Di-hadron beam spin asymmetry with CLAS data

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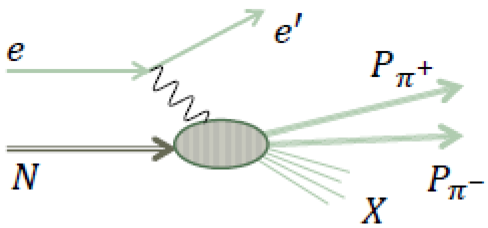
CLAS Collaboration Meeting – November 14, 2019

Physics motivation

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



Same cross section structure functions as in single hadron

- $\phi_H \rightarrow \phi_R$

$$\frac{d\sigma}{dx\,dy\,dz\,d\psi\,d\phi_R\,dM_h^2\,d\cos\theta} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \epsilon F_{UU,L} +$$
$$+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_R F_{UU}^{\cos\phi_R} + \epsilon\cos(2\phi_R) F_{UU}^{\cos(2\phi_R)} + \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_R F_{LU}^{\sin\phi_R}\Big\}$$

Easier extraction of PDF from structure functions

- **new dh fragmentation functions**

twist-3 PDF/FF

$$F_{LU}^{\sin\phi_R} = -x\frac{|\vec{R}|\sin\theta}{Q}\sum_q e_q^2\left[\frac{M}{M_h} x e^q(x) H_1^{\sphericalangle,q}(z,\cos\theta,M_h) + \frac{1}{z} f_1^q(x)\tilde{G}^{\sphericalangle,q}(z,\cos\theta,M_h)\right]$$

Measured by Belle

Data set and goals

e1f data set, April-June 2003

- **beam energy:** *5.5 GeV*
- **beam polarization:** $P_B = 0.751 \pm 0.022$
- **liquid hydrogen target**
- **total luminosity:** *21 fb^{-1}*
- **low torus field:** *2250 A (~50%)*

Physics observable:

- **Beam Spin Asymmetry**

$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin\phi_R} \sin\phi_R}{1 + A_{UU}^{\cos\phi_R} \cos\phi_R + A_{UU}^{\cos 2\phi_R} \cos 2\phi_R} \Longrightarrow BSA = \frac{1}{P_{beam}} \frac{N^+ - N^-}{N^+ + N^-}$$

- **1D kinematic dependencies: x_B, z, M($\pi\pi$)**

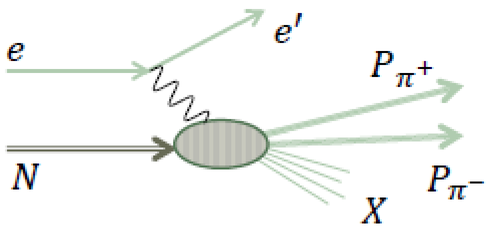
Status of the analysis

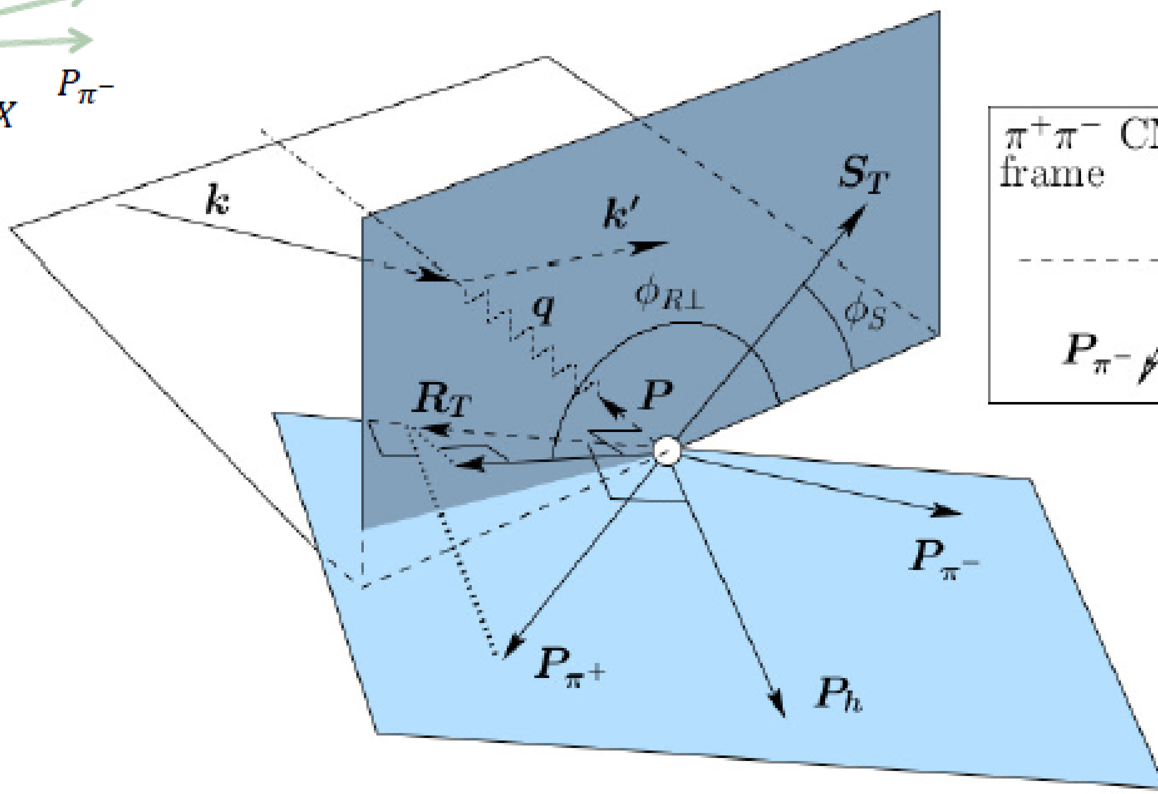
- **Analysis started around 2012 under responsibility of S. Pisano (LNF)**
  - **analysis completed in 2014**
  - **preliminary results presented at Conferences in 2013-14**
  - **theoretical interpretation of the data by A. Courtoy**

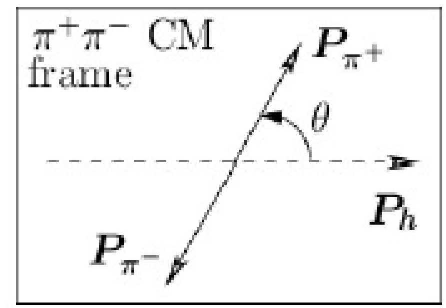
- **Analysis review started on April 24, 2014**
  - **review committee: Angela Biselli (Chair), Brian Raue , Sebastian Kuhn**
  - **4 rounds of review**
  - **last iteration on October 2016, never completed**
    - **open issues: some PID cut, fit of the BSA phi dependence, MC studies**
  - **draft of the paper ready**

- **The analysis was restarted beginning of 2019. Plan to resubmit an updated analysis note to the committee soon**

Di-Hadron angles







ϕ_h : azimuthal angle of the pion pair momentum

ϕ_R : azimuthal angle of the transvers component of the momentum difference

θ : angle between the pi+ and the dh in the CM frame

DH Fragmentation functions

Di-hadron FFs depend on z, M_h and cosθ

Angular dependence can be expanded in spherical harmonics

$$\begin{aligned}
D_1(x,\cos\theta,M_h) &= D^q_{1,ss+pp}(z,M_h) + D^q_{1,sp}(z,M_h)\cos\theta + D^q_{1,pp}(z,M_h)\frac{3\cos^2\theta-1}{4}\\
H_1^{\sphericalangle,q}(z,\cos\theta,M_h) &= H_{1,sp}^{\sphericalangle,q}(z,M_h) + H_{1,pp}^{\sphericalangle,q}(z,M_h)\cos\theta\\
\tilde{G}^{\sphericalangle,q}(z,\cos\theta,M_h) &= \tilde{G}_{sp}^{\sphericalangle,q}(z,M_h) + \tilde{G}_{pp}^{\sphericalangle,q}(z,M_h)\cos\theta
\end{aligned}$$

$$BSA = \underbrace{\sin\varphi_R\left[\frac{eH_{1,sp}\sin\vartheta}{f_1 D_{1,ss+pp}}\right]}_{\text{Leading PW term Fit function}} \underbrace{\left(\frac{1+A\cos\theta}{1+B\cos\theta+C\,{}^{(3\cos^2\theta-1)}/_{4}}\right)}_{\text{Point-by-point systematic uncertainty}}$$

