Thessaloniki, Greece, 28 August - 4 September 2016

XIIth Quark Confinement and the Hadronic Spectrum

[https://indico.cern.ch/event/353906/overview]

October 13, 2016

Sessions

1. Section A: **Vacuum Structure and Confinement**
2. Section B: **Light Quarks**
   [Chiral and soft collinear effective theories; sum rules; lattice; Schwinger-Dyson equations; masses of light quarks; light-quark loops; structure functions; phenomenology of light-hadron form factors, experiments.]
3. Section C: **Heavy Quarks**
4. Section D: **Deconfinement**
5. Section E: **QCD and New Physics**
6. Section F: **Nuclear and Astroparticle Physics**
7. Section G: **Strongly Coupled Theories**
8. **Future Perspectives, Upgrades, Instrumentation**
9. **Statistical Methods for Physics Analysis in the XXI Century**
10. **Poster session**

TUESDAY 30 AUGUST 2016

8:30-10:30 Plenary: Session III – Aristotelis, *Chair: Gastao Krein*

8:30	Roy-Steiner analysis of pion nucleon-scattering and a precision determination of the sigma-term	*Ulf-G. Meißner*
Yes 9:00	Precision physics with QCD No single word about APT. Interesting	*Antonio Pich*
9:30	Review of present experimental and theoretical status of the proton radius puzzle	*Richard Hill*
Yes 10:00	One and two nucleon matrix elements from lattice QCD for precision tests of the SM in NP environments	*Andre Walker-Loud*

10:30-11:00 Coffee Break

11:00-13:00 Plenary: Session IV – Aristotelis, *Chair: Joan Soto*

11:00	Hadron physics meets gravity	*Felipe J. Llanes-Estrada*
11:30	Flavour anomalies	*Thomas Blake*
12:00	ROUND TABLE: Flavour anomalies - New Physics or QCD effects?	*Marco Gersabeck* *Roman Zwicky* *Zhaofeng Liu* *Thomas Blake* *Lars Hofer* *Sebastian Jaeger*

13:00-15:00 Lunch

MONDAY 29 AUGUST 2016

VACUUM STRUCTURE AND CONFINEMENT A2
Alexandros II
Chair: Dmitry Antonov

Gauge engineering and propagators
17:30 Axel Maas

From QCD's n-point functions to nucleon resonances
18:00 Gernot Eichmann

Three-point functions in Yang-Mills Theory and QCD in Landau gauge
18:30 Adrian Lorenz Blum

Chiral symmetry breaking in continuum QCD
18:50 Mario Mitter

Dyson-Schwinger approach to Hamiltonian QCD
19:10 Davide Campagnari

LIGHT QUARKS B2
Aristotelis II
Chair: Nikolaos Stefanis

Meson Form Factors and Deep Exclusive Meson Production Experiments
17:30 Tanja Horn

Inclusive Cross Sections, Parton Density Functions and the strong coupling at HERA
18:00 Stefan Schmitt

Nucleon structure functions and longitudinal spin asymmetries
18:20 Harleen Dahiya

Pion-photon transition form factor at low-mid momenta within collinear QCD
18:40 Sergey Mikhailov

Neutral pion form factor measurement by the NA62 experiment
19:10 Monica Pepe

Electromagnetic transition form factor and radiative corrections in decays of neutral pions
19:30 Tomas Husek

LIGHT QUARKS B3
Amfitrion II
Chair: Jose Luis Goity

Roy-Steiner-equation analysis of pion-nucleon scattering
17:30 Jacobo Ruiz De Elvira

Unitary coupled channel approach to diffractive scattering and its application to axial vector states
18:00 Ed Berger

The anomalous triangle singulrity and its implications of threshold enhancements
18:30 Qiang Zhao

Pion-eta scalar-isovector 3-coupled channel amplitude fitted to branching ratio as and threshold plus subthreshold parameters
19:00 Robert Kaminski

Properties of exotic and non-exotic quark-bilinears within the Dyson-Schwinger – Bethe-Salpeter equation approach
19:20 Thomas Hilger

HEAVY QUARKS C2
Alexandros I
Chair: Antonio Vairo

Isospin-breaking in the decay constants of heavy mesons from QCD sum rules
17:30 Dmitri Melikhov

D and B mesons masses in chiral perturbation theory with heavy quark symmetry
17:50 Mohammad Alhakami

Approximate degeneracy of heavy-light mesons with the same *L*
18:10 Takayuki Matsuki

The bottom-quark mass from non-relativistic sum rules at NNNLO
18:30 Jan Piclum

Short-distance current correlators on the lattice
18:50 Shoji Hashimoto

Experimental highlights: Heavy Quark Physics in Heavy-Ion collisions at RHIC
19:10 Rachid Nouicer

DECONFINMENT D2
Aristotelis I
Chair: Piotr Bozek

The flow paradigm
17:30 Jean-Yves Ollitrault

Overview of experimental results on collective flow with identified particles at RHIC and the LHC
18:00 Panos Christakoglou

Collectivity / hydrodynamics
18:30 Wojciech Florkowski

Overview of collectivity in small systems
19:00 Wei Li

Anisotropic hydrodynamics
19:30 Michael Strickland

QCD AND NEW PHYSICS E2
Amfitrion I
Chair: Martha Constantinou, Felipe J. Llanes-Estrada, Marco Gersabeck

Perturbative and non-perturbative QCD parameters in Dispersive model.
17:30 Mohammad Ebrahim Zomorrodian

Search for heavy resonances in vector boson scattering
17:45 Guangyi Zhang

Measurement of the WZ boson pair production cross section at 13 TeV and limits on anomalous triple gauge couplings with the ATLAS detector
18:00 Dimitrios Iliadis

Measurement of the ZZ(*) production cross section in the four lepton channel at 8 TeV and 13 TeV and limits on anomalous triple gauge couplings with the ATLAS detector
18:15 Kostas Kordas

Break *18:30*

Recent progress on QCD inputs for axion phenomenology
18:45 Massimo D'elia

Controlling quark mass determinations non-perturbatively in three-flavour QCD
19:05 Patrick Fritzsch

Constraining anomalous Higgs couplings at high and low energy
19:20 Emanuele Mereghetti

Observation of Anomalous Internal Pair Creation in 8Be: A Possible Signature of a Light, Neutral Boson
19:35 Attila Krasznahorkay

STRONGLY COUPLED THEORIES G2
Erato
Chair: Ilias Kyritsis

Strong dynamics on the lattice
17:30 Daniel Nogradi

Infrared behaviors of two color gauge theory
18:00 Kimmo Tuominen

Composite Higgs Dynamics on the Lattice
18:30 Claudio Pica

Inverse magnetic catalysis in holographic models of QCD
19:00 Kiminad Mamo

Axion cosmology from lattice QCD
19:30 Sandor Katz

20:00-21:30 Welcome Drink

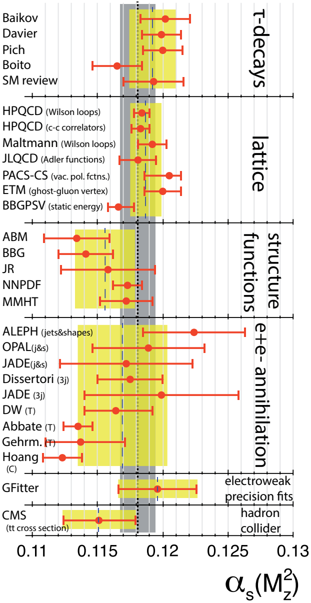
Precision Physics with QCD

Antonio Pich

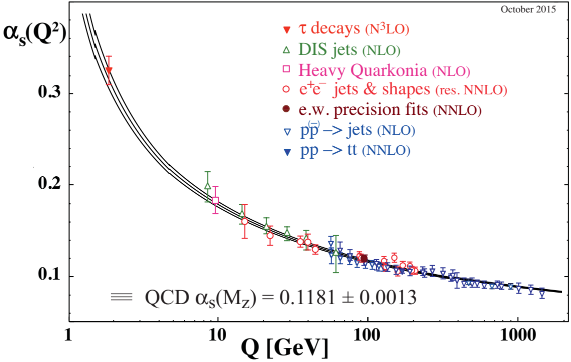
IFIC, Univ. Valencia – CSIC

XIIth Quark Confinement and the Hadron Spectrum
Thessaloniki, Greece, 29th August – 3th September 2016

PDG 2015



S. Bethke, G. Dissertori, G. Salam



See also: S. Alekhin et al., arXiv:1512.05194 [hep-ph]

New analysis of ALEPH data

Rodríguez-Sánchez, Pich, arXiv:1605.06830

Method (V + A)	$\alpha_s(m_\tau^2)$		
	CIPT	FOPT	Average
ALEPH moments [1]	$0.339\,^{+0.019}_{-0.017}$	$0.319\,^{+0.017}_{-0.015}$	$0.329\,^{+0.020}_{-0.018}$
Mod. ALEPH moments [2]	$0.338\,^{+0.014}_{-0.012}$	$0.319\,^{+0.013}_{-0.010}$	$0.329\,^{+0.016}_{-0.014}$
$A^{(2,m)}$ moments [3]	$0.336\,^{+0.018}_{-0.016}$	$0.317\,^{+0.015}_{-0.013}$	$0.326\,^{+0.018}_{-0.016}$
s_0 dependence [4]	0.335 ± 0.014	0.323 ± 0.012	0.329 ± 0.013
Borel transform [5]	$0.328\,^{+0.014}_{-0.013}$	$0.318\,^{+0.015}_{-0.012}$	$0.323\,^{+0.015}_{-0.013}$
Combined value	$\mathbf{0.335 \pm 0.013}$	$\mathbf{0.320 \pm 0.012}$	$\mathbf{0.328 \pm 0.013}$

→ $$\alpha_s(M_Z^2) = 0.1197 \pm 0.0015$$

1) $\omega_{kl}(x) = (1+2x)\,(1-x)^{2+k}\,x^l$ $\qquad (k,l) = (0,0),\ (1,0),\ (1,1),\ (1,2),\ (1,3)$

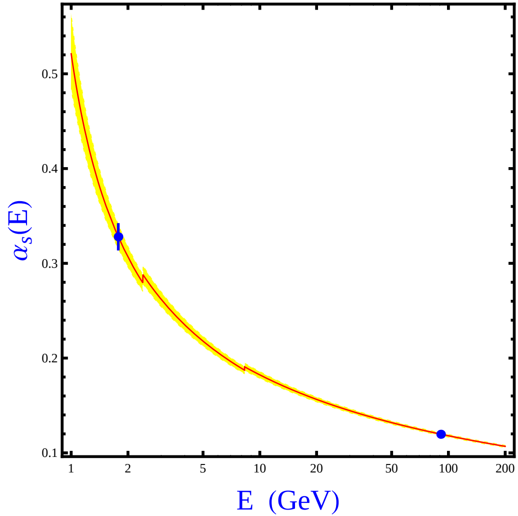
2) $\tilde{\omega}_{kl}(x) = (1-x)^{2+k}\,x^l$ $\qquad (k,l) = (0,0),\ (1,0),\ (1,1),\ (1,2),\ (1,3)$

3) $\omega^{(2,m)}(x) = (1-x)^2 \sum_{k=0}^{m} (k+1)\,x^k = 1 - (m+2)\,x^{m+1} + (m+1)x^{m+2}$, $\qquad 1 \le m \le 5$

4) $\omega^{(2,m)}(x)$ $\qquad 0 \le m \le 2$, 1 single moment in each fit

5) $\omega_a^{(1,m)}(x) = (1 - x^{m+1})\,\mathrm{e}^{-ax}$ $\qquad 0 \le m \le 6$

α_s at N^{3}LO from τ and Z



$$\alpha_s(m_\tau^2) = 0.328 \pm 0.013$$

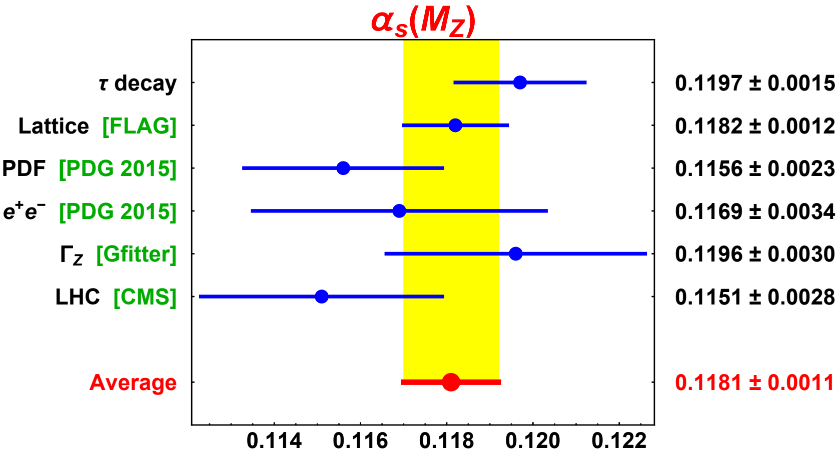
$$\alpha_s(M_Z^2) = 0.1197 \pm 0.0015$$

$$\alpha_s(M_Z^2)_{\text{Z width}} = 0.1196 \pm 0.0030$$

The most precise test of Asymptotic Freedom

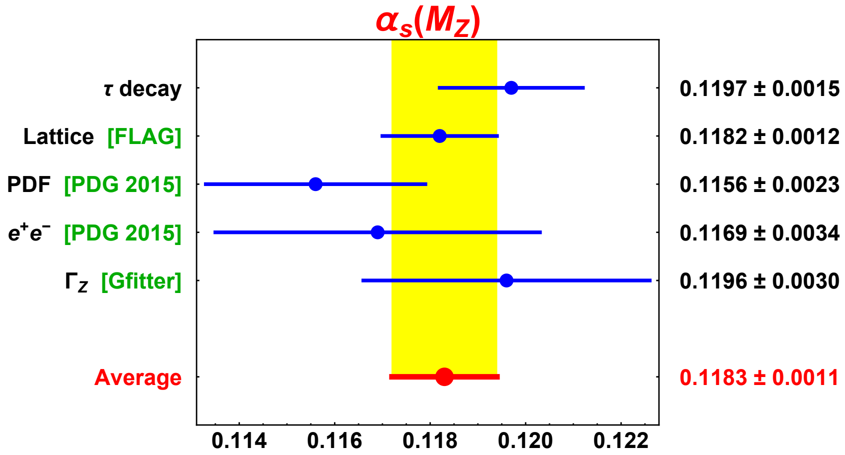
$$\alpha_s^\tau(M_Z^2) - \alpha_s^Z(M_Z^2) = 0.0001 \pm 0.0015_\tau \pm 0.0030_Z$$

$\alpha_s(M_Z^2)$: 2016 Average



PDG 2015: $\alpha_s(M_Z^2) = 0.1181 \pm 0.0013$

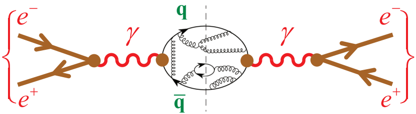
$\alpha_s(M_Z^2)$: 2016 Average



PDG 2015: $\alpha_s(M_Z^2) = 0.1181 \pm 0.0013$

Inclusive Observables: $R_{ee}(s)$

$\sigma \sim \mathrm{Im}$



$$R_{ee}(s) \; = \; 12\pi \; \mathrm{Im}\Pi_{\mathrm{em}}(s)$$

$$\Pi^{\mu\nu}_{\mathrm{em}}(q) \;\equiv\; i \int d^4x\, \mathrm{e}^{iqx}\, \langle 0|\, T\, [J^\mu_{\mathrm{em}}(x)\, J^\nu_{\mathrm{em}}(0)]\, |0\rangle \;=\; \left(-g^{\mu\nu} q^2 + q^\mu q^\nu\right)\; \Pi_{\mathrm{em}}(q^2)$$

$$R_{ee} \equiv \frac{\Gamma(e^+e^- \to \mathrm{hadrons})}{\Gamma(e^+e^- \to e^+e^-)} = \sum_q Q_q^2\, N_C \left\{ 1 + \sum_{n\geq 1} F_n \left[\frac{\alpha_s(M_Z^2)}{\pi}\right]^n \right\} + \mathcal{O}\left(\frac{m_q^2}{s}, \frac{\Lambda^4}{s^2}\right)$$

