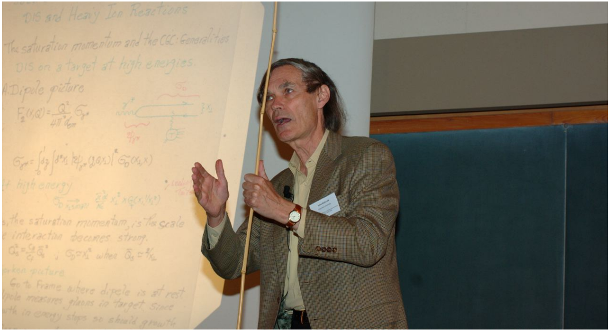
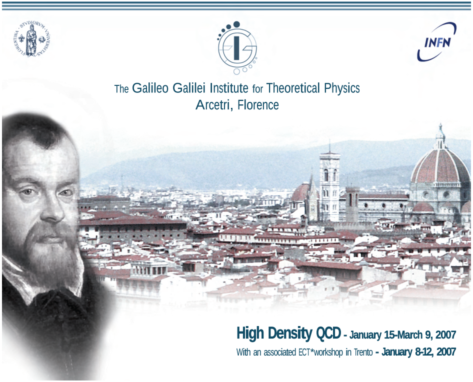
Parton Evolution with Truly Strong Interactions

Al's Journey from Particles and Partons to Nuclei and Fields

... within Extra Dimensions



It has all started in Florence ...



… then grew up through discussions in Calabria …

and consolidated through mini–workshops in Paris

Our motivation

- Our* original motivation was to show that all this excitement about strongly–coupled QGP at RHIC ...

'us' = Al Mueller, Yoshi Hatta & E.I.

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- ... was not very scientifically motivated ! (to put it polite)
- ... and we have been partially successful !

Our motivation

- But we get caught into this game ... and still we are !

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- ... because it is an interesting game to play !
  - no other method known to address dynamical problems at strong coupling
  - the potential to solve longstanding puzzles at RHIC (early thermalization, large elliptic flow, large jet quenching)
  - new perspectives on old problems (QGP = Black Hole, parton saturation, jets, transition from weak to strong coupling)
  - it teaches us the unity of physics (quantum field theory, statistical physics, gravity, hydrodynamics, ...)

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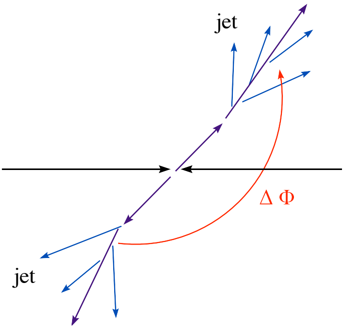
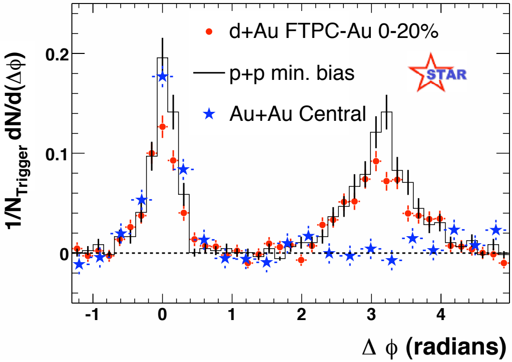
  - it teaches us the unity of physics (quantum field theory, statistical physics, gravity, hydrodynamics, ...)
- ... because we thought we have something to add to this field :

Our main contribution

Al's great physical intuition

Jets in proton–proton collisions



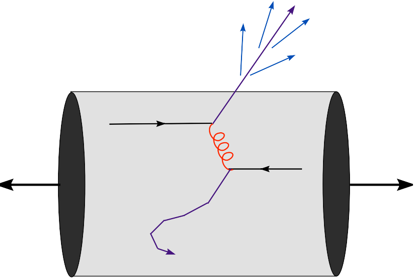


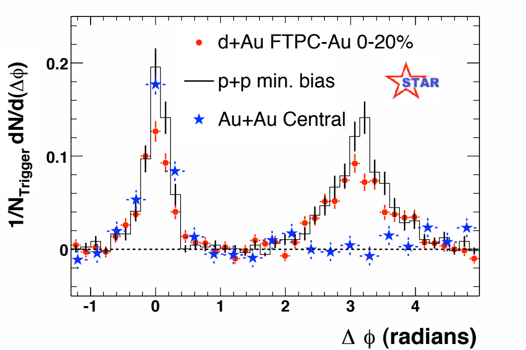
[Nucl.Phys.A783:249-260,2007]

- Azimuthal correlations between the produced jets:

  p+p or d+Au : a peak at $\Delta\Phi = 180^\circ$

Nucleus–nucleus collisions at RHIC





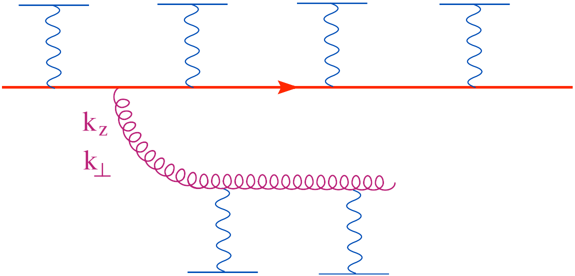
- The "away–side" jet has disappeared !

  absorbtion (or energy loss, or "jet quenching") in the medium

- The matter produced in a heavy ion collision is opaque

  high density, strong interactions, ... or both

Energy loss in pQCD: medium–induced radiation



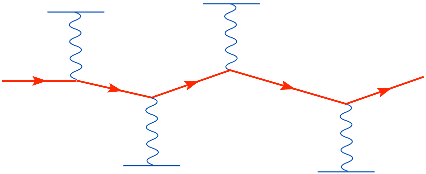
- Gluon radiation is permitted due to thermal rescattering
- A non–local process : gluon formation time $\Delta t_{\rm coh} \sim k_z/k_\perp^2$

$$-\frac{{\rm d}E}{{\rm d}t} \simeq \alpha_s N_c \frac{k_z}{\Delta t_{\rm coh}} \sim \alpha_s N_c \langle k_\perp^2 \rangle$$: relation to 'momentum broadening'

BDMPS *(Baier, Dokshitzer, Mueller, Peigne, Schiff, 97)*

Jet quenching in pQCD

- Medium rescattering $\Longrightarrow$ transverse momentum broadening



$$\frac{\mathrm{d}\langle k_\perp^2\rangle}{\mathrm{d}t} \equiv \hat{q} \simeq \alpha_s N_c\, xg(x, Q^2)$$

