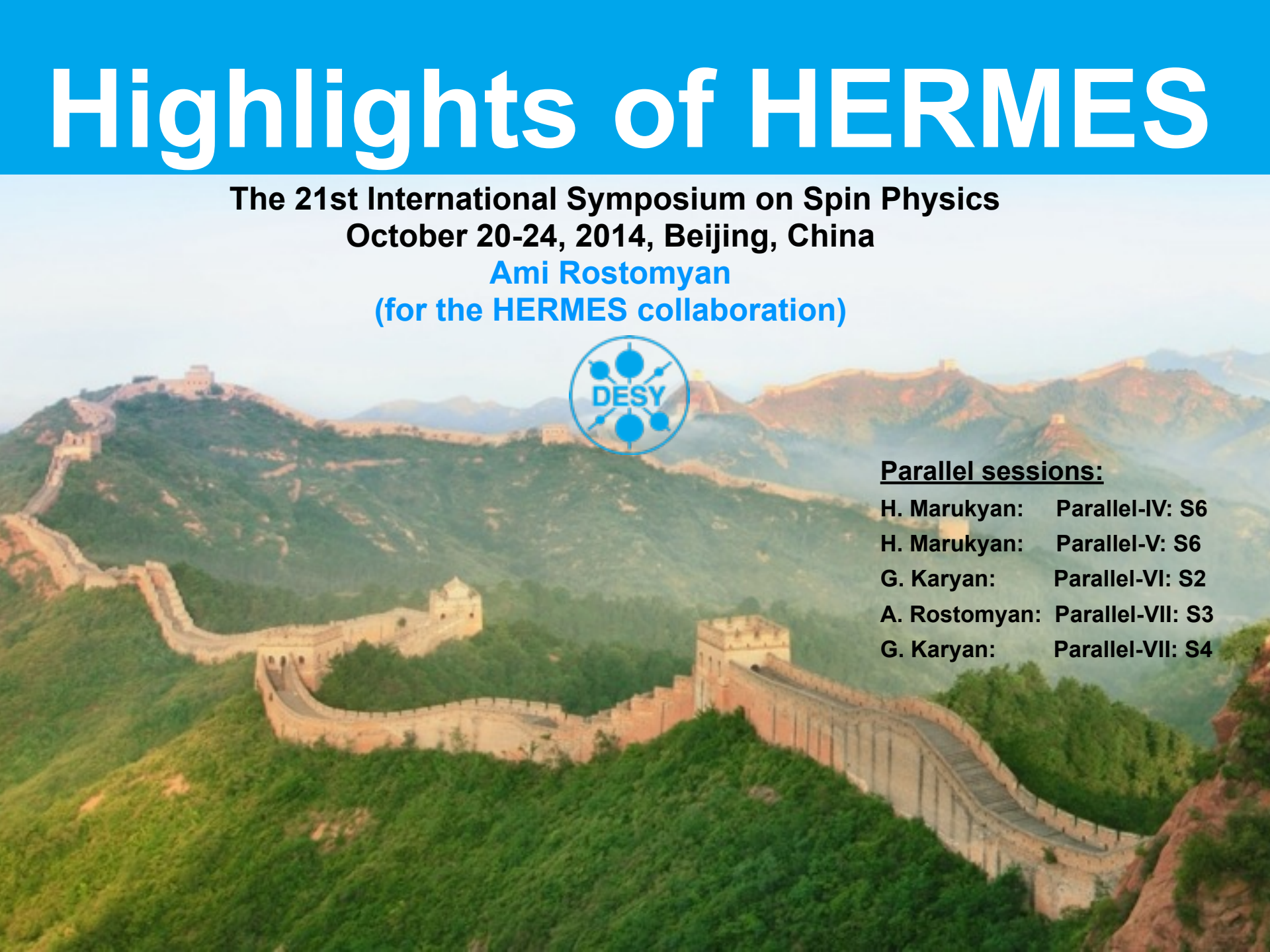
Highlights of HERMES

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

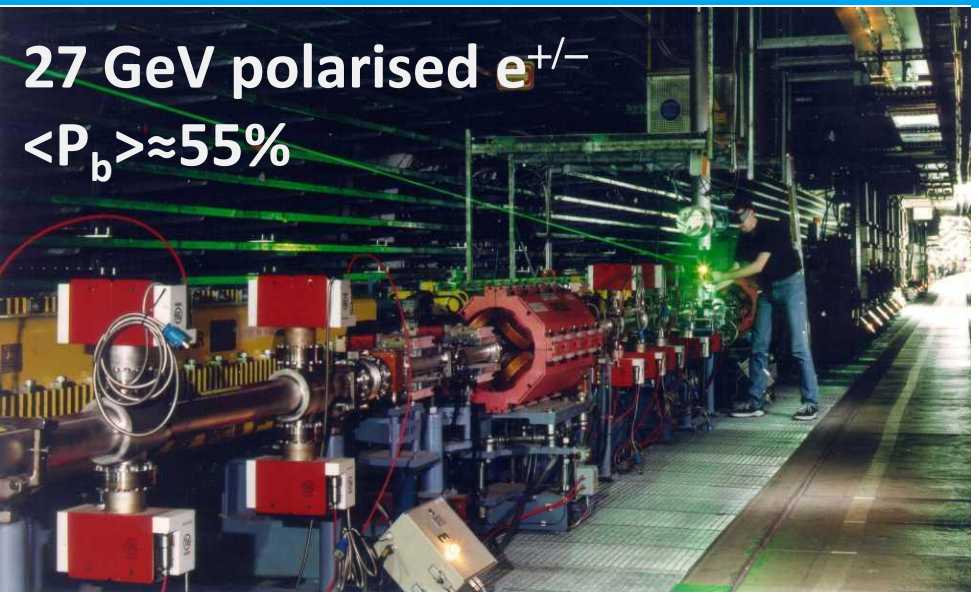
Ami Rostomyan
(for the HERMES collaboration)



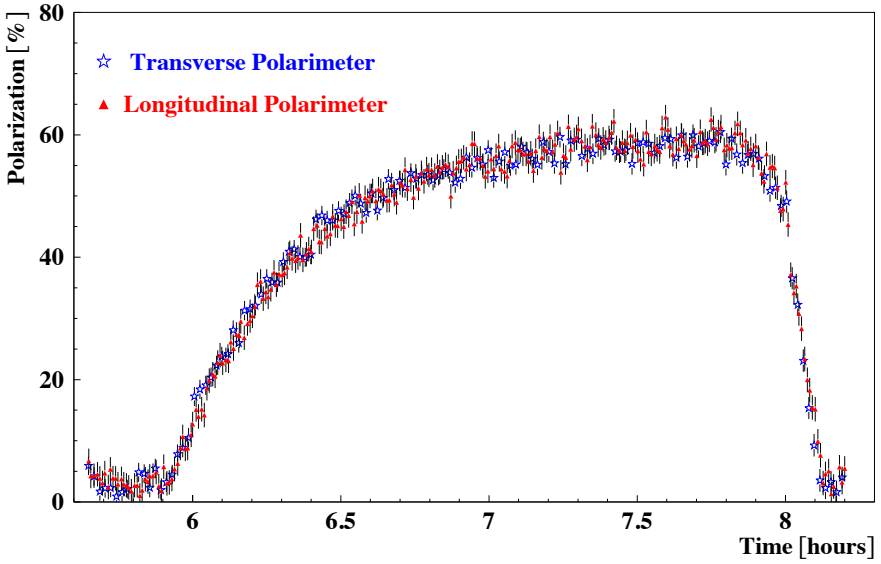
Parallel sessions:

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)



self-polarised e^+/e^-



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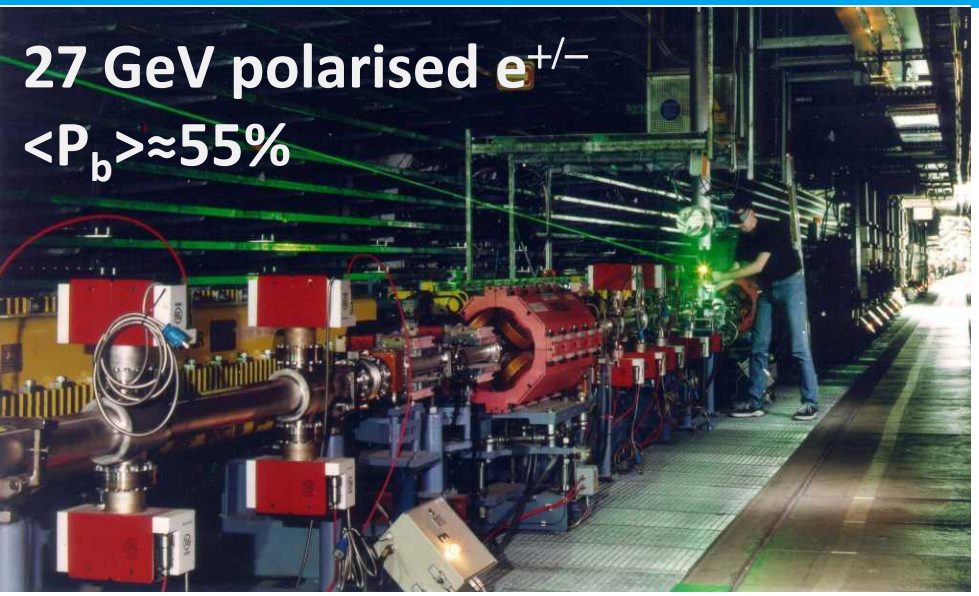
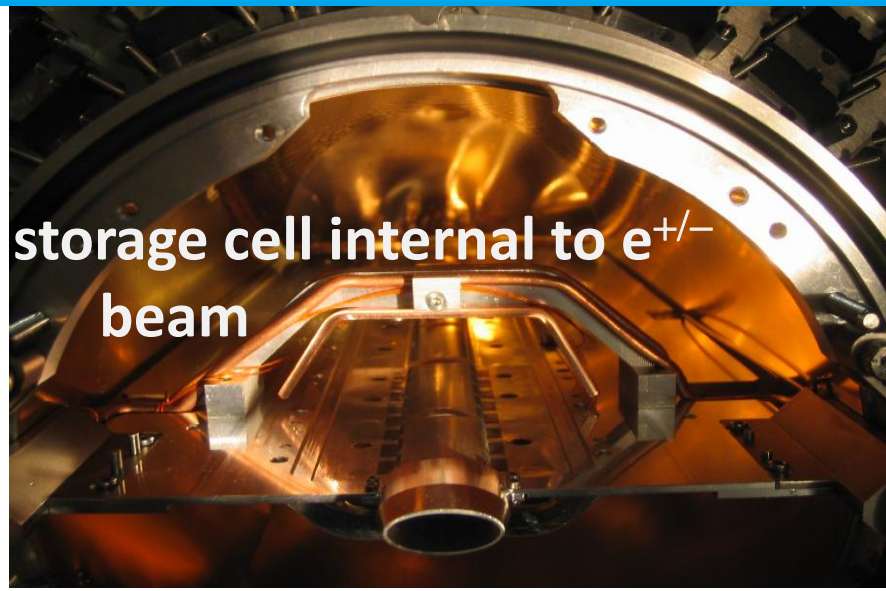
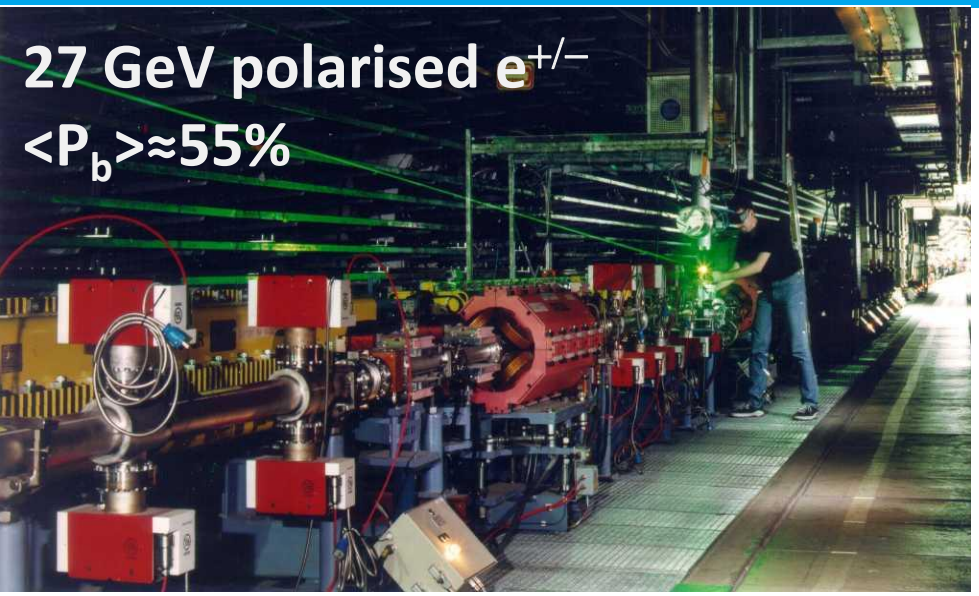


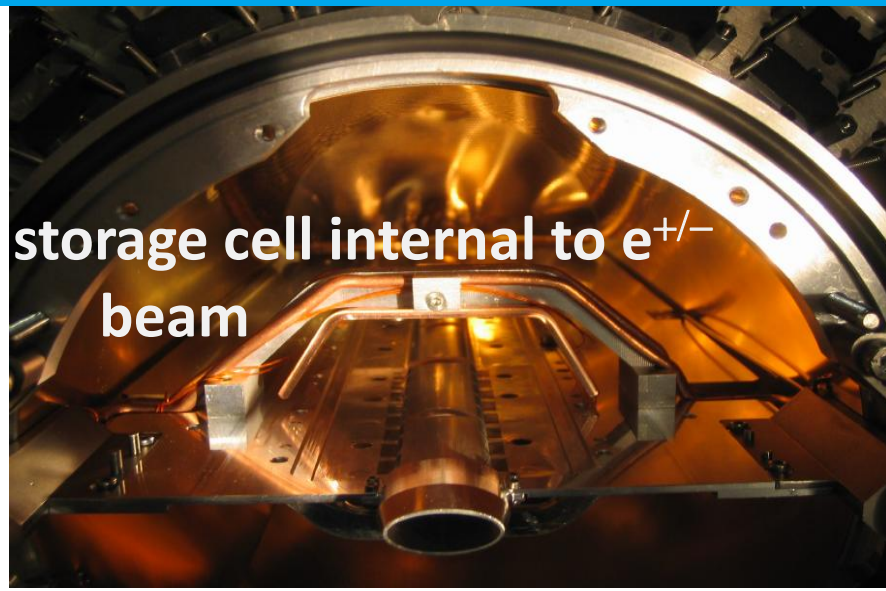


pure gas targets

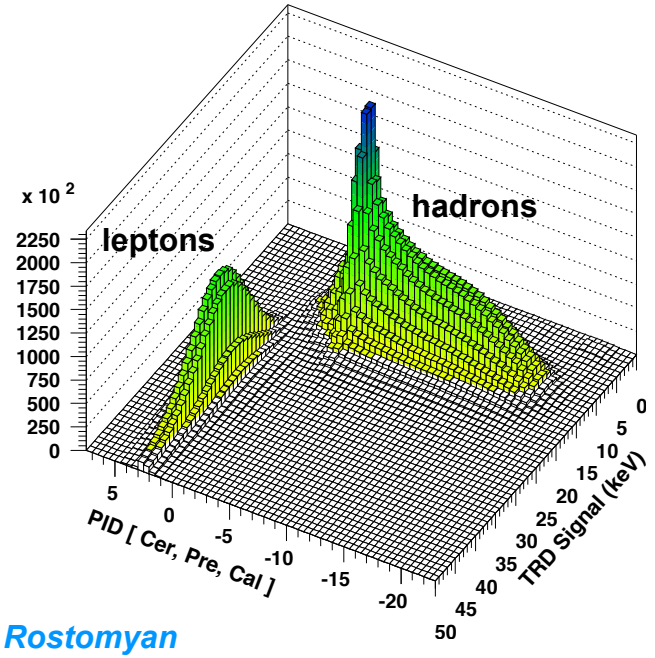
- longitudinal target polarisation:
  H, D, ^{3}He
- transverse target polarisation: H
- unpolarised targets:
  H, D, ^{4}He, ^{14}N, ^{20}Ne, ^{84}Kr, ^{131}Xe
- unpolarised targets with recoil detector: H, D

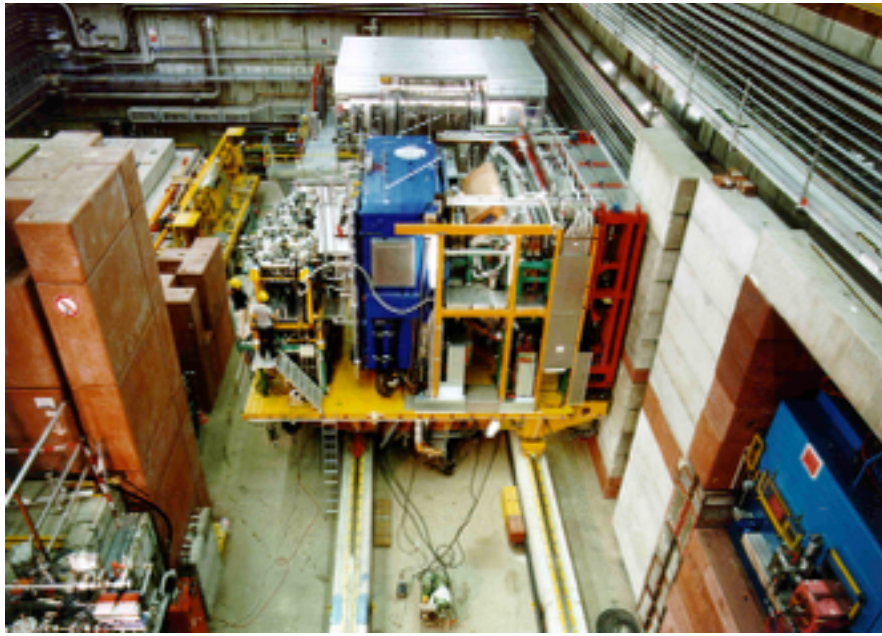
The HERMES experiment (1995-2007)





excellent lepton/hadron separation





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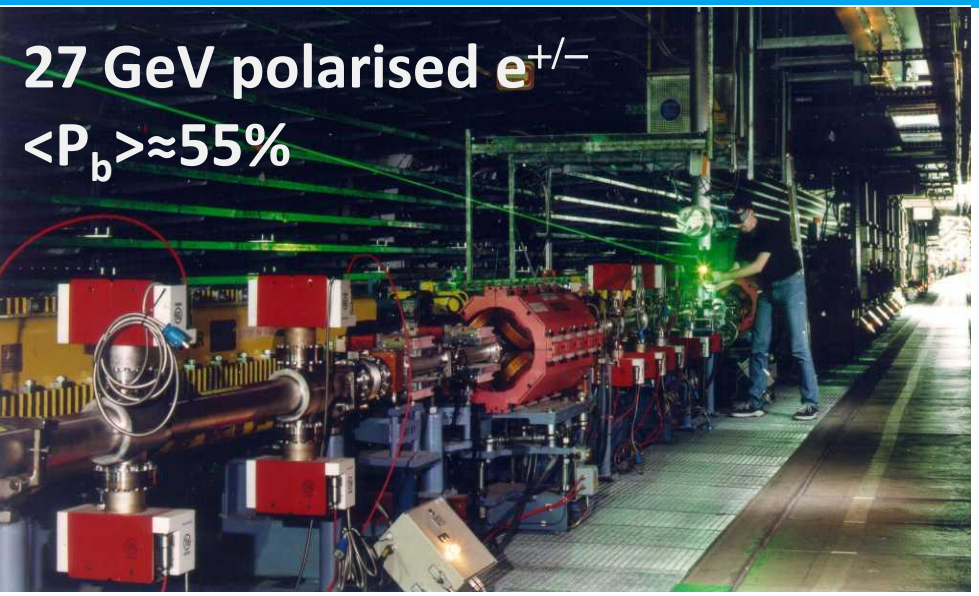
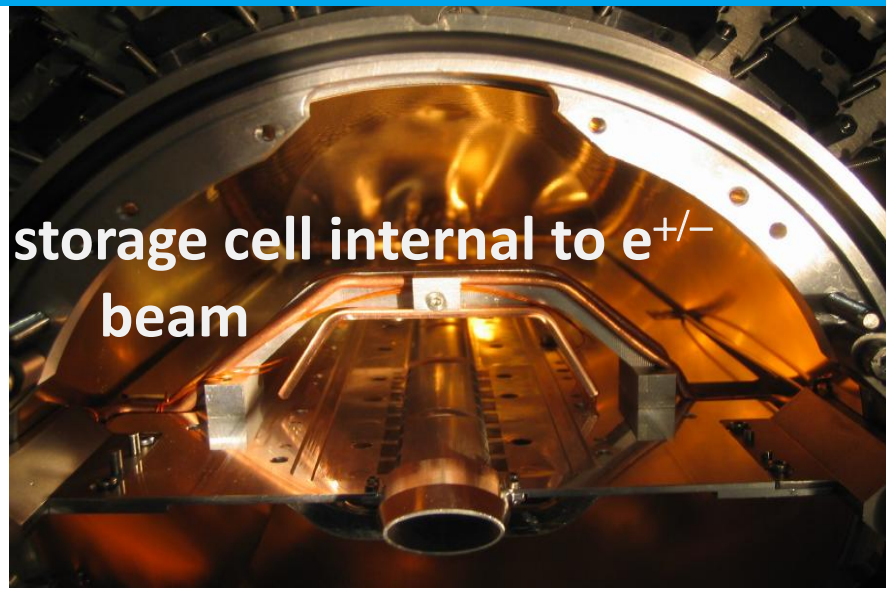
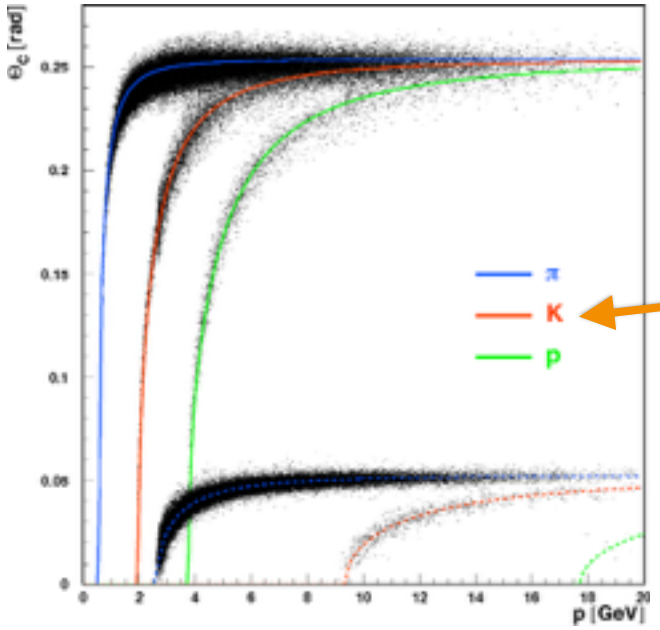
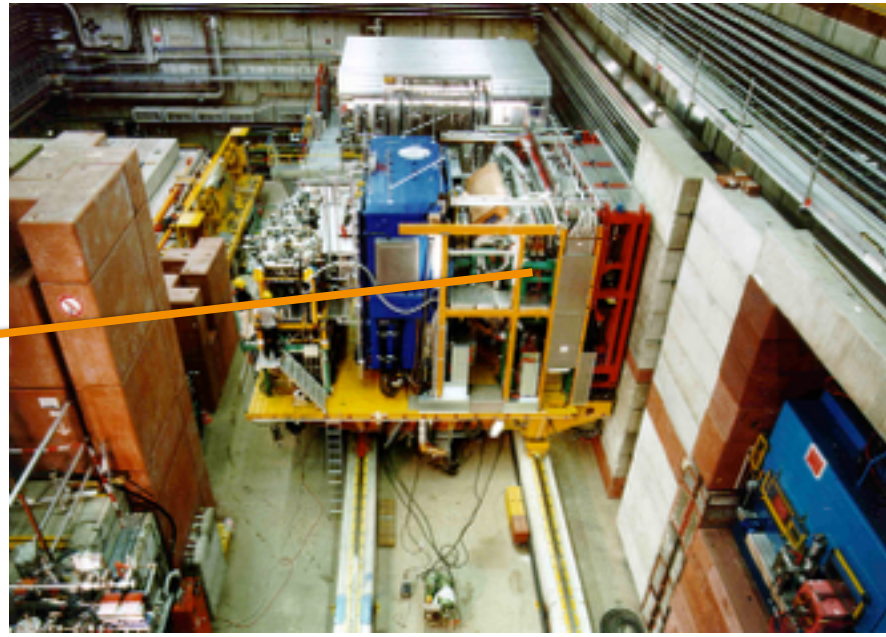




π / K / p separation over whole momentum range

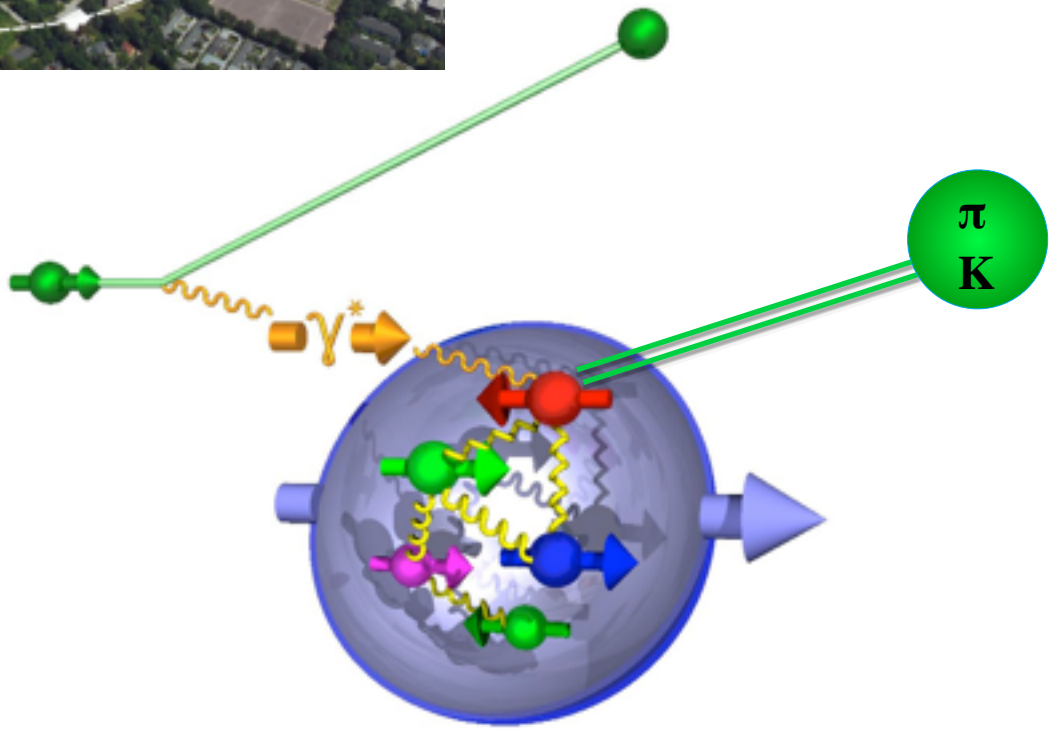




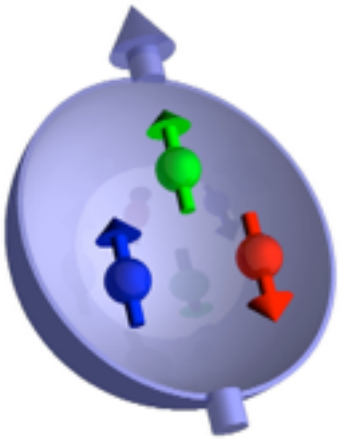
spin and hadronisation

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

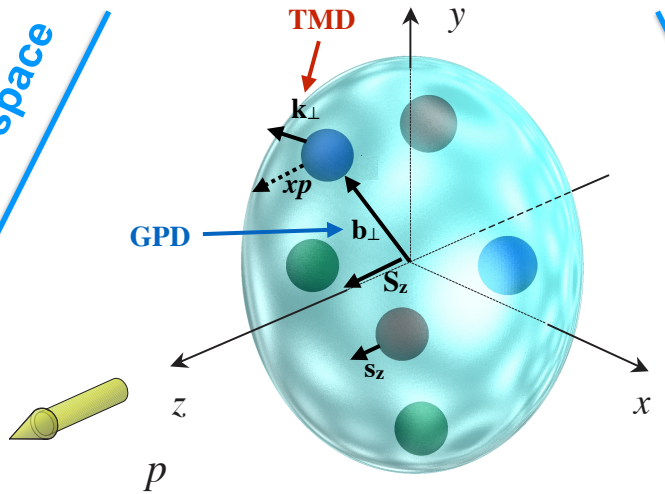
nucleon tomography

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

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

transfers coordinate space

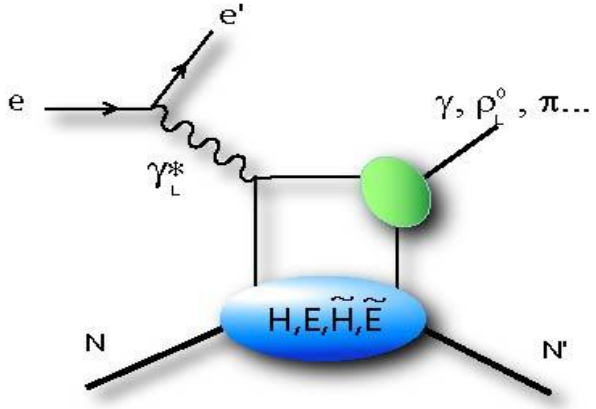
transfers momentum space



GPDs

[generalised parton distributions]

