COMPASS SIDIS

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(on behalf of the COMPASS Collaboration)

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What does “COMPASS” stand for?

COMPASS: NA58, EHN2, building 888:

COmmon

Muon

Proton

Apparatus for

Structure and

Spectroscopy

COMPASS was the *largest surface experiment* at CERN

COMPASS Collaboration

Дубна (LPP and LNP), Москва (INR, LPI, State University), Протвино

CERN

Bochum, Bonn (ISKP & PI), Erlangen, Freiburg, Mainz, München TU

Warsawa (NCBJ), Warsawa (TU) Warsawa (U)

Yamagata

UIUC

Praha

Lisboa

Saclay

Burden, Calcutta

Tel Aviv

Torino (University,INFN), Trieste (University,INFN)

Taipei (AS)

- about 220 members
- from 13 different countries
- involving 24 universities and research institutes

COMPASS, few facts

- Flagship measurement for COMPASS was ΔG
- TMDs were brand new objects and but we were very much interested in this field and we put their study in the proposal, even if with marginal beam request (i.e. 20% of the time devoted to ΔG)

As suggested by J. Collins [71], the fragmentation function for transversely polarised quarks should exhibit a specific azimuthal dependence. The transversely polarised quark fragmentation function $\mathcal{D}_q^h$ should be built up from two pieces, a spin-independent part D_q^h, and a spin-dependent part ΔD_q^h:

$$\mathcal{D}_q^h(z, \vec{p}_q^{\,h}) = D_q^h(z, p_q^h) + \Delta D_q^h(z, p_q^h) \cdot \sin(\phi_h - \phi_{S'}), \qquad (3.23)$$

We propose to measure in semi-inclusive DIS on transversely polarised proton and deuterium targets the transverse spin distribution functions $\Delta_T q(x) = q_\uparrow(x) - q_\downarrow(x)$, where $\uparrow$ ($\downarrow$) indicates a quark polarisation parallel (antiparallel) to the transverse polarisation of the nucleon. Hadron identification allows to tag the quark flavour.

- The measurement of the Sivers PDF was added to the program soon after … the other TMD with the developments over the years
- COMPASS was approved by CERN in 1997. R&D and construction from 1998 to 2001
- Measurements started in 2002 by HERMES (p) and COMPASS (d)
- This field has grown considerably in the last years and comes one of high priority measurements for the JLab12 program and for the EIC

Muon beam: SIDIS setup

- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

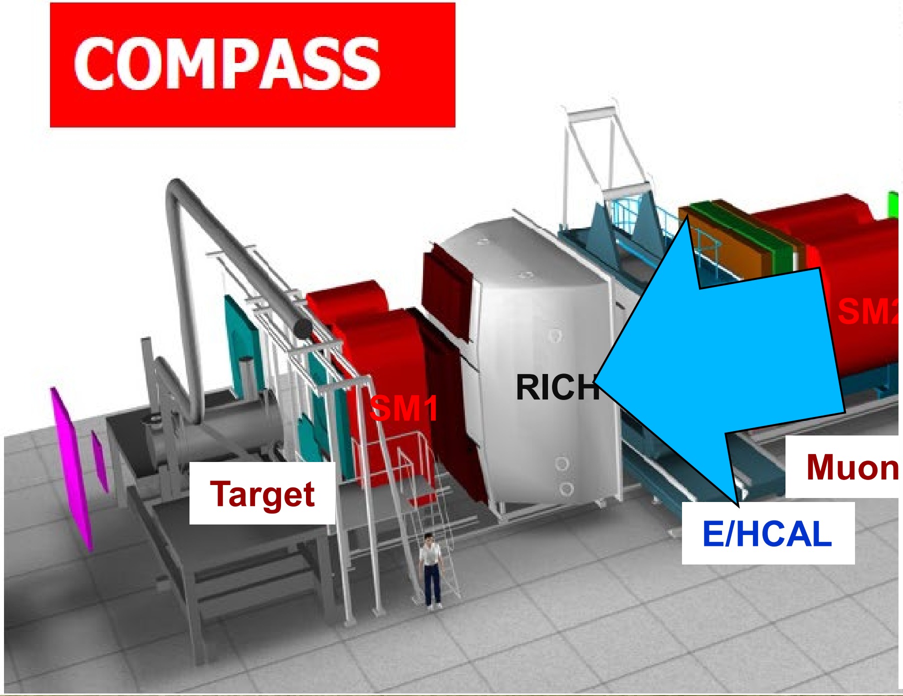
Large Angle Spectrometer (SM1)

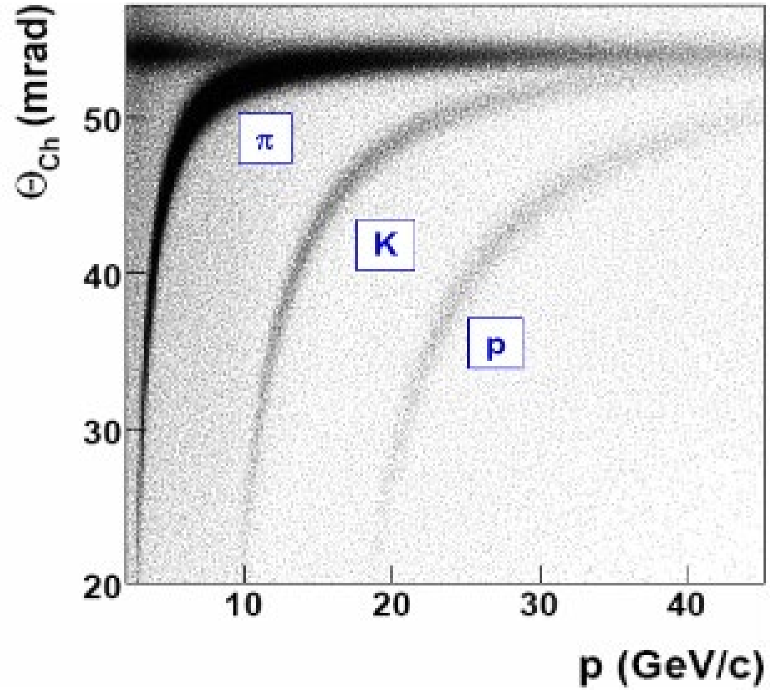
Small Angle Spectrometer (SM2)

radiator C_4F_{10}

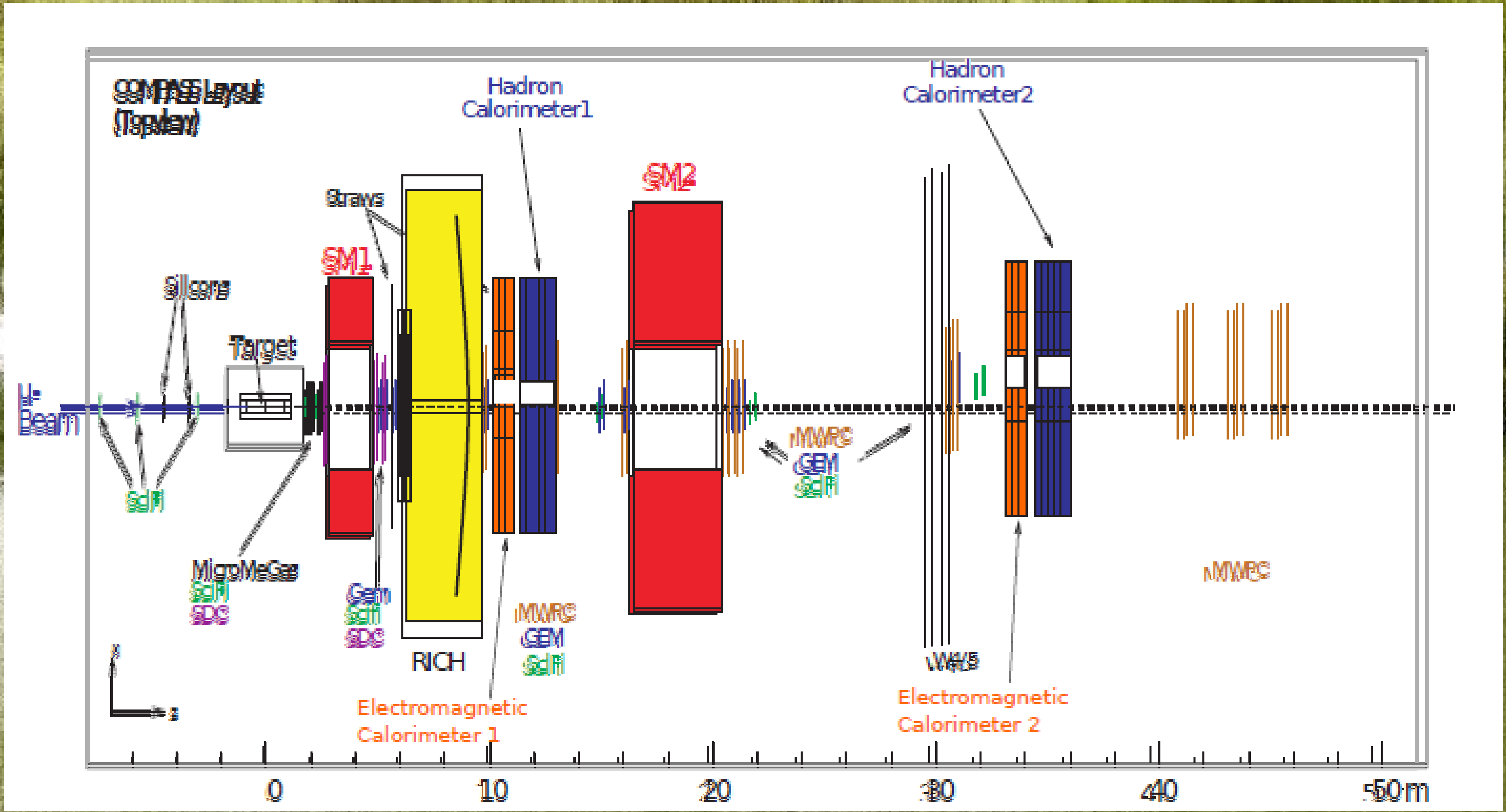
threshold: π ~2 GeV/c

K ~ 10 GeV/c

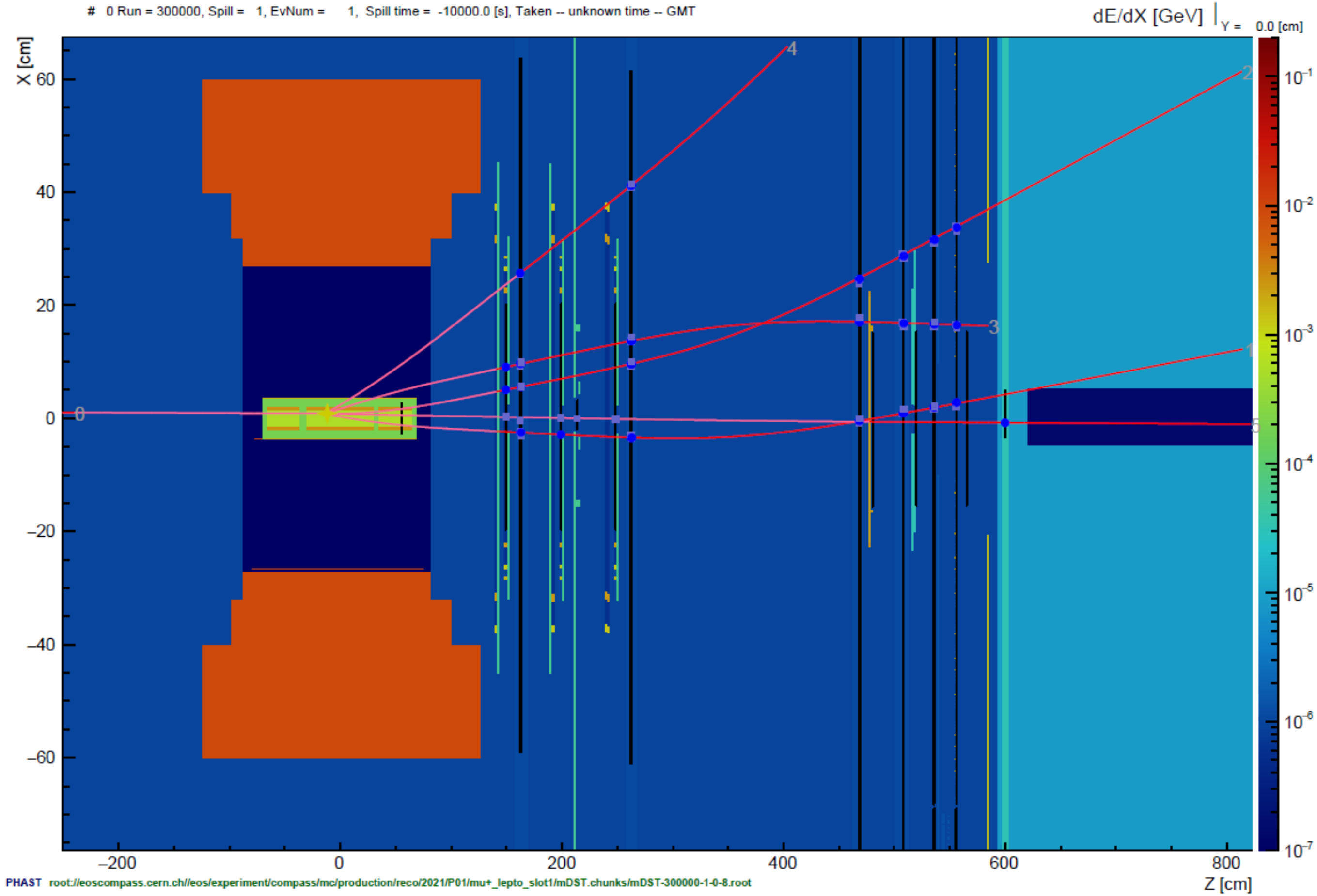




Spectrometer elements

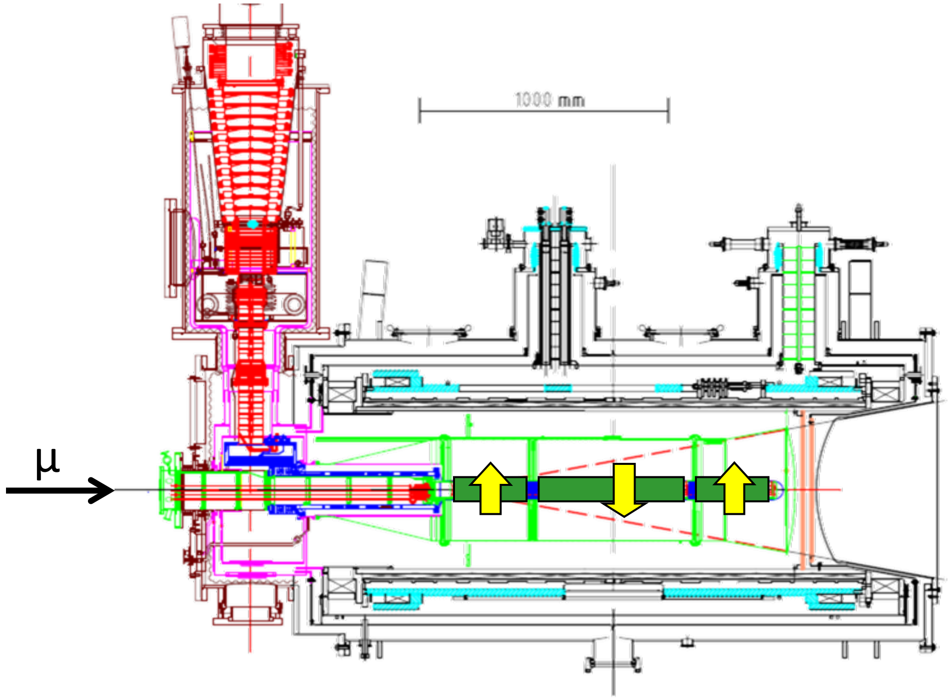


Spectrometer: 2021 event

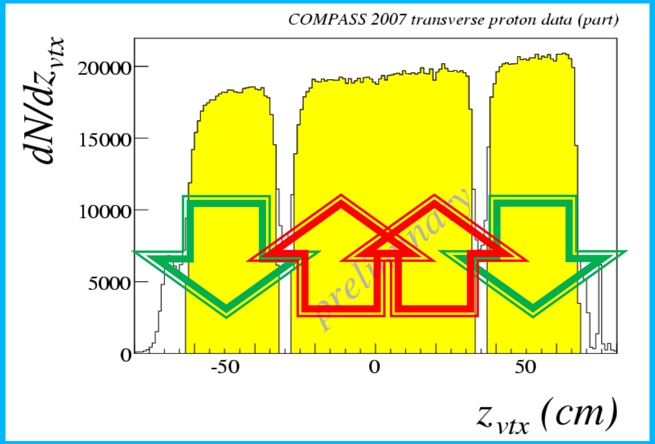


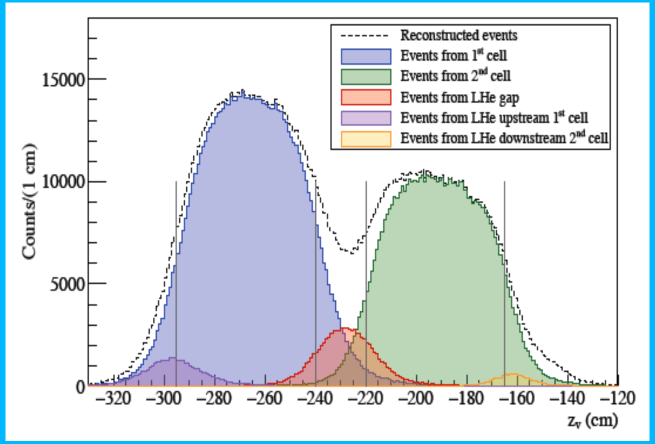
the polarized target system (>2005)

$^3He - ^4He$ dilution refrigerator (T~50mK)



solenoid 2.5T
dipole magnet 0.6T

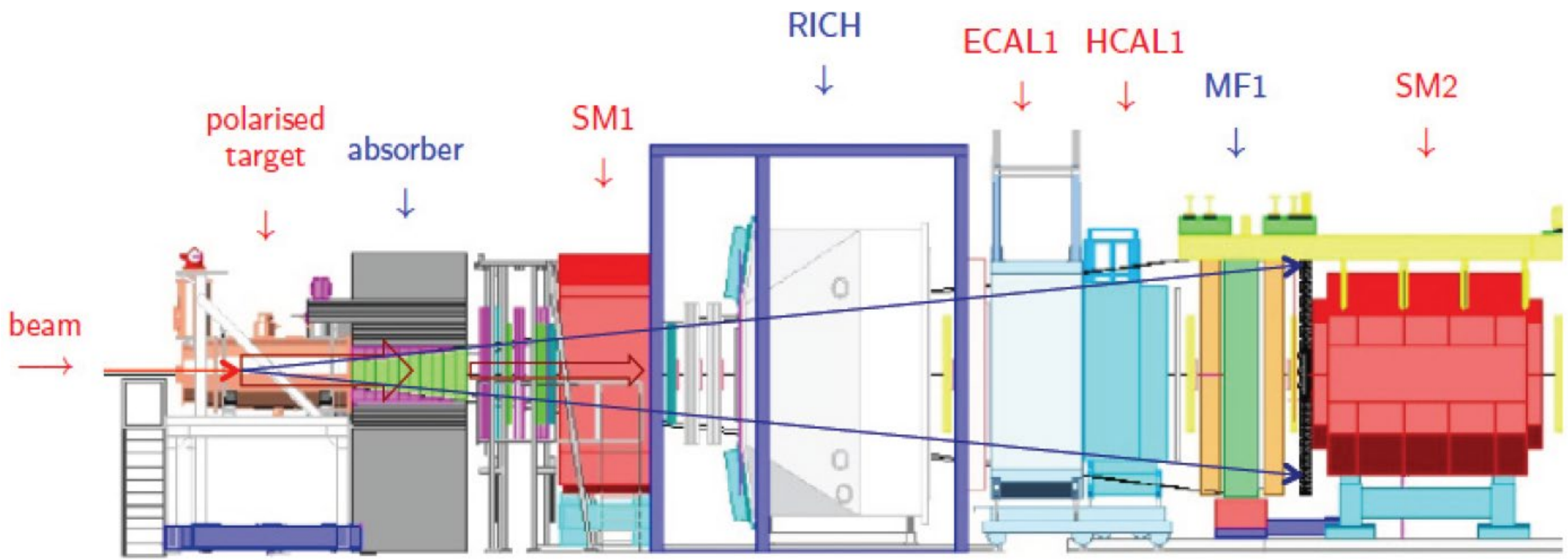




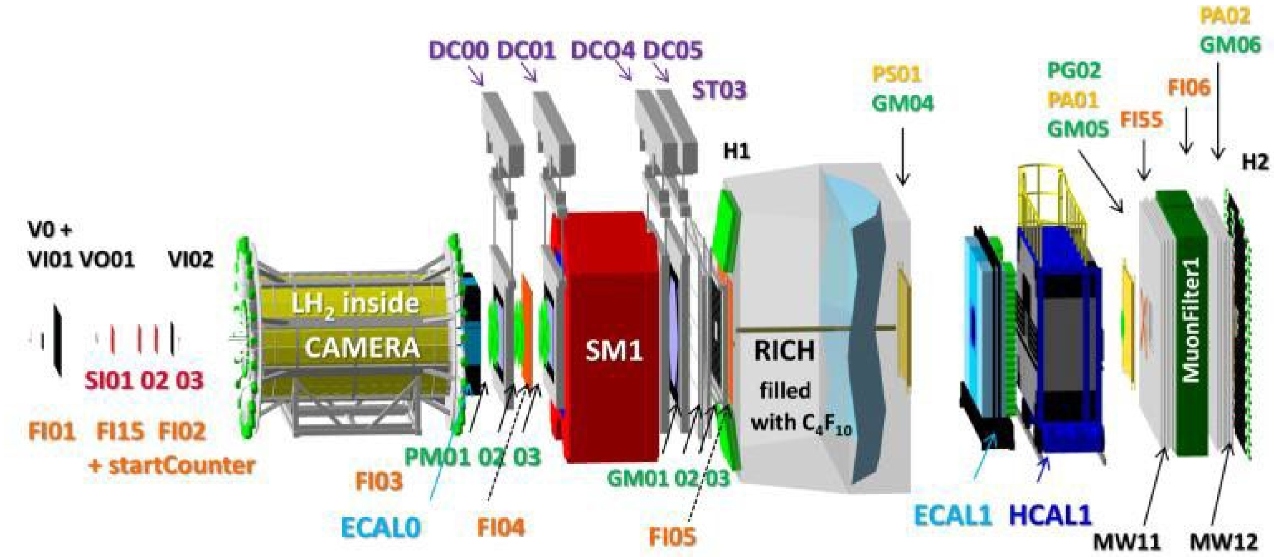
Polarized target

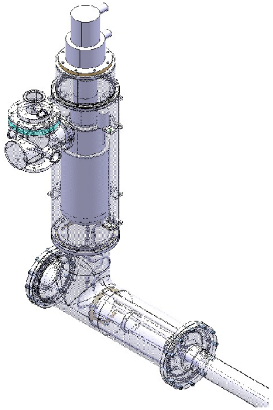
- 1.2 m long, 40 mm diameter, 5-6 l
- Temperature 60mK (-273.09 °C) with a record of 30 mK
- ^{6}LiD, deuterated lithium – deuterium acts as target
- NH_3 ammonia – hydrogen acts as target
- Polarization is obtained by Dynamic Nuclear Polarization
- Three things are needed: high magnetic field to align the spins, a very low temperature to reduce thermal energy and microwaves to transfer spin from the electrons to the nucleons
- A 2.5 T solenoid field is applied by a superconducting magnet with a 10^{-4} homogeneity over the target volume

