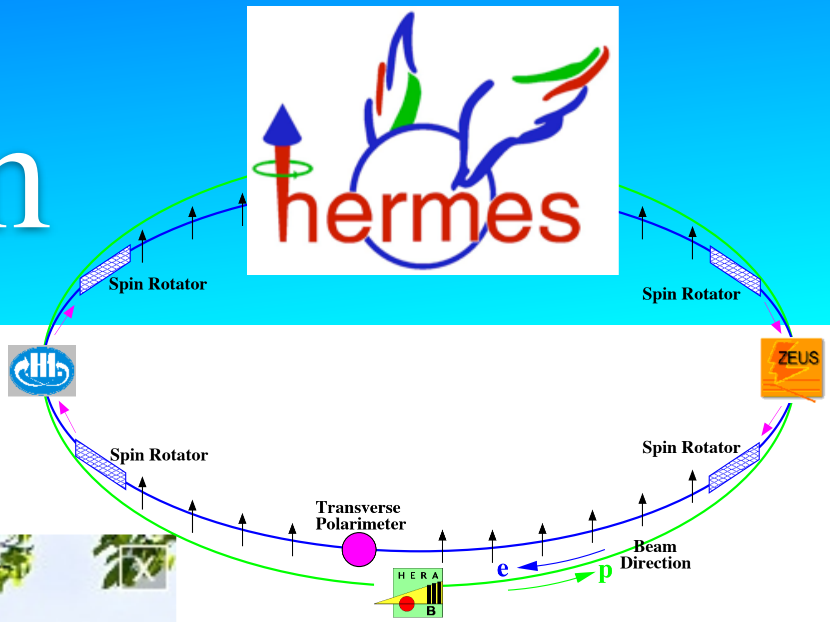
Recent Results on TMDs

from



20th Particles and Nuclei International Conference

25-29 August, 2014

Hamburg, Germany

Ami Rostomyan

(for the HERMES collaboration)

DESY

HELMHOLTZ ASSOCIATION

spin and hadronization

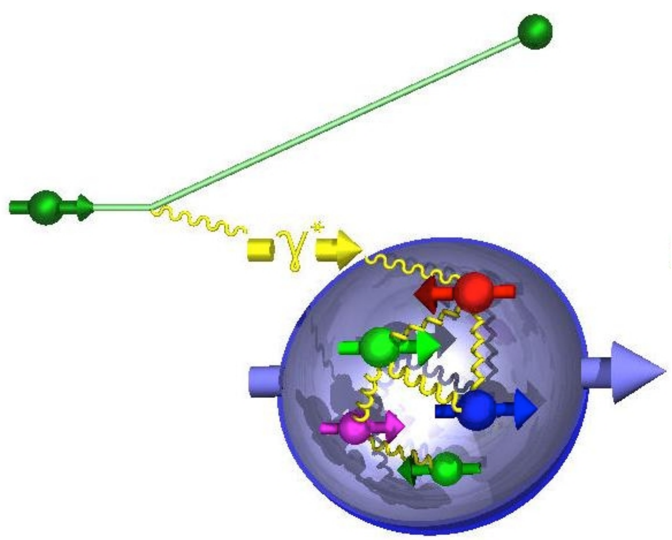
HERMES main research topics:

✓ **origin of nucleon spin**

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

✓ **hadronization/fragmentation**

spin and hadronization



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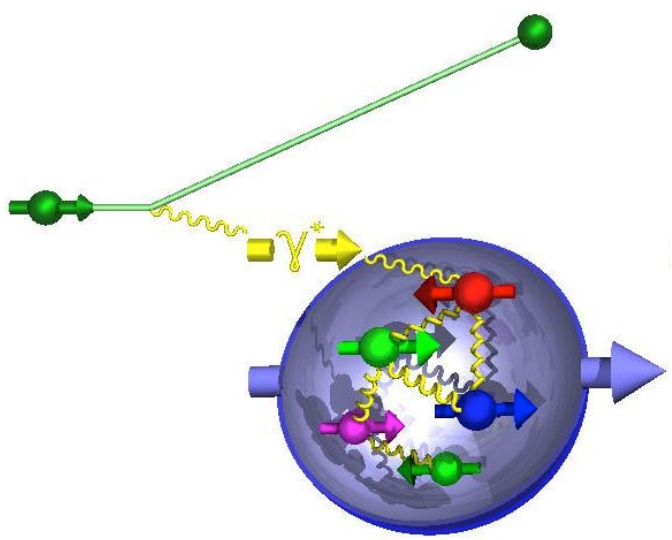
✓ nucleon properties (mass, charge, momentum, magnetic moment, spin...) should be explained by its constituents

☛ momentum: quarks carry ~ 50 % of the proton momentum

☛ spin: total quark spin contribution only ~30%

➡ **study of TMD DFs and GPDs**

spin and hadronization



HERMES main research topics:

- ✓ **origin of nucleon spin**
  - ☛ longitudinal spin/momentum structure
  - ☛ transverse spin/momentum structure
- ✓ **hadronization/fragmentation**

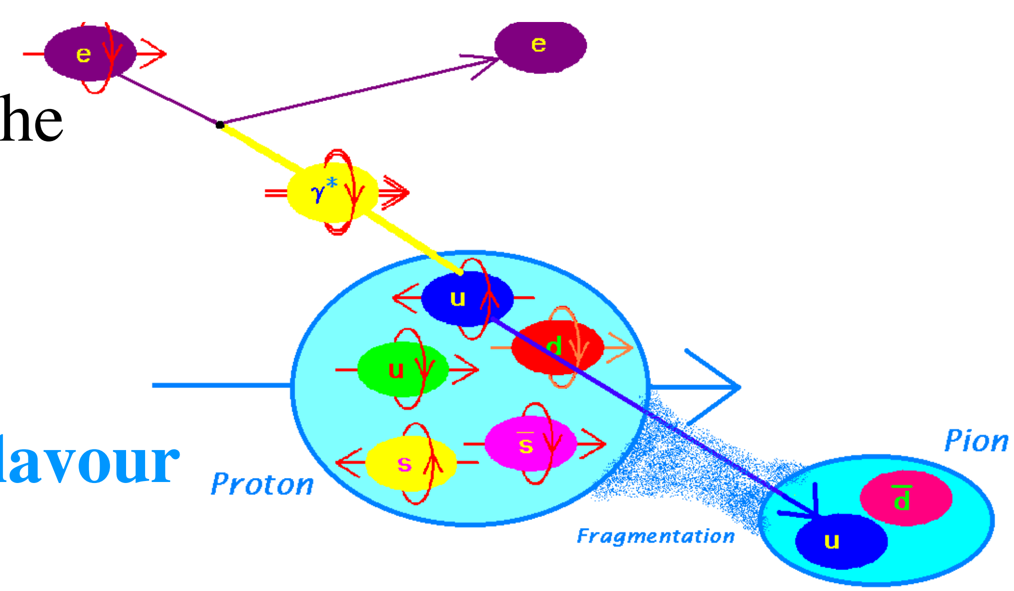
✓ nucleon properties (mass, charge, momentum, magnetic moment, spin...) should be explained by its constituents

- ☛ momentum: quarks carry ~ 50 % of the proton momentum
- ☛ spin: total quark spin contribution only ~30%
- ➡ **study of TMD DFs and GPDs**

✓ isolated quarks have never been observed in nature

✓ fragmentation functions were introduced to describe the hadronization

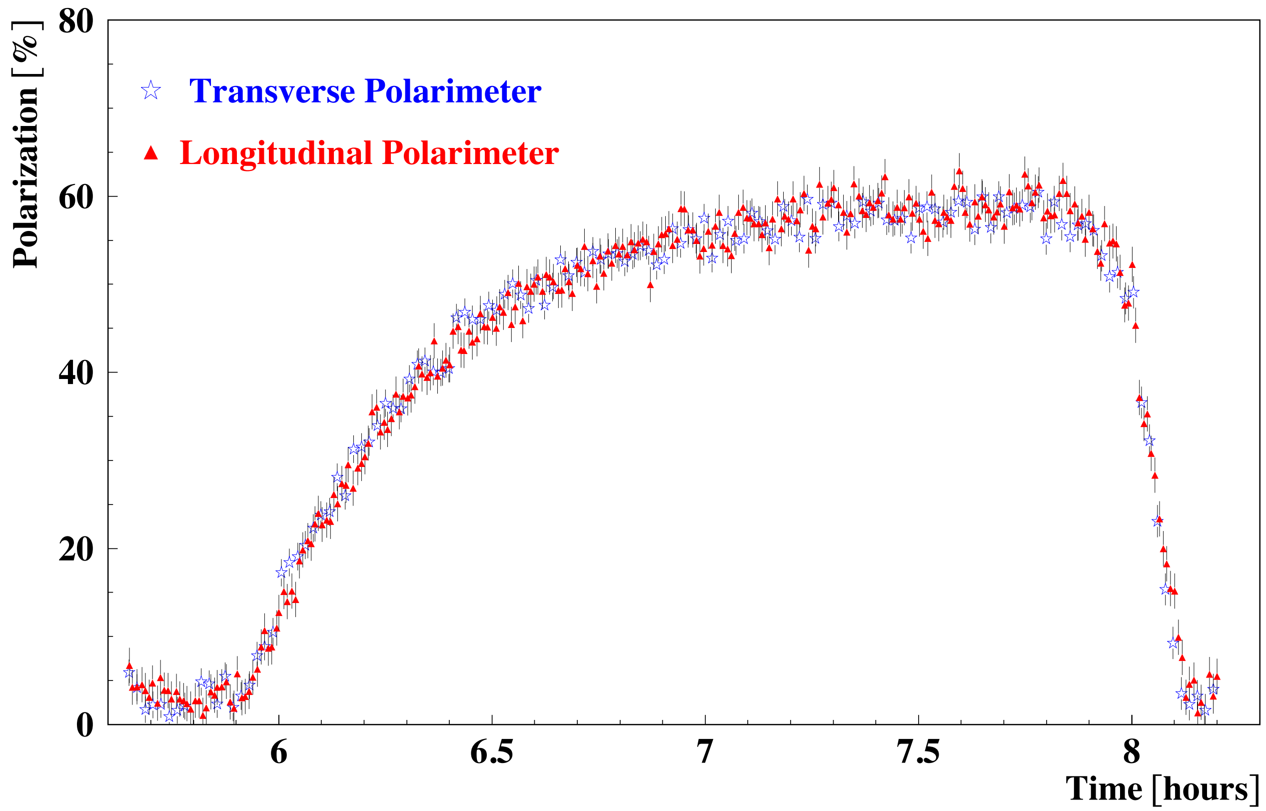
- ☛ non-pQCD objects
- ☛ universal but not well known functions
- ➡ **advantage of lepton-nucleon scattering data → flavour separation of fragmentation functions (FFs)**