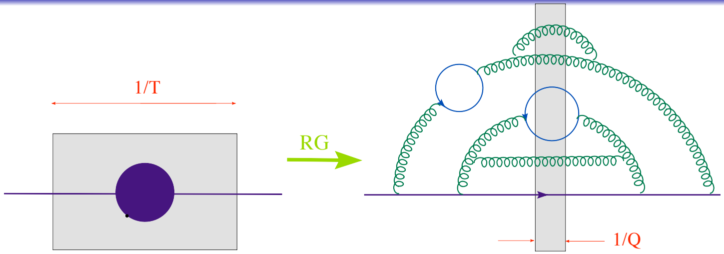
- $xg(x, Q^2)$: gluon distribution per unit volume in the medium

  on the resolution scales $Q^2 \sim \langle k_\perp^2\rangle$ and $1/x \sim \Delta t_{\rm coh}\, T$

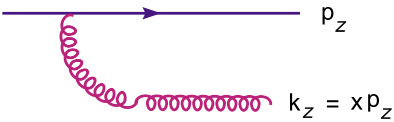
- Finite–T plasma : quarks and gluons with momenta $\sim T$
- This requires parton evolution from scale T up to $Q \gg T$

  jet quenching = a mesure of parton evolution

Parton evolution



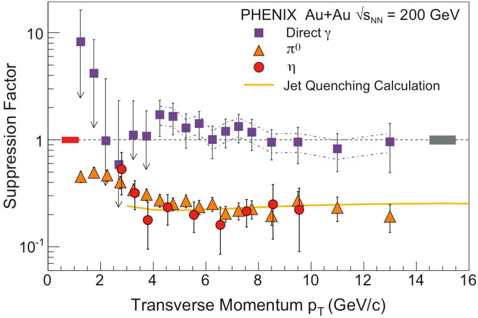
- A 'quasiparticle' on the scale T may reveal itself as highly composite on the harder scale $Q \gg T$
- Weak coupling: Bremsstrahlung



$$\mathrm{d}\mathcal{P}_{\rm Brem} \sim \alpha_s N_c \frac{\mathrm{d}^2 k_\perp}{k_\perp^2} \frac{\mathrm{d}x}{x}$$

$$xG(x, Q^2) \simeq \alpha_s N_c \ln(Q^2/T^2)$$

How to measure $\hat{q}$?



Nuclear modification factor

$$R_{AA}(p_\perp) \equiv \frac{Yield(A+A)}{Yield(p+p) \times A^2}$$

- RHIC data seem to prefer a rather large value for $\hat{q}$:

  $\hat{q}_{\rm RHIC} \simeq 5 \div 15$ vs. $\hat{q}_{\rm pQCD} \simeq 0.5 \div 1\,{\rm GeV}^2/{\rm fm}$

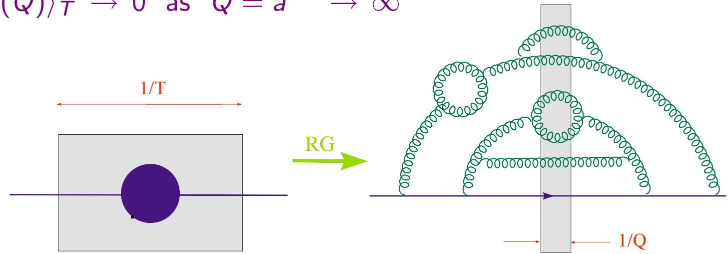
  $\Longrightarrow$ 5 to 10 times larger than the pQCD estimate !

- A signal of stronger parton evolution, hence of strong coupling

Parton evolution in lattice QCD *(E.I., A. Mueller 09)*

- Quark energy density in quenched QCD : $\mathcal{T}_q^{\mu\nu} \equiv \bar{q}\gamma^\mu iD^\nu q$
- Lowest–spin leading–twist operator ... which actually evolves !

$$\langle \mathcal{T}_q^{\mu\nu}(Q)\rangle_T \to 0 \quad \text{as} \quad Q = a^{-1} \to \infty$$



- Compare the lattice result with the ideal gas expectations:
  - if the difference is less than 30% $\Longrightarrow$ weak coupling
  - a much stronger reduction $\Longrightarrow$ strong coupling

Parton evolution at strong coupling

Deep Inelastic Scattering in AdS/CFT

- How to study parton evolution in a strongly coupled plasma ?
- Compute deep inelastic scattering within AdS/CFT !
- Pioneering work: Polchinski and Strassler, 2002

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  ... but they found no partons ! ☹
- We found the partons ! ☺ *(Hatta, E.I., Mueller, 07–08)*

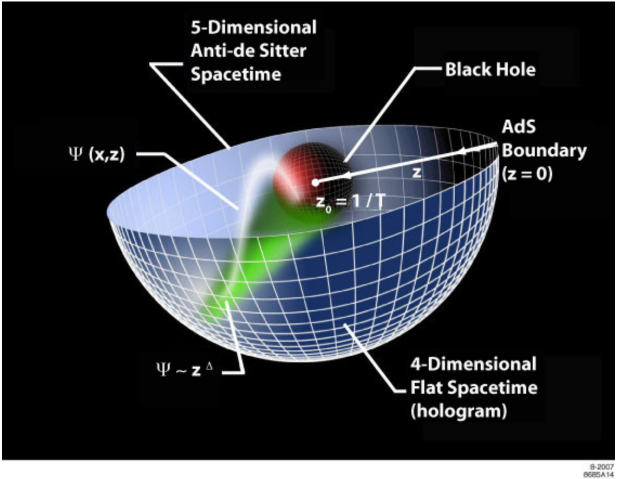
  DIS in the vicinity of the unitarity limit

The AdS/CFT correspondance *(Maldacena, 1997)*

- A gauge theory ($\mathcal{N} = 4$ SYM) in $D = 3 + 1$ at strong coupling
  - SU(N_c), conformal invariance, fixed coupling g, no confinement
- ... is equivalent to a string theory at weak coupling !
  - $D = 9 + 1$ curved space–time : $AdS_5 \times S^5$
  - our physical $3 + 1$ world: the boundary of AdS_5
- Strong 't Hooft coupling : $\lambda \equiv g^2 N_c \gg 1$ & $g^2 \ll 1$
  - string theory reduces to classical supergravity
  - classical EOM for the (super)gravity perturbations induced by the relevant operators on the 'boundary'
- $\mathcal{N} = 4$ SYM plasma at finite temperature: Black Hole in AdS_5
  - a Black Hole has entropy and thermal (Hawking) radiation

