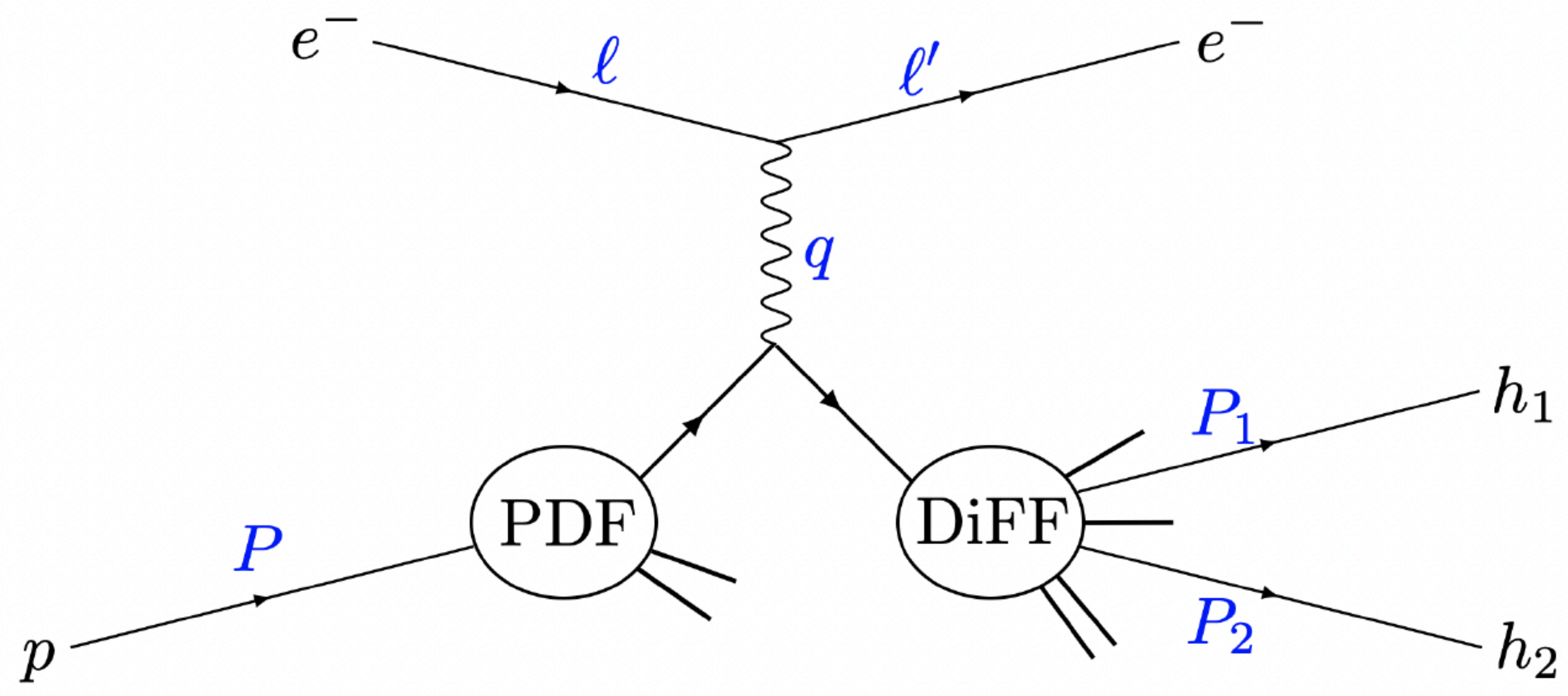
$\pi^+\pi^-$ dihadron asymmetries from RG-C



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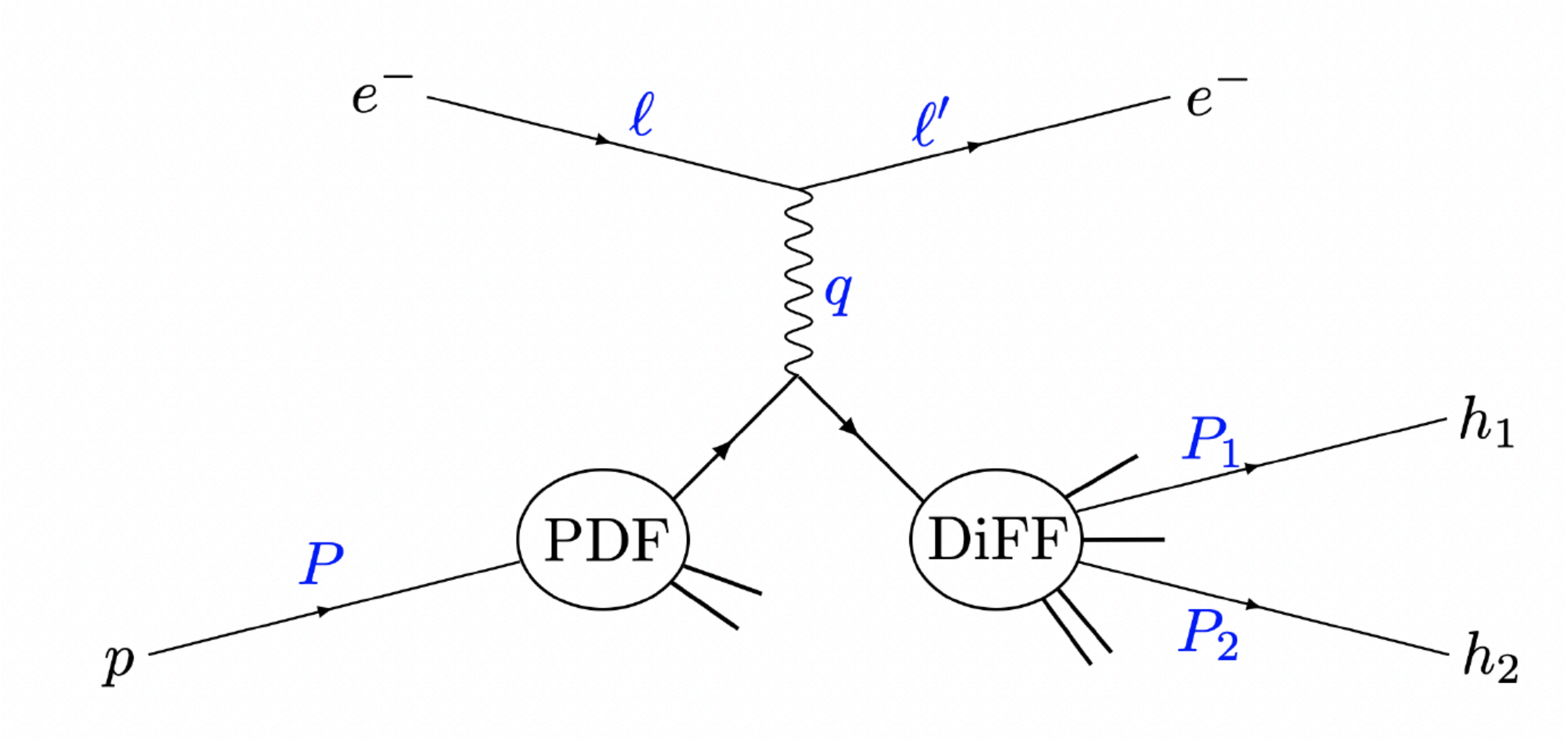
Collaboration Meeting

03/11/2026

Dihadron SIDIS



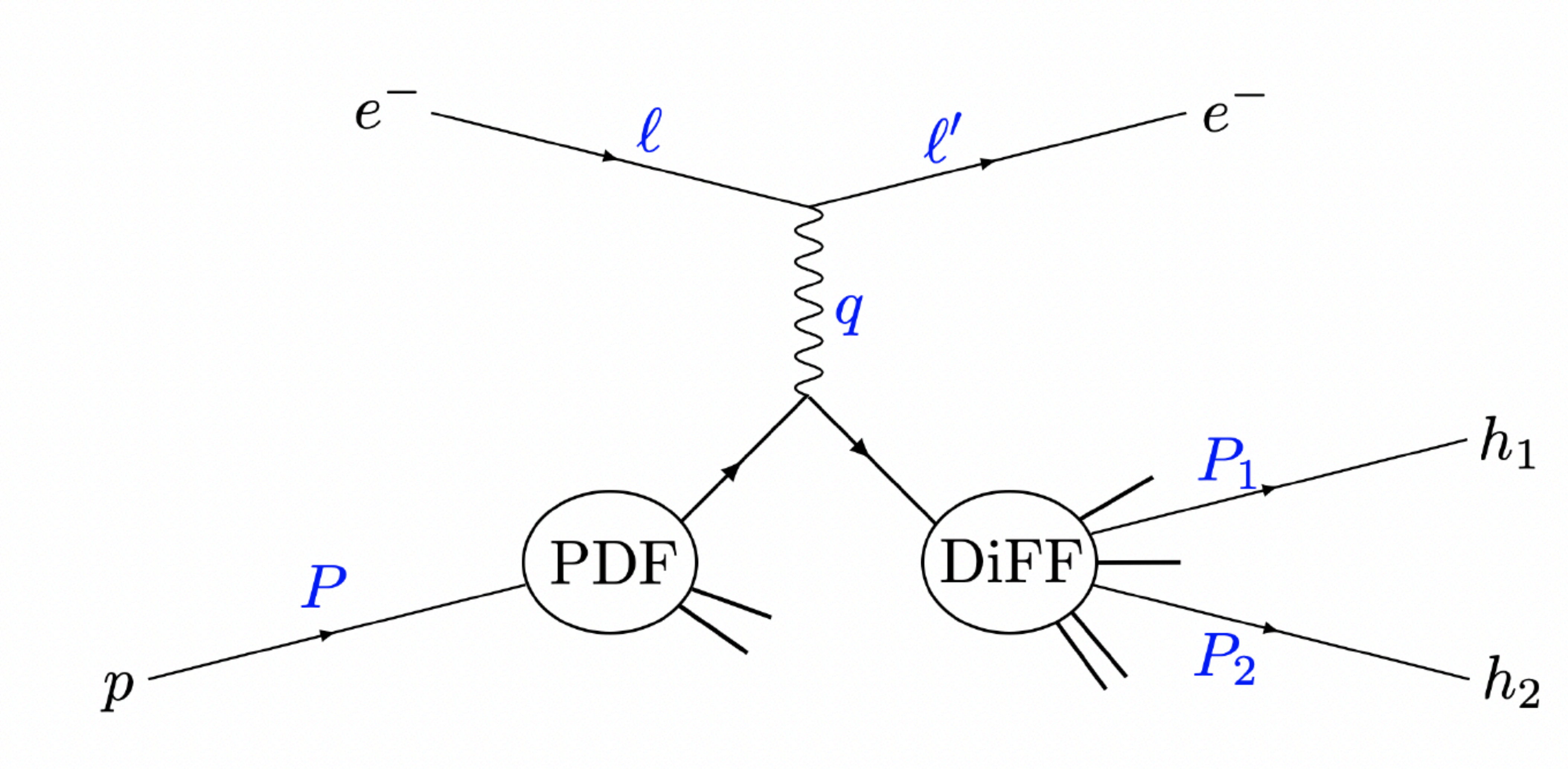
[1]

- In the dihadron SIDIS we detect two hadrons in the final state

$$e^- p \to e^- h_1 h_2 X$$

- Dihadron fragmentation function (DIFF) provide information on how the struck quark produces two hadrons
- Relative angular momentum between two hadrons provide more information on hadronization compared to single hadron case
    - Quark transverse momentum - angular momentum correlations
    - Access more structure functions

