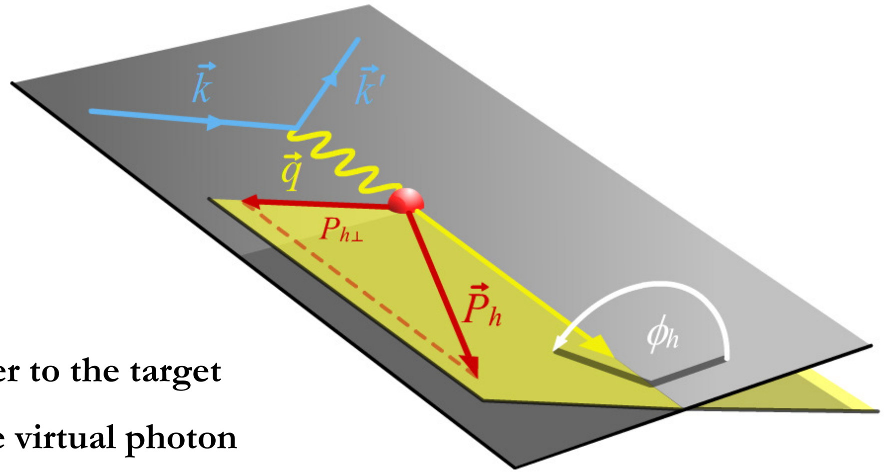
HERMES results on azimuthal modulations in the spin-independent SIDIS cross section

Madrid, DIS 2009

Francesca Giordano
DESY, Hamburg

For the hermes collaboration

Unpolarized Semi-Inclusive DIS



Q^2 **Negative square four-momentum transfer to the target**

y **Fractional energy of the virtual photon**

x **Bjorken scaling variable**

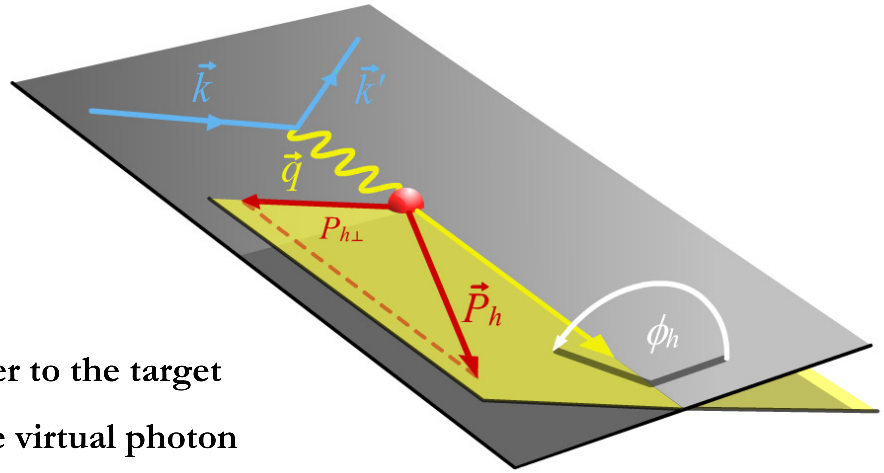
z **Fractional energy transfer to the produced hadron**

Collinear approximation

$$\frac{d^3\sigma}{dx\ dy\ dz} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\left\{A(y)\ F_{UU,T} + B(y)\ F_{UU,L}\right\}$$

$$F_{...} = F_{...}(x, y, z)$$

Unpolarized Semi-Inclusive DIS



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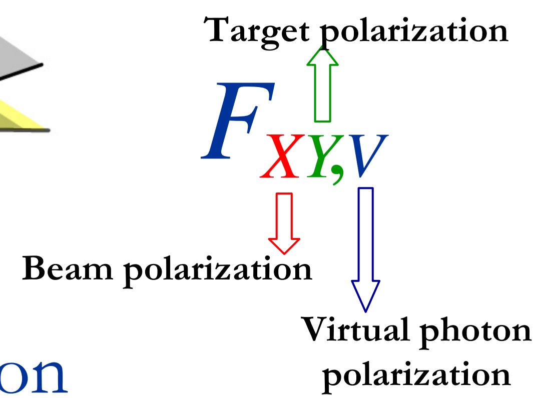

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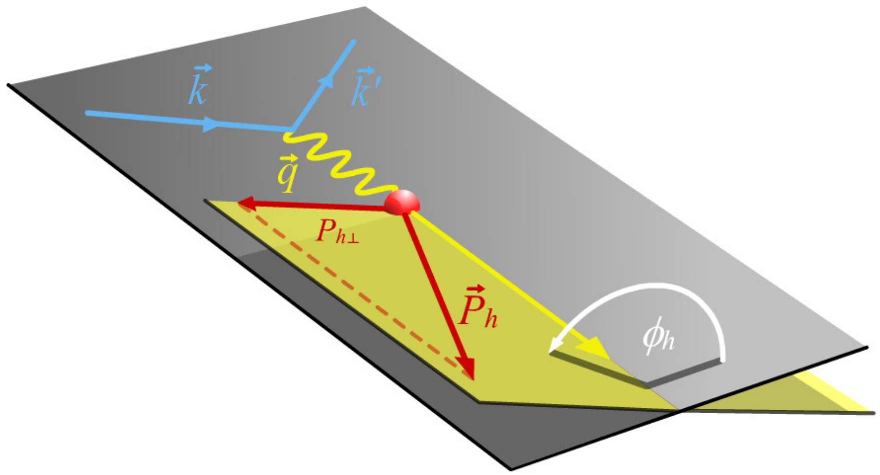
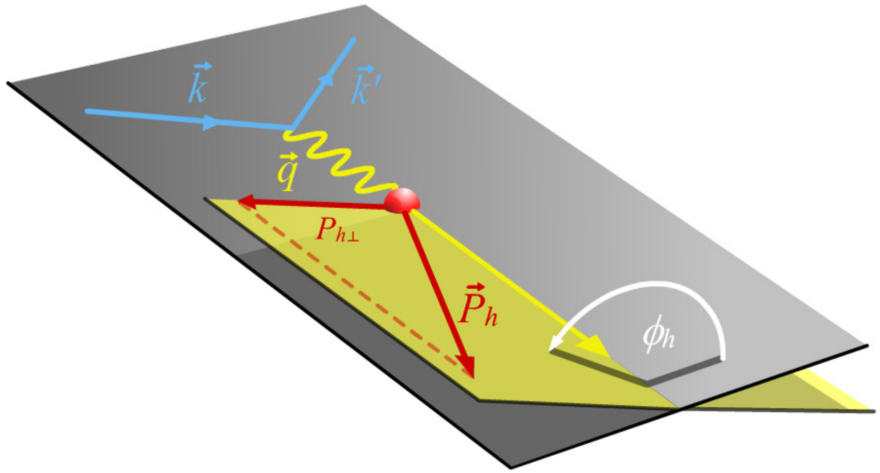


$$\frac{d^5\sigma}{dx\ dy\ dz\ d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\Big\{A(y)\ F_{UU,T} + B(y)\ F_{UU,L}$$

$$+C(y)\ \cos\phi_h\, F_{UU}^{\cos\phi_h} + B(y)\ \cos 2\phi_h\ F_{UU}^{\cos 2\phi_h}\Big\}$$

$$F_{...} = F_{...}(x, y, z, P_{h\perp})$$

Unpolarized Semi-Inclusive DIS



$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\Big\{A(y)\;F_{UU,T} + B(y)\;F_{UU,L}$$

$$+C(y)\;\cos\phi_h\,F_{UU}^{\cos\phi_h} + B(y)\;\cos 2\phi_h\;F_{UU}^{\cos 2\phi_h}\Big\}$$

$$\langle\cos n\phi_h\rangle(x,y,z,P_{h\perp}) = \frac{\int \cos n\phi_h\,\sigma^{(5)}\,d\phi_h}{\int \sigma^{(5)}\,d\phi_h}$$

Leading twist expansion

FF

$$F_{UU,T} \propto C\left[f_1 D_1\right]$$

DF

Leading twist expansion

Distribution Functions (DF)			
N / q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

Fragmentation Functions (FF)	
q/h	U
U	D_1
T	$H_1^\perp$

$$F_{UU,T} \propto C\left[f_1 D_1\right]$$

FF (D_1)

DF (f_1)

Leading twist expansion

Distribution Functions (DF)			
N / q	U	L	T
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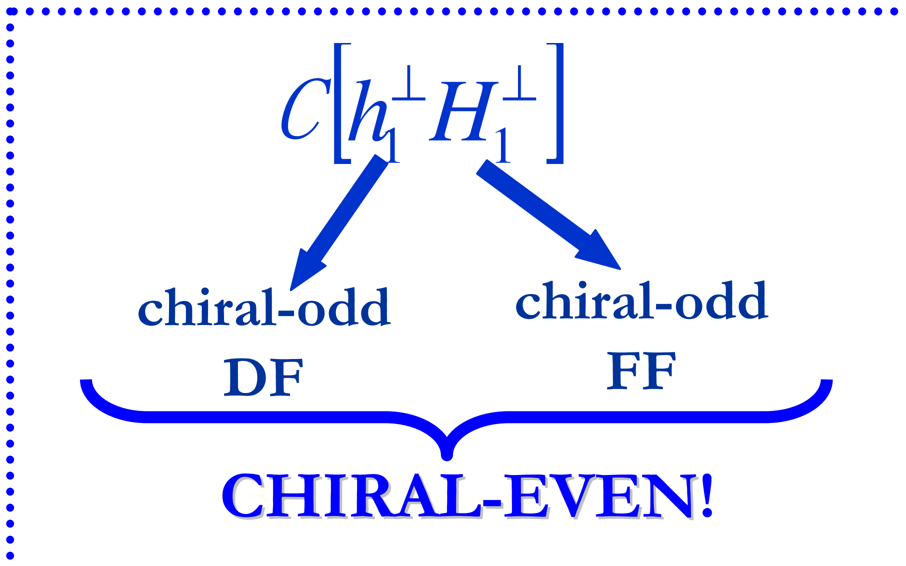
Fragmentation Functions (FF)	
q/h	U
U	D_1
T	$H_1^\perp$

$h_1^\perp$ = **Boer-Mulders function**

CHIRAL-ODD



Leading twist azimuthal modulation

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

(Implicit sum over quark flavours)

Leading & next to leading twist azimuthal modulation

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

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

...neglecting interaction dependent terms....

(Implicit sum over quark flavours)

Cahn and Boer-Mulders effects

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

CAHN EFFECT

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

Cahn and Boer-Mulders effects

BOER-MULDERS EFFECT

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

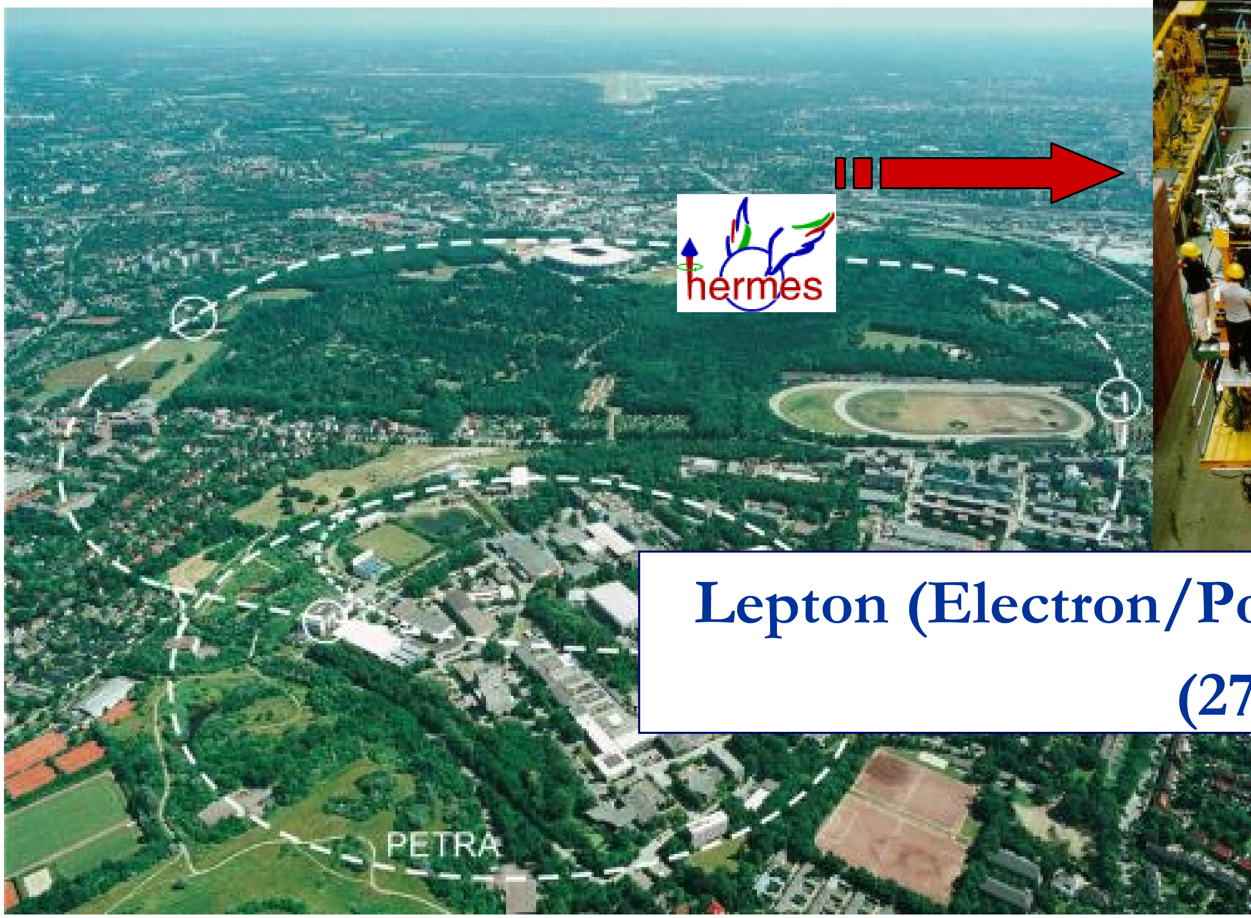
CAHN EFFECT

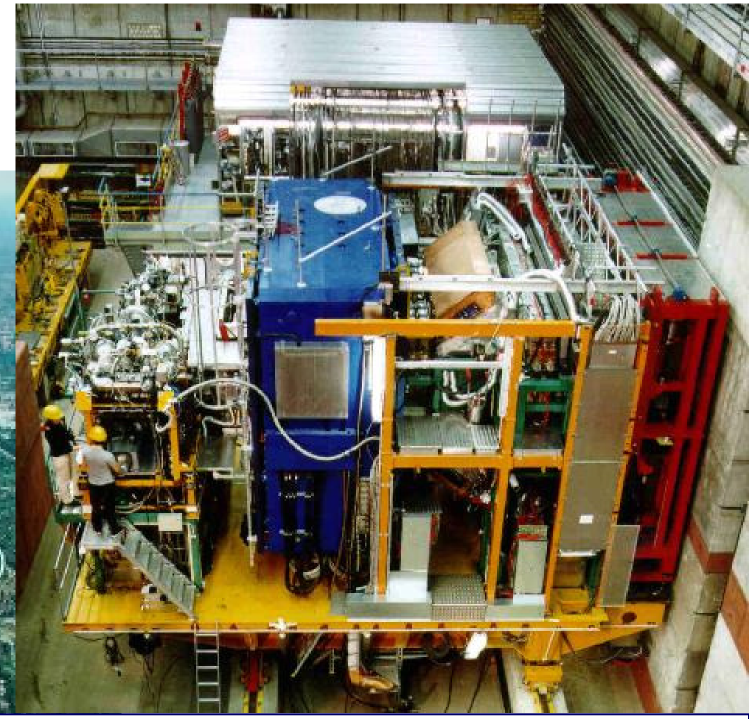
$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q} C\left[-\frac{\widehat{P}_{h\perp}\cdot\vec{p}_T}{M_h} x\, h_1^{\perp} H_1^{\perp} - \frac{\widehat{P}_{h\perp}\cdot\vec{k}_T}{M} x\, f_1 D_1 + \ldots \right]$$

