AdS/CFT for Heavy Ion Collisions

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  - tailored for the strong coupling limit of conformal theories
  - physical guidance for well chosen problems in QCD

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- AdS/CFT : a coherent framework from first–principles
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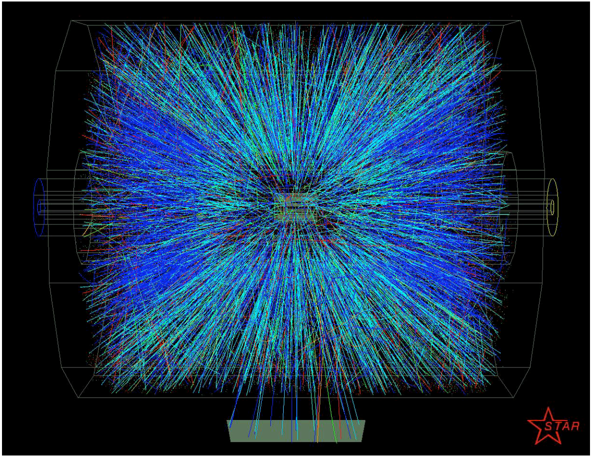
  - physical guidance for well chosen problems in QCD
- A fascinating field by itself : unexpected and potentially deep connections between different areas of physics
  QFT, string theory, gravity, hydrodynamics...

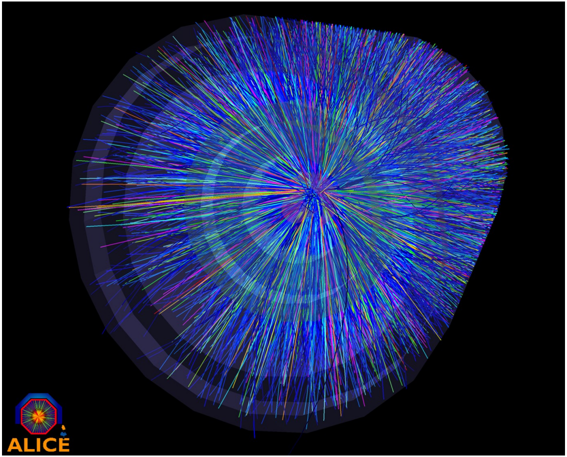
Heavy Ion Collisions @ RHIC & LHC

Hadron production in HIC



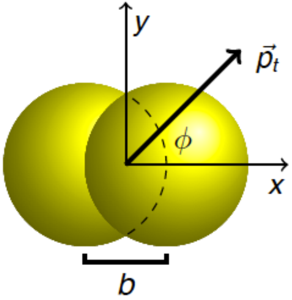
- Au+Au collisions at RHIC: ~ 3000 hadrons in the final state !
- Particle correlations are essential to disentangle phenomena

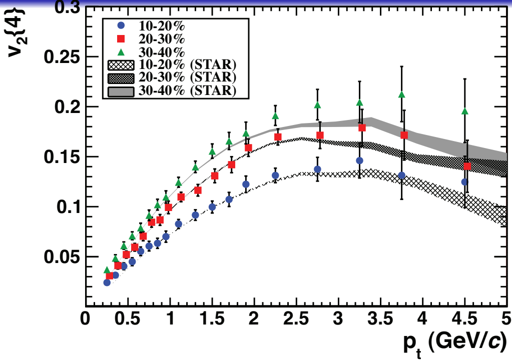
Hadron production in HIC



- Pb+Pb collisions at LHC: ~ 1600 hadrons at central rapidity !
- Particle correlations are essential to disentangle phenomena

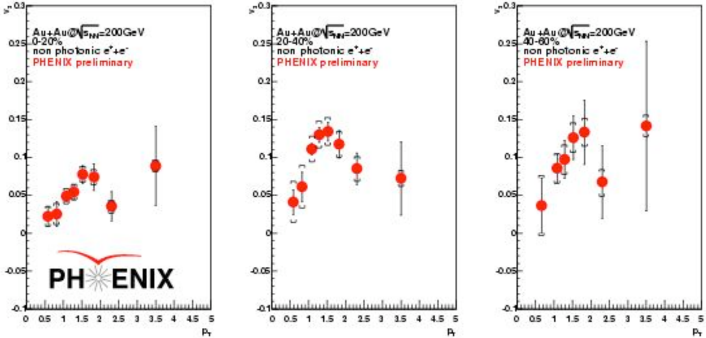
Elliptic flow v_2 *(cf. talks by Bailhache, Luzum, Mota, Beraudo)*