Dihadron kinematics



- Dihadron momentum is defined as sum of momenta of two hadrons

$$P_h = P_1 + P_2$$

M_h - dihadron mass

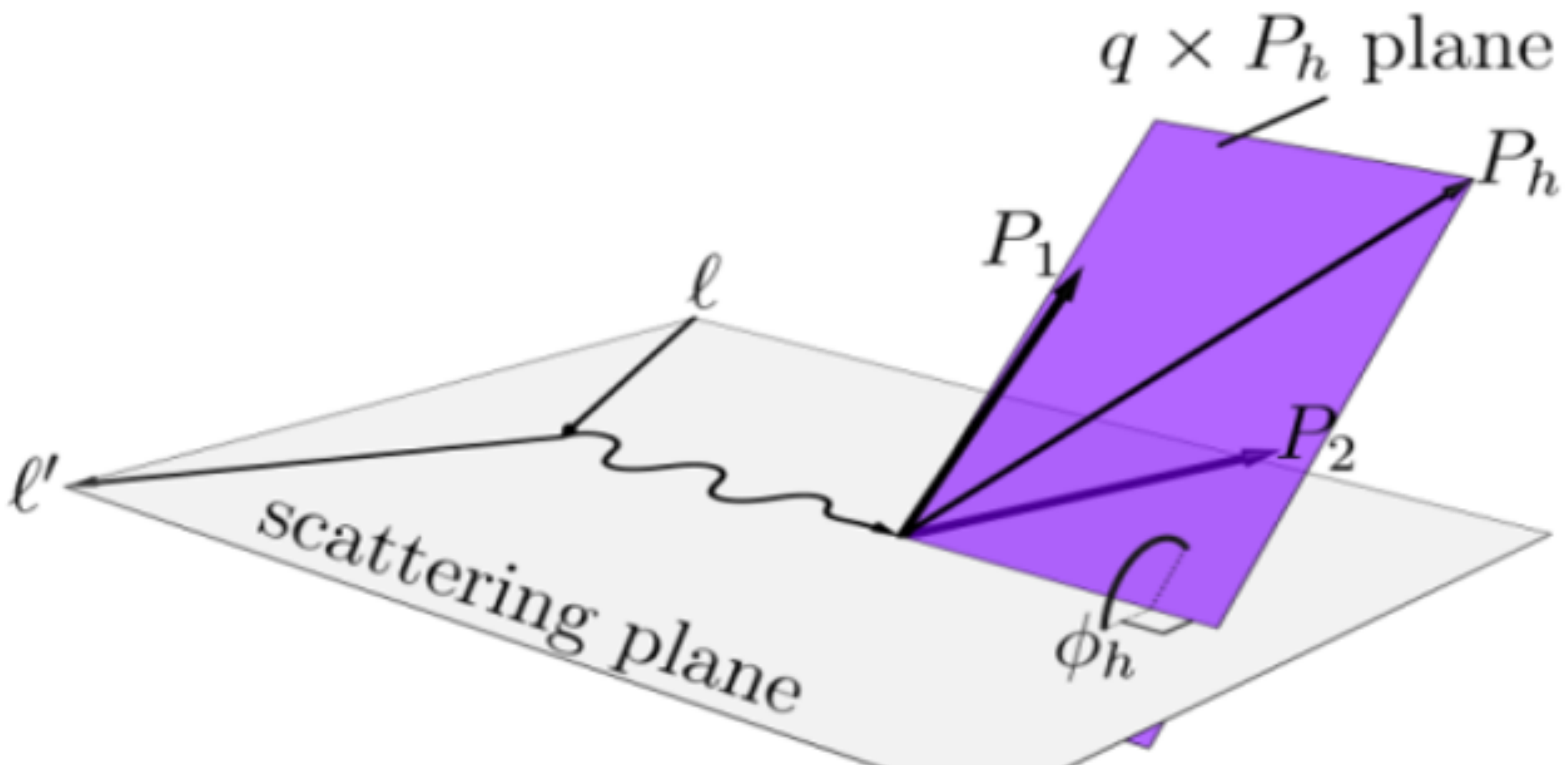
- Fractional energy of dihadron

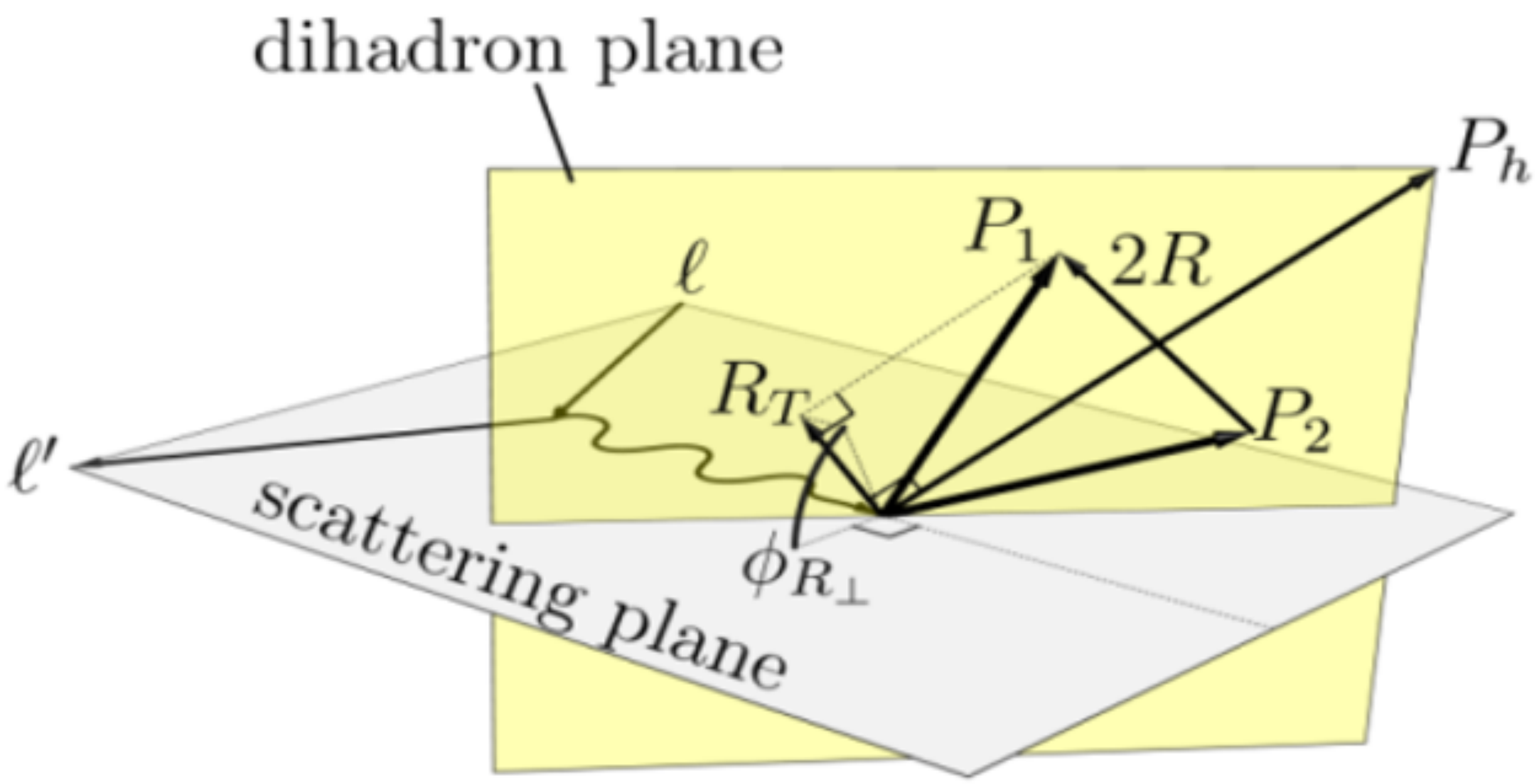
$$z = \frac{P \cdot P_h}{P \cdot q}$$

- Feynman-x variable used to consider current fragmentation region

$$x_F = \frac{2 P_h \cdot q}{|q| W}$$

Dihadron kinematics



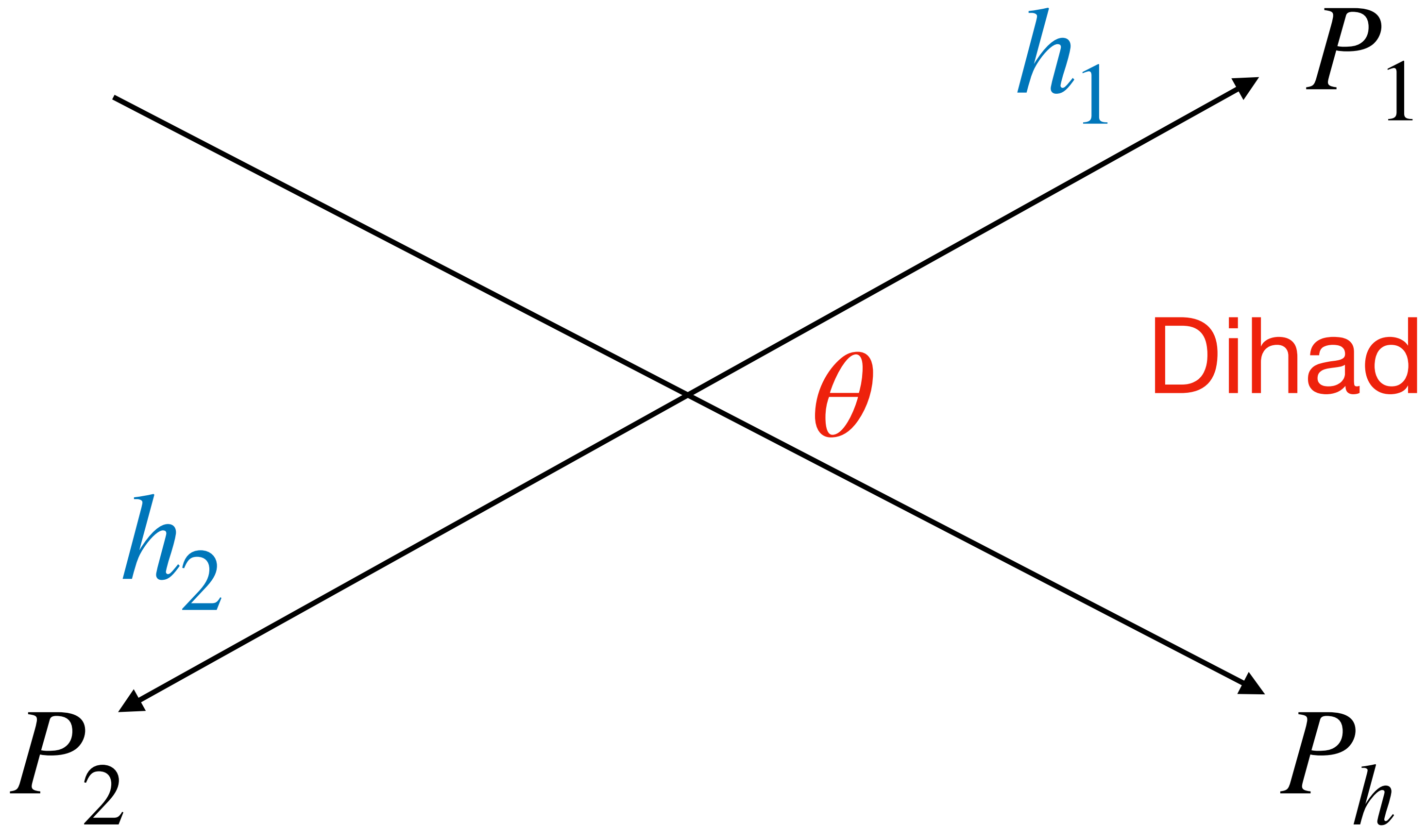


[1]

$$\phi_h = \frac{(\vec{q}\times\vec{l})\cdot\overrightarrow{P_h}}{|(\vec{q}\times\vec{l})\cdot\overrightarrow{P_h}|}\, arccos \frac{(\vec{q}\times\vec{l})\cdot(\vec{q}\times\overrightarrow{P_h})}{|\vec{q}\times\vec{l}\,||\vec{q}\times\overrightarrow{P_h}|}$$

$$\phi_R = \frac{(\vec{q}\times\vec{l})\cdot\overrightarrow{R_T}}{|(\vec{q}\times\vec{l})\cdot\overrightarrow{R_T}|}\, arccos \frac{(\vec{q}\times\vec{l})\cdot(\vec{q}\times\overrightarrow{R_T})}{|\vec{q}\times\vec{l}\,||\vec{q}\times\overrightarrow{R_T}|}$$

$$\vec{R}_T = \frac{z_2\overrightarrow{P_1}^{\perp} - z_1\overrightarrow{P_2}^{\perp}}{z}$$



Dihadron COM frame

Provides additional degrees of freedom
ϕ_R, θ and M_h compared to single hadron SIDIS

Dihadron SIDIS cross section

- Cross section components for certain polarization states of beam and target

$$d\sigma_{LU} = \frac{\alpha^2}{4\pi xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\lambda_e \sum_{l=0}^{l_{max}} \left\{ C(x,y)\sum_{m=1}^{l}\left[P_{l,m}\sin(m(\phi_h-\phi_{R_\perp}))\,2\left(F_{LU,T}^{P_{l,m}\sin(m(\phi_h-\phi_{R_\perp}))}+\epsilon F_{LU,L}^{P_{l,m}\sin(m(\phi_h-\phi_{R_\perp}))}\right)\right.\right.$$

$$\left.+W(x,y)\sum_{m=-l}^{l} P_{l,m}\sin((1-m)\,\phi_h+m\phi_{R_\perp})\,F_{LU}^{P_{l,m}\sin((1-m)\phi_h+m\phi_{R_\perp})}\right\}$$

- $F_{XY}^{m(\phi_h,\phi_R)}$'s are structure functions which can be written as convolutions of TMD PDF and DIFF

- $P_{l,m}$'s are Legendre polynomials depend on $\cos\,\theta$

- Limit l_{max} = 2 (dihadron invariant mass in CLAS12 limited to around 1 GeV)

- Consider integration over θ

- Cross section is related to azimuthal modulations of angles ϕ_h and ϕ_R

Dihadron SIDIS cross section

$$d\sigma_{UL} = \frac{\alpha^2}{4\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right)S_L\left\{A(x,y)\sum_{\ell=1}^{\ell_{\max}}\sum_{m=1}^{\ell}P_{\ell,m}\sin(-m\phi_h+m\phi_{R_\perp})F_{UL}^{P_{\ell,m}\sin(-m\phi_h+m\phi_{R_\perp})}\right.$$
$$+B(x,y)\sum_{\ell=0}^{\ell_{\max}}\sum_{m=-\ell}^{\ell}P_{\ell,m}\sin((2-m)\phi_h+m\phi_{R_\perp})F_{UL}^{P_{\ell,m}\sin((2-m)\phi_h+m\phi_{R_\perp})}$$
$$\left.+V(x,y)\sum_{\ell=0}^{\ell_{\max}}\sum_{m=-\ell}^{\ell}P_{\ell,m}\sin((1-m)\phi_h+m\phi_{R_\perp})F_{UL}^{P_{\ell,m}\sin((1-m)\phi_h+m\phi_{R_\perp})}\right\}.$$

[2]

$$d\sigma_{LL} = \frac{\alpha^2}{4\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right)\lambda_e S_L$$
$$\times\sum_{\ell=0}^{\ell_{\max}}\left\{C(x,y)\sum_{m=0}^{\ell}2^{2-\delta_{m0}}P_{\ell,m}\cos(m(\phi_h-\phi_{R_\perp}))F_{LL}^{P_{\ell,m}\cos(m(\phi_h-\phi_{R_\perp}))}\right.$$
$$\left.+W(x,y)\sum_{m=-\ell}^{\ell}P_{\ell,m}\cos((1-m)\phi_h+m\phi_{R_\perp})F_{LL}^{P_{\ell,m}\cos((1-m)\phi_h+m\phi_{R_\perp})}\right\}.$$

[2]

- Longitudinally polarized target data from RG-C sensitive to $d\sigma_{LU}$, $d\sigma_{UL}$ and $d\sigma_{LL}$

Structure functions, PDFs and DIFFs

Structure function and modulation	PDF and DIFF	Depolarization factor
$F_{LU}^{\sin(\phi_R)}$	$eH_1^{\perp}$	W
$F_{LU}^{\sin(\phi_h-\phi_R)}$	f_1G_1	C
$F_{UL}^{\sin(\phi_R)}$	$h_LH_1^{\perp}$	V
$F_{UL}^{\sin(2\phi_R)}$	$h_{1L}^{\perp}H_1^{\perp}$	B
$F_{UL}^{\sin(-\phi_h+\phi_R)}$	$g_{1L}G_1$	A
F_{LL}^{const}	$g_{1L}D_1$	C
$F_{LL}^{\cos(\phi_R)}$	$g_{1L}\tilde{D}$	W
F_{UU}	f_1D_1	A

$$A(\epsilon, y) = \frac{y^2}{2(1-\epsilon)}$$

$$V(\epsilon, y) = \frac{y^2}{2(1-\epsilon)}\sqrt{2\epsilon(1+\epsilon)}$$

$$B(\epsilon, y) = \frac{y^2}{2(1-\epsilon)}\epsilon$$

$$W(\epsilon, y) = \frac{y^2}{2(1-\epsilon)}\sqrt{2\epsilon(1-\epsilon)}$$

$$C(\epsilon, y) = \frac{y^2}{2(1-\epsilon)}\sqrt{1-\epsilon^2}$$

[3]

$$\epsilon = \frac{1 - y - \gamma^2 y^2/4}{1 - y + y^2/2 + \gamma^2 y^2/4}$$

$$\gamma = \frac{2Mx}{Q}$$

Event selection

$e^- p \rightarrow e^- \pi^+ \pi^- X$

- $Q^2 > 1$ GeV^2
- $W > 2$ GeV
- $y < 0.75$
- $M_X > 1.3$ GeV
- $x_F > 0$ for π^+, π^-
- $z < 0.85$ for dihadron

