Phenomenology of unpolarized cross sections

and azimuthal asymmetries

Vincenzo Barone

Università del Piemonte Orientale "A. Avogadro"

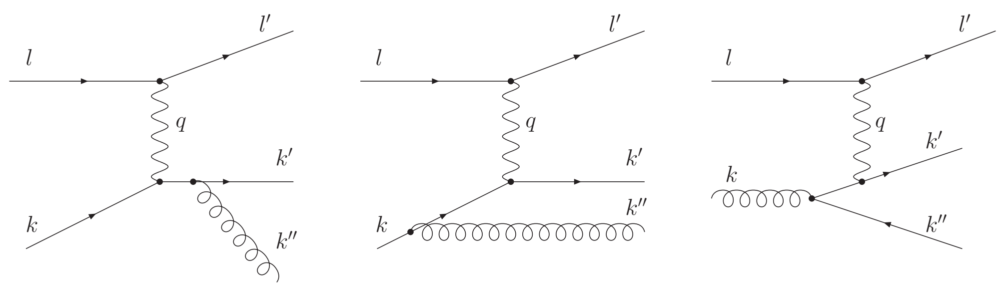
INFN, Gruppo Collegato, Alessandria, Italy

Outline

- Theoretical framework and Gaussian approach
- Transverse-momentum dependence of cross sections
- $\cos\phi_h$ and $\cos 2\phi_h$ azimuthal asymmetries
- Conclusions

Theoretical framework and Gaussian approach

In the early years of pQCD [Georgi & Politzer (1978)] it was pointed out that azimuthal asymmetries in unpolarized processes (SIDIS and DY) can be produced by gluon radiation and splitting



(SIDIS)

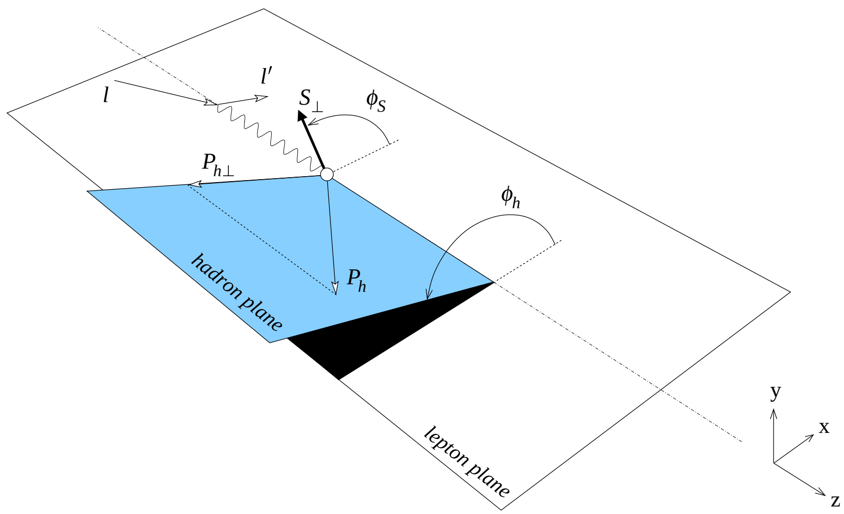
First experimental studies:

- SIDIS: EMC (1983, 1987)
- πN DY: NA10 (1986, 1988); E615 (1985, 1989)

pQCD radiative processes are relevant at high transverse momenta

At low $P_\perp$ intrinsic transverse motion of quarks plays a key rôle

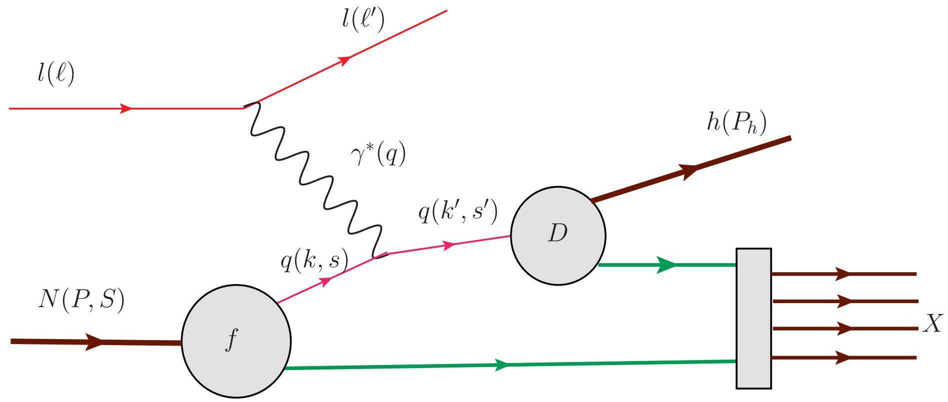
Semi-inclusive DIS: $l(\ell) + N(P) \rightarrow l(\ell') + h(P_h) + X(P_X)$



Invariants: $W^2 = (P+q)^2 \qquad x_B = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot \ell} \qquad z_h = \frac{P\cdot P_h}{P\cdot q}$

Light-cone components: $P^{\pm} \equiv \frac{1}{\sqrt{2}}(P^0 \pm P^3)$ $\quad \gamma^* N$ collinear frame: $P^+ = 0$

SIDIS in the current fragmentation region



Cross section : $$\frac{d\sigma}{dx_B\, dy\, dz_h} \sim \sum_a e_a^2\, f_a(x)\, \frac{d\hat{\sigma}}{dy}\, D_a(z)$$

Factorization in x (fraction of the nucleon momentum carried by the quark) and z (fraction of the momentum of the struck quark carried by the final hadron)

Neglecting $1/Q^2$ contributions, one has $x \simeq x_B$ and $z \simeq z_h$

Current fragmentation Vs. Target fragmentation

Rapidity separation between current and target fragments [Berger (1987)]:

$$\Delta y = \ln \frac{W^2}{M^2} = \ln \frac{Q^2(1 - x_B)}{x_B\, M^2}$$

If $\Delta y >$ few units, hadrons in the whole z_h range belong to CFR

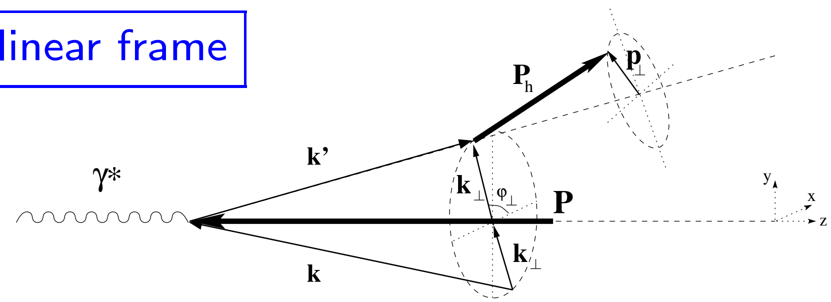
$\Delta y > 4$ (twice the typical hadronic correlation length) corresponds to $W > 7.4$ GeV

For smaller W, the low-z_h region is contaminated by target fragmentation

(CLAS, HERMES, COMPASS require W larger than 2, 3, 5 GeV, respectively)

[Anselmino, VB & Kotzinian (2011)]

Transverse kinematics: $\gamma^* N$ collinear frame



$\mathbf{k}_\perp$ Transverse momentum of the initial quark

$\mathbf{p}_\perp$ Transverse momentum of the hadron w.r.t. to the fragmenting quark

$\mathbf{P}_{h\perp}$ Transverse momentum of the hadron w.r.t. to the $\gamma^* N$ axis

Neglecting $1/Q^2$ corrections, the transverse momenta are related by

$$\mathbf{p}_\perp \simeq \mathbf{P}_{h\perp} - z_h\,\mathbf{k}_\perp$$

Transverse kinematics: hN collinear frame

Neglecting $1/Q^2$ corrections, transverse momenta in the hN frame ($_T$) are equal to transverse momenta in the $\gamma^* N$ frame ($_\perp$): $\mathbf{k}_T \simeq \mathbf{k}_\perp$

Unpolarized SIDIS cross section

$$\frac{d\sigma}{dx_B\, dy\, dz_h\, d\phi_h\, d\mathbf{P}_{h\perp}^2} = \frac{2\pi\,\alpha_{em}^2}{x_B y Q^2}$$
$$\times \Big\{ (1 - y + \frac{1}{2}y^2)\, F_{UU,T} + (1-y)\, F_{UU,L}$$
$$+ (2-y)\sqrt{1-y}\, \cos\phi_h F_{UU}^{\cos\phi_h} + (1-y)\, \cos 2\phi_h\, F_{UU}^{\cos 2\phi_h} \Big\}$$

Average transverse momentum of the produced hadron:

$$\langle \mathbf{P}_{h\perp}^2 \rangle \equiv \frac{\int d^2\mathbf{P}_{h\perp}\, \mathbf{P}_{h\perp}^2\, d\sigma}{\int d^2\mathbf{P}_{h\perp}\, d\sigma}$$

Azimuthal asymmetries:

$$A^{\cos\phi_h} = 2\,\langle \cos\phi_h \rangle = 2\, \frac{\int d\phi_h\, \cos\phi_h\, d\sigma}{\int d\phi_h\, d\sigma} \qquad A^{\cos 2\phi_h} = 2\,\langle \cos 2\phi_h \rangle \equiv 2\, \frac{\int d\phi_h\, \cos 2\phi_h\, d\sigma}{\int d\phi_h\, d\sigma}$$