A,B,C: ratios of IFF PW expansion terms

Kinematic coverage

DIS kinematics

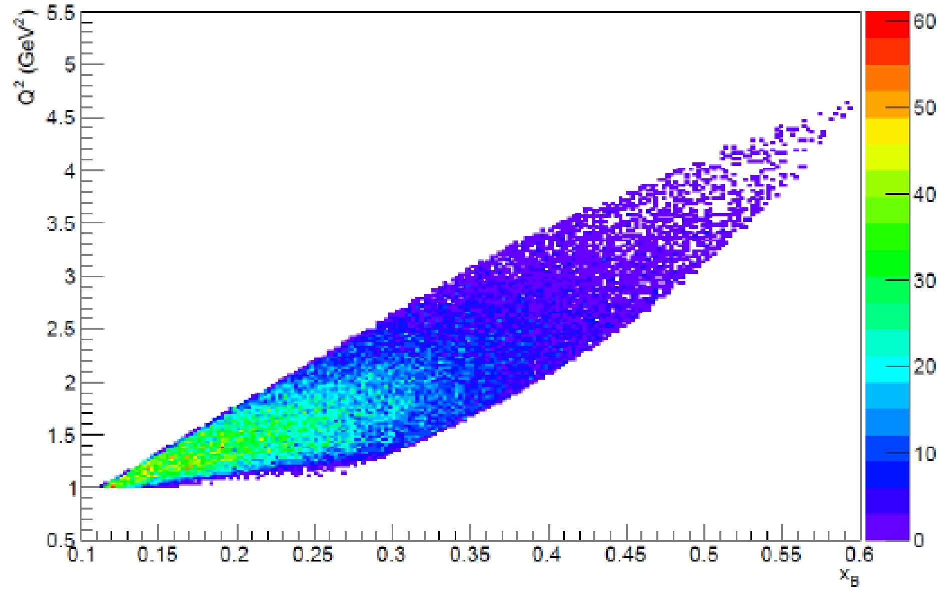
- **$Q^2 > 1$ GeV^2**
- **W > 2 GeV**

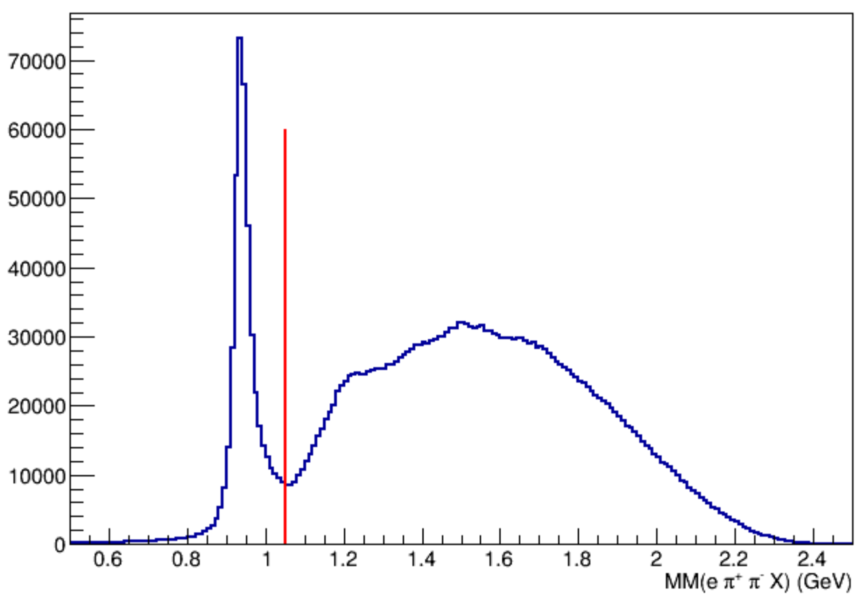
Inclusive cut

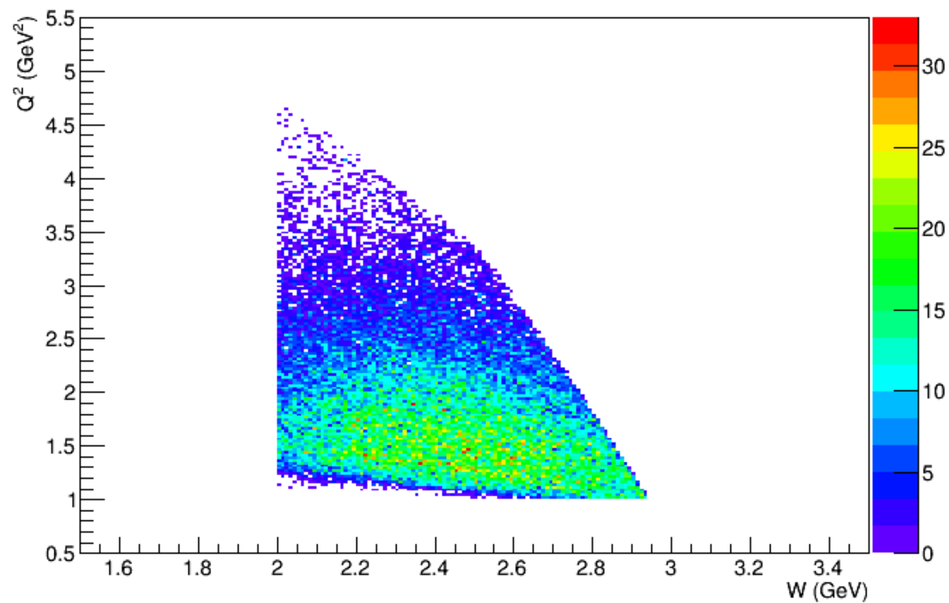
- **MM > 1.05 GeV**

Forward hadrons

- **$x_F > 0$**
- **z cut**

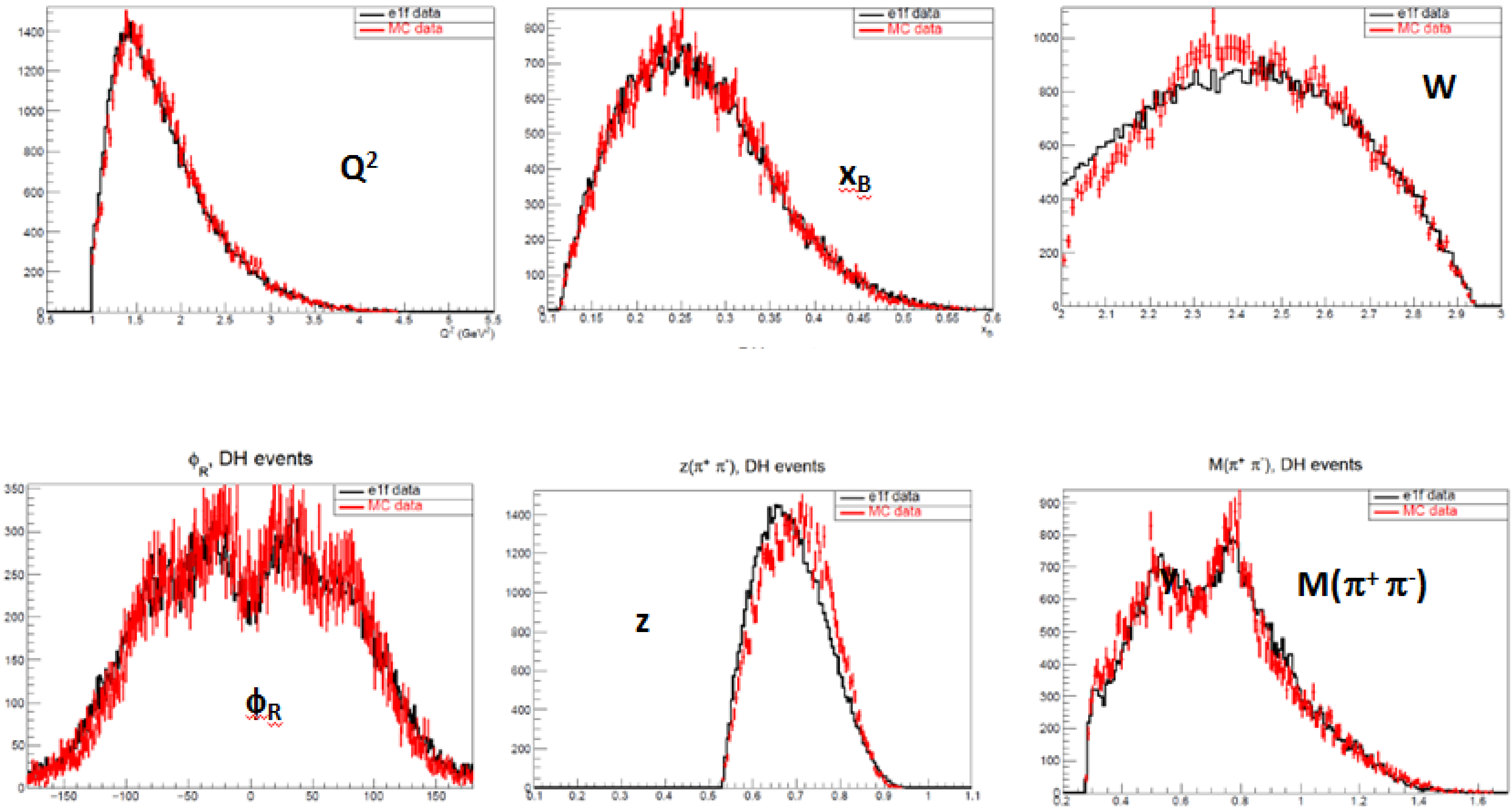






Monte Carlo simulations

clasDIS generator + gsim + gpp

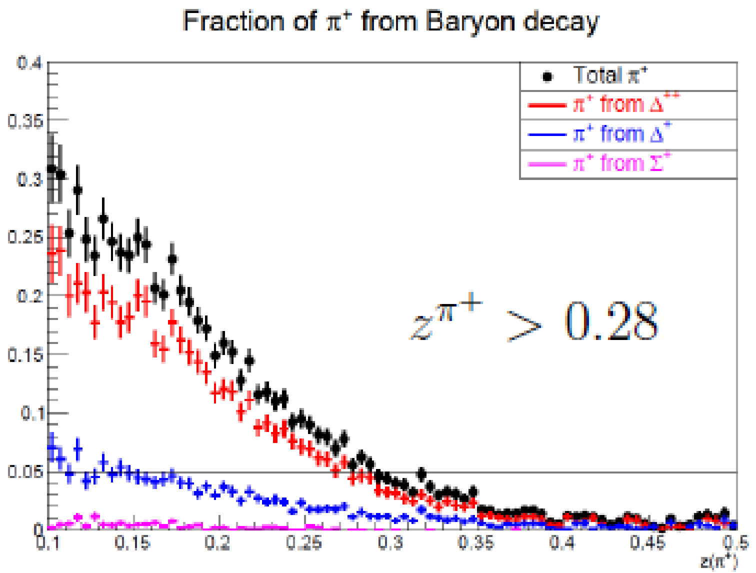


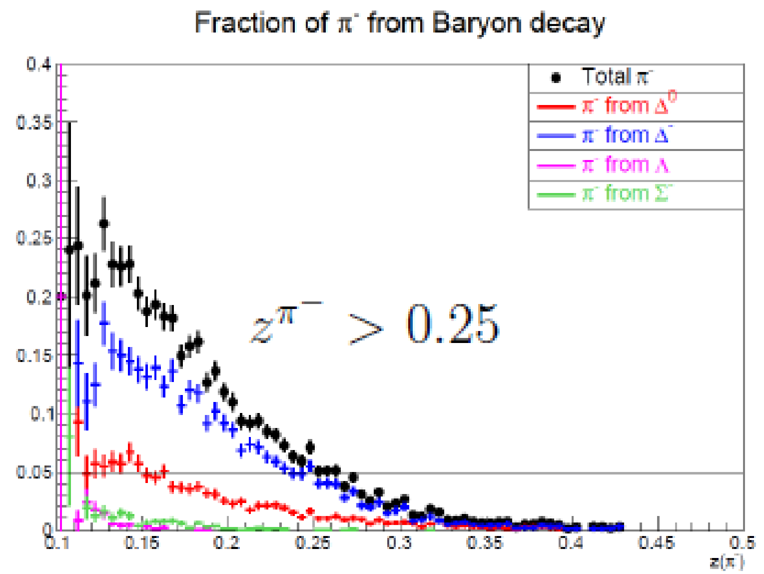
z- cut

Contamination of pions from baryon resonance decays at low z.

