Constraints on Pion DA from experiments

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Contents of Report

- CLEO data on $F_{\gamma\gamma^*\pi}(Q^2) \Rightarrow$ pion DA
  [PRD 67 (2003) 074012; 73 (2006) 056002]
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- Recent Lattice data vs.
  CLEO analysis and pion DA
  [PRD 73 (2006) 056002]

NLO Light-Cone SRs $\Rightarrow$

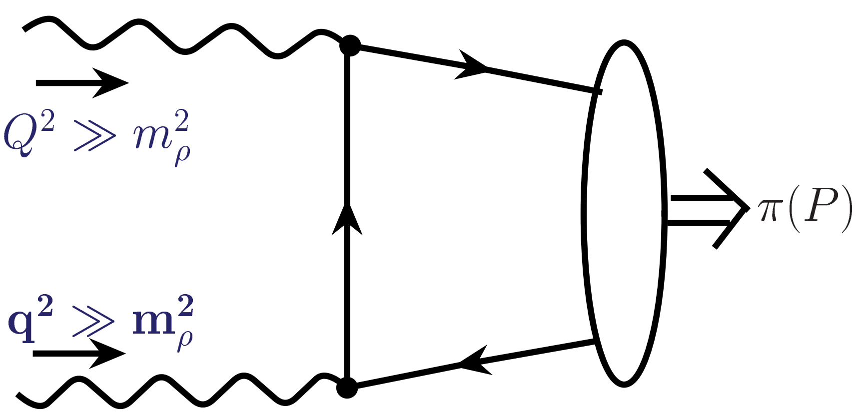
CLEO data on $F_{\gamma\gamma^*\pi}(Q^2) \Rightarrow$

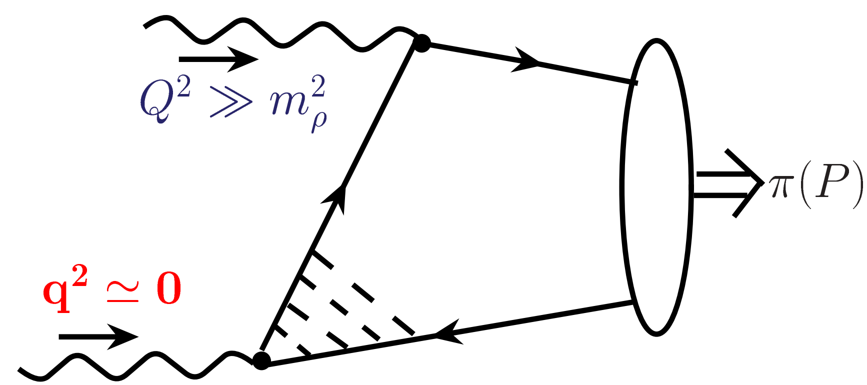
Constraints on Pion DA

$\gamma^*\gamma \to \pi$: *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 of order of $O(1/\sqrt{q^2})$





pQCD is OK **LCSRs should be applied**

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

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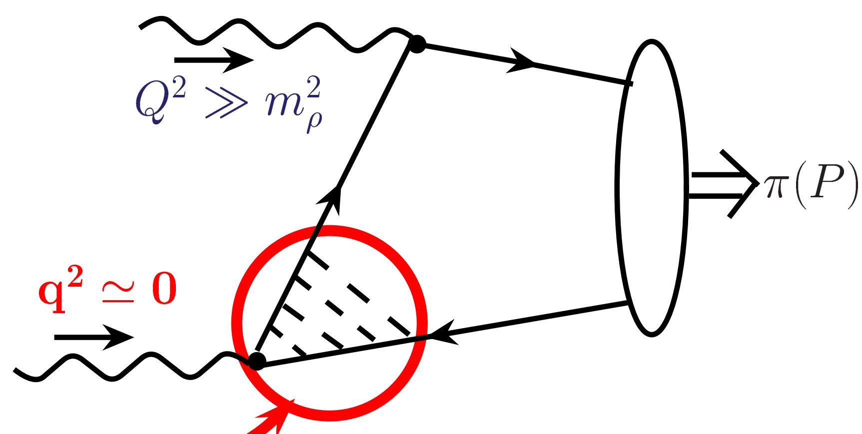

To account for long-distance effects in pQCD, one needs to introduce light-cone DA of real photon

$\gamma^*\gamma \to \pi$: *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

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[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

$$F_{\gamma\gamma^*\pi}(Q^2, q^2 \to 0) = \frac{1}{\pi}\int_0^{s_0} \frac{\text{Im}F^{\text{PT}}_{\gamma^*\gamma^*\pi}(Q^2, s)}{m_\rho^2} e^{(m_\rho^2 - s)/M^2} ds + \frac{1}{\pi}\int_{s_0}^{\infty} \frac{\text{Im}F^{\text{PT}}_{\gamma^*\gamma^*\pi}(Q^2, s)}{s} ds$$

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

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

CLEO-data analysis

- Accurate NLO evolution for both $\varphi(x, Q^2_{\text{exp}})$ and $\alpha_s(Q^2_{\text{exp}})$, taking into account quark thresholds;

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- The relation between **"nonlocality" scale** and **twist-4** magnitude $\boxed{\delta^2_{\text{Tw-4}} \approx \lambda_q^2/2}$ was used to re-estimate $\delta^2_{\text{Tw-4}} = 0.19 \pm 0.02$ at $\lambda_q^2 = 0.4$ **GeV**^{2}

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- New procedure of data processing to disentangle the statistical and theoretical uncertainties

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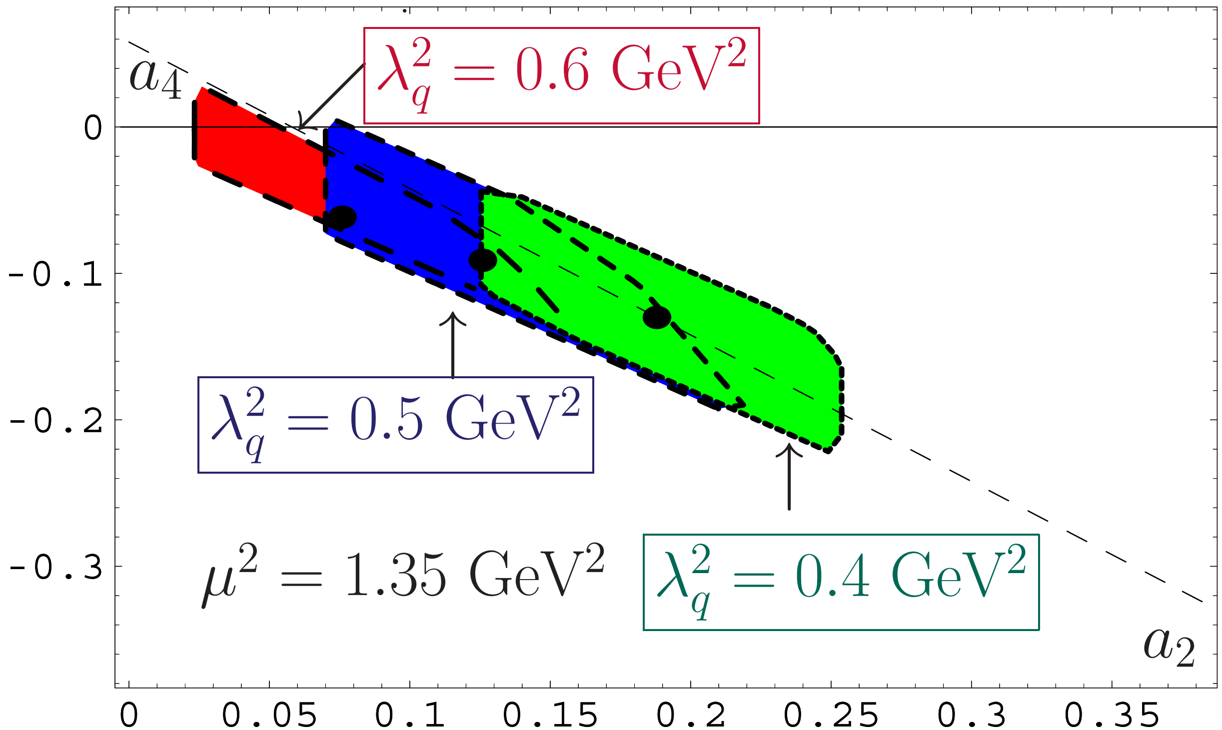
- New procedure of data processing to disentangle the statistical and theoretical uncertainties
- Constraints on $\langle x^{-1} \rangle_\pi$ from CLEO data.

