EMERGENT HADRON MASS and PION/KAON/NUCLEON FORM FACTORS

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EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
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NREC 2026

NREC

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A QCD EHM PRIMER

QCD LAGRANGIAN

$$\mathcal{L}_{\rm QCD} = \sum_{j=u,s,d,\ldots} \bar{q}_j \left[\gamma_\mu D_\mu + m_j\right] q_j + \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \frac{1}{2\xi}(\partial_\mu A^a_\mu)^2 + \partial_\mu \bar{c}^a \partial_\mu c^a + g f^{abc} (\partial_\mu \bar{c}^a) A^b_\mu c^c$$

(linear) gauge fixing

Faddeev-Popov ghost term

$$D_\mu = \partial_\mu + i g \frac{1}{2} \lambda^a A^a_\mu$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

GLUON SELF-INTERACTION

pure-glue QCD displays a **mass gap**

$$m_g \sim 0.5 \text{ GeV}$$

Cornwall, PRD 26 (1982)

GAUGE SYMMETRY IS FINE

2-point STI can be still satisfied with

$$\Delta_{\mu\nu}(q) = \frac{P_{\mu\nu}(q)}{q^2[1+\Pi(q^2)]}, \quad q^\mu P_{\mu\nu}(q) = 0$$

$$\lim_{q^2 \to 0} q^2 \Pi(q^2) = m_g$$

(“only” requires the presence of longitudinally coupled massless poles)

Schwinger, PR 125 and 128 (1962)

STRESS-ENERGY TENSOR IS ANOMALOUS

$$T_{\mu\mu} = \frac{\beta}{4} G^a_{\mu\nu} G^a_{\mu\nu}$$

but no size prescribed…

① RGI MASSES

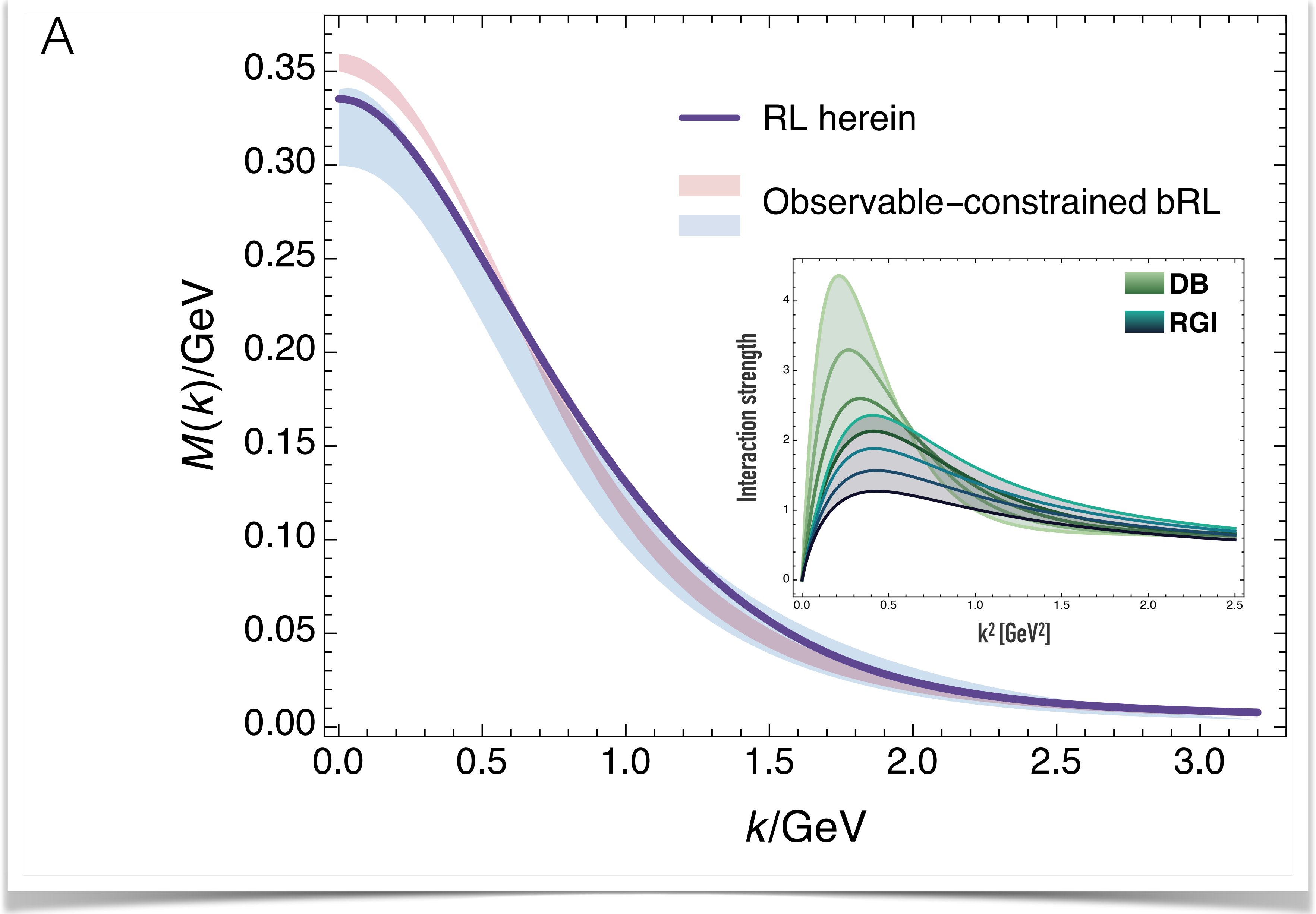
40 years+ non-perturbative methods uncover the size of the gluon mass

$$m_g = 0.43(1) \text{ GeV}$$

Aguilar et al., EPJC 80 (2020)

and reveal the associated RGI running masses, unifies matter-based and gauge-focused understanding of QCD interactions,…

DB et al., PLB 742 (2015)



② PI EFFECTIVE CHARGE

owing to the emergence of a non-zero gluon mass scale a process independent effective charge emerges

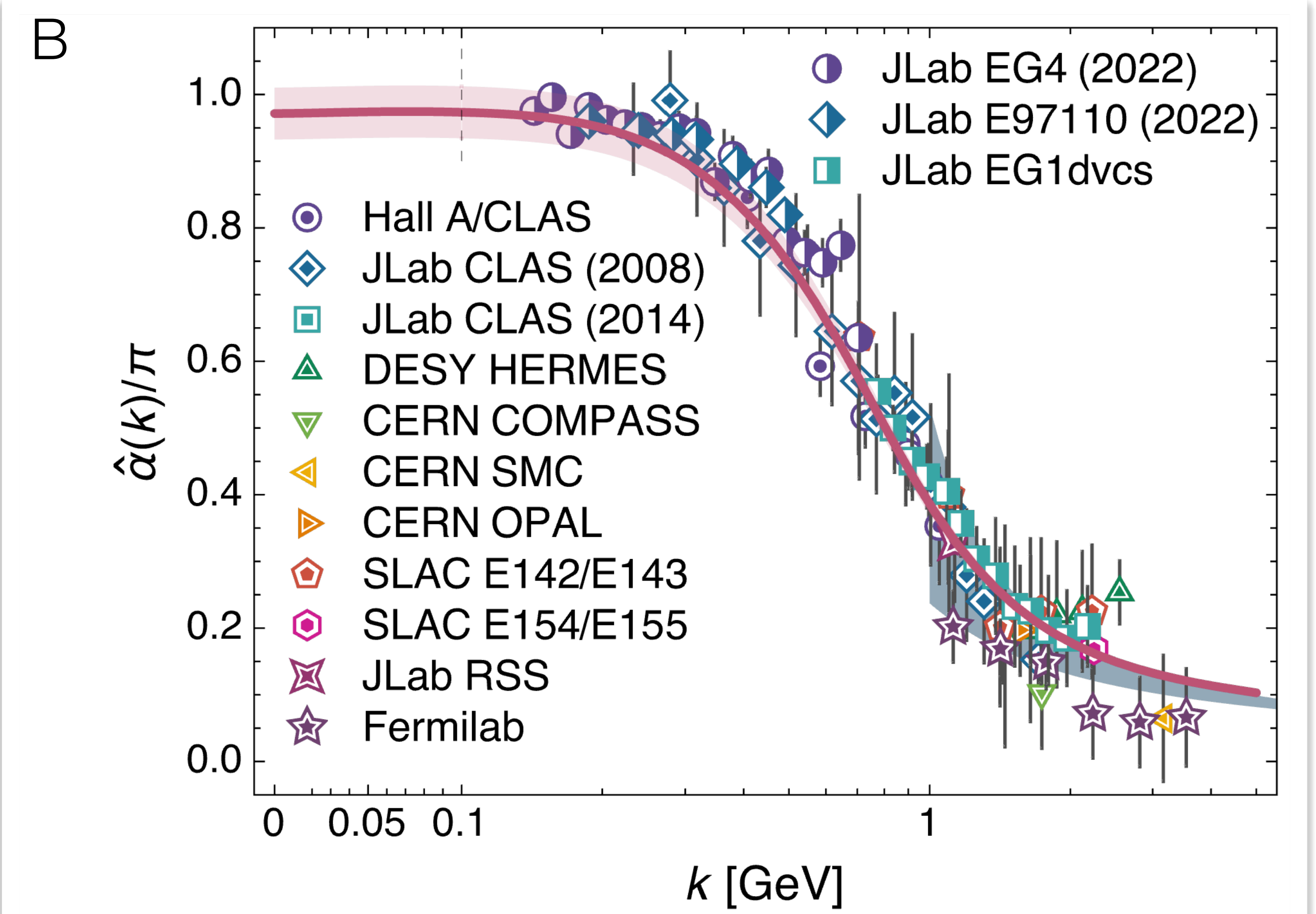
$$\hat{\alpha}(s) = \frac{4\pi}{(11 - 2n_f/3)\log[\mathcal{K}^2(s)/\Lambda^2]}, \quad \mathcal{K}^2(s) = \frac{a_0^2 + a_1 s + s^2}{b_0 + s}$$

