COM… larised SIDIS

COMPASS

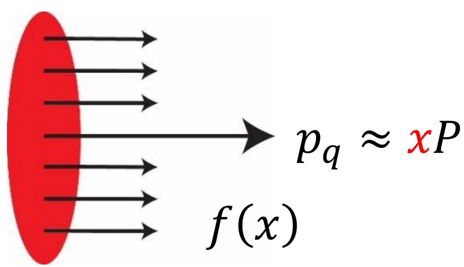
25th ANNIVERSARY

…adron Structure and

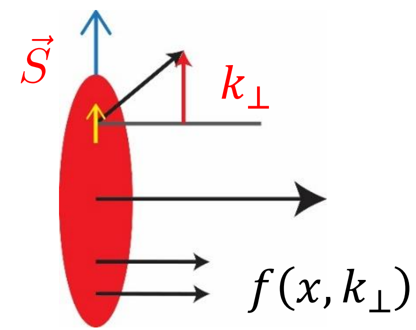
S…

Unpolarised Transverse Momentum dependent PDFs

- When we consider the transverse momentum of the quark in the calculation of the cross section Transverse Momentum Dependent parton distribution (TMDs)



Longitudinal motion only



Longitudinal + transverse motion

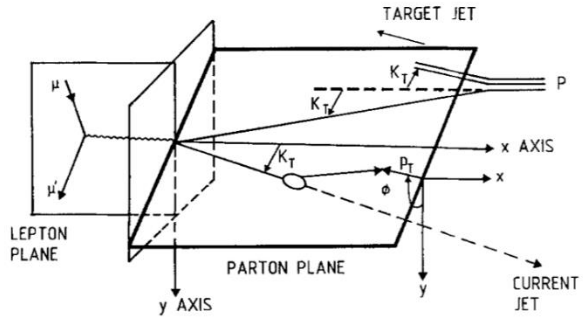
- The unpolarised number density of the quarks gains a dependence from the intrinsic transverse momentum $k_\perp$

$$f_1^q(x, k_\perp)$$

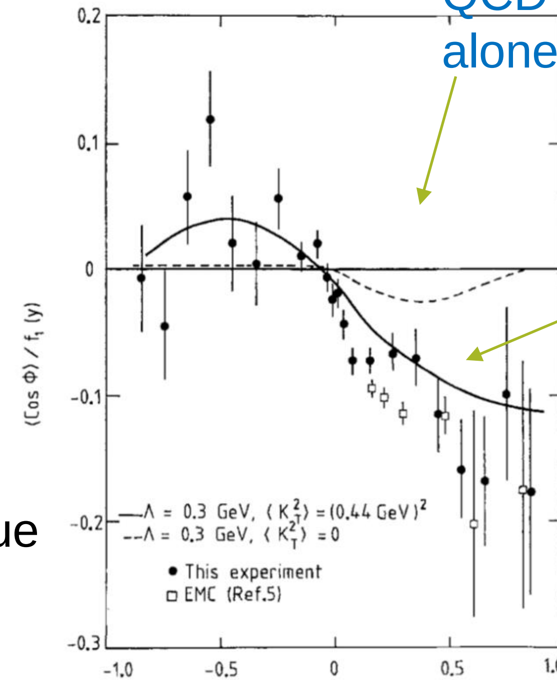
- New parton densities arise: the Boer-Mulders functions $h_1^{\perp,q}(x, k_\perp)$, describing the correlation between the intrinsic quark transverse momentum and the spin of the quark in an unpolarised nucleon

$$f_{q\uparrow}(x, k_\perp, \vec{s}) = f_1^q(x, k_\perp) - \frac{1}{M} h_1^{\perp,q}(x, k_\perp) \vec{s} \cdot (\hat{p} \times \vec{k}_\perp)$$

Intrinsic transverse motion; an old story



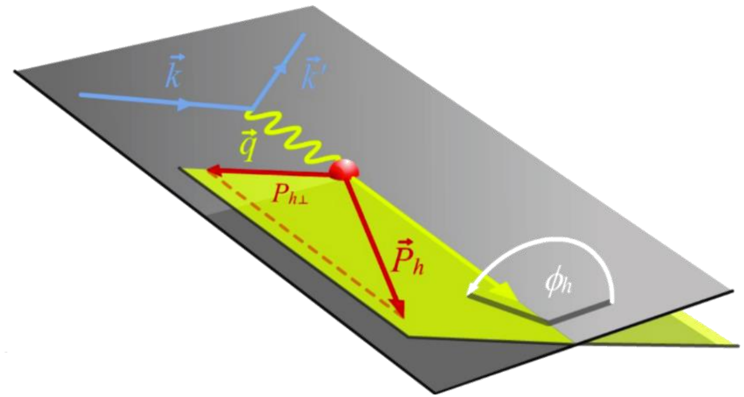
- Cross section for SIDIS process expected to be
$$d\sigma \sim \sigma_0[1 + A\cos\phi_h + B\cos 2\phi_h]$$
- Georgi and Politzer [1978]: azimuthal modulations of hadrons around the jet axis due to gluon radiation. Effect regarded as a clean QCD test [*Phys.Rev.Lett.* 40 (1978) 3].
- R.N. Cahn [1978]: same modulations can arise due to the quark intrinsic motion ($k_\perp$) [*Phys.Lett.B* 78 (1978) 269]



EMC experiment [1987]
Fit: Konig-Kroll model [1982]
+ Lund String

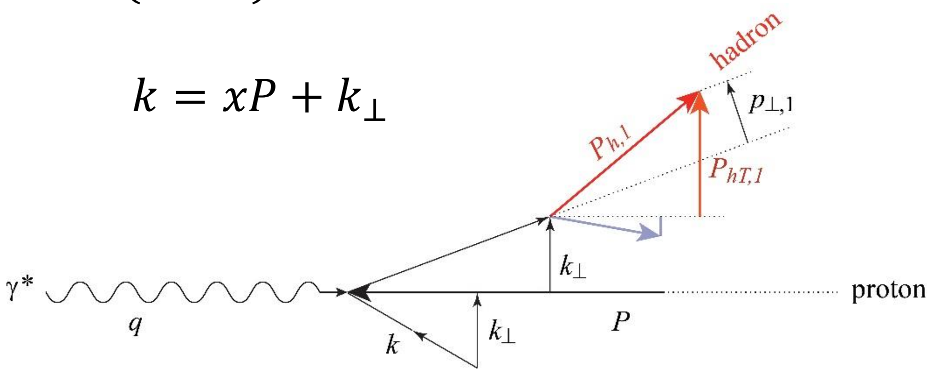
Unpolarised Azimuthal Modulation

The cross-section is $d\sigma^{\ell p\to\ell' hX} = \sum_q f_q(x,Q^2) \otimes d\sigma^{\ell q\to\ell' q} \otimes D_q^h(z,Q^2)$ with the partonic process is given by $d\sigma^{\ell q\to\ell' q} = \hat{s}^2 + \hat{u}^2$



$$\hat{s} \coloneqq (\ell + k)^2 \sim 2\ell \cdot k$$
$$\hat{u} \coloneqq (\ell - k)^2 \sim -2\ell \cdot k$$

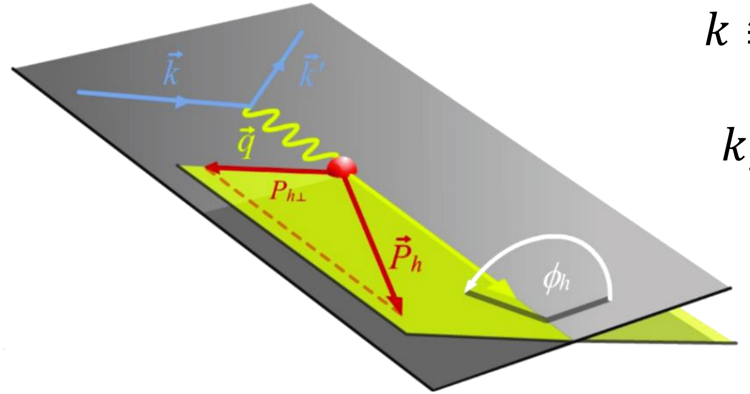
$$k = xP + k_\perp$$



In collinear PM $d\sigma^{\ell q\to\ell' q} = \hat{s}^2 + \hat{u}^2 = x[1 + (1-y)^2]$, i.e. no ϕ_h dependence.

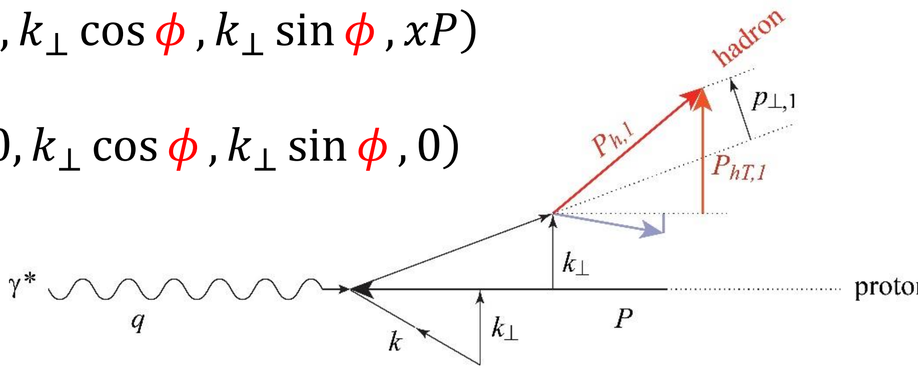
Unpolarised Azimuthal Modulation

When $k_\perp$ is taken into account:



$$k \cong (xP, k_\perp \cos\phi, k_\perp \sin\phi, xP)$$

$$k_\perp \cong (0, k_\perp \cos\phi, k_\perp \sin\phi, 0)$$



$$\hat{s} = sx\left[1 - \frac{2k_\perp}{Q}\sqrt{1-y}\cos\phi\right] + \mathcal{O}\left(\frac{k_\perp^2}{Q}\right) \quad \hat{u} = sx(1-y)\left[1 - \frac{2k_\perp}{Q\sqrt{1-y}}\cos\phi\right] + \mathcal{O}\left(\frac{k_\perp^2}{Q}\right)$$

and

$$d\sigma^{\ell q \to \ell' q} \propto \hat{s}^2 + \hat{u}^2 \propto \left[1 - \frac{2k_\perp}{Q}\sqrt{1-y}\cos\phi\right]^2 + (1-y)^2\left[1 - \frac{2k_\perp}{Q\sqrt{1-y}}\cos\phi\right]^2,$$

Resulting in the $\cos\phi_h$ and $\cos 2\phi_h$ modulations observed in the azimuthal distributions

Cahn: Phys.Lett.B 78 (1978) 269

These effects can be estimated by adopting a model for the transverse momentum distribution of partons in a hadron and for the transverse momentum given to hadrons in the quark decay. Suppose that both these distributions are gaussian:

$$f(x, p_\perp) \propto e^{-ap_\perp^2}, \qquad D(z, p_\perp) \propto e^{-bp_\perp^2}, \qquad (16a, b)$$

where f represents the quark distribution and D the fragmentation function. Let the z-direction be defined as in fig. 1. Then the longitudinal momentum of the struck parton is xP and that of the observed hadron is zxP. If the transverse momentum of the struck parton is $\boldsymbol{p}_{1\perp}$ and that of the observed hadron is $\boldsymbol{p}_\perp$, then the momentum of the observed hadron transverse to the parton direction is (for $zxP \gg |\boldsymbol{p}_{1\perp}|, |\boldsymbol{p}_\perp|$) just $\boldsymbol{p}_\perp - z\boldsymbol{p}_{1\perp}$.