- QADB cuts
- Only inbending data

Cuts for electron

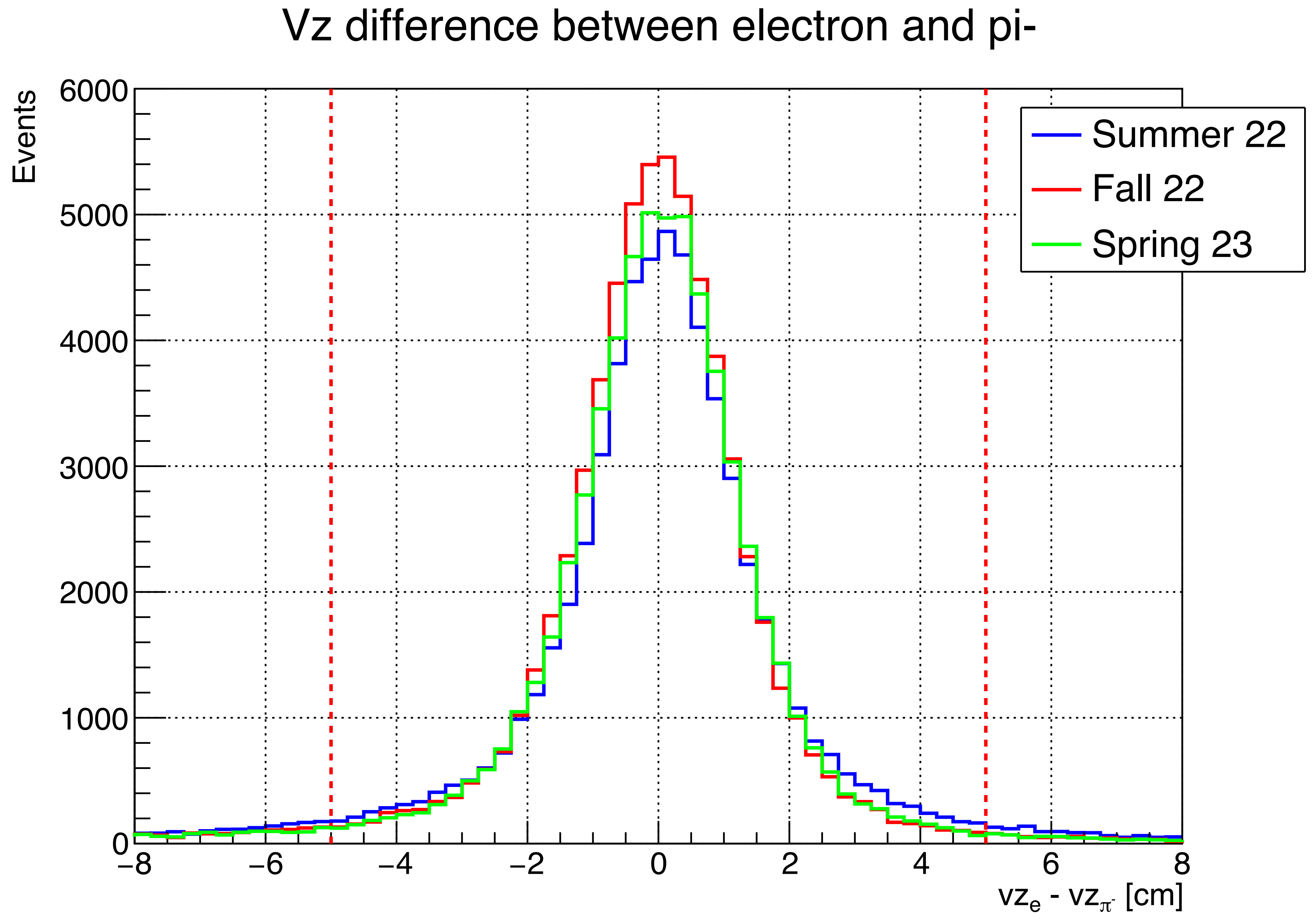
- Vertex z cut
  - Summer22: $-9.0 \leq V_z \leq 1.0$ cm
  - Fall22 & Spring23: $-7.5 \leq V_z \leq 2.5$ cm
- $|V_x| < 2$ cm, $|V_y| < 2$ cm
- DC fiducial cuts
  - EdgeR1 > 4 cm, EdgeR2 > 5 cm, EdgeR3 > 8 cm
- PCAL fiducial cuts
  - 9 cm < Lv, Lw < 400 cm
- Sampling fraction cuts
- Diagonal cut for E/p of EC_{in} vs PCAL

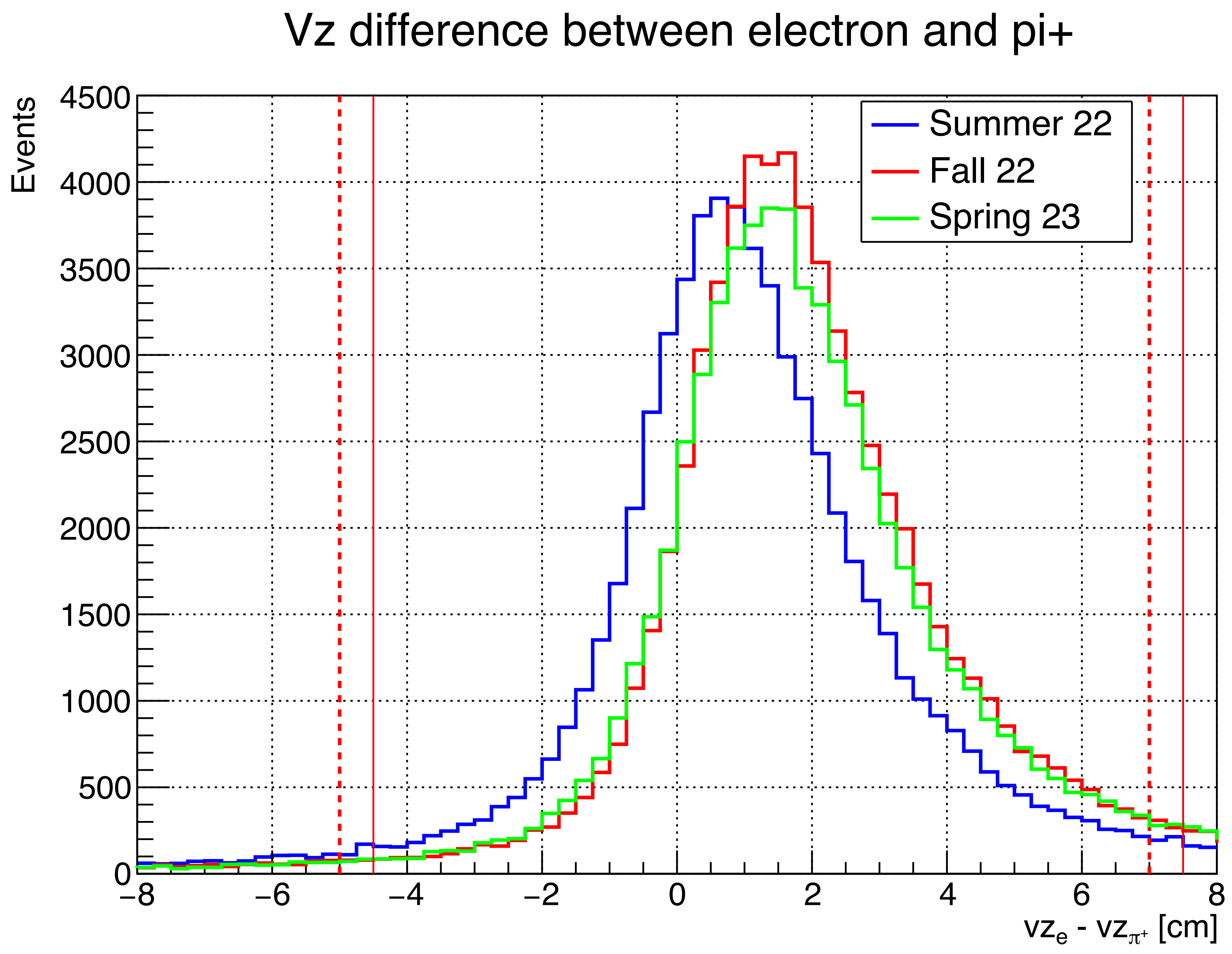
Event selection

$$e^- p \rightarrow e^- \pi^+ \pi^- X$$

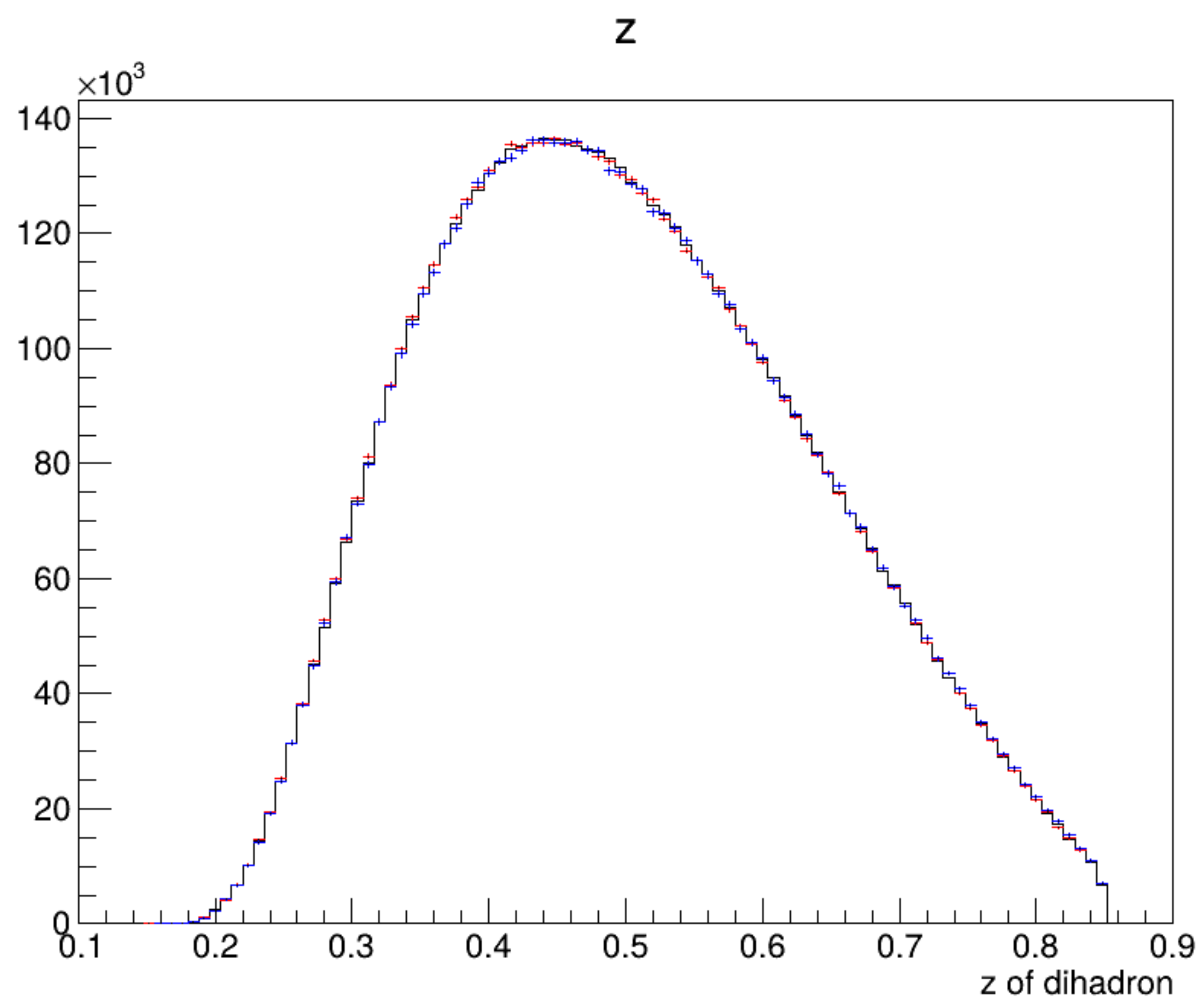
Cuts for π^+, π^-

- Vertex z difference between e- and pion
  - $\pi^- \rightarrow |V_z(e^-) - V_z(\pi)| < 5$ cm
  - $\pi^+ \rightarrow |V_z(e^-) - V_z(\pi) - 1| < 6$ cm Summer22
  - $\pi^+ \rightarrow |V_z(e^-) - V_z(\pi) - 1.5| < 6$ cm Fall22, Spring23
- χ^2_{PID} cuts
- $5^\circ < \theta < 35^\circ$