An artist view of AdS_5

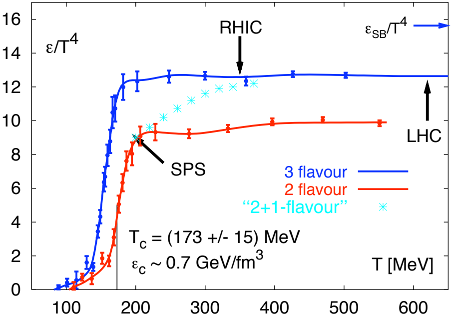
(the Artists: Dam Son, Stan Brodsky, and Guy de Teramond)

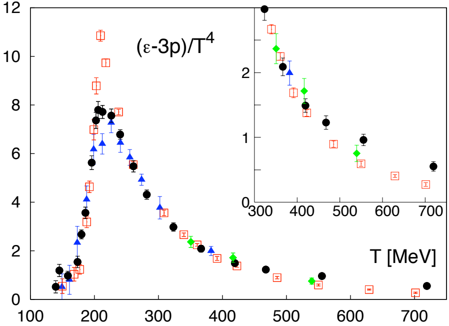


(curtesy of Guy de Teramond)

'Trace anomaly' in lattice QCD

- For $T \gtrsim 2T_c$, the QCD plasma itself is nearly conformal





$$\beta(g)\,\frac{\mathrm{d}p}{\mathrm{d}g} = \langle T^{\mu}_{\mu}\rangle = \mathcal{E} - 3p$$

- $(\mathcal{E}-3p)/\mathcal{E}_0 \lesssim 10\%$ for any $T \gtrsim 2T_c \simeq 400$ MeV

DIS off the Black Hole *(Hatta, E.I., Mueller, 07)*

- AdS_5 : Our physical world ($D = 4$) $\times$ a 'radial' dimension χ
- Virtual photon in 4D (J^μ) $\longleftrightarrow$ Maxwell wave A_μ in AdS_5 BH
- DIS cross section $\longleftrightarrow$ absorption of the wave by BH

- Physical world: $\chi = 0$

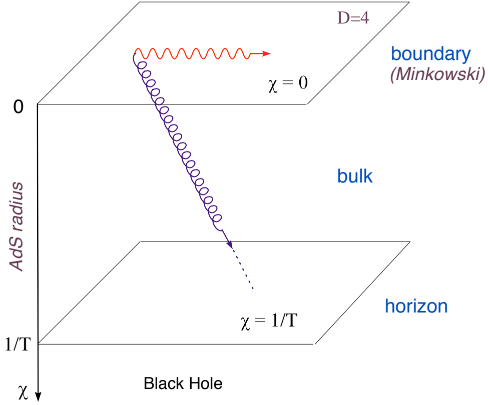
  Black Hole horizon: $\chi = 1/T$

- Maxwell equations in AdS_5 BH

$$\partial_m\left(\sqrt{-g}\, g^{mn} g^{pq} F_{nq}\right) = 0$$

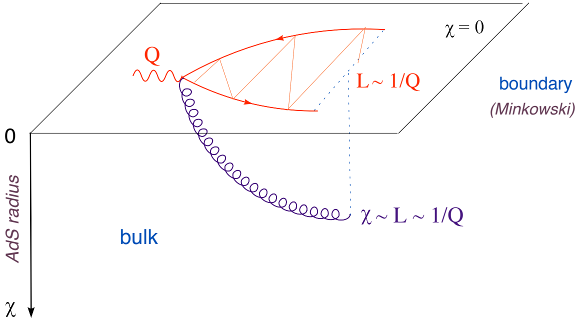
$$F_{mn} = \partial_m A_n - \partial_n A_m$$

- No explicit coupling constant



The 5th dimension: A reservoir of quantum fluctuations

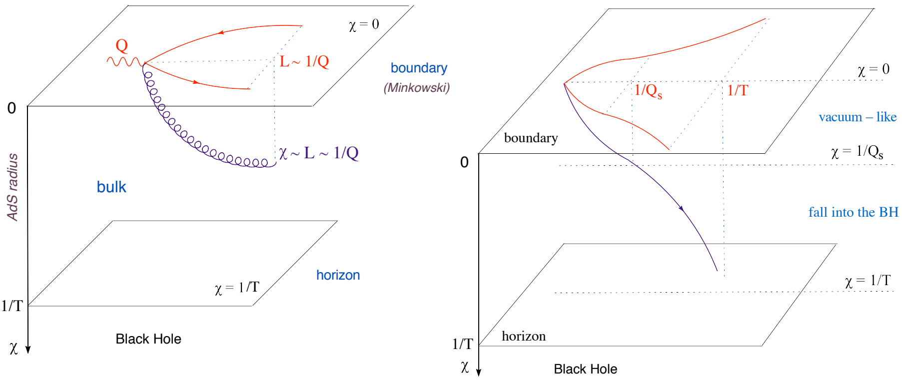
- Dual to the 'loop' momenta in the usual Feynman graphs (the momenta of the quantum fluctuations)



- Radial penetration χ of the wave packet in AdS_5 $\longleftrightarrow$ transverse size L of the partonic fluctuation on the boundary

Space–like photon in AdS$_5$

- For low energies, the photon does not 'see' the BH !



- ... while for large enough energies, it is completely absorbed !

Saturation line

- Gravitational interactions are proportional to the energy density in the wave (ω) and in the plasma (T)
- Large ωT is tantamount to small Bjorken's x

$$x \equiv \frac{Q^2}{2\omega T} \quad \text{and} \quad Q \gg T \quad \text{(photon virtuality)}$$

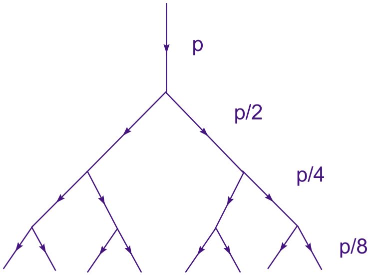
- Critical ('saturation') value $x_s(Q) \simeq \frac{T}{Q} \ll 1$
  - $x > x_s \simeq T/Q$: $F_2(x, Q^2) \approx 0$: no partons
  - $x < x_s \simeq T/Q$: $F_2(x, Q^2) \sim x N_c^2 Q^2$