NLC SR Constraints on a_2, a_4 of Pion DA



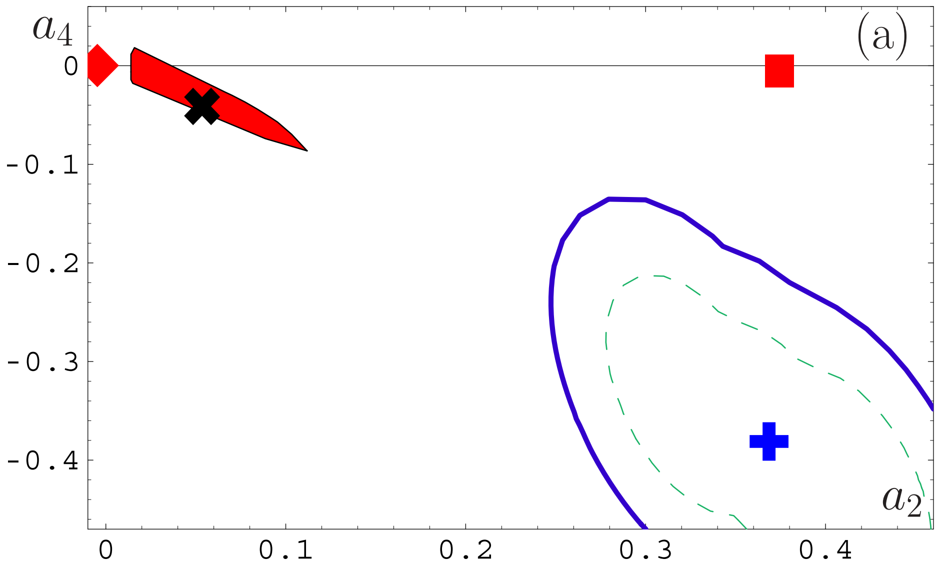
$\boldsymbol{\lambda_q^2}$ – average virtuality of vacuum quarks – the single parameter of NLC approach **[PLB 508(2001)279]**

Main purpose of analysis: **to use CLEO data to restrict λ_q^2**

☞

NLC SR Results vs NLO CLEO Constraints

[BMS, PRD 67 (2003) 074012]



$\Leftrightarrow \lambda_q^2 = 0.6$ **GeV^2**,
$\delta^2_{\text{Tw-4}} = 0.28(3)$ **GeV^2**

No agreement with CLEO data for $\lambda_q^2 = 0.6$ GeV^2

NLC SR Results vs NLO CLEO Constraints

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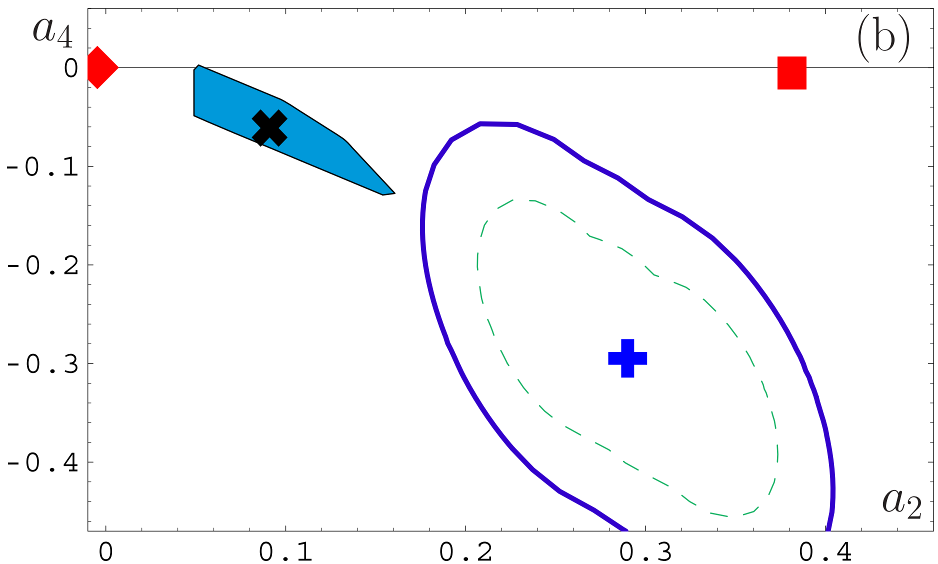


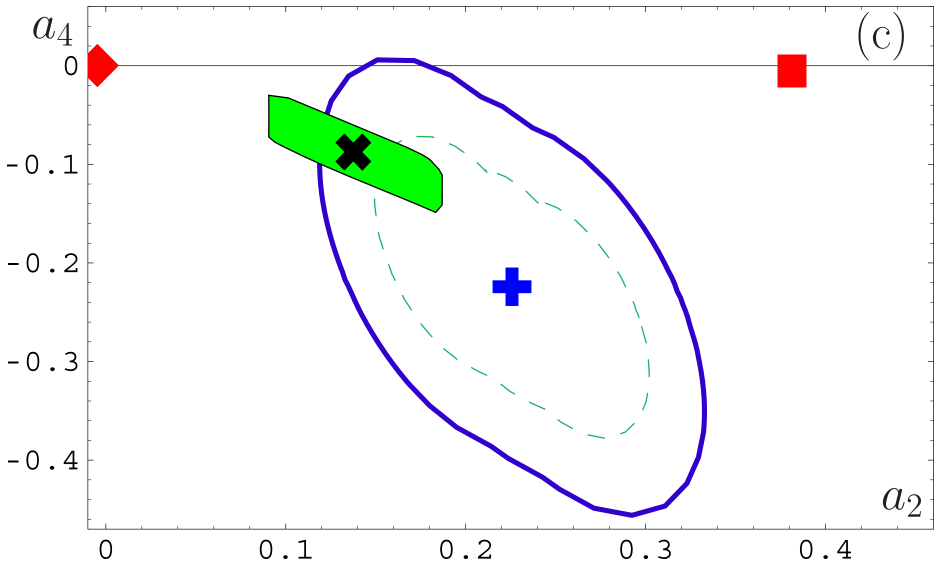
$\Leftrightarrow \lambda_q^2 = 0.5$ **GeV^2**,

$\delta^2_{\text{Tw-4}} = 0.23(2)$ **GeV^2**

Bad agreement with CLEO data for $\lambda_q^2 = 0.5$ GeV^2

NLC SR Results vs NLO CLEO Constraints

[BMS, PRD 67 (2003) 074012]



$\Leftrightarrow \lambda_q^2 = 0.4$ **GeV^2**,

$\delta^2_{\text{Tw-4}} = 0.19(2)$ **GeV^2**

Good agreement with CLEO data for $\lambda_q^2 = 0.4$ GeV^2 ☞

NLC SR Results vs NLO CLEO Constraints

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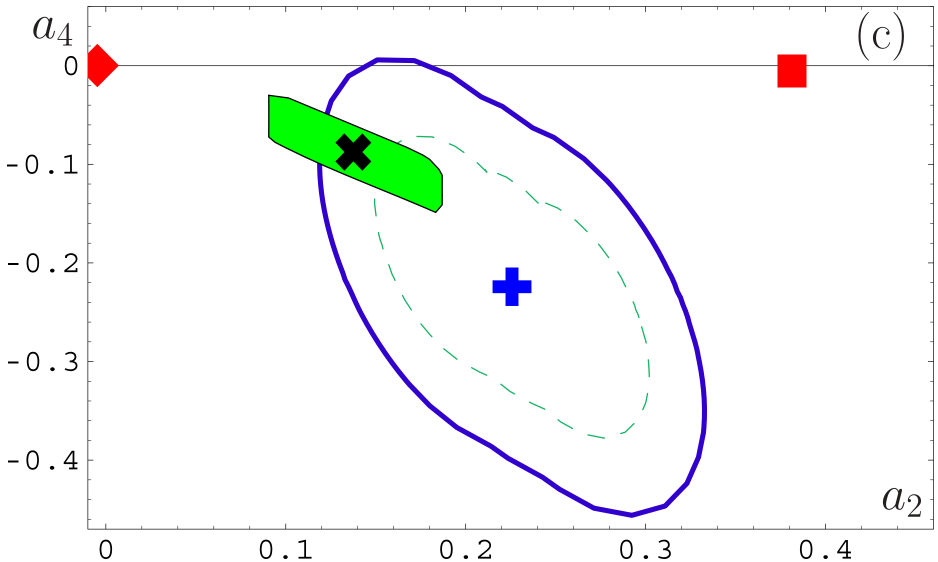


