KEK Inter-University Research Institute Corporation
High Energy Accelerator Research Organization

Workshops on the Proton Mass

at

Temple University and ECT*

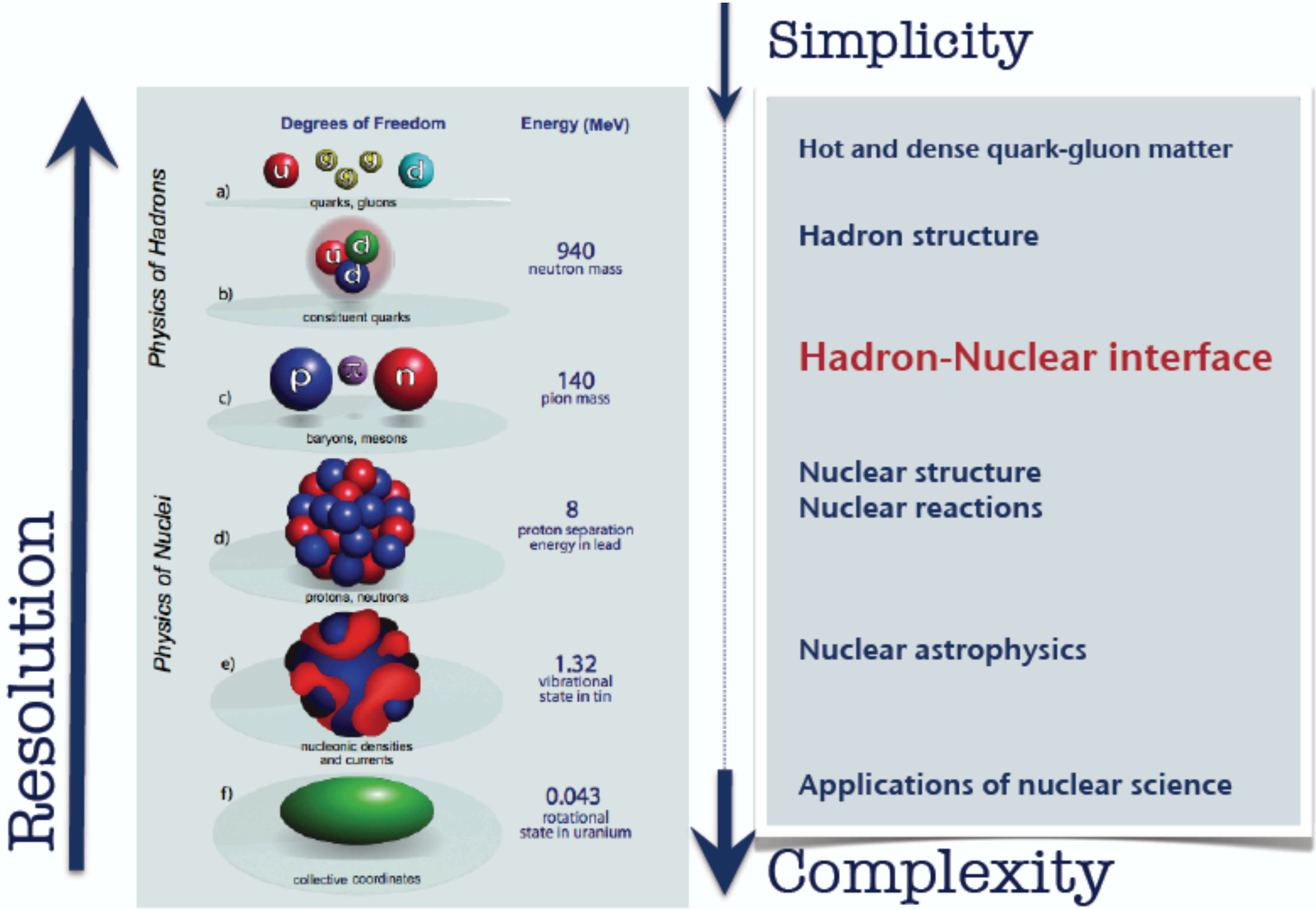
(A brief summary)

Jianwei Qiu
Theory Center, Jefferson Lab

Informal discussion on physics issues concerning the origin of hadron mass
September 1, 2017, KEK, Japan

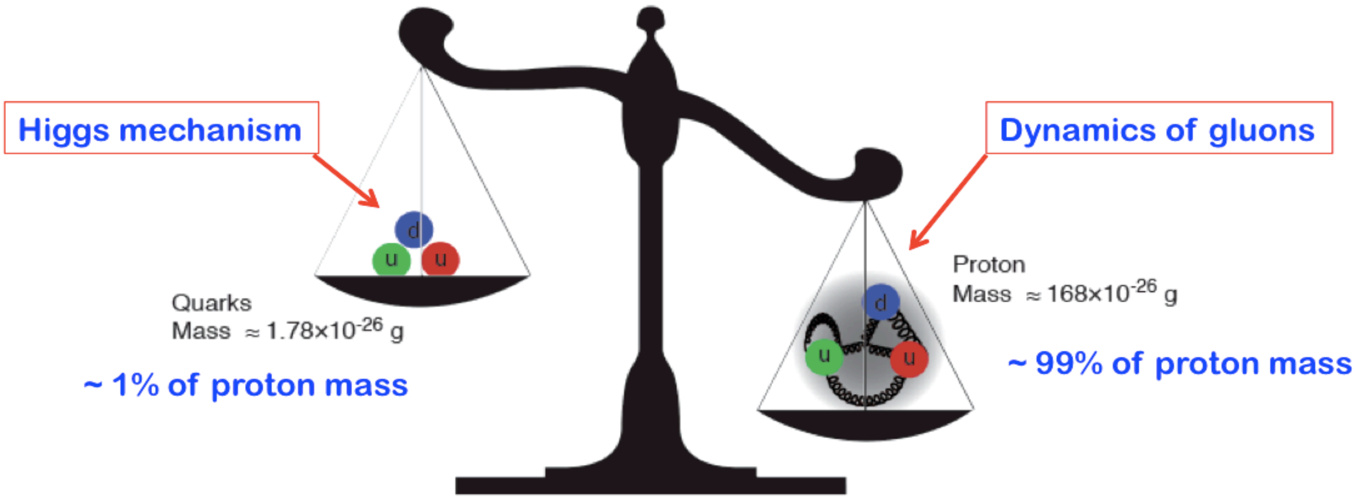
Theory Center
Jefferson Lab
EXPLORING THE NATURE OF MATTER

Scales in strong interactions



The proton mass?

- ❑ **Nucleon mass – dominates the mass of visible world:**



Higgs mechanism is not enough!!! *"Mass without mass!"*

- ❑ **How does QCD generate the nucleon mass?**

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

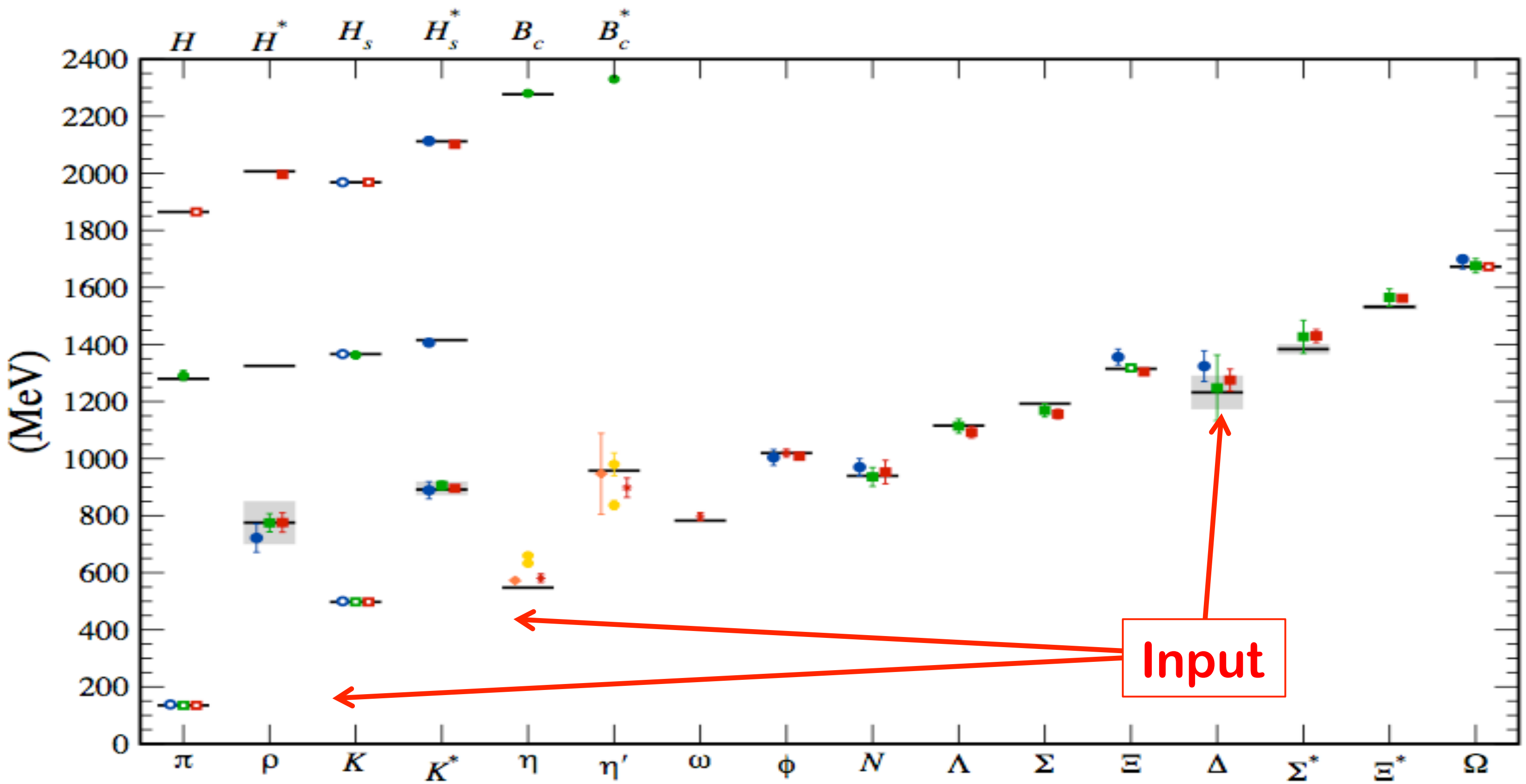
REACHING FOR THE HORIZON

The 2015 Long Range Plan for Nuclear Science

How to quantify and verify this, theoretically and experimentally?

