Back-to-back hadron asymmetries

H. Avakian (JLab), T. Hayward (W&M)

CLAS12 collaboration Meeting, March 3, 2021

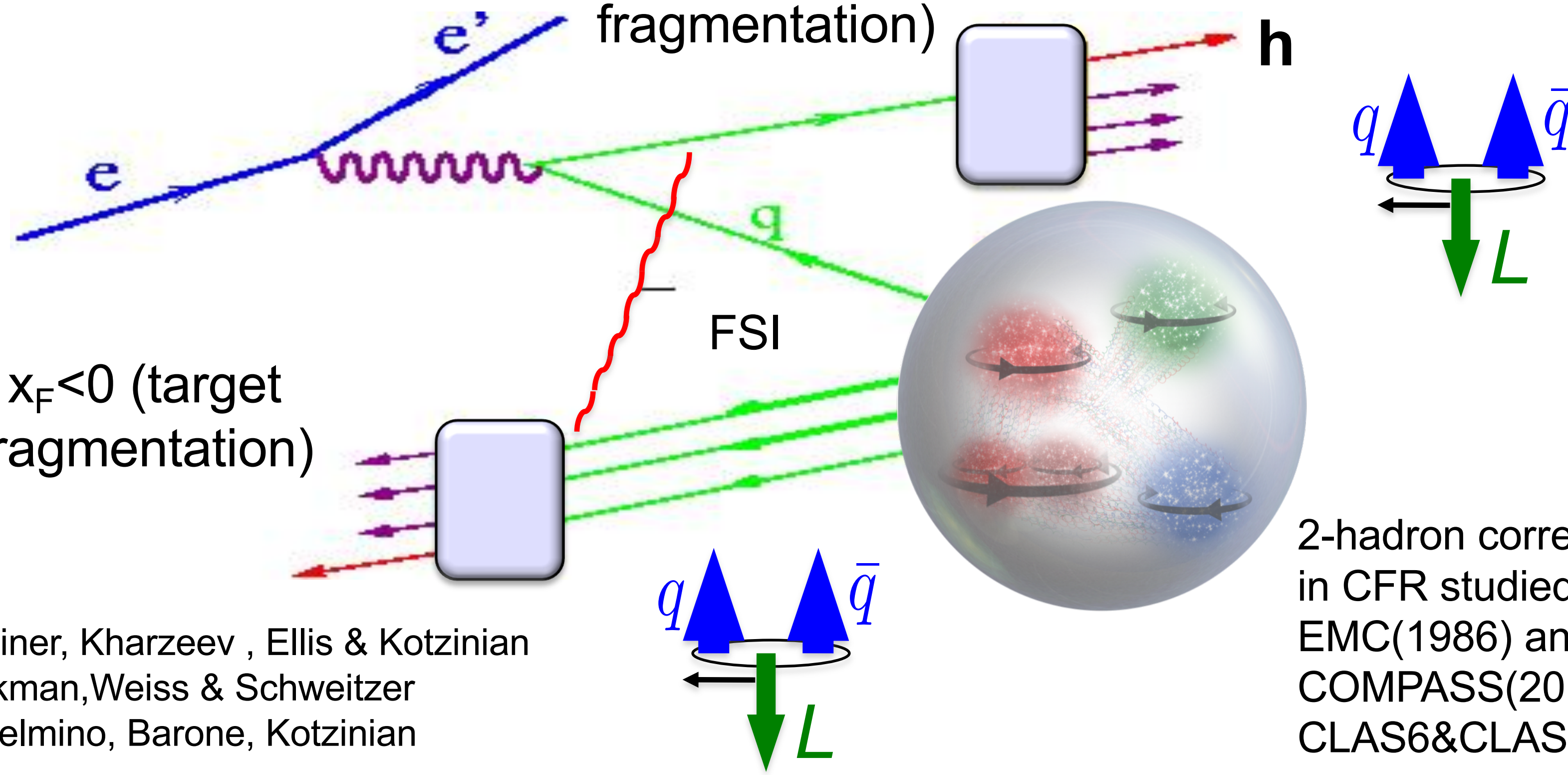
- Long range hadronic correlations and Fracture Functions
- SSA measurements in semi-inclusive nucleon-pion production
  - Inclusive proton pion SSAs
  - Inclusive proton di-hadrons SSAs
  - Other data sets
- LUND-MC and rec. efficiencies of protons and pions
  - Comparing data with MC: target vs current fragmentation
- Conclusions

Hadronic long-range correlations

x_F - momentum in the CM frame

$x_F = p_{L(CM)}/p_{Lmax} > 0$ (current fragmentation)

X. Artru & Z. Belghobsi



$x_F < 0$ (target fragmentation)

Karliner, Kharzeev , Ellis & Kotzinian
Strikman,Weiss & Schweitzer
Anselmino, Barone, Kotzinian

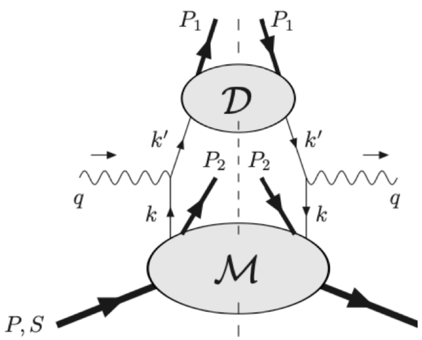
2-hadron correlations in CFR studied in EMC(1986) and COMPASS(2015) CLAS6&CLAS12

Modeling of q-q-bar correlations with spins and momenta in the process (not in PYTHIA) will be important for understanding of the dynamics

B2B hadron production in SIDIS: Theory

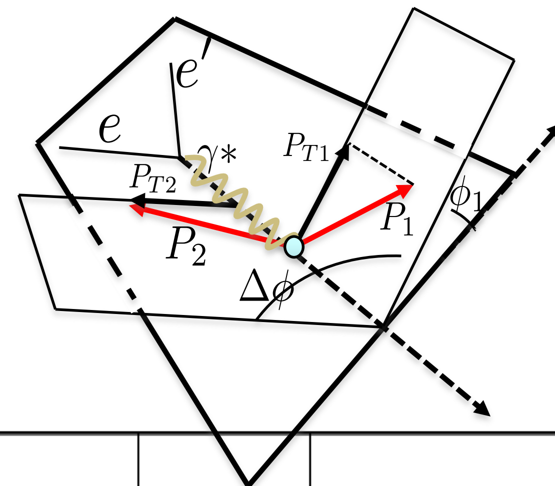
M. Anselmino, V. Barone and A. Kotzinian,
Physics Letters B 713 (2012)

$$ep \rightarrow e' p \pi^+ X$$



$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}} \sin\Delta\phi$$

$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2} \frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \times \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi,$$



Fracture Functions define the probability for hadron production (P2) given the struck quark q. Combined with the fragmentation function (defining probability for quark q to produce a hadron (P1) defines the x-section for 2 hadron production.

	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

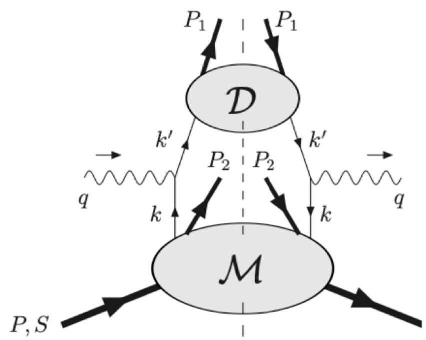
$$\mathcal{F}_{UU} = \mathcal{C}\left[\hat{u}_1 D_1\right]$$

$$\mathcal{C}\left[f(\mathbf{k}_\perp, \mathbf{k}'_\perp, \ldots)\right] \equiv \sum_a e_a^2 x_B \int \mathrm{d}^2\mathbf{k}_\perp \int \mathrm{d}^2\mathbf{k}'_\perp \times \delta^2(\mathbf{k}_\perp - \mathbf{k}'_\perp - \mathbf{P}_{1\perp}/z_1)\, f(\mathbf{k}_\perp, \mathbf{k}'_\perp, \ldots).$$

Probability to produce a hadron for a given longitudinally polarized quark

B2B hadron production in SIDIS: First measurements

M. Anselmino, V. Barone and A. Kotzinian,
Physics Letters B 713 (2012)

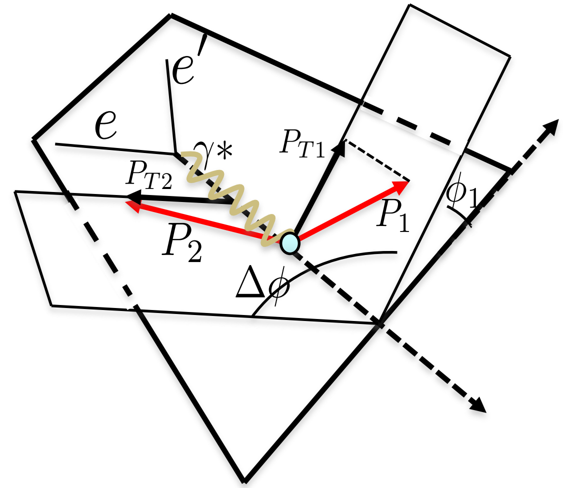


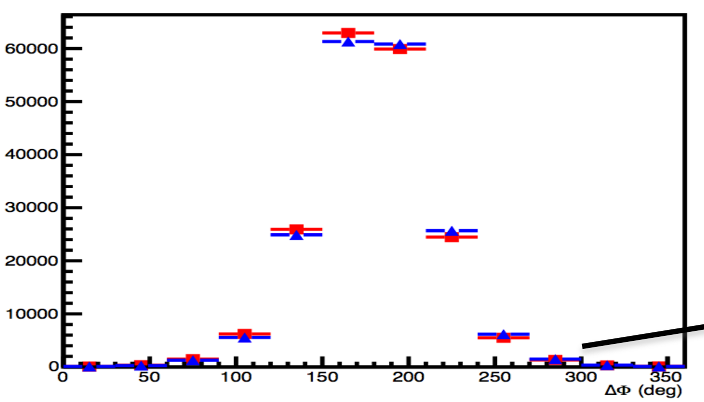
$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}} \sin\Delta\phi$$

$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2} \frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \times \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi,$$

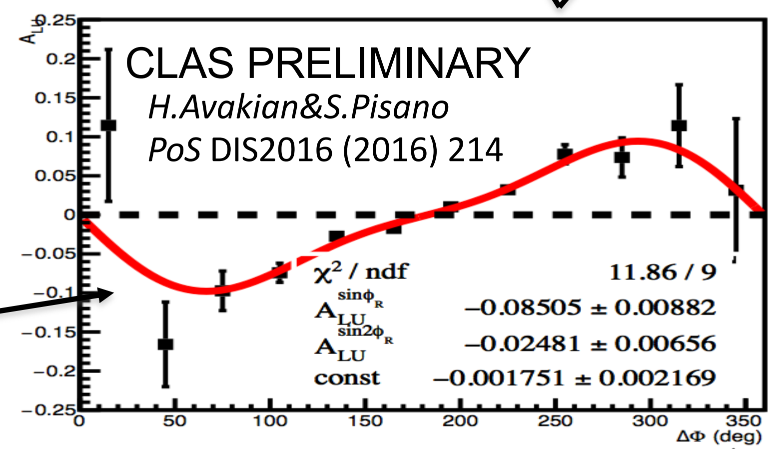
$$\mathcal{F}_{UU} = \mathcal{C}\left[\hat{u}_1 D_1\right]$$

$$ep \to e' p \pi^+ X$$





$\Delta\phi$

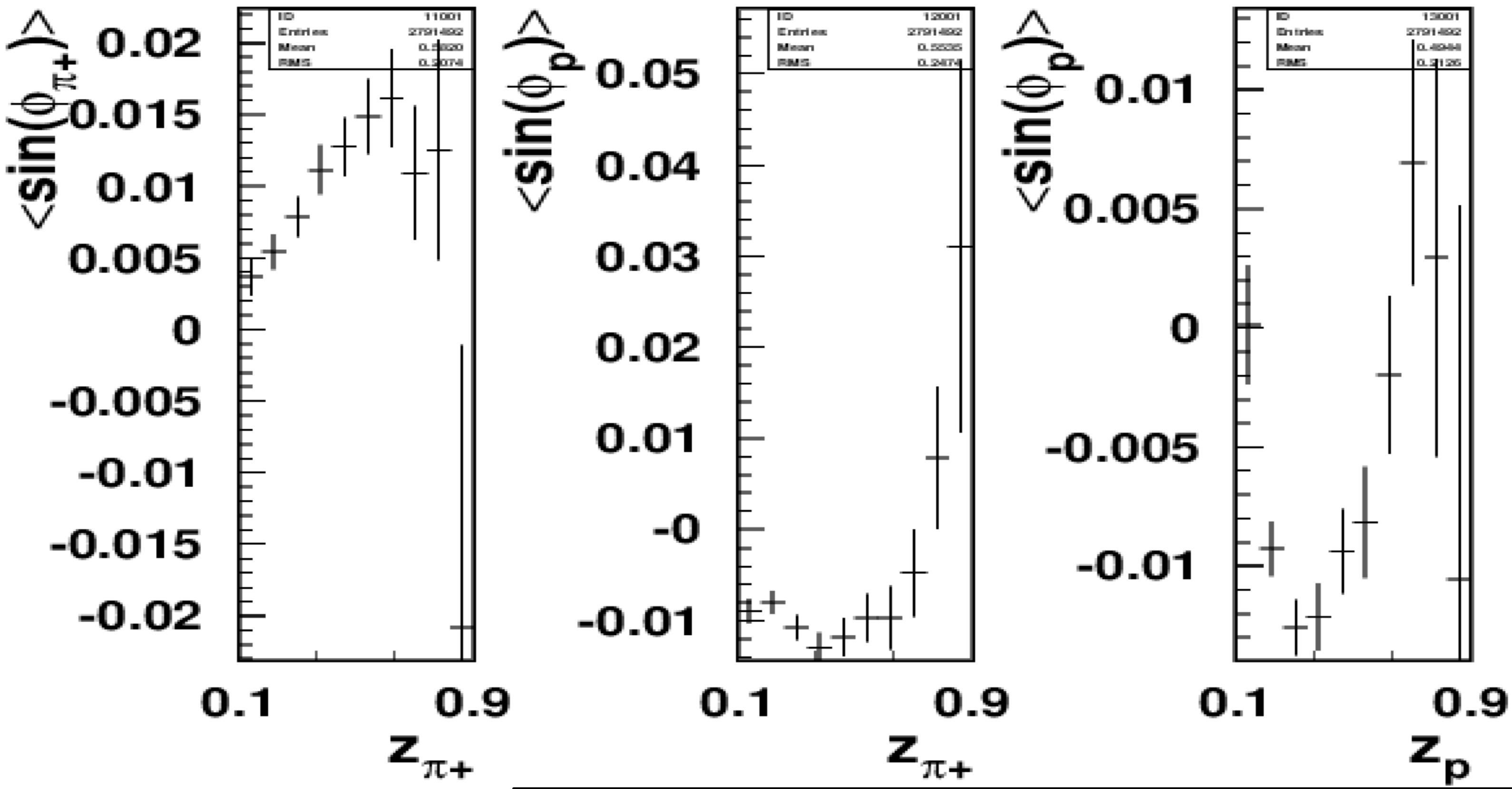


$\Delta\phi$

Significant correlation asymmetries observed by CLAS

SSAs in ep→e'pπ+X production

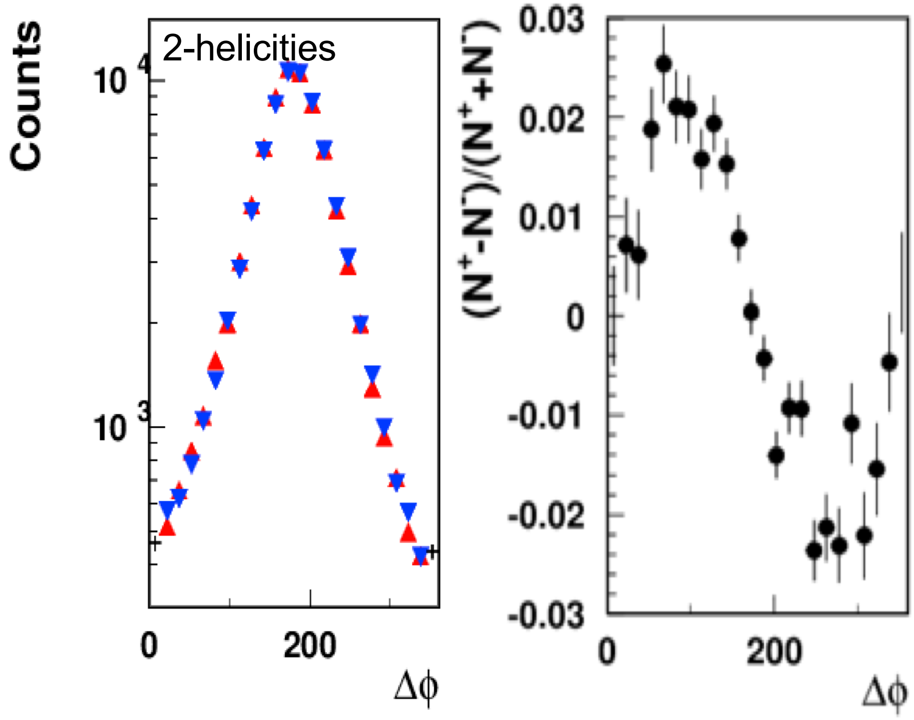
Comparing with single hadron SSAs:

