Jet quenching and the Pomeron

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‘Quark confinement and the Hadron Spectrum XI’
St-Petersburg Russia, Sep. 11th 2014

- Jets could offer controlled probes of heavy ion collisions
- Key parameter for jet quenching:

$$\langle q_\perp^2 \rangle \approx \hat{q} L$$

  Controls bremsstrahlung, broadening, color coherence...
- Experimental, model-independent determination difficult but underway
- Theory side: contributions from scales T and below becoming under control [Panero&Rummukainen; Laine&Meyers;Benzke et al]
- Large logarithms from $T \ll Q \ll Q_{jet}$ may also be important [Wu; Liou ,Mueller&Wu; Iancu;Iancu&Triantafyllopoulos]
- Could be useful to have a smooth interpolation between weak and strong coupling, even if only in N=4SYM!

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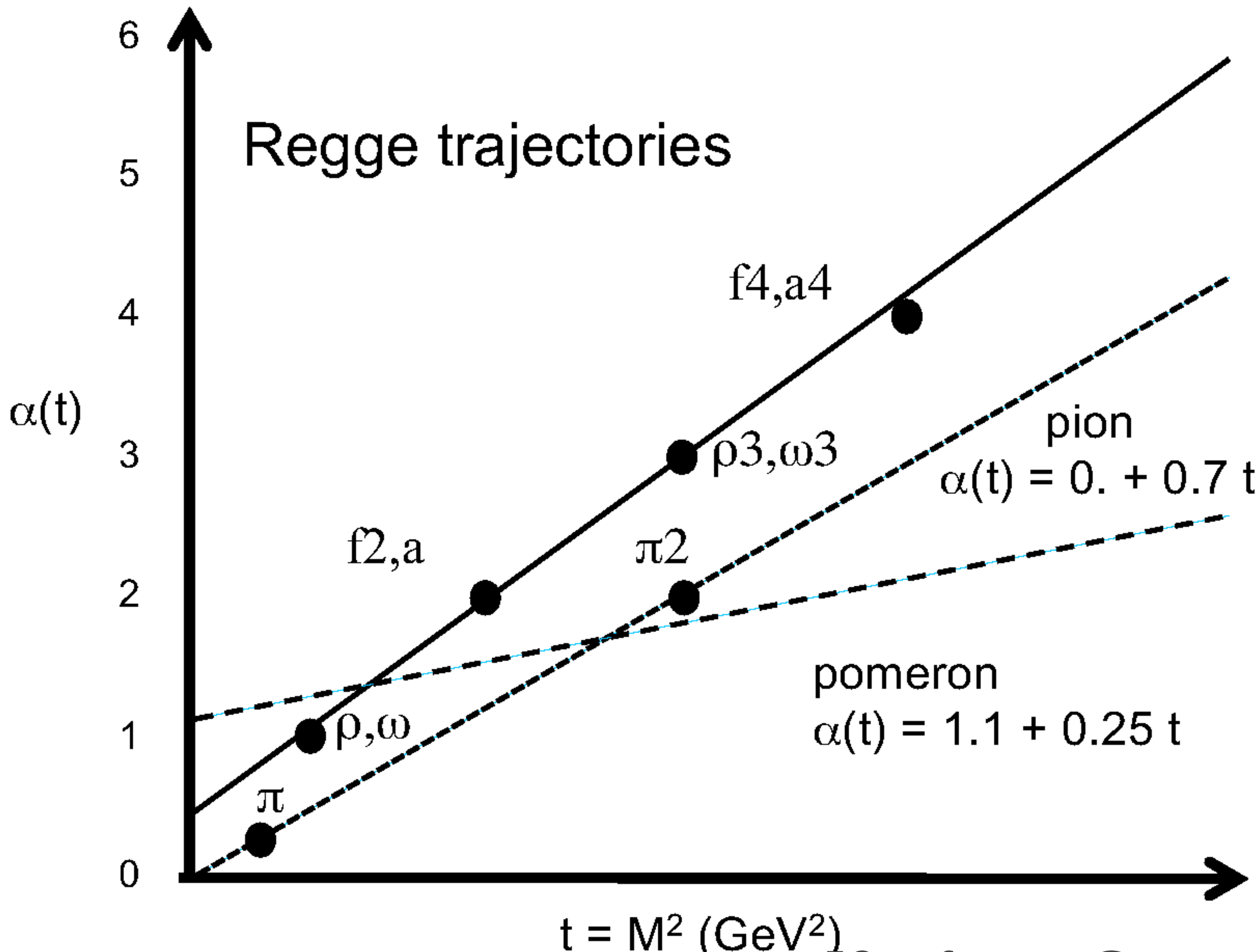
- To really define $\hat{q}$ quantum mechanically one needs *both* collinear and rapidity regulators
- I will consider the [time-ordered] dipole amplitude:

$$\frac{1}{N_c}\langle T\,\mathrm{Tr}W(x_\perp, L)\rangle_\beta \equiv e^{iLt(E,x_\perp)}$$

where: $\mathrm{Im}\,t(E,x_\perp) \equiv \hat{q}(E,x_\perp)\frac{x_\perp^2}{4}$ at small $x_\perp$

- $x_\perp$ is the explicit size of the dipole and E is a upper cutoff on the (plus)-energy in loops
- What is the dependence on the cutoffs?

- The jet and the plasma move fast in different directions [in some appropriate frame]; this motives the use of Regge theory



[fig. from Gotsman,Levin&Maor '14]

- As a warm-up consider scattering at large E and large impact parameter $b \gg 1/\Lambda_{QCD}$, at T=0
- Each individual trajectory produces

$$A(s,t) \sim \beta(t) \frac{1 \pm e^{-i\pi j(t)}}{\sin(\pi j(t))} s^{j(t)}$$

- In impact parameter space this becomes

$$A(s,b) \sim \int d^2\mathbf{p}\, e^{i\mathbf{p}\cdot\mathbf{b}} \left[\beta(t) \frac{1 \pm e^{-i\pi j(t)}}{\sin(\pi j(t))} s^{j(t)}\right]_{t=-\mathbf{p}^2}$$

- Can be controlled by either of 3 effects
    1. A pole of $\sin(\pi j)$, corresponding to a real physical particle
    2. A singularity in $\beta(t)$ (ex. a cut at $4m_\pi^2$)
    3. A saddle point,

whichever is closest to the real axis!

For large enough b the amplitude will generally be exponentially small (e.g $A(s,b) \sim s^j e^{-m|b|}$ for 1), justifying ignoring multi-Reggeon exchanges

- Back to a small jet probing a dense QCD medium
- At short distances we have (at least approximate) conformal symmetry
- In addition to *t* and *j* this means we can diagonalize a further quantum number ν. (This is the 'ν' in the BFKL eigenvalues)
- For small $x_\perp$ and zero momentum transfer (homogeneous medium) one has

$$A(E,x_\perp) \sim \int_{-\infty}^{\infty} d\nu \beta(\nu) \frac{1 \pm e^{i\pi j(\nu)}}{\sin(\pi j(\nu))} |x_\perp|^{i\nu+1} (E x_\perp)^{j(\nu)-1}$$

Similar to above!

