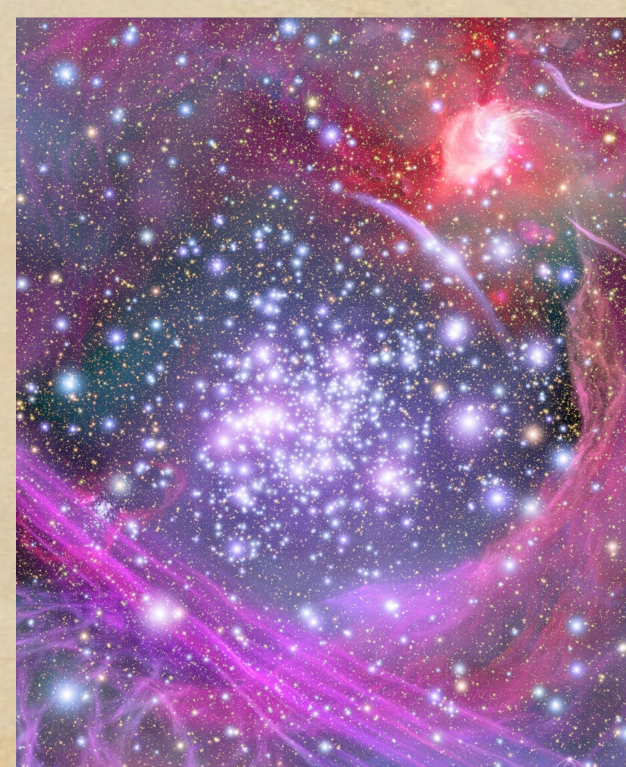
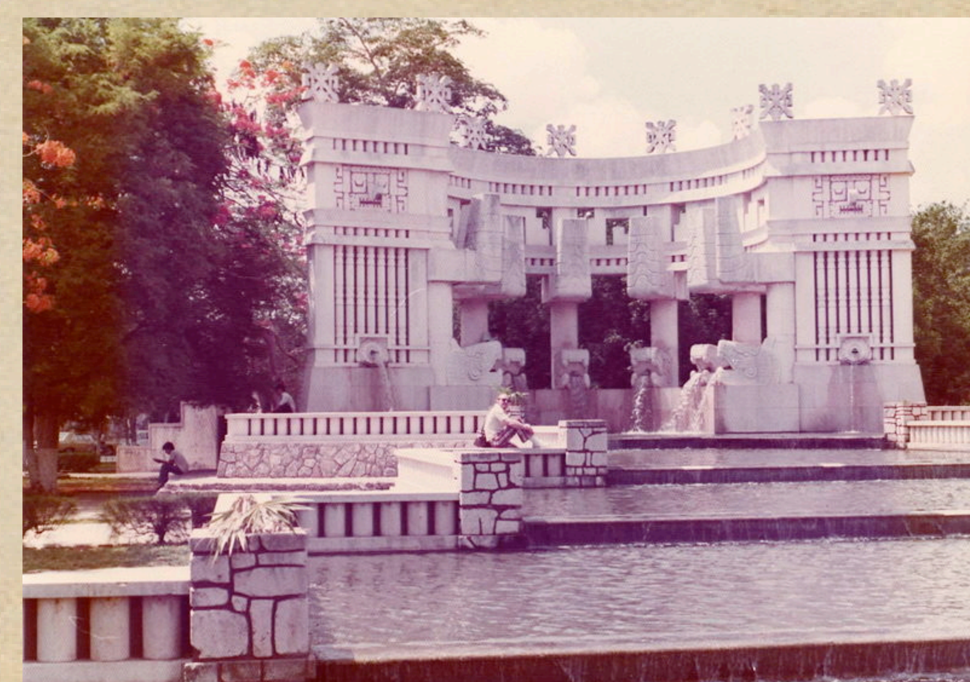
Does Confinement Decouple QCD Condensates from the Cosmological Constant ?

Peter C. Tandy

Dept of Physics
Kent State University USA

$$\langle 0 | \bar{q}q | 0 \rangle$$





Collaborators:

- Stan Brodsky, SLAC, Stanford Univ
- Robert Shrock, CN Yang Inst for Th Phys, Stony Brook
- Craig Roberts, Theory, Phys Div, Argonne National Lab
- Lei Chang, Peking Univ & Julich

Outline

- Are "vac quark & gluon condensates" really a property of the void?
- Strong evidence that quark condensate is really an in-hadron property
- Eliminates the big problem with conventional QCD prediction of vacuum energy density
- Quark and gluon confinement is necessary to the argument and suggests all QCD condensates are either in hadrons or are zero
- The QCD vacuum would be trivial as required by Light-front QFT

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References:

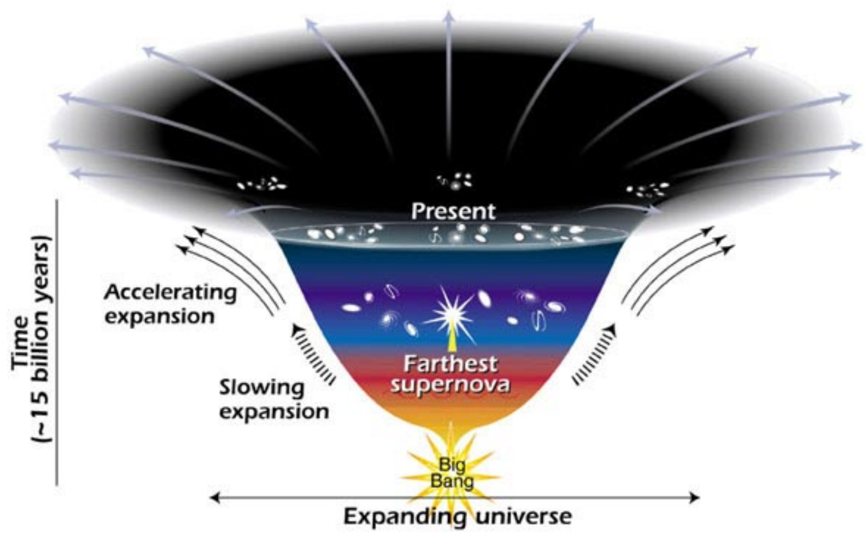
Condensates in QCD and the Cosmological Constant, S.J. Brodsky& R.Shrock, Proc. Nat. Acad. Sci., 108, 45 (2011).

New Perspectives on the Quark Condensate, S.J. Brodsky, C.D. Roberts, R.Shrock&P.C.Tandy, Phys. Rev, C82, 022201 (2010).

Expanding the Concept of In-hadron Condensates, L.Chang, C.D. Roberts&P.C. Tandy, Phys. Rev. C85, 012201 (2012)

Confinement Contains Condensates, S.J. Brodsky, C.D. Roberts, R.Shrock&P.C.Tandy, Phys. Rev, Cxx, accepted (2012).

1998: The universe is expanding at an accelerating rate



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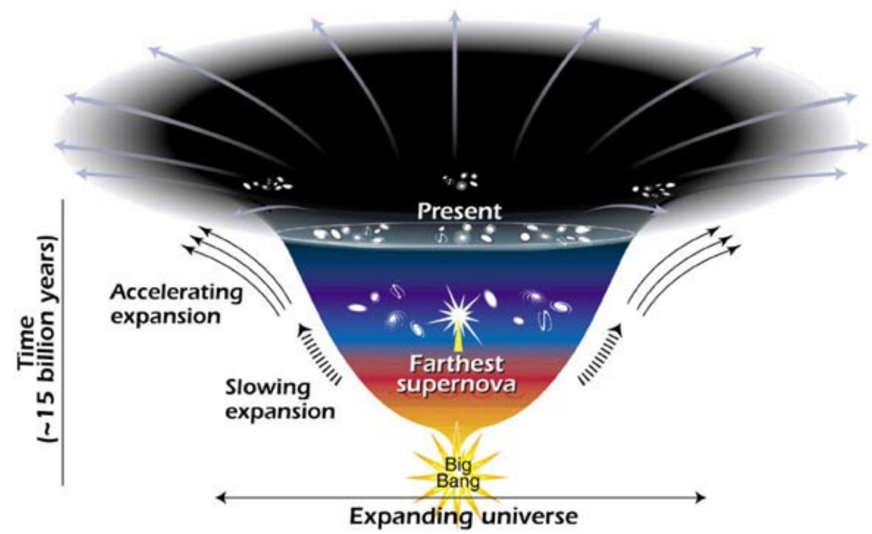
Nobel Physics Prize 2011



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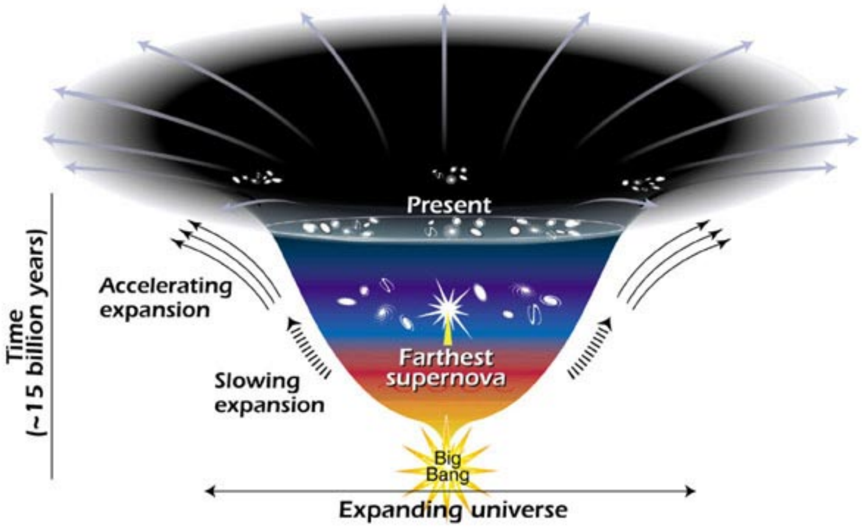
This dark energy repulsion is consistent with a cosmological constant:

$$\mathbf{R}_{\mu\nu} - \frac{1}{2}\mathbf{R}\,\mathbf{g}_{\mu\nu} = \frac{8\pi\mathbf{G}}{\mathbf{c}^4}\left\{\mathbf{T}^{\rm MAT}_{\mu\nu} - \mathbf{T}^{\rm DE}_{\mu\nu}\right\} \qquad \mathbf{\Lambda}\,\mathbf{g}_{\mu\nu} = \frac{8\pi\mathbf{G}}{\mathbf{c}^4}\mathbf{T}^{\rm DE}_{\mu\nu} = \rho_\Lambda\,\mathbf{c}^2\,\mathbf{g}_{\mu\nu}$$

$$\mathbf{\Lambda}_{\rm expt} \Rightarrow \rho_\Lambda \sim (\mathbf{2.3}\ \ \mathbf{10^{-3}\ eV})^{\mathbf{4}}$$



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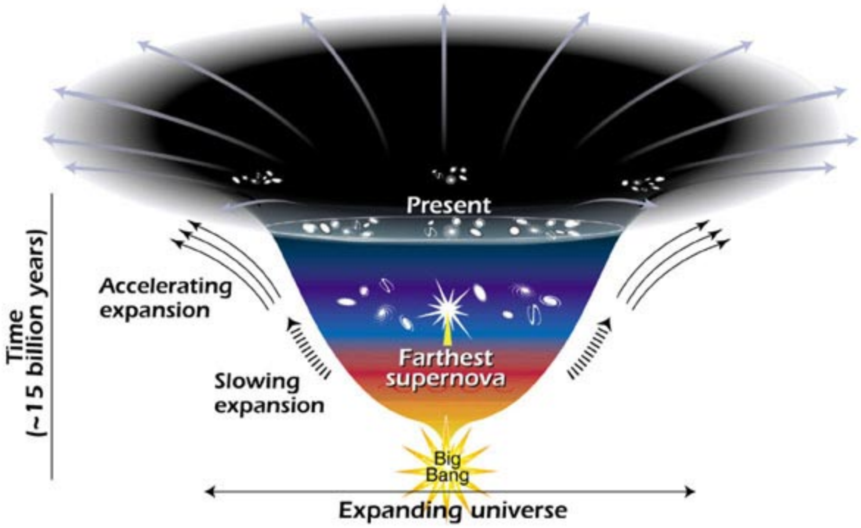
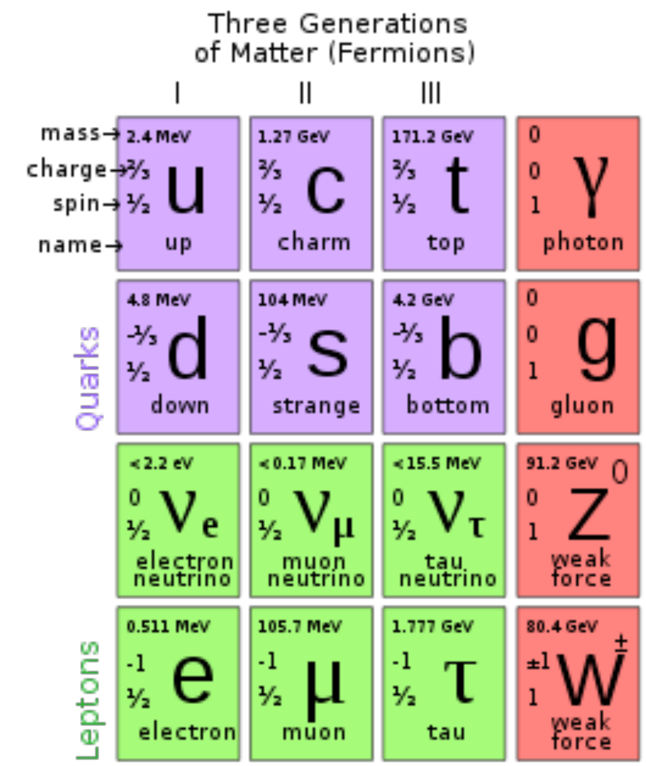
$$\Lambda_{\mathrm{expt}} \quad \Rightarrow \rho_\Lambda \sim (\mathbf{2.3\ \ 10^{-3}\ eV})^4$$

- Could be SUSY/BSM particles, ...
- Or could be QFT vacuum energy density, coming from:
- “vacuum” condensates of fields of the Standard Model, eg: QCD, Electroweak (esp Higgs field),...
- Problem: they overwhelm all else !



Typical Estimates of QFT Vacuum Energy Density from the Standard Model

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm QCD}(\mathbf{q},\, \mathbf{G}) + \mathcal{L}_{\rm EW}(l,\, \nu_l;\, \mathbf{q};\, \gamma,\, \mathbf{W},\, \mathbf{Z},\, \mathbf{H}) + \mathcal{L}_{\rm G}(\phi_{\mathbf{m}},\, \mathbf{g};\, \hbar = \mathbf{0})$$



$$\textbf{QFT vacuum fluctuations give } \left(\frac{\Lambda_{\rm theory}}{\Lambda_{\rm expt}}\right) : -$$

$$\mathcal{L}_{\rm QCD} \Rightarrow\ \mathbf{10^{46}}, \qquad \textbf{mostly due to } \langle \mathbf{0} \,|\, \bar{\mathbf{q}}\mathbf{q} \,|\, \mathbf{0} \rangle \sim \mathbf{\Lambda^3_{\rm QCD}} \sim (\mathbf{0.250}\ \text{GeV})^{\mathbf{3}}$$

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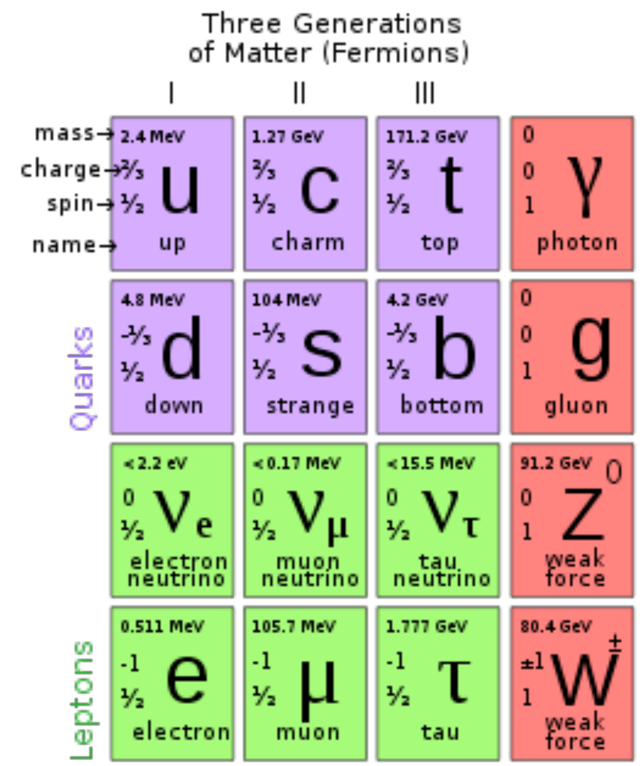

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$$\mathcal{L}_{\mathrm{EW}} \Rightarrow \; \mathbf{10^{56}}, \qquad \textbf{mostly due to } \langle \mathbf{0} \,|\, \mathbf{H} \,|\, \mathbf{0} \rangle \sim \mathbf{246}\ \mathrm{GeV}$$

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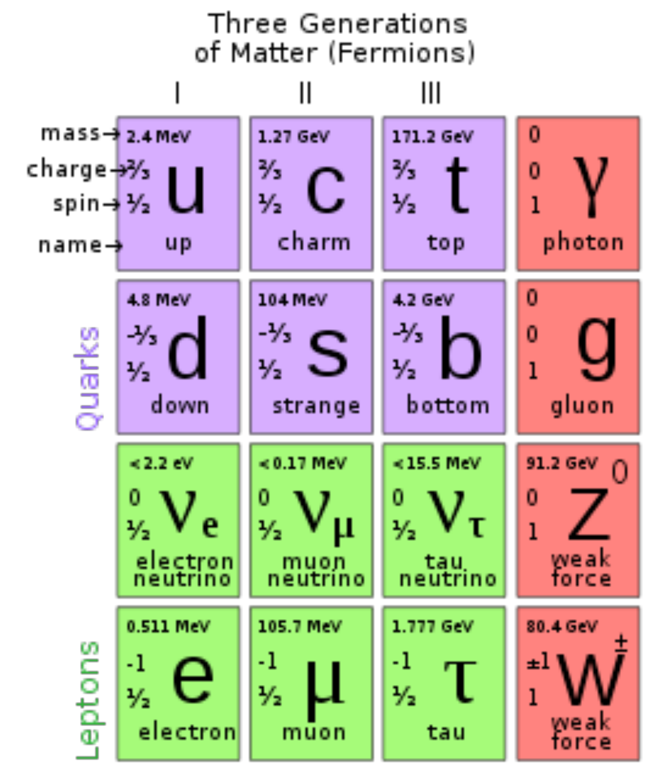

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$\mathcal{L}_{\rm G} + \mathcal{L}_{\rm SUSY} \Rightarrow\ \mathbf{10^{120}}$, **scaling arguments**

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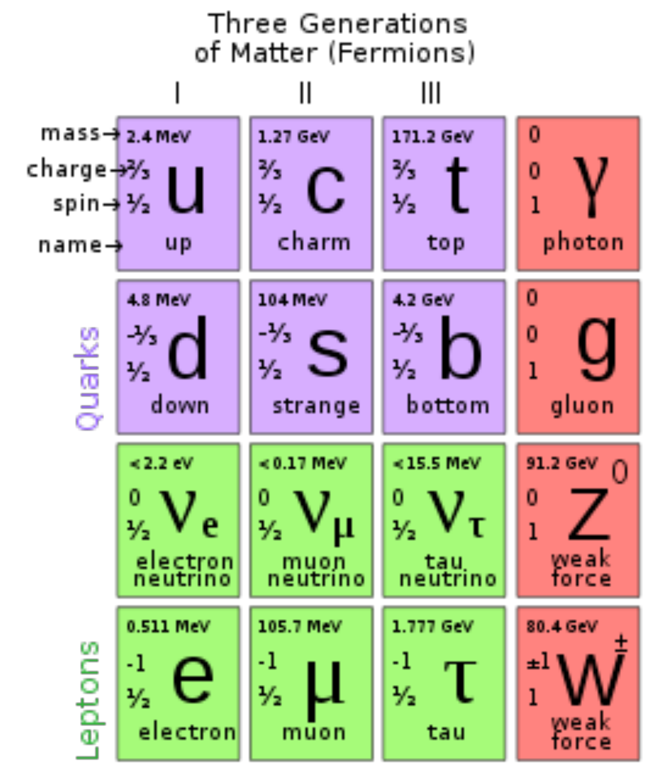

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Called the Worst Prediction Physics Ever Made

KENT STATE UNIVERSITY

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Example:

The QCD nature of Dark Energy.
Federico R. Urban, Ariel R. Zhitnitsky (British Columbia U.). Sep 2009. 41 pp.
Published in **Nucl.Phys. B835 (2010) 135-173**
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Detailed record - Cited by 47 records

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Low energy gravity as an effective QFT in interaction with QCD effective fields, eg Veneziano ghost of UA(1) fame

$$\Rightarrow \quad \rho_{\mathrm{vac}} = \mathbf{c}\,\frac{\mathbf{2H}}{\mathbf{m}_{\eta'}}\,\mathbf{m_q}\,|\langle\bar{\mathbf{q}}\mathbf{q}\rangle| \;\approx \mathbf{6}\,\rho_{\Lambda}^{\mathbf{obsv}}$$

(H = Hubble's constant)

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BUT, again relies upon QCD providing the (large) quark condensate filling all space. Does it really do that?