Unpolarized structure functions in the extended parton model, up to $\mathcal{O}(1/Q)$:

$$F_{UU,T} = \mathcal{C}\,[f_1 D_1]$$

$$F_{UU,\text{Cahn}}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M}\,f_1 D_1\right]$$

$$F_{UU,\text{BM}}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{(\hat{\mathbf{h}}\cdot\mathbf{k}'_T)\,\mathbf{k}_T^2}{M_h M^2}\,h_1^\perp\,H_1^\perp\right]$$

$$F_{UU,\text{BM}}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)(\hat{\mathbf{h}}\cdot\mathbf{k}'_T) - \mathbf{k}_T\cdot\mathbf{k}'_T}{M M_h}\,h_1^\perp\,H_1^\perp\right]$$

$$\mathcal{C}\,[w\,f\,D] \sim \int\!\!\int \mathrm{d}^2\mathbf{k}_T\,\mathrm{d}^2\mathbf{k}'_T\,\delta^2(\mathbf{k}_T - \mathbf{k}'_T - \mathbf{P}_{h\perp}/z)\,w(\mathbf{k}_T,\mathbf{k}'_T)\,f(x_B,\mathbf{k}_T^2)\,D(z_h,\mathbf{k}'^{\,2}_T)$$

Kinematic origin of the Cahn contribution [Cahn (1978, 1989)]:

$$\mathrm{d}\hat{\sigma} \sim \frac{\hat{s}^2+\hat{u}^2}{Q^4} \sim \frac{1}{y^2}\left[\left(1 - 4\frac{\mathsf{k}_\perp}{Q}\sqrt{1-y}\,\cos\varphi\right) + \left(1 - 4\frac{\mathsf{k}_\perp}{Q}\,\frac{\cos\varphi}{\sqrt{1-y}}\right)\right] + \mathcal{O}\left(\frac{\mathsf{k}_\perp^2}{Q^2}\right)$$

The extended parton model is the zeroth-order approximation of the TMD factorization theorem, valid for $\mathrm{P}_{h\perp} \ll Q$ [Ji, Ma, Yuan (2005)]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}z_h\,\mathrm{d}^2\mathbf{P}_{h\perp}} \sim \sum_a e_a^2 \int \mathrm{d}^2\mathbf{k}_T \int \mathrm{d}^2\mathbf{k}'_T \int \mathrm{d}^2\mathbf{l}_T\,\delta^2(\mathbf{k}_T - \mathbf{k}'_T + \mathbf{l}_T - \mathbf{P}_{h\perp}/z_h)$$

$$\times f_a(x, \mathbf{k}_T^2)\,\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}y}\,U(\mathbf{l}_T^2)\,D_a(z, {\mathbf{k}'_T}^2)$$

At order $1/Q$ quark-gluon interactions give rise to "tilde" distributions and $F_{UU}^{\cos\phi_h}$ gets the additional term [Bacchetta et al. (2007)]:

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}'_T}{M_h}\left(x\tilde{h}H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M}\left(x\tilde{f}^{\perp}D_1 + \frac{M_h}{M}h_1^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

However TMD factorization is not proven beyond leading twist

Cahn contribution to the $\cos 2\phi_h$ structure function at order $1/Q^2$:

$$F_{UU,\text{Cahn}}^{\cos 2\phi_h} = \frac{M^2}{Q^2}\,\mathcal{C}\left[\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)^2 - \mathbf{k}_T^2}{M^2} f_1\, D_1\right]$$

- This expression takes only part of the $1/Q^2$ kinematic corrections into account
- There are dynamical $1/Q^2$ corrections

Thus $F_{UU,\text{Cahn}}^{\cos 2\phi_h}$ is to be taken as an approximate estimate of the full $\mathcal{O}(1/Q^2)$ term

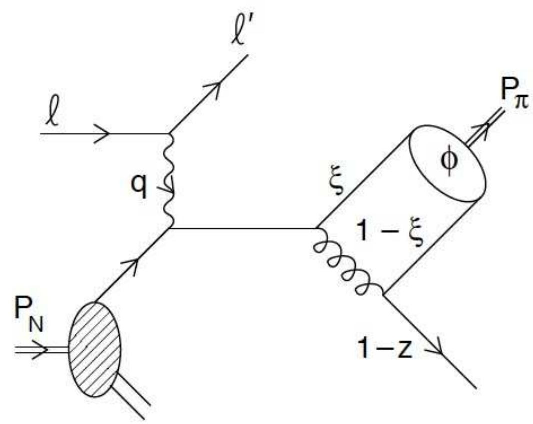
In summary:

$$\langle \cos\phi_h \rangle = \frac{1}{Q}\,\text{Cahn} + \frac{1}{Q}\,\text{BM} \qquad \langle \cos 2\phi_h \rangle = \text{BM} + \frac{1}{Q^2}\,\text{Cahn}$$

Another source of azimuthal asymmetries at higher twists

Berger-Brodsky effect [Berger & Brodsky (1979)]: semi-exclusive production of a hadron via one-gluon exchange (bound-state effect)

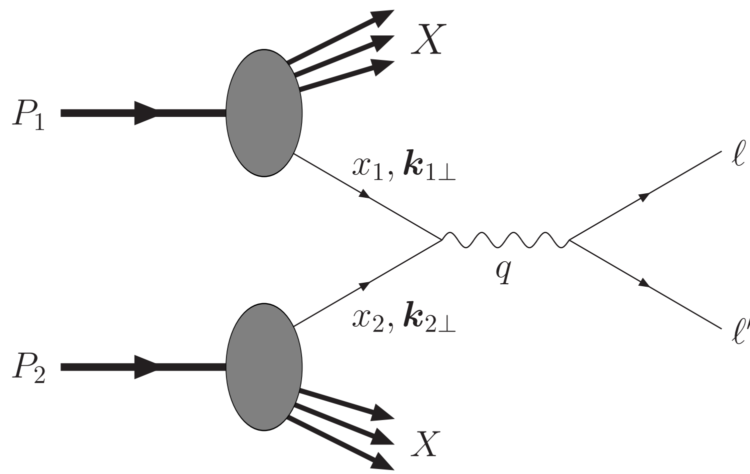
Generates $\cos\phi_h$ and $\cos 2\phi_h$ asymmetries at order $\mathrm{P}_{h\perp}/Q$ and $\mathrm{P}_{h\perp}^2/Q^2$ respectively



Potentially relevant at high z_h (above 0.7-0.8) [Brandenburg, Khoze & Müller (1994)]

An experimental/phenomenological study in [CLAS (2009)] ($\rightarrow$ *slide later*)

Drell-Yan production: $H_1(P_1) + H_2(P_2) \to l^+(\ell) + l^-(\ell') + X(P_X)$



Invariants: $s^2 = (P_1 + P_2)^2 \qquad x_1 = \frac{Q^2}{2P_1 \cdot q} \qquad x_2 = \frac{Q^2}{2P_2 \cdot q}$

Transverse kinematics (in the $H_1 H_2$ collinear frame): $\mathbf{k}_{1T} + \mathbf{k}_{2T} = \mathbf{q}_T$

Angles are usually expressed in the Collins-Soper dilepton rest frame

Unpolarized DY cross section

$$\frac{d^6\sigma_{UU}}{d^4q\, d\Omega} = \frac{\alpha_{\rm em}^2}{6sQ^2} \Big\{ (1+\cos^2\theta)\, W_{UU}^1 + \sin^2\theta\, W_{UU}^2 + \sin 2\theta\, \cos\phi\, W_{UU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, W_{UU}^{\cos 2\phi} \Big\}$$

Another common parametrization of the angular distribution of leptons

$$\frac{1}{N_{\rm tot}} \frac{dN}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda+3} \left(1 + \lambda\, \cos^2\theta + \mu\, \sin 2\theta\, \cos\phi + \frac{\nu}{2}\, \sin^2\theta \cos 2\phi \right)$$

with the correspondence

$$\lambda = \frac{W_{UU}^1 - W_{UU}^2}{W_{UU}^1 + W_{UU}^2}\,, \quad \mu = \frac{W_{UU}^{\cos\phi}}{W_{UU}^1 + W_{UU}^2}\,, \quad \nu = \frac{2\, W_{UU}^{\cos 2\phi}}{W_{UU}^1 + W_{UU}^2}$$

The Lam-Tung relation $\lambda + 2\nu = 1$ is valid in collinear QCD at order α_s

At leading twist, in the extended parton model:

$$\nu_{\text{BM}} = \frac{2\,\mathcal{C}\left[(2(\hat{\mathbf{h}}\cdot\mathbf{k}_{1T})(\hat{\mathbf{h}}\cdot\mathbf{k}_{2T}) - \mathbf{k}_{1T}\cdot\mathbf{k}_{2T})\,h_1^\perp\,\bar{h}_1^\perp\right]}{M_1\,M_2\,\mathcal{C}\left[f_1\,\bar{f}_1\right]}$$

