Probing a Pion with Photons

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DPC-SMF

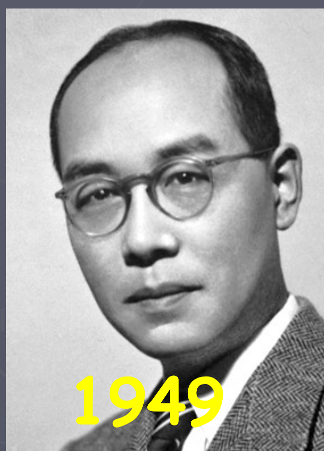
Contents

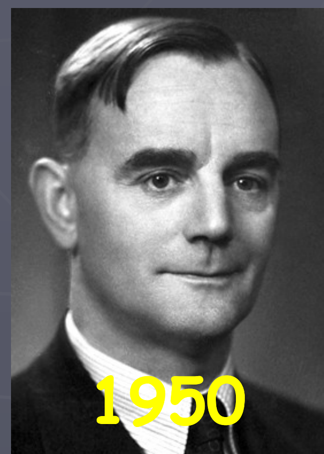
Facts and Challenges

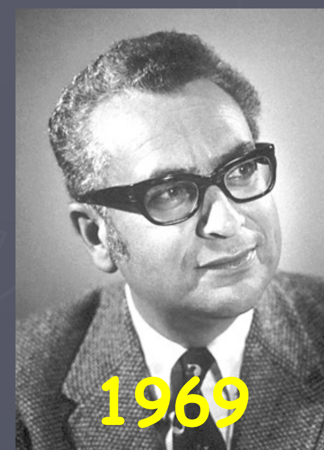
- Color degrees of freedom (quarks and gluons) are not observable (confinement).
- Dynamical mass generation for massless quarks; (dynamical chiral symmetry breaking).
- Both these phenomena are emergent and owe themselves to large coupling strength in the infrared.
- How do we study physics beyond perturbation theory?
- Studying QCD: lattice, Schwinger-Dyson and Bethe-Salpeter equations, chiral perturbation theory, effective quark models.

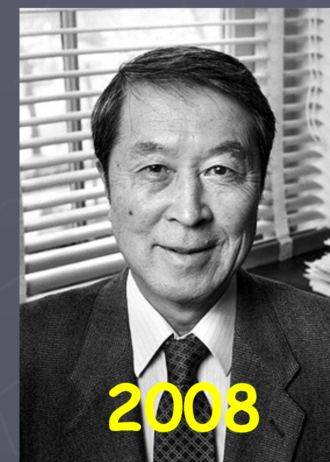
Pions and Chiral Symmetry Breaking

In October 1934, Hideki Yukawa predicted the existence of a "heavy quantum", meson, exchanging nuclear force between neutrons and protons.









It was discovered by Cecil Powel in 1949 in cosmic ray tracks in a photographic emulsion.

Pion was nicely accommodated in The Eight Fold way of Murray Gell –Mann in 1961.

Yoichiro Nambu associated it with CSB in 1960.

Pions and Chiral Symmetry Breaking

Pions are the lightest of hadrons. They do not have zero mass.

A typical meson like a ρ has a mass of 770 MeV while the nucleon has a mass of 940 MeV. This is consistent with a constituent u,d, mass of around 300 MeV.

However, pions only weigh about 140 MeV, which is 1/5th of the mass of the ρ.

This cannot be an accident.

The connection of pions with chiral symmetry breaking was present in the Gell-Mann-Oakes-Renner relation.

Pions and Chiral Symmetry Breaking

Dynamical chiral symmery breaking yields large effective quark masses and the existence of **Goldstone bosons: pions.**

PHYSICAL REVIEW VOLUME 122, NUMBER 1 APRIL 1, 1961

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. I*

Y. NAMBU AND G. JONA-LASINIO†
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois

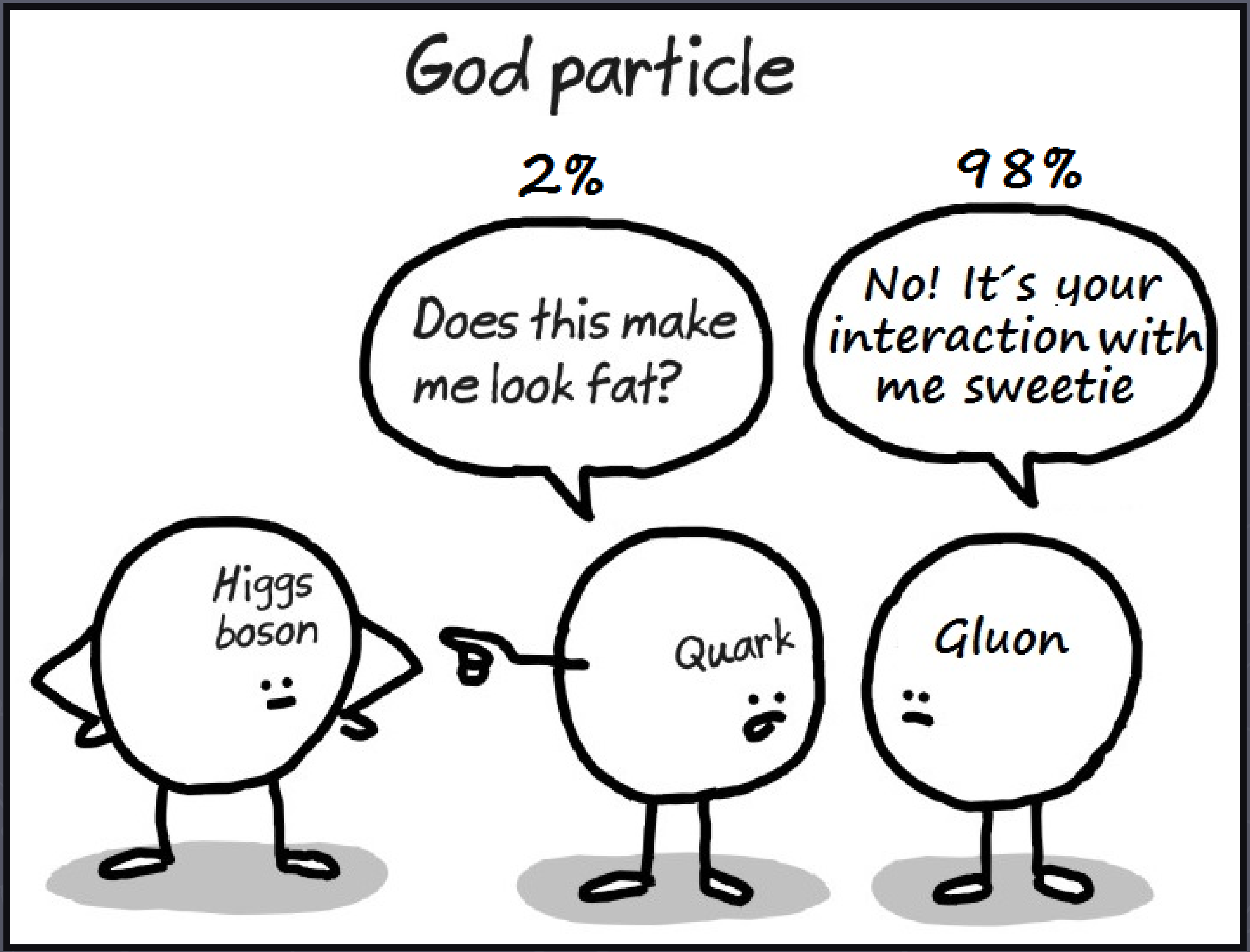
(Received October 27, 1960)

It is suggested that the nucleon mass arises largely as a self-energy of some primary fermion field through the same mechanism as the appearance of energy gap in the theory of superconductivity.

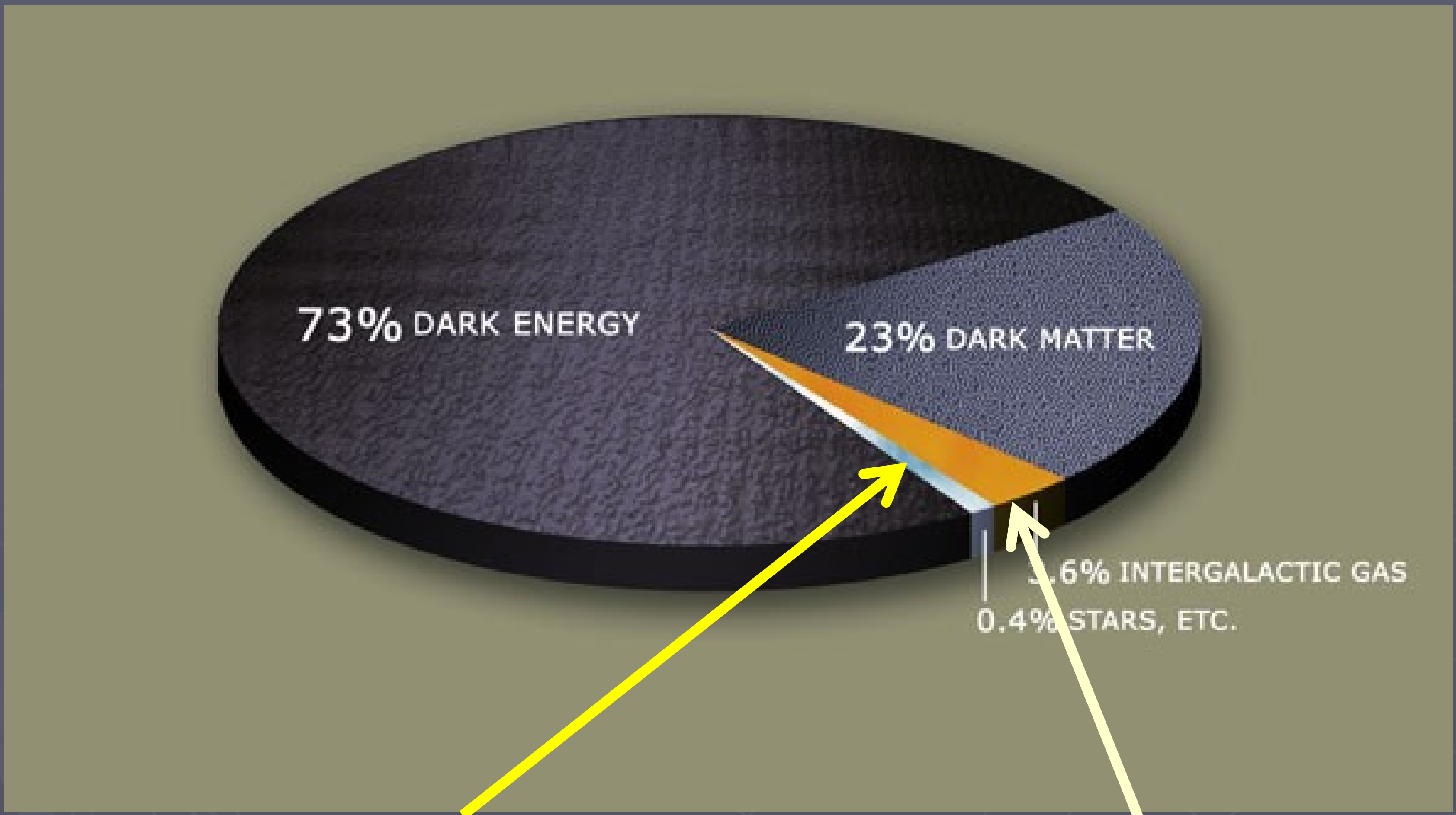
Nobel Prize 2008:
"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

quark-anti-quark

We consider a simplified model of nonlinear four-fermion interaction which allows a γ_5-gauge group. An interesting consequence of the symmetry is that there arise automatically pseudoscalar zero-mass bound states of nucleon-antinucleon pair which may be regarded as an idealized pion.