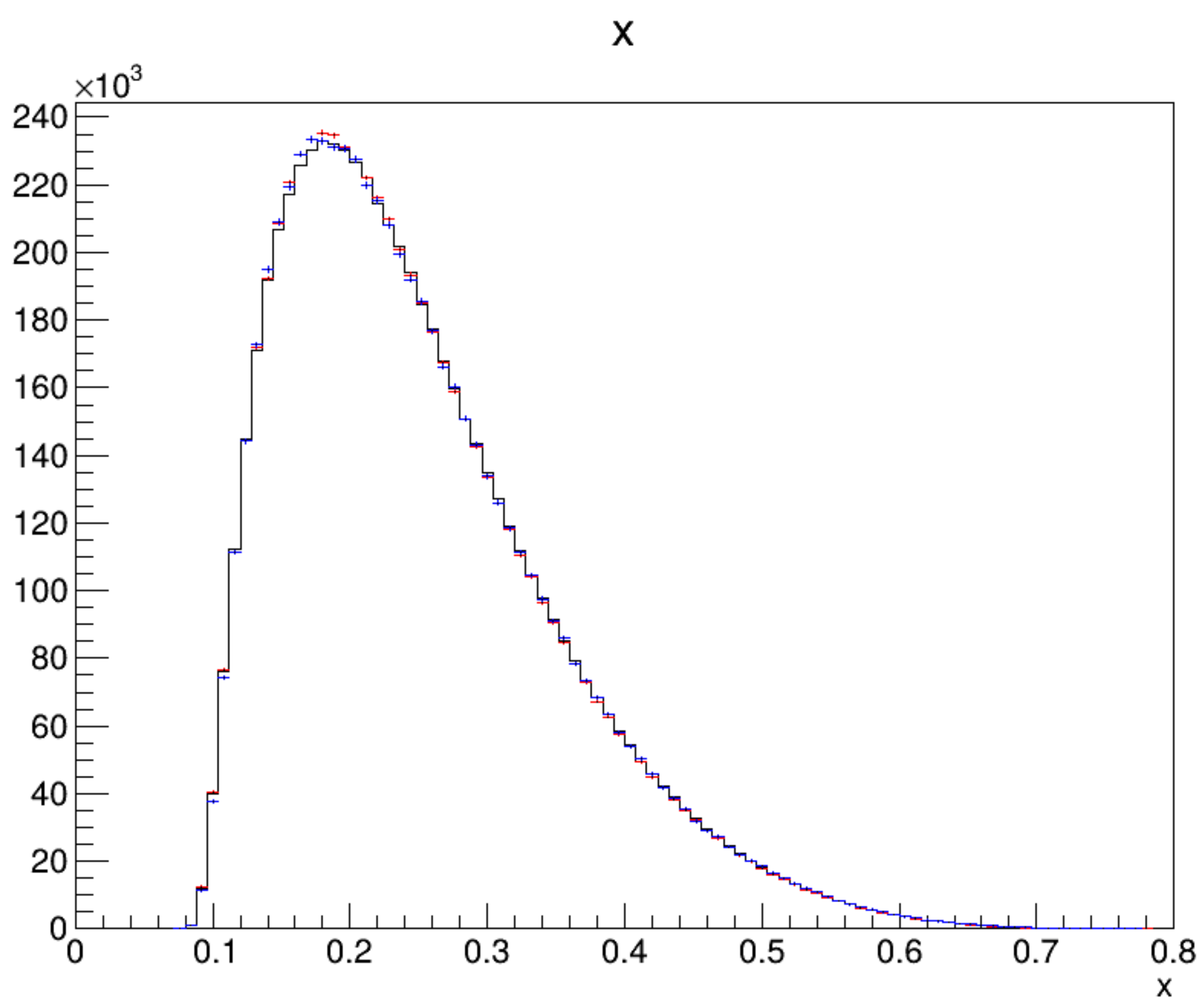




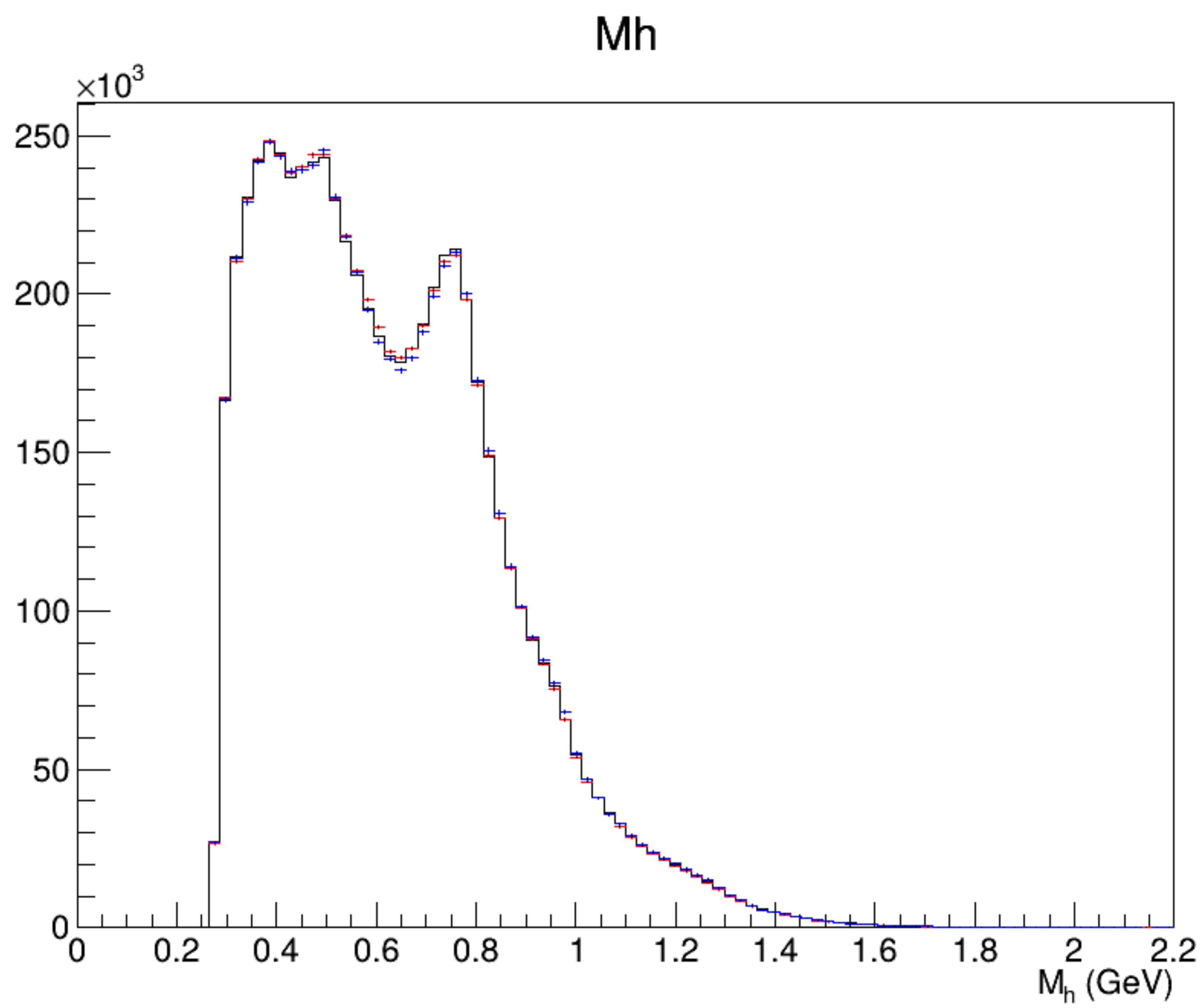
Kinematic variables



z



x



$M_{\pi^+\pi^-}$ (GeV)

- Asymmetries extracted for 10 bins in each kinematic variable
- Dilution factor calculated for each kinematic bin

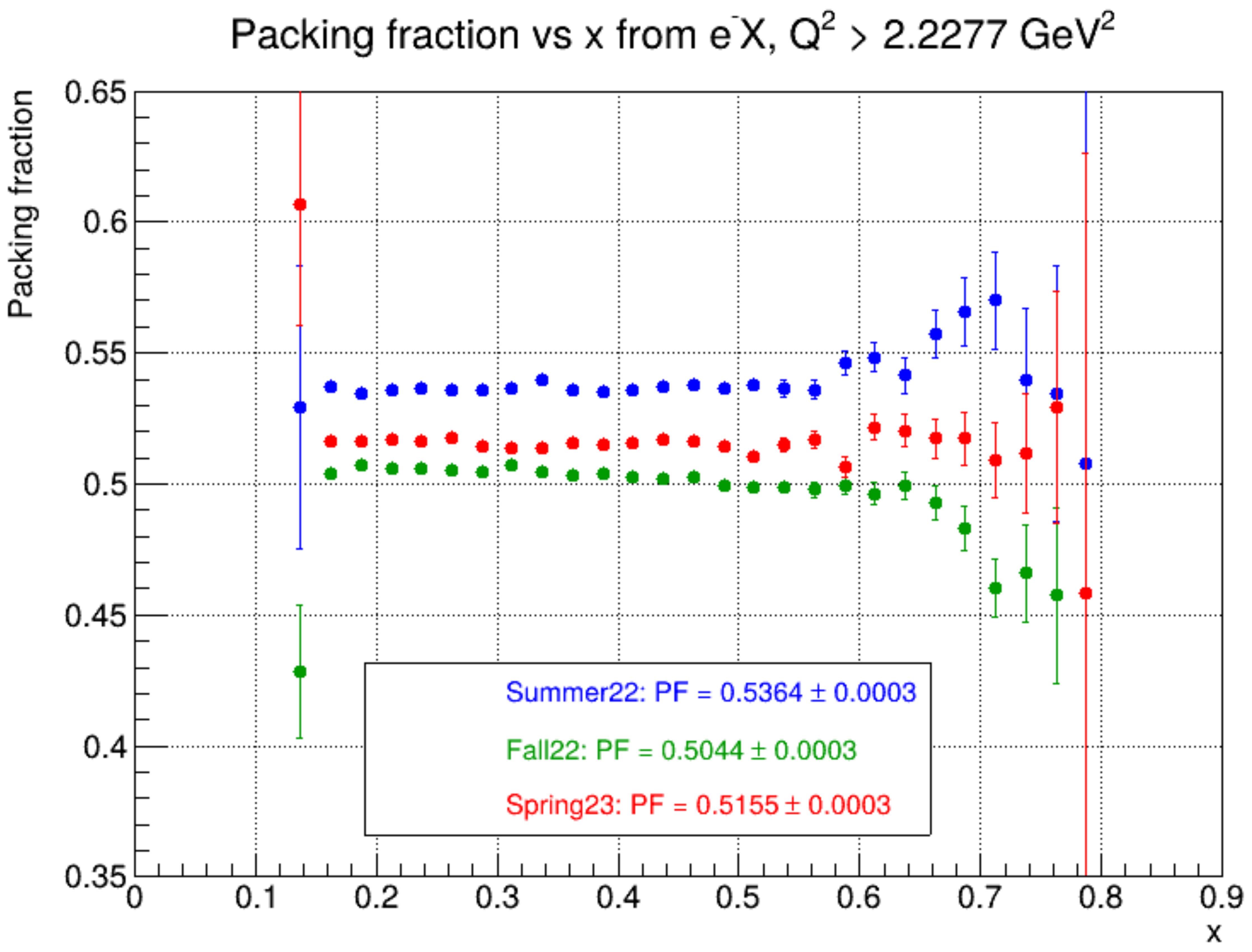
Calculating packing fraction and dilution factor

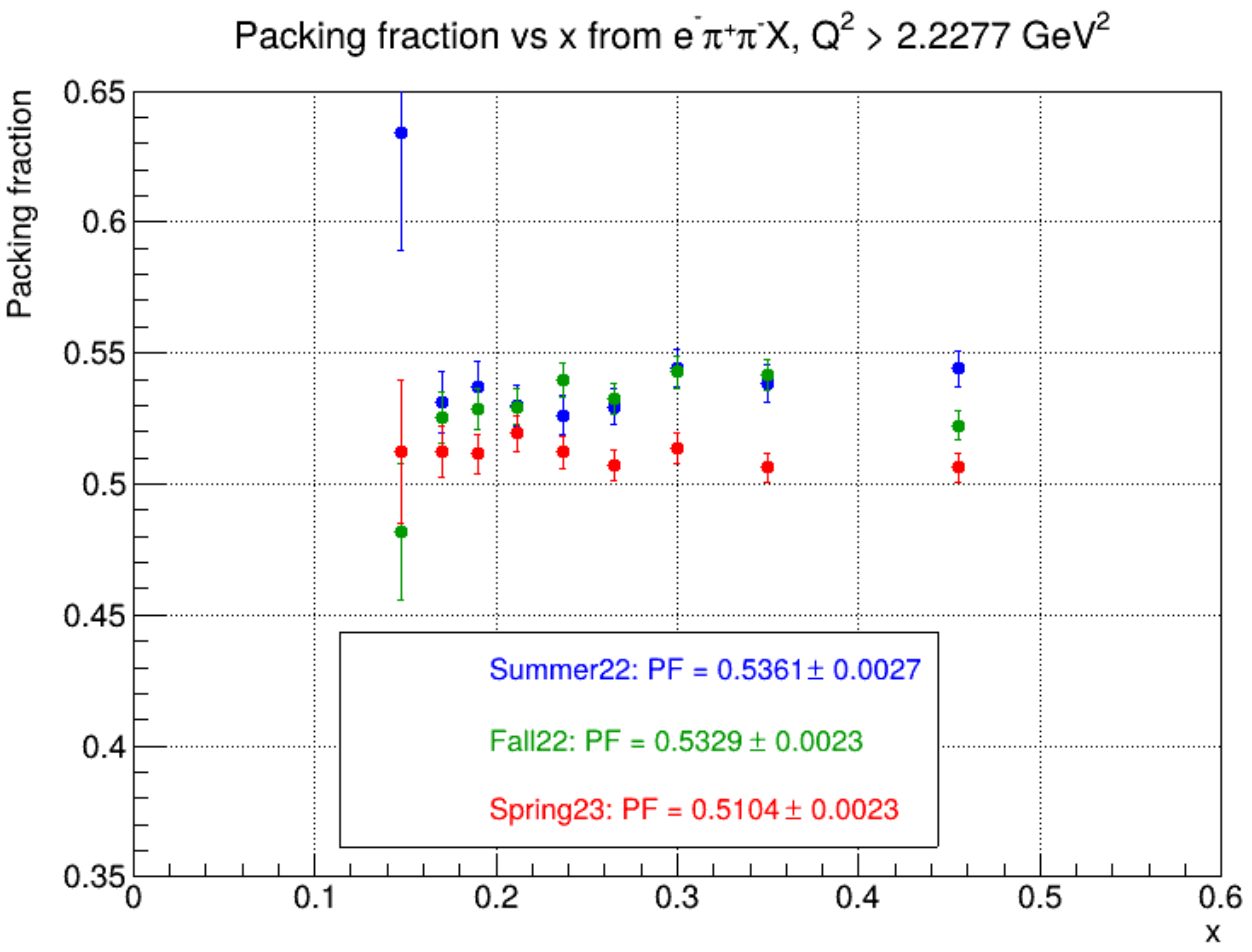
- Packing fraction - target volume fraction occupied by the ammonia crystals
- Dilution factor - fraction of events coming from polarized H in the target
- Compare two channels - inclusive and dihadron
- New equations to extract packing fraction and dilution factor ! (https://clasweb.jlab.org/wiki/images/4/46/RG-C_Dilution_v3.1.pdf)

$$PF = 0.50734 \frac{n_A - n_{MT}}{n_{CH} - 0.195667 n_C - 0.82744 n_{MT} + 0.023106 n_F}. \qquad (11)$$

$$DF = \frac{n_{CH} - 0.880502 n_C + 0.16604 n_{MT} - 0.285536 n_F}{n_{CH} - 0.195667 n_C - 0.82744 n_{MT} + 0.023106 n_F) + 0.50734 n_{MT}/PF}. \qquad (14)$$

Packing fraction comparison from two channels

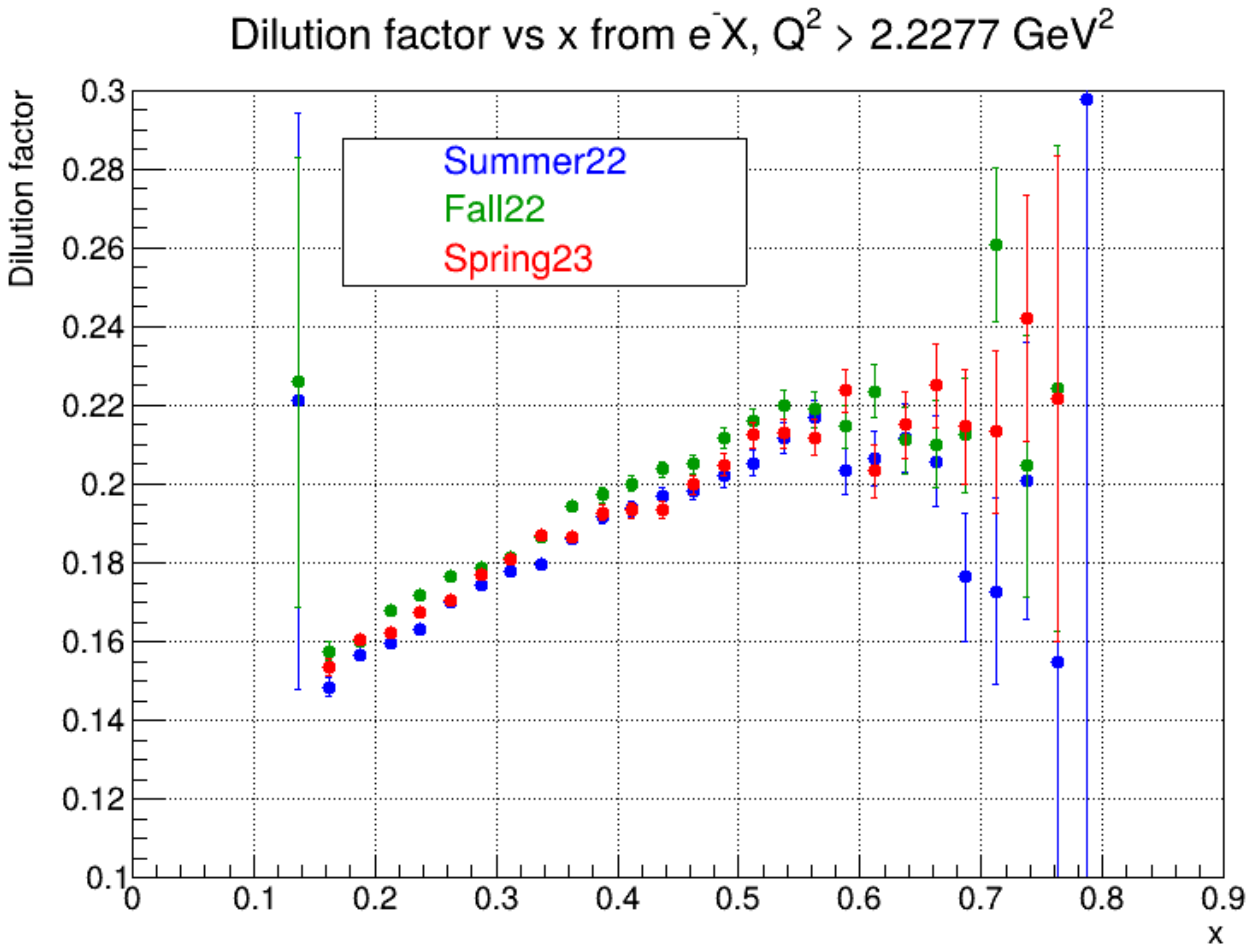


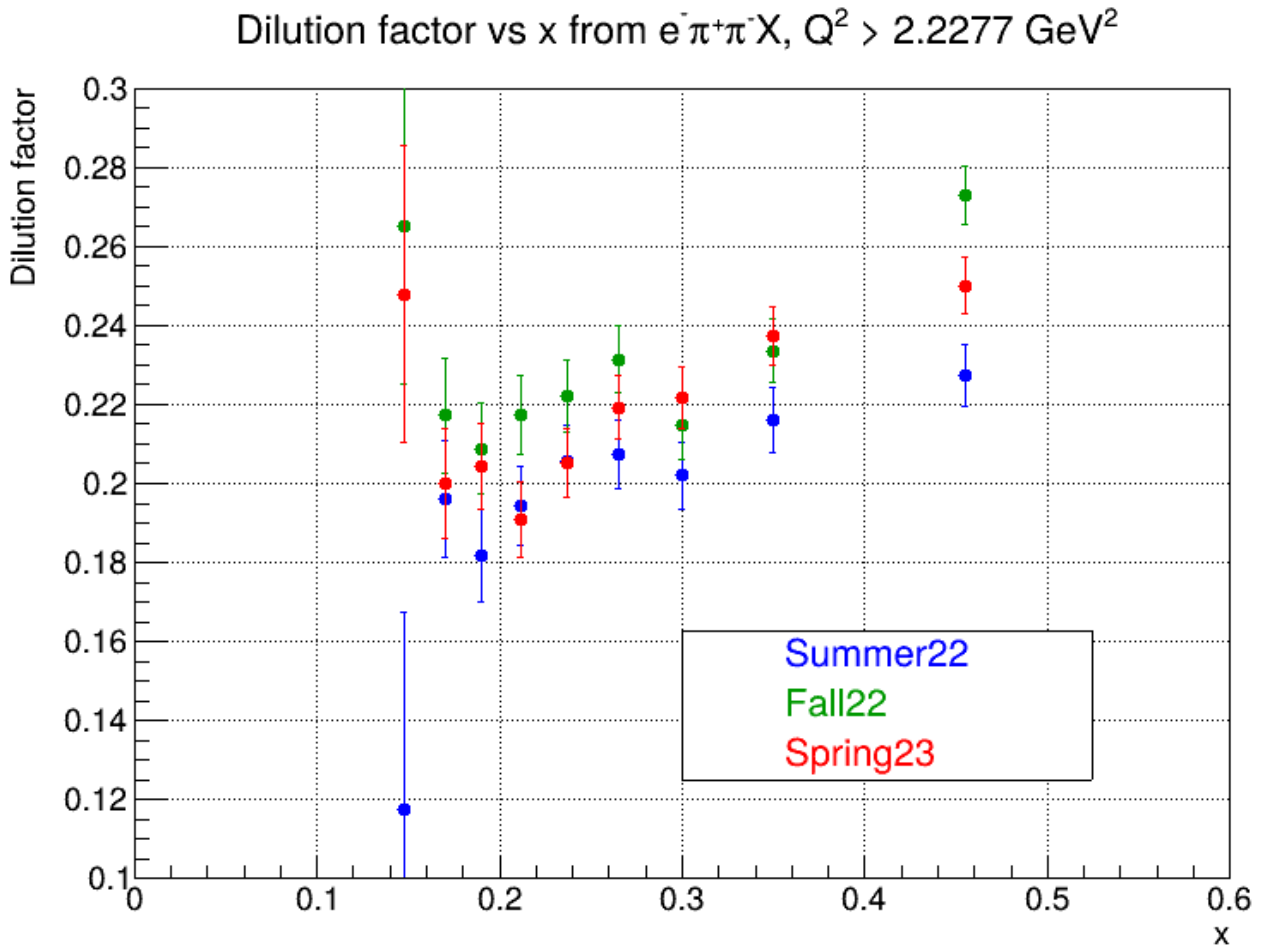


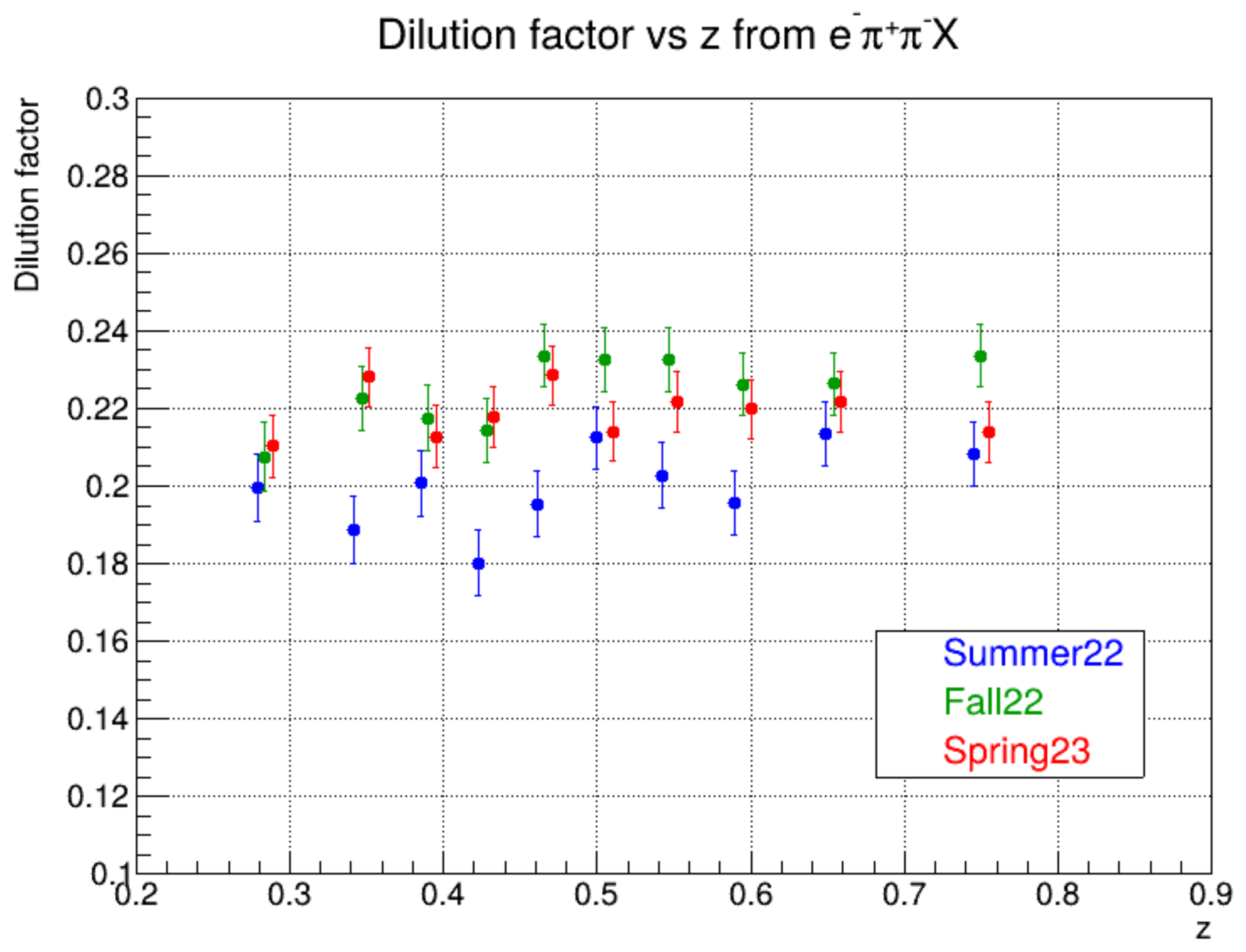
Run Period	$e^- X$	$e^- \pi^+ \pi^- X$
Summer 2022	0.5364 ± 0.0003	0.5361 ± 0.0027
Fall 2022	0.5044 ± 0.0003	0.5329 ± 0.0023
Spring 2023	0.5155 ± 0.0003	0.5104 ± 0.0023

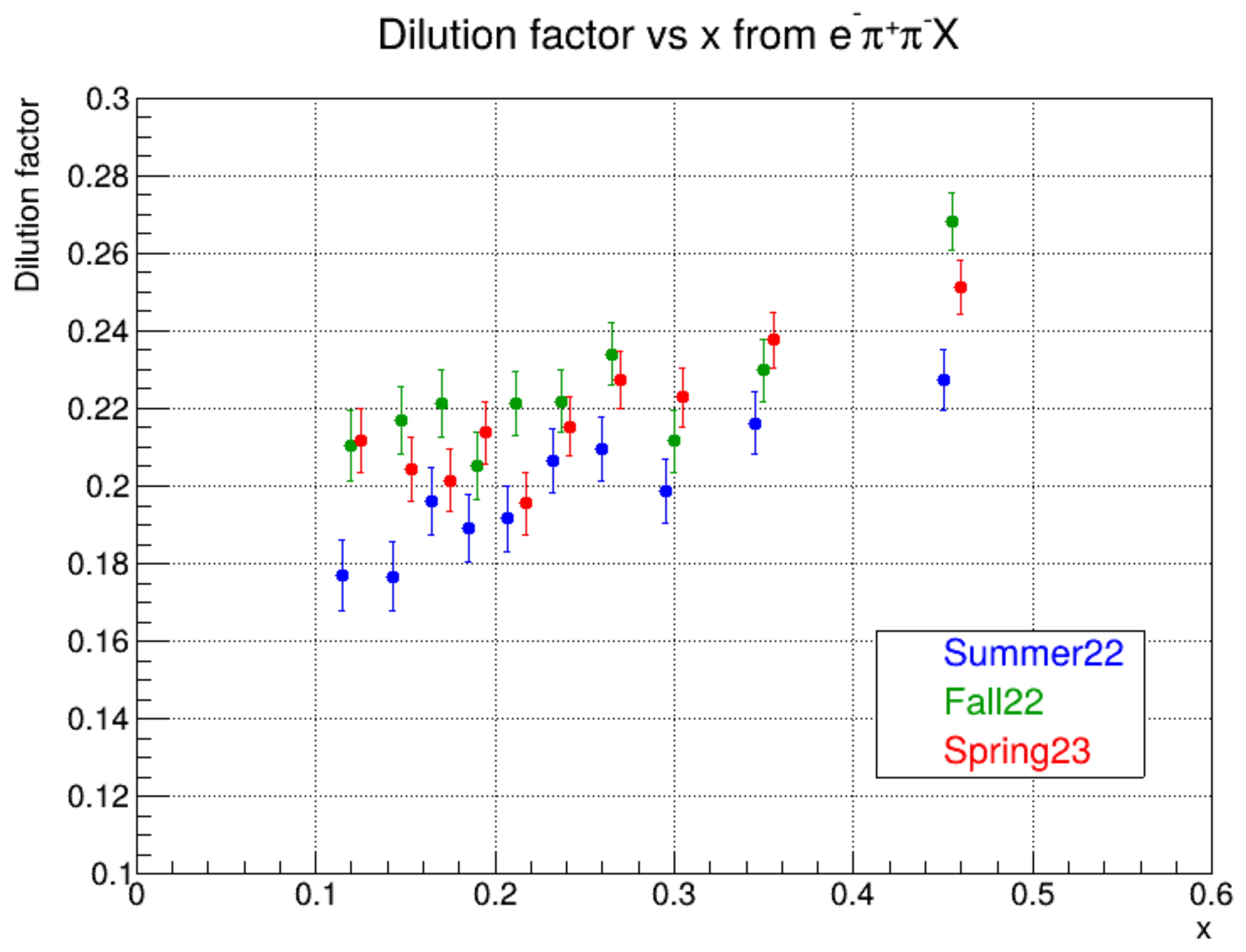
- Summer 2022 and Spring 2023 results agree between two channels
- Discrepancy for Fall 2022

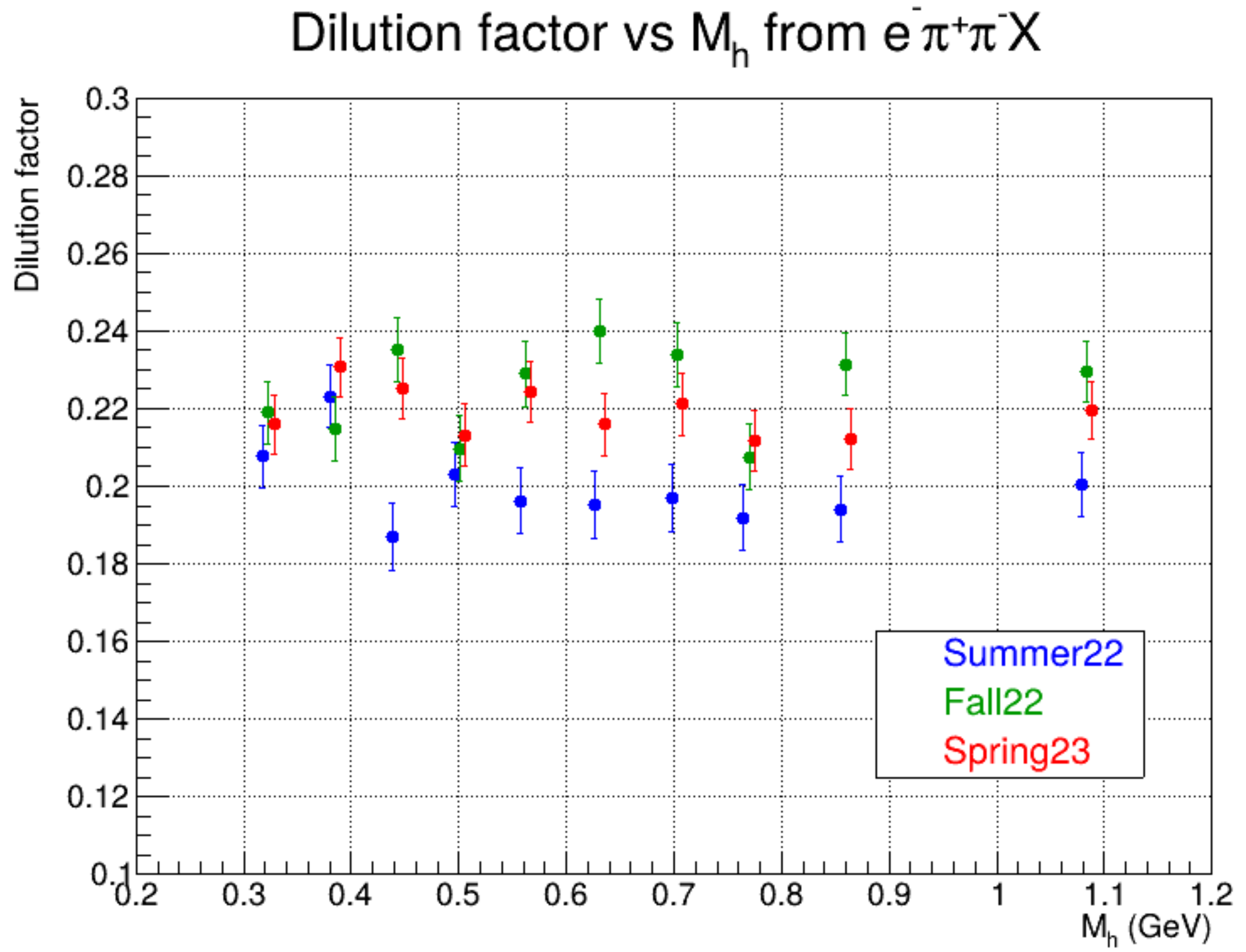
Dilution factor comparison from two channels











- Used packing fraction from inclusive channel ($Q^2 > 2.2277$ GeV^2)
- $Q^2 > 1$ GeV^2 for dihadron analysis

