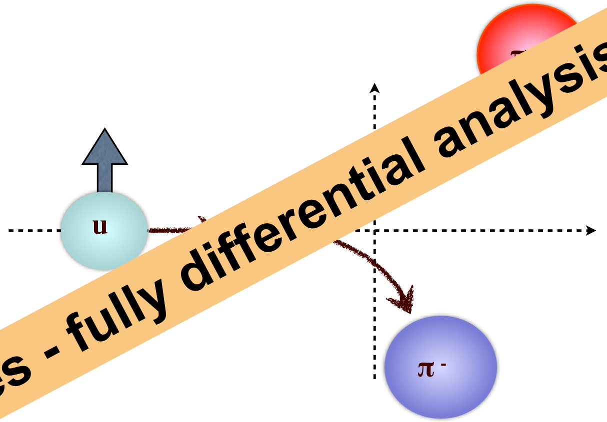
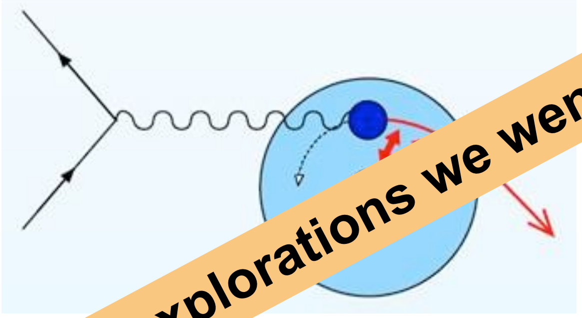


> correlation between the transverse ***spin*** of the fragmenting quark and the transverse momentum of the produced unpolarised hadron

From first explorations we went to detailed studies - fully differential analysis!!!



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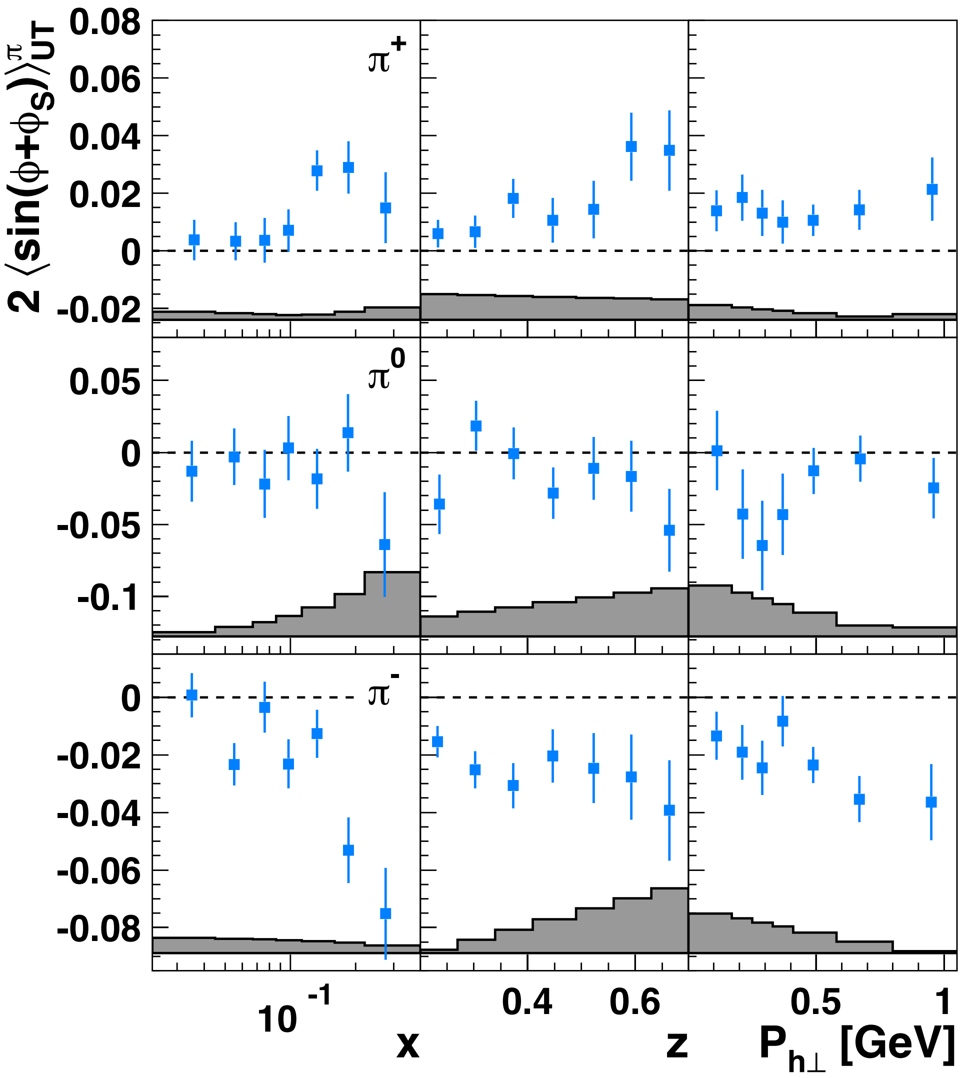
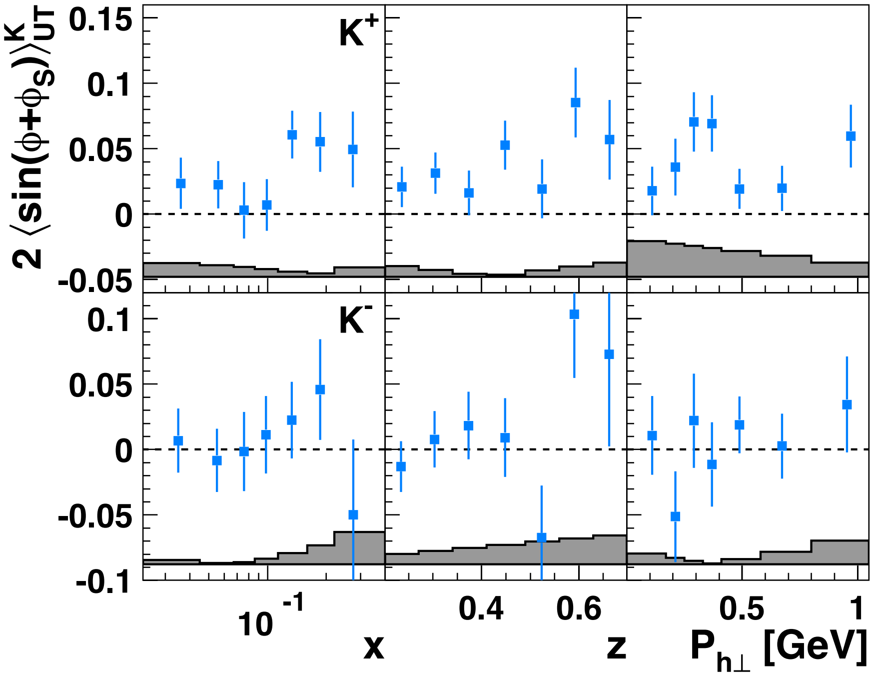
Collins asymmetries: 1D

$\sigma_{UT} \propto h_1^q \otimes H_1^{\perp q}$



Phys. Rev. Lett. 103 (2009) 152002

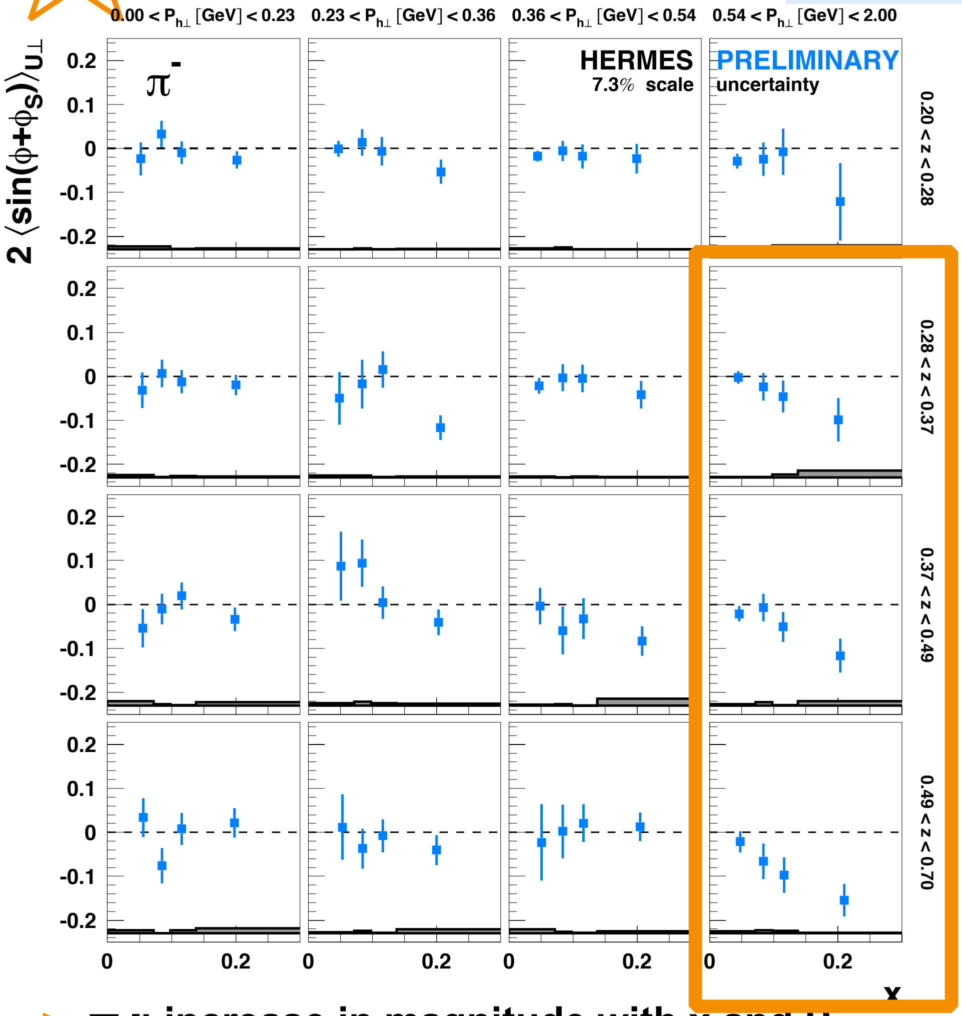


- > positive amplitude for π^+
- > large negative amplitude for π^-
- > K^+ are larger than π^+
- > K^- consistent with zero

Collins asymmetries: 3D

NEW

$$\sigma_{UT} \propto h_1^q \otimes H_1^{\perp\, q}$$



- π^-: increase in magnitude with x and $P_{h\perp}$
  - ➡ transversity mainly receives contribution from valence quarks

Collins asymmetries: 3D

NEW

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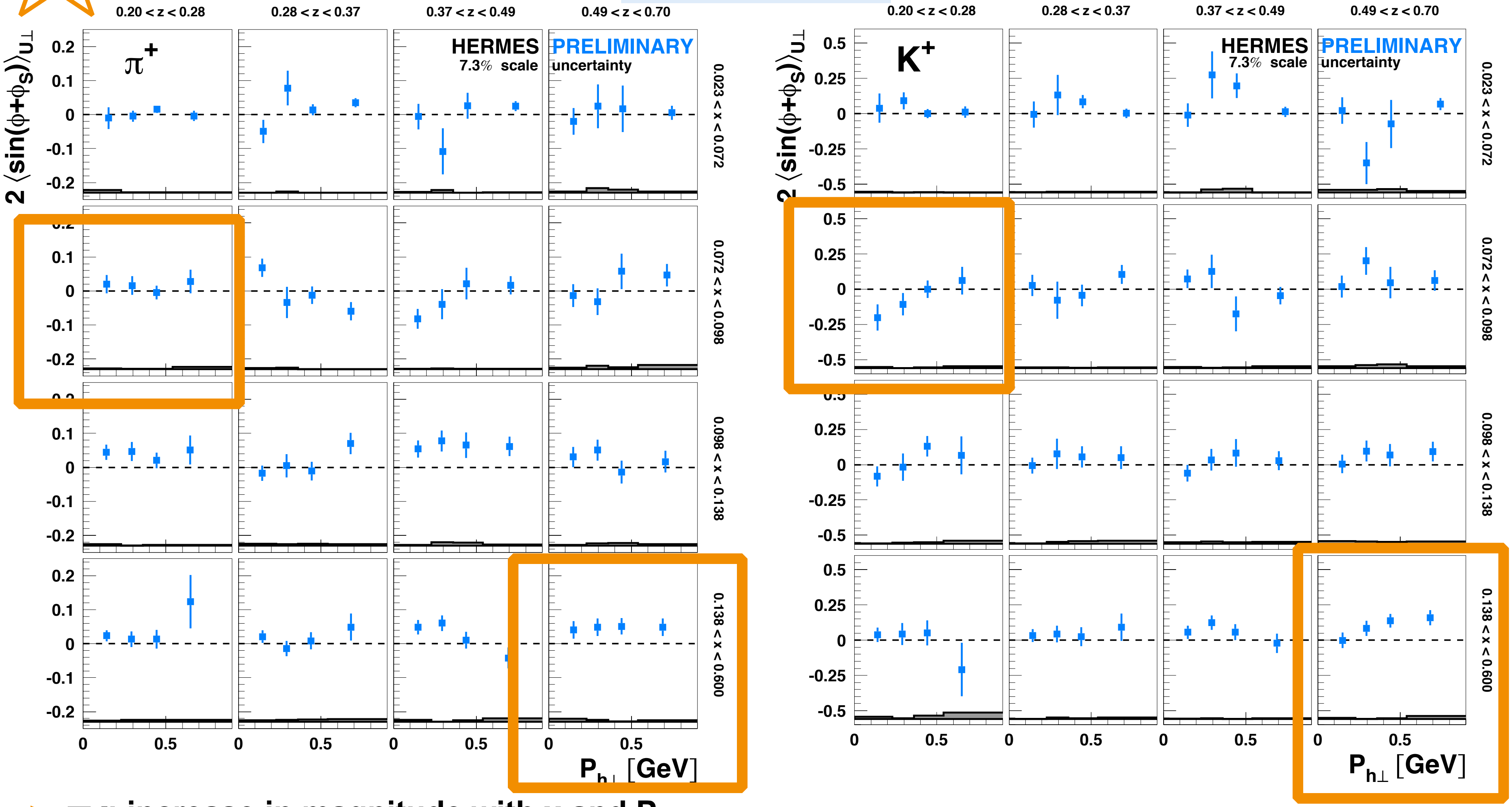
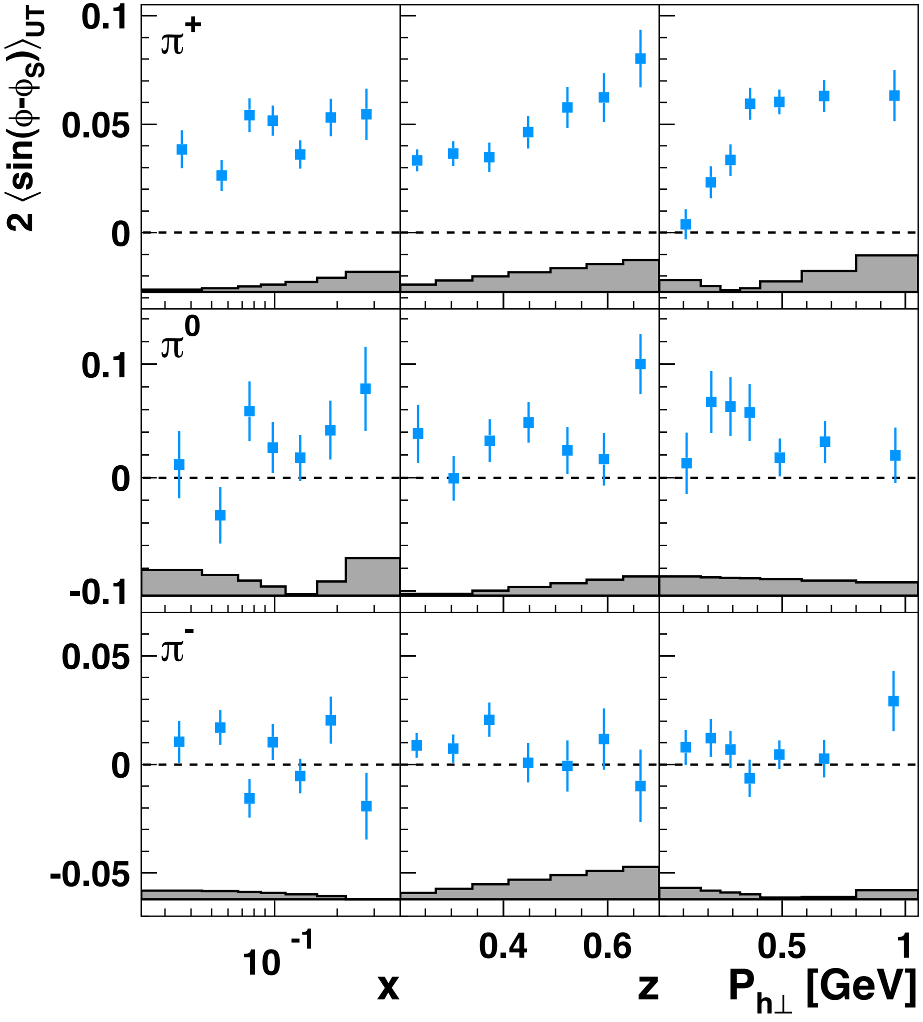


- **π^-: increase in magnitude with x and $P_{h\perp}$**
  - ➡ transversity mainly receives contribution from valence quarks
- ***K^+* amplitudes are larger than π^+**
  - ➡ role of sea quarks

Sivers asymmetries: 1D

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



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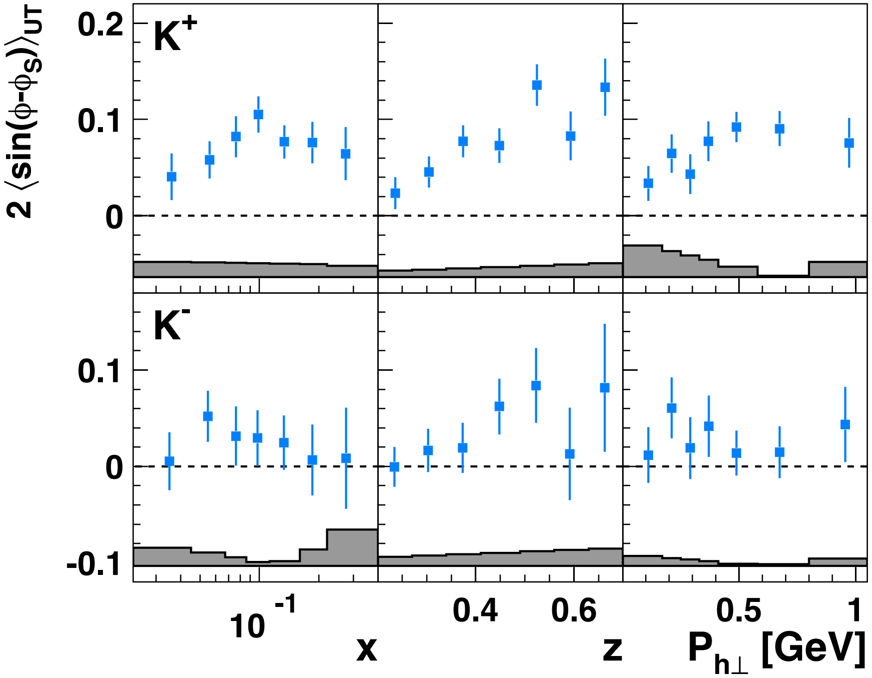


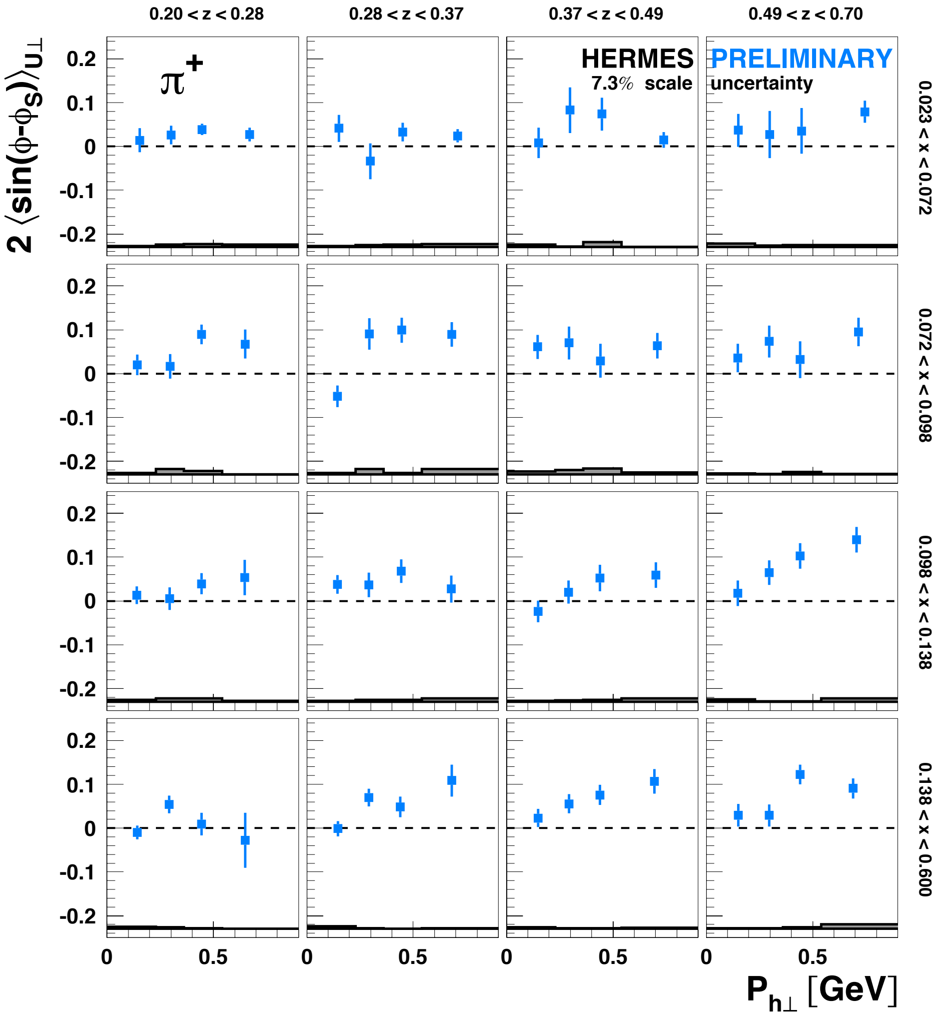
- K^+ are larger than π^+
- K^- slightly positive

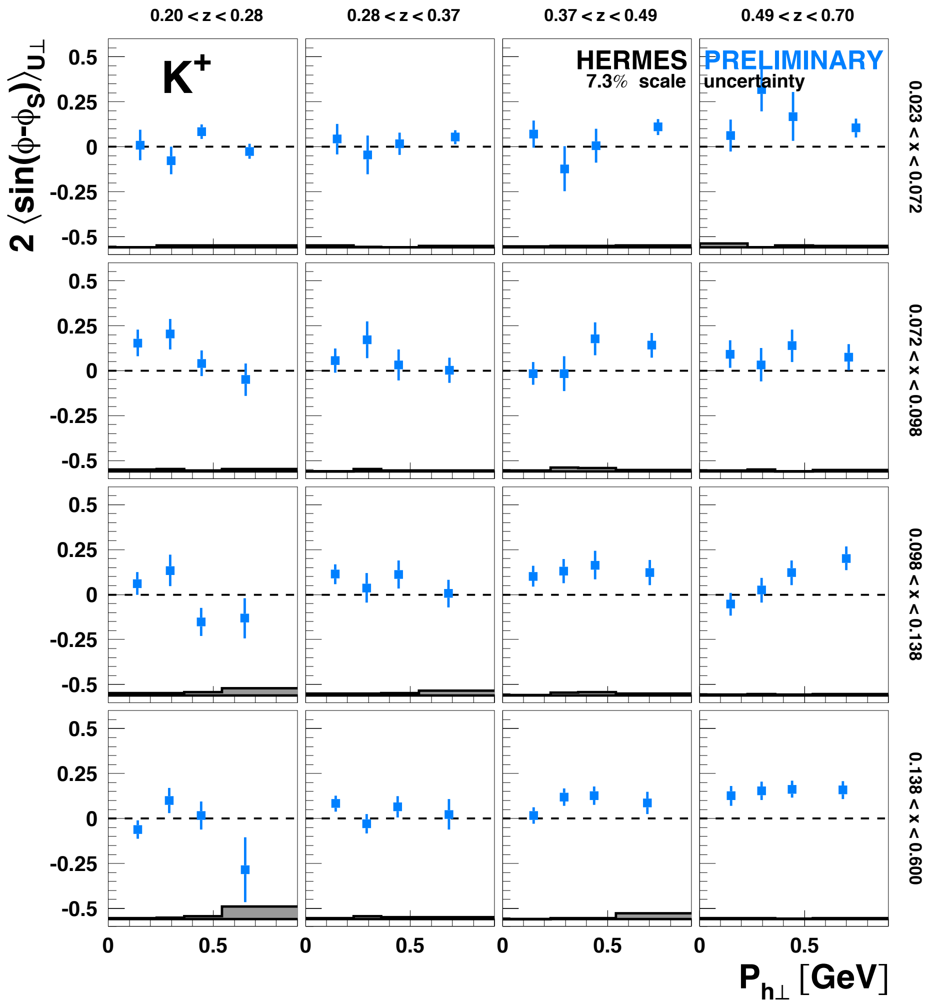
- positive amplitude for π^+
- consistent with zero for π^-