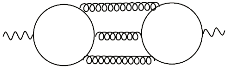
Perturbative series known to $\mathcal{O}(\alpha_s^4)$: $(n_F = 5)$ Baikov-Chetyrkin-Kühn-Rittinger

$$F_1 = 1 \qquad , \qquad F_2 = 1.9857 - 0.1153\, n_F = 1.4092$$

$$F_3 = -6.63694 - 1.20013\, n_F - 0.00518\, n_F^2 - 1.2395\, \eta = -12.805$$

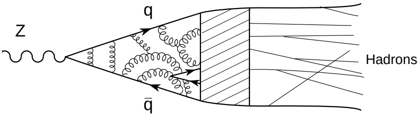
$$F_4^{\mathrm{NS}} = -156.608 + 18.7748\, n_F - 0.7974\, n_F^2 + 0.0215\, n_F^3 - 14.952\, \eta = -80.434$$

$$\eta \;=\; \left(\sum_q Q_q\right)^2 / \left(N_C \sum_q Q_q^2\right)$$



Singlet contributions

Z Hadronic Width



Vector + Axial

$$R_Z \equiv \frac{\Gamma(Z \to \mathrm{hadrons})}{\Gamma(Z \to e^+e^-)} = R_Z^{\mathrm{EW}}\, N_C \left\{ 1 + \sum_{n\geq 1} \tilde{F}_n \left[\frac{\alpha_s(M_Z^2)}{\pi}\right]^n \right\} + \mathcal{O}\left(\frac{m_q^2}{M_Z^2}, \frac{\Lambda^4}{M_Z^4}\right)$$

Perturbative series known to $\mathcal{O}(\alpha_s^4)$

$$\left[+ \mathcal{O}\left(\alpha_s^2 \frac{m_b^4}{M_Z^4}, \alpha_s^2 \frac{m_b^2}{m_t^2}, \alpha_s^3 \frac{M_Z^2}{m_t^2}\right)\right]$$

Baikov-Chetyrkin-Kühn-Rittinger

Z-pole data (EW fit) ➡ $\alpha_s(M_Z^2) = 0.1196 \pm 0.0030$

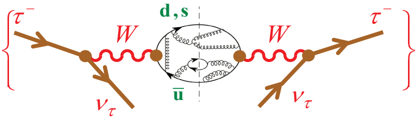
Gfitter 2014

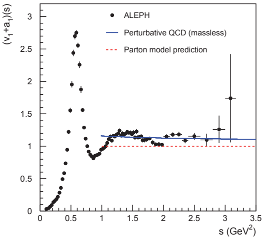
Assumes validity of the EW Standard Model

τ Hadronic Width: R_τ

Davier et al, 1312.1501

$$\Gamma_{\tau\to\nu_\tau+\text{had}} \sim \text{Im}\left\{ \quad \right\}$$





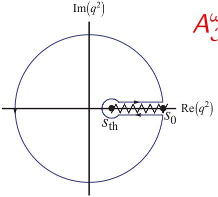
$$\Pi^{(J)}(s) \;\equiv\; |V_{ud}|^2 \left(\Pi^{(J)}_{ud,V}(s) + \Pi^{(J)}_{ud,A}(s)\right) \;+\; |V_{us}|^2\; \Pi^{(J)}_{us,V+A}(s)$$

$$v_1 \;=\; 2\pi\; \text{Im}\Pi^{(1)}_{ud,V}(s) \quad , \quad a_1 \;=\; 2\pi\; \text{Im}\Pi^{(1)}_{ud,A}(s)$$

$$R_\tau \;=\; \frac{\Gamma[\tau^- \to \nu_\tau \text{hadrons}]}{\Gamma[\tau^- \to \nu_\tau e^- \overline{\nu}_e]} \;=\; R_{\tau,V} + R_{\tau,A} + R_{\tau,S}$$

$$=\; 12\pi \int_0^{m_\tau^2} \frac{ds}{m_\tau^2} \left(1 - \frac{s}{m_\tau^2}\right)^2 \left[\left(1 + 2\frac{s}{m_\tau^2}\right) \text{Im}\,\Pi^{(0+1)}(s) - 2\frac{s}{m_\tau^2}\, \text{Im}\,\Pi^{(0)}(s)\right]$$

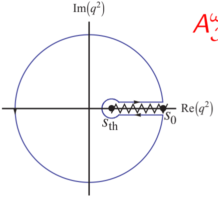
$$i \int d^4x \, e^{iqx} \, \langle 0 | \, T \left[\mathcal{J}_{ij}^{\mu}(x) \, \mathcal{J}_{ij}^{\nu\,\dagger}(0) \right] |0\rangle \; = \; (-g^{\mu\nu} q^2 + q^\mu q^\nu) \; \Pi_{ij,\mathcal{J}}^{(1)}(q^2) + q^\mu q^\nu \; \Pi_{ij,\mathcal{J}}^{(0)}(q^2)$$



$$A^{\omega}_{\mathcal{J}}(s_0) \; \equiv \; \int_{s_{th}}^{s_0} \frac{ds}{s_0} \, \omega(s) \; \mathrm{Im}\, \Pi^{(J)}_{\mathcal{J}}(s) \; = \; \frac{i}{2} \oint_{|s|=s_0} \frac{ds}{s_0} \, \omega(s) \, \Pi^{(J)}_{\mathcal{J}}(s)$$

$$\Pi^{(J)}_{\mathcal{J}}(s) \; \approx \; \Pi^{(J)}_{\mathcal{J}}(s)^{\rm OPE} \; = \; \sum_D \frac{\mathcal{O}^{(J)}_{D,\mathcal{J}}}{(-s)^{D/2}}$$

$$i \int d^4x \, e^{iqx} \, \langle 0 | \, T \left[\mathcal{J}^{\mu}_{ij}(x) \, \mathcal{J}^{\nu\,\dagger}_{ij}(0) \right] | 0 \rangle \; = \; (-g^{\mu\nu} q^2 + q^\mu q^\nu) \, \Pi^{(1)}_{ij,\mathcal{J}}(q^2) + q^\mu q^\nu \, \Pi^{(0)}_{ij,\mathcal{J}}(q^2)$$



$$A^{\omega}_{\mathcal{J}}(s_0) \equiv \int_{s_{th}}^{s_0} \frac{ds}{s_0} \, \omega(s) \, \mathrm{Im}\, \Pi^{(J)}_{\mathcal{J}}(s) = \frac{i}{2} \oint_{|s|=s_0} \frac{ds}{s_0} \, \omega(s) \, \Pi^{(J)}_{\mathcal{J}}(s)$$

$$\Pi^{(J)}_{\mathcal{J}}(s) \approx \Pi^{(J)}_{\mathcal{J}}(s)^{\rm OPE} = \sum_D \frac{\mathcal{O}^{(J)}_{D,\mathcal{J}}}{(-s)^{D/2}}$$

$$\mathbf{R_\tau = N_C \, S_{EW} \, (1 + \delta_P + \delta_{NP})}$$

Braaten-Narison-Pich '92

$$= 6\pi i \oint_{|x|=1} (1-x)^2 \left[(1+2x) \, \Pi^{(0+1)}(m_\tau^2 x) - 2x \, \Pi^{(0)}(m_\tau^2 x) \right]$$

$$\delta_{\rm P} = a_\tau + 5.20 \, a_\tau^2 + 26 \, a_\tau^3 + 127 \, a_\tau^4 + \cdots \approx 20\%$$

Baikov-Chetyrkin-Kühn '08

$a_\tau \equiv \alpha_s(m_\tau^2)/\pi$, $\mathbf{S_{EW}} = 1.0201 \, (3)$

Marciano-Sirlin, Braaten-Li, Erler

$\delta_{\rm NP} = -0.0064 \pm 0.0013$ (Fitted from data)

Davier et al '14

Perturbative Contribution $(m_q = 0)$

$a_\tau \equiv \frac{\alpha_s(m_\tau^2)}{\pi}$

$$-s\,\frac{d}{ds}\Pi^{(0+1)}(s) = \frac{1}{4\pi^2}\sum_{n=0} K_n\, a_s(-s)^n \quad \Rightarrow$$

$$\delta_{\mathrm{P}} = \underbrace{\sum_{n=1} K_n\, A^{(n)}(\alpha_s)}_{\text{CIPT}} = \underbrace{\sum_{n=1} r_n\, a_\tau^n}_{\text{FOPT}}$$

$$A^{(n)}(\alpha_s) \equiv \frac{1}{2\pi i}\oint_{|x|=1}\frac{dx}{x}\left(1-2x+2x^3-x^4\right)\left(\frac{\alpha_s(-m_\tau^2 x)}{\pi}\right)^n = a_\tau^n + \cdots$$

Perturbative Contribution $(m_q = 0)$

$a_\tau \equiv \frac{\alpha_s(m_\tau^2)}{\pi}$

$$-s\,\frac{d}{ds}\Pi^{(0+1)}(s) = \frac{1}{4\pi^2}\sum_{n=0} K_n\, a_s(-s)^n \quad \Longrightarrow \quad \delta_{\rm P} = \underbrace{\sum_{n=1} K_n\, A^{(n)}(\alpha_s)}_{\rm CIPT} = \underbrace{\sum_{n=1} r_n\, a_\tau^n}_{\rm FOPT}$$

$$A^{(n)}(\alpha_s) \equiv \frac{1}{2\pi i}\oint_{|x|=1}\frac{dx}{x}\left(1-2x+2x^3-x^4\right)\left(\frac{\alpha_s(-m_\tau^2 x)}{\pi}\right)^n = a_\tau^n + \cdots$$

1) The dominant corrections come from the contour integration

Large running of α_s along the circle $s = m_\tau^2\, e^{i\phi}$, $\phi \in [-\pi,\pi]$

n	1	2	3	4	5	
K_n	1	1.6398	6.37101	49.0757	?	Baikov-Chetyrkin-Kühn '08
r_n	1	5.2023	26.3659	127.079	$307.78 + K_5$	Le Diberder-Pich '92
$r_n - K_n$	0	3.5625	19.9949	78.0029	307.78	

Perturbative Contribution $(m_q = 0)$

$a_\tau \equiv \frac{\alpha_s(m_\tau^2)}{\pi}$

$$-s\,\frac{d}{ds}\Pi^{(0+1)}(s) = \frac{1}{4\pi^2}\sum_{n=0} K_n\, a_s(-s)^n \quad \Rightarrow \quad \delta_{\rm P} = \underbrace{\sum_{n=1} K_n\, A^{(n)}(\alpha_s)}_{\rm CIPT} = \underbrace{\sum_{n=1} r_n\, a_\tau^n}_{\rm FOPT}$$

$$A^{(n)}(\alpha_s) \equiv \frac{1}{2\pi i}\oint_{|x|=1}\frac{dx}{x}\left(1-2x+2x^3-x^4\right)\left(\frac{\alpha_s(-m_\tau^2 x)}{\pi}\right)^n = a_\tau^n + \cdots$$

2) CIPT gives rise to a well-behaved perturbative series

$a_\tau = 0.11$	$A^{(1)}(\alpha_s)$	$A^{(2)}(\alpha_s)$	$A^{(3)}(\alpha_s)$	$A^{(4)}(\alpha_s)$	$\delta_{\rm P}$
$\beta_{n>1} = 0$	0.14828	0.01925	0.00225	0.00024	0.20578
$\beta_{n>2} = 0$	0.15103	0.01905	0.00209	0.00020	0.20537
$\beta_{n>3} = 0$	0.15093	0.01882	0.00202	0.00019	0.20389
$\beta_{n>4} = 0$	0.15058	0.01865	0.00198	0.00018	0.20273
$\beta_{n>5} = 0$	0.15041	0.01859	0.00197	0.00018	0.20232
$\mathcal{O}(a_\tau^4)$ FOPT	0.16115	0.02431	0.00290	0.00015	0.22665

FOPT overestimates $\delta_{\rm P}$ by 11%

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Thessaloniki, August 29, 2016

PDFs from Jefferson Lab to the LHC

Wally Melnitchouk

Jefferson Lab

JLab Angular Momentum (JAM) collaboration: http://www.jlab.org/JAM

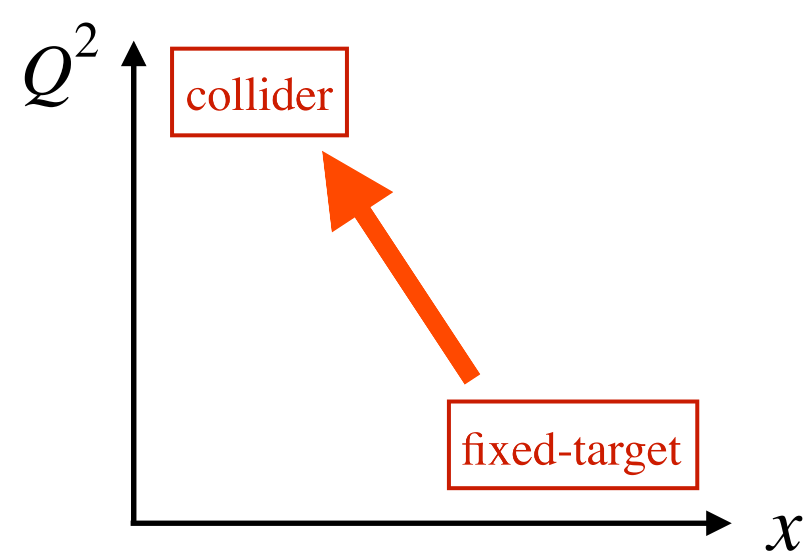
CTEQ-JLab (CJ) collaboration: http://www.jlab.org/CJ

- Universality of PDFs allows data from many different processes (DIS, SIDIS, weak boson/jet production in pp, Drell-Yan, $\ldots$) to be analyzed simultaneously

  $\rightarrow$ global QCD analyses of spin-averaged $(f = f^{\uparrow} + f^{\downarrow})$ and spin-dependent $(\Delta f = f^{\uparrow} - f^{\downarrow})$ PDFs

- Precision PDFs needed to
  (1) understand basic structure of QCD bound states
  (2) compute backgrounds in searches for BSM physics

  $\rightarrow$ Q^2 evolution feeds
  low x, high Q^2 ("LHC")
  from high x, low Q^2 ("JLab")



Valence quarks & QCD models

- Valence d/u ratio at high x of particular interest

→ testing ground for nucleon models in $x \to 1$ limit

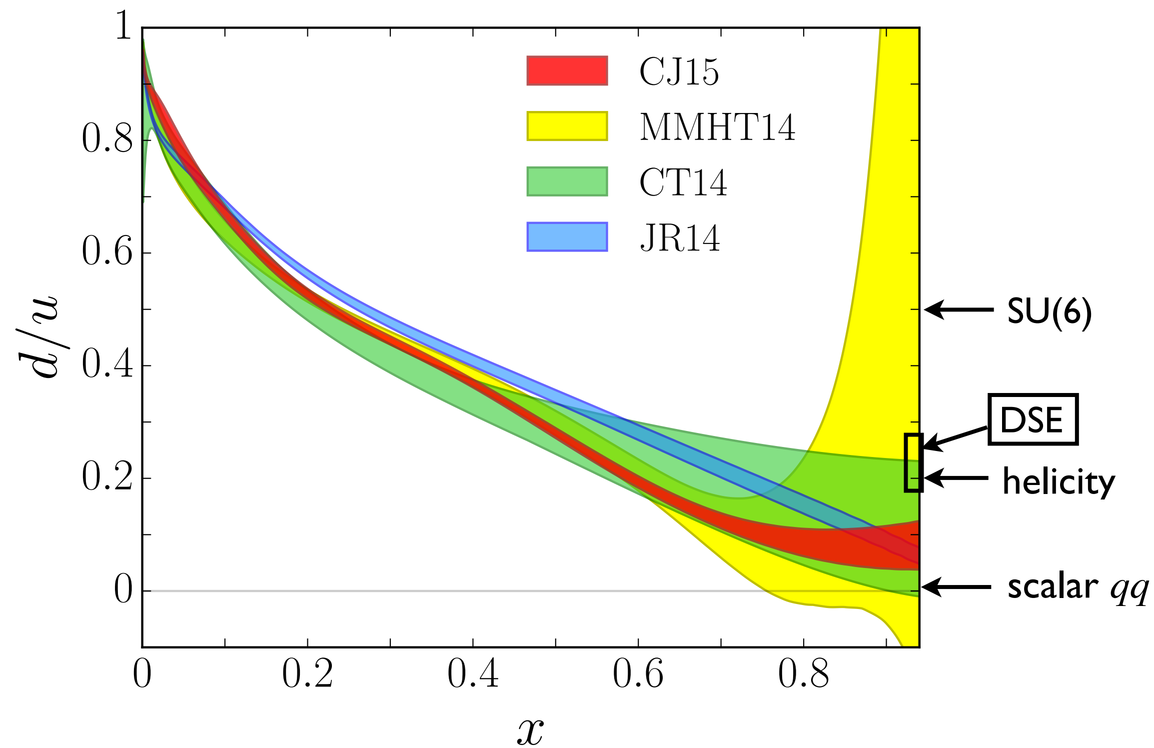
- $d/u \to 1/2$
  SU(6) symmetry

- $d/u \to 0$
  $S = 0$ qq dominance
  (color-hyperfine interaction)

- $d/u \to 1/5$
  $S_z = 0$ qq dominance
  (perturbative gluon exchange)

