Pion and rho-meson structure from Sum Rules

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In collaboration with

- Mikhailov S., Stefanis N.
  (BESIII data, LCSR for TFF at low momenta)

- Oganesian A., Teryaev O., Stefanis N.
  (LCSR vs. Anomaly SR)

- Stefanis N.
  (Pion and rho-meson twist-2 DA in QCD SR, arXiv:1506.01302)

- Presented studies performed within Heisenberg–Landau project

Outline:

- Experimental background
- Factorization of Pion-Photon Transition Form Factor (TFF)
- Twist-2 pion Distribution Amplitude (DA) from QCD Sum Rules
- Light Cone Sum Rule (LCSR) results
- LCSR at low energy: applicability and uncertainties

- Anomaly SR
- The Q^2-range of LCSR applicability

- Competing effects of DSEs and QCD SRs
- Chimera DAs, shorttailed platykurtic DAs of pion and rho-meson

Experiments to $e^+e^- \to e^+e^-\pi^0$

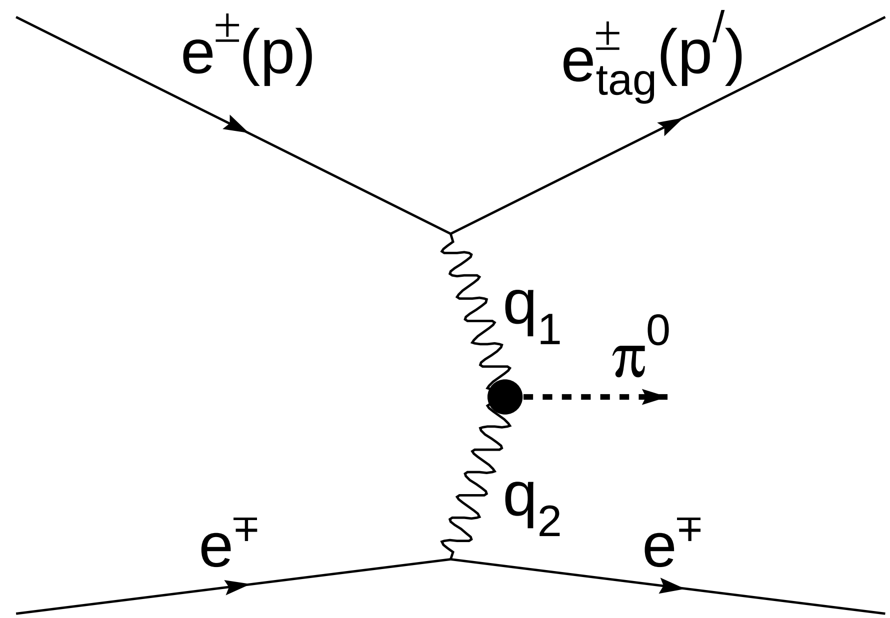
One of the **most accurate** results on exclusive reactions is provided by data on TFF $F^{\gamma^*\gamma^*\pi^0}(-Q^2 = q_1^2, q_2^2 \approx 0)$ provided by the experiments $e^+e^- \to e^+e^-\pi^0$.

CELLO (1991) $Q^2 : 0.7 - 2.2$ GeV^2 ,
CLEO (1998) $Q^2 : 1.6 - 8.0$ GeV^2 ,
agrees with collinear QCD.

BaBar (2009) $Q^2 : 4 - 40$ GeV^2
FF has growing tendency with Q^2,
creating the "BaBar puzzle",

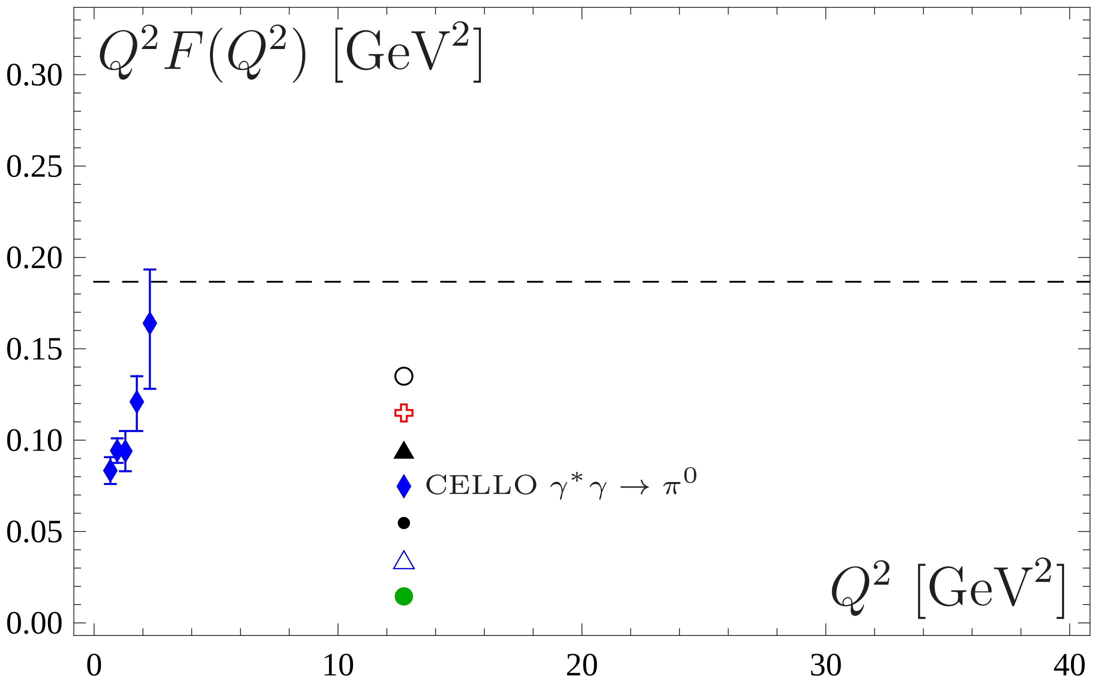
Belle (2012) $Q^2 : 4 - 40$ GeV^2
return to collinear QCD?

BESIII (????) $Q^2 \leq 5$ GeV^2,
promises very precise data



Data on pion-gamma transition FF

Experimental Data on $F_{\gamma\gamma^*\pi}$: **CELLO**, CLEO, **BaBar** and **Belle**



Data	Collab.
◆	**CELLO (1991)**
dashed line = $\sqrt{2}\, f_\pi$	

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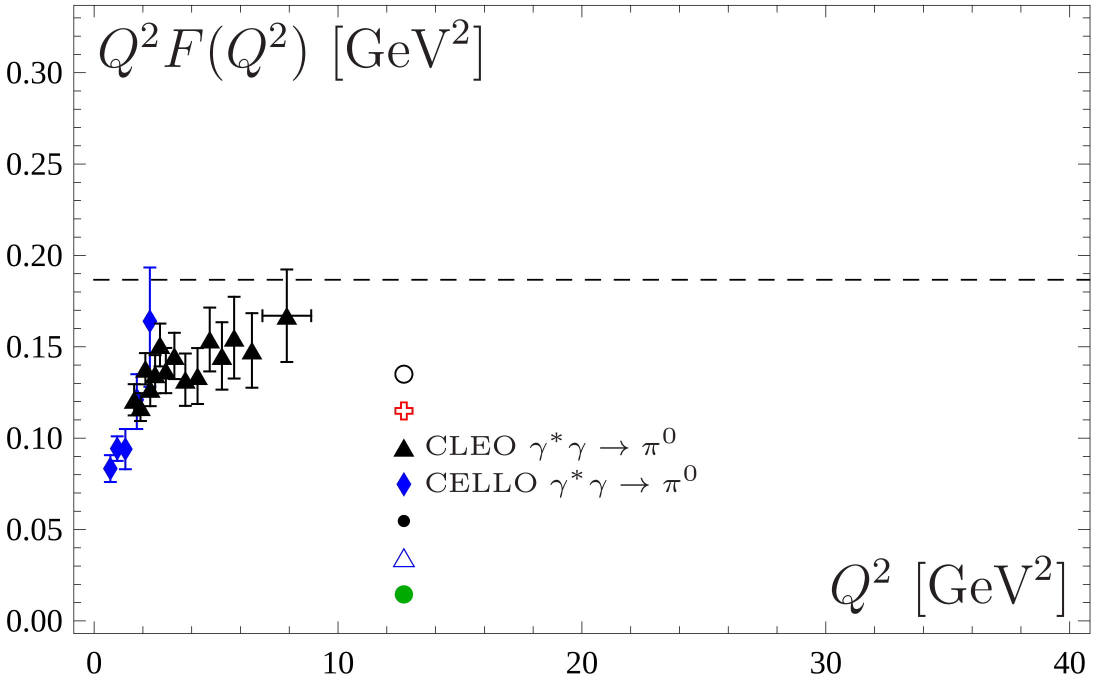

Data	Collab.
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▲	CLEO (1998)

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CELLO and CLEO data agree well with QCD collinear factorization, [BMS2003-06] within NLO QCD⊕twist-4⊕[end-point suppressed DA]