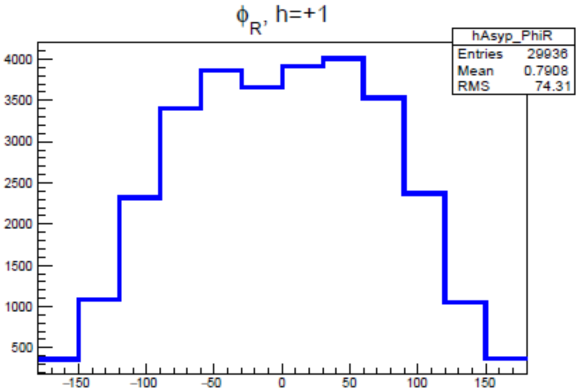
Use MC data to optimize the z cut

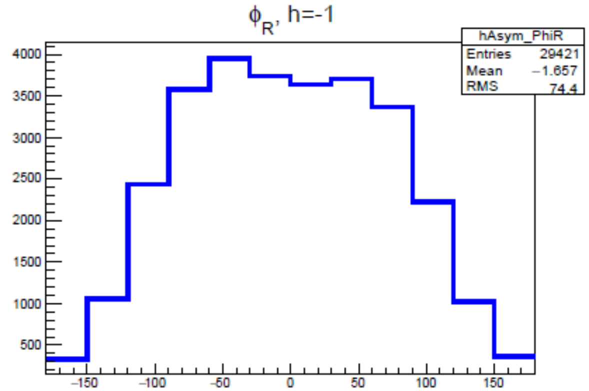
- the $\Delta^{++} \to \pi^+ p$ decay in the reaction $ep \to e'\Delta^{++}\pi^-(X)$;
- the $\Delta^{+} \to \pi^+ n$ decay in the reaction $ep \to e'\Delta^{+}\pi^-(X)$;
- the $\Delta^{0} \to \pi^- p$ decay in the reaction $ep \to e'\Delta^{0}\pi^+(X)$;
- the $\Delta^{-} \to \pi^- n$ decay in the reaction $ep \to e'\Delta^{-}\pi^+(X)$;
- the $\Lambda \to \pi^- p$ decay in the reaction $ep \to e'\Lambda\pi^+(X)$;
- the $\Sigma^{-} \to \pi^- n$ decay in the reaction $ep \to e'\Sigma^{-}\pi^+(X)$;
- the $\Sigma^{+} \to \pi^+ n$ decay in the reaction $ep \to e'\Sigma^{+}\pi^-(X)$;

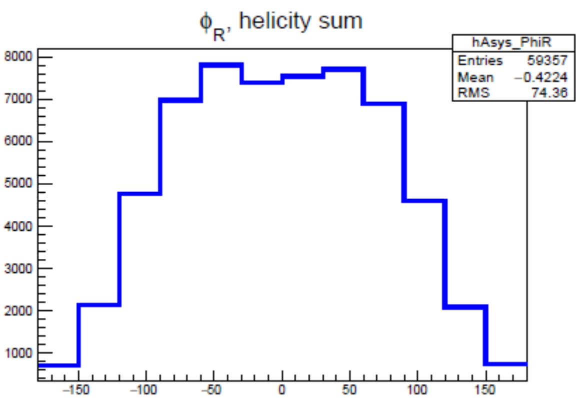


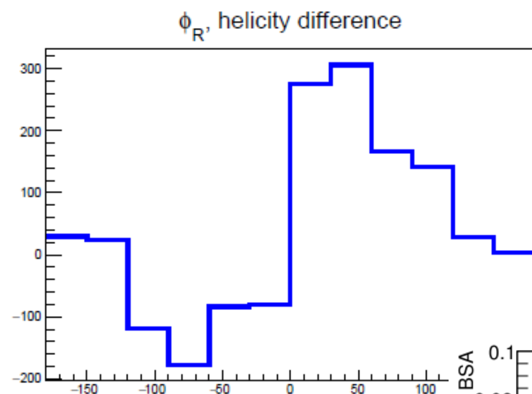


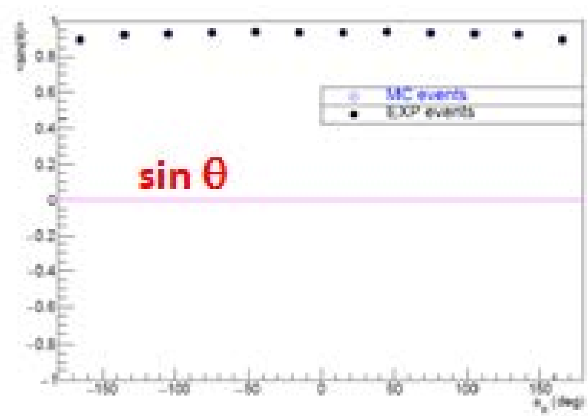
BSA fits

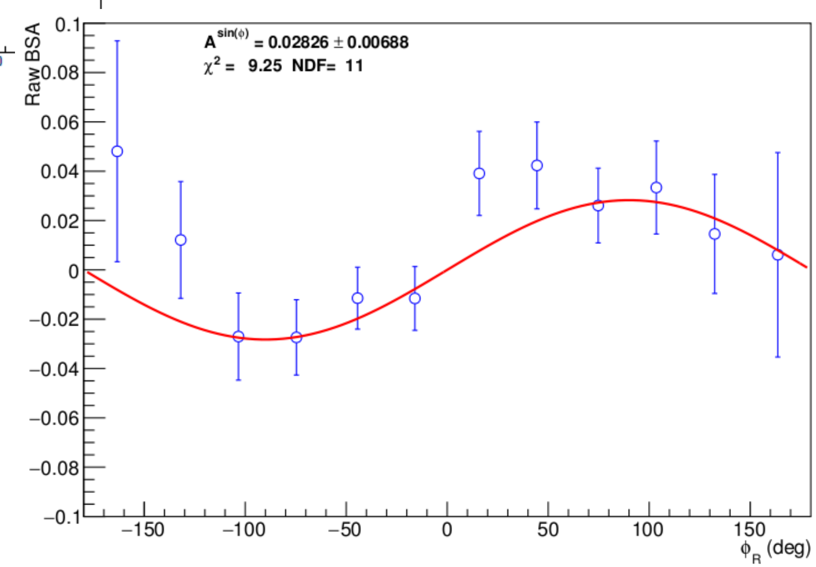








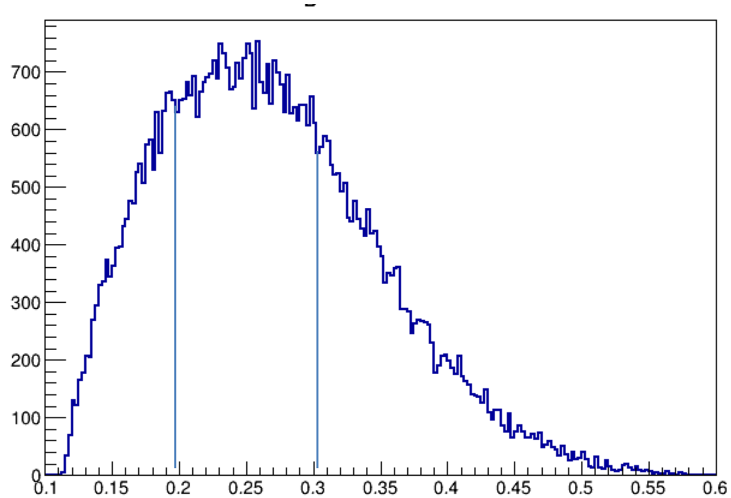




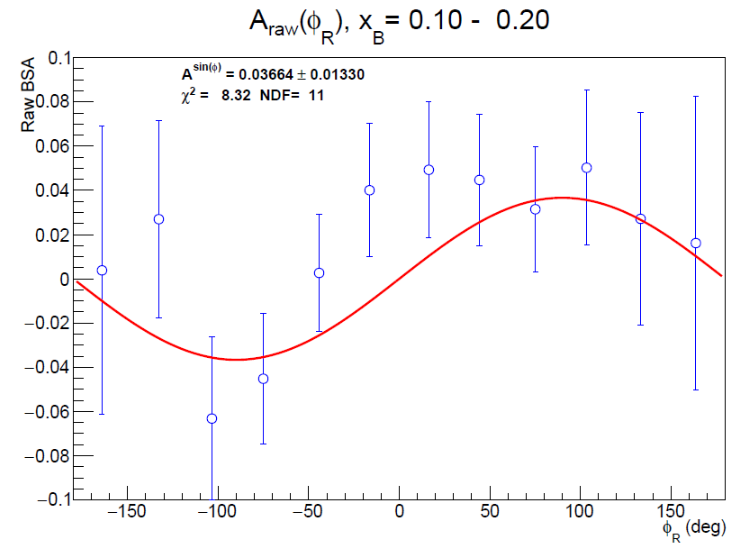
Fitting function

$$BSA(\varphi) = \sin\varphi_R \ \langle \sin\theta \rangle_\varphi A^{\sin\varphi}$$