God particle
2%
98%
Does this make me look fat?
No! It´s your interaction with me sweetie
Higgs boson
Quark
Gluon

Chiral Symmetry and Its Breaking



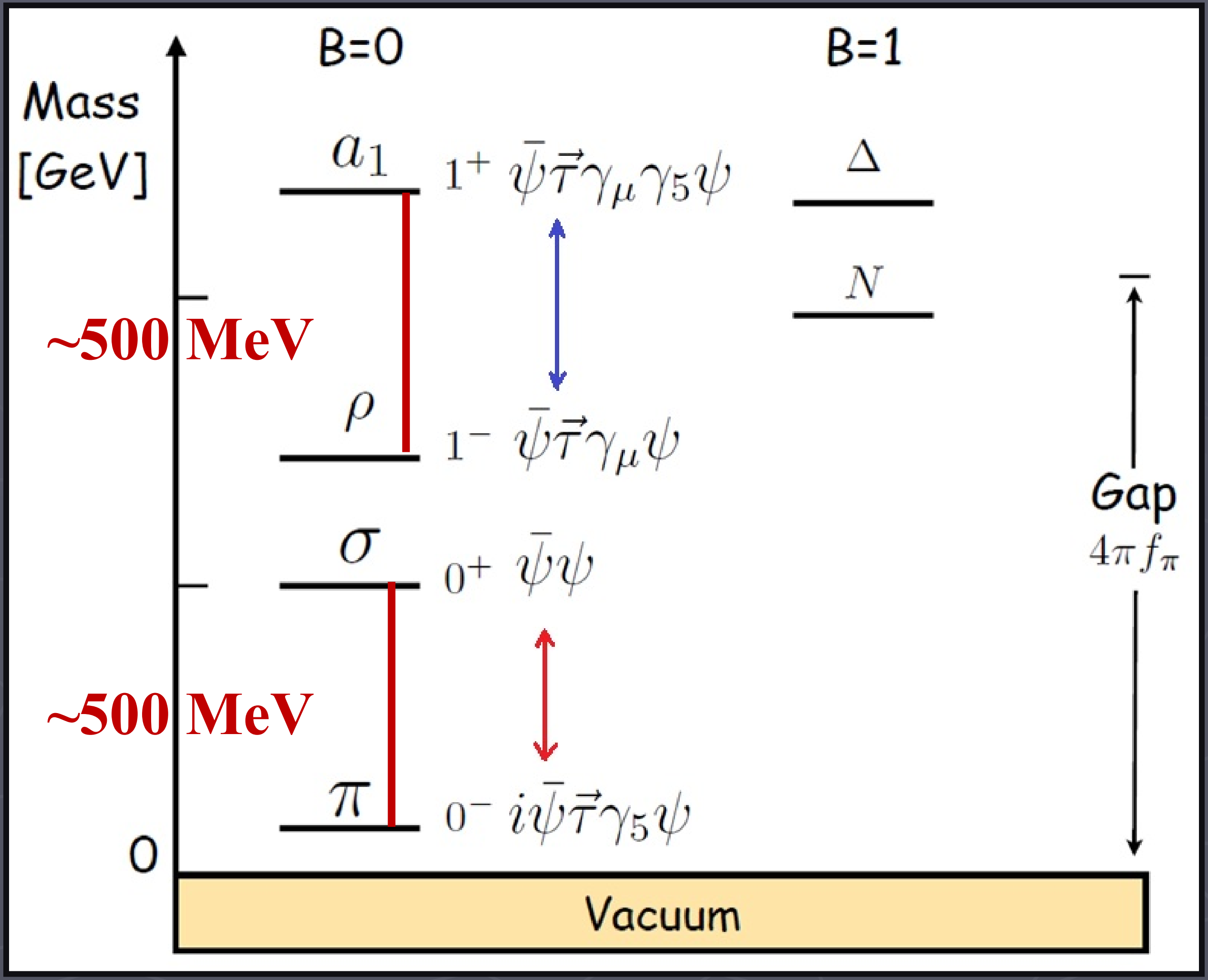
98% of visible mass is due to dynamical chiral symmetry breaking.

2% of visible mass is due to Higgs.

