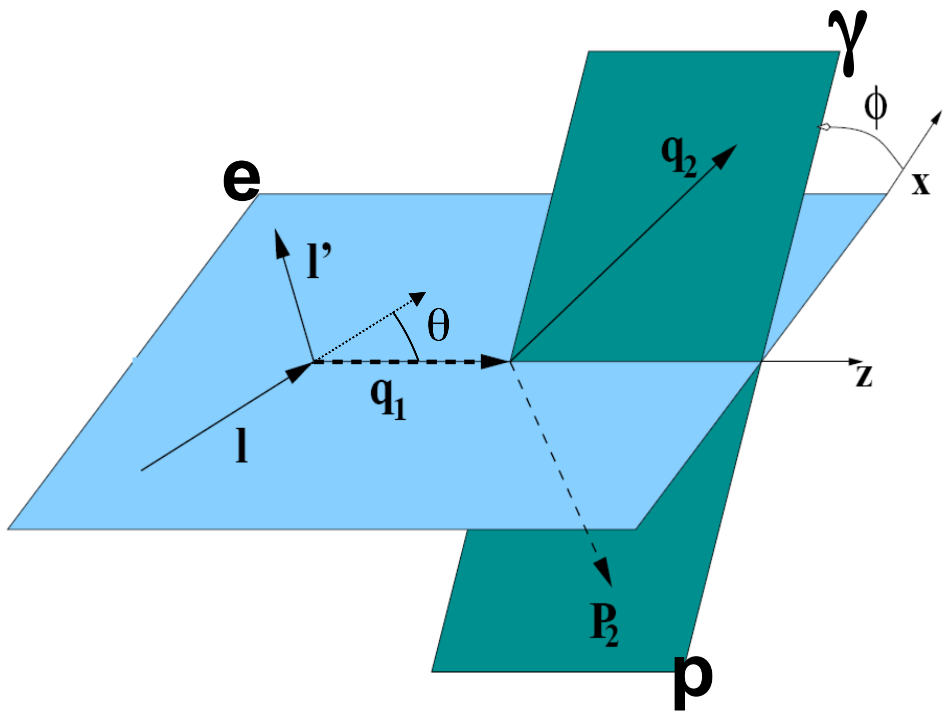
# Measuring $P_b P_T$ using exclusive photon production

**Harut Avakian**

**Deep processes working group meeting , JLab, June 17, 2016**

- Hard exclusive photon production
  - BH propagators
- Extracting PBPT from double spin asymmetry
- Summary & Conclusions

# Electroproduction Kinematics




$$Q^2 = -q_1^2 = 4EE' \sin(\theta/2)$$

$$\nu = E - E'$$

$$x_B = -q_1^2 / 2p_1q_1 = Q^2 / 2M\nu$$

$$y = \nu / E$$

$$t = (p_2 - p_1)^2 = \Delta^2$$

γ*–>γ require a finite longitudinal momentum transfer defined by the generalized Bjorken variable ξ

$$\xi = -\frac{(q_1 + q_2)^2}{2(p_1 + p_2)(q_1 + q_2)} \approx \frac{x_B}{2 - x_B}$$

$$\Delta_\perp^2 \approx (1 - \xi^2)(t - t_{\min})$$

$$t_{min} \approx \frac{M^2 x^2}{1 - x + xM^2/Q^2}$$

# Target Polarization Measurement from BH Double Spin Asymmetry

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Jefferson Lab, Newport News, VA 23606

## Abstract

We present studies of the double spin asymmetry in the hard exclusive photon production. The double spin asymmetry which is dominated by the BH, is discussed as an alternative source of information on the product of beam and target polarizations for CLAS12 polarized target runs.

$$A_{LL} = \frac{\left(\frac{N^{\downarrow\uparrow}}{Q^{\downarrow\uparrow}} - \frac{N^{\uparrow\uparrow}}{Q^{\uparrow\uparrow}}\right) + \left(\frac{N^{\uparrow\downarrow}}{Q^{\uparrow\downarrow}} - \frac{N^{\downarrow\downarrow}}{Q^{\downarrow\downarrow}}\right)}{f\left(\frac{N^{\uparrow\uparrow}}{Q^{\uparrow\uparrow}} + \frac{N^{\downarrow\uparrow}}{Q^{\downarrow\uparrow}} + \frac{N^{\uparrow\downarrow}}{Q^{\uparrow\downarrow}} + \frac{N^{\downarrow\downarrow}}{Q^{\downarrow\downarrow}}\right)}$$

$$A_{LL} \sim \frac{c_{0,\mathrm{LP}}^{\mathrm{BH}}}{c_{0,\mathrm{unp}}^{\mathrm{BH}}}$$

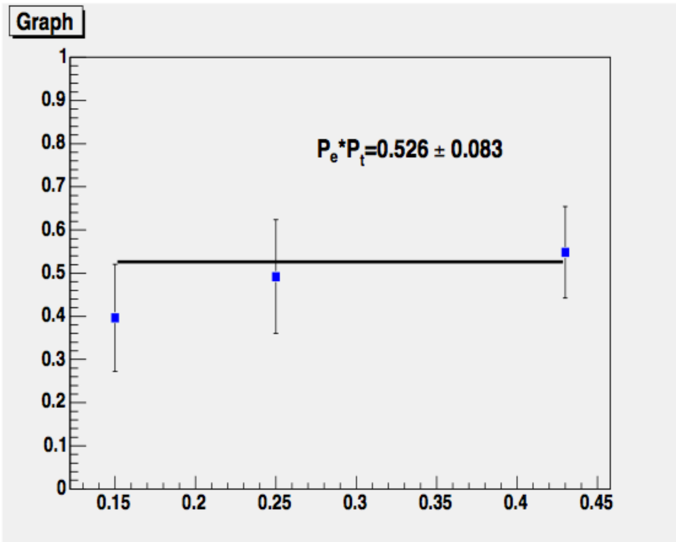
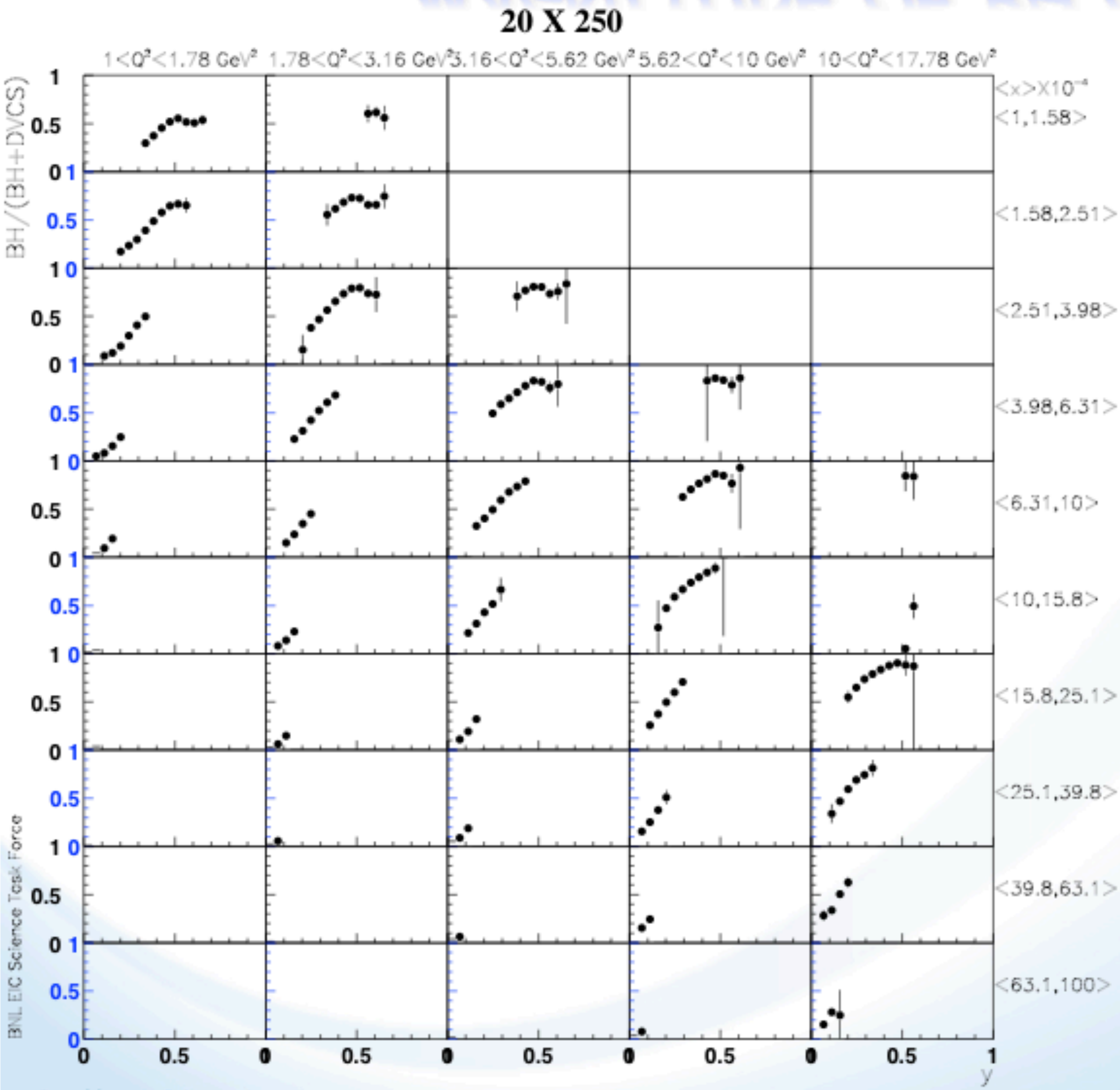



Figure 2: $P_B * P_T$ extracted using the $A_{LL}$ as a function of $t$ from EG1 data.

# EIC: MAGNITUDE OF BH CROSS SECTION



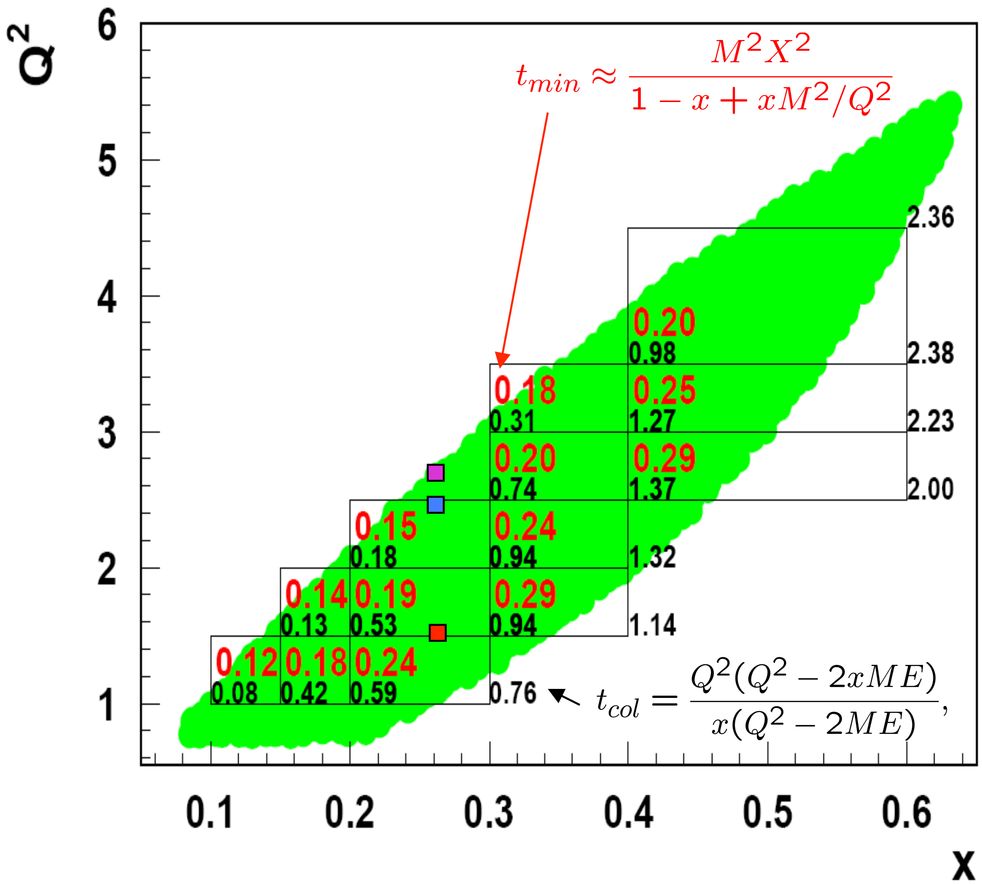

in bins....

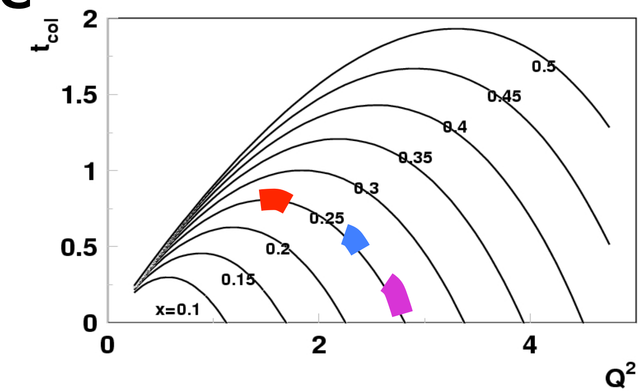
$0.01 < y < 0.6$
$0.01 < |t| < 1.0\ GeV^2$

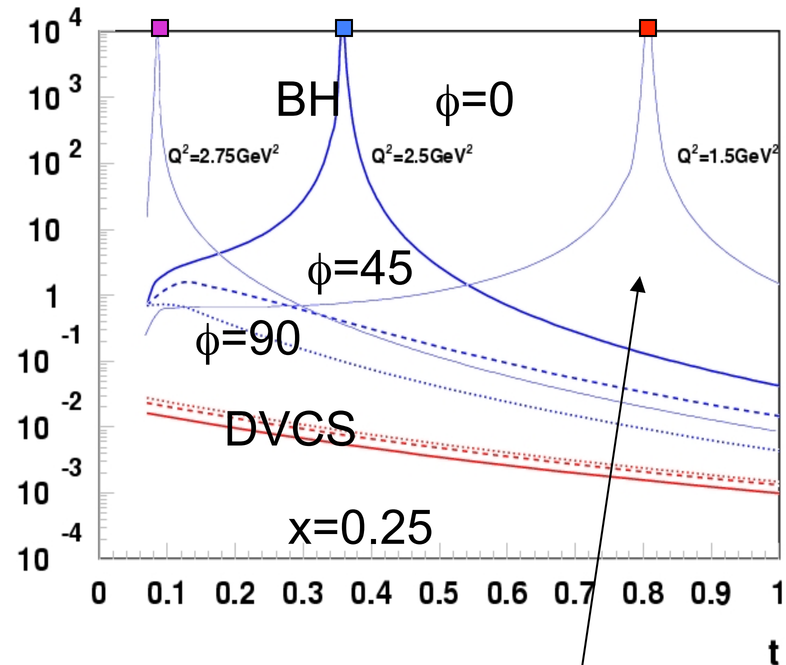
$Theta_{el} - Theta_{\gamma} > 0$
$Theta_{el} < \pi - 0.02$
$Theta_{\gamma} < \pi - 0.02$
$E_{el} > 1\ GeV$
$E_{\gamma} > 1\ GeV$

# DVCS: BH propagators

$$\mathcal{I} = \frac{\pm e^6}{x_B y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[ c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\},$$




- Strong dependence on kinematics of prefactor $\phi$-dependence, at $t=t_{col}$ $P_1(\phi)=0$ require special attention in interpretation of beam averaged beam SSA and in particular x-section differences
- Fraction of pure DVCS increases with **t** and $\phi$