Sivers asymmetries: 3D

NEW

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

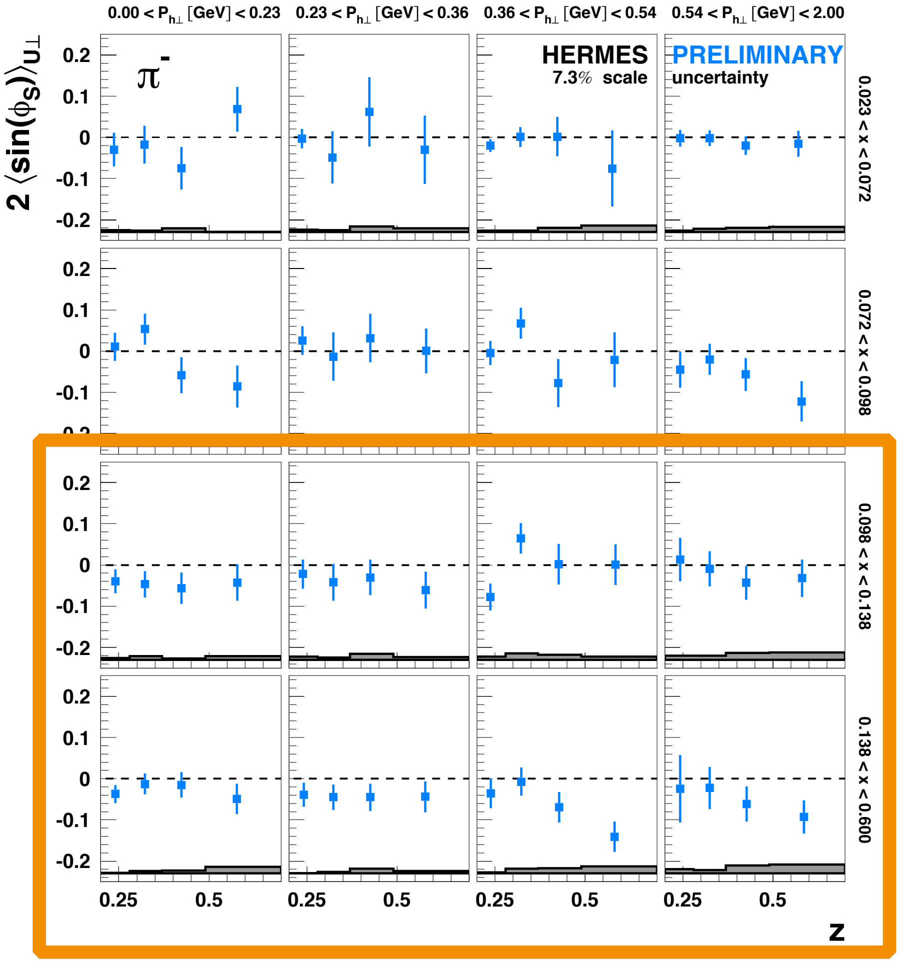




- ***K***⁺ **amplitudes are larger than π ⁺ in most kinematic regions**
  - ➡ role of sea quarks

NEW

multi-dimensional analysis



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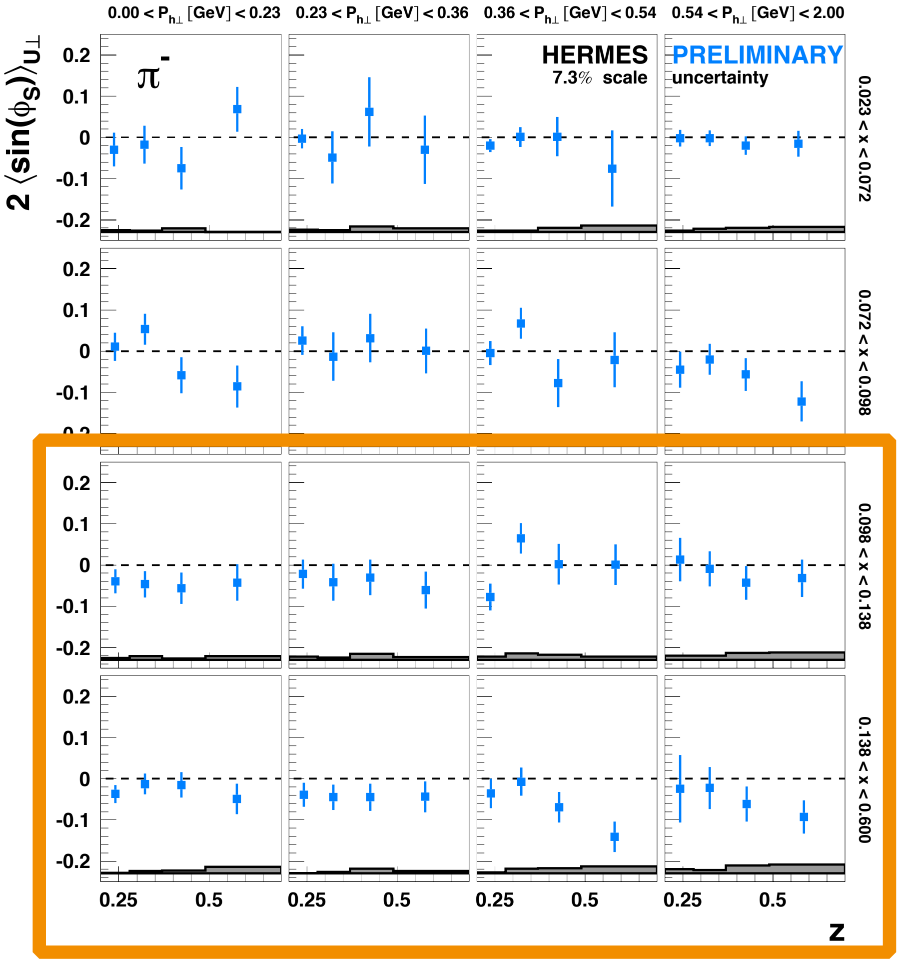

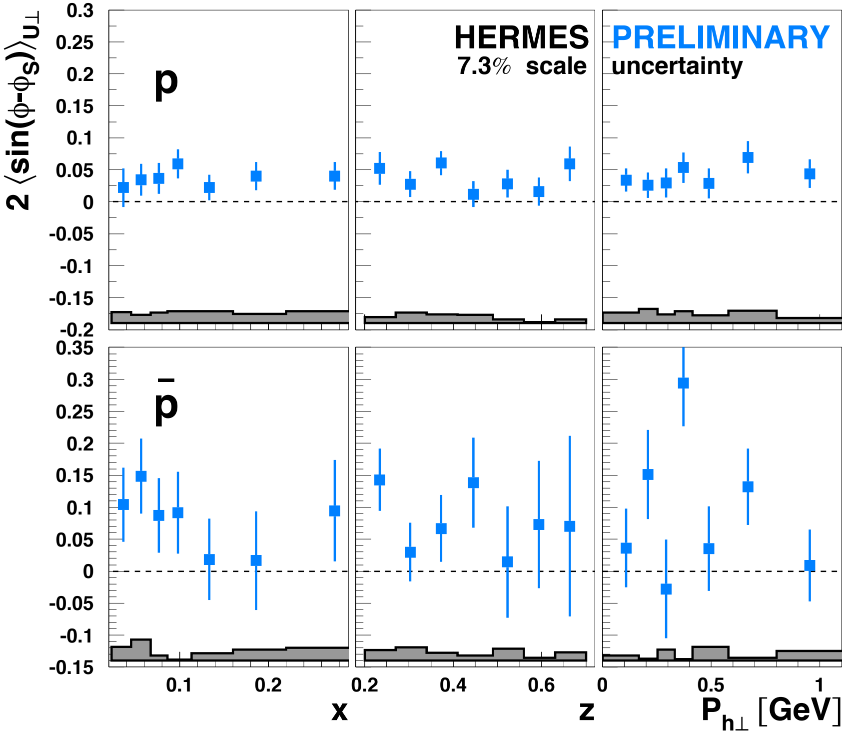

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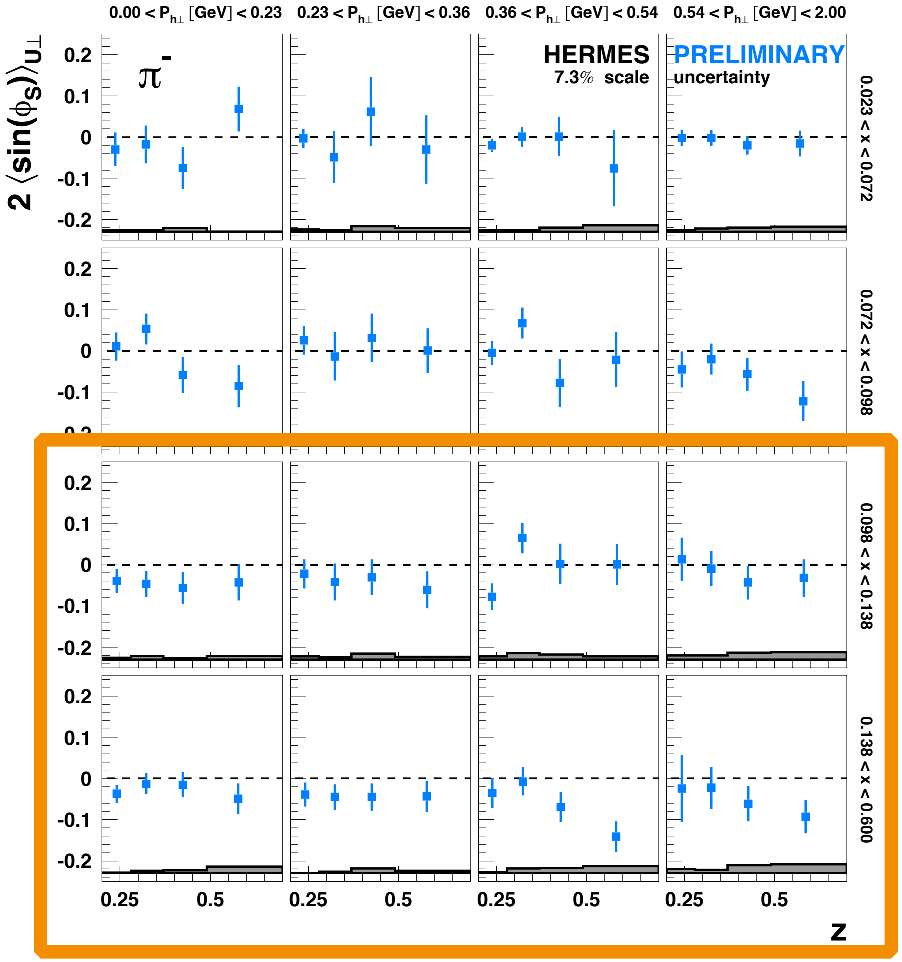
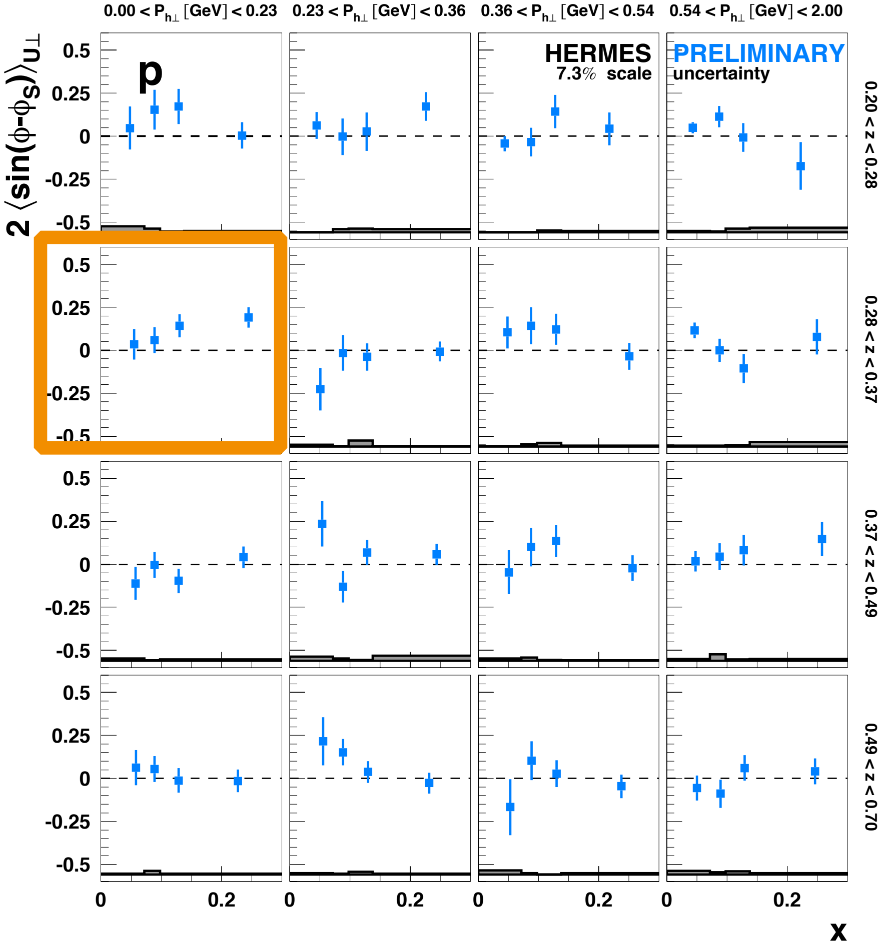




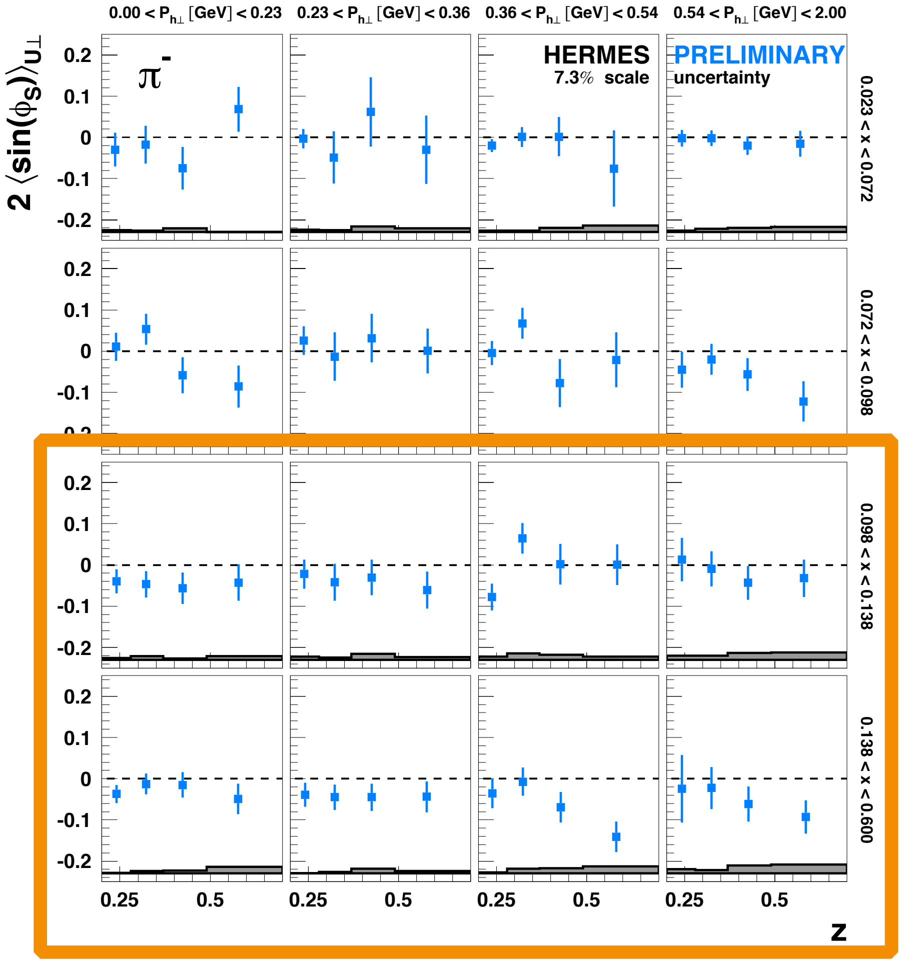
NEW

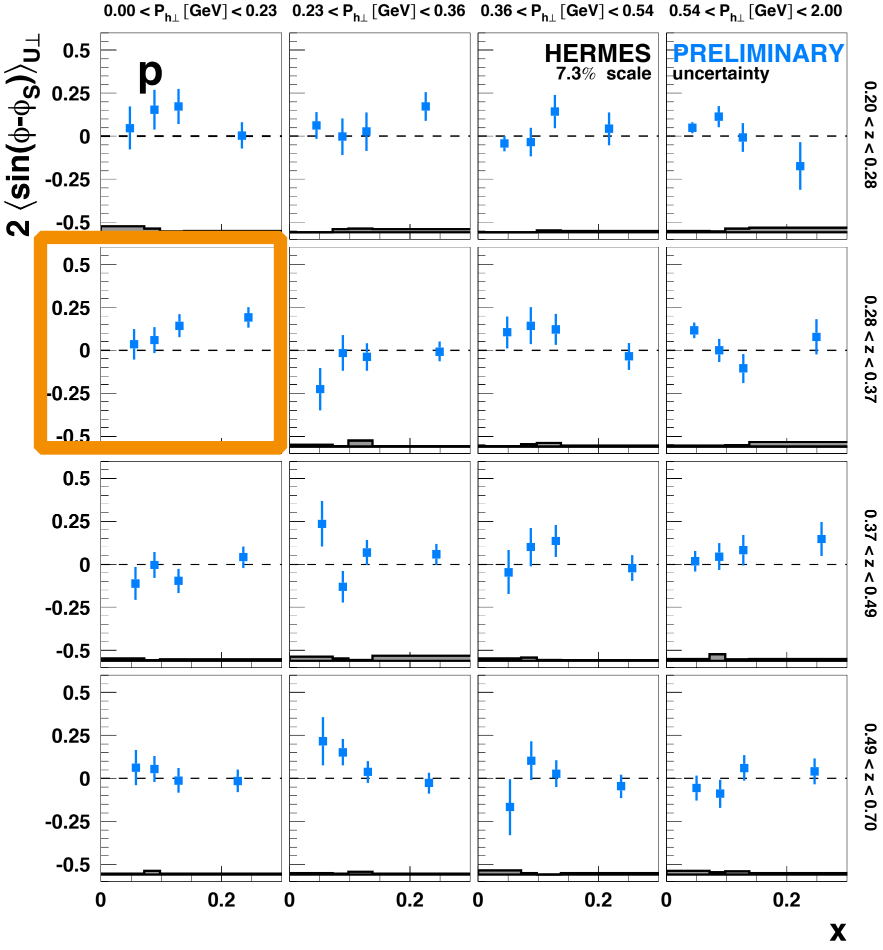
multi-dimensional analysis

- **complete set of asymmetries:**
  - for π, K, protons
  - transverse target
  - longitudinal beam

$$\begin{aligned} d\sigma &= d\sigma^0_{UU} \\ &+ S_T\Big[\sin(\phi-\phi_s)d\sigma^1_{U\perp}+\sin(\phi+\phi_s)d\sigma^2_{U\perp}+\sin(3\phi-\phi_s)d\sigma^3_{U\perp}+ \\ &\qquad \frac{1}{Q}\sin(2\phi-\phi_s)d\sigma^4_{U\perp}+\frac{1}{Q}\sin(\phi_s)d\sigma^5_{U\perp}+\frac{1}{Q}\sin(2\phi+\phi_s)d\sigma^6_{U\perp} \\ &+ P_l\Big(\cos(\phi-\phi_s)d\sigma^7_{L\perp}+\frac{1}{Q}\cos(\phi_s)d\sigma^8_{L\perp}+\frac{1}{Q}\cos(2\phi-\phi_s)d\sigma^9_{L\perp}+\frac{1}{Q}\cos(\phi+\phi_s)d\sigma^{10}_{L\perp}\Big)\Big] \end{aligned}$$

http://hermes.desy.de/notes/pub/trans-public-index.html





fragmentation of unpolarised quarks in unpolarised target

$$\sigma_{UU} \propto f_1 \otimes D_1$$

$$M^h = \frac{d\sigma^h_{SIDIS}(x, Q^2, z, P_{h\perp})}{d\sigma_{DIS}(x, Q^2)}$$

- HERMES Collaboration - Phys.Rev. D87 (2013) 074029

fragmentation of unpolarised quarks in unpolarised target

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- **LO interpretation of multiplicity results (integrated over $P_{h\perp}$):**

$$M^h \propto \frac{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2)}$$

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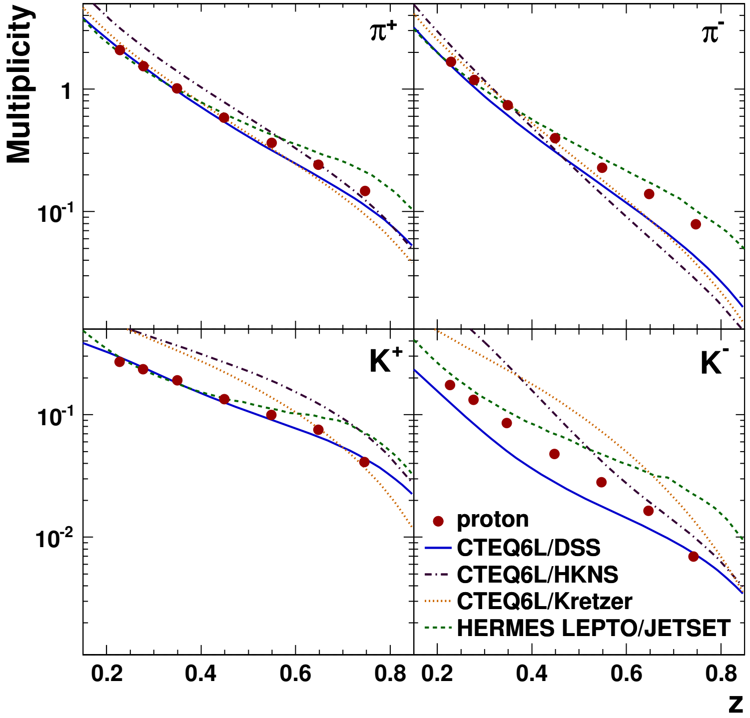

