High energy scattering: from weak to strong coupling

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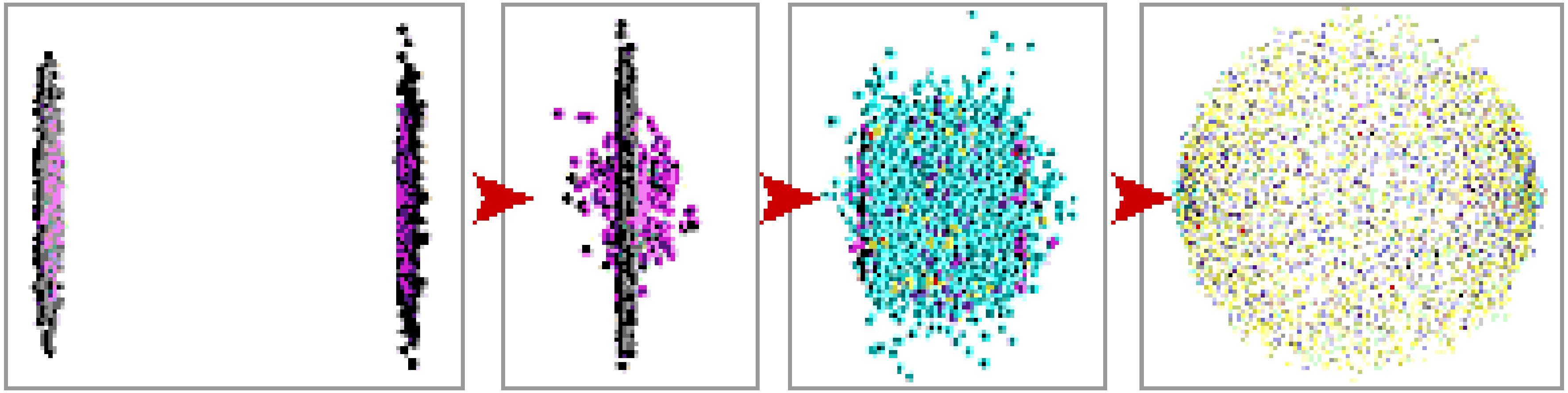
The Little Bang

- Ultrarelativistic heavy ion collisions @ RHIC and LHC



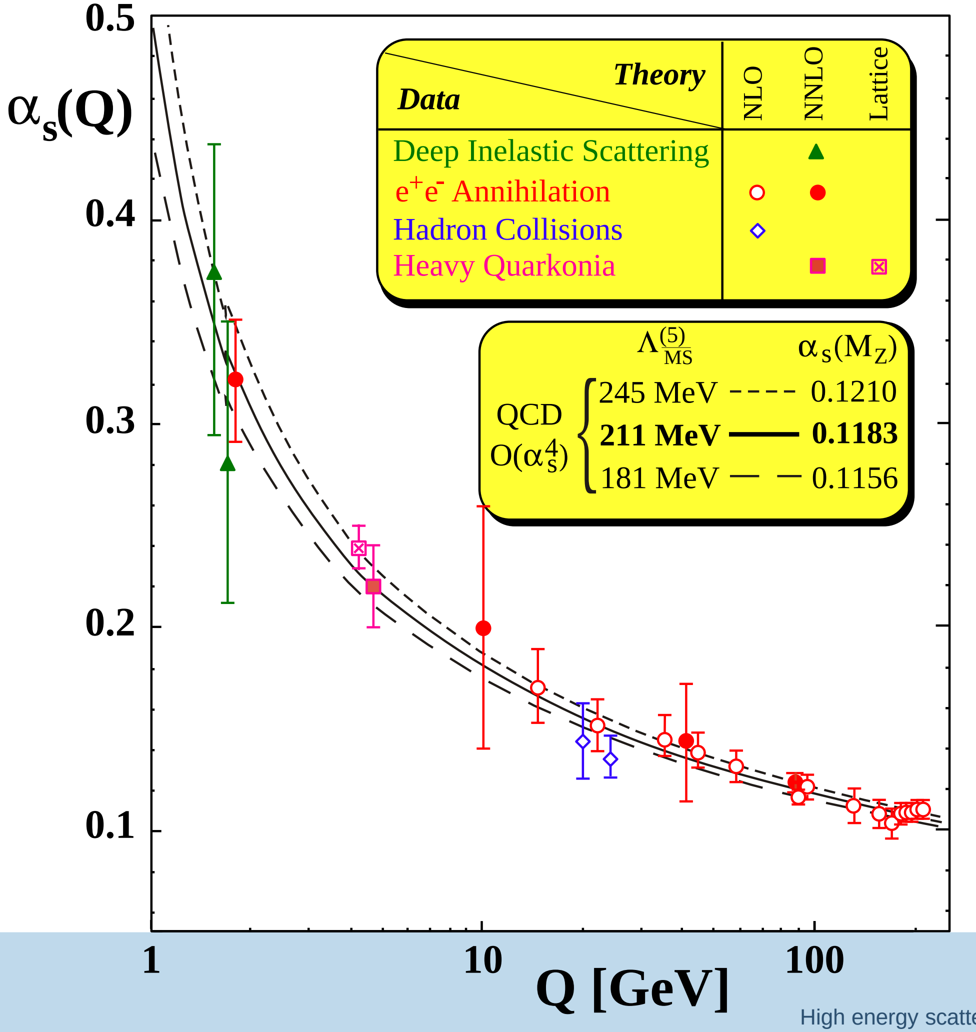
- An invitation to study high–energy scattering in QCD

  at both weak and strong coupling

Asymptotic freedom

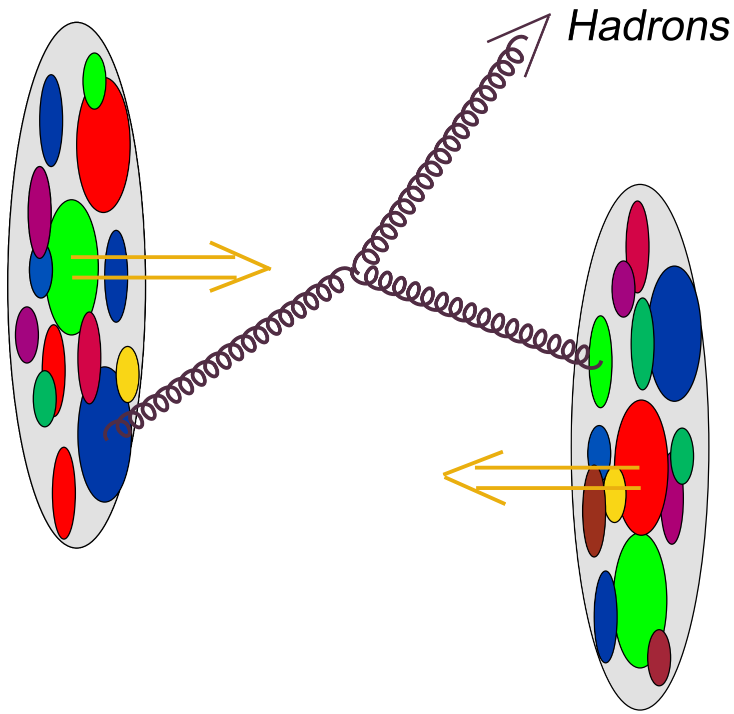
- QCD is weakly coupled at short distances or high density

$$\alpha_s(Q) \propto \frac{1}{\ln\left(Q^2/\Lambda^2_{\rm QCD}\right)} \quad \text{with} \quad \Lambda_{\rm QCD} \sim 200\,\text{MeV}$$



Early stages of a high–energy collision

- Highly energetic, strongly Lorentz contracted, nuclei: $\gamma \sim 100$

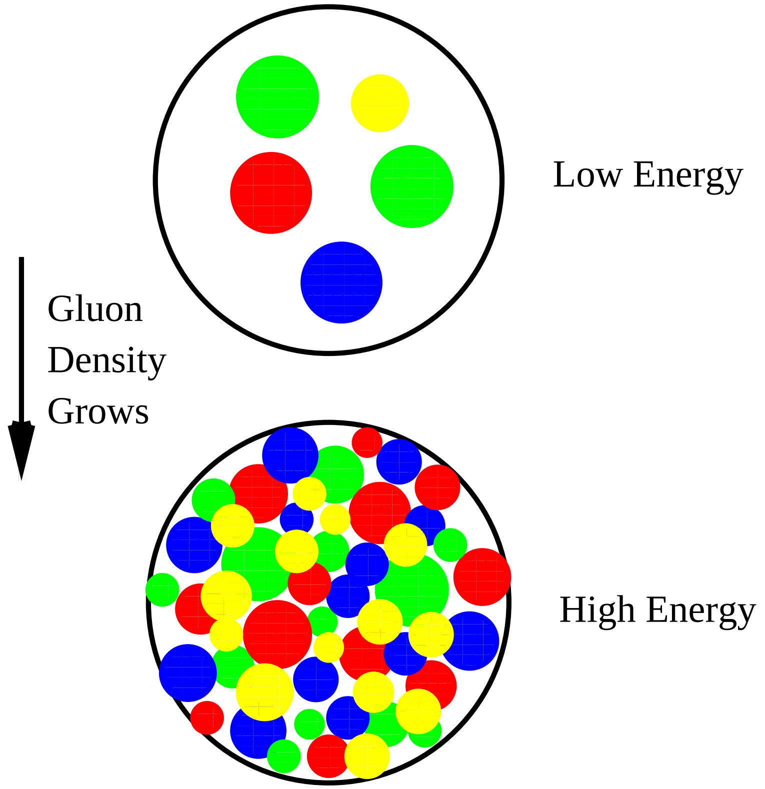


  - RHIC: Au–Au collision at 200 GeV/nucleon pair
  - LHC : 5.5 TeV/nucleon pair in Au–Au and 14 TeV in p–p

- At high energy, hadron wavefunctions are very dense !

Gluon evolution

- Gluon distribution grows very fast with increasing energy

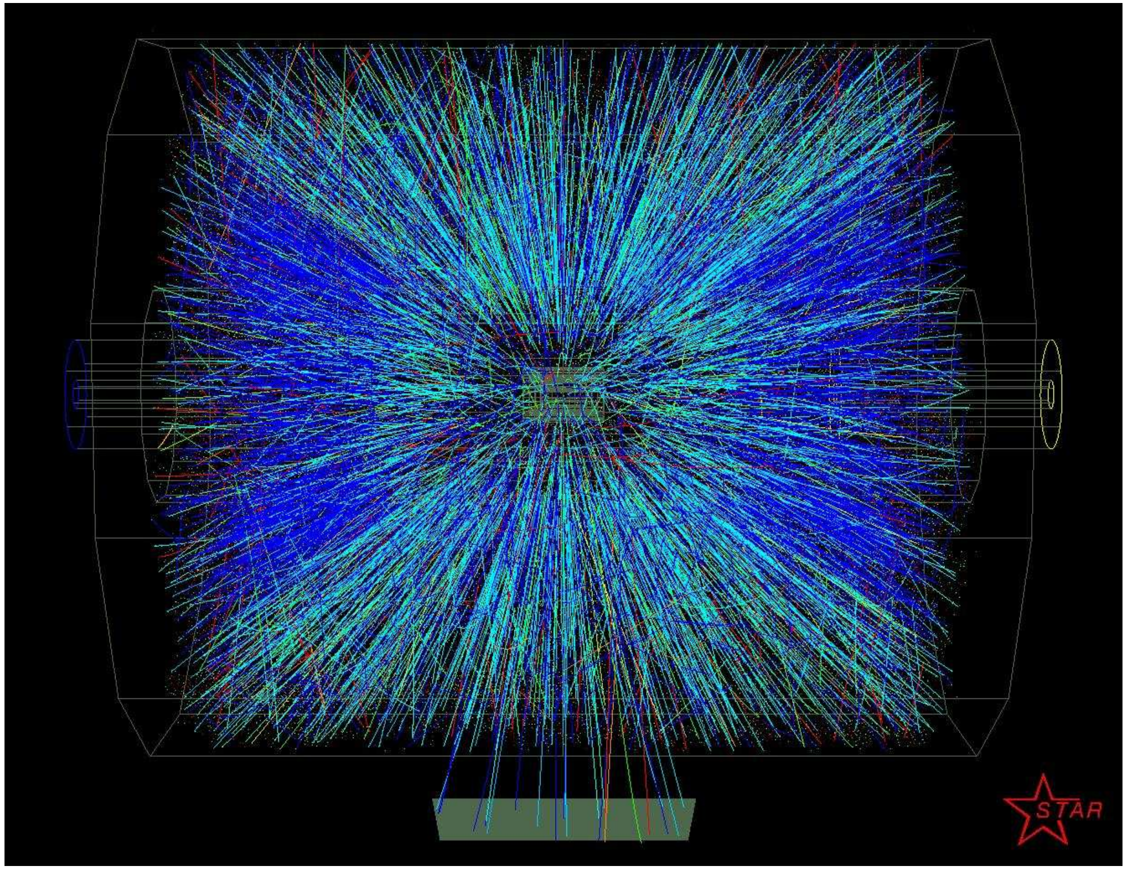


A head–on vue of a hadron

- Being dense, the gluonic matter is weakly coupled !

