QCD in Heavy Ion Collisions

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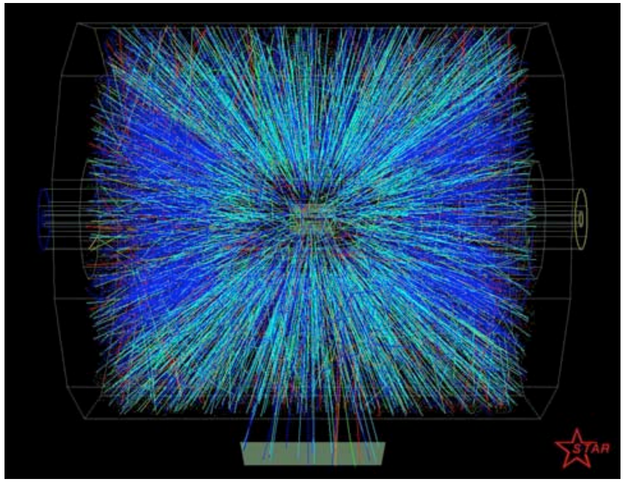
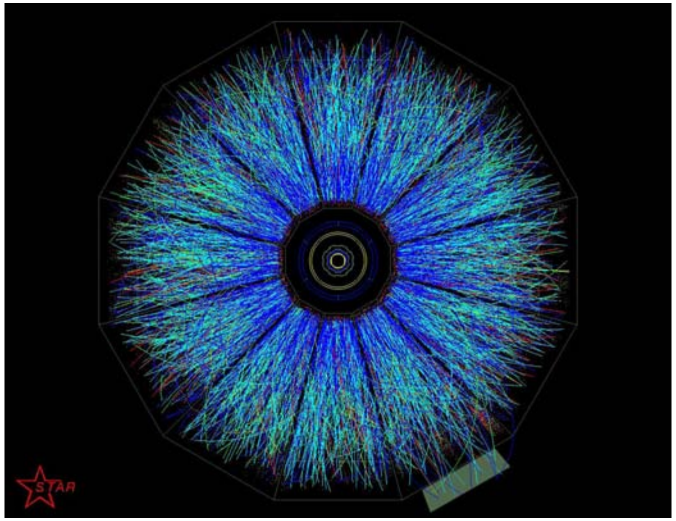
Heavy Ion Collisions @ RHIC & the LHC

Au+Au collisions at RHIC



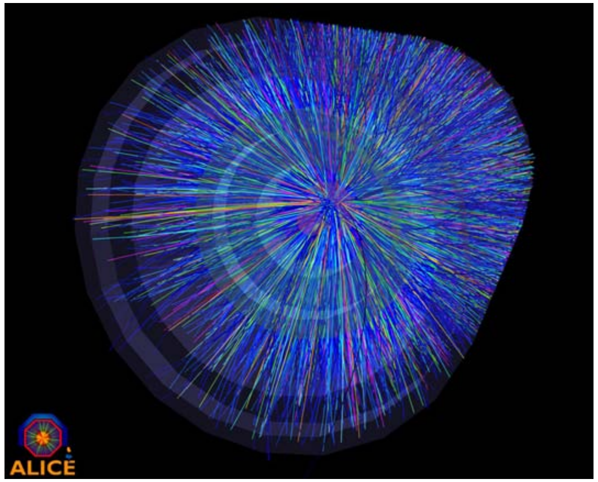
- Au+Au collision at STAR: longitudinal projection
- $\sim$ 3000 produced particles streaming into the detector

Au+Au collisions at RHIC



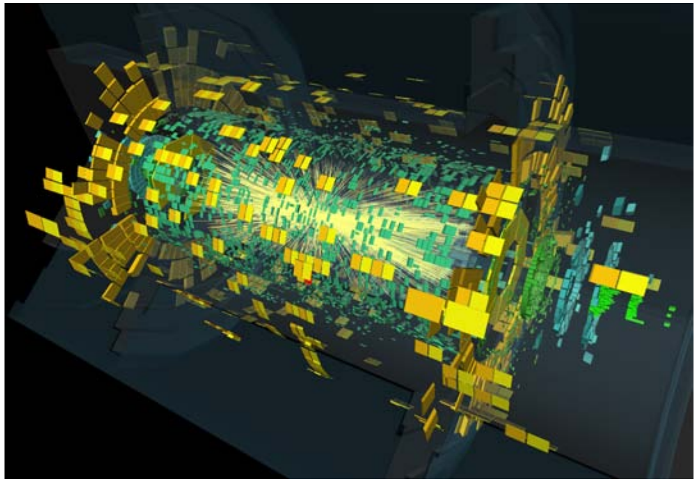
- Au+Au collision at STAR: transverse projection

Pb+Pb collisions at the LHC: ALICE



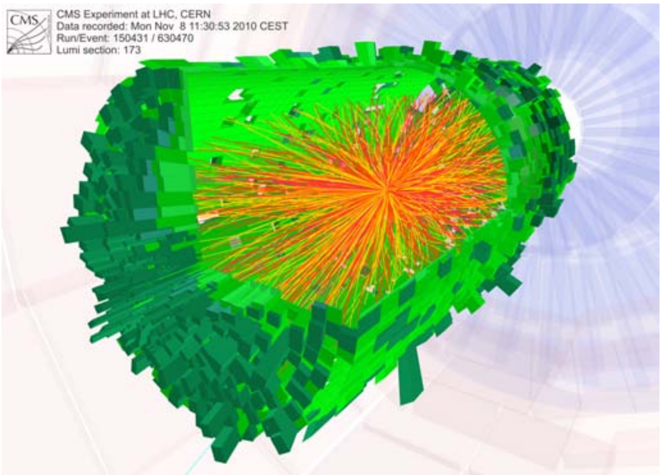
- Pb+Pb collision at ALICE: ~ 1600 hadrons per unit rapidity
- How to describe/understand such a complex system ?

Pb+Pb collisions at the LHC: ATLAS



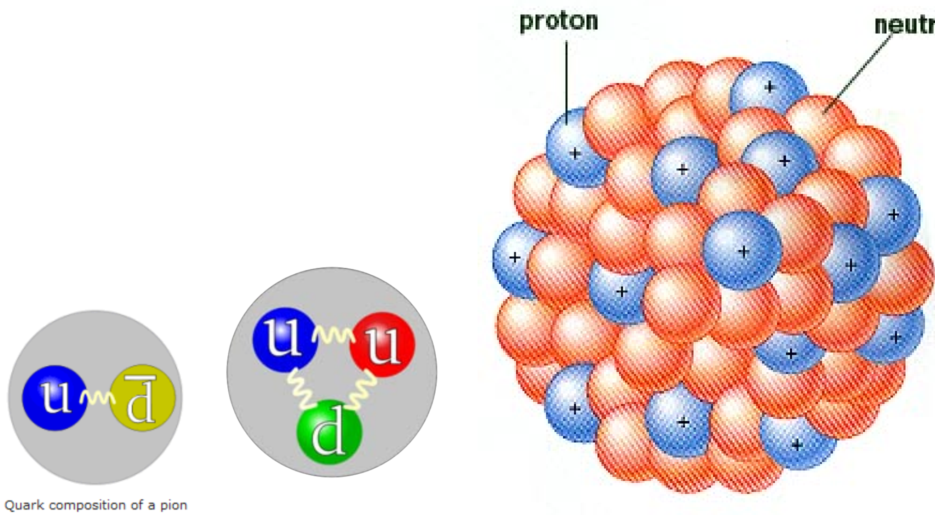
- Traditional perturbative methods become inappropriate (collective phenomena, multiple scattering ...)

Pb+Pb collisions at the LHC: CMS



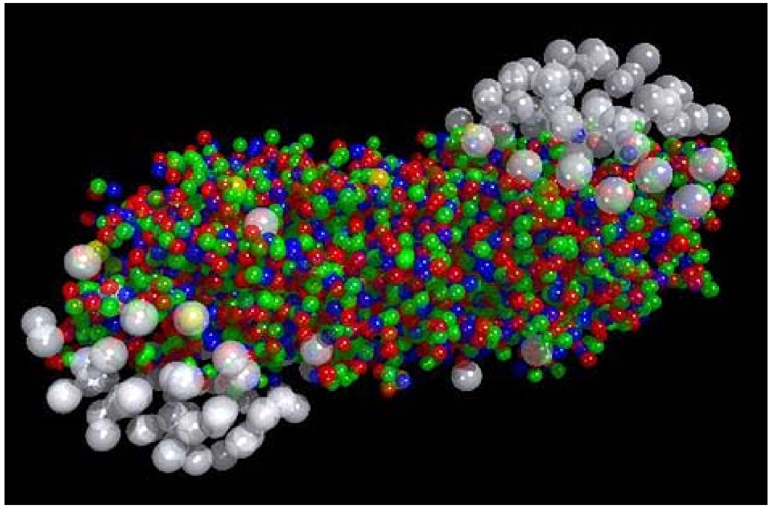
- The concept of particle is not so useful anymore ...
- One should rather speak about QCD matter

QCD matter: from hadrons ...



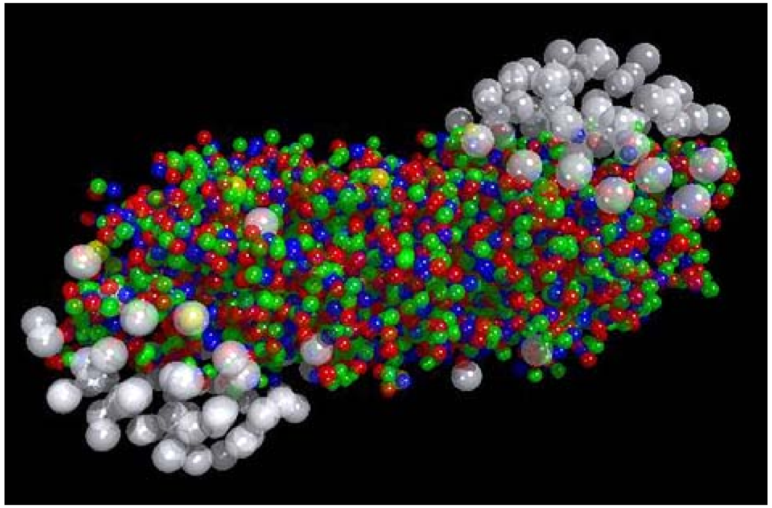
- At low energies, QCD matter exists only in the form of hadrons (mesons, baryons, nuclei)

QCD matter: ... to partons



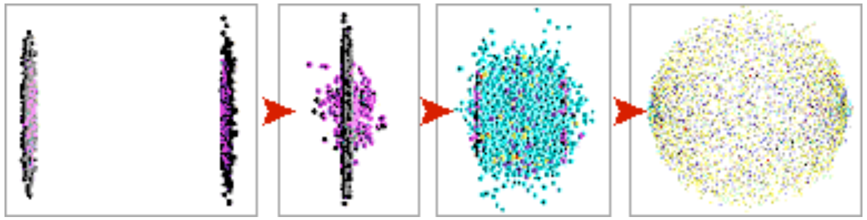
- At sufficiently high energies, the relevant degrees of freedom are partonic (quarks & gluons)
- True for both p+p collisions and A+A collisions ...

