Partons and jets in a strongly coupled plasma from AdS/CFT

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(lecture notes arXiv:0812.0500)

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- Experimental results at RHIC suggest that the deconfined hadronic matter ('Quark–Gluon Plasma') produced in a AA collision at high energy might be strongly interacting
- A challenge for the theory: lattice QCD cannot be used for such dynamical phenomena
- New method: string theory via AdS/CFT correspondence
  - not yet QCD: conformal symmetry, no confinement
  - at high energy and/or finite temperature, such issues are (presumably) less important, even in QCD
- A vigourous activity with many interesting results
  - conceptually interesting relations between particle physics, string theory, gravity, black holes
  - physical interpretation of the results is very challenging

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- Motivation : Heavy Ion Collisions at RHIC and LHC
- Weak coupling: Partons and jets in perturbative QCD
- Strong coupling: AdS/CFT Correspondence
- Finite–T plasma: Deep inelastic scattering & Parton saturation
- Finite–T plasma: Jet quenching & Momentum broadening

The Little Bang

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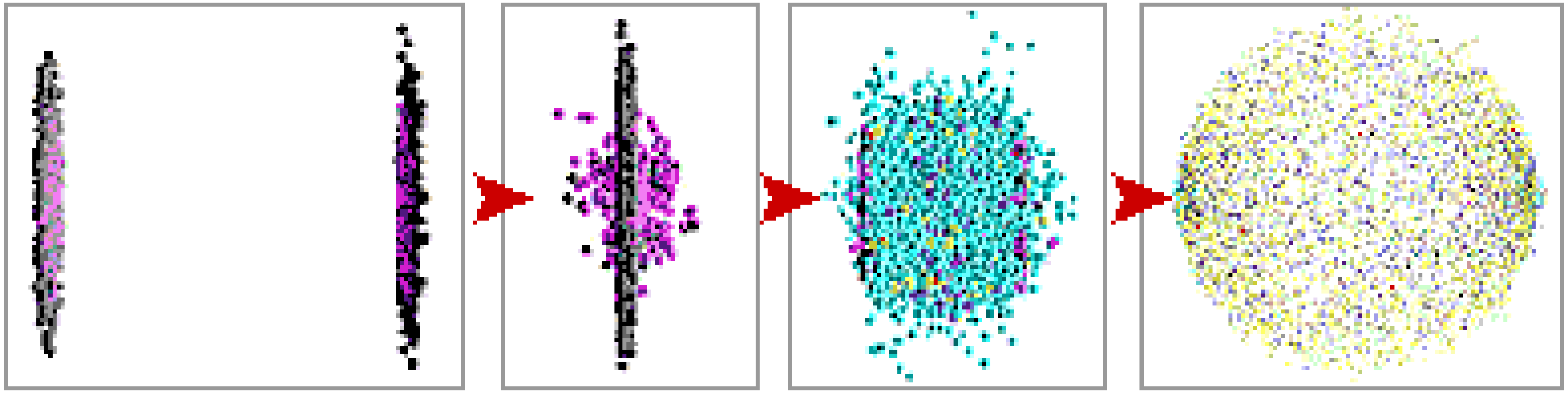
- Ultrarelativistic heavy ion collisions @ RHIC and LHC



- Extremely complex phenomena
  - high density partonic systems in the initial wavefunctions
  - multiple interactions during the collisions
  - complicated, non-equilibrium, dynamics after the collision
  - expansion, thermalization, hadronisation
- Is there any place for strong–coupling dynamics ?

Hadron production at RHIC

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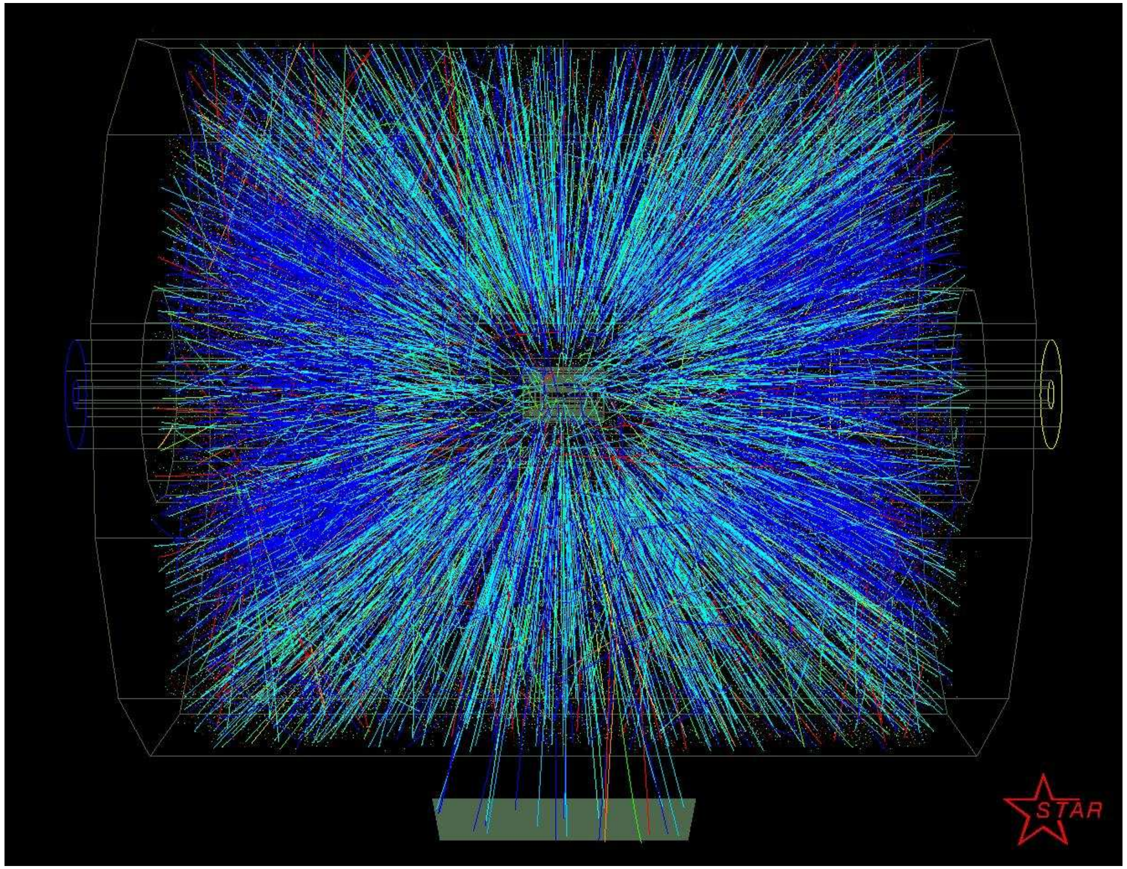

- ~ 3000 hadrons in the final state vs. 400 nucleons in AA
- Most of them arise as hadronized partons
- Particle correlations are essential to disentangle phenomena

Elliptic flow at RHIC: The perfect fluid

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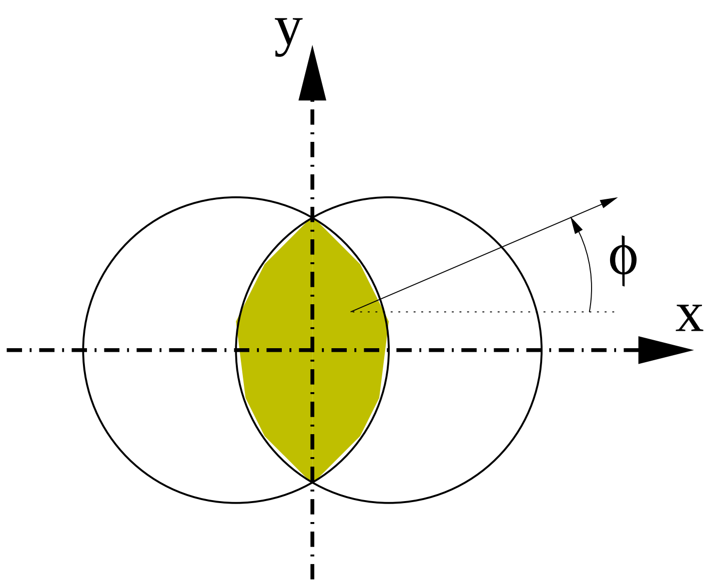

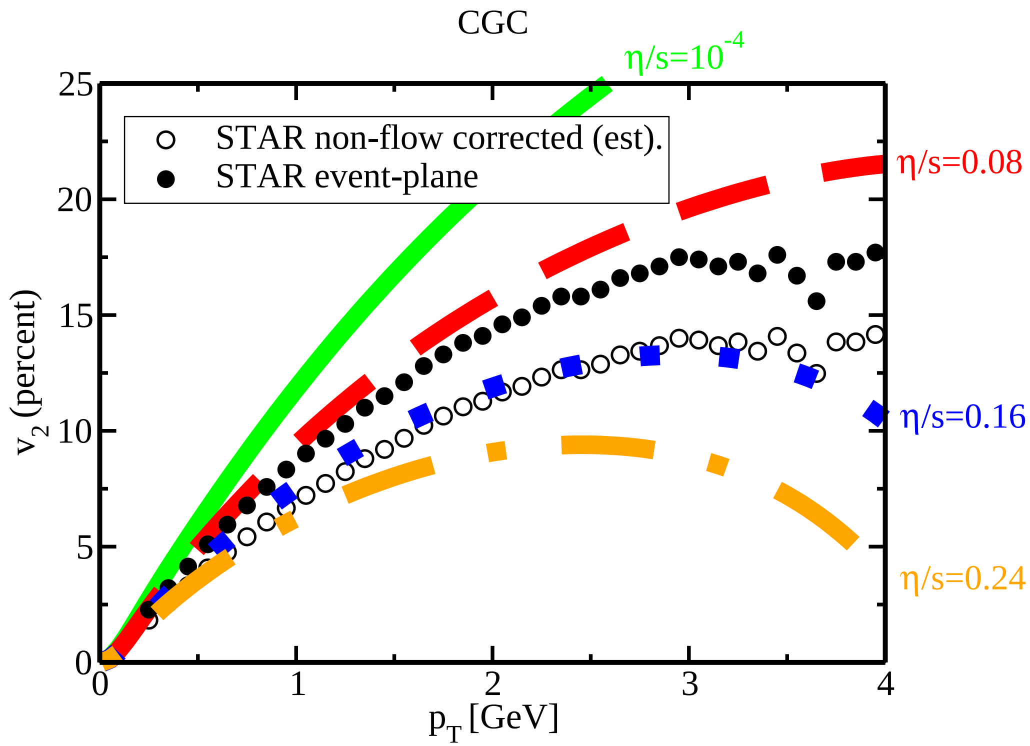

- Non–central AA collision: Pressure gradient is larger along x

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

- Well described by hydrodynamical calculations with very small viscosity/entropy ratio: “perfect fluid”

Viscosity over entropy density ratio

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- Viscosity/entropy density ratio at RHIC (in units of $\hbar$)

$$\frac{\eta}{s} = 0.1 \pm 0.1(\mathrm{theor}) \pm 0.08(\mathrm{exp}) \quad [\hbar]$$

- Weakly interacting systems have $\eta/s \gg \hbar$
- Kinetic theory: viscosity is due to collisions among molecules

$$\eta \sim \rho\, v\, \ell = \text{mass density} \times \text{velocity} \times \underbrace{\text{mean free path}}_{\sim 1/g^4}$$

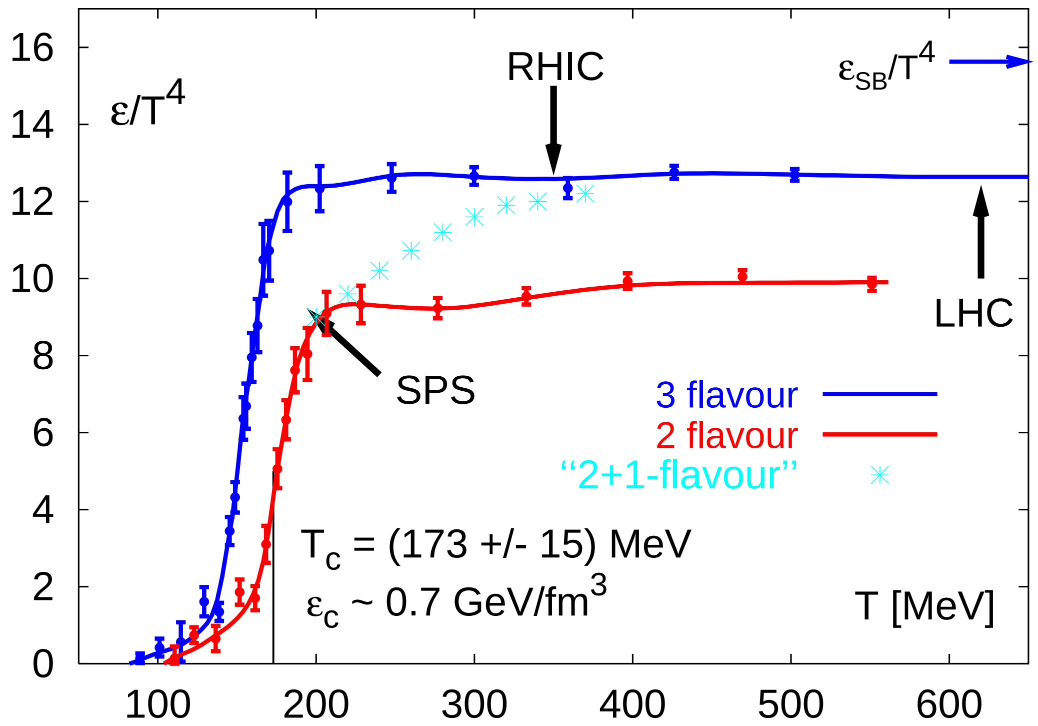
- Conjecture (from AdS/CFT) : *[Kovtun, Son, Starinets, 2003]*

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi} \qquad \text{[lower limit = infinite coupling]}$$

- The RHIC value is at most a few times $\hbar/4\pi$!

Heating QCD : Lattice results

- Energy density as a function of T (Bielefeld Coll.)



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

- Is this deviation from ideal gas small ? Or is it large ?
- AdS/CFT : $\mathcal{E}/\mathcal{E}_0 \to 3/4$ when $\lambda \to \infty$ ($\mathcal{N} = 4$ SYM)

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Finite–T : Resummed perturbation theory

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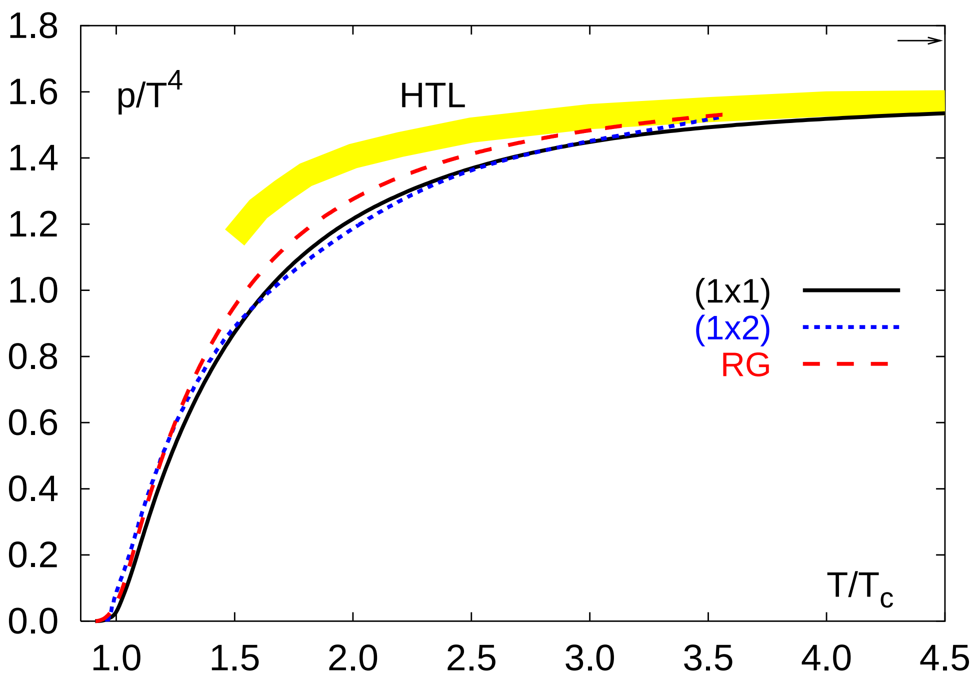
- This ratio $p/p_0 \approx 0.85$ can be also explained by resummed perturbation theory

  (collective phenomena: screening, thermal masses)

  (J.-P. Blaizot, A. Rebhan, E. Iancu, 2000)



- First principle calculation without free parameter

Jets in proton–proton collisions

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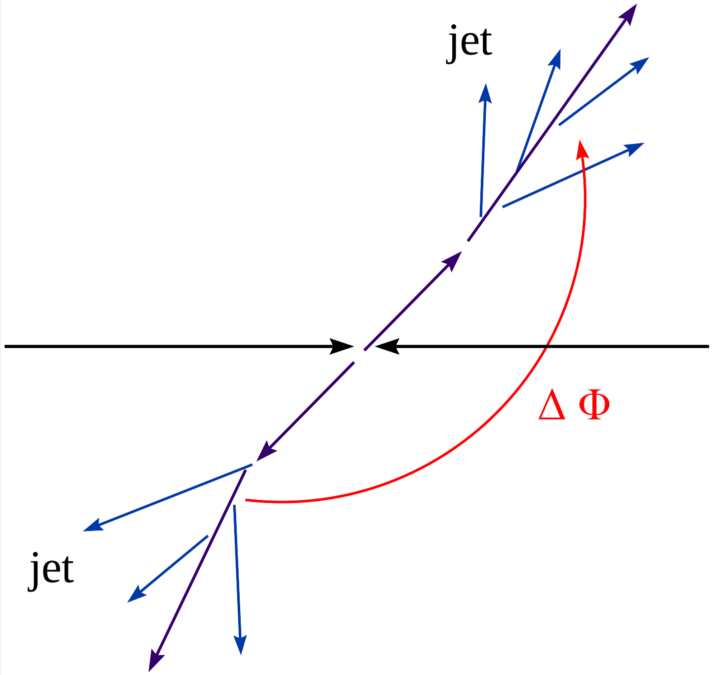

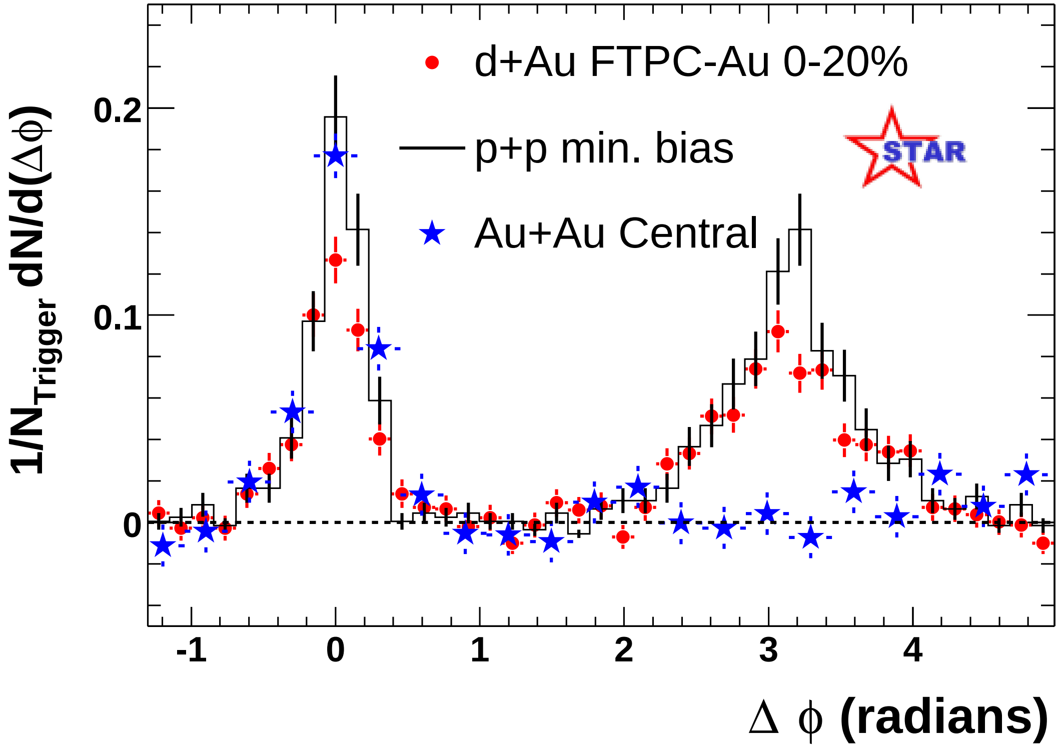

- Azimuthal correlations between the produced jets:

  a peak at $\Delta\Phi = 180°$

Nucleus–nucleus collision

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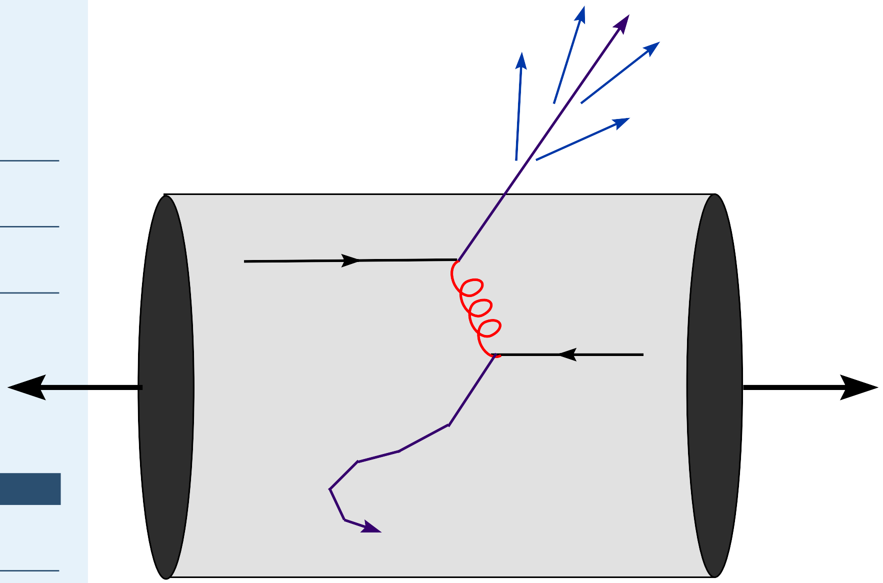

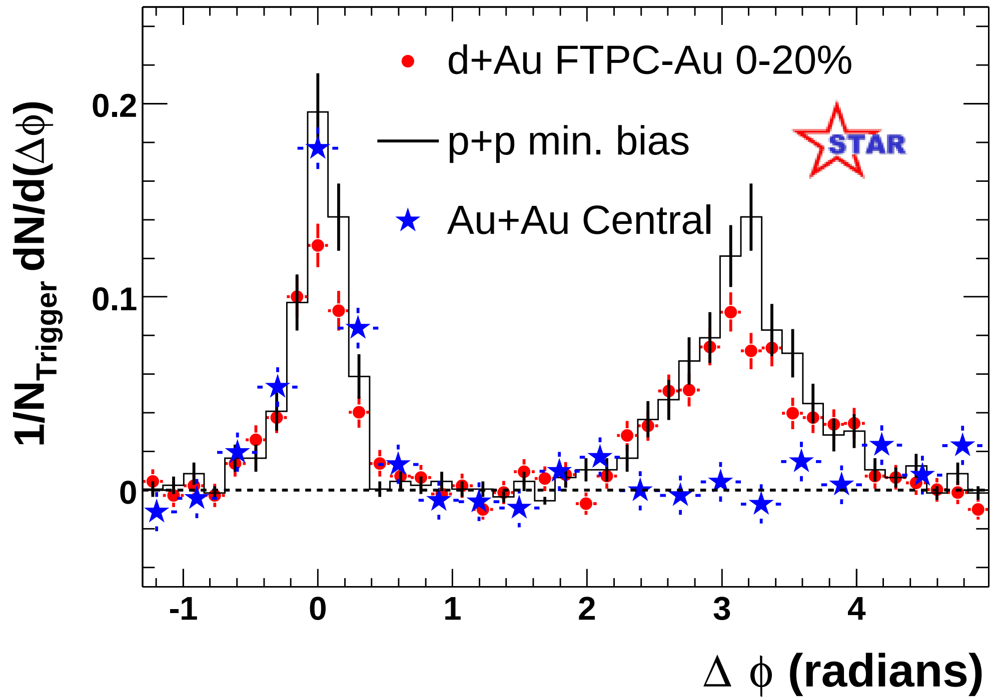

- The “away–side” jet has disappeared !
  absorbtion (or energy loss, or “jet quenching”) in the medium
- The matter produced in a heavy ion collision is opaque
  high density, strong interactions, ... or both

e^+e^- annihilation: Jets in pQCD

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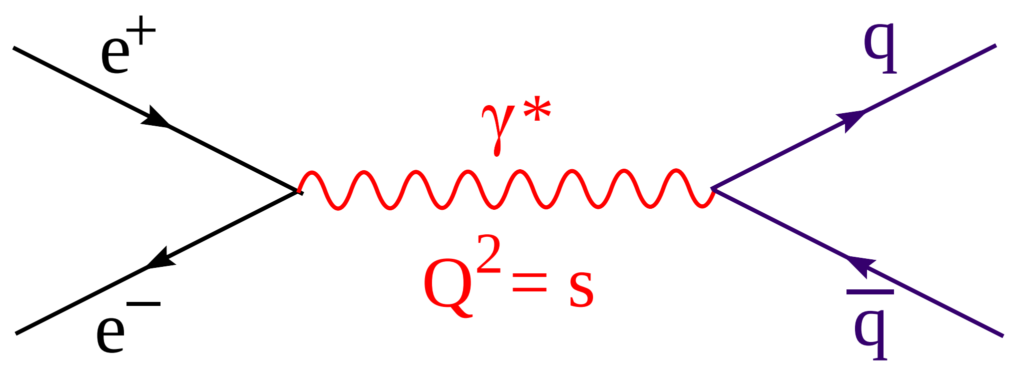
- How would a high–energy jet interact in a strongly coupled plasma ?
- How to produce jets in the first place ?
- Guidance from perturbative QCD: $e^+e^- \;\rightarrow\; \gamma^* \;\rightarrow\; q\bar{q}$



- Decay of a time–like photon: $Q^2 \;\equiv\; q^\mu q_\mu \;=\; s > 0$

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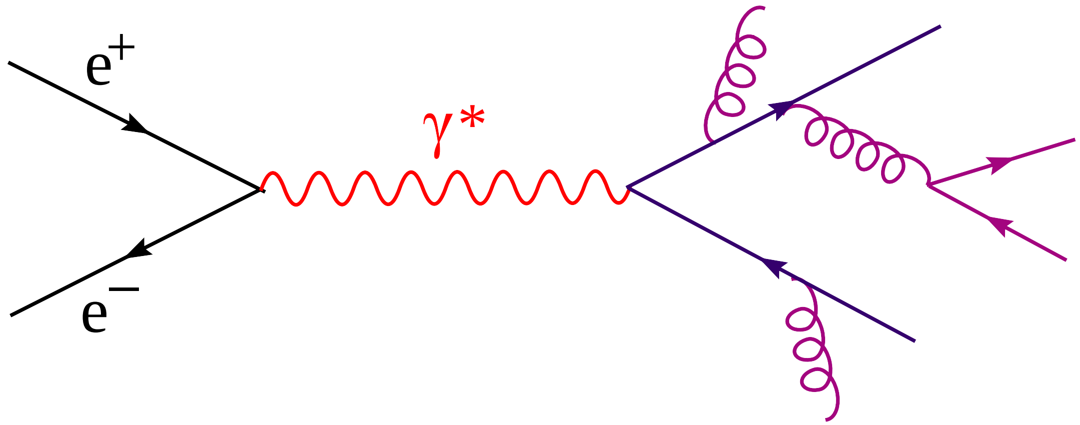

- The structure of the final state is determined by
  - parton branching & hadronisation

Bremsstrahlung

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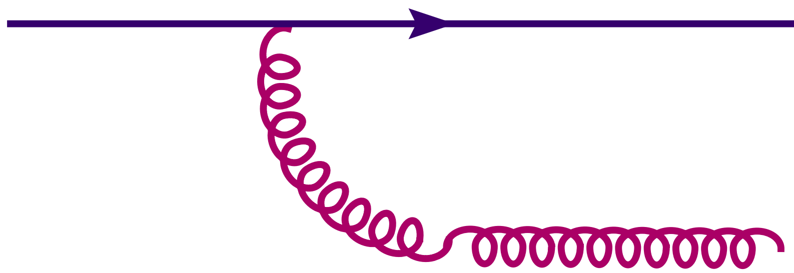
- Gluon emission to lowest order in perturbative QCD:



$$d\mathcal{P}_{\rm Brem} \sim \alpha_s(k_\perp^2)\, N_c \,\frac{d^2k_\perp}{k_\perp^2}\,\frac{dx}{x}$$

- Phase–space enhancement for the emission of
  - collinear $(k_\perp \to 0)$
  - and/or low–energy $(x \to 0)$ gluons
- Parton lifetime (or 'gluon formation time') : $\Delta t \sim \frac{k_z}{k_\perp^2}$

  Soft partons ($k_\perp \sim \Lambda_{\rm QCD}$) are produced later

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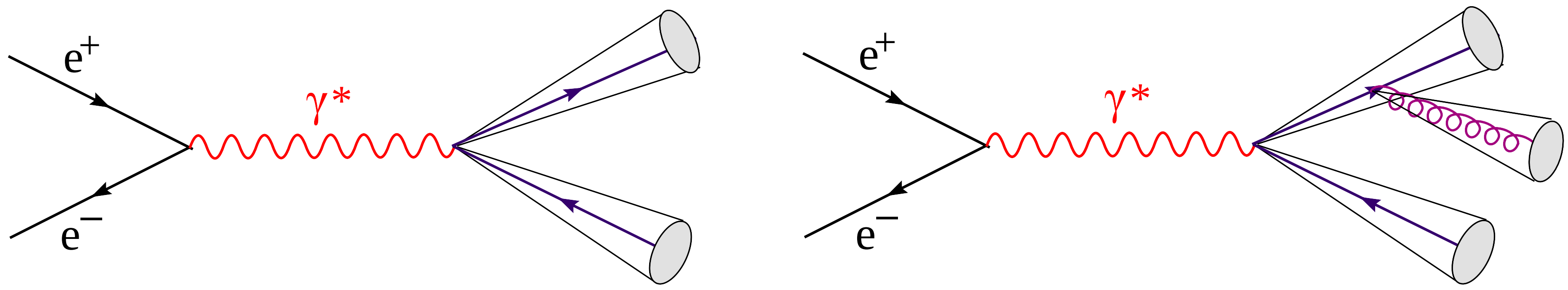
Jets in perturbative QCD



- Few, well collimated, jets
- e^+e^- cross–section computable in perturbation theory

$$\sigma(s) = \sigma_{\rm QED} \times \Big(3\sum_f e_f^2\Big)\left(1 + \frac{\alpha_s(s)}{\pi} + \mathcal{O}(\alpha_s^2(s))\right)$$

$\sigma_{\rm QED}$: cross–section for $e^+e^- \to \mu^+\mu^-$

- Multi–jet ($n \geq 3$) events appear, but are comparatively rare

3–jet event at OPAL (CERN)

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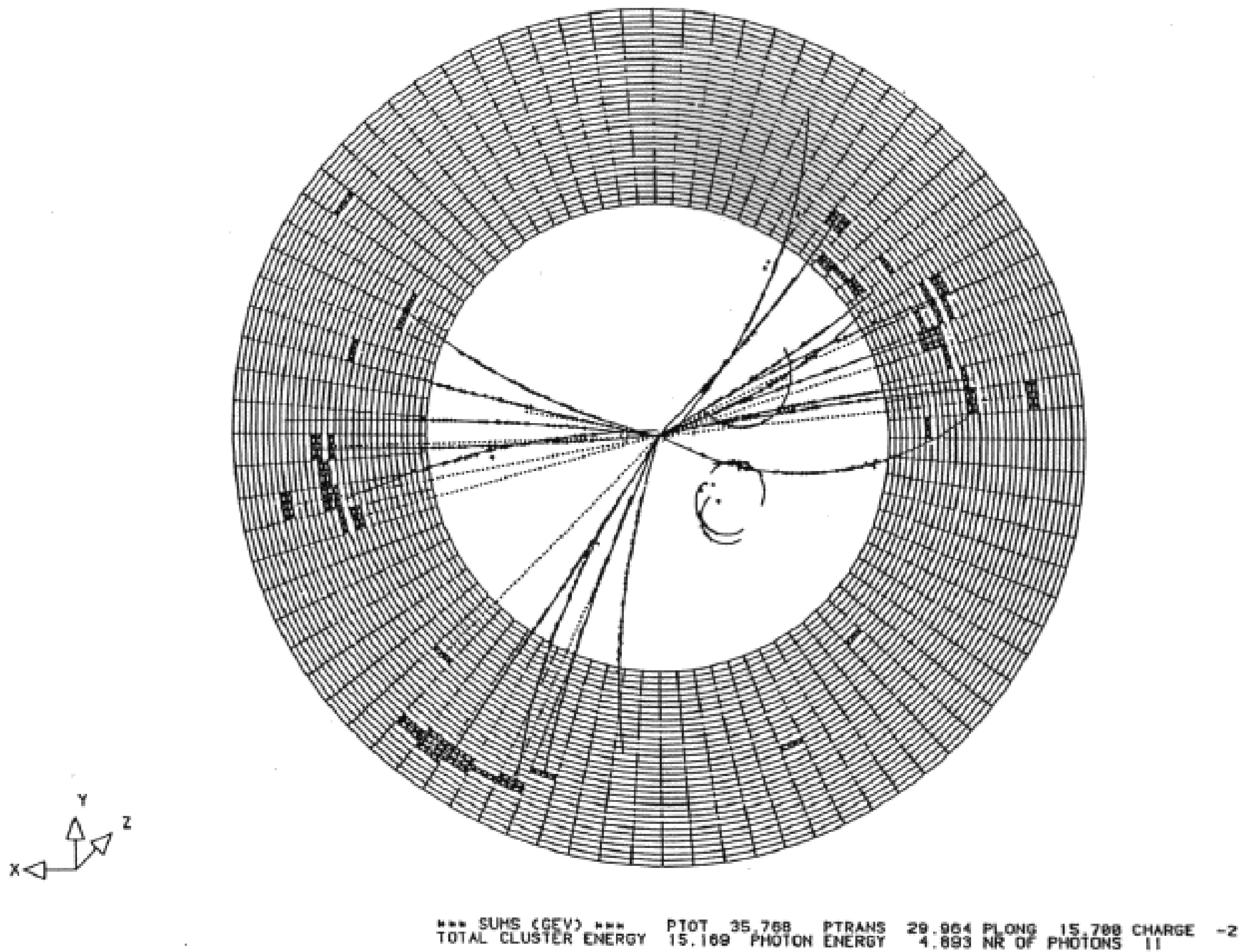

Deep inelastic scattering

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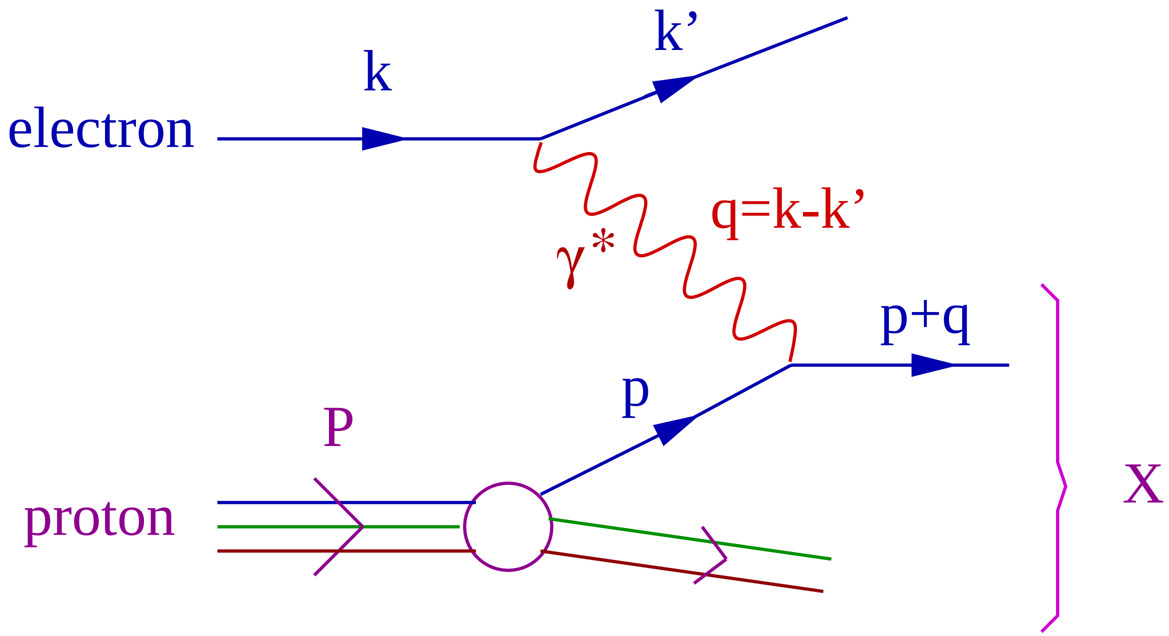

- Space–like current: $Q^2 \equiv -q^\mu q_\mu \geq 0$ and $x \equiv \frac{Q^2}{2P\cdot q}$
- Physical picture: γ^* absorbed by a quark excitation with
  - transverse size $\Delta x_\perp \sim 1/Q$
  - and longitudinal momentum $p_z = xP$

The proton structure function

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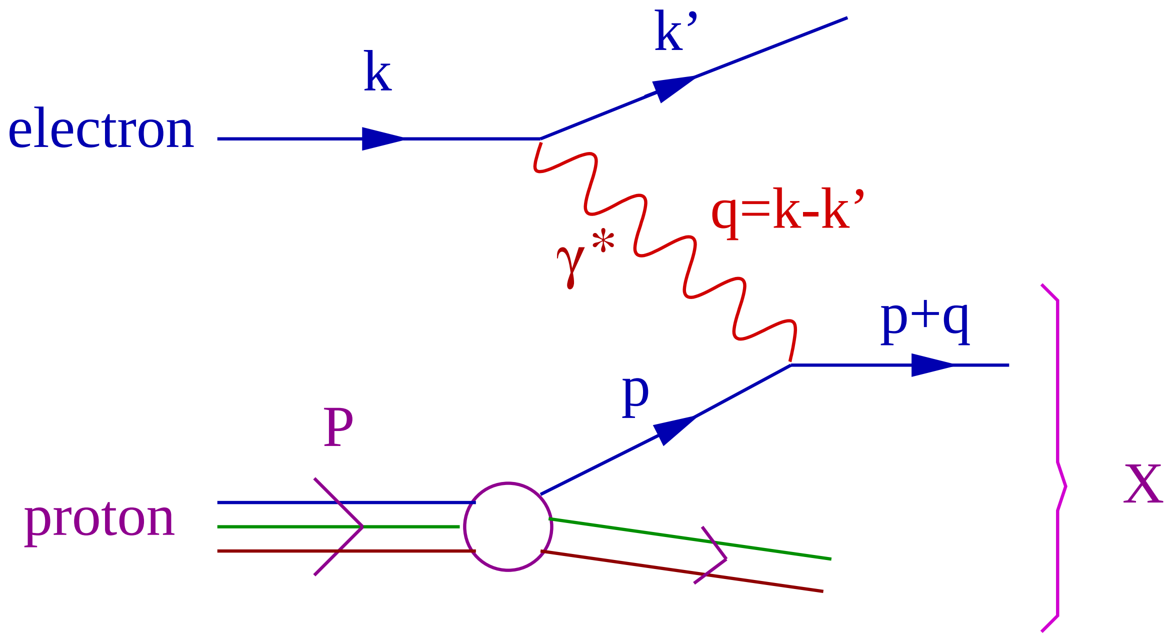
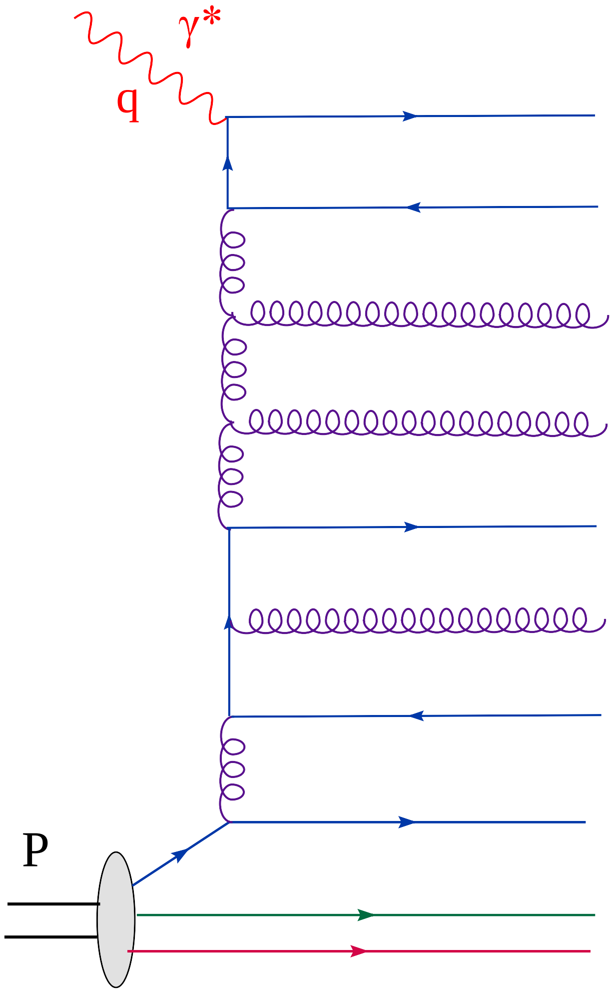


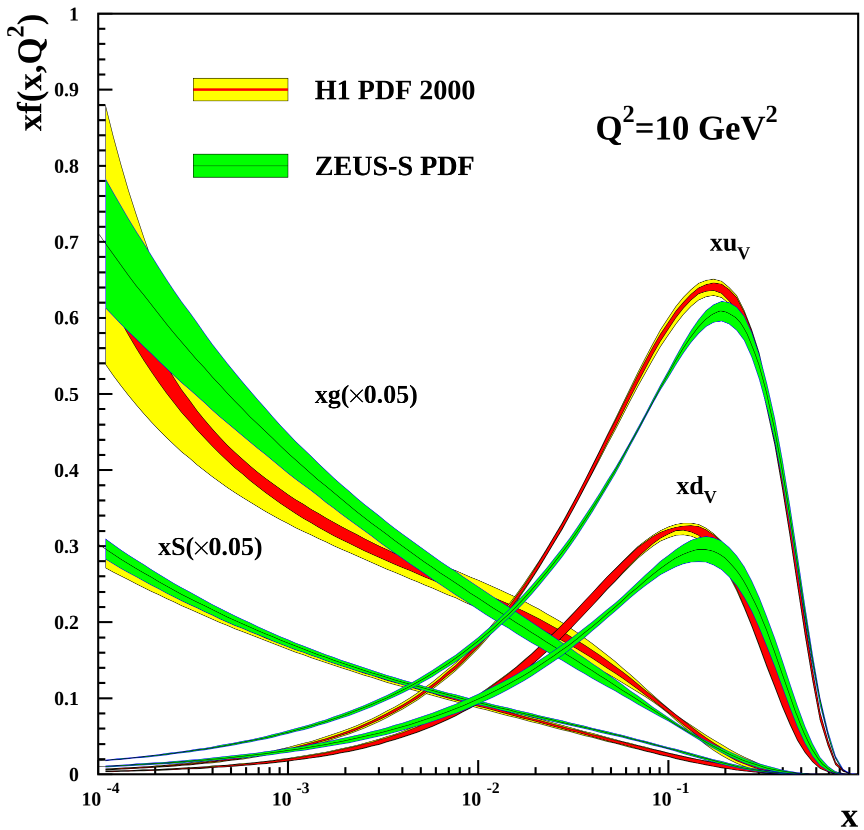
$$\sigma_{\gamma^* p}(x, Q^2) = \frac{4\pi^2 \alpha_{\rm em}}{Q^2} F_2(x, Q^2)$$

- $F_2(x, Q^2)$: 'quark distribution' = number of quarks with longitudinal momentum fraction x and transverse area $1/Q^2$

Parton evolution in pQCD

- Gluons are implicitly seen in DIS, via parton evolution





- Bremsstrahlung favors the emission of gluons with $x \ll 1$

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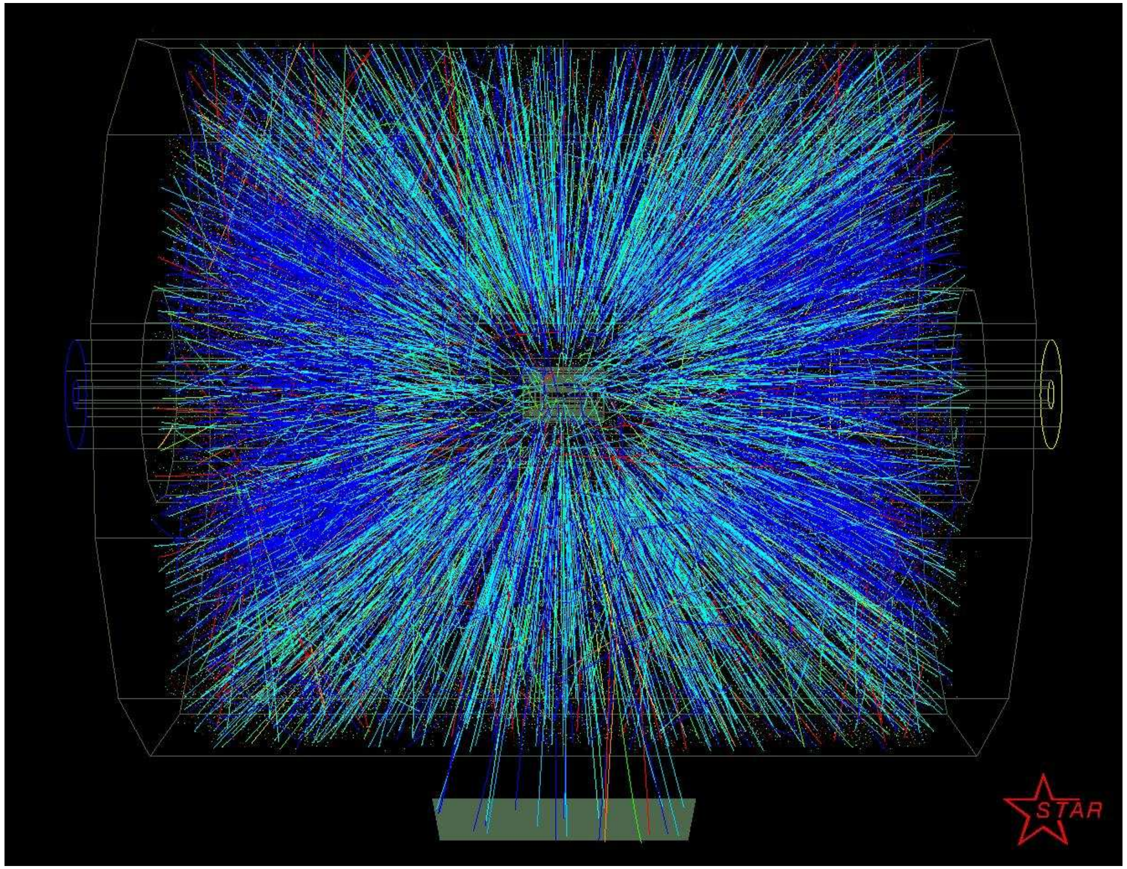

- Partons are actually 'seen' (liberated) in the high energy hadron–hadron collisions
  - central rapidity: small–x partons
  - forward/backward rapidities: large–x partons

Gluon Saturation

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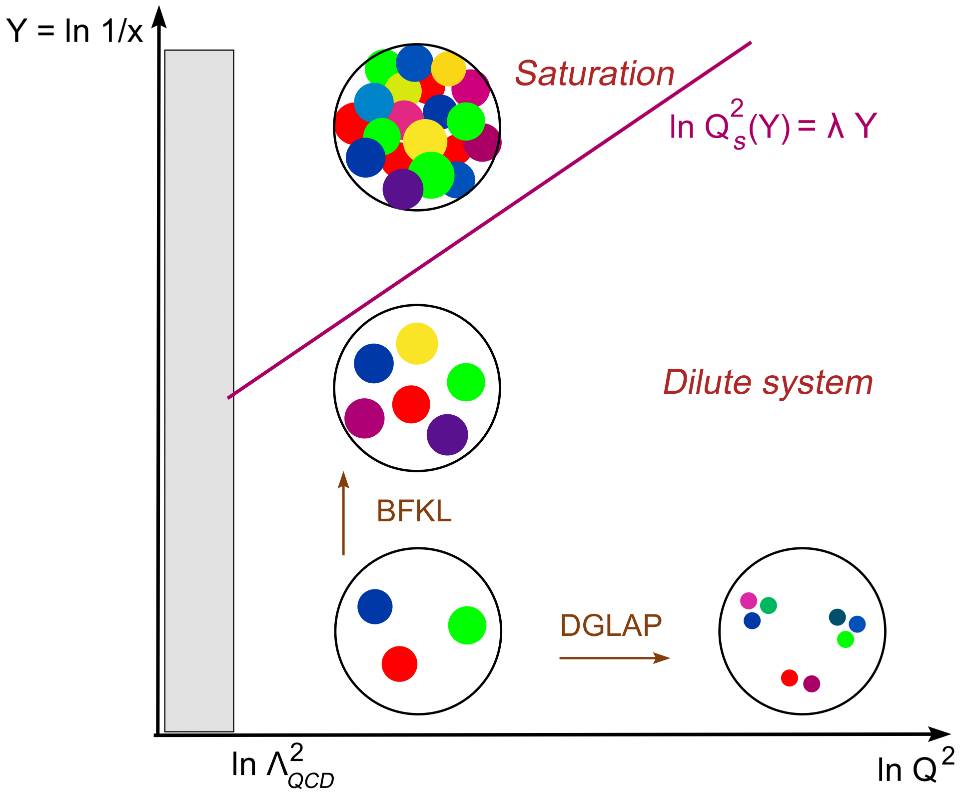
- When occupation number $\sim 1/\alpha_s \Longrightarrow$ strong repulsion

$$Q_s^2(x) \simeq \alpha_s \frac{xG(x,Q_s^2)}{\pi R^2} \sim \frac{1}{x^{\lambda_s}} \quad \text{with} \quad \lambda_s \sim 0.3$$



- When $n \sim 1/\alpha_s$, gluons form a Bose condensate: CGC

Hard probes in a strongly–coupled plasma

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- Virtual photon (electromagnetic current)
- Thermal expectation value (retarded polarization tensor) :

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

- 'Hard probe' : large virtuality $Q^2 \equiv |q^2| \gg T^2$
  - time–like current ($q^2 > 0$) : jets
  - space–like current ($q^2 < 0$) : DIS, partons
- Relativistic heavy quark : $M \gg T$ and $v \simeq 1$
  - energy loss towards the medium
  - transverse momentum broadening
- Strong coupling $\Longrightarrow$ AdS/CFT correspondence

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Gauge theory side: CFT

- $\mathcal{N} = 4$ Supersymmetric Yang–Mills theory
  - color gauge group SU(N_c)
  - supersymmetry (fermions $\leftrightarrows$ bosons)
  - gluons, fermions, scalars (all in the adjoint repres. !)
  - quantum conformal invariance (fixed coupling)
  - no confinement, no intrinsic scale
- Has this any relevance to QCD ??
- Perhaps better suited for QCD at finite temperature
  - deconfined phase (quark–gluon plasma)
  - quarks and gluons play rather similar roles
  - nearly conformal (small running–coupling effects)

Trace anomaly from lattice QCD

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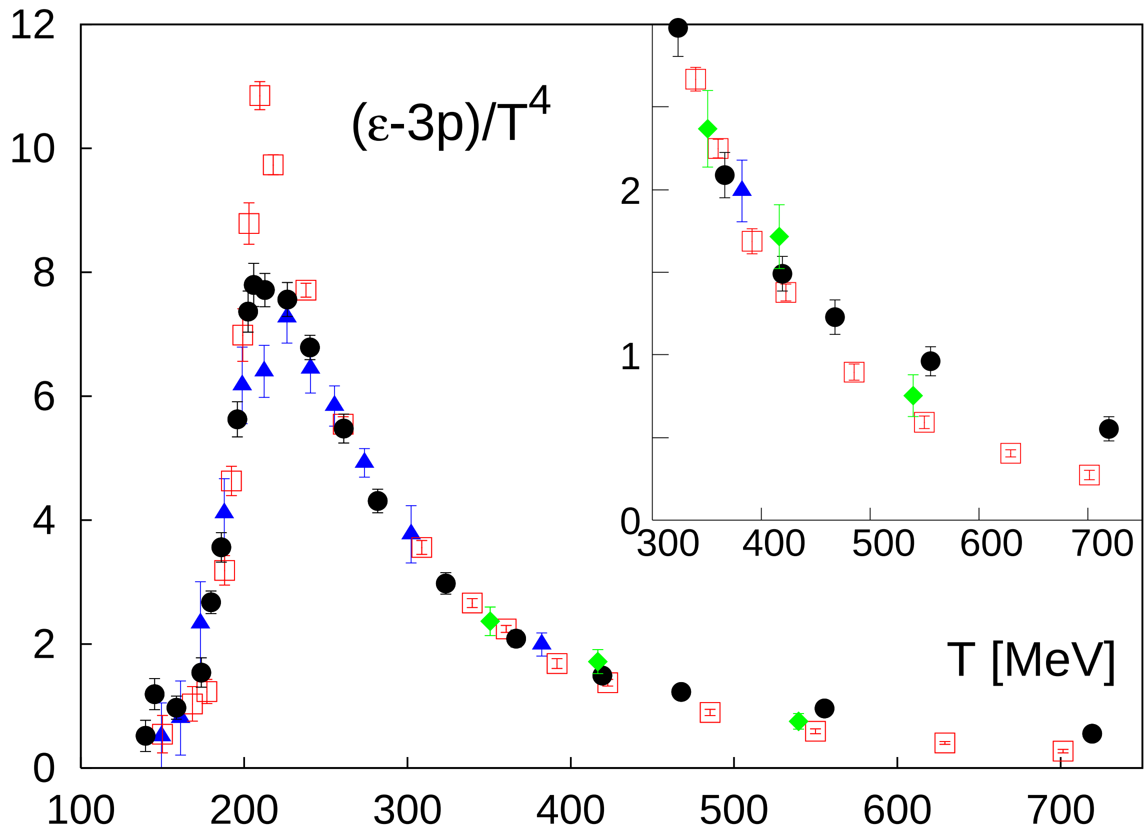

$$\beta(g)\,\frac{\mathrm{d}p}{\mathrm{d}g} = \langle T^{\mu}_{\mu}\rangle = \mathcal{E} - 3p$$

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

String theory side: AdS

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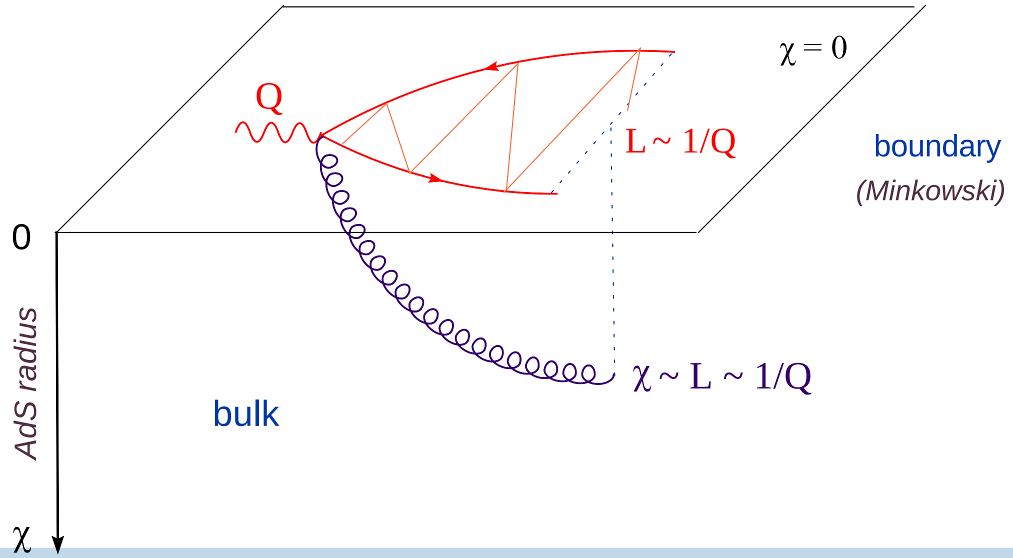
- Type IIB string theory living in $D = 10$: $AdS_5 \times S^5$

$$\mathrm{d}s^2 = \underbrace{\frac{R^2}{\chi^2}\underbrace{(-\mathrm{d}t^2 + \mathrm{d}\vec{x}^2)}_{\text{Minkowski}} + \frac{R^2}{\chi^2}\mathrm{d}\chi^2}_{AdS_5} + \underbrace{R^2\mathrm{d}\Omega_5^2}_{S^5}$$

  - $0 \leq \chi < \infty$: ‘radial’, or ‘5th’, coordinate
  - gauge theory lives at the Minkowski boundary $\chi = 0$



The Gauge/Gravity duality *(Maldacena, 1997)*

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- Gauge theory has two parameters:
  - coupling constant g (elementary charge)
  - number of colors N_c
  - weakly or strongly coupled depending upon $\lambda \equiv g^2 N_c$
- String theory has three parameters:
  - curvature radius of space R
  - string coupling constant g_s
  - string length l_s (typical size of string vibrations)
- Mapping of the parameters :

$$4\pi g_s = g^2 \,, \qquad (R/l_s)^4 = g^2 N_c$$

- Strong 't Hooft coupling (more properly, $N_c \to \infty$) :

$\lambda \equiv g^2 N_c \gg 1$ with $g^2 \ll 1 \implies$ classical (super)gravity

Heating AdS_5

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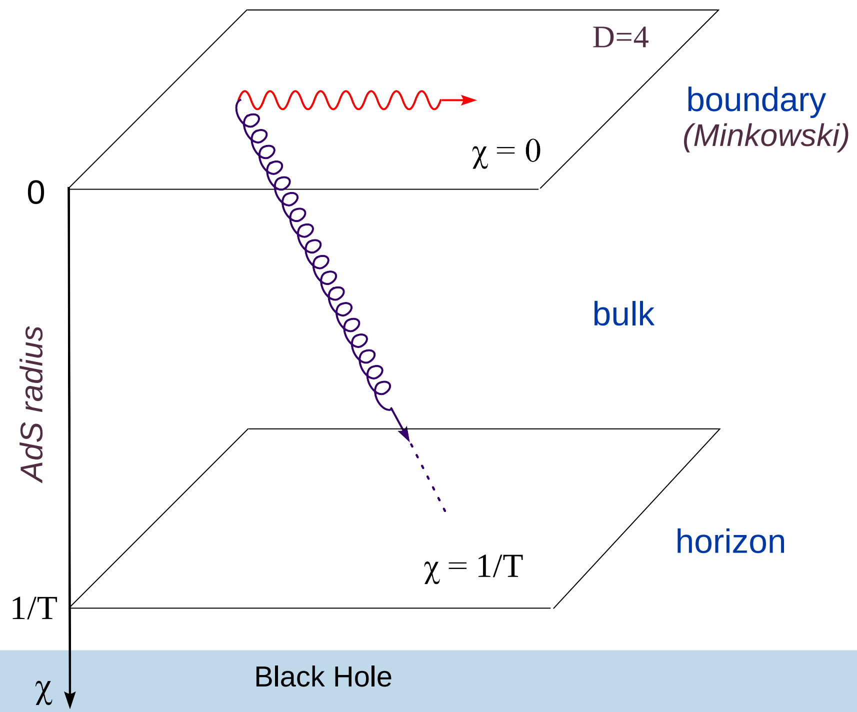
- $\mathcal{N}=4$ SYM at finite temperature $\Longleftrightarrow$ Black Hole in AdS_5

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

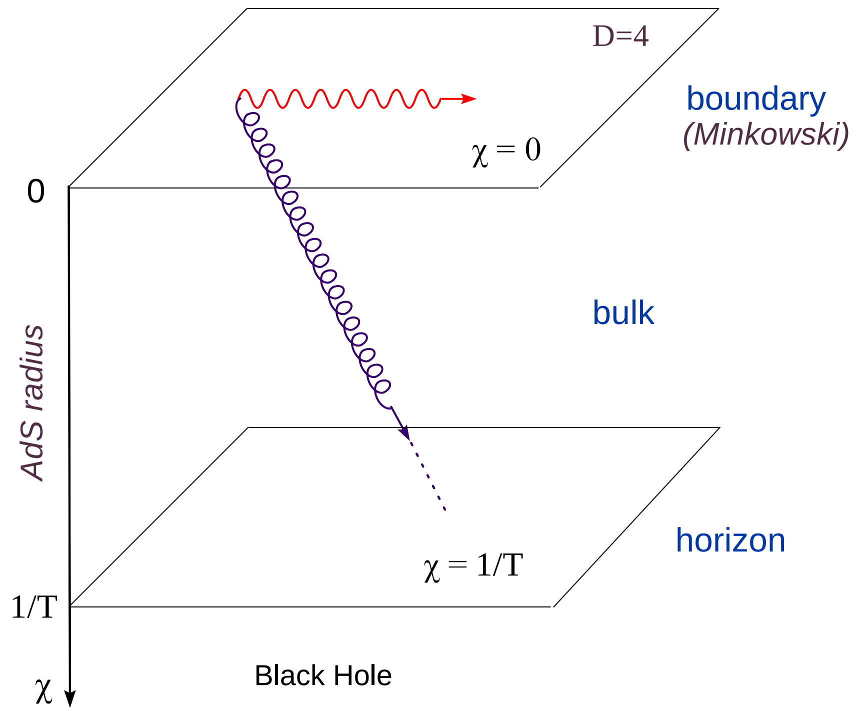
where $f(\chi) = 1-(\chi/\chi_0)^4$ and $\chi_0 = 1/\pi T$ = BH horizon

- A black hole has entropy and thermal (Hawking) radiation



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

- Abelian current J_μ in 4D $\longleftrightarrow$ Maxwell wave A_μ in AdS_5 BH
- Im $\Pi_{\mu\nu}$ $\longleftrightarrow$ absorption of the wave by the BH



- Maxwell equations in a curved space–time

$$\partial_m\left(\sqrt{-g}g^{mn}g^{pq}F_{nq}\right) = 0 \qquad \text{where} \qquad F_{mn} = \partial_m A_n - \partial_n A_m$$

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- Holography

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The Holographic principle

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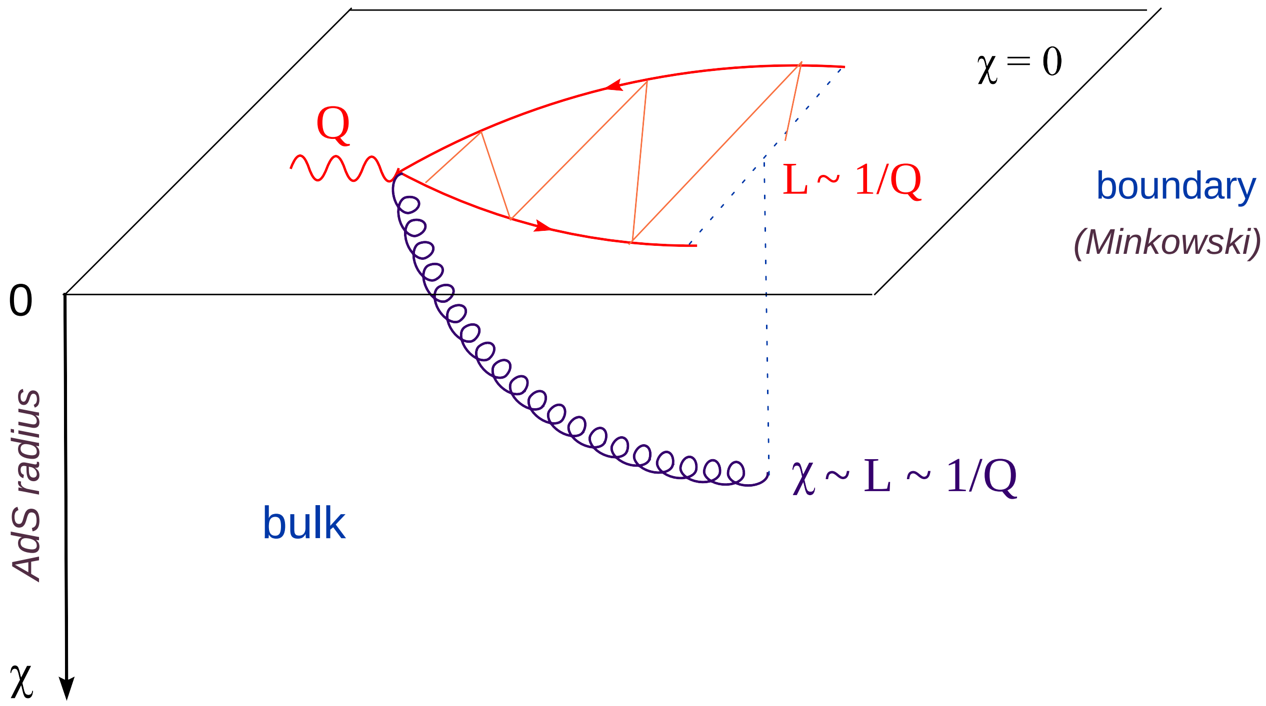
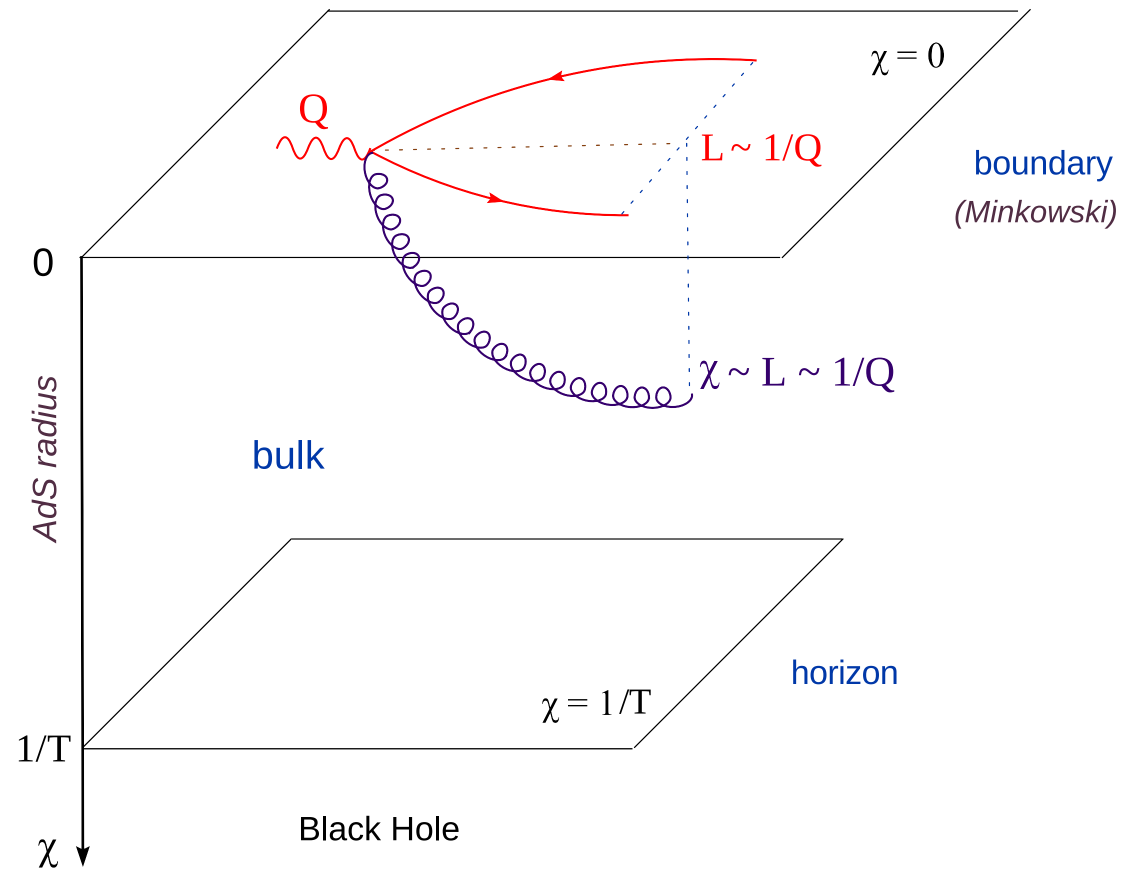
- 'Holography' : A quantum field theory in $D = 3+1 \iff$
  A theory with gravitation in higher dimensions



- Rôle of the 5th dimension: a reservoir of quantum flucts.
- Radial penetration χ of the wave packet in $AdS_5 \longleftrightarrow$ transverse size L of the partonic fluctuation on the boundary

Space–like current with $Q \gg T$

- The wave gets stuck near the boundary: $\chi \lesssim 1/Q \ll 1/T$



- Gravity calculation: Potential barrier proportional to Q

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Interpretation: Partonic fluctuation

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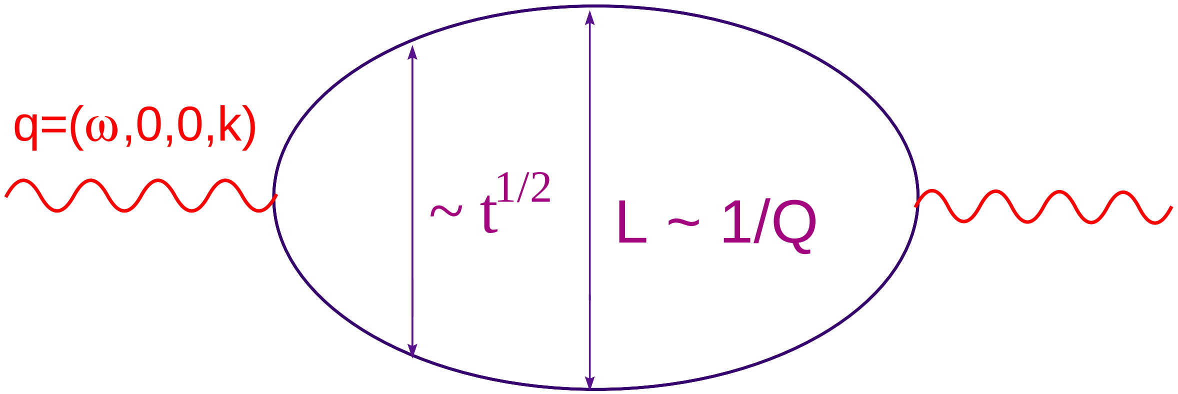
- By energy–momentum conservation, a space–like current cannot decay (in the vacuum)
- It can develop a virtual partonic fluctuation



- By uncertainty principle, this has a transverse size $L \sim 1/Q$

and a lifetime $\Delta t \sim \frac{1}{Q} \times \frac{\omega}{Q} \sim \frac{\omega}{Q^2}$

Partonic fluctuation in the plasma

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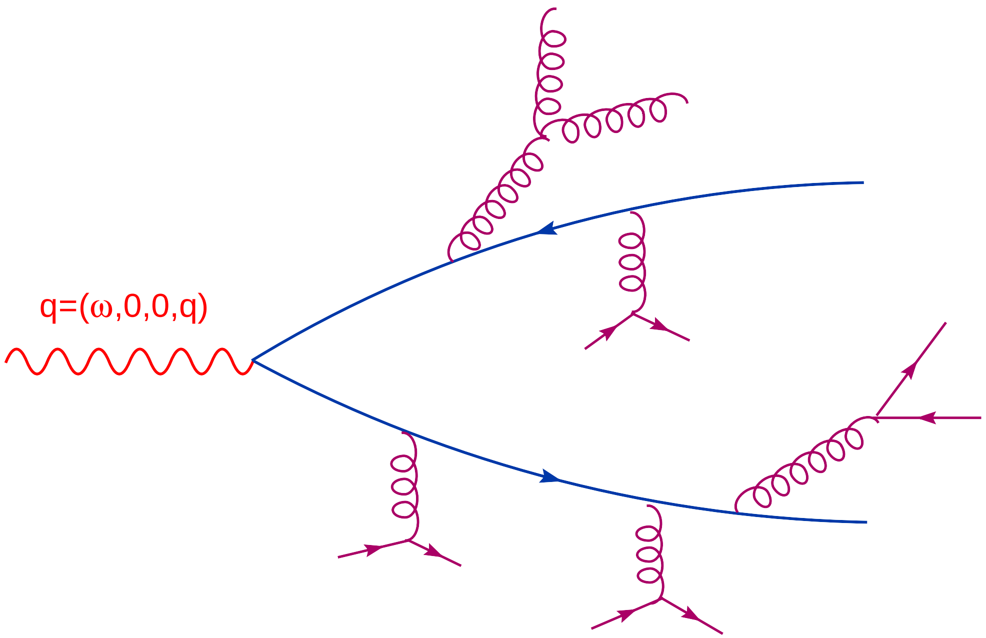
- The situation however changes at finite temperature



- The current can now decay due to the parton interactions in the plasma $\Longrightarrow$ Im $\Pi_{\mu\nu}$: a contribution to $F_2(x, Q^2)$
- The above picture is perturbative. How does this change at strong coupling ?

High energy: The fall

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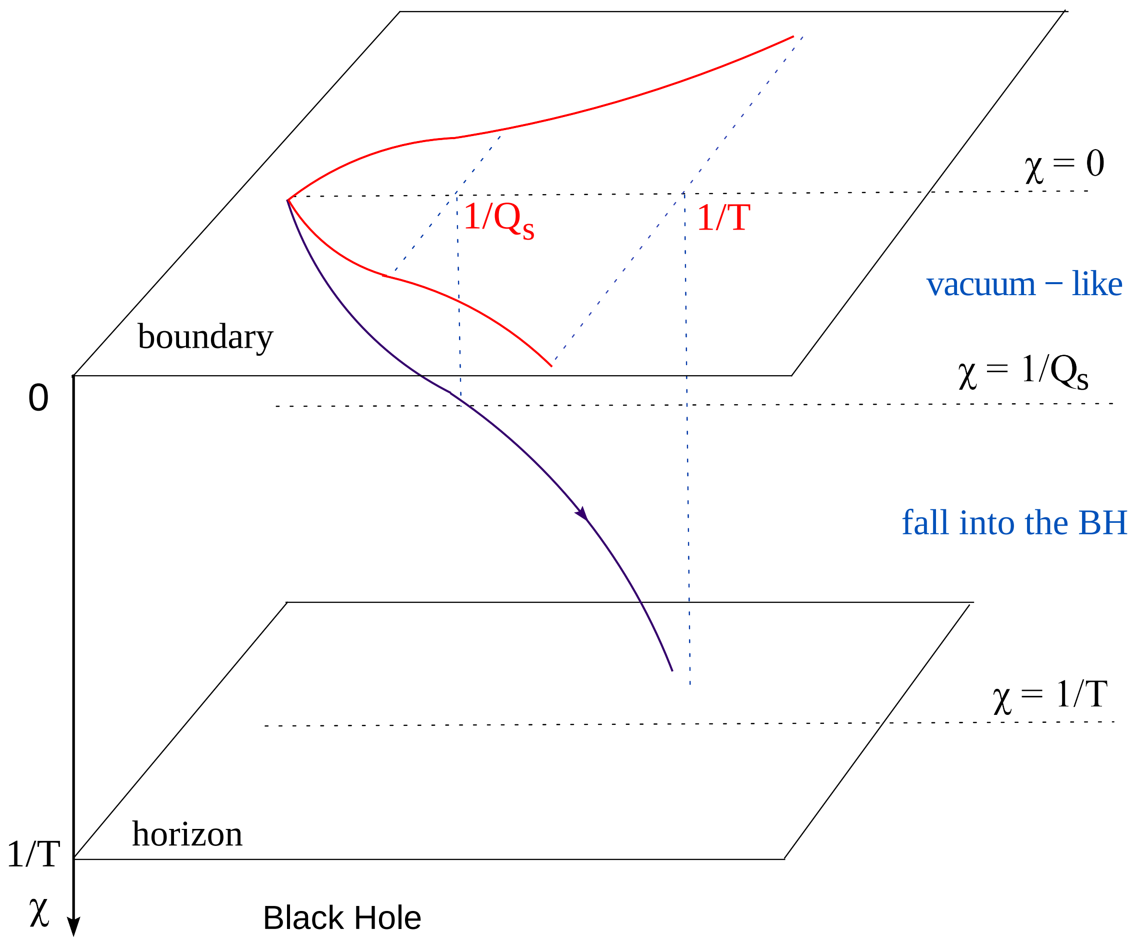
- Gravitational attraction becomes stronger with increasing energy and eventually washes out the repulsive barrier



- The wave falls into the BH along a massless geodesics

Saturation momentum

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- Gravitational interactions are proportional to the energy density in the wave (ω) and in the plasma (T)
- The criterion for strong interaction within the plasma

$$\underbrace{Q}_{\text{potential barrier}} \lesssim \underbrace{\frac{\omega T^2}{Q^2}}_{\text{gravitational potential}}$$

- Gravitational attraction must overcome the barrier due to energy conservation

Saturation momentum

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- Gravitational interactions are proportional to the energy density in the wave (ω) and in the plasma (T)
- The criterion for strong interaction within the plasma

$$\underbrace{Q}_{\text{virtuality barrier}} \lesssim \underbrace{\frac{\omega}{Q^2}}_{\text{lifetime}} \times \underbrace{T^2}_{\text{plasma force}}$$

- The partonic fluctuation must live long enough to feel the effects of the plasma

Saturation momentum

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- Gravitational interactions are proportional to the energy density in the wave (ω) and in the plasma (T)
- The criterion for strong interaction within the plasma

$$\underbrace{Q}_{\text{virtuality barrier}} \lesssim \underbrace{\frac{\omega}{Q^2}}_{\text{lifetime}} \times \underbrace{T^2}_{\text{plasma force}}$$

- High energy, or high T, or low Q : $Q \lesssim Q_s$ with

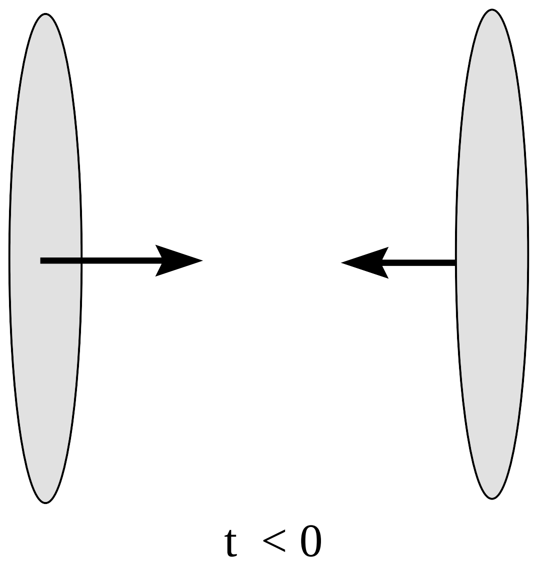
$$Q_s \simeq (\omega T^2)^{1/3} \simeq \frac{T}{x} \quad \text{where} \quad x \equiv \frac{Q^2}{2\omega T}$$

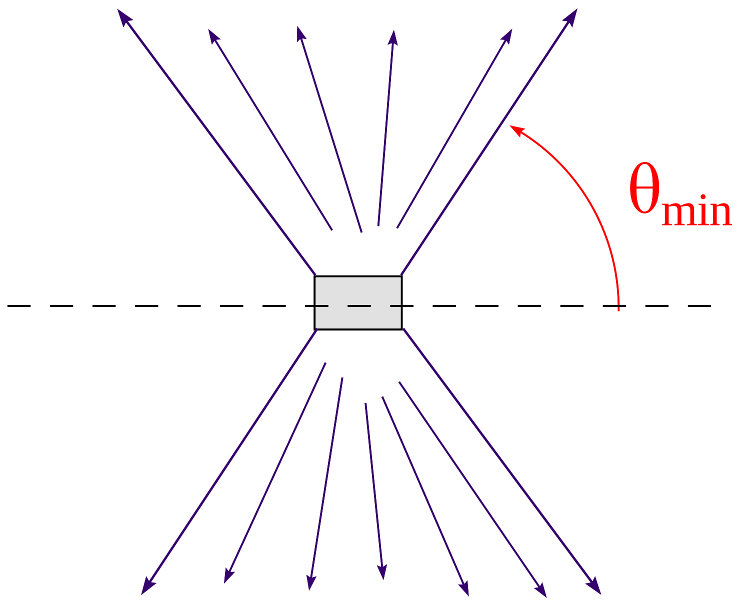
- $Q_s(x)$ plays the role of the plasma saturation momentum (borderline between weak and respectively strong scattering)
- Recall: the parton picture involves 2 variables : x and Q^2

DIS at large x : No partons !

- Low energy, or large x : $x > x_s(Q) \simeq T/Q$
- No scattering (except through tunneling) $\Longrightarrow F_2(x, Q^2) \approx 0$

  $\Longrightarrow$ no partons with large momentum fractions $x > x_s$
- No forward/backward jets in hadron–hadron collisions !





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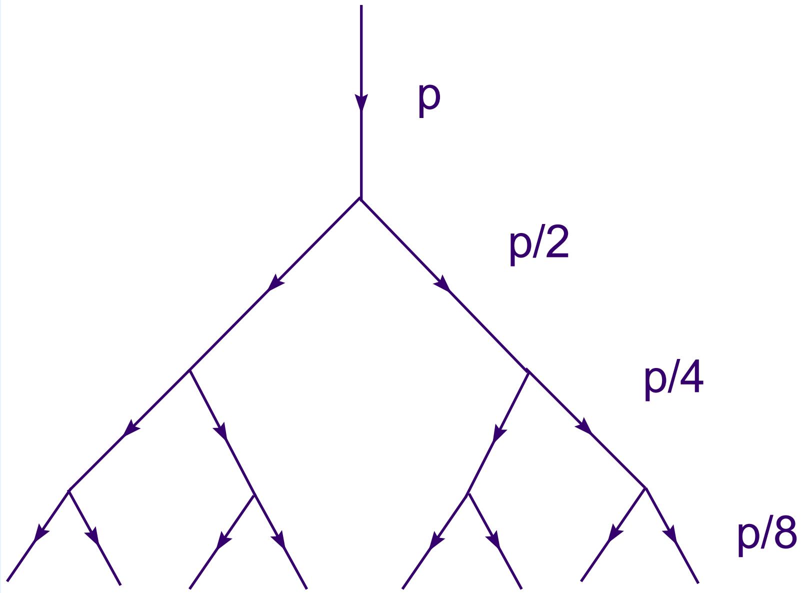
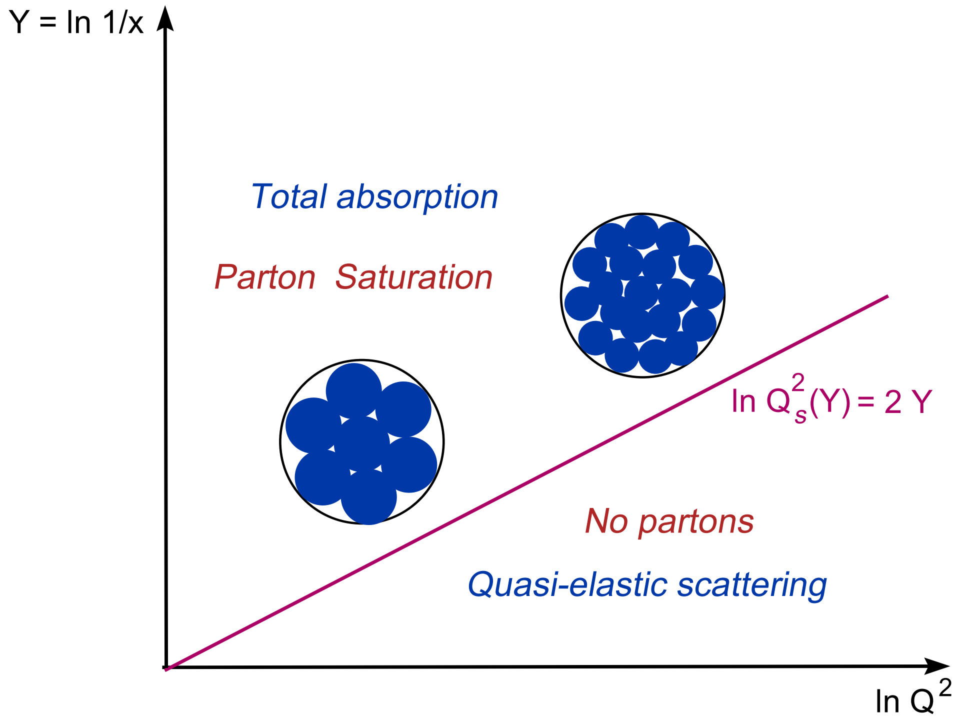
Low x : Parton saturation

- $x \lesssim x_s = T/Q$: strong scattering $\Longrightarrow$ $F_2(x, Q^2) \sim xN_c^2 Q^2$
- Parton occupation numbers of $\mathcal{O}(1) \Longrightarrow$ 'saturation' (CGC)
- Physical interpretation: 'Quasi–democratic' parton branching





- All partons have branched down to small values of x !

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Quasi–democratic parton branching

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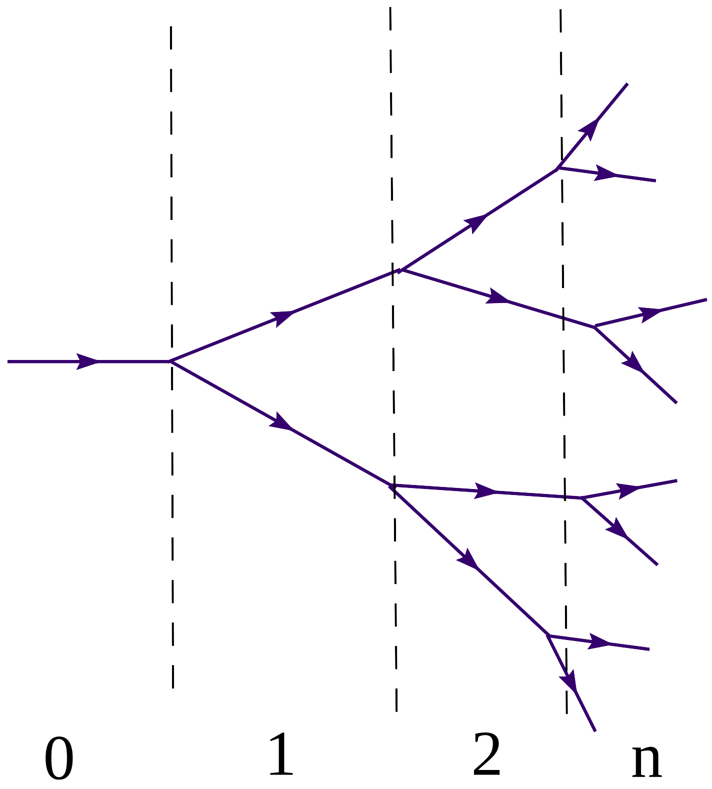
- Universal energy loss mechanism, active at partonic level
  - no reason why branching should stop at 2 parton level
  - no reason to favour special corners of phase–space



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

$$Q_n \sim \frac{Q_{n-1}}{2} \quad \text{(vacuum)}$$

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

$$\frac{\Delta Q_n}{\Delta t_n} \sim -T^2 \quad \text{(plasma)}$$

- Qualitative agreement with all the results from AdS/CFT

e^+e^- at strong coupling

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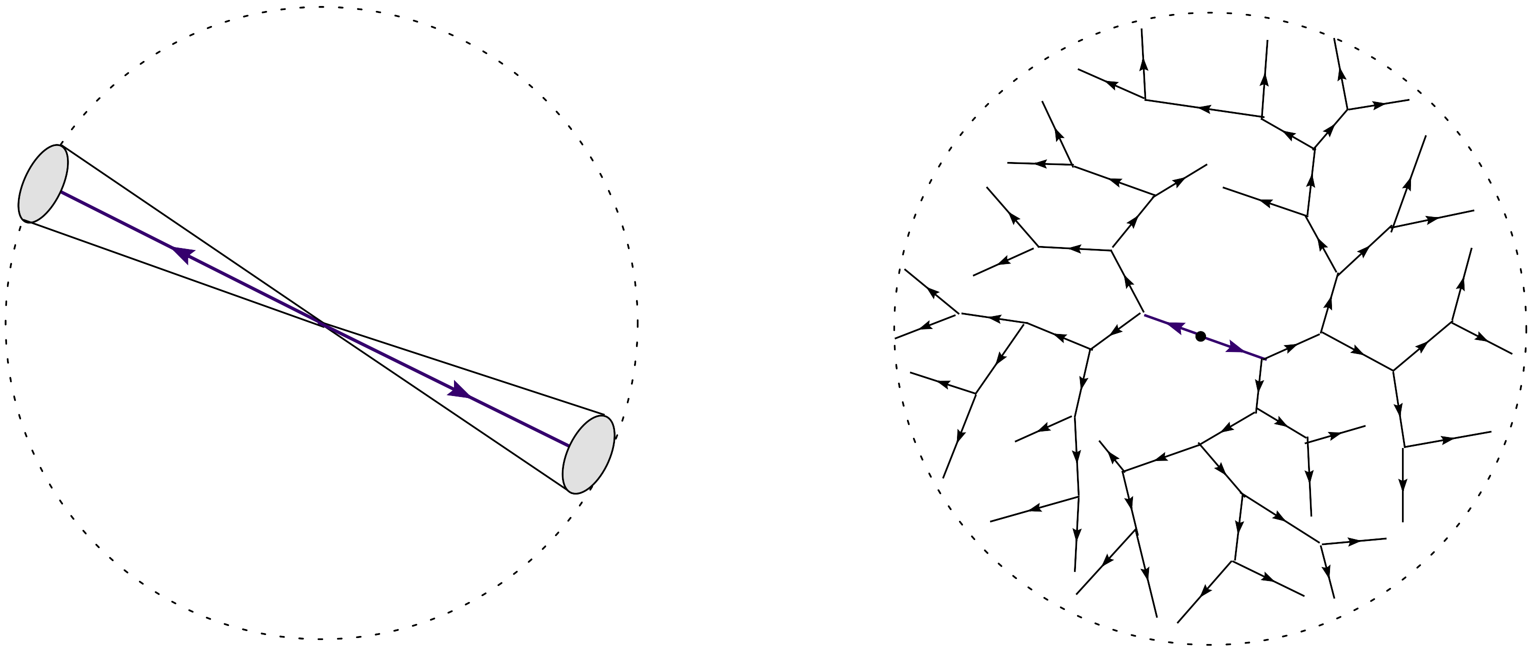
- Time–like current in the vacuum



- Infrared cutoff $\Lambda \longrightarrow$ splitting continues down to $Q \sim \Lambda$
- In the COM frame $\longrightarrow$ spherical distribution $\Longrightarrow$ no jets !

  (similar conclusion by Hofman and Maldacena, 2008)
- Final state looks very different as compared to pQCD !

Heavy Quark: Energy loss

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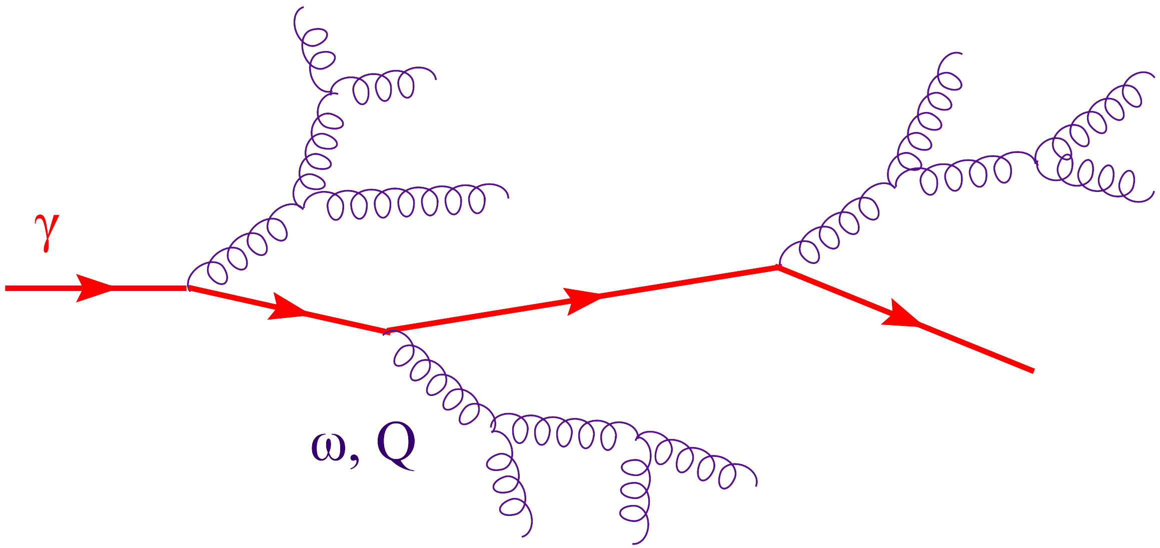


- Virtual quanta with $Q \lesssim Q_s$ are absorbed by the plasma
- Maximal energy loss: $\omega \sim \gamma Q_s$

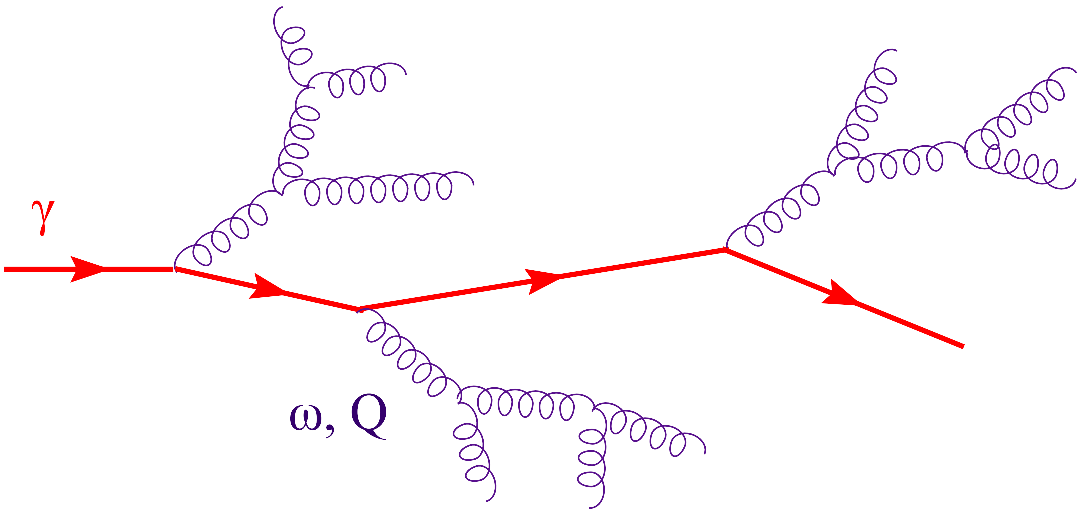
$$Q_s \simeq \frac{\omega}{Q_s^2} T^2 \simeq \frac{\gamma}{Q_s} T^2 \implies Q_s^2 \sim \gamma T^2$$

$$-\frac{\mathrm{d}E}{\mathrm{d}t} \simeq \sqrt{\lambda} \frac{\omega}{(\omega/Q_s^2)} \simeq \sqrt{\lambda} Q_s^2 \simeq \sqrt{\lambda} \gamma T^2$$

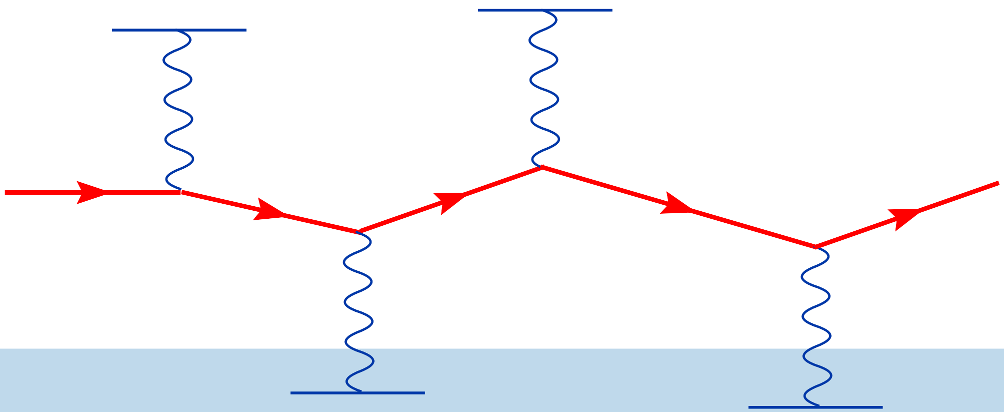
Herzog, Karch, Kovtun, Kozcaz, and Yaffe; Gubser, 2006 (trailing string)

Momentum broadening $\mathrm{d}\langle p_T^2\rangle/\mathrm{d}t$

- Strong coupling : fluctuations in the emission process



- Langevin eq. from AdS/CFT *(G. Giecold, E.I., A. Mueller, 09)*
- pQCD : thermal rescattering (different physics !)



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- Hard probes & high-energy physics appears to be quite different at strong coupling as compared to QCD
  - no forward/backward particle production in HIC
  - no jets in e^+e^- annihilation
  - different mechanism for jet quenching
- Are AdS/CFT methods useless for HIC ? Not necessarily so !
  - long–range properties (hydro, thermalization, etc) might be controlled by strong coupling
  - some observables receive contributions from several scales, from soft to hard: use AdS/CFT in the soft sector
  - most likely, the coupling is moderately strong, so it useful to approach the problems from both perspectives

Jet quenching

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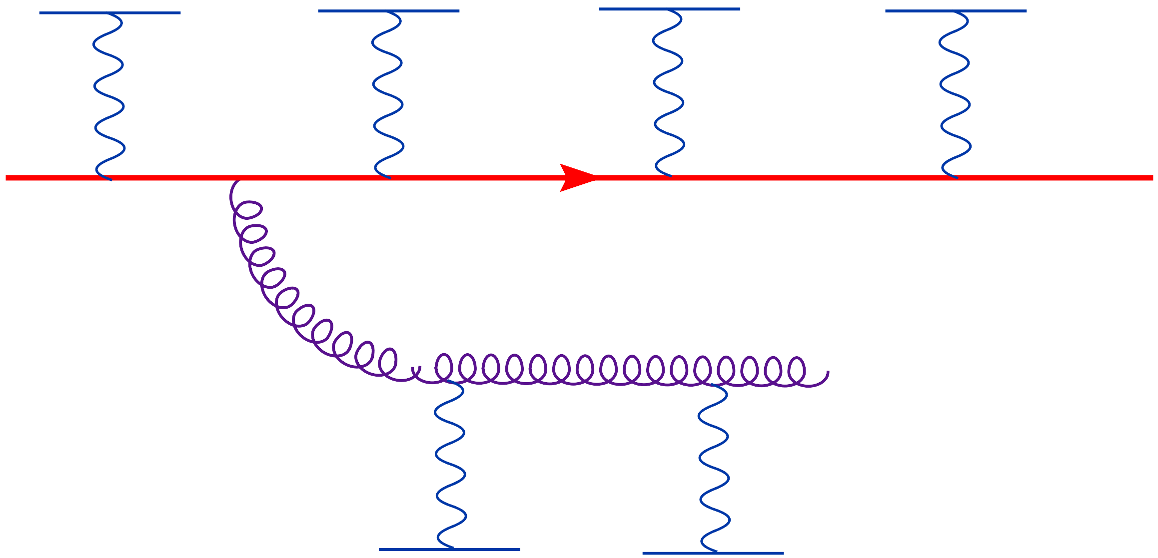
- Energy loss for a heavy quark: Medium induced radiation



$$-\frac{\mathrm{d}E}{\mathrm{d}t} \simeq \alpha_s N_c \langle p_\perp^2 \rangle$$: relation to 'momentum broadening'

Transverse momentum broadening

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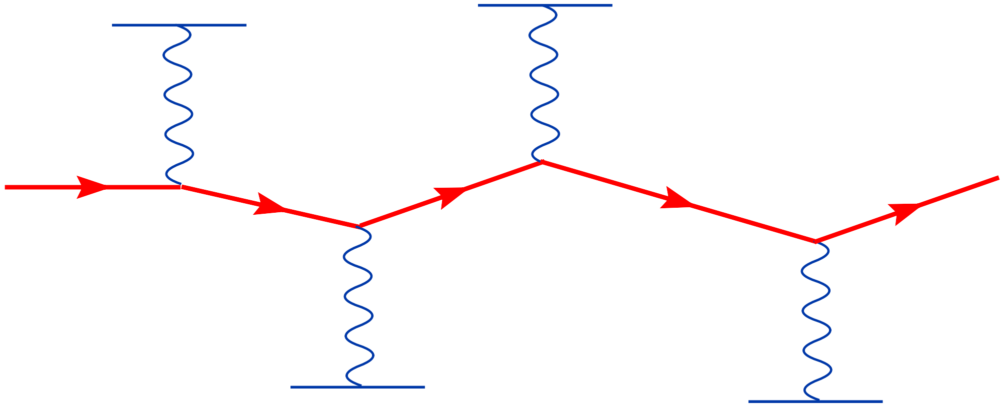
- A parton ('heavy quark') scatters off the plasma constituents on its own, hard, resolution scale



$$\frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}t} \equiv \hat{q} \simeq \alpha_s N_c \frac{xg(x,Q^2)}{N_c^2 - 1}$$

- $xg(x,Q^2)$: gluon distribution per unit volume in the medium
- Weakly–coupled QGP : incoherent sum of the gluon distributions produced by thermal quarks and gluons

$$xg(x,Q^2) \simeq n_q(T)\, xG_q + n_g(T)\, xG_g\,, \quad \text{with} \quad n_{q,g}(T) \propto T^3$$

Nuclear modification factor

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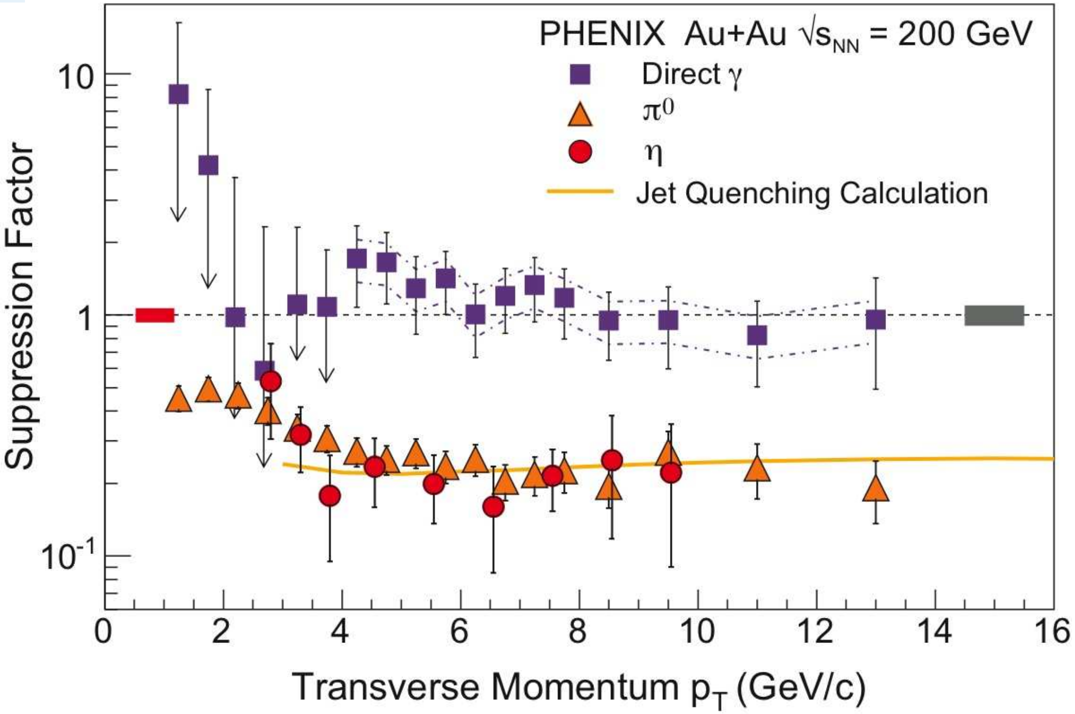
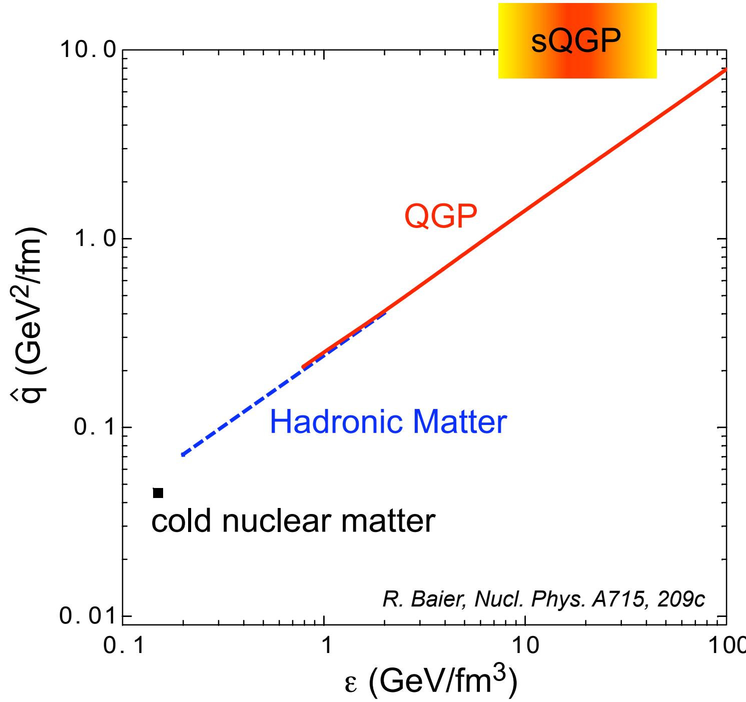
- How to measure $\hat{q}$? Compare AA collisions at RHIC to pp

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





- RHIC data seem to prefer $\hat{q} \simeq 10$ GeV^2/fm, which is too large to be accounted for by weakly–coupled QGP (??)

The ‘perfect fluid’

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- Uncertainty principle applied to viscosity:

$$\eta \sim \rho v \lambda_f \,, \qquad S \sim n \sim \frac{\rho}{m}$$

$$\frac{\eta}{S} \sim m v \lambda_f \sim \hbar \, \frac{\text{mean free path}}{\text{de Broglie wavelength}} \gtrsim \hbar$$

- Weakly interacting systems have $\eta/S \gg \hbar$
- Strongly coupled $\mathcal{N} = 4$ SYM plasma

$$\frac{\eta}{S} \rightarrow \frac{\hbar}{4\pi} \qquad \text{when} \qquad \lambda \rightarrow \infty$$

(Policastro, Son, and Starinets, 2001)

- This bound is believed to be universal : $\eta/S \geq \hbar/4\pi$
- The data at RHIC are consistent with the lower limit being actually reached : ‘sQGP’

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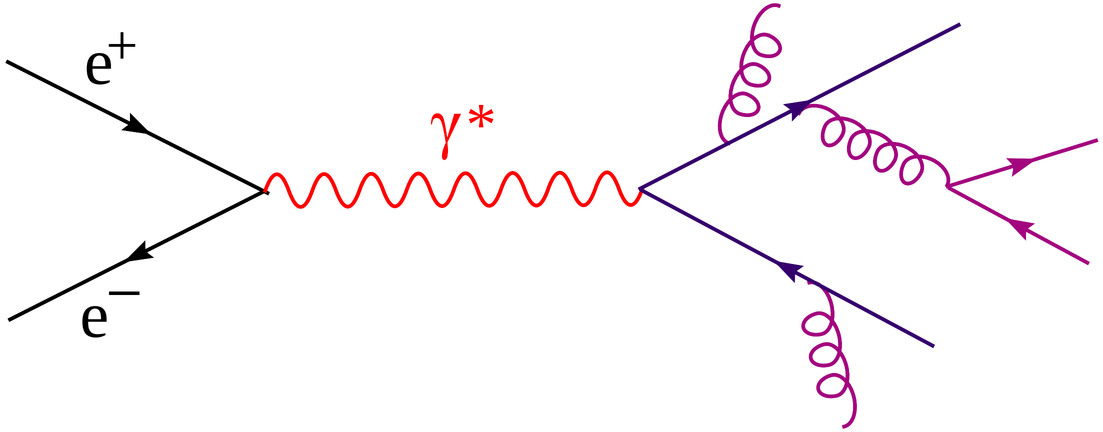
Jets



- ‘Multi–jet event’ : large emission angle & $x \sim \mathcal{O}(1)$

$$k_\perp \sim k \sim \sqrt{s} \implies \mathcal{P}_{\rm Brem} \sim \alpha_s(s) \ll 1$$

small probability for emitting an extra gluon jet !

- ‘Intra–jet activity’ : collinear and/or soft gluons

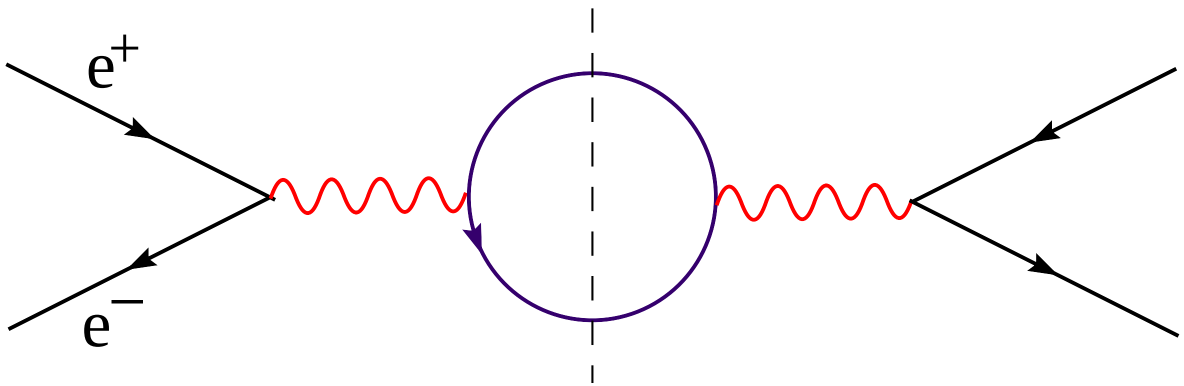
$$\Lambda_{\rm QCD} \ll k_\perp \ll k \ll \sqrt{s} \implies \mathcal{P}_{\rm Brem} \sim \alpha_s \ln^2 \frac{\sqrt{s}}{\Lambda_{\rm QCD}} \sim \mathcal{O}(1)$$

modifies particle multiplicity but not the number of jets

Optical theorem

- Total cross–section given by the optical theorem

$$\sigma(e^+e^-) = \frac{1}{2s}\,\ell^{\mu\nu}\,\mathrm{Im}\,\Pi_{\mu\nu}(q)$$



- The quark loop: The vacuum polarization tensor $\Pi_{\mu\nu}$ for a time–like photon (here, evaluated at one–loop order)
- This can be generalized to all–orders

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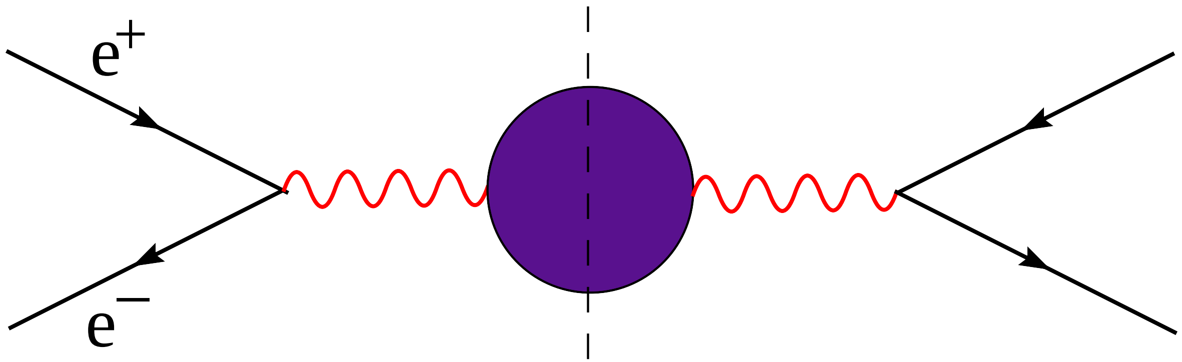
Current–current correlator

$$\sigma(e^+e^-) = \frac{1}{2s}\,\ell^{\mu\nu}\,\mathrm{Im}\,\Pi_{\mu\nu}(q)$$



- $\Pi_{\mu\nu}$ = current–current correlator to all orders in QCD

$$\Pi_{\mu\nu}(q) \equiv i\int \mathrm{d}^4x\,\mathrm{e}^{-iq\cdot x}\,\langle 0\,|\mathrm{T}\,\{J_\mu(x)J_\nu(0)\}\,|\,0\rangle$$

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

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

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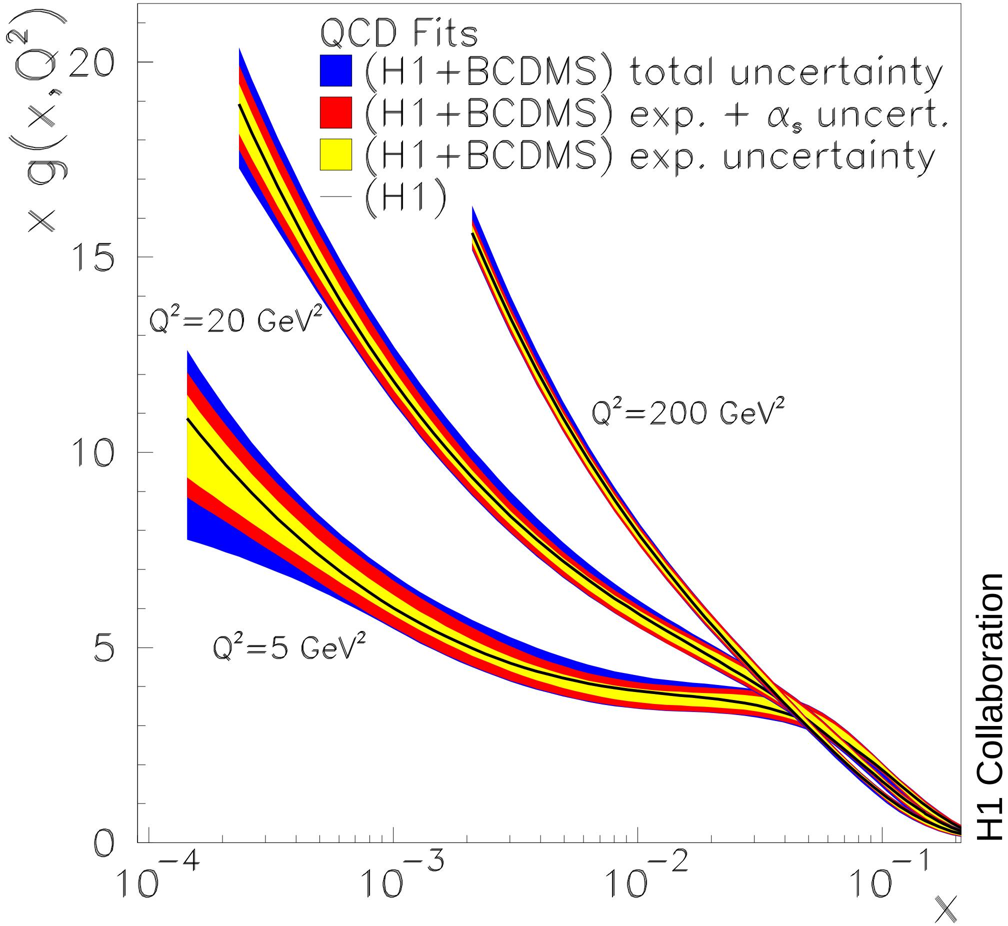
Gluons at HERA

$xg(x, Q^2) \;=$ # of gluons with transverse area $\sim 1/Q^2$ and $k_z = xP$



▷ Rapid rise with $1/x$: $xg(x, Q^2) \sim 1/x^{\lambda}$ with $\lambda = 0.2 \div 0.3$

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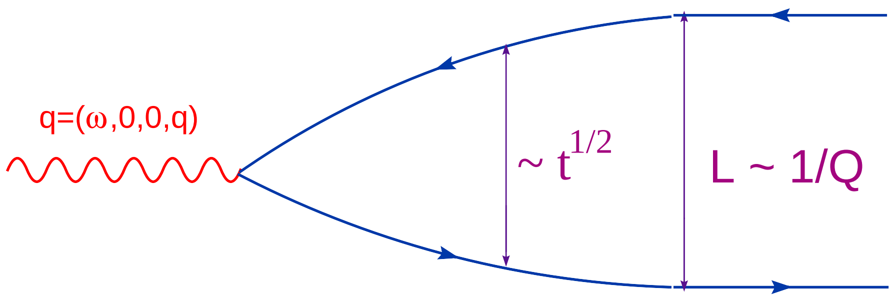
Screening length

- A small color dipole ('meson') with transverse size $L \ll 1/Q_s$ propagates through the strongly–coupled plasma with almost no interactions !



- Larger dipoles with $L \gtrsim 1/Q_s$ cannot survive in the plasma

$$L_s \sim \frac{1}{Q_s} \quad \& \quad \gamma \sim \frac{\omega}{Q} \quad \Longrightarrow \quad L_s \sim \frac{1}{\sqrt{\gamma}\,T} \ll \frac{1}{T}$$

- The dipole lifetime is short on natural time scales:

$$\Delta t \sim \frac{\omega}{Q_s^2} \sim \frac{\sqrt{\gamma}}{T} \ll \frac{\gamma}{T}$$

Momentum broadening

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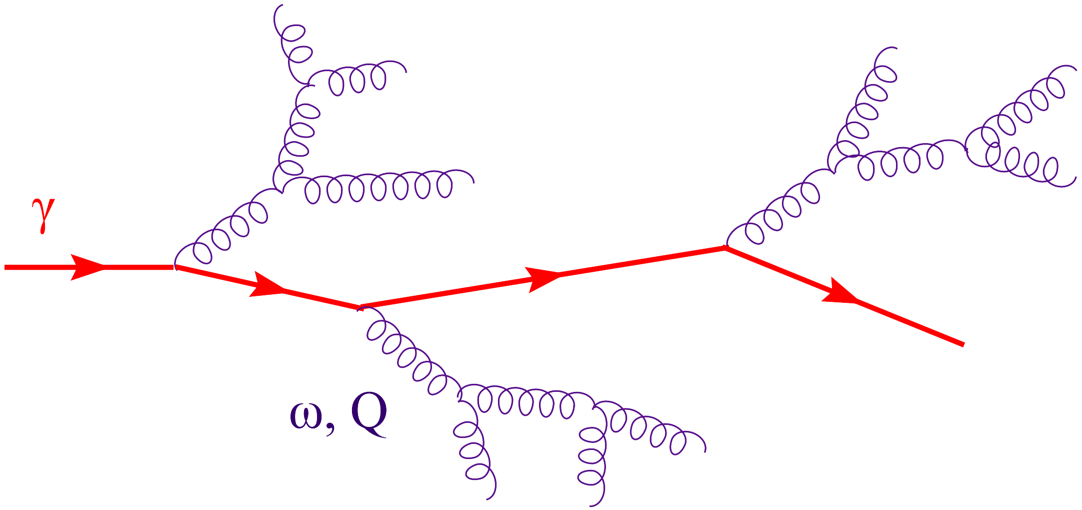
- Fluctuations in the medium–induced emission process



$$\frac{\mathrm{d}\langle p_T^2\rangle}{\mathrm{d}t} \sim \sqrt{\lambda}\,\frac{Q_s^2}{(\omega/Q_s^2)} \sim \sqrt{\lambda}\,\frac{Q_s^4}{\gamma Q_s} \sim \sqrt{\lambda}\sqrt{\gamma}\,T^3$$

$$\frac{\mathrm{d}\langle p_L^2\rangle}{\mathrm{d}t} \sim \sqrt{\lambda}\,\frac{\omega^2}{(\omega/Q_s^2)} \sim \sqrt{\lambda}\sqrt{\gamma}\,\gamma^2\,T^3$$

Casalderrey-Solana, Teaney; Gubser, 2006 (from trailing string)

Saturation line: weak vs. strong coupling

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Hard probes in AdS/CFT

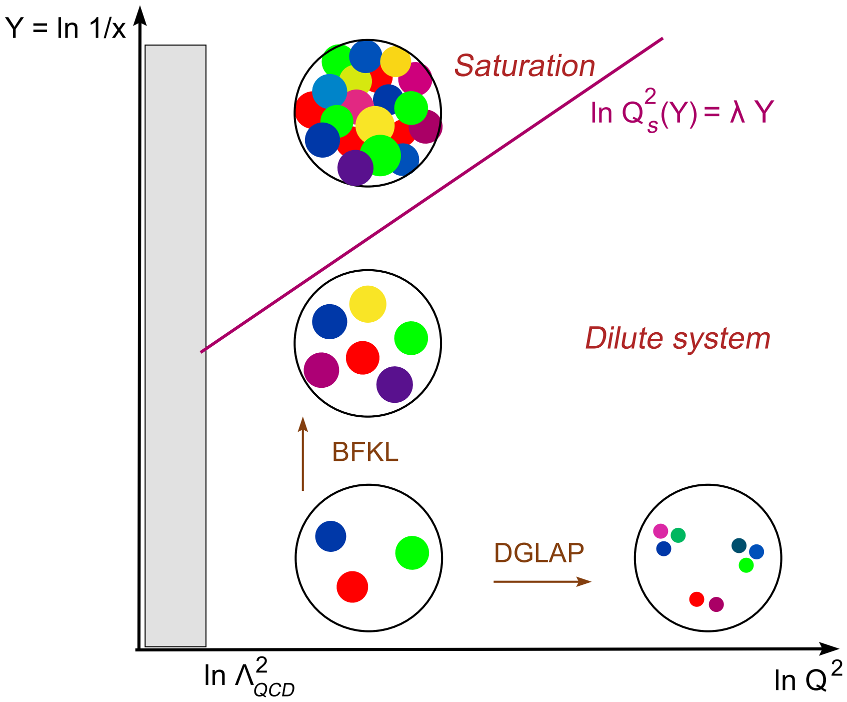
Partons from AdS/CFT

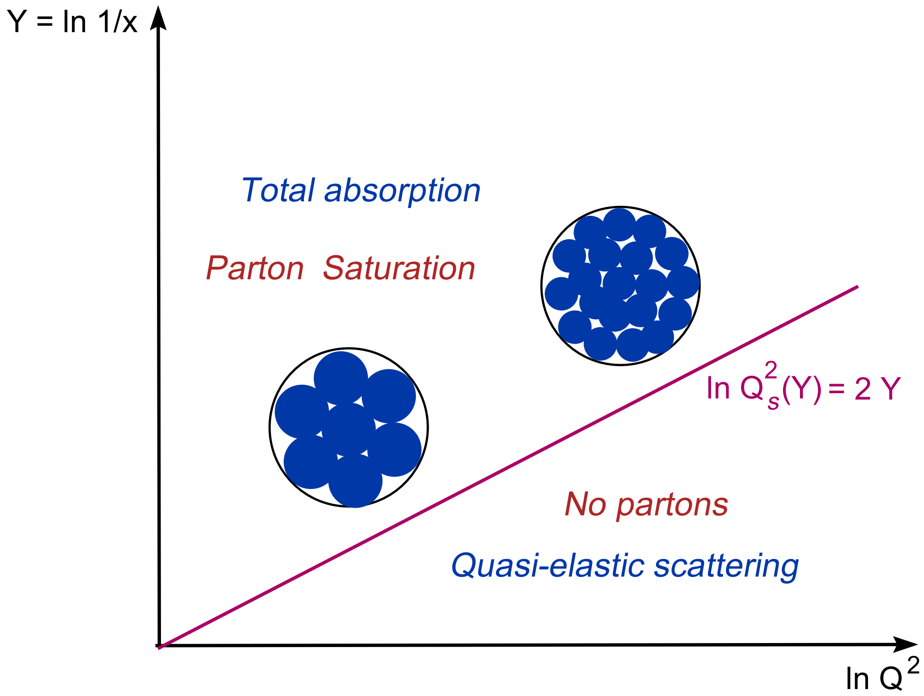
Jet quenching

Conclusions

Backup

- Jet quenching
- Momentum broadening
- RAA
- perfect fluid
- Jets
- Optical theorem
- Current correlator
- Gluons at HERA
- Screening length
- Saturation line
- String fluctuations





- Saturation exponent : $Q_s^2(x) \propto 1/x^{\lambda_s} \equiv \mathrm{e}^{\lambda_s Y}$
  - weak coupling (LO pQCD): $\lambda_s \approx 0.12\, g^2 N_c$
  - phenomenology & NLO pQCD: $\lambda_s \approx 0.2 \div 0.3$
  - strong coupling (plasma): $\lambda_s = 2$ (graviton)

Stochastic trailing string

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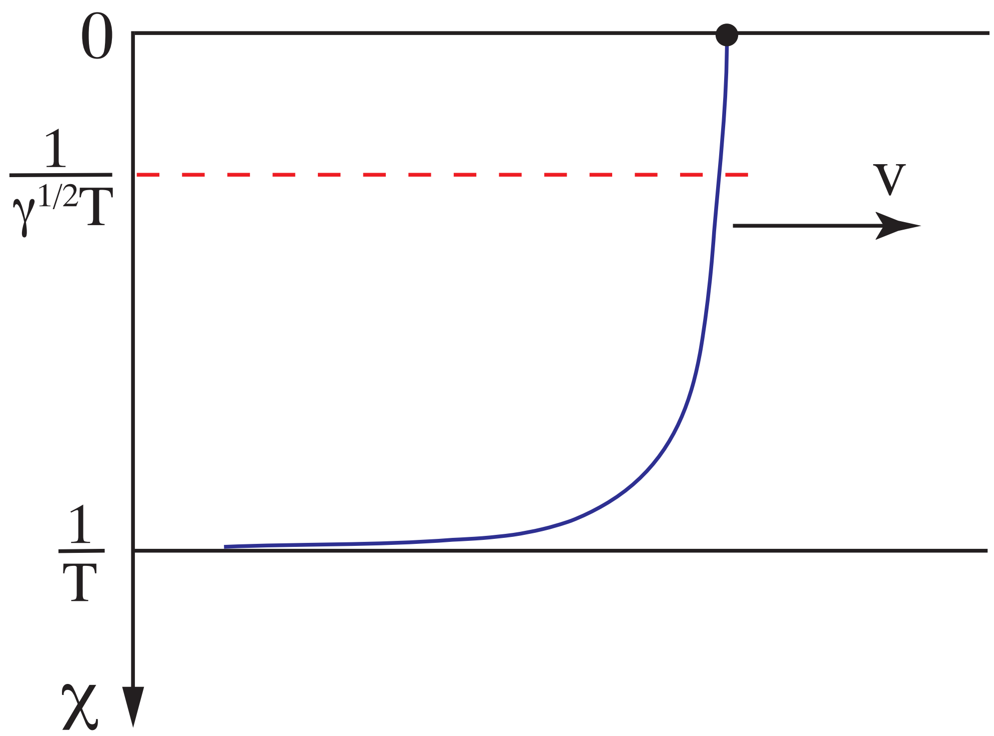
- How are quantum–mechanical (as opposed to thermal) fluctuations encoded in AdS/CFT ?



- World–sheet horizon at $\chi_s = 1/Q_s \sim 1/(\sqrt{\gamma}T) \ll 1/T$
- Hawking radiation (= thermal flucts.) plays no role (in contrast to a static string; cf. talk by Rangamani)

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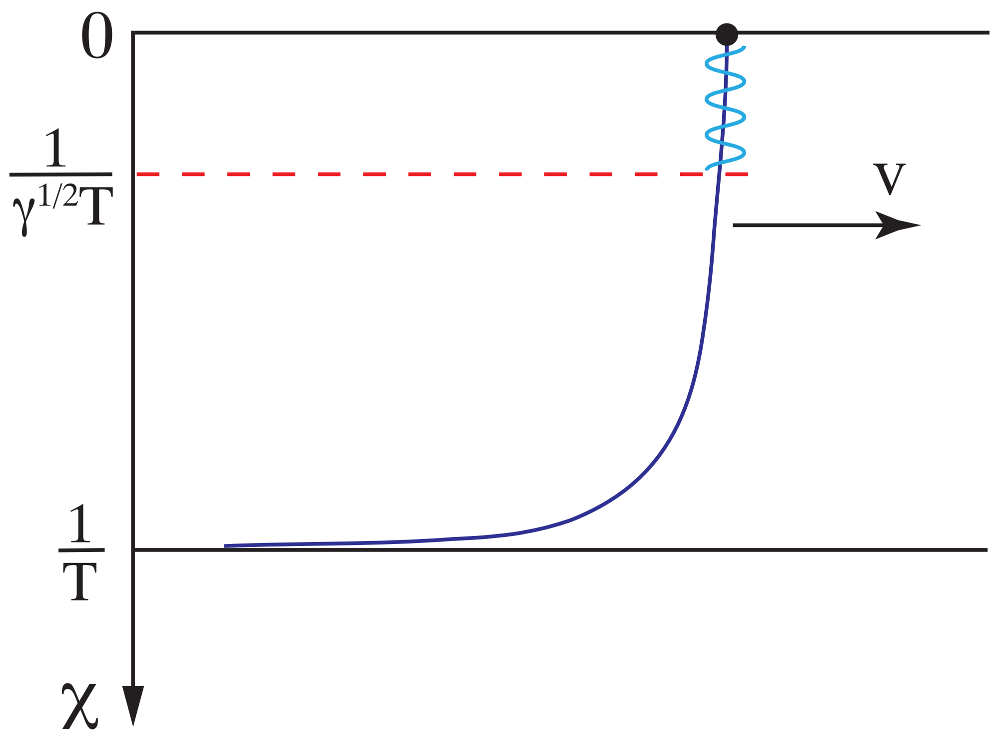
- Fluctuations on top of the world–sheet horizon χ_s

  $\Longrightarrow$ noise term on the 'stretched horizon' at $\chi = \chi_s + \epsilon$



- Langevin equation for the upper part of the string & the heavy quark *(G. Giecold, E.I., A. Mueller, 09)*
- Physics: Fluctuations in the parton cascades