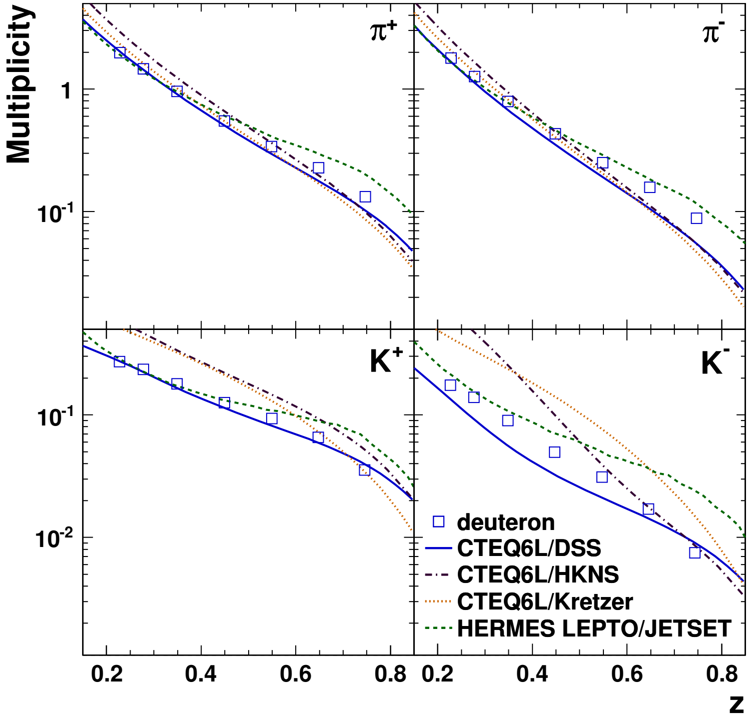

- **proton:**
  - fair agreement for positive hadrons
  - disagreement for negative hadrons
- **deuteron:**
  - results are in general in better agreement with the various predictions

fragmentation of unpolarised quarks in unpolarised target

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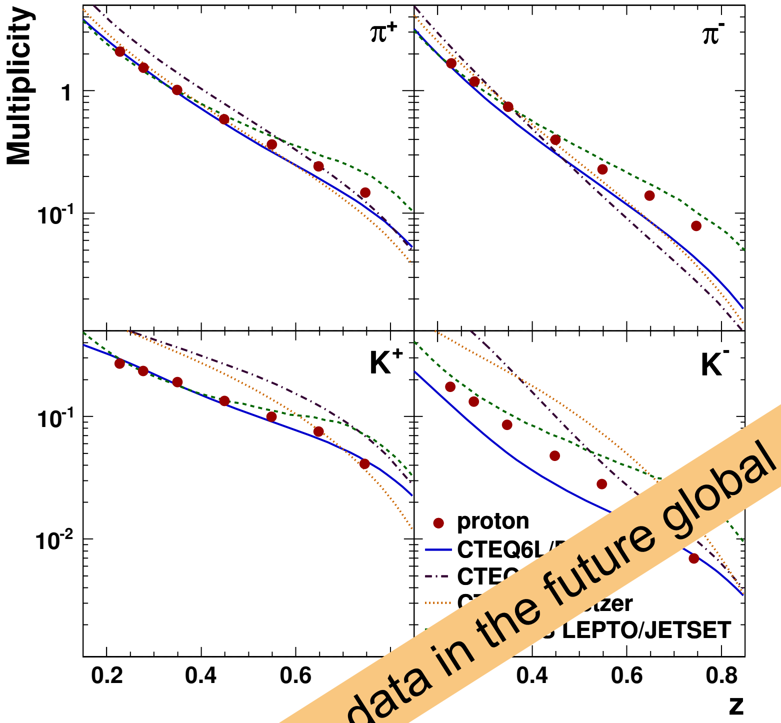
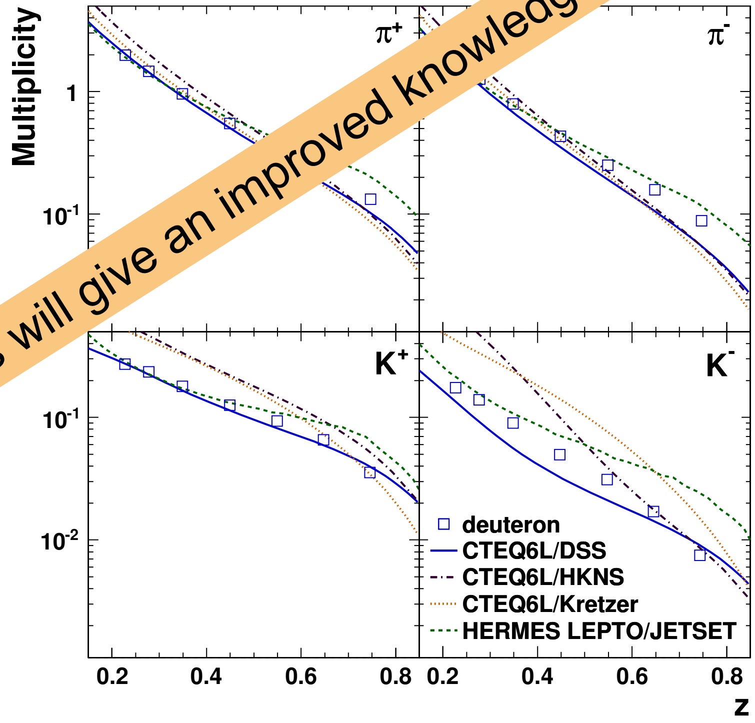
$$M^h \propto \frac{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2)}$$

$$M^h = \frac{d\sigma^h_{SIDIS}(x,Q^2,z,P_{h\perp})}{d\sigma_{DIS}(x,Q^2)}$$

- HERMES Collaboration - Phys.Rev. D87 (2013) 074029





- **proton:**
  - fair a ent for positive hadrons
  - di ement for negative hadrons
- **ron:**
  - results are in general in better agreement with the various predictions

✓ inclusion of the data in the future global analyses will give an improved knowledge on FF

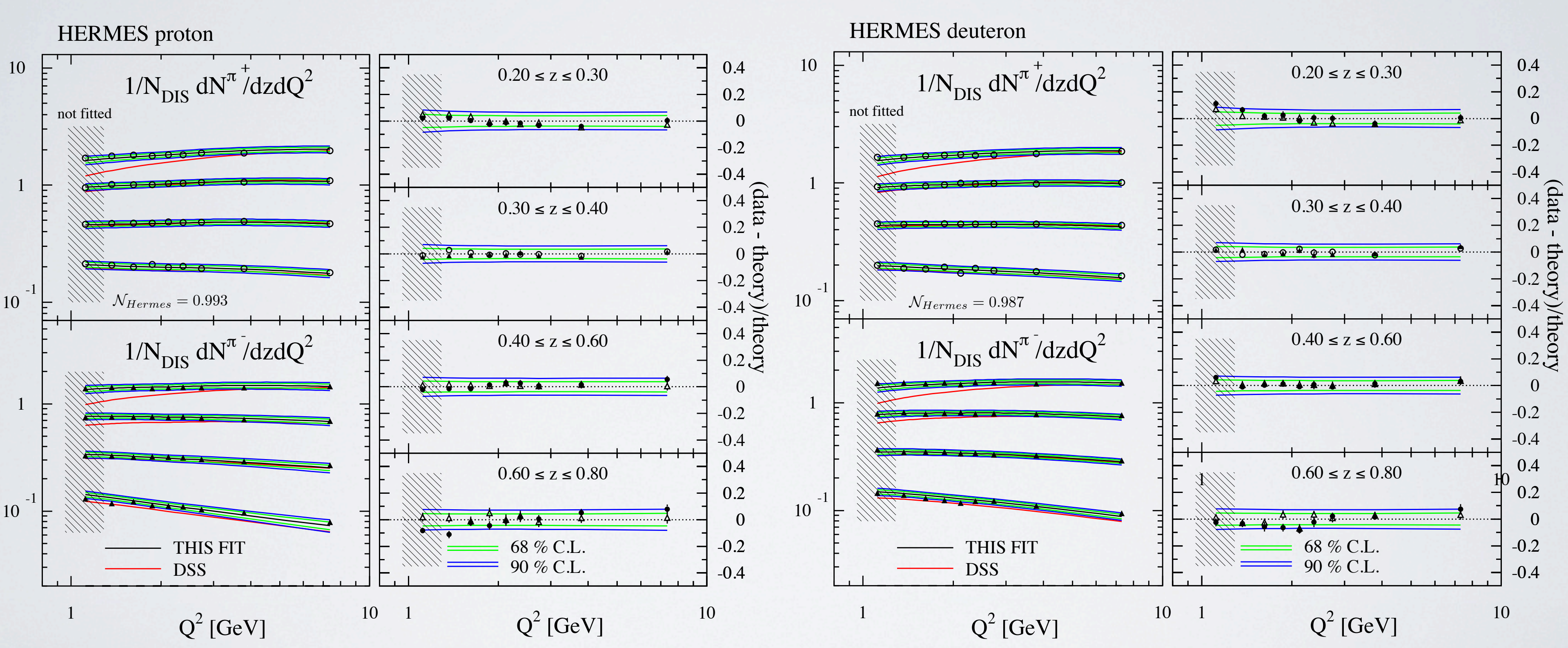
New global fit DSS+

$\sigma_{UU} \propto f_1 \otimes D_1$

new data sets in *global* analysis of DSS+

➡ Belle, BaBar, Compass, Hermes, Star, Alice

- Rodolfo Sassot -
Workshop on FFs, Bloomington, December 2013

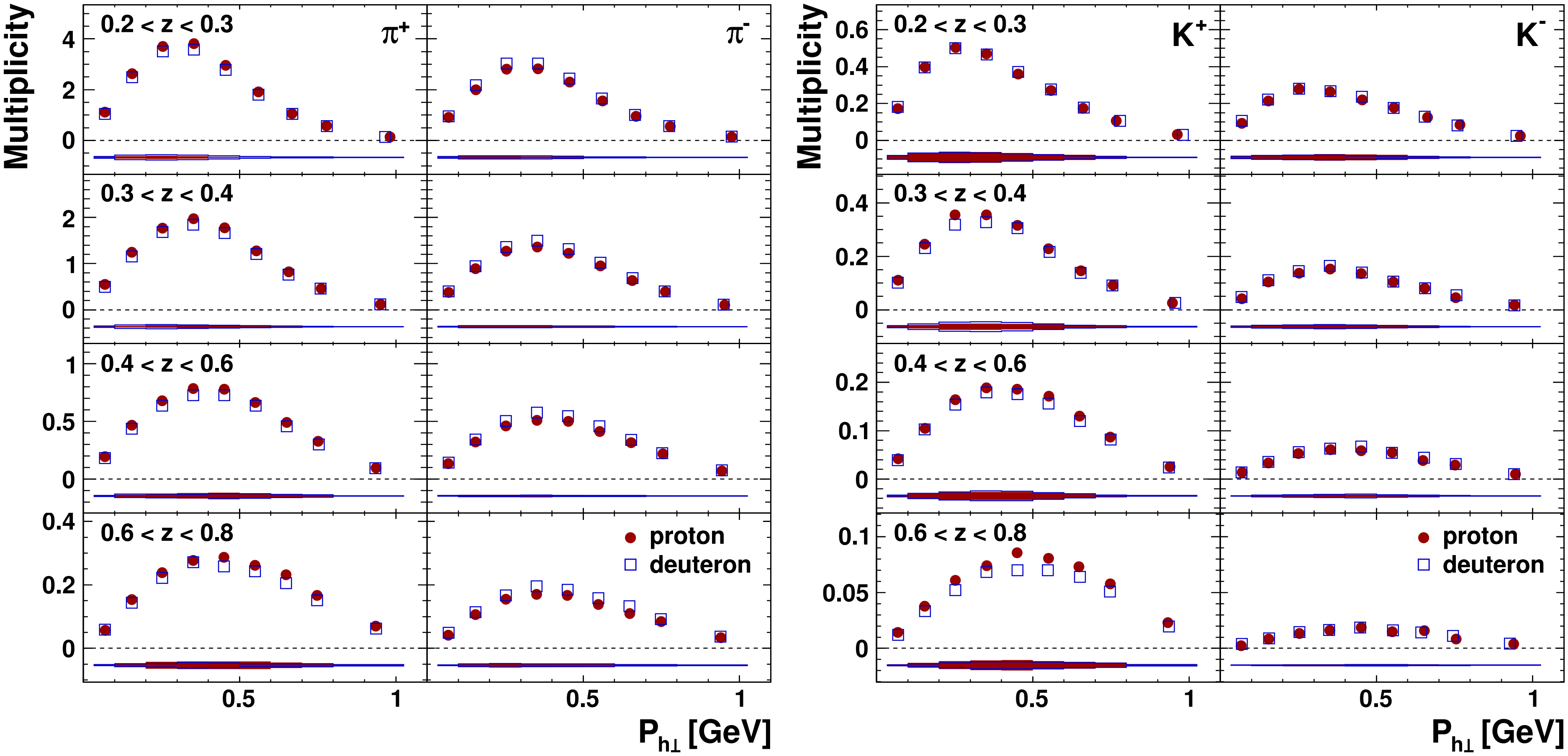


> better agreement for both π+ and π-

beyond the collinear factorisation

$\sigma_{UU} \propto f_1 \otimes D_1$

- HERMES Collaboration- Phys.Rev. D87 (2013) 074029



- multi-dimensional analysis allows exploration of new kinematic dependences
- broader $P_{h\perp}$ distribution for K^-

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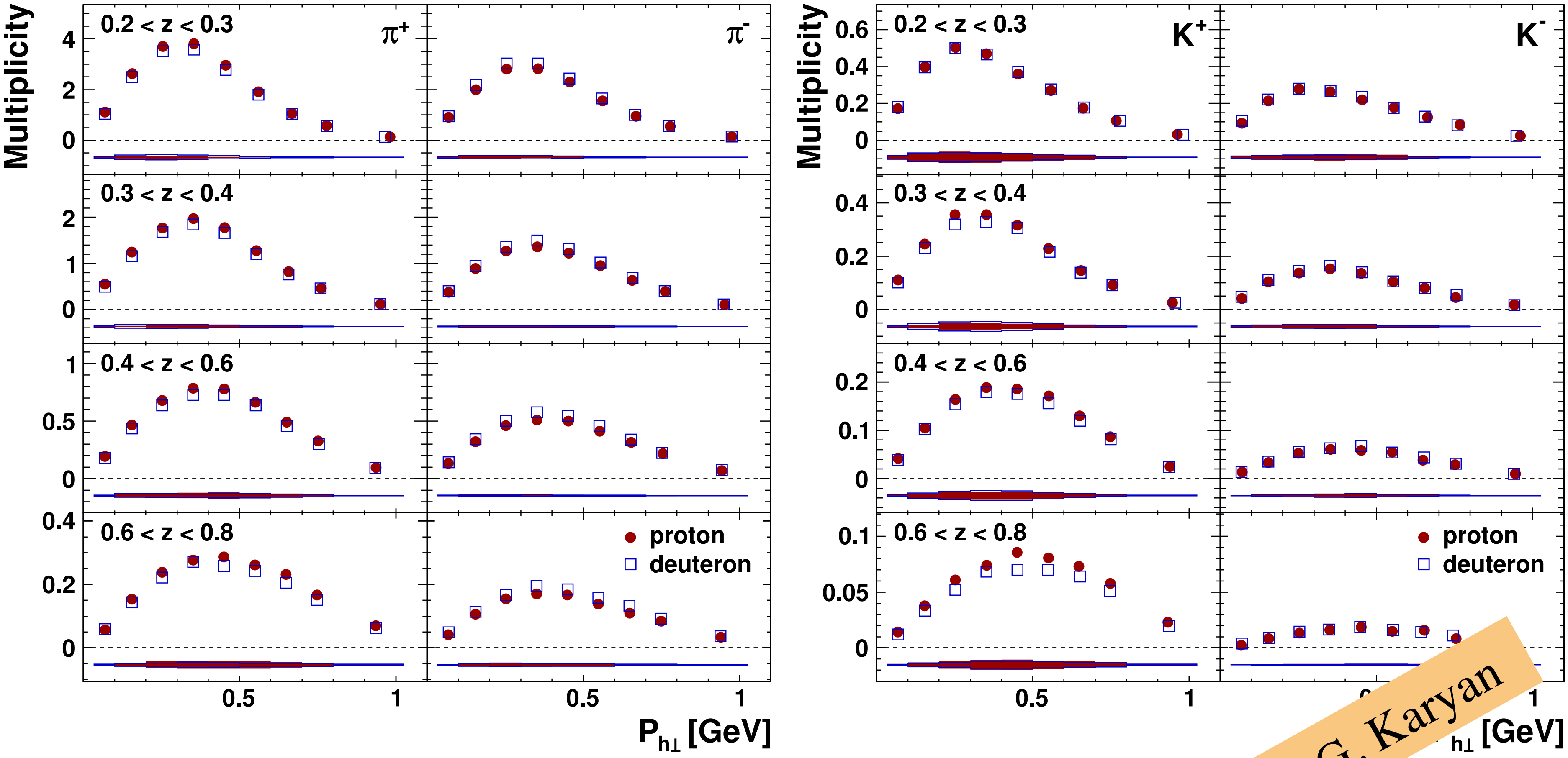
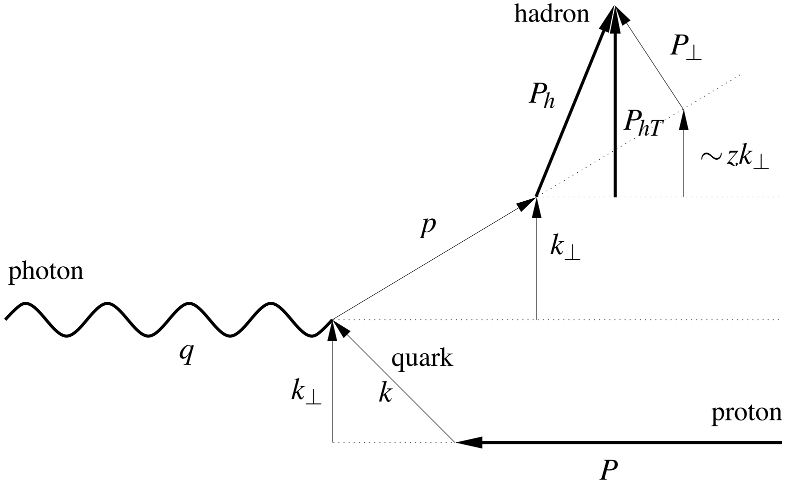
- HERMES Collaboration- Phys.Rev. D87 (2013) 074029



see the talk by G. Karyan

- **multi-dimensional analysis allows exploration of new kinematic d… …nces**
- **broader $P_{h\perp}$ distribution for K^-**

flavour-dependent and independent ansatzes



- **flavour-independent analysis**
  M. Anselmino, M. Boglione, J.O. Gonzalez, S. Melis, A. Prokudin JHEP (2014)

$$\boldsymbol{P}_T = z\,\boldsymbol{k}_\perp + \boldsymbol{p}_\perp$$

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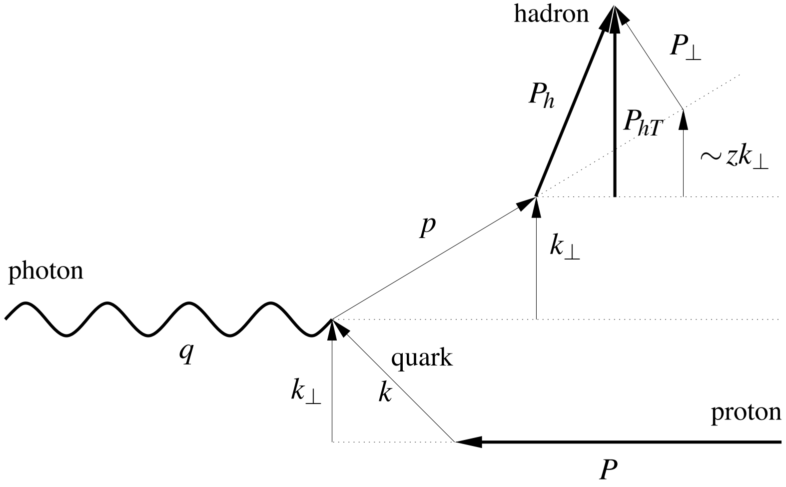
  A. Signori, A. Bacchetta, M. Radici and G. Schnell JHEP (2013)

$$\langle \boldsymbol{P}^2_{hT,a} \rangle = z^2 \langle \boldsymbol{k}^2_{\perp,a} \rangle + \langle \boldsymbol{P}^2_{\perp,a\to h} \rangle$$

flavour-dependent and independent ansatzes



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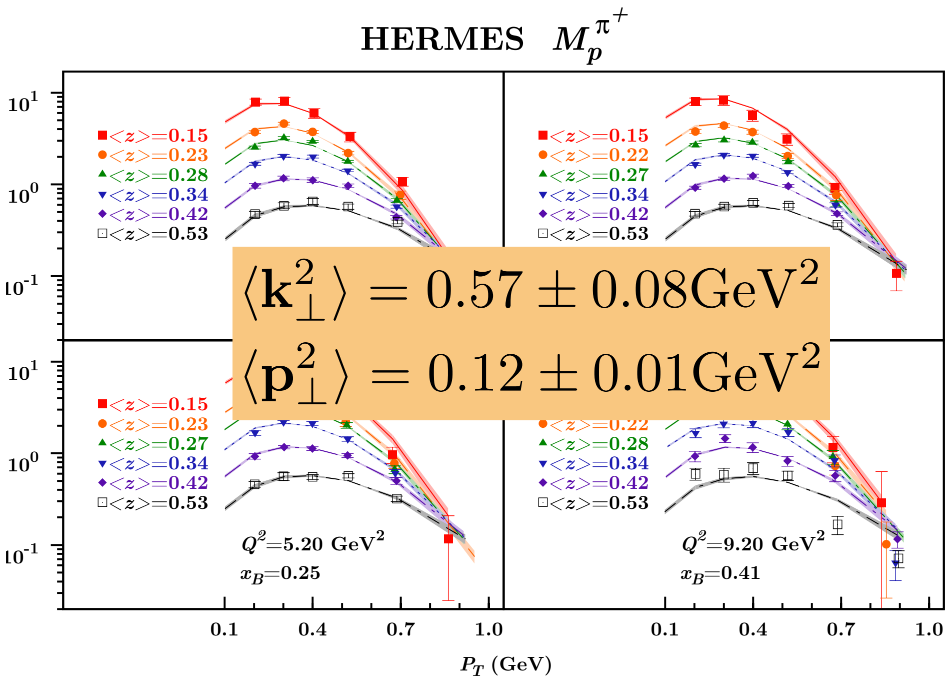
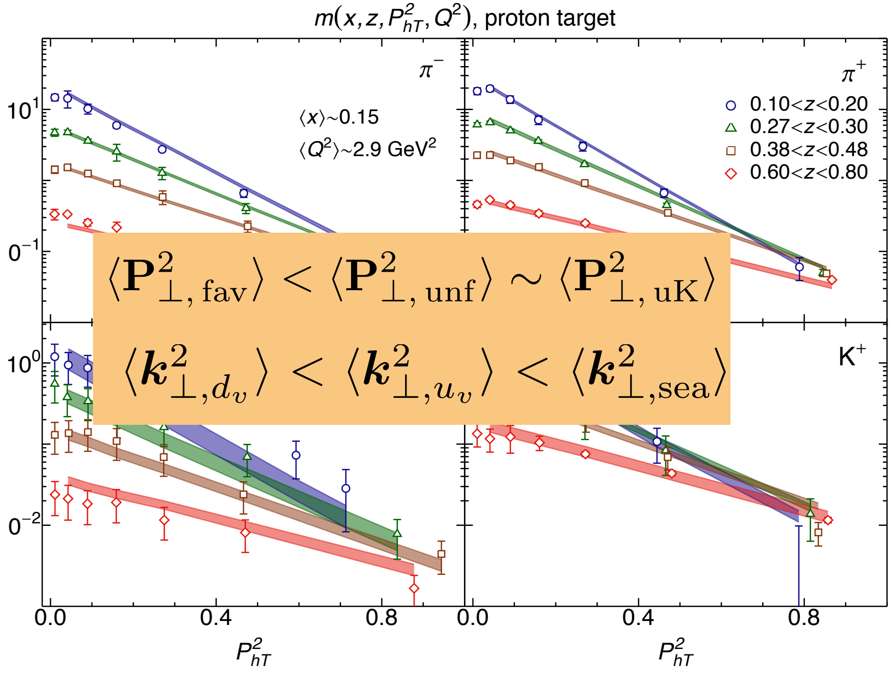


$$\langle \mathbf{k}^2_\perp\rangle = 0.57 \pm 0.08\mathrm{GeV}^2$$

$$\langle \mathbf{p}^2_\perp\rangle = 0.12 \pm 0.01\mathrm{GeV}^2$$



$$\langle \mathbf{P}^2_{\perp,\,\mathrm{fav}}\rangle < \langle \mathbf{P}^2_{\perp,\,\mathrm{unf}}\rangle \sim \langle \mathbf{P}^2_{\perp,\,\mathrm{uK}}\rangle$$

$$\langle \boldsymbol{k}^2_{\perp,d_v}\rangle < \langle \boldsymbol{k}^2_{\perp,u_v}\rangle < \langle \boldsymbol{k}^2_{\perp,\mathrm{sea}}\rangle$$

fragmentation of quarks involving transverse degrees of freedom

$$\sigma^1_{UU} \propto h_1^{\perp\, q} \otimes H_1^{\perp\, q}$$

$$\sigma_{UU} \propto f_1^q \otimes D_1^q$$

- D. Boer and P.J. Mulders -
Phys. Rev. D57 (1998)

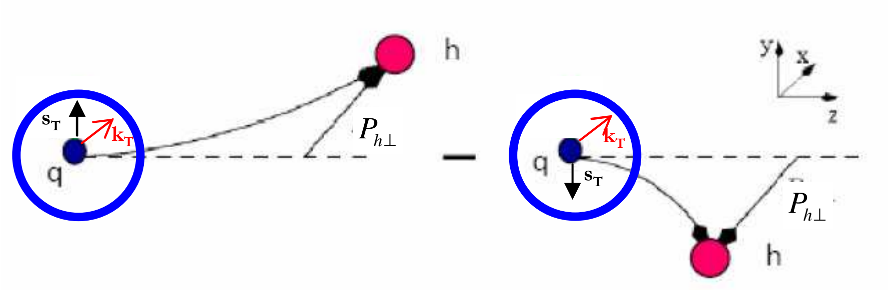
- R.N. Cahn -
Phys. Lett. B78 (1978)