The proton mass?

- Hadron mass from Lattice QCD calculation:



How does QCD generate this? The role of quarks vs that of gluons?

If we do not understand proton mass, we do not understand QCD

How to answer the "big" questions?

❑ **Three-pronged approach to explore the origin of hadron mass**

- ✧ **Lattice QCD**
- ✧ **Mass decomposition – roles of the constituents**
- ✧ **Model calculation – approximated analytical approach**

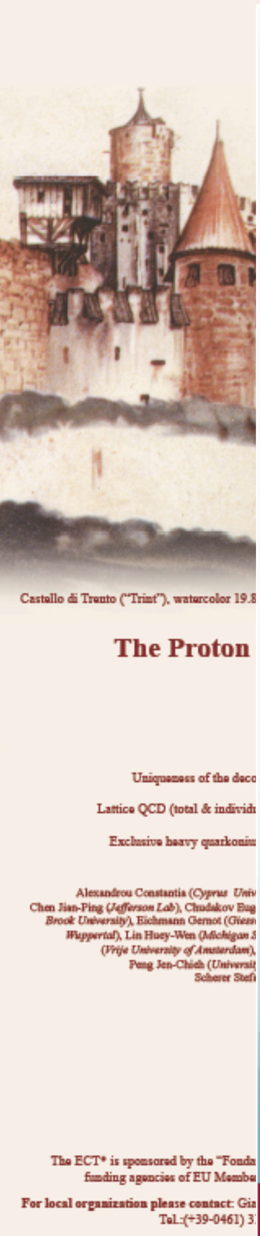
https://phys.cst.temple.edu/meziani/proton-mass-workshop-2016/

How to answer the "big" questions?

- **Three-pronged approach to explore the origin of hadron mass**
  - ✧ **Lattice QCD**
  - ✧ **Mass decomposition – roles of the constituents**
  - ✧ **Model calculation – approximated analytical approach**

http://www.ectstar.eu/node/2218

Theory and Experimental Summaries

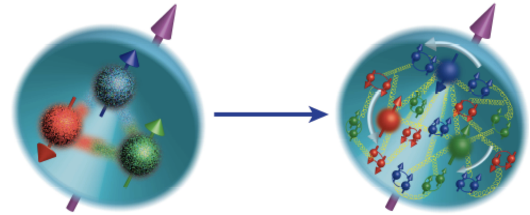


Proton Mass Workshop: Experimental Summary

Z.-E. Meziani

Temple University

The proton mass: from models to QCD

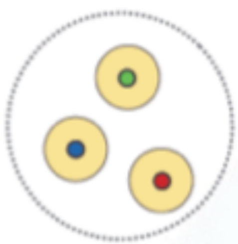


- **Dynamical scale:**
  - ✧ Asymptotic freedom ⟷ confinement:
  - ➡ A dynamical scale, Λ_{QCD}, consistent with $\frac{1}{R} \sim 200$ MeV

- **Bag model:**

  - ✧ Kinetic energy of three quarks: $K_q \sim 3/R$
  - ✧ Bag energy (bag constant B): $T_b = \frac{4}{3}\pi R^3\, B$
  - ✧ Minimize $K_q + T_b$: $M_p \sim \frac{4}{R} \sim \frac{4}{0.88 fm} \sim 912\text{MeV}$

- **Constituent quark model:**

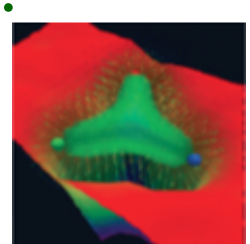


  - ✧ Spontaneous chiral symmetry breaking:

    Massless quarks gain ~300 MeV mass when traveling in vacuum

    ➡ $M_p \sim 3\, m_q^{\text{eff}} \sim 900$ MeV

- **Lattice QCD:**



  - ✧ With "heavy" (or slow moving) quarks

    Energy concentrated in the gluon junction!

    ➡ Gluon radius < Charge Radius   EIC!

    Mass scale: Lattice space – "a"

Scales in QCD

C. Roberts

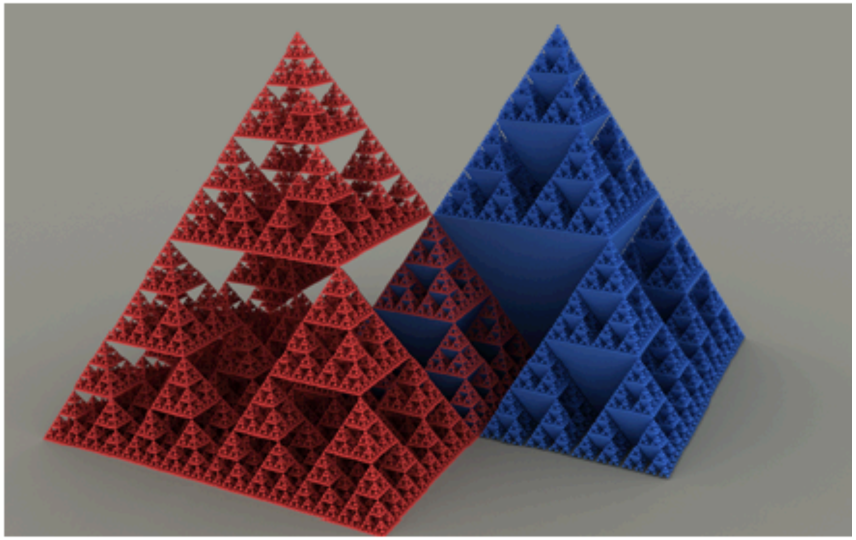
$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i (\gamma^\mu D_\mu)_{ij} - m\, \delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- Only apparent scale in chromodynamics is mass of the quark field
- In connection with everyday matter, that mass is 1/250th of the natural (empirical) scale for strong interactions,
  viz. more-than two orders-of-magnitude smaller
- Quark mass is said to be generated by Higgs boson.
- Plainly, however, that mass is very far removed from the natural scale for strongly-interacting matter
- *Nuclear physics mass-scale* – 1 GeV – is an *emergent feature of the Standard Model* **its absolute value is NOT explained by the Standard Model**
  - No amount of staring at L_{QCD} can reveal that scale
- Contrast with quantum electrodynamics, *e.g*. spectrum of hydrogen levels measured in units of m_e, which appears in L_{QED}

Scale invariance of QCD (classical)

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

in absence of quark masses



- Theory is invariant under scale transformation $x \to e^\lambda x$

- Noether current dilatation current: $s^\mu = T^{\mu\nu} x_\nu$

  ↑ energy momentum tensor

- scale invariant theory: dilatation current is conserved

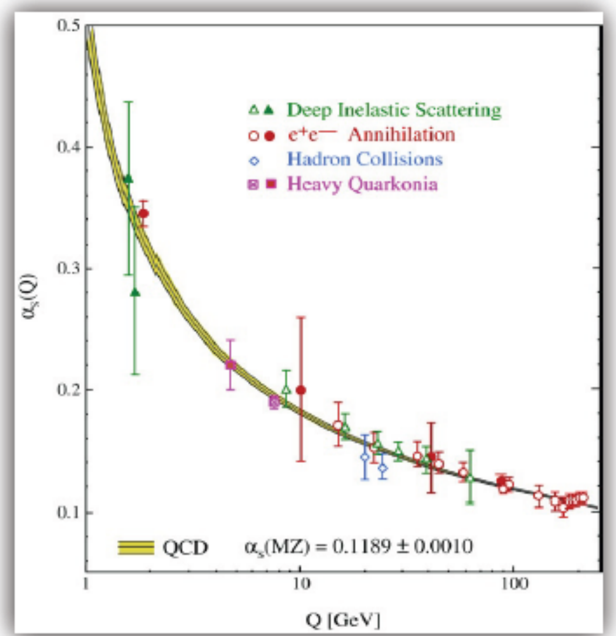
$$0 = \partial_\mu s^\mu = T^\mu_\mu$$

Scale-invariant classical theory: energy-momentum tensor is traceless

Trace anomaly – a quantum scale in QCD

- Quantum loop corrections:
  running coupling -> dimensional transmutation

$$\beta(g) = -b\frac{g^3}{16\pi^2} + \ldots, \quad b = 11 - \frac{2}{3}N_f$$



- **Quantum (loop) effects lead to a non-zero trace of energy-momentum tensor**

$$T^\mu_\mu = \frac{\beta(g)}{2g} G^a_{\alpha\beta} G^{a\alpha\beta} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l \bar{q}_l + \sum_{h=c,b,t} m_h (1+\gamma_{m_h}) \bar{Q}_h \bar{Q}_h$$

- at low energies: heavy quarks decouple

$$\sum_{h=c,b,t} m_h \bar{Q}_h \bar{Q}_h \rightarrow -\frac{2}{3} N_h \frac{g^2}{32\pi^2} G^a_{\alpha\beta} G^{a\alpha\beta} + \ldots$$

$$T^\mu_\mu = \frac{\tilde{\beta}(g)}{2g} G^a_{\alpha\beta} G^{a\alpha\beta} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l \bar{q}_l$$

Mass of hadrons

- $\langle P|T^{\mu\nu}|P\rangle = 2P^\mu P^\nu$

$$2M^2 = \langle P|\frac{\tilde{\beta}(g)}{2g}G^a_{\alpha\beta}G^{a\alpha\beta}|P\rangle + \langle P|\sum_{l=u,d,s} m_l(1+\gamma_{m_l})\bar{q}_l\bar{q}_l|P\rangle$$