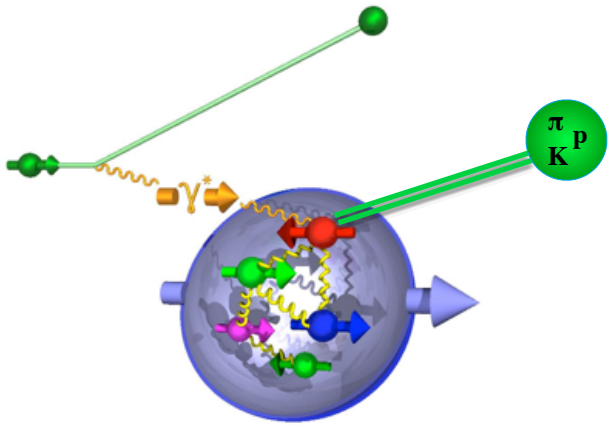
➡ **exclusive measurements**



TMDs

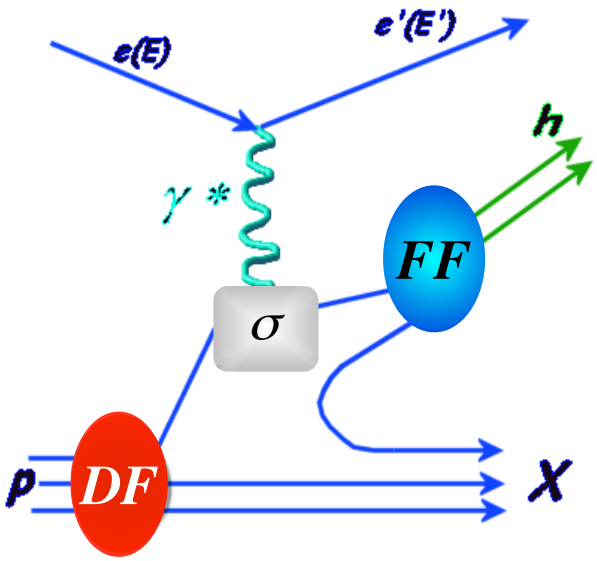
[transverse momentum dependent PDFs]

➡ **semi-inclusive measurements**



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

semi-inclusive DIS



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

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

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

- 4-momentum squared of virtual photon
- fraction of proton momentum carried by the struck quark
- energy fraction carried by the produced hadron

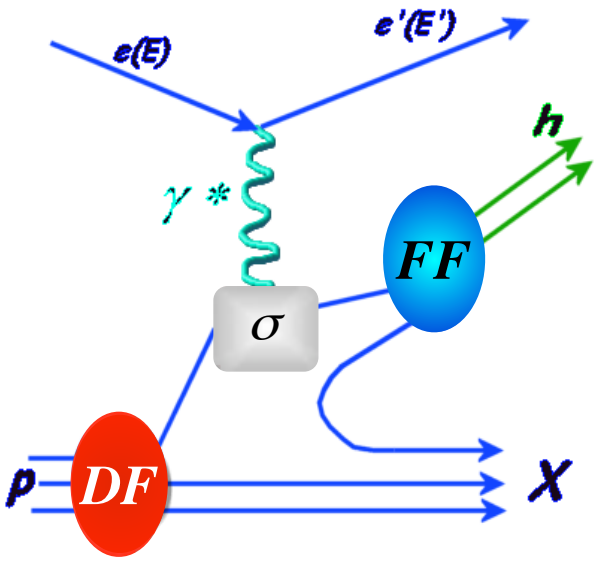
pQCD factorisation:

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

parameterise the nucleon structure

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

semi-inclusive DIS



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

- 4-momentum squared of virtual photon

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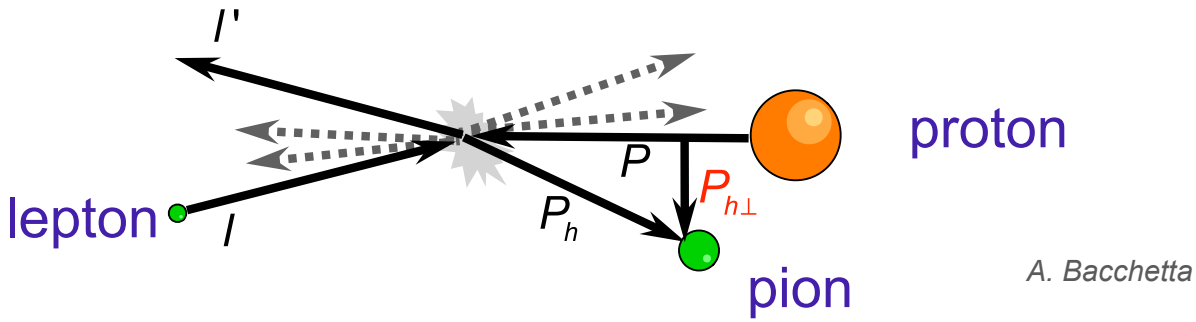
- fraction of proton momentum carried by the struck quark

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

- energy fraction carried by the produced hadron

$$P_{h\perp}$$

- transverse momentum of hadron



A. Bacchetta

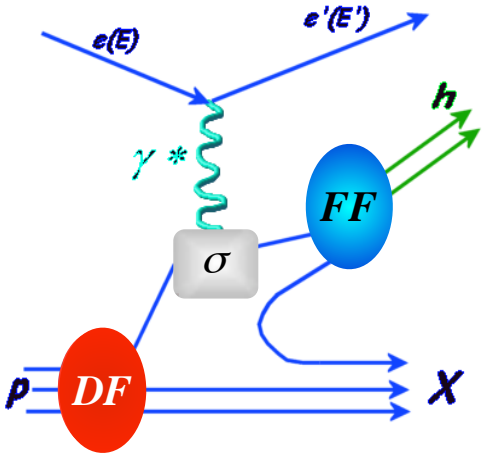
pQCD factorisation:

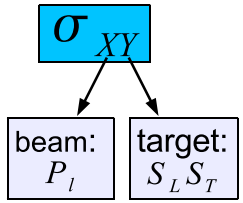
$$\sigma_{DIS} \propto \sum_f \hat{\sigma}_{part} \otimes DF(x, k_\perp) \otimes FF(z, P_{h\perp})$$

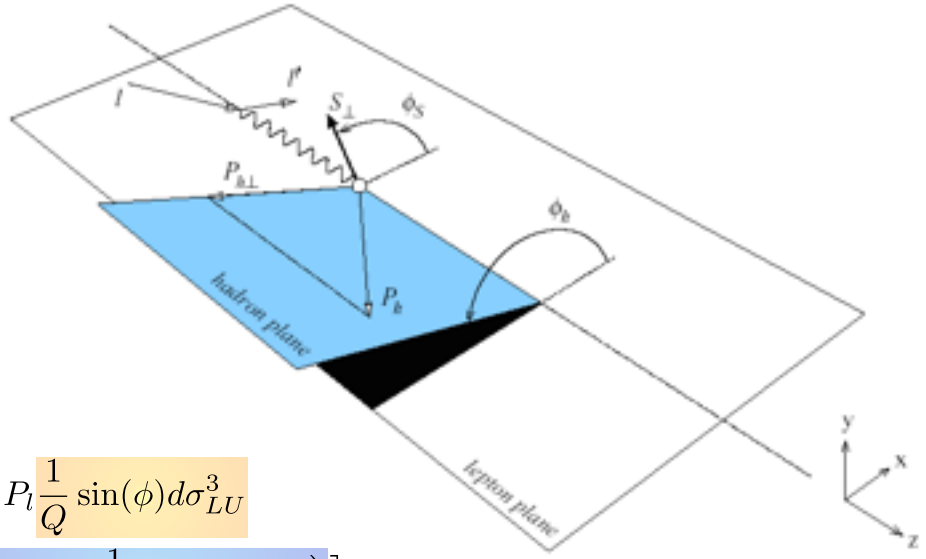
parameterise the nucleon structure

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

TMDs







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

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	$h_{1T}^\perp$

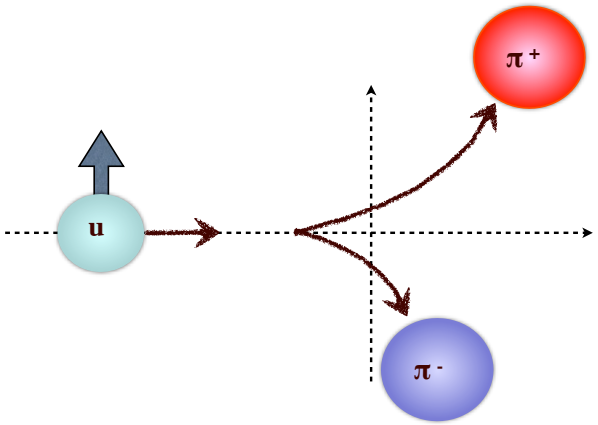
FF	quark polarisation	
	U	T
hadron polarisation: U	D_1	$H_1^\perp$

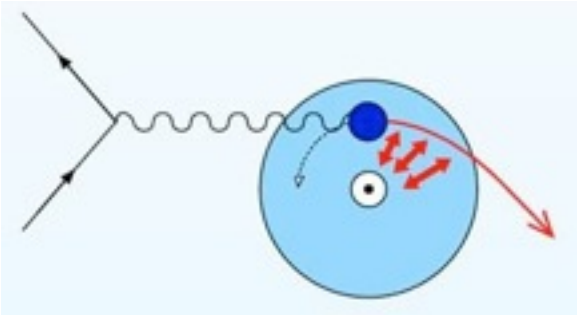
semi-inclusive measurements (probing TMDs)

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**

> **first demonstration of Sivers effect**

- ➡ *PRL 94 (2005) 012002*
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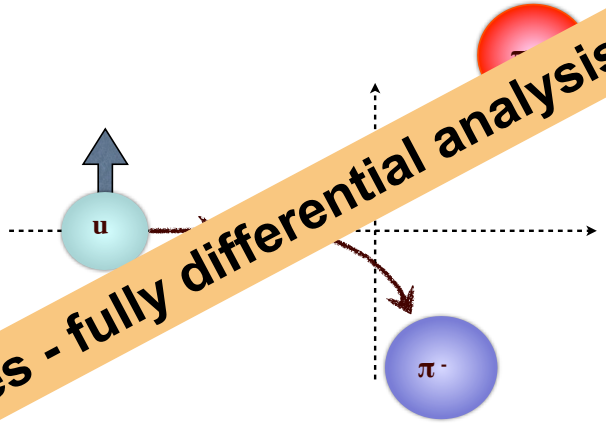
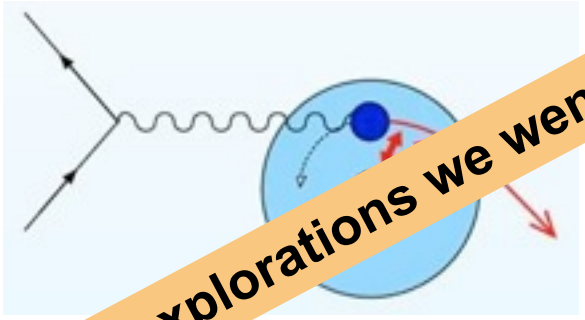




> correlation between the transverse ***spin*** of the fragmenting quark and the transverse momentum of the produced unpolarised hadron

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

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

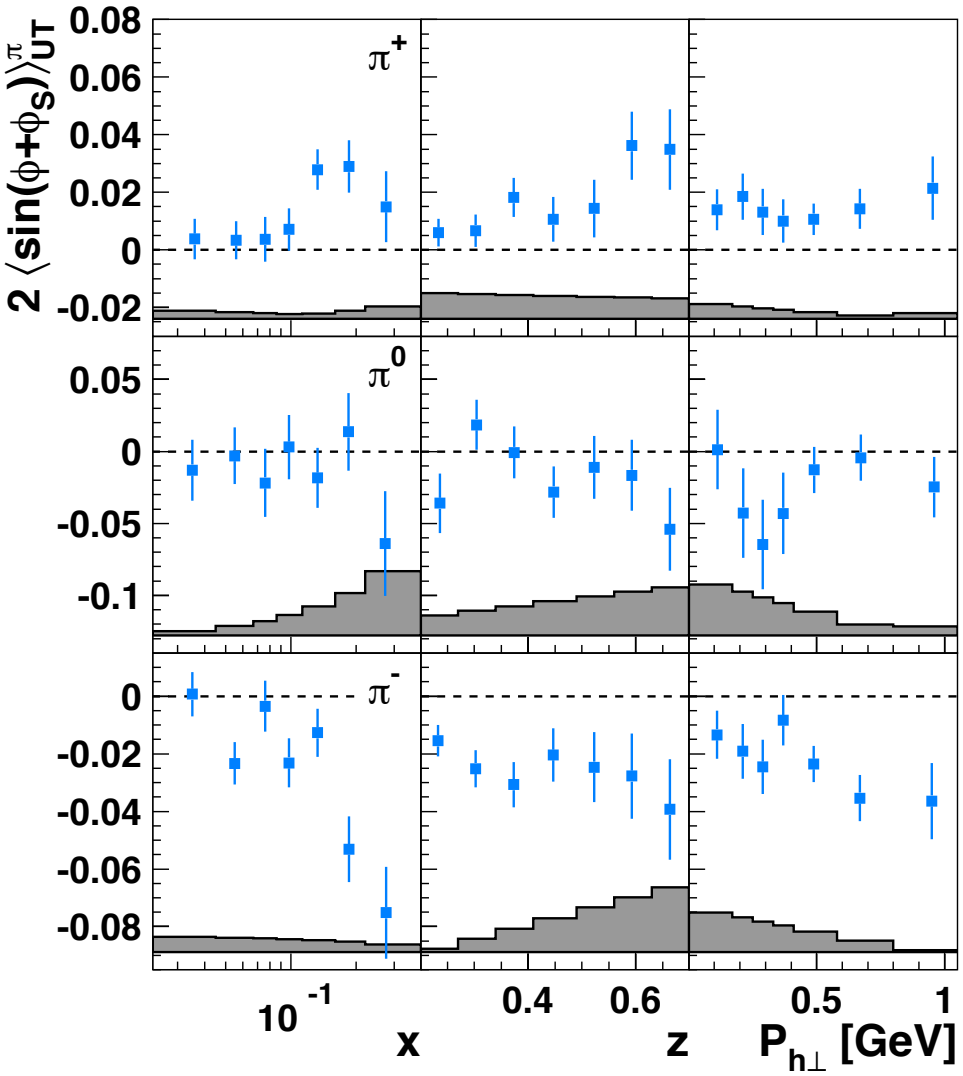
> **first evidence for Collins effect**

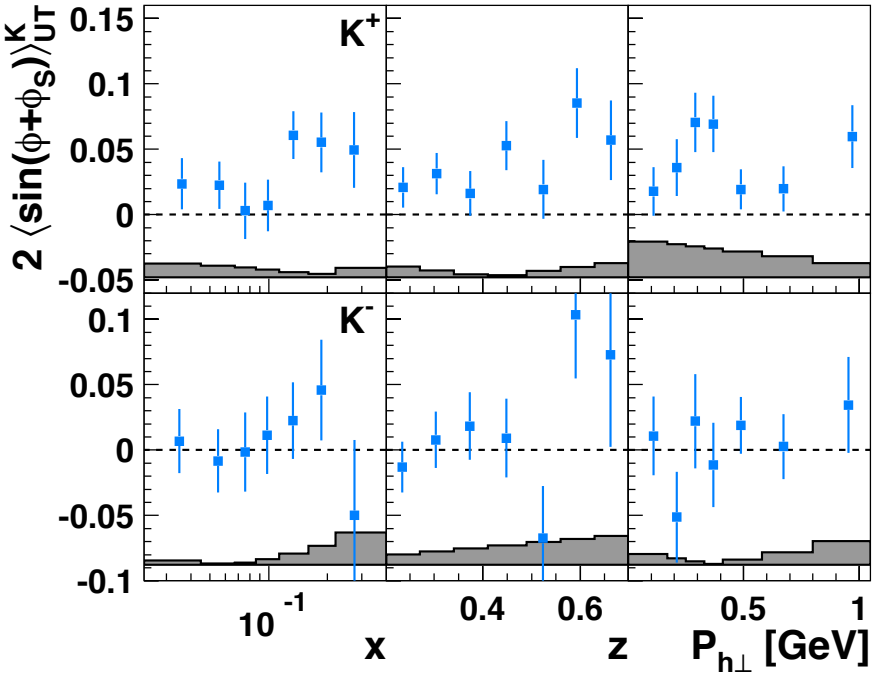
- ➡ *PRL 94 (2005) 012002*
- ➡ *JHEP 06 (2008) 017*
- ➡ *PLB 693 (2010) 11]*

Collins asymmetries: 1D

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

Phys. Rev. Lett. 103 (2009) 152002





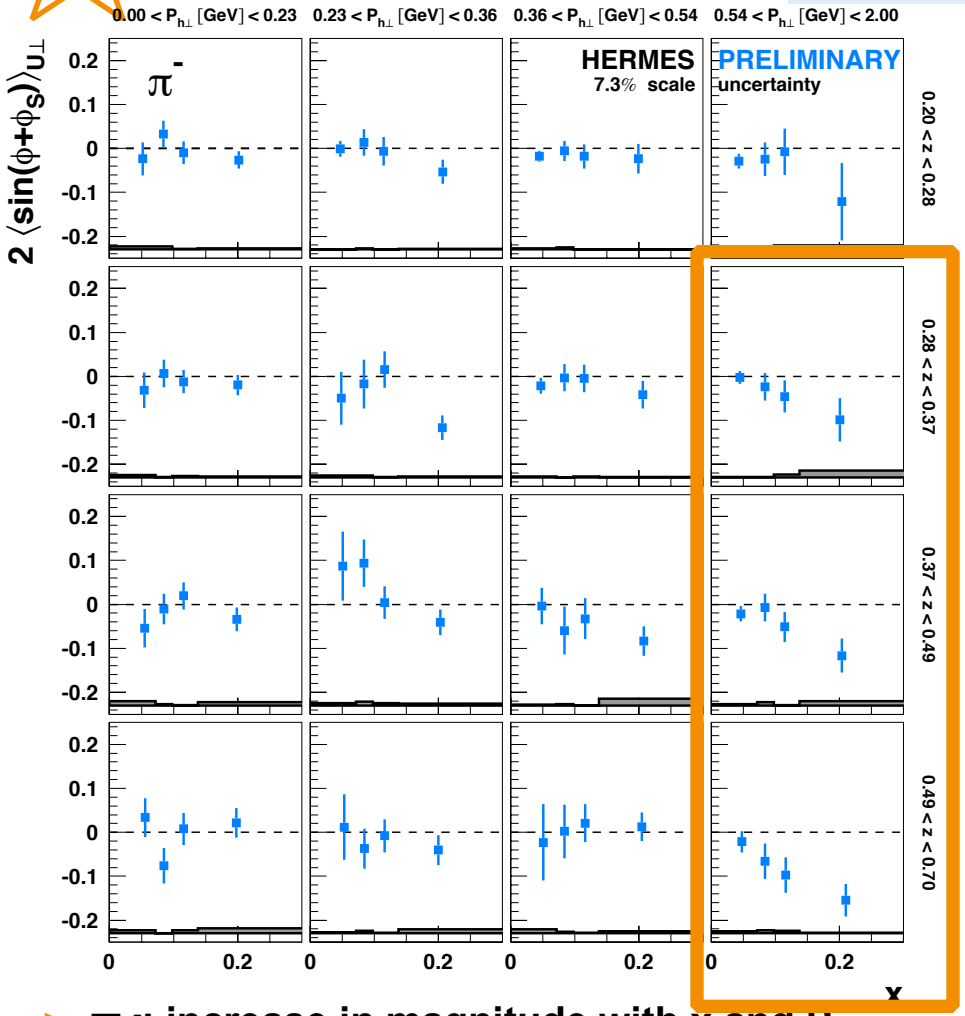
- positive amplitude for π^+
- large negative amplitude for π^-

- K^+ are larger than π^+
- K^- consistent with zero

Collins asymmetries: 3D

NEW

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

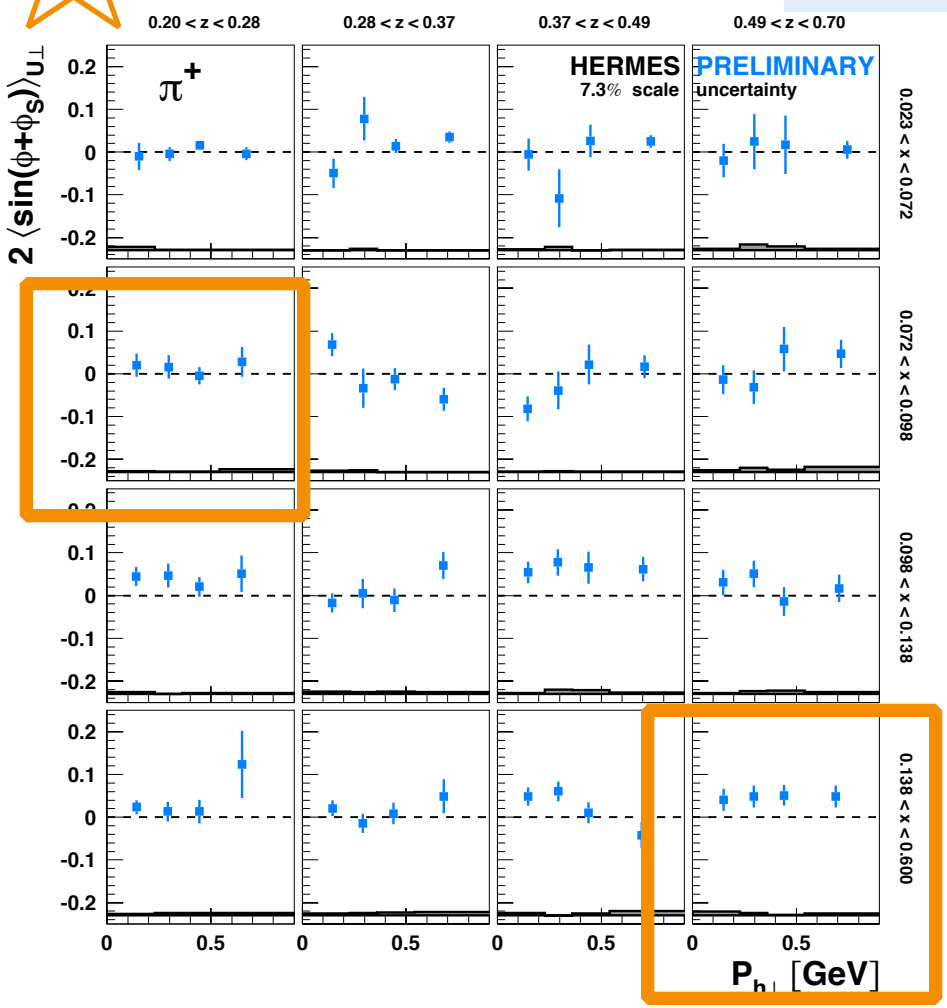


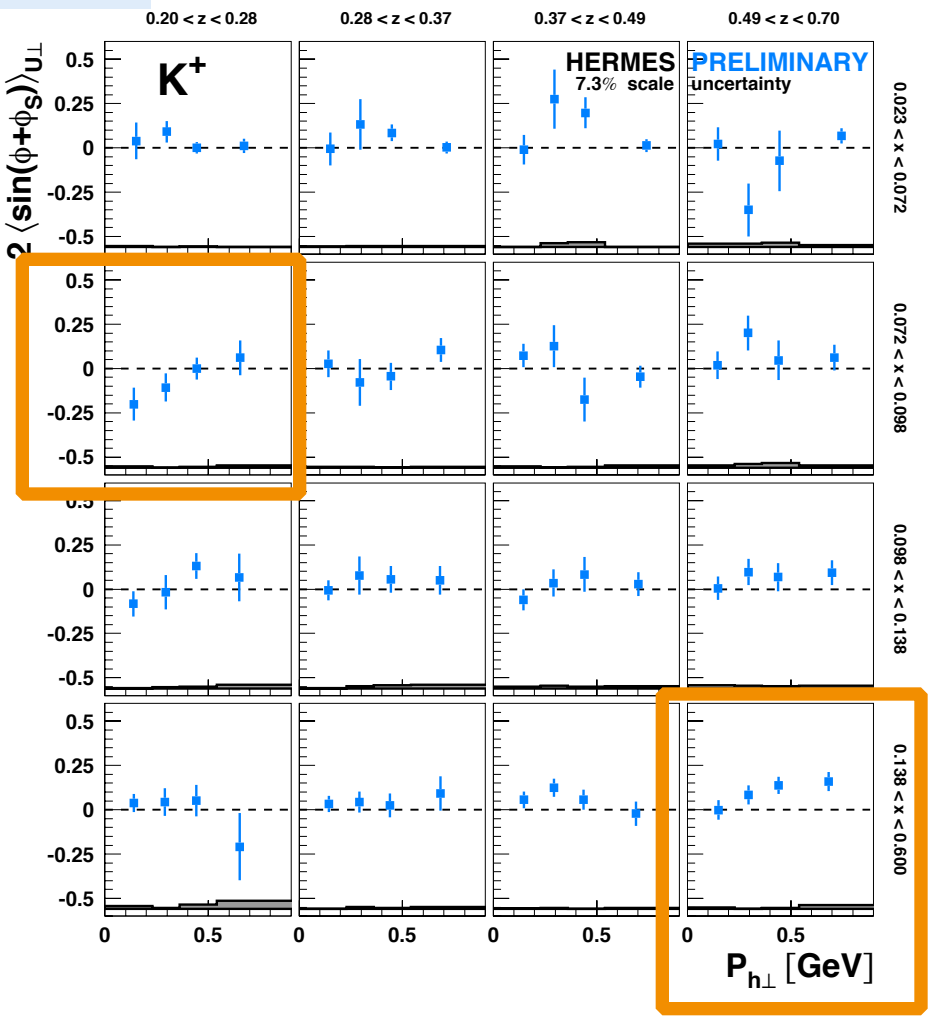
- **π^-: increase in magnitude with x and $P_{h\perp}$**
  - transversity mainly receives contribution from valence quarks

Collins asymmetries: 3D

NEW

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

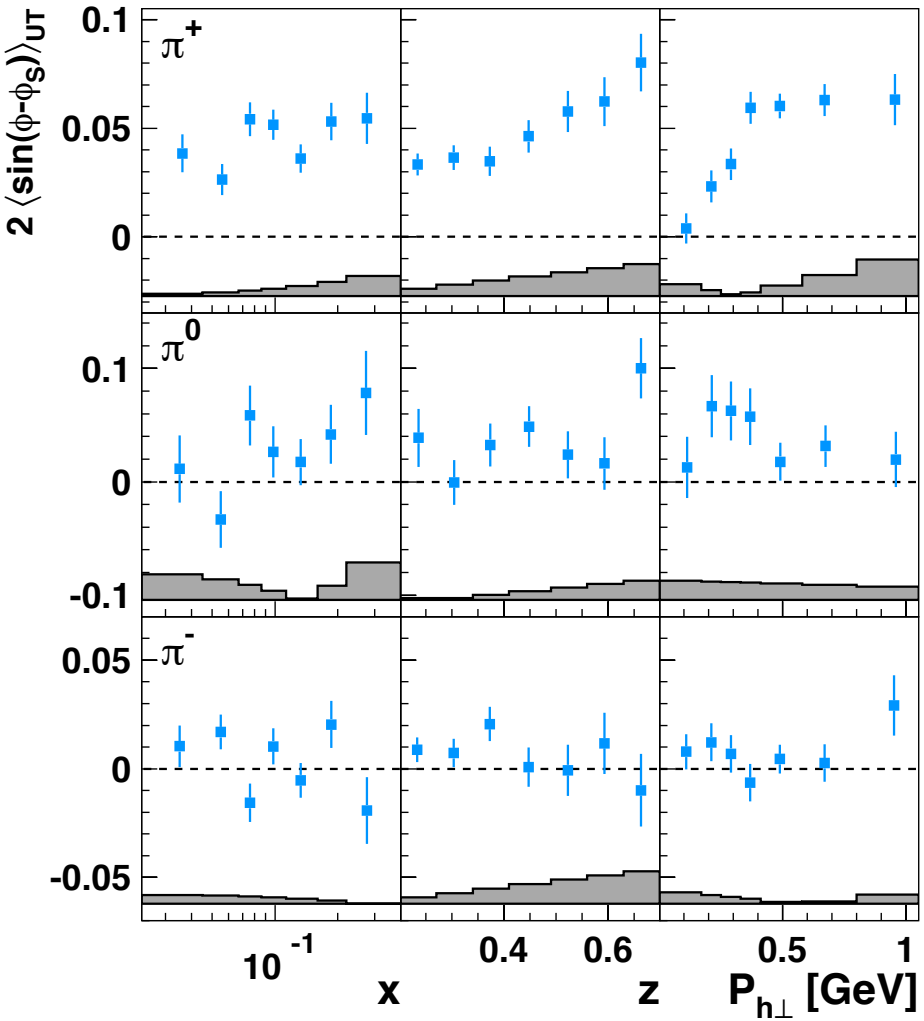




- **π^-: increase in magnitude with x and $P_{h\perp}$**
  - transversity mainly receives contribution from valence quarks
- **K^+ amplitudes are larger than π^+**
  - role of sea quarks