parameter free prediction

defines a screening mass of $\zeta_H \approx 1.4\Lambda = 0.331(2)$ GeV

practically identical to Bjorken sum rule coupling measured in DIS

candidate for QCD interaction strength @ all moment

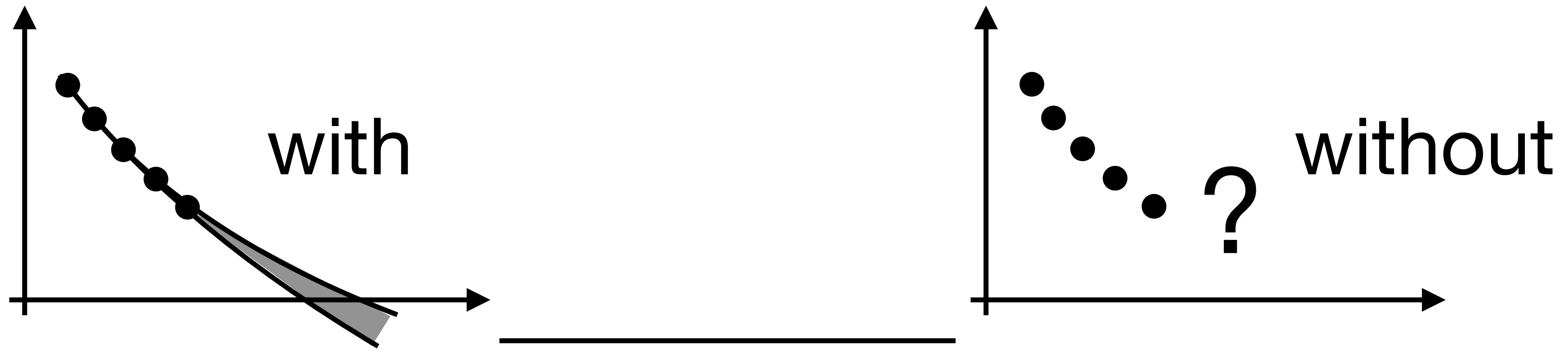


Cui et al., CPC 44 (2020)

π/K FORM FACTORS
ELECTROMAGNETIC

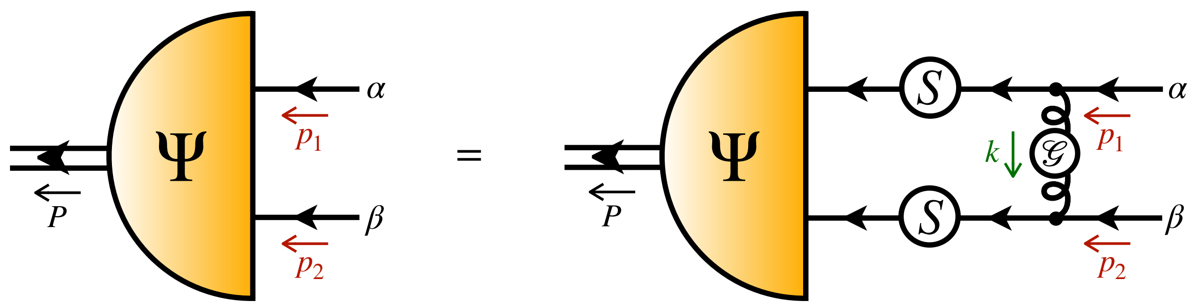
Yao, DB, Roberts, PLB 855 (2024)

singularities move in the complex k^2 domain sampled by the bound-state equations