QCD matter: ... to partons



- At sufficiently high energies, the relevant degrees of freedom are partonic (quarks & gluons)
- ... but HIC give us access to new forms of partonic matter

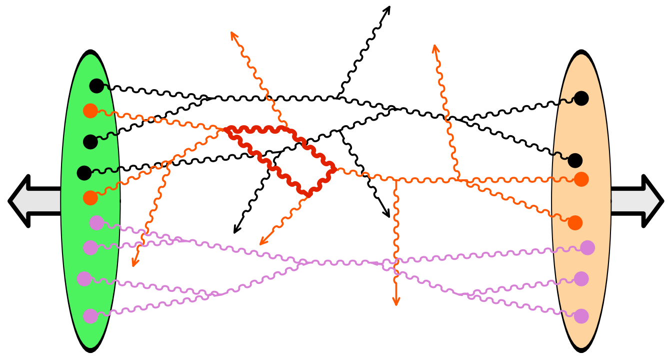
New forms of QCD matter produced in HIC



- Prior to the collision: 2 Lorentz–contracted nuclei ('pancakes')
  - 'Color Glass Condensate' (CGC)
- Right after the collision: non–equilibrium partonic matter
  - 'Glasma' (from 'Glass' + 'Plasma')
- At later stages ($\Delta t \gtrsim 1$ fm/c) : local thermal equilibrium
  - 'Quark–Gluon Plasma' (QGP)
- Final stage ($\Delta t \gtrsim 6$ fm/c) : hadrons
  - 'final event', or 'particle production'

How to study these new forms of matter ?

- Standard perturbation theory in QCD (= expansion in powers of the coupling 'constant' α_s) fails even at weak coupling, because of the high parton density.



- High–density effects (multiple scattering, parton saturation, Debye screening etc) must be resummed to all orders in α_s.
- This results into effective theories.

The possibility of a strong coupling

- Besides, there is no guarantee that the coupling is weak !

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

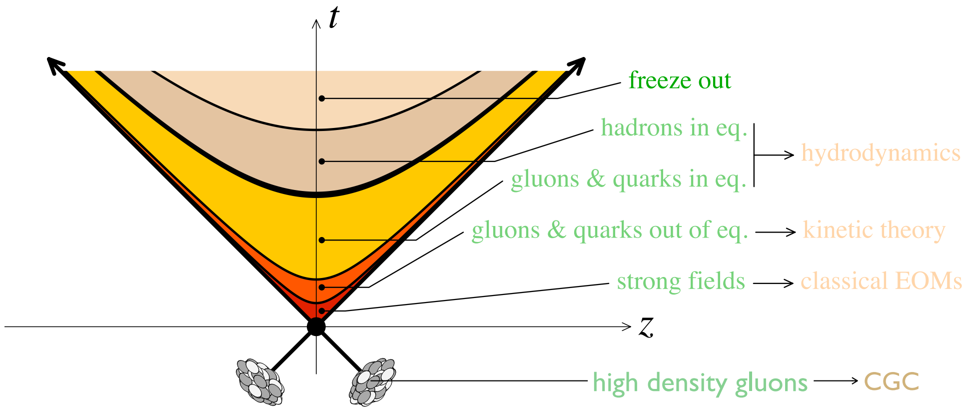
Monday, April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

- 'Perfect fluid' $=\ \alpha_s \to \infty$
- Interesting connection with string theory ('AdS/CFT correspondence').

Effective theories for Heavy Ion Collisions

- A space–time picture of a heavy ion collision



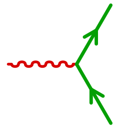
- Different effective theories apply at different stages.
- But they refer all to QCD !

Lecture 0: A QCD Primer

$$\mathcal{L} \;=\; -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a \;+\; \sum_f \bar{\psi}_f \Big(i\gamma^\mu D_\mu - m \Big) \psi_f$$

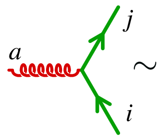
QCD: Quarks & Gluons

- Electromagnetic interactions: Quantum Electrodynamics (QED)
  - matter : electron; interaction carrier : photon
  - interaction vertex :

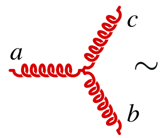


$\sim\ e$ (electric charge of the electron)

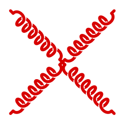
- Strong interactions: Quantum Chromodynamics (QCD)
  - matter : quarks; interaction carriers : gluons
  - interaction vertices :



$\sim\ g\,(t^a)_{ij}$



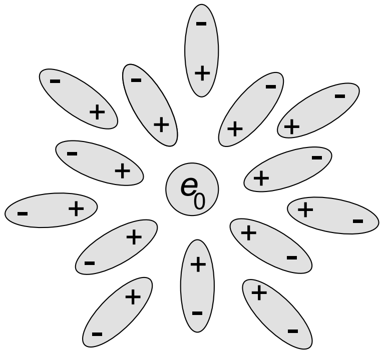
$\sim\ g\,(T^a)_{bc}$



  - $i,\,j$: color indices of the quarks ($N_c = 3$ possible values)
  - $a,\,b,\,c$: color indices of the gluons ($N_c^2 - 1 = 8$ possible values)

Running coupling: QED

- An electric charge polarizes the surrounding medium:

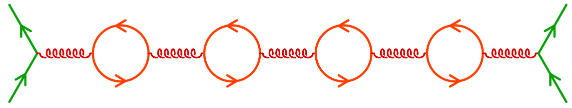


$$V(R) = \frac{e_{\mathrm{eff}}(R)}{R}$$

- The effective charge depends upon the distance R from the bare one.
- Normally this leads to screening: $e_{\mathrm{eff}}(R)$ decreases with R.

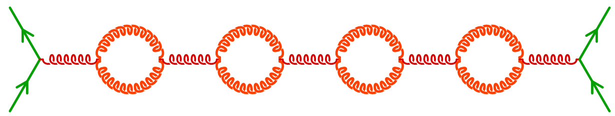
Running coupling: from QED to QCD

- The vacuum itself is a polarisable 'medium' !



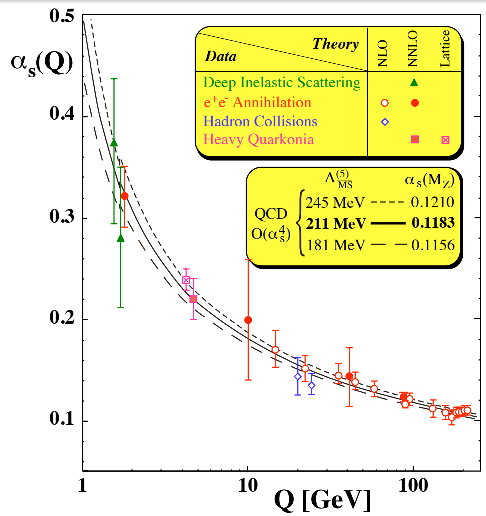
$$QED: \quad \alpha_{\mathrm{eff}}(R) = \frac{\alpha}{1 - \frac{2\alpha}{3\pi}\ln(1/mR)}, \quad \alpha \equiv \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

- In QCD, the (longitudinal) gluons yield antiscreening !



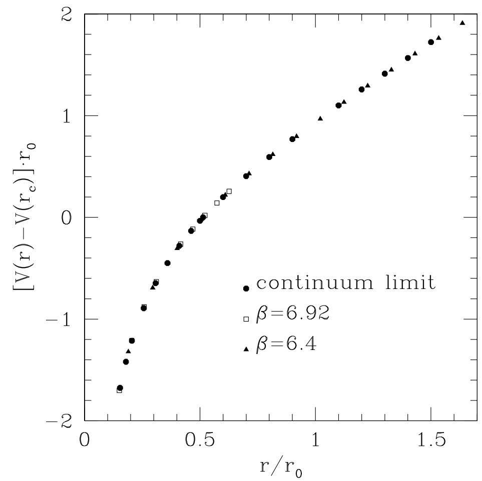
$$QCD: \quad \alpha_s(R) \equiv \frac{g^2(R)}{4\pi} = \frac{2\pi N_c}{(11N_c - 2N_f)\ln(1/\Lambda_{\mathrm{QCD}}R)}$$

Asymptotic freedom



- The coupling is weak at short distances, or large transferred momenta: $Q \sim 1/R \gg \Lambda_{\mathrm{QCD}} \simeq 200$ MeV

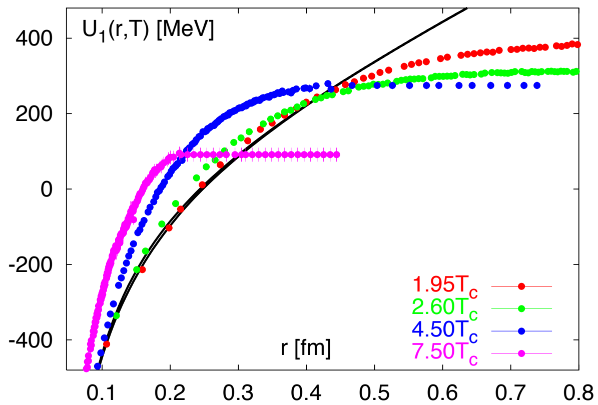
Confinement



- The quark–antiquark potential increases linearly with the distance.
- Quarks (and gluons) are confined into colorless hadrons

Quark–antiquark potential at finite T

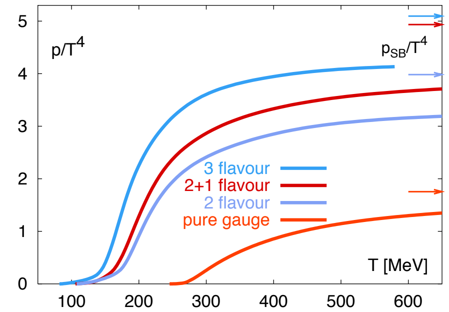
- With increasing the temperature T, the potential flattens at shorter and shorter distances.