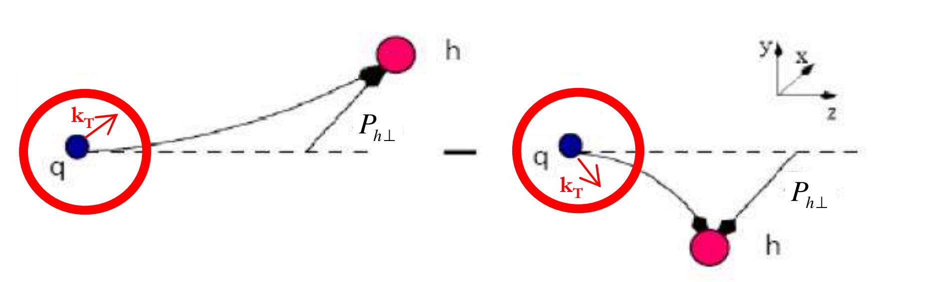
Boer-Mulders effect

- correlation between quark's transverse momentum, transverse spin and transverse momentum of the produced unpolarised hadron

Cahn effect

- kinematic effect caused by quark intrinsic transverse momentum





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$$d\sigma \quad = \quad d\sigma^0_{UU} + \cos(2\phi) d\sigma^1_{UU} + \frac{1}{Q} \cos(\phi) d\sigma^2_{UU}$$

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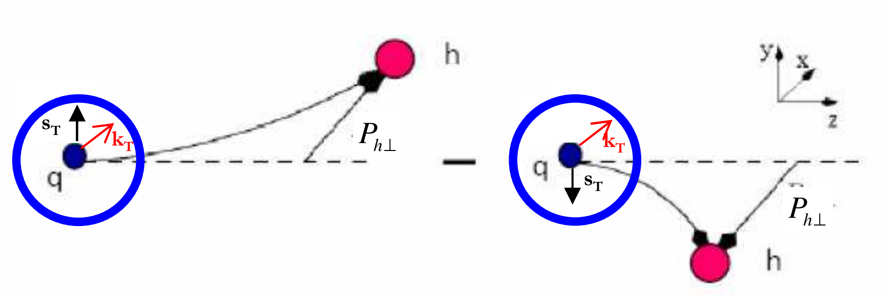
$$\cos 2\phi_{\mathbf{h}}$$



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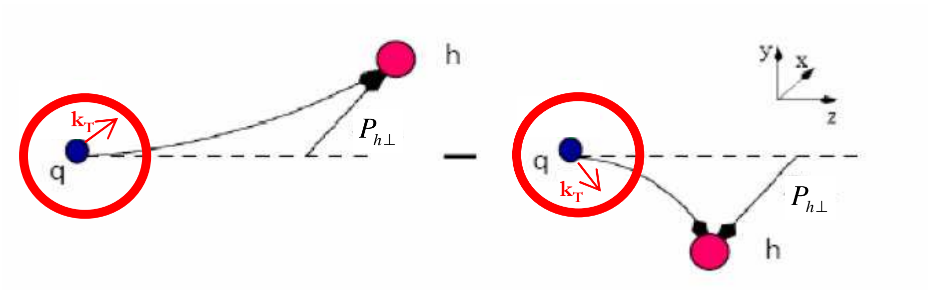
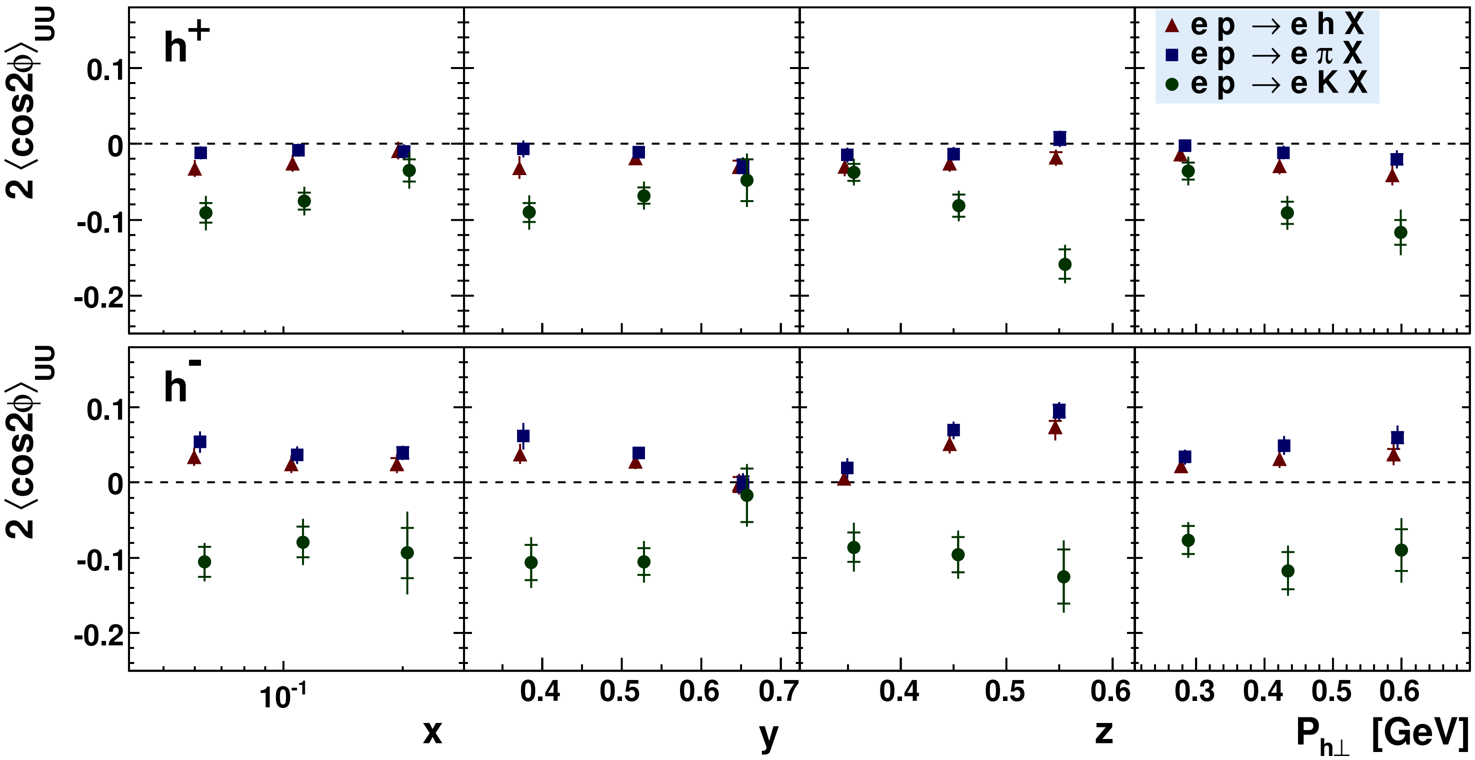


quarks’ transverse degrees of freedom

- HERMES Collaboration - Phys.Rev. D87 (2013) 012010

$$\sigma^1_{UU} \propto h_1^{\perp\, q} \otimes H_1^{\perp\, q}$$



fully differential 4D extraction of asymmetry amplitudes (900 bins in x, y, z, Ph)

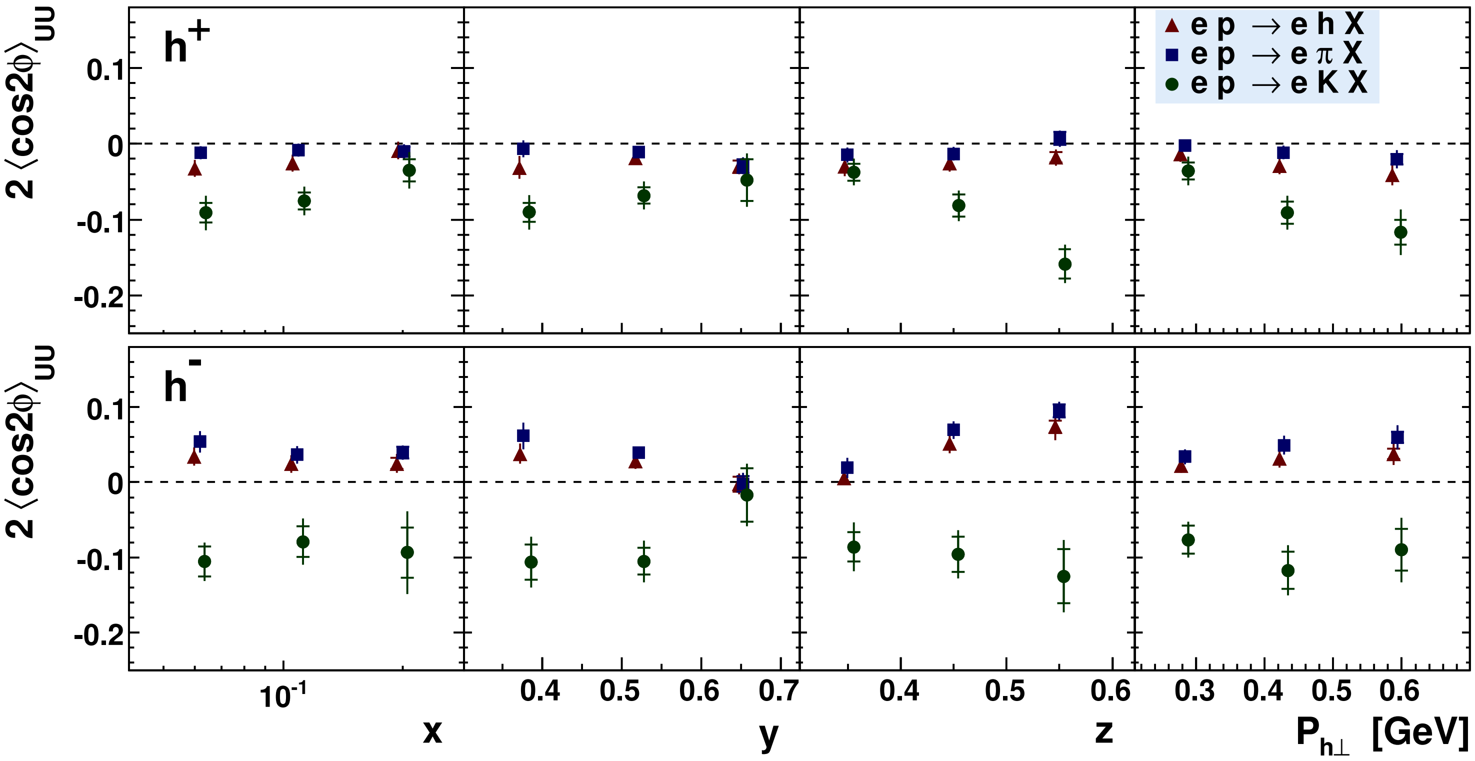
http://www-hermes.desy.de/cosnphi/

$$H_1^{\perp\, u\to\pi^+} = -H_1^{\perp\, u\to\pi^-}$$

quarks’ transverse degrees of freedom

- HERMES Collaboration - Phys.Rev. D87 (2013) 012010

$$\sigma_{UU}^{1} \propto h_1^{\perp\, q} \otimes H_1^{\perp\, q}$$



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  - data supports Boer-Mulders DF $h_1^{\perp}$ of same sign for u and d quarks

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- HERMES Collaboration - Phys.Rev. D87 (2013) 012010

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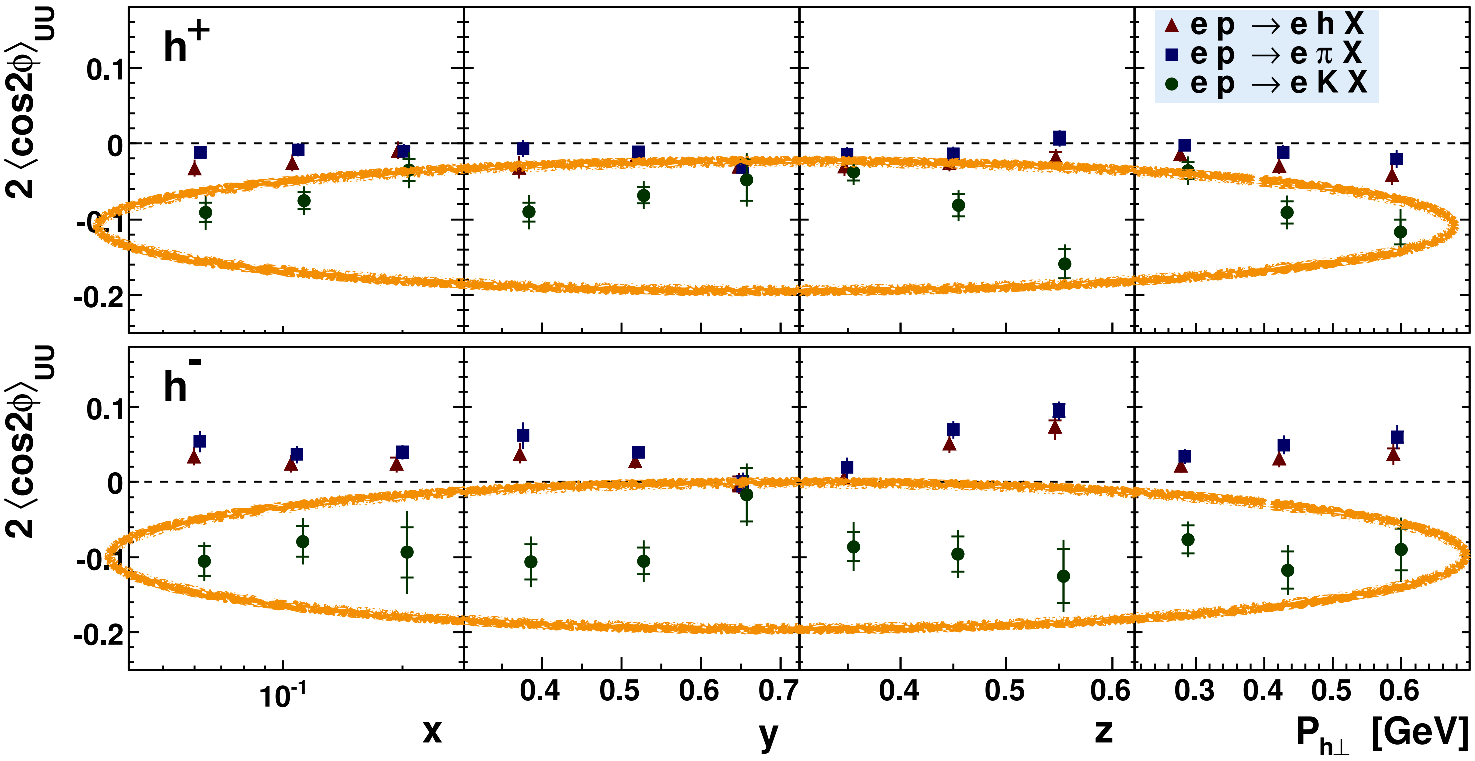

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- **K^- and K^+ : striking differences w.r.t. pions**
  - role of the sea in DF and FF

quarks' transverse degrees of freedom

- HERMES Collaboration - Phys.Rev. D87 (2013) 012010

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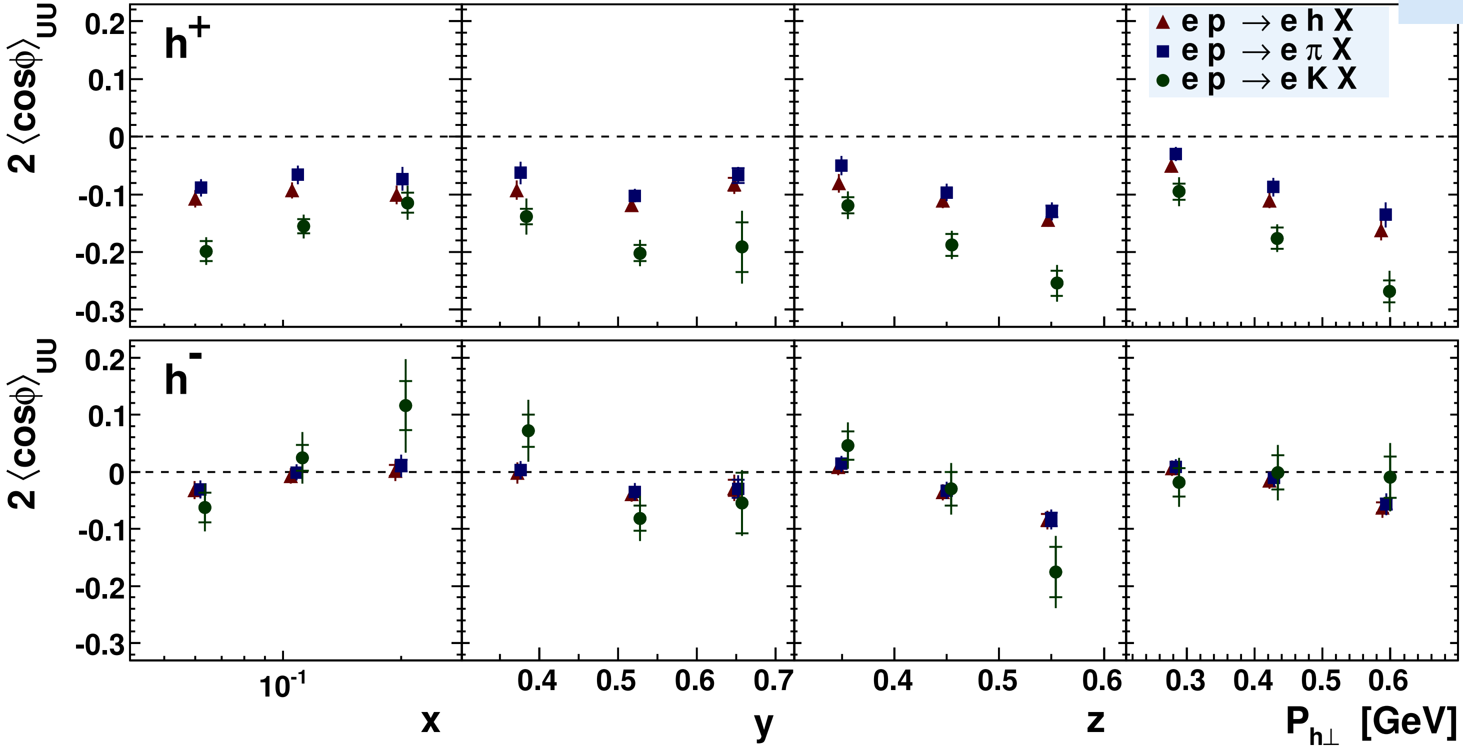

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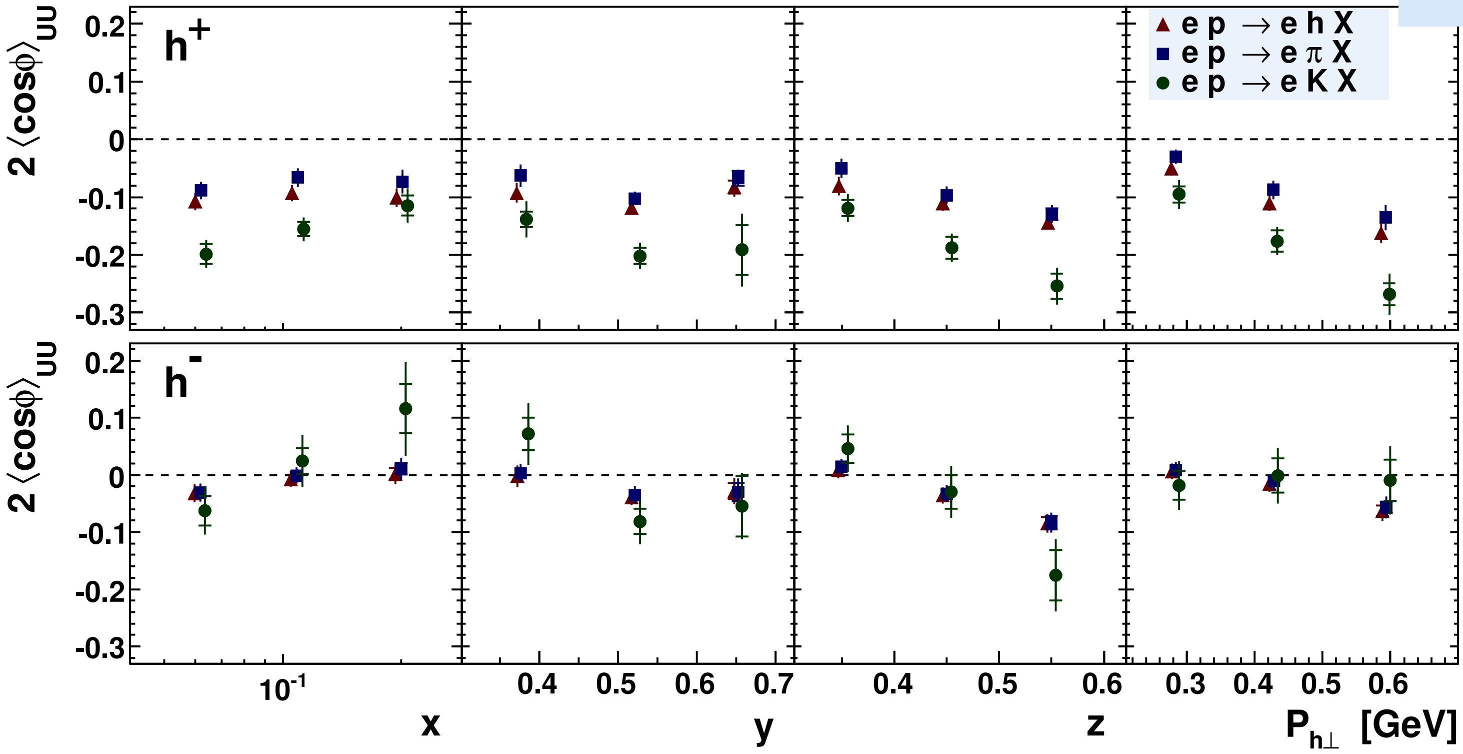

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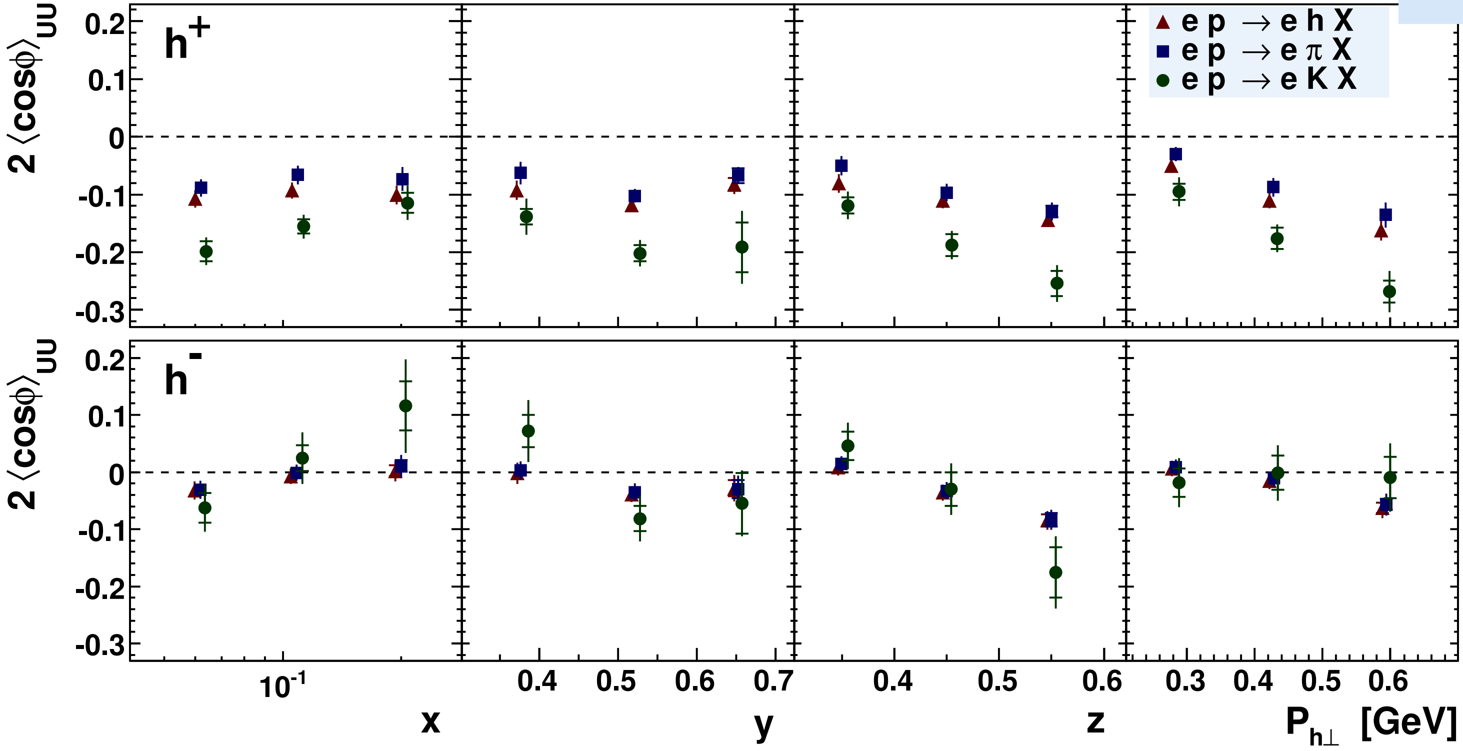