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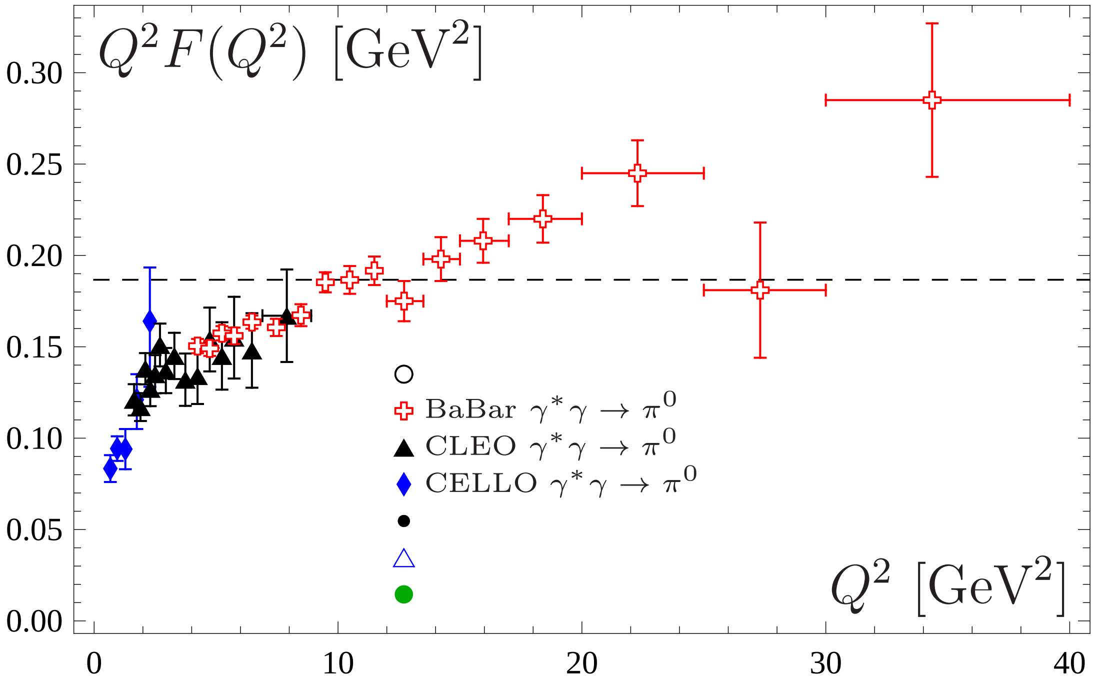

Data	Collab.
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✚	**BaBar (2009)**

dashed line = $\sqrt{2}\, f_\pi$

If the experiment is correct, many theoretical predictions should be revised.

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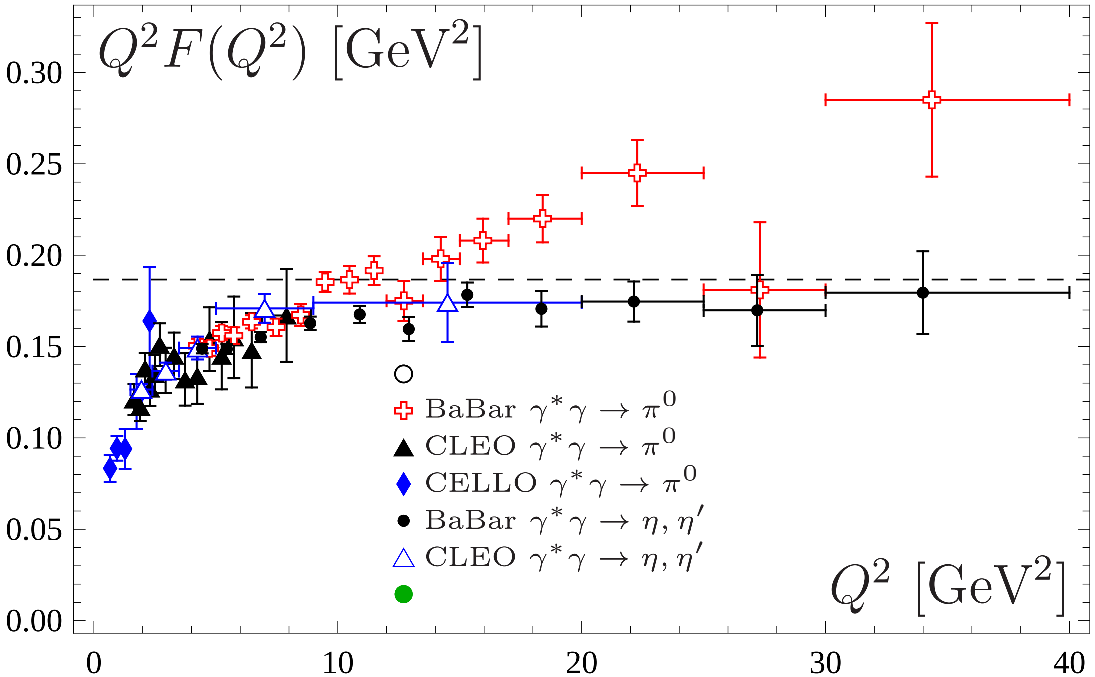

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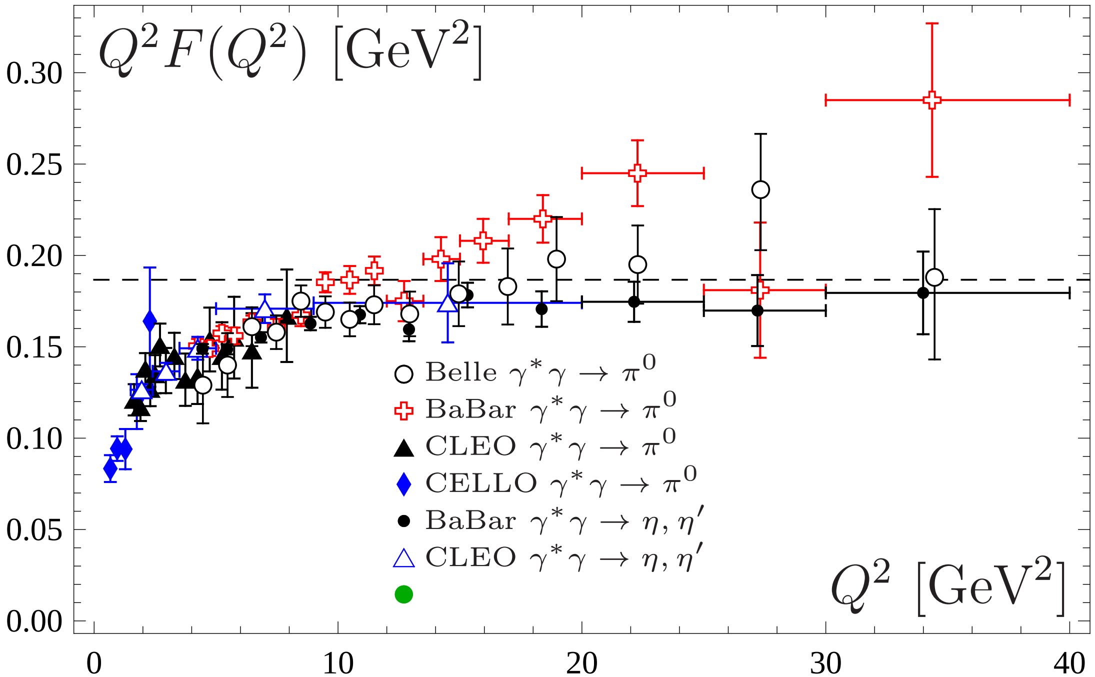
●	**BaBar$^{\eta}_{\eta'}$ (2011)**

dashed line = $\sqrt{2} f_\pi$

BaBar [NPBSuppl.,234,2013]: "It comes out as a surprising result that the Q^2 dependence of the non-strange TFF is in strong disagreement with the π^0 TFF."

Data on pion-gamma transition FF

Experimental Data on $F_{\gamma\gamma^*\pi}$: **CELLO**, CLEO, **BaBar** and **Belle**



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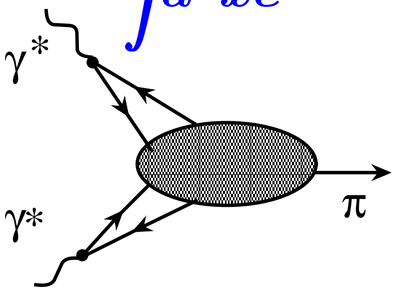
BaBar [NPBSuppl.,234,2013]: "Recent Belle data is in conflict with BaBar."

They do not confirm auxetic form factor behavior above 10 GeV^2.