Semi Inclusive unpolarised DIS Cross Section

The account of the transverse motion of the quark result in the following general form of the unpolarised semi-inclusive deep inelastic cross-section

$$\frac{d^5\sigma}{dxdydzdP_{hT}^2 d\phi_h} = \frac{\alpha^2}{xyQ^2}\left[(1-y)+\frac{y^2}{2}\right]F_2(x,Q^2)\times$$
$$M_{UU}^h\left\{1+\frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}A_{UU}^{\cos\phi_h}\cos\phi_h+\frac{2(1-y)}{1+(1-y)^2}A_{UU}^{\cos 2\phi_h}\cos 2\phi_h\right\}$$

Where we have introduced the amplitude of the azimuthal asymmetries as

$$A_{UU}^{\cos X\phi_h}(x,z,P_{hT}^2;Q^2)=\frac{F_{UU}^{\cos X\phi_h}(x,z,P_{hT}^2;Q^2)}{F_{UU}^h(x,z,P_{hT}^2;Q^2)}$$

An the angular independent ratio

$$M_{UU}^h(x,z,P_{hT}^2;Q^2)=\frac{F_{UU}^h(x,z,P_{hT}^2;Q^2)}{F_2(x,Q^2)}$$

Experimentally these are more difficult measurements than spin asymmetries, since we have to correct for the apparatus acceptance

Unpolarised Azimuthal Modulation

When looking at the content of the structure functions/modulations in terms of TMD PDFs for the $\cos\phi_h$ and $\cos 2\phi_h$ we can write:

$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q} C\left[\frac{\hat{h}\cdot\vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M}\frac{\vec{P}_{hT} - z\left(\hat{h}\cdot\vec{k}_\perp\right)}{zM_h M} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

$$F_{UU}^{\cos 2\phi_h} = C\left[\frac{\left(\hat{h}\cdot\vec{k}_\perp\right)\left(\hat{h}\cdot\vec{p}_\perp\right) - \vec{p}_\perp\cdot\vec{k}_\perp}{MM_h} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

In the $\cos 2\phi_h$ Cahn effects enters only at twist4

$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$

1D vs multi D

- The asymmetries are:

$$A_{UU}^{w(\phi_h)}(x, z, P_{hT}^2; Q^2) = \frac{F_{UU}^{w(\phi_h)}}{F_2(x, Q^2)}$$

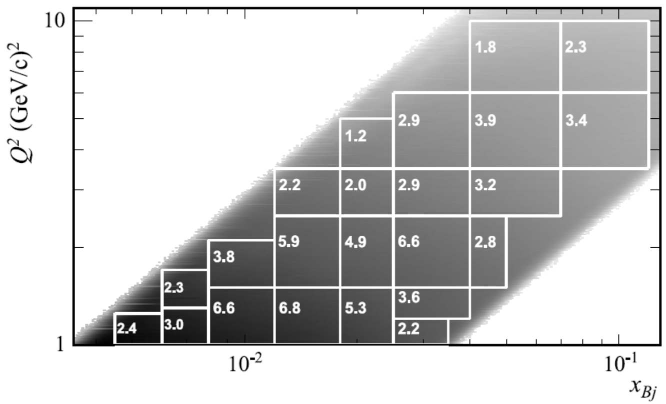
- When we measure on 1D, i.e. as a function of x, we integrate over the phase space of the other variables

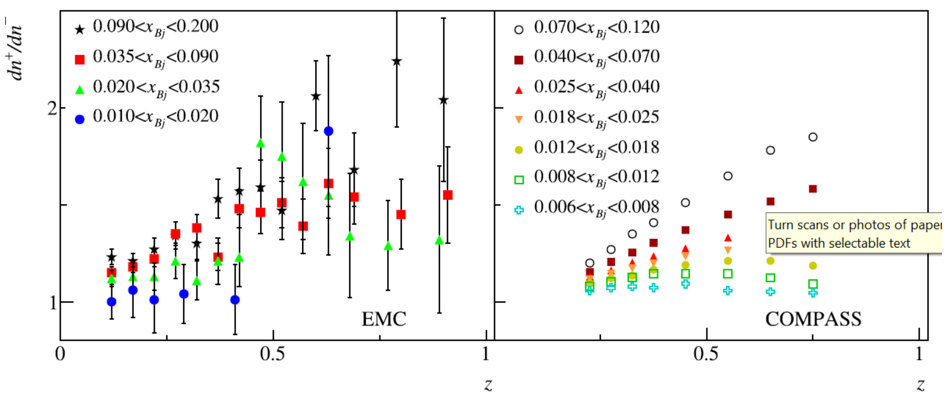
$$A_{UU}^{w(\phi_h)}(x) = \frac{\int_{Q_{min}^2}^{Q_{max}^2} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} dP_{hT}^2 F_{UU}^{w(\phi_h)}}{\int_{Q_{min}^2}^{Q_{max}^2} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} dP_{hT}^2 \left(F_2(x, Q^2)\right)}$$

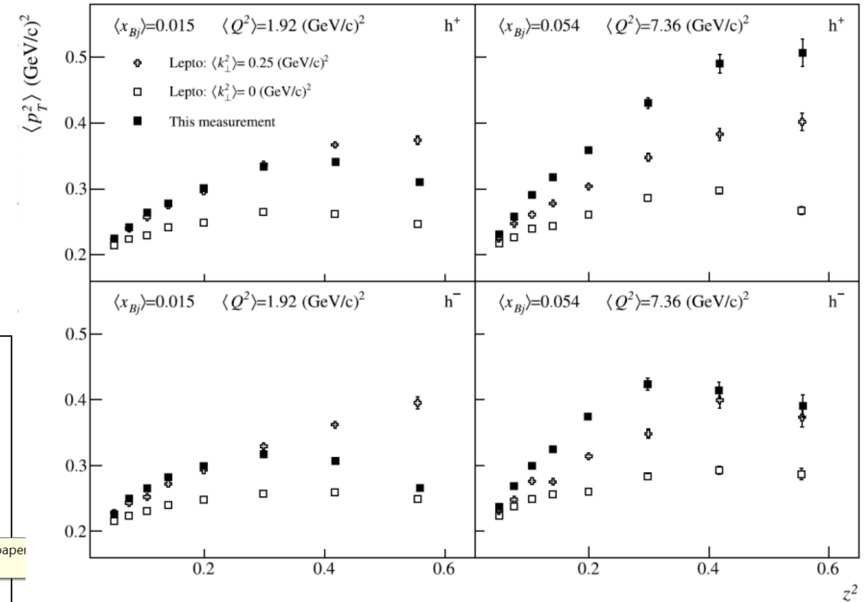
Covered Results

- Hadron transverse momentum distributions in muon deep inelastic scattering at 160 GeV/c, **Eur. Phys. J. C (2013) 73:2531**
- Measurement of azimuthal hadron asymmetries in semi-inclusive deep inelastic scattering off unpolarised nucleons, **Nuclear Physics B 886 (2014) 1046–1077**
- Transverse-momentum-dependent multiplicities of charged hadrons in muon-deuteron deep inelastic scattering**, PHYSICAL REVIEW D 97, 032006 (2018)**
- Contribution of exclusive diffractive processes to the measured azimuthal asymmetries in SIDIS, **Nuclear Physics B 956 (2020) 115039**
- Preliminary results from 2016 with a proton target

1st publication on P_{hT} distributions;







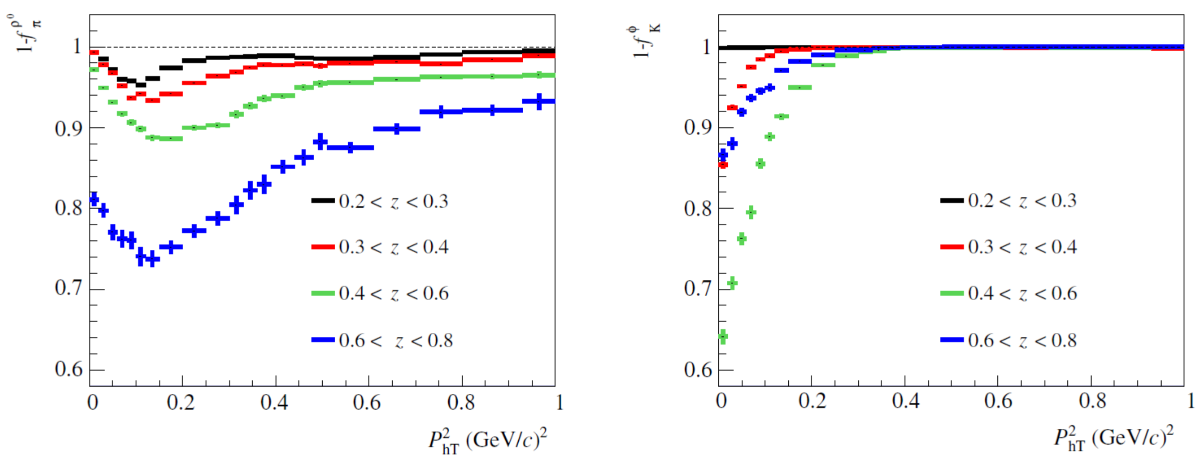
2nd publication on P_{hT} distributions;

Improved binning

TABLE I. Bin limits for the four-dimensional binning in x, Q^2, z and $P^2_{\rm hT}$.