On what basis can one question that the quark condensate fills all space ?

GMOR Relation

Behavior of current divergences under SU(3) x SU(3),
Murray Gell-Mann, R.J. Oakes , B. Renner, Phys.Rev. 175 (1968) 2195-2199

- $\mathbf{Today's\ useage:}\quad \mathbf{f_\pi^2\, m_\pi^2 \;=\; 2\, m_q(\mu)\, \langle 0|\, \bar{q}q\, |0\rangle_\mu}$

- **On what basis can one question that the quark condensate fills all space ?**

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- Quick tour of present capabilities in continuum (non – lattice) modeling of QCD for hadron physics, based on the Dyson – Schwinger eqns of QCD........

DSE-based modeling of Hadron Physics

- Soft physics: truncate DSEs to min: 2-pt, 3-pt fns
- Should be relativistically covariant—-convenient for decays, Form Factors, etc
  - No boosts needed on wavefns of recoiling bound st.
  - ∞ d.o.f. $\rightarrow$ few quasi-particle effective d.o.f.
- Do not make a 3-dimensional reduction
- Preserve 1-loop QCD renorm group behavior in UV
- Preserve global symmetries, conserved em currents, etc
- Preserve PCAC $\Rightarrow$ Goldstone's Thm
- Can't preserve local color gauge covariance—-just choose Landau gauge [RG fixed pt]
- Parameterize the deep infrared (large distance) QCD coupling

Summary of light meson results

$m_{u=d} = 5.5$ MeV, $m_s = 125$ MeV at $\mu = 1$ GeV

Pseudoscalar (PM, Roberts, PRC56, 3369)

	expt.	calc.
$-\langle \bar{q}q \rangle^0_\mu$	$(0.236\ \text{GeV})^3$	$(0.241^\dagger)^3$
m_π	0.1385 GeV	$0.138^\dagger$
f_π	0.0924 GeV	$0.093^\dagger$
m_K	0.496 GeV	$0.497^\dagger$
f_K	0.113 GeV	0.109

Charge radii (PM, Tandy, PRC62, 055204)

r^2_π	0.44 fm^2	0.45
$r^2_{K^+}$	0.34 fm^2	0.38
$r^2_{K^0}$	-0.054 fm^2	-0.086

$\gamma\pi\gamma$ transition (PM, Tandy, PRC65, 045211)

$g_{\pi\gamma\gamma}$	0.50	0.50
$r^2_{\pi\gamma\gamma}$	0.42 fm^2	0.41

Weak K_{l3} decay (PM, Ji, PRD64, 014032)

$\lambda_+(e3)$	0.028	0.027
$\Gamma(K_{e3})$	$7.6 \cdot 10^6\ \text{s}^{-1}$	7.38
$\Gamma(K_{\mu 3})$	$5.2 \cdot 10^6\ \text{s}^{-1}$	4.90

Vector mesons (PM, Tandy, PRC60, 055214)

$m_{\rho/\omega}$	0.770 GeV	0.742
$f_{\rho/\omega}$	0.216 GeV	0.207
m_{K^*}	0.892 GeV	0.936
f_{K^*}	0.225 GeV	0.241
m_ϕ	1.020 GeV	1.072
f_ϕ	0.236 GeV	0.259

Strong decay (Jarecke, PM, Tandy, PRC67, 035202)

$g_{\rho\pi\pi}$	6.02	5.4
$g_{\phi KK}$	4.64	4.3
$g_{K^*K\pi}$	4.60	4.1

Radiative decay (PM, nucl-th/0112022)

$g_{\rho\pi\gamma}/m_\rho$	0.74	0.69
$g_{\omega\pi\gamma}/m_\omega$	2.31	2.07
$(g_{K^*K\gamma}/m_K)^+$	0.83	0.99
$(g_{K^*K\gamma}/m_K)^0$	1.28	1.19

Scattering length (PM, Cotanch, PRD66, 116010)

a^0_0	0.220	0.170
a^2_0	0.044	0.045
a^1_1	0.038	0.036

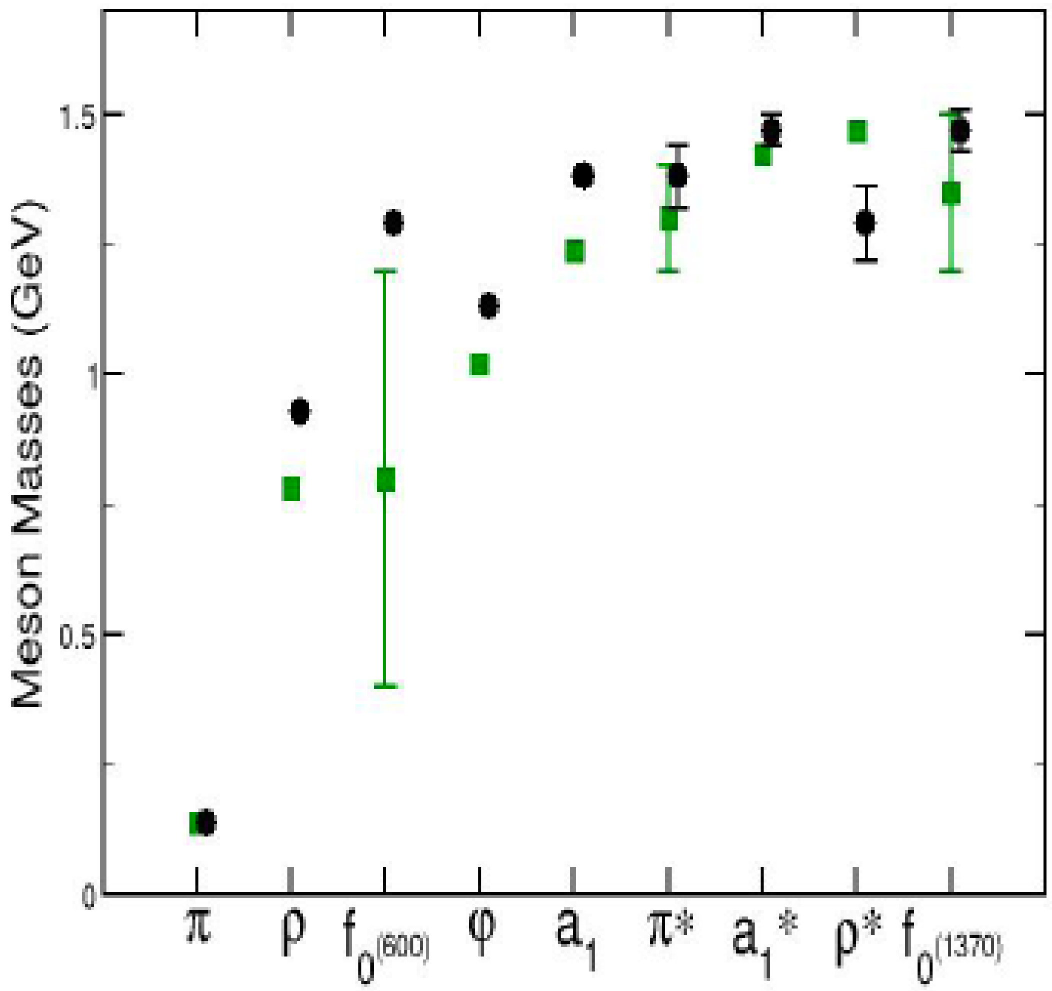
In summary: 31 exptl data @ RMS error of 15%

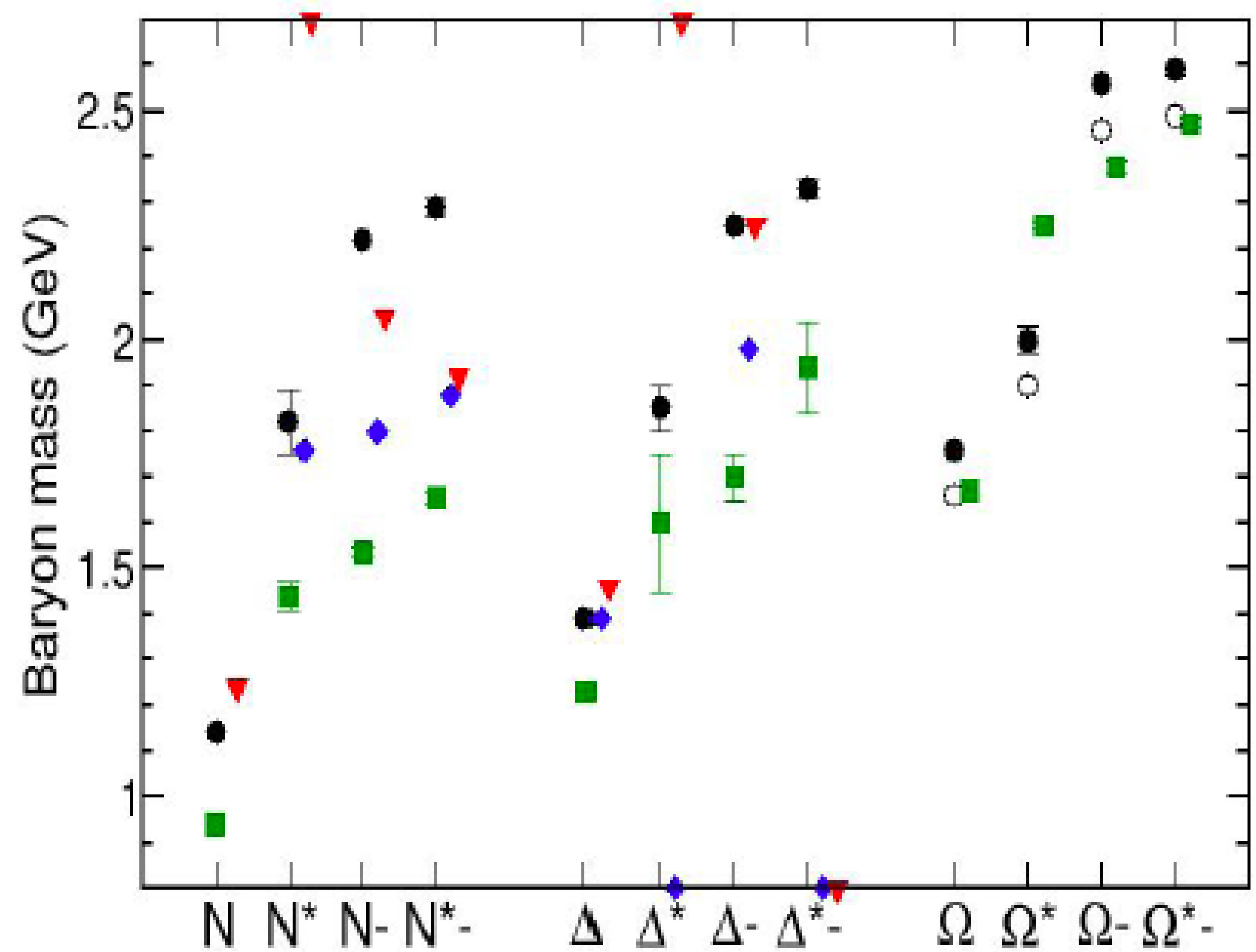
Hadron Spectrum

Legend:
- Particle Data Group
- H.L.L. Roberts *et al.* nucl-th/1102.4376
- EBAC
- Jülich

DSE contact model

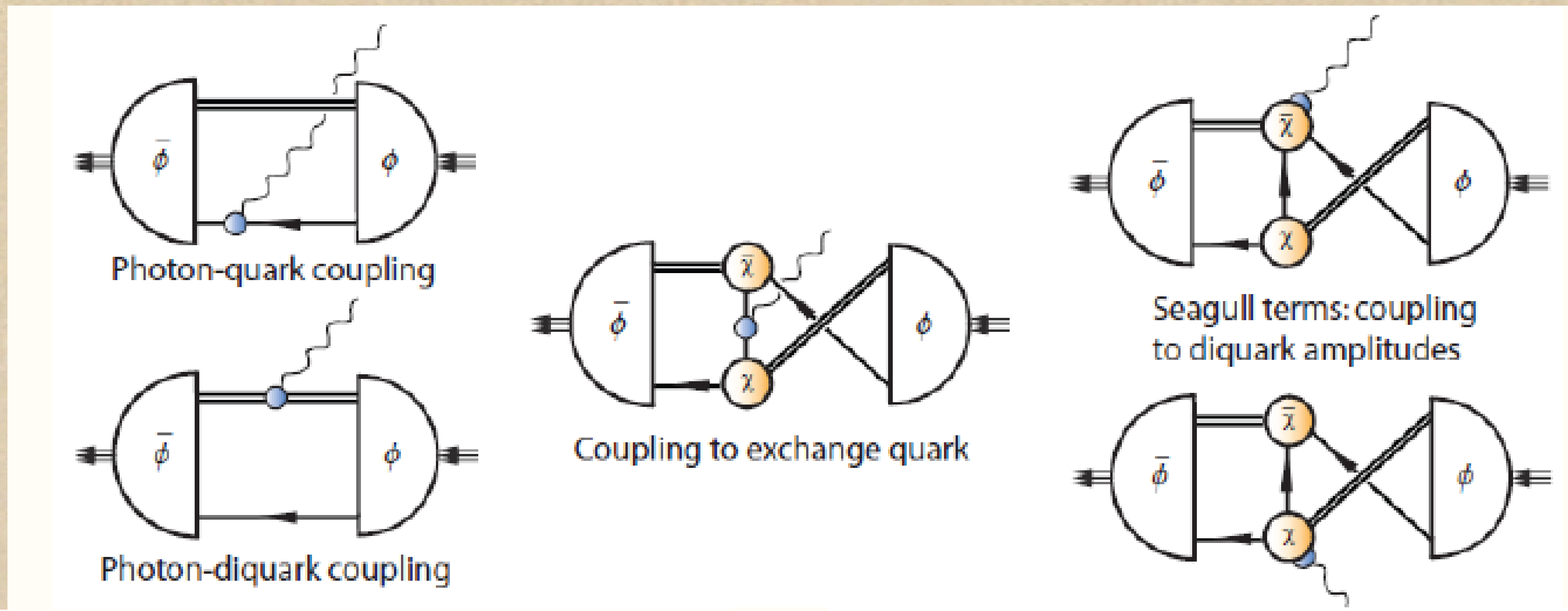
- Symmetry-preserving unification of the computation of meson & baryon masses
- rms-rel.err./deg-of-freedom = 13%
- PDG values (almost) uniformly overestimated in both cases - room for the pseudoscalar meson cloud?!

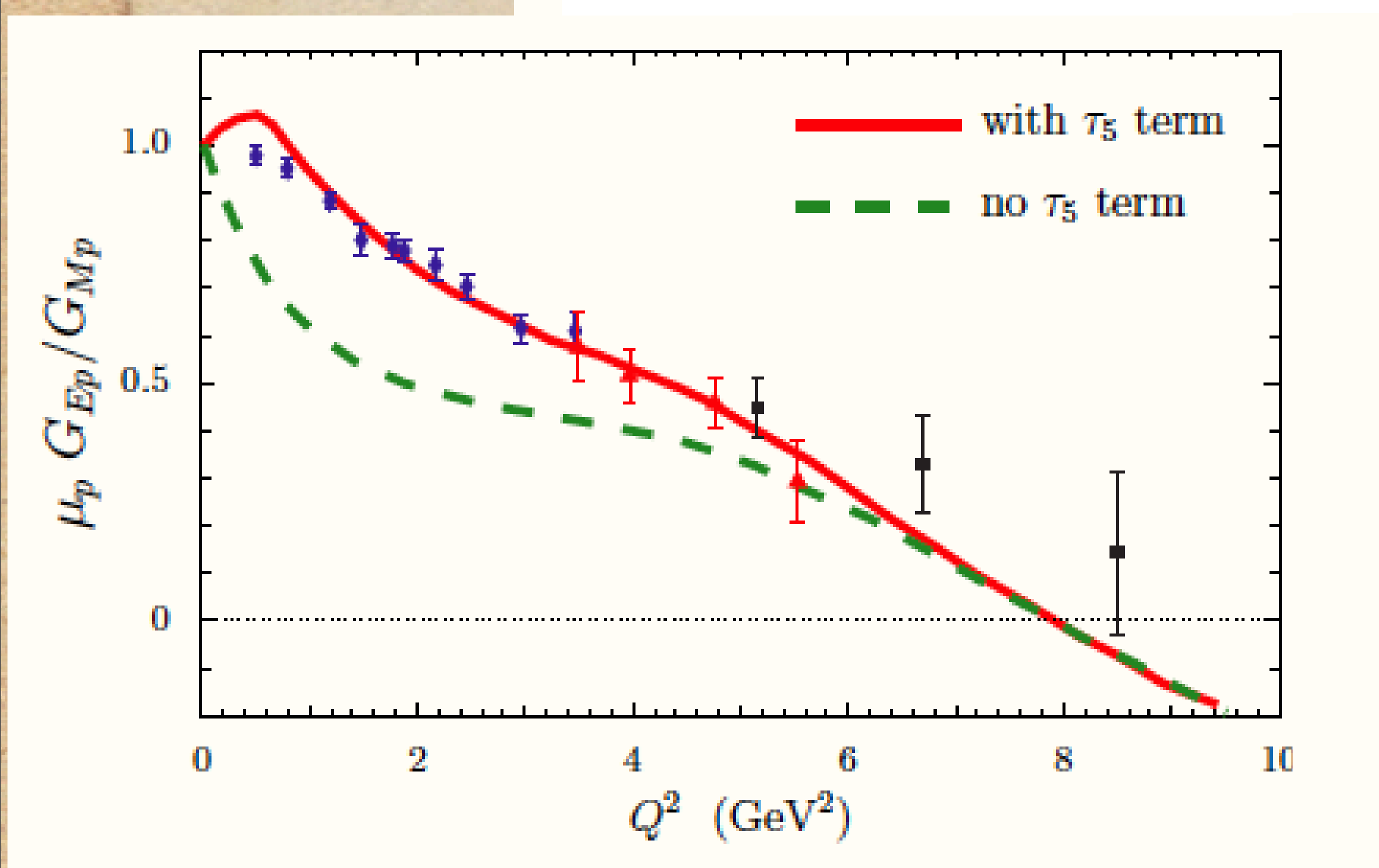


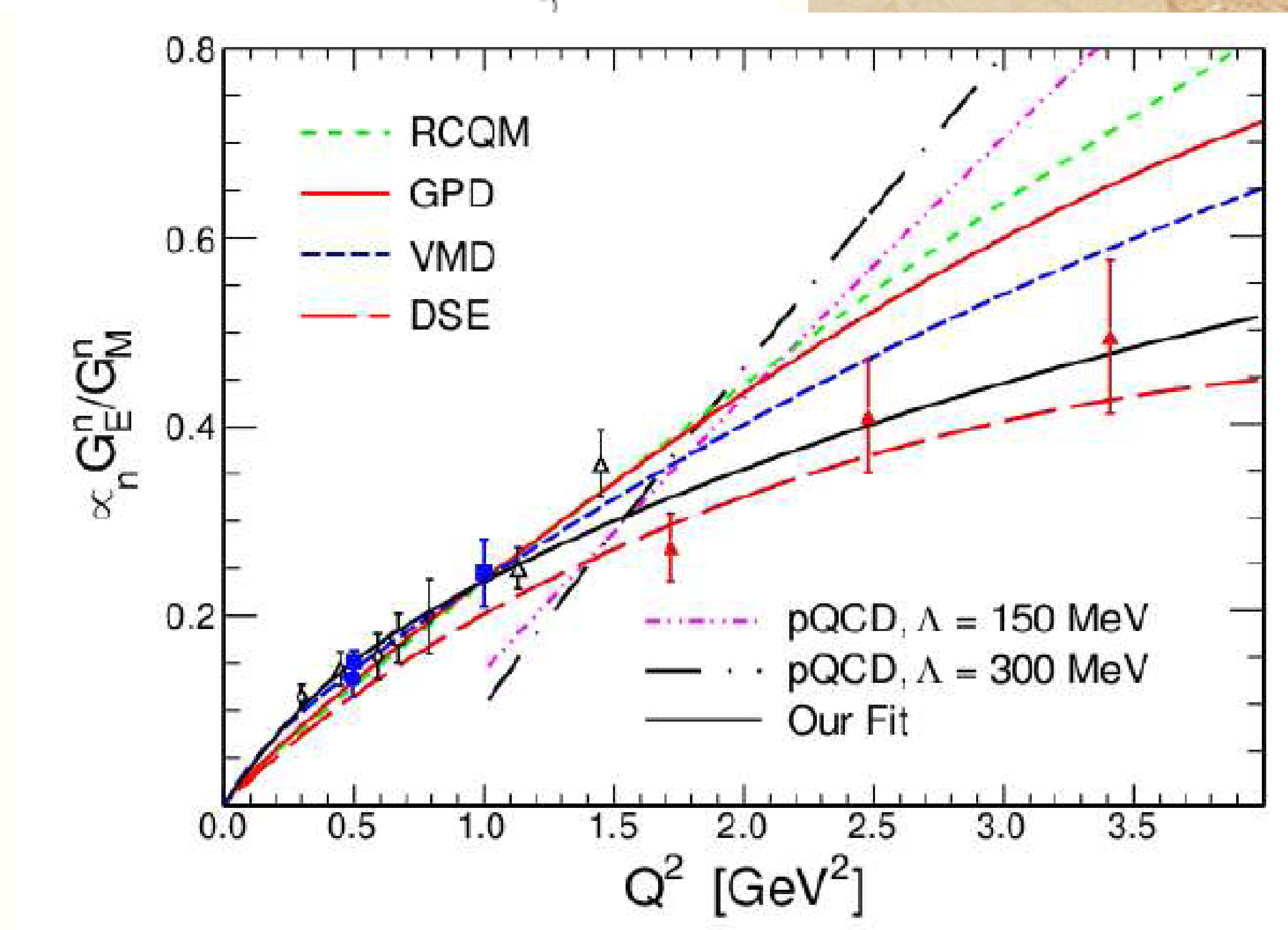


Craig Roberts: Opportunities and Challenges of the N* Programme.