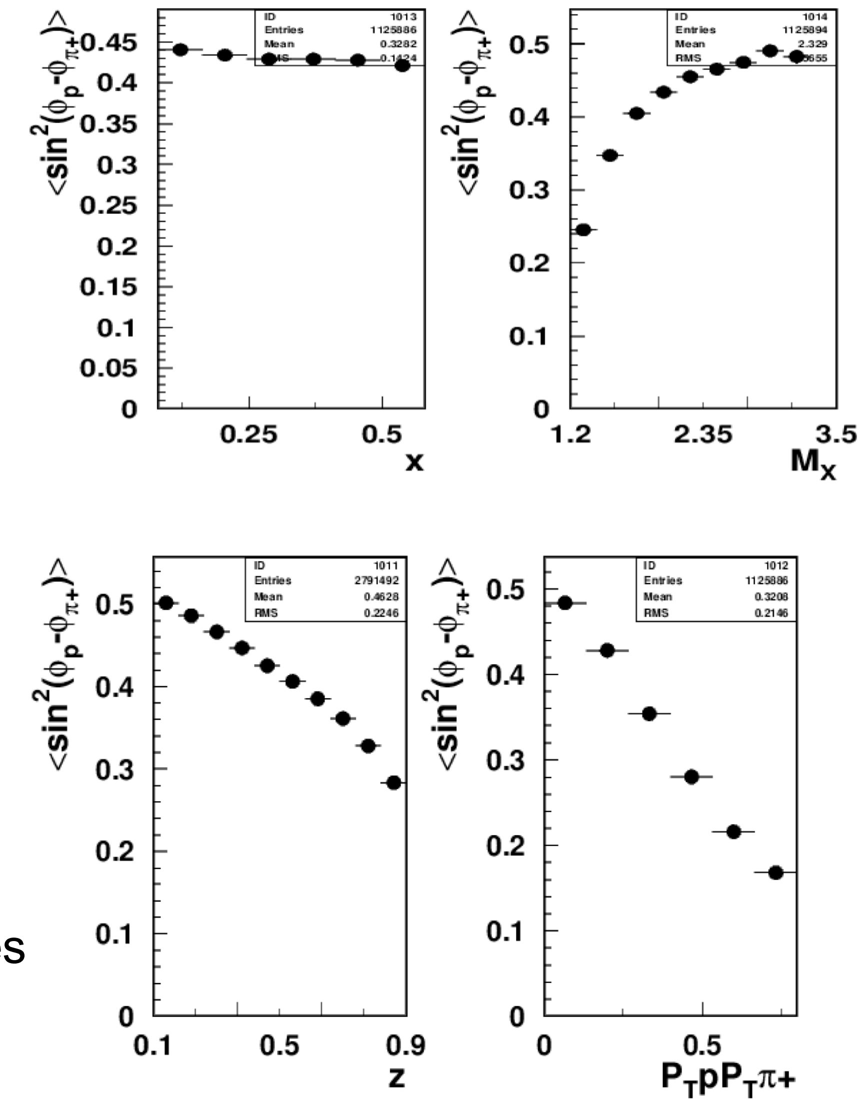


Observed e'π+X consistent with our sinle pi+X in size and kinemtical depenences.

- Observed for the first time proton SSA e'pX is negative and significant
- Should be extracted separately in multi-dim. bins!!!

$\vec{e}p \rightarrow e'p\pi X$: Correlation SSAs



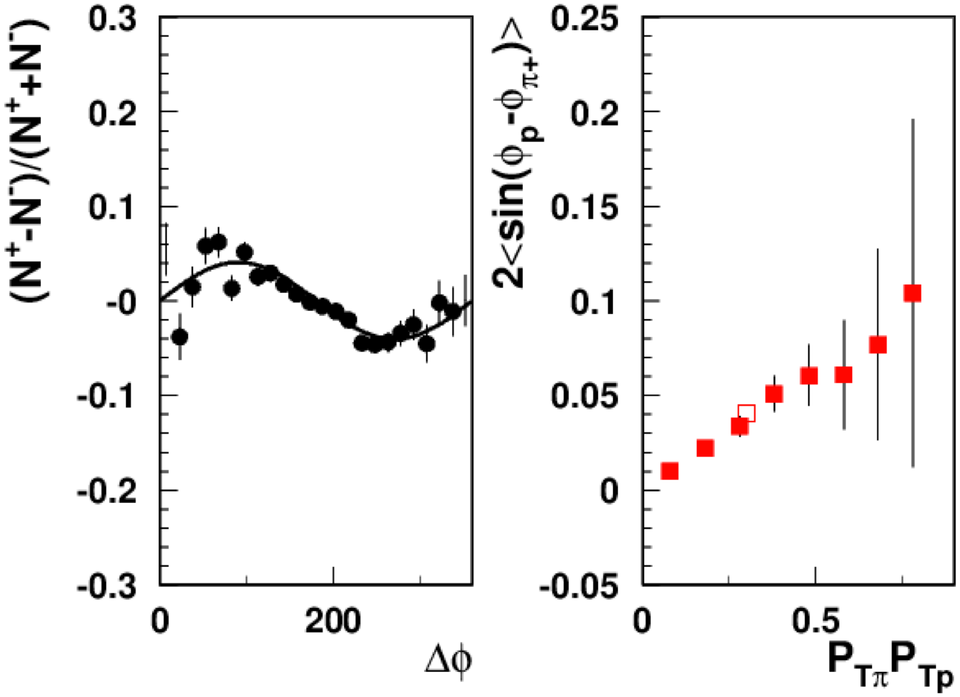


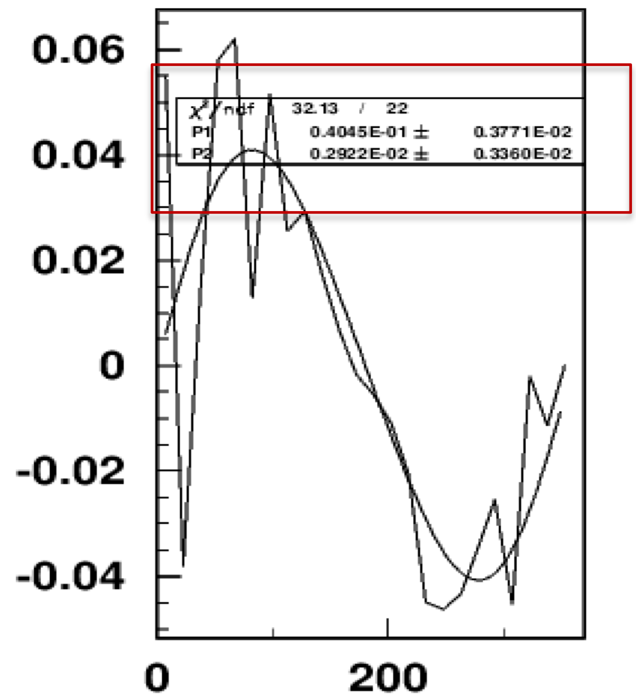
Using the RGA "golden" run list

$\Delta\phi=\phi_p-\phi_\pi$

Average $<\sin^2\Delta\phi>$ provides info on the shape of the distributions

B2B SSA Extraction methods





$$A_{LU}^{\sin\phi} = \frac{\sum_{i=1}^{N^{\pm}} \sin\phi_i}{P\sum_{i=1}^{N^{\pm}} \sin^2\phi_i}$$

$$A(\phi)_{LU} = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}.$$

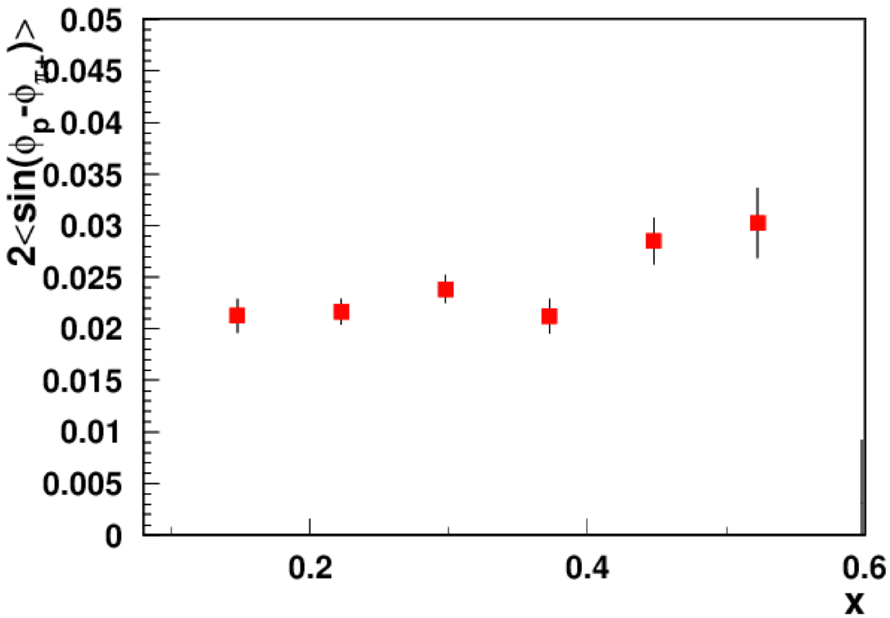
Two approaches with different sensitivity to acceptance and statistics, yield consistent values for the sinΔϕ, moment sin2Δϕ seem to be small, and require more detailed studies

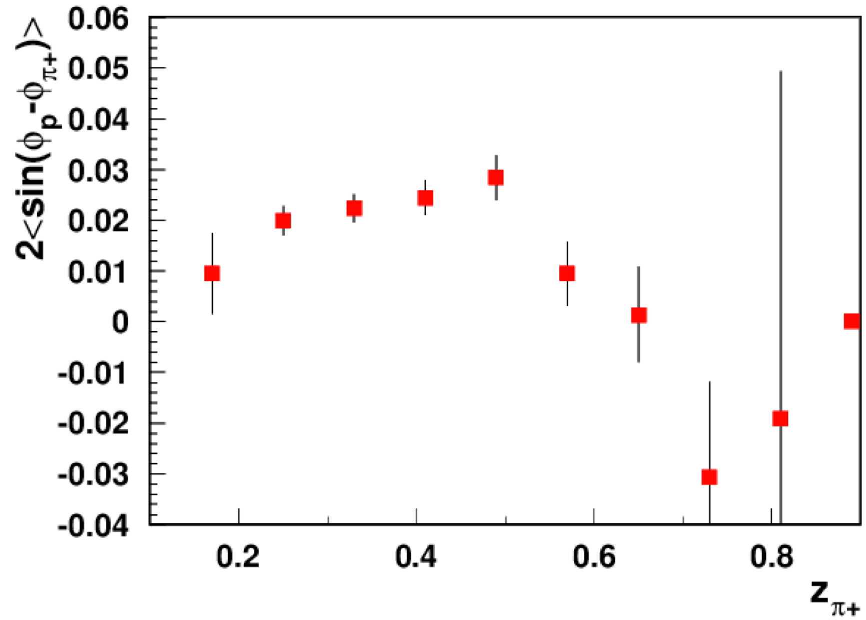
SSAs kinematic dependences: ep→e'pππX

RGA-inbending

$Q^2>1, W^2>4, E_e>2.6$ GeV
$E_p>0.5, E\pi+>1.2$
$\Delta Vz(p-\pi+)<2$cm
$M_{e\pi X}>1.6$, $M_{ep\pi X}>0.6$ (suppress exclusive)
$\Delta\eta(p-\pi+)>1$(current/target)

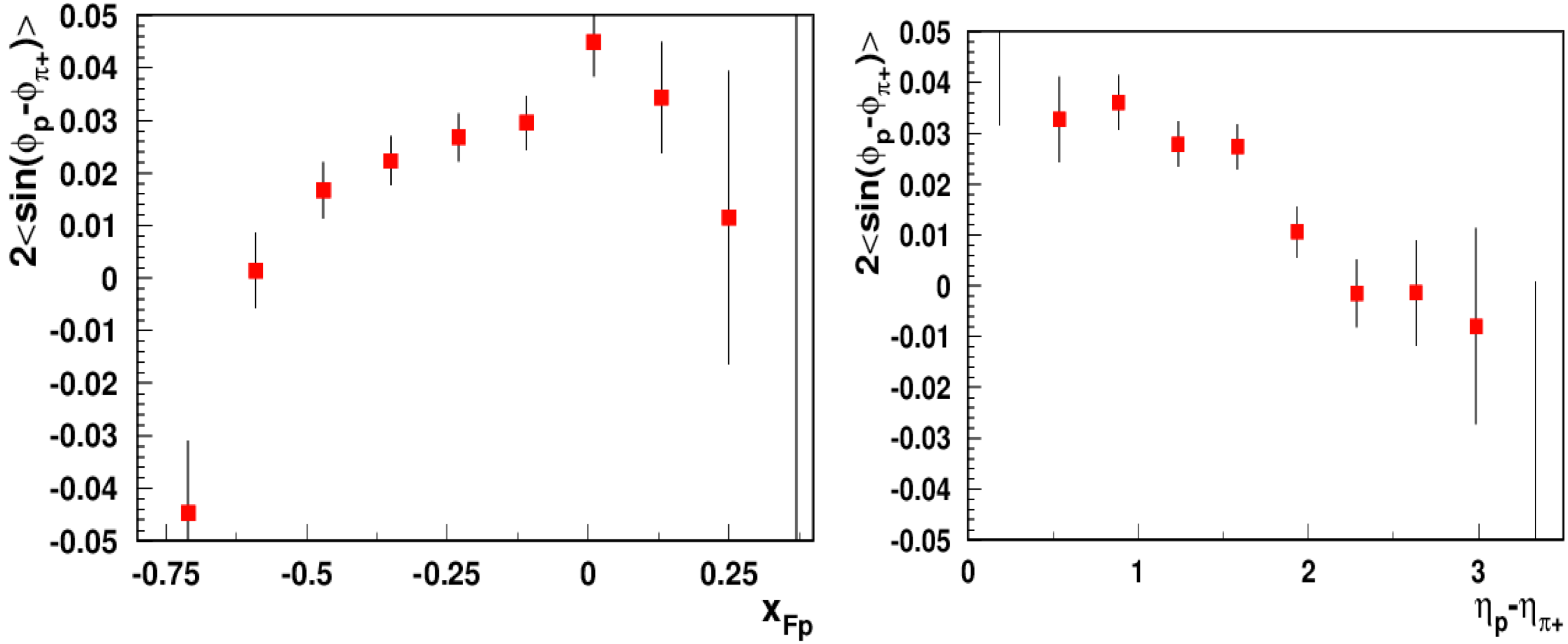
The SSA seem to have week dependence on x, dropping at large z (phase space for large P_T limited)





SSAs kinematic dependences: ep→e'pππX

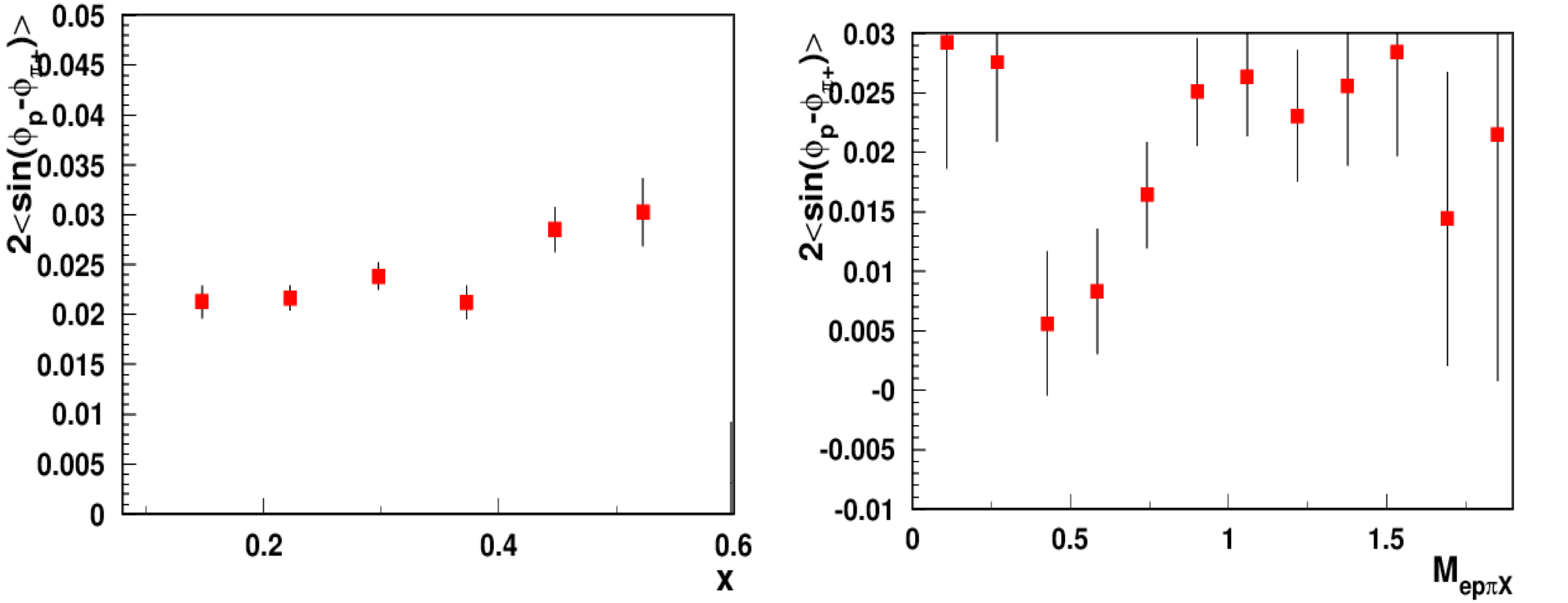
$x_F = 2P_L^{CM}/W$ RGA-inbending $\eta = \frac{1}{2}\frac{E^{CM}+P_L^{CM}}{E^{CM}-P_L^{CM}}$