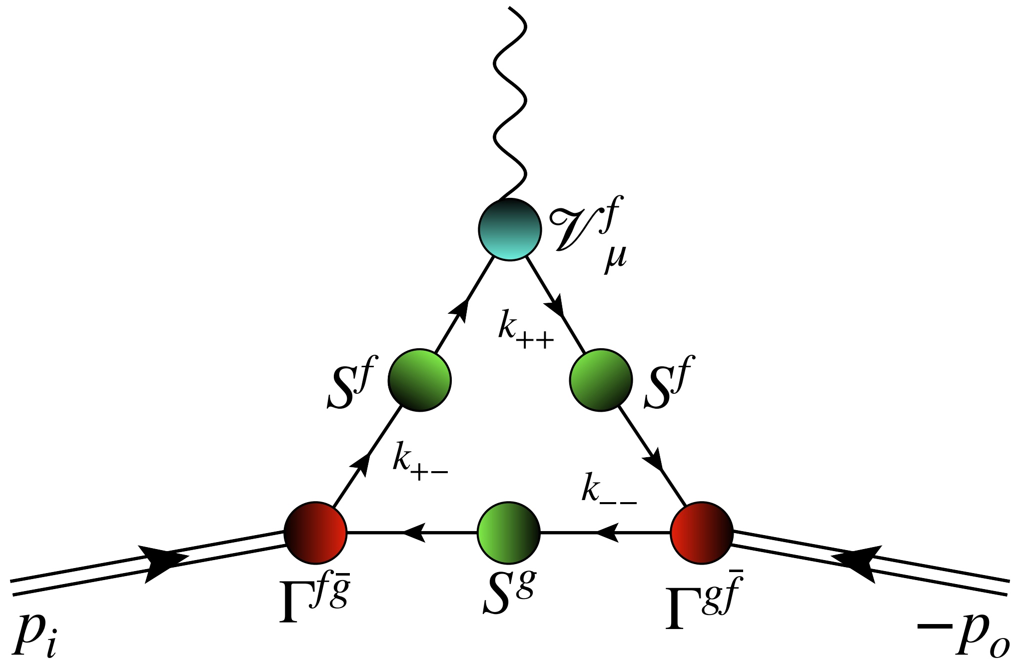
Q^2_{max}

BETHE-SALPETER EQUATION



dressed-quark propagators singularities limit mass of bound-state

TRIANGULAR DIAGRAM



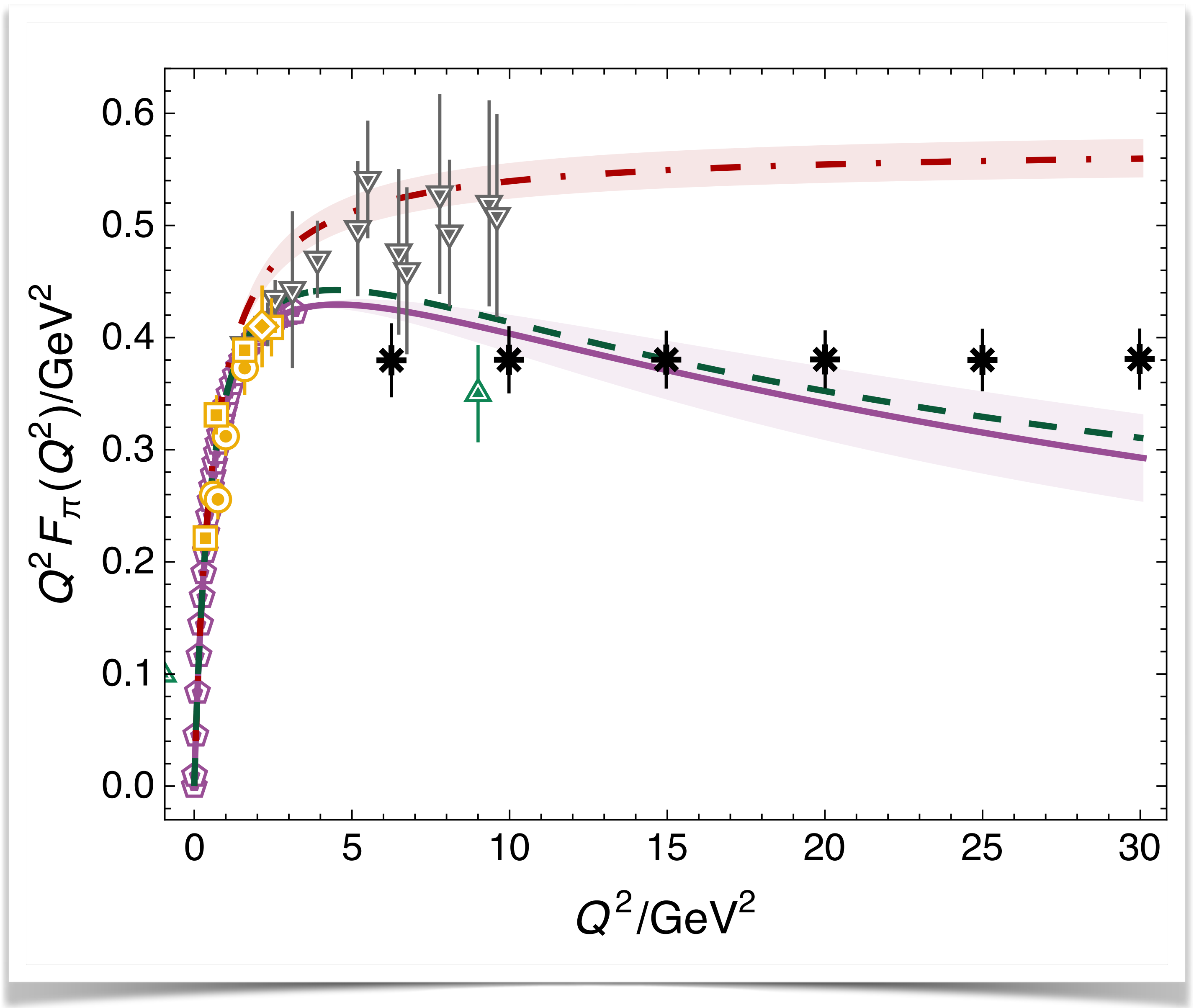
SPM INTERPOLATION

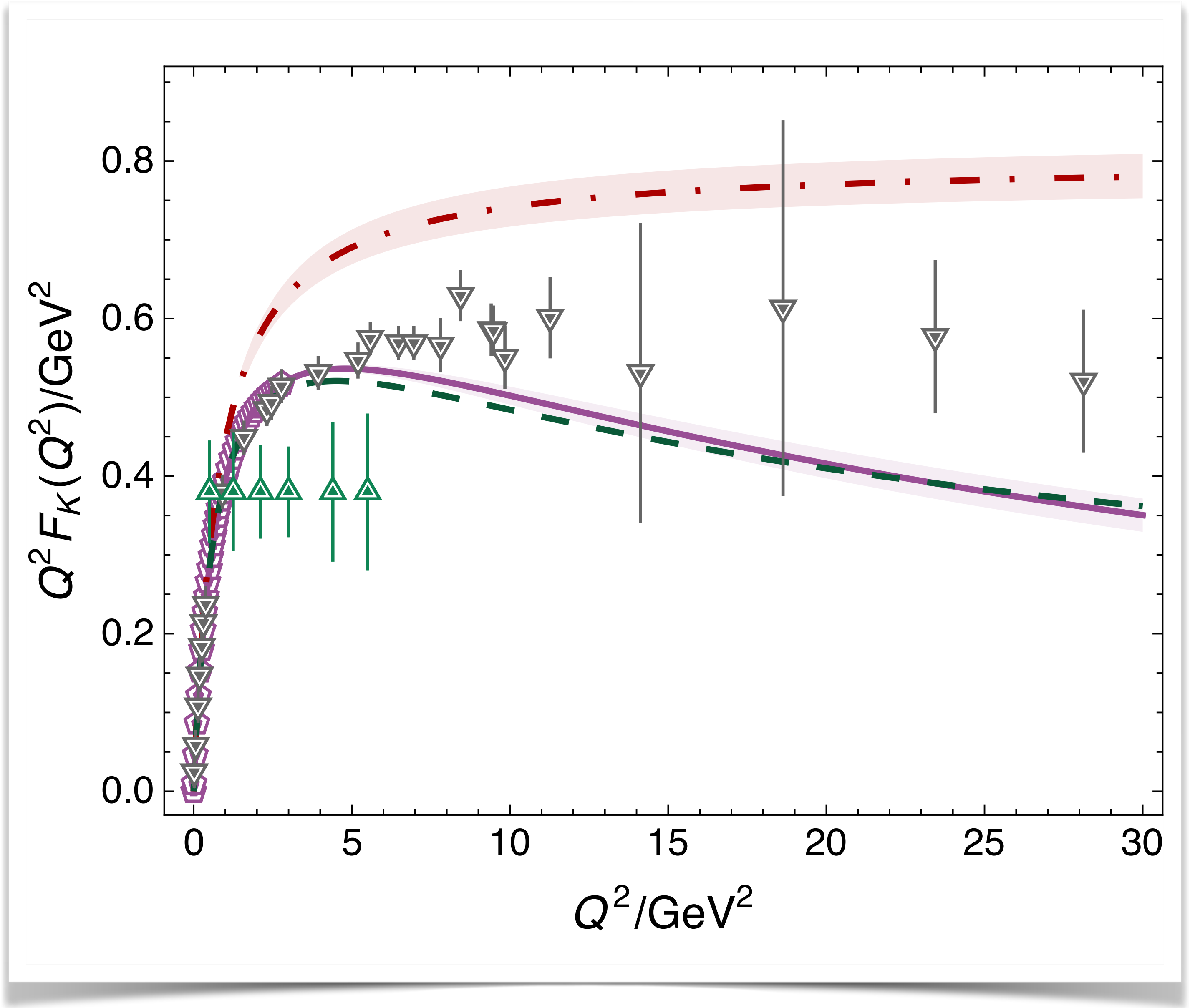
$$\mathrm{D} = \{(x_i, y_i = f(x_i)),\ i = 1, \ldots, N\}$$

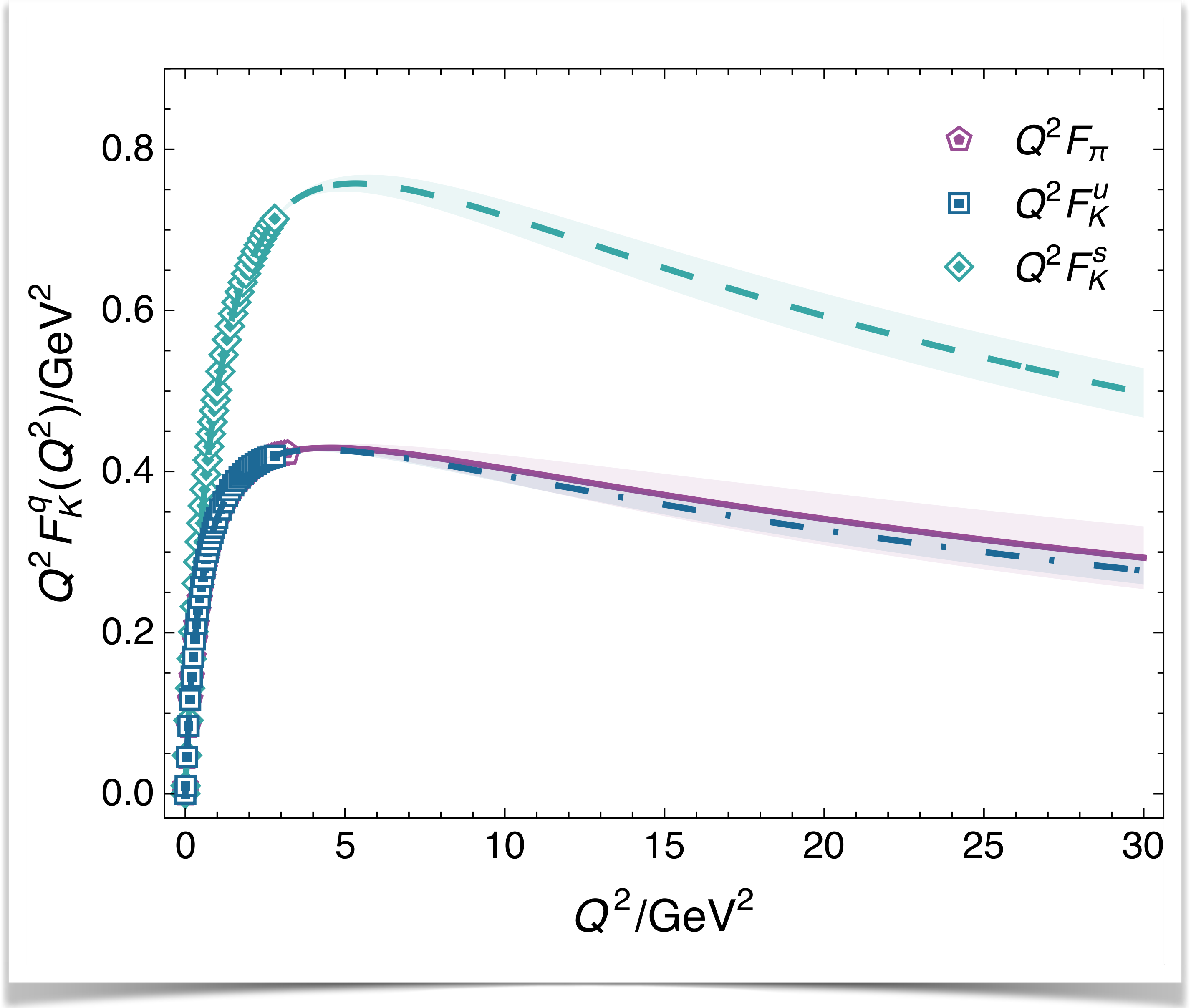
$$C_N(x) = \frac{y_1}{1+}\,\frac{a_1(x-x_1)}{1+}\,\frac{a_2(x-x_2)}{1+}\cdots\frac{a_{N-1}(x-x_{N-1})}{1}$$

$$C_N(x_i) = y_i \qquad \forall x_i \in \mathrm{D}$$

Schlessinger, PR 167 (1968)