Chiral Symmetry and Its Breaking

Parity Partners &

Chiral Symmetry Breaking



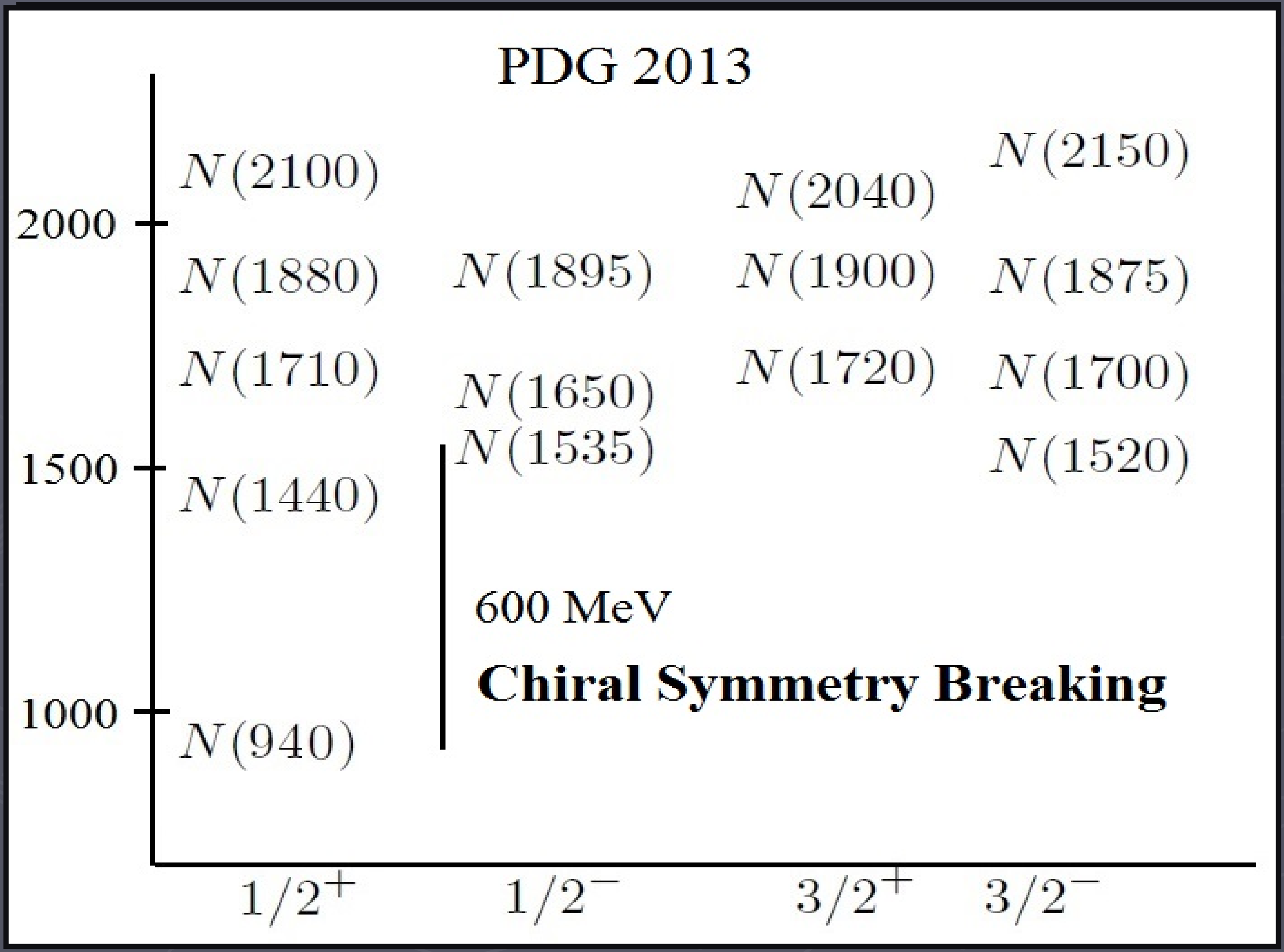
Chiral Symmetry and Its Breaking

Nucleon

And its

Parity

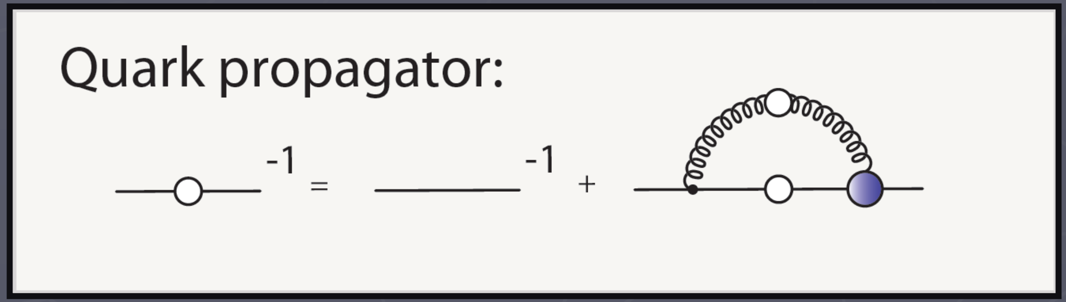
Partner



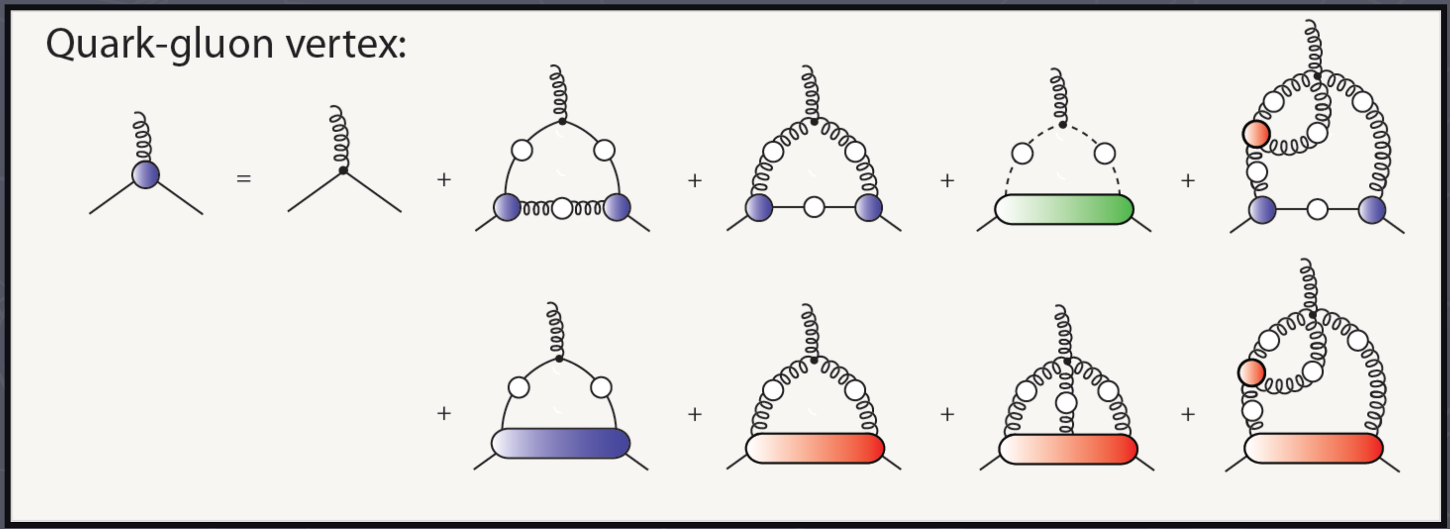
Schwinger-Dyson Equations

Schwinger-Dyson equations in covariant gauges

The inverse quark propagator:

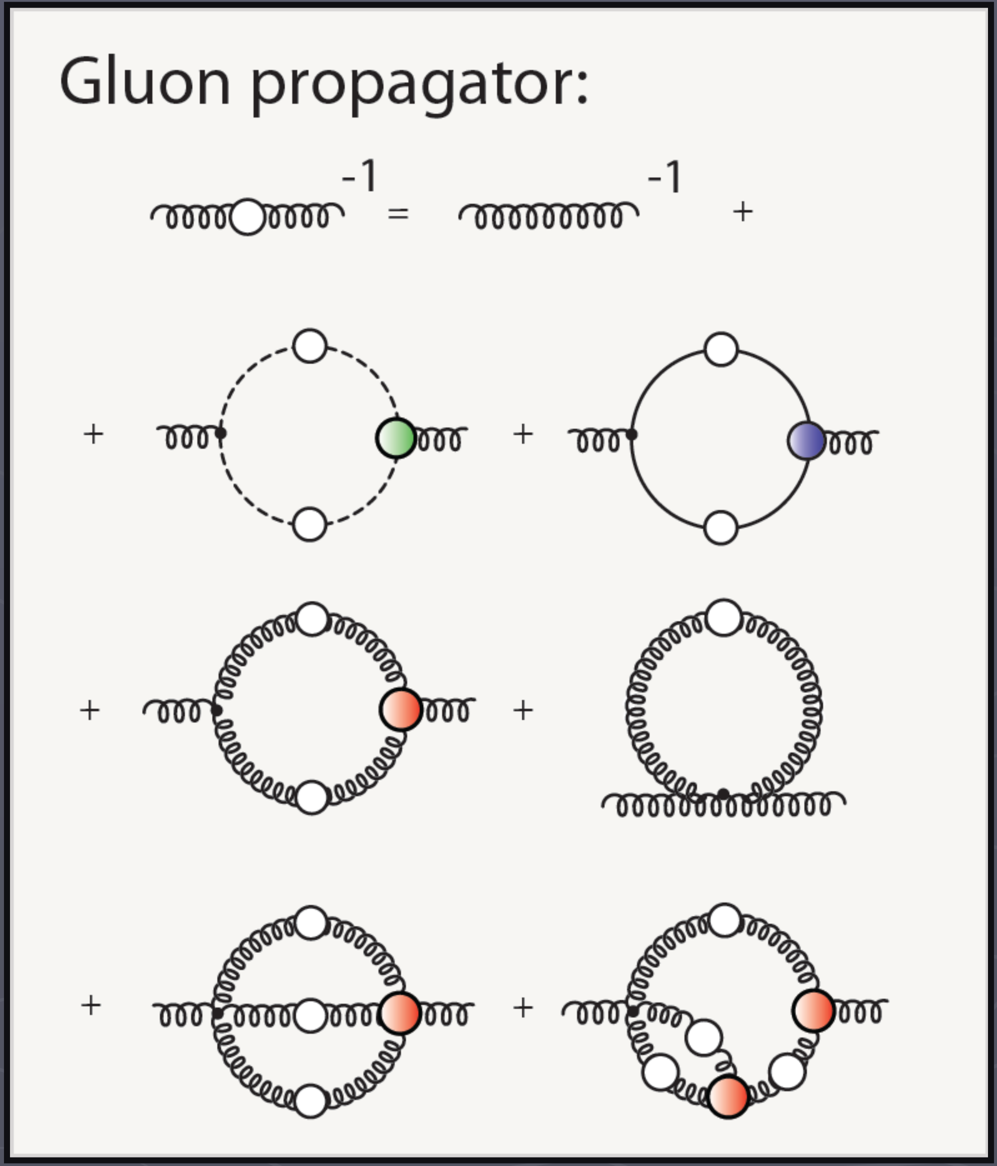


The quark-gluon vertex:



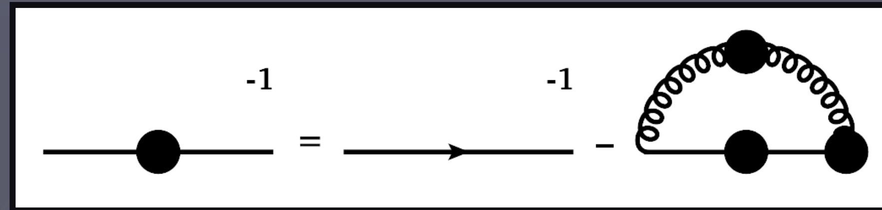
Schwinger-Dyson Equations

The inverse gluon propagator:



The Quark Propagator

The quark propagator:



$$S_B^{-1}(p,\Lambda) = S_0^{-1}(p) + \int d^4q\; g_B^2(\Lambda) D^B_{\mu\nu}(p-q,\Lambda)\frac{\lambda^a}{2}\gamma_\mu S_B(q;\Lambda)\Gamma^a_{B\nu}(q,p;\Lambda)$$

$$\begin{aligned} g_B(\Lambda) &= \mathcal{Z}_g g(p-q,\mu) \\ D^B_{\mu\nu}(p-q,\Lambda) &= \mathcal{Z}_3 D_{\mu\nu}(p-q,\mu) \\ S_B(q;\Lambda) &= \mathcal{Z}_{2F} S(p,\mu) \\ \Gamma^a_{B\nu}(q,p;\Lambda) &= \mathcal{Z}_{1F}^{-1}\Gamma(p,q,\mu) \end{aligned}$$

$$\frac{\mathcal{Z}_1}{\mathcal{Z}_3} = \frac{\tilde{\mathcal{Z}}_1}{\tilde{\mathcal{Z}}_3} = \frac{\mathcal{Z}_5}{\mathcal{Z}_1} = \frac{\mathcal{Z}_{1Fj}}{\mathcal{Z}_{2Fj}}$$

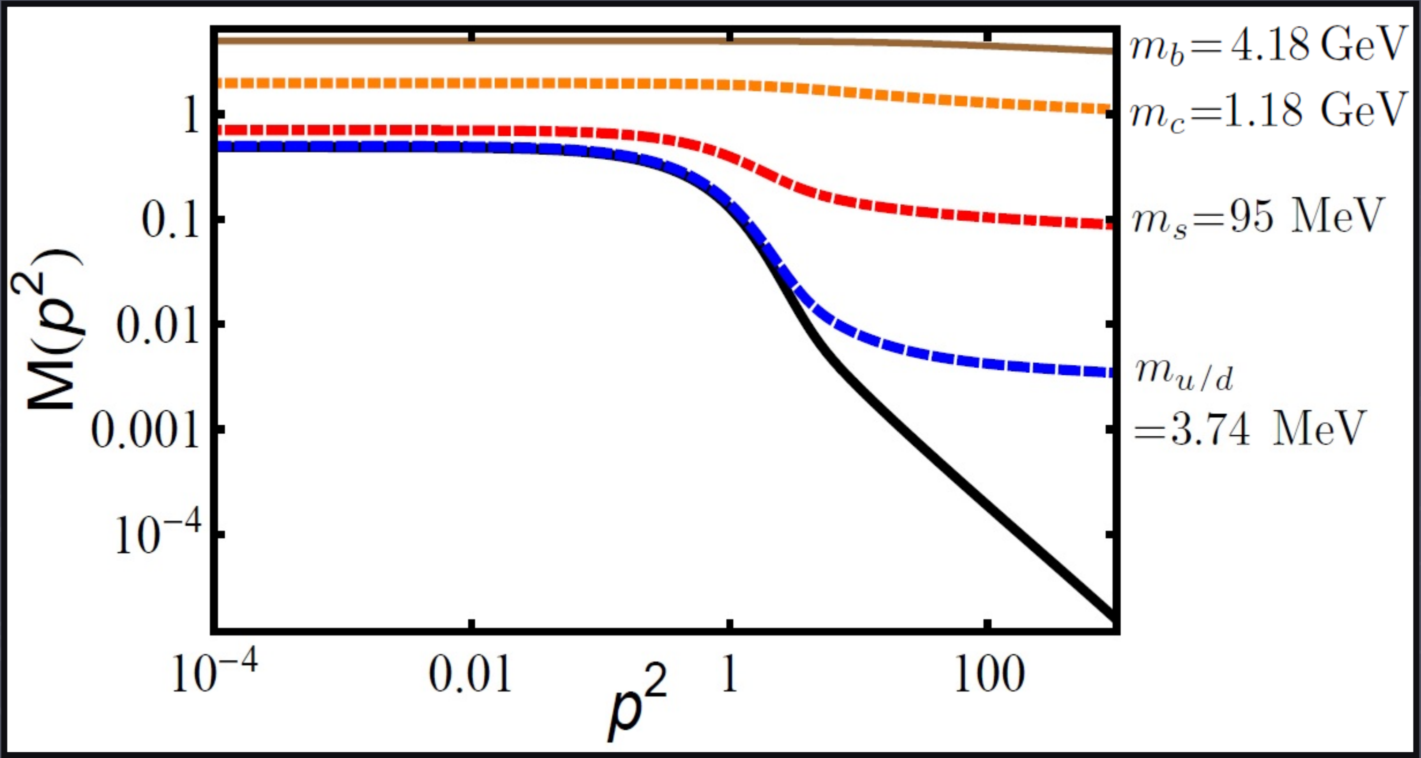
$$S^{-1}(p,\mu) = \mathcal{Z}_{2F}\, i\gamma\cdot p + \mathcal{Z}_4 m(\mu) + \mathcal{Z}_{1F}\int \frac{d^4q}{(2\pi)^4} g^2 D_{\mu\nu}(p-q,\mu)\frac{\lambda^a}{2}\gamma_\mu S(p,\mu)\Gamma(p,q,\mu)$$

$$S^{-1}(p,\mu) = \mathcal{Z}_{2F} S_0^{-1}(p) + \frac{\tilde{\mathcal{Z}}_1 \mathcal{Z}_{2F}}{\tilde{\mathcal{Z}}_3}\int \frac{d^4q}{(2\pi)^4} g^2 D_{\mu\nu}(p-q,\mu)\frac{\lambda^a}{2}\gamma_\mu S(p,\mu)\Gamma(p,q,\mu)$$

The Quark Propagator

The quark propagator:

$$S(p^2,\mu^2) = i\,\gamma\cdot p\,A(p^2,\mu^2) + B(p^2,\mu^2) = \frac{Z(p^2,\mu^2)}{i\,\gamma\cdot p + M(p^2)}$$



K. Raya, Ph.D. Student, University of Michoacán

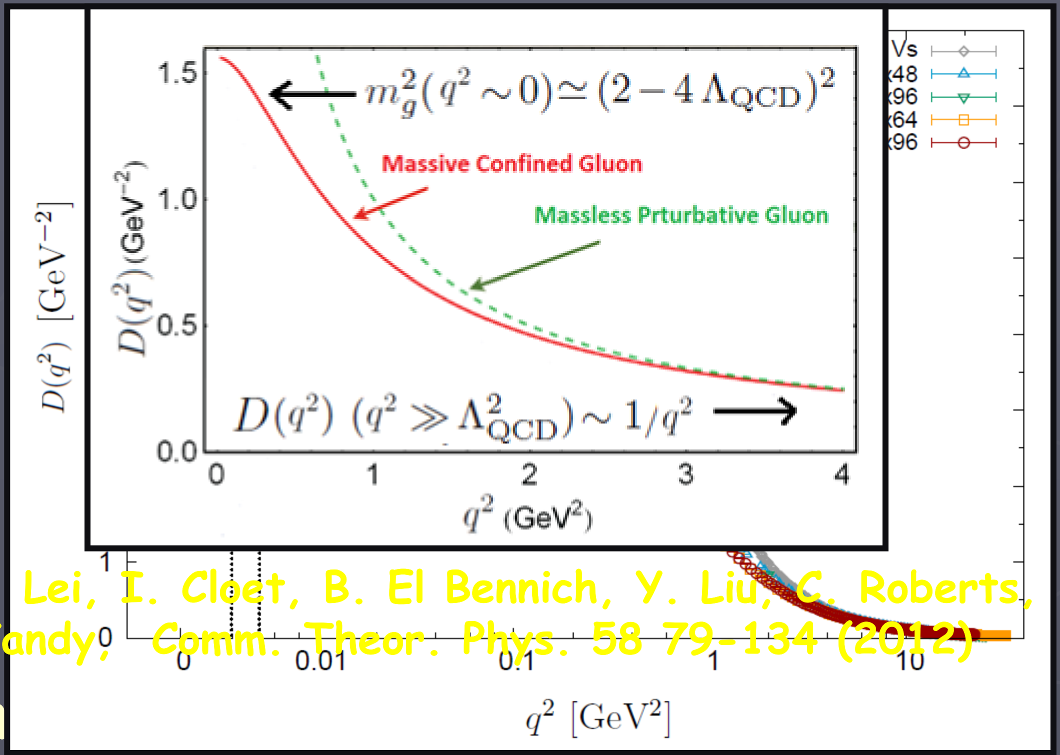
"Bridging a gap between continuum-QCD and ab initio predictions of hadron observables", Binosi,, Chang, Papavassiliou, Roberts, Phys.Lett. B742 183 (2015).

The Gluon Propagator

Gluon Propagator:

$$\Delta^{ab}_{\mu\nu}(q) \;=\; \delta^{ab}\, D(q^2) \left(\delta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)$$

Several SDE and lattice results support decoupling solution for the gluon propagator.



AB, C. Lei, I. Cloet, B. El Bennich, Y. Liu, C. Roberts, P. Tandy, Comm. Theor. Phys. 58 79-134 (2012).

Momentum dependent gluon mass function.

momentum dependent quark mass function.

I.L. Bogolubsky, et. al. Phys. Lett. B676 69 (2009).

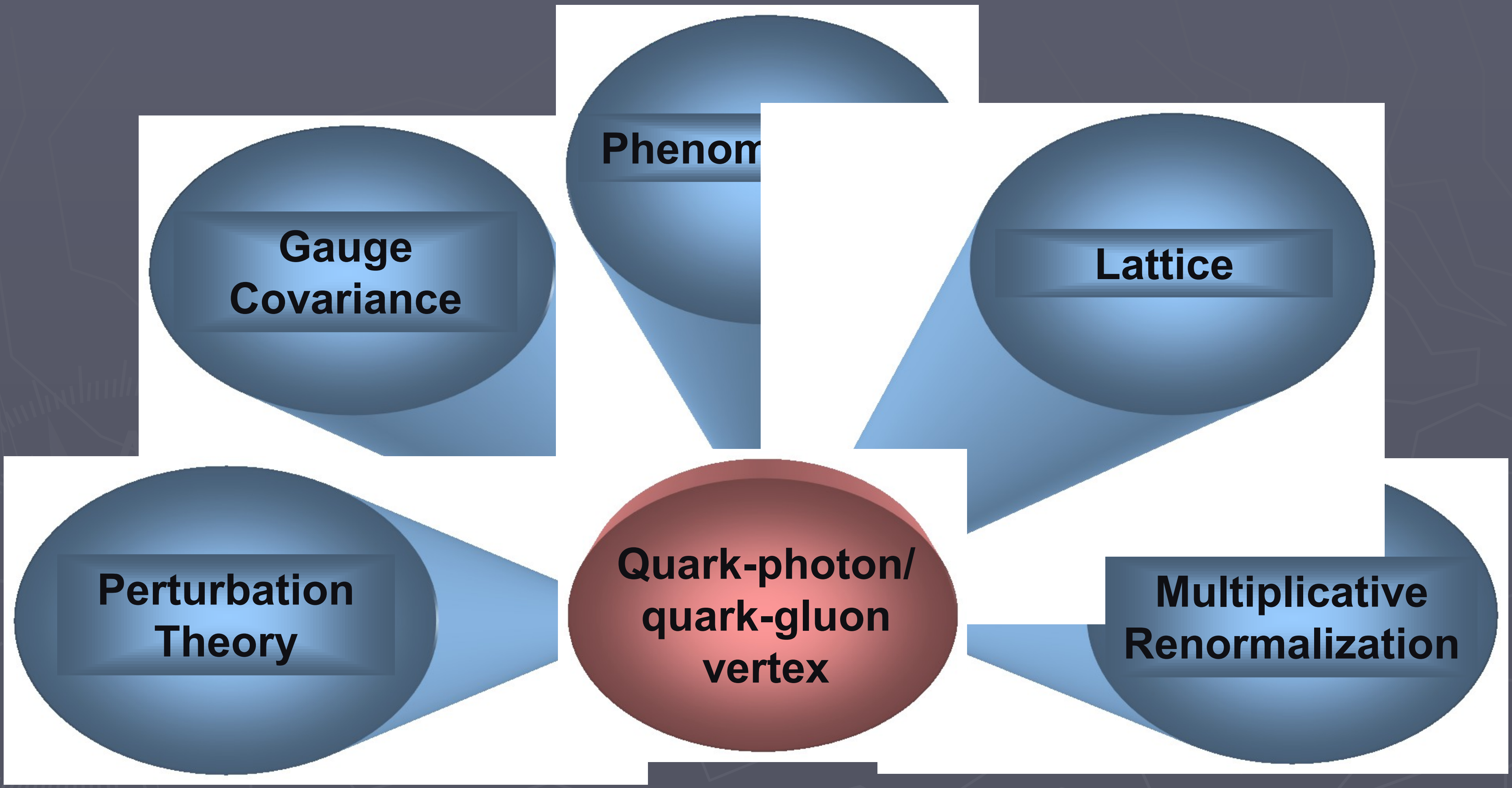
A. Ayala et. al. Phys. Rev. D86 074512 (2012).

It is in accord with the improved GZ-picture.

AB, A. Raya, J. Rodrigues-Quintero, Phys. Rev. D88 054003 (2013).

$$D^{\rm RGZ}(q^2) \;=\; \frac{q^2+M^2}{q^4+q^2(m^2+M^2)+2g^2N_c\gamma^2+M^2m^2}$$

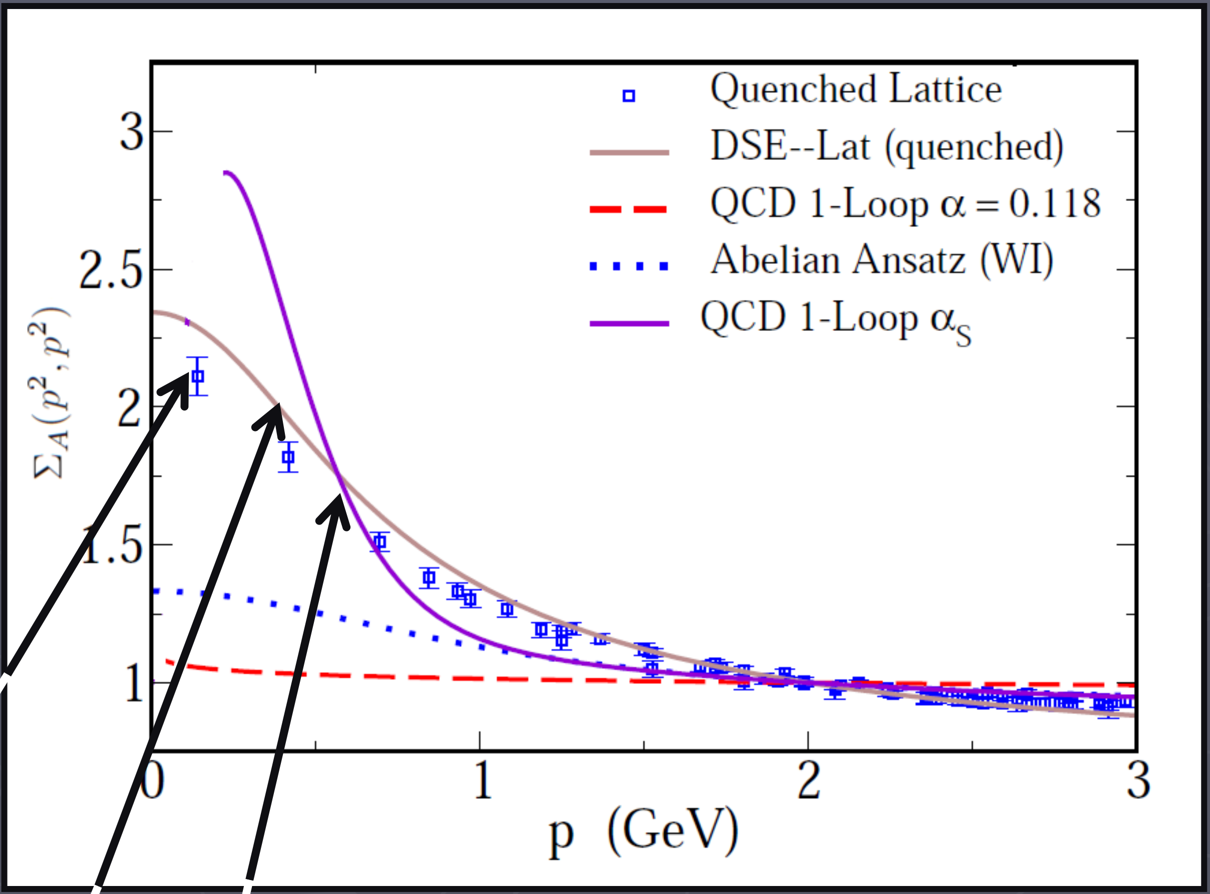
The Quark-Gluon Vertex



The Quark-Gluon Vertex

The Quark-Gluon Vertex:

One of the 12 form factors



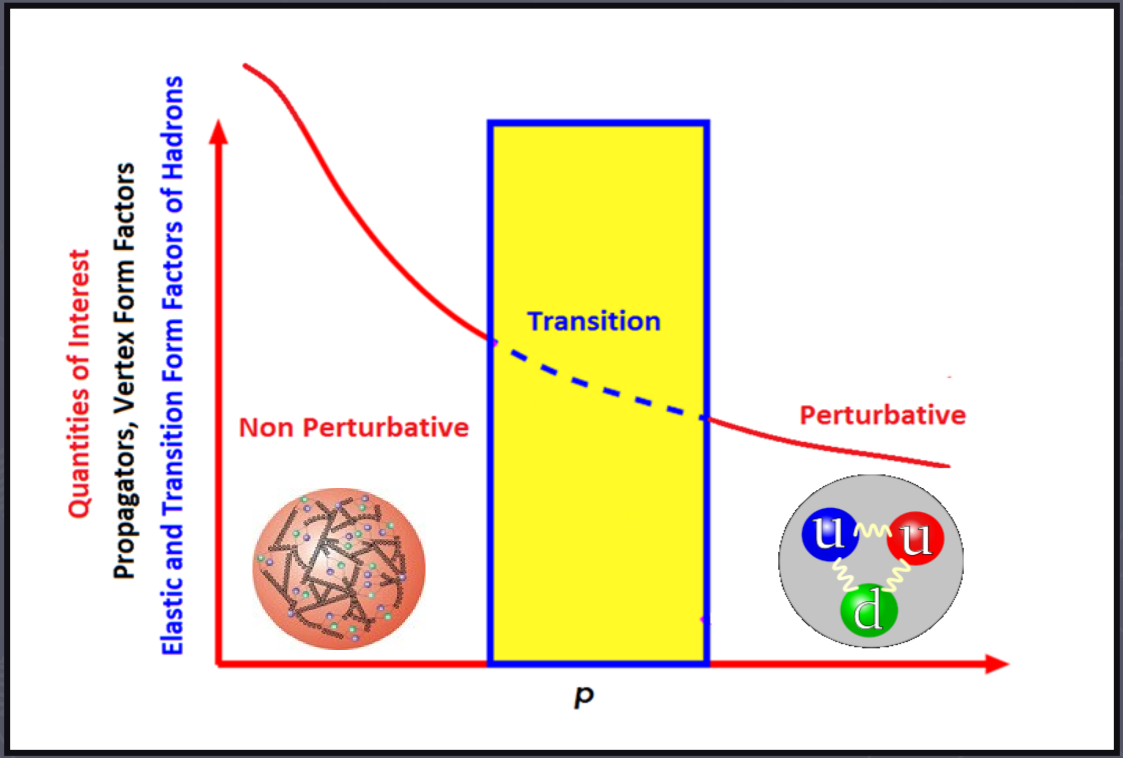
J. Skullerud, P. Bowman, A. Kizilersu, D. Leinweber, A. Williams, J. High Energy Phys. 04 047 (2003)

M. Bhagwat, M. Pichowsky, C. Roberts, P. Tandy, Phys. Rev. C68 015203 (2003).

AB, L. Gutiérrez, M. Tejeda, AIP Conf. Proc. 1026 262 (2008).

The Quark-Gluon Vertex

Schwinger-Dyson equations are the fundamental equations of QCD and combine its UV and IR behaviour.

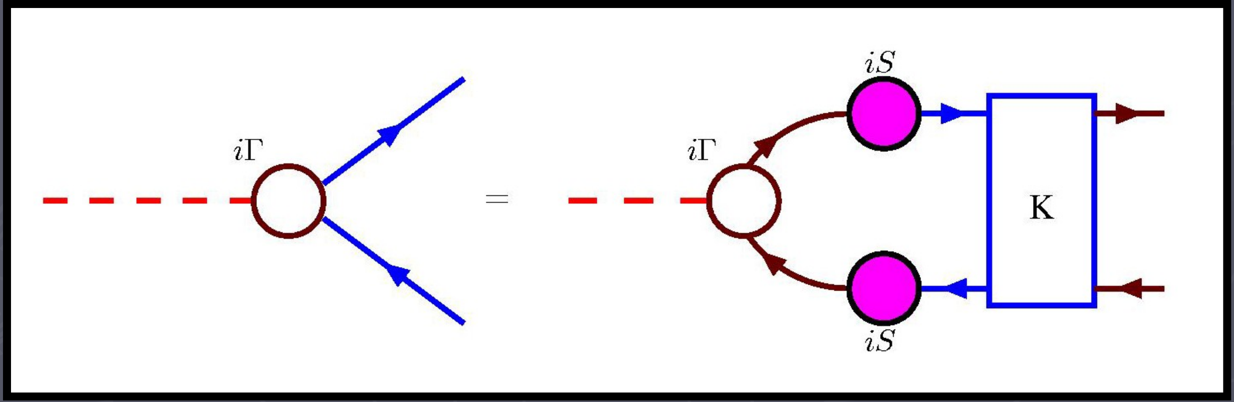


Studying the transition of hadrons from them being made of a sea of quarks and gluons to valence quarks alone can be studied naturally through SDE.

The Bethe-Salpeter Amplitudes

Bethe-Salpeter amplitude for the pion:

$$\Gamma_\pi(k,P) = \gamma_5 \left[iE_\pi(k;P) + \gamma \cdot P F_\pi(k;P) + \gamma \cdot k k \cdot P G_\pi(k;P) + \sigma_{\mu\nu} k_\mu P_\nu H_\pi(k;P) \right]$$

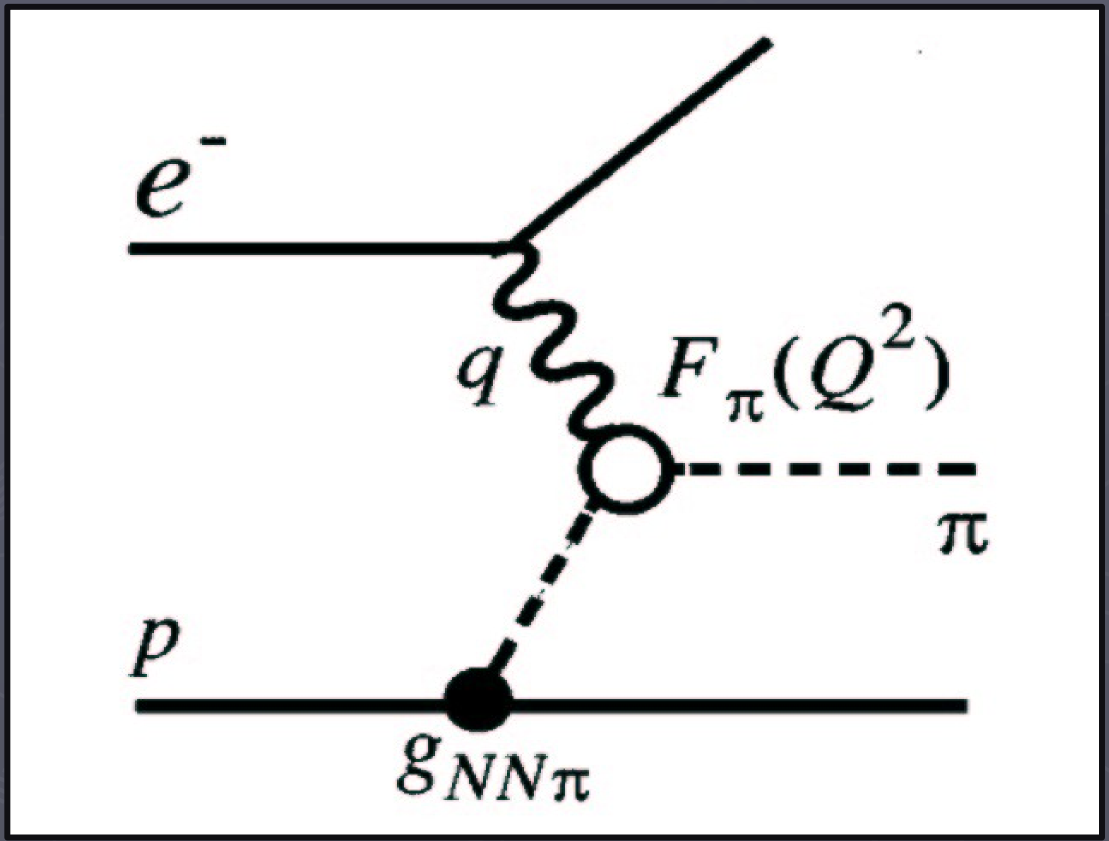


$$S(p) = \frac{1}{i\gamma \cdot p A(p^2) + B(p^2)}$$

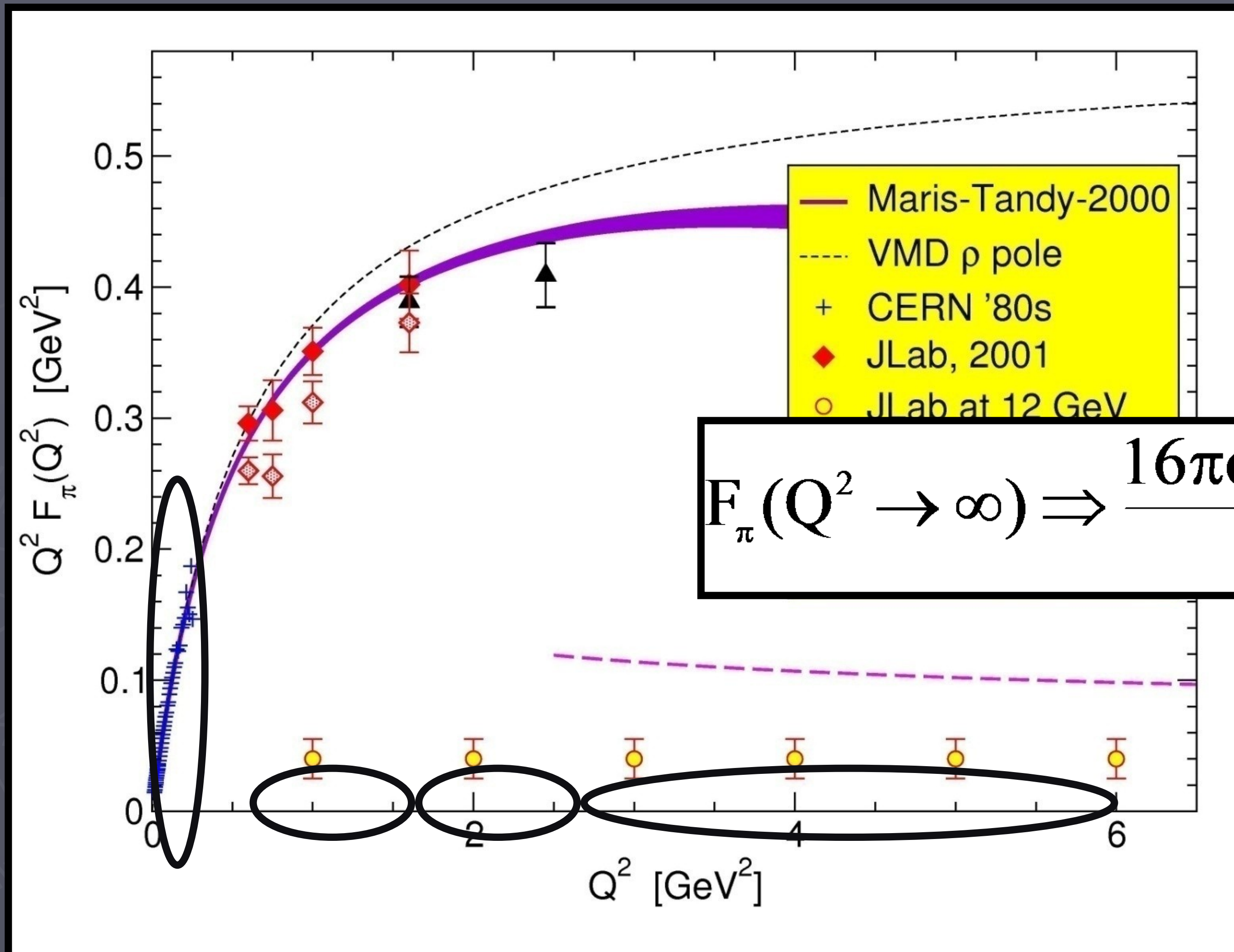
Goldberger-Triemann relations:

$$\begin{aligned}
f_\pi \; E_\pi(k;P=0) &= B(k^2) \\
F_R(k;0) + 2f_\pi \; F_\pi(k;0) &= A(k^2) \\
G_R(k;0) + 2f_\pi \; G_\pi(k;0) &= 2A'(k^2) \\
H_R(k;0) + 2f_\pi \; H_\pi(k;0) &= 0
\end{aligned}$$

Pion Electromagnetic Form Factor



Pion Electromagnetic Form Factor



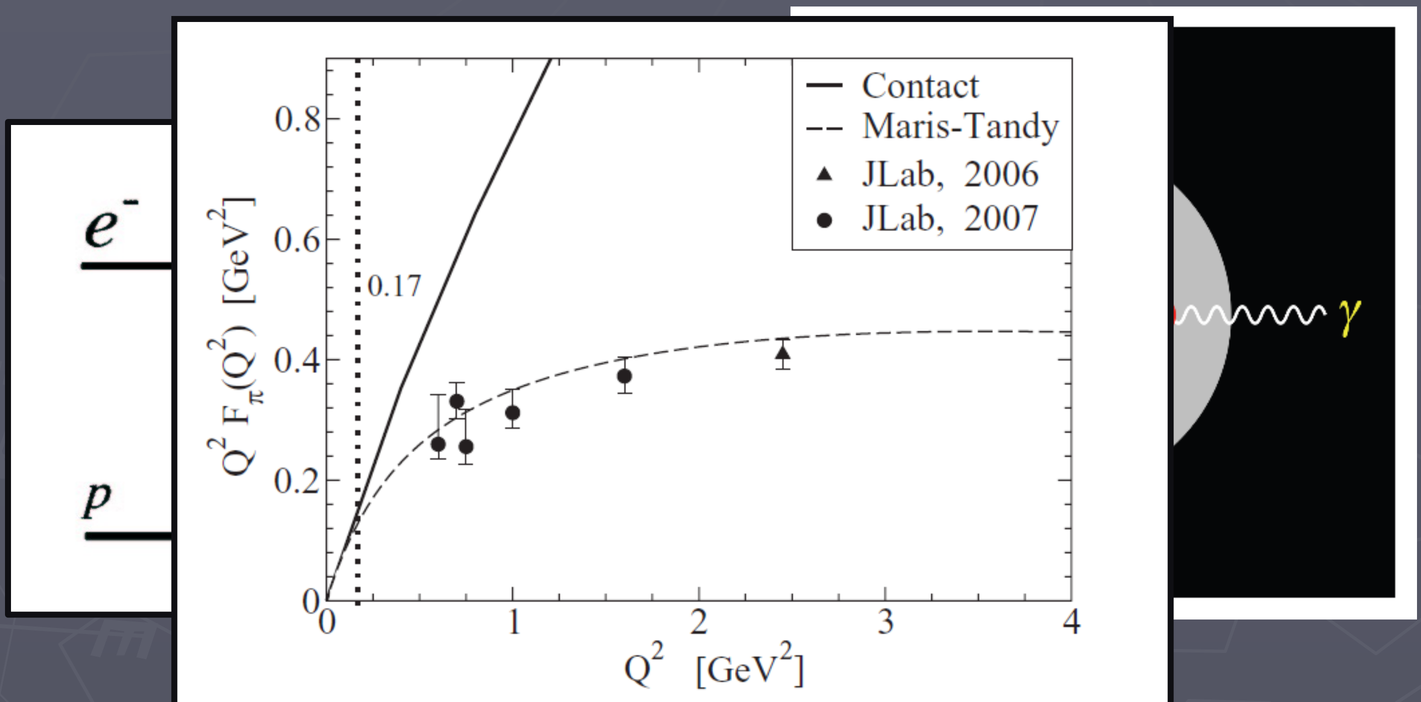
$$F_\pi(Q^2 \to \infty) \Rightarrow \frac{16\pi\alpha_s(Q^2)f_\pi^2}{Q^2}$$

1980's 2001 2006

2017?

Pion Electromagnetic Form Factor

The pattern of chiral symmetry breaking dictates the momentum dependence of the elastic pion form factor.

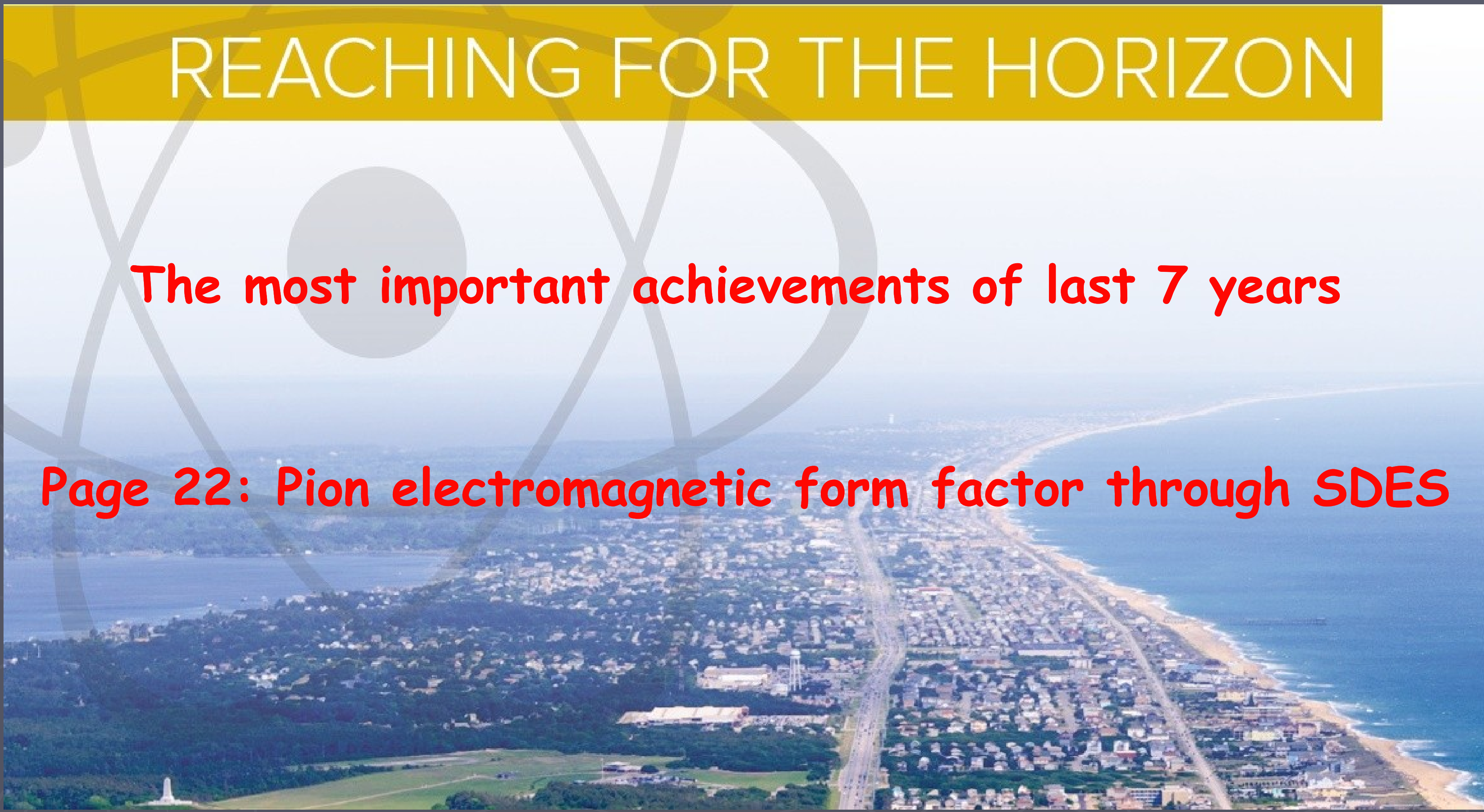


Experiments on pions indicate a contact like interaction?

L. Gutiérrez, AB, I.C. Cloet, C.D. Roberts, Phys. Rev. C81 065202 (2010).

Pion Electromagnetic Form Factor

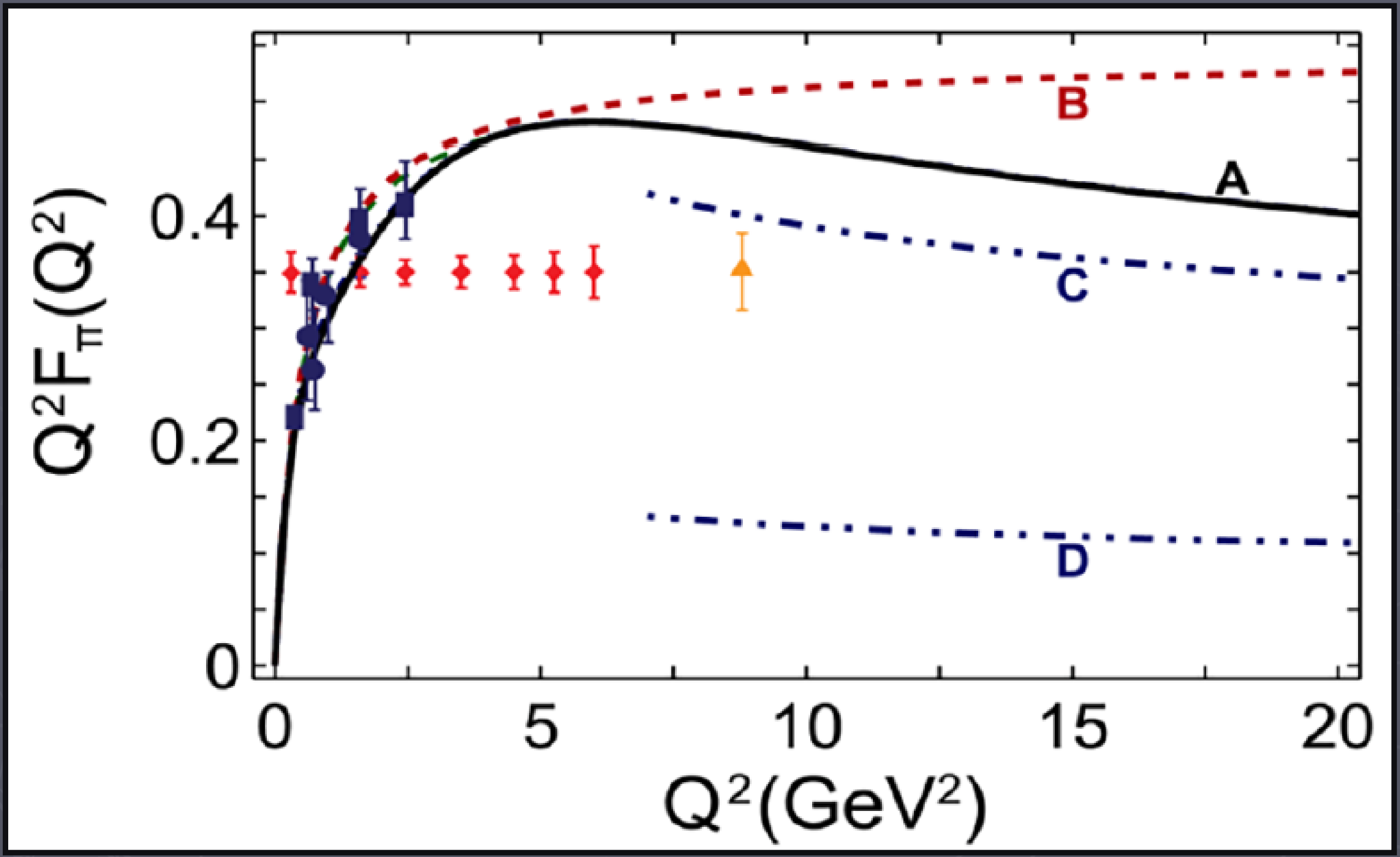
Pion Electromagnetic Form Factor



The most important achievements of last 7 years

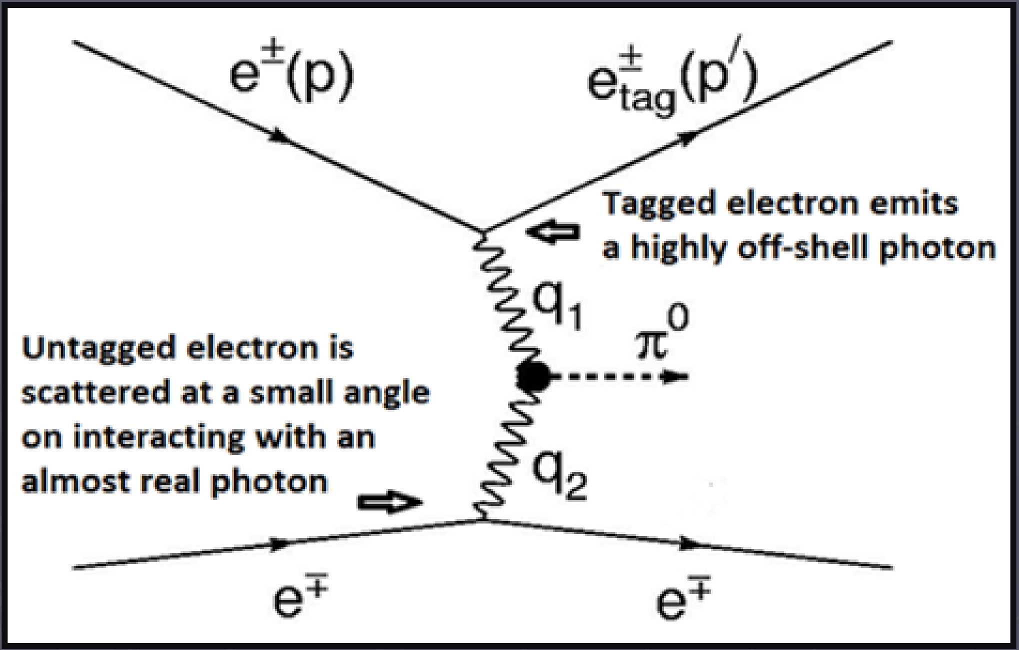
Page 22: Pion electromagnetic form factor through SDES

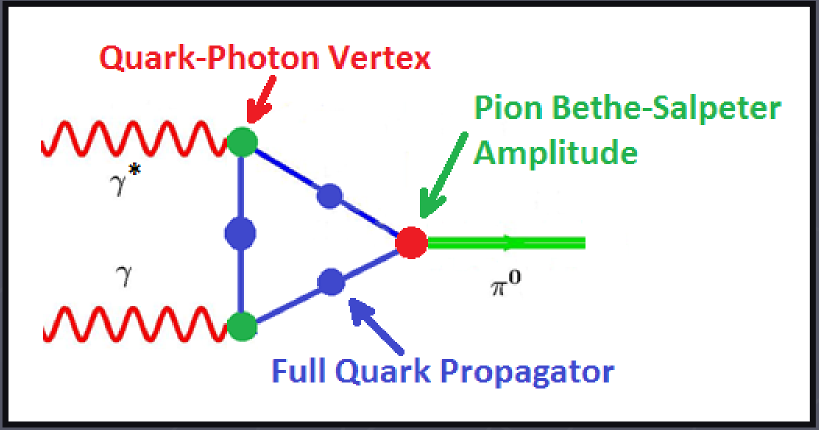
Pion Electromagnetic Form Factor



L. Chang, I.C. Cloët, C.D. Roberts, S.M. Schmidt, P.C. Tanday, Phys. Rev. Lett. 111, 14 141802 (2013)

Pion to γγ* Transition Form Factor



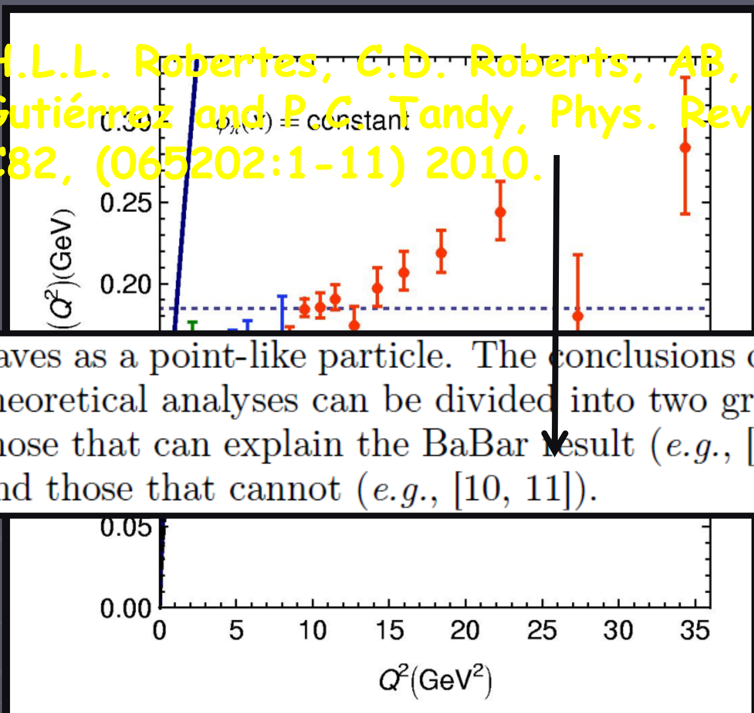


$$T_{\mu\nu}(k_1, k_2) = \frac{\alpha_{em}}{\pi f_\pi} \epsilon_{\mu\nu\alpha\beta} k_{1\alpha} k_{2\beta} G(k_1^2, k_2^2, k_1 \cdot k_2)$$

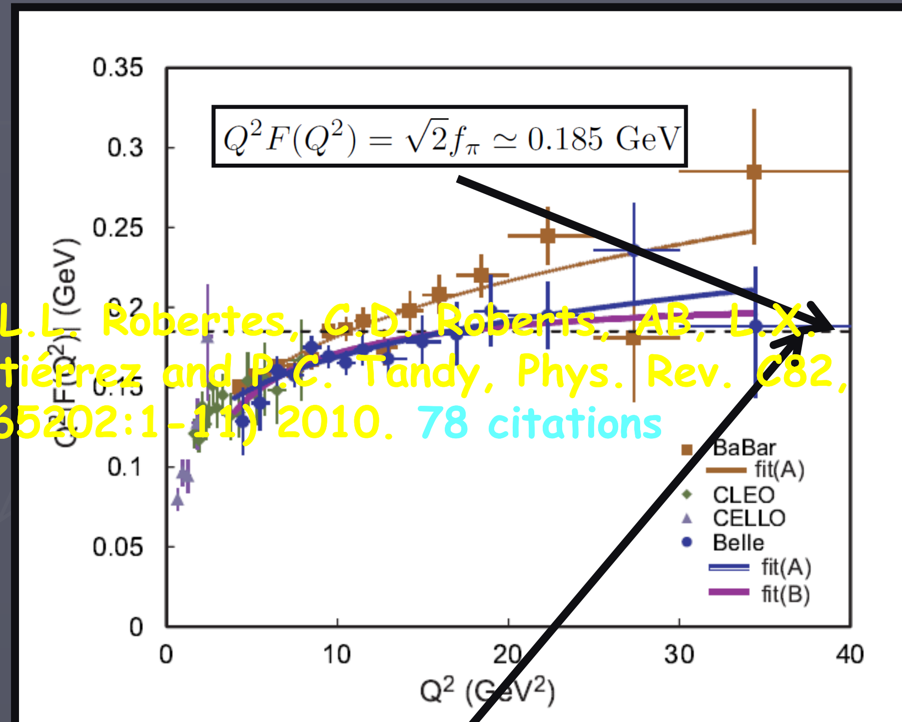
Pion to γγ* Transition Form Factor

The $\gamma^*\gamma \to \pi^0$ transition form factor:

H.L.L. Robertes, C.D. Roberts, AB, L.X. Gutiérrez and P.C. Tandy, Phys. Rev. C82, (065202:1-11) 2010.



haves as a point-like particle. The conclusions of the theoretical analyses can be divided into two groups: those that can explain the BaBar result (*e.g.*, [6, 9]) and those that cannot (*e.g.*, [10, 11]).



H.L.L. Robertes, C.D. Roberts, AB, L.X. Gutiérrez and P.C. Tandy, Phys. Rev. C82, (065202:1-11) 2010. 78 citations

CELLO H.J. Behrend et.al., Z. Phys C49 401 (1991). 0.7 – 2.2 GeV²

CLEO J. Gronberg et. al., Phys. Rev. D57 33 (1998). 1.7 – 8.0 GeV²

Lowest order in perturbation theory and the leading twist asymptotic QCD calculation:

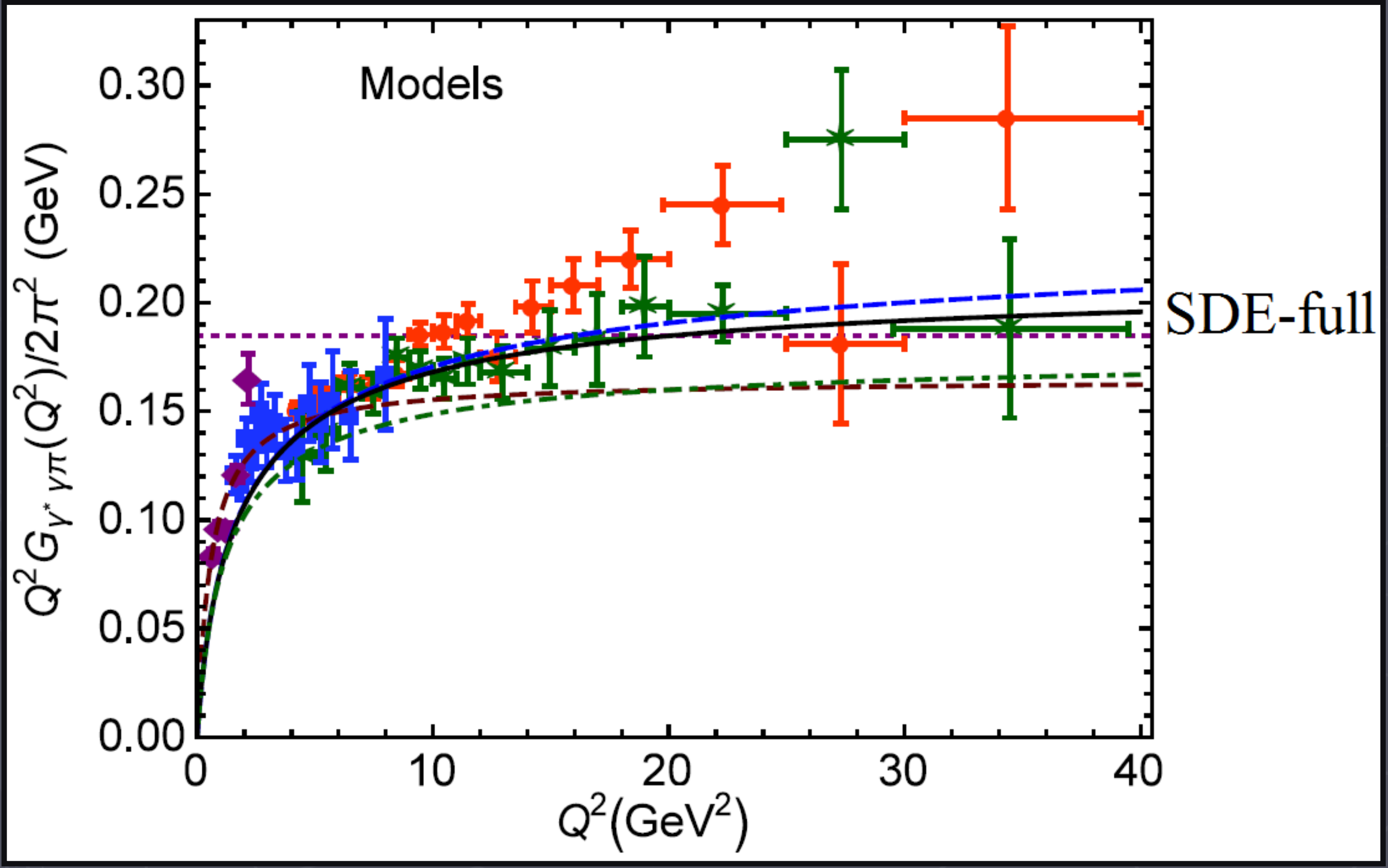
G.P. Lepage and S.J. Brodsky, Phys. Rev. D22, 2157 (1980)

BaBar R. Aubert et. al., Phys. Rev. D80 052002 (2009). 4.0 – 40.0 GeV²

Belle S. Uehara et. al., Phys. Rev. D86 092007 (2012). 4.0 – 40.0 GeV²

Pion to γγ* Transition Form Factor

The $\gamma^*\gamma \to \pi^0$ transition form factor:

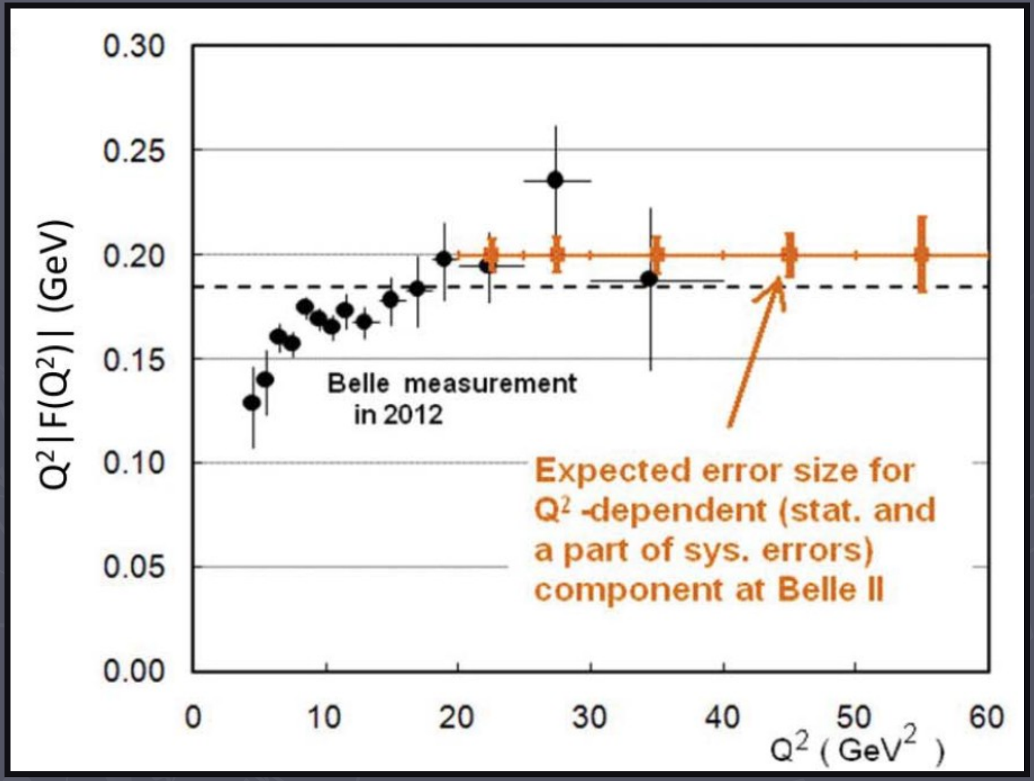


K. Raya, L. Chang, AB, J.J. Cobos-Martinez, L.X. Gutiérrez-Guerrero, C.D. Roberts, P.C. Tandy, e-Print: arXiv:1510.02799. (2015)

Pion to γγ* Transition Form Factor

The $\gamma^* \gamma \to \pi^0$ transition form factor:

- Belle II will have 40 times more luminosity.



Vladimir Savinov:
5th Workshop of the APS Topical Group on Hadronic Physics, 2013.

Precise measurements at large Q^2 will provide a stringent constraint on the pattern of chiral symmetry breaking.

Challenges within Standard Model

Pion after 80 years.

First excited states of nucleon after 50 years. Inverted hierarchy in lattice.

Gluon mass in the infrared. Last 10 years.

BRST symmetry breaking?

Dynamical diquarks within baryons.

Elastic and transition form factors at large virtualities.