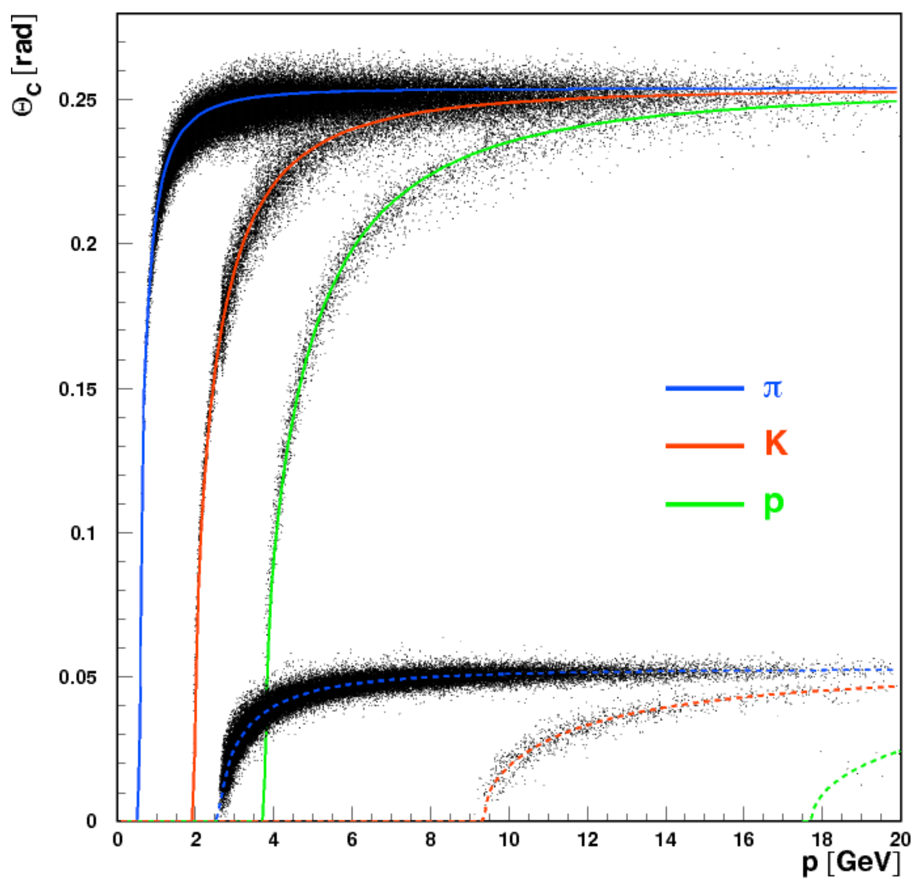
advantages of the experiment

The HERMES experiment, located at HERA, with its pure gas targets and advanced particle identification (π, K, p) is well suited for TMD and GPD measurements and for studies of hadronisation process.

self-polarized e^+/e^- beam



hadron identification with RICH detector



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

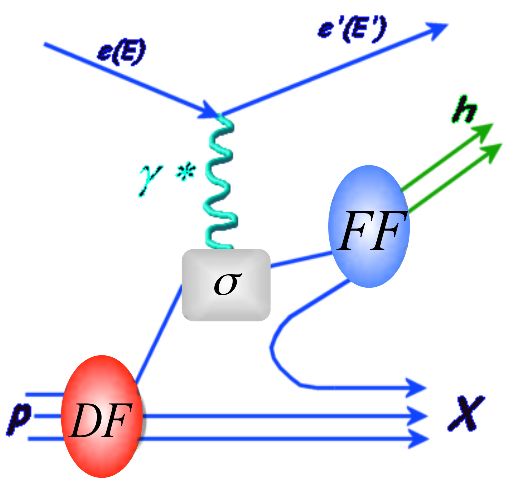
semi-inclusive DIS cross section and TMDs

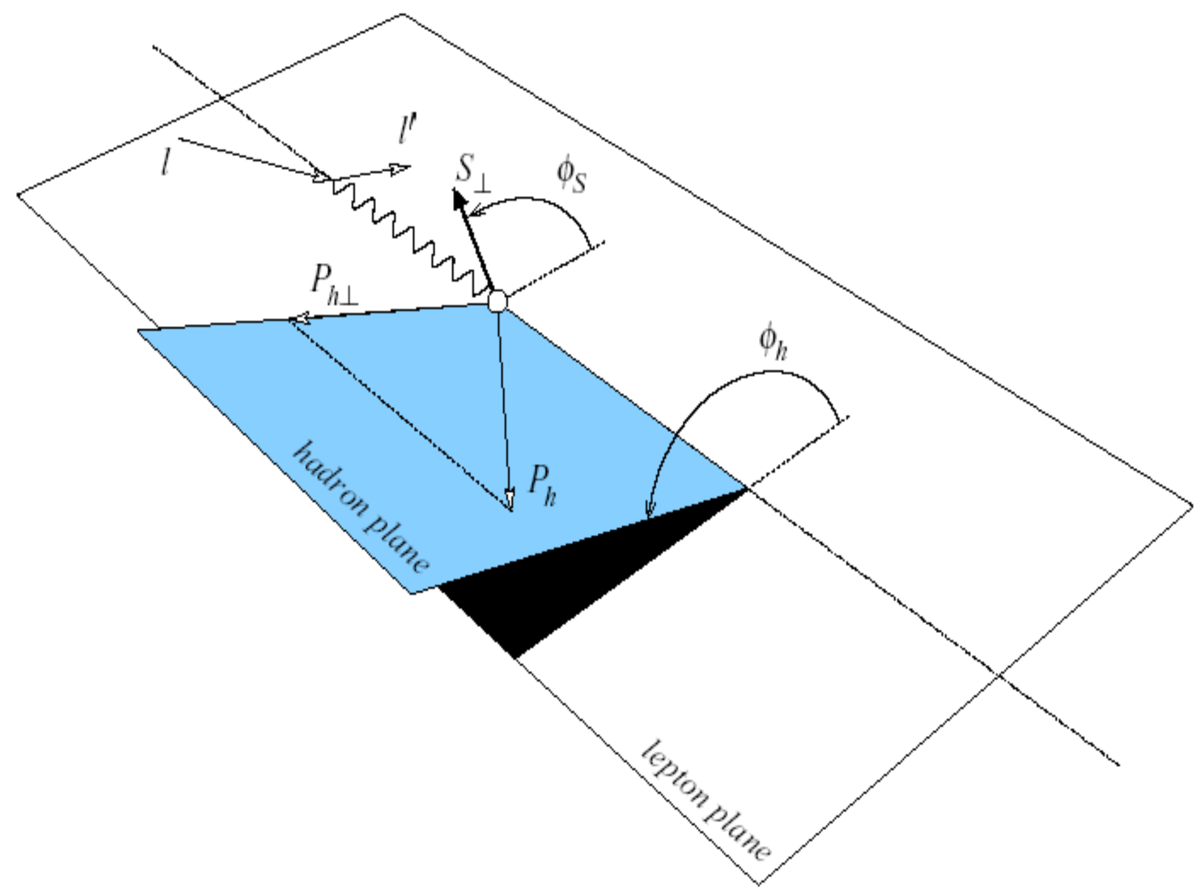
F_{XY}

beam λ_e — target $S_\perp, S_{||}$

$$\frac{d^6\sigma}{dx\, dy\, dz\, dP_{h\perp}^2\, d\phi\, d\phi_s} \propto \left\{ F_{UU} + \sqrt{2\epsilon(1+\epsilon)} F_{UU}^{\cos\phi} \cos\phi + \epsilon\, F_{UU}^{\cos 2\phi} \cos 2\phi \right\}$$

$$+ \quad \lambda_e \left\{ \sqrt{2\epsilon(1-\epsilon)} F_{LU}^{\sin\phi} \sin\phi \right\} + S_{||}\left\{ \dots \right\} + S_\perp \left\{ \dots \right\}$$





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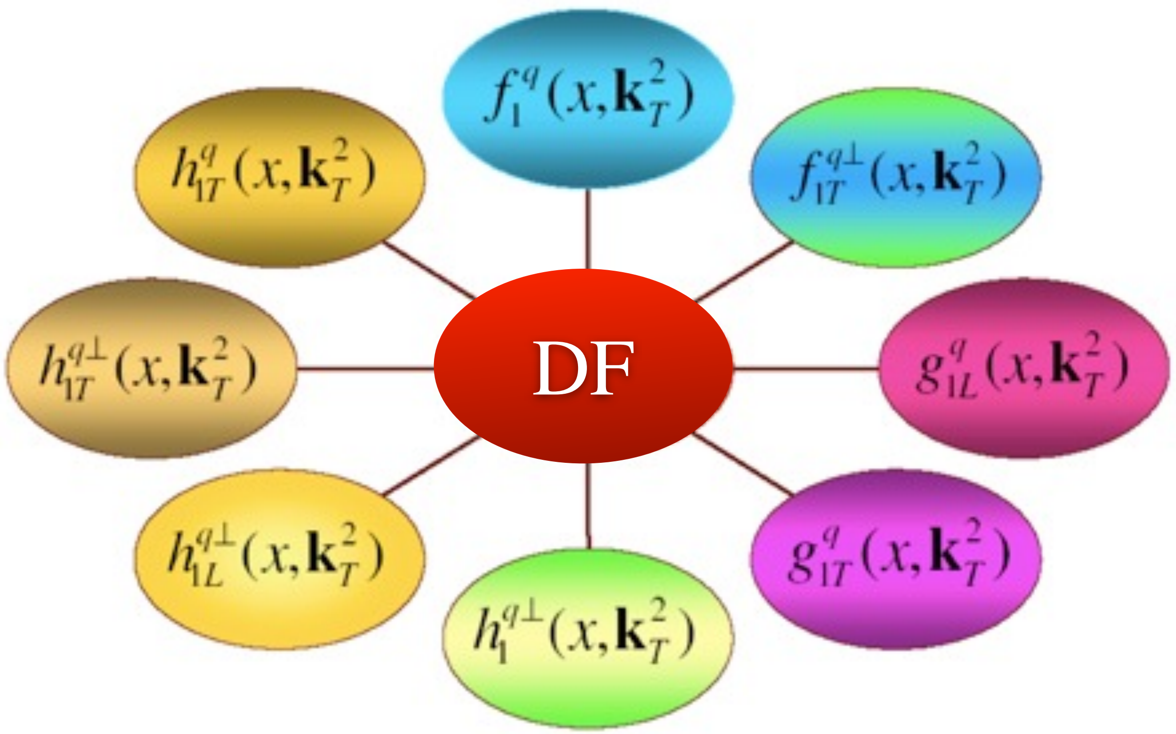
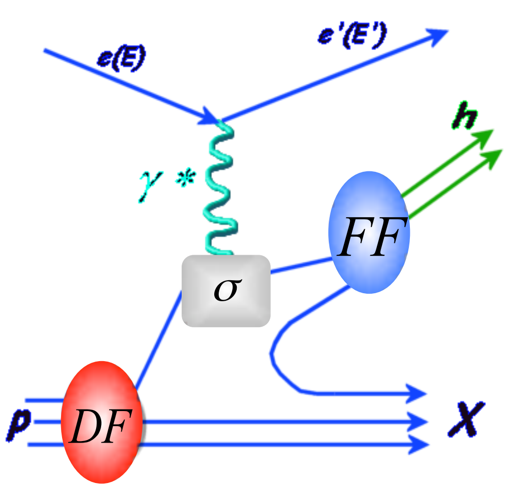
leading twist TMD DF:
parameterise the quark-flavour structure of the nucleon