- $d/u \to 0.18 - 0.28$
  DSE with qq correlations

Roberts

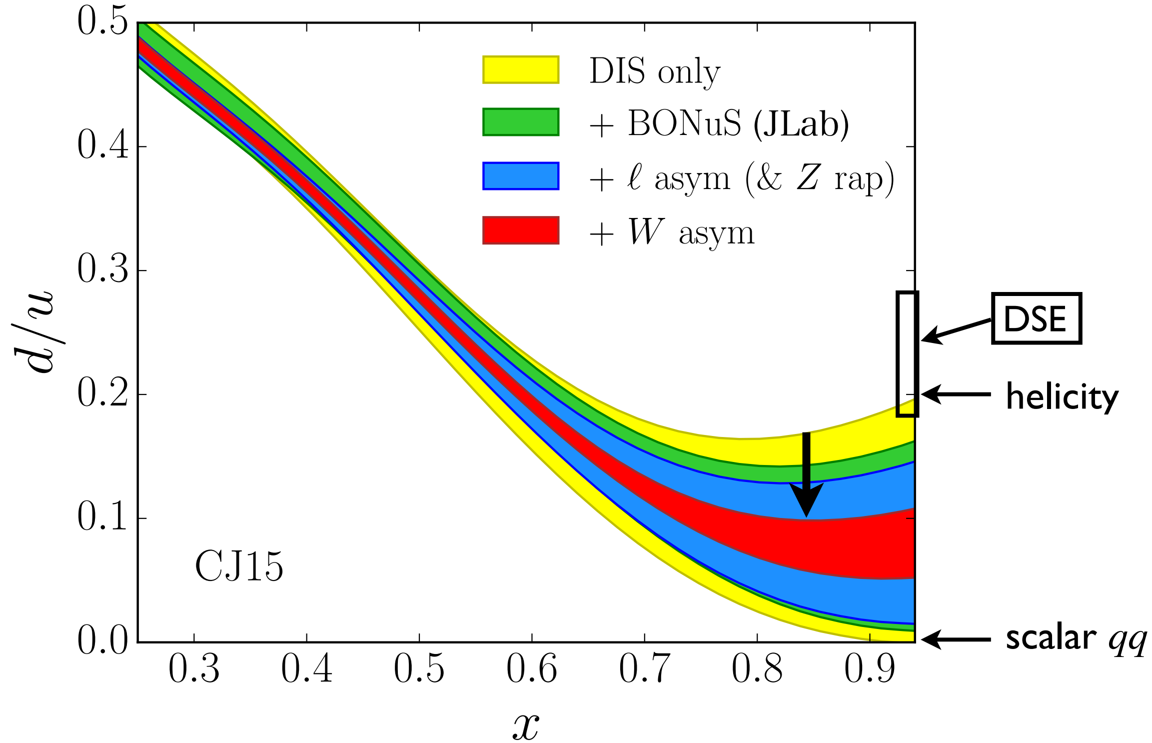


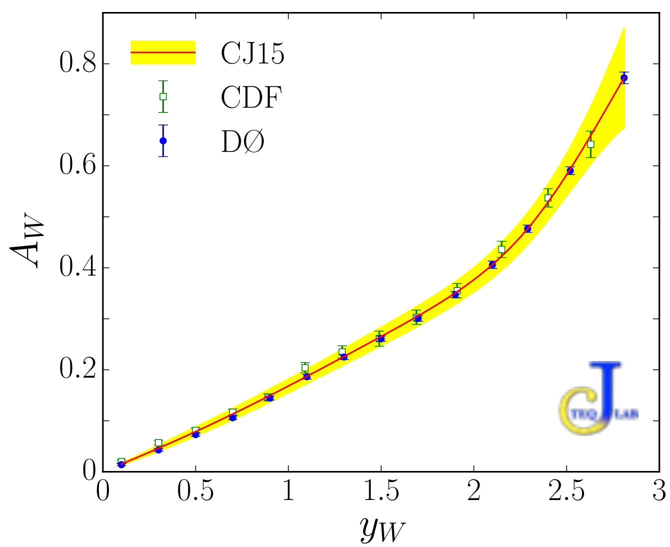
→ considerable uncertainty at high x from deuterium corrections (no free neutrons!)

Valence quarks & QCD models

- Valence d/u ratio at high x of particular interest

→ significant reduction of PDF errors with new JLab tagged neutron & FNAL W-asymmetry data





Accardi et al. (2016)

→ extrapolated ratio at $x = 1$

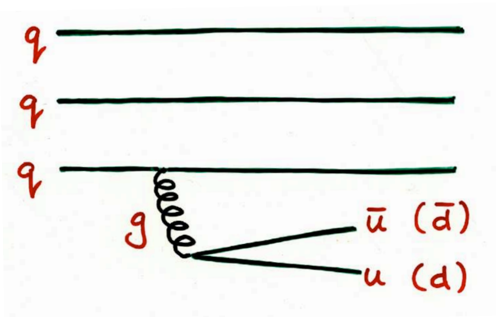
$$d/u \to 0.09 \pm 0.03$$

does not match any model!

→ upcoming experiments at JLab (MARATHON, BONuS, SoLID) will determine d/u up to $x \sim 0.85$

Light quark sea

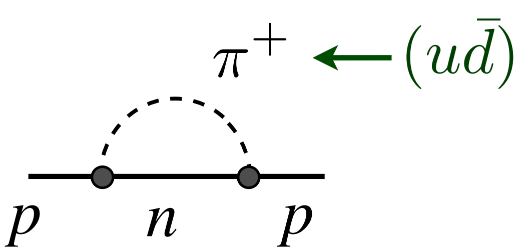
- From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)



→ since u and d quarks nearly degenerate, expect flavor-symmetric light-quark sea

$$\bar{d} \approx \bar{u}$$

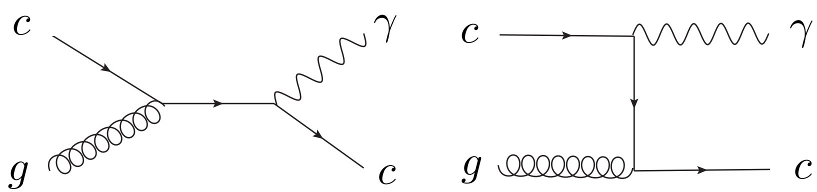
- In 1984 Thomas made audacious suggestion that chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)



→ $\boxed{\bar{d} > \bar{u}}$

Charm in the nucleon

- Associated prompt photon + charm production
  $pp \to \gamma + c + X$ may reveal "intrinsic" charm component



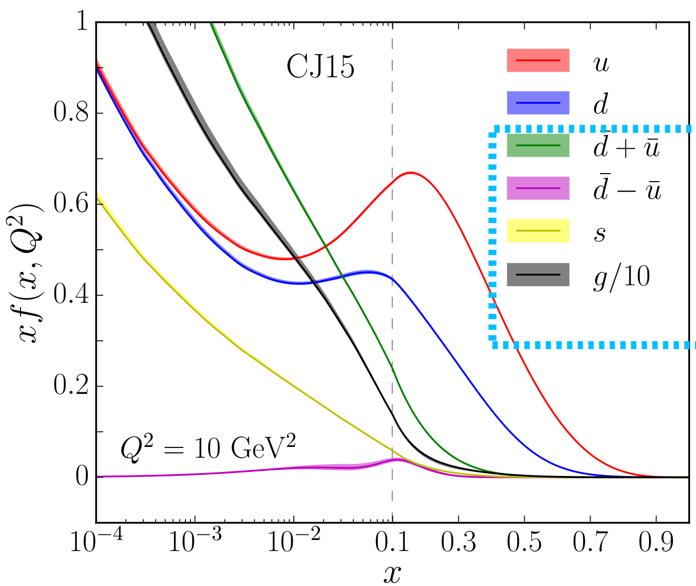
Bednyakov et al. (2014)

→ "smoking gun" would be observation of asymmetric distributions $c(x) \neq \bar{c}(x)$

→ ***Tim Hobbs talk***
Tue. 18:30

Outlook and new directions

- Study of PDFs has brought together essential elements of nuclear and high-energy physics



nucleon structure

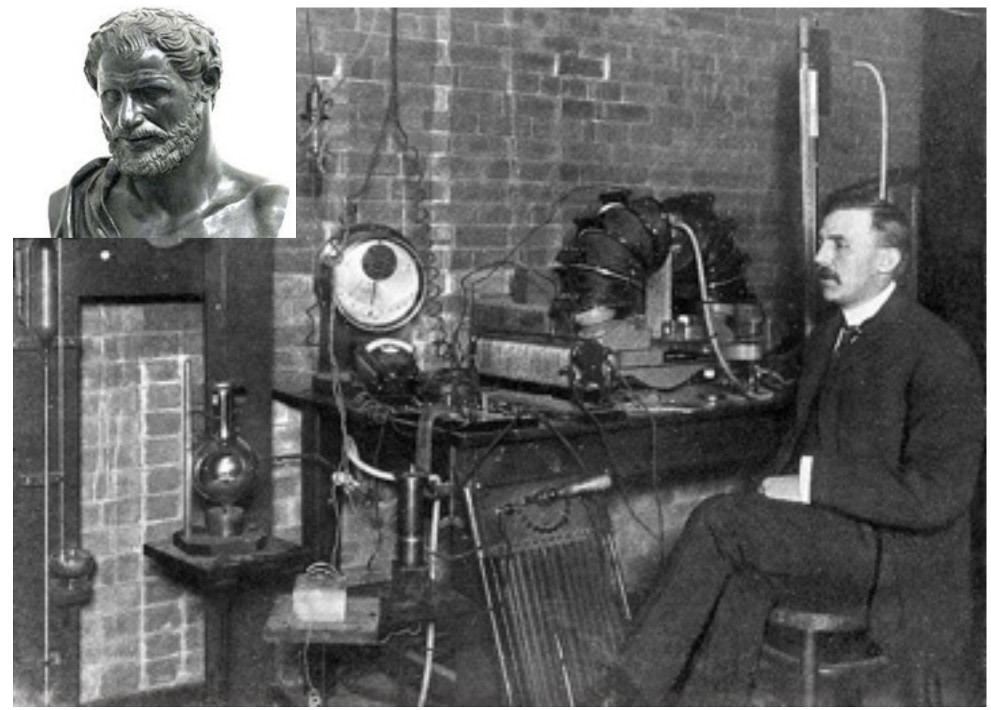
neutrino oscillations

chiral physics

quark-hadron duality

astrophysics

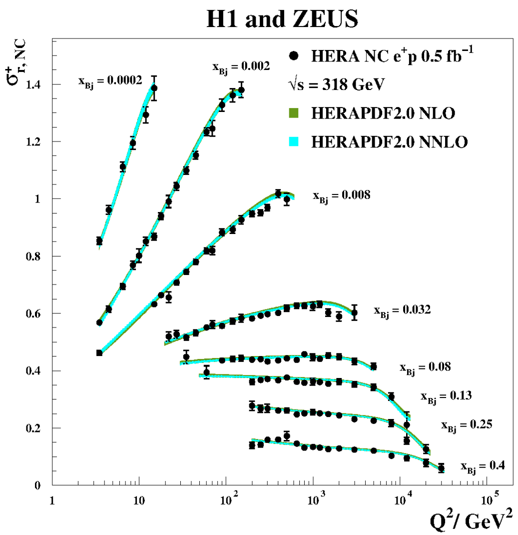
BSM physics



PDF and α_s measurements at HERA

XII Quark Confinement and the Hadron Spectrum

from 29 August 2016 to 3 September 2016
Europe/Athens timezone



HCHS2016
Thessaloniki, Greece

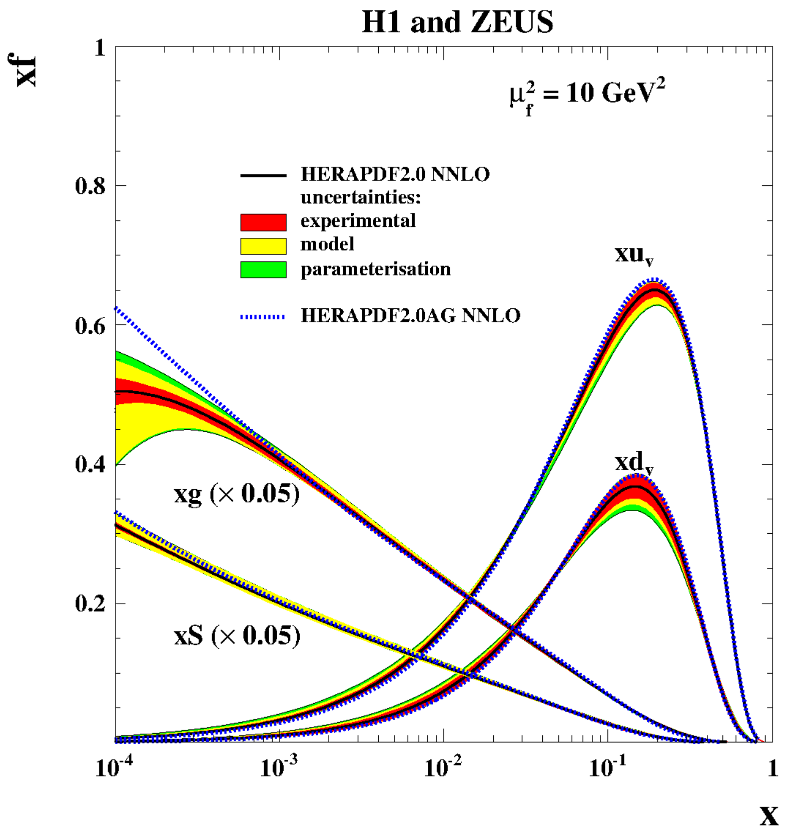
Stefan Schmitt, DESY
For the HERA collaborations
H1 and ZEUS

Outline

- The HERA collider
- Deep-inelastic scattering
- Data combination
- The combined HERA data
- The HERAPDF2.0 fit
- Jet production and α_s

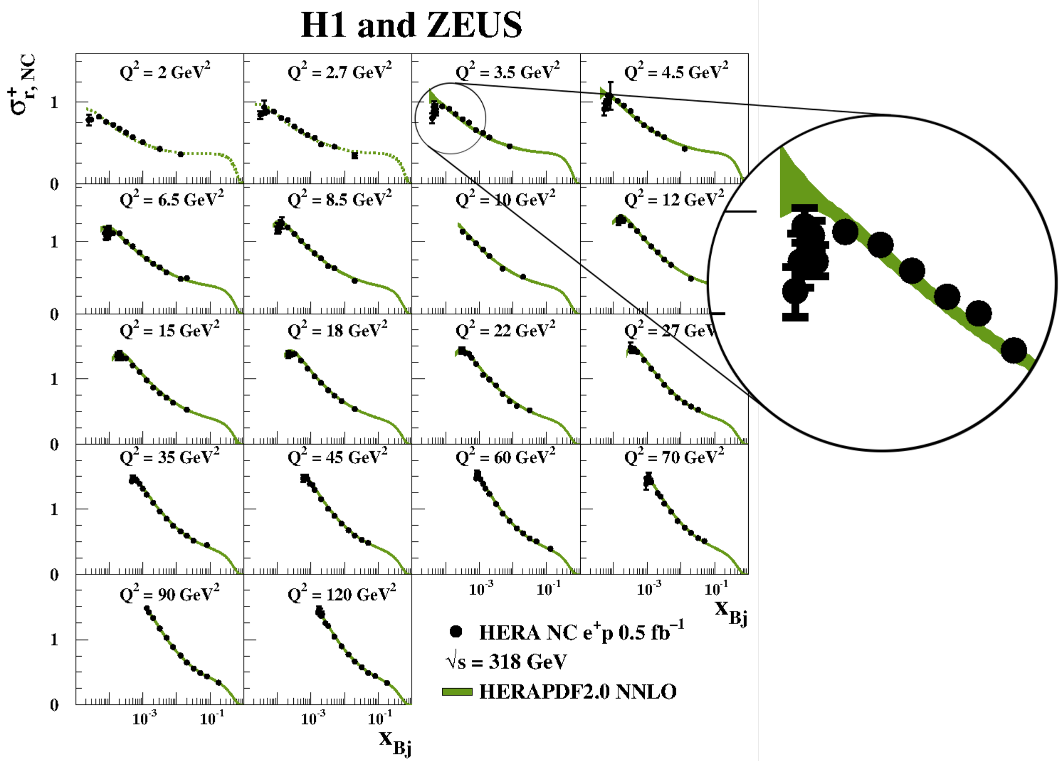
HERAPDF2.0

- HERAPDF2.0 PDFs: family of fits based on HERA data alone, at NLO and NNLO
- All fit variants are available in the LHAPDF library
- Shown here:
  - Default NNLO fit with uncertainty bands: “HERAPDF2.0 NNLO”
  - Variant with non-negative gluon “HERAPDF2.0AG NNLO”