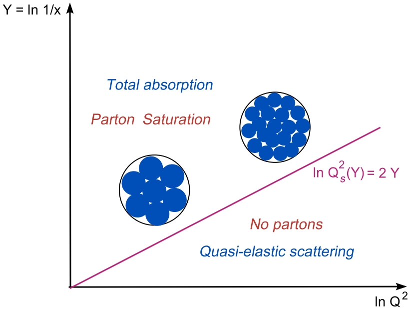
  $\Longrightarrow$ Parton saturation with occupation numbers $\mathcal{O}(1)$

- The energy of the plasma is carried mostly by the partons along the saturation line: $x_s \simeq T/Q \ll 1$

Physical interpretation: Parton evolution

- All partons branch down to the smallest value of x consistent with energy conservation $\Longrightarrow$ no pointlike constituents



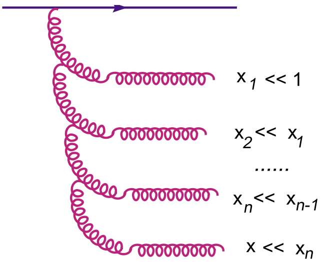


- Q_s grows very fast: graviton $\Longrightarrow$ intercept $\alpha_{\mathbb{G}} = j = 2$

  ... compare to BFKL 'Pomeron' in pQCD: $\alpha_{\mathbb{P}} = 1 + \mathcal{O}(\alpha_s)$

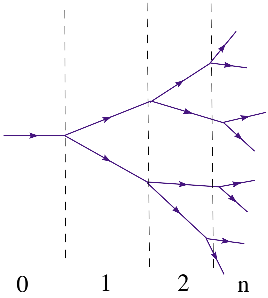
Parton evolution: weak vs. strong coupling

- Weak coupling



- Bremsstrahlung
- Soft & collinear emissions
- Slow process : $\Delta t \sim k_z/k_\perp^2 \gg 1/k_z$
- Low multiplicity : $N \propto \ln E$

- Strong coupling



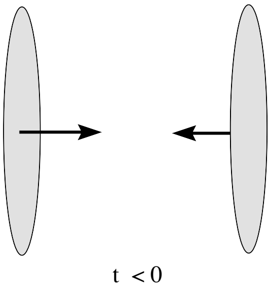
- Quasi–democratic branching :

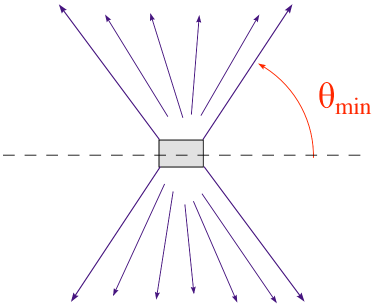
$$\omega_n \sim \omega_{n-1}/2$$

- Hard & fast $\Longrightarrow$ very efficient
- High multiplicity : $N \propto E/\Lambda$

No forward/backward jets !

- No large–x partons $\Longrightarrow$ no hard ($Q \gg \Lambda$) particle production at forward/backward rapidities

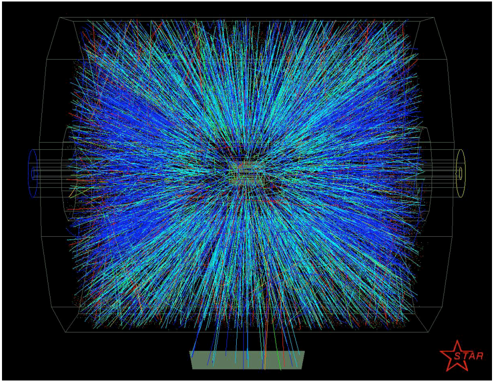




- All the energy is carried out by soft particles with $p \sim \Lambda$

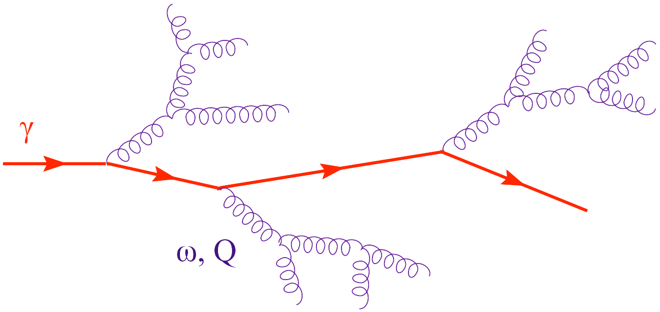
See also the talk by Yoshi Hatta !

Partons at RHIC



- Partons are actually 'seen' (liberated) in the high energy hadron–hadron collisions
  - central rapidity: small–x partons
  - forward/backward rapidities: large–x partons

Heavy Quark in a strongly–coupled plasma

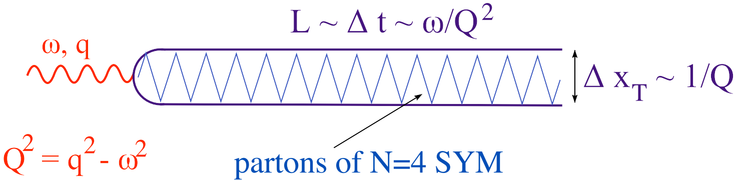


- Medium–induced radiation
  - virtual quanta with $Q \lesssim Q_s$ are liberated into the plasma
  - energy loss, momentum broadening
- Different mechanism than in pQCD: radiation vs. rescattering

Beyond QCD ... beyond weak coupling

Happy Birthday Al ! ... What's next ?

Physical interpretation: Energy considerations



- Partonic fluctuation: transverse area $1/Q^2$ and lifetime ω/Q^2
- Plasma energy within the volume of the fluctuation:

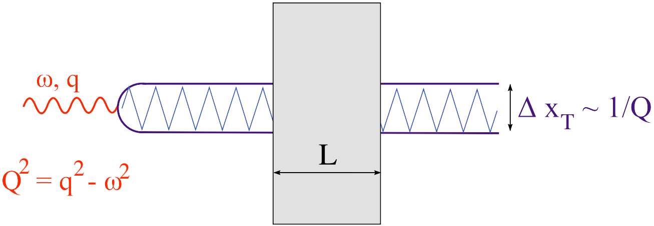
$$\Delta E \sim \Delta V \times \epsilon \sim \frac{1}{Q^2}\frac{\omega}{Q^2} \times T^4 \sim \frac{\omega T^4}{Q^4}$$

- The fluctuation becomes timelike (on–shell) when

$$\omega \times \Delta E \gtrsim Q^2 \quad \Longrightarrow \quad Q^2 \lesssim \frac{T^2}{x^2}$$

