From Colour Glass Condensate to Quark–Gluon Plasma

Edmond Iancu
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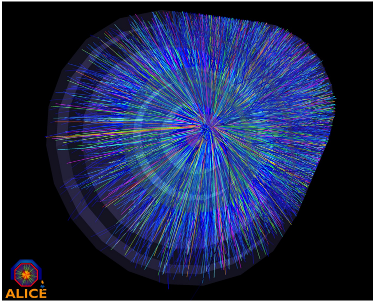
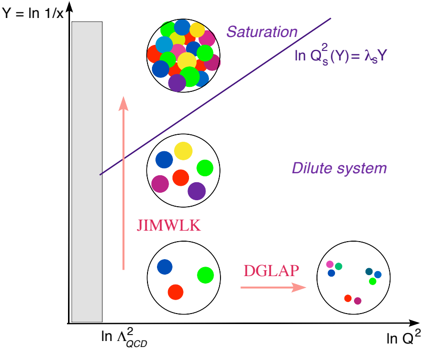
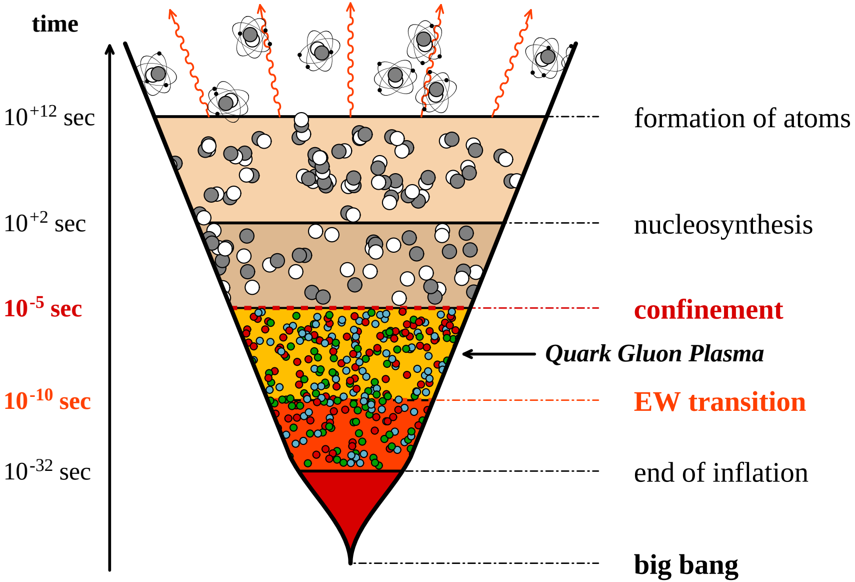


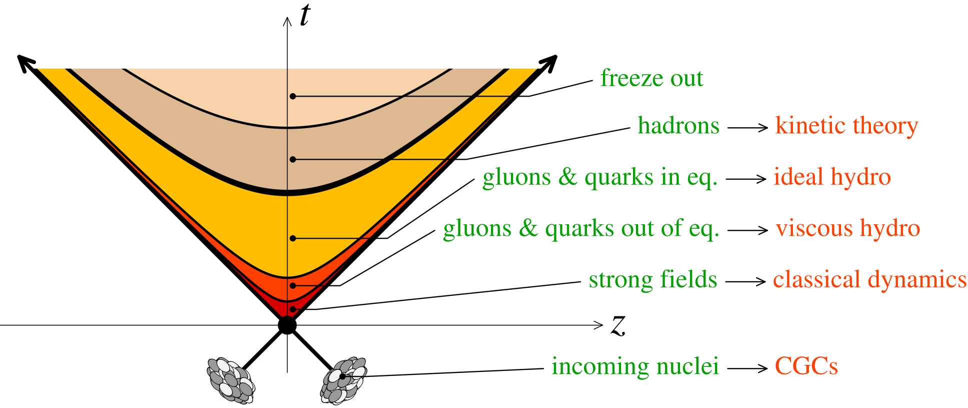


The Big Bang



time
10^{+12} sec
10^{+2} sec
10^{-5} sec
10^{-10} sec
10^{-32} sec
formation of atoms
nucleosynthesis
confinement
Quark Gluon Plasma
EW transition
end of inflation
big bang

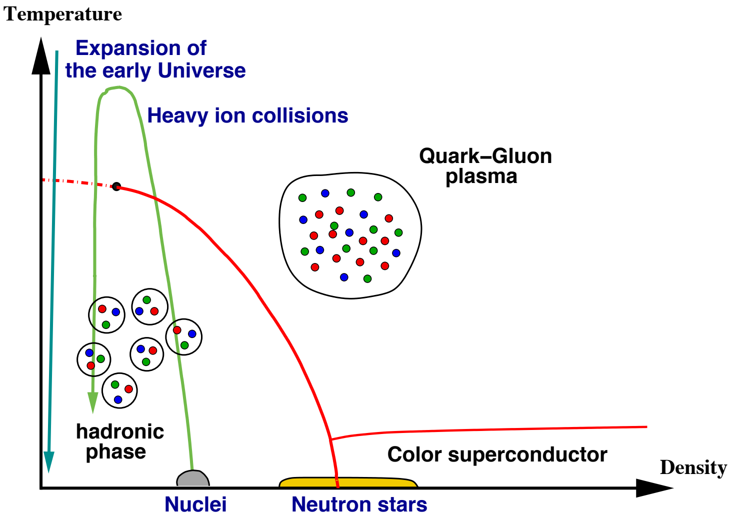
- A space–time picture of a heavy ion collision (HIC)



- 'Initial singularity' : the collision between the two incoming nuclei
- The QGP is re-created in the intermediate stages

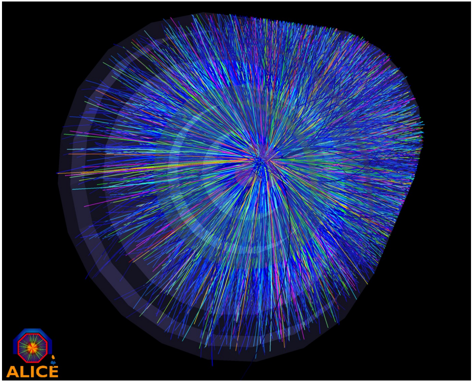
Phase–diagram for QCD

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



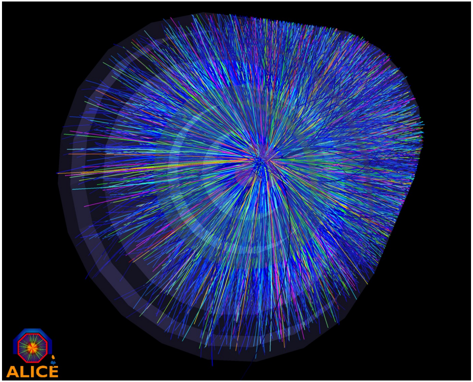
- ... and in the ultrarelativistic heavy ion collisions.