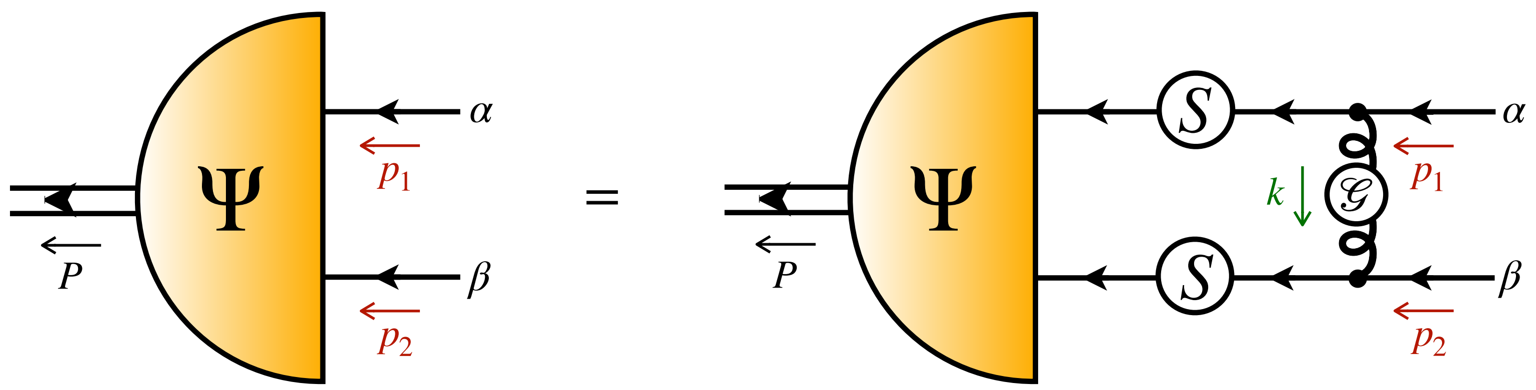






π/K PDFs

BETHE-SALPETER EQUATION



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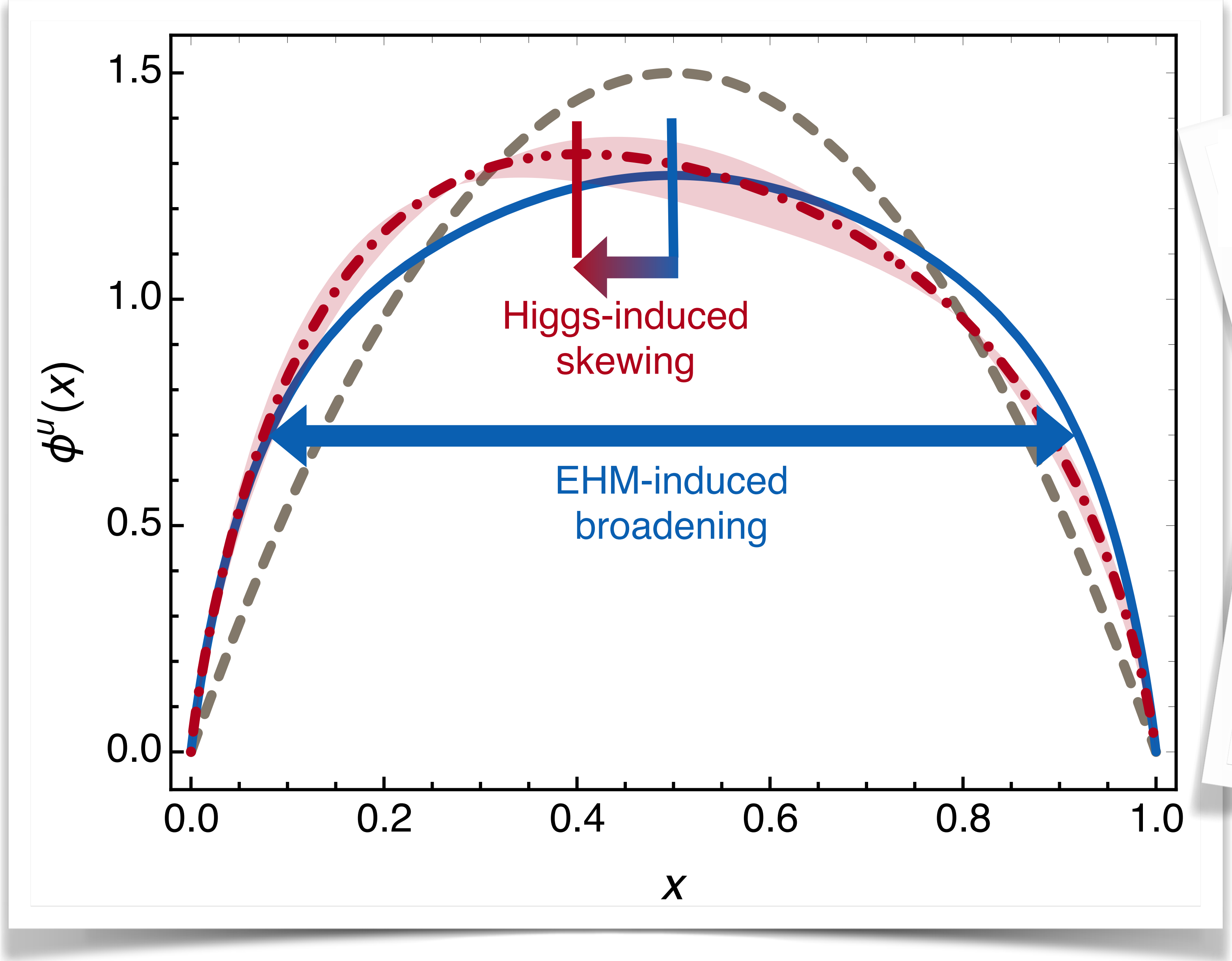
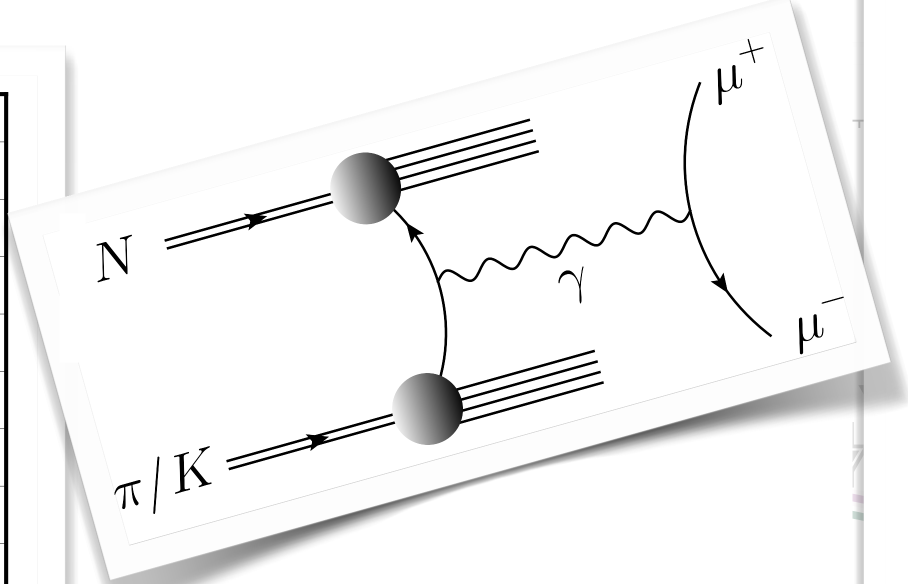
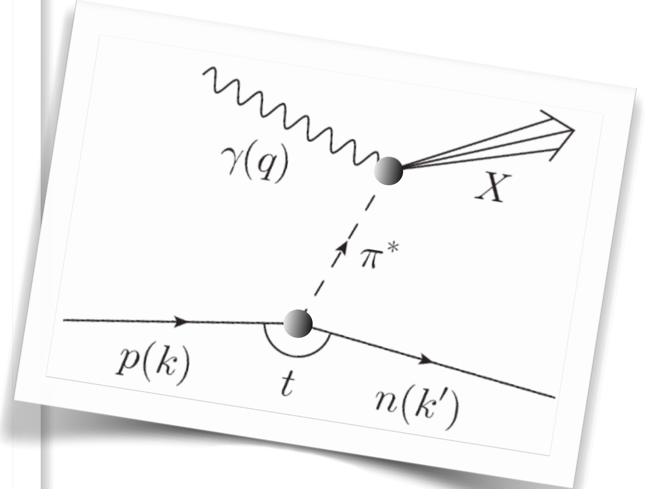
TRIANGULA