Saturation momentum for a ‘nucleus’

(Mueller, Shoshi, and Xiao, 2008;
Avsar, E.I., McLerran and Triantafyllopoulos, 2009)



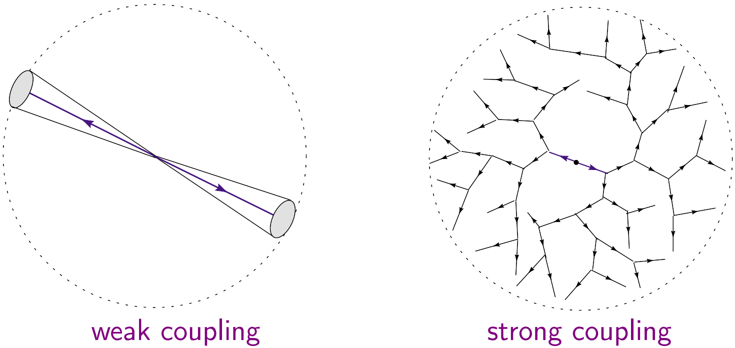
- Finite length medium with N_c^2 degrees of freedom per unit volume (a slice of deconfined plasma)

$$\Delta E \sim \frac{LT^4}{Q^2} \quad \Longrightarrow \quad Q_s^2 \sim \frac{LT^3}{x}$$

- ... to be compared to $Q_s^2 \sim 1/x^{0.3}$ from the HERA data

No jets at strong coupling !

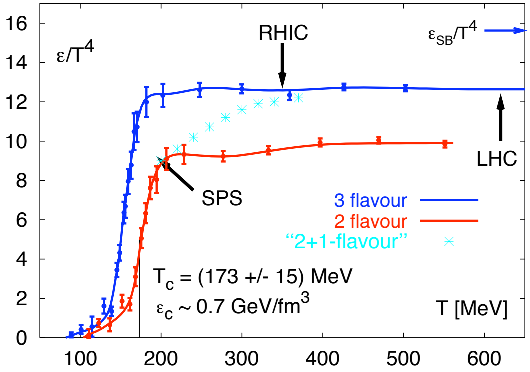
- No jets in e^+e^- annihilation at strong coupling !



- An isotropic distribution of soft hadrons in the detector

  (similar conclusions by Hofman and Maldacena, 2008)

Lattice QCD *(RBC–Bielefeld Coll.)*

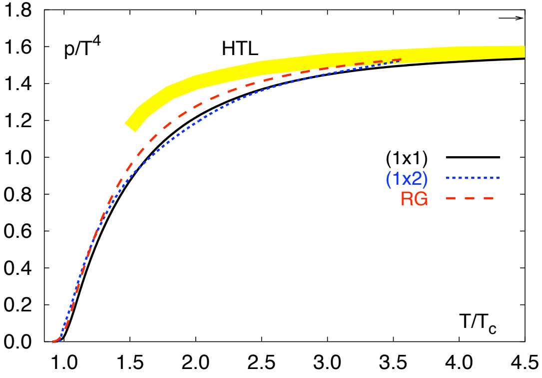


$$\mathcal{E}/\mathcal{E}_0 \approx 0.85 \qquad \text{for} \qquad T = 3T_c$$

- Is this suggestive of weak interactions ? Or of strong ones ?

Resummed perturbation theory

- For $T \gtrsim 2.5\,T_c$, the lattice results are well reproduced by resummed perturbation theory! (Blaizot, Rebhan, E. I., 2000)

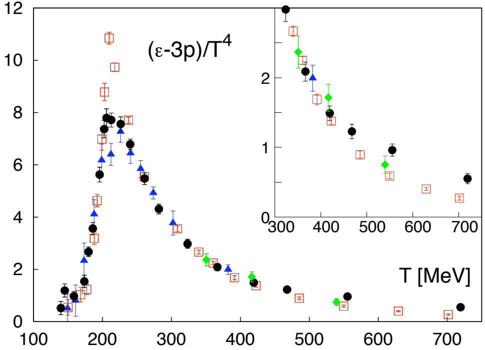


- Weakly coupled quasiparticles (quarks and gluons)

The strong coupling scenario

- AdS/CFT for $\mathcal{N} = 4$ SYM : $P/P_0 \to 0.75$ when $\lambda \to \infty$

$$\beta(g)\,\frac{\mathrm{d}p}{\mathrm{d}g} = \langle T^{\mu}_{\mu} \rangle = \mathcal{E} - 3p$$



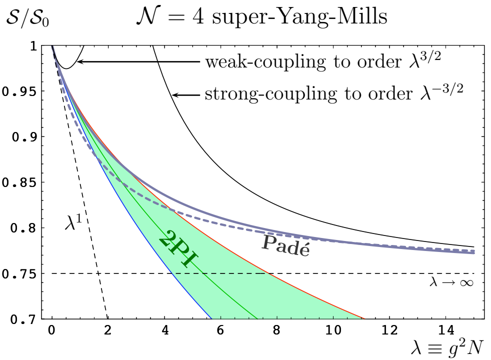
- $(\mathcal{E} - 3p)/\mathcal{E}_0 \lesssim 10\%$

  for any $T \gtrsim 2T_c \simeq 400$ MeV

- For $T \gtrsim 2T_c$, the quark–gluon plasma is nearly conformal

$\mathcal{N}=4$ SYM plasma: weak vs. strong coupling

- Weak–coupling to $\mathcal{O}(\lambda^{3/2})$, strong–coupling to $\mathcal{O}(\lambda^{-3/2})$
- Unique Padé approximant *(J.-P. Blaizot, A. Rebhan, E. I., 06)*



- $\mathcal{S}/\mathcal{S}_0 = 0.85$ corresponds to intermediate coupling ($\lambda \simeq 4$)
- $\mathcal{N}=4$ SYM plasma: A convenient theoretical laboratory

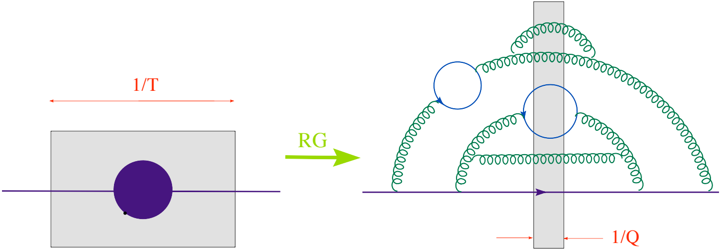
A lattice test of strong coupling *(E.I., A. Mueller 09)*