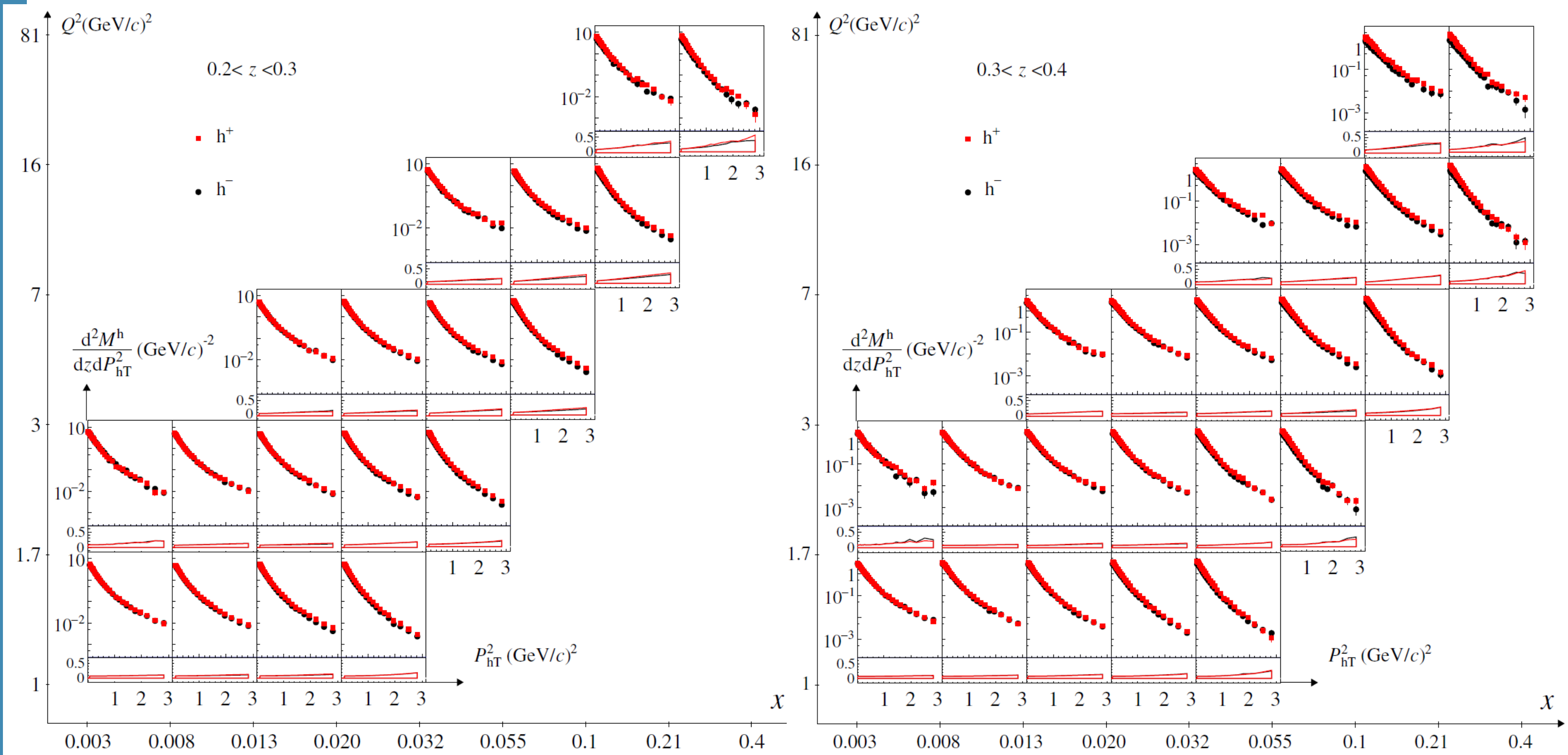
	Bin limits								
x	0.003	0.008	0.013	0.02	0.032	0.055	0.1	0.21	0.4
Q^2 $({\rm GeV}/c)^2$	1.0	1.7	3.0	7.0	16	81			
z	0.2	0.3	0.4	0.6	0.8				
$P^2_{\rm hT}$ $({\rm GeV}/c)^2$	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.17	0.196
	0.23	0.27	0.30	0.35	0.40	0.46	0.52	0.60	0.68
	0.76	0.87	1.00	1.12	1.24	1.38	1.52	1.68	1.85
	2.05	2.35	2.65	3.00					

Subtraction of Diffractive Vector Mesons

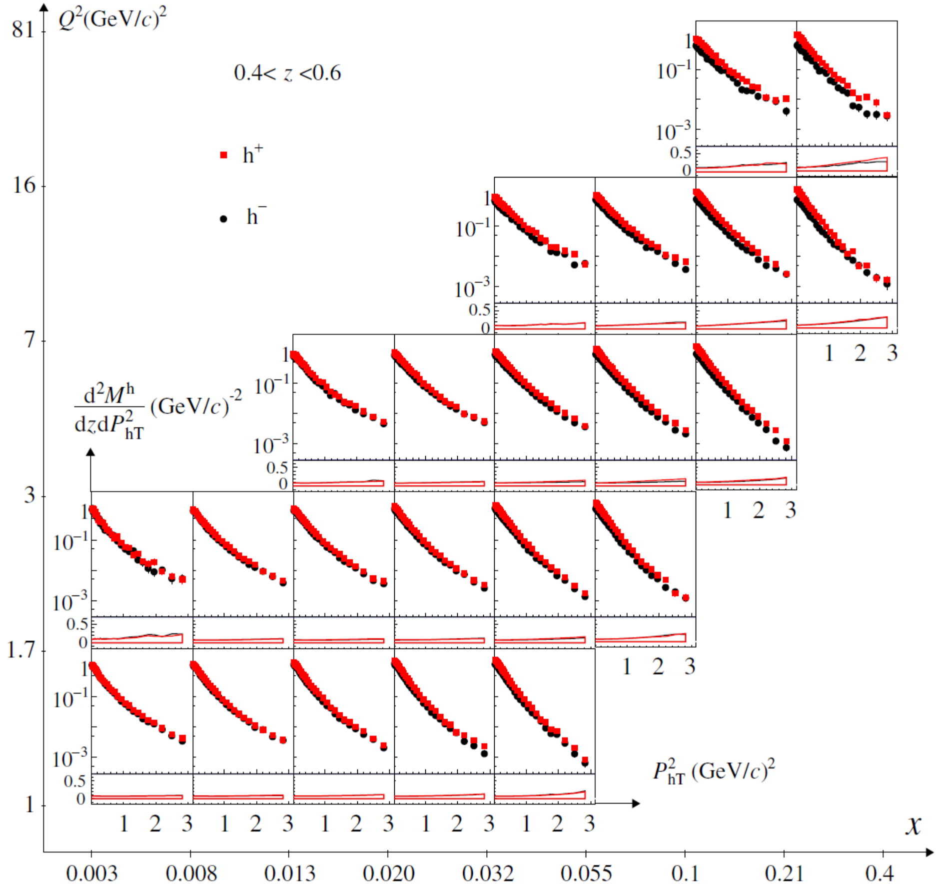


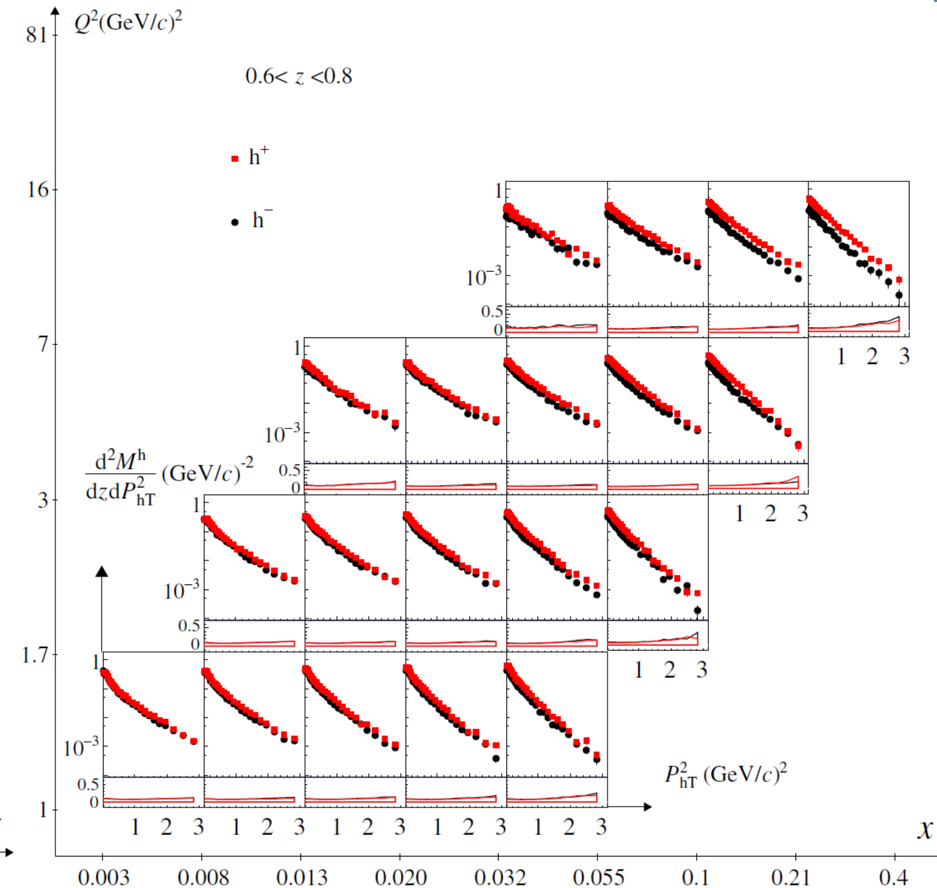
(a) (b)

2nd publication on P_{hT} distributions;



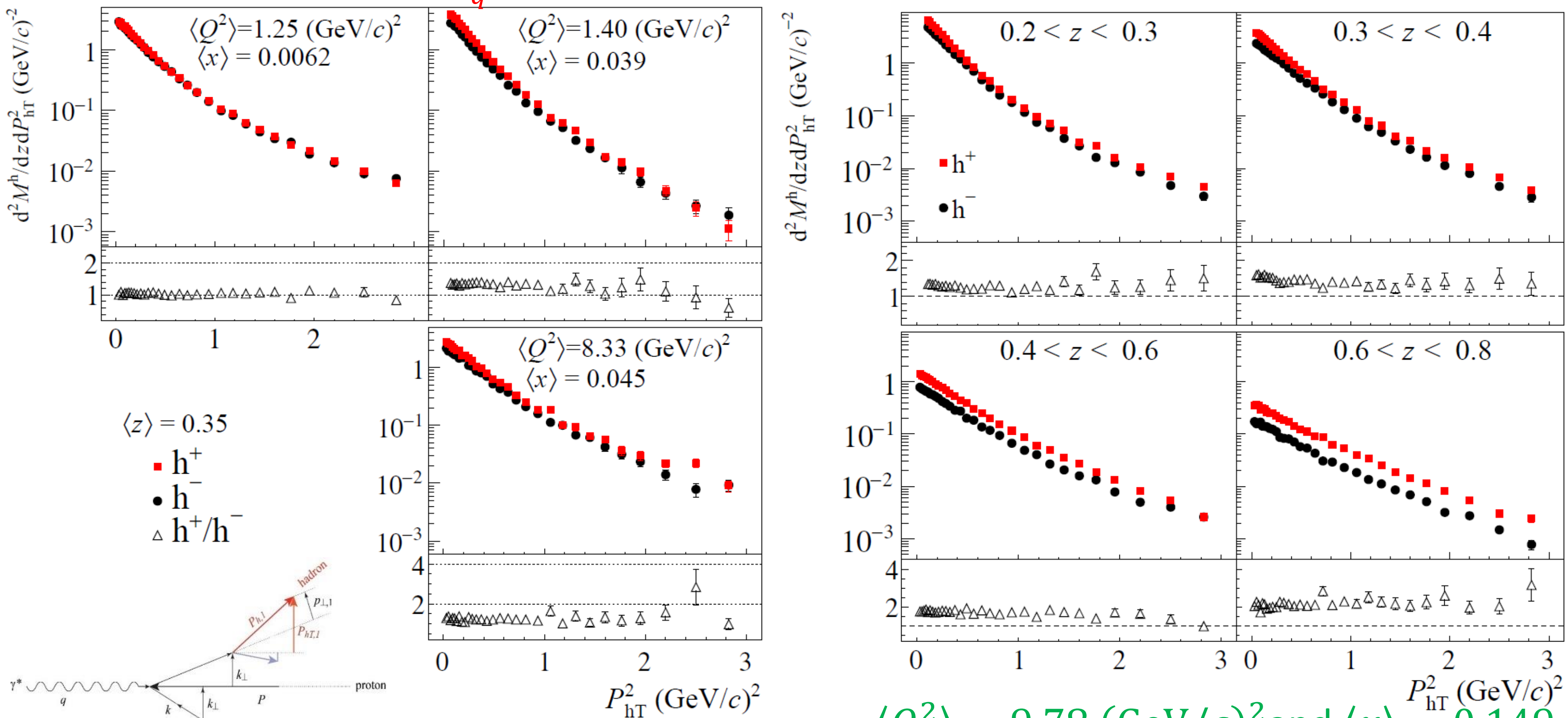
2nd publication on P_{hT} distributions;