Sivers asymmetries: 1D

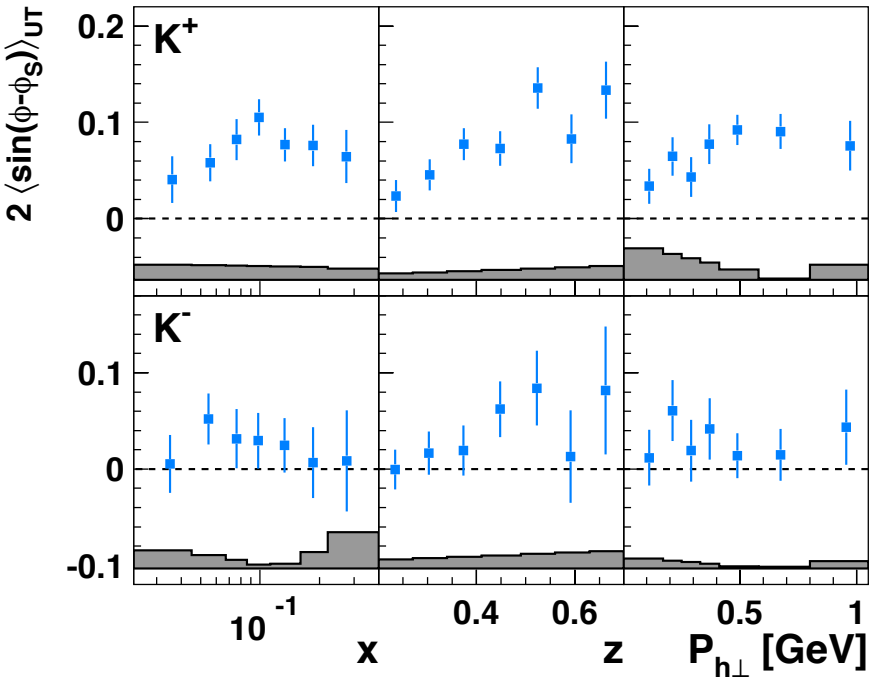
$\sigma_{UT} \propto f_{1T}^{\perp q} \otimes D_1^q$



> positive amplitude for π^+

> consistent with zero for π^-

Phys. Rev. Lett. 103 (2009) 152002



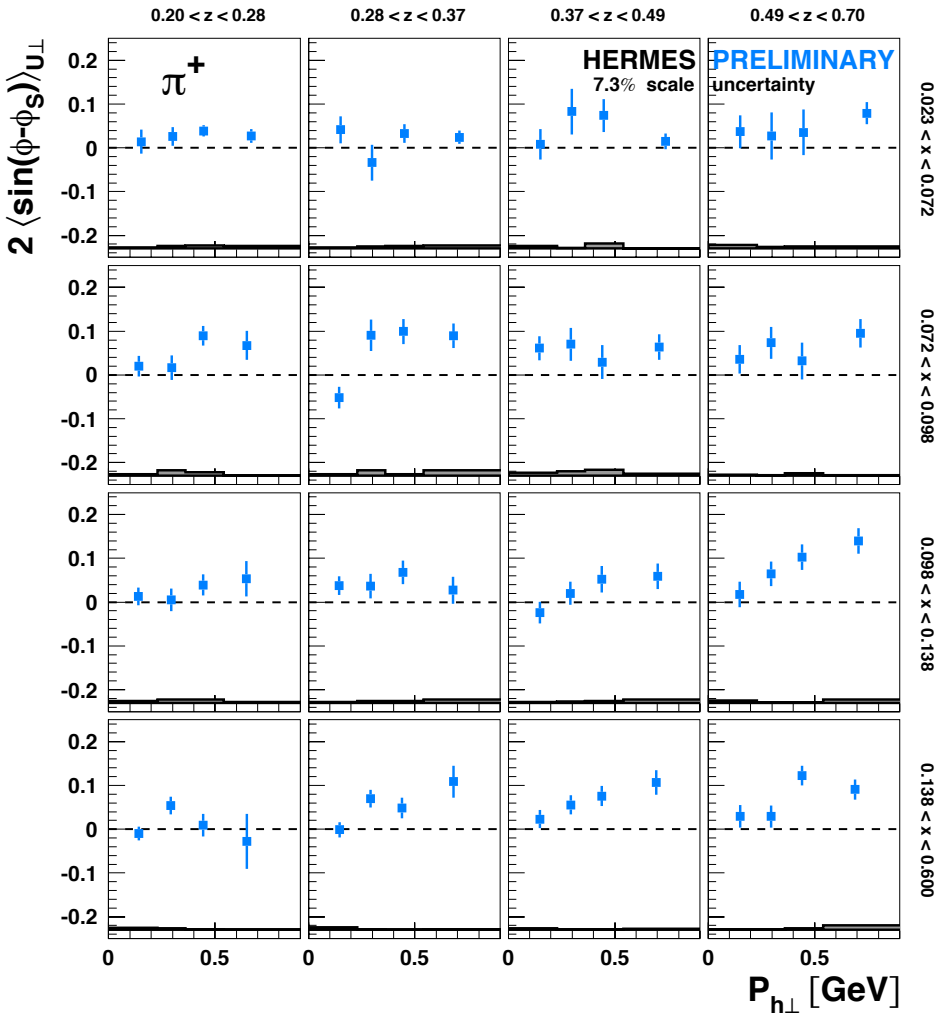
> K^+ are larger than π^+

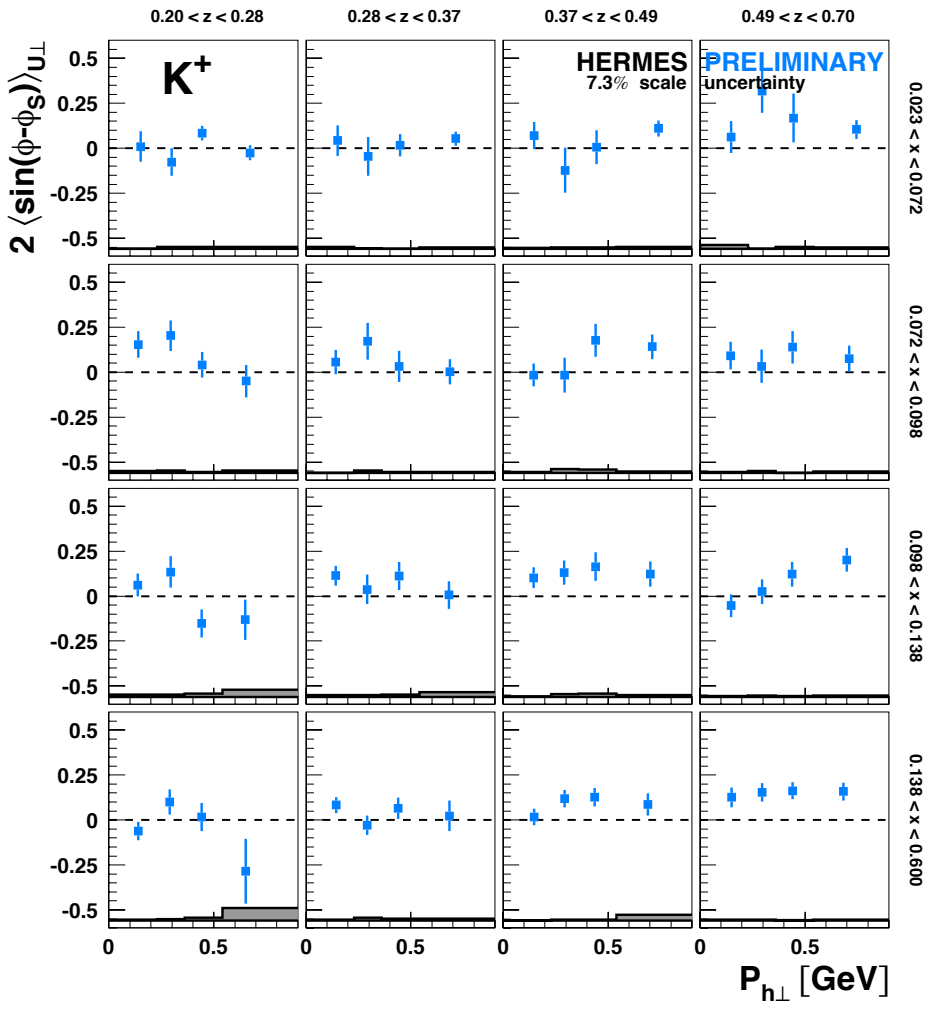
> K^- slightly positive

Sivers asymmetries: 3D

NEW

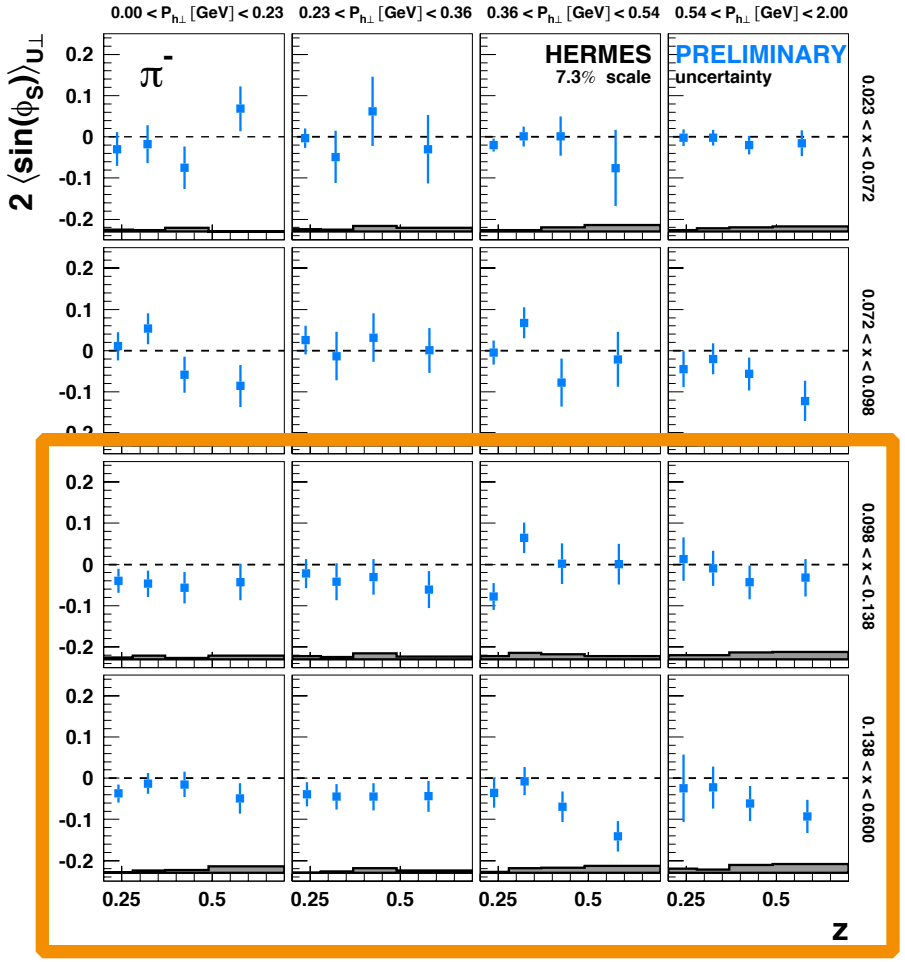
$$\sigma_{UT} \propto f_{1T}^{\perp q} \otimes D_1^q$$





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

multi-dimensional analysis



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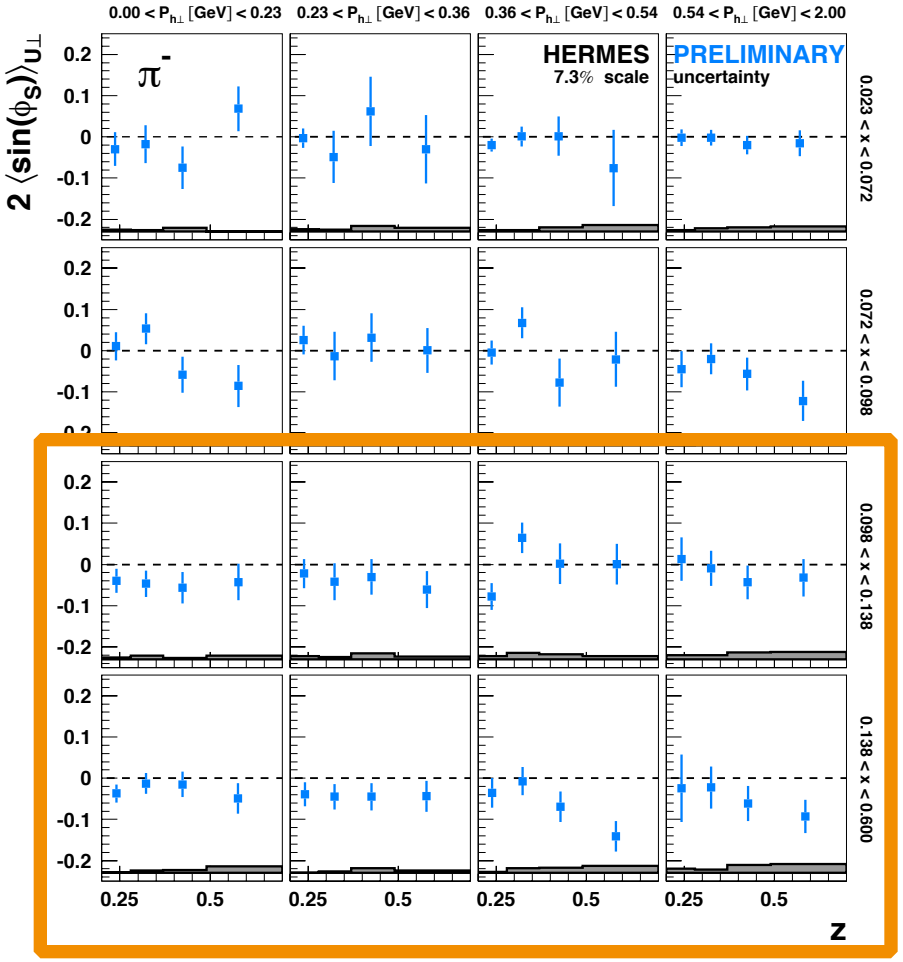
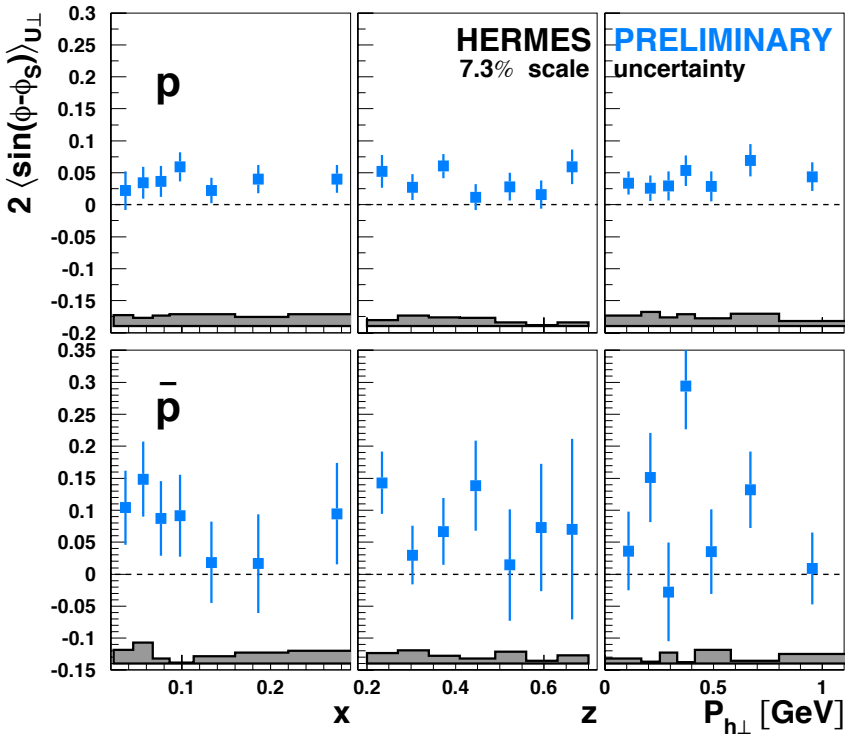
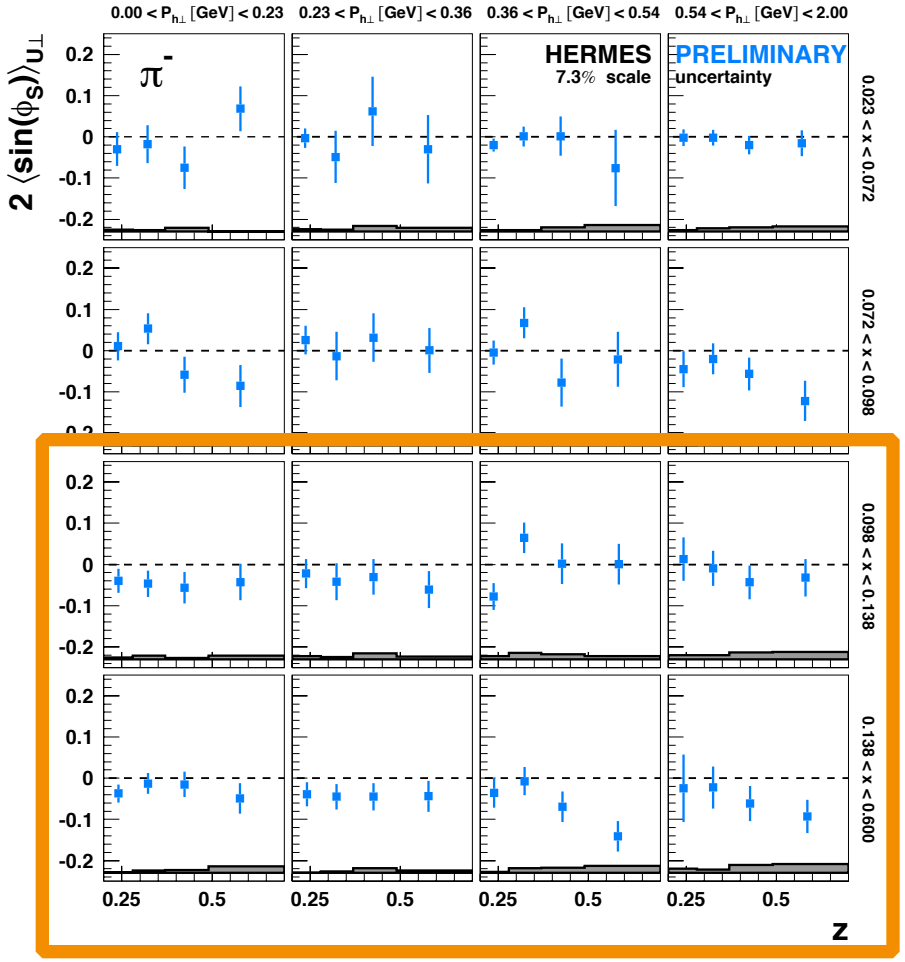
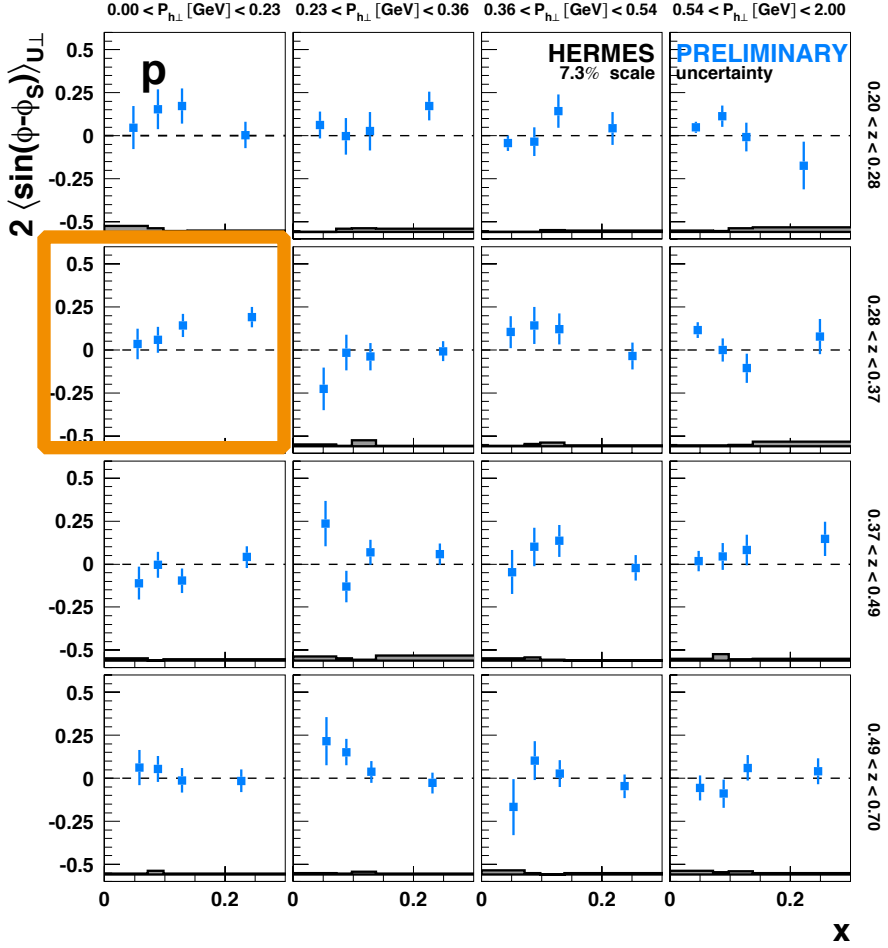




multi-dimensional analysis



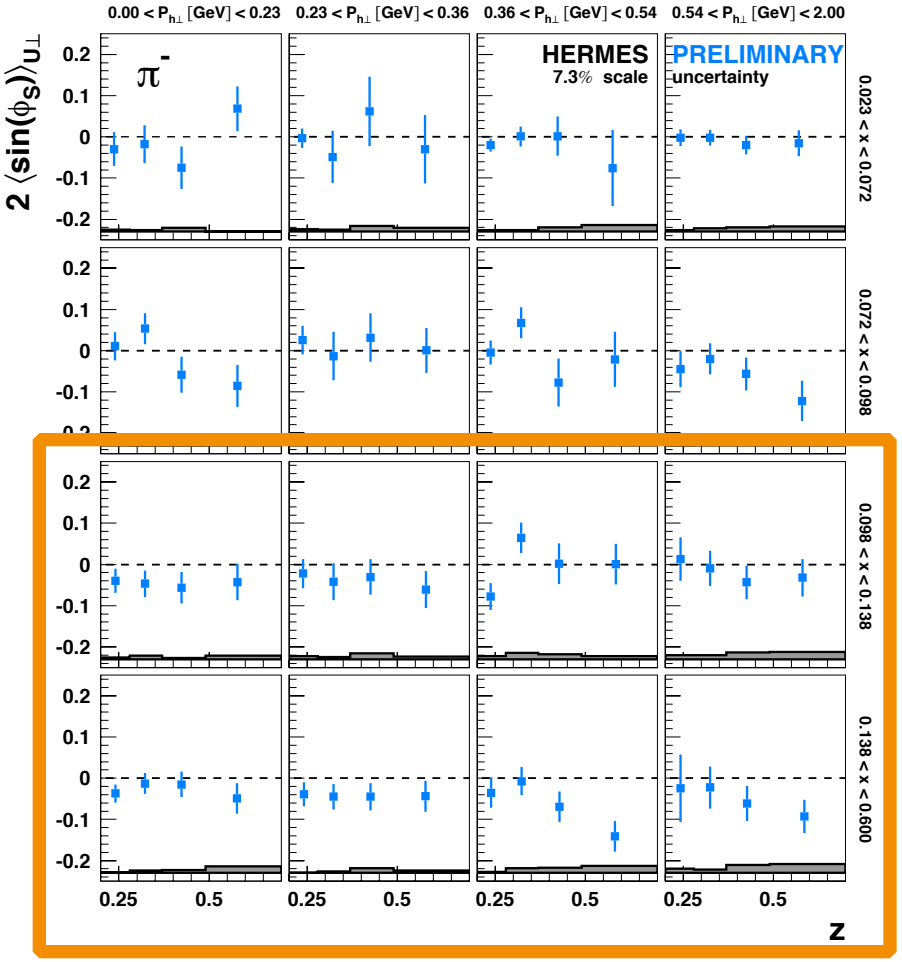


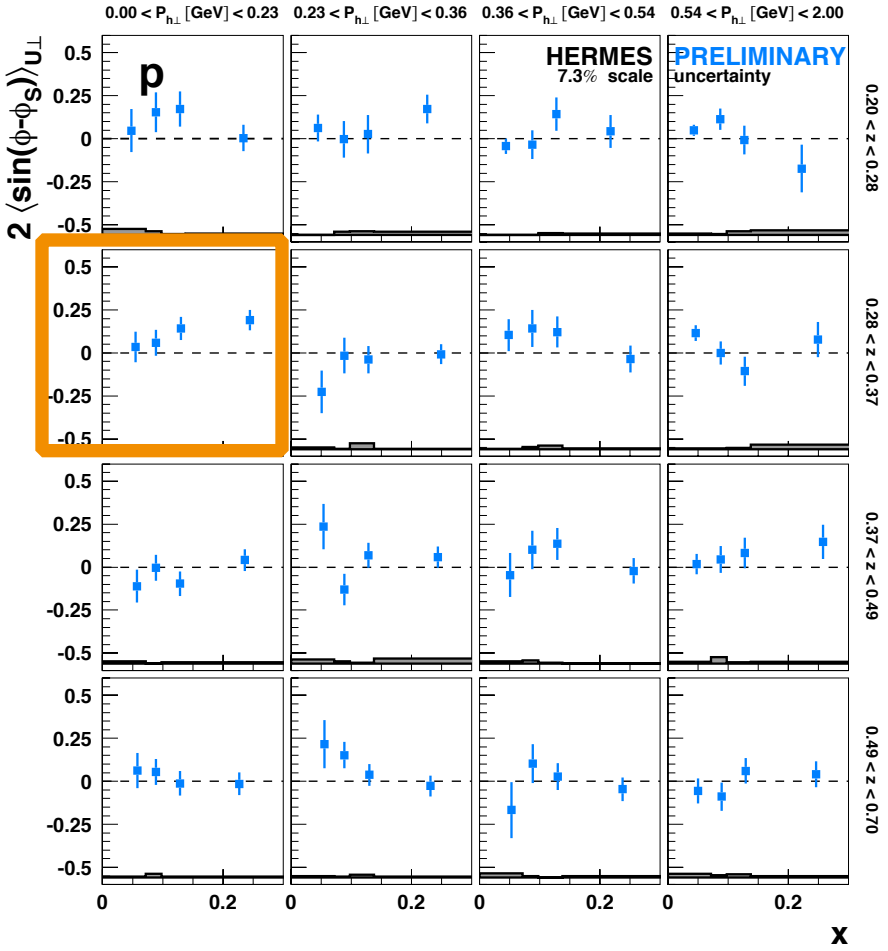
multi-dimensional analysis

- **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

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

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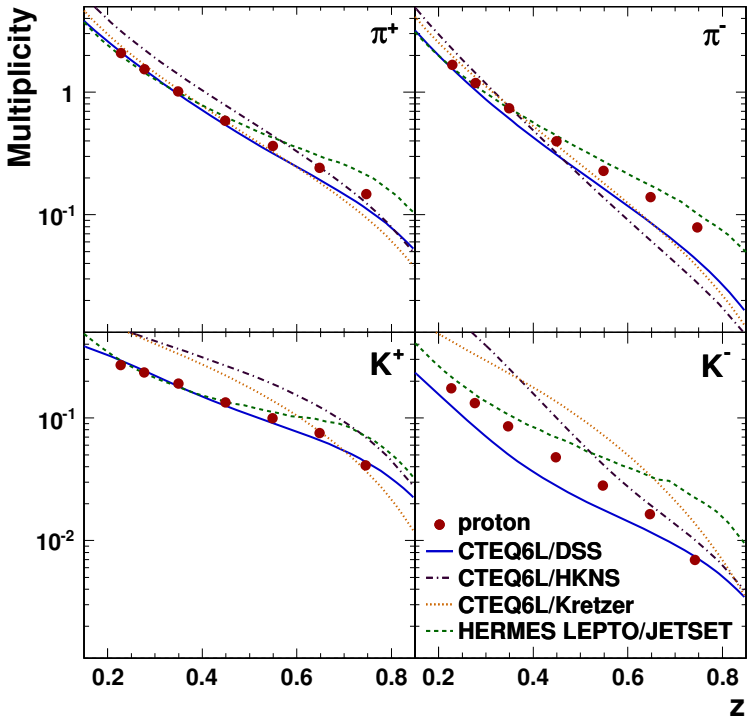