Factorization of Pion-Photon Transition Form Factor

Factorization $\gamma^*(q_1)\gamma^*(q_2) \to \pi^0(P)$ in pQCD



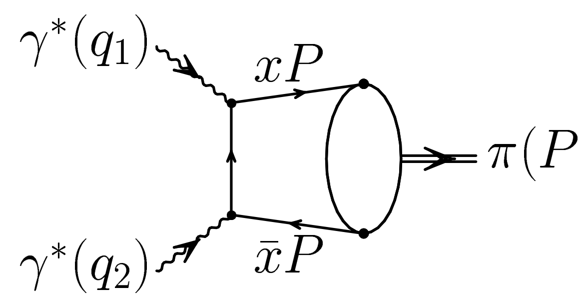
$$\int d^4x e^{-iq_1\cdot z}\langle \pi^0(P)|T\{j_\mu(z)j_\nu(0)\}|0\rangle = i\epsilon_{\mu\nu\alpha\beta}q_1^\alpha q_2^\beta \cdot F^{\gamma^*\gamma^*\pi}(Q^2,q^2)\,,$$

where $-q_1^2 = Q^2 > 0, \quad -q_2^2 = q^2 \geq 0$

Collinear factorization at $Q^2, q^2 \gg$ **(hadron scale $\sim m_\rho$)^2** for the leading twist

$$F^{\gamma^*\gamma^*\pi}(Q^2,q^2) = T(Q^2,q^2,\mu_F^2;x) \otimes \varphi_\pi(x;\mu_F^2) + O(\frac{1}{Q^4})\,,$$

μ_F^2 – boundary between large scale Q^2 and hadronic one. At the parton level



$$F^{\gamma^*\gamma^*\pi}(Q^2,q^2) = \frac{\sqrt{2}}{3}f_\pi \int_0^1 dx \frac{1}{Q^2x + q^2\bar{x}}\varphi_\pi(x).$$

$$Q^2F^{\gamma^*\gamma\pi}(Q^2,q^2\to 0) = \frac{\sqrt{2}}{3}f_\pi \int_0^1 \frac{dx}{x}\varphi_\pi(x) \equiv \frac{\sqrt{2}}{3}f_\pi\langle x^{-1}\rangle_\pi$$

Twist 2 contributions

Collinear factorization **[Efremov&Radyushkin 1978, Brodsky&Lepage 1979]**

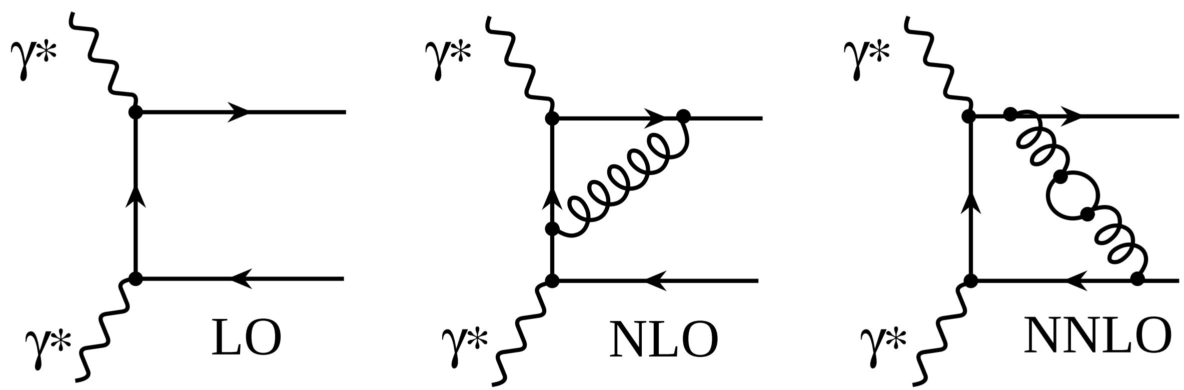
$$F^{\gamma^*\gamma^*\pi}_{\text{tw2}} \sim \Big(T_0(Q^2,q^2;x) + a_s^1\, T_1(Q^2,q^2;\mu_F^2;x) + a_s^2\, T_2(Q^2,q^2;\mu_{\text{F}}^2;\mu_{\text{R}}^2;x) + \ldots\Big) \otimes \varphi_\pi^{(2)}(x;\mu_{\text{F}}^2)$$

T_i — hard amplitudes, calculable in pQCD, $a_s = \alpha_s(\mu_{\text{R}}^2)/(4\pi)$ — coupling constant.
Usual setting $\mu_{\text{R}}^2 = \mu_F^2 = \langle Q^2 \rangle$ to simplify and minimize rad. corrections.

LO hard amplitude: $$T_0(Q^2,q^2;x) = \frac{1}{x\,Q^2 + \bar{x}\,q^2}$$

NLO: **[Bakulev&Mikhailov&Stefanis(2003),Melić&Müller&Passek(2003)]**

$$T_1(x) \otimes \varphi(x) = T_0(Q^2,q^2;y) \otimes \Big\{ C_{\text{F}}\mathcal{T}^{(1)}(y,x) + \mathbf{L}(y)\cdot V^{(0)}(y,x) \Big\} \otimes \varphi(x;\mu_F^2)$$



NNLO hard amplitude

NNLO: $T_2 \otimes \varphi = T_0 \otimes \left(\beta_0 \cdot T_\beta + T_{\Delta V} + T_c\right) \otimes \varphi$, at $\mu_R^2 = \mu_F^2$

- β_0-part of NNLO $\beta_0 \cdot T_\beta$: **[Melić&Müller&Passek(2003)]**
- $T_{\Delta V} = (V_+^{(1)} - \beta_0 V_{\beta+}^{(1)} + \mathcal{T}^{(1)} \otimes V_+^{(0)} + V_+^{(0)} \otimes V_+^{(0)} \frac{L}{2})L$,
  $T_0 \otimes ImT_{\Delta V}$ calculated here
- T_c unknown yet

β_0-term gives the sign and size of NNLO effect following to BLM prescription.
$T_\beta = \mathcal{T}_\beta^{(2)} - L \cdot \mathcal{T}^{(1)} + L(y) \cdot V_{\beta+}^{(1)} - \frac{1}{2} L^2 \cdot V_+^{(0)}$.

$V_+^{(0)}$, $V_+^{(1)}$ – 1- and 2-loop full ERBL-evolution kernels;
$V_{\beta+}^{(1)}$ – β_0-part of 2-loop ERBL kernel;
$\mathcal{T}^{(1)}$, $\mathcal{T}_\beta^{(2)}$ – 1-loop part and 2-loop β_0-part of hard amplitude
$L \equiv \ln\left((Q^2 y + q^2(1-y))/\mu_F^2\right)$

Pion Distribution Amplitude from QCD Sum Rules

Pion distribution amplitude $\varphi_\pi(x,\mu^2)$

- Pion twist-2 DA parameterizes this matrix element

$$\langle 0|\,\bar{d}(z)\gamma_\nu\gamma_5[z,0]u(0)\,|\,\pi(P)\rangle\Big|_{z^2=0} = if_\pi P_\nu \int_0^1 dx\, e^{ix(zP)}\varphi_\pi(x,\mu^2)\,,$$

where path-ordered exponential

$$[z,0] = \mathcal{P}\,exp\left[ig\int_0^z t^a A_\mu^a(y)dy^\mu\right],$$

i.e., light-like gauge link, ensures gauge invariance. It's set to 1 on account of light-cone gauge $A^+ = 0$.

- Pion DA describes transition of physical pion into two valence quarks, separated by a lightlike distance on the light-cone.

Pion distribution amplitude $\varphi_\pi(x,\mu^2)$

- Pion twist-2 DA parameterizes this matrix element

$$\langle 0|\, \bar{d}(z)\gamma_\nu\gamma_5[z,0]u(0)\,|\,\pi(P)\rangle\Big|_{z^2=0} = i f_\pi P_\nu \int_0^1 dx\; e^{ix(zP)}\varphi_\pi(x,\mu^2)\,,$$

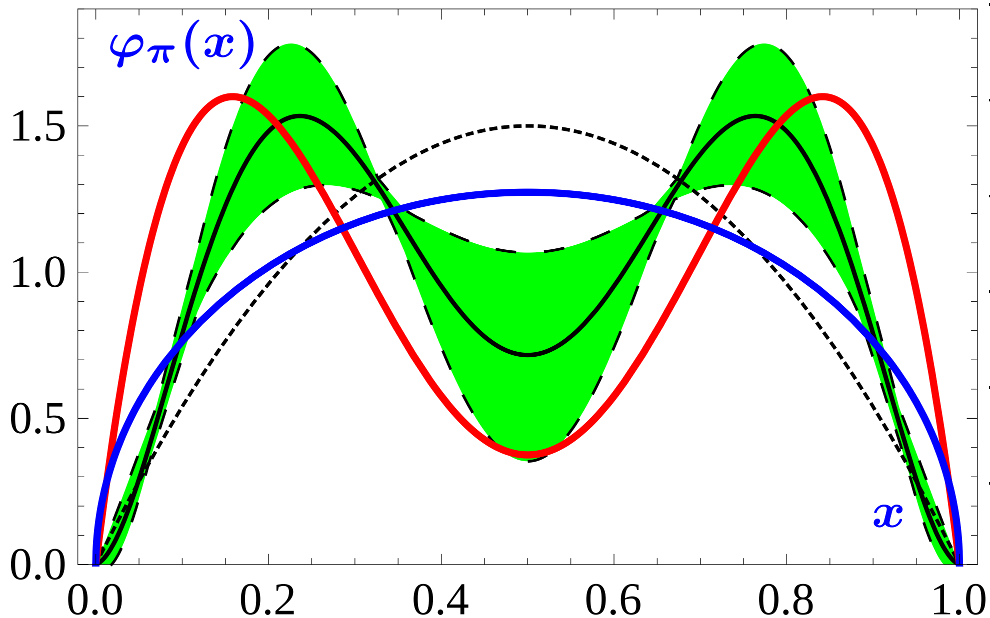
Distribution amplitudes are **nonperturbative** quantities to be derived from