The Cahn $\cos 2\phi$ contribution in DY is very small

In the Gaussian model [Arnold, Metz, Schlegel (2009)]:

$$\nu_{\text{Cahn}} \sim \frac{Q_T^2}{Q^2}\left(\frac{\mathbf{k}_{1T}^2\rangle - \langle\mathbf{k}_{2T}^2\rangle}{\langle\mathbf{k}_{1T}^2\rangle + \langle\mathbf{k}_{2T}^2\rangle}\right)^2$$

Transverse motion of quarks leads to a violation of the Lam-Tung relation

Gaussian Ansatz for distributions

Transverse-momentum dependent distribution and fragmentation functions:

$$f_1(x,\mathbf{k}_\perp^2) = N\, f_1(x)\, \mathrm{e}^{-\mathbf{k}_\perp^2/\overline{\mathbf{k}_\perp^2}} \quad D_1(z,\mathbf{p}_\perp^2) = N\, D_1(z)\, \mathrm{e}^{-\mathbf{p}_\perp^2/\overline{\mathbf{p}_\perp^2}}$$

Average squared momenta:

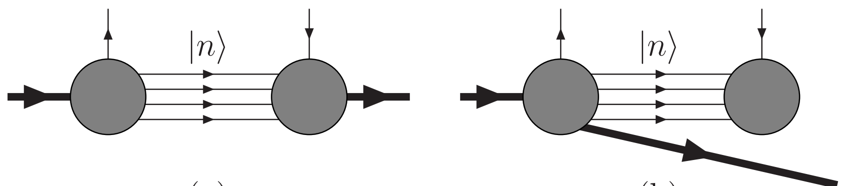
$$\langle \mathbf{k}_\perp^2 \rangle \equiv \int \mathrm{d}^2\mathbf{k}_\perp\, \mathbf{k}_\perp^2\, f_1(x,\mathbf{k}_\perp^2) \quad \langle \mathbf{p}_\perp^2 \rangle \equiv \int \mathrm{d}^2\mathbf{p}_\perp\, \mathbf{p}_\perp^2\, D_1(z,\mathbf{p}_\perp^2)$$

Average values coincide with Gaussian widths,

$$\langle \mathbf{k}_\perp^2 \rangle = \overline{\mathbf{k}_\perp^2} \quad \langle \mathbf{p}_\perp^2 \rangle = \overline{\mathbf{p}_\perp^2}$$

only if we integrate over $\mathbf{k}_\perp$ and $\mathbf{p}_\perp$ between 0 and ∞

"Intrinsic" quark momentum



(a) (b)

Bounds on $x \equiv k^-/P^-$: lessons from parton model [Jaffe 1983]

(b) No semi-connected diagrams $\Rightarrow x > 0$

(a) Physical intermediate states, $P_n^- \geq 0 \Rightarrow x \leq 1$

Momentum of the intermediate states $P_n^\mu = (\frac{xM^2 - \mathbf{k}_\perp^2}{2xP^-}, (1-x)P^-, -\mathbf{k}_\perp)$

The condition $M_n^2 \geq 0$ implies [Sheiman 1980]

$$\mathbf{k}_\perp^2 \leq x(1-x)M^2$$

This is the "intrinsic" quark transverse momentum

For recent discussions see [D'Alesio, Leader & Murgia (2010); Zavada (2011)]

Numerically the upper limit on the intrinsic transverse momentum of quarks is $\mathbf{k}_\perp^2 < 0.25$ GeV^2. The average value $\langle \mathbf{k}_\perp^2 \rangle$ must be smaller

On the other hand, various phenomenological analyses (see later) point to $\langle \mathbf{k}_\perp^2 \rangle \sim 0.25 - 0.40$ GeV^2

Is there a contradiction?

- The bound $\mathbf{k}_\perp^2 < x(1-x)M^2$ refers to a "static" nucleon $(Q^2 = 0)$
- The value of $\langle \mathbf{k}_\perp^2 \rangle$ extracted from experiments effectively accounts for "non-intrinsic" transverse momentum generated at a given Q^2

  $\langle \mathbf{k}_\perp^2 \rangle$ is not a fixed, universal, quantity

A popular relation

Start from:

$$F_{UU} = \sum_a e_a^2 \int \mathrm{d}^2\mathbf{k}_\perp \int \mathrm{d}^2\mathbf{p}_\perp \, \delta^2(\mathbf{p}_\perp + z_h \mathbf{k}_\perp - \mathbf{P}_{h\perp}) \, f_1^a(x_B, \mathbf{k}_\perp^2) \, D_1^a(z_h, \mathbf{p}_\perp^2)$$

Use Gaussian functions (assuming factorization in the collinear and transverse variables) and integrate between 0 and ∞:

$$F_{UU} = \sum_a e_a^2 \, f_1^a(x_B) \, D_1^a(z_h) \, \frac{\mathrm{e}^{-\mathbf{P}_{h\perp}^2 / \overline{\mathbf{P}_{h\perp}^2}}}{\pi \, \overline{\mathbf{P}_{h\perp}^2}}$$

with

$$\overline{\mathbf{P}_{h\perp}^2} = \overline{\mathbf{p}_\perp^2} + z_h^2 \, \overline{\mathbf{k}_\perp^2}$$

Note that:

- A cutoff on $\mathbf{k}_\perp^2$ invalidates this relation
- $\overline{\mathbf{P}_{h\perp}^2}$ differs from the measured $\langle \mathbf{P}_{h\perp}^2 \rangle$, due to experimental cuts
- There are (complicated) $1/Q^2$ corrections

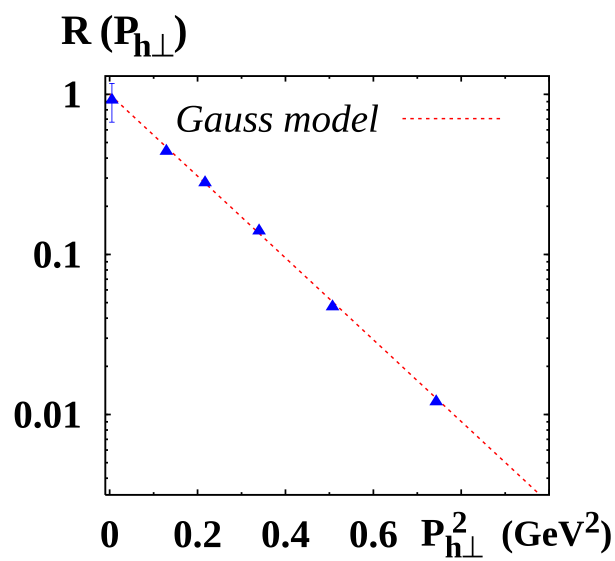
Transverse-momentum dependence of cross sections

Gaussian Ansatz for the cross section

Unpolarized cross section (integrated over angles)

$$\frac{\mathrm{d}\sigma_{UU}(\mathrm{P}_{h\perp})}{\mathrm{d}z\,\mathrm{d}\mathbf{P}_{h\perp}^2} = \frac{\mathrm{d}\sigma_{UU}(0)}{\mathrm{d}z\,\mathrm{d}\mathbf{P}_{h\perp}^2}\,\mathrm{e}^{-\mathbf{P}_{h\perp}^2/\overline{\mathbf{P}_{h\perp}^2}}$$

$$R(\mathrm{P}_{h\perp}) \equiv \frac{\mathrm{d}\sigma_{UU}(\mathrm{P}_{h\perp})}{\mathrm{d}\sigma_{UU}(0)}$$

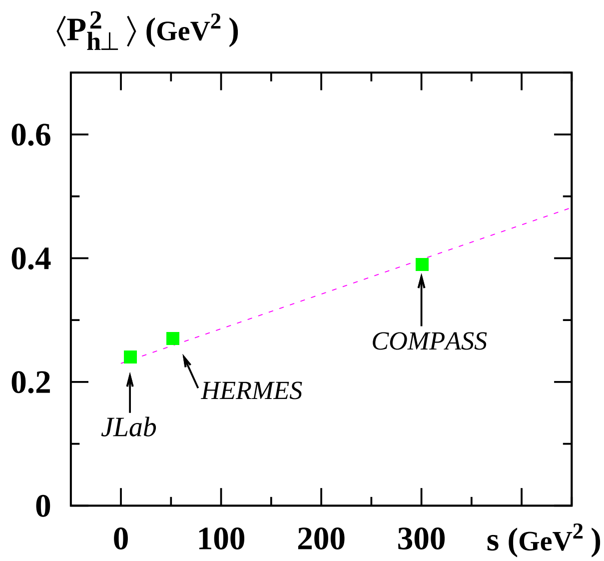


CLAS data: $Q^2 = 2.4$ GeV^2, $x = 0.24$, $z = 0.30$; Gaussian width: $\overline{\mathbf{P}_{h\perp}^2} = 0.17$ GeV^2