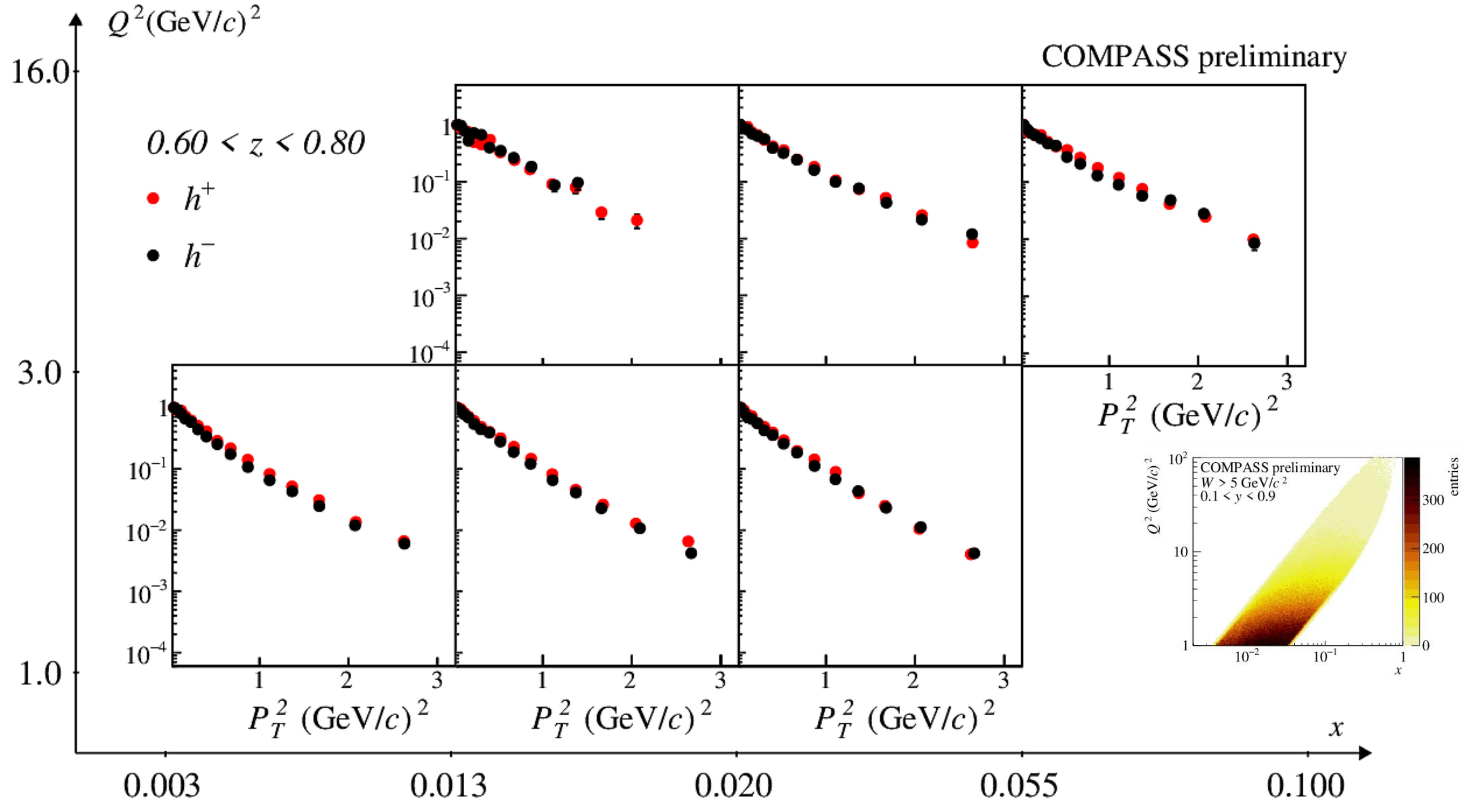
Positive vs Negative charged hadrons (^{6}LiD)

$$F_{UU}^{h}(x,z,P_{hT}^{2};\,Q^{2}) = x\sum_{q} e_q^2 \int d^2\vec{k}_{\perp} d^2\vec{p}_{\perp}\delta(\vec{p}_{\perp} + z\vec{k}_{\perp} - \vec{P}_{hT})\; f_1^q(x,k_{\perp}^2;Q^2) D_1^{q\to h}(z,p_{\perp}^2;Q^2)$$

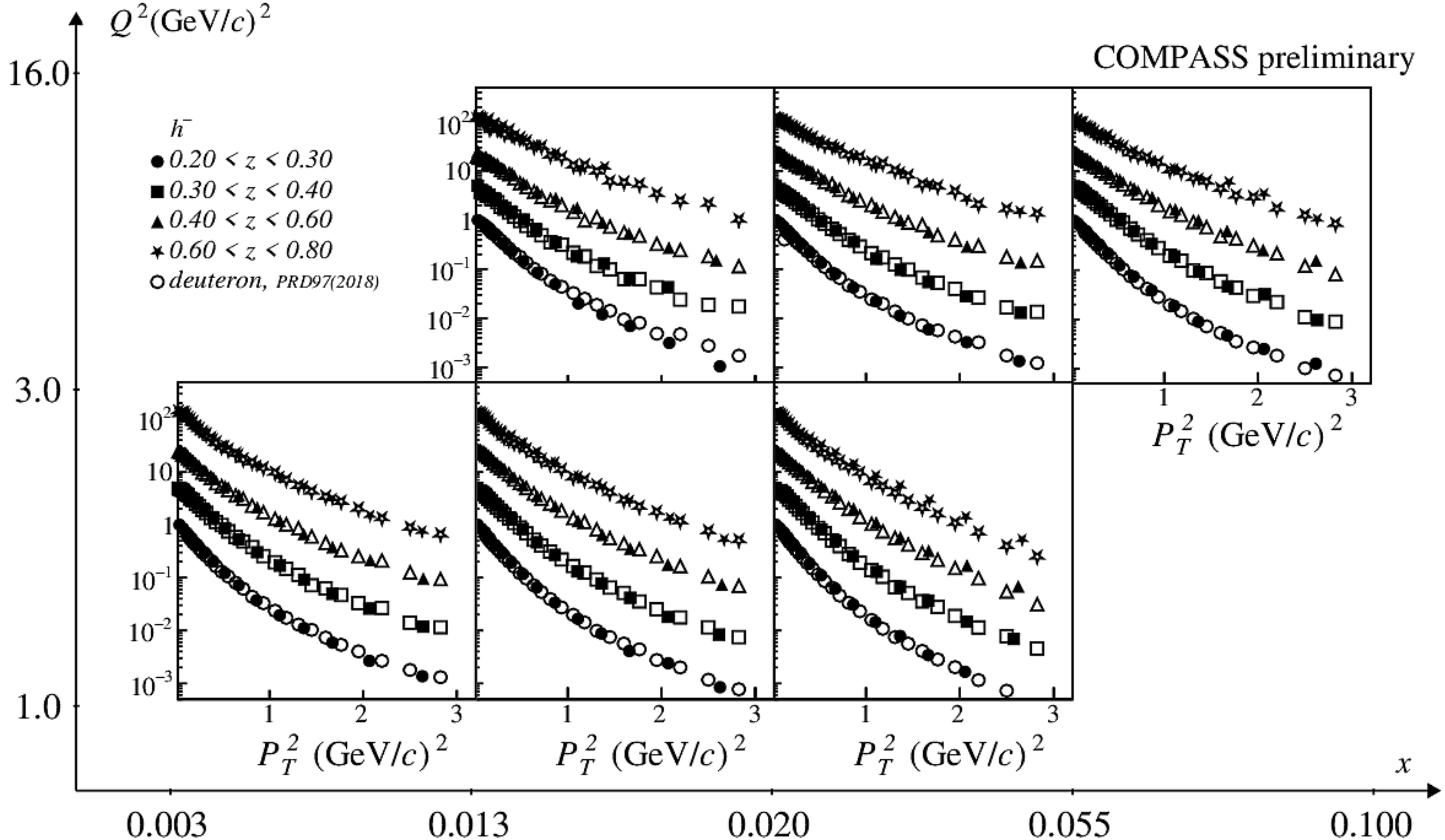


$\langle Q^2\rangle = 9.78\ (\mathrm{GeV}/c)^2$ and $\langle x\rangle = 0.149$

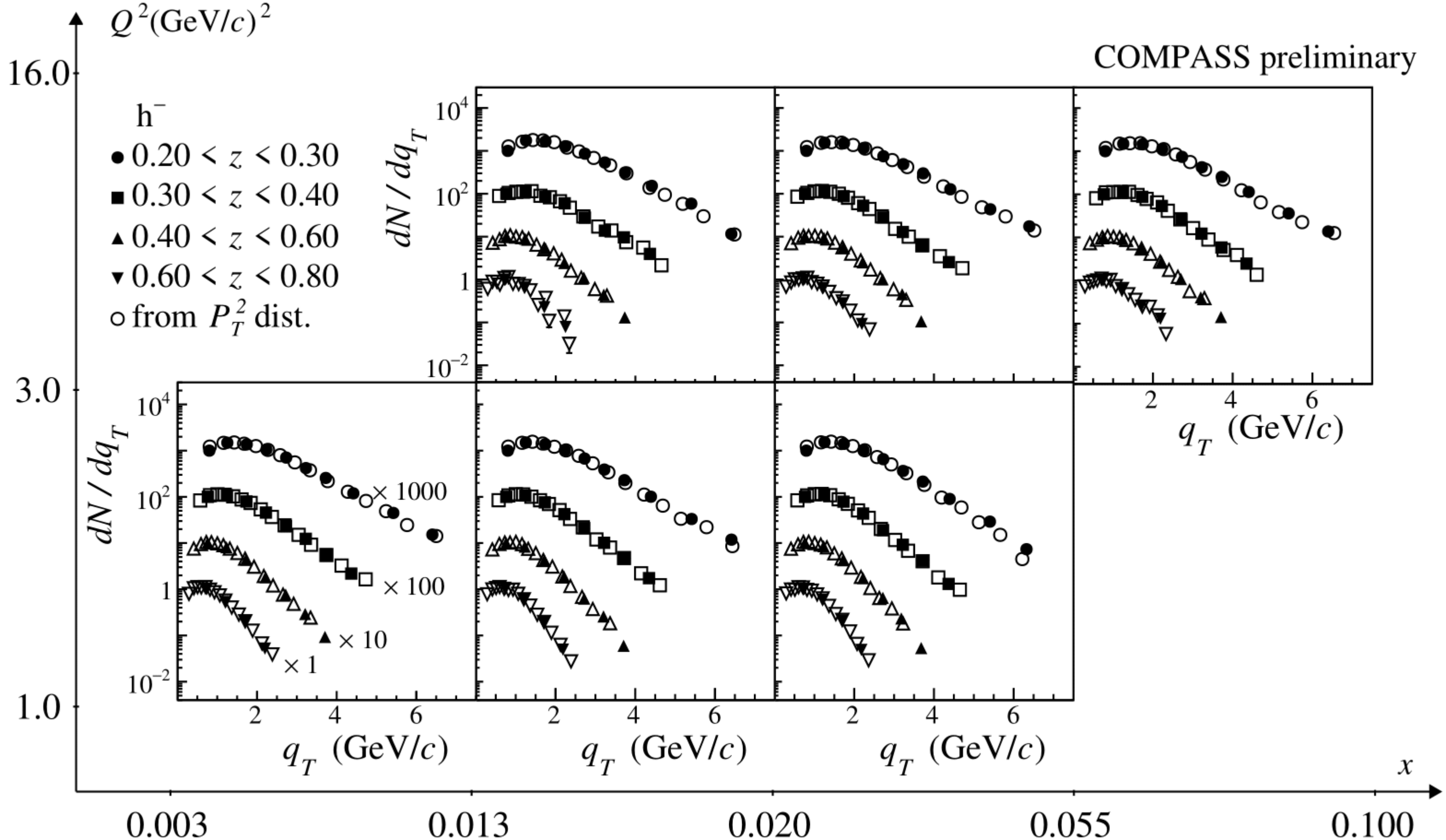
Positive vs Negative charged hadrons (LH_2)