- QCD SR **[CZ 1984]**,
  NLC QCD SR **[Mikhailov&R 1986-91, Bakulev&Mikhailov&Stefanis 1998,2001–04]**
- instanton-vacuum approaches, e.g.
  [Polyakov *et al.* 1998, 2009; Dorokhov *et al.* 2000,07]
- Light-front quark model **[Choi&Ji 2007]**
- Lattice QCD, **[Braun *et al.* 2006,2015; Donnellan *et al.* 2007;Arthur *et al.* 2011]**
- from experimental data
  [Schmedding&Yakovlev 2000, BMS 2003–2006, Khodjamirian *et al.* 2000, 2002]
- DSE approach **[Roberts *et al.*, 2014]**
- AdS/QCD **[Brodsky&de Teramond, 2008]**

Pion distribution amplitude $\varphi_\pi(x,\mu^2)$

- Pion twist-2 DA parameterizes this matrix element

$$\langle 0|\,\bar{d}(z)\gamma_\nu\gamma_5[z,0]u(0)\,|\,\pi(P)\rangle\Big|_{z^2=0} = i f_\pi P_\nu \int_0^1 dx\, e^{ix(zP)}\varphi_\pi(x,\mu^2)\,,$$



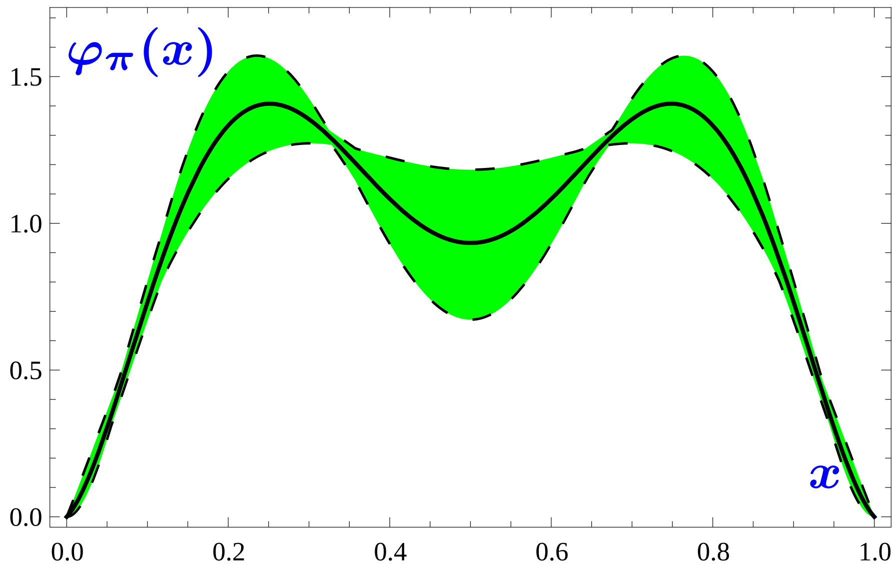
Curve	Approach
- - - - -	Asymptotic
(black line with green band)	BMS DA, NLC QCD SR
(red line)	CZ from QCD SR
(blue line)	AdS/QCD result

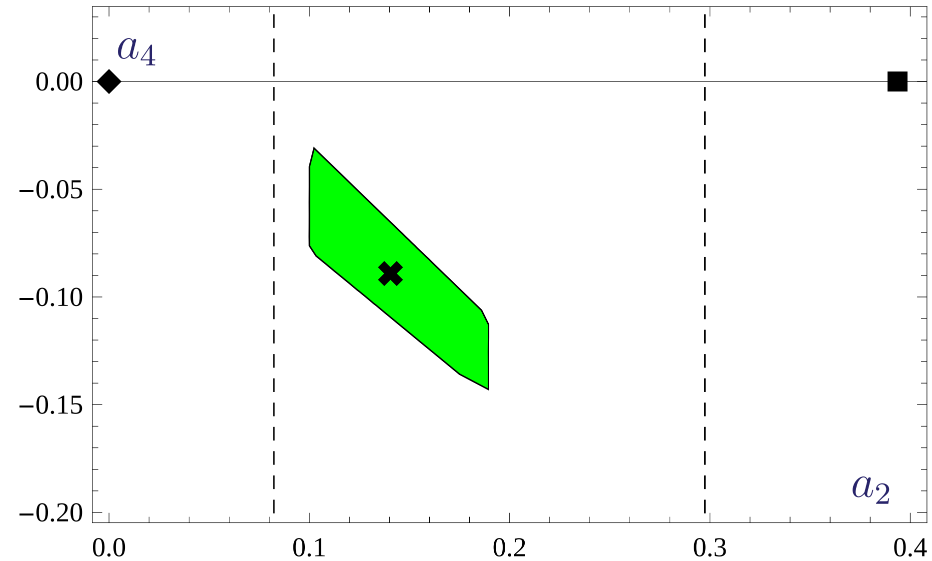
Scale $\mu^2 = 1.35\text{GeV}^2$

- DA evolution with μ^2, according to ERBL equation **[1979-1980]**.
- Gegenbauer expansion of pion DA: $\varphi_\pi(x,\mu^2) \Leftrightarrow a_2, a_4, \ldots, a_n$

$$\varphi_\pi(x,\mu^2) = 6x\bar{x}(1 + a_2(\mu^2)C_2^{(3/2)}(x-\bar{x}) + a_4(\mu^2)C_4^{(3/2)}(x-\bar{x}) + \ldots)$$

Pion DA from QCD SR with NLC





Scale $\mu^2 = 1.35\text{GeV}^2$

BMS DA model and DA "bunch" were obtained using minimal Gaussian condensate model with single nonlocality parameter $\lambda_q^2 = 0.4\,\text{GeV}^2$.

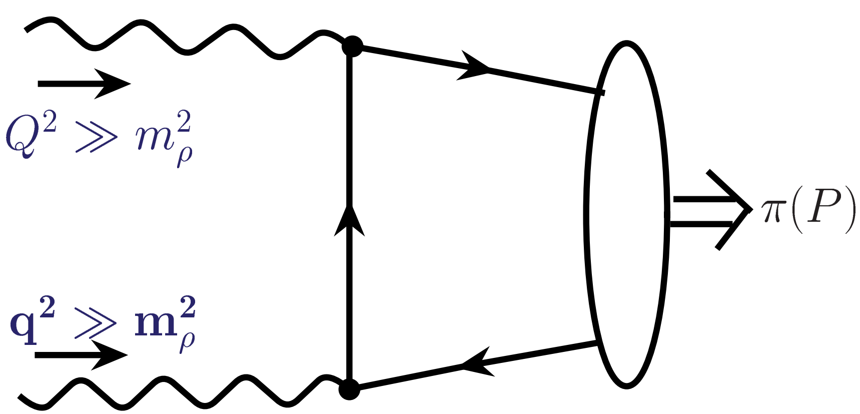
- Higher Gegenbauer coefficients can be put to zero $a_{n\geq 6} = 0$, negligible but with large errors.
- QCD SR with NLC provides end-point suppressed pion DA with slope $\varphi_\pi'(0) \approx 6$ that depends on the scale behavior of quark-condensate.

Light Cone Sum Rule (LCSR)

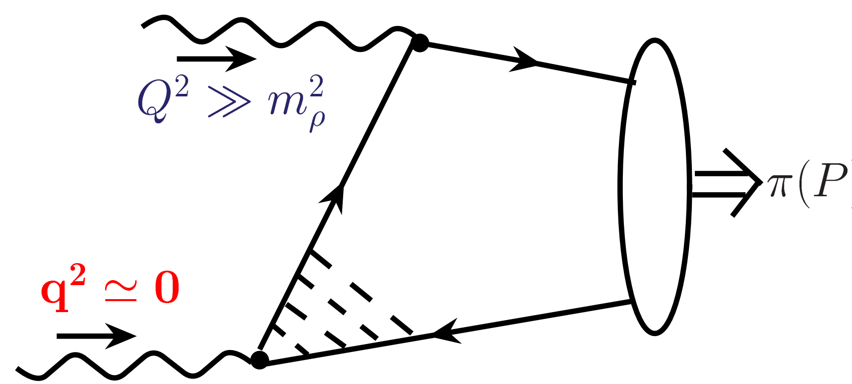
$\gamma^*\gamma \to \pi$: Why Light-Cone Sum Rules?

- For $Q^2 \gg m_\rho^2, \;\; q^2 \ll m_\rho^2$ pQCD factorization valid only in leading twist and higher twists are important **[Radyushkin–Ruskov, NPB (1996)]**.

- Reason: if $q^2 \to 0$, one needs to take into account interaction of real photon at long distances $\sim O(1/\sqrt{q^2})$



pQCD is OK



LCSRs better applicable

$\gamma^*\gamma \to \pi$: Light-Cone Sum Rules

LCSR effectively accounts for long-distance effects of real photon using quark-hadron duality in vector channel and dispersion relation in q^2 (Balitsky et. al.-89, Khodjamirian **[EJPC (1999)]**)

$$F_{\gamma\gamma^*\pi}(Q^2, q^2) \;=\; \int_0^{s_0} \frac{\rho^{\text{PT}}(Q^2,s)}{m_\rho^2 + q^2} e^{(m_\rho^2 - s)/M^2} ds + \int_{s_0}^{\infty} \frac{\rho^{\text{PT}}(Q^2,s)}{s + q^2} ds \,,$$

where $s_0 \simeq 1.5$ **GeV^2** – effective threshold in vector channel,
M^2 – Borel parameter ($0.7 - 1$ GeV^2).
Real-photon limit $q^2 \to 0$ can be easily done.