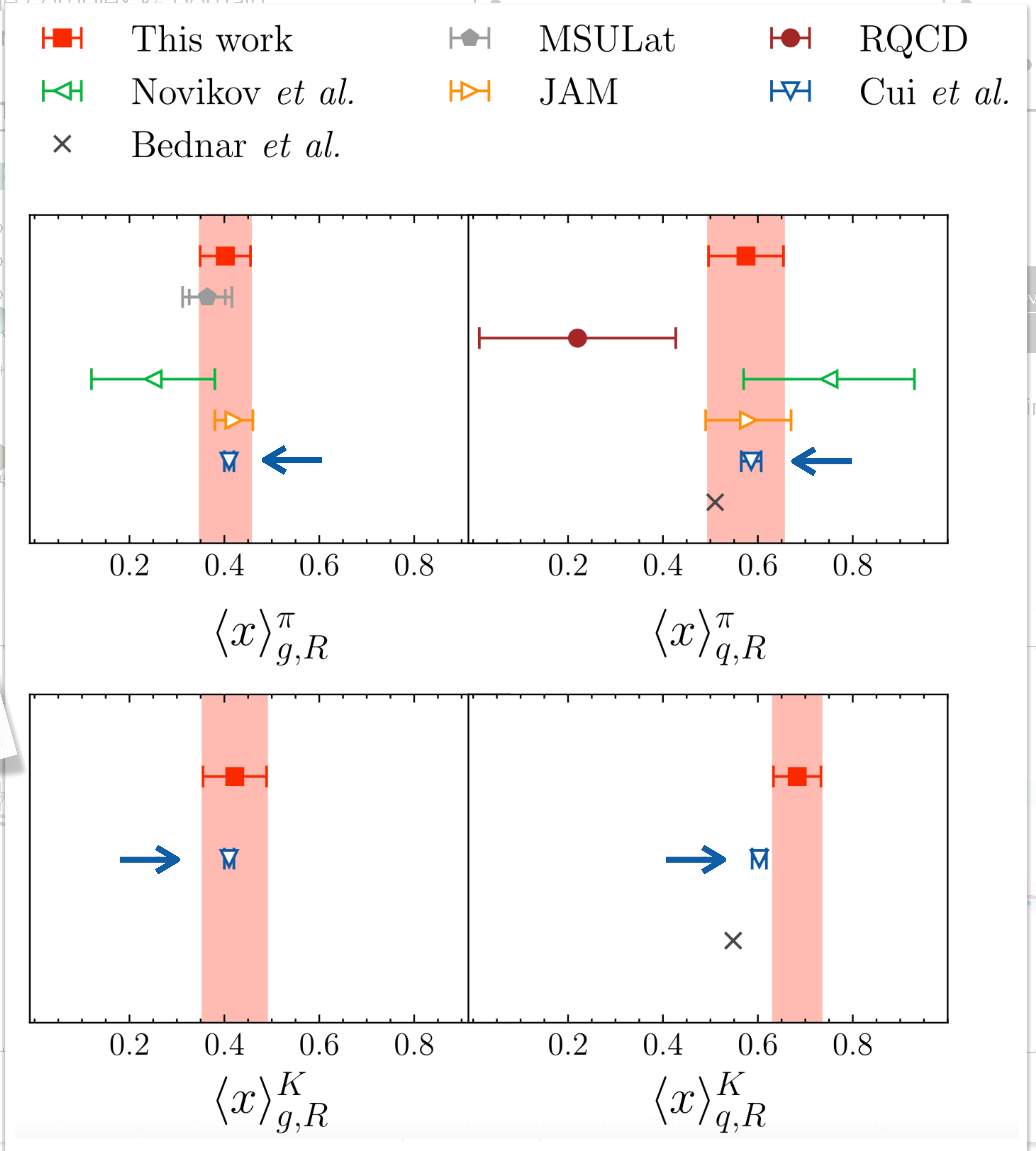
without

inger, PR 167 (1968)







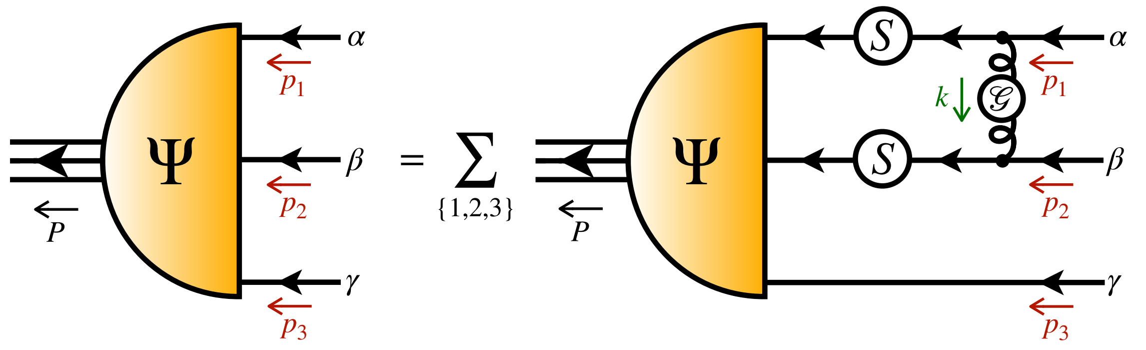


Alexandrou et al., PRL 134 (2025)

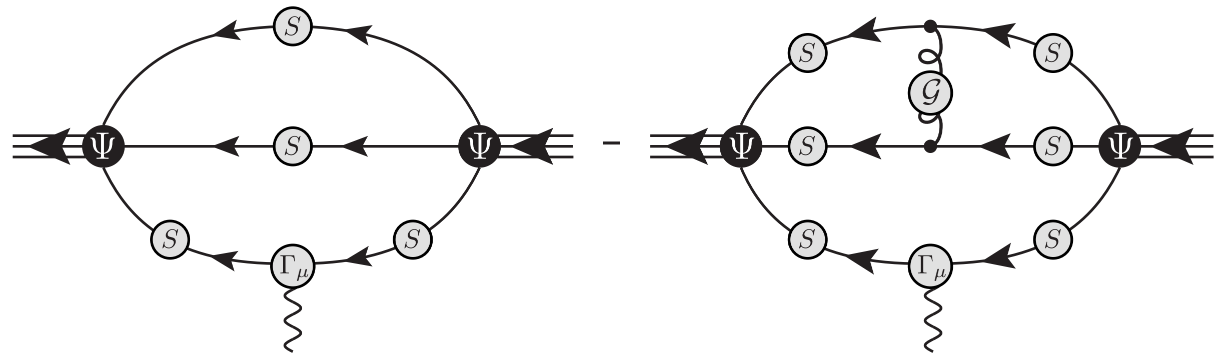
p/n ELECTROMAGNETIC FORM FACTORS

Yao, DB, Cui, Roberts, 2403.08088 (FR in press)