Comparison with the publish deuteron

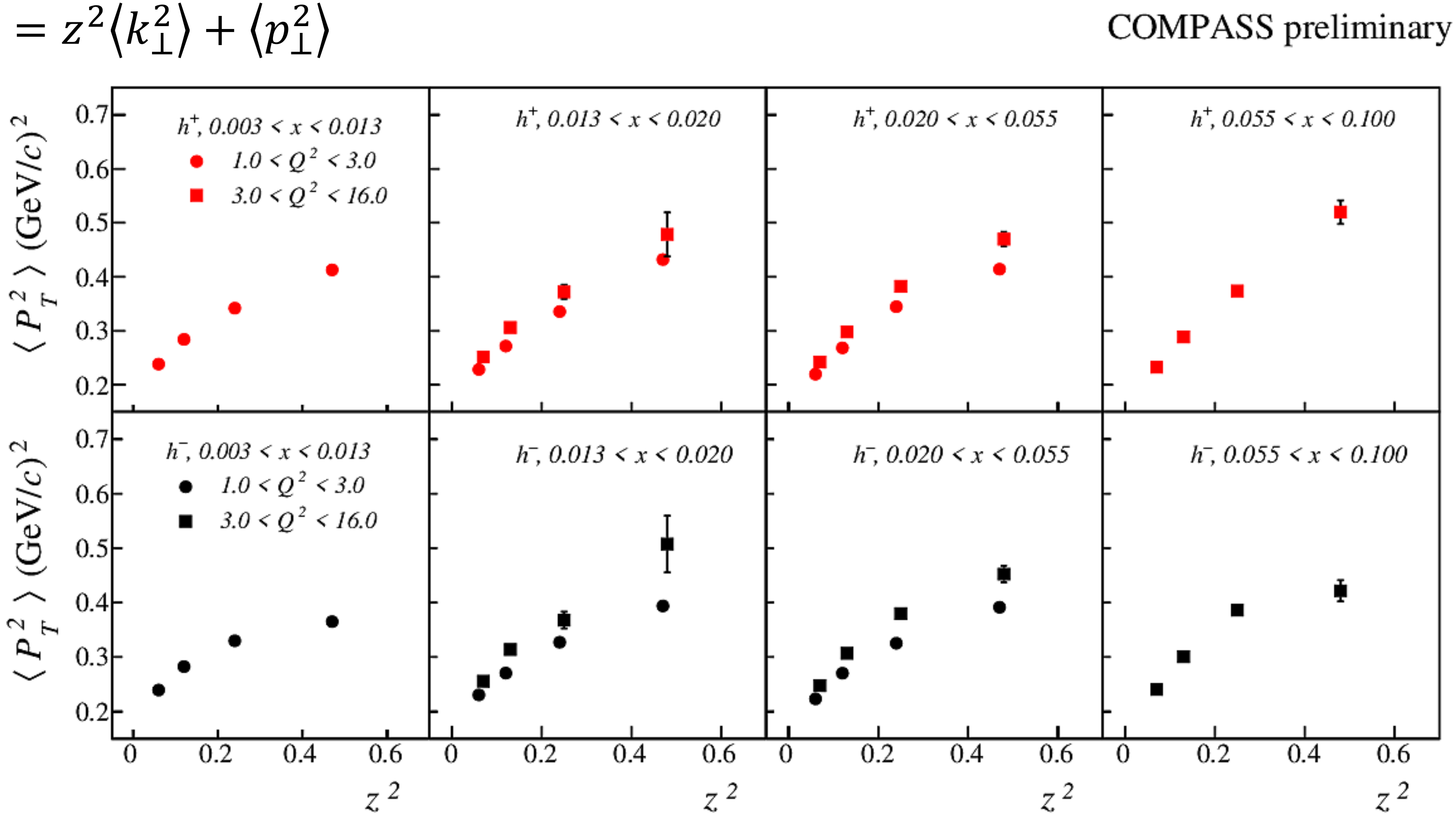


q_T distributions



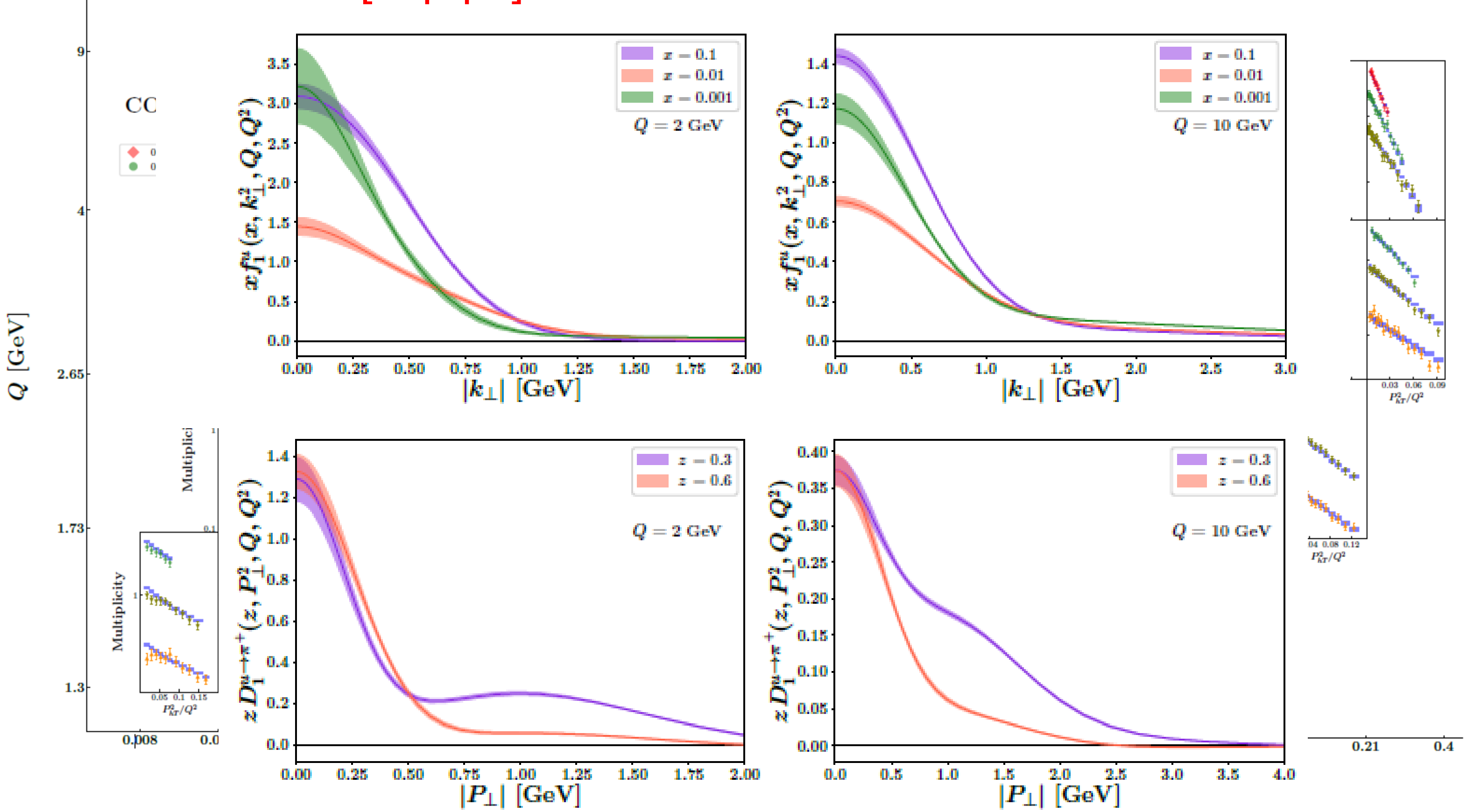
Slope dependence

A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
$\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$