- This eventually leads to a phase transition at some critical temperature T_c

Quark–Gluon Plasma

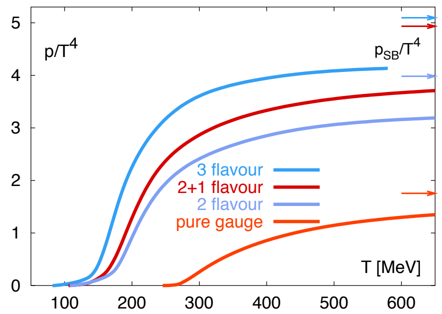
- Lattice calculations of the pressure in QCD at finite T



- Rapid increase of the pressure
  - at $T \simeq 270$ MeV with gluons only
  - at $T \simeq 150$ to 180 MeV with light quarks
- Interpreted as a rise in the number of active degrees of freedom due to the liberation of quarks and gluons

Quark–Gluon Plasma

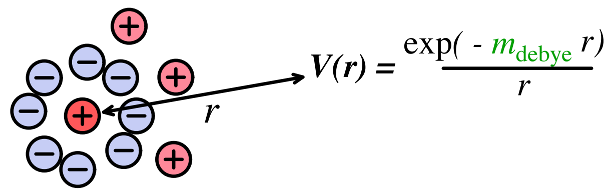
- Lattice calculations of the pressure in QCD at finite T



- Rapid increase of the pressure
  - at $T < T_c$: 3 light mesons $(\pi^0, \pi^\pm)$
  - at $T < T_c$: 52 d.o.f. (gluons: $8 \times 2 = 16$; quarks: $3 \times 3 \times 2 \times 2 = 36$)
- Interpreted as a rise in the number of active degrees of freedom due to the liberation of quarks and gluons

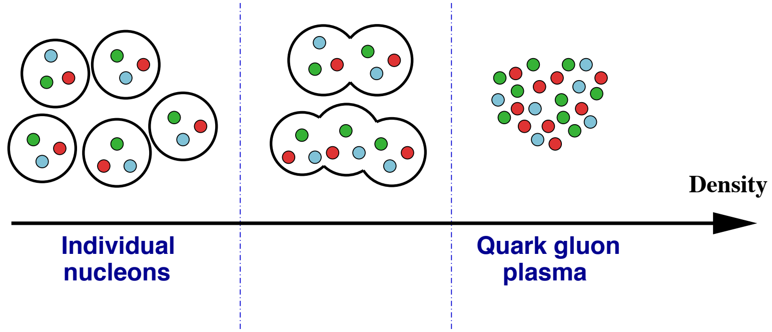
Debye screening

- Quark–Gluon Plasma (QGP) : a system of quarks and gluons which got free of confinement !
- How is that possible ???



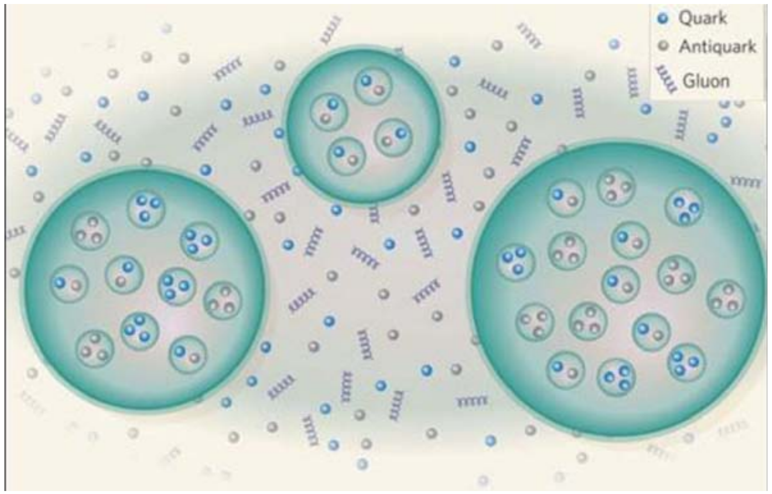
- In a dense medium, color charges are screened by their neighbors
- The interaction potential decreases exponentially beyond the Debye radius $r_{\text{Debye}} = 1/m_{\text{Debye}}$
- Hadrons whose sizes are larger than r_{Debye} cannot bind anymore

Deconfinement phase transition



- When the nucleon density increases, they merge, enabling quarks and gluons to hop freely from a nucleon to its neighbors
- This phenomenon extends to the whole volume when the phase transition ends
- Note: if the transition was first–order, it would go through a mixed phase containing a mixture of nucleons and plasma

Possible first–order scenario with critical bubbles



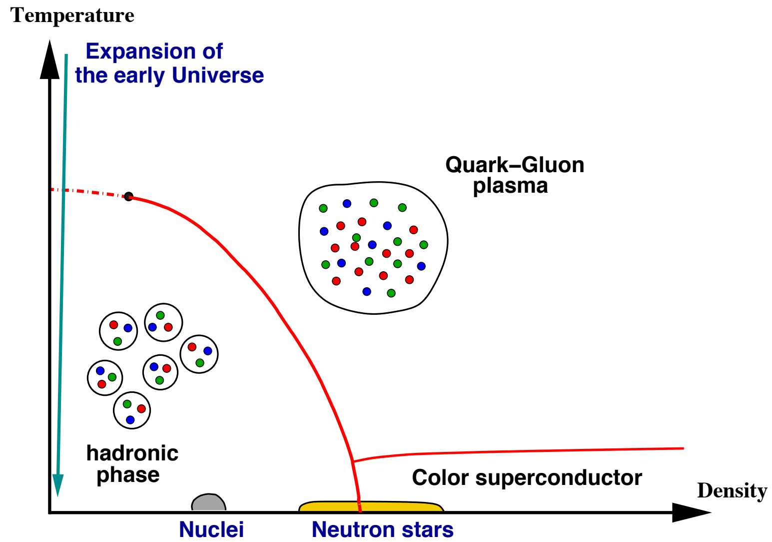
... but this is not what really happens !

The actual scenario is a 'cross–over'

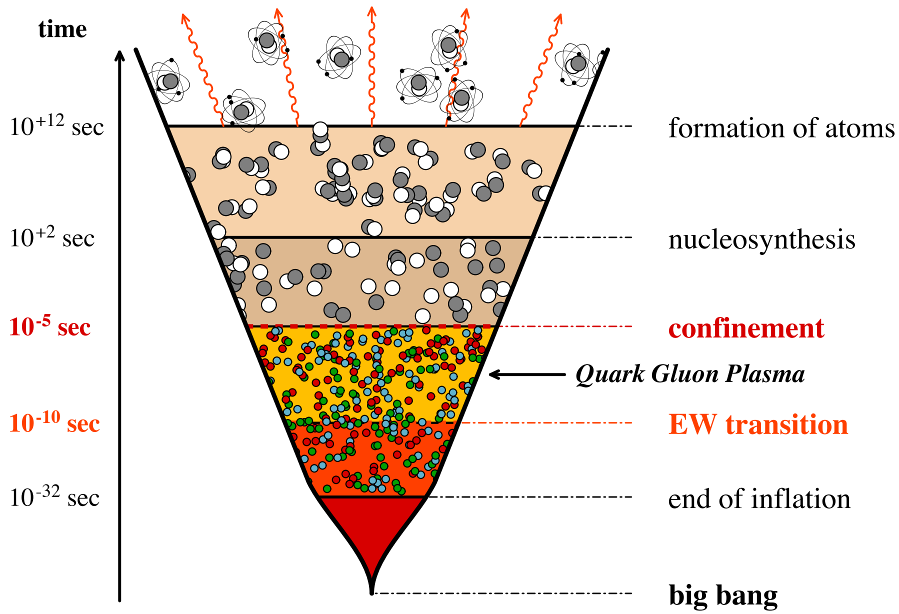
▷ This was firmly established by the Wuppertal–Budapest lattice group *(Aoki et al., Nature, 443 (2006) 675)*

Phase–diagram for QCD

- ... as explored by the expansion of the Early Universe ...

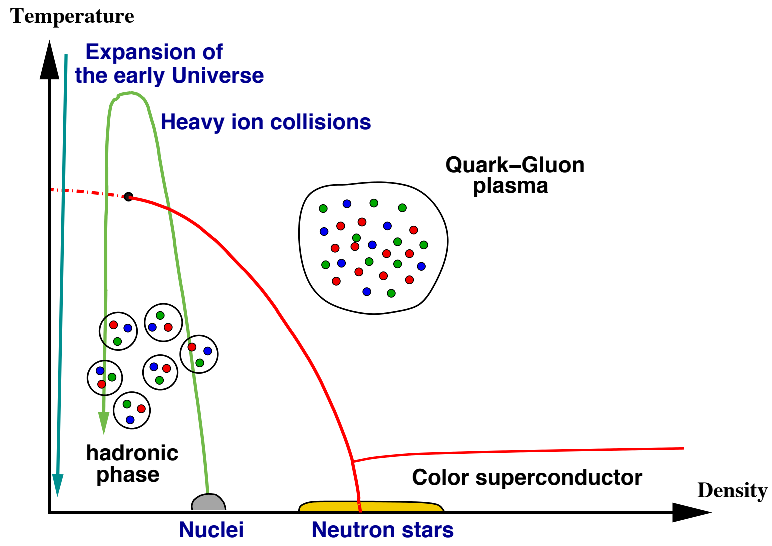


The Big Bang



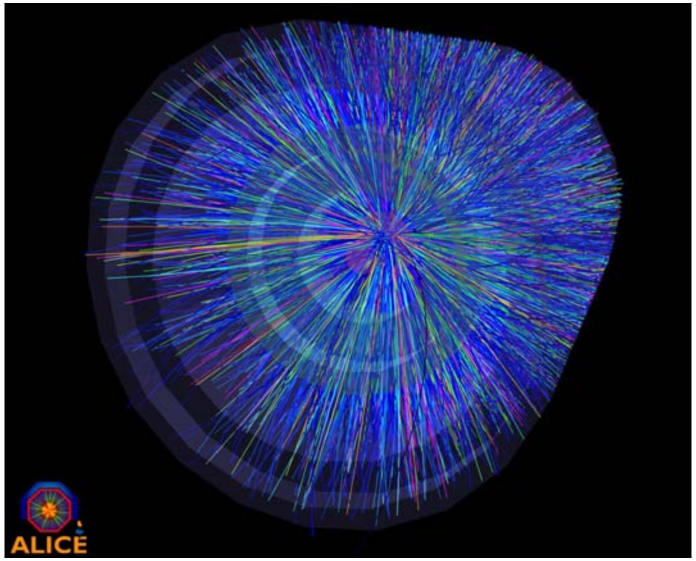
Phase–diagram for QCD

- ... as explored by the expansion of the Early Universe ...