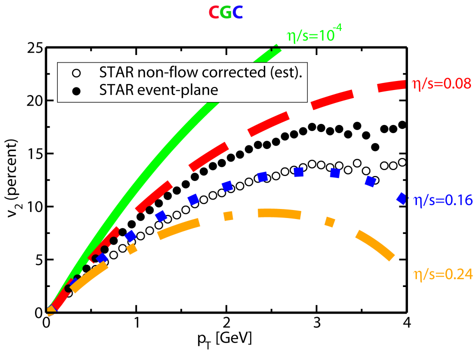
- Non–central AA collision: Particle distribution is not axially symmetric : $\mathrm{d}N/\mathrm{d}\phi \propto 1 + 2v_2 \cos 2\phi$ ($v_2 = 0$ for 'dust')
- RHIC & LHC find a very large v_2. Natural for a liquid : Pressure gradient is larger along the smaller axis (x)

Elliptic flow for heavy quarks



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

Hydro simulations for v_2 *(Luzum and Romatschke, 08)*



- A good hydro description of the data requires :
  - a very short equilibration (isotropisation ?) time $\tau_{eq} \lesssim 1$ fm/c
  - a very small viscosity/entropy ratio $\eta/s \sim 0.1$
- The hallmarks of a system with strong interactions !
  - η is proportional to the mean free path $\ell \propto 1/\sigma \sim 1/g^4$

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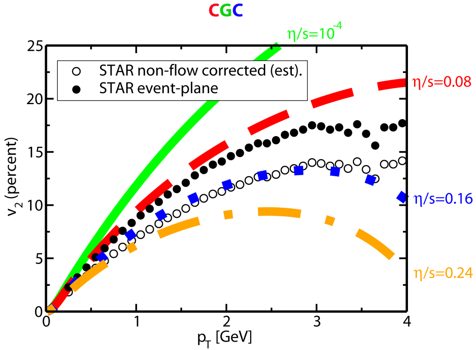
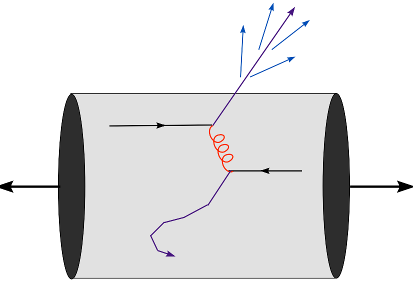


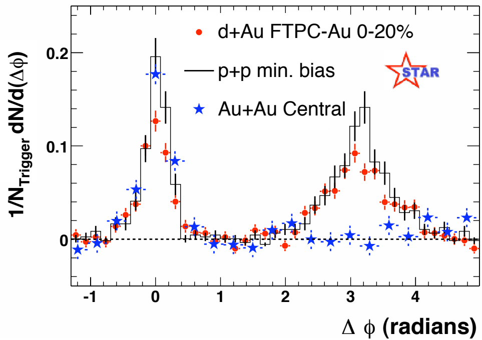
- AdS/CFT prediction for $\mathcal{N} = 4$ SYM at strong coupling *(Policastro, Son, Starinets, 2001)*

$$\eta/s \;\rightarrow\; 1/4\pi \quad \text{when} \quad \lambda \equiv g^2 N_c \;\rightarrow\; \infty$$

- *"strongly–coupled quark–gluon plasma"* or *"perfect fluid"*

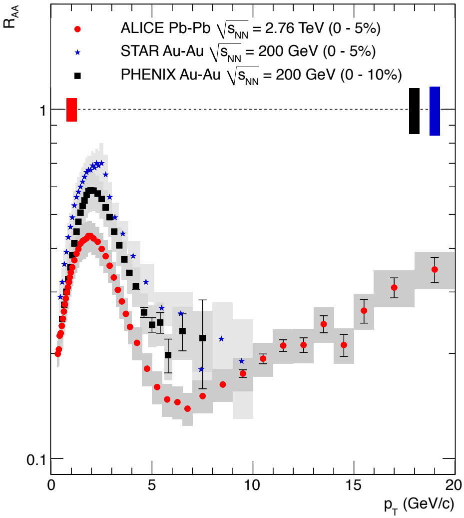
Jet ‘quenching’ in nucleus–nucleus collisions