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leading twist TMD DF:
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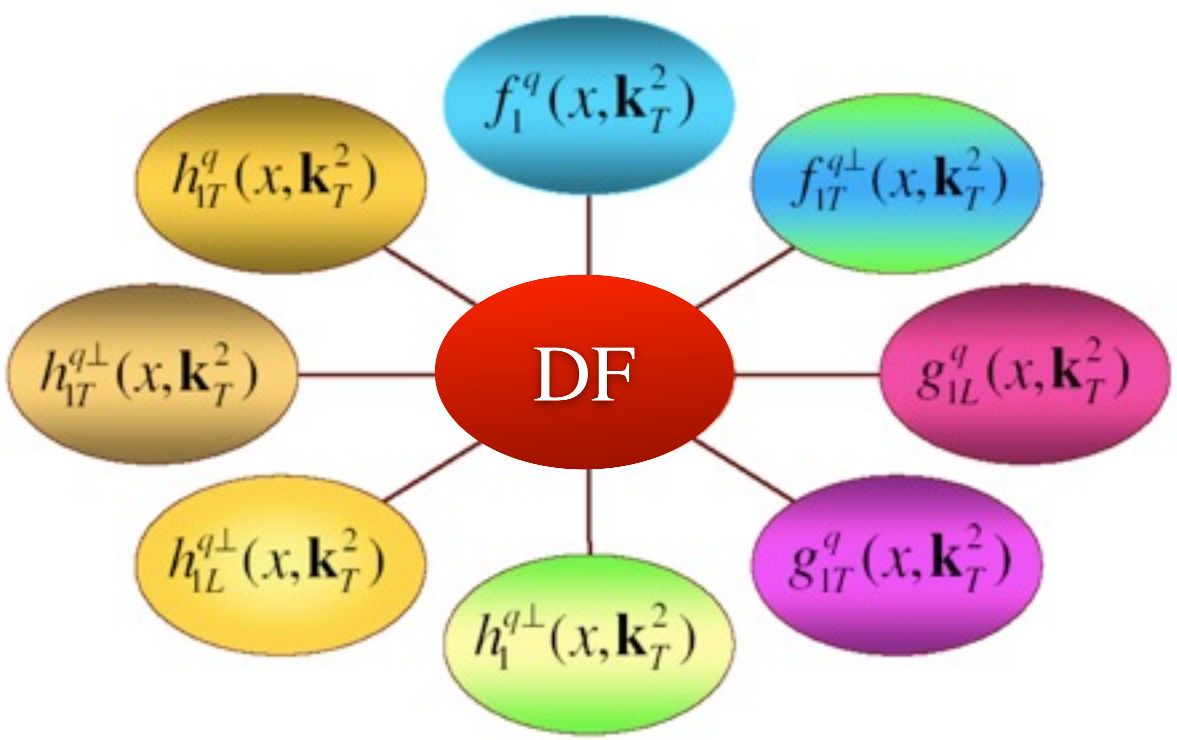
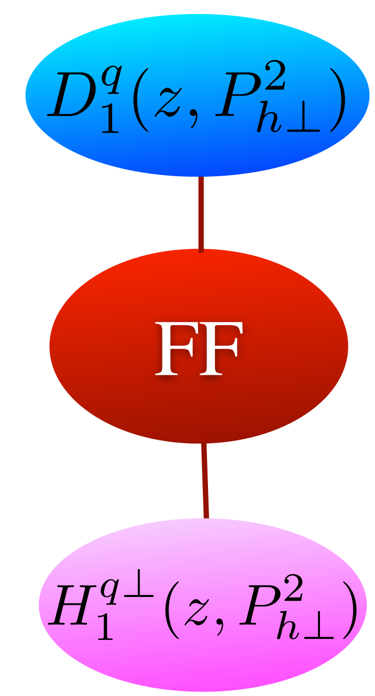
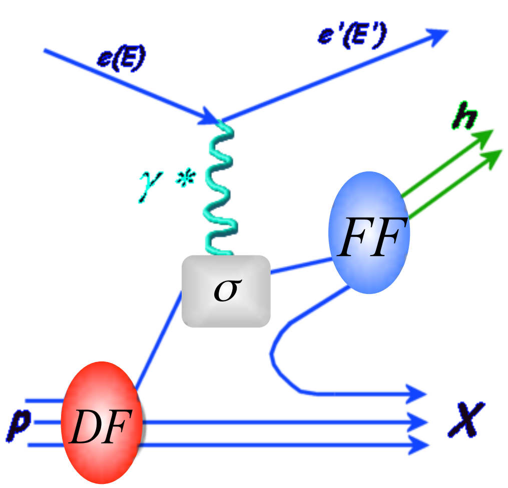
leading twist TMD FF:
number densities for the conversion of a quark of a certain type to a specific hadron







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JHEP 05 (2011) 126

PRL 94 (2005) 012002
PLB 693 (2010) 11

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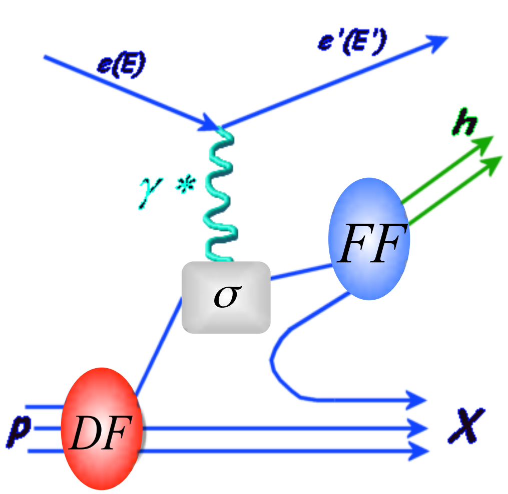
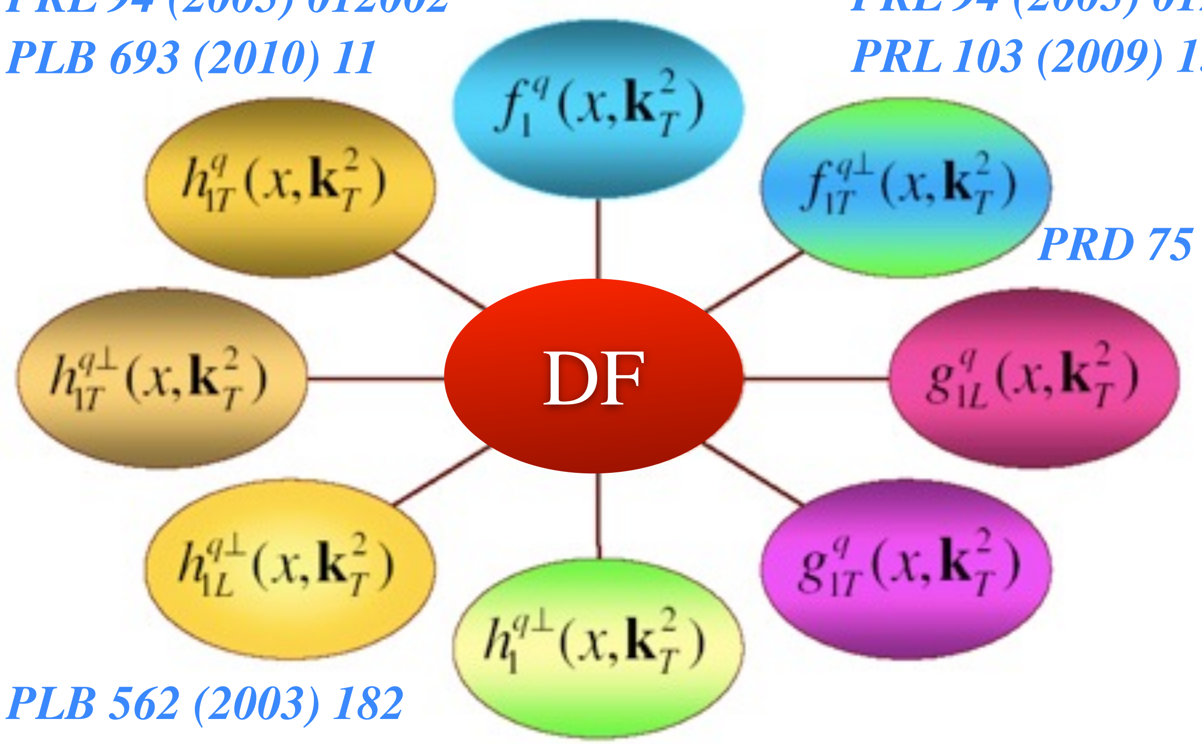
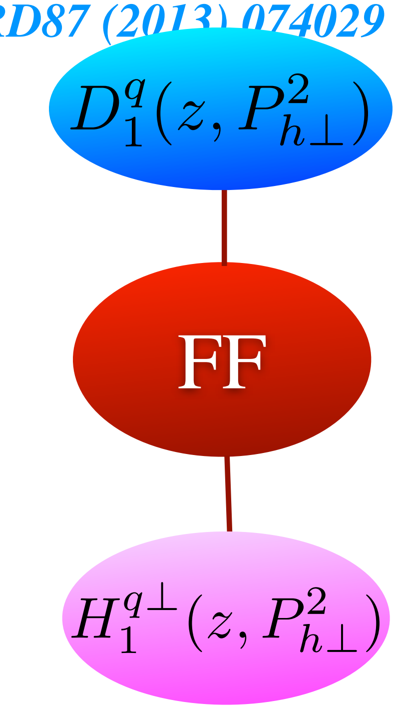
PRD 75 (2007) 012007

PRD87 (2013) 074029







PLB 562 (2003) 182
PRL 84 (2000) 4047

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HERMES: access to all TMDs thanks to the polarised beam and target

semi-inclusive DIS cross section and TMDs

$f_1 \otimes D_1$

$h_1^{\perp q} \otimes H_1^{\perp q}$

$- \quad f_1^q \otimes D_1^q$

$h_1^{\perp} \otimes H_1^{\perp}$

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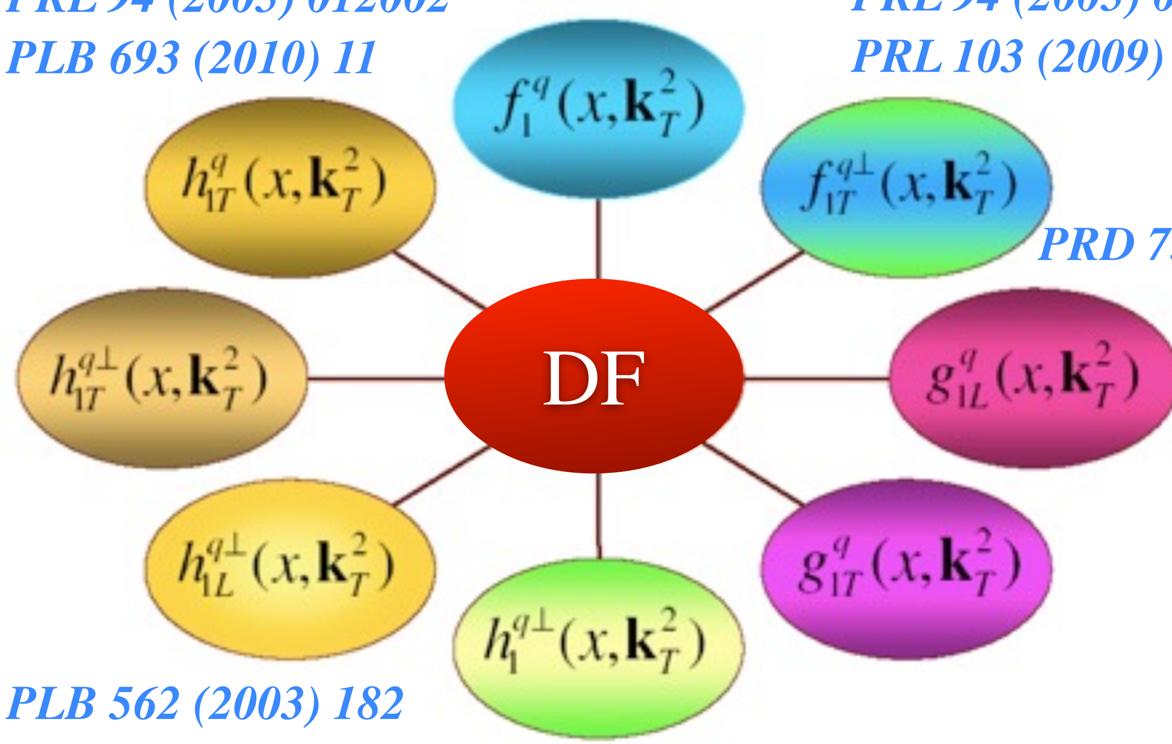