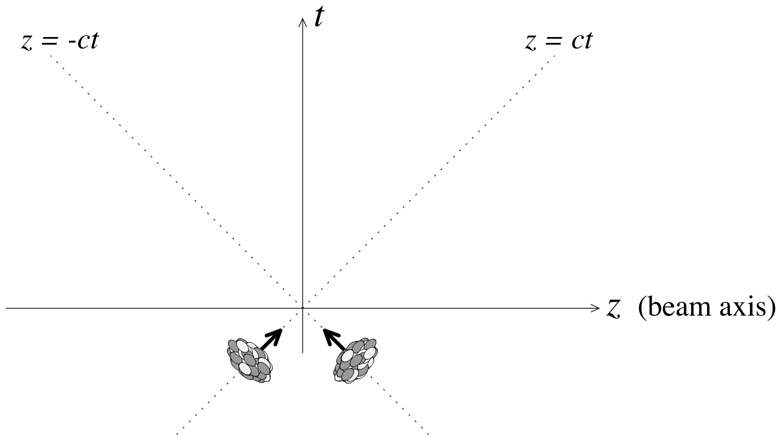
- ... and in the ultrarelativistic heavy ion collisions.

The Little Bang



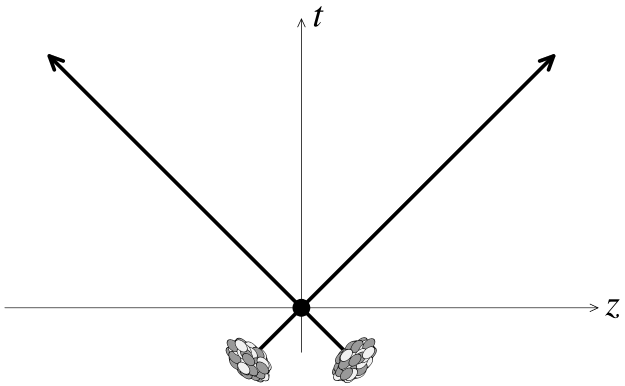
- The subject of these lectures

Lecture I: Initial conditions



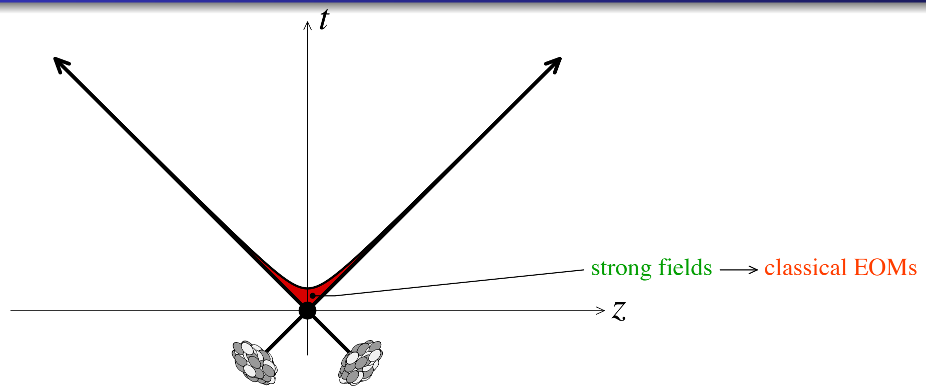
- $\tau < 0$: hadronic wavefunctions prior to the collision
  - high–energy evolution & the Color Glass Condensate
  - it applies to any highly energetic hadron (proton or nucleus)

Lecture I: Initial conditions



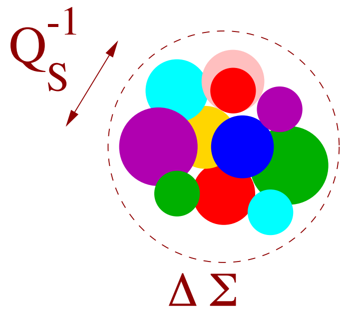
- $\tau < 0$: hadronic wavefunctions prior to the collision
- $\tau \sim 0$ fm/c : the hard scattering
  - production of hard particles: jets, direct photons, heavy quarks
  - calculable within (standard) perturbative QCD ('leading twist')

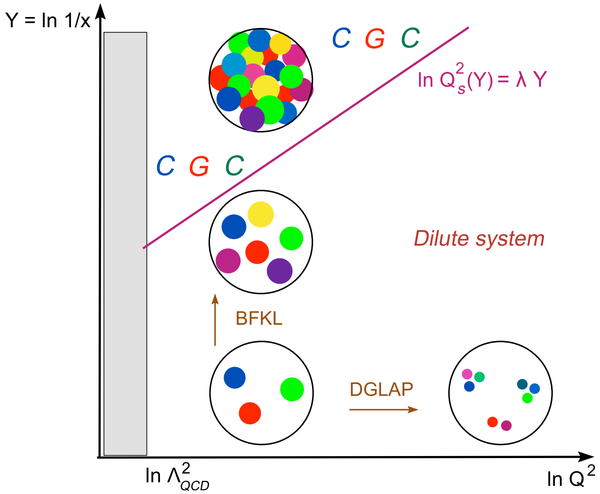
Lecture I: Initial conditions



- $\tau < 0$: hadronic wavefunctions prior to the collision
- $\tau \sim 0$ fm/c : the hard scattering
- $\tau \sim 0.2$ fm/c : strong color fields (or 'glasma')
  - semi–hard quanta ($p_\perp \lesssim 2$ GeV): gluons, light quarks
  - make up for most of the multiplicity
  - sensitive to the physics of saturation ('higher twist')

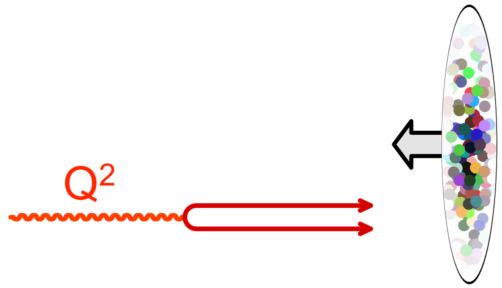
Color Glass Condensate





Parton picture

- When an energetic hadron is probed on a hard resolution scale (momentum transfer $Q^2 \gg \Lambda^2_{\rm QCD}$), one sees a bunch of partons ...
- with transverse area $\sim 1/Q^2$ ...
- and longitudinal momentum fraction $x = k_z/P$ fixed by the kinematics

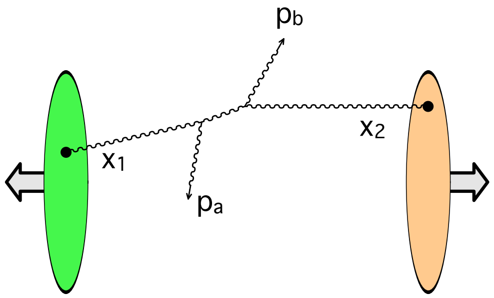


- E.g. : in Deep Inelastic Scattering (DIS)

$$x = \frac{Q^2}{s} \qquad s = \text{center-of-mass energy squared}$$

- N.B.: high energy $\Longleftrightarrow$ small x

Particle production in hadron–hadron collisions

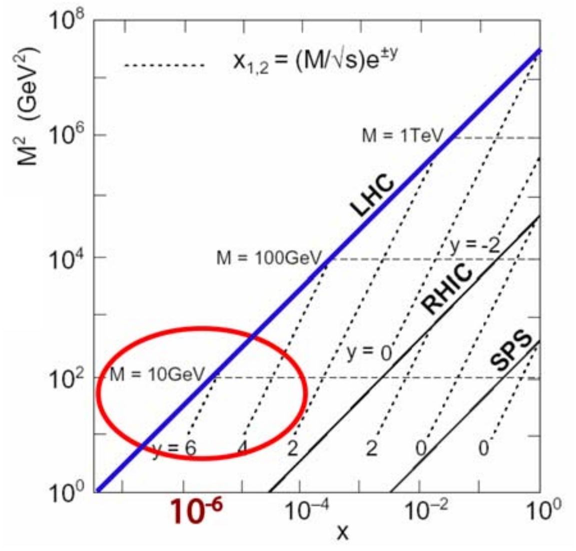


- The partons relevant for the process under consideration carry the longitudinal momentum fractions

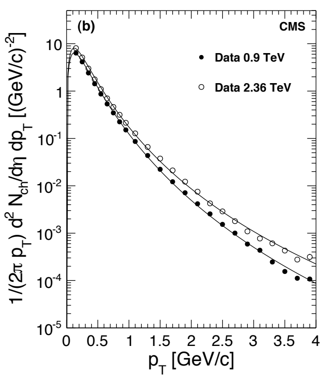
$$x_1 = \frac{p_{a\perp}}{\sqrt{s}}\, e^{Y_a} + \frac{p_{b\perp}}{\sqrt{s}}\, e^{Y_b}\,, \qquad x_2 = \frac{p_{a\perp}}{\sqrt{s}}\, e^{-Y_a} + \frac{p_{b\perp}}{\sqrt{s}}\, e^{-Y_b}$$

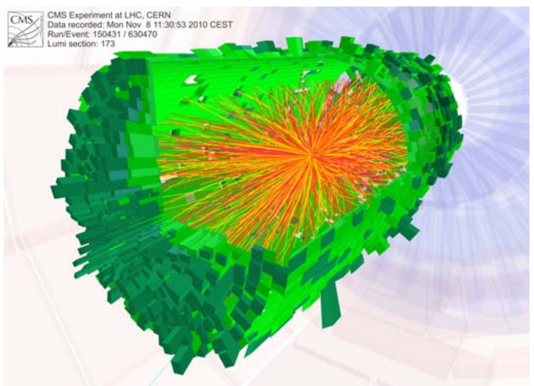
  - $p_\perp$: transverse momenta of the produced particles
  - Y : their rapidities
  - $\sqrt{s}$: collision energy