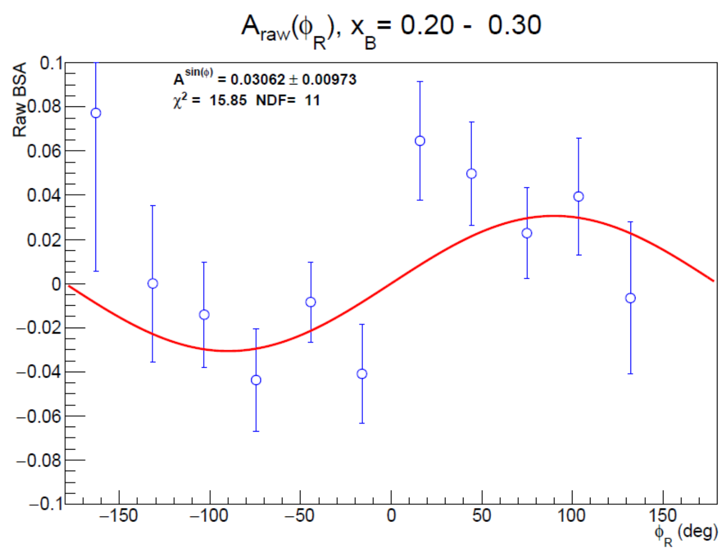
Raw BSA vs xB



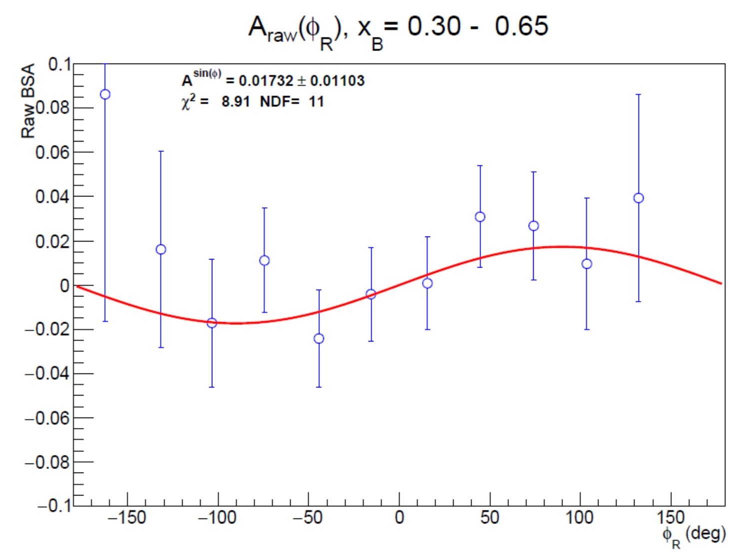
700
600
500
400
300
200
100
0
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6



$A_{raw}(\phi_R)$, x_B = 0.10 - 0.20
$A^{\sin(\phi)}$ = 0.03664 ± 0.01330
χ^2 = 8.32 NDF= 11
Raw BSA
ϕ_R (deg)



$A_{raw}(\phi_R)$, x_B = 0.20 - 0.30
$A^{\sin(\phi)}$ = 0.03062 ± 0.00973
χ^2 = 15.85 NDF= 11
Raw BSA
ϕ_R (deg)



$A_{raw}(\phi_R)$, x_B = 0.30 - 0.65
$A^{\sin(\phi)}$ = 0.01732 ± 0.01103
χ^2 = 8.91 NDF= 11
Raw BSA
ϕ_R (deg)

Systematics

- **Point-by-point systematics**
  - **30% due to the unknown higher terms in the PW expansion of the IFF**

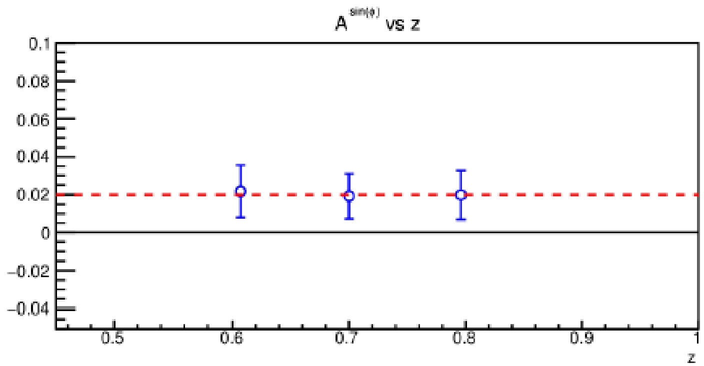
- **sin ϕ_R moments systematics**
  - **beam polarization: 3 %**
  - **baryonic resonance decays: 2 to 9 %**
  - **radiative corrections: 3 %**
  - **acceptance: negligible**
  - **fitting function: 10 %**

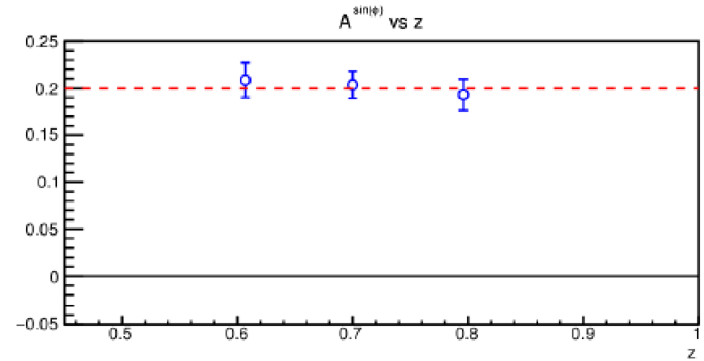
- **Total systematics 14% maximum**

Acceptance studies

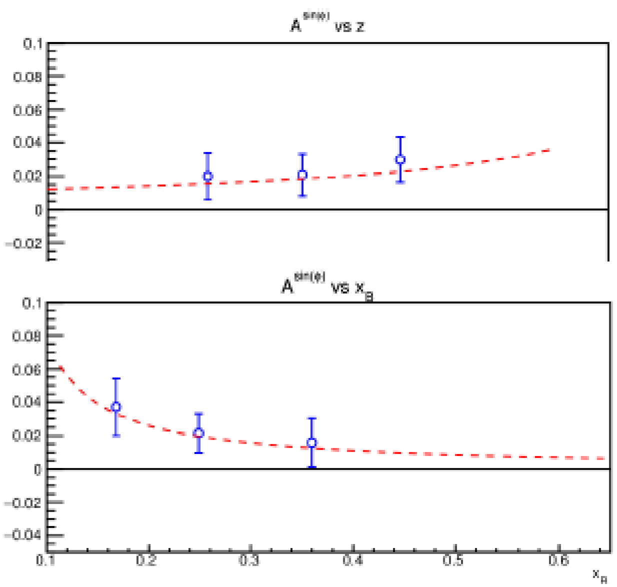
- inject a known asymmetry in the MC, process the data, compare the result
- several "models" introduced

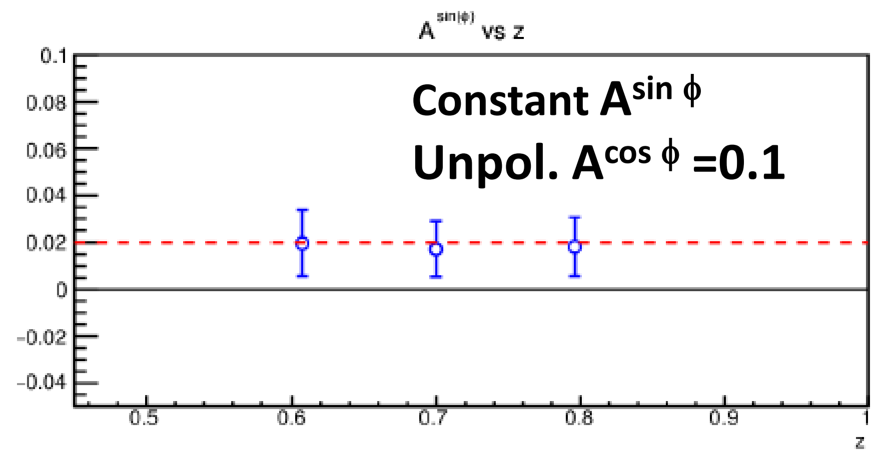
Constant $A^{\sin\phi}$





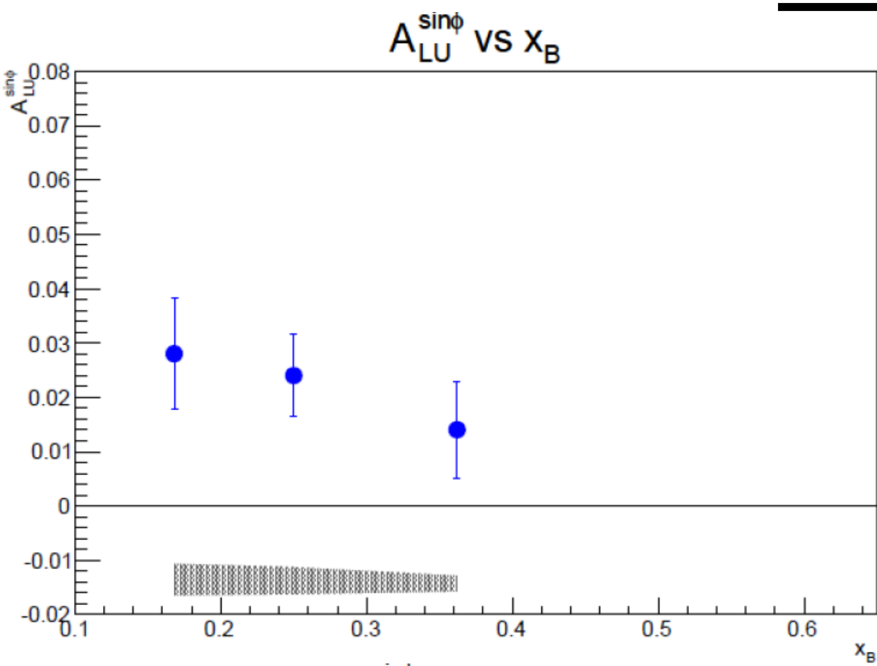
$A^{\sin\phi}$ with z and x_B dep.