At higher proton momenta in CM frame (target fragmentation) the SSA drops, as the average P_Ts get suppressed due to phase space

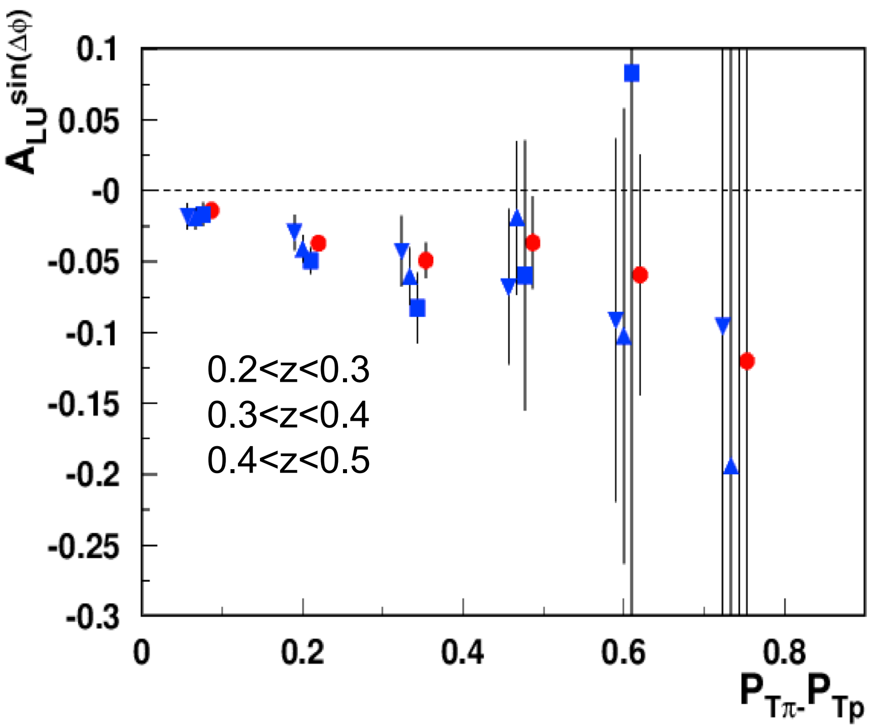
SSAs kinematic dependences: ep→e'pππX

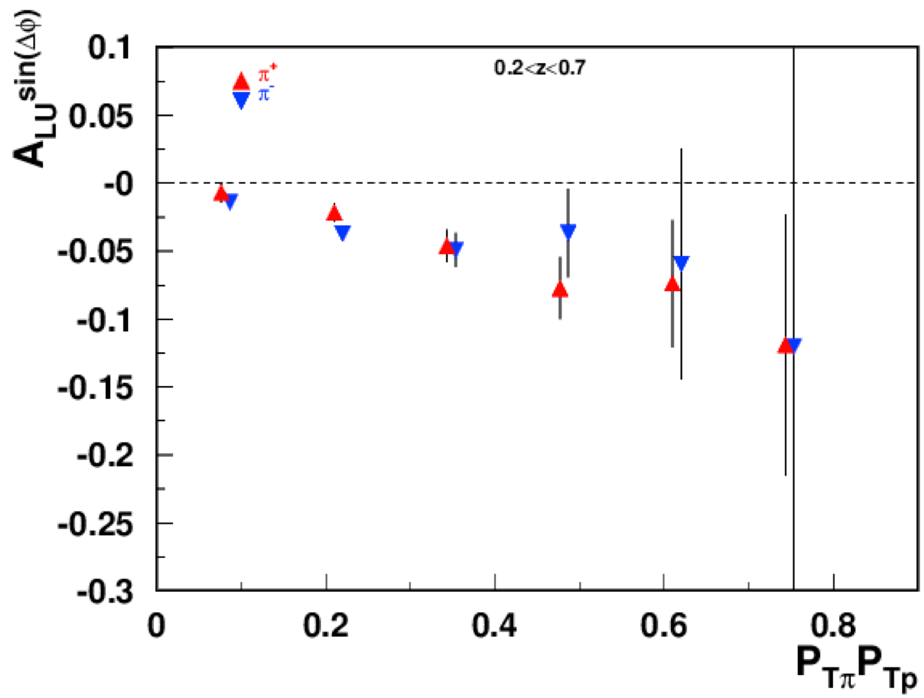
RGA-inbending



The SSA seem to depend on the missing mass of the the e'pπX (more studies needed to define the source)

B2B SSAs: ep→e'pπ–X vs ep→pπ+X



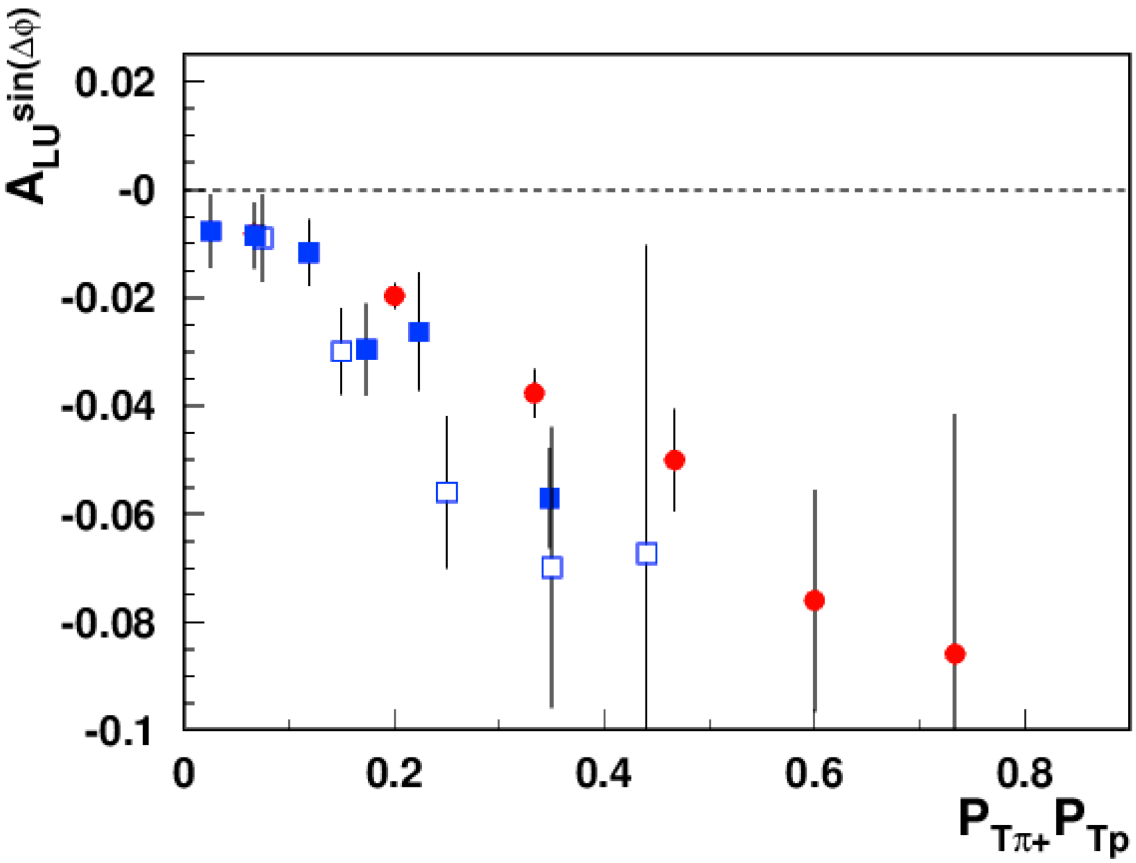


Using the RGA "golden" run list

B2B SSA has unique features

- There is no significant z-dependence
- π^-p and π^+p SSAs are practically the same in the z-region of 0.2<z<0.6 (ρ0?)

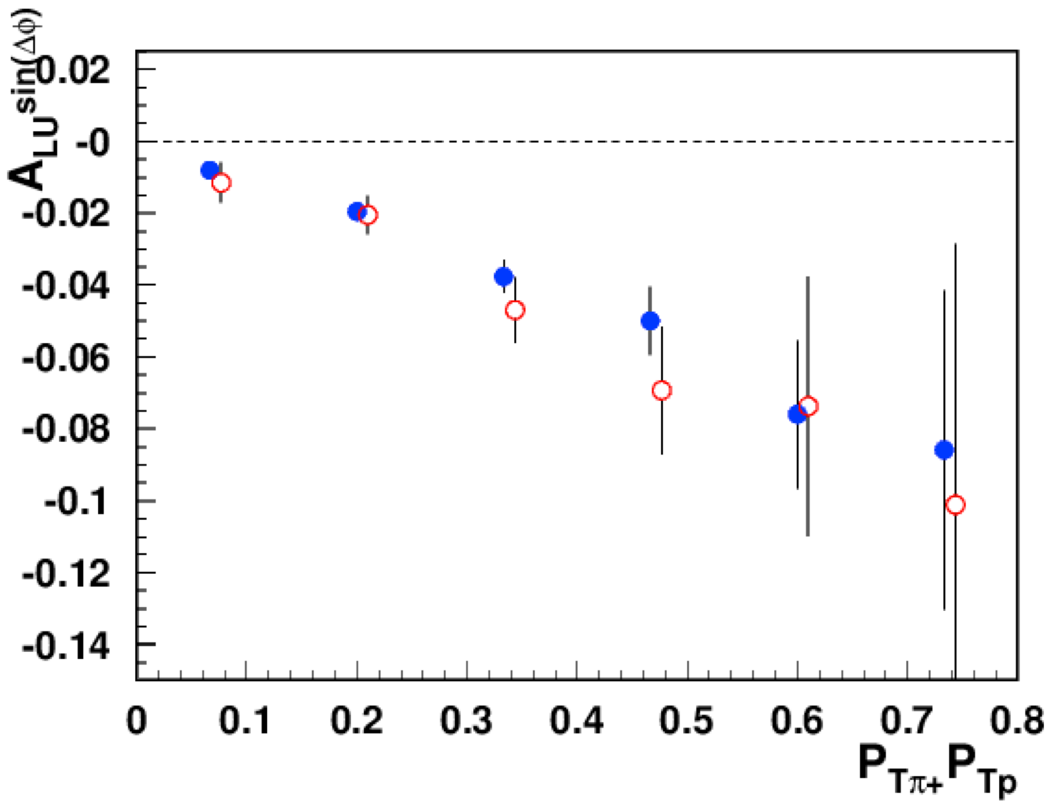
B2B SSA: ep→pπ+X compatibility with CLAS6



Blue symbols e1f(filled) and e16(empty)
Red CLAS12-RGA2018-inbending

The behavior and the magnitude of observed SSAs consistent with studies performed with CLAS6 data sets

B2B SSA $ep \rightarrow p\pi+X$: inbending vs outbending

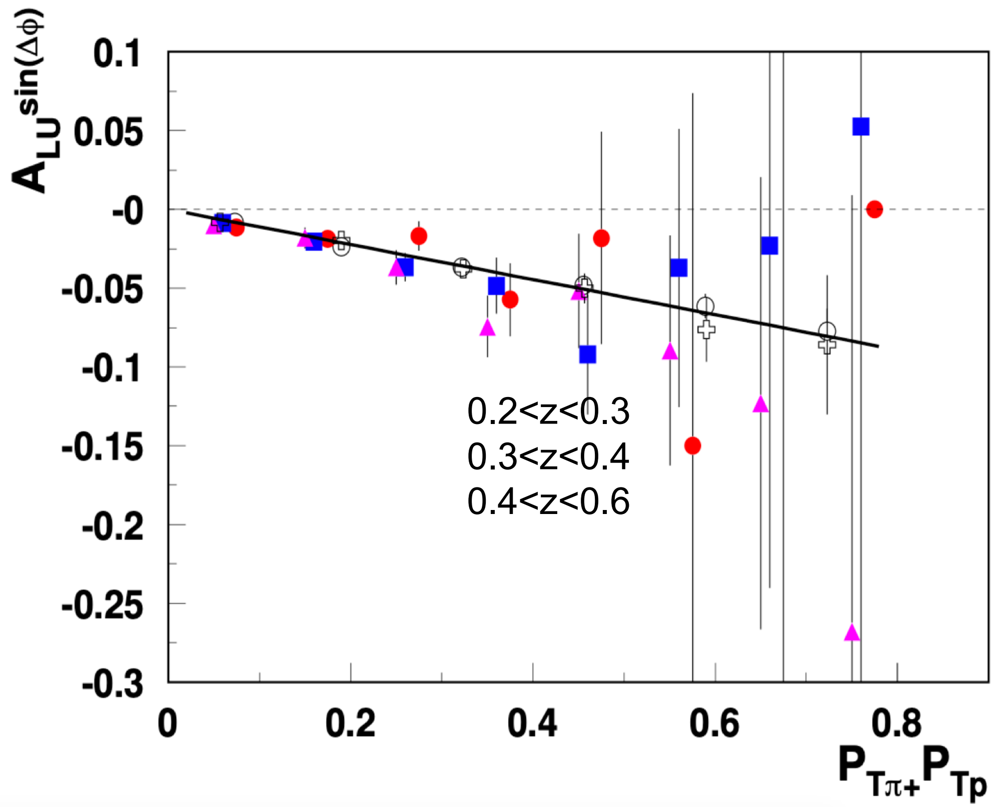


Blue symbols RGA2018 inb
Red outbending (~10%)

$Q^2>1, W^2>4, E_e>2.6$ GeV
$E_p>0.5, E\pi+>1.2$
$\Delta Vz(p-\pi+)<2$cm
$M_{e\pi X}>1.6$, $M_{ep\pi X}>0.6$ (suppress exclusive)
$\Delta\eta(p-\pi+)>1$(current/target)

The behavior and the magnitude of observed SSAs consistent for inbending and outbending RGA sets

B2B SSAs ep→pπ+X" the cross check



Open circles T.Hayward
Croses 0.2<z<0.7

$$A_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

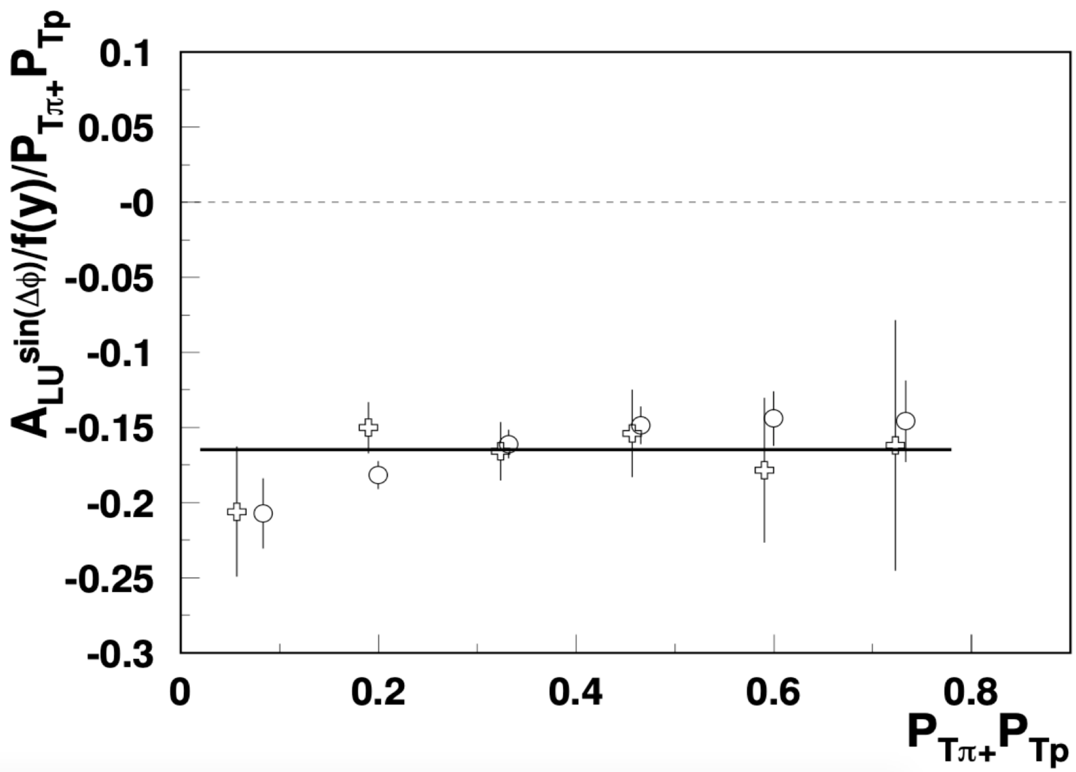
$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2}\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \times \frac{\mathcal{C}[w_5\,\hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}\sin\Delta\phi,$$

