UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

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Analysis of nuclear effects in azimuthal asymmetries of π^+ off SIDIS processes with CLAS

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On behalf of the CLAS collaboration

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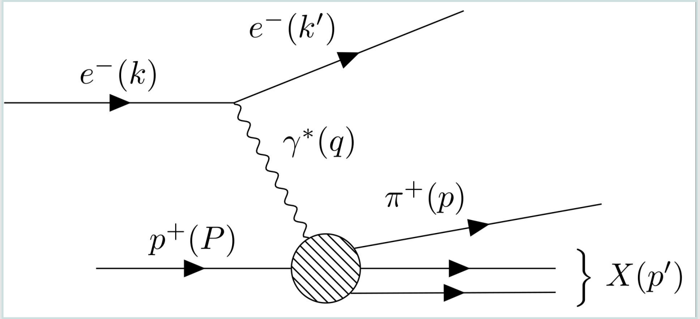
Overview

- Motivation
  - Semi Inclusive Deep Inelastic Scattering (SIDIS) and hadronization
  - Cross section and asymmetry terms
- Data, simulation, and acceptance
  - Closure test
- Azimuthal asymmetries
  - First asymmetry and ratios
  - Effect of same sector events
- Conclusions

Motivation: SIDIS and hadronization

- Semi Inclusive Deep Inelastic Scattering (SIDIS) process involves a **lepton** (e^-) and a **nucleon** in the production of **hadrons as final state particles** (we are mainly interested in π^+)

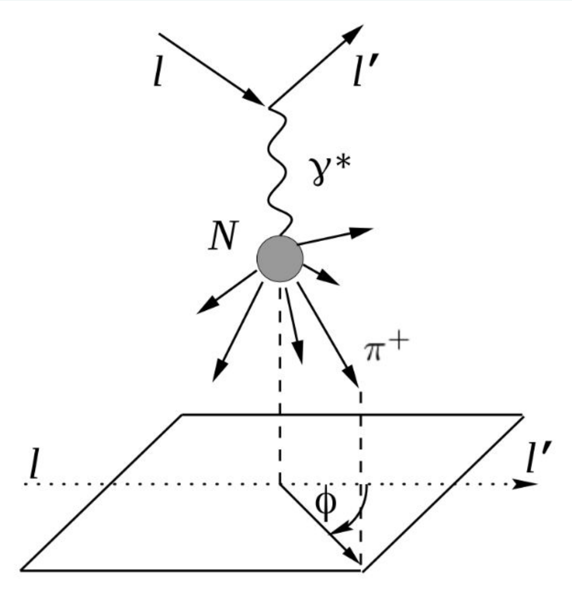
- The strong interaction involves two main properties that cannot be directly measured: *Asymptotic freedom* and *Color confinement*



- Question: **Do different nuclear media affect the internal interactions in nucleons?**
- **Is the usual semi-classical picture enough to describe processes inside nuclei?**

Definition of variables

- An **unpolarized SIDIS process** can be fully described with 5 variables
- We commonly use two leptonic and three hadronic variables:
  - Only two of the usual leptonic variables are independent

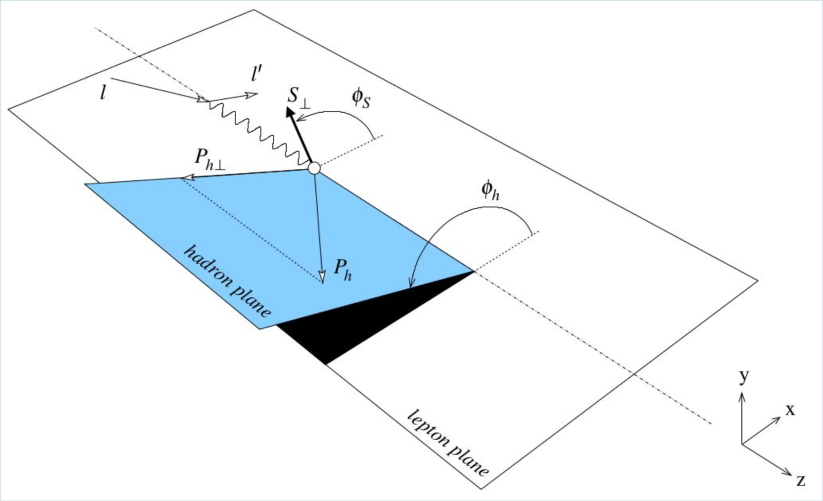


$$Q^2 = -q^2 = 4EE' \sin^2(\theta/2)$$
(Lab frame)

$$\nu = \frac{P \cdot q}{M} = E' - E$$
(Lab frame)

Definition of variables (continued)

- The three hadronic variables are:



$$Z_h = \frac{P_h \cdot p}{P_h \cdot q} = \frac{E_h}{\nu}$$

Interpreted as the energy transferred to the final hadron by the virtual photon (Lab frame)

$$P_t^2 = (P_{h\perp})^2$$

Transverse component of the momentum w.r.t. virtual photon

$$\phi_{PQ} = \phi_h$$

Azimuthal angle formed by the hadron and lepton planes defined by the detected hadron and scattered lepton

* Image taken from: A. Bacchetta et al., Journal of High Energy Physics, vol. 2007, no. 02, p. 093, Feb. 2007. doi: 10.1088/1126-6708/2007/02/093.

Cross section

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_t^2} = \frac{\alpha^2}{xQ^2}\frac{y}{2(1-\epsilon)}$$

$$\times\left\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}+\epsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}\right.$$

$$+\lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{UL}^{\sin\phi_h}+\epsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}\right]$$

$$\frac{d^5\sigma}{dQ^2 d\nu dZ_h dP_t^2 d\phi_{PQ}} \equiv A + B\cos(\phi_{PQ}) + C\cos(2\phi_{PQ})$$

$$\propto 1 + 2\langle cos\phi\rangle\, cos(\phi_{PQ}) + 2\langle cos2\phi\rangle\, cos(2\phi_{PQ})^{*}$$

$$+\epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}+\epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+|S_\perp|\lambda_e\left[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}\right.$$

- Full cross section considers contributions from polarized beam and targets
  - These terms are removed in the unpolarized case
- The unpolarized cross section can be described by **three linearly independent terms**, in principle

* Usual notation, described in eq. 9 of: H., Airapetian *et al.* HERMES Collaboration (2012), 'Azimuthal distributions of charged hadrons, pions, and kaons produced in deep-inelastic scattering off unpolarized protons and deuterons.' arXiv. https://doi.org/10.1103/PhysRevD.87.012010

Asymmetry terms

- We will refer to the $\langle cos\phi \rangle$ term as 'first asymmetry'
- Theoretically, this term has contributions from two main effects
  - Cahn effect: Due to the intrinsic transverse momentum of quarks inside nucleon
  - Boer-Mulders: Due to coupling of the internal spin of the quarks with the whole target

- The first asymmetry is expected to be negative and dominated by the Cahn term
- The second asymmetry would be smaller in comparison

Cahn effect *Boer-Mulders term*

$$F_{UU}^{\cos\varphi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{(\hat{h}\cdot\vec{k}_T)}{M}f_1 D_1 - \frac{(\hat{h}\cdot\vec{p}_\perp)k_T^2}{M^2 M_h}h_1^\perp H_1^\perp + \cdots\right]$$

Boer-Mulders term

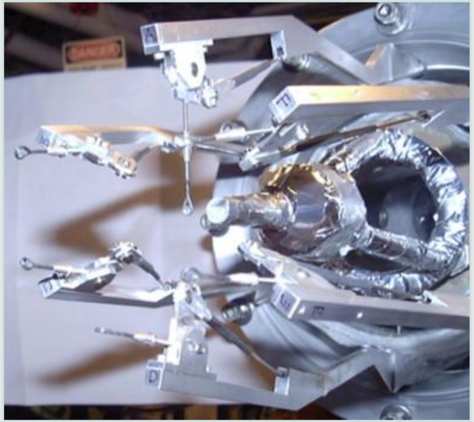
$$F_{UU}^{\cos 2\varphi_h} = \mathcal{C}\left[-\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_\perp) - \vec{k}_T\cdot\vec{p}_\perp}{M\,M_h}h_1^\perp H_1^\perp\right]$$

* A. Moretti et al., 'TMD observables in unpolarised SIDIS at COMPASS', 2021. arXiv:2107.10740 [hep-ex].