Pb+Pb collisions at the LHC: ALICE



- Pb+Pb collision at the LHC: $>$ 20,000 hadrons in the detectors !
- Where are all these hadrons coming from ?
- How to trace back their history ?
- How to understand that from first principles (QCD) ?

Pb+Pb collisions at the LHC: ALICE



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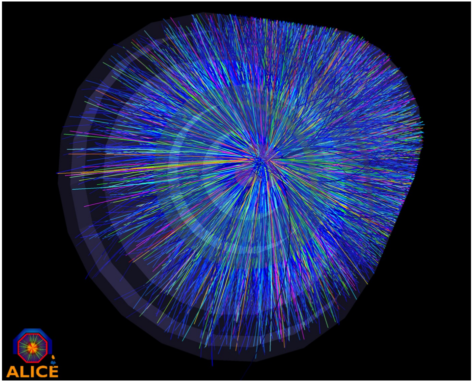

- Pb+Pb collision at the LHC: $>$ 20,000 hadrons in the detectors !
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- They leave imprints on the hadron distribution in the final state.
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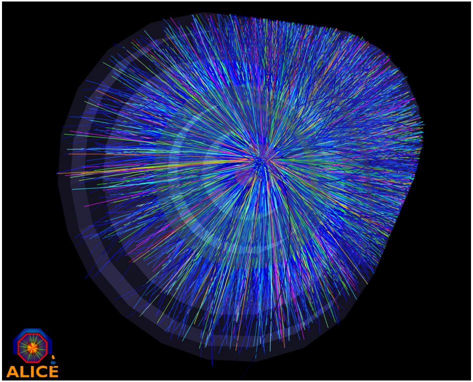
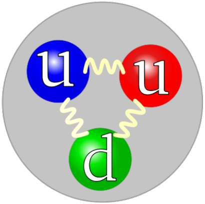
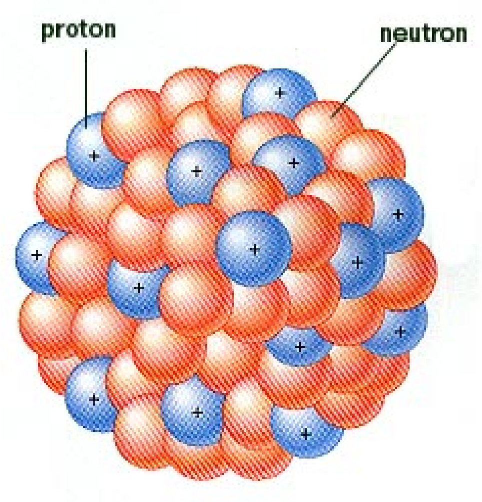


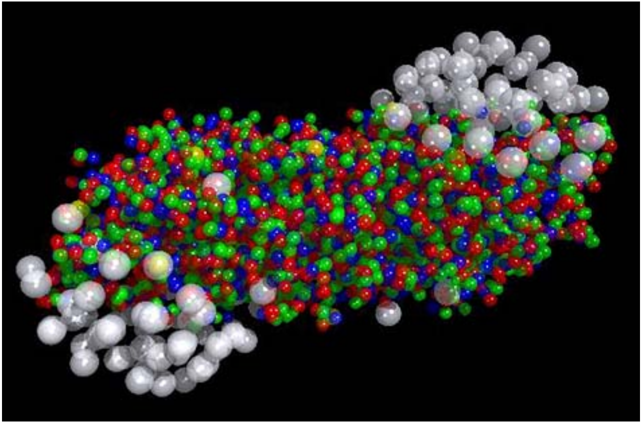
- Pb+Pb collision at the LHC: > 20,000 hadrons in the detectors !
- Partons which have been liberated by the collision.
- They leave imprints on the hadron distribution in the final state.
- Build effective theories for the relevant degrees of freedom.

Quark composition of a pion



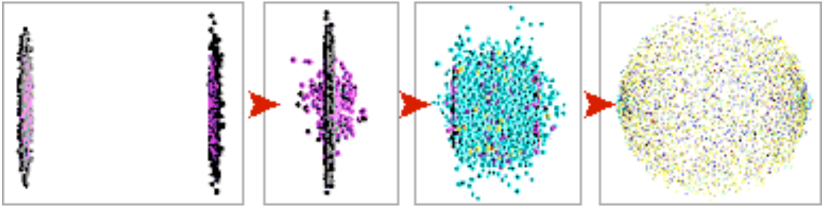


- At low energies, QCD matter exists only in the form of hadrons (mesons, baryons, nuclei) ... as a consequence of confinement

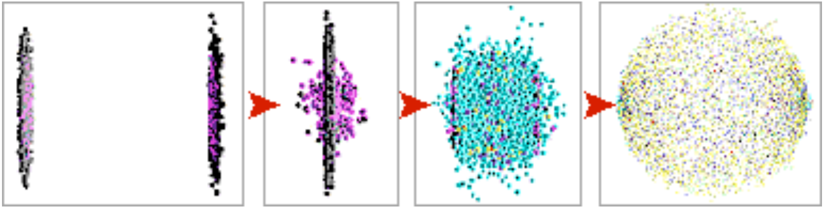


- At high energies, the relevant d.o.f. are partonic (quarks & gluons)
  ▷ interactions occur over distances much shorter than the confinement scale
- The HIC's give us access to dense forms of partonic matter

New forms of QCD matter produced in HIC



- Prior to the collision: 2 Lorentz–contracted nuclei ('pancakes')
  - 'Color Glass Condensate' : highly coherent form of gluonic matter
- Right after the collision: non–equilibrium partonic matter
  - 'Glasma' : color fields break into partons
- At later stages ($\Delta t \gtrsim 1$ fm/c) : local thermal equilibrium
  - 'Quark–Gluon Plasma' (QGP)
- Final stage ($\Delta t \gtrsim 10$ fm/c) : hadrons
  - 'final event', or 'particle production'



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- My focus here: the partonic phases at early and intermediate stages

Outline

- The wavefunctions of the incoming hadrons:

  Color Glass Condensate

- Particle production at early stages :

  proton-proton (pp), proton-nucleus (pA), nucleus-nucleus (AA)

- AA collisions : Glasma

- Thermalization

- Flow and hydrodynamics

- Thermodynamics of the Quark Gluon Plasma

- Hard probes of the QGP: jet quenching

Disclaimer

- Main emphasis: what do heavy ion collisions teach us about QCD
- A vast topics, many subfields, a lot of material, many issues that I do not understand myself (and that I will not try to cover)
- No aim to completeness, or to being systematic
- No technicalities, no real formulae, no systematic references
- Lots of cartoons and hand-waving arguments

Disclaimer

- For more references, formulae, cartoons and hand-waving arguments, have a look at this review paper

arXiv.org > hep-ph > arXiv:1205.0579

Search or Artic

High Energy Physics – Phenomenology

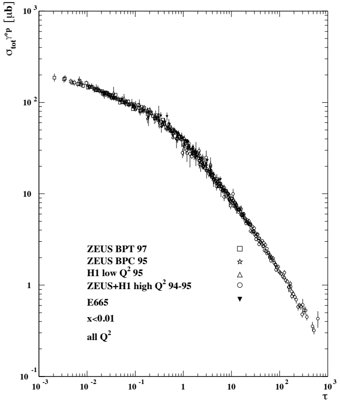
QCD in heavy ion collisions

Edmond Iancu

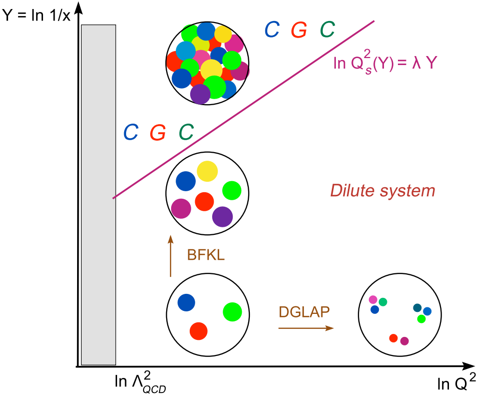
(Submitted on 2 May 2012)

These lectures provide a modern introduction to selected topics in the physics of ultrarelativistic heavy ion collisions which shed light on the fundamental theory of strong interactions, the Quantum Chromodynamics. The emphasis is on the partonic forms of QCD matter which exist in the early and intermediate stages of a collision -- the colour glass condensate, the glasma, and the quark-gluon plasma -- and on the effective theories that are used for their description. These theories provide qualitative and even quantitative insight into a wealth of remarkable phenomena observed in nucleus-nucleus or deuteron-nucleus collisions at RHIC and/or the LHC, like the suppression of particle production and of azimuthal correlations at forward rapidities, the energy and centrality dependence of the multiplicities, the ridge effect, the limiting fragmentation, the jet quenching, or the dijet asymmetry.

Comments:	Based on lectures presented at the 2011 European School of High-Energy Physics, 7-20 September 2011, Cheile Gradistei, Romania. 73 pages, many figures
Subjects:	**High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex); Nuclear Theory (nucl-th)
Cite as:	arXiv:1205.0579 **[hep-ph]**
	(or arXiv:1205.0579v1 **[hep-ph]** for this version)

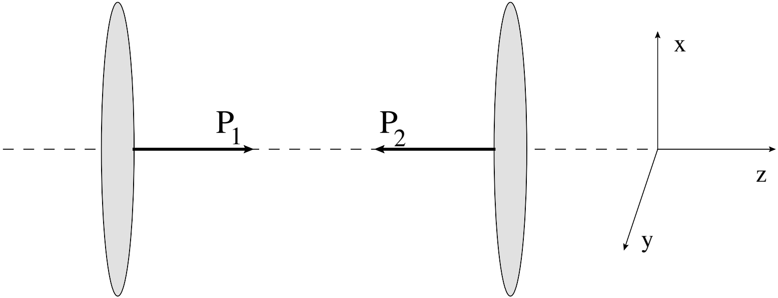


$\sigma_{tot}^{\gamma^* p}$ [μb]
ZEUS BPT 97
ZEUS BPC 95
H1 low Q^2 95
ZEUS+H1 high Q^2 94-95
E665
x<0.01
all Q^2
τ



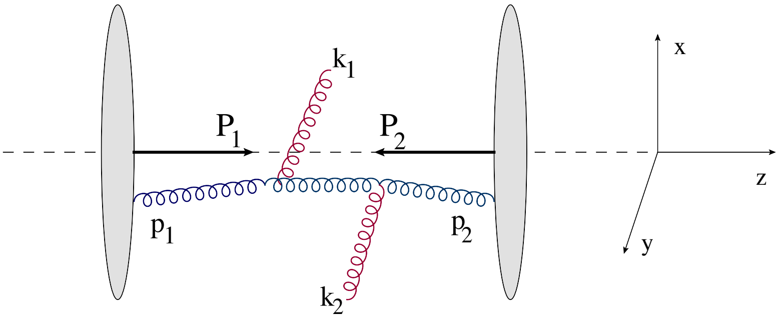
Y = ln 1/x
C G C
$\ln Q_s^2(Y) = \lambda Y$
C G C
Dilute system
BFKL
DGLAP
$\ln \Lambda^2_{QCD}$
$\ln Q^2$

The geometry of a hadron–hadron collision



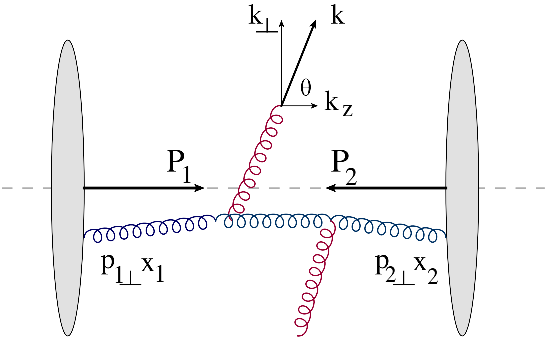
- z : longitudinal (or 'beam') axis; $\boldsymbol{x}_\perp = (x, y)$: transverse plane
- Center-of-mass frame : $P_1^\mu = (P, 0, 0, P)$, $P_2^\mu = (P, 0, 0, -P)$

The geometry of a hadron–hadron collision



- z : longitudinal (or 'beam') axis; $\boldsymbol{x}_\perp = (x, y)$: transverse plane
- Center-of-mass frame : $P_1^\mu = (P, 0, 0, P)$, $P_2^\mu = (P, 0, 0, -P)$
- $2 \to 2$ subcollision : $g(p_1) + g(p_2) \;\to\; g(k_1) + g(k_2)$
- Distinguish between transverse and longitudinal momenta