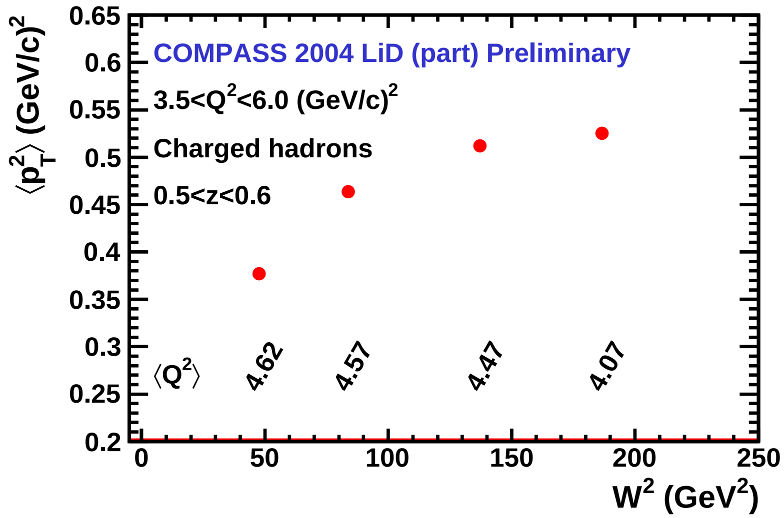
[Schweitzer, Teckentrup, Metz (2010)]

Energy dependence of $\langle \mathbf{P}_{h\perp}^2 \rangle$

[Schweitzer, Teckentrup, Metz (2010)]



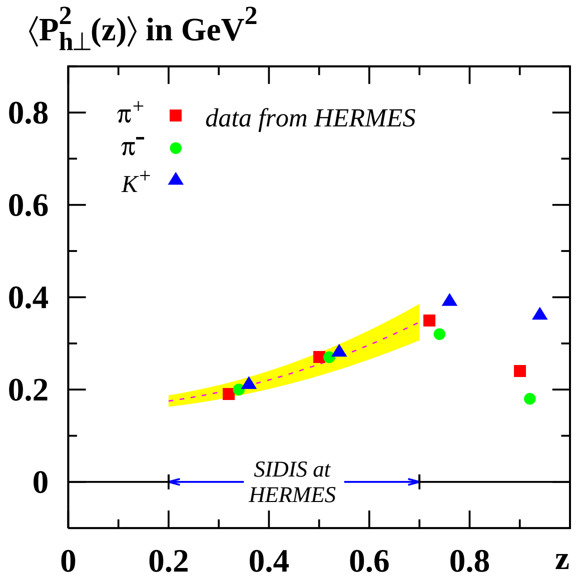
[Rajotte (COMPASS) (2010)]



Indirect indication of a possible broadening of $\langle \mathbf{k}_\perp^2 \rangle$ and $\langle \mathbf{p}_\perp^2 \rangle$ with W^2

Analysis of HERMES (2010) data using $\langle \mathbf{P}^2_{h\perp} \rangle = \overline{\mathbf{p}^2_\perp} + z_h^2\, \overline{\mathbf{k}^2_\perp}$

[Schweitzer, Teckentrup, Metz (2010)]

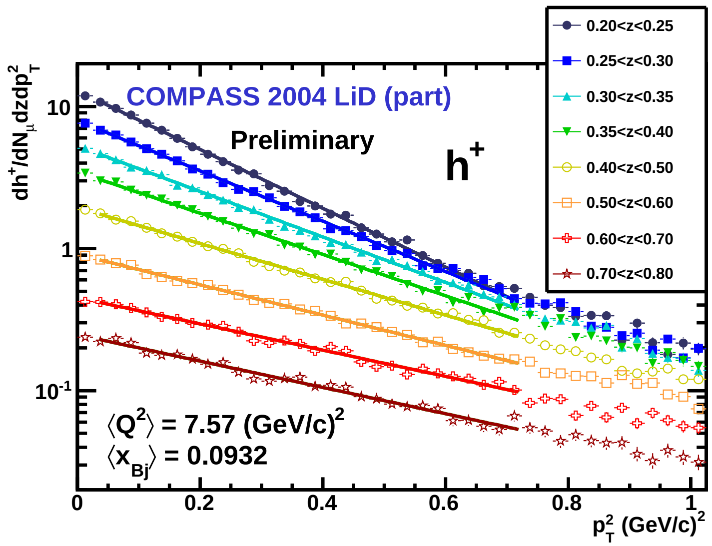


$\overline{\mathbf{k}^2_\perp} = (0.38 \pm 0.06)$ GeV^2 $\overline{\mathbf{p}^2_\perp} = (0.16 \pm 0.01)$ GeV^2

Good agreement found also with CLAS data in the current fragmentation region

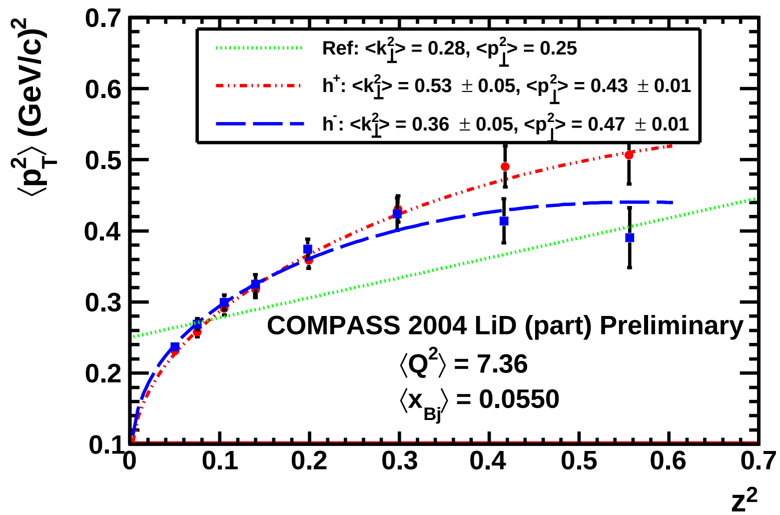
Gaussian fits to COMPASS unpolarized cross section

[Rajotte, COMPASS (2010)]



Gaussian width $\overline{\mathbf{P}_{h\perp}^2}$ studied as a function of x_B (mild dependence), Q^2 (clear increase) and z_h ($\rightarrow$ *next slide*)

$\overline{\mathbf{P}_{h\perp}^2} = \overline{\mathbf{p}_\perp^2} + z_h^2\,\overline{\mathbf{k}_\perp^2}$ vs. COMPASS data



Departure from a linear dependence on z_h^2 at large z_h

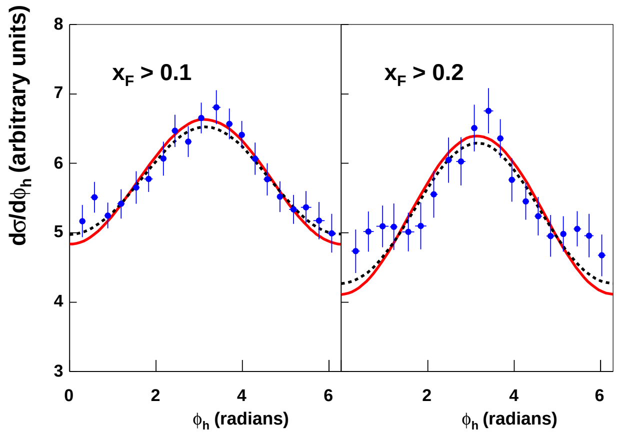
Curves are fits of the type

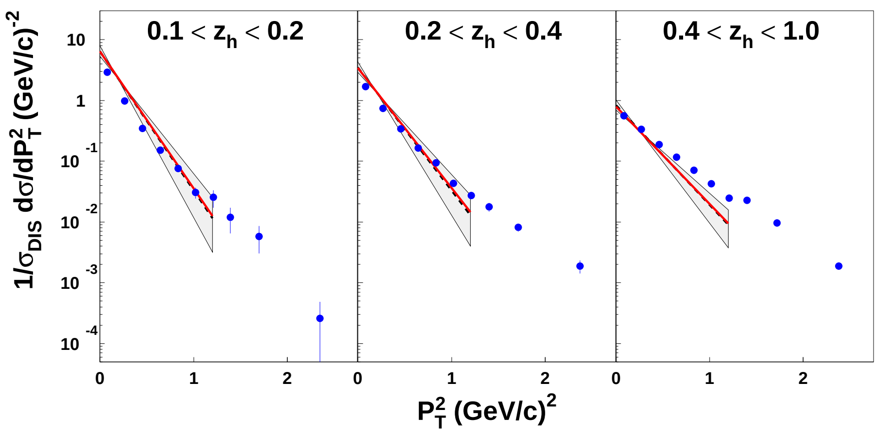
$$\overline{\mathbf{P}_{h\perp}^2} = z_h^{0.5}(1 - z_h)^{1.5}\,\overline{\mathbf{p}_\perp^2} + z_h^2\,\overline{\mathbf{k}_\perp^2}$$

Azimuthal asymmetries

Analysis of EMC data on $\langle \cos\phi_h \rangle$ and $\mathrm{d}\sigma/\mathrm{d}\mathbf{P}_{h\perp}^2$

[Anselmino et al. (2005)]