HERAPDF2.0

- HERAPDF2.0 PDFs: family of fits based on HERA data alone, at NLO and NNLO
- Overall good description of the data down to low Q²
- Some deviations in the region of low x at low Q²



Summary

- Recent publication of combined HERA inclusive cross section data: precision better than 1.5% for $Q^2<500$ GeV^2
- A unique dataset probing the proton structure over more than five orders of magnitude in Q^2 and x
- Parton densities HERPDF2.0 derived from HERA data alone
- Together with DIS jet data, the strong coupling can be measured

  alpha_s(M_z) = 0.1183
- Aim to reduce scale uncertainties on α_s from DIS jets in the near future using NNLO calculations

XII Quark Confinement & the Hadron Spectrum

X, Y, Z States

Marina Nielsen
Universidade de São Paulo

Lots of X, Y and Z states observed by BaBar, Belle, BESIII, CDF, CLEOIII, CLEO-c, CMS, D0 and LHCb Collaborations

N. Branbilla et al., arXiv:1404.3723

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [810, 1030] (>10), BaBar [1031] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [1032, 1033] (11.6), D0 [1034] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb [1035, 1036] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [1037] (4.3), BaBar [1038] (4.0)	2005	Ok
				$B \to K(\gamma J/\psi)$	Belle [1039] (5.5), BaBar [1040] (3.5)	2005	Ok
					LHCb [1041] (> 10)		
				$B \to K(\gamma\psi(2S))$	BaBar [1040] (3.6), Belle [1039] (0.2)	2008	NC!
					LHCb [1041] (4.4)		
				$B \to K(D\bar{D}^*)$	Belle [1042] (6.4), BaBar [1043] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [1044] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
					T. Xiao et al. [CLEO data] [1047] (>5)		
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1088] (8), BaBar [1038, 1089] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1090] (7.7), BaBar [1091] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1092] (5.3), BaBar [1093] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1086, 1087] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1046, 1094] (7.4)	2007	NC!
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1048] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1049] (10)	2013	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (5.0), Belle [1099] (1.9),	2009	NC!
					LHCb [1100] (1.4), CMS [1101] (>5)		
					D0 [1102] (3.1)		

$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$??^+$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1087] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$??^+$	$\bar{B}^0 \to K^-(\pi^+ \chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1104, 1105] (8), CLEO [1106, 1107] (11) Belle [1046, 1094] (15), BES III [1045] (np)	2005	Ok
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1105] (np), Belle [1046] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
				$e^+e^- \to (\gamma X(3872))$	BES III [1108] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$??^+$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (3.1), LHCb [1100] (1.0), CMS [1101] (>3), D0 [1102] (np)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1109] (3.2)	2009	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (8), BaBar [1111] (np)	2007	Ok
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [1112, 1113] (6.4), BaBar [1114] (2.4) LHCb [1115] (13.9)	2007	Ok
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (4.0)	2014	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [1116] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (5.8), BaBar [1111] (5)	2007	Ok

in 2014: 23 new states, many not confirmed

many candidates for exotic states

up to now: 9 reported charged states which are not quark-antiquark states

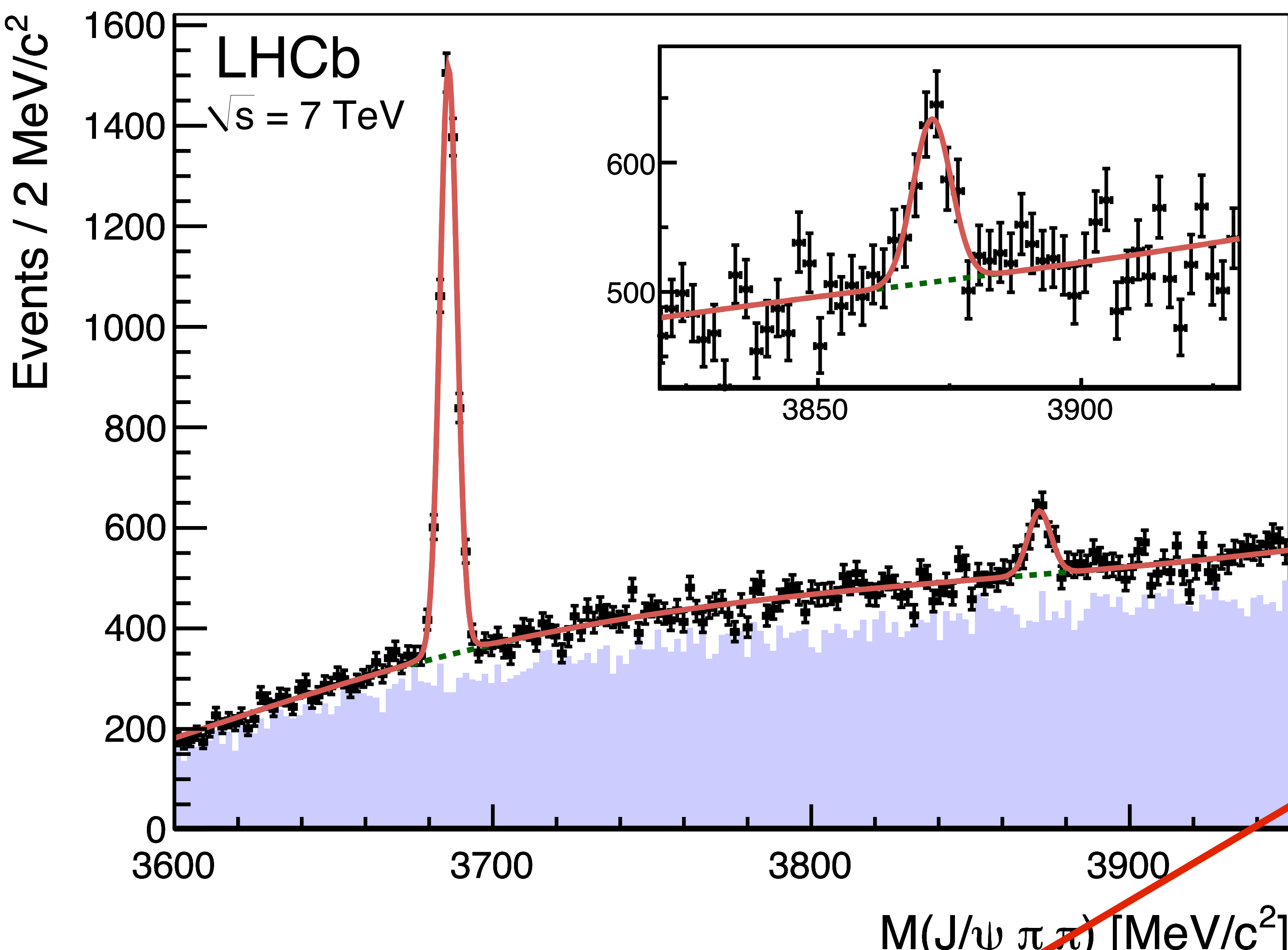
$Z^+(4430)$ 2007	$Z_1^+(4050)$ 2008	$Z_2^+(4250)$ 2008
$Z_c^+(3900)$ 2013	$Z_c^+(4025)$ 2013	$Z_c^+(4020)$ 2013
$Z_c^+(3885)$ 2013	$Z_c^+(4200)$ 2014	$X^+(5568)$ 2016

not a charmonium state

X(3872) Belle II @ KEK (PRL91(2003))

very narrow state observed in the decay: $B^{\pm} \to K^{\pm}(J/\psi \pi^{+}\pi^{-})$

best studied charmonium exotic candidate



M_X = (3872.20 ± 0.39) MeV
Γ < 2.3 MeV

$c\bar{c}$ spec. for $J^{PC} = 1^{++}$ (Barnes & Godfrey, PRD69 (2004))

$2\ ^3P_1$ (3990)

$3\ ^3P_1$ (4290)

$$\frac{X \to J/\psi\ \pi^+\pi^-\pi^0}{X \to J/\psi\ \pi^+\pi^-} = 0.8 \pm 0.3$$ ➡ strong isospin and G parity violation

$$M(D^{*0}\bar{D}^0) = (3871 \pm 1)$$

X(3872): molecular $(D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0)$ state (Swanson, Close, Voloshin, Wong ...)

Maiani et al. (PRD71 (05)) tetraquark $J^{PC} = 1^{++}$ state

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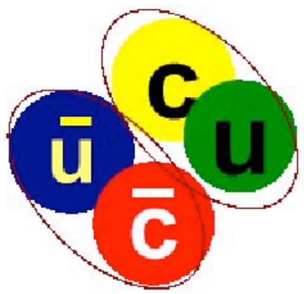
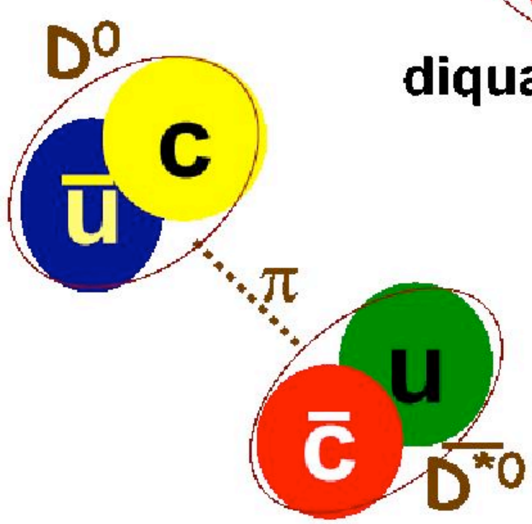


diquark-diantiquark



$D^0 - \bar{D}^{*0}$ "molecule"

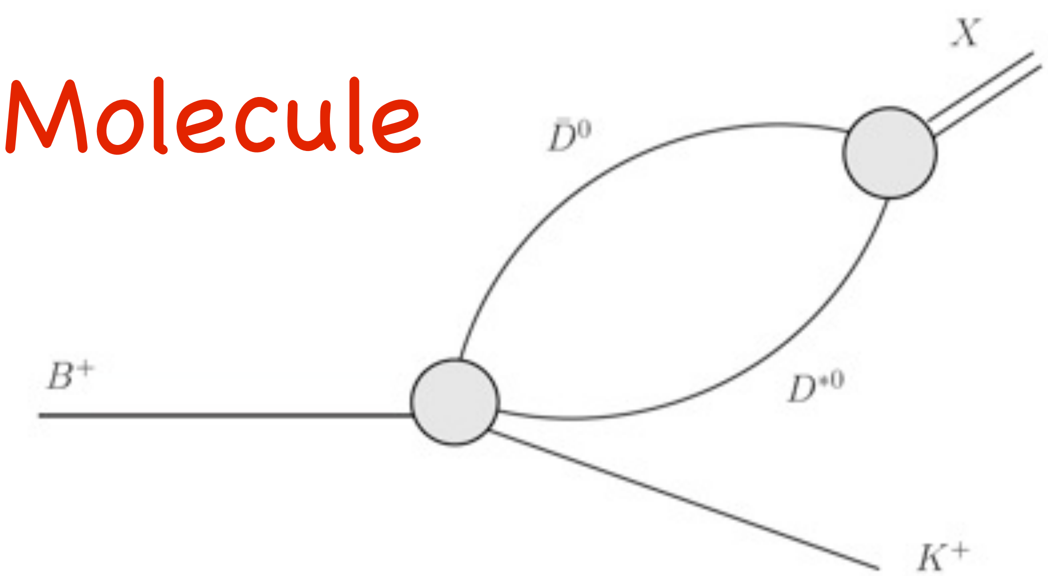
molecular and tetraquark interpretations differ by the way quarks are organized in the state

X(3872) production

B decays at B factories

$$B^{\pm} \to X(3872)K^{\pm}$$

Meson Molecule



Meson coalescence

Small binding energy

Agreement with data !

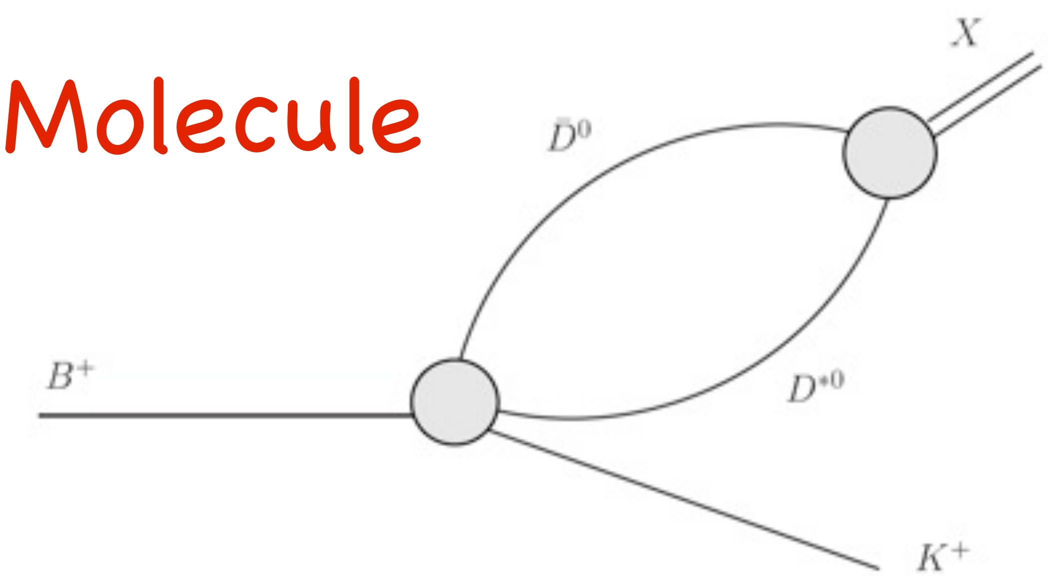
E. Braaten, M. Kusunoki, hep-ph/0404161

X(3872) production

B decays at B factories

$B^{\pm} \to X(3872)K^{\pm}$

Meson Molecule



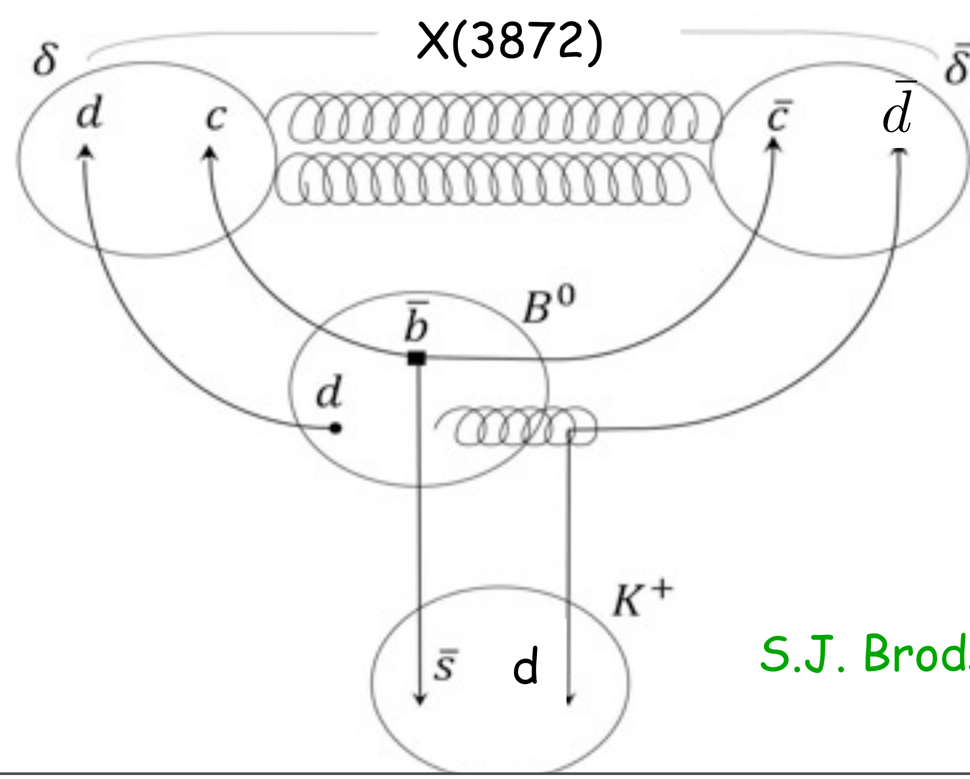
Meson coalescence

Small binding energy

Agreement with data !

E. Braaten, M. Kusunoki, hep-ph/0404161

Tetraquark



Diquark-antidiquark picture

Non-relativistic potential

Agreement with data !

