Unpolarised SIDIS measurements at COMPASS

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7th International Workshop on “Transverse phenomena in hard processes and the transverse structure of the proton - June 3 – 7, 2024 Trieste

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, toward the publication (improving on RCs)

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

$$\frac{d^5\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\phi_h} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{2xM^2}{Q^2}\right)\left[(1-y)+\frac{y^2}{2}\right]$$

$$\left\{F_{UU,T}^h + \varepsilon F_{UU,L}^h + \sqrt{2\varepsilon(1+\varepsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \cdots\right\}$$

We can then introduce 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

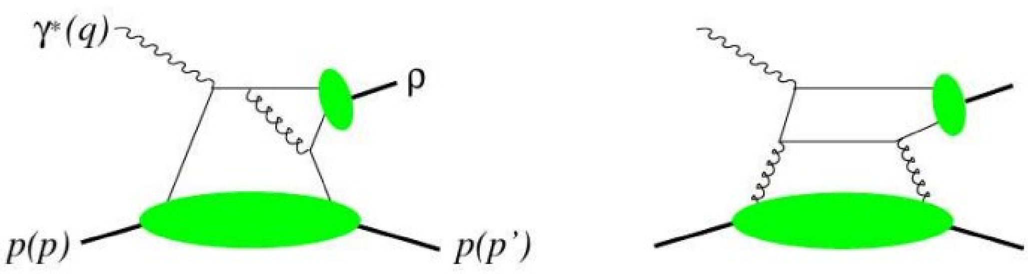
$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$

Experimentally

1. In the case of unpolarized SIDIS the measured rates need to be corrected for the effect of the apparatus (acceptance corrections, including geometrical acceptance, detector efficiencies ...)
2. Events from processes different from SIDIS may be present in the final sample, and we know that charged hadron SIDIS sample at large z and at small P_{hT} contains a non-negligible contribution of hadrons from the decay of vector mesons (VM) produced in exclusive processes
3. Radiative effects change both the LO cross section and the reconstructed event kinematics

- With the COMPASS data sample increasing over the years we were able to address with improved precision these effects

Background from exclusive VMs



- Contributions from ρ^0, ω and ϕ
- Exclusive ρ^0 leptoproduction can be viewed as a virtual photon fluctuation into a $q\bar{q}$-pair followed by the scattering of this pair off the nucleon and formation of the final state.
- These are spin-1 objects, i.e. $J = 1$. Decay particles have spin 0, so $L = 1$ for the decay. In words when the VM decays, its spin-state will be reflected in the orbital momentum of the decay particles.
- Due to the nature of the process we can reject some/most, not all, of these hadrons from our sample

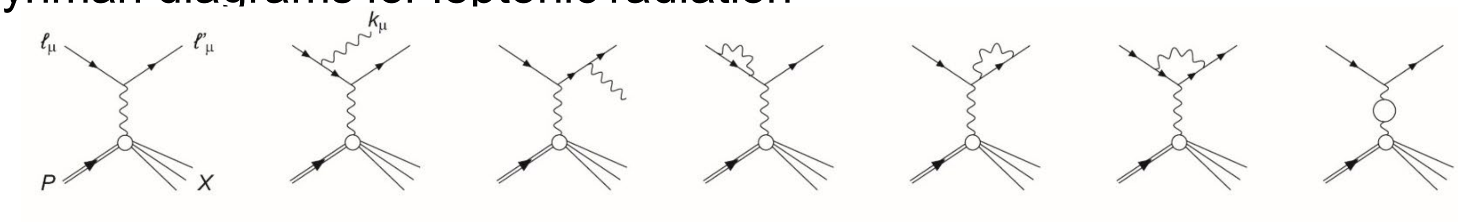
- Exclusive VMs can be removed from the sample when both final hadrons detected (VISIBLE PART). **EVM cut**:

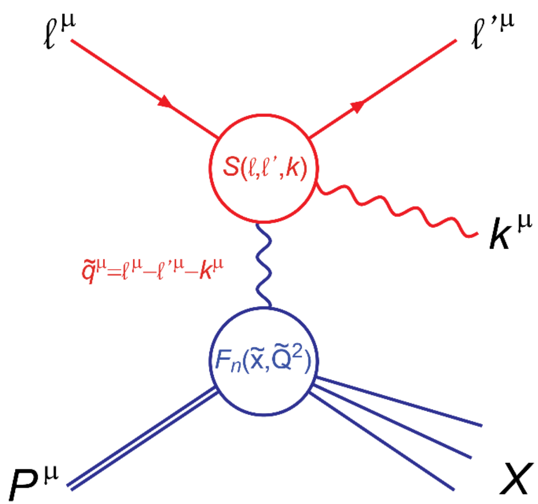
$$z_t = z_{h^+} + z_{h^-} < 0.95$$

- If one hadron is miss, this is no longer true (INVISIBLE PART).
- Strategy:
  - have a MC for exclusive VMs with Spin Density Matrix Elements.
  - Compare MC with our exclusive data normalize MCs
  - Use this normalization to subtract the invisible fraction from our data. **EVM subtraction**

LEPTONIC RADIATION

Feynman diagrams for leptonic radiation





- The radiative leptonic tensor $S(\ell,\ell',k)$, include Born + loops at $\sigma(\alpha_{em}^2)$:
  - Gauge invariant
  - Infrared finite
  - Universal (for 1γ exchange)
  - The kinematic is shifted $\tilde{q}^\mu = q^\mu - k^\mu$

Effects on SIDIS

- Photon radiation from the muon lines changes the DIS kinematics on the event by event basis
- The direction of the virtual photon is changed with respect to the one reconstructed from the muons creating
  - false asymmetries in the azimuthal distribution of hadrons calculated with respect to the virtual photon direction
  - Smearing of the kinematic distributions (f.i. z and P_{hT})
- Due to the energy unbalance, in the lepton plane the true virtual photon direction is always at larger angles with respect to the reconstructed one
- In SIDIS, having an hadron in the final state, only the inelastic part of the radiative corrections plays a role

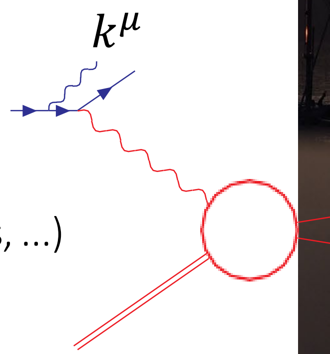
LEPTONIC RADIATION

Observed cross section: convolution of true cross section ⊗ radiator function

$$d\sigma^{\text{obs}}(p,q) = \int_{\text{exp cond's}} \frac{d^3\vec{k}}{2k^0} R(\ell,\ell',k)\, d\sigma^{\text{true}}(p,q-k)$$

- Shifted kinematics: $q \to q-k$, e.g., $Q^2 = -(\ell-\ell')^2 \Longrightarrow \tilde{Q}^2 = -(\ell-\ell'-k)^2$
- but integration may be restricted by experimental conditions, also indirectly:
  - leptonic variables: measure E and θ of scattered lepton ➔ and Q^2
  - real photon detection: possibility to reject radiative events by detecting the radiated photon

NOTE the $\tilde{Q}^2 \ll Q^2$ is possible: $\tilde{Q}^2_{\text{min}} = \frac{x^2}{1-x} M_N^2$

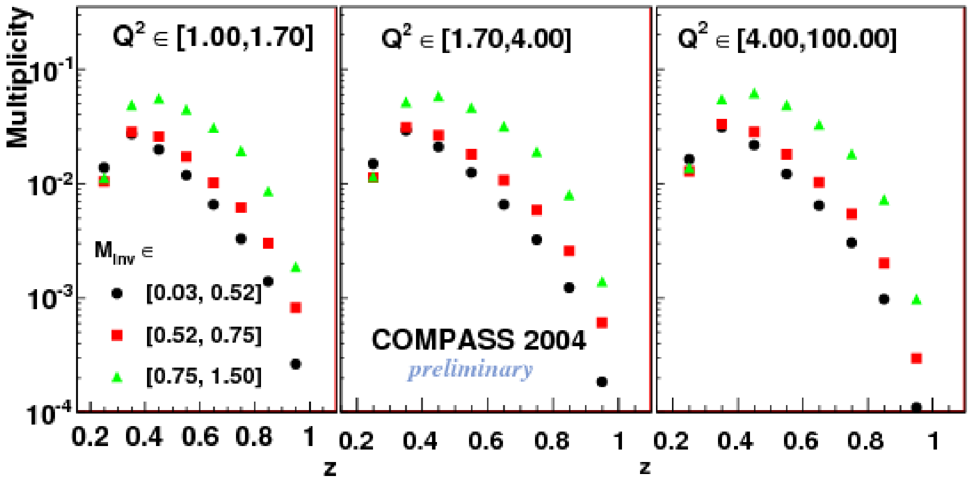


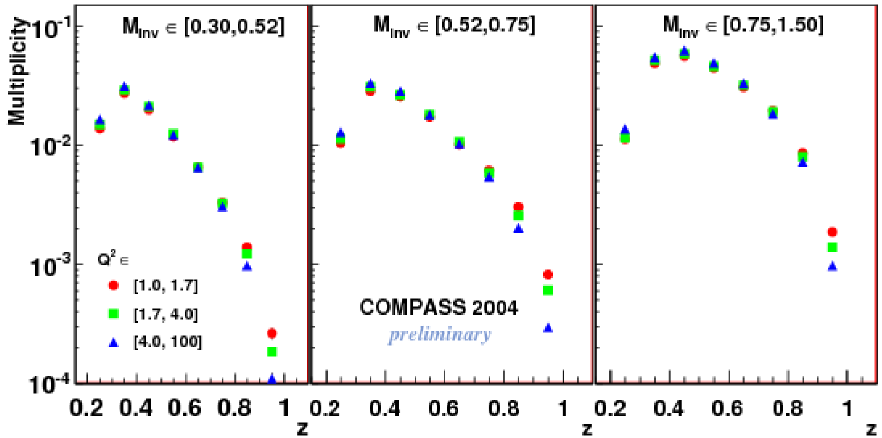
➔ Difficult to treat radiative and detector effects separately (acceptance cuts, efficiencies, ...)

need full Monte-Carlo treatment DJANGOH

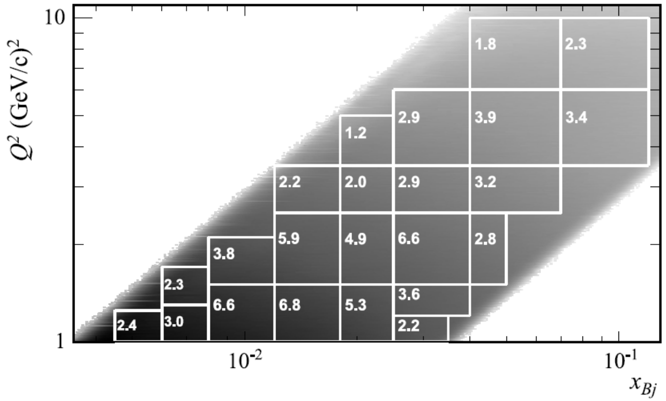
P_{hT}-dependent multiplicities

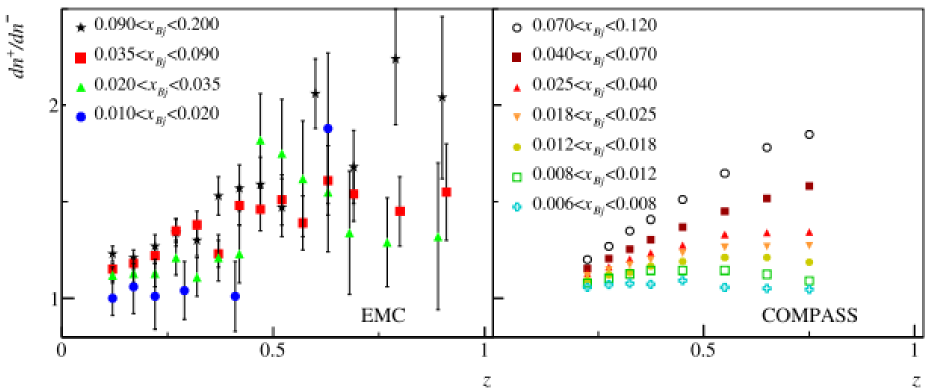
2h Multiplicities (>10 years ago)

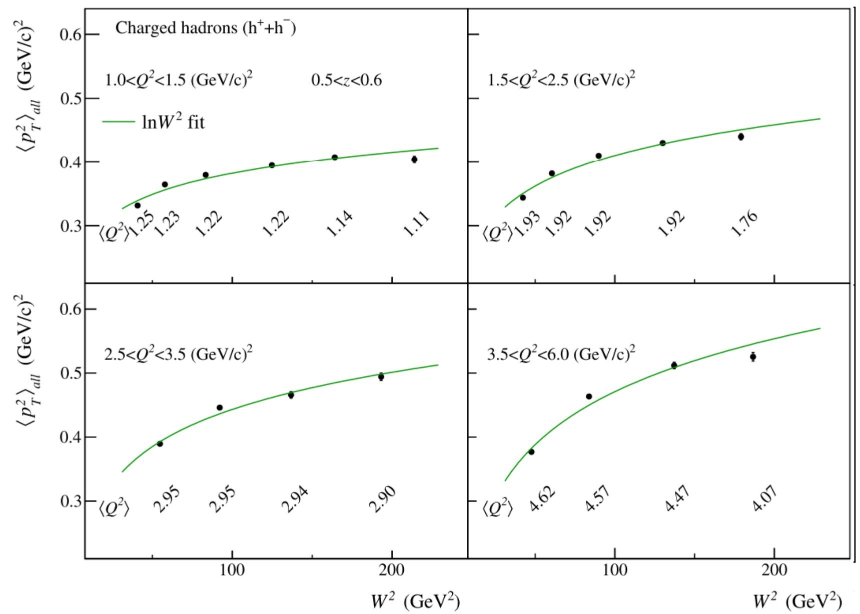




1st publication on P_{hT} distributions (2013);







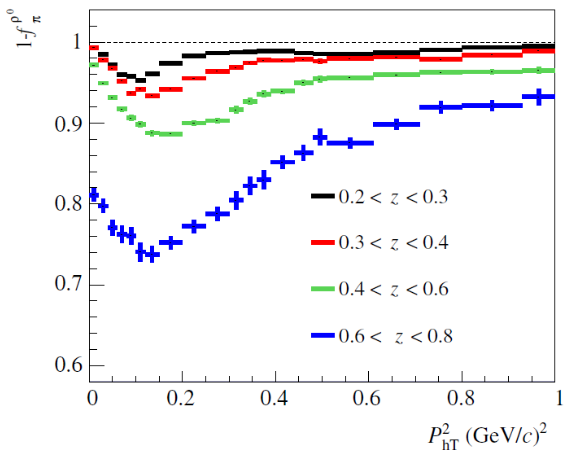
2^{nd} publication on P_{hT} distributions (2018);

Improved binning

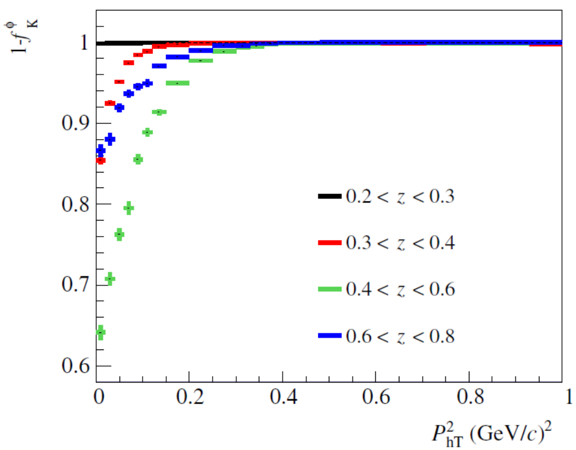
TABLE I. Bin limits for the four-dimensional binning in x, Q^2, z and P^2_{hT}.