# $\phi$-dependent amplitude

$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6}{x_B^2 y^2 (1+\epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \times \left\{ c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH} \cos(n\phi) + s_1^{\rm BH} \sin(\phi) \right\}$$

$C_{BH}$

$$|\mathcal{T}_{\rm DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{\rm DVCS} + \sum_{n=1}^{2} \left[ c_n^{\rm DVCS} \cos(n\phi) + s_n^{\rm DVCS} \sin(n\phi) \right] \right\}$$

$$\mathcal{P}_1 = -\frac{1}{y(1+\epsilon^2)} \{ J + 2K \cos(\phi) \}$$

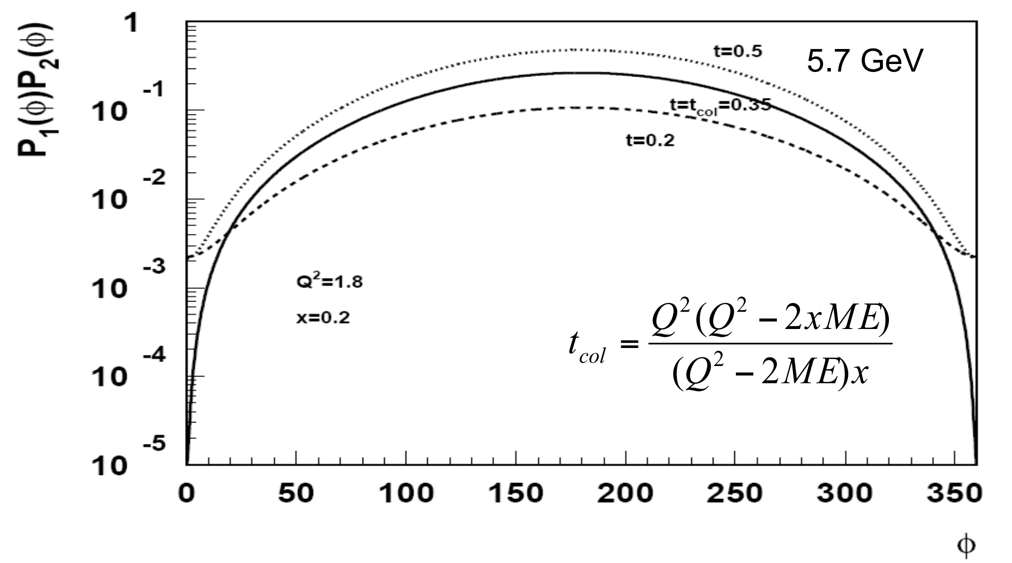
kinematic factors

$$\mathcal{I} = \frac{\pm e^6}{x_B y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[ c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\},$$

$$J = \left(1 - y - \frac{y\epsilon^2}{2}\right)\left(1 + \frac{\Delta^2}{Q^2}\right) - (1-x)(2-y)\frac{\Delta^2}{Q^2}$$

$C_{Int}$

$$A_{UL}(\phi) \sim \frac{s_{1,\rm LP}^{\mathcal{I}} \sin\phi}{c_{0,\rm unp}^{\rm BH} + (c_{1,\rm unp}^{\rm BH} + c_{1,\rm unp}^{\mathcal{I}} + \ldots)\cos\phi + \ldots}$$



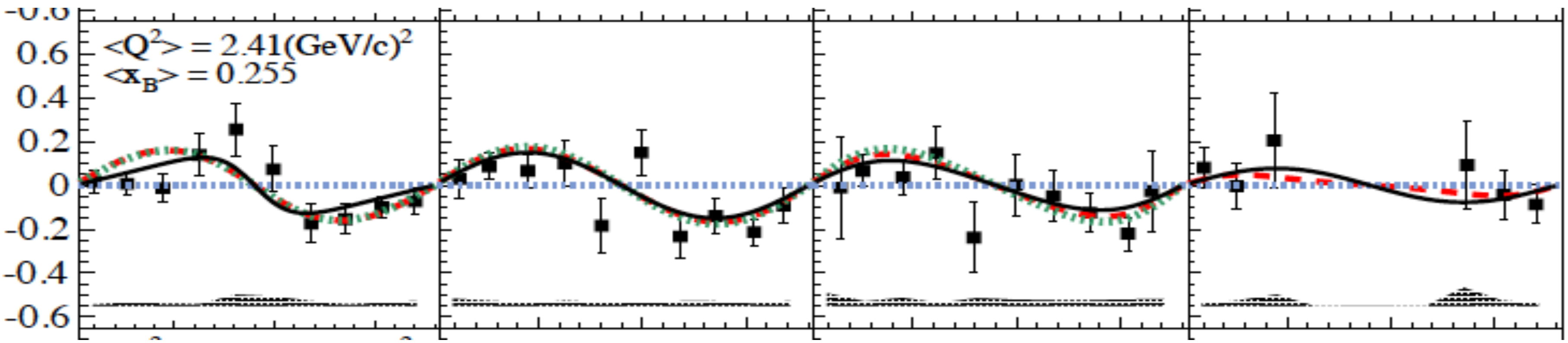

$$C_{Int} = C_{BH} * x/y * (1+\varepsilon^2)^2$$

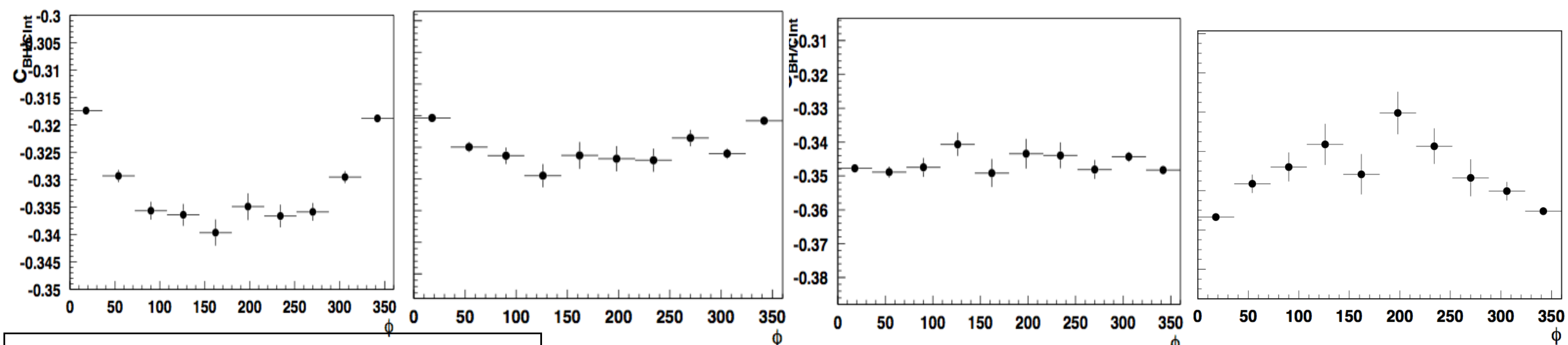
- **Strong dependence on kinematics of prefactor $\phi$-dependence, at $t \approx t_{col}$, $P_1(\phi) \to 0$**
- **Do the kinematic factors with propagators in $T_{BH}$ and $I$ cancel in the ratio of**

# $\phi$-dependent amplitude

| Bin | $x_B$ bin | $\theta_e$ bin | $\langle x_B \rangle$ | $\langle Q^2 \rangle$ $((\mathrm{GeV}/c)^2)$ |
|---|---|---|---|---|
| 1 | $0.1 < x_B < 0.2$ | $15^o < \theta_e < 48^o$ | 0.179 | 1.52 |
| 2 | $0.2 < x_B < 0.3$ | $15^o < \theta_e < 34^o$ | 0.255 | 1.97 |
| 3 | $0.2 < x_B < 0.3$ | $34^o < \theta_e < 48^o$ | 0.255 | 2.41 |
| 4 | $0.3 < x_B < 0.4$ | $15^o < \theta_e < 45^o$ | 0.345 | 2.60 |
| 5 | $x_B > 0.4$ | $15^o < \theta_e < 45^o$ | 0.453 | 3.31 |

| Bin | $-t$ range $(\mathrm{GeV}/c)^2$ | $\langle -t \rangle$ $(\mathrm{GeV}/c)^2$ |
|---|---|---|
| 1 | $0.08 < -t < 0.18$ | 0.137 |
| 2 | $0.18 < -t < 0.3$ | 0.234 |
| 3 | $0.3 < -t < 0.7$ | 0.467 |
| 4 | $0.7 < -t < 2.0$ | 1.175 |



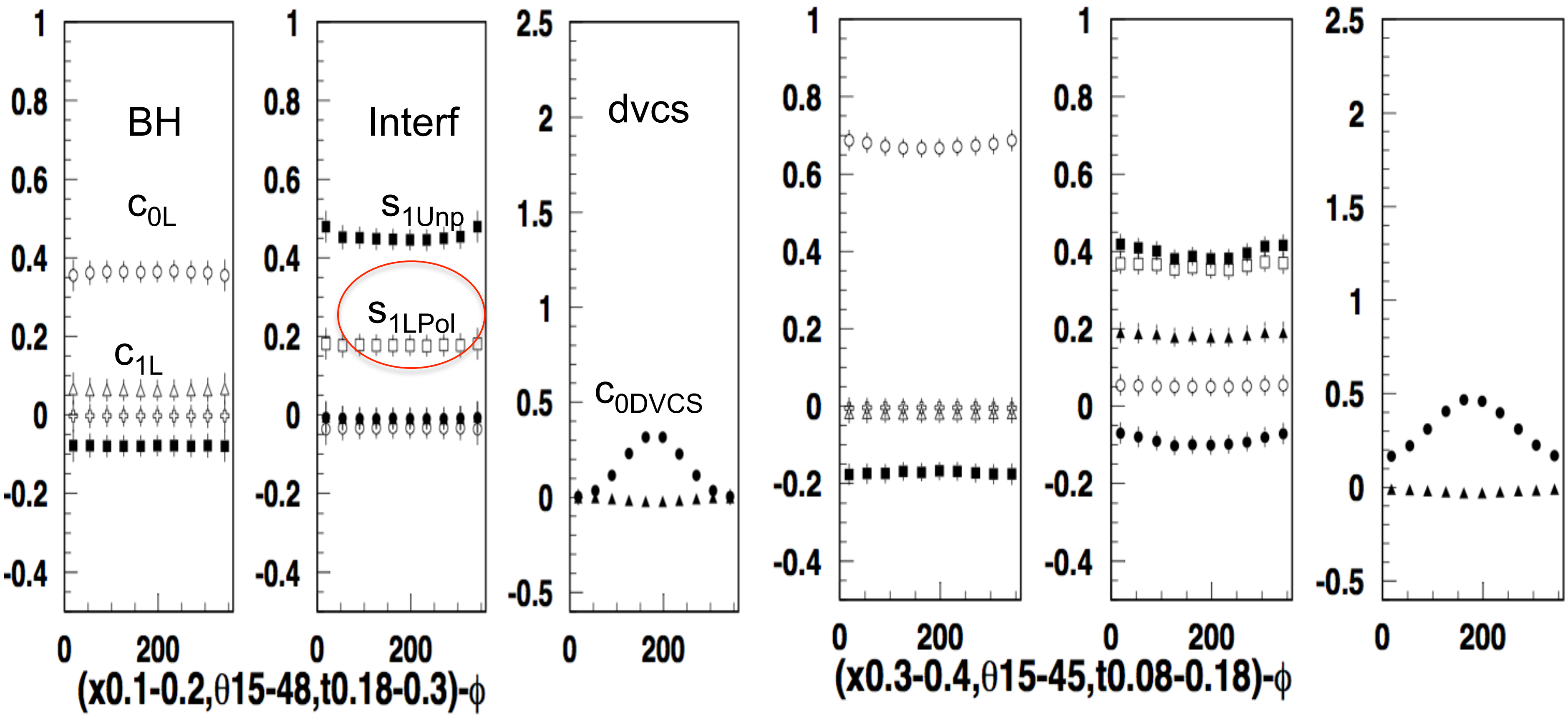




$C_{int}/C_{BH}$=-x/y*(1+$\varepsilon^2$)$^2$

•**The $\phi$-dependence of prefactor doesn't cancel: should be accounted in calculations**

# Azimuthal moments in ep->e'p'γ

Ratio of different contributions to $c_{0BH}$




Different azimuthal moments become relevant
in different kinematical regions

# azimuthal moments in DVCS (example)

$$\mathcal{I} = \frac{\pm e^6}{x_B y^3 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)\Delta^2}\left\{c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)\right]\right\},$$

$$\left\{\begin{array}{c} c_{1,\mathrm{unp}}^{\mathcal{I}} \\ s_{1,\mathrm{unp}}^{\mathcal{I}} \end{array}\right\} = 8K\left\{\begin{array}{c} -(2-2y+y^2) \\ \lambda y(2-y) \end{array}\right\}\left\{\begin{array}{c} \Re\mathrm{e} \\ \Im\mathrm{m} \end{array}\right\}\mathcal{C}_{\mathrm{unp}}^{\mathcal{I}}(\mathcal{F}),$$

$$\mathcal{C}_{\mathrm{LP}}^{\mathcal{I}} = \frac{x_B}{2-x_B}(F_1+F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right) + F_1\widetilde{\mathcal{H}} - \frac{x_B}{2-x_B}\left(\frac{x_B}{2}F_1 + \frac{\Delta^2}{4M^2}F_2\right)\widetilde{\mathcal{E}},$$

All moments involve several contributions with different Form Factors and GPDs multiplied by a kinematic term involving propagators

# $\phi$-dependent ratios (eg1dvcs paper)

| Bin | $x_B$ bin | $\theta_e$ bin | $\langle x_B \rangle$ | $\langle Q^2 \rangle$ ((GeV/c)$^2$) |
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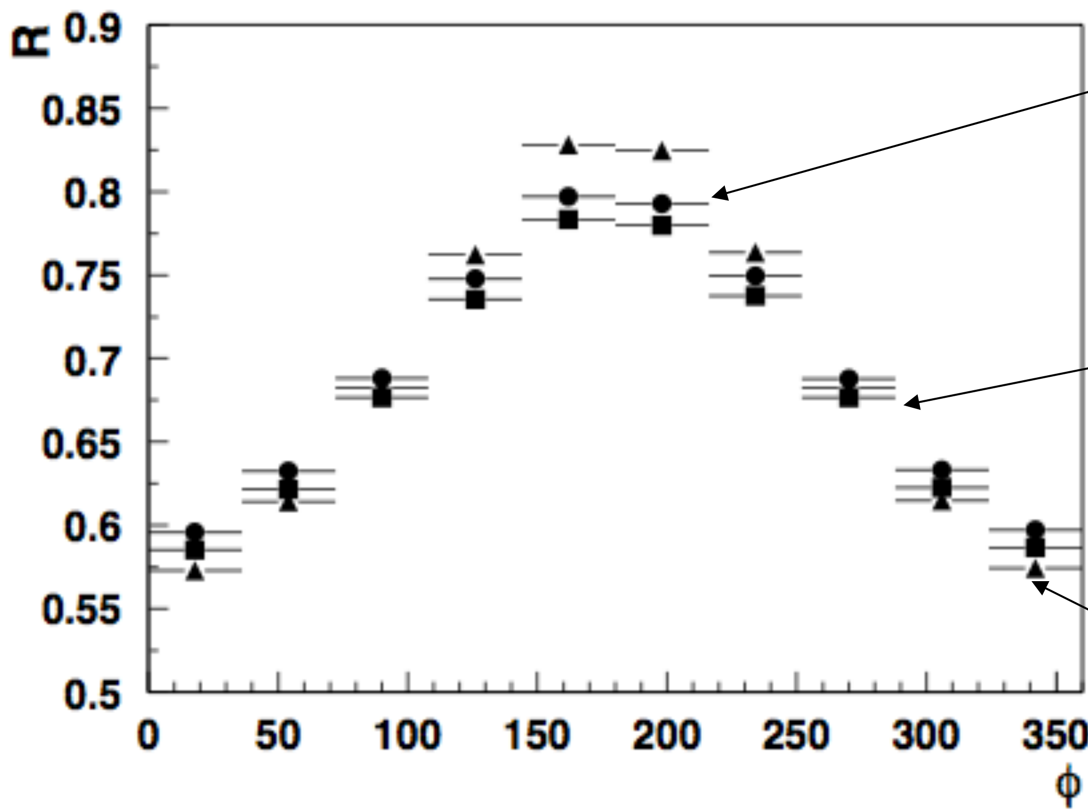


$$\frac{C^{BH}_{0LP} + C^{BH}_{1LP} cos\phi}{C^{BH}_{0Unp} + C^{BH}_{1Unp} cos\phi + C^{BH}_{2Unp} cos2\phi}$$