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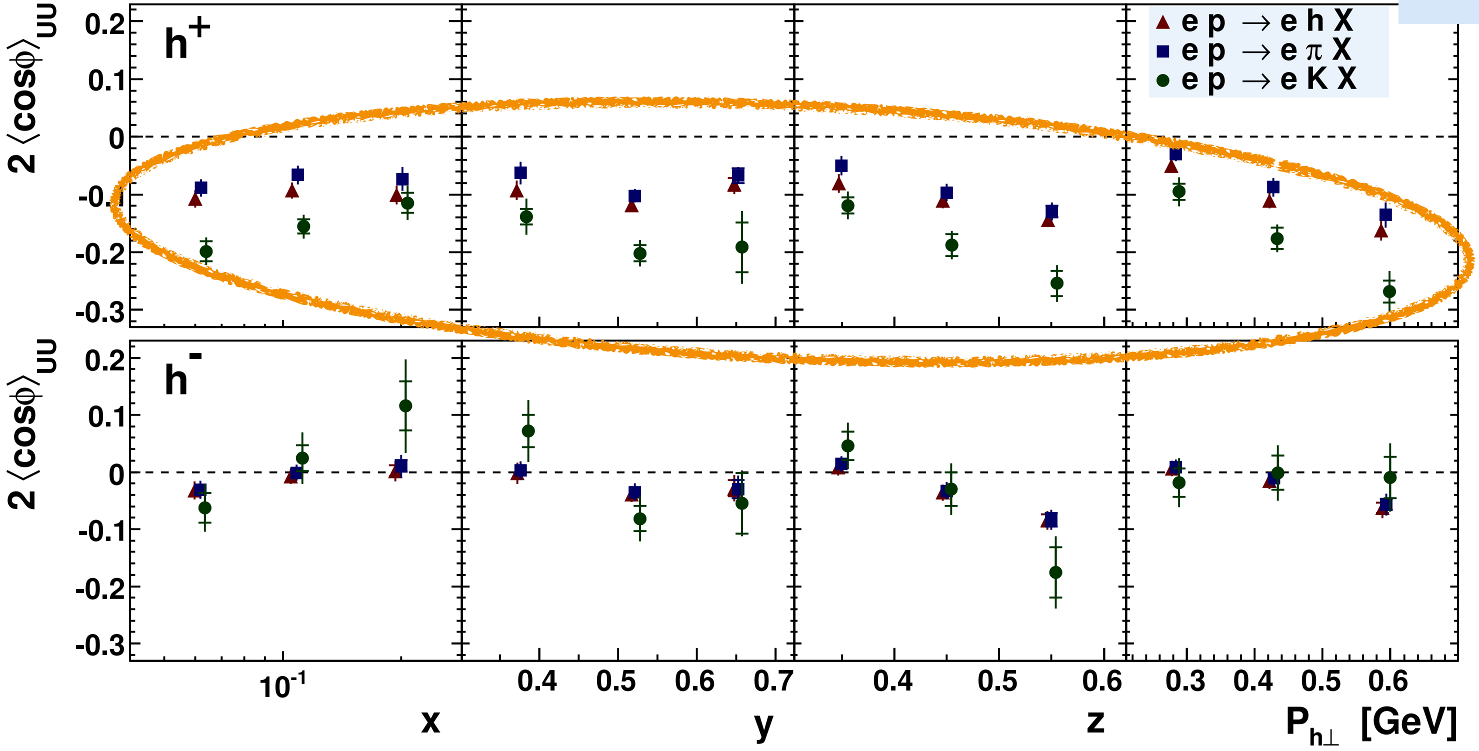

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- **even larger amplitudes in magnitude for K^+ than those for π^+**

beyond the leading twist: quark-gluon correlations

$$d\sigma = d\sigma^0_{UU} \quad + \quad ... \quad + \quad P_l \frac{1}{Q}\sin(\phi) d\sigma^3_{LU}$$

convolutions of twist-2 and twist-3 functions

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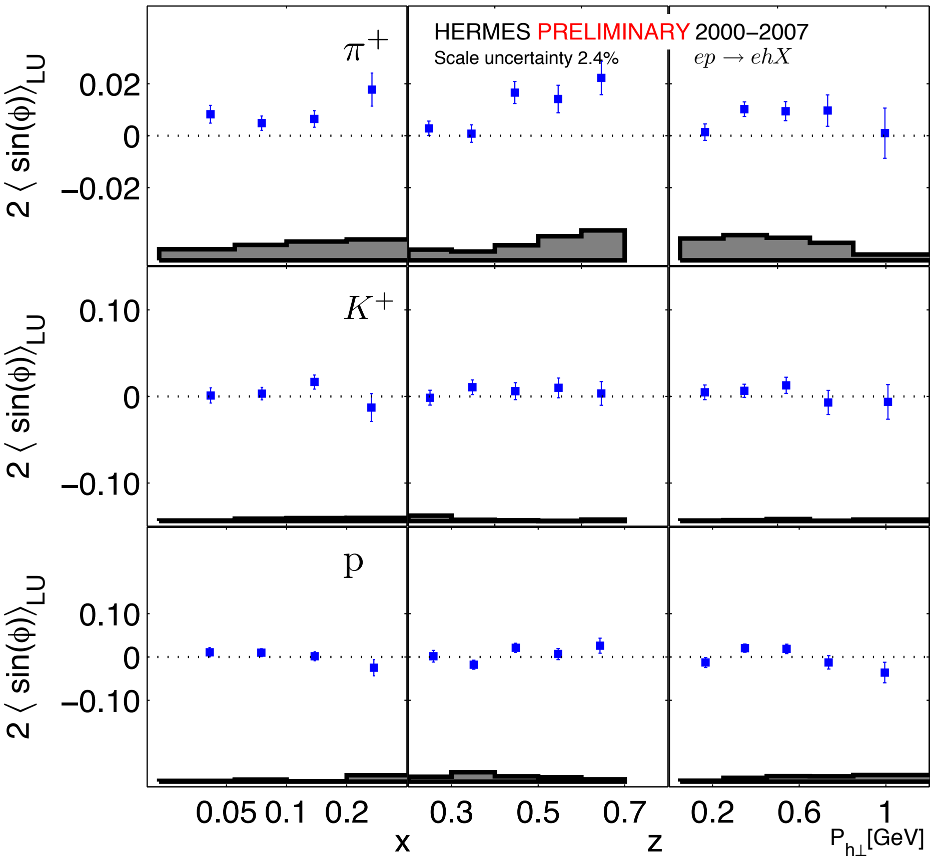

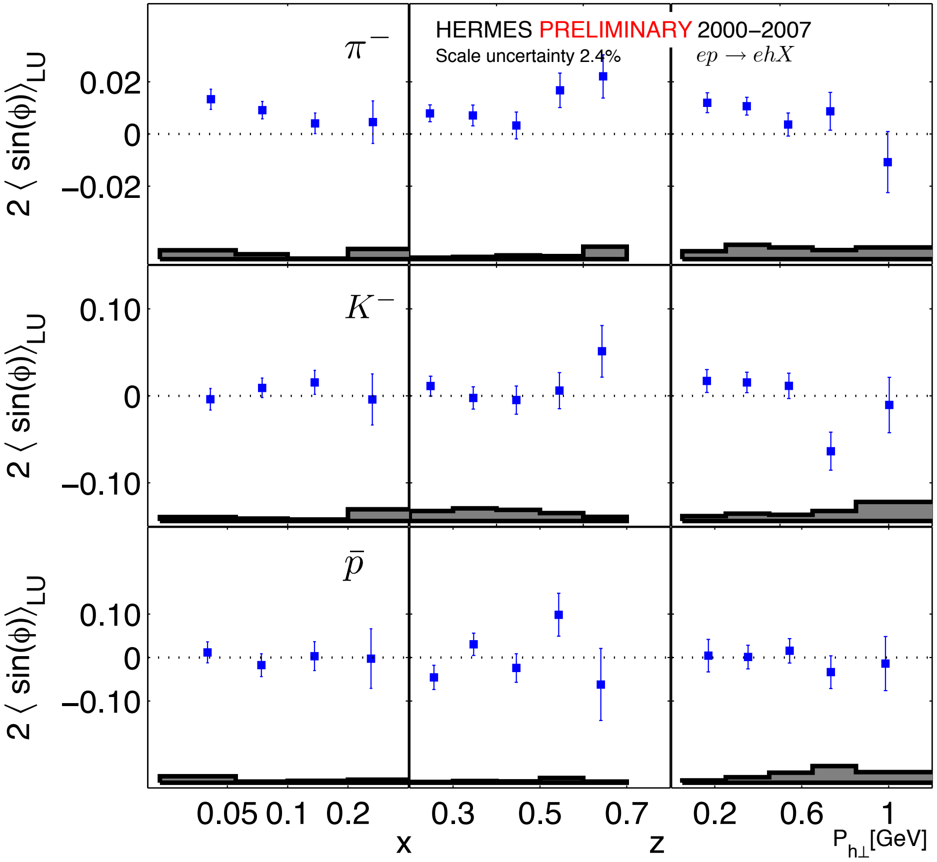

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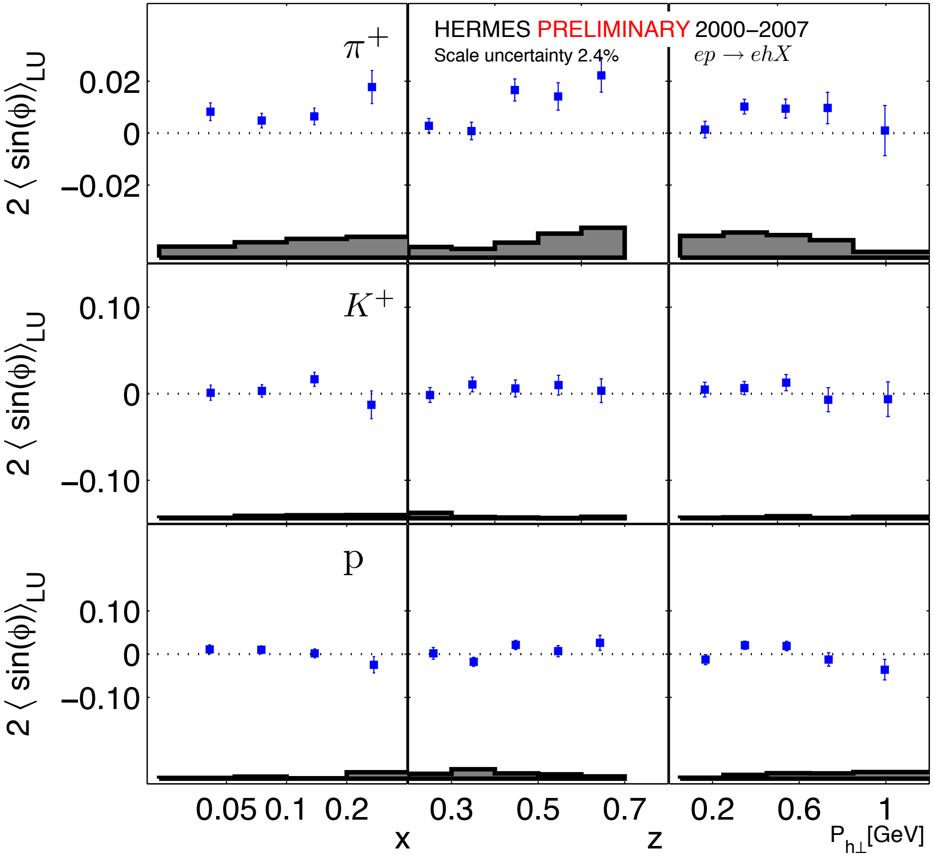

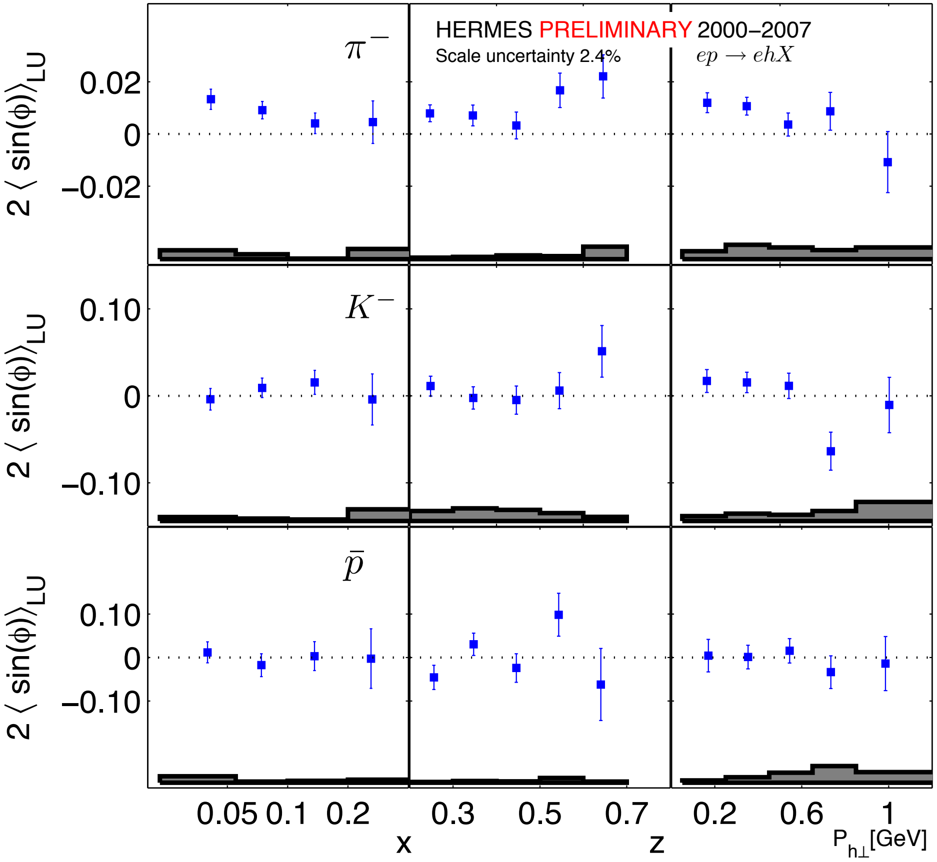

- **π+ and π-**
  - the role of the twist-3 DF or FF is sizeable

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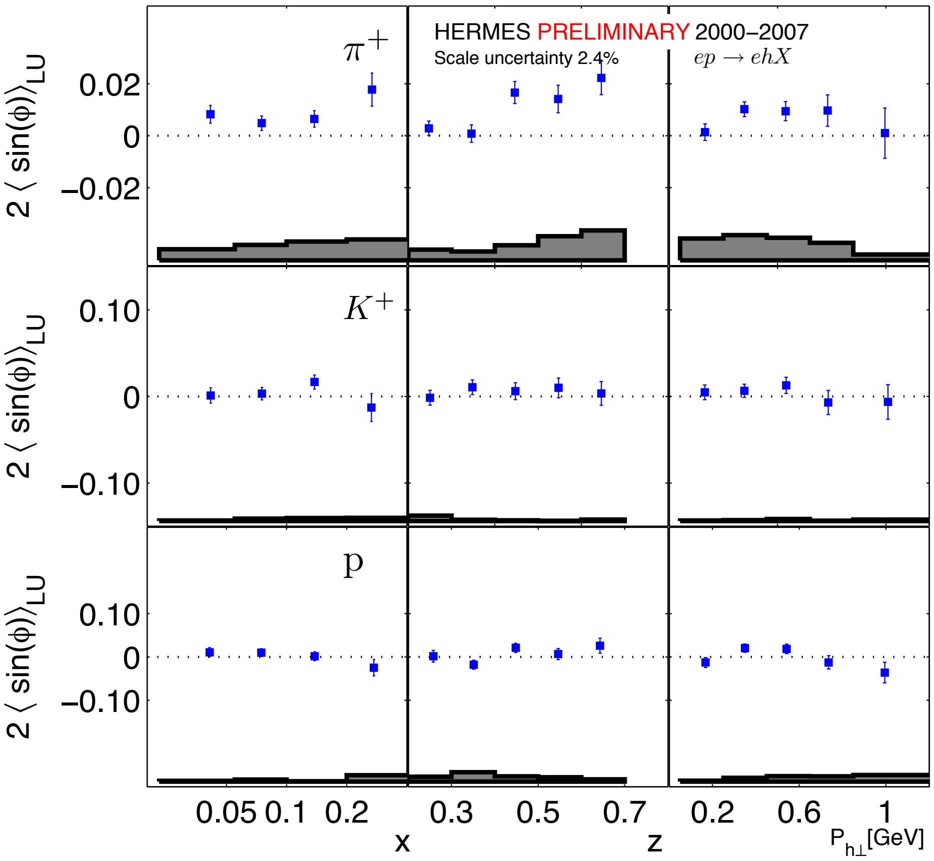

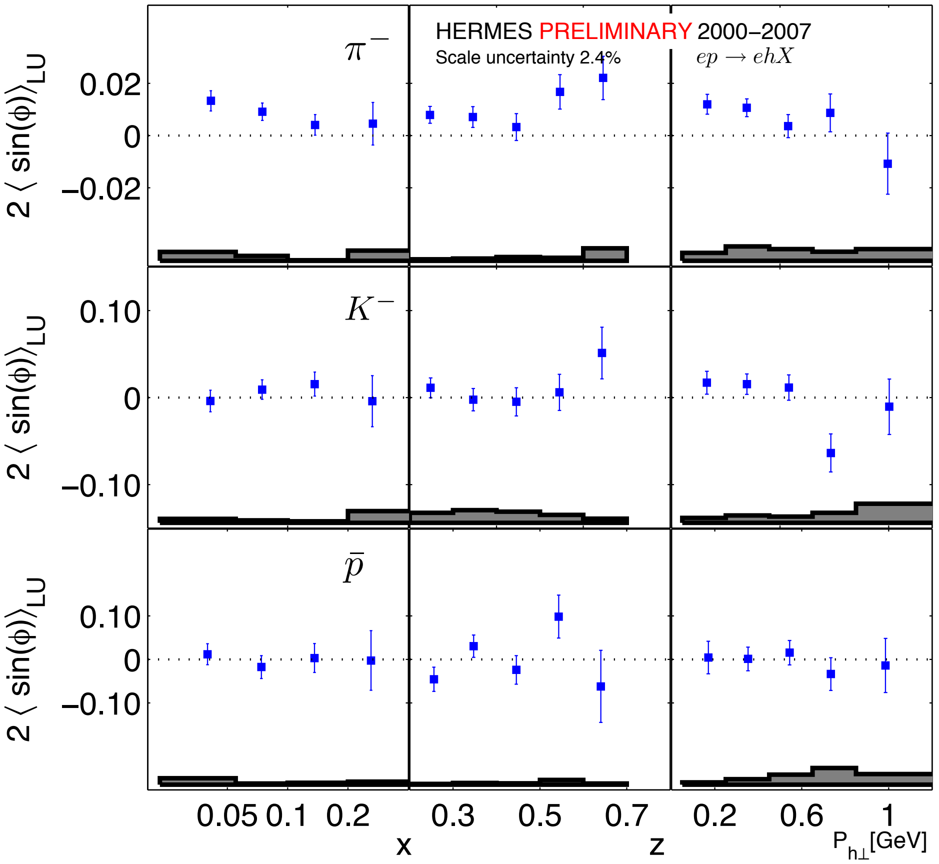

- **π+ and π-**
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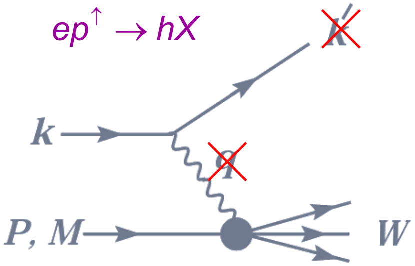
towards differential 3D (in x, y, z, Ph) extraction of asymmetry amplitudes

going to fully inclusive measurements

- first measurement in ep scattering
- High statistics (100 Mil hadrons: K and pions)

$ep^{\uparrow} \rightarrow hX$



$$x_F = 2p_L / \sqrt{s}$$

$$p_T = p\cos\theta$$

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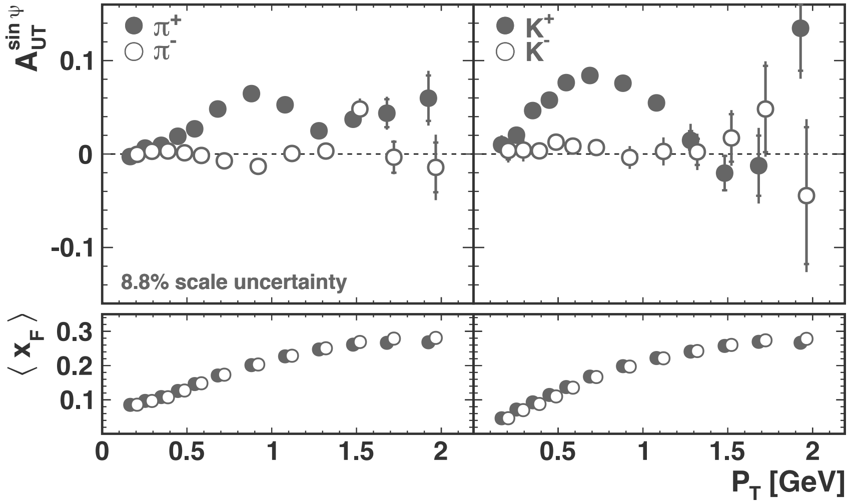
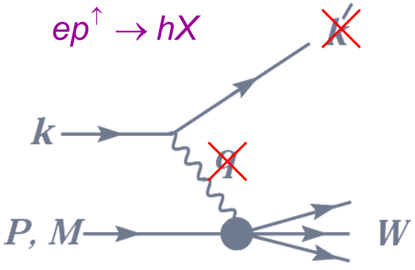
- HERMES Collaboration - Phys. Lett. B 728 (2014) 183





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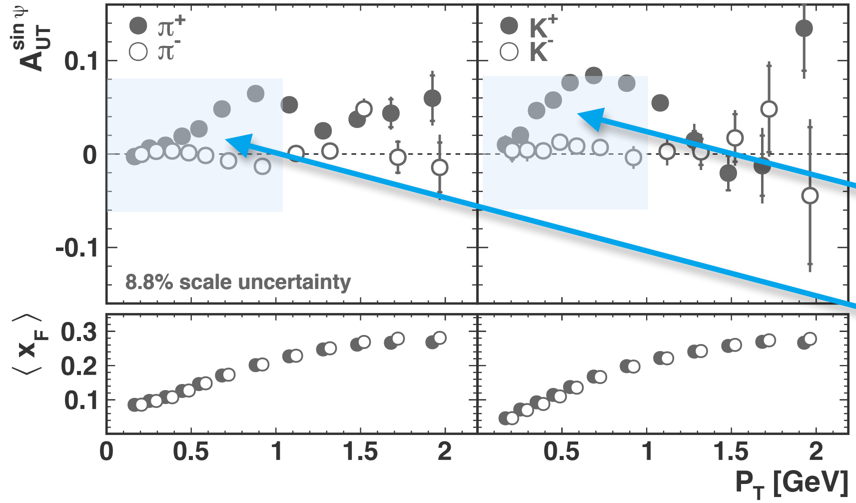
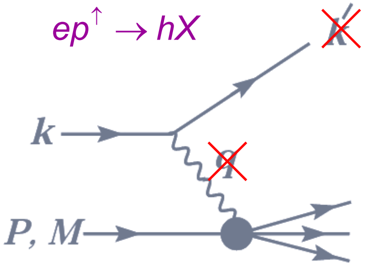


- **Sivers effect or higher twist effects ?**



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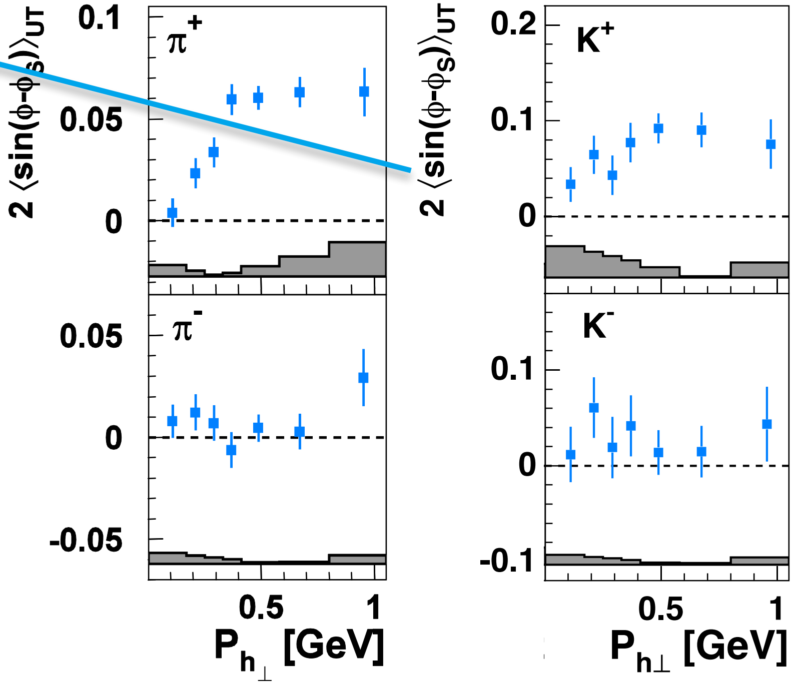
- HERMES Collaboration - Phys. Rev. Lett. 103 (2009) 152002