Spectral density was calculated in QCD:

$$\rho^{\text{PT}}(Q^2, s) = \frac{1}{\pi}\text{Im} F^{\text{PT}}_{\gamma^*\gamma^*\pi}(Q^2, -s - \imath\varepsilon) = \text{Tw-2} + \text{Tw-4} + \text{Tw-6} + \ldots \,,$$

where twist contributions are given in form of convolution with pion DA:

$$\text{Tw-2} \sim \frac{1}{\pi}\text{Im}\left(T_{\text{LO}} + T_{\text{NLO}} + T_{\text{NNLO}_{\beta_0}} + \ldots\right) \otimes \varphi_\pi^{\text{Tw2}}(x, \mu) \,.$$

Snapshot of LCSR

From QCD SR:

- Borel param. $M^2_{\text{LCSR}} \sim [0.7, 1]$ GeV^2
- Vector Channel Threshold s_0
- "Twist-6" $(\alpha_S \langle \bar{q} q \rangle^2)$
- $\lambda_q^2/2 \approx$Twist-4 $\delta^2 \pm 20\%$
  [BMS2003]

From PDG:

- $\alpha_s(m_Z^2)$
- Masses m_ρ, m_ω
- Decay Widths Γ_ρ, Γ_ω

Light-Cone Sum Rules:

$$\text{FF} = (\text{LO} + \text{NLO}) \otimes (\pi\text{-DA}_{\text{NLO}}) + \text{Tw-4} \pm \Delta\text{FF}$$

$$\Delta\text{FF} = \pi\text{-}\Delta\text{DA} + \Delta\text{Tw-4} + \left[\text{NNLO}_{\beta_0} \otimes (\pi\text{-DA}) + \text{Tw-6}\right]$$

π-DA model

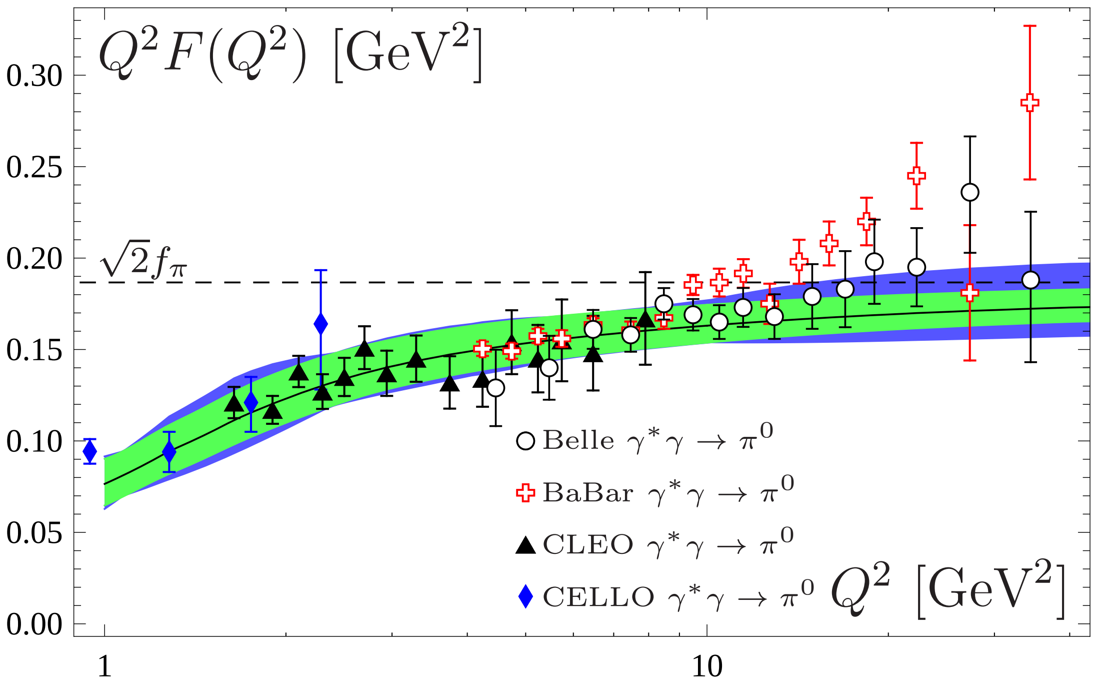
Data on FF

FF Prediction

Fitting π-DA (a_n)

Pion-gamma transition FF data

Experimental Data on $F_{\gamma\gamma^*\pi}$: **CELLO**, CLEO, **BaBar** and **Belle**



Data	Collab.
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✚	**BaBar (2009)**
○	**Belle (2012)**
green band with black line	our result **BMPS**

PRD86(2012)031501

Belle data do not confirm auxetic form factor behavior above 10 GeV^2

(except outlier at $Q^2 = 27.33$ GeV^2).

Predicted FF agrees well with CELLO, CLEO, BaBar$_{Q^2<9\ \text{GeV}^2}$ (2009), BaBar$^{\eta}_{\eta'}$ (2011), and most Belle (2012).

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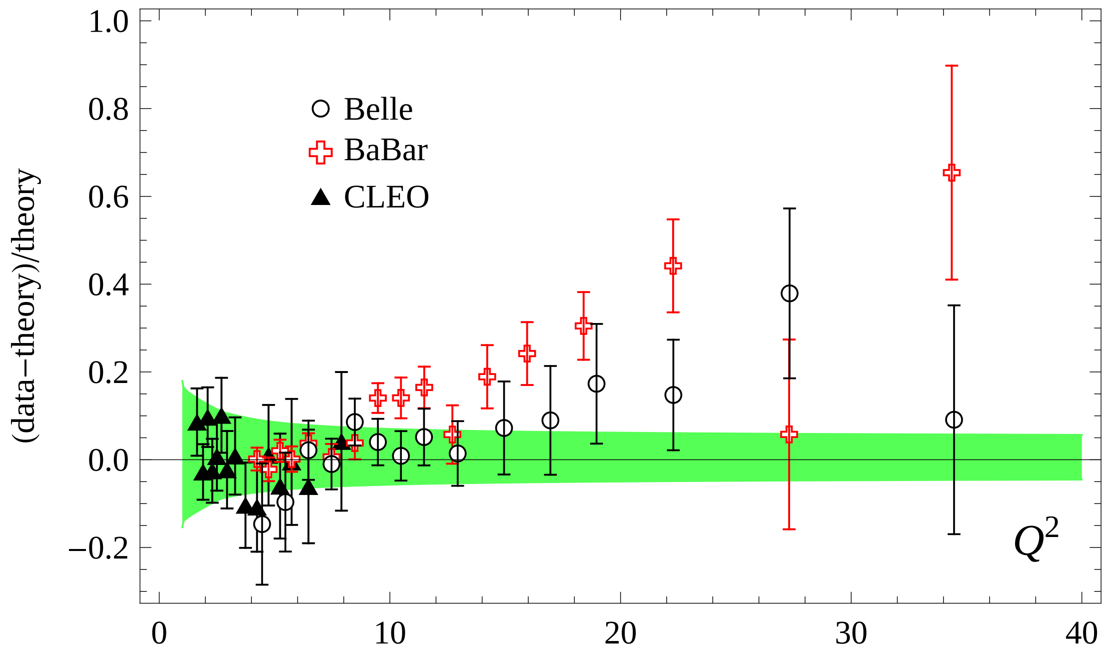

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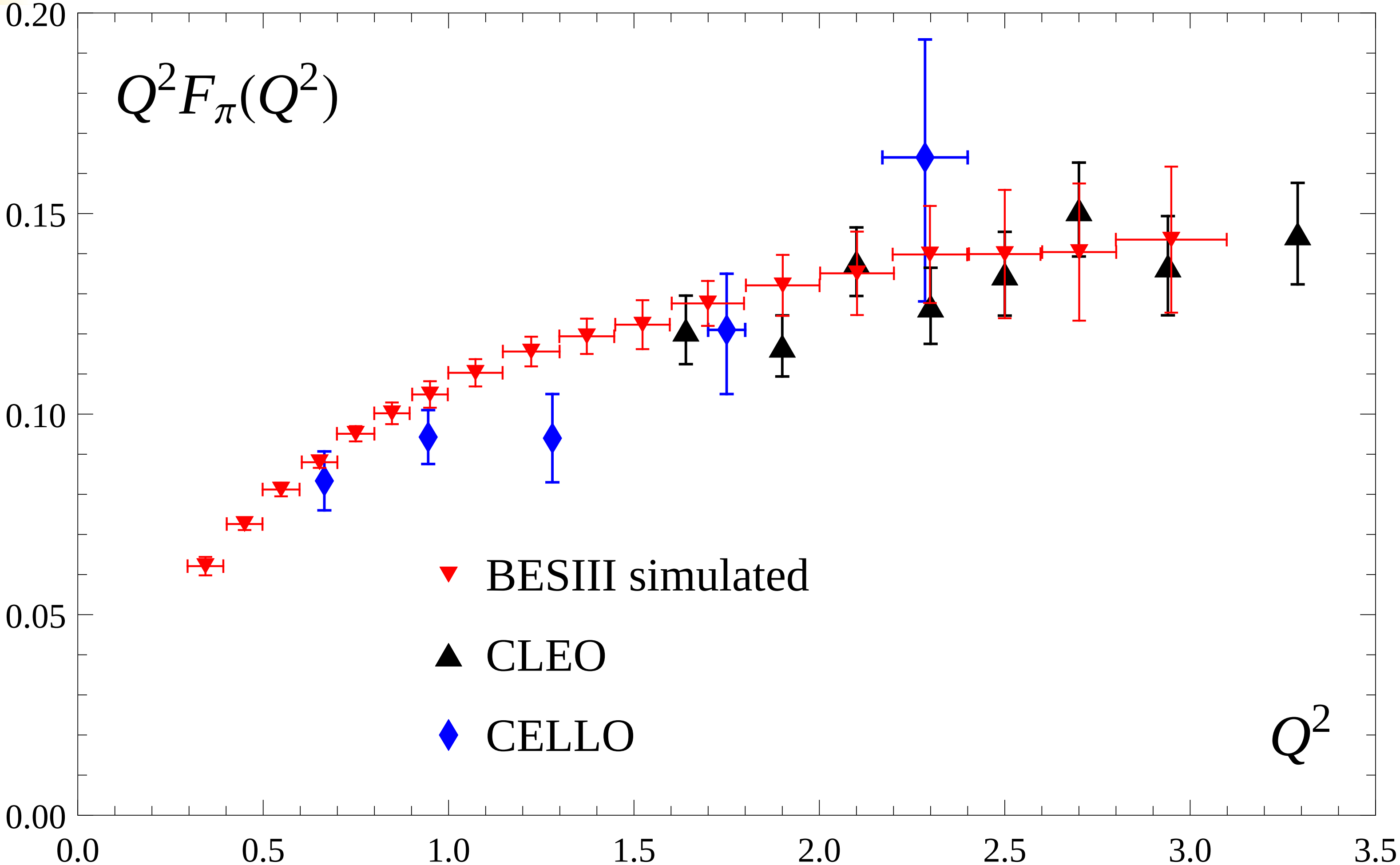
Expected BESIII data [Denig, NPPProc, 260 (2015)]



