Measurement of the cos(ϕ) and cos(2 ϕ) azimuthal moments of the unpolarized deep inelastic scattering cross-section

at hermes

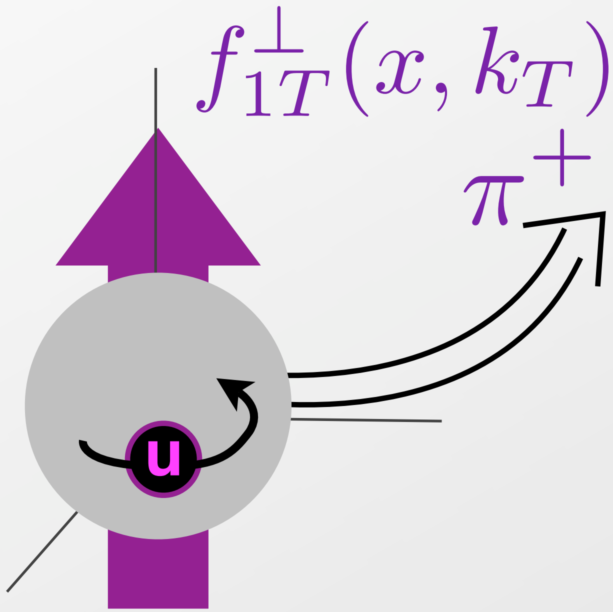
Rebecca Lamb
on behalf of the HERMES collaboration

Introduction
HERMES Procedure
Results and Interpretation

Spin, orbital motion, quarks, and protons

Already Measured

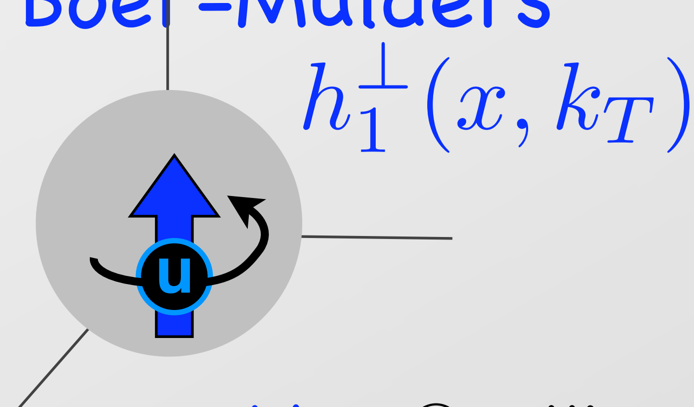
Sivers



- $L_u \parallel S_{proton}$
- $L_d \parallel -S_{proton}$
- hints of large $L_{\bar{q}}$

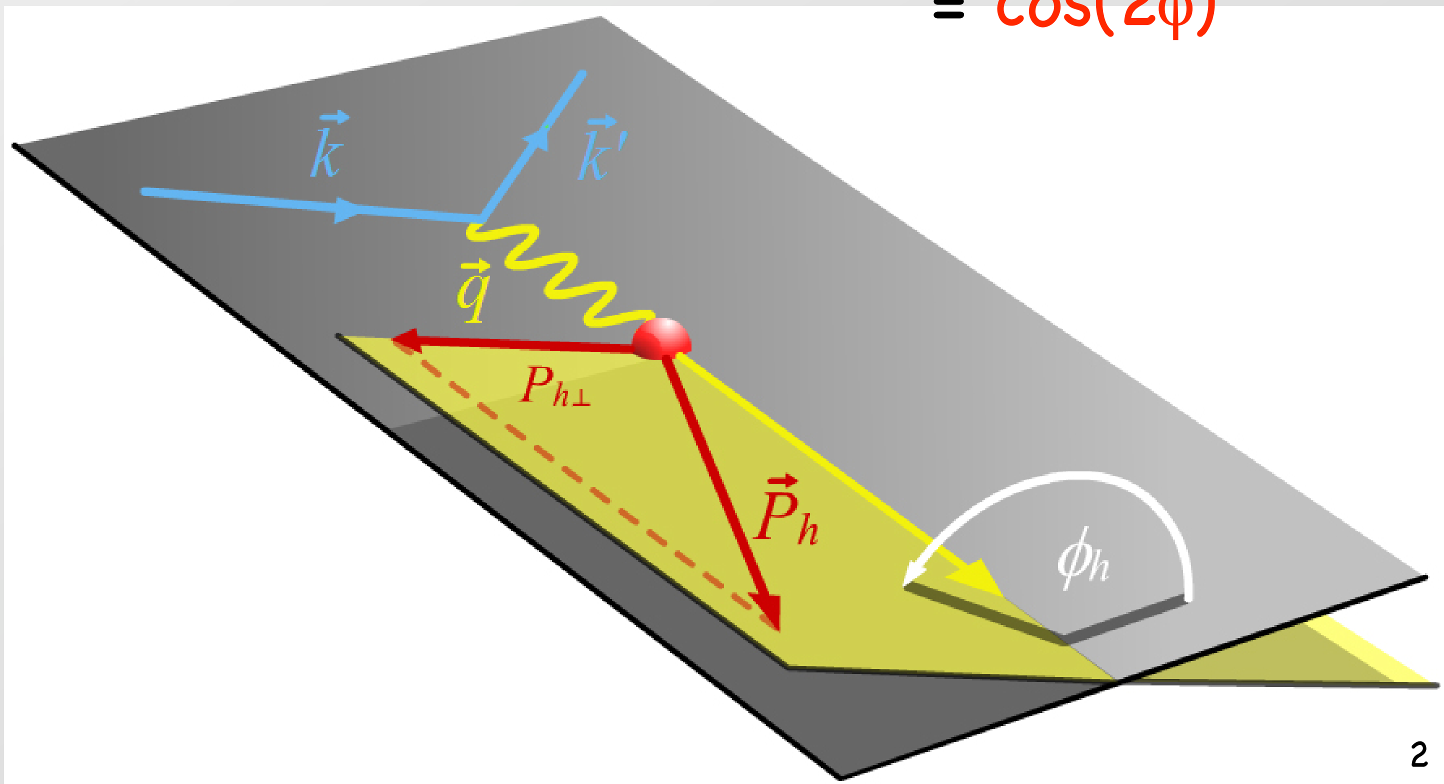
This measurment

Boer-Mulders



Boer-Mulders⊗Collins

= cos(2ϕ)



Spin, orbital motion, quarks, and protons

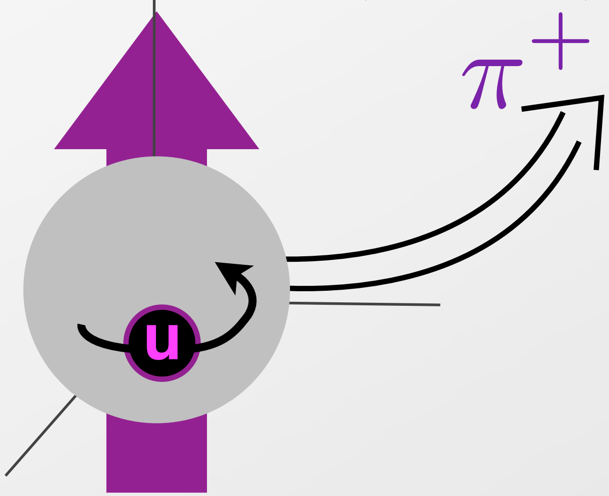
hermes

Already Measured

This measurment

Sivers

$f_{1T}^{\perp}(x, k_T)$



- $L_u \parallel S_{proton}$
- $L_d \parallel -S_{proton}$
- hints of large $L_{\bar{q}}$

Cahn

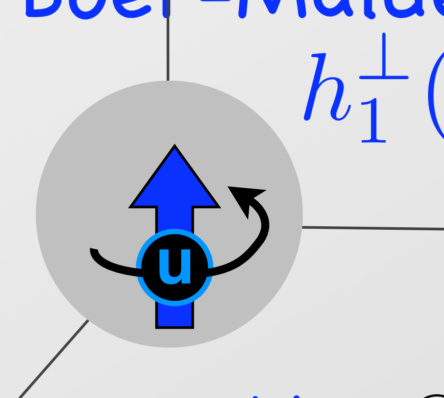
$f(x)D(x)$

- Kinematic effect
- Known since EMC
- Sensitive to <k_T>

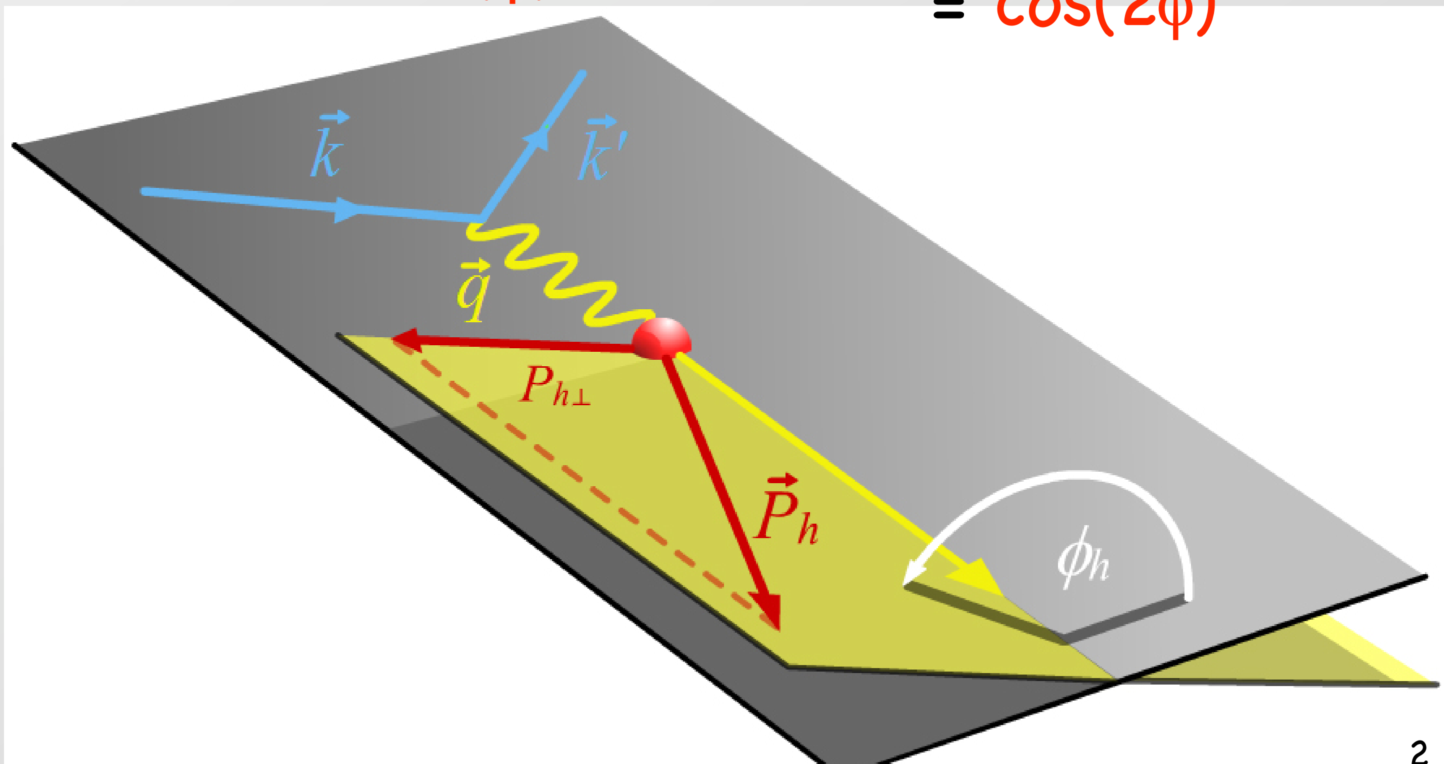
Cahn = cos(ϕ)

Boer-Mulders

$h_1^{\perp}(x, k_T)$



Boer-Mulders⊗Collins = cos(2ϕ)



The LO, subleading twist (3) unpolarized SIDIS cross section

$$\frac{d\sigma}{dx\ dy\ dz\ d\phi\ dP_{h\perp}^2} =$$

$$2\pi\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left[F_{UU,T}+\sqrt{2\epsilon(1+\epsilon)}\cos\phi F_{UU}^{\cos\phi}+\epsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right]$$

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

subleading twist

interaction dependent terms

Cahn+Boer-Mulders

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

Cahn

Boer-Mulders

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

leading twist

Boer-Mulders Collins

The unpolarized SIDIS cross section

$$\frac{d\sigma}{dx\ dy\ dz\ d\phi\ dP_{h\perp}^2} =$$

$$2\pi \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left[F_{UU,T} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi F_{UU}^{\cos\phi} + \epsilon \cos(2\phi) F_{UU}^{\cos(2\phi)}\right]$$

$$= A + B\cos(\phi) + C\cos(2\phi)$$

$$\langle\cos(\phi)\rangle(x, y, z, P_{h\perp}) = \frac{\int \cos(\phi)\sigma^{(5)} d\phi}{\int \sigma^{(5)} d\phi} = \frac{1}{2}\frac{B}{A}$$

$$\langle\cos(2\phi)\rangle(x, y, z, P_{h\perp}) = \frac{\int \cos(2\phi)\sigma^{(5)} d\phi}{\int \sigma^{(5)} d\phi} = \frac{1}{2}\frac{C}{A}$$

Existing Measurements

Boer-Mulders: $\cos(2\phi)$

- EMC, Zeus ($h^{\pm}$ on H)
- COMPASS (h^+ & h^- on ^{6}LiD)
- HERMES (h^+ & h^- on H & D
  ~1.5M SIDIS on h^+
  ~1.0M SIDIS on h^-)

Cahn + Boer-Mulders: $\cos(\phi)$

- E665, EMC, Zeus ($h^{\pm}$ on H)
- COMPASS (h^+ & h^- on ^{6}LiD)
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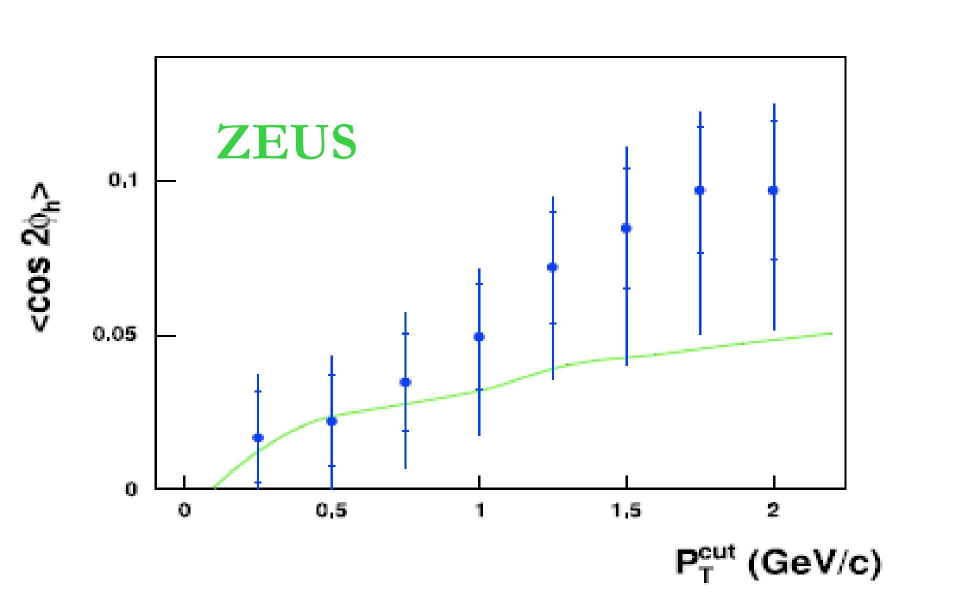


Until this year:

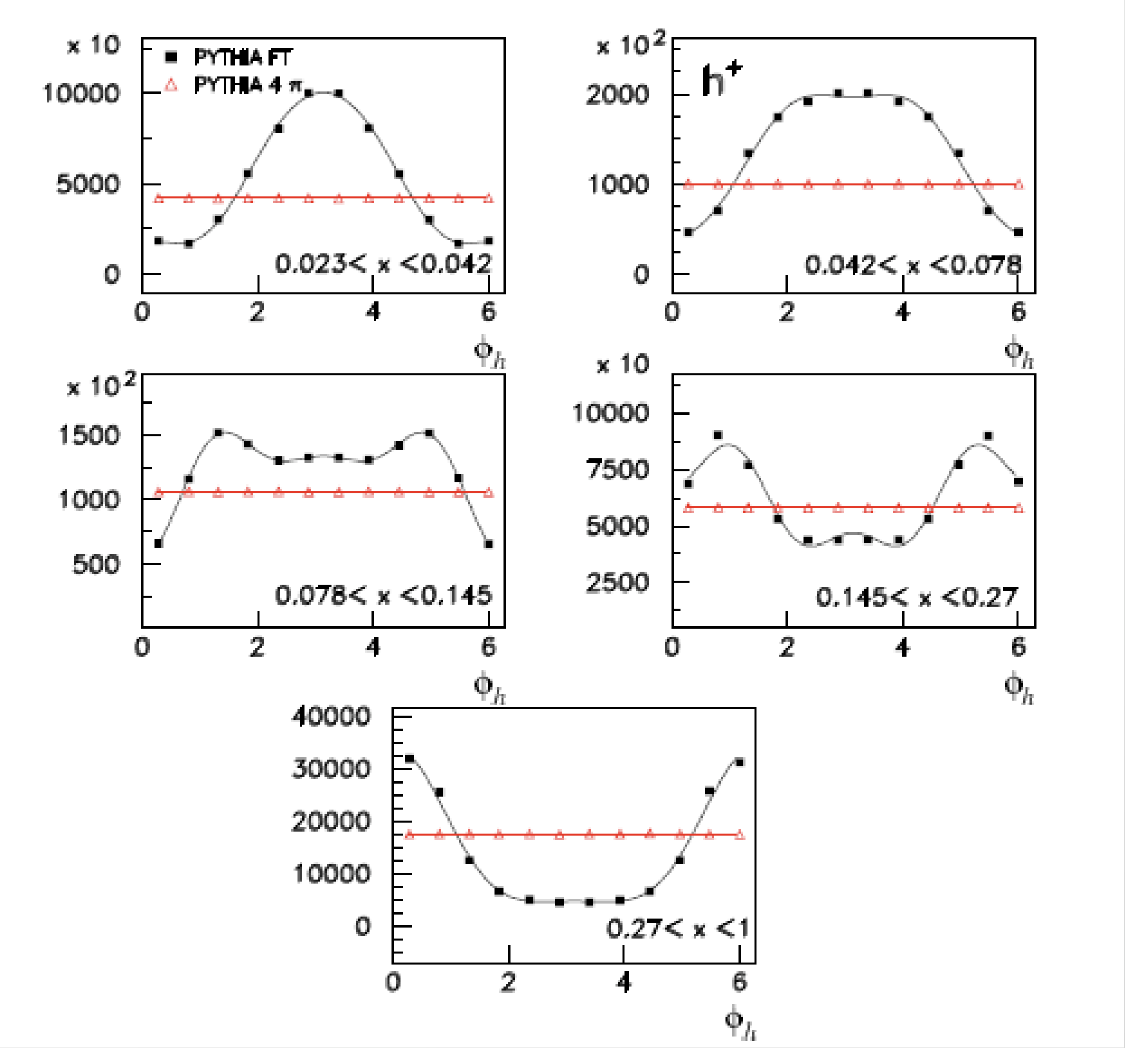
- No charge separation
- Only H target
- No sensitivity to quark flavors!!

Procedure

Analysis Challenge!

Monte Carlo:

- Generated in 4π (red)
- Measured inside acceptance (black)



Our acceptance and radiative effects generate cos(ϕ) moments

which depend on

x, y, z, $P_{h\perp}$, ϕ,

and so does PHYSICS!

Unfolding for detector and radiative effects

$$S(i,j) = \frac{\sigma^{MC}_{rec}(i,j)}{\sigma^{MC}_{born}(j)}$$

Fully tracked Pythia MC

4π Pythia MC

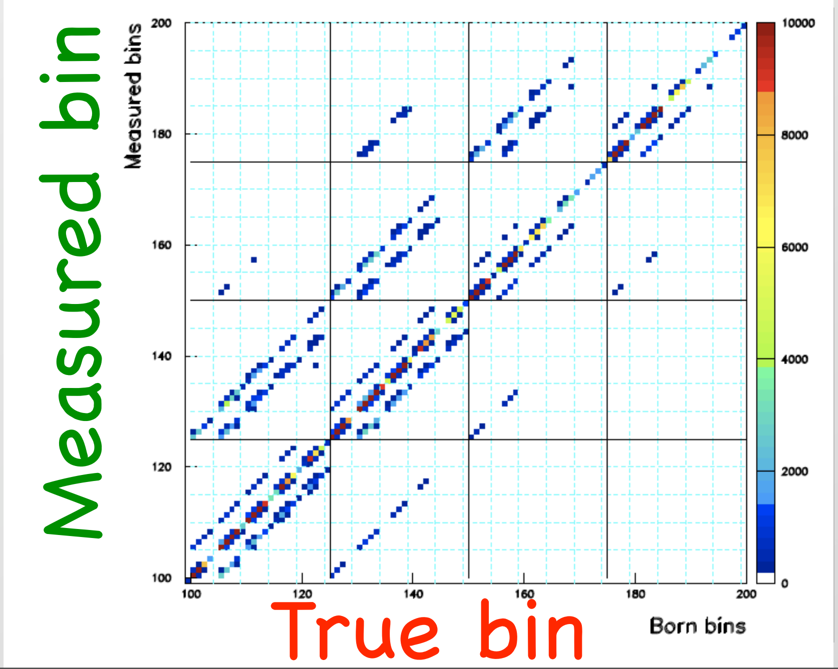
What we'd like to know!

i = index of "measured" bins 1-4800

$$\sigma_{measured}(i) = \sum_{j=0}^{N} S(i,j)\,\sigma_{true}(j)$$

j = index of "true" bins 0-4800

What we actually measure



Five Dimensional Binning

$x =$	0.023	0.042	0.078	0.145	0.27	1
$y =$	0.3	0.45	0.6	0.7	0.85	
$z =$	0.2	0.3	0.45	0.6	0.75	1
$P_{h\perp} =$	0.05	0.2	0.35	0.5	0.75	
$\phi =$	12 bins					

400 kinematic bins * 12 ϕ bins = 4800 bins!

$Q^2 > 1$ GeV

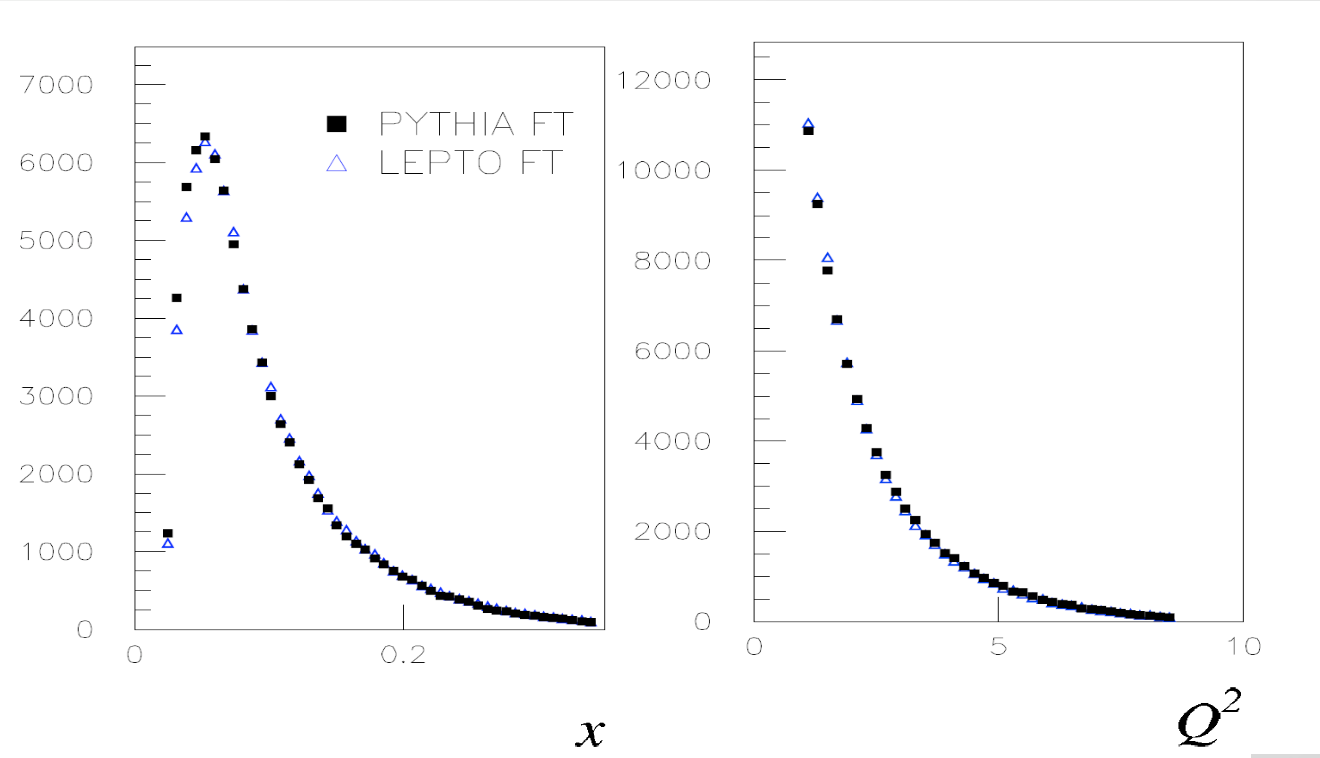
$W^2 > 10$ GeV

Highest z bin not included in projections vs other variables

Why a full differential analysis?

Monte Carlo Test:

- One MC production as "data" $\langle\cos(n\phi)\rangle=0$
- A different MC production use to unfold $\langle\cos(n\phi)\rangle=0$

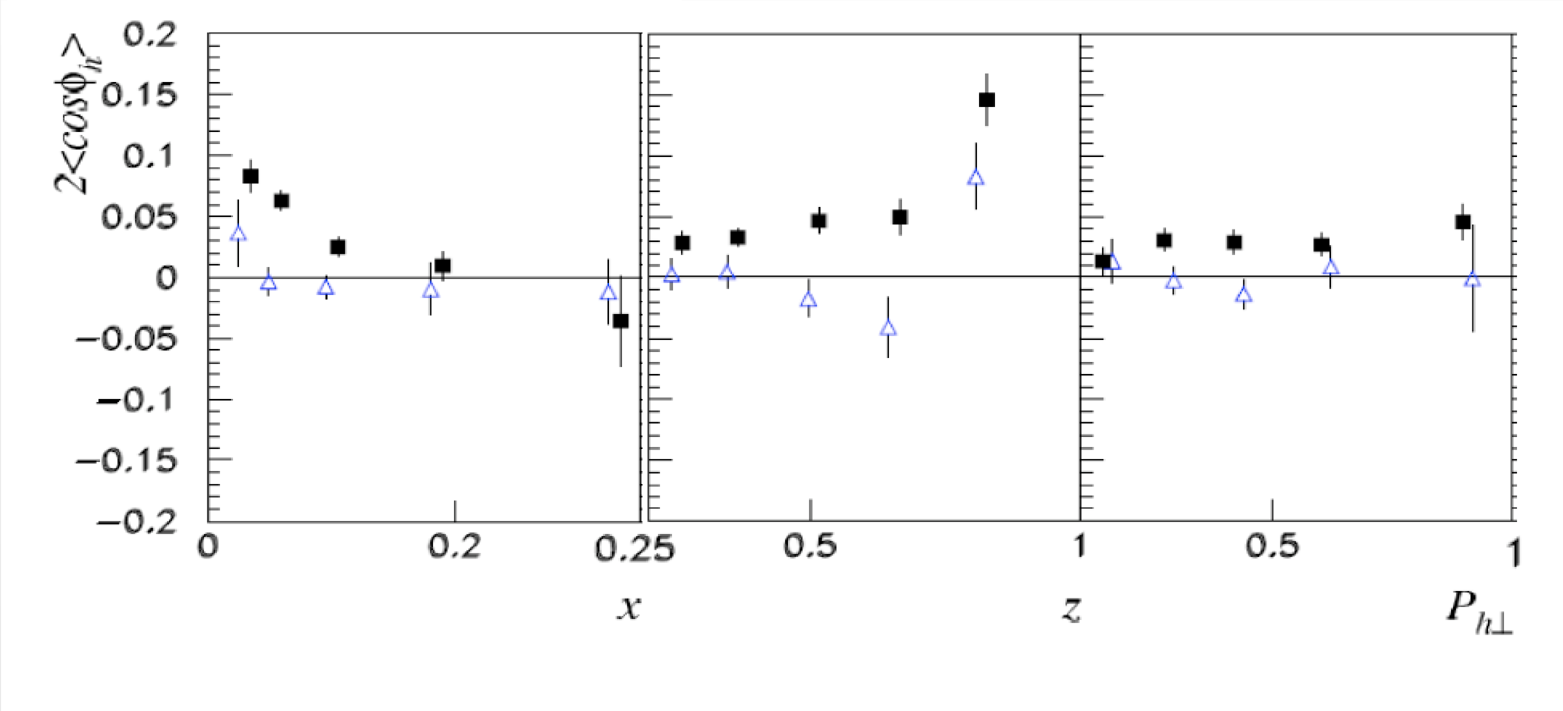


Why a full differential analysis?