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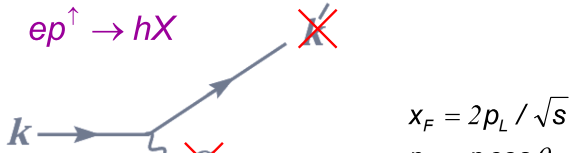

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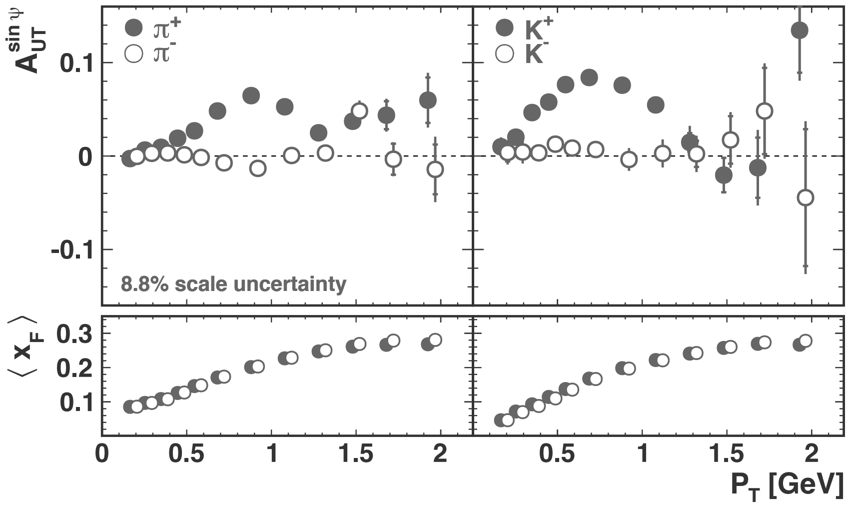
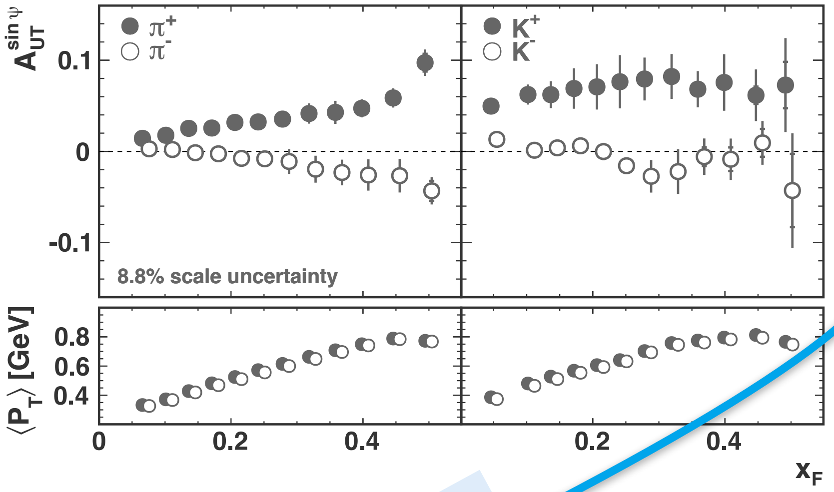
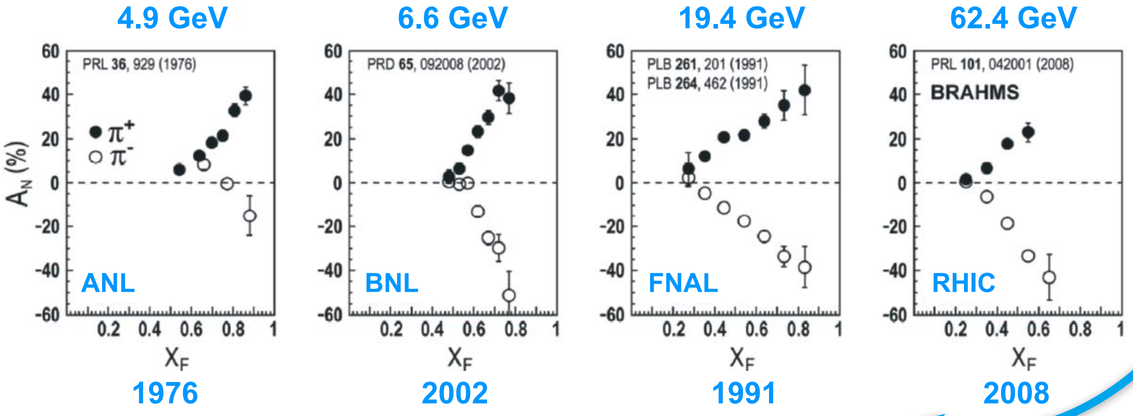




$$A_N = -\frac{2}{\pi} A_{UT}^{\sin\psi}$$

- **Sivers effect or higher twist effects ?**
- **similarities with** $\mathrm{p}^{\uparrow}\mathrm{p} \rightarrow \pi \mathrm{X}$ **?**



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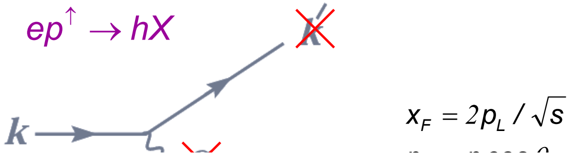

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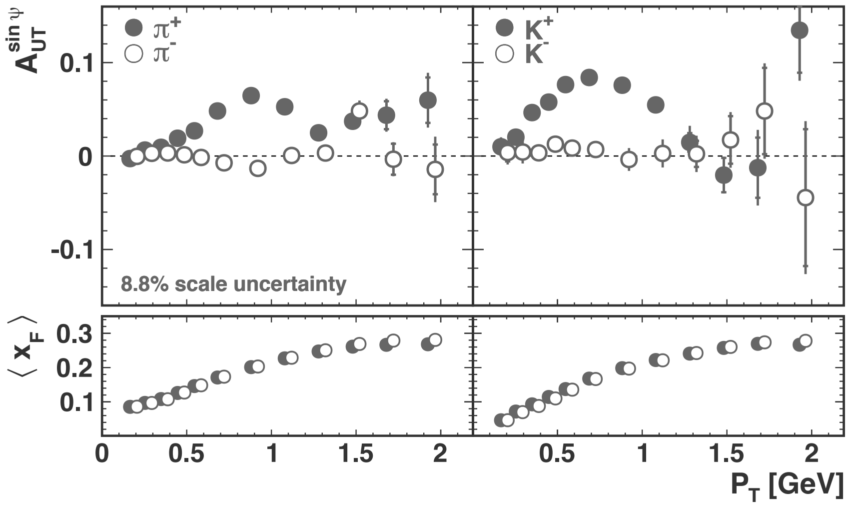
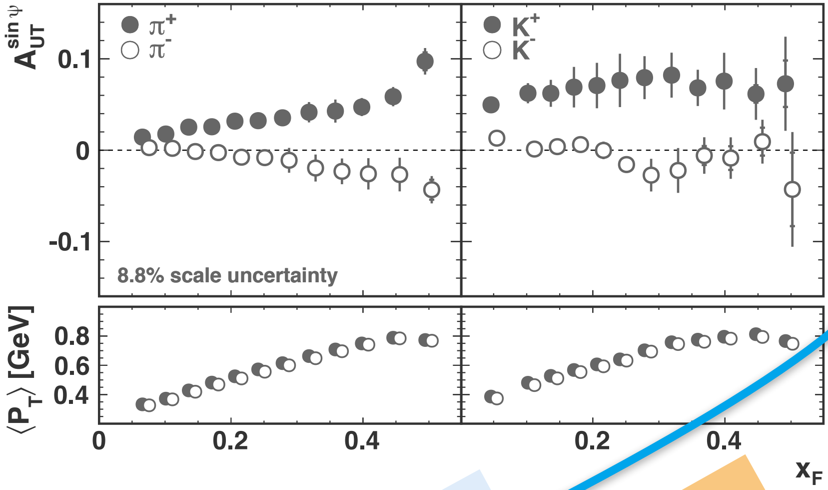
- HERMES Collaboration - Phys. Lett. B 728 (2014) 183





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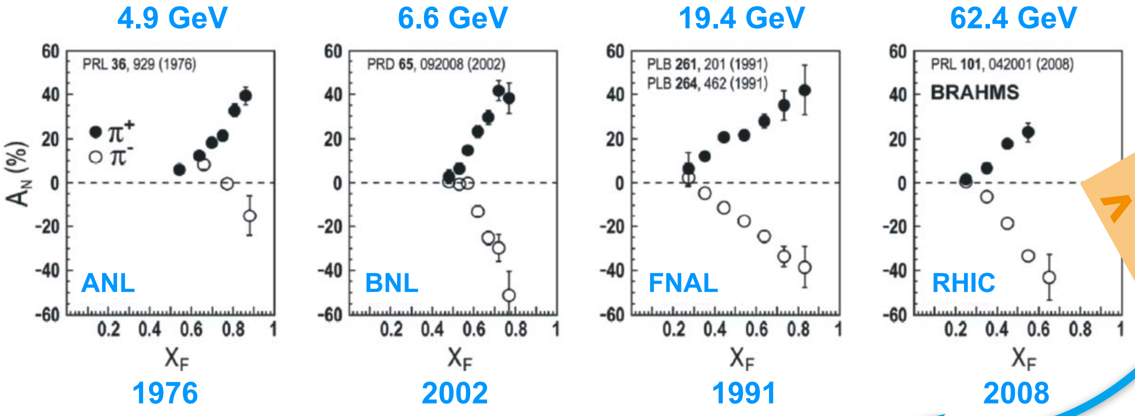


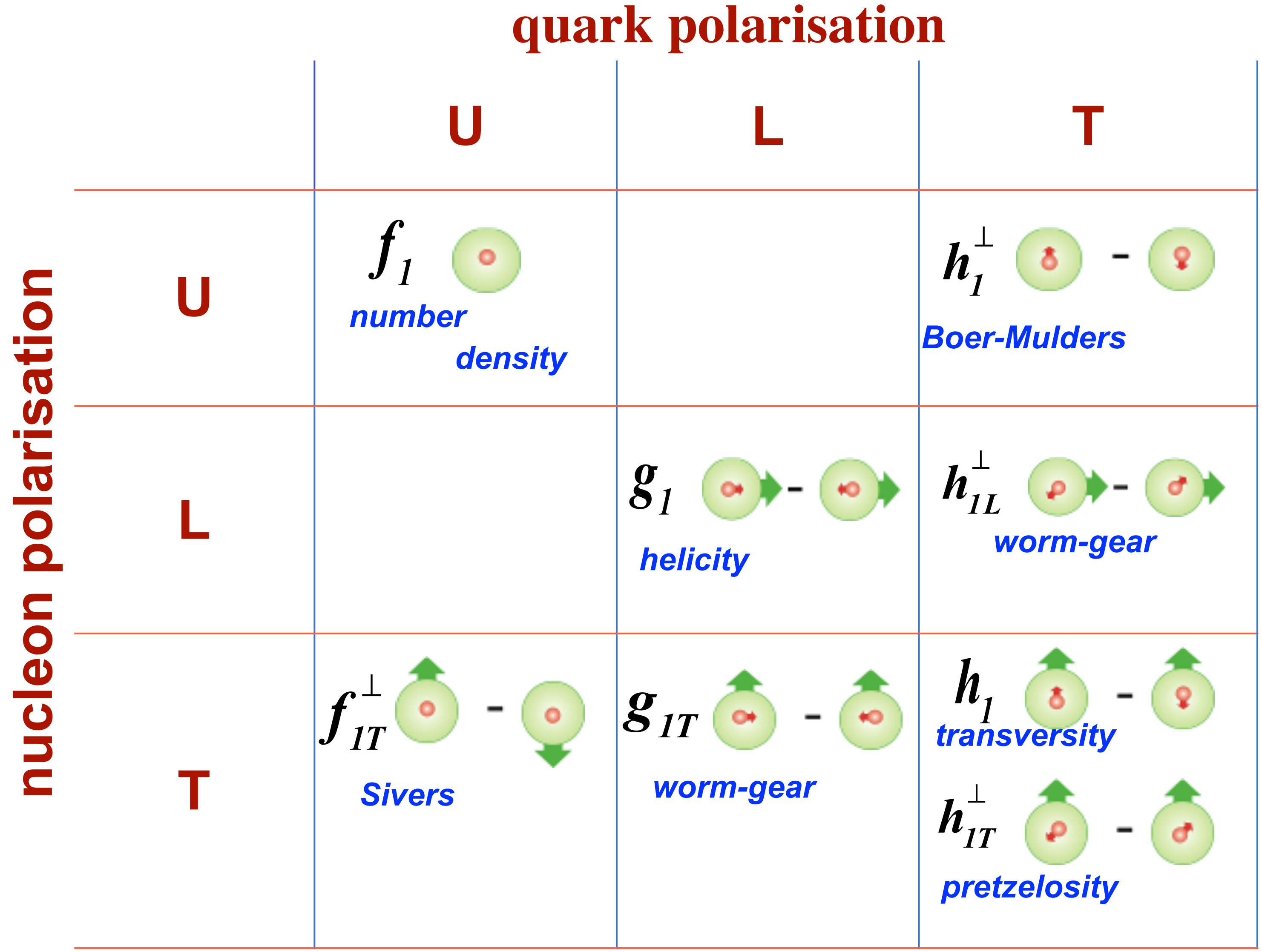
$$A_N = -\frac{2}{\pi} A_{UT}^{\sin\psi}$$

- **x_F and P_T highly correlated**
  - ➡ clear conclusions require multi- dimensional extraction

see the talk by A. Rostomyan

HERMES TMD program:

access to all TMDs thanks to the polarised beam and target



		quark polarisation		
		U	L	T
nucleon polarisation	U	f_1 number density		$h_1^\perp$ Boer-Mulders
	L		g_1 helicity	$h_{1L}^\perp$ worm-gear
	T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 transversity $h_{1T}^\perp$ pretzelosity

HERMES TMD program:

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quark polarisation

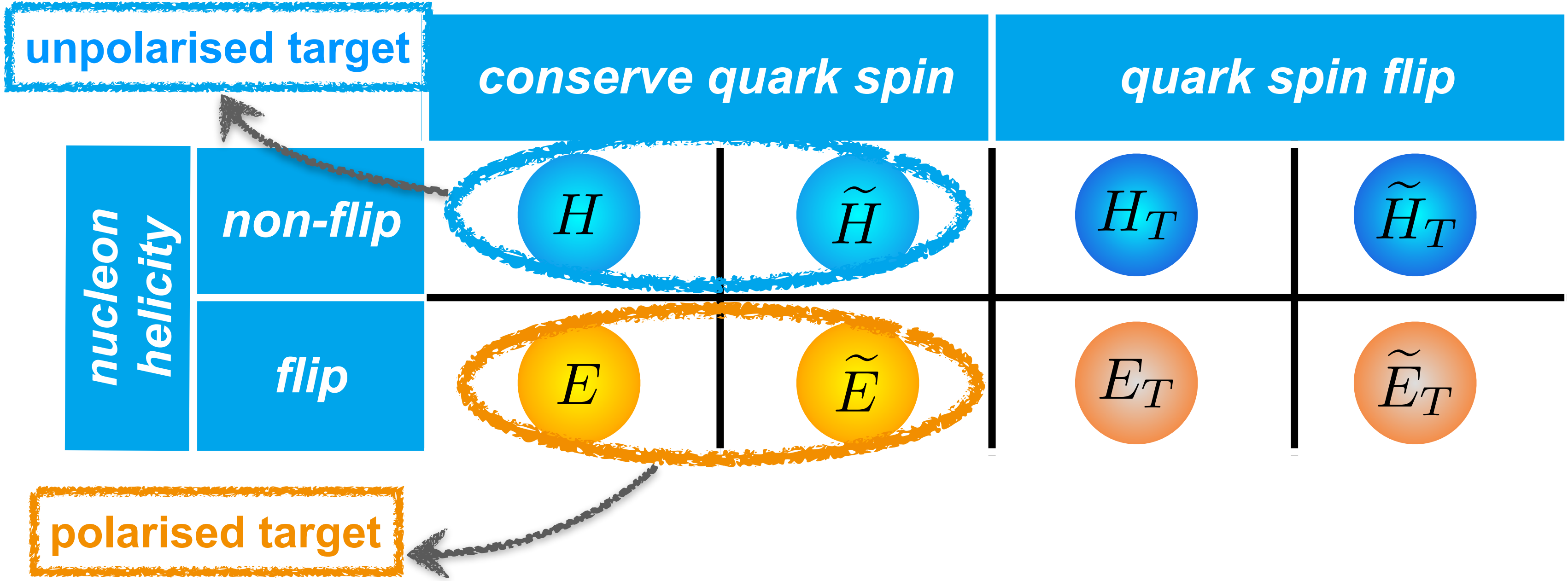
nucleon polarisation

	U	L	T	
U	f_1 number density PRD 87 (2013) 074029		$h_1^\perp$ - Boer-Mulders PRD87 (2013) 012010	
L		g_1 - helicity PRD 75 (2007) 012007	$h_{1L}^\perp$ - worm-gear	PLB 562 (2003) 182 PRL 84 (2000) 4047
T	$f_{1T}^\perp$ - Sivers PRL 94 (2005) 012002 PRL 103 (2009) 152002	g_{1T} - worm-gear released	h_1 - transversity $h_{1T}^\perp$ - pretzelosity released	PRL 94 (2005) 012002 PLB 693 (2010) 11

GPDs

		conserve quark spin		quark spin flip	
nucleon helicity	non-flip	H	$\widetilde{H}$	H_T	$\widetilde{H}_T$
	flip	E	$\widetilde{E}$	E_T	$\widetilde{E}_T$

GPDs



unpolarised target

		conserve quark spin		quark spin flip	
nucleon helicity	non-flip	H	$\widetilde{H}$	H_T	$\widetilde{H}_T$
	flip	E	$\widetilde{E}$	E_T	$\widetilde{E}_T$

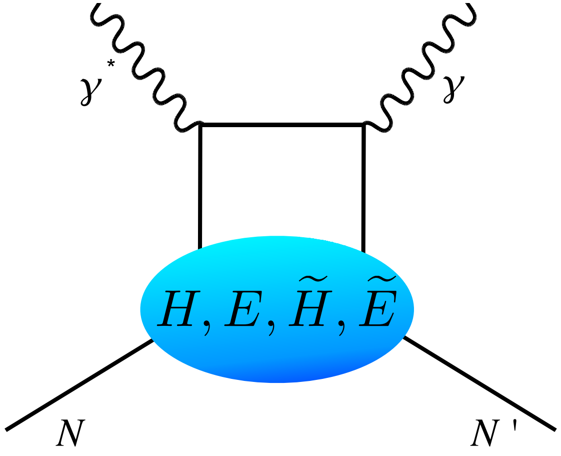
polarised target

GPDs

- **DVCS**
  - at leading twist:

H E $\widetilde{H}$ $\widetilde{E}$

- **deeply virtual Compton scattering**

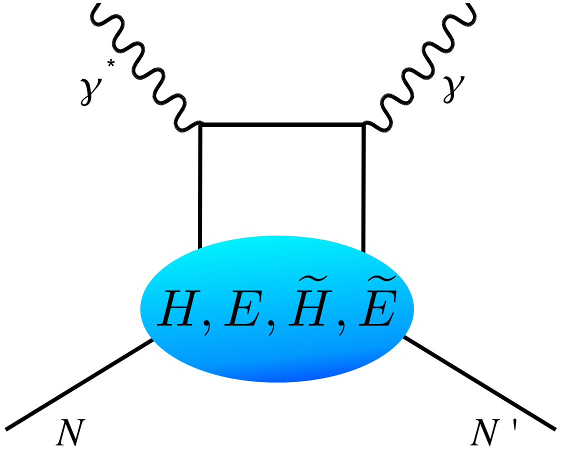


GPDs

- **DVCS**
  - at leading twist:

H E $\widetilde{H}$ $\widetilde{E}$

- **deeply virtual Compton scattering**



- **vector mesons:**
  - at leading twist:

H E

  - higher twist:

$\widetilde{H}$ $\widetilde{E}$

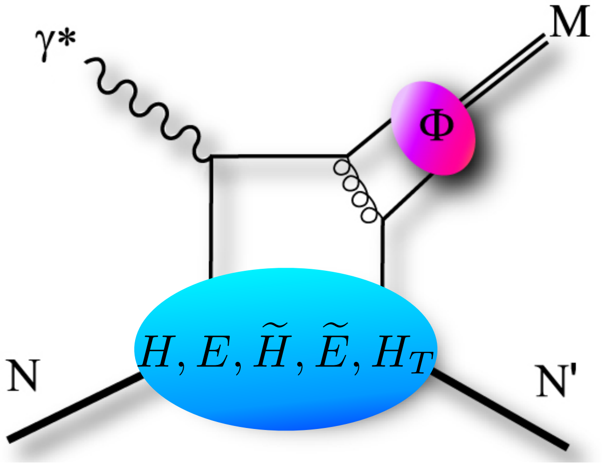
- **pseudoscalar mesons**
  - at leading twist:

$\widetilde{H}$ $\widetilde{E}$

  - higher twist:

H_T

- **vector and pseudoscalar meson production**



exclusive measurements
(probing GPDs)

hermes highlights

γ

- > measured complete set of beam helicity, beam charge and target polarisation asymmetries
- > first measurement of associated DVCS

ρ^0 ω ϕ

- > complete set of SDMEs on unpolarised H and D targets
- > first measurement of SDMEs on a transversely polarised target

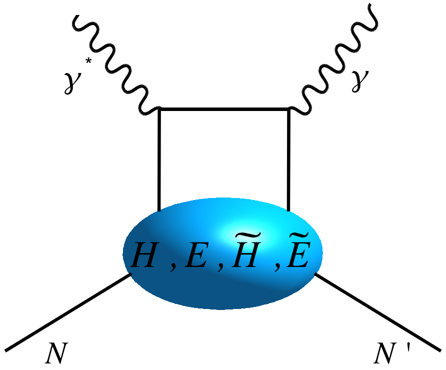
π^+

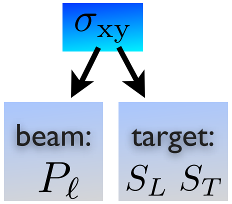
- > first measurement of asymmetry on transversely polarised target sensitive to H_T

DVCS

theoretically the cleanest probe of GPDs

$$\gamma^* N \to \gamma N : H, E, \widetilde{H}, \widetilde{E}$$





σ_{xy}

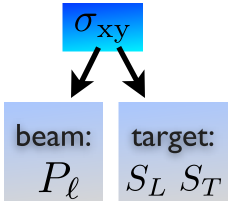
beam: P_ℓ

target: $S_L\ S_T$

DVCS

theoretically the cleanest probe of GPDs

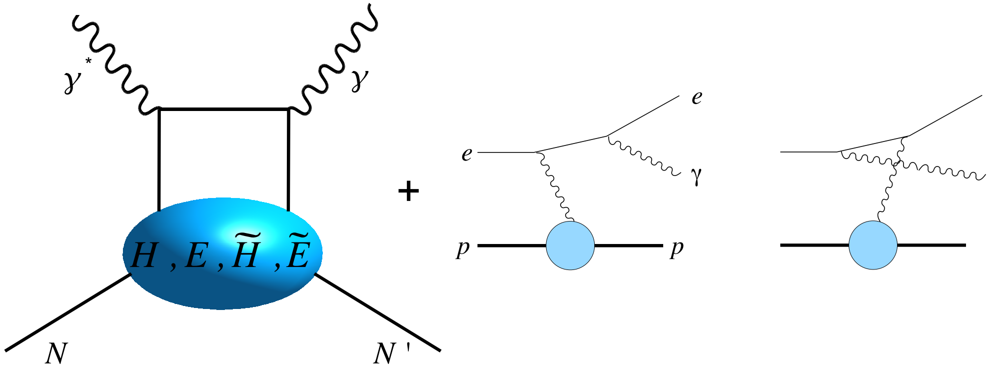
$$\gamma^* N \rightarrow \gamma N : H, E, \widetilde{H}, \widetilde{E}$$