HERa MEasurement of Spin

HERA storage ring @ DESY

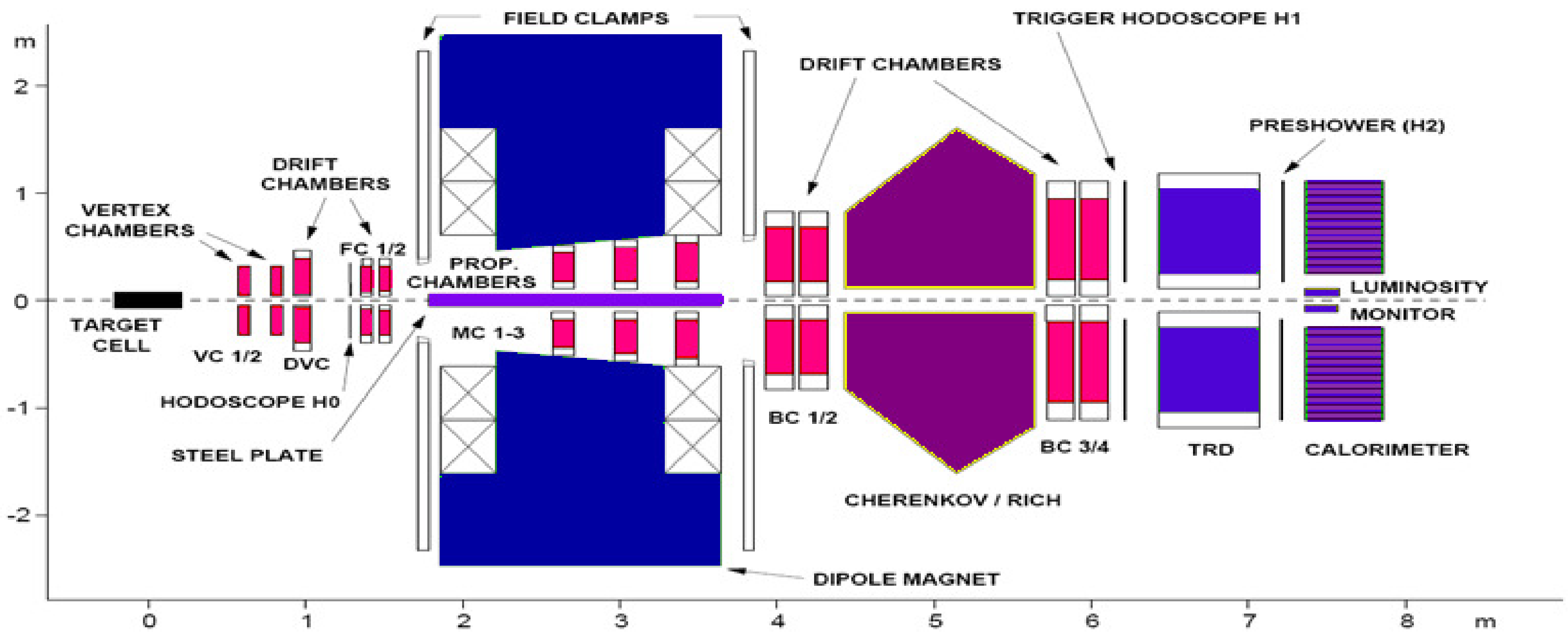
HERa MEasurement of Spin





Lepton (Electron/Positron) HERA beam (27.6 GeV)

HERMES spectrometer

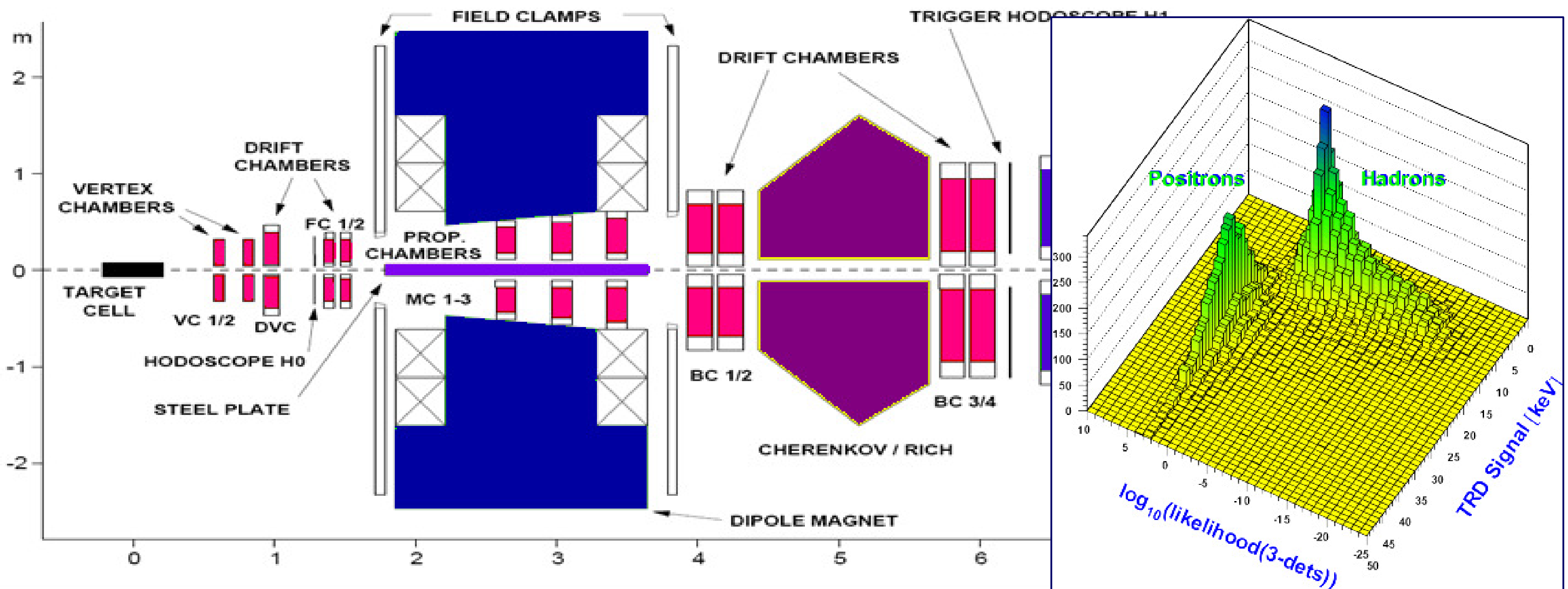


Resolution: $\Delta p/p \sim$ 1-2% $\Delta\theta$ <~0.6 mrad

Electron-hadron separation efficiency ~ 98-99%

Hadron identification with dual-radiator RICH

HERMES spectrometer



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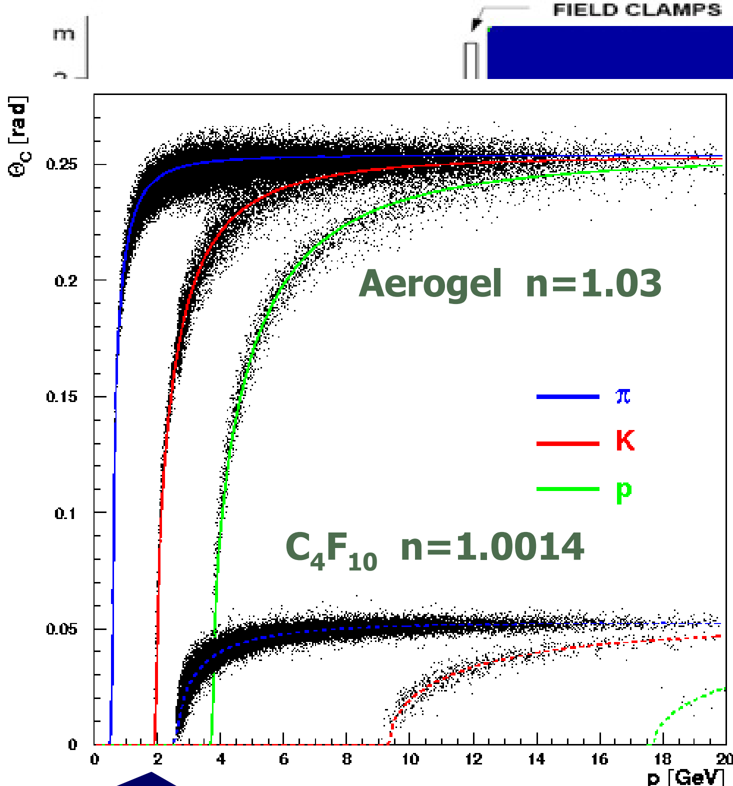

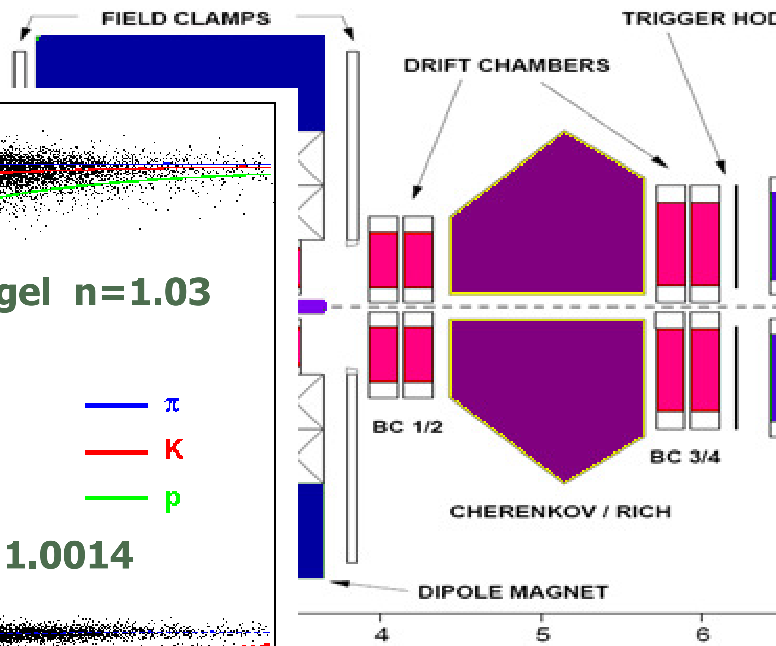

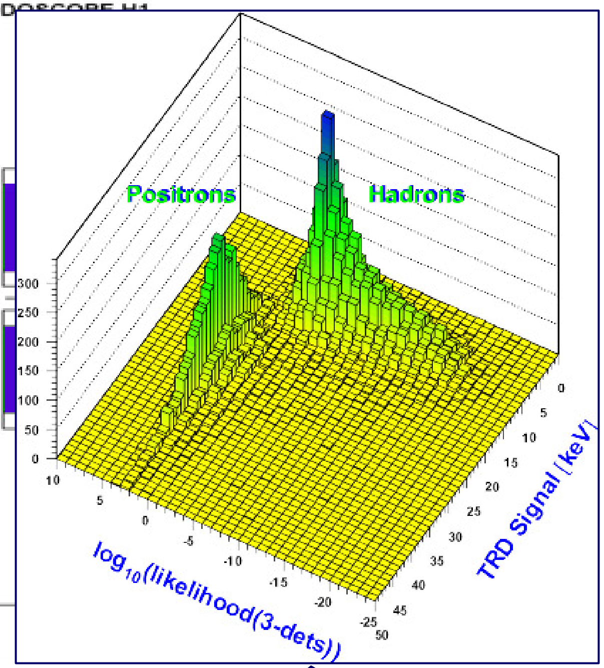

/p ~ 1-2% Δθ <~0.6 mrad

Electron-hadron separation efficiency ~ 98-99%

Hadron identification with dual-radiator RICH

Experimental extraction

$$n^{EXP} = \int \sigma_0(w) \left[1 + A(w)\ \cos\phi_h + B(w)\ \cos 2\phi_h\right] L\, dw$$

$$w = (x, y, z, P_{h\perp})$$

$$A = 2\left\langle \cos\ \phi_h \right\rangle$$

$$B = 2\left\langle \cos\ 2\phi_h \right\rangle$$

Experimental extraction

$$n^{EXP} = \int \sigma_0(w)\ \left[1 + A(w)\cos\phi_h + B(w)\cos 2\phi_h\right]\ \varepsilon_{acc}(w,\phi_h)\varepsilon_{RAD}(w,\phi_h)\ L\ dw$$

$$w = (x, y, z, P_{h\perp})$$

Experimental extraction

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unfolding procedure

Experimental extraction

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$$w = (x, y, z, P_{h\perp})$$