In chiral limit all of hadron mass is due to the trace anomaly

Quark contributions to hadron mass: sigma-terms σ_{ud}, σ_s

Lattice QCD, dispersion relations, ChPT

- For pion: zero mass in chiral limit implies cancellation between different components: dynamical chiral symmetry breaking — C. Roberts

- Physics pictures (non-perturbative models) how hadron masses can be understood:
Shed light on the non-trivial nature of bound state in QCD / confinement
effective degrees of freedom at hadronic scale / relevant symmetries, breaking patterns
  - relativistic bound states — P. Hoyer
  - Holographic QCD — S. Brodsky, G. de Teramond
  - Dyson-Schwinger Eq. — D. Binosi, I. Cloët, J. Papavassiliou, C. Roberts
  - Rest frame decompositions (e.g bag, soliton,...models) — X. Ji
  - Partonic interpretations — C. Lorcé, L. Mantovani, M. Burkardt
  - Instanton liquid — P. Faccioli

Light quarks and confinement

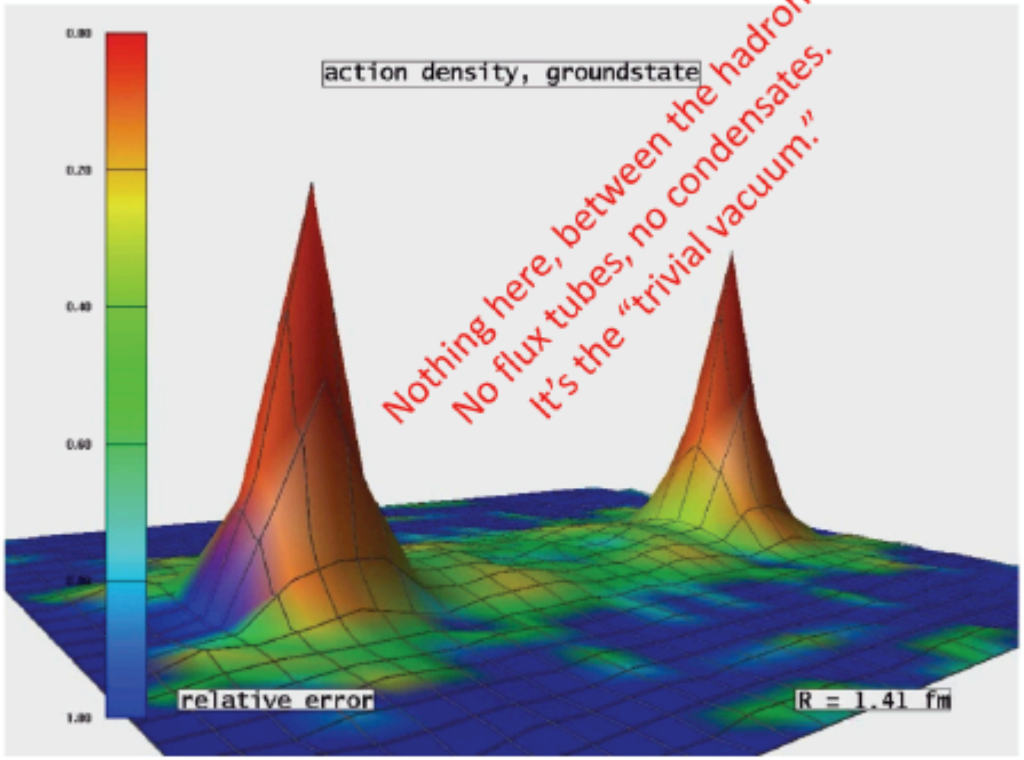
Understanding the origin and absence of mass in QCD likely inseparable from understanding of confinement

C. Roberts

- In the presence of light quarks, *pair creation seems to occur non-localized and instantaneously*
- No flux tube in a theory with light-quarks.
- ***Flux-tube is not the correct paradigm for confinement in hadron physics***

Confinement contains condensates
Brodsky, Roberts, Shrock, Tandy
arXiv:1202.2376 [nucl-th], Phys. Rev. C85 (2012) 065202

G. Bali et al., *PoS LAT2005 (2006) 308*



Dyson-Schwinger (I)

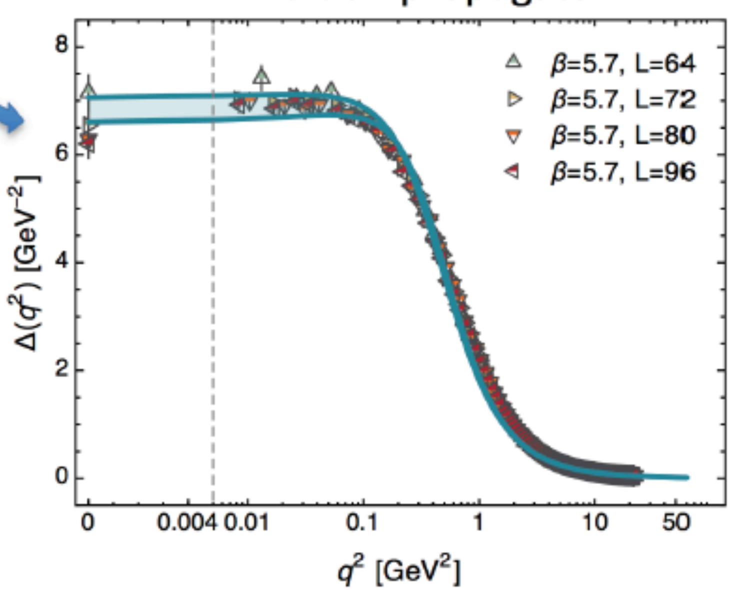
D. Binosi, I. Cloët, J. Papavassiliou, C. Roberts

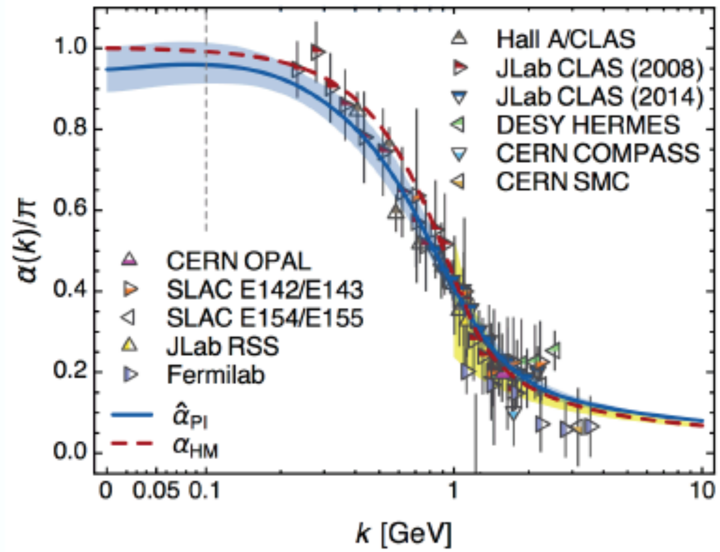
dynamical confinement:
massless gauge bosons acquire a mass
(IR cut-off in QCD)

QCD effective charge:
Coupling possesses IR fixed point

$\Delta(0)$ "sets the scale"

Gluon propagator





- **Equivalence in the perturbative domain**
  reasonable definitions of the charge

$$\alpha_{g_1}(k^2) = \alpha_{\overline{\rm MS}}(k^2)[1 + 1.14\alpha_{\overline{\rm MS}}(k^2) + \cdots]$$
$$\widehat{\alpha}_{PI}(k^2) = \alpha_{\overline{\rm MS}}(k^2)[1 + 1.09\alpha_{\overline{\rm MS}}(k^2) + \cdots]$$

- **Equivalence in the non-perturbative domain**
  highly non-trivial (ghost-gluon interactions)

- **Agreement with light-front holography**
  model for α_{g_1}

Dyson-Schwinger (II)

D. Binosi, I. Cloët, J. Papavassiliou, C. Roberts

pion exists if and only if mass is dynamically generated

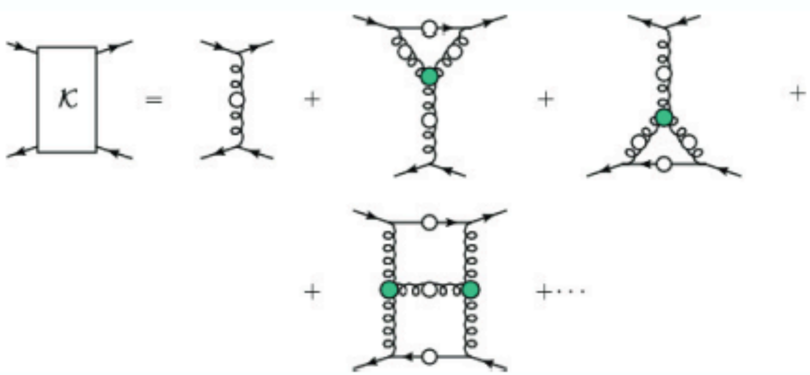
Dressed-quark propagator $S(p) = \frac{1}{i\gamma \cdot p\, A(p^2) + B(p^2)}$

