From the space-time structure of partonic scattering to parton-hadron duality

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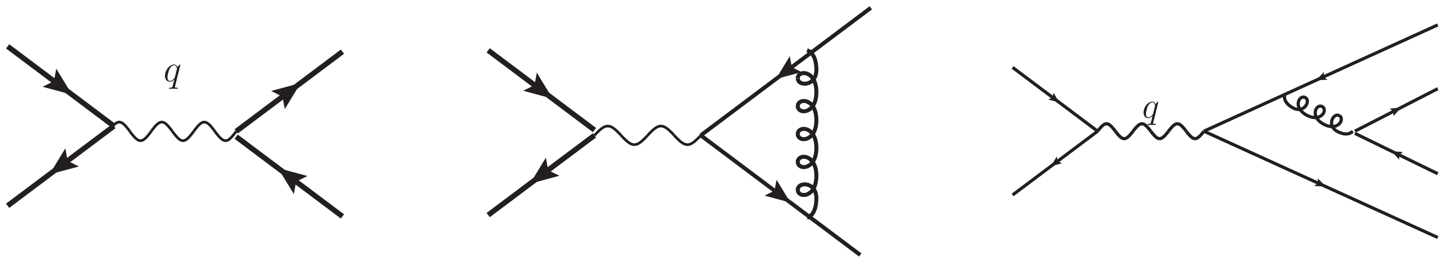
- Aim: relation between coordinate-space happenings at partonic level, quantum mechanical interference, and resonance phenomena.
- A view of dynamical parton-hadron interface.
- For simplicity: $e^+e^- \to$ partons $\to$ hadrons.
- Rough quantitative analysis with naive string model.

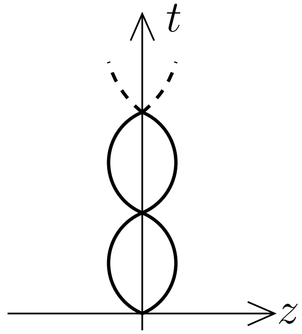
Inspired by: Gupta-Quinn, Poggio-Quinn-Weinberg, JCC's QCD book.

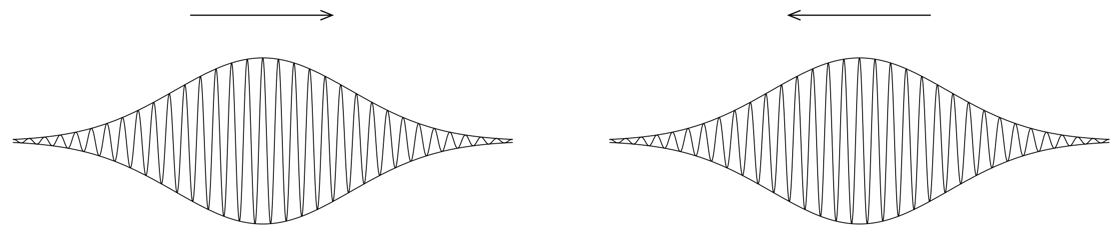
Are pQCD predictions absolute first principles predictions?



- Standard successful absolute pQCD predictions for total cross section, jet distributions, etc. (No fragmentation functions here.)
- (One parameter, e.g., $\alpha_s(m_Z)$.)
- Textbook scattering: On-shell quarks and gluons: at $t \to \infty$ in final state.
- Only hadrons in real final state, so we are really referring to *finite* t for partonic quasi-particles.
- *There's something missing in justification of pQCD predictions.*