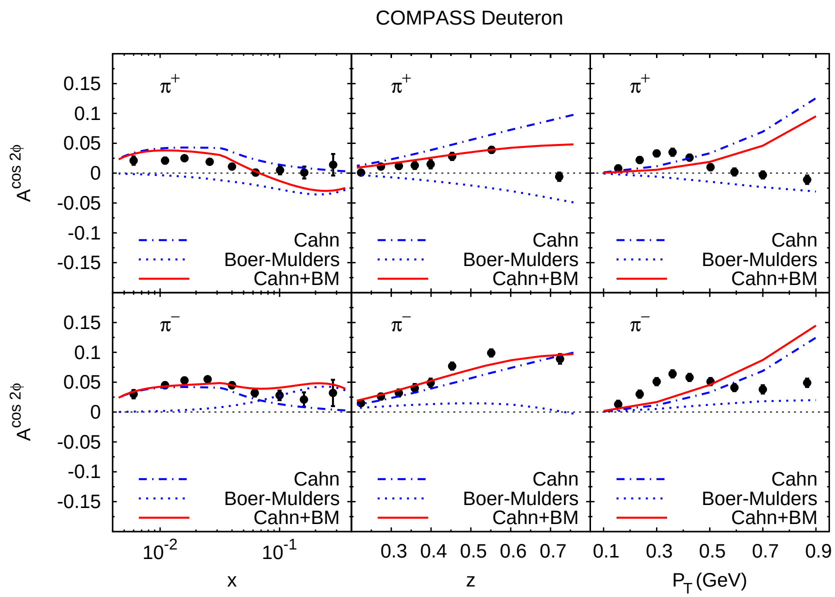


- $\langle \cos\phi_h \rangle$ fit does not include the Boer–Mulders term
- Gaussian widths: $\overline{\mathbf{k}_\perp^2} = 0.25$ GeV^2, $\overline{\mathbf{p}_\perp^2} = 0.20$ GeV^2

See also the analysis of HERMES data by [Collins et al. (2006)]

Analysis of $\langle \cos 2\phi_h \rangle$ asymmetries in SIDIS

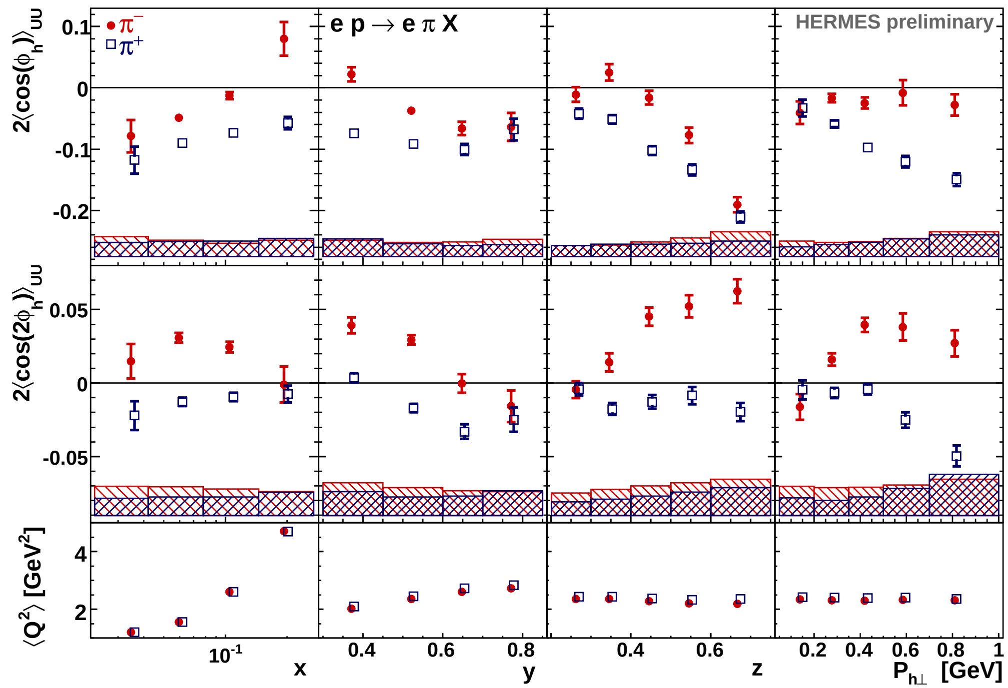
[VB, Ma, Melis, Prokudin (2008, 2010)]



- Signs and magnitudes of the Boer-Mulders function ($h_1^{\perp u} \sim 2 f_{1T}^{\perp u}$, $h_1^{\perp d} \sim -f_{1T}^{\perp d}$) in agreement with theoretical expectations (impact-parameter + lattice, large N_c)
- Signature of the Boer-Mulders effect: $\langle \cos 2\phi_h \rangle_{\pi^-} > \langle \cos 2\phi_h \rangle_{\pi^+}$ (as a consequence of $H_1^{\perp \text{fav}} \approx -H_1^{\perp \text{unf}}$)
- Cahn contribution relatively large in spite of being $\mathcal{O}(1/Q^2)$
- Since $h_1^{\perp u}$ has the same sign as $h_1^{\perp d}$, the BM effect is not suppressed in deuteron

HERMES preliminary results: $\langle \cos\phi_h \rangle$ and $\langle \cos 2\phi_h \rangle$ for $\pi^{\pm}$

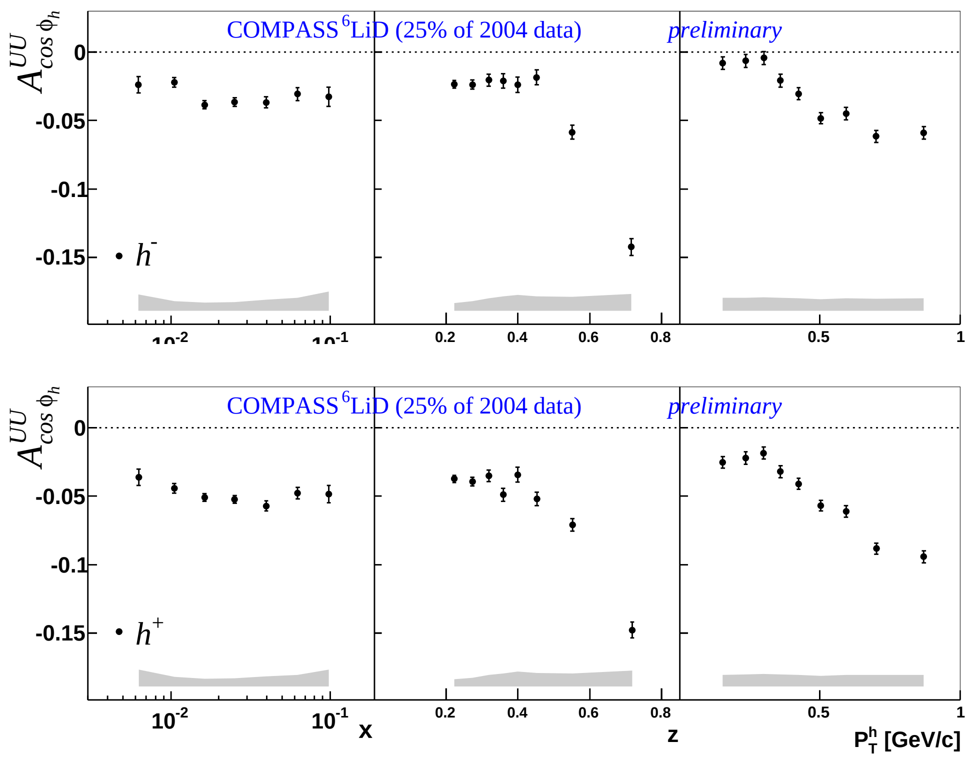
[Giordano & Lamb, HERMES (2010)]



- $\langle \cos\phi_h \rangle_{\pi^-}$ remarkably big in magnitude
- $\langle \cos 2\phi_h \rangle_{\pi^-}$ much larger than $\langle \cos 2\phi_h \rangle_{\pi^+}$
- $\langle \cos 2\phi_h \rangle_{\pi^+}$ slightly negative

COMPASS preliminary results: $\langle \cos \phi_h \rangle$ for $h^{\pm}$

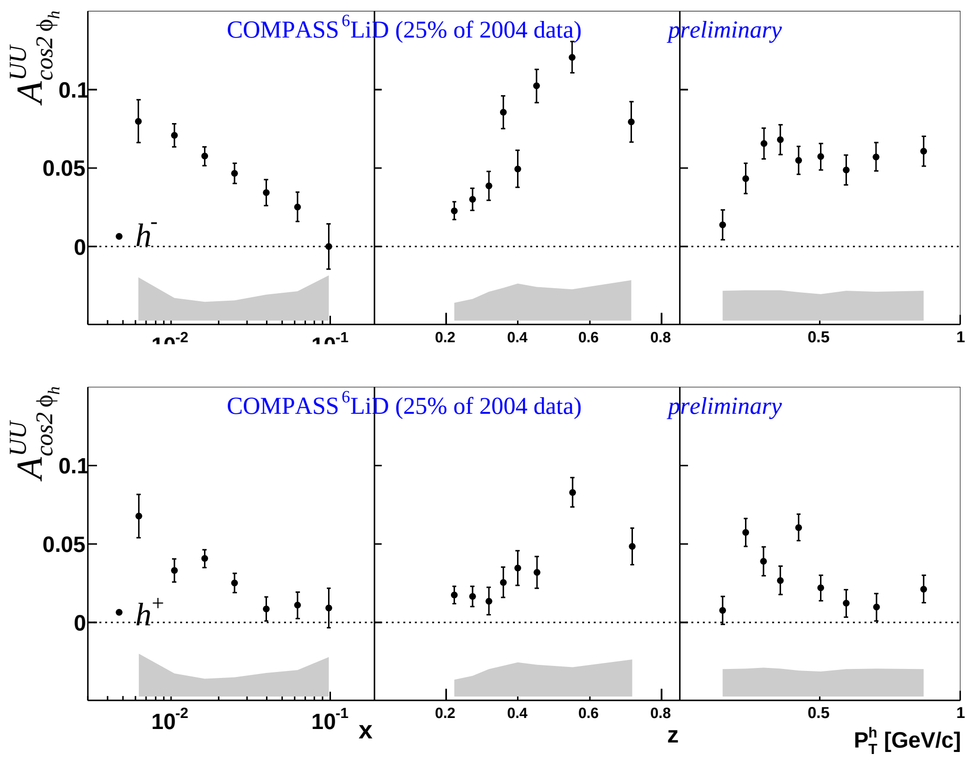
[Sbrizzai, COMPASS (2011)]



