Kinematical higher-twist contributions in two-photon reactions

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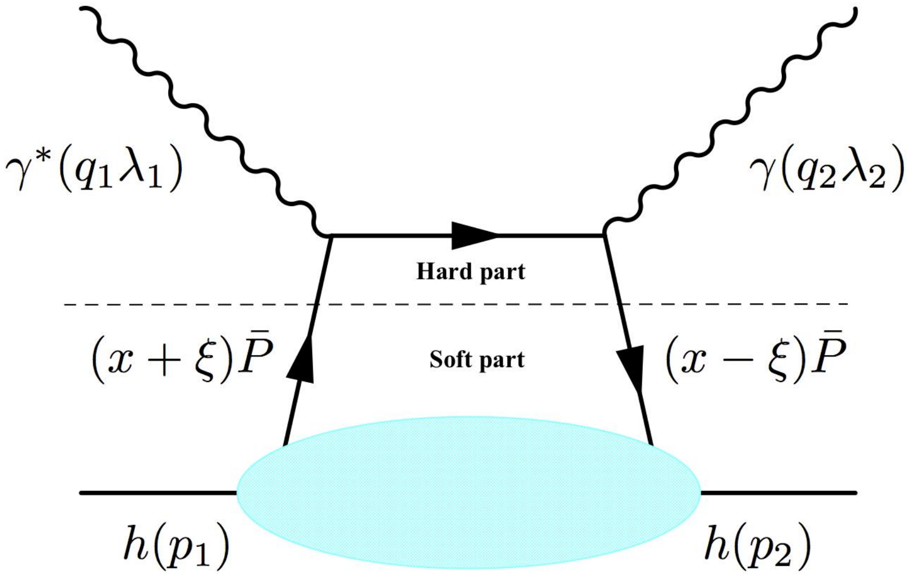
References:
C. Lorce, B. Pire and Qin-Tao Song, Phys. Rev. D106 (2022), 094030.
B. Pire and Qin-Tao Song, Phys. Rev. D 107 (2023), 114014.
B. Pire and Qin-Tao Song, Phys. Rev. D 109 (2024), 074016

Outline

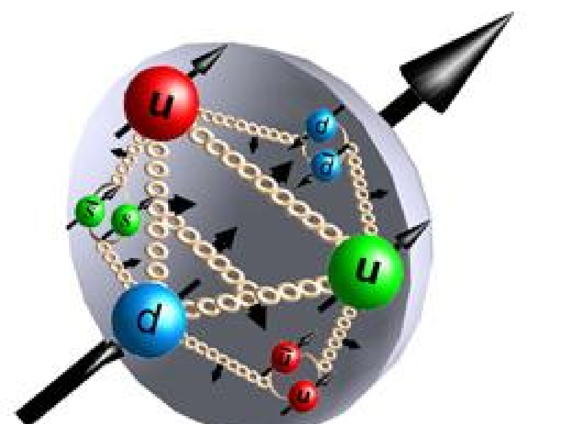
- GPDs and GDAs of hadrons
- Gravitational (EMT) FFs of hadrons
- Kinematical higher-twist corrections
- Exotic hybrid mesons and shear viscosity term (a new gravitational FF) at BESIII and Belle II

Generalized Parton distributions (GPDs，广义部分子函数)



$\gamma^* h \rightarrow \gamma\ h$

Deeply Virtual Compton Scattering
(DVCS，深度虚康普顿散射)



Spin puzzle of proton: $\Delta u^+ + \Delta d^+ + \Delta s^+ \approx 0.3$

$\Delta g + \Delta L \neq 0$

Generalized Parton Distributions (GPDs) provide information on ΔL to solve the proton spin puzzle!

X.D. Ji, PRL 78(1997), 610.

Generalized Parton distributions (GPDs)

GPDs

- Proton spin puzzle
- Energy momentum tensor (EMT) form factors of hadrons
- mass radius, mass distribution, pressure distribution and shear force distribution

Interesting, little known

↓

Recent Reviews:

M. V. Polyakov and P. Schweitzer, Int. J. Mod. Phys. A 33 (2018) no.26, 1830025.

V. D. Burkert, L. Elouadrhiri, F. Girod, C. Lorce, P. Schweitzer and P. Shanahan, Rev. Mod. Phys. 95 (2023), 041002.

EMT form factors and mass radius of pions?

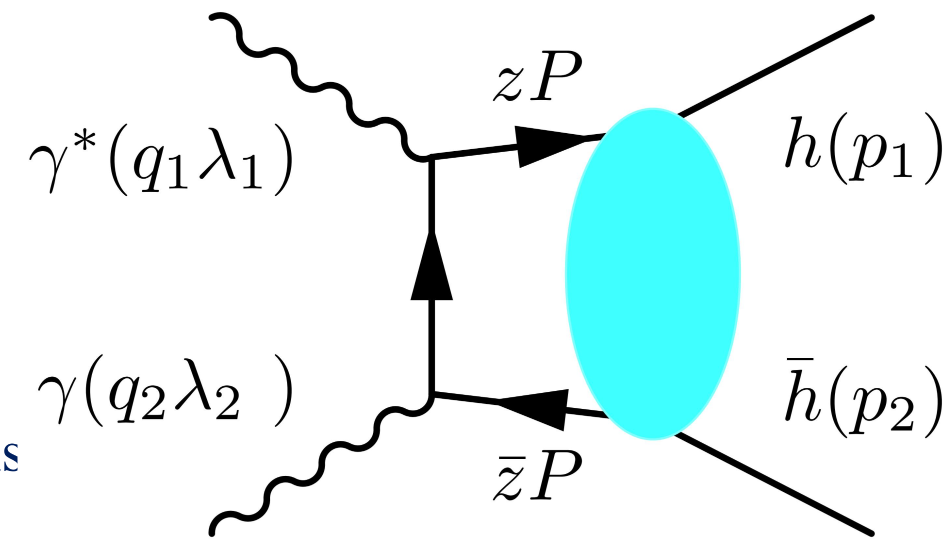
The GPDs of pions cannot be accessed by DVCS, since there is currently no such a facility. $\gamma^* + \pi \rightarrow \gamma + \pi$

How to obtain EMT form factors of pions?

Option 1: Model calculations of EMT form factors.