The kinematics of a $2 \to 2$ subcollision



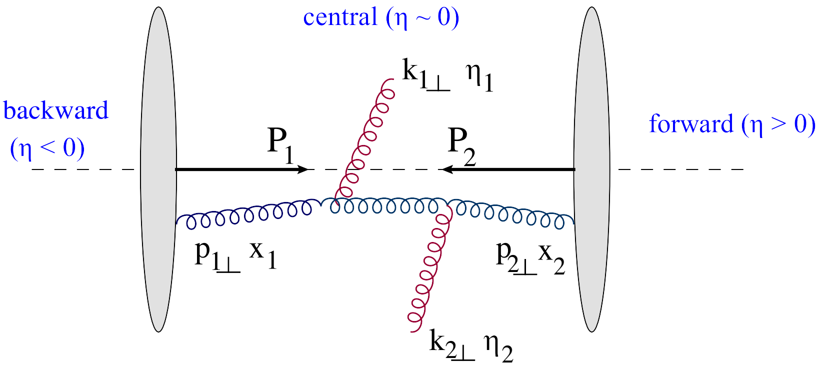
$$\eta = \frac{1}{2} \ln \frac{k + k_z}{k - k_z}$$

$$\eta = -\ln \tan \frac{\theta}{2}$$

$$\cos\theta = \frac{k_z}{k}$$

- Initial partons : $p^\mu = xP^\mu + p_\perp^\mu$ with $p_\perp^\mu = (0, \boldsymbol{p}_\perp, 0)$
  - transverse momentum $\boldsymbol{p}_\perp$
  - longitudinal momentum fraction $x = p_z/P$
- Final (or 'produced') partons :
  - transverse momentum $\boldsymbol{k}_\perp$
  - polar angle θ or rapidity $\eta \equiv -\ln\tan(\theta/2)$

The kinematics of a $2 \to 2$ subcollision (2)

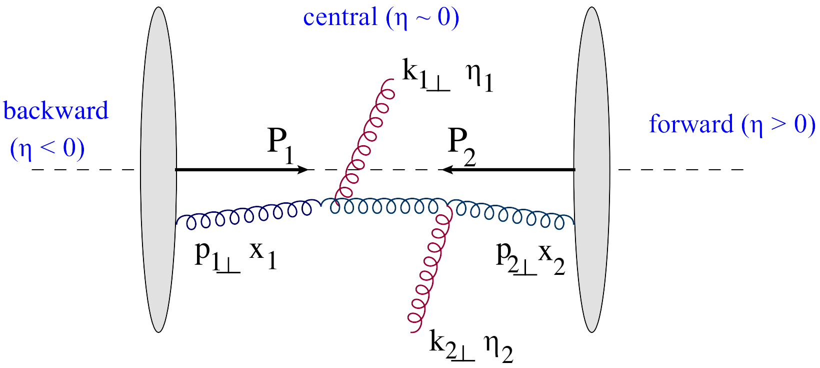


- Energy–momentum conservation $\Rightarrow$ $\boldsymbol{p}_{1\perp} + \boldsymbol{p}_{2\perp} = \boldsymbol{k}_{1\perp} + \boldsymbol{k}_{2\perp}$

$$x_1 = \frac{k_{1\perp}}{\sqrt{s}}\,\mathrm{e}^{\eta_1} + \frac{k_{2\perp}}{\sqrt{s}}\,\mathrm{e}^{\eta_2}\,, \qquad x_2 = \frac{k_{1\perp}}{\sqrt{s}}\,\mathrm{e}^{-\eta_1} + \frac{k_{2\perp}}{\sqrt{s}}\,\mathrm{e}^{-\eta_2}$$

- Exercice ! Hint : use $P = \sqrt{s}/2$, $k = k_\perp \cosh\eta$, $k_z = k_\perp \sinh\eta$

The kinematics of a $2 \to 2$ subcollision (2)



- Energy–momentum conservation ⇒ $\boldsymbol{p}_{1\perp} + \boldsymbol{p}_{2\perp} = \boldsymbol{k}_{1\perp} + \boldsymbol{k}_{2\perp}$

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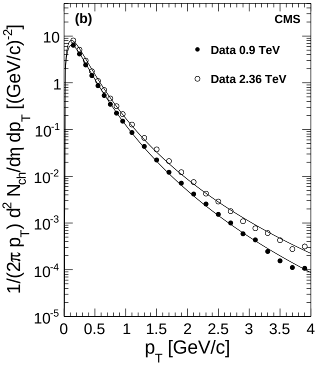
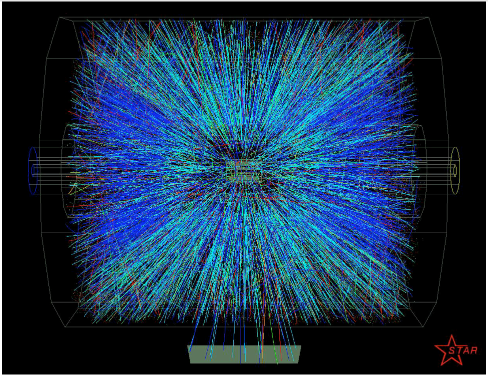
- What are the typical values of x for the participating partons ?

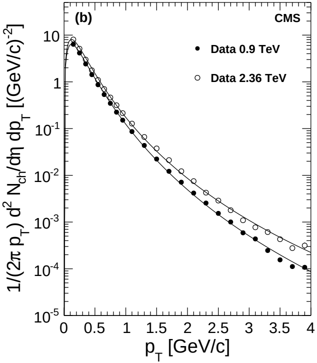
Multiplicity in pp, pA, AA : $\mathrm{d}N/\mathrm{d}\eta$

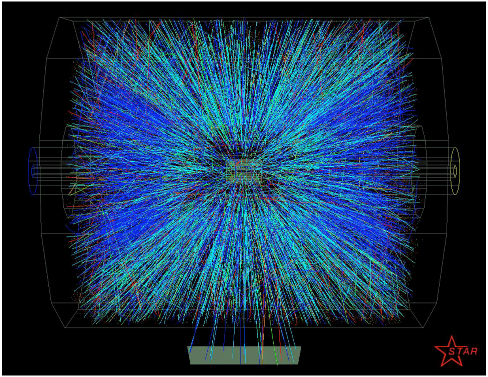




- 99% of the total multiplicity lies below $p_\perp = 2$ GeV
- $x \sim 10^{-2}$ at RHIC ($\sqrt{s} = 200$ GeV & $\eta = 0$)
- $x \sim 4 \times 10^{-4}$ at the LHC ($\sqrt{s} = 5$ TeV & $\eta = 0$)
- $x_2 \sim 10^{-5}$ at the LHC & forward rapidity ($\sqrt{s} = 5$ TeV & $\eta = 4$)