FADDEEV EQUATION



TRIANGULAR DIAGRAM



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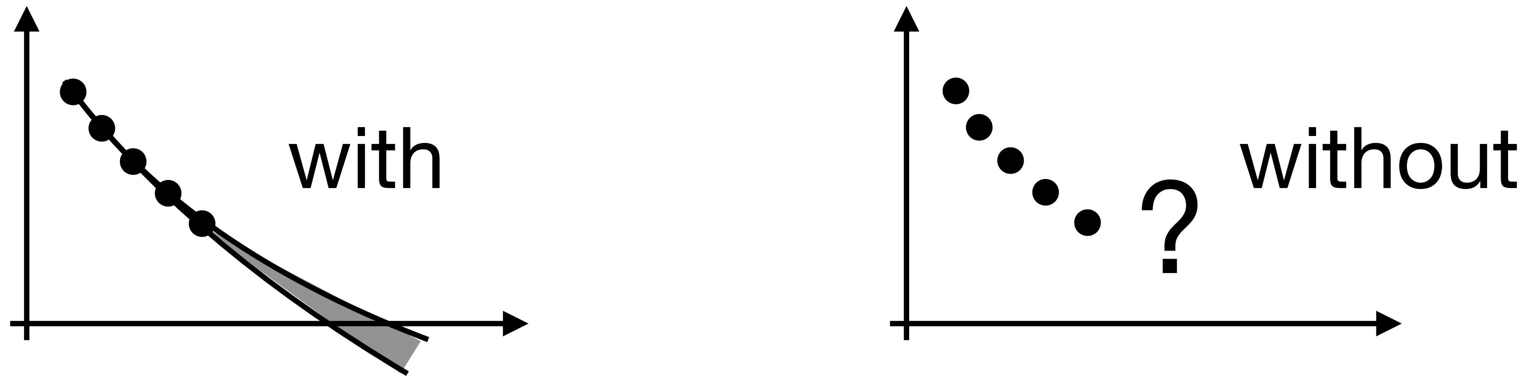
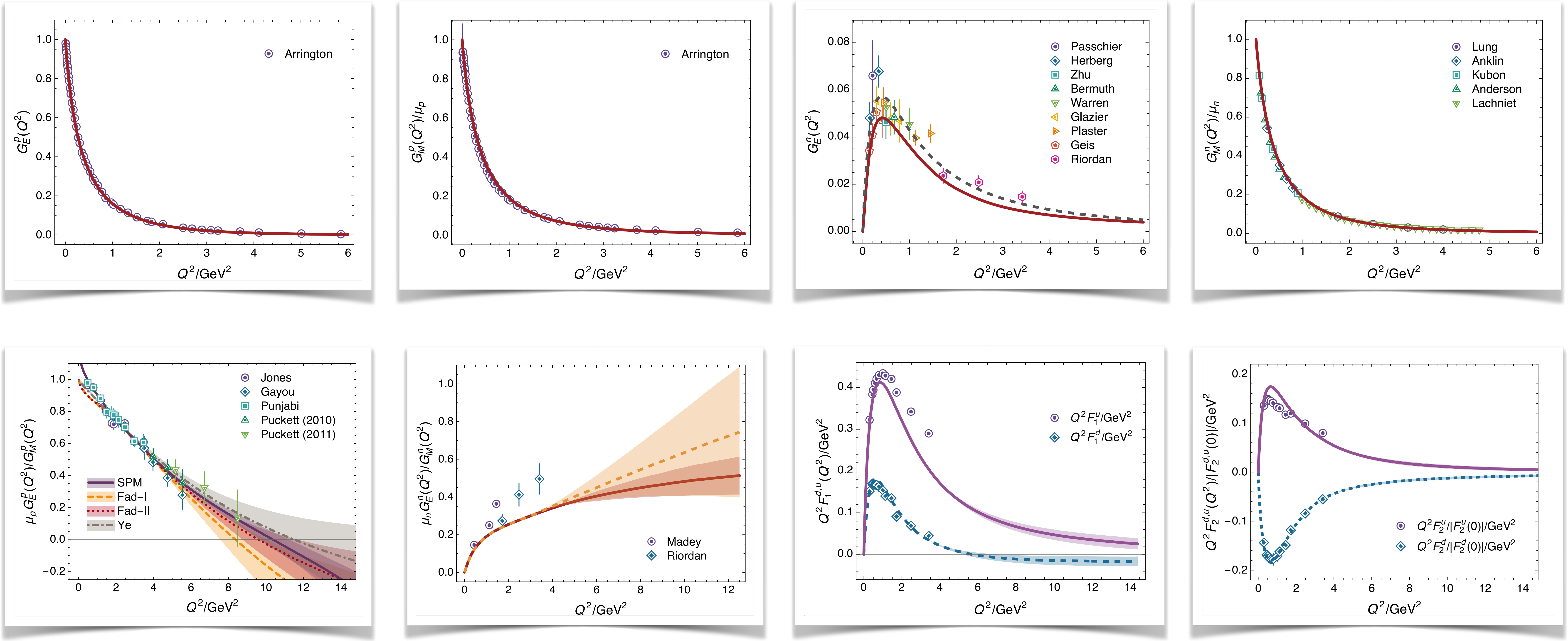
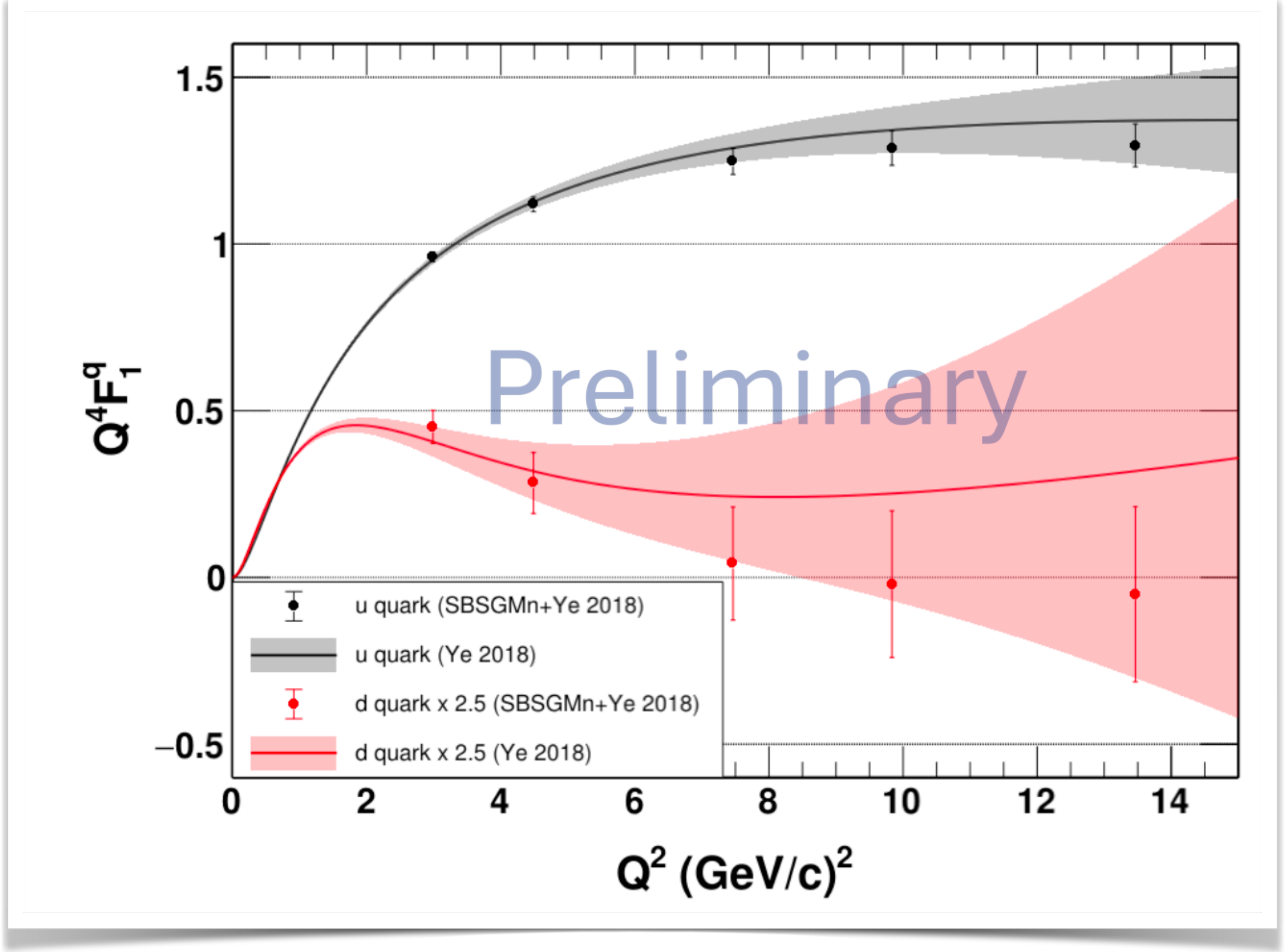






Jefferson Lab
Exploring the Nature of Matter

SUPER BIGBITE SPECTROMETER

Zero-crossing of F_1^d (linear fit to data)

$$Q^2 = 9.8 \pm 1.8\ \mathrm{GeV}^2$$

EHM prediction

$$Q^2 = 5.7^{+1.5}_{-0.5}\ \mathrm{GeV}^2$$

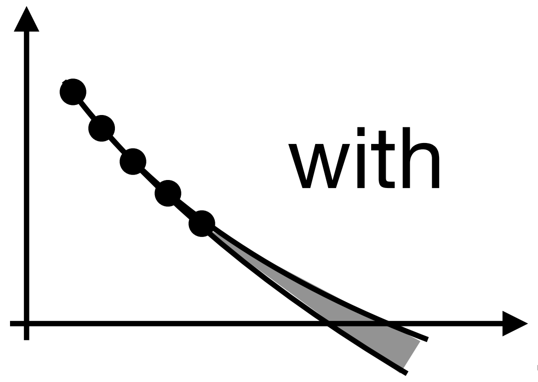
experiment is only 1.4σ away from our prediction!