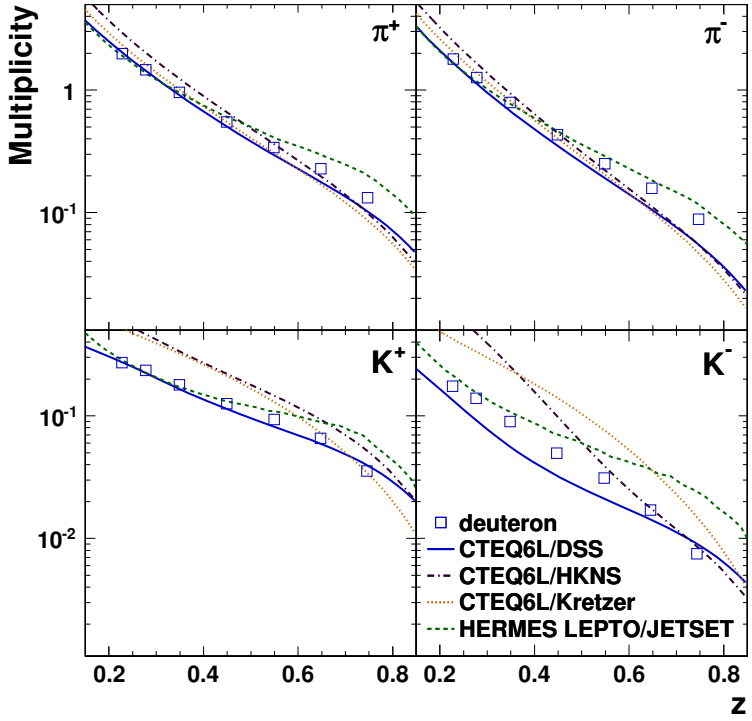

> **proton:**
- ➡ fair agreement for positive hadrons
- ➡ disagreement for negative hadrons

> **deuteron:**
- ➡ results are in general in better agreement with the various predictions

fragmentation of unpolarised quarks in unpolarised target

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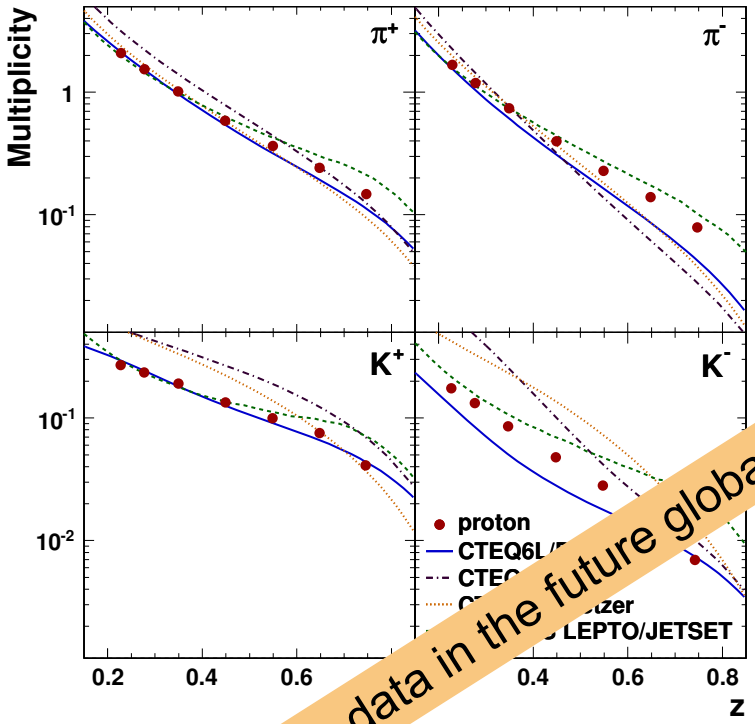

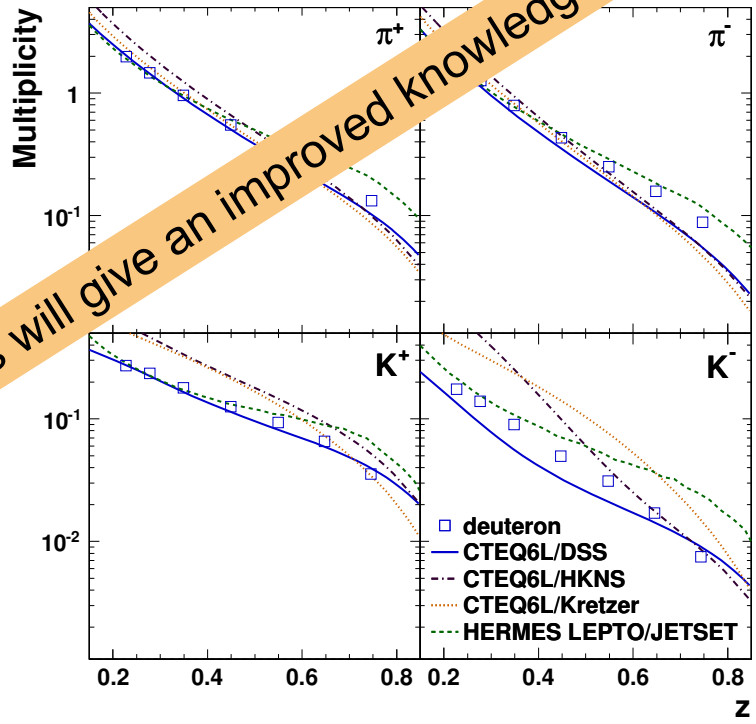

inclusion of the data in the future global analyses will give an improved knowledge on FF

> **proton:**
- fair a… ent for positive hadrons
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> **…on:**
- results are in general in better agreement with the various predictions

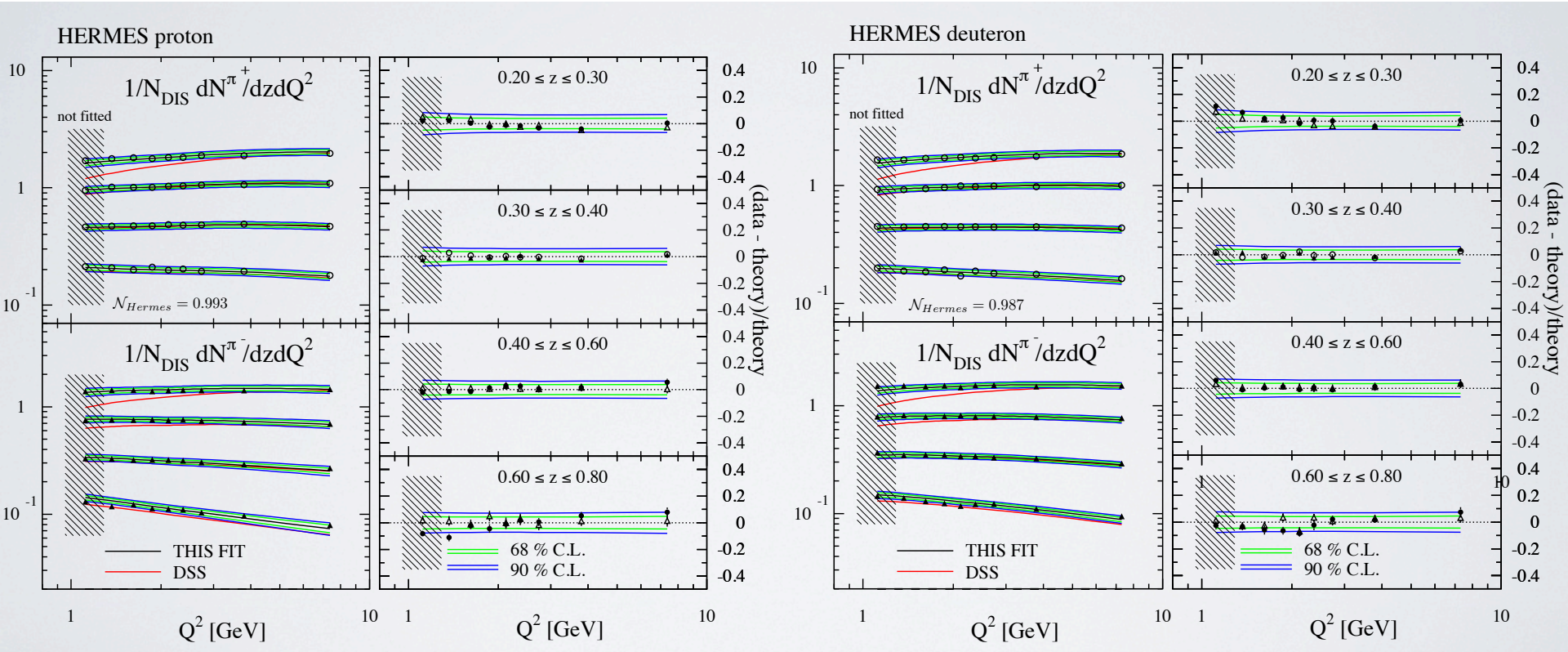
New global fit DSS+

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

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

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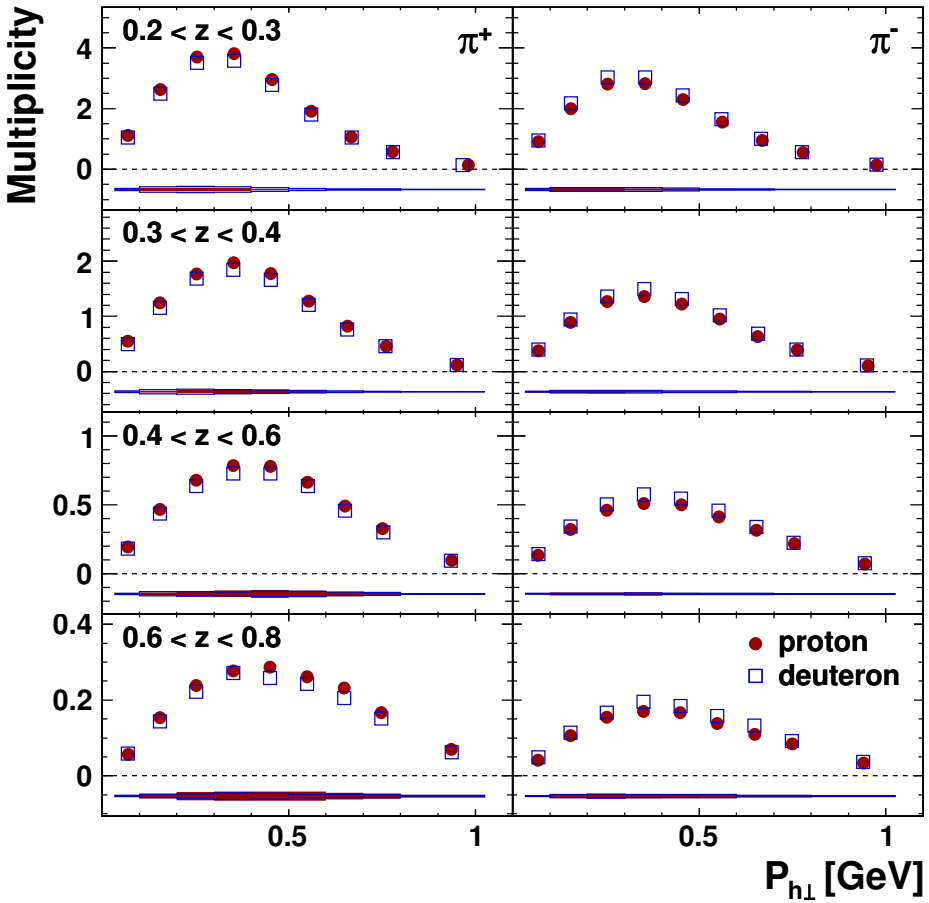
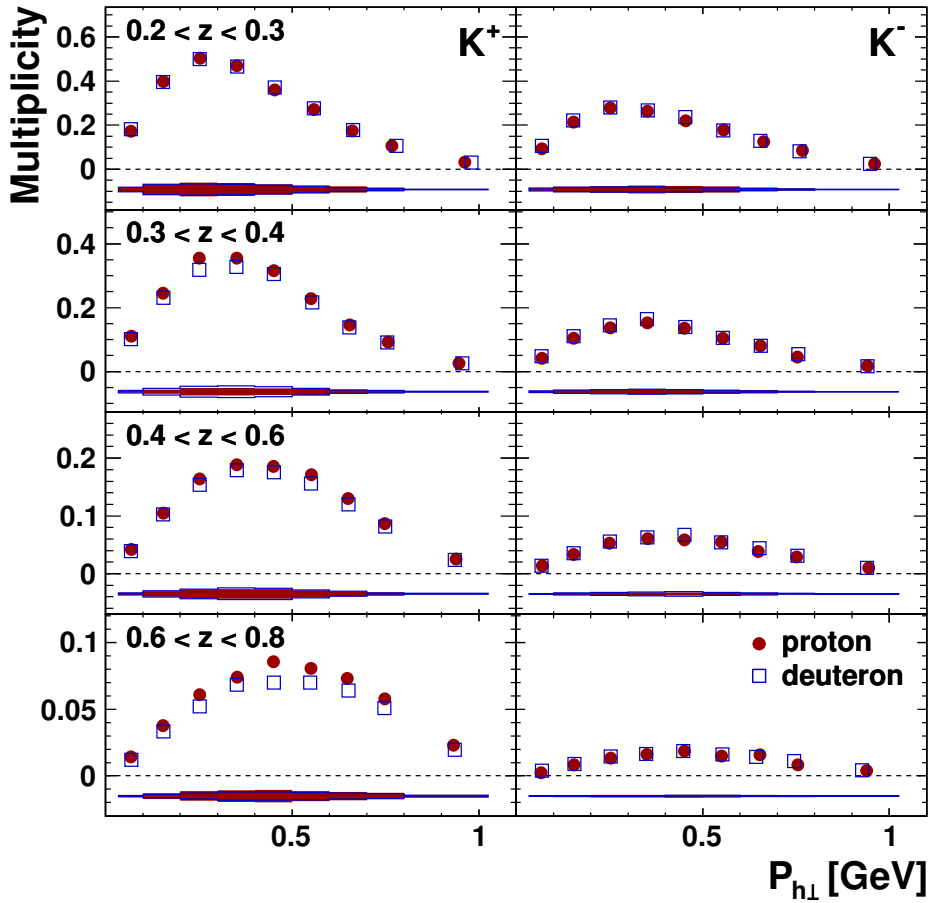
- HERMES Collaboration- Phys.Rev. D87 (2013) 074029





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

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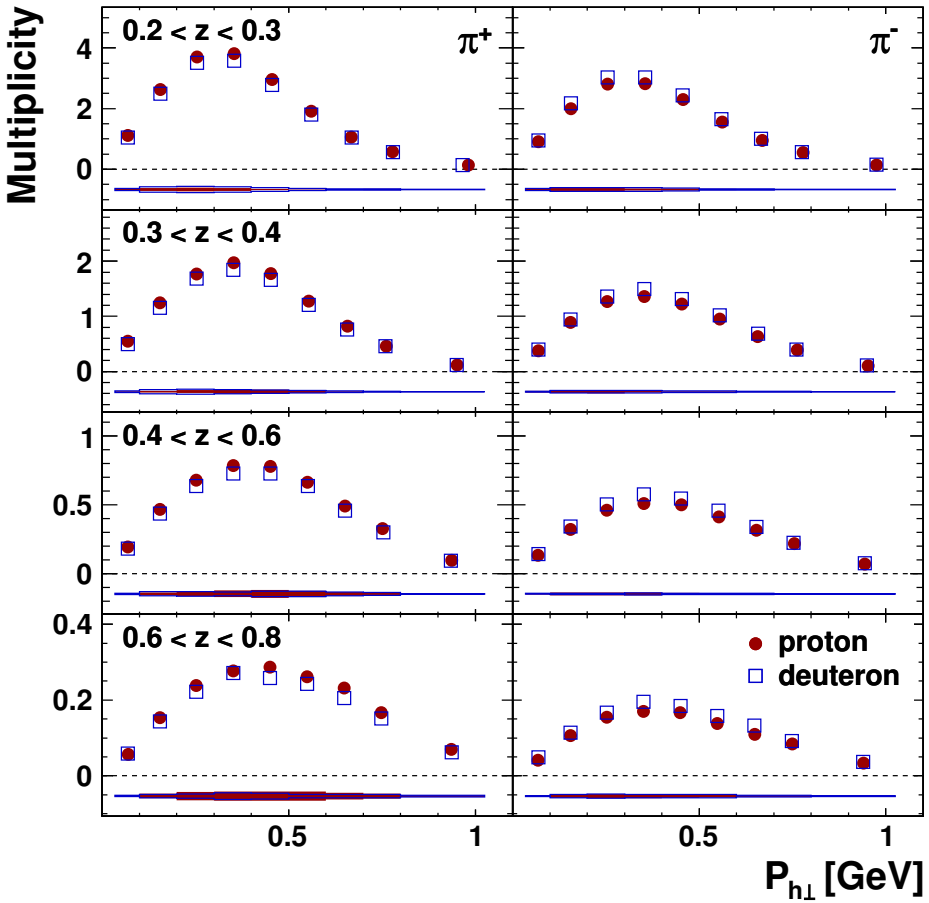
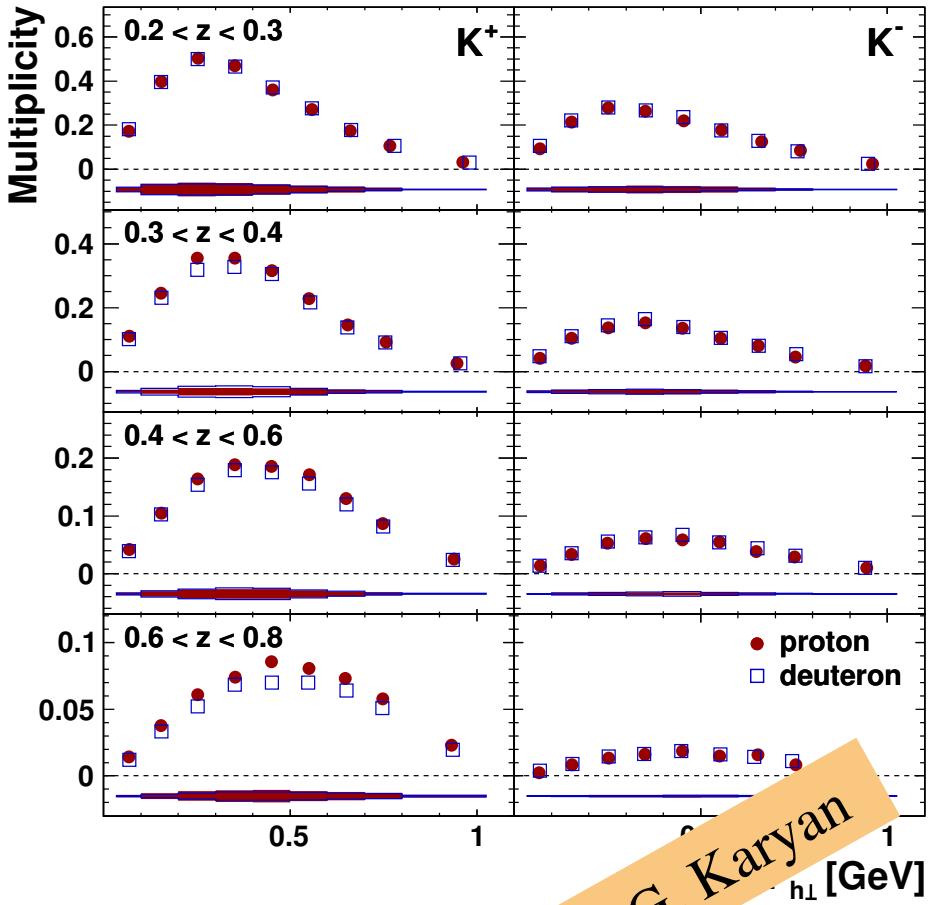
- HERMES Collaboration- Phys.Rev. D87 (2013) 074029





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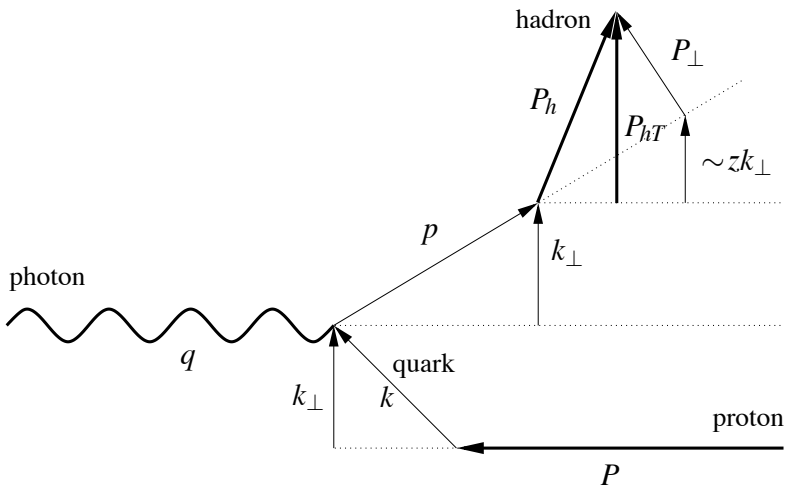
see the talk by G. Karyan

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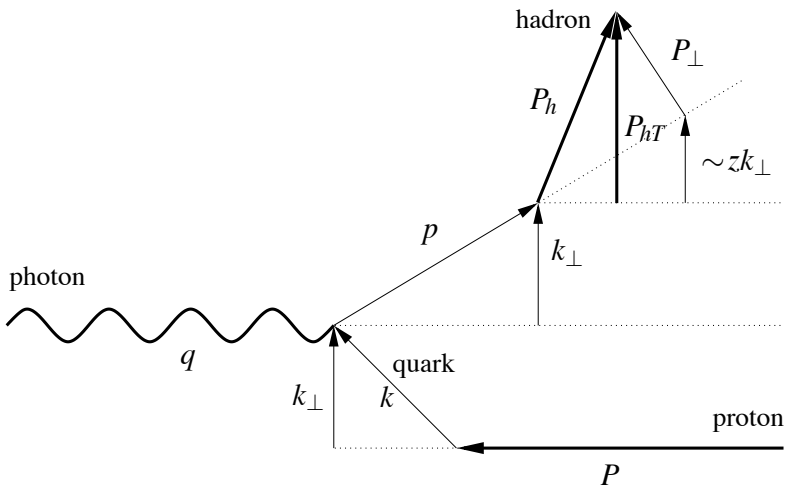
$$\langle \boldsymbol{P}^2_{hT,a} \rangle = z^2 \langle \boldsymbol{k}^2_{\perp,a} \rangle + \langle \boldsymbol{P}^2_{\perp,a\to h} \rangle$$

flavour-dependent and independent ansatzes



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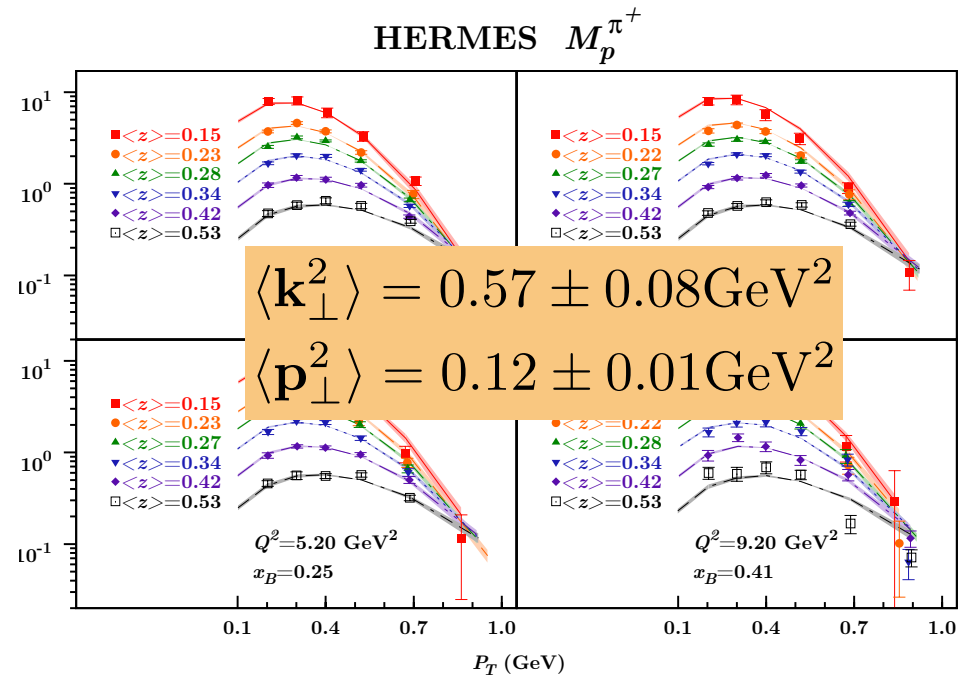
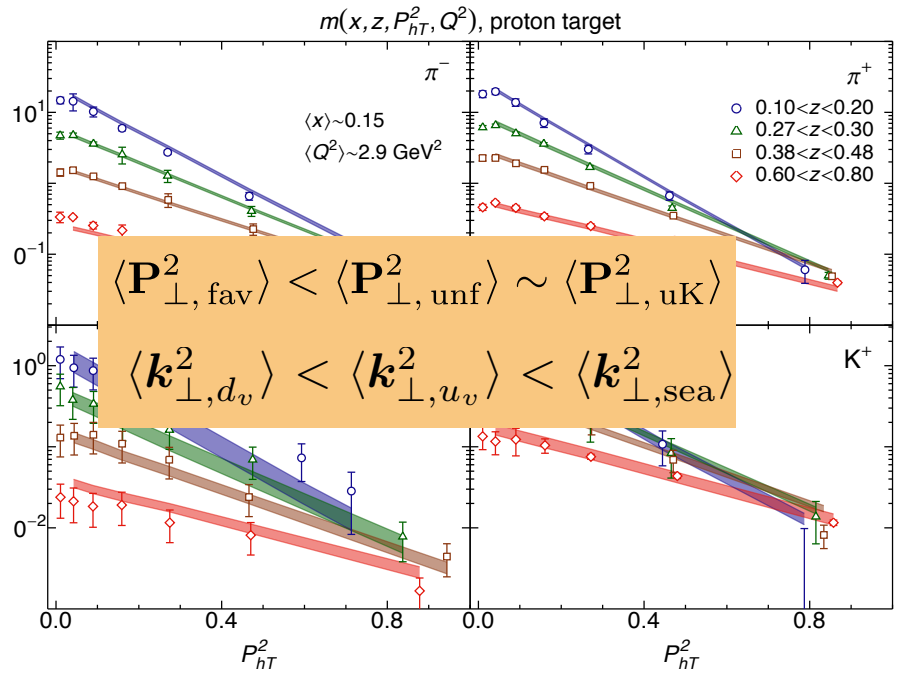


$$\langle \mathbf{k}^2_\perp \rangle = 0.57 \pm 0.08 \mathrm{GeV}^2$$
$$\langle \mathbf{p}^2_\perp \rangle = 0.12 \pm 0.01 \mathrm{GeV}^2$$



$$\langle \mathbf{P}^2_{\perp,\,\mathrm{fav}} \rangle < \langle \mathbf{P}^2_{\perp,\,\mathrm{unf}} \rangle \sim \langle \mathbf{P}^2_{\perp,\,\mathrm{uK}} \rangle$$
$$\langle \boldsymbol{k}^2_{\perp,d_v} \rangle < \langle \boldsymbol{k}^2_{\perp,u_v} \rangle < \langle \boldsymbol{k}^2_{\perp,\mathrm{sea}} \rangle$$

fragmentation of quarks involving transverse degrees of freedom

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

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Phys. Rev. D57 (1998)

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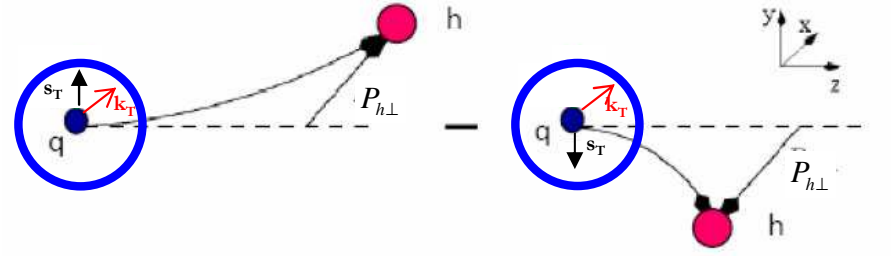
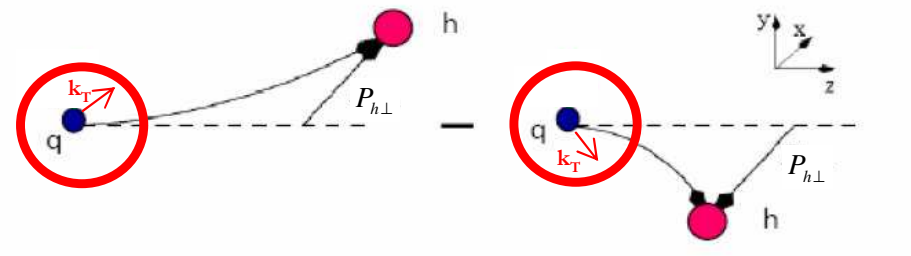
Boer-Mulders effect