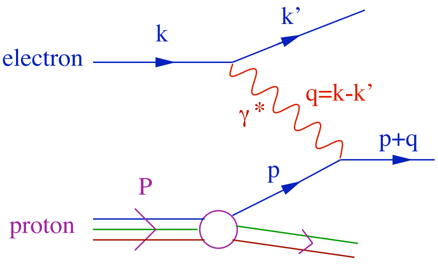
Multiplicity in pp, pA, AA : $\mathrm{d}N/\mathrm{d}\eta$



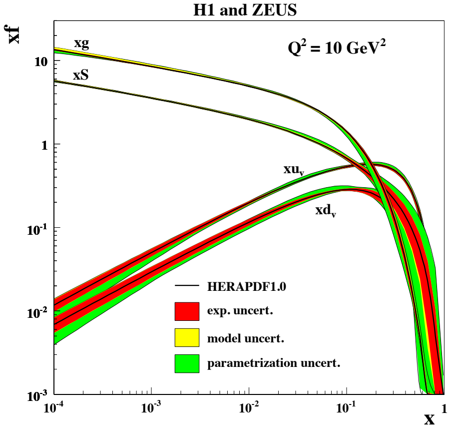


- The bulk of particle production is controlled by partons at small $x \ll 1$
- Where do all these partons come ?!

  ▷ 'a nucleon is built with 3 valence quarks, each one carrying $x \sim 1/3$'
- Need to better understand the parton structure of a hadron

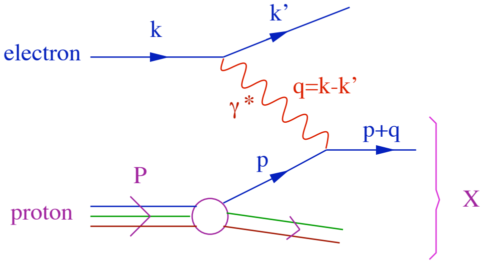


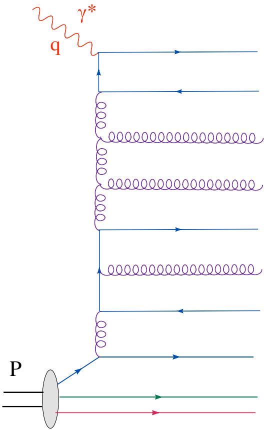
$$Q^2 = -q^\mu q_\mu > 0\,, \quad x = \frac{Q^2}{s}$$



- Parton distribution functions: $xq(x, Q^2)$, $xG(x, Q^2)$

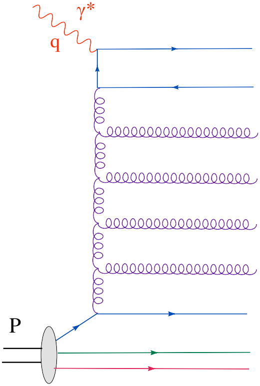
▷ number of partons (quark, gluons) with transverse size $\Delta x_\perp \sim 1/Q$ and longitudinal momentum fraction $x \sim Q^2/s$ per unit rapidity

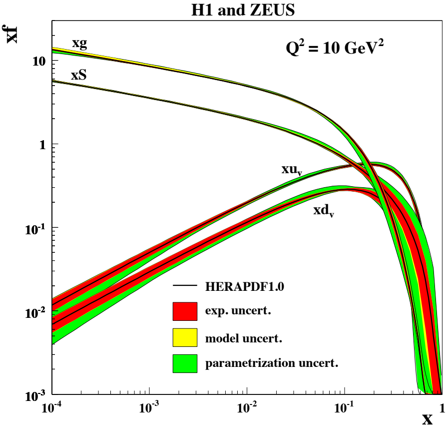




- The virtual photon γ^* couples to the (anti)quarks inside the proton
- Gluons are measured indirectly, via their effect on quark distribution
- Quantum evolution : change in the partonic content when changing the resolution scales x and Q^2, due to additional radiation

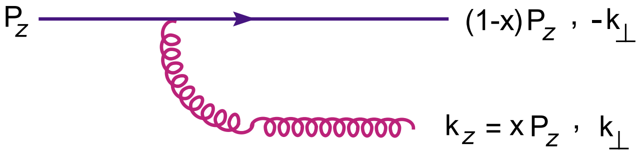
The small–x partons are mostly gluons





- For $x \leq 0.01$ the hadron wavefunction contains mostly gluons !
- The gluon distribution is rapidly amplified by the quantum evolution with decreasing x (or increasing energy s)

Bremsstrahlung



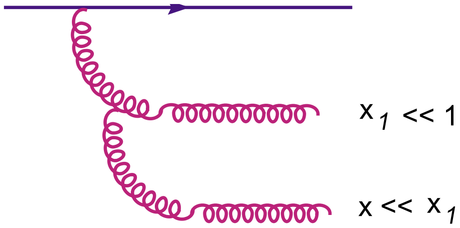
$$\mathrm{d}\mathcal{P}_{\rm Brem} \;\sim\; \alpha_s(k_\perp^2)\, C_R\, \frac{\mathrm{d}^2 k_\perp}{k_\perp^2}\, \frac{\mathrm{d}x}{x}$$

- 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:

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

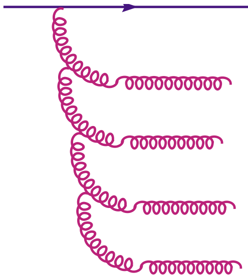
- Formally, a process of higher order in α_s, but which is enhanced by the large available rapidity interval
- $Y \equiv \ln(1/x)$: rapidity difference between the parent quark and the last emitted gluon
- When $\alpha_s Y \gtrsim 1 \Longrightarrow$ need for resummation !