- Data at very low momenta.
- High accuracy expected.

LCSR upgrade

Light-Cone Sum Rules:

$$\text{FF} = (\text{LO} + \text{NLO}) \otimes (\pi\text{-DA}_{\text{NLO}}) + \text{Tw-4} \pm \Delta\text{FF}$$

$$\Delta\text{FF} = \pi\text{-}\Delta\text{DA} + \Delta\text{Tw-4} + \left[\text{NNLO}_{\beta_0} \otimes (\pi\text{-DA}) + \text{Tw-6}\right]$$

↓

Light-Cone Sum Rules, updated:

$$\text{FF} = \text{Tw-2} + \text{Tw-4} + \text{Tw-6} \pm \Delta\text{FF}$$

$$\text{Tw-2} = (\text{LO} + \text{NLO} + \text{NNLO}_{\beta_0} + \text{NNLO}_{\Delta V}) \otimes (\pi\text{-DA}_{\text{NLO}})$$

$$\Delta\text{FF} = \pi\text{-}\Delta\text{DA} + (\text{NNLO-}\mathcal{T}^{(2)}_{\beta_0}) \otimes (\pi\text{-DA}_{\text{NLO}}) + \Delta\text{Tw-4} + \Delta\text{Tw-6}$$

- Additional NNLO term, calculated here, gives negligible contribution to FF: $\text{NNLO}_{\Delta V} \ll \text{NNLO}_{\beta_0}$.

Uncertainties of LCSR

Theoretical:

Tw-2: DA parameters a_n

Tw-2: $T_{2\beta}$ – NNLO$_{\beta_0}$

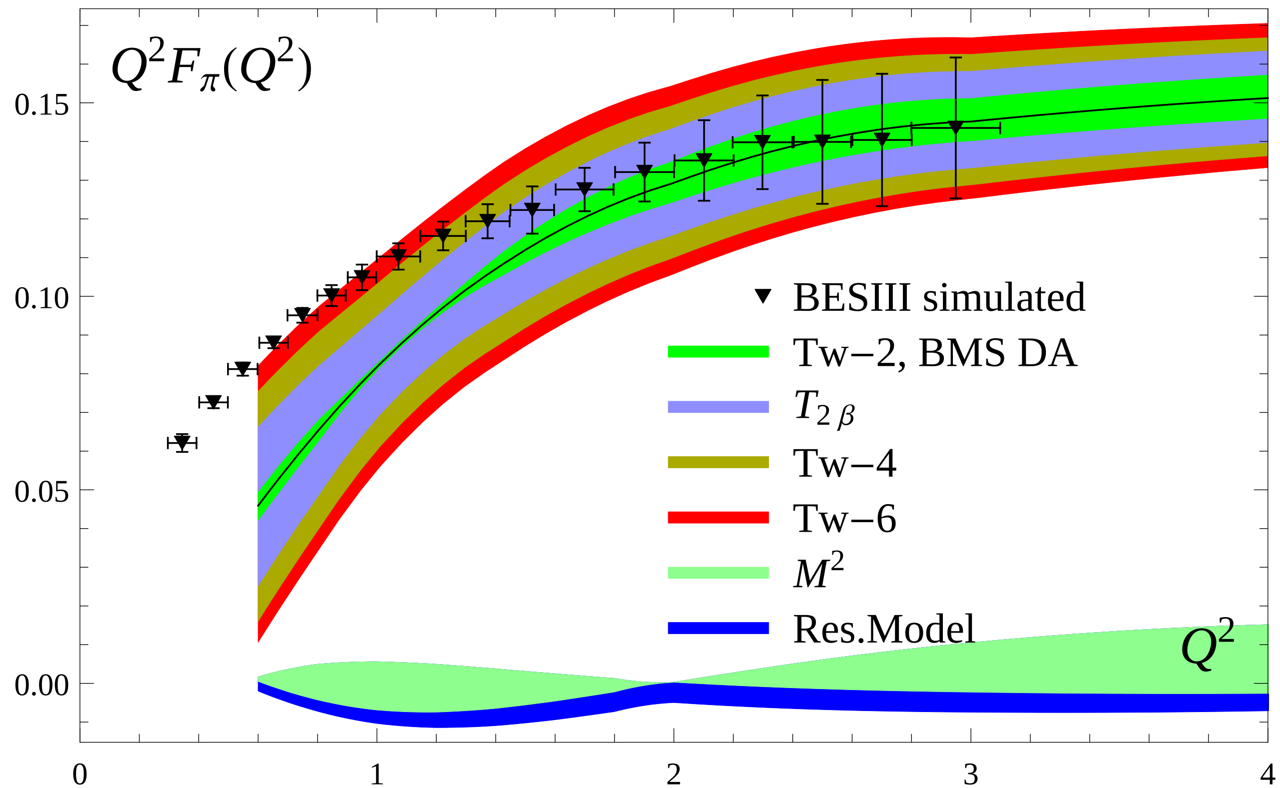
Tw-4: $\delta_{\text{tw4}} \sim \langle \bar{q} D^2 q \rangle$

Tw-6: $\langle \bar{q} q \rangle$

Methodological:

Borel parameter M^2

rho-meson resonance modelling



- Most of uncertainties correlated at different momenta
- At low momentum, FF is more sensitive to Tw4,Tw6 variation rather than to DA a_n parameters
- Applicability limit $1 - 2$ GeV^2

Anomaly SR

$$\int d^4x d^4y e^{(ikx+iqy)} \langle 0|T\{J^3_{\alpha 5}(0) J_\mu(x) J_\nu(y)\}|0\rangle = T_3(k,q) k_\nu \varepsilon_{\alpha\mu\rho\sigma} k^\rho q^\sigma + \ldots .$$

Anomaly SR: $\int_0^\infty ImT_3(s,Q^2)ds = \frac{1}{2\pi} N_c C$. [Horejsi&Teryaev,ZPC65-1995]

Charge factor $C = 1/(3\sqrt{2})$, momentum $Q^2 = -q^2$.

Anomaly SR for FF: $\pi f_\pi F_{\pi\gamma}(Q^2) = \frac{1}{2\pi} N_c C - \int_{s_3}^\infty ImT_3(s,Q^2)ds$.