Multidimensional (w)
unfolding procedure

The unfolding procedure

$$n_{EXP} = S \; n_{BORN} + n_{Bg}$$

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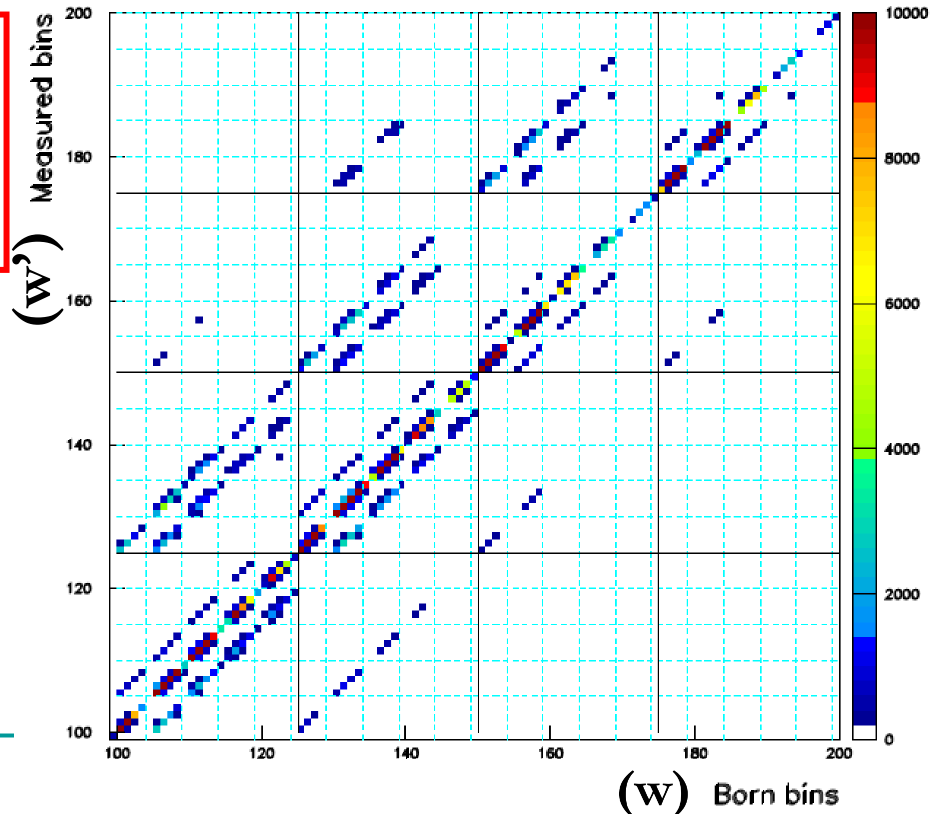
$$n_{EXP} = S \; n_{BORN} + n_{Bg}$$

Probability that an event generated with kinematics w is measured with kinematics w'



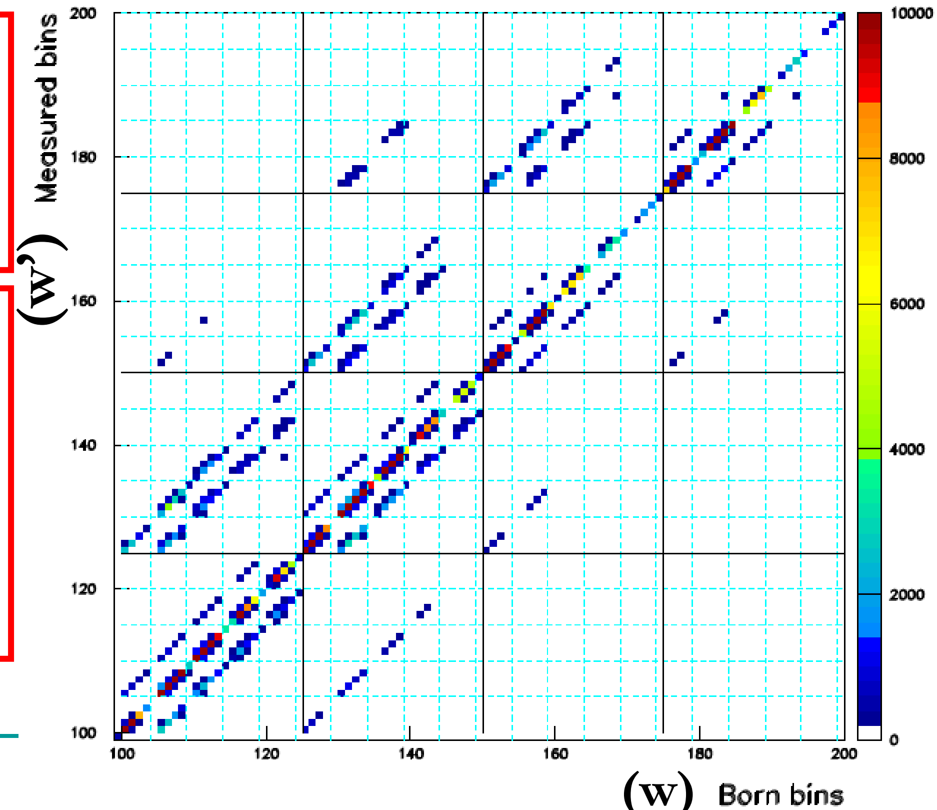
The unfolding procedure

$$n_{EXP} = S \; n_{BORN} + n_{Bg}$$

Probability that an event generated with kinematics w is measured with kinematics w'

Accounts for acceptance, radiative and smearing effects

depends only on instrumental and radiative effects



The unfolding procedure

$$n_{EXP} = S \; n_{BORN} + n_{Bg}$$

Probability that an event generated with kinematics w is measured with kinematics w'

Accounts for acceptance, radiative and smearing effects

➔ depends only on instrumental and radiative effects

Includes the events smeared into the acceptance

The unfolding procedure

$$n_{EXP} = S \; n_{BORN} + n_{Bg}$$

$$n_{BORN} = S^{-1}\left[n_{EXP} - n_{Bg}\right]$$

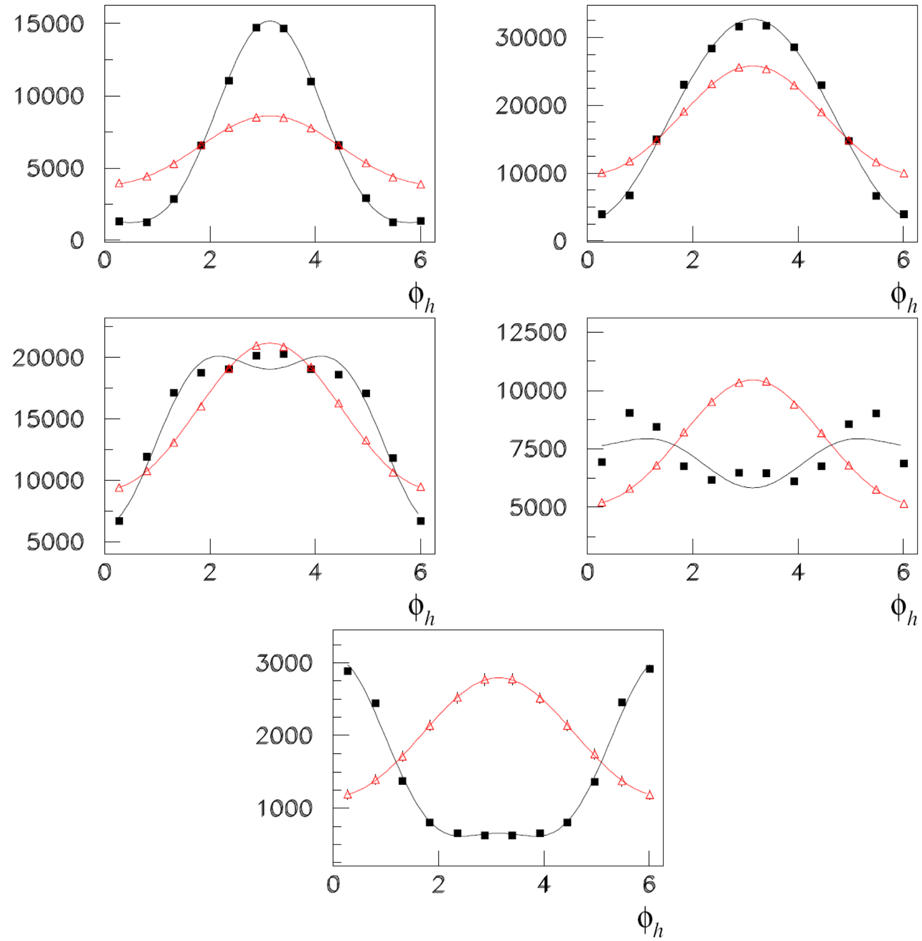
Why a multi-dimensional analysis?

$$n^{MC+Cahn} = \int \sigma_0(w)\ \left[1 + A(w)\cos\phi_h + B(w)\cos 2\phi_h\right]\ \varepsilon_{acc}(w,\phi_h)\varepsilon_{RAD}(w,\phi_h)\ L\ dw$$

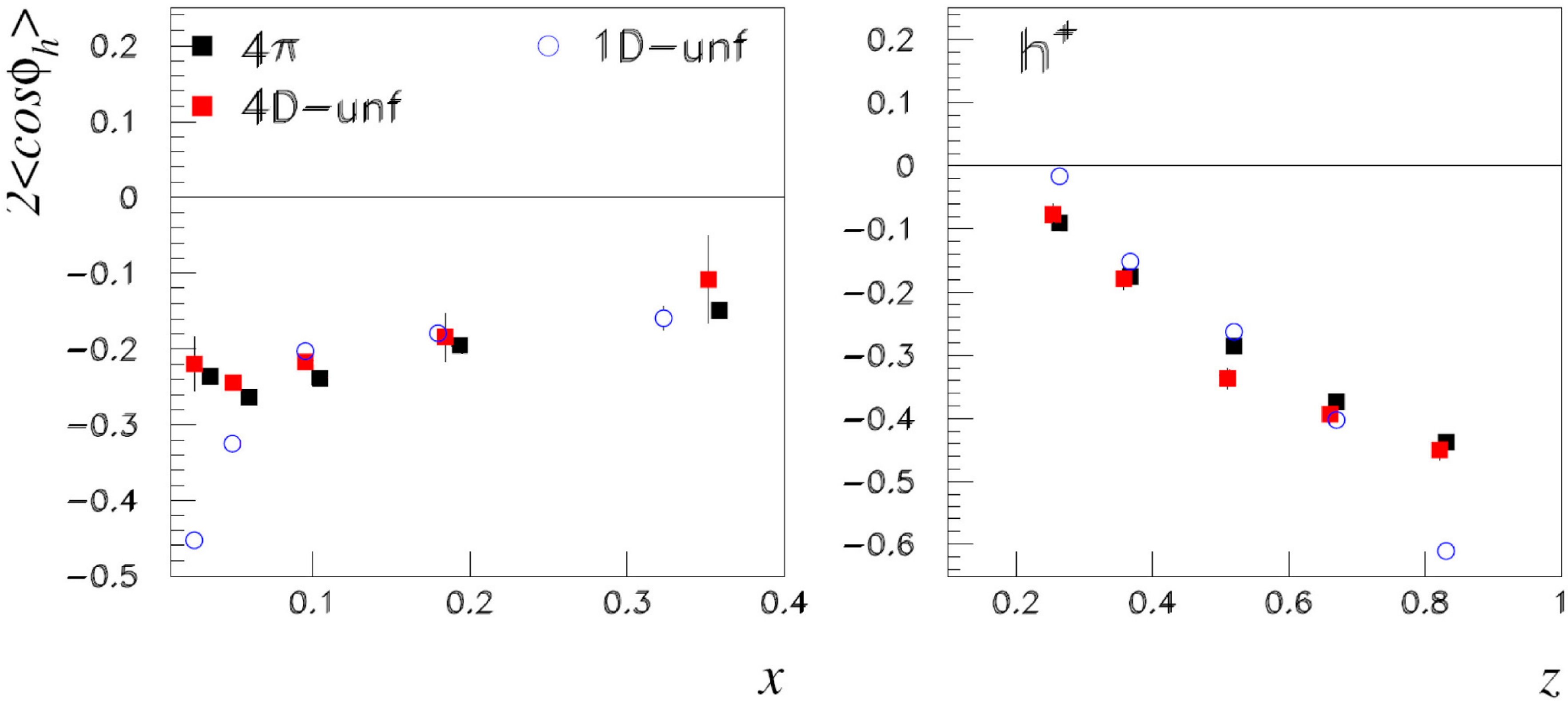
Monte Carlo + Cahn model

Generated in 4π

Measured inside acceptance



Why a multi-dimensional analysis?