Data taking

- Data was taken as part of the Eg2 group in Hall B with an unpolarized electron beam of 5.014 GeV in early 2004

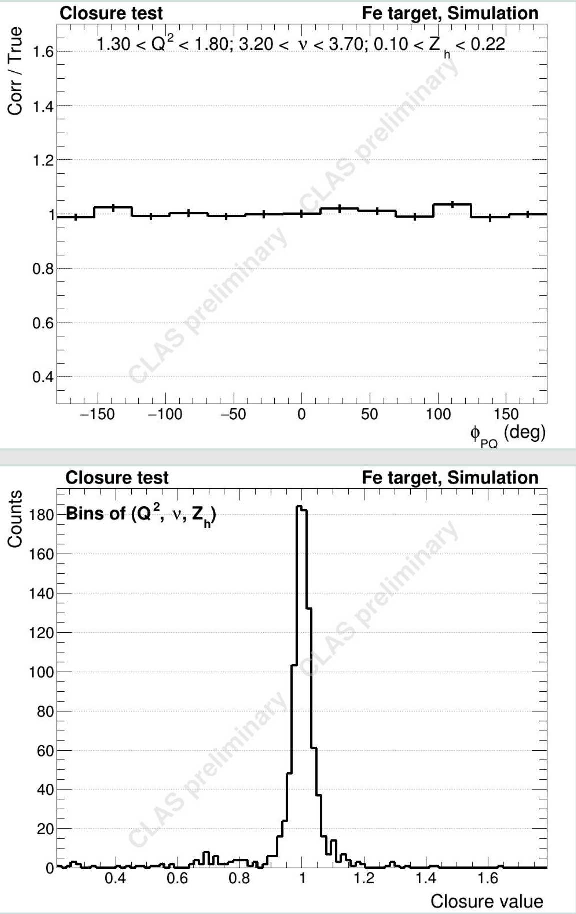
- Solid targets of Carbon (*C*), Iron (*Fe*), and Lead (*Pb*) were tested
  - A liquid Deuterium (*D*) target was tested **simultaneously** with each solid target to reduce time dependent systematic effects
  - A double target system was developed to fulfill this requirement
  - The liquid target is placed before (upstream) the solid one and both are aligned along the beamline axis



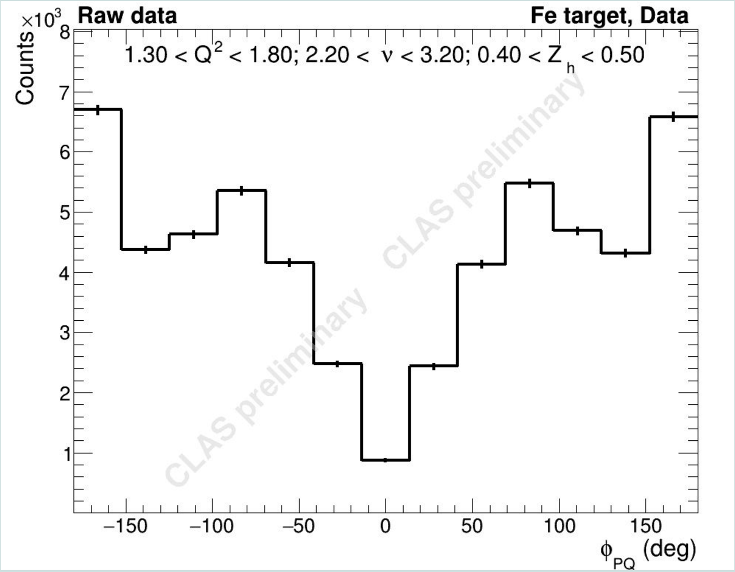
Acceptance and Closure test

- Simulations made with Pythia 6.319 by H. Hakobyan
  - Detector and migration effects are removed by means of a **5-fold acceptance correction** implemented event by event to the data

- The closure test is introduced as a method to measure the *quality* of the acceptance correction
  - A ratio of 1 means a perfect correction!
  - Z_h bins: 0.98 ± 0.12
  - P_t^2 bins: 0.99 ± 0.07

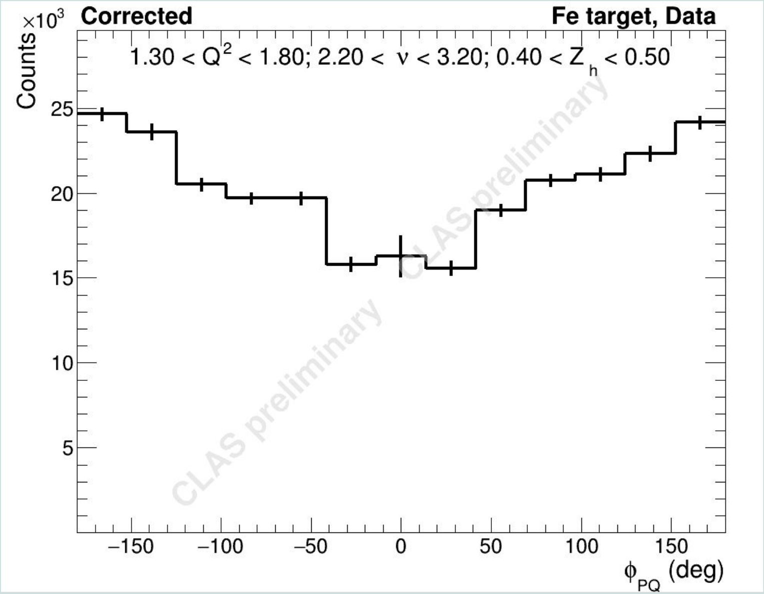


Correcting data!



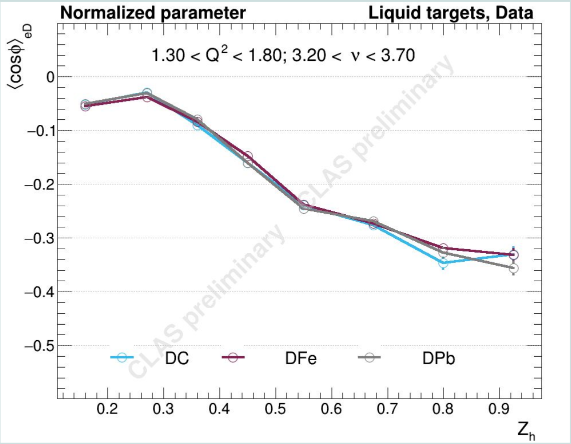
Applying

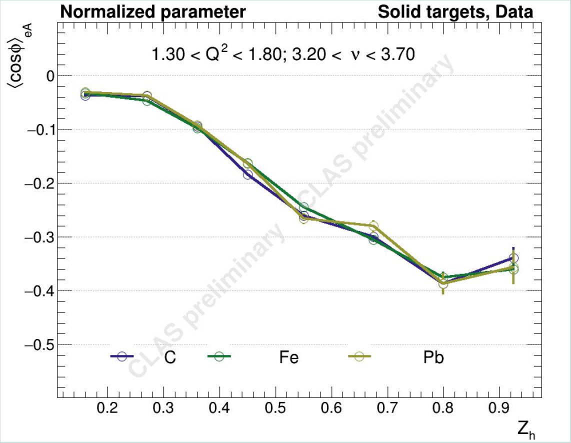
Acceptance



First asymmetry: Z_h dependence

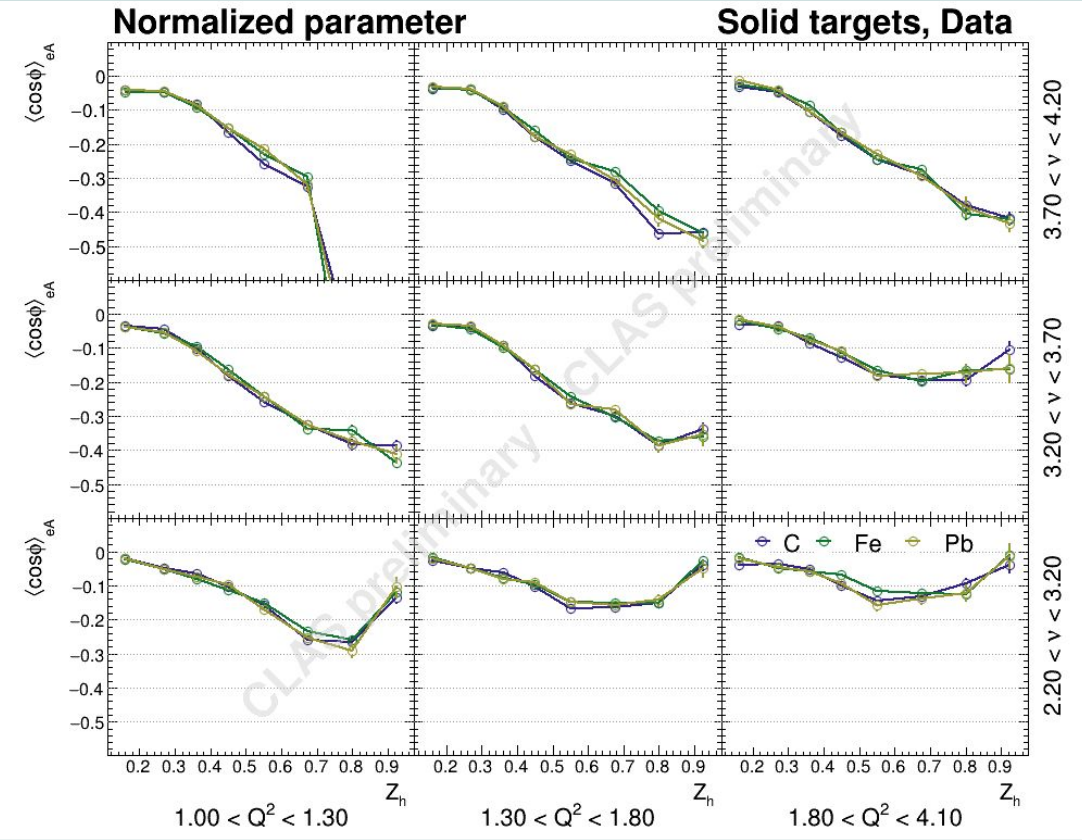
- These next results are integrated in P_t^2
- Deuterium should behave similarly with all solid targets, thus presenting a quality check
  - Most of the bins are within one sigma of uncertainty
- Similar trend is followed by all solid targets
  - Increase of more than four times (x4) at high Z_h
  - No substantial differences with respect to deuterium(!)