GPD model independent

$$\frac{C^{BH}_{0LP} + C^{BH}_{1LP} cos\phi + C^{Int}_{0LP} + C^{Int}_{1LP} cos\phi}{C^{BH}_{0Unp} + C^{BH}_{1Unp} cos\phi + C^{BH}_{2Unp} cos2\phi}$$

GPD model dependent (systematics from models)

$$\frac{C^{BH}_{0LP} + C^{BH}_{1LP} cos\phi + C^{Int}_{0LP} + C^{Int}_{1LP} cos\phi}{C^{BH}_{0Unp} + C^{BH}_{1Unp} cos\phi + C^{BH}_{2Unp} cos2\phi + C^{Int}_{0Unp} + C^{Int}_{1Unp} cos\phi}$$

- **The $\phi$-dependence of prefactor doesn't cancel: should be accounted in calculations**

# ϕ-dependent amplitude

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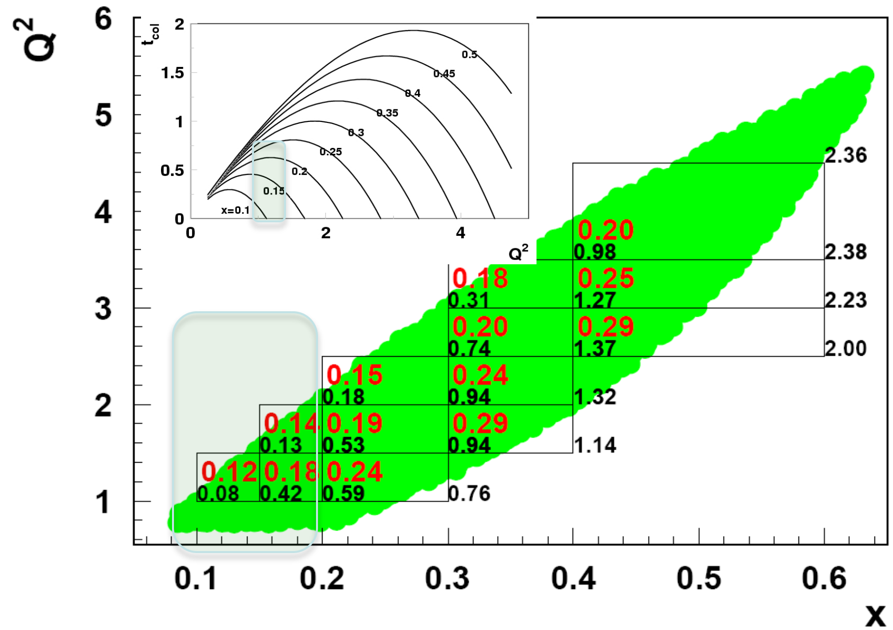


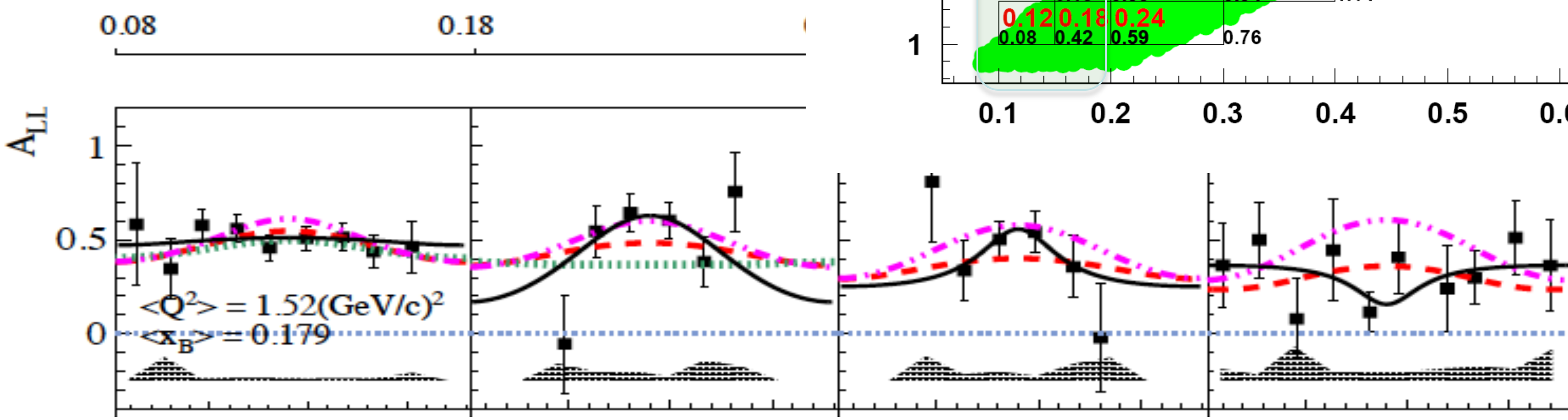


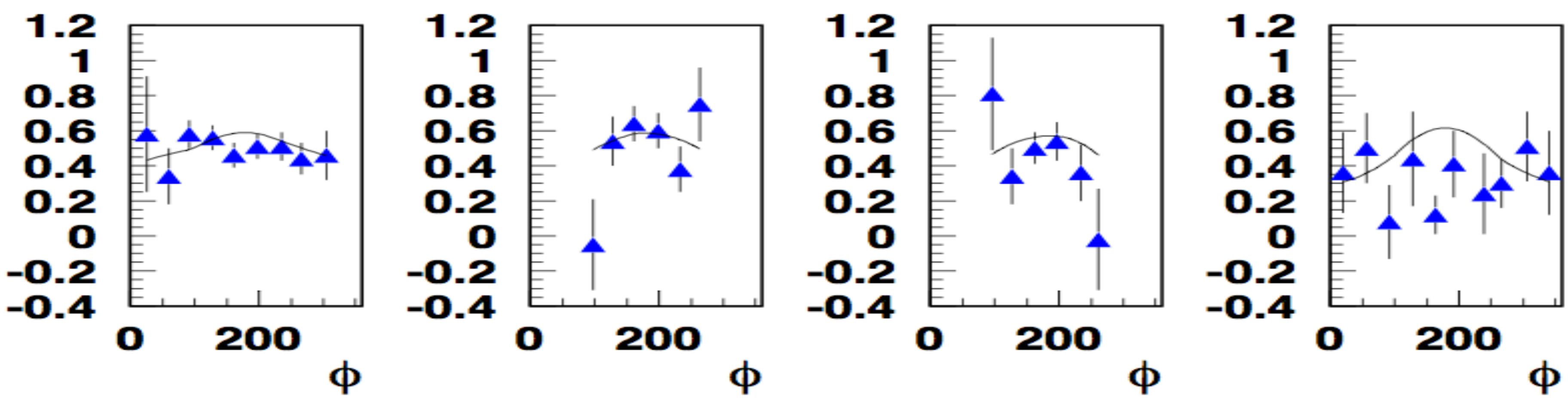

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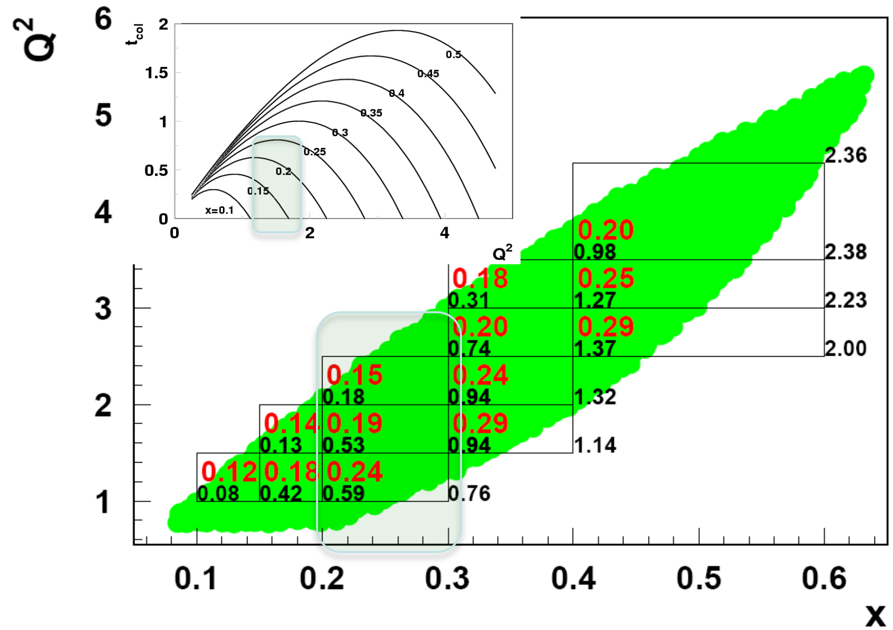