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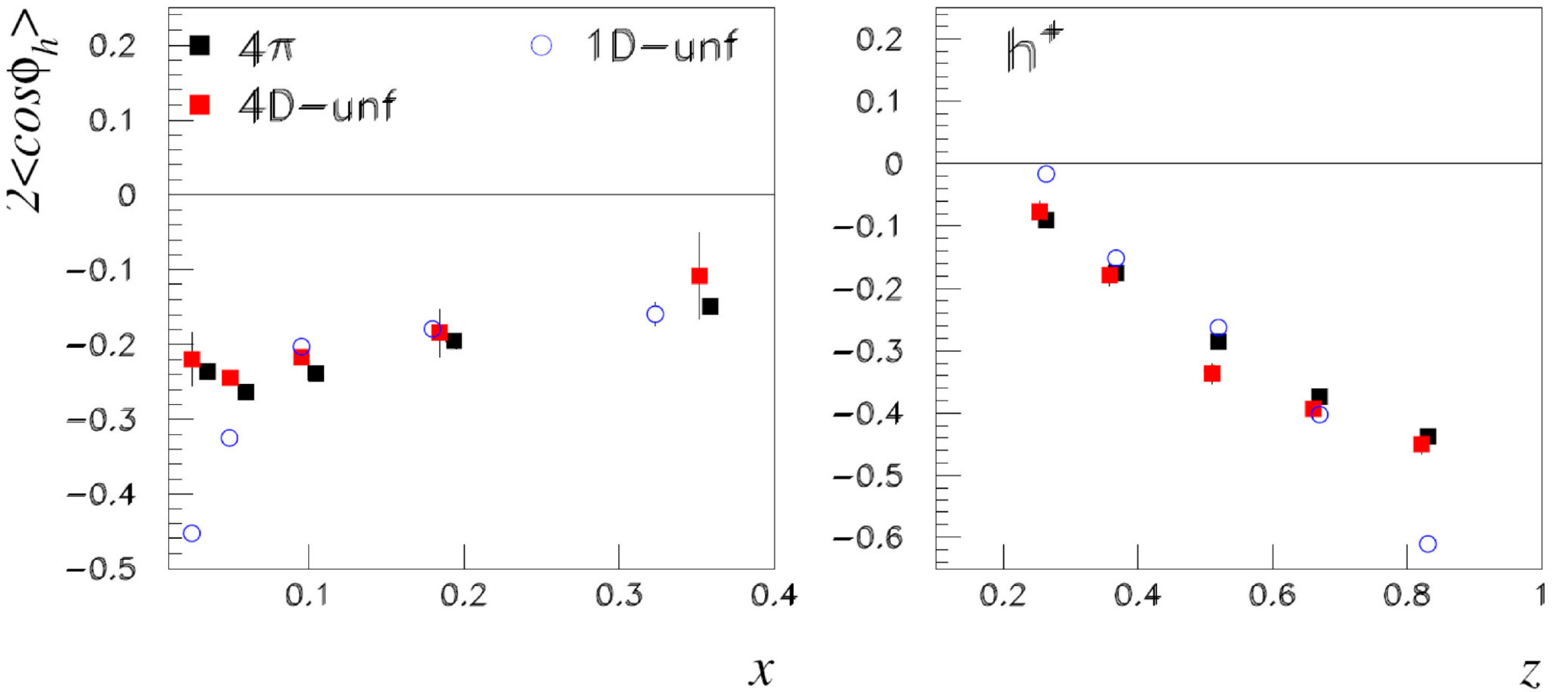
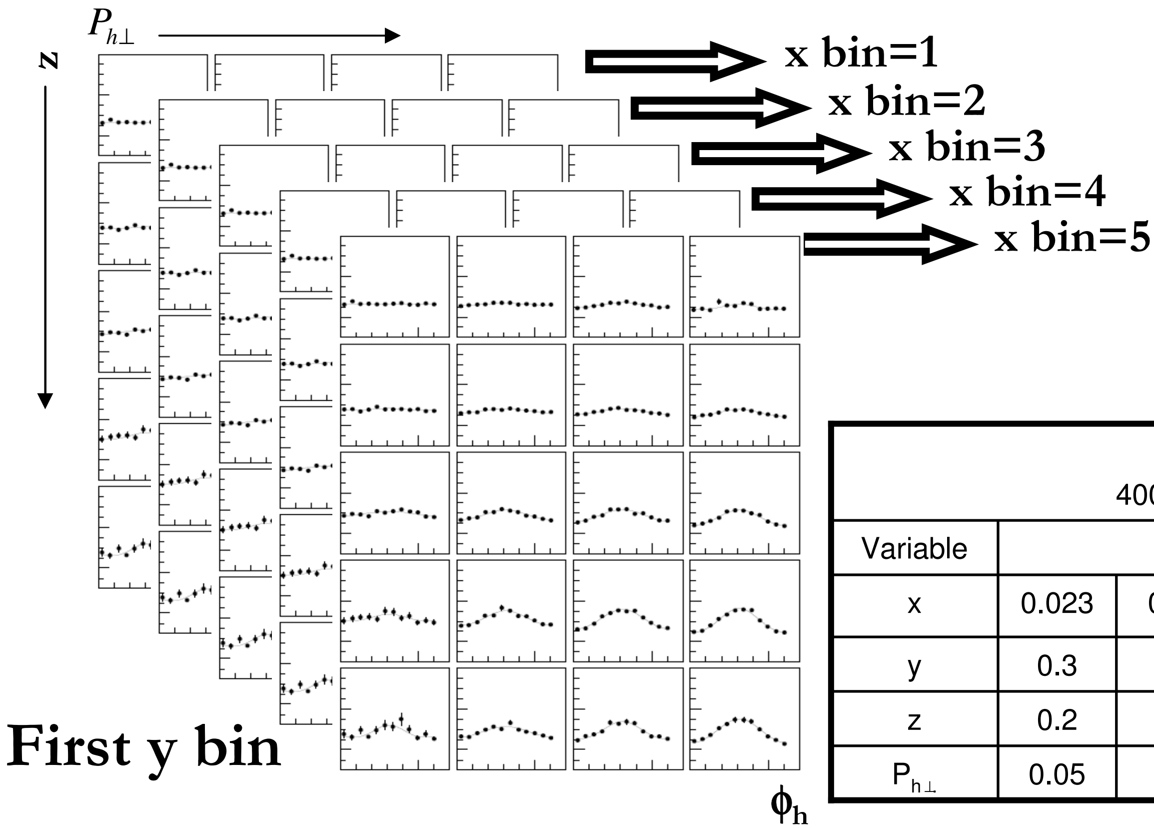


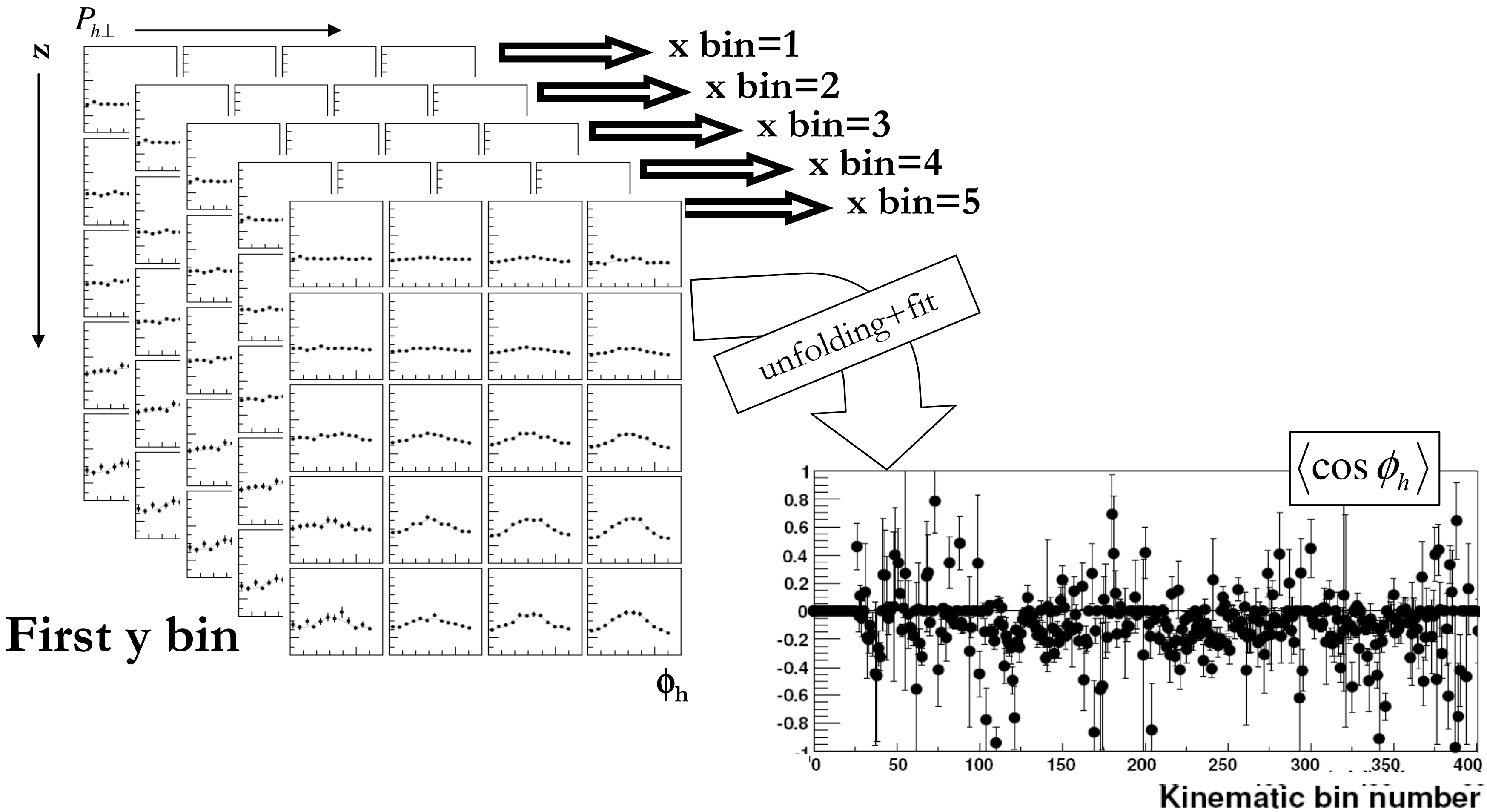
4D ➡ **binned in** $(x, y, z, P_{h\perp})$

The multi-dimensional analysis

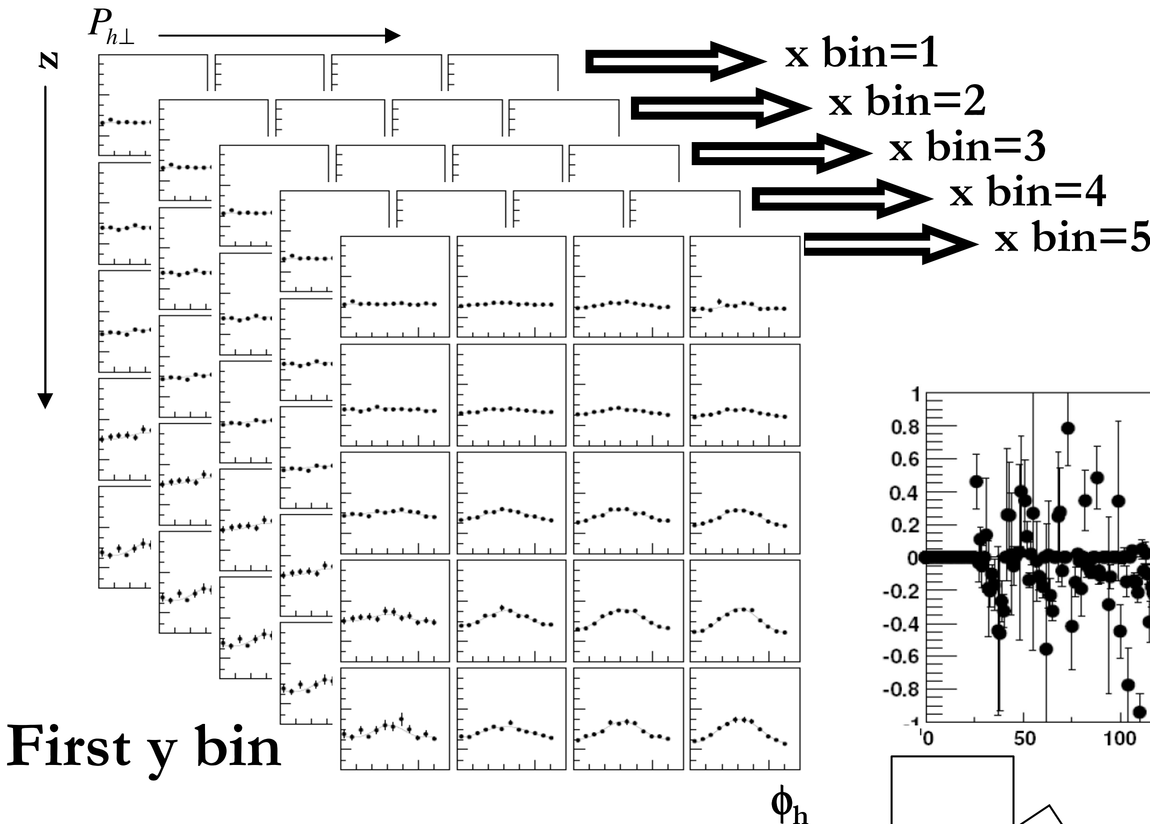


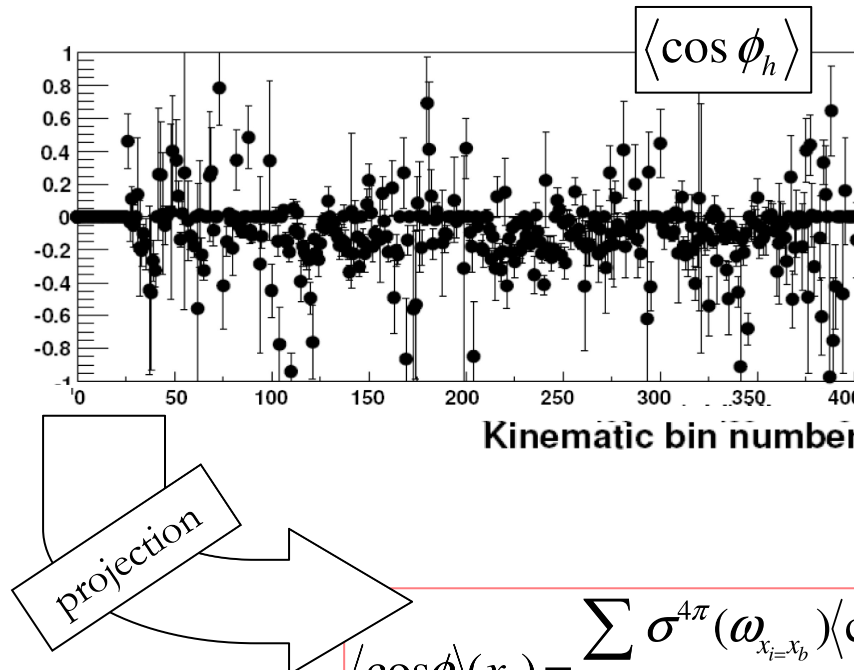
BINNING 400 kinematical bins x 12 ϕ_η-bins							
Variable	Bin limits						#
x	0.023	0.042	0.078	0.145	0.27	1	5
y	0.3	0.45	0.6	0.7	0.85		4
z	0.2	0.3	0.45	0.6	0.75	1	5
$P_{h\perp}$	0.05	0.2	0.35	0.5	0.75		4