- Both $\langle \cos \phi_h \rangle_{\pi^+}$ and $\langle \cos \phi_h \rangle_{\pi^-}$ negative
- $\langle \cos \phi_h \rangle_{h^-}$ slightly larger than $\langle \cos \phi_h \rangle_{h^+}$

COMPASS preliminary results: $\langle\cos 2\phi_h\rangle$ for $h^{\pm}$

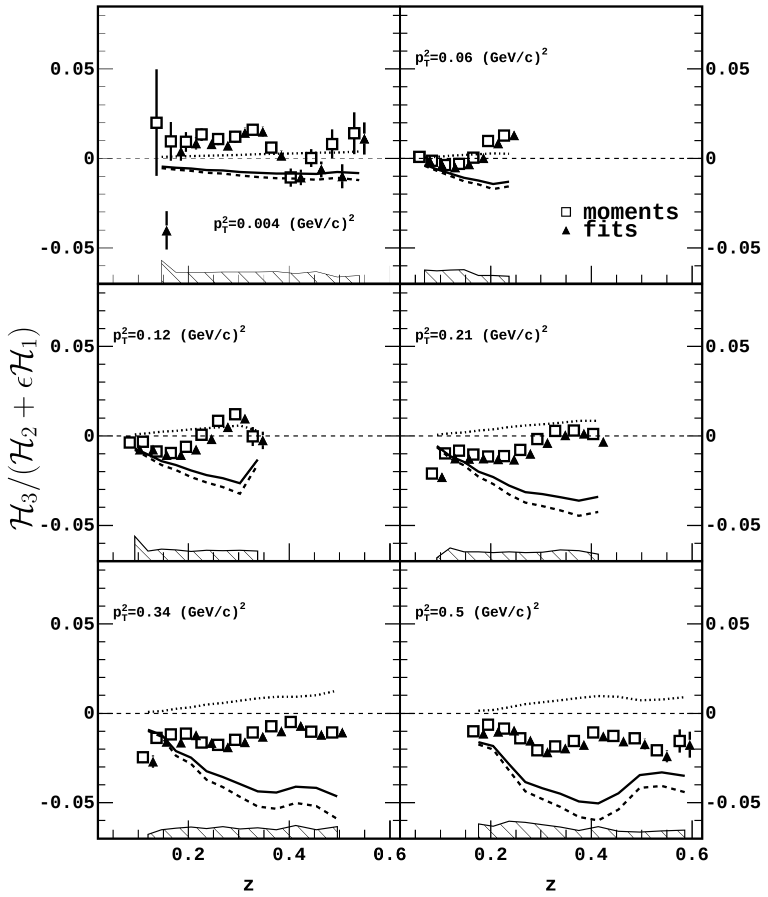
[Sbrizzai, COMPASS (2011)]



- Both $\langle\cos 2\phi_h\rangle_{\pi^+}$ and $\langle\cos 2\phi_h\rangle_{\pi^-}$ positive
- $\langle\cos 2\phi_h\rangle_{\pi^-}$ larger than $\langle\cos 2\phi_h\rangle_{\pi^+}$

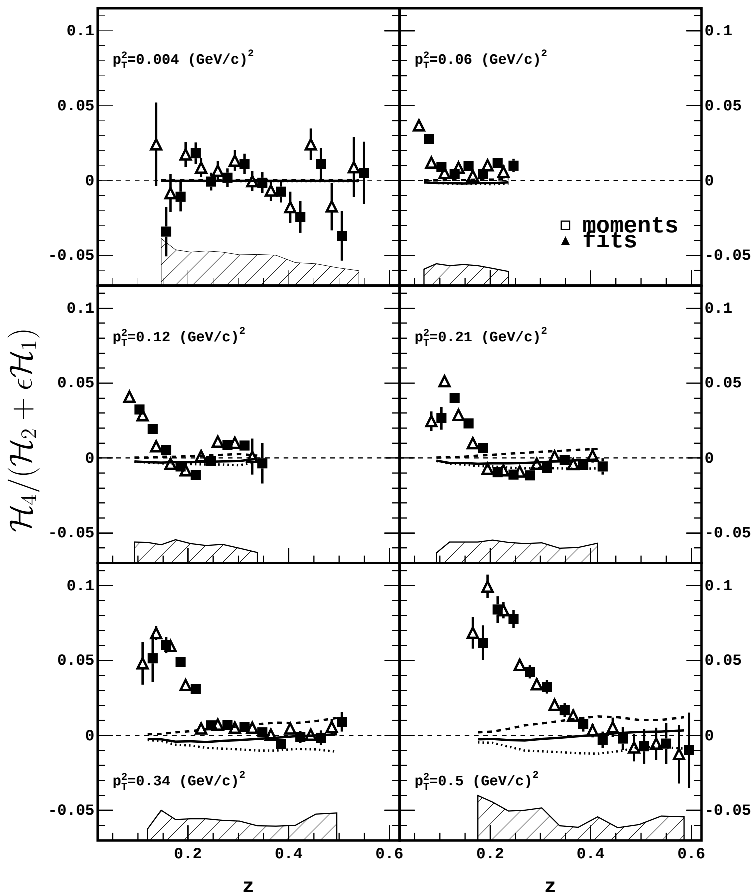
CLAS results: $\langle \cos\phi_h \rangle$ for π^+

[CLAS (2009)]



- Large disagreement between data and Cahn effect predictions (dashed lines)

CLAS results: $\langle \cos 2\phi_h \rangle$ for π^+



- Non-zero signal at small z_h (where target fragmentation may be important)
- Berger-Brodsky effect (dotted) small and with opposite sign for $\langle \cos \phi_h \rangle$ and $\langle \cos 2\phi_h \rangle$

Two types of problems....

- Experimental problem: compatibility of HERMES and COMPASS

  Fairly good agreement for $\langle \cos\phi_h \rangle$, but a large disagreement for $\langle \cos 2\phi_h \rangle$

  $\langle \cos 2\phi_h \rangle$ (COMPASS) systematically larger than $\langle \cos 2\phi_h \rangle$ (HERMES)

- Theoretical problem

  Only partial analyses so far. If we simply extrapolate them:

  - Cahn contribution to $\langle \cos\phi_h \rangle$ huge (largely overshoots the data)
  - BM contribution to $\langle \cos 2\phi_h \rangle$ small but apparently in the wrong direction (the BM term has opposite sign in $\langle \cos\phi_h \rangle$ and $\langle \cos 2\phi_h \rangle$ but data show a similar π^+-π^- pattern)

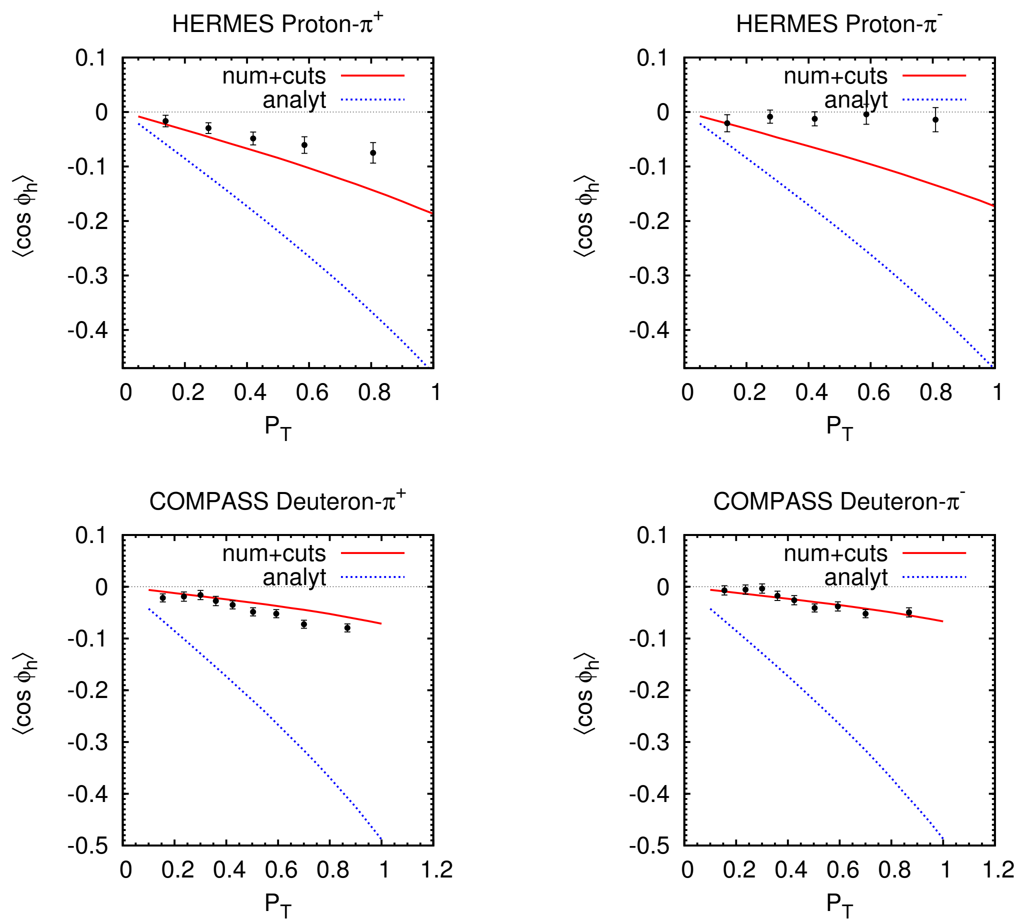
Effects of a cutoff on $\mathbf{k}_\perp$