- Leading–twist, spin n operators (OPE for DIS) :

$$\mathcal{O}_f^{(n)\,\mu_1\cdots\mu_n} \equiv \bar{q}\,\gamma^{\mu_1}(iD^{\mu_2})\cdots(iD^{\mu_n})q$$

$$\mathcal{O}_g^{(n)\,\mu_1\cdots\mu_n} \equiv -F^{\mu_1\nu}(iD^{\mu_2})\cdots(iD^{\mu_{n-1}})F^{\mu_n}{}_{\nu}$$

- The operators depend upon the resolution scale



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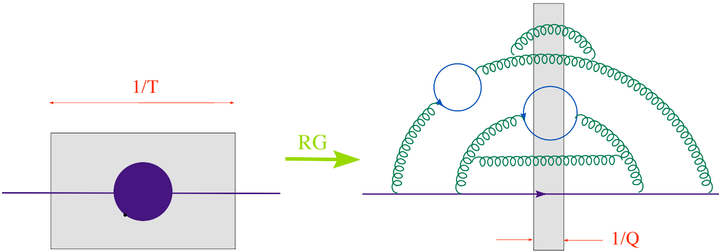


$$\langle\mathcal{O}^{(n)}\rangle_{Q^2} \propto \langle x^{n-1}\rangle_{Q^2}\,, \qquad x = \text{longitudinal momentum fraction}$$

Renormalization group flow

- RG flow $\Longrightarrow$ negative anomalous dimensions

$$\mu^2 \frac{\mathrm{d}}{\mathrm{d}\mu^2}\, \mathcal{O}^{(n)} = \gamma^{(n)} \mathcal{O}^{(n)} \quad \text{with} \quad \gamma^{(n)} \leq 0$$

- Only exception: energy momentum tensor for which $\gamma_T^{(2)} = 0$

$$T^{\mu\nu} = \mathcal{O}_f^{(2)\,\mu\nu} + \mathcal{O}_g^{(2)\,\mu\nu}$$

- QCD at weak coupling: slow evolution

$$\gamma^{(n)}(\mu^2) = -a^{(n)} \frac{\alpha_s(\mu^2)}{4\pi} \quad \Longrightarrow \quad \frac{\mathcal{O}^{(n)}(Q^2)}{\mathcal{O}^{(n)}(\mu_0^2)} = \left[\frac{\ln(\mu_0^2/\Lambda^2)}{\ln(Q^2/\Lambda^2)}\right]^{a^{(n)}/b_0}$$

- Conformal theory, arbitrary coupling: $\frac{\mathcal{O}^{(n)}(Q^2)}{\mathcal{O}^{(n)}(\mu_0^2)} = \left[\frac{\mu_0^2}{Q^2}\right]^{|\gamma^{(n)}|}$

Anomalous dimensions from lattice QCD

- $\mathcal{N}=4$ SYM at strong 't Hooft coupling: $\lambda \equiv g^2 N_c \gg 1$

$$\gamma^{(n)} \simeq -\sqrt{\frac{n}{2}}\,\lambda^{1/4} \quad \text{for} \quad 1 \ll n \ll \sqrt{\lambda}$$

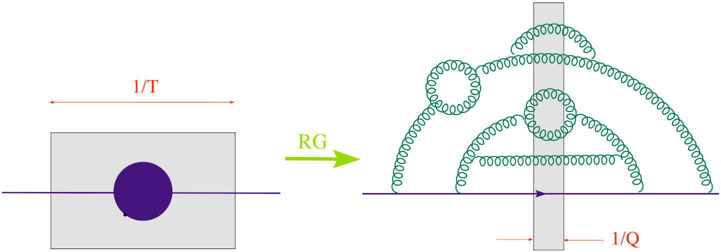
- All the unprotected leading–twist operators are strongly suppressed in the continuum limit $Q \equiv a^{-1} \to \infty$
- Measure unprotected operators in lattice thermal QCD !
- High–spin operators with $n \geq 4$ are difficult to measure ☹
- One $n=2$ unprotected operator: orthogonal to $T^{\mu\nu}$ ☺

$$\Theta^{\mu\nu}(\mu^2) = \mathcal{O}_f^{(2)\,\mu\nu}(\mu^2) + C(\mu^2)\mathcal{O}_g^{(2)\,\mu\nu}(\mu^2)$$

- ... but we cannot compute $C(\mu^2)$ except at weak coupling ☹

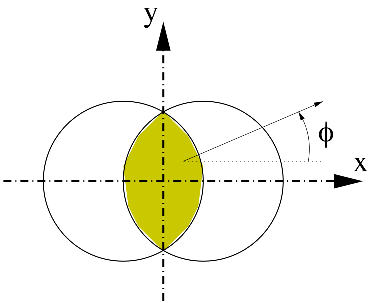
Quenched QCD

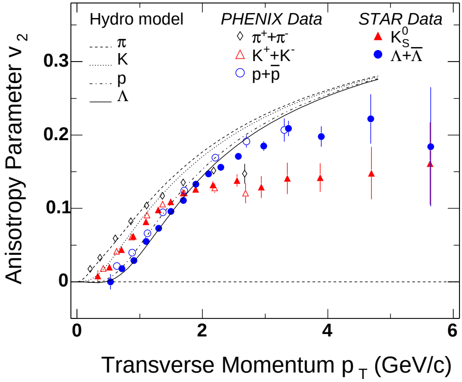
- … or in quenched QCD (no quark loops), where $C(\mu^2) = 0$ ☺



- Measure the quark energy density in quenched lattice QCD
  …compare the result with the weak coupling expectation (SB)
  - If the difference is less than 30% $\Longrightarrow$ weak coupling
  - A reduction by a large factor $\gtrsim 5 \Longrightarrow$ strong coupling

Elliptic flow



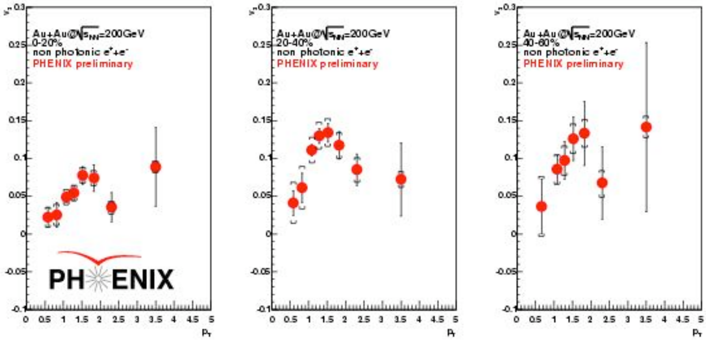


- Non–central *AA* collision: Pressure gradient is larger along x

$$\mathrm{d}N/\mathrm{d}\phi \,\propto\, 1 + 2v_2 \cos 2\phi\,, \qquad v_2 \;=\; \text{“elliptic flow”}$$