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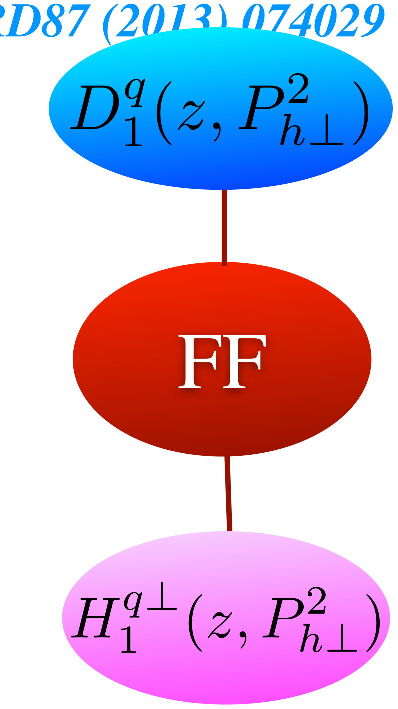

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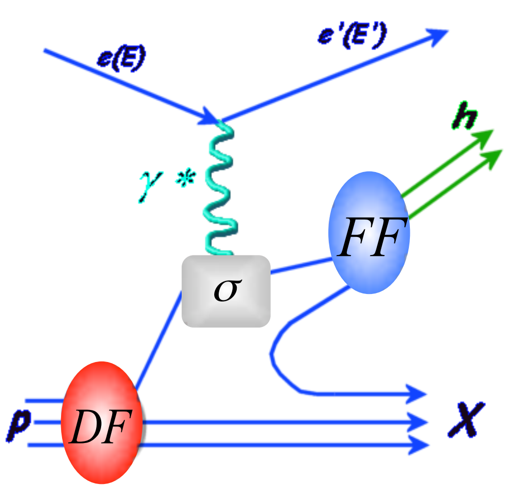

HERMES: access to all TMDs thanks to the polarised beam and target

unpolarised quarks

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

$$f_1 =$$ 

unpolarised quarks

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$f_1 =$ 

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

unpolarised quarks

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

$f_1 =$ 

LO interpretation of multiplicity results (integrated over $\mathbf{P}_{h\perp}$):

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

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

✓ charge-separated multiplicities of pions and kaons sensitive to the individual quark and antiquark flavours in the fragmentation process

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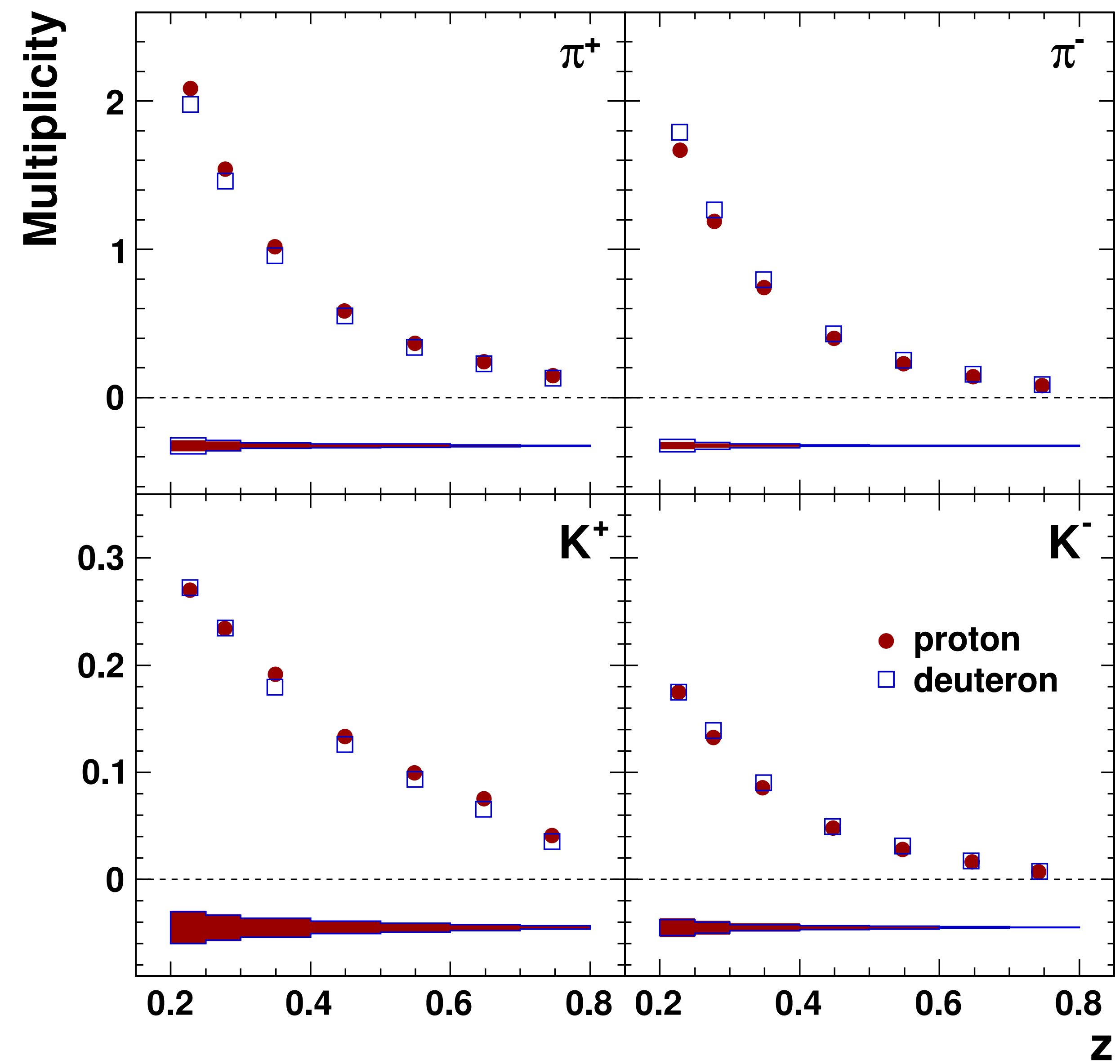
- HERMES Collaboration-
Phys. Rev. D87 (2013) 074029



π^+ and K^+:

☛ favoured fragmentation on proton

π^-:

☛ increased number of d-quarks in D target and favoured fragmentation on neutron

K^-:

☛ cannot be produced through favoured fragmentation from the nucleon valence quarks

unpolarised quarks

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Phys.Rev. D87 (2013) 074029

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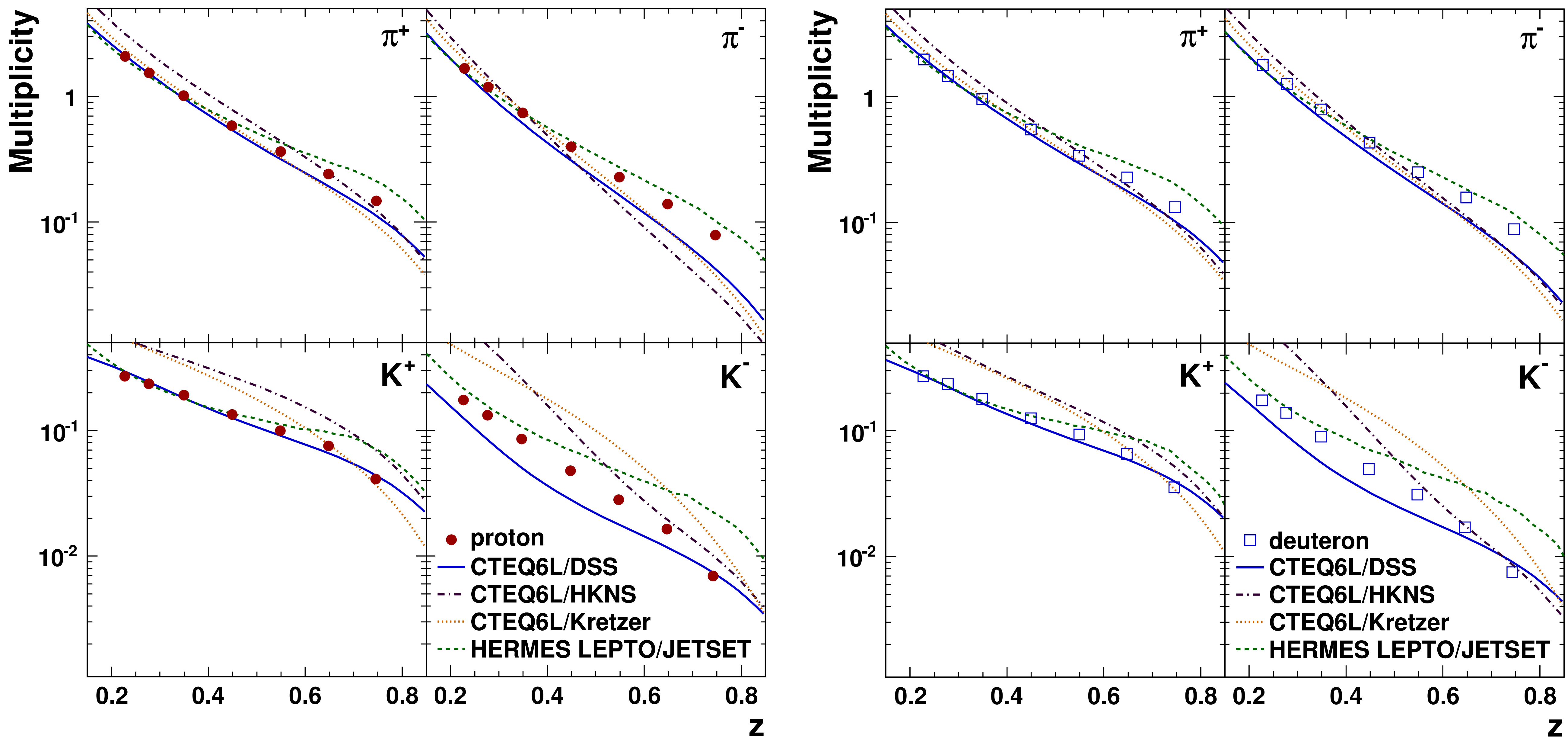

✓calculations using DSS, HNKS and Kretzer FF fits together with CTEQ6L PDFs

proton:

- fair agreement for positive hadrons
- disagreement for negative hadrons

deuteron:

- results are in general in better agreement with the various predictions

unpolarised quarks

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

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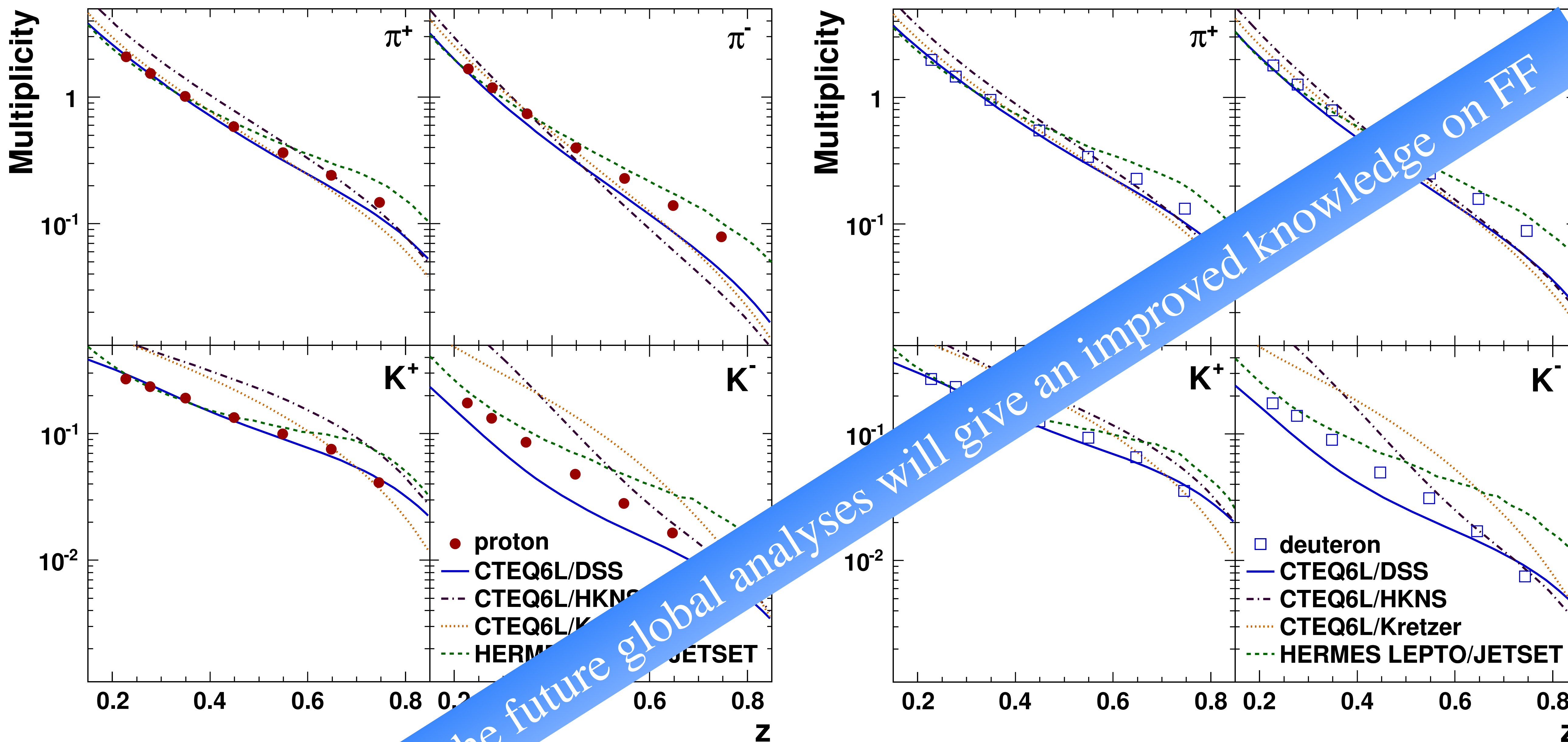

√ inclusion of the data in the future global analyses will give an improved knowledge on FF

√calculations using D... KS and Kretzer FF fits together with CTEQ6L PDFs

proton:

- fai... ent for positive hadrons
- ... ement for negative hadrons

de...

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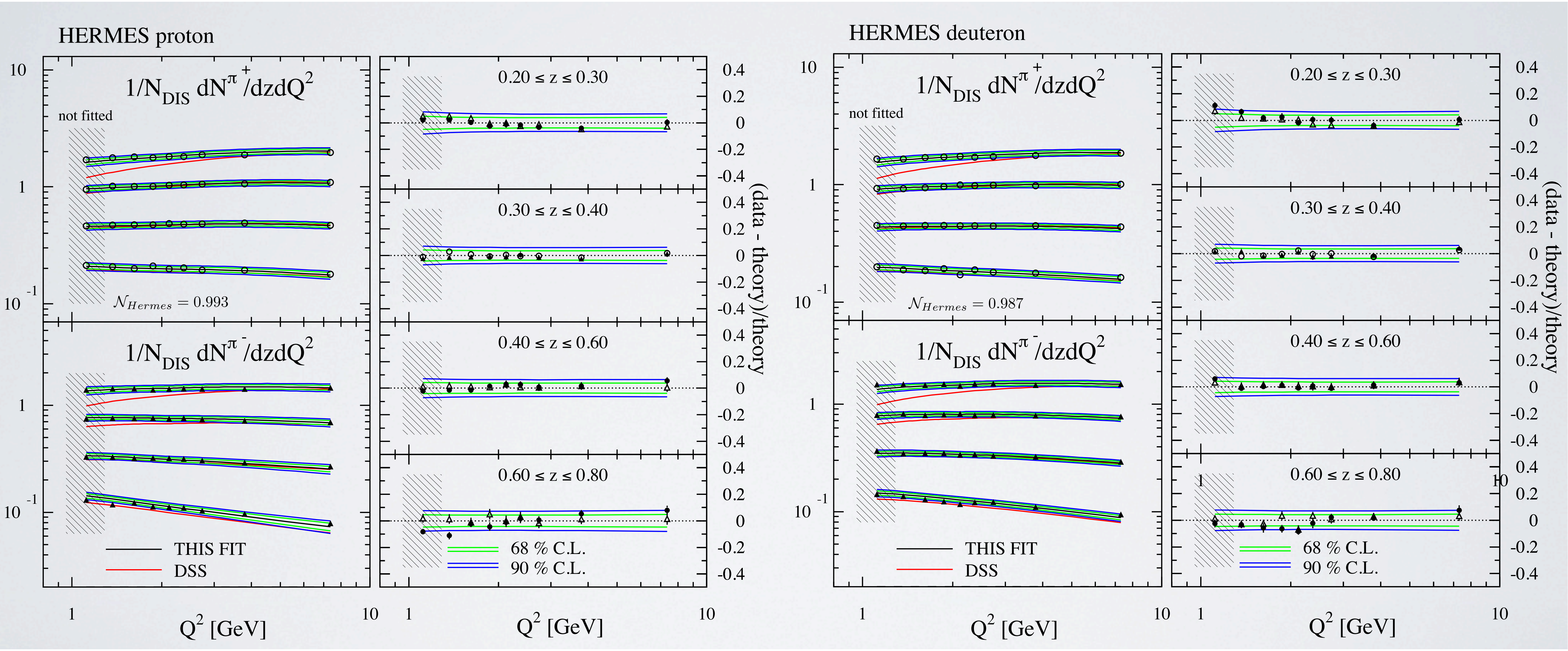
New global fit DSS+

new data sets since DSS

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

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



✓ better agreement for both π^+ and π^-

evaluation of strange quark distribution

✓ in the absence of experimental constraints, many global QCD fits of PDFs assume

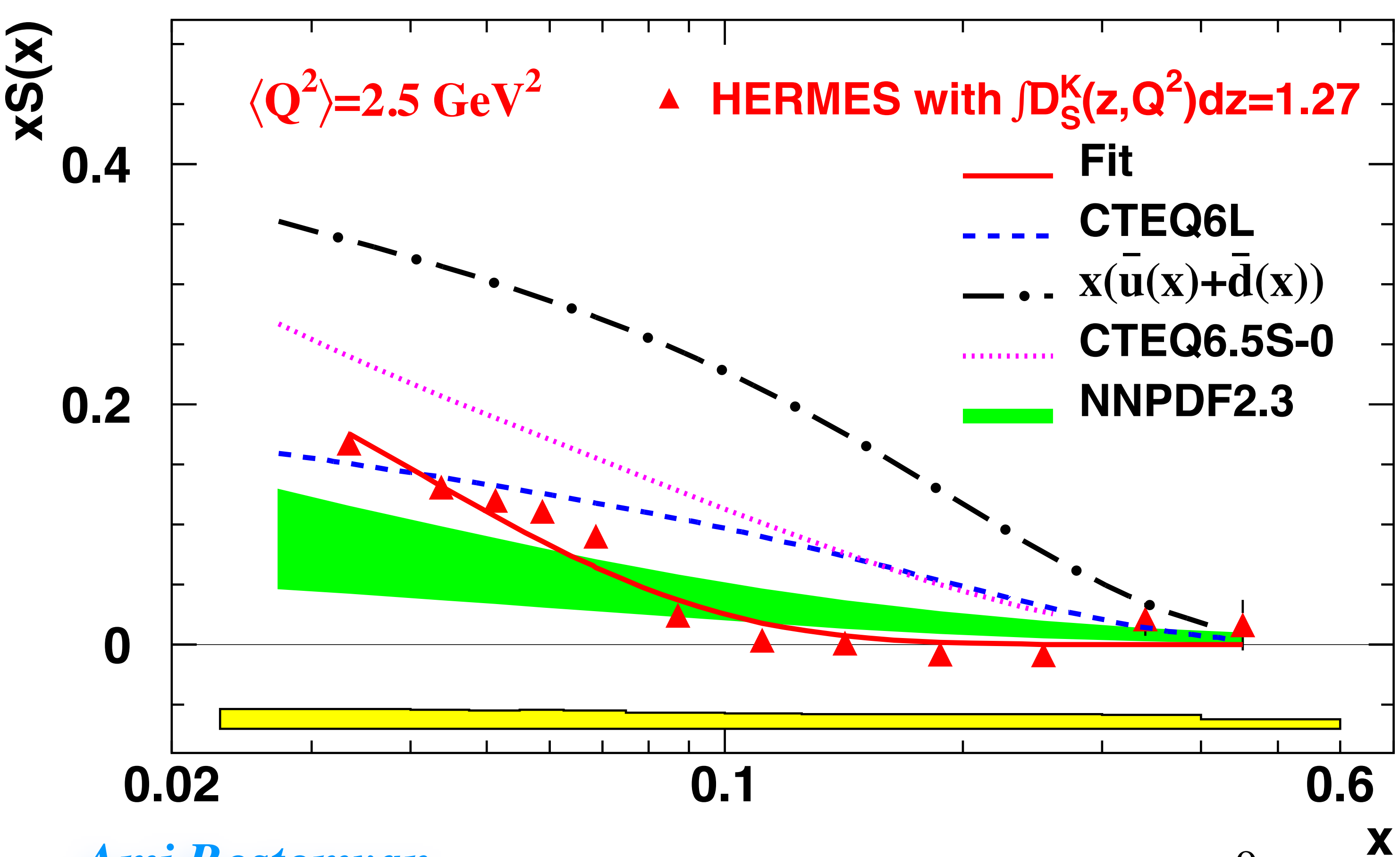
$$s(x) = \bar{s}(x) = r[\bar{u}(x) + \bar{d}(x)]/2$$

✓ isoscalar extraction of $S(x)\mathcal{D}_S^K$ based on the multiplicity data of K+ and K- on D

$$S(x)\int \mathcal{D}_S^K(z)dz \simeq Q(x)\left[5\frac{\mathrm{d}^2N^K(x)}{\mathrm{d}^2N^{DIS}(x)} - \int \mathcal{D}_Q^K(z)dz\right]$$

$$\begin{aligned} S(x) &= s(x) + \bar{s}(x) \\ Q(x) &= u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \\ \mathcal{D}_S^K &= D_1^{s\to K^+} + D_1^{\bar{s}\to K^+} + D_1^{s\to K^-} + D_1^{\bar{s}\to K^-} \\ \mathcal{D}_Q^K &= D_1^{u\to K^+} + D_1^{\bar{u}\to K^+} + D_1^{d\to K^+} + D_1^{\bar{d}\to K^+} + \dots \end{aligned}$$