- 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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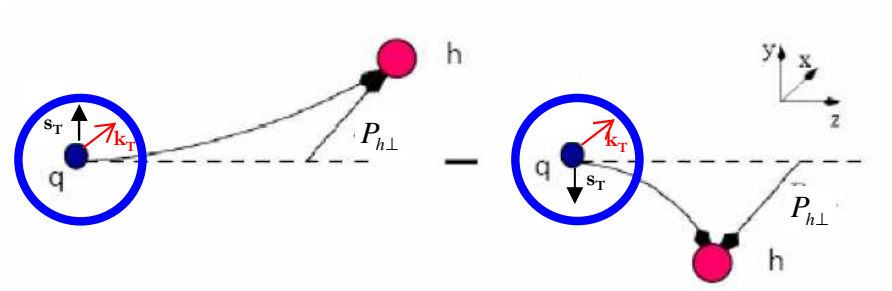
$\cos 2\phi_h$



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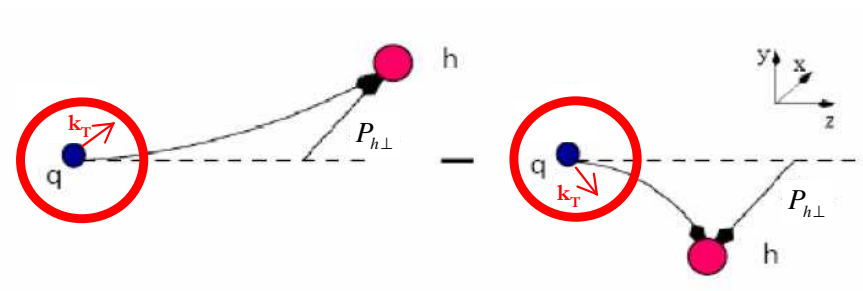

quarks' transverse degrees of freedom

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

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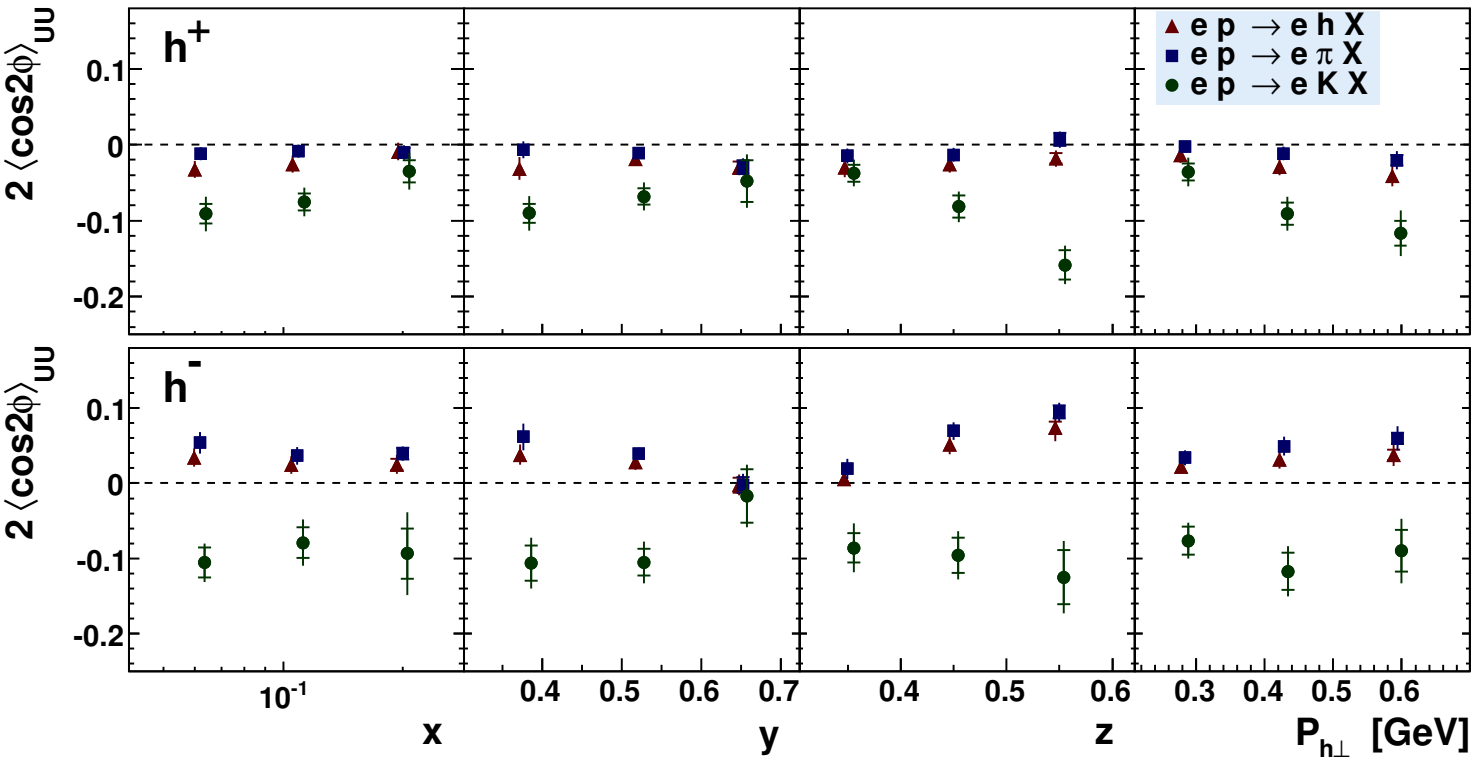

fully differential 4D extraction of asymmetry amplitudes (900 bins in x, y, z, Ph)

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

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

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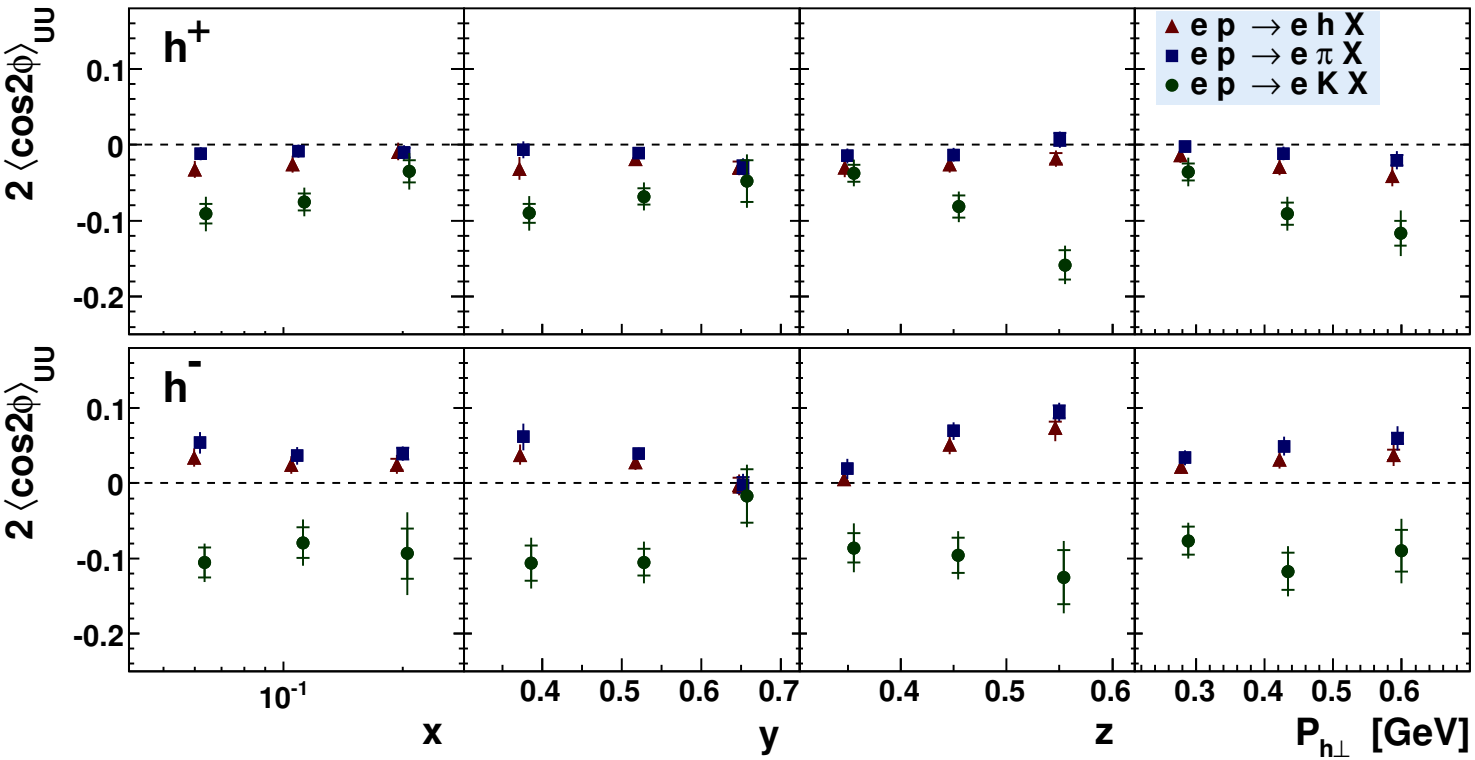

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  - data supports Boer-Mulders DF $h_1^{\perp}$ of same sign for u and d quarks

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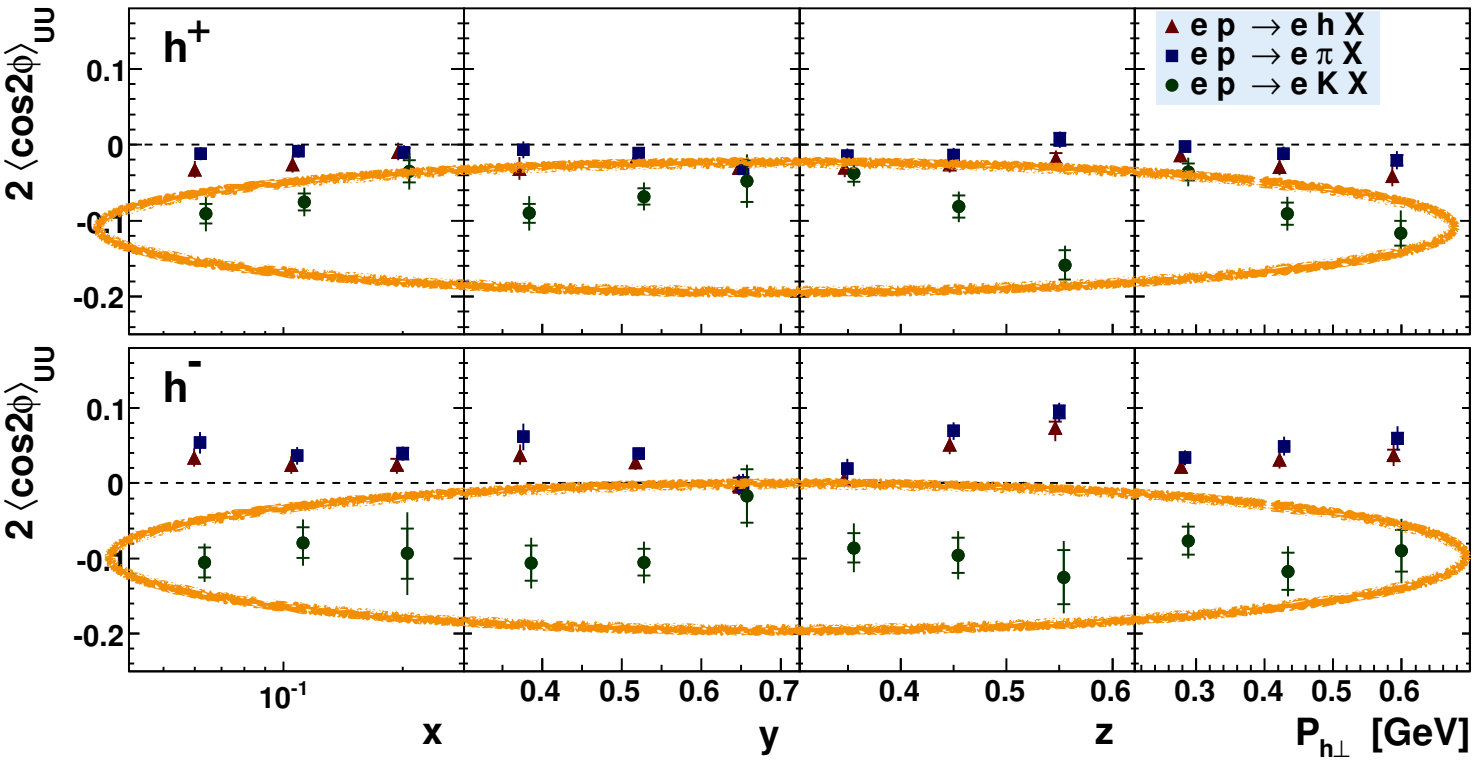

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  - role of the sea in DF and FF

quarks' transverse degrees of freedom

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

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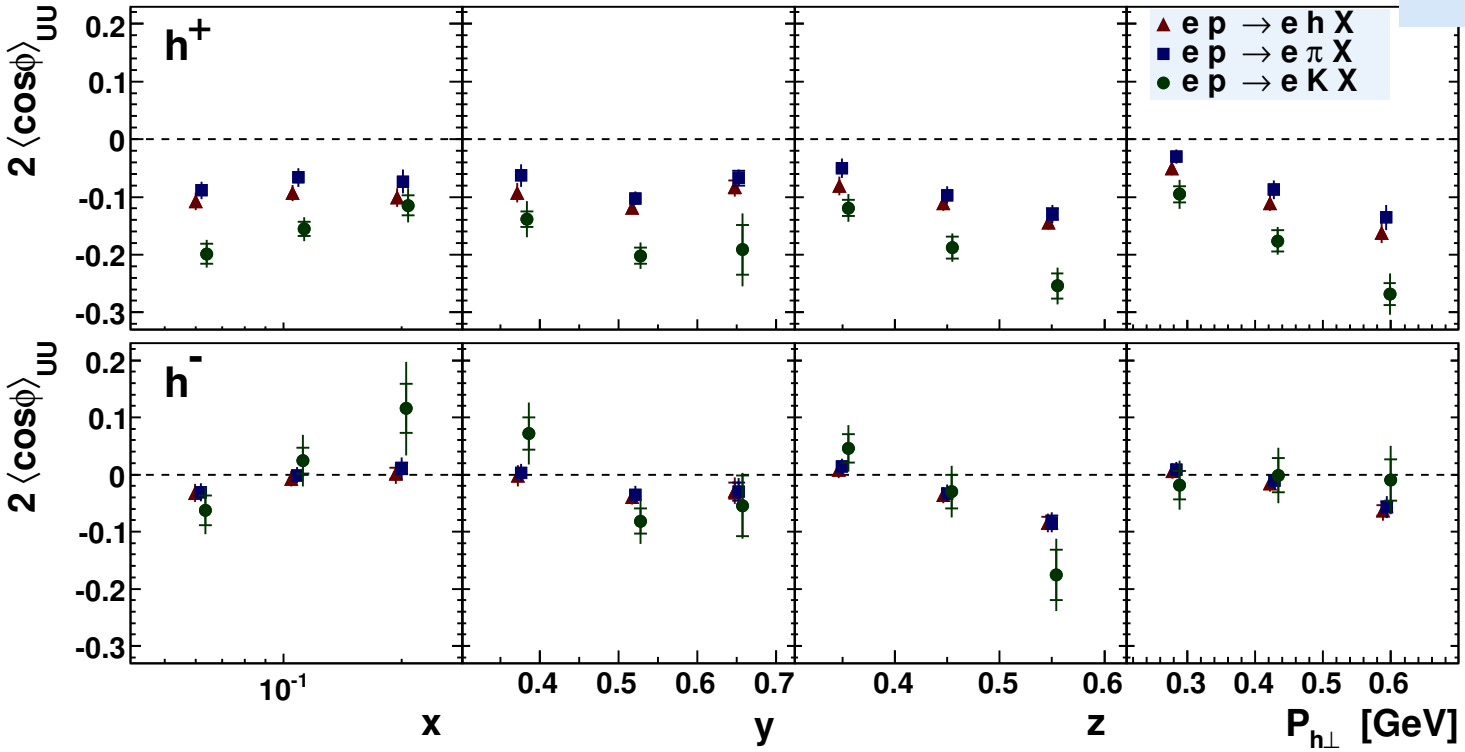

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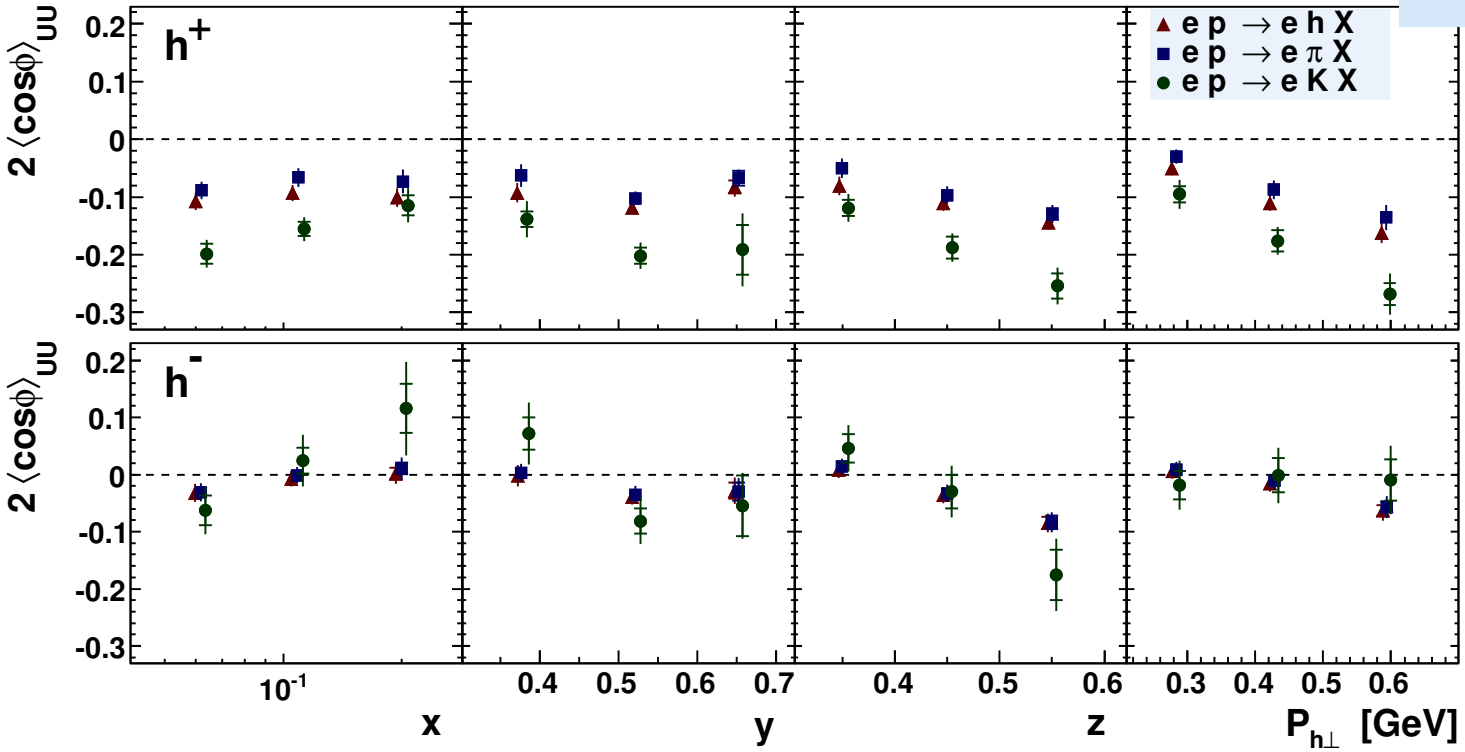

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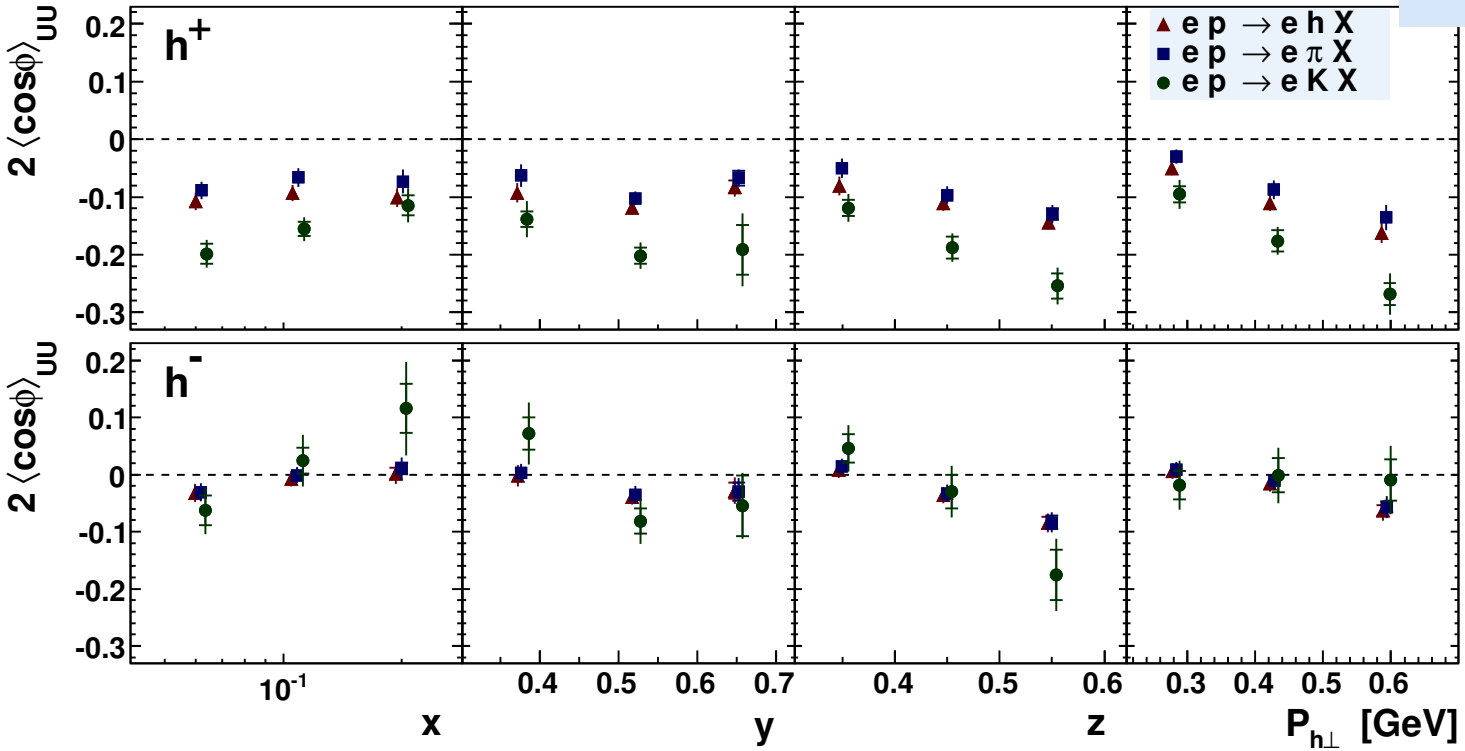

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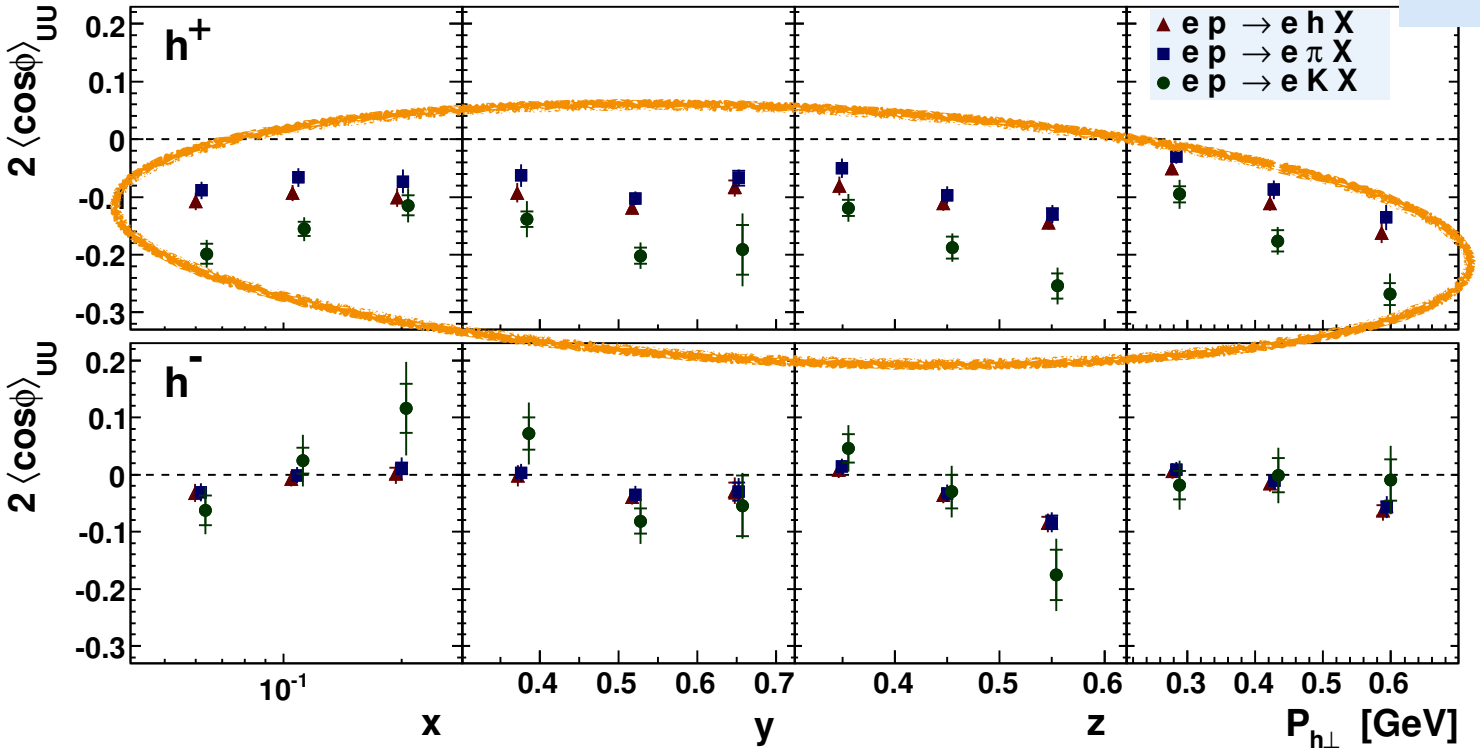

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  - suggest a large contribution from the Boer–Mulders effect
- **even larger amplitudes in magnitude for K^+ than those for π^+**

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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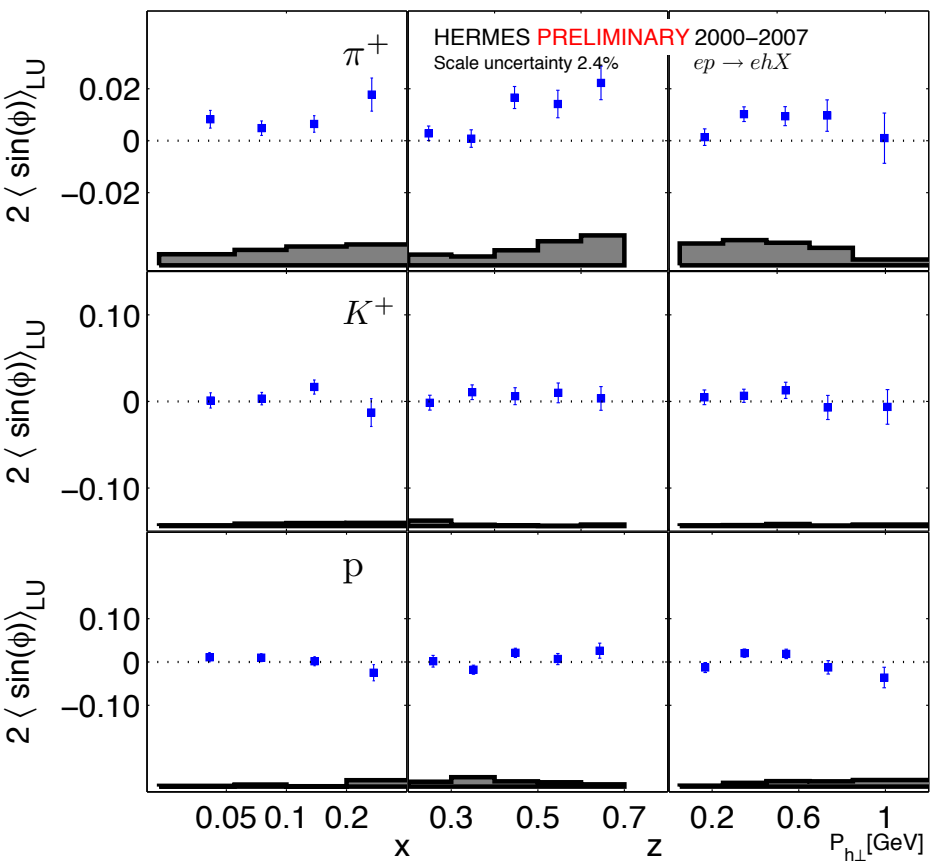