Option 2: EMT form factors can be obtained from generalized distribution amplitudes (GDAs) of pions

GDAs in $\gamma^* + \gamma \rightarrow h + \bar{h}$:



Hard part: $\gamma^* + \gamma \rightarrow q + \bar{q}$

Soft part: $q + \bar{q} \rightarrow h + \bar{h}$, GDAs

Quark GDA of a scalar meson is defined as:

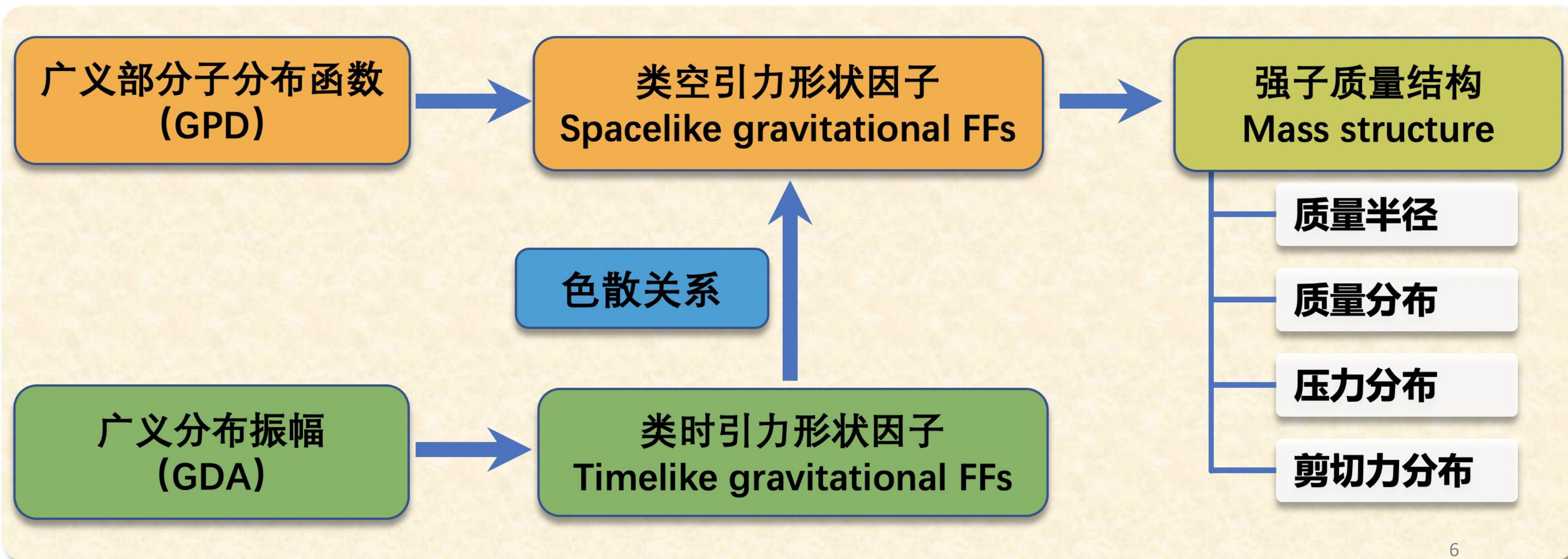
$$\Phi(z,\ \cos\theta, s\ ) \ = \int \frac{dx^-}{2\pi} e^{-iP^+x^-} \langle h(p)\bar{h}(p')|\bar{q}(x^-)\gamma^+ q(0)|0\rangle$$

M. Diehl, T. Gousset, B. Pire and O. Teryaev, PRL **81** (1998) 1782.
M. Diehl, T. Gousset and B. Pire, PRD **62** (2000) 07301.
M. V. Polyakov, NPB **555** (1999) 231.

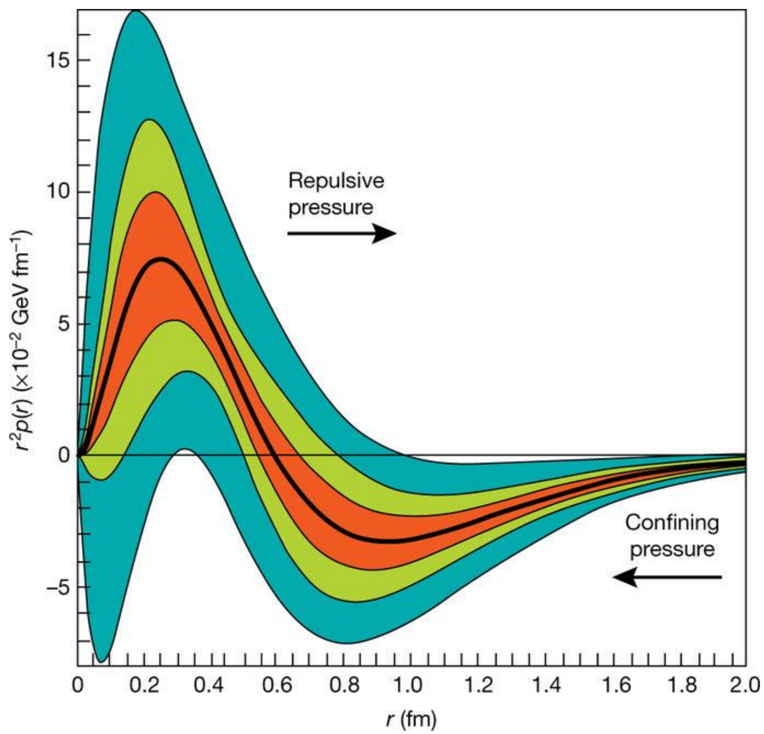
GDAs are also important inputs for decays of B mesons.

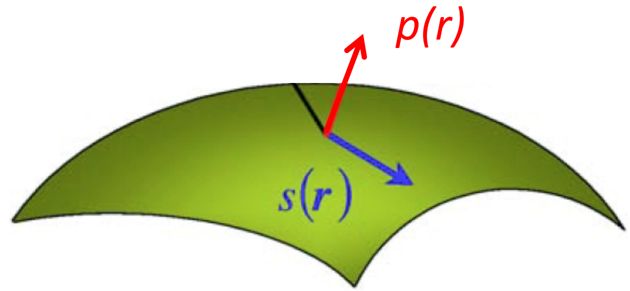
W. F. Wang, H. N. Li, W. Wang and C. D. Lu, PRD 91 (2015), 094024.
Y. Li, A. J. Ma, W. F. Wang and Z. J. Xiao, PRD 95 (2017), 056008.
M. K. Jia, C. Q. Zhang, J. M. Li and Z. Rui, PRD 104 (2021), 073001.

