Hard processes in AdS/CFT

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Based on works done in collaboration with
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Outline

- Motivation
- High energy QCD with a virtual photon
- Deep inelastic scattering in gauge/string duality
- Jets in the vacuum
- Jets at finite temperature

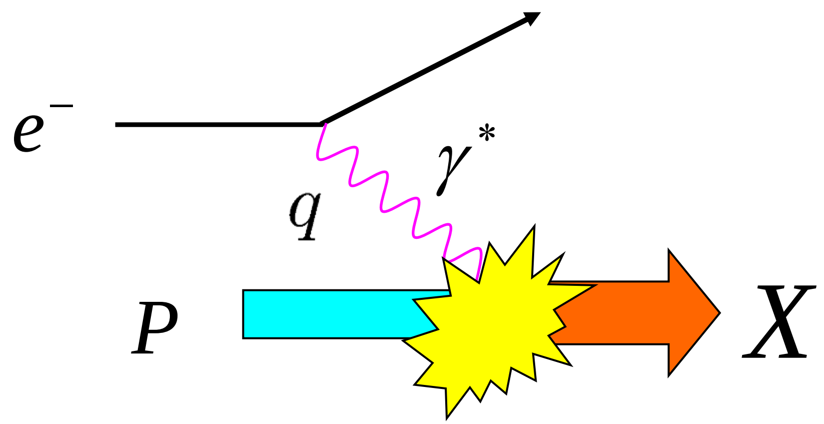
Why AdS/CFT?

- Perturbative QCD very successful for hard processes.
  Why bother AdS?

- Regge (small-x) scattering historically important for strings. New perspectives from AdS/CFT?

- Possible applications to strongly coupled QGP at RHIC, and hidden conformal sectors at the LHC (Strassler)

Spacelike photon—Deep inelastic scattering



Photon virtuality

$$q^2 = Q^2 > 0 \qquad \text{(spacelike)}$$

Bjorken-x

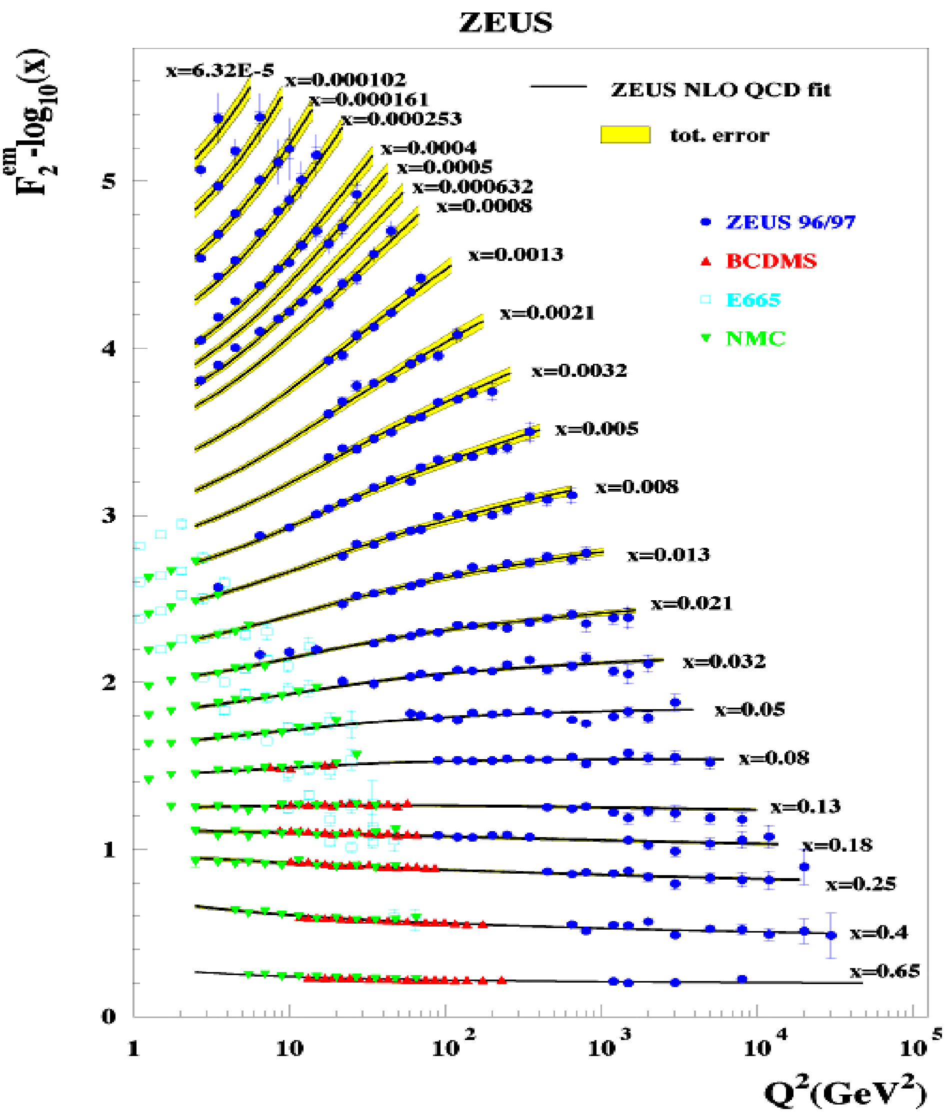
$$x = \frac{Q^2}{-2P\cdot q} \approx \frac{Q^2}{s} \quad (x \ll 1)$$

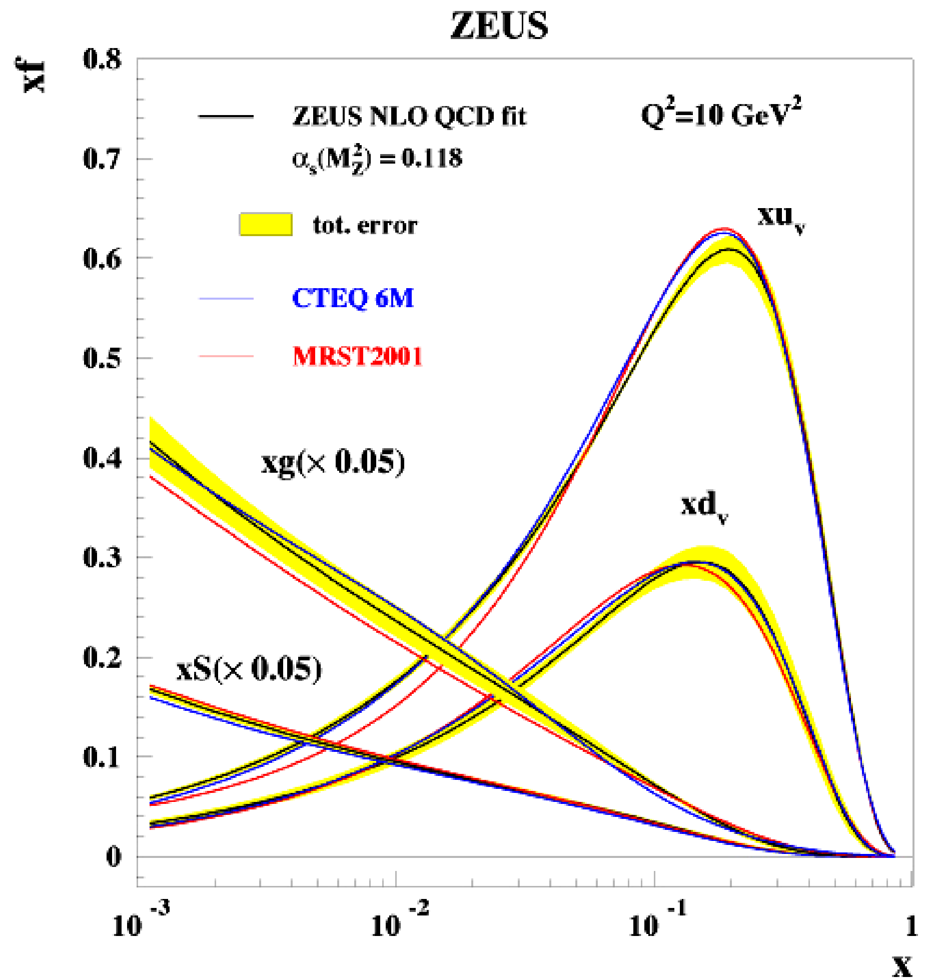
Probing partons with energy xP^+ and transverse size $1/Q^2$

$$\frac{1}{2\pi} Im\, i \int d^4y e^{iqy} \langle P|T\{J^\mu(y)J^\nu(0)|P\rangle$$

$$= \left(-\eta^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) F_1(x,Q^2) + \left(P^\mu - \frac{Pq}{q^2}q^\mu\right)\left(P^\nu - \frac{Pq}{q^2}q^\nu\right)\frac{F_2(x,Q^2)}{Pq}$$