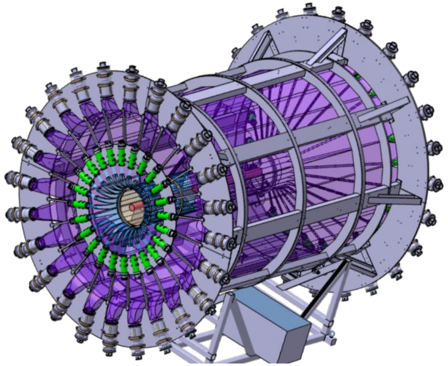
Hadron beam: Drell-Yan setup

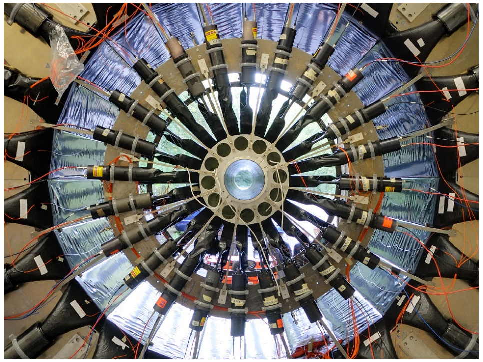


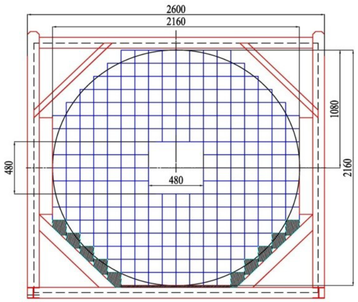
Muon beam – DVCS setup



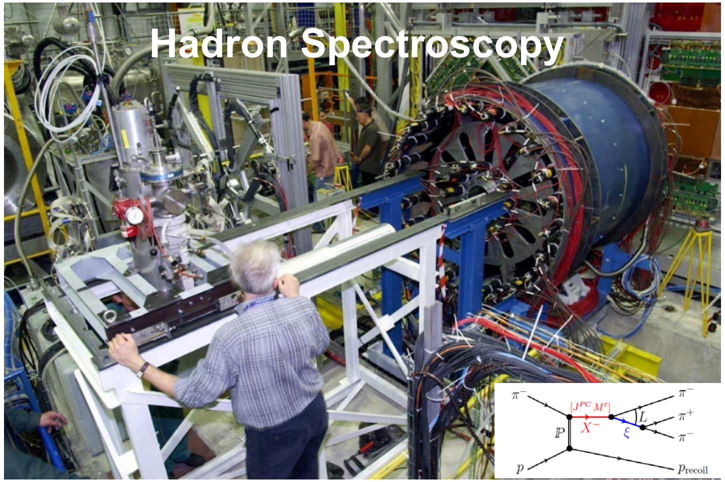


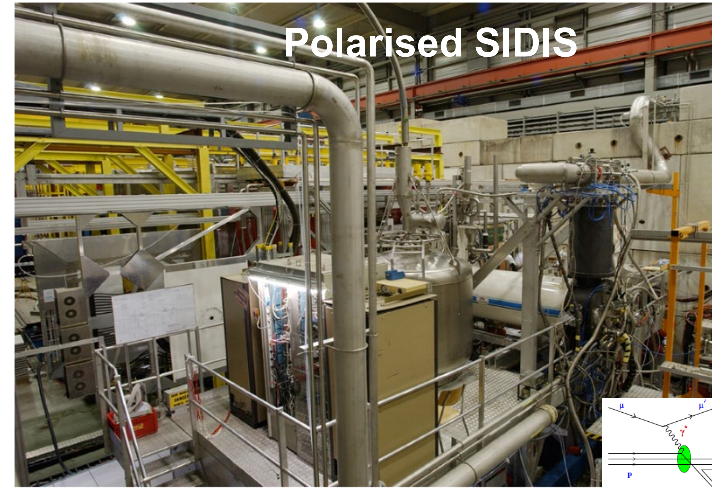




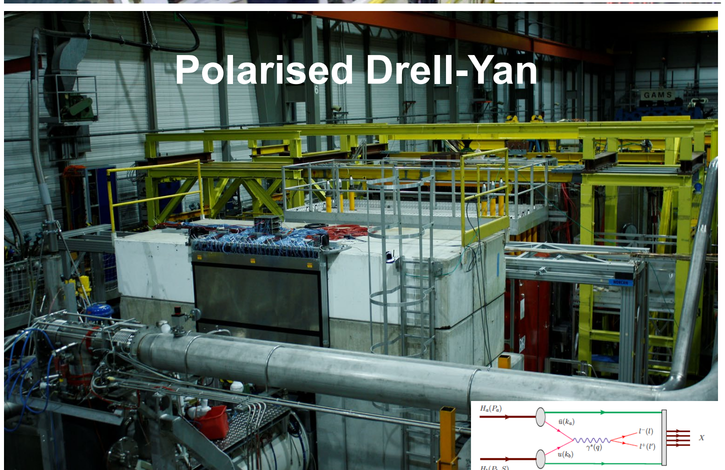


COMPASS target area

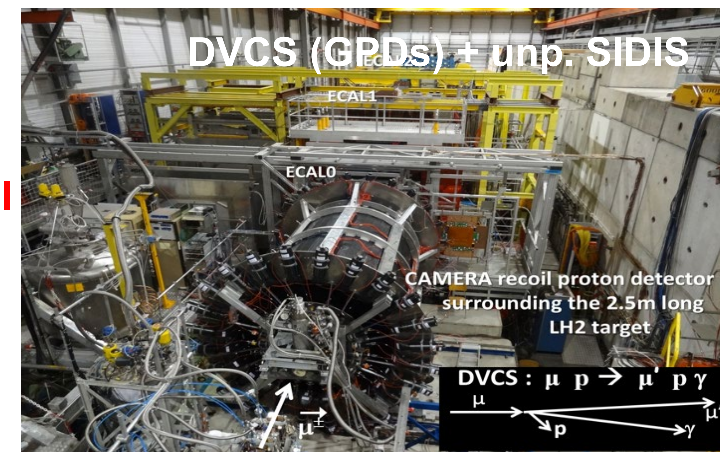




COMPASS-I
1997-2011
and back in
2022



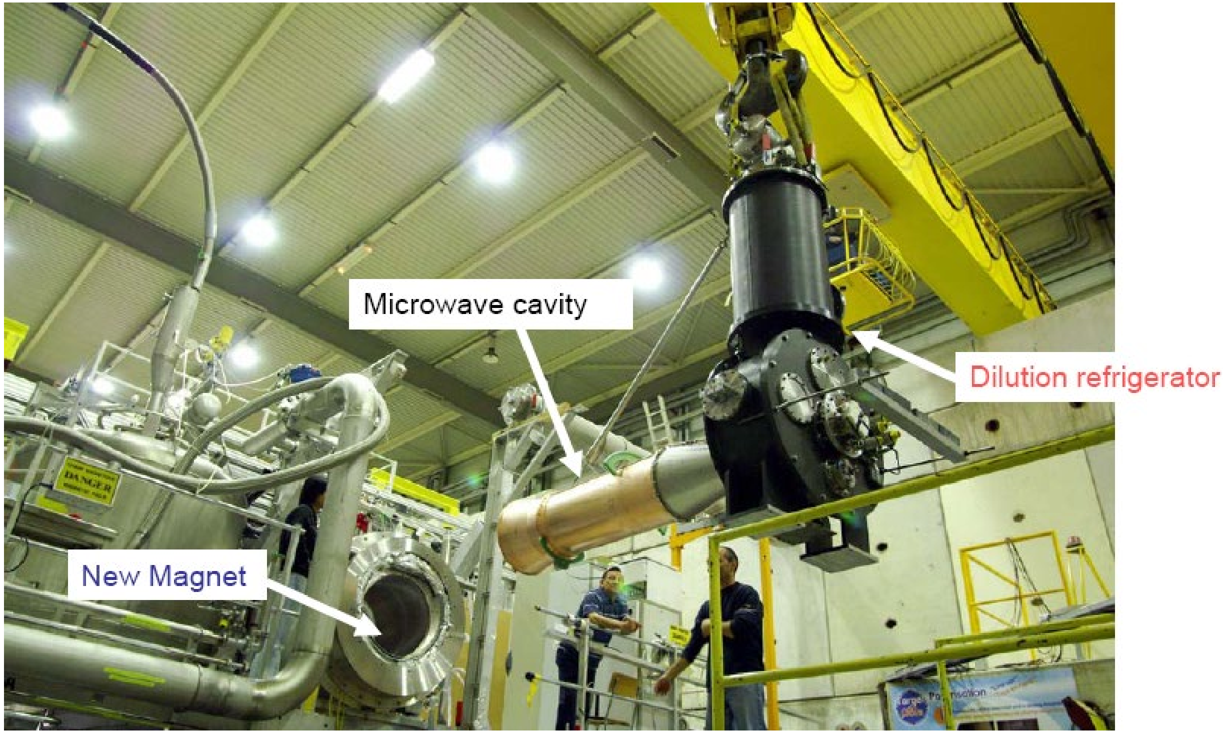
COMPASS-II
2012-2020



Operations on the target area

Targets


27 09 2012


Microwave cavity
Dilution refrigerator
New Magnet
DANGER

COMPASS data taking

muon beam	deuteron (^{6}LiD) PT	2002 2003 2004	80% L/20% T target polarisation
		2006	L target polarisation
	proton (NH_3) PT	2007	50% L /50% T target polarisation
Hadron	LH target	2008 2009	
muon beam	proton (NH_3) PT	2010	T target polarisation
		2011	L target polarisation
Hadron	Ni target	2012	Primakoff
muon beam	LH2 target	2012	Pilot DVCS & unpol. SIDIS
Hadron	Proton (NH3) DT PT	2014 2015 2018	Pilot DY run DY run DY run
muon beam	LH2 target	2016 2017	DVCS & unpol. SIDIS
muon beam	deuteron (^{6}LiD) PT	2022	T target polarisation

Kinematics of Deep Inelastic Scattering

- DIS variables:

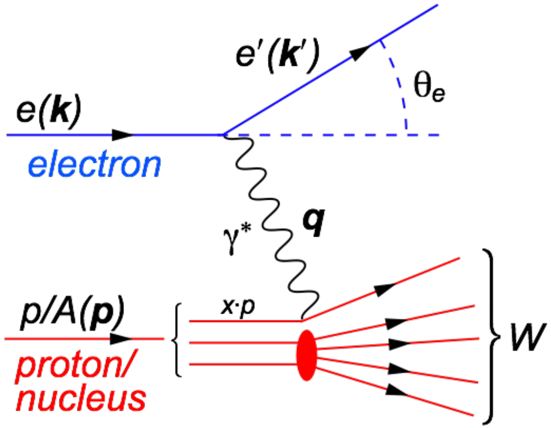
$$s = (k+P)^2 \simeq 2k \cdot P + m_P^2$$

$$Q^2 = -q^2 = -(k-k')^2 \simeq 2k \cdot k'$$

$$x = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$

$$W^2 = (P+q)^2 = P^2 - Q^2 + 2P \cdot q$$



- SIDIS variables:

$$z_h = \frac{P \cdot P_h}{P \cdot q} \qquad \vec{P}_{hT} = \vec{P}_h - \frac{\vec{P}_h \cdot \vec{q}}{|\vec{q}|}\hat{q}$$

NB: always use invariants for invariant quantities (not their expression in a particular frame). This will help you when moving from 1 experiment to another.

$$\ell p \longrightarrow \ell X$$

Beam lepton ℓ: $k = [E, \vec{k}]$

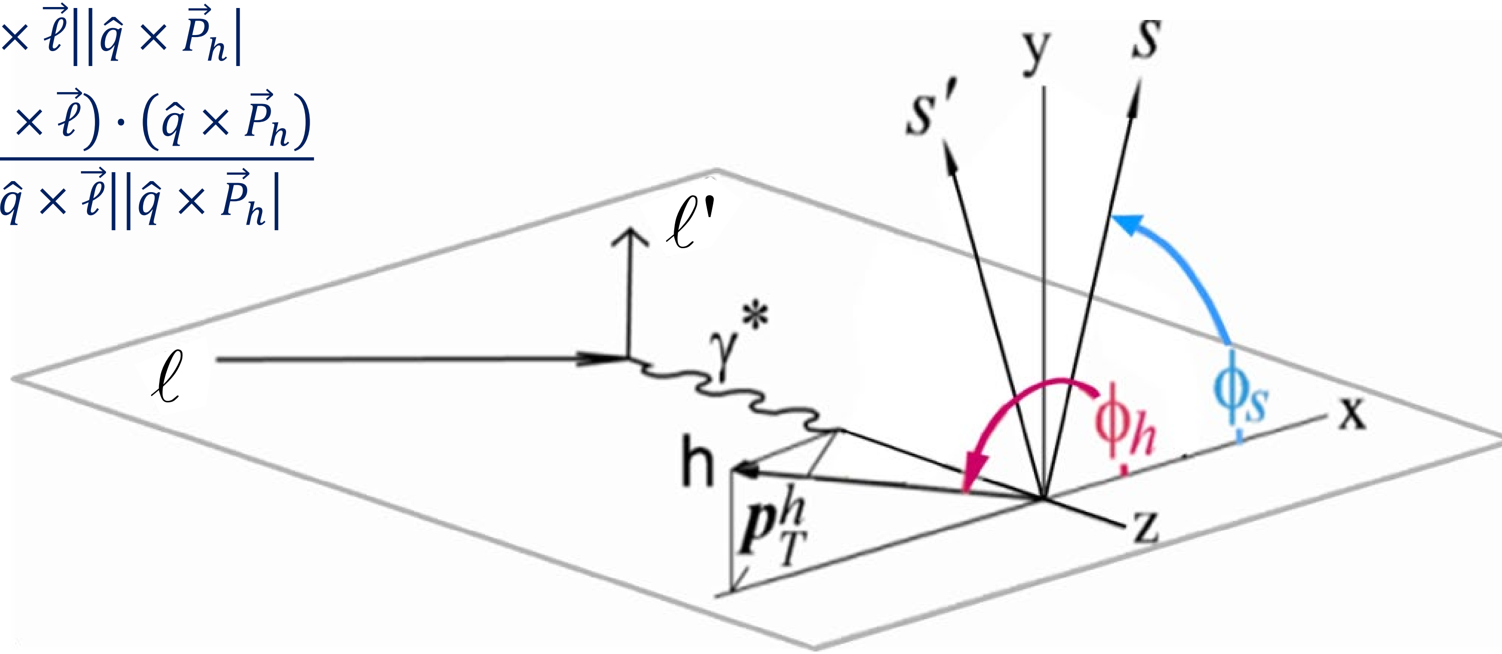
Scat. lepton ℓ': $k' = [E', \vec{k}']$

Virtual Photon γ^*: $q = [\nu, \vec{k} - \vec{k}']$

Azimuthal angles in the GNS or Breit

$$\sin\phi_h = \frac{(\hat{q}\times\vec{\ell})\cdot\vec{P}_h}{|\hat{q}\times\vec{\ell}||\hat{q}\times\vec{P}_h|}$$

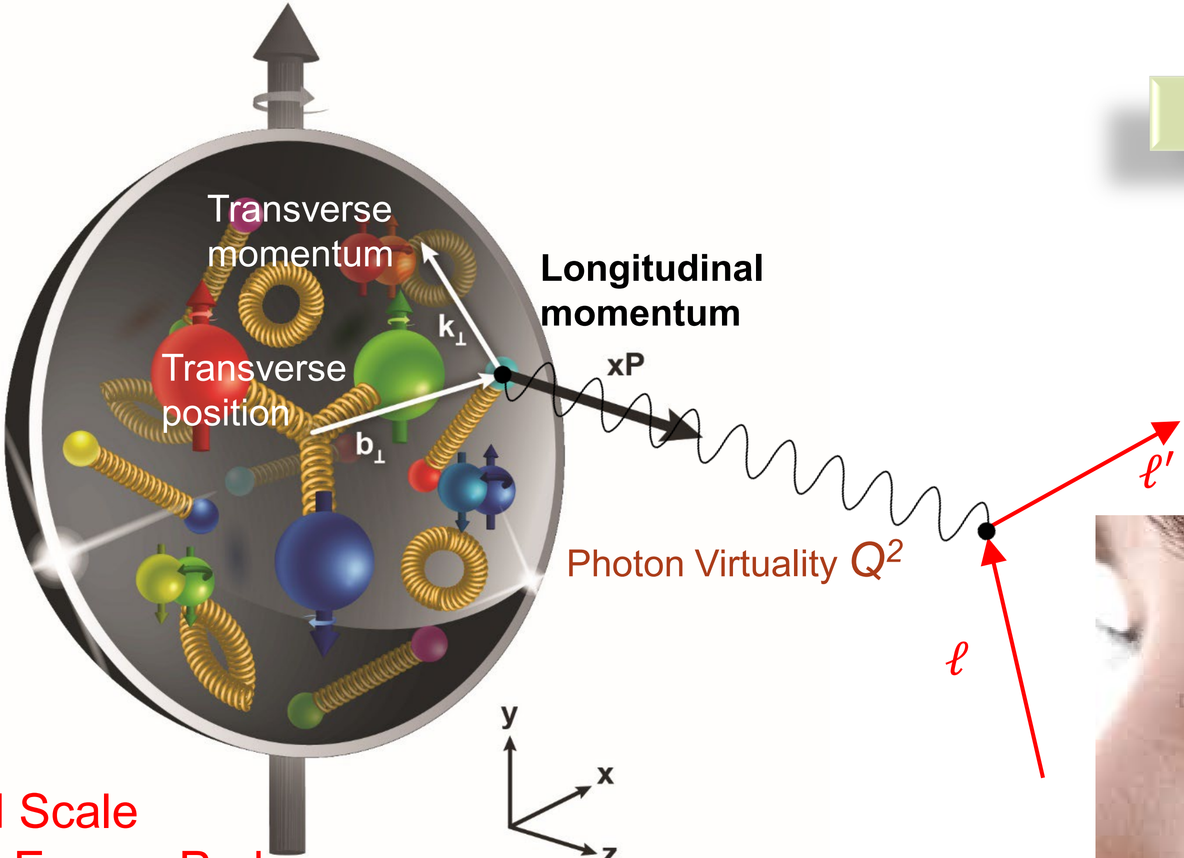
$$\cos\phi_h = \frac{(\hat{q}\times\vec{\ell})\cdot(\hat{q}\times\vec{P}_h)}{|\hat{q}\times\vec{\ell}||\hat{q}\times\vec{P}_h|}$$



We look at our events in the Gamma Nucleon System (GNS) or Breit Frame, i.e. **we need a perfectly reconstructed lepton kinematic**.

Transverse structure of the Nucleon

Confinement Scale

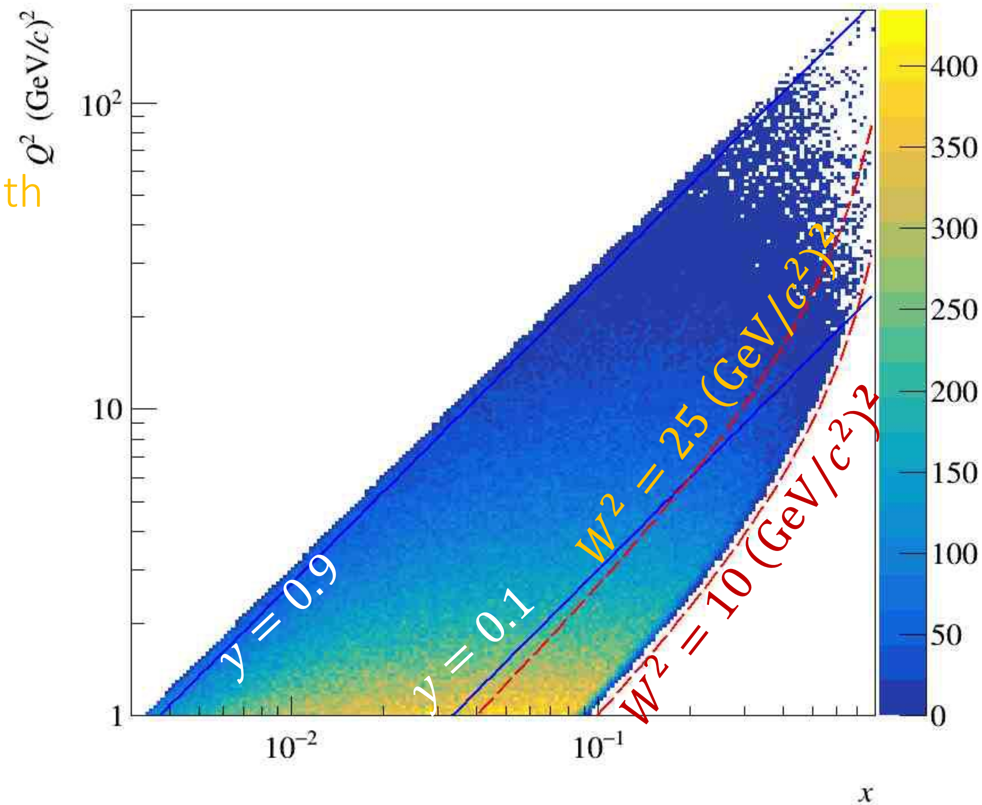


$$W_p^q(x, \vec{k}_\perp, \vec{b}_T)$$

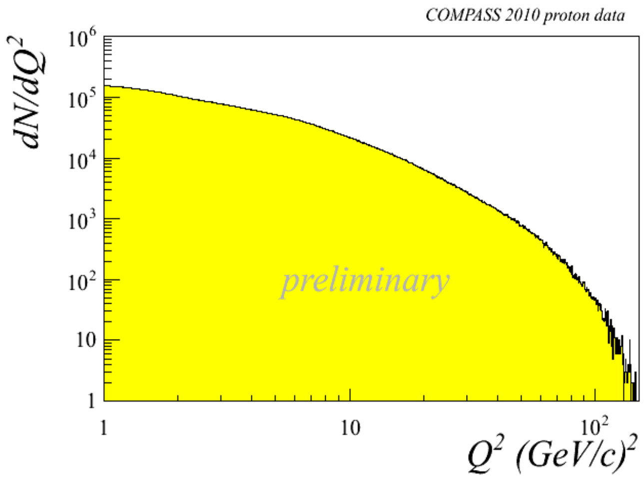
Hard Scale
High Energy Probe

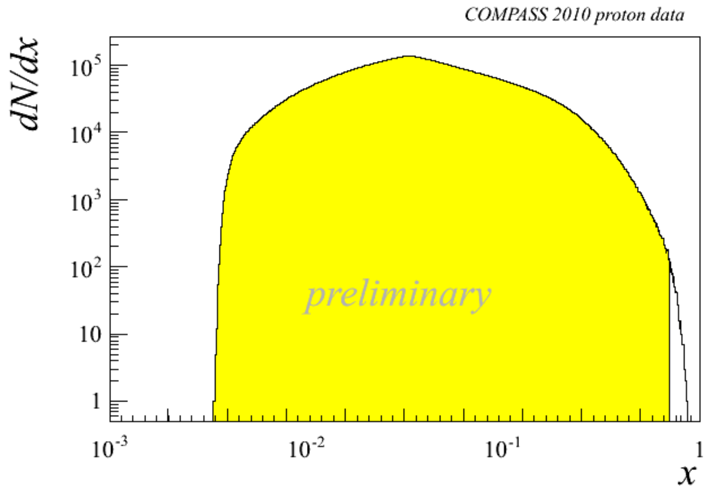
Standard Cuts @ $\sqrt{s}\sim 17$ GeV

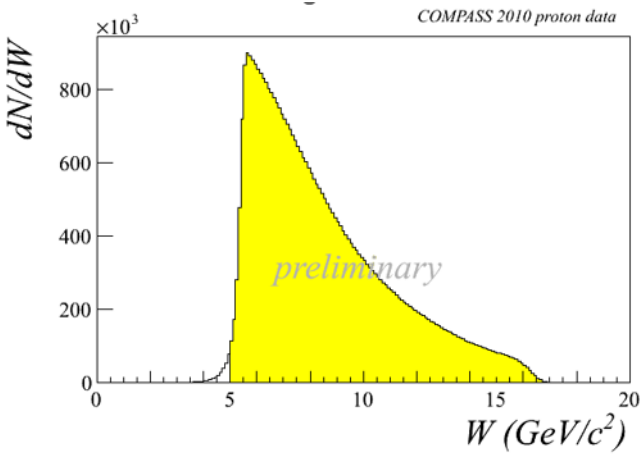
- $Q^2 > 1\ (\mathrm{GeV}/c)^2$
  To be in the dis REGIME
- $0.1 < y < 0.9$
  Limits RC effects and select a region with good resolution
- $W^2 > 25\ (\mathrm{GeV}/c^2)^2$
  Enough space for hadrons and…
  together with z select current hadronization region
- $0.2 < z < 0.85$
  CFR and cut exclusive process
- $P_{hT} > 0.05\ \mathrm{GeV}/c$ Resolution on ϕ_h