Any correction that is <5D is **model dependent**

Monte Carlo Test:

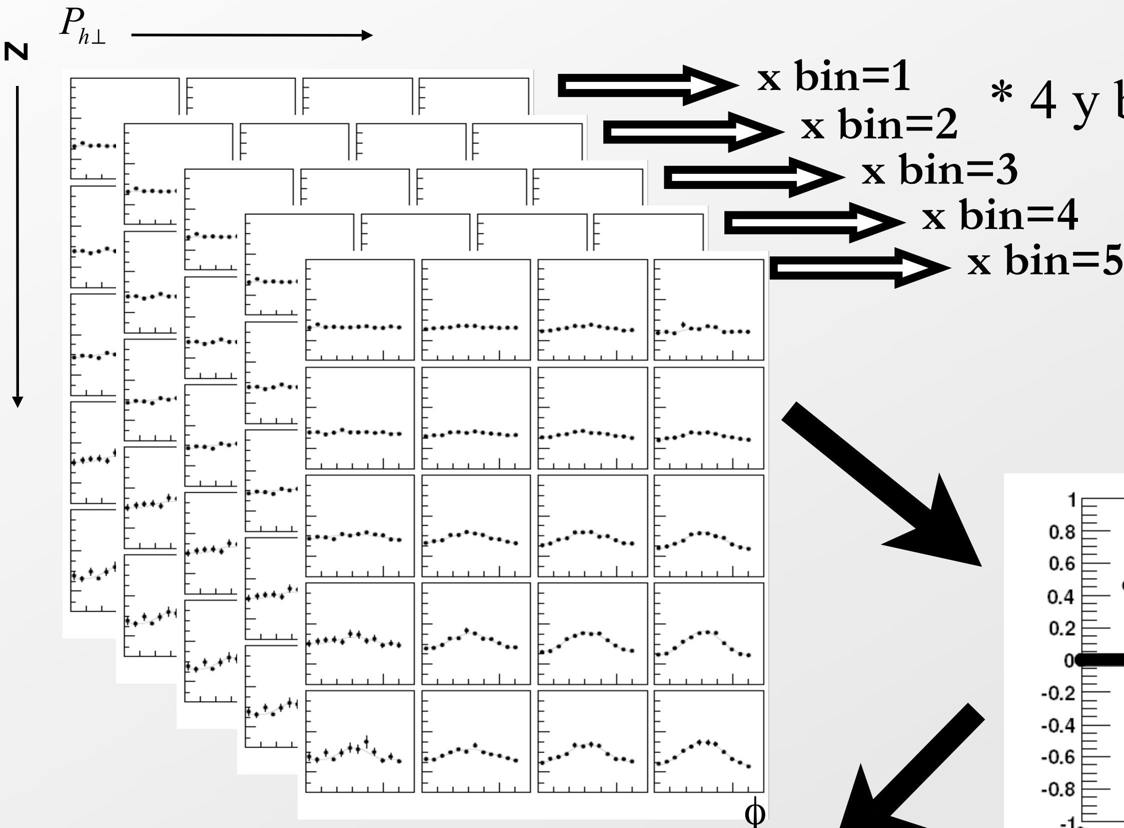
- One MC production as "data" <cos(nϕ)>=0
- A different MC production use to unfold <cos(nϕ)>=0



■ One-dimensional unfolding → Introduces FALSE moments

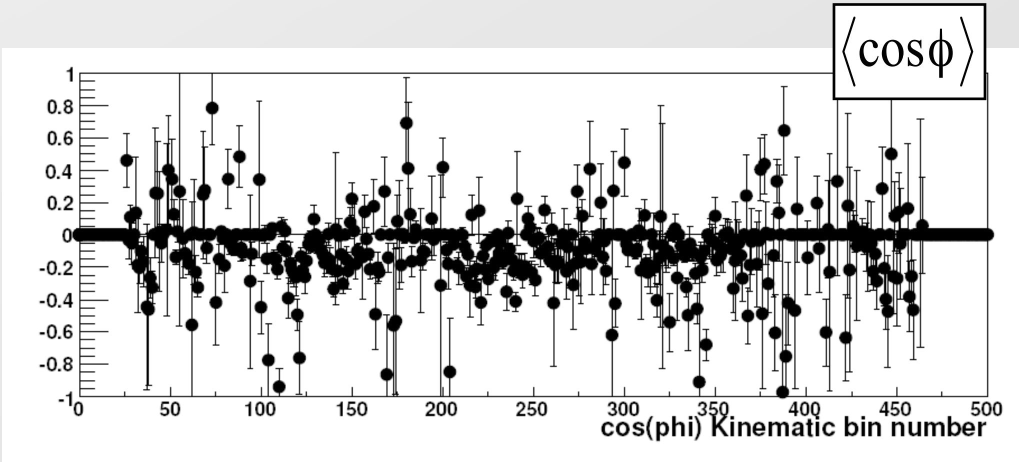
△ Multi-dimensional unfolding

Analysis Summary

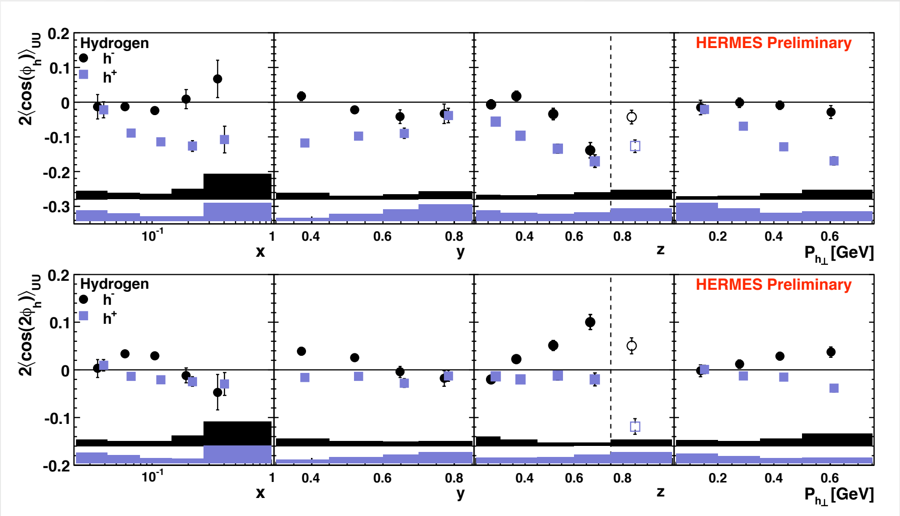


* 4 y bins

4800 measurements are unfolded and fit in 400 bins



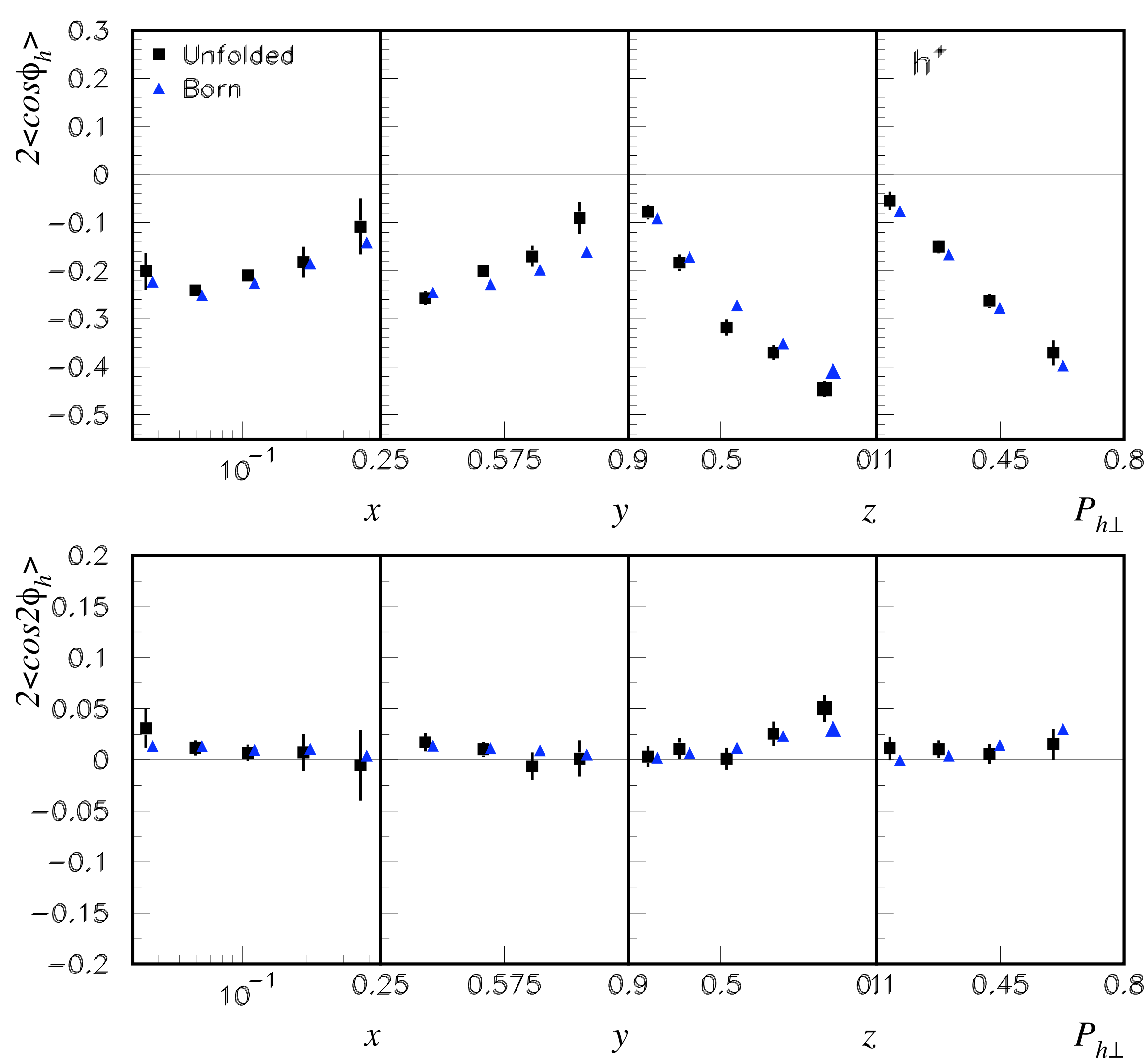
400 moments are calculated by ratios of the A, B and C parameters



1-dimensional projection are calculated as the integral over the other 3 variables

Monte Carlo test

- One MC production as “data” <cos(ϕ)>=Cahn Model
- A different MC production use to unfold <cos(ϕ)>=0



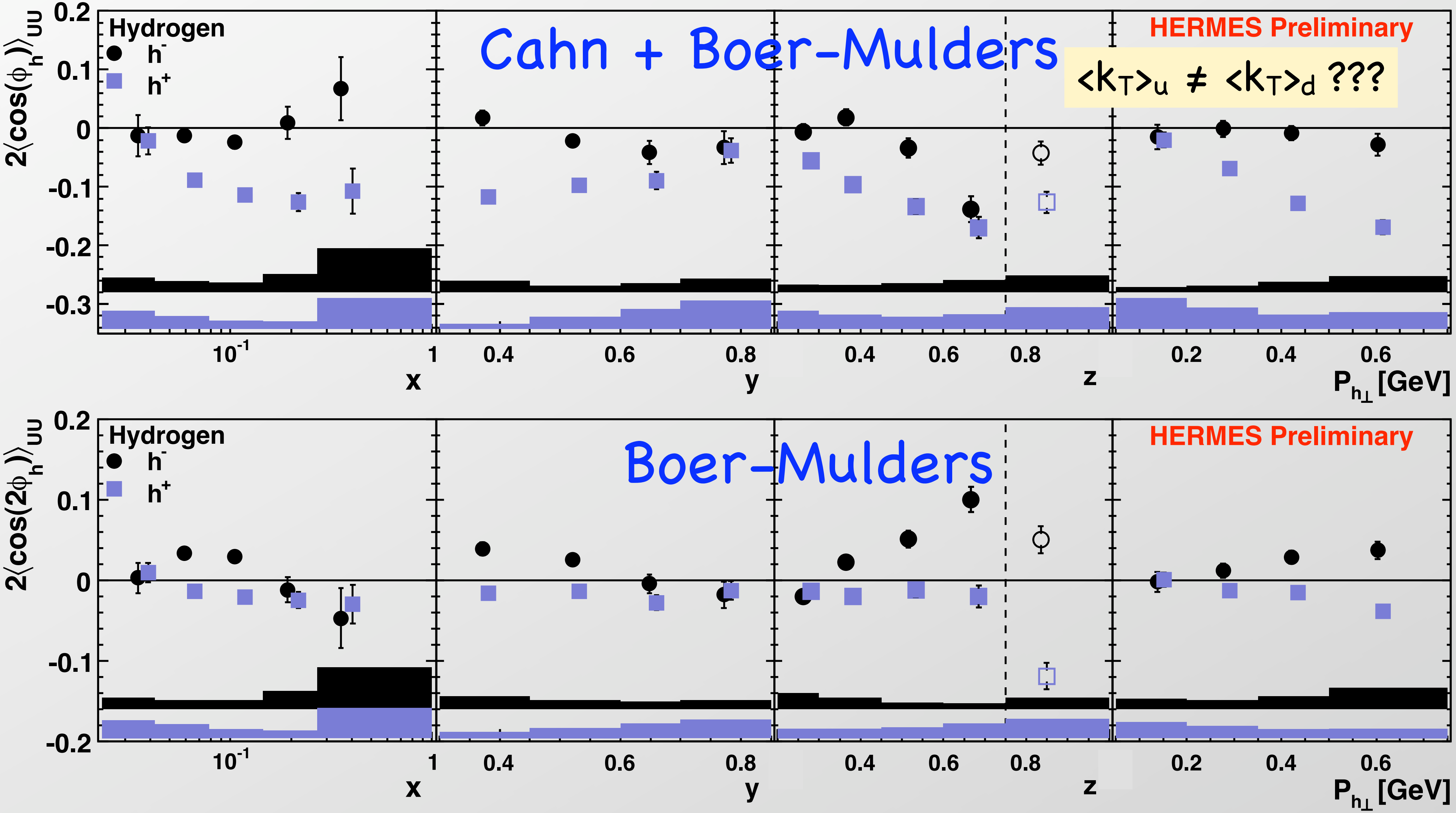
▲ Cahn Model in 4π
■ Unfolded

It works!!