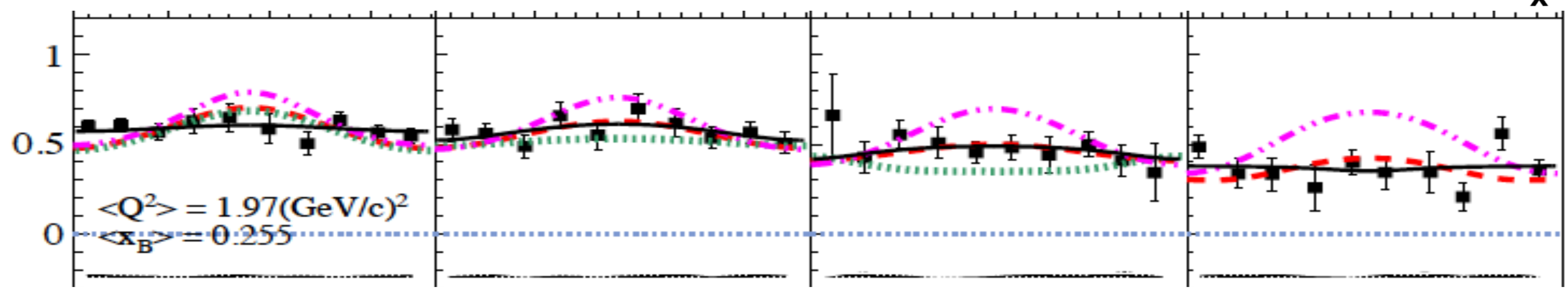


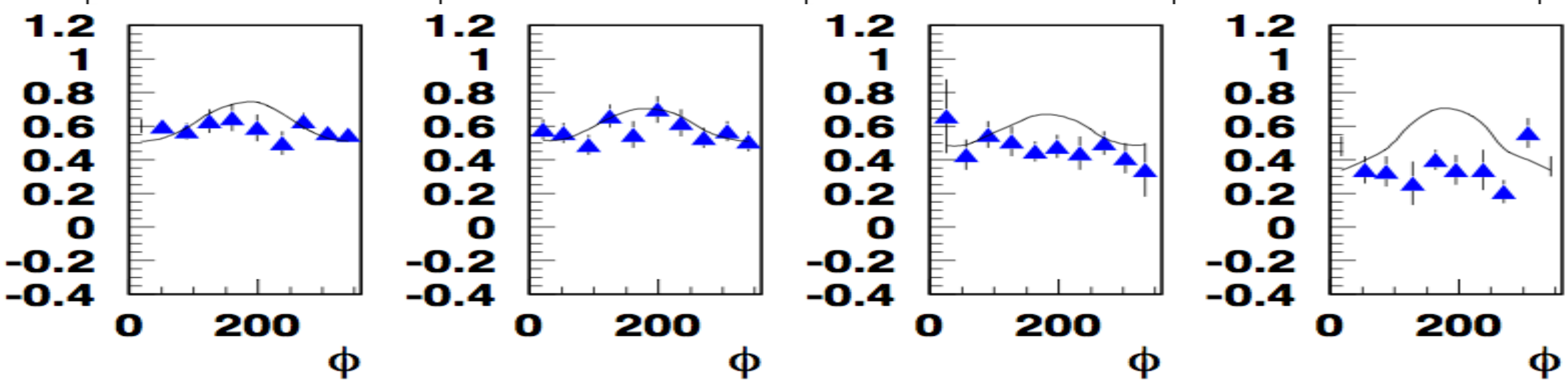

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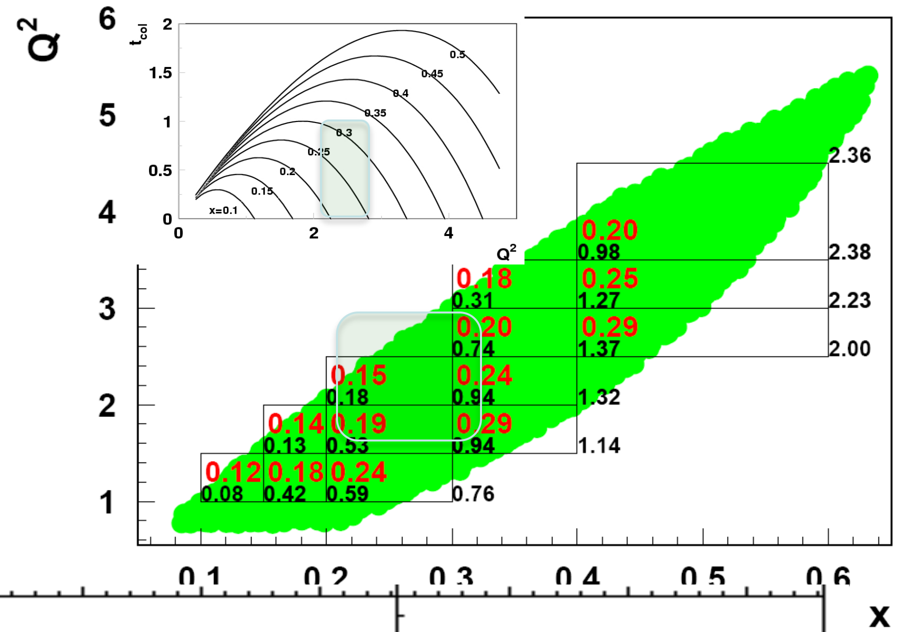
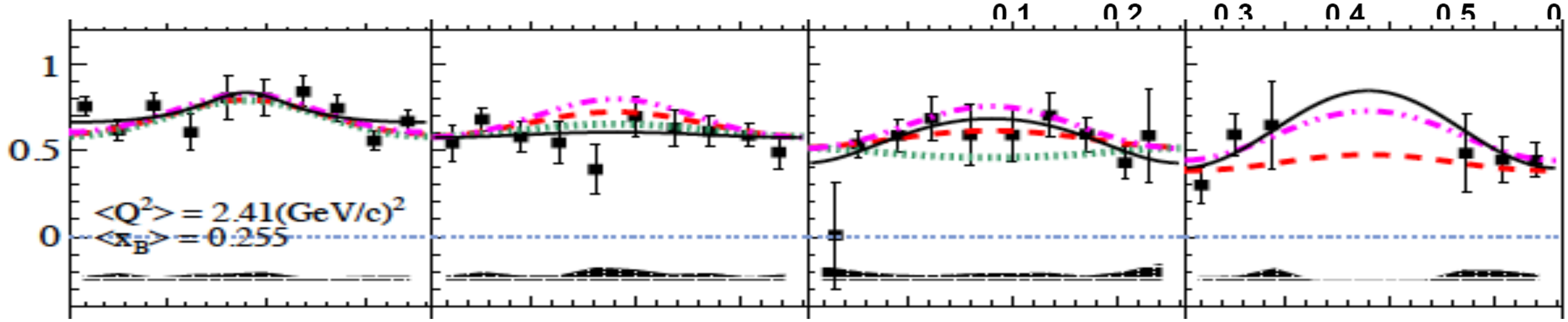
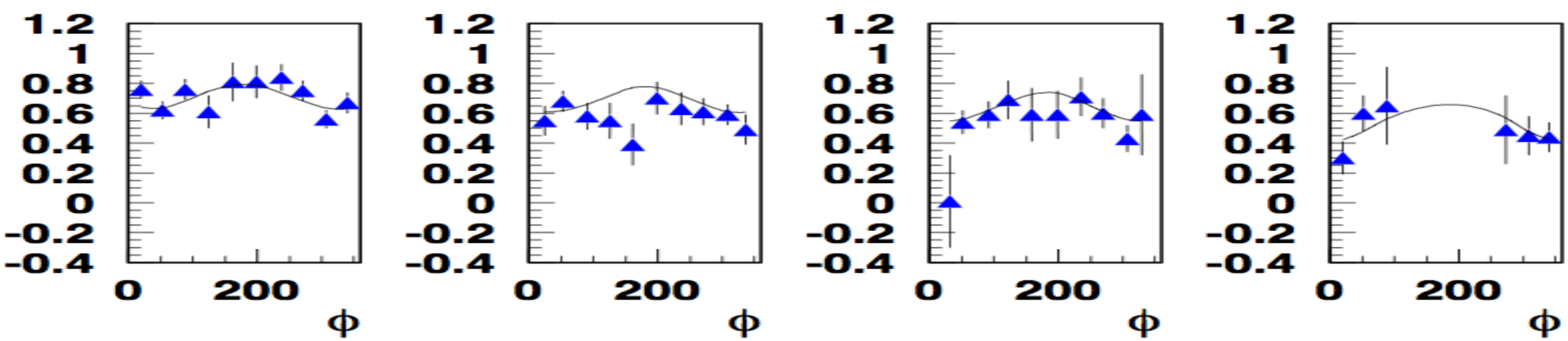
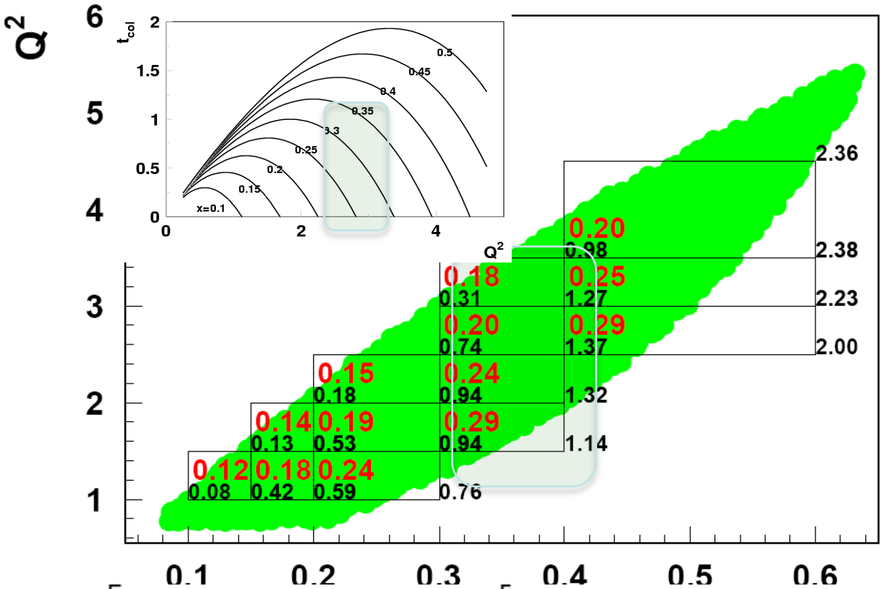


# ϕ-dependent amplitude

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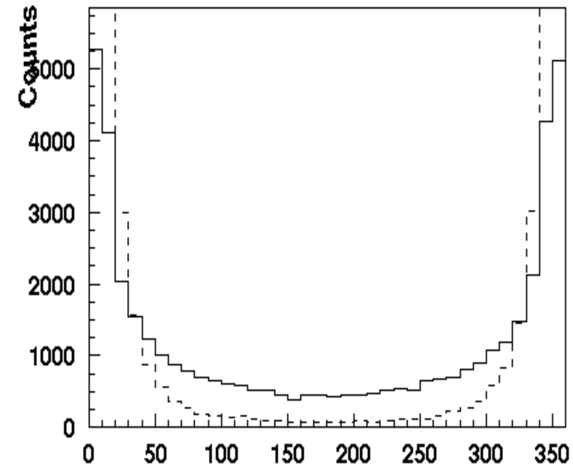
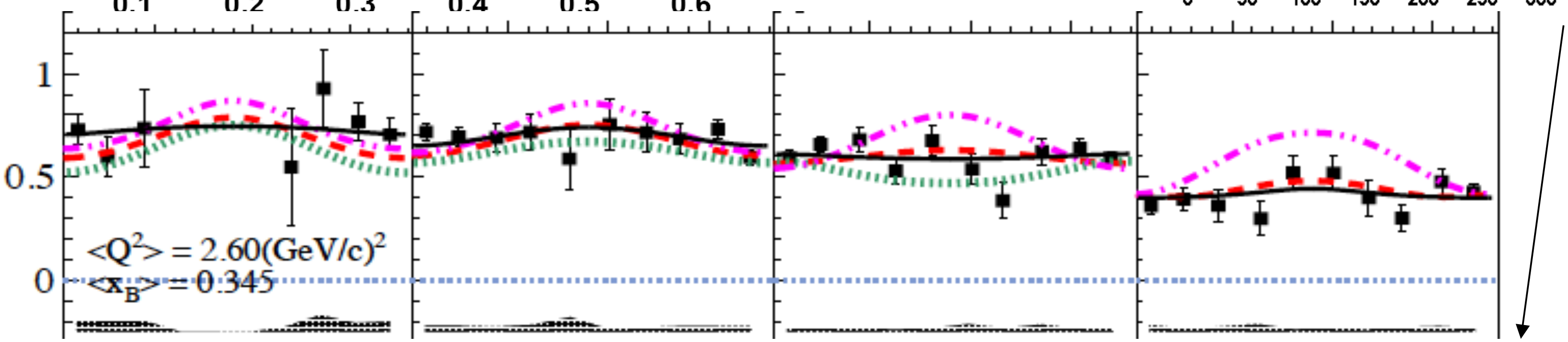
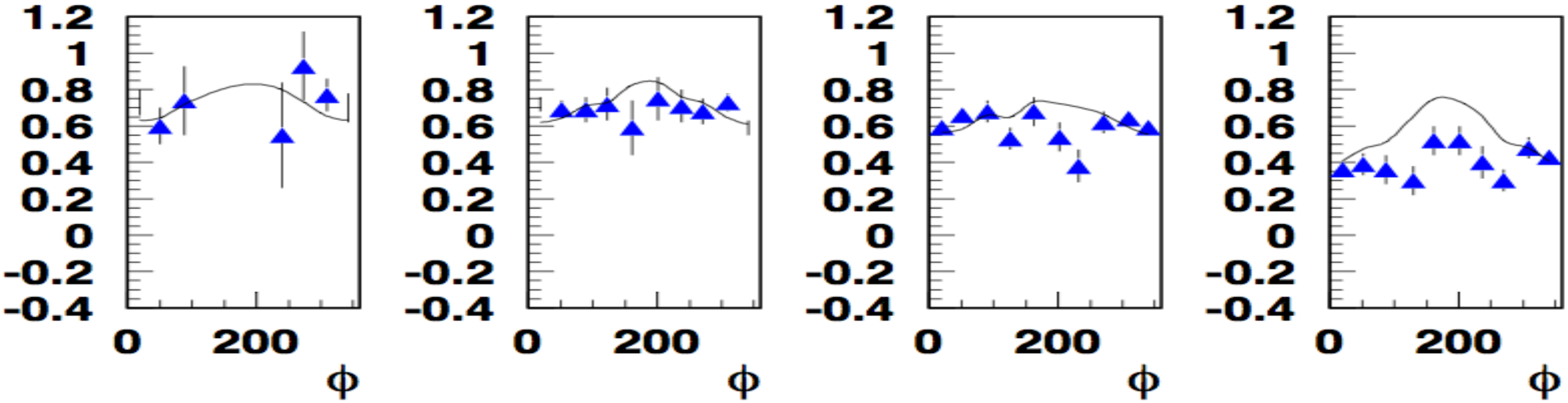
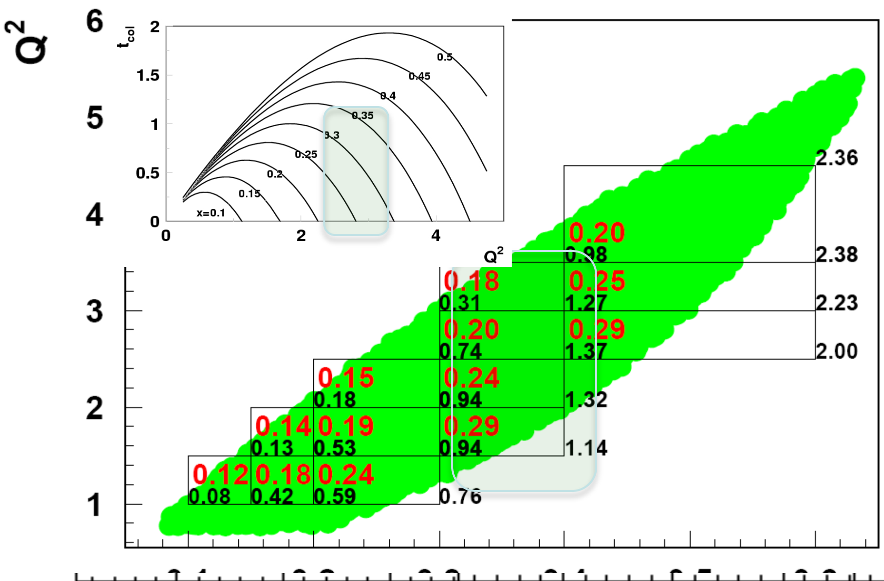


# $\phi$-dependent amplitude

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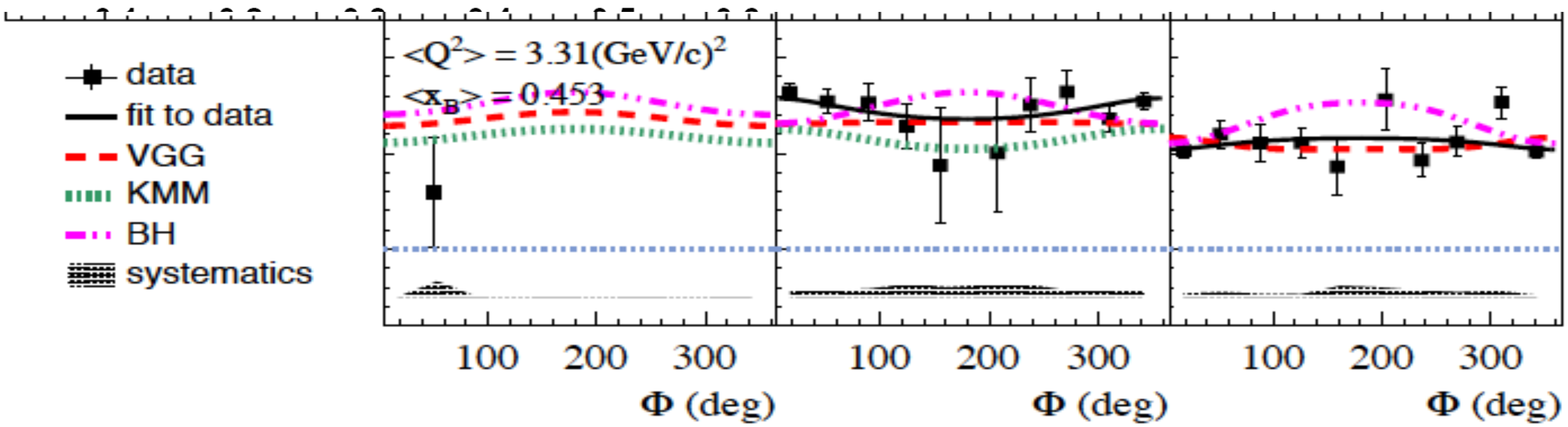
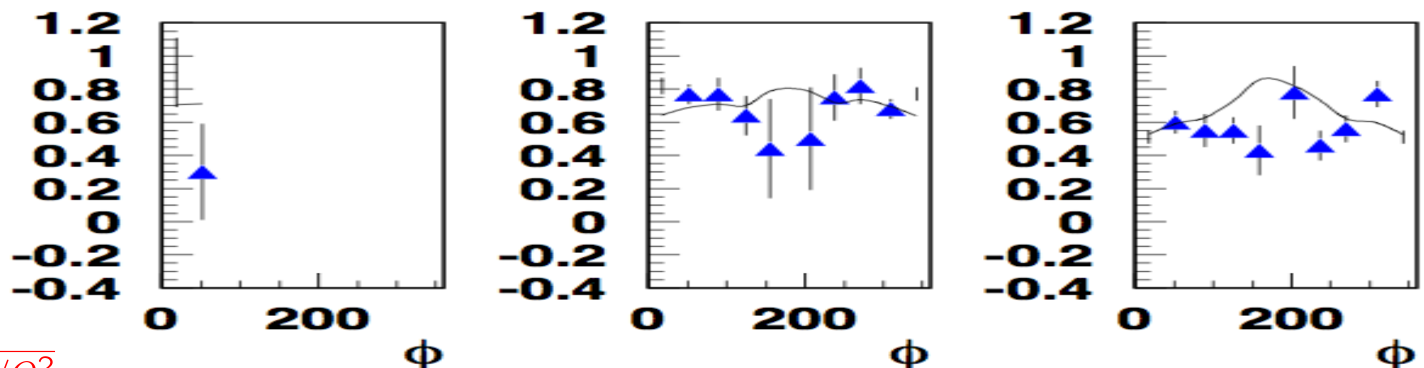
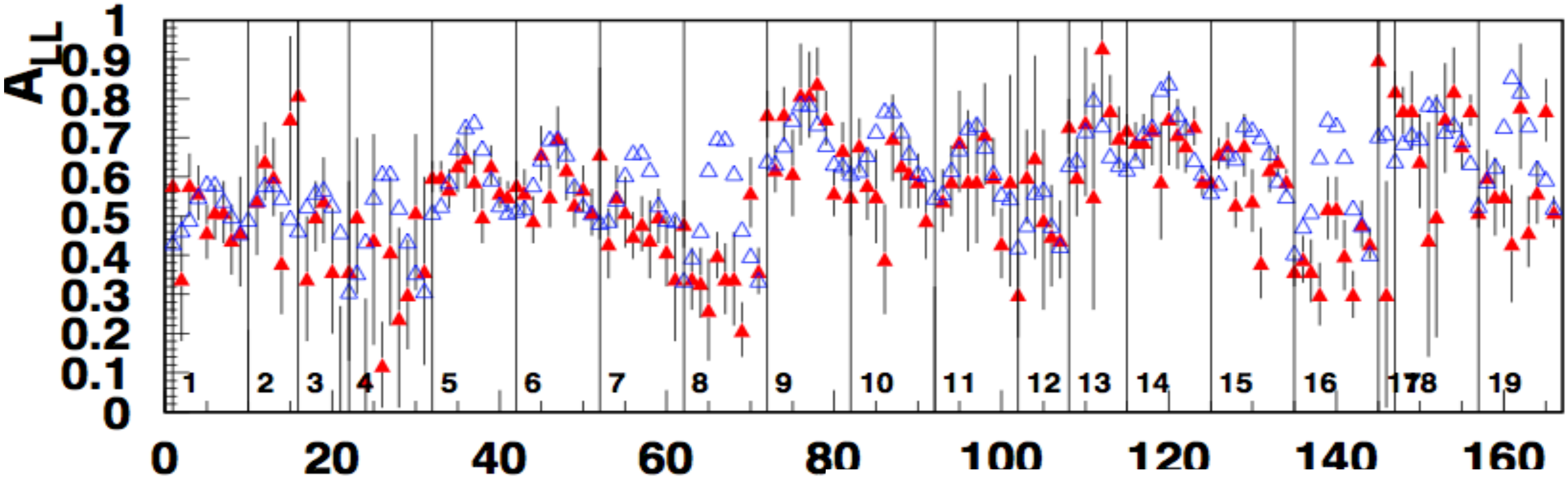
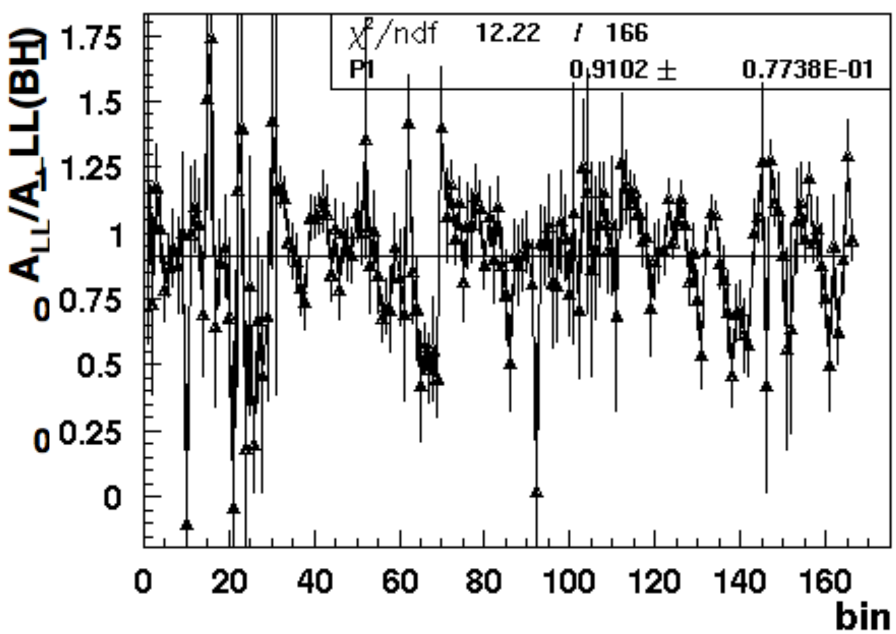


