The Impact of Vector Meson Production on Multiplicities and Azimuthal Asymmetries in Unpolarised SIDIS

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(Un)polarised SIDIS: x-section, structure functions and TMDs

- SIDIS x-section at leading twist:

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_T^2} \propto (F_{UU,T} + \varepsilon F_{UU,T})$$

$$\Big\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h$$

$$+ S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL}$$

$$+ S_T \Big[A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S)$$

$$+ \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S)$$

$$+ \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \Big]$$

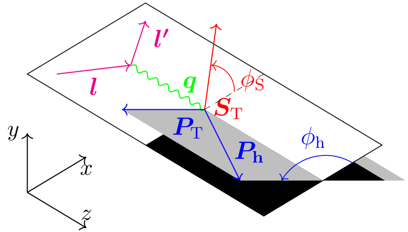
$$+ S_T \lambda \Big[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \Big] \Big\}$$

- Interpretation of $F_{XU}^{f(\phi_h)}$:

$$A_{XY}^{f(\phi_h)} \propto F_{XY}^{f(\phi_h)} = \mathscr{C}[w f D] =$$

$$x \sum_q e_q^2 \int d^2 k_T d^2 P_\perp \delta^{(2)}(z k_T + P_\perp - P_T)$$

$$w(k_T, P_\perp) f^q(x, k_T, Q^2) D^{q \to h}(z, P_\perp, Q^2)$$



(Un)polarised SIDIS: x-section, structure functions and TMDs

- Unpolarised SIDIS x-section at sub-leading twist:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}\phi_{\mathrm{h}}\mathrm{d}P_{\mathrm{T}}^2} \propto$$

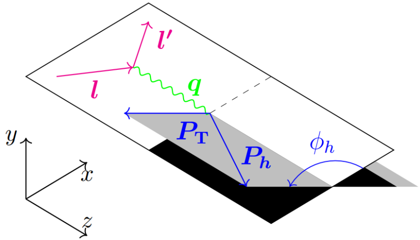
$$(F_{\mathrm{UU,T}} + \varepsilon F_{\mathrm{UU,T}})\Big\{1 + \varepsilon_1 A_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}} \cos\phi_{\mathrm{h}}$$

$$+ \varepsilon_2 A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}} \cos 2\phi_{\mathrm{h}} + \lambda\varepsilon_3 A_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}} \sin\phi_{\mathrm{h}}\Big\}$$

- Absence of cancellation of polarisation-independent effects, requiring dedicated corrections
- EMMI-RRTF focus: impact of background from DVMs

- Interpretation of $F_{\mathrm{XU}}^{f(\phi_{\mathrm{h}})}$:

$$A_{\mathrm{XY}}^{f(\phi_{\mathrm{h}})} \propto F_{\mathrm{XY}}^{f(\phi_{\mathrm{h}})} = \mathscr{C}[wfD] =$$
$$x\sum_q e_q^2 \int \mathrm{d}^2k_{\mathrm{T}}\mathrm{d}^2P_\perp \delta^{(2)}(zk_{\mathrm{T}} + P_\perp - P_{\mathrm{T}})$$
$$w(k_{\mathrm{T}}, P_\perp) f^q(x, k_{\mathrm{T}}, Q^2) D^{q\to h}(z, P_\perp, Q^2)$$



(Un)polarised SIDIS: x-section, structure functions and TMDs

- Unpolarised SIDIS x-section integrated over ϕ_h and normalised to the σ^{DIS}:

$$M^{\mathrm{h}^\pm}(x,Q^2,z,P_\mathrm{T}^2) \equiv \frac{\mathrm{d}\sigma^\mathrm{h}}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z\mathrm{d}P_\mathrm{T}^2} \Big/ \frac{\mathrm{d}\sigma^{\mathrm{DIS}}}{\mathrm{d}x\mathrm{d}Q^2}$$
$$= \frac{1}{\Delta P_\mathrm{T}^2 \Delta z}\frac{N^{\mathrm{h}^\pm}(x,Q^2,z,P_\mathrm{T}^2)}{N^{\mathrm{DIS}}(x,Q^2)}$$
$$\propto F_{\mathrm{UU}} = (F_{\mathrm{UU,T}} + \varepsilon F_{\mathrm{UU,T}})$$

- Absence of cancellation of polarisation-independent effects, requiring dedicated corrections
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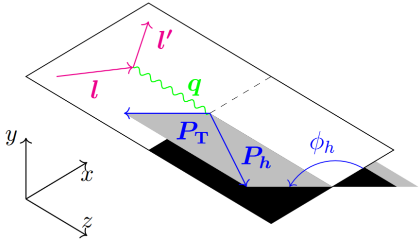
- Interpretation of $F_{\mathrm{XU}}^{f(\phi_\mathrm{h})}$:

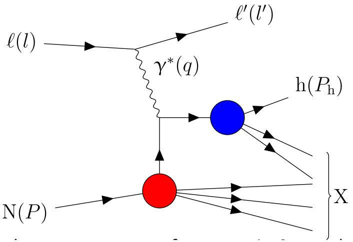
$$F_{\mathrm{XY}}^{f(\phi_\mathrm{h})} = \mathscr{C}[wfD] =$$
$$x\sum_q e_q^2 \int \mathrm{d}^2k_\mathrm{T}\mathrm{d}^2P_\perp \delta^{(2)}(zk_\mathrm{T}+P_\perp - P_\mathrm{T})$$
$$w(k_\mathrm{T},P_\perp) f^q(x,k_\mathrm{T},Q^2) D^{q\to h}(z,P_\perp,Q^2)$$



SIDIS event selection

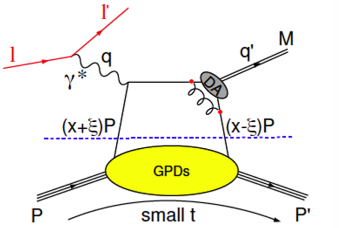
- Kinematical requirements:

$$0.2 < y < 0.9 \qquad 0.003 < x < 0.130$$
$$0.1\ \mathrm{GeV}/c < P_{\mathrm{T}} < 1.0\ \mathrm{GeV}/c \qquad W > 5\ \mathrm{GeV}/c^2$$
$$0.2 < z < 0.85 \qquad Q^2 > 1\ \mathrm{GeV}^2/c^2$$



- BUT Exclusive processes may satisfy those requirements as well
- Problem: mesons produced in exclusive processes decaying into charged hadrons

$$\mu \mathrm{N} \to \mu' \mathrm{V} \mathrm{N}' \quad \text{followed by} \quad \mathrm{V} \to \mathrm{h}^+\mathrm{h}^-$$



- Non-negligible contributors: $\rho \to \pi^+\pi^-$ and $\phi \to K^+K^-$

Looking for hadrons from DVMs in the visible pairs

- ρ and ϕ mesons visible in invariant mass distributions of candidates for exclusive processes:

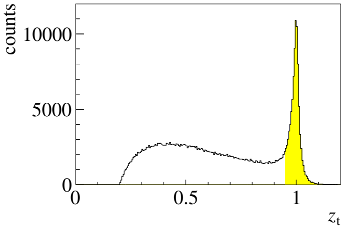
→ hadrons from an event with only 2 oppositely charged hadrons in the final state

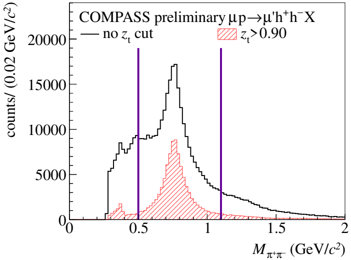
→ additional requirement on exclusivity of the process: $z_\mathrm{t} = z_{\mathrm{h}^+} + z_{\mathrm{h}^-} > 0.9$

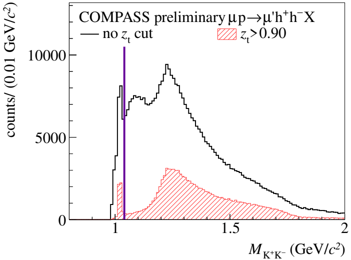
→ Peaks for ρ and ϕ nicely visible in the measured data, limits used for further analyses:

$\rho \to \pi^+\pi^-$: $M_{\mathrm{K}^+\mathrm{K}^-} \in [1.04, \infty]$ GeV/c^2
and $M_{\pi^+\pi^-} \in [0.5, 1.1]$ GeV/c^2

$\phi \to \mathrm{K}^+\mathrm{K}^-$: $M_{\mathrm{K}^+\mathrm{K}^-} \in [0, 1.04]$ GeV/c^2







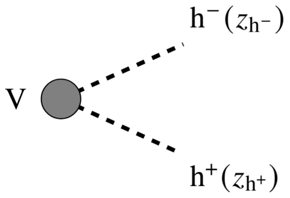
Visible and invisible hadrons from decays of DVMs

- Current approach used for analysis of **2016 data**

→ excluding hadrons from DVMs from analysis in 2 steps:

- **visible hadron pairs**
  - both hadrons reconstructed
  - rejected using:

$$\boxed{z_{\mathrm{t}} = z_{\mathrm{h}^+} + z_{\mathrm{h}^-} < 0.9}$$



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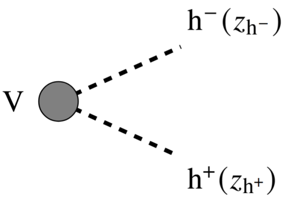
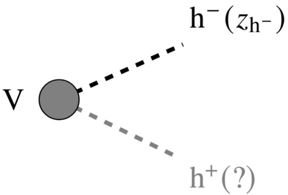


- **invisible hadrons**
  - 1 hadron reconstructed
  - determination of z_t not possible

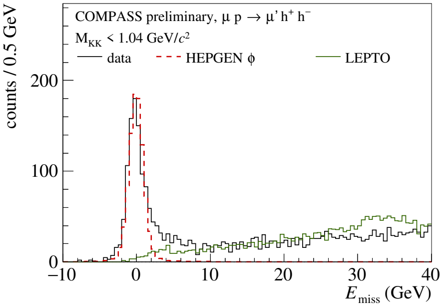
subtracted using HEPGEN MC

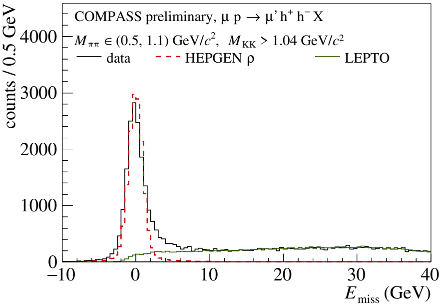


HEPGEN normalisation: how much to subtract?

- Normalization of HEPGEN is estimated using E_{miss} distributions of **visible hadron pairs**

$$E_{\text{miss}} = \frac{M_X^2 - M_p^2}{2M_p} \qquad M_X^2 = (p + q - P_{h^+} - P_{h^-})^2$$





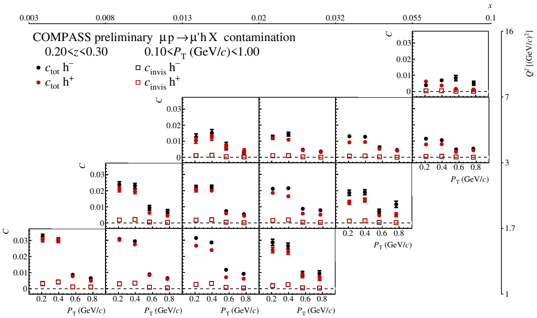
- HEPGEN is normalised to the size of the peak in E_{miss} for measured data minus LEPTO

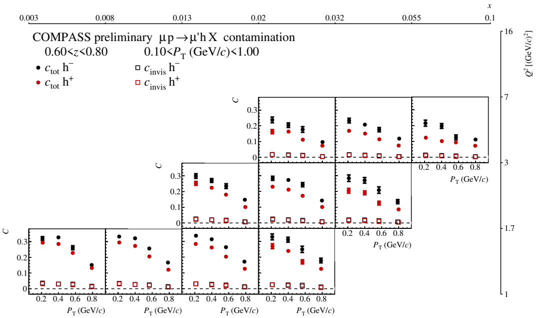
Affected kinematical regions

- Determined mainly by contamination:

$$c_{\text{tot}} = \frac{N_{\text{h}}^{\text{visible}} + N_{\text{h}}^{\text{invisible}}}{N_{\text{h}}^{\text{total}}} \quad \text{and} \quad c_{\text{invis}} = \frac{N_{\text{h}}^{\text{invisible}}}{N_{\text{h}}^{\text{total}}},$$

$$\text{where} \quad N_{\text{h}}^{\text{total}} = N_{\text{h}}^{\text{visible}} + N_{\text{h}}^{\text{invisible}} + N_{\text{h}}^{\text{true SIDIS}}$$

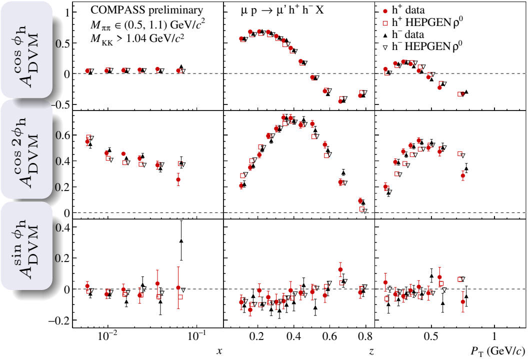


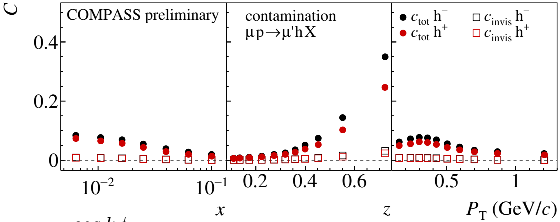


Affected kinematical regions

- In case of azimuthal asymmetries, also the size of the modulations of hadrons from decay of DVMs plays key role (obtained by assuming SIDIS x-section)

$$\frac{\mathrm{d}\sigma^{\mathrm{hDVM}}}{\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}\phi_{\mathrm{h}}\mathrm{d}P_{\mathrm{T}}^{2}} \propto \sigma_0 \left\{ 1 + \varepsilon_1 A_{\mathrm{DVM}}^{\cos\phi_{\mathrm{h}}} \cos\phi_{\mathrm{h}} + \varepsilon_2 A_{\mathrm{DVM}}^{\cos 2\phi_{\mathrm{h}}} \cos 2\phi_{\mathrm{h}} + \lambda\varepsilon_3 A_{\mathrm{DVM}}^{\sin\phi_{\mathrm{h}}} \sin\phi_{\mathrm{h}} \right\}$$





→ $A_{\mathrm{DVM}}^{\cos k\phi_{\mathrm{h}}}$ are large, well represented by HEPGEN MC

→ Large contamination cannot be avoided only by $z < 0.8$

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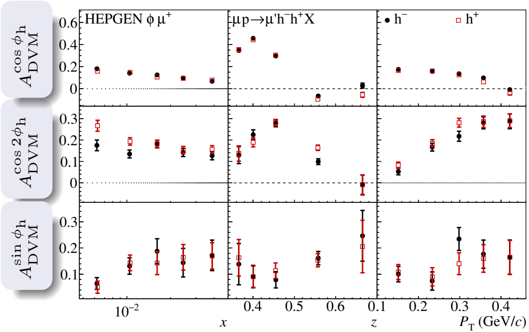
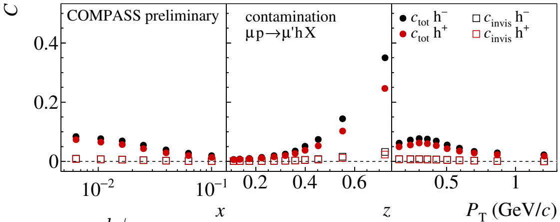
$$\frac{d\sigma^{\mathrm{hDVM}}}{dx\,dy\,dz\,d\phi_{\mathrm{h}}\,dP_{\mathrm{T}}^2} \propto \sigma_0 \left\{ 1 + \varepsilon_1 A_{\mathrm{DVM}}^{\cos\phi_{\mathrm{h}}} \cos\phi_{\mathrm{h}} + \varepsilon_2 A_{\mathrm{DVM}}^{\cos 2\phi_{\mathrm{h}}} \cos 2\phi_{\mathrm{h}} + \lambda\varepsilon_3 A_{\mathrm{DVM}}^{\sin\phi_{\mathrm{h}}} \sin\phi_{\mathrm{h}} \right\}$$



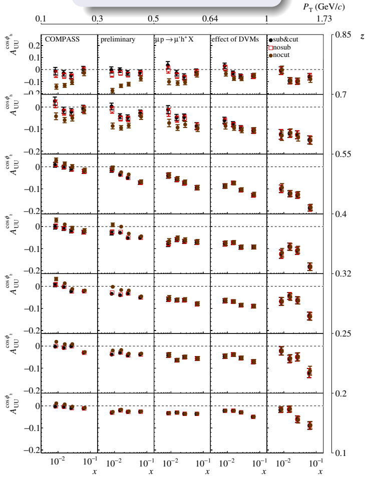


→ $A_{\mathrm{DVM}}^{\cos k\phi_{\mathrm{h}}}$ are large, well represented by HEPGEN MC

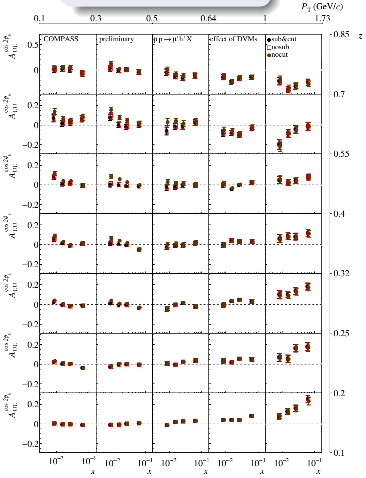
→ Large contamination cannot be avoided only by $z < 0.8$

Effect of background treatment on 3D $A_{\mathrm{XY}}^{f(\phi_\mathrm{h})}$: h$^+$

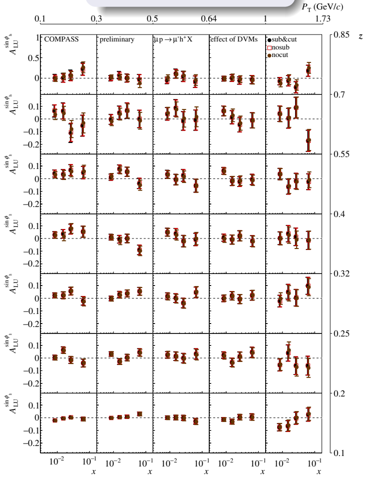
$A_{\mathbf{UU}}^{\cos\phi_\mathrm{h}}$



$A_{\mathbf{UU}}^{\cos 2\phi_\mathrm{h}}$

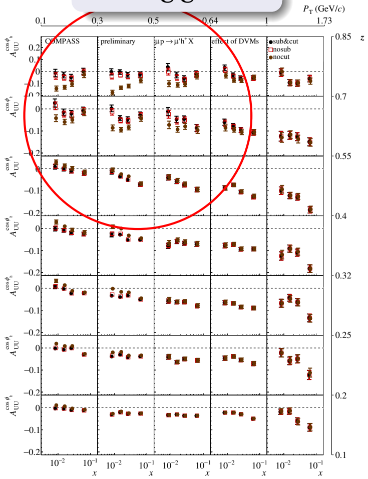


$A_{\mathbf{LU}}^{\sin\phi_\mathrm{h}}$

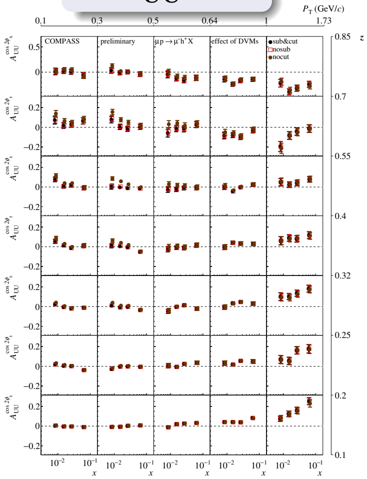


Effect of background treatment on 3D $A_{XY}^{f(\phi_h)}$: h$^+$

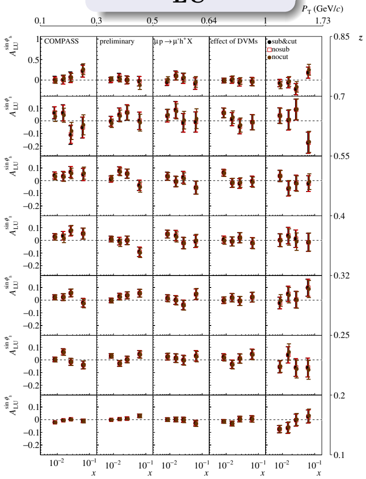
$A_{UU}^{\cos\phi_h}$



$A_{UU}^{\cos 2\phi_h}$

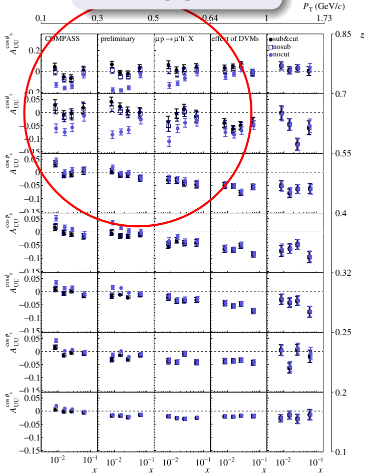


$A_{LU}^{\sin\phi_h}$

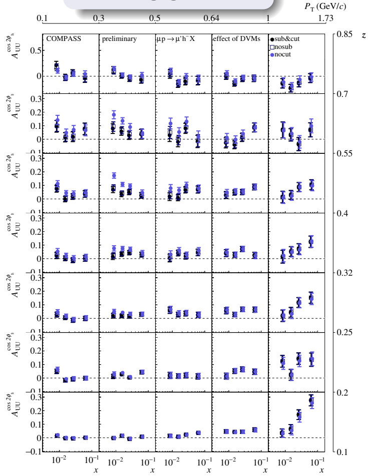


Effect of background treatment on 3D $A_{\mathrm{XY}}^{f(\phi_h)}$: h^-

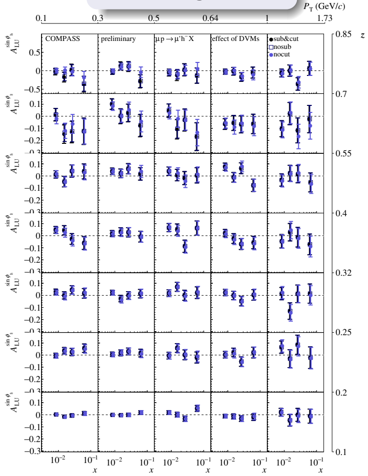
$A_{\mathbf{UU}}^{\cos\phi_h}$



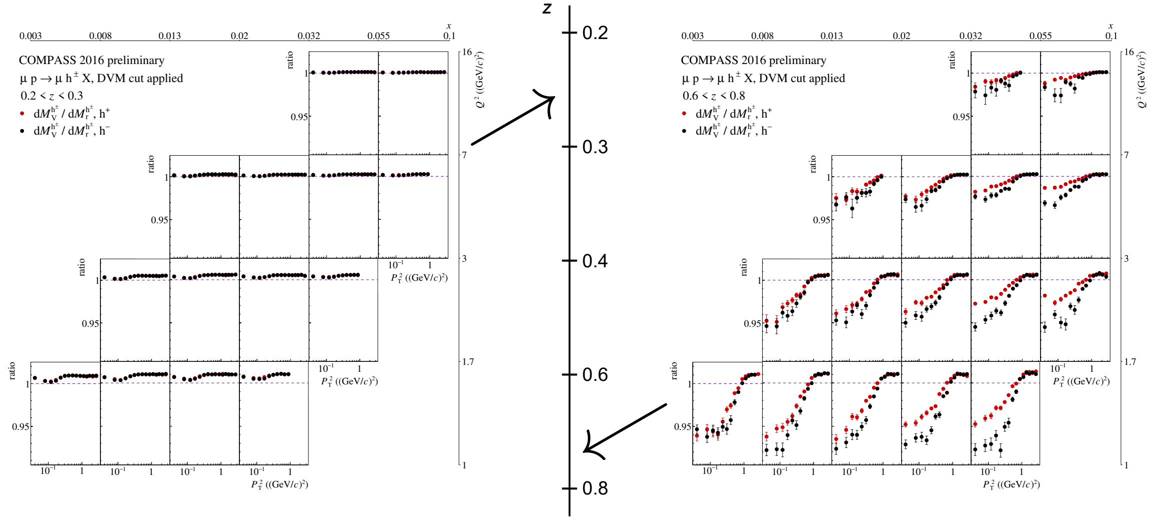
$A_{\mathbf{UU}}^{\cos 2\phi_h}$



$A_{\mathbf{LU}}^{\sin\phi_h}$



Effect of background **subtraction** on $M^{\mathrm{h}^\pm}$ (1st and last z bin)



History of treatment of DVMs as background to SIDIS

- First unpolarised measurements published without **any treatment of DVMs**:
  - **Azimuthal asymmetries from 2006 data** [NPB 886 (2014) 1046-1077]
  - **$P_{\mathbf{T}}^2$-dependent multiplicities from 2004 data** [EPJC 73 (2013) 8, 2531]
- Around 2017, the impact of DVMs was found to be bigger than initially expected

→ **$P_{\mathbf{T}}^2$-dependent multiplicities from 2006 data** [PRD 97 (2018) 032006] already account for contamination of DVMs by employing **HEPGEN-based multiplicative correction**:

$$\frac{C_{\mathrm{h}}}{C_{\mathrm{DIS}}} \propto \frac{1 - c_{\mathrm{tot}}}{1 - c_{\mathrm{tot,DIS}}} \qquad \text{(simplified expression)}$$

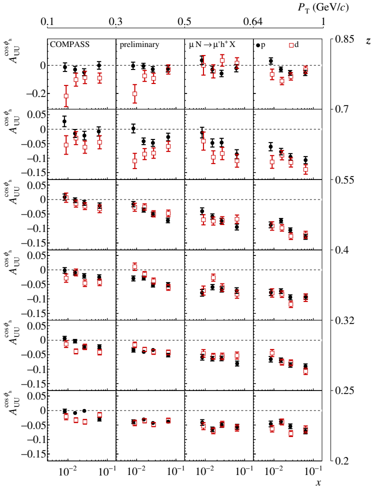
→ **Ad-hoc HEPGEN-based correction** of azimuthal asymmetries evaluated using contamination and $A_{\mathrm{DVM}}^{\cos k\phi_{\mathrm{h}}}$

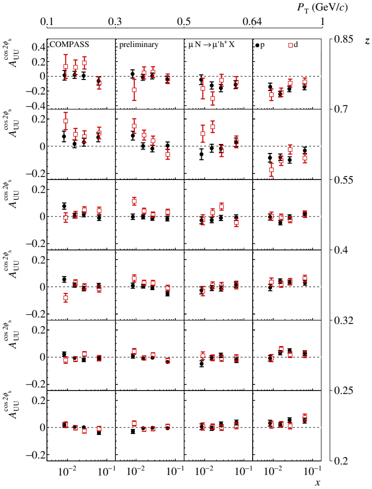
$$A_{\mathrm{UU}}^{\cos k\phi_{\mathrm{h}}} = \frac{1}{1 - c_{\mathrm{tot}}} \left(A_{\mathrm{UU,uncor}}^{\cos k\phi_{\mathrm{h}}} - \frac{c_{\mathrm{tot}}}{\varepsilon_k} A^{\cos k\phi_{\mathrm{h}}} \right) \qquad k \in \{1, 2\}$$

→ Updated paper with corrected results for 2004 azimuthal asymmetries off isoscalar target [NPB 956 (2020) 115039]

Comparison of proton and isoscalar target in 3D h$^+$

- Comparison with COMPASS results on isoscalar target [NPB201407 019] (both no RC)





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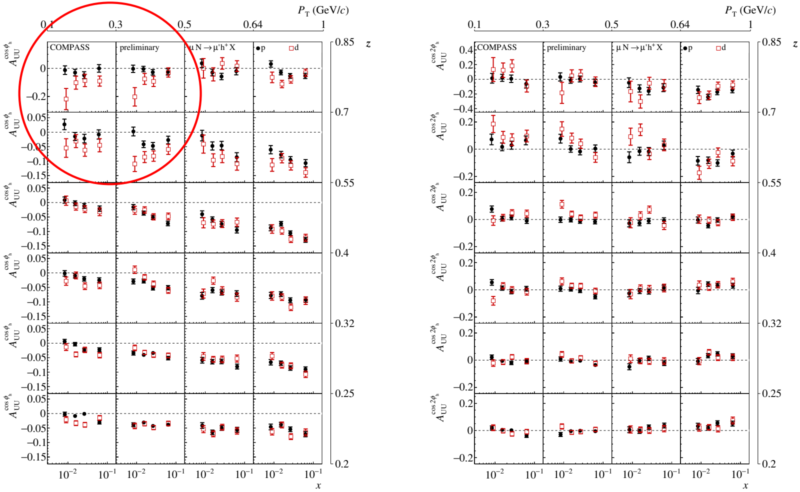
- Difference at high z and low P_T hinting flavour dependence



Comparison of proton and isoscalar target in 3D h^-

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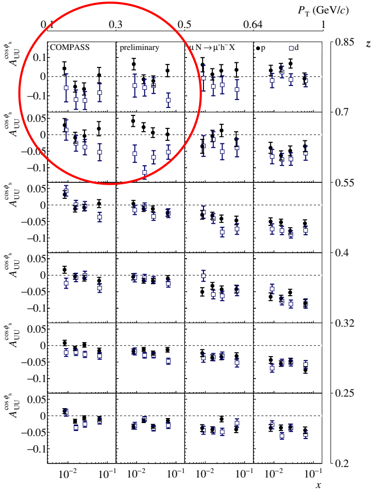
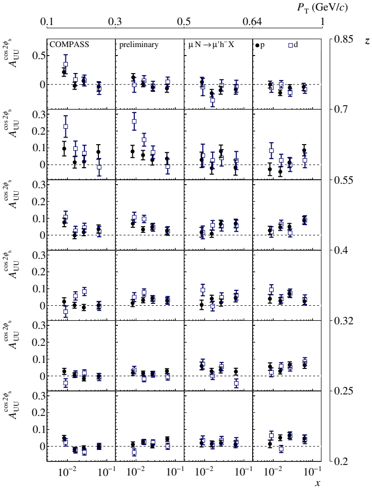
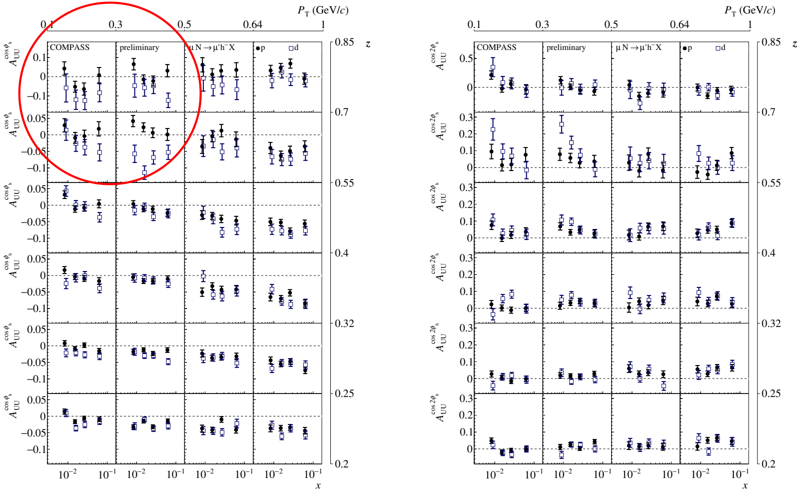




Comparison of proton and isoscalar target in 3D h^-

- Comparison with COMPASS results on isoscalar target [NPB201407 019] (both no RC)
- BUT: High z and low P_T is the region of the biggest effect of the correction



Summary and conclusions

The impact of DVMs on current analyses

- Most of the background removed by cutting off the exclusive peak ($z_{h^+} + z_{h^-} < 0.9$)
- Agreement between data and HEPGEN MC, which has SDMEs measured on COMPASS plugged in
- Only a small correction is done by subtraction of HEPGEN MC
- Q^2 dependence of SDMEs included in systematics
- Analyses with this approach have not been published yet (will be soon!)

The impact on older results

- First results accounted for DVMs only by employing upper limit on z
- Ad-hoc corrections are large and carry large systematics

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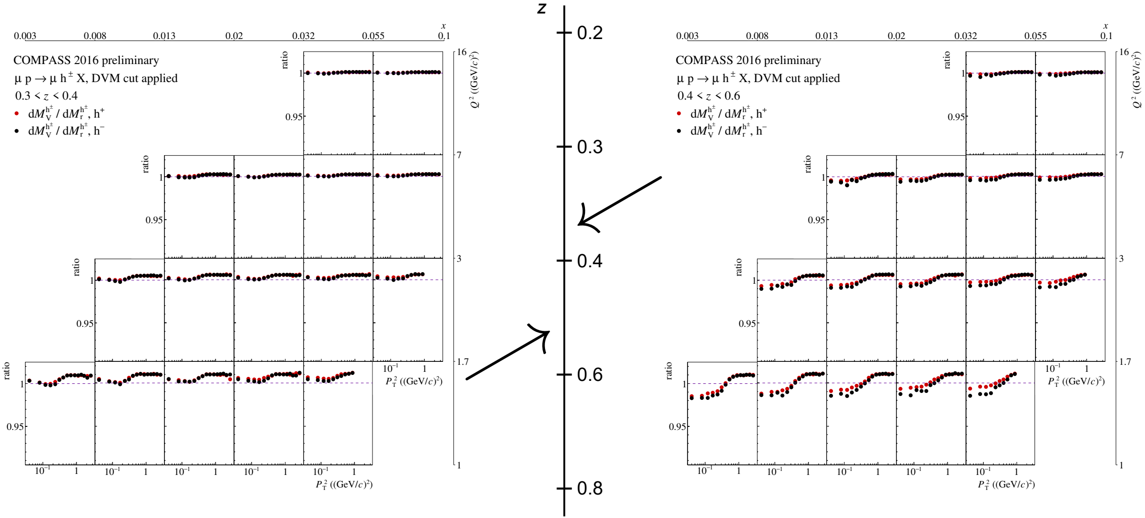
Thank you for your attention!

Backup

Effect of background subtraction on $M^{\mathrm{h}^{\pm}}$ (2nd and 3rd z bin)



Systematics from the ρ polarization

- Contribution arise from the difference in z-range used in the analysis and for the normalisation $f(z)$ and from $R_{\text{HEPGEN}}(Q^2) = 1 \neq R_{\text{DATA}}$:

$$\sigma = |A_{\text{DVM}}^{f(\phi_{\text{h}})} - A_{\text{XU}}^{f(\phi_{\text{h}})}| \cdot c_{\text{inv}} \cdot |a-1| \qquad a = \frac{\displaystyle\int_{z_a}^{z_b} f_{\text{DATA}}(z)\,\mathrm{d}z}{\displaystyle\int_{z_m}^{z_M} f_{\text{DATA}}(z)\,\mathrm{d}z} \cdot \frac{\displaystyle\int_{z_m}^{z_M} f_{\text{HEPGEN}}(z)\,\mathrm{d}z}{\displaystyle\int_{z_a}^{z_b} f_{\text{HEPGEN}}(z)\,\mathrm{d}z}$$

$$f(z) = 1 + (2R-1)\,(2z-1)^2$$

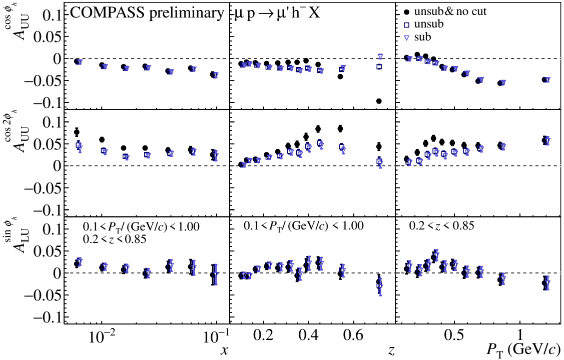
$$R \approx \frac{r_{00}^{04}}{1-r_{00}^{04}} \qquad R_{\text{DATA}} \approx 0.62 \cdot \langle Q^2 \rangle^{0.76} \qquad R_{\text{HEPGEN}} = 1$$

- z_a z_b given by kinematical bin limits, if no z binning $z_a = 0.2$ $z_b = 0.85$
- z_m z_M – given by range for normalization: $z_m = 0.1 \quad z_M = 1$
- Contribution from ρ polarisation is mostly small in comparison to other sources

Effect of background treatment on 1D $A_{\mathrm{XY}}^{f(\phi_{\mathrm{h}})}$: $\mathrm{h}^{\pm}$

- The background of hadrons from DVM decays has a significant impact on the results
- Most of the correction is due to the cut on z_{t}

negative hadrons



positive hadrons