Kinematical domain for the LHC



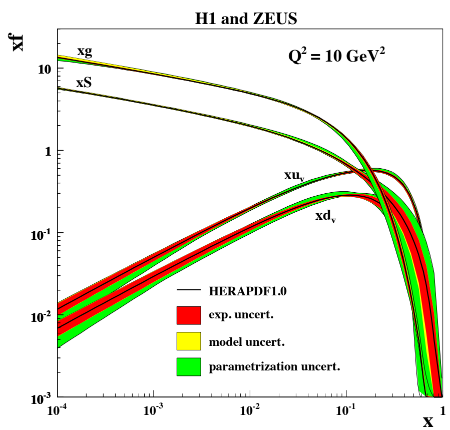
AA collisions at RHIC & LHC





- 99% of the total multiplicity lies below $p_\perp = 2$ GeV
- $x \sim 10^{-2}$ at RHIC ($\sqrt{s} = 200$ GeV)
- $x \sim 4 \times 10^{-4}$ at the LHC ($\sqrt{s} = 5.5$ TeV)
  ▷ partons at small x are the most important

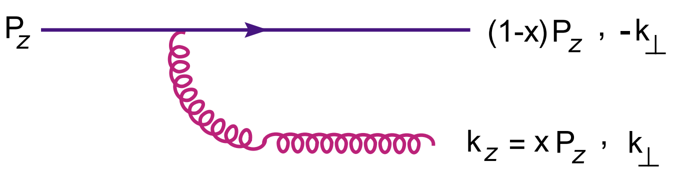
Parton distributions at HERA



The gluon distribution rises very fast with increasing energy

- Gluon distribution $xg(x, Q^2)$: # of gluons with transverse size $\Delta x_\perp \sim 1/Q$ and longitudinal momentum $k_z = xP$

Bremsstrahlung

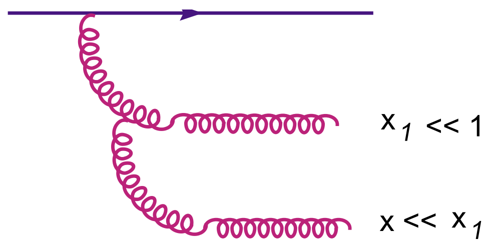


$$d\mathcal{P}_{\rm Brem} \sim \alpha_s(k_\perp^2)\, C_R\, \frac{d^2 k_\perp}{k_\perp^2}\, \frac{dx}{x}$$

- Phase–space enhancement for the emission of
  - collinear $(k_\perp \to 0)$
  - and/or soft (low–energy) $(x \to 0)$ gluons
- The parent parton can be either a quark or a gluon

  $C_F = t^a t^a = \frac{N_c^2-1}{2N_c} = \frac{4}{3}\,, \quad C_A = T^a T^a = N_c = 3$
- The daughter gluon can in turn radiate an even softer gluon !

2 gluons



- The 'cost' of the addition gluon:

$$\alpha_s \int_x^1 \frac{dx_1}{x_1} = \alpha_s \ln \frac{1}{x}$$

Formally, a process of higher order in α_s, but which is enhanced by the available rapidity interval

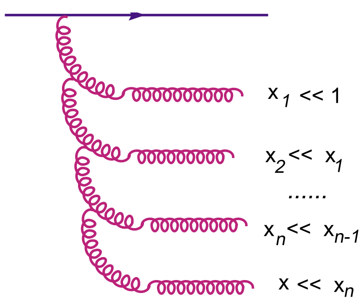
- $Y \equiv \ln(1/x)$: rapidity difference between the parent quark and the last emitted gluon
- When $\alpha_s Y \gtrsim 1 \Longrightarrow$ need for resummation !

Gluon cascades

- n gluons strictly ordered in x
- The n–gluon cascade contributes

$$\frac{1}{n!}(\alpha_s Y)^n$$

- The sum of all the cascades exponentiates :



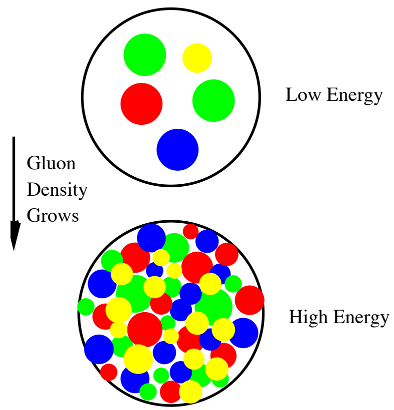
$$xg(x, Q^2) \propto e^{\omega \alpha_s Y} \qquad \text{BFKL evolution}$$

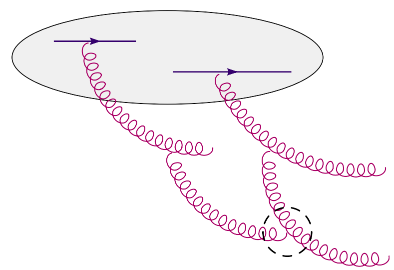
(Balitsky, Fadin, Kuraev, Lipatov, 75–78)

- This evolution is linear :
  the emitted gluons do not interact with each other

Gluon recombination

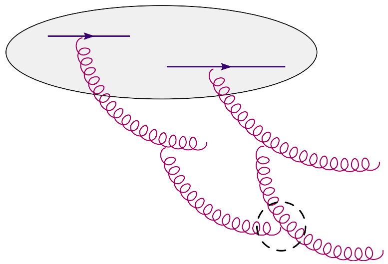
- The gluon density rises with decreasing x (increasing energy)





- Eventually gluons start overlapping with each other and then they interact: $2 \to 1$ gluon recombination
- These interactions stop the growth: saturation

Saturation momentum



- Number of gluons per unit area:

$$\mathcal{N} \sim \frac{x\, g_A(x, Q^2)}{\pi R_A^2}$$

- Recombination cross–section

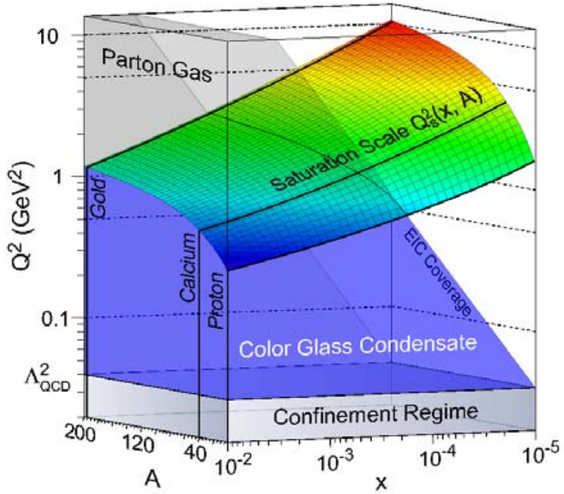
$$\sigma \sim \frac{\alpha_s}{Q^2}$$

- Recombination happens if $\mathcal{N}\sigma \gtrsim 1$, i.e. $Q^2 \lesssim Q_s^2$, with

$$Q_s^2(x, A) \simeq \alpha_s \frac{x g_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} \frac{1}{x^{0.25}}$$

- Low Q^2 $\Longrightarrow$ large area $\sim 1/Q^2$ $\Longrightarrow$ strong overlapping

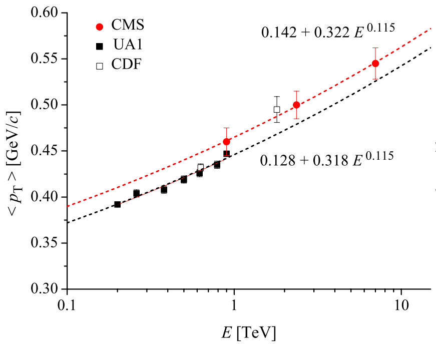
Saturation scale as a function of x and A

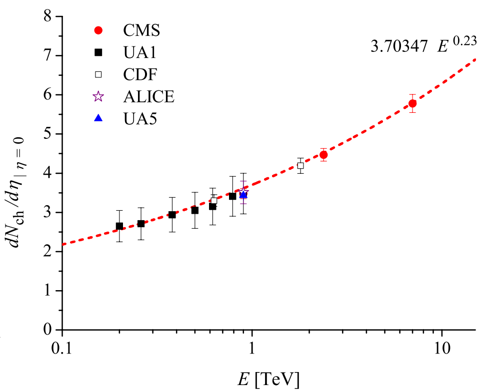


- $x \sim 10^{-5}$: $Q_s \sim 1$ GeV for proton and ~ 3 GeV for Pb or Au

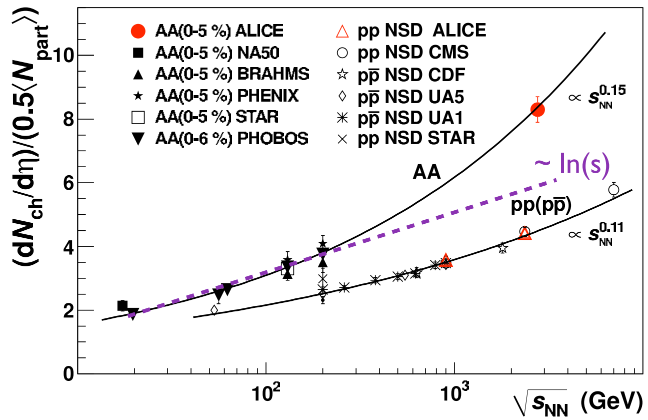
Multiplicities at the LHC: p+p

- In a high–energy scattering, the saturated gluons are released in the final state
  - typical transverse momentum $\langle p_T \rangle \sim Q_s(E)$
  - average multiplicity $dN/d\eta \sim Q_s^2(E)$





Multiplicities in HIC: RHIC & LHC



- Logarithmic growth $(\ln s)$ excluded by the LHC data
- Larger energy exponent (E^λ) for A+A than for p+p
  - ▷ this difference is theoretically understood

Geometric scaling

- A very robust, qualitative, prediction of saturation:
  DIS at HERA, Au+Au at RHIC, p+p at the LHC ...
  (looking forward to the relevant Pb+Pb data at the LHC)
- The single–inclusive spectra for particle production depend...
  - ... upon the particle transverse momentum p_T
  - ... and the COM energy of the collision $\sqrt{s}$