(green band) $\Leftrightarrow \lambda_q^2 = 0.4$ **GeV^2**,
$\delta^2_{\text{Tw-4}} = 0.19(2)$ **GeV^2**

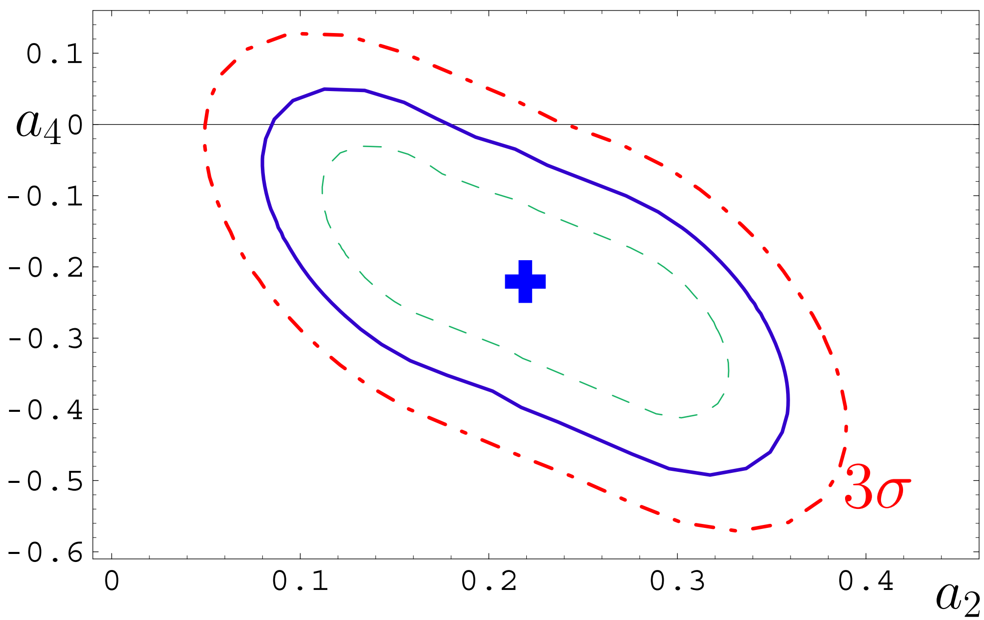
Good agreement with CLEO data for $\lambda_q^2 = 0.4$ GeV^2 ☞

For $\lambda_q^2 \lesssim 0.35$ GeV^2 agreement may be better, but:

- QCD SRs become **unstable**
- **disagreement** with lattice estimates **[Bakulev&Mikhailov, PRD 65 (2002) 114511]**

NLC SRs vs CLEO Constraints

NLO Light-Cone SR $\oplus$ **Twist-4** $\oplus(\mu^2 = Q^2)$
with 20% uncertainty of $\delta^2_{\text{Tw-4}}$: $\delta^2_{\text{Tw-4}} = 0.19(4)$ **GeV^2**
BMS [PLB 578 (2004) 91]: $\lambda_q^2 = 0.4$ **GeV^2**



✚= best-fit BMS point

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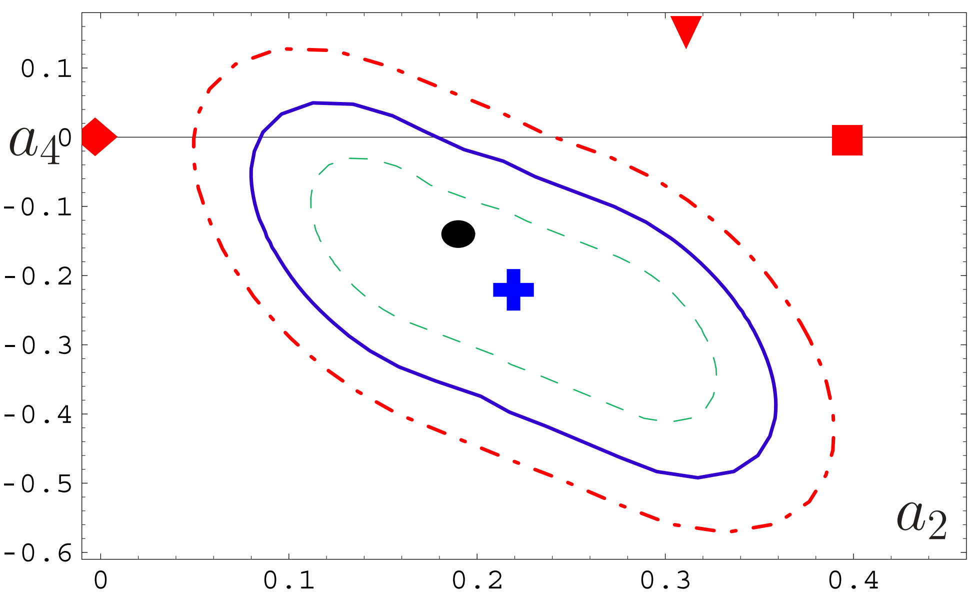

✚= best-fit BMS, ●=SY points
◆= Asymptotic DA
■= CZ DA, ▼= BF DA

Even with 20% uncertainty in twist-4
CZ, BF DA excluded **at least** at 4σ-level!
As DA — at 3σ-level.

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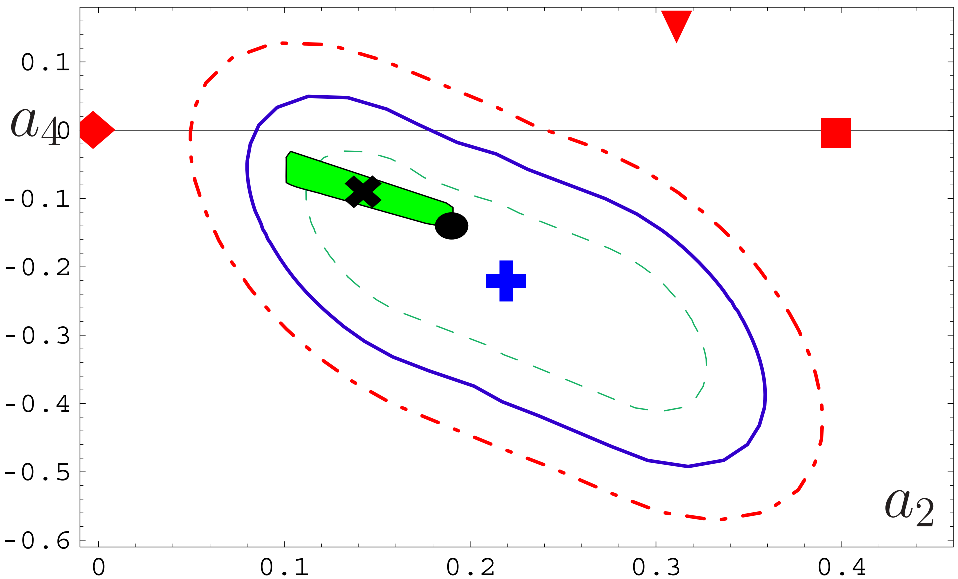

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✖ = BMS model

CZ DA excluded **at least** at 4σ-level! **As** DA — at 3σ-level.
BMS DA and most of **BMS bunch** — inside 1σ-domain.