Parton distribution function





Hard (BFKL) Pomeron

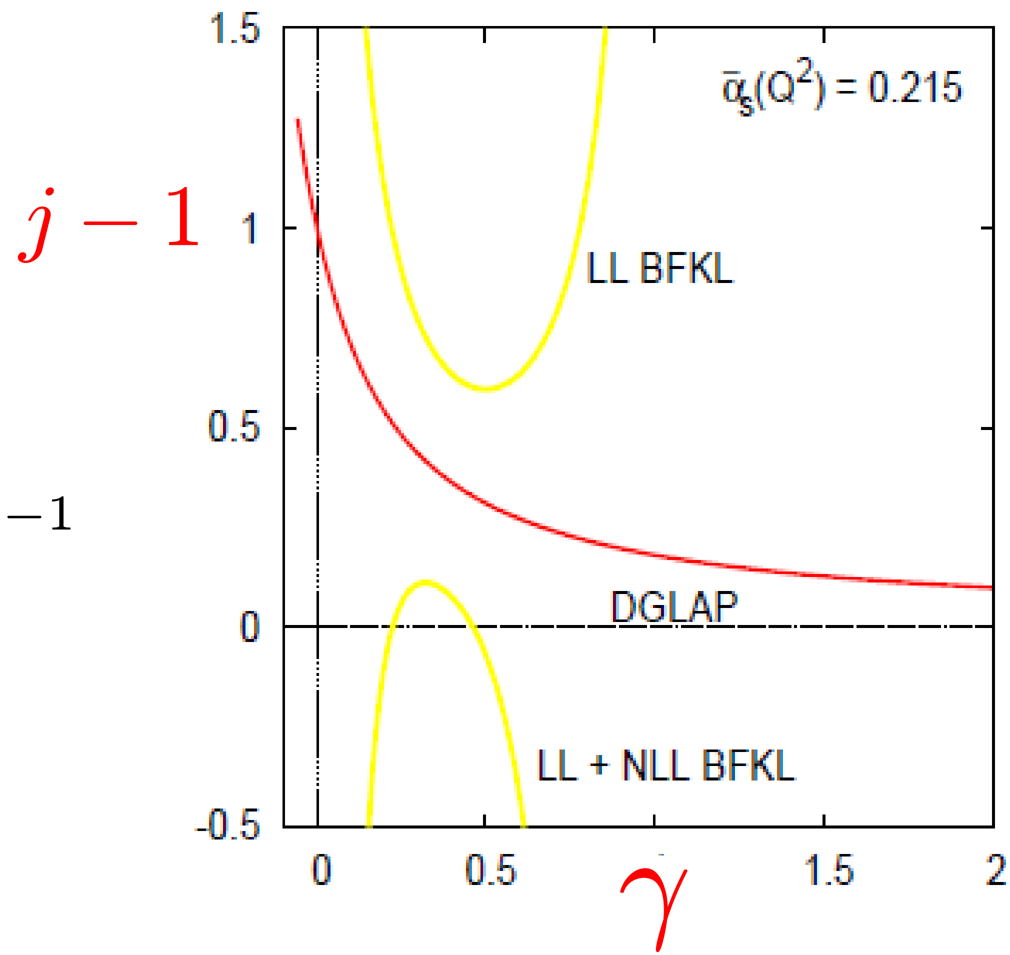
$$\int_0^1 dx\, x^{j-2} F_2(x, Q^2) \sim \left(\frac{Q^2}{\mu^2}\right)^{\gamma(j)}$$

Anomalous dim. of the twist-two operators

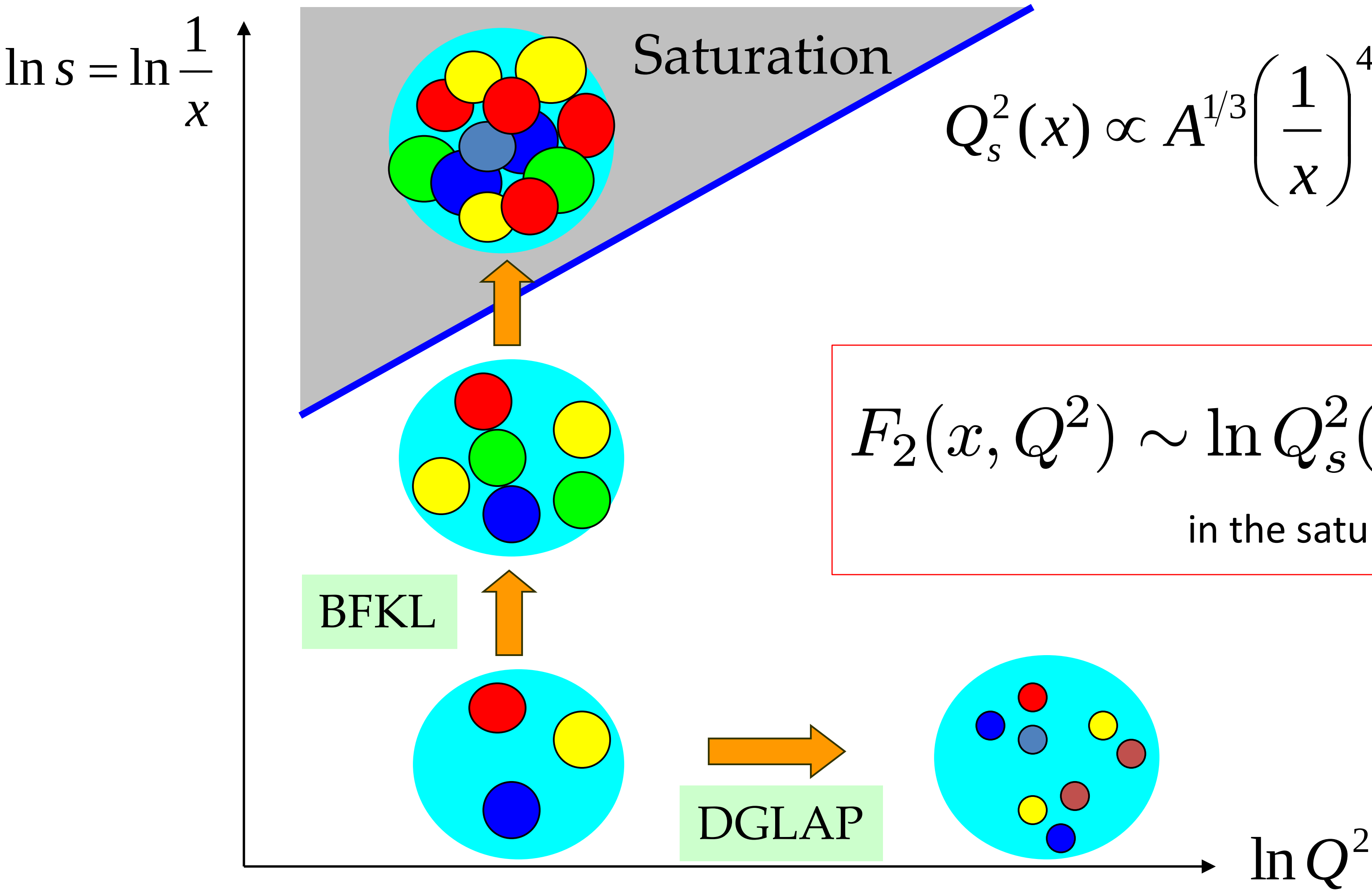
$$F_2(x, Q^2)$$

$$\sim \int \frac{dj}{2\pi i} \left(\frac{Q^2}{\mu^2}\right)^{\gamma(j)} \left(\frac{1}{x}\right)^{j-1}$$

$$\sim \left(\frac{1}{x}\right)^{0.5} \sim s^{0.5}$$



`Phase diagram' of QCD

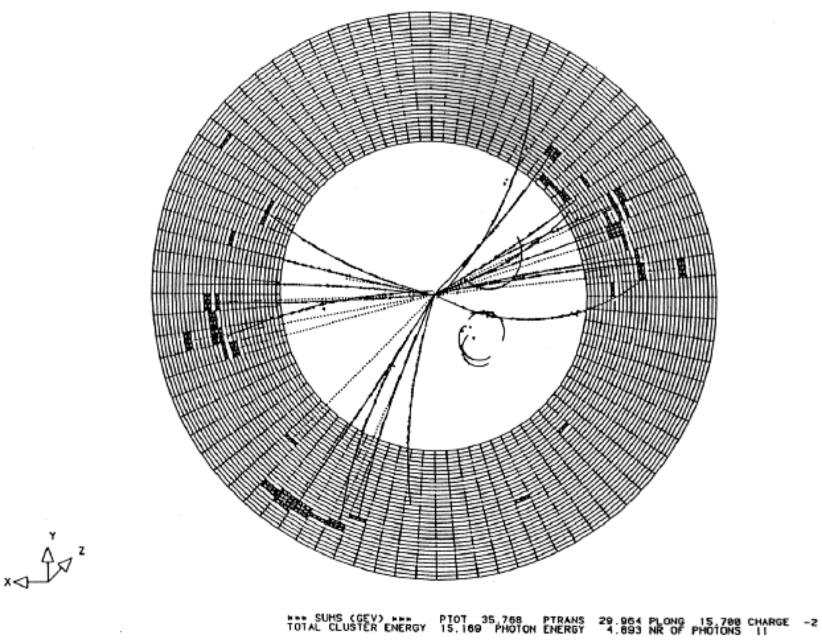


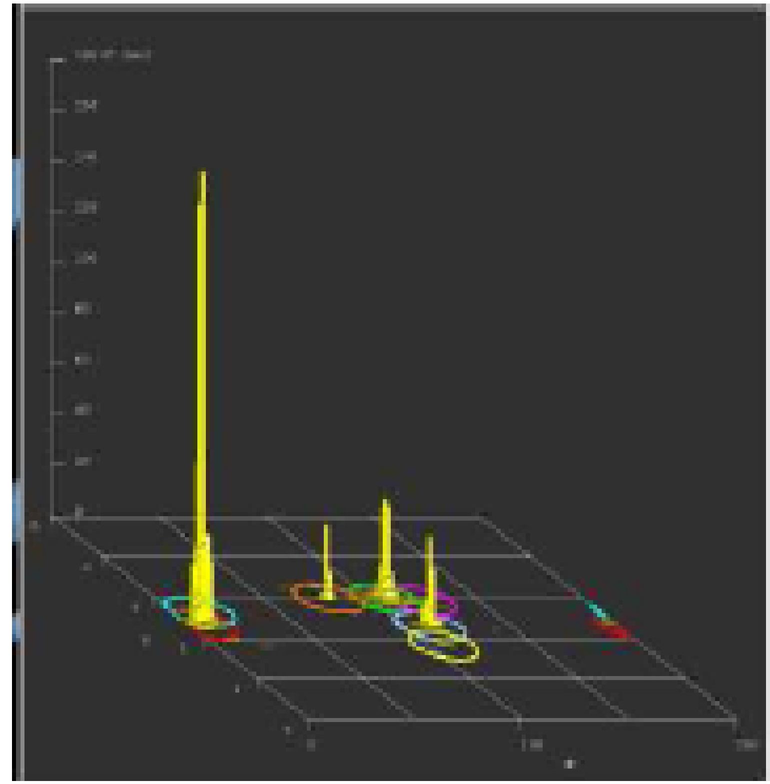
$$Q_s^2(x) \propto A^{1/3}\left(\frac{1}{x}\right)^{4.9\bar{\alpha}_s}$$

$$F_2(x, Q^2) \sim \ln Q_s^2(x)/Q^2$$

in the saturation region

Timelike photon—Jets in QCD





In e+e- annihilation, some of the most stringent tests of pQCD have been done.