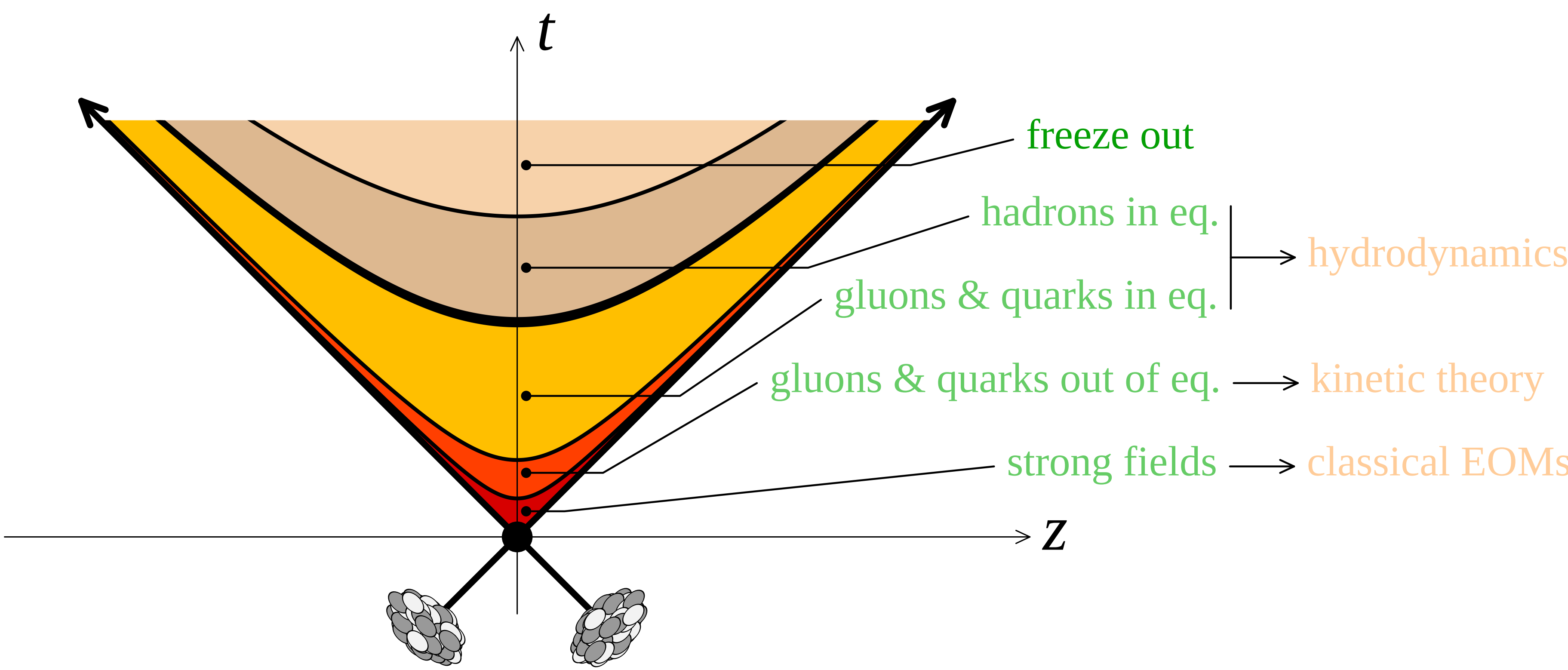
  Color Glass Condensate

Partons at RHIC



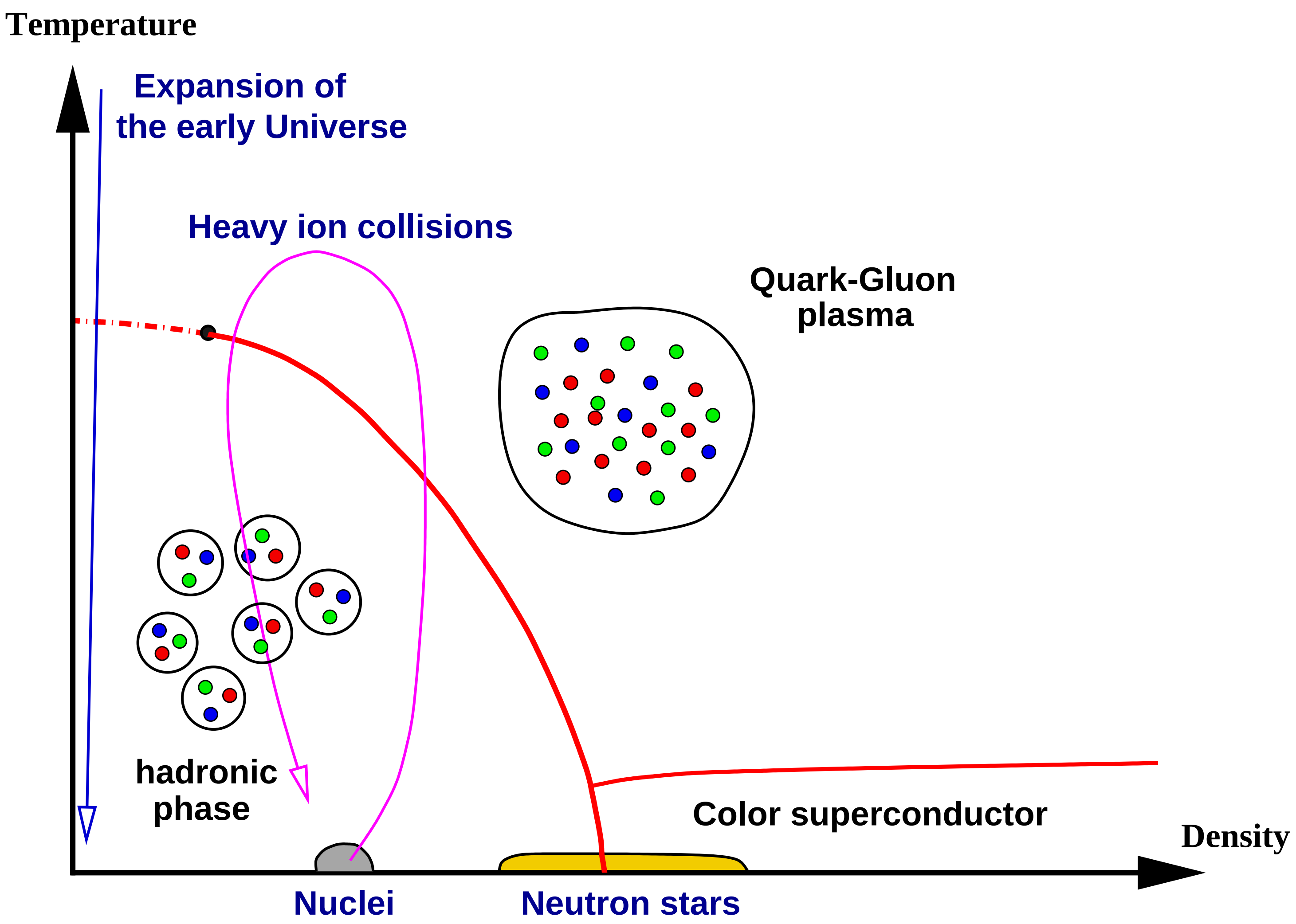
- Partons are actually 'seen' (liberated) in AA collisions
  - ~ 3000 hadrons in the final state vs. 400 nucleons in AA
  - most of them arise as hadronized partons

The stages of a heavy ion collision



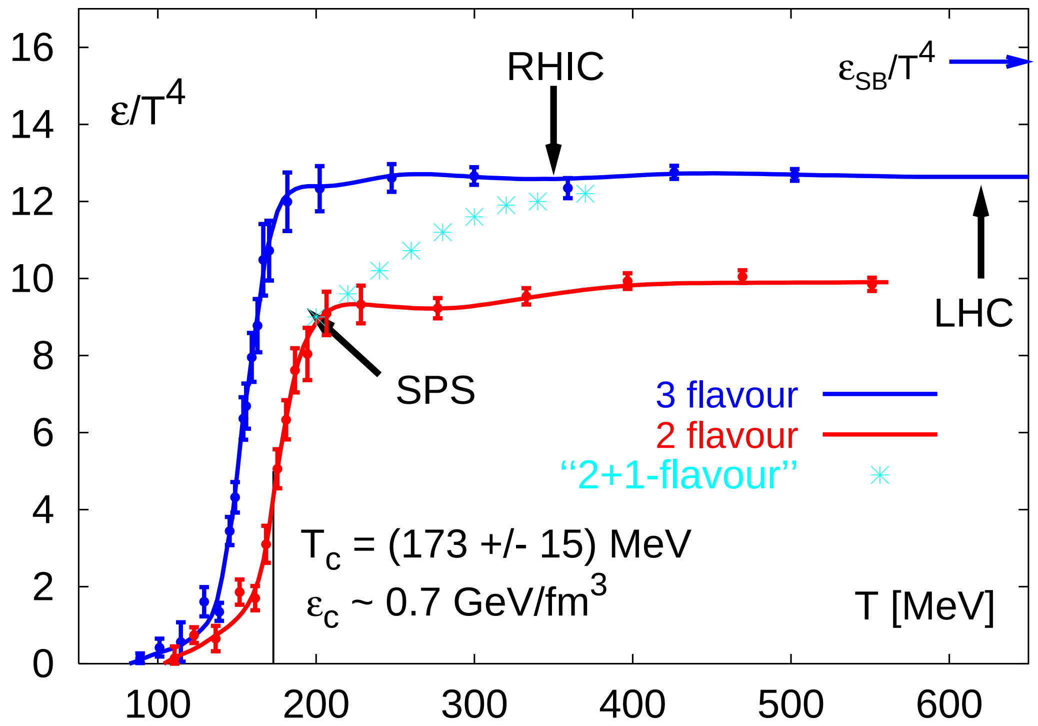
- Right after the collision: a hot ‘soup’ of quark and gluons
- Later times: the matter expands and becomes more dilute
- Thermal phase at intermediate times: Quark Gluon Plasma

Phases of QCD



Heating QCD : Lattice results

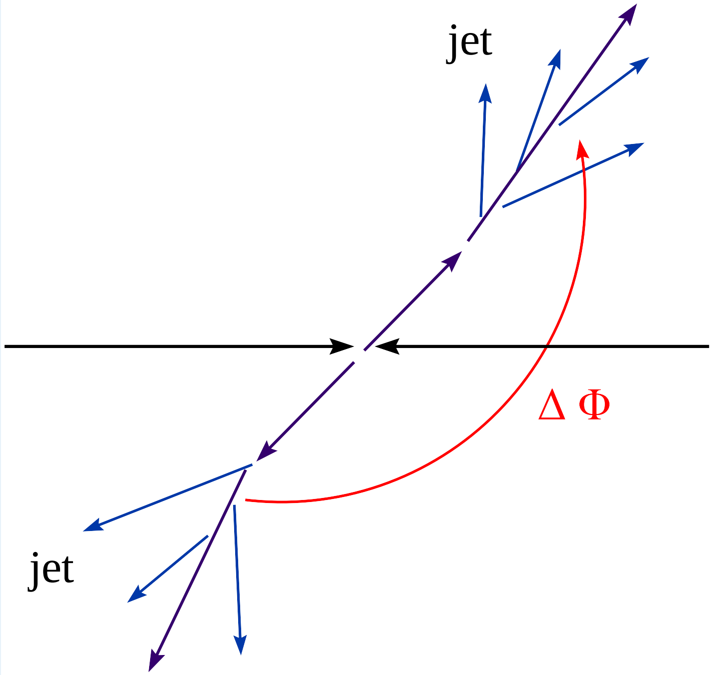
- Energy density as a function of T (Bielefeld Coll.)

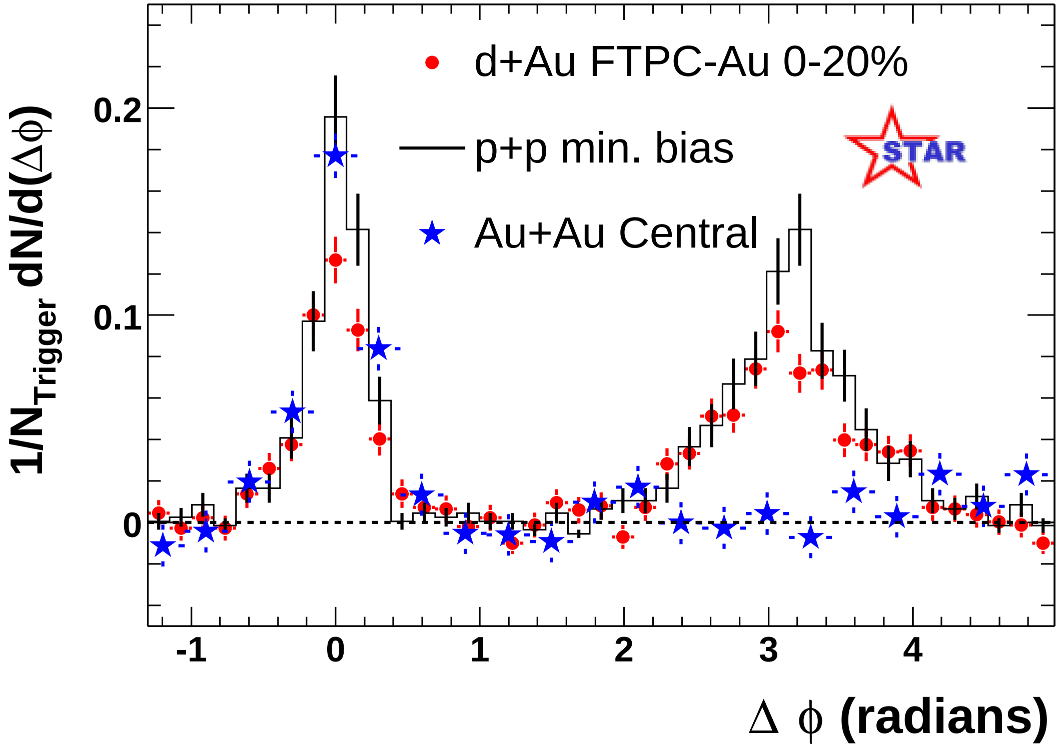


$$\mathcal{E}/\mathcal{E}_0 \approx 0.85 \qquad \text{for} \qquad T = 3T_c$$

- 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)

Jets in proton–proton collisions

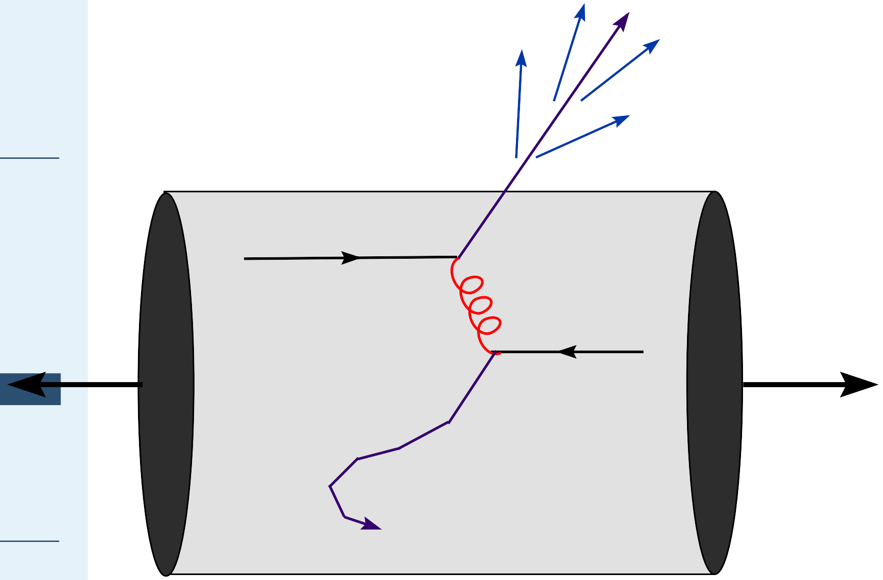


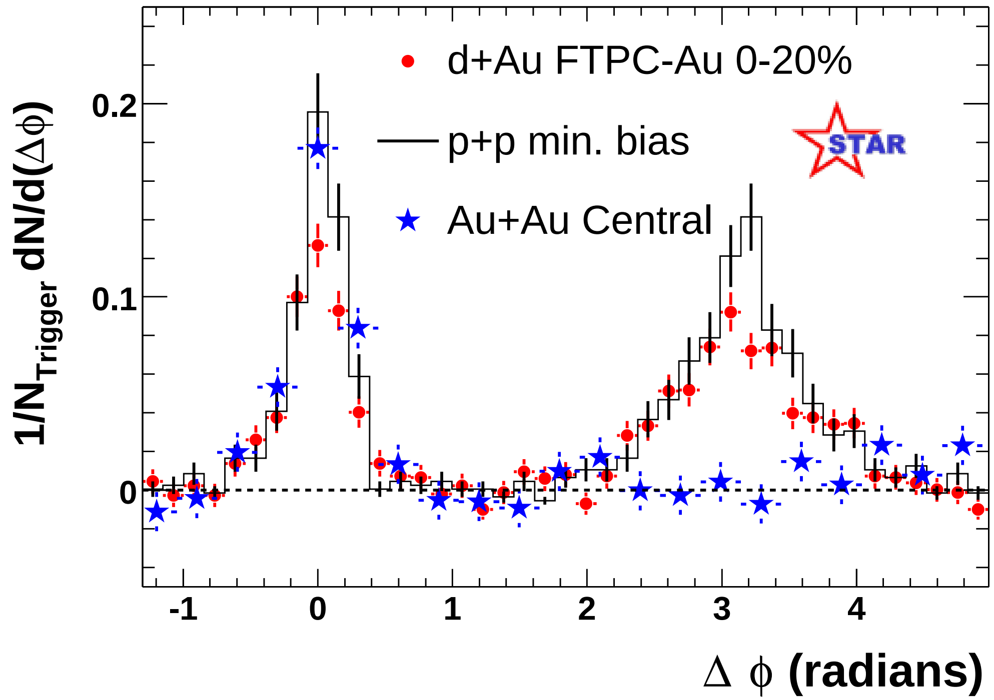


- Azimuthal correlations between the produced jets:

  a peak at $\Delta\Phi\, =\, 180°$

Nucleus–nucleus collision: Jet quenching





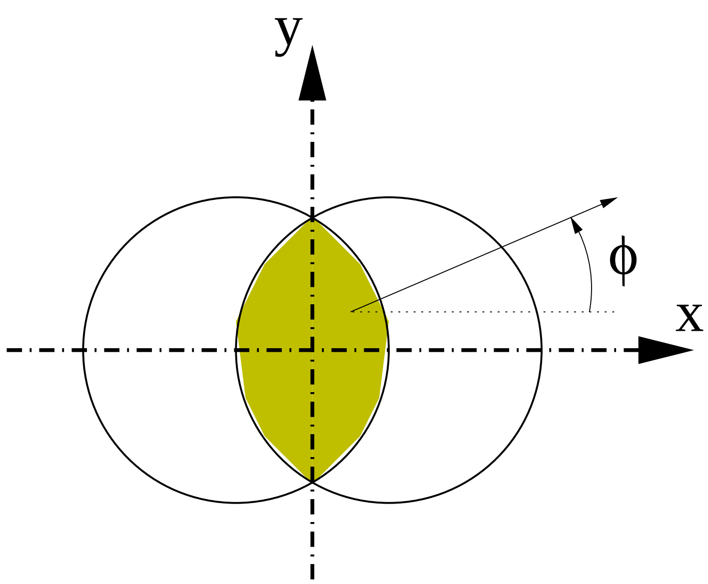
- The "away–side" jet has disappeared !