Axial-vector Ward-Takahashi identity entails

$$f_\pi E_\pi(k; P = 0) = B(k^2)$$

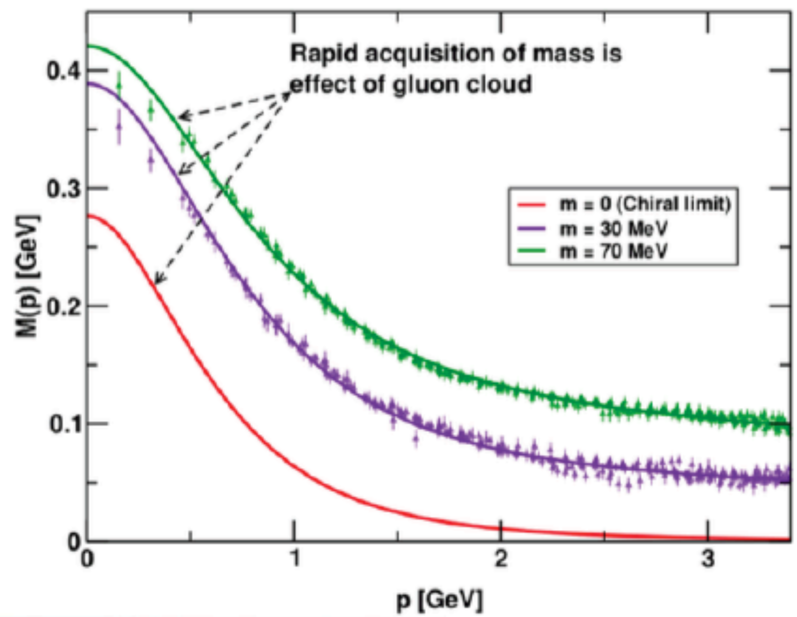
PS Bethe-Salpeter amplitude

in pseudo scalar channel:
the dynamically generated mass of the two fermions is precisely cancelled by the attractive interactions between them



dynamical chiral symmetry breaking (quark-gluon dynamics):
origin of mass

[M. S. Bhagwat *et al.*, Phys. Rev. **C 68**, 015203 (2003)]



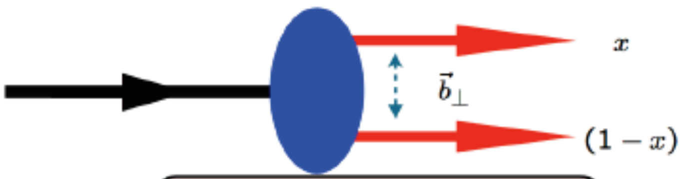
Holographic QCD

S.J. Brodsky, G. de Teramond

Light-Front QCD

$\mathcal{L}_{QCD} \rightarrow H^{LF}_{QCD}$

Fixed $\tau = t + z/c$



$$\zeta^2 = x(1-x)b^2_\perp$$

$$(H^0_{LF} + H^I_{LF})|\Psi> = M^2|\Psi>$$

Coupled Fock states

Eliminate higher Fock states and retarded interactions

$$\left[\frac{\vec{k}^2_\perp + m^2}{x(1-x)} + V^{LF}_{\rm eff}\right] \psi_{LF}(x, \vec{k}_\perp) = M^2 \ \psi_{LF}(x, \vec{k}_\perp)$$

Effective two-particle equation

$$\left[-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = M^2\psi(\zeta)$$

Azimuthal Basis ζ, ϕ

$m_q = 0$

Single variable ζ

AdS/QCD:

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L + S - 1)$$

Confining AdS/QCD potential!

Semiclassical first approximation to QCD

Sums an infinite # diagrams

Holographic QCD

S.J. Brodsky, G. de Teramond

Massless pion!

Meson Spectrum in Soft Wall Model

$$m_\pi = 0 \text{ if } m_q = 0$$

Pion: Negative term for J=0 cancels positive terms from LFKE and potential

- Effective potential: $U(\zeta^2) = \kappa^4\zeta^2 + 2\kappa^2(J-1)$
- LF WE

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4\zeta^2 + 2\kappa^2(J-1)\right)\phi_J(\zeta) = M^2\phi_J(\zeta)$$

- Normalized eigenfunctions $\langle\phi|\phi\rangle = \int d\zeta\, \phi^2(z)^2 = 1$

$$\phi_{n,L}(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{1/2+L}e^{-\kappa^2\zeta^2/2}L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2\left(n + \frac{J+L}{2}\right)$$

Holographic QCD

S.J. Brodsky, G. de Teramond

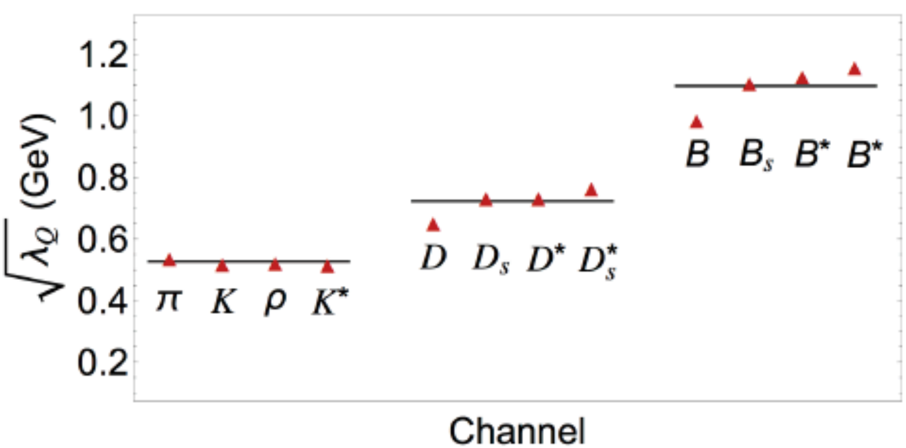
supersymmetric and superconformal constraints on meson and baryon masses

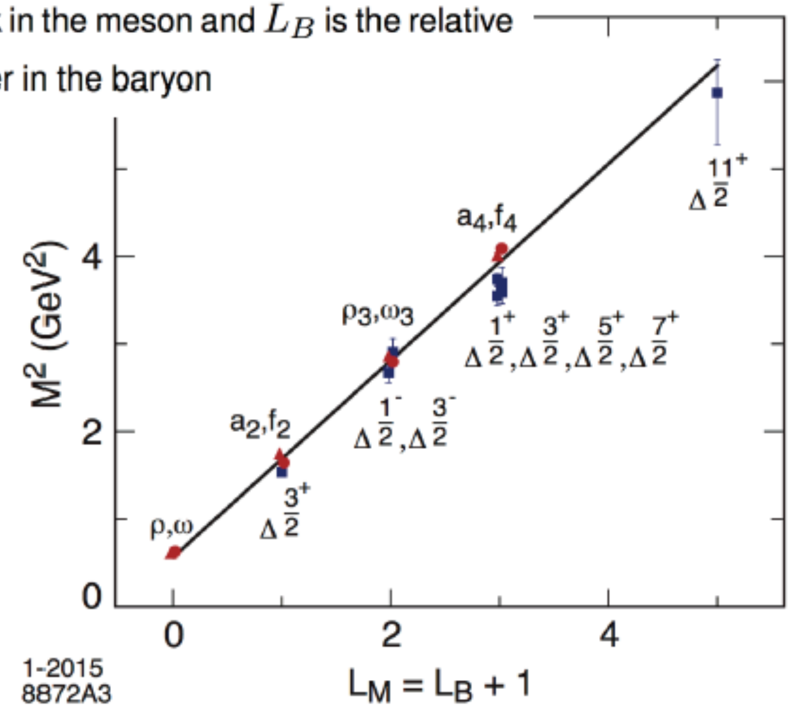
$$\left(-\frac{d^2}{d\zeta^2}+\frac{4L_M^2-1}{4\zeta^2}+\lambda_M^2\zeta^2+2\lambda_M(L_M-1)\right)\phi_{Meson}=M^2\phi_{Meson}$$

$$\left(-\frac{d^2}{d\zeta^2}+\frac{4L_N^2-1}{4\zeta^2}+\lambda_B^2\zeta^2+2\lambda_B(L_N+1)\right)\phi_{Baryon}=M^2\phi_{Baryon}$$

Superconformal QM imposes the condition $\lambda=\lambda_M=\lambda_B$ (equality of Regge slopes) and the remarkable relation $\Rightarrow$ $L_M=L_B+1$

L_M is the LF angular momentum between the quark and antiquark in the meson and L_B is the relative angular momentum between the active quark and spectator cluster in the baryon





Proton mass decompositions

"Hey Einstein, how about converting some of your mass into energy and getting this place cleaned up?"

Proton mass decompositions

❑ Sum rules for Proton Mass:

X. Ji, J.W. Qiu

Sum rules are only useful if individual terms can be measured independently

Relativistic motion — Chiral Symmetrybreaking — Quantum fluctuation

$$M_p = \frac{\langle P| \int d^3x\, T^{00} |P\rangle}{\langle P|P\rangle}\Bigg|_{\text{at rest}} = M_q + M_g + M_m + M_a$$

Quark Energy — Gluon Energy — Quark Mass — Trace Anomaly

✧ Hadron state:

$|P\rangle$ **With the normalization:** $\langle P|P\rangle = (E/M)(2\pi)^3\delta^3(\mathbf{0})$

✧ Hamiltonian:

$$H_{\text{QCD}} = \int d^3\vec{x}\, T^{00}(0,\vec{x}) \qquad \langle P|H_{\text{QCD}}|P\rangle = (E^2/M_p)(2\pi)^3\delta^3(0)$$

✧ QCD energy-momentum tensor:

$$T^{\mu\nu} = \overline{T^{\mu\nu}} + \widehat{T^{\mu\nu}} \qquad \langle P|T^{\mu\nu}|P\rangle = P^\mu P^\nu / M_p$$

No $g^{\mu\nu}$ term!

