$\pi\gamma$ Transition FF in LCSRs and πDA: Global data fit

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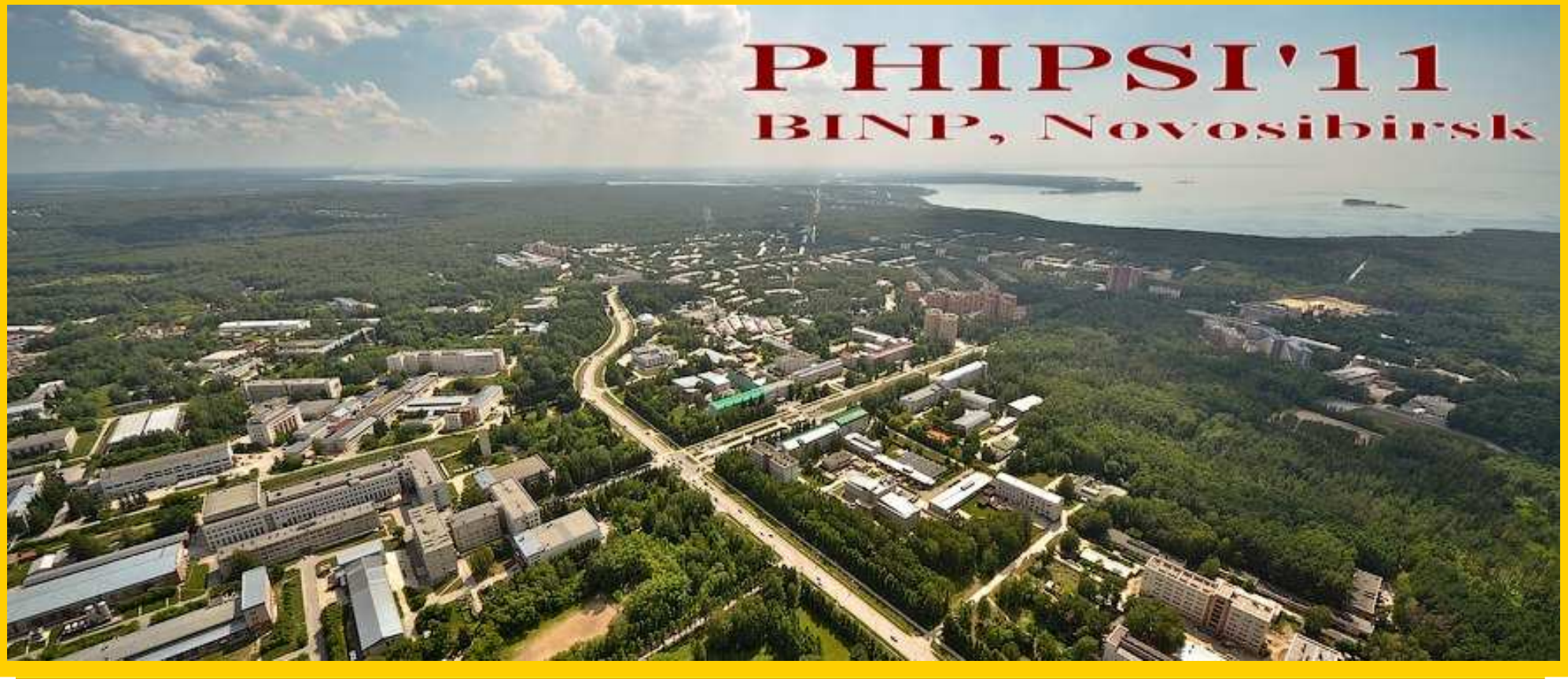


Outline:

- Pion Distribution Amplitude (DA)
- Light-Cone Sum Rules (LCSRs) Approach
- LCSRs Results for $\pi\gamma$ Transition Form Factor (FF)
- Fitting Pion DA — Confidential Regions
- Confidential Region for Pion DA Moments vs. Lattice QCD
- Fit Results and Pion DA Models
- Conclusions

Publications

Authors: A. B., S. Mikhailov, A. Pimikov, and N. Stefanis

Publications:

- A. B., S. M., N. S. PLB 508 (2001) 279
- A. B., S. M., N. S. PRD 67 (2003) 074012
- A. B., S. M., N. S. PLB 578 (2004) 91
- A. B., S. M., N. S. PRD 73 (2006) 056002
- A. B., A. P. APPB 37 (2006) 3627
- A. B., A. P., N. S. PRD 79 (2009) 093010
- S. M., N. S. NPB 821 (2009) 291
- S. M., N. S. MPLA 24 (2009) 2858
- A. B., S. M., N. S. APPB PS3 (2010) 943
- A. B., S. M., A. P., N. S. PRD 84 (2011) 034014
- A. B., S. M., A. P., N. S. arXiv:1108.4344 [hep-ph]
- N. S. arXiv:1109.2718 [hep-ph]

Pion Distribution Amplitude (DA)

Pion distribution amplitude (DA)

- **Matrix element of nonlocal axial current on light cone**

$$\langle 0 \mid \bar{d}(z)\gamma_\mu\gamma_5 E(z,0)u(0) \mid \pi(P)\rangle\Big|_{z^2=0} =$$

$$if_\pi P_\mu \int_0^1 dx\, e^{ix(zP)}\, \varphi_\pi^{\text{Tw-2}}(x,\mu^2)$$

- **gauge-invariance due to Fock–Schwinger string:**

$$E(z,0) = \mathcal{P} e^{ig\int_0^z A_\mu(\tau)d\tau^\mu}$$

- **Physical meaning of $\varphi_\pi(x;\mu^2)$ — amplitude for transition $\pi \to u + d$**

Representation of Pion DA

- **It is convenient to represent the pion DA:**

  $$\varphi_\pi(x;\mu^2) = \varphi^{\mathrm{As}}(x)\times$$
  $$\times\left[1 + a_2(\mu^2)C_2^{3/2}(2x-1) + a_4(\mu^2)C_4^{3/2}(2x-1) + \ldots\right]$$

  where $C_n^{3/2}(2x-1)$ are the Gegenbauer polynomials (1-loop eigenfunctions of ER-BL kernel)

- **That means**

$$\left\{a_2(\mu^2), a_4(\mu^2), \ldots\right\} \Leftrightarrow \varphi_\pi(x;\mu^2)$$

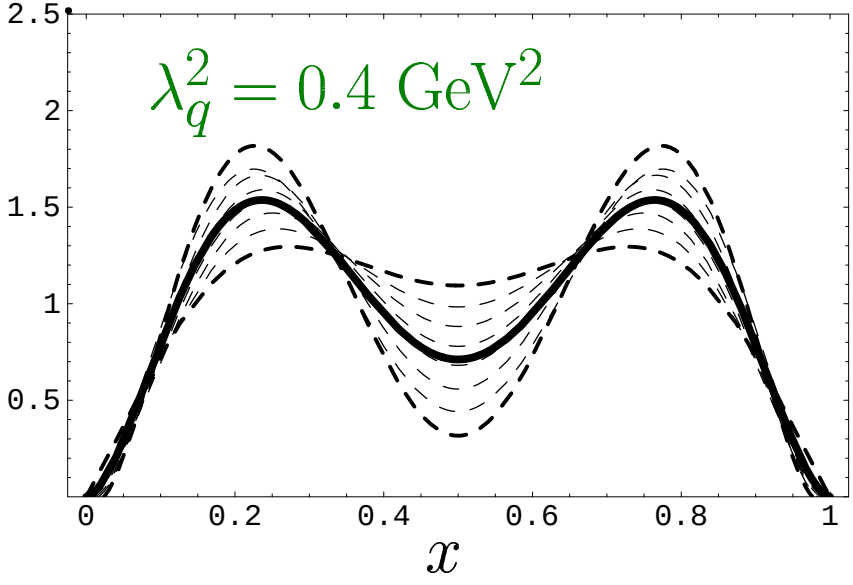
- **ER-BL solution at 2-loop level**

  [Mikhailov&Radyushkin; 1986
  Müller; 1994–95
  A.B.&Stefanis; 2005]