Nucleon Form Factors







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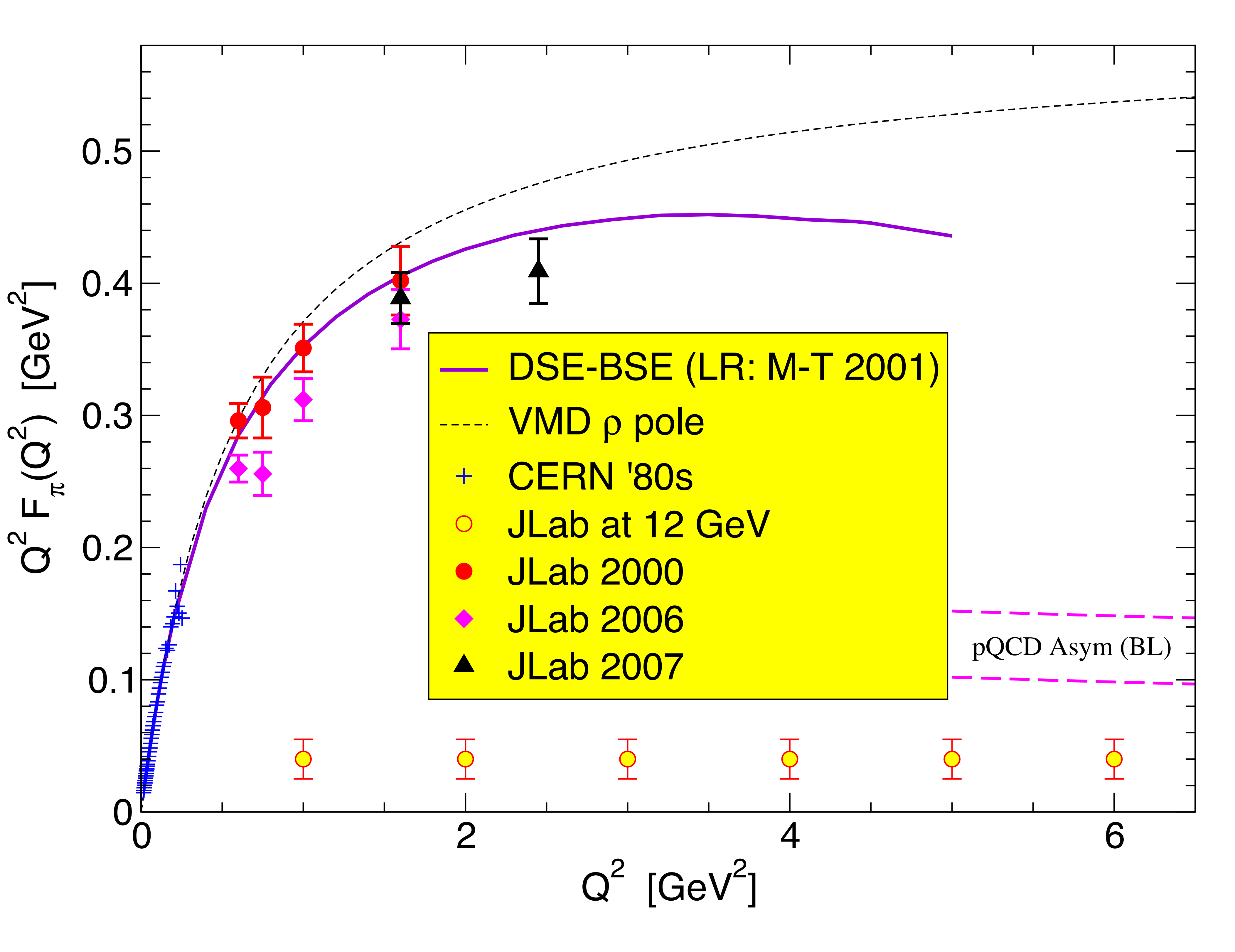
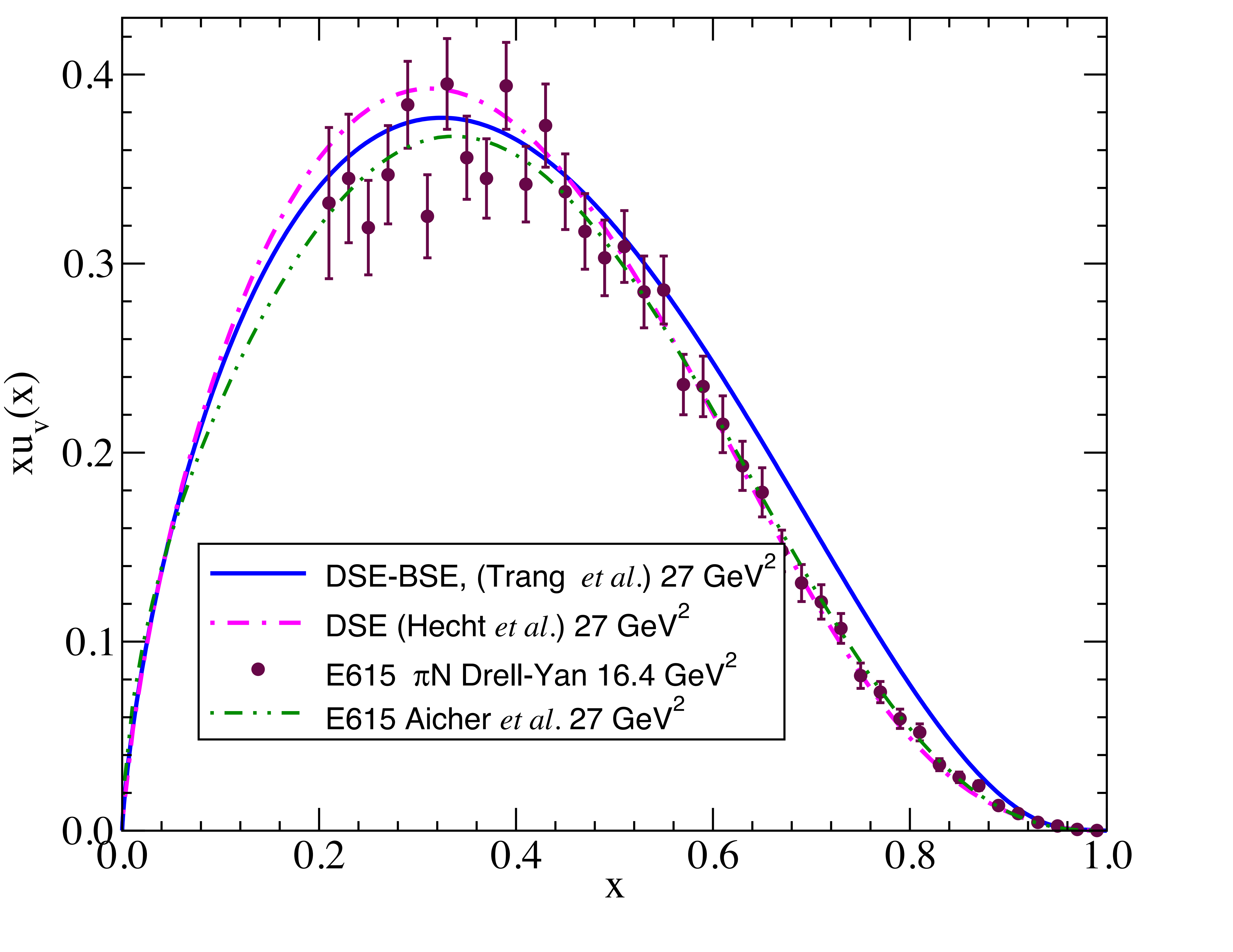
--I. Cloet et al (2011)

S. Riordan, *et al* Phys. Rev. Lett. **105**, 262302 (2010)



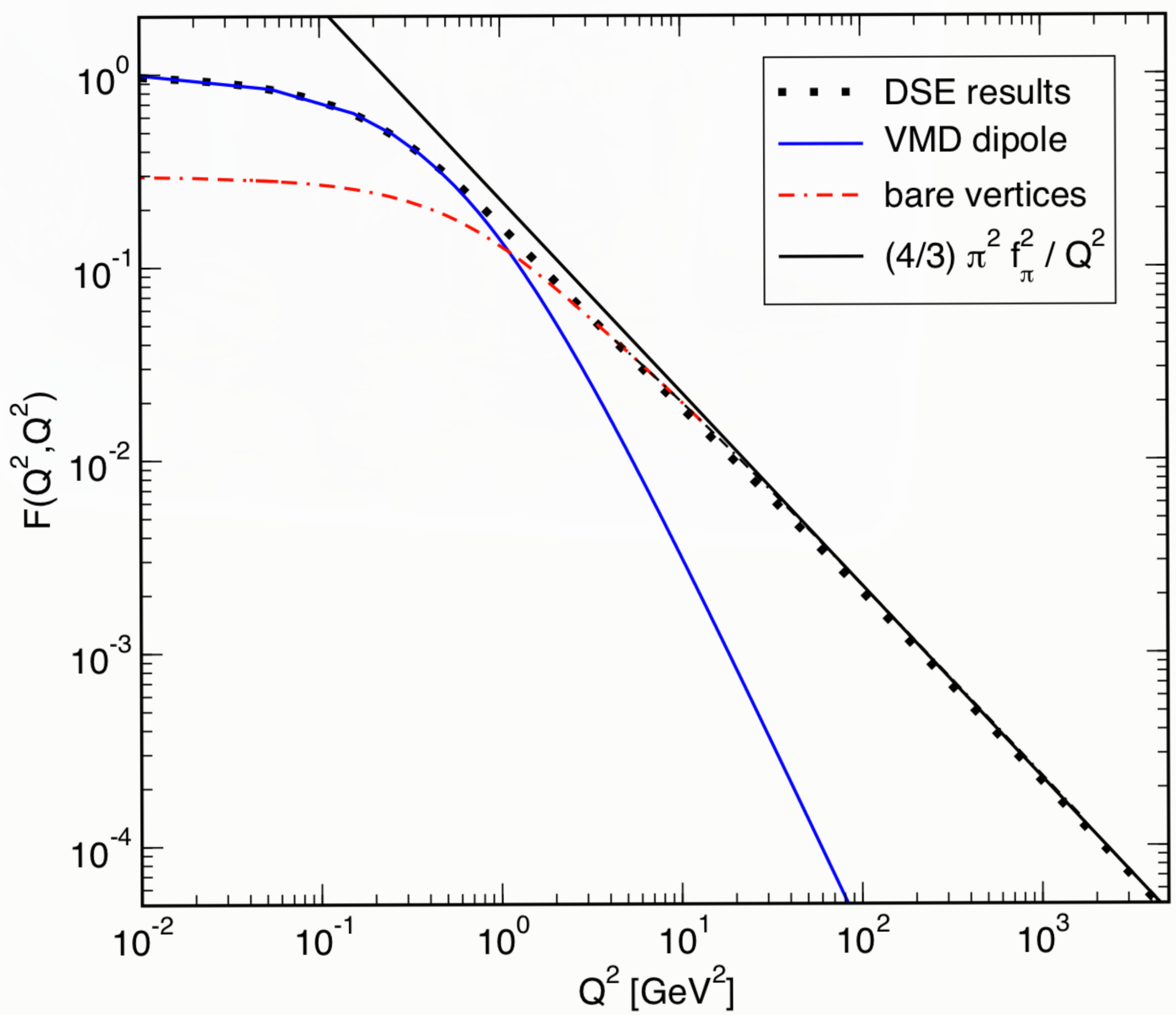
DSE-BSE (LR: M-T 2001)
VMD ρ pole
CERN '80s
JLab at 12 GeV
JLab 2000
JLab 2006
JLab 2007
pQCD Asym (BL)
$Q^2 F_\pi(Q^2)$ [GeV^2]
Q^2 [GeV^2]
0
0.1
0.2
0.3
0.4
0.5
0
2
4
6

Nguyen, Bashir, Roberts, PCT, PRC 83 062201 (2011); arXiv:1102.2448



$\gamma^\star\pi\gamma^\star$ Asymptotic Limit

Lepage and Brodsky, PRD22, 2157 (1980): LC-QCD/OPE ⇒

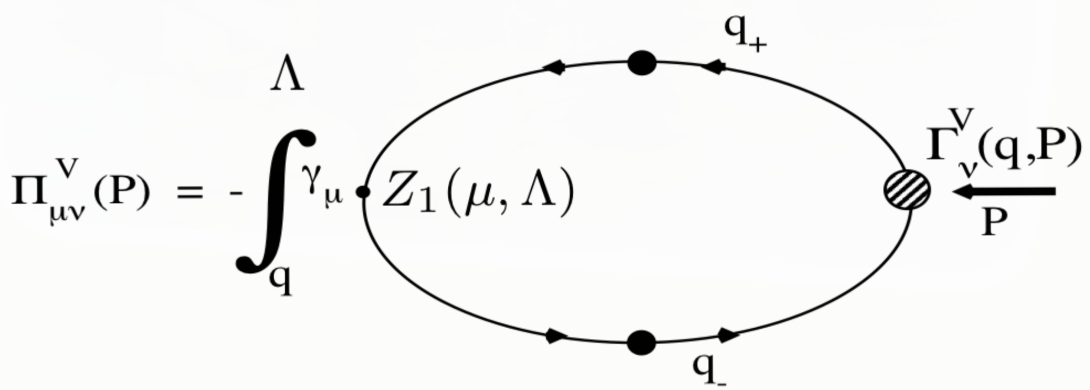


The V-A Current Correlator

- $\Pi^V_{\mu\nu}(x) = \langle 0 | \, T \, j_\mu(x) j^\dagger_\nu(0) \, | 0 \rangle$, isovector currents $j_\mu = \bar{u}\gamma_\mu d, \quad j^5_\mu = \bar{u}\gamma_5\gamma_\mu d$

$$\Pi^V_{\mu\nu}(P) = (P^2\delta_{\mu\nu} - P_\mu P_\nu) \, \Pi^V(P^2)$$

$$\Pi^A_{\mu\nu}(P) = (P^2\delta_{\mu\nu} - P_\mu P_\nu) \, \Pi^A(P^2) + P_\mu P_\nu \, \Pi^L(P^2)$$



- $m_q = 0 : \quad \Pi^V - \Pi^A = 0$, to all orders in pQCD
- $\Pi^V - \Pi^A$ probes the scale for onset of non-perturbative phenomena in QCD

Physics from the V-A correlator:

OPE:

$$\Pi^{V-A}(P^2) = \frac{32\pi\alpha_s\langle\bar{q}q\bar{q}q\rangle}{9\ P^6}\left\{1+\frac{\alpha_s}{4\pi}\left[\frac{247}{4\pi}+\ln\left(\frac{\mu^2}{P^2}\right)\right]\right\} + \mathcal{O}\left(\frac{1}{P^8}\right)$$

Model	$-<\bar{q}q>_{\mu=19}\ (GeV)^3$	$<\bar{q}q\bar{q}q>_{\mu=19}\ (GeV)^6$	$R(\mu=19)$
LR DSE	$(0.216)^3$	$(0.235)^6$	1.65

Weinberg et al Sum Rules:

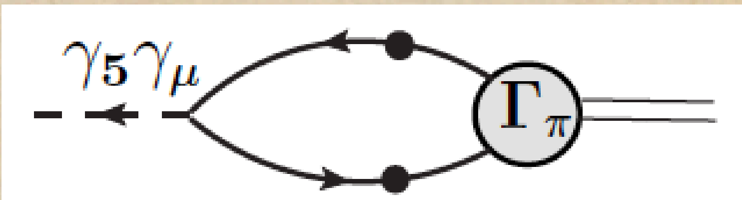
- I: $\frac{1}{4\pi^2}\int_0^\infty ds[\rho_v(s)-\rho_a(s)] = [P^2\,\Pi^{V-A}(P^2)]_{P^2\to 0} = -f_\pi^2$
- II: $P^2\,[P^2\,\Pi^{V-A}(P^2)]|_{P^2\to\infty} = 0$
- DGMLY: $\int_0^\infty dP^2\,[P^2\,\Pi^{V-A}(P^2)] = -\frac{4\pi f_\pi^2}{3\alpha}[m_{\pi^\pm}^2 - m_{\pi^0}^2]$

Model	$f_\pi^2\,(GeV^2)$	$f_\pi\,(MeV)$	f_π^{exp}/f_π^{num}	$\Delta m_\pi\,(MeV)$	$(\Delta m_\pi)_{exp}$
LR DSE	0.0081	90.0	1.03	4.88	4.43 ± 0.03

16 —T. Nguyen, PCT, in prep (2010)

QCD: Two In-Hadron Quantities

$$if_\pi P_\mu = \langle 0|\bar{q}\gamma_5\gamma_\mu q|\pi\rangle$$
$$= Z_2(\zeta,\Lambda)\,\mathrm{tr}_{CD}\int^\Lambda \frac{d^4q}{(2\pi)^4} i\gamma_5\gamma_\mu S(q_+)\Gamma_\pi(q;P)S(q_-), \quad (5)$$



$$i\rho_\pi = -\langle 0|\bar{q}i\gamma_5 q|\pi\rangle$$
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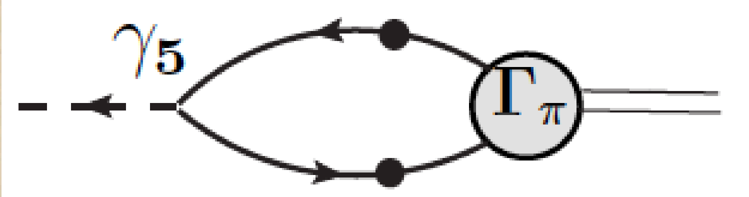

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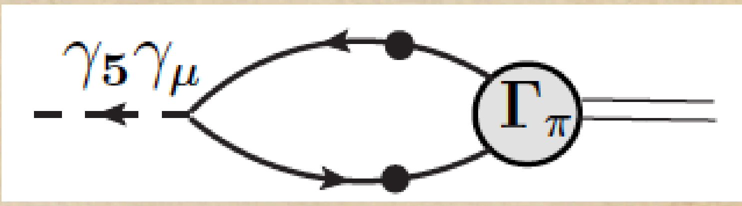

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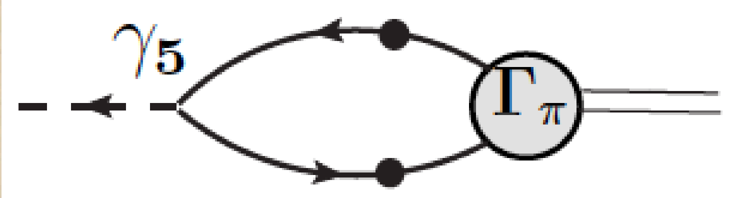

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QCD: Two In-Hadron Quantities

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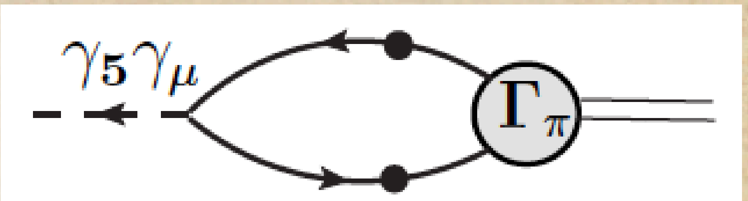