S.J. Brodsky, D.S. Hwang, R.F. Lebed, arXiv:1406.7281

Conclusions

$X(3872)$ ➜ mixture χ_{c1} and a $D^*\bar{D}$ molecule

$Z_c^+(3900)$ ➜ $J^P=1^+$ tetraquark state

$Z_c^+(3900)$ and $Z_c^+(3885)$ ➜ not the same state

$Z_c^+(4025)$ ➜ $J^P=1^+,2^+$ $D^*\bar{D}^*$ resonance, or D-wave background

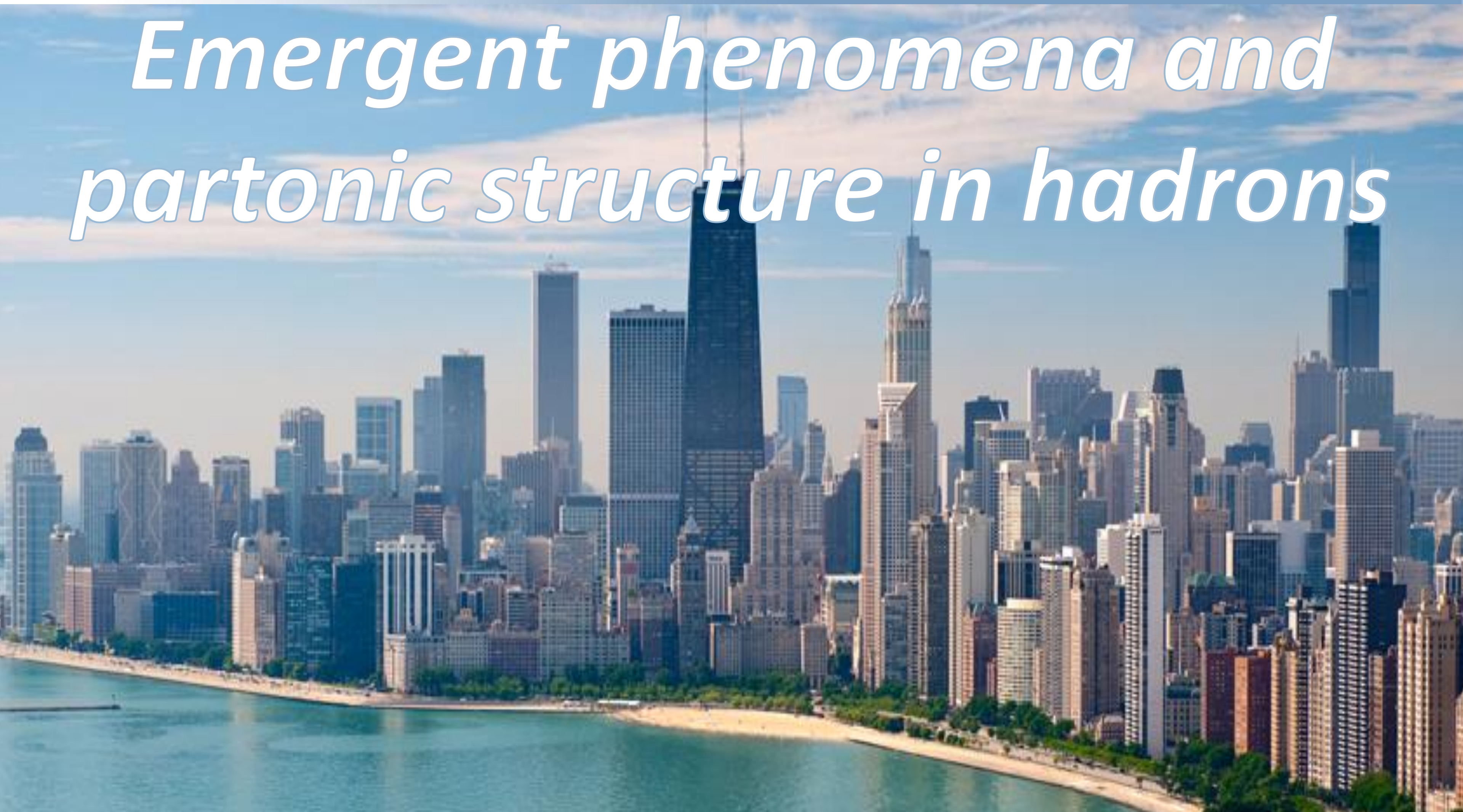
- Z^+ states need confirmation. A bump in the spectra near the threshold does not indicate, necessarily, the existence of a state

$X^+(5568)$ ➜ needs confirmation, probably not a real state


Questions?

Argonne
NATIONAL LABORATORY

Emergent phenomena and partonic structure in hadrons



Craig Roberts, Physics Division

U.S. DEPARTMENT OF ENERGY

Collaborators: 2013-Present

Students, Postdocs, Profs.

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6. *Chien-Yeah SENG (UM-Amherst) ;*
7. *Kun-lun WANG (PKU);*
8. *Chen CHEN (UNESP, São Paulo);*
9. *Zhu-Fang CUI (Nanjing U.) ;*
10. *J. Javier COBOS-MARTINEZ (U Michoácan);*
11. *Minghui DING (Nankai U.) ;*
12. *Fei GAO (Peking U.) ;*
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24. Lei Chang (Nankai U.) ;
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36. Sebastian Schmidt (IAS-FZJ & JARA);
37. Peter Tandy (KSU);
38. Tony Thomas (U.Adelaide) ;
39. Shaolong WAN (USTC) ;
40. Hong-Shi ZONG (Nanjing U)

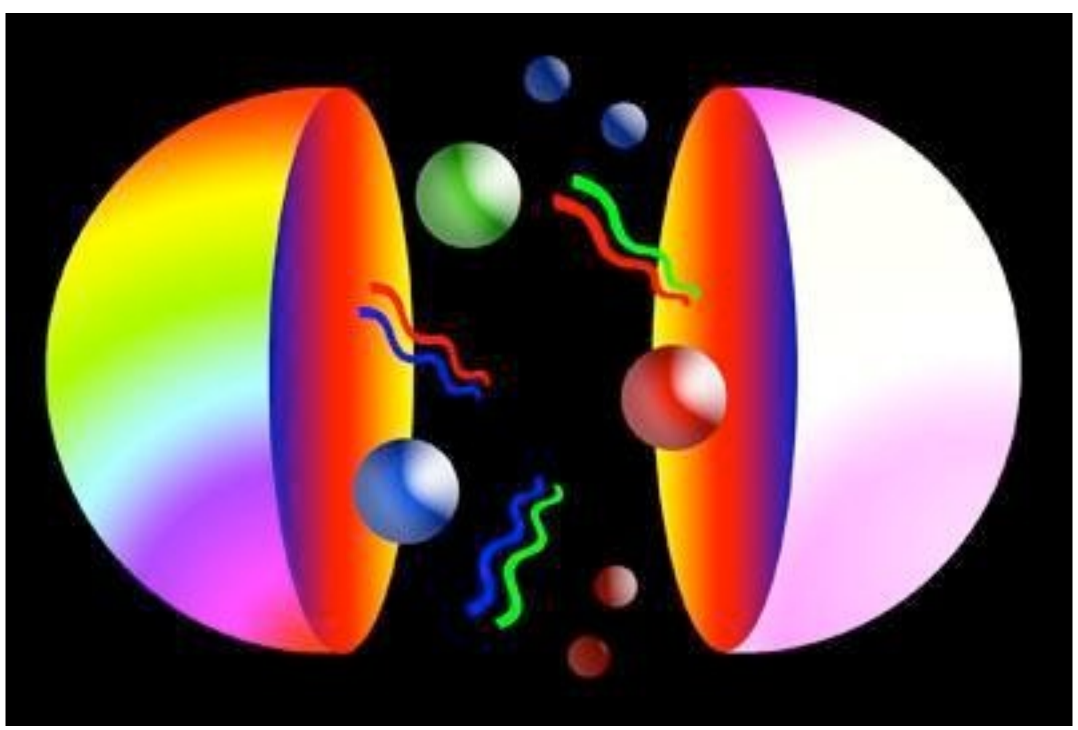
Epilogue

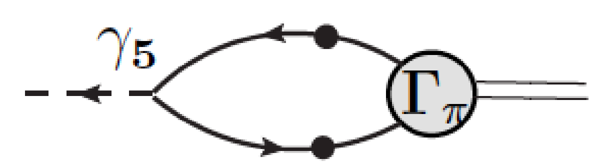
- Conformal anomaly ... *gluons and quarks acquire momentum-dependent masses* ... values are large in the infrared $m_g \propto 500$ MeV & $M_q \propto 350$ MeV ... underlies DCSB; and has numerous observable consequences
- Universe with light quarks ⇒ confinement is a dynamical phenomenon *Confinement and DCSB are intimately linked* in real-QCD
- Origin and distribution of mass depend on the observer's preferred frame of reference and scale ... Contemporary and planned experiments, DCSB paradigm is the best way to explicate and understand the associated, emerging phenomena. Numerous verifiable predictions accessible
  - form factors, PDAs and PDFs, GPDs and TMDs, etc.
- What can experiments at an EIC add to this?
  - Valence-quark region will be accessible
  - However, focus is on low-*x*, where gluons dominate ... mass generation in the gluon sector ... must affect potential for gluon saturation; how?
- Ability to compute valence-quark PDAs and PDFs has provided many new insights ... must now begin to do the same for sea-quarks *and glue*

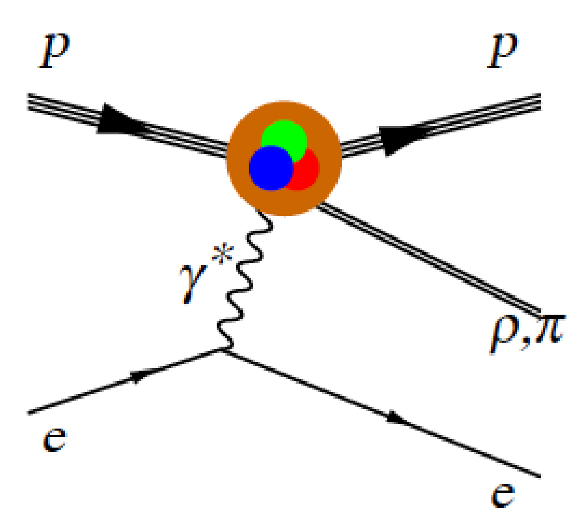
Pion and Kaon Properties from Dyson-Schwinger Eqns

Peter C. Tandy

Dept of Physics
Kent State University USA







KENT STATE UNIVERSITY

Conf XII Thessaloniki Aug 2016

Topics

- DSE continuum approach to QCD
- Old work on pion and kaon properties and decays
- Parton distribution amplitudes and PDFs—mainly mesons as an example. DSE-model calculations with direct connection to QCD. Comparison to LQCD.
- Some applications to uv physics (Form Factors, HS behavior)
- PDFs including X. Ji's space-like correlator approximation for LQCD—a model investigation.

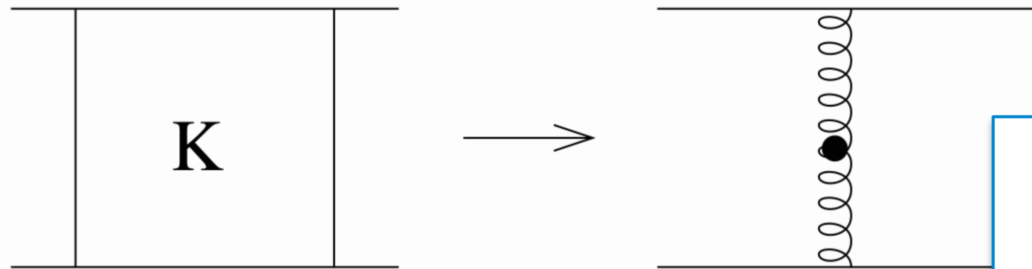
DSE Modeling of Hadron Physics

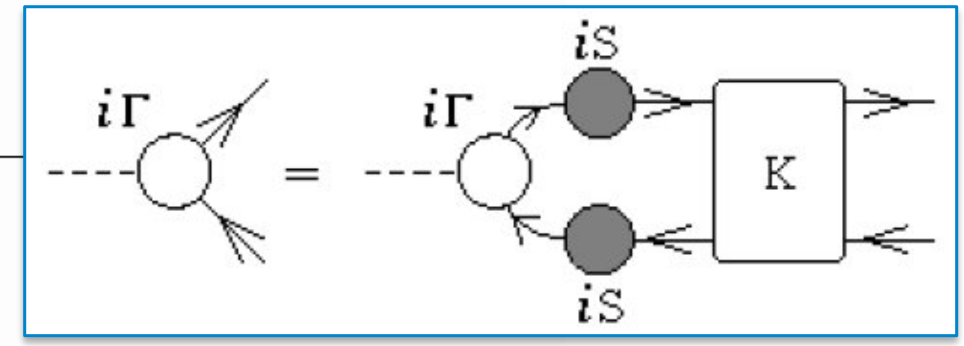
- **Most common: Rainbow-ladder truncation of QCD's eqns of motion. Approximation to full BSE kernel now starting to produce results……**
- **Constrain modeling by preserving AV-Ward-Takahashi Id, V-WTI. [Color singlet] Naturally implements DCSB, conserved vector current, Goldstone Thm, PCAC…**
- **RL truncation only good for ground state vector & pseudoscalar mesons, q-qq descriptions of baryons with AV and S diquarks.**
- **At the very least: DSE continuum QCD modeling suited for surveying the landscape quickly from large to small scales; finding out which underlying mechanisms are dominant. Applicable to all scales, high Q^2 form factors, etc. Do not expect ab initio final-precision QCD results, except in special cases. [pion, kaon..]**
- **Unifying DSE treatment of light front quantities (PDFs, GPDs, DA) with other aspects of hadron structure: masses, decays, charge form factors, transition form factors.....**
- **Pion & kaon q-qbar Bethe-Salpeter wavefn is very well known**

$$\mathrm{AV-WTI: m_q \to 0, P \to 0 \Rightarrow} \; \Gamma_{\pi q\bar{q}}(k^2) = i\gamma_5 \frac{\frac{1}{4}\mathrm{tr}S_0^{-1}(k)}{f_\pi^0} + \mathcal{O}(P)$$

Ladder-Rainbow Model

Landau gauge only

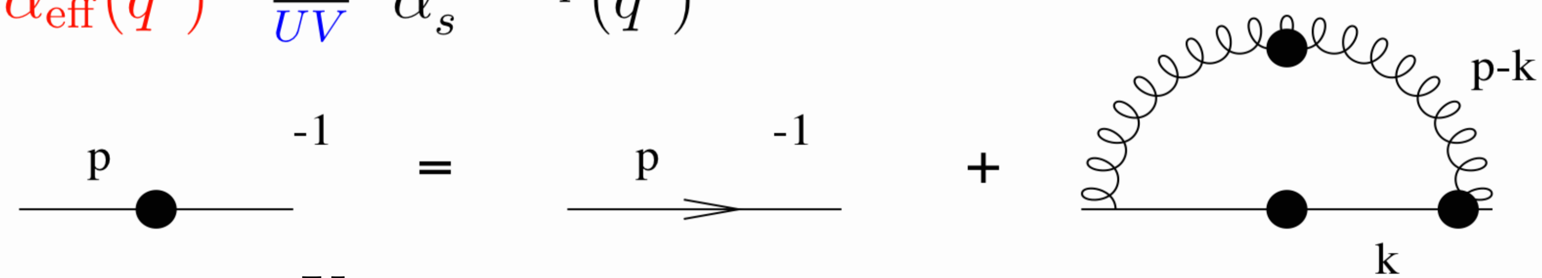




- $K_{\rm BSE} \rightarrow -\gamma_\mu \frac{\lambda^a}{2}\ \ 4\pi\alpha_{\rm eff}(q^2)\ \ D^{\rm free}_{\mu\nu}(q)\ \gamma_\nu \frac{\lambda^a}{2}$

1 true phen parameter

- $\alpha_{\rm eff}(q^2)\ \ \overrightarrow{IR}\ \ \langle \bar{q}q\rangle_{\mu=1\ {\rm GeV}} = -(240\text{MeV})^3$, incl vertex dressing
- $\alpha_{\rm eff}(q^2)\ \ \overrightarrow{UV}\ \ \alpha_s^{1-{\rm loop}}(q^2)$



modern π, K qDSE-BSE strategy: Maris & Roberts, PRC56, 3369 (1997)

- 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% $[\mathbf{fit}: \mathbf{m}_\pi, \mathbf{m_K}, \mathbf{f}_\pi], \mathbf{f_K}(2\%)$

An Ansatz for the FULL QCD kernel: L. Chang, C.D. Roberts, PRL103, 081601 (2009), + S. Qin (2015).

A more modern RL kernel: S. Qin, L. Chang, C.D. Roberts, D.J. Wilson, PRC84, 042202 (2011).