NLC SRs for Pion DA

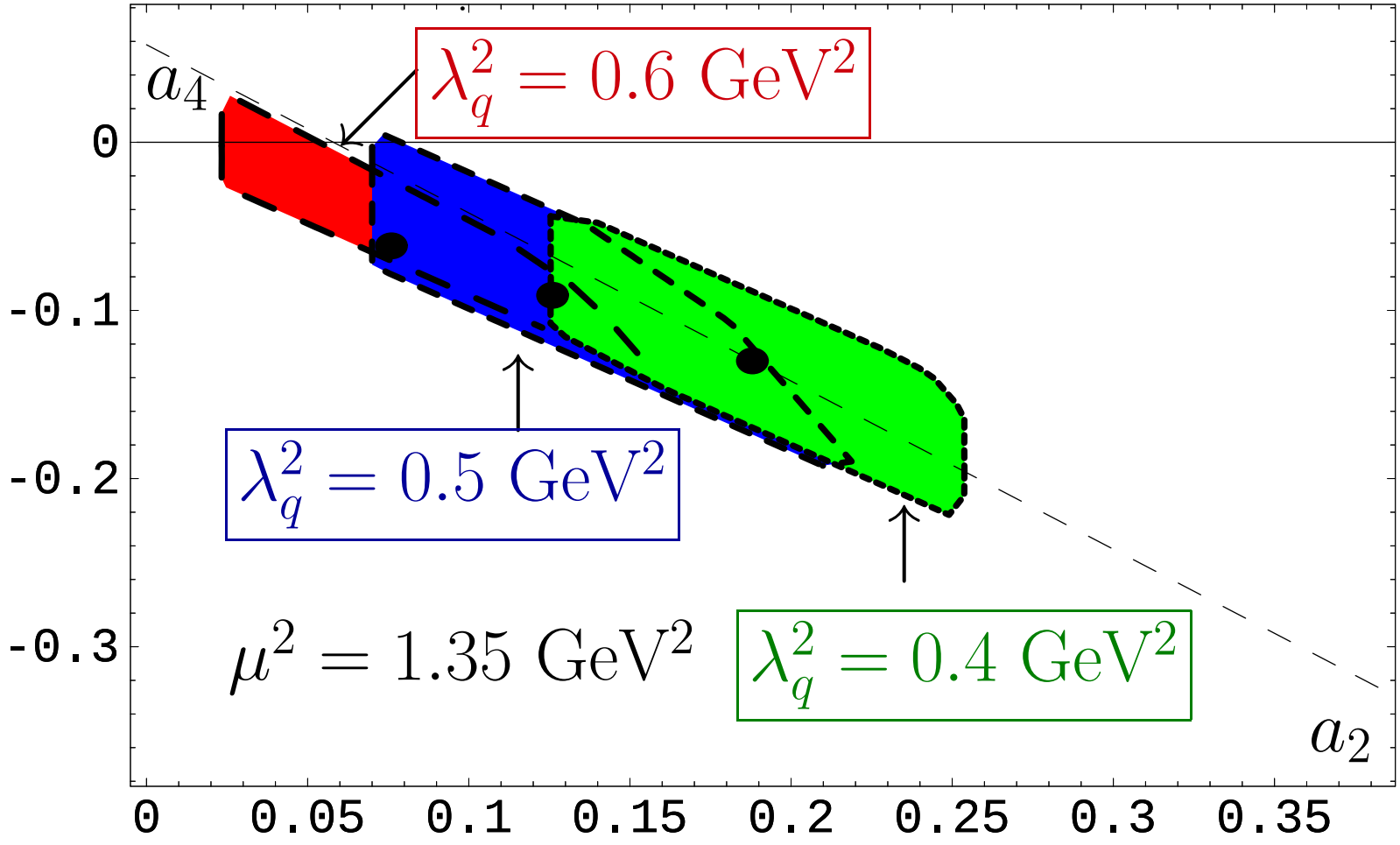
produce bunch of self-consistent 2-parameter models $\varphi_\pi(x)$ at $\mu^2 \simeq 1$ GeV^2:

$$\varphi_\pi(x) = \varphi^{\text{As}}(x)\left[1 + a_2\, C_2^{3/2}(2x-1) + a_4\, C_4^{3/2}(2x-1)\right]$$



$$\begin{aligned} a_2^{\text{b.f.}} &= +0.188 \\ a_4^{\text{b.f.}} &= -0.130 \\ \chi^2 &\approx 0.001 \\ \langle x^{-1}\rangle^{\text{SR}} &= 3.30(30) \end{aligned}$$

NLC SR Constraints on a_2, a_4 of Pion DA



Estimated bunches of pion DAs for different values of λ_q^2.

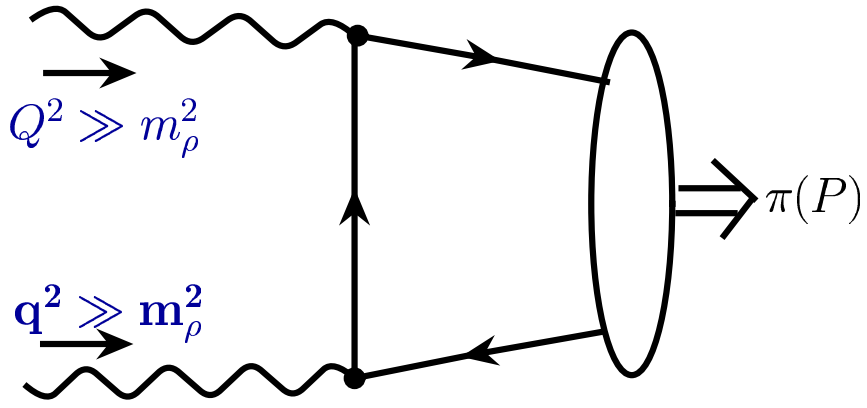
NLO Light-Cone SRs $\Rightarrow$

CLEO data on $F_{\gamma\gamma^*\pi}(Q^2) \Rightarrow$

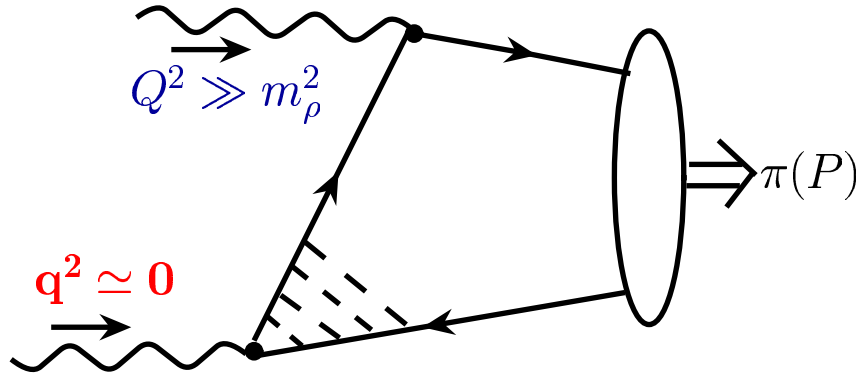
Constraints on Pion DA

$\gamma^*\gamma \to \pi$: 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 of importance[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 should be applied

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

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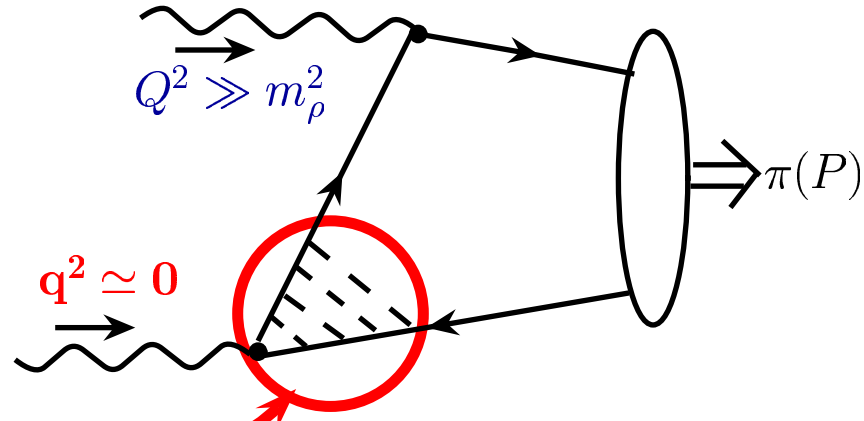

To account for long-distance effects in pQCD one needs to introduce light-cone DA of real photon

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

Khodjamirian [EJPC (1999)]: LCSR effectively accounts for long-distances effects of real photon using quark-hadron duality in vector channel and dispersion relation in q^2

$$F_{\gamma\gamma^*\pi}(Q^2,q^2) = \frac{1}{\pi}\int_0^{s_0} \frac{\text{Im}F^{\text{PT}}_{\gamma^*\gamma^*\pi}(Q^2,s)}{m_\rho^2+q^2} e^{(m_\rho^2-s)/M^2} ds + \frac{1}{\pi}\int_{s_0}^{\infty} \frac{\text{Im}F^{\text{PT}}_{\gamma^*\gamma^*\pi}(Q^2,s)}{s+q^2} ds$$

$s_0 \simeq 1.5$ GeV^2 – effective threshold in vector channel, M^2 – Borel parameter ($0.5-0.9$ GeV^2).

Real-photon limit $q^2 \to 0$ can be easily done ...

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

Khodjamirian [EJPC (1999)]: LCSR effectively accounts for long-distances effects of real photon using quark-hadron duality in vector channel and dispersion relation in q^2

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$s_0 \simeq 1.5$ GeV^2 – effective threshold in vector channel, M^2 – Borel parameter ($0.5 - 0.9$ GeV^2).

... as demonstrated here.

Main Ingredients of Spectral Density

We denote

$$\rho(Q^2,s)=\rho^{(0)}(Q^2,s)+a_s\rho^{(1)}(Q^2,s)+a_s^2\rho^{(2)}(Q^2,s)$$

- **NLO Spectral Density — in [Mikhailov&Stefanis(2009)], partially corrected in [ABOP(2011)]:**

$$\rho^{(1)}(Q^2,s)=\frac{\mathbf{Im}}{\pi}\left[\left(T_1\otimes\varphi_\pi\right)(Q^2,-s-i\varepsilon)\right]\,,s\geq 0$$

- **NNLO$_{\beta_0}$ Spectral Density — in [M&S(2009)]**

$$\rho^{(2,\beta)}(Q^2,s)=\beta_0\frac{\mathbf{Im}}{\pi}\left[\left(T_{2\beta}\otimes\varphi_\pi\right)(Q^2,-s-i\varepsilon)\right]\,,\;s\geq 0$$

Both $\rho^{(1)}$ and $\rho^{(2,\beta)}$ are obtained for arbitrary Gegenbauer harmonic.