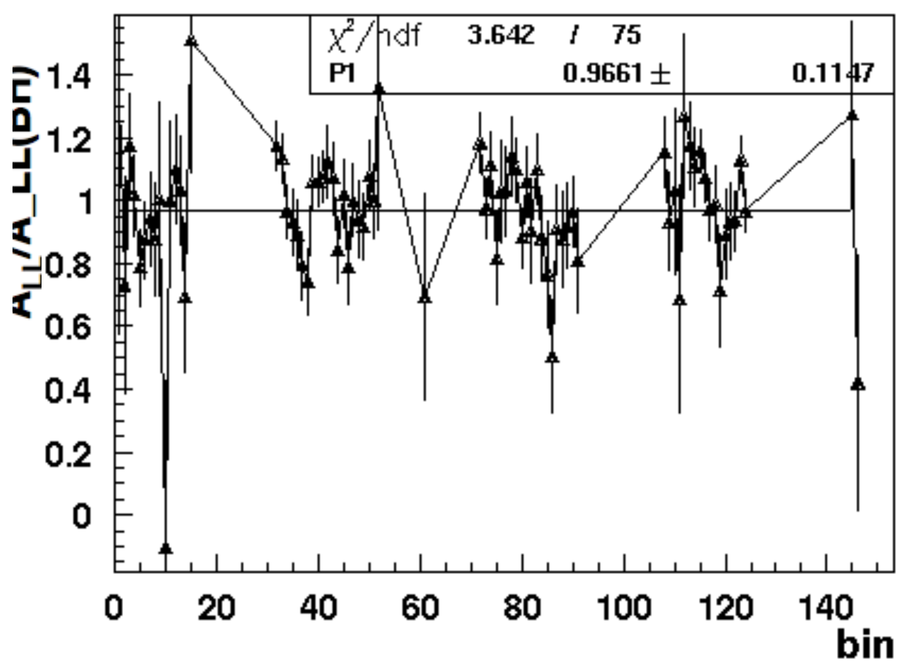




$$t_{min} \approx \frac{M^2 X^2}{1 - x + xM^2/Q^2}$$

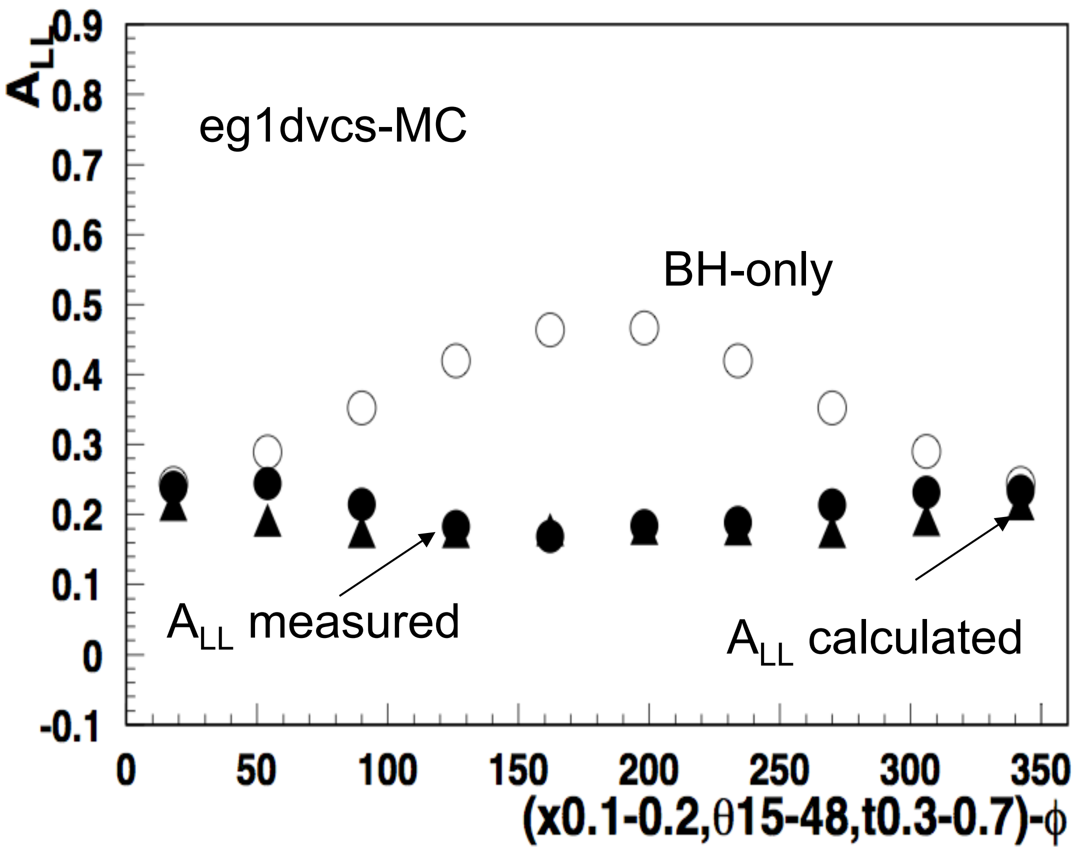
# $A_{LL}$-data vs BH

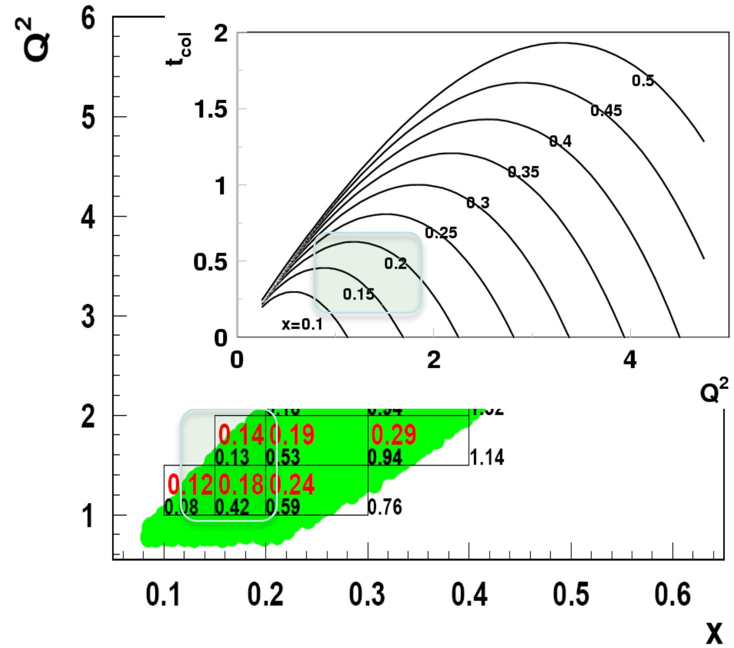


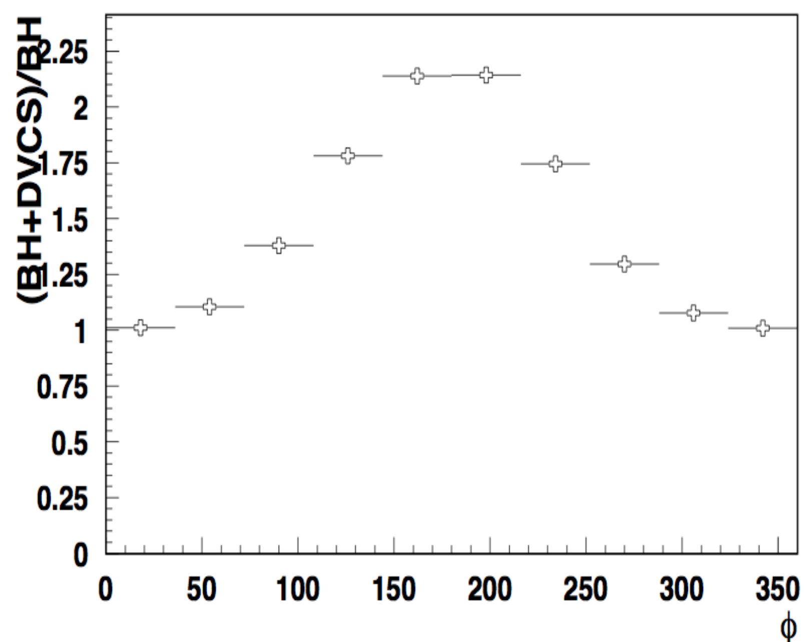



# MC studies: BH in $A_{LL}$




The $A_{LL}$ $\phi$-dependence dominated by BH only at relatively small $\phi$

# ϕ-dependent ratios (eg1dvcs paper)

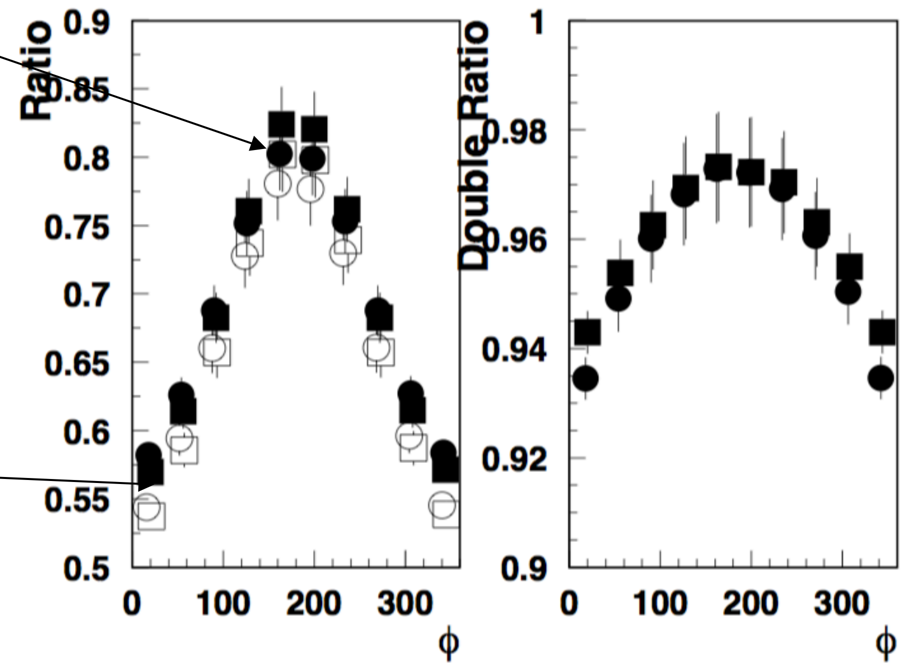
| Bin | $x_B$ bin | $\theta_e$ bin | $\langle x_B \rangle$ | $\langle Q^2 \rangle$ ((GeV/c)$^2$) |
|---|---|---|---|---|
| 1 | $0.1 < x_B < 0.2$ | $15^o < \theta_e < 48^o$ | 0.179 | 1.52 |
| 2 | $0.2 < x_B < 0.3$ | $15^o < \theta_e < 34^o$ | 0.255 | 1.97 |
| 3 | $0.2 < x_B < 0.3$ | $34^o < \theta_e < 48^o$ | 0.255 | 2.41 |
| 4 | $0.3 < x_B < 0.4$ | $15^o < \theta_e < 45^o$ | 0.345 | 2.60 |
| 5 | $x_B > 0.4$ | $15^o < \theta_e < 45^o$ | 0.453 | 3.31 |

$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{e^6}{x_{\mathrm{B}}^2 y^2 (1+\epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \times \left\{ c_0^{\mathrm{BH}} + \sum_{n=1}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + s_1^{\mathrm{BH}} \sin(\phi) \right\}$$

| Bin | $-t$ range (GeV/c)$^2$ | $\langle -t \rangle$ (GeV/c)$^2$ |
|---|---|---|
| 1 | $0.08 < -t < 0.18$ | 0.137 |
| 2 | $0.18 < -t < 0.3$ | 0.234 |
| 3 | $0.3 < -t < 0.7$ | 0.467 |
| 4 | $0.7 < -t < 2.0$ | 1.175 |

GPD model independent

$$\frac{C^{BH}_{0LP} + C^{BH}_{1LP} cos\phi}{C^{BH}_{0Unp} + C^{BH}_{1Unp} cos\phi + C^{BH}_{2Unp} cos2\phi}$$