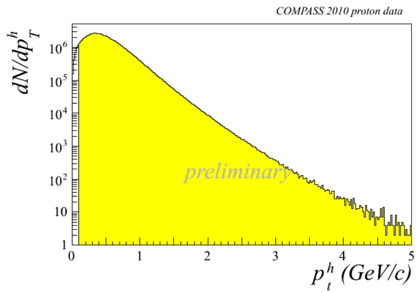


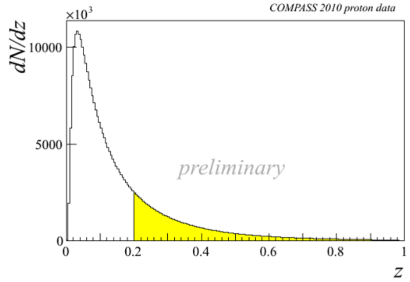
Kinematic distributions



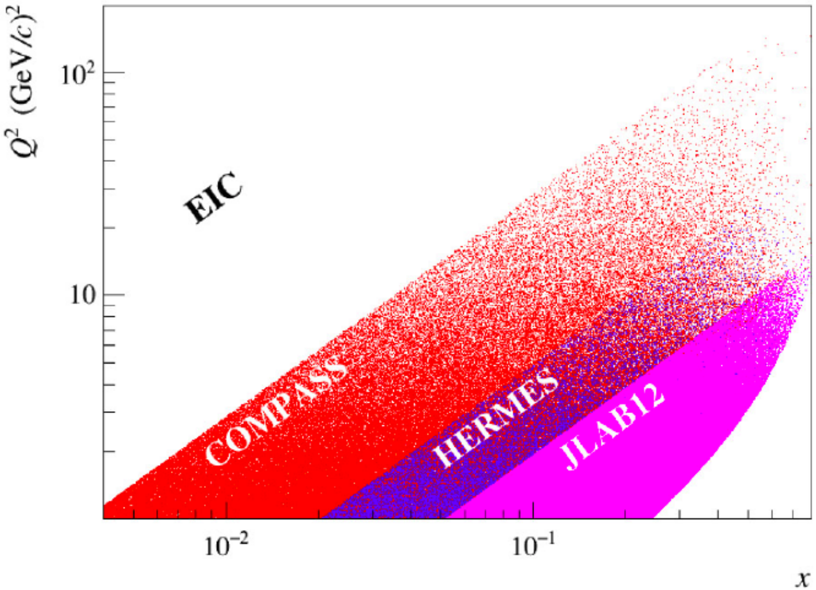


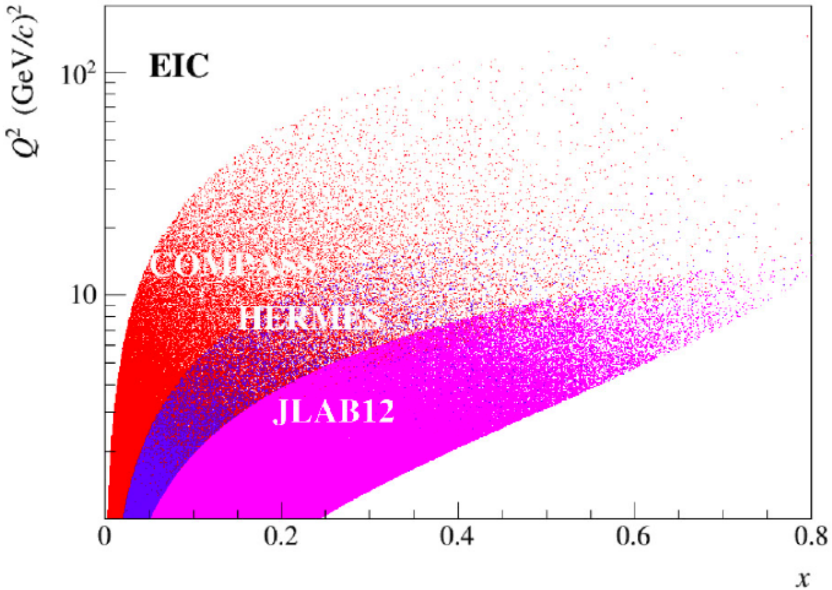






Kinematic coverage





Results with the longitudinally polarized target

Year	Obs.	
2006	$A_{LL}^{2h}(Q^2 < 0)$	$\Delta g/g$
2007	$g_1^d(x)$,	$\Gamma_1^d, \Delta\Sigma$
2008	$A_{1,d}^{h^+-h^-}$	$\Delta u_v + \Delta d_v$
2009	$A_{1,d}, A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}$	$\Delta u_v + \Delta d_v, \Delta\bar{u} + \Delta\bar{d}, \Delta s(= \Delta\bar{s})$
2010	$g_1^p(x)$,	$\Gamma_1^{NS}, \lvert g_A/g_V \rvert$
2010	$A_{1,d}, A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}, A_{1,p}, A_{1,p}^{\pi^\pm}, A_{1,p}^{K^\pm}$	$\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta\bar{d}, \Delta s, \Delta\bar{s}$
2010	$\sin\phi$, $\sin 2\phi$, $\sin 3\phi$, $\cos\phi$ asyms	$h_L, f_L^\perp, h_1, f_{1T}^\perp, h_{1L}^\perp, h_{1T}^\perp, h_{1L}^\perp, g_L^\perp, g_{1T}$
2013	A_{LL}^{2h}	$\Delta g/g$
2013	$A_D^{\gamma N}$	$\Delta g/g$ in LO and NLO
2015	$g_1^p(x)$	$\Gamma_1^{NS}, \Delta\Sigma, \Delta u + \Delta\bar{u} \cdots$
2015	A_{LL}^p	NLO QCD fits for $\Delta g/g$
2016	Final COMPASS results on $g_1^d(x)$	$\Gamma_1^d, \Delta\Sigma$
2017	$A_{1,p}$ and g_1^p at small x and Q^2	

Results for the transversely polarized target

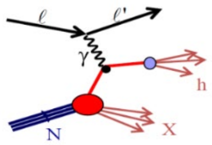
Year	Obs	
2005	$A^h_{Siv,d}, A^h_{Col,d}$	First ^{6}LiD data
2006	$A^h_{Siv,d}, A^h_{Col,d}$	2002-2004 ^{6}LiD statistics
2009	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	2002-2004 ^{6}LiD statistics
2010	$A^h_{Siv,p}, A^h_{Col,p}$	2007 NH_3 data
2012	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	2002-2004 ^{6}LiD
2012	$A^h_{Siv,p}, A^h_{Col,p}$	Full NH_3statistics
2012	$A^{sin(\phi_\rho-\phi_S)}_{UT,d}, A^{sin(\phi_\rho-\phi_S)}_{UT,p}$	Exclusive ρ^0
2013	$A^{(\phi_\rho,\phi_S)}_{UT,d}, A^{(\phi_\rho,\phi_S)}_{UT,p}$	Exclusive ρ^0, all asyms.
2014	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD and NH_3
2014	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	Full NH_3 statistics
2015	Interplay $A^{sin\phi_{RS}}_{UT,p}$ vs $A^h_{Col,p}$	Full NH_3 statistics
2016	$A^h_{Siv,h}$ in SIDIS at the hard scale of the Drell-Yan	Full NH_3 statistics
2018	P_{hT}-weighted Sivers asymmetries	Full NH_3 statistics
2019	transversity-induced polarisation of Λ and $\overline{\Lambda}$	Full NH_3 statistics
2022	Collins and Sivers for ϱ^0	Full NH_3 statistics
2022	TSAs for π and K	Full NH_3 statistics, 2002-2004 ^{6}LiD
2023	$A^h_{Siv,d}, A^h_{Col,d}$	70% of 2022 ^{6}LiD data

Measurements with unpolarised targets:

Year	Obs	
2013	$dn^h/(dN^\mu dz\, dp_T^2)$	multiplicities on d, 2004
2014	$A_{UU,d}^{\cos\phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin\phi_h}$	2004, part
2016	$dn^\pi/(dN^\mu dz)$	multiplicities on d, 2006
2016	$dn^h/(dN^\mu dz\, dp_T^2)$	multiplicities on d, 2006
2016	$dn^K/(dN^\mu dz)$	multiplicities on d, 2006
2017	$dn^h/(dxdQ^2dz\, dp_T^2)$	multiplicities on d, 2006
2018	$(dn^{K^-}/dn^{K^+})//(dN^\mu dz)$	Multiplicity ratios for Kaons, 2006
2019	Contribution of exclusive diffractive processes to $A_{UU,d}^{\cos\phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin\phi_h}$	ϱ^0, ϕ, ω
2020	$(dn^{p\bar{p}}/dn^p)\ and\ (dn^{K^-}/dn^{K^+})//(dN^\mu dz)$	Hight z

Accessing TMD PDFs and FFs

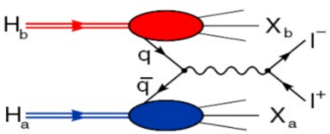
- TMD factorization works in the domain where there are two observed momenta in the process, such as SIDIS, DY, e^+e^-. $Q \gg q_T$: Q is large to ensure the use of pQCD, q_T is much smaller such that it is sensitive to parton's transverse momentum
- SIDIS off (un)polarized p, d, n targets



HERMES
COMPASS
JLab12
future: ***EIC***

$$\sigma^{\ell p\to\ell' hX} \sim q(x) \otimes \hat{\sigma}^{\gamma q\to q} \otimes D_q^h(z)$$

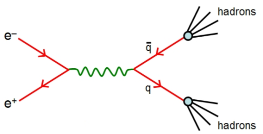
- (un)polarised Drell-Yan



COMPASS
RHIC
FNAL
future: ***FAIR, JPark, NICA***

$$\sigma^{hp\to\mu\mu} \sim \bar{q}_h(x_1) \otimes q_p(x_2) \otimes \hat{\sigma}^{\bar{q}q\to\mu\mu}(\hat{s})$$

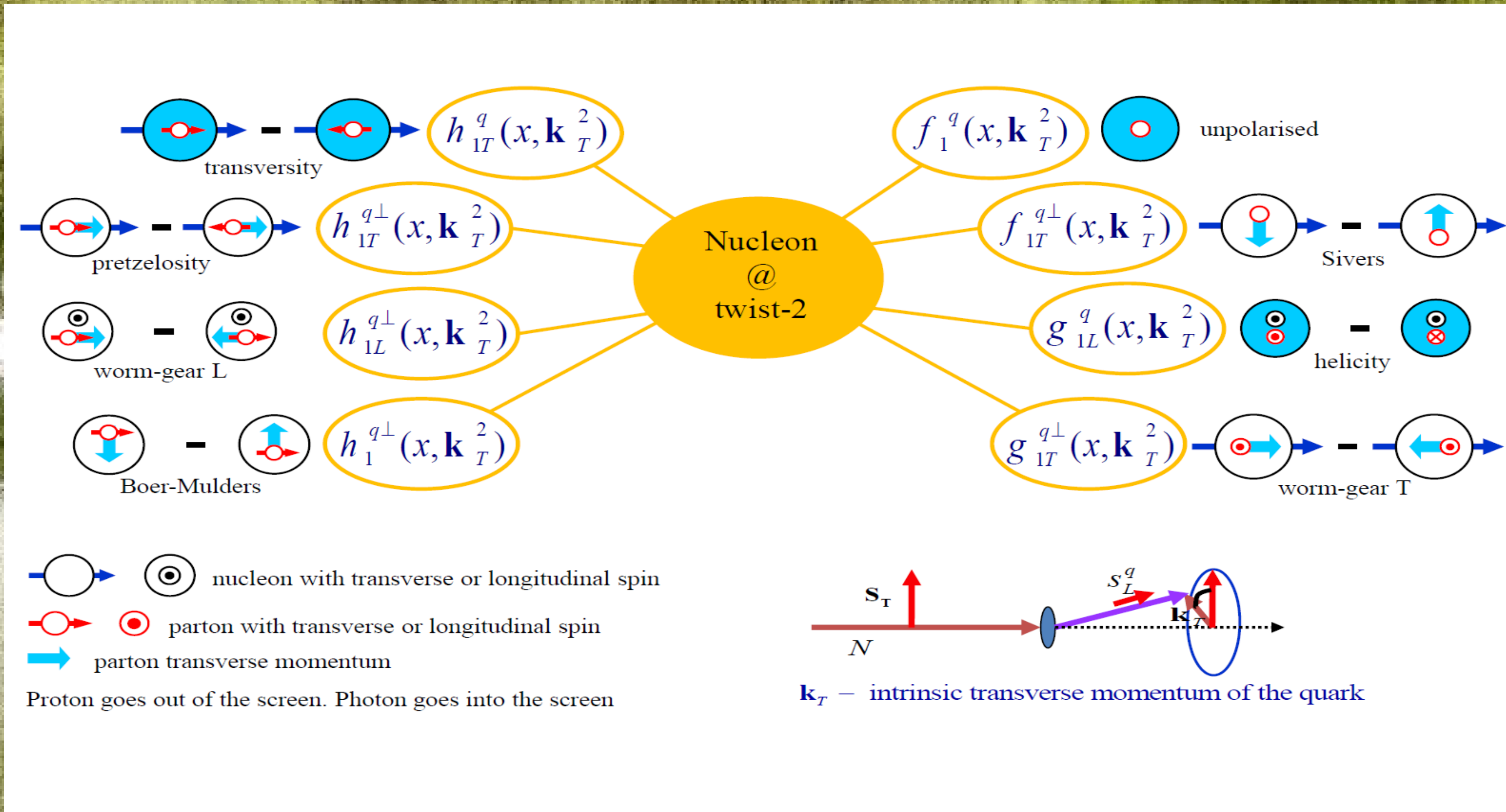
- $e^+e^- \to h_1 h_2$



BaBar
Belle
Bes III

$$\sigma^{e^+e^-\to h_1 h_2} \sim \hat{\sigma}^{\ell\ell\to\bar{q}q}(\hat{s}) \otimes D_q^{h_1}(z_1) \otimes D_q^{h_2}(z_2)$$

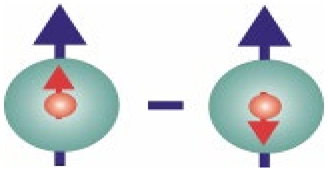
TMD Distribution Functions



Single spin asymmetries

Transversity PDF

$$h_1^q(\mathbf{x}) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$$



$q = u_v, d_v, q_{sea}$

quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

- probes the relativistic nature of quark dynamics
- no contribution from the gluons → simple Q^2 evolution
- Positivity: Soffer bound…………….. $2|h_1^q| \leq f_1^q + g_1^q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge………. $\delta q(Q^2) = \int_0^1 dx[h_1^q(x) - h_1^{\bar{q}}(x)]$
- is chiral-odd: decouples from inclusive DIS *Bakker, Leader, Trueman, PRD 70 (04)*

Transversity

is chiral-odd:

observable effects are given only by the product of h_1^q (x) and an other chiral-odd function

can be measured in SIDIS on a transversely polarised target via "quark polarimetry"

$\ell N^{\uparrow} \rightarrow \ell' \, h \, X$ — "Collins" asymmetry
"Collins" Fragmentation Function

$\ell N^{\uparrow} \rightarrow \ell' \, h \, h \, X$ — "two-hadron" asymmetry
"Interference" Fragmentation Function

$\ell N^{\uparrow} \rightarrow \ell' \, \Lambda \, X$ — Λ polarisation
Fragmentation Function of $q^{\uparrow} \rightarrow \Lambda$

From Collins asymmetries to transversity

- Following Physical Review D 91, 014034 (2015), in the valence region

$$x h_1^u = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\left(x f_p^+ A_p^+ - x f_p^- A_p^-\right) + \frac{1}{3}\left(x f_d^+ A_d^+ - x f_d^- A_d^-\right)\right]$$

$$x h_1^d = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\frac{4}{3}\left(x f_d^+ A_d^+ - x f_d^- A_d^-\right) - \left(x f_p^+ A_p^+ - x f_p^- A_p^-\right)\right]$$

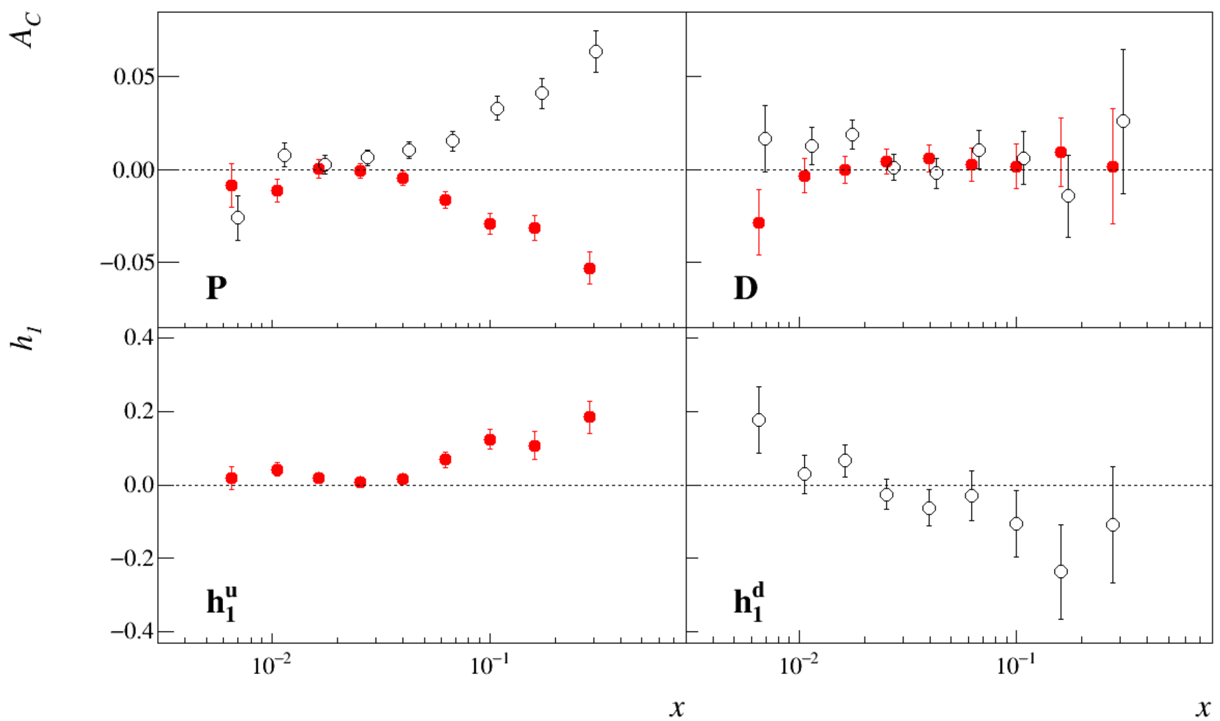
With $\tilde{a}_P^h$ and $\tilde{\alpha}$ constants

$$A_p^{\pm} = \frac{\sum_q e_q^2\, h_1^q(k_\perp) \otimes H_1^{\perp q\to h}(p_\perp)}{\sum_q e_q^2\, f_1^q \otimes D_1^{q\to h}}$$

$$A_{UT}^{\sin(\phi_R+\phi_S-\pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q\to h_1h_2}^{\measuredangle}\left(z, \mathcal{M}_{h_1h_2}^2\right)}{\sum_q e_q^2 q(x) D_q^{h_1h_2}\left(z, \mathcal{M}_{h_1h_2}^2\right)}$$

2022 Deuteron run

- Benchmark: h_1 extraction from Collins asymmetries

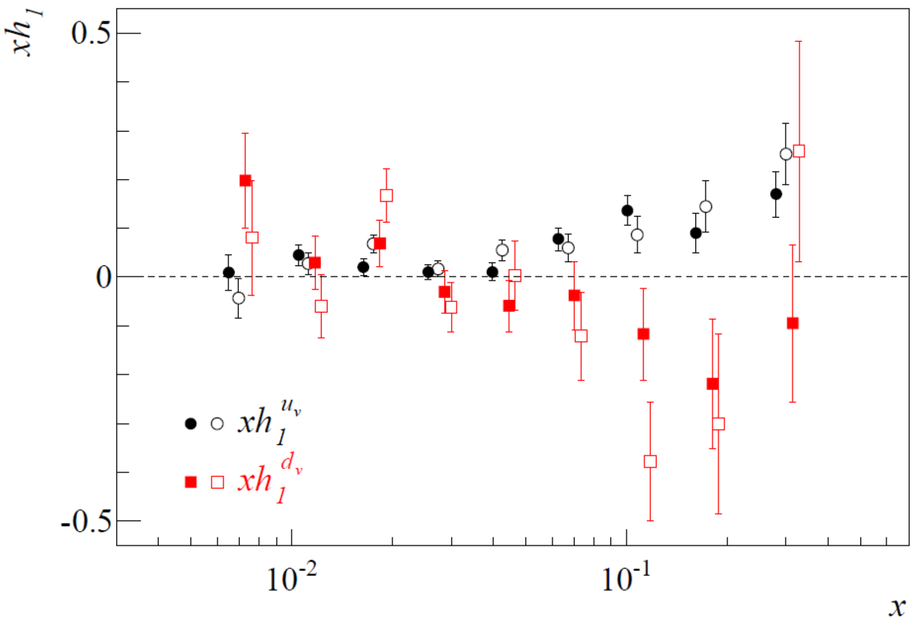


Transversity extracted as in PRD 91(2015) 014034

Transversity from our data

- Point-to-point extraction [Physical Review D 91, 014034 (2015)]
- Only COMPASS measured TSA on deuteron