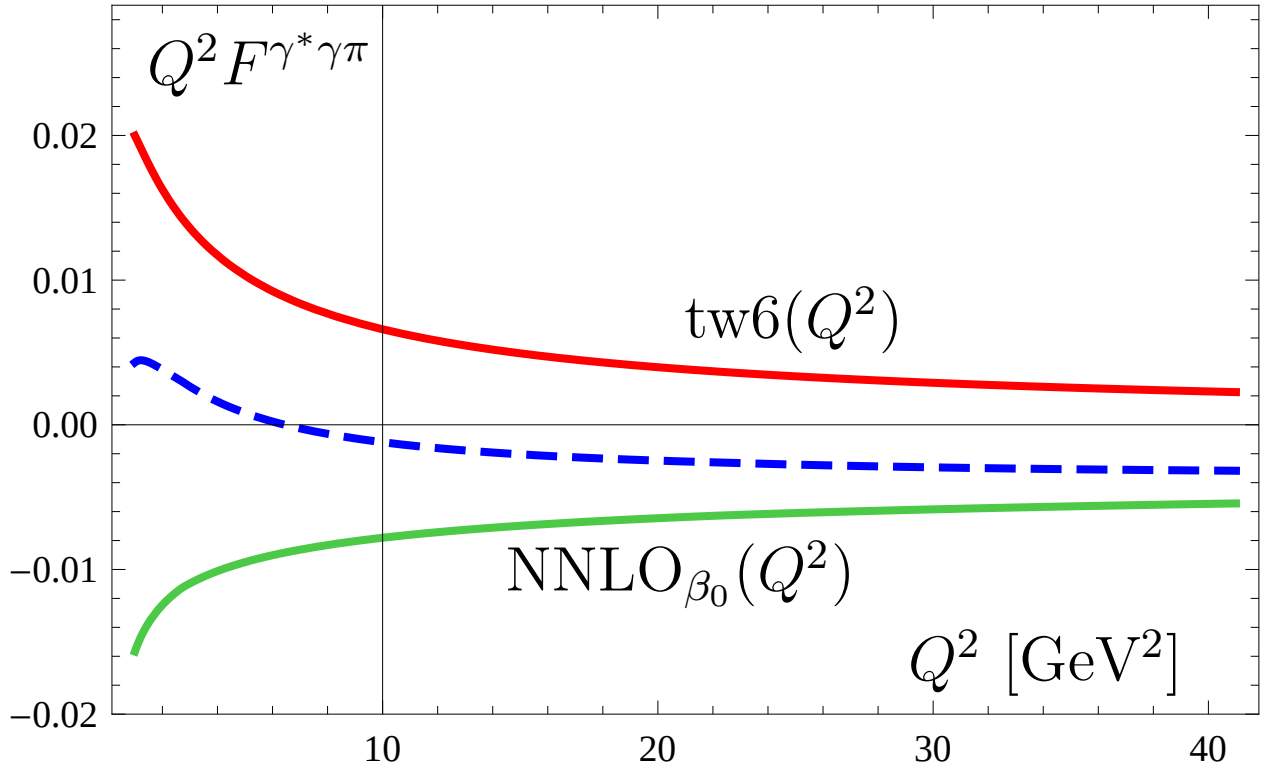
- **"Tw-6" contribution — in [ABOP–PRD83(2011)0540020]**

$$\rho^{\text{tw6}}(Q^2,x)=8\pi C_F\frac{\alpha_s\langle\bar{q}q\rangle^2}{N_c f_\pi^2}\frac{x^2}{Q^6}\left[2x\ln x\bar{x}-x+2\delta(\bar{x})-\left[\frac{1}{1-x}\right]_+\right]$$

High order corrections result

Twist-6 and NNLO$_{\beta_0}$ contributions to the $Q^2 F^{\gamma^*\gamma\pi}(Q^2)$ with BMS-like Pion DA

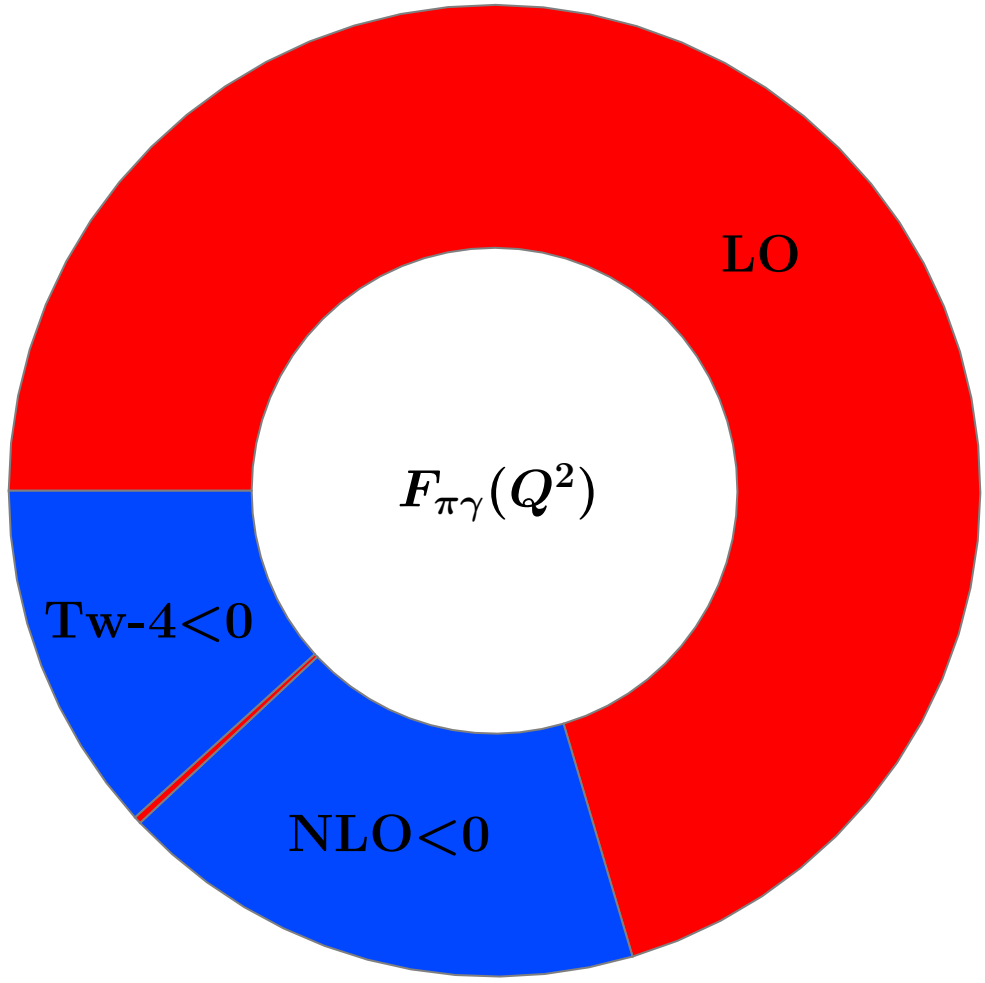
They practically cancel out each other [BMPS(2011)]



We use this residual as theoretical uncertainty of our prediction, that provides us with an additional 3%-uncertainty.

Pie chart for Pion-Photon TFF at $Q^2 = 8\,GeV^2$

- **Result is dominated by Hard Part of Twist-2 LO contribution.**

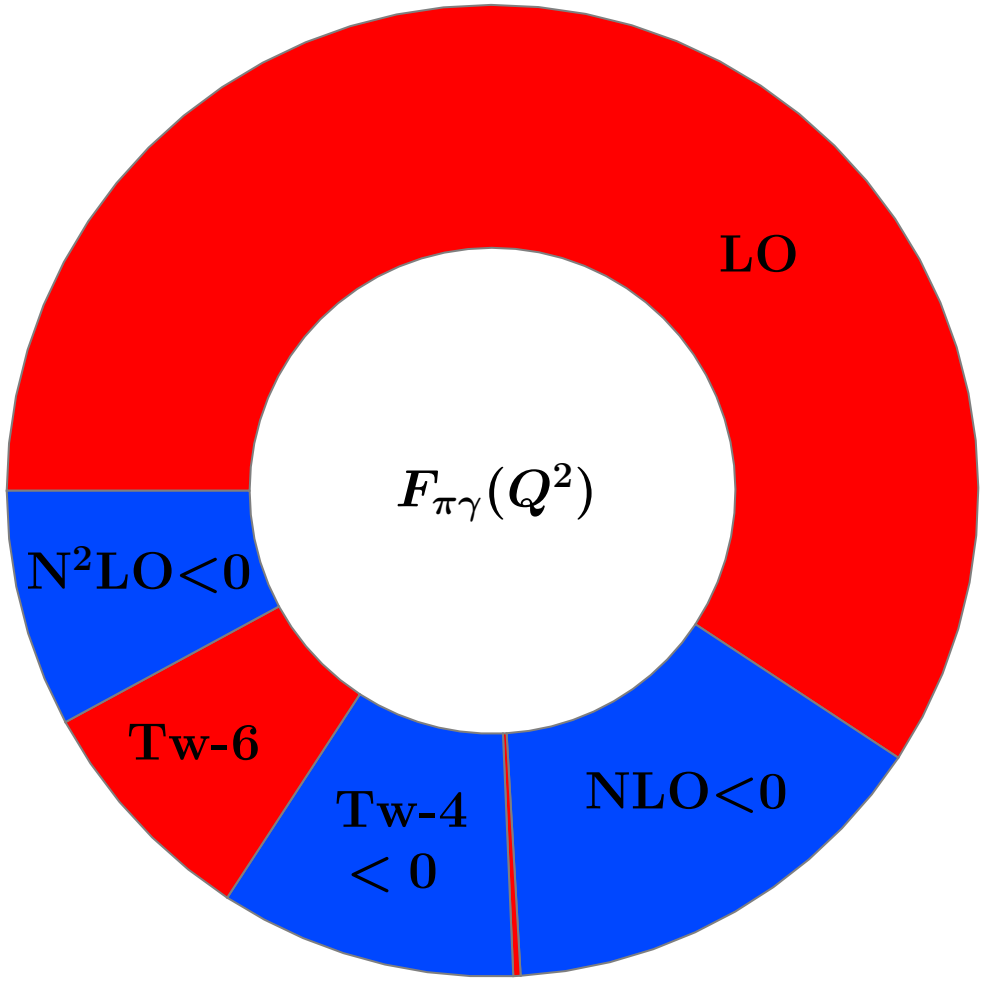


Blue = negative terms

Red = positive terms

Pie chart for Pion-Photon TFF at $Q^2 = 8\,GeV^2$

- Result is dominated by Hard Part of Twist-2 LO contribution.
- Twist-6 contribution is taken into account together with NNLO$_{\beta_0}$ one — they has close absolute values and opposite signs.