High pt jets at the LHC could be an important discovery channel of BSM

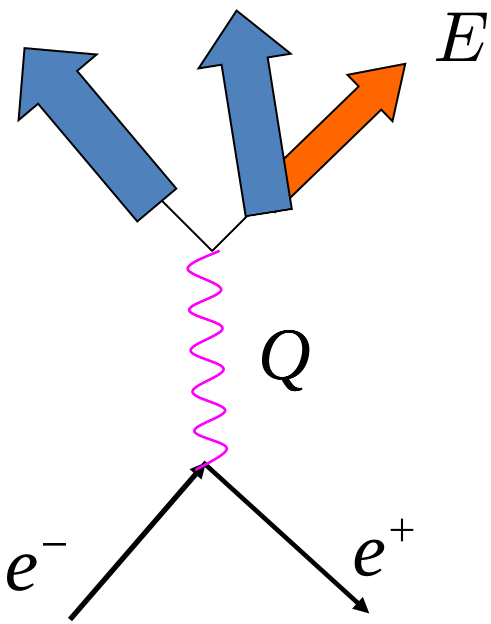
Number distribution inside a jet

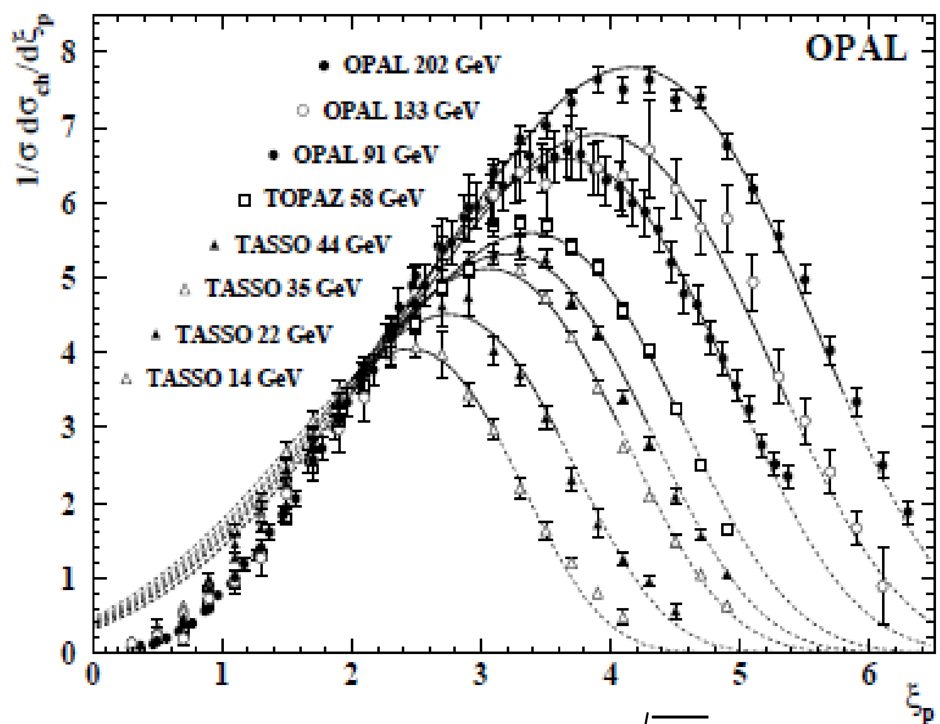
Fragmentation function

$$\frac{d\sigma}{dx} = D_T(x, Q^2)$$

$$x = \frac{2E}{Q}$$

Feynman-x



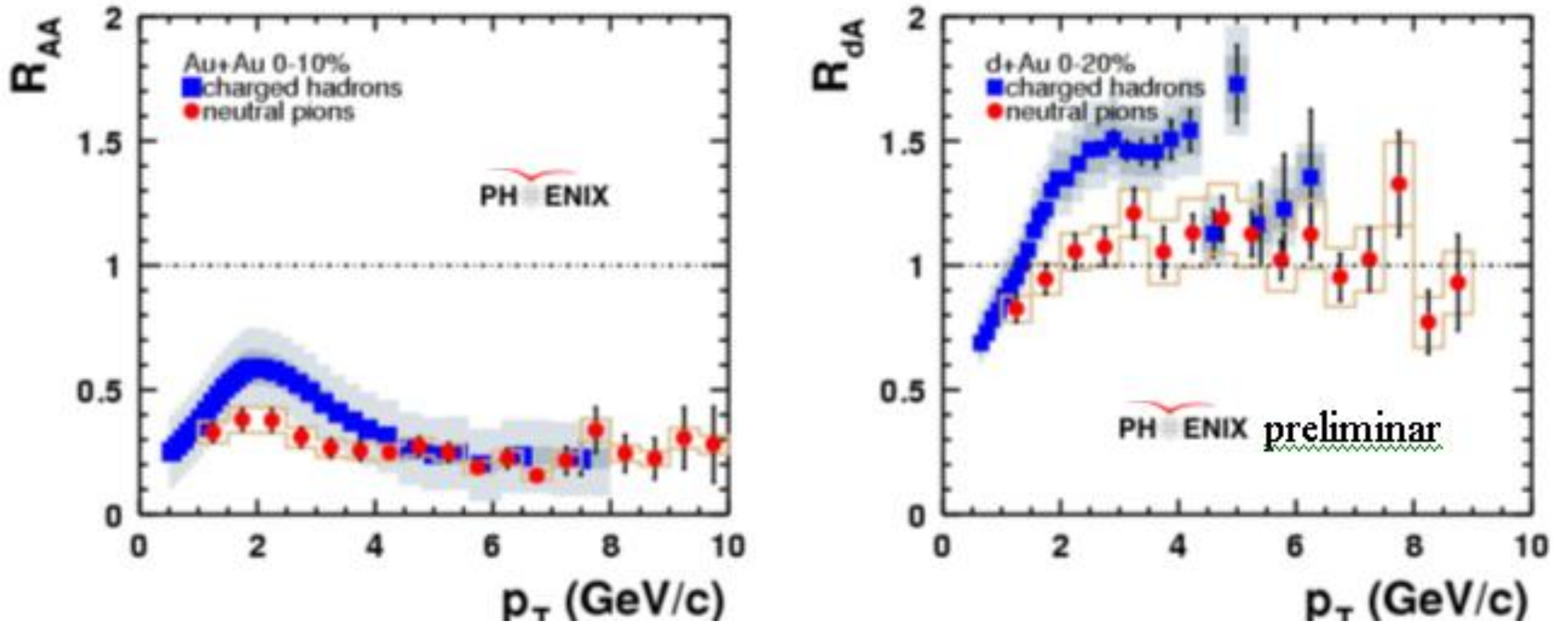


peak at $\frac{1}{x} = \sqrt{\frac{Q}{\mu}}$

Jets in heavy-ion collisions

Nuclear modification factor

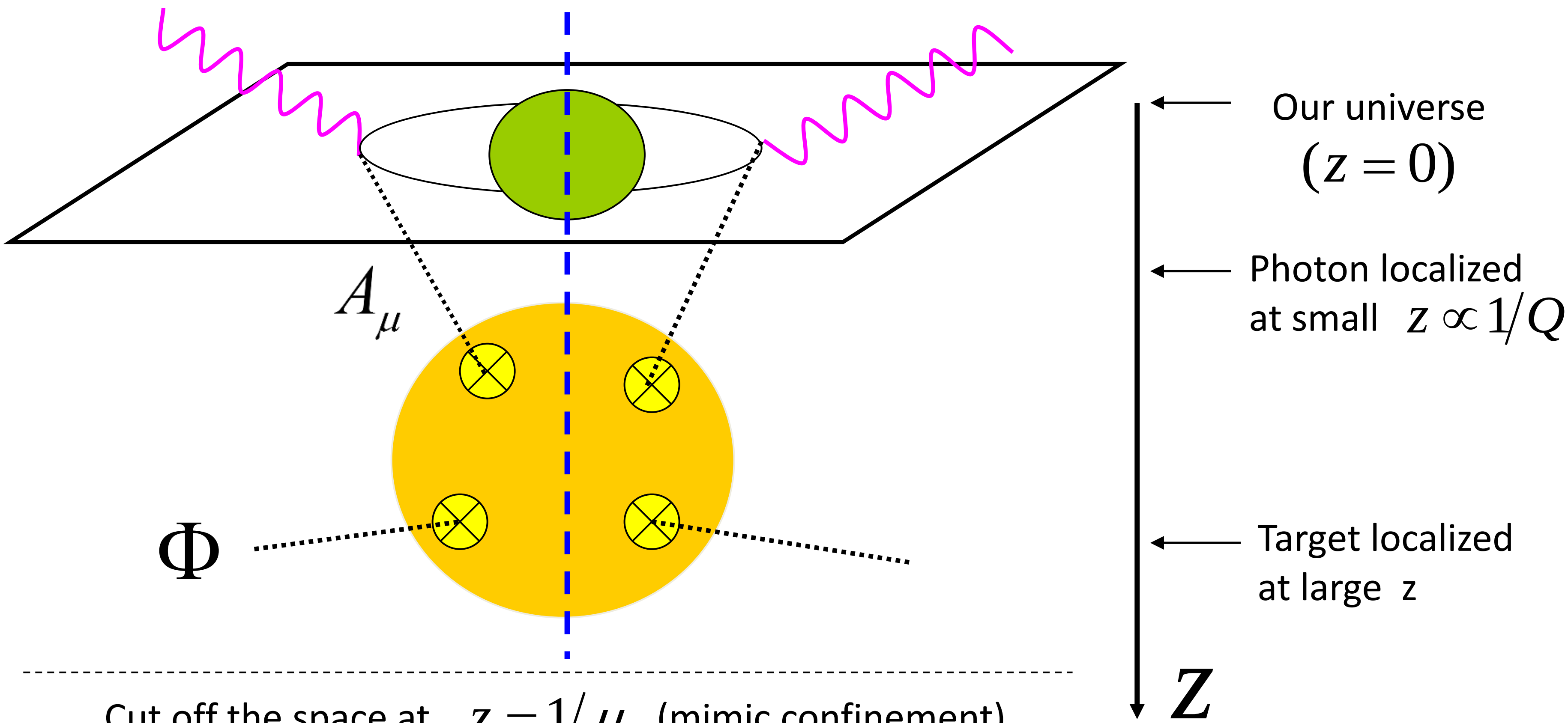
$$R_{AA} = \frac{\frac{dN_{AA}}{dp_T}}{N_{coll}\frac{dN_{pp}}{dp_T}}$$