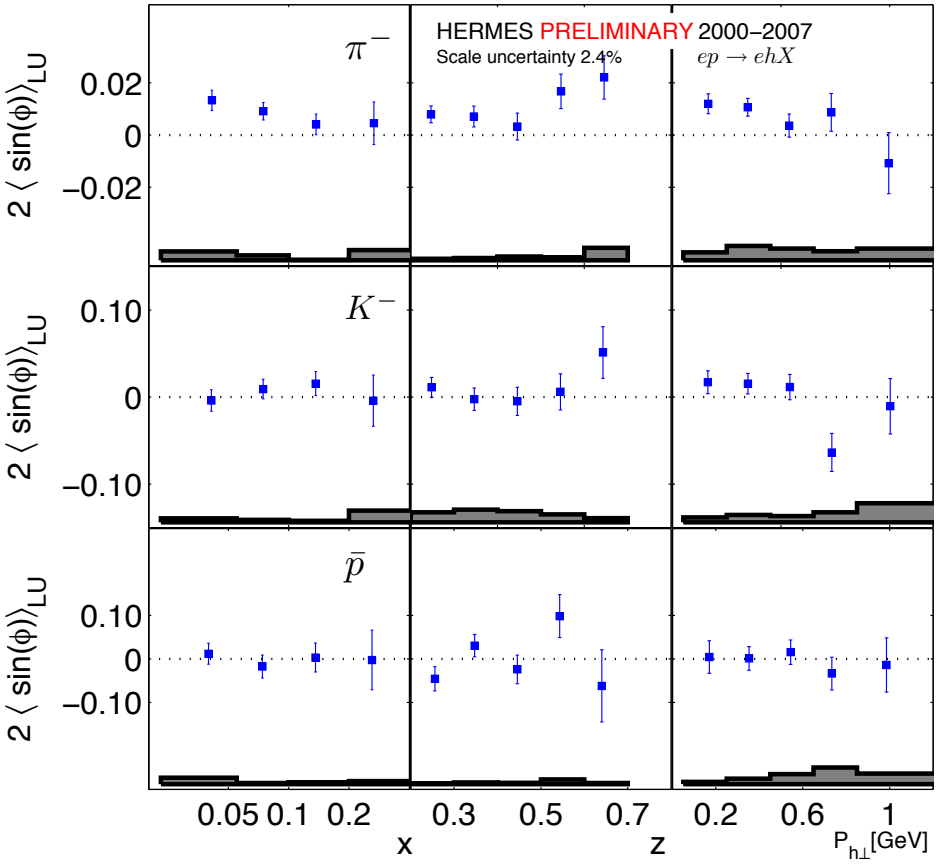

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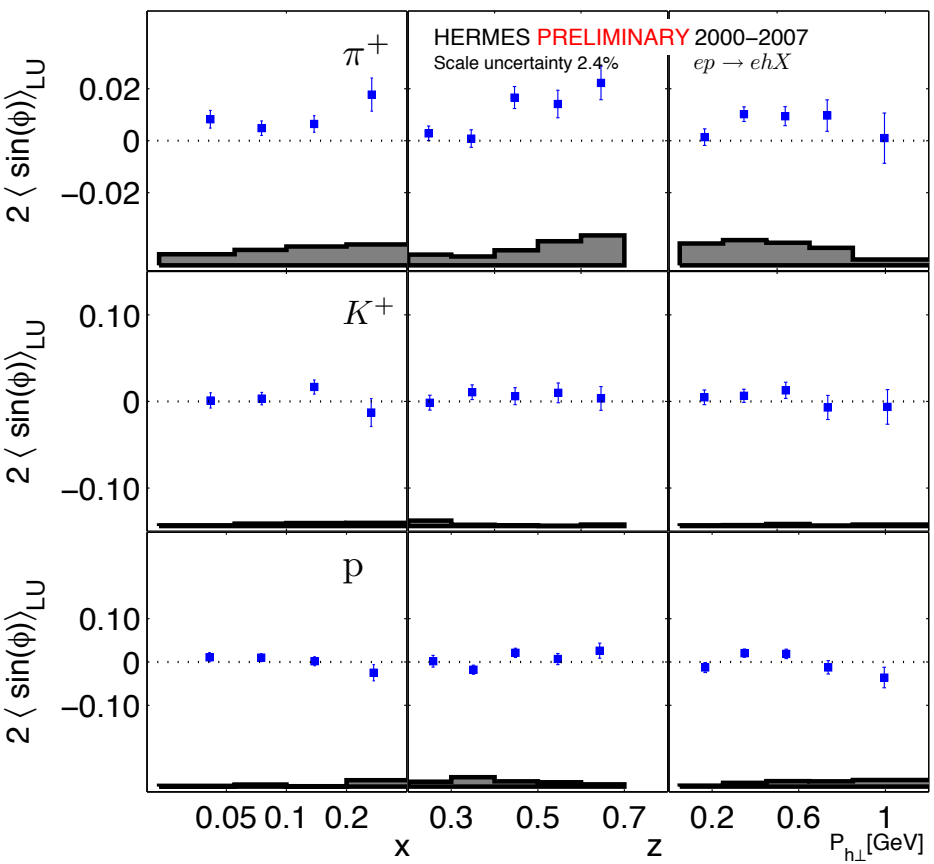

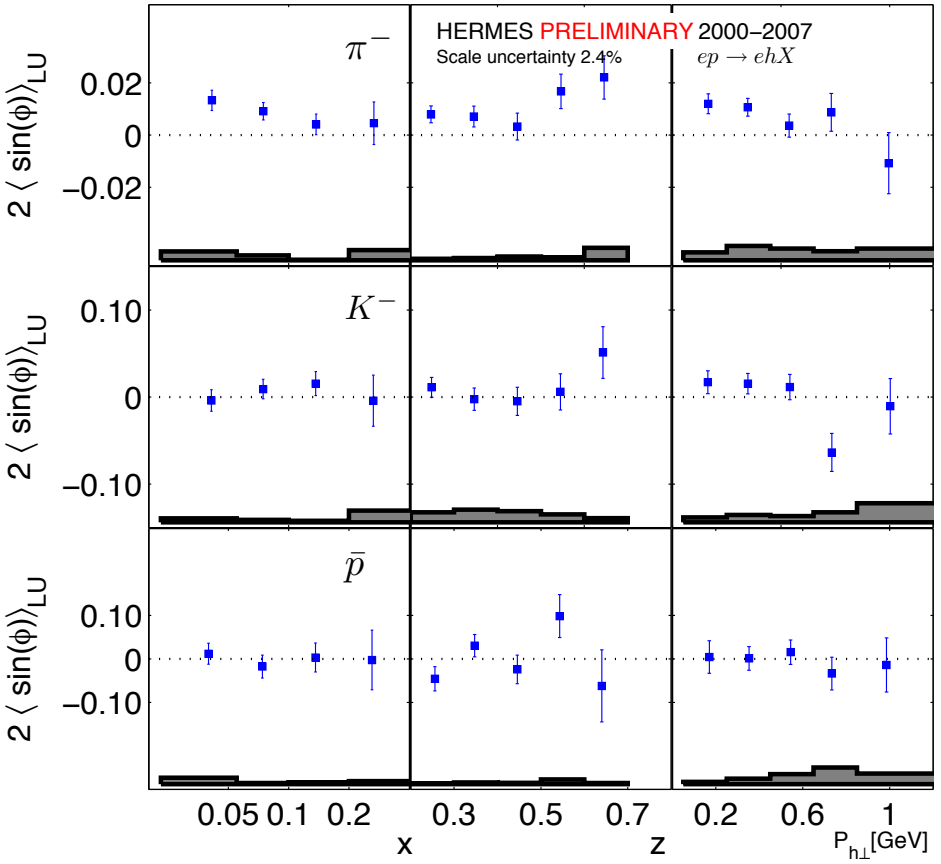

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  - the role of the twist-3 DF or FF is sizeable

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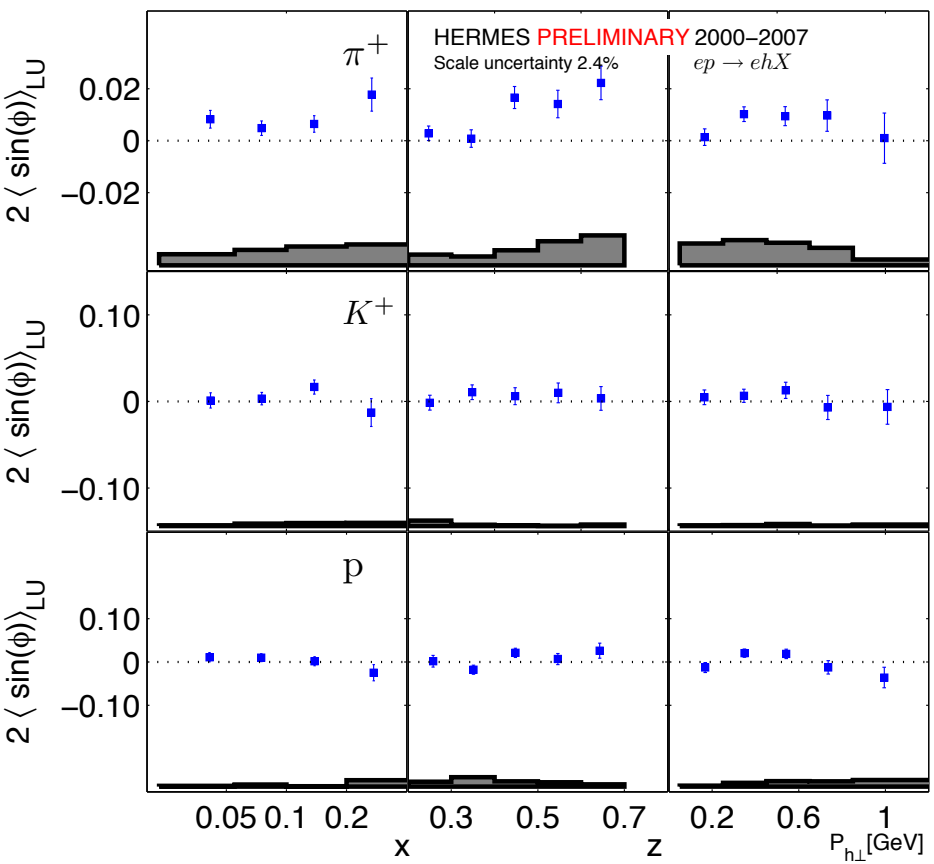

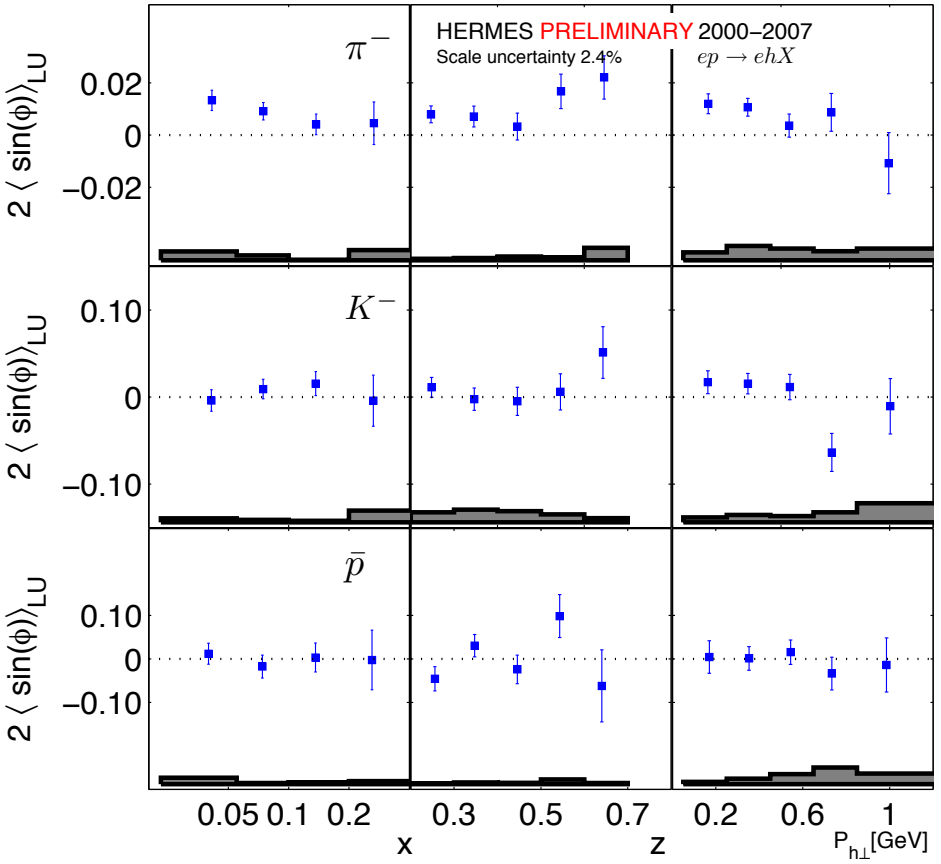

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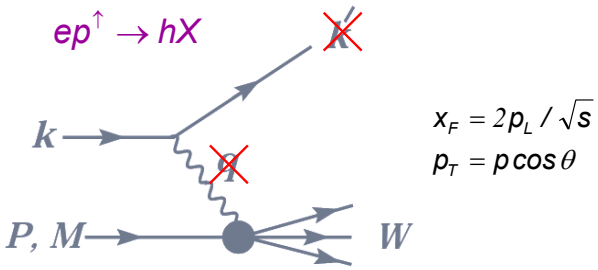
towards differential 3D (in x, y, z, Ph) extraction of asymmetry amplitudes

going to fully inclusive measurements

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



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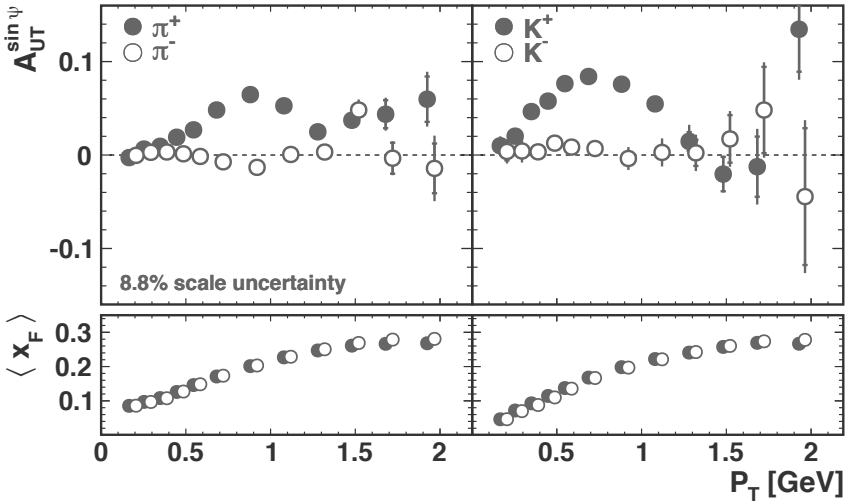
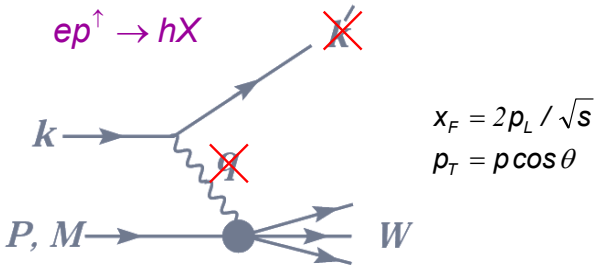
- HERMES Collaboration - Phys. Lett. B 728 (2014) 183





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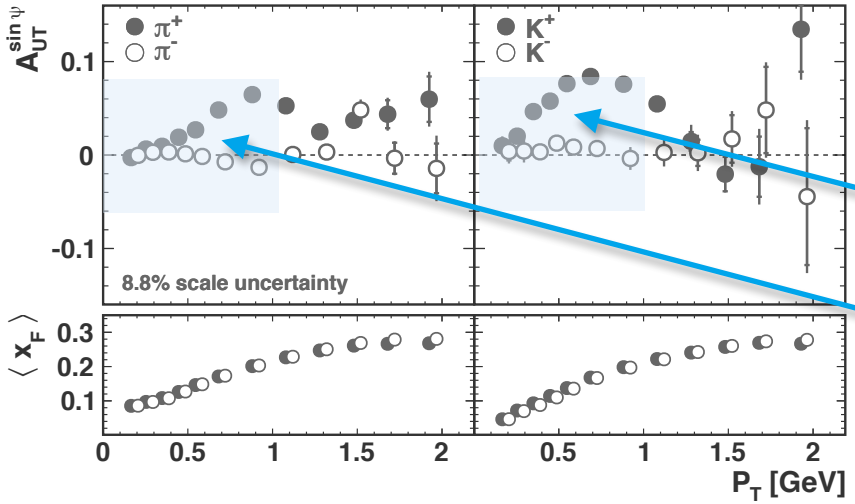
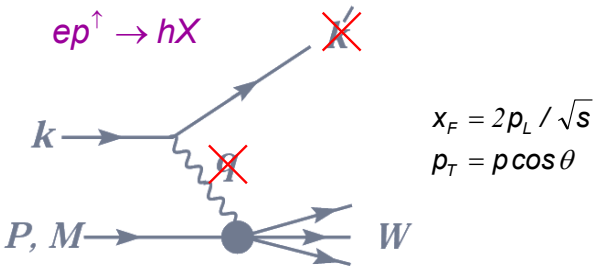
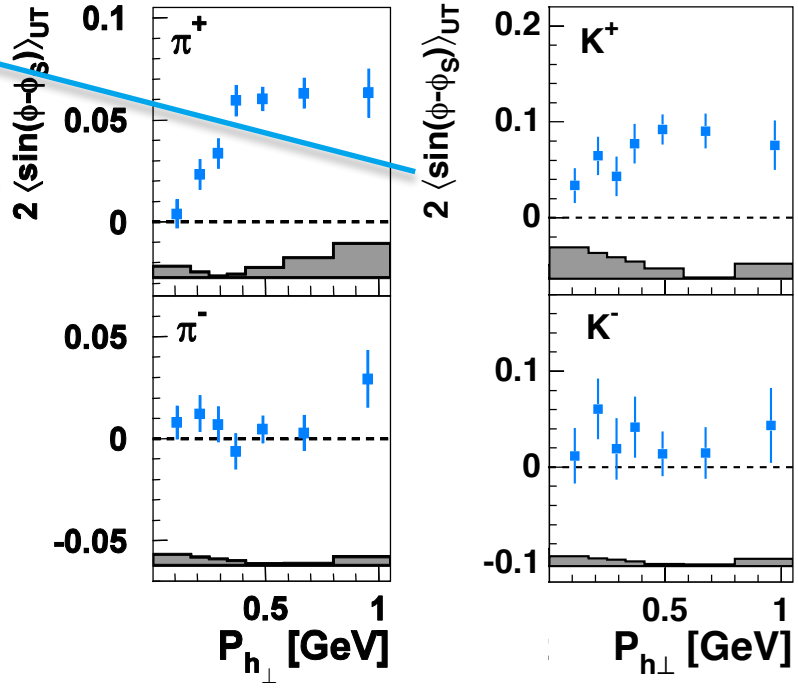


- **Sivers effect or higher twist effects ?**

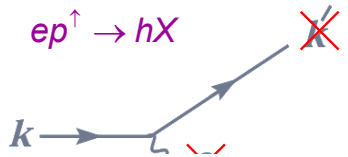


- HERMES Collaboration - Phys. Rev. Lett. 103 (2009) 152002

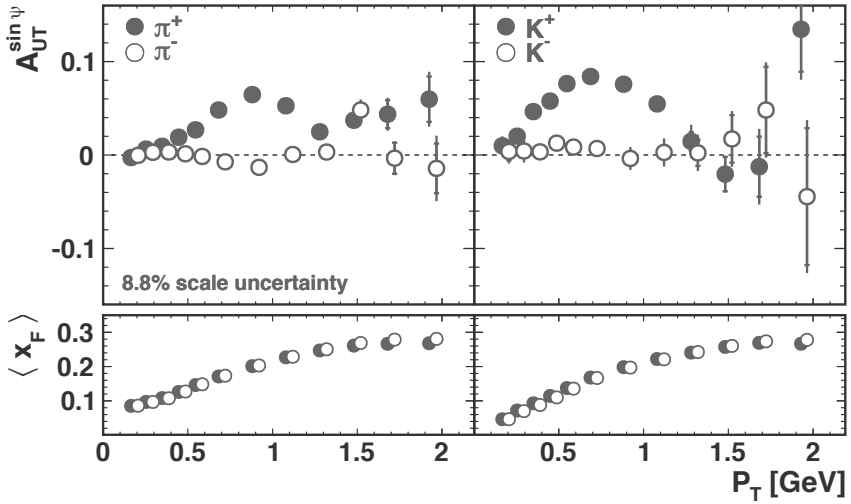


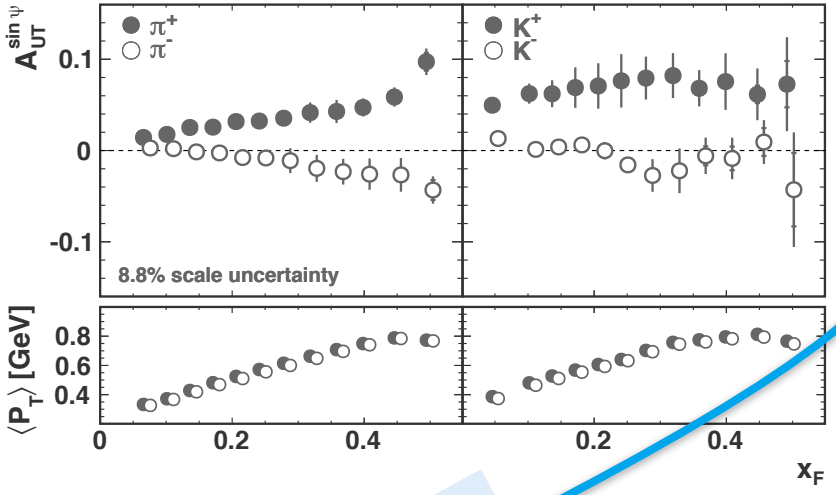
going to fully inclusive measurements

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



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

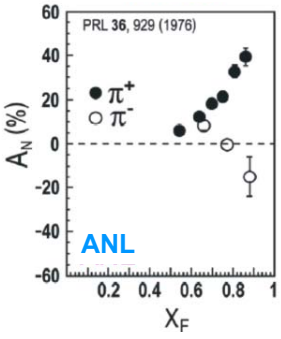




- **Sivers effect or higher twist effects ?**
- **similarities with** $p^{\uparrow}p \to \pi X$ **?**

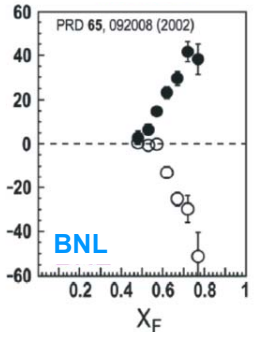
$$A_N = -\frac{2}{\pi} A_{UT}^{\sin\psi}$$

4.9 GeV



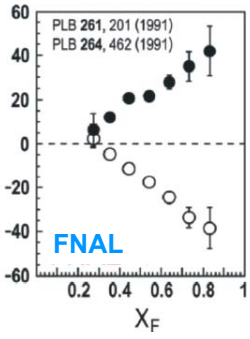
1976

6.6 GeV



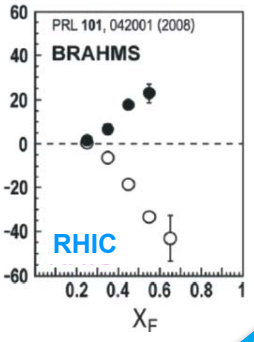
2002

19.4 GeV



1991

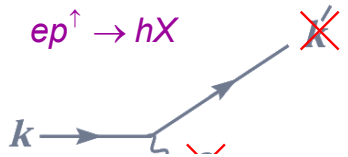
62.4 GeV



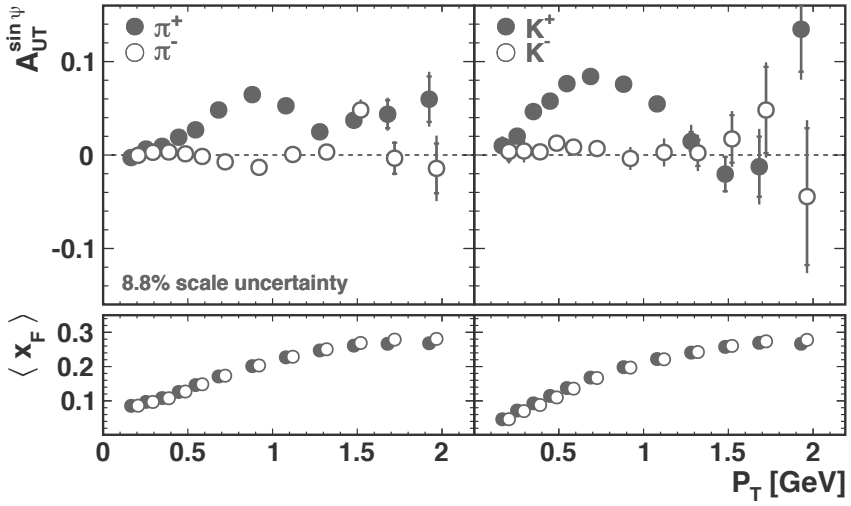
2008

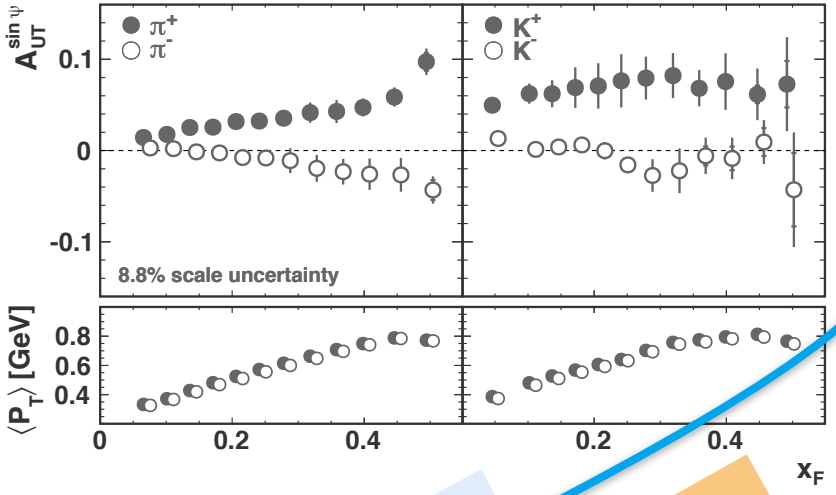
going to fully inclusive measurements

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

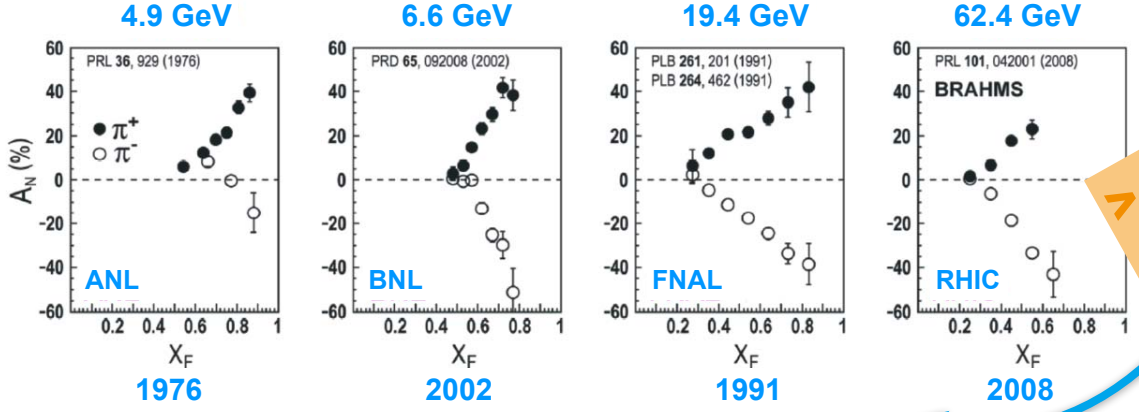


- HERMES Collaboration - Phys. Lett. B 728 (2014) 183





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



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

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

see the talk by A. Rostomyan

HERMES TMD program:

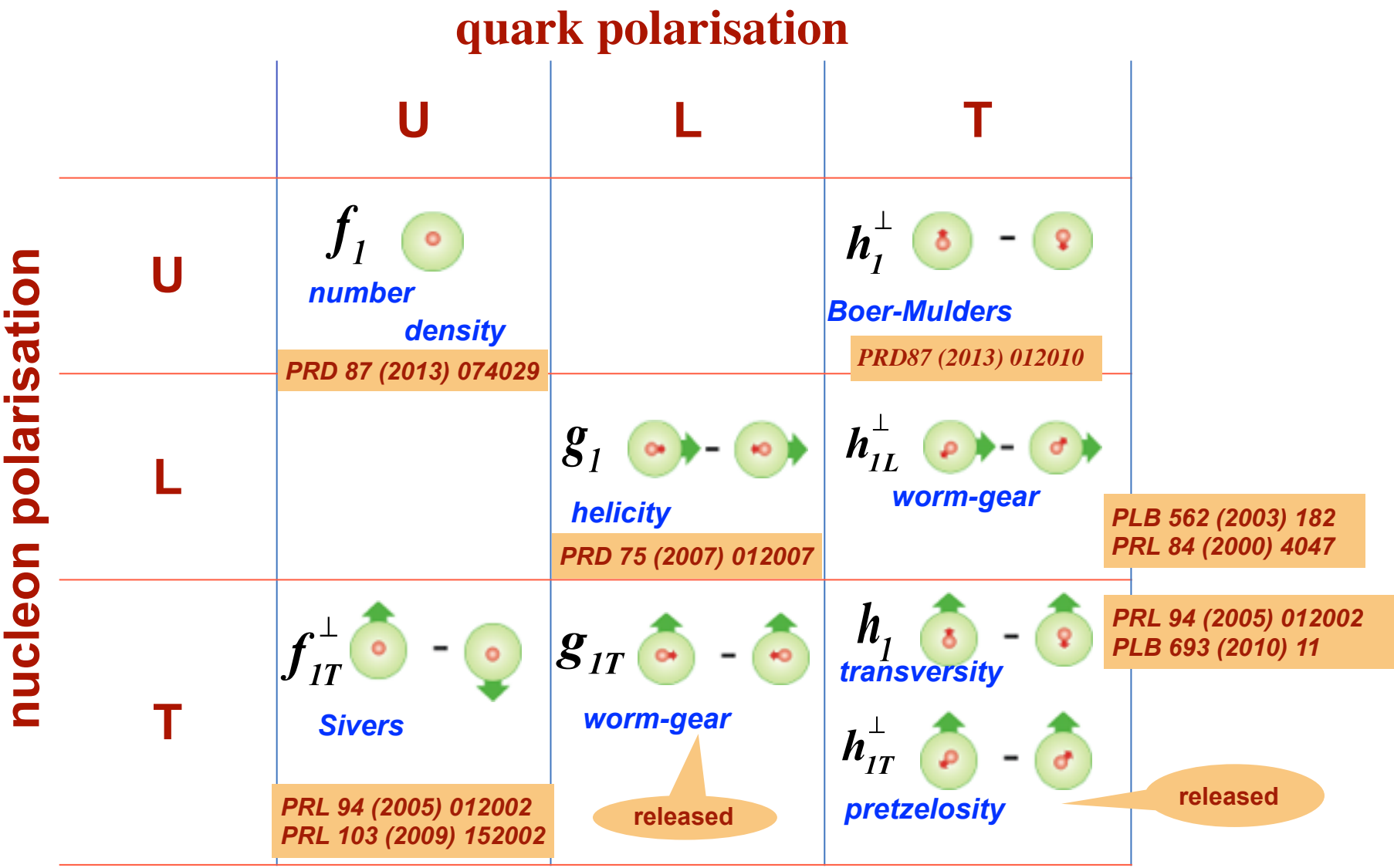
access to all TMDs thanks to the polarised beam and target

quark polarisation

nucleon polarisation	U	L	T
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:

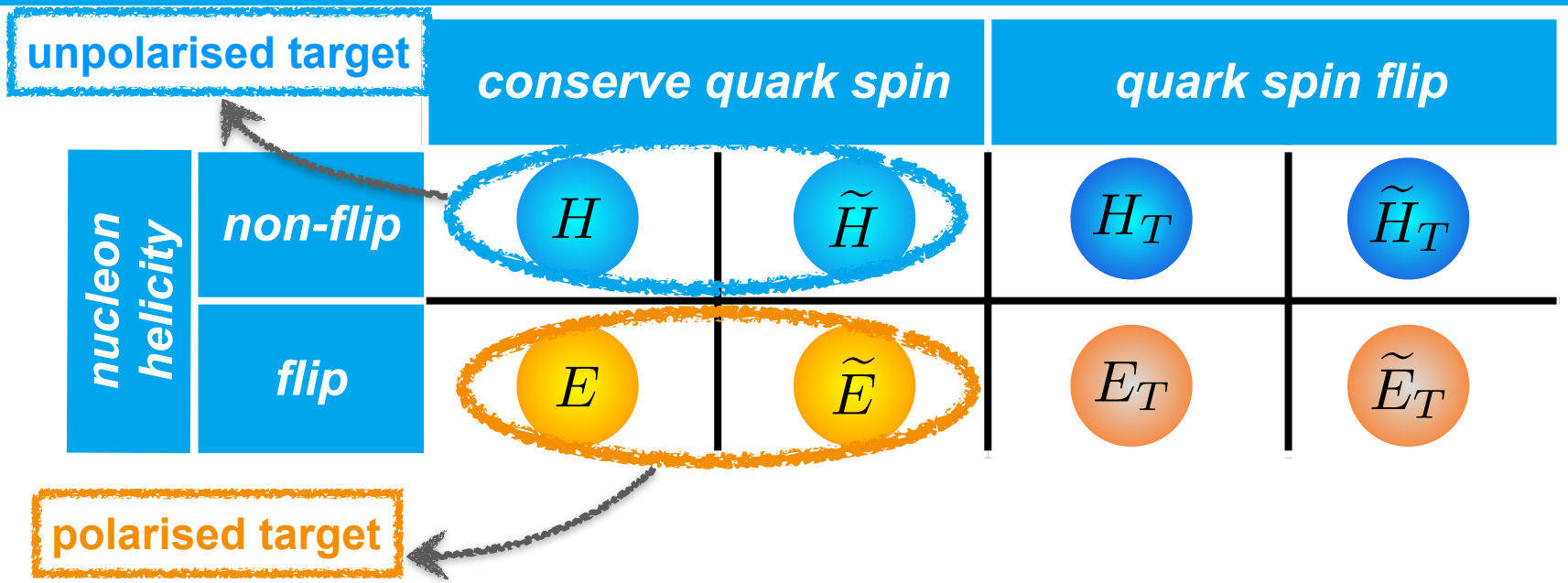
access to all TMDs thanks to the polarised beam and target



GPDs

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

GPDs

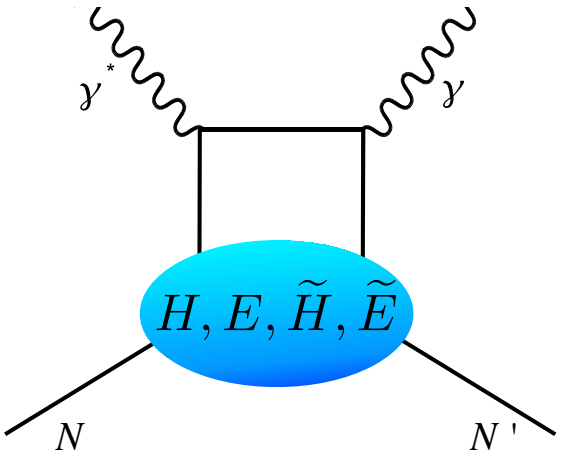

unpolarised target
conserve quark spin
quark spin flip
nucleon helicity
non-flip
flip
H
$\widetilde{H}$
H_T
$\widetilde{H}_T$
E
$\widetilde{E}$
E_T
$\widetilde{E}_T$
polarised target

GPDs

- **DVCS**
  - at leading twist:

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

  - **deeply virtual Compton scattering**

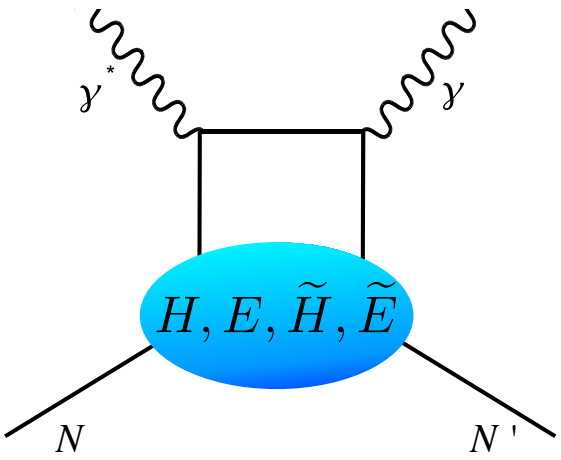


GPDs

- **DVCS**
  - at leading twist:

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

- **deeply virtual Compton scattering**



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

H E

  - higher twist:

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

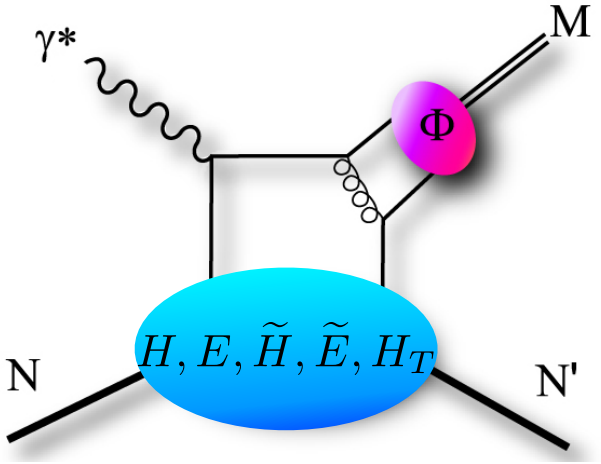
- **pseudoscalar mesons**
  - at leading twist:

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

  - higher twist:

H_T

- **vector and pseudoscalar meson production**

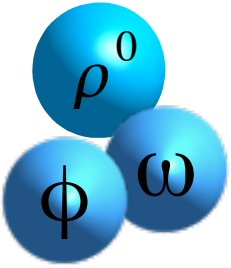


exclusive measurements (probing GPDs)

hermes **highlights**

> measured complete set of beam helicity, beam charge and target polarisation asymmetries

> first measurement of associated DVCS



> complete set of SDMEs on unpolarised H and D targets

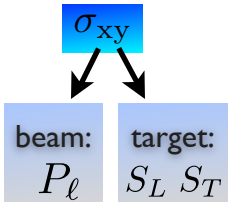
> first measurement of SDMEs on a transversely polarised target

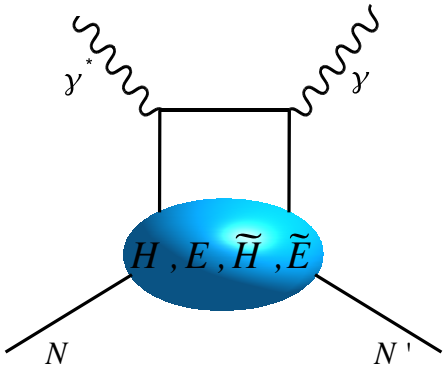
> first measurement of asymmetry on transversely polarised target sensitive to H_T

DVCS

theoretically the cleanest probe of GPDs

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





DVCS

theoretically the cleanest probe of GPDs

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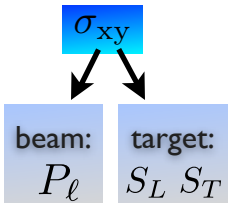
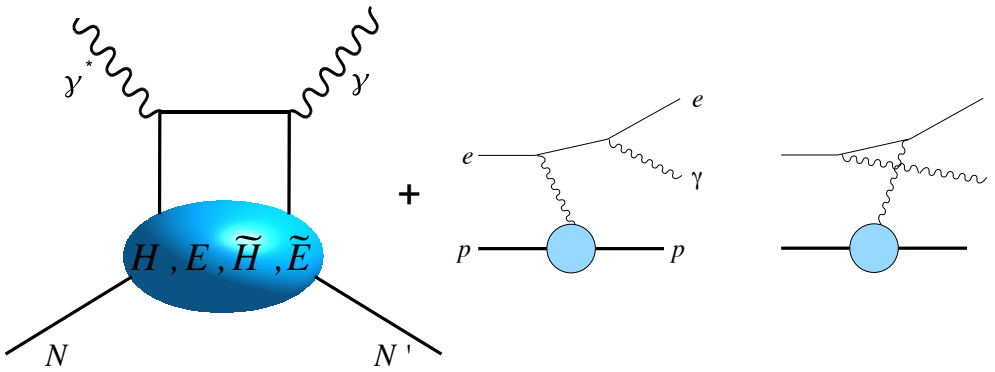
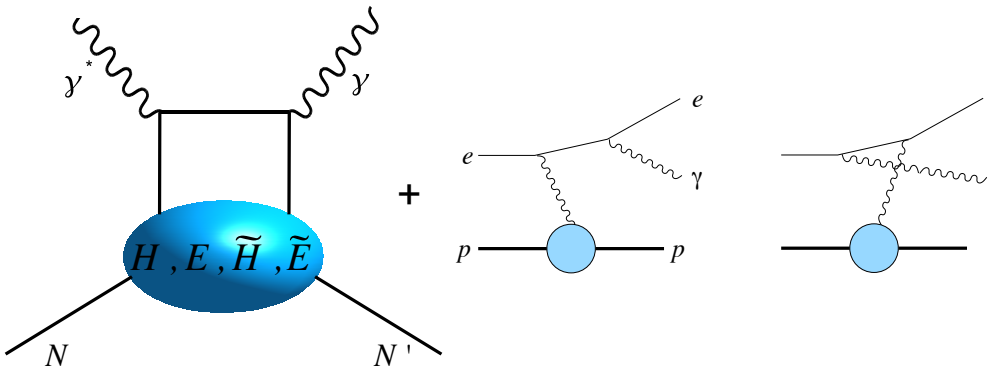




DVCS

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

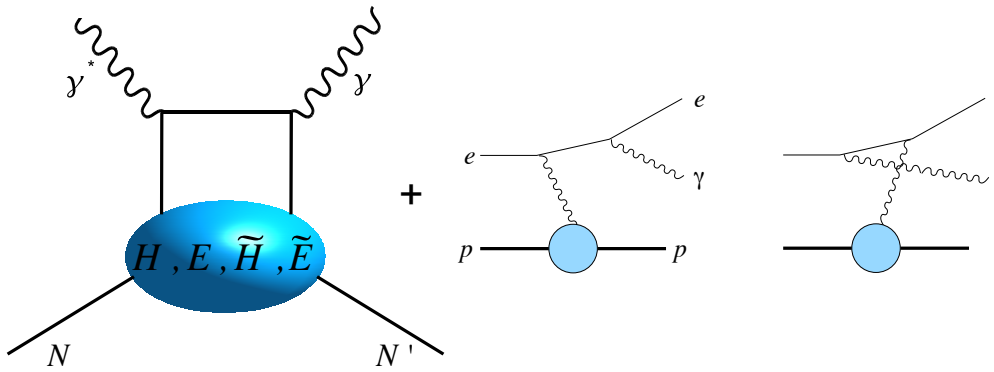
Bethe–Heitler | interference | DVCS

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

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

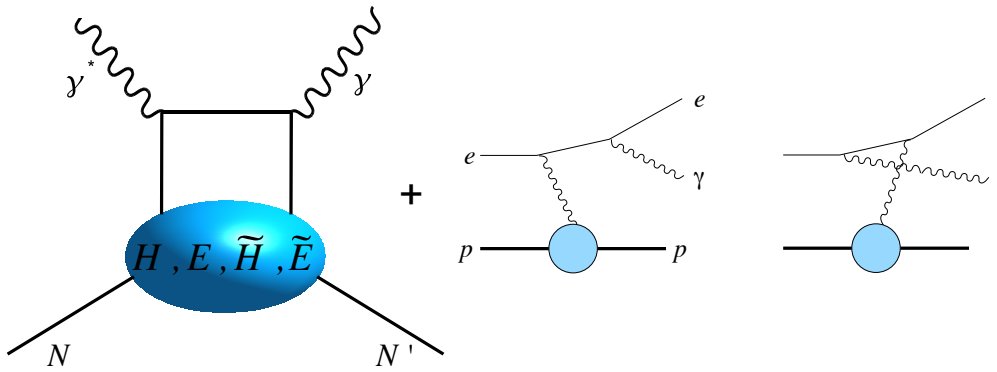
Bethe–Heitler | interference | DVCS

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

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

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

> **unpolarised target**

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

> **longitudinally polarised target**

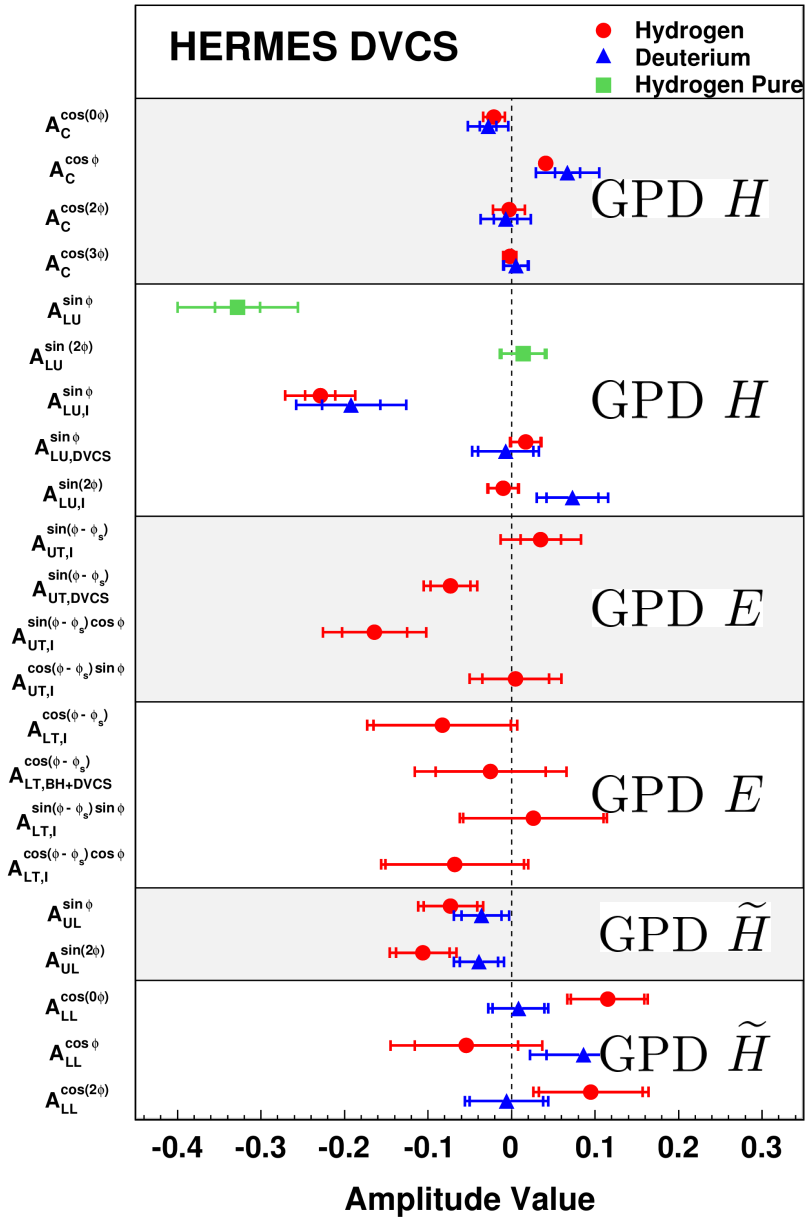
$$\frac{x_B}{2-x_B}(F_1+F_2)\left(\mathcal{H}+\frac{x_B}{2}\mathcal{E}\right)$$

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

> **transversely polarised target**

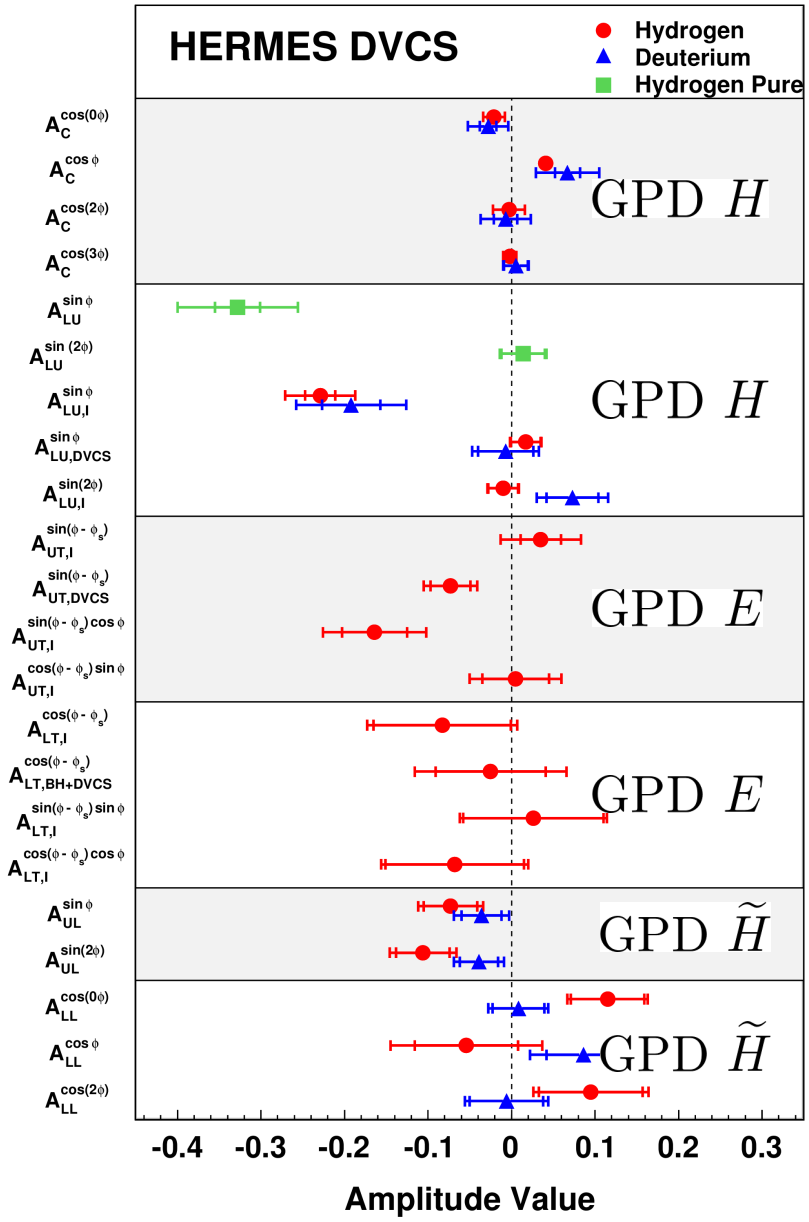
$$\frac{t}{4M^2}\left[(2-x_B)F_1\mathcal{E} - 4\frac{1-x_B}{2-x_B}F_2\mathcal{H}\right]$$

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



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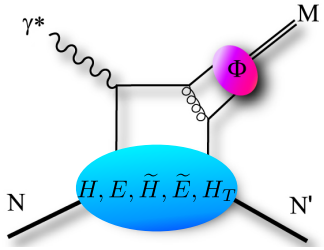
- Longitudinal target spin asymmetry
  - *JHEP 06 (2010) 019*
- Longitudinal target & double spin asymmetry
  - *Nucl. Phys. B 842 (201*

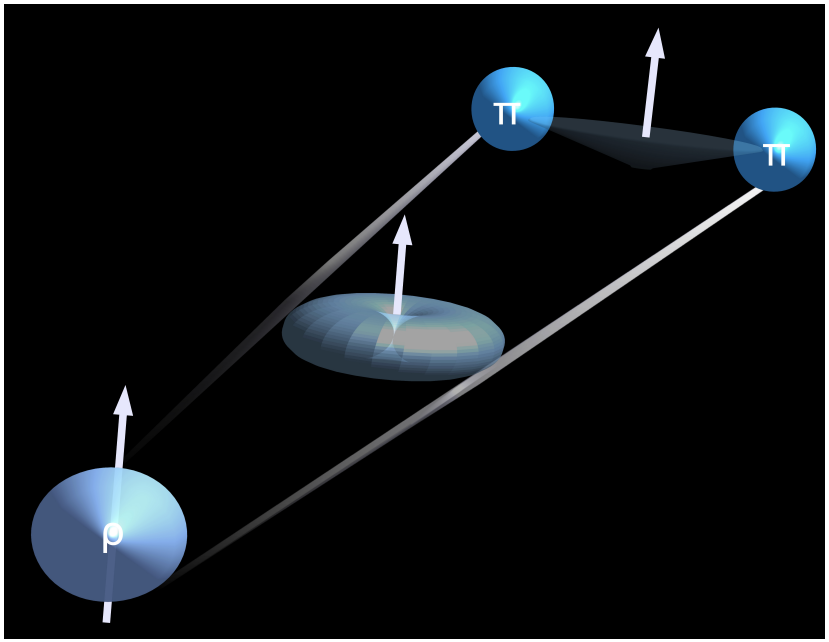
see the talk by H. Marukyan

vector meson production cross section

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

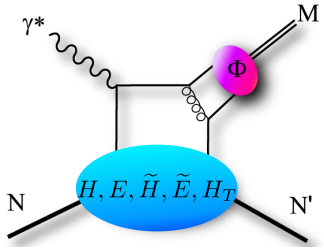


- the spin-state of the vector meson is reflected in the orbital angular momentum of the decay particles



vector meson production cross section

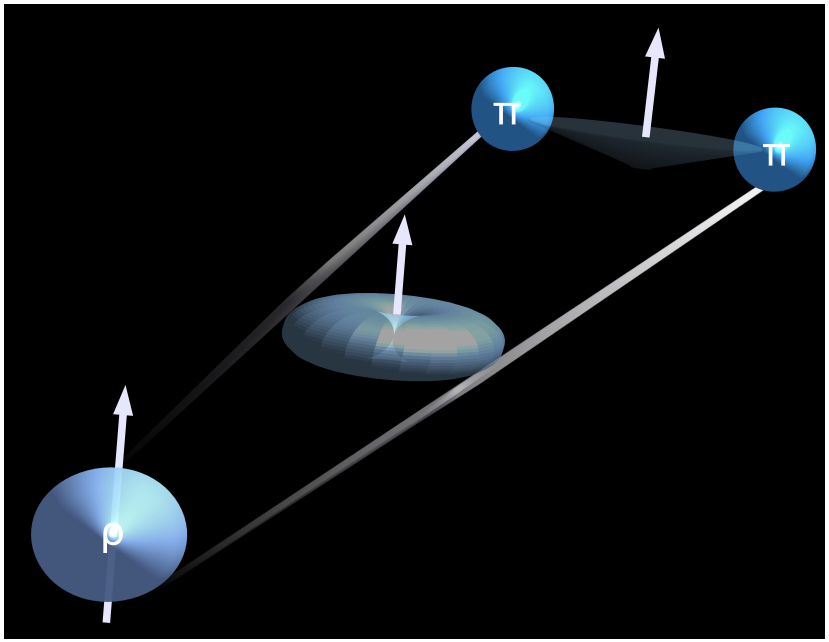
$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_s\, d\phi\, d\cos\vartheta\, d\varphi} \sim \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)$$



> **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

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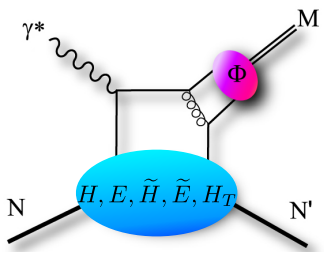
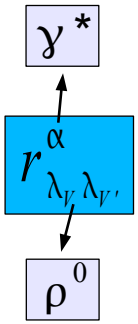


> **production and decay angular distributions:**

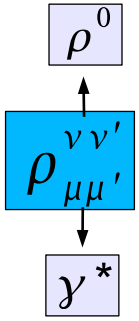
$$W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}$$