Blue = negative terms

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Parameters of LCSRs

From PDG:

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

From QCD SR:

- Borel parameter M^2_{LCSR}
- Vector Chan. Threshold s_0
- Twist-4 $\delta^2 \pm 20\%$
- Twist-6 ($\alpha_S \langle \bar{q} q \rangle$)

Light-Cone Sum Rules:

$$\overbrace{\text{LO} + \text{NLO} + \text{Tw-4} + (\text{NNLO}_{\beta_0} + \text{Tw-6})}$$

π-DA model

Data on FF

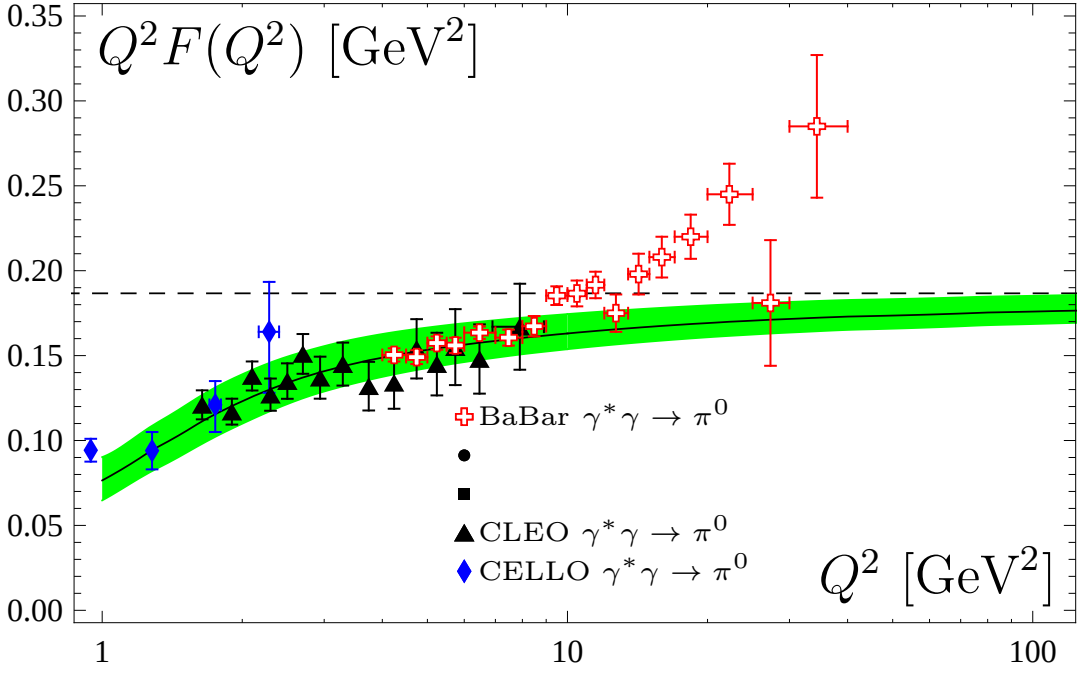
FF Prediction

Fitting π-DA (a_n)

LCSRs Results for Pion-Gamma Transition FF

Pion-gamma FF vs Experimental Data

Comparison with all data: CELLO, CLEO and BaBar



curve	DA
– – – – –	Asymp.QCD
▬	BMS bunch

- **BMS bunch describes very good all data for $Q^2 \leq 9$ GeV^2.**

Pion-gamma FF vs Experimental Data

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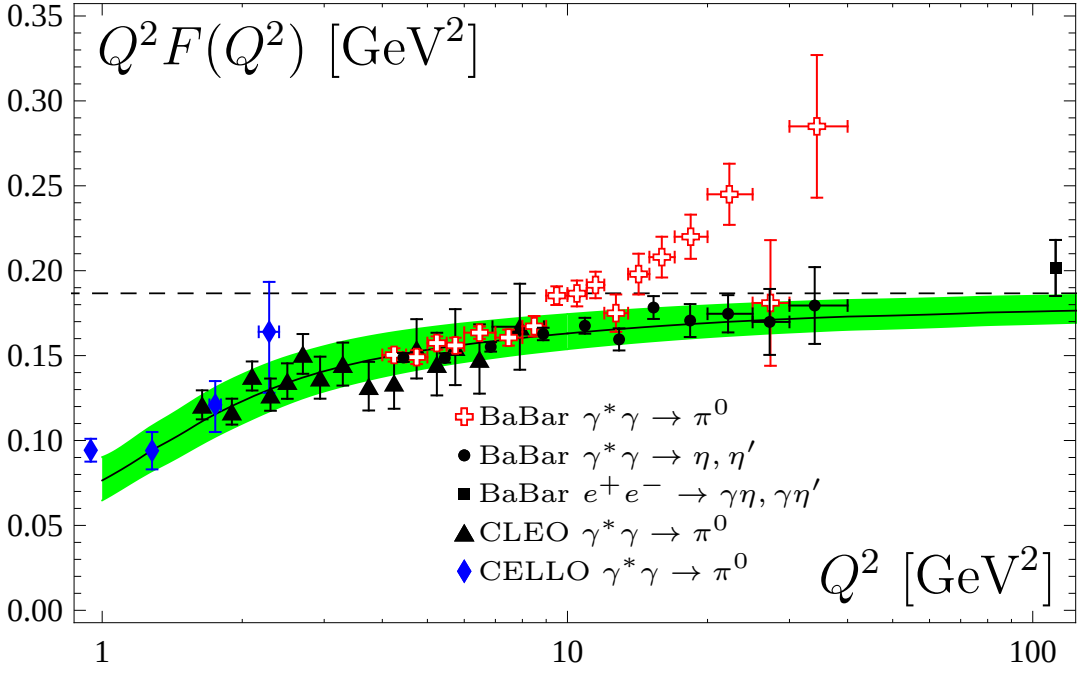

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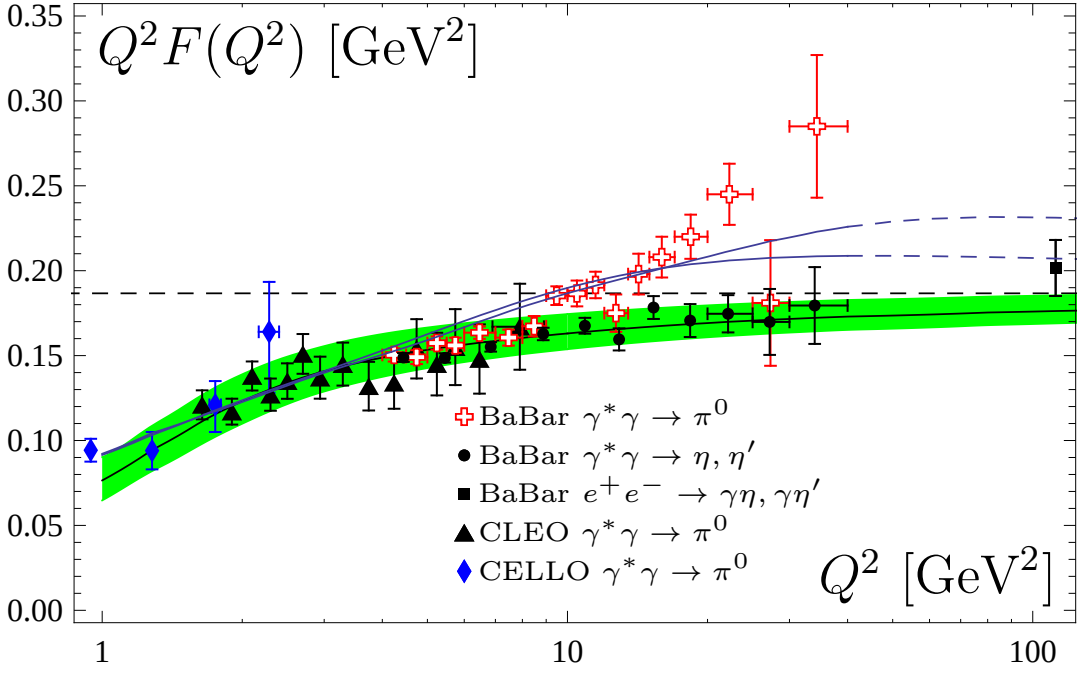
- **Note added BaBar $\gamma^*\gamma \to \eta, \eta'$ and $e^+e^- \to \gamma\eta, \gamma\eta'$ data (1101.1142[hep-ex]): All they are inside BMS strip !**

Pion-gamma FF vs Experimental Data

Comparison with all data: CELLO, CLEO and BaBar



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———	ABOP-1,3
Agaev et al	PRD83-054020

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- **Note added BaBar $\gamma^*\gamma \to \eta, \eta'$ and $e^+e^- \to \gamma\eta, \gamma\eta'$ data (1101.1142[hep-ex]): All they are inside BMS strip !**
- **ABOP models are in between two sets of BaBar data.**