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 :

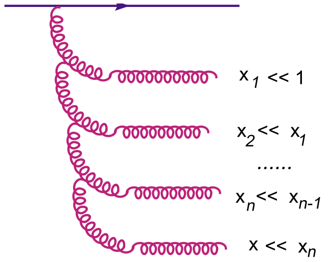


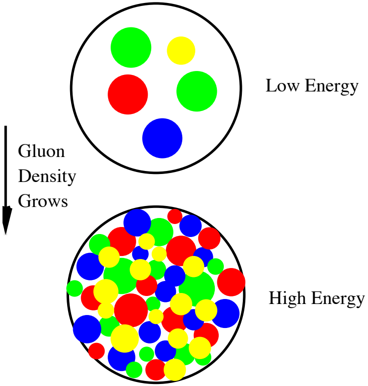
$$xg(x,Q^2)\;\propto\;\mathrm{e}^{\omega\alpha_s Y}\;\sim\;\frac{1}{x^{\omega\alpha_s}}$$ BFKL evolution

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

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

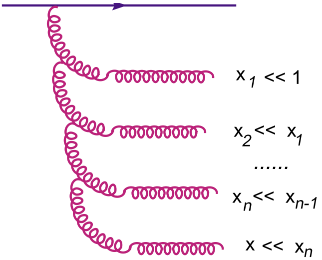
Gluon evolution at small x

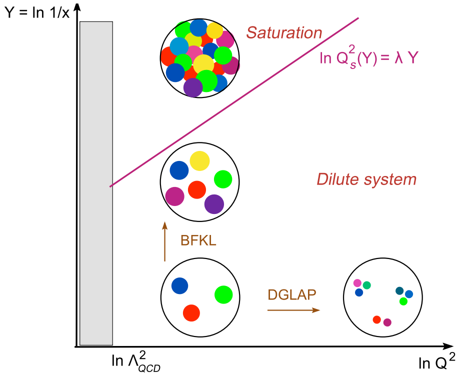




- BFKL: an evolution towards increasing density

Gluon evolution at small x

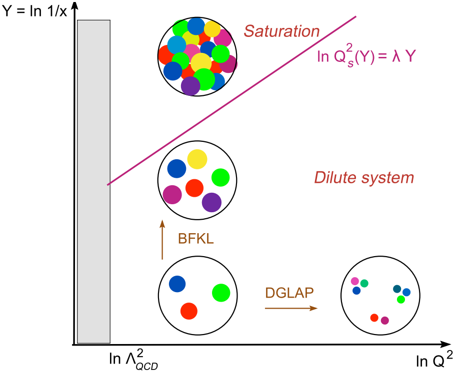




- BFKL: an evolution towards increasing density
- Non–trivial: not true for the DGLAP evolution !
  - the BFKL gluons have similar transverse momenta, hence similar transverse areas $\Longrightarrow$ they can overlap with each other
- The relevant quantity: not the gluon number, but ...

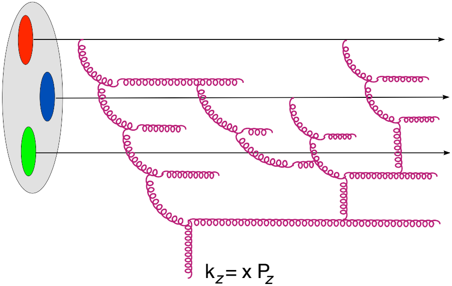
- The gluon occupation number (or 'packing factor')

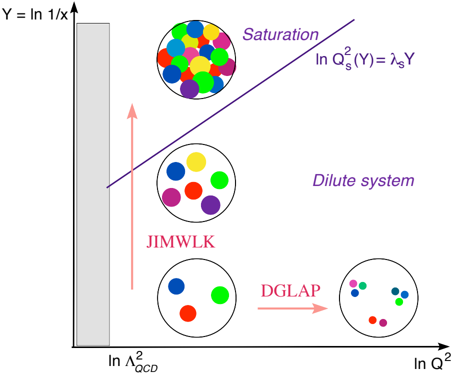
$$n(x, Q^2) = \frac{\pi}{Q^2} \times \frac{xG(x, Q^2)}{\pi R^2}$$



- When $n \gtrsim 1$: gluons overlap, so they are coherent with each other:
  - ▷ better described as a semi-classical, color field: 'condensate'
- Event–by–event: the field is frozen in some random configuration
  - ▷ average over the frozen configurations : 'glass'
- Cannot exceed a value $n \sim 1/\alpha_s$: 'gluon saturation'

Gluon saturation





- $\alpha_s n \sim 1$: strong overlapping which compensates small coupling
- The evolution becomes non–linear :

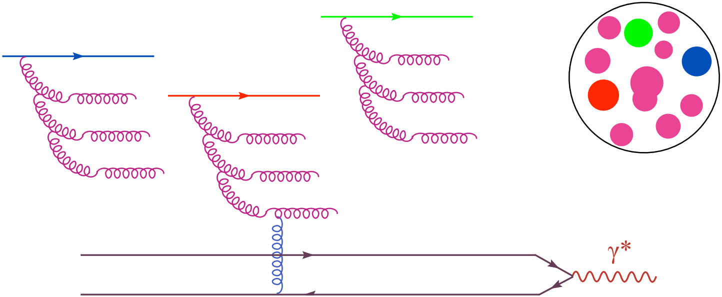
  ▷ emissions + recombination $\Longrightarrow$ gluon saturation

- BFKL gets replaced by the non–linear JIMWLK equation

  Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner (97–00)

A cartoon of the evolution equations : BFKL

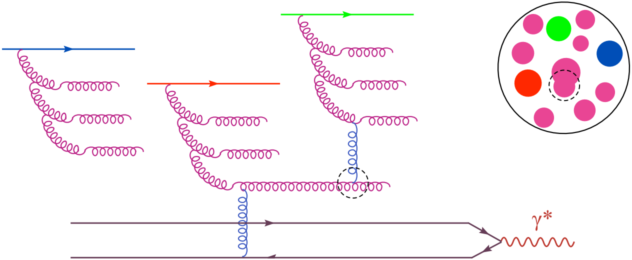
- $n(Y, Q^2)$: gluon occupation number
- Rapidity increment $Y \rightarrow Y + \mathrm{d}Y$: a probability $\alpha_s \mathrm{d}Y$ to emit an additional gluon out of any of the preexisting ones



$$\frac{\partial n}{\partial Y} \simeq \alpha_s n \qquad \Longrightarrow \qquad n(Y) \propto \mathrm{e}^{\omega \alpha_s Y}$$

- Valid so long as $n(Y, Q^2) \ll 1/\alpha_s$ (dilute system)