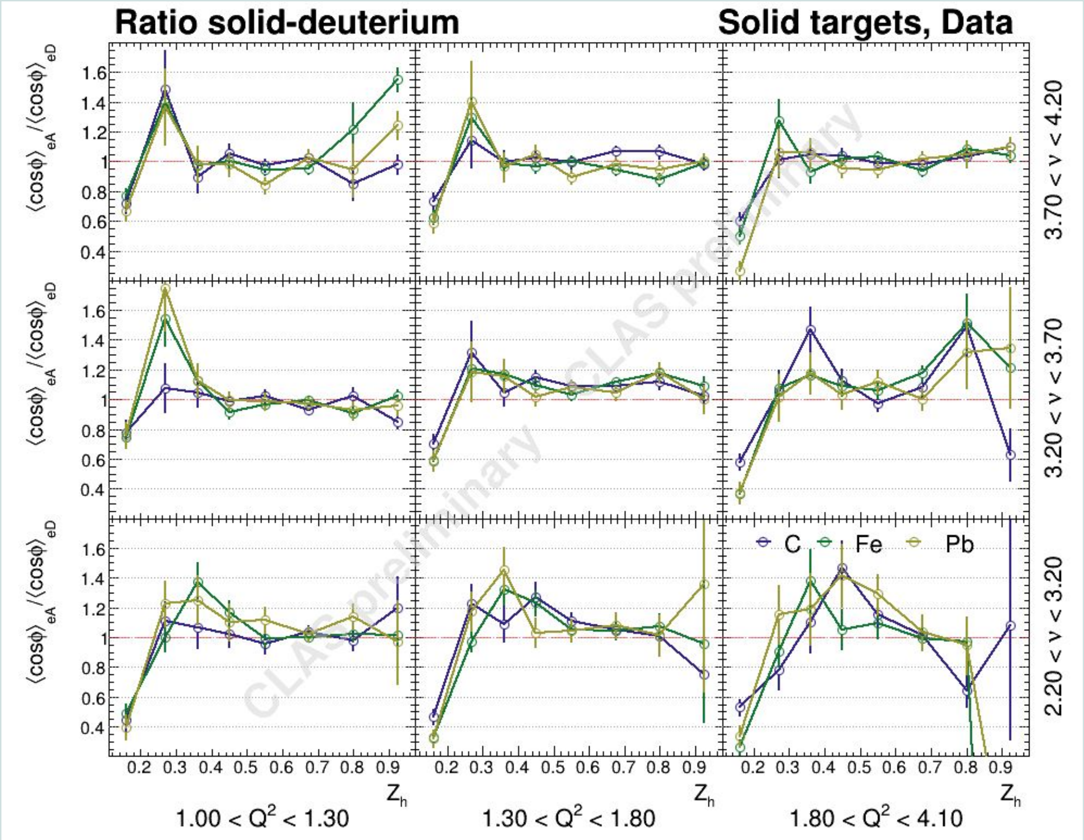


First asymmetry: Z_h dependence (all bins, solid)

- Some Z_h regions with small statistics have non-reliable results
- The effect is stronger mainly at high Z_h:
  - Accentuated at low virtuality (Q^2)
  - Increasing ν also enhances the asymmetry



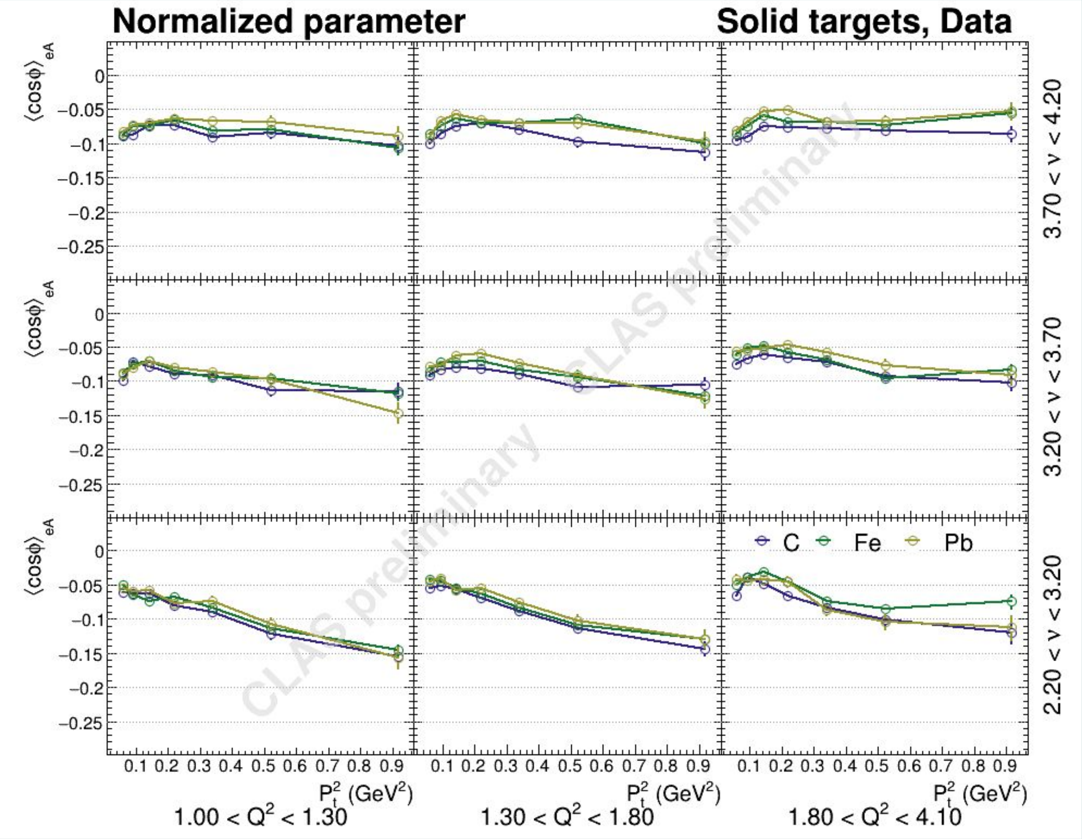
Solid-Liquid ratio: Z_h dependence



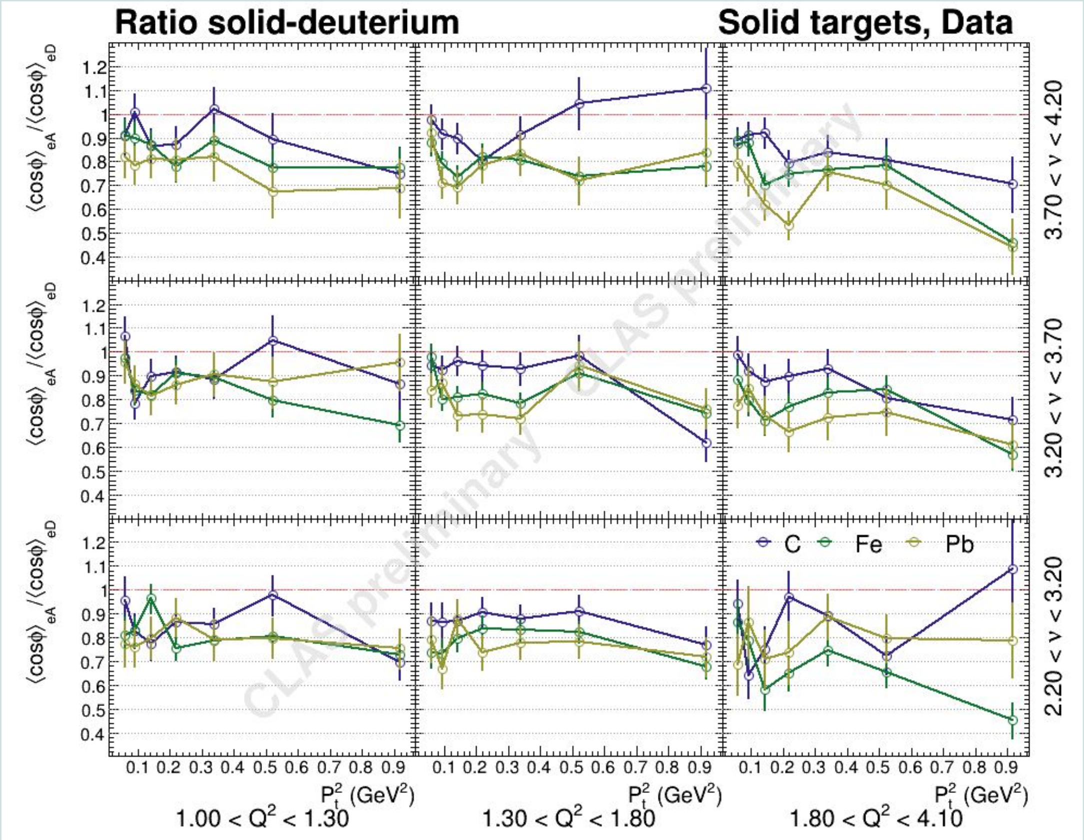
- No clear nuclear size hierarchy is observed
  - First overshoot looks systematic as it is present in every bin
  - Reduction in asymmetry is present previous to first overshoot
  - No conclusive effect at higher values