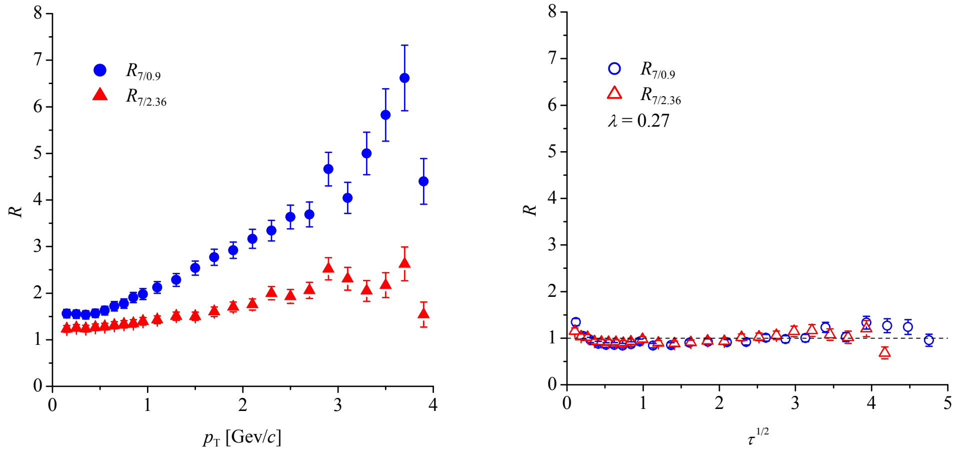
  ... only via the ratio of p_T to the saturation momentum Q_s :

$$\frac{\mathrm{d}N}{\mathrm{d}\eta\,\mathrm{d}^2 p_T} \simeq F(\tau) \qquad \text{with} \qquad \tau \equiv \frac{p_T^2}{Q_s^2(p_T/\sqrt{s})}$$

- At high energy, Q_s is the only intrinsic scale in the problem !

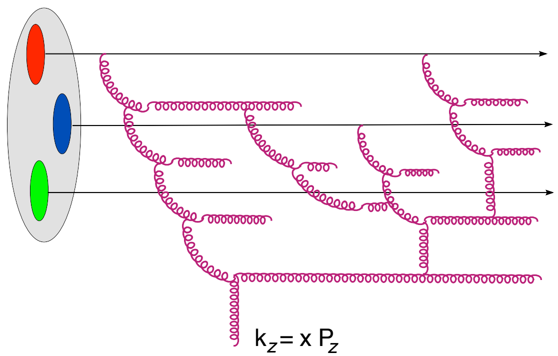
Geometric scaling at the LHC: p+p

$$R_{s_1/s_2} = \frac{(\mathrm{d}N/\mathrm{d}\eta\,\mathrm{d}^2 p_T)\big|_{s_1}}{(\mathrm{d}N/\mathrm{d}\eta\,\mathrm{d}^2 p_T)\big|_{s_2}} \to 1 \quad \text{as a function of } \tau \text{ ... if scaling}$$



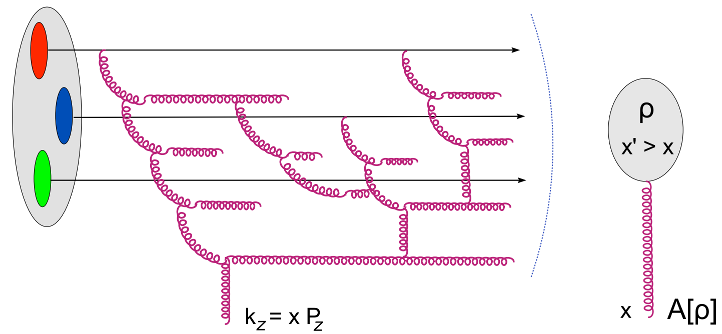
The need for an effective theory

- How to compute the saturation scale from first principle ?



- Relatively hard scale ($Q_s \gg \Lambda_{\rm QCD}$) $\Longrightarrow$ weak coupling !
- ... but high density $\Longrightarrow$ strong non–linear effects
- Solution: a reorganization of perturbation theory !
  (McLerran and Venugopalan, 94; E.I., McLerran, and Leonidov, 00)

Color Glass Condensate



- Small–x gluons: classical color fields A_a^μ radiated by fast color charges ρ_a with $x' \gg x$, frozen in some random configuration
- $W_Y[\rho]$: probability distribution for the charge density at Y
- Evolution equation for $W_Y[\rho]$ with increasing $Y = \ln 1/x$

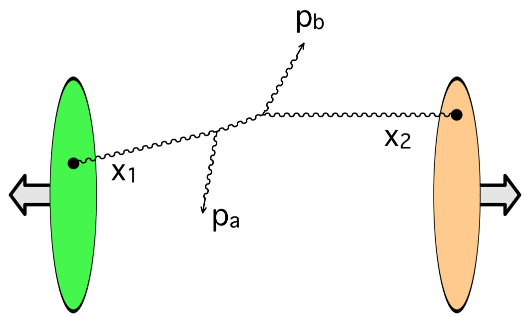
$$\frac{\partial}{\partial Y} W_Y[\rho] = H\, W_Y[\rho] \qquad \text{(JIMWLK)}$$

How to scatter 2 CGC's ?

- A heavy ion collision at high energy

- Main difficulty: How to treat collisions involving a large number of partons ?

Proton–proton collisions



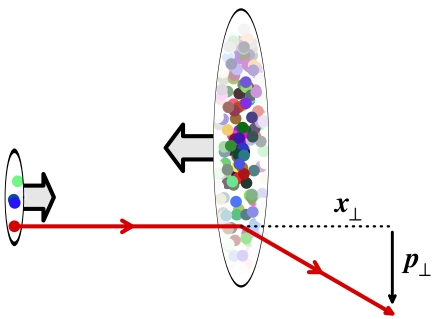
$$x_1 \sim \frac{p_\perp}{\sqrt{s}} e^{Y}$$

$$x_2 \sim \frac{p_\perp}{\sqrt{s}} e^{-Y}$$

- Dilute–Dilute: one parton from each projectile interact
- Collinear factorization scheme of perturbative QCD
  - usual pdf's + DGLAP evolution
  - partonic cross–sections

▷ Caution: forward rapidity ($Y \gg 1$) & not too hard $p_\perp \Rightarrow x_2 \ll 1$

Proton–nucleus collisions (1)



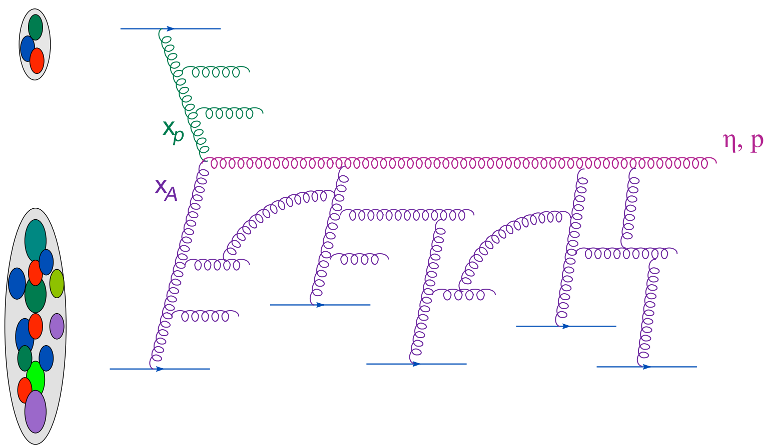
$$x_1 \sim \frac{p_\perp}{\sqrt{s}} e^{Y} \sim \mathcal{O}(1)$$

$$x_2 \sim \frac{p_\perp}{\sqrt{s}} e^{-Y} \ll 1$$

- Most interesting situation: forward particle production ($Y \gtrsim 3$) at 'semi–hard' momenta ($p_\perp \sim 1 \div 5$ GeV)
  - very small $x_2 \ll 1$ in the nucleus
  - $p_\perp$ comparable to $Q_s(A, x_2)$
- Dilute–Dense: new factorization scheme needed

▷ similar to deep inelastic scattering at small x

Proton–nucleus collisions (2)



- How to include both multiple scattering and saturation ?
  - proton = collinear factorization (large x_1)
  - nucleus = described as a CGC
  - parton—CGC cross–section to all orders in the gluon density

CGC factorization for 'dilute–dense'

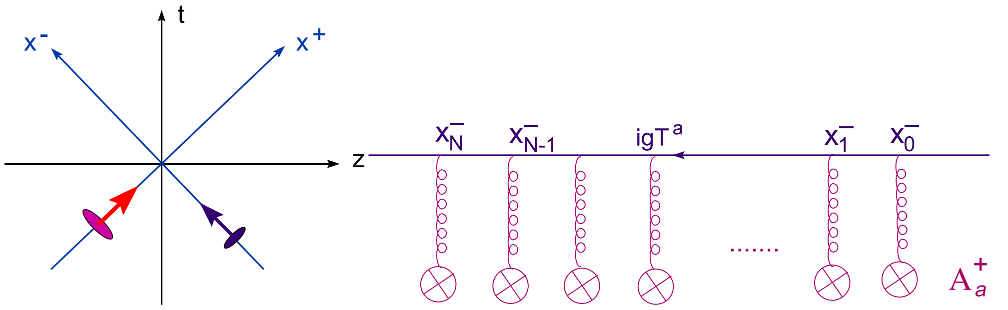
- The color charges in the target (ρ_a) are 'frozen' during the collision (by Lorentz time dilation)
  - compute the scattering between the parton and a fixed configuration of color charges
  - average over all the configurations by integrating over ρ_a with the CGC weight function

$$\left\langle \frac{\mathrm{d}N}{\mathrm{d}Y\,\mathrm{d}^2p_\perp} \right\rangle_Y = \int [\mathcal{D}\rho]\; W_Y[\rho]\; \frac{\mathrm{d}N}{\mathrm{d}Y\,\mathrm{d}^2p_\perp}[\rho]$$

- The target color field A_a^μ (as generated by ρ_a) is strong and must be resummed to all orders