Results and Interpretation

Hydrogen h^+ and h^- vs x, y, z, and $P_{h\perp}$

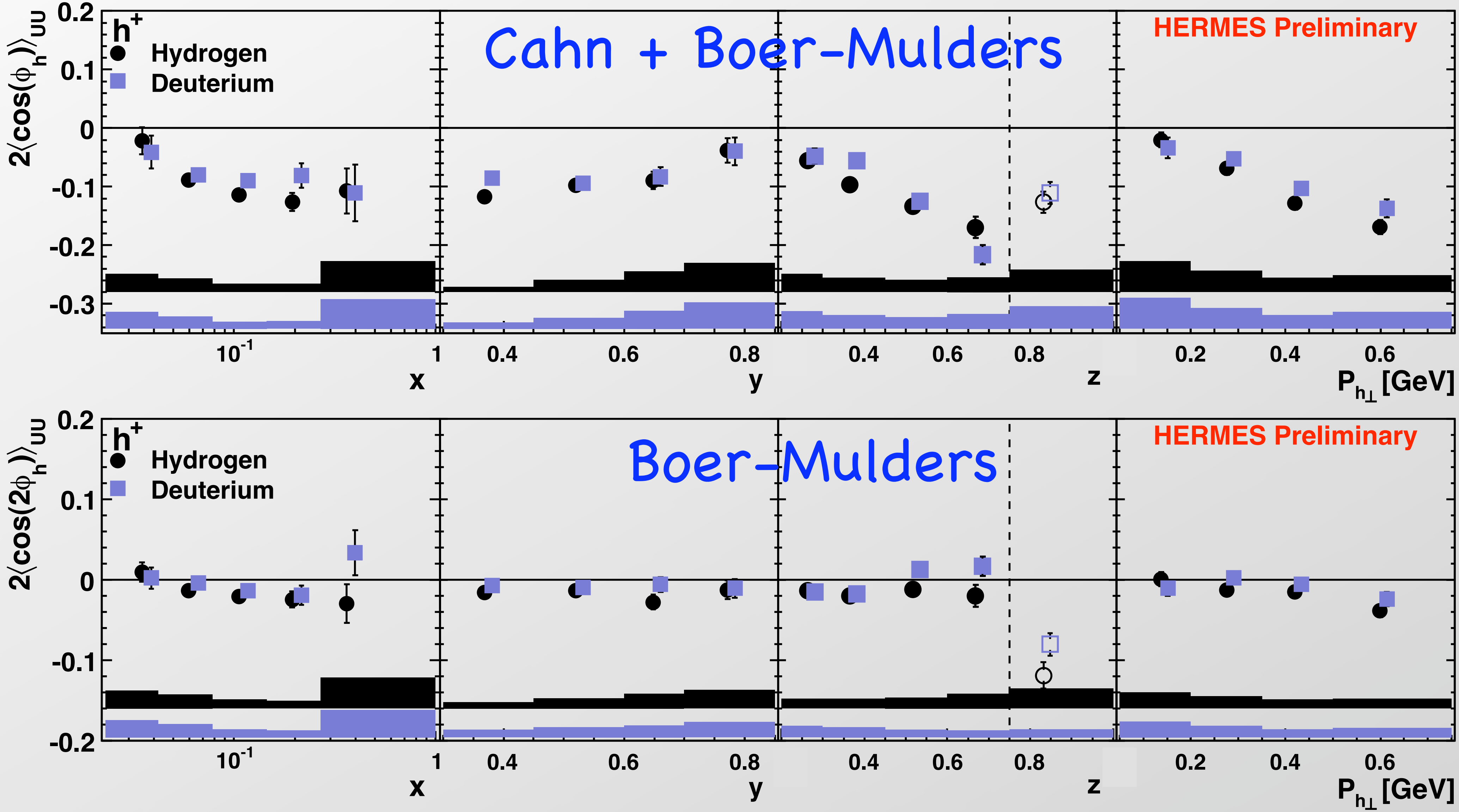
h^+ and h^- are quite different



$\langle Q^2\rangle=2.5$

Hydrogen and Deuterium h^+ vs x, y, z, and $P_{h\perp}$

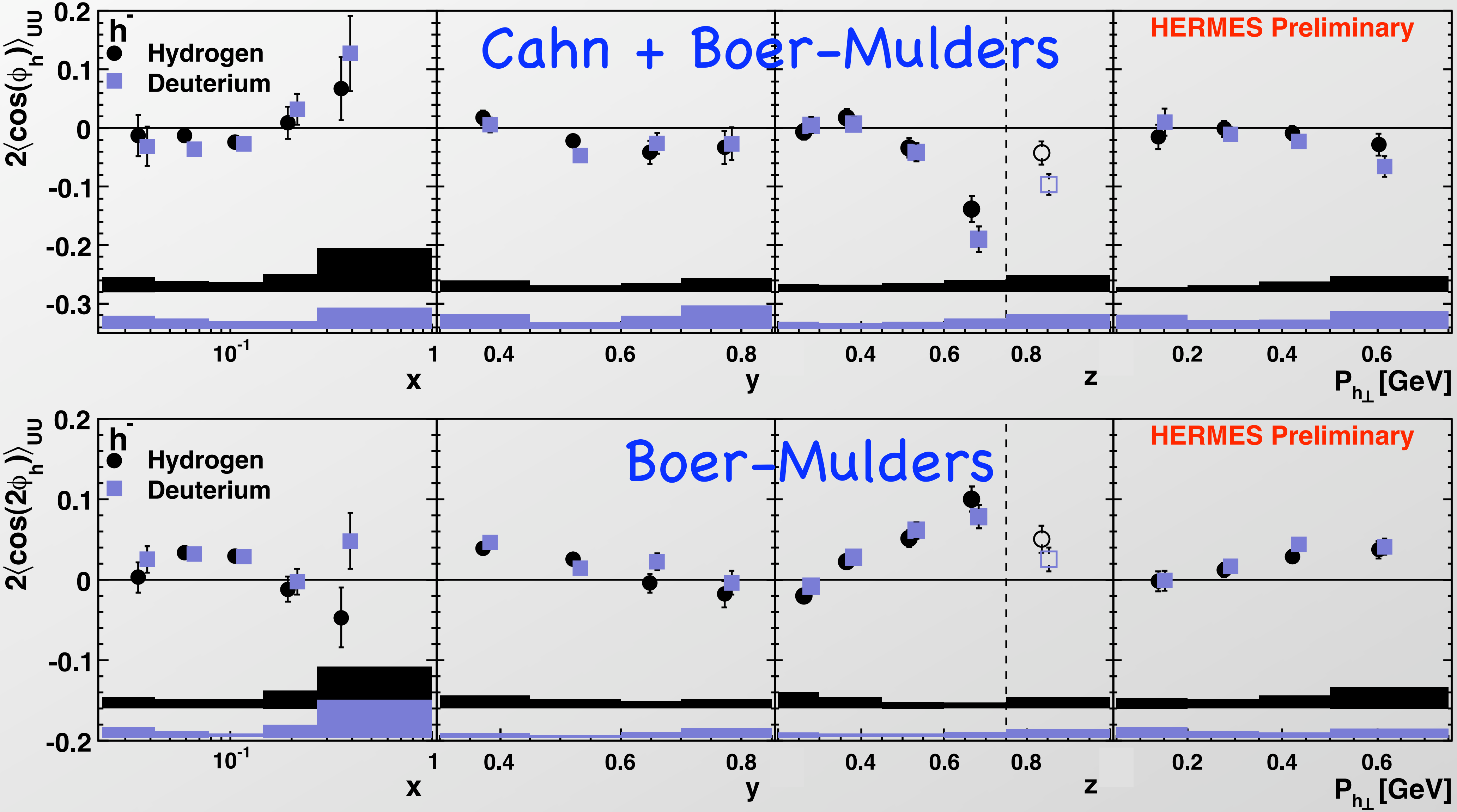
H and D are quite similar



$\langle Q^2 \rangle = 2.5$

Hydrogen and Deuterium h^- vs x, y, z, and $P_{h\perp}$

H and D are quite similar



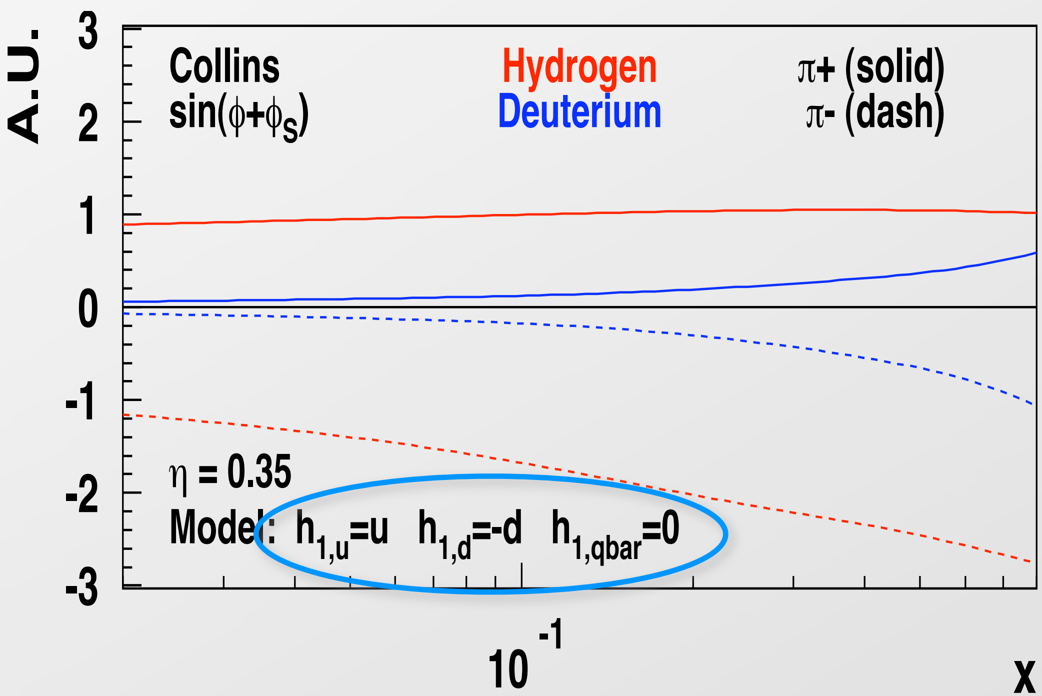
$<Q^2>=2.5$

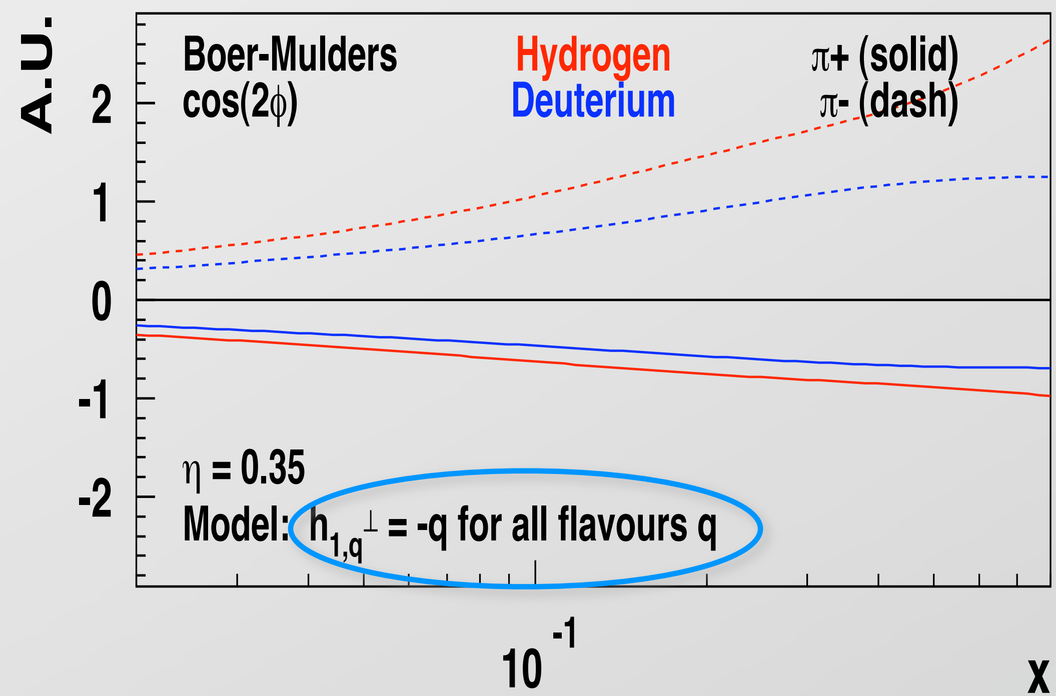
Understanding

Boer-Mulders Hydrogen vs Deuterium

a back-of-the-envelope calculation

Assume: $\eta \equiv \frac{\int D_{1,\text{disfav}}}{\int D_{1,\text{fav}}} \simeq 0.35$ $\frac{\int H^{\perp}_{1,\text{disfav}}}{\int H^{\perp}_{1,\text{fav}}} = -1$





Hydrogen-Deuterium similarity → same sign for Boer-Mulders u & d!

Understanding

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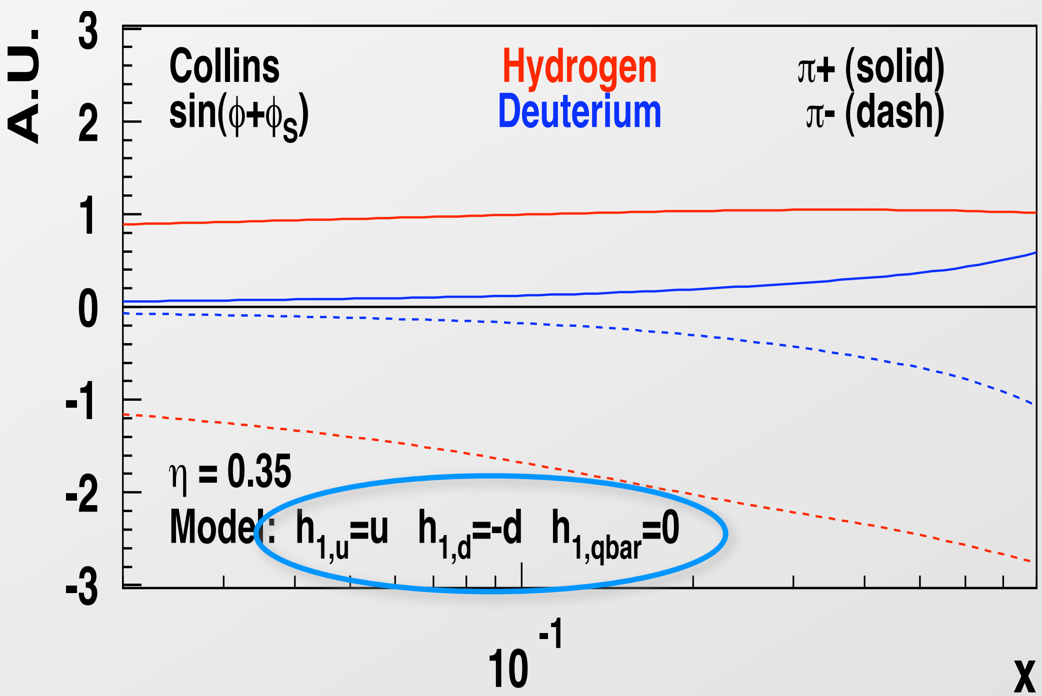
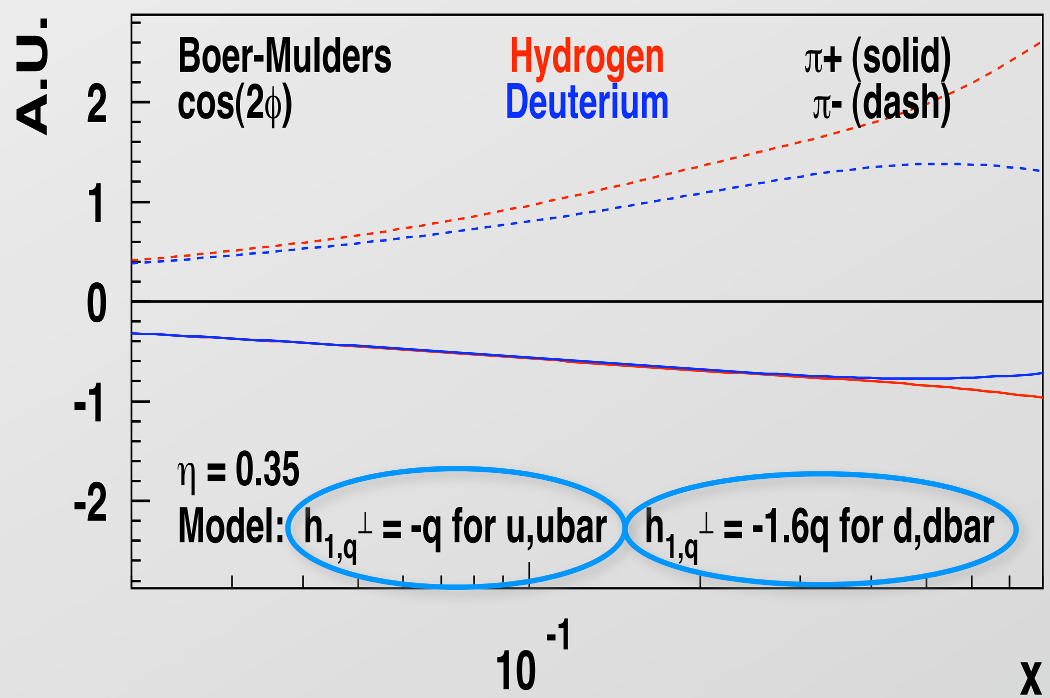
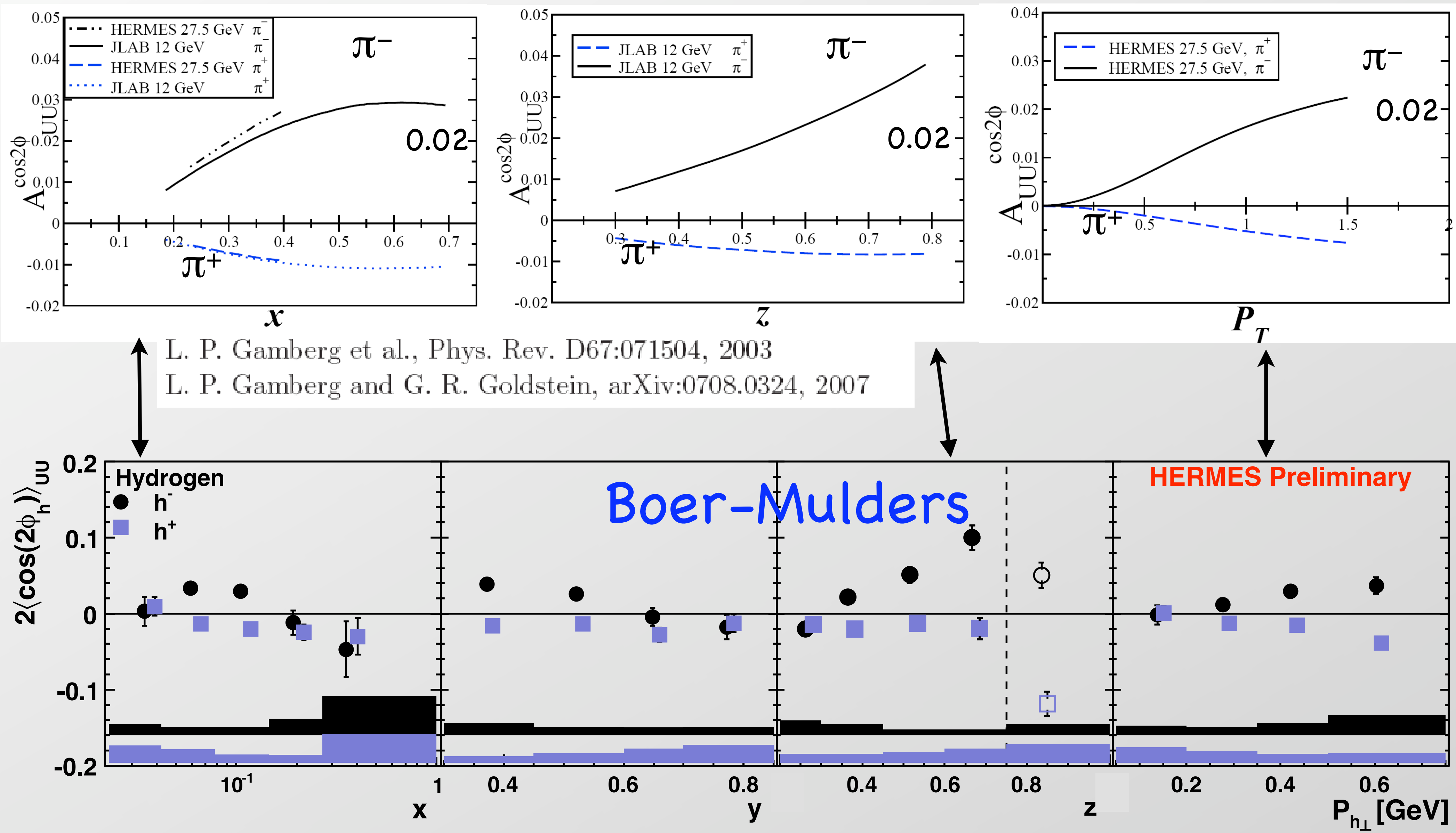




Hydrogen-Deuterium similarity → same sign for Boer-Mulders u & d!