Extracting asymmetries - likelihood PDF

- Use a "combined fit" to extract $A_{LU}^{\psi_i}, A_{UL}^{\psi_i}$ and $A_{LL}^{\psi_i}$ simultaneously
- Probability distribution has the form

$$p = 1 + P_b h_b \frac{W(\epsilon, y)}{A(\epsilon, y)} \frac{F_{LU}^{\sin\phi_R}}{F_{UU}^{const}} \sin\phi_R + \dots$$

$$+ P_t h_t f \frac{V(\epsilon, y)}{A(\epsilon, y)} \frac{F_{UL}^{\sin\phi_R}}{F_{UU}^{const}} \sin\phi_R + \dots$$

$$+ P_b h_b P_t h_t f \frac{C(\epsilon, y)}{A(\epsilon, y)} \frac{F_{LL}^{const}}{F_{UU}^{const}} + P_b h_b P_t h_t f \frac{W(\epsilon, y)}{A(\epsilon, y)} \frac{F_{LL}^{\cos\phi_h}}{F_{UU}^{const}} \cos\phi_h + P_b h_b P_t h_t f \frac{W(\epsilon, y)}{A(\epsilon, y)} \frac{F_{LL}^{\cos\phi_R}}{F_{UU}^{const}} \cos\phi_R + \dots)$$

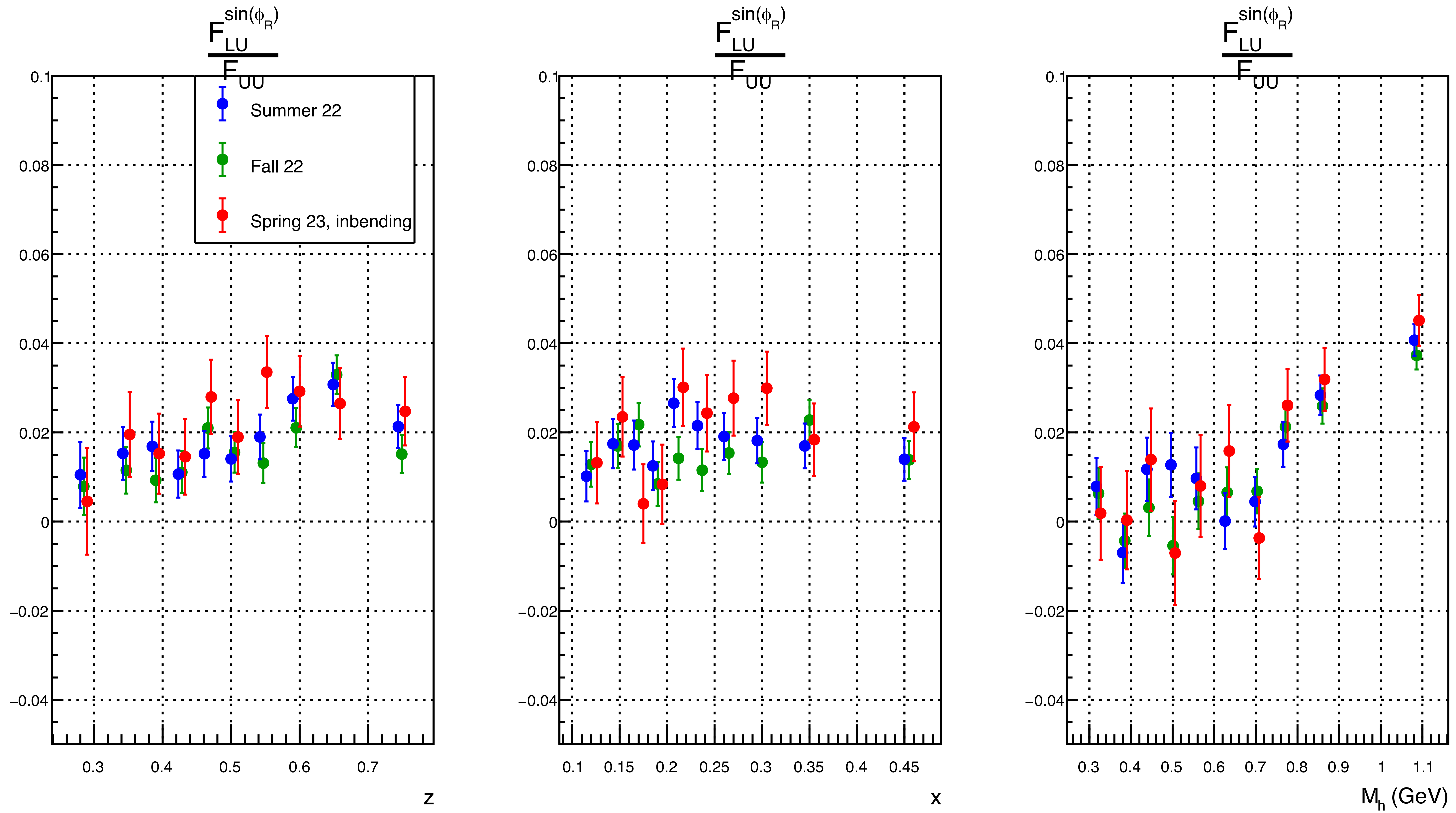
A, C, V, W - depolarization factors

weight was applied (p^w) to account for imbalance between accumulated charges for +,- helicity states of beam, target (https://clas12-docdb.jlab.org/DocDB/0011/001176/001/CLAS_MLM_Analysis_Note.pdf)

- Total of 27 modulation amplitudes

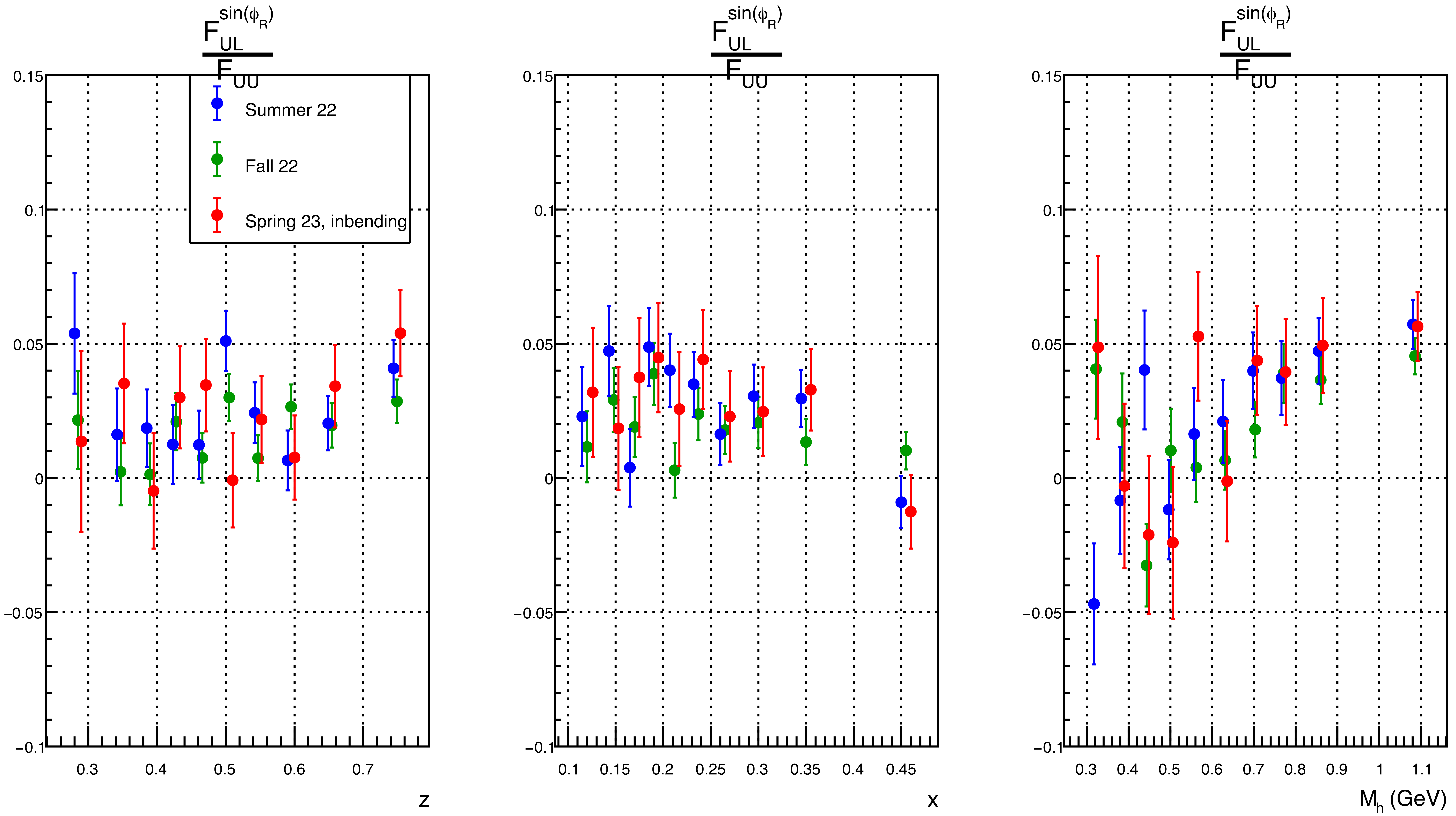
(fit parameters give structure functions ratio $\frac{F_{XY}^{\psi_i}}{F_{UU}^{const}}$)

Asymmetry results for different run periods

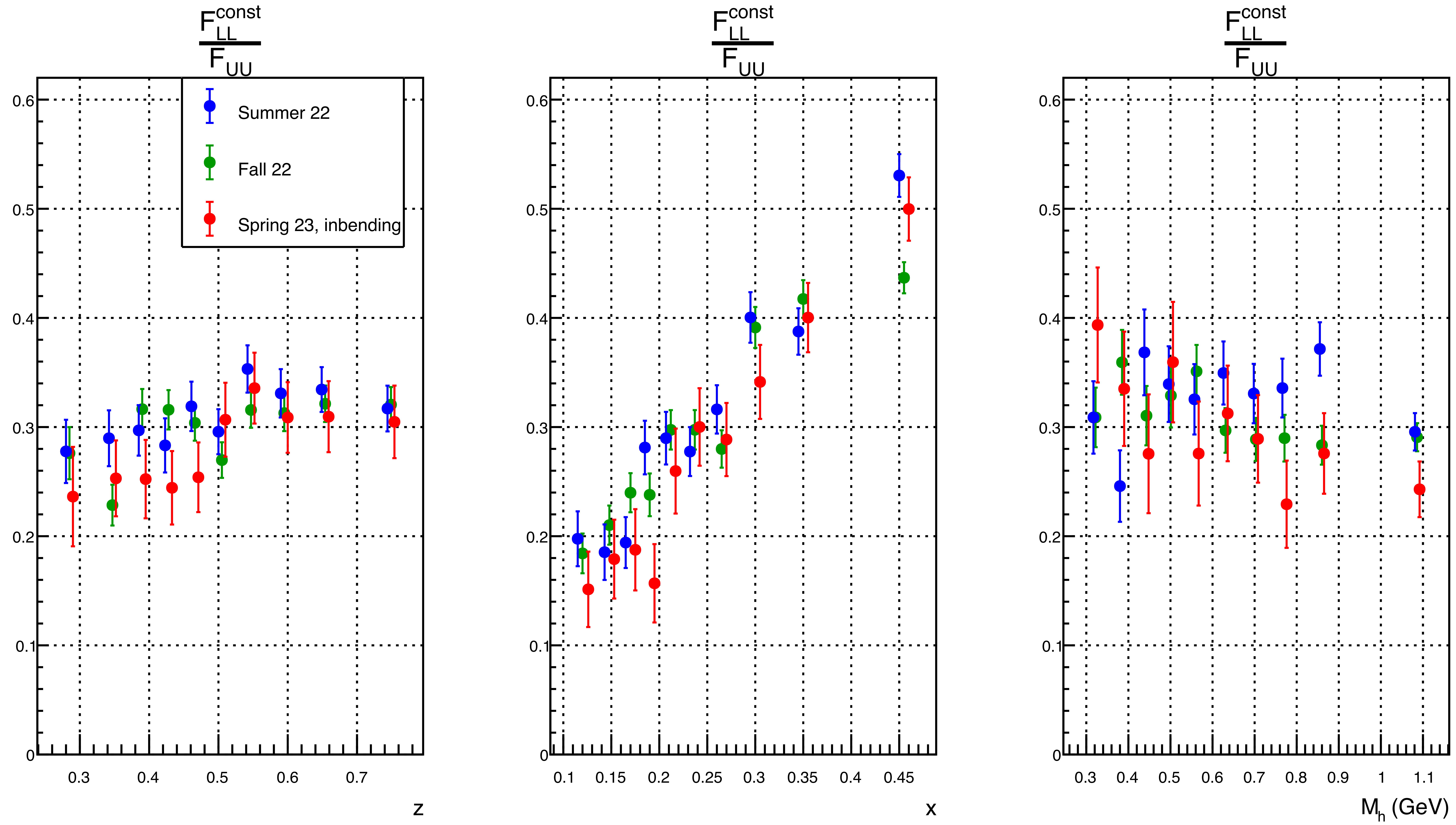


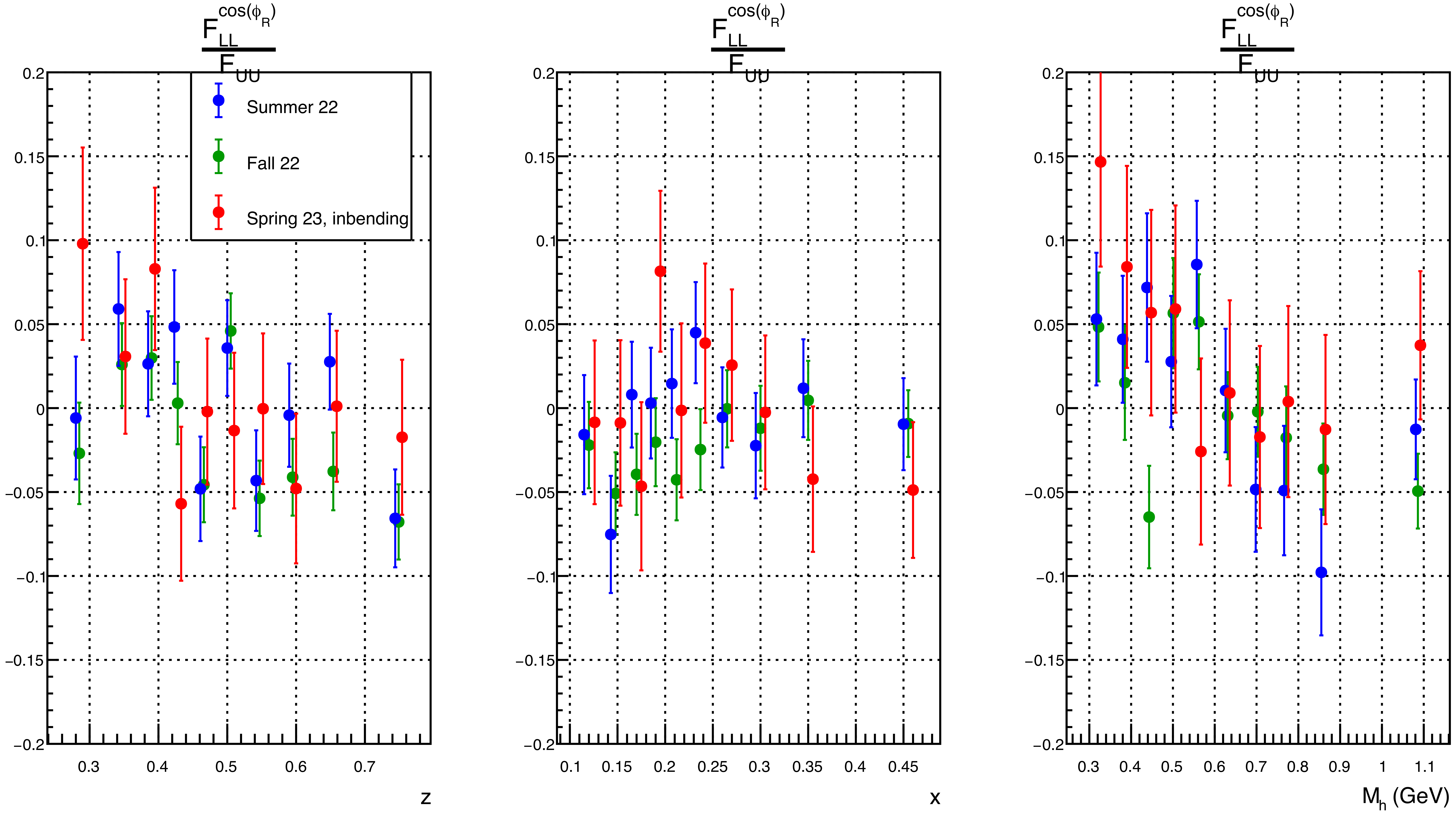
- Use weighted average method to combine results from 3 run periods

$$\bar{y} = \frac{\sum (y_i/\sigma_i^2)}{\sum (1/\sigma_i^2)} \qquad \sigma_{\bar{y}} = \sqrt{\frac{1}{\sum (1/\sigma_i^2)}}$$