	Bin limits								
x	0.003	0.008	0.013	0.02	0.032	0.055	0.1	0.21	0.4
Q^2 $(\mathrm{GeV}/c)^2$	1.0	1.7	3.0	7.0	16	81			
z	0.2	0.3	0.4	0.6	0.8				
P^2_{hT} $(\mathrm{GeV}/c)^2$	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

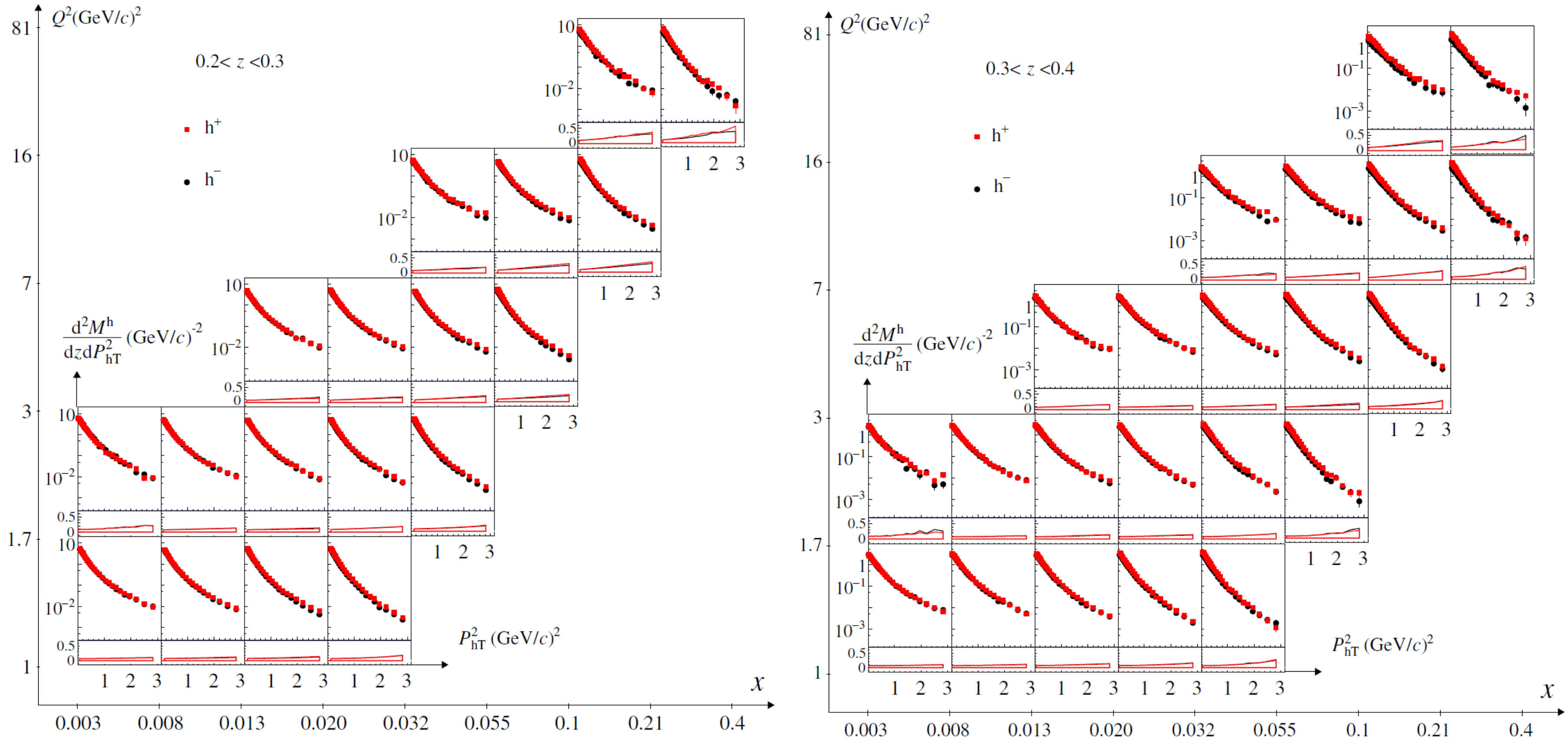


(a)

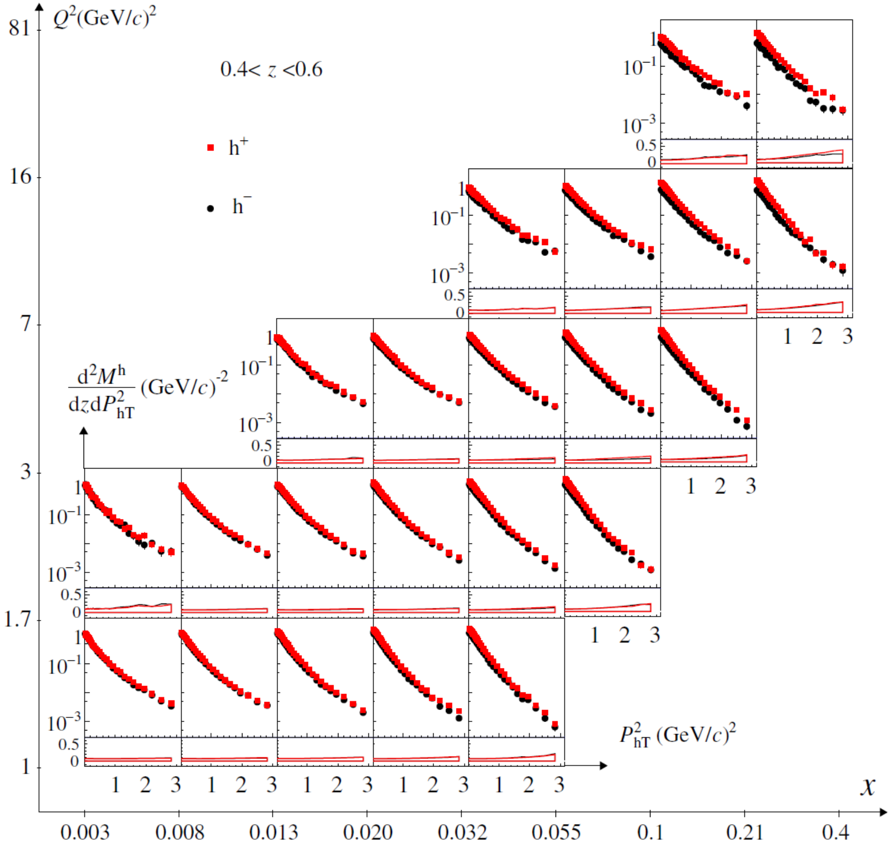


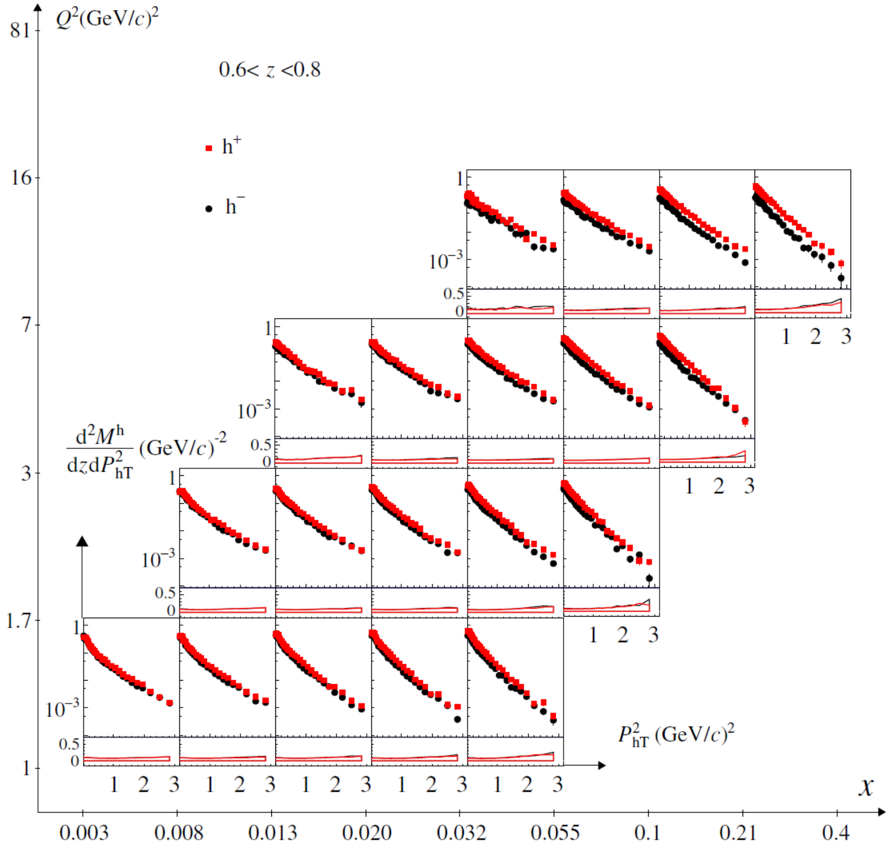
(b)

2nd publication on P_{hT} distributions;



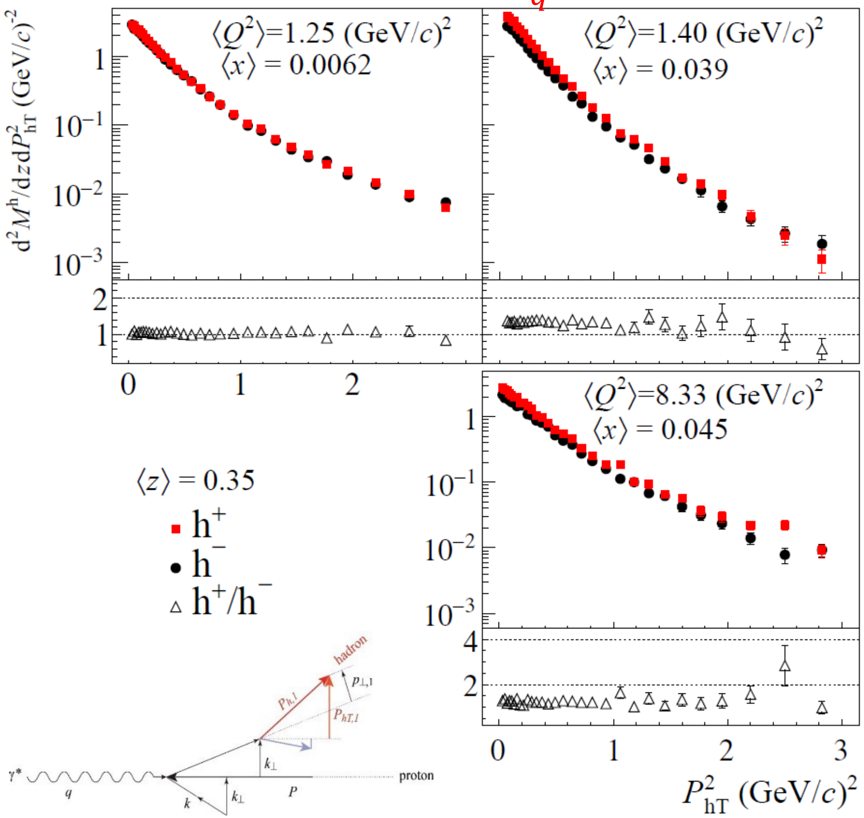
2nd publication on P_{hT} distributions;