➡ $\langle P|\overline{T}^{\mu\nu}|P\rangle = (P^\mu P^\nu - \frac{1}{4}M_p^2\, g^{\mu\nu})/M_p \qquad \langle P|\widehat{T}^{\mu\nu}|P\rangle = \frac{1}{4}M_p\, g^{\mu\nu}$

➡ $\frac{\langle P| \int d^3x\, \overline{T}^{00} |P\rangle}{\langle P|P\rangle}\Big|_{\text{at rest}} = \frac{3}{4}M_p \qquad \frac{\langle P| \int d^3x\, \widehat{T}^{00} |P\rangle}{\langle P|P\rangle}\Big|_{\text{at rest}} = \frac{1}{4}M_p$

"Traceless" term — *"Trace" term*

Proton mass decompositions

X. Ji, J.W. Qiu

❑ Identities:

$$\frac{\langle P|\int d^3x\, T^\alpha_{\ \alpha}|P\rangle}{\langle P|P\rangle} = 4\,\frac{\langle P|\int d^3x\, \widehat{T}^{00}|P\rangle}{\langle P|P\rangle}\Bigg|_{\text{at rest}} = \frac{4}{3}\,\frac{\langle P|\int d^3x\, \overline{T}^{00}|P\rangle}{\langle P|P\rangle}\Bigg|_{\text{at rest}}$$

❑ Traceless terms:

$$\overline{T}^{\mu\nu} = \overline{T}^{\mu\nu}_q + \overline{T}^{\mu\nu}_g \qquad \bar{T}^{\mu\nu}_q = \frac{1}{2}\bar{\psi} i\overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi - \frac{1}{4}g^{\mu\nu}\bar{\psi}m\psi, \qquad \bar{T}^{\mu\nu}_g = \frac{1}{4}g^{\mu\nu}F^2 - F^{\mu\alpha}F^{\nu}{}_{\alpha}$$

➡ $$\langle P|\overline{T}^{\mu\nu}_q|P\rangle \equiv a(\mu^2)(P^\mu P^\nu - \frac{1}{4}M_p^2\, g^{\mu\nu})/M_p$$

$$\langle P|\overline{T}^{\mu\nu}_g|P\rangle \equiv [1-a(\mu^2)](P^\mu P^\nu - \frac{1}{4}M_p^2\, g^{\mu\nu})/M_P$$

Let $\mu \to + \quad \nu \to +$

➡ $$a(\mu^2) = \sum_f \int_0^1 x[q_f(x,\mu^2) + \overline{q}_f(x,\mu^2)]dx$$

Total momentum fraction carried by the quarks - reasonably known!

$$\frac{\langle P|\int d^3x\, \overline{T}^{00}_q|P\rangle}{\langle P|P\rangle}\Bigg|_{\text{at rest}} = a(\mu^2)\,\frac{3}{4}\,M_p \qquad \frac{\langle P|\int d^3x\, \overline{T}^{00}_g|P\rangle}{\langle P|P\rangle}\Bigg|_{\text{at rest}} = [1-a(\mu^2)]\,\frac{3}{4}\,M_p$$

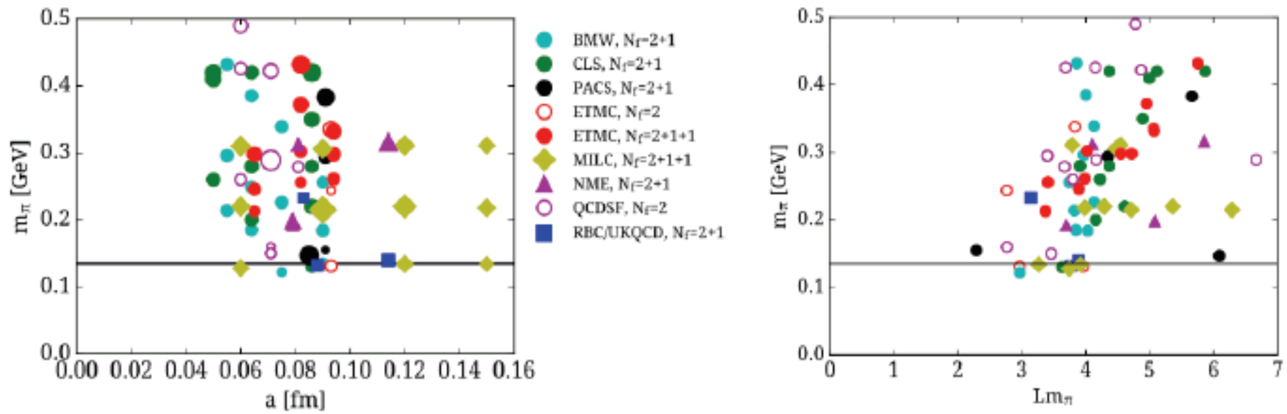
❑ Trace terms:

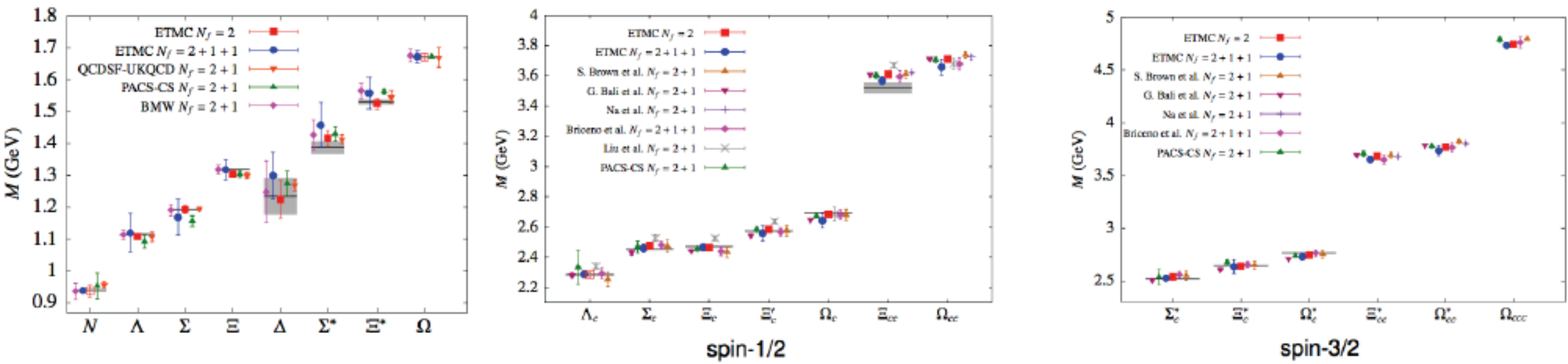
$$\widehat{T}^{\mu\nu} = \widehat{T}^{\mu\nu}_m + \widehat{T}^{\mu\nu}_a$$ ➡ $$\langle P|\widehat{T}^{\mu\nu}_m|P\rangle \equiv b\,\frac{1}{4}M_p\, g^{\mu\nu} \qquad \langle P|\widehat{T}^{\mu\nu}_a|P\rangle \equiv [1-b]\,\frac{1}{4}M_p\, g^{\mu\nu}$$

$$\frac{\langle P|\int d^3x\, \widehat{T}^{00}_m|P\rangle}{\langle P|P\rangle}\Bigg|_{\text{at rest}} = b\,\frac{1}{4}\,M_p \qquad \frac{\langle P|\int d^3x\, \widehat{T}^{00}_a|P\rangle}{\langle P|P\rangle}\Bigg|_{\text{at rest}} = [1-b]\,\frac{1}{4}\,M_p$$

Hadron masses (lattice)

C. Alexandrou, C. Hoelbling, H.W. Lin, K.F. Liu, D. Richards, Y. Yang

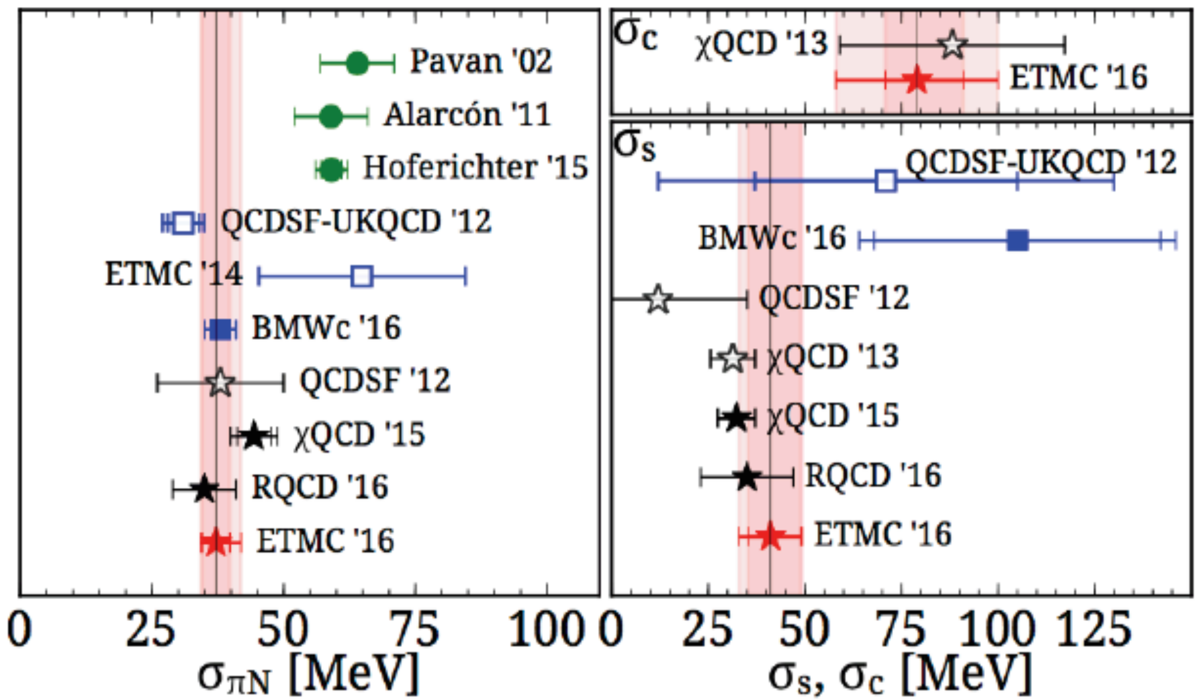




Quark mass contributions (lattice)

C. Alexandrou, C. Hoelbling, H.W. Lin, K.F. Liu, D. Richards, Y. Yang

lattice calculations at physical point (solid symbols)



New preliminary BMW results:

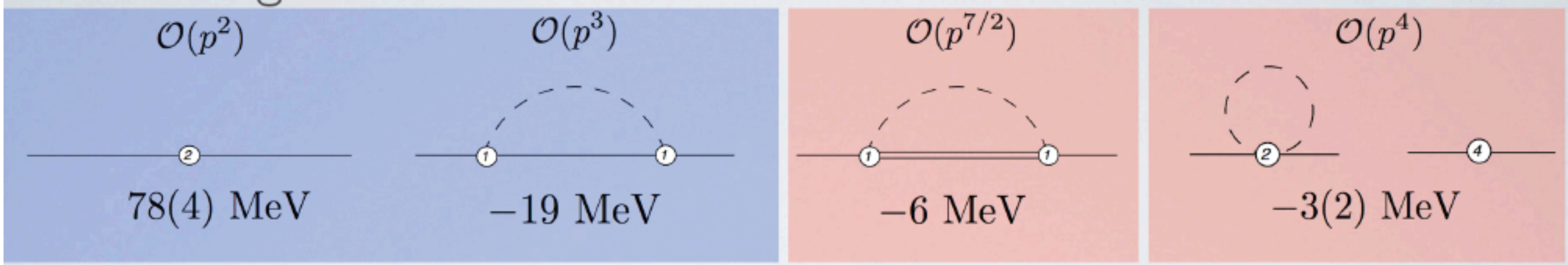
$$M_N|_{m_{ud}=0, m_s \text{ const.}} = 896(13)(5)\text{MeV} \quad \sigma_{ud}^N = 39.5(1.4)(1.8)\text{MeV}$$

$$M_N|_{m_s=0, m_{ud} \text{ const.}} = 881(13)(4)\text{MeV} \quad \sigma_s^N = 55.5(5.5)(4.1)\text{MeV}$$

Pion-nucleon σ-terms: ChPT

J.M. Alarcon

- Convergence



$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}}\ \underbrace{-19}_{\text{NLO}}\ \underbrace{(6)}_{\text{N}^2\text{LO}}\ \text{MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.})\ \text{MeV} = 59(7)\ \text{MeV}$$

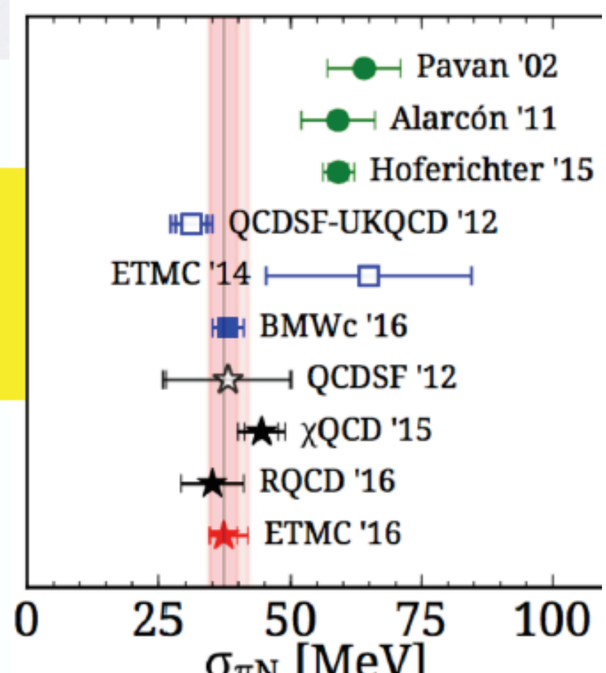
Modern πN scattering data

π-atoms [Baru, et al. NPA 872 (2011)]

$$\sigma_{\pi N} = 59(7)\ \text{MeV}$$

[Alarcón, Martin Camalich and Oller, PRD 85 (2012)]

~ 3 σ tension between recent lattice and ChPT / DR



Pion-nucleon σ-terms: dispersion theory

J.Ruiz de Elvira

$$\sigma_{\pi N} = F_\pi^2 \left(d_{00}^+ + 2M_\pi^2 d_{01}^+ \right) + \Delta_D - \Delta_\sigma - \Delta_R$$

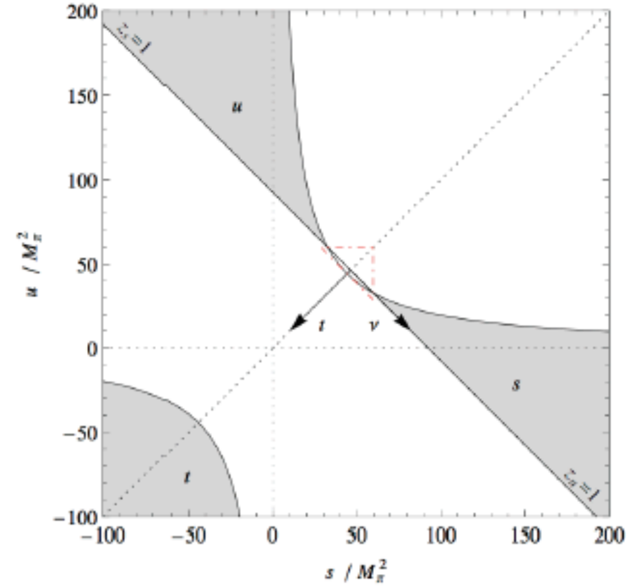
- subthreshold parameters output of the Roy–Steiner equations

$$d_{00}^+ = -1.36(3) M_\pi^{-1} \quad [\text{KH: } -1.46(10) M_\pi^{-1}],$$

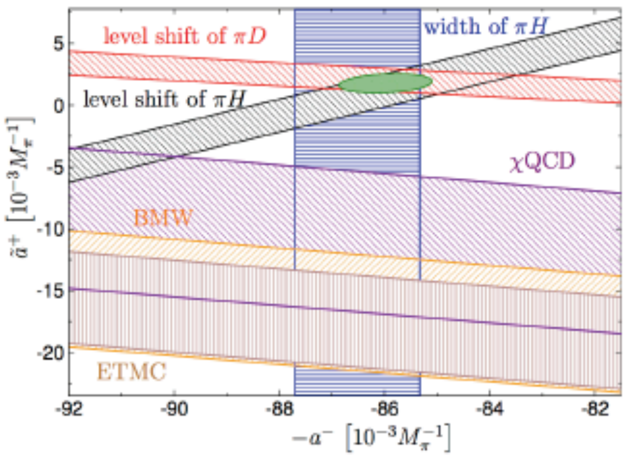
$$d_{01}^+ = 1.16(2) M_\pi^{-3} \quad [\text{KH: } 1.14(2) M_\pi^{-3}]$$

- $|\Delta_R| \lesssim 2$ MeV [Bernard, Kaiser, Meißner 1996]
- $\Delta_D - \Delta_\sigma = -(1.8 \pm 0.2)$ MeV [Hoferichter at al. 2012]
- Isospin breaking in the CD theorem shifts $\sigma_{\pi N}$ by $+3.0$ MeV
- Final results: $\sigma_{\pi N} = (59.1 \pm 1.9_{\mathrm{RS}} \pm 3.0_{\mathrm{LET}})$ MeV$=(59.1 \pm 3.5)$ MeV [MH, JRE, Kubis, Meißner]
- $\sigma_{\pi N}$ depends linearly on the scattering lengths:

$$\sigma_{\pi N} = 59.1 + \textstyle\sum_{I_s} c_{I_s} \Delta a_{0+}^{I_s}$$

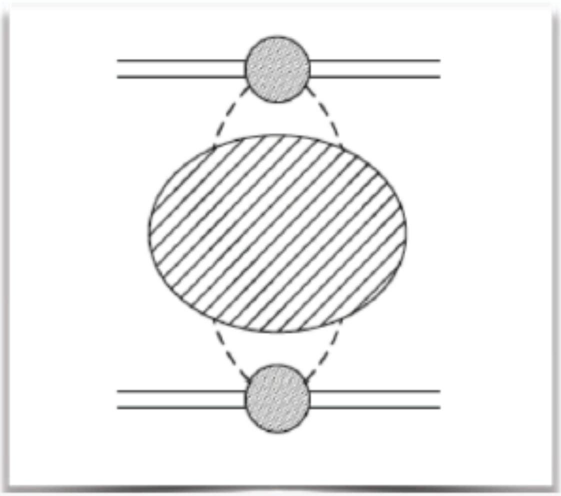


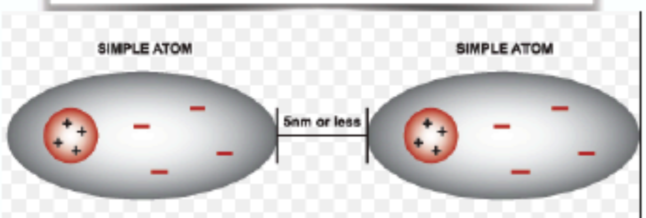
- The linear dependence of $\sigma_{\pi N}$ on the scattering lengths introduces an additional constraint



Threshold photoproduction of J/ψ on nucleons

D. Kharzeev





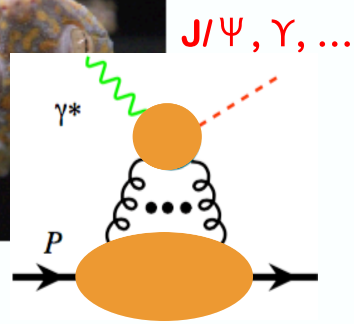
- heavy quarkonium: color dipole
- interaction with hadrons may be estimated from its chromoelectric polarizability (QCD van der Waals force)
  - 2-gluon exchange
  - at very large distances: interaction dominated by pions

calculated from trace of energy momentum tensor θ^{μ}_{μ}

Peskin (1979); Voloshin, Zakharov (1980);
Fujii, Kharzeev (1999)

- quarkonium-proton interaction at low energies probes distribution of mass in proton

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} d_n \langle h | \frac{1}{2} G^a_{0i} (D^0)^{n-2} G^a_{0i} | h \rangle$$



1. Interaction is attractive (VdW force of QCD)

S.Brodsky, I.Schmidt, G. de Teramond '90

2. For n=2 (low energy) the amplitude is proportional to the trace of the energy-momentum tensor

M.Luke, A.Manohar, M.Savage '92

Existence of J/ψ-nuclear bound states?