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.
$-\langle \bar{q}q \rangle_\mu^0$	(0.236 GeV)^3	(0.241†)^3
m_π	0.1385 GeV	0.138†
f_π	0.0924 GeV	0.093†
m_K	0.496 GeV	0.497†
f_K	0.113 GeV	0.109

Charge radii (PM, Tandy, PRC62, 055204)

r_π^2	0.44 fm^2	0.45
$r_{K^+}^2$	0.34 fm^2	0.38
$r_{K^0}^2$	-0.054 fm^2	-0.086

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

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

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

$\lambda_+(e3)$	0.028	0.027
$\Gamma(K_{e3})$	$7.6 \cdot 10^6$ s^{-1}	7.38
$\Gamma(K_{\mu3})$	$5.2 \cdot 10^6$ 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
$m_{K^\star}$	0.892 GeV	0.936
$f_{K^\star}$	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
$g_{K^\star K\pi}$	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
$(g_{K^\star K\gamma}/m_K)^+$	0.83	0.99
$(g_{K^\star K\gamma}/m_K)^0$	1.28	1.19

Scattering length (PM, Cotanch, PRD66, 116010)

a_0^0	0.220	0.170
a_0^2	0.044	0.045
a_1^1	0.038	0.036

Modern Context for DSE Interaction Kernel

Landau gauge, lattice – QCD gluon propagator,
I.L.Bogolubisky *et al.*, PosLAT2007, 290 (2007)

$\Rightarrow m_G(k^2)$ $\quad$ $m_G(0) \sim 0.38$ GeV

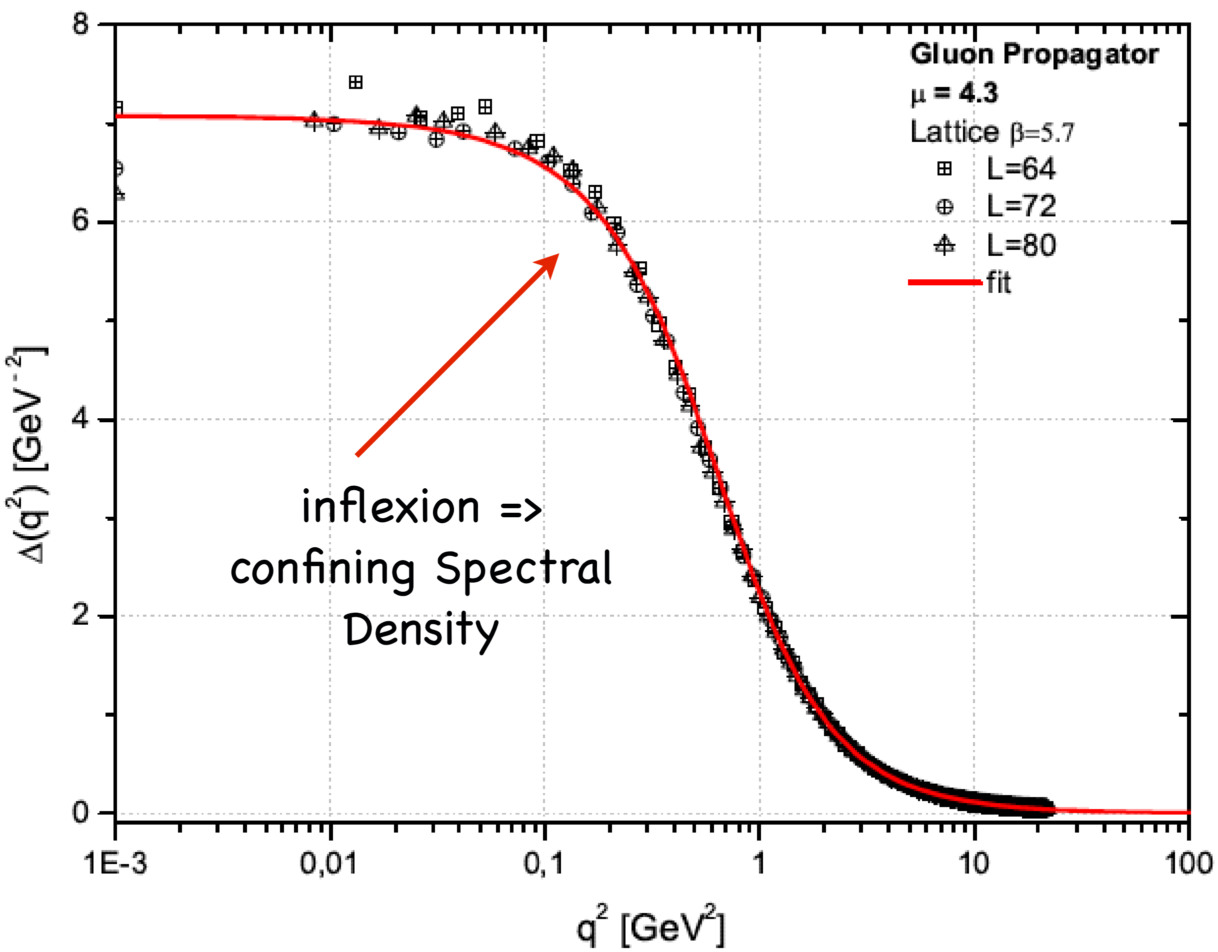
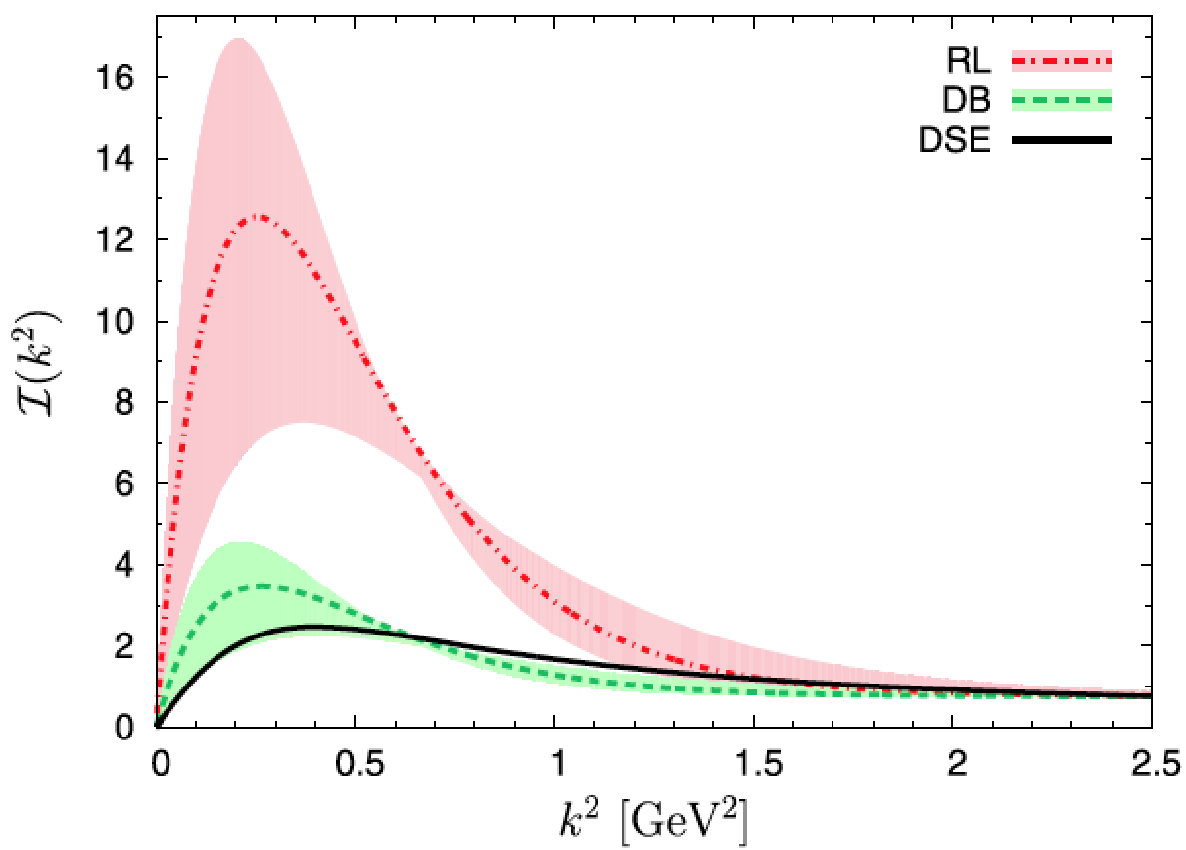


Table 1
Row 1 – Computed values determined from the interaction tension in Eq. (23), quoted in GeV; and Row 2 – the difference: $\varepsilon_\varsigma := \varsigma_{\mathcal{I}}/\varsigma_{\mathcal{I}_d} - 1$. So as to represent the domain of constant ground-state physics, described in connection with Eq. (5), we list values obtained with bottom-up interactions using $\omega = 0.5$, 0.6 GeV.

$\mathcal{I}$	$\mathcal{I}_d$	$\mathcal{I}_{DB}^{\omega=0.5}$	$\mathcal{I}_{DB}^{\omega=0.6}$	$\mathcal{I}_{RL}^{\omega=0.5}$	$\mathcal{I}_{RL}^{\omega=0.6}$
$\varsigma_{\mathcal{I}}$	1.86	1.91	1.82	3.14	2.90
ε_ς	0	2.8%	−2.4%	68.5%	55.8%

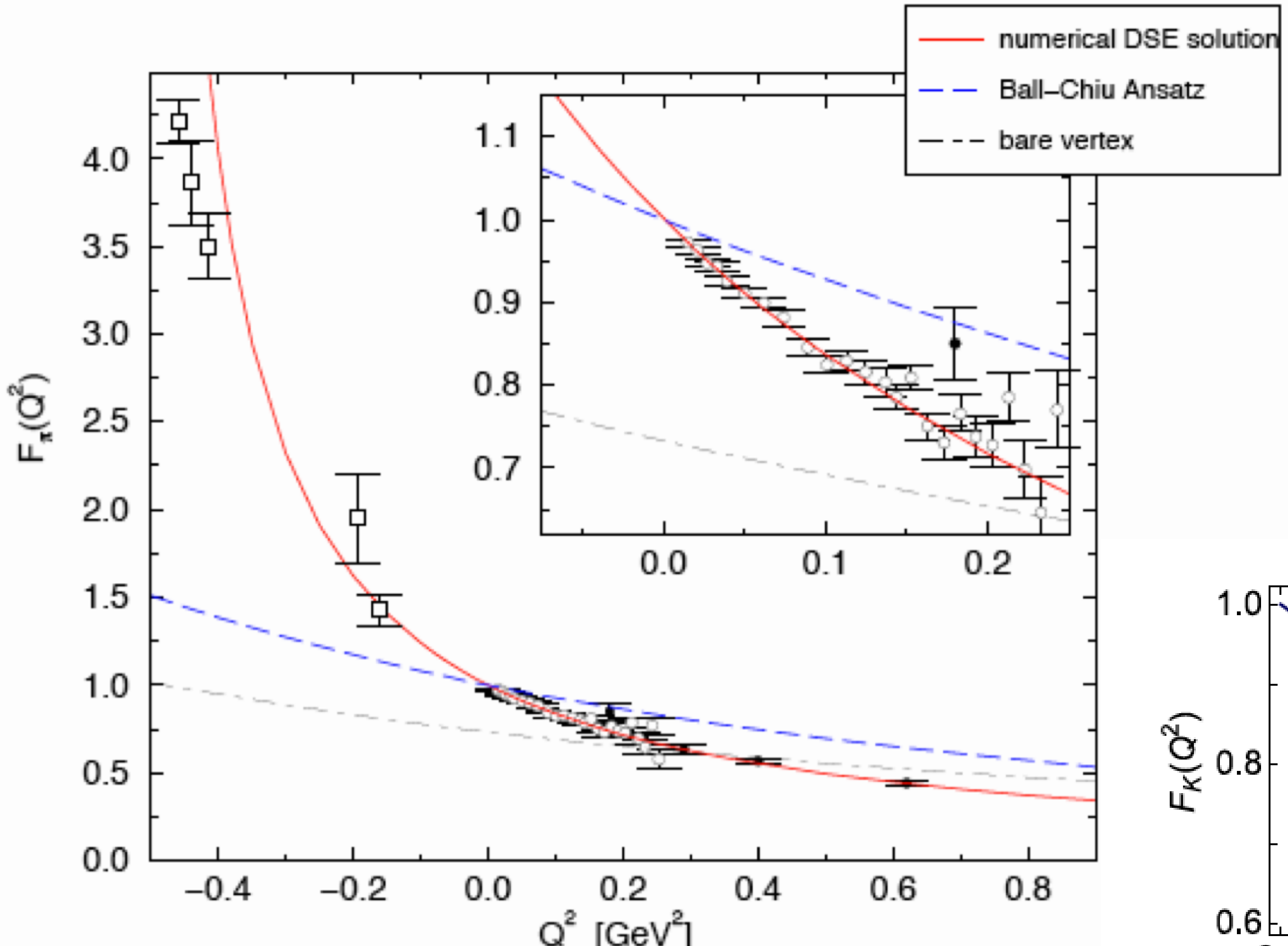
Bridging a gap between continuum-QCD and ab initio predictions of hadron observables
Daniele Binosi (ECT, Trento & Fond. Bruno Kessler, Trento), Lei Chang (Adelaide U., Sch. Chem. Phys.), Joannis Papavassiliou (Valencia U. & Valencia U., IFIC), Craig D. Roberts (Argonne, PHY). Dec 15, 2014. 6 pp.
Published in **Phys.Lett. B742 (2015) 183-188**



Pion $F(Q^2)$: Low Q^2

(P Maris & PCT, PRC 61, 045202 (2000)
(P. Maris & PCT, PRC 62, 0555204 (2000)

$r_\pi^{\rm DSE} = 0.68$ fm $\qquad r_\pi^{\rm expt} = 0.663 \pm .006$ fm

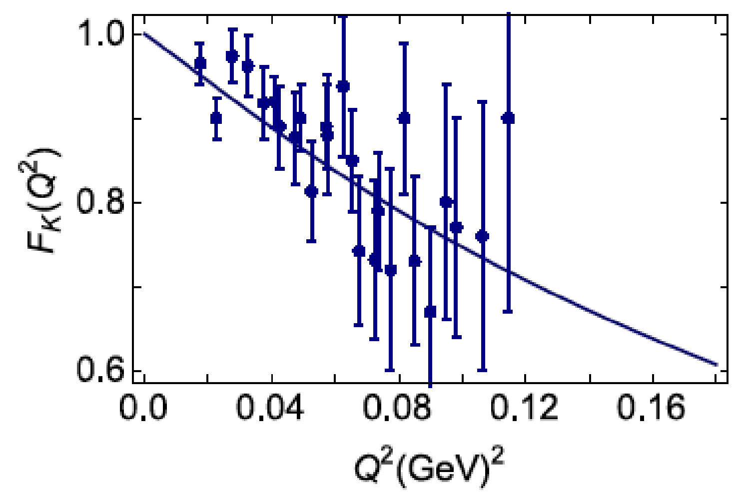


$$\Gamma_\pi = \sqrt{1-\alpha^2}\,\Gamma^{\rm RL}_{q\bar q} + \alpha\,\Gamma_{\pi q\bar q}$$