σ_{xy}

beam: P_ℓ

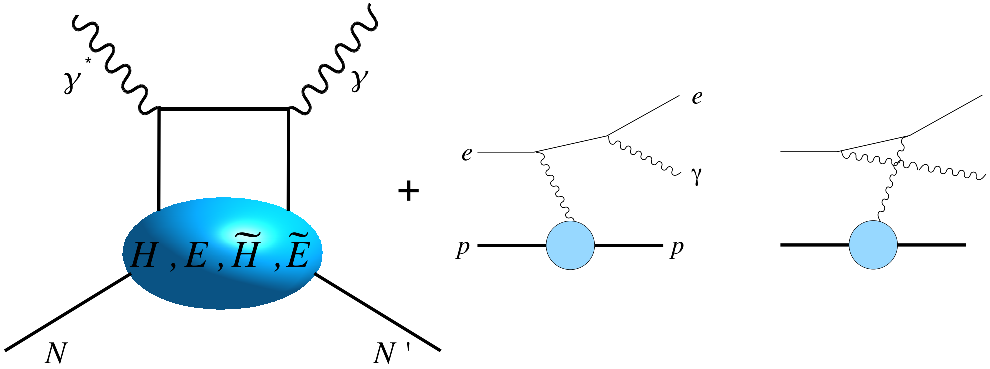
target: S_L S_T

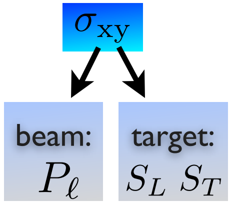


DVCS

theoretically the cleanest probe of GPDs

$$\gamma^* N \to \gamma N : H, E, \widetilde{H}, \widetilde{E}$$




σ_{xy}

beam: P_ℓ

target: $S_L\ S_T$

Bethe–Heitler

interference

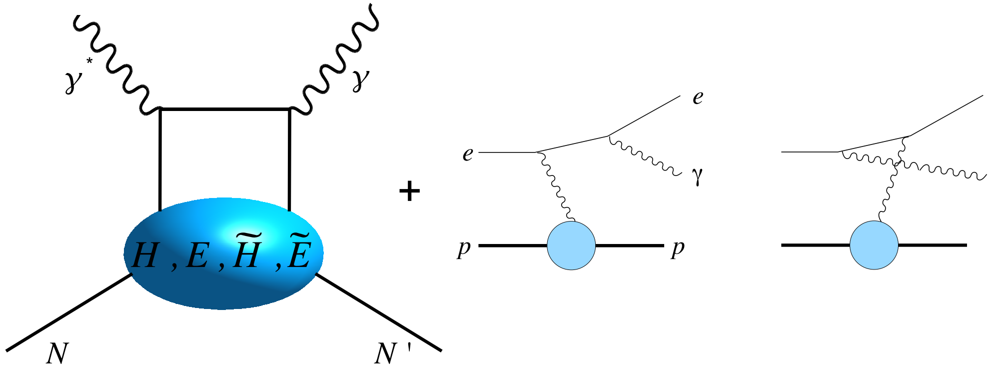
DVCS

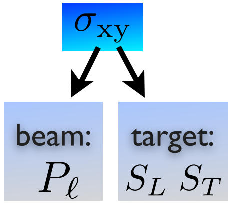
$$\begin{aligned}
d\sigma \sim d\sigma^{BH}_{UU} \quad &+ \quad e_\ell d\sigma^{I}_{UU} + d\sigma^{DVCS}_{UU} \\
&+ \quad e_\ell P_\ell d\sigma^{I}_{LU} + P_\ell d\sigma^{DVCS}_{LU} \\
&+ \quad e_\ell S_L d\sigma^{I}_{UL} + S_L d\sigma^{DVCS}_{UL} \\
&+ \quad e_\ell S_T d\sigma^{I}_{UT} + S_T d\sigma^{DVCS}_{UT} \\
+P_\ell S_L d\sigma^{BH}_{LL} \quad &+ \quad e_\ell P_\ell S_L d\sigma^{I}_{LL} + P_\ell S_L d\sigma^{DVCS}_{LL} \\
+P_\ell S_T d\sigma^{BH}_{LT} \quad &+ \quad e_\ell P_\ell S_T d\sigma^{I}_{LT} + P_\ell S_T d\sigma^{DVCS}_{LT}
\end{aligned}$$

DVCS

theoretically the cleanest probe of GPDs

$$\gamma^* N \to \gamma N : H, E, \widetilde{H}, \widetilde{E}$$





beam: P_ℓ

target: $S_L\ S_T$

Bethe–Heitler

beam charge: e_ℓ

interference

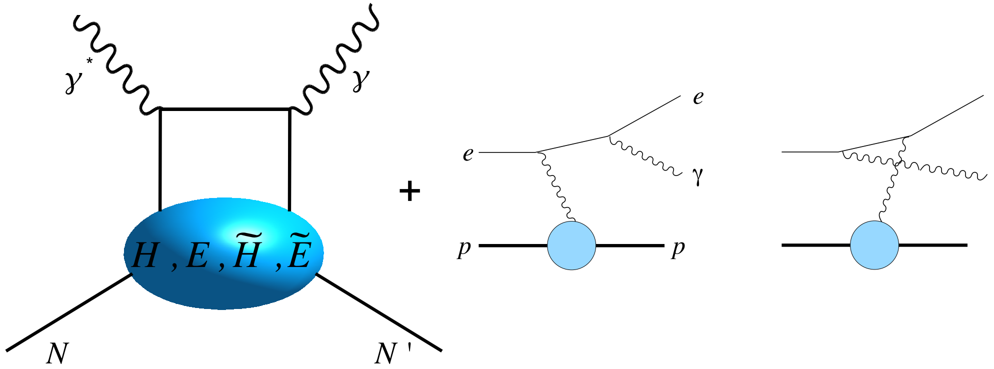
DVCS

$$
\begin{array}{rcl}
d\sigma \sim d\sigma^{BH}_{UU} & + & e_\ell d\sigma^{I}_{UU} + d\sigma^{DVCS}_{UU} \\
 & + & e_\ell P_\ell d\sigma^{I}_{LU} + P_\ell d\sigma^{DVCS}_{LU} \\
 & + & e_\ell S_L d\sigma^{I}_{UL} + S_L d\sigma^{DVCS}_{UL} \\
 & + & e_\ell S_T d\sigma^{I}_{UT} + S_T d\sigma^{DVCS}_{UT} \\
+P_\ell S_L d\sigma^{BH}_{LL} & + & e_\ell P_\ell S_L d\sigma^{I}_{LL} + P_\ell S_L d\sigma^{DVCS}_{LL} \\
+P_\ell S_T d\sigma^{BH}_{LT} & + & e_\ell P_\ell S_T d\sigma^{I}_{LT} + P_\ell S_T d\sigma^{DVCS}_{LT}
\end{array}
$$

DVCS

theoretically the cleanest probe of GPDs

$$\gamma^* N \to \gamma N : H, E, \widetilde{H}, \widetilde{E}$$



σ_{xy}

beam: P_ℓ

target: $S_L\ S_T$

beam charge: e_ℓ

Bethe–Heitler

interference

DVCS

$$\begin{aligned} d\sigma \sim d\sigma_{UU}^{BH} \quad &+ \quad e_\ell d\sigma_{UU}^{I} + d\sigma_{UU}^{DVCS} \\ &+ \quad e_\ell P_\ell d\sigma_{LU}^{I} + P_\ell d\sigma_{LU}^{DVCS} \\ &+ \quad e_\ell S_L d\sigma_{UL}^{I} + S_L d\sigma_{UL}^{DVCS} \\ &+ \quad e_\ell S_T d\sigma_{UT}^{I} + S_T d\sigma_{UT}^{DVCS} \\ +P_\ell S_L d\sigma_{LL}^{BH} \quad &+ \quad e_\ell P_\ell S_L d\sigma_{LL}^{I} + P_\ell S_L d\sigma_{LL}^{DVCS} \\ +P_\ell S_T d\sigma_{LT}^{BH} \quad &+ \quad e_\ell P_\ell S_T d\sigma_{LT}^{I} + P_\ell S_T d\sigma_{LT}^{DVCS} \end{aligned}$$

- **unpolarised target**

$$F_1 \boxed{\mathcal{H}} + \frac{x_B}{2 - x_B}(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$$

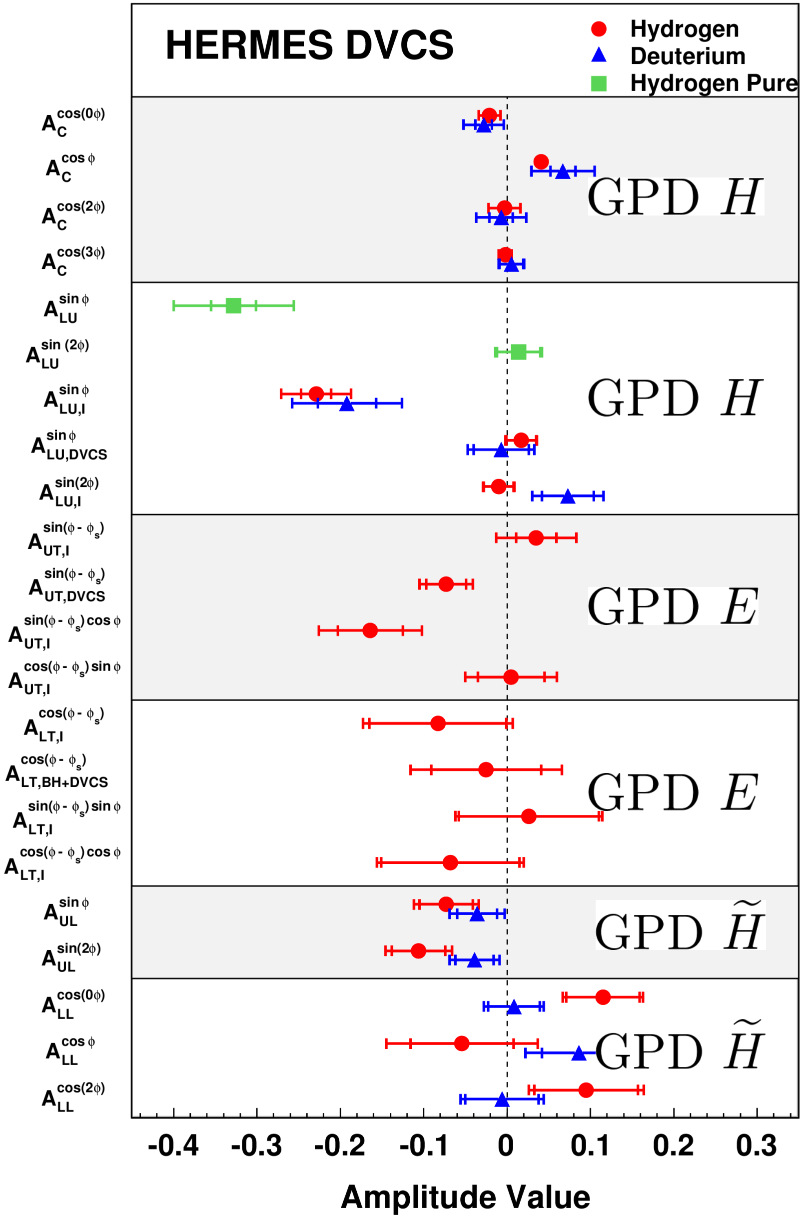
- **longitudinally polarised target**

$$\frac{x_B}{2 - x_B}(F_1 + F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right)$$
$$+F_1 \boxed{\widetilde{\mathcal{H}}} - \frac{x_B}{2 - x_B}\left(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right)\widetilde{\mathcal{E}}$$

- **transversely polarised target**

$$\frac{t}{4M^2}\left[(2 - x_B)F_1 \boxed{\mathcal{E}} - 4\frac{1 - x_B}{2 - x_B}F_2\mathcal{H}\right]$$

complete set of DVCS asymmetries



- Beam-charge and beam-spin asymmetry

  PRL 87 (2001) 182001

  PRD 75 (2007) 011103

  JHEP 11 (2009) 083

  JHEP 07 (2012) 032, *JHEP 10 (2012) 042*

  Nucl. Phys. B 829 (2010) 1

- Transverse target-spin asymmetry

  JHEP 06 (2008) 066

- Transverse double-spin asymmetry

  Phys. Lett. B 704 (2011) 15

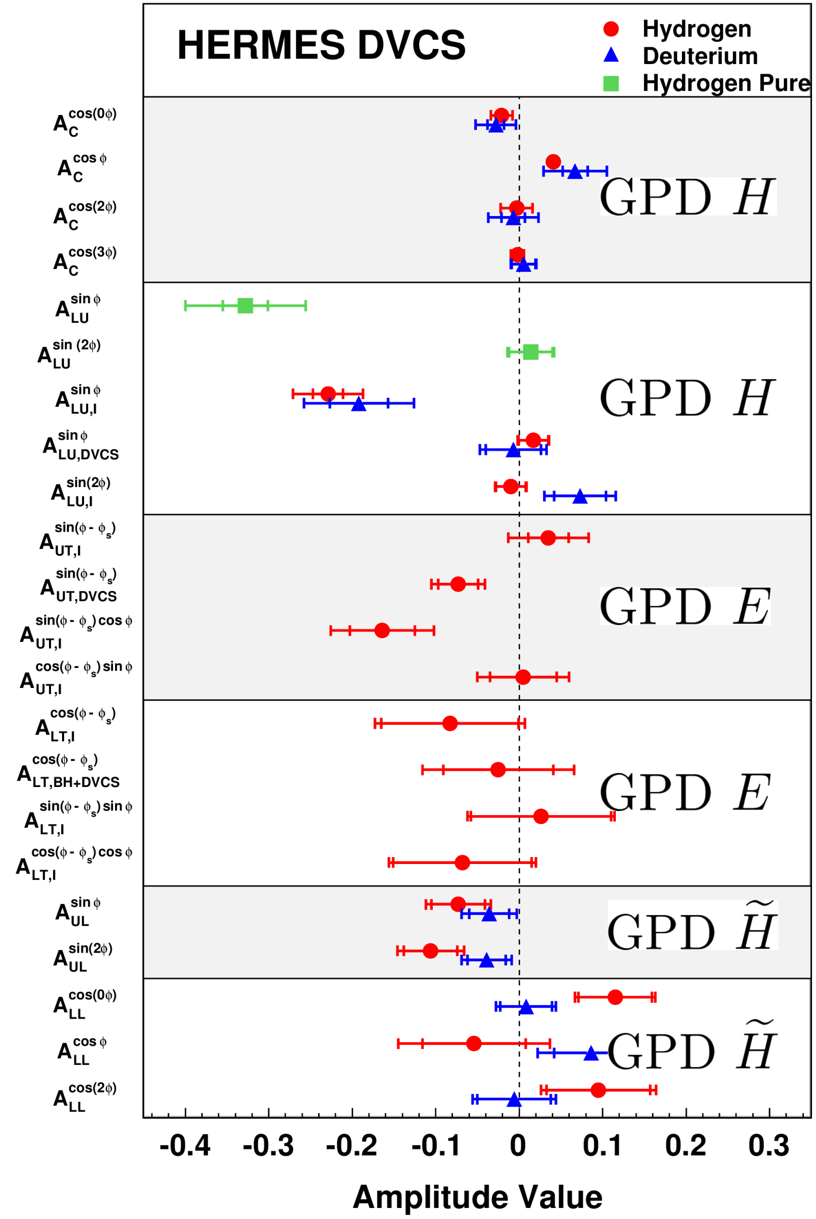
- Longitudinal target spin asymmetry

  JHEP 06 (2010) 019

- Longitudinal target & double spin asymmetry

  Nucl. Phys. B 842 (2011) 265

complete set of DVCS asymmetries



- Beam-charge and beam-spin asymmetry

  PRL 87 (2001) 182001

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  JHEP 06 (2010) 019

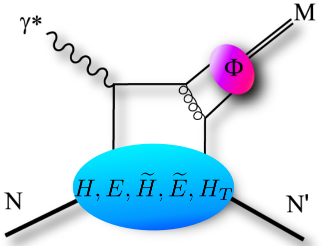
- Longitudinal target & double spin asymmetry

  Nucl. Phys. B 842 (201

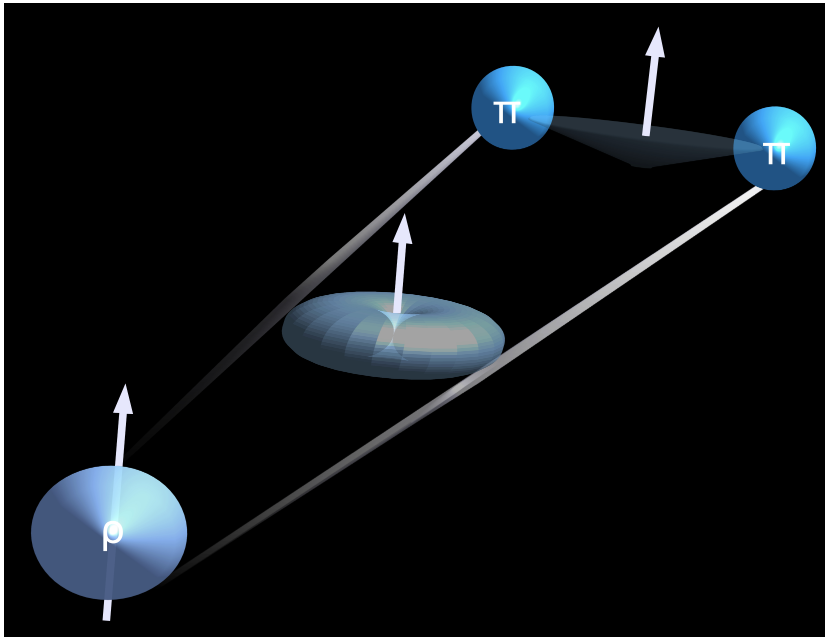
see the talk by H. Marukyan

vector meson production cross section

$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_s\, d\phi\, d\cos\vartheta\, d\varphi} \sim \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)$$

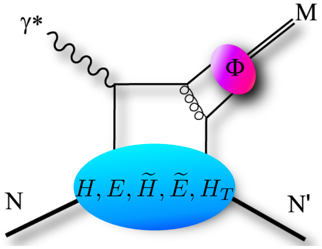


- the spin-state of the vector meson is reflected in the orbital angular momentum of the decay particles



vector meson production cross section

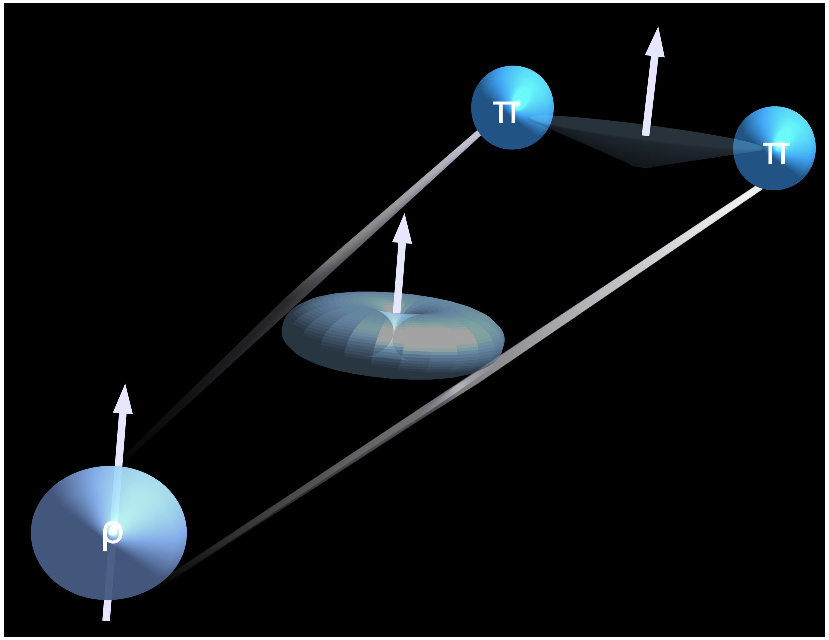
$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_s\, d\phi\, d\cos\vartheta\, d\varphi} \sim \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)$$



- **production and decay angular distributions:**

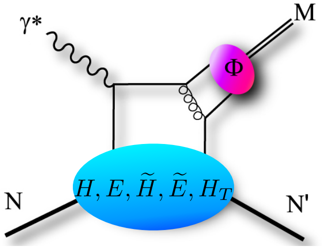
$$W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}$$

- the spin-state of the vector meson is reflected in the orbital angular momentum of the decay particles



vector meson production cross section

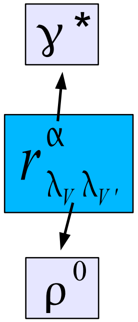
$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_s\, d\phi\, d\cos\vartheta\, d\varphi} \sim \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)$$



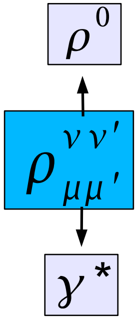
- **production and decay angular distributions:**

$$W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}$$

- **parametrised by SDMEs**
  - 15 SDMEs → unpolarised target
  - 8 SDMEs → longitudinally polarised beam
  - 30 SMDEs → transversely polarised target