May be canceling out in large x
(true for u-quark dominance)

$$-\ln\mathcal{L} = (N_+ + N_-) - \sum_{j=1}^{N_+}\ln\left[1+PA_{LU}(\phi_P,\phi_\pi;A_{LU}^{\Psi_i})\right] - \sum_{j=1}^{N_-}\ln\left[1-PA_{LU}(\phi_P,\phi_\pi;A_{LU}^{\Psi_i})\right]$$

No significant z-dependence below z~0.7
Extractions of SSA consistent between 2 completely independent analysis (minimizing the negative log of the likelihood)

B2B SSA ep→pπ+X: SF ratio



Open circles T.Hayward
Crosses 0.2<z<0.7

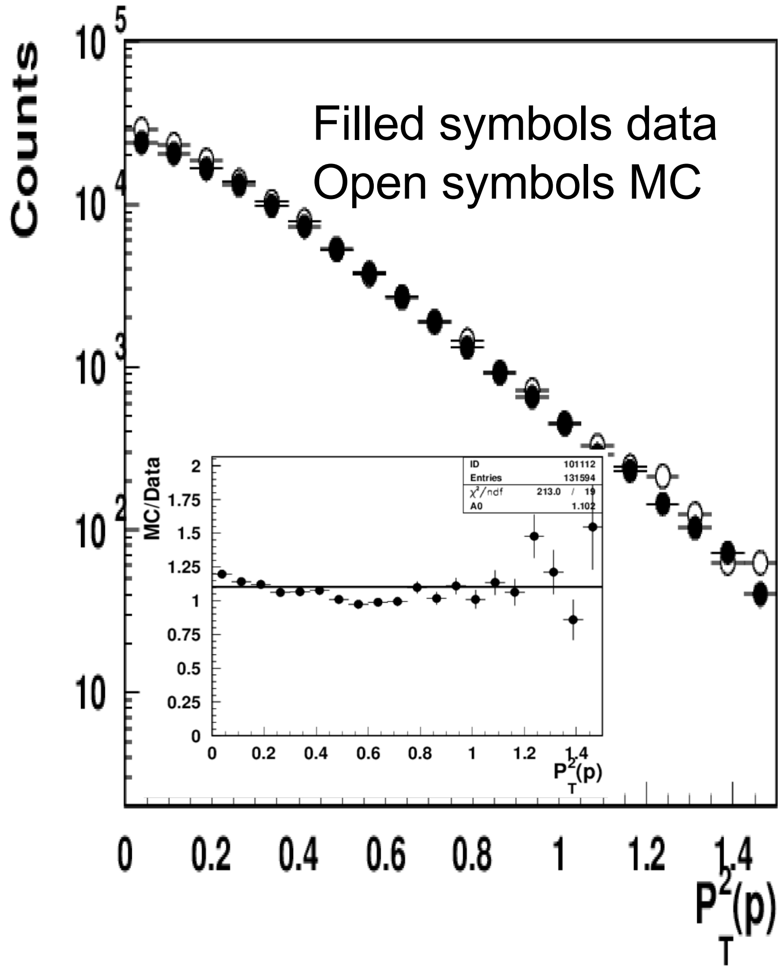
$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$
$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2}\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}$$
$$\times\frac{\mathcal{C}[w_5\,\hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}\sin\Delta\phi,$$

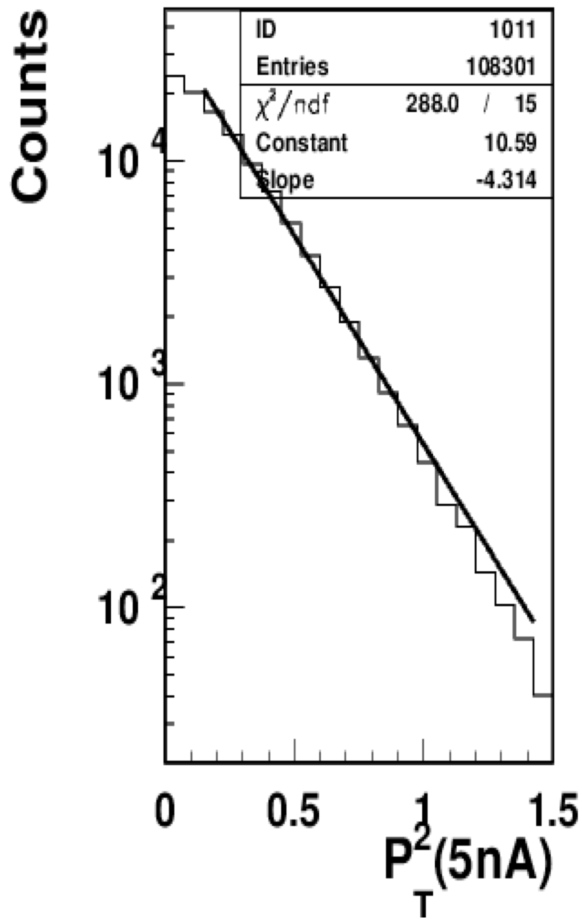
No indication for a significant P_T-dependence for the sample integrated up to z=0.7

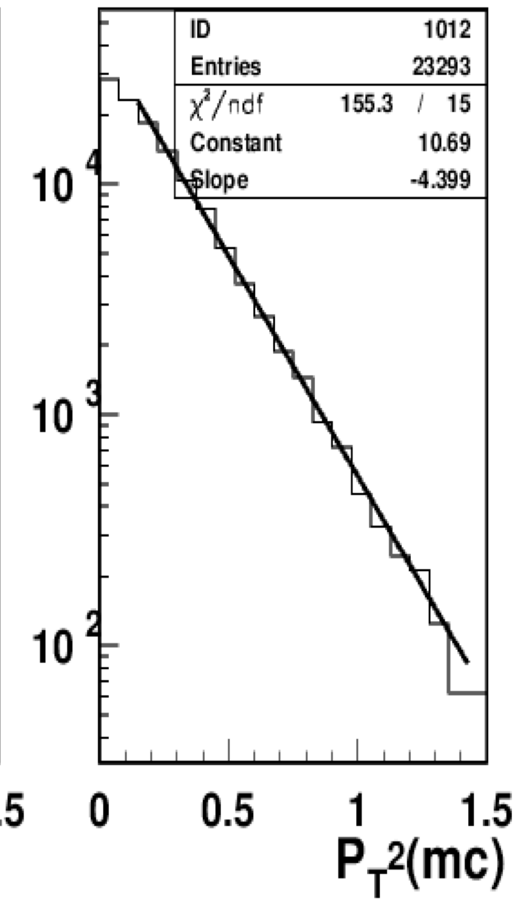
The long range correlation observed between hadrons in target and current fragmentation is directly related to the ratio >16%

CLAS12 TFR Studies: Data vs MC

Using PEPSI (LUND) generator



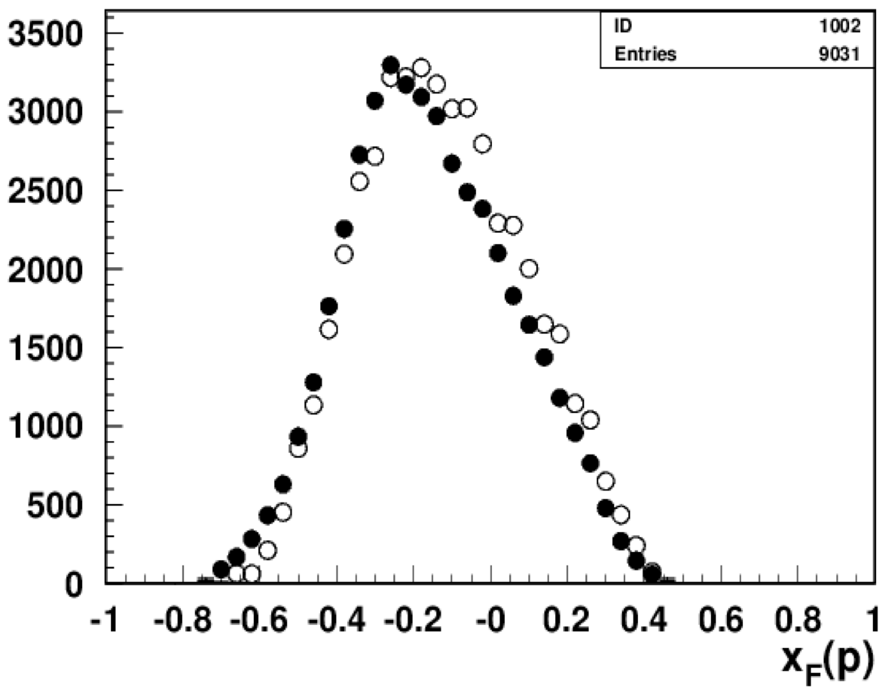


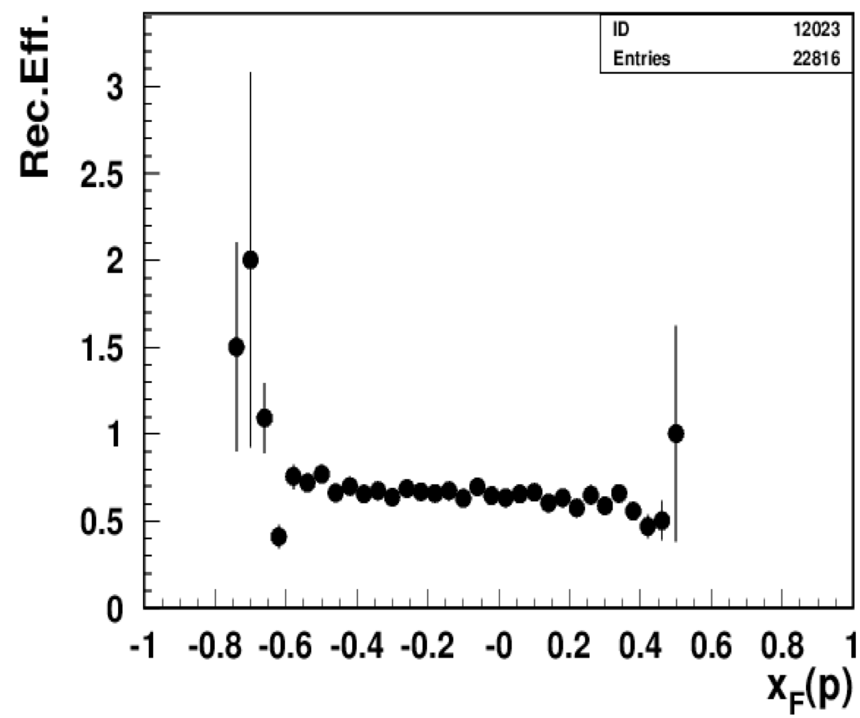


- P_T-distributions of protons, and widths are in good agreement with LEPTO
- May be a source for widths in hadronization

Protons: data vs clasdis

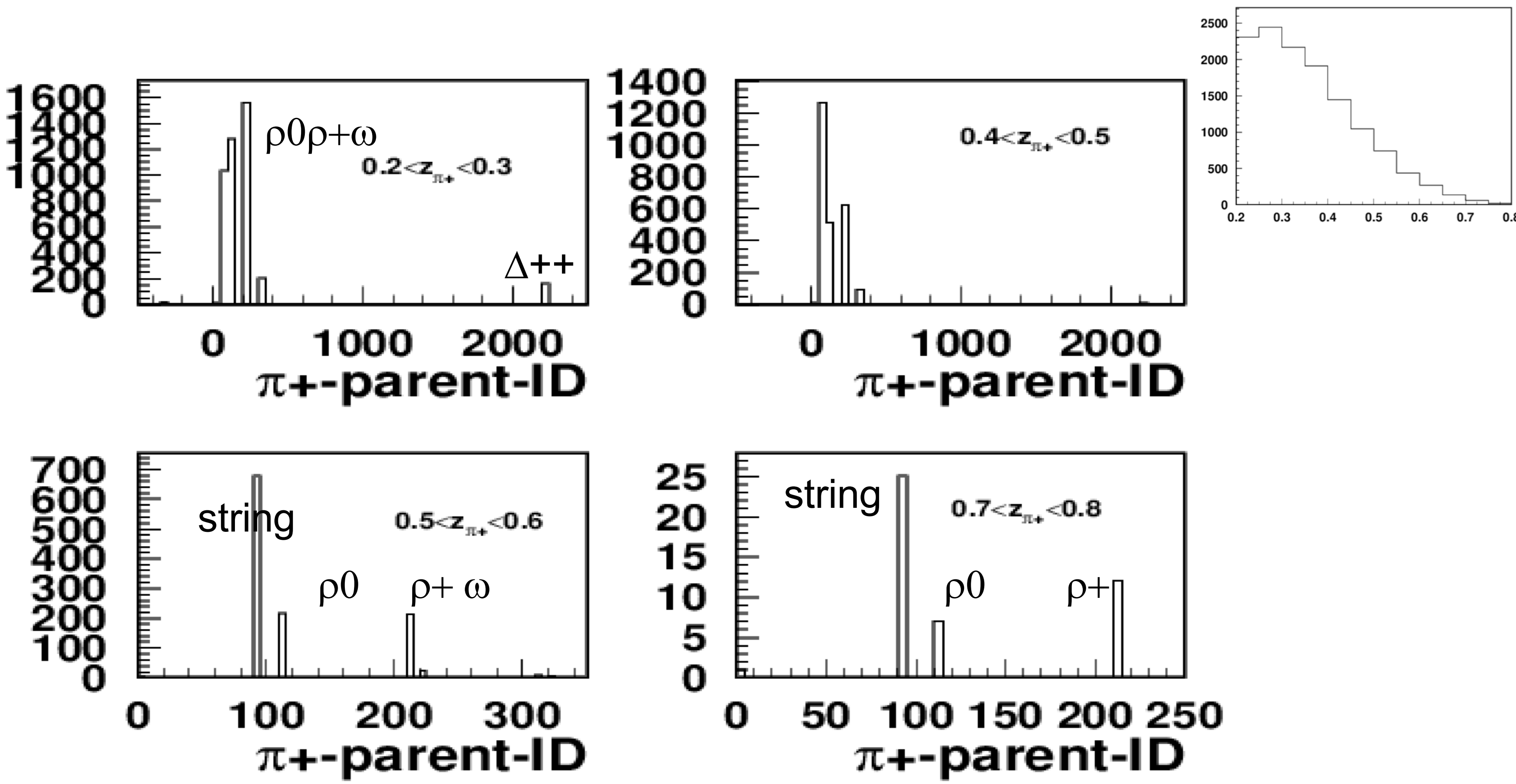
Variables used to see the kinematics in current and target fragmentation
X_F,rapidity





Data and clasdis clas12 MC are consistent
No significant dependence on kinematical variables for rec.eff.