Hydrogen <cos(2ϕ)> vs model calculations

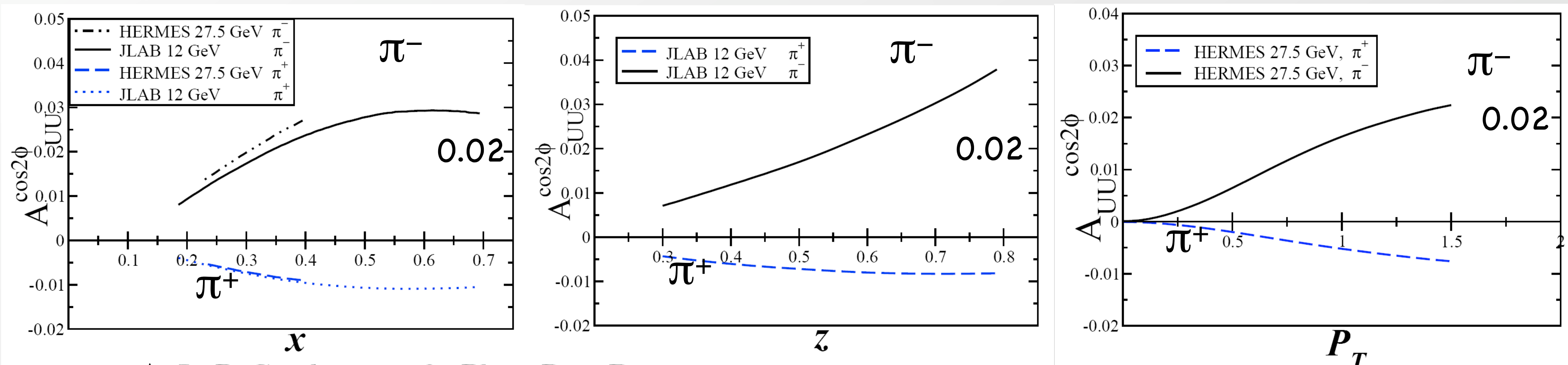


L. P. Gamberg et al., Phys. Rev. D67:071504, 2003

L. P. Gamberg and G. R. Goldstein, arXiv:0708.0324, 2007

Hydrogen <cos(2ϕ)> vs model calculations

Results consistent with diquark spectator model



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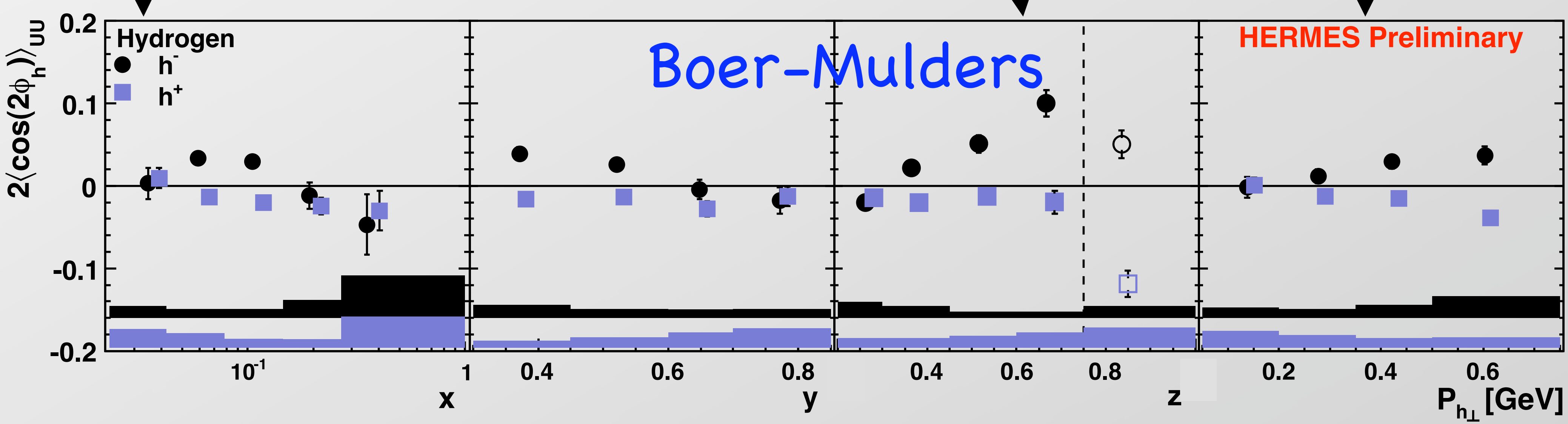
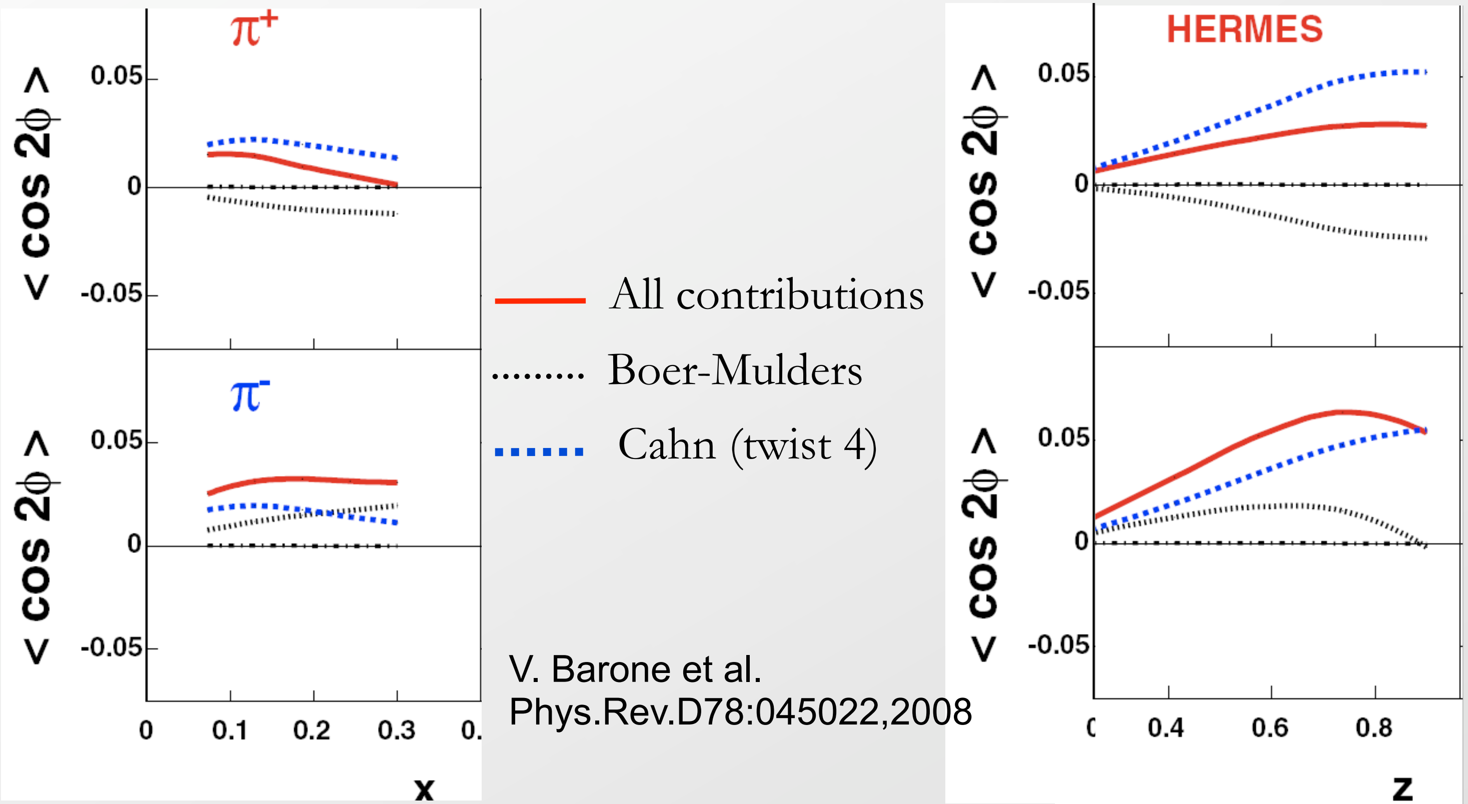
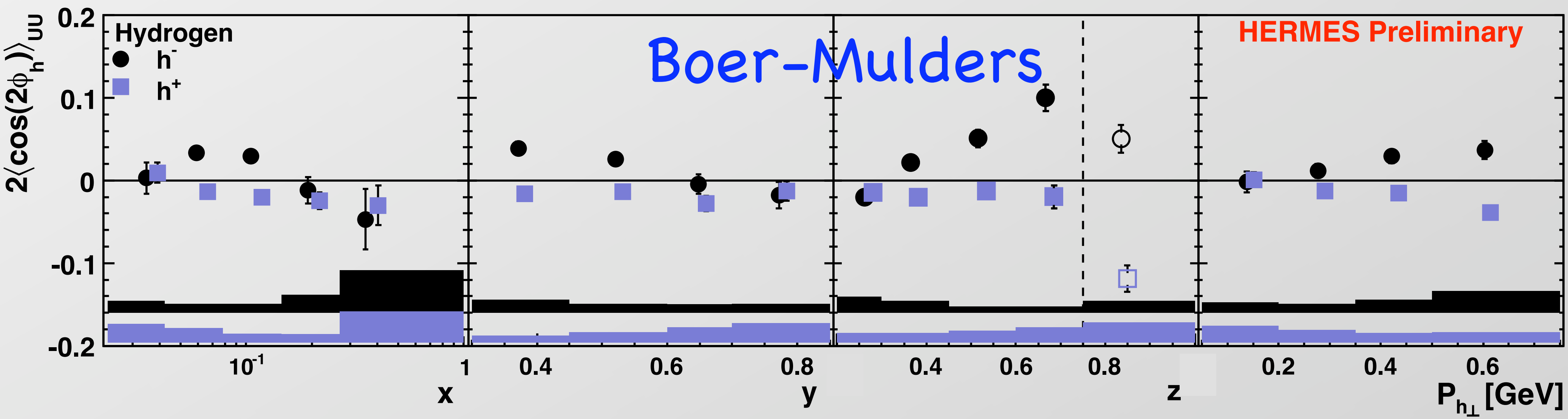


Hydrogen <cos(2ϕ)> vs model calculations



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



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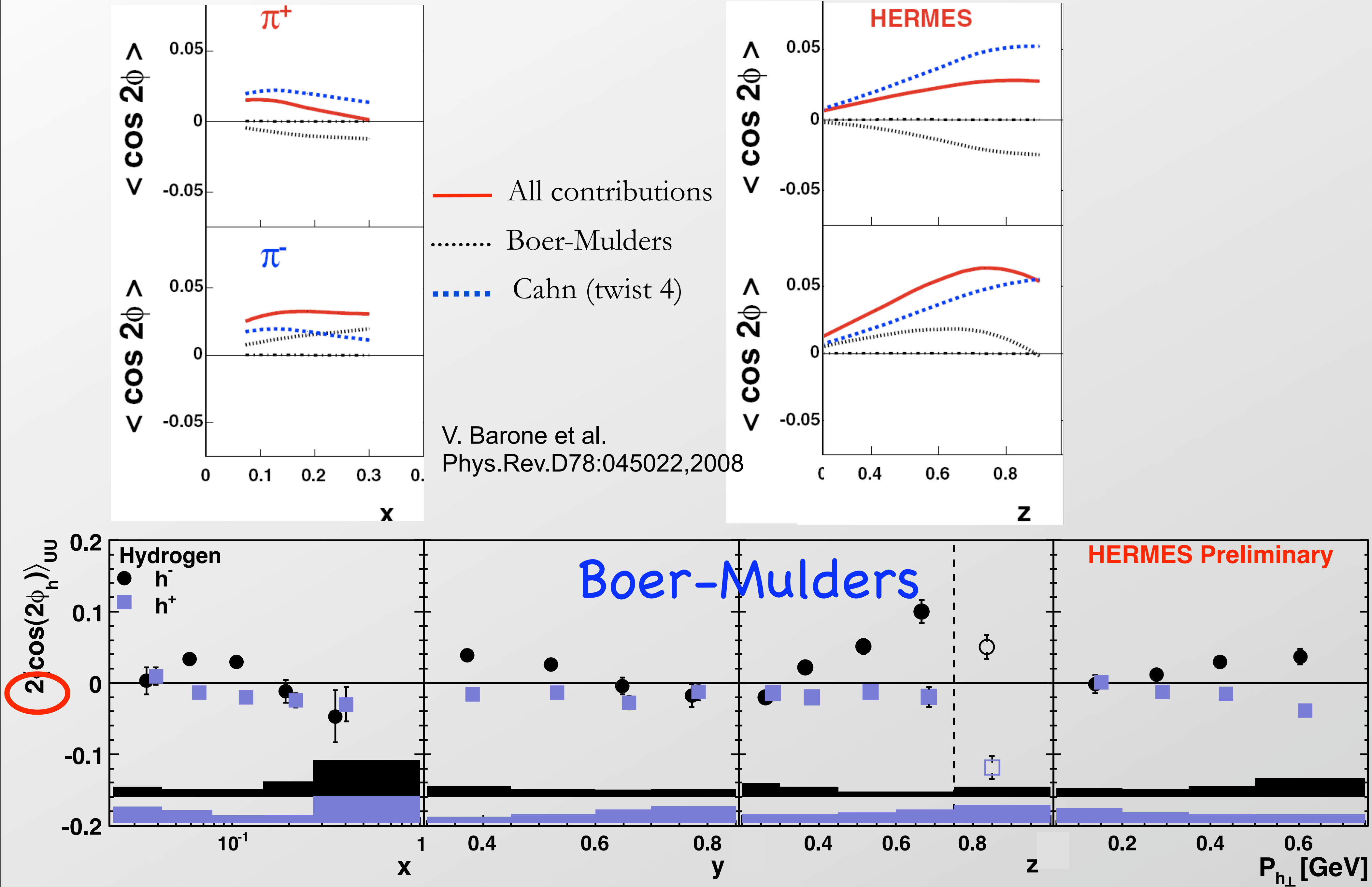