From GPDs and GDAs to hadron gravitational FFs:



Recent progress on the hadron EMT FFs





Pressure distribution p(r) and shear force (剪切力) distribution can be obtained from gravitational FFs.

DVCS measurements at JLab:
$\gamma^* + \text{proton} \to \gamma + \text{proton}$

Pressure distribution p(r) of the proton

Nature 557 (2018) 7705, 396.

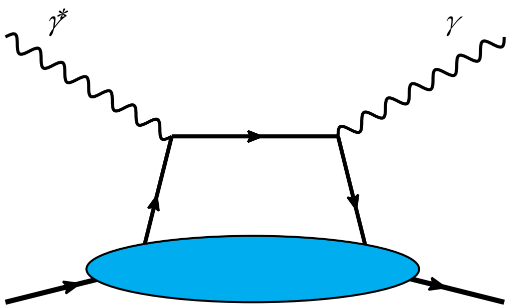
Cross section of $\gamma^* + \gamma \to \pi\,\pi$ at Belle:
M. Masuda et al. [Belle Collaboration], PRD 93 (2016), 032003.

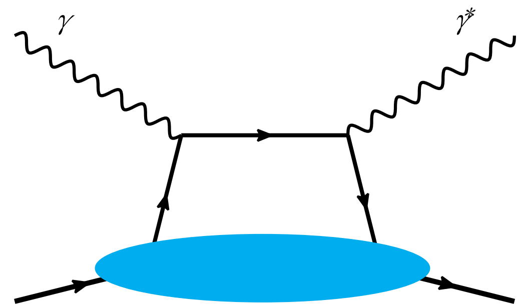
GDAs and EMT FFs of pion:
S. Kumano, Qin-Tao Song and O. Teryaev, PRD **97** (2018) 014020.

First extraction from experimental data, 127 citations (Inspire)

GPDs and GDAs are measured in two-photon reactions

GPDs:

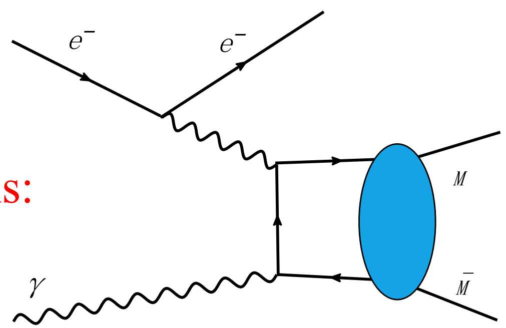




DVCS@JLAB, Compass,
EIC-US, EicC

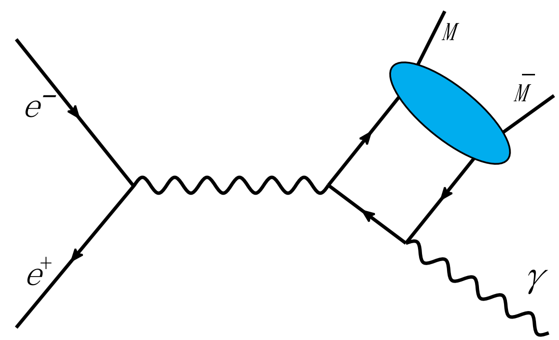
Timelike Compton scattering(TCS)
@JLAB, EIC-US, EicC
First measurement of TCS: PRL 127 (2021), 262501

GDAs:



$e^- + \gamma \to e^- + \mathrm{M} + \bar{\mathrm{M}}$
@Belle and Belle II

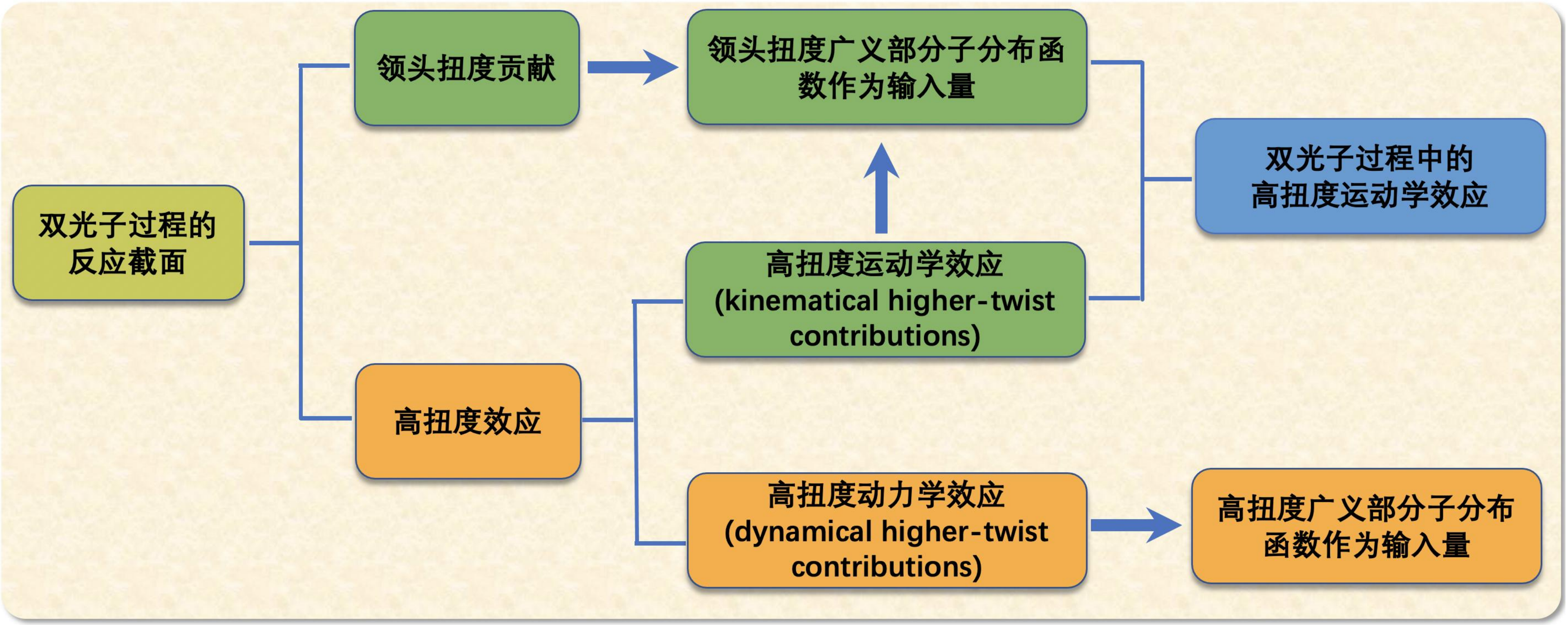
M. Masuda et al. [Belle], PRD 93 (2016), 032003.
M. Masuda et al. [Belle], PRD 97 (2018), 052003.