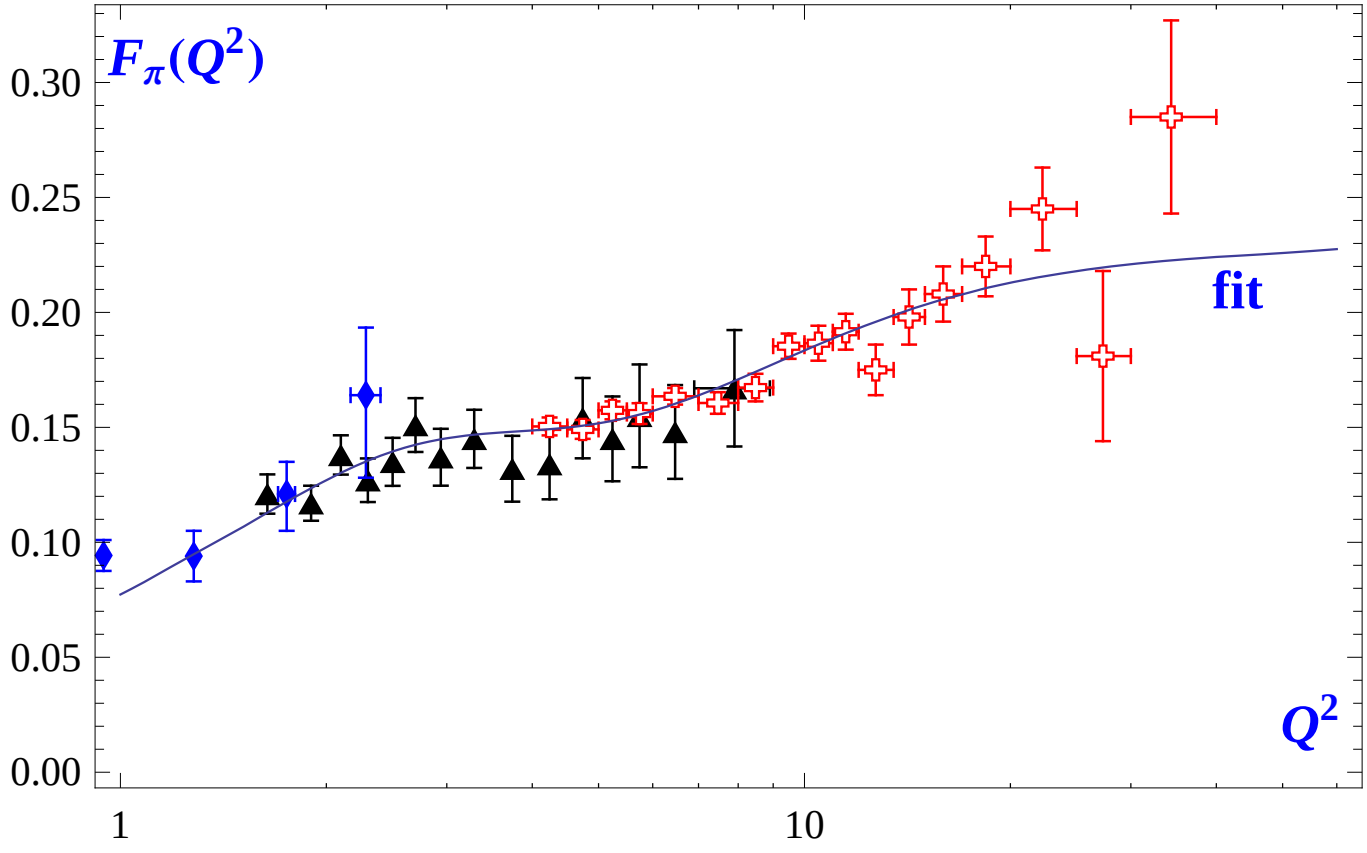
Fitting Pion DA

—

Confidential Regions

Fitting pion DA under LCSR

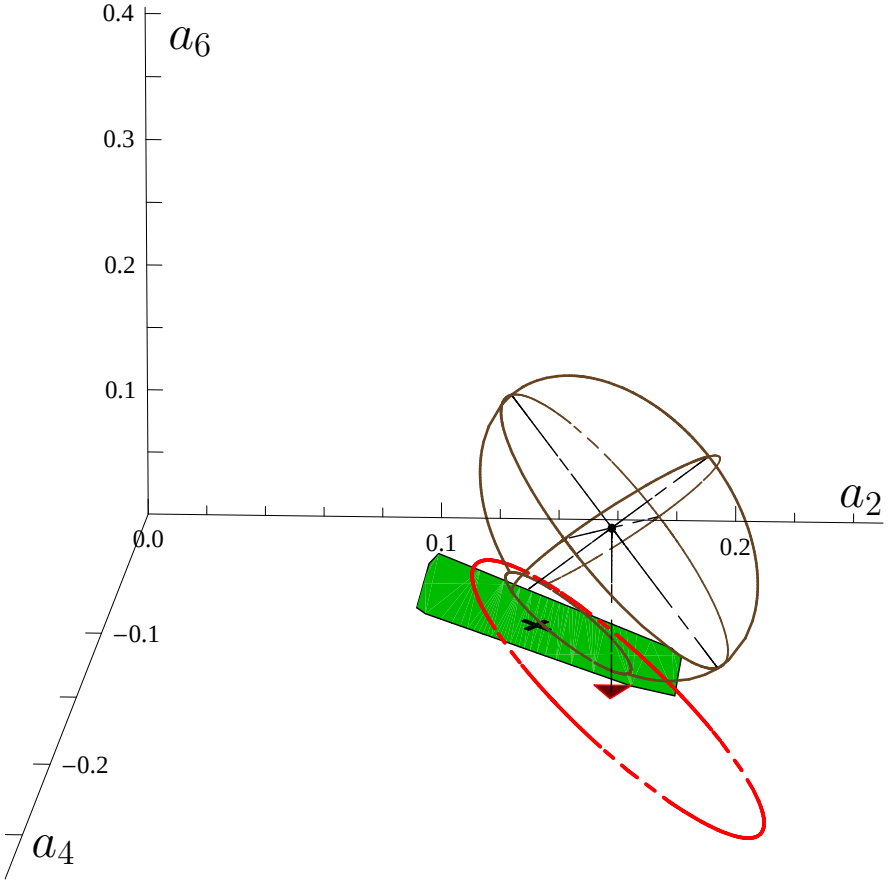
- We fitted experimental data on $\pi\gamma$ TFF by varying Gegenbauer coefficients of Pion DA.
- Two sets of experim. data ($1-9\,\mathrm{GeV}^2$ & $1-40\,\mathrm{GeV}^2$) were analyzed to show the influence of BaBar Data on Pion DA.



Fit based on LCSRs with NLO+Tw4+3 Gegenbauers

NLC SR Results vs 3D Constraints

BMPS [PRD84(2011)034014]: 3D 1σ-error ellipsoid at $\mu_{SY} = 2.4$ GeV scale without $\Delta\delta^2_{tw4}$ uncertainty



Data Set $1 - 9\,\text{GeV}^2$

— ⇔ 2D projection of 1σ-error ellipsoid

▼ ⇔ $\chi^2_{ndf} \approx 0.4$

✕ ⇔ BMS model with $\chi^2_{ndf} \approx 0.5$

Best-fit $= (0.17, -0.14, 0.12 \pm 0.14)$

BMS $= (0.14, -0.09)$

Good agreement of all data at $Q^2 \leq 9$ GeV^2

At 68.3% CL we have good intersection 2D∩3D∩4D$\neq \oslash$

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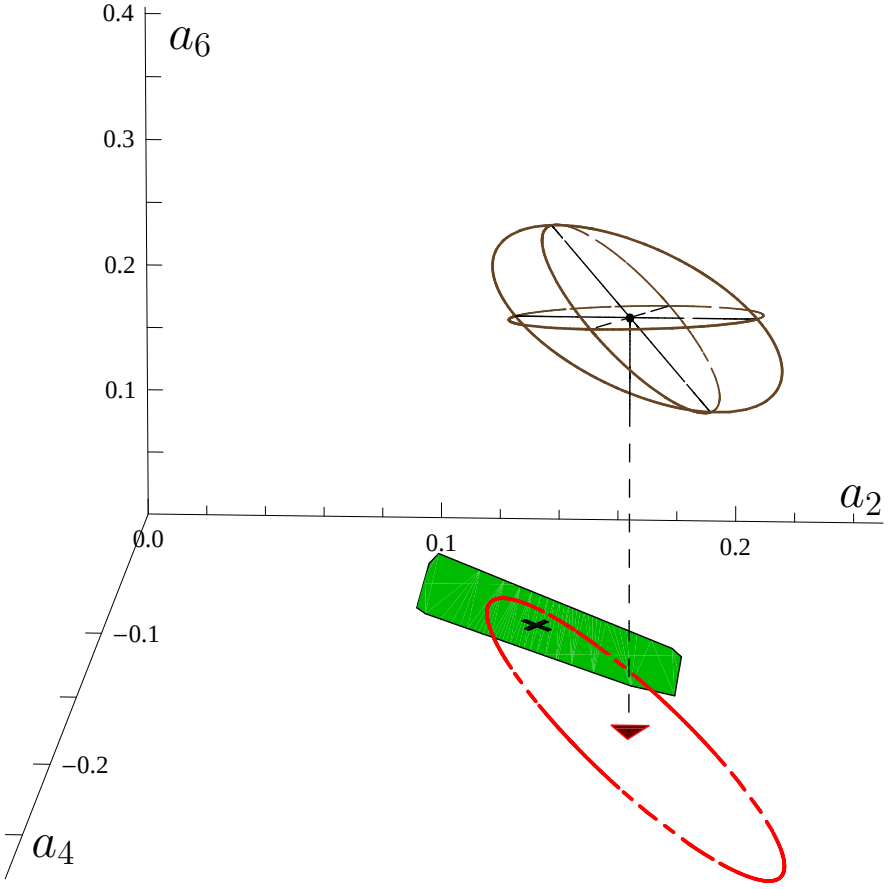