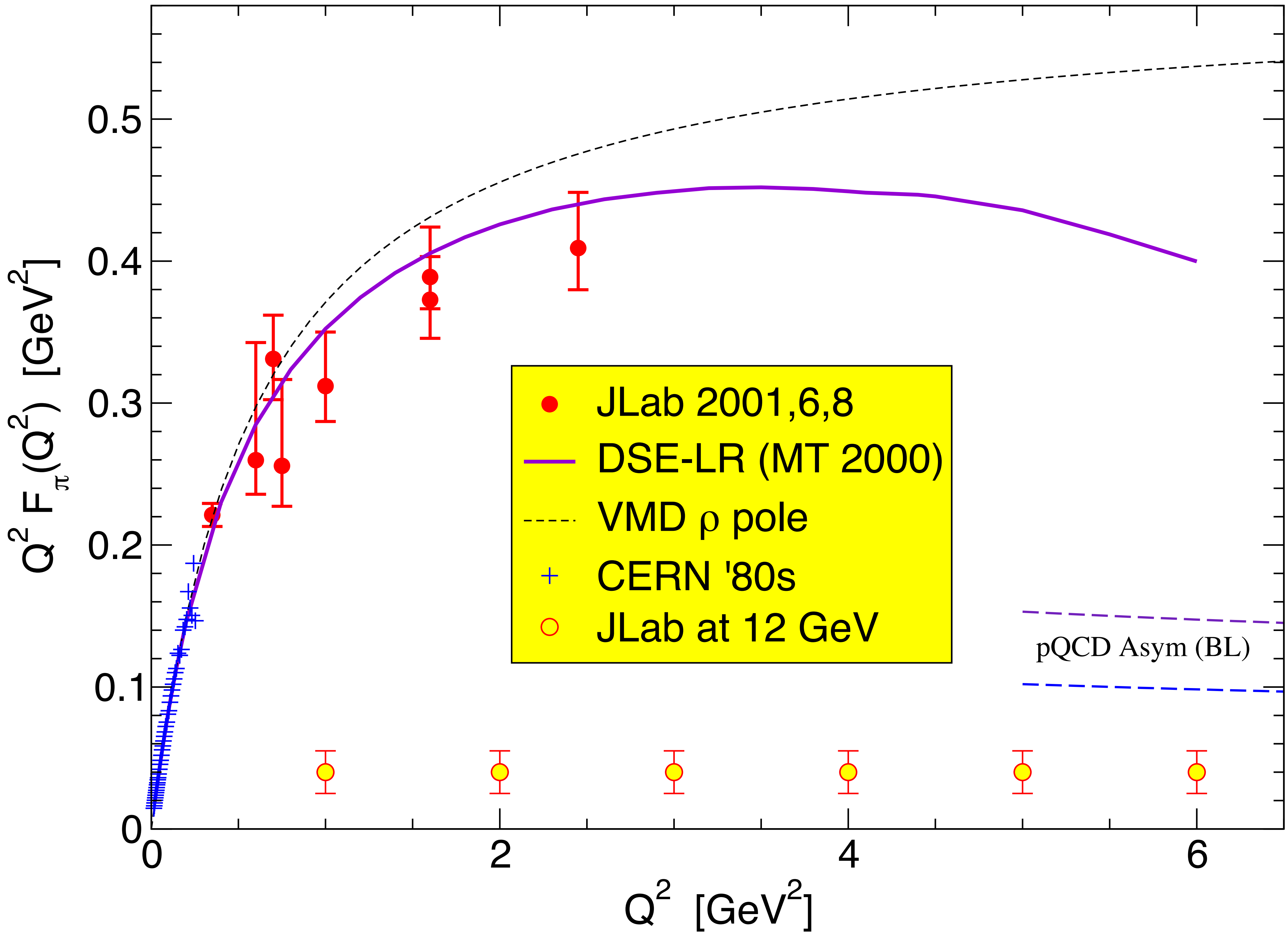
CPT: 18% effect

$$r^2_{\rm ch} = (1-\alpha^2)\,r^2_{\rm RL} + \alpha^2\,r^2_{\pi-{\rm lp}}$$

DSE-RL: $r^2_{\rm RL} = r^2_{\rm ch} \Rightarrow \alpha^2 = 18\%$

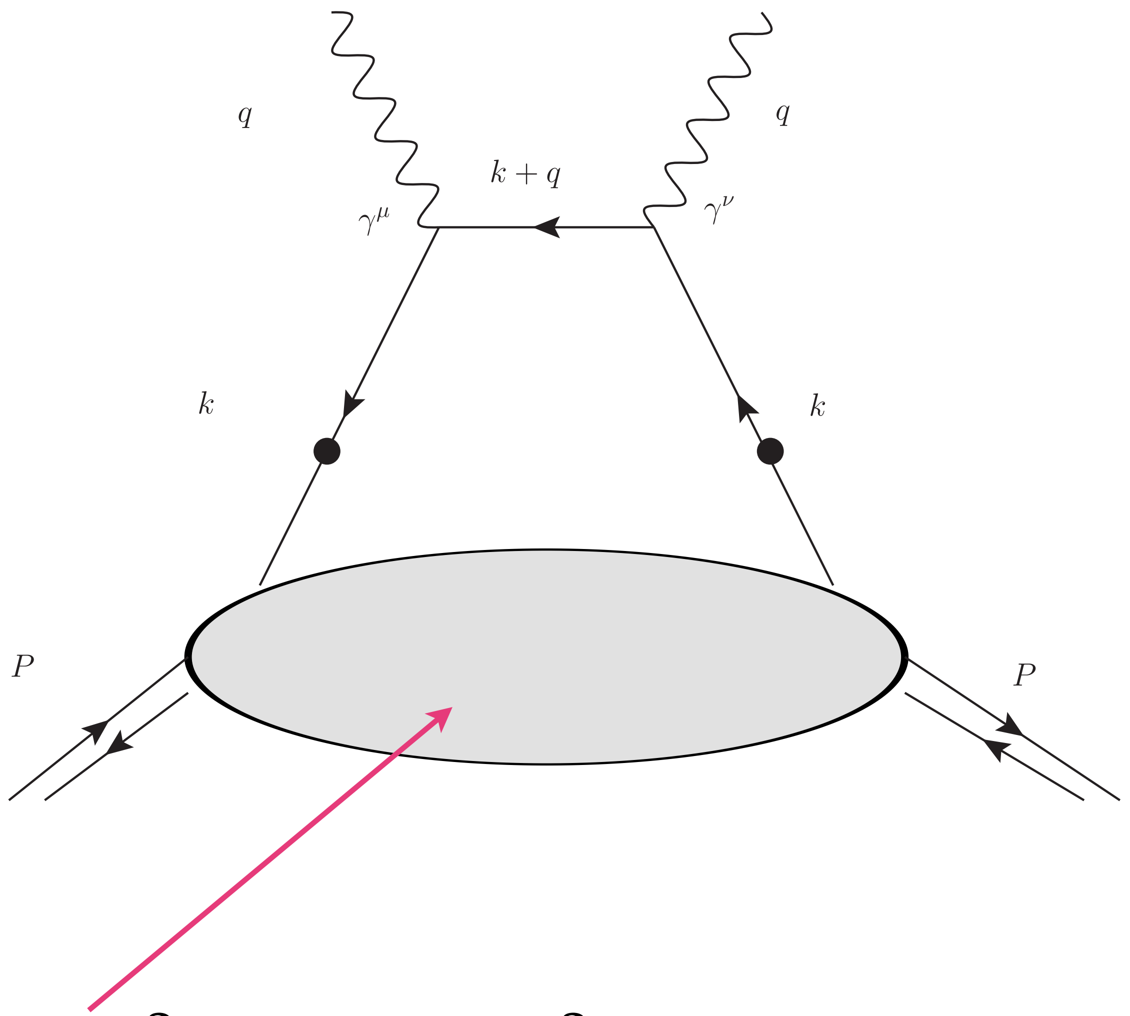


P. Maris and P.C. Tandy, PRC62, 055204, (2000)



Jab data: G. Huber et al., PRC78, 045203 (2008)

Parton Distribution Functions

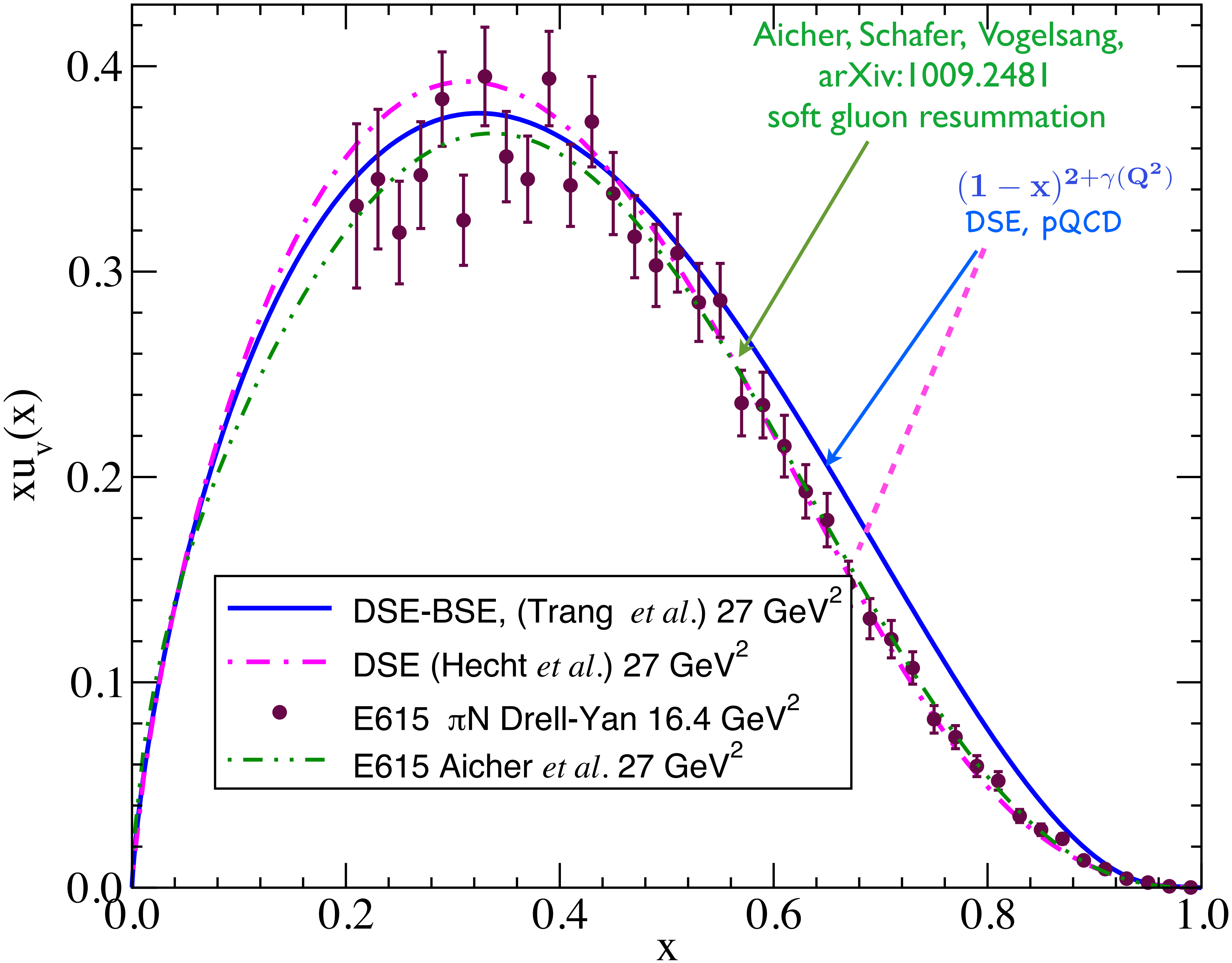


Covariant formulation
and calculation

$$\int \mathbf{d^4q\ \ F(q^2, q\cdot P, q\cdot k, k^2)}$$

Pion Valence PDF

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



q_0

prev PDF expt parm $(1-x)^{1.5}$

CQM, duality.. $(1-x)^1$

NJL (pt π) : $(1-x)^0$

One Lattice-QCD Moment Almost Determines Pion DA

PRL 111, 092001 (2013) PHYSICAL REVIEW LETTERS week ending 30 AUGUST 2013

Pion Distribution Amplitude from Lattice QCD

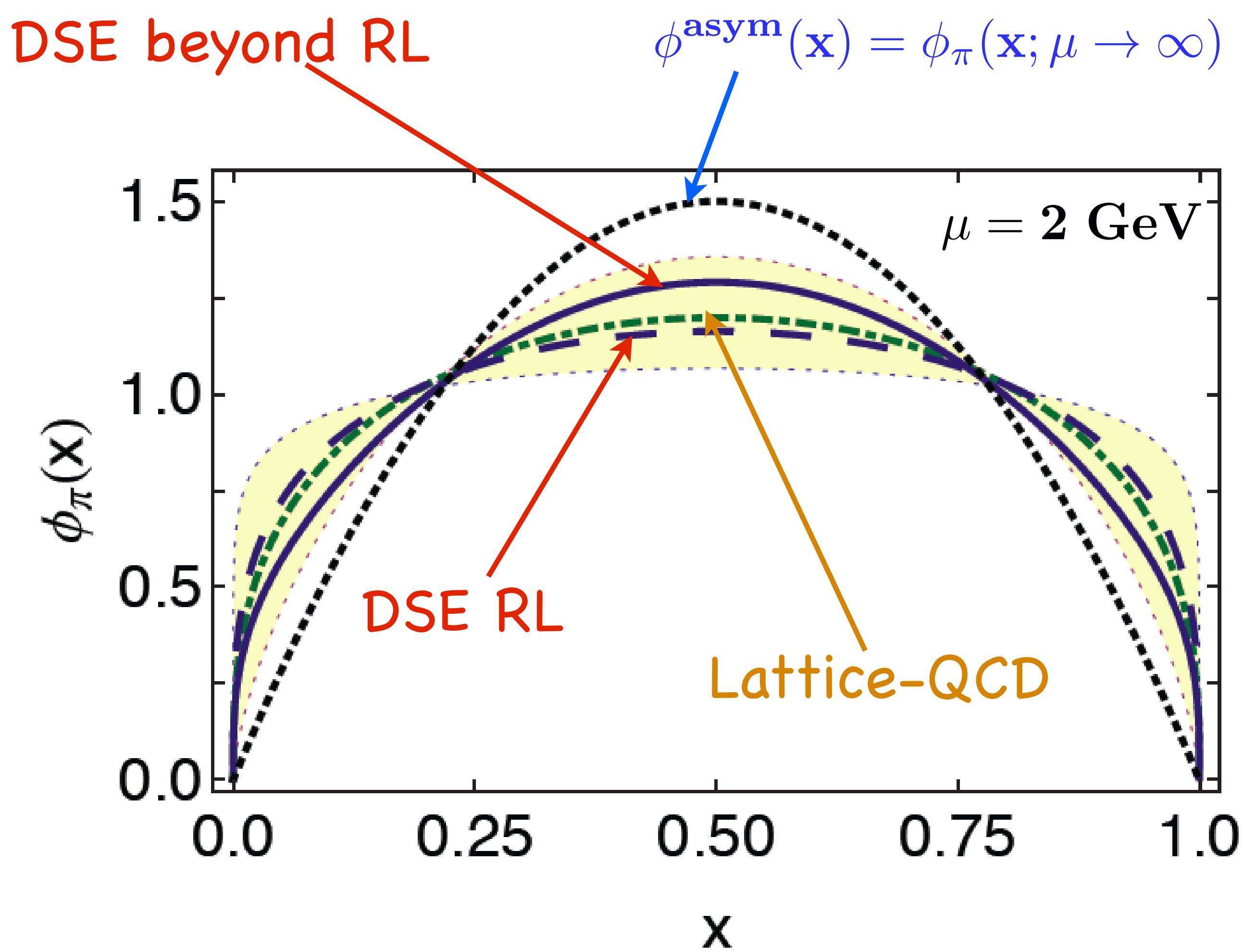
I. C. Cloët,[1] L. Chang,[2] C. D. Roberts,[1] S. M. Schmidt,[3] and P. C. Tandy[4]

$$\phi_\pi^{\mathbf{LQCD}}(\mathbf{x};\mu=\mathbf{2}) = \mathbf{N}\,\mathbf{x}^{\alpha}(\mathbf{1}-\mathbf{x})^{\alpha}$$

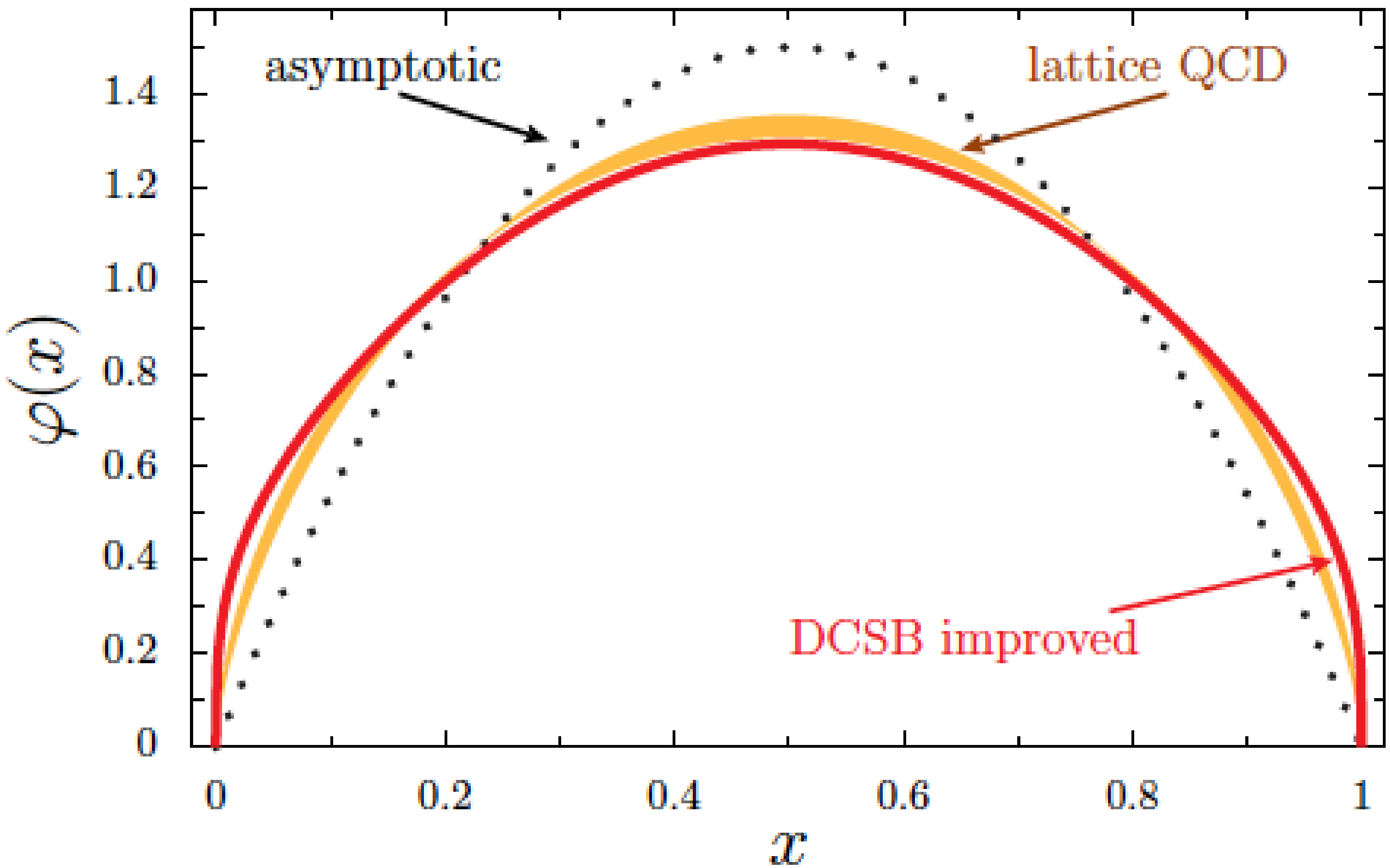
$$\alpha = \mathbf{0.35} + \mathbf{0.32} - \mathbf{0.24}$$

$$\langle(\mathbf{2x}-\mathbf{1})^{\mathbf{2}}\rangle_{\mu=\mathbf{2}}^{\mathbf{LQCD}} = \mathbf{0.27} \pm \mathbf{0.04}$$

V. Braun et al., PRD74, 074501 (2006)



Pion Distribution Amplitude



$$\langle (2x-1)^2 \rangle^{LQCD}_{\mu=2\ GeV} = 0.2361\,(41)\,(39)$$

V. Braun et al., arXiv:1503.03656 [hep=lat]

DSE prediction: 0.251

The Pion Charge Form Factor: Transition from npQCD to pQCD

$$\mathbf{F_\pi(Q^2 = uv) = \int_0^1 dx \int_0^1 dy\ \phi^\star_\pi(x;Q)\ [T_H(x,y;Q^2)]\ \phi_\pi(y;Q)}$$ + NLO/higher twist.....