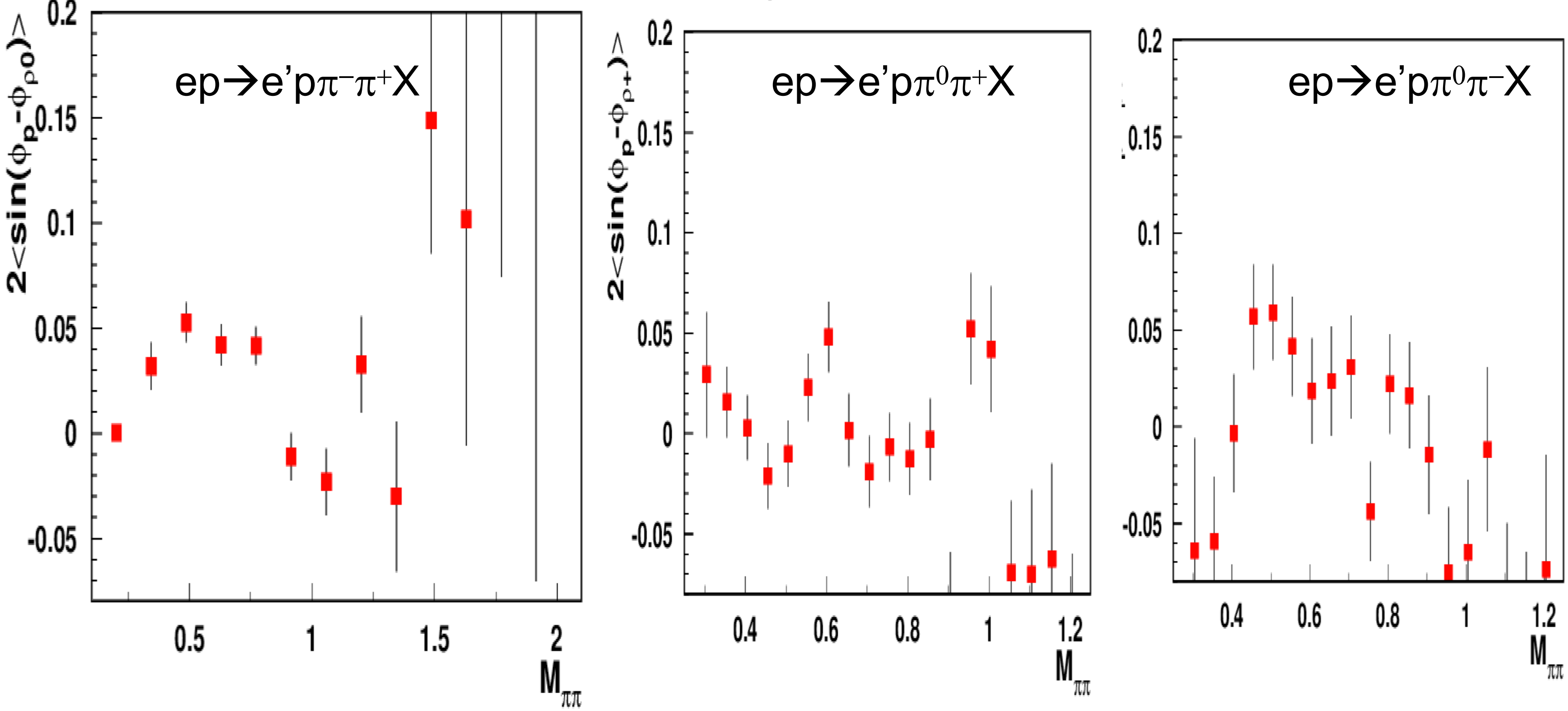
π+ parents in ep→e'pπ^+X events



Tiny fraction of pions come from Δ++ at z~0.2, and at large z mainly from string and ρ

SSAs for other hadrons: ep→e'pππX

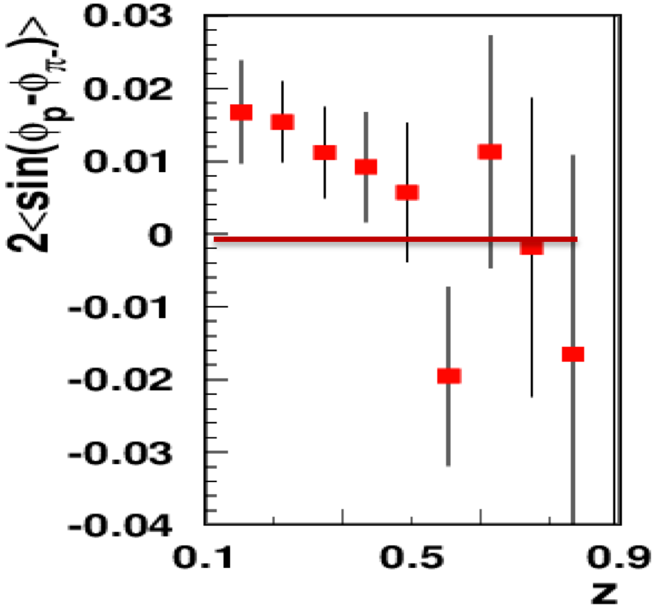
RGA-inbending

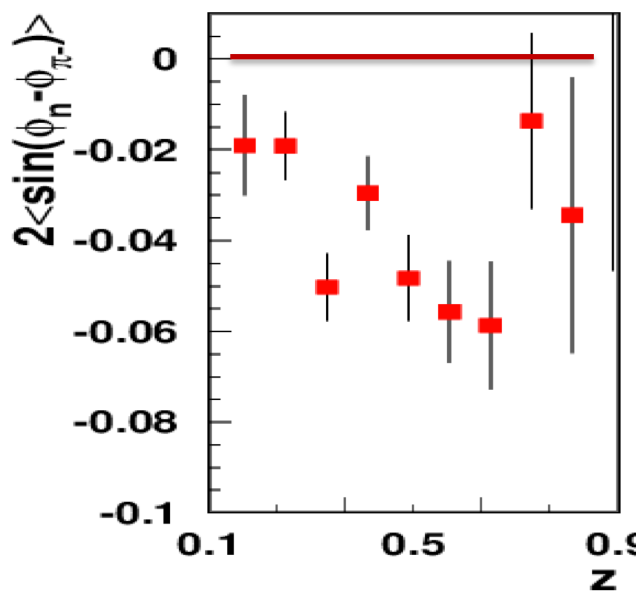


The SSA seem to depend on the invariant mass of the pion pair (more studies needed to define the source)

RGB SSAs: ed→e'pπ–X vs ed→e'nπ–X

RGB-inb+outbending (10%)





RGB ed→e'pπ–X ed→e'nπ–X seem to have opposite signs for low z
Crucial to have a good neutron ID !!!

SUMMARY

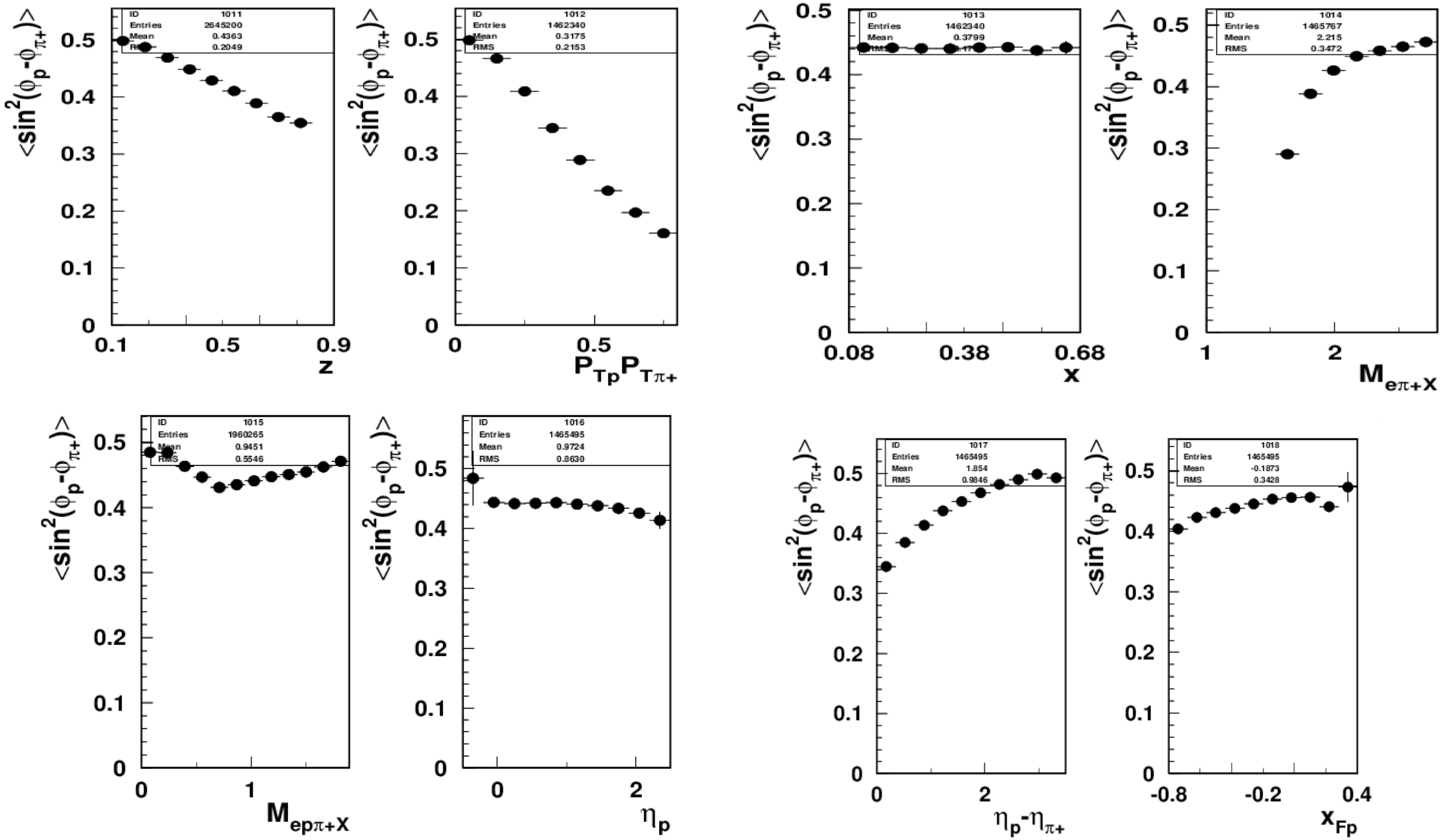
- Significant B2B asymmetries observed with CLAS12 indicating strong long range correlations between target and current fragmentation regions
- B2B asymmetries observed with CLAS12 are consistent with preliminary studies performed with clas6
- Significant SSAs observed in nucleon-pion correlations for all pions in RGA and RGB, could be addressed in separate studies
- Significant negative SSA is expected for inclusive proton production (may be also neutron)
- LUND-MC describes well the proton-pion data in a major part of accessible energy range and can be used to extract the acceptance in multidimensional bins (neutrons are flooded by photon)

Plans:
Converge with the cross check in multi-dimensional space
Publish first the ep→e'pπ^+X (the analysis note and the draft of the paper in progress)

Extend studies to RGB, both for ed →e'p$\pi^{+/-}$X, ed →e'n$\pi^{+/-}$X (D. Thi Nguyen, A. Gadsby)
Extend studies of sin$\Delta\phi$ moment to 2pion correlations (C.Dilks)
Extract the beam SSA in ep→epX (D. O'Neil)
Studies of cos2$\Delta\phi$ moment for pions and nucleons(M. Arratia, S. Paul)

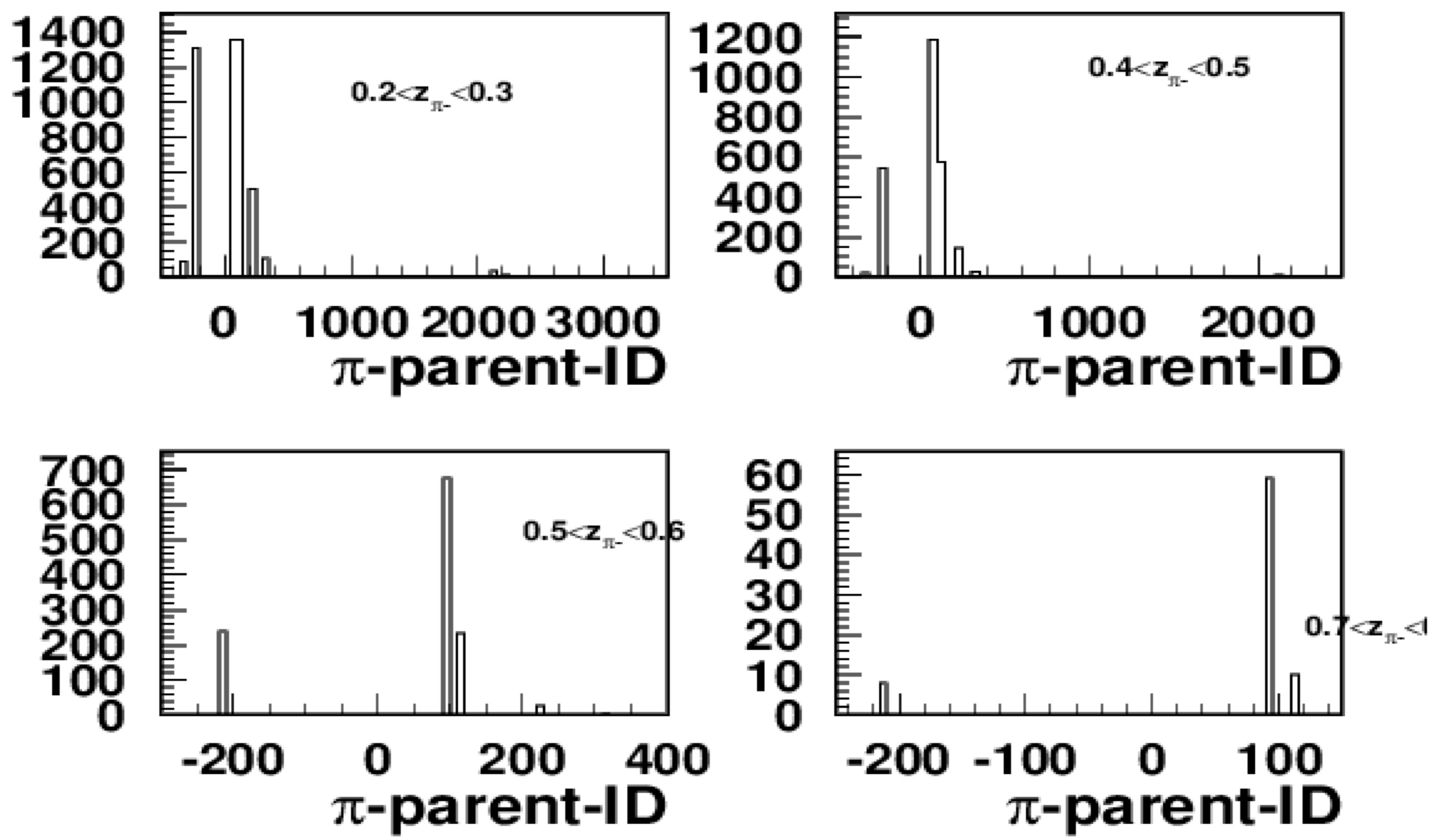
Support slides

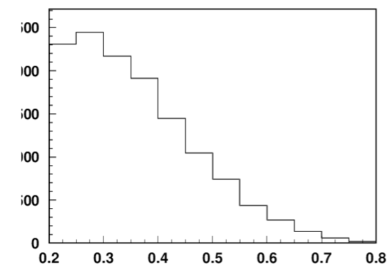
ep→e'pπ⁺X: distribution shapes



Shape of distributions is described by the $<\sin^2\Delta\phi>$

π– parents in ep→e'pπ⁻X events

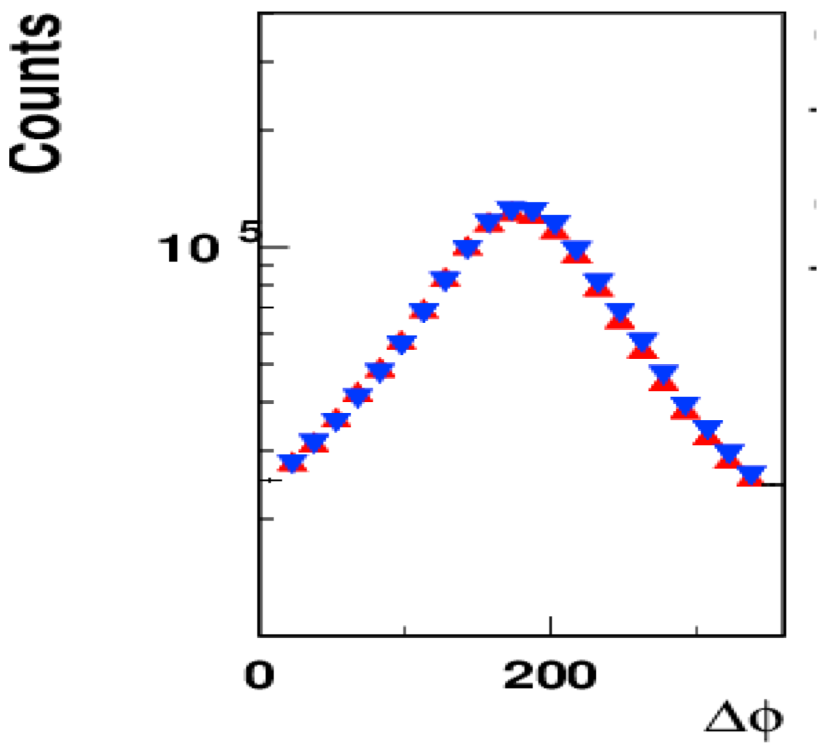




Tiny fraction of pions come from Δ at z~0.2, and at large z mainly from string and ρ

B2B SSA Extraction methods

https://userweb.jlab.org/~avakian/tmp/clasnotedvcs.pdf



3 methods

$$A_{LU}^{\sin\phi} = \frac{\sum_{i=1}^{N^\pm} \sin\phi_i}{P\sum_{i=1}^{N^\pm} \sin^2\phi_i}$$