> **parametrised by SDMEs**

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

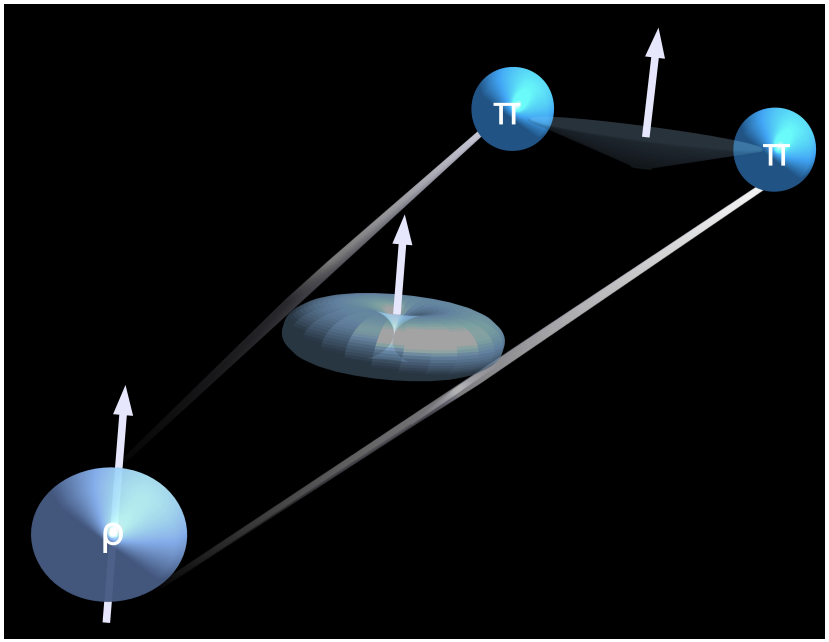


-Schilling, Wolf (1973)-

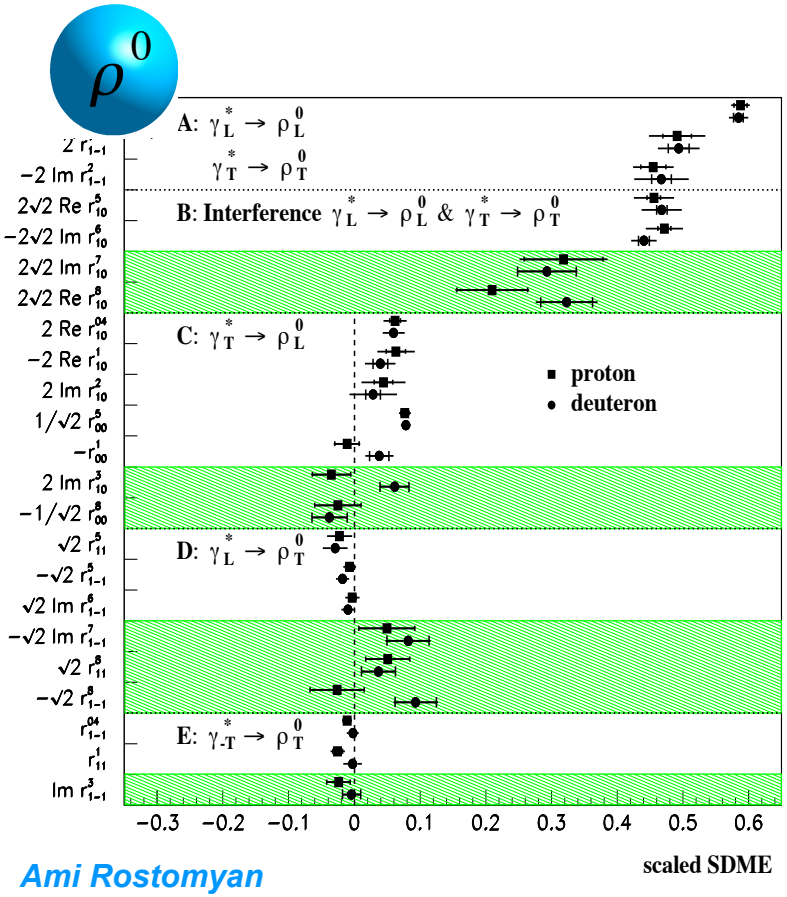


-Diehl (2007)-

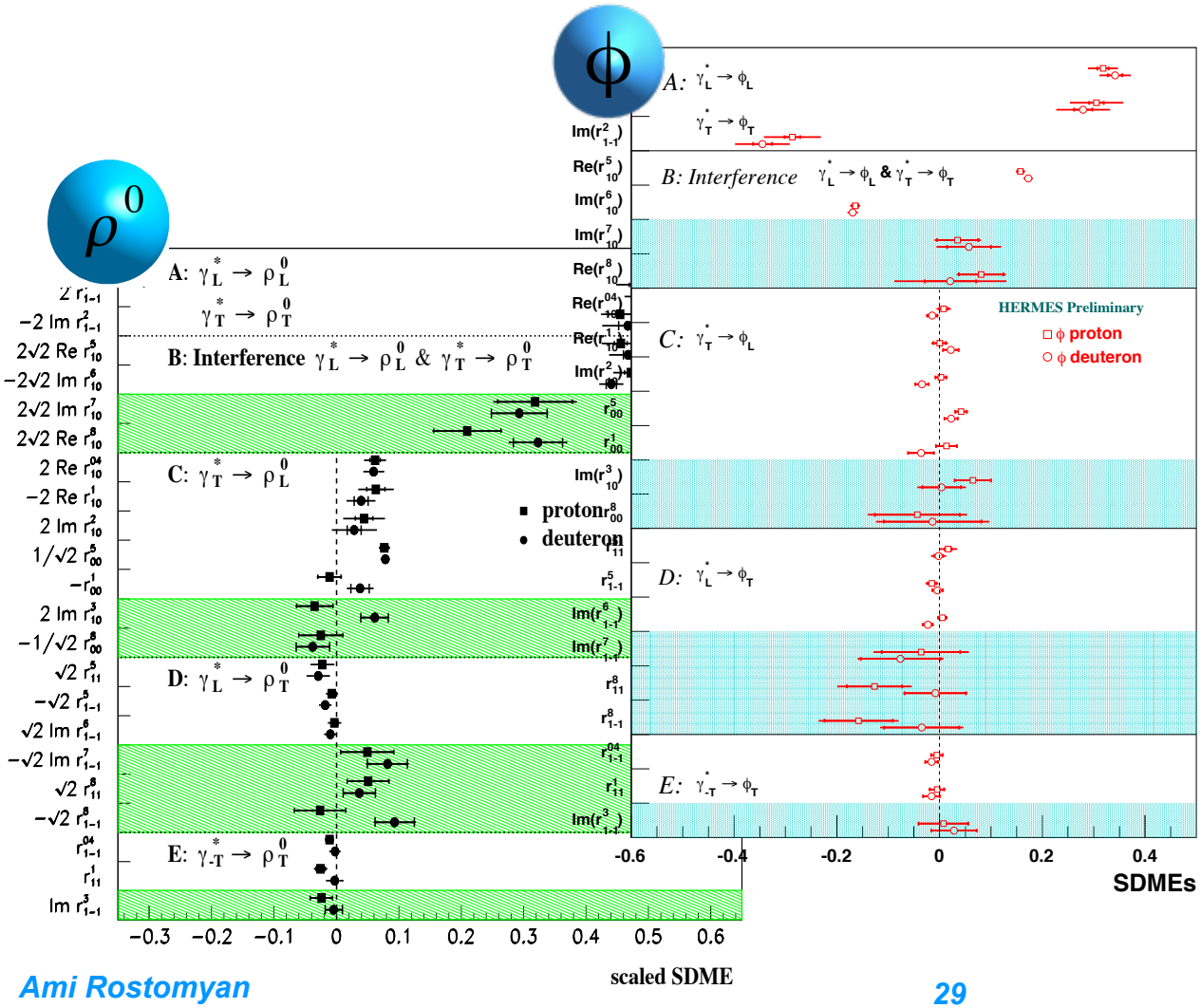
> the spin-state of the vector meson is reflected in the orbital angular momentum of the decay particles



SDMEs of vector meson production

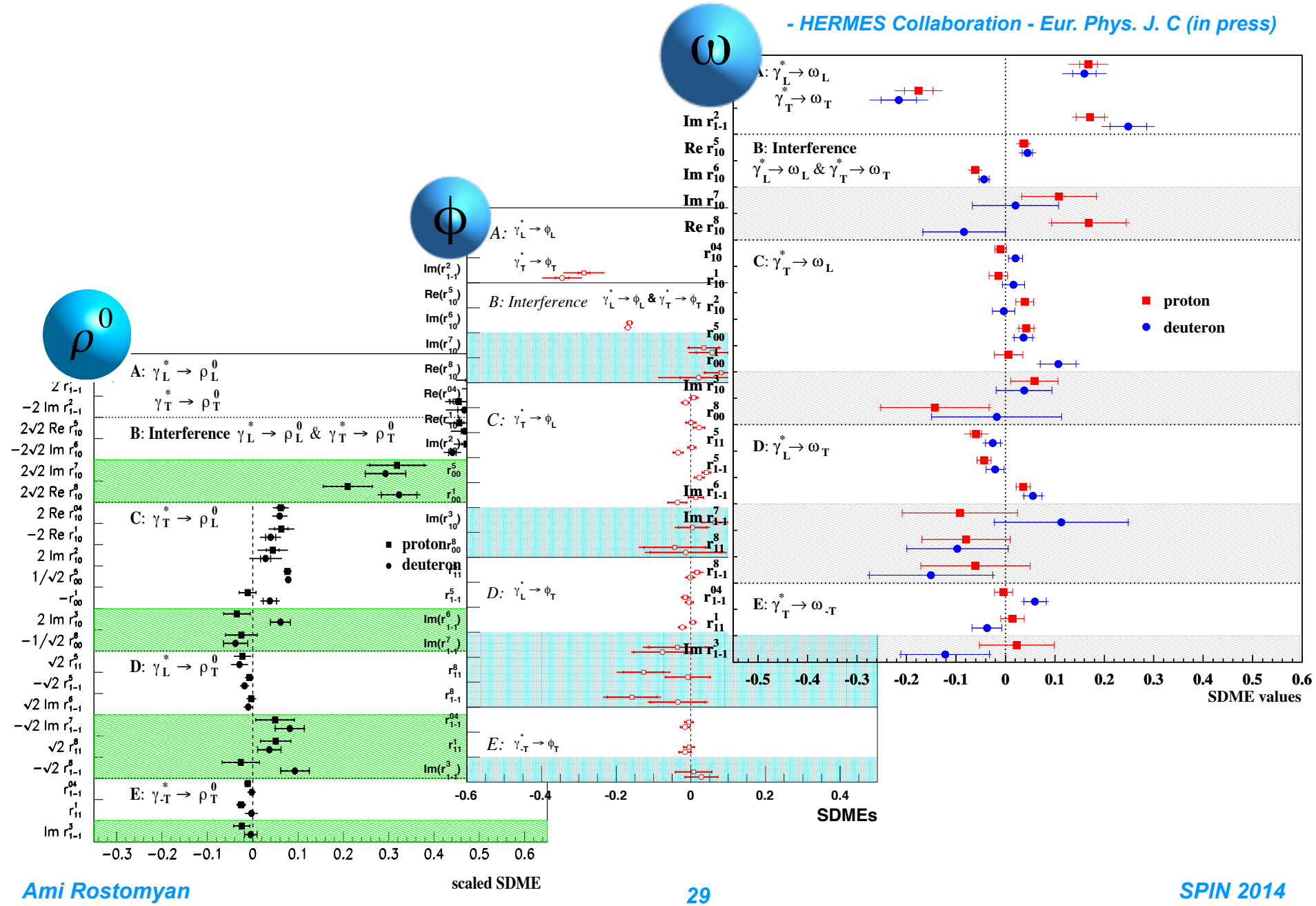


SDMEs of vector meson production



SDMEs of vector meson production

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



SDMEs of vector meson production

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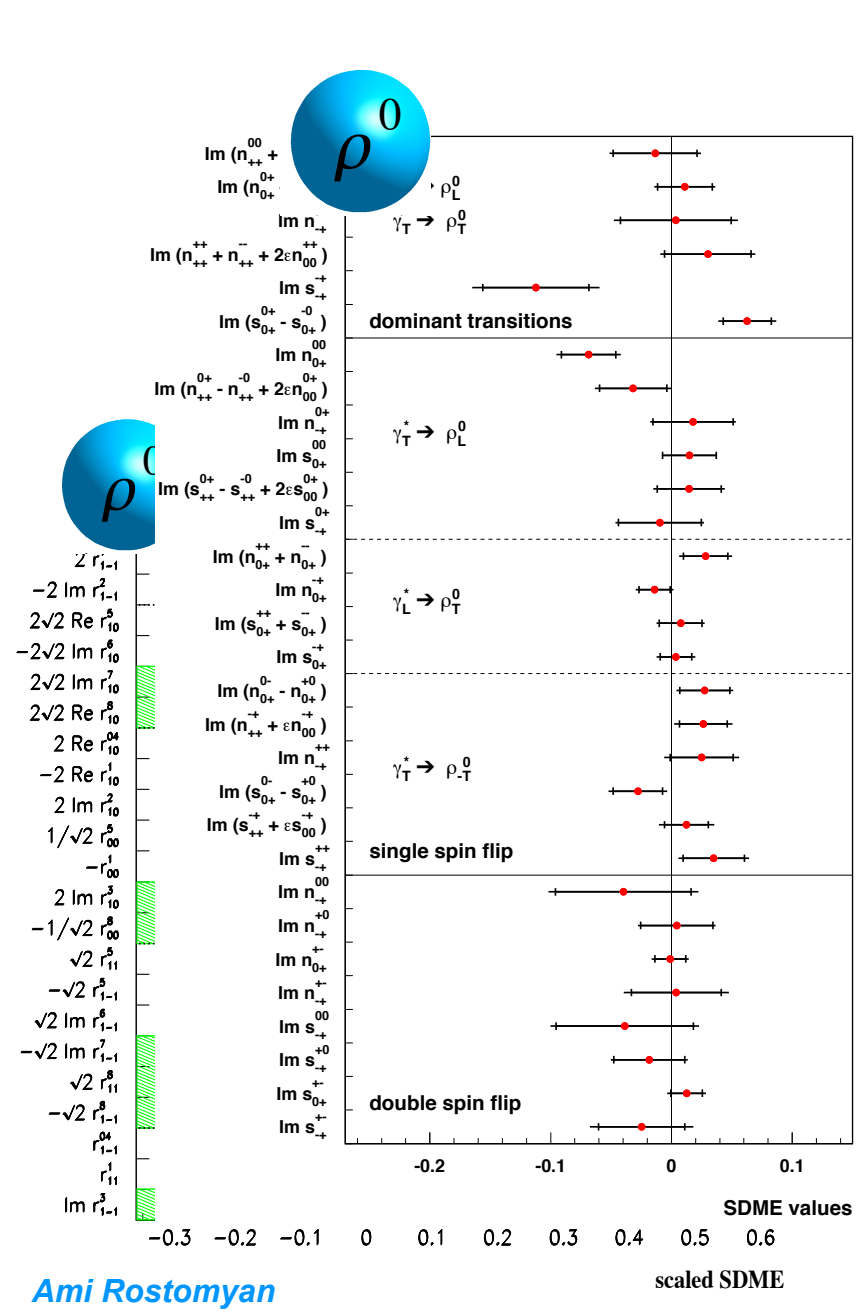

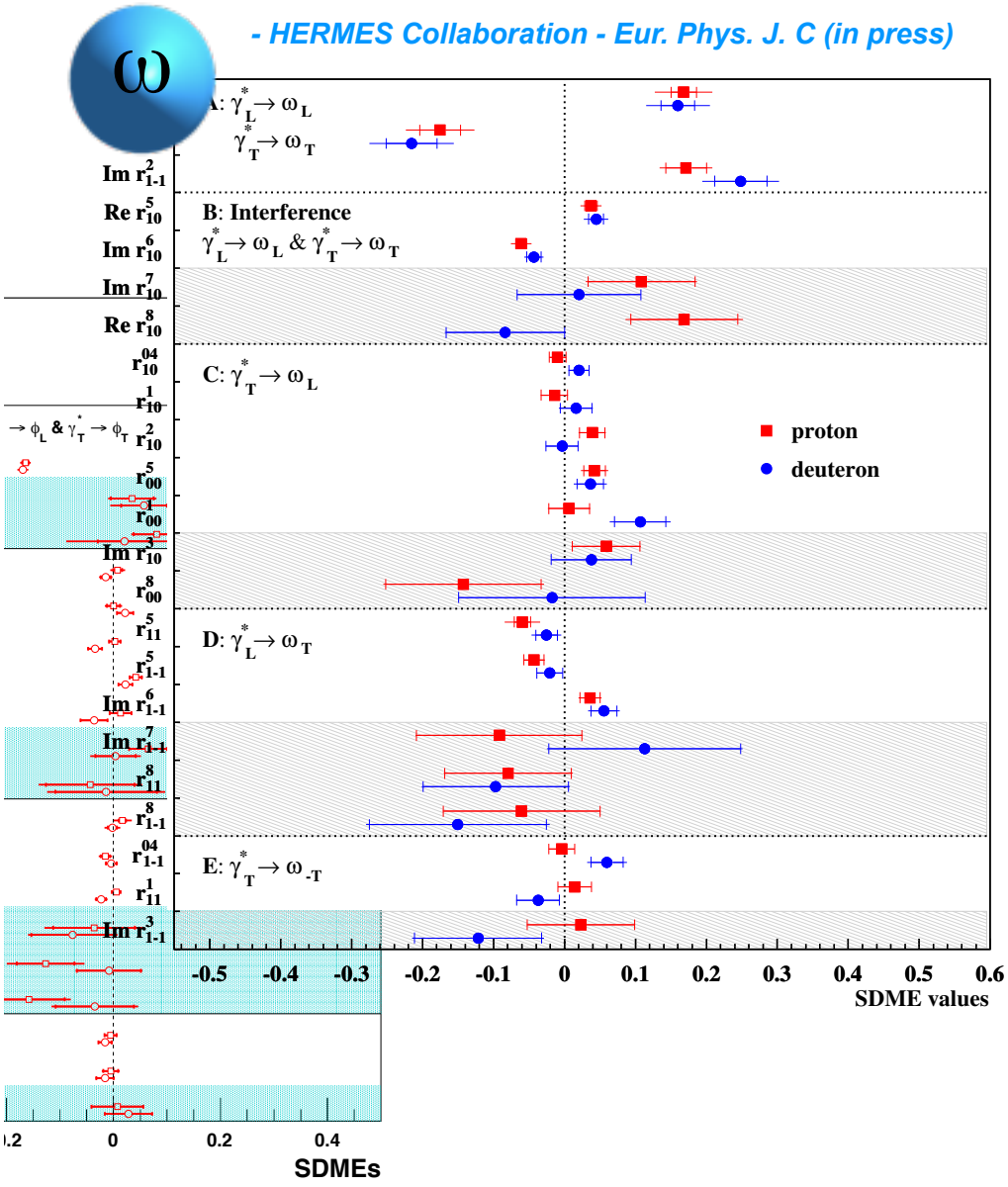

SDMEs of vector meson production

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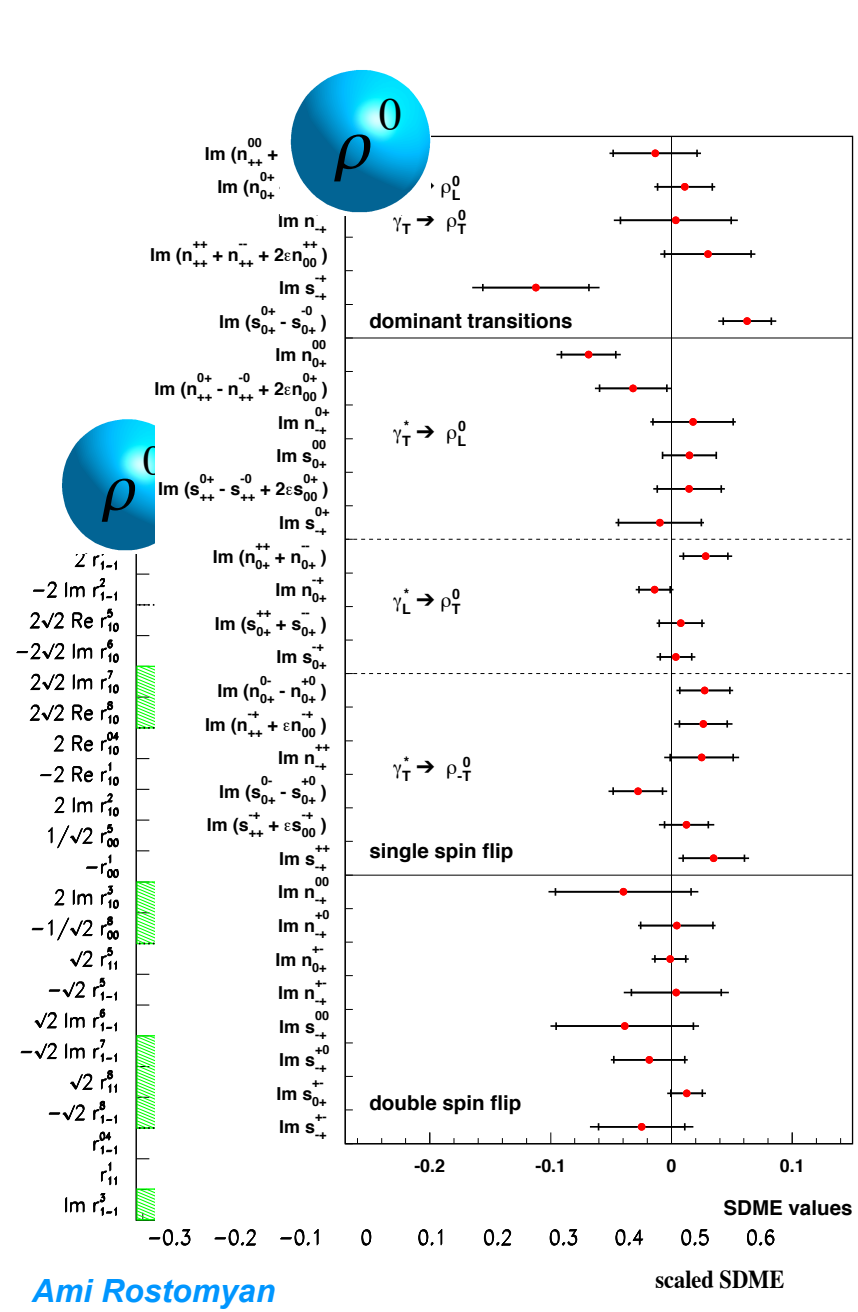
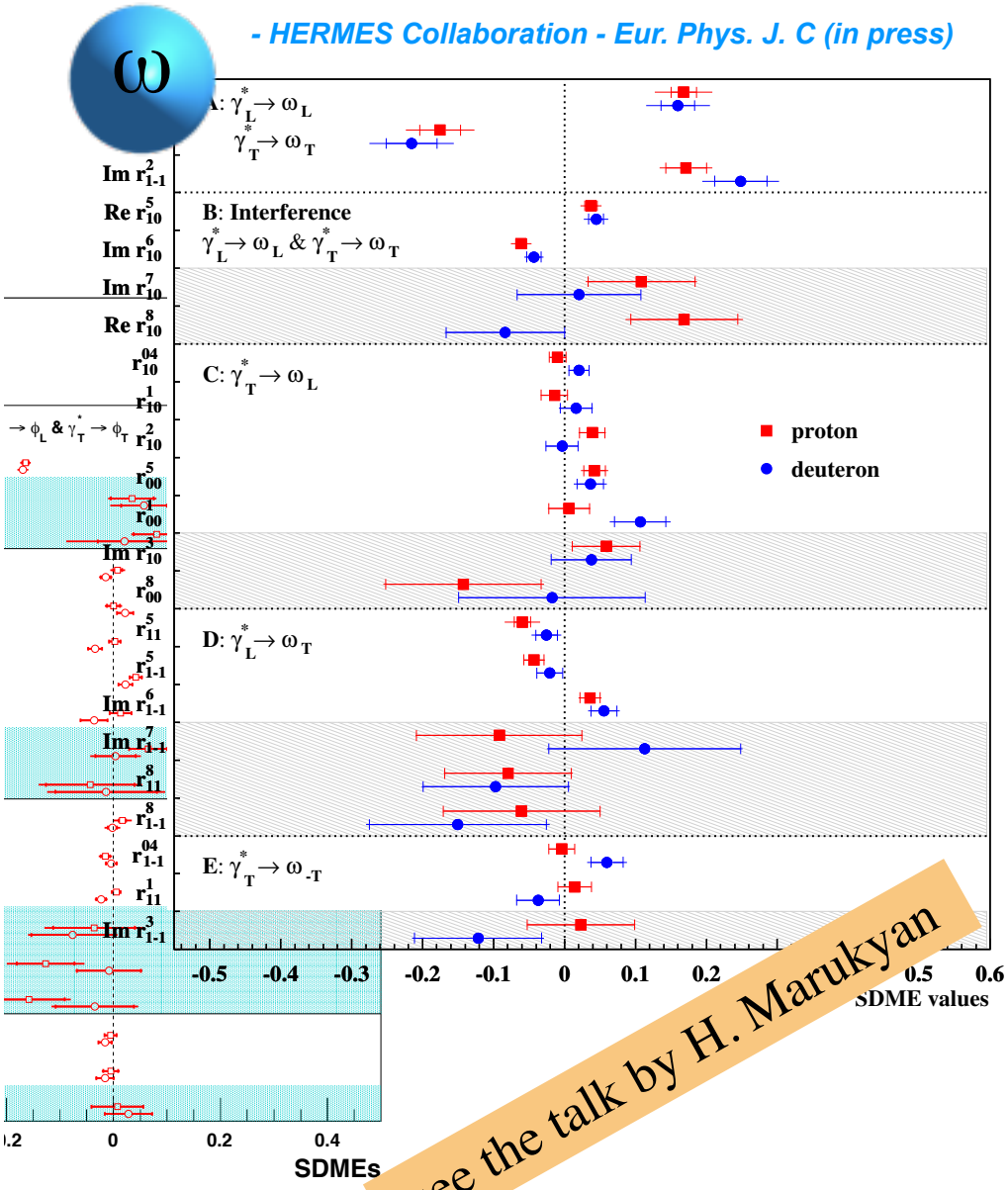
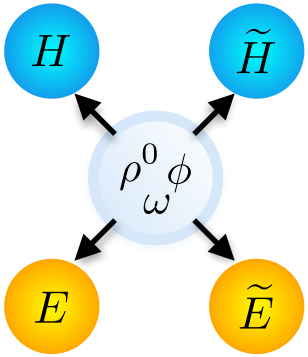
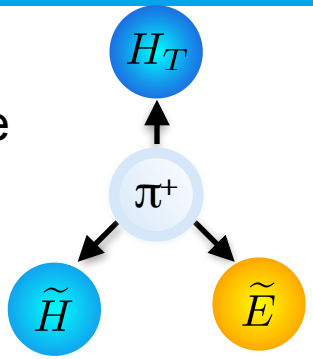




see the talk by H. Marukyan

universality of GPDs





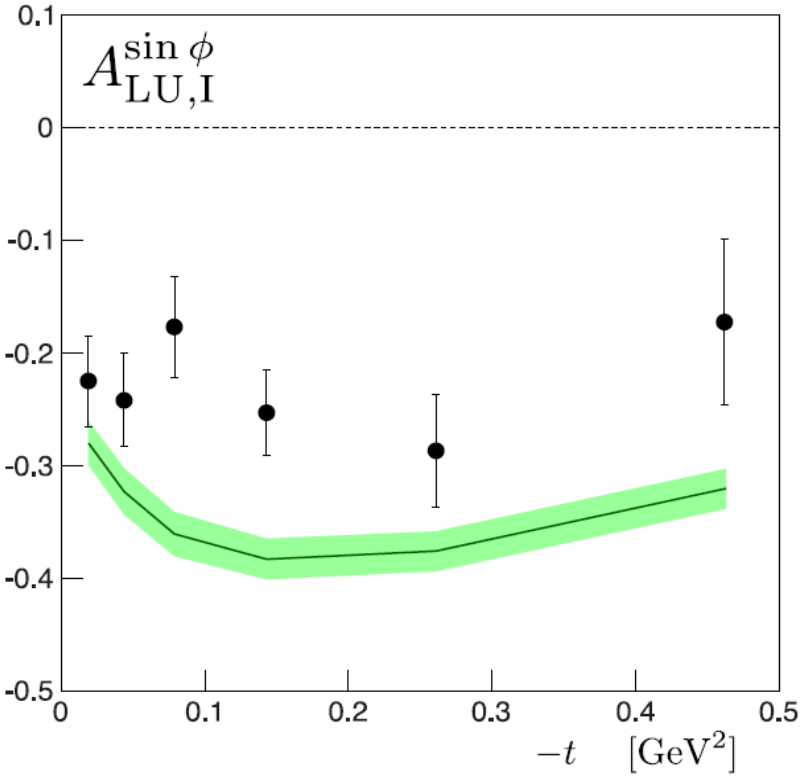
> GPD model originally developed to describe exclusive meson production

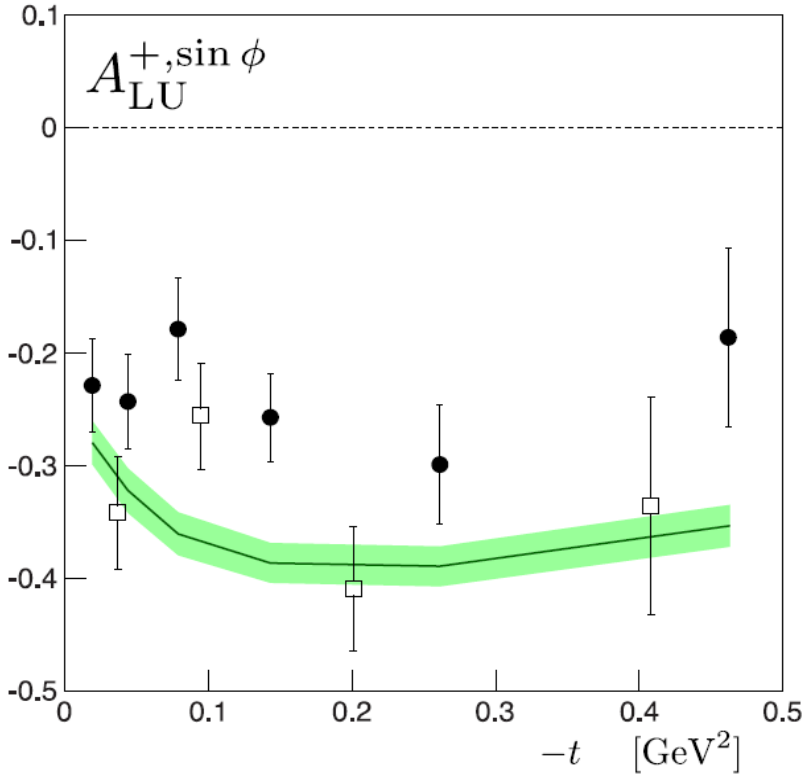
- P. Kroll, H. Moutarde, F. Sabatié - Eur. Phys. J. C (2013) 73

in comparison with HERMES data

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

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





☛ **HERMES** has been a pioneering collaboration

☛going beyond the collinear factorisation towards TMDs and GPDs

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

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