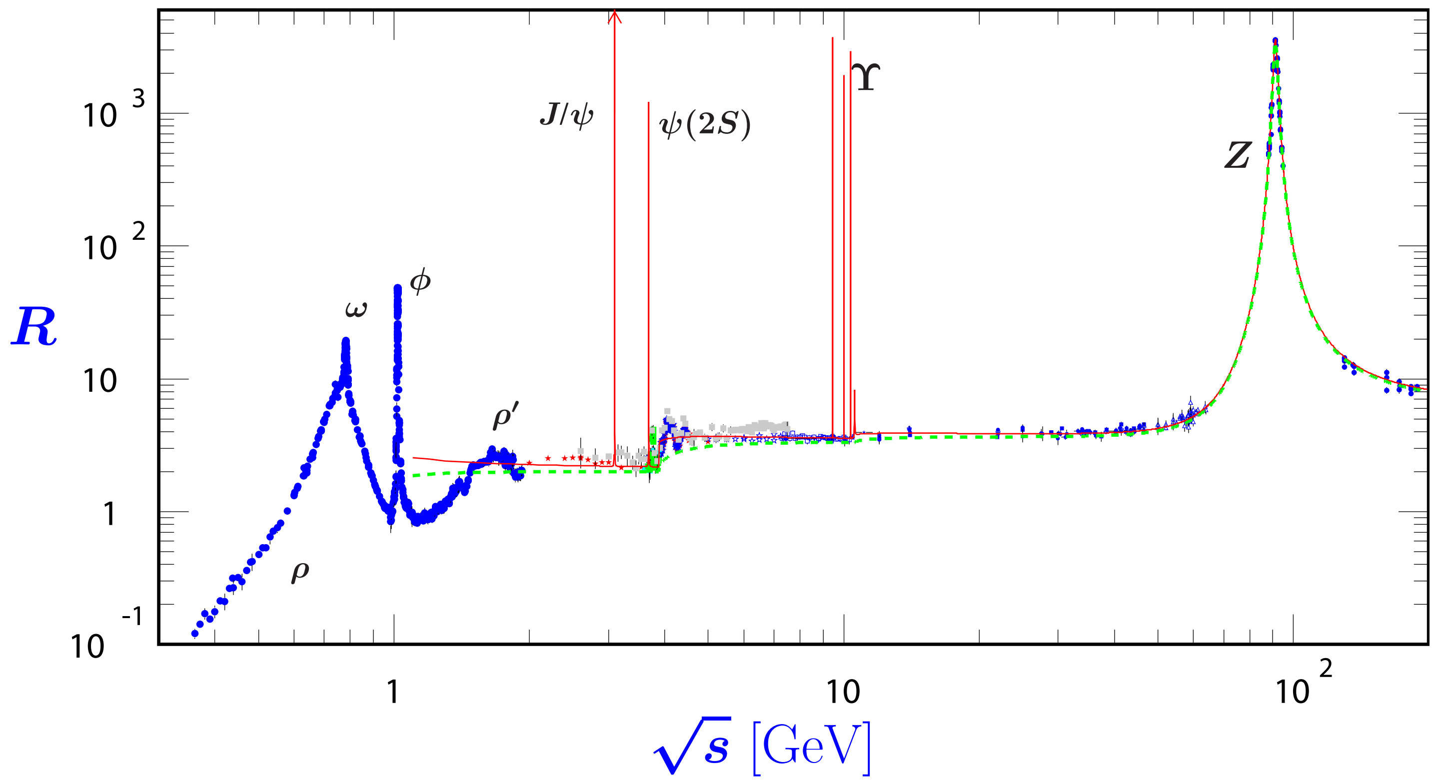
Gupta and Quinn argument [PRD 25, 838 (1982)]





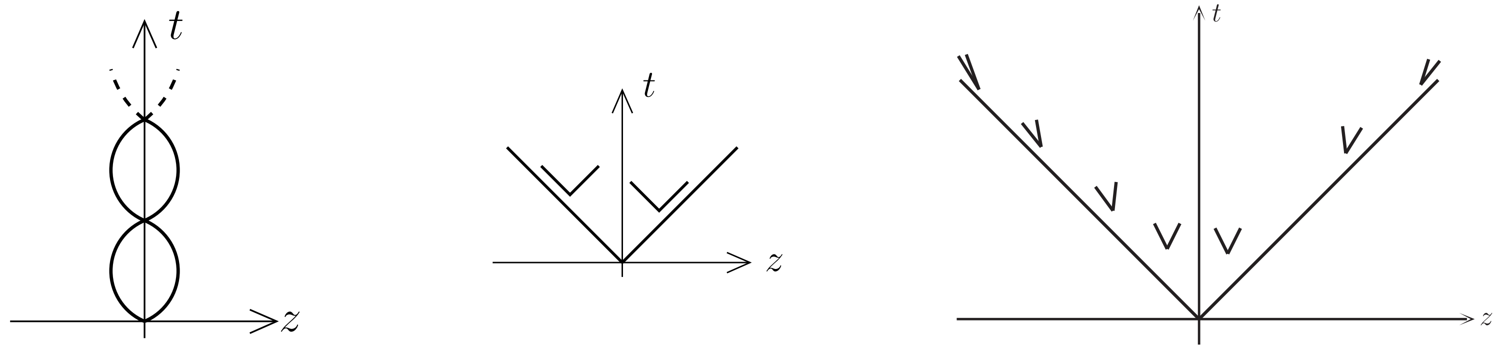
- Consider alternate world where all quarks are heavy $(\alpha_s(M_q) \ll 1)$.
- Still have confining linear potential κr from gluons.
- $q\bar{q}$ pair production perturbatively small. Until Q is extremely large, string doesn't break.
- $\sigma_{\text{had. tot.}}(Q)$ is series of long-lived resonances, probably with lots of glueballs.
- Jet calculations surely fail.
- Actual cross section are *not* equal to the perturbative results, even though we can take $M/Q \to 0$ in perturbative calculations.