GPD model dependent (systematics from models)

$$\frac{C^{BH}_{0LP} + C^{BH}_{1LP} cos\phi + C^{Int}_{0LP} + C^{Int}_{1LP} cos\phi}{C^{BH}_{0Unp} + C^{BH}_{1Unp} cos\phi + C^{BH}_{2Unp} cos2\phi + C^{Int}_{0Unp} + C^{Int}_{1Unp} cos\phi}$$

Empty symbols correspond to separate nominator and denominator calculations and filled symbols to calculation of the ratio (right plot is for ratio)

•Difference ~5% from calculating as ratio of structure functions

# summary & plans

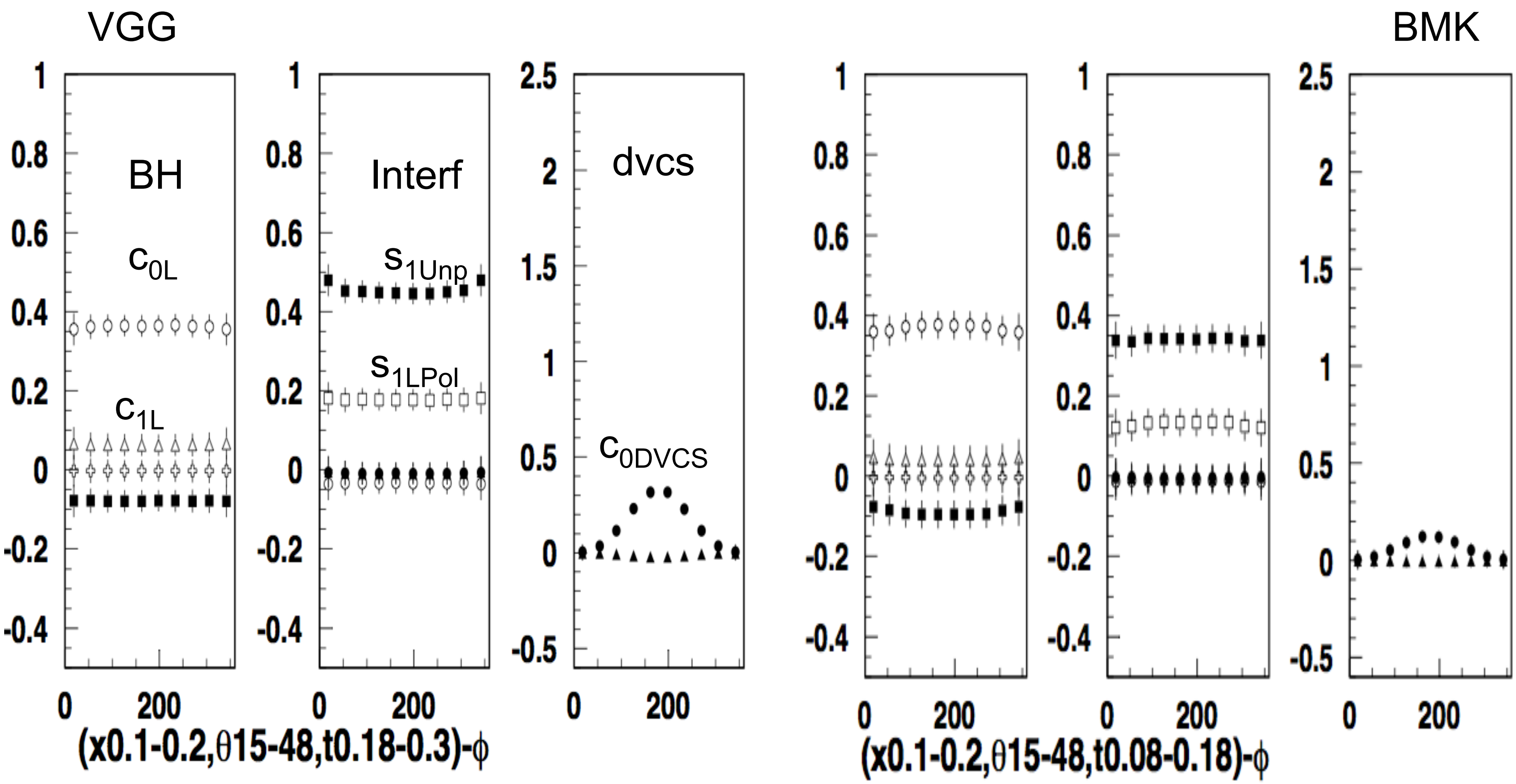
- Comparing with theory calculations should be done by integration over bins within the acceptance of numerator and denominator separately
- Smaller bins will reduce the systematics

- Compare the $A_{LL}$ with calculations (eg1dvcs data) and develop procedure for extraction of the $P_B P_T$ from CLAS12/EIC
- Extract x-section differences for polarized case with and without asymmetries

support slides…

# Azimuthal moments in ep->e'p'$\gamma$

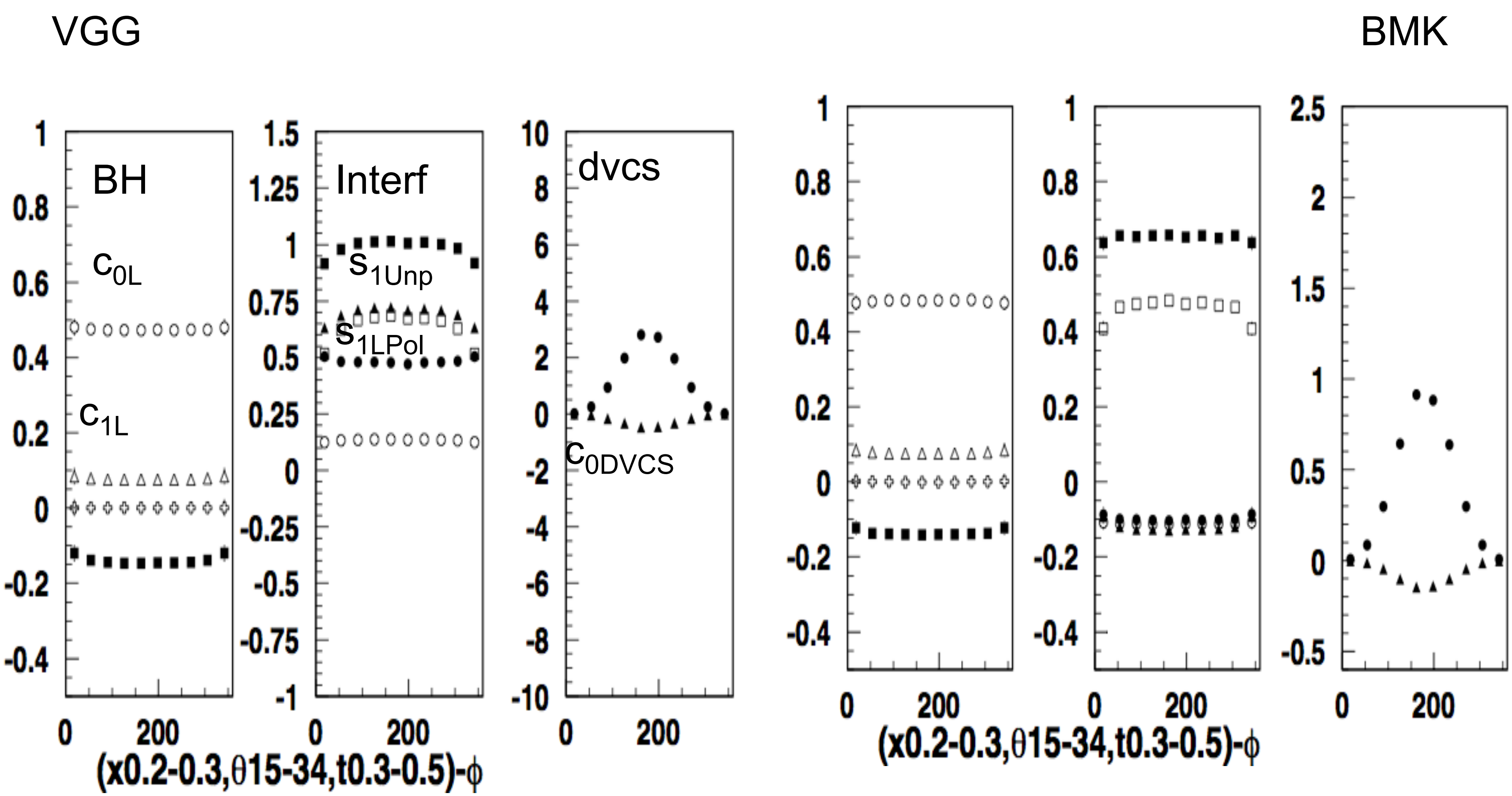
## Ratio of different contributions to $c_{0BH}$




Different azimuthal moments become relevant in different kinematical regions

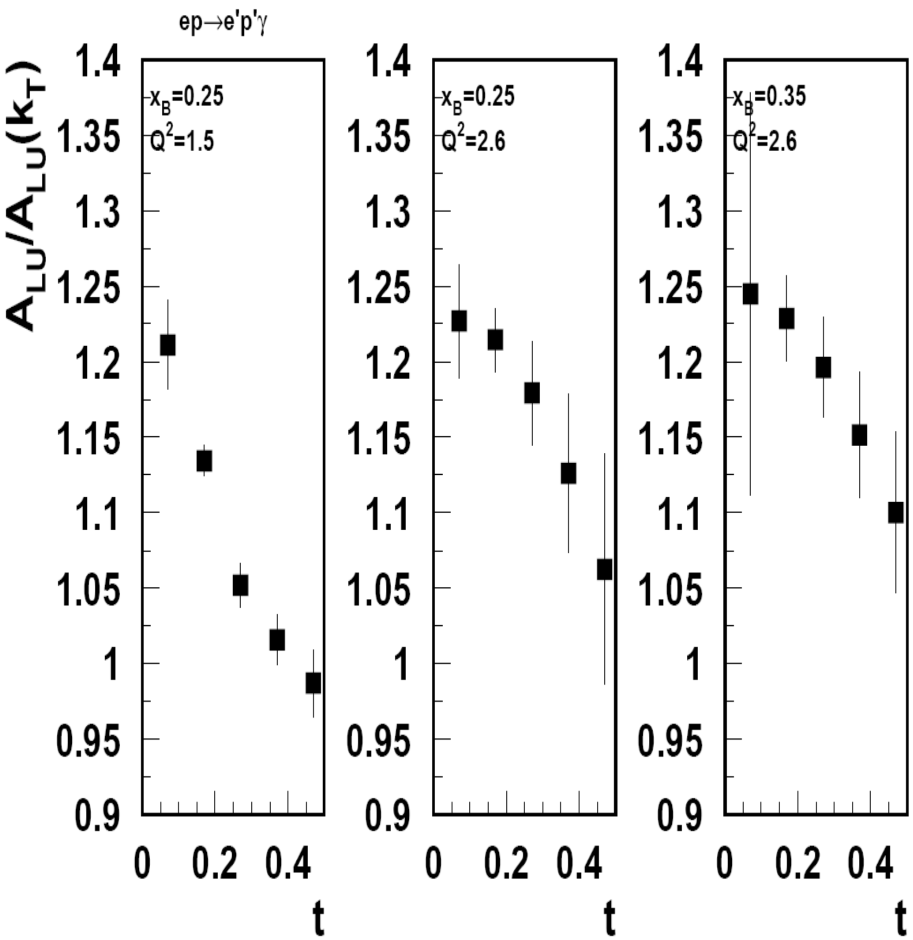
# Azimuthal moments in ep->e'p'γ

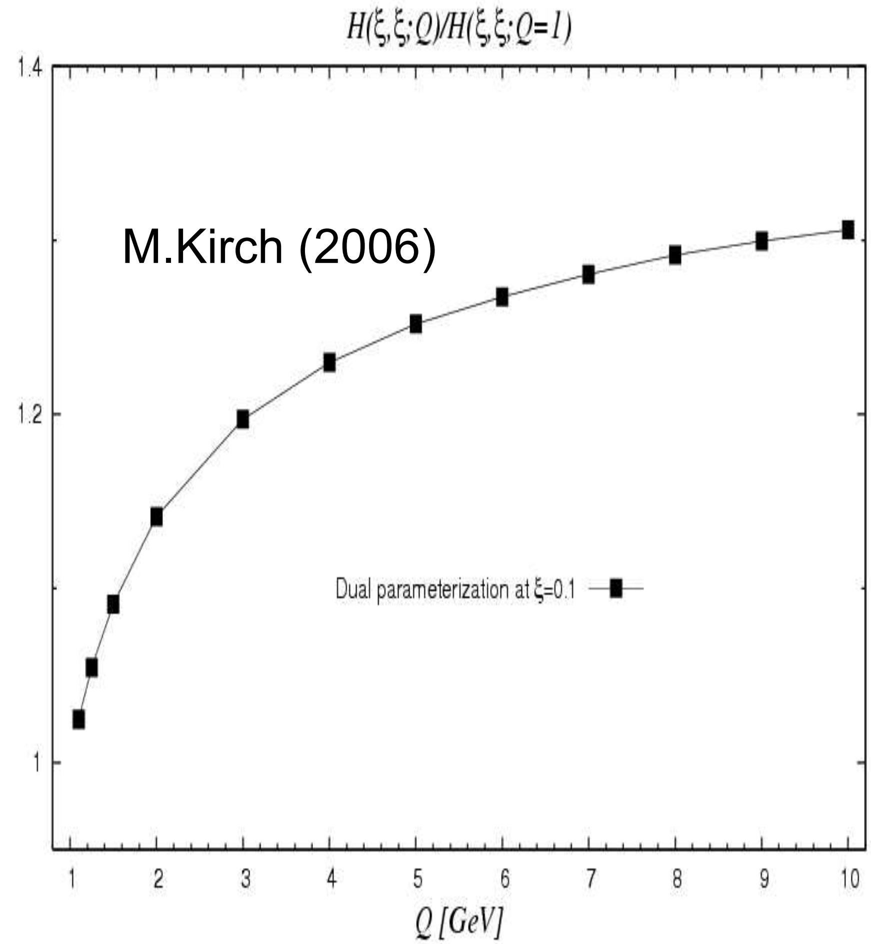
## Ratio of different contributions to $c_{0BH}$