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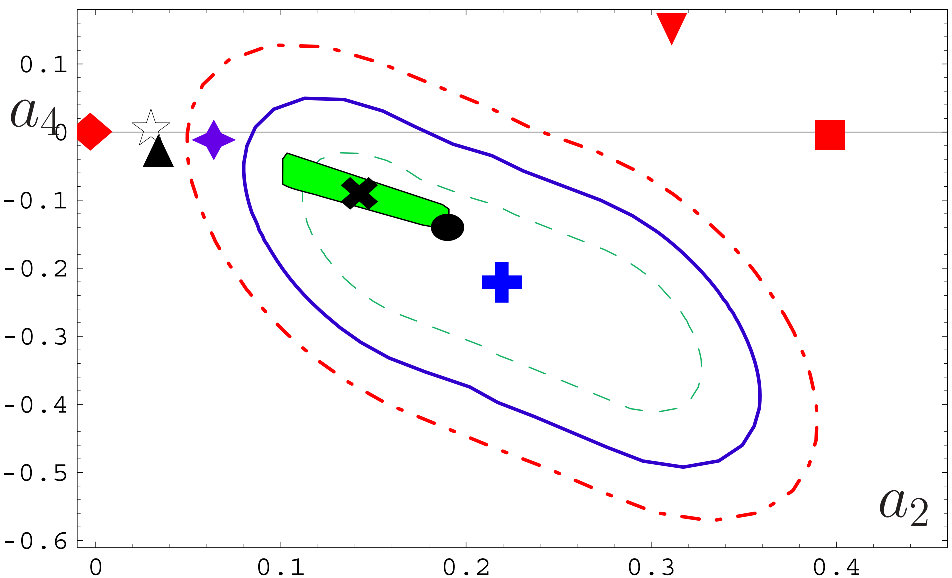

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☆, ▲ and ✧ = instantons

BMS DA and most of **BMS bunch** — inside 1σ-domain.
Instanton-based models — near 3σ-boundary
(Praszalowicz et al -model is close to 2σ-boundary).

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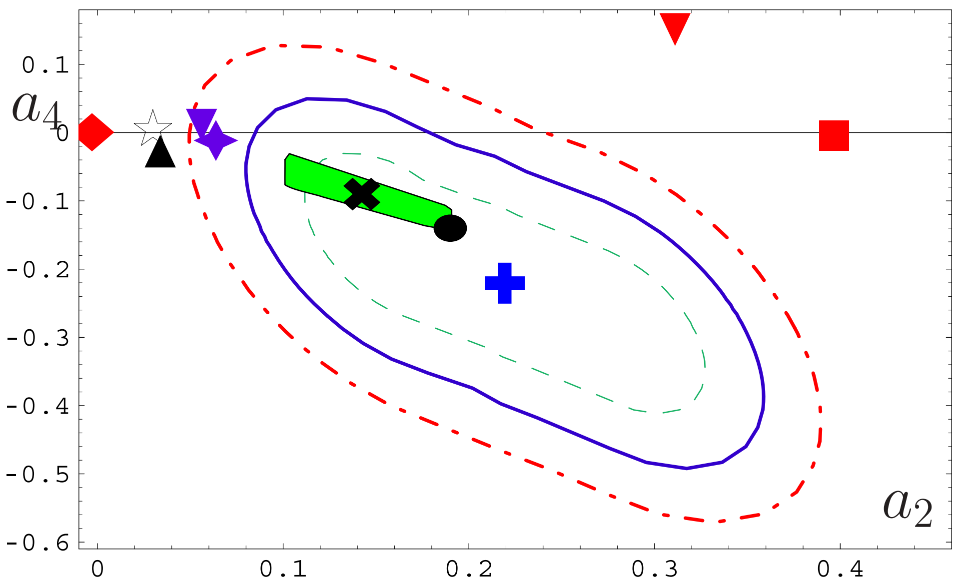

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BMS DA and most of **BMS bunch**–**inside** 1σ-domain. ☞
Transverse lattice model — near 3σ-boundary.

NLC SRs vs CLEO Constraints

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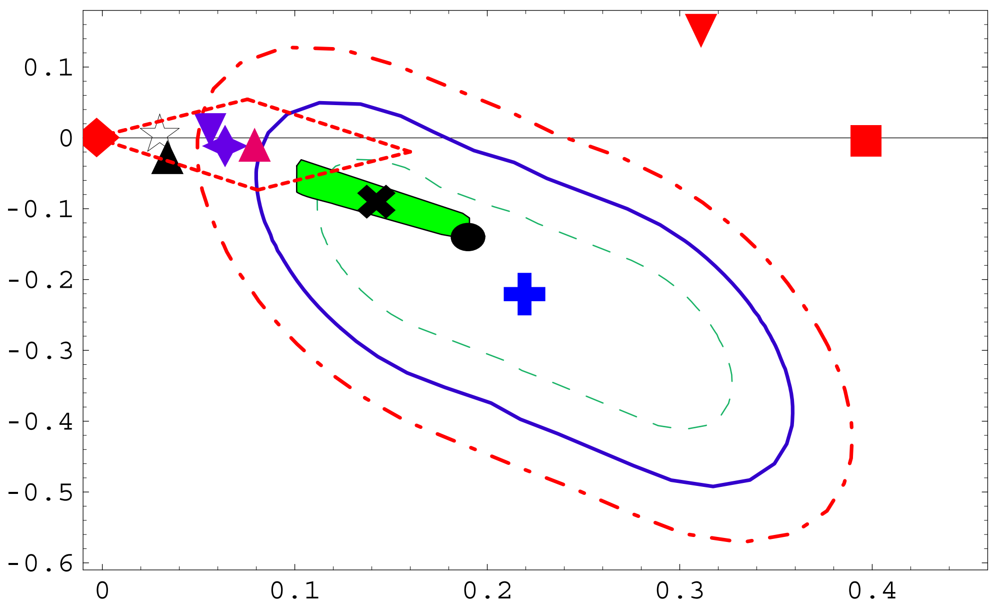

- ✚ = best-fit BMS, ● = SY points
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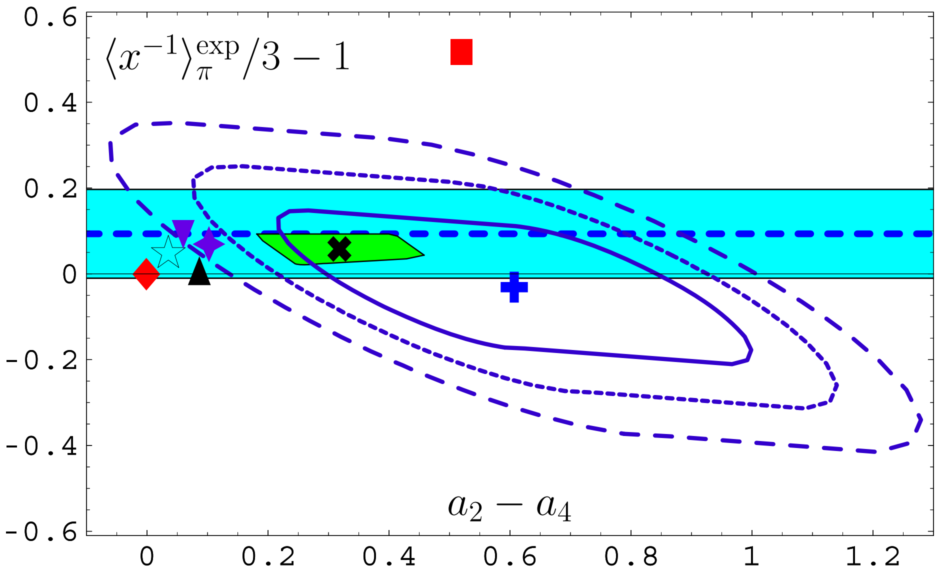
- ✖ = BMS model
- ☆, ▲ and ✦ = instantons
- ▼ = transverse lattice
- ▲ = BZ model

▲ in diamond = **[Ball and Zwicky (2005)]** constraint at 2σ-boundary.

New CLEO data constraints for $\langle x^{-1} \rangle_\pi$

BMS [PLB 578 (2004) 91]: evolution to $\mu^2 = 1$ **GeV**^{2}



$\lambda_q^2 = 0.4$ **GeV**^{2},

$\frac{1}{3}\langle x^{-1}\rangle_\pi^{\textbf{SR}} - 1 = 0.1 \pm 0.1$ ☞

See also **Bijnens&Khodjamirian [EPJC (2002)]**:

$\frac{1}{3}\langle x^{-1}\rangle_\pi - 1 = 0.24 \pm 0.16$

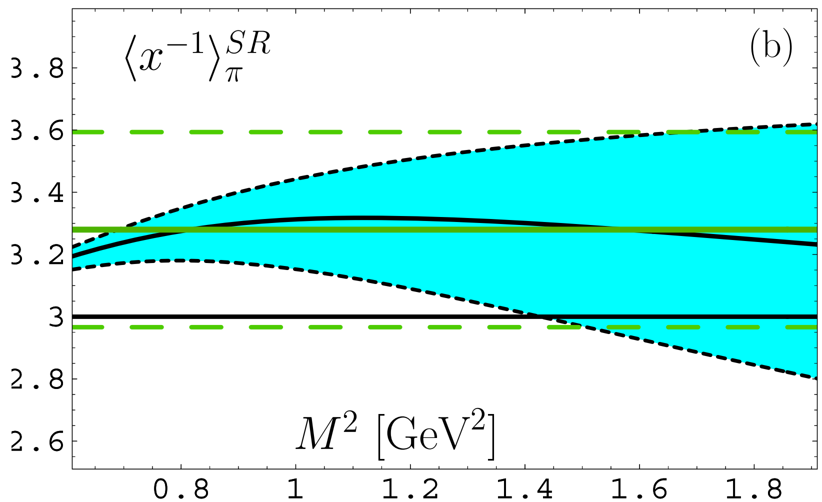
Again:

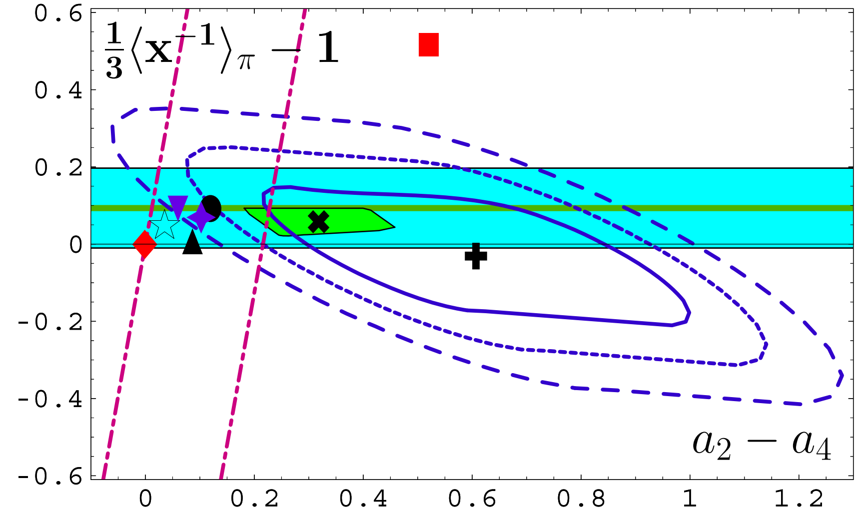
Good agreement of a theoretical “tool” of different origin with CLEO data

New CLEO data constraints for $\langle x^{-1}\rangle_\pi$

BMS [Ann. Phys.(Leipzig)13(2004) 629]:

evolution to $\mu^2 = 1$ **GeV**^{2}





$$\lambda_q^2 = 0.4 \text{ GeV}^2, \quad \frac{1}{3}\langle x^{-1}\rangle_\pi^{\text{SR}} - 1 = 0.1 \pm 0.1$$

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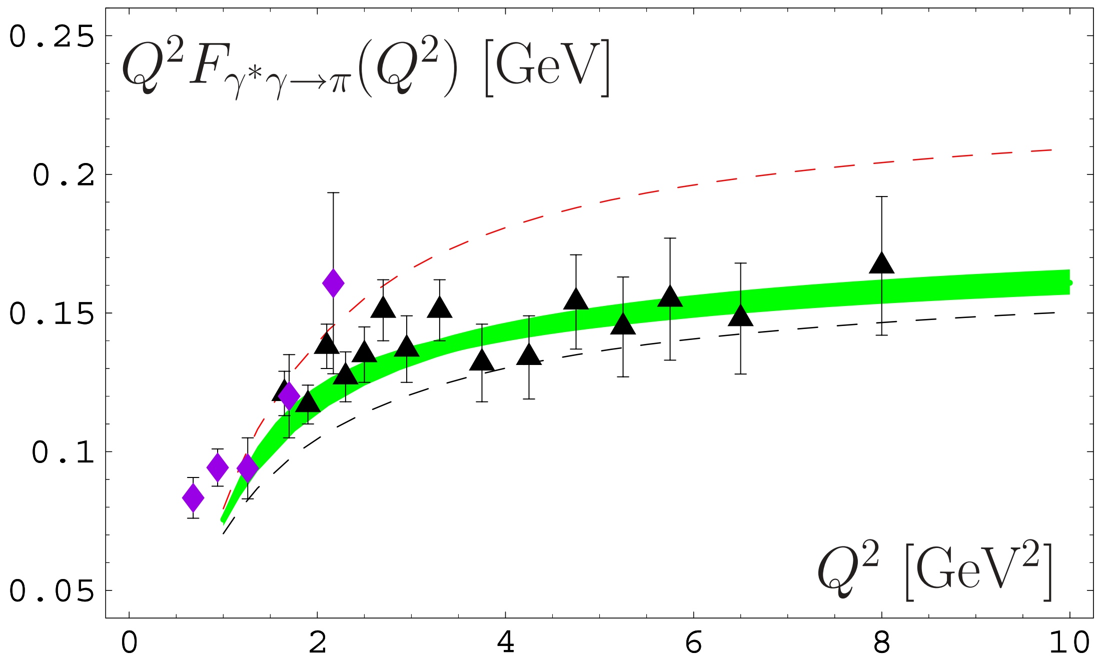
LCSR vs. CELLO (♦) & CLEO (▲) data



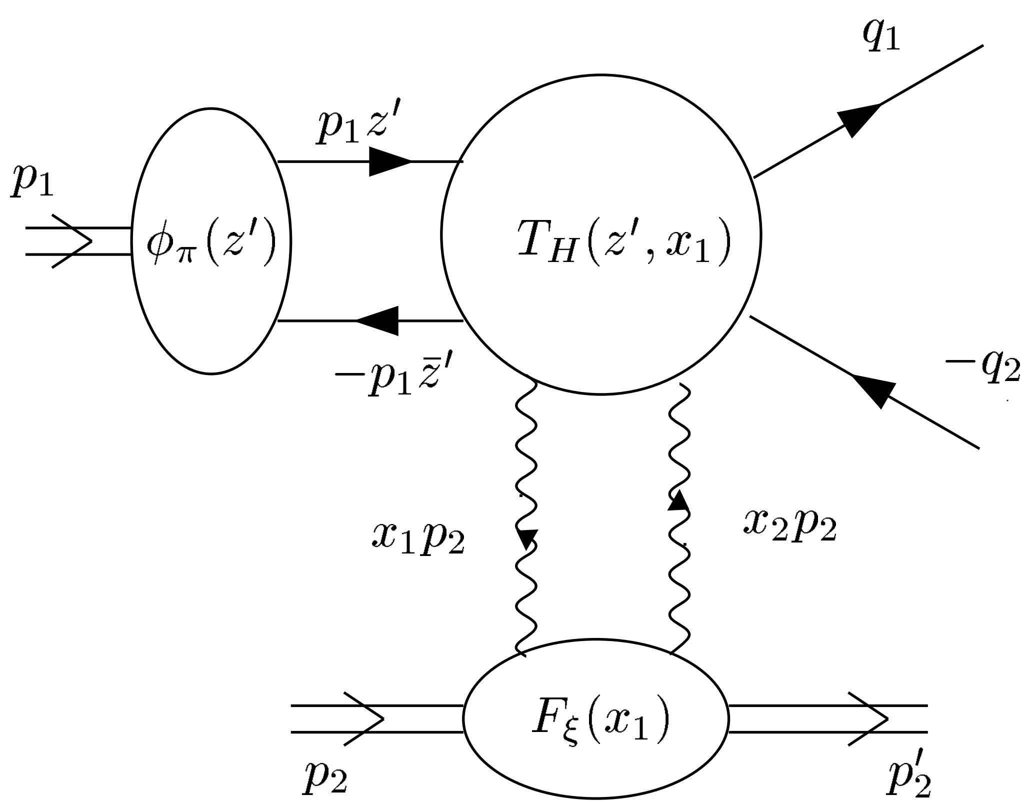
curve	DA
red dashed	CZ
green band	**BMS bunch**
black dashed	Asymp.

- **BMS bunch** describes rather well all data above $Q^2 \gtrsim 1.5$ **GeV^2**;
- Low-Q^2 CELLO data (only statistical errors shown) **excludes As DA** and high-Q^2 CLEO data **excludes CZ DA**.

What can E791 data add?