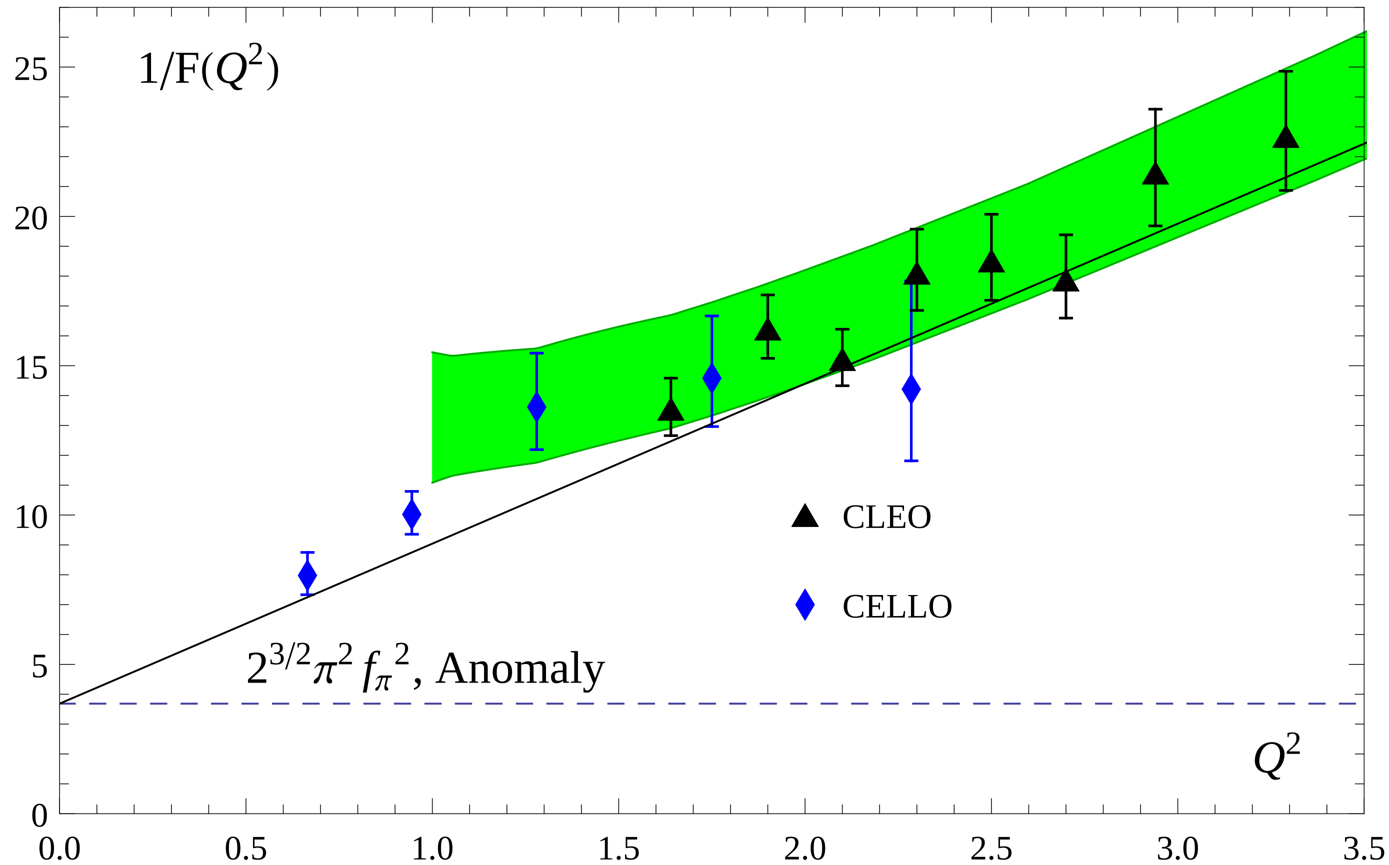
[Klopot&Oganesian&Teryaev, PRD84-2011-051901]

Applying LO result for ImT_3 one can obtain

$$F_{\pi\gamma}(Q^2) = \frac{1}{2\sqrt{2}\pi^2 f_\pi} \frac{s_3(Q^2)}{s_3(Q^2) + Q^2}$$

- Pion duality interval (threshold) $s_3(Q^2)$ is undetermined parameter in ASR. It could be a function of momentum Q^2.
- From asymptotic limit $s_3 = 4\pi^2 f_\pi^2 \simeq 0.67$ GeV^2.

LCSR applicability from Anomaly SR



- Green bunch — LCSR result
- Dashed line — value of inverse FF from anomaly at $Q^2 = 0$.
- Solid line — monopole behavior (anomaly SR) adjusted to anomaly value and asymptotic behavior.

Alternative expansion of DA

Conformal expansion:

$$\varphi_\pi(x) = 6x\bar{x}\left[1 + a_2(\mu^2)C_2^{(3/2)}(x-\bar{x}) + a_4(\mu^2)C_4^{(3/2)}(x-\bar{x}) + \ldots\right]$$

Gegenbauer-α expansion [Roberts et al.]:

$$\varphi_\pi^{(\alpha)}(x,\mu^2) = \frac{(x\bar{x})^{\alpha_-}}{B(\alpha_-+1,\alpha_-+1)}[1 + a_2^\alpha C_2^{(\alpha_-+1/2)}(x-\bar{x}) + \ldots]$$

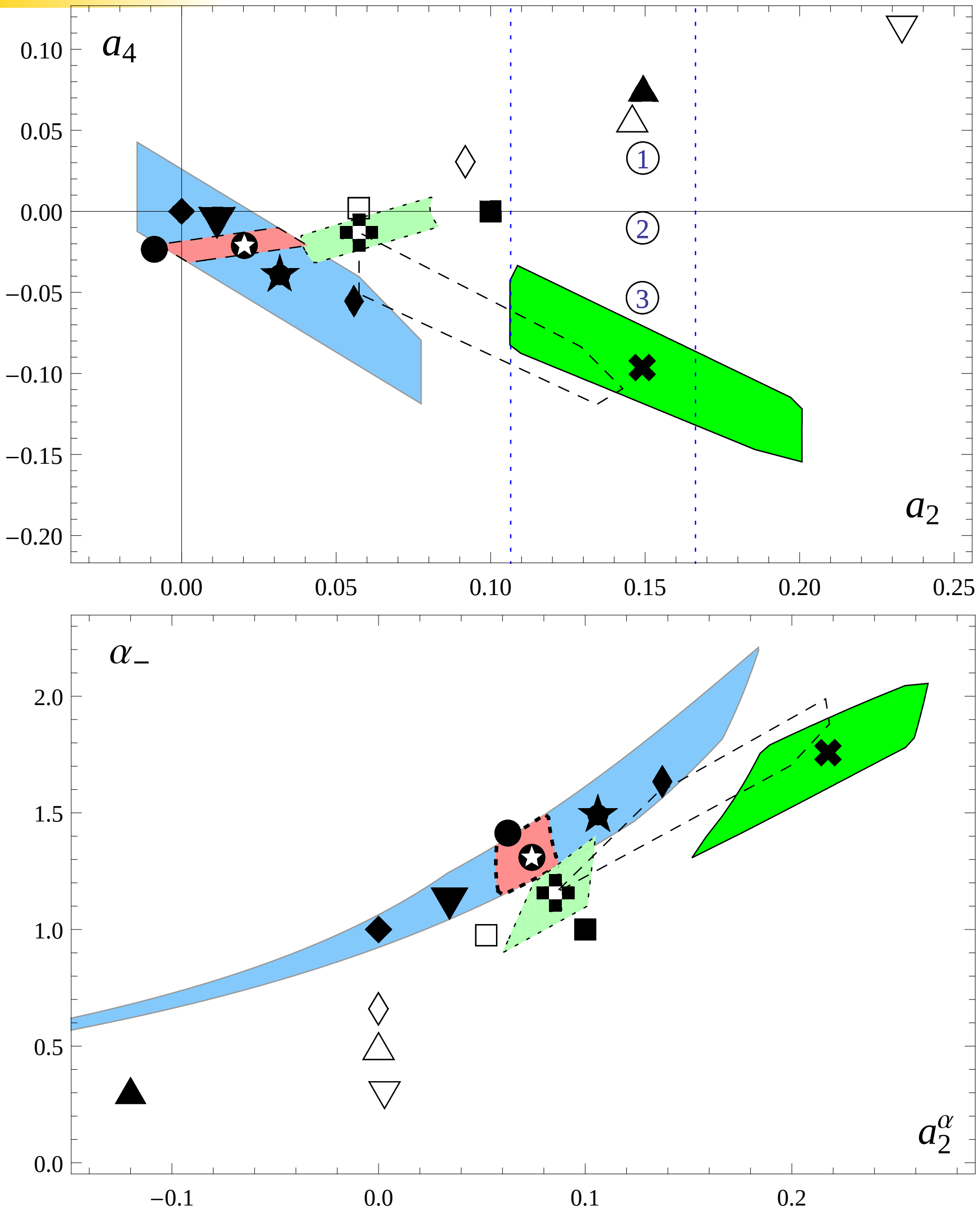
- Does not respect ERBL evolution equation
- Better representation for broad DAs (like DSE, AdS/QCD) because in conformal expansion > 50 terms needed.

We relate these two representations by fixing second and fourth moments:

$$(a_2\,, a_4) \iff (\alpha_-\,, a_2^\alpha)$$

$$\int_0^1 dx\varphi_\pi(x,\mu^2)(1-2x)^n \quad = \quad \int_0^1 dx\varphi_\pi^{(\alpha)}(x,\mu^2)(1-2x)^n\,, \text{ for } n = 2,4\,.$$

Parameter space comparison



◆ — asymptotic DA;

▲/▽ — DSE-DB/RL π DA [Chang13];

✖ — BMS π DA [BMS01];

- - - - — NLC SR, $\lambda_q^2 = 0.45$ GeV^2

✚ — platykurtic π DA [S14];

★ — NLC-QCD SR (PMS13),

✪ — $\rho_{||}$ DA, platykurtic (here);

♦ — $\rho_{||}$ DA, NLC-QCD [BM98];

▼ — $\rho_{||}$ DA, lightfront model [Choi07]

● — $\rho_{||}$ DA, instanton model [Dorokhov06];

■ — $\rho_{||}$ DA from QCD sum rules [Ball07];

◊ — $\rho_{||}$ DSE DA [Gao14];