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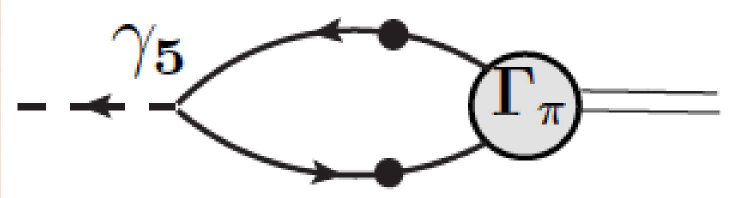

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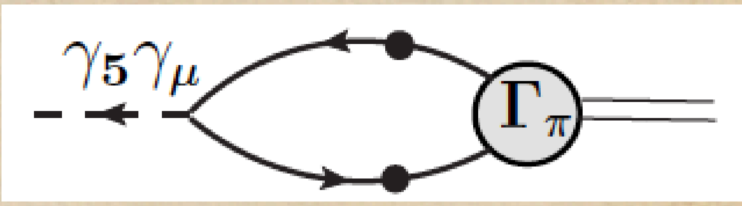

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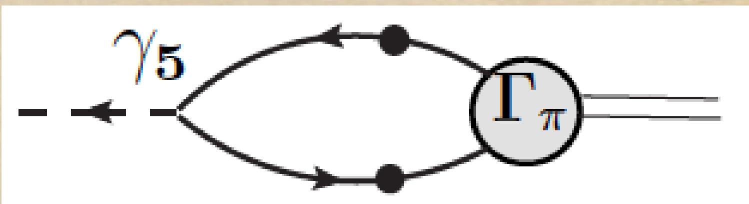

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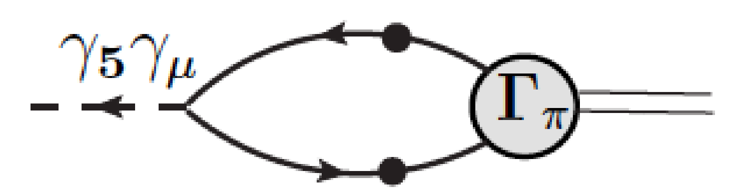

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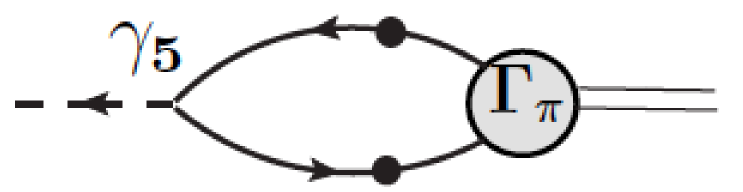

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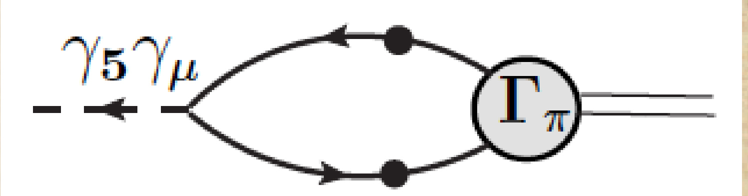

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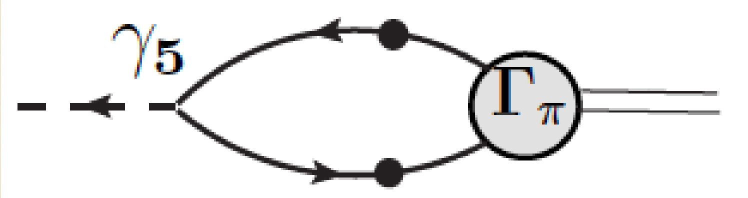

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- But, does $\langle 0|\bar{q}\gamma_5 q|\pi\rangle$ play a role in hadron physics? Yes, because........

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Maris, Roberts, PCT, Phys. Lett. B420, 267(1998) – –an exact result in QCD

$$\mathbf{PCAC} \;\Rightarrow\; \langle\, \bar{\mathbf{q}}(\mathbf{x})\mathbf{q}(\mathbf{y})\;(\partial_\mu \mathbf{J}_{5\,\mu} = 2\mathbf{m_q}\,\mathbf{J_5})\,\rangle \;\Rightarrow \mathbf{AV-WTI}:$$

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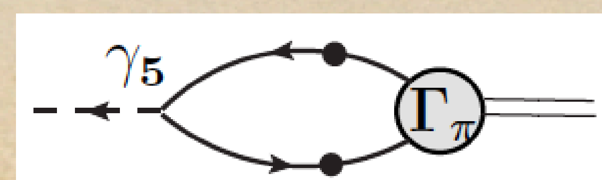
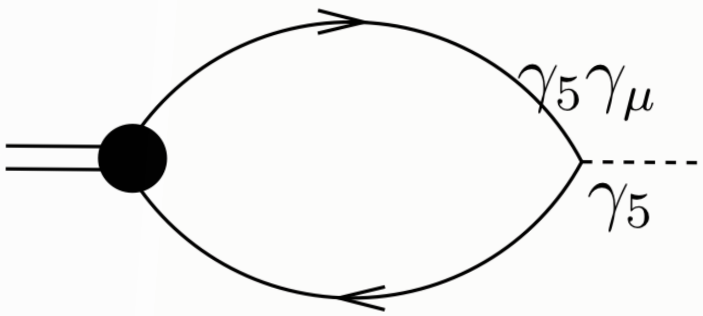
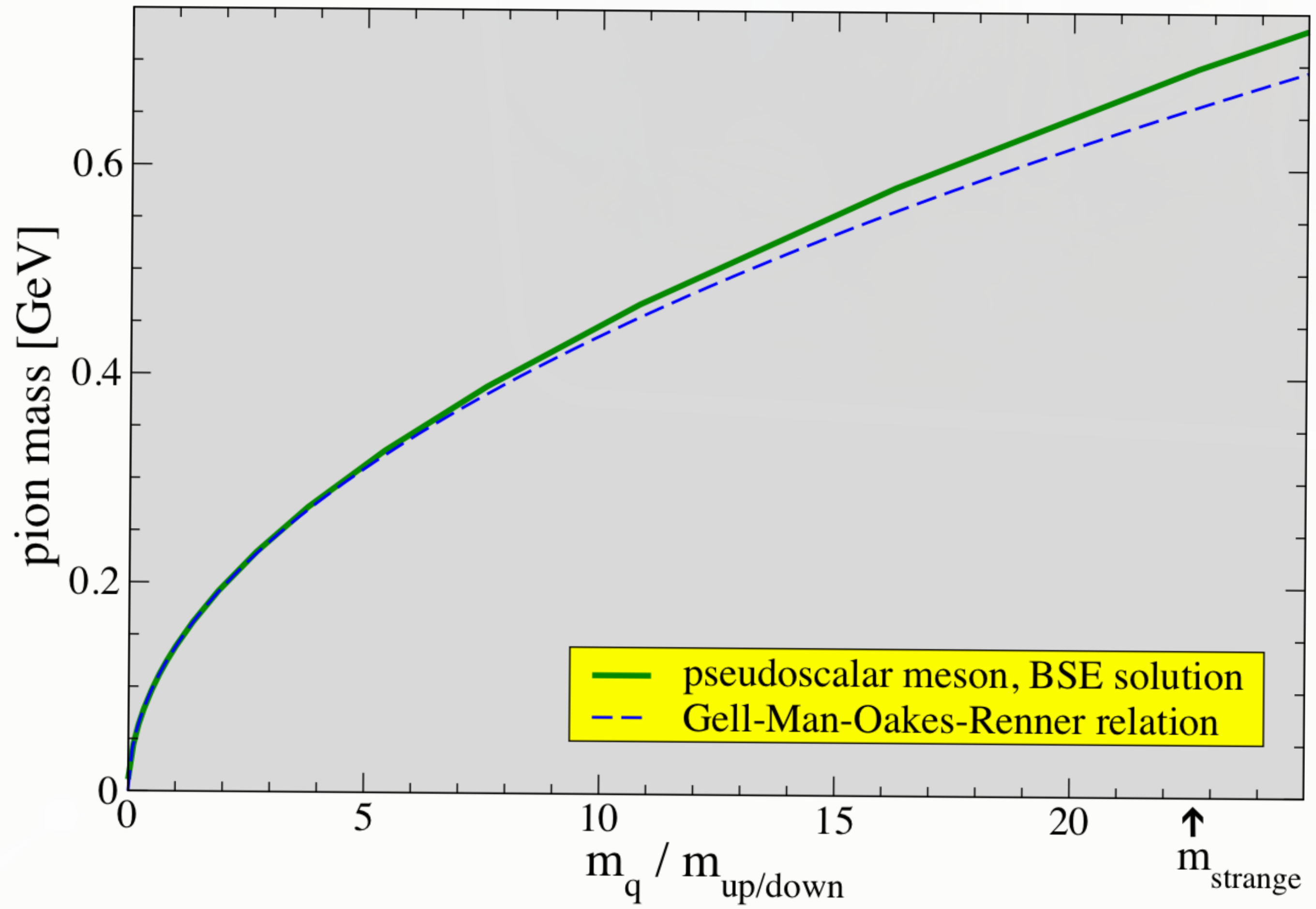


Flavor Non-singlet PS Mass Relation

$$f_H \; m_H^2 = 2\, m_q(\mu)\; \rho_H(\mu)$$





$$i\, f_\pi\, P_\mu = \langle 0 |\, \bar q\, \gamma_5\, \gamma_\mu q\, | \pi \rangle$$

$$i\, \rho_\pi = -\langle 0 |\, \bar q\, i\gamma_5\, q\, | \pi \rangle$$

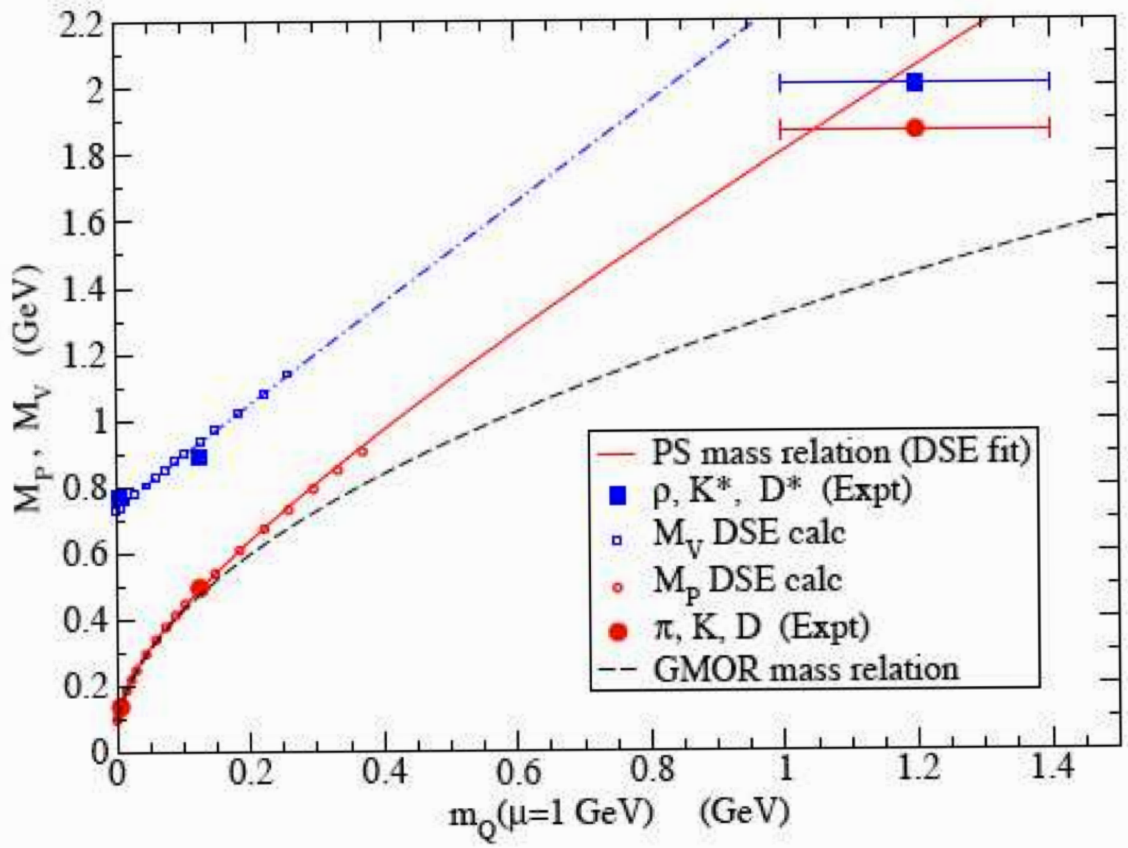
$$\frac{\lim}{m \to 0}\, f_\pi\, \rho_\pi = -\langle \bar q\, q \rangle_\mu$$

$$-\langle \bar q\, q \rangle_\mu^\pi = f_\pi(m)\, \rho_\pi(m)$$

PM, Roberts, Tandy, PLB420, 267 (1998) [nucl-th/9707003]

Inaccuracy of GMOR

qQ case:



GMOR: 0.2%(π); 4%(K); 14%(0.4GeV); 30%(D)

PASCOS12 Merida

New Concept of In-hadron Condensates

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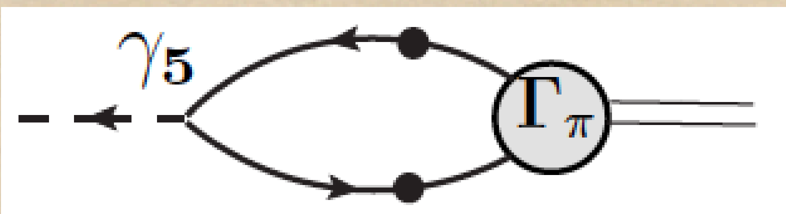

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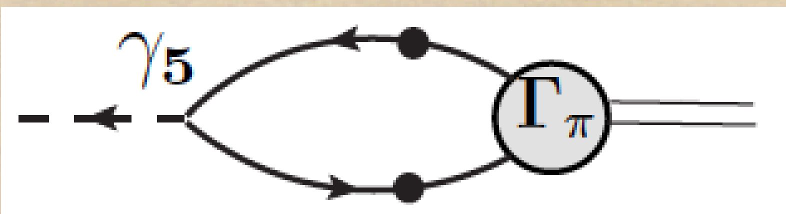

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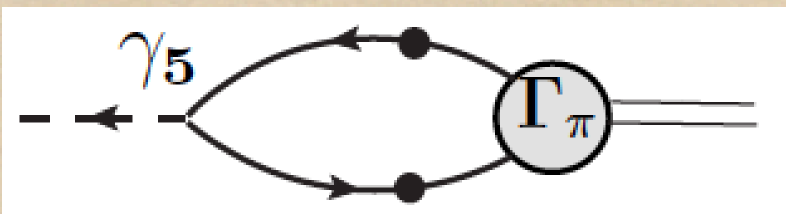

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In-pion condensate:

$$\langle \bar{\mathrm{q}}\mathrm{q}\rangle_\mu^\pi = \mathrm{i\; f_\pi\; tr_{cs}} \int_{\mathrm{k}}^{\mathrm{E}} \gamma_5\, \bar{\chi}_\pi(\mathrm{k}; -\mathrm{P}) \;=\; \mathrm{f_\pi}\, \langle 0|\, \bar{\mathrm{q}}(0)\, \gamma_5\, \mathrm{q}(0)\, |\pi(\mathrm{P})\rangle_\mu$$

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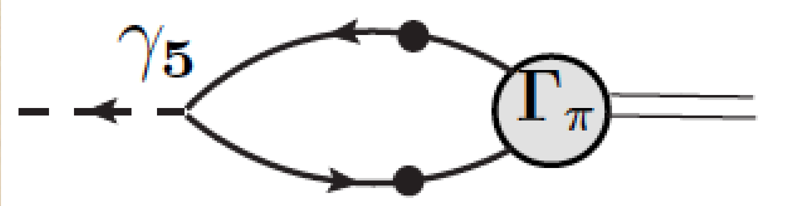

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Confinement Implies all QCD Condensates are within Hadrons

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- Lattice-QCD and DSE modeling find that the dynamically generated IR masses of the gluon and u/d quarks are about 0.4-0.6 GeV
- Gives dynamical suppression of low momenta of these virtual fields in hadrons
- Gives suppression of wavelengths > 1-2 fm of .. ..
- Vacuum fluctuations? Casimir effect----interpretation under debate today:
- "No evidence for vacuum QCD fluctuations in absence of matter"---R. Jaffe, New Scientist, Feb 2012.
- Quark and gluon "propagators" are non-observable intermediate elements of theory to be used in construction of color singlet observables
- QCD Sum Rule approach: color singlet current-current correlators involve finite size matter distributions at one vertex; params are fixed by observable hadron data
- No virtual quark-gluon d.o.f. is needed more than a strong interaction distance from color singlet matter
- Lattice-QCD signal for quark condensate is pionic due to Goldstone/GT reln

Modern Context for Ladder-Rainbow Kernel

$\mathbf{Landau\ gauge,\ lattice-QCD\ gluon\ propagator,}$
$\mathbf{I.L.Bogolubisky}\ \mathit{et al.},\ \mathbf{PosLAT2007, 290\ (2007)}$

$\mathbf{DSE\ Study w/\ modern\ n-pt\ fns}$
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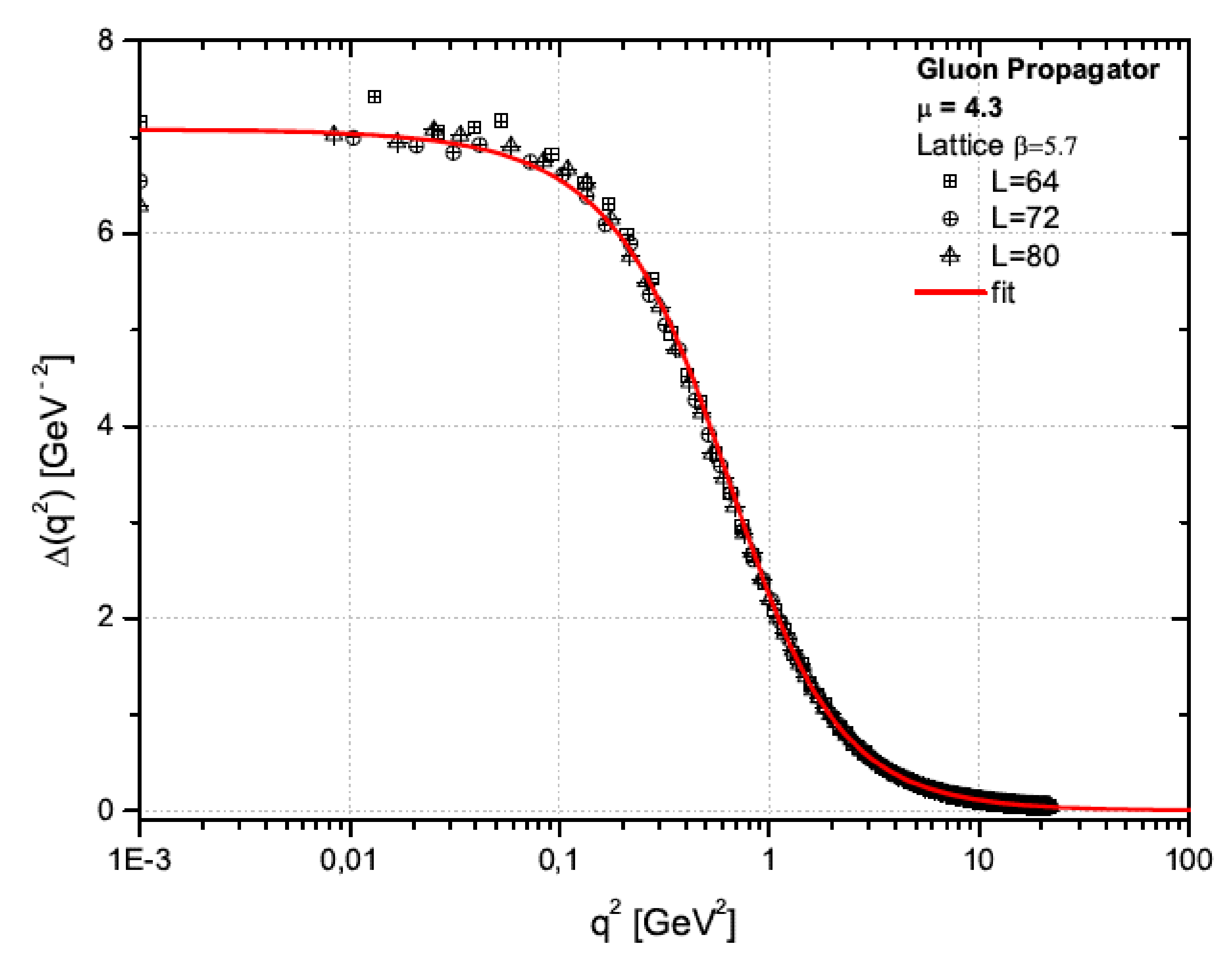