Data Set $1 - 40\,\text{GeV}^2$

— ⇔ 2D projection of 1σ-error ellipsoid

▼ ⇔ $\chi^2_{ndf} \approx 1.0$

✕ ⇔ BMS model with $\chi^2_{ndf} \approx 3.1$

Best-fit $= (0.18, -0.17, 0.31 \pm 0.1)$

BMS $= (0.14, -0.09)$

Bad agreement of all data at $Q^2 \leq 40$ GeV^2

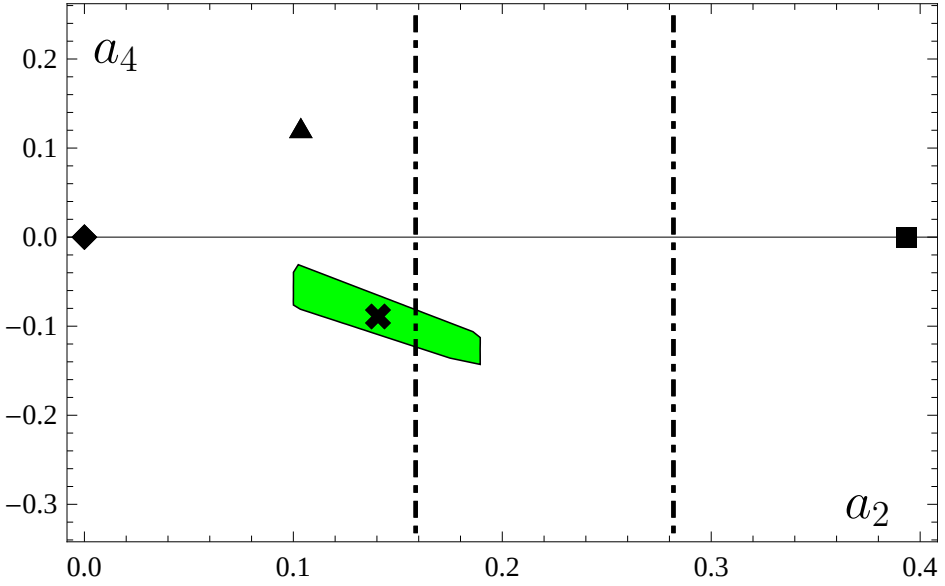
At 68.3% CL we have no intersection 2D∩3D$= \varnothing$, 3D∩4D$= \varnothing$.

NLC SR Results vs 2D Constraints

NLC-bunch and lattice prediction at $\mu_{SY} = 2.4$ GeV scale with accounting for $\Delta\delta^2_{tw4}$ uncertainty.

DAs: ◆ ⇔ Asymp., ▲ ⇔ ABOP-3, ✖ ⇔ BMS, ■ ⇔ CZ

Lattice'10 estimate of a_2 are shown by vertical lines.



Data Set $1 - 9\,\mathrm{GeV}^2$

BMS bunch agrees well with the lattice data

NLC SR Results vs 2D Constraints

2D-Analysis of the data at $\mu_{SY} = 2.4$ GeV scale with accounting for $\Delta\delta^2_{tw4}$ uncertainty.

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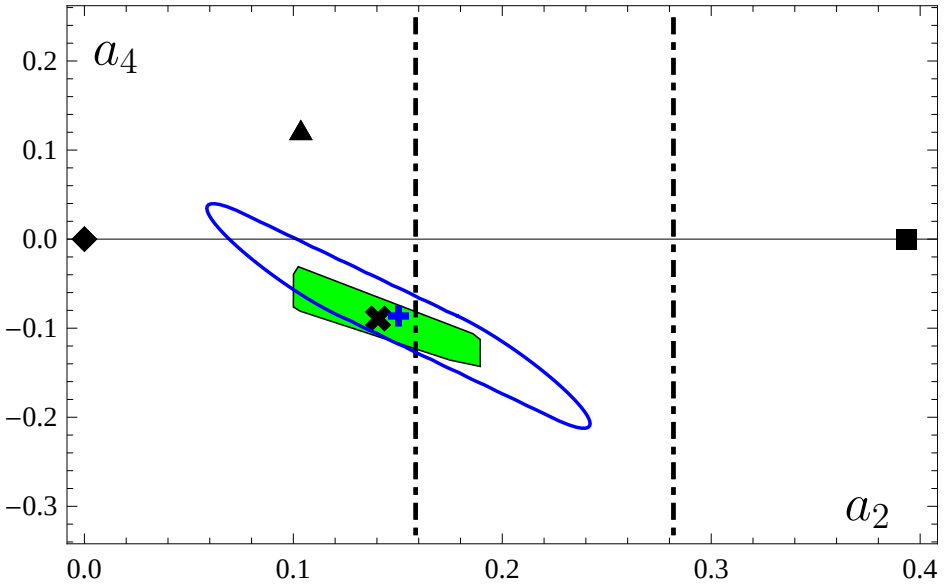

Data Set $1 - 9$ GeV^2

—— ⇔2D 1σ-error ellipse

BMS bunch agrees well with the lattice data

BMS bunch has better agreement with data up 9 GeV^2 than with CLEO data only.

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2D-Analysis of the data at $\mu_{SY} = 2.4$ GeV scale with accounting for $\Delta\delta^2_{tw4}$ uncertainty.

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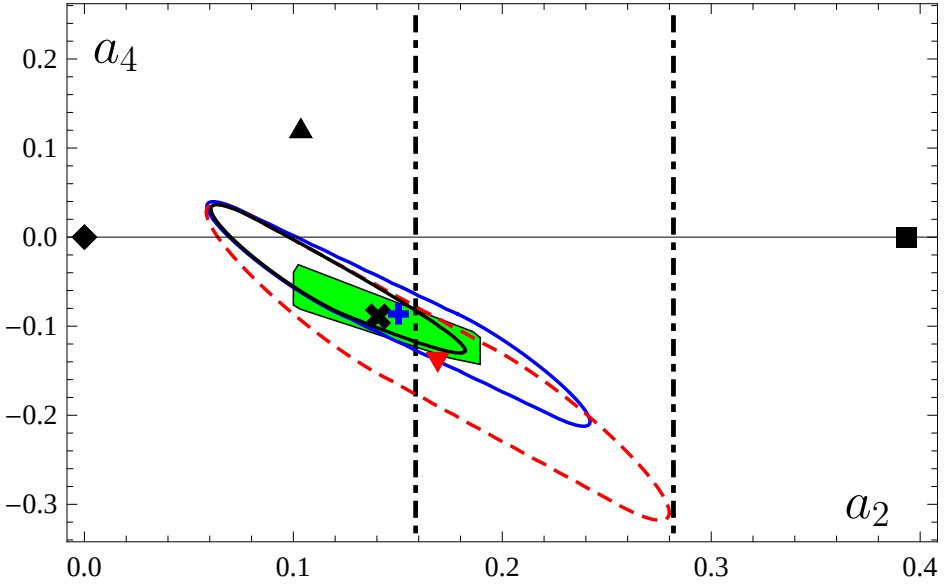


Data Set $1 - 9$ GeV^2

—— ⇔ 2D 1σ-error ellipse

– – – ⇔ 2D-Proj. 3D-ellipsoid

—— ⇔ $a_6 = 0$ cut of 3D-ellipsoid

BMS bunch agrees well with the lattice data

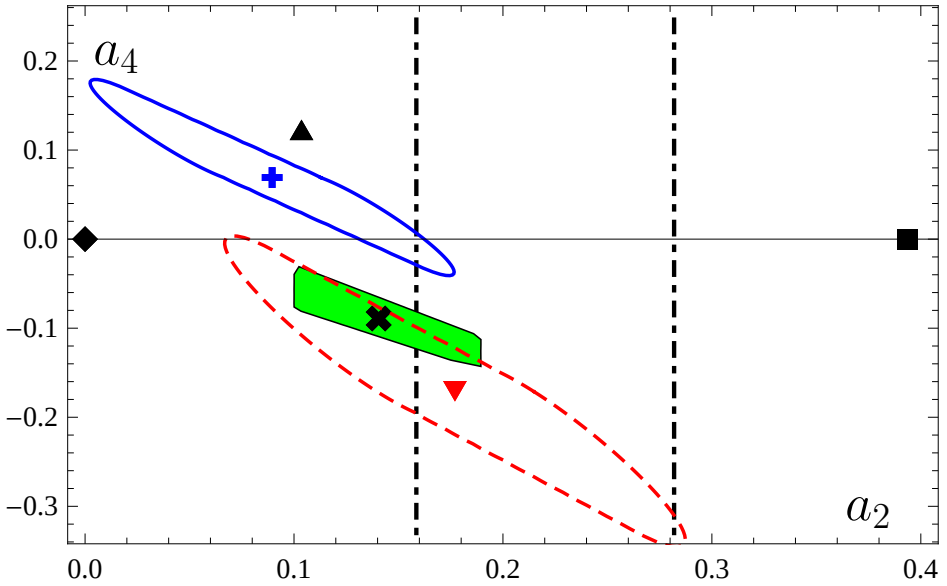
BMS bunch has better agreement with data up 9 GeV^2 than with CLEO data only.

NLC SR Results vs 2D Constraints

BMPS [arXiv:1105.2753 [hep-ph]]: 2D 1σ-error ellipses at $\mu_{SY} = 2.4$ GeV scale with accounting for $\Delta\delta^2_{tw4}$ uncertainty.

DAs: ◆ ⇔ Asymp., ▲ ⇔ ABOP-3, ✖ ⇔ BMS, ■ ⇔ CZ

Lattice'10 estimate of a_2 are shown by vertical lines.