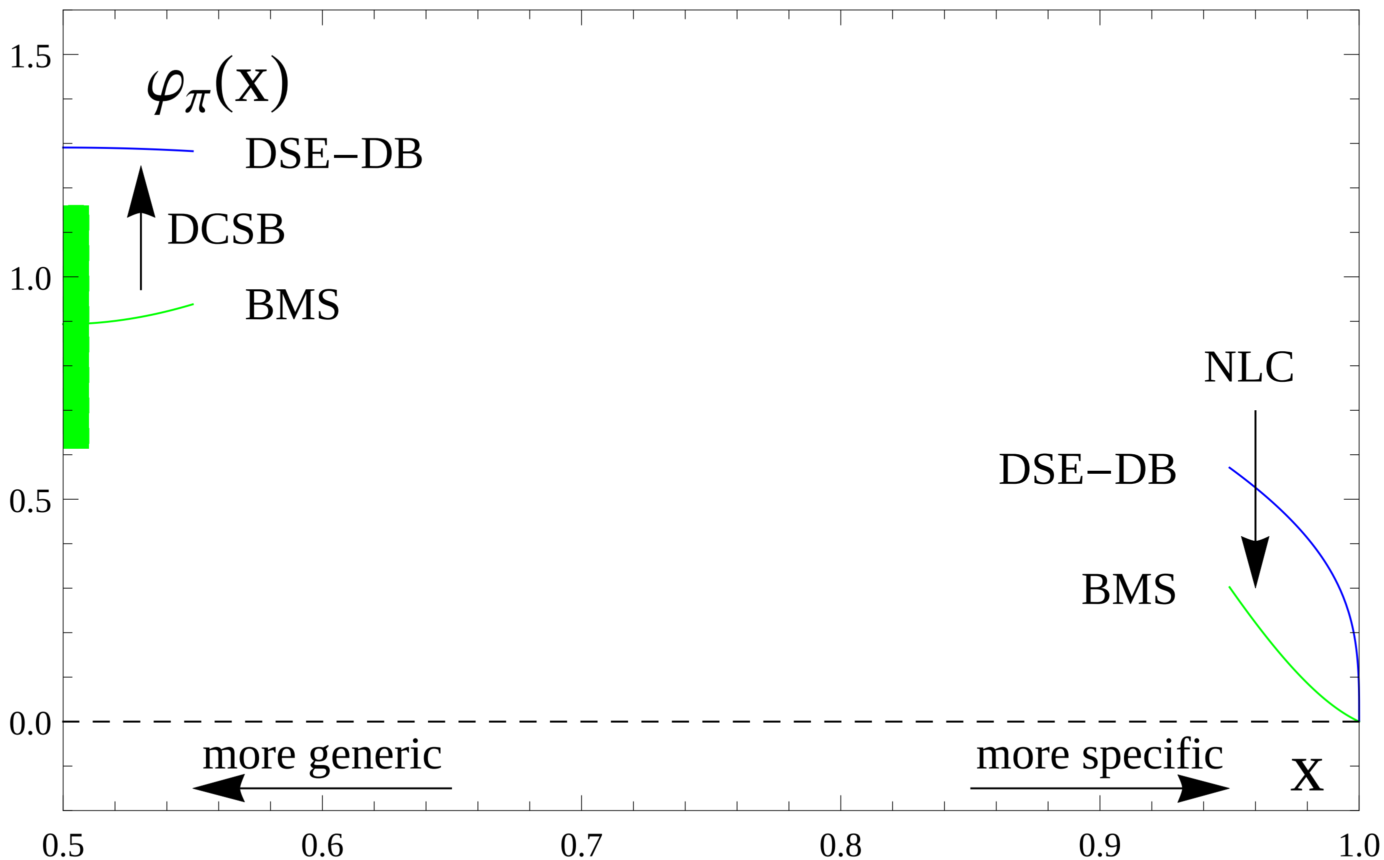
□ — $\rho_{||}$ DA, AdS/QCD [Ahmady12];

△ — π AdS/QCD [Brodsky07];

dotted v. lines — lattice [Braun15]

Scale 2 GeV

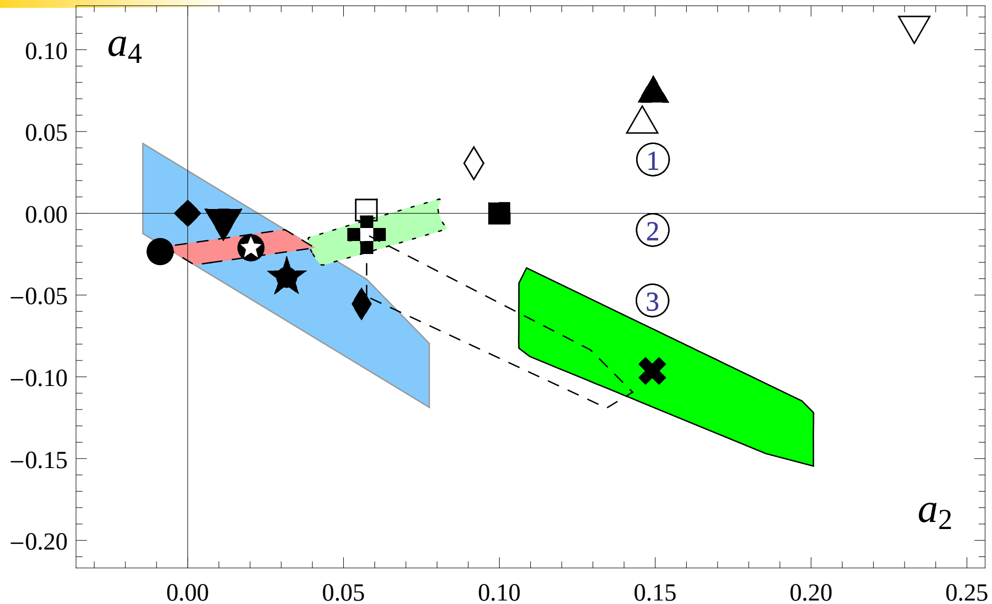
Competing effects of DSE and NLC

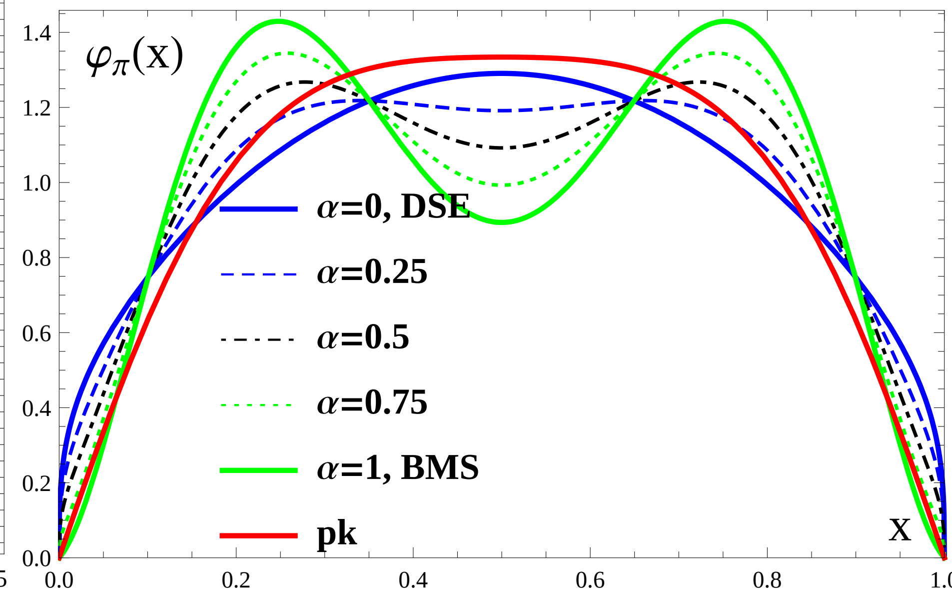


- DCSB $\to$ DSE $\to$ higher value at midpoint, unimodal
- NLC $\to$ NLC SR $\to$ endpoint suppression, bimodal

Synthetic DA, [Stefanis,14]: $\varphi_\pi^{\text{synt}}(x,a) = a\varphi_\pi^{\text{BMS}}(x) + (1-a)\varphi_\pi^{\text{DSE}}(x)$

Chimera DA





Scale 2 GeV

Synthetic DA, [Stefatis,14]: $\varphi_{\pi}^{\text{synt}}(x,a) = a\varphi_{\pi}^{\text{BMS}}(x) + (1-a)\varphi_{\pi}^{\text{DSE}}(x)\,.$

▲ — DSE-DB π DA [Chang13] ;

✖ — BMS π DA [BMS01] ;

✜ — platykurtic π DA [Stefanis14] .

- Unlike synthetic DAs (①, ②, ③), chimera DA (✜) [SP1506.01302] combines property of DSE and NLC SR approaches: endpoint suppression, unimodality.

Conclusions

1. New NNLO contributions to pion TFF were calculated within LCSR and found to be small compared to leading β_0 part of NNLO contribution.

2. Different sources of LCSR uncertainties were studied at low Q^2 to estimate the region of SR applicability.

3. At low momentum ~ 1 GeV^2, TFF is more sensitive to twist-4 and twist-6 variation rather than to leading twist DA a_n parameters.

4. Expected BESIII data could be used to refine the twist-4 and twist-6 parameters

5. Assuming that anomaly SR gives reliable result at $1-2$ GeV^2 the LCSR could be applicable down to momenta $Q^2 \sim 1.5$ GeV^2.

6. Presented shorttailed platykurtic rho-meson and pion DAs are chimera DAs that at the same time include correlations induced by NLC $\lambda_q \sim 0.3$ fm and DCSB as realized in DSEs.