High energy particles are a diagnostic tool of the strongly coupled quark gluon plasma

DIS at strong coupling

Polchinski, Strassler; Brower, Tan; YH, Iancu, Mueller; Cornalba, Costa; Ballon Bayona, Braga, Nelson; …



Cut off the space at $z = 1/\mu$ (mimic confinement)

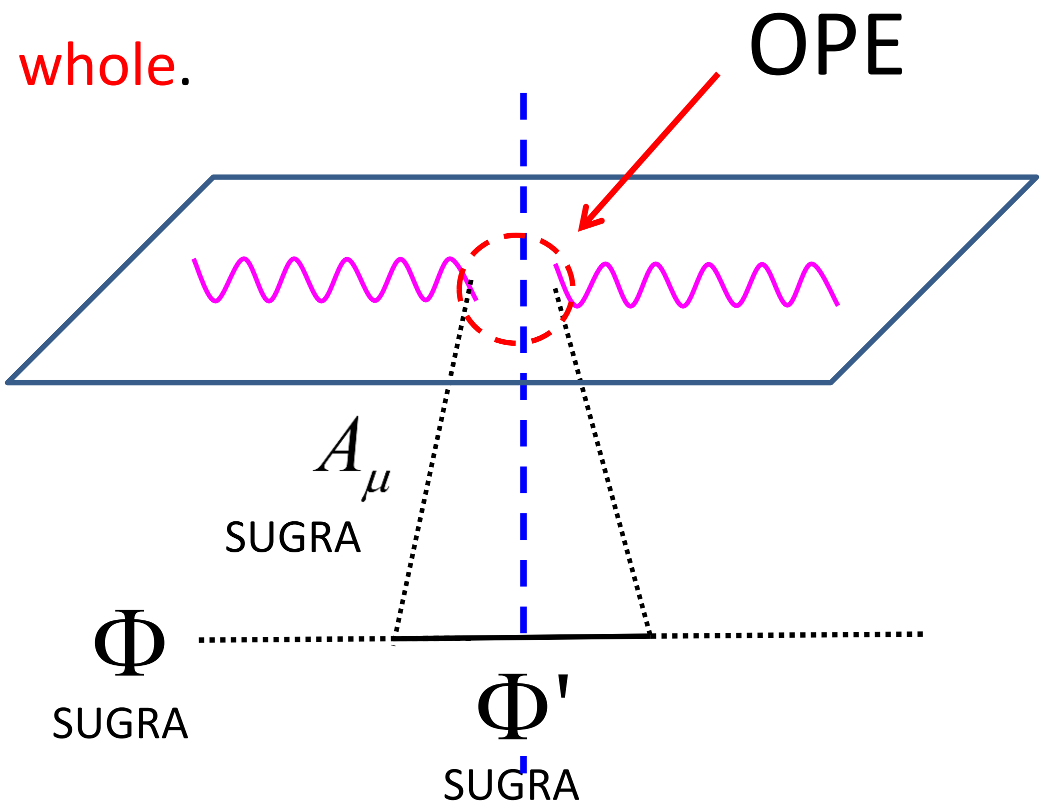
Large-x : No partons !

At large-x, a hadron scatters as a whole.

$$s_{4D} = \frac{Q^2}{x}$$

$$s_{5D} = \frac{R^2}{r_{int}^2} s_{4D} < \frac{1}{\alpha'}$$

$$\Rightarrow \quad \frac{1}{\sqrt{\lambda}} < x < 1$$



Double trace operators dominate the OPE at large-x.

Twist-two operators : $\gamma(j) \sim \lambda^{1/4}$, contribution strongly suppressed.

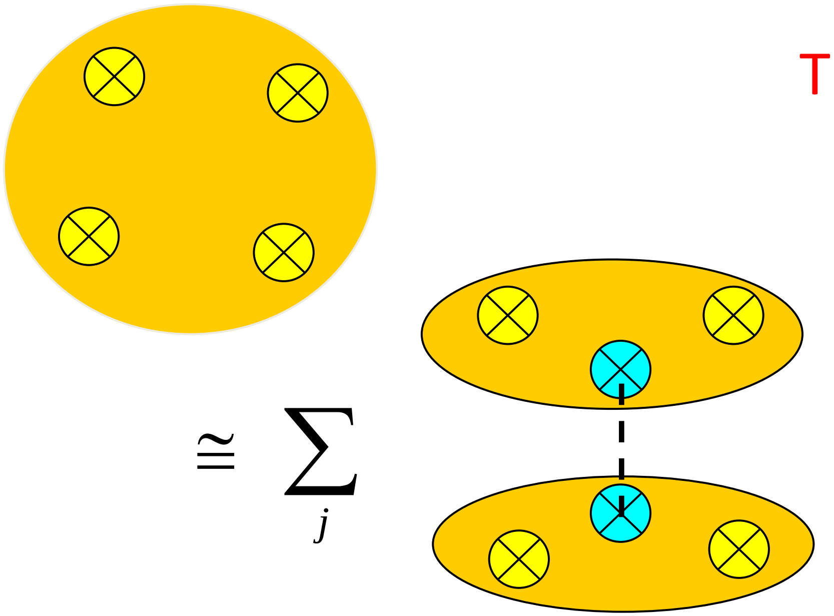
Small-x : Regge scattering

Large-x region does not contribute to the energy-momentum sum rule.

$$\int_0^1 dx F_2(x, Q^2) \sim \left(\frac{Q^2}{\mu^2}\right)^{\gamma(2)} = const.$$

Small—x → small—j

The anomalous dimension remains small in the vicinity of $j = 2$



The "Pomeron vertex operator"

$$V_j \sim z^{\Delta(j)-j}\left(\partial X^+ \bar{\partial} X^+\right)^{\frac{j}{2}}$$