- 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

How to measure jet quenching ? *(cf. talk by Bailhache)*

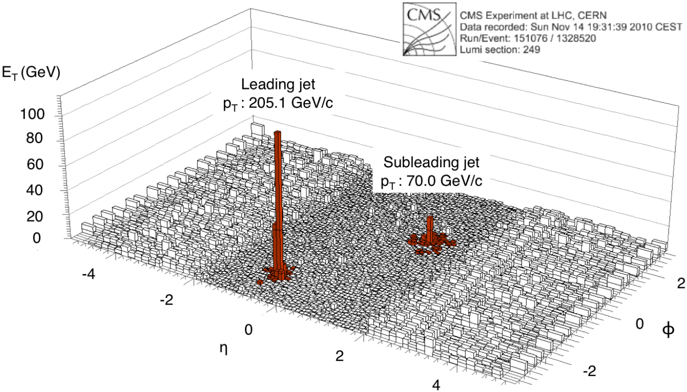


- Nuclear modification factor

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

- $R_{AA} \simeq 0.15$ at the LHC
- This seems hard to understand at weak coupling

ATLAS & CMS *(cf. talks by Newman & Bora)*



- How to explain the medium broadening of a ... 200 GeV jet ??
- Scenarios for jet quenching at weak coupling

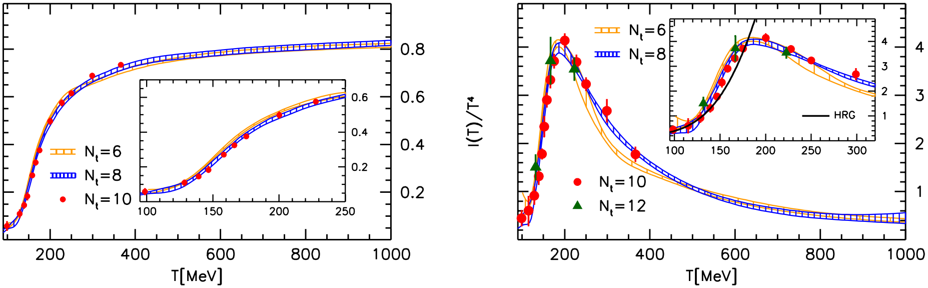
  cf. the talks by Y. Mehtar-Tani and J. Casalderrey–Solana

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

- A 'duality' (equivalence) between 2 very different theories
- A supersymmetric gauge theory in $D = 3 + 1$ ($\mathcal{N} = 4$ SYM)
  - SU(N_c), conformal invariance, fixed coupling, no confinement
- A string theory in $D = 9 + 1$ (type IIB in $AdS_5 \times S^5$)
- Strong 't Hooft coupling limit : $\lambda \equiv g^2 N_c \gg 1$ & $g^2 \ll 1$

  $\Longleftrightarrow$ Semiclassical limit of the string theory ('supergravity')
  - no string loops, no internal string excitations
- $\mathcal{N} = 4$ SYM at finite temperature $\Longrightarrow$ Black Hole in AdS_5
  - a Black Hole has entropy and thermal (Hawking) radiation

Finite T lattice QCD *(cf. talk by Fodor)*



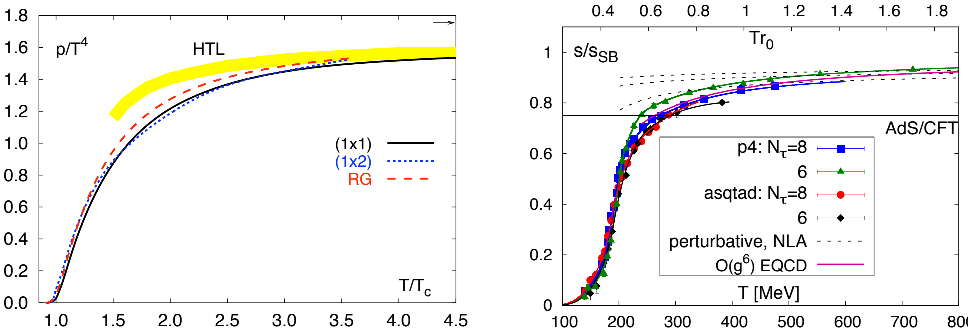
- $\alpha_s \approx 0.3 \implies g \approx 2 \implies \lambda \equiv g^2 N_c \simeq 10$

trace anomaly : $\beta(g)\,\dfrac{\mathrm{d}p}{\mathrm{d}g} = \langle T^\mu_\mu \rangle = \mathcal{E} - 3p$

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

$\Longrightarrow$ nearly conformal, rather strongly coupled

Lattice QCD: weak or strong coupling ?