E791: Diffractive dijet production

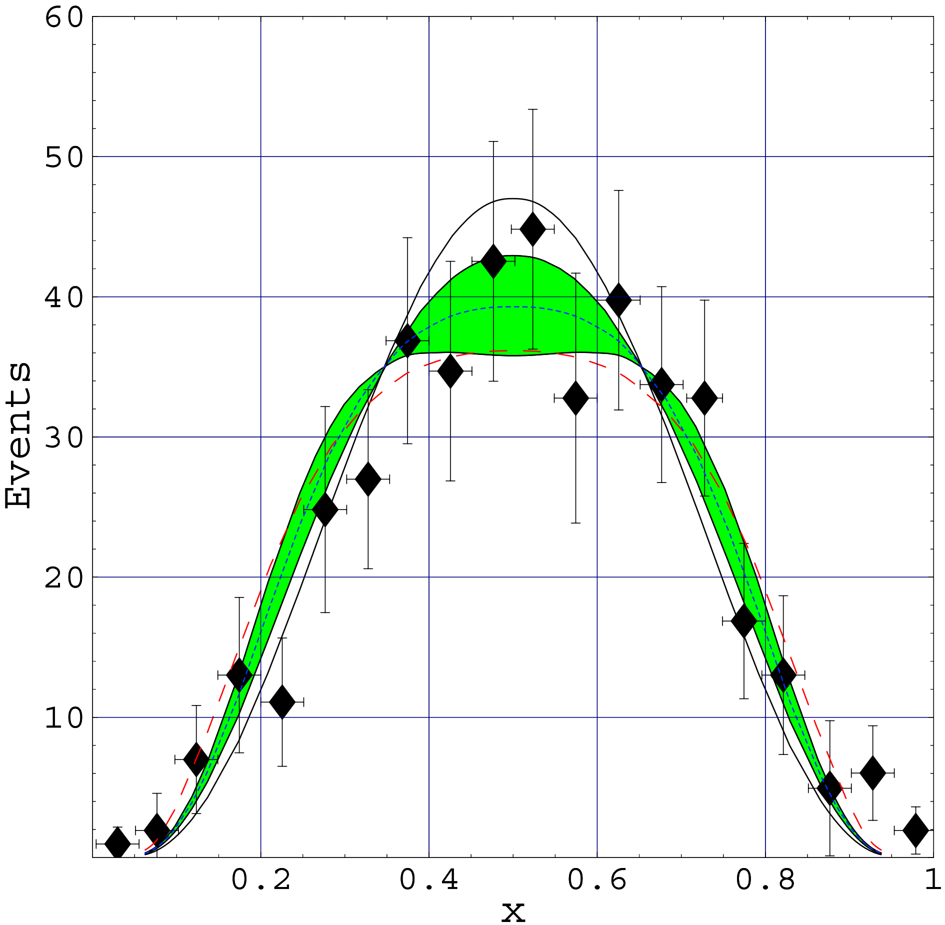
Frankfurt et al. [PLB (1993)]: Rough estimations
Braun et al. [NPB (2002)]: Account for hard GEXs



$q_\perp^2 \simeq 4$ **GeV^2**
$s \simeq 1000$ **GeV^2**

E791: Good agreement with BMS bunch

Following convolution procedure of **Braun et al.**, we found



[PLB 578 (2004) 91]

	DA	χ^2
—	Asymp.	**12.56**
(green band)	**BMS bunch**	**10.96**
- - -	**CZ**	**14.15**

(accounting for 18 data points)

Our bunch of pion DAs has maximum uncertainty in the central region, but **agrees well** with E791 data!

JLab data for $F_\pi(Q^2)$ in Analytic NLO pQCD

Analytic Perturbation Theory

Analyticization means procedure to obtain analyticity of hadronic observables in whole Q^2 region via dispersion relations (**Radyushkin, Krasnikov&Pivovarov, Dokshitzer, Beneke&Braun, Shirkov&Solovtsov**): Analytization combines

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- **RG invariance** $\Longrightarrow$ resummation of UV logs and correct QCD asymptotics
- **Causality** $\Longrightarrow$ spectral representation
  $\Longrightarrow$ **no Landau singularity**

Analytic Perturbation Theory

Analytic Perturbation Theory expresses QCD observables over **non-power sequences** $\{\mathcal{A}_k^{(L)}(Q^2)\}$ in L-loop order **[Shirkov, NPB Proc. 64 (1998) 106]**.
At 1-loop:

$$\mathcal{A}_k^{(1)}(Q^2) = \frac{1}{\pi}\int_0^\infty \frac{\rho_k^{(1)}(\sigma)\,d\sigma}{\sigma + Q^2 - i\epsilon}\ ;\ \rho_k^{(1)}(\sigma) = \textbf{Im}\left(\frac{4\pi}{b_0\ \ln(-\sigma/\Lambda^2)}\right)^k$$

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with 1-loop explicit expressions

- $\mathcal{A}_1^{(1)}(Q^2) = \dfrac{4\pi}{b_0}\left[\dfrac{1}{\ln(Q^2/\Lambda^2)} + \dfrac{\Lambda^2}{\Lambda^2 - Q^2}\right]$

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- $$\mathcal{A}_1^{(1)}(Q^2) = \frac{4\pi}{b_0}\left[\frac{1}{\ln(Q^2/\Lambda^2)} + \frac{\Lambda^2}{\Lambda^2 - Q^2}\right]$$
- $$\mathcal{A}_2^{(1)}(Q^2) = \left(\frac{4\pi}{b_0}\right)^2\left[\frac{1}{\ln^2(Q^2/\Lambda^2)} + \frac{Q^2\Lambda^2}{(\Lambda^2 - Q^2)^2}\right]$$

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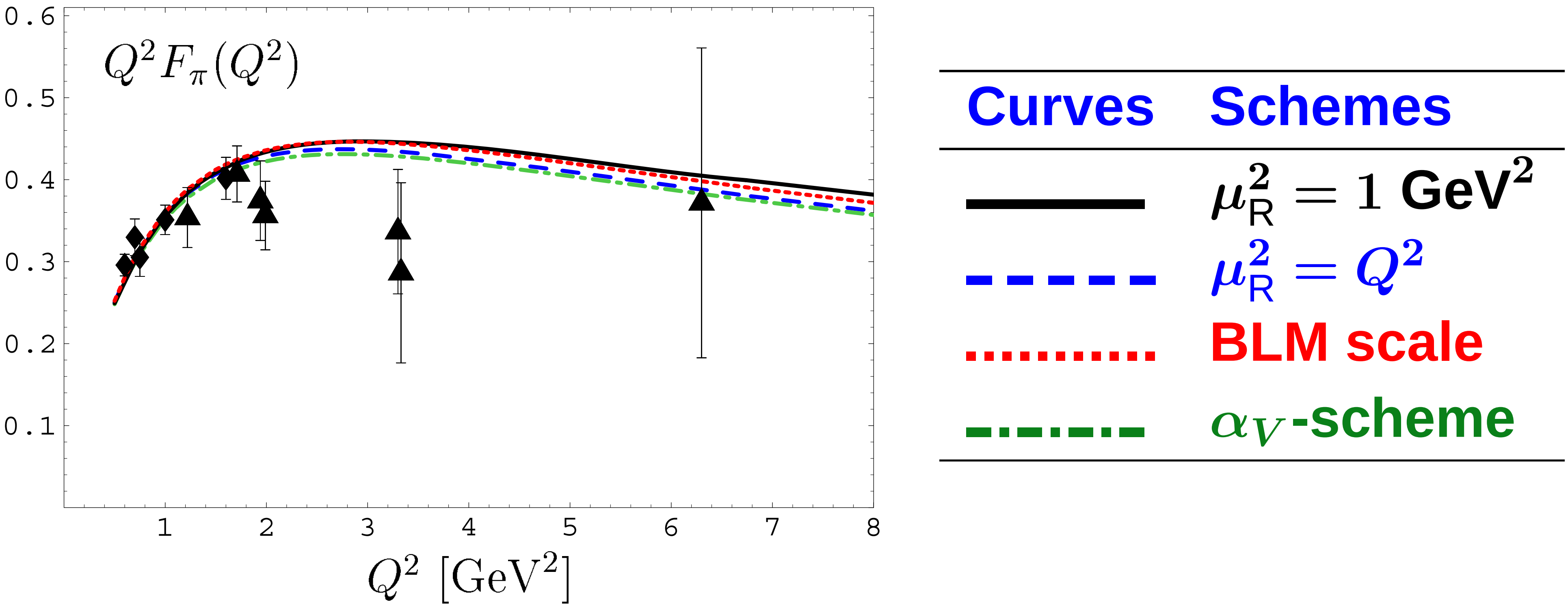
Important: $\mathcal{A}_2(Q^2) \neq \left[\mathcal{A}_1(Q^2)\right]^2$