Data Set $1 - 40$ GeV^2

——— ⇔ 2D 1σ-error ellipse

– – – ⇔ 2D-Proj. 3D-ellipsoid

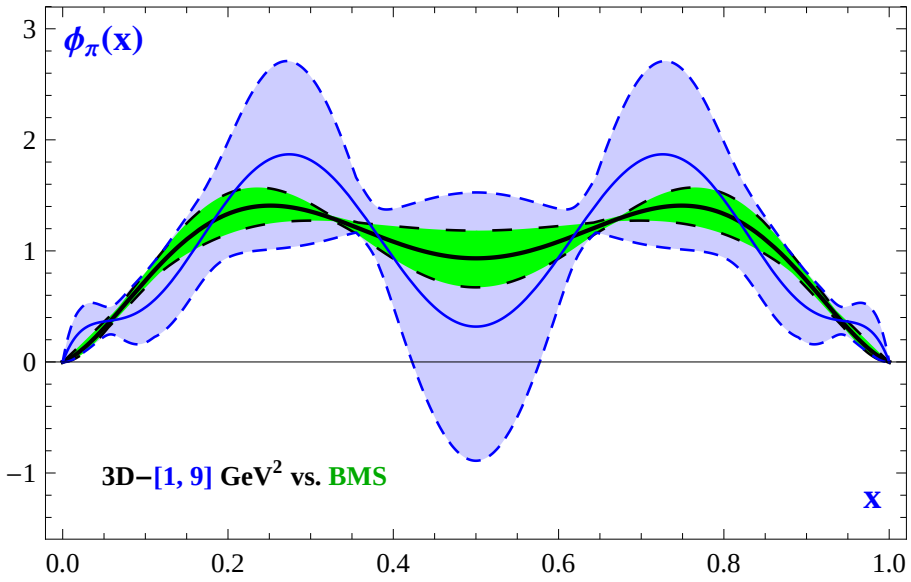
Bad agreement with 2D 1σ-error ellipse

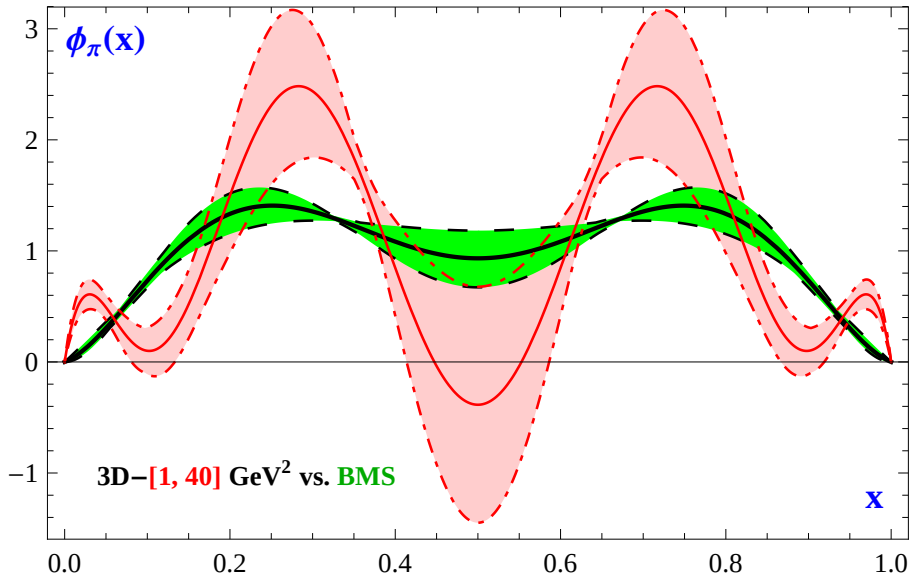
No cross-section with $a_6 = 0$ plane.

3D Data Fit of Pion DA vs BMS (QCD SR)

:= BMS, $:= 1 - 9\,\mathrm{GeV}^2$, $:= 1 - 40\,\mathrm{GeV}^2$

at $\mu_{SY} = 2.4\,\mathrm{GeV}$ scale.





- BMS bunch agrees well with Data Set $1 - 9\,\mathrm{GeV}^2$;
- New BaBar Data do not agree with BMS bunch based on NLC QCD SRs.
- Both data sets does not match each other.

End-point Bechavior of Pion DA

Integral derivative $D^{(2)}\varphi(x) = \frac{1}{x}\int_0^x \frac{\varphi(y)}{y} dy$

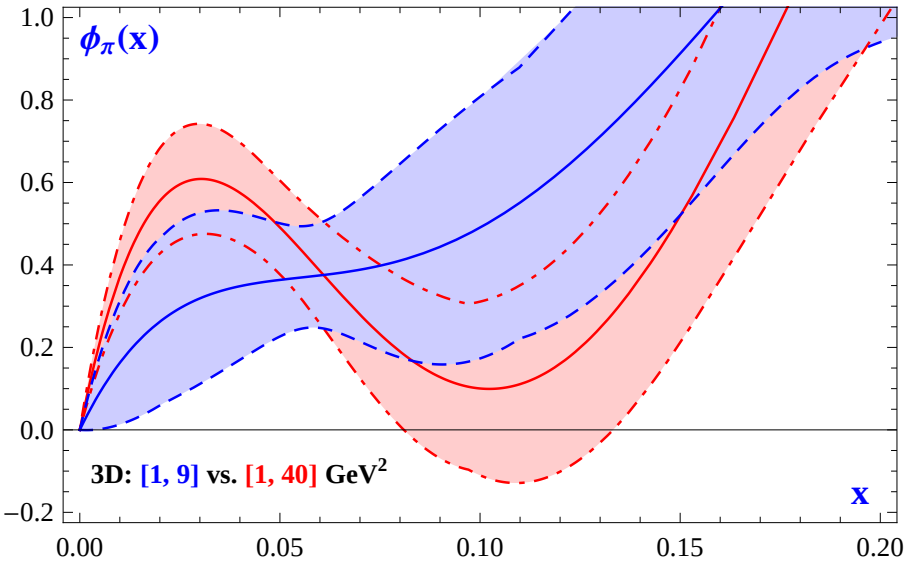
is an average derivative $\varphi'_\pi(x)$ **near the end-point** $x = 0$**.**

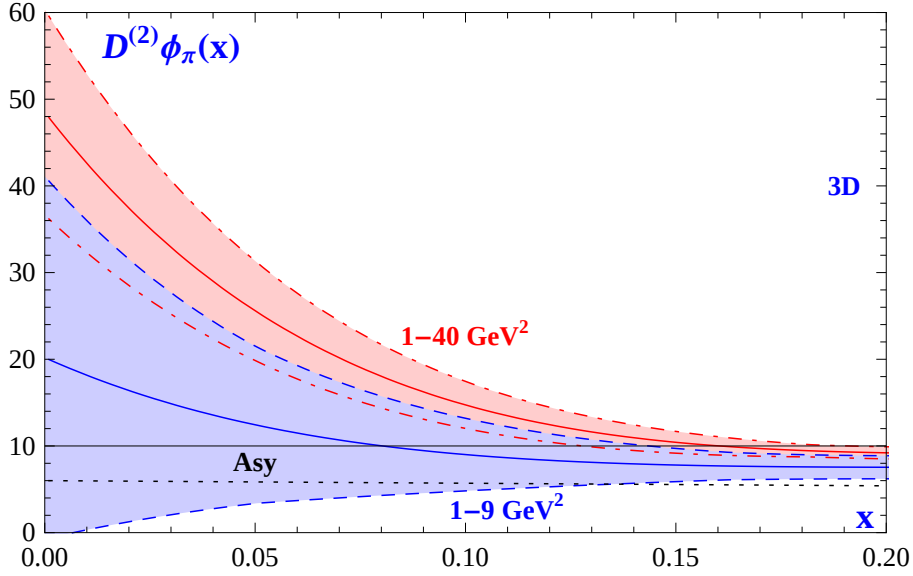
Important property: $\lim\limits_{x\to 0} D^{(2)}\varphi(x) = \varphi'_\pi(0)$**.**

End-point Bechavior of Pion DA

Integral derivative $D^{(2)}\varphi(x) = \frac{1}{x}\int_0^x \frac{\varphi(y)}{y}dy$

at $\mu_{SY} = 2.4$ **GeV scale.**





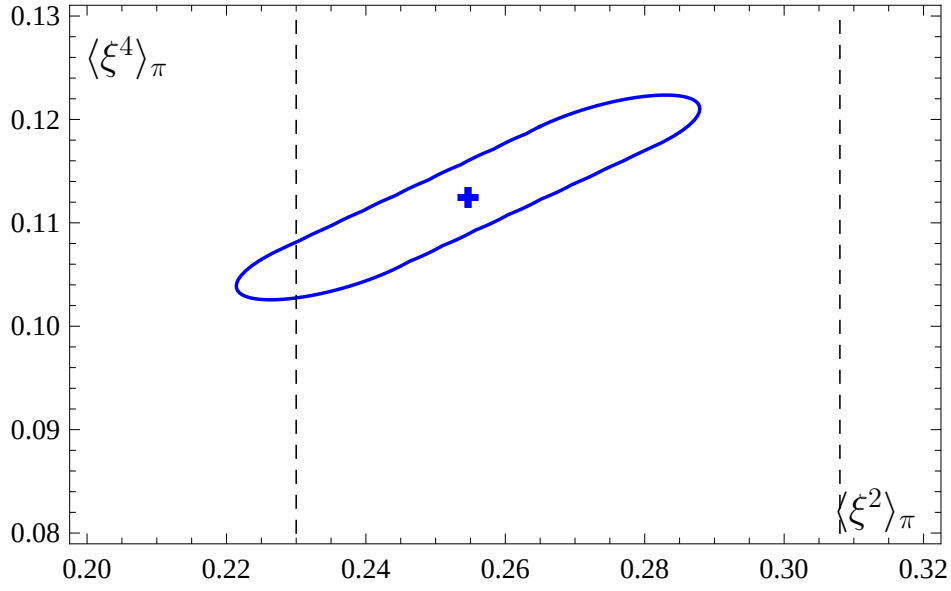
- $DA^{1-9\ \mathrm{GeV}^2}$ **and** $DA^{1-40\ \mathrm{GeV}^2}$ **are separated near the origin.**
- **BaBar Data demands End-Point Enhanced Pion DA.**