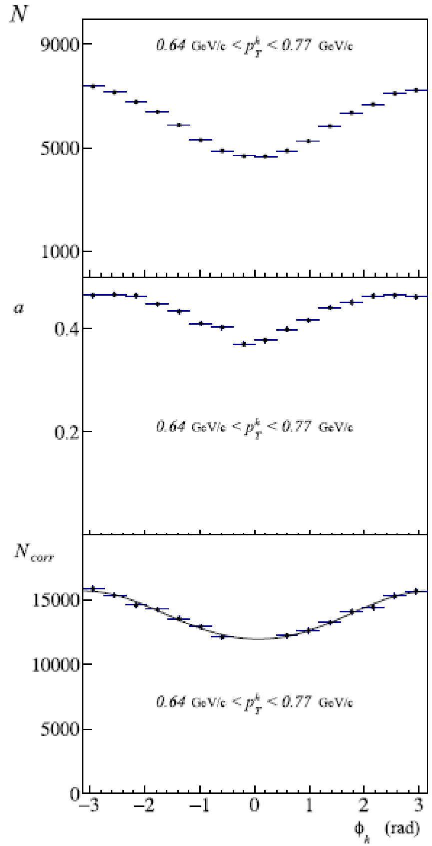
Phenomenological fits

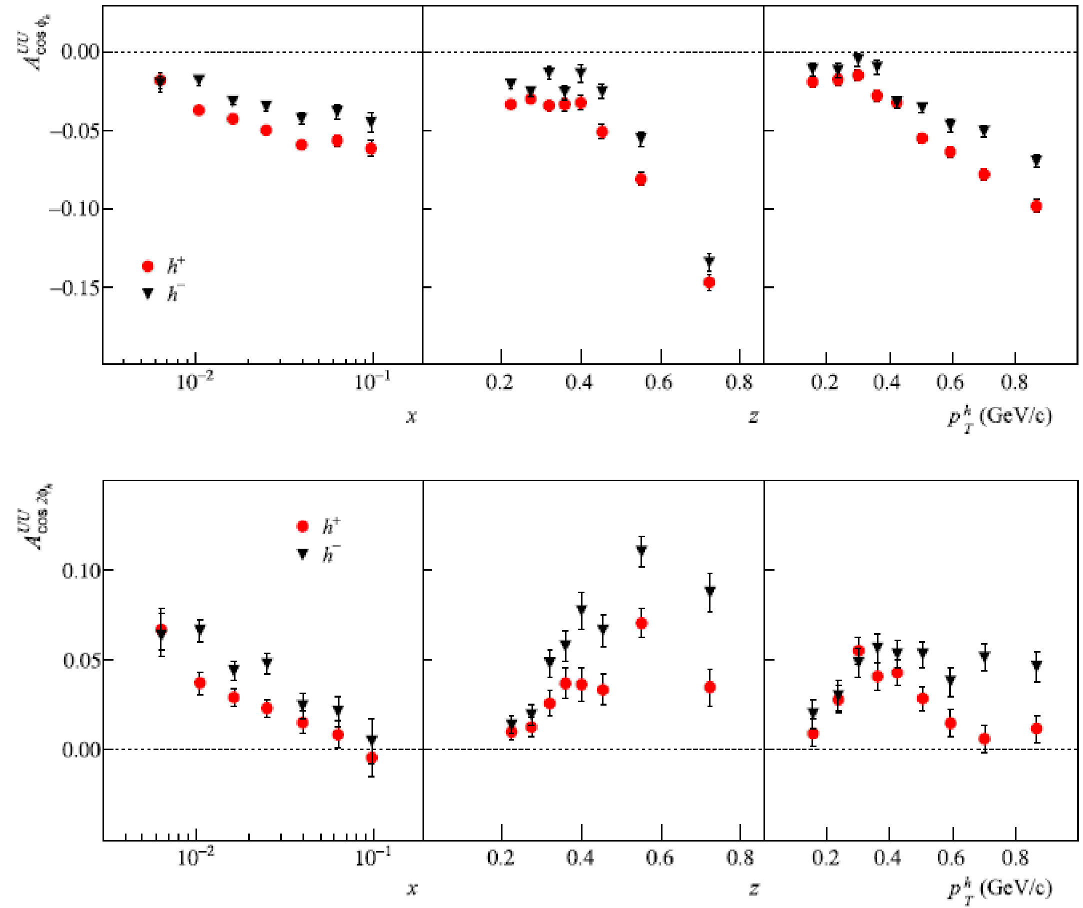
arXiv:2206.07598v1 [hep-ph] 15 Jun 2022



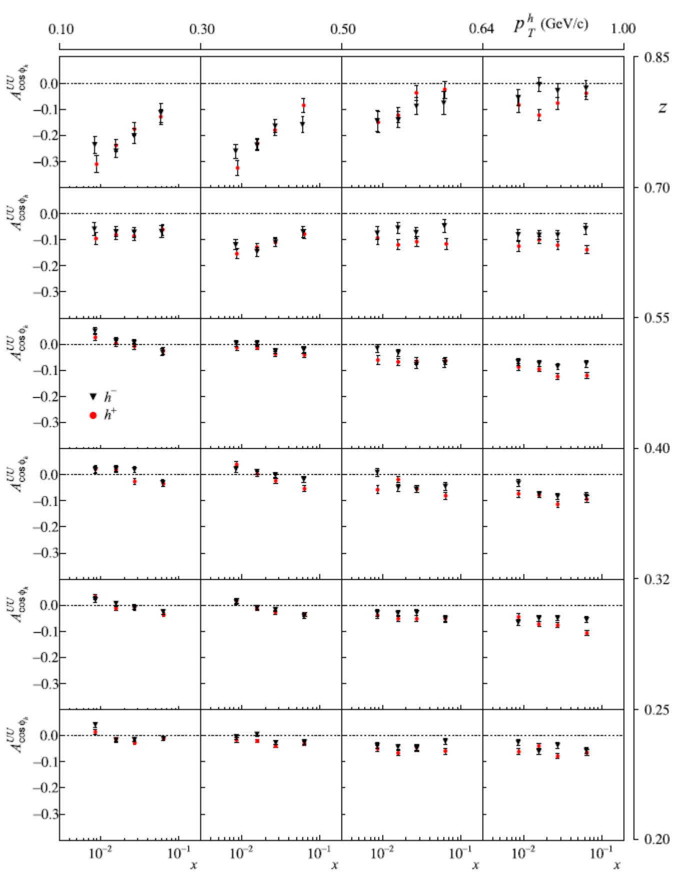
Azimuthal modulations on ^{6}LiD

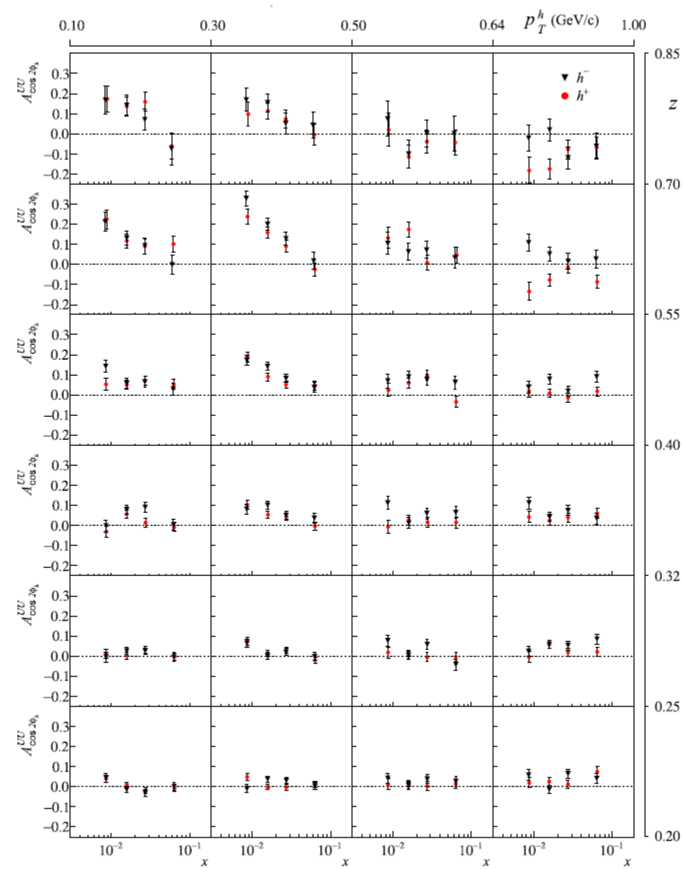
C. Adolph et al. / Nuclear Physics B 886 (2014) 1046–1077