The multi-dimensional analysis



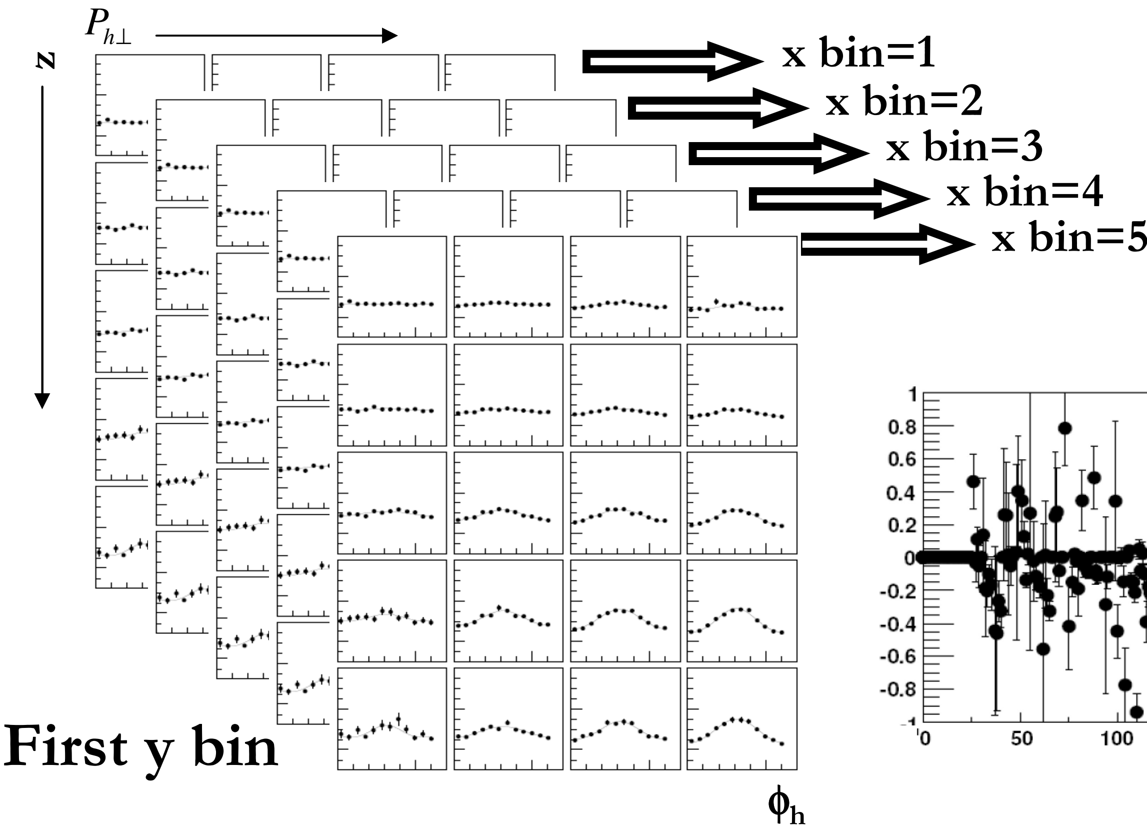
The multi-dimensional analysis

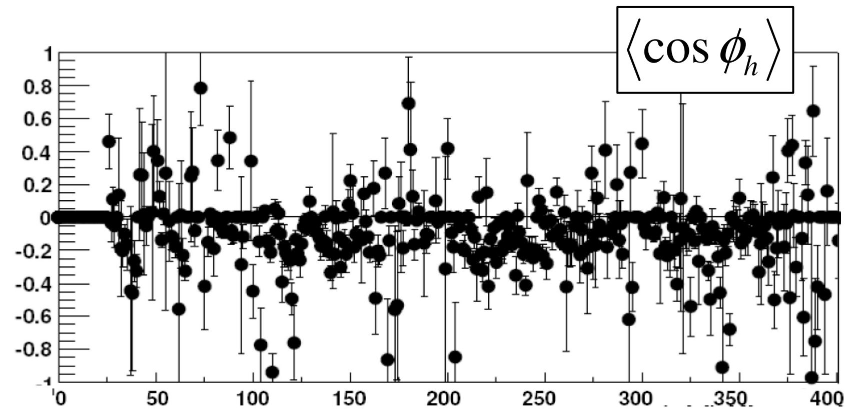




$$\langle \cos\phi \rangle (x_b) = \frac{\sum \sigma^{4\pi}(\omega_{x_i=x_b}) \langle \cos\phi \rangle_{x_i=x_b}}{\sum \sigma^{4\pi}(\omega_{x_i=x_b})}$$

The multi-dimensional analysis



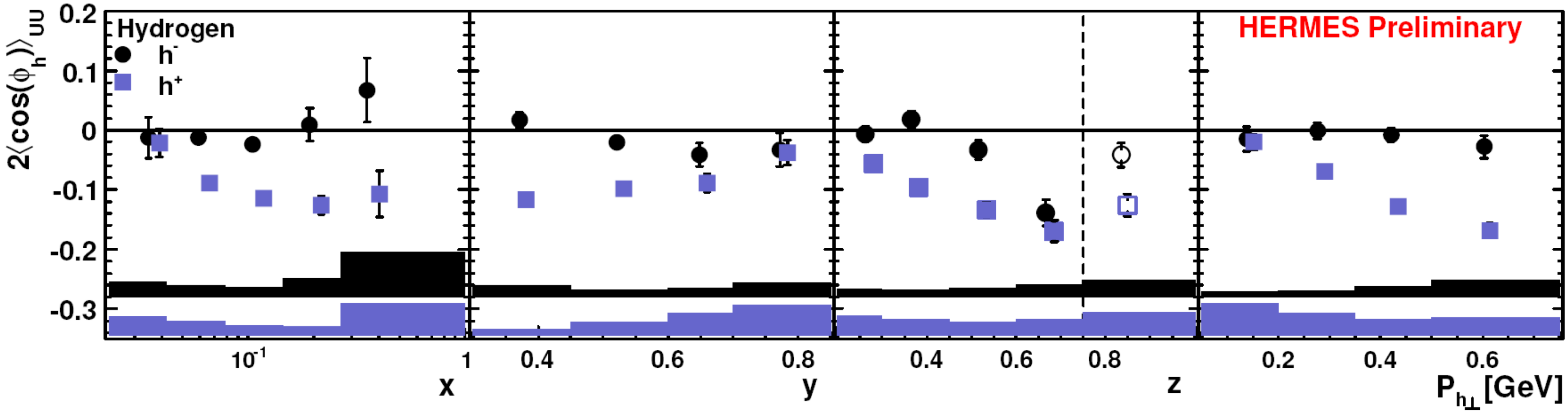


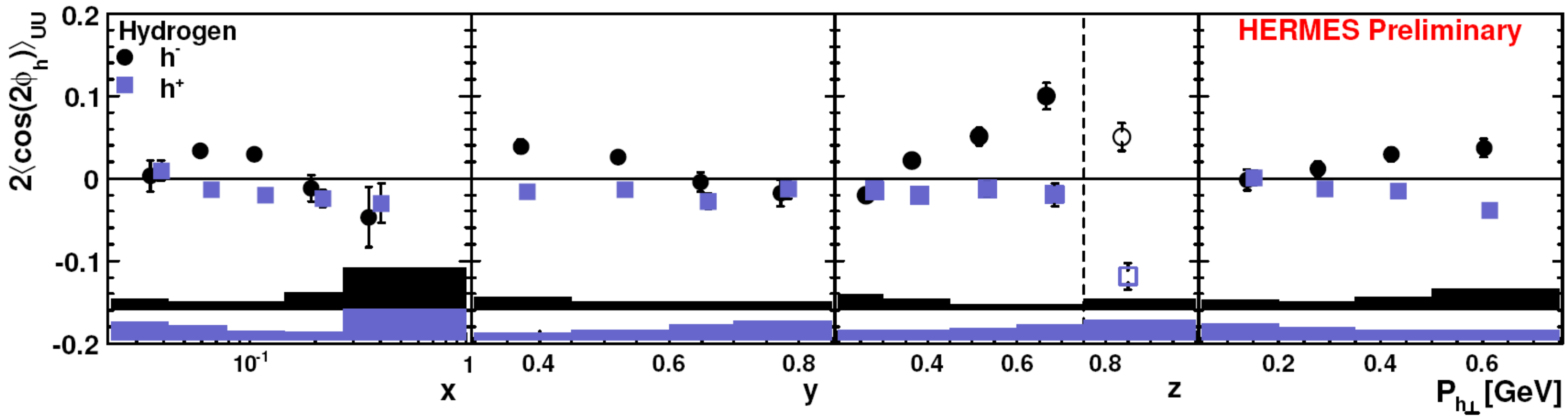
$$\langle \cos\phi \rangle (x_b) = \frac{\sum \sigma^{4\pi}(\omega_{x_i=x_b}) \langle \cos\phi \rangle_{x_i=x_b}}{\sum \sigma^{4\pi}(\omega_{x_i=x_b})}$$

$$\langle \cos\phi \rangle (x_b) \approx \frac{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{4\pi}(\omega_{x_i=x_b}) \langle \cos\phi \rangle_{x_i=x_b}}{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{4\pi}(\omega_{x_i=x_b})}$$

Results

Hydrogen data





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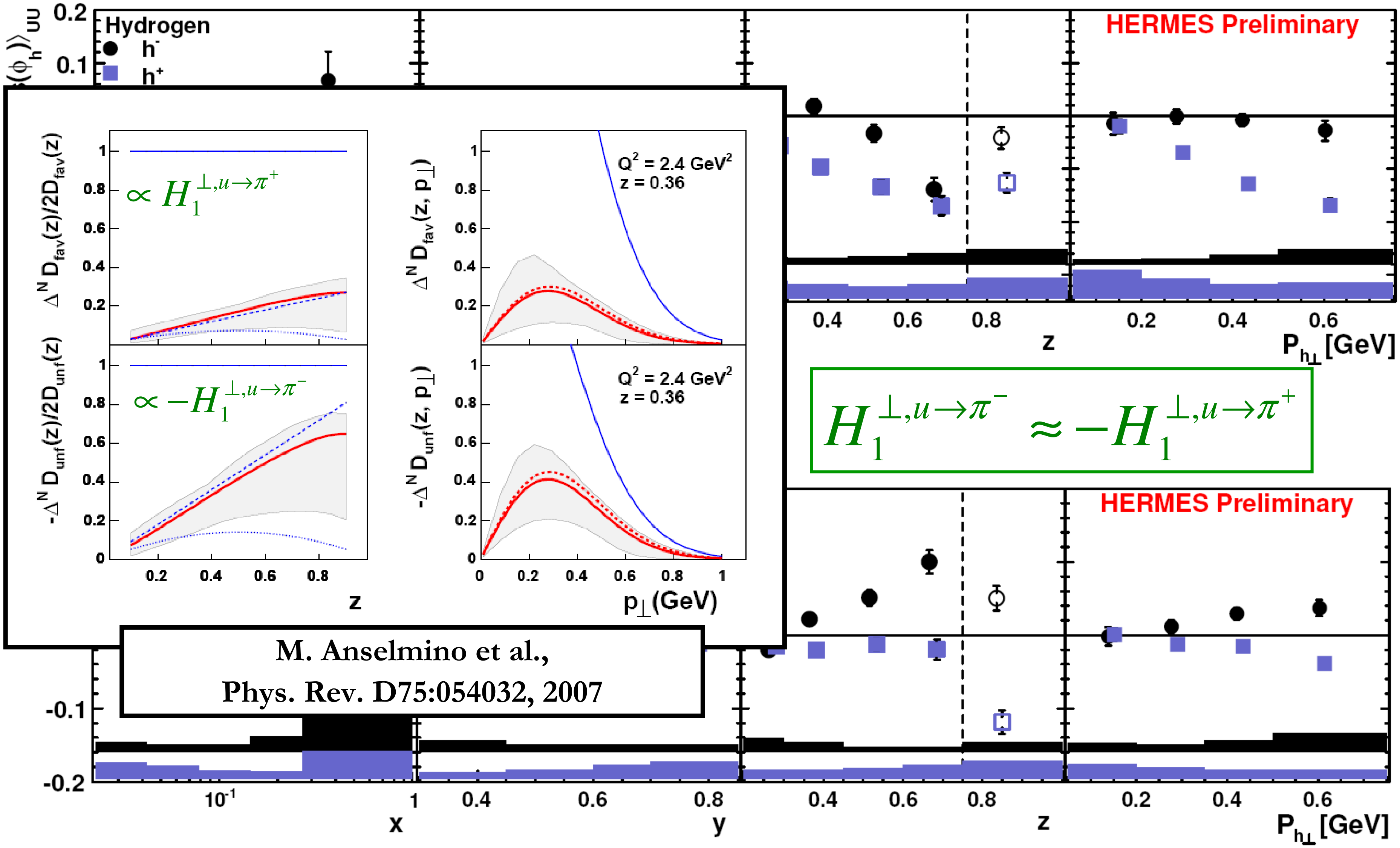
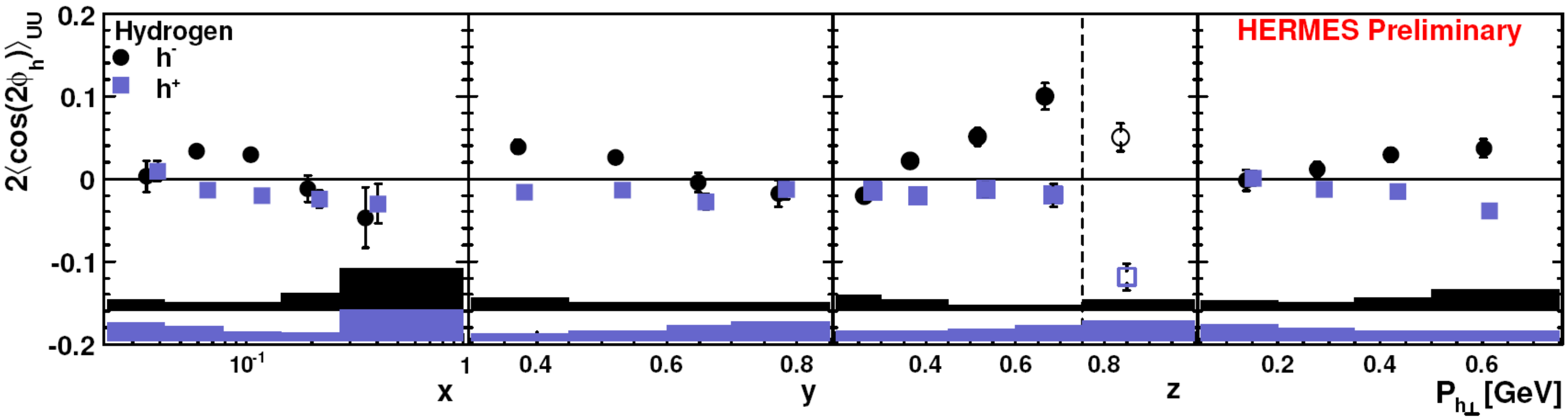