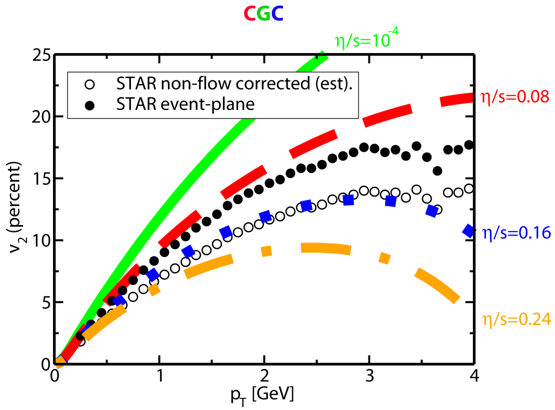
- Large observed flow ! Inconsistent with weak coupling

Elliptic flow



- Even heavy quarks (c, b) seem to flow !

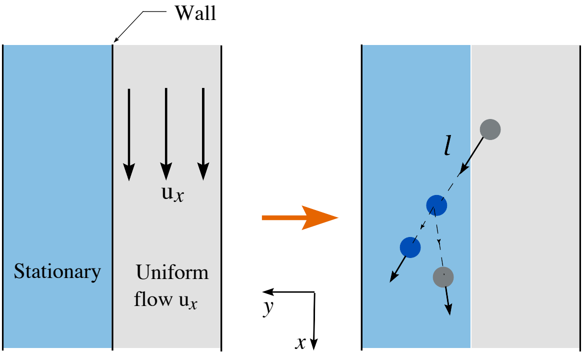
Elliptic flow



- Well described by hydrodynamical calculations with very small viscosity/entropy ratio: "perfect fluid", or "sQGP"

Viscosity

- Shear viscosity η : a measure of a fluid ability to transfer p_x momentum in the y direction



$$\frac{1}{A}\frac{\mathrm{d}p_x}{\mathrm{d}t} = -\eta\,\frac{\mathrm{d}u_x}{\mathrm{d}y}$$

- Proportional to the mean free path $\ell \sim 1/g^4$

$\Longrightarrow$ larger at weak coupling !

Viscosity over entropy density ratio

- Uncertainty principle: $\eta/s \gtrsim \hbar$
- Weakly interacting systems have $\eta/s \gg \hbar$
- A small η/s ratio is a hint towards strong coupling
- AdS/CFT *(Kovtun, Son, Starinets, 2003)*

$$\frac{\eta}{s} \to \frac{\hbar}{4\pi} \quad \text{when} \quad \lambda \equiv g^2 N_c \to \infty$$

- This limiting value is believed to be 'universal'
  "any gauge theory which admits a gravity dual"
- The RHIC value is at most a few times $\hbar/4\pi$!
  "strongly–coupled quark–gluon plasma", or sQGP

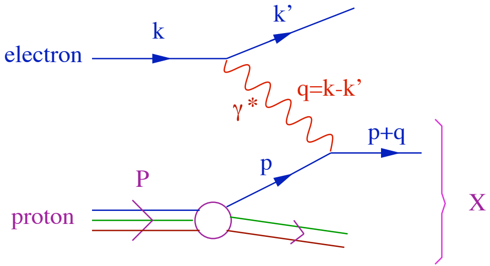
Deep inelastic scattering

- The most direct device to probe parton evolution

- Space–like photon
- 2 independent variables:

$$Q^2 \equiv -q^\mu q_\mu \geq 0$$

$$x \equiv \frac{Q^2}{2P \cdot q}$$

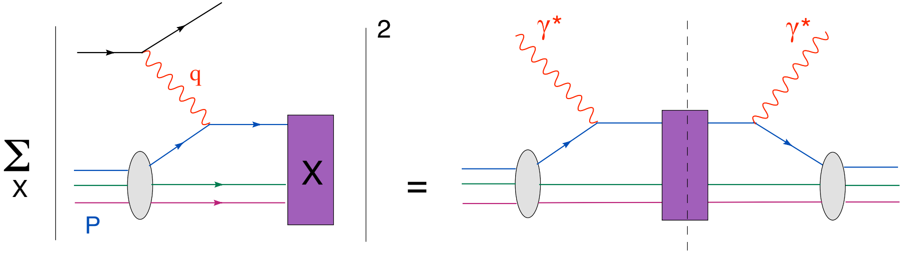


- Physical picture: γ^* absorbed by a quark excitation with
  - transverse size $\Delta x_\perp \sim 1/Q$
  - and longitudinal momentum $p_z = xP$

- Structure function $F_2(x, Q^2)$: quark distribution

Current–current correlator

- Total cross–section (“structure functions”): optical theorem



$$F_{1,2}(x, Q^2) \;\sim\; \mathrm{Im} \int \mathrm{d}^4x\, \mathrm{e}^{-iq\cdot x}\, i\, \langle P \,|\, \mathrm{T}\,\{J_\mu(x) J_\nu(0)\} \,|\, P \rangle$$

$$J^\mu \;=\; \sum_f e_f\, \bar{q}_f\, \gamma^\mu\, q_f$$: quark electromagnetic current

- Valid to leading order in $\alpha_{\rm em}$ but all orders in α_s

DIS off the strongly coupled plasma

- Thermal expectation value $(Q^2 \equiv |q^2| \gg T^2)$

$$\Pi_{\mu\nu}(q) \equiv \int \mathrm{d}^4x\, \mathrm{e}^{-iq\cdot x}\, i\theta(x_0)\, \langle\, [J_\mu(x), J_\nu(0)]\, \rangle_T$$

- $\mathcal{N} = 4$ SYM at finite temperature & $\lambda \equiv g^2 N_c \to \infty$:
  classical gravity in the $AdS_5 \times S^5$ Black Hole geometry

$$\mathrm{d}s^2 = \frac{R^2}{\chi^2}\big(-f(\chi)\mathrm{d}t^2 + \mathrm{d}\boldsymbol{x}^2\big) + \frac{R^2}{\chi^2 f(\chi)}\mathrm{d}\chi^2 + R^2\mathrm{d}\Omega_5^2$$

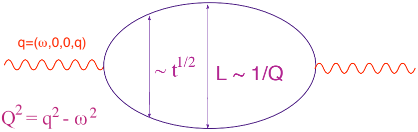
where $f(\chi) = 1 - (\chi/\chi_0)^4$ and $\chi_0 = 1/T$ = BH horizon

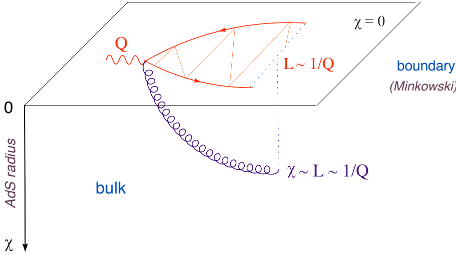
- A Black Hole has entropy and thermal (Hawking) radiation

Space–like photon in the vacuum

- A space–like photon cannot decay in the vacuum :

  virtual fluctuation with size $L \sim 1/Q$ and lifetime $\Delta t \sim \omega/Q^2$



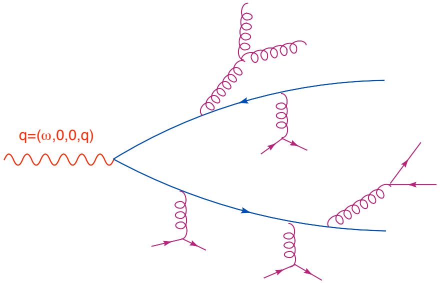


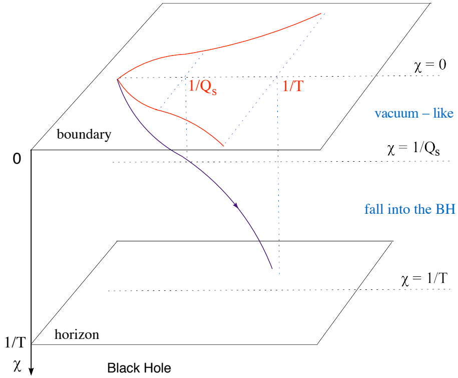
- AdS : The Maxwell wave penetrates into AdS_5 up to a

  radial distance $\chi \sim 1/Q$

Space–like photon in the plasma

- … but it can decay in the presence of the plasma





- This is what happens in the strongly coupled plasma

  … but only for sufficiently high energy ω

Space–like photon in the plasma

- Gravitational interactions are proportional to the energy density in the wave (ω) and in the plasma (T)

- High Q^2/large Bjorken x

  The wave gets stuck near the boundary

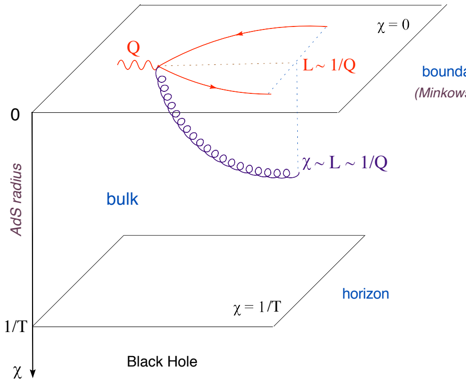
  $$\chi \lesssim 1/Q \ll 1/T$$

  $\Longrightarrow$ No interaction with the BH

- Low Q^2/small x

  $$x \equiv \frac{Q^2}{2\omega T} \lesssim x_s(Q) \simeq \frac{T}{Q}$$

  $\Longrightarrow$ The wave falls into the BH



The energy–momentum sum rule

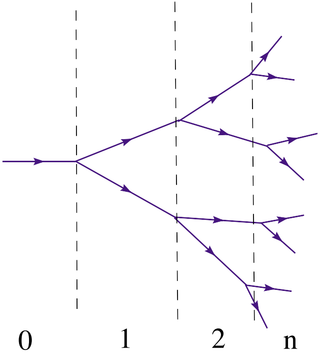
$$\int_0^1 \mathrm{d}x\, F_2(x, Q^2) = \textit{const.} \qquad \text{as} \quad Q^2 \to \infty$$

- ... is still dominated by the few partons remaining at $x \sim \mathcal{O}(1)$
- As $x \to 0$, F_2 rises 'only' like $F_2(x, Q^2) \sim x^{-\lambda}$ with $\lambda \lesssim 0.3$
- The small–x gluons are numerous, but carry very little energy
- Pointlike valence quarks

... to be contrasted with the situation at strong coupling !

Parton branching at strong coupling

- At strong coupling, branching is fast and quasi–democratic



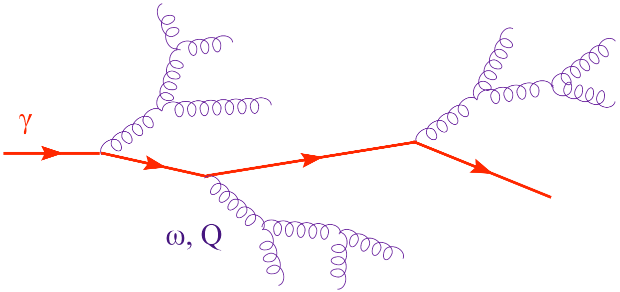
$$\omega_n \sim \frac{\omega_{n-1}}{2} \sim \frac{\omega}{2^n}$$

$$Q_n \sim \sim \frac{Q_{n-1}}{2}$$

$$\Delta t_n \sim \frac{\omega_n}{Q_n^2}$$

- When $\omega_n \sim Q_n \sim T$, the quanta disappear into the plasma
- Dominant mechanism for energy loss and momentum broadening at strong coupling

Heavy Quark in a strongly–coupled plasma

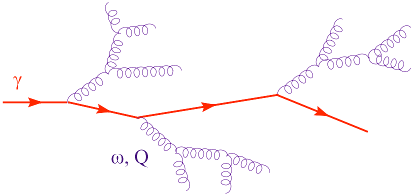


- Medium–induced radiation
  - virtual quanta with $Q \lesssim Q_s$ are liberated into the plasma
  - energy loss, momentum broadening
  - Langevin equation from AdS/CFT

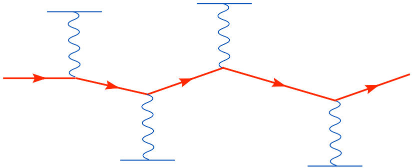
  Casalderrey-Solana, Teaney, 2006; Gubser, 2006; Dominguez et al, 2008

Momentum broadening

- Strong coupling : fluctuations in the emission process



- pQCD : thermal rescattering



See talk by Cyrille Marquet