Eikonal approximation

- A very energetic particle is not deflected by its interactions



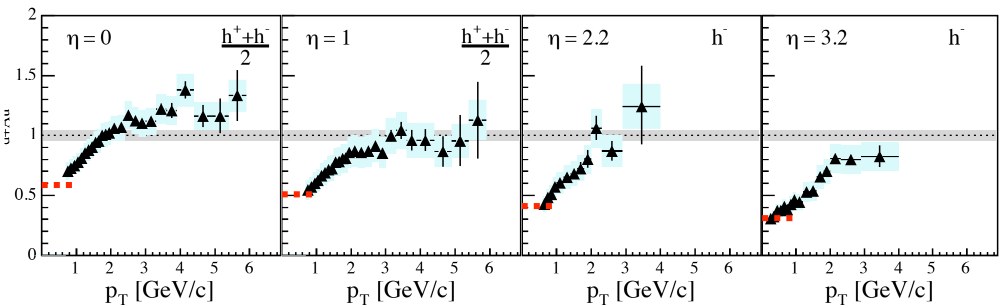
- The sum of all the interactions simply exponentiates
- The single–particle state gets multiplied by a complex exponential known as Wilson line

$$\Psi_i(x_\perp) \;\rightarrow\; U_{ij}(x_\perp)\,\Psi_j(x_\perp), \quad U(x_\perp) = \mathrm{T}\exp\left\{ i\int \mathrm{d}x^- A_a^+(x^-, x_\perp) t^a \right\}$$

Nuclear modification factor in d+Au at RHIC

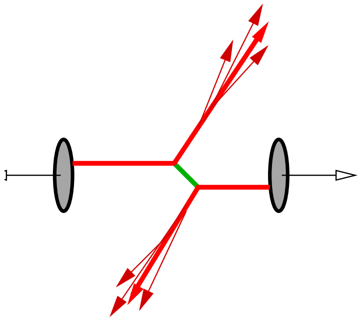
$$R_{\mathrm{d+Au}} \equiv \frac{1}{2A}\,\frac{\mathrm{d}N_{\mathrm{d+Au}}/\mathrm{d}^2p_\perp \mathrm{d}\eta}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}^2p_\perp \mathrm{d}\eta}$$

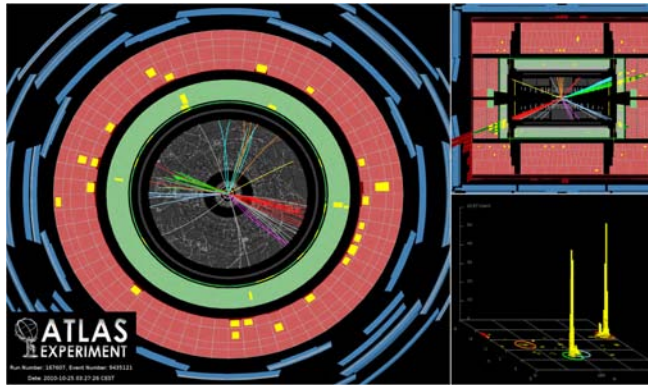
- $R_{\mathrm{d+Au}}$ would be one in the absence of nuclear effects



- $R_{\mathrm{d+Au}}$ decreases with increasing rapidity
- Strong suppression ($R \sim 0.5$) for $\eta = 3$: coherent scattering

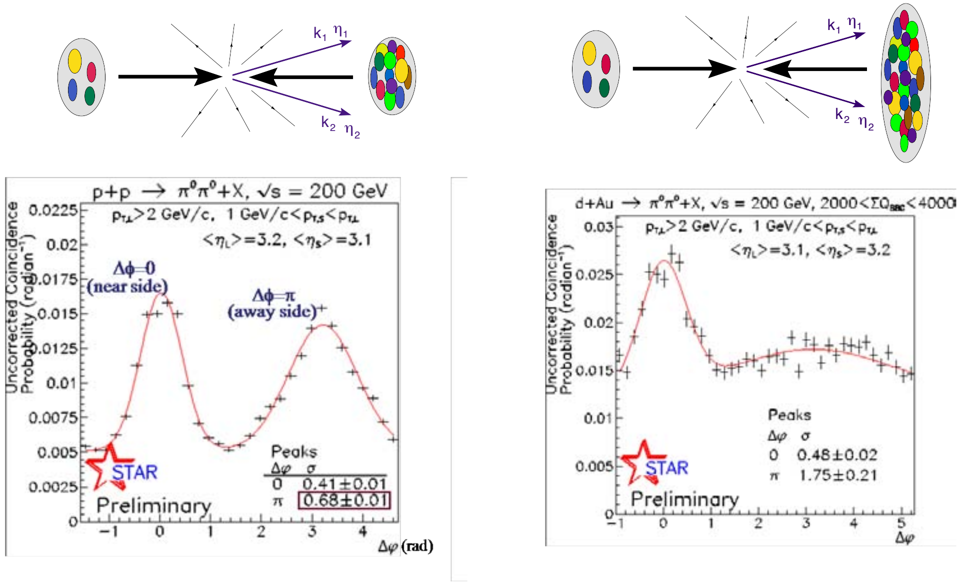
Jets





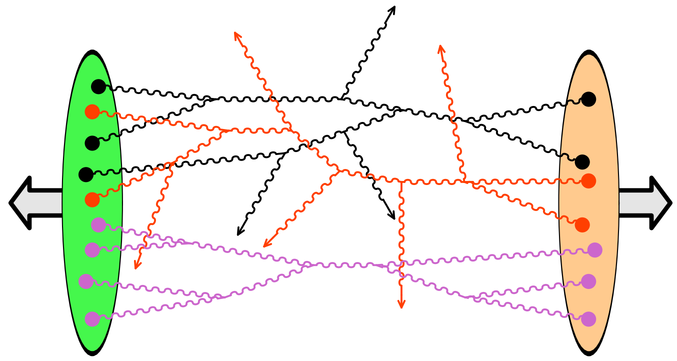
- Two back–to–back jets in the transverse plane: visible via 2–particle azimutal correlations

Di–jet correlations at RHIC: p+p vs. d+Au



- d+Au : the 'away jet' gets smeared out = saturation in Au

Nucleus–nucleus collisions

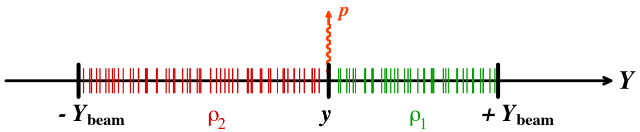


- Non–linear effects in the wavefunctions: gluon saturation
  - 2 CGC weight functions: $W_{Y_1}[\rho_1]$, $W_{Y_2}[\rho_2]$
  - generalized pdf's : multi–parton correlations
- ... and in the scattering: multiple interactions
  - classical Yang–Mills equations with 2 sources

The CGC factorization

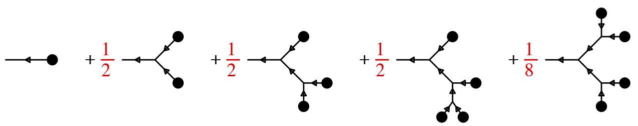
- Gluon production in the scattering between 2 CGC's :

$$\left\langle \frac{\mathrm{d}N}{\mathrm{d}Y\,\mathrm{d}^2p_\perp}\right\rangle = \int [\mathcal{D}\rho_1\mathcal{D}\rho_2]\, W_{Y_{\rm beam}-y}[\rho_1]\, W_{Y_{\rm beam}+y}[\rho_2]\, \frac{\mathrm{d}N}{\mathrm{d}Y\,\mathrm{d}^2p_\perp}\bigg|_{\rm class}$$



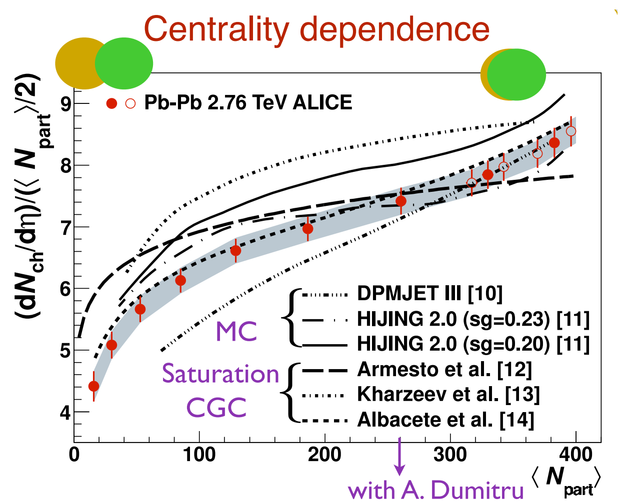
- The classical solution is non–linear to all orders in ρ_1 and ρ_2 :

$$D_\nu F^{\nu\mu}(x) = \delta^{\mu+}\rho_1(x) + \delta^{\mu-}\rho_2(x)$$



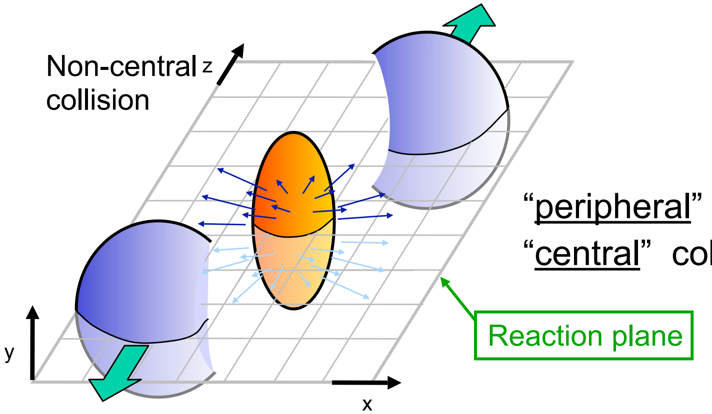
- All the leading logs of $1/x_{1,2}$ are absorbed in the W's.