BFKL '76-...
Cornalba '07

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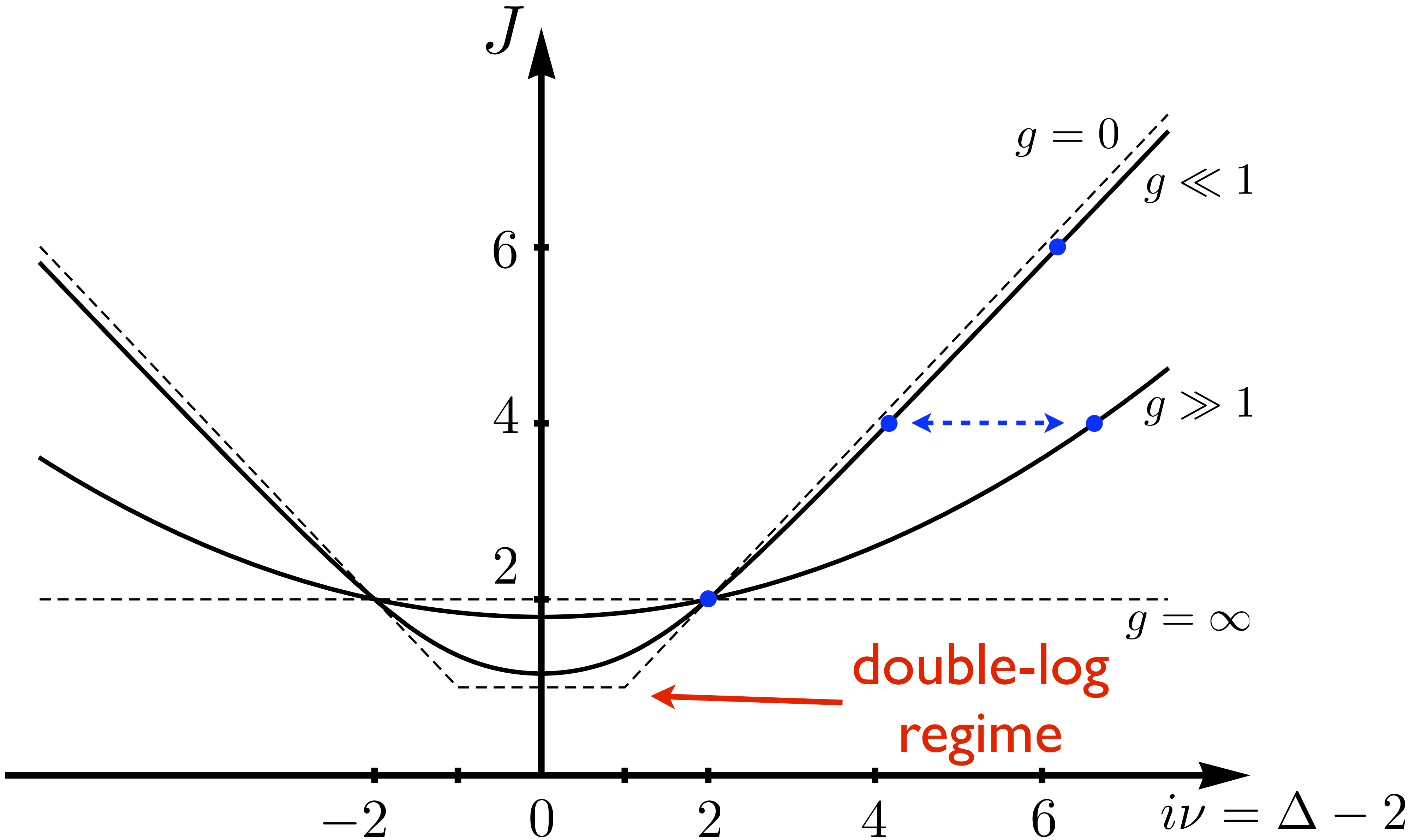
- Simple dictionary:
  b (impact parameter) ↔ log (1/*r*) (dipole size)
  p (momentum) ↔ ν (conformal momentum)
- Thus we can analyze the small-projectile, high-energy limit ($x_\perp \ll 1/T$) in the same way as large-distances in a gapped theory
- [Not a coincidence. Both limits correspond to large distance in a kinematic AdS_3 space [BPST]]

- The key information we need is contained in the Chew-Frautschi plot of the Pomeron



[Cornalba,Costa,Penedones et al; Brower,Polchinski,Strassler&Tan]

At weak coupling the closest singularity is a cut near iν=1

At strong coupling it is the stress-tensor pole at iν=2

$$t(E, x_\perp) \sim \int_{2-i\infty}^{2+i\infty} d\Delta\, \beta(\Delta) \frac{1 \pm e^{i\pi j(\Delta)}}{\sin(\pi j(\Delta))} |x_\perp|^{\Delta-1} (E x_\perp)^{j(\Delta)-1}$$

From just the general features of the plot one deduces:

- Weak coupling: cut at $\Delta \approx 3, j \approx 1$

  $$\rightarrow t(E, x_\perp) \sim i x_\perp^2 T^3 [\times \log 1/(T x_\perp)]$$

- Strong coupling: cut at $\Delta \approx 4, j \approx 2$

  $$\rightarrow t(E, x_\perp) \sim x_\perp^4 T^4 E$$

- Again for $x_\perp$ small enough we do not expect non-linear effects to be important

- At weak coupling

$$t(E, x_\perp) \sim i x_\perp^2 \left(C_1 \log(T|x_\perp|) + C_2\right)$$
$$\equiv \frac{i}{4} \hat{q} x_\perp^2$$

- This gives us, as expected $\hat{q}$ (which is log-divergent)
- The amplitude is pure imaginary (e.g. exponent is real): *dipole dissociation* at weak coupling measures scattering off individual constituents:

$$\mathrm{Im}\, t(E, x_\perp) = \int d^2q \frac{d\Gamma_{\mathrm{el}}}{d^2q} \left(1 - e^{iq\cdot x_\perp}\right)$$

[similar to quarkonium dissociation, see Brambilla et al]