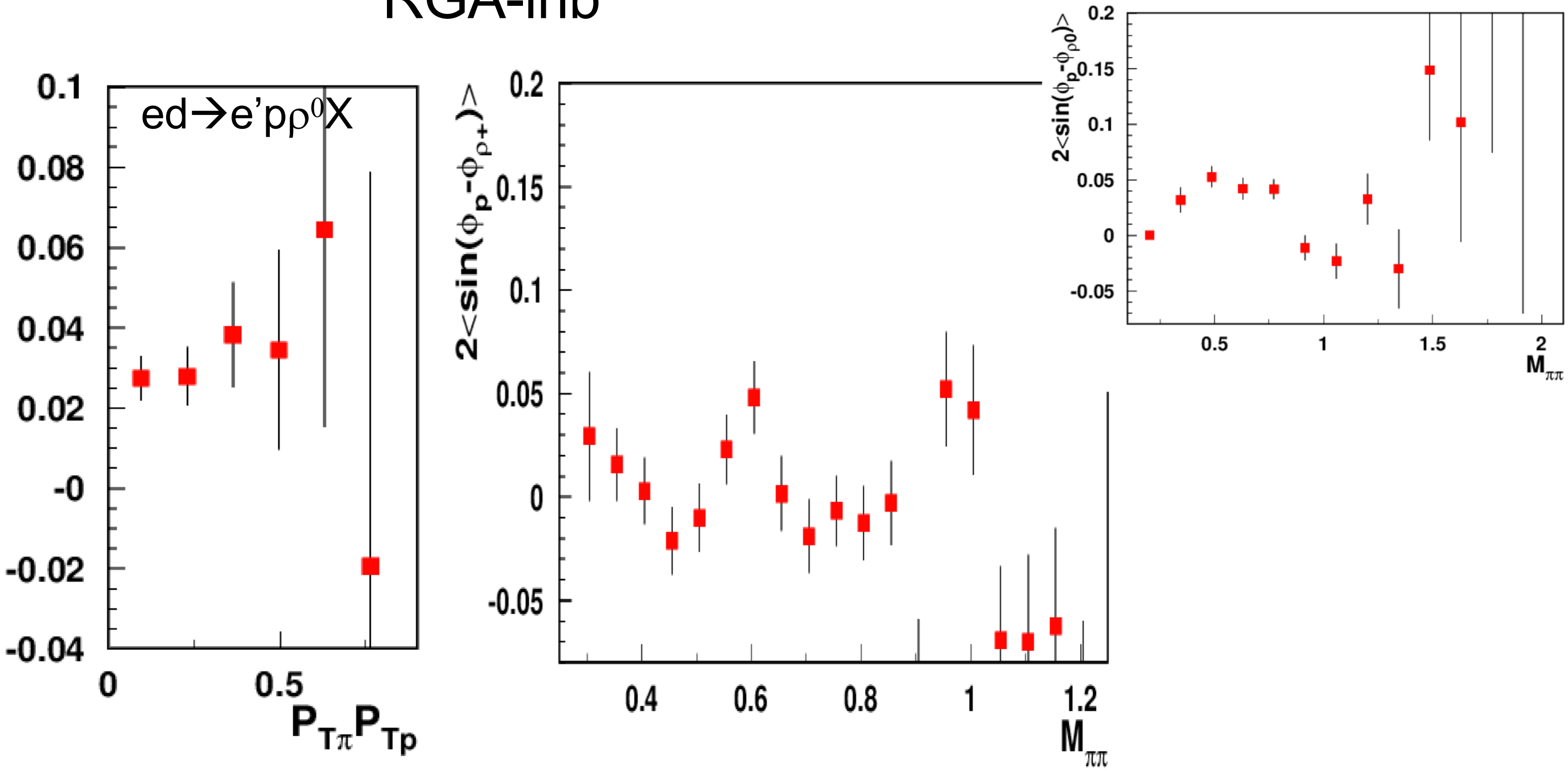
$$A(\phi)_{LU} = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}.$$

$$A(\phi)_{LU} = \frac{\pi}{2P}\frac{N(0<\phi<\pi) - N(\pi<\phi<2\pi)}{N(0<\phi<\pi) + N(\pi<\phi<2\pi)}$$

Significant non-uniformity in azimuthal distribution requires the sin2f term.

SSAs for other hadrons: ed→e'pπ–X vs ed→e'nπ–X

RGA-inb



RGB ed→e'pπ+X ed→e'nπ–X seem to have opposite signs for low z
Crucial to have a good neutron ID !!!

Unintegrated DSIDIS cross-section

$$\frac{d\sigma^{\ell(l,\lambda)+N(P_N,S)\to\ell(l')+h_1(P_1)+h_2(P_2)+X}}{dx\,dQ^2\,d\phi_S\,dz\,d^2P_{T1}\,d\zeta\,d^2P_{T2}} =$$

$$= \frac{\alpha^2 x}{Q^4 y}\left(1+(1-y)^2\right)\left(\begin{array}{l}\hat{u}^{h_2}\otimes D_1^{h_1} + \lambda D_{ll}(y)\hat{l}^{h_2}\otimes D_1^{h_1} \\ +\hat{t}^{h_2}\otimes \dfrac{\mathbf{p}_T\times\mathbf{s}'_T}{m_{h_1}} H_1^{h_1}\end{array}\right)$$

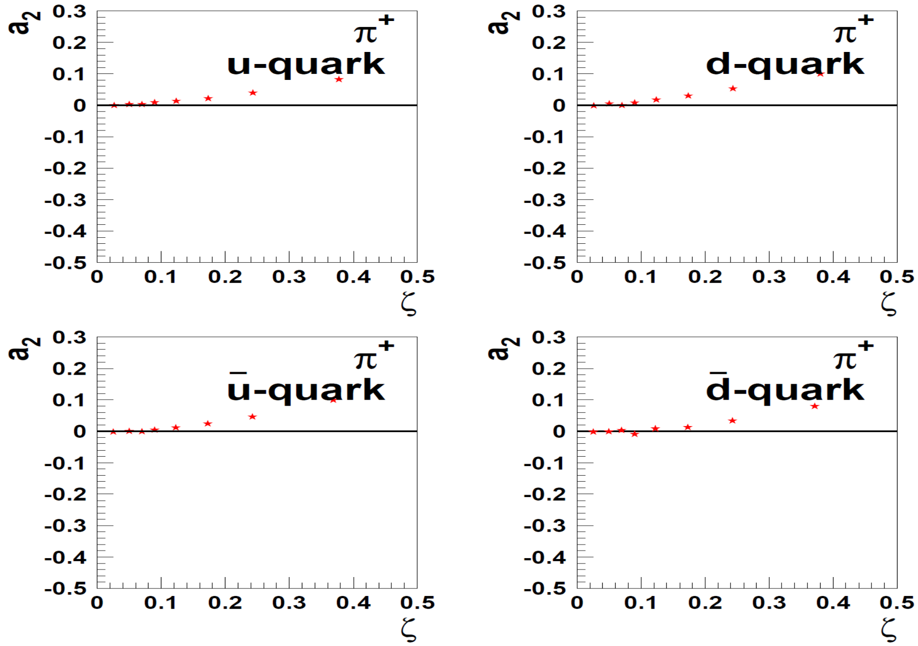
$$= \frac{\alpha^2 x}{Q^4 y}\left(1+(1-y)^2\right)\left(\begin{array}{l}\sigma_{UU} + S_L\sigma_{UL} + S_T\sigma_{UT} + \\ \lambda D_{ll}\left(\sigma_{LU} + S_L\sigma_{LL} + S_T\sigma_{LT}\right)\end{array}\right)$$

Unintegrated DSIDIS cross-section

$F_{\dots}^{\hat{u}\cdot D}$ depend on $x, z, \zeta, P_{T1}^2, P_{T2}^2$ and $(\mathbf{P}_{T1}\cdot\mathbf{P}_{T2})$

$$\hat{u}_{q/p}^{\pi^\pm}(x, k_T^2, \zeta, P_T^2, \mathbf{k}_T\cdot\mathbf{P}_T) = u_{q/p}^{\pi^\pm}(x, k_T^2, \zeta, P_T^2)\left(1 + a_1\cos(\phi_h - \phi_q) + a_2\cos 2(\phi_h - \phi_q) + \cdots\right)$$

$$a_i = a_i(x, k_T^2, \zeta, P_T^2)$$

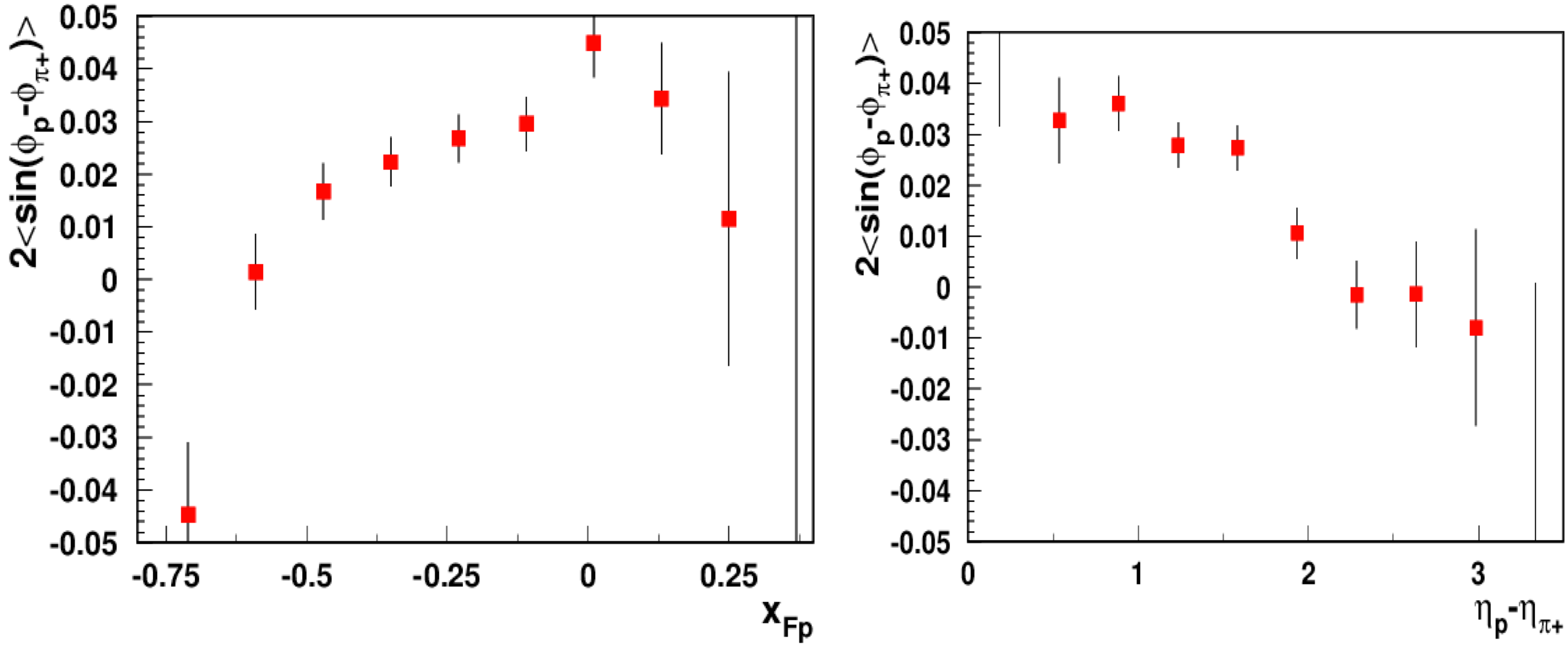


$$a_2 \ll a_1$$

For pions cos2Δϕ seem to be small
To be checked on proton-pion pairs

SSAs kinematic dependences: ep→e'pππX

$x_F = 2P_L^{CM}/W$ RGA-inbending $\eta = \frac{1}{2}\frac{E^{CM}+P_L^{CM}}{E^{CM}-P_L^{CM}}$



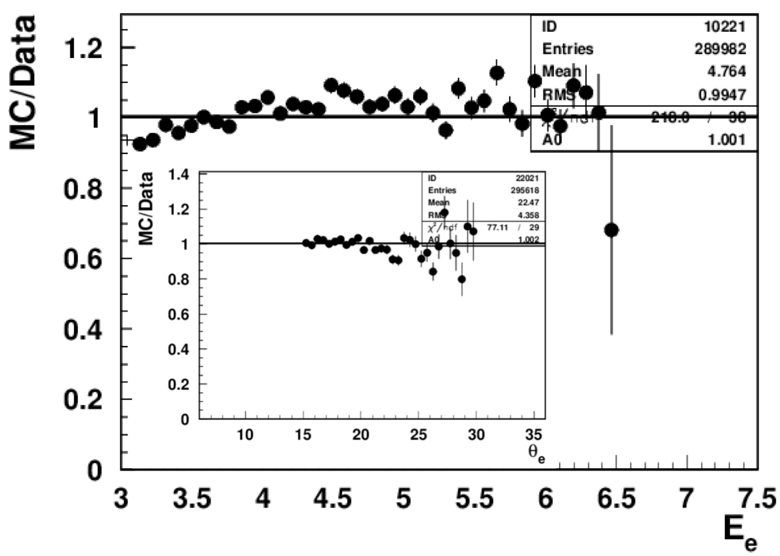
At higher proton momenta in CM frame (target fragmentation) the SSA drops, as the average P_Ts get suppressed due to phase space

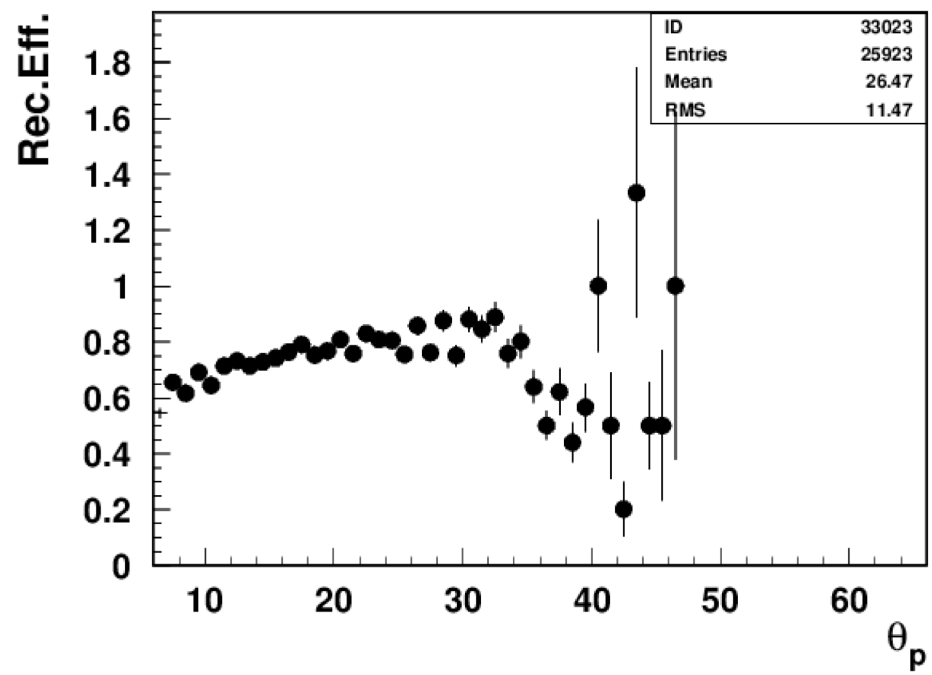
In the Breit frame

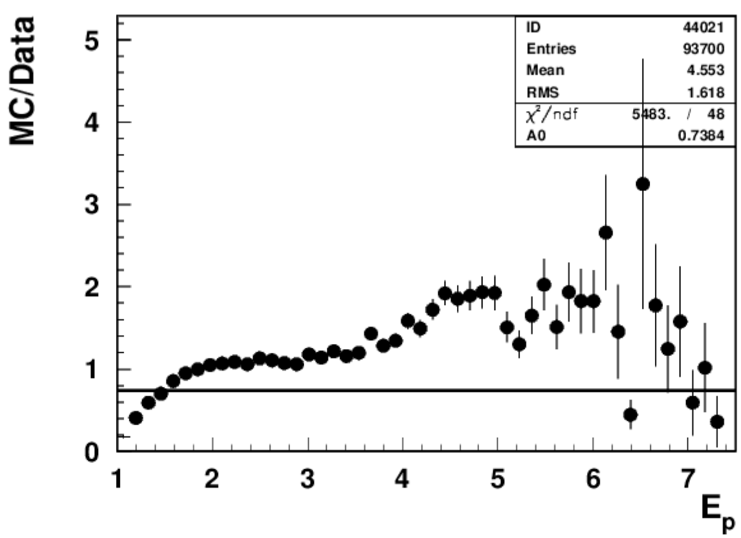
$$\eta_b = -ln\sqrt{\frac{x_n^2 M^2 + x_n Q^2}{(1-x_n)Q^2}} - \eta$$