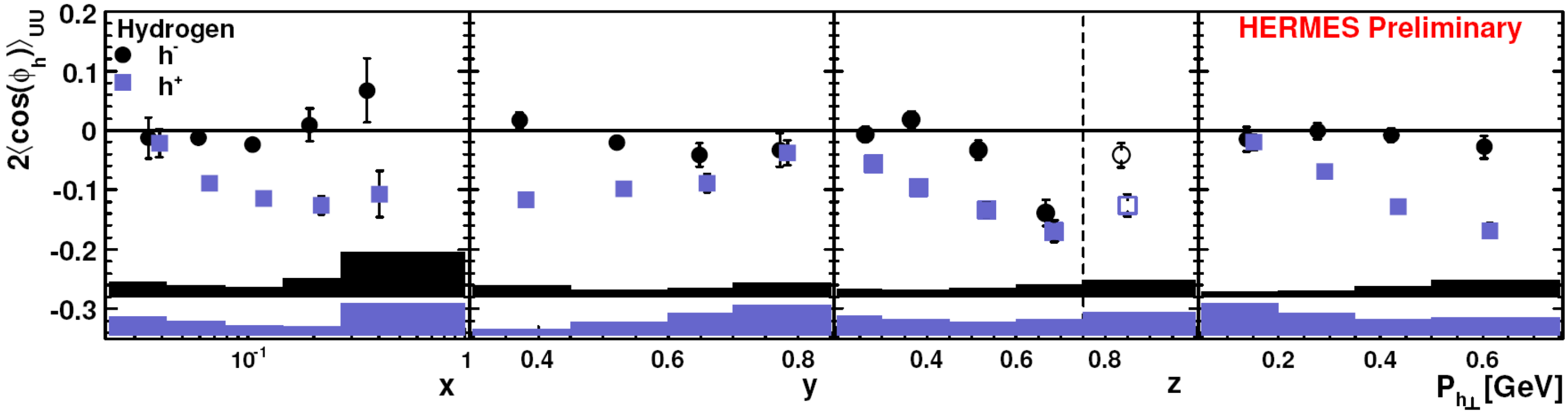
Hydrogen data

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

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



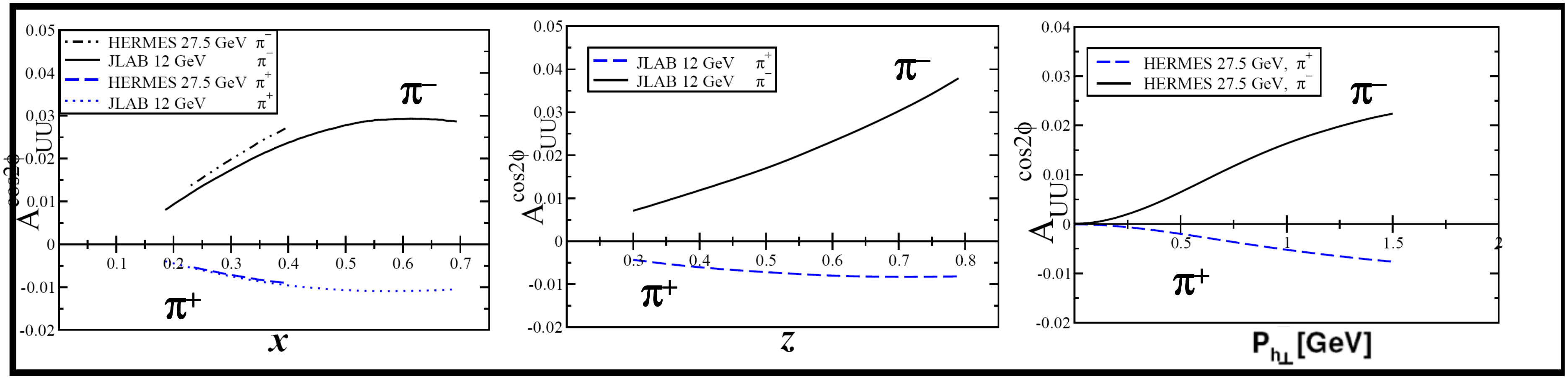
Hydrogen data



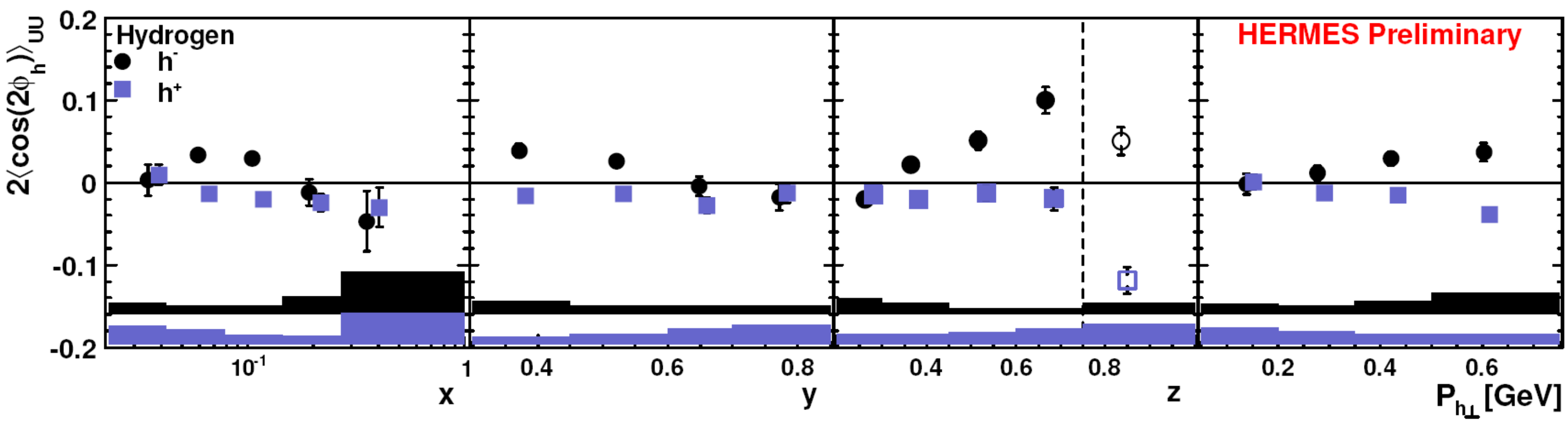
$$H_1^{\perp,u\to\pi^-} \approx -H_1^{\perp,u\to\pi^+}$$

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

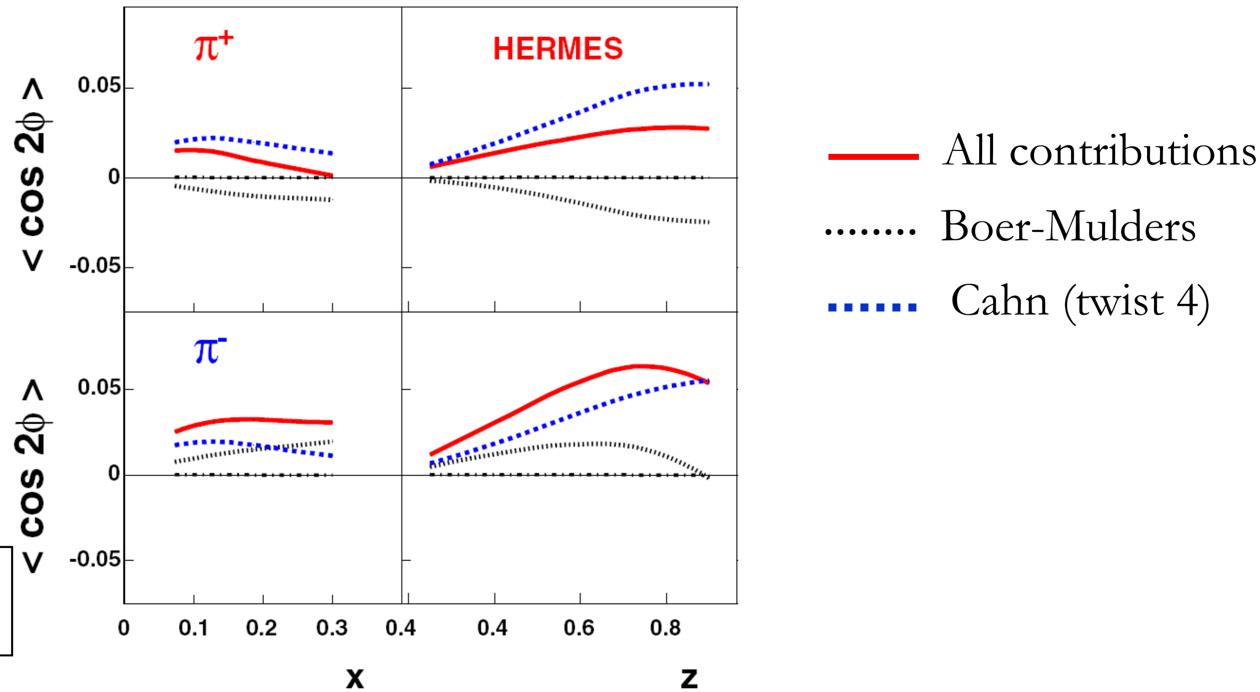
$\cos 2\phi_h$ interpretation



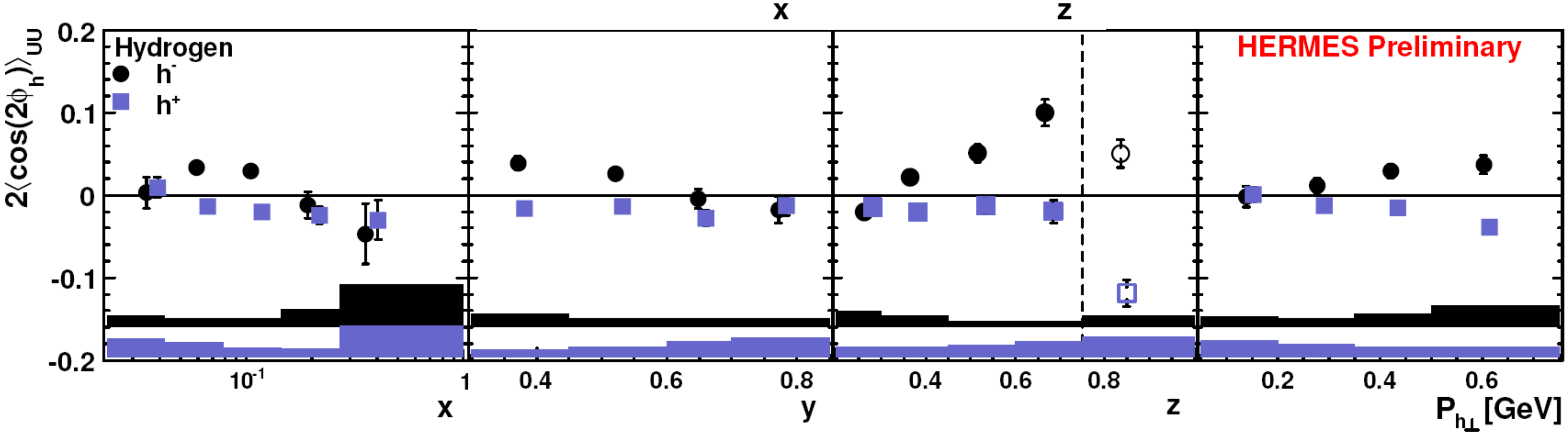
L. P. Gamberg and G. R. Goldstein,
Phys. Rev. D77:094016, 2008



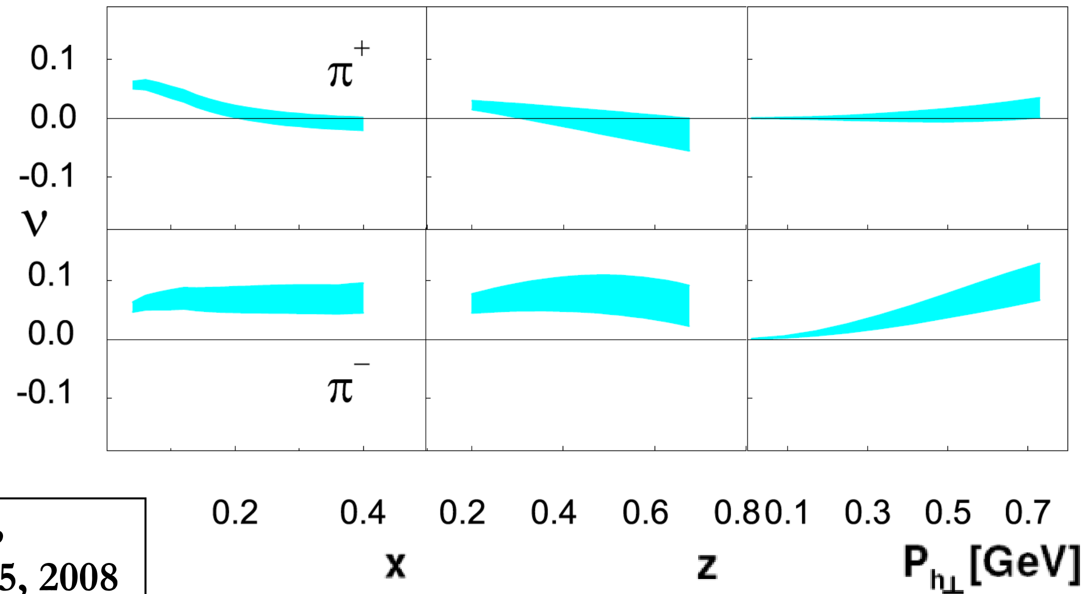
cos2ϕ_h interpretation



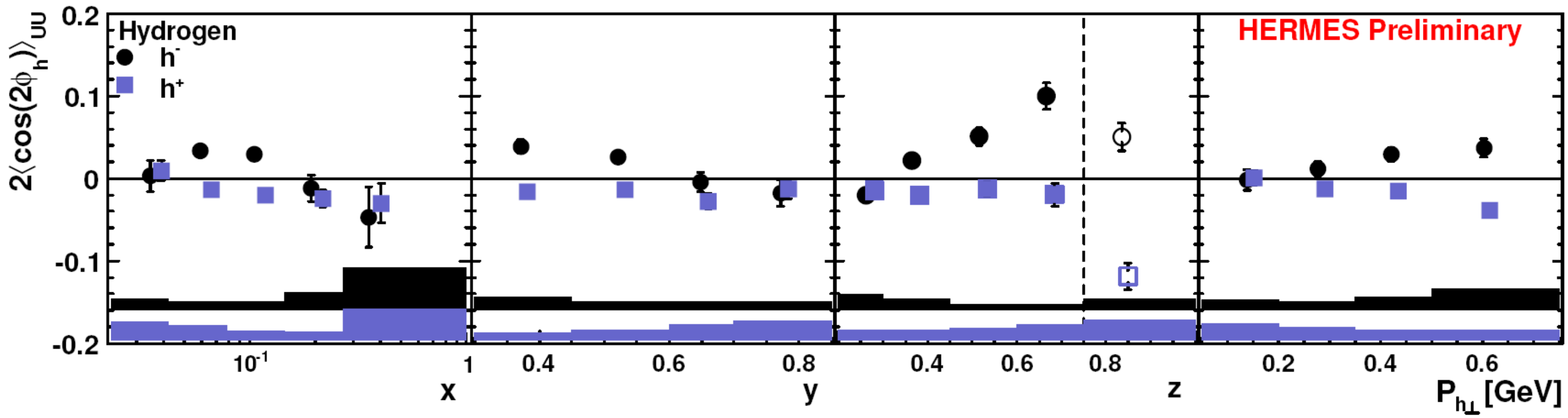
V. Barone et al.
Phys.Rev. D78:045022, 2008