[Boglione, Melis, Prokudin (2011)]

$$\mathbf{k}_\perp^2 \leq \eta(x_B)\, Q^2 = \begin{cases} (2-x_B)(1-x_B)Q^2 & \text{(parton energy} \leq \text{hadron energy)} \\ \frac{x_B(1-x_B)Q^2}{(1-2x_B)^2} & \text{(forward direction)} \end{cases}$$

Caveat: this is a frame-dependent cut (derived in the $\gamma^* N$ center-of-mass frame)

- The Cahn contribution gets largely suppressed
- The BM contribution is almost unaffected


HERMES Proton-π+
HERMES Proton-π-
COMPASS Deuteron-π+
COMPASS Deuteron-π-
num+cuts
analyt
⟨cos ϕh⟩
PT
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
0.2
0.4
0.6
0.8
1
1.2

- We clearly need a new combined fit of $\langle \cos \phi_h \rangle$ and $\langle \cos 2\phi_h \rangle$, possibly dropping some simplifying assumptions of the previous fits
- Be prepared to the possibility that the scheme

$$\langle \cos \phi_h \rangle = \frac{1}{Q}\,\text{Cahn} + \frac{1}{Q}\,\text{BM} \qquad \langle \cos 2\phi_h \rangle = \text{BM} + \frac{1}{Q^2}\,\text{Cahn}$$

  might not work

- Corrections to this scheme:
  - "Genuine" twist-3 contributions (quark-gluon correlations $\Rightarrow$ tilde TMDs)
  - Further $1/Q^2$ kinematic terms and dynamical twist-4 contributions

What we can do with higher twists.....

- Disentangle them from leading twist

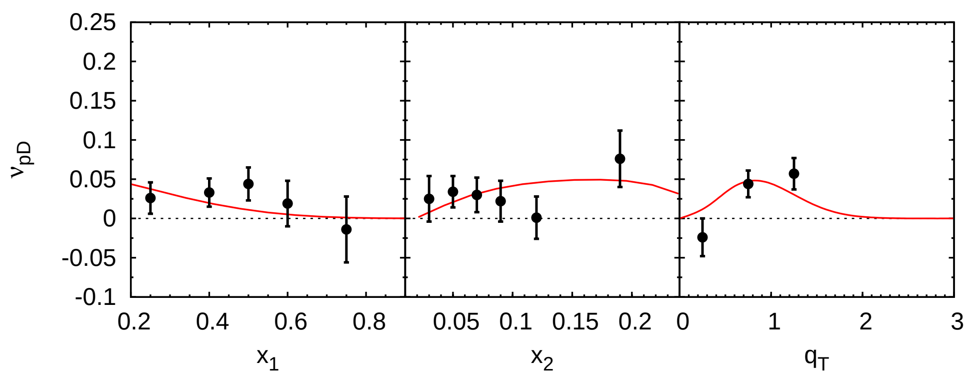
  Need a wide Q^2 range (as stressed yesterday by Harut and Alessandro)

- Get rid of them $\Rightarrow$ Drell-Yan production

  At low Q_T, the $\cos 2\phi$ asymmetry in DY is dominated by the leading-twist Boer-Mulders contribution (the Cahn term is negligible)

  But in pp DY $\langle \cos 2\phi \rangle$ is small [E866/NuSea (2007, 2009)] because of sea dominance

  Need valence-dominated DY: $p\bar{p}$ especially



Conclusions

- Nothing magic about Gaussians. It's just a parametrization, working pretty well for cross sections at low $P_{h\perp}$

  Concerning quark distributions, there is a strong (and arbitrary) assumption behind: separation of x and $k_\perp$

  No surprise if some simple relation based on Gaussians fails

- The parameters $\overline{\mathbf{k}_\perp^2}$ and $\overline{\mathbf{p}_\perp^2}$ are likely to be Q^2 (and W^2) dependent. They cannot be fixed once forever and used anywhere

  One should do as for normal PDFs: take a TMD at small Q^2 from some model, evolve it and fit the data [see Aybat's talk yesterday]

- Although we have clear signals of relatively large azimuthal asymmetries, the experimental situation is unsettled

- Higher-twist effects are quantitatively relevant
  $\langle \cos\phi_h \rangle$ is entirely $\mathcal{O}(1/Q)$
  In present kinematics even $1/Q^2$ contributions are important
  The $1/Q^2$ components should be fully worked out (further $\mathbf{k}_\perp/Q^2$ kinematic corrections, target mass corrections, twist-4 terms)

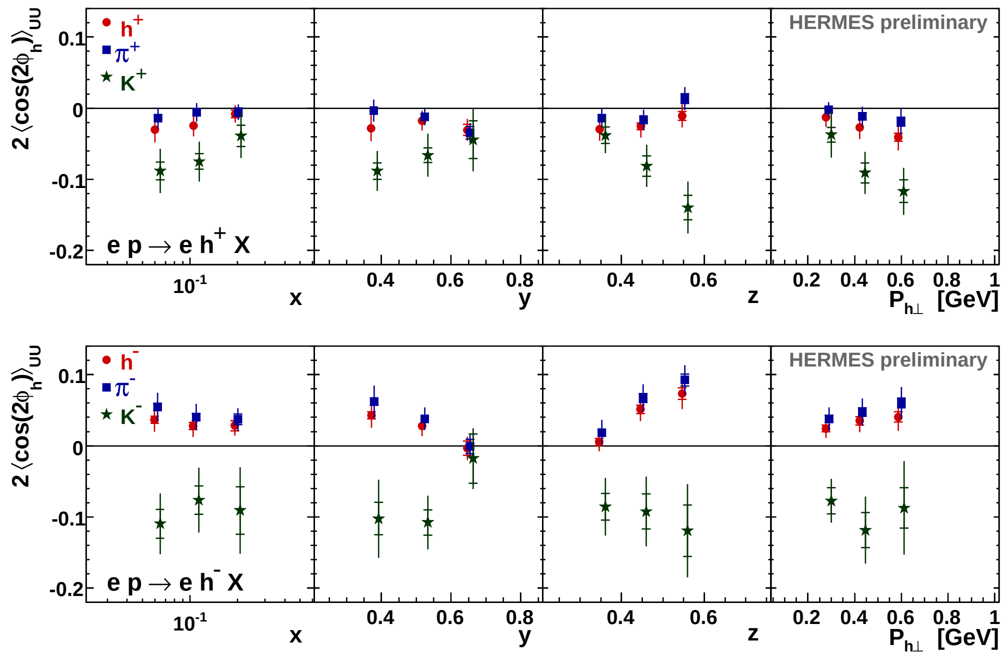
- A combined state-of-the-art fit of $\langle \cos\phi_h \rangle$ and $\langle \cos 2\phi_h \rangle$ is needed
  Drell-Yan data for valence-dominated processes will be extremely helpful