$R(e^+e^- \to \textbf{hadrons})$



$[R(e^+e^- \to \text{hadrons}) = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)]$

Quantitative analysis with light quarks (real QCD) I



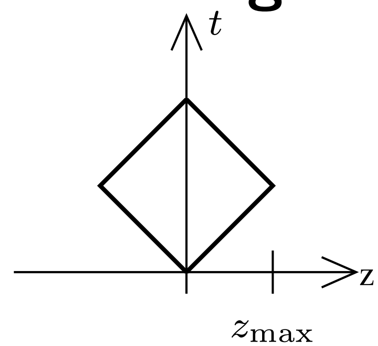
No string breaking   Little breaking   Much breaking

- Use very elementary string model of Artru-Mennessier [NPB 70,93 (1974)] with parameters from data.
- String tension κ (energy/unit length); pair production rate $\mathcal{P}$ per unit t, z:

$$\kappa = 0.8\,\mathrm{Gev/fm}, \qquad \mathcal{P} = 1.9\,\mathrm{fm}^{-2}$$

- Analyze ranges of Q
  - Where is there an identifiable short-distance scattering?
  - Where does string breaking dominate over bounce back?

Quantitative analysis with light quarks (real QCD) II



- String tension κ (energy/unit length); pair production rate $\mathcal{P}$ per unit t, z:

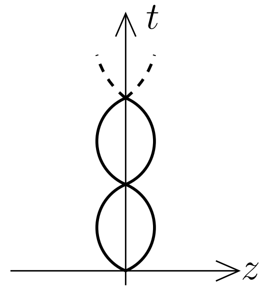
$$\kappa = 0.8\,\mathrm{Gev/fm}, \qquad \mathcal{P} = 1.9\,\mathrm{fm}^{-2}$$

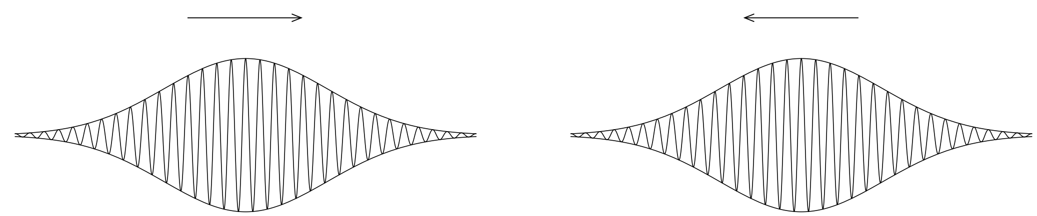
- Hence:

Q (GeV)	$z_{\sf max}$ (fm)	$t_{\sf bounce}$ (fm/c)	$\langle$pairs$\rangle$ in triangle
1	0.6	1.2	0.7
2	1.2	2.4	2.7
10	6	12	68 (?!?)
10	60	120	

- Once string has broken somewhere, later nearby breaking doesn't occur. (Stay inside space-like region $z^2 - t^2 \lesssim 1\,\mathrm{fm}^2$ w.r.t. hard scattering.)

Derivation of validity of pQCD predication for smoothed total cross section I





- To restrict interaction to region much less than "bounce-back" time but reasonably much larger than $1/Q$, use wave packet in-state:

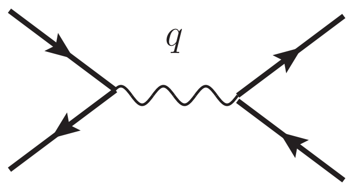
$$|\psi\rangle = \sum_{\mathbf{l}_1,\mathbf{l}_2,\lambda_1,\lambda_2} \left| e^+(\mathbf{l}_1,\lambda_1),\, e^-(\mathbf{l}_2,\lambda_2);\ \text{in} \right\rangle\ \psi_1(\mathbf{l}_1,\lambda_1)\,\psi_2(\mathbf{l}_2,\lambda_2)$$