First asymmetry: P_t^2 dependence (all bins, solid)

- Effect is always present
  - Stronger at high P_t^2, though the increment is three times at most
- Asymmetry is not particularly affected by Q^2
- Low ν values show a bigger impact at high P_t^2



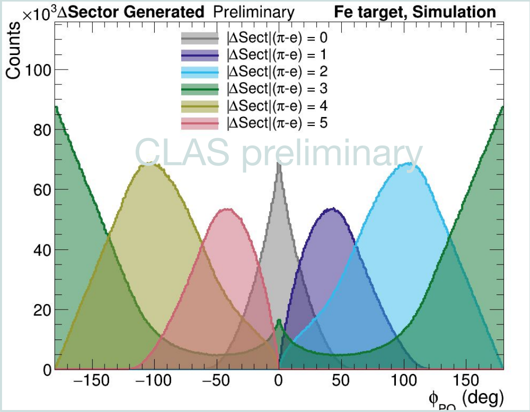
Solid-Liquid ratio: P_t^2 dependence

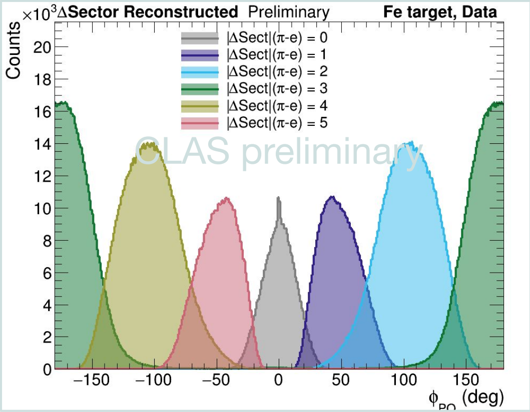


- Hints of a nuclear hierarchy
  - Higher reduction with bigger nuclear sizes (!)
  - Reductions up to 30% were observed

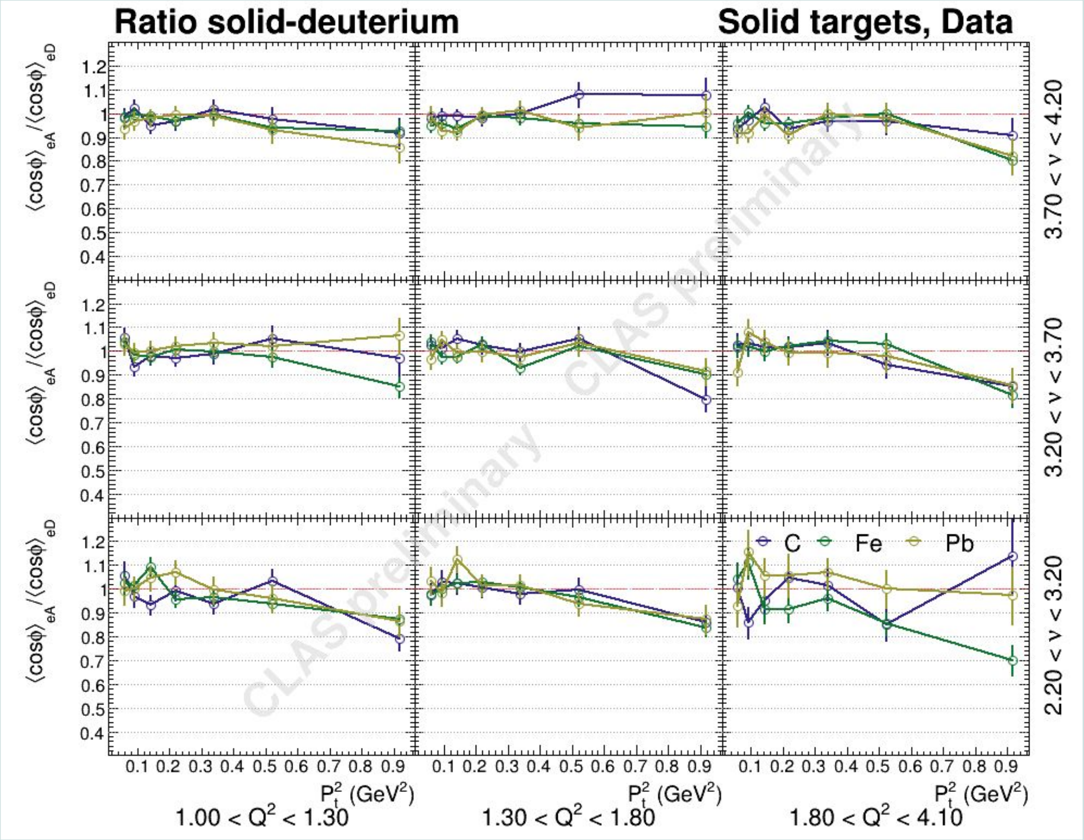
Contributions of ϕ_{PQ} distribution

- By definition, ϕ_{PQ} requires an electron and a pion correctly detected
    - This motivates the study on how the detection of different sectors impact on the whole distribution
    - Simulations show how the different peaks are introduced by hits in the same sector ($|\Delta S| = 0$), neighbor sector ($|\Delta S| = 1$), next to neighbor sectors ($|\Delta S| = 2$), and so on
- Data has presented an anomalous peak in the region of $\phi_{PQ} \sim 0°$ → How does the peak affect the results?





Effect of same sector events



- In the extreme limit of having all same sector events removed, the suppression of the possible nuclear hierarchy is evident
  - Nuclear asymmetries are mainly visible in events with collimated products (!)

Conclusions

- A 5-fold acceptance correction was implemented
  - Values were in line with previous studies of our group
  - A Closure test was successfully conducted
- No significant nuclear effects
  - Though hints of hierarchy were found, results are not conclusive → Further studies required
  - At best we can assert limits of the effect (in general, nuclear composition attenuates or maintains the asymmetry)
- First asymmetries are dominant in collimated events

Thanks for your attention!

Backup slides

Structure functions and factorization

- Begin with parton model (semi classical picture) to model hadronization
  - Partons (quarks and gluons) are point-like structures
  - Though it's a first approximation of the internal process, we can extend its validity by means of the factorization theorem

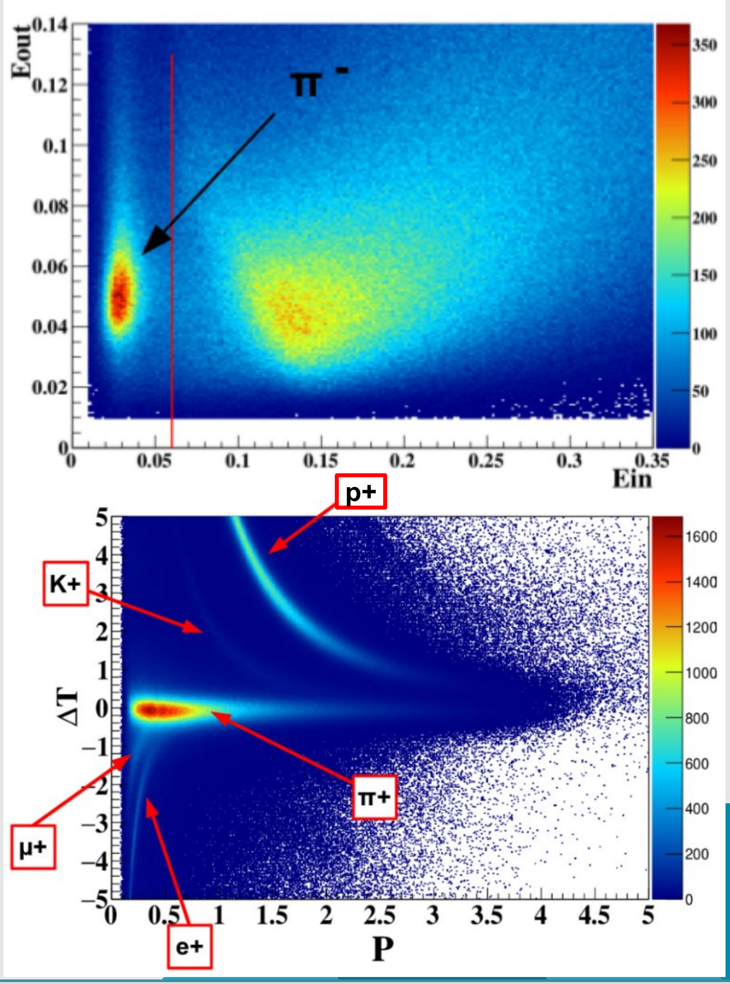
- A Structure Function is the most general way of accounting for the internal (unknown) structure of a nucleon
  - Partons can be extended to non-localized entities by introducing Parton Distribution Functions (PDF)
  - Extra terms, as a hard scattering part (pQCD) and Fragmentation Function (FF) are included and, in principle, independent one of the other

$$F(Q^2, x, Z_h) = \sum_i H_i(Q^2) f_i^N(x, Q^2) D_{i \to h}(Z_h, Q^2)$$

Particle identification (pid)