- HERMES Collaboration-
Phys.Rev. D89 (2014) 09710



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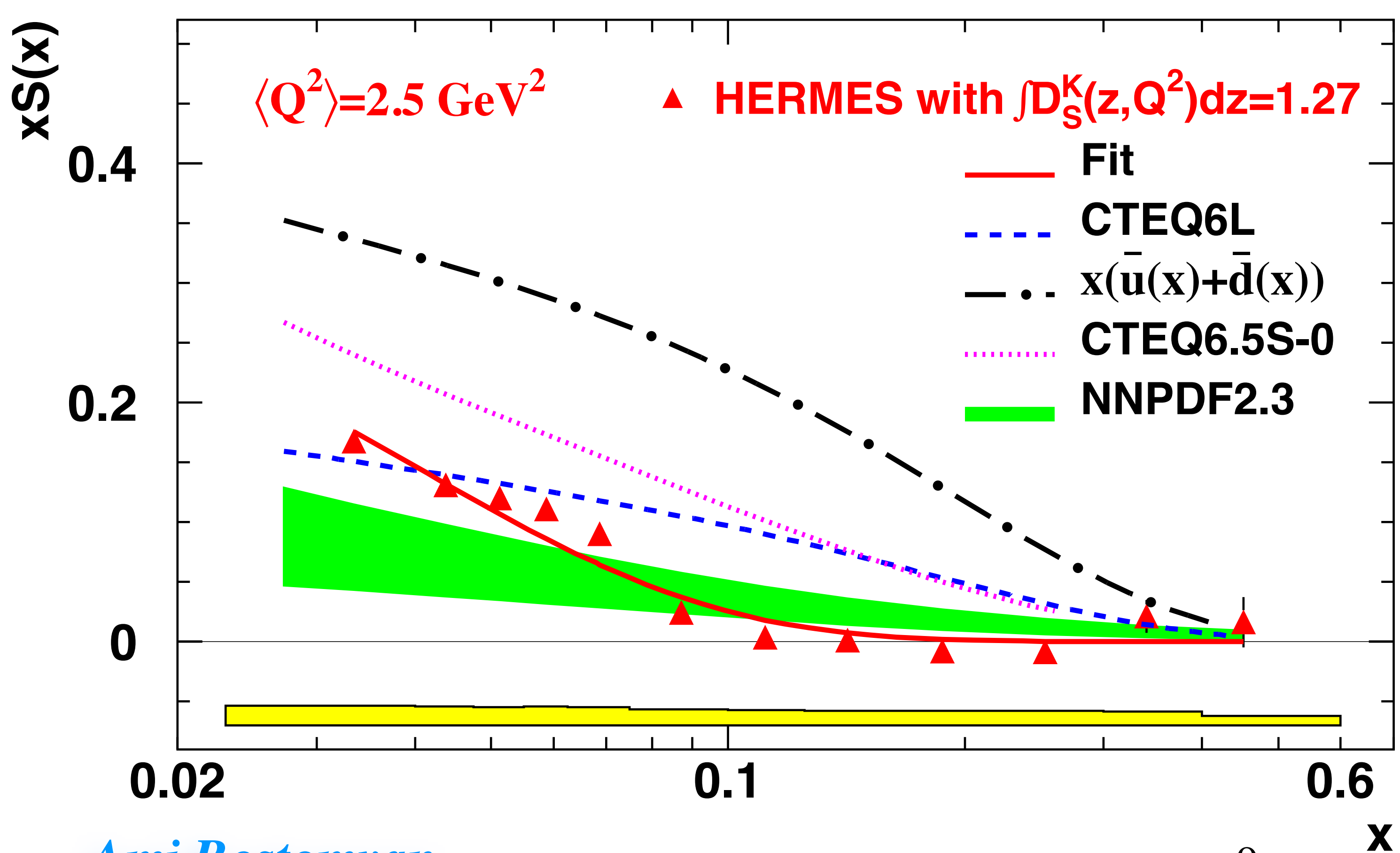
$$S(x) = s(x) + \bar{s}(x)$$
$$Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x)$$
$$\mathcal{D}_S^{\mathcal{K}} = D_1^{s\to K^+} + D_1^{\bar{s}\to K^+} + D_1^{s\to K^-} + D_1^{\bar{s}\to K^-}$$
$$\mathcal{D}_Q^{\mathcal{K}} = D_1^{u\to K^+} + D_1^{\bar{u}\to K^+} + D_1^{d\to K^+} + D_1^{\bar{d}\to K^+} + \ldots$$

- HERMES Collaboration-
Phys.Rev. D89 (2014) 09710



✓ the distribution of S(x) is obtained for a certain value of $\mathcal{D}_S^{\mathcal{K}}$

✓ the normalization of the data is given by that value

✓ whatever the normalization, the shape is incompatible with the predictions

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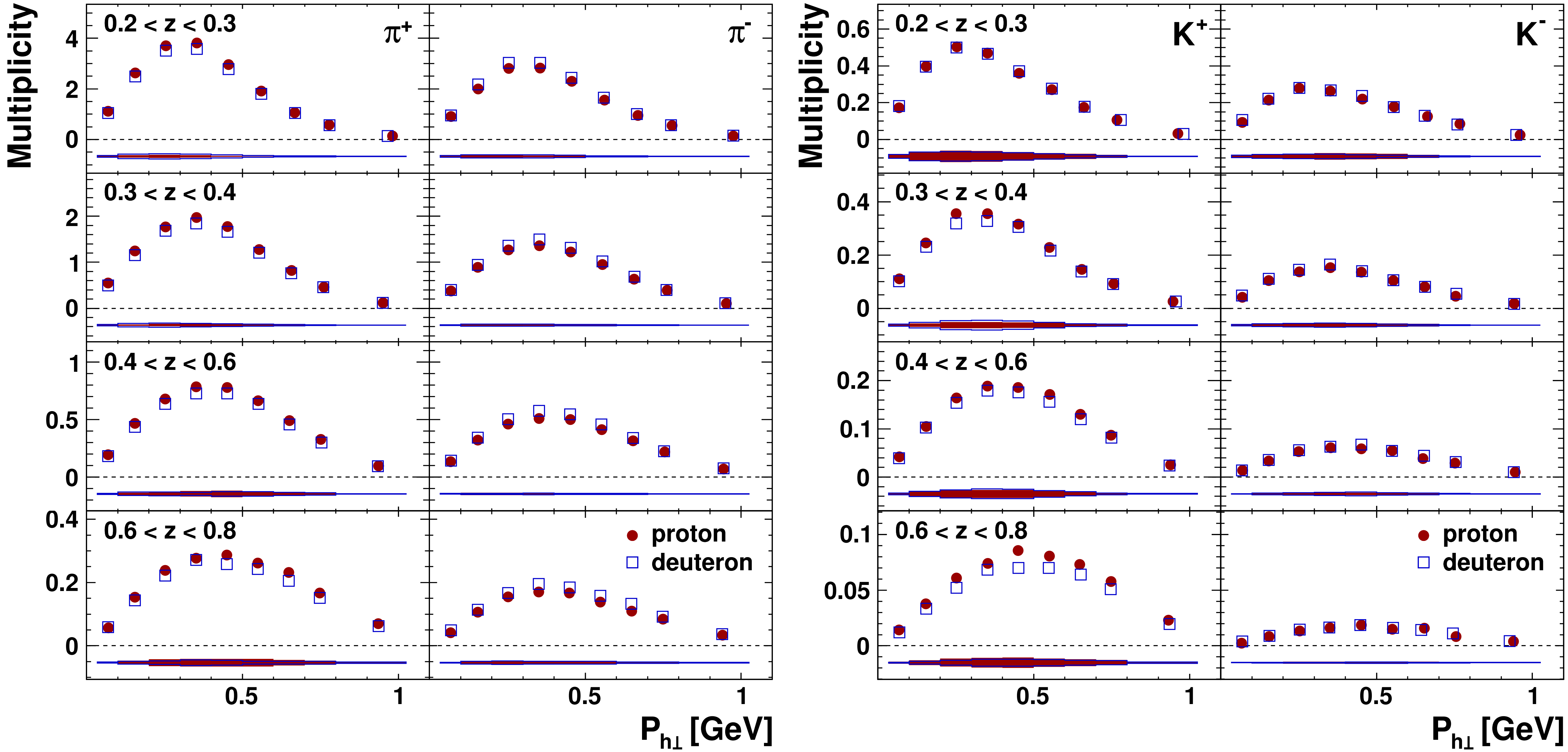
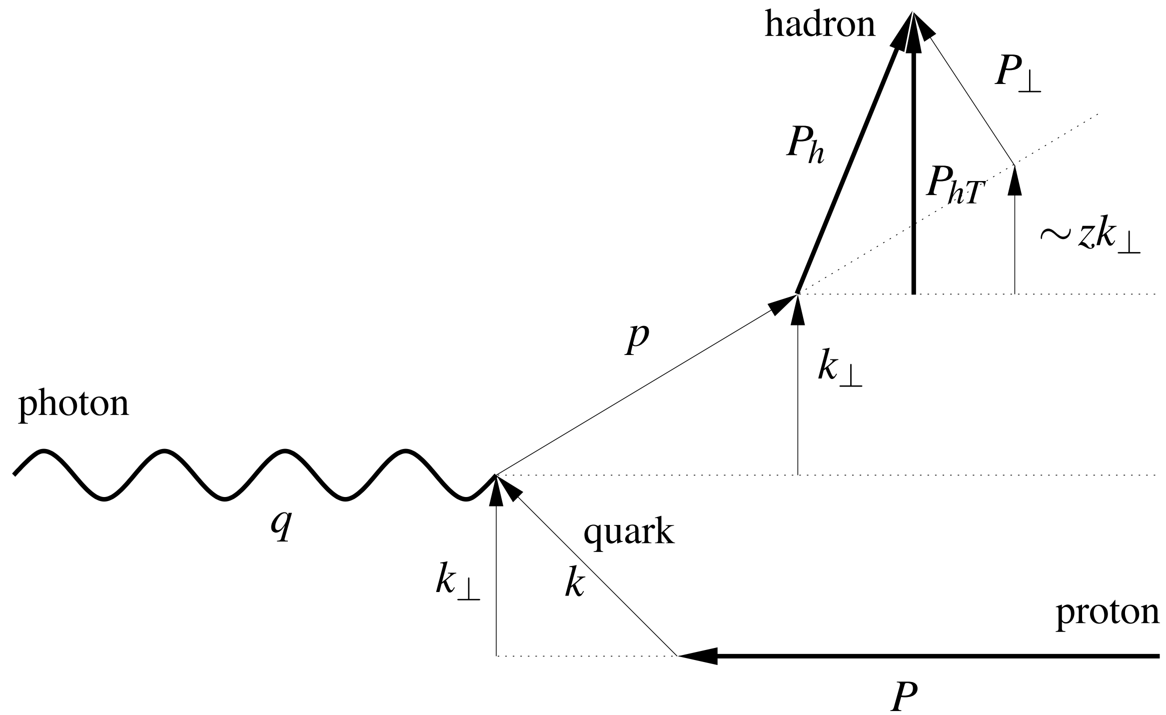
Phys.Rev. D87 (2013) 074029



✓ multi-dimensional analysis allows exploration of new kinematic dependences

✓ broader $P_{h\perp}$ distribution for K^-

flavour-dependent and independent anzatses



M. Anselmino, M. Boglione, J.O. Gonzalez H., S. Melis, A. Prokudin JHEP (2014)

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

➡ flavour-independent analysis

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

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

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

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

➡ different widths for the Gaussian forms of the valence and sea TMD PDFs

➡ four different Gaussian shapes for TMD FFs

$$f_1^a(x,\boldsymbol{k}_\perp^2;Q^2) = \frac{f_1^a(x,Q^2)}{\pi\langle \boldsymbol{k}_{\perp,a}^2\rangle}\; e^{-\boldsymbol{k}_\perp^2/\langle \boldsymbol{k}_{\perp,a}^2\rangle}$$

$$D_1^{a\to h}(z,\boldsymbol{P}_\perp^2,Q^2) = \frac{D_1^{a\to h}(z;Q^2)}{\pi\langle \boldsymbol{P}_{\perp,a\to h}^2\rangle}\; e^{-\boldsymbol{P}_\perp^2/\langle \boldsymbol{P}_{\perp,a\to h}^2\rangle}$$