Landau gauge, lattice – QCD gluon propagator,
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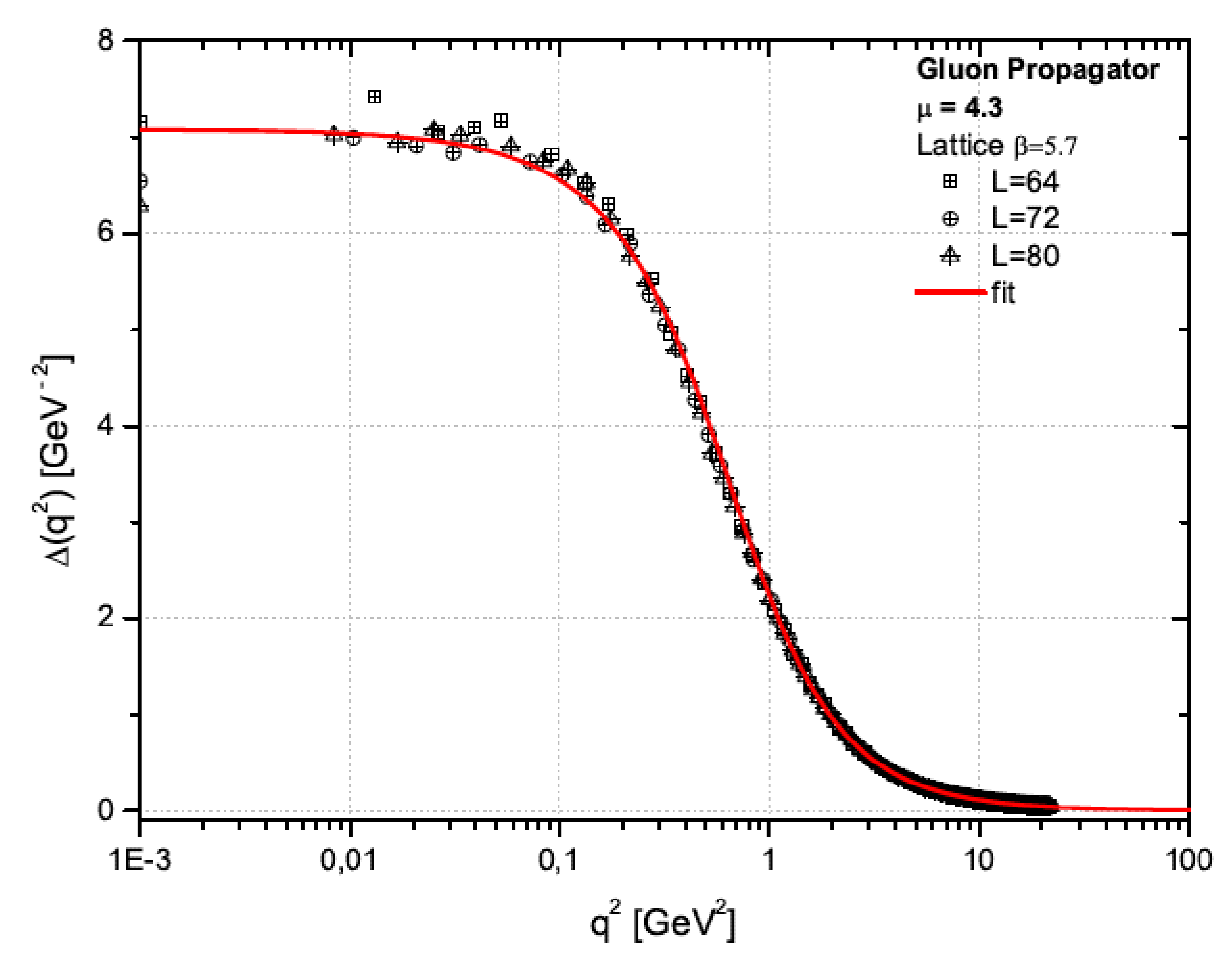

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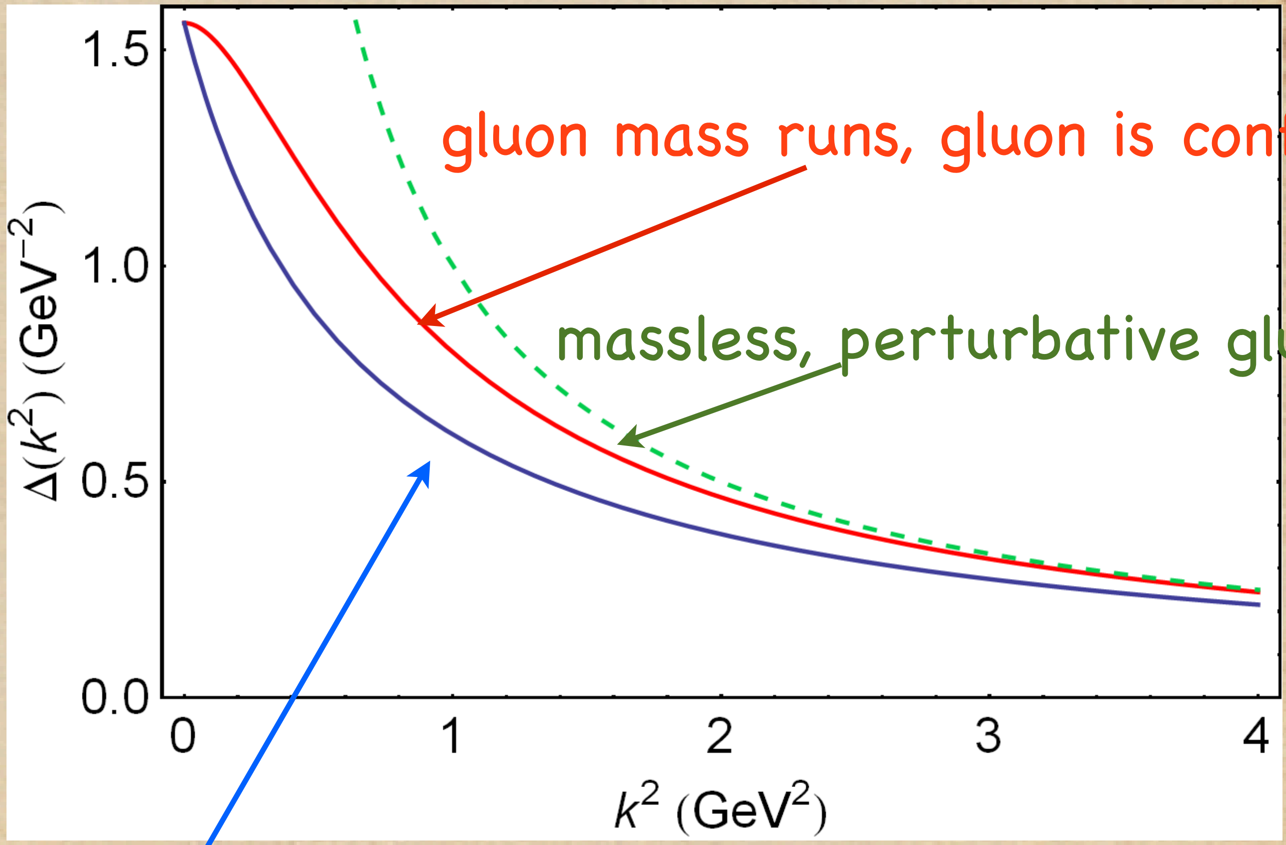
$$K_{BSE}^{RL} = \frac{4\pi\hat{\alpha}_{eff}(q^2)}{m_G^2(q^2) + q^2}$$

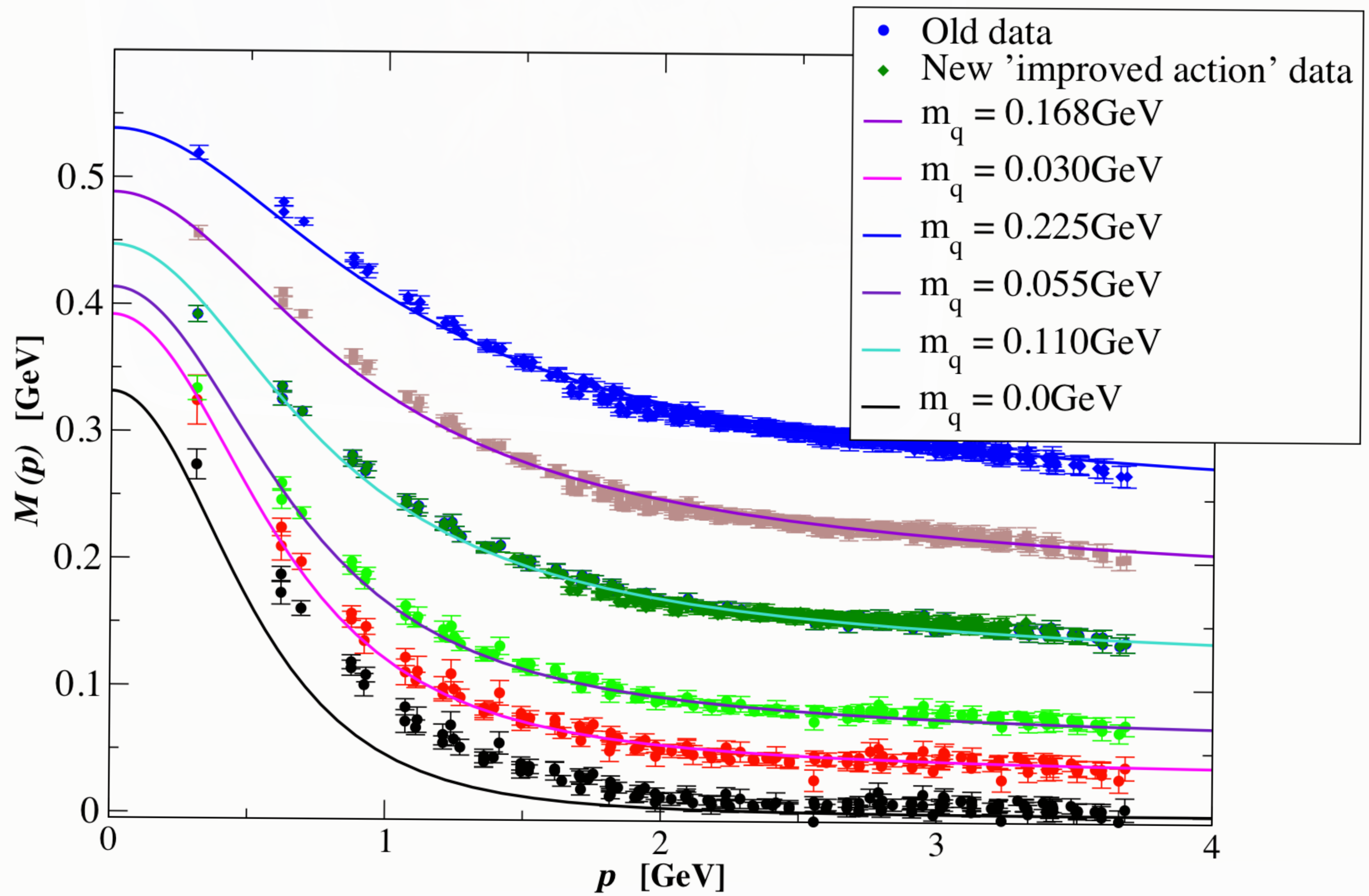
$$\Rightarrow \frac{\hat{\alpha}_{eff}(0.1)}{\pi} \approx 3 - 4$$



constant mass, unconfined gluon

Qu-lattice $S(p), D(q)$ mapped to a DSE kernel

$$S(p) = Z(p)\,[i\,\not p + M(p)]^{-1}$$



Does this contradict GMOR Relation?

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- no contradiction, but DCSB as a vacuum phenomena took root as a neat idea

A Note of Caution: Casher & Susskind (1974)

Chiral Magnetism (or Magnetohadrochironics)
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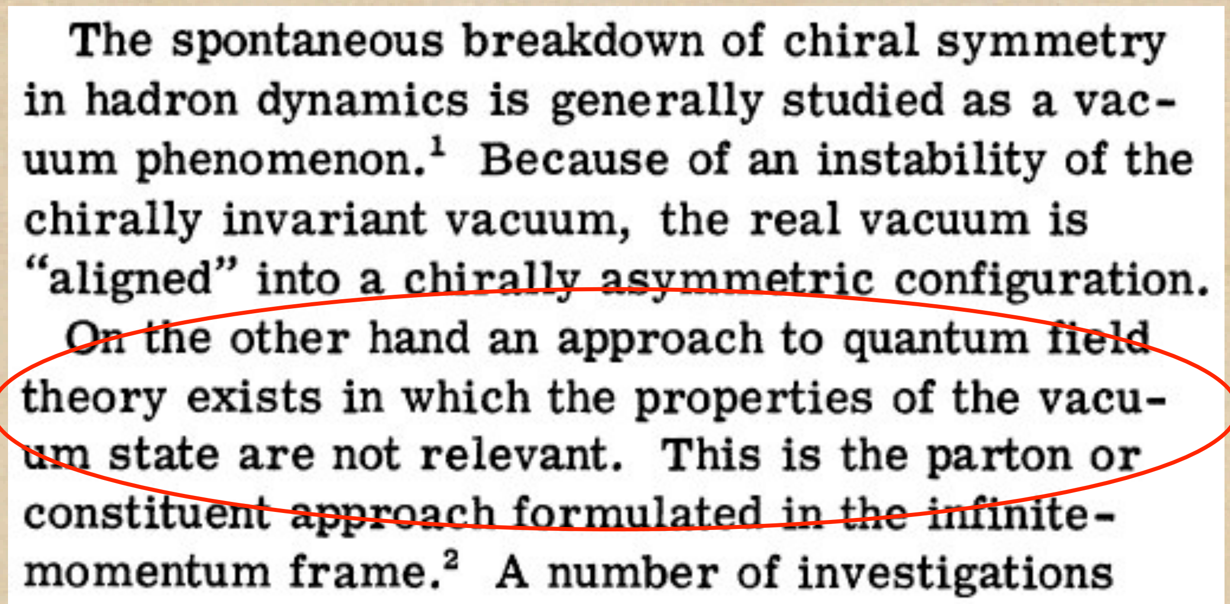
The spontaneous breakdown of chiral symmetry in hadron dynamics is generally studied as a vacuum phenomenon.[1] Because of an instability of the chirally invariant vacuum, the real vacuum is "aligned" into a chirally asymmetric configuration.

On the other hand an approach to quantum field theory exists in which the properties of the vacuum state are not relevant. This is the parton or constituent approach formulated in the infinite-momentum frame.[2] A number of investigations

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- Authors argue that DCSB can be realized as a property of hadrons
- No need for a non-trivial vac exterior to the measurable d.o.f
- Compatible with light-front field theory with its trivial vacuum
- Infinite # d.o.f. is the essential element for DCSB
- Brodsky and Shrock picked up this theme & advocate max wavelength for quarks and gluons (relative to matter)
- Brodsky and Shrock advocate LF-QCD gives cosmological const = 0

Condensates of Confined Fields

PHYSICAL REVIEW C **82**, 022201(R) (2010)

New perspectives on the quark condensate

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- So-called vacuum chiral quark condensate is really a property of the Goldstone boson BSE wavefunction
- Its a constant mass scale that does not leak outside of its containers (hadrons): An in-hadron condensate.
- Above relation is dictated by DCSB: $\mathbf{GT_q}: \;\; \Gamma_\pi(\mathbf{k}^2; 0) = \mathbf{i}\gamma_5 \, \tau \, \frac{\frac{1}{4}\mathrm{tr}\, \mathbf{S}_0^{-1}(\mathbf{k})}{\mathbf{f}_\pi^0} + \cdots$
- (1-body problem and 2-body problem coincide)
- Removes the 46 orders of magnitude in QCD's vacuum energy over-estimate of cosmological constant

Doesn't the pion get fat and fill all space in the chiral limit?

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- (So its in-pion condensate of quarks is spread throughout the vacuum?)
- Indeed the em charge radius of the pion does diverge in chiral limit due to virtual chiral meson loops
- But, it's due to the virtual tightly correlated PS qqbar pairs that fluctuate far from the pion's qqbar core
- There is no quark separated more than a strong interaction length from a qbar
- The in-hadron condensate is the qqbar-projected bound state wavefunction at zero separation---it is never in the vacuum
- The large distance fluctuations of virtual PS qqbar pairs carry their condensates inside them, the vacuum/void is left as is---empty

In-hadron Condensate and Scalar Charge

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Lei Chang, Craig D. Roberts and Peter C. Tandy
arXiv:1109.2903 [nucl-th], Phys. Rev. C85 (2012) 012201(R)

- $\forall \mathbf{m_q} \sim 0, \quad \mathbf{m}_\pi^2(\mathbf{m_q}) = 2\mathbf{m_q}\,\langle\,\pi(\mathbf{P})\,|\bar{\mathbf{q}}\mathbf{q}\,|\,\pi(\mathbf{P})\,\rangle = 2\mathbf{m_q}\,\frac{\partial}{\partial \mathbf{m_q}}\,\mathbf{m}_\pi^2 = 2\mathbf{m_q}\,\mathcal{S}_\pi(\mathbf{0})$
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- Can be extended to scalar charge of vector and scalar mesons, baryons

Hadronic Charges $\langle\, \mathbf{H}(\mathbf{P}) \,|\, \bar{\mathbf{q}}\, \mathcal{O}\, \mathbf{q} \,|\, \mathbf{H}(\mathbf{P}) \,\rangle$

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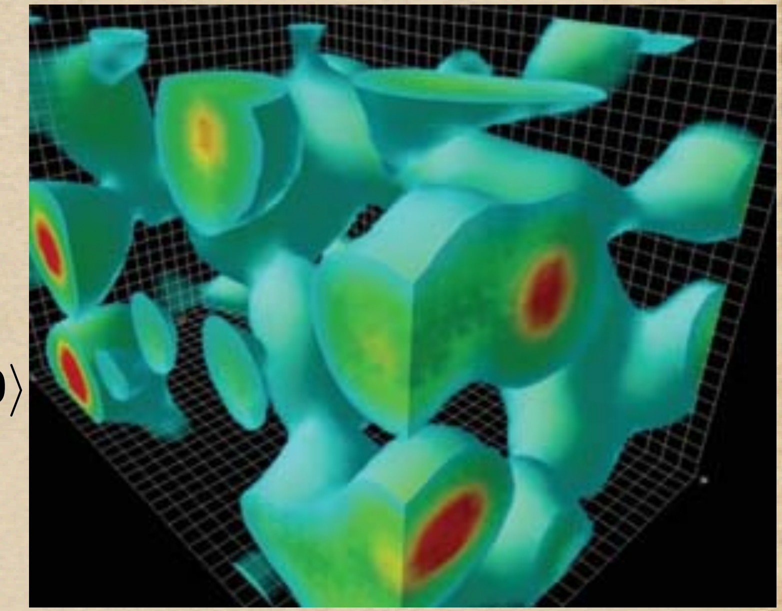
They are all properties internal to hadrons.