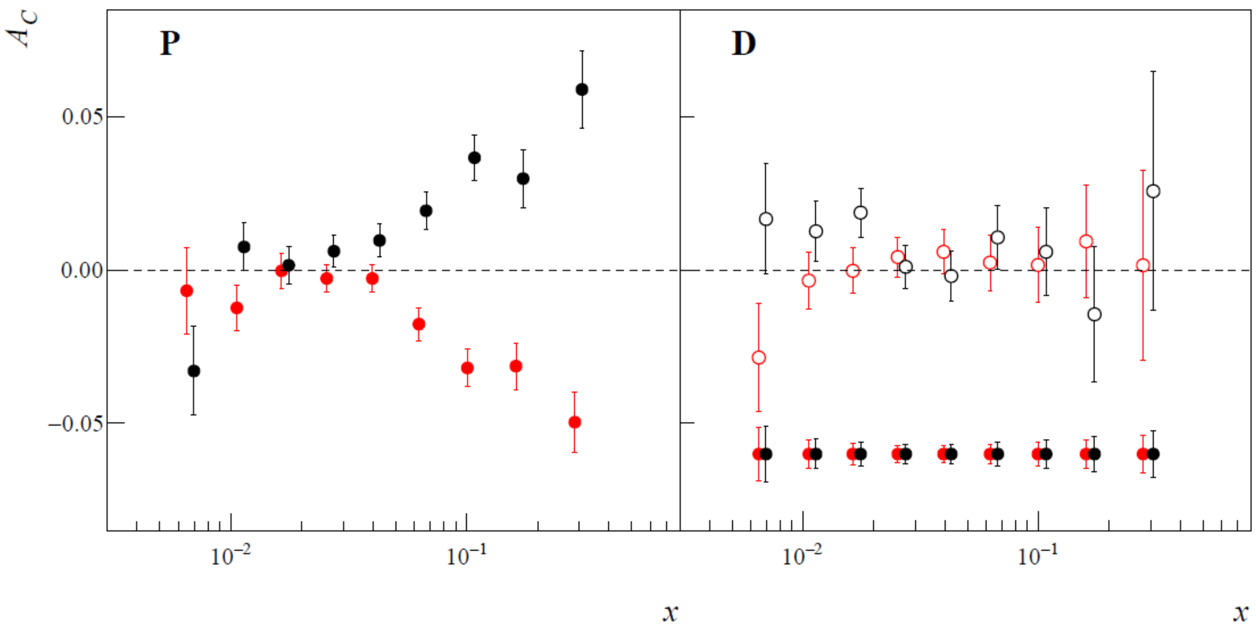
Open points/squares – from dihadron
Closed points/squares – from Collins



ERRORS ON h_1^d ARE A FACTOR 4 LARGER THAT THE ONES ON h_1^u

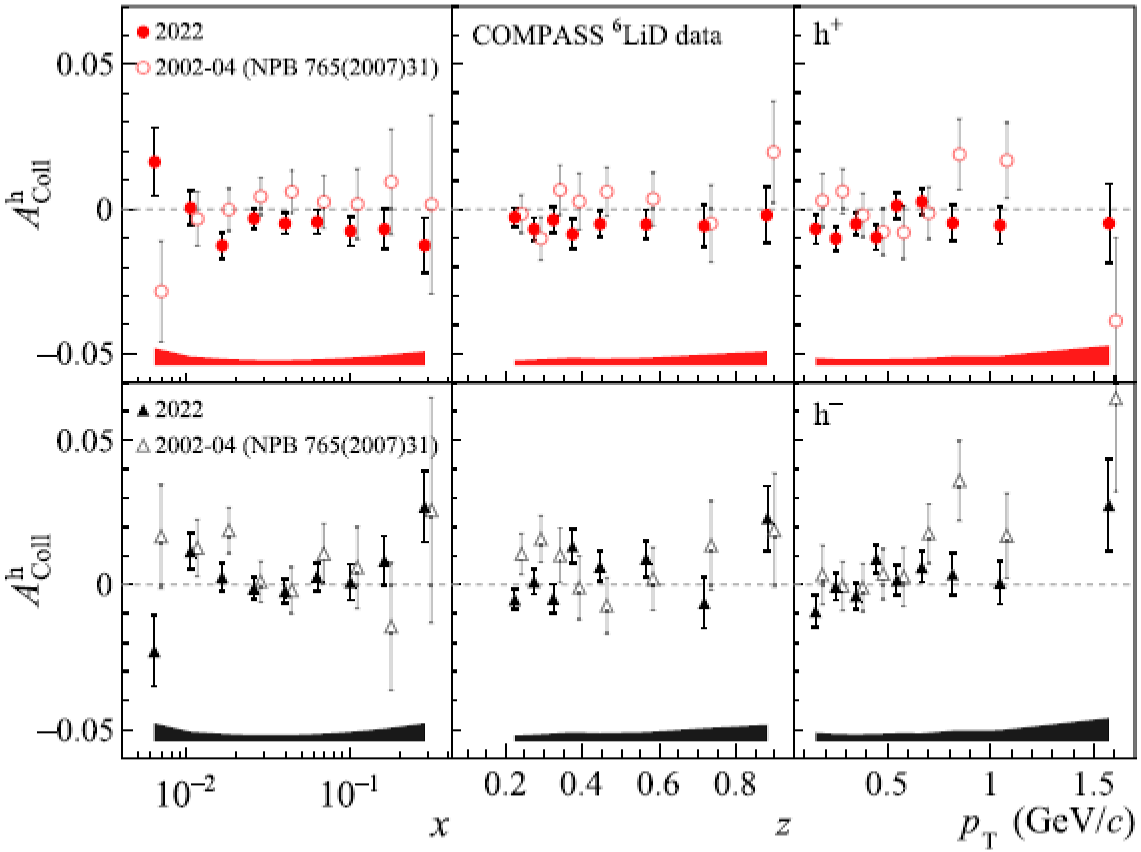
2022 Deuteron Run

- COMPASS proposed to CERN to run a full year with the transversely polarized deuteron target and this proposal has been approved



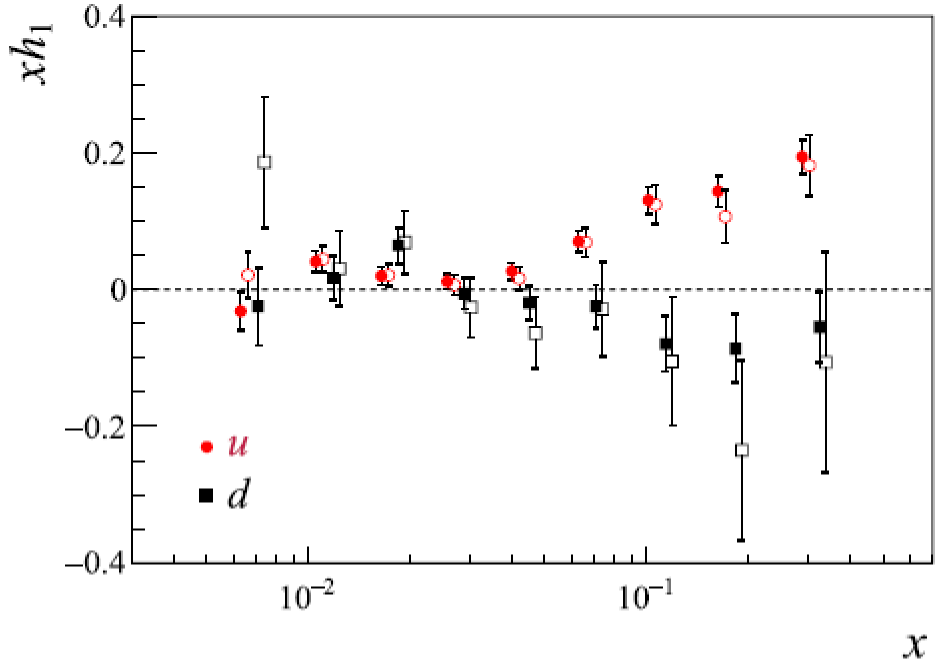
First results from 2022 deuteron run

PRL 133, 101903 (2024)



First results from 2022 deuteron run

PRL 133, 101903 (2024)



Sivers Asymmetry

Sivers: correlates nucleon spin & quark transverse momentum k_T /T-ODD

at LO:

$$A_{Siv} = \frac{\sum_q e_q^2 f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

$$\mu p^{\uparrow} \rightarrow \mu X h^{\pm}$$

The Sivers PDF	
1992	Sivers proposes $f_{1T}^{\perp}$
1993	J. Collins proofs $f_{1T}^{\perp} = 0$ for T invariance
2002	S. Brodsky, Hwang and Schmidt demonstrate that $f_{1Tq}^{\perp}$ may be $\neq 0$ due to FSI
2002	J. Collins shows that $(f_{1T}^{\perp})_{DY} = -(f_{1T}^{\perp})_{SIDIS}$
2004	HERMES on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$
2004	COMPASS on d: $A_{Siv}^{\pi^+} = 0$ and $A_{Siv}^{\pi^-} = 0$
2008	COMPASS on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$

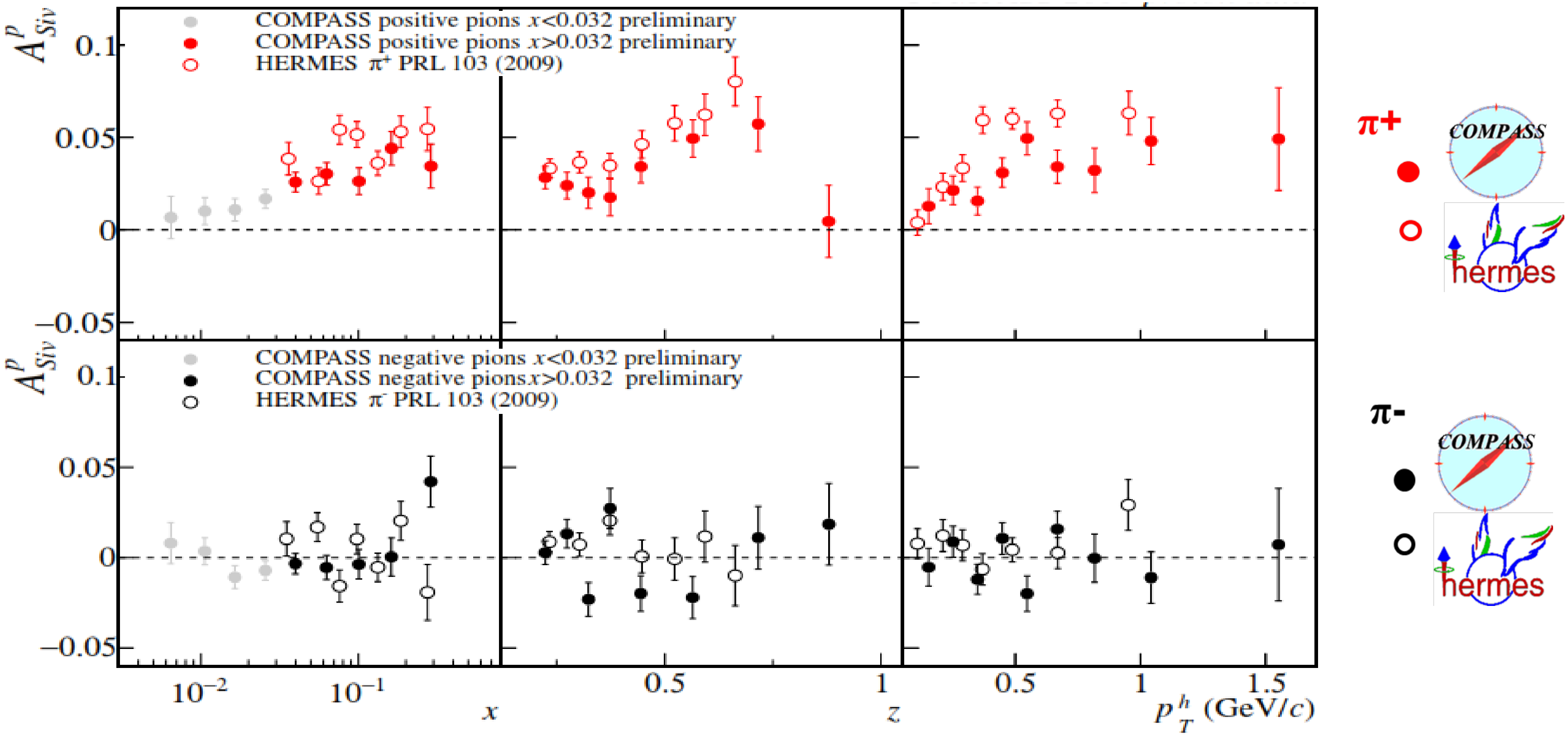
Sivers Asymmetry

$$A_{Siv}(x,z) = \frac{F_{UT}^{\sin\Phi_{Siv}}(x,z)}{F_{UU}(x,z)} = \frac{\sum_q e_q^2 x f_{1T}^{\perp q}(x,k_\perp^2) \otimes D_{1q}^h(z,p_\perp^2)}{\sum_q e_q^2 x f_1^q(x,k_\perp^2) \otimes D_{1q}^h(z,p_\perp^2)}$$

- To evaluate it we need to solve the convolutions (i.e. make hypothesis on the transverse momenta dependences of the TMDs)
- Gaussian ansatz: $f_{1T}^{\perp q}(x)\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_S}}{\pi\langle k_\perp^2\rangle_S}$ $D_{1q}^h(z)\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$
- Leading to: $A_{Siv,G}(x,z) = \frac{\sqrt{\pi}M}{\sqrt{z^2\langle k_T^2\rangle_S + \langle p_T^2\rangle}} \frac{\sum_q e_q^2\, x f_{1T}^{\perp(1)q}(x) z D_{1q}^h(z)}{\sum_q e_q^2 x f_1^q(x) D_{1q}^h(z)}$ with $f_{1T}^{\perp(1)q}(x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x,k_T^2)$

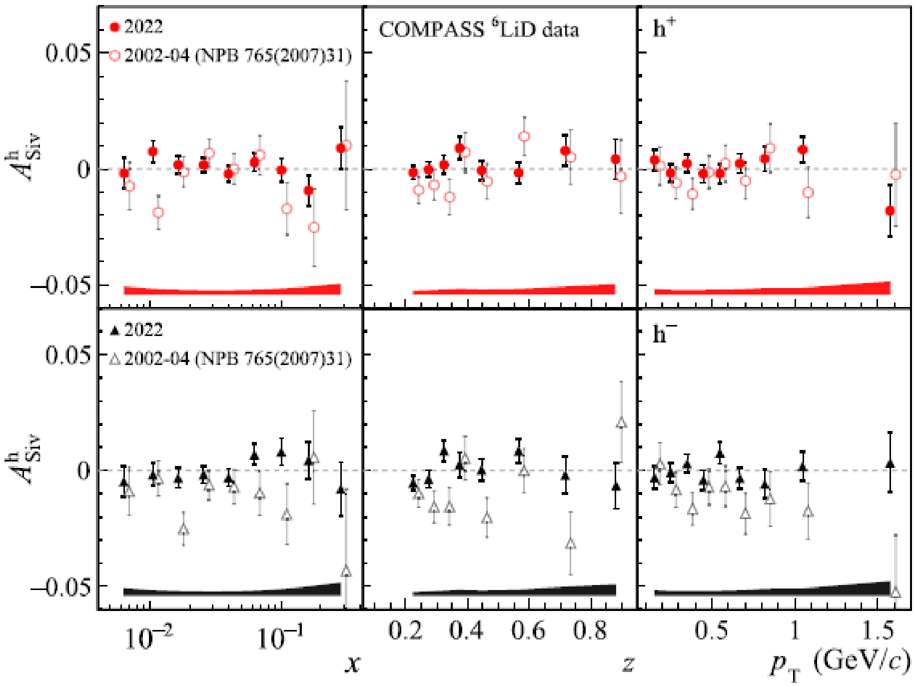
Sivers asymmetry on p

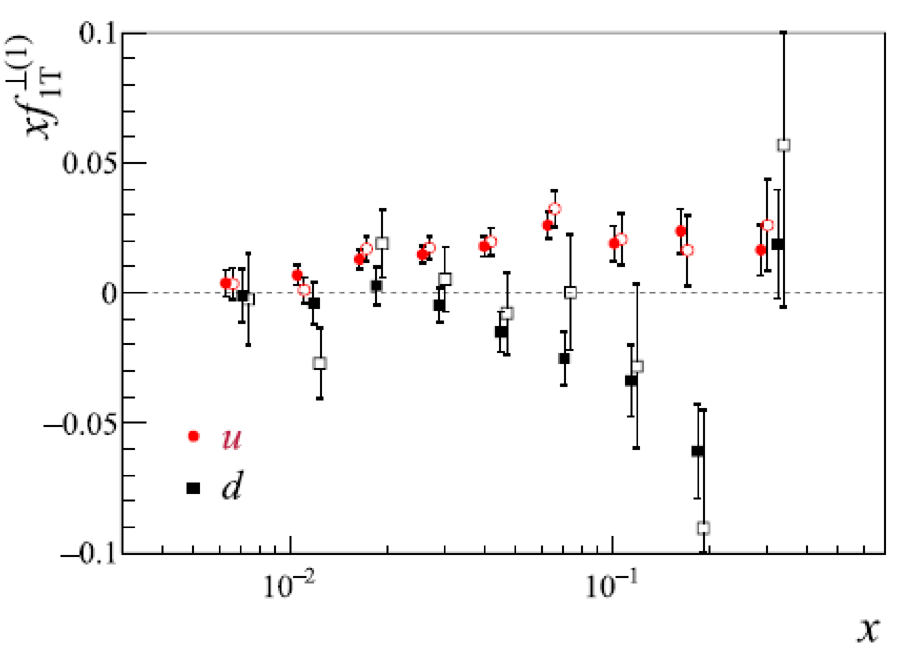
charged pions (and kaons), HERMES and COMPASS

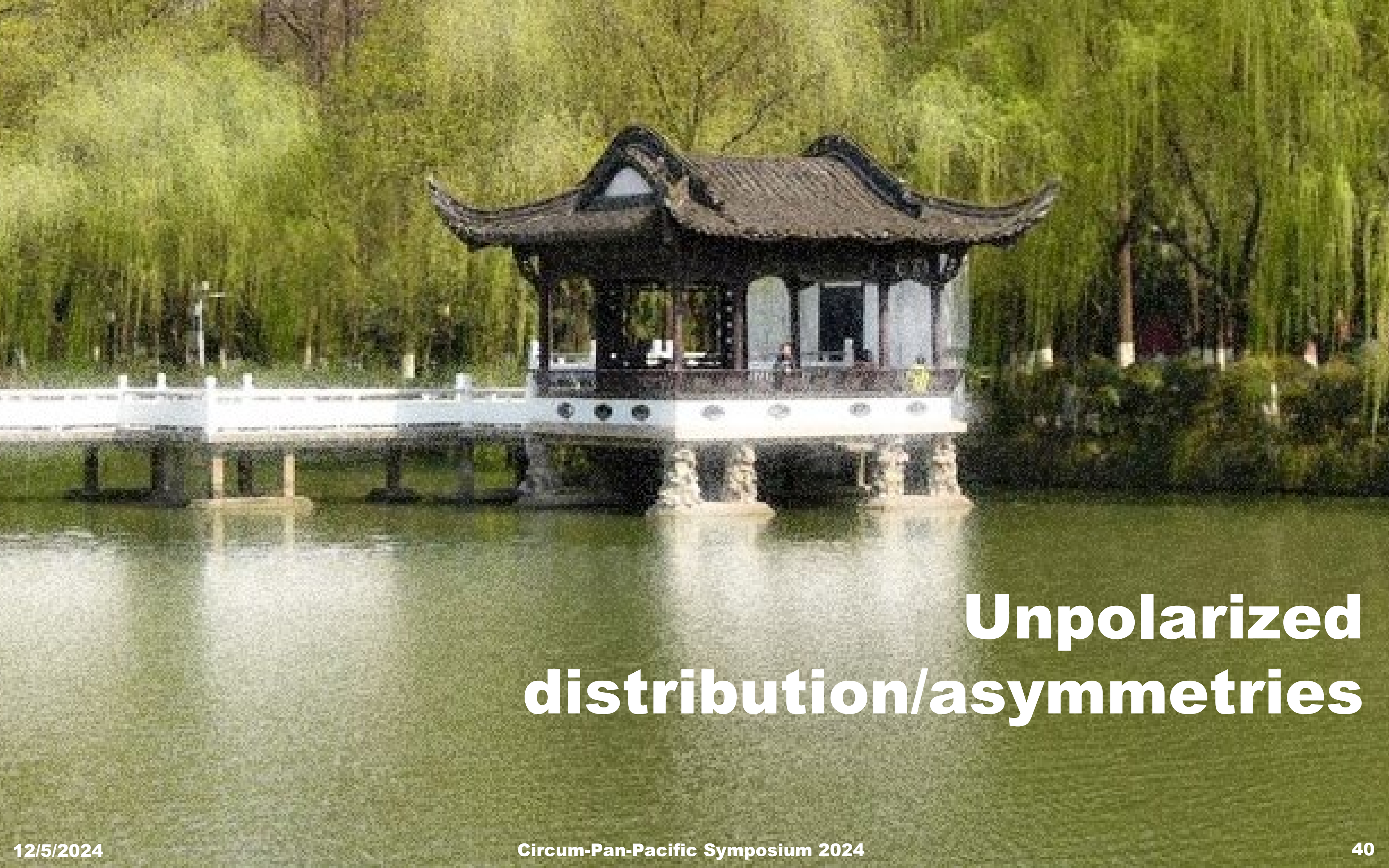


First results from 2022 deuteron run

PRL 133, 101903 (2024)







Unpolarized distribution/asymmetries

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

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

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

We can then introduce amplitude of the azimuthal asymmetries as

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

An the angular independent ratio

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

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

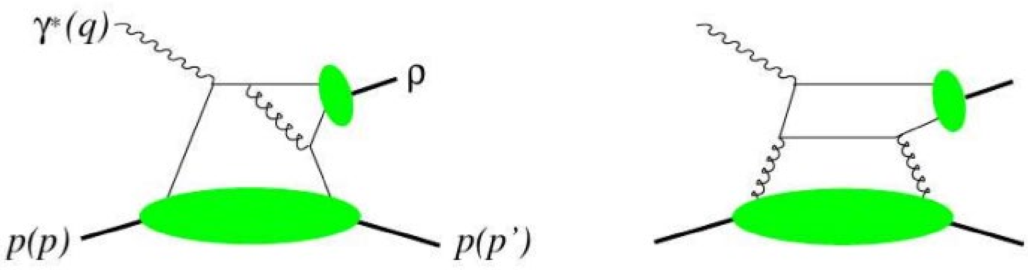
$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$