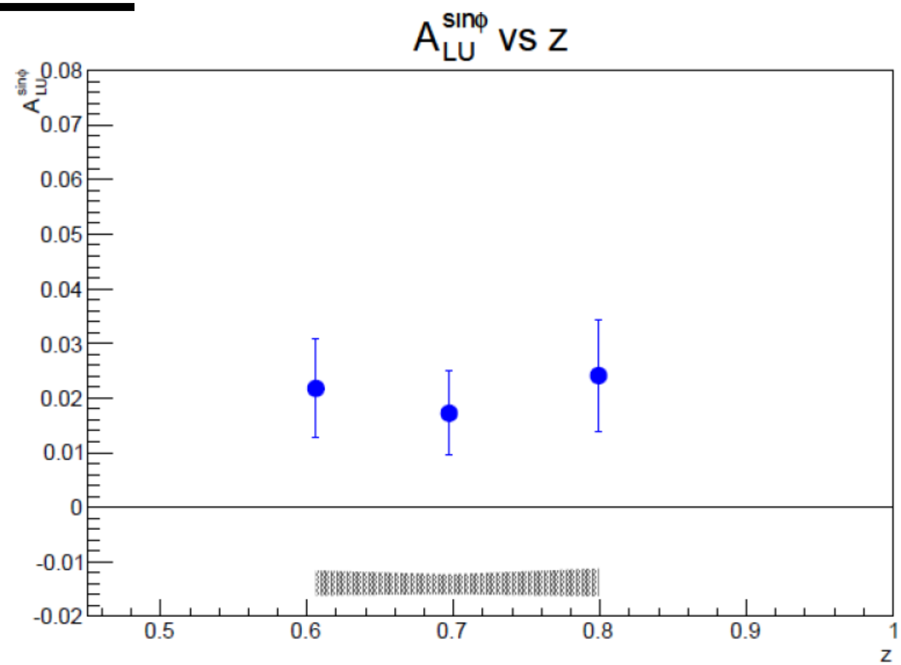


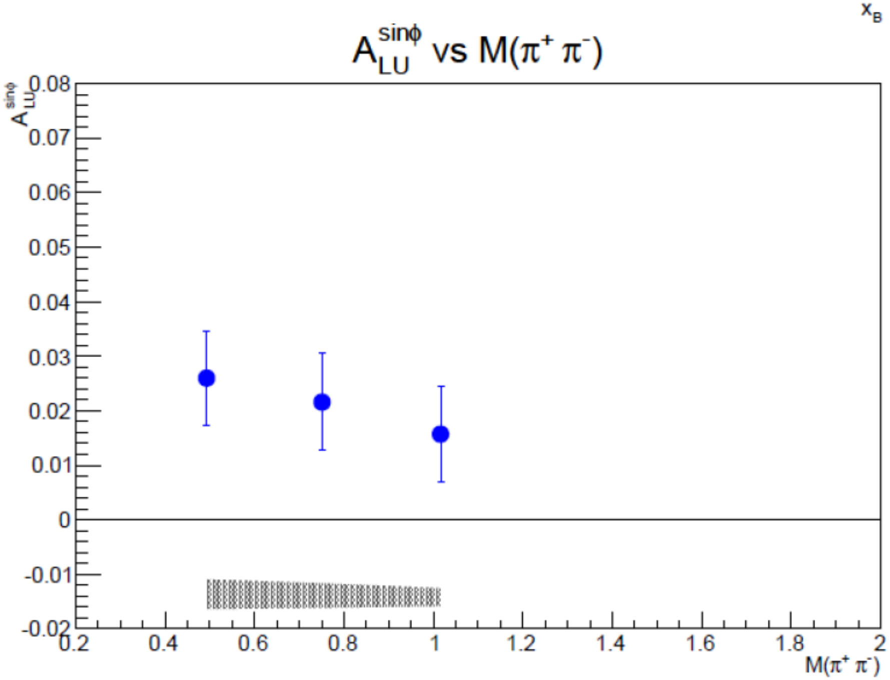


➢ no sensitivity with the available statistics

Results







- **Asymmetry amplitudes of the order of 2%**
- **Small kinematic dependence**

Summary

- **The di-hadron BSA has been extracted from the CLAS e1f data set**
  - **1D projections in x_B, z, M_h**

- **The signal if of the order of 2 % with weak kinematic dependence**

- **The analysis is basically completed**
  - **need to finalize some of the systematics studies**
  - **interplay between ϕ_R and ϕ_H**

- **Plan to re-submit the analysis note to have (hopefully) a quick approval**

- **Draft of the paper is ready**

Polarized cross section

Unintegrated beam polarization terms

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

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

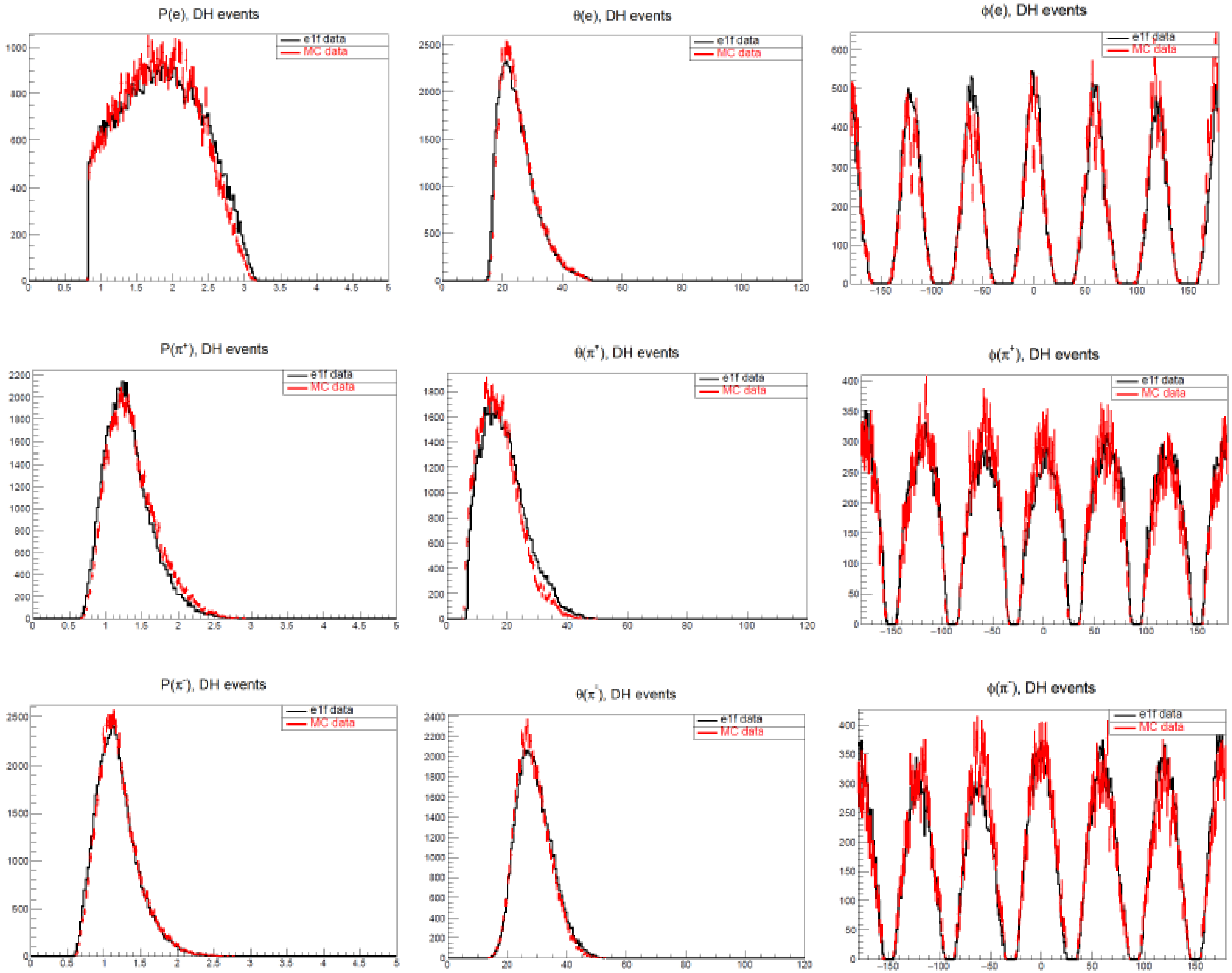
Transverse momentum integrated

$$\frac{d\sigma}{dx_B dy d\psi dz_h d\phi_{R_\perp} dM_h d\cos\theta} = \frac{\alpha^2}{x_B y Q^2}\left(1+\frac{\gamma^2}{2x_B}\right)$$

$$\times \Bigg\{ A(x,y) F_{UU,T} + B(x,y) F_{UU,L} + \frac{1}{2} V(x,y) \cos\phi_{R_\perp} F_{UU}^{\cos\phi_{R_\perp}} + B(x,y)\cos(2\phi_{R_\perp}) F_{UU}^{\cos 2\phi_{R_\perp}}$$

$$+ \lambda_e \frac{1}{2} W(x,y) \sin\phi_{R_\perp} F_{LU}^{\sin\phi_{R_\perp}} \Bigg\}$$