Confidential Region for Pion DA Moments vs. Lattice QCD

2D Constraints and Lattice QCD

1σ region in $(\langle\xi^2\rangle_\pi, \langle\xi^4\rangle_\pi)$ plane from 2D$(1-9\ \text{GeV}^2)$ analysis vs QCDSF&UKQCD Lattice Data [PRD74(2006)074501] at $\mu_{\text{lat}} = 2$ GeV scale:

curve	meaning
———	2D-1σ-ellipse
– – – – –	Lattice'06

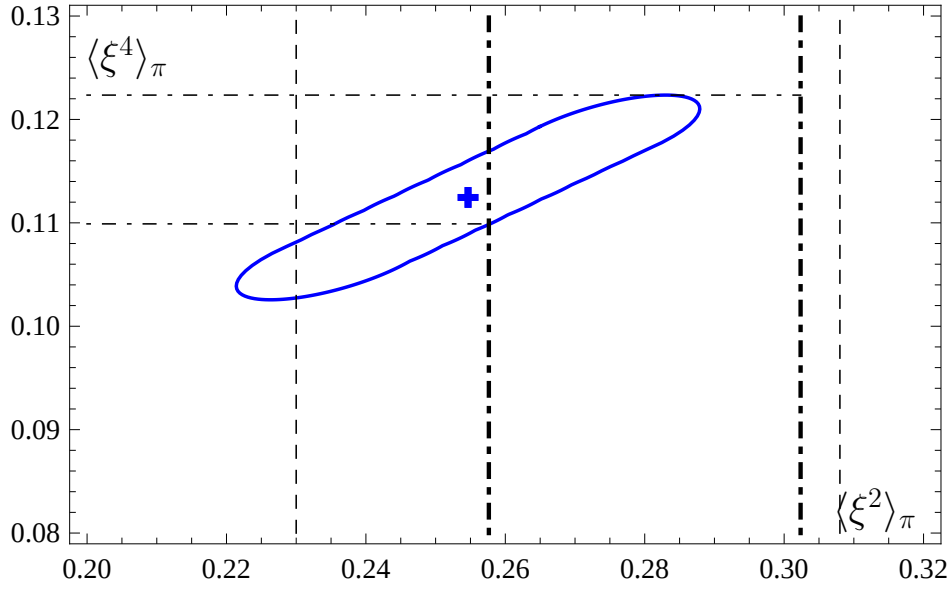


Our 2D-1σ region is almost completely inside Lattice'06 constraint.

2D Constraints and Lattice QCD

1σ region in $(\langle\xi^2\rangle_\pi, \langle\xi^4\rangle_\pi)$ plane from 2D$(1-9\ \text{GeV}^2)$ analysis vs RBC&UKQCD Lattice Data [PRD83(2011)074505] at $\mu_{\text{lat}} = 2$ GeV scale:

curve	meaning
———	2D-1σ-ellipse
– – – – –	Lattice'06
– · – · – · –	Lattice'10

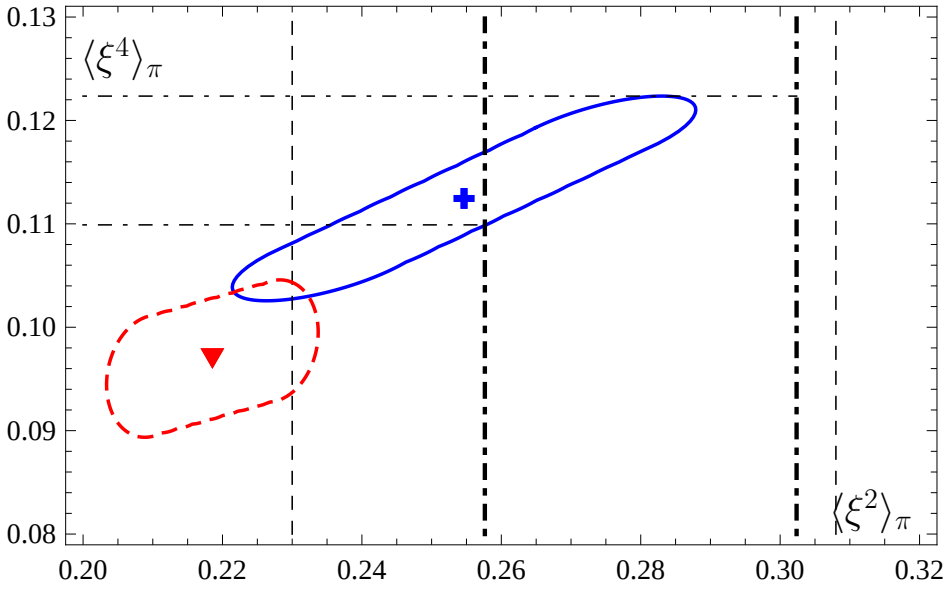


Our 2D-1σ region is one-half inside Lattice'10 constraint.

2D Constraints and Lattice QCD

1σ region in $(\langle\xi^2\rangle_\pi, \langle\xi^4\rangle_\pi)$ plane from 2D$(1-9\ \text{GeV}^2)$ analysis vs RBC&UKQCD Lattice Data [PRD83(2011)074505] at $\mu_{\text{lat}} = 2$ GeV scale:

curve	meaning
———	2D$^{0.7}$-1σ-ellipse
– – – – –	Lattice'06
–·–·–·–	Lattice'10
– – – – –	2D$^{1.5}$-1σ-ellipse



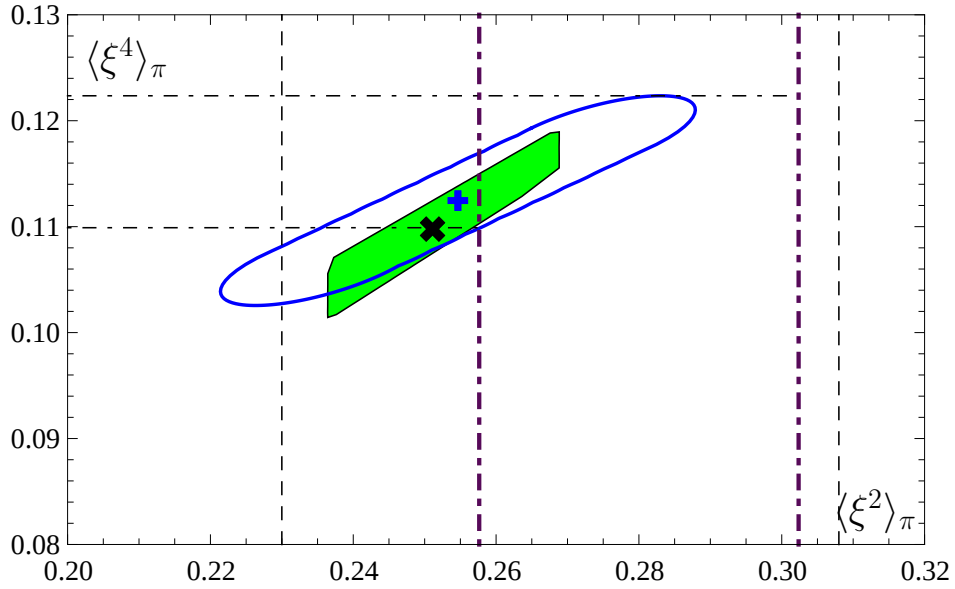
Our 2D-1σ region with $(M^2 \approx 0.7\,\text{GeV}^2)$ is one-half inside Lattice'10 constraint,

whereas the 2D-1σ region with ABOP value $(M^2 = 1.5\ \text{GeV}^2)$ is completely out of Lattice'10 constraint!

2D Constraints and Lattice QCD

1σ region in $(\langle\xi^2\rangle_\pi, \langle\xi^4\rangle_\pi)$ plane from 2D$(1-9\ \text{GeV}^2)$ analysis vs RBC&UKQCD Lattice Data [PRD83(2011)074505] at $\mu_{\text{lat}} = 2$ GeV scale:

curve	meaning
———	2D-1σ-ellipse
– – – – –	Lattice'06
– · – · – · –	Lattice'10



Intersection of Lattice and 2D-1σ region leads to prediction:

$\langle\xi^4\rangle_\pi \in [0.11, 0.122]$ — in a good agreement with estimation $\langle\xi^4\rangle_\pi \in [0.095, 0.134]$ in [Stefanis, NPB.PS.181(2008)199].

Fit Results and Pion DA Models

Comparing Fit Results with Pion DA models

Model/Fit	Values of a_n	χ^2/ndf ($1-9\,\text{GeV}^2$)	χ^2/ndf ($1-40\,\text{GeV}^2$)
a_2, a_4, a_6 Fit	$(0.18, -0.17, 0.31)$	0.4	1.0
BMS	$(0.14, -0.09)$	0.5	3.1
Agaev et al	$(0.08, 0.14, 0.09)$	2.8	2.4
Kroll	$(0.21, 0.01)$	3.8	4.4
AdS/QCD	$0.15, 0.06, 0.03$	2.3	2.8
CZ	(0.39)	32.3	25.5
Asympt.	$(0, 0)$	4.7	7.9

All values given at $\mu_{\text{SY}} = 2.4$ GeV scale.

- BMS DA gives best LCSR Description of $\pi\gamma$TFF for $Q^2 \leq 9\,\text{GeV}^2$.
- All-Data LCSR-Fit Result is far from All Considered Pion DA Models.

Comparing Different Data Set Analyses

Q^2 regions	$[1-9]\,\text{GeV}^2$	$[1-40]\,\text{GeV}^2$
BMS bunch	Agreement	No!
η and η'	Agreement	No!
Number of harmonics n	$2, 3$	$3, 4$
Best χ^2_{ndf}	$0.53,\ \ 0.44$	$1.0,\ \ 0.77$
Derivative $\varphi_\pi(x)\vert_{x=0}$	$20.2 \pm 19.8 \pm 1.1$	$48.5 \pm 11.4 \pm 0.4$
Derivative $D^{(2)}\varphi_\pi(0.4)$	$6.6 \pm 1.1 \pm 0.4$	$8.1 \pm 0.7 \pm 0.3$

Conclusions

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- Evident conflict between ($\eta\gamma$ and $\eta'\gamma$) and $\pi^0\gamma$ BaBar Data may signal about strong isospin symmetry violation in pseudoscalar meson sector.
- To resolve BaBar puzzle we need Belle verification of $\pi\gamma$Transition FF Data.