- For $T \gtrsim 2.5 T_c$, lattice results are well reproduced by resummed perturbation theory! *(cf. talks by Blaizot and Vuorinen)*

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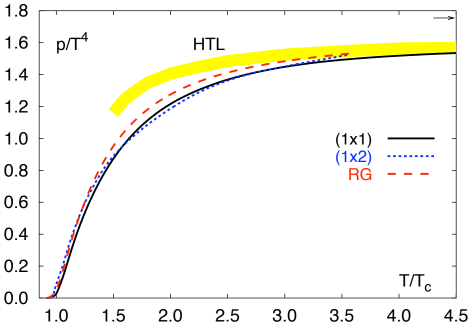

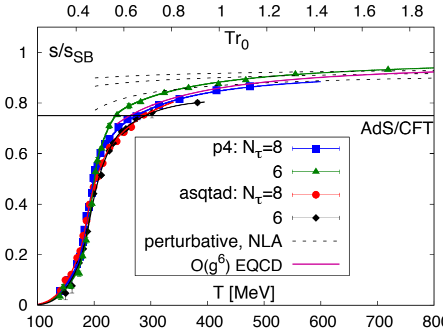

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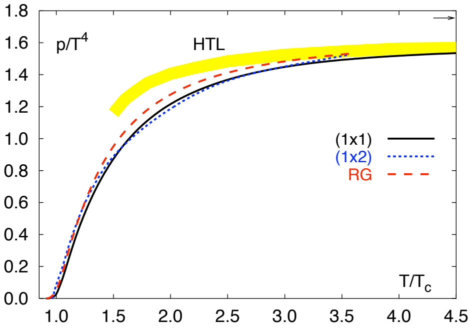

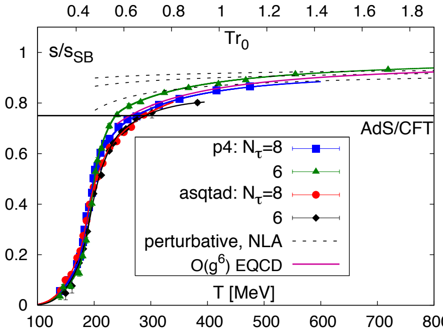

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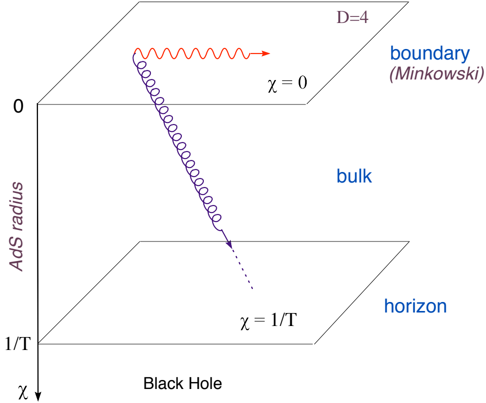
- ... but AdS/CFT is not very far away either : $s/s_0 = 3/4$
- Very soft modes ($k \sim g^2 T$) are anyway strongly coupled and they seem to significantly contribute to the pressure.

AdS_5 Black Hole space–time

- AdS_5 : our Minkowski world $\times$ a 'radial' dimension χ

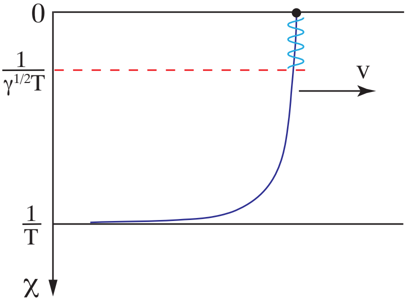
- 'radial', or '5th', coordinate :
  $0 \leq \chi < \infty$
- the gauge theory lives at the
  Minkowski boundary $\chi = 0$
- finite temperature T:
  black hole horizon at $\chi = 1/T$



$$S_{\rm BH} = \frac{\text{Horizon area}}{4G_{10}} \Longrightarrow s \equiv \frac{S_{\rm BH}}{V_{3D}} = \frac{\pi^2}{2} N_c^2 T^3 = \frac{3}{4}\, s_0$$

Heavy Quark in a strongly–coupled plasma

- Physical sources on the boundary (*i.e.* in the gauge theory) act as perturbations of the bulk
- Heavy quark in 4D $\longleftrightarrow$ 'Trailing string' in AdS_5 BH
- Energy loss $\mathrm{d}E/\mathrm{d}t$ $\longleftrightarrow$ Energy flux down the string



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

Casalderrey–Solana, Teaney (2006); Giecold, E.I., Al Mueller (2009)

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

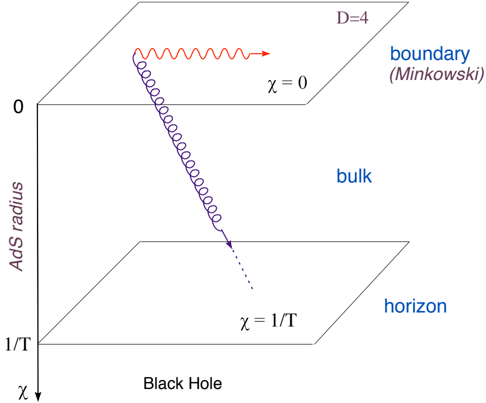
- Deep inelastic scattering or e^+e^- annihilation: virtual photon
- E.m. current J^μ_{em} in 4D $\longleftrightarrow$ Maxwell wave A_μ in AdS$_5$ BH
- DIS cross section $\longleftrightarrow$ absorption of the wave by BH

- Maxwell equations in AdS$_5$ BH

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

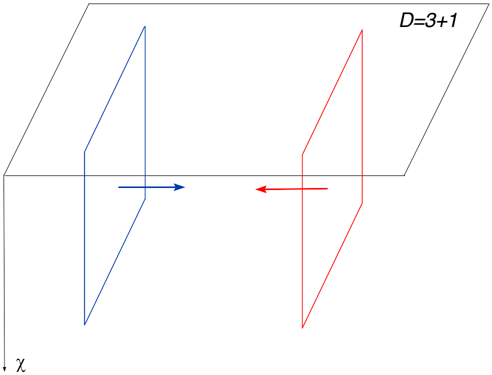
$$F_{mn} = \partial_m A_n - \partial_n A_m$$

- BH is implicit in the metric g^{mn}
- No explicit coupling



Heavy Ion Collisions

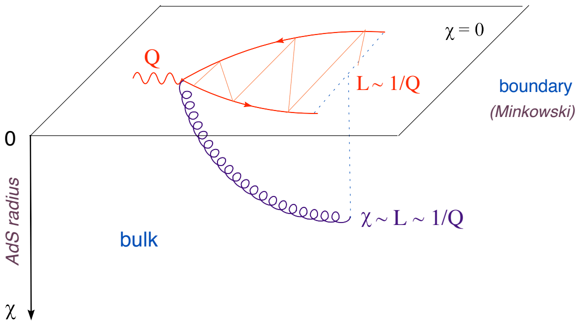
- Ultrarelativistic Heavy Ion Collision in 4D $\longleftrightarrow$
  The scattering between two gravitational shock–waves in AdS_5



- Thermalization $\longleftrightarrow$ Formation of a BH horizon

The UV/IR correspondence (or 'holographic principle')

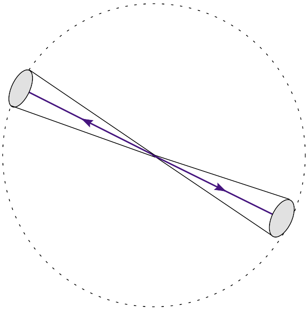
- The 5th dimension plays the rôle of the quantum virtuality



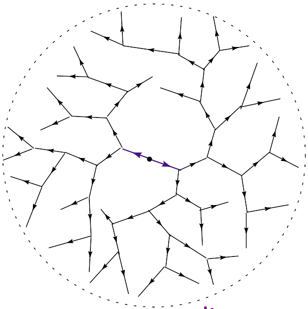
- Radial penetration χ of the space–like 'photon' in AdS_5 $\longleftrightarrow$ transverse size $L \sim 1/Q$ of the partonic fluctuation
- Allows for the physical interpretation of the results.