Multiplicity in HIC at the LHC



- Excellent fit by the CGC approach
- All the models include some form of saturation
  - ▷ HIJING : energy dependent low–p_T cutoff

The geometry of a HIC



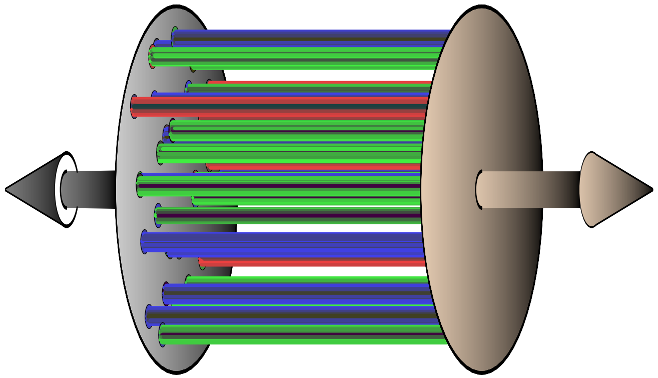
"peripheral" collision ($b \sim b_{max}$)

"central" collision ($b \sim 0$)

Number of participants (N_{part}): number of incoming nucleons (participants) in the overlap region

Glasma

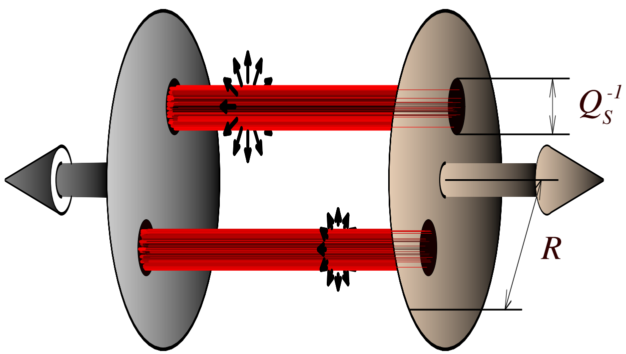
- Immediately after the collision, the chromo-electric and chromo-magnetic fields are purely longitudinal
- They form flux tubes extending between the projectiles



- Glasma : the intermediate stage between the CGC and the Quark Gluon Plasma *(McLerran and Lappi, 06)*

Color flux tubes

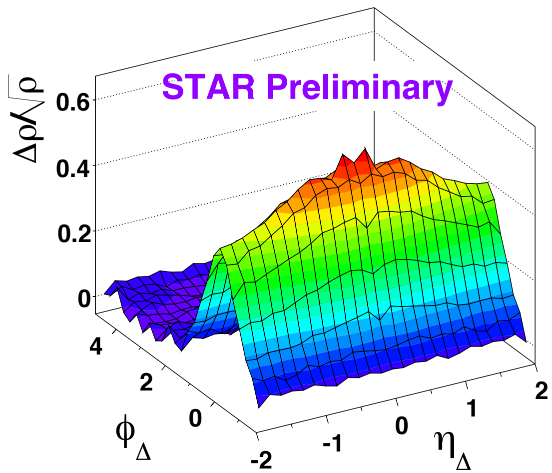
- Correlation length in the transverse plane: $\Delta r_\perp \sim 1/Q_s$
- Correlation length in rapidity (y or η): $\Delta\eta \sim 1/\alpha_s$



- The color fluxes eventually break into 'particles' (gluons)
- Gluons emitted from different flux tubes are not correlated

The ridge in HIC at RHIC

- A natural explanation for the the 'ridge'

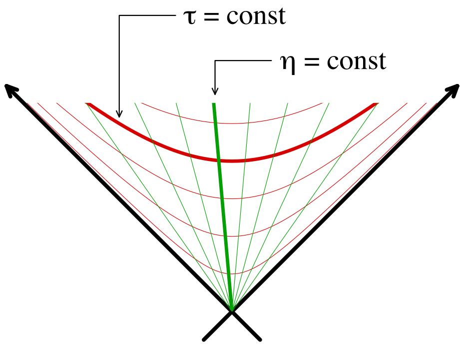


- Long–range correlations in rapidity $\Delta\eta$
- Narrow correlation in azimuthal angle $\Delta\phi$

Di–hadron correlations

- In a given even count the number of particles N_1 in a given bin centered at (η_1, ϕ_1) and similarly N_2.

$$\mathcal{R} \equiv \frac{\langle N_1\, N_2\rangle - \langle N_1\rangle \langle N_2\rangle}{\langle N_1\rangle \langle N_2\rangle} \qquad \Delta\eta = \eta_1 - \eta_2, \quad \Delta\phi = \phi_1 - \phi_2$$



- Recall: pseudo–rapidity

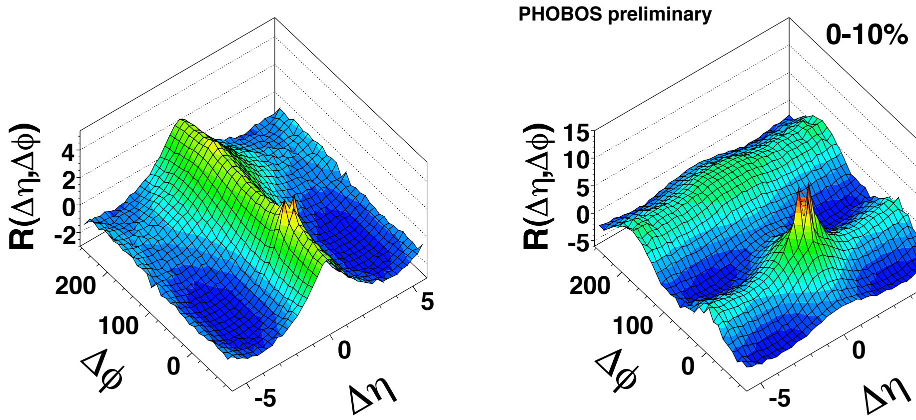
$$\eta \;=\; \frac{1}{2}\,\ln\frac{p+p_z}{p-p_z}$$

$$\eta \;=\; -\ln\tan\frac{\theta}{2}, \quad \theta = \frac{p_z}{p}$$

$$\tau \;=\; \sqrt{t^2 - z^2}$$

Di–hadron correlations: p+p vs Au+Au

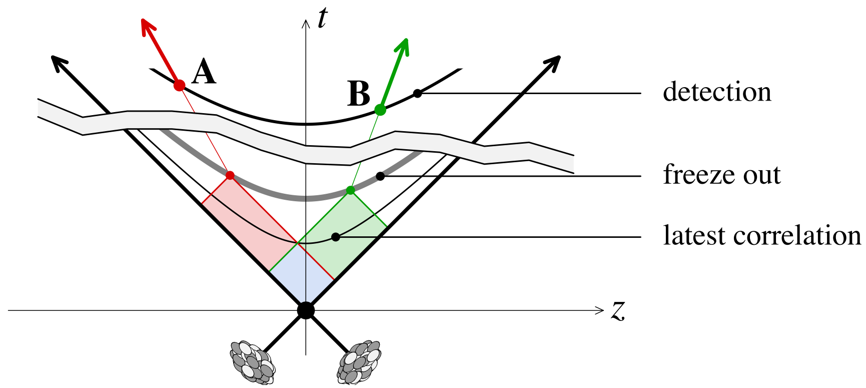
- p+p : peak around $\Delta\eta = 0$ & flat in $\Delta\phi$
  ▷ correlated particles make similar angles with the beam axis



- Au+Au :
  almost flat over $\Delta\eta \simeq 10$ & 2 peaks at $\Delta\phi = 0$ and $\Delta\phi = \pi$

Long–range rapidity correlations probe early times

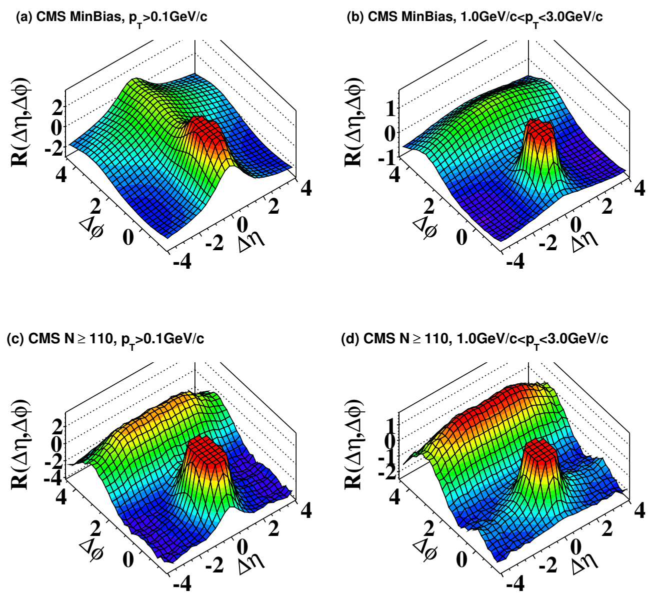
- Generated at early stages, where particles with different longitudinal velocities were still causally connected



$$\tau_{\text{correlation}} \;\leq\; \tau_{\text{freeze-out}}\; e^{-|\eta_A - \eta_B|/2}$$

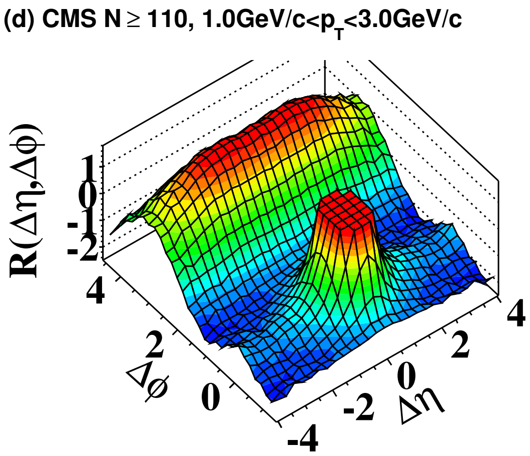
The ridge in p+p at CMS (1)

- A small ridge has been seen in p+p collisions at the LHC



The ridge in p+p at CMS (2)

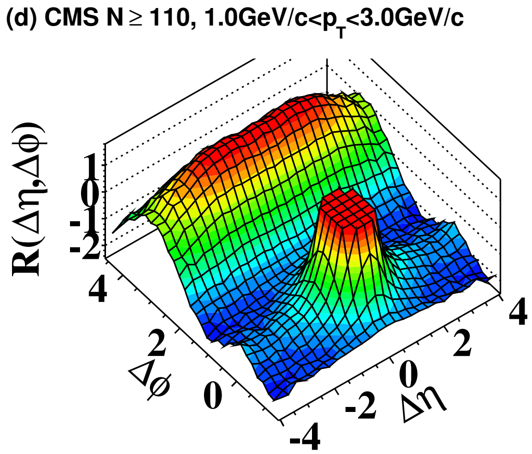
- ... but only in specially selected events !



- High–multiplicity ($\Longrightarrow$ very central): $N \geq 110$ particles
- Narrow interval in transverse momentum: $1 \leq p_\perp \leq 3$ GeV

The ridge in p+p at CMS (2)

- ... but only in specially selected events !



- ... which look a lot like a heavy ion collision !!
  - ▷ N.B. $1 \leq p_\perp \leq 3$ GeV is similar to the proton Q_s at LHC