Why use a different interpretation for the $\mathcal{O} = 1$ **case?**

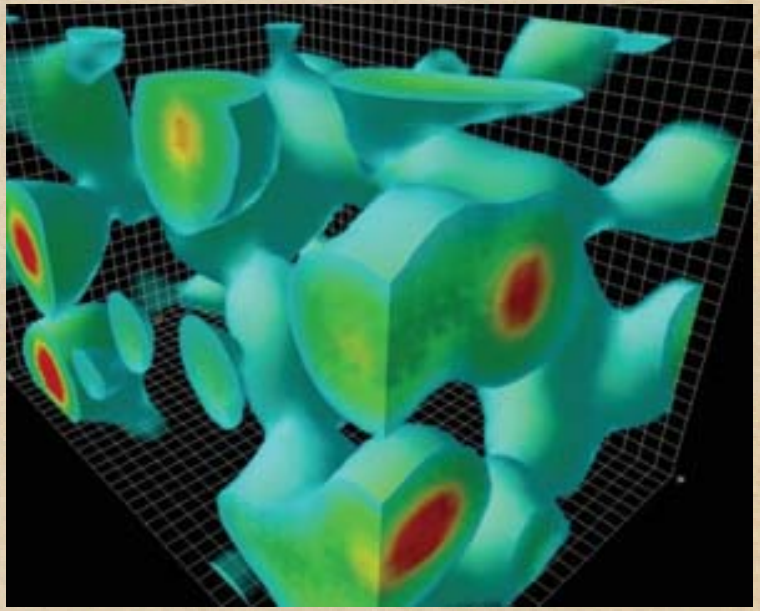
QCD Sum Rule Approach

QCD and Resonance Physics. Sum Rules.
M.A. Shifman, A.I. Vainshtein, and V.I. Zakharov
Nucl.Phys. B147 (1979) 385-447; citations: 3713



- Current – current correlators $\Pi(x-y) = \langle 0|\, T\, J(x)\, J(y)\, |0\rangle$
- OPE eg : $T\, J(x)\, J(y) = \Sigma_\alpha\, C_\alpha(x-y)\, N_\alpha(\frac{x+y}{2})$
- Introduced vac gluon condensate : $\frac{\alpha}{\pi}\langle 0|\, G_{\mu\nu}G^{\mu\nu}\, |0\rangle \sim (0.33\, \mathrm{GeV})^4$
- Calculate Π [ie the $C'_\alpha s$] from spacelike UV end perturbatively
- Analytic (Borel) continuation to timelike end, fit universal $\langle 0|\, N_\alpha(0)\, |0\rangle$ to hadron data
- Today we have extremely well constrained representations of npQCD to calculate $\Pi(x{-}y)$ without recourse to QCD condensate phenomenology at a few leading orders at uv end

Lattice-QCD Simulations of Gauge Sector



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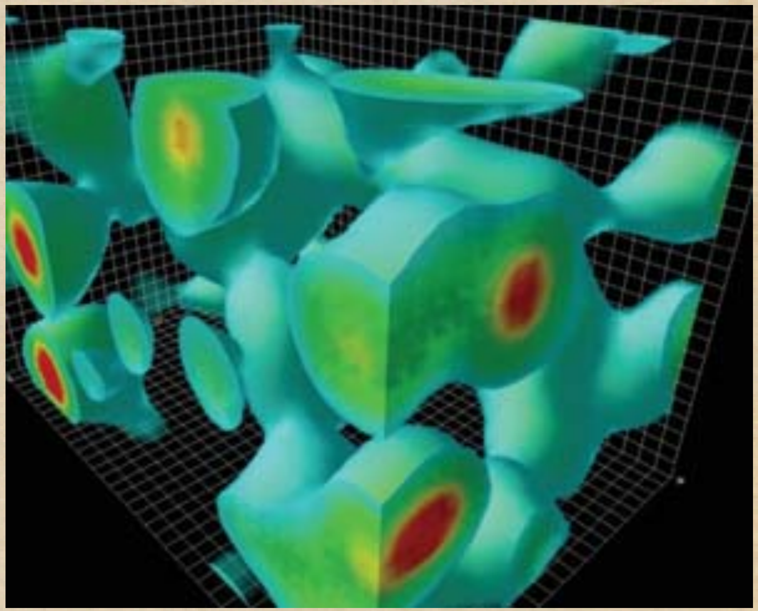

- Topological structures in "vacuum" energy density after some amount of cooling
- No physical length scale identified
- No matter (eg quarks) present, can't relate to physical observables

Many Ways to Obtain the Chiral Quark Condensate

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- $\langle \bar{\mathbf{q}}\mathbf{q} \rangle_\mu = -\mathbf{Z_4}(\mu, \mathbf{\Lambda}) \, \mathrm{tr_{cd}} \int^{\mathbf{\Lambda}} \frac{\mathbf{d^4q}}{(\mathbf{2}\pi)^\mathbf{4}} \, \mathbf{S_0}(\mathbf{q}; \mu)$

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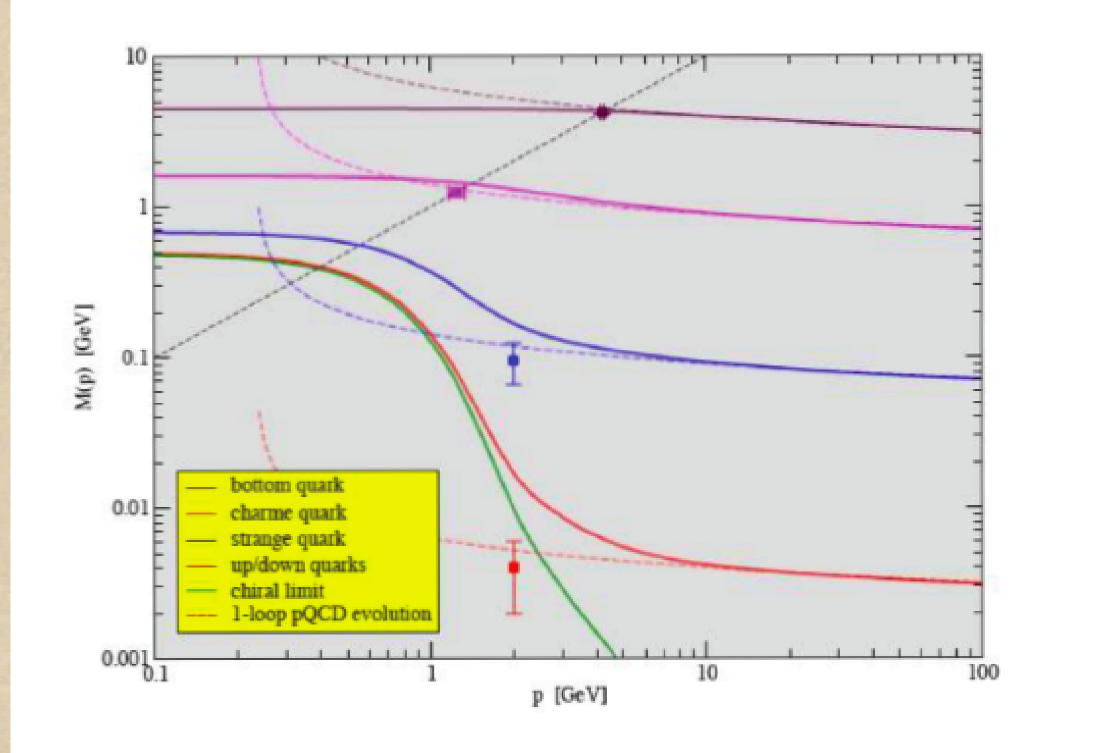

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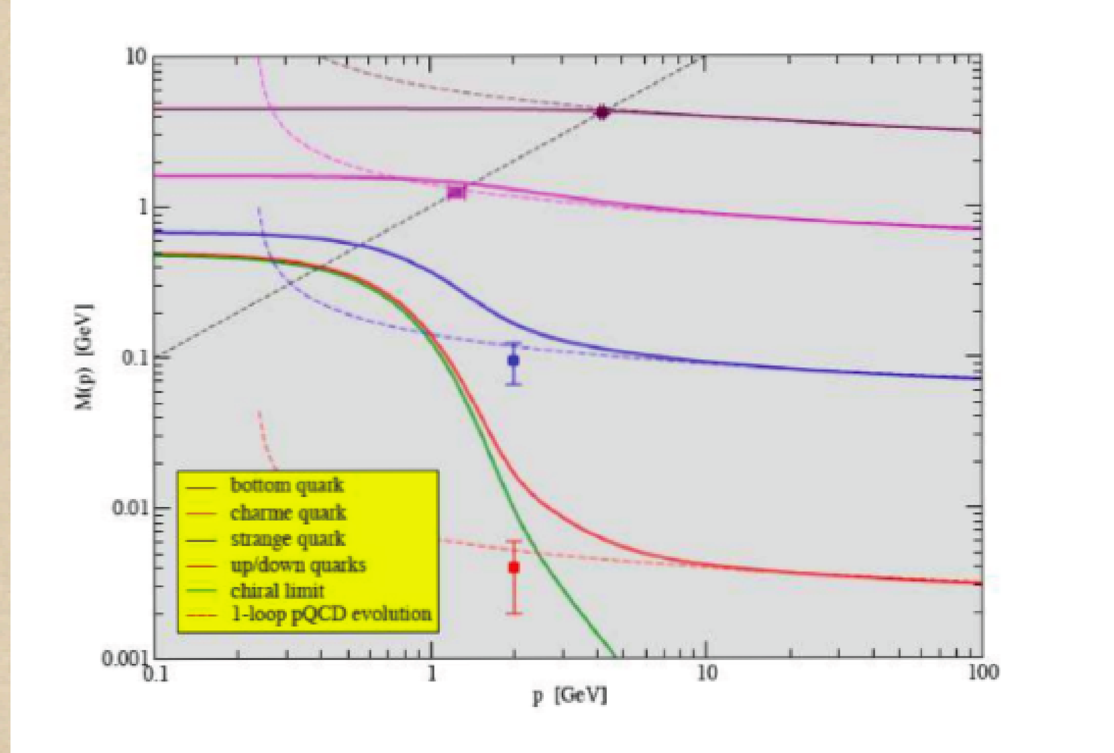
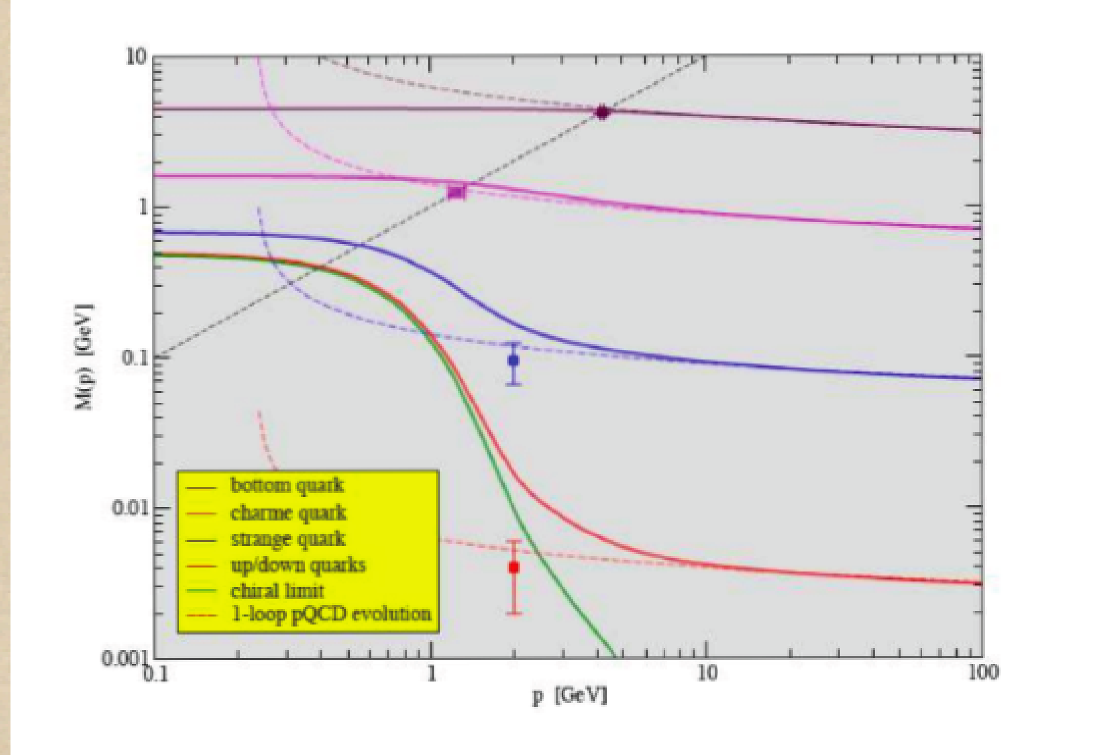


- $\mathbf{Via\ PS\ proj^n\ at\ r = 0\ of\ PS\ bound\ state\ wfn:}\ \langle \bar{\mathbf{q}}\mathbf{q} \rangle_\mu = \lim_{\hat{\mathbf{m}}\to 0} \mathbf{f}_\pi\ \langle 0 | \bar{\mathbf{q}}\, \gamma_5\, \mathbf{q} \,|\, \mathbf{ps} \rangle_\mu$

Many Ways to Obtain the Chiral Quark Condensate

- $\langle \bar{\mathbf{q}}\mathbf{q} \rangle_\mu = -\mathbf{Z_4}(\mu, \mathbf{\Lambda})\ \mathrm{tr_{cd}} \int^{\Lambda} \frac{\mathbf{d^4q}}{(\mathbf{2}\pi)^\mathbf{4}}\ \mathbf{S_0}(\mathbf{q}; \mu)$



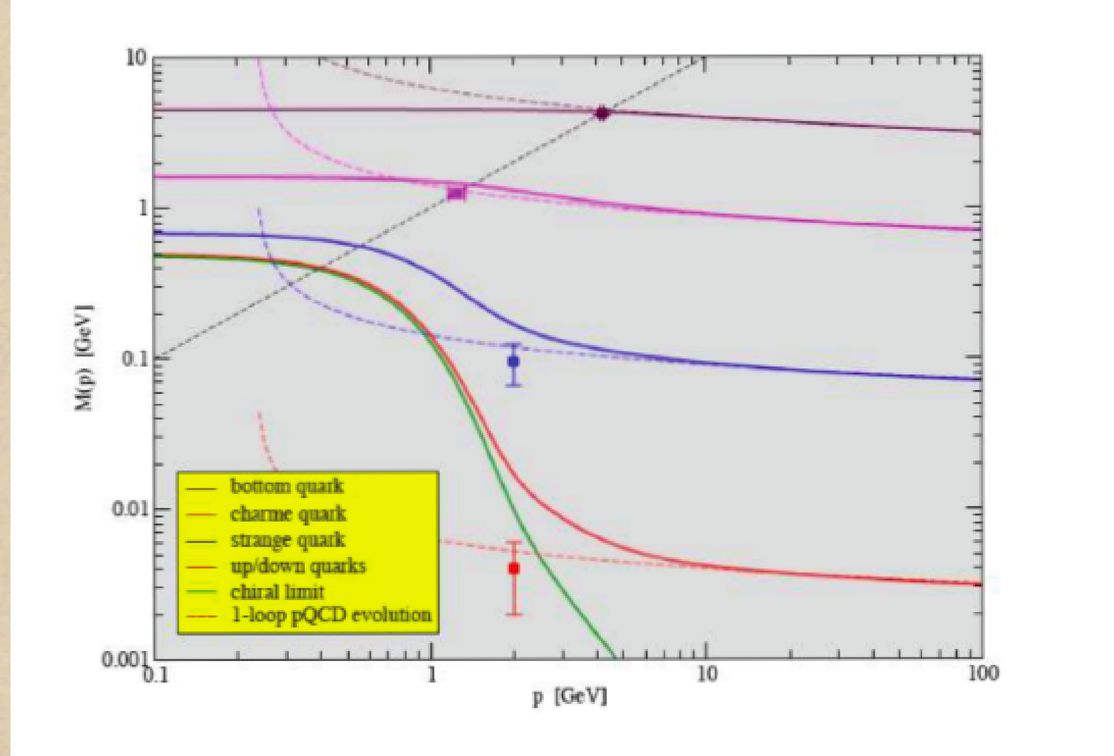
- $M_0(p^2) \overset{\text{large}-p^2}{=} \frac{2\pi^2\gamma_m}{3} \frac{-\langle \bar{q}q \rangle^0}{p^2 \left(\frac{1}{2} \ln \left[\frac{p^2}{\Lambda^2_{QCD}} \right] \right)^{1-\gamma_m}}$

- **Via PS proj$^\mathbf{n}$ at r = 0 of PS bound state wfn :** $\langle \bar{\mathbf{q}}\mathbf{q} \rangle_\mu = \lim_{\hat{\mathbf{m}} \to \mathbf{0}} \mathbf{f}_\pi \langle \mathbf{0} | \bar{\mathbf{q}}\, \gamma_\mathbf{5}\, \mathbf{q} | \mathbf{ps} \rangle_\mu$

- **Via Casher − Banks formula :** $\langle \bar{\mathbf{q}}\mathbf{q} \rangle_\mu = \lim_{\mathbf{m} \to \mathbf{0}} -\mathbf{2m} \int_\mathbf{0}^\infty \mathbf{d}\lambda\, \frac{\rho_{\not{D}}(\lambda)}{\lambda^\mathbf{2} + \mathbf{m^2}}$

Many Ways to Obtain the Chiral Quark Condensate

- $$\langle \bar{q}q \rangle_\mu = -Z_4(\mu, \Lambda)\, \mathrm{tr}_{cd} \int^\Lambda \frac{d^4q}{(2\pi)^4} S_0(q;\mu)$$



- $$M_0(p^2) \overset{\text{large}-p^2}{=} \frac{2\pi^2\gamma_m}{3} \frac{-\langle \bar{q}q \rangle^0}{p^2\left(\frac{1}{2}\ln\left[\frac{p^2}{\Lambda^2_{\mathrm{QCD}}}\right]\right)^{1-\gamma_m}}$$

- Via PS proj^{n} at $r = 0$ of PS bound state wfn : $\langle \bar{q}q \rangle_\mu = \lim_{\hat{m}\to 0} f_\pi \langle 0 | \bar{q}\gamma_5 q | ps \rangle_\mu$

- Via Casher – Banks formula : $\langle \bar{q}q \rangle_\mu = \lim_{m\to 0} -2m \int_0^\infty d\lambda \frac{\rho_{\not{D}}(\lambda)}{\lambda^2 + m^2}$

- Via scalar charge : $\langle \bar{q}q \rangle_\mu = \lim_{m_q\to 0} f_M^2 \langle M | \bar{q}(0)q(0) | M \rangle_\mu$, M = PS, S Mesons

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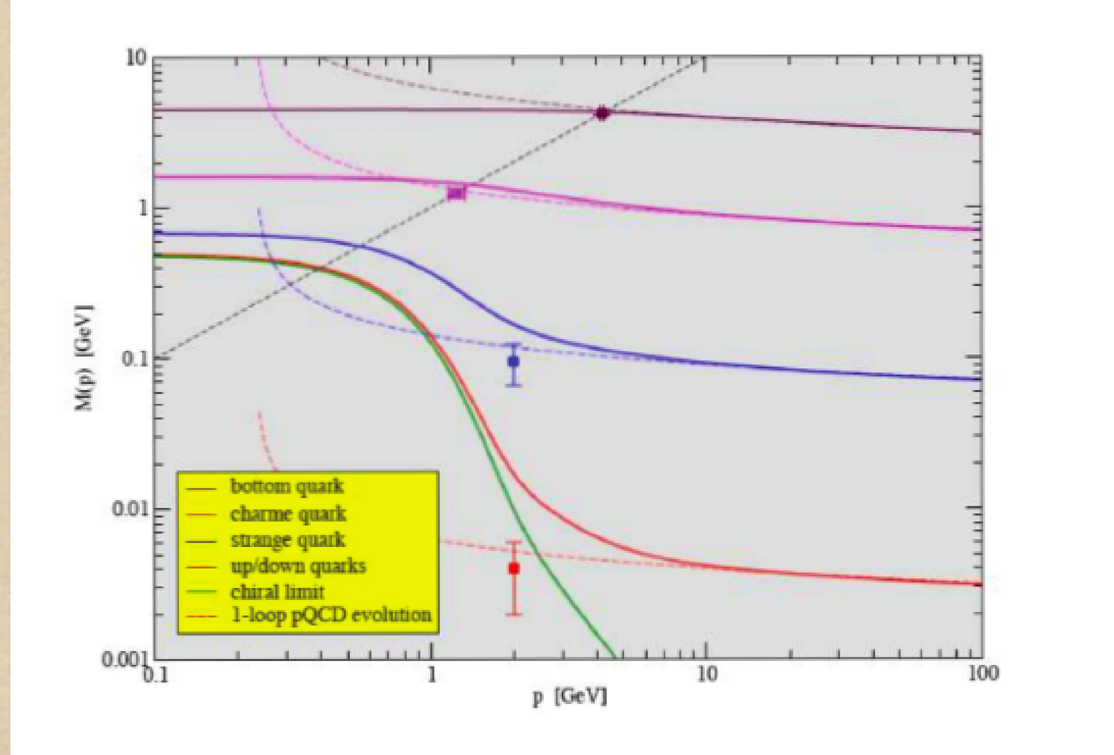
Many Ways to Obtain the Chiral Quark Condensate

- $\langle \bar{\mathbf{q}}\mathbf{q} \rangle_\mu = -\mathbf{Z_4}(\mu, \mathbf{\Lambda})\ \mathrm{tr_{cd}} \int^{\mathbf{\Lambda}} \frac{\mathbf{d^4 q}}{(\mathbf{2}\pi)^{\mathbf{4}}}\ \mathbf{S_0}(\mathbf{q}; \mu)$



- $M_0(p^2) \stackrel{\text{large}-p^2}{=} \frac{2\pi^2 \gamma_m}{3} \frac{-\langle \bar{q}q \rangle^0}{p^2 \left(\frac{1}{2} \ln \left[\frac{p^2}{\Lambda^2_{\text{QCD}}} \right] \right)^{1-\gamma_m}}$