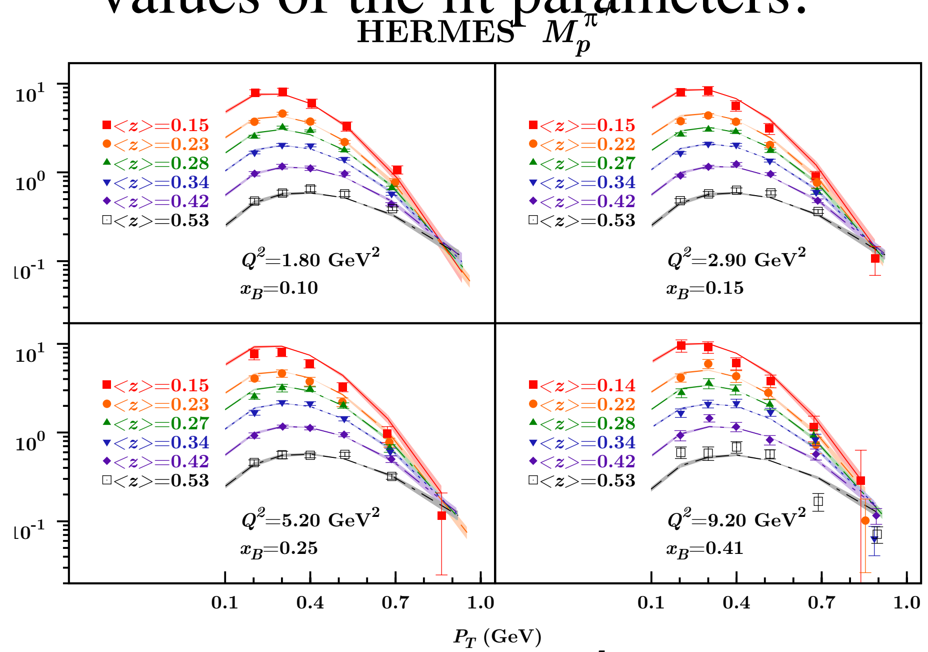
flavour-dependent and independent fits

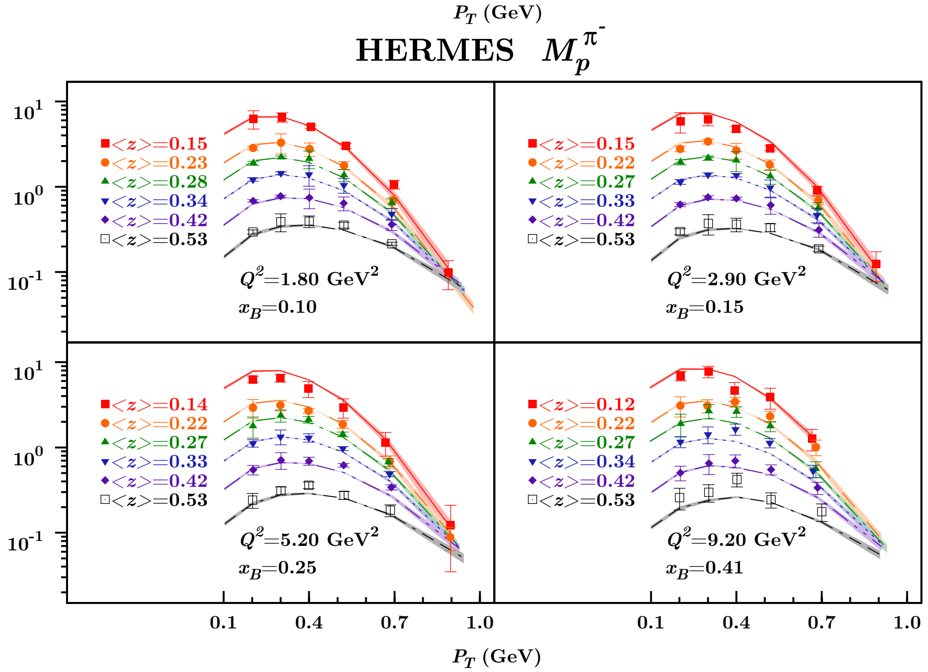
M. Anselmino, M. Boglione, J.O. Gonzalez H., S. Melis, A. Prokudin JHEP (2014)

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

no fit on K data:

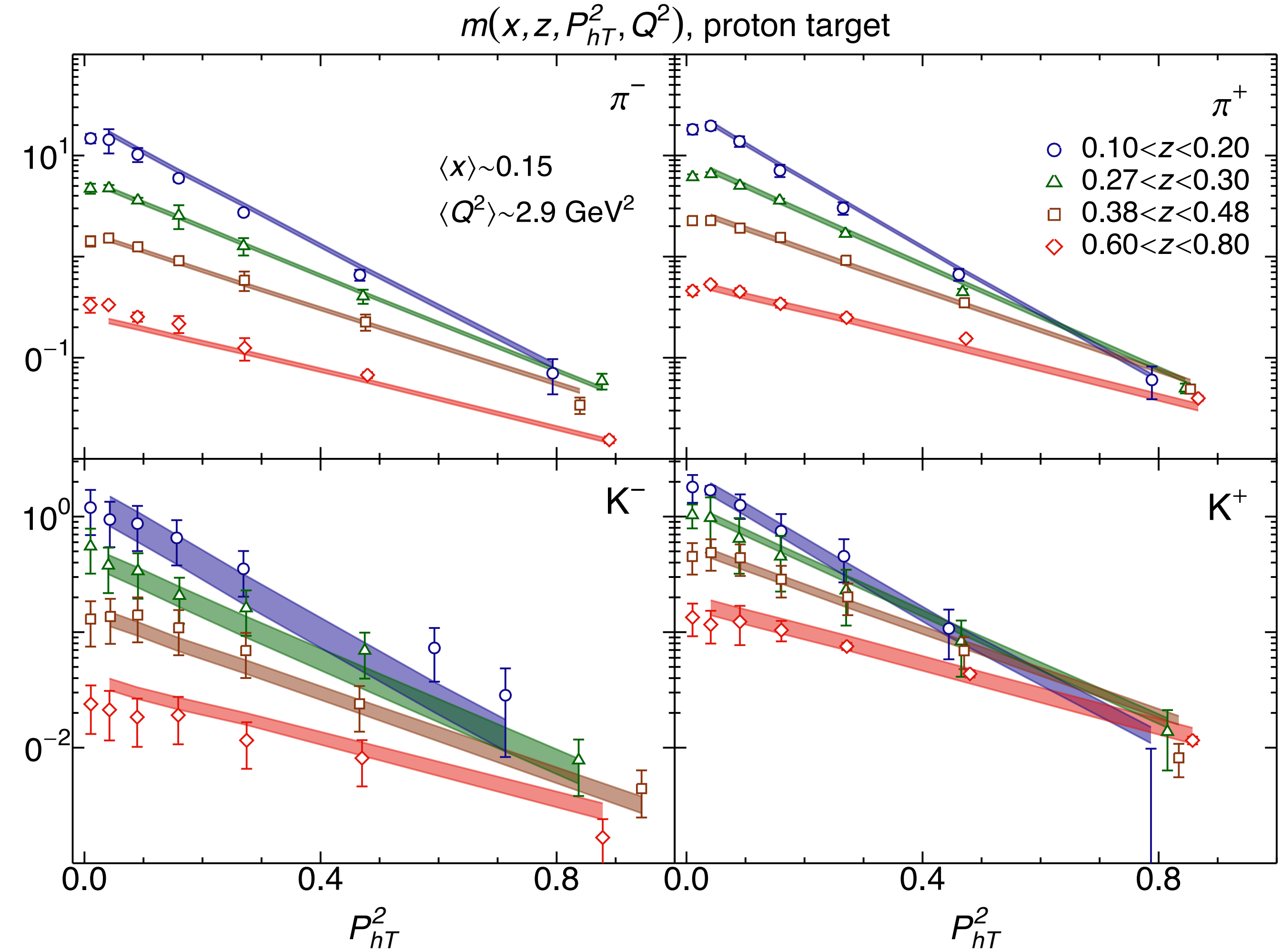
➡ the precision and accuracy of the kaon data do not help in constraining the values of the fit parameters.





$$\langle k_\perp^2 \rangle = 0.57 \pm 0.08 \text{ GeV}^2 \,, \qquad \langle p_\perp^2 \rangle = 0.12 \pm 0.01 \text{ GeV}^2$$

fit of eight different target–hadron combinations



$$\langle P^2_{\perp,\,\text{fav}} \rangle < \langle P^2_{\perp,\,\text{unf}} \rangle \sim \langle P^2_{\perp,\,\text{u}K} \rangle$$

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

quarks' transverse degrees of freedom

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

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

Cahn effect

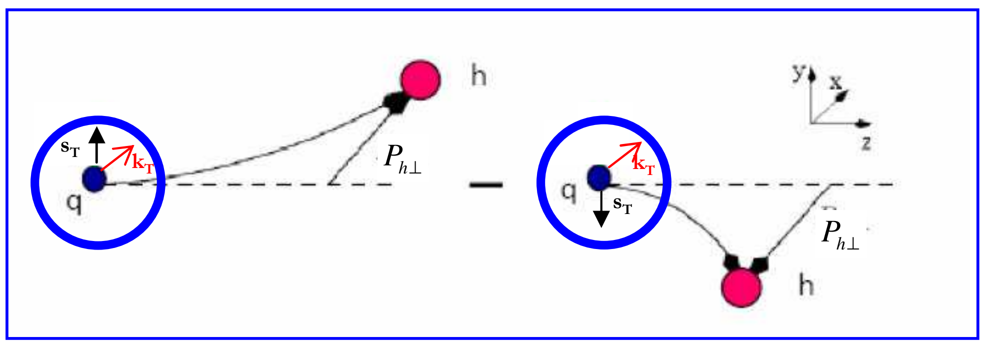
kinematic effect caused by quark intrinsic transverse momentum.

Boer-Mulders effect

correlation between quark transverse momentum and quark transverse spin.