- At strong coupling, the imaginary part vanishes!
- This may seem counter-intuitive
- However this is unavoidable for a near-flat trajectory: the phases originate entirely from the signature factors:

weak coupling:

$$A \propto - \lim_{j \to 1} \frac{1+e^{-i\pi j}}{\sin(\pi j)} = i$$

strong coupling:

$$A \propto \mathrm{Res}_{j=2} \frac{1+e^{-i\pi j}}{\sin(\pi j)} = \frac{2}{\pi}$$

- To interpret we recall that $t(E,x_\perp)$ is the (time-ordered) dipole amplitude, not a scattering rate
- The vanishing imaginary part indicates that at strong coupling it becomes harder to break up the constituents from each other
- This is the statement that ‘partons are not seen at strong coupling’ in DIS-type experiments

[Polchinski&Strassler ’07]
[Hatta,Iancu&Mueller ’07]

- However there are some indications that ‘partons’ may be visible in forward (Regge) scattering

[from successes of BFKL approach at strong coupling; BPST ’07; Basso,SCH&Sever ’13]

- Break-up the dipole amplitude at strong coupling:

$$t(E, x_\perp) \approx + x_\perp^4 \, T^4 \, E$$

gravity is attractive

color transparency

real: no dissociation

stress tensor

Pomeron=graviton, couples to energy!

[Hatta,Iancu&Mueller '07]

- A partonic picture at strong coupling has been proposed in the past --- one views all objects as made of infinitely many partons [Hatta,Iancu,Mueller,Tryantafyllopoulos]

- The restricted picture proposed recently is less ambitious but more constraining: it states that the forward scattering of any object is fully determined by the positions of a small (fixed) number of point-like carriers

- For two carriers in a plasma there is a unique simple-minded 'partonic' equation one can write down:

$$i\frac{\partial}{\partial t}\psi(x_\perp,t)=\left[\frac{p_\perp^2}{E}-Cx_\perp^4T^4E\right]\psi(x_\perp,t)$$

entirely kinematic

$t(E,x_\perp)$

- Ex.1: absorption of a on-shell current. (related to high-energy photon production rate in equilibrium)

- Such a probe is as small as possible, but it cannot be smaller than quantum diffusion

$$x_\perp^2 \sim L/E$$

- The probe is absorbed when the effect of the potential becomes O(1)

$$\int dL\, T^4 E(L/E)^2 \sim 1 \to L \sim E^{1/3} T^{-4/3}$$

- The E is as found from supergravity calculation at strong coupling

[SCH,Kovtun,Moore,Starinets&Yaffe '06]

- Ex.2: A color-singlet 'jet' (highly-boosted energy lump) produced in a finite time δL
- Due to initially uncertain initial transverse momentum $\delta p_\perp \sim \sqrt{E/\delta L}$, classical trajectories may spread faster than quantum diffusion

$$i\frac{\partial}{\partial t}\psi(x_\perp, t) = \left[\frac{p_\perp^2}{E} - Cx_\perp^4 T^4 E\right]\psi(x_\perp, t)$$

classical limit: $\rightarrow \frac{d^2}{dt^2}x_\perp \sim x_\perp^3 T^4$

=geodesic equation in AdS_5, with $x_\perp$=radial coordinate (large)

Solution blows up in finite time $L_{\max} \sim \frac{1}{T\sqrt{|\dot{x}_\perp(0)|}} \sim (E\delta L)^{1/4} T^{-1}$

Exactly as found by [Arnold&Vaman]!

Conclusions

- Smooth interpolation between weak and strong coupling seems possible for dipole amplitude
- The energy dependence is absolutely crucial
- Nontrivial scaling laws ($L \sim E^{1/3}$, etc.) can be reproduced from extremely simple-minded partonic picture at strong coupling, assuming just a $j \approx 2$ Pomeron in the UV
- Directions:
  -Try to apply simple partonic picture to other observables [energy deposition, colored jets..?]
  -Learn to control Schwinger-Keldysh dipoles

Backup.

- Is that consistent with $q \sim \lambda^{1/2} T^3$ found by Casalderrey-Solana, Liu, Rajagopal?
- Key difference is that we have an energy cutoff
- Curiously, if we add some typical thermal mass effect $m \sim \lambda^{1/2} T$ and integrate over E, we get theirs:

$$\int dE \, e^{L(iT^4 x_\perp^4 E - i\frac{\lambda T^2}{E})} \sim e^{-L\#\sqrt{\lambda} T^3}$$

- If correct, this suggests that our C(q) is consistent with Liu et al, but generalizes it to include energy-dependence