- Events are triggered by an electron addressed as the scattered lepton, requiring:
  - $Q^2 > 1$ GeV (DIS limit)
  - $W > 2$ GeV (avoid Delta resonances)
  - $y_b < 0.85$ (minimum sensitivity)

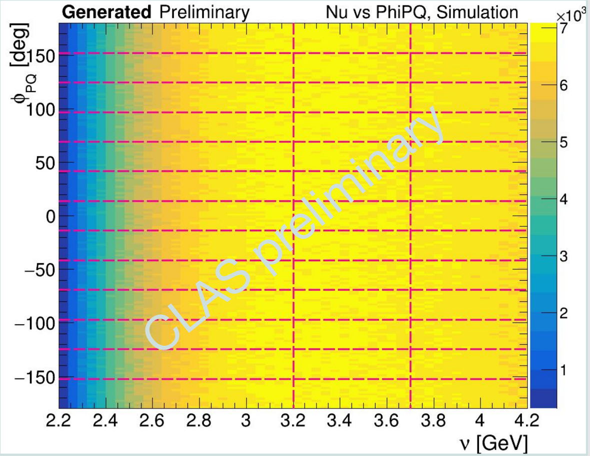
- Next, look for pid candidates:
  - e^- with: DC and ECAL fiducial cuts, energy deposited and sampling ratio in ECAL, momentum reconstructed in DC, arrival time in TOF, signal in CC, etc…
  - If fails, π^- is the next candidate in the list: Arriving time in TOF, signal in CC, etc…
  - Same for their antiparticles ($e^+ \rightarrow \pi^+$)

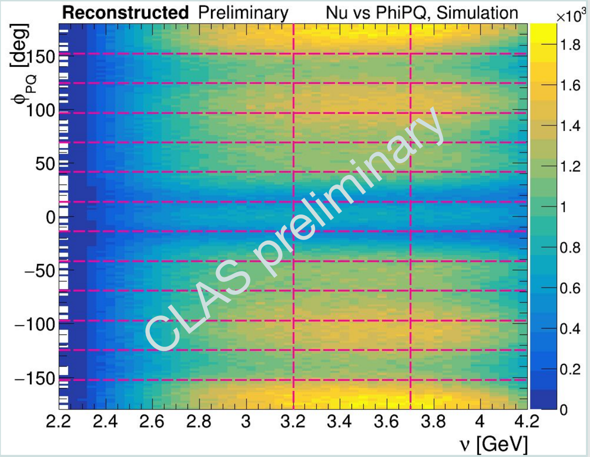


Simulations and Acceptance

- A series of simulations of the process were made with Pythia 6.319 by H. Hakobyan
- Simulations model detector effects
  - These effects are removed by means of an **acceptance correction** to the data
  - 5-fold acceptance was implemented event by event

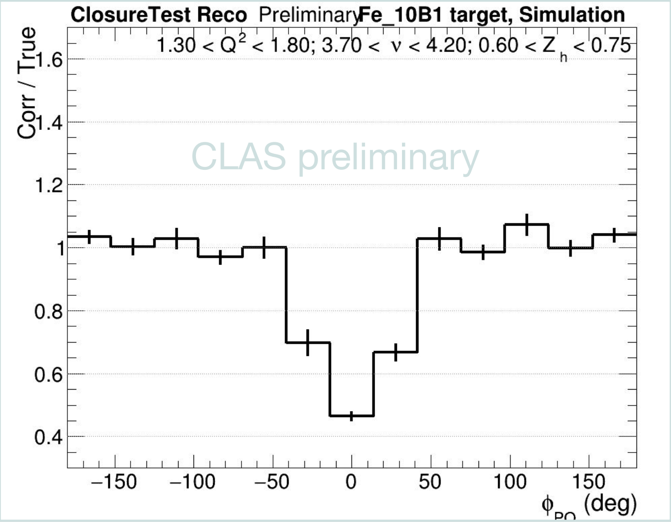
$$A(Q^2,\nu,Z_h,P_t^2,\phi_{PQ}) = \frac{N_{\text{reconstructed}}(Q^2,\nu,Z_h,P_t^2,\phi_{PQ})}{N_{\text{generated}}(Q^2,\nu,Z_h,P_t^2,\phi_{PQ})}$$





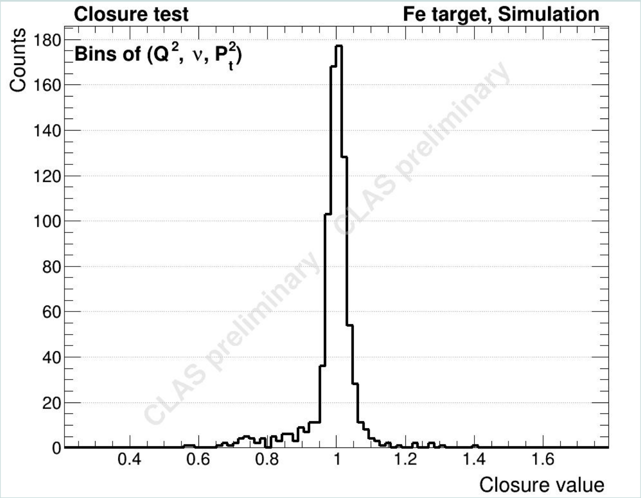
Closure Test: Bad behaved bins

- Values around $\phi \approx 0°$ usually get a bad performance, especially at high Z_h
  - This feature has not the same source as the data peak issue, since this is full simulation!
- Big error bars are also a symptom of this problem



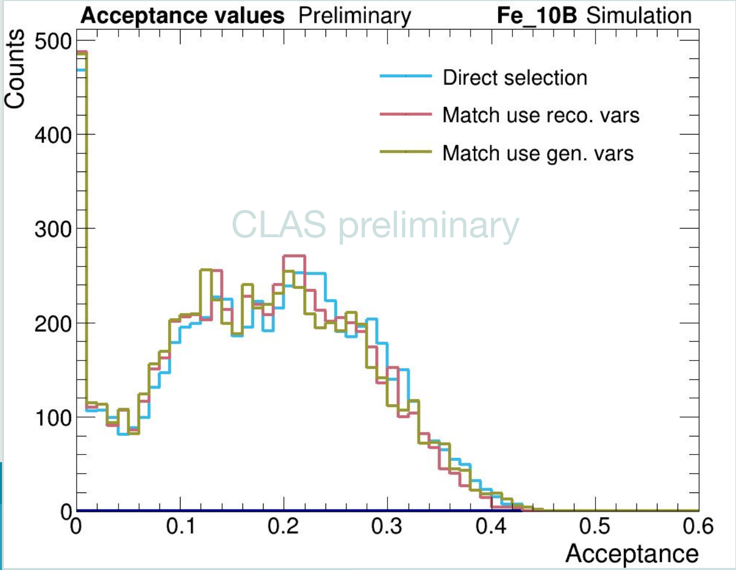
Closure Test: Pt2

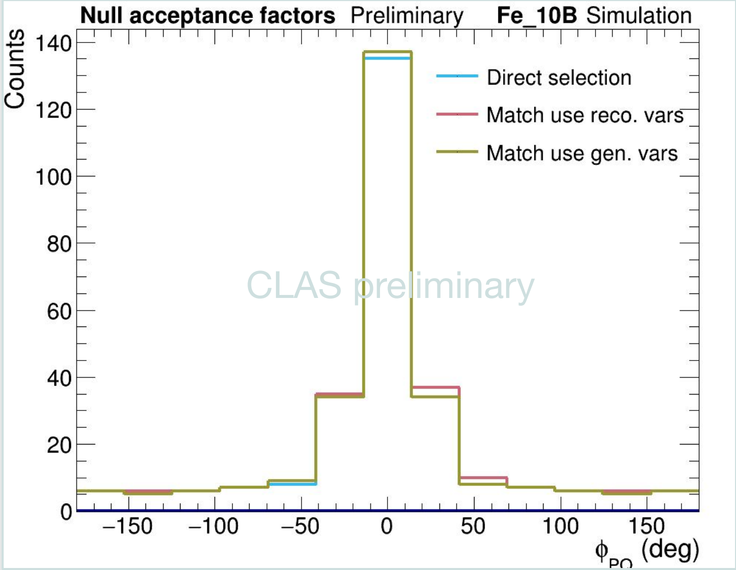
- Similar values as in Zh
  - Though closer to 1 (!)