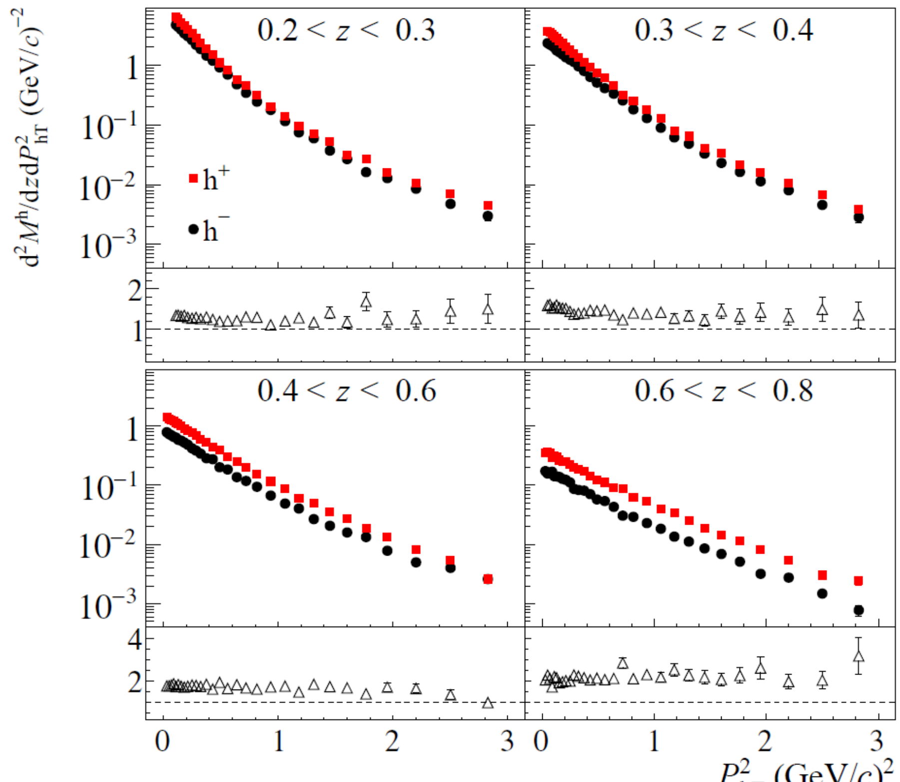




Positive vs Negative charged hadrons (^{6}LiD)

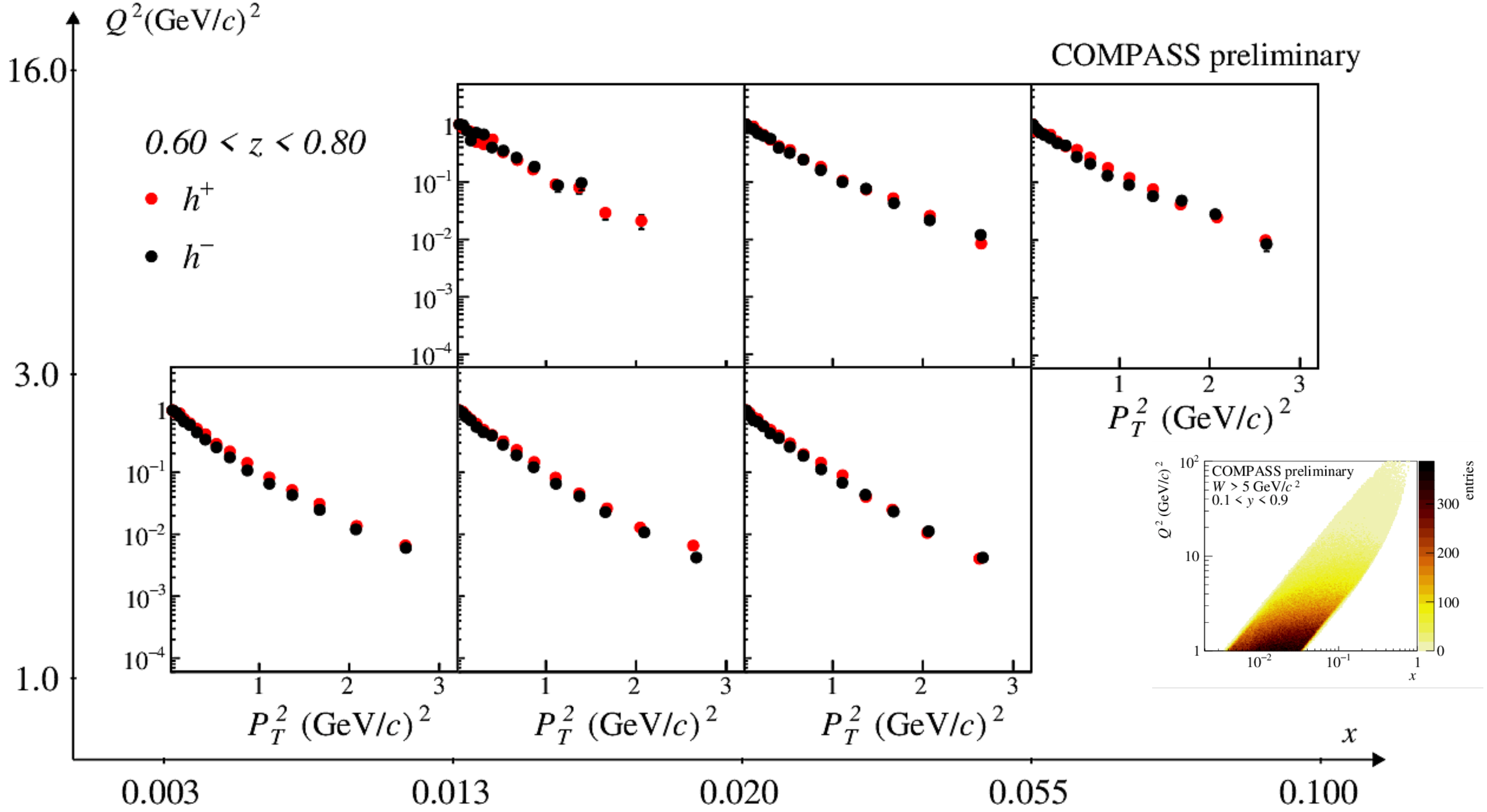
$$F_{UU}^{h}(x,z,P_{hT}^2;\,Q^2) = x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp - z\vec{k}_\perp - \vec{P}_{hT})\; f_1^q(x,k_\perp^2;Q^2) D_1^{q\to h}(z,p_\perp^2;Q^2)$$





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

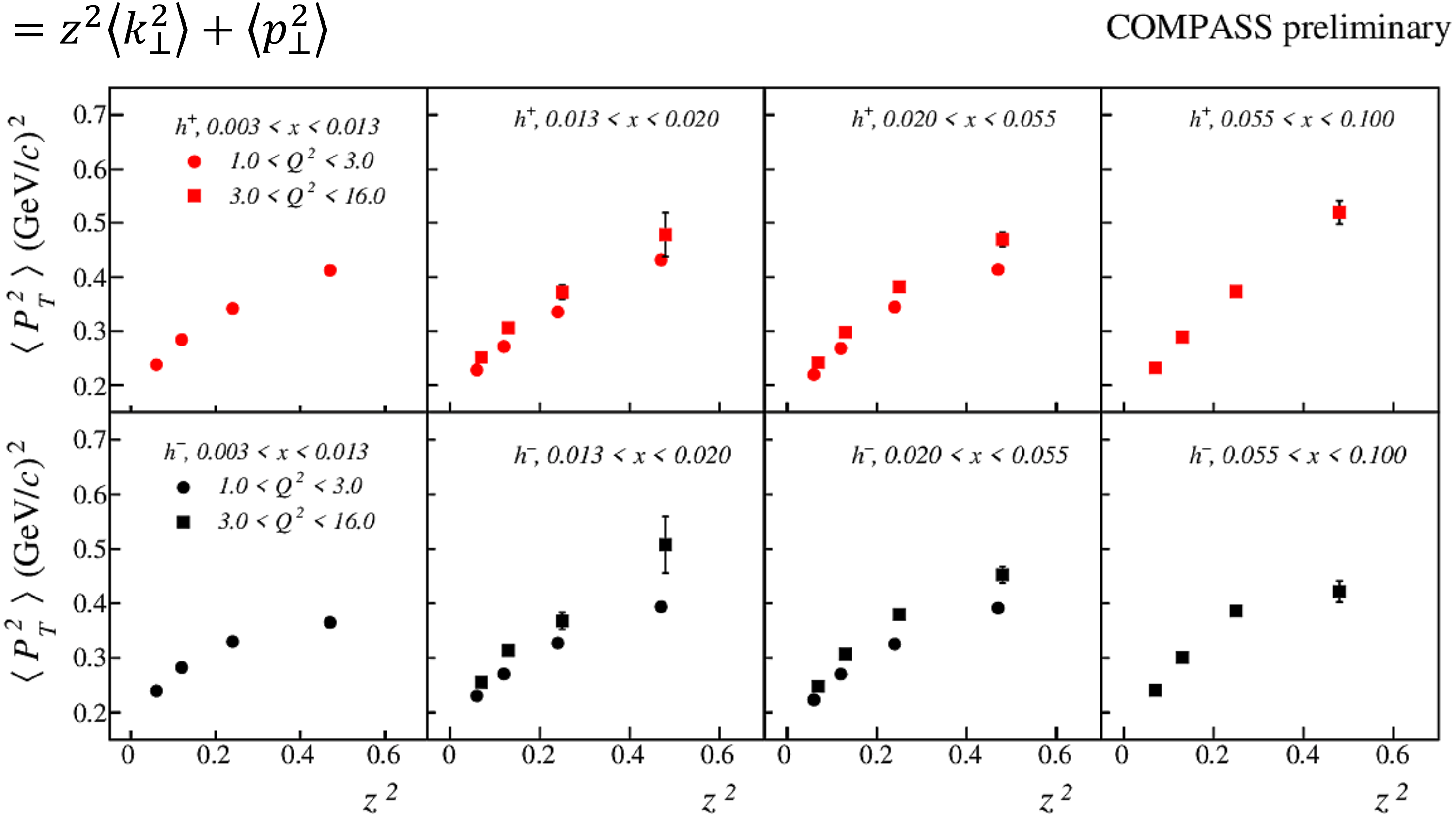
Positive vs Negative charged hadrons (LH_2)



Slope dependence

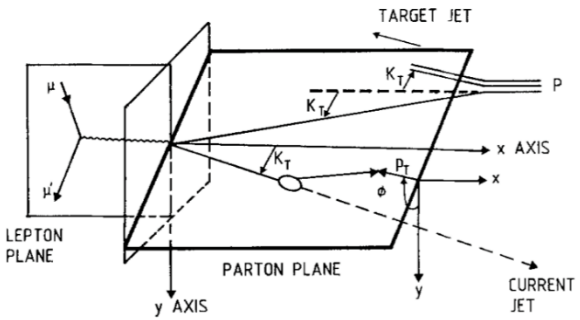
A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to

$$\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$$



Azimuthal Modulations

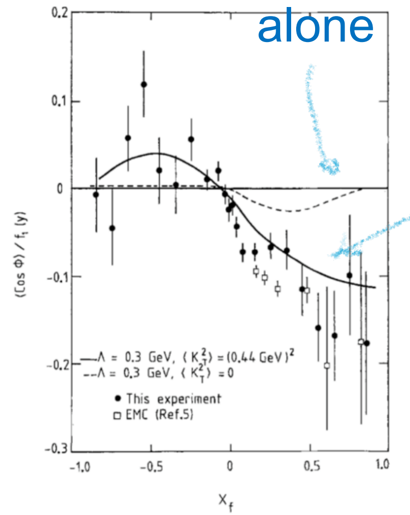
An old story



- 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]

QCD alone

QCD + quark transverse motion



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

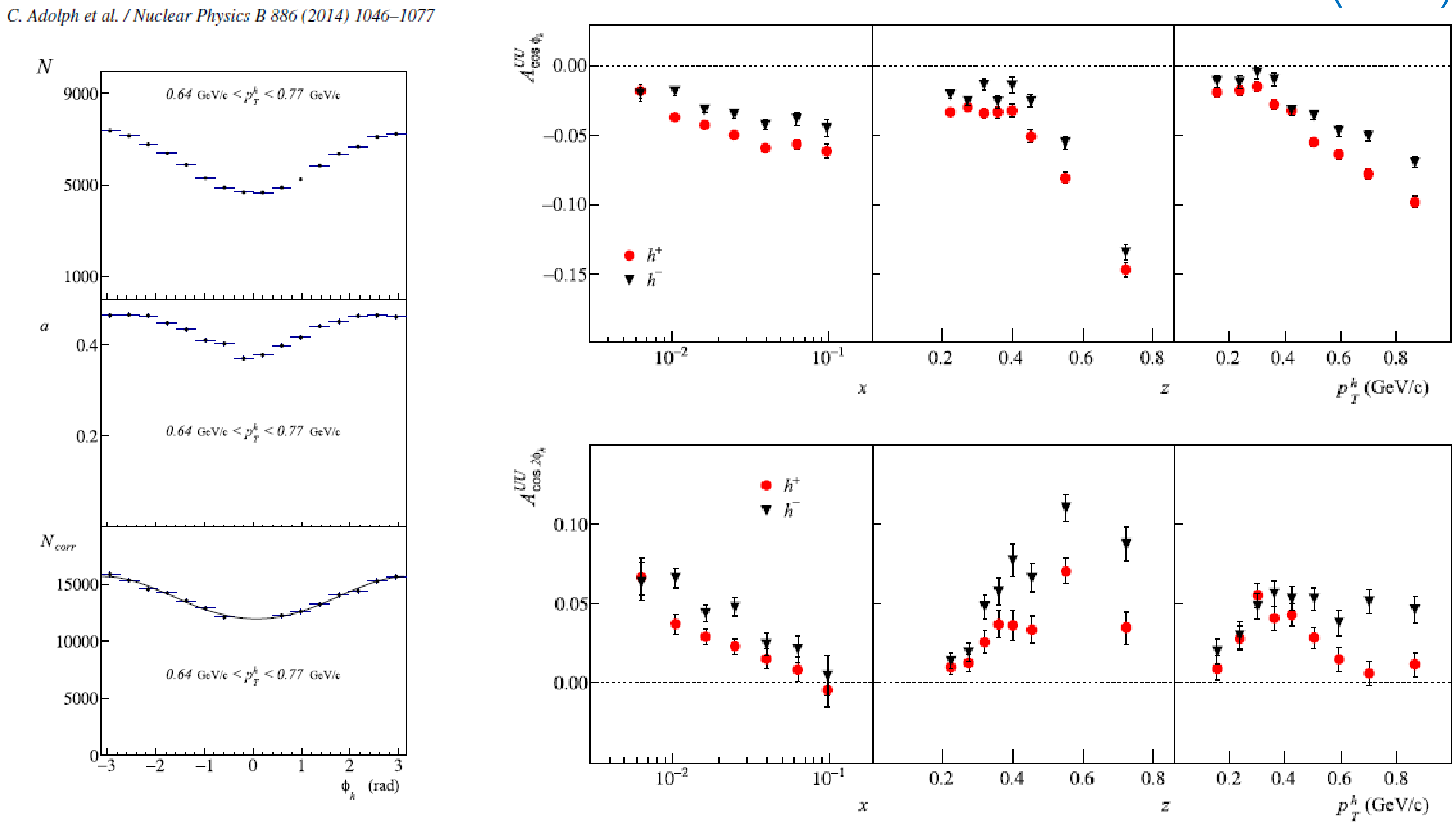
These effects can be estimated by adopting a model for the transverse momentum distribution of partons in a hadron and for the transverse momentum given to hadrons in the quark decay. Suppose that both these distributions are gaussian:

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

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 $\boldsymbol{p}_\perp - z\boldsymbol{p}_{1\perp}$.