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

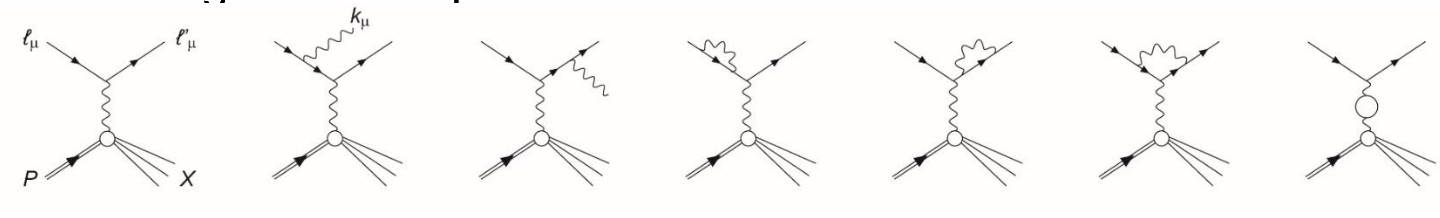


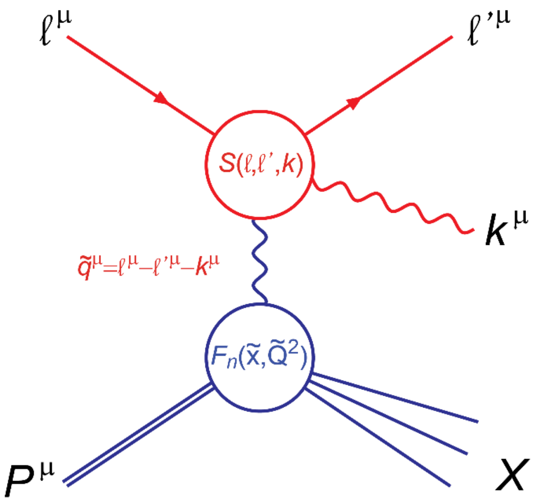
- Contributions from ρ^0, ω and ϕ
- Exclusive ρ^0 leptoproduction can be viewed as a virtual photon fluctuation into a $q\bar{q}$-pair followed by the scattering of this pair off the nucleon and formation of the final state.
- These are spin-1 objects, i.e. $J = 1$. Decay particles have spin 0, so $L = 1$ 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

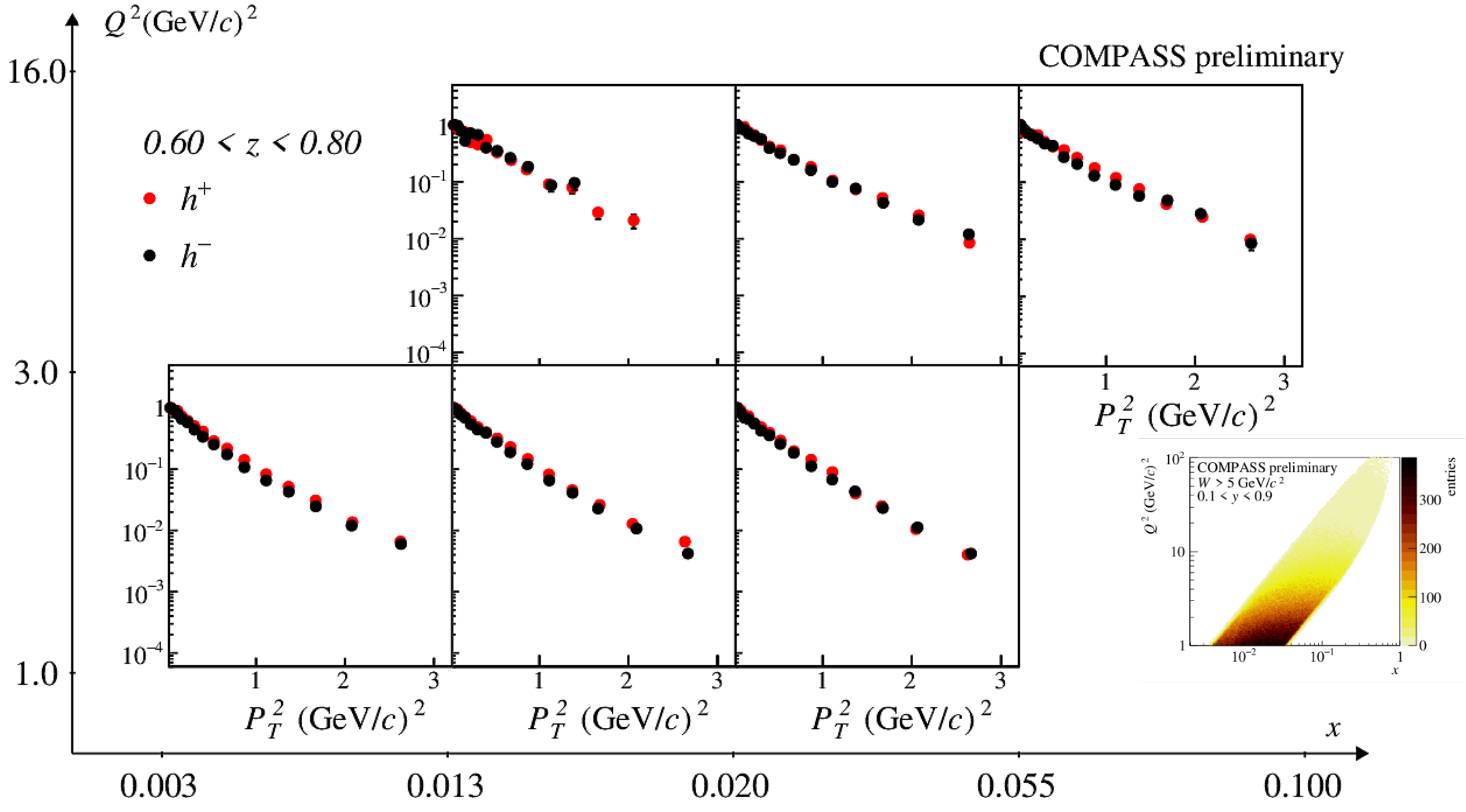




- The radiative leptonic tensor $S(\ell, \ell', k)$, include Born + loops at $\mathcal{O}(\alpha_{em}^2)$:
  - Gauge invariant
  - Infrared finite
  - Universal (for 1γ exchange)
  - The kinematic is shifted $\tilde{q}^\mu = q^\mu - k^\mu$

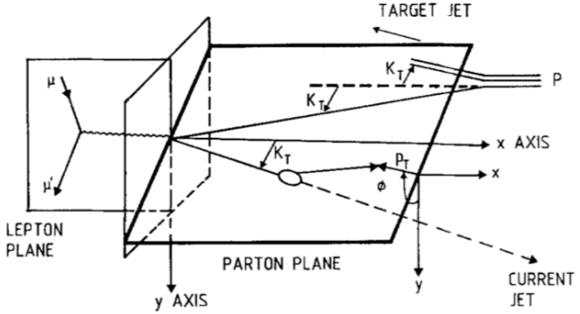
P_{hT}-dependent multiplicities

Positive vs Negative charged hadrons (LH_2)



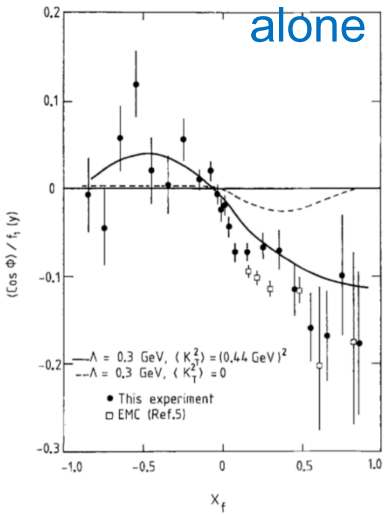
Azimuthal Modulations

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

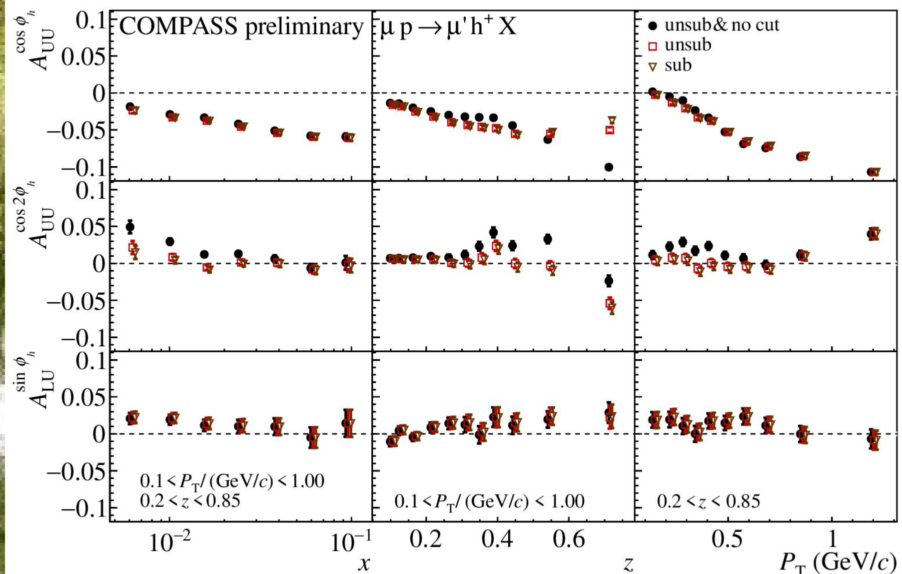
EMC experiment [1987]
Fit: Konig-Kroll model [1982] + Lund String

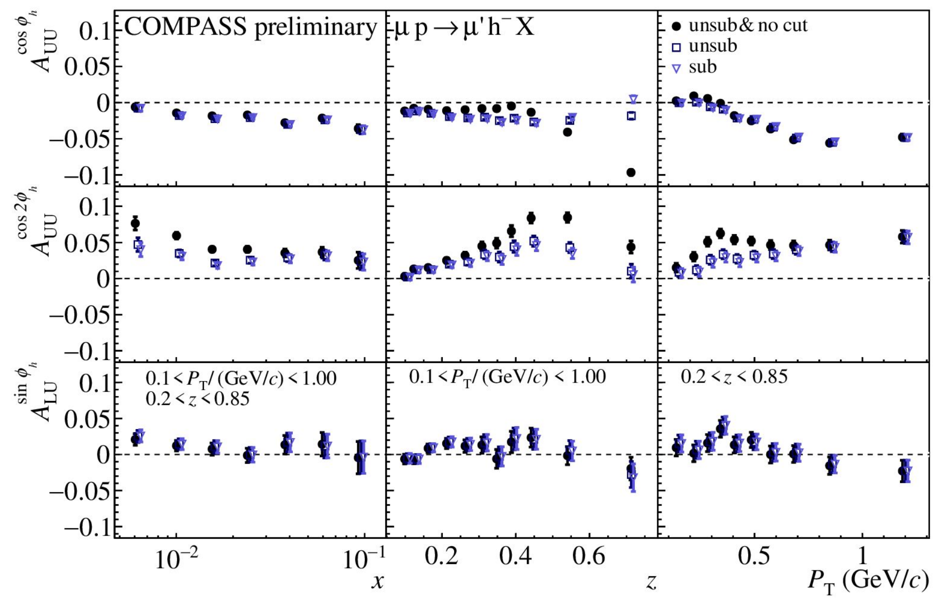
These effects can be estimated by adopting a model for the transverse momentum distribution of partons in a hadron and for the transverse momentum given to hadrons in the quark decay. Suppose that both these distributions are gaussian:

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

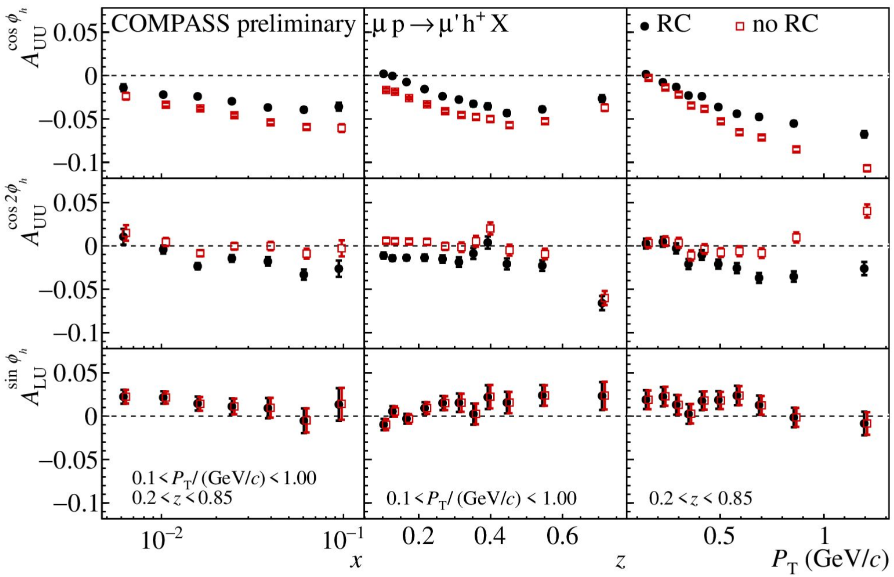
where f represents the quark distribution and D the fragmentation function. Let the z-direction be defined as in fig. 1. Then the longitudinal momentum of the struck parton is xP and that of the observed hadron is zxP. If the transverse momentum of the struck parton is $\boldsymbol{p}_{1\perp}$ and that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

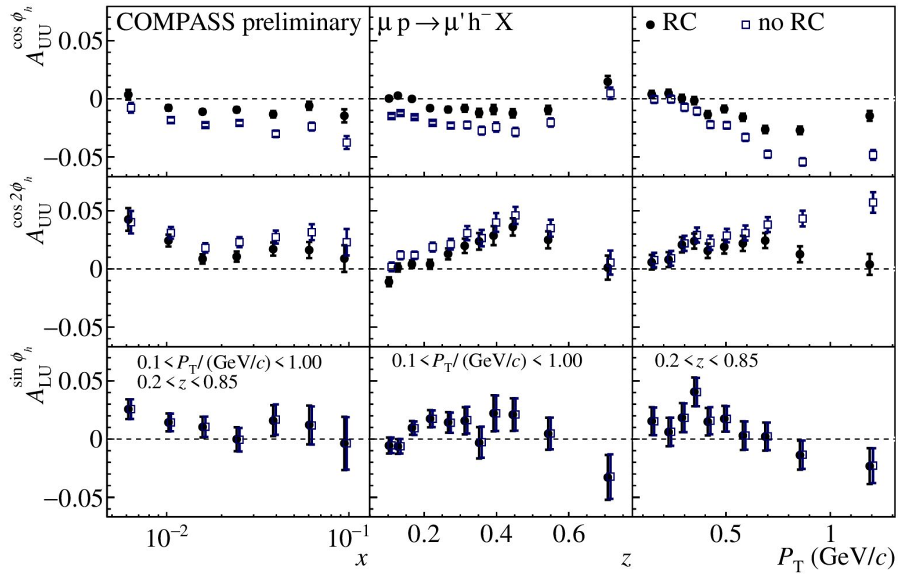
Effect of Exclusive VM subtraction



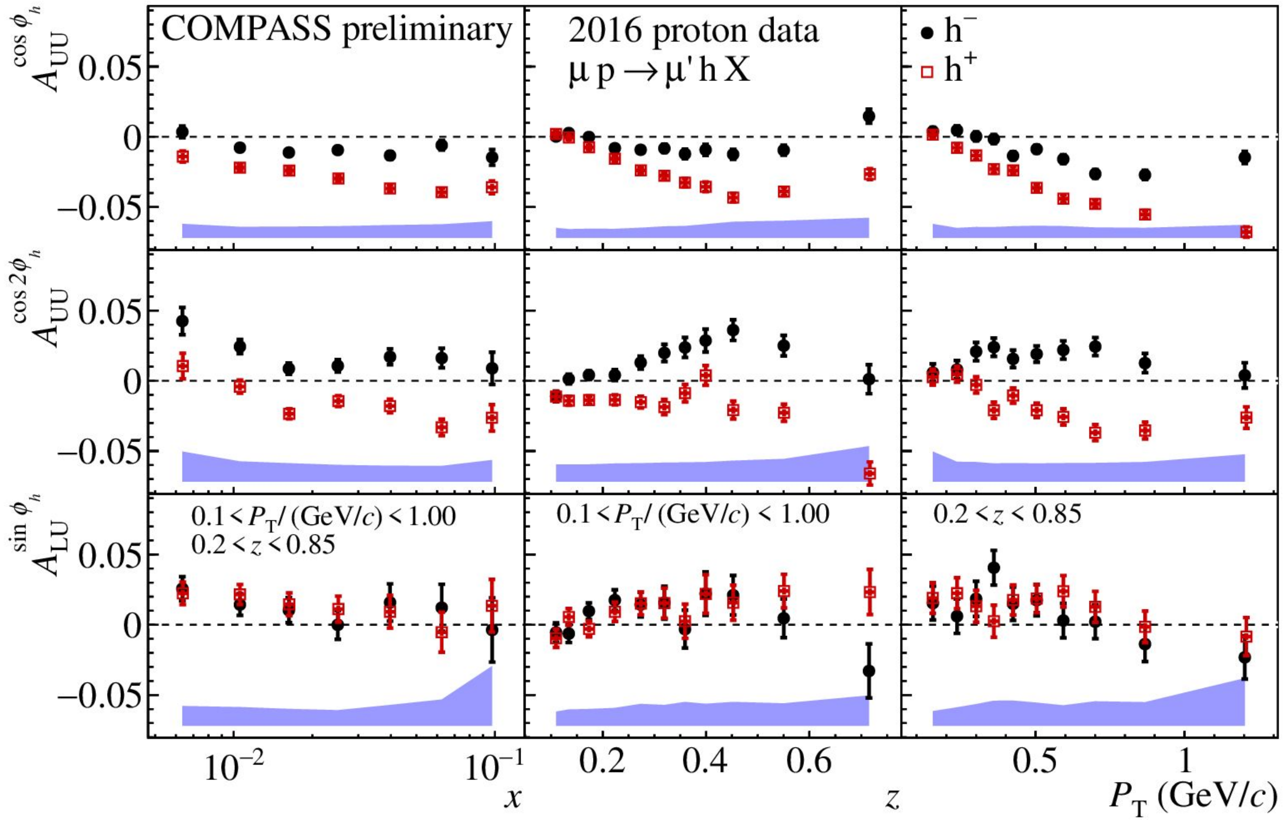


Radiative effects





Corrected results



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

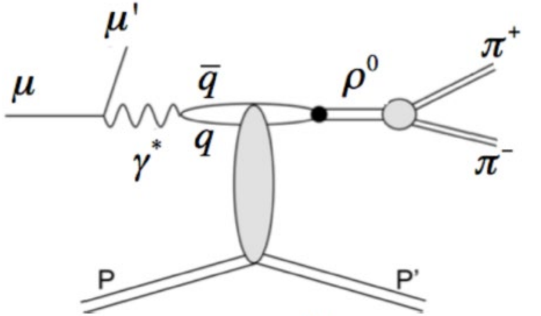
Outlook

- Deuteron data by COMPASS 2022 run will remain a unique data set for the next decade and beyond, before EIC operation with D beams.
- It allows a precise and valuable extraction of “d” quarks TMD PDFs
- 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

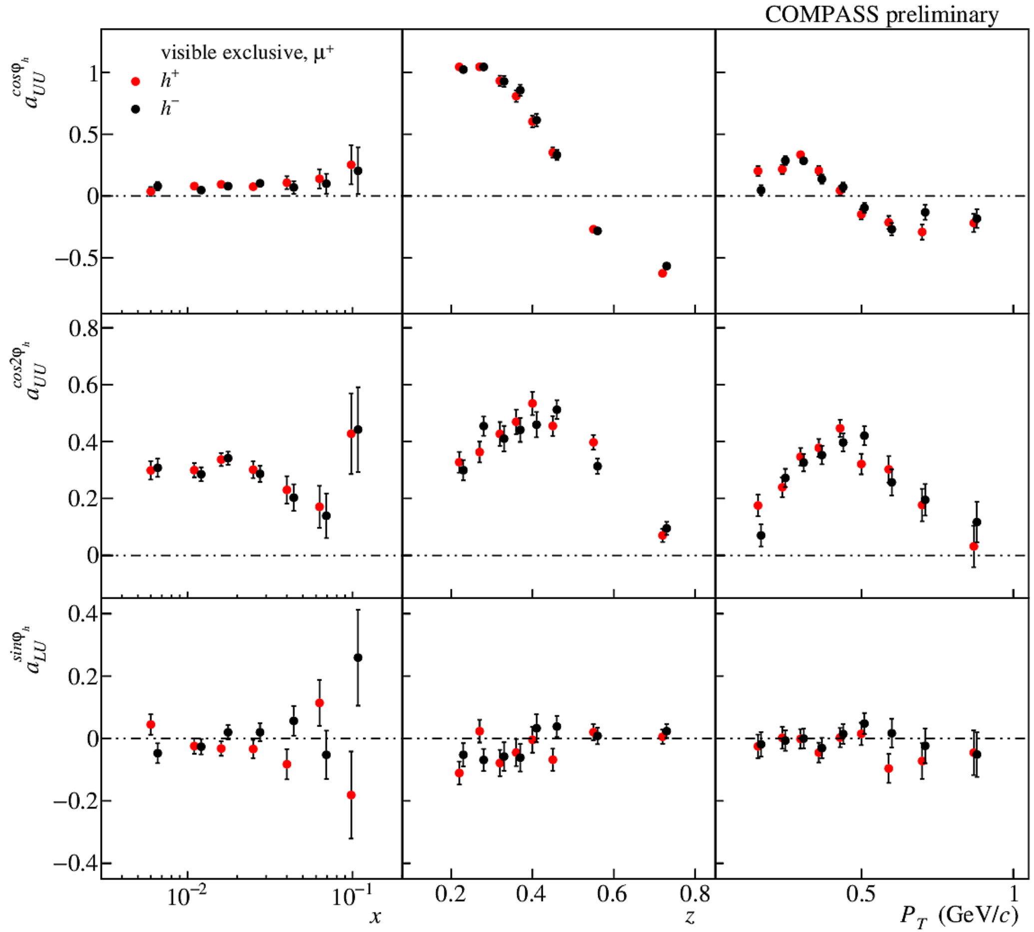

Thank you

Contamination on (LH_2) – 1D

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

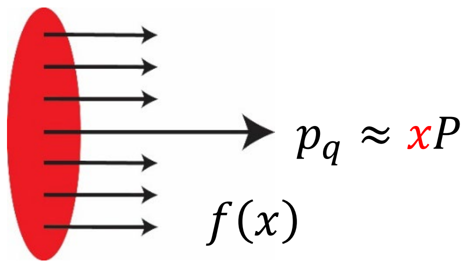


The diffractive ρ^0 production and decay.