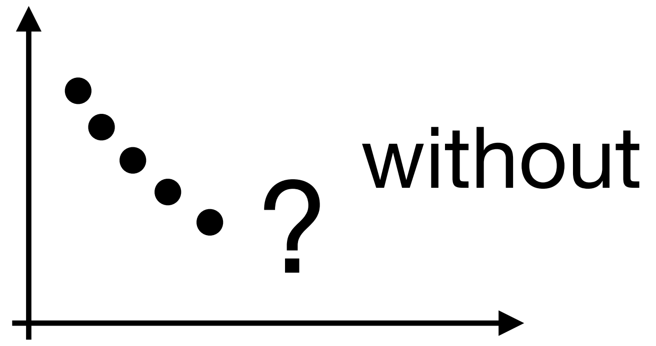
p/n GRAVITATIONAL FORM FACTORS

Yao et al, EPJA 61 (2025)

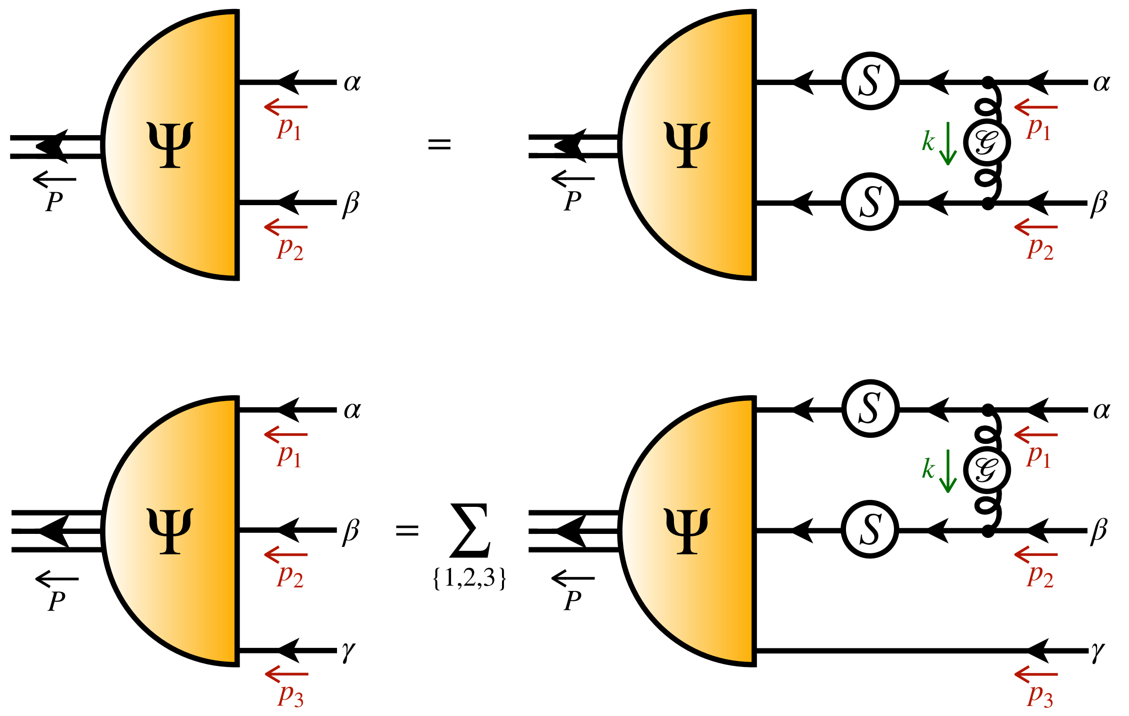
$A(0)=1$
$J(0)=½$

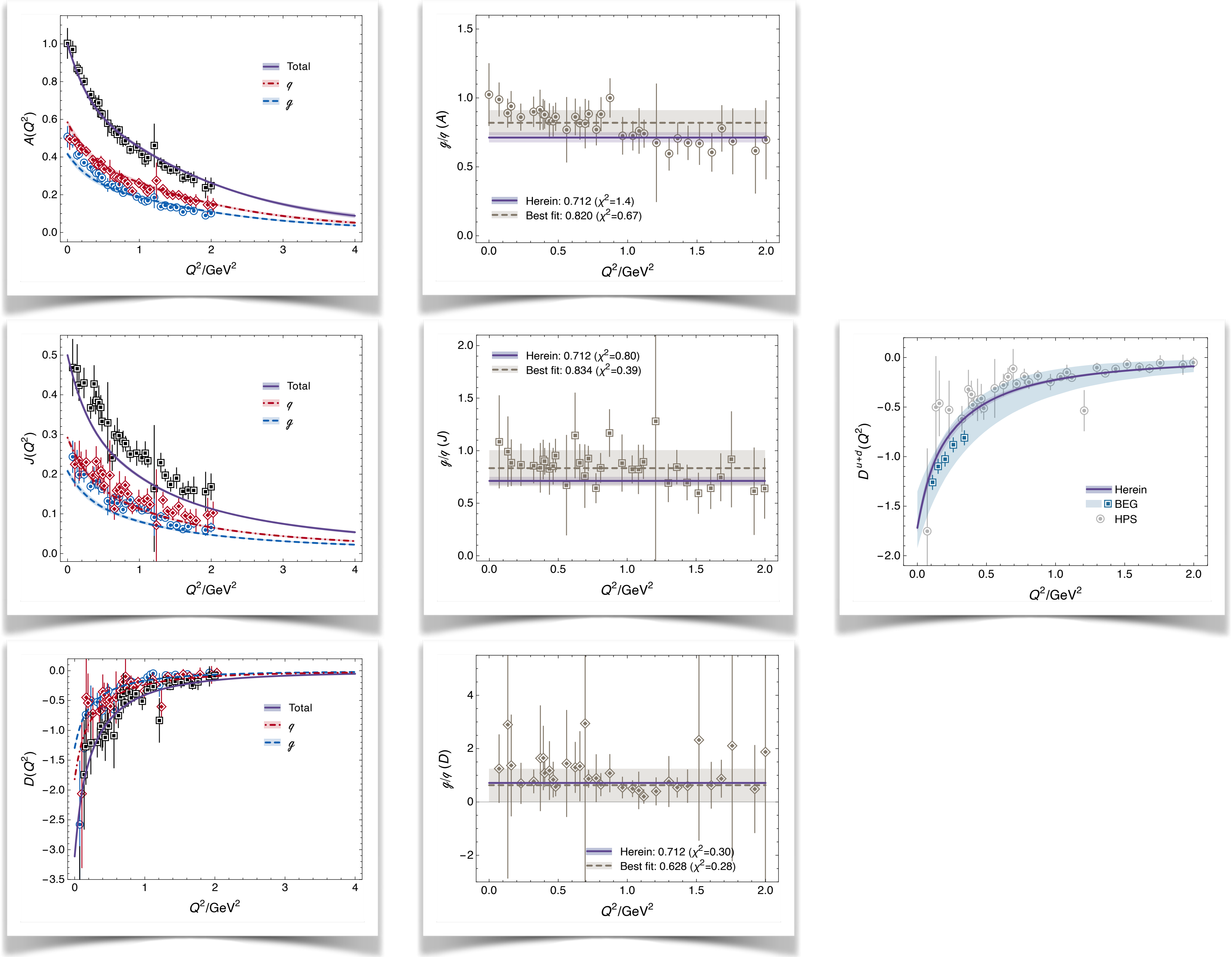
$D(0)=?$ …the last unknown property of the nucleon…





BETHE-SALPETER + FADDEEV EQUATIONS





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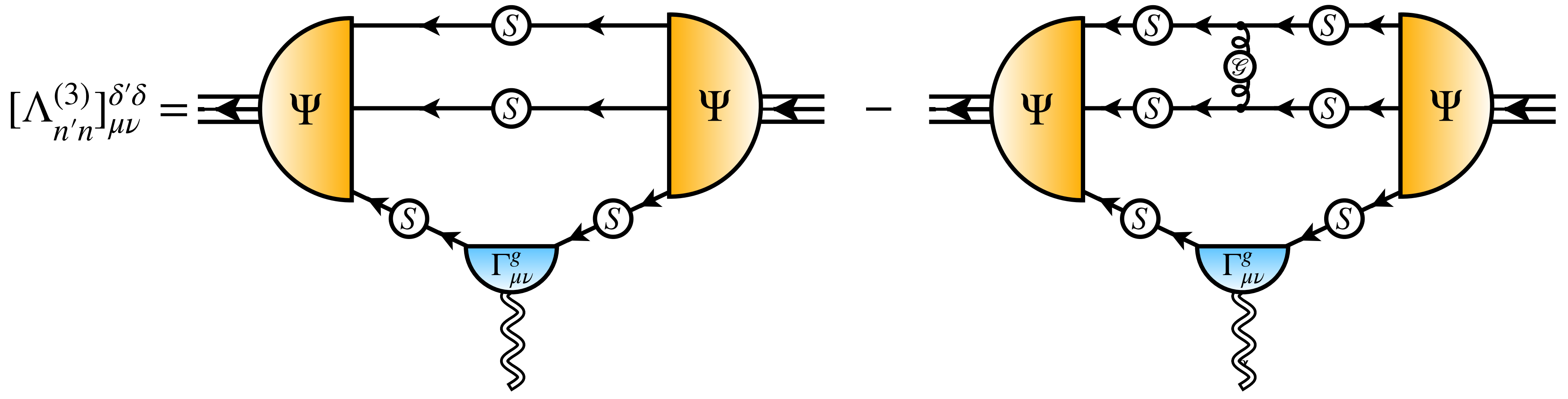

$$m_N \Lambda^{Ng}_{\mu\nu}(Q) = -\Lambda_+(p_f)[K_\mu K_\nu A(Q^2) + iK_{\{\mu}\sigma_{\nu\}\rho} Q_\rho J(Q^2) + \tfrac{1}{4}(Q_\mu Q_\nu - \delta_{\mu\nu}Q^2)D(Q^2)]\Lambda_+(p_i)$$