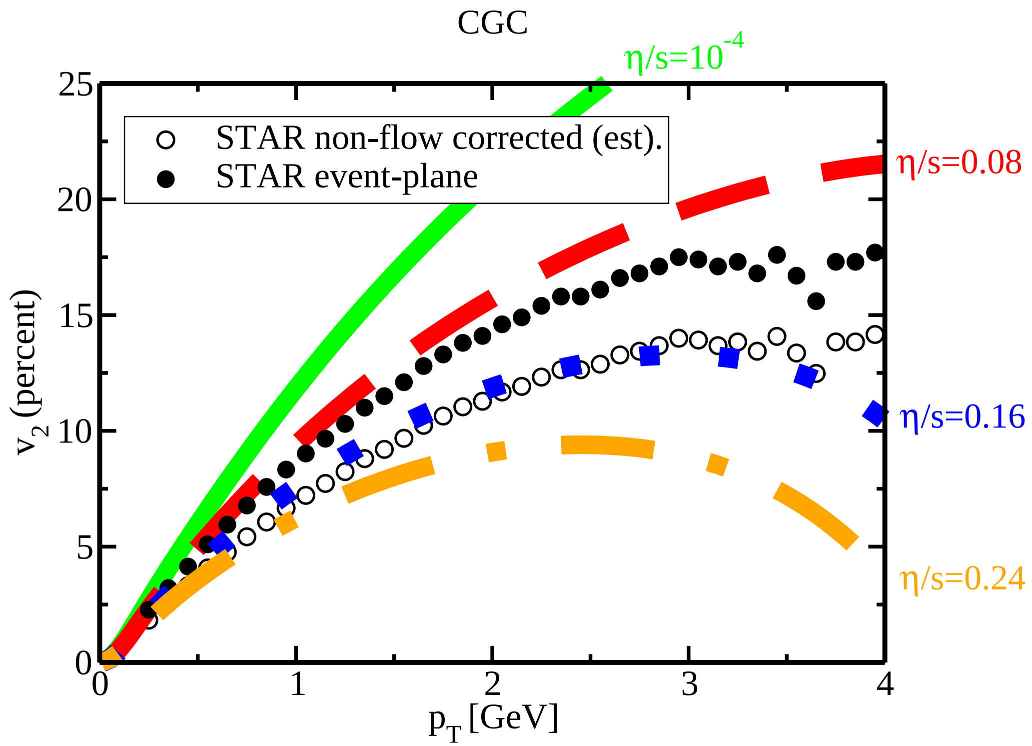
  absorbtion (or energy loss, or "jet quenching") in the medium

- The matter produced in a heavy ion collision is opaque

  high density, strong interactions, ... or both

Elliptic flow at RHIC: The perfect fluid





- 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

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

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

- This ratio is small when the coupling is strong !
- Kinetic theory: viscosity is due to collisions among molecules

$$\eta \sim \rho\, v\, \ell = \text{mass density} \times \text{velocity} \times \text{mean free path}$$

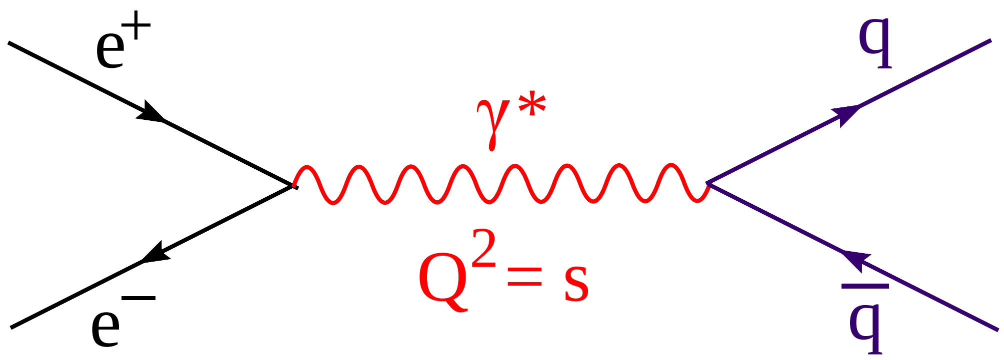
- Conjecture (from AdS/CFT) : *[Kovtun, Son, Starinets, 2003]*

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

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

e^+e^- annihilation: Jets in pQCD

- 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: $Q^2 \; \equiv \; q^\mu q_\mu \; = \; s > 0$

e^+e^- annihilation: Jets in pQCD

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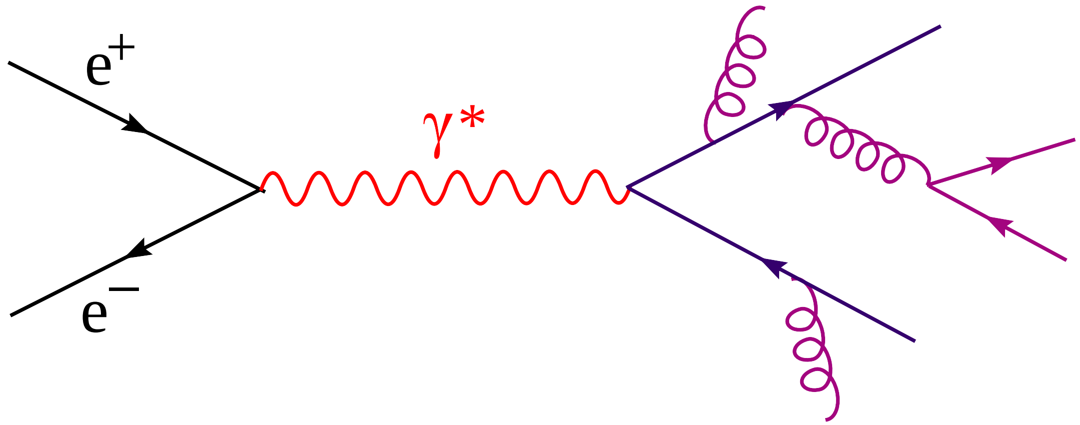
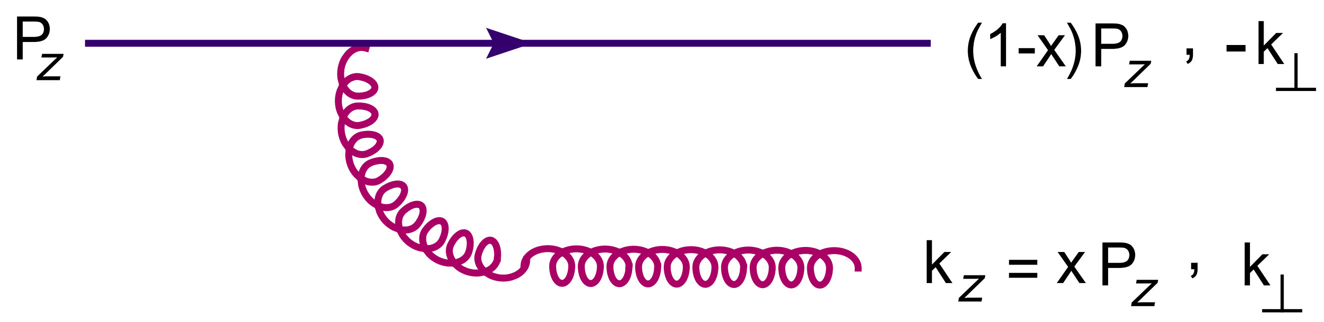


- The structure of the final state is determined by
  - parton branching & hadronisation

Bremsstrahlung

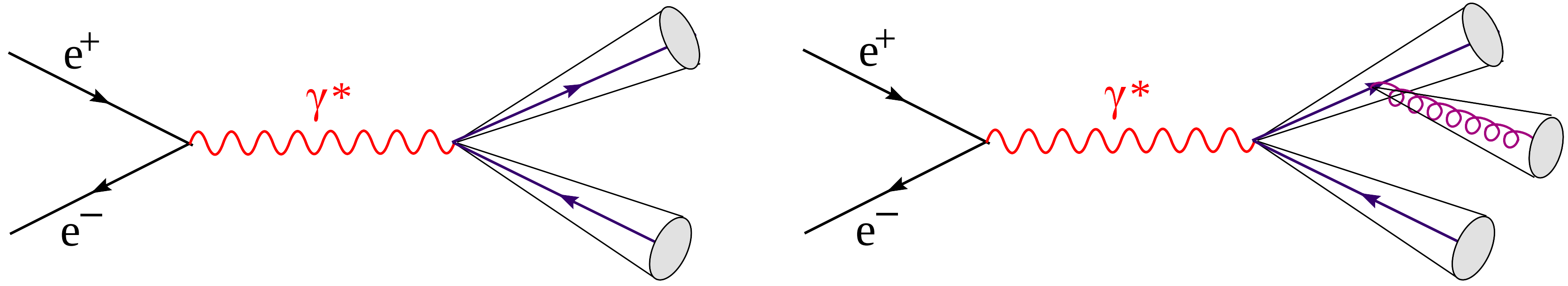
- Gluon emission to lowest order in perturbative QCD:



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

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

Jets in perturbative QCD



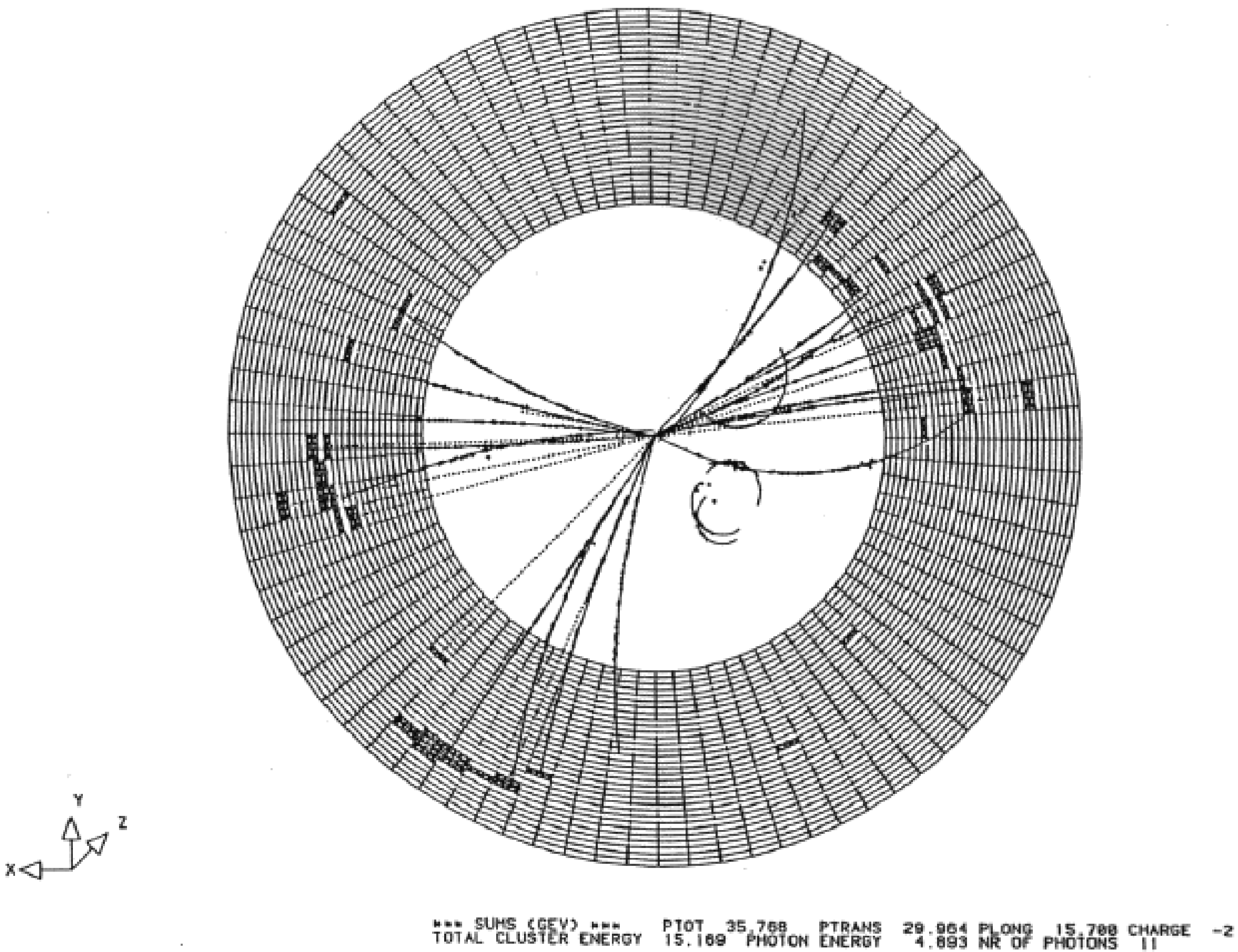
- Few, well collimated, jets
- e^+e^- cross–section computable in perturbation theory

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

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

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

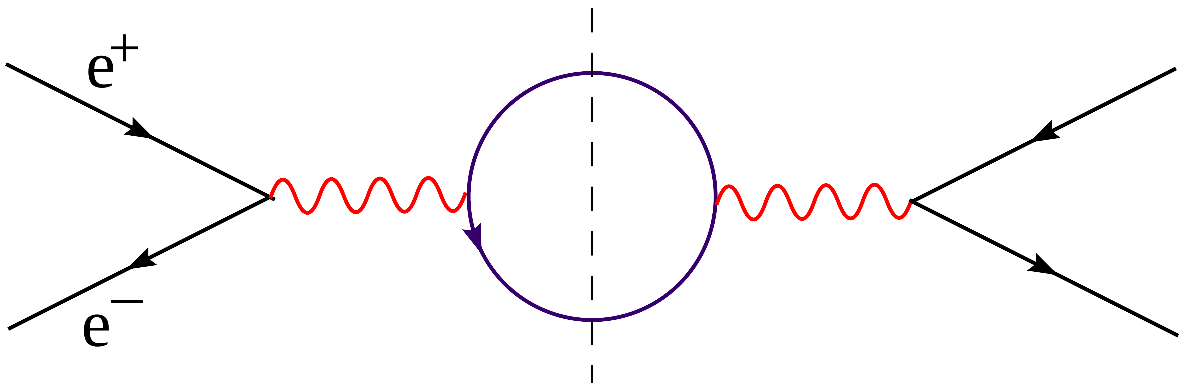
3–jet event at OPAL (CERN)



Optical theorem

- Total cross–section given by the optical theorem

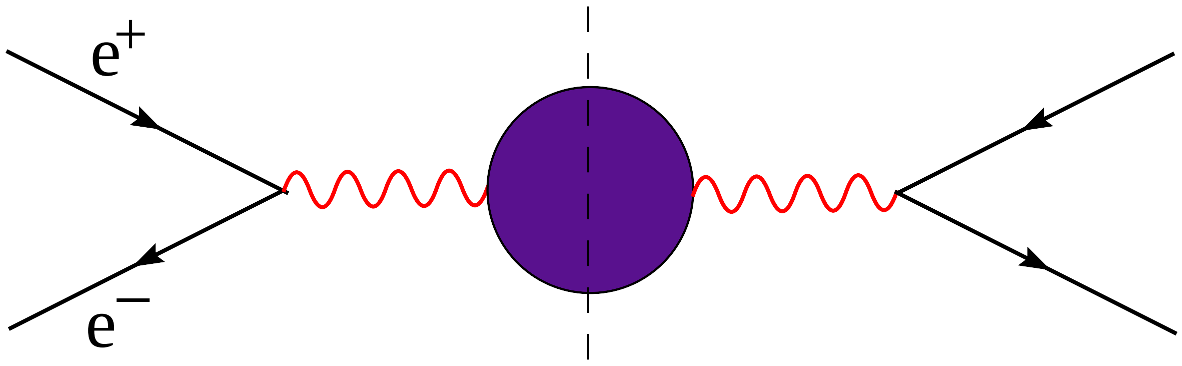
$$\sigma(e^+e^-) = \frac{1}{2s}\,\ell^{\mu\nu}\,\mathrm{Im}\,\Pi_{\mu\nu}(q)$$



- 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

Current–current correlator

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



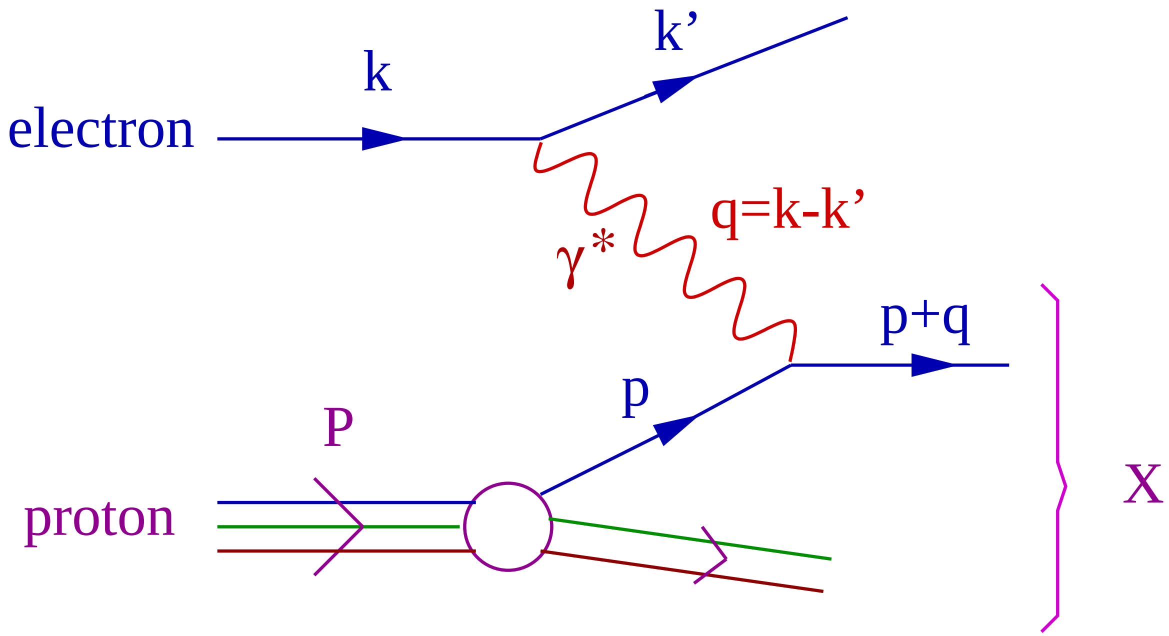
- $\Pi_{\mu\nu}$ = current–current correlator to all orders in QCD

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

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

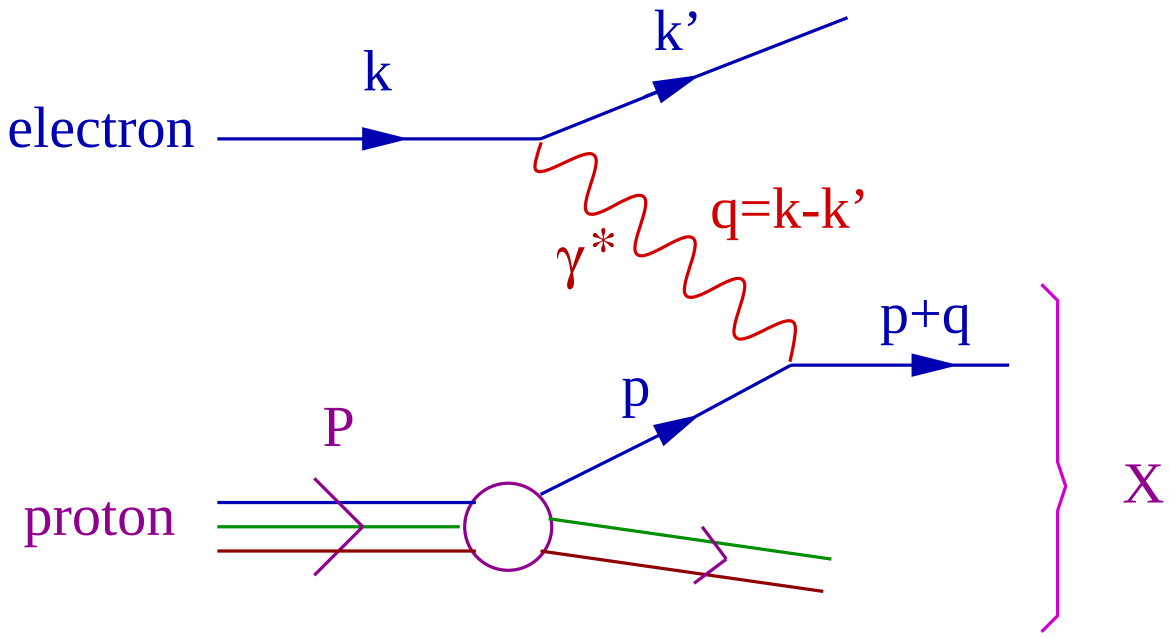
- Valid to leading order in $\alpha_{\rm em}$ but all orders in α_s

Deep inelastic scattering



- 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

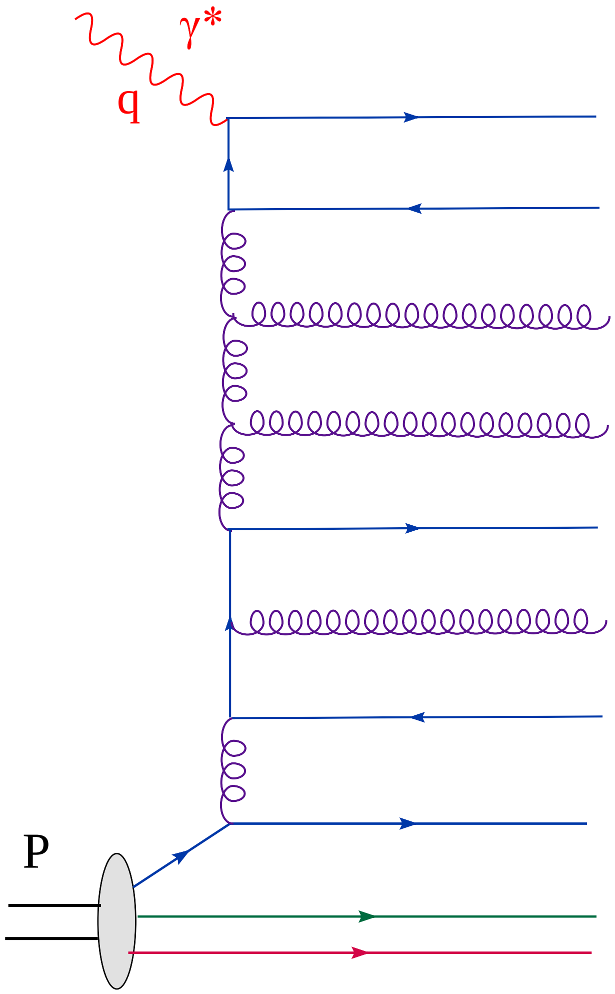


$$\sigma_{\gamma^* p}(x, Q^2) \;=\; \frac{4\pi^2\alpha_{\rm em}}{Q^2}\,F_2(x, Q^2)$$

- $F_2(x, Q^2)$: '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



$$d\mathcal{P}_{g\to g} \sim \alpha_s N_c \frac{d^2k_\perp}{k_\perp^2}\frac{dx}{x}$$

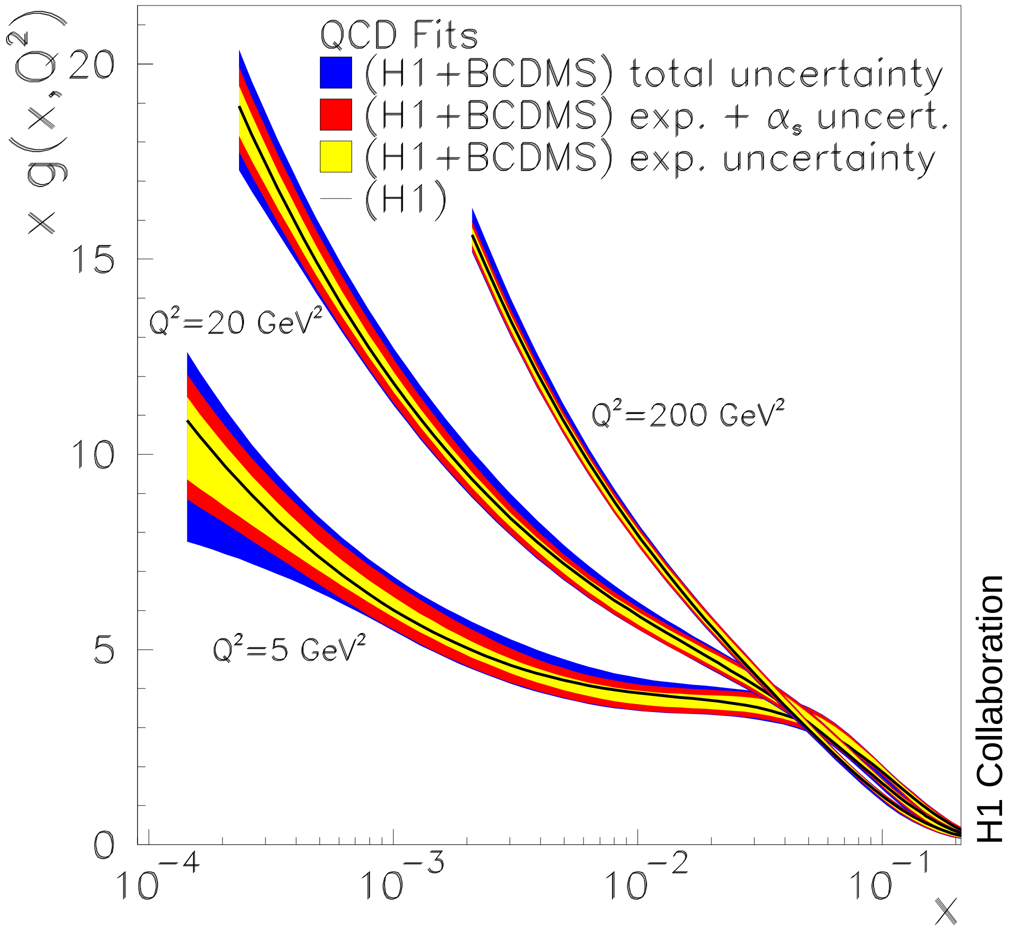
$$d\mathcal{P}_{q\to g} \sim \alpha_s C_F \frac{d^2k_\perp}{k_\perp^2}\frac{dx}{x}$$

$$d\mathcal{P}_{q\to q} \sim \alpha_s C_F \frac{d^2k_\perp}{k_\perp^2}\frac{dx}{1-x}$$

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

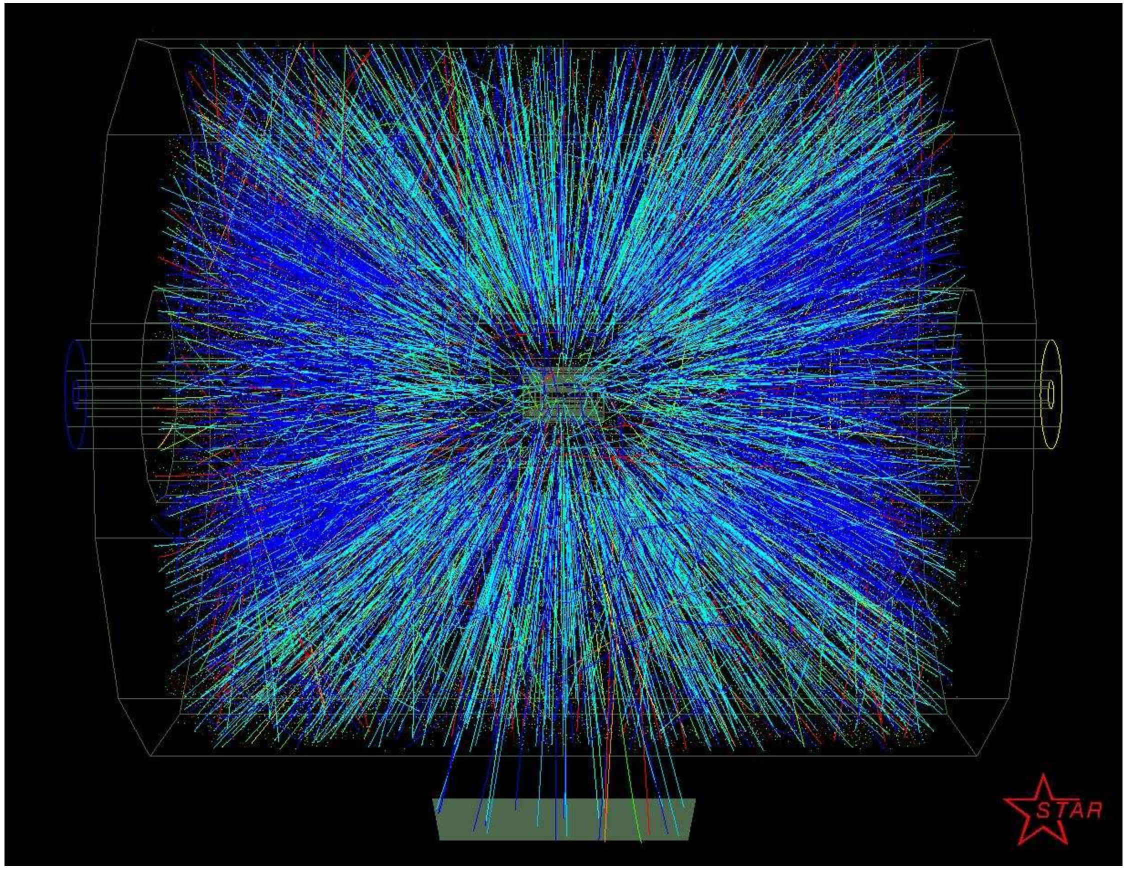
Gluons at HERA

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



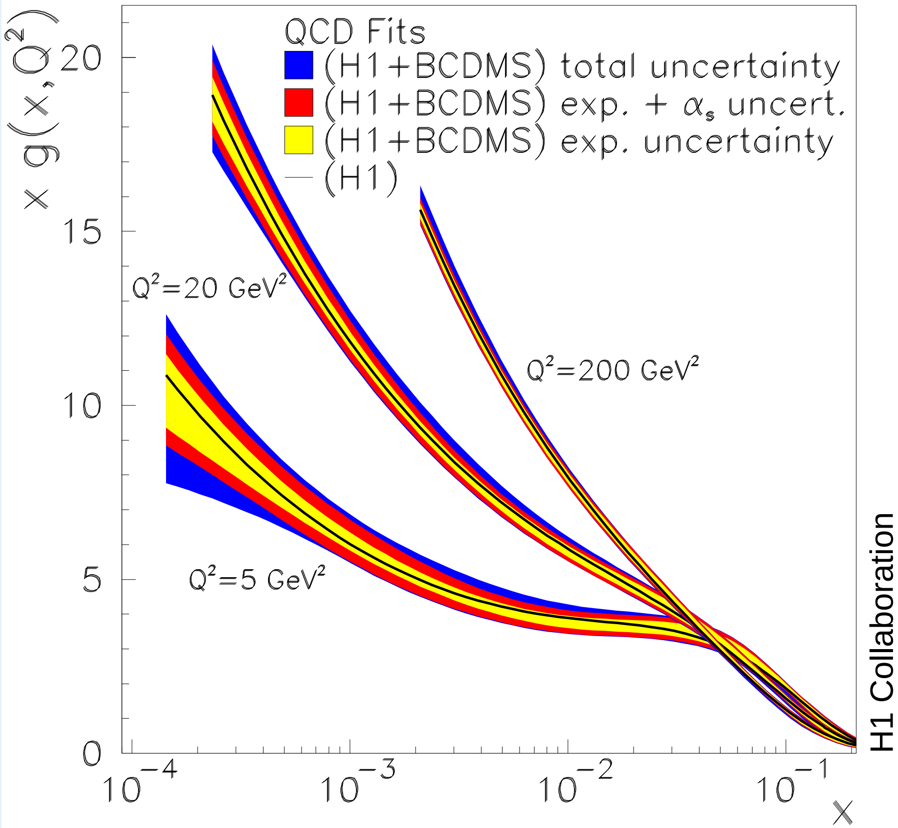
▷ Rapid rise with $1/x$: $xg(x,Q^2) \sim 1/x^{\lambda}$ with $\lambda = 0.2 \div 0.3$

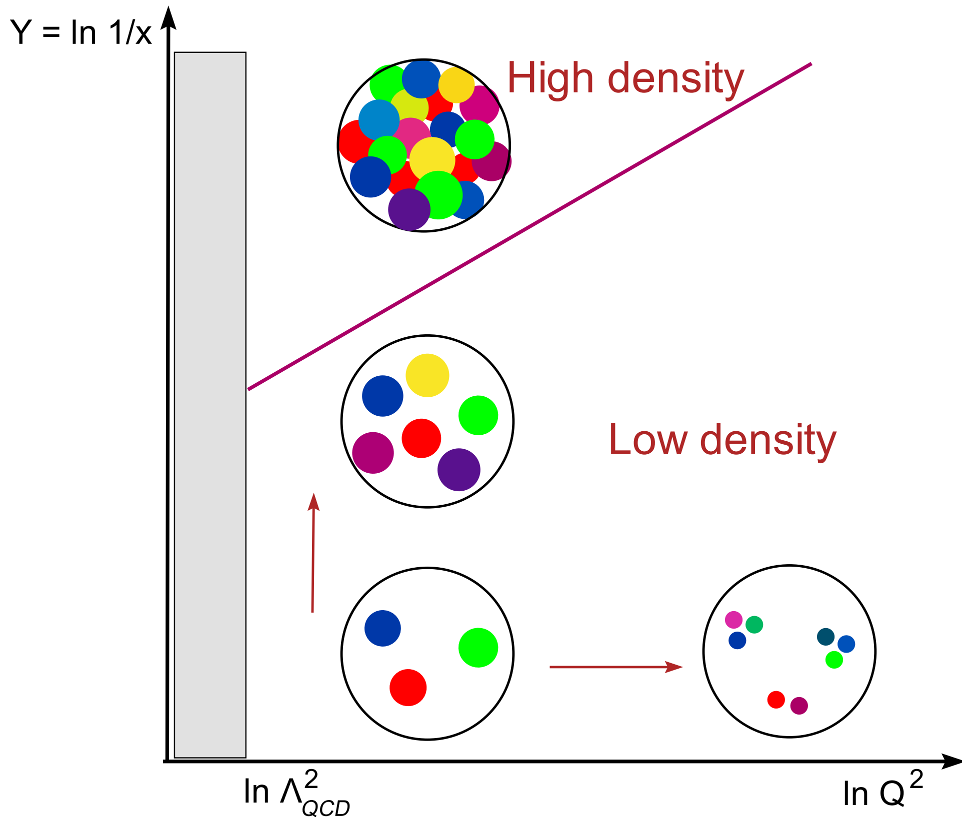
Partons at RHIC



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

Gluons at HERA



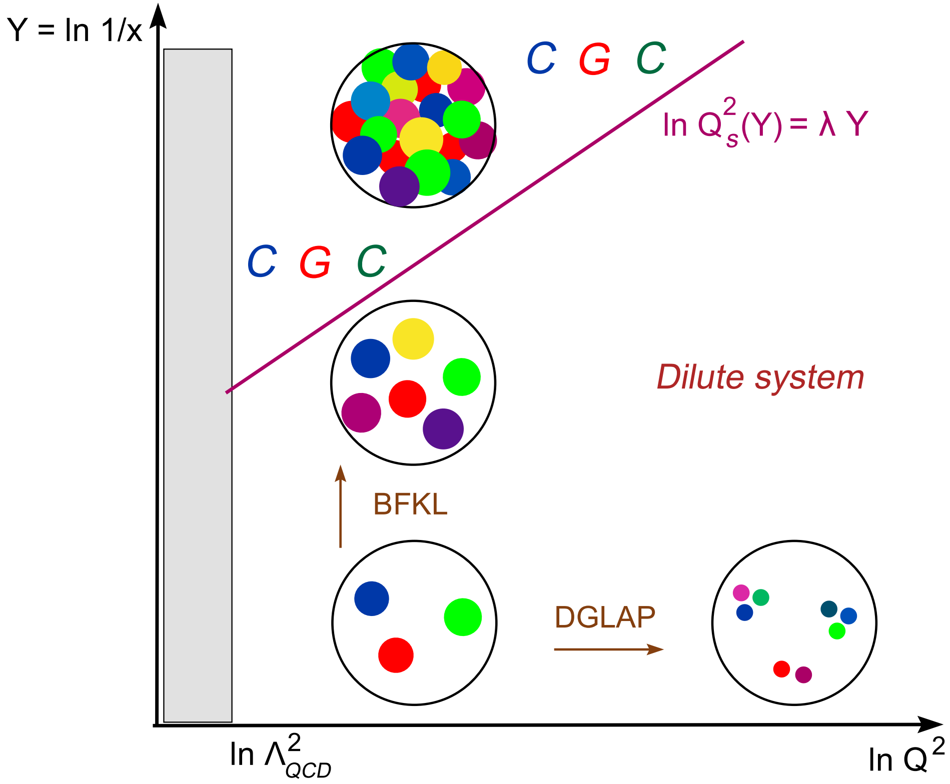


- High–Q^2 evolution : The parton density is decreasing
- Small–x evolution: An evolution towards increasing density
- The gluon density cannot become arbitrarily high !

Color Glass Condensate

- The gluon occupation number cannot be larger than $1/\alpha_s$:

$$n(x, Q^2) \sim \frac{1}{Q^2} \times \frac{xG(x, Q^2)}{\pi R^2}$$

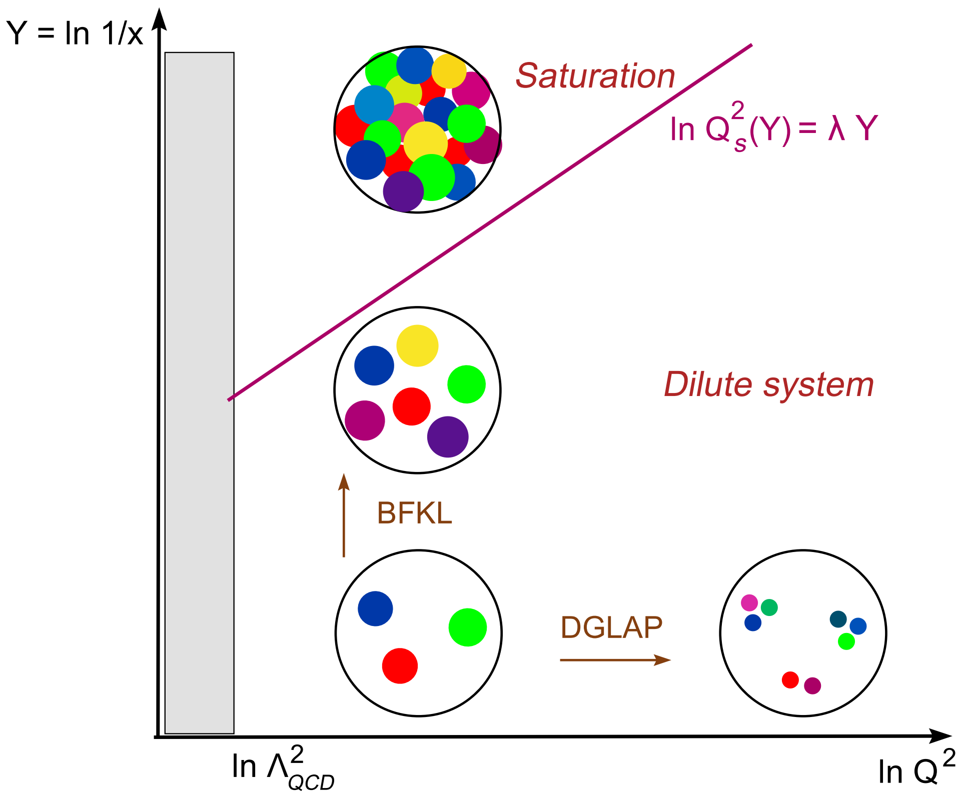


- When $n \sim 1/\alpha_s$, gluons form a Bose condensate: CGC

The Saturation Momentum

- $n(x, Q^2) \sim 1/\alpha_s \Longrightarrow$ the saturation line $Q^2 = Q_s^2(x)$

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



Electromagnetic current in a plasma

- Thermal expectation value (retarded polarization tensor) :

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

- '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
- Strong coupling $\Longrightarrow$ AdS/CFT correspondence
- A 'cousin' of QCD: $\mathcal{N} = 4$ Super Yang–Mills theory
  - conformal invariance: coupling is fixed !
  - no confinement, no fundamental quarks ...

A Gauge/Gavity duality *(Maldacena, 1997)*

- A conformal gauge field theory in $D = 4$: $\mathcal{N} = 4$ SYM
- Type IIB string theory living in $D = 10$: $AdS_5 \times S^5$

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

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

- Strong ‘t Hooft coupling (more properly, $N_c \to \infty$) :

$\lambda \equiv g^2 N_c \gg 1$ with $g^2 \ll 1 \Longrightarrow$ classical supergravity

(no massive string excitations, no string loops)

- Generating functional for the correlations of an operator $\hat{\mathcal{O}}$

$$\left\langle \mathrm{e}^{i\int \mathrm{d}^4x \hat{\mathcal{O}}\phi} \right\rangle_{4D} \approx \mathrm{e}^{iS_{\mathrm{SUGRA}}[\phi_{cl}]} \quad \text{with} \quad \phi_{cl}(x, \chi = 0) = \phi(x)$$

Heating AdS_5

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

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

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

- Example: compute the plasma entropy density for $\lambda \to \infty$
- The black hole entropy: Bekenstein–Hawking formula

$$S_{\rm BH} = \frac{A}{4G} \quad \text{with } A = \text{horizon area}$$

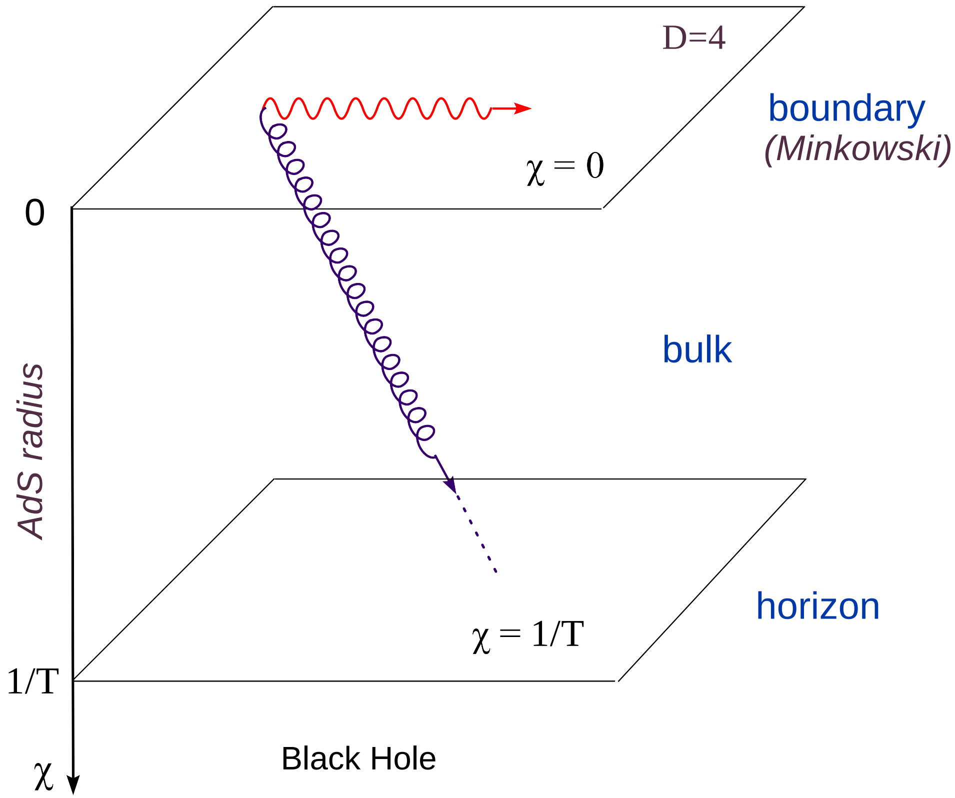
- ... is identified with the entropy of the $\mathcal{N} = 4$ plasma:

$$\Longrightarrow s \equiv \frac{S_{\rm BH}}{V_{3D}} = \frac{\pi^2}{2} N_c^2 T^3 = \frac{3}{4}\, s_0$$

DIS off the Black Hole

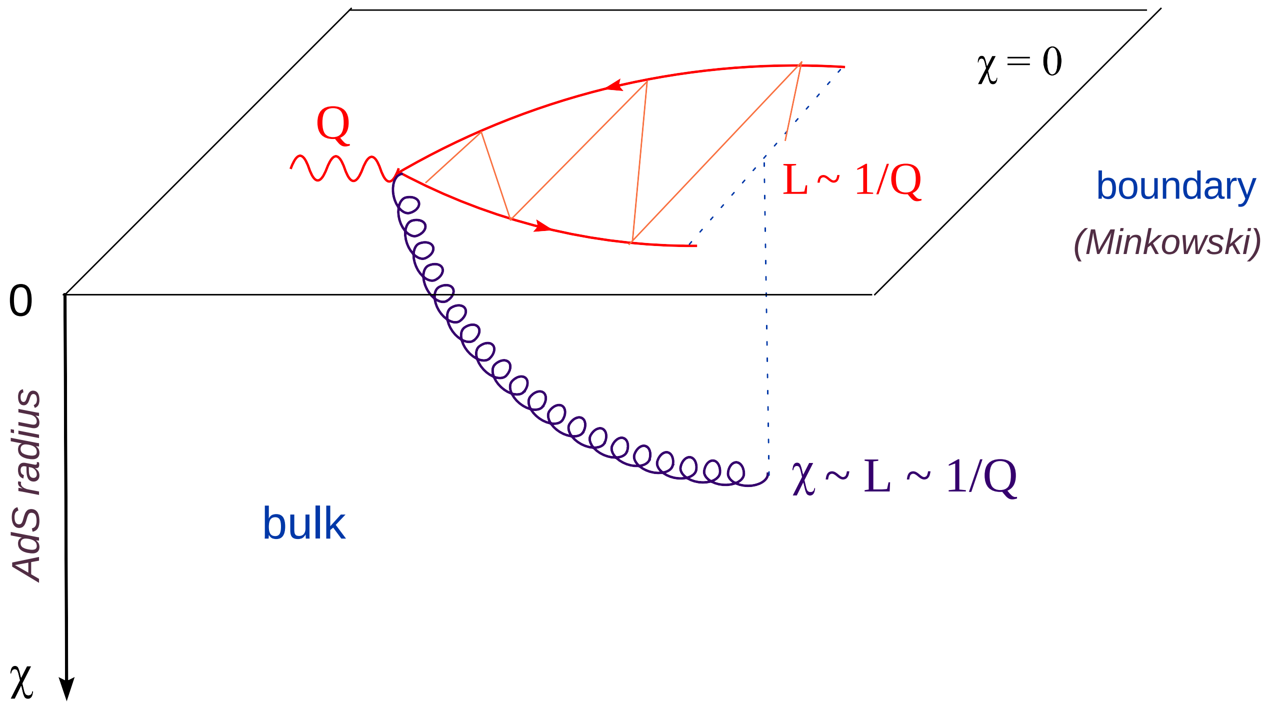
(Polchinki, Strassler, 02; Hatta, E.I., Mueller, 07)

- 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



The Holographic principle

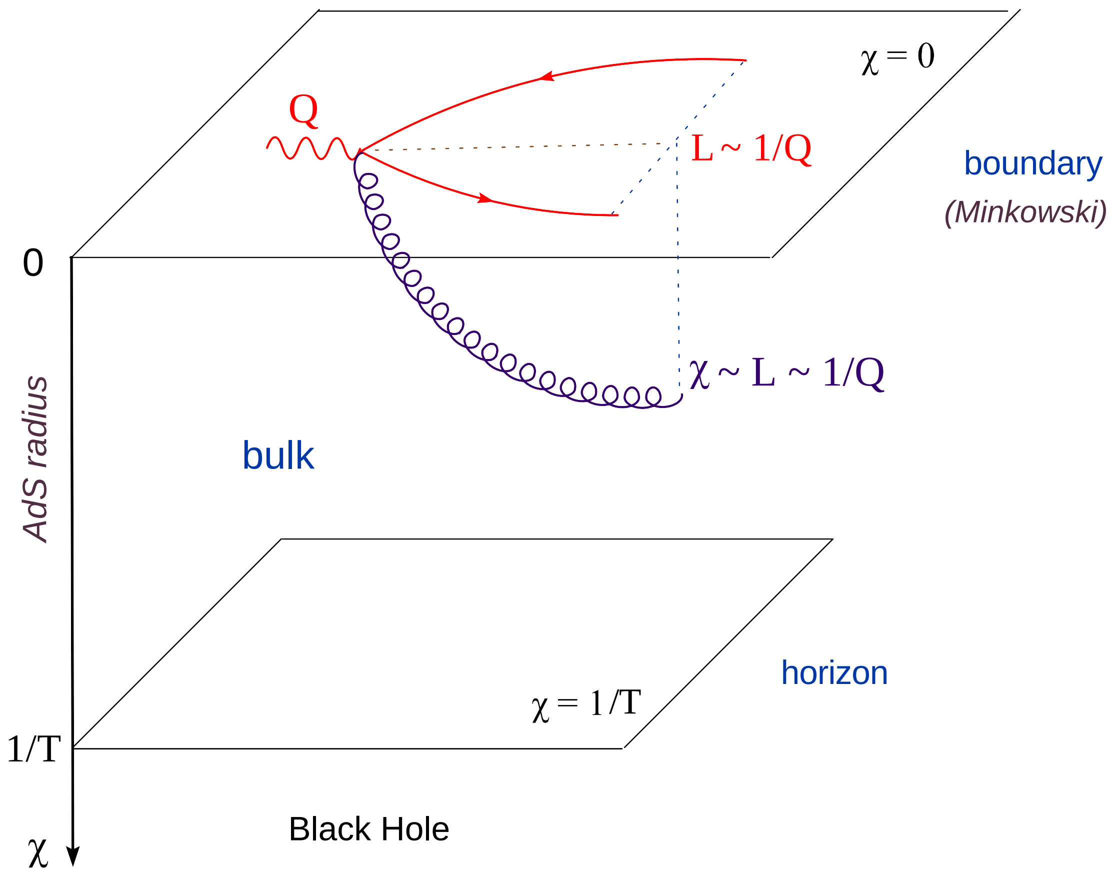
- 'Holography' : A quantum field theory in $D = 3 + 1 \iff$
  A theory with gravitation in higher dimensions



- 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 $Q \gg T$

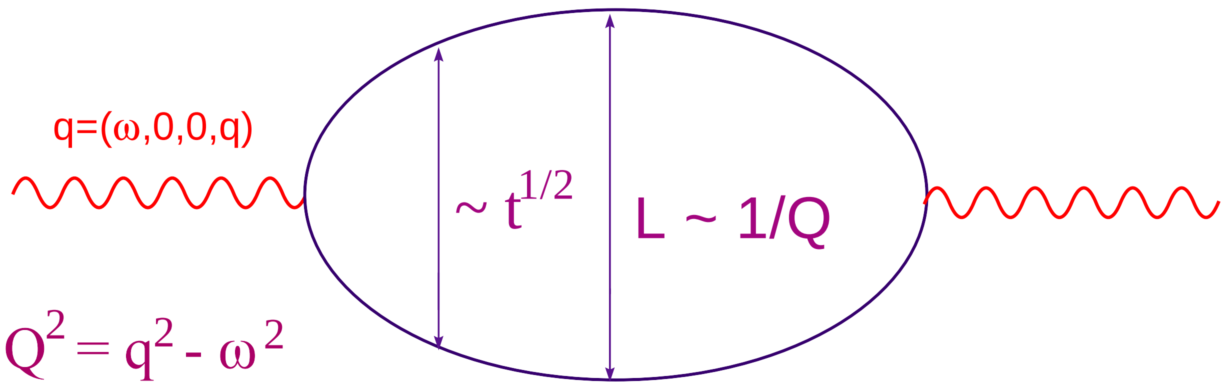
- The wave gets stuck near the boundary: $\chi \lesssim 1/Q \ll 1/T$



- Gravity calculation: Potential barrier proportional to Q

Interpretation: Partonic fluctuation

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

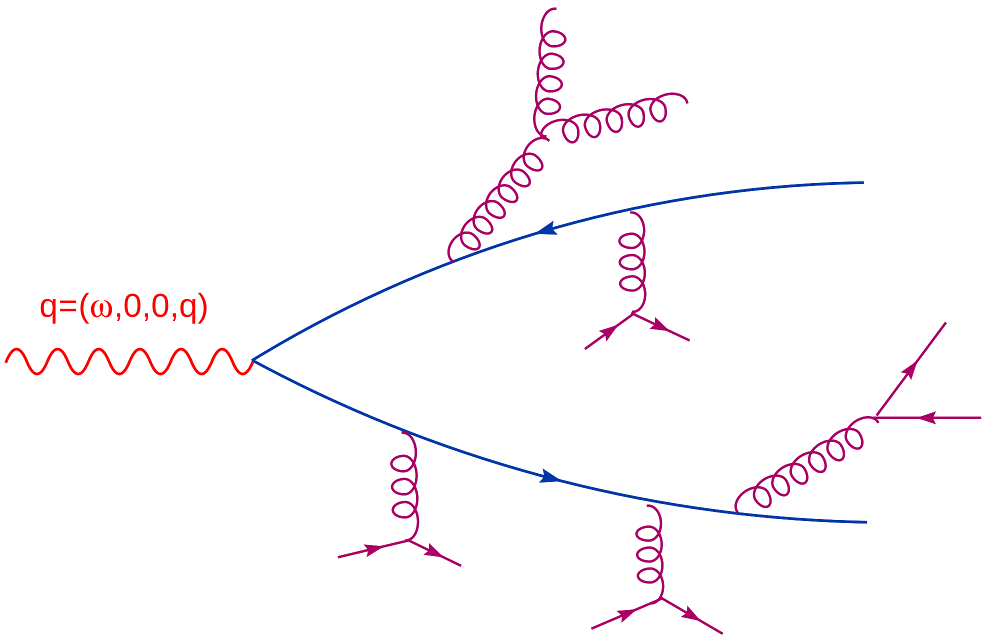


- By uncertainty principle, this has a transverse size $L \sim 1/Q$

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

Partonic fluctuation in the plasma

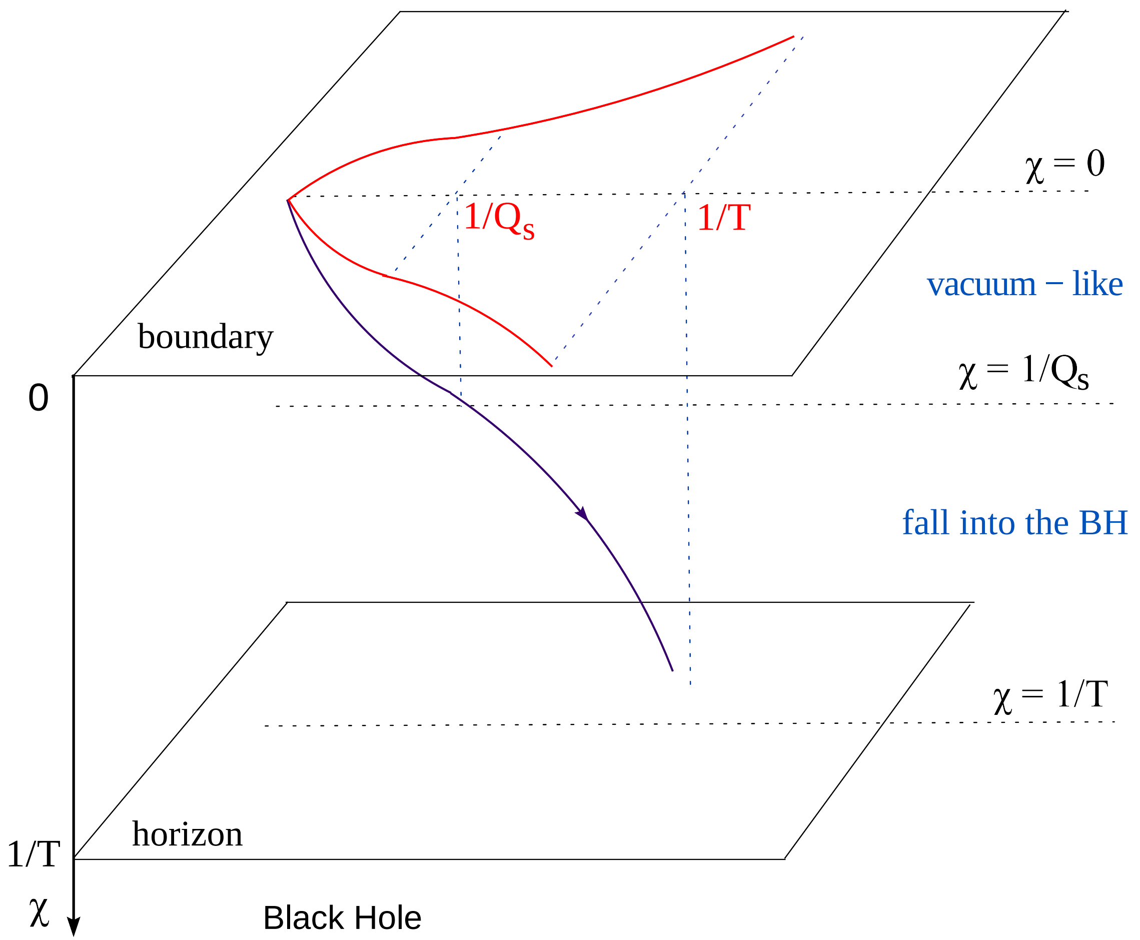
- The situation however changes at finite temperature



- 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

- 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

- 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

- 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

- 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

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

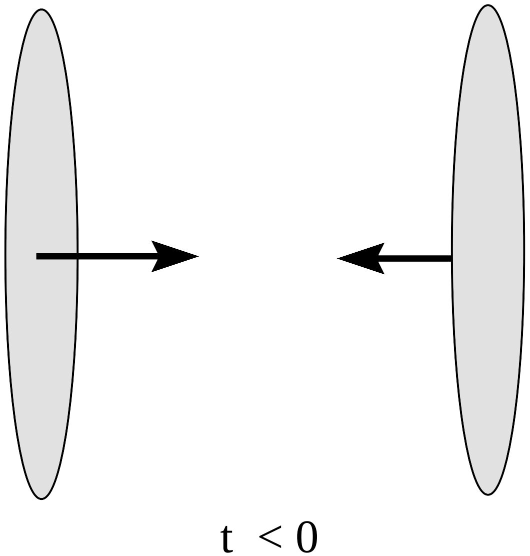
- $Q_s(x)$ plays the role of the plasma saturation momentum

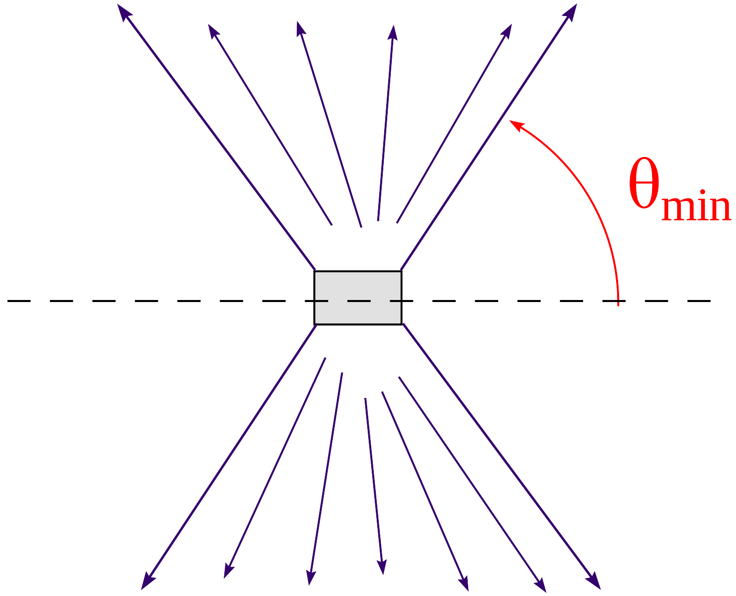
  (borderline between weak and respectively strong scattering)
- Recall: the parton picture involves 2 variables : x and Q^2

DIS at large x : No partons !

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

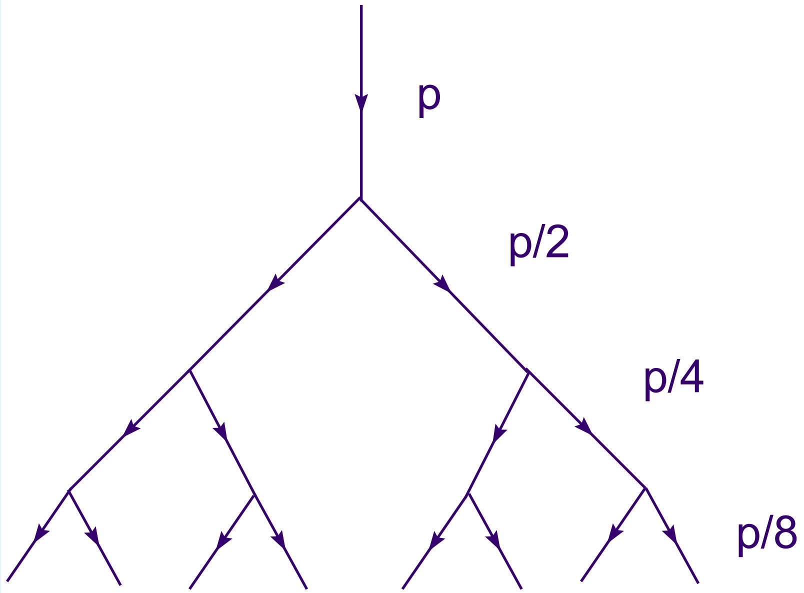
  $\Longrightarrow$ no partons with large momentum fractions $x > x_s$
- No forward/backward jets in hadron–hadron collisions !

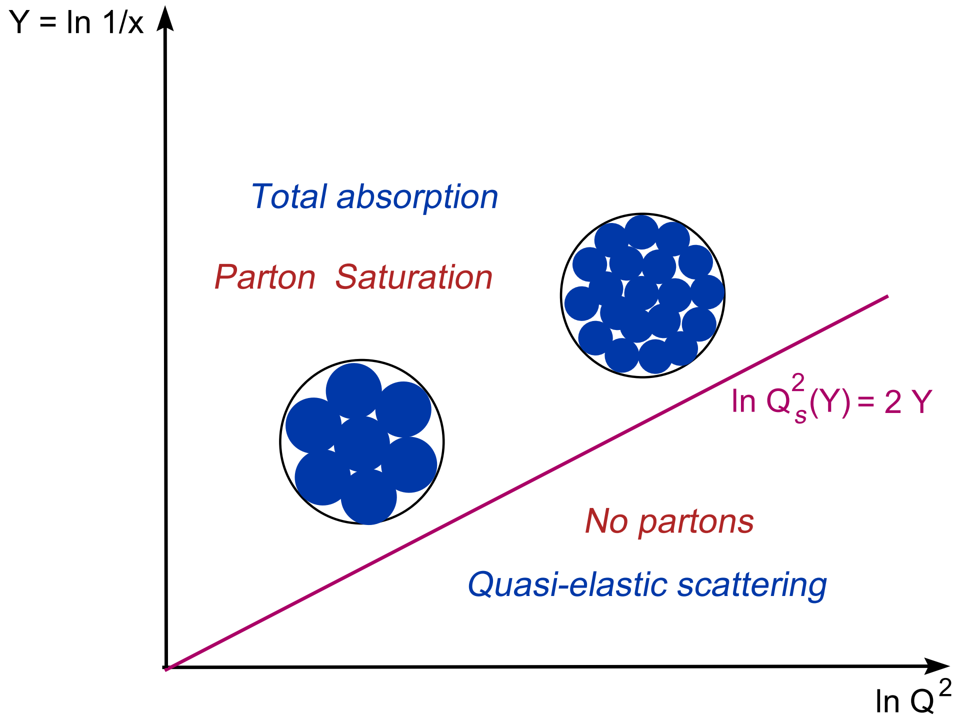




Low x : Parton saturation

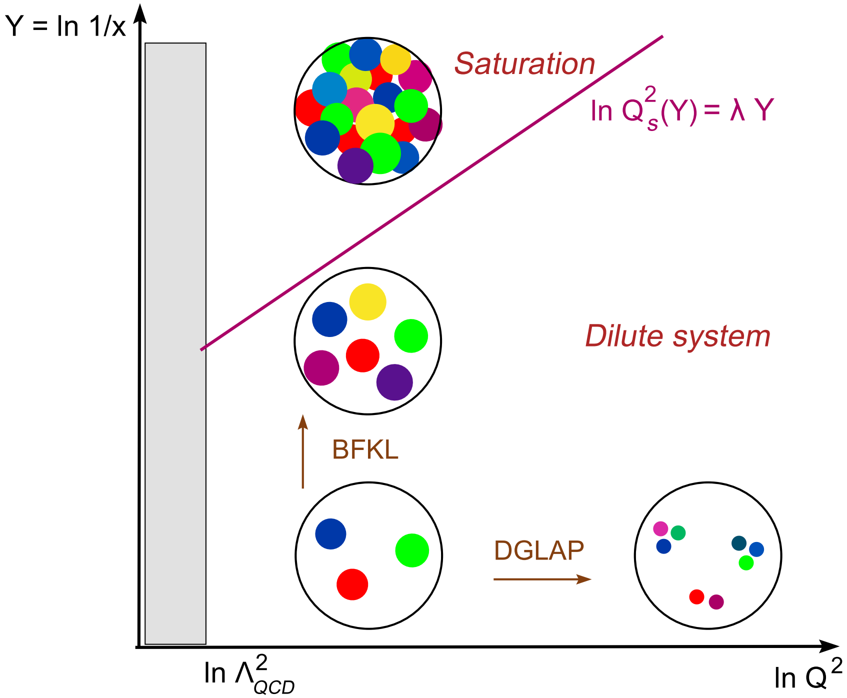
- $x \lesssim x_s = T/Q$: strong scattering $\Longrightarrow$ $F_2(x, Q^2) \sim xN_c^2 Q^2$
- Parton occupation numbers of $\mathcal{O}(1)$ $\Longrightarrow$ 'saturation' (CGC)
- Physical interpretation: 'Quasi–democratic' parton branching

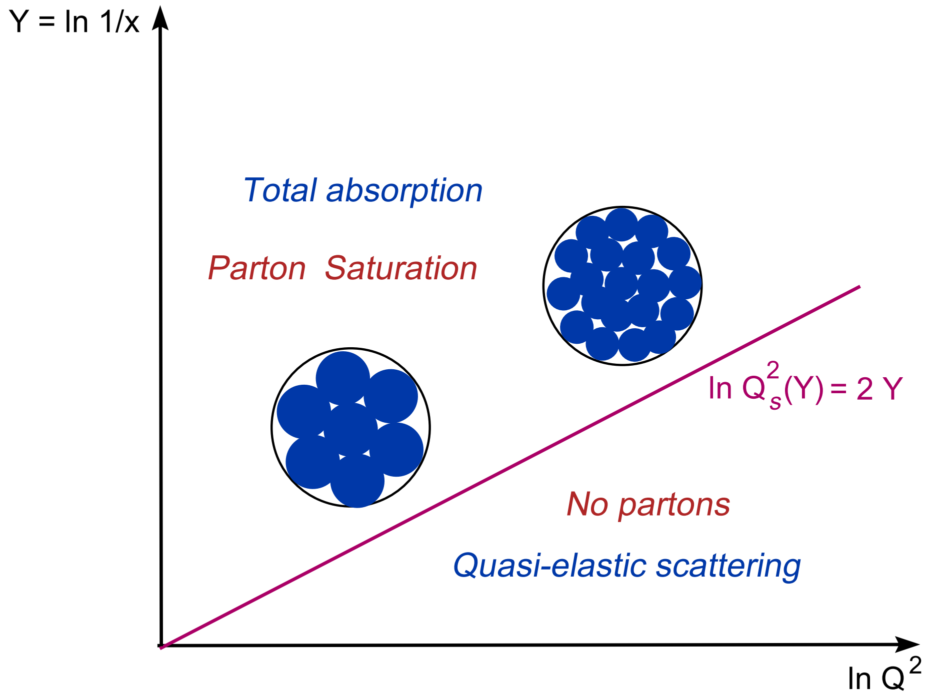




- All partons have branched down to small values of x !

Saturation line: weak vs. strong coupling

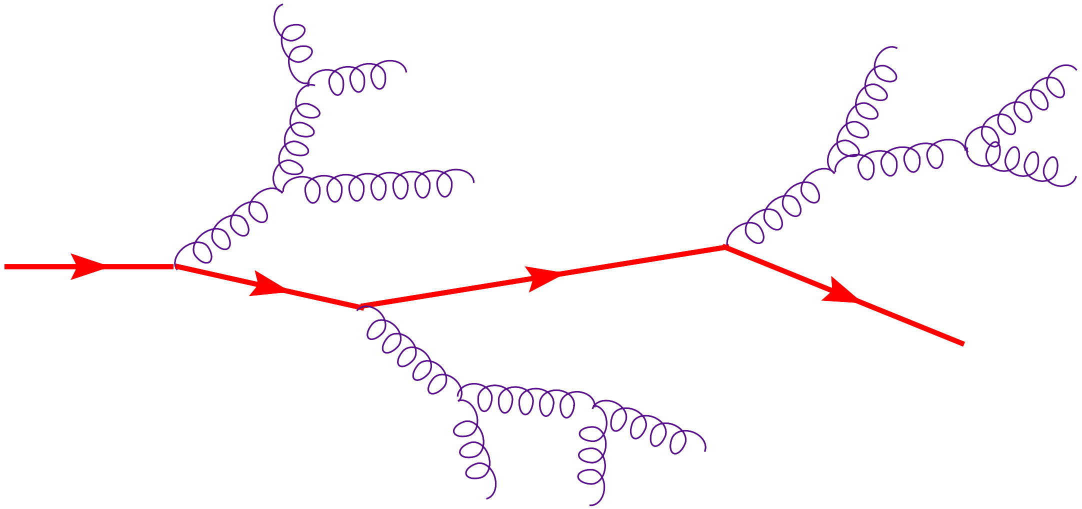




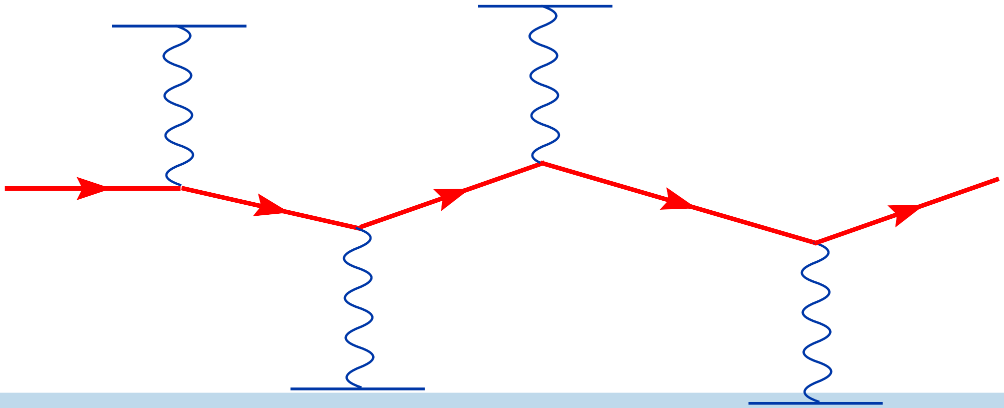
- Saturation exponent : $Q_s^2(x) \propto 1/x^{\lambda_s} \equiv e^{\lambda_s Y}$
  - weak coupling (LO pQCD): $\lambda_s \approx 0.12\, g^2 N_c$
  - phenomenology & NLO pQCD: $\lambda_s \approx 0.2 \div 0.3$
  - strong coupling (plasma): $\lambda_s = 2$ (graviton)

Jet quenching

- Strong coupling : medium induced parton branching

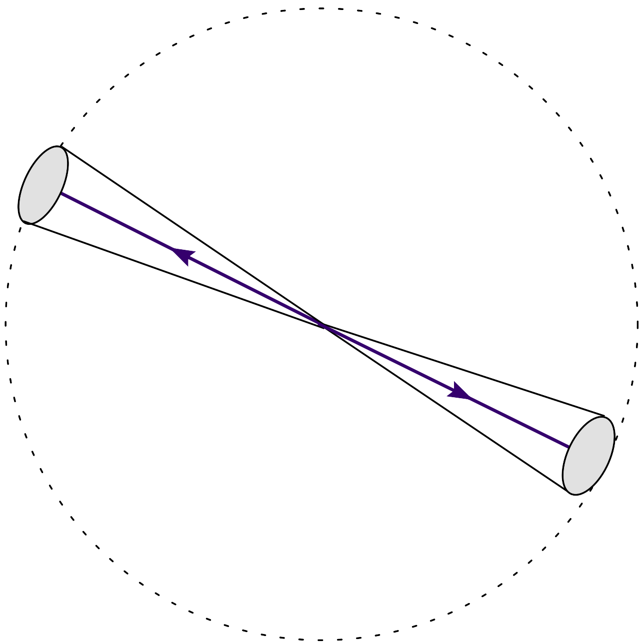


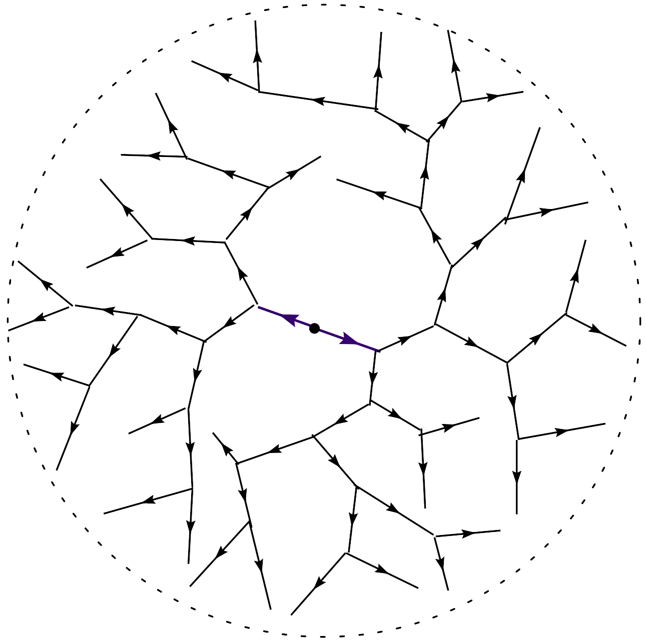
- pQCD : thermal rescattering (different physics !)



e^+e^- at strong coupling

- 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 !

Conclusions

- 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
- Not so surprising: by asymptotic freedom, hard & high–energy physics in QCD is weakly coupled
- Are AdS/CFT methods useless for HIC ? Not necessarily so !
  - some observables receive contributions from several scales, from soft to hard: use AdS/CFT in the soft sector
  - long–range properties (hydro, thermalization, etc) might be controlled by strong coupling

The 'perfect fluid'

- Uncertainty principle applied to viscosity:

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

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

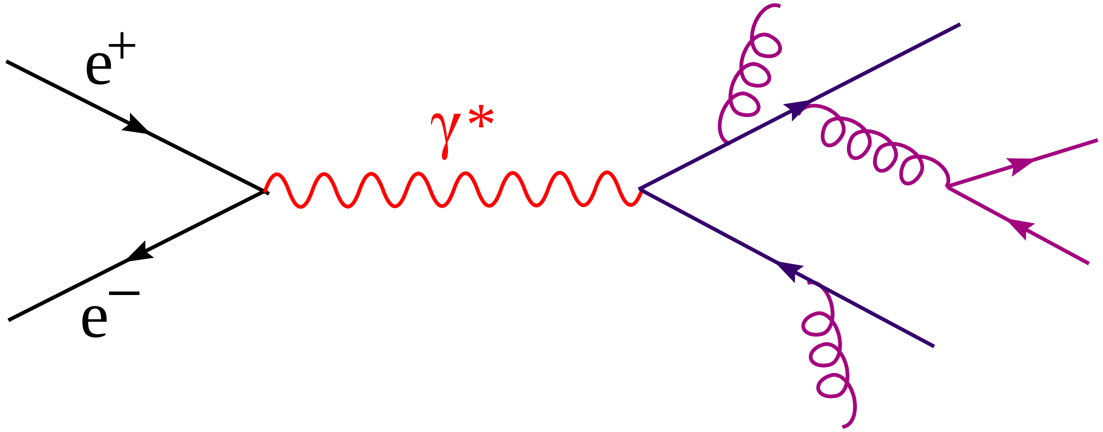
- Weakly interacting systems have $\eta/S \gg \hbar$
- Strongly coupled $\mathcal{N} = 4$ SYM plasma

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

(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'

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 !

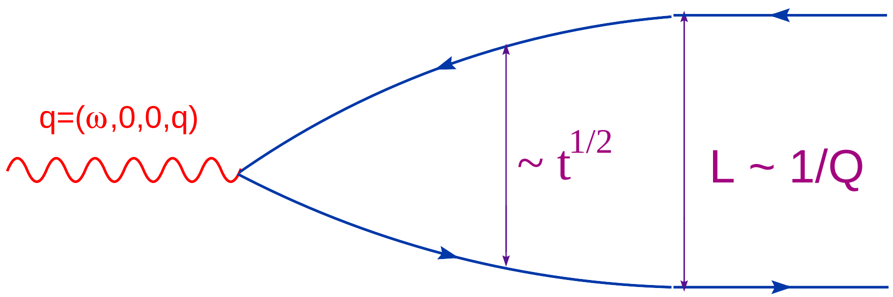
- ‘Intra–jet activity’ : collinear and/or soft gluons

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

modifies particle multiplicity but not the number of jets

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 !



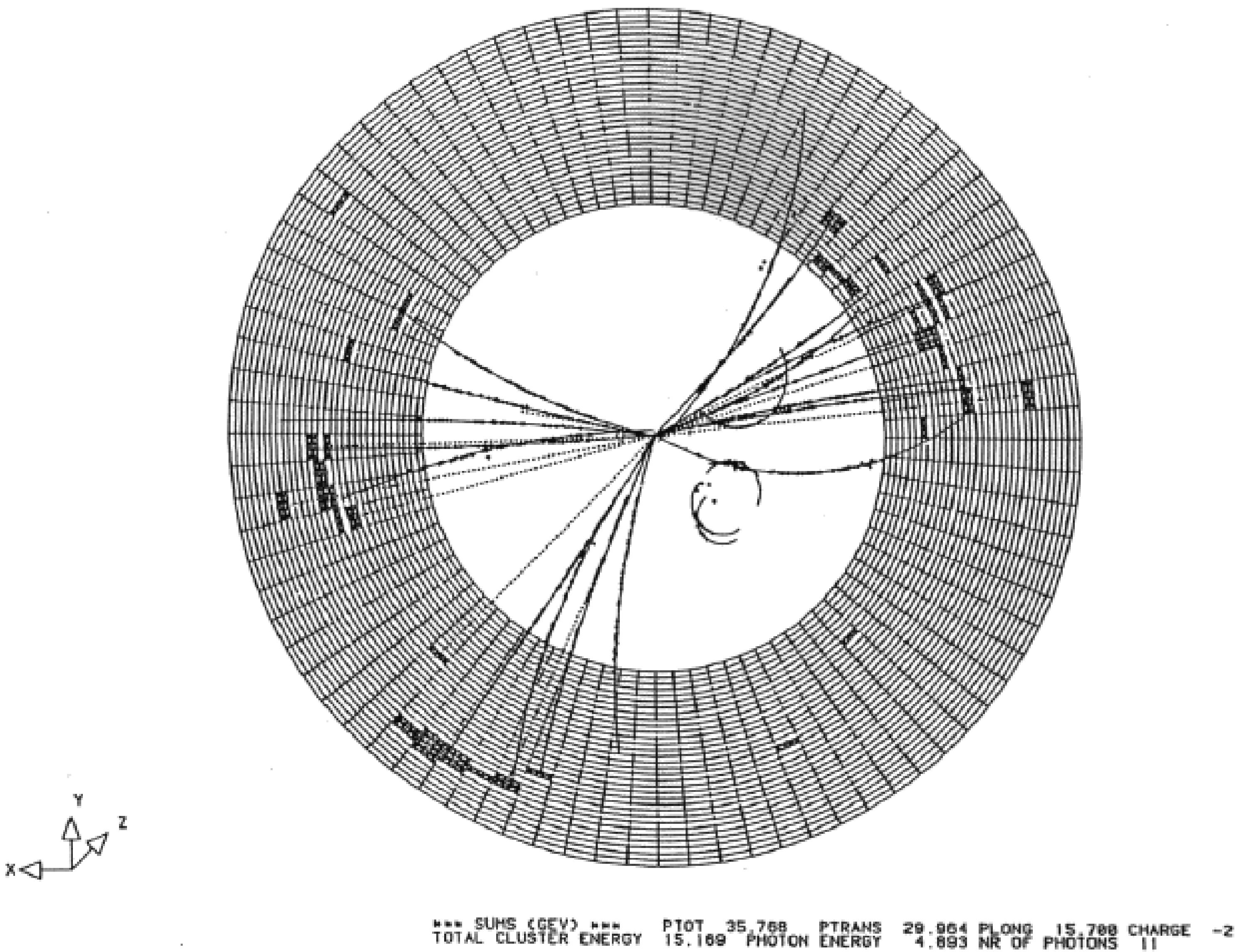
- Larger dipoles with $L \gtrsim 1/Q_s$ cannot survive in the plasma

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

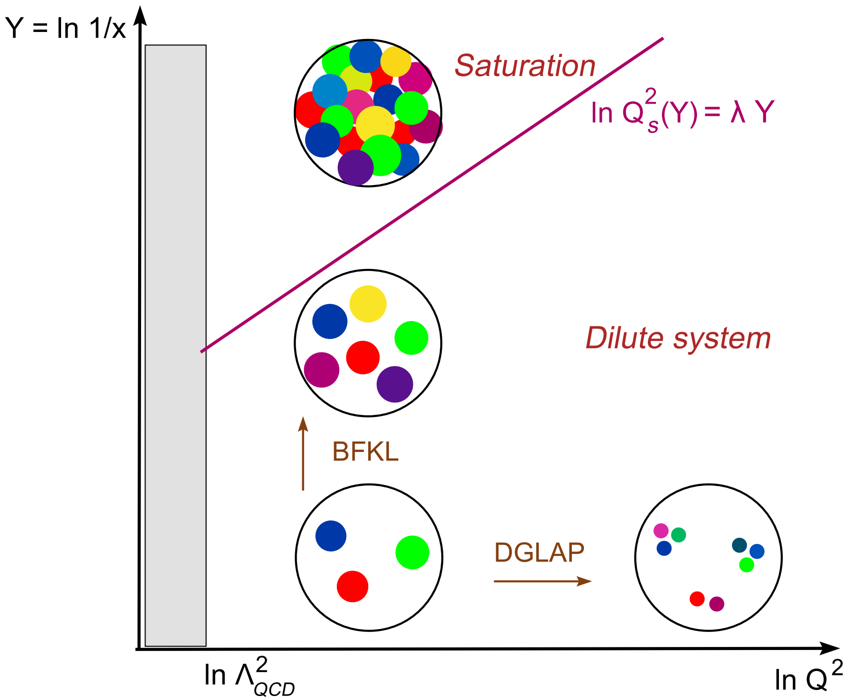
- The dipole lifetime is short on natural time scales:

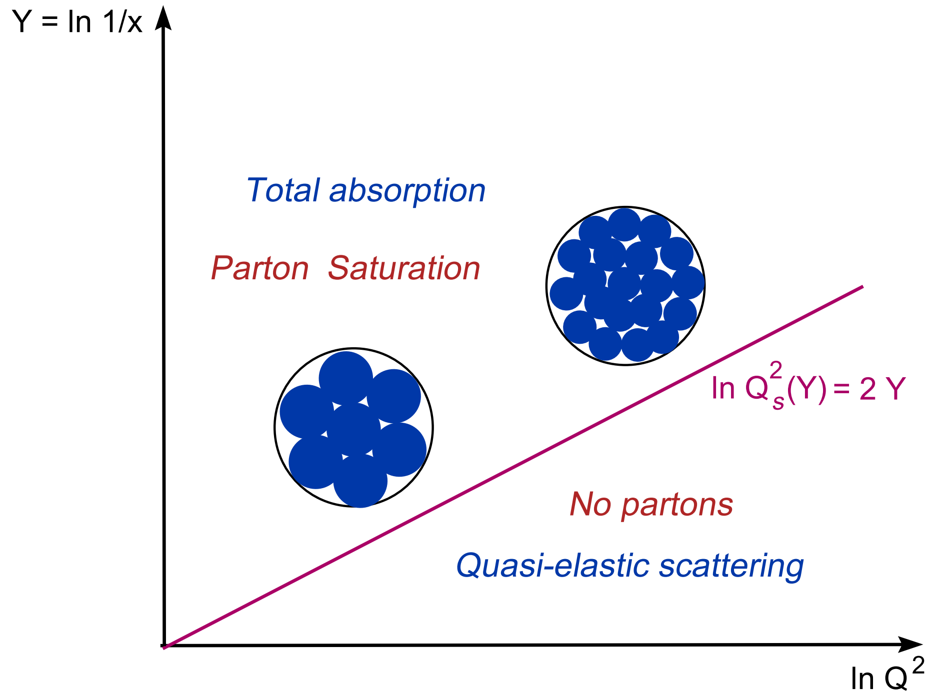
$$\Delta t \sim \frac{\omega}{Q_s^2} \sim \frac{\sqrt{\gamma}}{T} \ll \frac{\gamma}{T}$$

3–jet event at OPAL (CERN)



Saturation line: weak vs. strong coupling

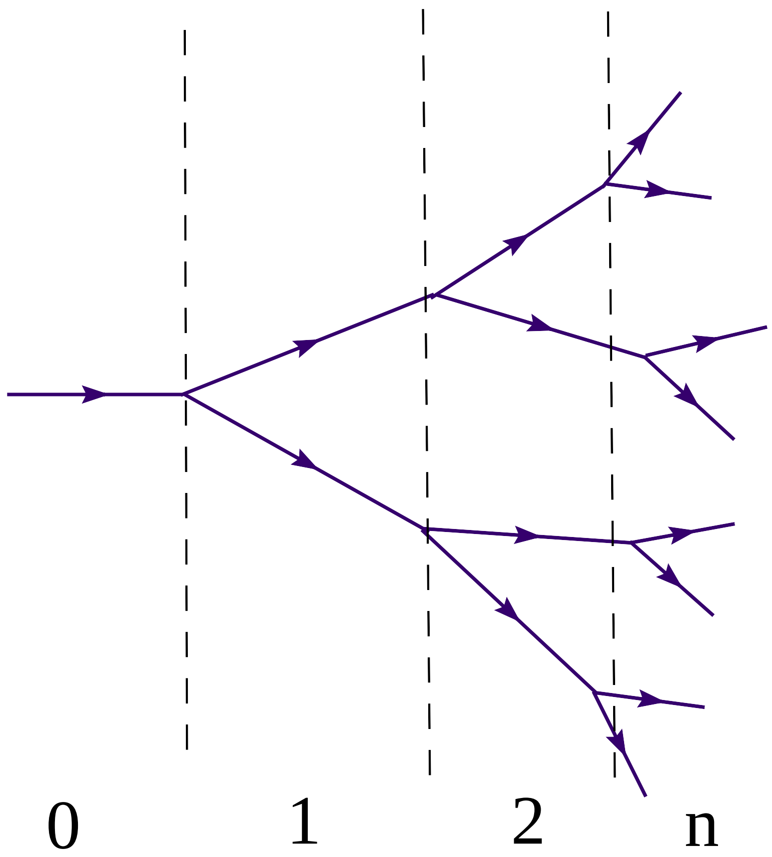




- Saturation exponent : $Q_s^2(x) \propto 1/x^{\lambda_s} \equiv e^{\lambda_s Y}$
  - weak coupling (LO BFKL): $\lambda_s \approx 1.23\, g^2 N_c$
  - phenomenology & NLO BFKL: $\lambda_s \approx 0.2 \div 0.3$
  - strong coupling (plasma): $\lambda_s = 2$ (graviton)
  - strong coupling (dilaton): $\lambda_s = 1$ (graviton)

Quasi–democratic parton branching

- No reason why branching should stop at 2 parton level !
- No reason to favour special corners of phase–space !



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

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

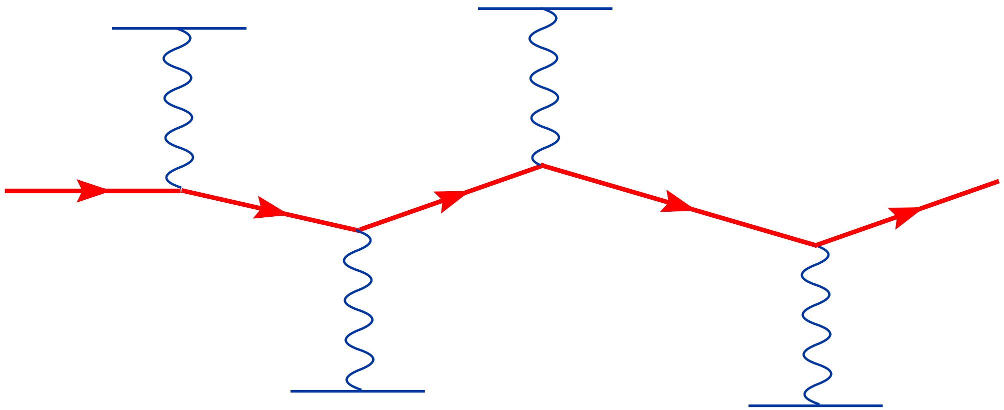
$$\Delta t_n \sim \frac{\omega_n}{Q_n^2}$$

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

- Qualitative agreement with all the results from AdS/CFT

Transverse momentum broadening

- A parton (say, heavy quark) undergoes multiple scattering (random kicks) off the plasma constituents



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

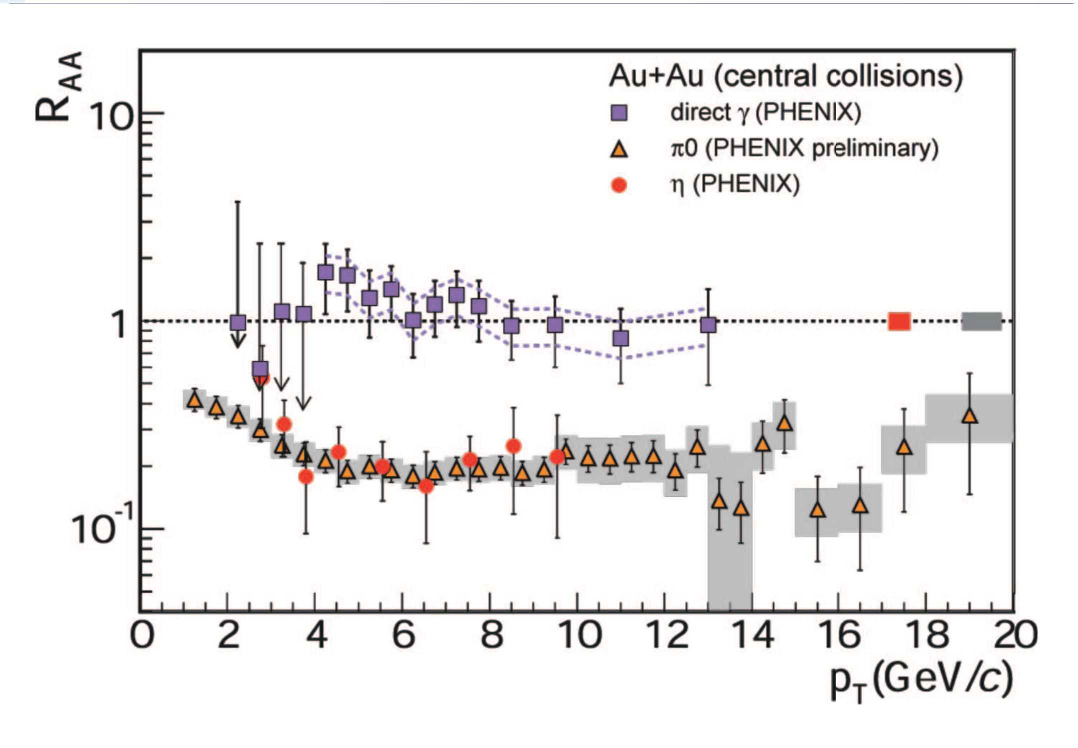
- $xg(x,Q^2)$: gluon distribution per unit volume in the medium
- Weakly–coupled QGP : incoherent sum of the gluon distributions produced by thermal quarks and gluons

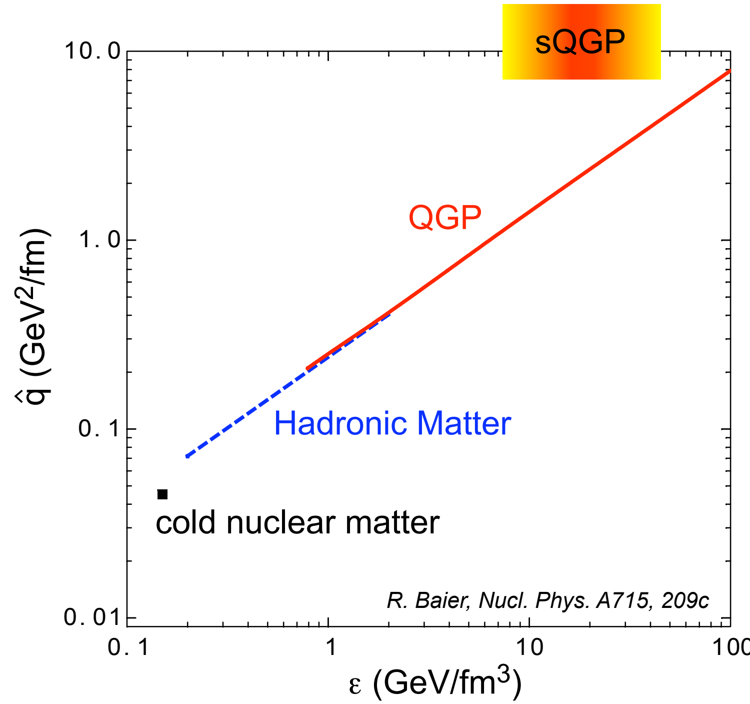
$$xg(x,Q^2) \simeq n_q(T)\, xG_q + n_g(T)\, xG_g\,, \quad \text{with} \quad n_{q,g}(T) \propto T^3$$

Nuclear modification factor

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

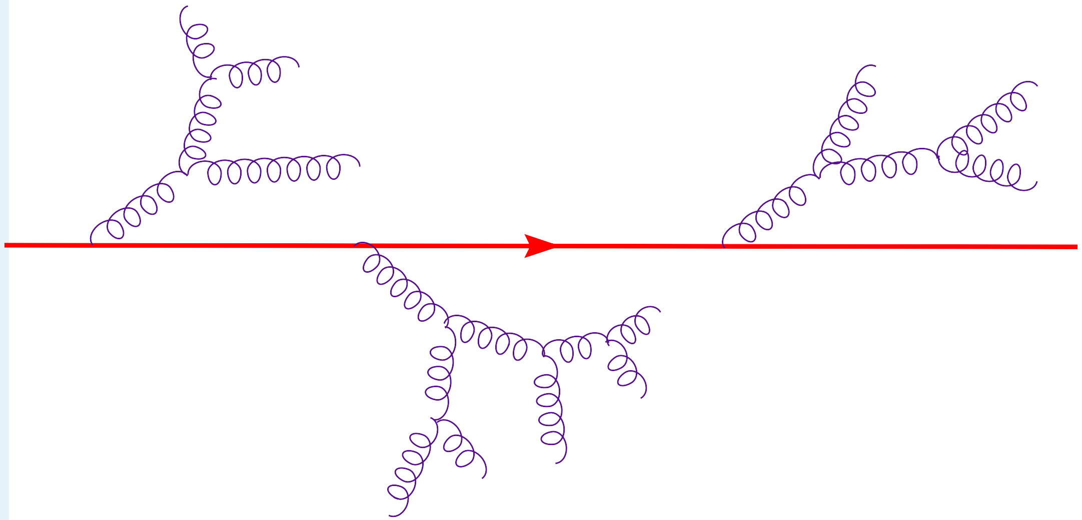
$$R_{AA}(p_\perp) \equiv \frac{Yield(A+A)}{Yield(p+p)\,\times\,A^2}$$





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

Heavy Quark: Energy loss

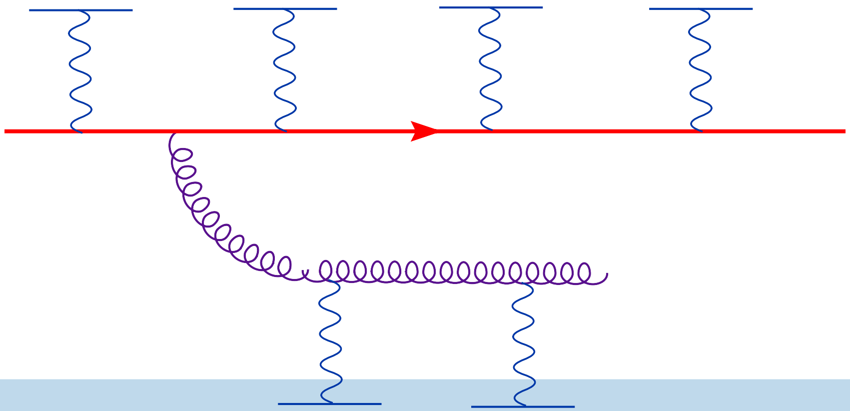


$$Q_s^2 \sim \left(t_{\rm br} T^2\right)^2 \sim \gamma T^2$$

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

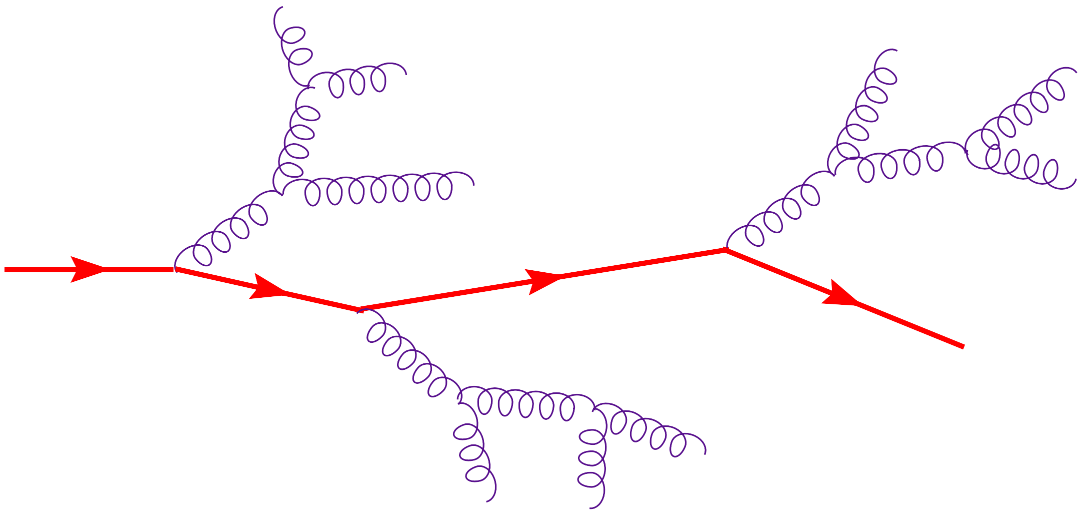
(Herzog et al; Gubser, 2006)

- pQCD : same formula, but with $\sqrt{\lambda} \rightarrow g^2 N_c$ and different Q_s



$$Q_s^2 \sim t_{\rm br}\,\hat{q}$$ (quenching param.)

Transverse momentum broadening

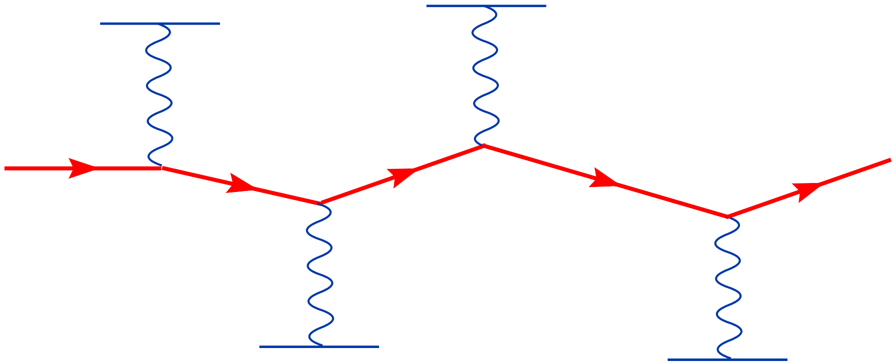


$$\frac{\mathrm{d}p_\perp^2}{\mathrm{d}t} \sim \sqrt{\lambda}\, T^2 Q_s$$

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

see talks by Al Mueller and Cyrille Marquet

- pQCD : different physics ! thermal rescattering



$$\frac{\mathrm{d}p_\perp^2}{\mathrm{d}t} \sim \hat{q}$$