$$\Delta(j) = 2 + \sqrt{2\sqrt{\lambda}(j-2) + 4}$$

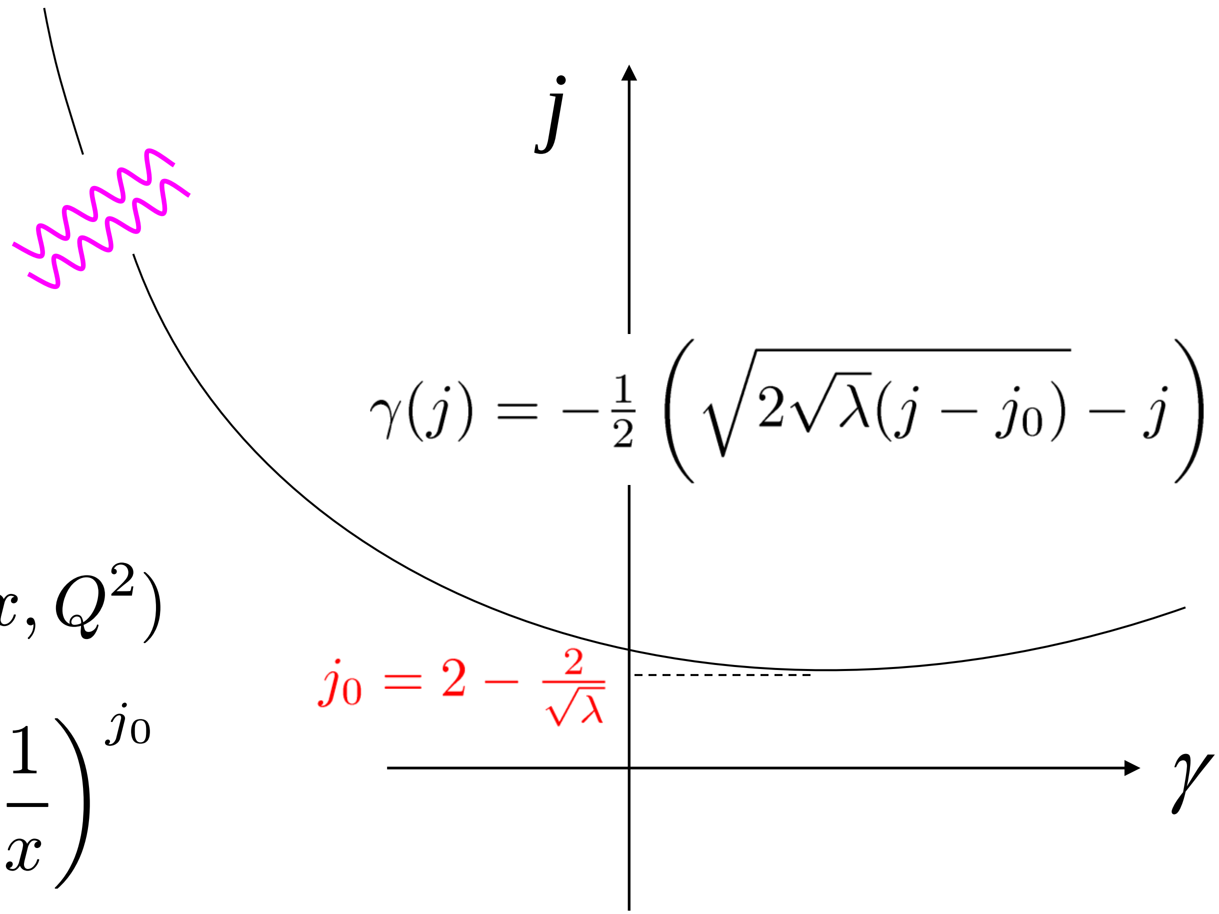
Brower, Polchinski, Strassler, Tan

Spacelike anomalous dimension in N=4

Energy-momentum operator (twist-two) relevant at exponentially small-x

$$x \sim \frac{1}{s} \sim e^{-\sqrt{\lambda}}$$

$$\gamma(j) \approx -\frac{1}{2}\frac{\sqrt{\lambda}}{\pi} \ln j$$



$$\gamma(j) = -\frac{1}{2}\left(\sqrt{2\sqrt{\lambda}(j-j_0)} - j\right)$$

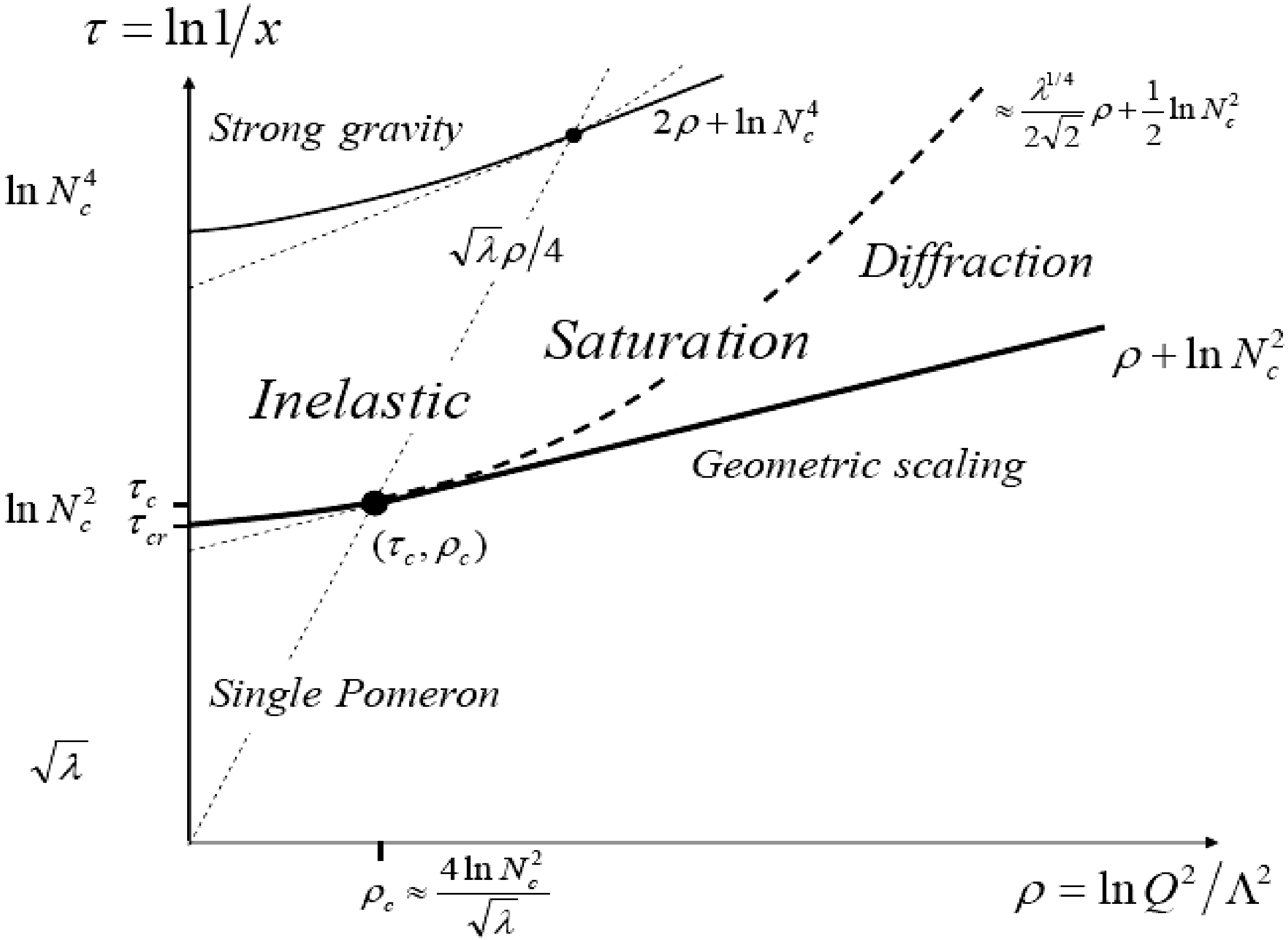
$$j_0 = 2 - \frac{2}{\sqrt{\lambda}}$$

$$F_1(x,Q^2) \sim \frac{1}{x}F_2(x,Q^2)$$

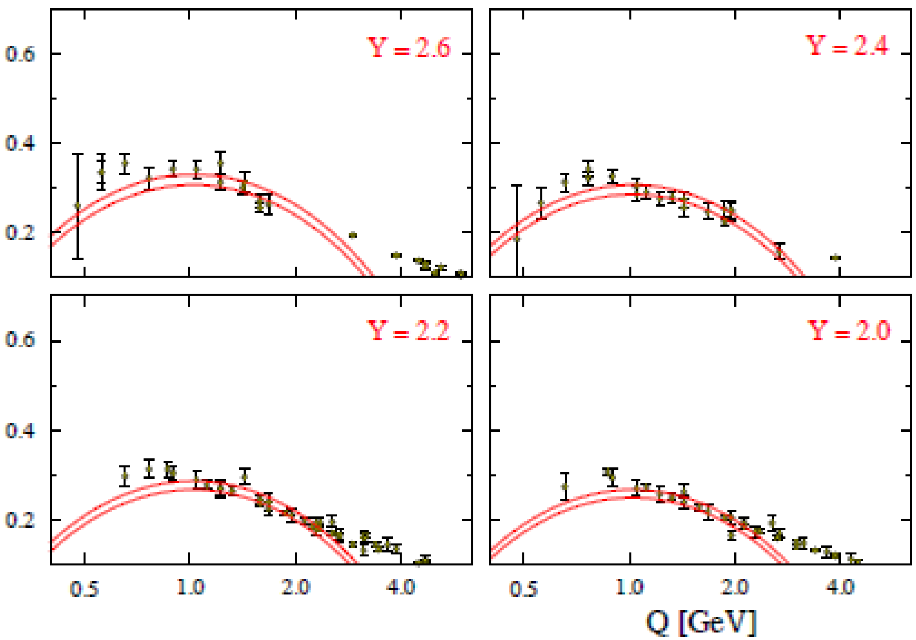
$$\sim \frac{1}{N_c^2}\left(\frac{1}{x}\right)^{j_0}$$