Particle kinematics



IFF θ dependence

From PW expansion (and neglecting the ϕ-dependent unpolarized SF)

$$BSA = \underbrace{\sin\varphi_R\left[\frac{eH_{1,sp}\sin\vartheta}{f_1 D_{1,ss+pp}}\right]}_{\text{Leading PW term}}\underbrace{\left(\frac{1+A\cos\theta}{1+B\cos\theta+C\,{}^{(3\cos^2\theta-1)}/_{4}}\right)}_{\text{Point-by-point systematic uncertainty}}$$

A,B,C: ratios of IFF PW expansion terms

Systematic uncertainty estimate

- assume all the A,B,C are of the order of 1
- replace the q-dependence with their averages
- take maximum variation as systematics

harmonics	average value
$\sin\theta$	0.931
$\cos\theta$	-0.093
$\sin\theta\cos\theta$	-0.162
$(3\cos^2\theta - 1)/4$	-0.159

→ Point-by-point systematics δA=30 %

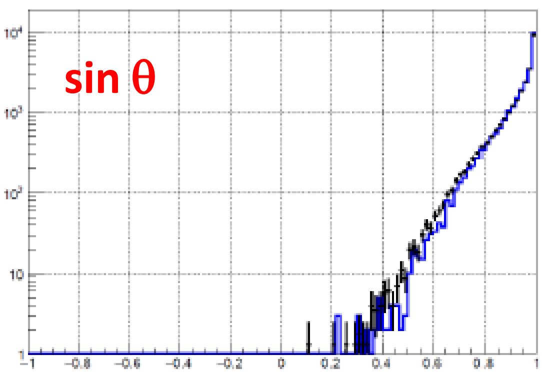
- added in quadrature to the statistic uncertainty

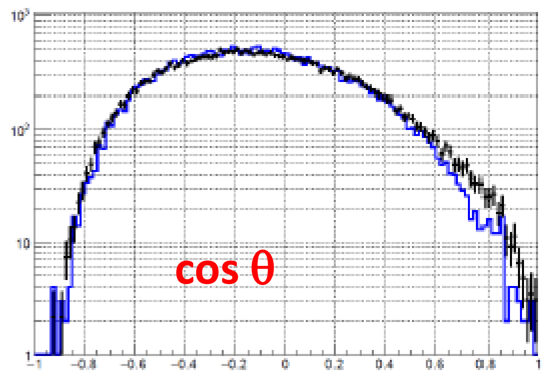
→ sinθ divided out from the BSA bin-by-bin

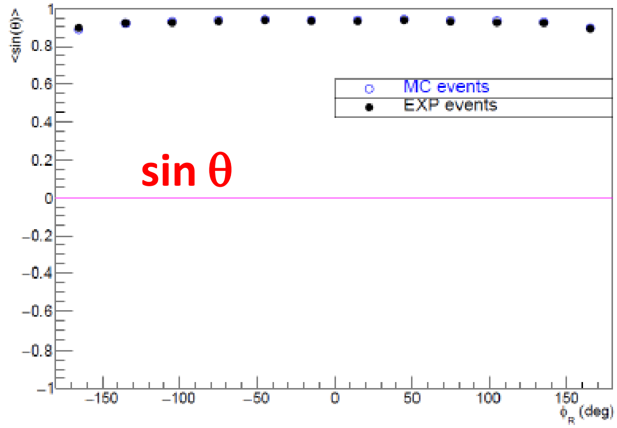
θ distributions

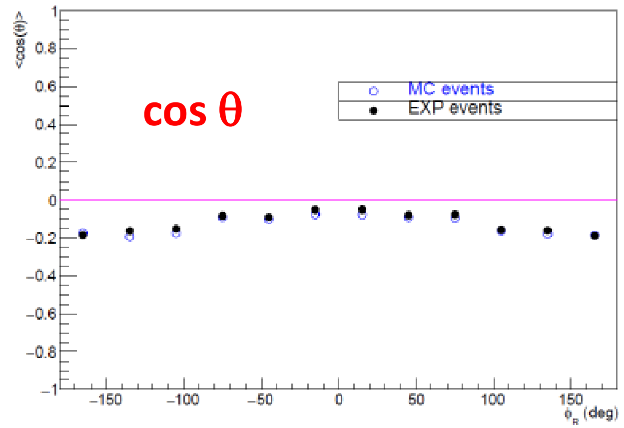
black: exp data
blue: MC data

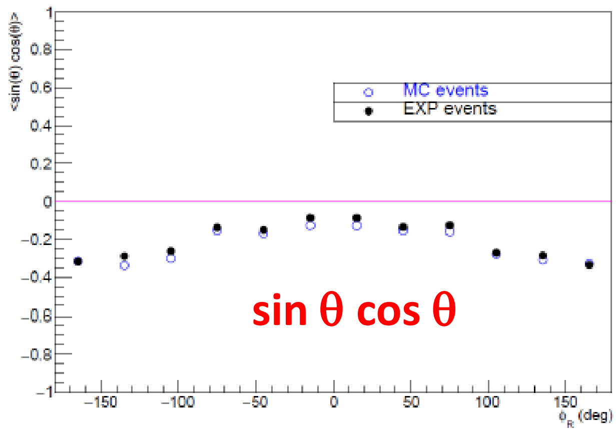
Average values vs ϕ_R

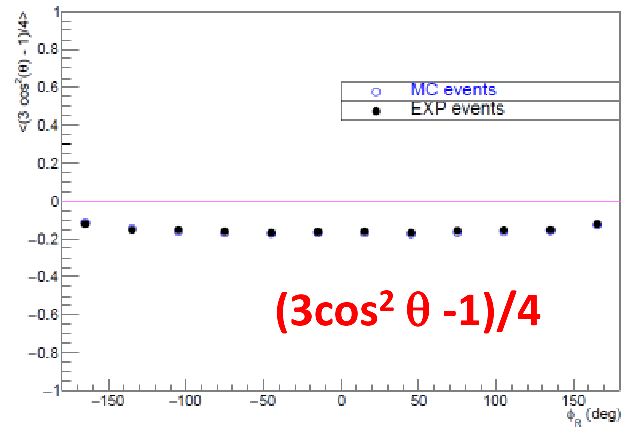










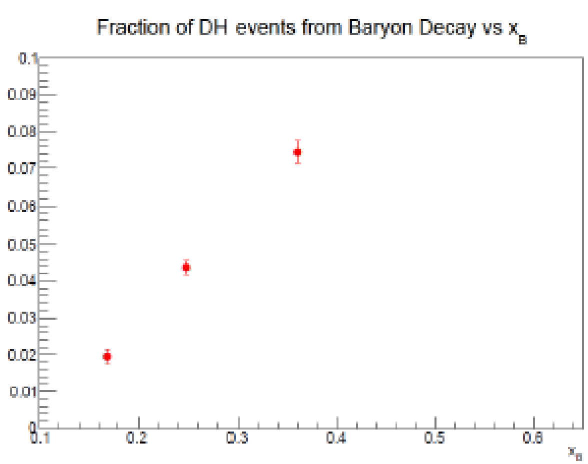


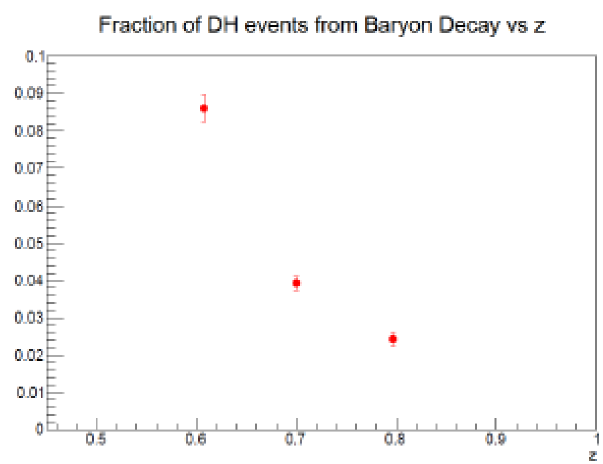
Systematic uncertainties - 1

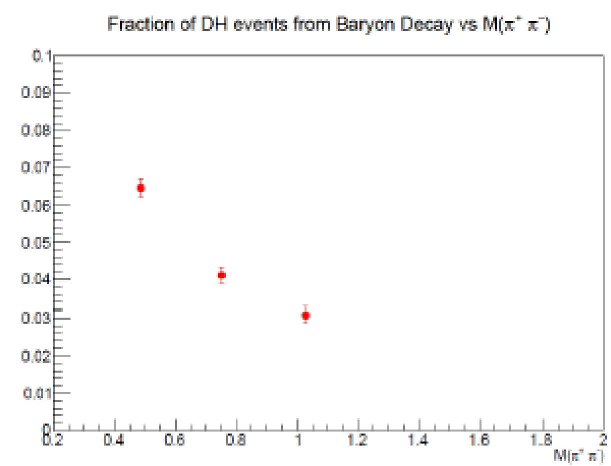
- **Beam polarization**
  - **$\Delta A / A = 3\ \%$**

$$P_B = 0.751 \pm 0.022$$

- **Baryonic resonances**
  - **residual contamination between 2 and 9 % depending on the kinematics**
  - **expected to have zero asymmetry, therefore they dilute the measured asymmetry**
  - **$\Delta A / A = 1 / (1 - f)$**

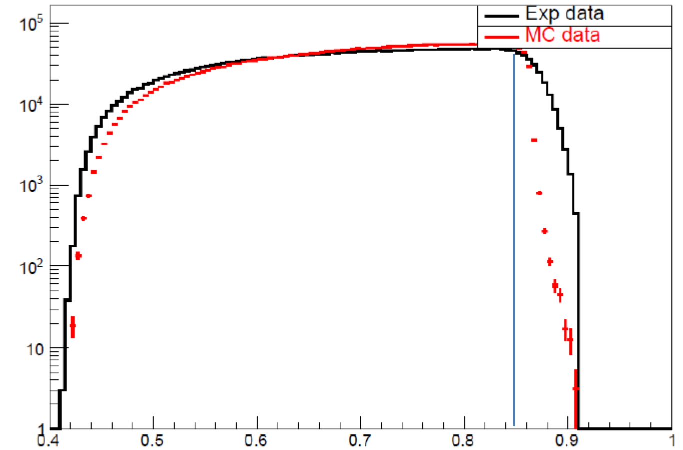




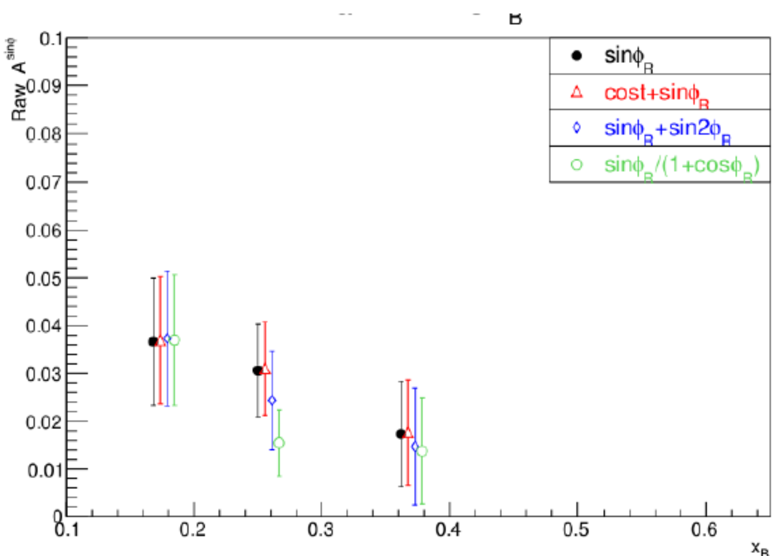


Systematic uncertainties - 2

- **Radiative corrections**
  - **basically unknown for the di-hadron final state**
  - **mostly suppressed by the y cut**
  - **estimation for the single pion is few % on the cross section**
  - **$\Delta A / A = 3\%$**



- **Fitting function**
  - **results obtained with 1par fit: $A = p0 \sin \phi_R$**
  - **add more terms in the ϕ_R expansion and re-extract $A^{\sin \phi R}$**
  - **$\Delta A / A \approx 10\%$**

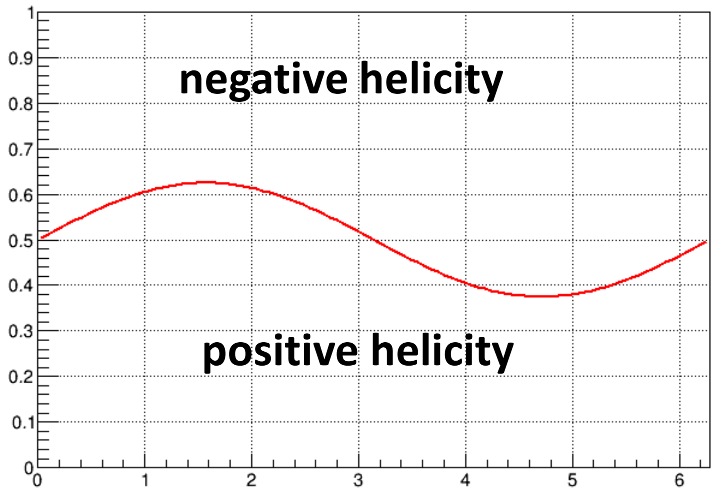


Polarizing the MC

$N \propto 1 + hA\sin\varphi$

- **Probability to have helicity h as a function of ϕ**

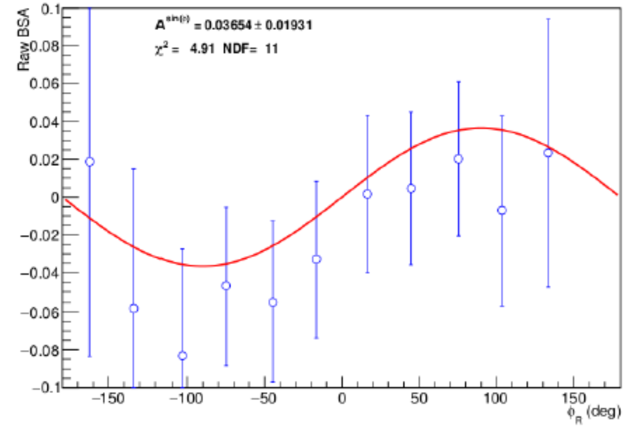
$$P(h=+1) = 0.5(1 + A\sin\varphi)$$
$$P(h=-1) = 0.5(1 - A\sin\varphi)$$

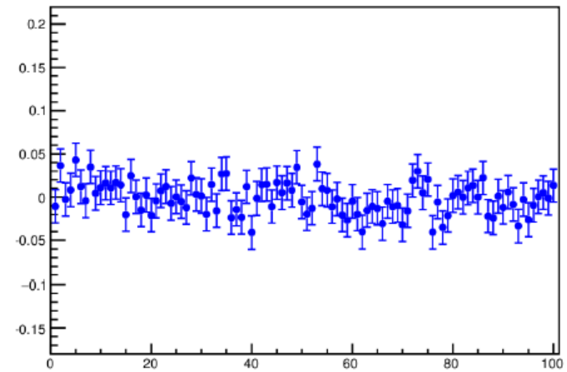


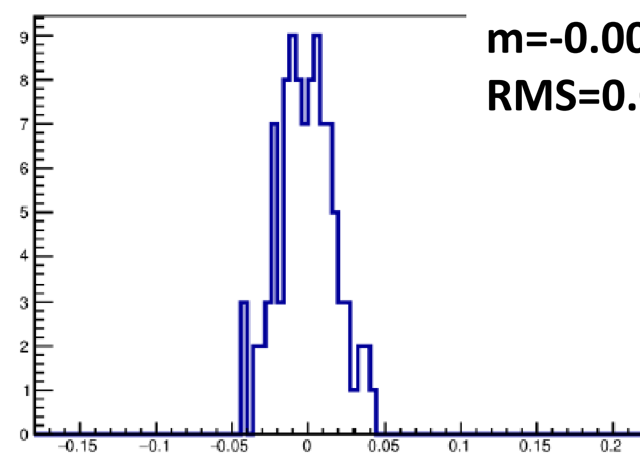
- **Assign the helicity to the event**

$$x < 0.5(1 + A\sin\varphi_i) \rightarrow h = +1$$
$$x > 0.5(1 + A\sin\varphi_i) \rightarrow h = -1$$