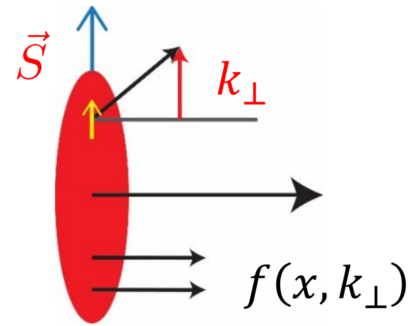


Unpolarised Transverse Momentum dependent PDFs

- 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 $k_\perp$

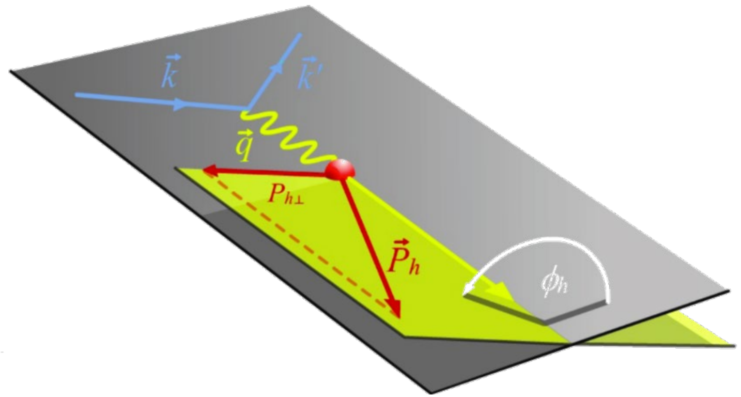
$$f_1^q(x, k_\perp)$$

- 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

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

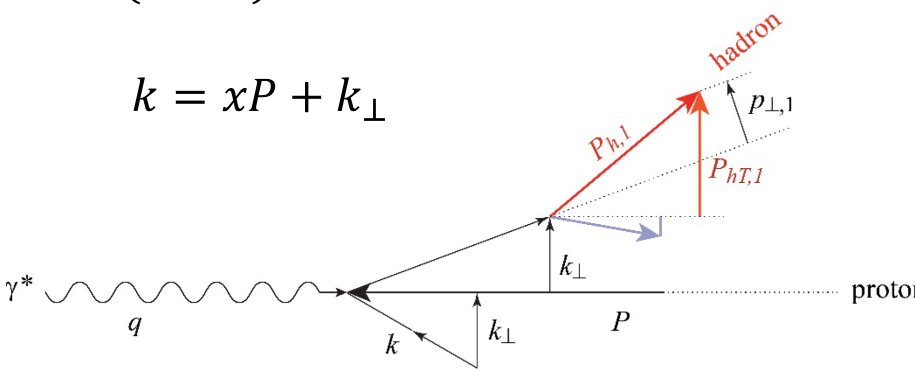
Unpolarised Azimuthal Modulation

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



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

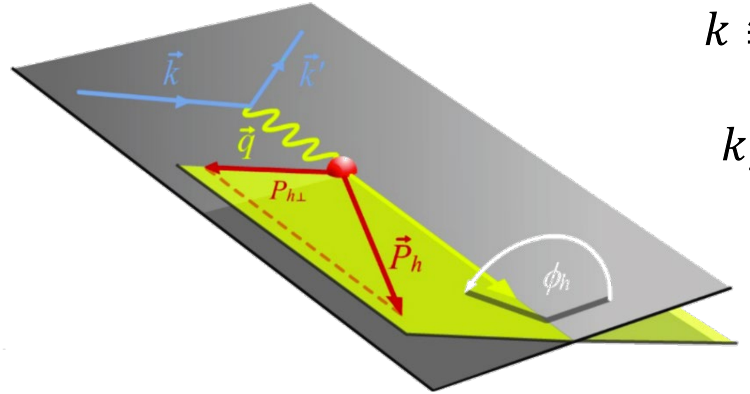
$$k = xP + k_\perp$$



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.

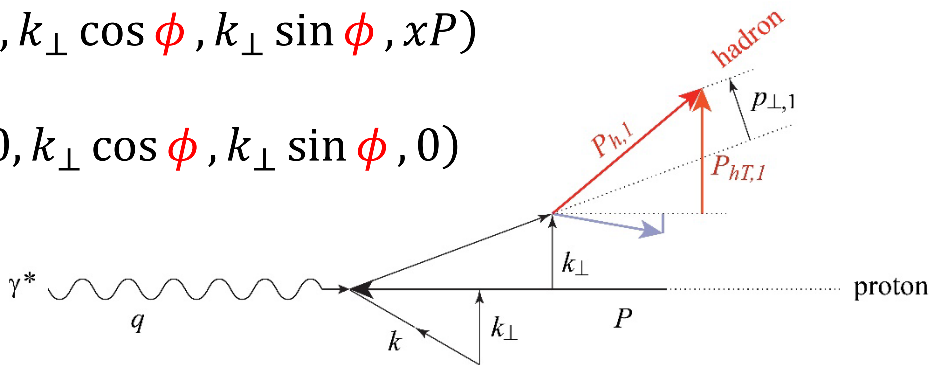
Unpolarised Azimuthal Modulation

When $k_\perp$ is taken into account:



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

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



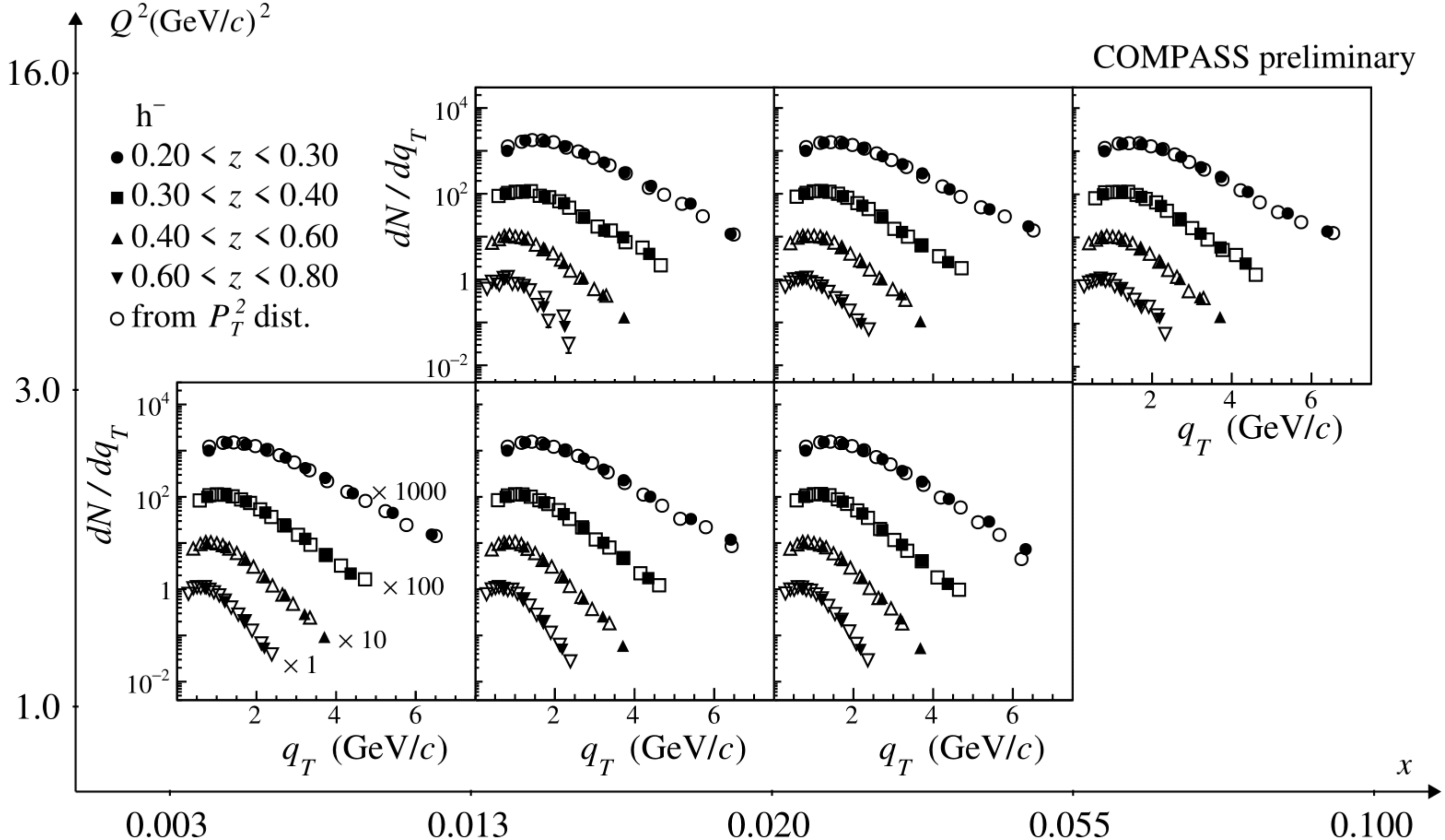
$$\hat{s} = sx\left[1 - \frac{2k_\perp}{Q}\sqrt{1-y}\cos\phi\right] + \sigma\left(\frac{k_\perp^2}{Q}\right) \quad \hat{u} = sx(1-y)\left[1 - \frac{2k_\perp}{Q\sqrt{1-y}}\cos\phi\right] + \sigma\left(\frac{k_\perp^2}{Q}\right)$$

and

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

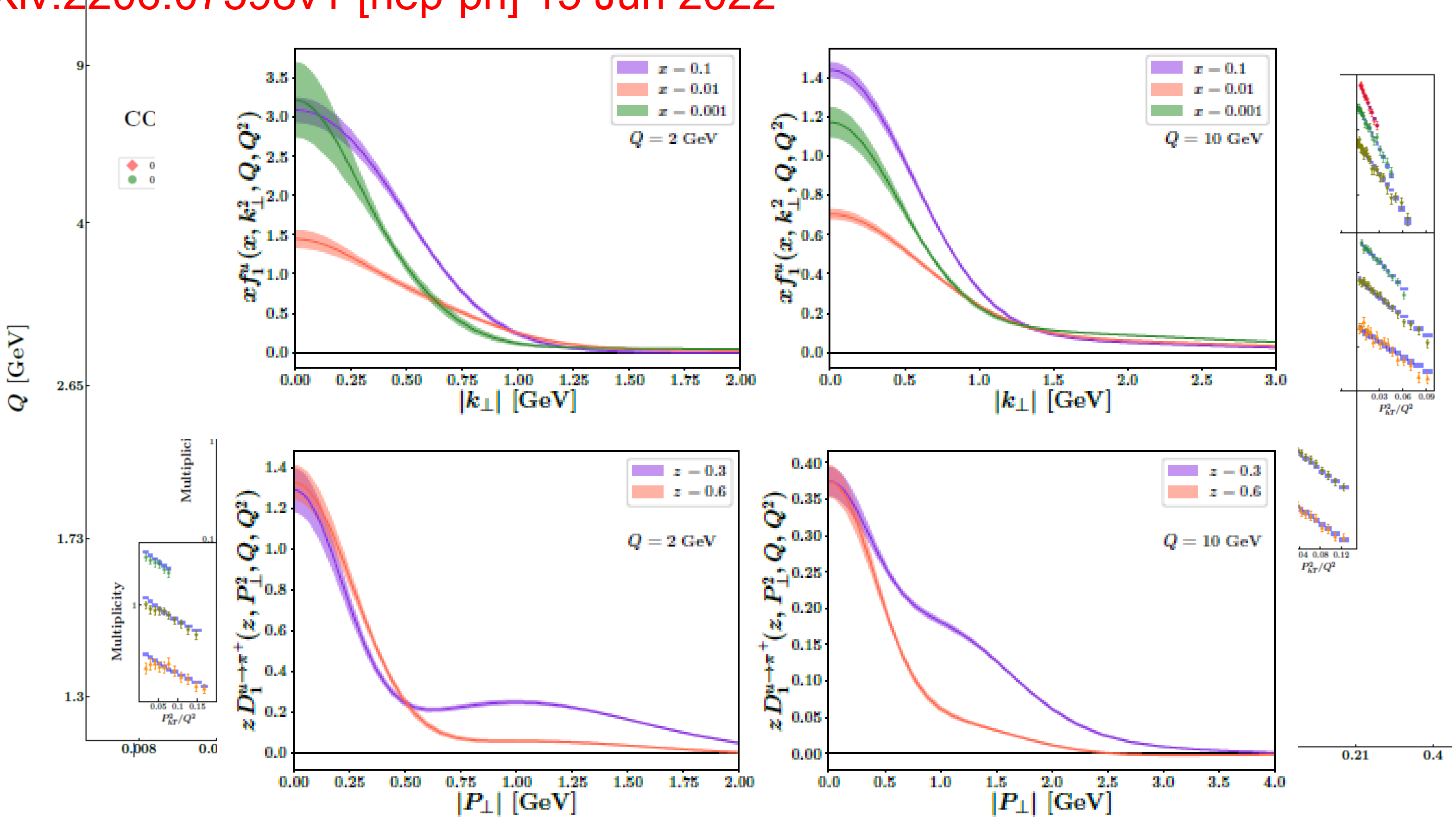
Resulting in the $\cos\phi_h$ and $\cos 2\phi_h$ modulations observed in the azimuthal distributions