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$$C_N(x_i) = y_i \qquad \forall x_i \in \mathrm{D}$$

Schlessinger, PR 167 (1968)

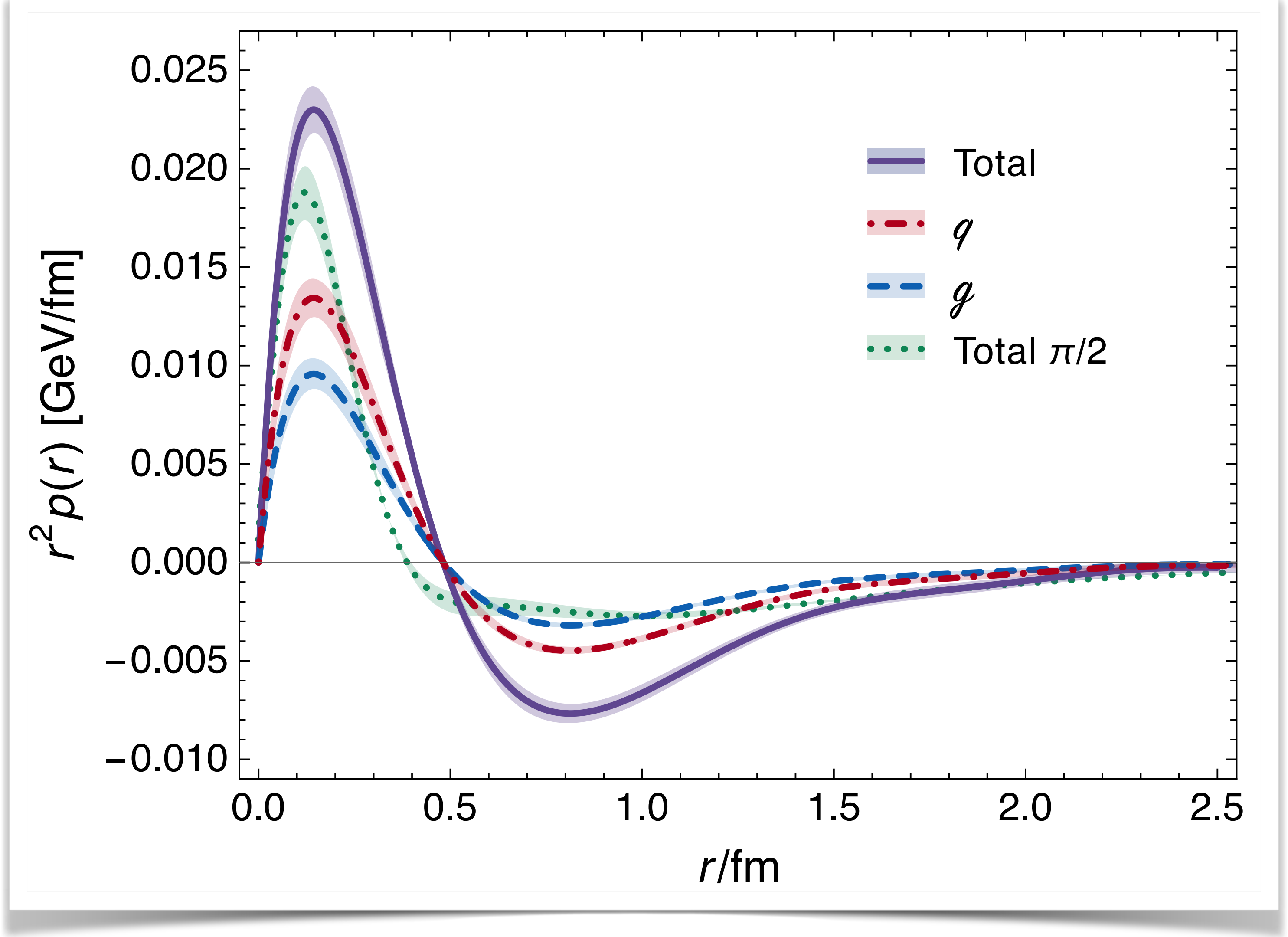
EHM predictions

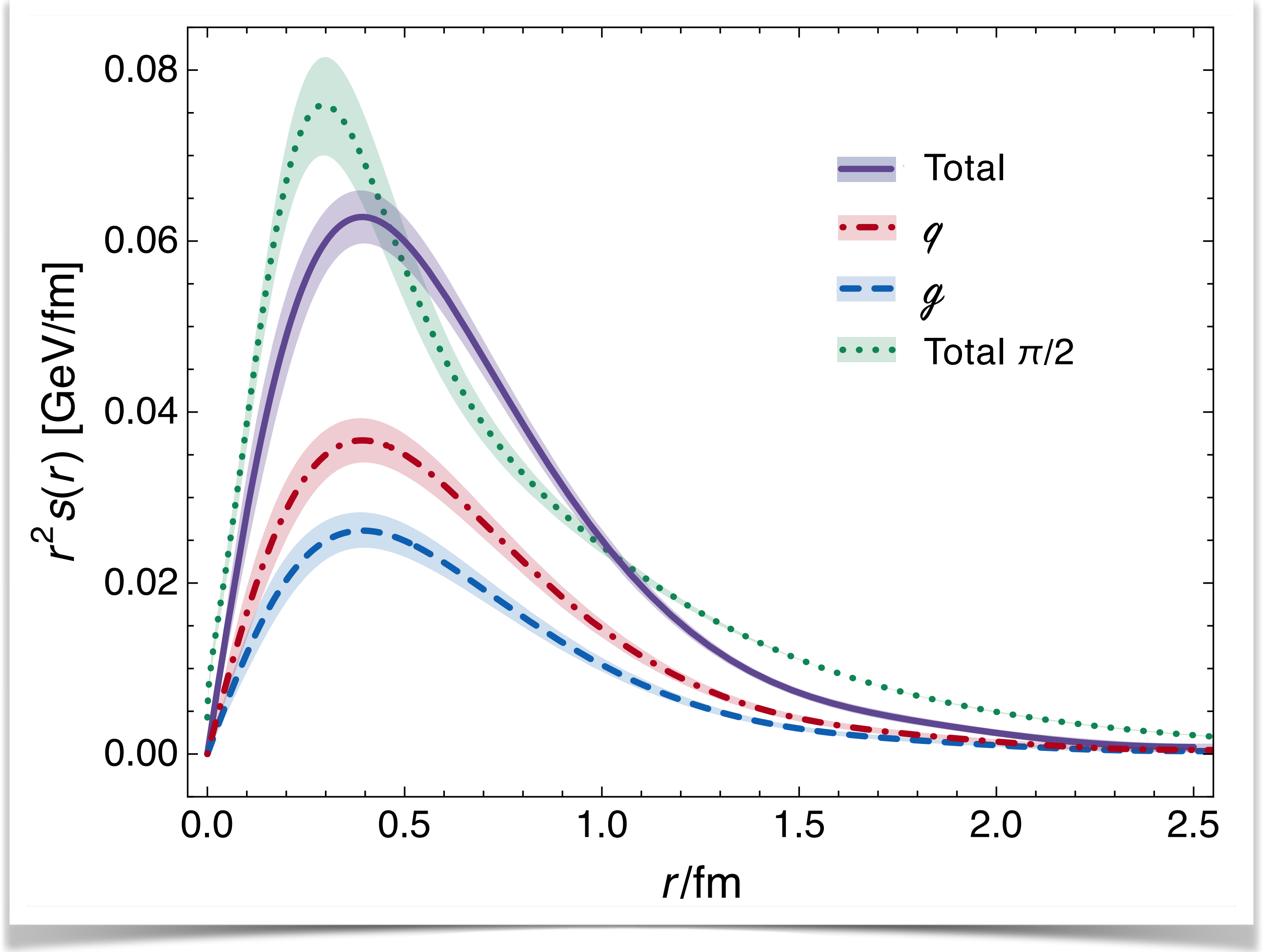
$D(0)$=-3.11(1)

$r_{\text{ch}} > r_{\text{mass}} > r_{\text{mech}}$

$r_{\text{mass}} = 0.81(5) r_{\text{ch}}$ $\quad r^{q,\zeta_2}_{\text{mass}} = 0.62(4) r_{\text{ch}}$ $\quad r^{g,\zeta_2}_{\text{mass}} = 0.52(3) r_{\text{ch}}$

$r_{\text{mech}} = 0.72(2) r_{\text{ch}}$ $\quad r^{q,\zeta_2}_{\text{mech}} = 0.55(2) r_{\text{ch}}$ $\quad r^{g,\zeta_2}_{\text{mech}} = 0.47(2) r_{\text{ch}}$





THANK YOU