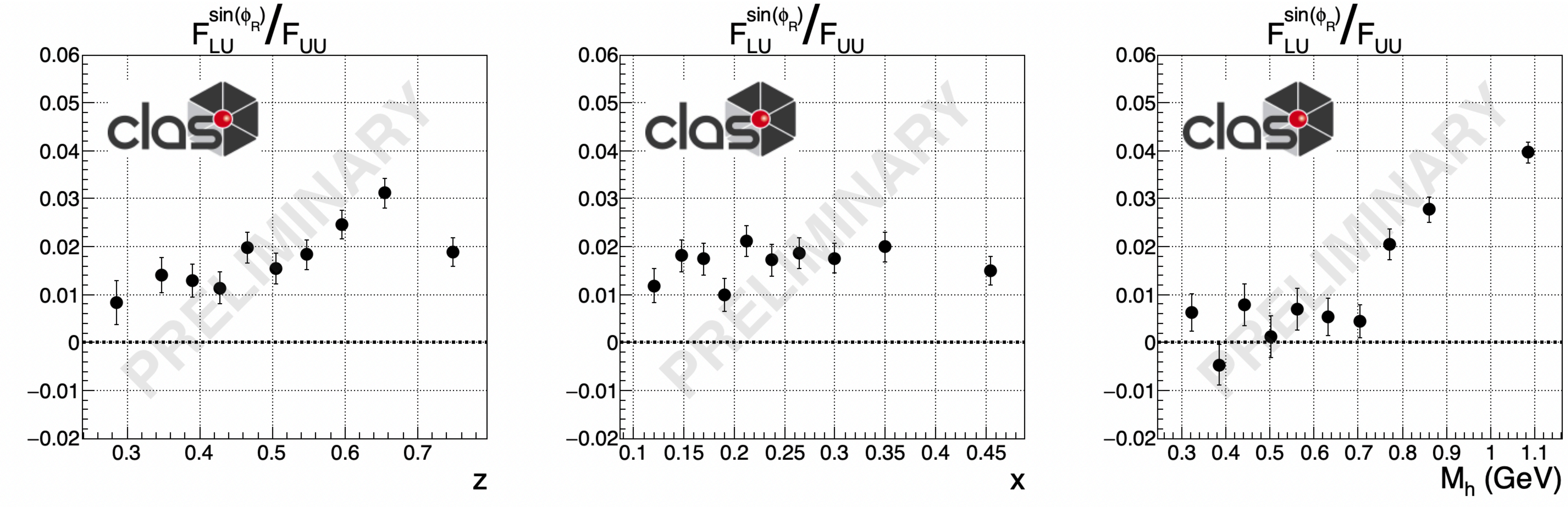
$\frac{F_{UL}^{\sin(\phi_R)}}{F_{UU}}$
Summer 22
Fall 22
Spring 23, inbending
0.15
0.1
0.05
0
−0.05
−0.1
0.3
0.4
0.5
0.6
0.7
z
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
x
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
M_h (GeV)


F_{LL}^{const}/F_{UU}
Summer 22
Fall 22
Spring 23, inbending
z
x
M_h (GeV)

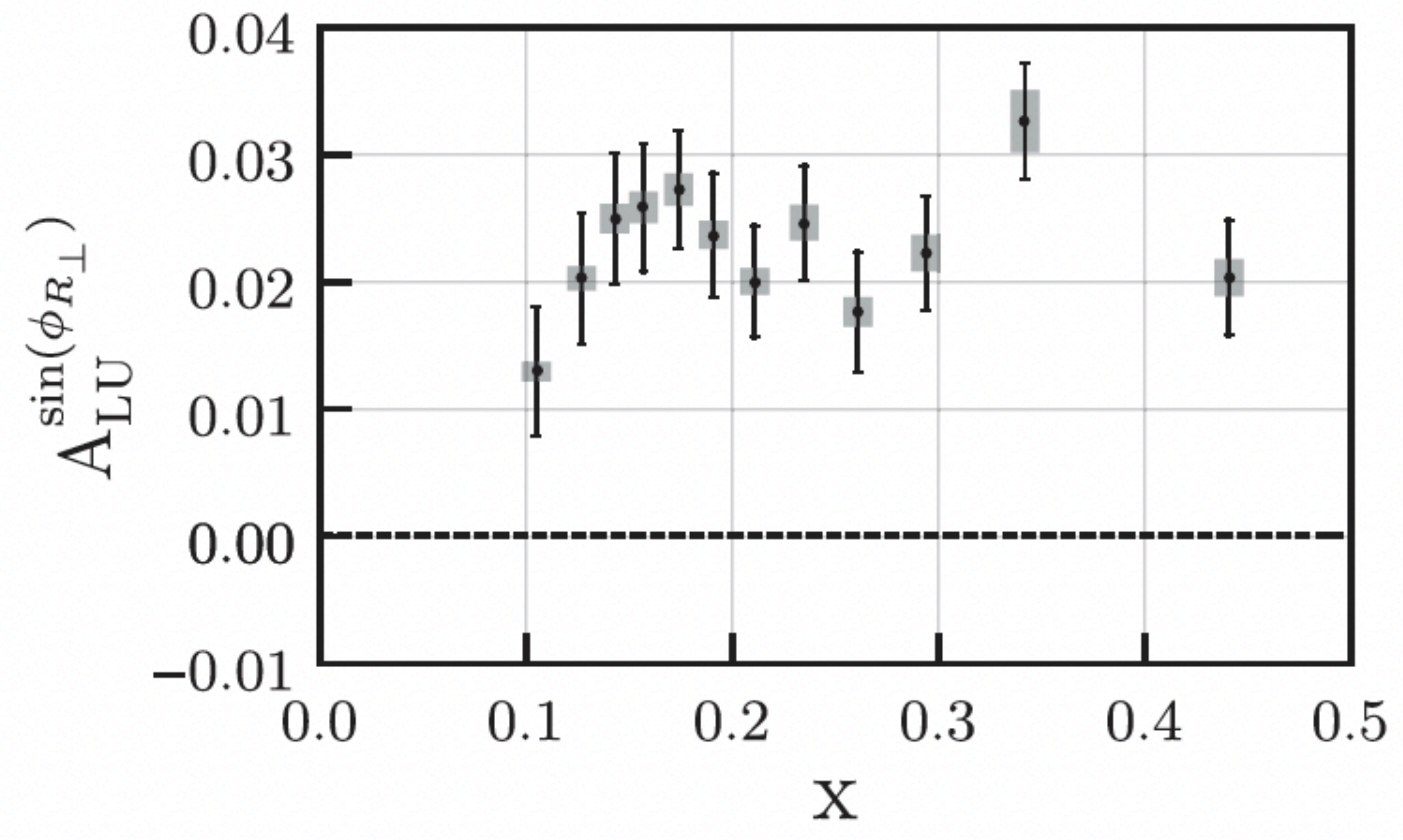


$\frac{F_{LL}^{\cos(\phi_R)}}{F_{UU}}$
Summer 22
Fall 22
Spring 23, inbending
z
x
M_h (GeV)

Weighted average results - $F_{LU}^{\sin(\phi_R)}/F_{UU}$



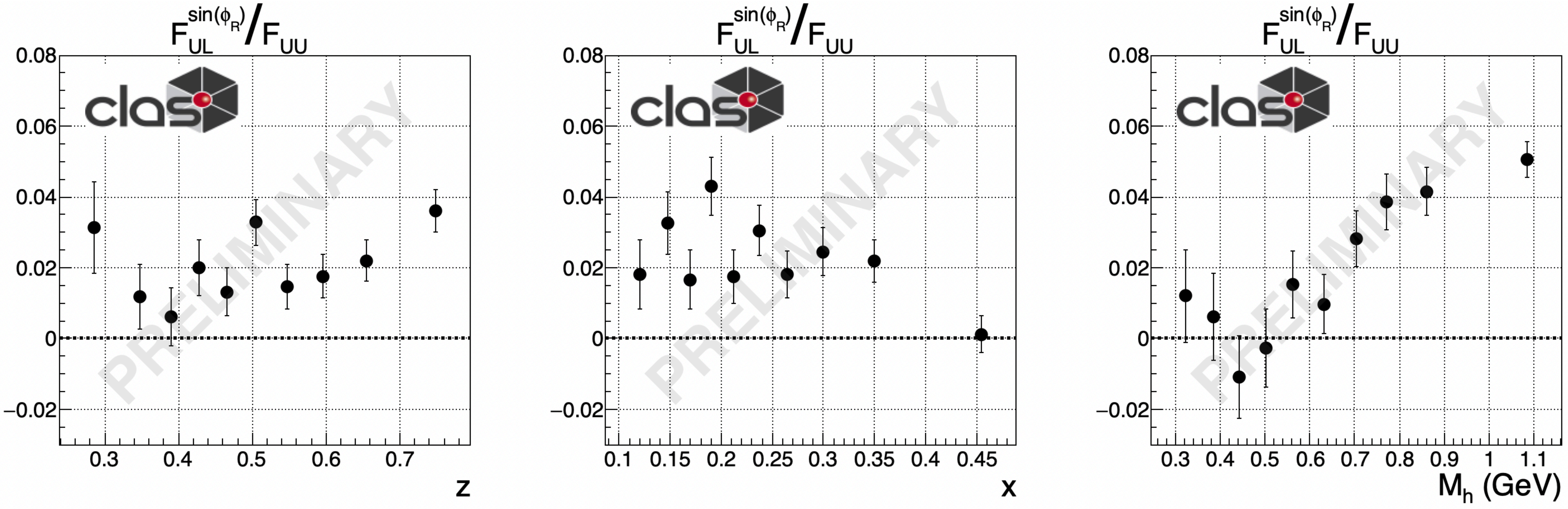
- Flat wrt x (Consistent with published results from RG-A data)



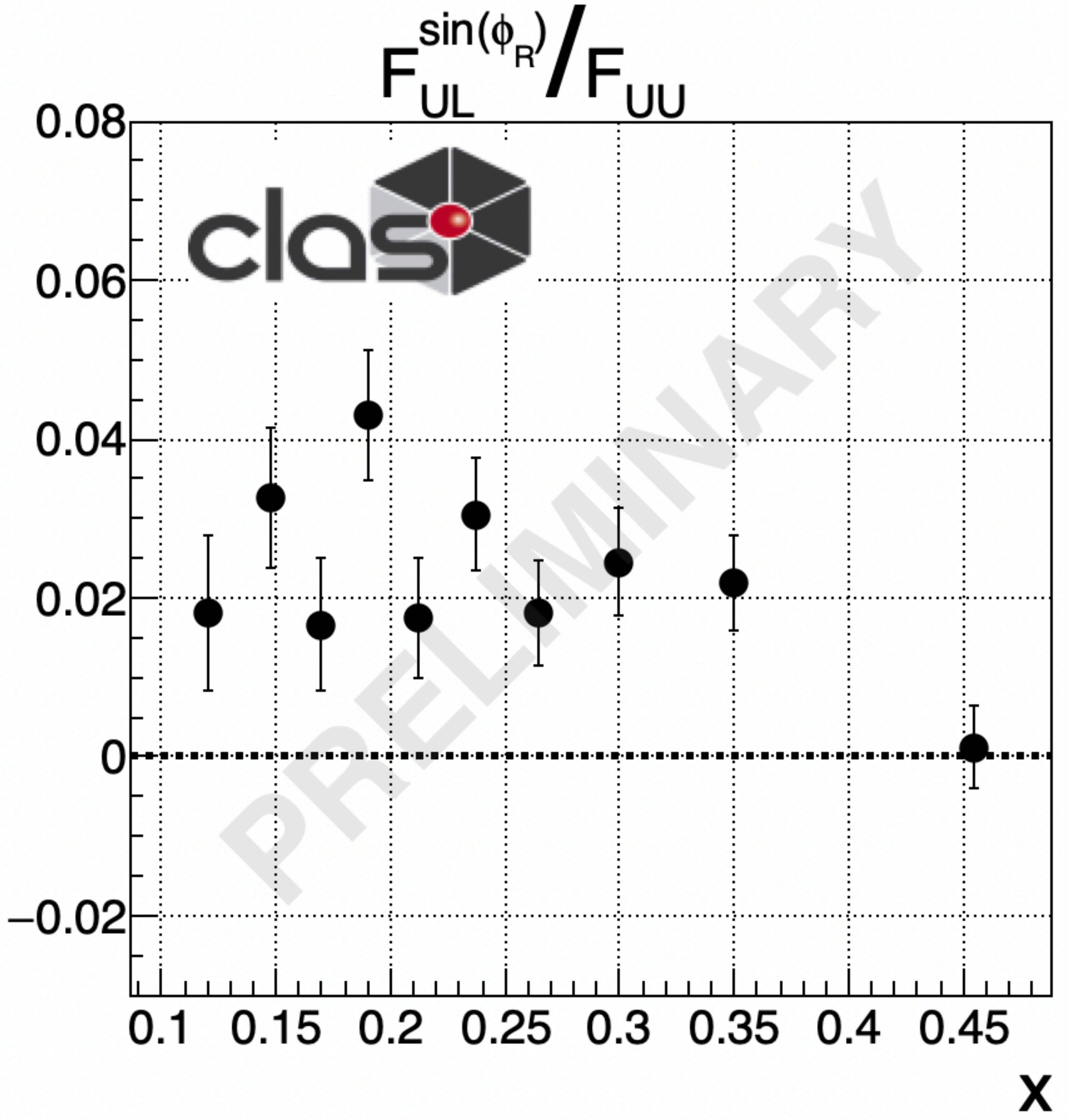
CLAS12
PRL 126, 152501 (2021)

