Hard exclusive single charged pion electroproduction off the proton

Beam Spin Asymmetry

K. Park [HUPTI] Sep. 21, 2020

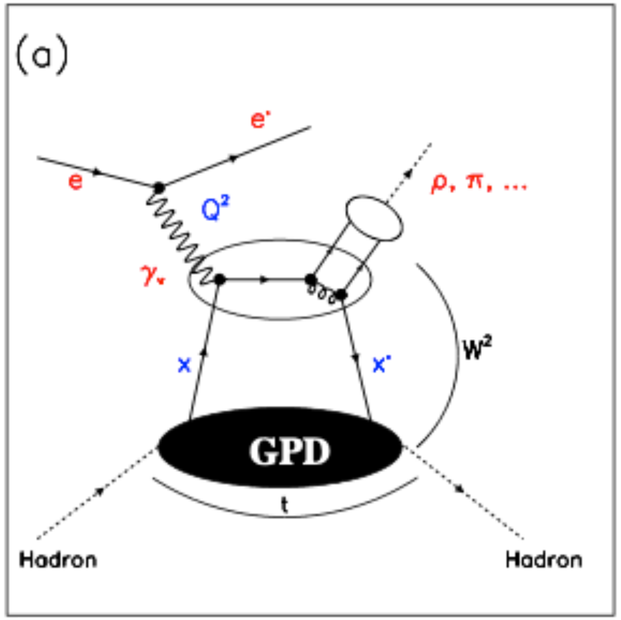
Content

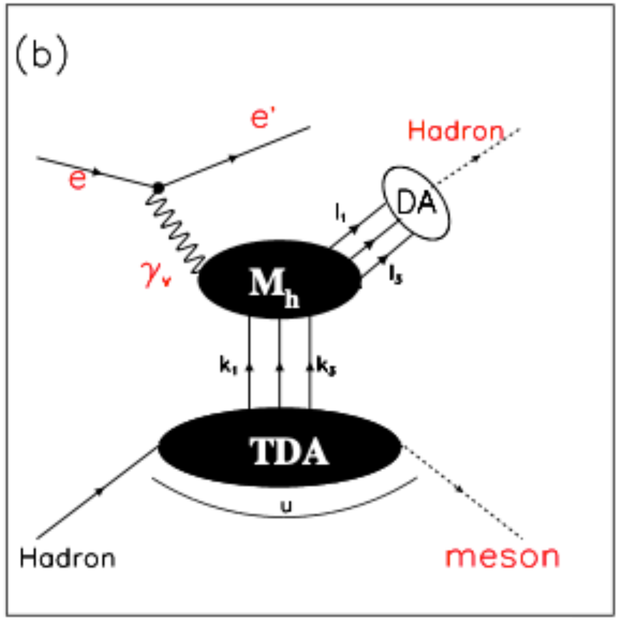
- Introduction
- Theoretical approach
- Experimental approach
- Pioneering study - cross sections measurements
- Recent experimental results review (PLB2018)
- Extended study (new) - beam spin asymmetry
- Asymmetry data in this presentation (preliminary)
- Summary

Diagram & variables

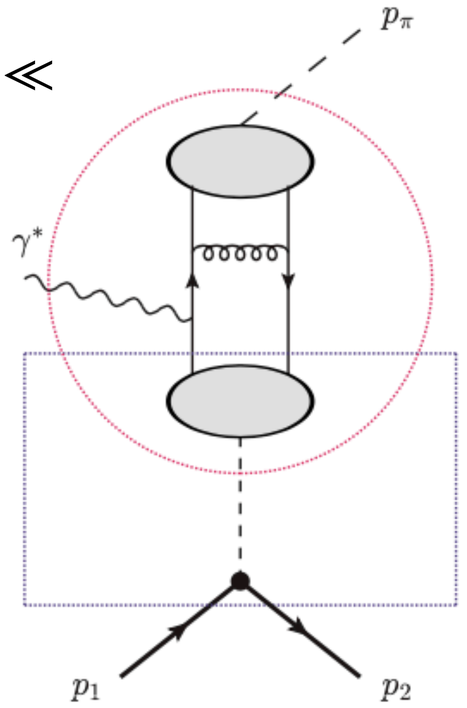
$$
\begin{aligned}
p_P &= (1+\xi)\hat{p} + \frac{m_p^2}{1+\xi}\hat{n}\ , \\
p_{\gamma_v} &\sim -2\xi\Big(1+\frac{\Delta_T^2-m_p^2}{Q^2}\Big)\hat{p} + \frac{Q^2}{2\xi(1+\frac{\Delta_T^2-m_p^2}{Q^2})}\hat{n}\ , \\
p_\pi &= (1-\xi)\hat{p} + \frac{m_\pi^2-\Delta_T^2}{1-\xi}\hat{n} + \Delta_T\ , \\
p_N &\sim -2\xi\frac{\Delta_T^2-m_p^2}{Q^2}\hat{p} + \Big(\frac{Q^2}{2\xi(1+\frac{\Delta_T^2-m_p^2}{Q^2})} - \frac{m_\pi^2-\Delta_T^2}{1-\xi} + \frac{m_p^2}{1+\xi}\Big)\hat{n} - \Delta_T\ , \\
\Delta &= -2\xi\hat{p} + \Big(\frac{m_\pi^2-\Delta_T^2}{1-\xi} - \frac{m_p^2}{1+\xi}\Big)\hat{n} + \Delta_T\ .
\end{aligned}
$$

- $\hat{p}$, $\hat{n}$ are the light-cone vectors ($\hat{p}^2 = \hat{n}^2 = 0,\ 2\hat{p}\cdot\hat{n} = 1$)
- $P = \frac{1}{2}(p_P + p_\pi)$: the average momentum of the pion and nucleon. It is collinear along z.
- $\Delta = p_\pi - p_P$: the momentum transfer.
- Δ_T : the transverse component of Δ (i.e. transverse component of pion momentum in the center-of-mass system.)
- $x_i (i = 1, 2, 3)$: the light-cone momentum fraction of the quark i
- $\xi = -\frac{\Delta\cdot n}{2P\cdot n}$: the skewness variable, $2\xi = x_1 + x_2 + x_3$. ξ describes the loss of plus-momentum of the incident proton.

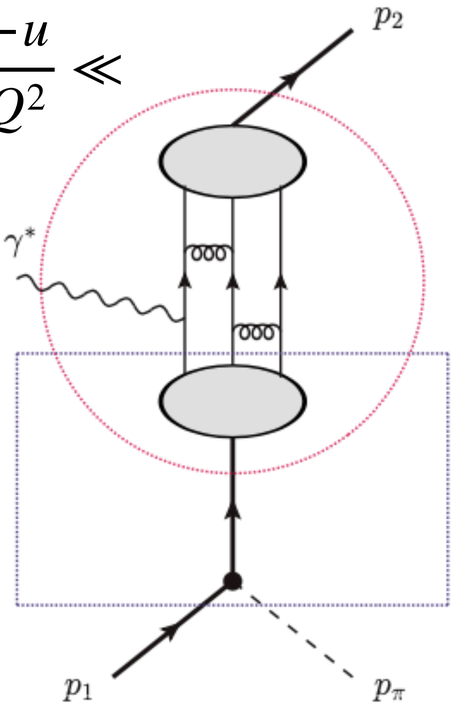




$$\frac{-t}{Q^2} \ll$$

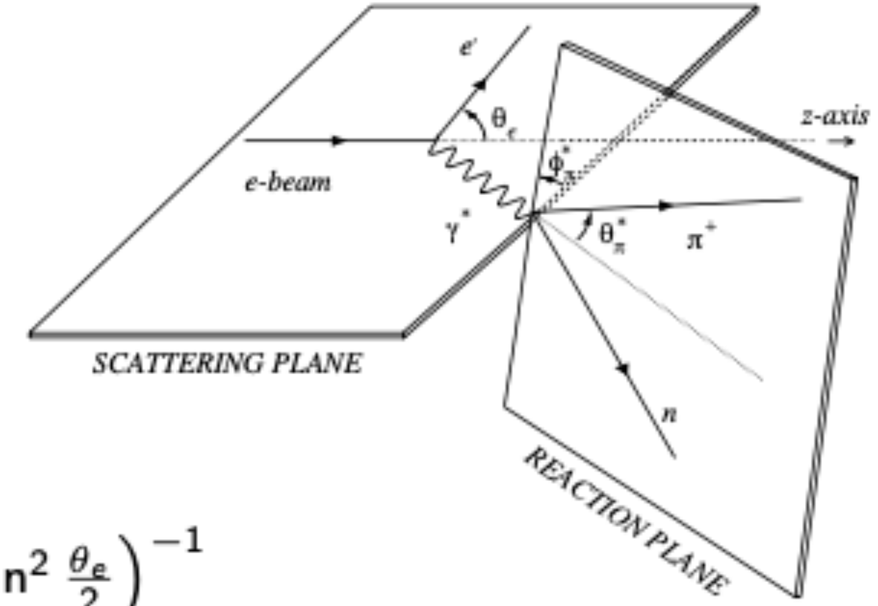


$$\frac{-u}{Q^2} \ll$$



- assume: one photon exchange approximation

$$\frac{d^5\sigma}{dE_f d\Omega_e d\Omega_\pi^*} = \Gamma_\nu \cdot \frac{d^2\sigma}{d\Omega_\pi^*}$$



where,

Γ_ν:virtual photon flux: $\frac{\alpha}{2\pi^2 Q^2}\frac{(W^2-M_p^2)E_f}{2M_p E_e}\frac{1}{1-\epsilon}$,

ϵ: virtual photon polarization: $\left(1+2\left(1+\frac{\nu^2}{Q^2}\right)\tan^2\frac{\theta_e}{2}\right)^{-1}$

Experimental approach

$$\frac{d^2\sigma}{d\Omega_\pi^*} = \frac{p_\pi^*}{k_\pi^*}\left(\sigma_0 + h\sqrt{2\epsilon(1-\epsilon)}\sigma'_{LT}\sin\theta_\pi^*\sin\phi_\pi^*\right)$$

$$\sigma_0 = \sigma_U + \epsilon\sigma_{TT}\sin^2\theta_\pi^*\cos 2\phi_\pi^* + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\sin\theta_\pi^*\cos\phi_\pi^*$$

where,

h: beam helicity state

σ_0: unpolarized cross-section

$\sigma_U = \sigma_T + \epsilon\sigma_L$

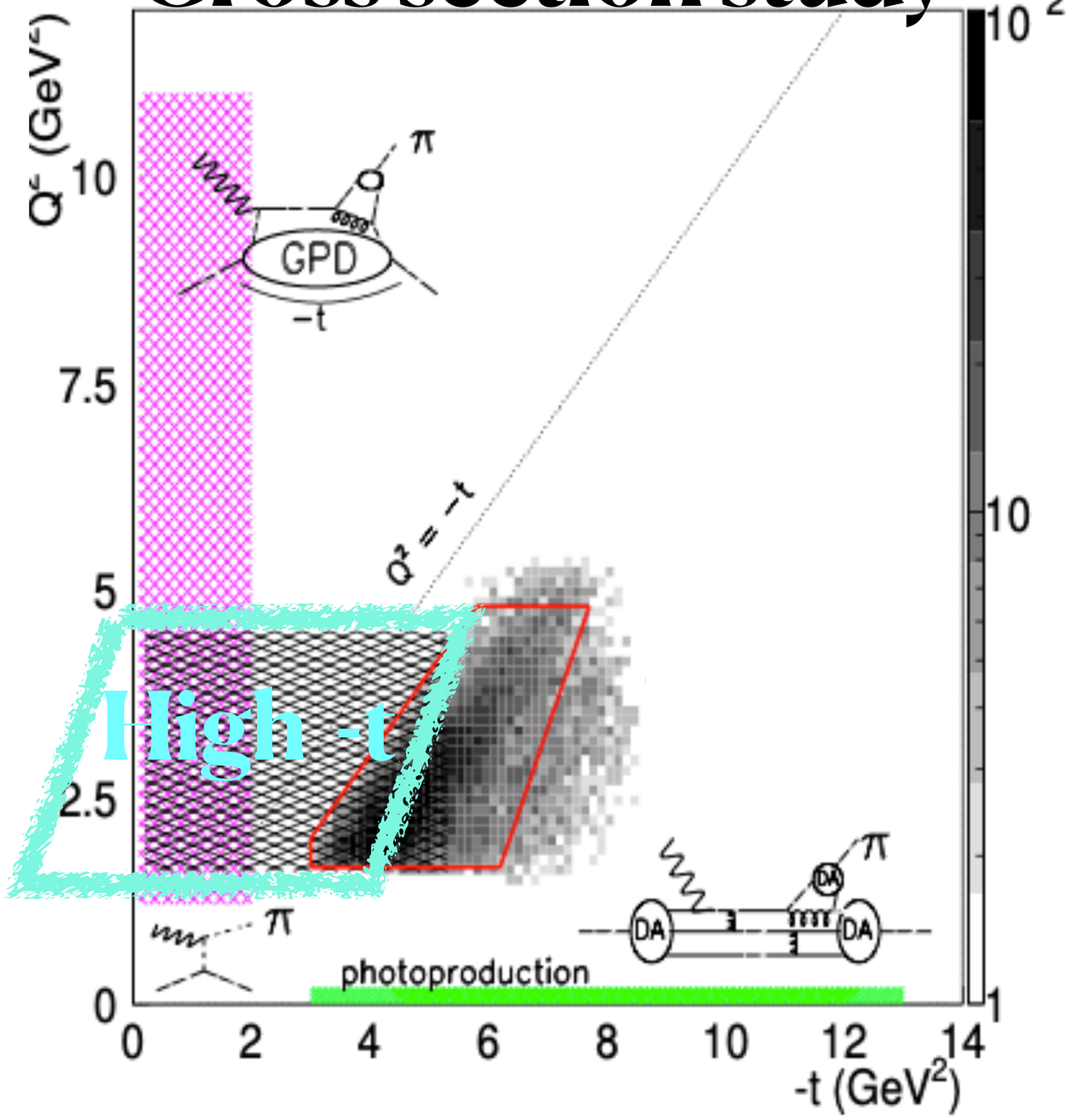
Kinematics is completely defined by five variables (Q^2, W, θ_π^*, ϕ_π^*, and ϕ_e)

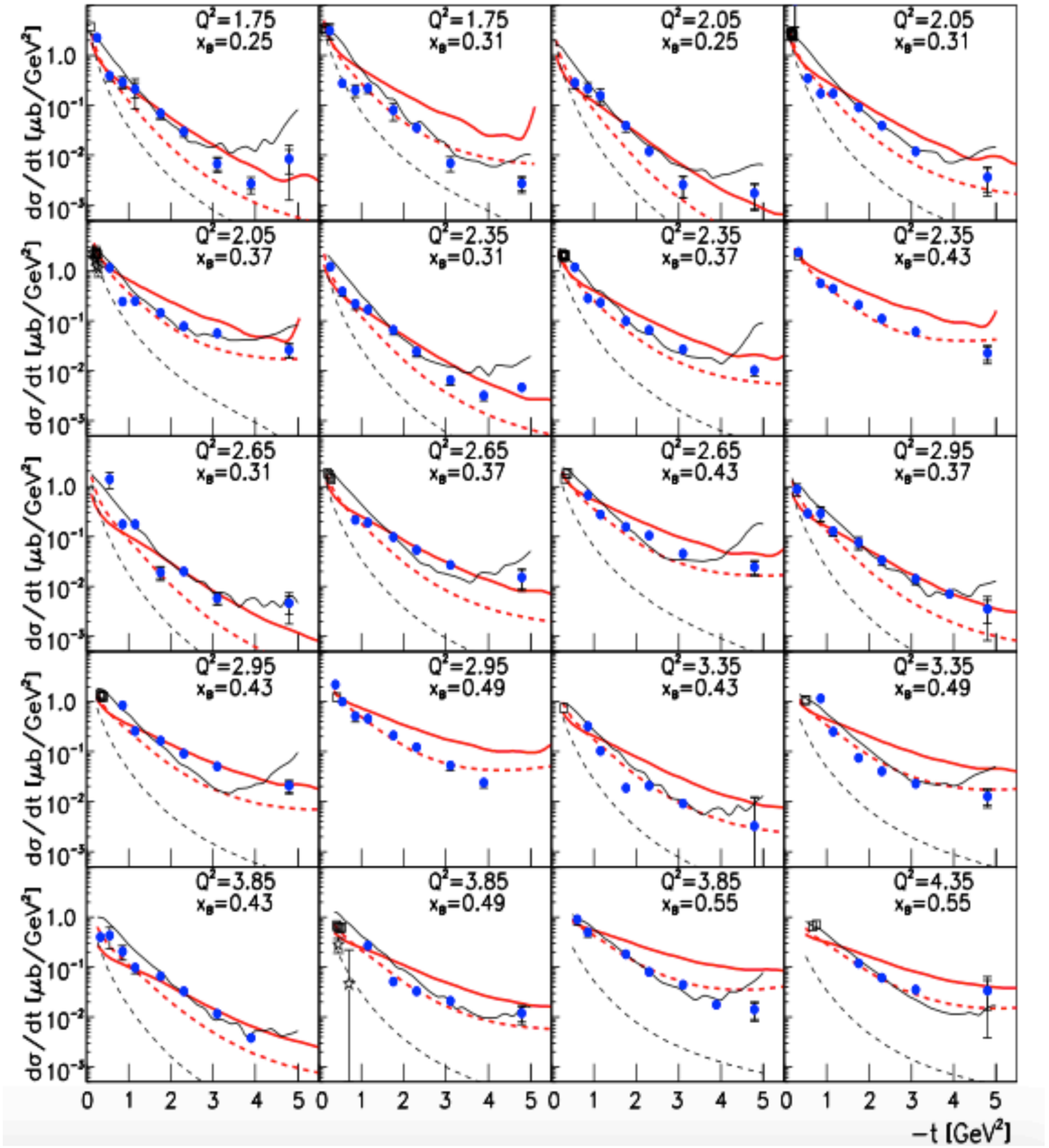
Cross section data review

Publications 2013, 2018

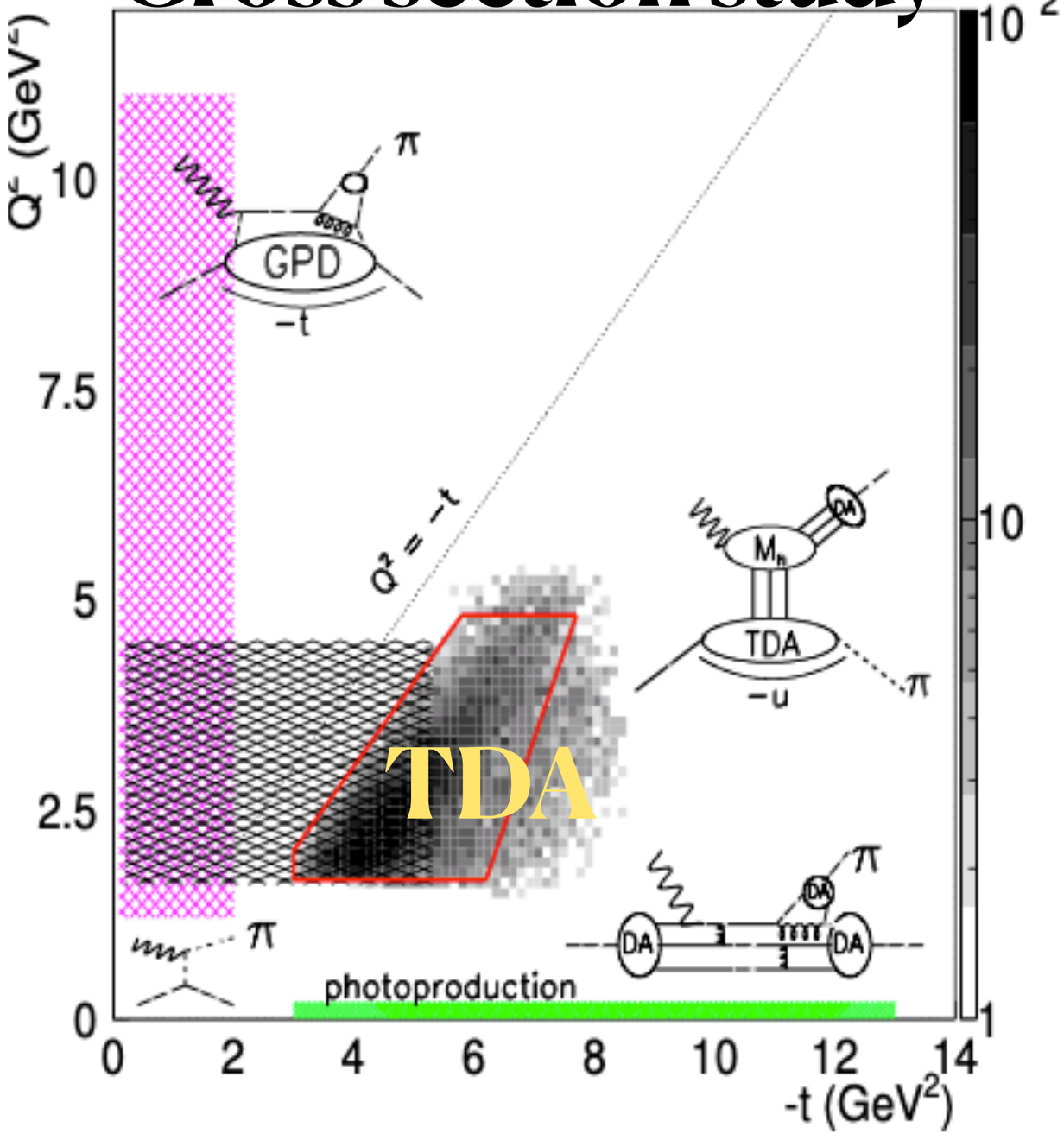
Cross section study

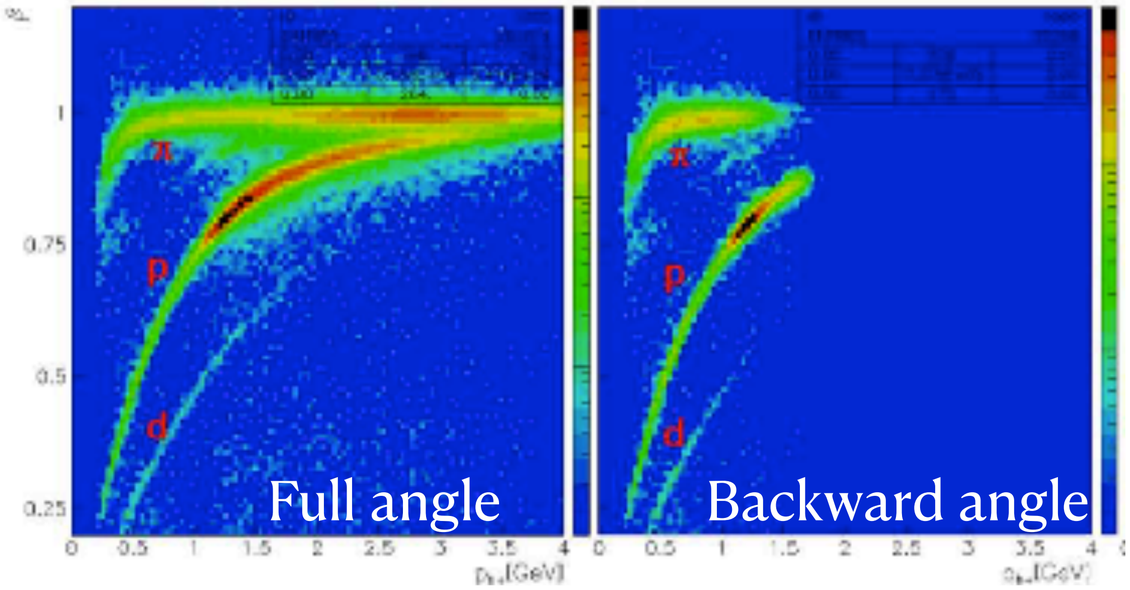
K.Park et al., EPJA 49, (2013).





Cross section study





Transition between hadronic and parsonic picture of the strong interaction

GPD regime

1. Correlations of the longitudinal momentum fraction with transfers spatial position
2. Connection to the transversely GPD

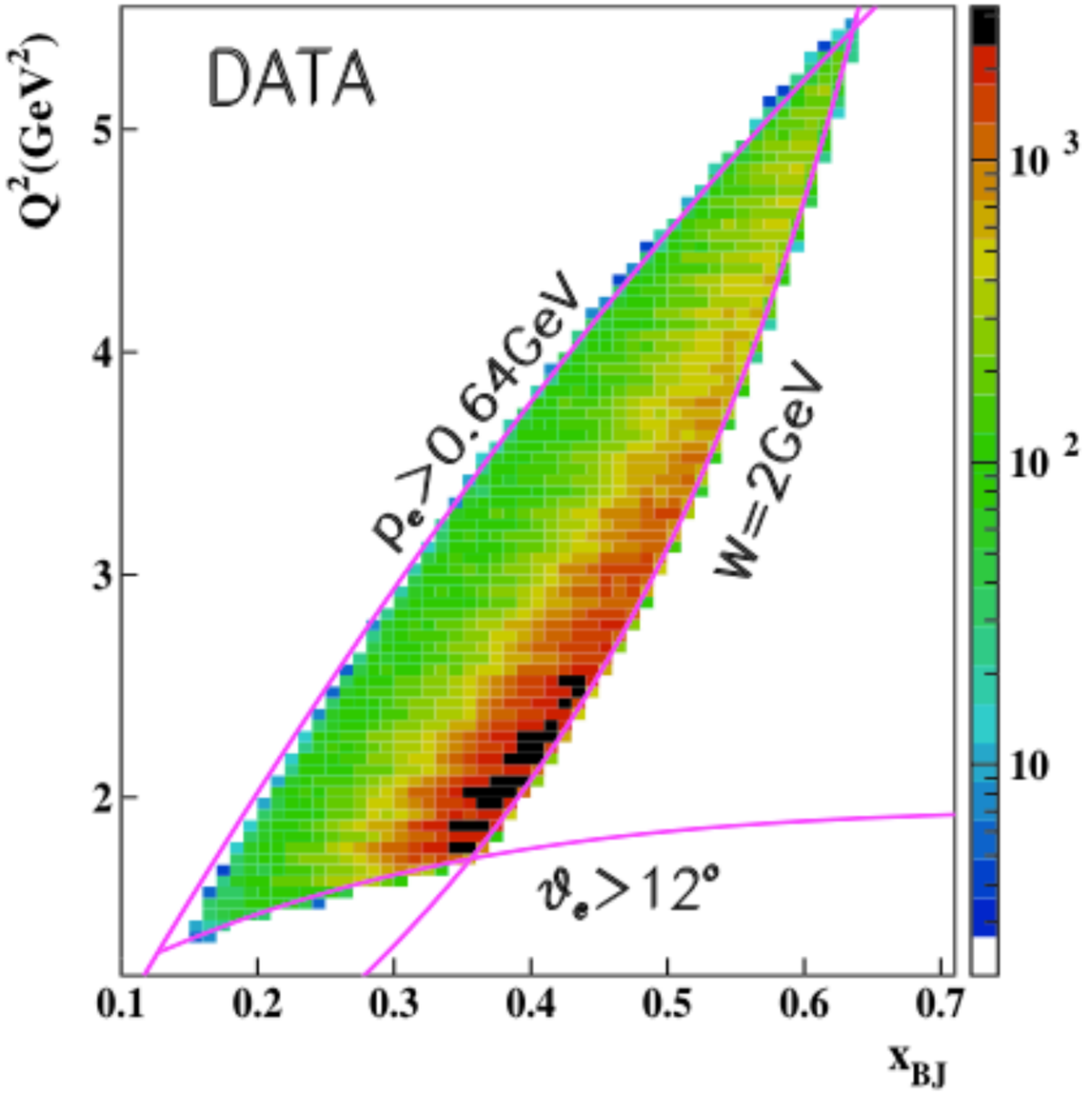
DVMP: N(e,e'NM), M=π, ρ, ϕ, ...

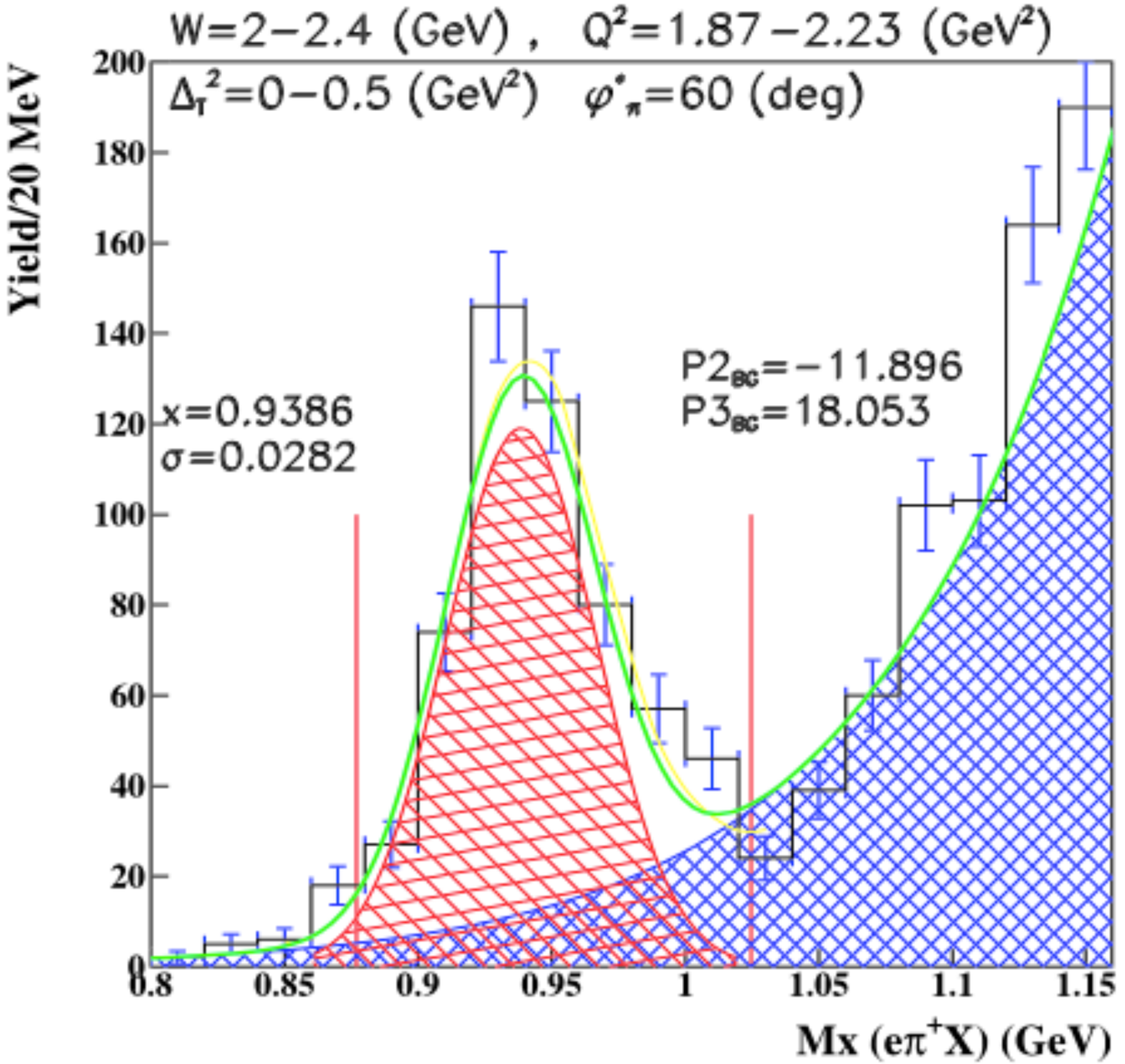
Kinematic variables: x_{BJ}, Q^2, -t

Black hashed area: **K.Park et al., EPJA 49, (2013).**

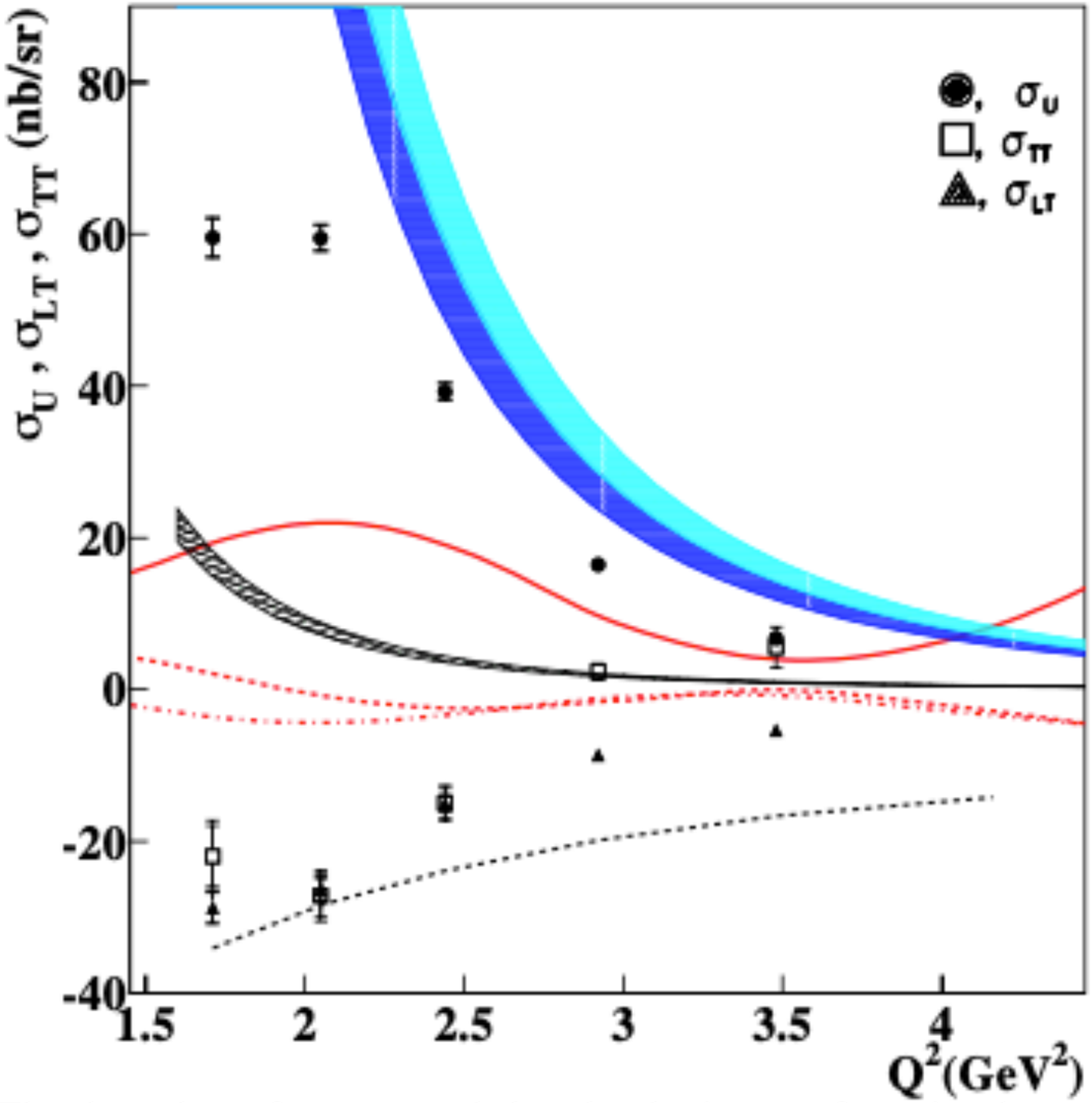
Red solid line: **K.Park et al., PLB 780 340, (2018).**

Event selection (PLB2018)





Structure function (PLB2018)



1. A theoretical calculation (TDA) as function of $\xi \sim Q^2/(Q^2 + 2W^2)$
2. Nucleon to Meson TDAs provide new information: correlation of partons insides of hadrons
3. Nucleon pole exchange in the u-channel contribution determinant for smaller ξ (D-term GPDs)
4. Theoretical understanding is growing up / spectral representation for πN TDA based on quadruple distribution / Factorization ansatz for the quadruple distributions with input at $\xi = 1$

The bands refer to model calculations of σ*u* in the *stat sys*

TDA description, black band: BLW NNLO, dark blue band: COZ, and light blue band: KS. The lower black dashed curve represents an educated guess to a fit of the higher twist cross section σ*LT* and σ*TT* in the TDA picture. The red curves are the predictions of Regge for bold solid: σ*U* , dashed: σ*L T* , dot-dashed: σ*T T* .

Beam spin asymmetry

Preliminary data 2020

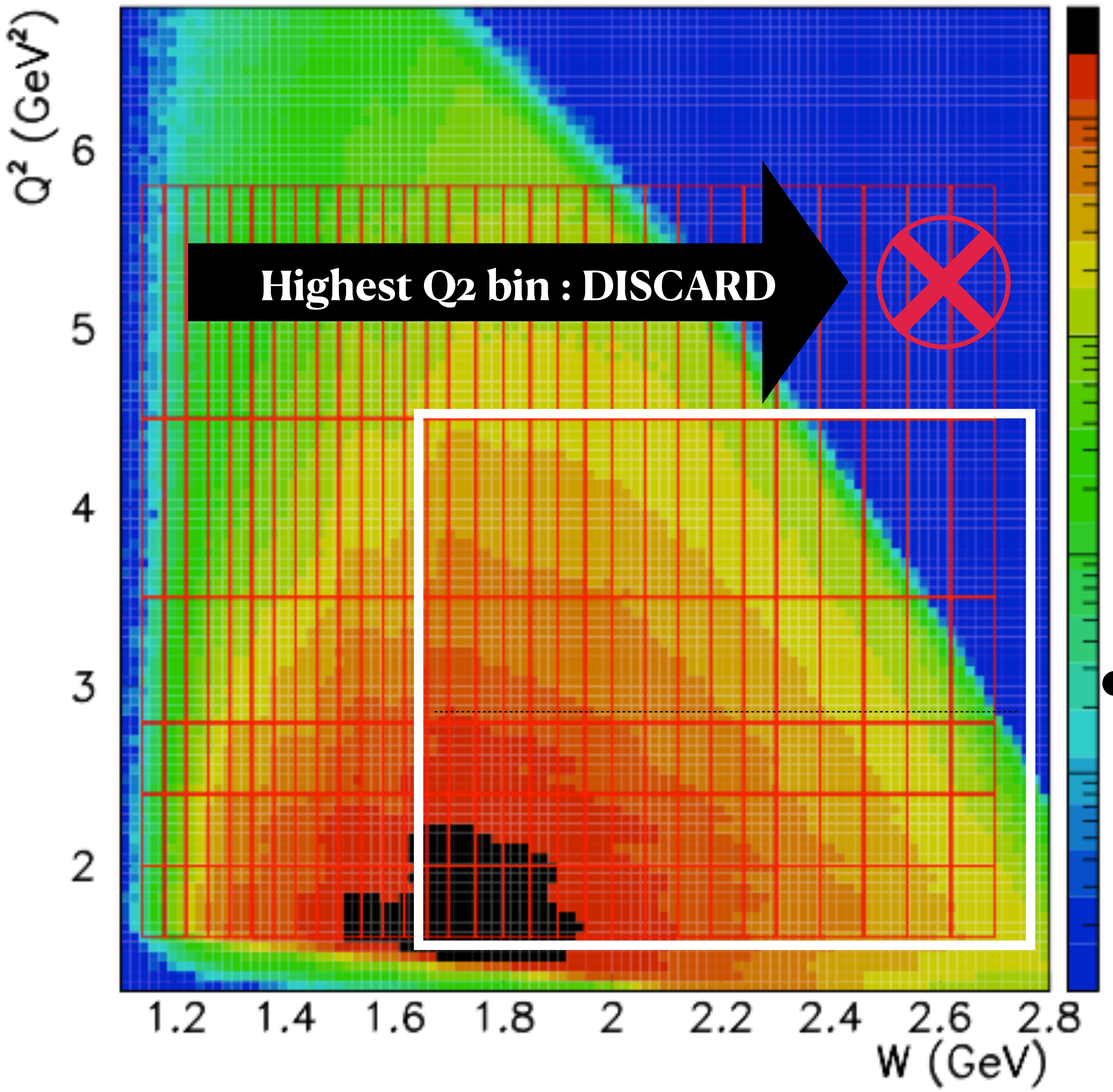
Event selection & Kinematic coverage

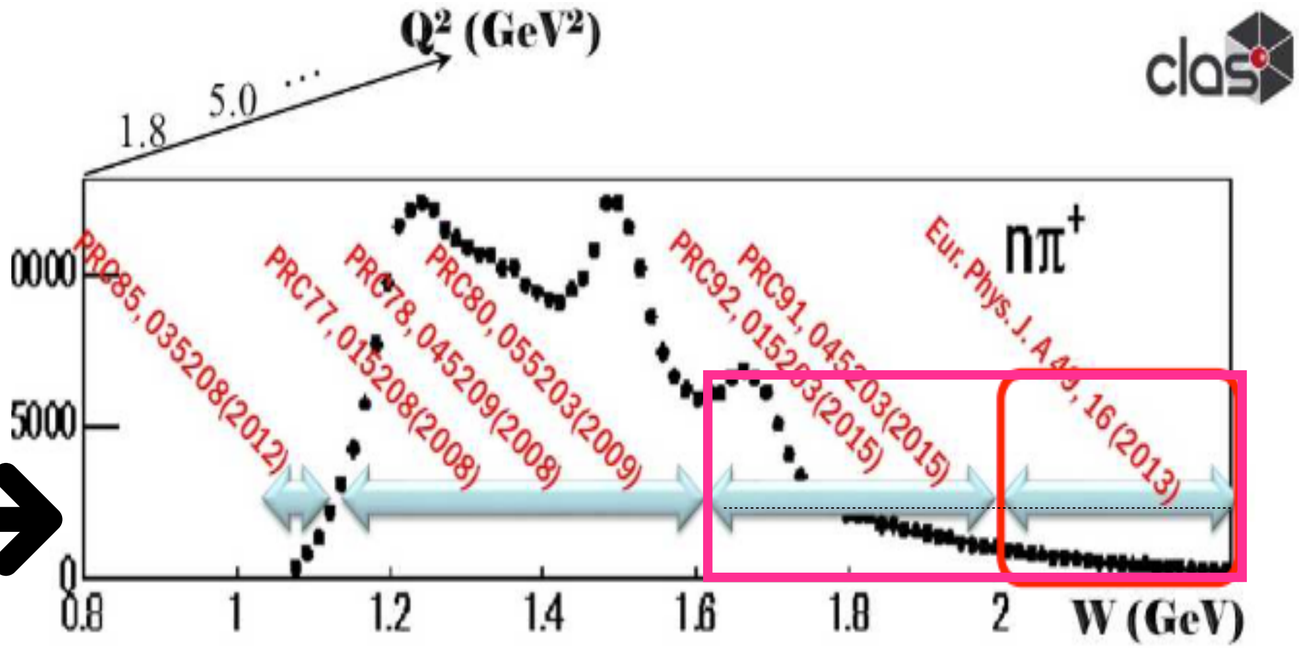
- **Electrons (e):** At the trigger level by requiring a minimum amount of energy in the EC in coincidence with a signal in the CC
- **Pions (π+):** By a coincidence of the drift chamber (DC) and time-of-flight scintillation counter (TOF-SC) in the same sector
- **Neutrons (n) :** missing mass tech

Variable	Number of bins	Range	Bin size
h	2	$\pm$	helicity state
W	25	$1.34 - 2.62$ GeV	varying with 40, 50, 60, 80 MeV
Q^2	5	$1.6 - 4.5$ GeV^2	varying
$\cos\theta^*_\pi$	2	$(-1:0)$	0.5
	4	$(0:+1)$	0.25
φ^*_π	8	$0^\circ - 360^\circ$	45°

Kinematical region

Kinematic range W (excitation), Q^2(resolution)

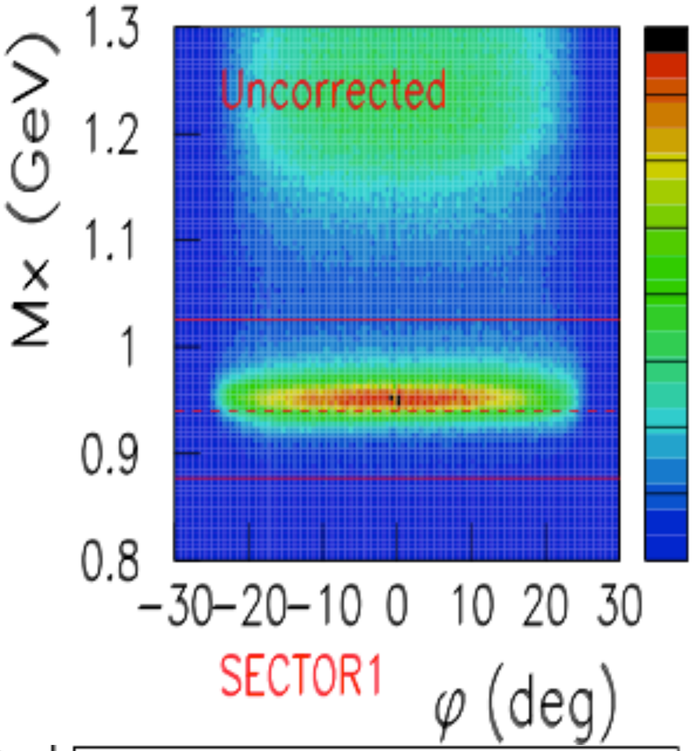


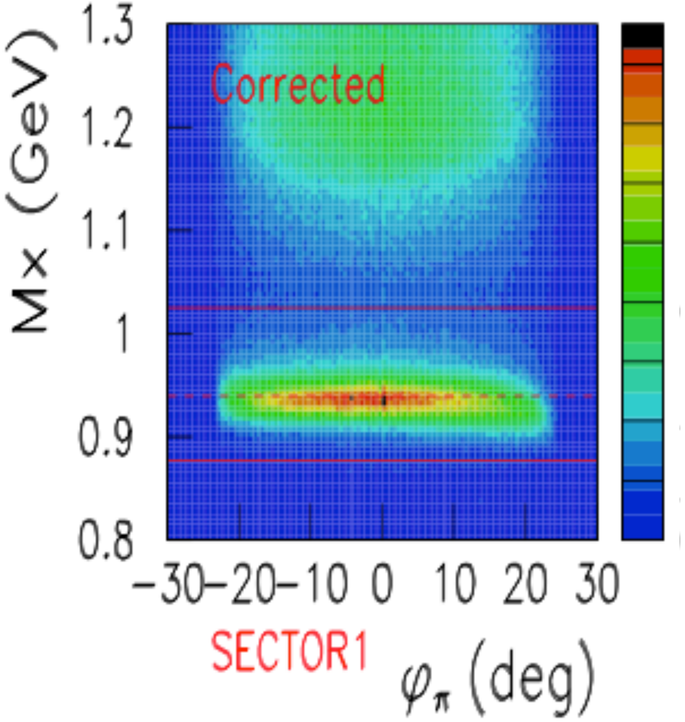


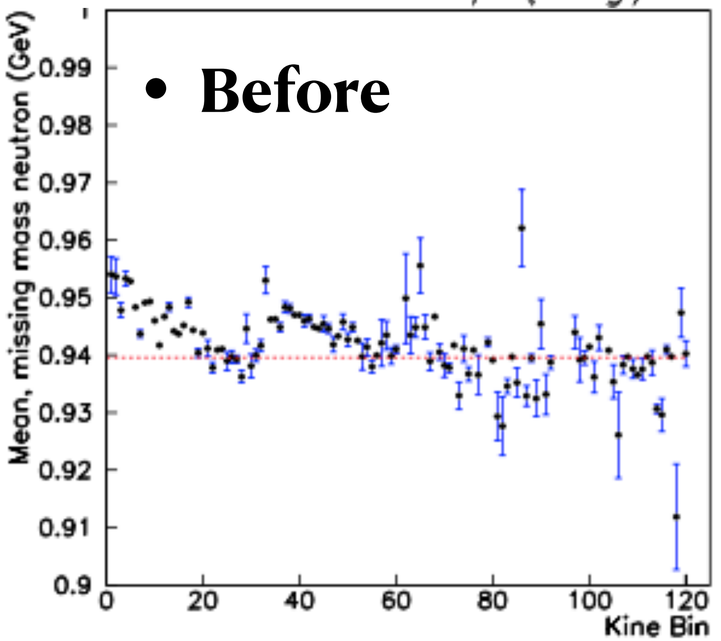
Momentum corrections

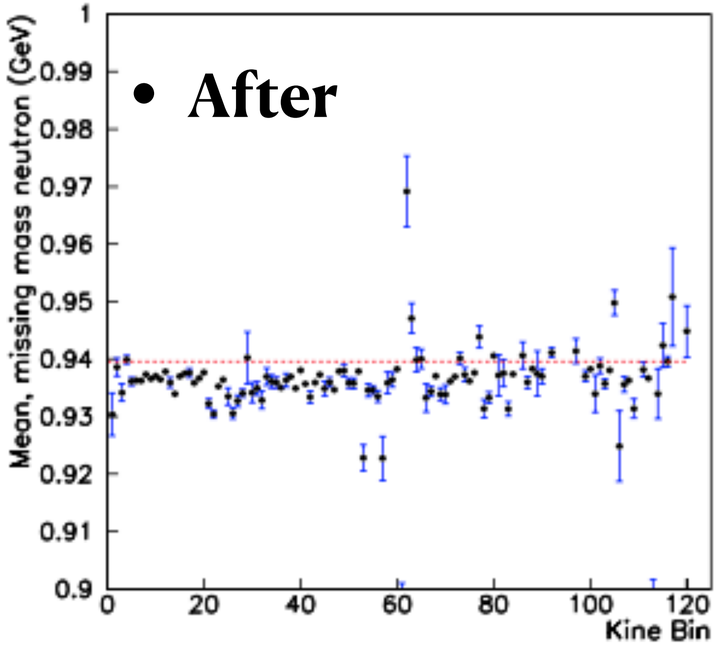
- Kinematic corrections : electrons and hadrons using both elastic and Bethe-Heitler (BH) event methods
- Both correction methods rely on the calculation of the fixed angles and momenta of protons in the selected event

1. We equated the beam energy to the energy as measured by the Hall A (elastic scattering and energy measurement in the arcs). Both measurements agreed within less than 0.1% accuracy.
2. The effect of mini-torus to main torus field was of the order of O(1%) in momentum and O(1 mrad) in angles.
3. The particle's polar angle were reconstructed correctly for scattering angles greater than 35.
4. Assumed that the angle corrections were independent of the particle's charge.

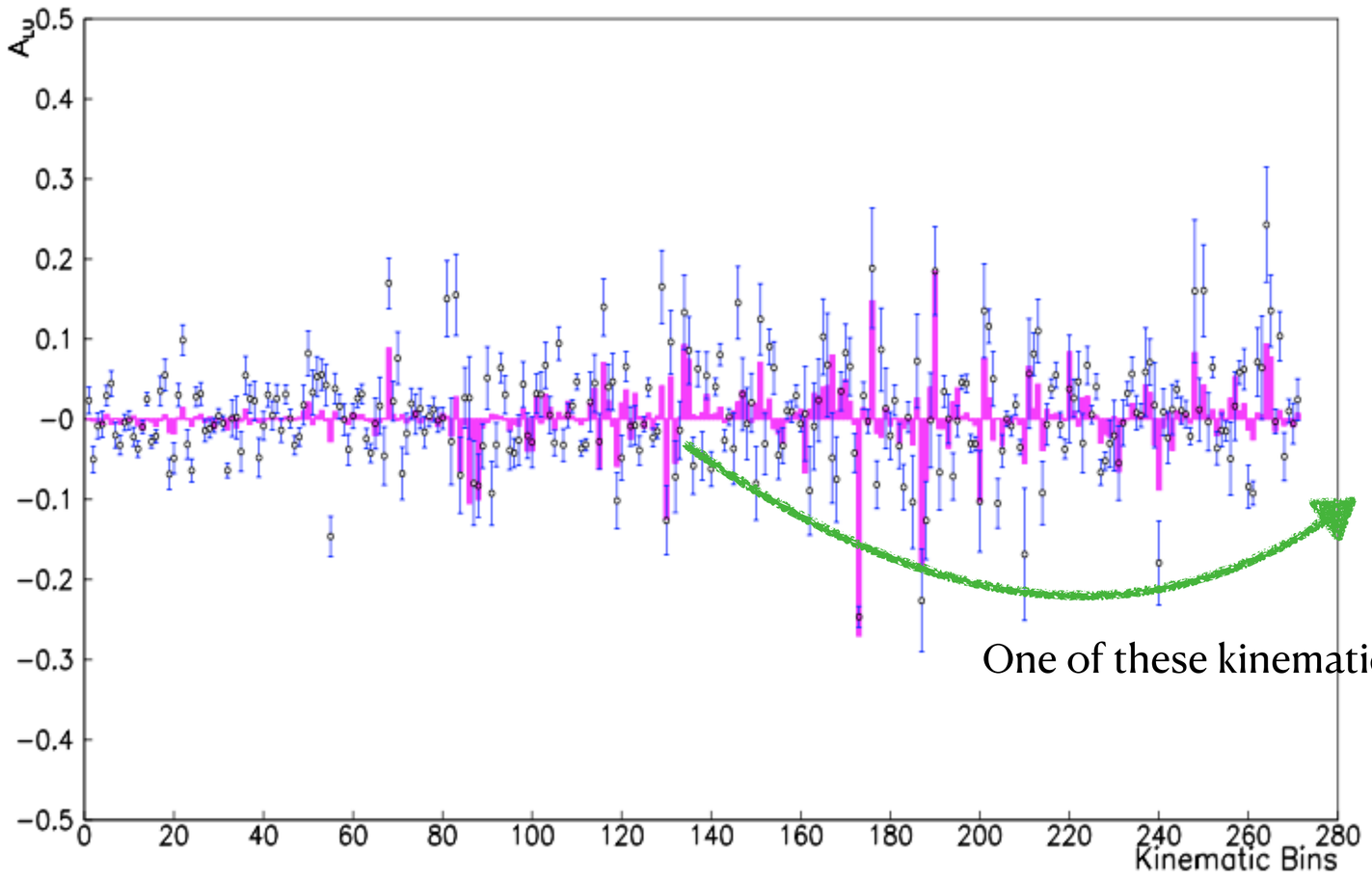




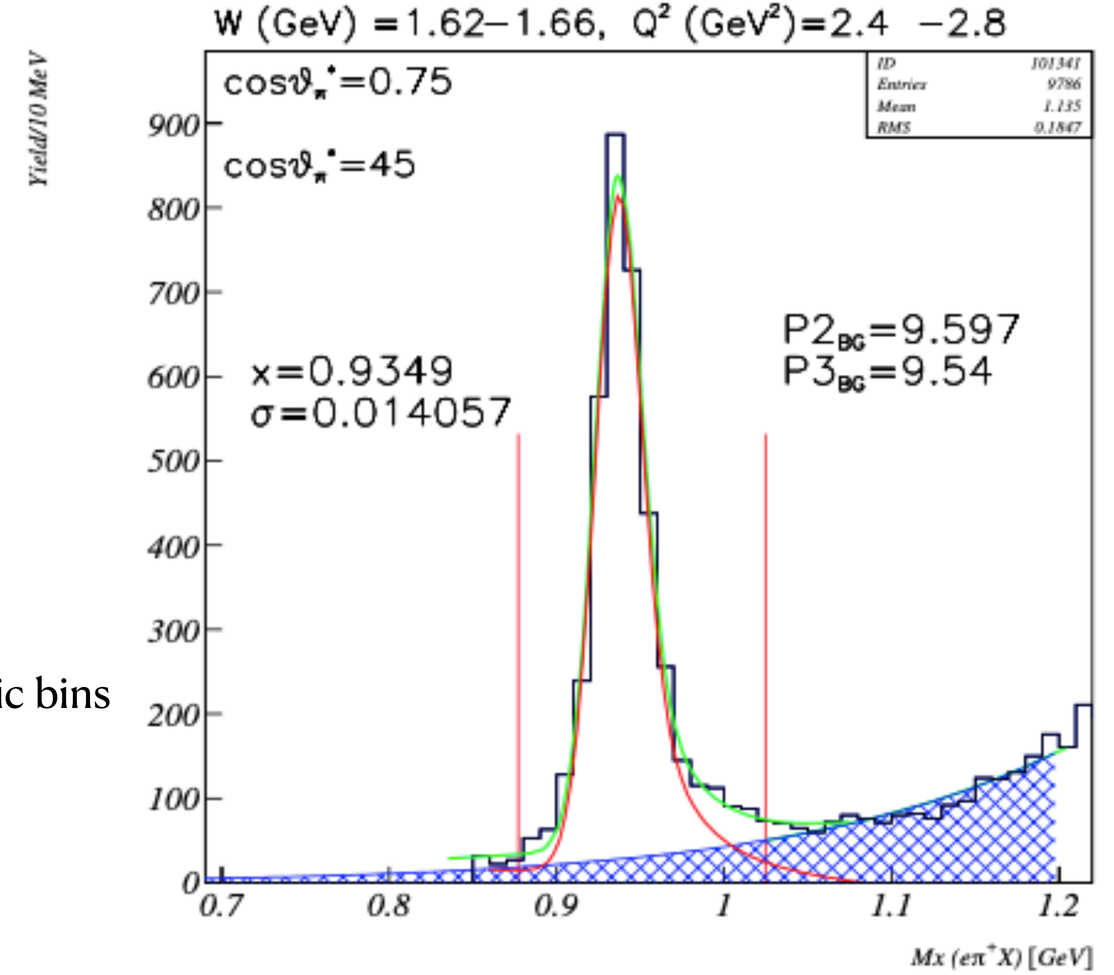




Background subtraction



One of these kinematic bins



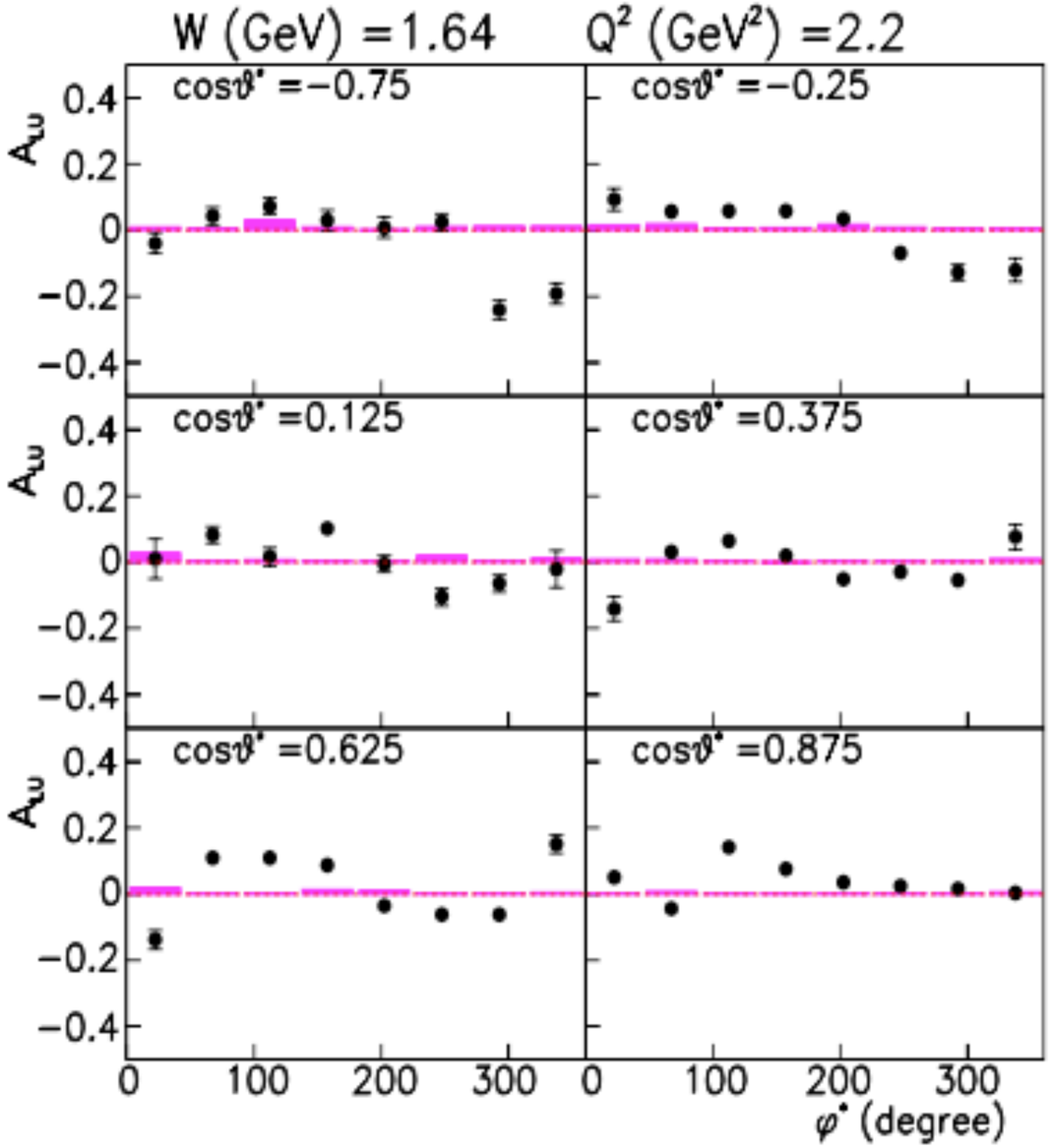
Sophisticated study for BG function determination
Function : as simple as possible
Parameter/Range : case-by-case

Peak: the skewness Gaussian
BG: convoluted exponential

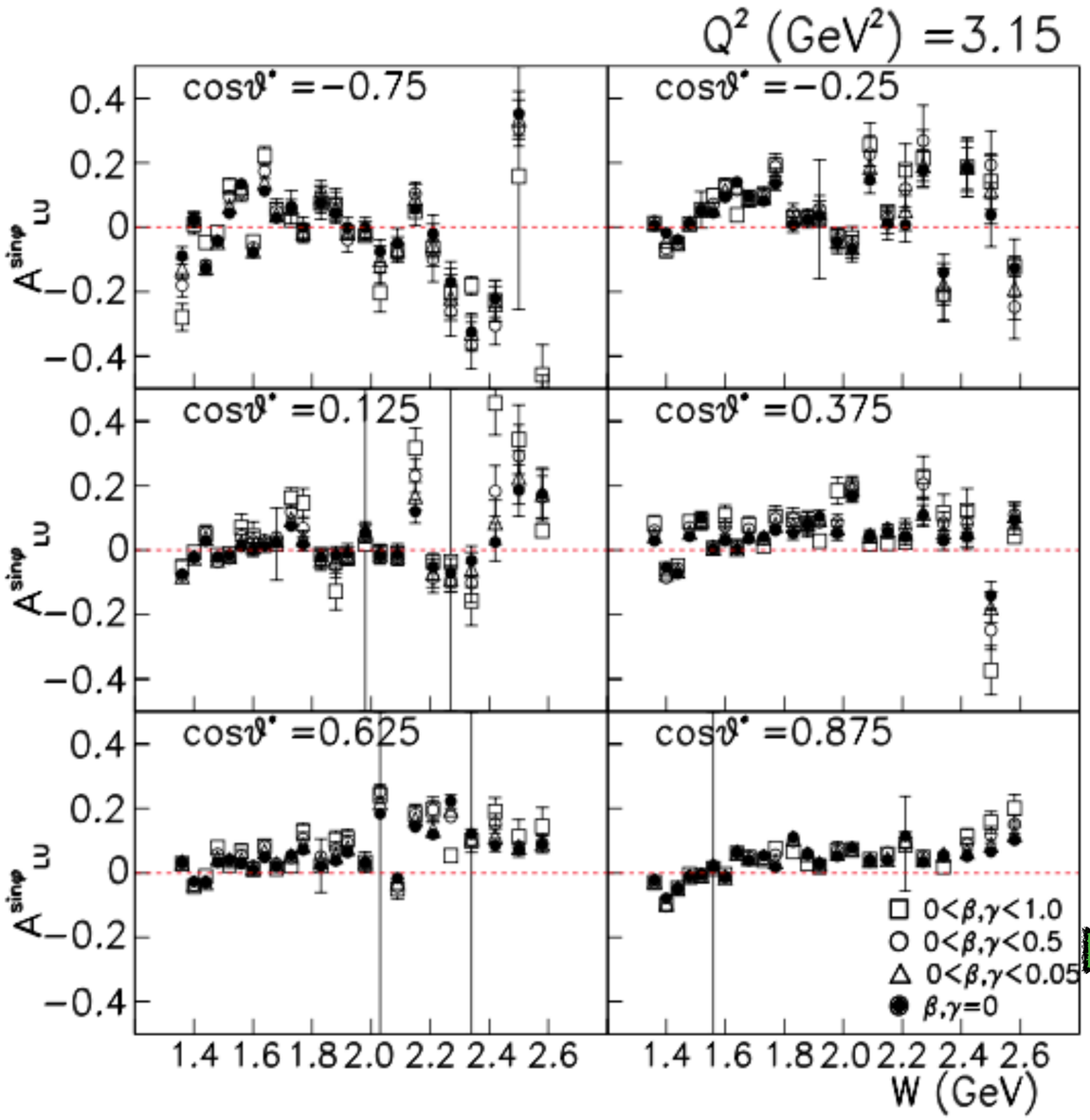
Beam spin asymmetry

$$A_{LU}(W, Q^2, \cos\theta^*, \varphi^*) = \left(\frac{N^+}{N^+_{total}} - \frac{N^-}{N^-_{total}}\right)\left(\frac{N^+}{N^+_{total}} + \frac{N^-}{N^-_{total}}\right)$$

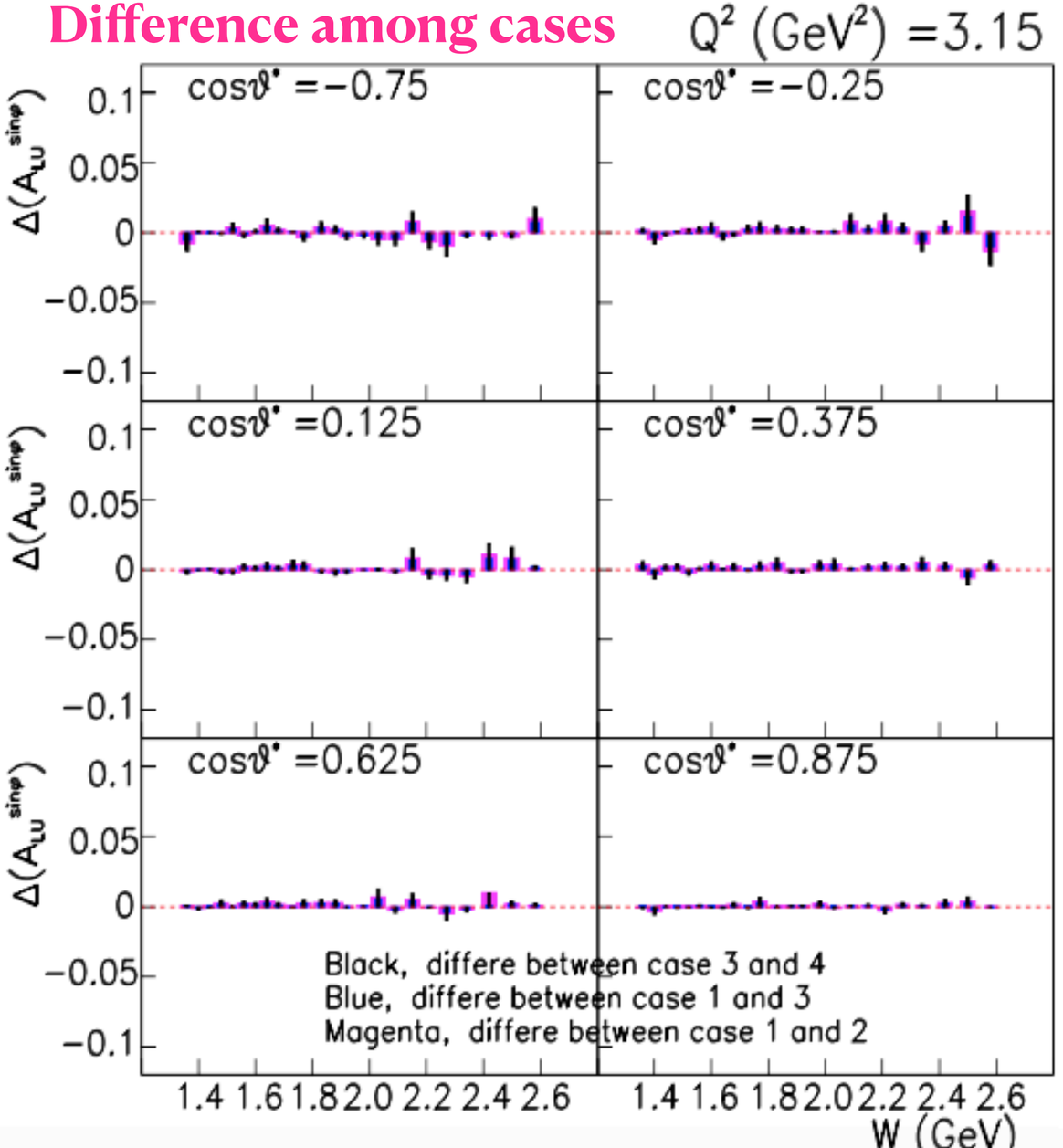
$$A_{LU} = \frac{\alpha \sin\varphi^*}{1 + \beta\cos\varphi^* + \gamma\cos 2\varphi^*} \ .$$



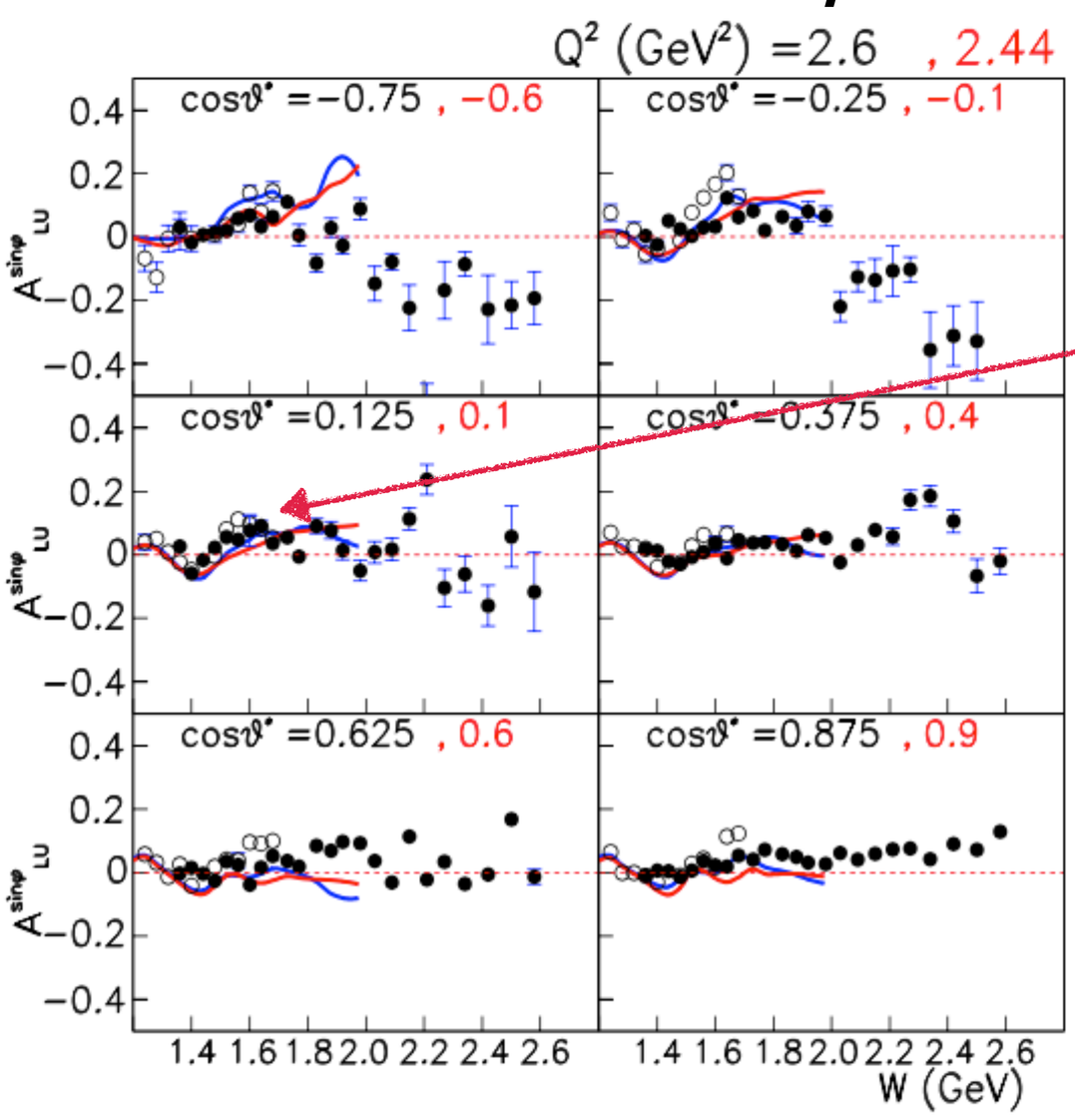
Moment extraction and comparison

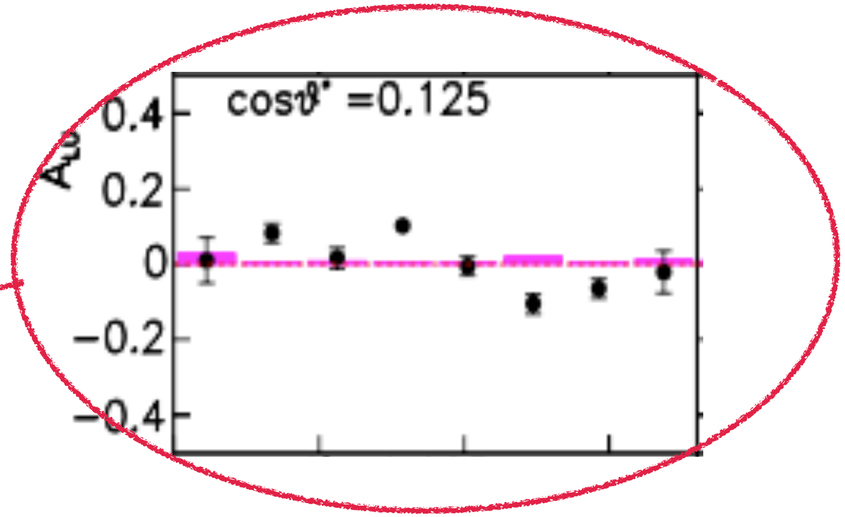


Difference among cases

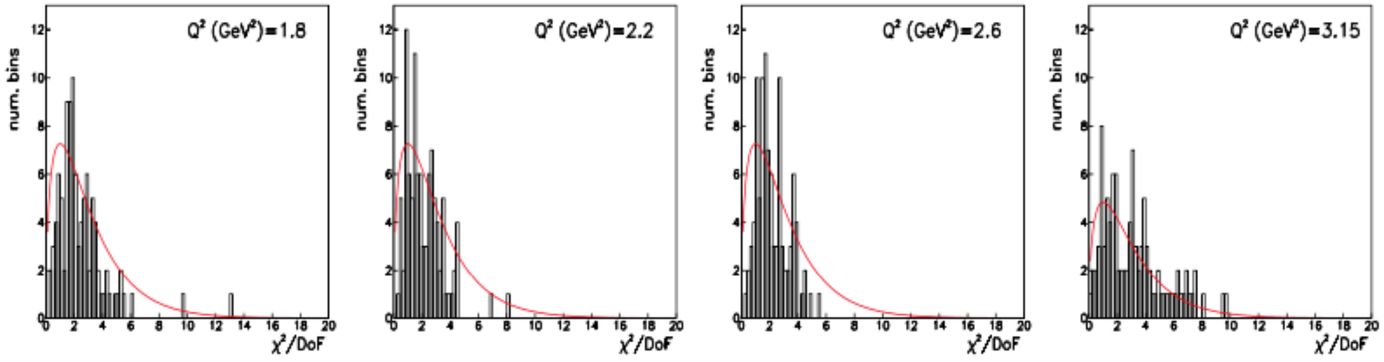


sinϕ moment extraction





W=1.64 GeV, Q2=2.6 GeV2



χ^2 distribution

Color curves:

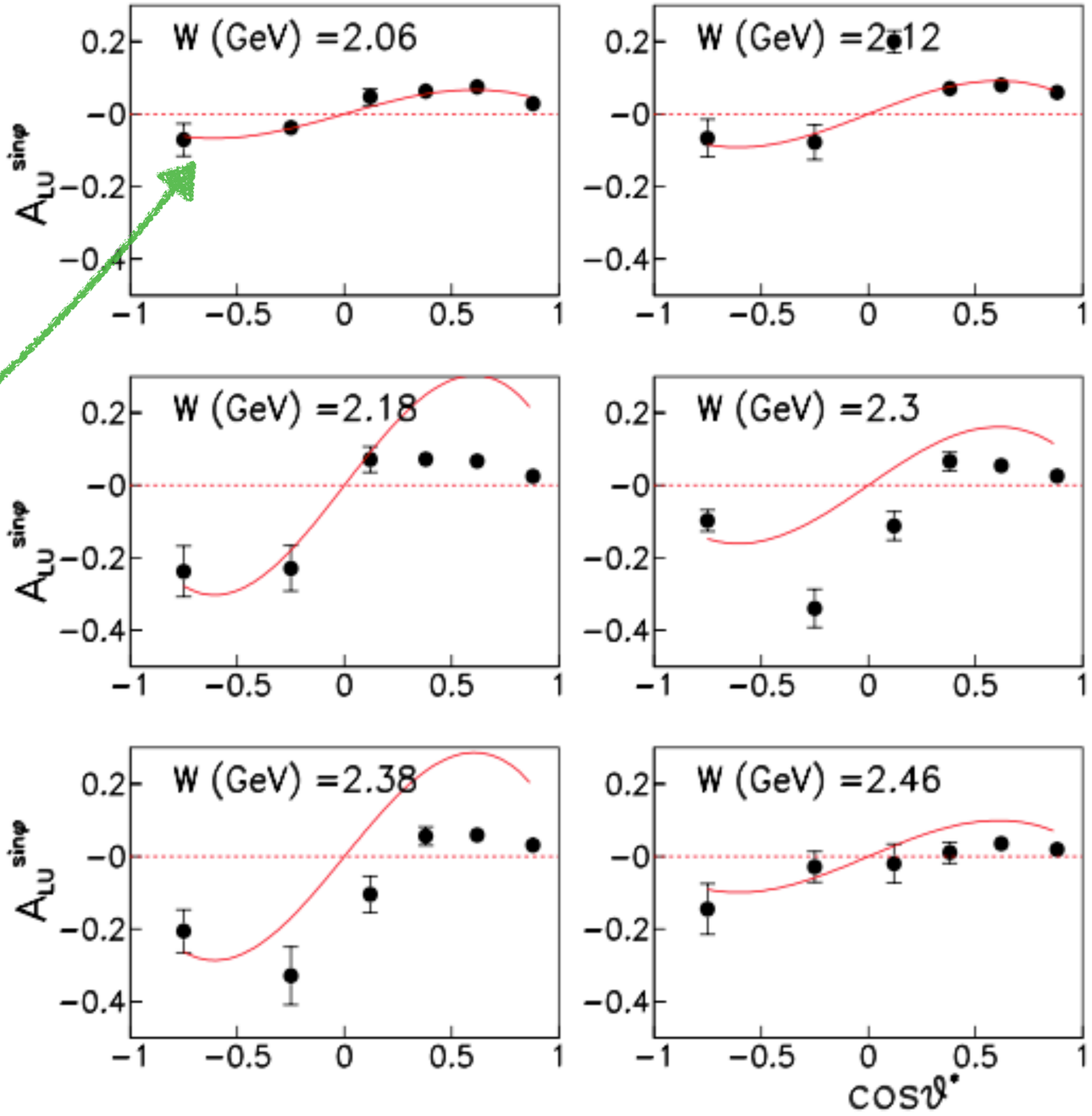
Blue solid lines: MAID2007

Red solid lines: JANR

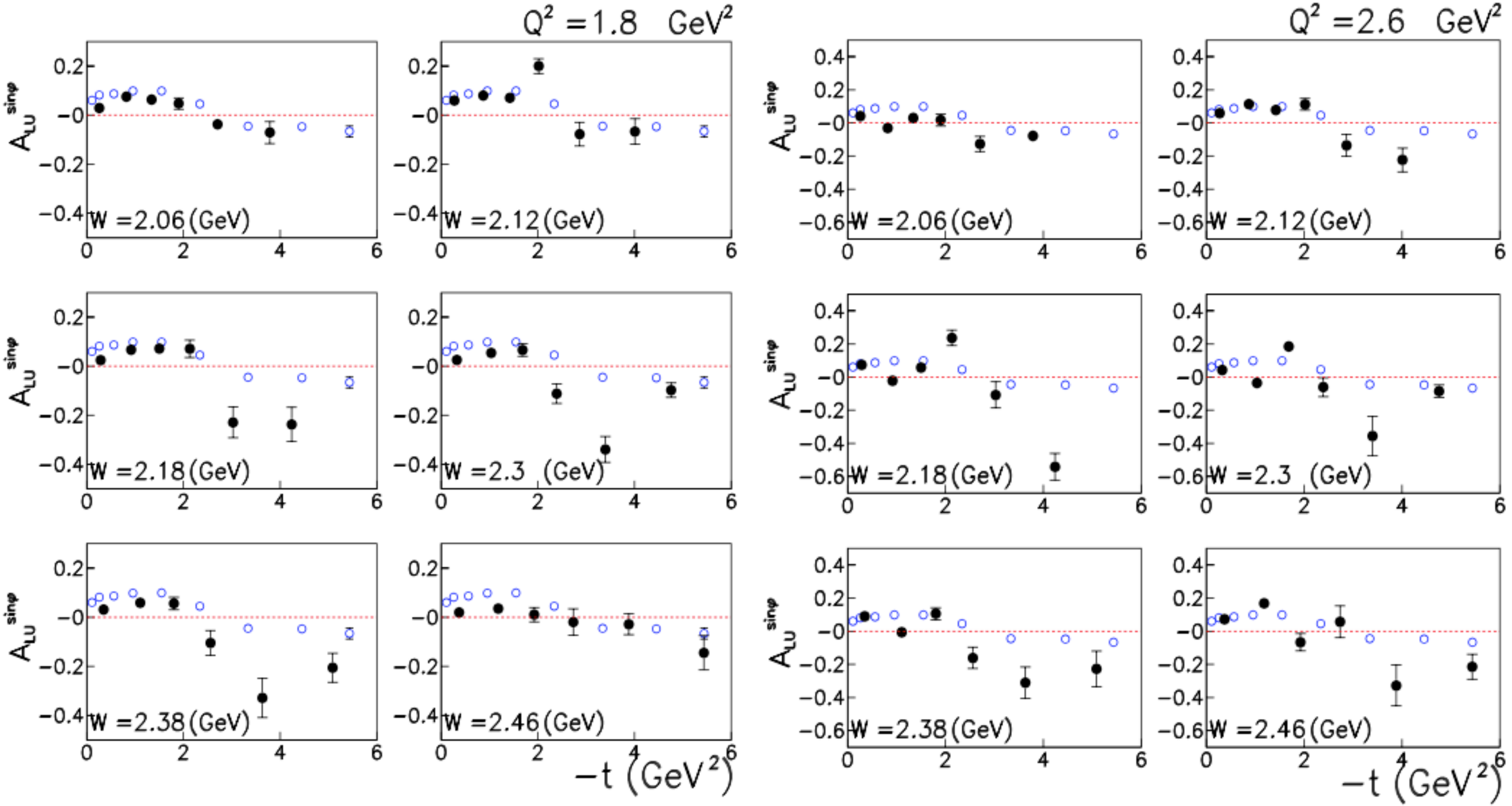
$\sin\varphi$ moment trend as a function of $\cos\theta^*$

- A single bin of $Q^2 = 1.8\ \mathrm{GeV}^2$
- A simple fit for guidance

- $A\sin(x)$,where $x = \cos\theta^*$



sinφ moment trend as a function of -t (compare to W, Q2 integrated result: S. Deihl's data, e1f)



sinφ moment trend as a function of -t (compare to GK model)

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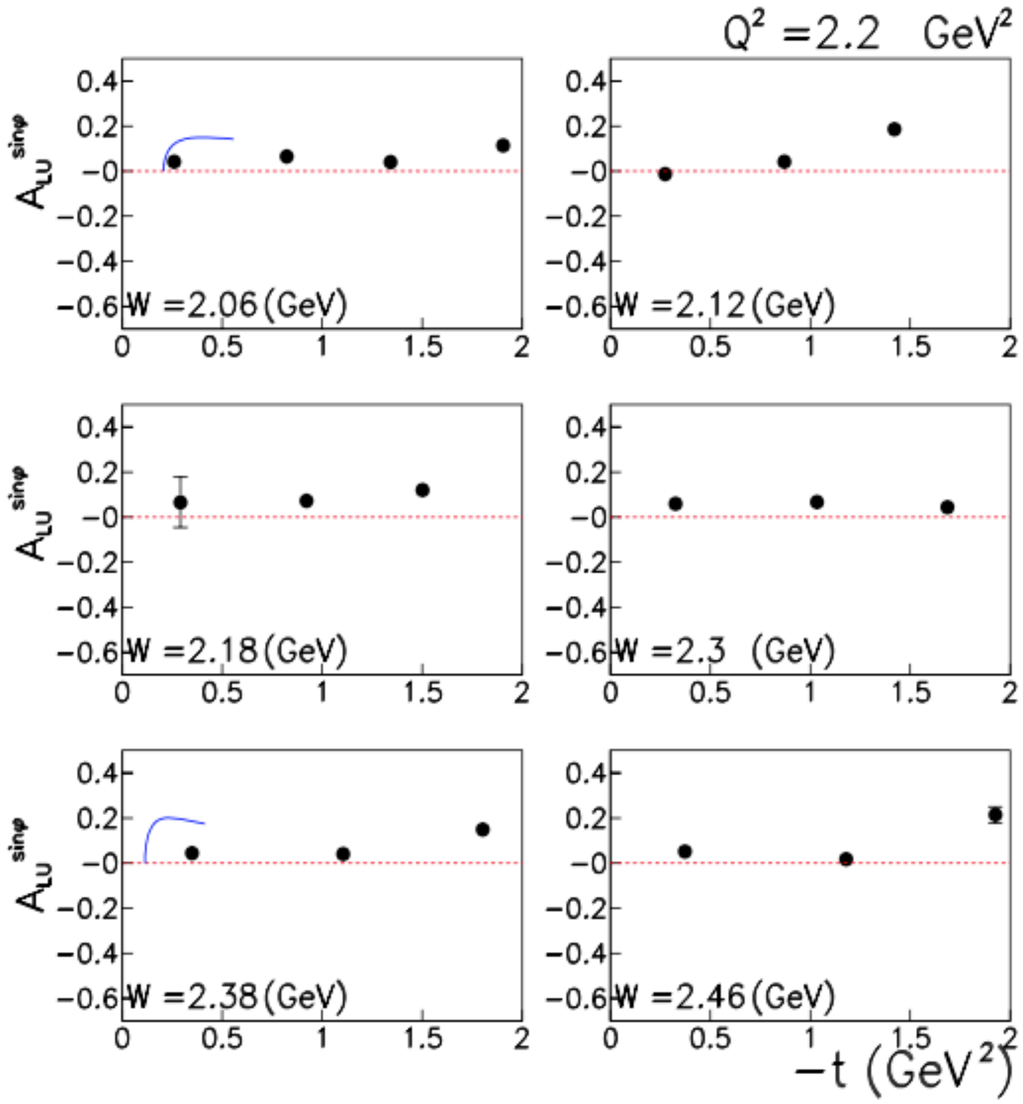
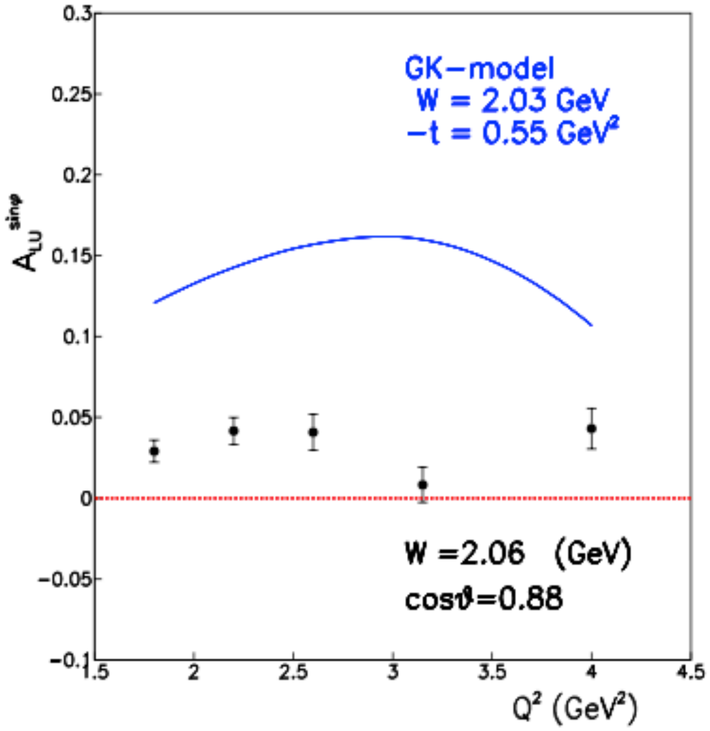
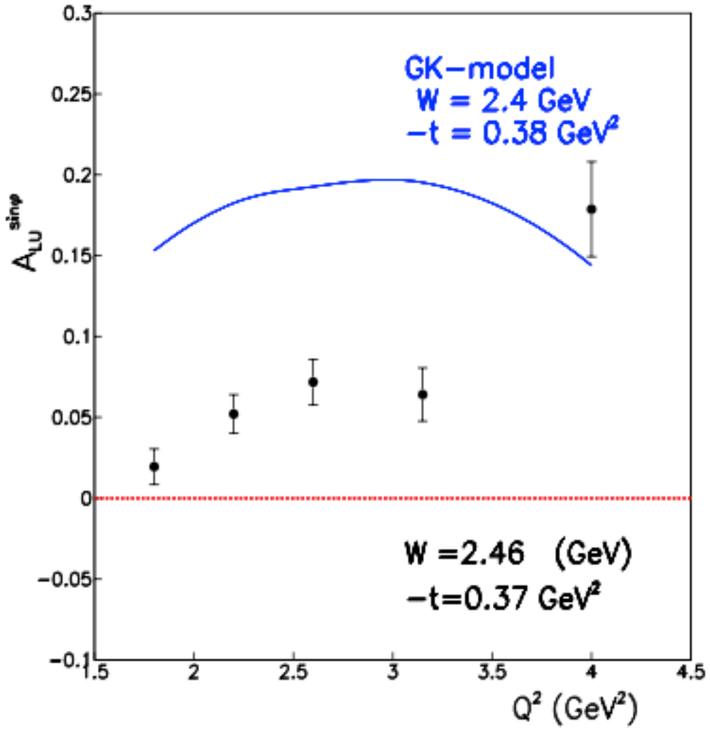




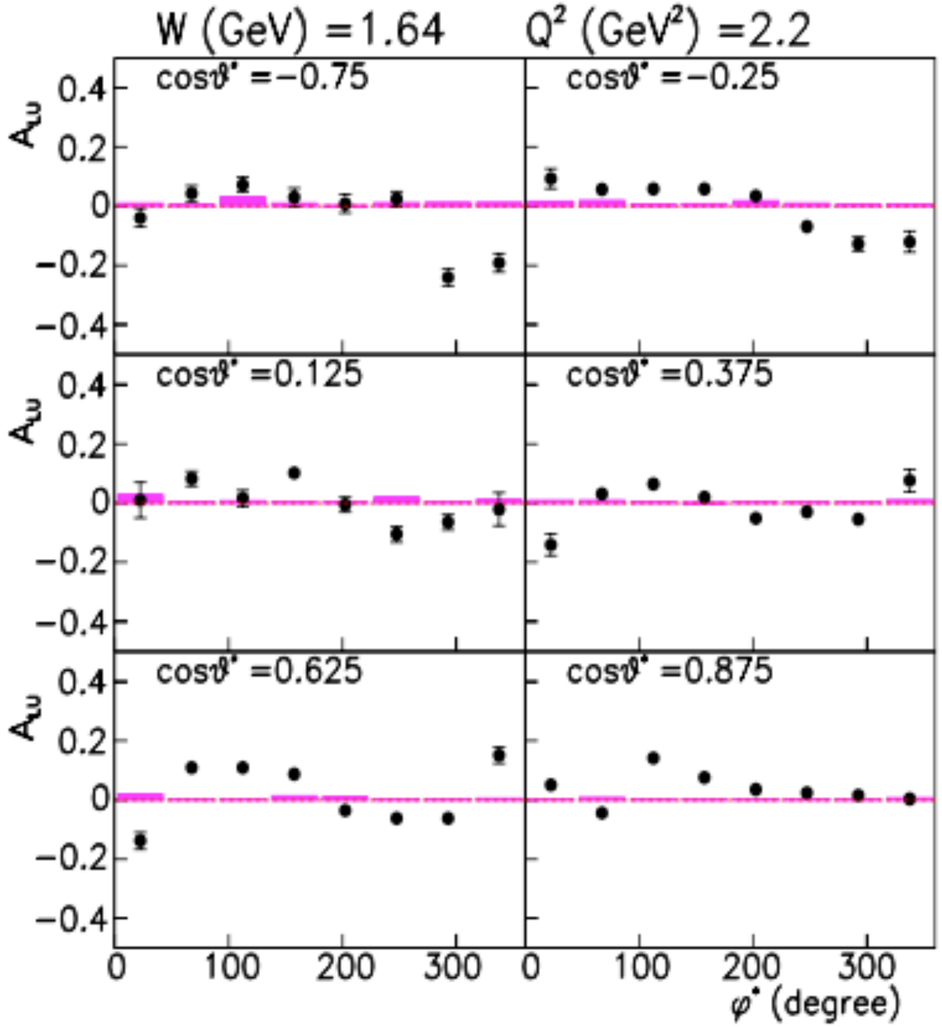


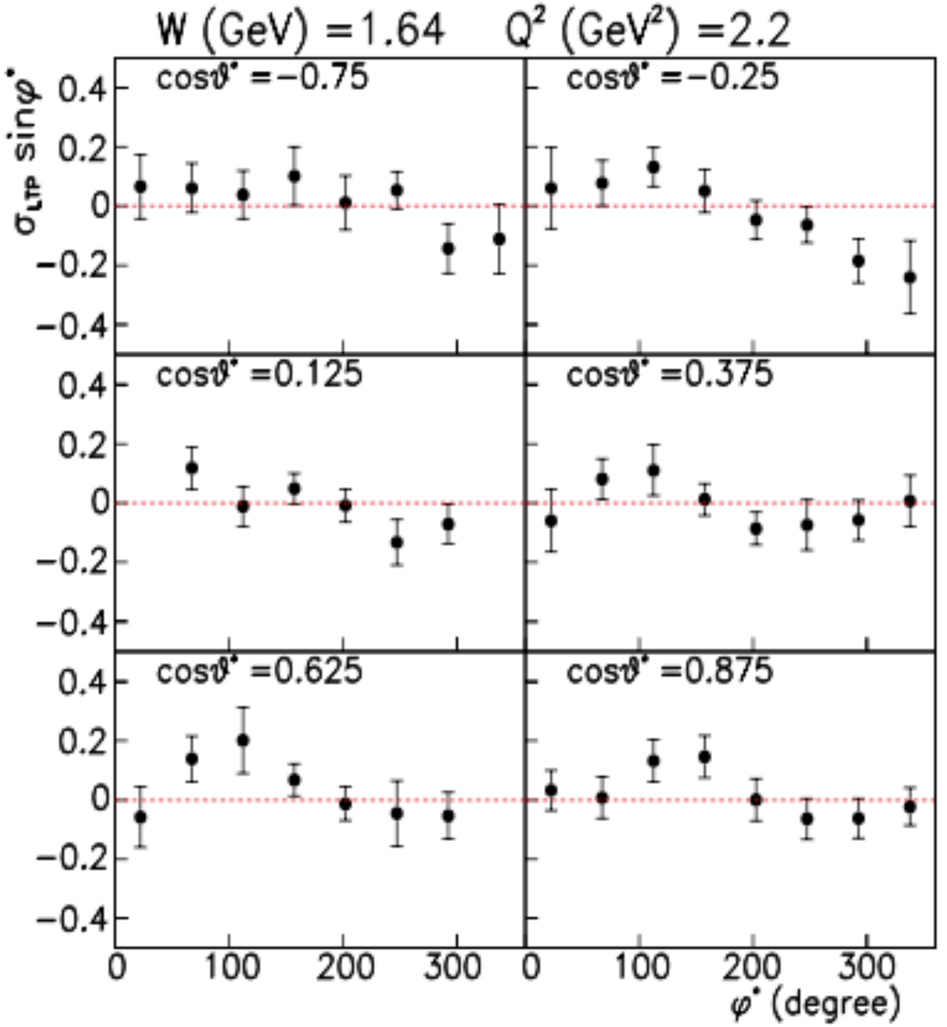
Solid blue curves: GK model

Polarized structure function

$$\sigma'_{LT} = \frac{A_{LU}^{\sin\varphi}(\sigma_T + \epsilon\sigma_L)}{\sqrt{2\epsilon(1-\epsilon)}} \left[1 + \frac{1}{2}\frac{\epsilon\sigma_{TT}}{\sigma_T + \epsilon\sigma_L}\right]^{-1}$$

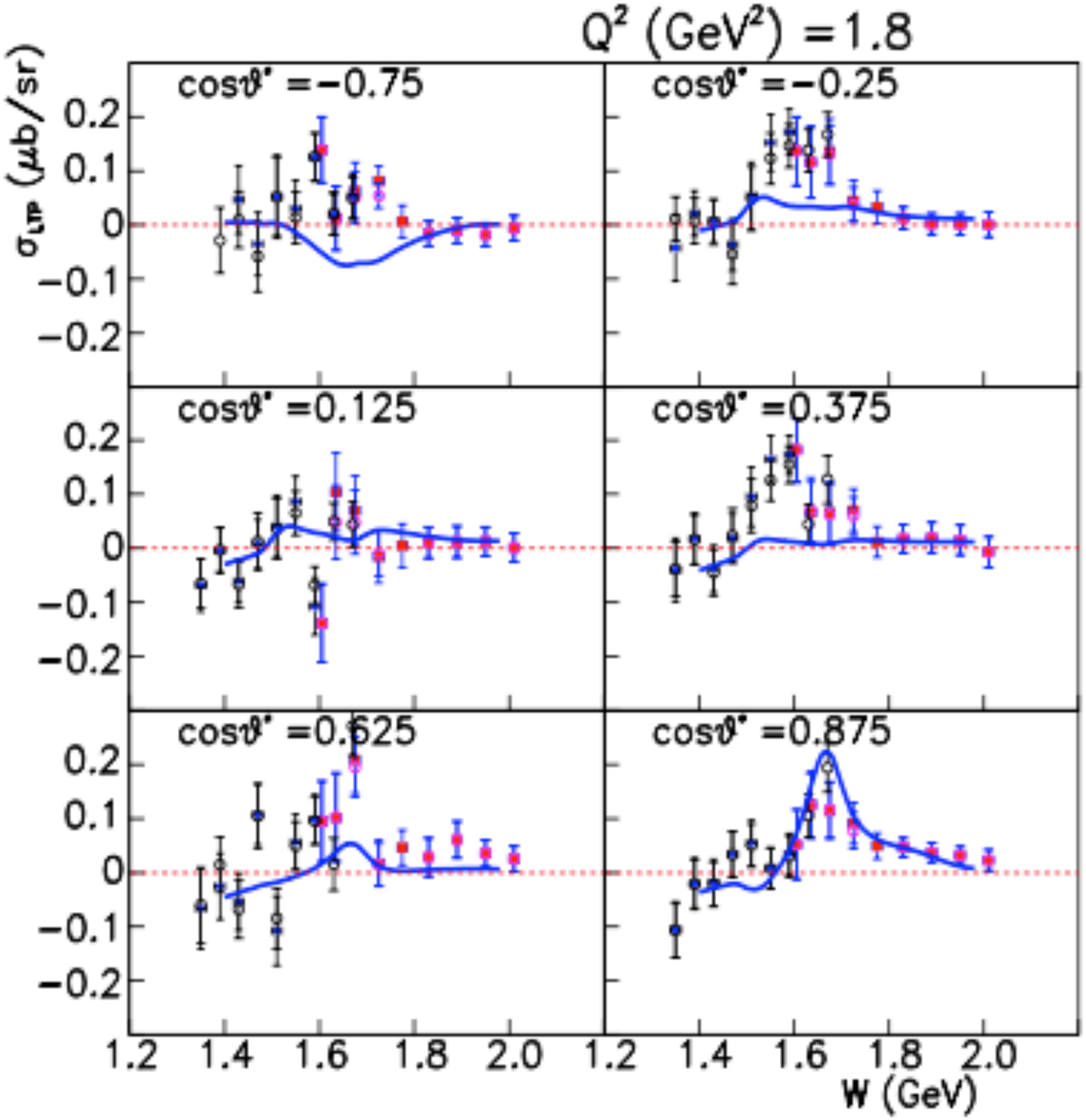
Combine data: 2015 and This analysis

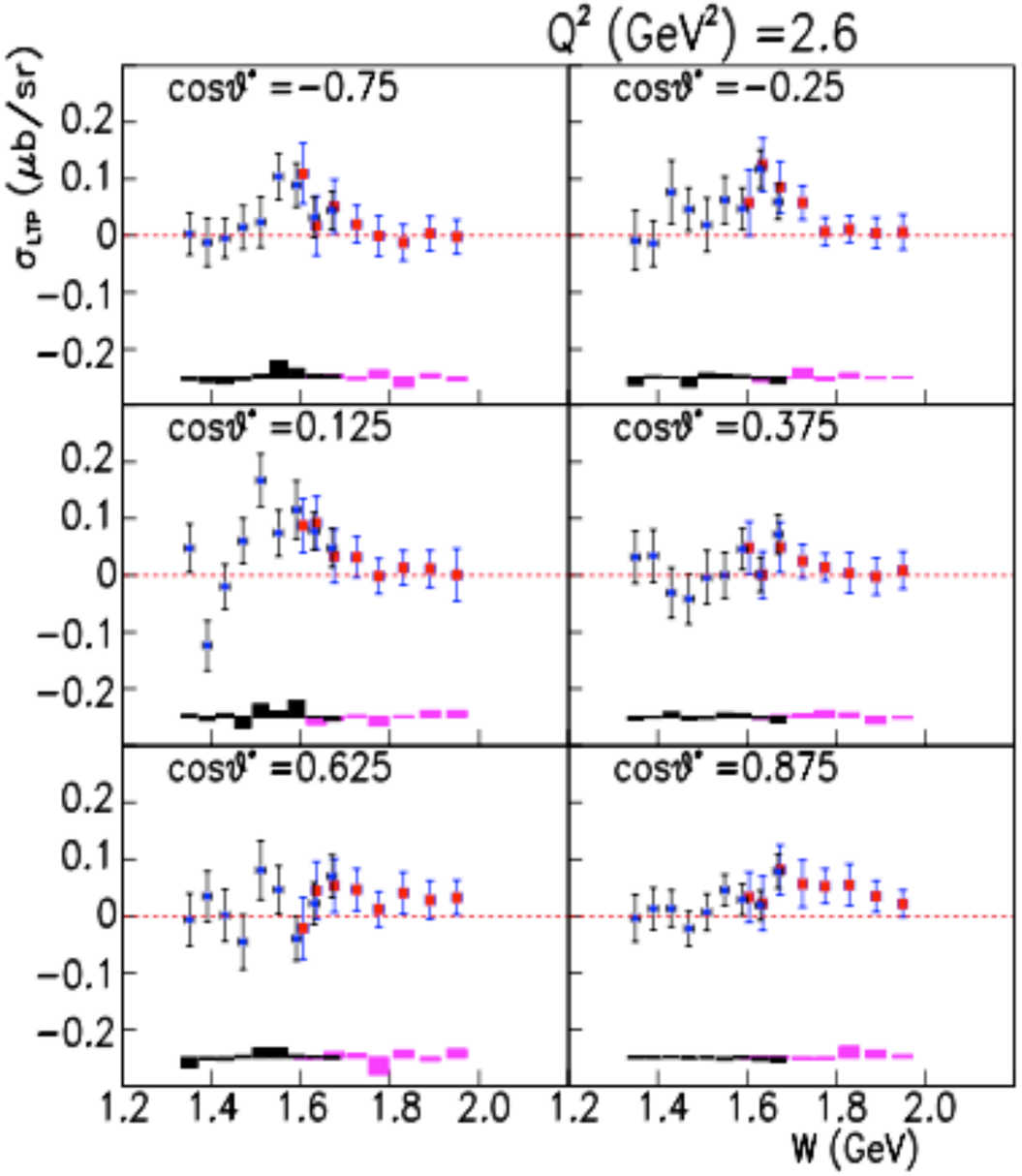




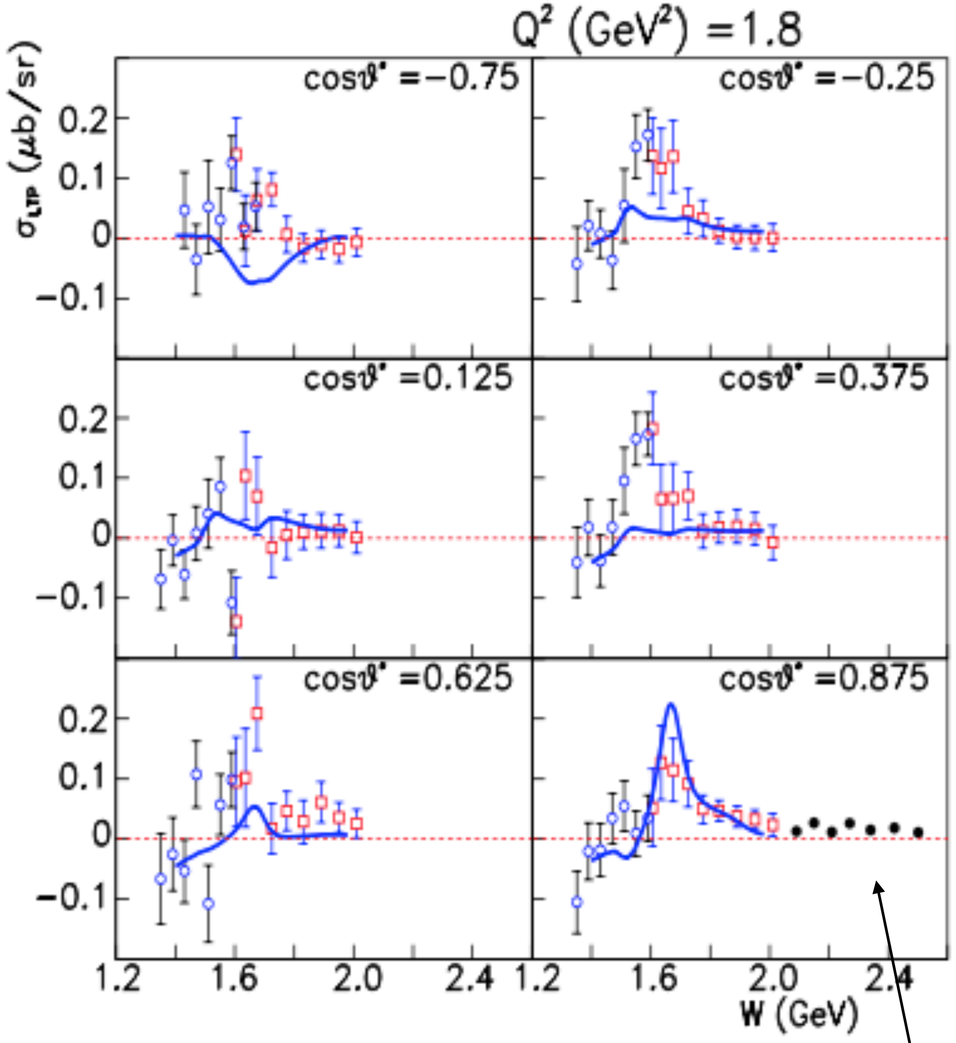
Polarized structure function (σ'_{LT})

Red solid circles : This analysis
Black circles : 2008
Blue solid lines: MAID2007





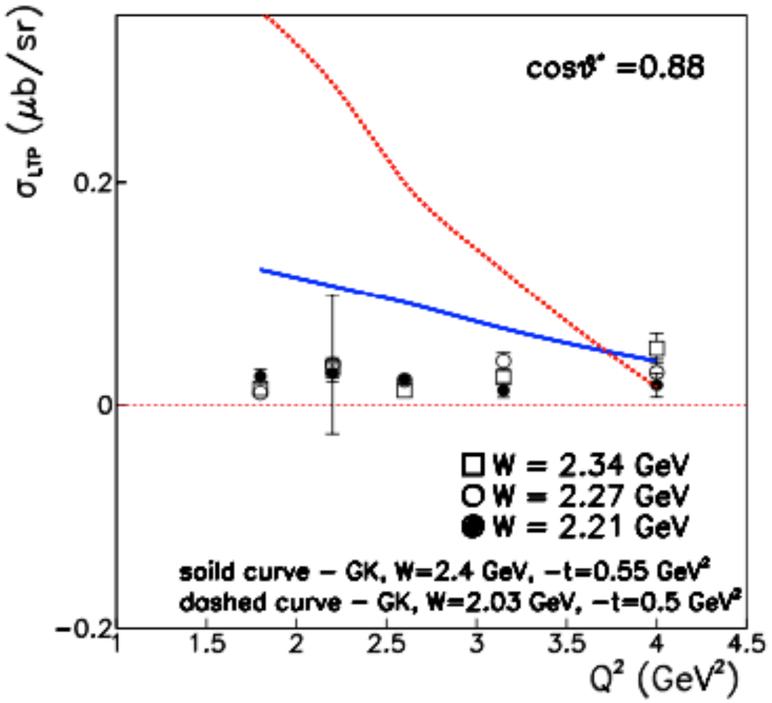
Polarized structure function



Blue curves : MAID2007

Black solid circles

Combine data: 2013 and This analysis



Near forward angles

Solid curves : GK model

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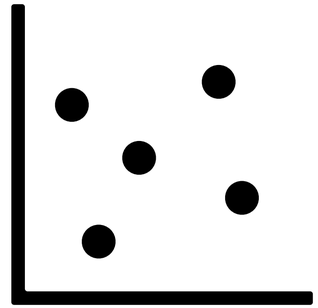

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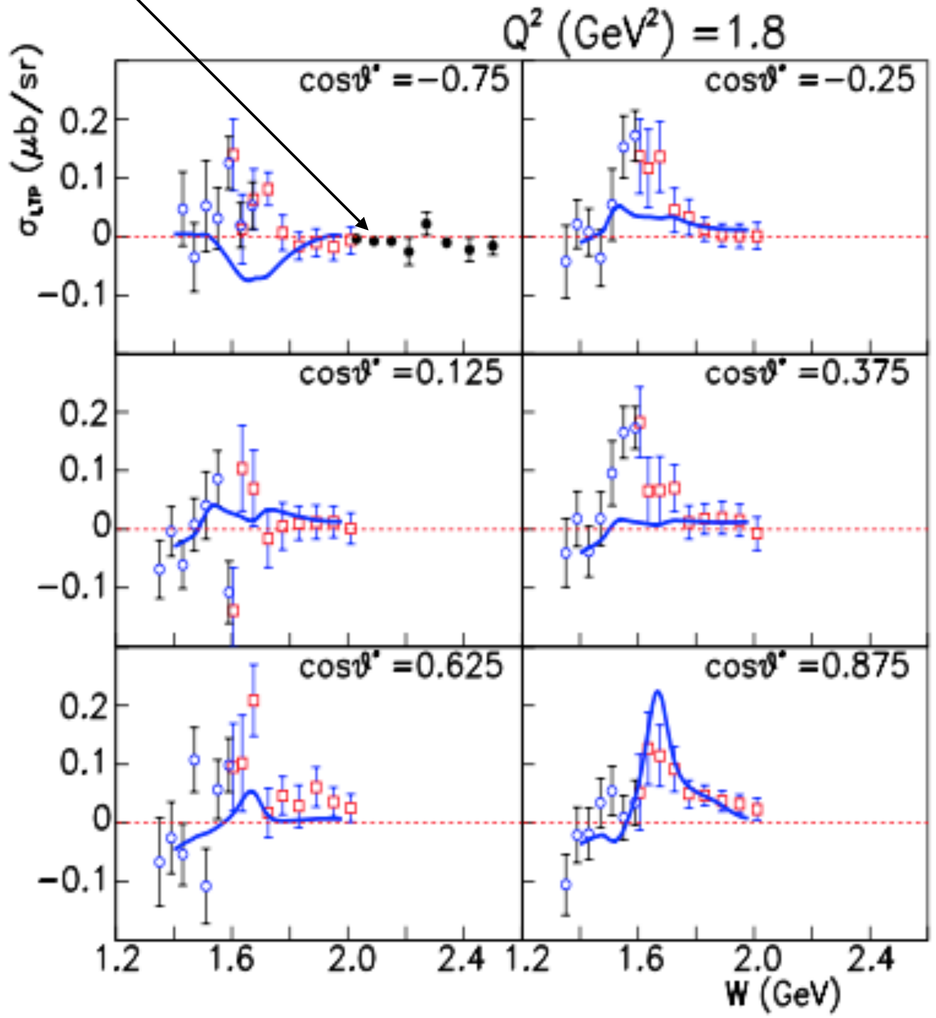
Near backward angles

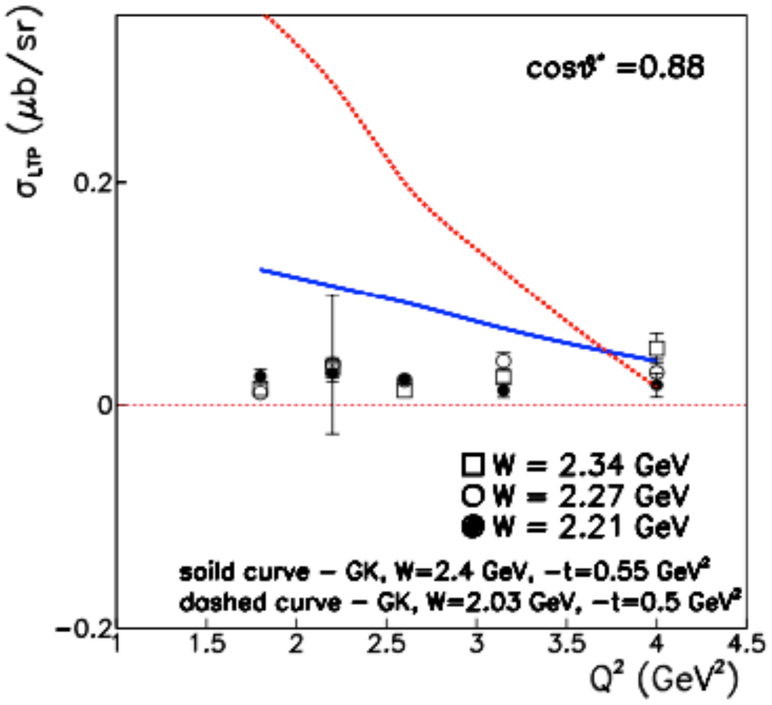
Polarized structure function

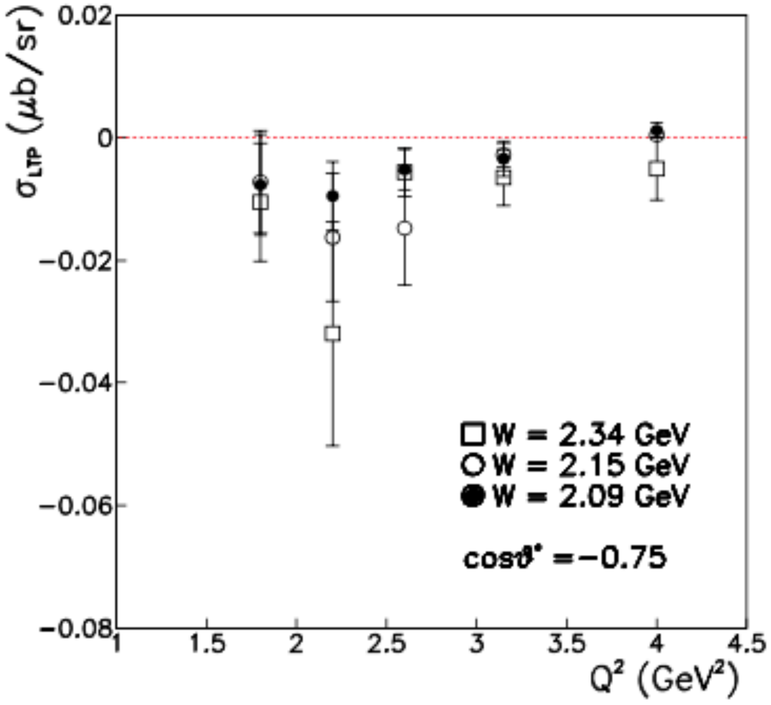
Black solid circles



Blue curves : MAID2007

Combine data: 2018 and This analysis





Near forward angles **Near backward angles**

Solid (red, blue) curves : GK model

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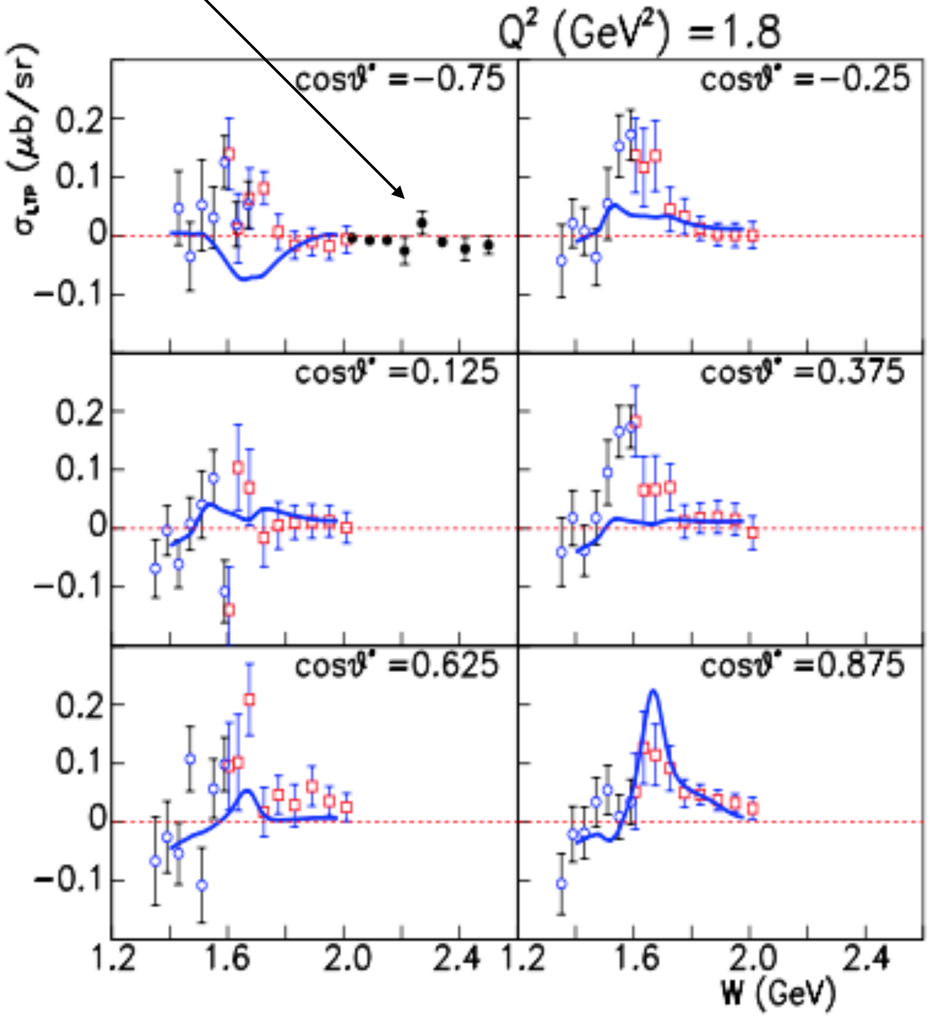
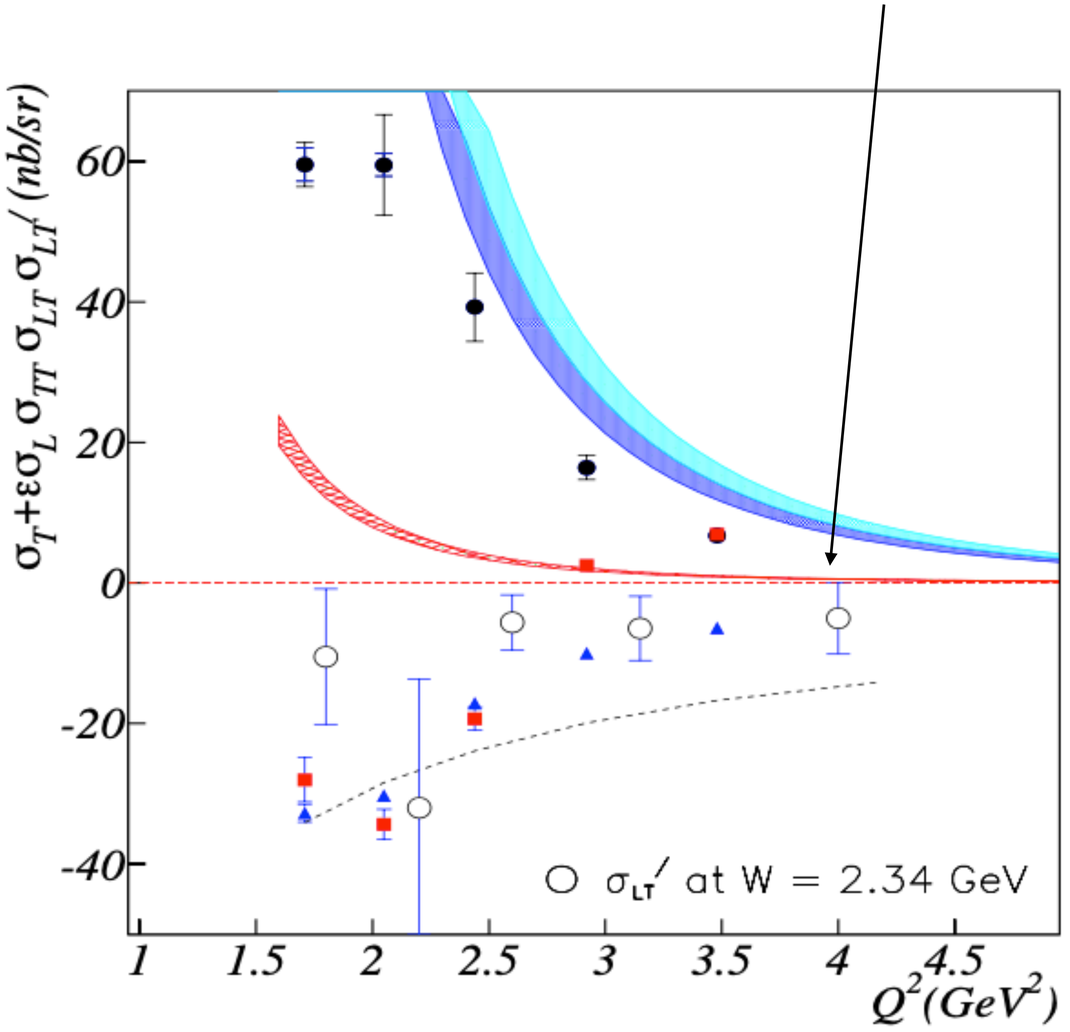
Polarized structure function at near backward angles (TDA model)

Black solid circles



Open blue circles



Summary

- The beam spin asymmetry (A_{LU}) for the exclusive single π+ electroproduction was obtained from the e1-6 data set where 5.754 GeV

$$W = 1.34 - 2.62 \text{ GeV} \quad Q^2 = 1.6 - 4.5 \text{ GeV}^2$$

- A significant ϕ^*-dependence of $A_{LU}^{\sin\phi}$ above ⟨W⟩ = 1.7 GeV was observed at large angle ($\cos\theta^* < 0$), Almost no dependence on W was observed at very forward angles

- Sign change of $A_{LU}^{\sin\phi}$ has been confirmed in the fine kinematics

- Polarized structure function at near forward and backward have been extracted and compared to the model calculations (GPD, TDA)

- Combine study of the GPD, TDA will provide more insight (universality) of nucleon structure function in terms of the collinear factorization

Thank you for your attention

Legendre moment vs. W (compare to MAID2017)

$$\sigma_T + \epsilon\sigma_L = \sum_{l=0}^{n} D_l^{T+L} \; P_l(\cos\theta^*) \; ,$$

$$\sigma_{LT} = \sin\theta^* \sum_{l=0}^{n-1} D_l^{LT} \; P_l(\cos\theta^*) \; ,$$

$$\sigma_{TT} = \sin^2\theta^* \sum_{l=0}^{n-2} D_l^{TT} \; P_l(\cos\theta^*) \; , \text{and}$$

$$\sigma'_{LT} = \sin\theta^* \sum_{l=0}^{n-1} D_l^{LT'} \; P_l(\cos\theta^*) \; .$$