H.W. Lin

- threshold ψ-p scattering amplitude:

$$T_{\psi p} = 8\pi(M + M_\psi)a_{\psi p}$$

→ s-wave ψ-p scattering length (positive: attraction)

- if ψ-p attraction is strong enough → formation of ψ-nuclear bound states possible

in linear density approximation
ψ-nuclear matter binding energy

$$B_\psi \simeq \frac{8\pi(M + M_\psi)a_{\psi p}}{4MM\psi}\rho_{nm}$$

Kaidalov, Volkovitsky (1992)

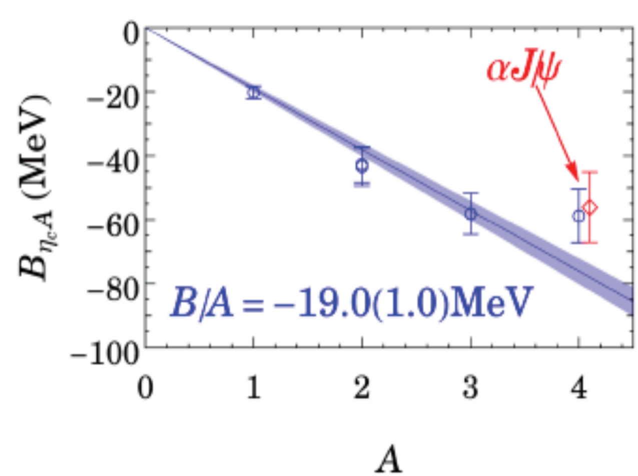
- many estimates:

  - perturbative calculation of chromoelectric polarizability (2-gluon exchange) $B_\psi \sim 10$ MeV

    Brodsky, Schmidt, de Teramond (1990);
    Wason (1991); Luke, Manohar, Savage (1992)

  - lattice QCD: Beane et al. (2015)

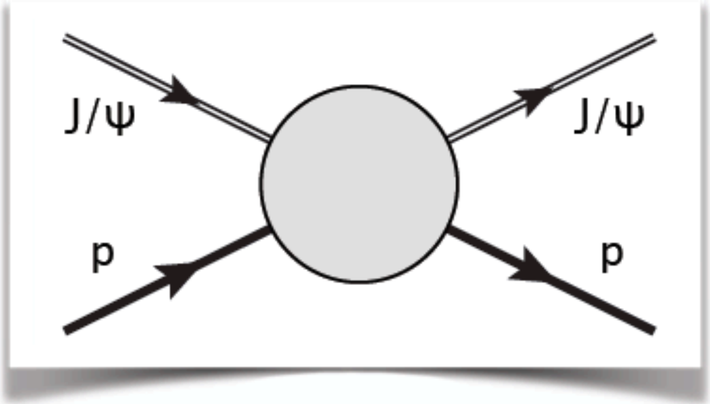
    $B_\psi \leq 40$ MeV ($m_\pi \sim 805$ MeV)



Forward J/ψ-p scattering (I)

O. Gryniuk

spin-averaged amplitude: $T_{\psi p}(\nu)$



kinematic variable: $\nu \equiv p\, q = \dfrac{s-u}{4}$

unitarity

$$\mathrm{Im}\, T_{\psi p}(\nu) = 2\sqrt{s}\, q_{\psi p}\, \sigma^{tot}_{\psi p}(\nu)$$

causality + crossing

subtracted dispersion relation:

$$\mathrm{Re}\, T_{\psi p}(\nu) = T_{\psi p}(0) + \frac{2}{\pi}\nu^2 \int_{\nu_{el}}^{\infty} d\nu' \frac{1}{\nu'} \frac{\mathrm{Im}\, T_{\psi p}(\nu')}{\nu'^2 - \nu^2}$$

directly sensitive to $a_{\psi p}$

parameterizing cross section:

$$\sigma^{tot}_{\psi p} = \sigma^{el}_{\psi p} + \sigma^{inel}_{\psi p}$$

$$\sigma^{el}_{\psi p} \propto C_{el}\left(1 - \frac{\nu_{el}}{\nu}\right)^{b_{el}} \left(\frac{\nu}{\nu_{el}}\right)^{a_{el}}$$

$$\sigma^{inel}_{\psi p} \propto C_{in}\left(1 - \frac{\nu_{in}}{\nu}\right)^{b_{in}} \left(\frac{\nu}{\nu_{in}}\right)^{a_{in}}$$

Forward J/ψ-p scattering (II)

Vector meson dominance (VMD) assumption:

Barger, Phillips (1975)

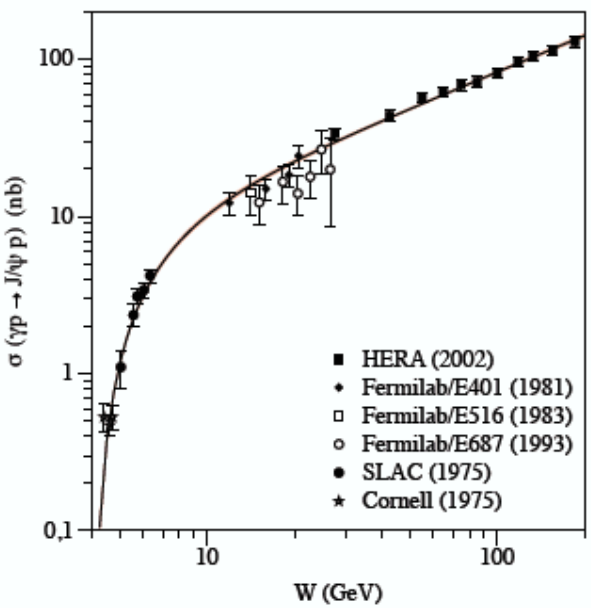
Redlich, Satz, Zinovjev (2000)

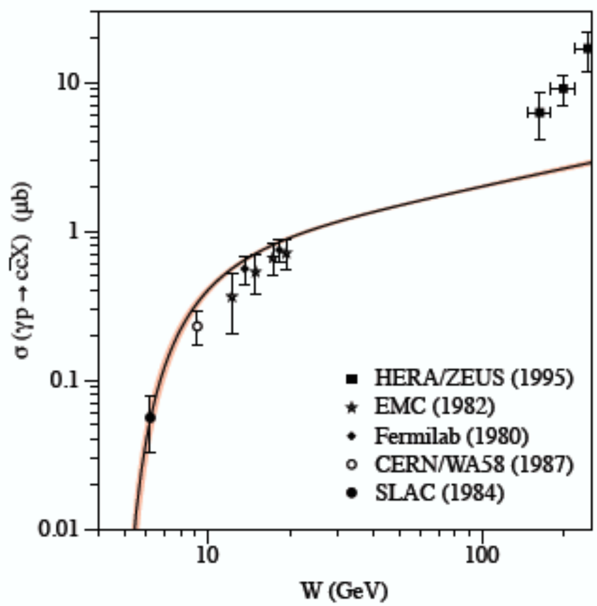
$$\sigma^{el}_{\psi p} = \left(\frac{M_\psi}{e f_\psi}\right)^2 \left(\frac{q_{\gamma p}}{q_{\psi p}}\right)^2 \sigma(\gamma p \to \psi p)$$

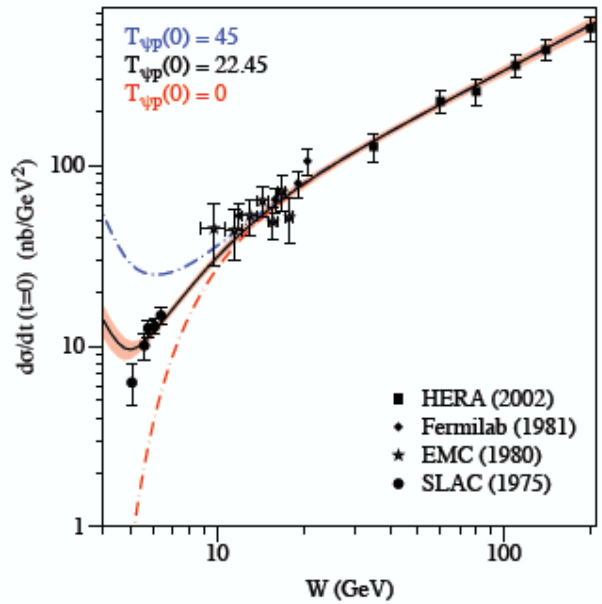
$$\sigma^{inel}_{\psi p} = \left(\frac{M_\psi}{e f_\psi}\right)^2 \left(\frac{q_{\gamma p}}{q_{\psi p}}\right)^2 \sigma(\gamma p \to c\bar{c}X)$$

forward differential cross section:

$$\left.\frac{d\sigma}{dt}\right|_{t=0}(\gamma p \to \psi p) = \left(\frac{e f_\psi}{M_\psi}\right)^2 \left(\frac{q_{\psi p}}{q_{\gamma p}}\right)^2 \left.\frac{d\sigma}{dt}\right|_{t=0}(\psi p \to \psi p)$$







simultaneously fitting

Gryniuk, Vdh (2016)

$a_{\psi p} \sim 0.05$ fm $\qquad B_\psi \sim 3$ MeV

Approved J/ψ experiments at JLab

- GlueX (**Hall D**, *γp*)
  - Luminosity: **low**
    - <100 **MHz** photon rate
  - Acceptance: **very high**
    - First access to 2D *J/ψ* cross section
    - Harder to separate P_c from *t*-channel background
  - Timeline: **ongoing!**

- E12-12-001 (**CLAS12**, HallB, *ep*)
  - Luminosity: **medium**
    - luminosity: 2 x $\mathbf{10^{35}}$ s^{-1} cm^{-2}
  - Acceptance: **high**
    - Access 2D *J/ψ* cross section
    - Harder to separate P_c from *t*-channel background
  - Timeline: **~few years**

- E12-16-007 (**Hall C**, *γp*)
  - luminosity: **very high**
    - 8000 **GHz** photon rate
    - equiv. *ep*-luminosity: $\mathbf{10^{39}}$ s^{-1} cm^{-2}
  - Acceptance: **limited**
    - Optimized for **maximal P_c sensitivity**
    - cannot do 2D *J/ψ* cross section
  - Timeline: **soon (high-impact!)**