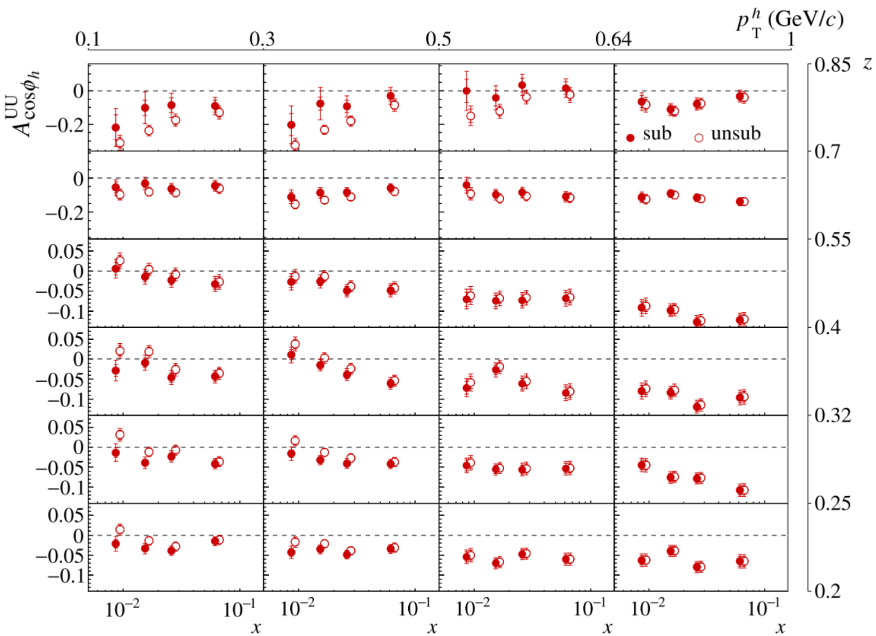


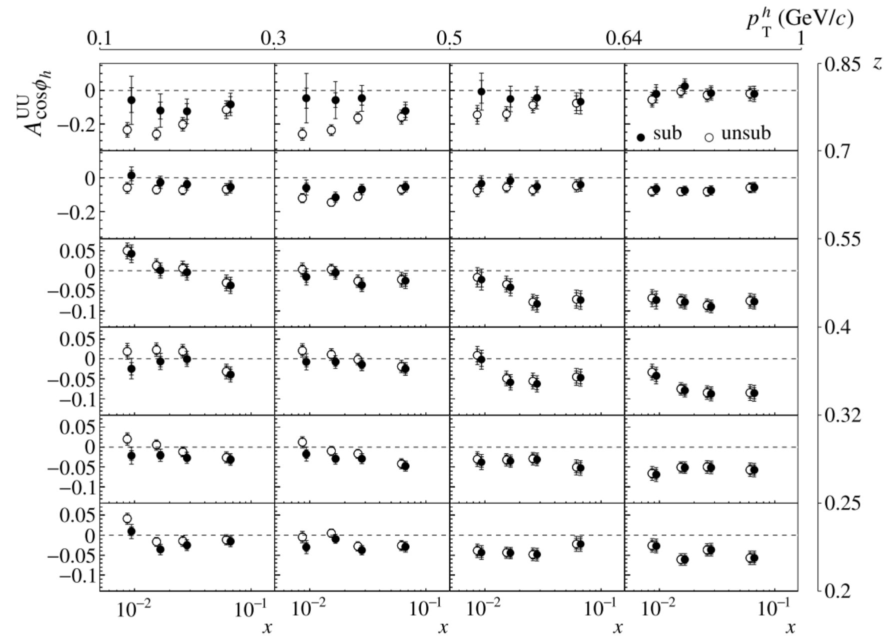
Azimuthal modulations on ^{6}LiD



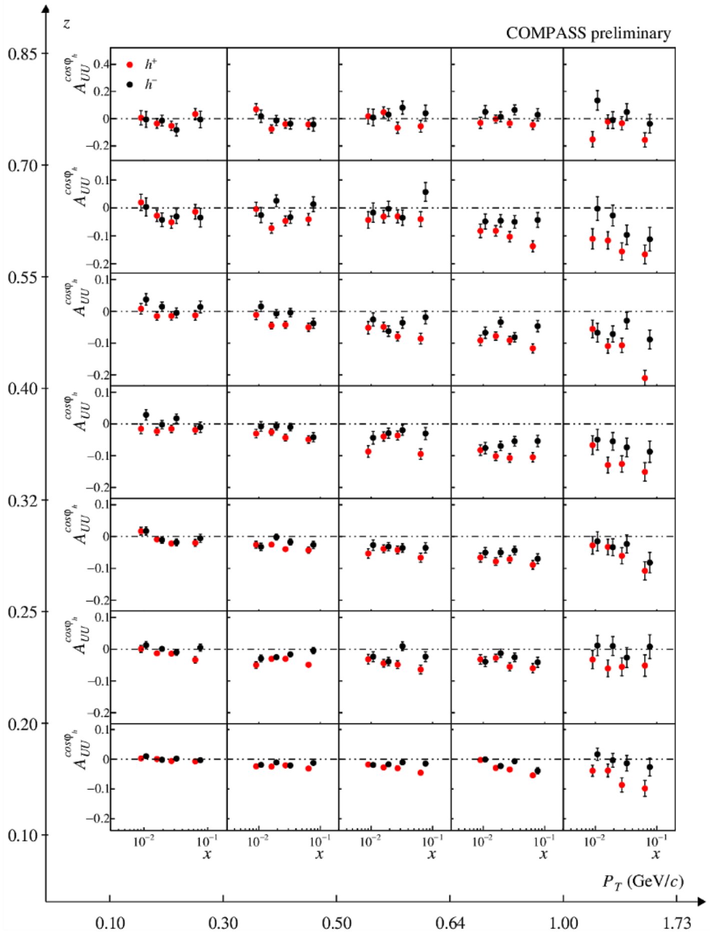


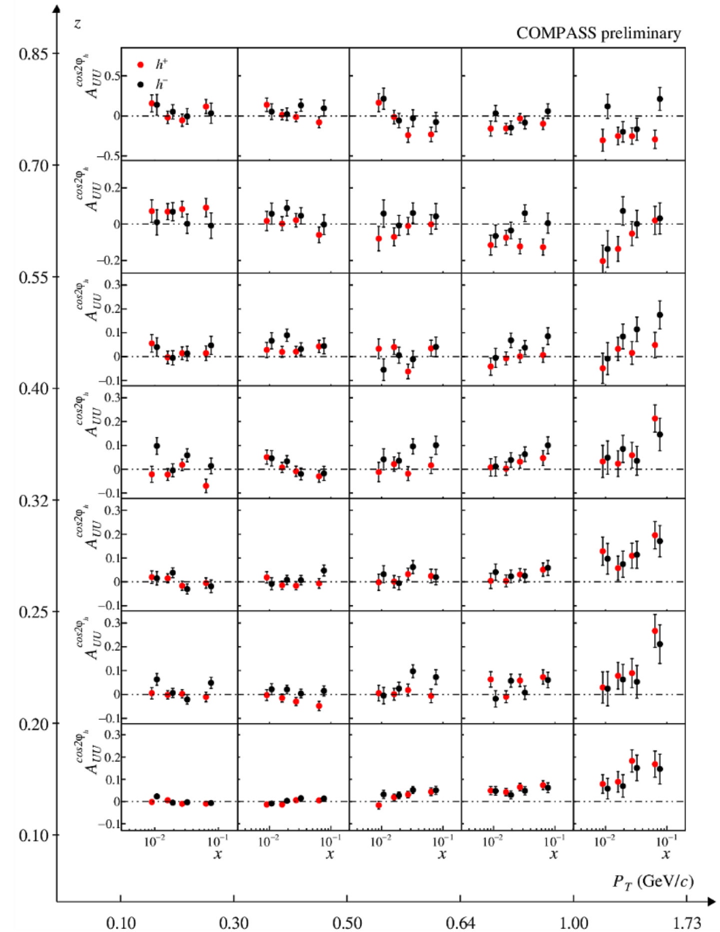
VM subtraction from ^{6}LiD



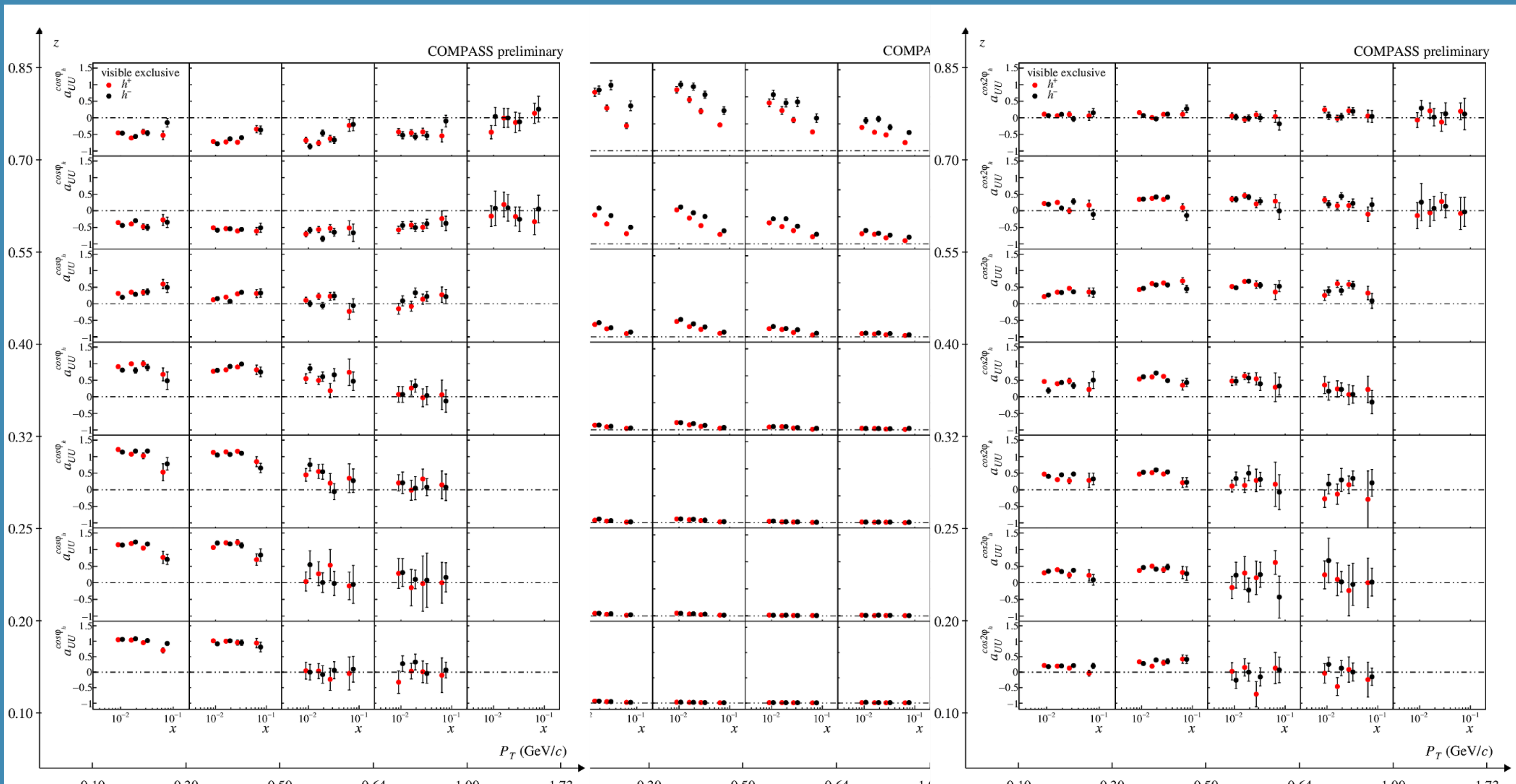


Azimuthal modulations on (LH_2) – 3D

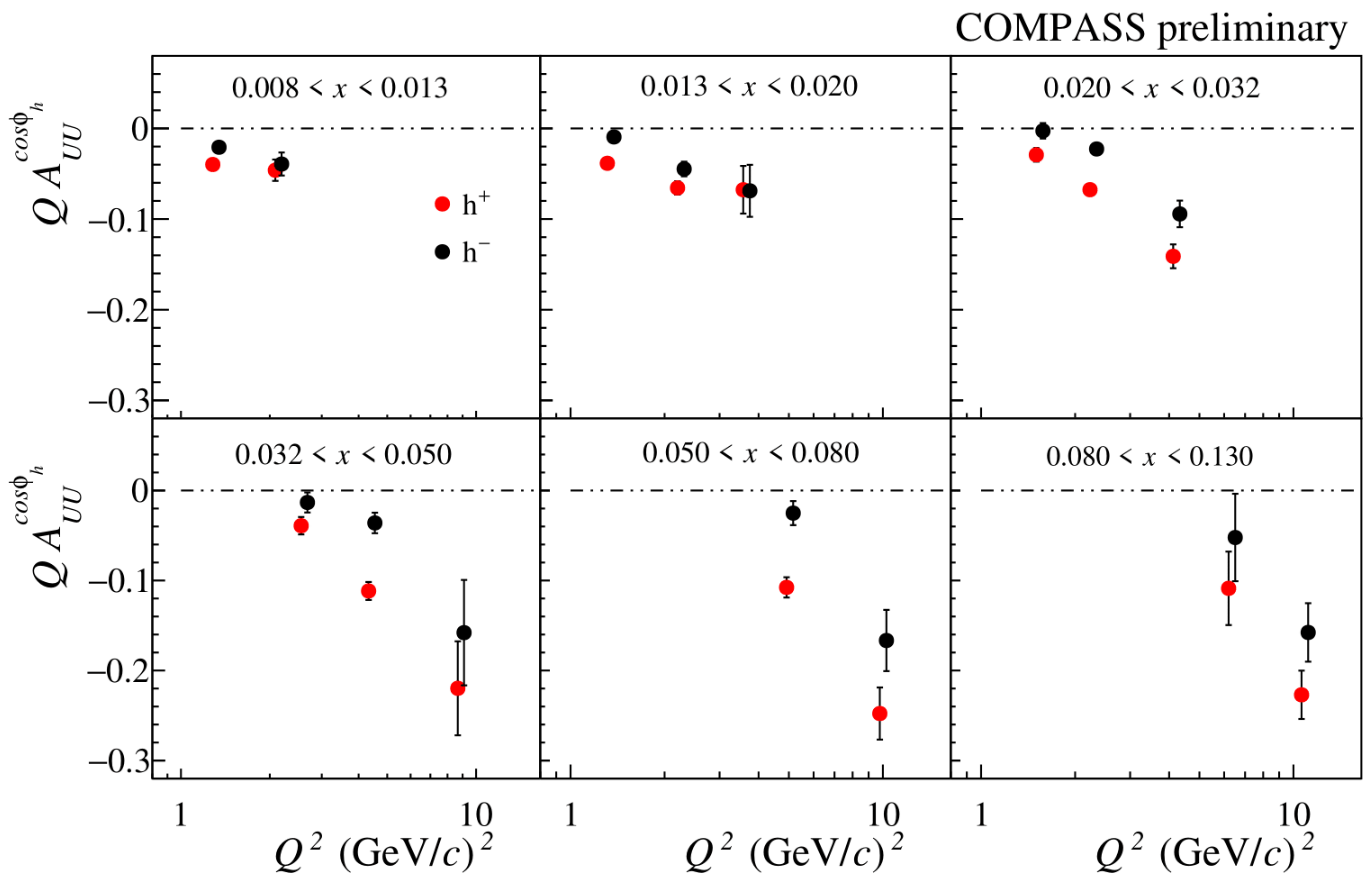




Contamination on (LH_2) – 3D



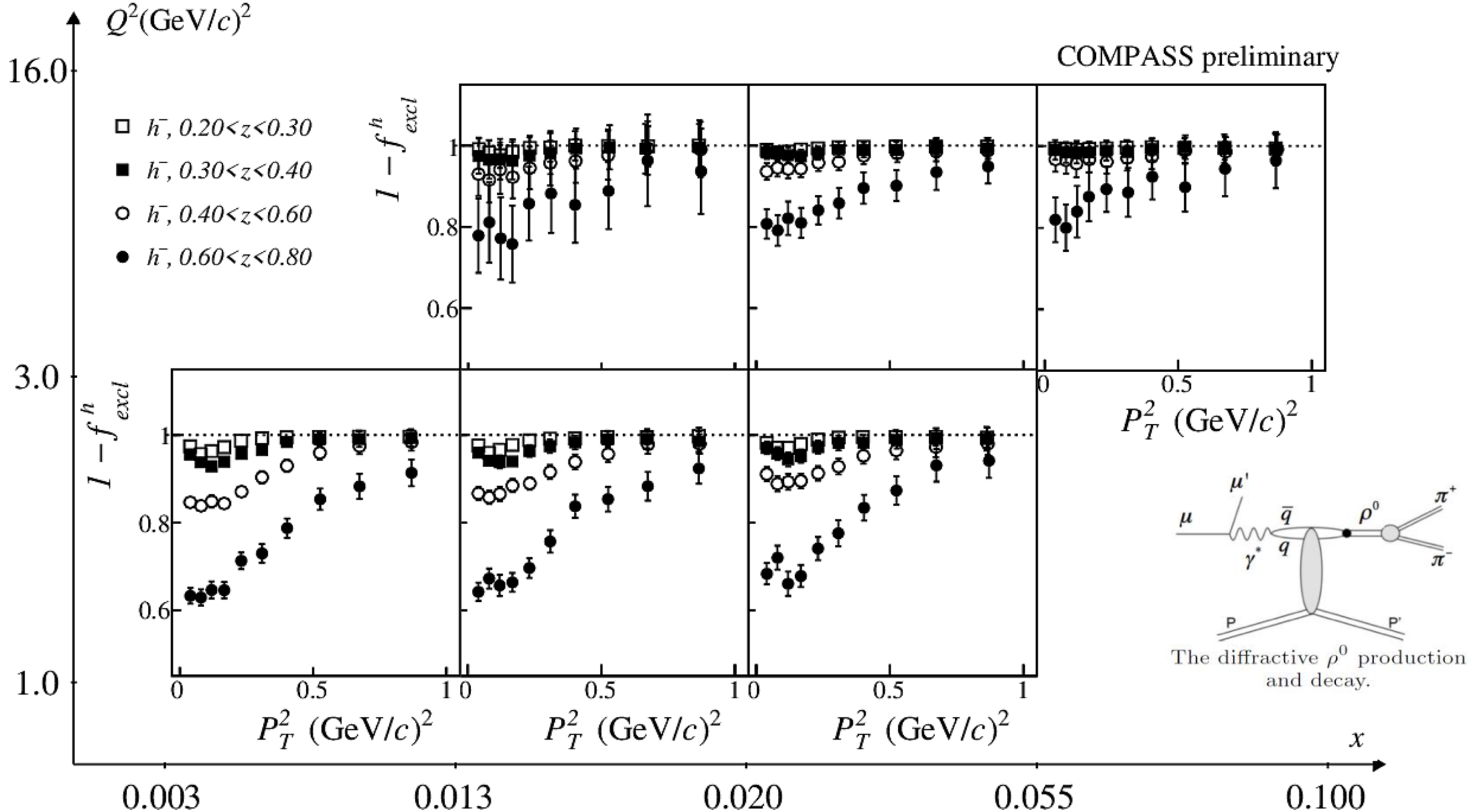
Q^2 behavior


COMPASS preliminary
0.008 < x < 0.013
0.013 < x < 0.020
0.020 < x < 0.032
0.032 < x < 0.050
0.050 < x < 0.080
0.080 < x < 0.130
$Q A_{UU}^{\cos\phi_h}$
h+
h−
0
−0.1
−0.2
−0.3
1
10
Q^2 (GeV/c)^2

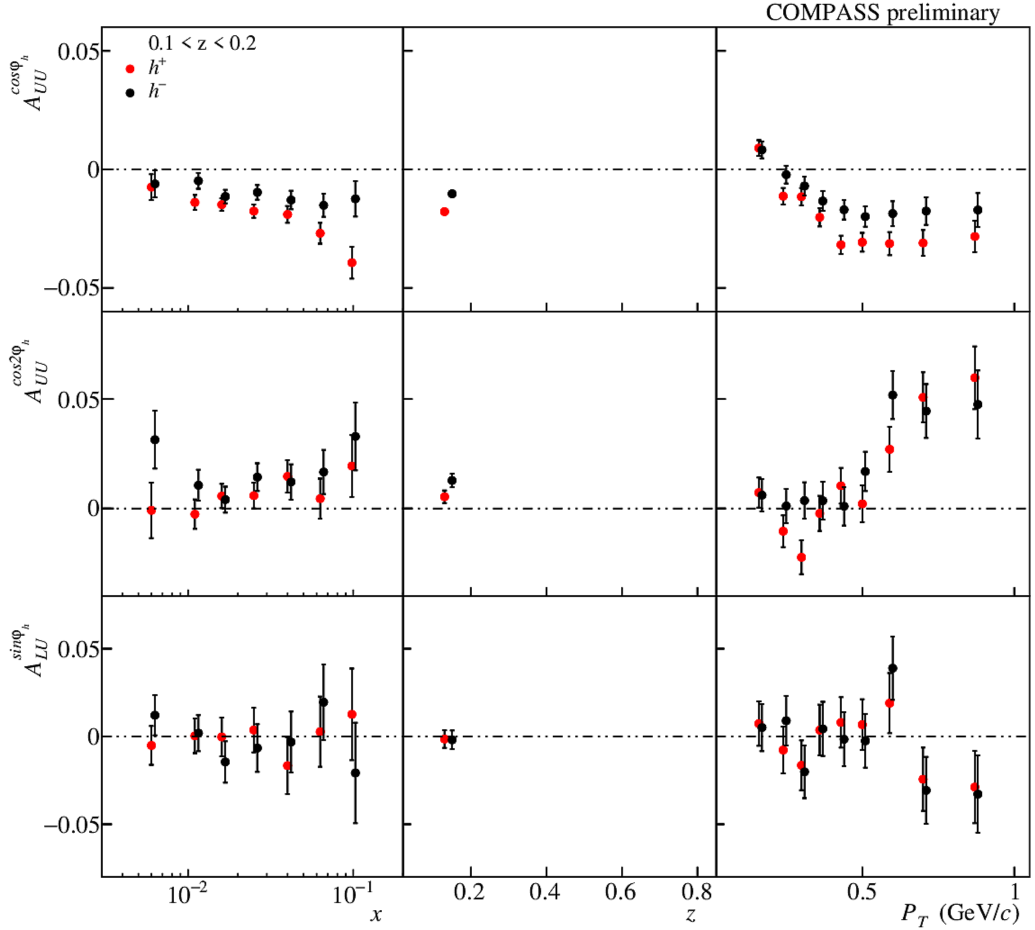
Outlook

- An impressing amount of results