($\cos\phi_h$)

($\cos2\phi_h$)

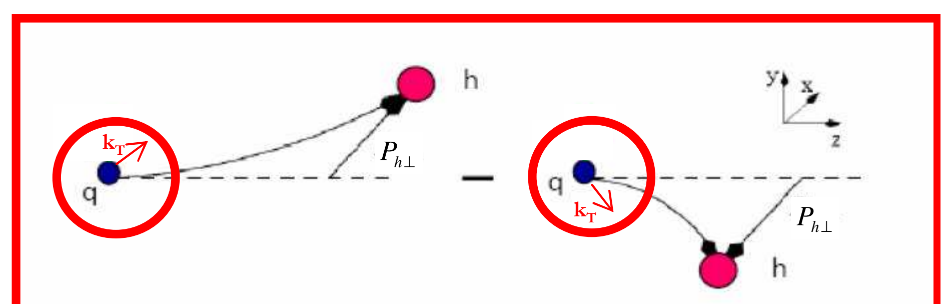


BOER-MULDERS EFFECT

$$F_{UU}^{\cos 2\phi} = C\left[-\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_T) - \vec{k}_T\cdot\vec{p}_T}{MM_h} h_1^\perp H_1^\perp \right]$$

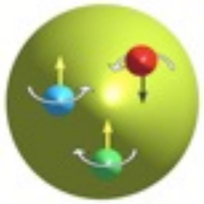
CAHN EFFECT

$$F_{UU}^{\cos\phi} = \frac{2M}{Q} C\left[-\frac{\hat{h}\cdot\vec{p}_T}{M_h} x\, h_1^\perp H_1^\perp - \frac{\hat{h}\cdot\vec{k}_T}{M} x\, f_1 D_1 + \ldots\ldots \right]$$



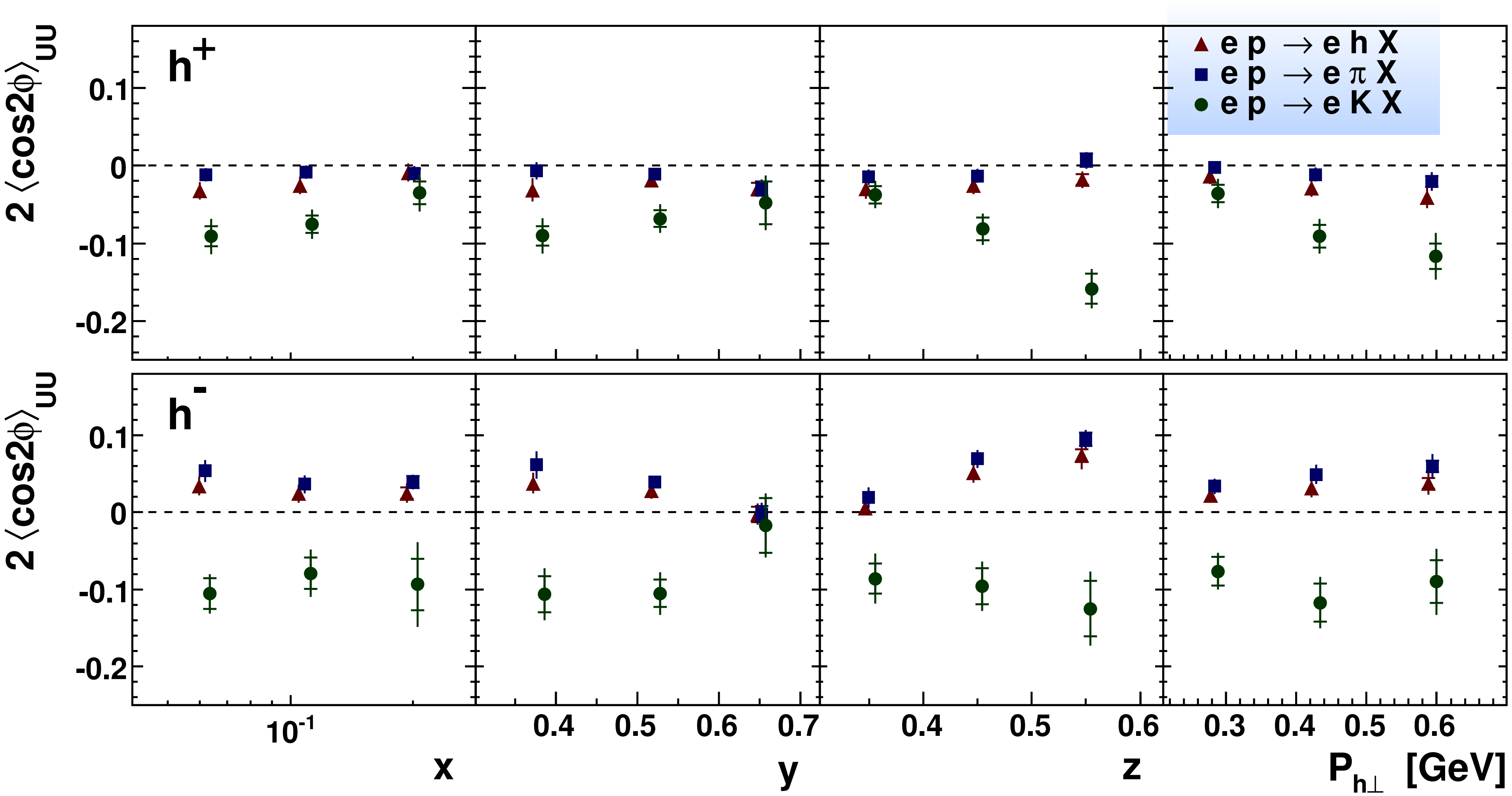
quarks' transverse degrees of freedom

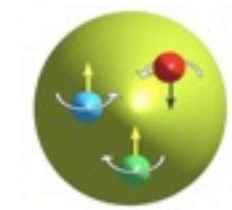
$$\sigma_{UU} \propto h_1^{\perp} \otimes H_1^{\perp}$$

$h_1^{\perp} =$ 

quarks' transverse degrees of freedom

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



$$h_1^{\perp} =$$ 

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✓ negative asymmetry for π^+ and positive for π^-

☛ from previous publications (*PRL 94 (2005) 012002, PLB 693 (2010) 11-16*):

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

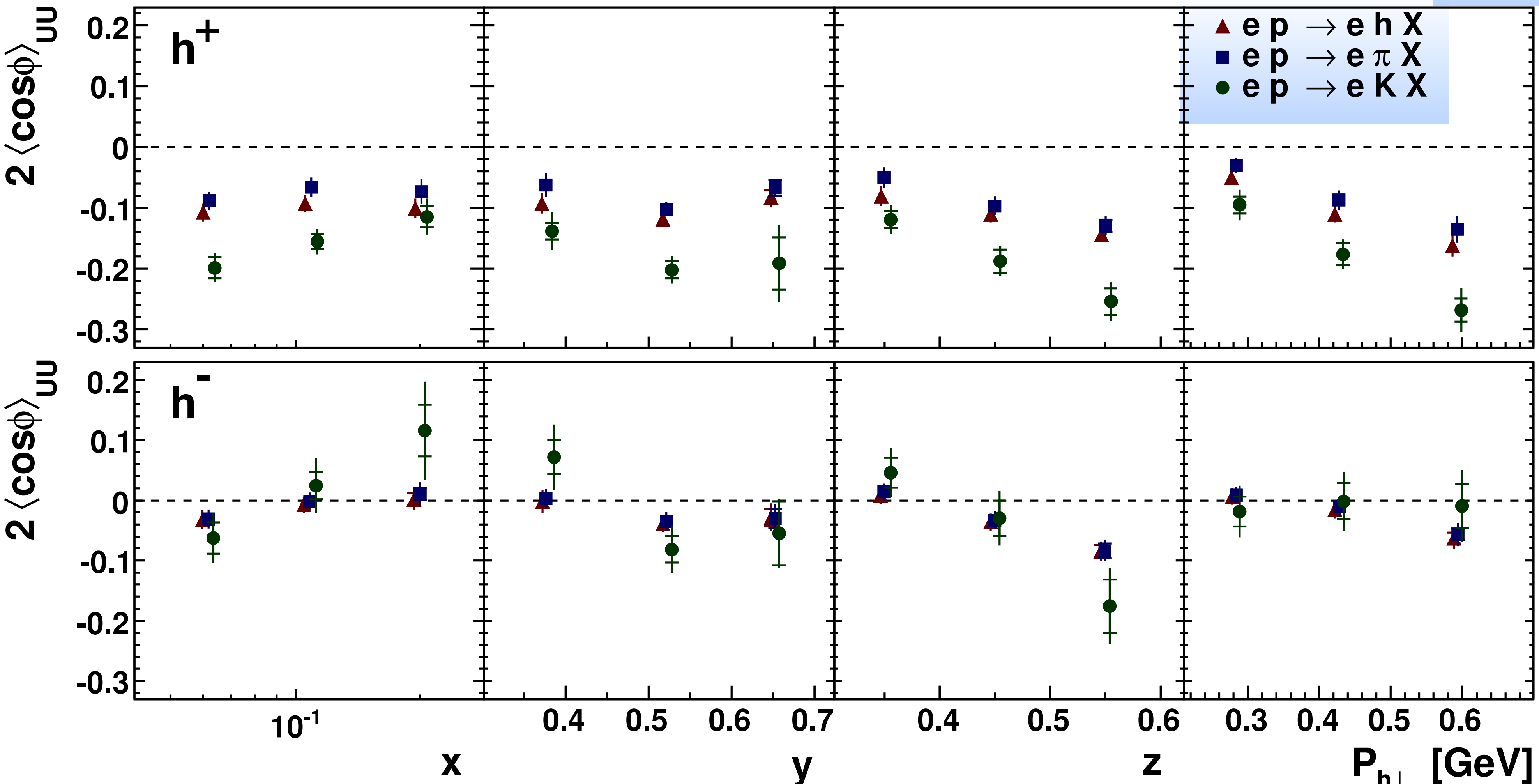
☛ **data support Boer-Mulders DF $h_1^{\perp}$ of same sign for u and d quarks**

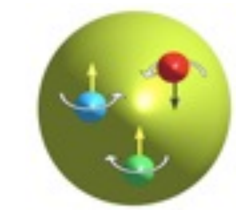
✓ K^- and K^+ : striking differences w.r.t. pions

☛ role of the sea in DF and FF

quarks' transverse degrees of freedom

$$\sigma_{UU} \propto h_1^{\perp\, q} \otimes H_1^{\perp\, q} - f_1^q \otimes D_1^q$$



$h_1^\perp =$ 

$f_1 =$ 

✓ negative asymmetries for π^+ and π^-

☛ larger effect at high z

☛ larger magnitude for π^+

✓ negative asymmetries for K^+

☛ even larger amplitudes in magnitude than those for π^+

☛ suggest a large contribution from the Boer–Mulders effect

✓ compatible with zero asymmetries for K^-

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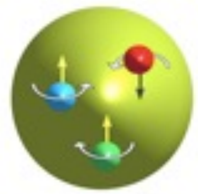
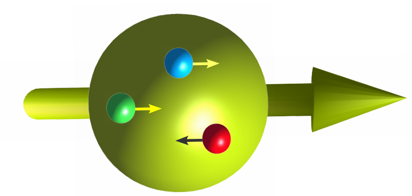
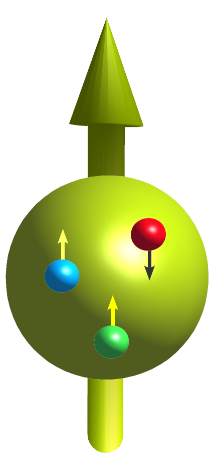
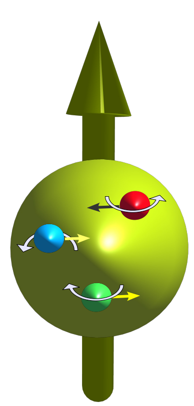
Outlook

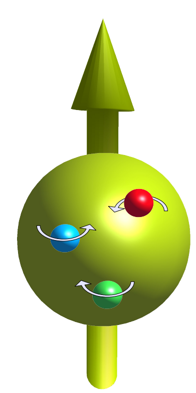


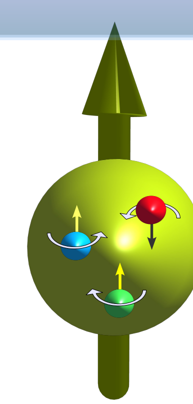
$$
\begin{aligned}
d\sigma \;=\;& d\sigma^{0}_{UU} + \cos(2\phi)\, d\sigma^{1}_{UU} + \frac{1}{Q}\cos(\phi)\, d\sigma^{2}_{UU} \;+\; P_l\, \frac{1}{Q}\sin(\phi)\, d\sigma^{3}_{LU} \\
&+\; S_L \left[\sin(2\phi)\, d\sigma^{4}_{UL} + \frac{1}{Q}\sin(\phi)\, d\sigma^{5}_{UL} \;+\; P_l \left(d\sigma^{6}_{LL}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











Outlook

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

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