Acceptance values

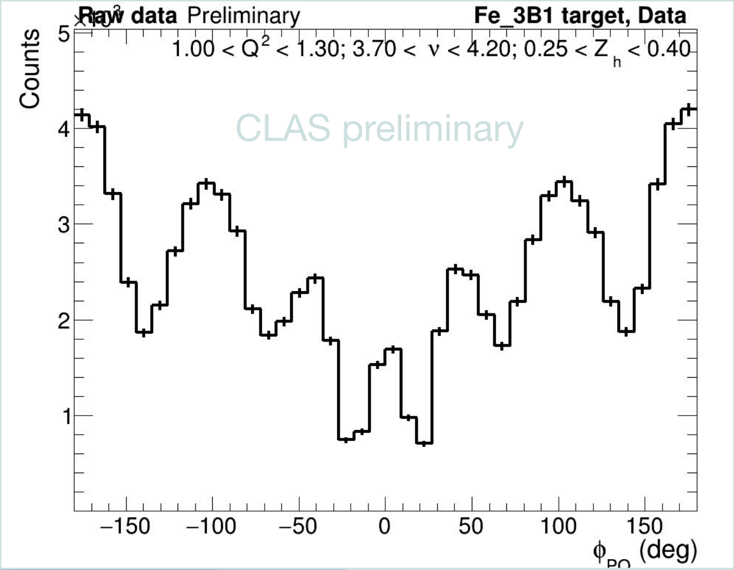
- Values obtained for Fe
- Single factors (left) and ϕ dependence of empty bins (right)

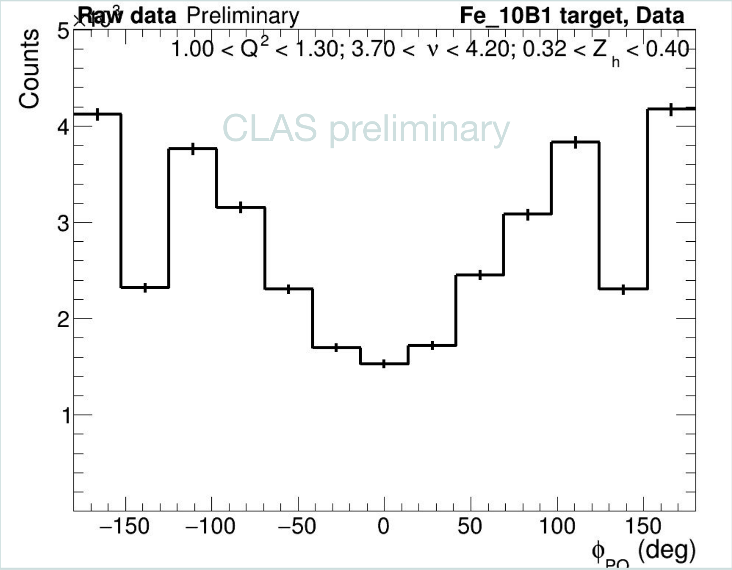




Binning selection

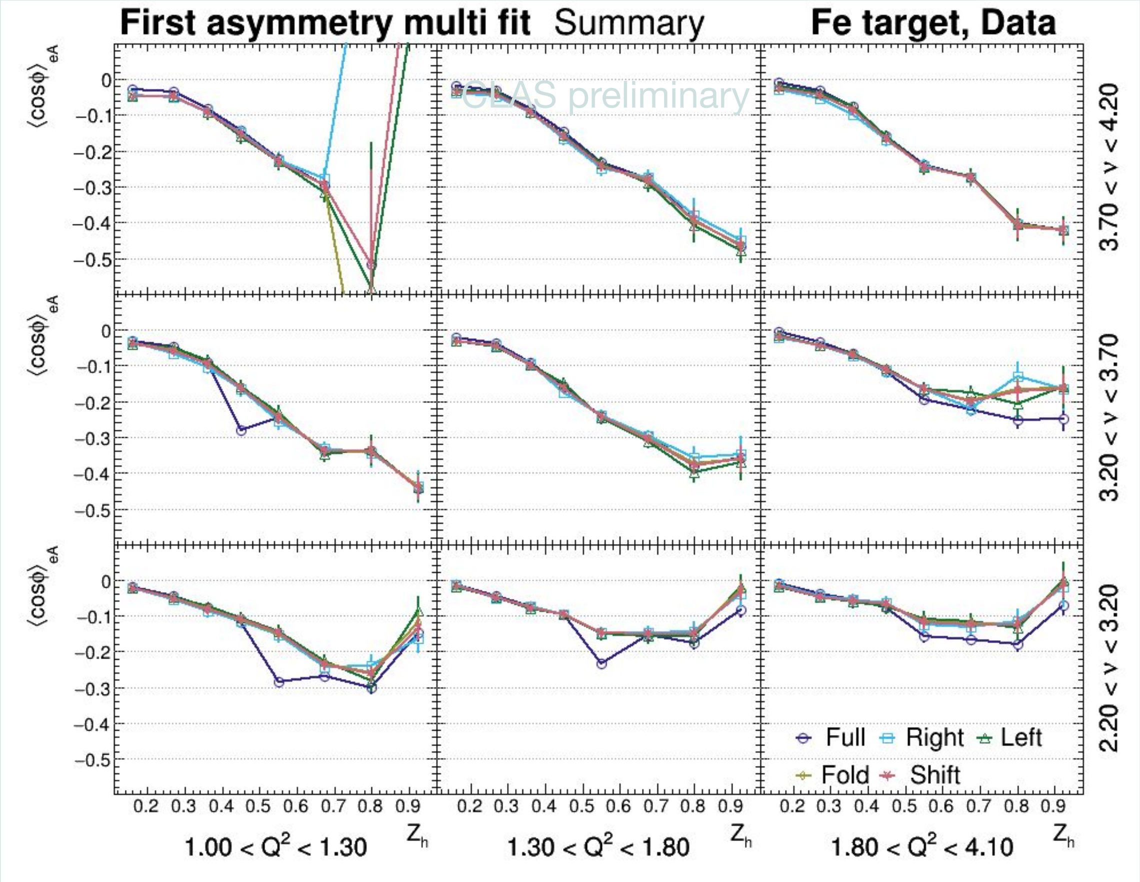
- Note the impact of the granularity (bin width) when dealing with several features



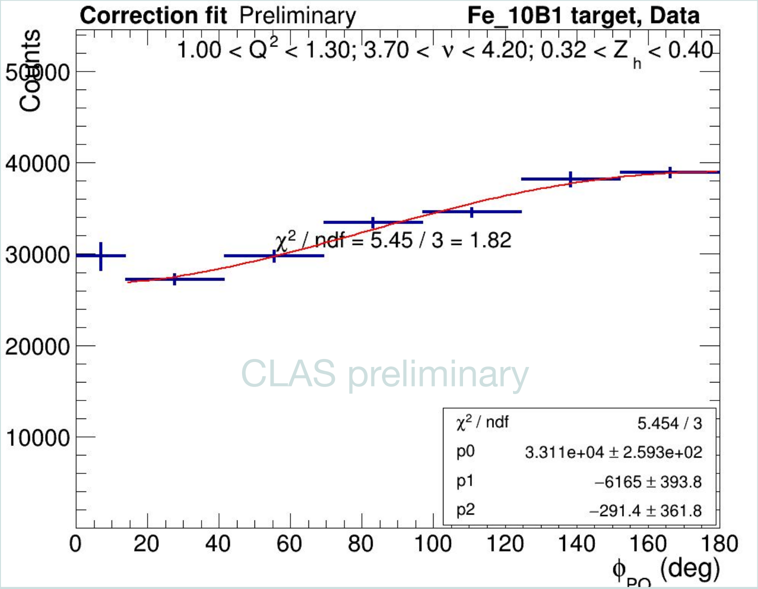


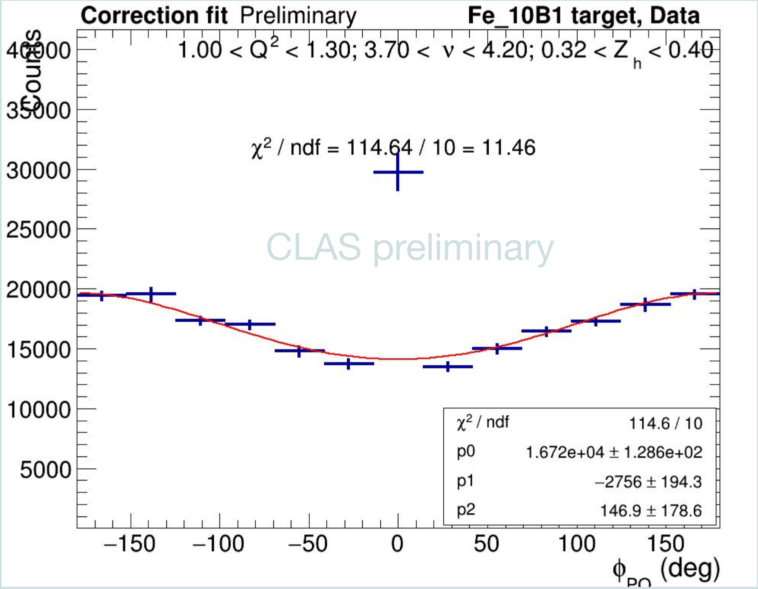
Fitting methods

- Different techniques were developed to skip the problematic section
  - Shift, Fold, Left and Right tails, Full fit
- In general, the peak produces effects at high Z_h