$\mathrm{e^+e^-} \to \gamma^* \to \mathrm{M} + \bar{\mathrm{M}} + \gamma$@BESIII
@STCF

Higher-twist contributions of order s/Q^2 and m^2/Q^2 are important in the measurements.
Kinematical higher-twist corrections of the above reactions are discussed in this talk.

Kinematical higher-twist contributions



- Higher-twist corrections: leading and higher-twist GPDs(GDAs).
- Kinematical higher-twist corrections: leading-twist GPDs(GDAs)!
- Higher-order corrections of α_s: leading-twist quark and gluon GPDs(GDAs).

V. M. Braun and A. N. Manashov, PRL 107(2011), 202001;JHEP 01 (2012), 085; PPNP 67 (2012), 162–167.

The kinematical corrections are included in recent DVCS measurements.

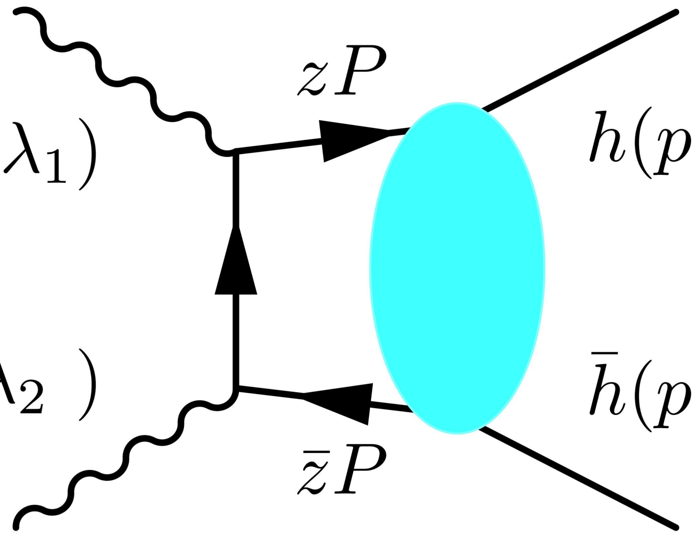
F. Georges et al. [Jefferson Lab Hall A], PRL. 128 (2022), 252002.
M. Defurne et al., Nature Communication 8(2017), 1408.
M. Defurne et al., Hall A collaboration, PRC92 (2015) no.5, 055202

Kinematical higher-twist corrections in $\gamma^* + \gamma \to \mathrm{M} + \bar{\mathrm{M}}$

Kinematical contributions in $\gamma^* + \gamma \rightarrow \mathrm{M} + \bar{\mathrm{M}}$

We can also calculte the amplitudes of $\gamma^* + \gamma \rightarrow \mathrm{M} + \bar{\mathrm{M}}$ by using the operator results of the kinematical contributions in two electromagnetic currents.

$$T_{\mu\nu} = \mathrm{T}\{j_\mu(\mathrm{z}_1\mathrm{x}) j_\nu(\mathrm{z}_2\mathrm{x})\}$$



Helicity amplitudes of a scalar meson:

$$\mathrm{A}_{\lambda_1\lambda_2} = \mathrm{T}_{\mu\nu}\epsilon^\mu(\lambda_1)\epsilon^\nu(\lambda_2)$$

There are three independent helicity amplitudes: A_{++}, A_{0+} and A_{+-}.

Leading twist amplitude: A_{++}
Higher twist amplitudes: A_{0+} and A_{+-}.

M. Diehl, T. Gousset, B. Pire and O. Teryaev, PRL **81** (1998) 1782.
M. Diehl, T. Gousset and B. Pire, PRD **62** (2000) 07301.
M. V. Polyakov, NPB **555** (1999) 231.

Helicity amplitudes (up to twist 4):

$$A^{(0)} = \chi \left\{ \left(1 - \frac{s}{2Q^2}\right) \int_0^1 dz\, \frac{\Phi(z,\eta,s)}{1-z} - \frac{s}{Q^2} \int_0^1 dz\, \frac{\Phi(z,\eta,s)}{z} \ln(1-z) \right.$$
$$\left. - \left(\frac{2s}{Q^2}\eta + \frac{\Delta_T^2}{\beta_0^2 Q^2}\frac{\partial}{\partial\eta}\right) \frac{\partial}{\partial\eta} \int_0^1 dz\, \frac{\Phi(z,\eta,s)}{z} \left[\frac{\ln(1-z)}{2} + \mathrm{Li}_2(1-z) - \mathrm{Li}_2(1)\right] \right\},$$

$$A^{(1)} = \frac{2\chi}{\beta_0 Q}\frac{\partial}{\partial\eta} \int_0^1 dz\, \Phi(z,\eta,s)\, \frac{\ln(1-z)}{z},$$

$$A^{(2)} = -\frac{2\chi}{\beta_0^2 Q^2}\frac{\partial^2}{\partial\eta^2} \int_0^1 dz\, \Phi(z,\eta,s)\, \frac{2z-1}{z} \ln(1-z),$$

$\eta = \cos\theta$

C. Lorce, B. Pire and Qin-Tao Song, PRD 106 (2022) , 094030

$A_{++} = A^{(0)}$

$A_{0+} = -A^{(1)} \Delta \cdot \epsilon(-)$ ⟶ $\propto \Delta_T$

$A_{-+} = -A^{(2)} [\Delta \cdot \epsilon(-)]^2$ ⟶ $\propto (\Delta_T)^2$

Δ is the relative momentum of final meson pair.