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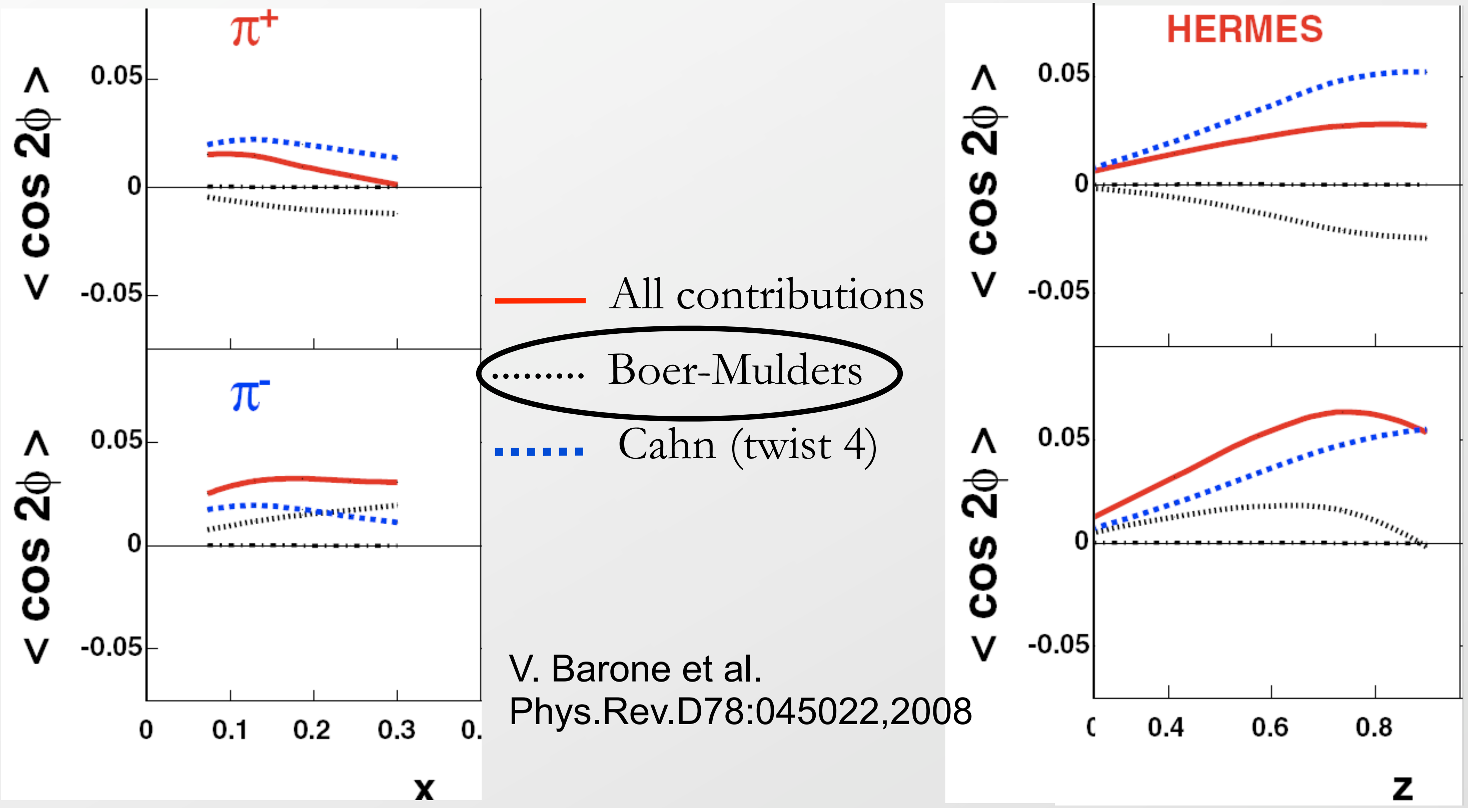

V. Barone et al.
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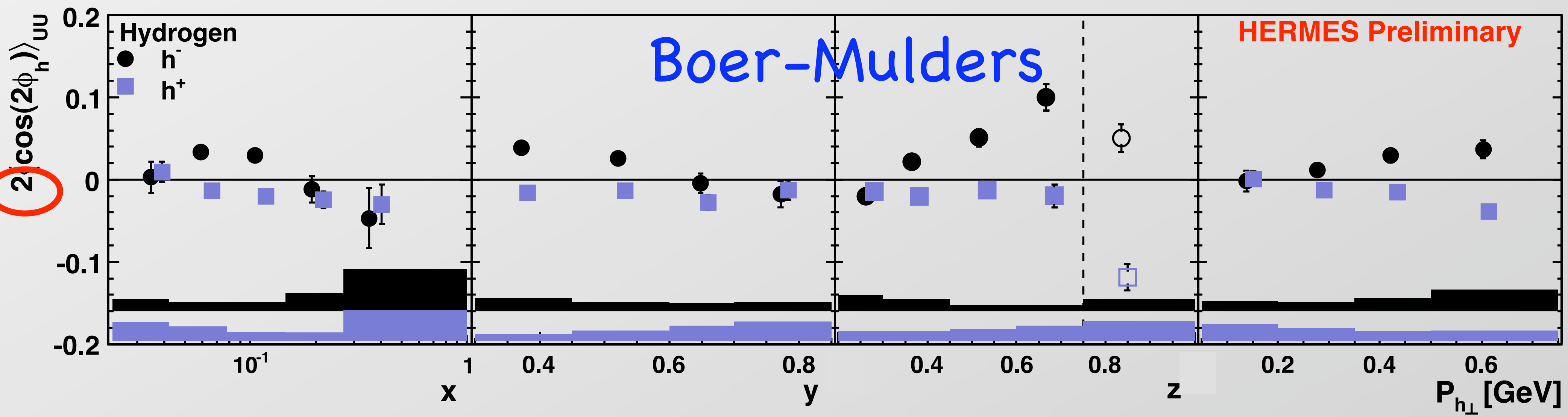
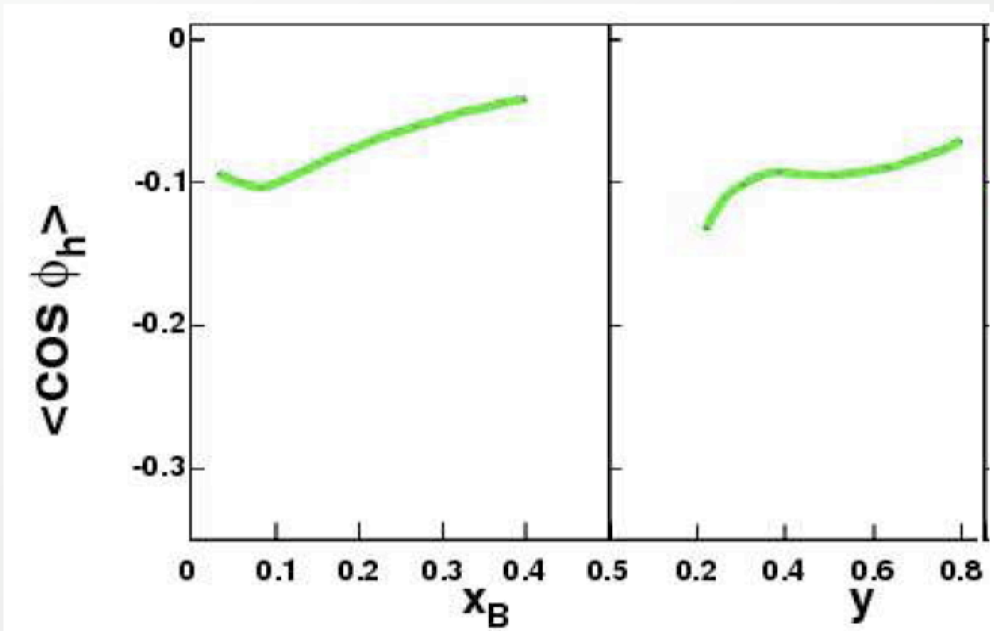
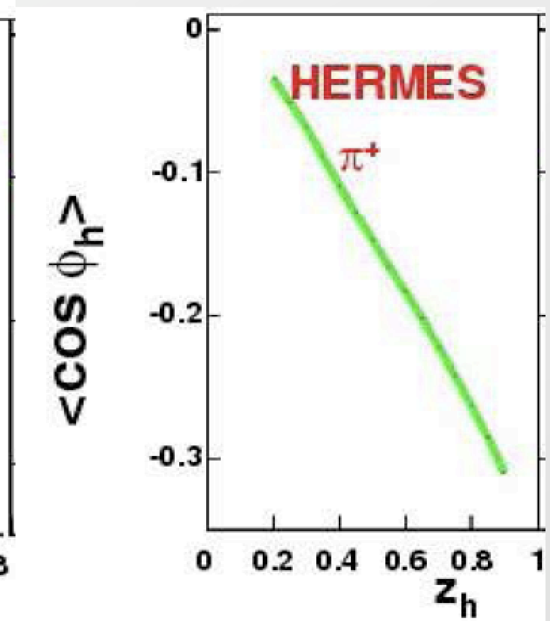
Results consistent with Boer-Mulders alone, Cahn (twist 4) appears suppressed

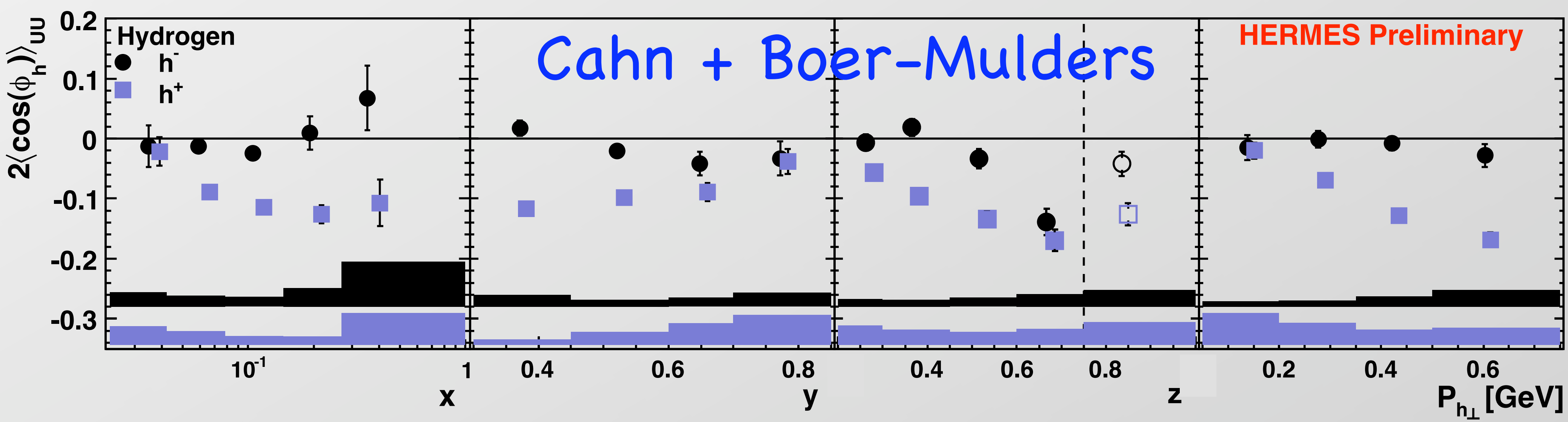


Hydrogen <cos(φ)> vs model calculations

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







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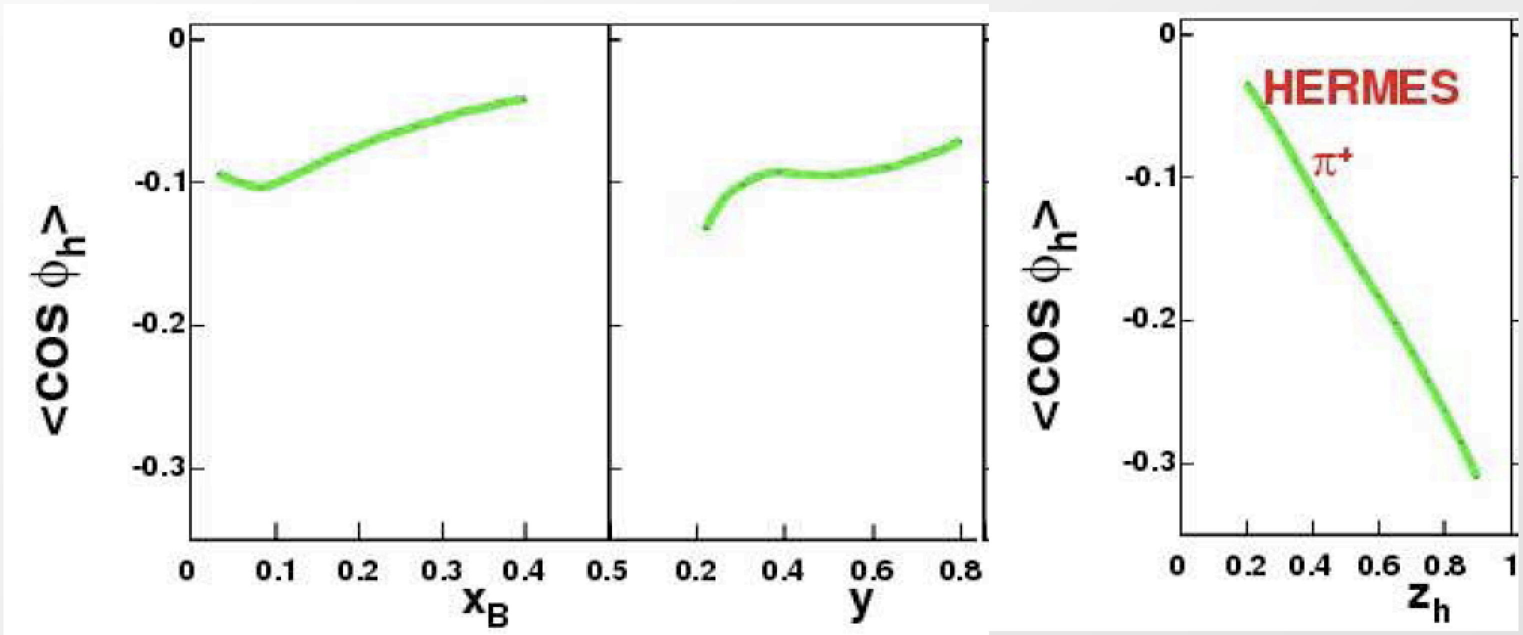