q_T distributions

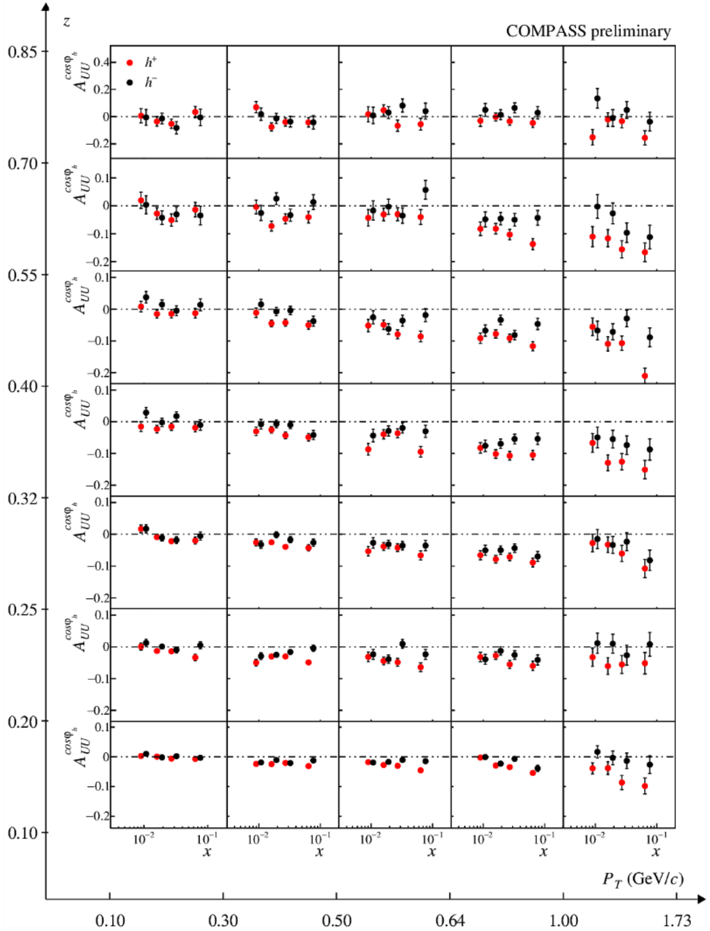


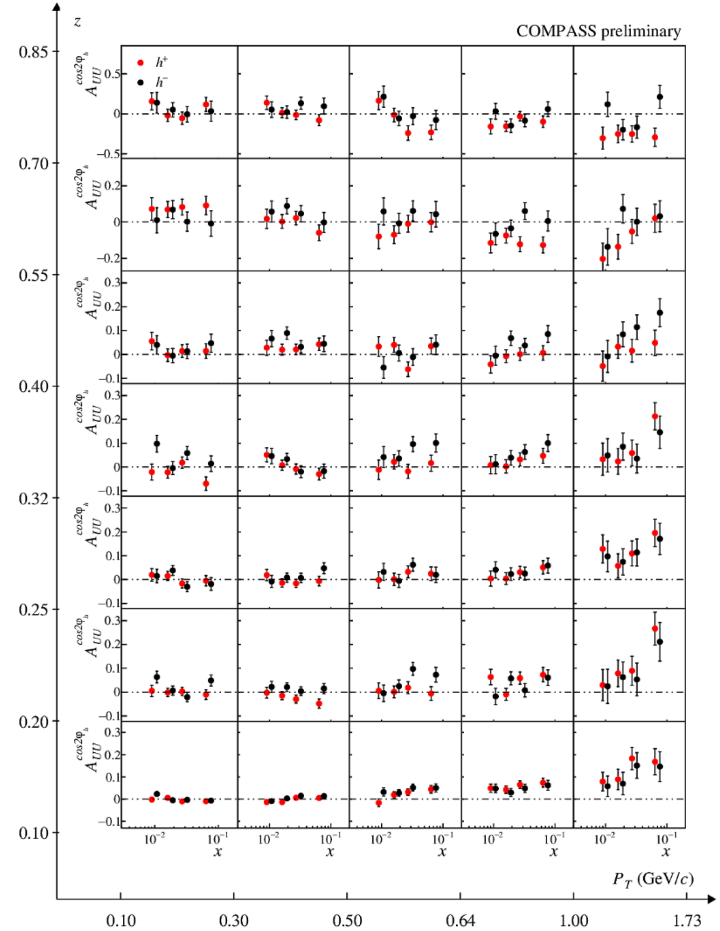
Phenomenological fits

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

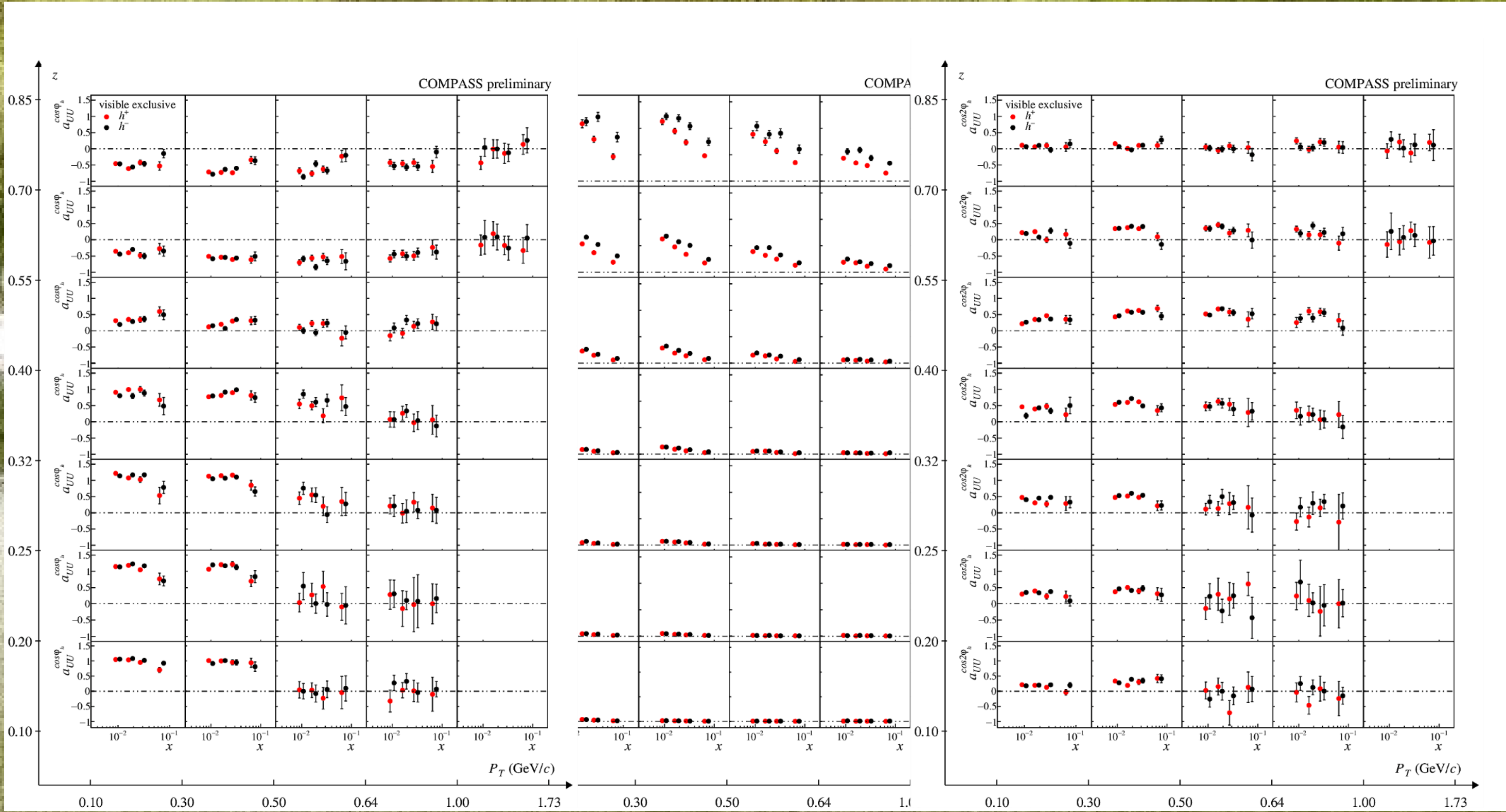


Azimuthal modulations on (LH_2) – 3D

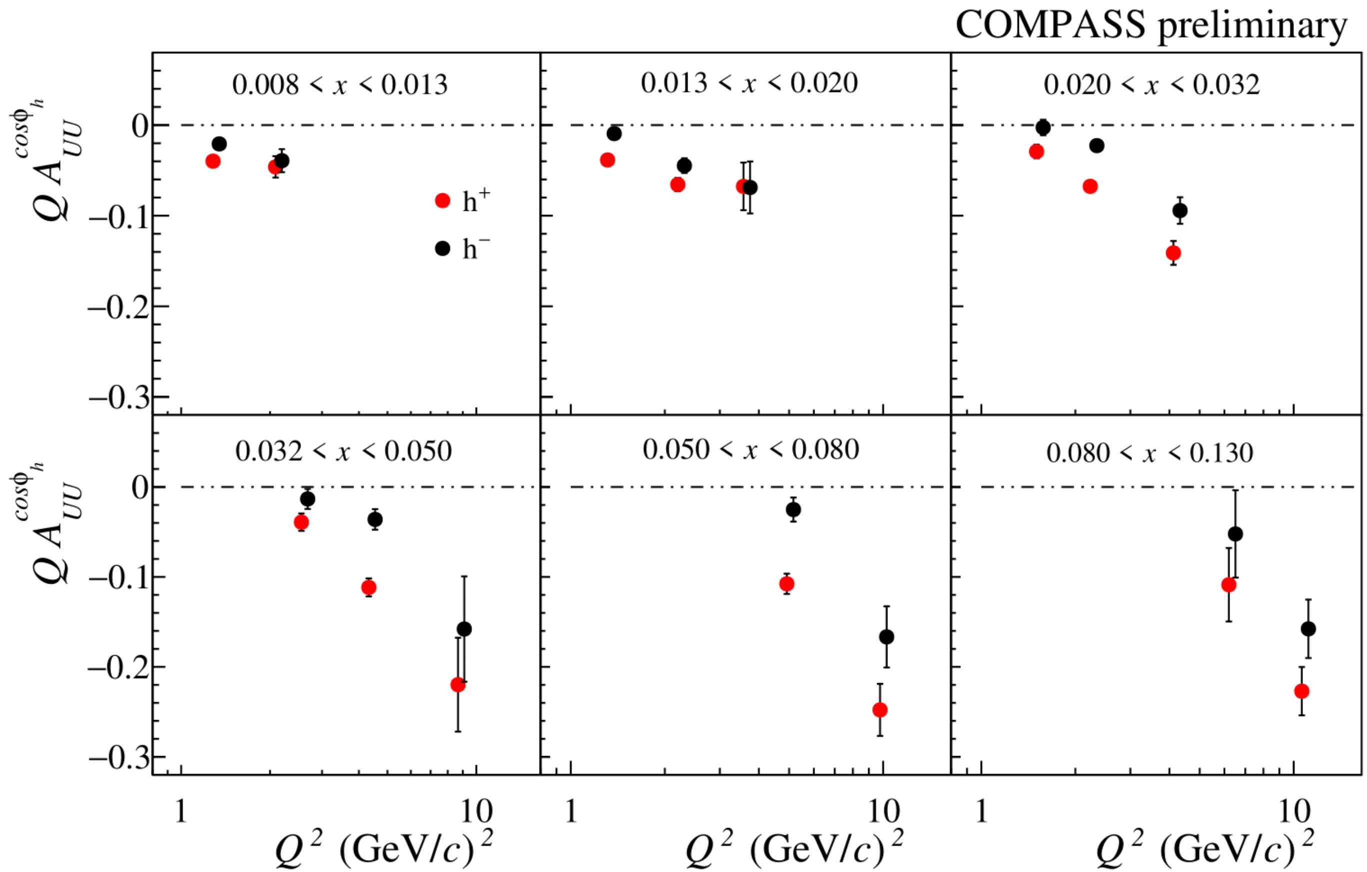




Contamination on (LH_2) – 3D

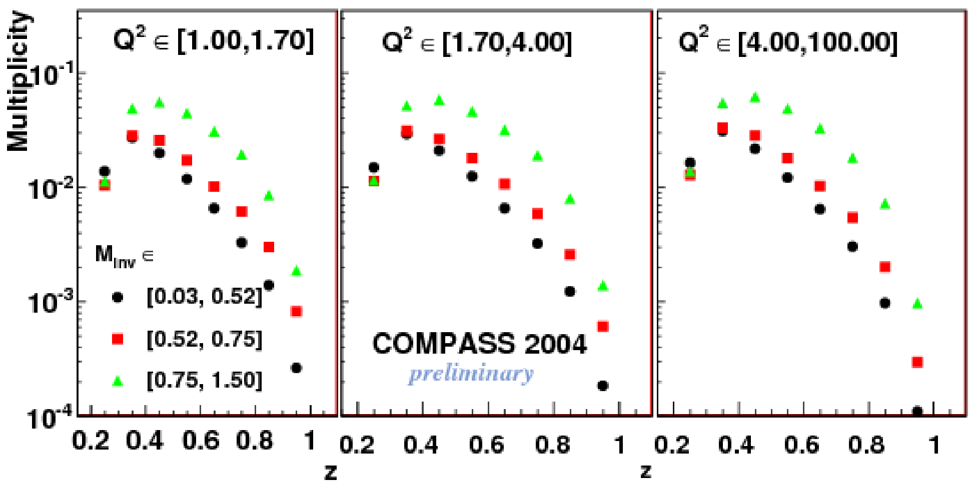


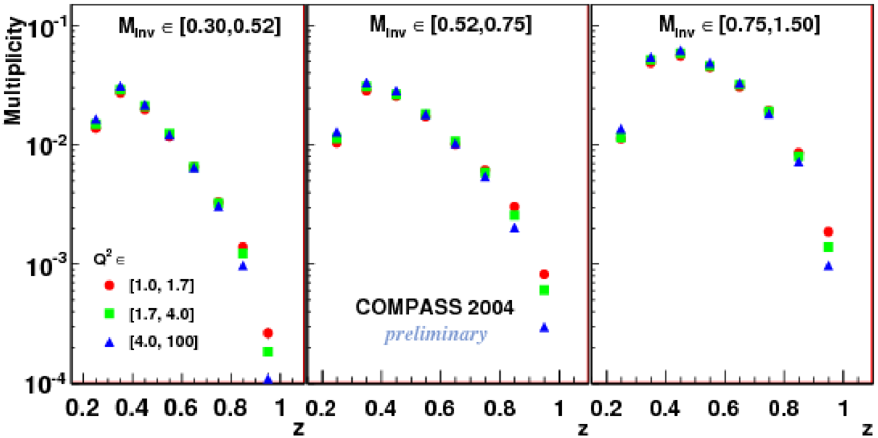
Q^2 behavior



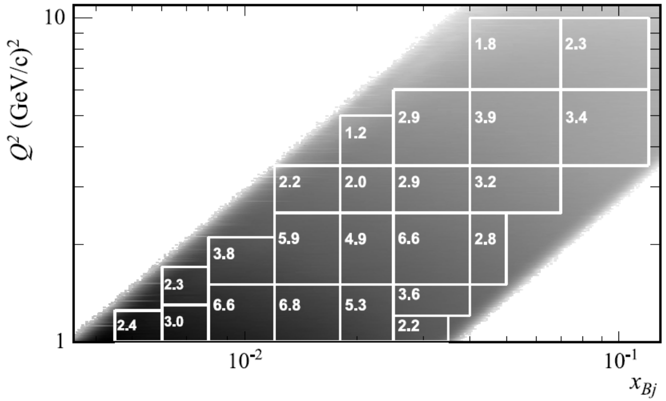
COMPASS preliminary
0.008 < x < 0.013
0.013 < x < 0.020
0.020 < x < 0.032
0.032 < x < 0.050
0.050 < x < 0.080
0.080 < x < 0.130
$Q\,A_{UU}^{\cos\phi_h}$
h^+
h^-
0
−0.1
−0.2
−0.3
1
10
Q^2 (GeV/c)^2

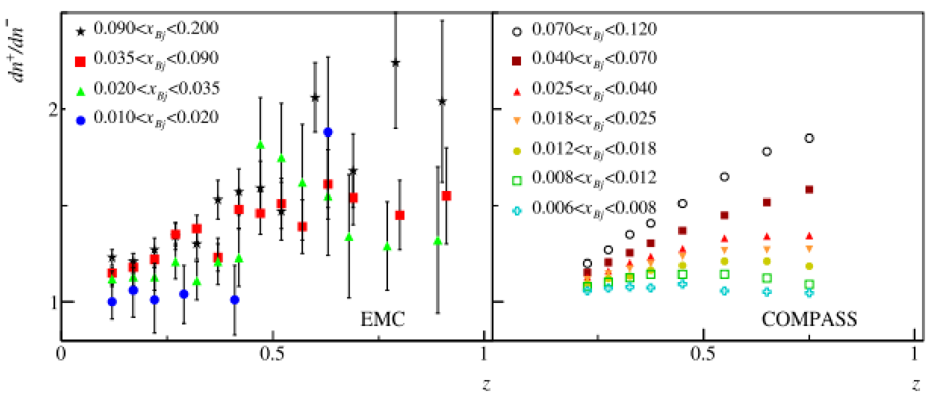
2h Multiplicities (>10 years ago)

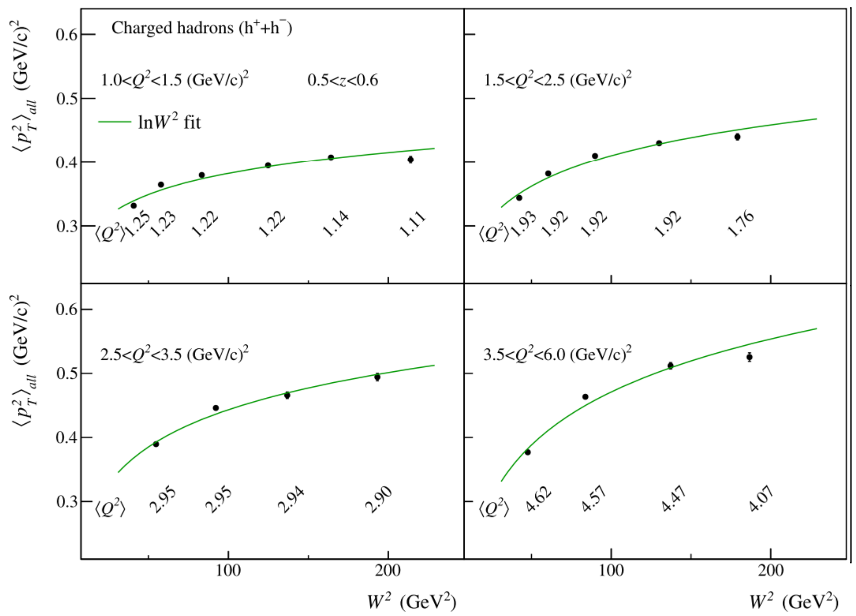




1^{st} publication on P_{hT} distributions (2013);

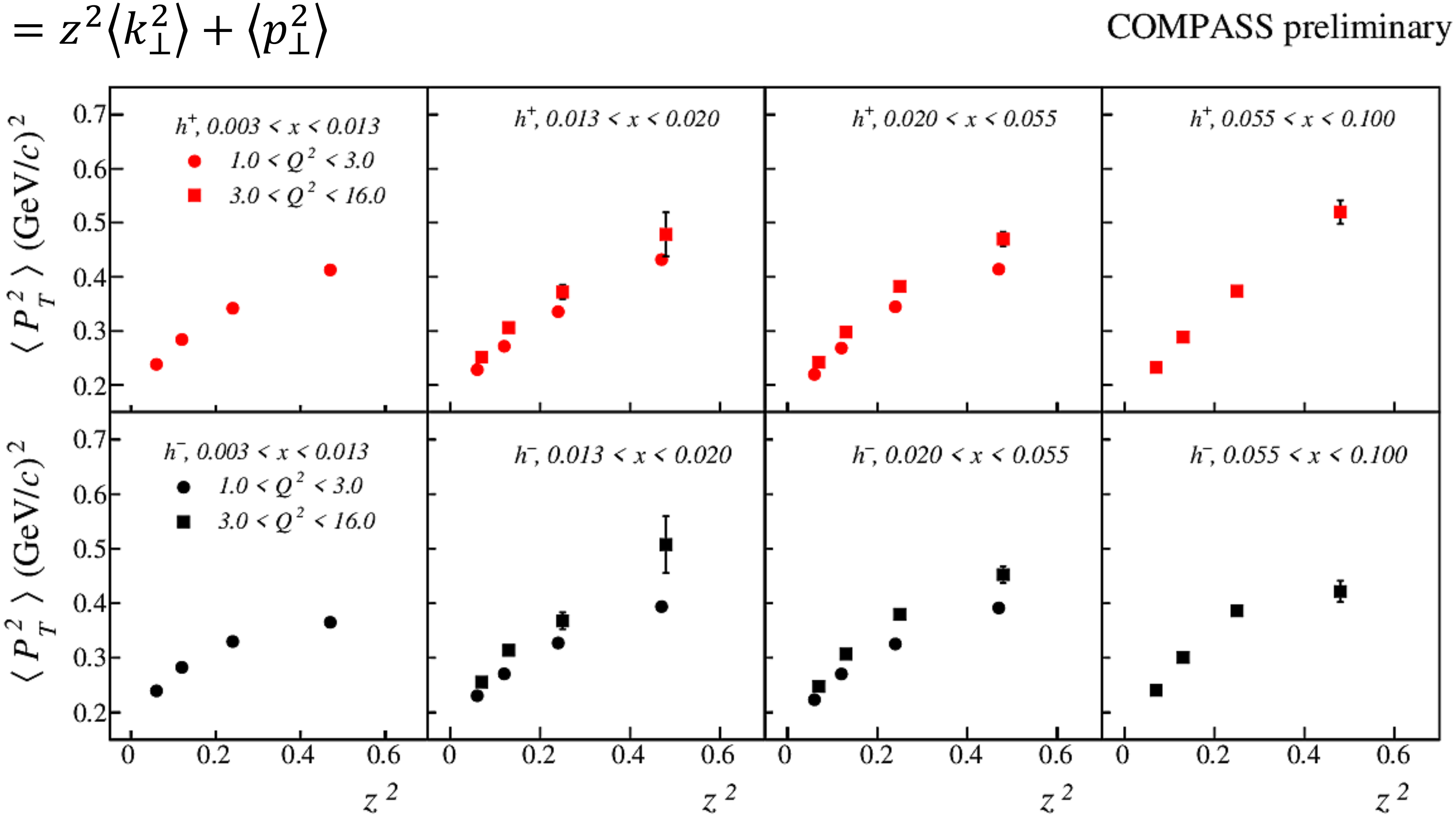




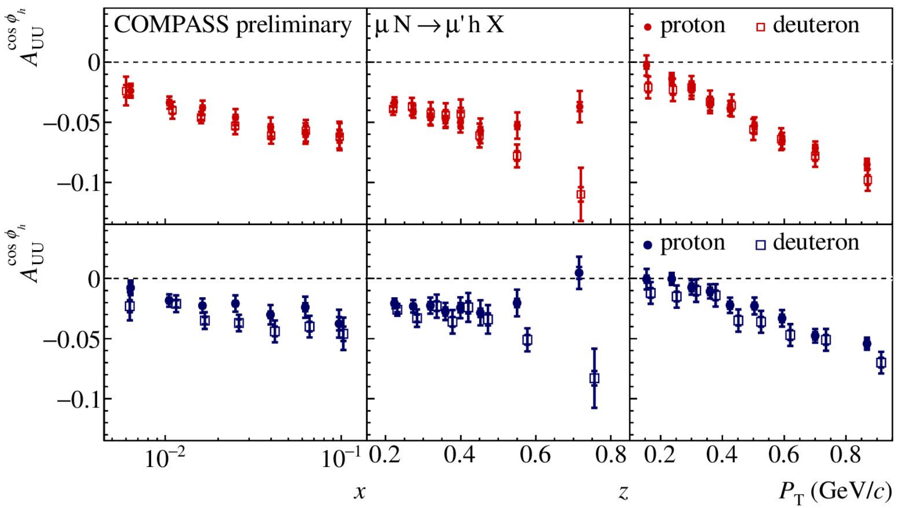


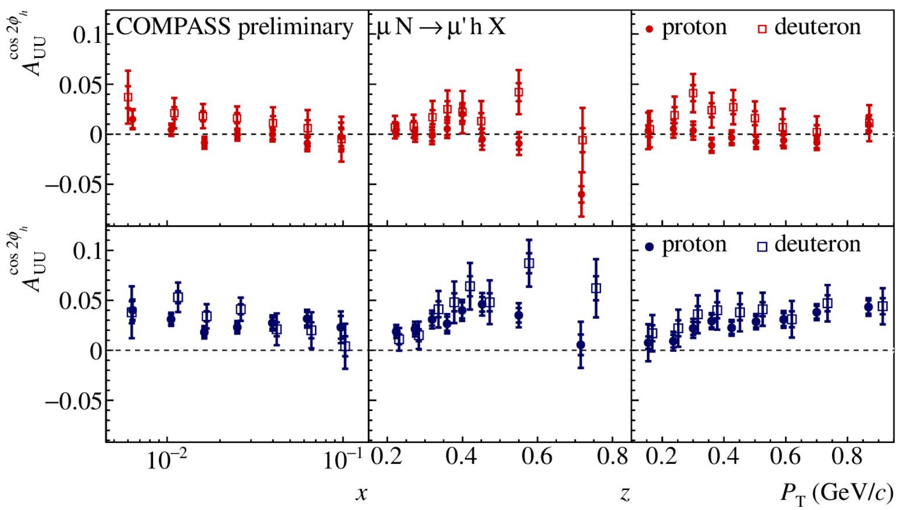
Slope dependence

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

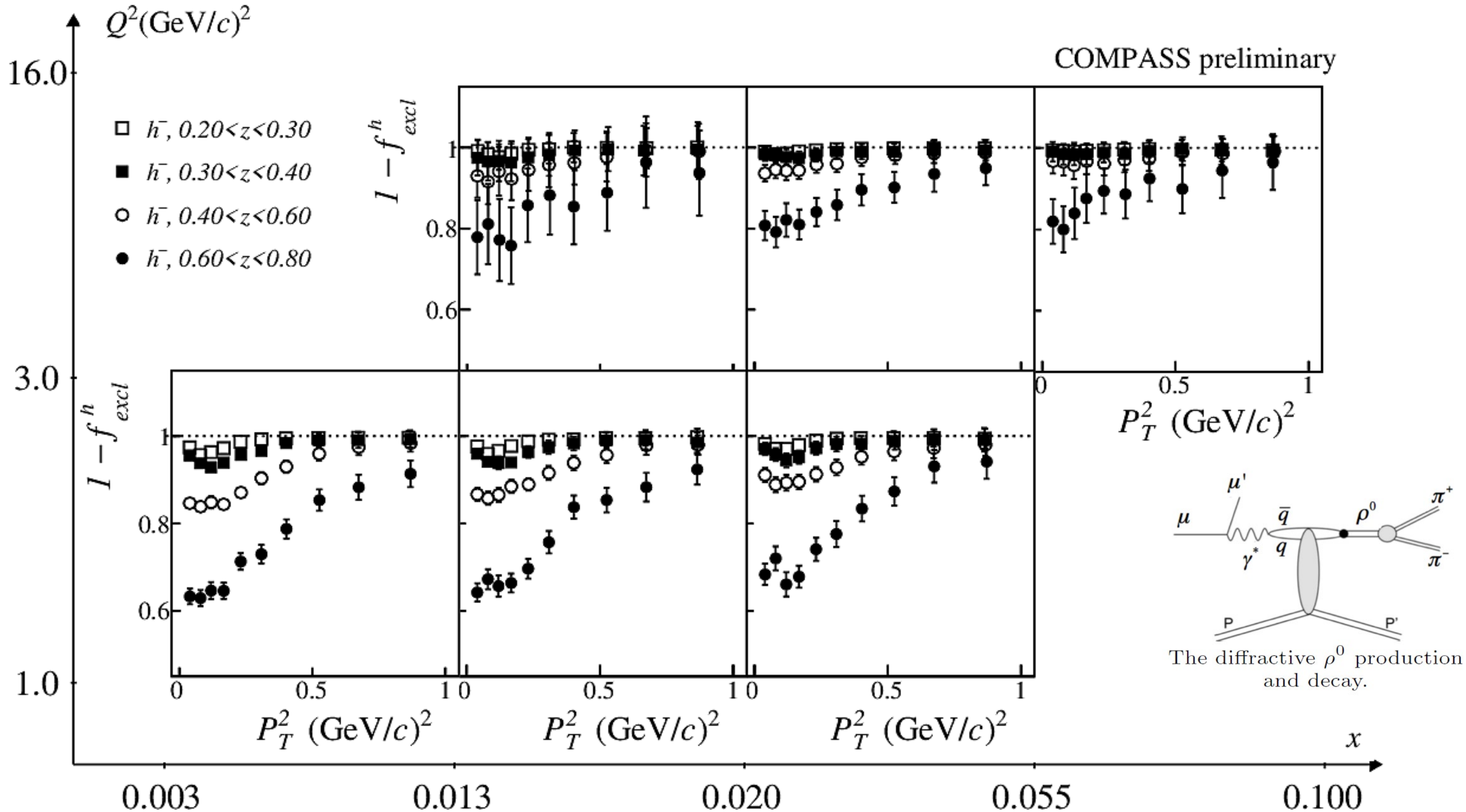


P vs D


COMPASS preliminary
μ N → μ' h X
proton
deuteron
$A_{UU}^{\cos\phi_h}$
x
z
P_T (GeV/c)

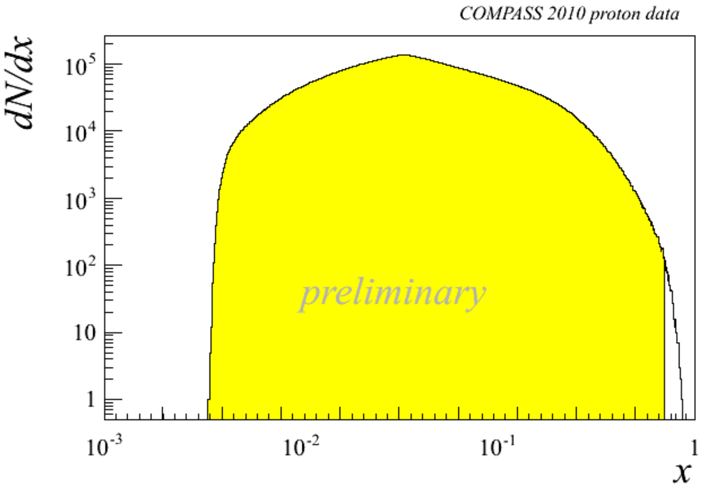

COMPASS preliminary
μ N → μ' h X
proton
deuteron
$A_{UU}^{\cos 2\phi_h}$
x
z
P_T (GeV/c)