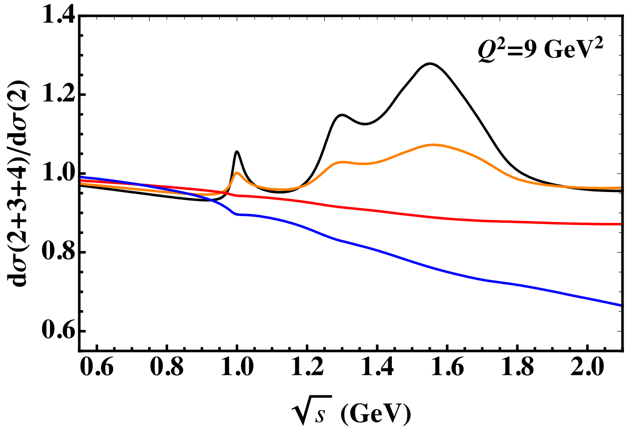
Asymptotic form of pion GDAs:

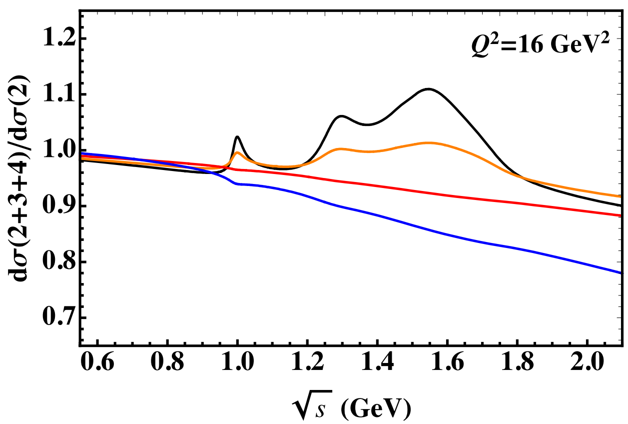
$$\Phi(z, \cos\theta, s) = 18z(1-z)(2z-1)[\widetilde{B}_{10}(s) + \widetilde{B}_{12}(s)\, P_2(\cos\theta)]$$

The nonvanishing helicity-flip amplitudes A_{0+} and A_{+-} indicate the existence of the D-wave GDAs.

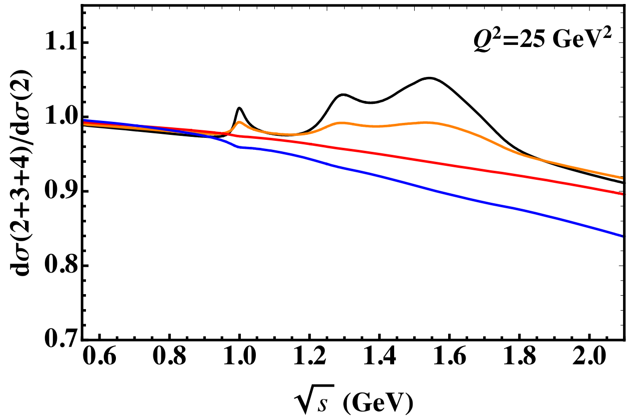
Ratios are estimated with the asymptotic π π GDA

Ratio=(twist 2+twist 3+twist 4)/ twist 2





Kinematics are chosen according to Belle(II)



Both types of π π GDAs indicate that the higher-twist kinematical contributions cannot be neglected if s > 1 GeV²

GDAs ⟶ Timelike EMT form factors

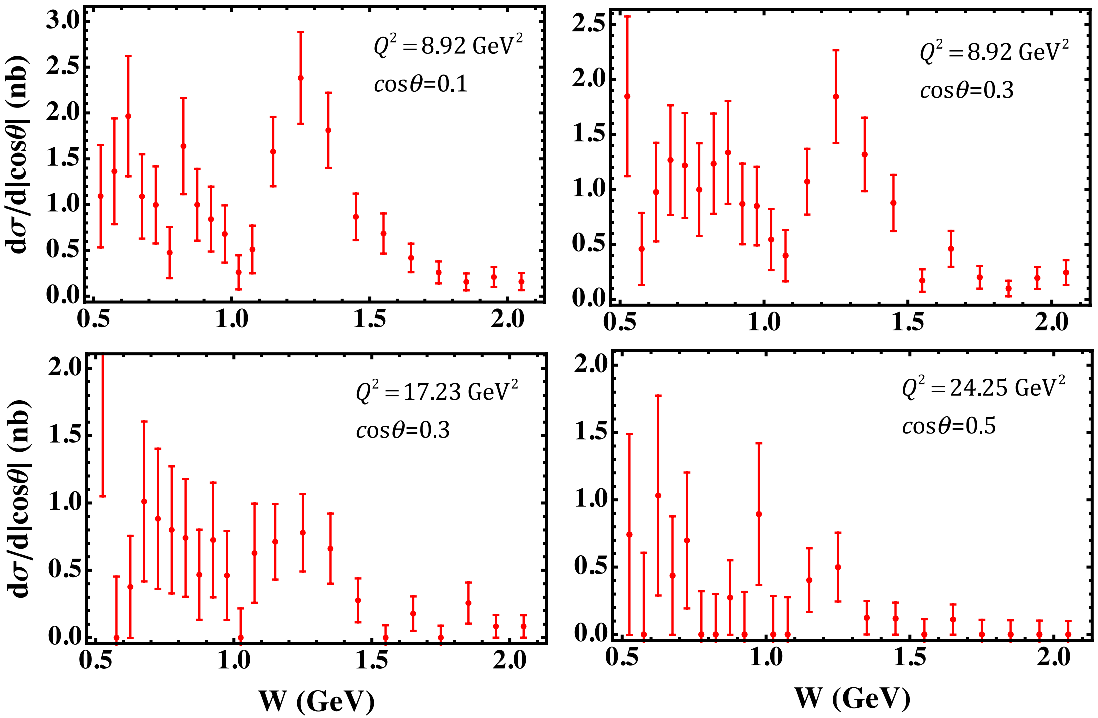
$\Lambda \geq 3\ \mathrm{GeV}^2$ is necessary for pion EMT form factor, PRD 97 (2018) 014020.

Dispersion relation: Spacelike form factor t<0

$$F(t) = \int_{4m^2}^{\Lambda} \frac{ds}{\pi} \frac{\mathrm{Im}[F(s)]}{s - t - i\varepsilon}$$

Timelike form factor s>0

Future measurements of $\gamma^* + \gamma \to \mathrm{M} + \bar{\mathrm{M}}$ at Belle II



Belle measurements on

$\gamma^*\gamma \to \pi^0\pi^0$ in 2016

$8\ \mathrm{GeV}^2 < Q^2 < 24\ \mathrm{GeV}^2$

$0.2\ \mathrm{GeV}^2 < s < 4\ \mathrm{GeV}^2$

$\sim s/Q^2$, $\sim m^2/Q^2$

kinematical corrections

The errors are large, and statistical errors are dominant, however, this situation can be improved by Belle II.