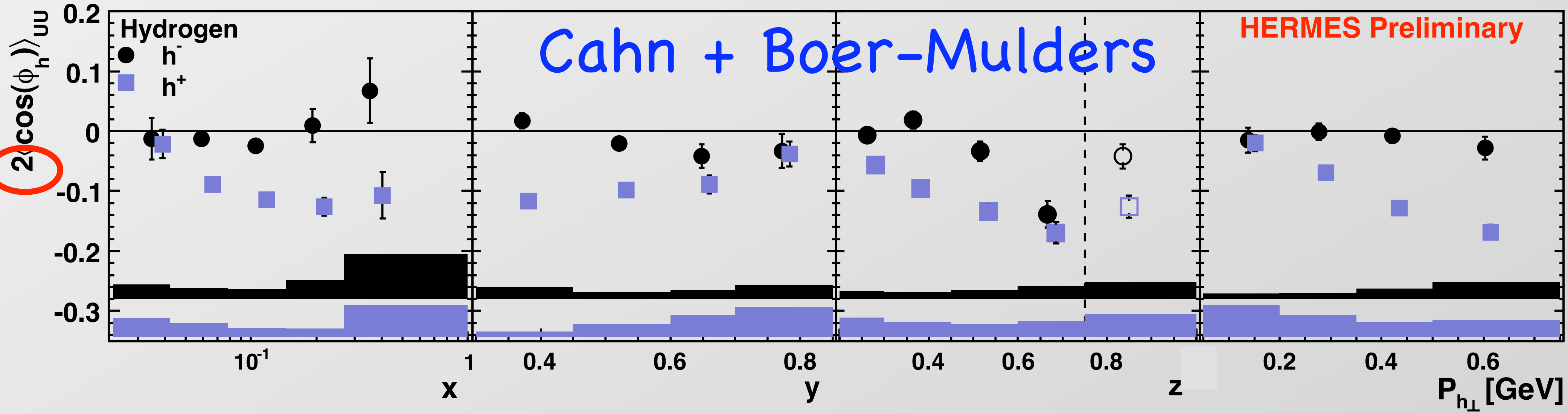

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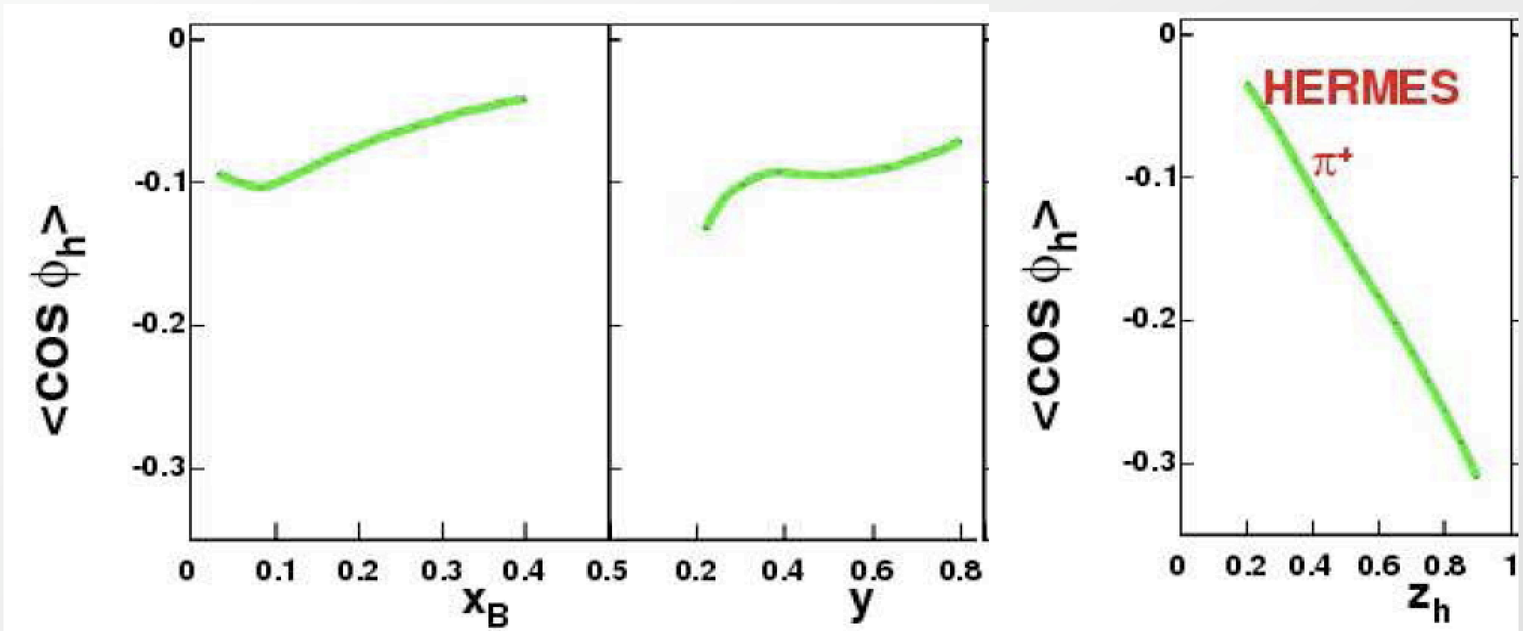
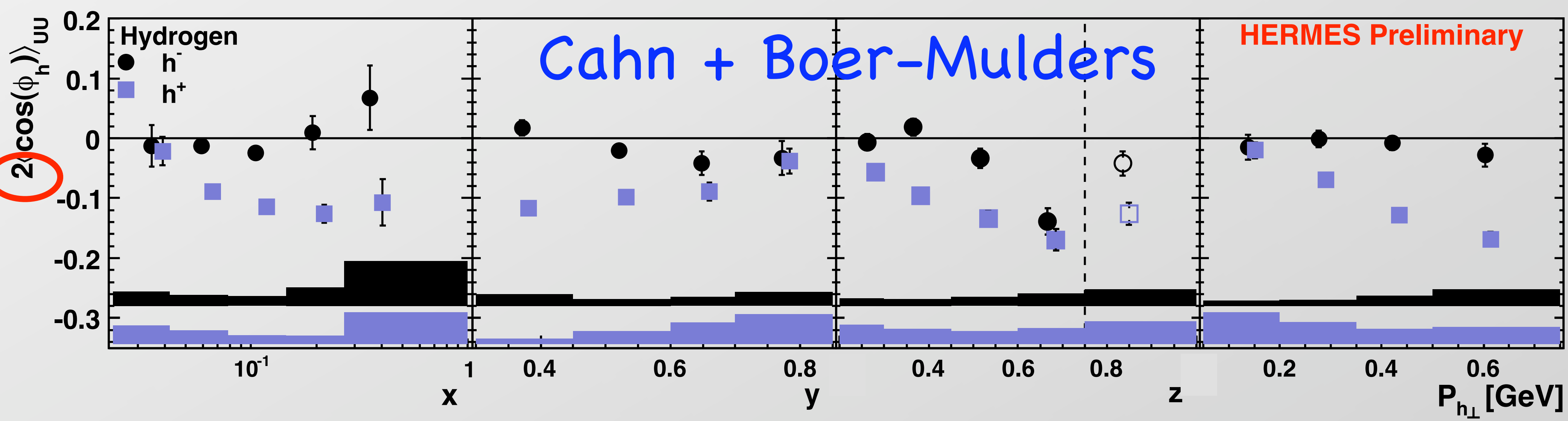


Shape consistent with Anselmino's predictions, but magnitude too large



What's next?

- Our dual-radiator RICH has **improved** software for beautifully identified **pions**, **kaons**, and protons
- This analysis: ~1.5M SIDIS on both H and D

  Additional **~5M** SIDIS on both H and D available

Conclusions

NEW HERMES results!

- <cos(ϕ)> and <cos(2ϕ)> on Hydrogen and Deuterium

- <cos(ϕ)>
  - $h^+ \neq h^-$ ➡ $\langle k_T \rangle$ flavor dependent??

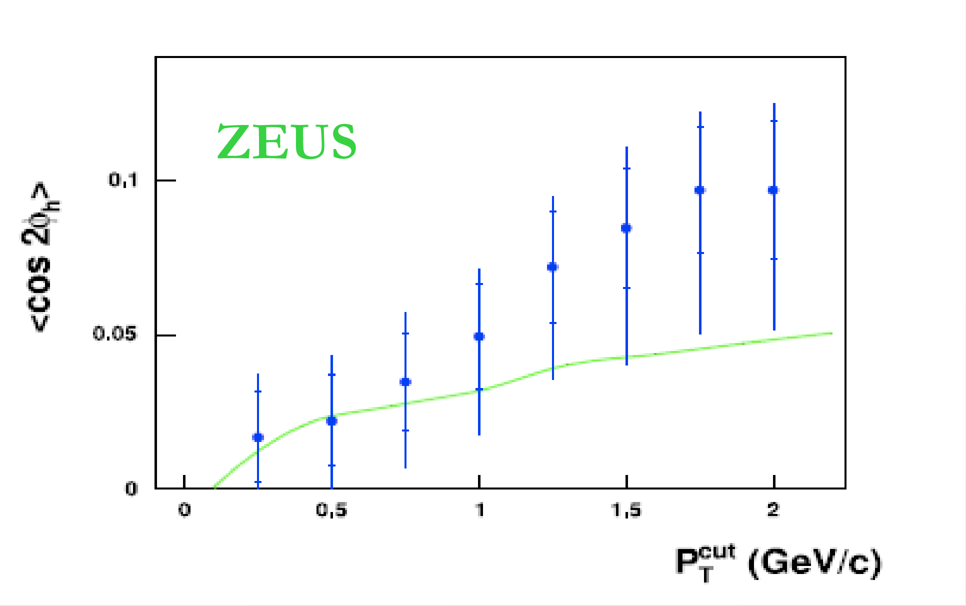
- <cos(2ϕ)>
  - H ≈ D ➡ Boer-Mulders same sign for u and d
  - $L_u \parallel S_u, \ L_d \parallel S_d$ (Burkardt model)

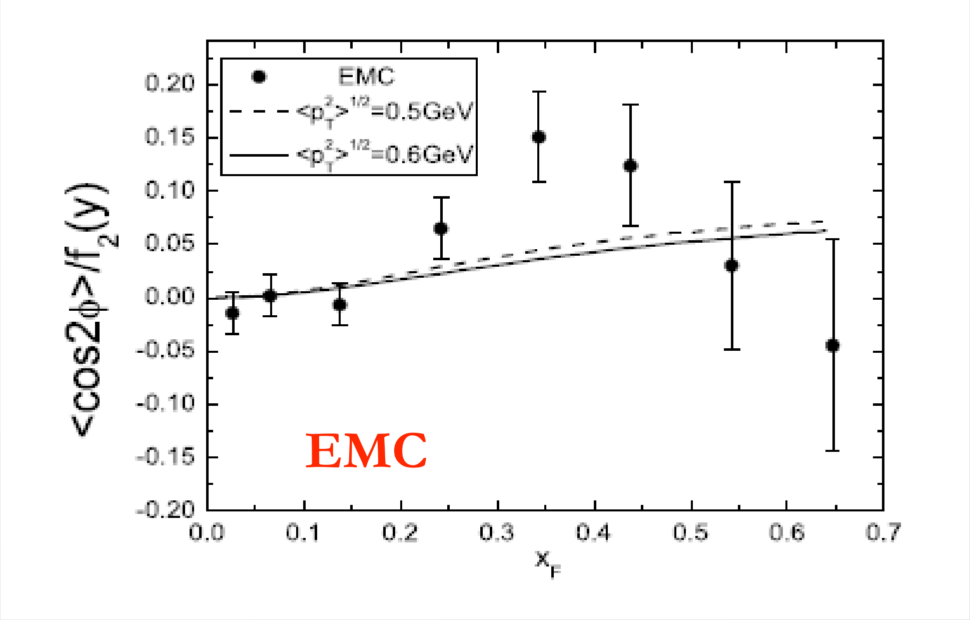
- Challenge: reconcile HERMES and COMPASS results
  - HERMES see dominance of Boer-Mulders in cos(2ϕ)
  - COMPASS sees dominance of Cahn in cos(ϕ) and cos(2ϕ)

Backup Slides

Existing Measurements

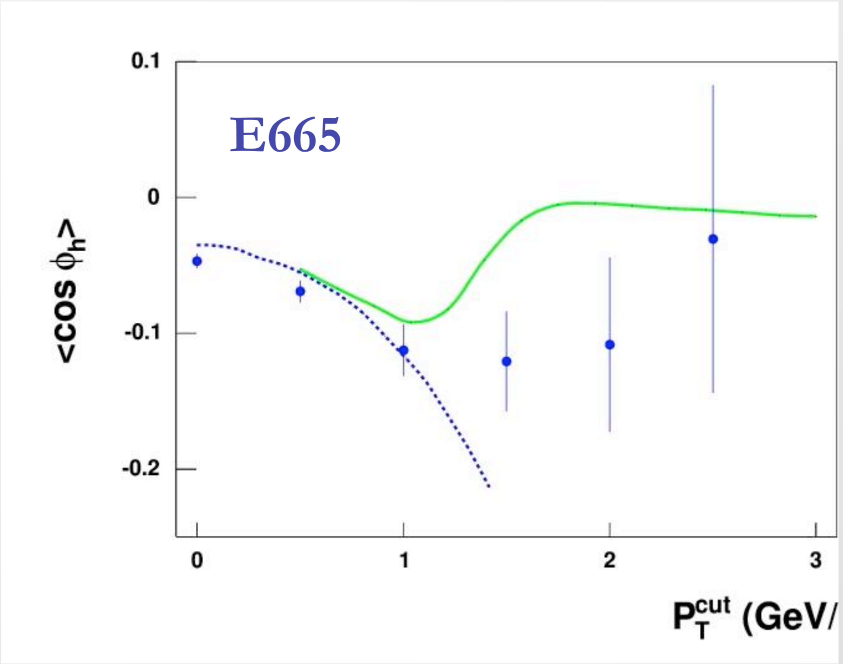
cos(2ϕ)