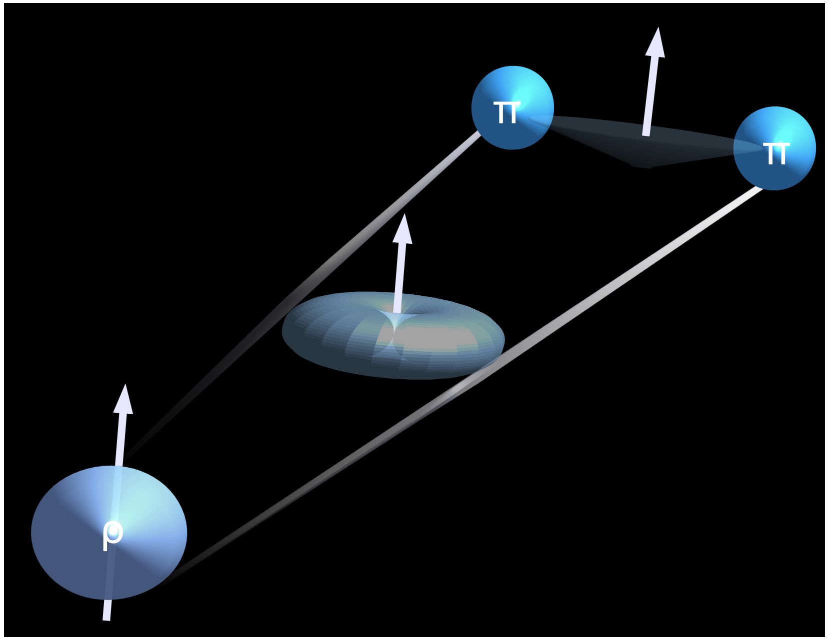


-Schilling, Wolf (1973)-

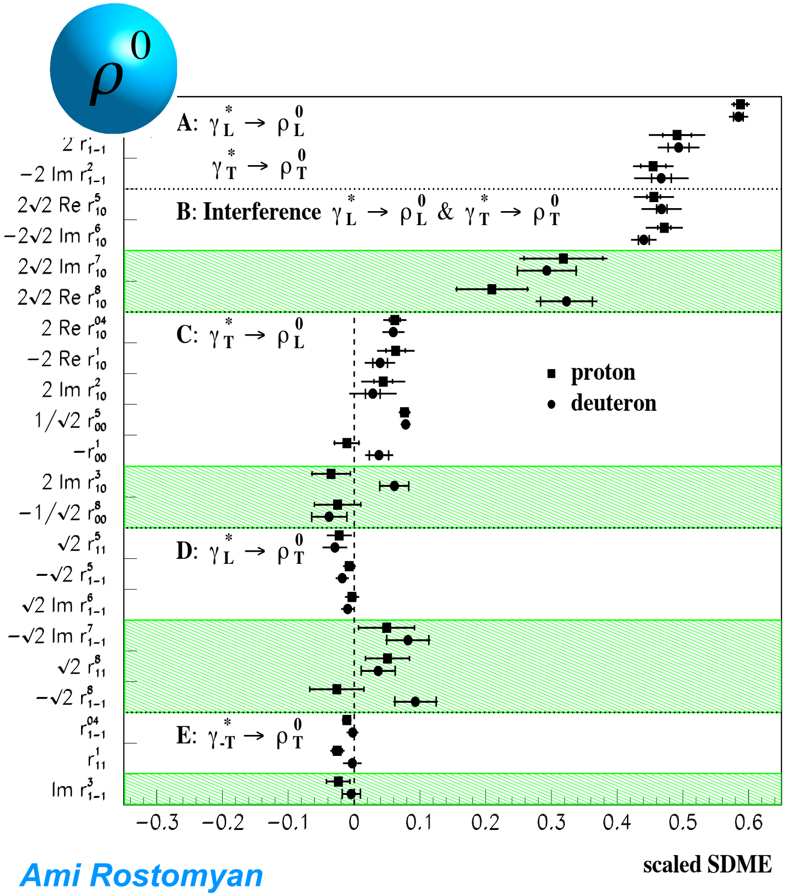


-Diehl (2007)-

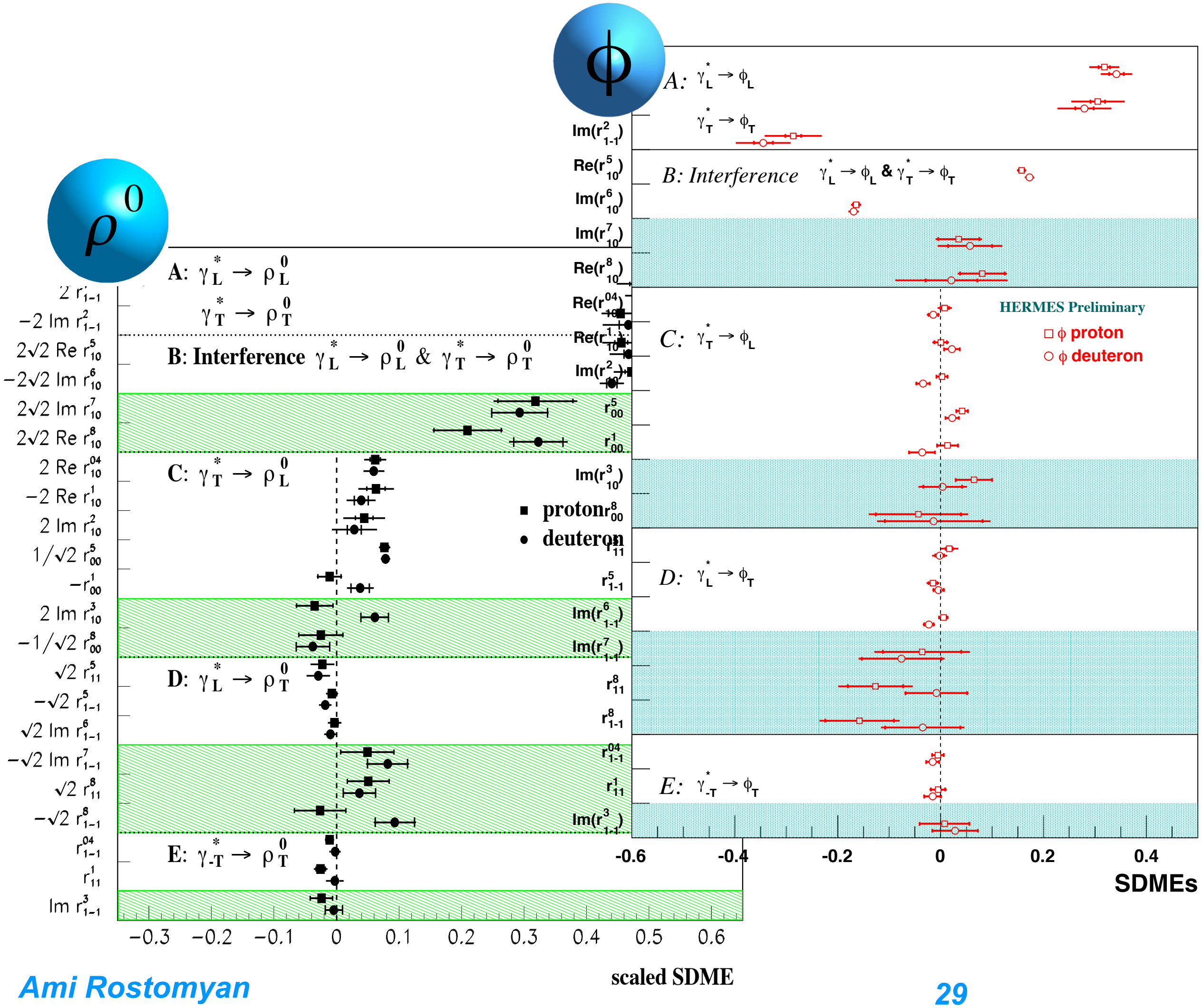
- the spin-state of the vector meson is reflected in the orbital angular momentum of the decay particles



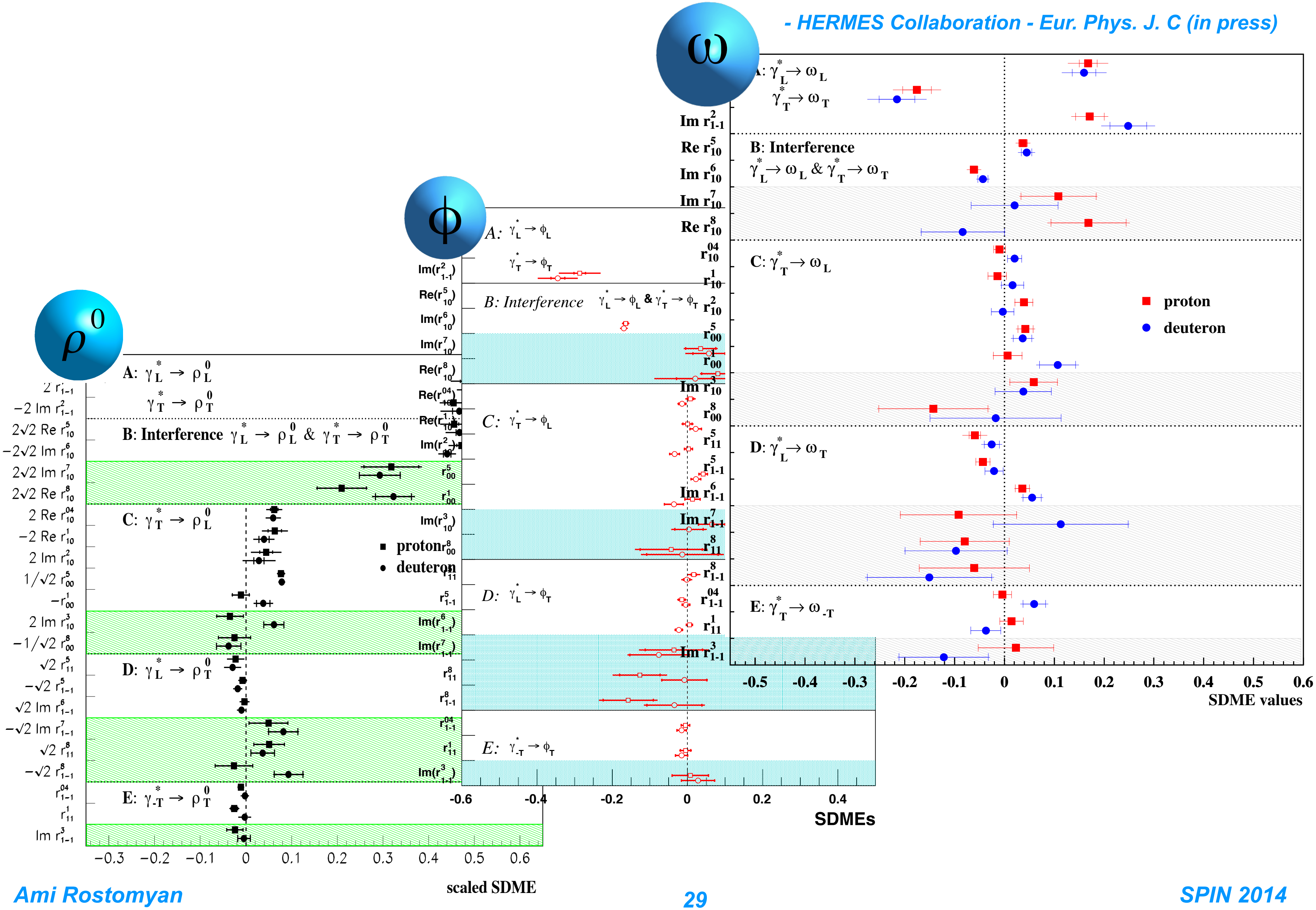
SDMEs of vector meson production



SDMEs of vector meson production



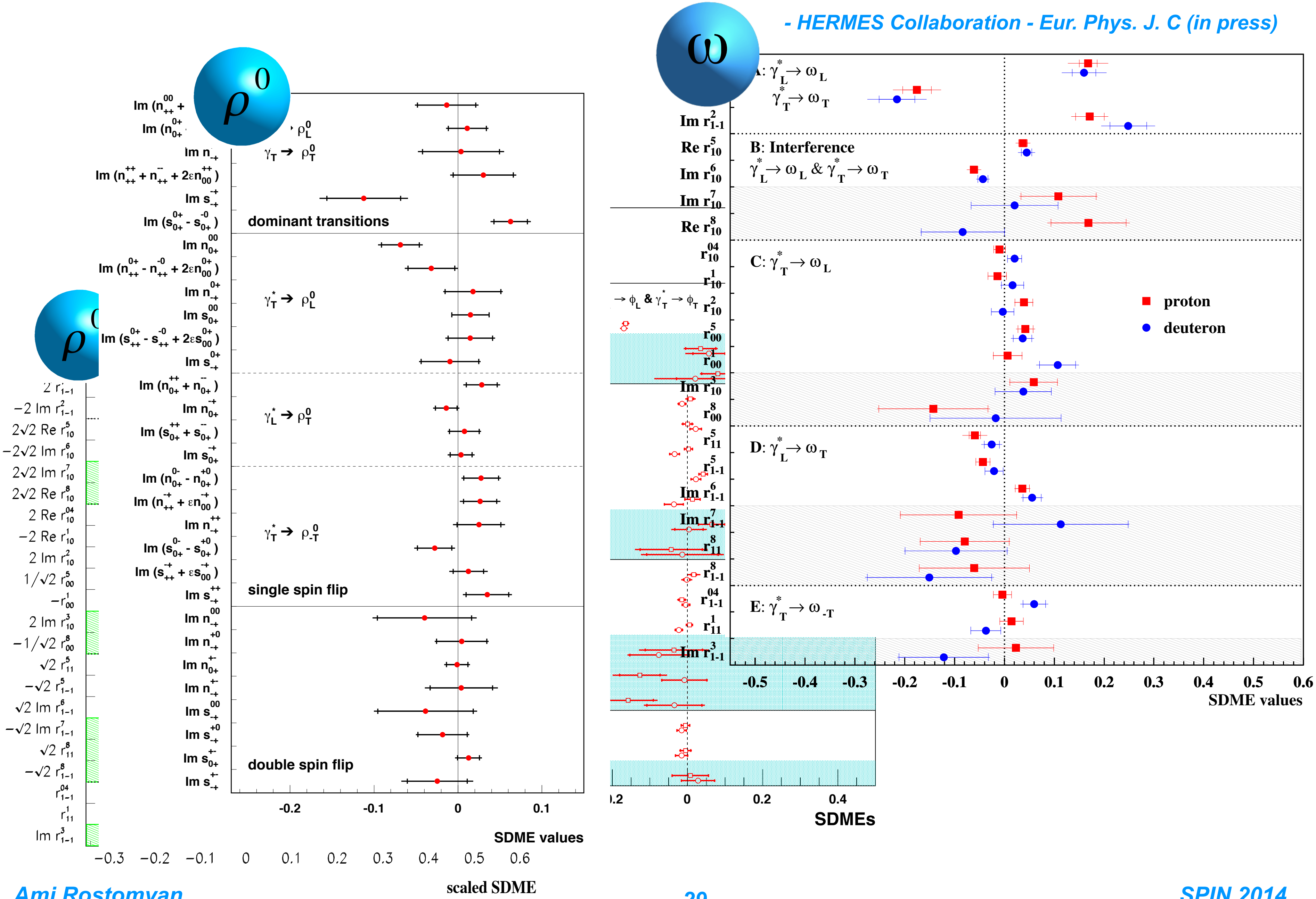
SDMEs of vector meson production



- HERMES Collaboration - Eur. Phys. J. C (in press)

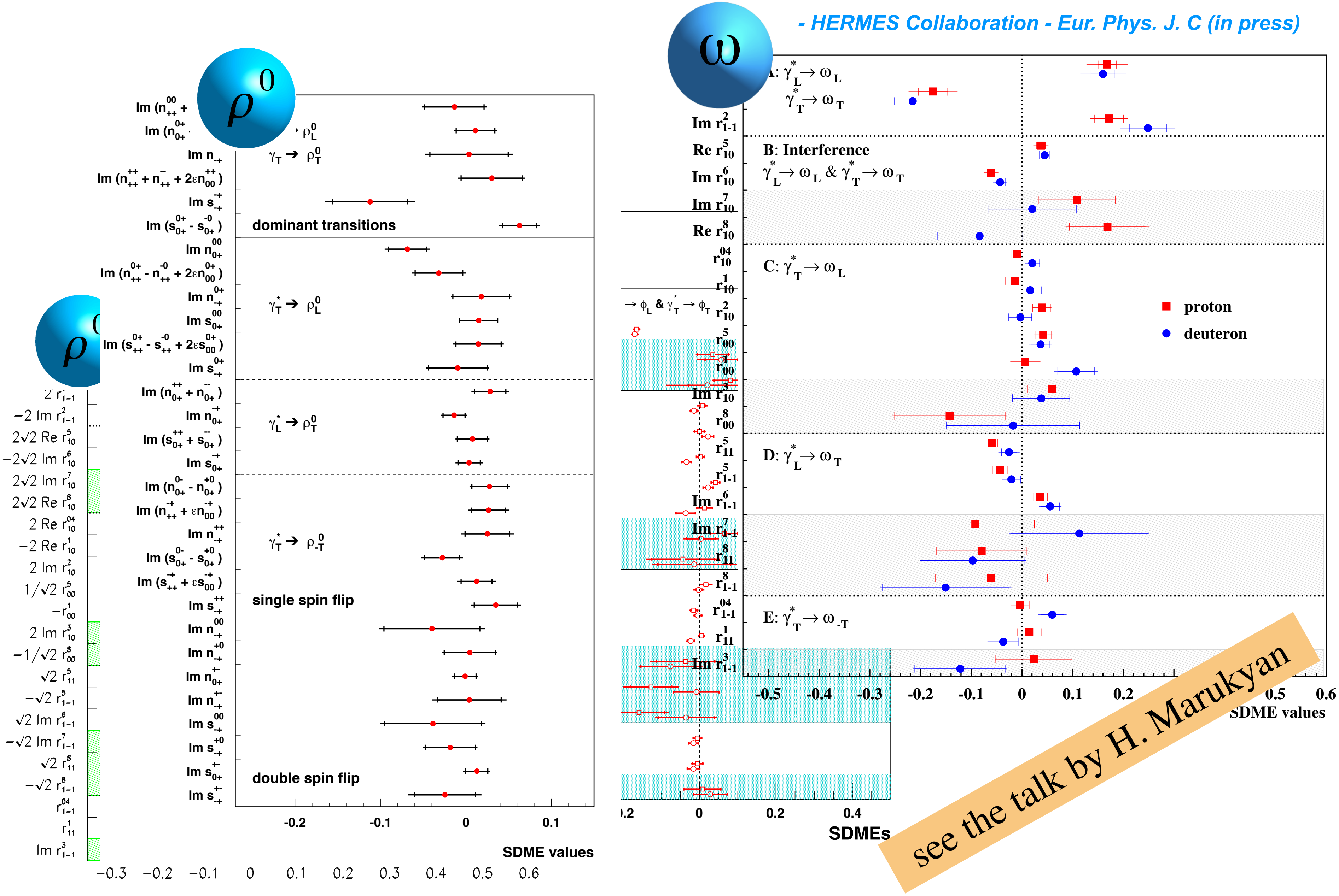
SDMEs of vector meson production

- HERMES Collaboration - Eur. Phys. J. C (in press)



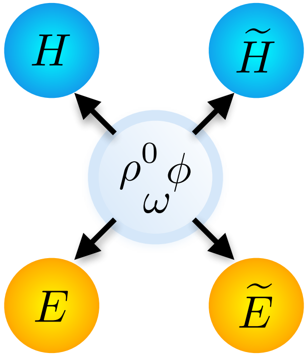
SDMEs of vector meson production

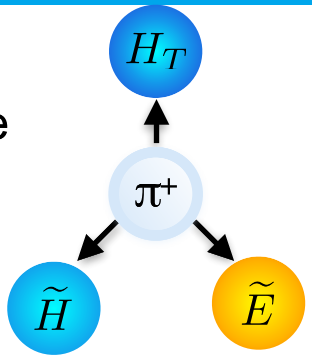
- HERMES Collaboration - Eur. Phys. J. C (in press)



see the talk by H. Marukyan

universality of GPDs





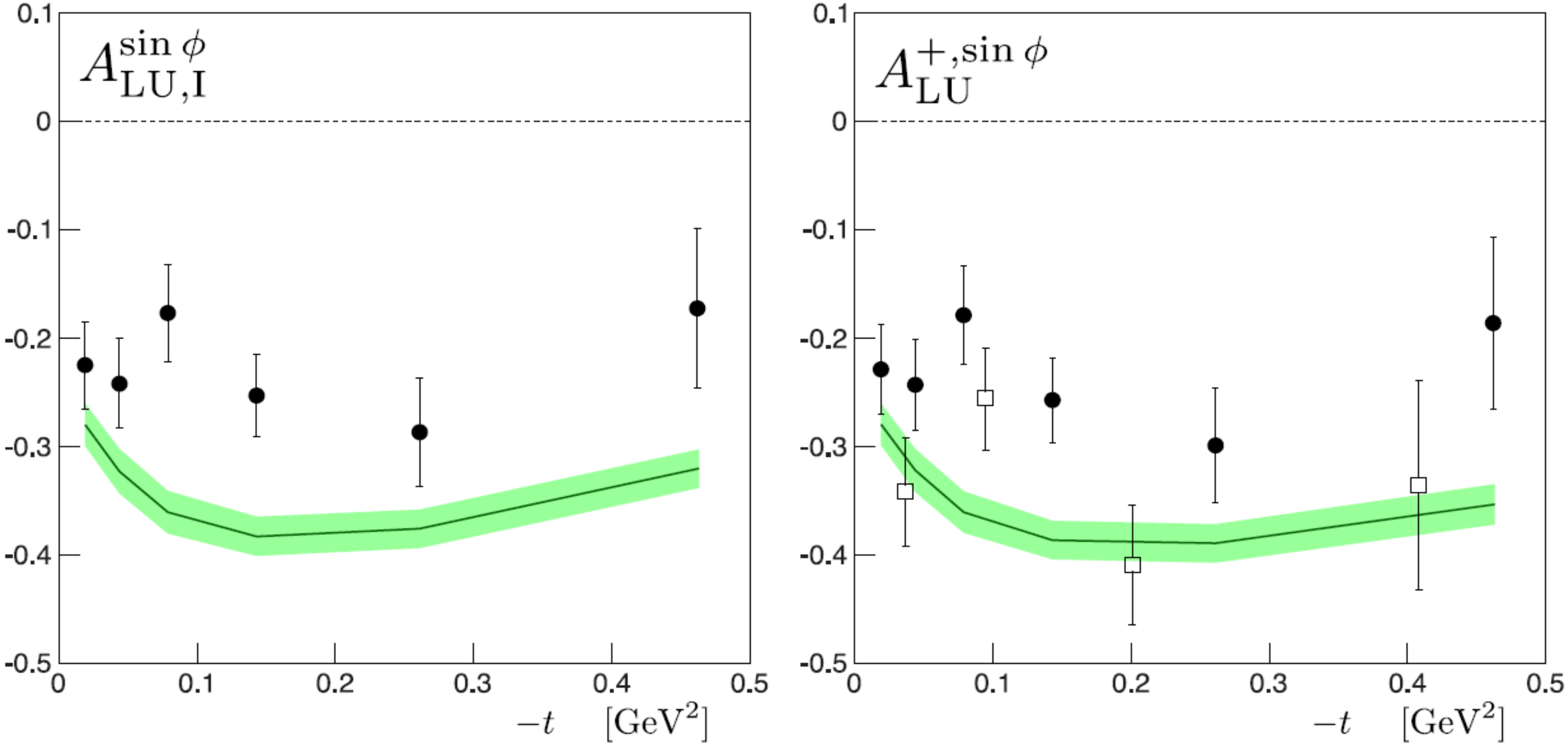
> GPD model originally developed to describe exclusive meson production

- P. Kroll, H. Moutarde, F. Sabatié - Eur. Phys. J. C (2013) 73

in comparison with HERMES data

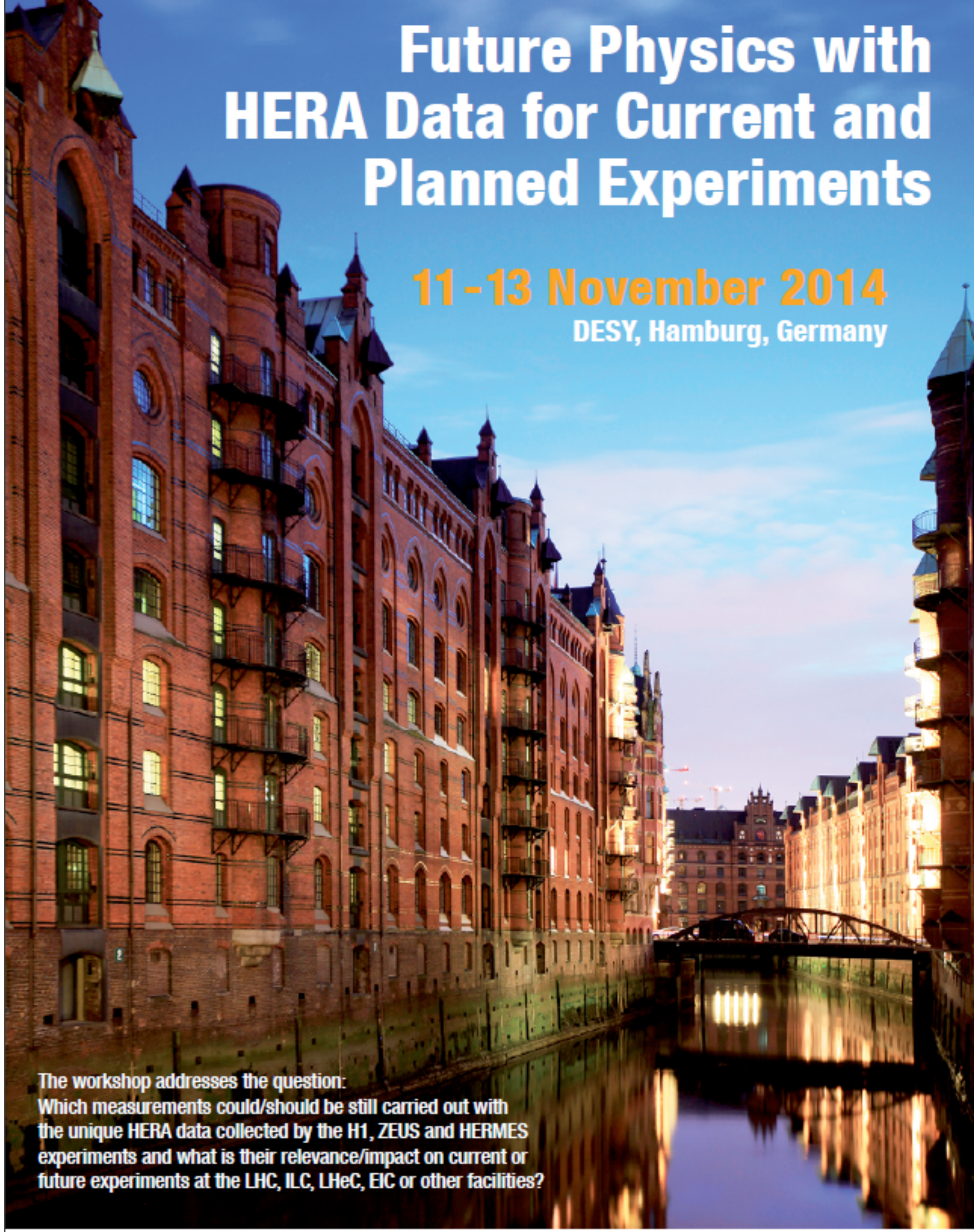
● *- DVCD pre-recoil data - JHEP 07 (2012) 032*

☐ *- DVCD recoil data - JHEP 10 (2012) 042*



The Spin Community And **The World**

- ☛ **HERMES** has been a pioneering collaboration
  - ☛going beyond the collinear factorisation towards TMDs and GPDs



Future Physics with HERA Data for Current and Planned Experiments

11 - 13 November 2014

DESY, Hamburg, Germany

The workshop addresses the question:
Which measurements could/should be still carried out with the unique HERA data collected by the H1, ZEUS and HERMES experiments and what is their relevance/impact on current or future experiments at the LHC, ILC, LHeC, EIC or other facilities?

Local Organising Committee:
Matthew Wing (Chair), Olaf Behnke, Markus Diehl, Achim Geiser, Sergey Levonian,
Ami Rostomyan, Gunar Schnell, Stefan Schmitt

https://indico.desy.de/event/futurehera

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

DESY