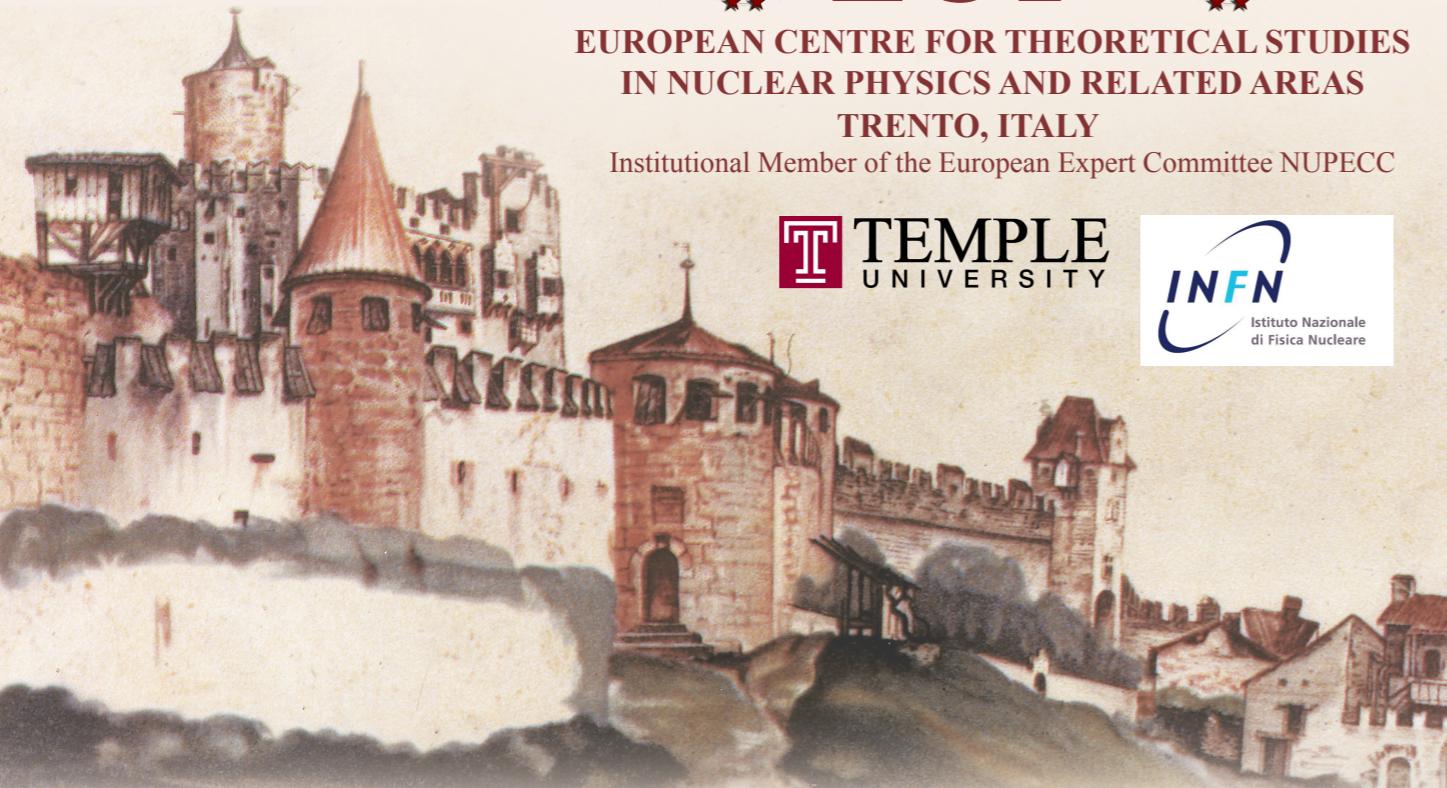




EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY

Institutional Member of the European Expert Committee NUPECC



Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum, London

The Proton Mass: At the Heart of Most Visible Matter

Trento, April 3 - 7, 2017

Main Topics

Hadron mass decomposition in terms of constituents:

Uniqueness of the decomposition, Quark mass, and quark and gluon energy contribution, Anomaly contribution, ...

Hadron mass calculations:

Lattice QCD (total & individual mass components), Approximated analytical methods, Phenomenological model approaches, ...

Experimental access to hadron mass components:

Exclusive heavy quarkonium production at threshold, nuclear gluonometry through polarized nuclear structure function, ...

Confirmed keynote speakers

Alexandrou Constantia (*Cyprus University*), Brodsky Stan (*SLAC*), Burkhardt Matthias (*New Mexico State University*), Camalich Jorge Martin (*CERN*), Chen Jian-Ping (*Jefferson Lab*), Chudakov Eugene (*Jefferson Lab*), Cloët Ian (*Argonne National Lab*), de Teramond Guy (*University Costa Rica*), Deshpande Abhay (*Stony Brook University*), Eichmann Gérard (*Gießen University*), Gao Haiyan (*Duke University*), Hafidi Kawtar (*Argonne National Lab*), Hoelbling Christian (*University of Wuppertal*), Lin Huey-Wen (*Michigan State University*), Liu Keh-Fei (*University of Kentucky*), Lorcé Cédric (*École Polytechnique, Palaiseau*), Mulders Piet (*Vrije University of Amsterdam*), Papavassiliou Joannis (*Valencia University*), Pascalutsa Vladimir (*Johannes Gutenberg University of Mainz*), Peng Jen-Chieh (*University Illinois Urbana-Champaign*), Richards David (*Jefferson Lab*), Roberts Craig (*Argonne National Lab*), Scherer Stefan (*Johannes Gutenberg University of Mainz*), Slifer Karl (*University of New Hampshire*).

Organizers

Zein-Eddine Meziani (*Temple University*)

Barbara Pasquini (*University of Pavia*)

Jianwei Qiu (*Jefferson Lab*)

Marc Vanderhaeghen (*Universität Mainz*)

Director of the ECT*: Professor Jochen Wambach (ECT*)

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Theory Summary

Barbara Pasquini / Marc Vanderhaeghen

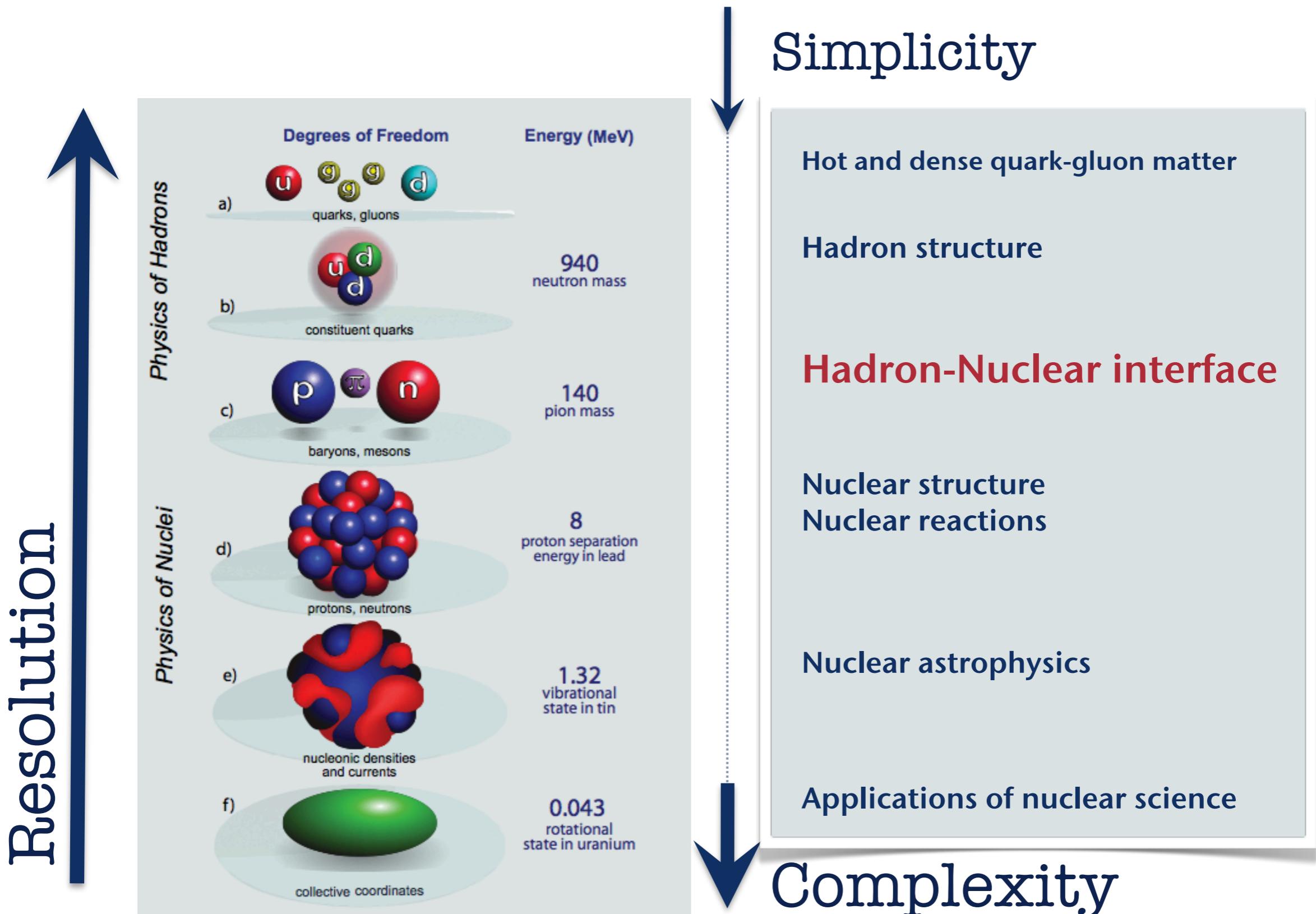
scales in QCD

C. Roberts

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} - m \delta_{ij}) \psi_j - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$

- 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 \mathcal{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 \mathcal{L}_{QED}

Scales in strong interactions



Scale invariance of QCD (classical)

in absence of quark masses

- Theory is invariant under scale transformation

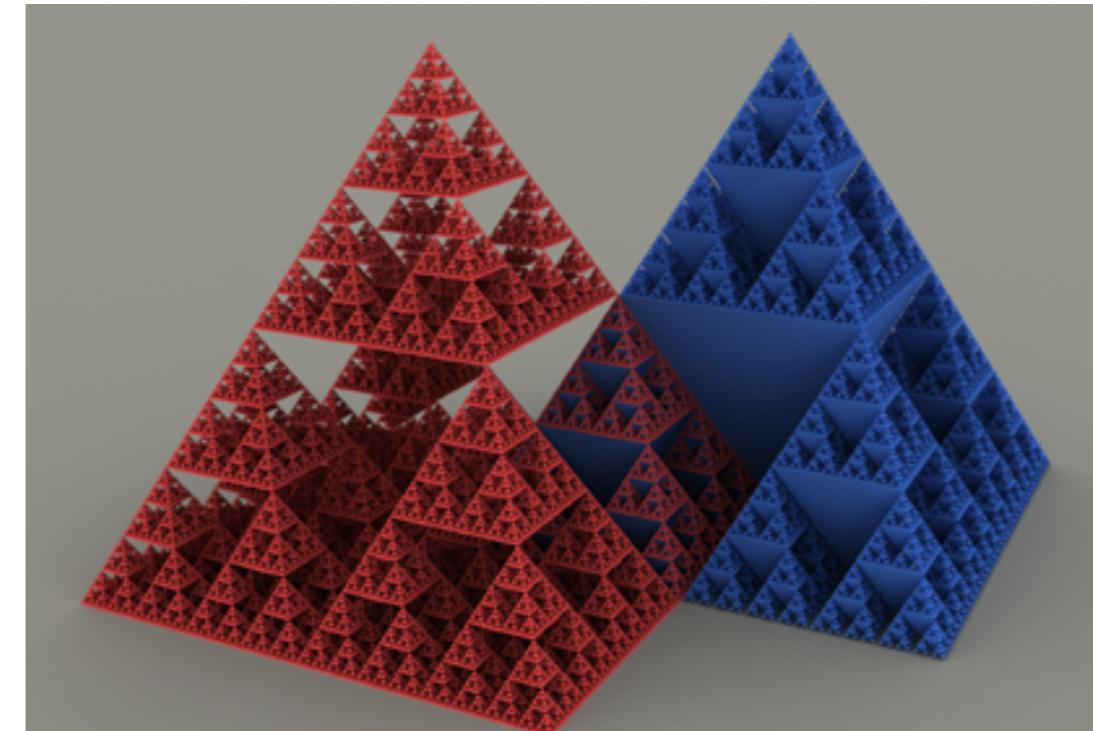
$$x \rightarrow e^\lambda x$$

- Noether current dilatation current:

$$s^\mu = T^{\mu\nu} x_\nu$$



energy momentum tensor



- scale invariant theory: dilatation current is conserved

$$0 = \partial_\mu s^\mu = T_\mu^\mu$$

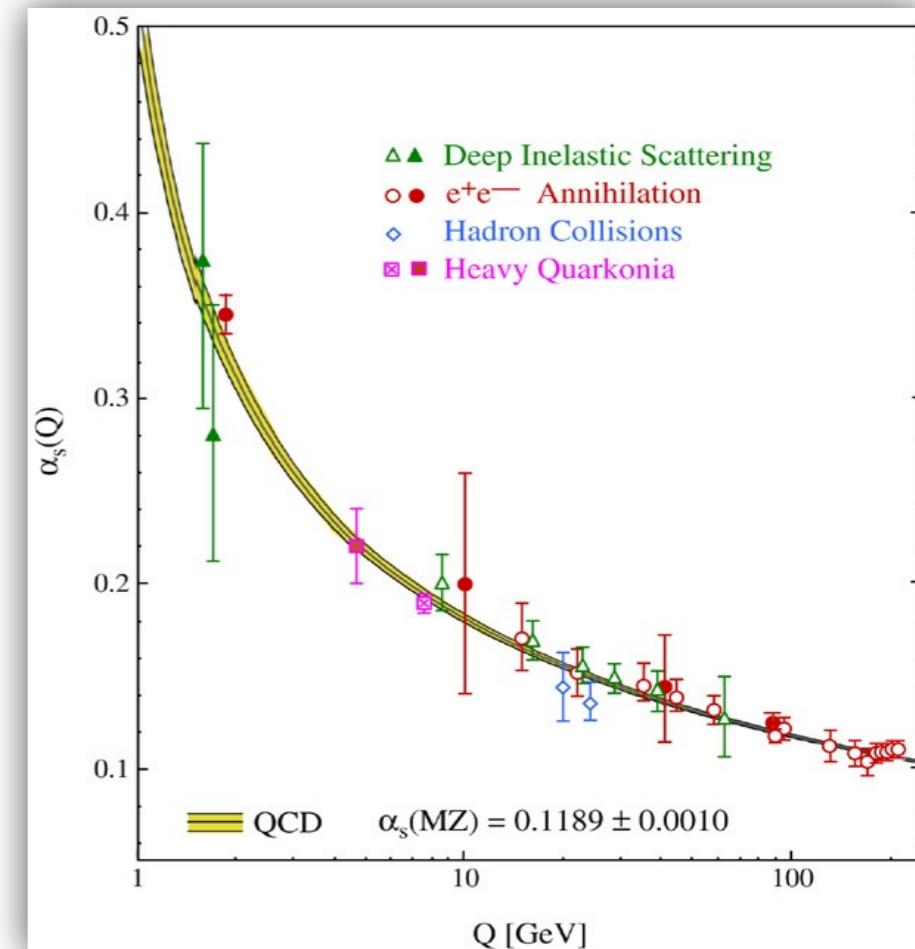
Scale-invariant classical theory: energy-momentum tensor is traceless

Scale/trace anomaly in QCD

→ Quantum loop corrections:
running coupling \rightarrow dimensional transmutation

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

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



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

→ at low energies:
heavy quarks decouple

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

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

Mass of hadrons

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

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

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

Quark contributions to hadron mass: sigma-terms

$$\sigma_{ud}, \sigma_s$$

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

Models / Interpretations

Light quarks and confinement

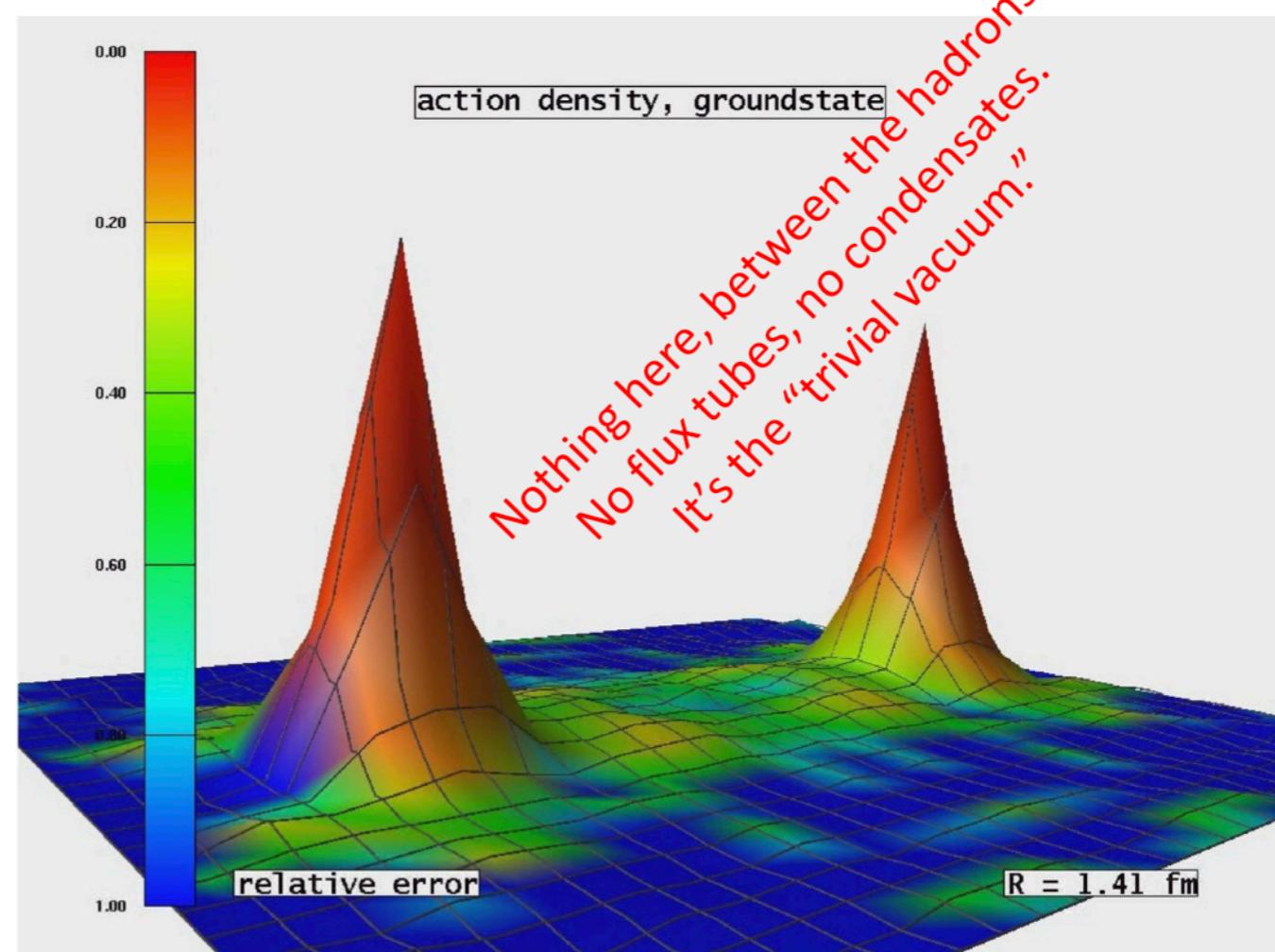
Understanding the origin and absence of mass in QCD likely inseparable from understanding of confinement

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 \[nucl-th\]](https://arxiv.org/abs/1202.2376), Phys. Rev. C85 (2012) 065202

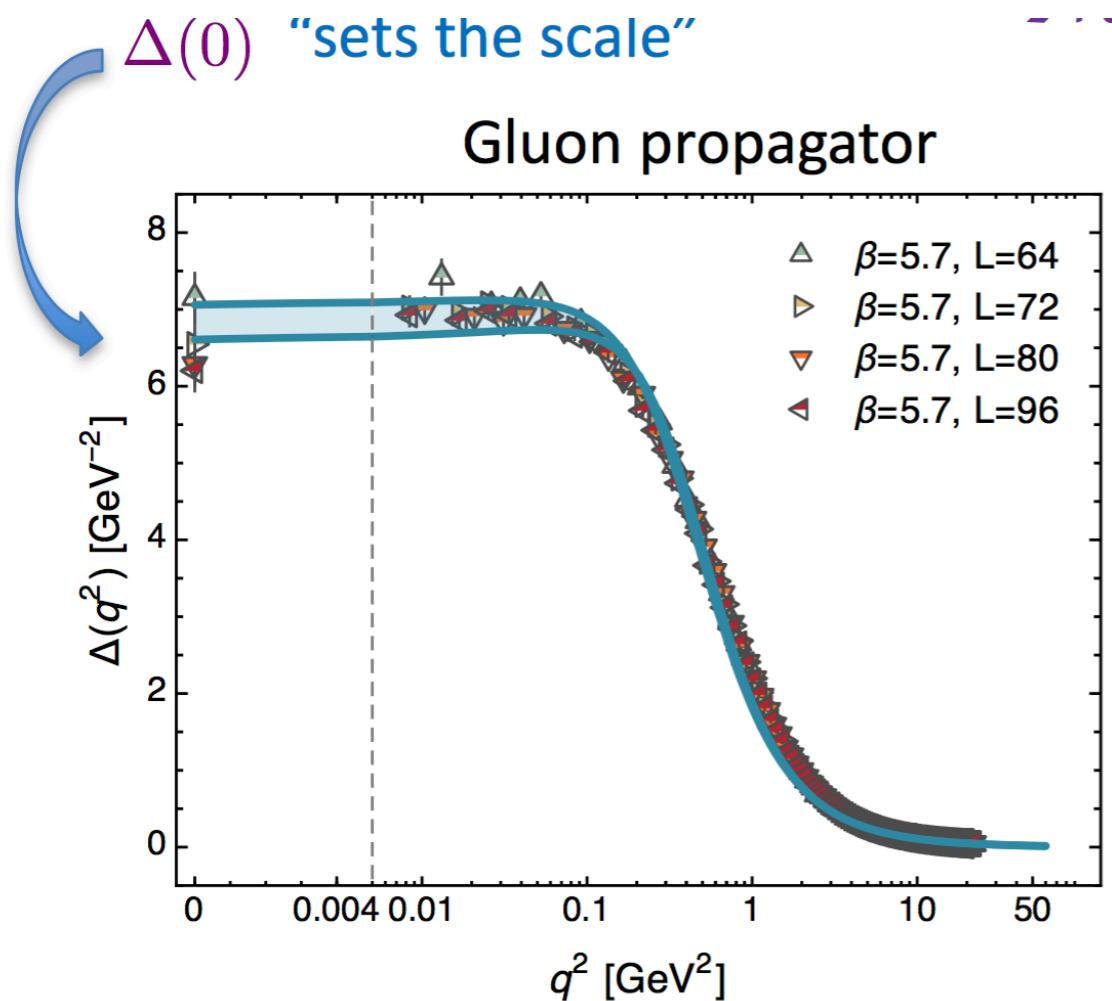
G. Bali et al., [PoS LAT2005 \(2006\) 308](https://pos.sissa.it/10/308)



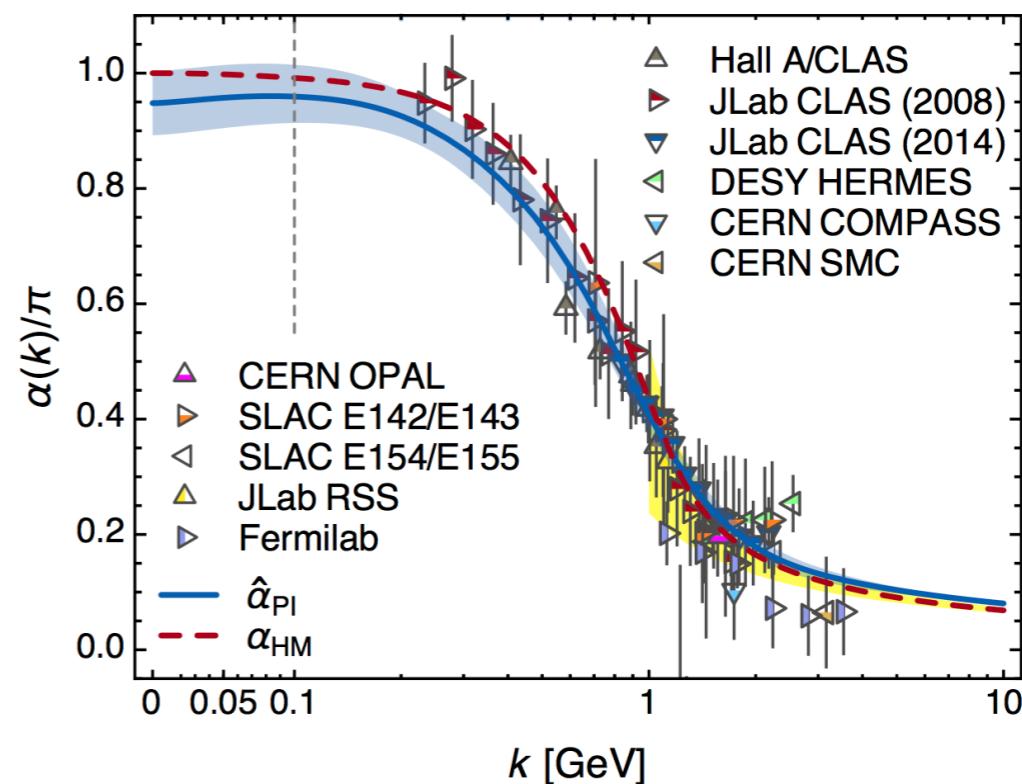
Continuum truncation: Dyson-Schwinger (I)

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



- **Equivalence in the perturbative domain**
reasonable definitions of the charge
$$\alpha_{g_1}(k^2) = \alpha_{\overline{\text{MS}}}(k^2)[1 + 1.14\alpha_{\overline{\text{MS}}}(k^2) + \dots]$$
$$\hat{\alpha}_{\text{PI}}(k^2) = \alpha_{\overline{\text{MS}}}(k^2)[1 + 1.09\alpha_{\overline{\text{MS}}}(k^2) + \dots]$$
- **Equivalence in the non-perturbative domain**
highly non-trivial (ghost-gluon interactions)
- **Agreement with light-front holography**
model for α_{g_1}

Continuum truncation: Dyson-Schwinger (II)

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

pion exists if and only if mass is dynamically generated

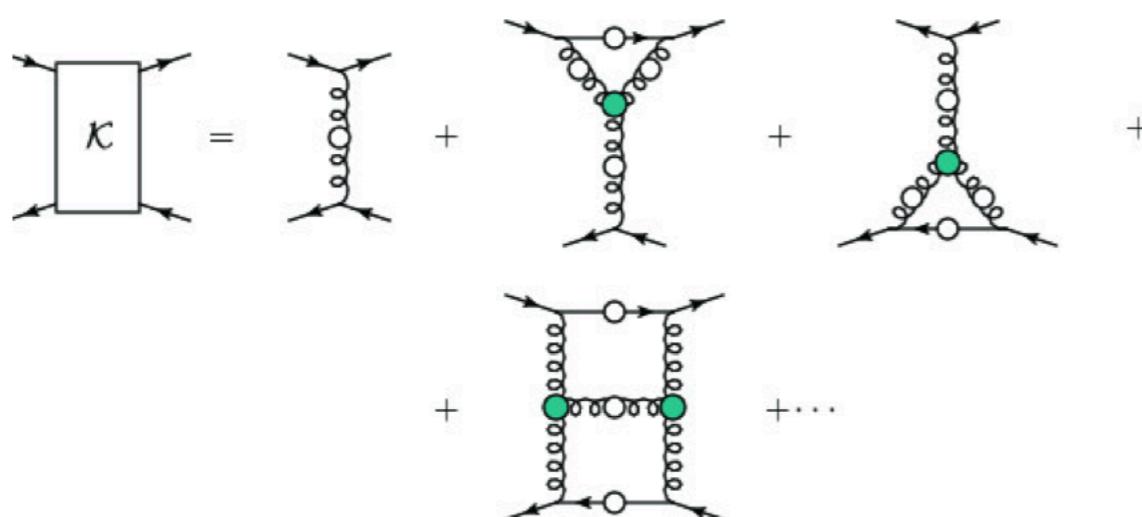
Dressed-quark propagator $S(p) = \frac{1}{i\gamma \cdot p A(p^2) + B(p^2)}$

Axial-vector Ward-Takahashi identity entails

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

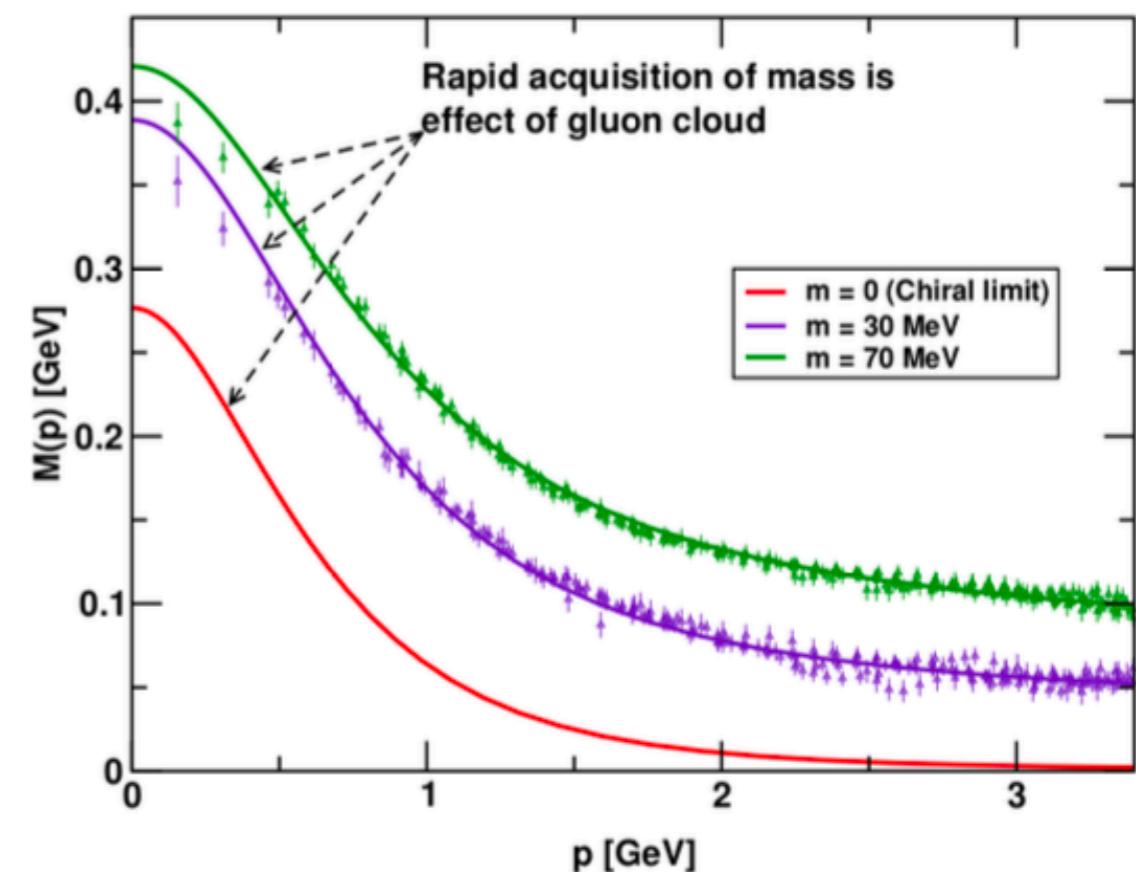
PS Bethe-Salpeter amplitude

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)]

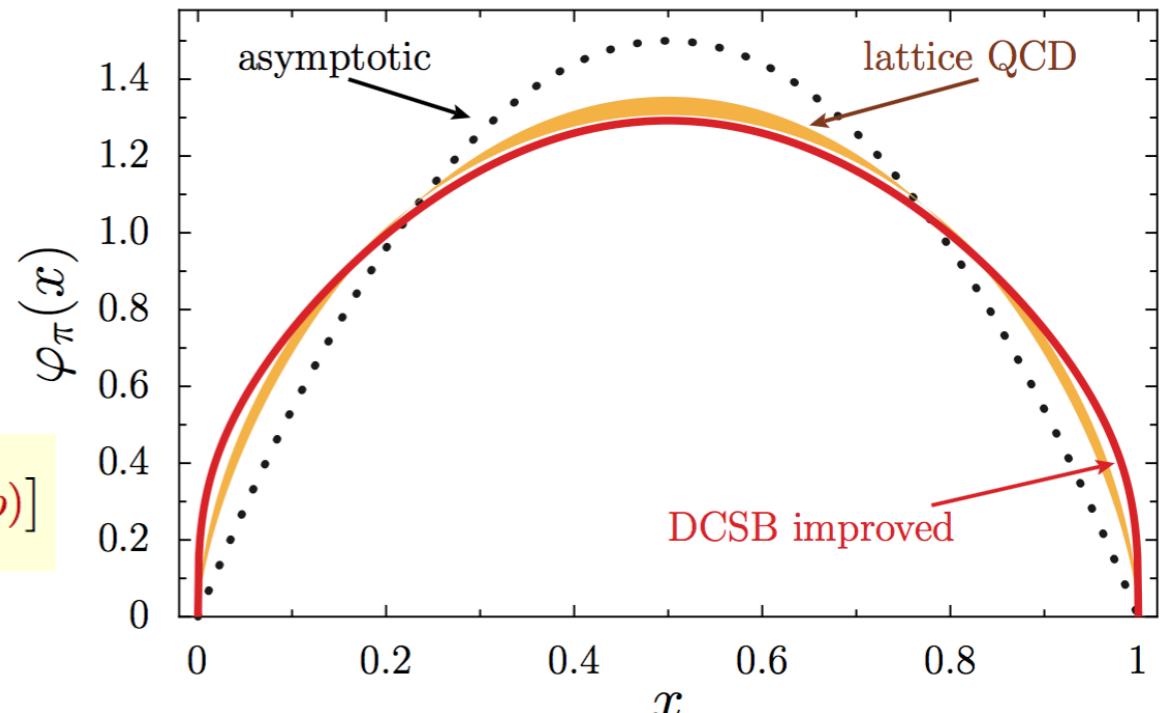


Continuum truncation: Dyson-Schwinger (III)

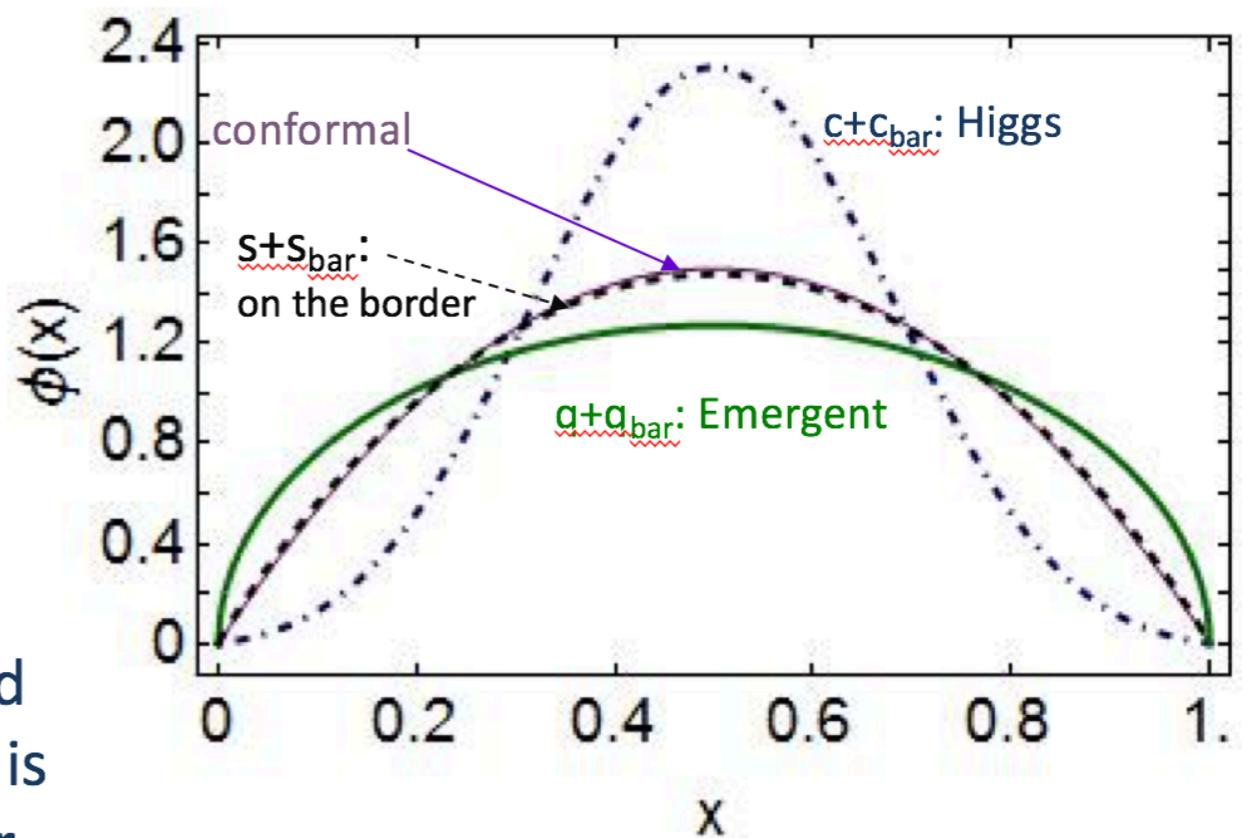
I. Cloët, C. Roberts

pion DA can be obtained as projection of pion's Bethe-Salpeter amplitude onto light-front

$$f_\pi \varphi_\pi(x) = Z_2 \int \frac{d^4 k}{(2\pi)^2} \delta(k^+ - x p^+) \text{Tr} [\gamma^+ \gamma_5 S(k) \Gamma_\pi(k, p) S(k - p)]$$



- limit $m_{\text{quark}} \rightarrow \infty$
 $\varphi(x) \rightarrow \delta(x - \frac{1}{2})$
- limit $m_{\text{quark}} \rightarrow 0$
 $\varphi(x) \sim (8/\pi) [x(1-x)]^{1/2}$
- Transition boundary lies just above m_{strange}
- Comparison between distributions of light-quarks and those involving strange-quarks is obvious place to find signals for strong-mass generation



Holographic QCD

S.J. Brodsky, G. de Teramond

Light-Front QCD

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

$$(H_{LF}^0 + H_{LF}^I)|\Psi\rangle = M^2|\Psi\rangle$$

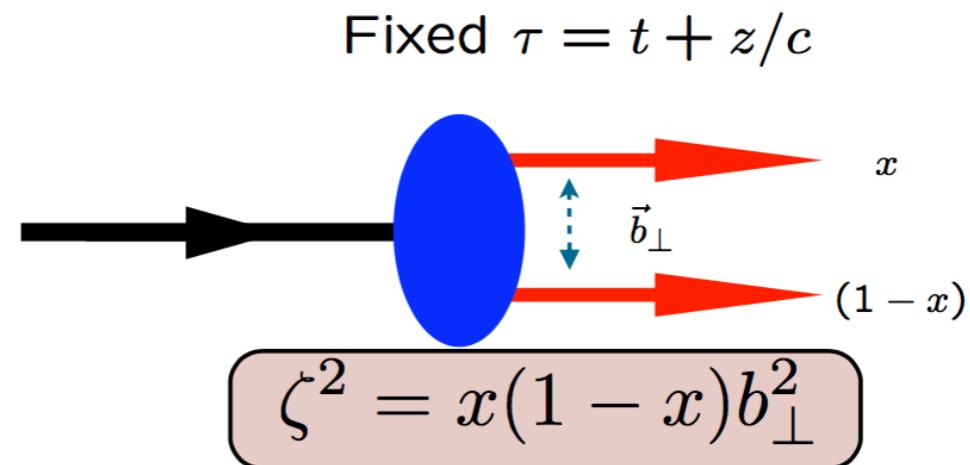
$$[\frac{\vec{k}_\perp^2 + m^2}{x(1-x)} + V_{\text{eff}}^{LF}] \psi_{LF}(x, \vec{k}_\perp) = M^2 \psi_{LF}(x, \vec{k}_\perp)$$

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

AdS/QCD:

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

Semiclassical first approximation to QCD



Coupled Fock states

*Eliminate higher Fock states
and retarded interactions*

Effective two-particle equation

Azimuthal Basis ζ, ϕ
 $m_q = 0$

Single variable ζ

*Confining AdS/QCD
potential!*

Sums an infinite # diagrams

Holographic QCD

S.J. Brodsky, G. de Teramond

Meson Spectrum in Soft Wall Model

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

Massless pion!

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

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

Holographic QCD

S.J. Brodsky, G. de Teramond

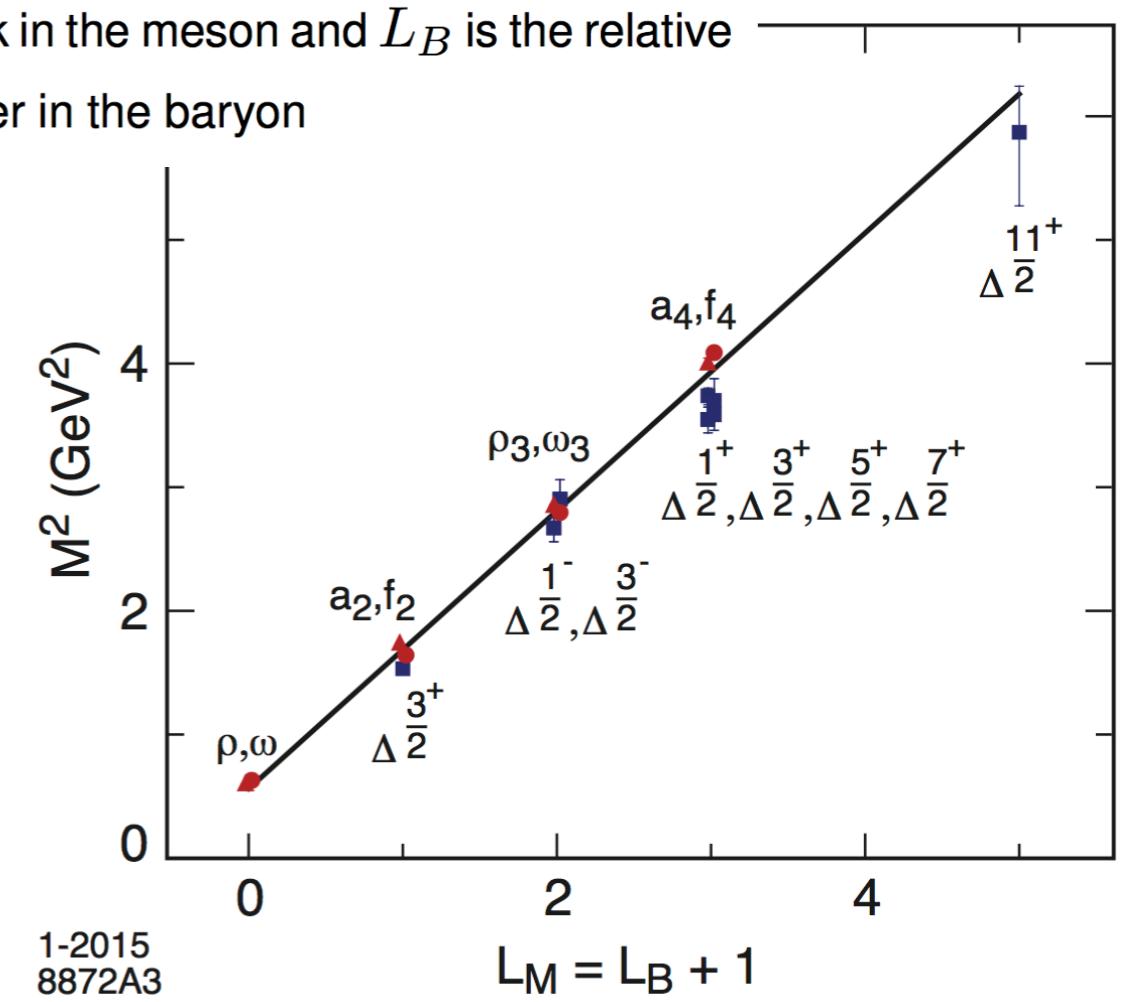
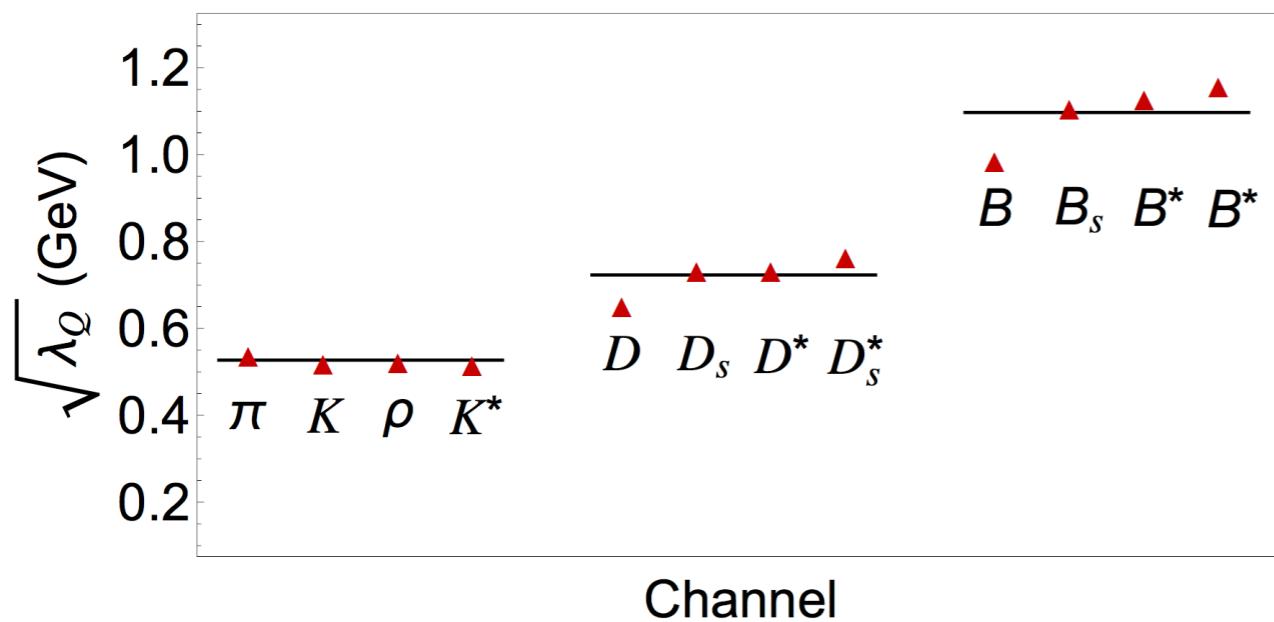
supersymmetric and
superconformal constraints
on meson and baryon masses

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

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

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

X. Ji, J.W. Qiu



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

Relativistic motion Quantum fluctuation
Quark Energy Gluon Energy Quark Mass Trace Anomaly

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

❖ Hadron state:

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

❖ Hamiltonian:

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

❖ QCD energy-momentum tensor:

$$\begin{aligned}
 T^{\mu\nu} &= \overline{T^{\mu\nu}} + \widehat{T^{\mu\nu}} & \langle P | T^{\mu\nu} | P \rangle &= P^\mu P^\nu / M_p & \text{No } g^{\mu\nu} \text{ term!} \\
 \rightarrow \langle P | \overline{T}^{\mu\nu} | P \rangle &= (P^\mu P^\nu - \frac{1}{4} M_p^2 g^{\mu\nu}) / M_p & \langle P | \widehat{T}^{\mu\nu} | P \rangle &= \frac{1}{4} M_p g^{\mu\nu} \\
 \rightarrow \left. \frac{\langle P | \int d^3x \overline{T}^{00} | P \rangle}{\langle P | P \rangle} \right|_{\text{at rest}} &= \frac{3}{4} M_p & \left. \frac{\langle P | \int d^3x \widehat{T}^{00} | P \rangle}{\langle P | P \rangle} \right|_{\text{at rest}} &= \frac{1}{4} M_p
 \end{aligned}$$

“Traceless” term

“Trace” term

Proton mass decompositions

X. Ji, J.W. Qiu

□ Traceless terms:

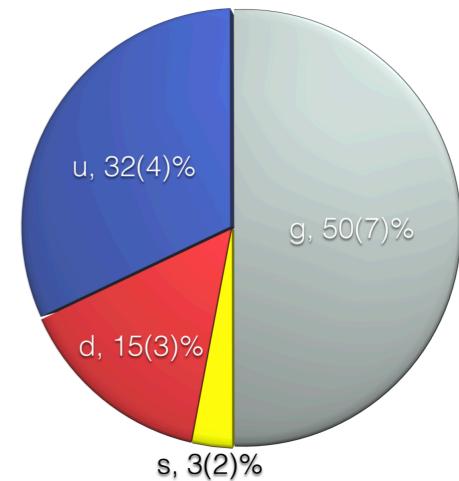
$$\bar{T}^{\mu\nu} = \bar{T}_q^{\mu\nu} + \bar{T}_g^{\mu\nu} \quad \bar{T}_q^{\mu\nu} = \frac{1}{2} \bar{\psi} i \overleftrightarrow{D}^{(\mu} \gamma^{\nu)} \psi - \frac{1}{4} g^{\mu\nu} \bar{\psi} m \psi, \quad \bar{T}_g^{\mu\nu} = \frac{1}{4} g^{\mu\nu} F^2 - F^{\mu\alpha} F^\nu_\alpha.$$

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

Let $\mu \rightarrow + \quad \nu \rightarrow +$

→ $a(\mu^2) = \sum_f \int_0^1 x [q_f(x, \mu^2) + \bar{q}_f(x, \mu^2)] dx$ *Total momentum fraction carried by the quarks - reasonably known!*

$$\left. \frac{\langle P | \int d^3x \bar{T}_q^{00} | P \rangle}{\langle P | P \rangle} \right|_{\text{at rest}} = a(\mu^2) \frac{3}{4} M_p \quad \left. \frac{\langle P | \int d^3x \bar{T}_g^{00} | P \rangle}{\langle P | P \rangle} \right|_{\text{at rest}} = [1 - a(\mu^2)] \frac{3}{4} M_p$$



□ Trace terms:

$$\hat{T}^{\mu\nu} = \hat{T}_m^{\mu\nu} + \hat{T}_a^{\mu\nu} \quad \rightarrow \quad \langle P | \hat{T}_m^{\mu\nu} | P \rangle \equiv b \frac{1}{4} M_p g^{\mu\nu} \quad \langle P | \hat{T}_a^{\mu\nu} | P \rangle \equiv [1 - b] \frac{1}{4} M_p g^{\mu\nu}$$

$$\left. \frac{\langle P | \int d^3x \hat{T}_m^{00} | P \rangle}{\langle P | P \rangle} \right|_{\text{at rest}} = b \frac{1}{4} M_p \quad \left. \frac{\langle P | \int d^3x \hat{T}_a^{00} | P \rangle}{\langle P | P \rangle} \right|_{\text{at rest}} = [1 - b] \frac{1}{4} M_p$$

Partonic interpretations

C. Lorcé

Quark energy-momentum tensor

$$\hat{T}_q^{\mu\nu} = \bar{\psi} \gamma^\mu \frac{i}{2} \overleftrightarrow{D}^\nu \psi$$

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

Non-conservation Asymmetry
 Higher twist

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

Sum rules

$$J_z = \frac{1}{2} [A(0) + B(0)] \quad [\text{Ji (1997)}]$$

$$L_z = \frac{1}{2} [A(0) + B(0) + D(0)] \quad [\text{Shore, White (2000)}]$$

$-2S_z$

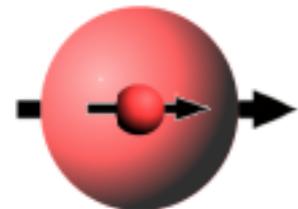
Chiral decomposition

Parity-odd EMT

$$\hat{T}_5^{\mu\nu} = \bar{\psi} \gamma^\mu \gamma_5 \frac{i}{2} \overleftrightarrow{D}^\nu \psi$$

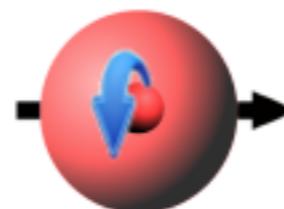
[C.L. (2014)]

Quark Spin



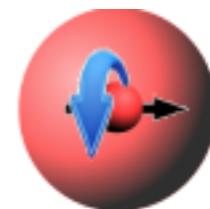
$$\langle S_z^N S_z^q \rangle$$

Quark OAM



$$\langle S_z^N L_z^q \rangle$$

Quark spin-orbit correlation



$$\langle S_z^q L_z^q \rangle$$

Transversity decomposition

Chiral-odd EMT

$$\hat{T}_5^{\lambda\mu\nu} = \bar{\psi} i\sigma^{\lambda\mu} \gamma_5 \frac{i}{2} \overleftrightarrow{D}^\nu \psi$$

Transverse spin-orbit correlations

[Bhoonah, C.L. (2017)]

Kinetic EMT



Belinfante EMT

$$T_{\text{kin},q}^{\mu\nu}(x) = \frac{1}{2} \bar{\psi}(x) \gamma^\mu i \overleftrightarrow{D}^\nu \psi(x)$$

$$T_{\text{Bel},q}^{\mu\nu} = \frac{1}{2} T_{\text{kin},q}^{\{\mu\nu\}}$$

Total AM

$$J_q^{\mu\alpha\beta}(x) = L_q^{\mu\alpha\beta}(x) + S_q^{\mu\alpha\beta}(x)$$



$$\mathbf{J}(x) = \mathbf{L}(x) + \mathbf{S}(x)$$

Total AM

$$J_{\text{Bel},q}^{\mu\alpha\beta}(x) = J_q^{\mu\alpha\beta}(x) + \frac{1}{2} \partial_\lambda [x^\alpha S_q^{\lambda\mu\beta}(x) - x^\beta S_q^{\lambda\mu\alpha}(x)]$$



$$\mathbf{J}(x) = \mathbf{J}_{\text{Bel}}(x) + \mathbf{M}(x)$$

Non-symmetric

$$\begin{aligned} \langle p', s' | T^{\mu\nu}(0) | p, s \rangle &= \bar{u}(p', s') \left[\frac{P^\mu P^\nu}{M} A(t) + \frac{P^\mu i\sigma^{\nu\lambda}\Delta_\lambda}{4M} (A + B + D)(t) \right. \\ &\quad \left. + \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{M} C(t) + M g^{\mu\nu} \bar{C}(t) + \frac{P^\nu i\sigma^{\mu\lambda}\Delta_\lambda}{4M} (A + B - D)(t) \right] u(p, s) \end{aligned}$$

$$T^{[\mu\nu]} \neq 0 \implies D(t) \neq 0$$

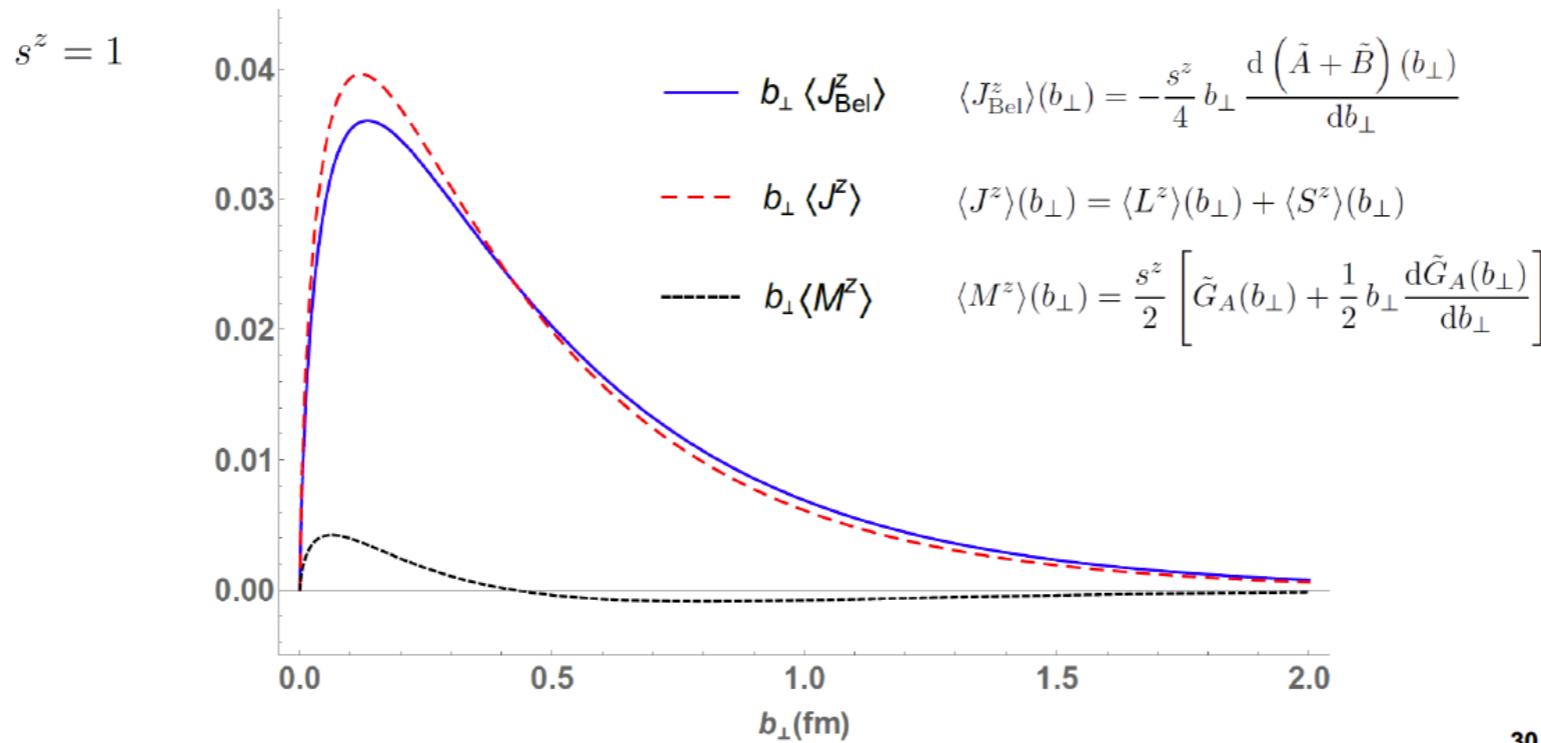
EOM



$$D_q(t) = -G_A^q(t)$$

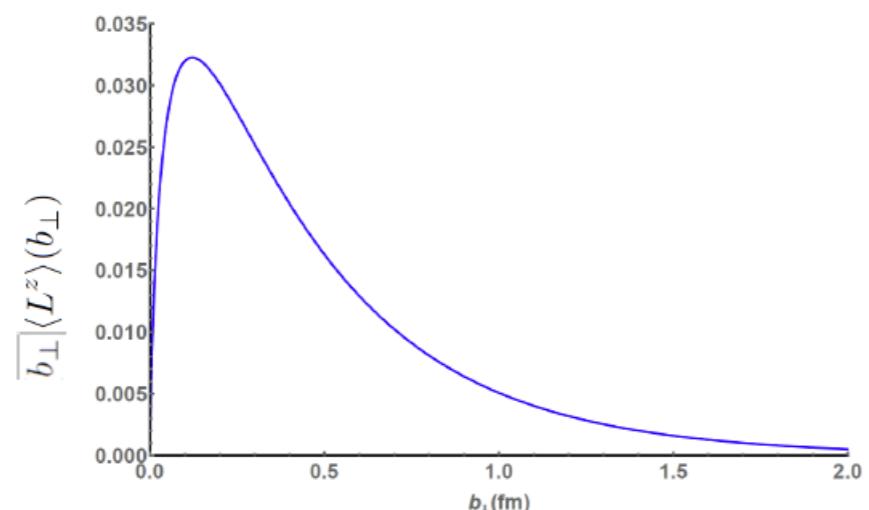
Interpretation in scalar diquark model

L. Mantovani

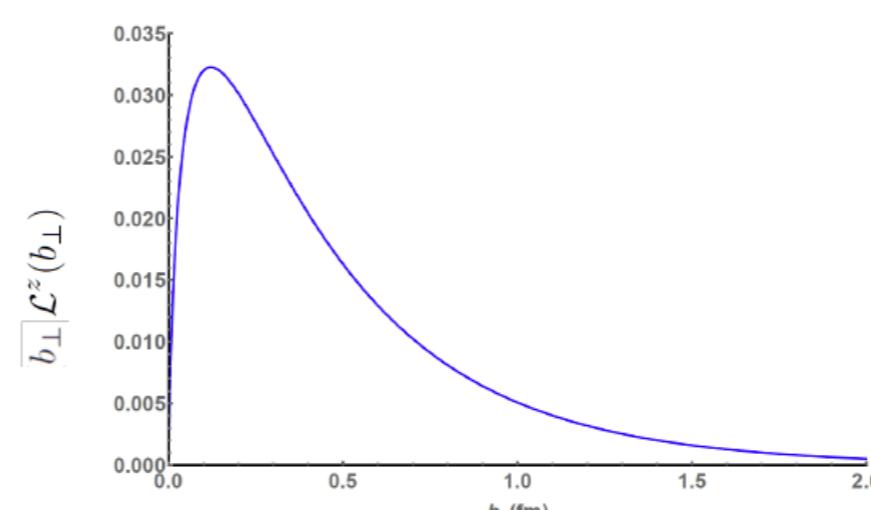


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Scalar Diquark Model has no gauge field



$$\begin{aligned} \langle L^z \rangle(b_\perp) = & -\frac{1}{8\pi} b_\perp \frac{d}{db_\perp} \int_0^1 dx \left\{ x \left[|\Psi_+^+|^2 + |\Psi_-^+|^2 \right. \right. \\ & \left. \left. + \Psi_+^+ * \Psi_+^- + \Psi_-^+ * \Psi_-^- \right] - |\Psi_+^+|^2 + |\Psi_-^+|^2 \right\} \end{aligned}$$



$$\mathcal{L}^z(b_\perp) = \frac{1}{2(2\pi)} \int_0^1 dx (1-x) |\Psi_-^+|^2$$

Jaffe-Manohar OAM

in absence of gluons: Kinetic OAM = Jaffe-Manohar OAM

Quark OAM from Wigner distributions

M. Burkardt

straight line ($\rightarrow J_i$)

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

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

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

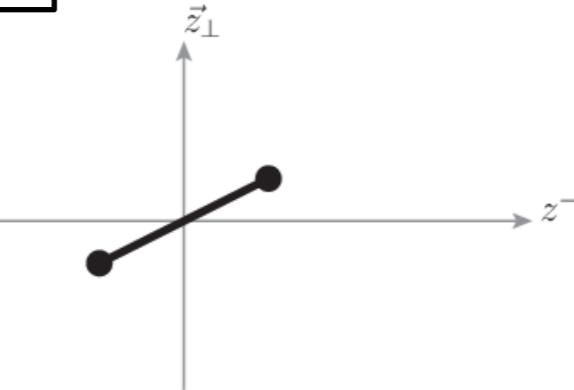
light-cone staple (\rightarrow Jaffe-Manohar)

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

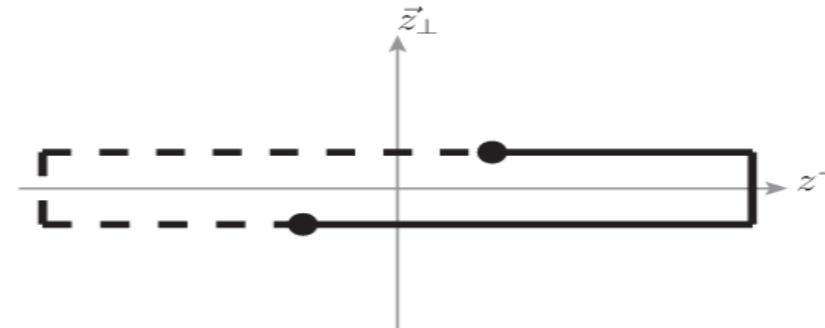
$$\mathcal{L}_q = \int d^3x \langle P, S | \bar{q}(\vec{x}) \gamma^+ (\vec{x} \times i\vec{D})^z q(\vec{x}) | P, S \rangle$$

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

Kinetic



Canonical



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

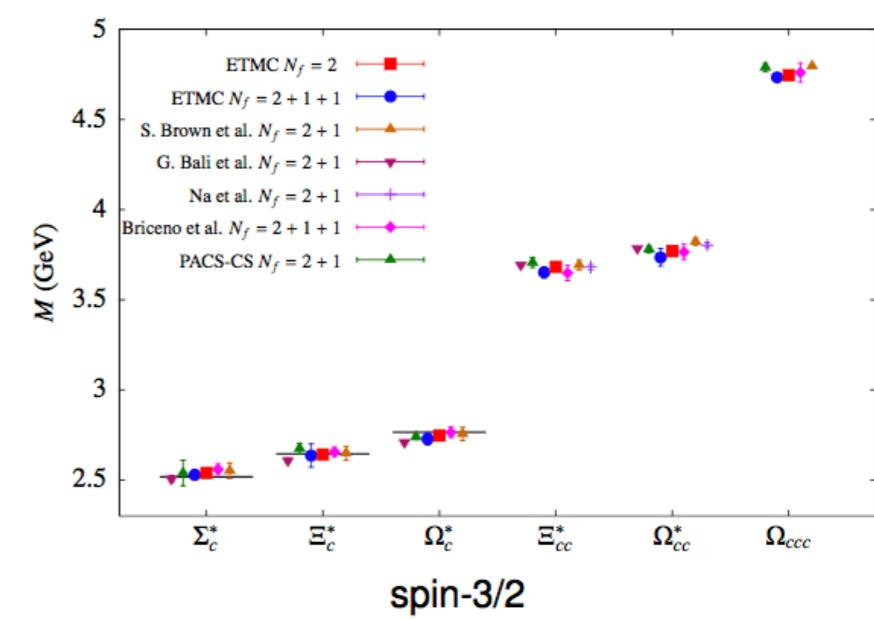
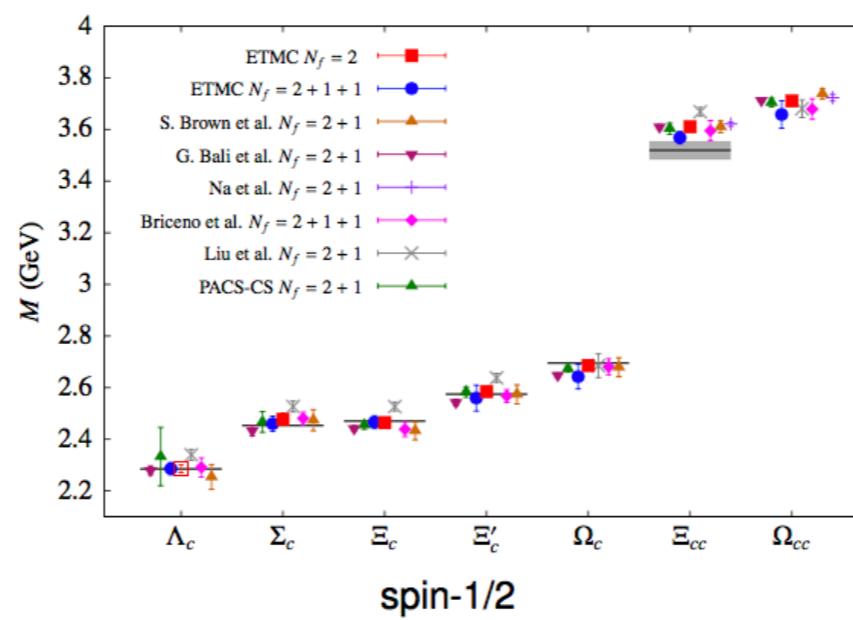
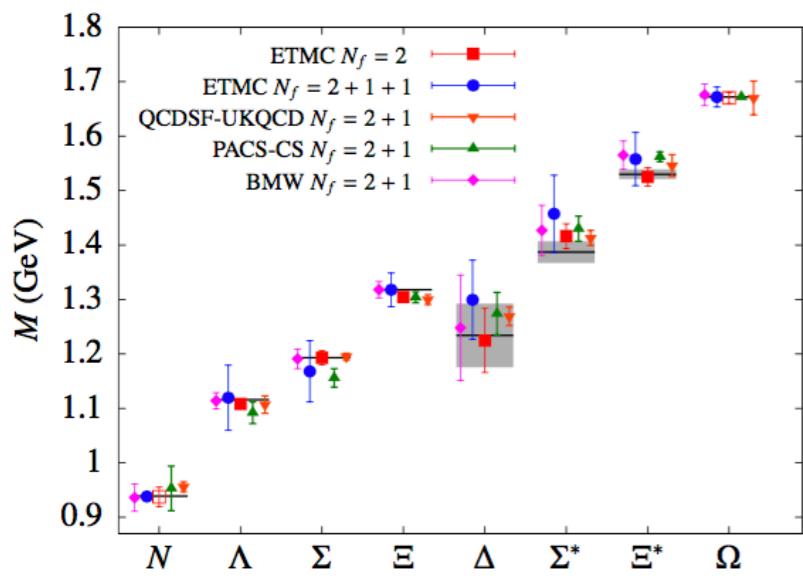
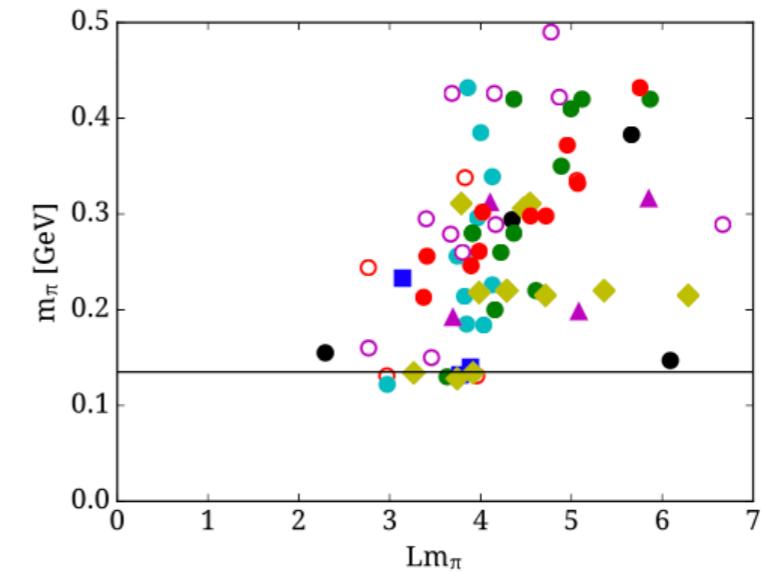
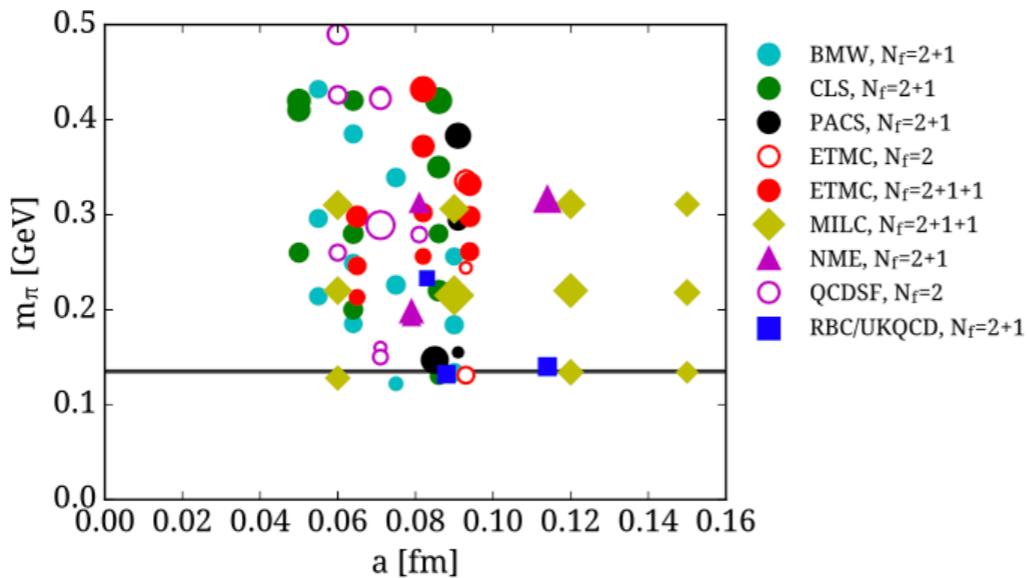
$$\mathcal{L}_{JM}^q - L_{Ji}^q = -g \int d^3x \langle P, S | \bar{q}(\vec{x}) \gamma^+ [\vec{x} \times \int_{x^-}^\infty dr^- F^{+\perp}(r^-, \mathbf{x}_\perp)]^z q(\vec{x}) | P, S \rangle$$

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

What is known or
can be learned from
lattice QCD/
phenomenology ?

Hadron masses (lattice)

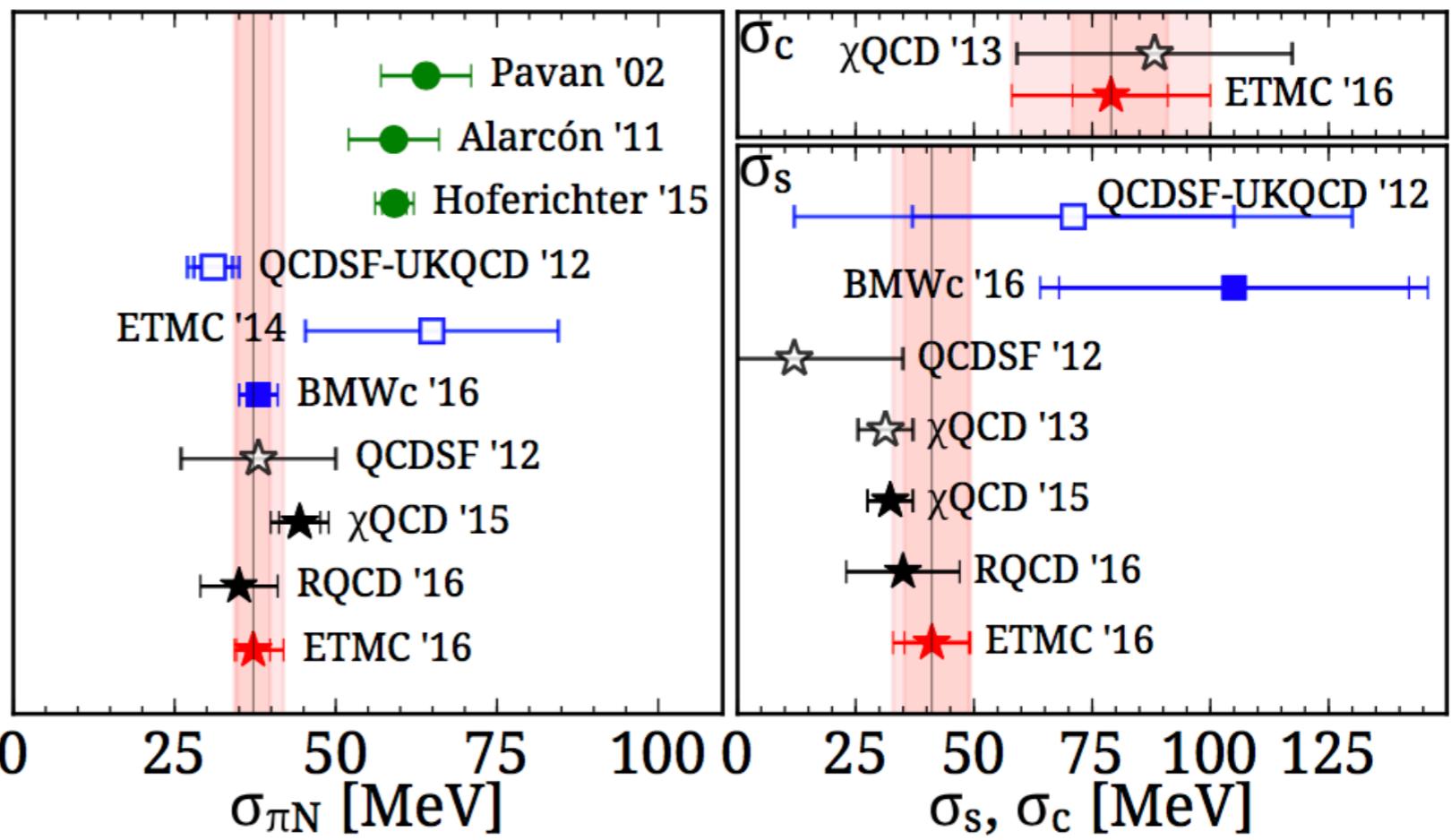
C. Alexandrou, C. Hoelbling, H.W. Lin, K.F. Liu, D. Richards, Y. Yang



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:

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

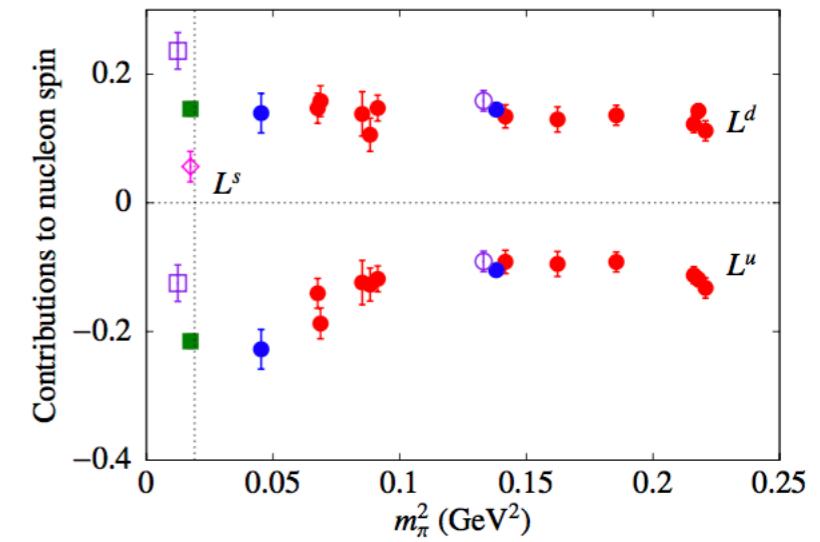
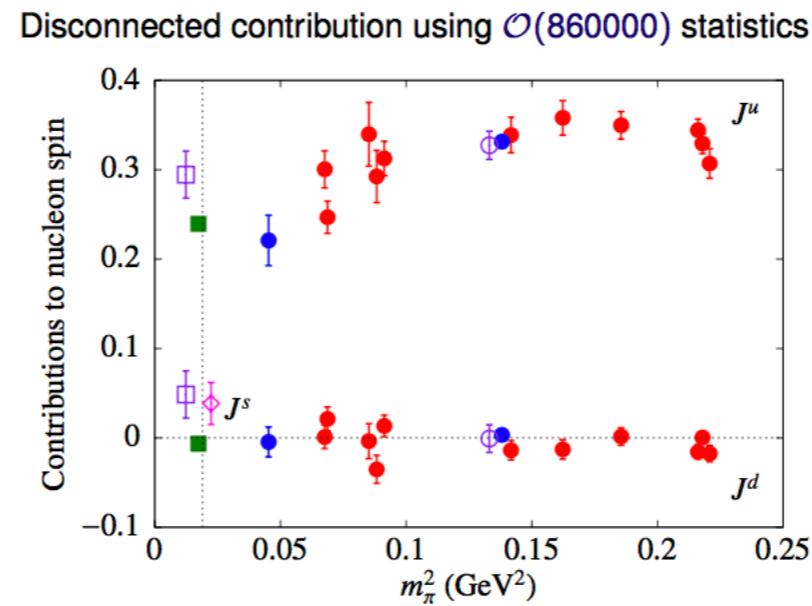
$$M_N|_{m_s=0, m_{ud} \text{ const.}} = 881(13)(4) \text{ MeV} \quad \sigma_s^N = 55.5(5.5)(4.1) \text{ MeV}$$

Nucleon spin (lattice)

C. Alexandrou

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

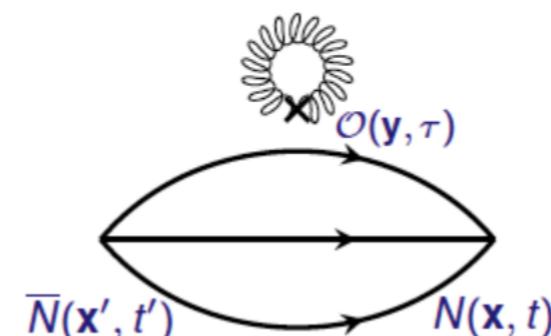
$$\begin{aligned} \frac{1}{2} \Delta \Sigma^u &= 0.413(13), & \frac{1}{2} \Delta \Sigma^d &= -0.193(7), & \frac{1}{2} \Delta \Sigma^s &= -0.021(5) \\ J^u &= 0.310(26), & J^d &= 0.056(26), & J^s &= 0.046(21) \\ L^u &= -0.104(29), & L^d &= 0.249(27), & L^s &= 0.067(21) \end{aligned}$$



→ Gluonic contribution calculated on lattice !

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

$$\langle x \rangle_g^R = Z_{gg} \langle x \rangle_g + Z_{gq} \langle x \rangle_{u+d+s} = 0.273(23)(24)$$



$B_g(0) = 0$

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

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

pion-nucleon σ -terms: ChPT

J.M. Alarcon

- Convergence

$$\mathcal{O}(p^2)$$

②

$$78(4) \text{ MeV}$$

$$\mathcal{O}(p^3)$$

①

$$-19 \text{ MeV}$$

$$\mathcal{O}(p^{7/2})$$

$$-6 \text{ MeV}$$

$$\mathcal{O}(p^4)$$

②

④

$$-3(2) \text{ MeV}$$

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

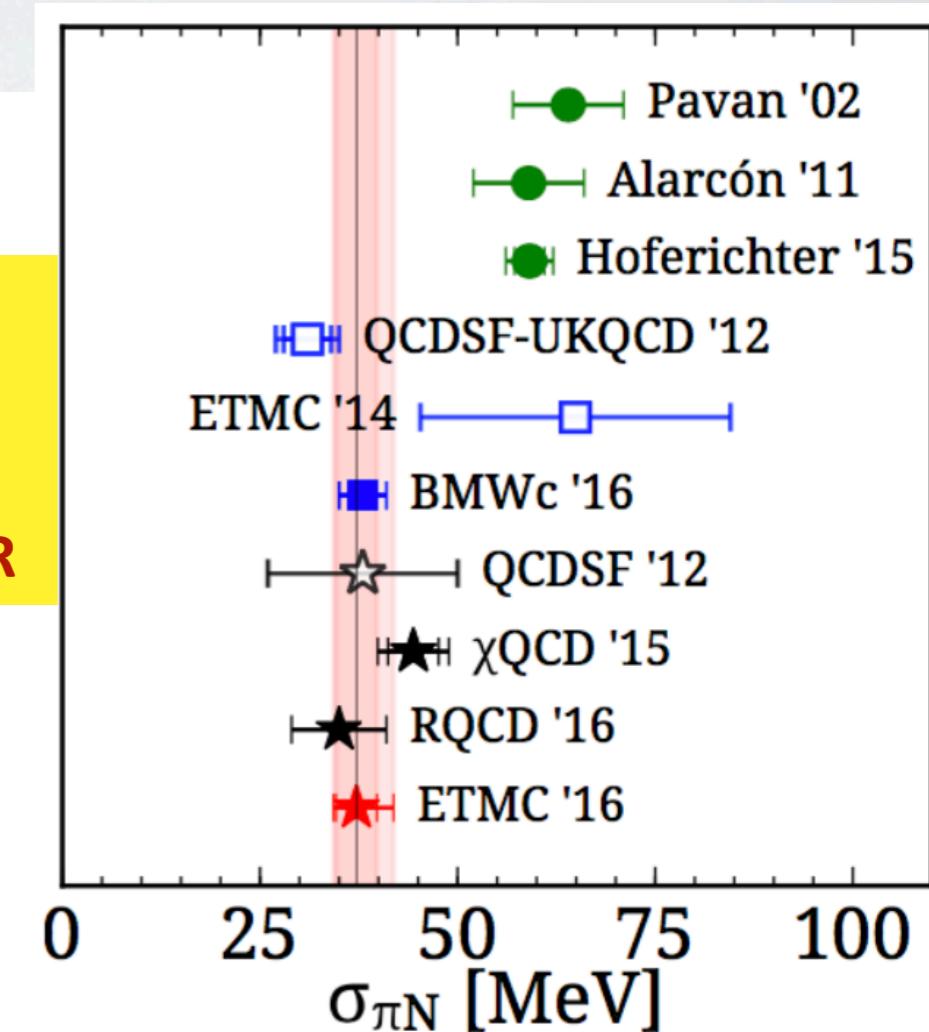
Modern πN
scattering data

π -atoms
[Baru, et al. NPA
872 (2011)]

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

~ 3 σ tension
between
recent lattice
and ChPT / DR

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



pion-nucleon σ -terms: dispersion theory

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

- 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, Mei  ner 1996]

- $\Delta_D - \Delta_\sigma = -(1.8 \pm 0.2)$ MeV

[Hoferichter et al. 2012]

- Isospin breaking in the CD theorem shifts $\sigma_{\pi N}$ by +3.0 MeV

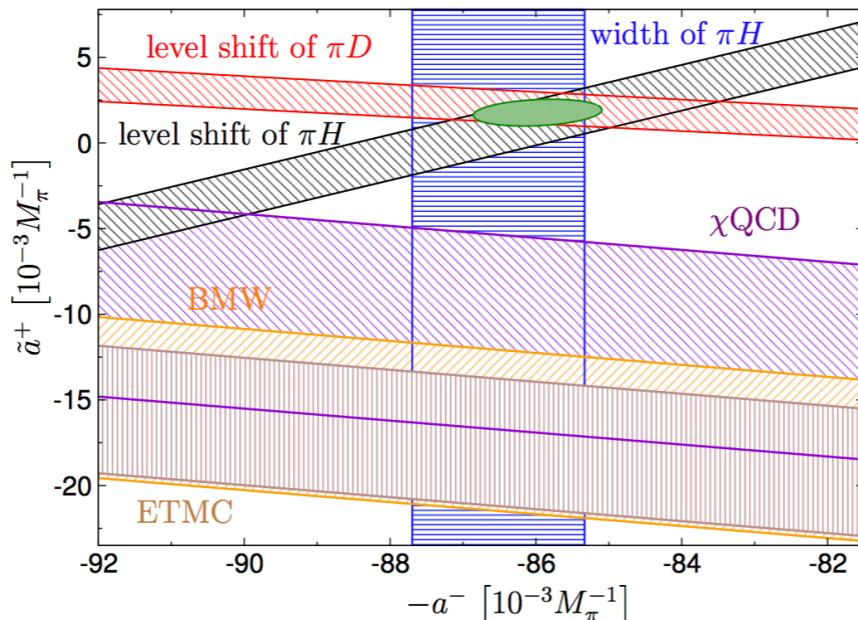
- Final results: $\sigma_{\pi N} = (59.1 \pm 1.9_{\text{RS}} \pm 3.0_{\text{LET}})$ MeV = (59.1 ± 3.5) MeV

[MH, JRE, Kubis, Mei  ner]

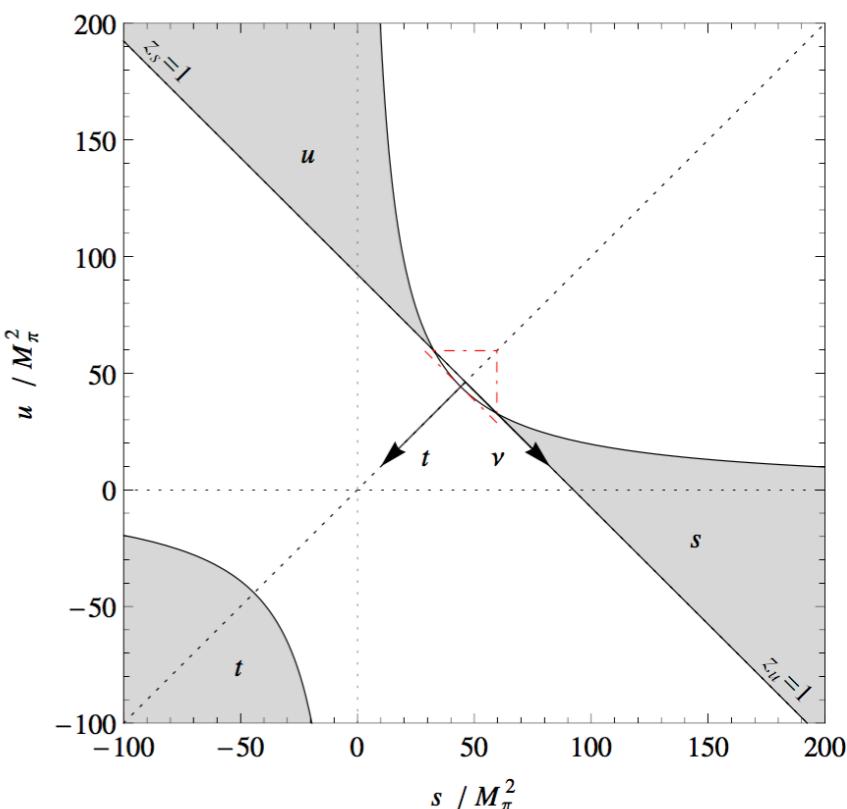
- $\sigma_{\pi N}$ depends linearly on the scattering lengths:

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

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



J.Ruiz de Elvira



pion-nucleon σ -terms: ChPT

J.M. Alarcon

- Phenomenological extractions rely on two different sources:

πN -scattering data

- Inconsistent data base
($\pi^\pm N \rightarrow \pi^\pm N$ vs CEX reactions)
- Coulomb [Tromborg, Waldenstrom and Overbo, PRD 15 (1977)].

π -atom spectroscopy

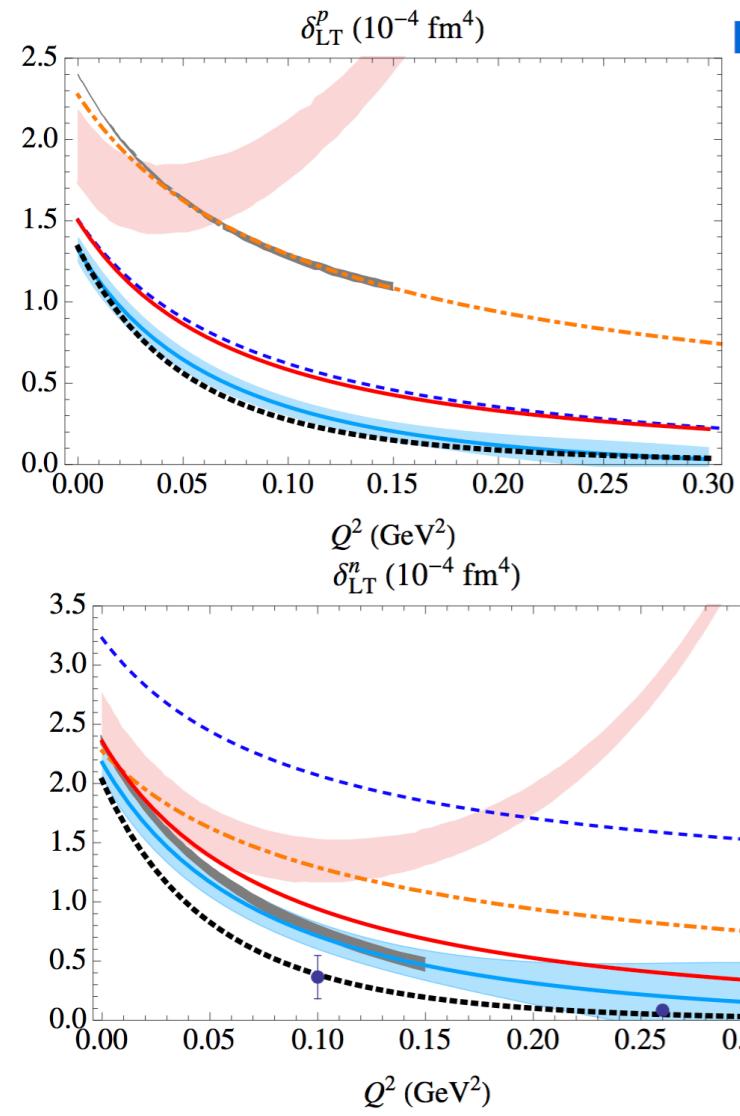
- Experimental uncertainties negligible compared to theoretical error relating (ϵ, Γ) to a^\pm .
- πD scattering, isospin violation, Coulomb...

What can be done?

- Analysis of the πN world data base.
- Reanalysis of Coulomb corrections.
- Reanalysis of extraction of SL through ϵ and Γ .

Nucleon structure corrections to precision observables

V. Pascalutsa



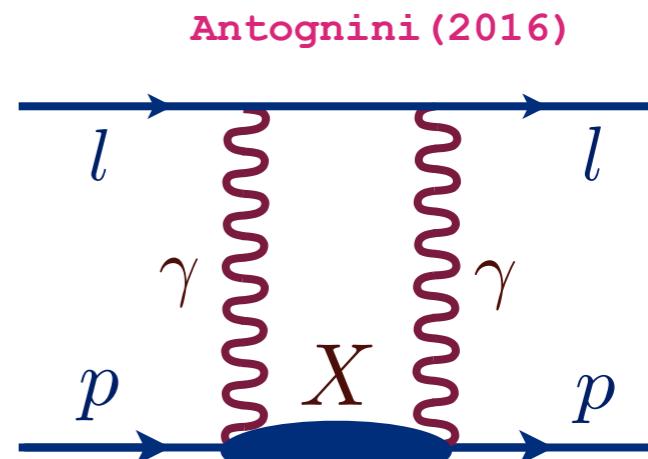
LT spin polarizability

Curves:

- MAID (empir.)
- LO-HBChPT
- NLO-HBChPT
- NLO-IRBChPT
[Bernard et al (2006)]
- LO-BChPT
- NLO-BChPT
[Lensky, Alarcon & V.P, PRC (2014)]
- NLO-BChPT
[Bernard et al (2013)]

Data points:
K. Slifer, J.-P. Chen, S. Kuhn, A. Deur et al
[Jefferson Lab Spin Program]

forthcoming PSI
1S-HFS measurement in μH
with 1 ppm accuracy



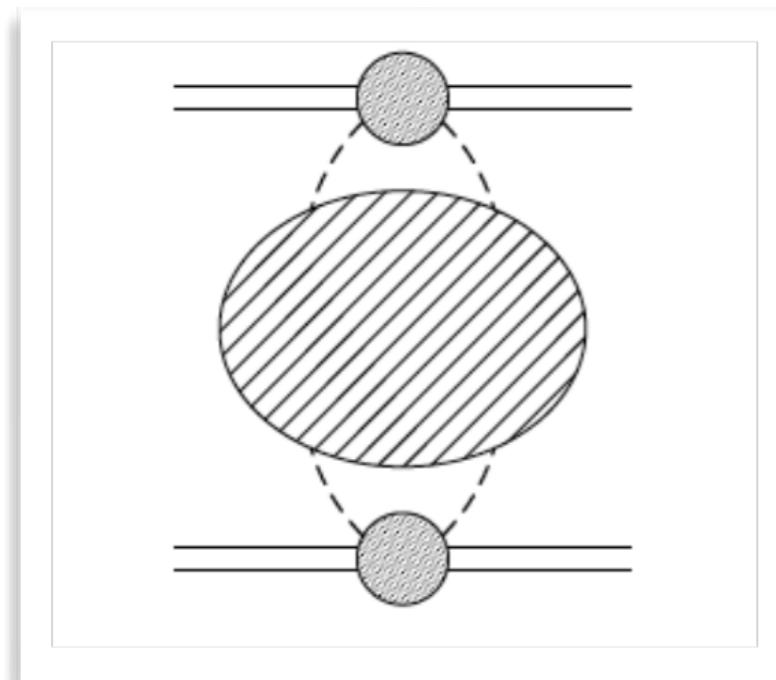
	relative contribution ($\times 10^{-3}$)	relative uncertainty
X=p (Zemach)	-7,36	140 ppm
X=p (recoil)	0,8476	0.8 ppm
X=p, $\pi N, \dots$ (polarizability)	0,363	86 ppm
total	-6,149	164 ppm

Carlson, Nazaryan, Griffioen (2011)

Tomalak et al. (2016)

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

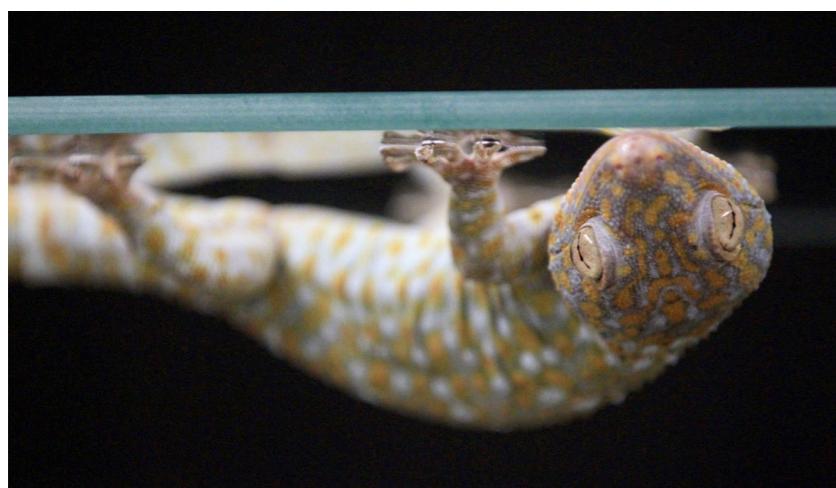
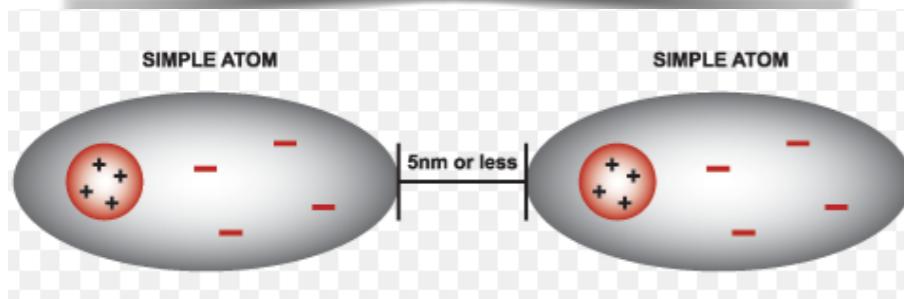
$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} d_n \langle h | \frac{1}{2} G_{0i}^a (D^0)^{n-2} G_{0i}^a | h \rangle$$

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



J/ ψ -p scattering amplitude, existence of J/ ψ -nuclear bound states ?

H.W. Lin

- threshold ψ -p scattering amplitude:

$$T_{\psi p} = 8\pi(M + M_\psi) \color{red}{a_{\psi p}} \rightarrow \text{s-wave } \psi\text{-p scattering length} \quad (\text{positive: attraction})$$

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

in linear density approximation
 ψ -nuclear matter binding energy

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

Kaidalov, Volkovitsky
 (1992)

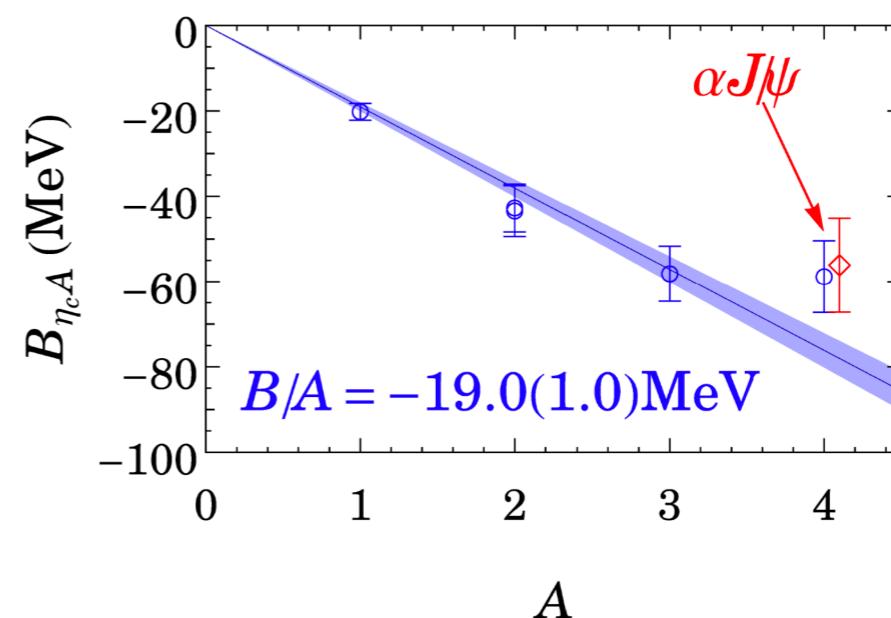
- many estimates:

- 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)



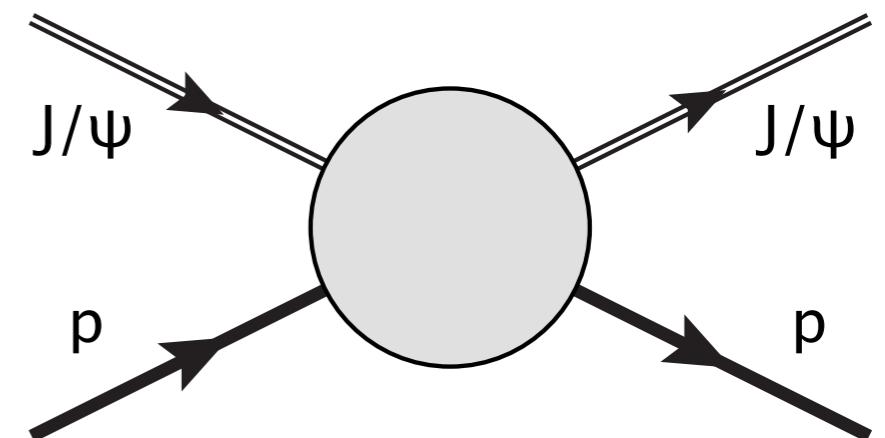
forward J/ ψ - p scattering (I)

O. Gryniuk

spin-averaged amplitude:

$$T_{\psi p}(\nu)$$

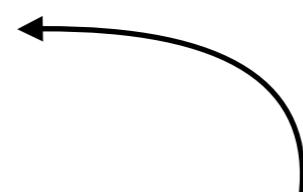
kinematic variable: $\nu \equiv p \cdot q = \frac{s-u}{4}$



unitarity



$$\text{Im } T_{\psi p}(\nu) = 2\sqrt{s} q_{\psi p} \sigma_{\psi p}^{tot}(\nu)$$



causality + crossing

subtracted dispersion relation:

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

parameterizing cross section:

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

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

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

directly sensitive to $a_{\psi p}$
31

forward J/ ψ - p scattering (II)

Vector meson dominance (VMD) assumption:

Barger, Phillips (1975)

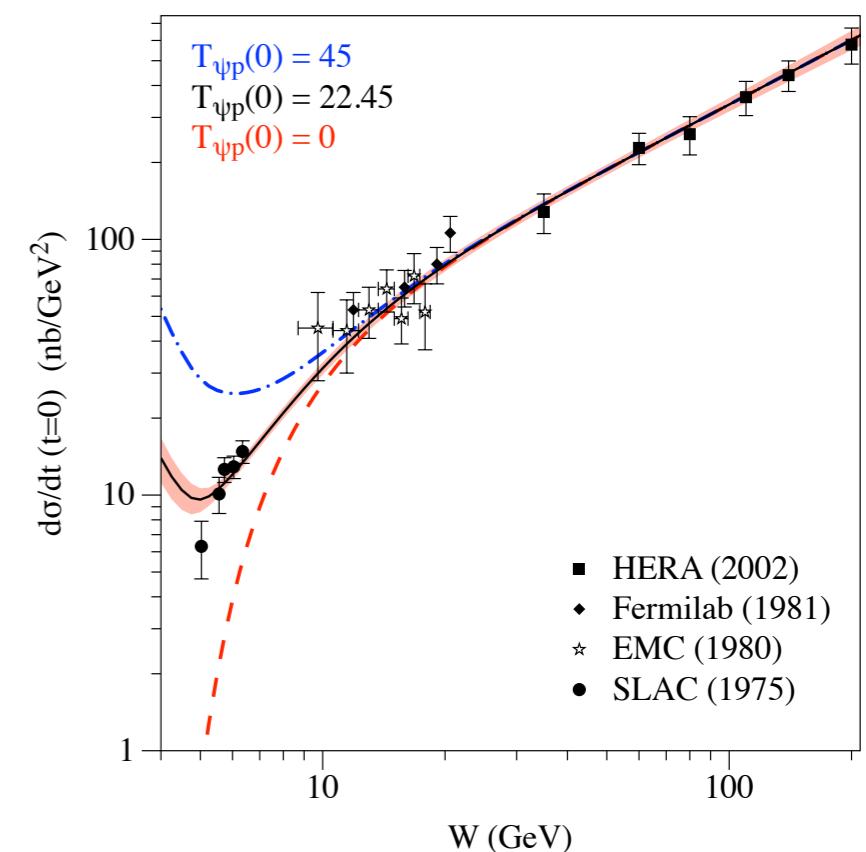
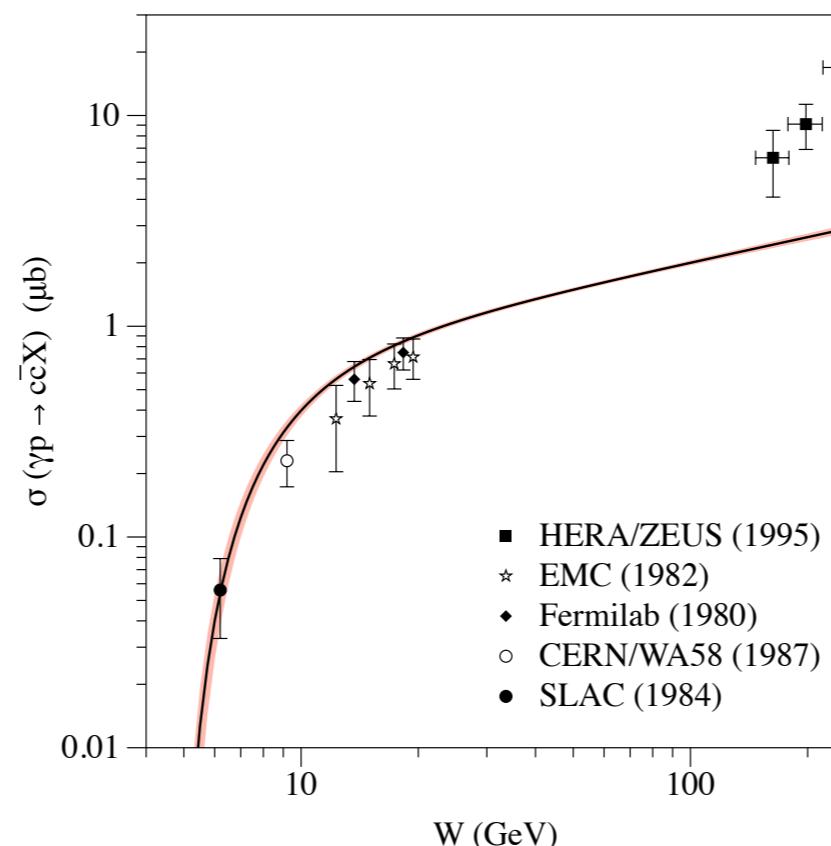
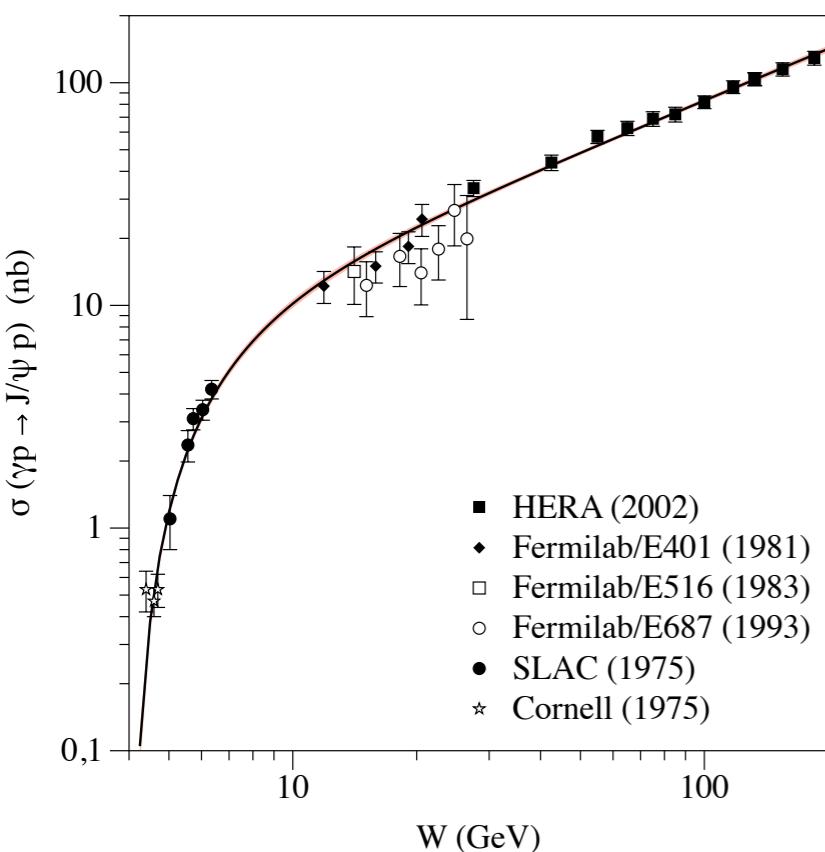
Redlich, Satz, Zinovjev (2000)

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

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

forward differential cross section:

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



simultaneously fitting

Gryniuk, vdh (2016)



$a_{\psi p} \sim 0.05$ fm

$B_\psi \sim 3$ MeV

Thanks for your
attention and
participation !