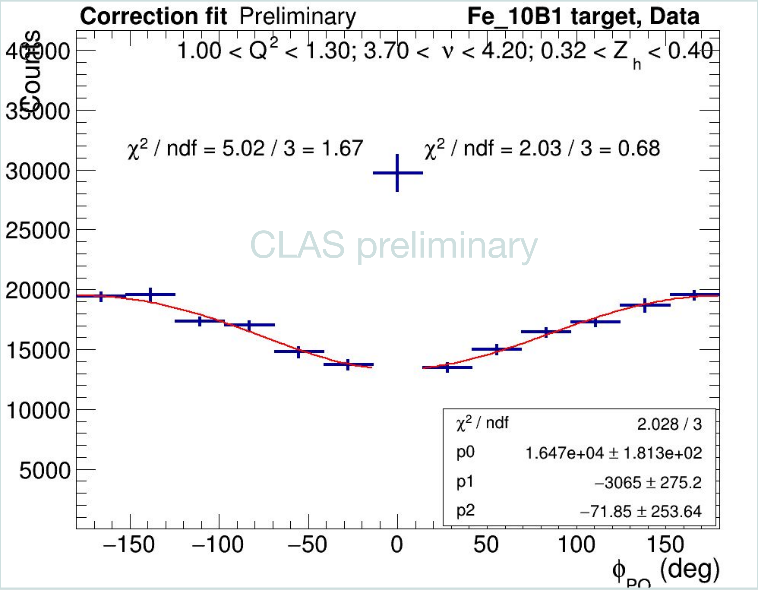


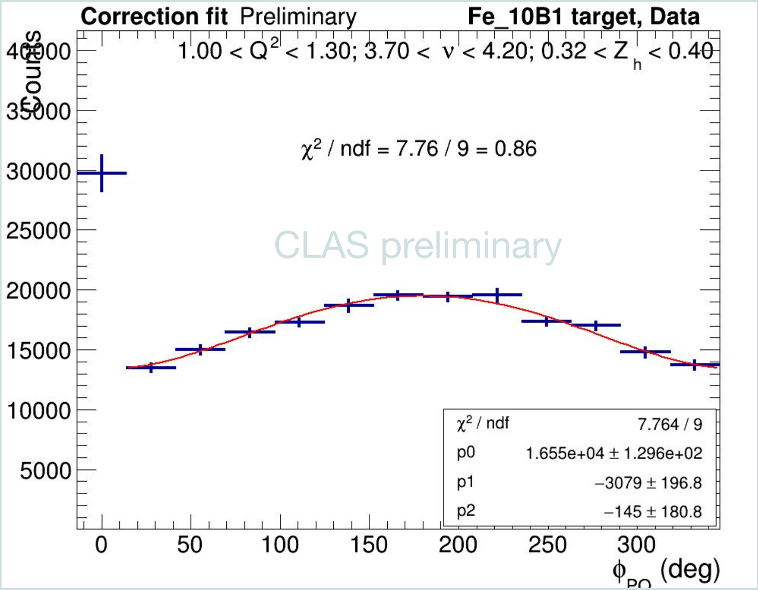
Fit methods: Fold and Full





Fit methods: Left/Right and Shift

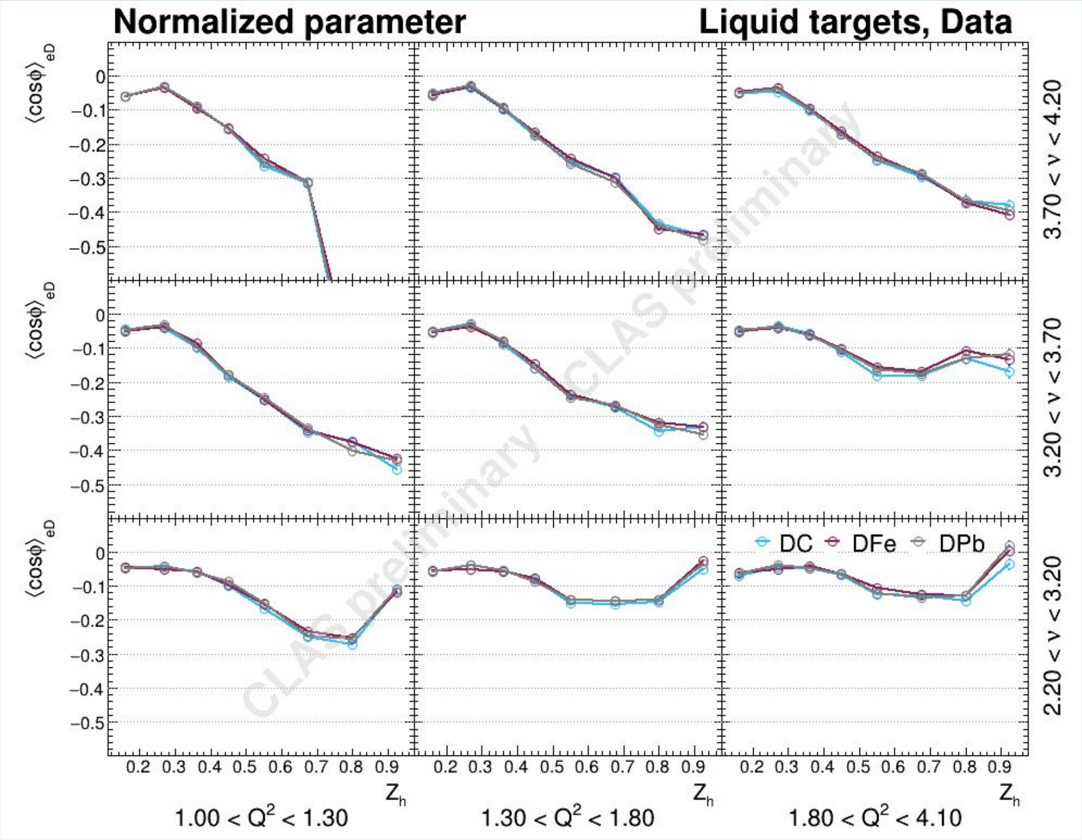




First asymmetry: Z_h dependence (all bins, liquid)

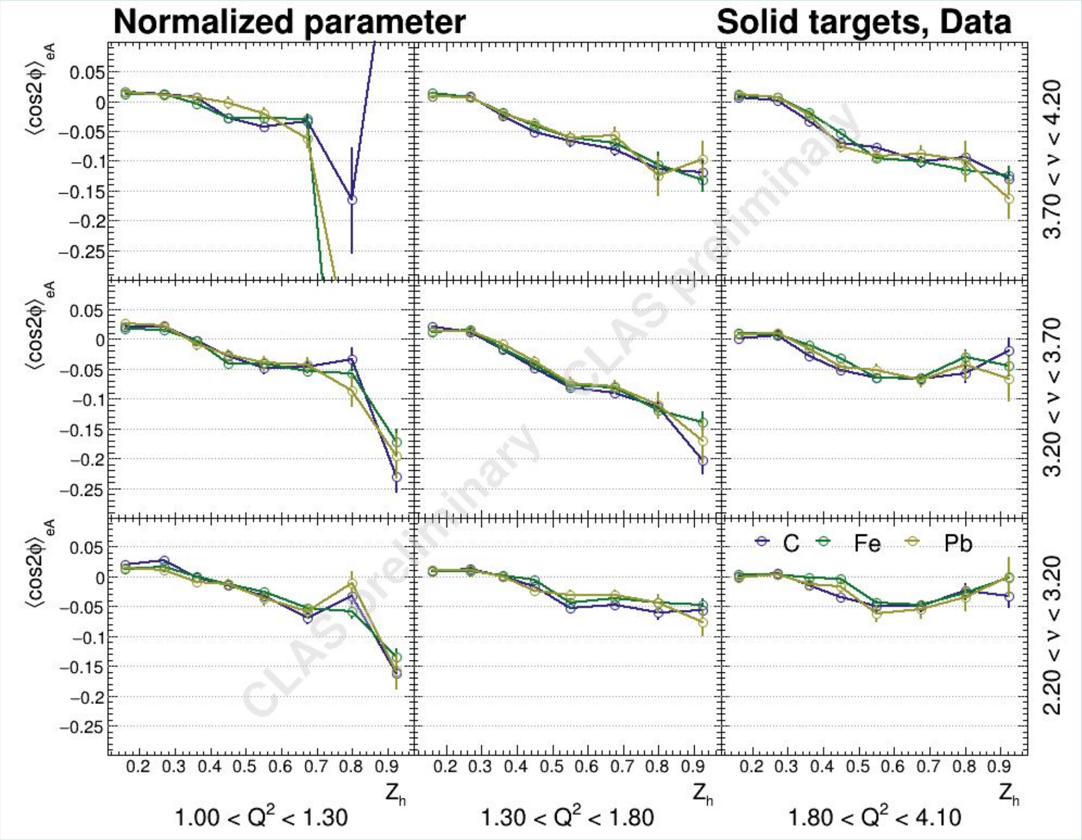
- Almost all bins present the same trend and got values within uncertainties

- The effect proves to be the same as in solid targets, at least qualitatively (!)



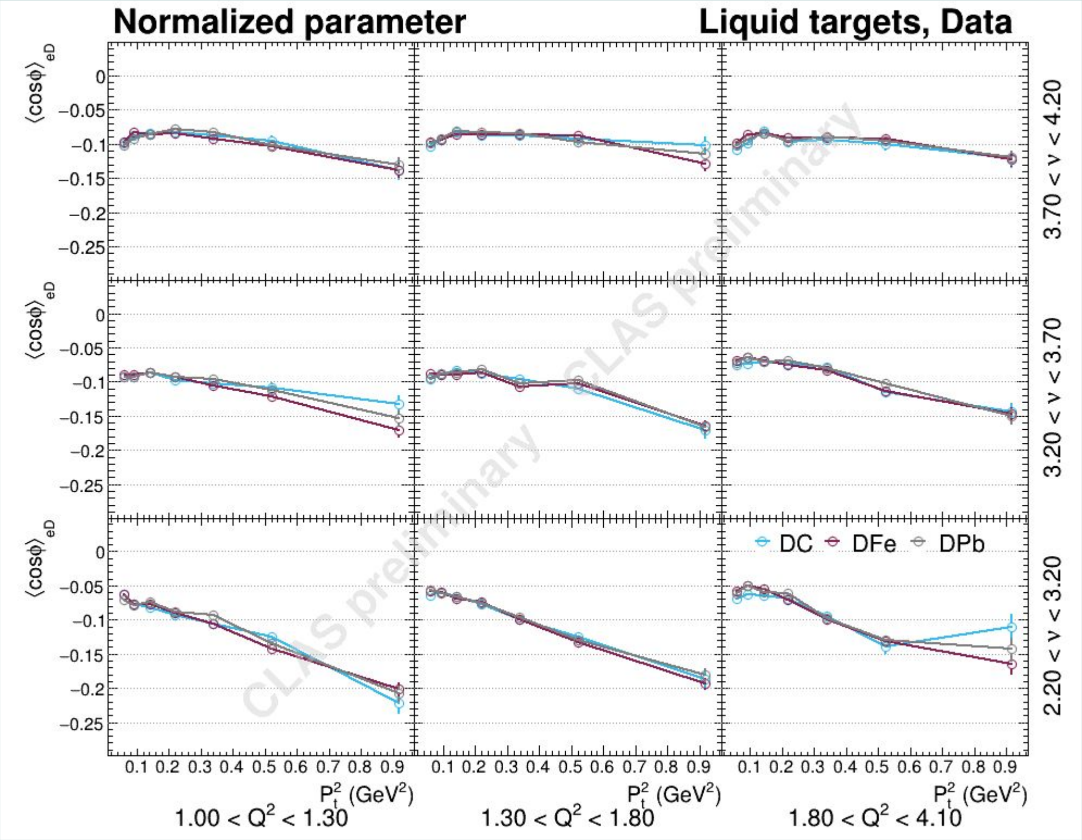
Second asymmetry (continued)

- Bigger uncertainties are found
- No strong leptonic dependency is reported

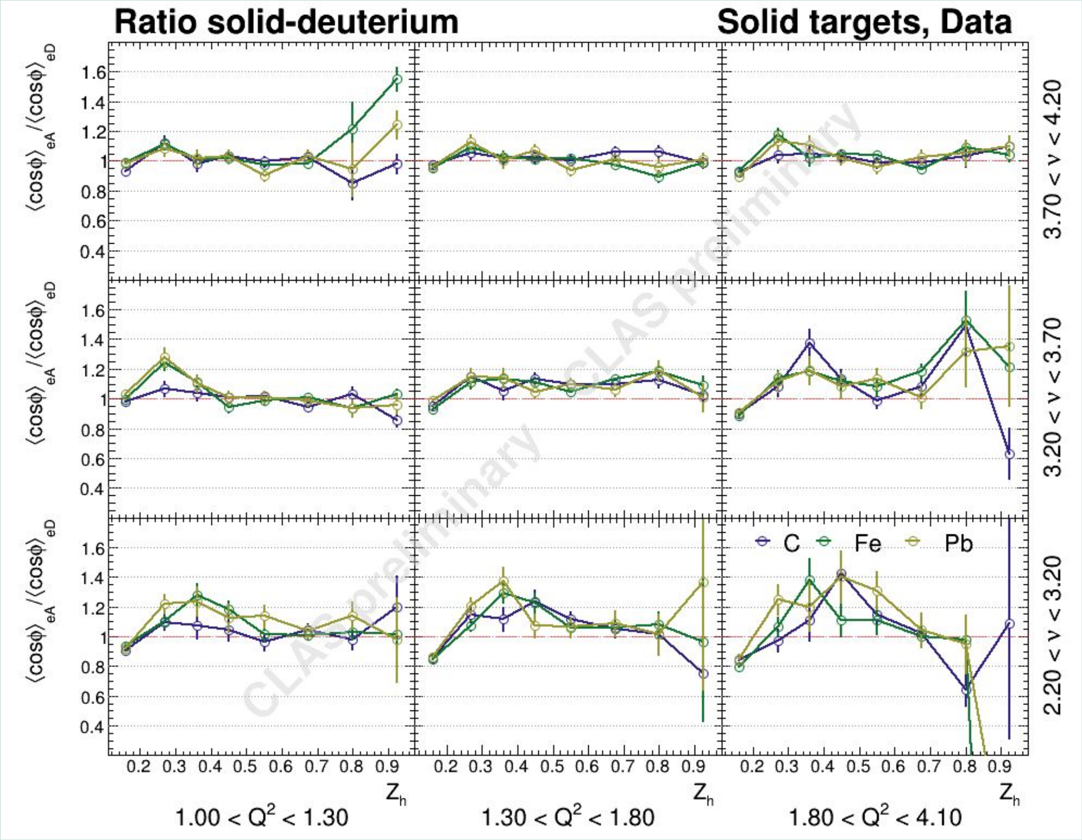


First asymmetry: P_t^2 dependence (all bins, liquid)

- Effect is consistently higher overall with respect to solid target
- Same trend of dependency is followed



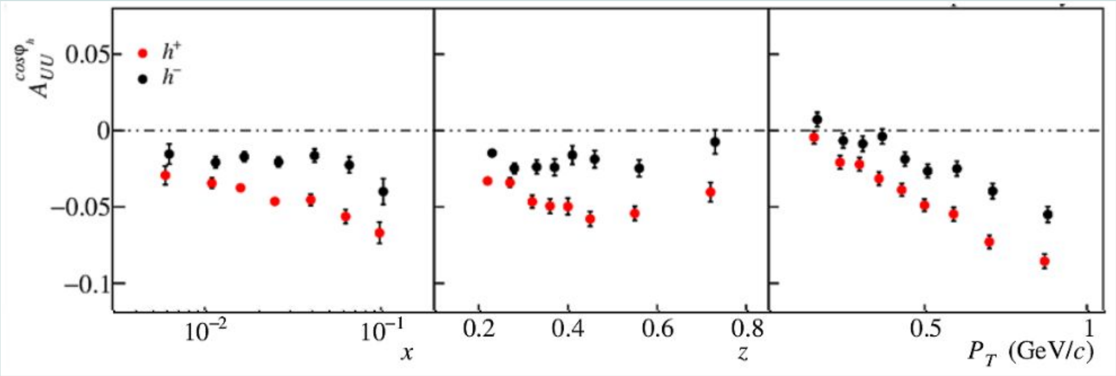
Effect of same sector events



- This could be regarded as an extreme limit
- The suppression of the possible nuclear hierarchy is evident

COMPASS first asymmetry*

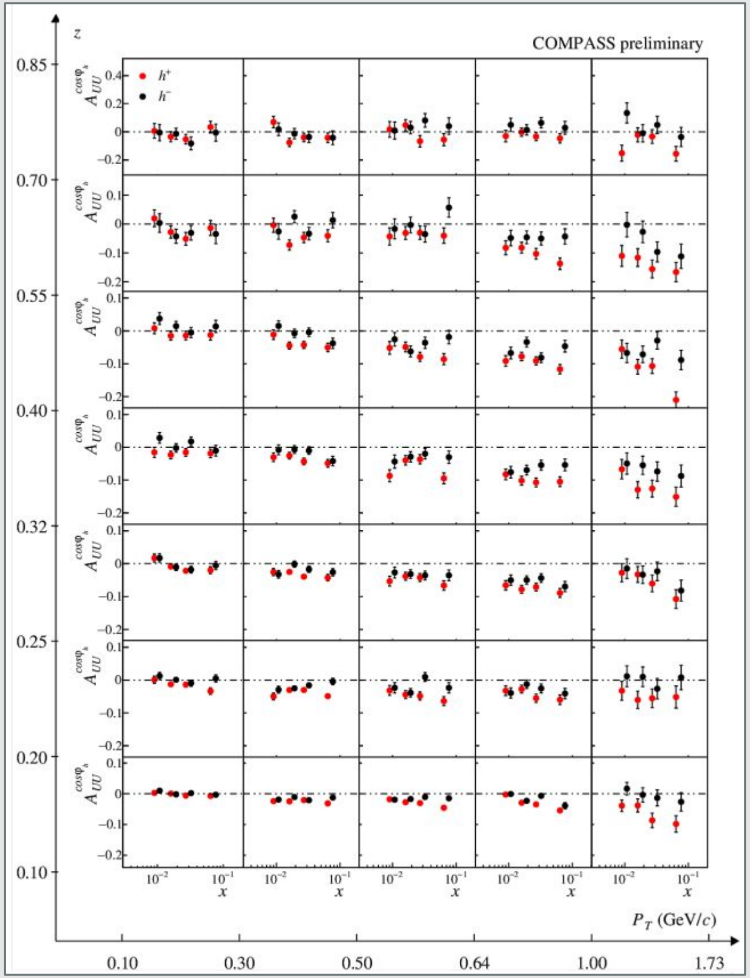
- Note the Pt tendency
- This is an integrated result (1D) so it's not directly compatible



* A. Moretti et al., 'TMD observables in unpolarised SIDIS at COMPASS', 2021. arXiv:2107.10740 [hep-ex].

COMPASS first asymmetry*

- This is a 3D result in bins of hadronic variables
  - Note small effect at low Pt in general!
  - Asymmetry increases at high Pt and xb



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