- In the study of unpolarized multiplicities and azimuthal asymmetries we are able already today to obtain precise multidimensional results, allowing the start for the transition from “exploratory/consolidation” to the “maturity” era that will arrive with the EIC
- It also offers the glimpse on the challenges that this “precision” will bring for both the experimentalist and the theoreticians

Contamination of hadrons from ρ^0 and ϕ produced in exclusive reactions

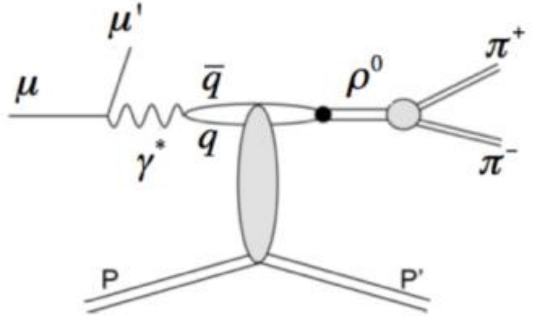


Azimuthal modulations on (LH_2) – 1D

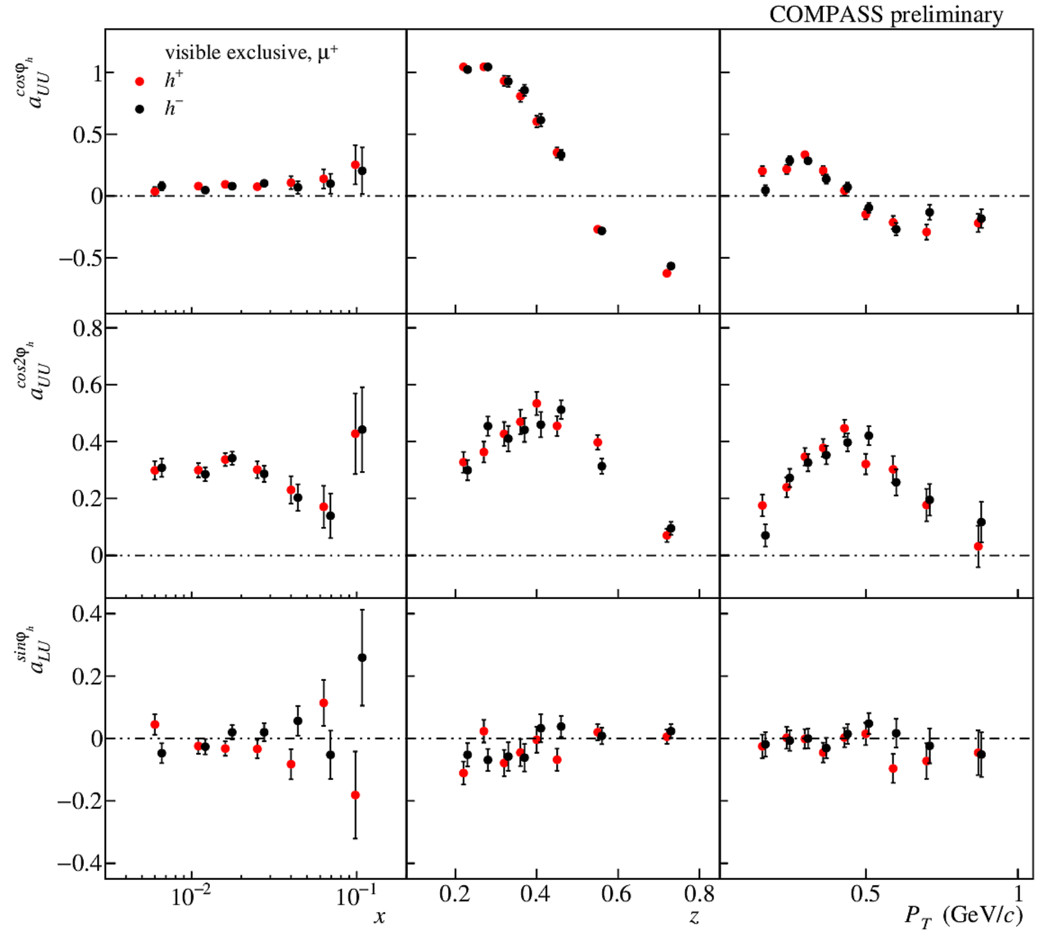


Contamination on (LH_2) – 1D

- Determined from $z_1 + z_2 > 0.95$
- Selecting ρ^0, ω and ϕ



The diffractive ρ^0 production and decay.



P_{hT} distributions vs W