`Phase diagram' at strong coupling

YH, Iancu, Mueller

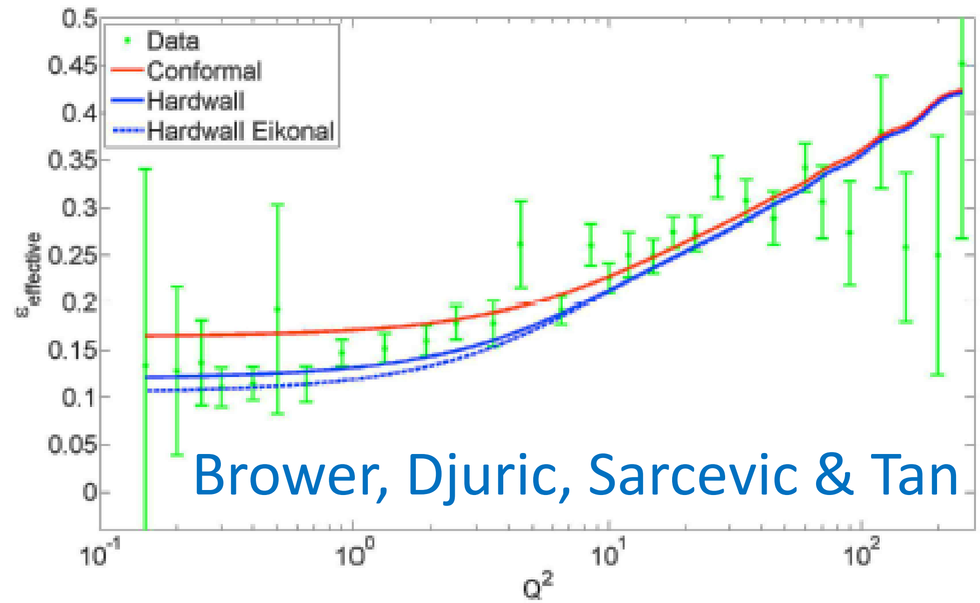


Fits to the HERA F_2 data



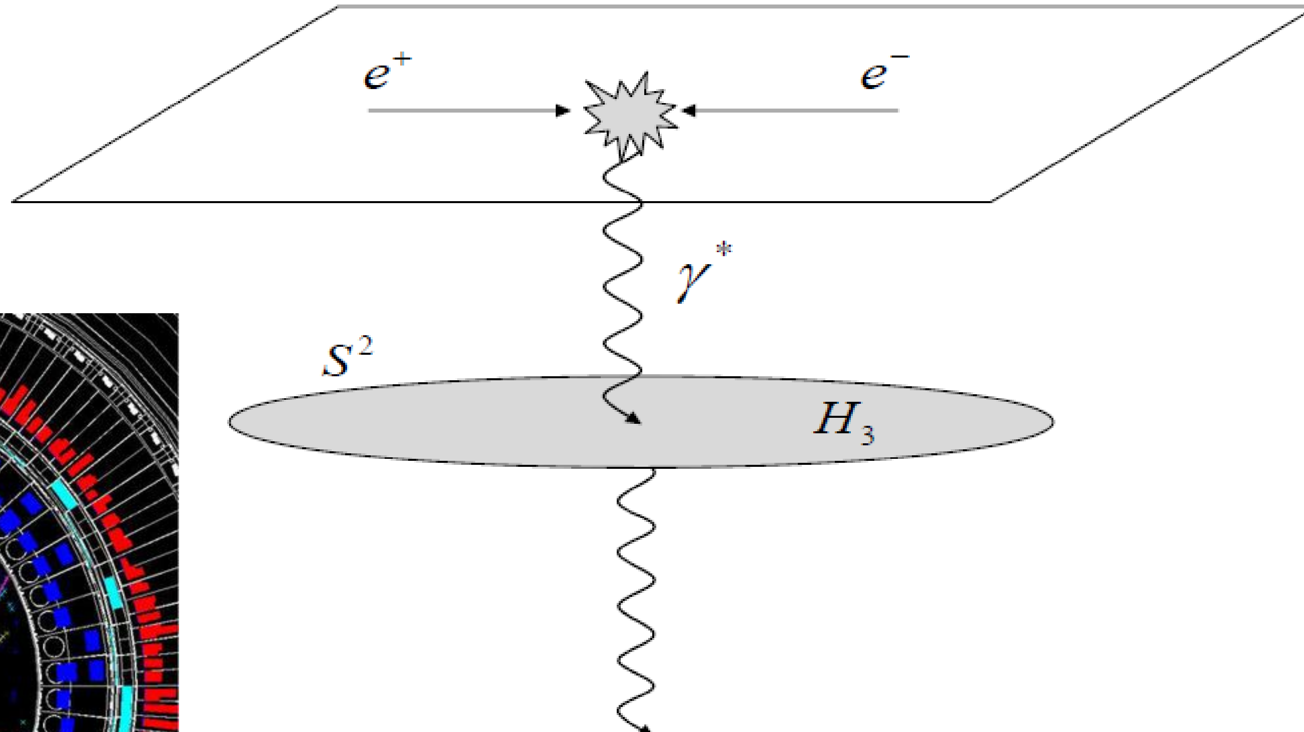
Cornalba & Costa

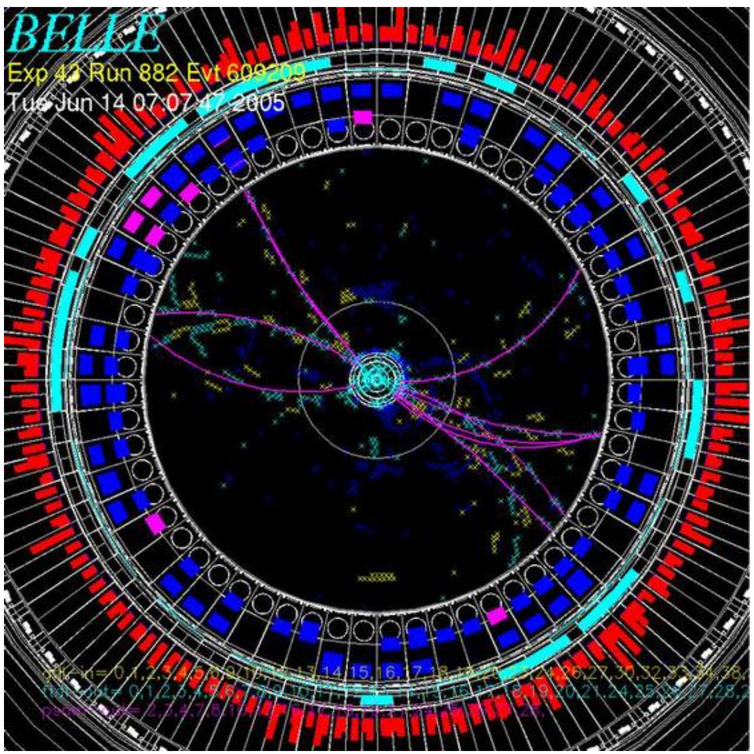
$$F_2(x, Q^2) \sim \left(\frac{1}{x}\right)^{\epsilon(Q^2)}$$



Brower, Djuric, Sarcevic & Tan

e+e- annihilation in N=4 SYM



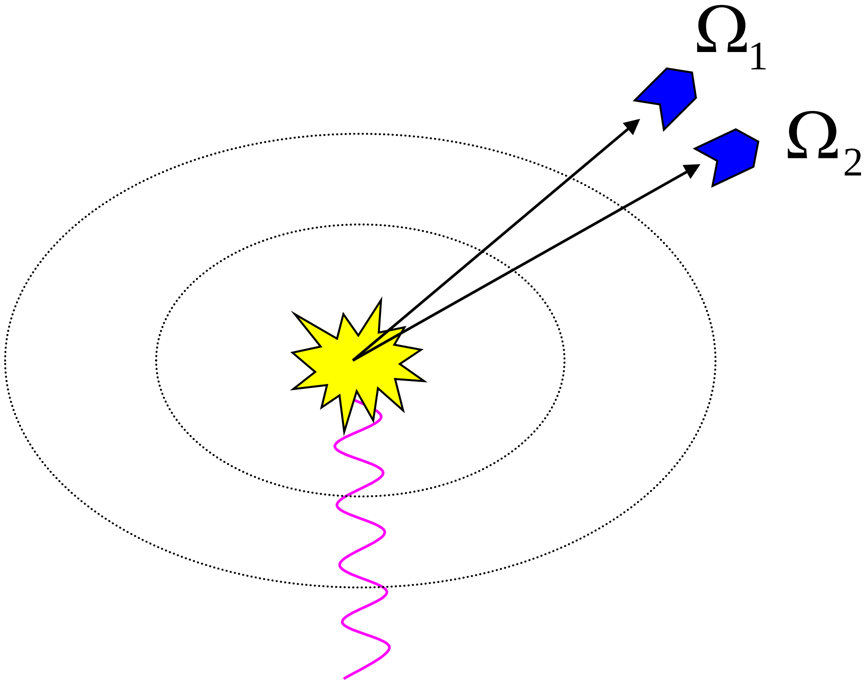


Energy correlation function

Hofman, Maldacena (2008)

Energy distribution is spherical for any λ
Correlations disappear as $\lambda \to \infty$

$$\langle \mathcal{E}(\Omega_1)\mathcal{E}(\Omega_2) \rangle \sim \frac{1}{|\theta_{12}|^{2+2\gamma_S(3)}}$$



$$\gamma(3) = \mathcal{O}(\lambda) \ll 1$$ weak coupling

$$= -\lambda^{1/4}/\sqrt{2}$$ strong coupling

$$\langle \mathcal{E}\mathcal{E} \rangle \to 0$$

There are no jets !

Energy distribution at strong coupling

Fragmentation function $$\frac{d\sigma}{dx} \sim D_T(x, Q^2/\mu_{IR}^2)$$

satisfies the Altarelli-Parisi equation

$$\frac{\partial}{\partial \ln Q^2} D_T(x, Q^2) = \int_x^1 \frac{dz}{z} P_T(z) D_T\left(\frac{x}{z}, Q^2\right)$$

Mellin transform

$$\frac{\partial}{\partial \ln Q^2} D_T(j, Q^2) = \underline{\gamma_T(j)} D_T(j, Q^2)$$

Timelike anomalous dimension

Timelike anomalous dimension in N=4

weak coupling

$$\gamma(j) = \frac{\lambda}{4\pi^2}(\psi(1) - \psi(j-1))$$

Lipatov, et al.

strong coupling

$$\gamma(j) = -\frac{1}{2}\left(j - j_0 - \frac{j^2}{2\sqrt{\lambda}}\right)$$

YH, Matsuo

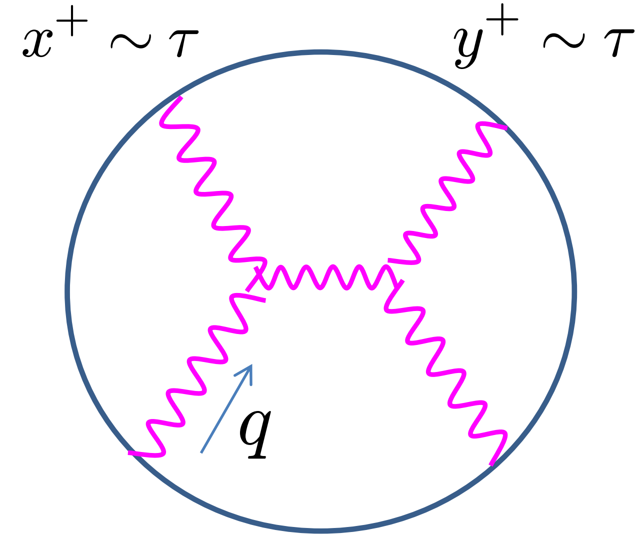
$$x^2 D(x, Q^2/\mu_{IR}^2) = \int dj \left(\frac{1}{x}\right)^{j-2} \left(\frac{Q^2}{\mu_{IR}^2}\right)^{\gamma(j)}$$