Pion form factor in analytic NLO pQCD

[Bakulev-Passek-Schroers-Stefanis, PRD 70 (2004) 033014]



★ **De facto insensitive to scheme/scale setting**

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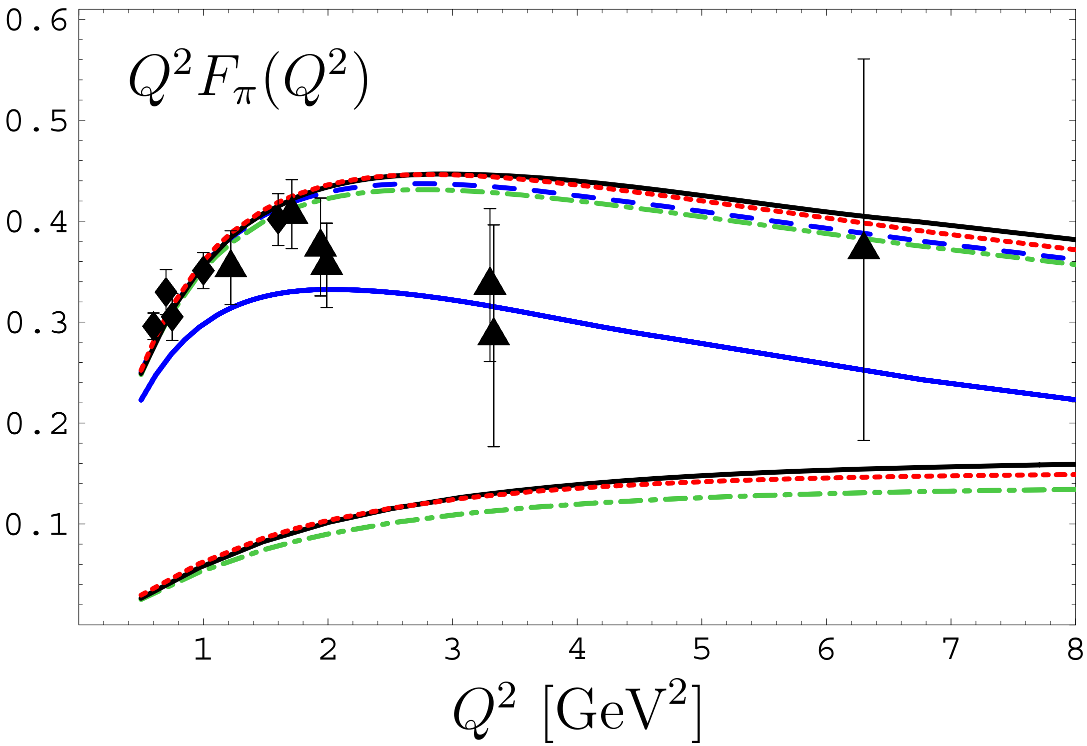
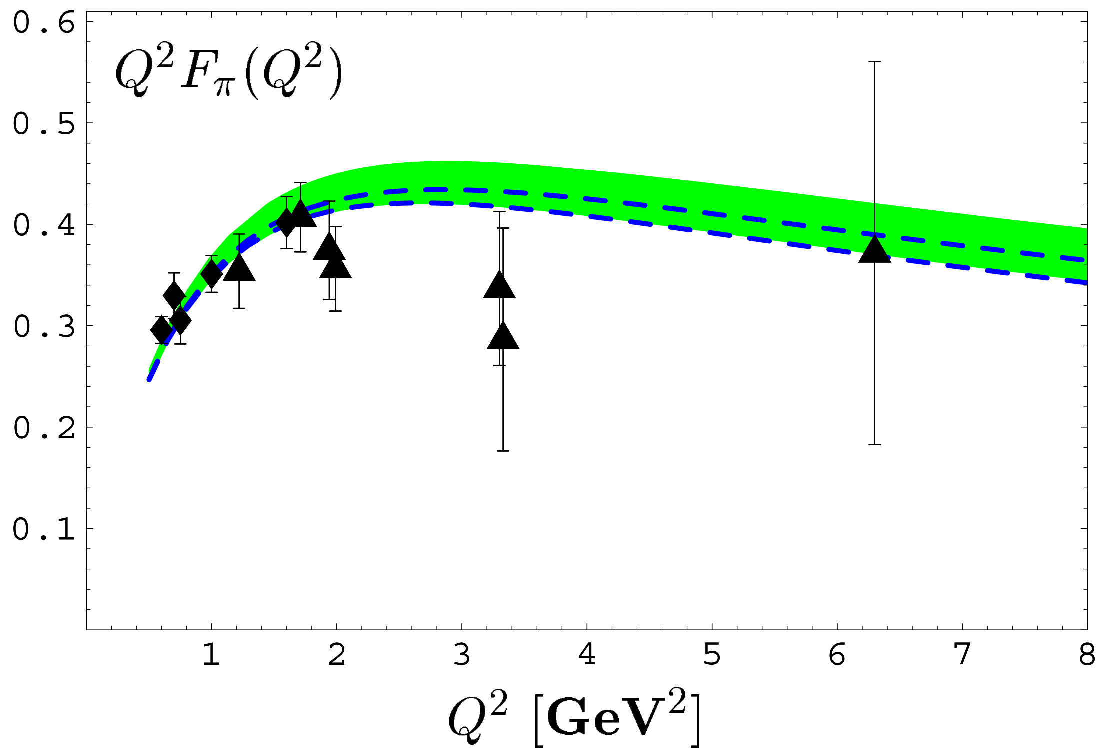


Curves	Schemes
	$\mu_R^2 = 1$ GeV^2
	$\mu_R^2 = Q^2$
	BLM scale
	α_V-scheme
	soft part

★ **De facto insensitive to scheme/scale setting**

Pion FF in analytic NLO pQCD



Green strip includes

- **NLC QCD SRs uncertainties** (**pion DA bunch**);
- **scale-setting ambiguities** at NLO level.

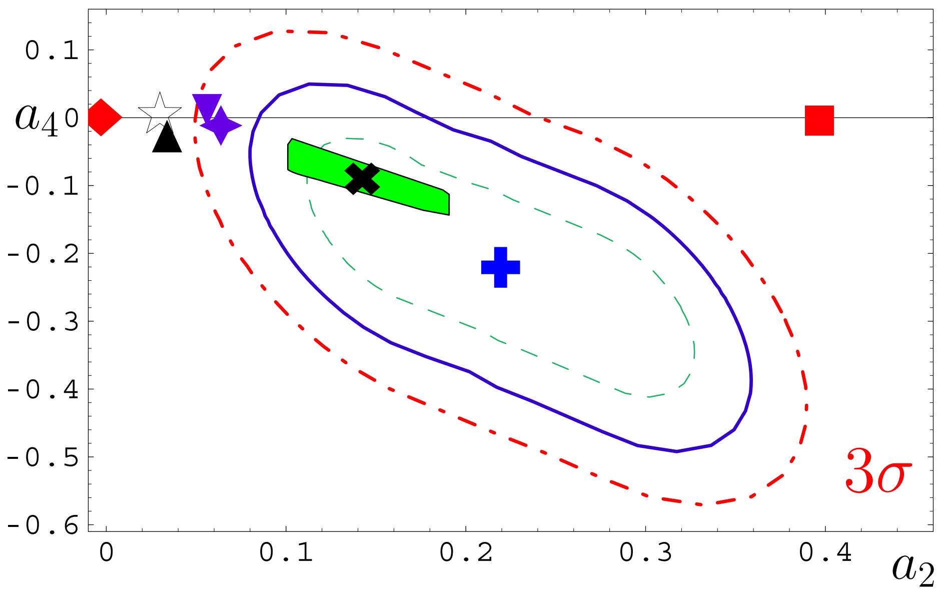
New Lattice Data
for
pion DA

CLEO Constraints and Lattice Data

NLO Light-Cone SR $\oplus$ **Twist-4** $\oplus(\mu^2 = Q^2)$

with 20% uncertainty of $\delta^2_{\text{Tw-4}}$: $\delta^2_{\text{Tw-4}} = 0.19 \pm 0.04$ **GeV^2**

BMS [PLB 578 (2004) 91]: $\lambda_q^2 = 0.4$ **GeV^2**



✚ = best-fit point
◆ = Asymptotic DA
■ = CZ DA
✖ = BMS model
☆, ▲ and ✧ = instantons
▼ = transverse lattice

BMS DA and most of **BMS bunch** — inside 1σ-domain.
Transverse lattice model — near 3σ-boundary.