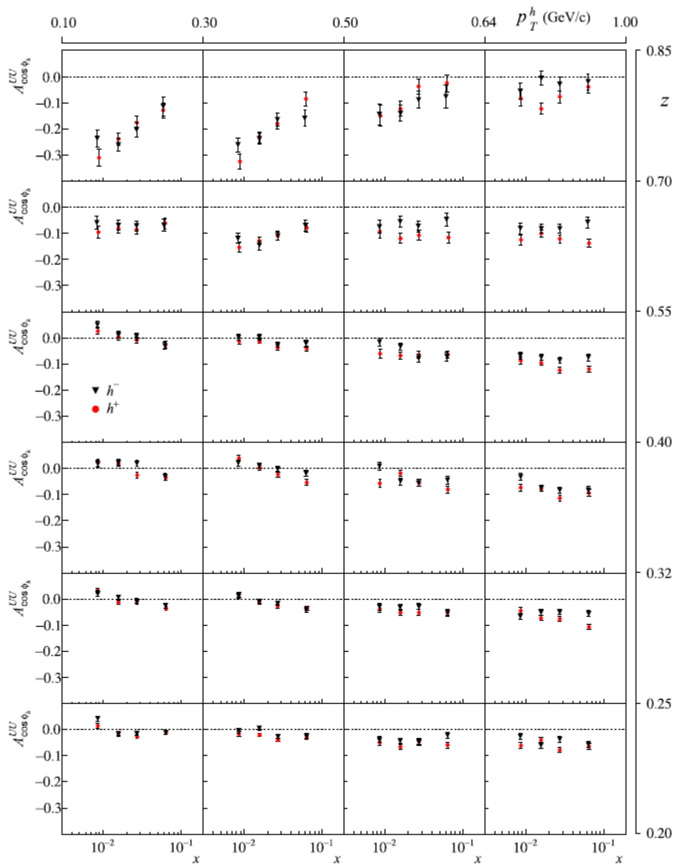
Azimuthal modulations on ^{6}LiD

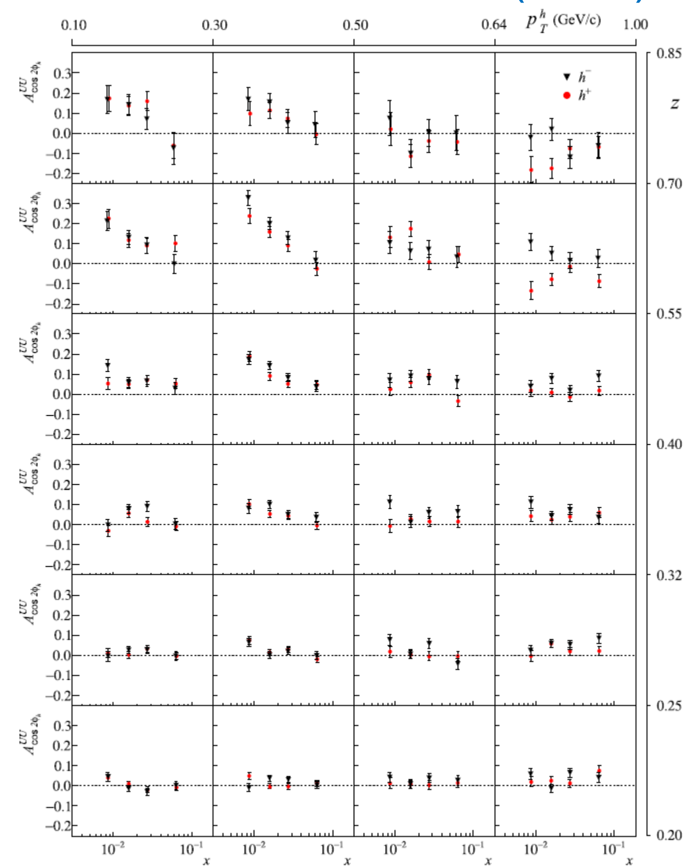
NPB 886 (2014)



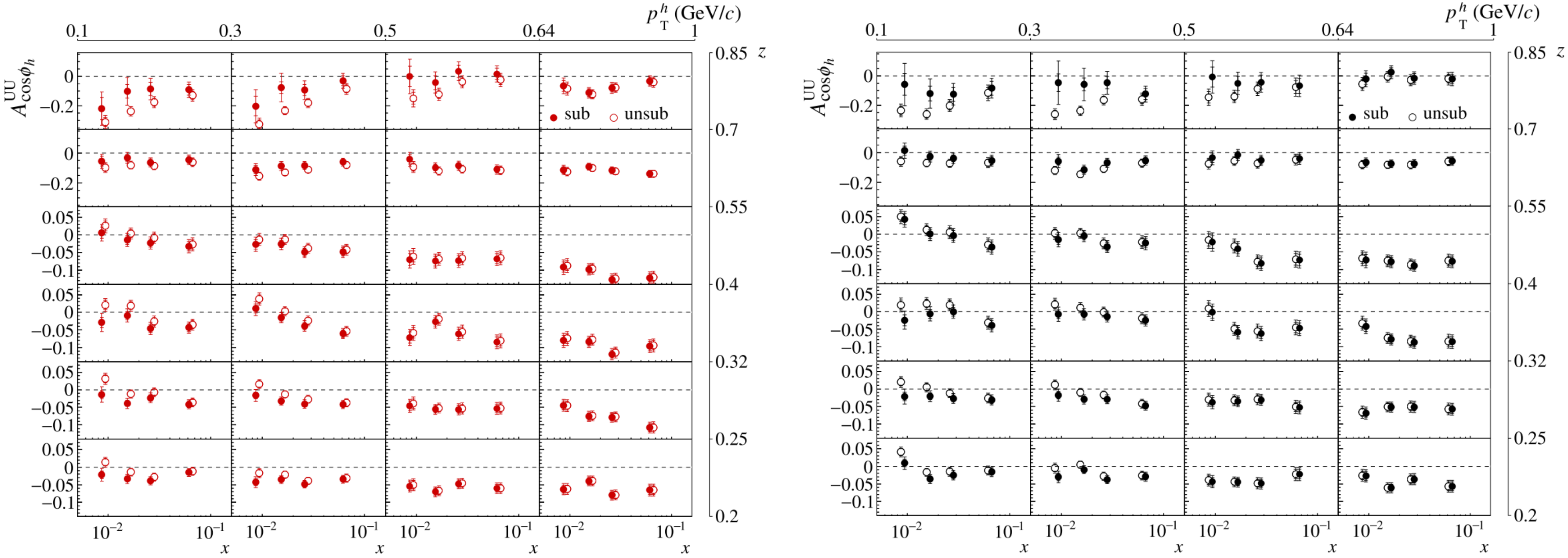
Azimuthal modulations on ^{6}LiD

NPB 886 (2014)