Input Asym. 2%
Extracted Asym 3.7±1.9



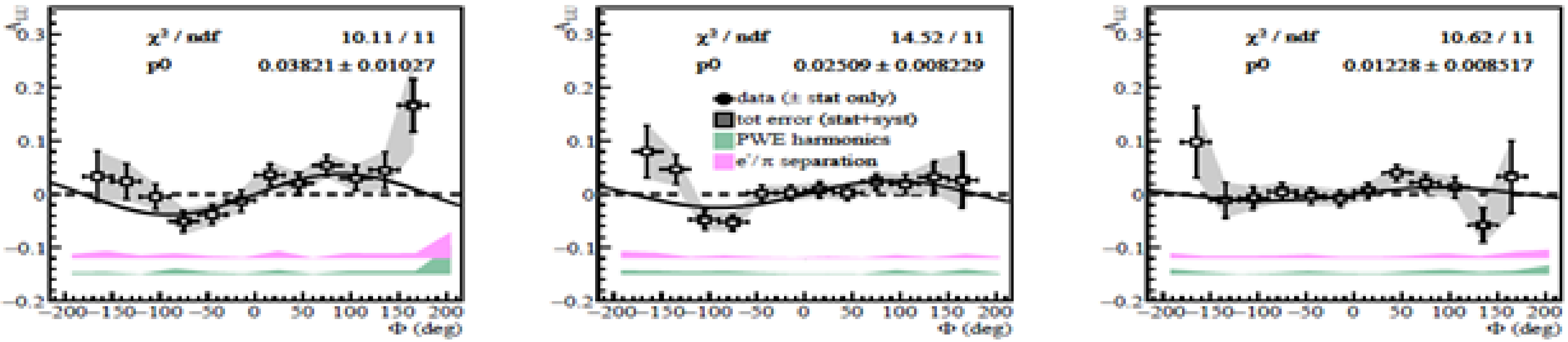




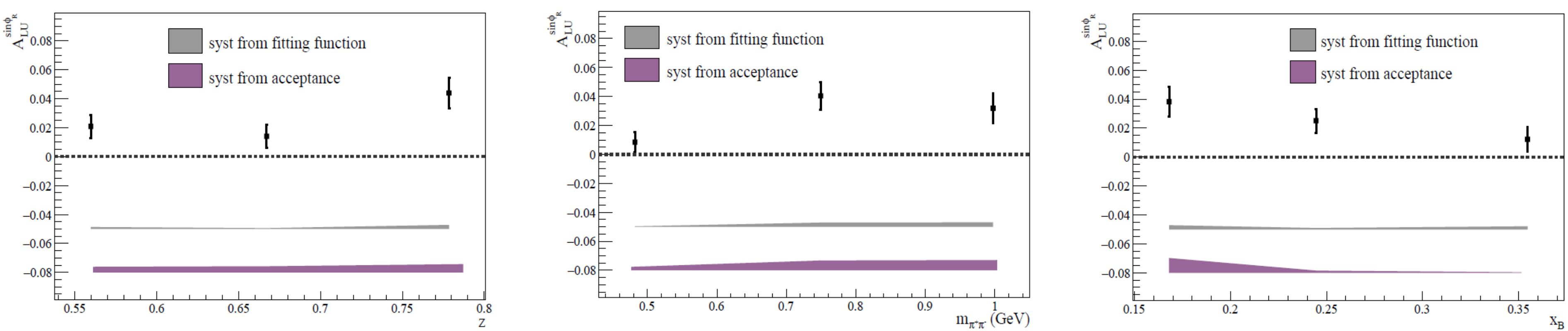
m=-0.001
RMS=0.018

Silvia's results

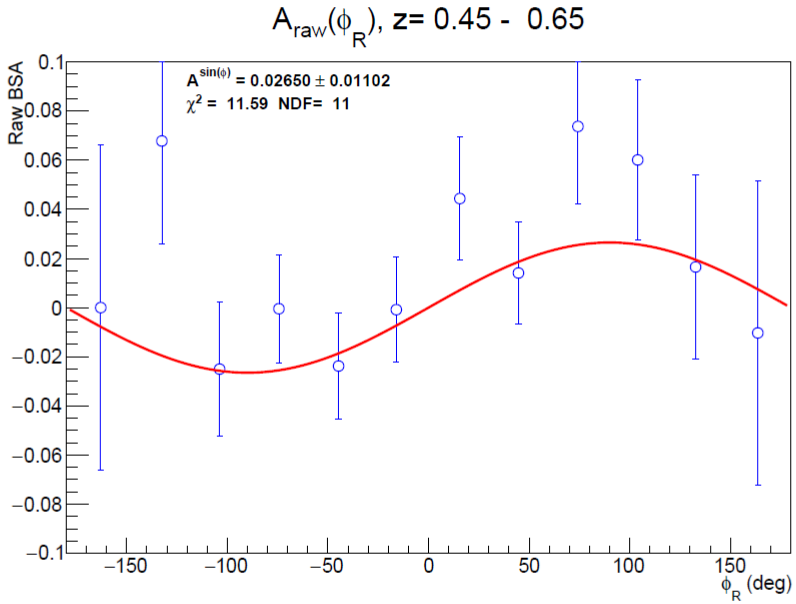
ϕ_R fits in bins of x_B

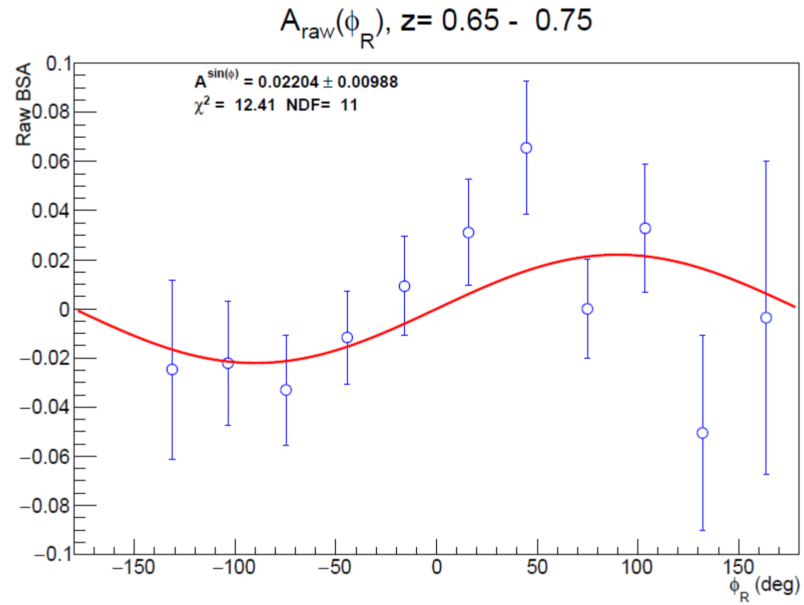


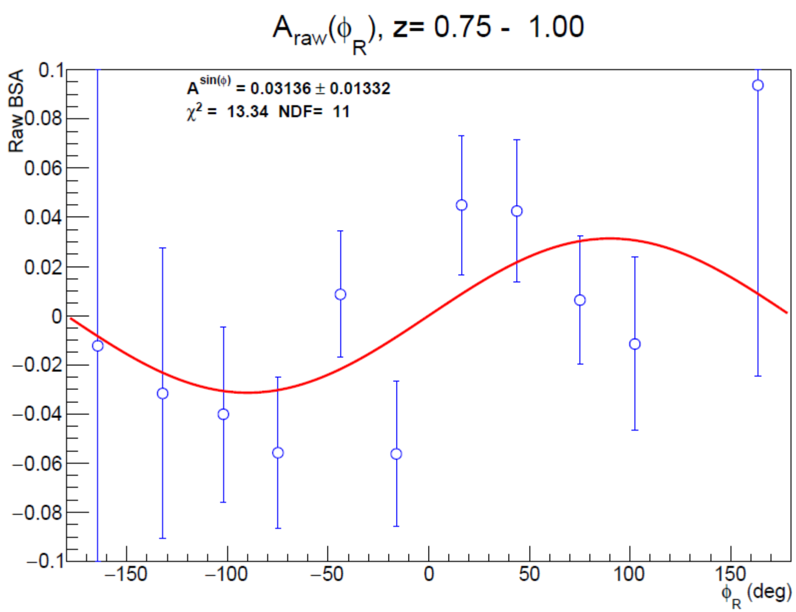
sin ϕ_R moments as a function of z, M(pi pi), x_B



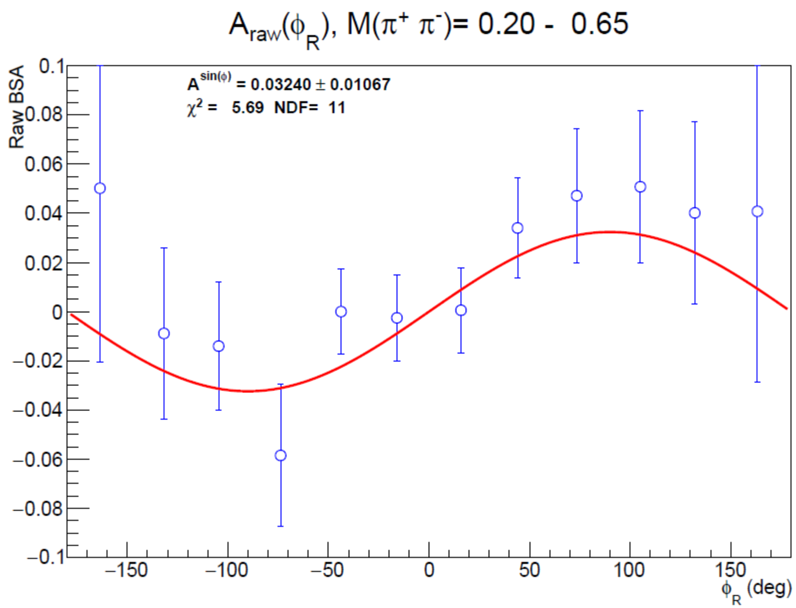
Raw Asymmetry vs z

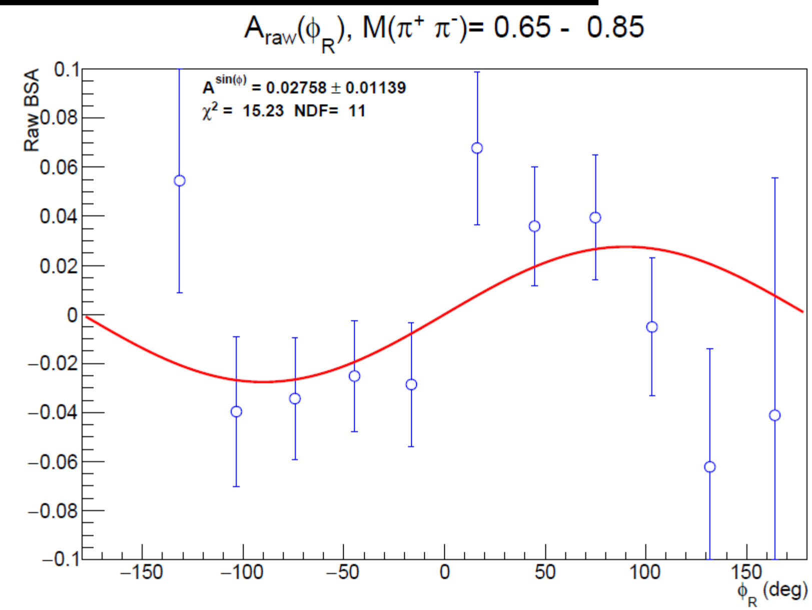


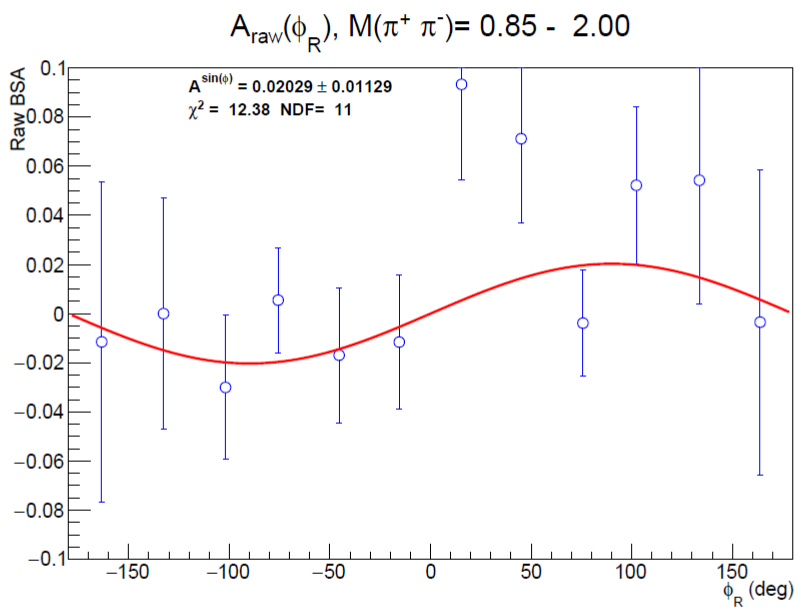




Raw Asymmetry vs M(pi pi)







Results vs kinematics