Different azimuthal moments become relevant in different kinematical regions

# Sensitivity on theory input



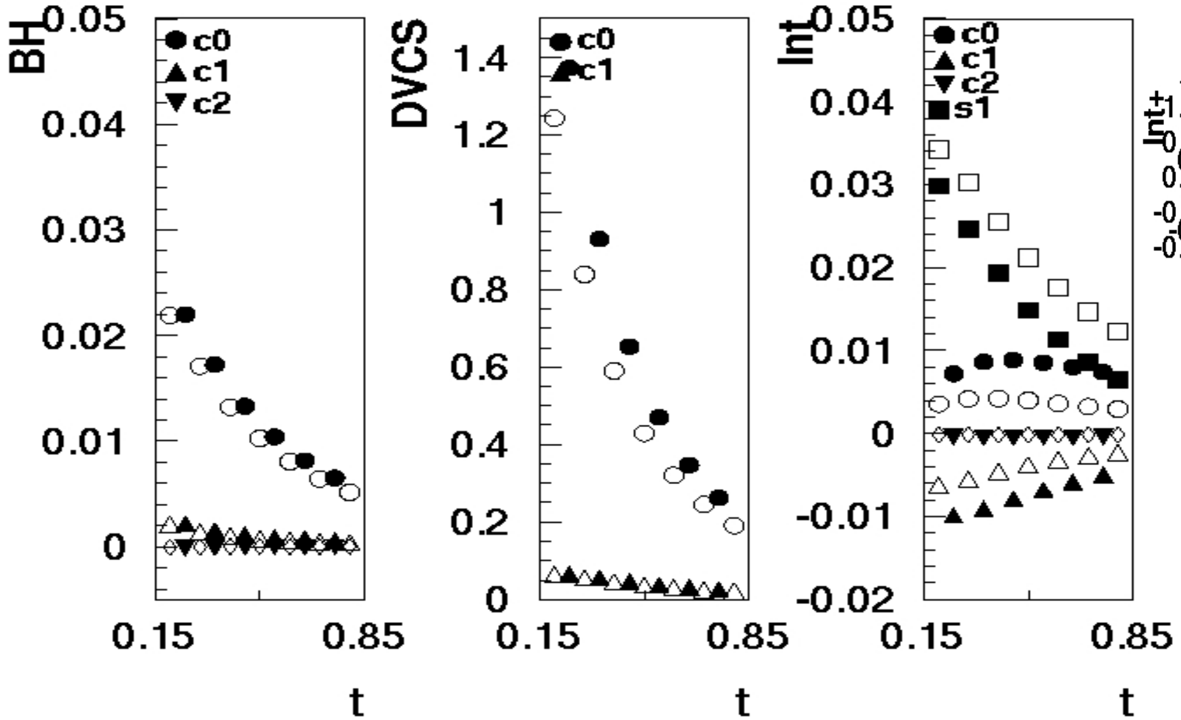




Dynamical HT may decrease the beam SSA at small **t**

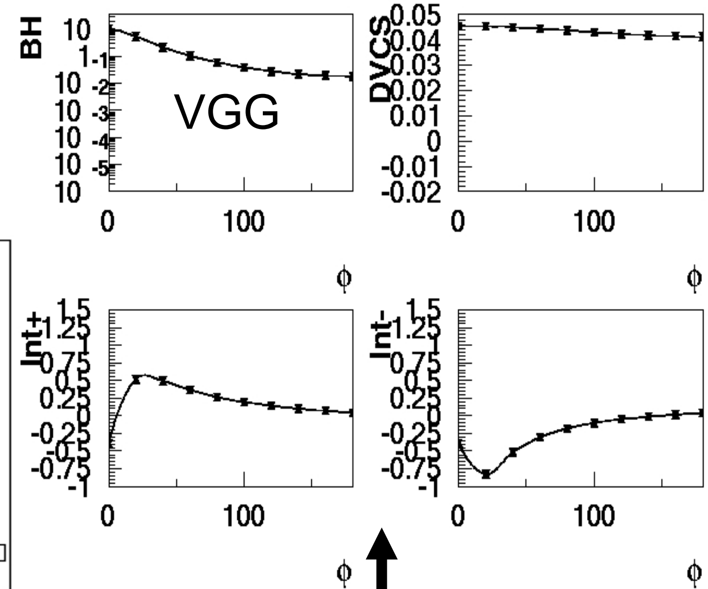
Evolution effects significant at small **Q2**

# Contributions to the DVCS cross section

| | VGG | BMK |
|---|---|---|
| BH | exact | exact |
| Int | $BH_e*DVCS_a$ | $(BH*DVCS)_a$ |



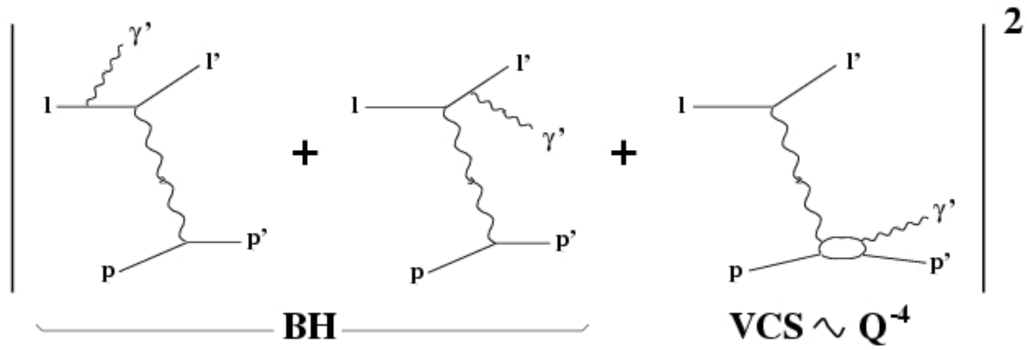

Azimuthal moments in the DVCS MC (BMK-open symbols) and Vanderhaeghen et al (filled symbols).



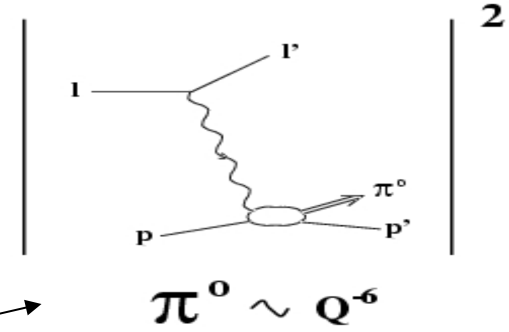

VGG x-section described as a sum of moments

Reason for difference under studies (2002)

# GPDs from ep->e'p'$\gamma$




Requirements for precision (<15%) measurements of GPDs from DVCS SSA:




- Define the procedure to extract GPDs from $A_{LU}$
  - effect of finite bins (prefactor variations) ~10%
  - other moments
- Define background corrections (>1$\gamma$)
  - pion contamination ~10%
  - radiative background
  - ADVCS

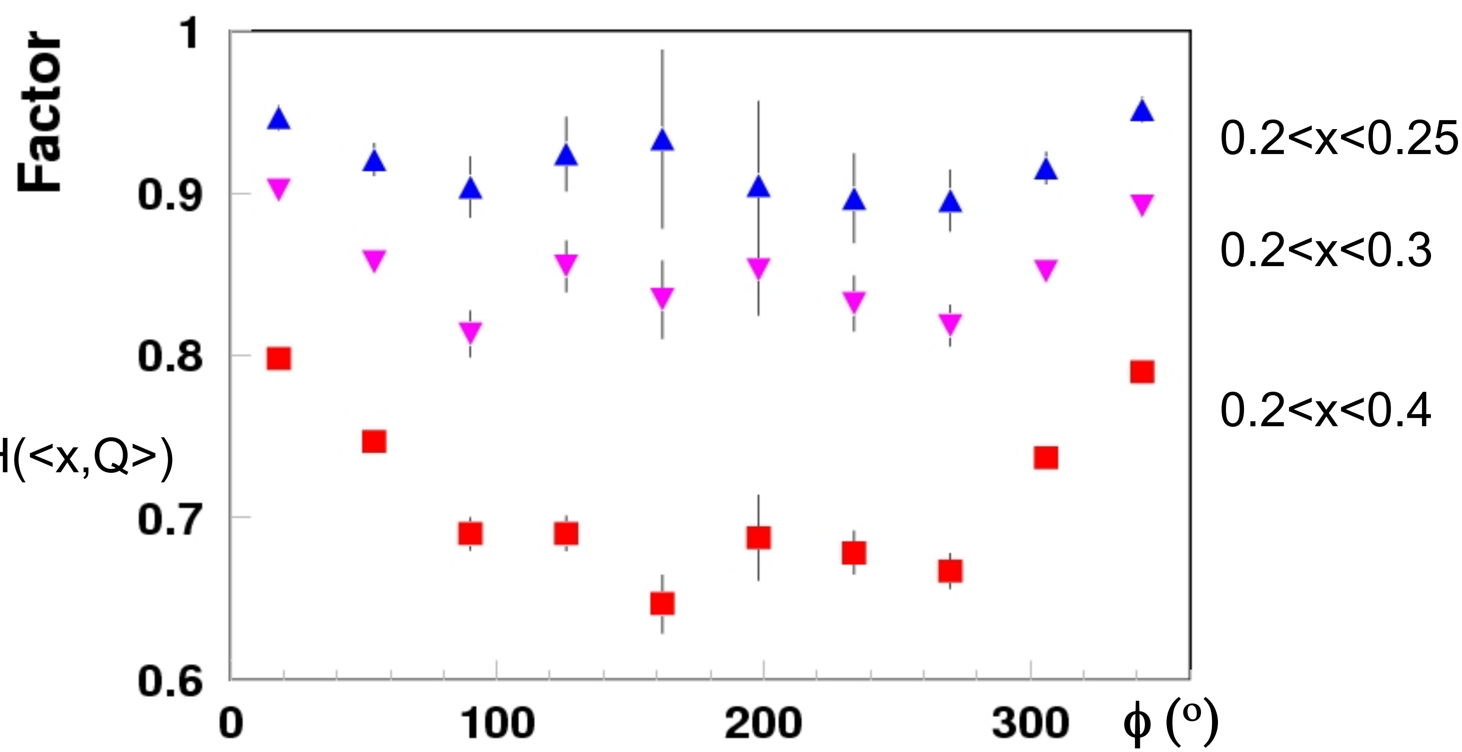
A complete simulation of the whole chain from particle detection to GPD extraction, including the DVCS and background (counts, asymmetries) as well as extraction procedure (averaging over kinematic factors) required to ensure the reliability of measured GPDs.

# Correction factor as a function of bin size

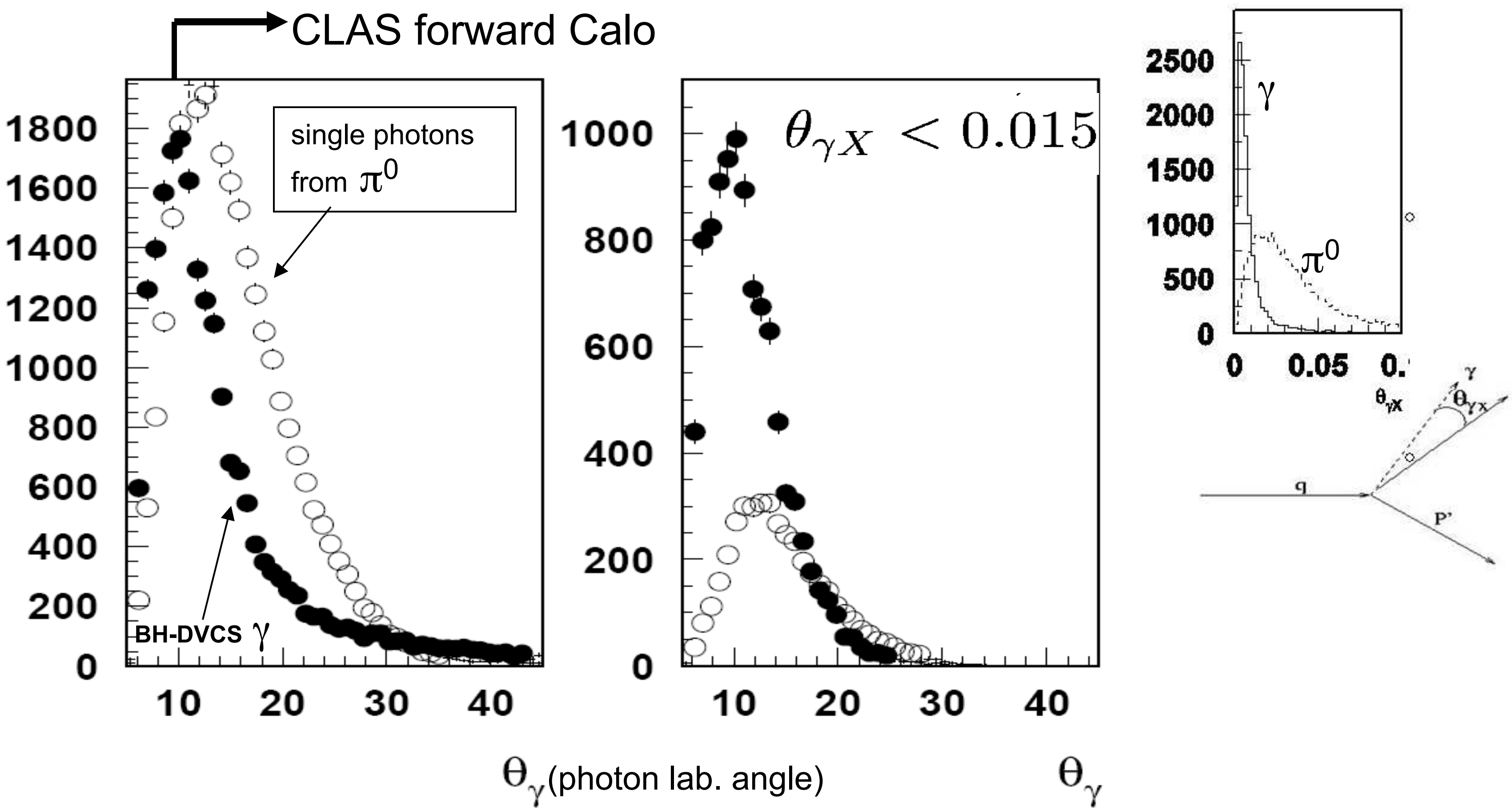
$\phi$ – dependence of $\mathcal{P}_1 = -\frac{1}{y(1+\epsilon^2)}\{J + 2K\cos(\phi)\}$

in BH and INT terms doesn’t cancel for finite bins

$$\frac{\langle Int\rangle/\langle BH\rangle}{Int(\langle x,Q\rangle)/BH(\langle x,Q\rangle)}$$



# $\pi^0$ contamination in ep$\gamma$-sample




•At large angles detected photon can be used as veto (epX-sample).
•Cut on the direction of the measured photon (require detection of proton) significantly reduce the contamination (ep$\gamma$-sample).

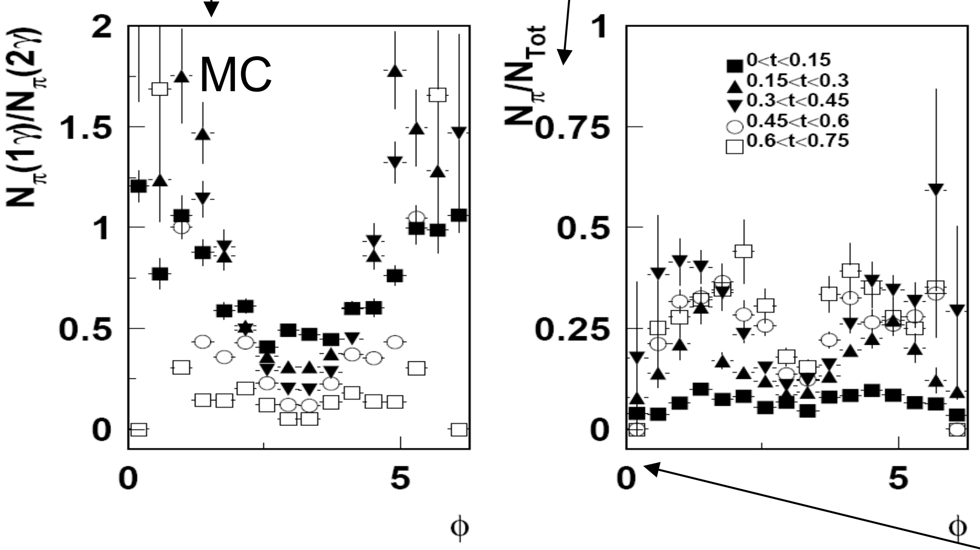
# $\pi^0$ contamination

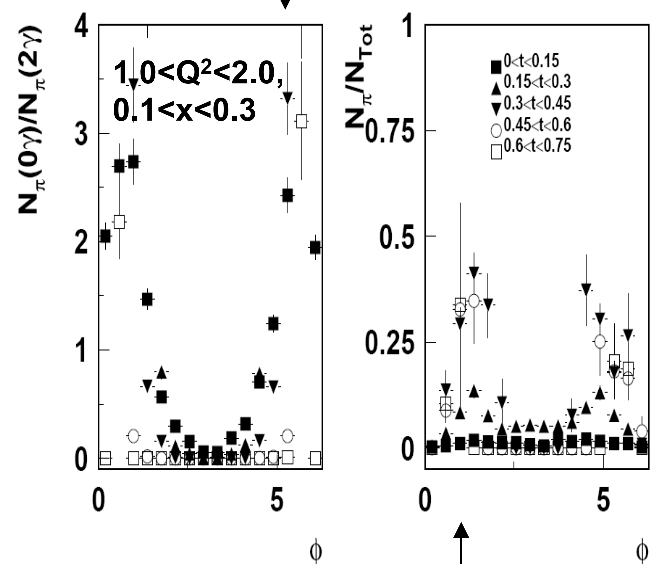
Main unknown in corrections of photon SSA are the $\pi^0$ contamination and its beam SSA.