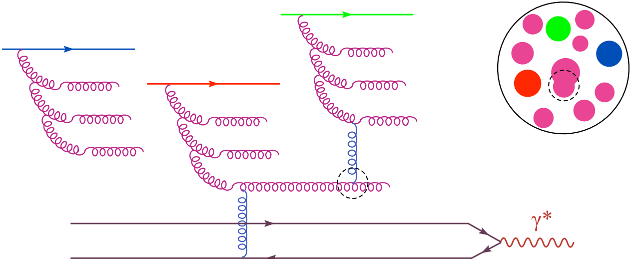
- High gluon density: recombination processes leading to saturation



$$\frac{\partial n}{\partial Y} \simeq \alpha_s n - \alpha_s^2 n^2 = 0 \quad \text{when} \quad n \sim \frac{1}{\alpha_s} \gg 1$$

- Fixed point : the evolution stops when $\alpha_s n(Y, Q^2) \sim 1$
- The saturation condition involves Y and Q^2
  $\Longrightarrow$ saturation momentum $Q_s(Y)$

- High gluon density: recombination processes leading to saturation



$$\frac{\partial n}{\partial Y} \simeq \alpha_s n - \alpha_s^2 n^2 = 0 \quad \text{when} \quad n \sim \frac{1}{\alpha_s} \gg 1$$

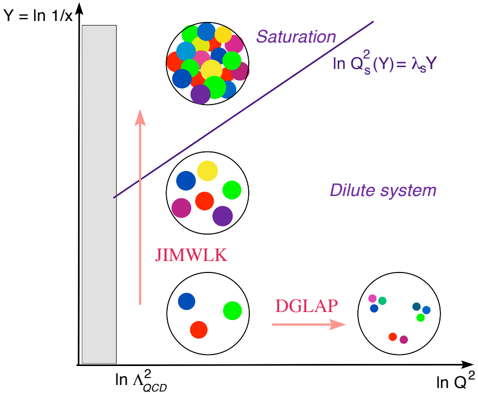
- The simplest equation with saturation *(Gribov, Levin, Ryskin, 83)*
- Cartoon version of the Balitsky–Kovchegov equation (BK)
- Mean field approximation (valid at large N_c) to JIMWLK

- The transverse momentum (or virtuality) scale where saturation effects start to be important

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

$$n\big(x, Q_s^2(x)\big) \sim \frac{1}{\alpha_s}$$

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



- Q_s is rapidly rising with $1/x$, i.e. with the center-of-mass energy :

$\lambda_s \simeq 0.2 \div 0.3$ at NLO accuracy *(Triantafyllopoulos, 2003)*

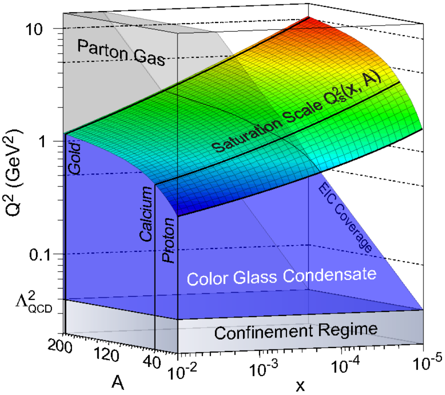
The saturation momentum

- The transverse momentum (or virtuality) scale where saturation effects start to be important

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

$$n\big(x,Q_s^2(x)\big) \;\sim\; \frac{1}{\alpha_s}$$

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



- ... and also with the atomic number A for a large nucleus ($A \gg 1$)

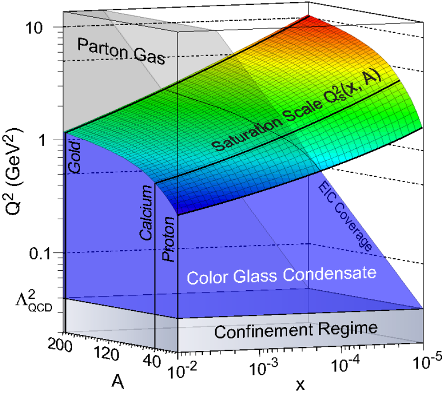
The saturation momentum

- The transverse momentum (or virtuality) scale where saturation effects start to be important

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

$$n\big(x,Q_s^2(x)\big) \sim \frac{1}{\alpha_s}$$

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

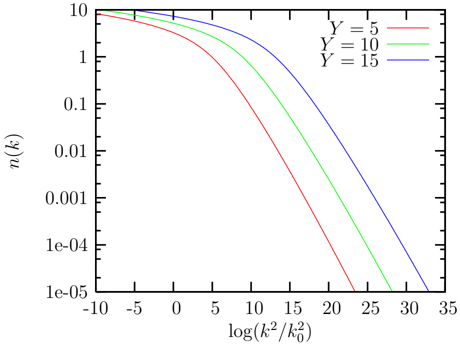


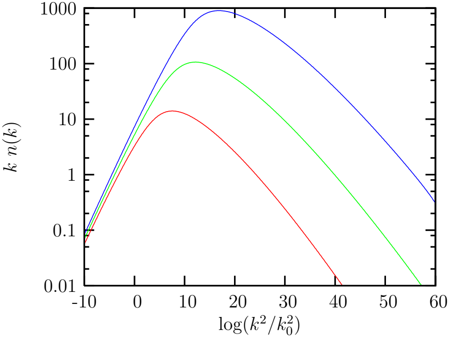
- $x \sim 10^{-5}$: $Q_s \sim 1$ GeV for proton and ~ 3 GeV for Pb or Au

Semi-hard intrinsic $k_\perp$

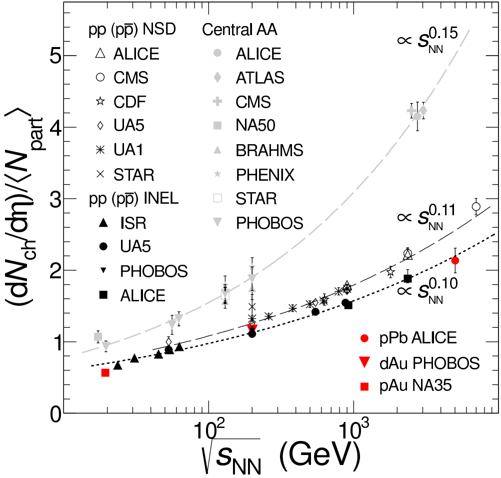
- $Q_s^2(x) \propto$ the gluon density per unit transverse area
- $Q_s(x)$: the typical transverse momentum of the gluons with a given x

$$xG(x,Q^2) = \int \mathrm{d}^2 b_\perp \int^Q \mathrm{d}k_\perp\, k_\perp\, n(x,b_\perp,k_\perp)$$