Dominant value of x where the energy is concentrated

$$x_{weak} \sim \left(\frac{\mu}{Q}\right)^{\lambda/12} \quad >> \quad x_{strong} \sim \left(\frac{\mu}{Q}\right)^{1-2/\sqrt{\lambda}}$$

Time-evolution in the final state

$$D\left(x, Q^2, \mu^2 = \frac{xq^+}{\tau}\right) \sim$$

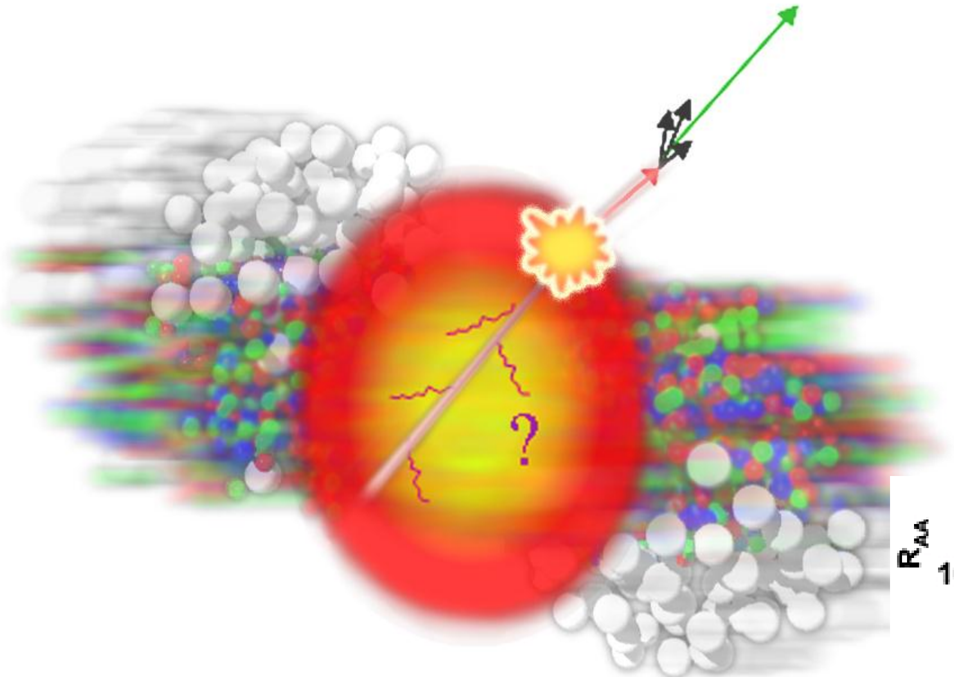


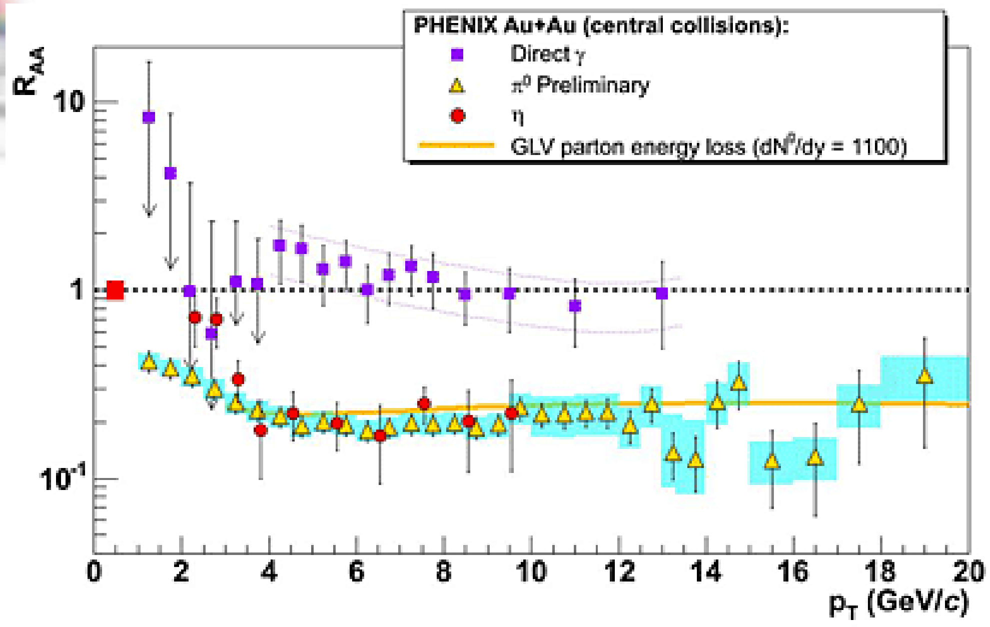
Measurement time $\quad \tau \sim \frac{xq^+}{\mu^2} \sim \frac{q^+}{xQ^2}$

Typical size of `partons' $\quad \Delta x^- \sim \frac{1}{xq^+} \sim \frac{\tau}{\gamma^2}, \quad \Delta x_\perp \sim \frac{1}{\mu} \sim \frac{\tau}{\gamma}$

The same as the size of the whole system.
→ No pointlike structure at strong coupling.

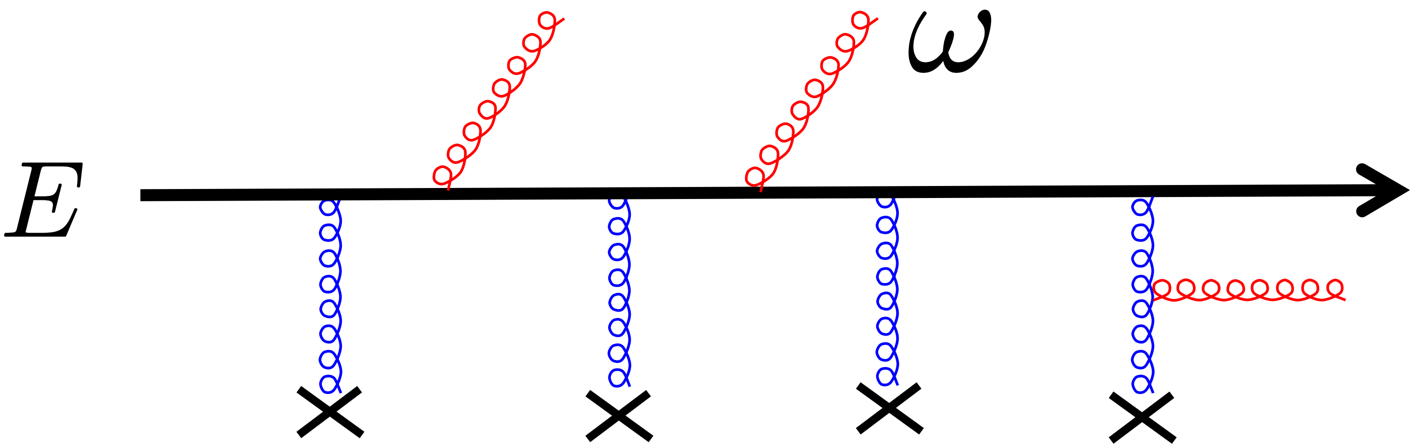
Jets at finite-T : Jet quenching in N=4





Jet quenching at weak coupling

Energy loss by coherent Bremsstrahlung (LPM effect)



$$\Delta E \sim \int^{E} \frac{\omega dI}{d\omega dz} d\omega dz \sim \alpha_s \sqrt{\hat{q}E}\, L$$

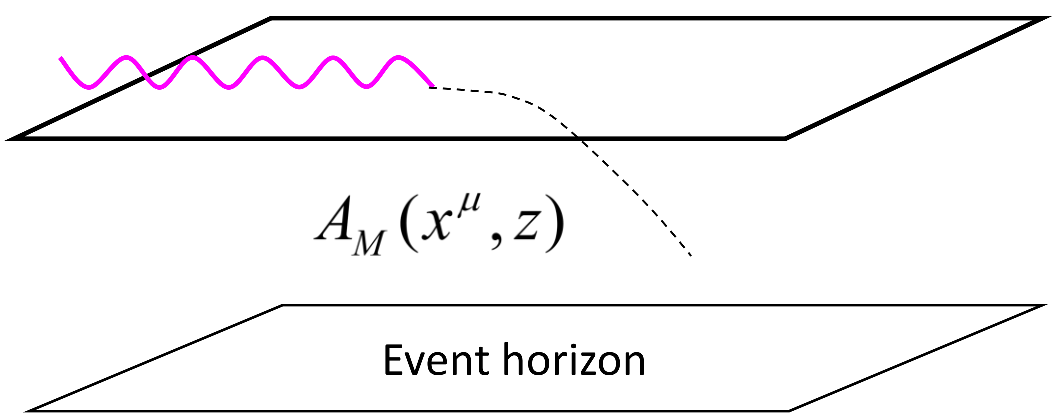
$$L_{max} \sim E^{1/2}$$

Jet quenching at strong coupling

Solve the Maxwell equation

$D_N F^{MN} = 0$ in the background of Schwarzschild AdS_5

$$ds^2 = \frac{R}{z^2}\left(-\left(1-\frac{z^4}{z_0^4}\right)dt^2 + (d\vec{x})^2\right) + \frac{R^2}{z^2}\frac{dz^2}{1-\frac{z^4}{z_0^4}}$$