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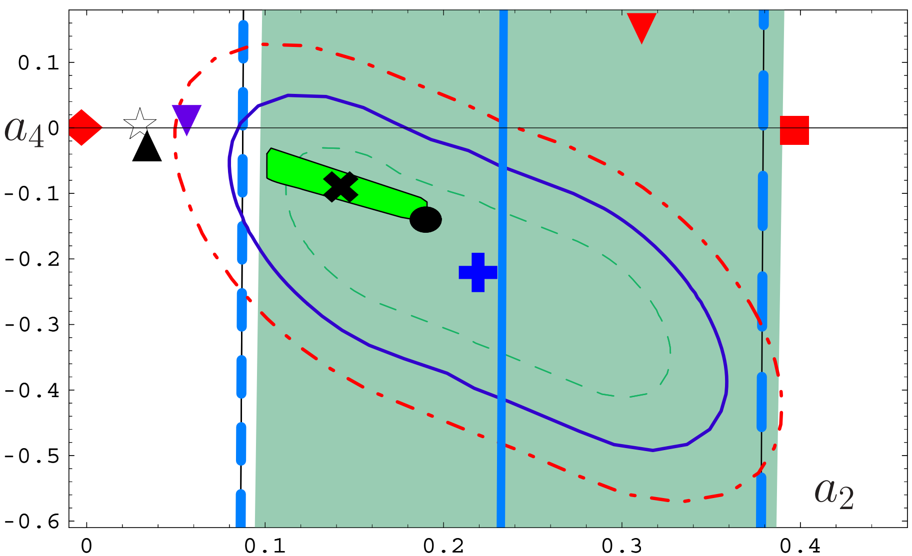

◆ = Asymptotic DA

■ = CZ DA

▼ = BF DA

✚ = best-fit point, ●=SY point

✖ = BMS model

☆, ▲ = instantons

▼ = transverse lattice

gray strip = L.Del Debbio'04

BMS DA and most of **BMS bunch** — inside 1σ-domain and inside **2004 lattice strip** **[PRD 73 (2006) 056002]**.

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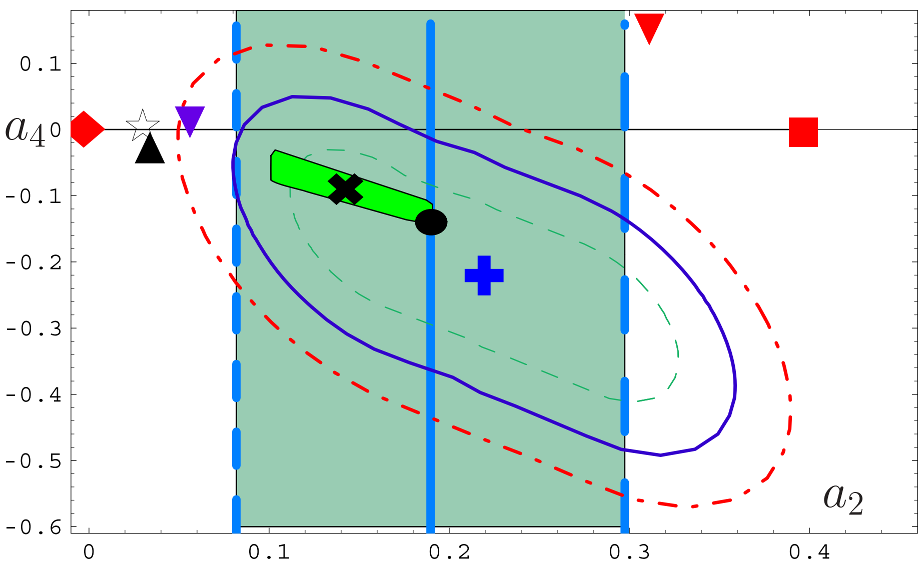
BMS [PLB 578 (2004) 91]: $\lambda_q^2 = 0.4$ **GeV**^{2}



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gray strip =QCD SF/UK'06

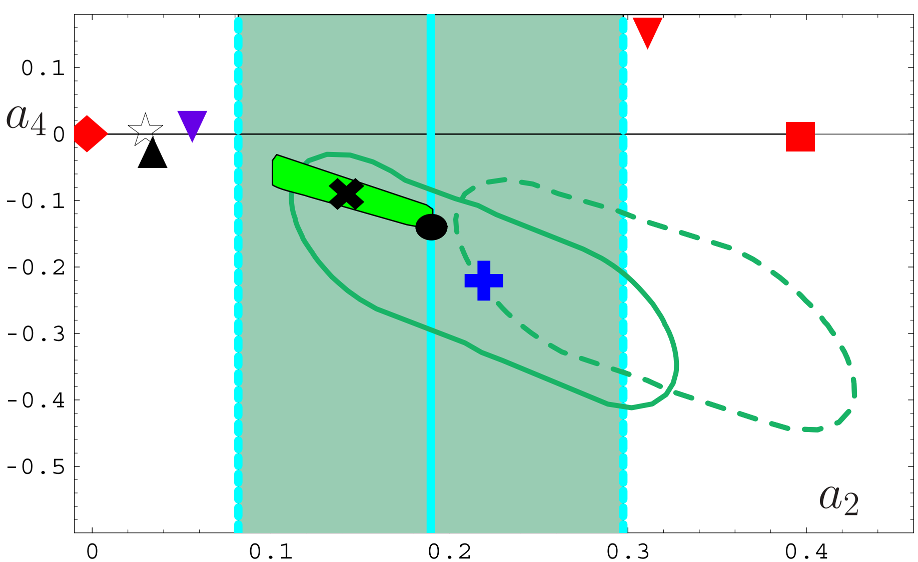
BMS DA and most of **BMS bunch** — inside 1σ-domain and **inside new** **2006 lattice strip** **[hep-lat/0606012]**. ☞

CLEO Constraints and Lattice Data

NLO Light-Cone SR $\oplus$ **Twist-4** $\oplus(\mu^2 = Q^2)$

with 10% uncertainty of $\delta^2_{\text{Tw-4}}$: $\delta^2_{\text{Tw-4}} = 0.19 \pm 0.02$ **GeV**^{2}

[PRD 73 (2006) 056002]: $\lambda_q^2 = 0.4$ **GeV**^{2}



◆ = Asymptotic DA

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✚ = best-fit point, ●=SY point

✖ = BMS model

☆, ▲ = instantons

▼ = transverse lattice

gray strip =QCD SF/UK'06

BMS DA and most of **BMS bunch** — inside 1σ-domain and inside **lattice strip**. **Dashed contour** = renormalon model estimation of Twist-4 in CLEO data analysis.

CONCLUSIONS

- **QCD SR** with **NLC** for pion DA **gives us** admissible sets**(bunches)** of DAs for each λ_q^2 value.☛

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- NLO LCSR **produces new constraints** on pion DA parameters (a_2, a_4) in conjunction with CLEO data.☛

CONCLUSIONS

- **QCD SR** with **NLC** for pion DA **gives us** admissible sets of DAs for each λ_q^2 value.
- Comparing **NLC SRs** with new CLEO **constraints allows to fix** the value of QCD vacuum nonlocality $\lambda_q^2 = 0.4$ **GeV^2**.
- NLO LCSR **produces new constraints** on pion DA parameters (a_2, a_4) in conjunction with CLEO data.
- **This bunch** of pion DAs **agrees well** with **E791** data on diffractive dijet production, with **JLab F(pi)** data on pion EM form factor and with recent **lattice** data. ☚

Collaborators & Publications

Collaborators

- A. P. Bakulev BLTPh, JINR, Dubna
- S. V. Mikhailov BLTPh, JINR, Dubna
- A. I. Karanikas University of Athens, Athens

Publications

- A.P.B., S.V.M., N.G.S. **PLB 508 (2001) 279**
- A.P.B., S.V.M., N.G.S. **PRD 67 (2003) 074012**
- A.P.B., S.V.M., N.G.S. **PLB 578 (2004) 91**
- A.P.B. *et al.* **PRD 70 (2004) 033014**
- A.P.B., N.G.S. **NPB 721 (2005) 50**
- A.P.B., A.I.K., N.G.S. **PRD 72 (2005) 074015**
- A.P.B., S.V.M., N.G.S. **PRD 73 (2006) 056002**