Extract from ep$\pi^0$ MC the ratio of single to double photon detection probability

$$N_\gamma^{Data}(\pi^0) = N_{\pi^0}^{Data} \frac{N_\gamma^{MC}(\pi^0)}{N_{\pi^0}^{MC}},$$

MC the ratio for 0 $\gamma$

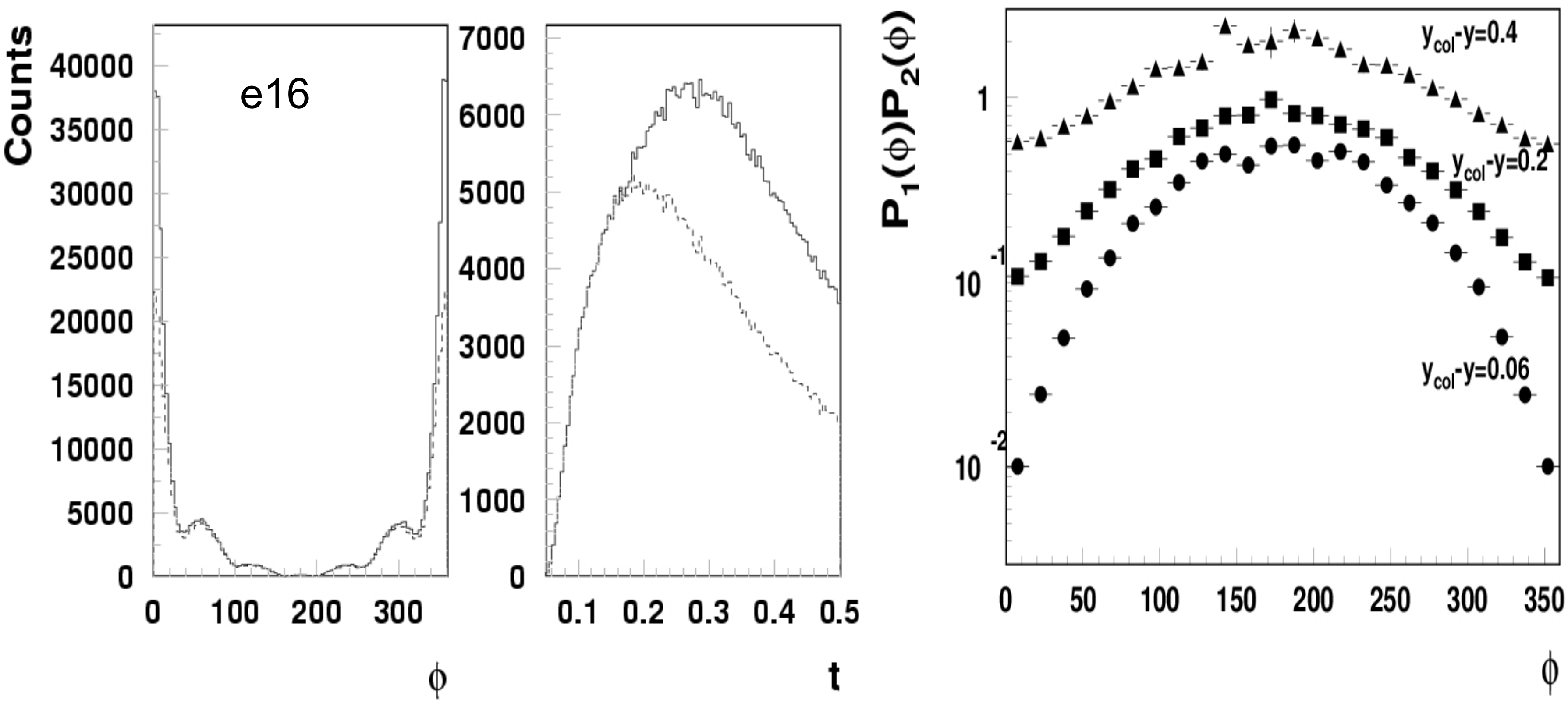



Use ep$\pi^0$ MC and data to estimate the contribution of $\pi^0$ in the ep$\gamma$ and epX samples

Contamination from $\pi^0$ photons increasing at large t and x .

# $\phi$-dependence and collinearity cut

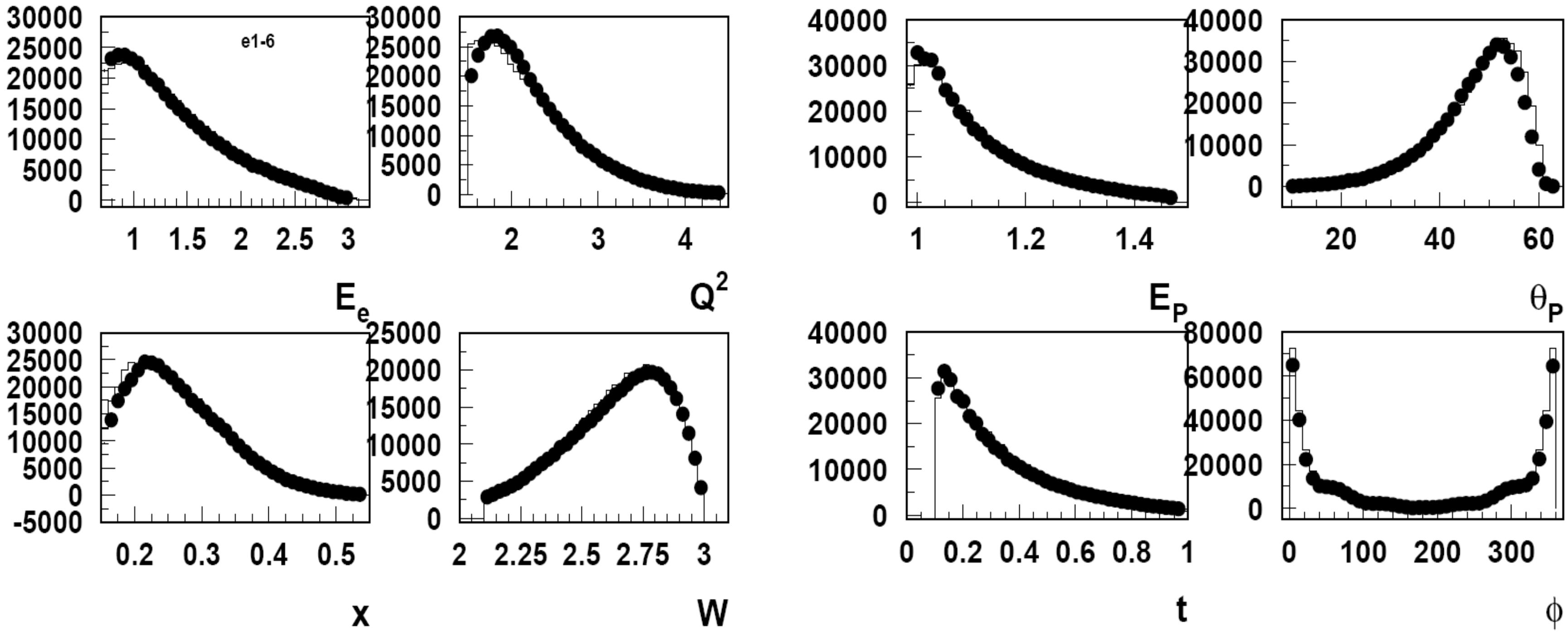



Collinearity cut $y_{col}$-y>0.025 eliminates low $\phi$ and large **t** (the beam direction)

$$y = y_{\rm col} \equiv \frac{Q^2 + \Delta^2}{Q^2 + x\Delta^2}$$

# γ MC vs Data

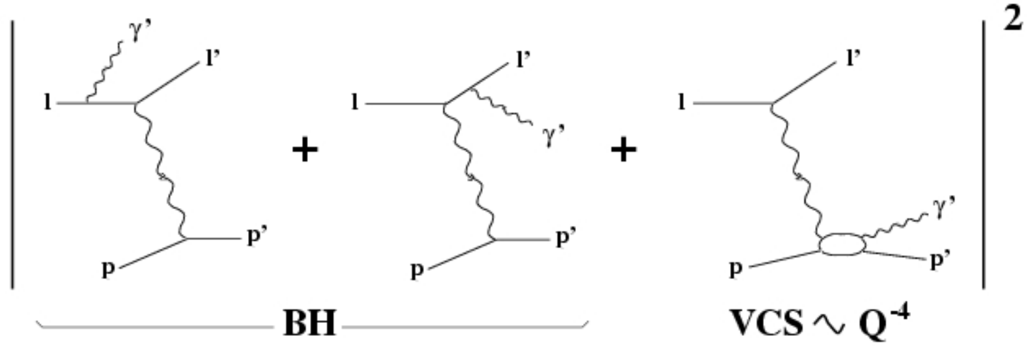
•Exclusive photon production simulated using a realistic MC(based on S.Korotkov's code)




•Exclusive photon production simulated using a realistic MC(based on S.Korotkov's code)

•Kinematic distributions in x,$Q^2$,t consistent with the CLAS data

# GPDs from ep->e'p'$\gamma$




Requirements for precision (<10%) measurements of GPDs from DVCS SSA

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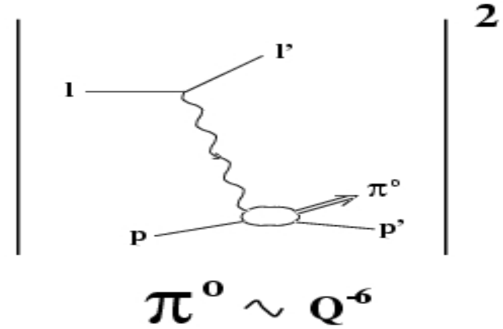
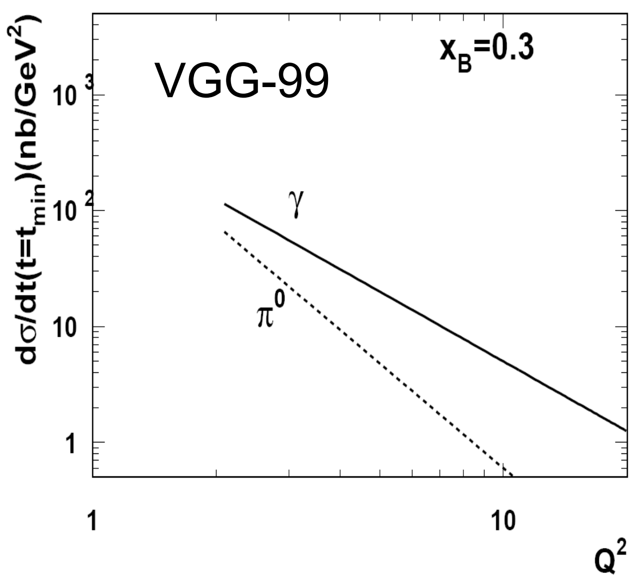
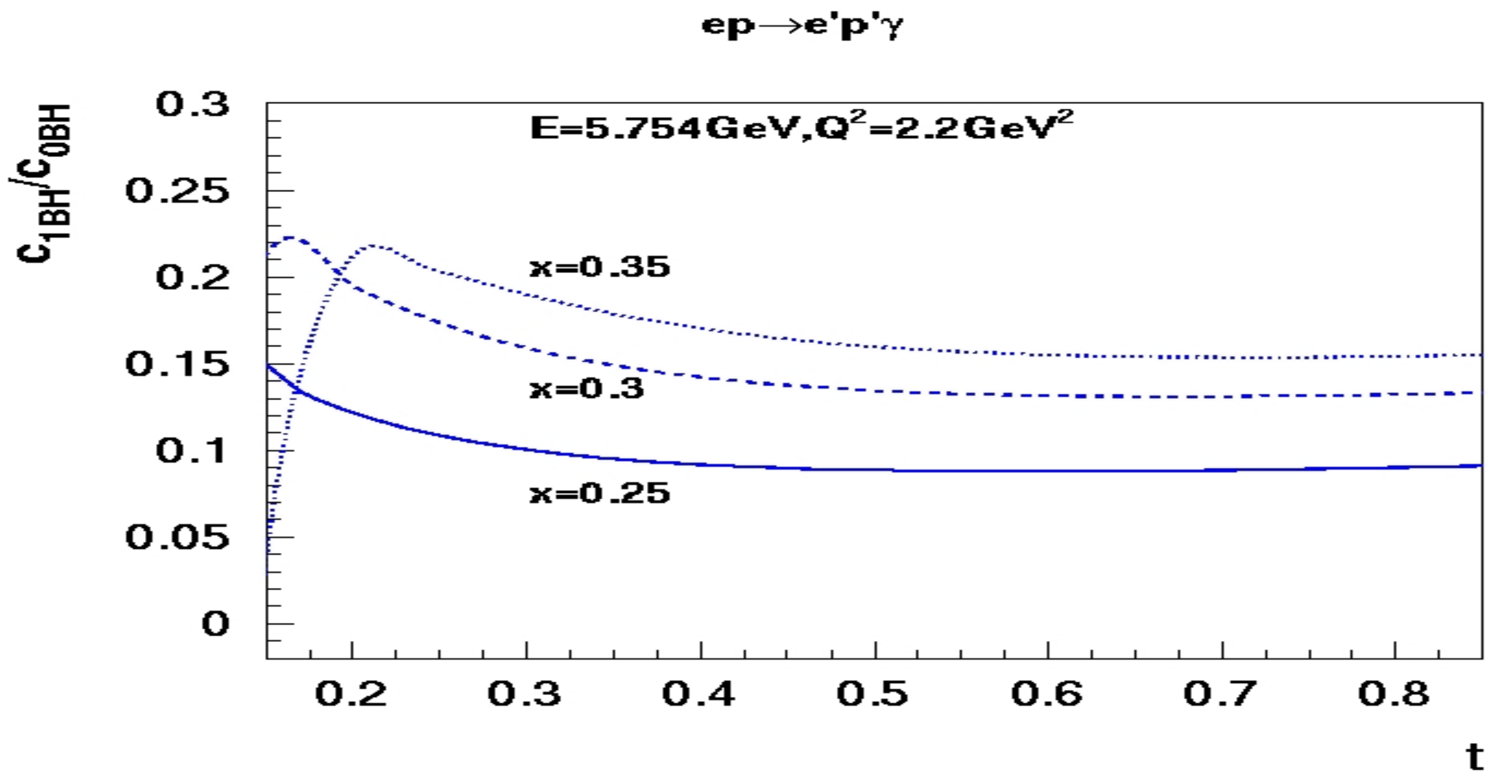



$\pi^0$ dominates the single photon sample at low $Q^2$ in the kinematics where BH is small

# BH cosϕ moment




$$A_{LU} \propto \frac{\lambda s_2^I \sin\phi}{c_0^{BH}(1 + c_1^{BH}/c_0^{BH}\cos\phi)} \approx \frac{\lambda s_2^I \sin\phi - \lambda s_2^I (c_1^{BH}/2c_0^{BH})\sin 2\phi}{c_0^{BH}}$$

BH cosϕ moment can generate ~3% sin2ϕ in the $A_{LU}$