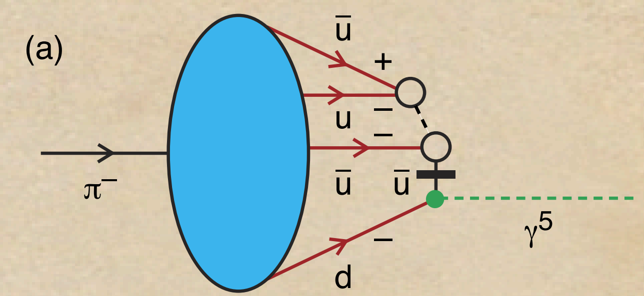
- $\mathbf{Via\ PS\ proj^n\ at\ r = 0\ of\ PS\ bound\ state\ wfn:}\ \langle \bar{\mathbf{q}}\mathbf{q} \rangle_\mu = \lim_{\hat{\mathbf{m}} \to \mathbf{0}} \mathbf{f}_\pi\ \langle \mathbf{0} | \bar{\mathbf{q}}\, \gamma_\mathbf{5}\, \mathbf{q} \,|\, \mathbf{ps} \rangle_\mu$

- $\mathbf{Via\ Casher-Banks\ formula:}\ \langle \bar{\mathbf{q}}\mathbf{q} \rangle_\mu = \lim_{\mathbf{m} \to \mathbf{0}} -\mathbf{2m} \int_\mathbf{0}^\infty \mathbf{d}\lambda\ \frac{\rho_{\not{D}}(\lambda)}{\lambda^\mathbf{2} + \mathbf{m^2}}$

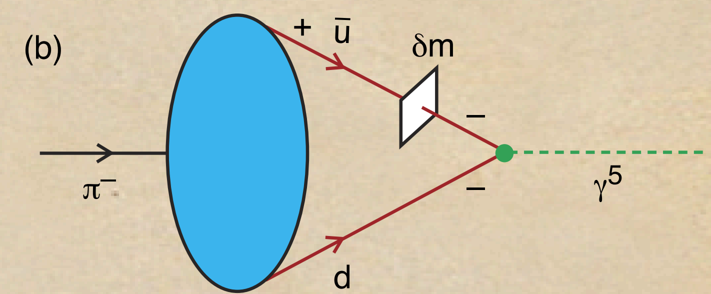
- $\mathbf{Via\ scalar\ charge:}\ \langle \bar{\mathbf{q}}\mathbf{q} \rangle_\mu = \lim_{\mathbf{m_q} \to \mathbf{0}} \mathbf{f^2_M}\ \langle \mathbf{M} \,|\, \bar{\mathbf{q}}(\mathbf{0})\mathbf{q}(\mathbf{0}) \,|\, \mathbf{M} \rangle_\mu, \mathbf{M = PS,\ S\ Mesons}$

- **Via PS or AV current – current correlators in lattice – QCD**

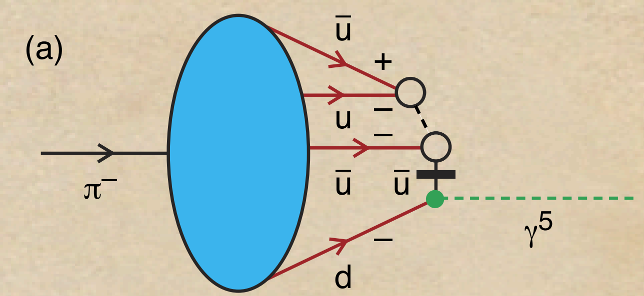
DCSB in Pion in LF Field Theory & its Trivial Vacuum



New Perspectives on the Quark Condensate,
S.J.Brodsky, C.D.Roberts, R.Schrock&PCT, Phys.Rev. C82, 022201 (2010).



DCSB in Pion in LF Field Theory & its Trivial Vacuum



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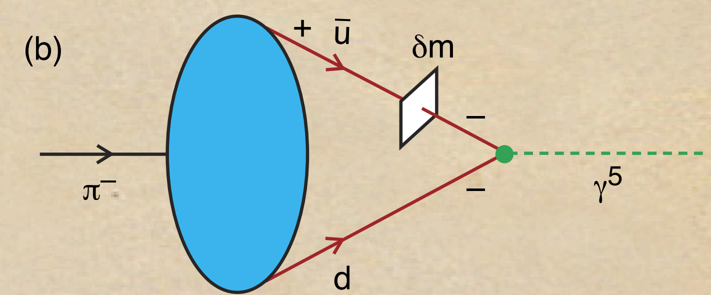

- Higher Fock state components & the LF instantaneous interaction can combine to simulate the required helicity non-conservation
- Effect would look like a dynamically generated mass function
- Infinite # d.o.f. is the essential element for DCSB
- Does this in fact happen? Under investigation.

Summary

Condensates in QCD and the Cosmological Constant, S.J. Brodsky& R.Shrock, Proc. Nat. Acad. Sci., 108, 45 (2011).

New Perspectives on the Quark Condensate, S.J. Brodsky, C.D. Roberts, R.Shrock&P.C.Tandy, Phys. Rev, C82, 022201 (2010).

Expanding the Concept of In-hadron Condensates, L.Chang, C.D. Roberts&P.C. Tandy, Phys. Rev. C85, 012201 (2012)

Confinement Contains Condensates, S.J. Brodsky, C.D. Roberts, R.Shrock&P.C.Tandy, Phys. Rev, Cxx, accepted (2012).

Summary

- Presented strong evidence that quark condensate is better thought of as a hadron property---explict ps & scalar meson matrix elements given
- Would solve the QCD vac energy problem for the Cosmological Constant
- Assumed confinement.   Consistent with the dynamically genentated IR mass scale (max wavelength of confined fields in hadrons)
- Suggests all the "vac condensates" of QCD Sum Rule fame are really inside hadrons

Condensates in QCD and the Cosmological Constant, S.J. Brodsky& R.Shrock, Proc. Nat. Acad. Sci., 108, 45 (2011).

New Perspectives on the Quark Condensate, S.J. Brodsky, C.D. Roberts, R.Shrock&P.C.Tandy, Phys. Rev, C82, 022201 (2010).

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The End

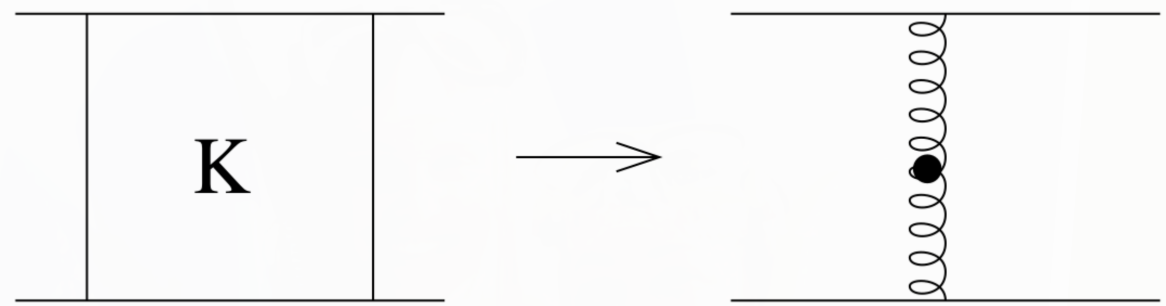
Thank you !

Lattice-QCD and DSE-based modeling

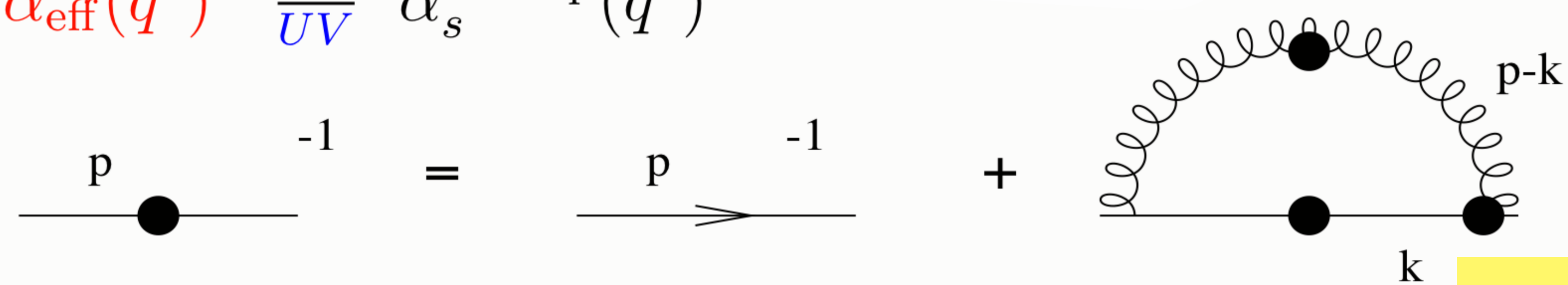
- Lattice: $\langle \mathcal{O} \rangle = \int \; D\bar{q}qG \;\; \mathcal{O}(\bar{q}, q, G) \;\; e^{-\mathcal{S}[\bar{q},q,G]}$
  - Euclidean metric, x-space, Monte-Carlo
  - Issues: lattice spacing and vol, sea and valence m_q, fermion Det
  - Large time limit $\Rightarrow$ nearest hadronic mass pole
- EOMs (DSEs): $0 = \int \; D\bar{q}qG \;\; \frac{\delta}{\delta q(x)} \; e^{-\mathcal{S}[\bar{q},q,G]+(\bar{\eta},q)+(\bar{q},\eta)+(J,G)}$
  - Euclidean metric, p-space, continuum integral eqns
  - Issues: truncation and phenomenology—not full QCD
  - Analtyic contin. $\Rightarrow$ nearest hadronic mass pole
  - Can be quick to identify systematics, mechanisms, $\cdots$

Ladder-Rainbow Model

Landau gauge only



- $K_{\rm BSE} \rightarrow -\gamma_\mu \frac{\lambda^a}{2}\ \ 4\pi\alpha_{\rm eff}(q^2)\ \ D_{\mu\nu}^{\rm free}(q)\ \gamma_\nu \frac{\lambda^a}{2}$
- $\alpha_{\rm eff}(q^2)\ \ \underset{IR}{\rightarrow}\ \ \langle\bar{q}q\rangle_{\mu=1\ {\rm GeV}} = -(240\text{MeV})^3$, incl vertex dressing
- $\alpha_{\rm eff}(q^2)\ \ \underset{UV}{\rightarrow}\ \ \alpha_s^{1-\rm loop}(q^2)$

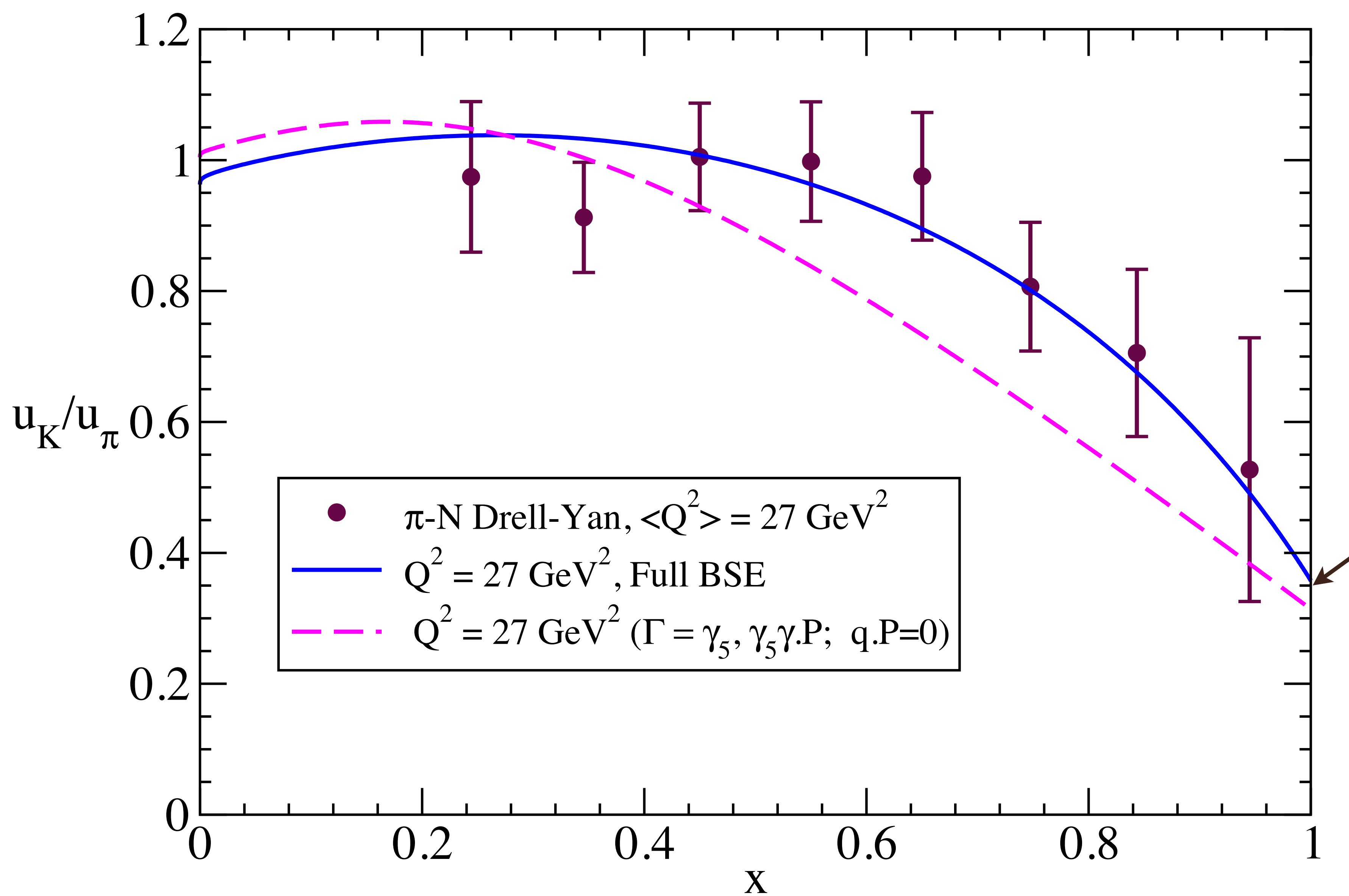


- P. Maris & P.C. Tandy, PRC60, 055214 (1999)
  $M_\rho, M_\phi, M_{K^\star}$ good to 5%, $f_\rho, f_\phi, f_{K^\star}$ good to 10%

See Si-xue Qin, Tues pm for new simplified model

Environmental Dependence of Valence $u(x)$

Nguyen, Bashir, Roberts, PCT, arXiv : 1102.2448 (2011).



scale invariant

- CERN-SPS data: J. Badier et al, PLB **93**, 354 (1980) (valence is not isolated)

The 2009 BaBar data

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k-indepn gluon propagator : H.Roberts, C. Roberts, A. Bashir, L. Gutierrez-Guerrero, PCT: arXiv:1009.0067 (point-pion)

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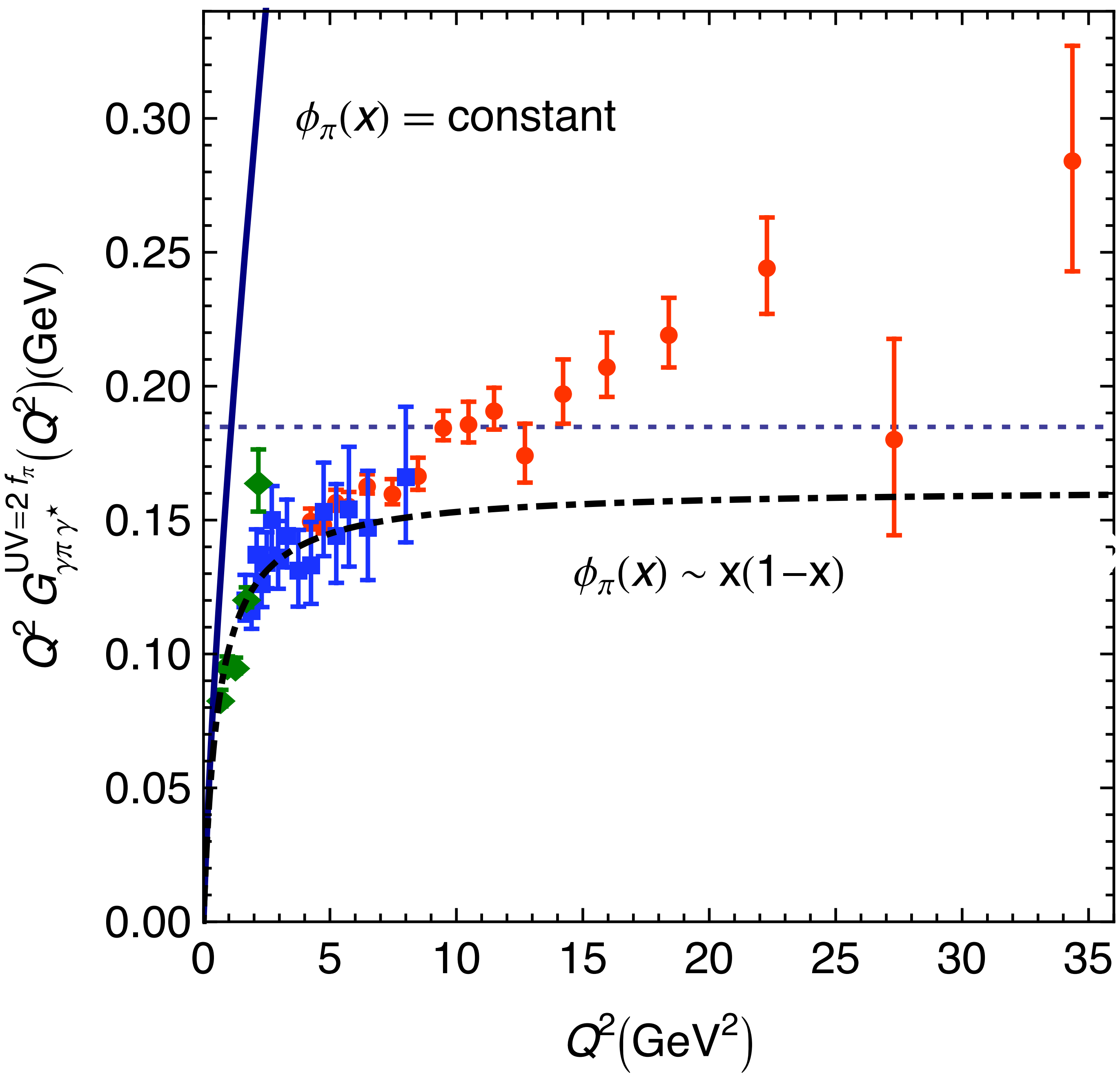