  with

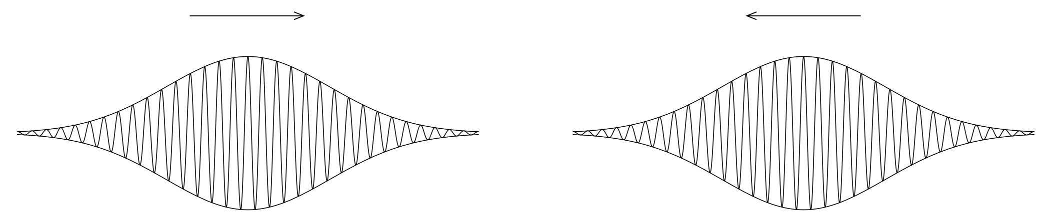
$$1/Q \ll \Delta z \ll t_{\text{bounce}}, \qquad 1/t_{\text{bounce}} \ll \Delta Q \ll Q.$$

- Aim: relate to experimental measurements with precise beam energy.

Derivation of validity of pQCD predication for smoothed total cross section II



$+$ etc



- Hadronic part of final state:

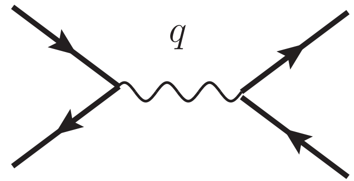
$$|\phi; \text{hadron, out}\rangle = \int \mathrm{d}^4x\, j^\mu(x)\, |0\rangle\, e^{-iq\cdot x} \phi_\mu(x)$$

$\phi_\mu(x)$ is from: lepton wave functions, vertex to photon, photon propagator.

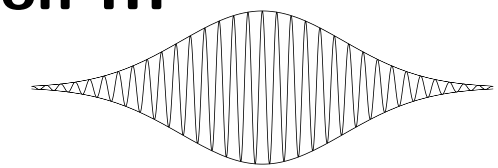
- Oscillation factor $e^{-iq\cdot x}$ extracted $\Longrightarrow$ $\phi_\mu(x)$ is envelope of a kind of wave packet.
- . . . (see my QCD book)
- Then $R = \sigma(\text{had.})/\sigma(\mu^+\mu^-)$ with *wave-packet beams* is

$$\bar{R}(Q^2, \Delta^2) = \int \mathrm{d}s\; F(s - Q^2, \Delta^2)\, R_{\text{std.}}(s)$$

Derivation of validity of pQCD predication for smoothed total cross section III



$+$ etc



- Then $R = \sigma(\text{had.})/\sigma(\mu^+\mu^-)$ with *wave-packet beams* is

$$\bar{R}(Q^2, \Delta^2) = \int \mathrm{d}s \; F(s - Q^2, \Delta^2) \, R_{\text{std.}}(s)$$

  - Δ is momentum width of wave function;
  - Q is central value of $\sqrt{(l_1 + l_2)^2}$ for wave function;
  - $F(s - Q^2, \Delta^2)$ obtained from wave function, positive, peaked at $s = Q^2$.

- $\bar{R}(Q^2, \Delta^2)$ is local average of usual R, which is normalization times Fourier transform of

$$\langle 0 | \, j^\mu(x) j^\nu(y) \, | 0 \rangle = \sum_X \langle X | \, j^\mu(x) \, | 0 \rangle^* \, \langle X | \, j^\nu(y) \, | 0 \rangle$$

  QM interference between production of QCD stuff at different x and y.

- Wave function gives restriction to times of $x - y$ less than bounce back.

Ranges of Q

$Q < Q_0$	pQCD not applicable.
$Q_0 < Q < Q_1$	Resonances, but parton-hadron duality.
$Q_1 < Q$	String breaks, normal pQCD methods including jets, fragmentation functions, etc

Where should parton-hadron duality apply or not apply?

- Applies where we aren't sensitive to detailed final state:
  - $e^+e^- \to$ hadrons total cross section
  - DIS
- Where it may well not apply, or will need modification:
  - Jet distributions.
  - Hadron-inclusive cross sections. (Anything with a fragmentation function.)
- Not clear:
  - Drell-Yan,

Note: Carefully examined proofs of factorization: They often apply to locally averaged cross sections.

Overview

- Parton-hadron duality is at some level and in some cases a theorem.
- It applies when "bounce-back" from string tension doesn't lose to pair production rate in string, if there's such a range.
- String model gives quantitative link between microscopic parton propagation etc, and measured cross sections.
- Future: better mesh coordinate-space and semi-classical view with momentum space and fully quantum view.