- E12-12-006 (**SoLID,** Hall A, *ep*)
  - Luminosity: **high**
    - luminosity: 2 x $\mathbf{10^{38}}$ s^{-1} cm^{-2}
  - Acceptance: **high**
    - Precision 2D *J/ψ* cross section
    - Good sensitivity for Pc resonance due to very high statistics
  - Timeline: **~5-10 years**

Moving forward

- A proton mass "White Paper"
  – summary of this workshop and thoughts on future efforts
  - ✧ Three-pronged approach to the "Proton Mass"
    - Lattice QCD effort
    - Mass decomposition – roles of quarks and gluons
    - Approximated analytical approach
  - ✧ Summary of current understanding in QCD
  - ✧ Outstanding questions and challenges
  - ✧ Future efforts – Homework
- Plan/Proposal:
  - ✧ Every speaker/participant submits ONE page summary of his/her work on the "proton mass" and thoughts for the future work
  - ✧ With the ONE-page inputs, the organizers draft the "White Paper", and send it to all participants for improvements

"Summary"

- The proton mass closely connected to quantum anomalies

  Non-perturbative QCD generates a new scale: $\langle 0|F^2|0\rangle \neq 0$

- Three-pronged approach to explore the origin hadron mass

  lattice QCD
  mass decomposition – roles of the constituents
  approximated analytical approach

- Questions:

  - What can lattice QCD do to explore the role of "individual" constituent in making up the proton mass?
  - What can the mass decomposition teach us?
  - How well can we control the approximation of the analytical or model approaches
  - …

Thanks you!

Backup slides

Partonic interpretations

C. Lorcé

Quark energy-momentum tensor $\hat{T}^{\mu\nu}_q = \overline{\psi}\gamma^\mu \frac{i}{2}\overleftrightarrow{D}^\nu\psi$

$$\langle p'|\hat{T}^{\mu\nu}|p\rangle = \overline{u}(p')\left[\frac{P^{\{\mu}\gamma^{\nu\}}}{2}A(t) + \frac{P^{\{\mu}i\sigma^{\nu\}\Delta}}{4M}B(t) + \frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M}C(t) + Mg^{\mu\nu}\bar{C}(t) + \frac{P^{[\mu}\gamma^{\nu]}}{2}D(t)\right]u(p)$$

Non-conservation ($Mg^{\mu\nu}\bar{C}(t)$) — Asymmetry ($\frac{P^{[\mu}\gamma^{\nu]}}{2}D(t)$)

Higher twist

$$A_q + A_G = 1$$
$$B_q + B_G = 0$$
$$\bar{C}_q + \bar{C}_G = 0$$

Sum rules

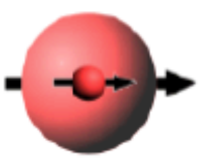
$$J_z = \tfrac{1}{2}\left[A(0) + B(0)\right]$$ [Ji (1997)]

$$L_z = \tfrac{1}{2}\left[A(0) + B(0) + D(0)\right]$$ [Shore, White (2000)]

$D(0) = -2S_z$

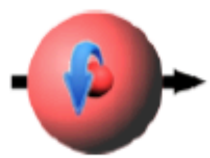
Chiral decomposition ⟶ **Parity-odd EMT** $\hat{T}^{\mu\nu}_5 = \overline{\psi}\gamma^\mu\gamma_5 \frac{i}{2}\overleftrightarrow{D}^\nu\psi$ [C.L. (2014)]

Quark Spin



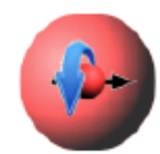
$\langle S^N_z S^q_z\rangle$

Quark OAM



$\langle S^N_z L^q_z\rangle$

Quark spin-orbit correlation



$\langle S^q_z L^q_z\rangle$

Transversity decomposition ⟶ **Chiral-odd EMT** $\hat{T}^{\lambda\mu\nu}_5 = \overline{\psi}i\sigma^{\lambda\mu}\gamma_5 \frac{i}{2}\overleftrightarrow{D}^\nu\psi$

Transverse spin-orbit correlations [Bhoonah, C.L. (2017)]

Quark OAM – different definitions

M. Burkardt

straight line (→Ji)

$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + L_q + J_g$

$L_q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x}\times i\vec{D}\right)^z q(\vec{x})|P,S\rangle$

- $i\vec{D} = i\vec{\partial} - g\vec{A}$

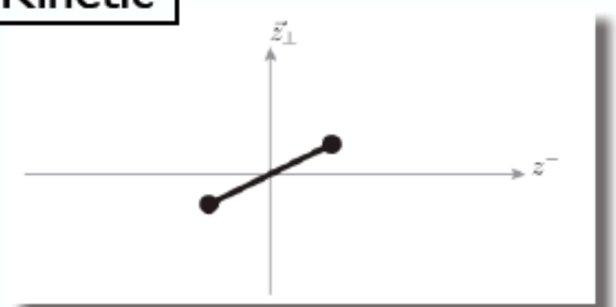
light-cone staple (→ Jaffe-Manohar)

$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + \mathcal{L}_q + \Delta G + \mathcal{L}_g$

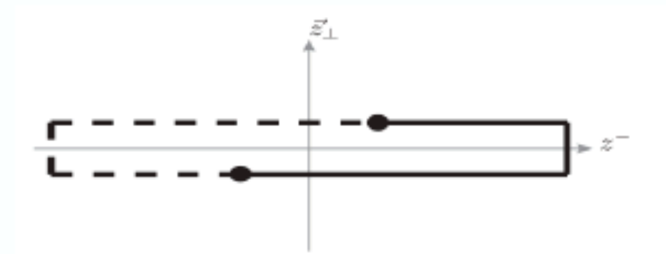
$\mathcal{L}^q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x}\times i\vec{\mathcal{D}}\right)^z q(\vec{x})|P,S\rangle$

$i\mathcal{D}^j = i\partial^j - gA^j(x^-,\mathbf{x}_\perp) - g\int_{x^-}^{\infty} dr^- F^{+j}$

Kinetic



Canonical



difference $\mathcal{L}^q - L^q$

$$\mathcal{L}^q_{JM} - L^q_{Ji} = -g\int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left[\vec{x}\times\int_{x^-}^{\infty} dr^- F^{+\perp}(r^-,\mathbf{x}_\perp)\right]^z q(\vec{x})|P,S\rangle$$

- change in OAM as quark leaves nucleon due to torque from FSI on active quark

Nucleon spin (Lattice)

- Spin sum: $\frac{1}{2} = \sum_q \underbrace{\left(\frac{1}{2}\Delta\Sigma^q + L^q\right)}_{J^q} + J^g$

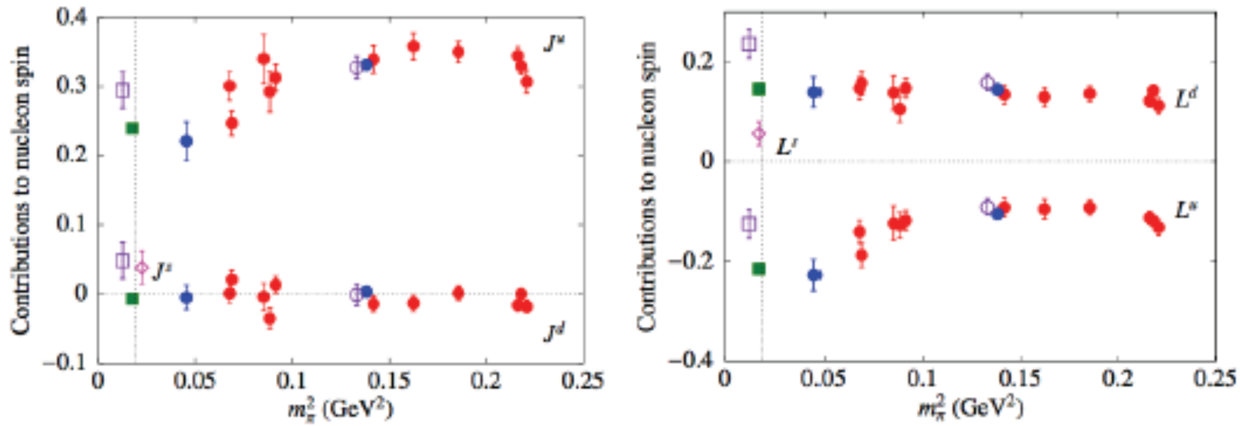
$$\frac{1}{2}\Delta\Sigma^u = 0.413(13), \quad \tfrac{1}{2}\Delta\Sigma^d = -0.193(7), \quad \frac{1}{2}\Delta\Sigma^s = -0.021(5)$$

$$J^u = 0.310(26), \quad J^d = 0.056(26), \quad J^s = 0.046(21)$$

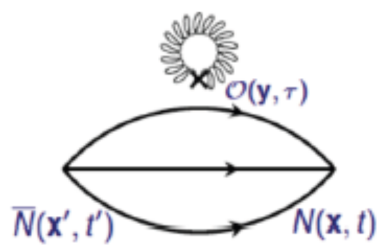
$$L^u = -0.104(29), \quad L^d = 0.249(27), \quad L^s = 0.067(21)$$

C. Alexandrou

Disconnected contribution using $\mathcal{O}(860000)$ statistics



- Gluonic contribution calculated on lattice !



$$\sum_q \langle x\rangle_q + \langle x\rangle_g = \langle x\rangle^{CI}_{u+d} + \langle x\rangle^{DI}_{u+d+s} + \langle x\rangle_g = 1.01(10)(2)$$

$$< x >^R_g = Z_{gg} < x >_g + Z_{gq} < x >_{u+d+s} = 0.273(23)(24)$$

$$B_g(0) = 0$$

$$J_N = (0.310)_u + (0.056)_d + (0.046)_s + (0.136)_g = 0.51(5)(4)$$

$$\sum_q \langle x\rangle_q \approx \sum_q 2J_q$$