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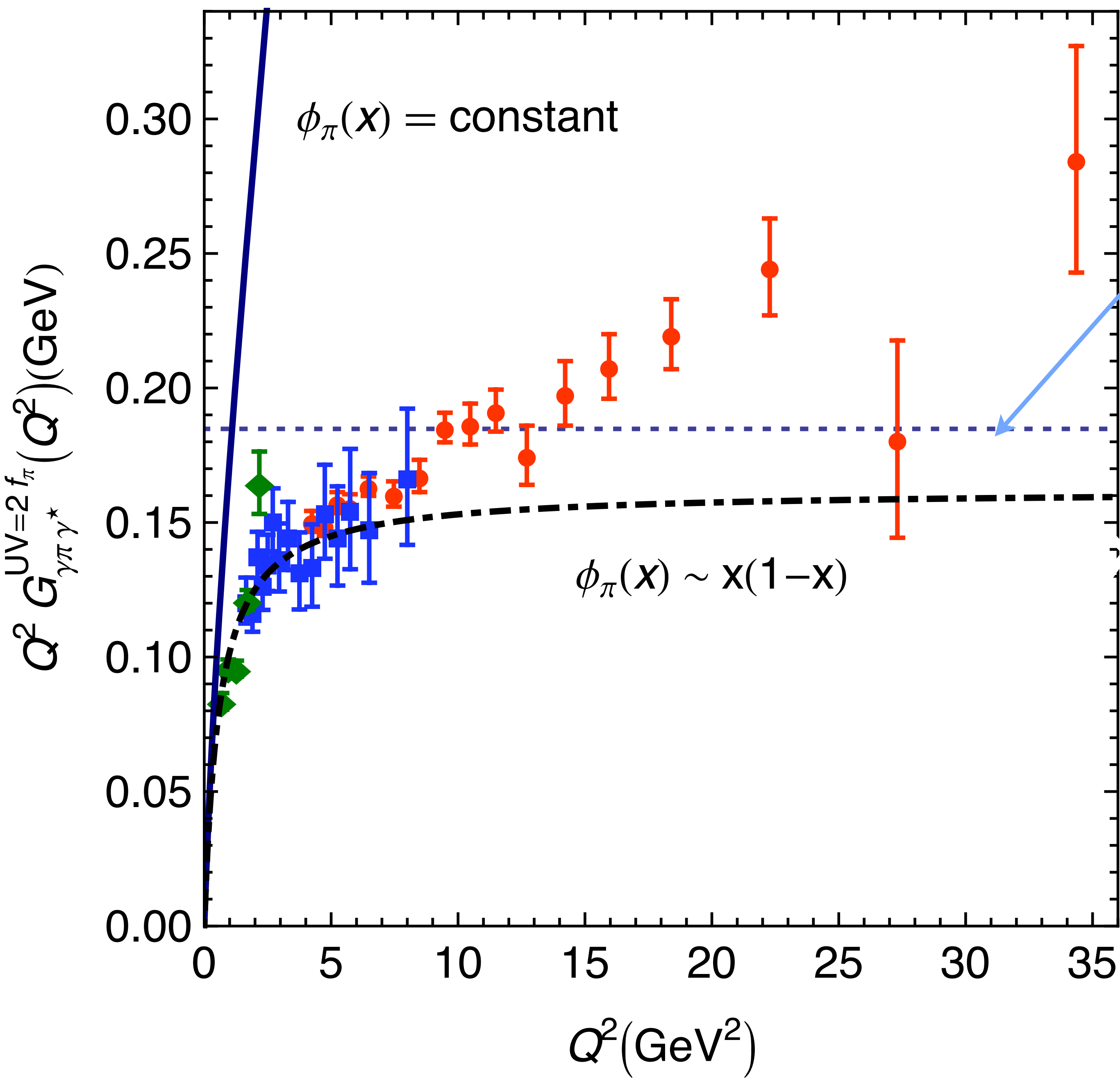
pQCD(BL):

$$\frac{8\pi^2 f_\pi^2 = M^2}{Q^2+M^2} \Rightarrow M \approx M_\rho$$



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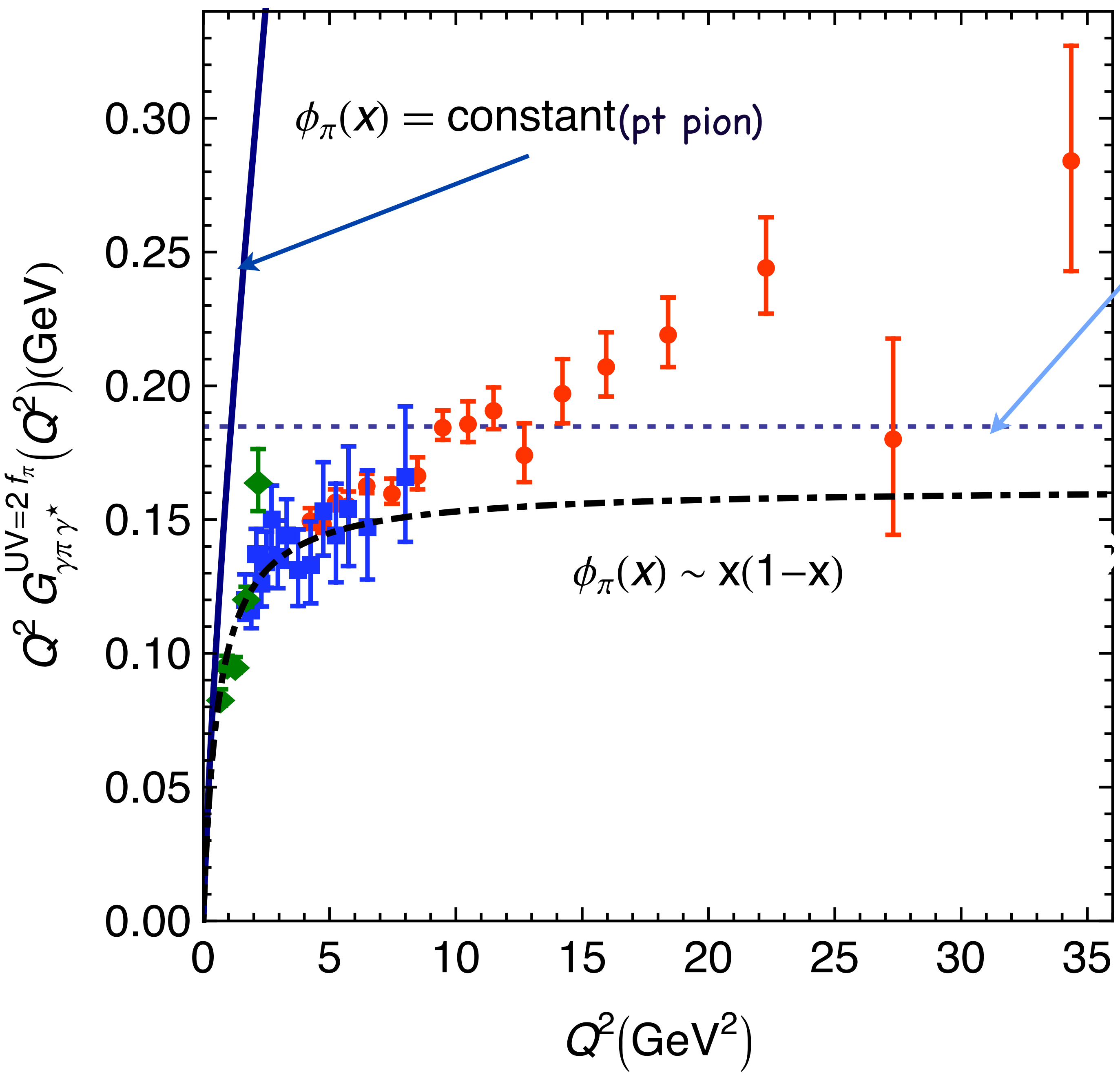

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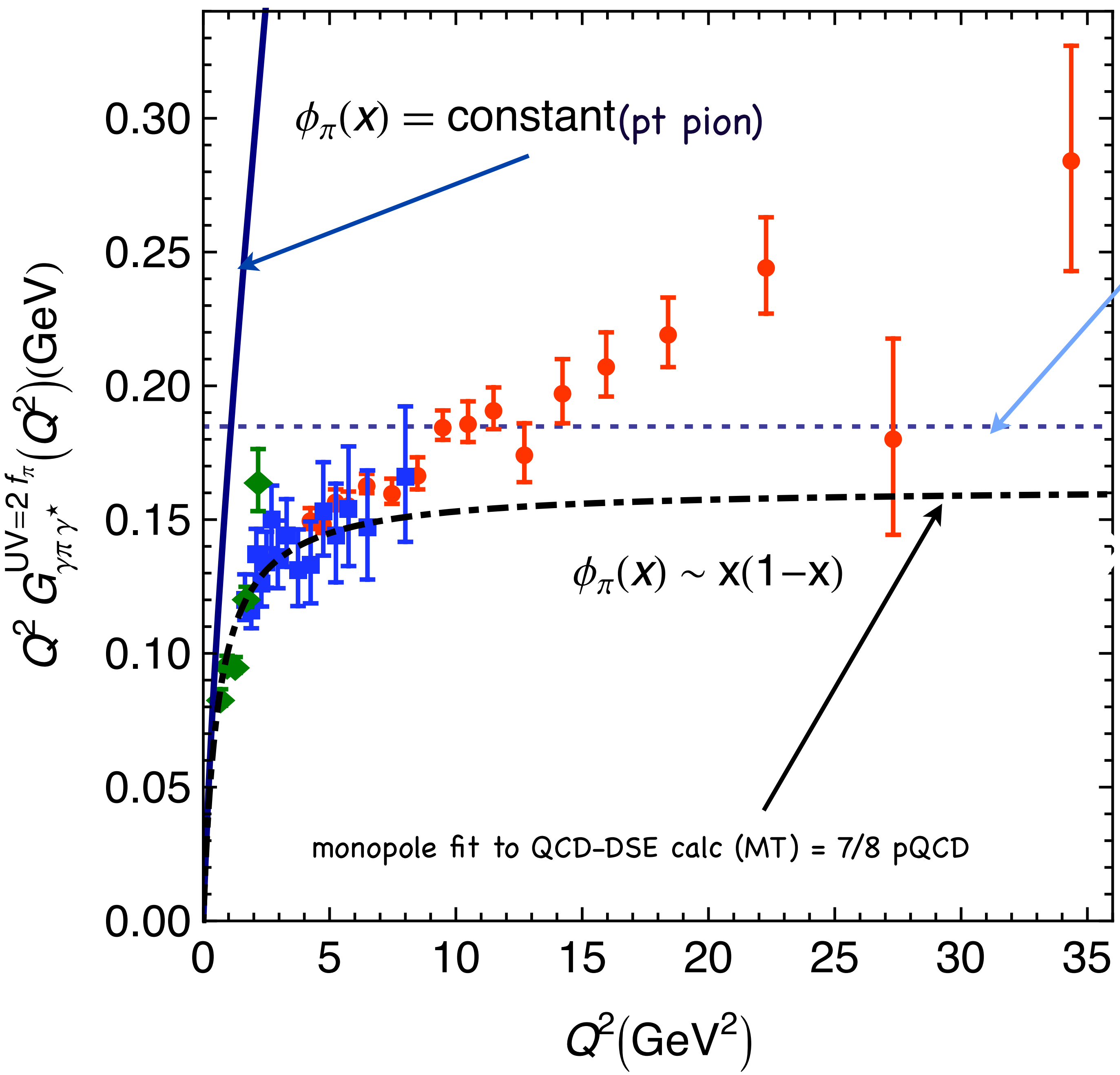

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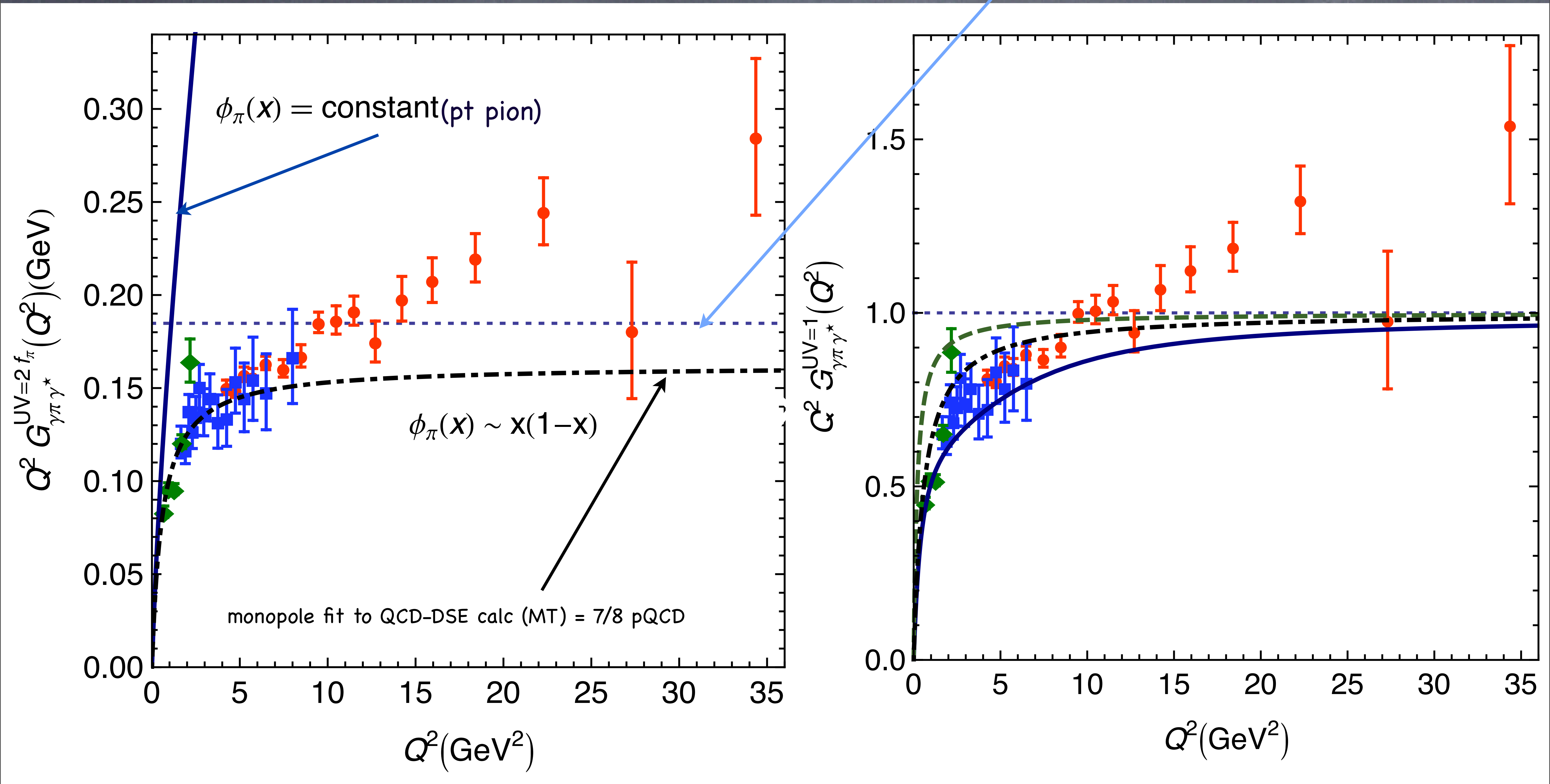

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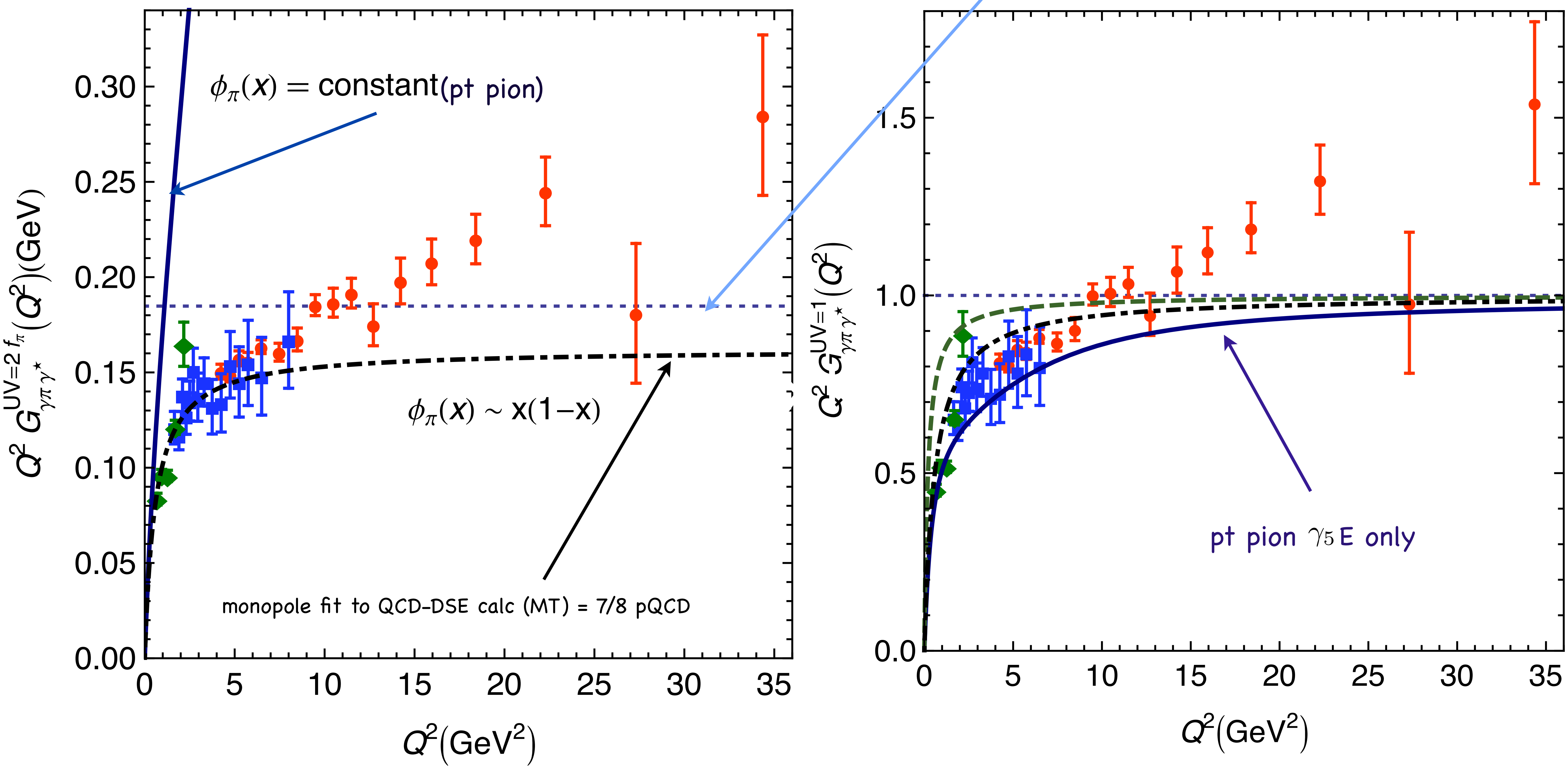

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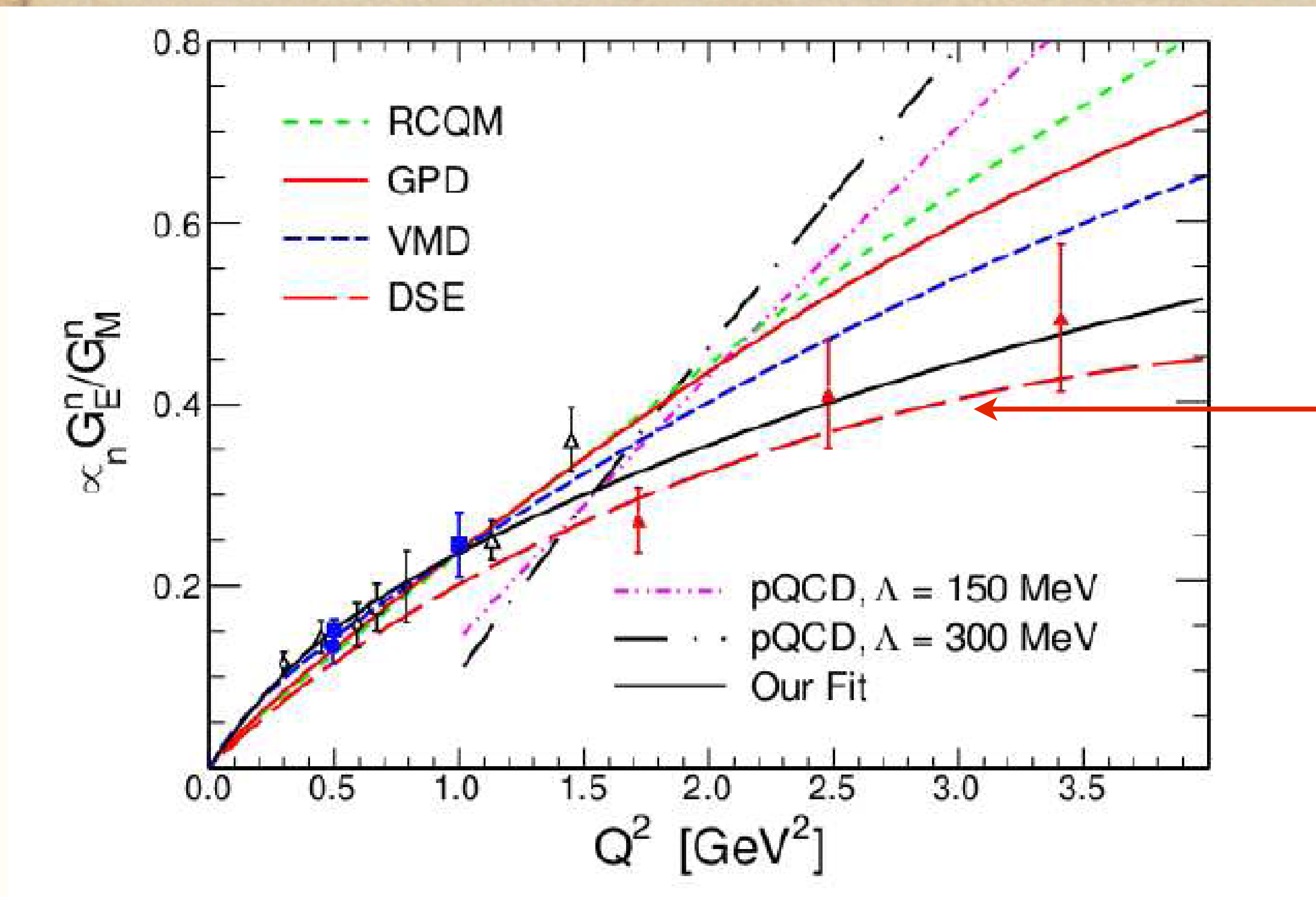
DSE-Faddeev Result for Neutron Form Factors



--- Cloet, Roberts, et al (2010)

S. Riordan, *et al* Phys. Rev. Lett. **105**, 262302 (2010)

Running mass effect on FFs
they fall faster: