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Effective particles in quantum field theory

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The concept of effective particles is introduced in the Minkowski space-time Hamiltonians in quantum field theory using a new kind of the relativistic renormalization group procedure that does not integrate out high-energy *modes* but instead integrates out the large *changes* of invariant mass. The new procedure is explained using examples of known interactions. Some applications in phenomenology, including processes measurable in colliders, are briefly presented.

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Outline

Renormalization group procedure for effective particles (**RGPEP**)

in quantum field theory, is illustrated with a few examples

- asymptotic freedom in QCD
- jet production in TeV pion-nucleus collisions

Insights mentioned concerning:
ridge effect in pp collisions, proton radius in QED and CQM potential in AdS/QCD.

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Basic premise

QCD is a laboratory for studying problems concerning mass generation, symmetry breaking, and confinement, with potential implications in other areas of particle theory.

Basic theoretical issues: size of quanta and RG scale

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Drawback of the concept of a quantum field operator

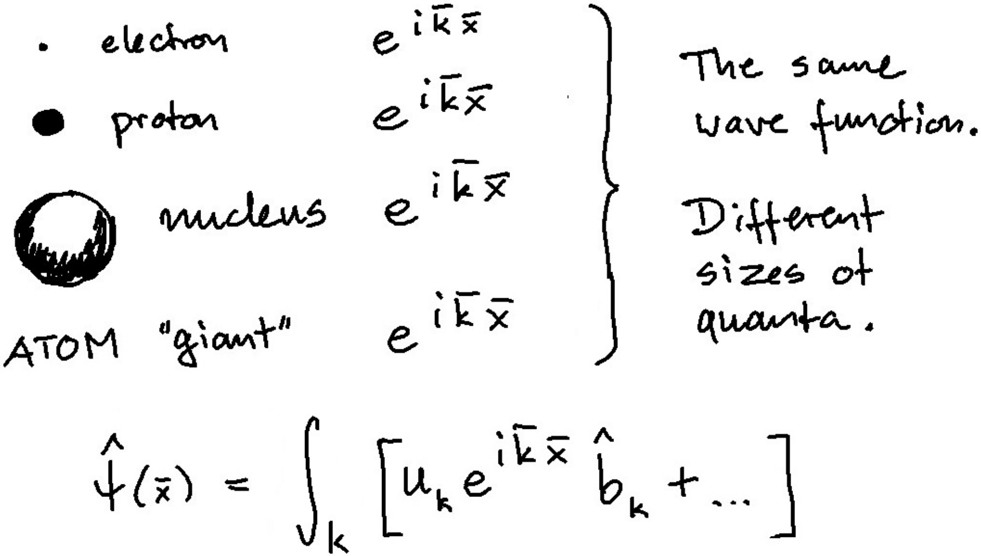

FIG. 1: **Quantum field operators are blind to the size of individual quanta.**

Canonical quantization of the YM field

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{2}\,\mathrm{tr}\,F^{\mu\nu}F_{\mu\nu} \\
F^{\mu\nu} &= \partial^\mu A^\nu - \partial^\nu A^\mu + ig[A^\mu, A^\nu] \\
\mathcal{T}^{\mu\nu} &= -F^{a\mu\alpha}\partial^\nu A^a_\alpha + g^{\mu\nu}F^{a\alpha\beta}F^a_{\alpha\beta}/4 \\
P^\nu &= \int d\sigma_\mu \, \mathcal{T}^{\mu\nu} \\
\mathcal{H} &= \mathcal{T}^{00}
\end{aligned}
$$

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$$\mathcal{H}_{YM} = \mathcal{H}_{A^2} + \mathcal{H}_{A^3} + \mathcal{H}_{A^4}$$

quantization $\quad \hat{A}^\mu = \sum_{\sigma c} \int_k \left[t^c \, \varepsilon^\mu_{k\sigma} \, a_{k\sigma c} \, e^{-ikx} + t^c \, \varepsilon^{\mu *}_{k\sigma} \, a^\dagger_{k\sigma c} \, e^{ikx} \right]_{on \ \Sigma}$

$$\hat{H}_{YM} = \int_\Sigma \, : \mathcal{H}_{YM}(\hat{A}) :$$

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$$\mathcal{H}_{A^3} = g\ i\partial_\alpha A^a_\beta\ [A^\alpha, A^\beta]^a$$

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$$\hat{H}_{A^3} = \int_{x \in \Sigma} : g \; i\partial_\alpha A^a_\beta(x) \; [A^\alpha(x), A^\beta(x)]^a :$$

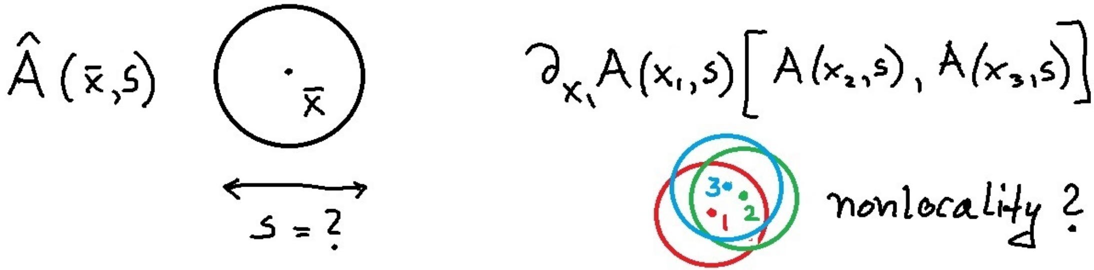

FIG. 2: Nonlocality is approximated by a local interaction for wavelengths greater than s. The particle size s is the scale parameter in the RGPEP.

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$$\hat{H}_{A^3,s} = \int_{x_i \in \Sigma} g_s(x_1, x_2, x_3) \; : i\partial_\alpha A^a_\beta(x_1, s) \, [A^\alpha(x_2, s), A^\beta(x_3, s)]^a :$$

$$g_s(x_1, x_2, x_3) = \, ?$$

SDG, K. G. Wilson, Phys. Rev. D **48**, 5863 (1993)

K. G. Wilson *et al.*, Phys. Rev. D **49**, 6720 (1994)

F. J. Wegner, Ann. Phys. (Leipzig) **3**, 77 (1994)

. . .

SDG, Acta Phys. Pol. B **43**, 1843 (2012)

M. Gomez-Rocha, SDG, Phys. Rev. D **92**, 065005 (2015)

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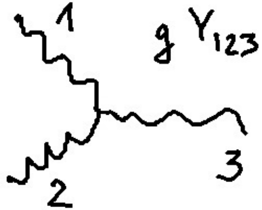
RGPEP initial condition at $s = 0$ for local QCD

$$\hat{H}_{A^3, s=0} = \int_{x \in \Sigma} : g \; i\partial_\alpha A^a_\beta(x,0) \; [A^\alpha(x,0), A^\beta(x,0)]^a :$$

$$\hat{A}^\mu(x, s=0) = \sum_{\sigma c} \int_k \left[t^c \, \varepsilon^\mu_{k\sigma} \, a_{k\sigma c, s=0} \, e^{-ikx} + t^c \, \varepsilon^{\mu *}_{k\sigma} \, a^\dagger_{k\sigma c, s=0} \, e^{ikx} \right]_{on \; \Sigma}$$

$$\hat{H}_{A^3, s=0} = \sum_{123} \int_{123} \delta_{12.3} \; \left[g \, Y_{123} \; a^\dagger_{1,0} \, a^\dagger_{2,0} \, a_{3,0} + g \, Y^*_{123} \; a^\dagger_{3,0} \, a_{2,0} \, a_{1,0} \right]$$



RGPEP

$$H_0(a_0) = \sum_{n=2}^{\infty} \sum_{i_1,i_2,...,i_n} c_0(i_1, ..., i_n)\ a^\dagger_{i_1,0} \cdots a_{i_n,0}$$

$$\boxed{c_0 = \text{the initial condition, including } CT_R}$$

$$H_s(a_s) = \sum_{n=2}^{\infty} \sum_{i_1,i_2,...,i_n} c_s(i_1, ..., i_n)\ a^\dagger_{i_1,s} \cdots a_{i_n,s}$$

$$\boxed{c_s = ?}$$

$g_s(i_1, i_2, i_3)$, among others

RGPEP generator and non-perturbative QCD

$$H_s(a_s) = H_0(a_0)$$

$$a_s = U_s \, a_0 \, U_s^\dagger$$

$$H_s = H_f + H_I$$

$$H_s' = [G_s, H_s]$$

$$G_s = [H_f, \tilde{H}_s]$$

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$$\textbf{NP} \quad \textbf{QCD} \;\rightarrow\; H_s' = \Big[[H_f, \tilde{H}_s], H_s\Big]$$

$$\textbf{AF} \;\; \textbf{pQCD} \;\rightarrow\; H_s = H_f + gH_{1s} + g^2 H_{2s} + g^3 H_{3s} + \ldots$$

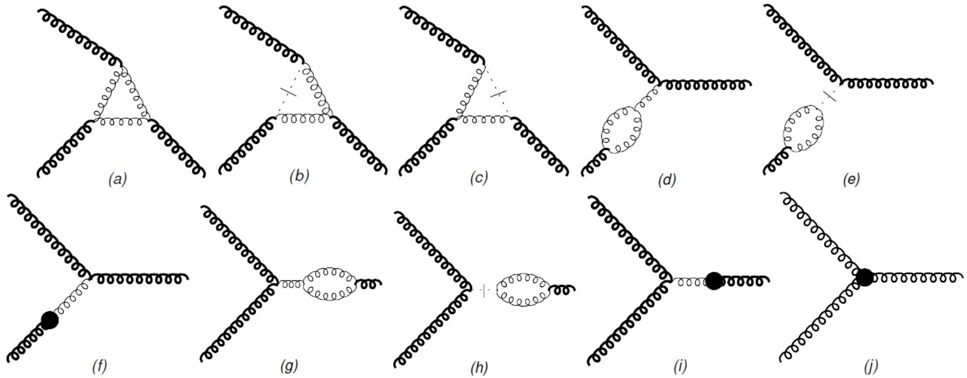

FIG. 3: Third-order contributions to the three-gluon vertex

$$\dot{H}_{A^3\,(1+3)s} = \sum_{123} \int_{123} \delta_{12.3}\; e^{-s^4\,\mathcal{M}_{12}^4} \left[V_{s123}\, a_{1,s}^\dagger a_{2,s}^\dagger a_{3,s} + V_{s123}^*\, a_{3,s}^\dagger a_{2,s} a_{1,s} \right]$$

$$\lim_{\kappa^\perp \to 0} V_{s123} = g_s\, Y_{123} \qquad\qquad g_s \;=\; g_0 + \frac{g_0^3}{48\pi^2} N_c\, 11\, \ln\frac{s}{s_0}$$

RGPEP Hamiltonian $\beta(s)$ $\quad\leftrightarrow\quad$ Gross-Wilczek-Politzer $\beta(\lambda)$

Minkowskian s $\quad\leftrightarrow\quad$ $1/\lambda$ Euclidean

three-dimensional length $\quad\leftrightarrow\quad$ four-dimensional length

M. Gomez-Rocha, SDG, Phys. Rev. D **92**, 065005 (2015)

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Effective-particle picture of nucleons

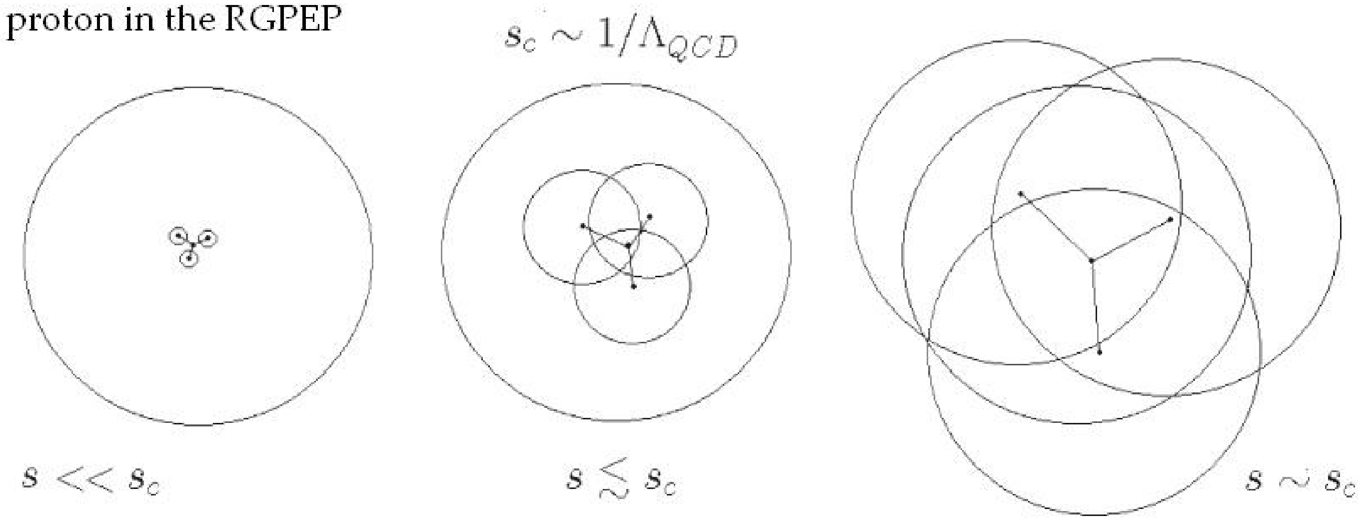

FIG. 4: The RGPEP scale-dependent proton picture

Effective-particle color arrangement

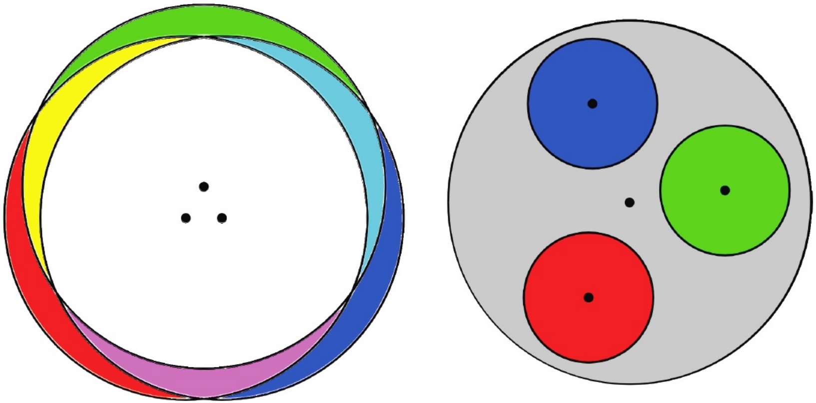

FIG. 5: Nucleon white interior with colored boundary coupling to mesons

Ridge effect in *pp* collisions from 7 TeV to 13 TeV

P. Kubiczek, SDG, Lith. J. Phys. **55**, 155 (2015)

Proton radius in QED

How do we go from QFT to the Schrödinger equation

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\partial\!\!\!/ - eA\!\!\!/ - m)\psi$$

$$\mathcal{L} \to \mathcal{H} \to \hat{H} = \int d^3x\, \hat{\mathcal{H}} \to \hat{H}_R = \int d^3x\, \hat{\mathcal{H}}_R \to \hat{H}_R + \hat{H}_{CT} \to \hat{H}_s$$

$\boxed{\text{Family of effective Hamiltonians: } \hat{H}_{QEDs}}$ $\qquad s = 0$ in canonical theory

$$\boxed{\hat{H}_{QEDs}|\psi_s\rangle = E|\psi_s\rangle \quad \to \quad \hat{H}_{Sch} = ?}$$

How does the parameter s enter in $\hat{H}_{Sch}$?

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The RGPEP interpretation of atomic valence constituents

$$\begin{bmatrix} \cdots \\ \cdot\cdot \\ e\gamma e\bar{e}p\gamma \\ e\gamma p\gamma \\ e\gamma p \\ \boxed{ep} \end{bmatrix} \rightarrow \begin{bmatrix} \cdots \\ \cdot\cdot \\ e\gamma e\bar{e} \\ e\gamma\gamma \\ e\gamma \\ e \end{bmatrix} \times \begin{bmatrix} \cdots \\ \cdot\cdot \\ pe\bar{e} \\ p\gamma\gamma \\ p\gamma \\ p \end{bmatrix} + \ldots \quad \sim \quad |e_s p_s\rangle + \ldots$$

$$\psi_0(e_0, p_0) + \infty \quad \rightarrow \quad \psi_s(e_s, p_s) + corrections$$

SDG, Phys.Rev. D **90**, 045020 (2014).

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"True" Schrödinger equation in QED $\quad \hat{H}_{QEDs}|\psi_s\rangle = E|\psi_s\rangle$

$$\frac{\vec{p}^{\,2}}{2\mu}\,\psi_s(\vec{p}) + \int \frac{d^3k}{(2\pi)^3}\, V_s(\vec{p},\vec{k}\,)\,\psi_s(\vec{k}\,) = -E_B\,\psi_s(\vec{p})$$

$$V_s(\vec{p},\vec{k}\,) = e^{-s^4(\vec{p}^{\,2}-\vec{k}^{\,2})^2/c^4}\;\frac{-4\pi}{(\vec{p}-\vec{k}\,)^2}\;G_E(\vec{q}^{\,2}) \qquad \mathbf{4\%}\ !$$

definition of $\vec{p}$ in atoms matches **AdS/QFT** SDG, Acta Phys. Pol. B **42**, 1933 (2011)

$$\beta = m_l/(m_p + m_l)\ , \qquad c = \sqrt{m_l m_p}/(m_l + m_p)\ , \qquad x = p_l^+/(p_l^+ + p_p^+)$$

$$p^\perp = c\ \left[(1-x)\,p_l^\perp - x\,p_p^\perp\right]/\sqrt{x(1-x)} \qquad \text{Brodsky} - \text{de Teramond}$$

$$p^z = c\,(m_l + m_p)\,(x-\beta)/\sqrt{x(1-x)} \qquad \text{holography}$$

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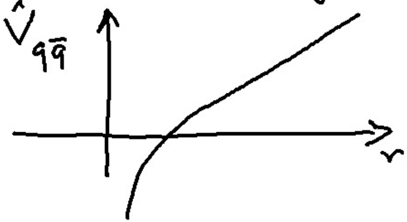
CQM potential in AdS/QCD

Instant form of dynamics



$$\hat E = \hat E_q + \hat E_{\bar q} + \hat V_{q\bar q}$$

$$\hat V_{q\bar q} \sim \sigma r \;\Rightarrow\; M \sim \sigma r$$

Front form of dynamics

$$\hat M^2 = \left(\hat p_q^- + \hat p_{\bar q}^- + \hat U_{q\bar q}\right)\hat P^+ - \hat P^{\perp 2}$$

$$\hat U_{q\bar q} \sim \frac{1}{4}\varkappa^4 r^2 \;\Rightarrow\; M^2 \sim \frac{1}{4}\varkappa^4 r^2$$

A. Trawiński, SDG, *Model of the AdS/QFT duality,* Phys. Rev. D **88**, 105025 (2013)

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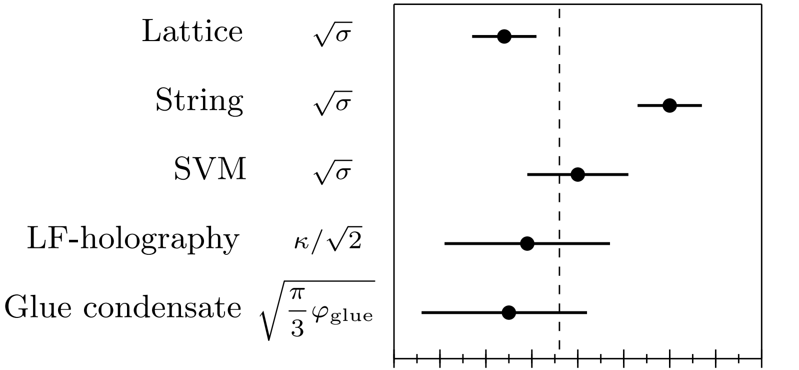
Hadron masses at maximal separation of effective $q\bar{q}$ pair



WKB comparison of $M \sim \sigma r_{\max}$ and $M^2 \sim \frac{\kappa^4}{4} r_{\max}^2$.

A. Trawiński, S. Głazek, S. Brodsky, G. de Teramond, H. Dosch, Phys. Rev. D **90**, 074017 (2014).

Jet production in pion-nucleus collisions

A. P. Trawiński, PhD Thesis, UW 2016

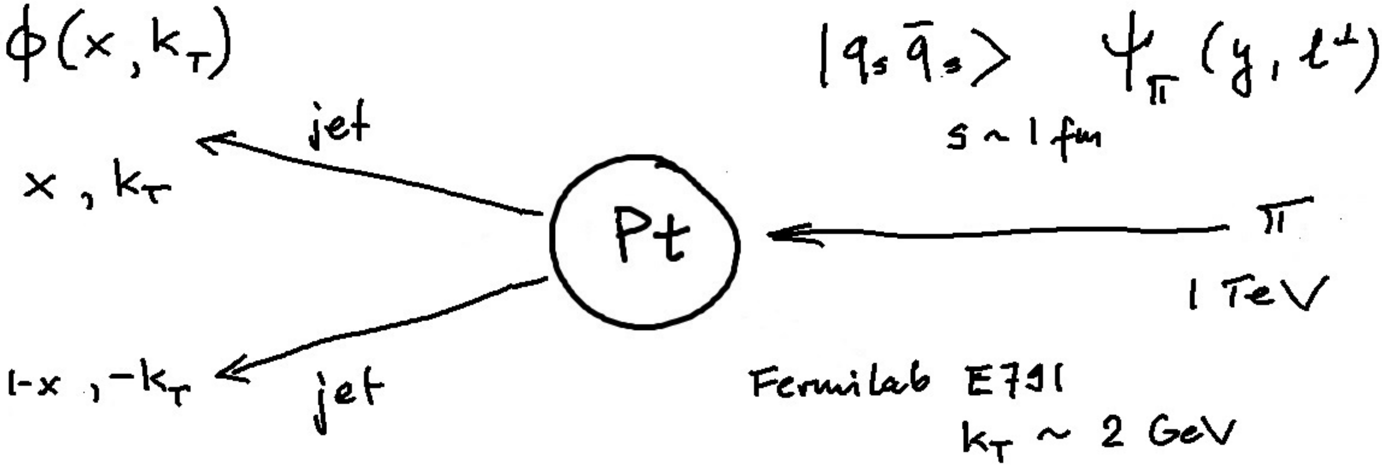
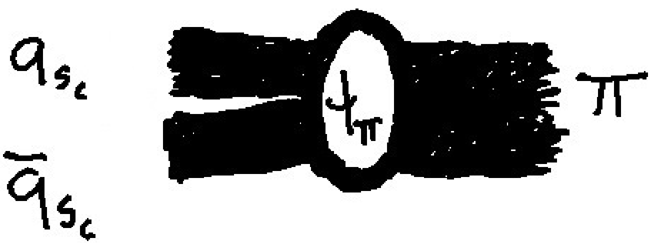


FIG. 6: Pion is wedged into two quark jets by a nucleus.

The RGPEP pion with U_{eff} from AdS/QCD

the RGPEP scale $s_c \sim 1/\Lambda_{QCD}$



$$\psi_\pi \sim e^{-s_c^2 \mathcal{M}^2_{q\bar{q}}}$$

$$\mathcal{M}^2_{q\bar{q}} = \frac{k^{\perp 2} + m^2_{s_c}}{x(1-x)}$$

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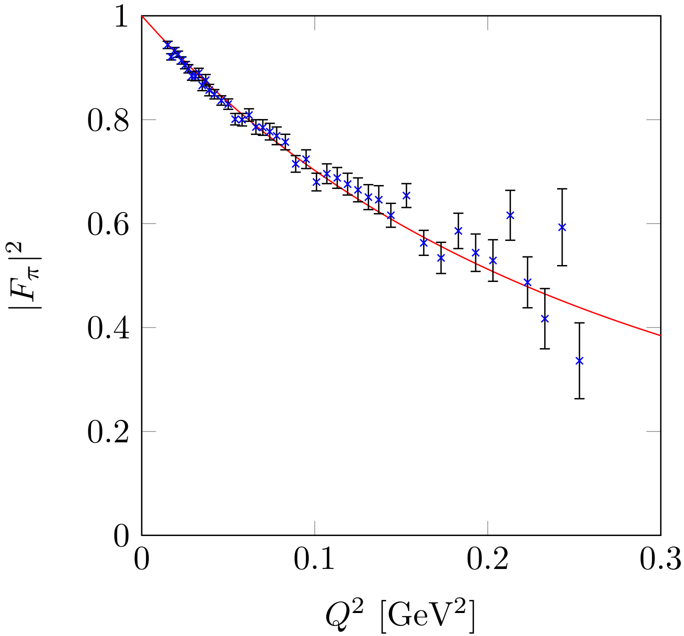
The RGPEP pion of ~ 1 fm quarks with $U_{\rm eff}$ from AdS/QCD



Data: A. R. Amendolia, Nucl. Phys. B **277**, 168 (1986) Theory: A. P. Trawiński, PhD Thesis, UW 2016

$|\pi\rangle = |q_{s_c}\bar{q}_{s_c}\rangle$ in terms of quarks and gluons with $1/s \sim 100$ GeV

$$q_s = U_s \, q_0 \, U_s^\dagger$$

$$q_{s_1} = U_{s_1} U_{s_2}^\dagger \, q_{s_2} \, U_{s_2} U_{s_1}^\dagger$$

$$W = U_{s_1} U_{s_2}^\dagger$$

$$|\pi\rangle = |q_{s_c}\bar{q}_{s_c}\rangle$$

$$= W \, |q_s \bar{q}_s\rangle$$

$$s \sim 1/100 \text{ GeV}$$

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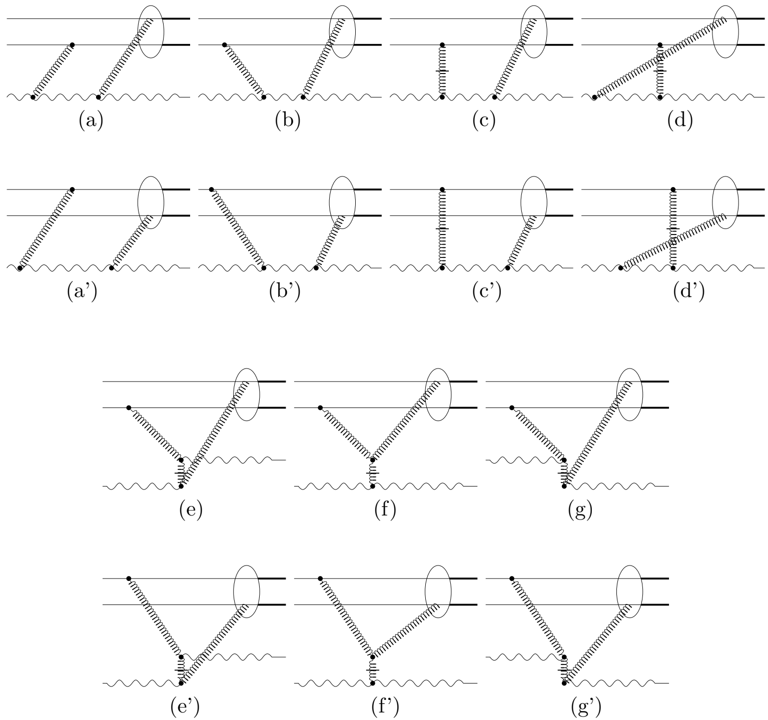

FIG. 7: Examples of pion splitting on gluons in a nucleus, described using H_{QCDs} with $1/s \sim 100$ GeV.

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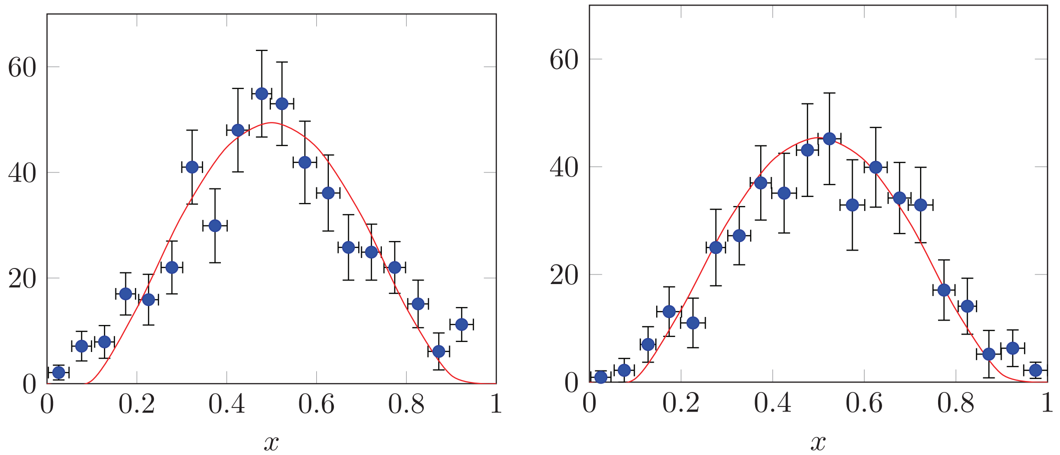
$1.25\ \mathrm{GeV} < |k^{\perp}| < 1.5\ \mathrm{GeV}$ $\quad$ $1.5\ \mathrm{GeV} < |k^{\perp}| < 2.5\ \mathrm{GeV}$



Jet counts distribution $\phi(x, k_T)$, for jets induced by pions impinging on Pt, in two jet-k_T bins.

Data from E791, Phys. Rev. Lett. **86**, 4768 (2001); theory from A. P. Trawiński, PhD Thesis, UW 2016.

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Conclusion:

RGPEP opens new options for developing QFT

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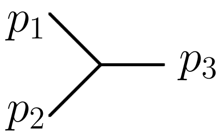
Regularization example $\hat{H}_{A^3} \to \hat{H}_{A^3\,R}$

$$\hat{H}_{A^3} = \sum_{123} \int_{123} \delta_{12.3} \left[g\, Y_{123}\, a_1^\dagger a_2^\dagger a_3 + g\, Y_{123}^*\, a_3^\dagger a_2 a_1 \right]$$

$$\hat{H}_{A^3\,R} = \sum_{123} \int_{123} \delta_{12.3}\ R \left[g\, Y_{123}\, a_1^\dagger a_2^\dagger a_3 + g\, Y_{123}^*\, a_3^\dagger a_2 a_1 \right]$$



$$x_1 = p_1^+/p_3^+ = x \qquad k_1^\perp = p_1^\perp - x_1 p_3^\perp = \kappa^\perp$$

$$x_2 = p_2^+/p_3^+ = 1 - x \qquad k_2^\perp = p_2^\perp - x_2 p_3^\perp = -\kappa^\perp$$

$$r_i = x_i^\delta\, e^{-k_i^{\perp 2}/\Delta^2} \qquad i = 1, 2, 3 \qquad x_3 = 1 \qquad k_3^\perp = 0^\perp$$

$$\boxed{R = \Pi_{i=1}^3\, r_i}$$

$$Y_{123} = i f^{c_1 c_2 c_3} \left[\varepsilon_1^* \varepsilon_2^* \cdot \varepsilon_3 \kappa - \varepsilon_1^* \varepsilon_3 \cdot \varepsilon_2^* \kappa \frac{1}{x_2} - \varepsilon_2^* \varepsilon_3 \cdot \varepsilon_1^* \kappa \frac{1}{x_1} \right]$$

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Suggestion concerning glueballs

$$\overset{\text{bare gluons of size } 0}{\begin{bmatrix} \ldots \\ |gggggg\rangle \\ |ggggg\rangle \\ |gggg\rangle \\ |ggg\rangle \\ |gg\rangle \end{bmatrix}} = \overset{\text{gluons of size } s}{\begin{bmatrix} \ldots \\ |ggggg\rangle \\ |gggg\rangle \\ |ggg\rangle \\ |gg\rangle \\ |g\rangle \end{bmatrix} \otimes \begin{bmatrix} \ldots \\ |ggggg\rangle \\ |gggg\rangle \\ |ggg\rangle \\ |gg\rangle \\ |g\rangle \end{bmatrix}} + \ldots$$

$$|gg\rangle + |ggg\rangle + \ldots = |g_s g_s\rangle + |g_s g_s g_s\rangle + \ldots$$

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QCD bound states and QED Hydrogen atom analogy

$$V_c = -\frac{\alpha_{\rm atom}}{r} \quad \sim \alpha_{\rm atom} = \alpha(s_{\rm atom})$$

$$\psi(\vec{r}\,) \sim e^{-\alpha_{\rm atom}\mu|\vec{r}\,|} \qquad \tilde{\psi}(\vec{k}\,) \sim \frac{1}{[\vec{k}^{\,2} + \alpha_{\rm atom}^2\mu^2]^2}$$

$$\left[P^+ \hat{H}_{QED}(s_{atom}) - P^{\perp\,2}\right] |\psi_{\rm atom}\rangle = M_{\rm atom}^2 |\psi_{\rm atom}\rangle$$

$H_{QCD} \neq H_{QED}$ in the RGPEP $\quad m_g(s) =? \quad \rightarrow \quad$ hadrons

Eigenvalue problem ↔ Operators creating hadrons

$$\mathbf{NP} \;\to\; H'_t = \Big[[H_f, \tilde{H}_t], H_t\Big]$$

$$\mathbf{AF} \;\to\; H_t = H_f + gH_{1t} + g^2 H_{2t} + g^3 H_{3t} + \ldots$$

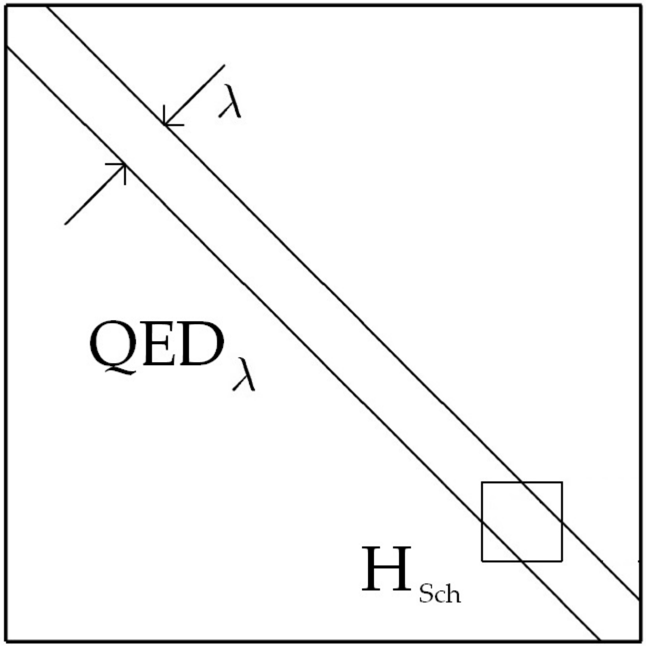
$$H'_{1t} = \Big[[H_f, \tilde{H}_{1t}], H_f\Big]$$

$$H'_{1t\,mn} = -(\mathcal{M}_m^2 - \mathcal{M}_n^2)^2 H_{10\,mn}$$

$$H_{1t} = f_t \; H_{10}$$

$$f_t = e^{-t(\mathcal{M}_c^2 - \mathcal{M}_a^2)^2}$$

$$H_{A^3\,1t} = \sum_{123} \int_{123} \delta_{12.3} \; e^{-t\,\mathcal{M}_{12}^4} \; \Big[Y_{123}\, a_{t1}^\dagger a_{t2}^\dagger a_{t3} + Y_{123}^*\, a_{t3}^\dagger a_{t2} a_{t1} \Big]$$



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