$$x_n = 2x/(1+\sqrt{1+4x^2M^2/Q^2})$$

Data vs MC Rec. eff. of protons



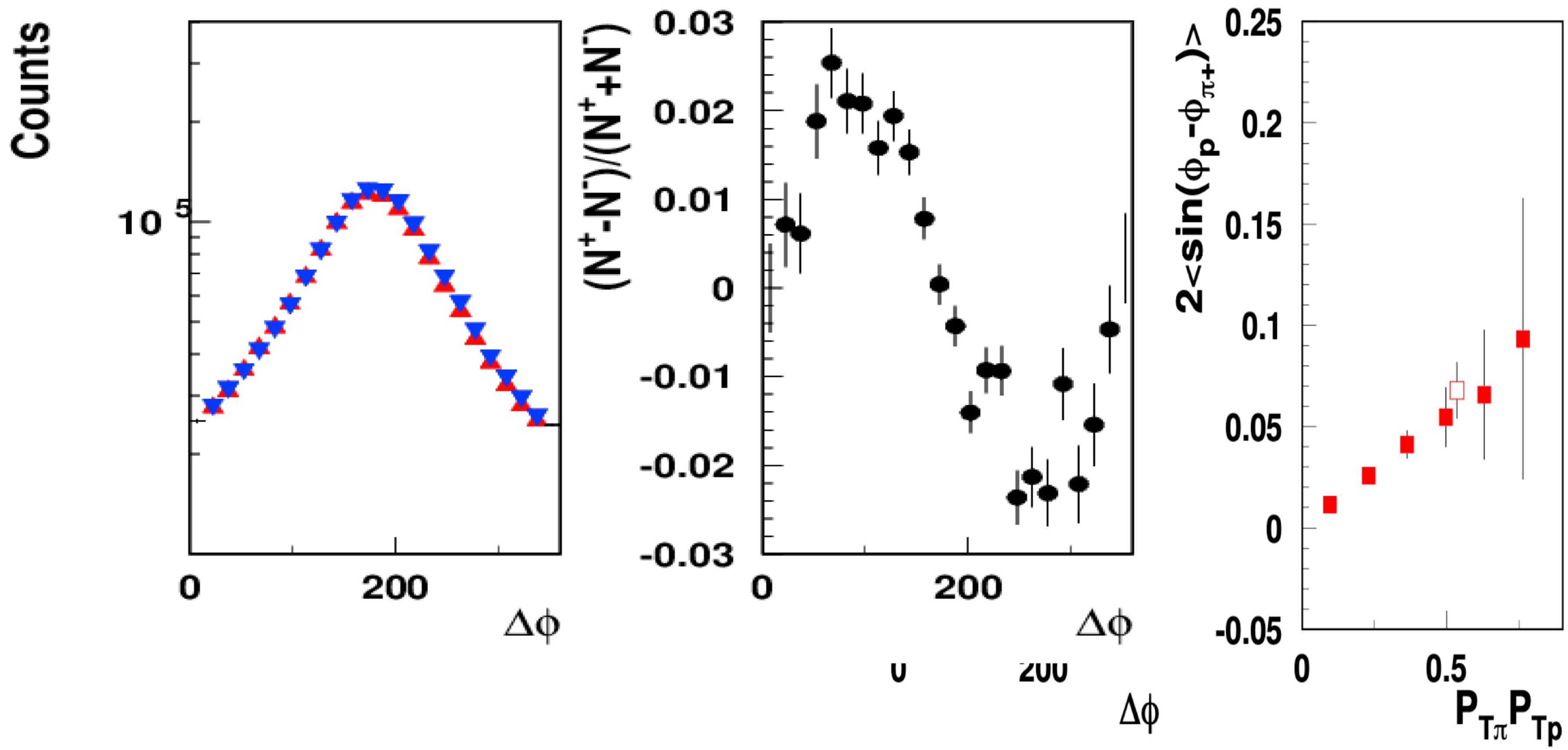




Some decrease of rec. eff. In CND
Most plots were for Forward Detector

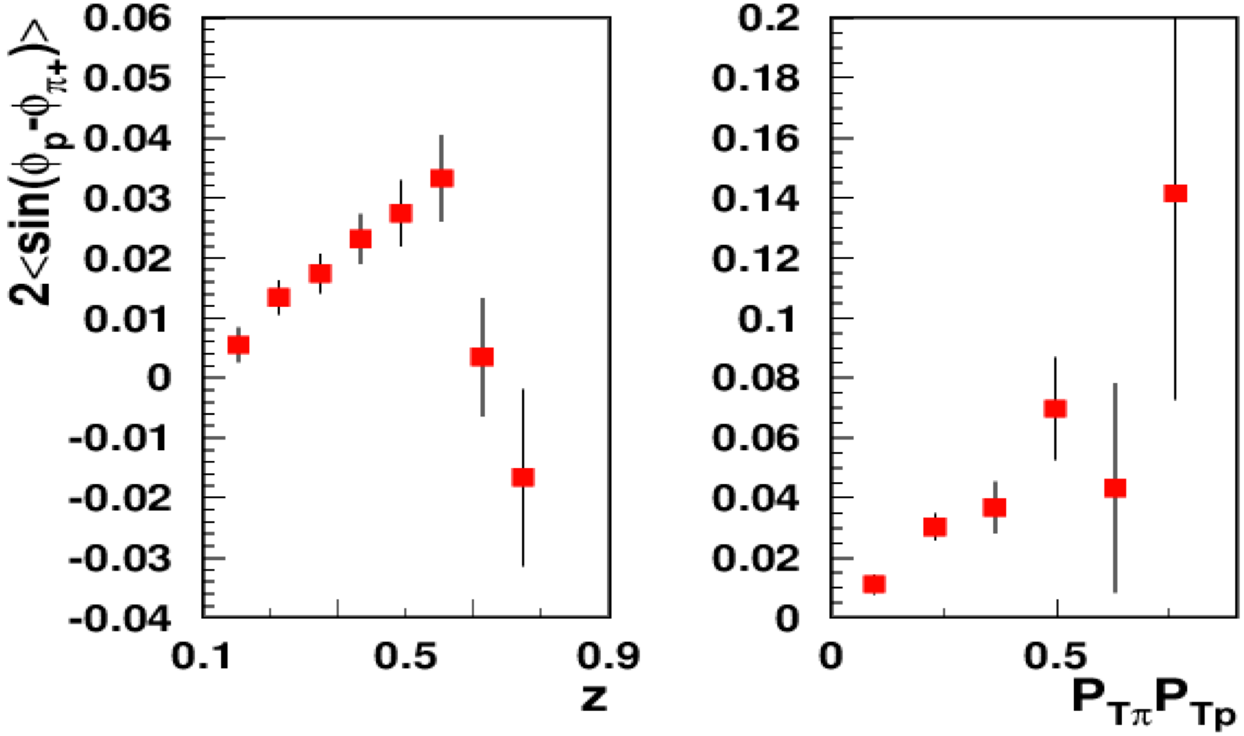
B2B SSA Extraction methods

https://userweb.jlab.org/~avakian/tmp/clasnotedvcs.pdf



Significant correlation asymmetries observed by CLAS will be extended to CLAS12 and possibly EIC

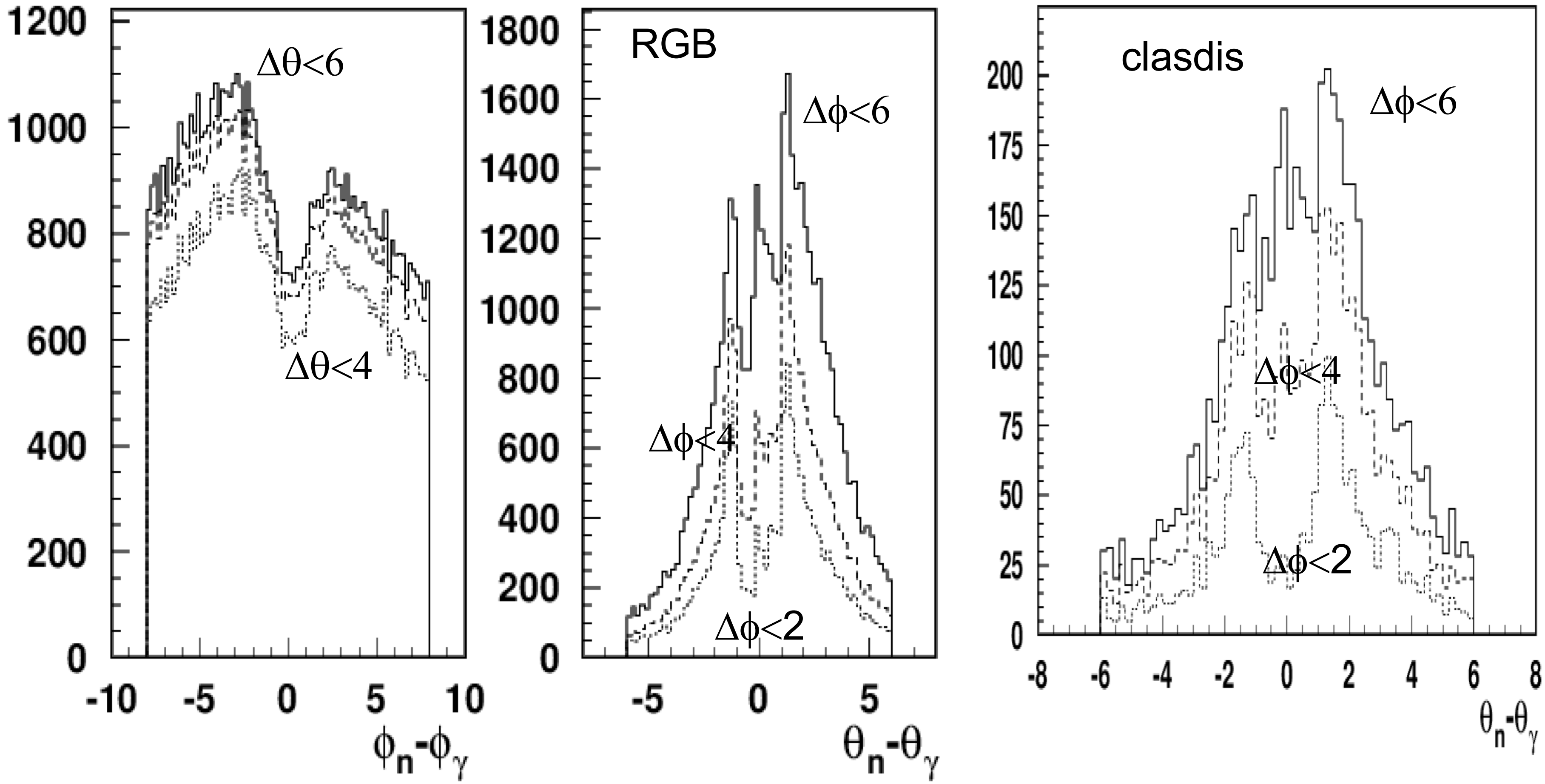
SSAs in ep→e'pπ+X production (RGA)



Using the RGA "golden" run list (~30%)

Observed SSAs consistent in kinematic dependences and size with SSA observed by CLAS6!

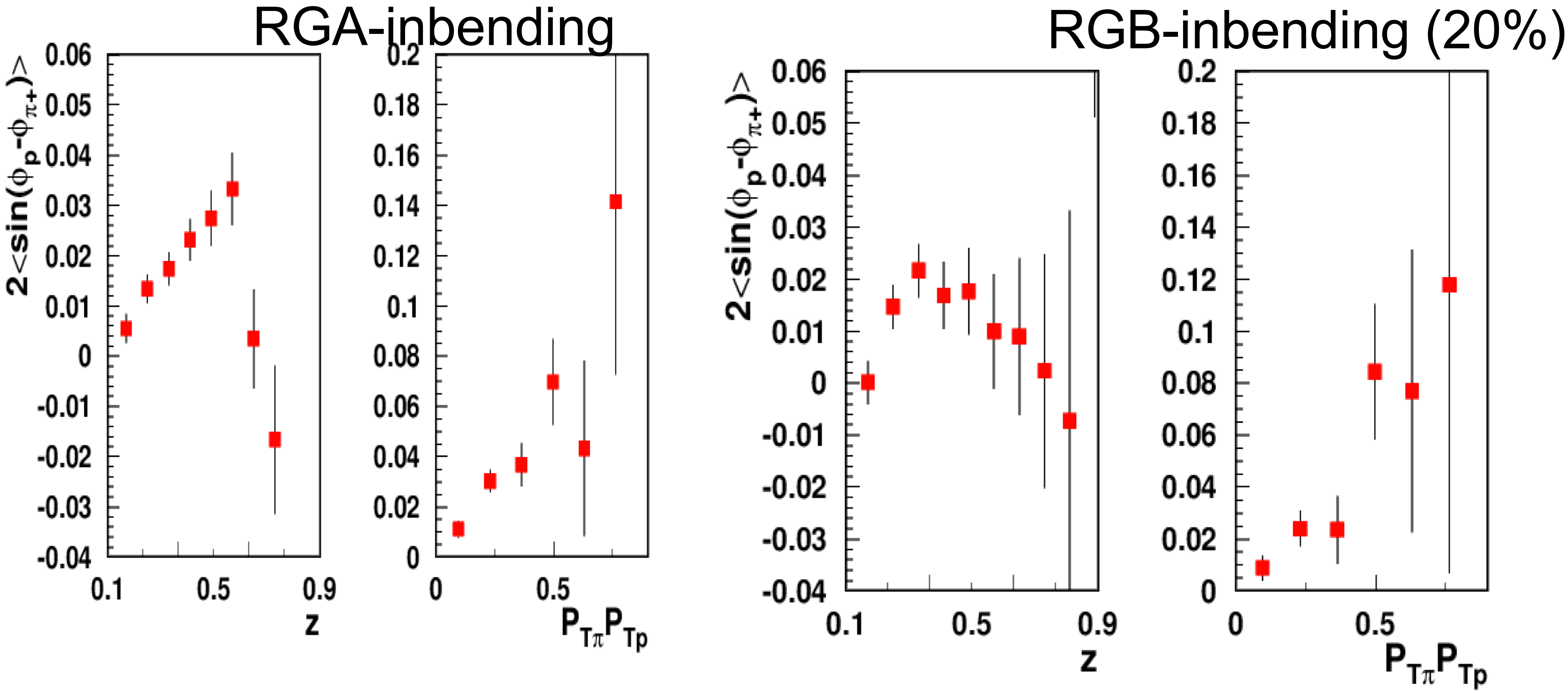
Neutrons in RGB (inb) vs clasdis MC



Quite a few events have a photon in addition to the neutron at practically the same theta and phi

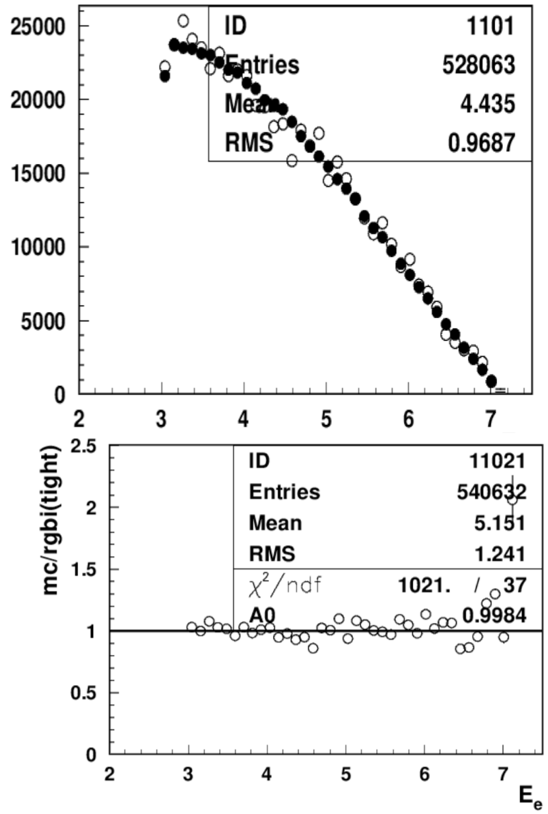
Most neutrons are most likely photons

SSAs in ep→e’pπ+X: RGA vs RGB

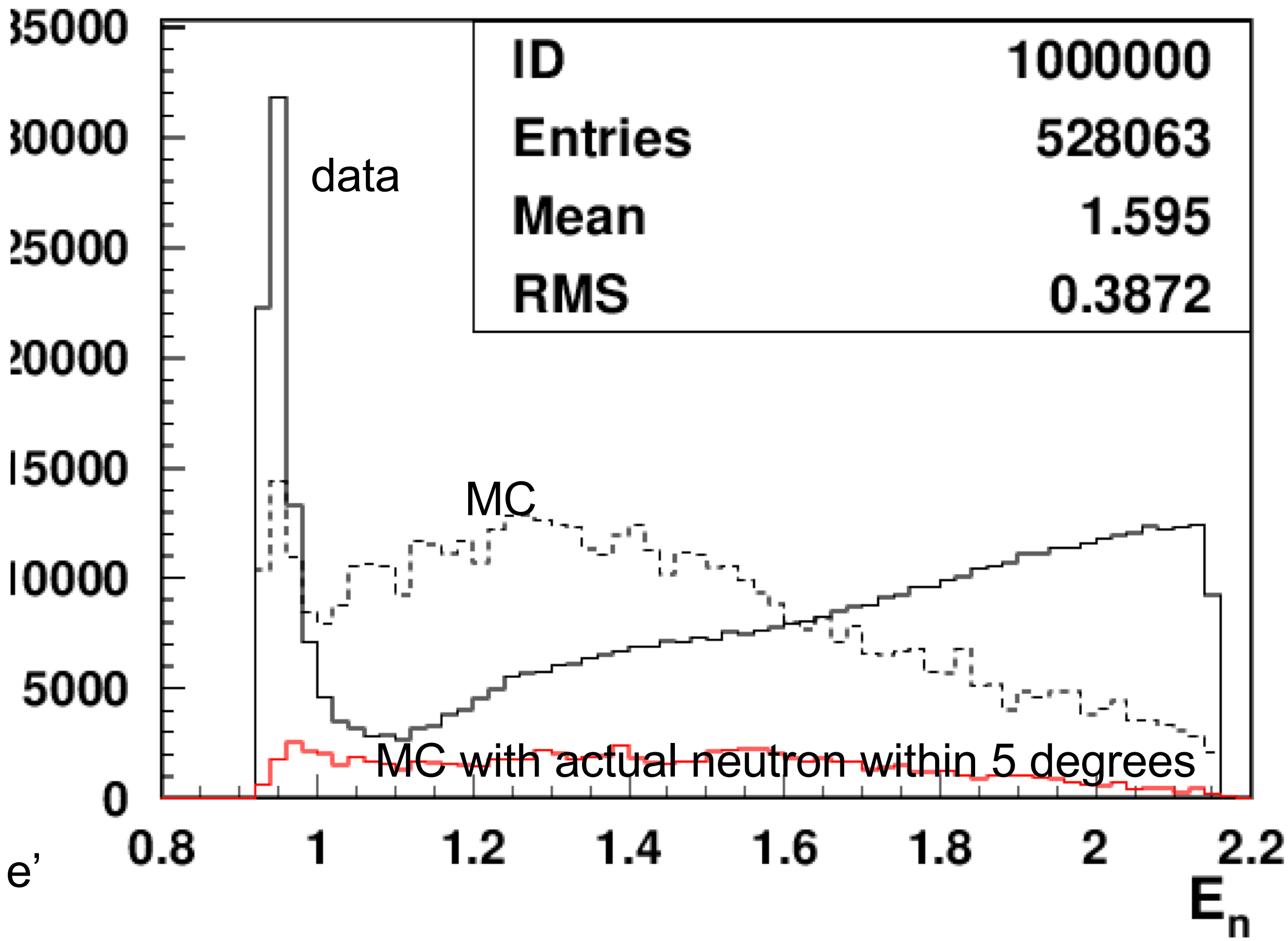


ep→e’pπ+X SSAs in RGB consistent in kinematic dependences and size with SSA from RGA