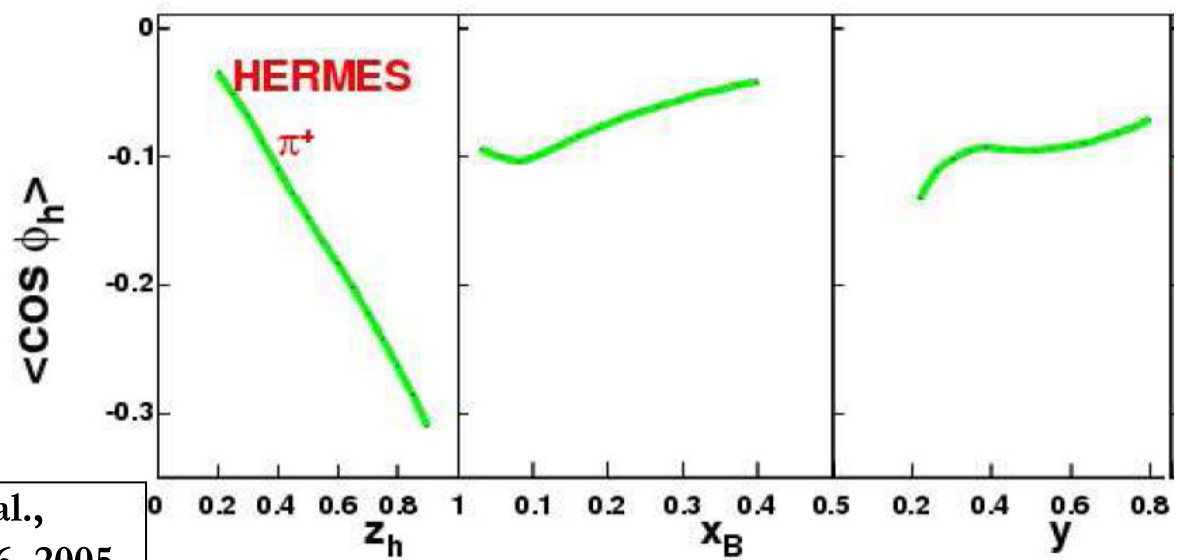
$\cos 2\phi_h$ interpretation



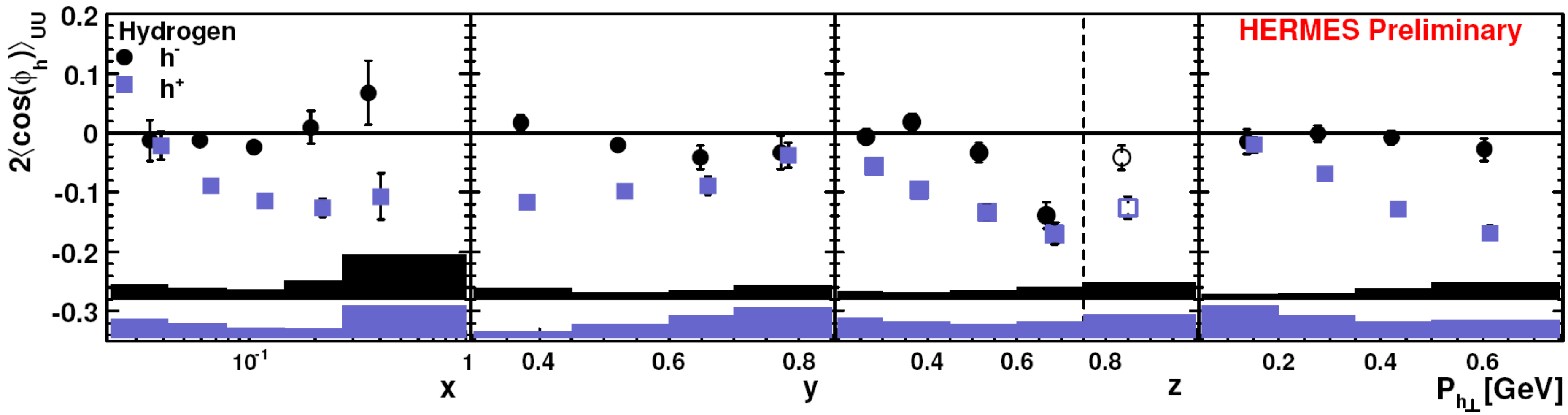
B. Zhang et al.,
Phys. Rev. D78:034035, 2008