Sensitive to $eH_1^{\perp}$

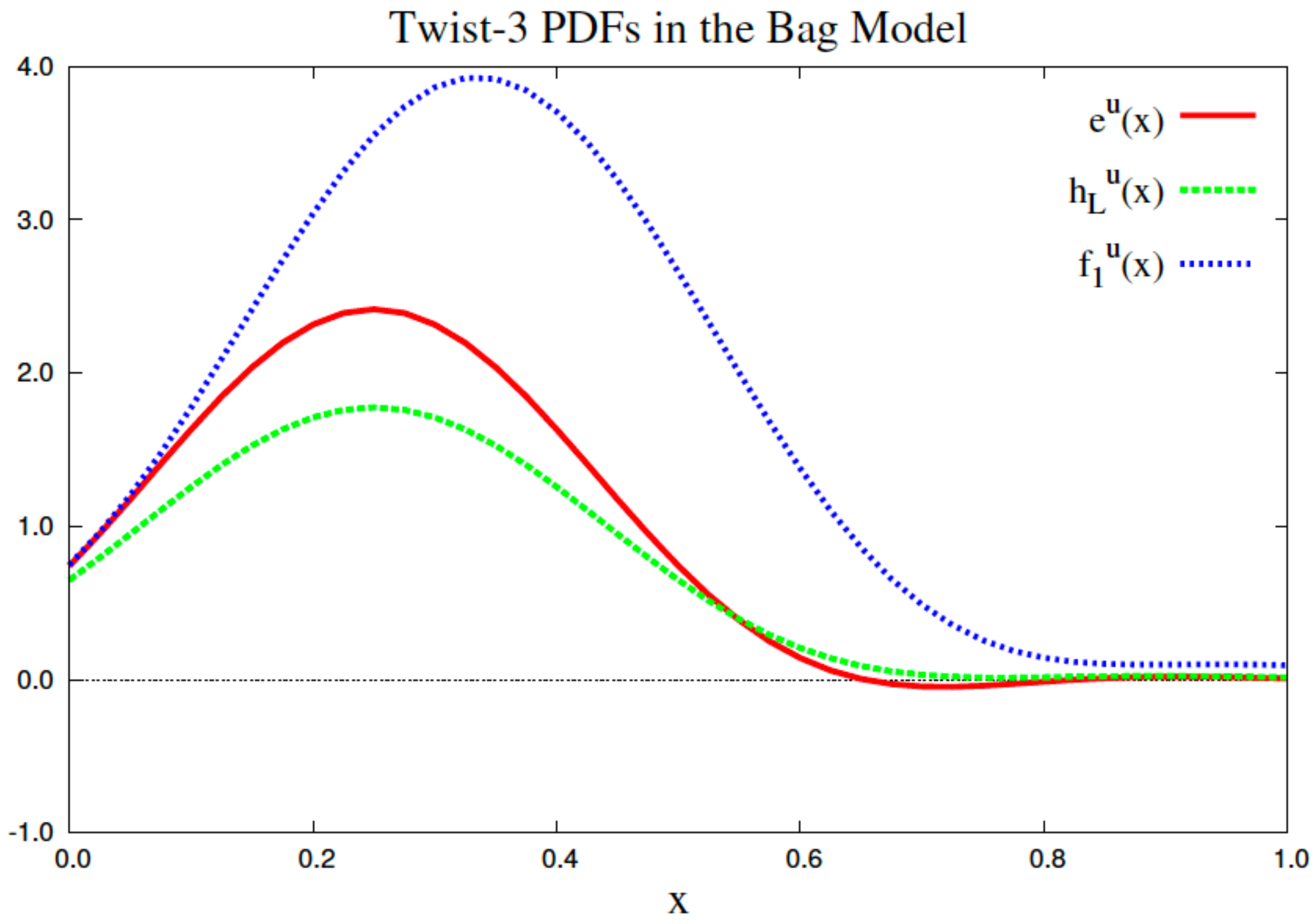
$F_{UL}^{\sin(\phi_R)}/F_{UU}$

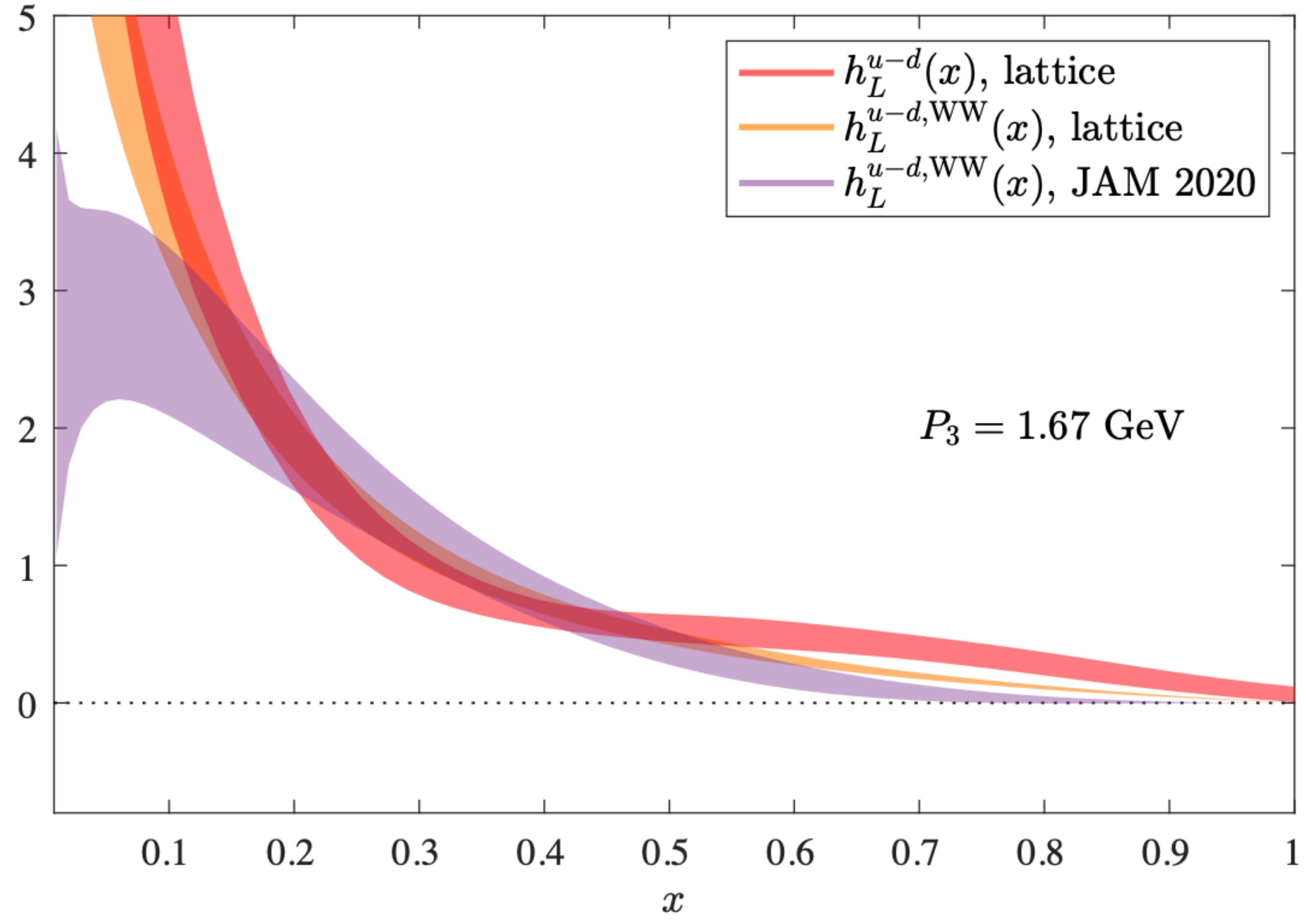


- Non-zero and positive amplitude
- Sensitive to $h_L H_1^{\perp}$
- No published results on twist-3 PDF h_L



Nucl. Phys. B375, 527 (1992)





CLAS12 results will allow extraction of h_L from data

arXiv:2111.01056

F_{LL}/F_{UU}

$$\frac{F_{LL}^{const}}{F_{LL}^{\cos(\phi_R)}}$$ Sensitive to $$\frac{g_{1L}D_1}{g_{1L}\tilde{D}}$$

- Suggests $\tilde{D}$ is roughly one order of magnitude smaller than D_1

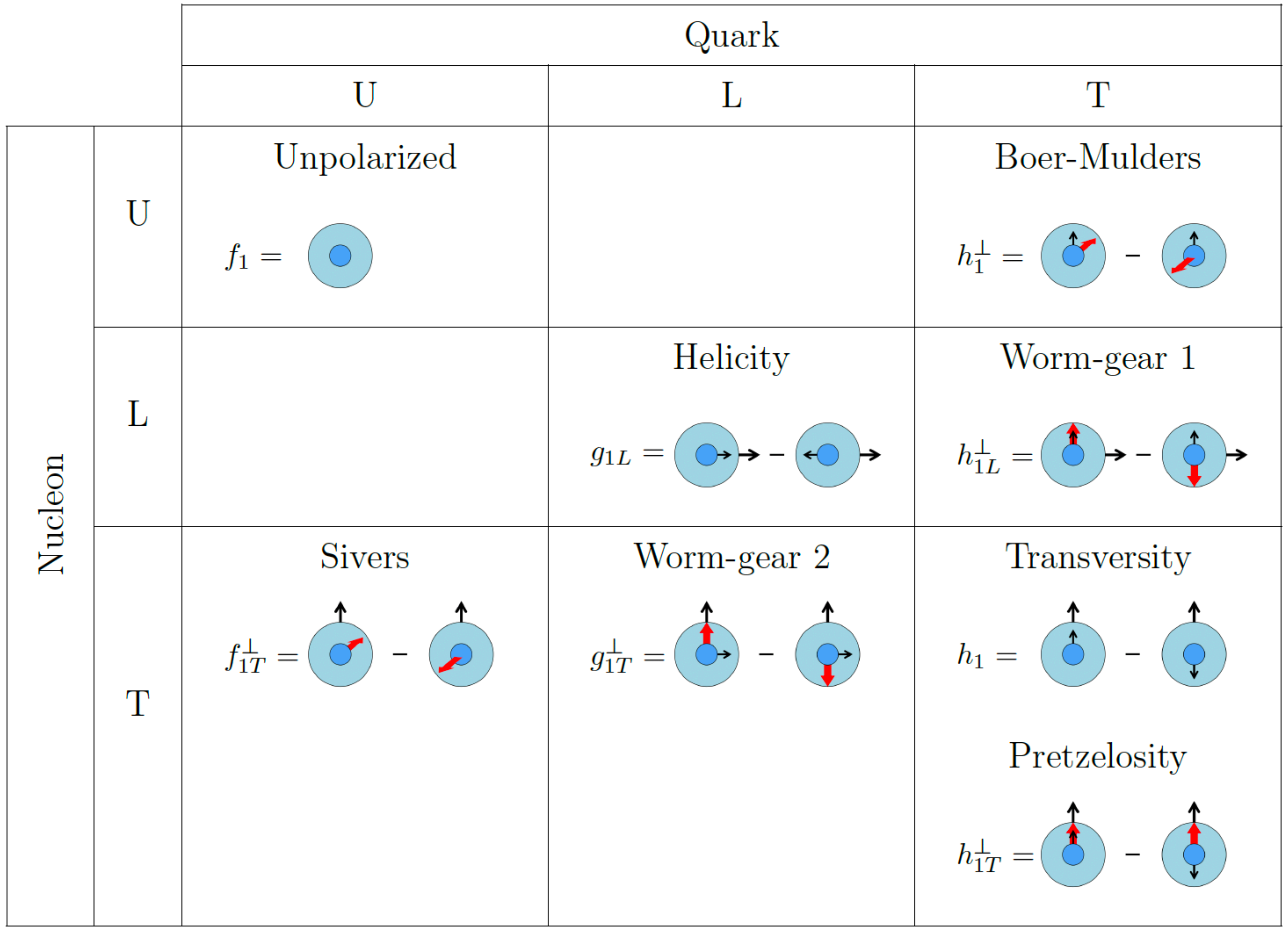
Outlook

- Dilution factor values calculated for $e^- p \rightarrow e^- \pi^+ \pi^- X$ channel
- Results of beam, target and double spin asymmetries obtained from longitudinally polarized NH_3 target data
- Analysis note mostly complete (except for systematics)
- Systematic studies will be done with new MC (correct vertex positions for RG-C)

Backup - transverse momentum dependent PDFs

- Depends on x and transverse momentum p_T^2 of struck quark

- Twist-t means contribution to cross section suppressed by $\left(\frac{M}{Q}\right)^{t-2}$



Twist-2

U - unpolarized
L - longitudinally polarized
T - transversely polarized

[4]

		Quark		
		U	L	T
Nucleon	U	$f^\perp$	$g^\perp$	$h,\ e$
	L	$f_L^\perp$	$g_L^\perp$	$h_L,\ e_L$
	T	$f_T,\ f_T^\perp$	$g_T,\ g_T^\perp$	$h_T,\ e_T,\ h_T^\perp,\ e_T^\perp$

Twist-3

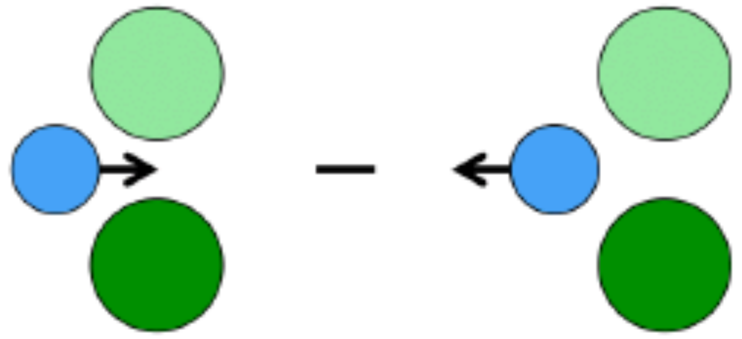
sensitive to quark-gluon correlations

Dihadron fragmentation functions

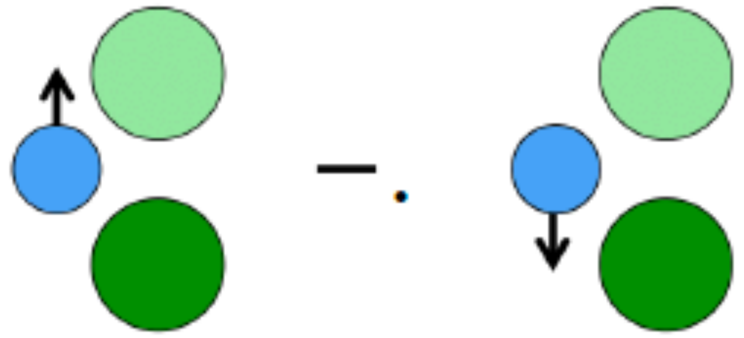
- Depends on z, M_h and transverse momentum k_T^2 of fragmenting quark $(k = p + q)$
- Probability difference of quark with a certain polarization to fragment into unpolarized hadrons

Unpolarized $D_1 =$

Longitudinally polarized $G_1^{\perp} =$



Transversely polarized $\overline{H}_1^{\angle}, H_1^{\perp} =$



[4]

Twist-2

$\tilde{D}^{\perp}$

$\tilde{E}$

$\tilde{G}^{\perp}$

$\tilde{H}$

Twist-3

References

[1] T. Hayward, Ph.D. thesis - “Dihadron beam spin asymmetries on an unpolarized hydrogen target with CLAS12” (2021)

[2] S. Gliske, A. Bacchetta, and M. Radici, Phys. Rev. D90, 114027 (2014)

[3] A. Bacchetta, M. Diehl, K. Goeke, A. Metz, P. J. Mulders, and M. Schlegel, JHEP 02, 093 (2007)

[4] S. Sirtl, Ph.D. thesis - “Azimuthal asymmetries in semi-inclusive deep-inelastic hadron muoproduction on longitudinally polarized protons” (2016)