Neutrons in RGB (inb) vs MC

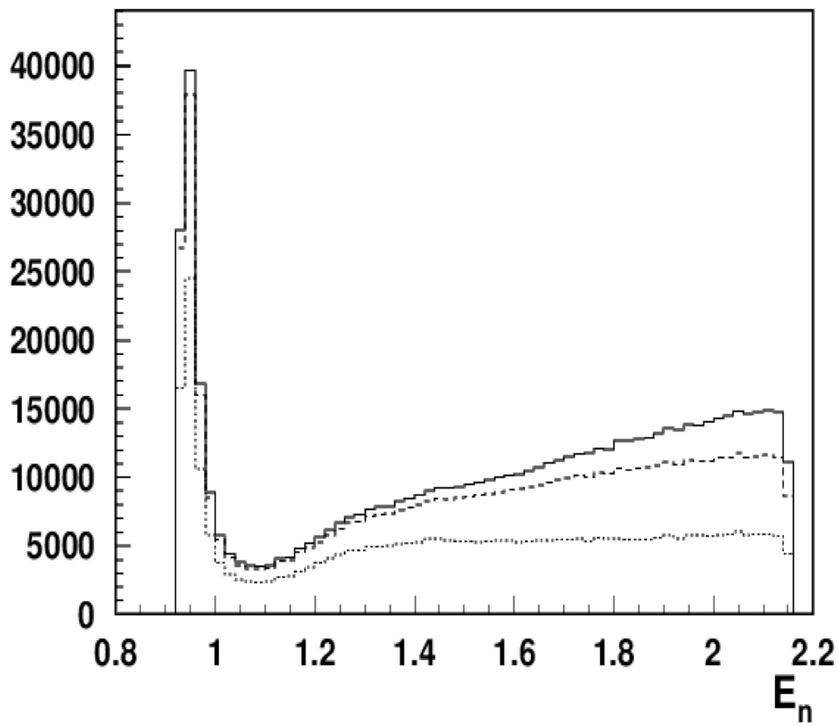


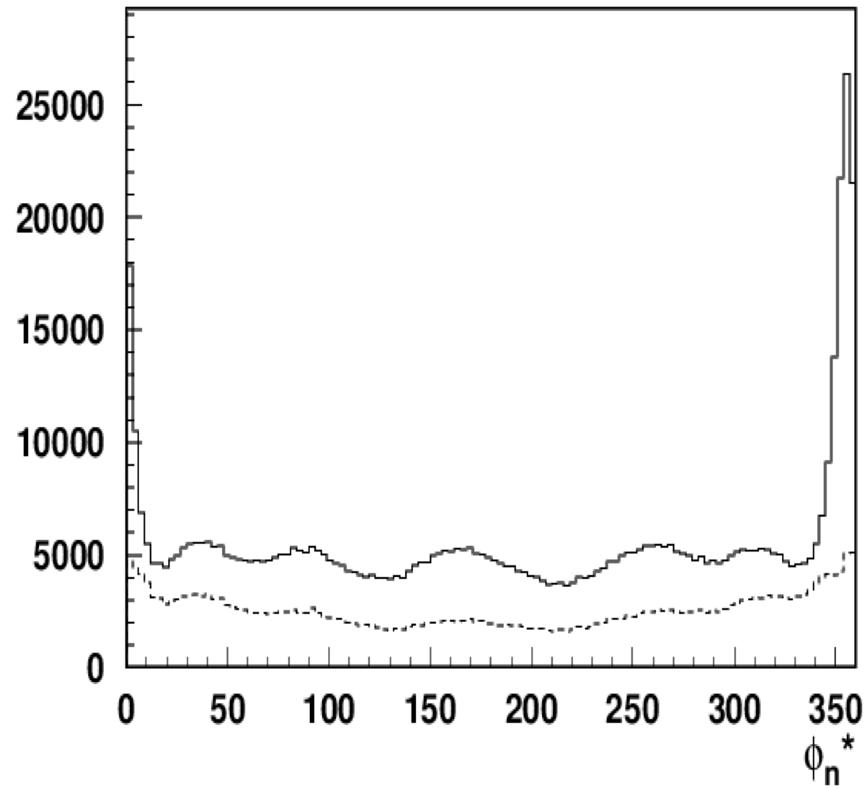
Normalizing data./mc for e'



Small fraction of MC reconstructed neutrons have link to neutrons

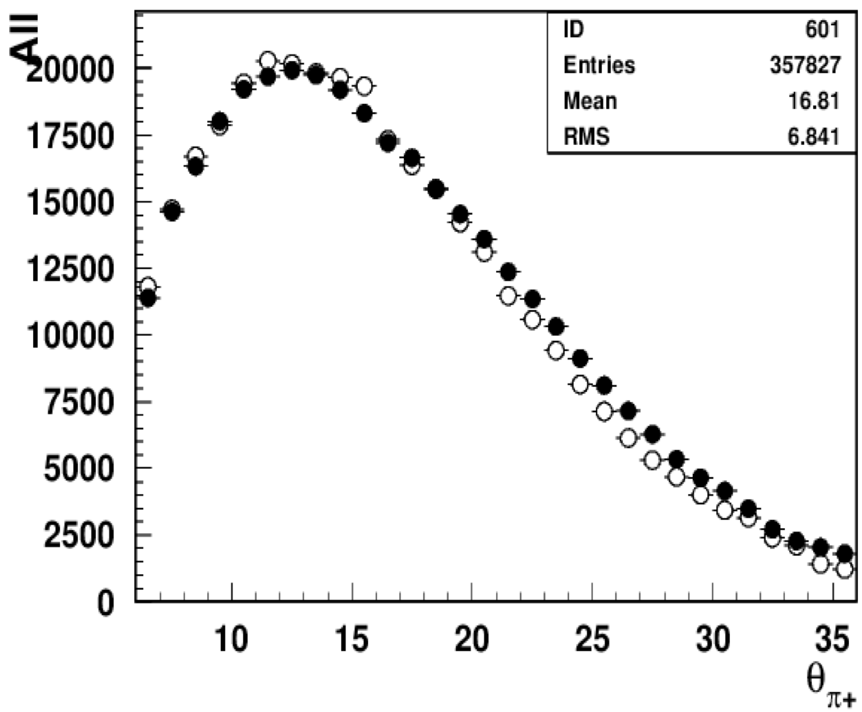
Neutrons in RGB (inb)

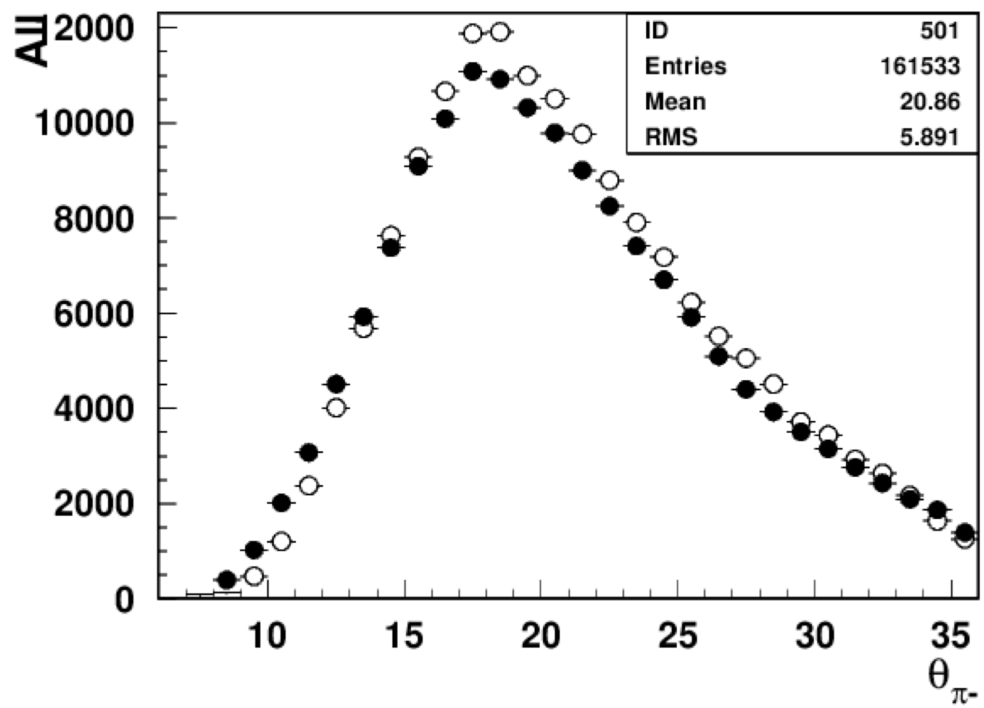




Edges in phi contribute to higher energies, most likely photons

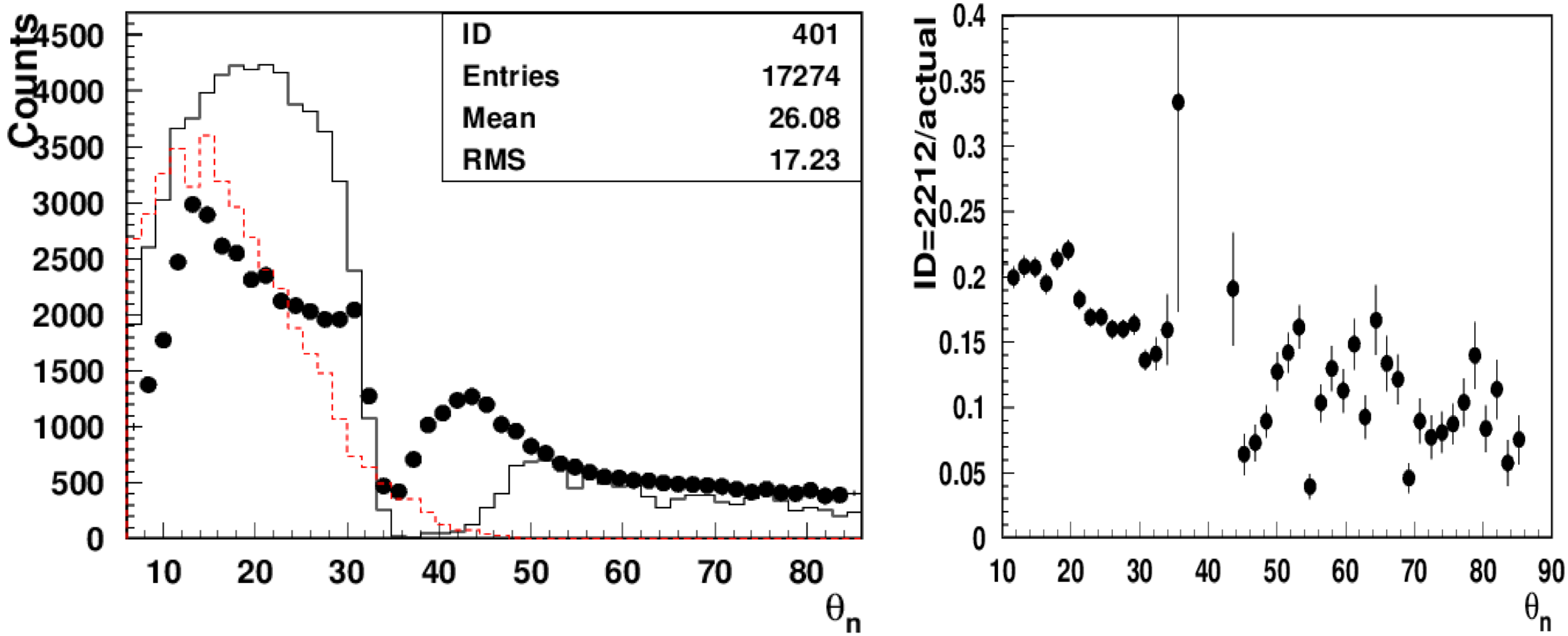
RGB: MC vs 5nA data





Reasonable description of the data (filled circles) by MC (open circles)

Neutron eff.



Counts
ID 401
Entries 17274
Mean 26.08
RMS 17.23
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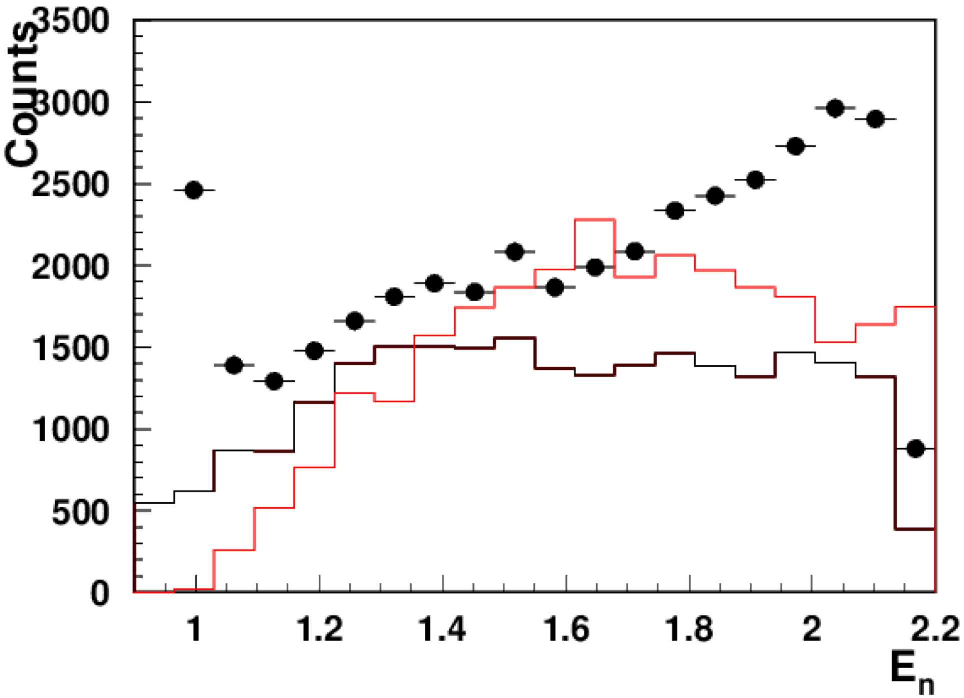
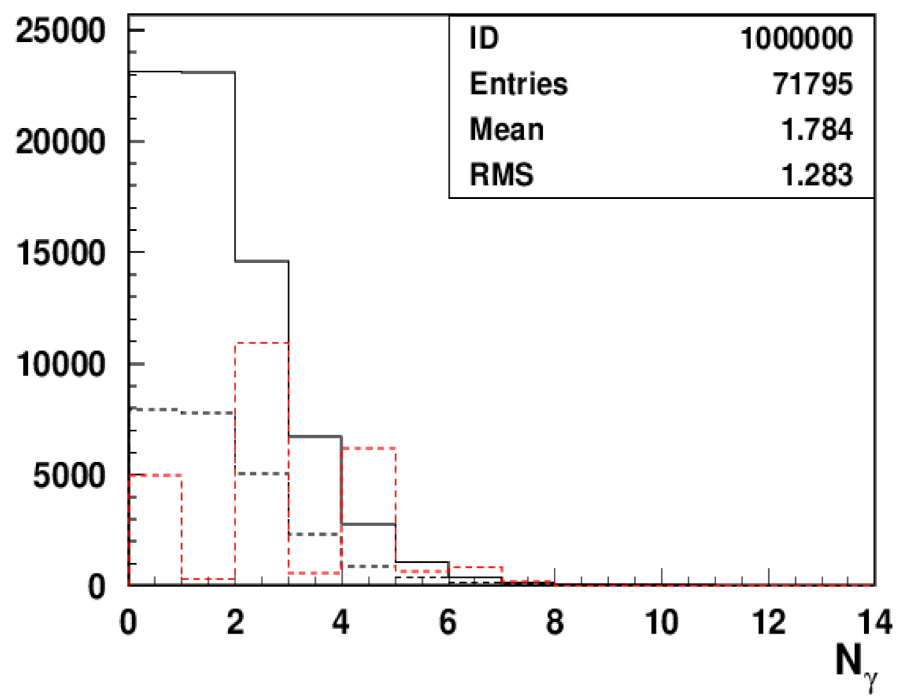
1000
1500
2000
2500
3000
3500
4000
4500
10
20
30
40
50
60
70
80
θn
ID=2212/actual
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
10
20
30
40
50
60
70
80
90
θn

Neutron eff.





Red→ generated
Line→ reconstructed
Circles RGB-inbending