THANK YOU

Extra slides

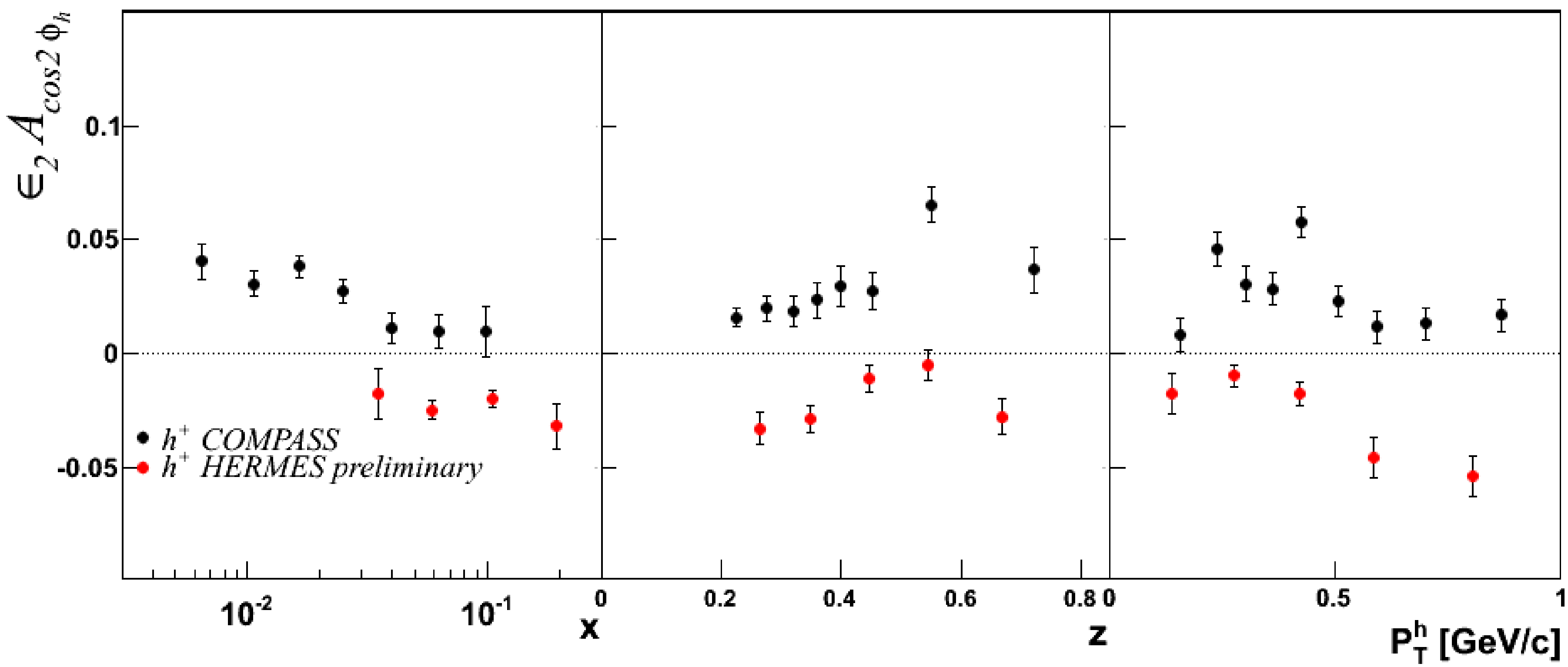
HERMES preliminary results: $\langle\cos\phi_h\rangle$ and $\langle\cos 2\phi_h\rangle$ for $K^{\pm}$

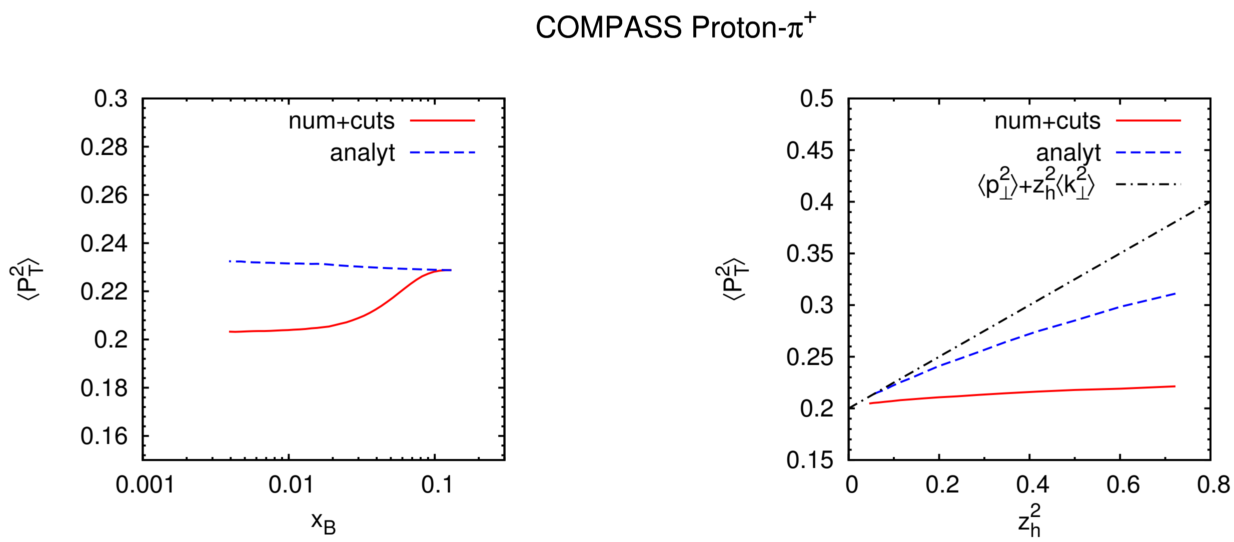
[Giordano & Lamb, HERMES (2010)]



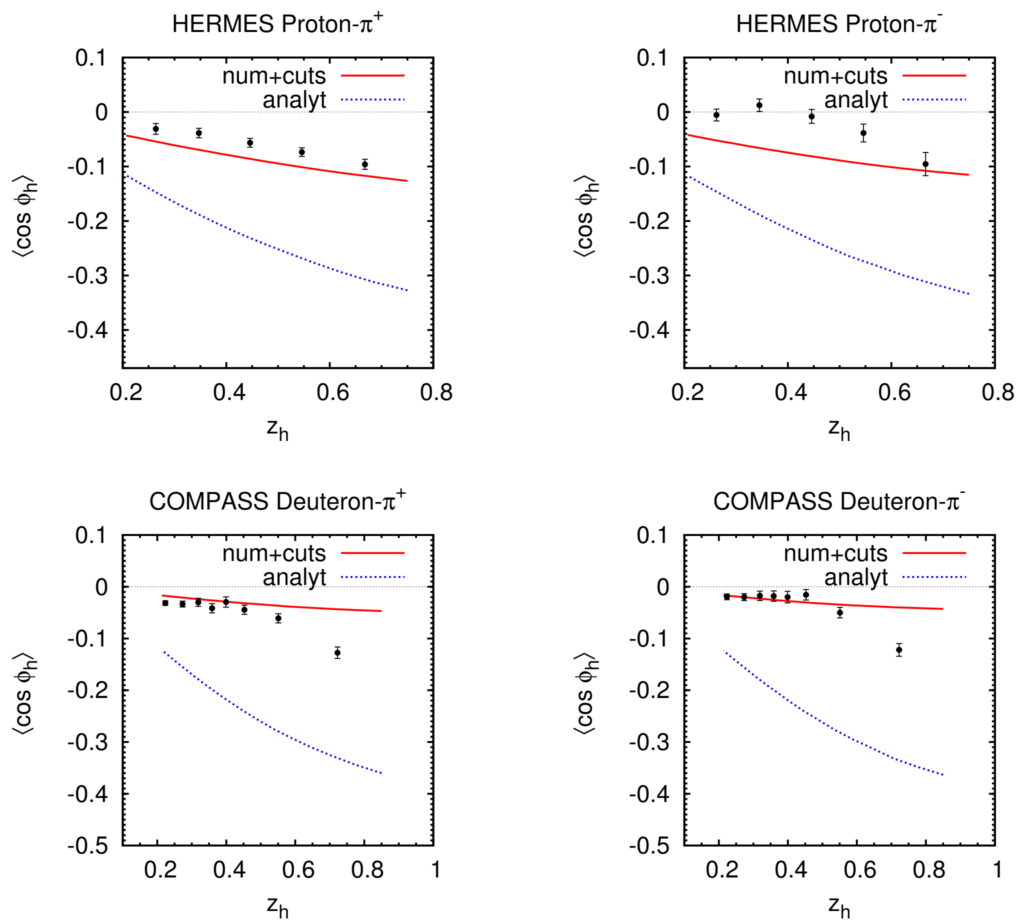
HERMES–COMPASS comparison

[Sbrizzai, Ph.D. Thesis (2011)]





$\mathbf{k}_\perp$ cuts Vs. $\left\{ \begin{array}{l} \text{No cuts (but exp. } \mathbf{P}_{h\perp}^2 \text{ range)} \\ \text{Relation } \overline{\mathbf{p}_\perp^2} + z_h^2 \overline{\mathbf{k}_\perp^2} \end{array} \right.$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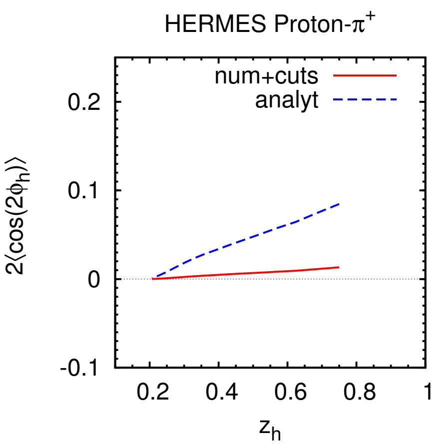
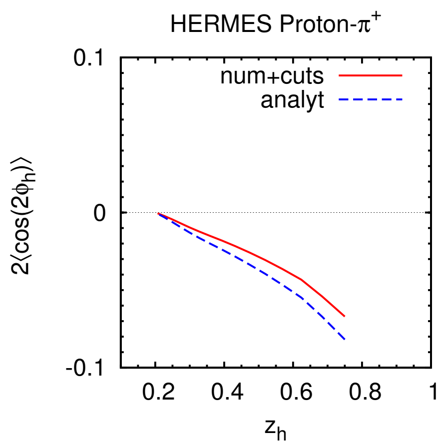


Cahn



Boer-Mulders