No jets at strong coupling !

- e^+e^- annihilation in center of mass frame (time-like photon)



weak coupling



strong coupling

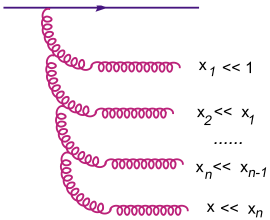
- Weak coupling: a pair of back-to-back jets.
- Strong coupling: isotropic distribution of many soft hadrons
- Quasi-democratic parton branching: $\omega_n \approx \frac{\omega_{n-1}}{2}$, $Q_n \approx \frac{Q_{n-1}}{2}$

No partons with large x

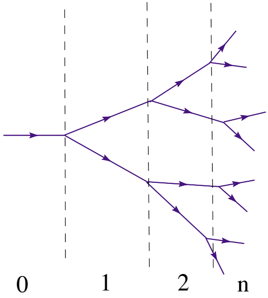
- $x \equiv p_z/P$: longitudinal momentum fraction of a parton

- Weak coupling: Bremsstrahlung

$\Longrightarrow$ soft & collinear emissions



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



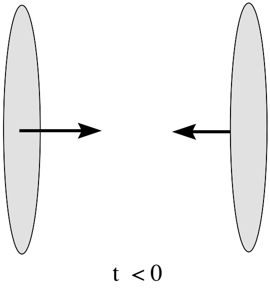
- Weak coupling: the energy is carried by partons with $x \sim 1$

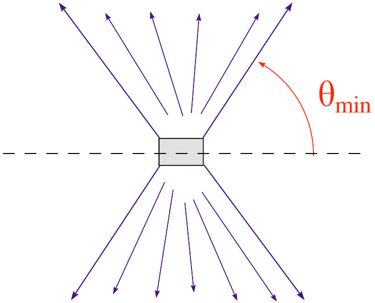
$\Longrightarrow$ valence quarks, pointlike constituents, hard scattering

- Strong coupling: 'hadron' = a jelly of soft partons

No forward/backward jets !

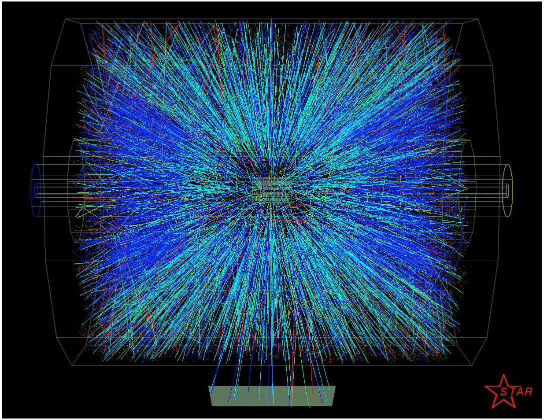
- No large–x partons $\Longrightarrow$ no forward/backward particles (no particle production close to the collision axis)





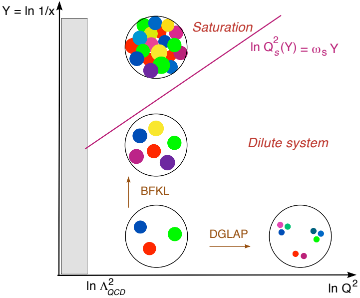
- Forward particles are beam remnants (partons) with large x
- This is of course contradicted by the RHIC and LHC data !

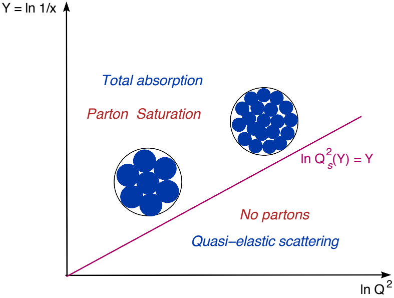
Partons at RHIC



- Central rapidity: small–x partons
- Forward/backward rapidities: large–x partons

Parton saturation: weak vs. strong coupling

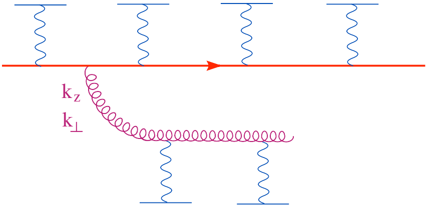


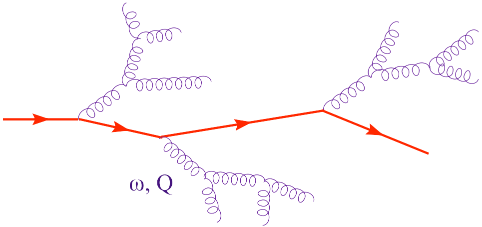


- Weak coupling : $Q_s^2(x) \propto 1/x^{0.3}$
  - $Q > Q_s(x)$: 'leading–twist' pdf
  - $Q < Q_s(x)$: $n \sim 1/\alpha_s$ (CGC)
- Strong coupling : $Q_s^2(x) \propto 1/x$
  - $Q > Q_s(x)$: no partons
  - $Q < Q_s(x)$: $n \sim 1$

Heavy Quark in a strongly–coupled plasma

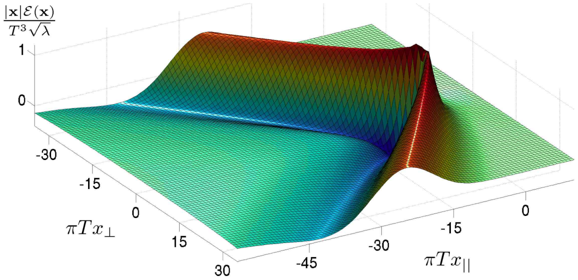
- Heavy quark ($M \gg T$): medium–induced radiation





- Weak coupling: thermal rescattering
- Strong coupling: medium induced parton branching
  (there are no plasma constituents to scatter off !)
- Plasma acts on partons with a tidal force which splits them apart $\Longrightarrow$ gravity out of the gauge interactions !

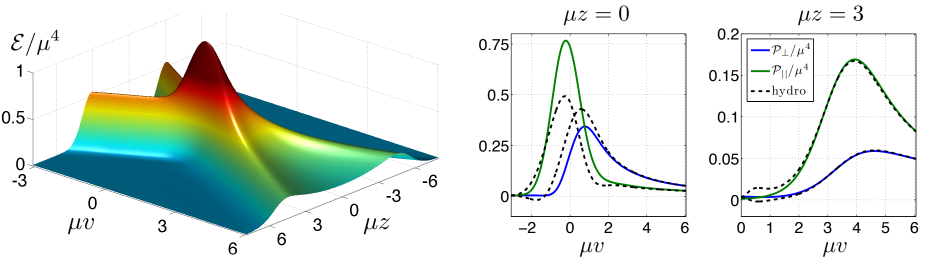
Energy distribution on the boundary



- Energy is transferred from the heavy quark to the plasma
- If the quark velocity is larger than the speed of sound ($c_s = 1/3$) $\implies$ Mach cone *(Chesler and Yaffe, 2007)*
- The experimental evidence at RHIC is still under debate

Thermalization from shock–wave scattering

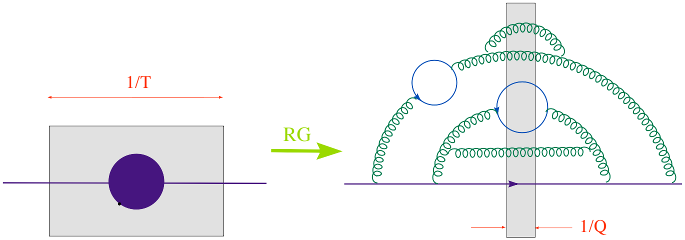
(Chesler and Yaffe, 2010)



- The remnants of the two shock waves move away from each other, but with velocities $v < 1$
- The pressure shows isotropisation

Instead of conclusions: Why gravity ?

- Why should gravity describe gauge theory at strong coupling ?
- OPE for DIS: Partons $\longleftrightarrow$ 'twist–2' operators
- The operators depend upon the resolution scale



- $\lambda \to \infty$: rapid evolution $\Rightarrow$ all operators are suppressed
- ... with one exception: the energy momentum tensor $T^{\mu\nu}$

$\Longrightarrow$ the effective theory for scattering must be gravity !