---LFQCD, Brodsky, LePage PRD (1980)

$$\mathbf{Q^2 >> \Lambda^2_{QCD} :\ Q^2 F_\pi(Q^2) \to 16\,\pi\, f_\pi^2\, \alpha_s(Q^2)\, \omega_\phi^2(Q^2)\ +\ \mathcal{O}(1/Q^2)}$$

$$\mathbf{\omega_\phi(Q^2) = \frac{1}{3}\int_0^1 dx\ \frac{\phi_\pi(x;Q)}{x}}$$

$$\mathbf{\to 1\ ,\quad Q^2 \to \infty}$$

at $\mathbf{Q^2 \sim 3-4\ GeV^2}$, $\Rightarrow$ 0.1

JLab expt, Theory $\Rightarrow$ 0.45

But, recent DSE theory $\Rightarrow \mathbf{\phi_\pi(x;\mu = 2\ GeV) \Rightarrow \omega_\phi^2 = 3.3}$

PRL **111,** 141802 (2013) PHYSICAL REVIEW LETTERS week ending 4 OCTOBER 2013

Pion Electromagnetic Form Factor at Spacelike Momenta

L. Chang,[1] I. C. Cloët,[2] C. D. Roberts,[2] S. M. Schmidt,[3] and P. C. Tandy[4]

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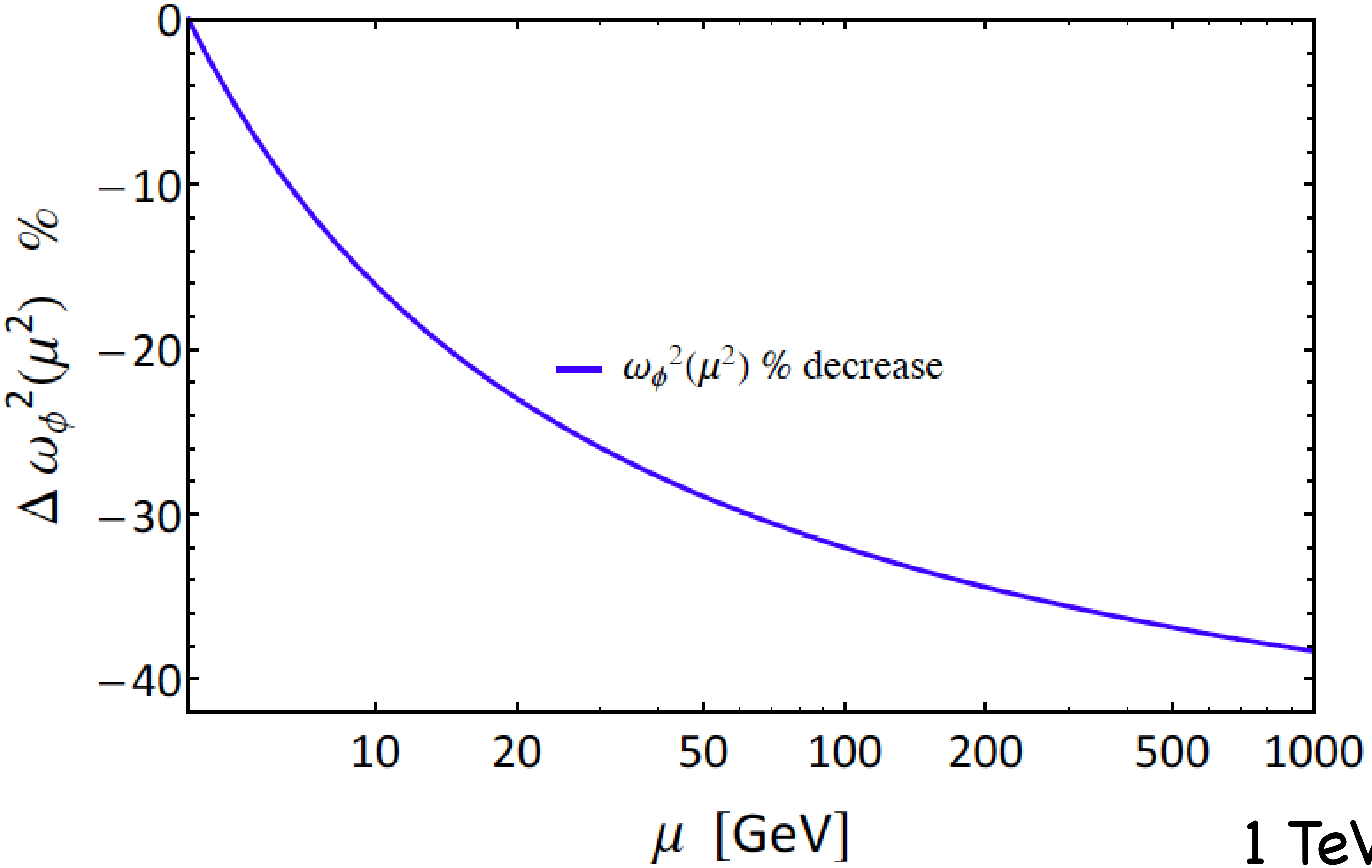
UV-QCD is not Asymptotic QCD

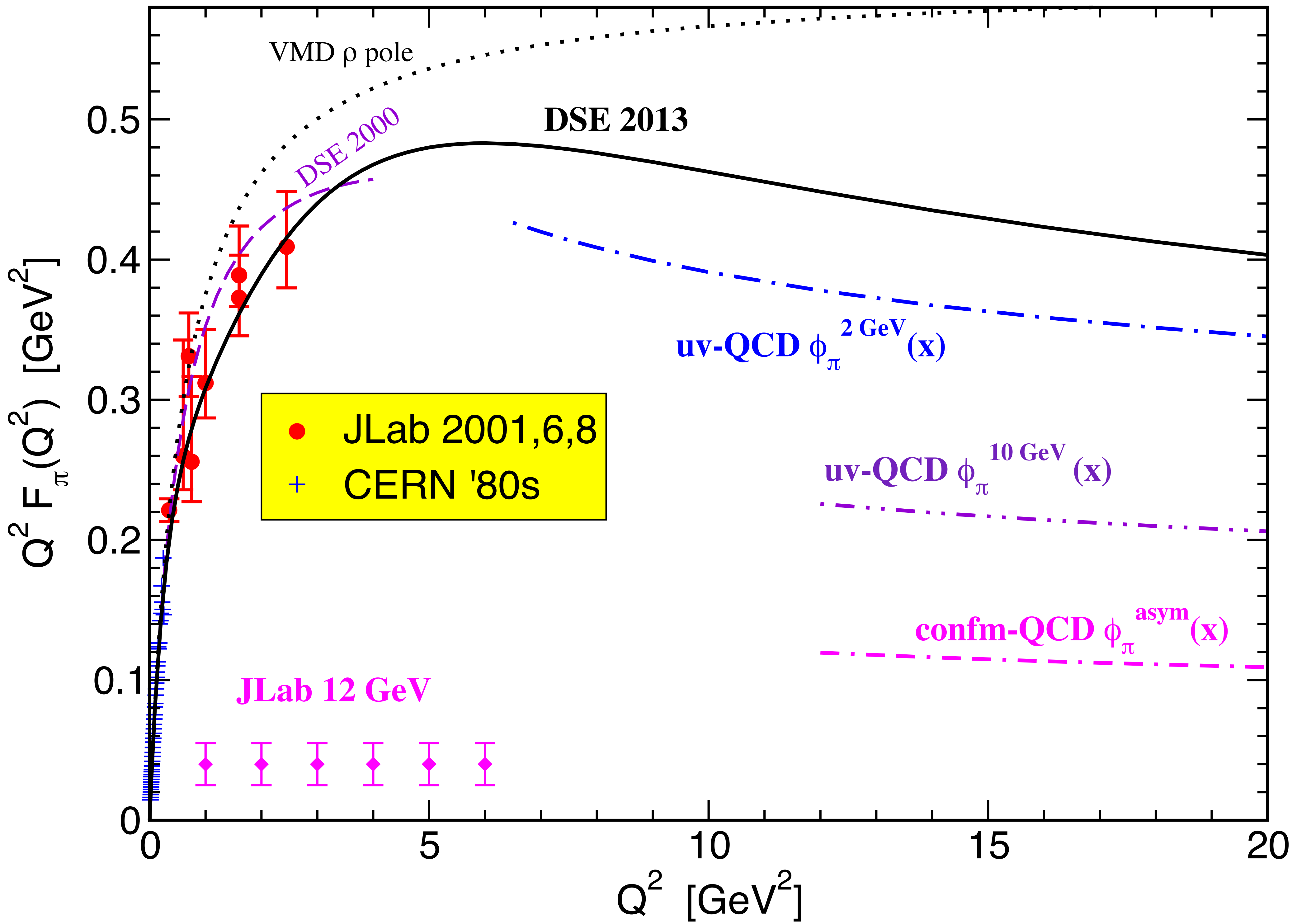
$$\mathbf{Q^2} >> \mathbf{\Lambda^2_{\rm QCD}} : \; \mathbf{Q^2 F_\pi(Q^2)} \to \mathbf{16}\,\pi\,\mathbf{f_\pi^2}\,\alpha_\mathbf{s}(\mathbf{Q^2})\;\omega_\phi^\mathbf{2}(\mathbf{Q^2}) \; + \; \mathcal{O}(\mathbf{1/Q^2})$$



1 TeV

Pion Electromagnetic Form Factor at Spacelike Momenta

L. Chang,[1] I.C. Cloët,[2] C.D. Roberts,[2] S.M. Schmidt,[3] and P.C. Tandy[4]

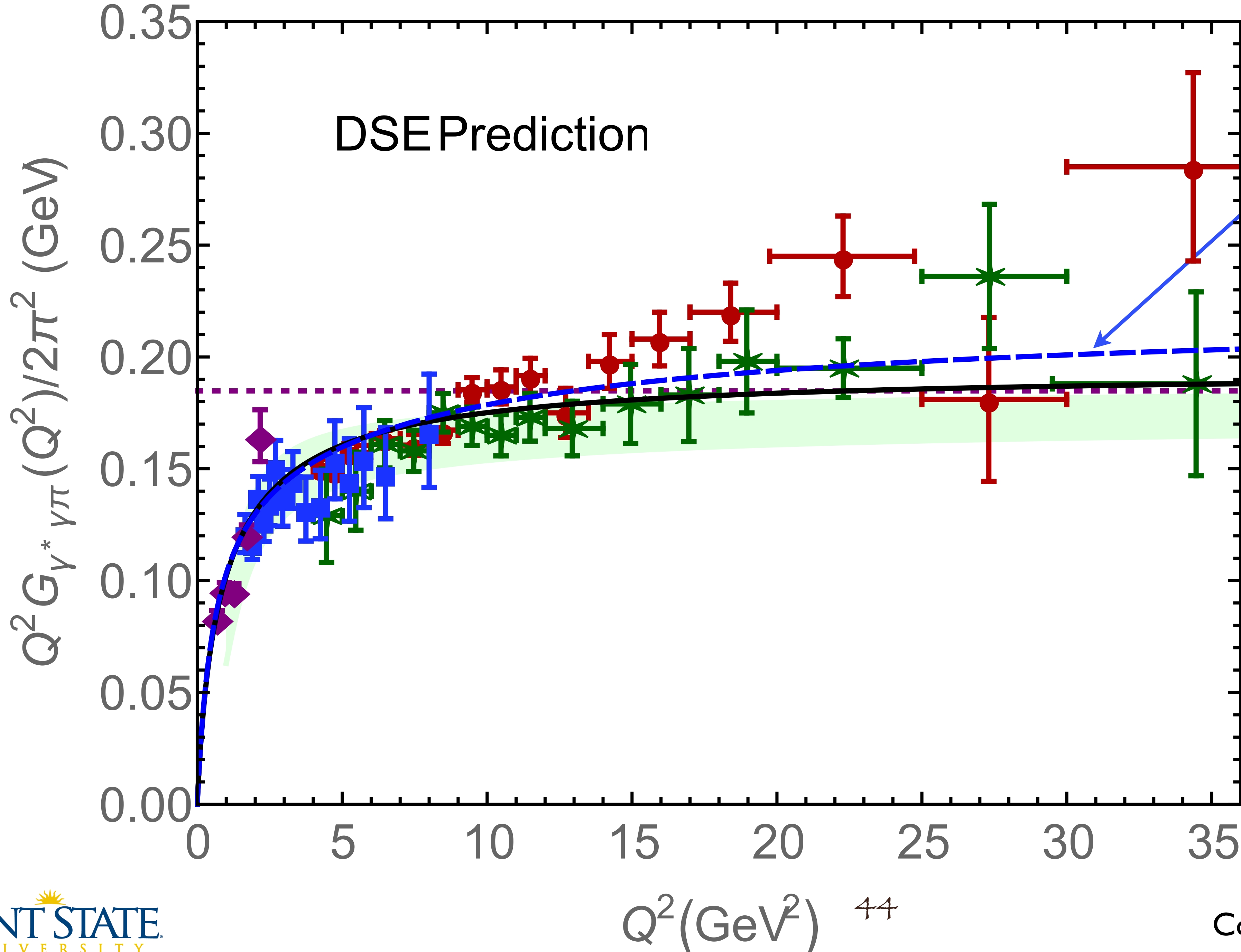


Jab data: G. Huber et al., PRC78, 045203 (2008)

Pion Transition Form Factor

K. Raya, L. Chang, A. Bashir, J.J.Cobos-Martinez, L.X. Gutierez-Guerrero, C.D.Roberts, P.C.Tandy,
PRD93, 074017 (2016)

From unified treatment of DA, elastic FF, and transition FF



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Summary

- **DSE approach works extremely well for pion & kaon due to symmetry dominance.**
- **Parton Distribution Amplitudes (pion, kaon). DSE approach shows good contact with available lattice-QCD moments. Flavor symmetry breaking & dynamical chiral symmetry breaking evident and quantitative in the shapes.**
- **Pion Transition & Elastic Form Factors DSE TFF calculation for all Q^2—-agrees with Belle not BaBar. DSE elFF——Connection with ultraviolet /hard scattering QCD reconciled. Identify that the ultraviolet partonic behavior is within reach of proposed JLab pion FF experiments.**
- **Parton Distribution Functions (pion). Qualitative behavior of empirical data fits reproduced by DSE q-qbar + pion loop analysis.**
- **Time to declare we understand the pion and kaon in QCD ?**
- **X. Ji's space-like correlator approach to PDFs—a model investigation. Spurious anti-quark contributions seem unavoidable if Pz < 2 GeV. For x > 0.8, need Pz > 4 GeV for confidence in the qualitative shape. Further work in progress.**