Luminosity: $2\times 10^{34}\ \mathrm{cm}^{-2}s^{-1} \to 8\times 10^{35}\ \mathrm{cm}^{-2}s^{-1}$

Previous measurements at Belle focused on EM FFs, however, the extraction of EMT FFs will be the main physical target for measurements of two-photon reactions at Belle II.

See talk of Dr. Masuda at Joint Meeting the APS and JPS 2023.

Kinematical higher-twist corrections in $e^+e^- \to \gamma^* \to M + \bar{M} + \gamma$: neutral meson pair

Helicity amplitudes (up to twist 4):

The leading-twist amplitude: Z. Lu and I. Schmidt, PRD 73 (2006), 094021

Higher-twist helicity amplitudes (up to twist 4): B. Pire and Q. T. Song, PRD 107 (2023), 114014

$$A^{(0)} = \chi\left\{\left(1+\frac{\hat{s}}{2s}\right)\int_0^1 dz\,\frac{\Phi(z,\eta,\hat{s})}{1-z} + \frac{\hat{s}}{s}\int_0^1 dz\,\frac{\Phi(z,\eta,\hat{s})}{z}\ln(1-z)\right.$$
$$\left. + \left(\frac{2\hat{s}}{s}\eta + \frac{\Delta_T^2}{\beta_0^2 s}\frac{\partial}{\partial\eta}\right)\frac{\partial}{\partial\eta}\int_0^1 dz\,\frac{\Phi(z,\eta,\hat{s})}{z}\left[\frac{\ln(1-z)}{2} + \mathrm{Li}_2(1-z) - \mathrm{Li}_2(1)\right]\right\},$$

$$A^{(1)} = -\frac{2\chi}{\beta_0\sqrt{s}}\frac{\partial}{\partial\eta}\int_0^1 dz\,\Phi(z,\eta,\hat{s})\,\frac{\ln(1-z)}{z},$$

$\eta = \cos\theta$

$$A^{(2)} = \frac{2\chi}{\beta_0^2 s}\frac{\partial^2}{\partial\eta^2}\int_0^1 dz\,\Phi(z,\eta,\hat{s})\,\frac{2z-1}{z}\ln(1-z),$$

$A_{++} = A^{(0)}$

$A_{0+} = -A^{(1)}\Delta\cdot\varepsilon(-)$ ⟶ $\propto \Delta_T$

$A_{-+} = -A^{(2)}[\Delta\cdot\epsilon(-)]^2$ ⟶ $\propto (\Delta_T)^2$

Δ is the relative momentum of final meson pair.

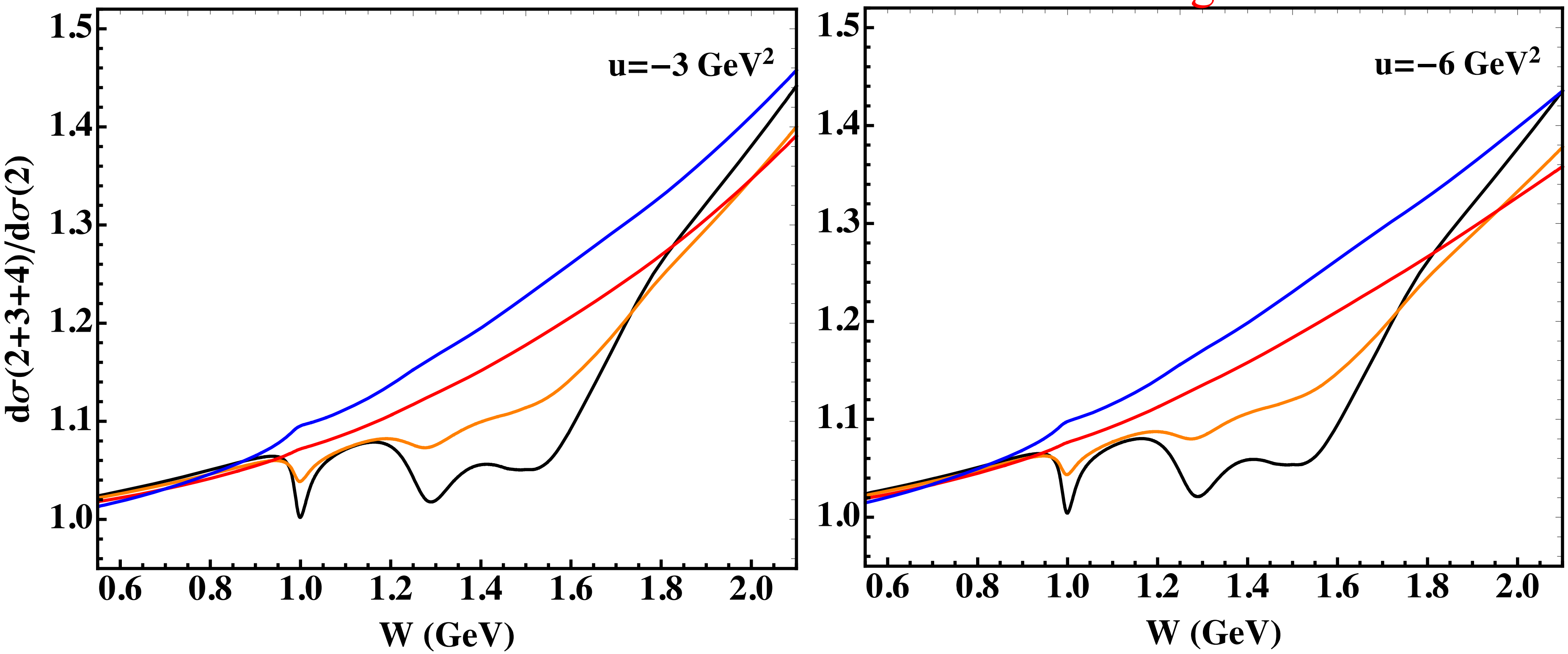
Asymptotic form of pion GDAs:

$$\Phi(z,\ \cos\theta, s) = 18z(1-z)(2z-1)[\widetilde{B}_{10}(s) + \widetilde{B}_{12}(s)\,P_2(\cos\theta)]$$

Ratios are estimated with the asymptotic π π GDA

Ratio=(twist 2+twist 3+twist 4)/ twist 2

Kinematics are chosen according to BESIII



Both types of π π GDAs indicate that the higher-twist kinematical contributions cannot be neglected if W > 1 GeV.

GDAs ⟶ Timelike EMT form factors ↘ Dispersion relation: the region of W > 1 GeV is necessary. ↗ Spacelike EMT form factors

Kinematical higher-twist corrections in $\mathrm{e^+e^-} \to \gamma^* \to M_1 + M_2 + \gamma$ and $e + \gamma \to e + M_1 + M_2$

Exotic hybrid mesons

One can search for the candidates of the hybrid mesons from the P-wave of $M_1 M_2$ in $\gamma^* \to M_1 + M_2 + \gamma$ and $\gamma^* + \gamma \to M_1 + M_2$.

$M_1 M_2$: $\pi\eta$, $\pi\eta'$

Isovector hybrid mesons

$I^G(J^{PC}) = 1^-(1^{-+})$

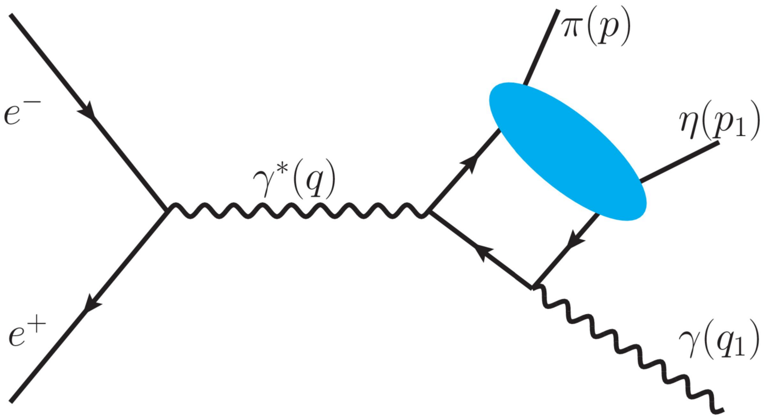
$\pi_1(1400)$, $\pi_1(1600)$

$M_1 M_2$: $\eta\eta'$

Isoscalar hybrid mesons

$I^G(J^{PC}) = 0^+(1^{-+})$

$\eta_1(1855)$



$\gamma^* \to \pi + \eta + \gamma$ at BESIII

The exotic quantum number($J^{PC} = 1^{-+}$) does not exit in quark model.

$\eta_1(1855)$ was observed by BESIII in $J/\psi \to \eta + \eta' + \gamma$ recently.

M. Ablikim et al. [BESIII], PRL 129 (2022), 192002.
M. Ablikim et al. [BESIII], PRD 106 (2022), 072012.

$J/\psi \to \gamma^*$: $\gamma^* \to \eta + \eta' + \gamma$ can be also measured by BESIII.

B. Pire and Q. T. Song, PRD 107 (2023), 114014.

Shear viscosity term (a new gravitational FF)

If the hybrid mesons are observed in $\gamma^* \to M_1 + M_2 + \gamma$ and $\gamma^* + \gamma \to M_1 + M_2$, it will indicate the existence of a new EMT FF.

$$\langle M_2(p_2) M_1(p_1) | T_q^{\mu\nu} | 0 \rangle \sim E_q(s) P^\mu \Delta^\nu$$

O. Teryaev, JPS Conf. Proc. 37(2022), 020406.

The shear viscosity term could exist in matrix element of EMT.

Its sum over quarks and gluons should be zero which is a consequence of the conserved EMT, however, it will exist for a single flavor q on condition that there is P-wave GDA.

The study of shear viscosity term and hybrid mesons by GDAs at BESIII and Belle II.

$\gamma^* \to M_1 M_2 \gamma$
$\gamma^* \gamma \to M_1 M_2$

P wave $M_1 M_2$ →

Shear viscosity term exists

Resonances in P wave →

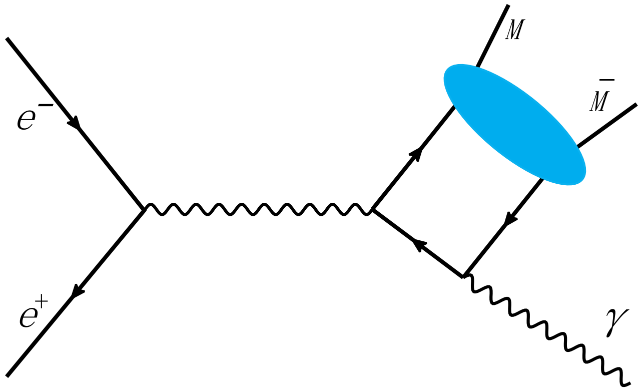
Exotic (hybrid) mesons observed

Extracted from cross sections ↑

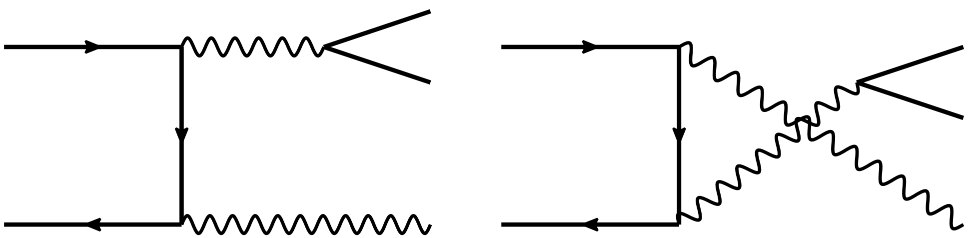
GDAs and EMT FFs

Kinematical higher-twist corrections in $e^+e^- \to M + \bar{M} + \gamma$: charged meson pair

Charged meson pair: $\pi^+\pi^-$ and K^+K^-



GDA process
C even meson pair



ISR process: meson EM FFs
C odd pair

Three types of contribution in the cross section:

Interference term

$$d\sigma_{\mathrm{G}} : d\sigma_{\mathrm{I}} : d\sigma_{\mathrm{ISR}} \sim \hat{s} : \sqrt{\hat{s}s} : s$$