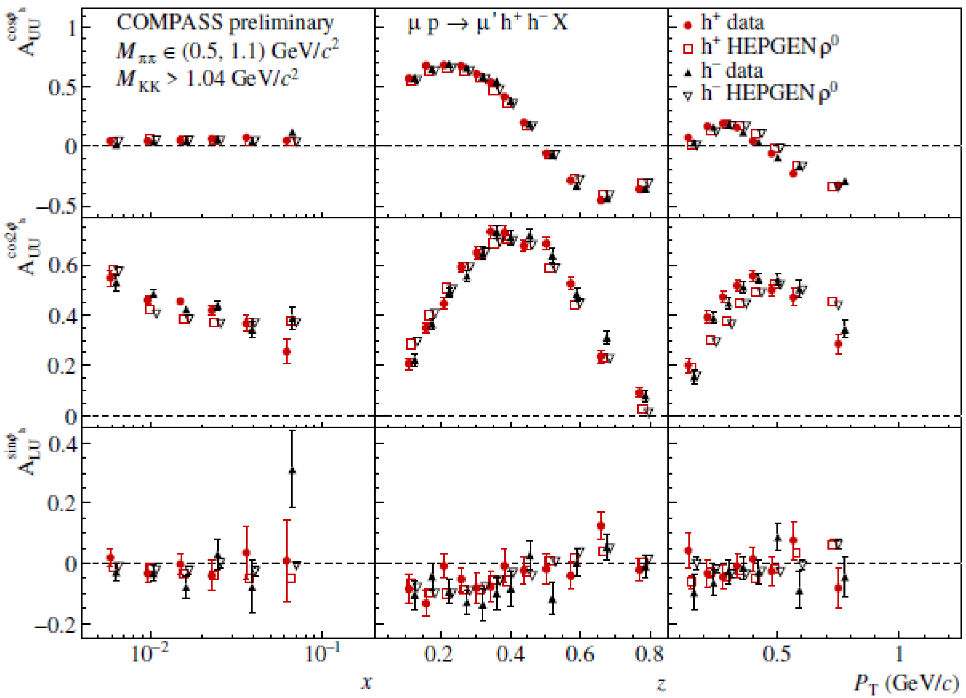


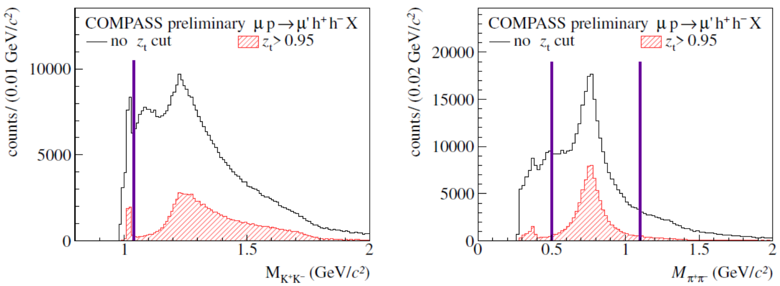
VM subtraction from ^{6}LiD results



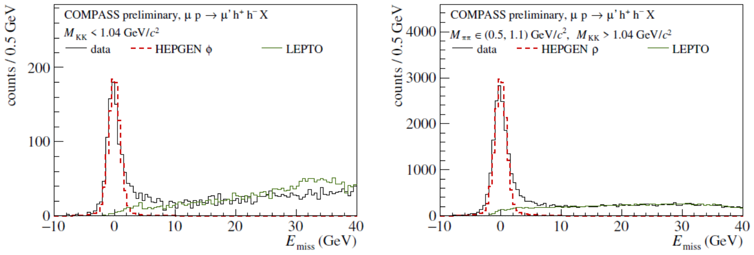
NPB 956 (2020) 115039

Study of VM contamination LH_2

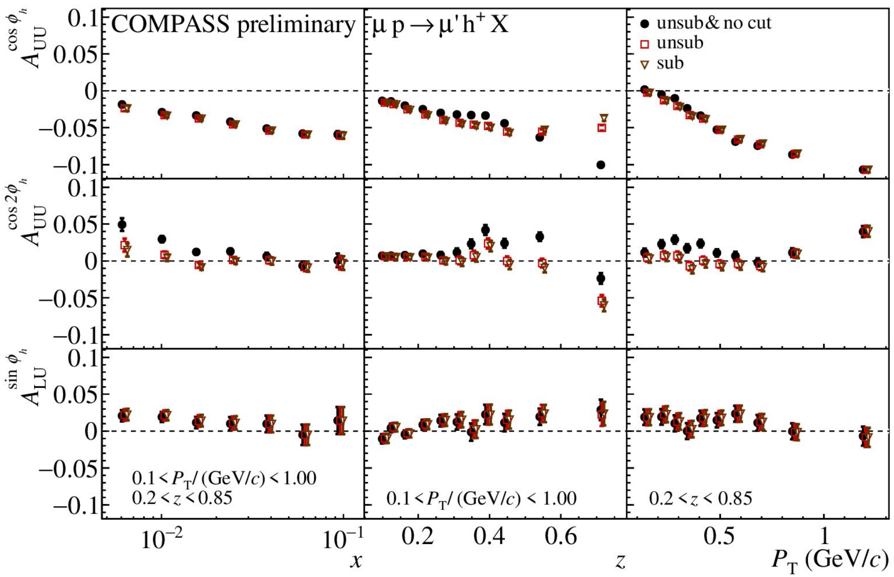


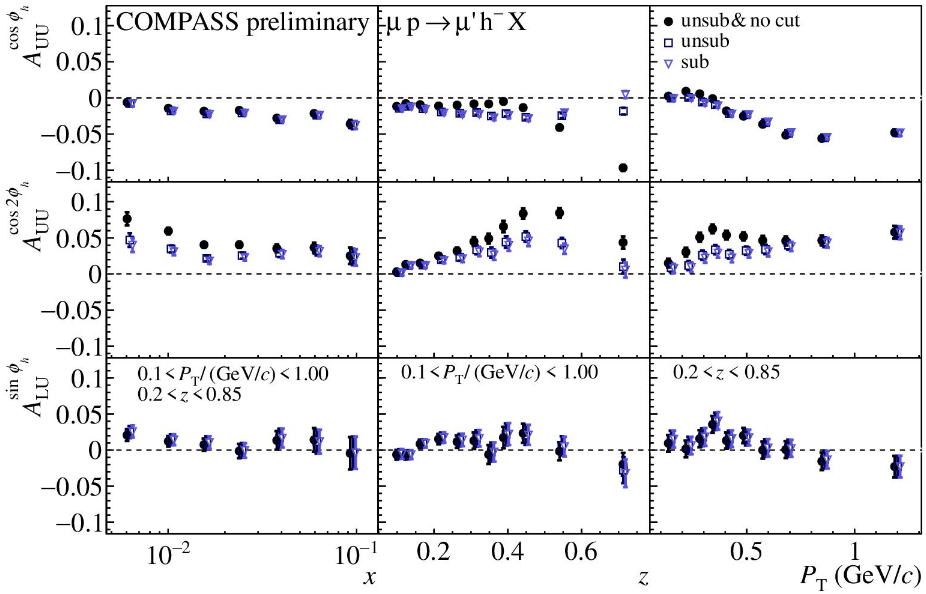


Normalization of HEPGEN

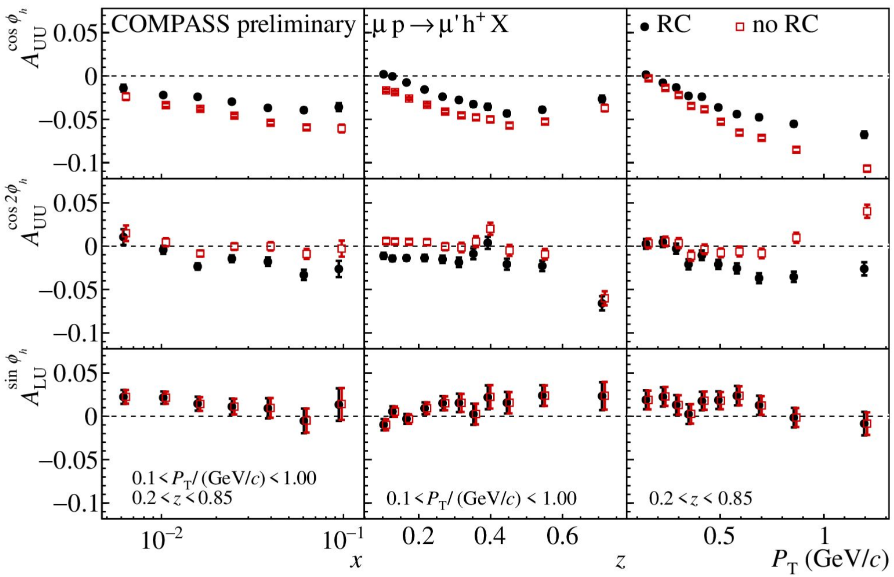


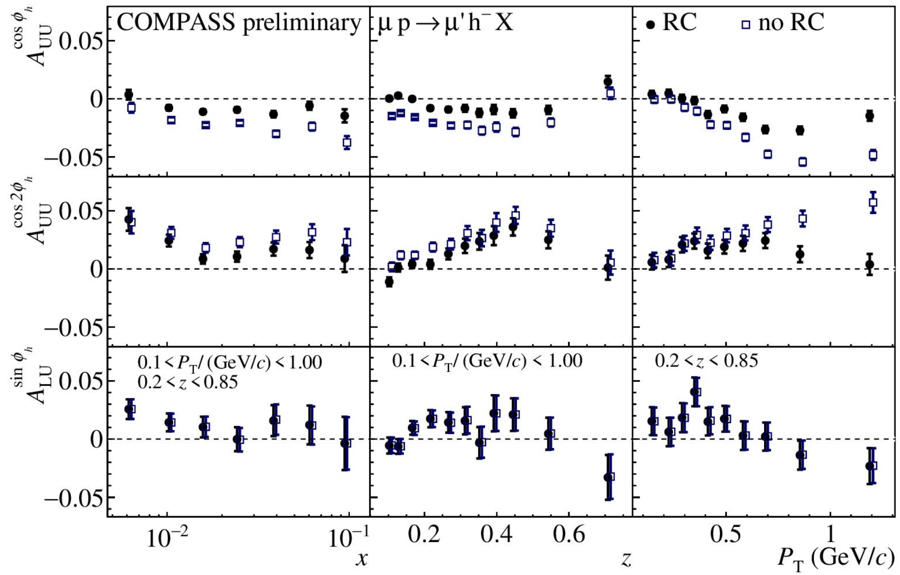
Effect of Exclusive VM subtraction



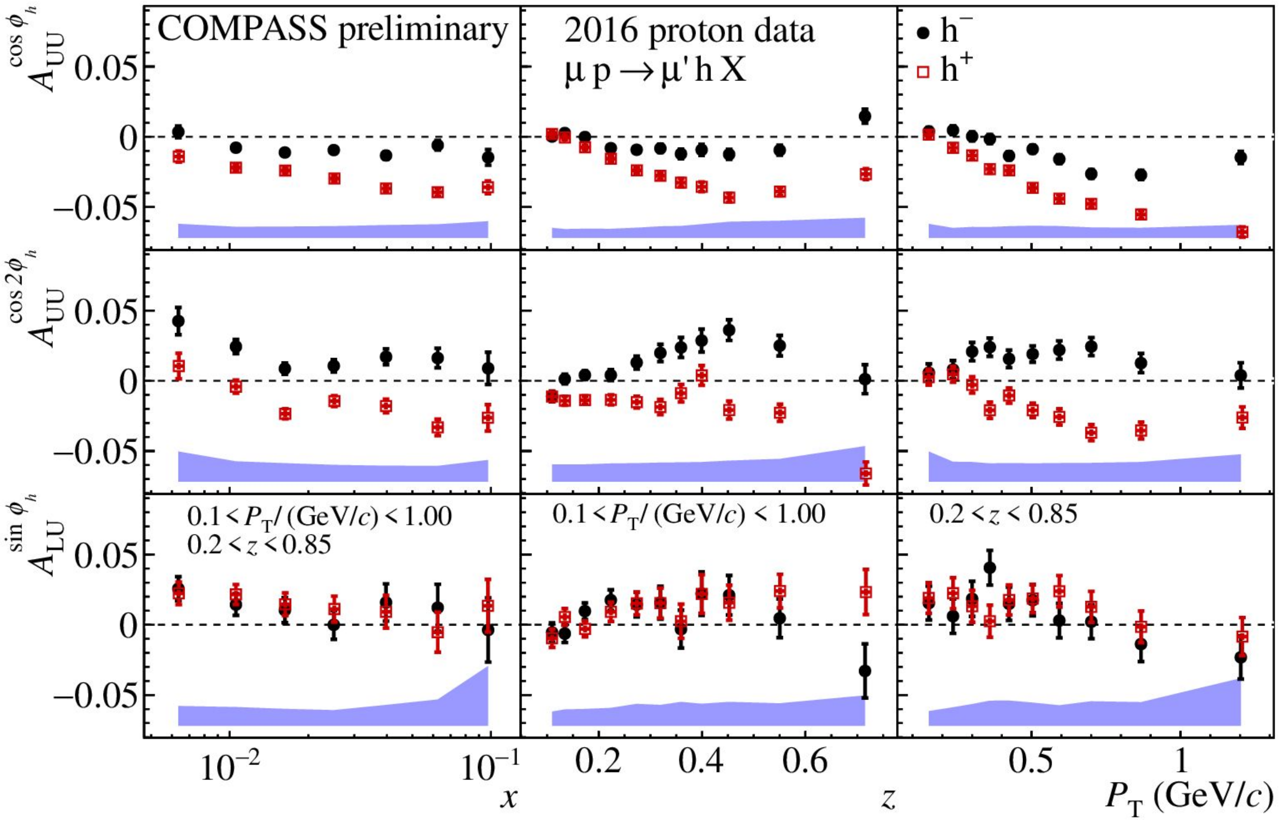


Radiative effects





Corrected results



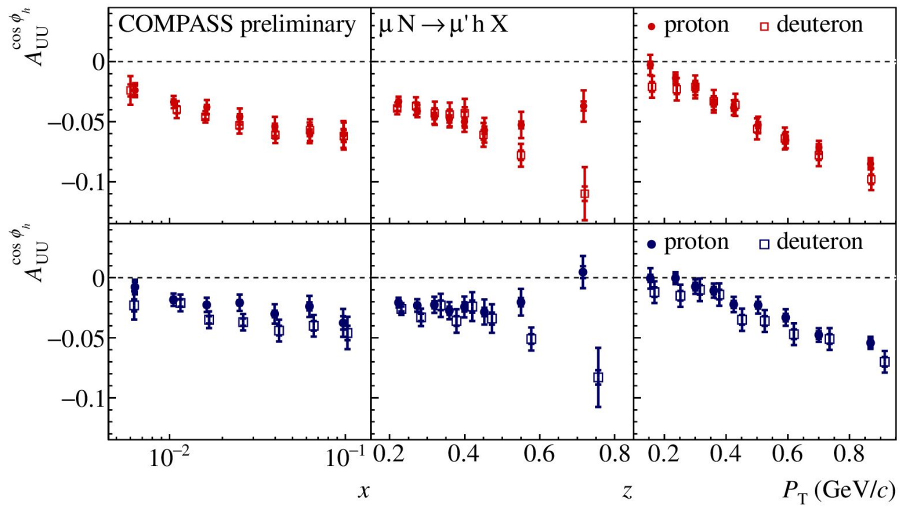
MultiD on LH2, corrected for both VM and RC is coming

Outlook

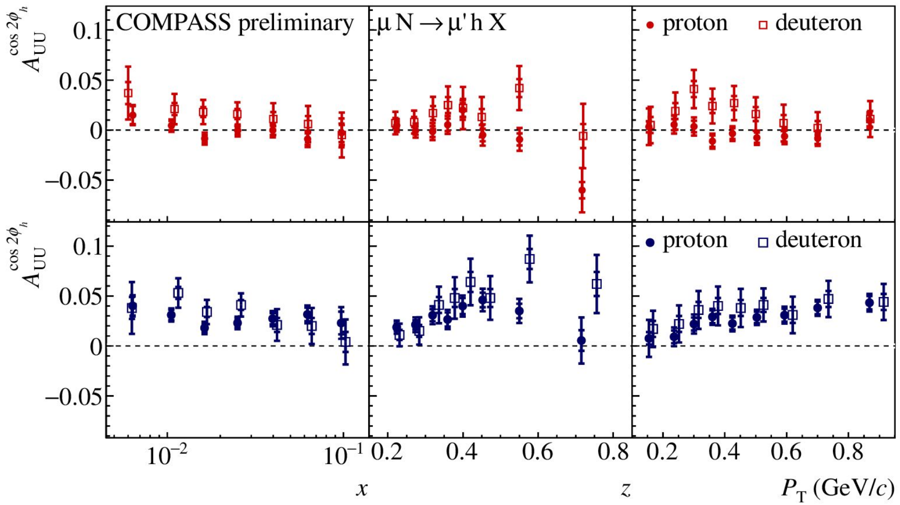
- In the study of unpolarized multiplicities and azimuthal asymmetries we are able already today to obtain precise multidimensional results
- This should allow the start for the transition from “exploratory/consolidation” to the “maturity” era that will arrive with the EIC
- But also offers us the glimpse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

Thank you

P vs D

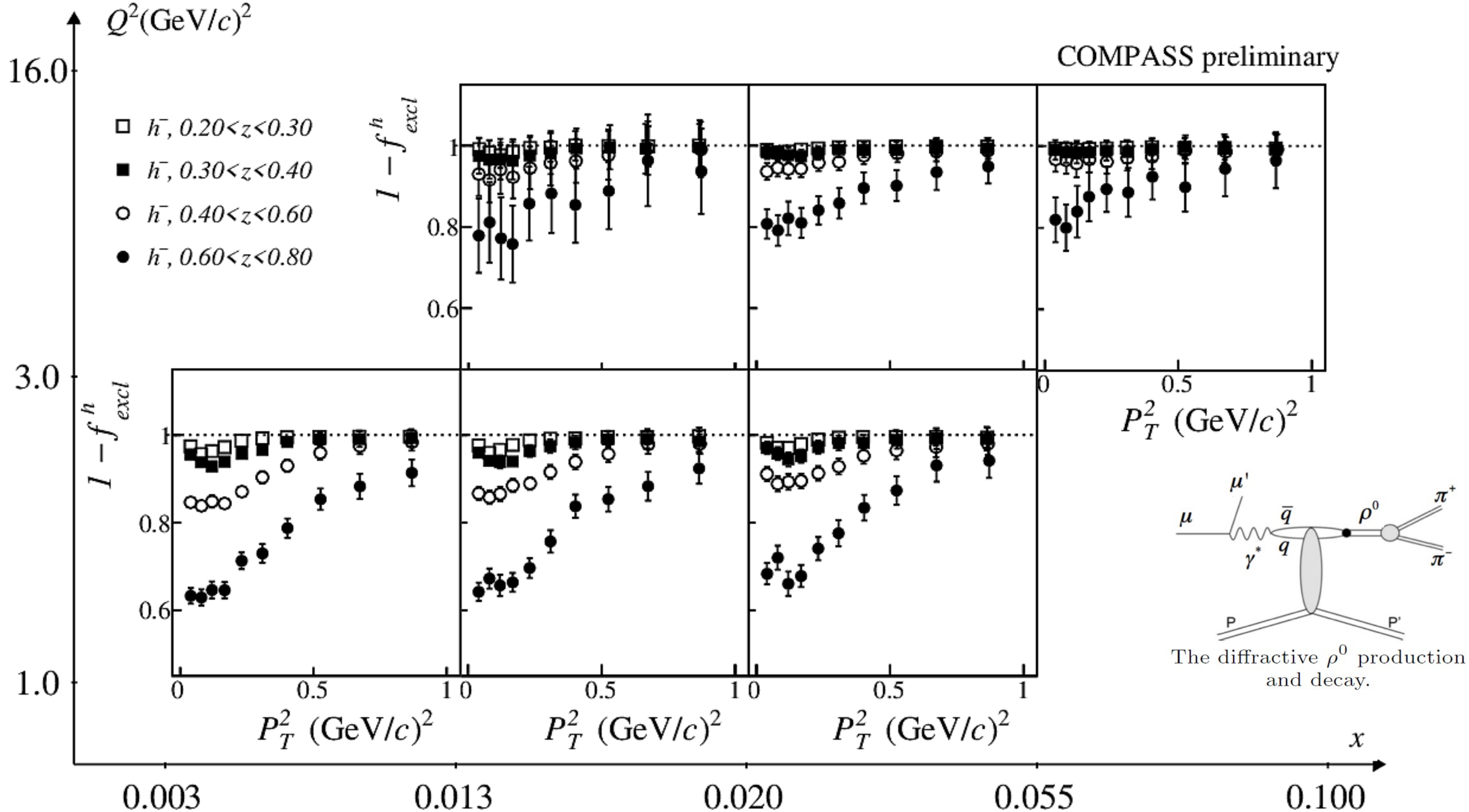


COMPASS preliminary
μ N → μ' h X
proton
deuteron
$A_{UU}^{\cos\phi_h}$
0
−0.05
−0.1
10^{-2}
10^{-1}
0.2
0.4
0.6
0.8
x
z
P_T (GeV/c)