$z = 0$

$z = z_0 = \frac{1}{\pi T_H}$

Effective Schrodinger equation

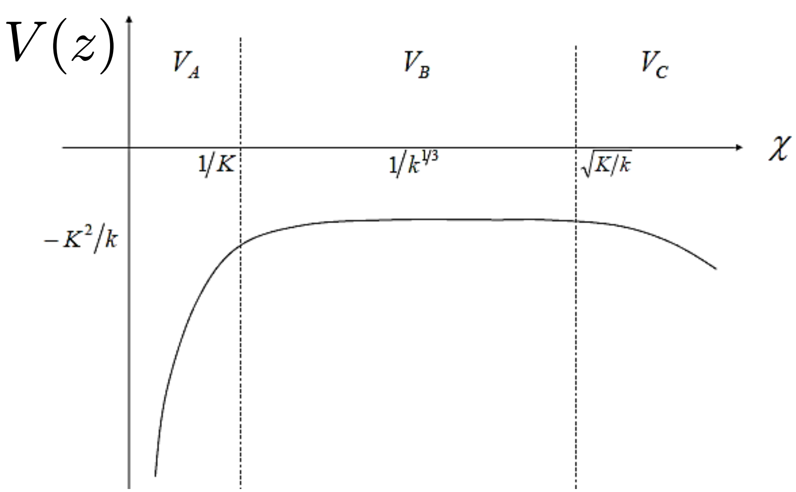
$$A_\mu(t,x,z) = e^{-iEt+iqx}\psi(t,z)$$

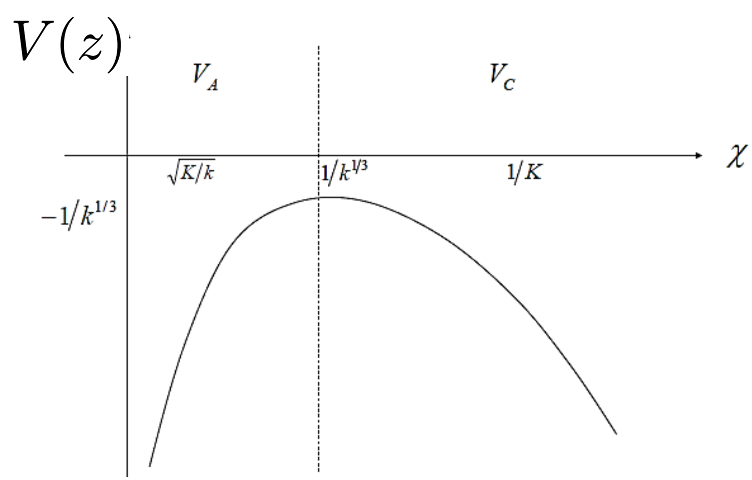
weak, residual t-dependence

$$D_N F^{MN} = 0 \quad \Longrightarrow \quad i\frac{\partial\psi}{\partial t} = \left(-\frac{1}{2q}\frac{\partial^2}{\partial z^2} + V(z)\right)\psi$$

"Potential" qualitatively different between

'low energy' $Q^3 > ET^2$ 'high energy' $Q^3 < ET^2$

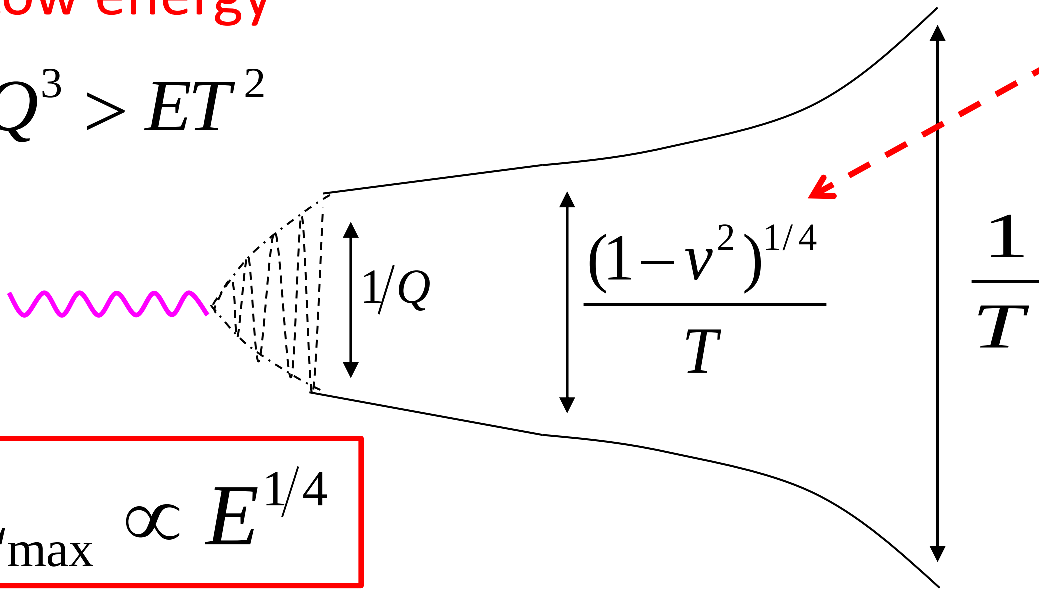




Stopping distance and spacetime evolution

Low energy

$$Q^3 > ET^2$$



$$L_{max} \propto E^{1/4}$$

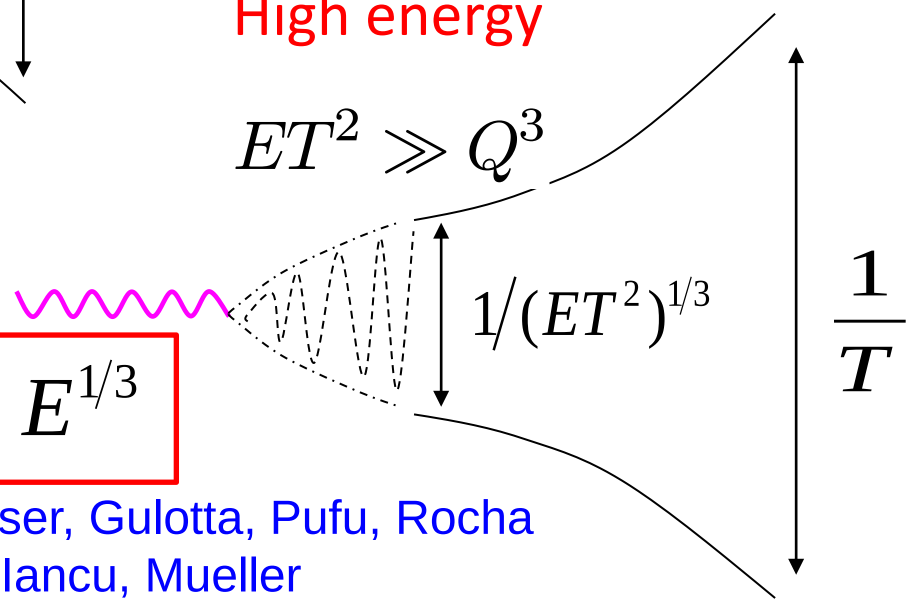
YH, Iancu, Mueller,
Arnold, Vaman

`meson screening length'

Liu, Rajagopal, Wiedemann

High energy

$$ET^2 \gg Q^3$$

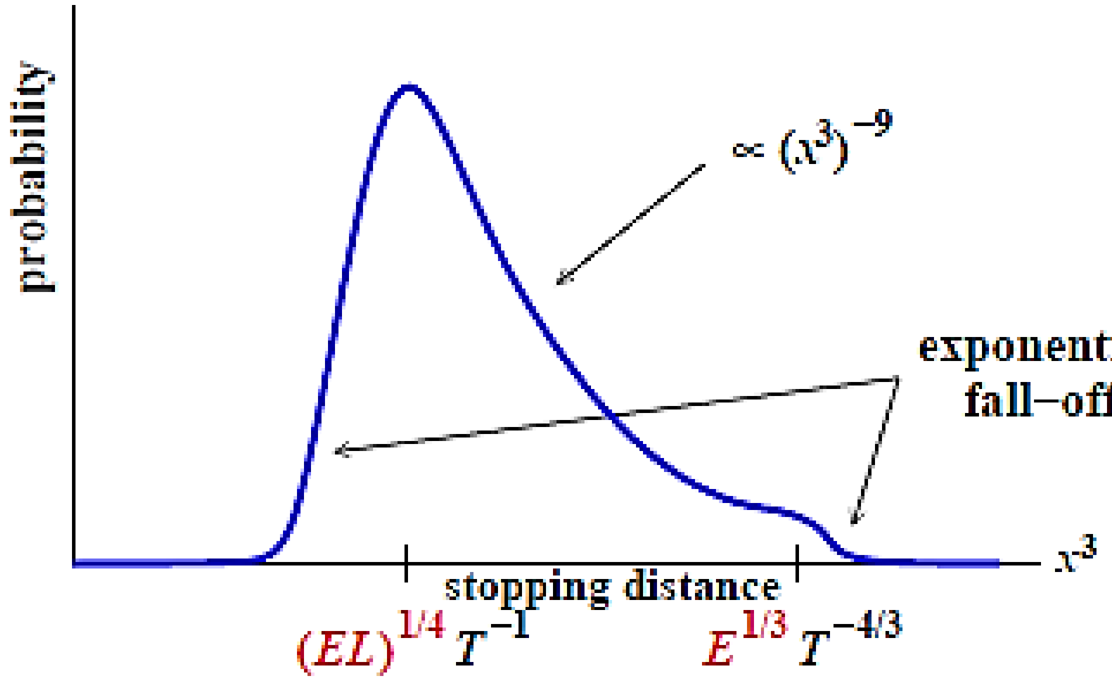


$$L_{max} \propto E^{1/3}$$

Gubser, Gulotta, Pufu, Rocha
YH, Iancu, Mueller
Chesler, Jensen, Karch, Yaffe

Recent developments

Arnold, Vaman (2011); 1203.6658 [hep-th]



$$L_{max} \propto E^{1/3}\left(1 + \#\lambda^{-3/2} + \cdots\right)$$

$$\lambda \to \infty$$

$$L_{\max} \propto E^{1/2}$$

$$\lambda \ll 1$$

Conclusions

- AdS/CFT offers an interesting framework to study nonperturbative aspects of high energy processes.

- Beware, some features are completely different from QCD.

- At strong coupling, all the interesting physics is at small-x due to the strong fragmentation.