GDA process, same as neutral meson pair

ISR process, largest, no GDAs

Advantages of interference term in charged meson production

- Larger cross section

- Extraction of the complete information of GDAs

$$d\sigma_{\mathrm{I}} \propto \mathrm{Re}(A_{ij} F_M^*(\hat{s}))$$

$$d\sigma_{\mathrm{G}} \propto \mathrm{Re}(A_{ij} A_{kl}^*)$$

$\longrightarrow$ Imaginary phases of GDAs cannot be extracted.

$$\frac{d\sigma_{\mathrm{I}}}{d\hat{s}\, du\, d(\cos\theta)\, d\varphi} = \frac{\alpha_{\mathrm{em}}^3 \beta_0}{8\pi s^2} \frac{\sqrt{2}\beta_0}{\sqrt{\hat{s} s \epsilon (1+\epsilon)}} \left[C_0 + C_1 \cos\varphi + C_2 \cos(2\varphi) + C_3 \cos(3\varphi) \right]$$

$$C_0 = -\,\mathrm{sgn}(\rho)\sqrt{\epsilon(1-\epsilon)}\sqrt{2x(x-1)}\mathrm{Re}(A_{++}F_M^*)\cos\theta + \mathrm{sgn}(\rho)\,(x-1)\sqrt{\epsilon(1-\epsilon)}\mathrm{Re}(A_{0+}F_M^*)\sin\theta,$$
$$C_1 = -\,[1-(1-x)(1-\epsilon)]\,\mathrm{Re}(A_{++}F_M^*)\sin\theta + 2\epsilon\sqrt{2x(x-1)}\mathrm{Re}(A_{0+}F_M^*)\cos\theta + (x-1)\mathrm{Re}(A_{-+}F_M^*)\sin\theta,$$
$$C_2 = \mathrm{sgn}(\rho)\sqrt{\epsilon(1-\epsilon)}x\mathrm{Re}(A_{0+}F_M^*)\sin\theta + \mathrm{sgn}(\rho)\sqrt{\epsilon(1-\epsilon)}\sqrt{2x(x-1)}\mathrm{Re}(A_{-+}F_M^*)\cos\theta,$$
$$C_3 = -\,\epsilon x \mathrm{Re}(A_{-+}F_M^*)\sin\theta.$$

B. Pire and Qin-Tao Song, PRD 109 (2024), 074016

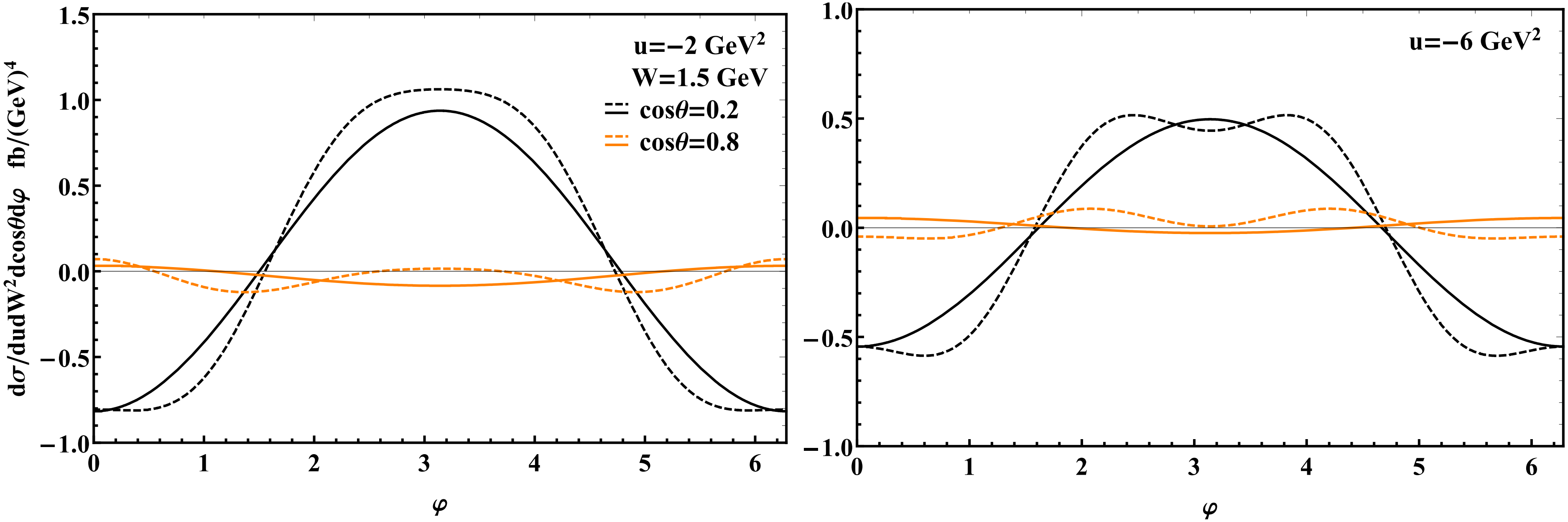
Only the interference term remains if one interchanges meson pair

$$d\sigma(M\bar{M}) - d\sigma(\bar{M}M) = 2d\sigma_{\mathrm{I}}$$

BaBar measurement of pion meson pair : PRD 92 (2015), 072015.

Numerical estimate of interference term

The dashed curves denote the twist-2 cross sections, and the solid ones include the kinematical higher-twist contributions, s=12 GeV² for BESIII.



The higher-twist kinematical contributions cannot be neglected.

B. Pire and Qin-Tao Song, PRD 109 (2024), 074016

Summary

- GDAs can be considered as an alternative way to investigate the EMT form factors of pions.
- Kinematical higher-twist contributions are calculated for $\gamma^* + \gamma \to \mathrm{M} + \bar{\mathrm{M}}$ and $\gamma^* \to \mathrm{M} + \bar{\mathrm{M}} + \gamma$ from which the GDAs can be extracted. The numerical calculation indicates that kinematical contributions are significant for Belle (II) and BESIII (STCF).
- The measurements of $\gamma^* \to \mathrm{M} + \bar{\mathrm{M}} + \gamma$ at BESIII (STCF) can be a new research direction.
- In future, one can search for exotic hybrid mesons and study the new EMT FF (shear viscosity) in $\gamma^* \to M_1 + M_2 + \gamma$ and $\gamma^* + \gamma \to M_1 + M_2$.

Thank you very much