$\cos\phi_h$ interpretation

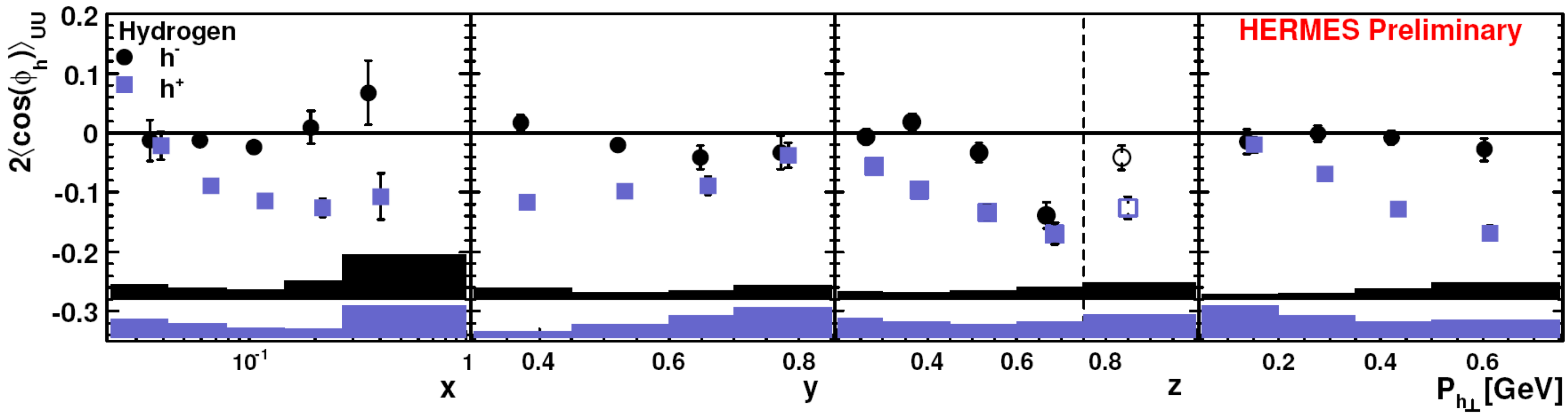


M. Anselmino et al.,
Phys. Rev. D71:074006, 2005
Eur. Phys. J. A31:373, 2007

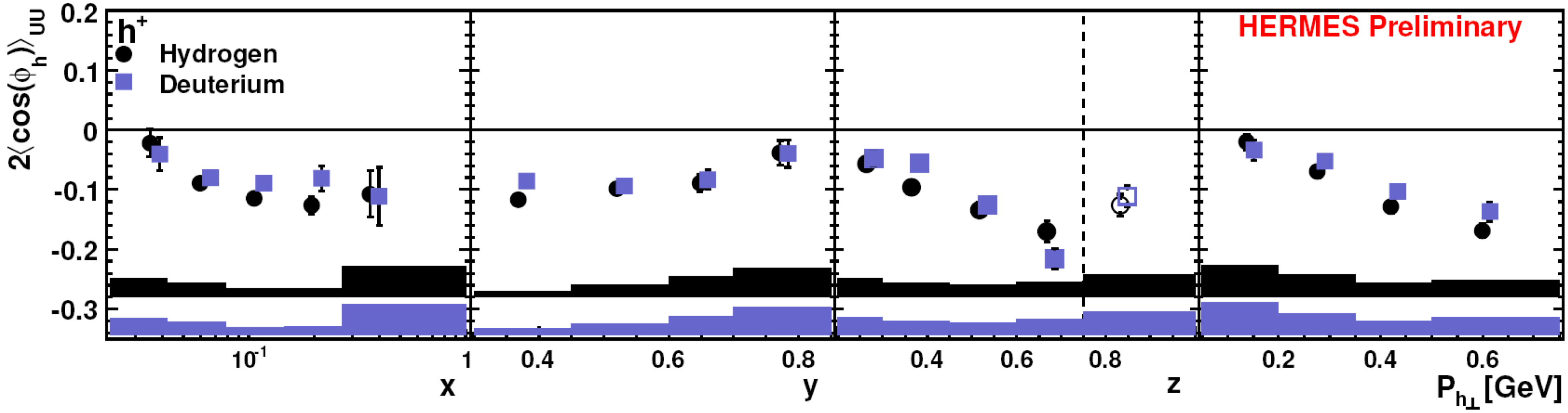


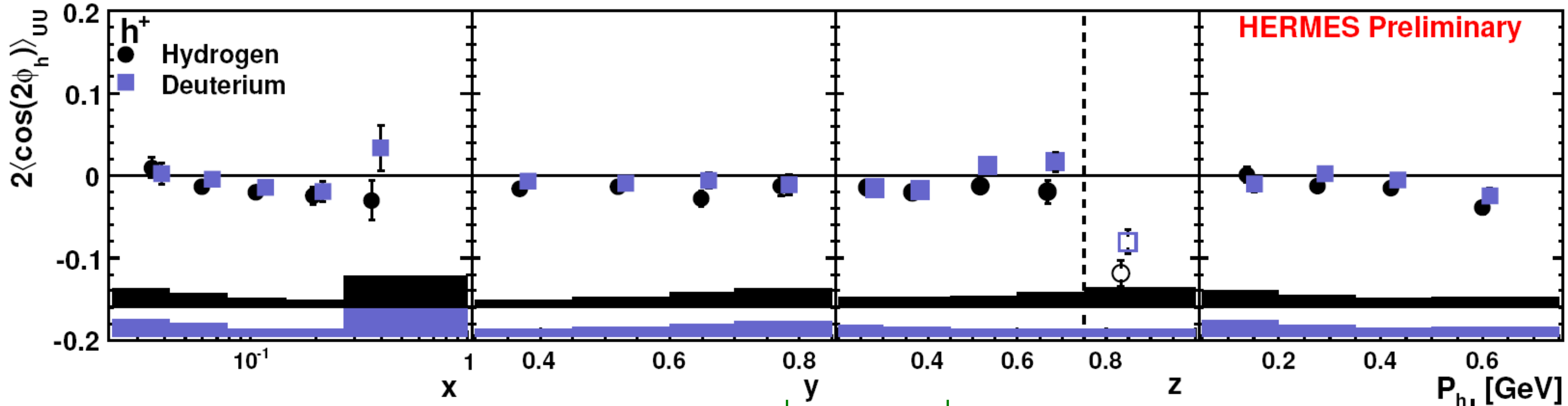
$\cos\phi_h$ interpretation

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



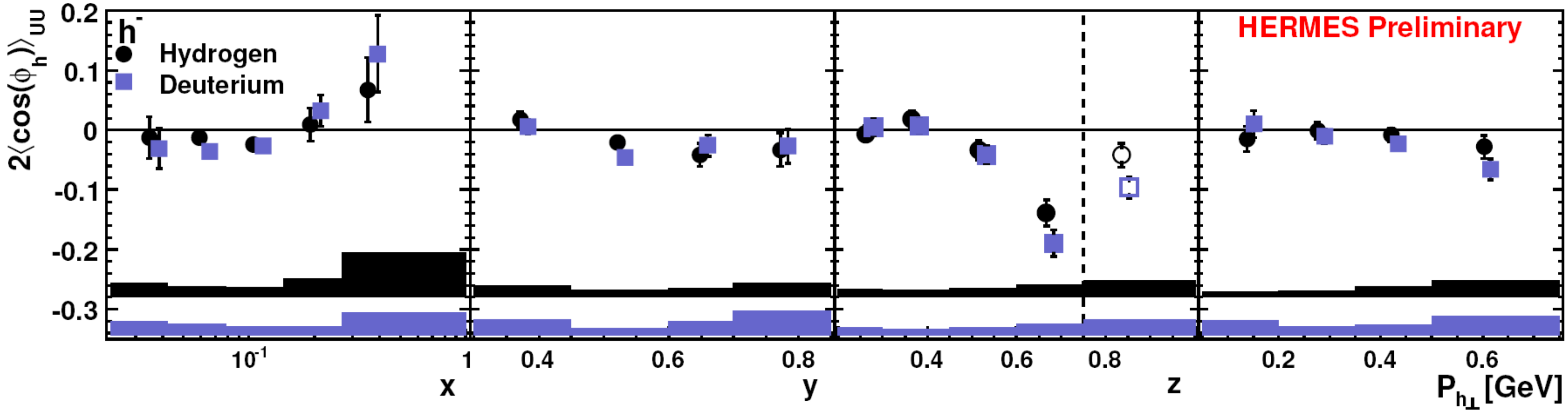
Hydrogen vs. Deuterium data h^+

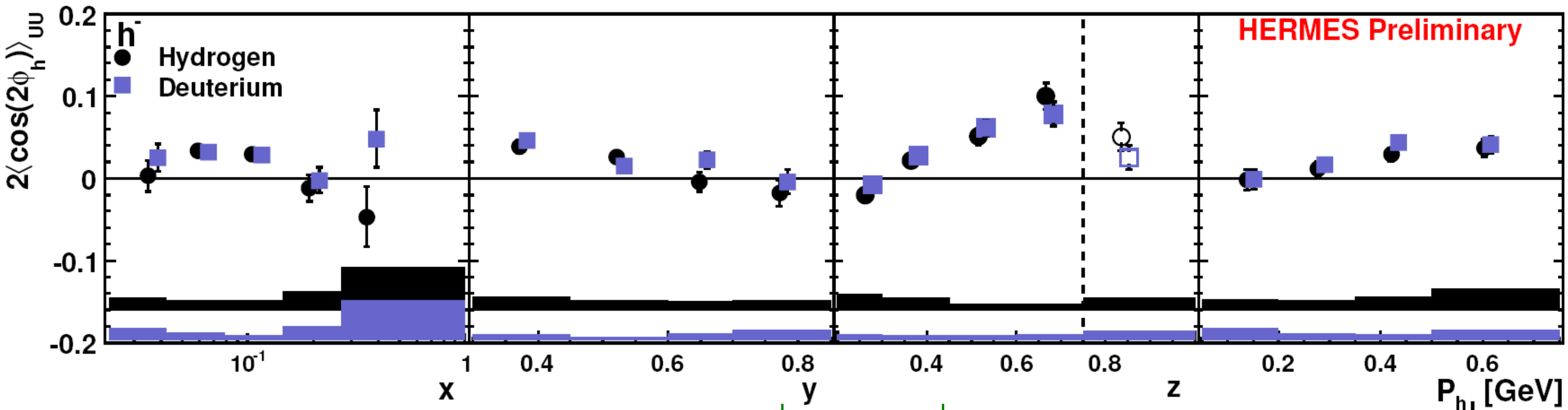




$$h_{1,u}^{\perp} \approx h_{1,d}^{\perp}$$

Hydrogen vs. Deuterium data h^-





$$h_{1,u}^{\perp} \approx h_{1,d}^{\perp}$$

Summary

- The existence of an intrinsic **quark transverse motion** gives origin to an azimuthal asymmetry in the hadron production direction:
  - **Cahn effect**: an (higher twist) azimuthal modulation related to the existence of intrinsic quark motion;
  - **Boer-Mulders effect**: a leading twist asymmetry originated from the correlation between the quark transverse motion and transverse spin (a kind of *spin-orbit effect*).

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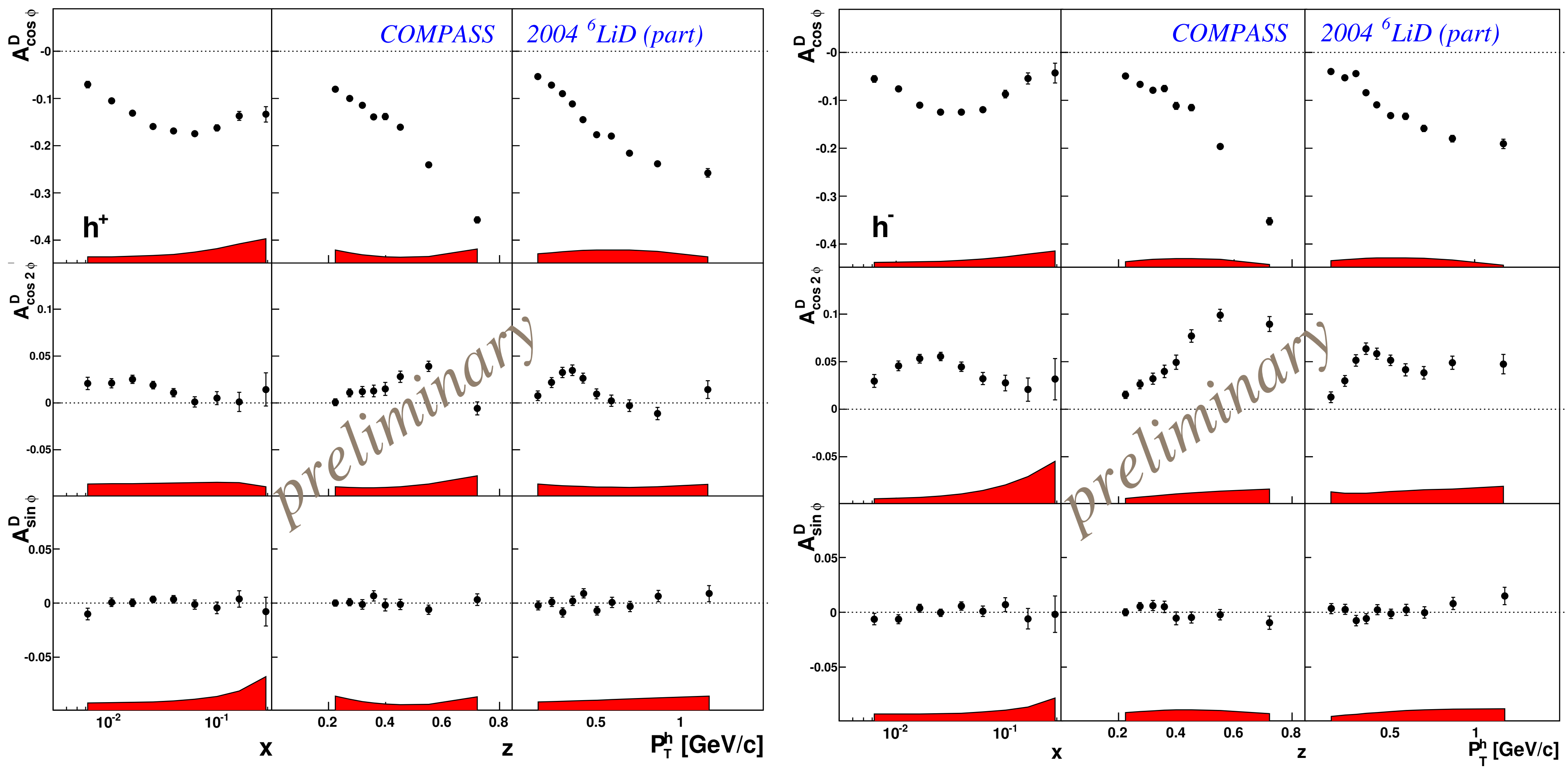
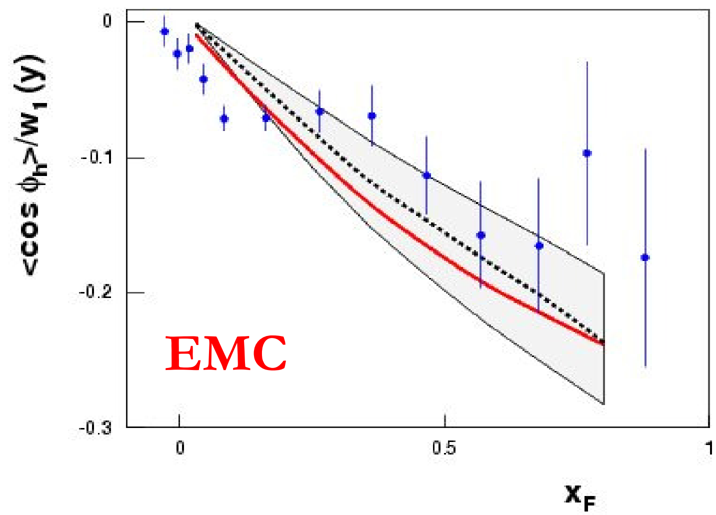
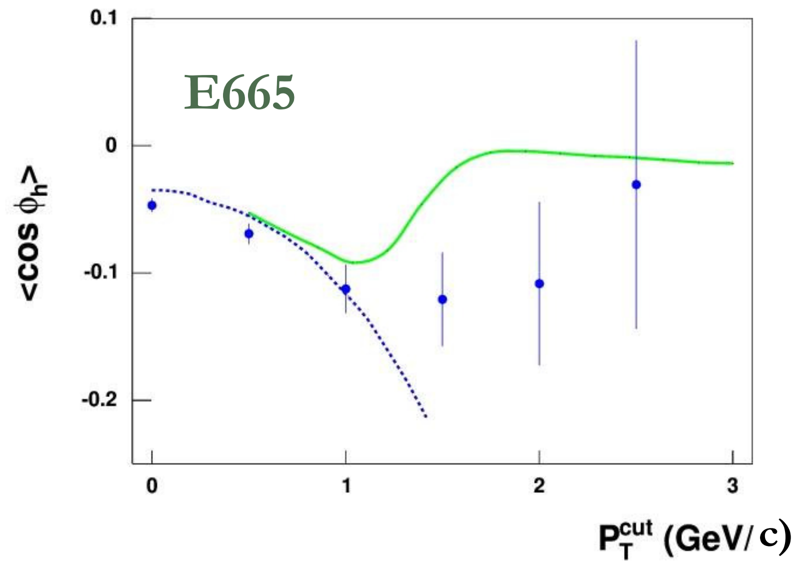
THANK YOU!

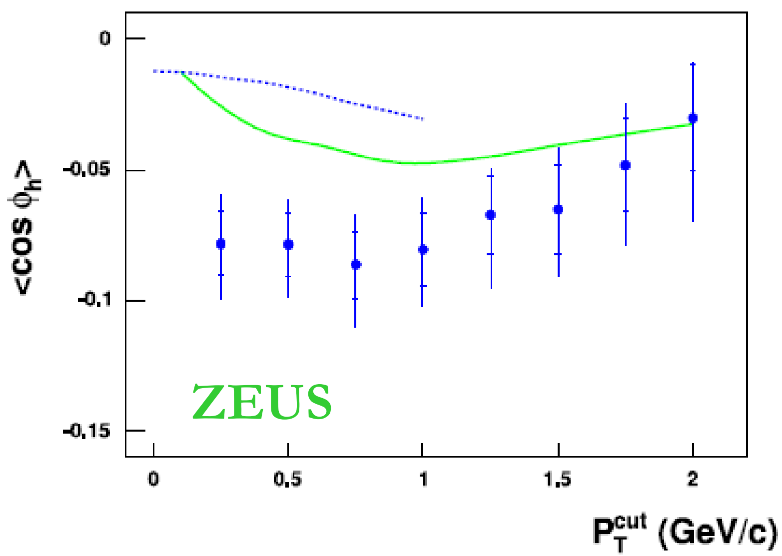
Compass results



Experimental status: $\langle \cos\phi_h \rangle$







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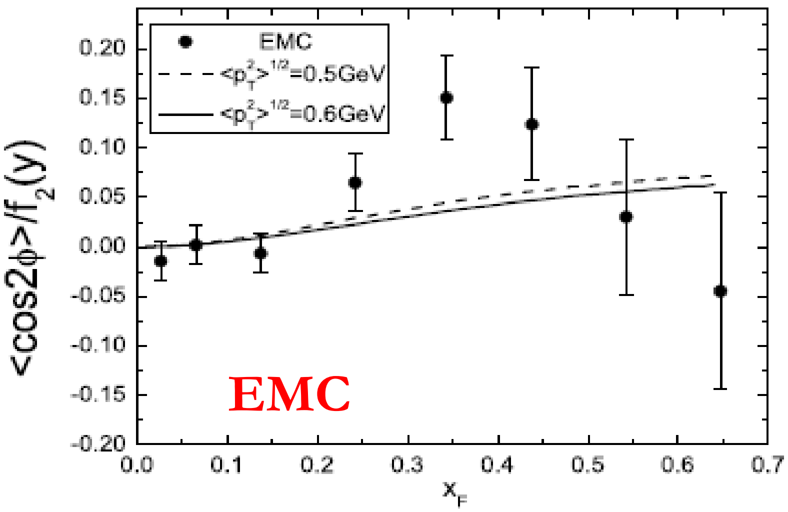
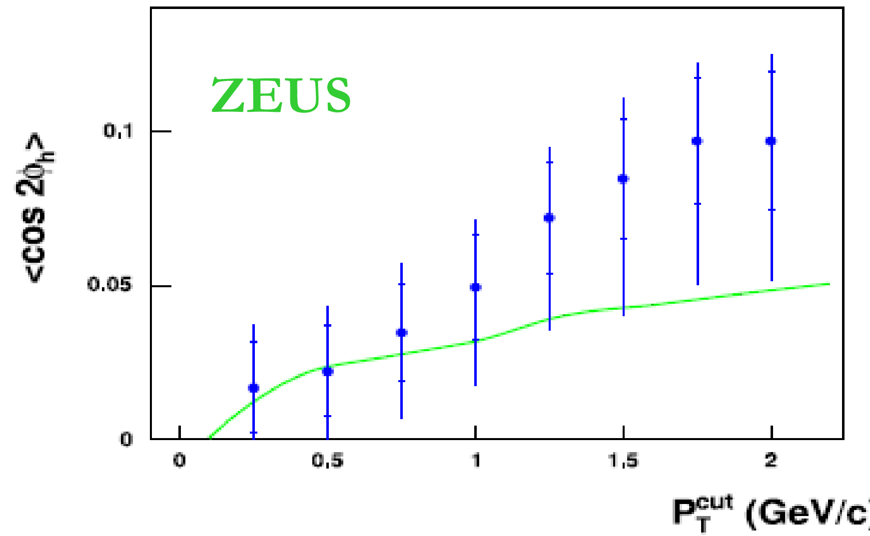
- **No distinction between hadron type or charge**

Experimental status: $\langle \cos 2\phi_h \rangle$





- Positive results in all the existing measurements
- No distinction between hadron type or charge (in SIDIS experiments)
- Indication of small Boer-Mulders function for the sea quark (from Drell-Yan experiments)