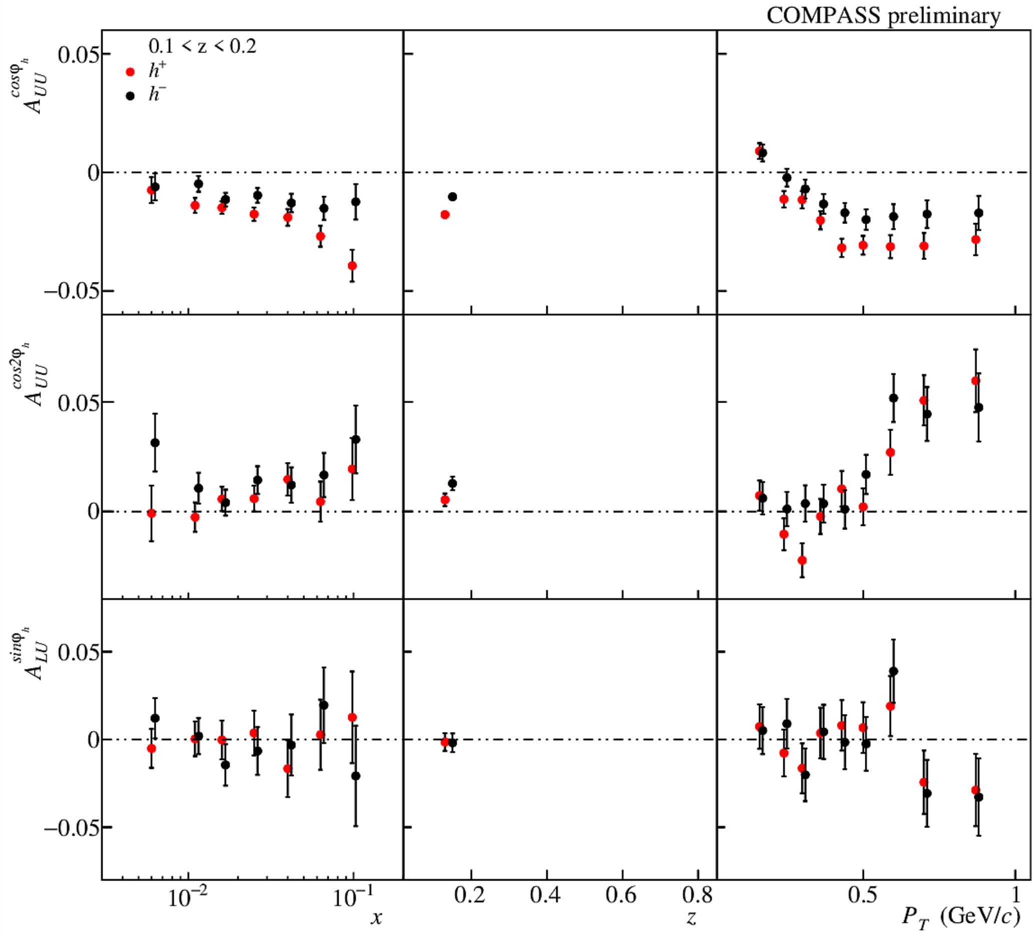


COMPASS preliminary
μ N → μ' h X
proton
deuteron
$A_{UU}^{\cos 2\phi_h}$
0.1
0.05
0
−0.05
10^{-2}
10^{-1}
0.2
0.4
0.6
0.8
x
z
P_T (GeV/c)

Contamination of hadrons from ρ^0 and ϕ

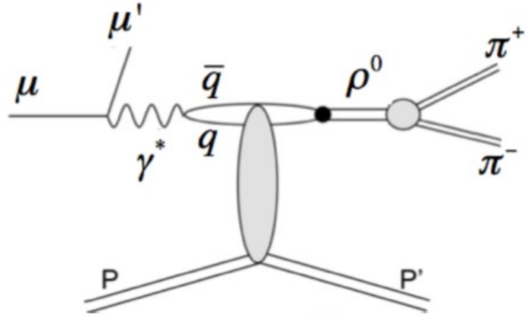


Azimuthal modulations on (LH_2) – 1D

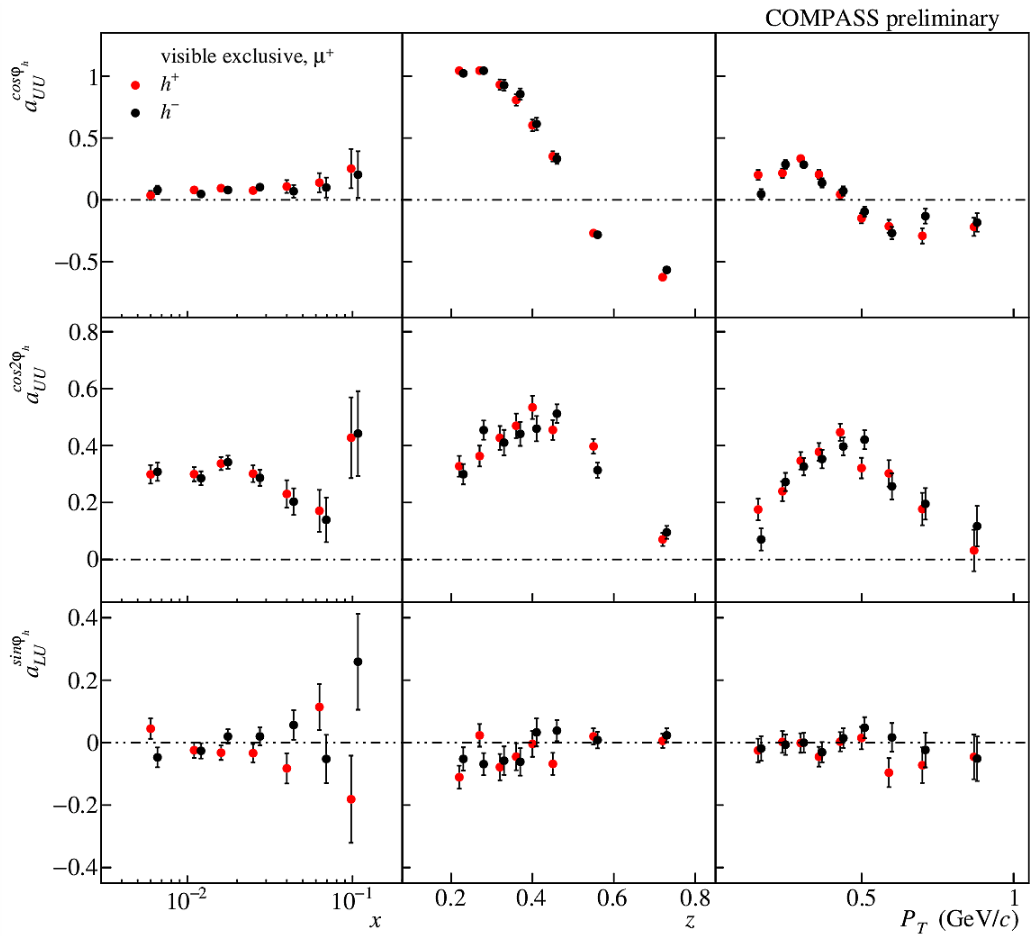


Contamination on (LH_2) – 1D

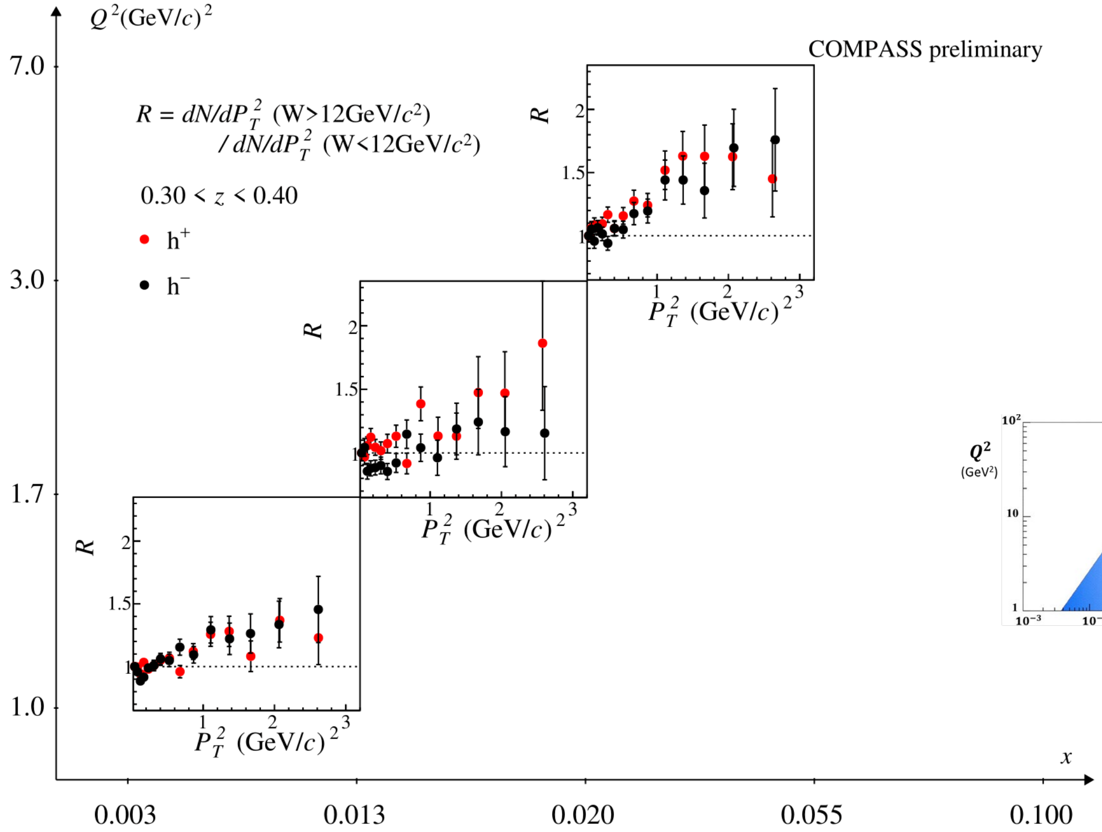
- Determined from $z_1 + z_2 > 0.95$
- Selecting ρ^0, ω and ϕ

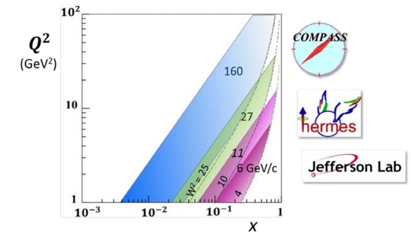


The diffractive ρ^0 production and decay.



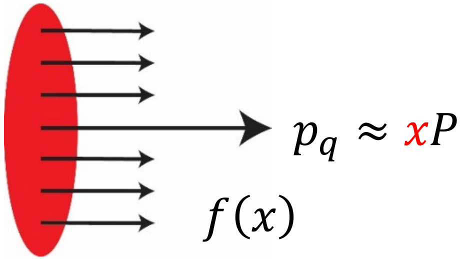
P_{hT} distributions vs W



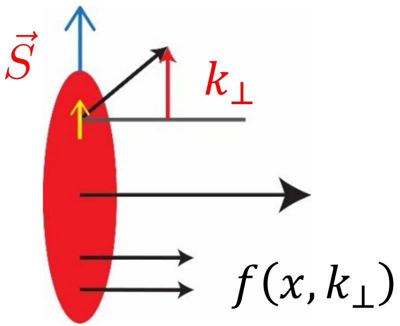


Unpolarised Transverse Momentum dependent PDFs

- 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 $k_\perp$

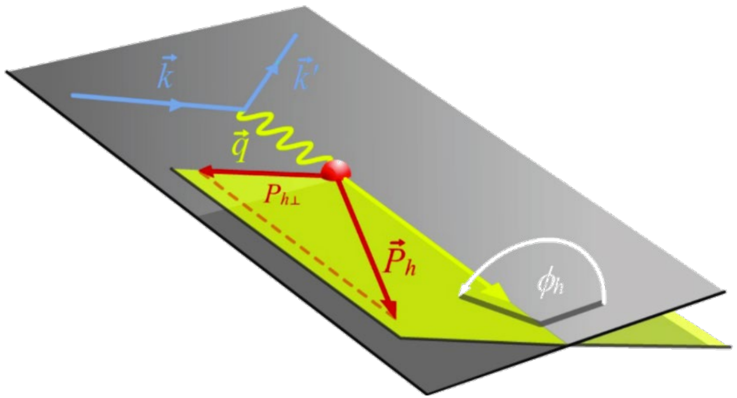
$$f_1^q(x, k_\perp)$$

- 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

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

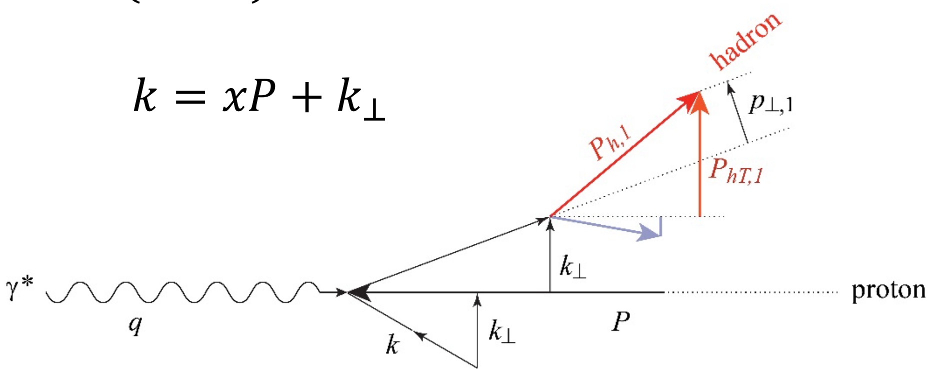
Unpolarised Azimuthal Modulation

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 $d\sigma^{\ell q\to\ell' q} = \hat{s}^2 + \hat{u}^2$



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

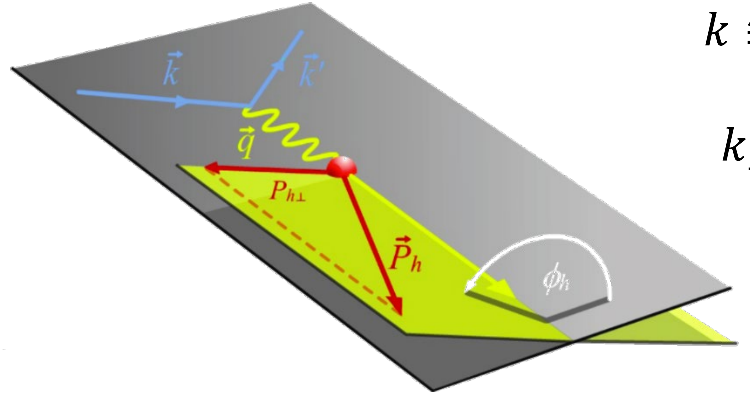
$$k = xP + k_\perp$$



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.

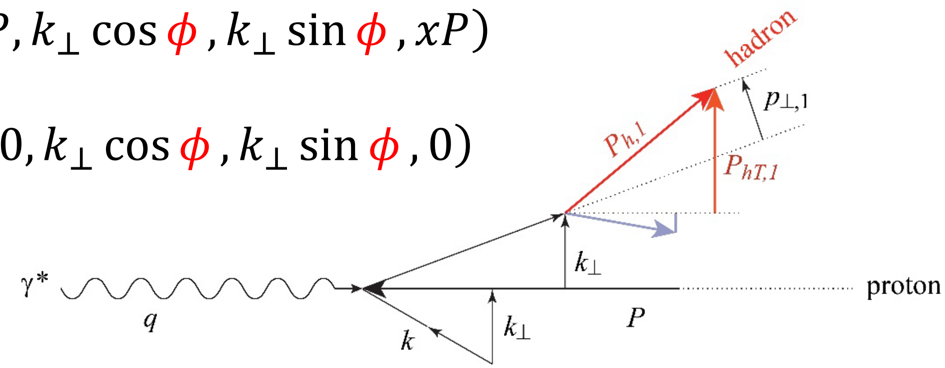
Unpolarised Azimuthal Modulation

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

1D vs multi D

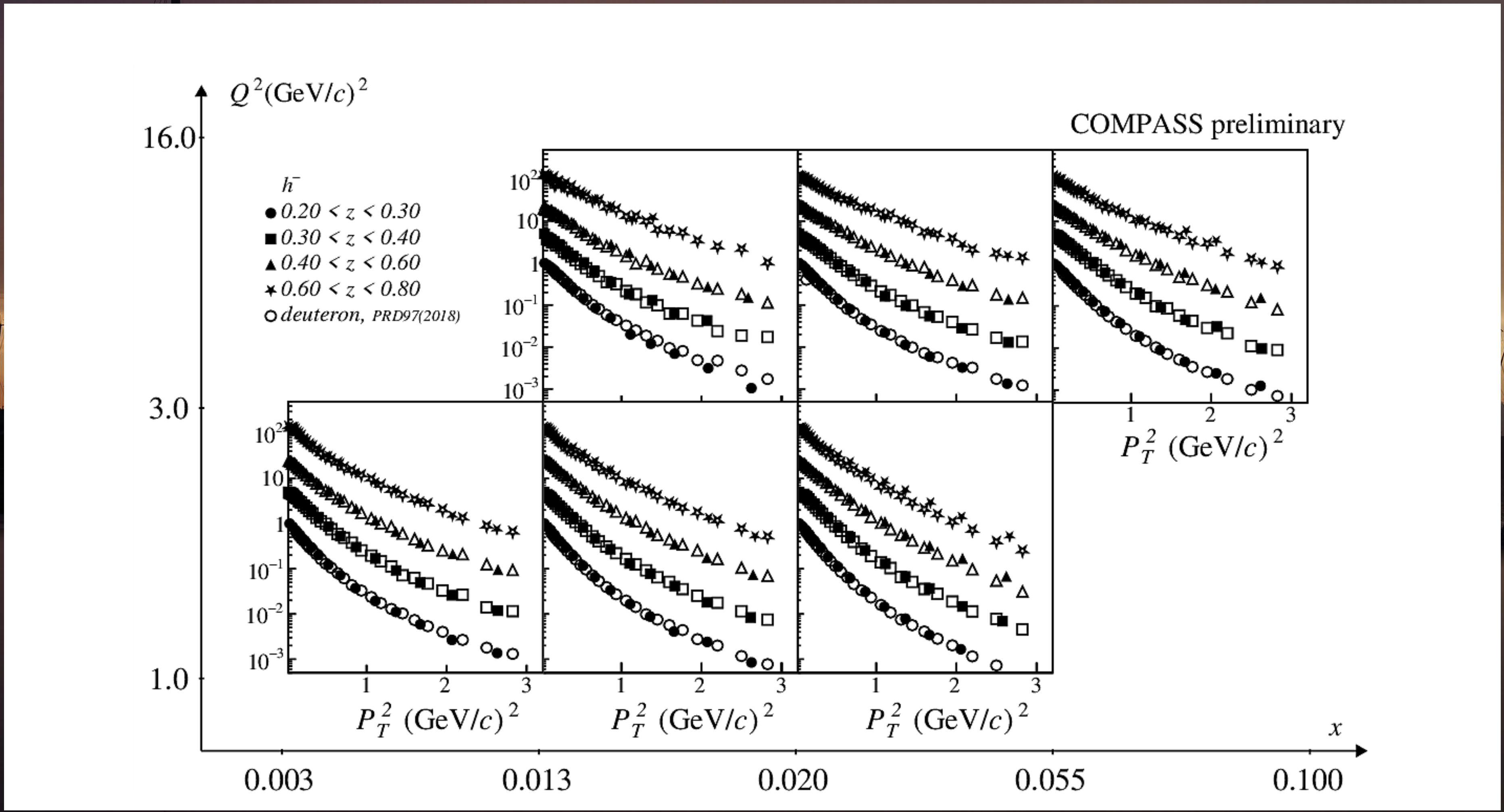
- The asymmetries are:

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

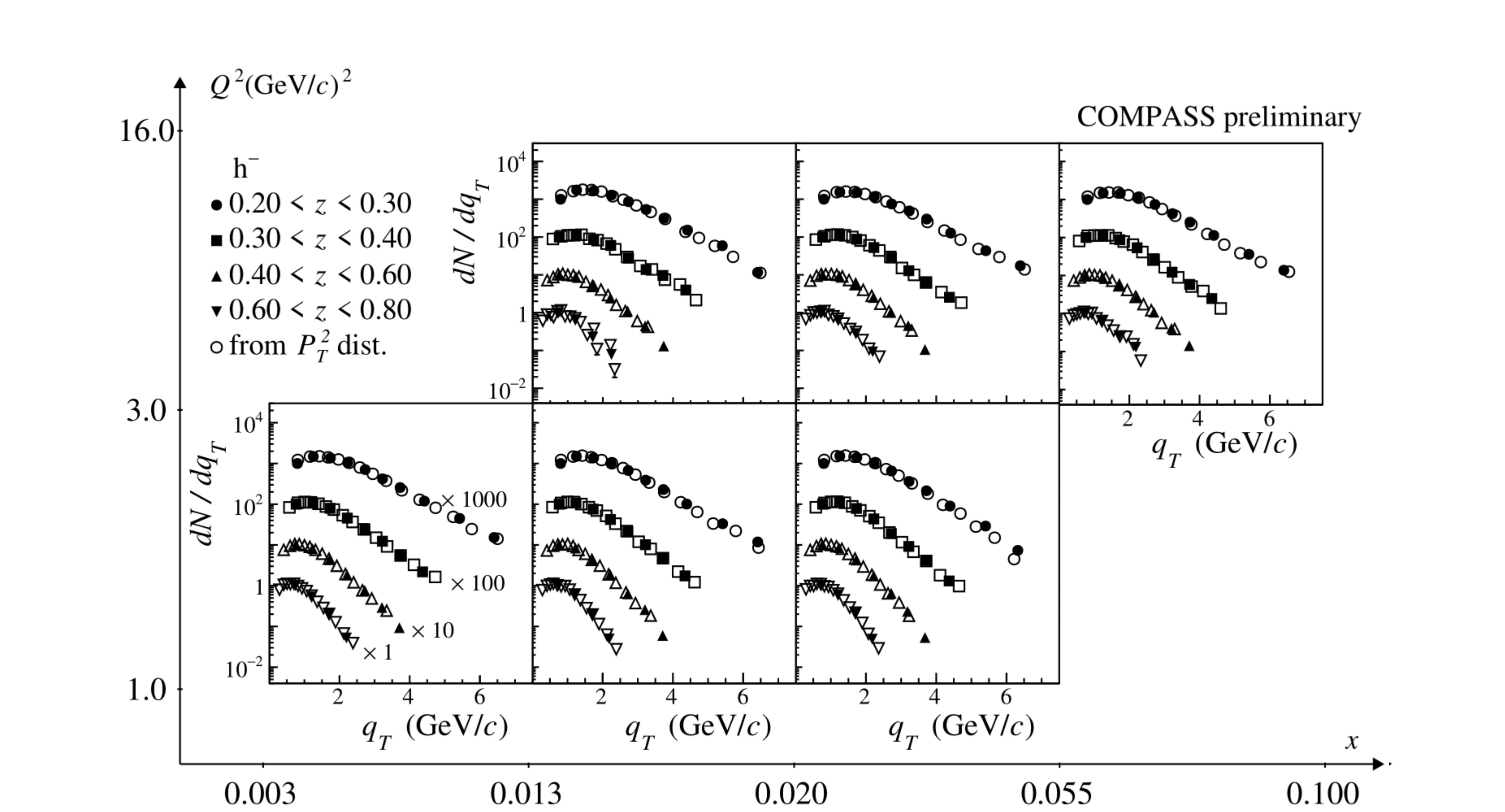
- When we measure on 1D, i.e. as a function of x, we integrate over the phase space of the other variables

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

Comparison with the publish deuteron

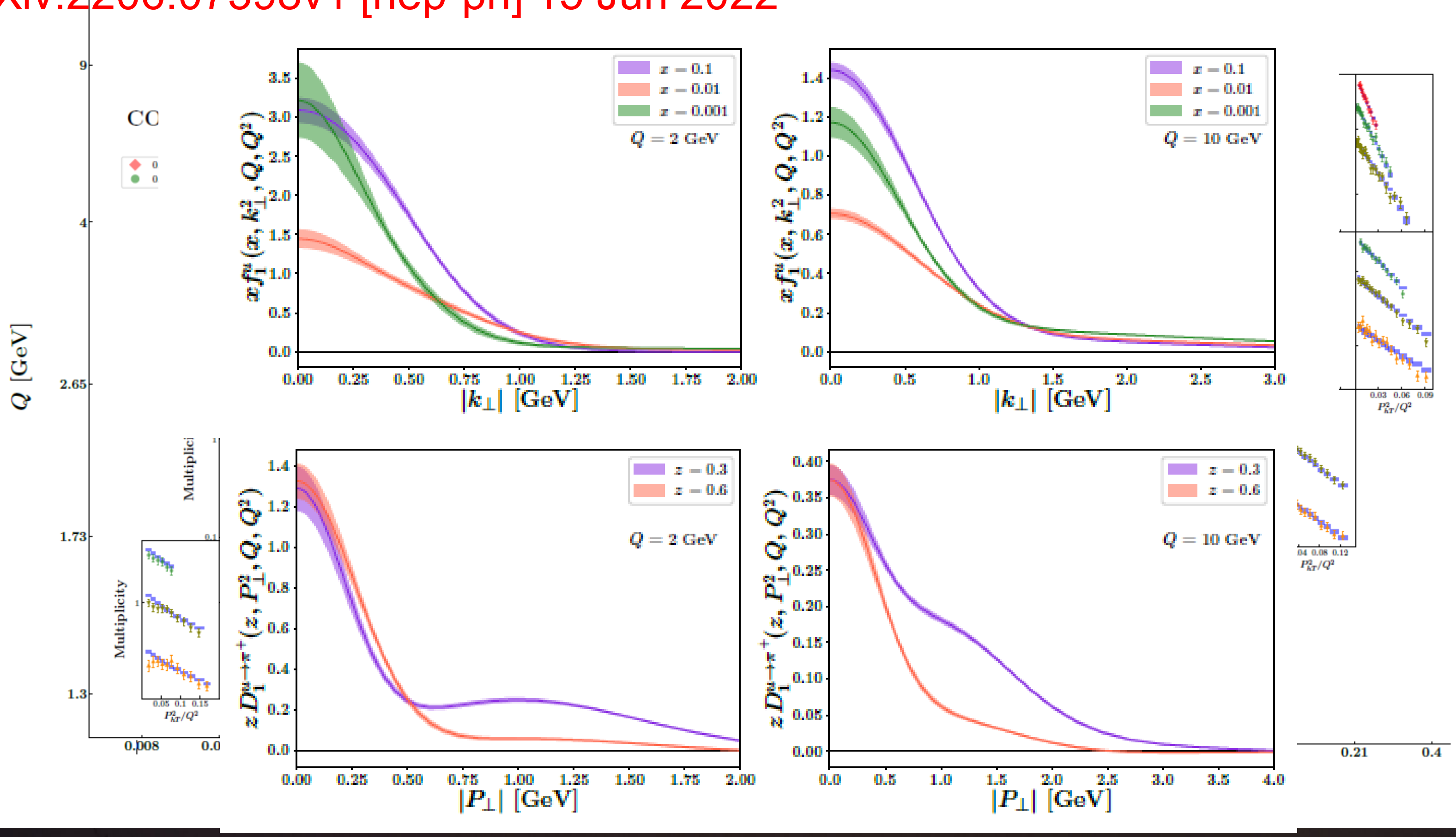


q_T distributions

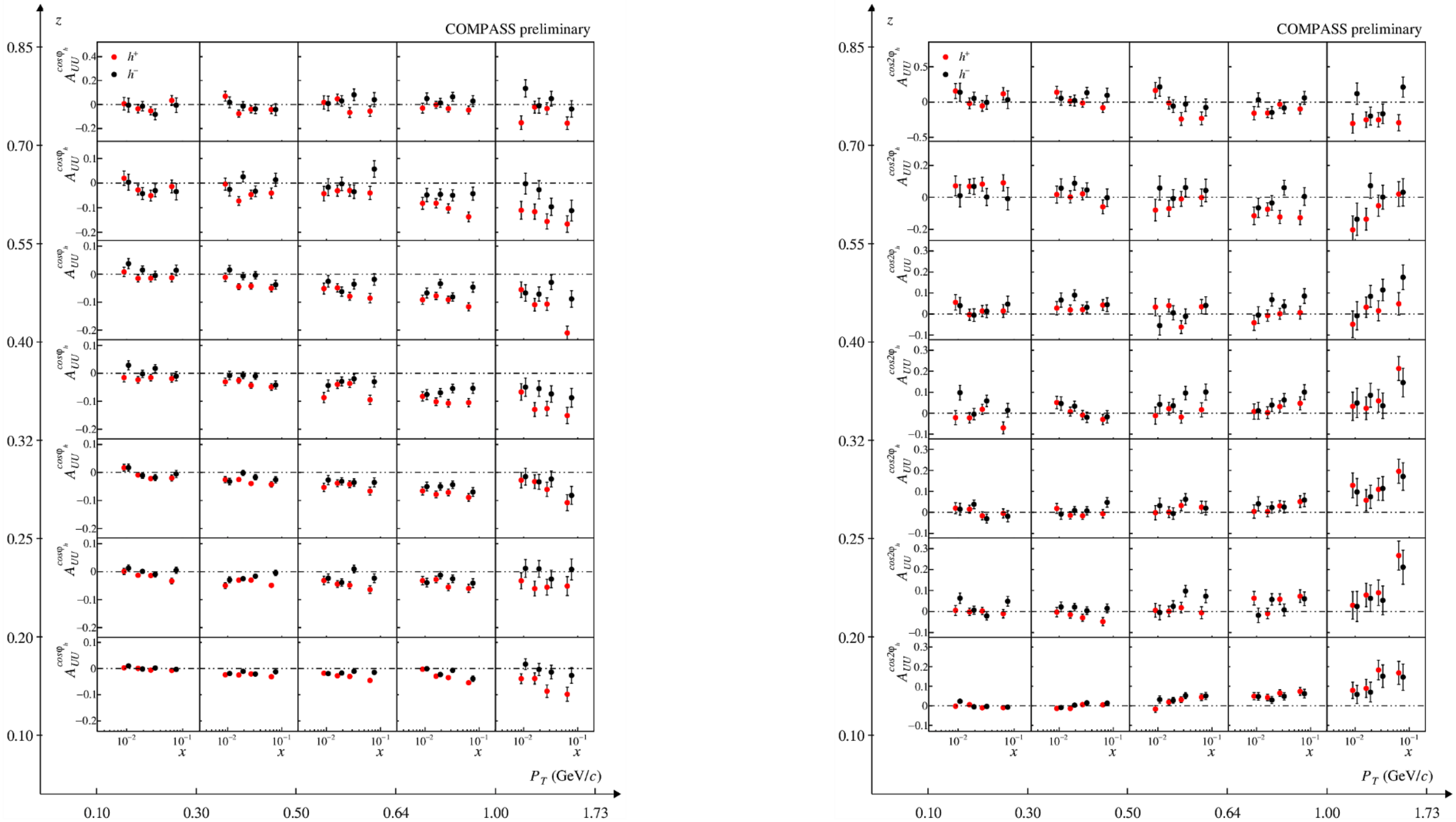


Phenomenological fits

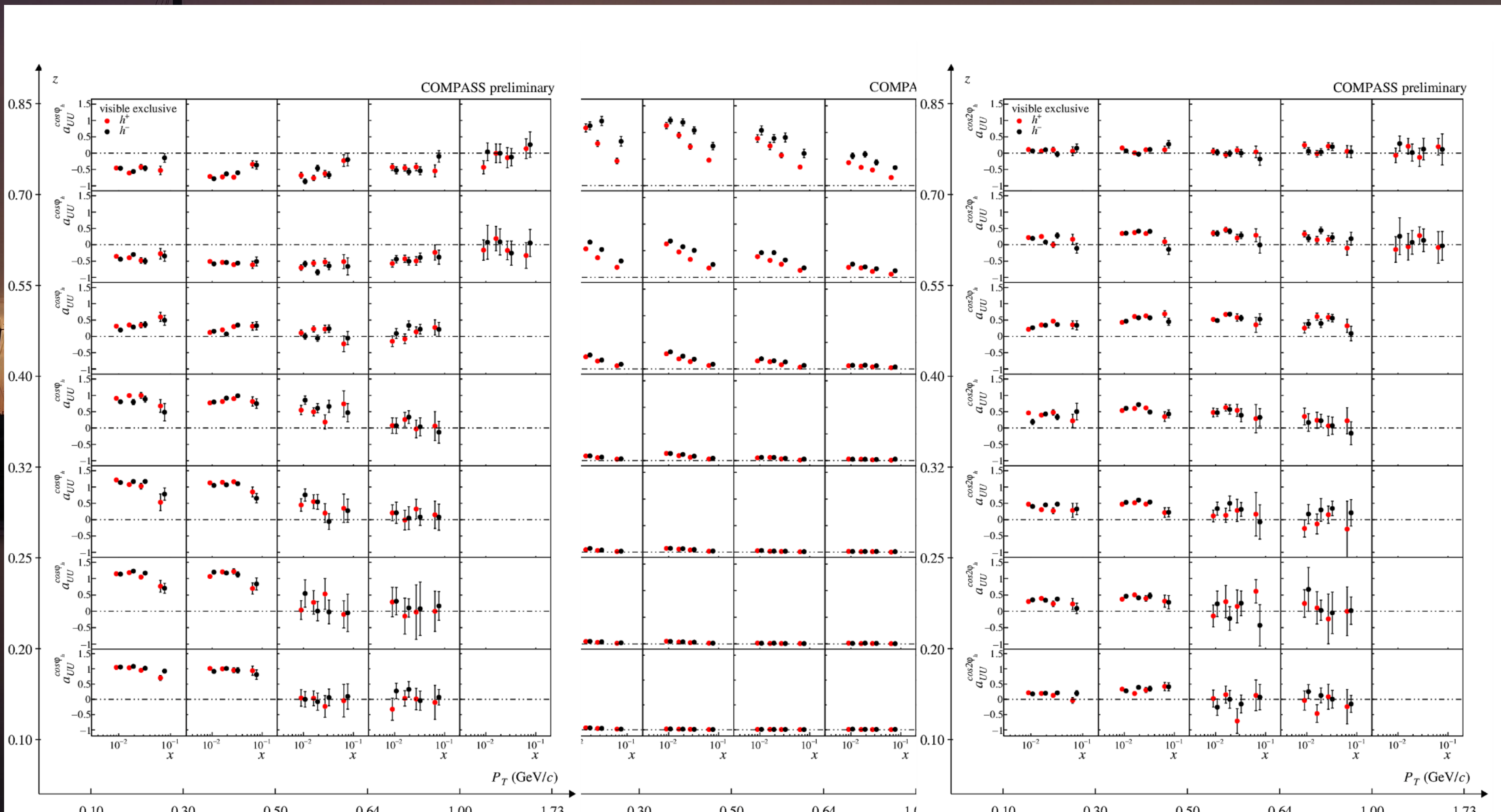
arXiv:2206.07598v1 [hep-ph] 15 Jun 2022



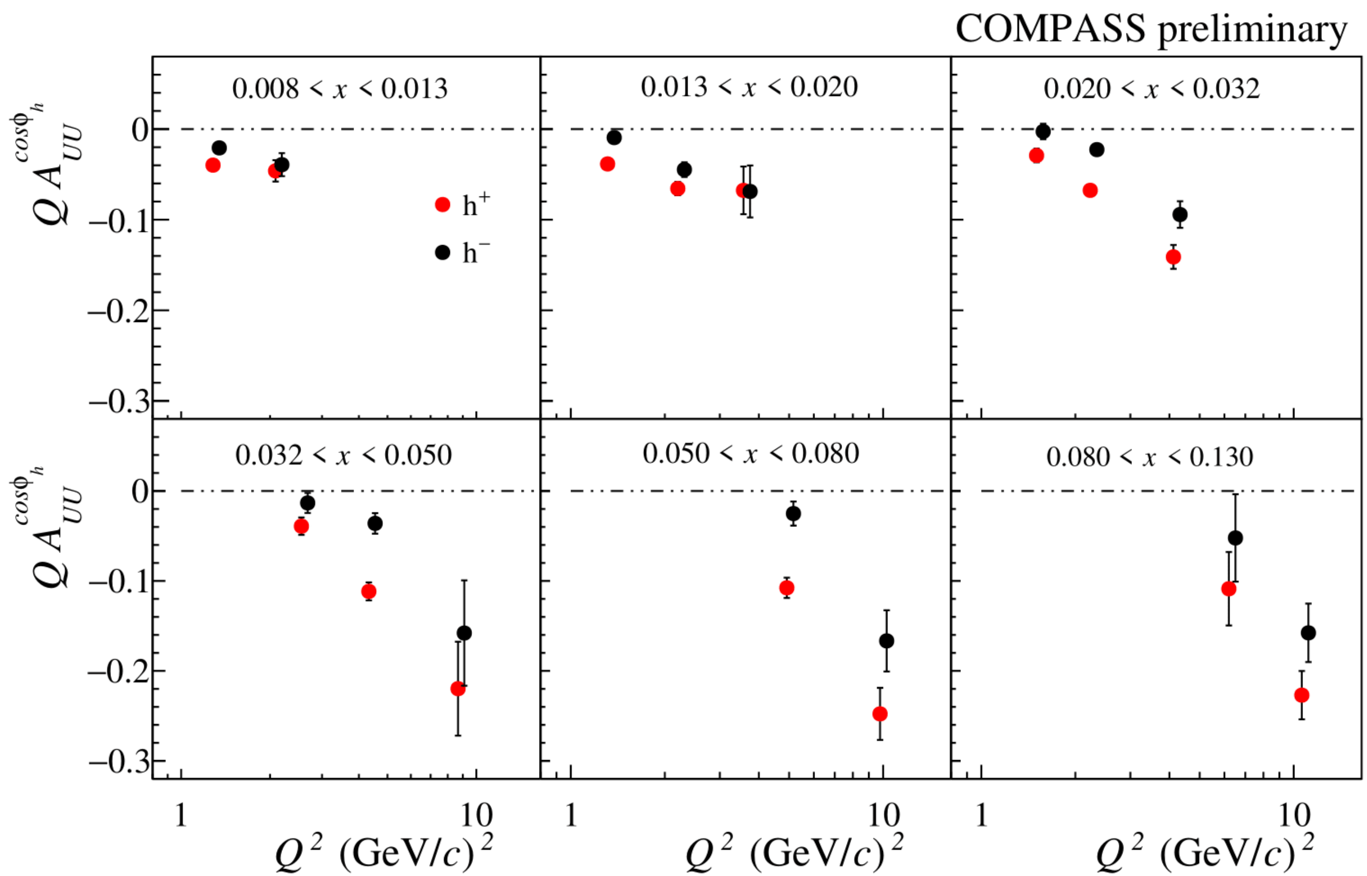
Azimuthal modulations on (LH_2) – 3D



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
$Q\,A_{UU}^{\cos\phi_h}$
0
−0.1
−0.2
−0.3
h^+
h^-
1
10
Q^2 (GeV/c)^2

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

RADIATIVE CORRECTIONS

- Measure FFs, PDFs, etc. by comparing data with theoretical predictions:

$$\sigma_{\mathrm{exp}} = \sigma_{\mathrm{theory}}[PDFs, TMDs \ldots]$$

- High precision requires knowledge of higher-order corrections

$$\sigma_{\mathrm{theory}} = \sigma^{(0)}[\equiv \sigma_{\mathrm{Born}}] + \alpha_{em}\sigma^{(1)} + \alpha_{em}^2\sigma^{(2)} + \cdots$$

- Emission of real photons
    - experimentally often not distinguished from non-radiative processes: soft photons, collinear photons

➔ ”radiative corrections”

- Virtual corrections: loop diagrams
    - needed to cancel infrared divergences