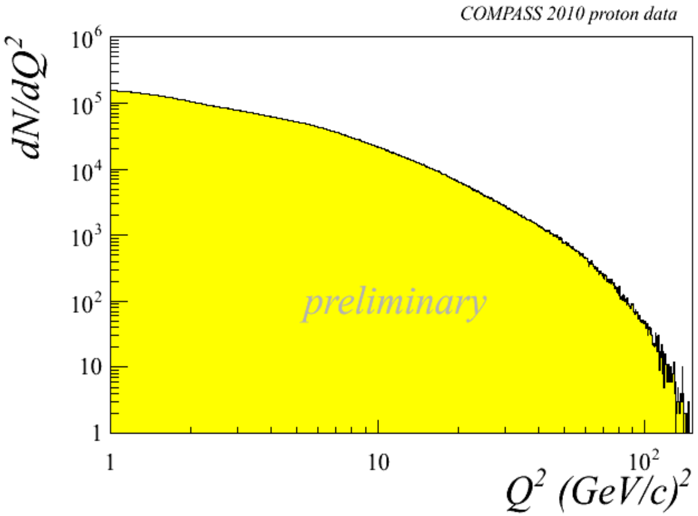
Contamination of hadrons from ρ^0 and ϕ

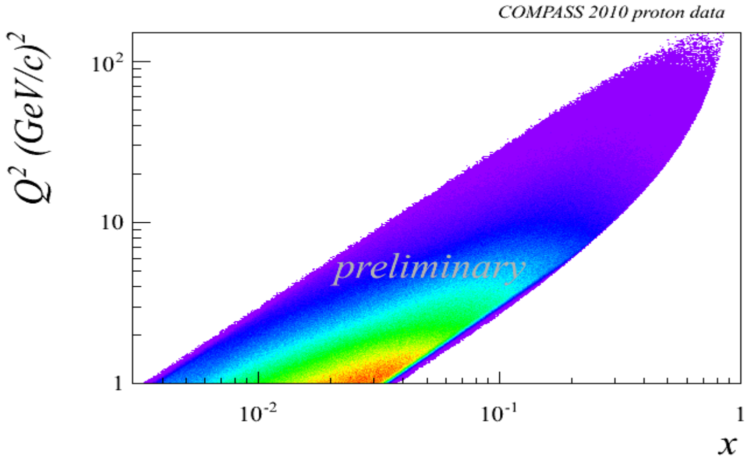


Kinematic distributions

DIS Cuts
$Q^2 > 1\ (\mathrm{GeV}/c)^2$
$0.1 < y < 0.9$
$W > 5\ \mathrm{GeV}/c^2$

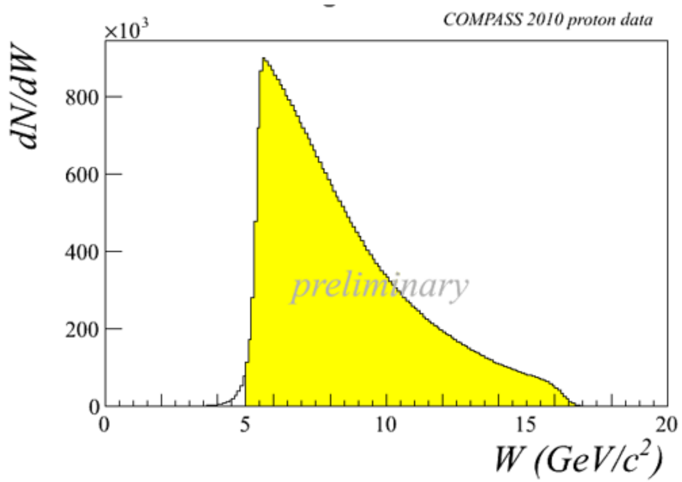


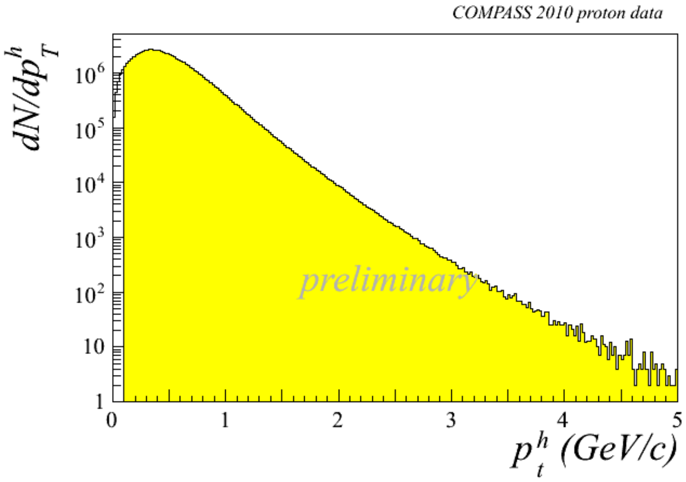


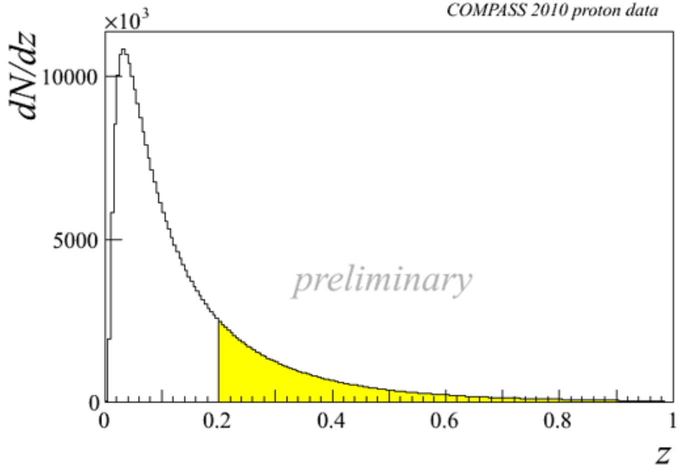


Kinematic distributions - 2

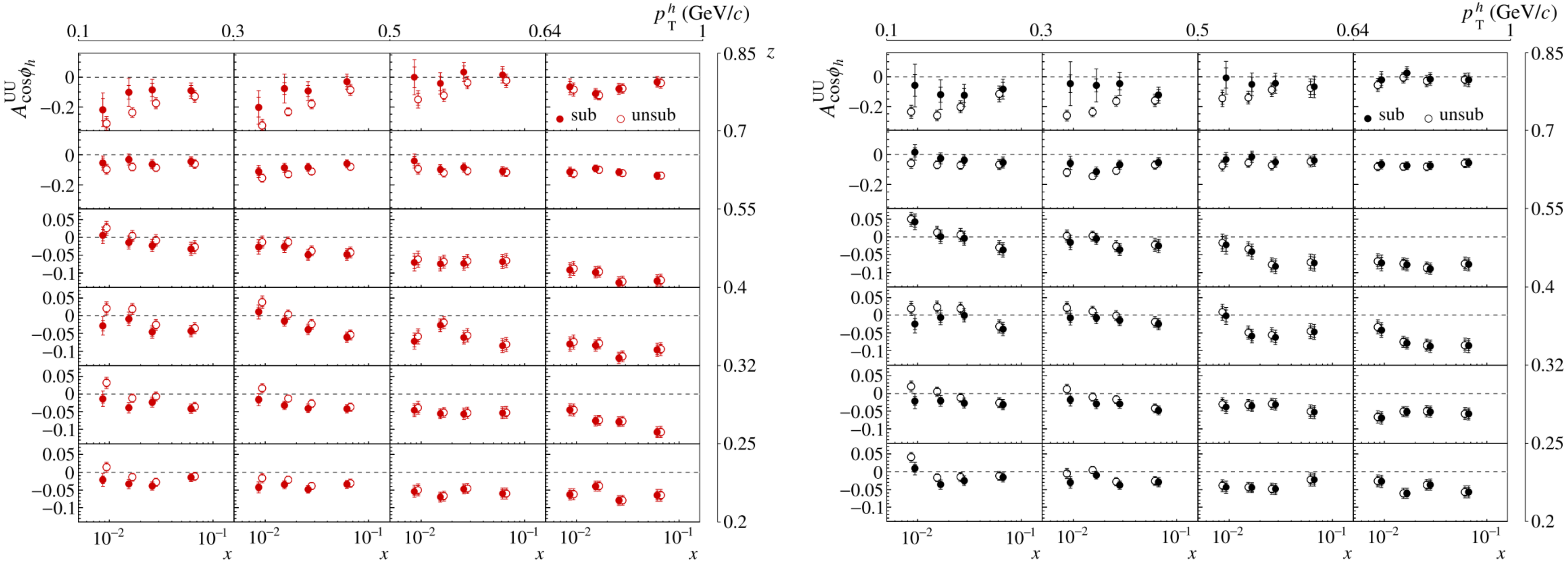
DIS Cuts	Hadron Cuts
$Q^2 > 1\ (\mathrm{GeV}/c)^2$	$z > 0.2$
$0.1 < y < 0.9$	$P_{hT} > 0.1\ \mathrm{GeV}/c$
$W > 5\ \mathrm{GeV}/c^2$	







VM subtraction from ^{6}LiD results



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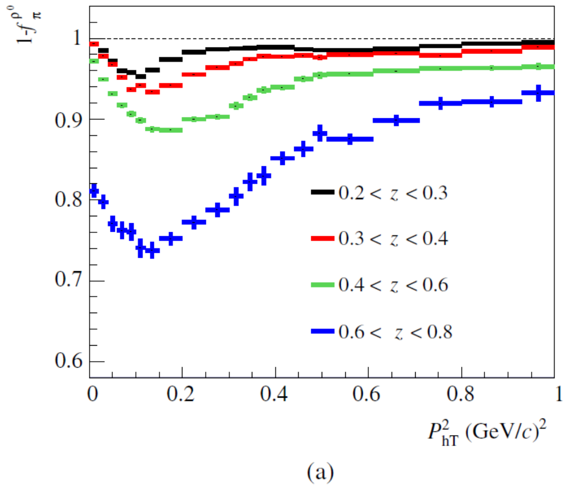
2nd publication on P_{hT} distributions (2018);

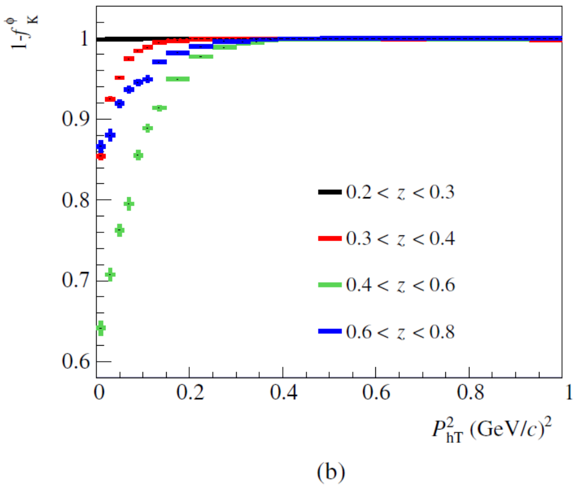
Improved binning

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

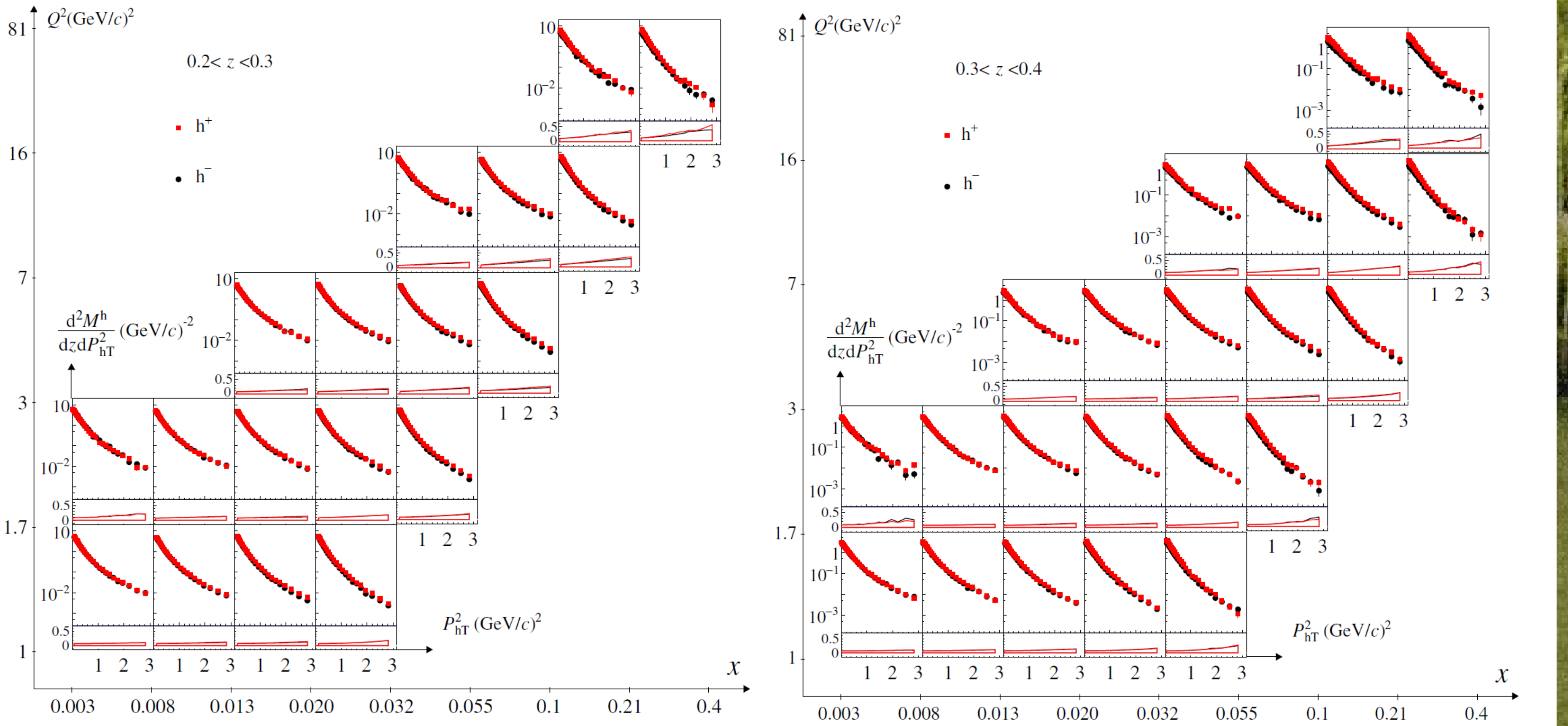
	Bin limits								
x	0.003	0.008	0.013	0.02	0.032	0.055	0.1	0.21	0.4
Q^2 (GeV/c)^2	1.0	1.7	3.0	7.0	16	81			
z	0.2	0.3	0.4	0.6	0.8				
P_{hT}^2 (GeV/c)^2	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.17	0.196
	0.23	0.27	0.30	0.35	0.40	0.46	0.52	0.60	0.68
	0.76	0.87	1.00	1.12	1.24	1.38	1.52	1.68	1.85
	2.05	2.35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

Subtraction of Diffractive Vector Mesons

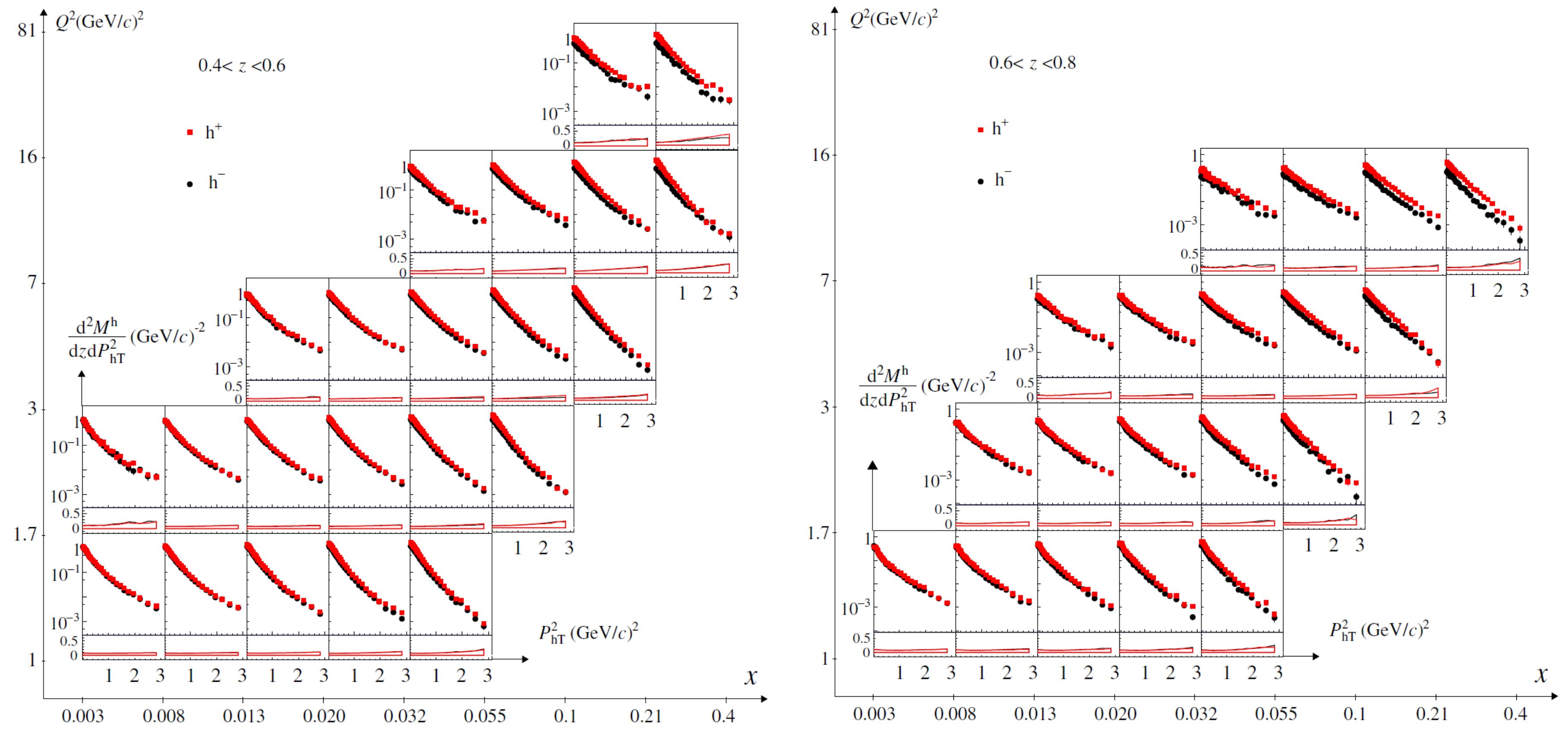




2^{nd} publication on P_{hT} distributions;

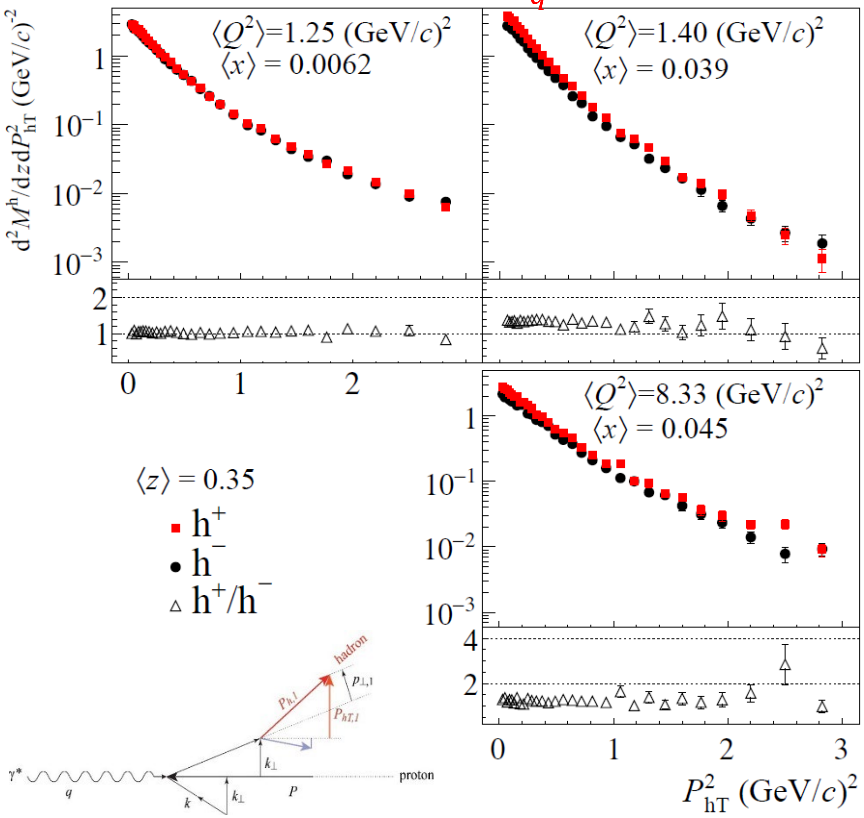


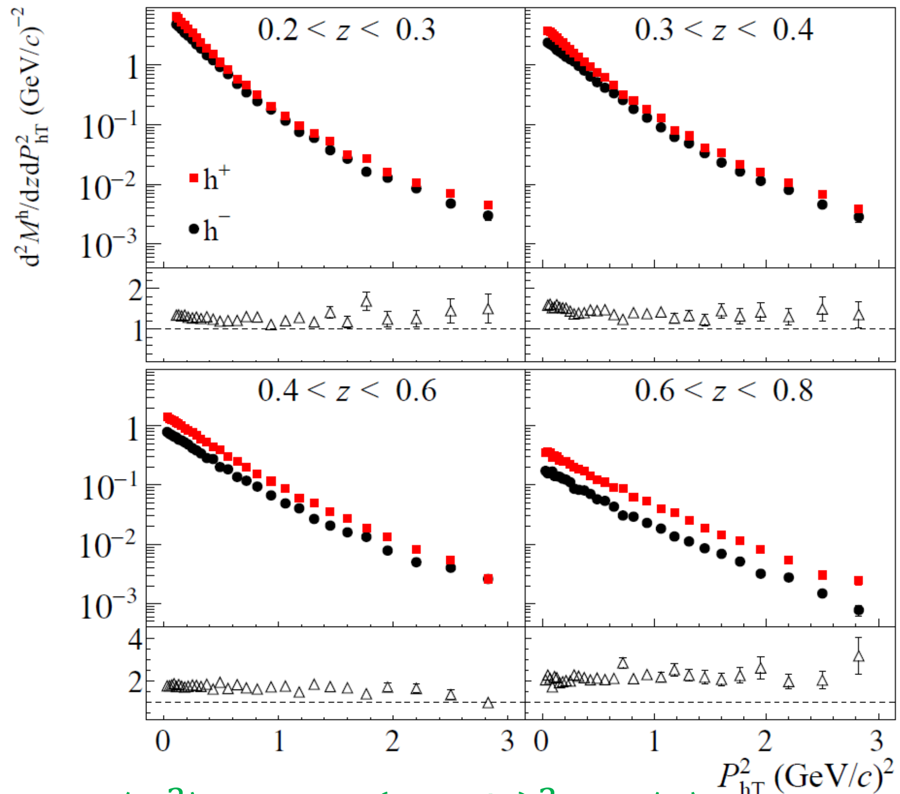
2nd publication on P_{hT} distributions;



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

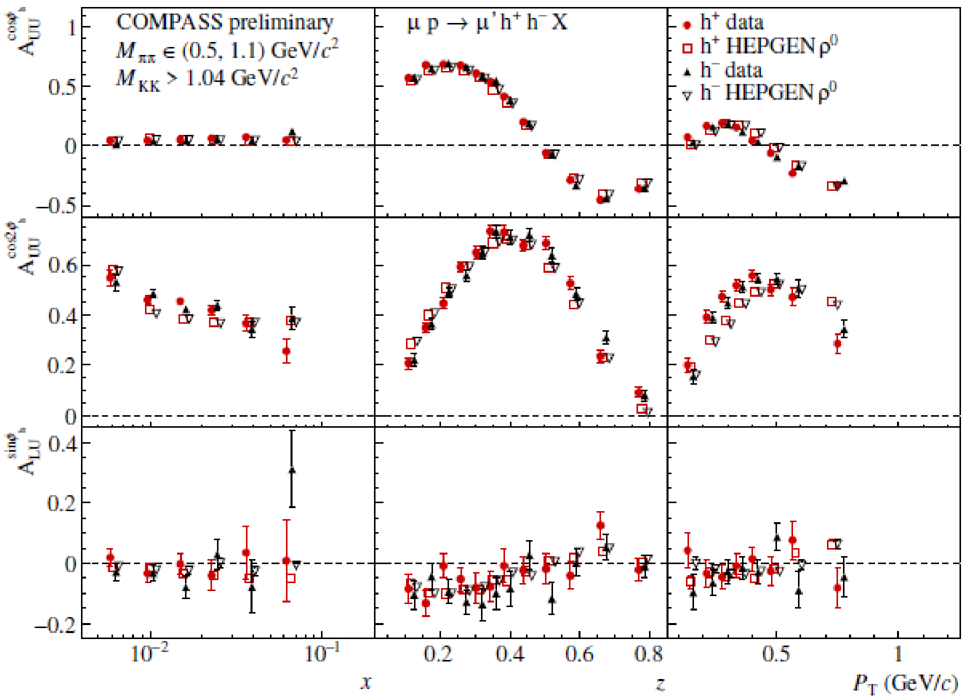
$$F_{UU}^{h}(x,z,P_{hT}^2;\ Q^2) = x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp - z\vec{k}_\perp - \vec{P}_{hT})\ f_1^q(x,k_\perp^2;Q^2) D_1^{q\to h}(z,p_\perp^2;Q^2)$$

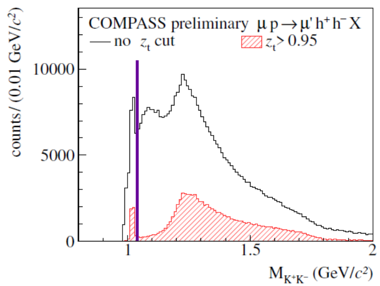


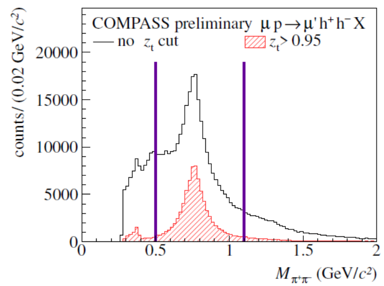


$\langle Q^2\rangle = 9.78\ (\mathrm{GeV}/c)^2$ and $\langle x\rangle = 0.149$

Study of VM contamination LH_2







Normalization of HEPGEN