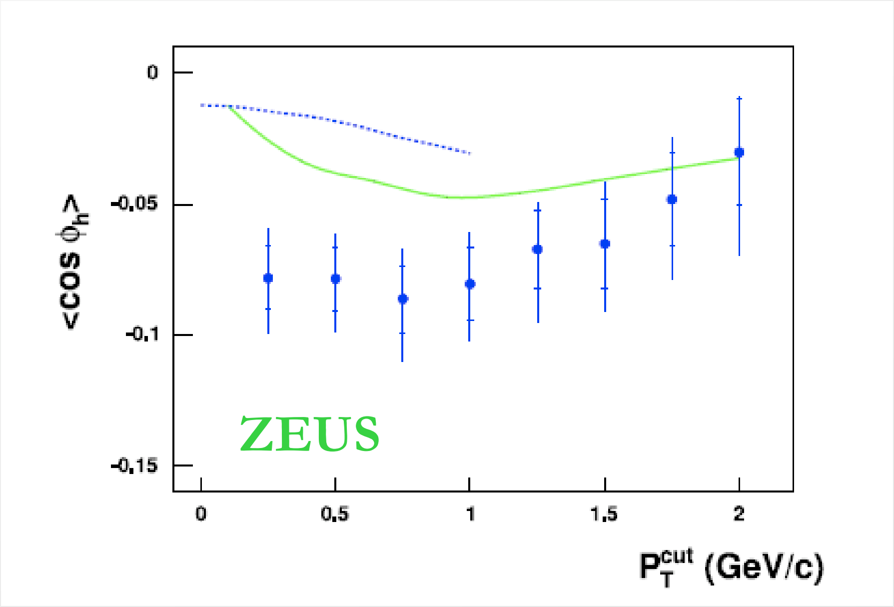


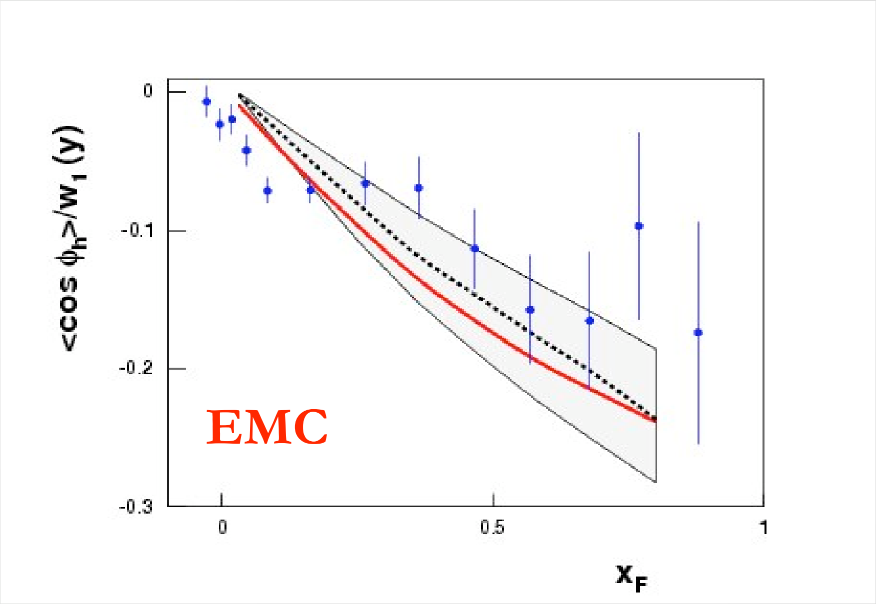


Existing Measurements

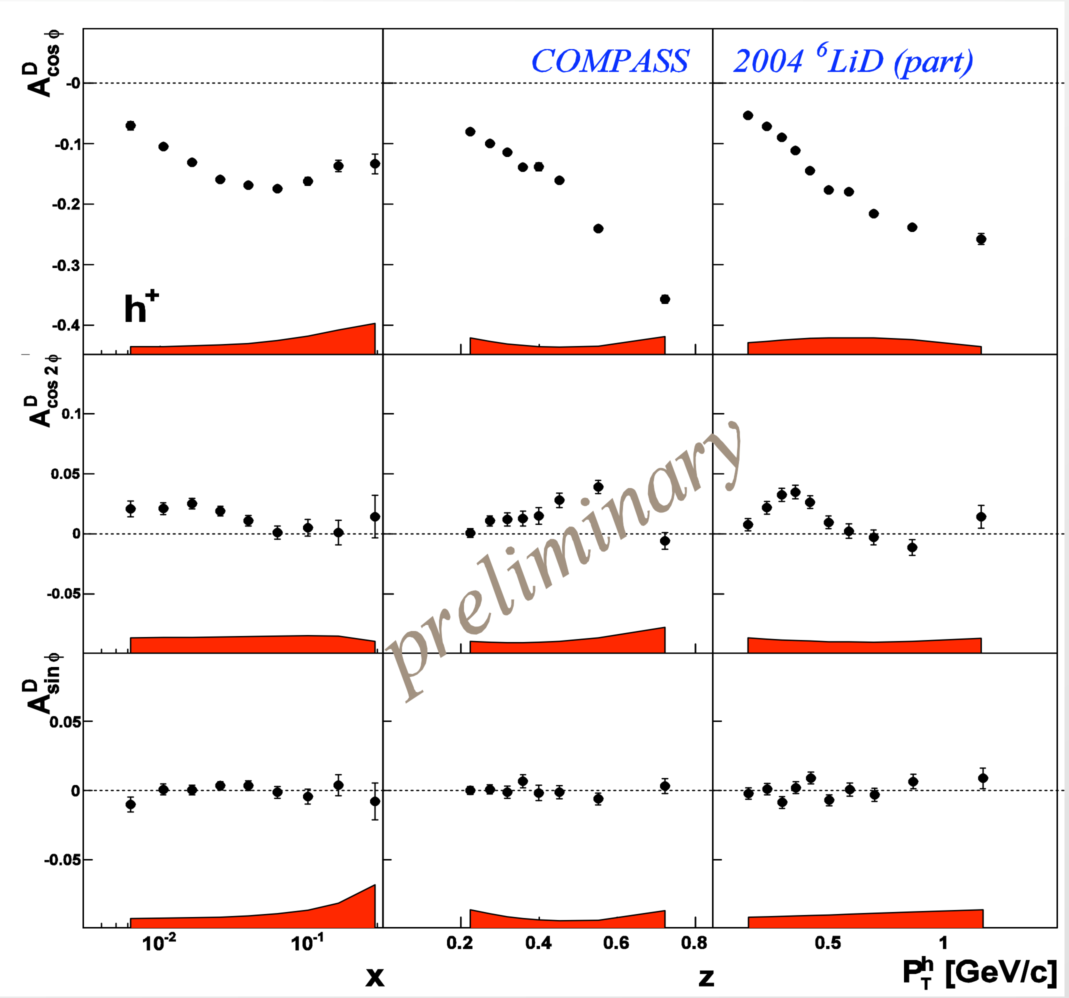
cos(ϕ)

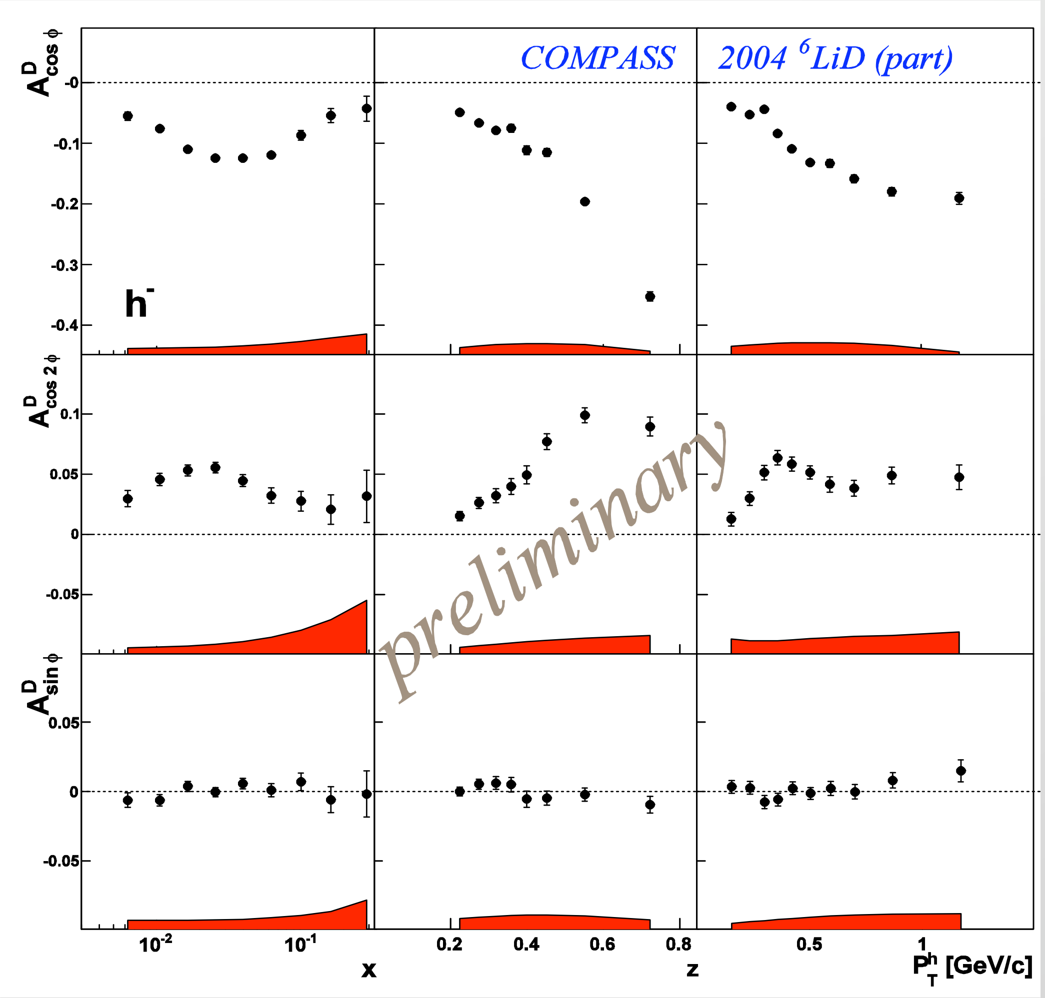




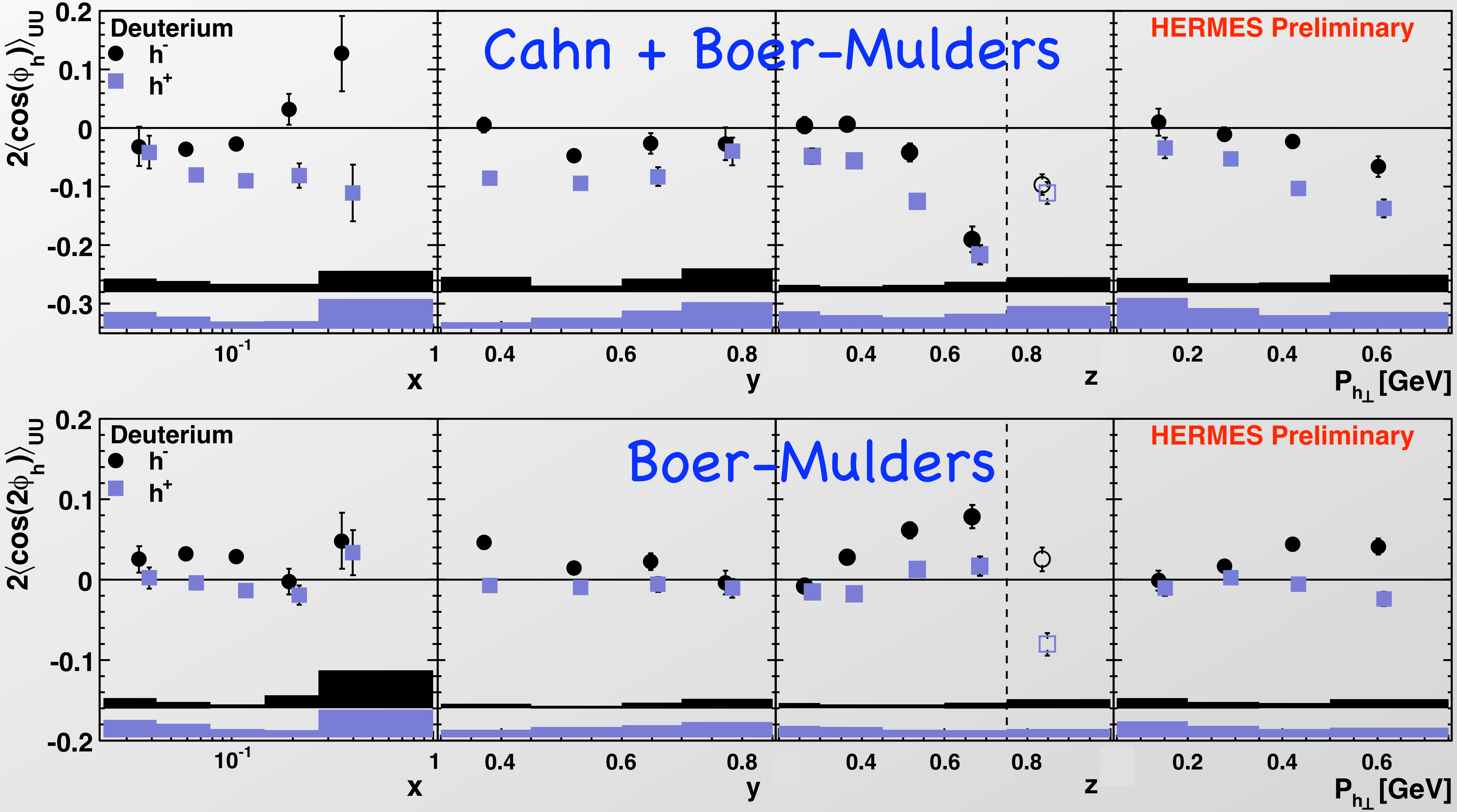


Existing Measurements





Deuterium h⁺ and h⁻ vs x, y, z, and $P_{h\perp}$

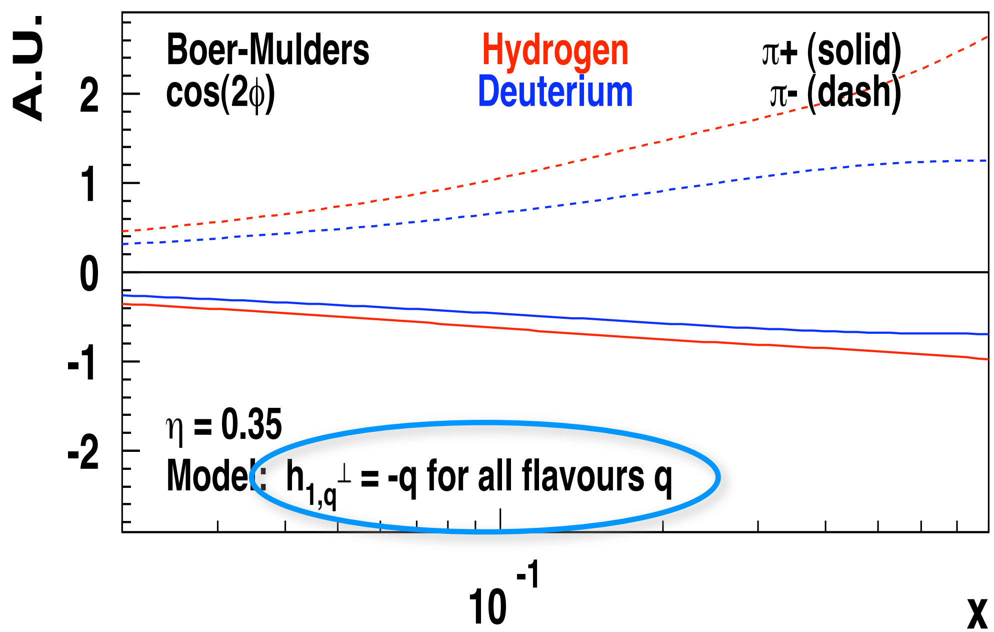


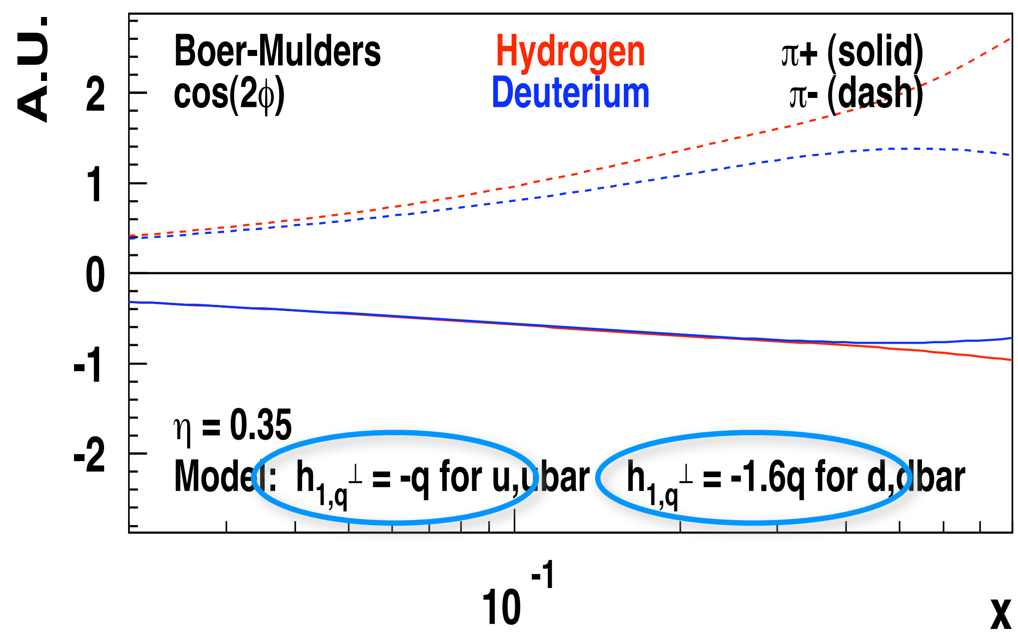
Back-of-envelope estimates for <cos(2Φ)>(x)

Using $\delta q(x) \equiv h^{\perp}_{1,q}(x)$ for convenience $\qquad \eta \equiv \frac{\int D_{1,\mathrm{disfav}}}{\int D_{1,\mathrm{fav}}} \simeq 0.35 \qquad \frac{\int H^{\perp}_{1,\mathrm{disfav}}}{\int H^{\perp}_{1,\mathrm{fav}}} = -1$

$$\langle\cos(2\phi)\rangle^{\pi^+}_H \sim \frac{4\delta u_v - \delta d_v}{4u + \eta d + 4\eta\bar{u} + \bar{d}} \qquad \langle\cos(2\phi)\rangle^{\pi^+}_D \sim \frac{3\delta u_v + 3\delta d_v}{(4+\eta)(u+d) + (4\eta+1)(\bar{u}+\bar{d})}$$

$$\langle\cos(2\phi)\rangle^{\pi^-}_H \sim \frac{-4\delta u_v + \delta d_v}{4\eta u + d + 4\bar{u} + \eta\bar{d}} \qquad \langle\cos(2\phi)\rangle^{\pi^-}_D \sim \frac{-3\delta u_v - 3\delta d_v}{(4\eta+1)(u+d) + (4+\eta)(\bar{u}+\bar{d})}$$





Hydrogen–Deuterium similarity → same sign for Boer-Mulders u & d!

cos(2Φ)

The Boer-Mulders distribution function

$$h_1^\perp(x, k_T) \otimes H_1^\perp(z, p_T) \;\rightarrow\; \cos(2\phi) \text{ modulation}$$

Boer-Mulders: correlation between S_q and L_q