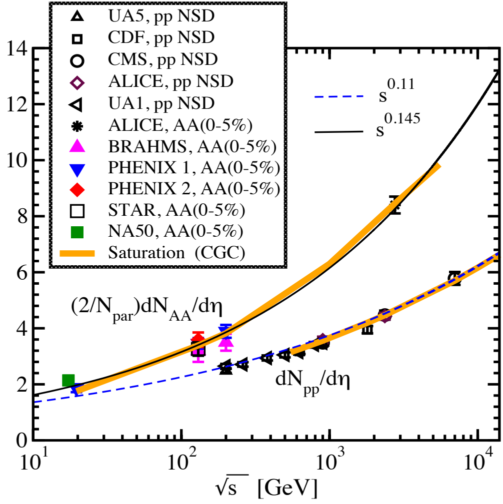


- Particle multiplicity $\mathrm{d}N/\mathrm{d}\eta \propto Q_s^2 \sim s^{\lambda_s/2}$
- $\lambda_s \simeq 0.2 \div 0.3$ in agreement with the data



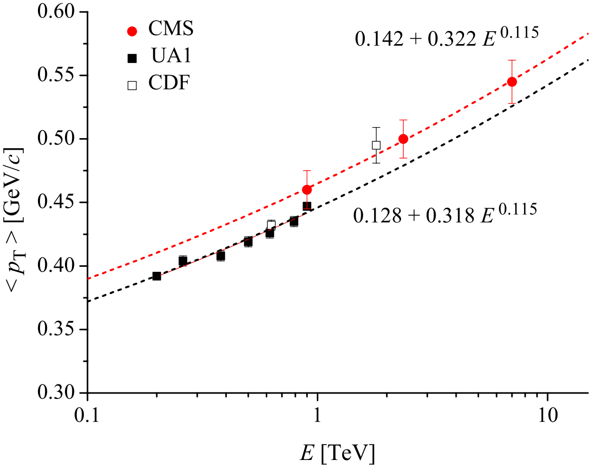
Multiplicity : energy dependence (2)

- CGC + MLLA: angular ordering in gluon cascade
- Explains the difference between pp and AA *(Levin, Rezaeian, '11)*



Average transverse momentum in p+p

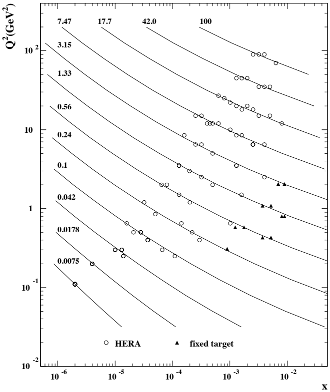
- Typical transverse momentum $\langle p_T \rangle \propto Q_s(E) \sim E^{\lambda_s/2}$

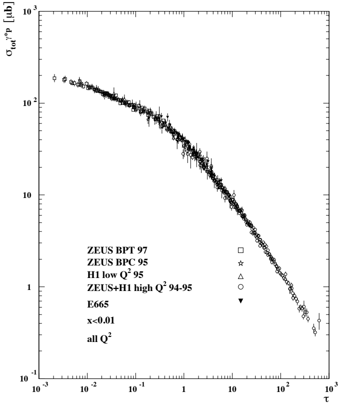


(McLerran and Praszalowicz, 2010)

- $Q_s(x)$ is the characteristic target scale in $p_\perp$ or virtuality $\Longrightarrow$ physics should depend upon the ratio $Q^2/Q_s^2(x)$: geometric scaling
- DIS cross–section at HERA *(Staśto, Golec-Biernat, Kwieciński, 2000)*

$$\sigma(x, Q^2) \ \text{vs.}\ \tau \equiv Q^2/Q_s^2(x) \propto Q^2/x^{0.3} : x \leq 0.01, \quad Q^2 \leq 450 \text{ GeV}^2$$

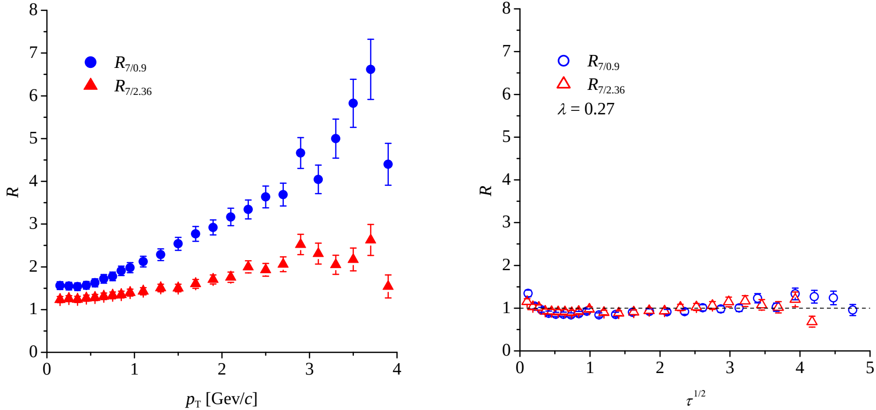


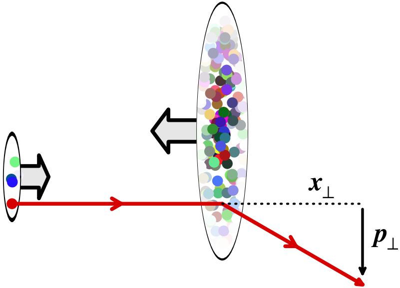


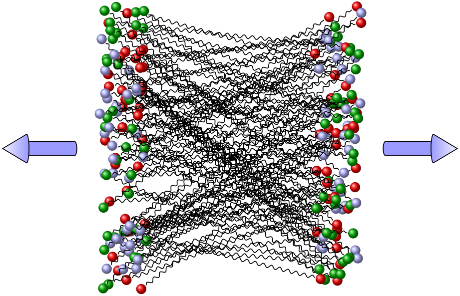
Geometric scaling in p+p at the LHC

- Particle production at 2 different energies *(McLerran, Praszalowicz, '10)*

$$R_{s_1/s_2} = \frac{(\mathrm{d}N/\mathrm{d}\eta\,\mathrm{d}^2p_\perp)\big|_{s_1}}{(\mathrm{d}N/\mathrm{d}\eta\,\mathrm{d}^2p_\perp)\big|_{s_2}} \to 1 \text{ as a function of } \tau \equiv \frac{p_T^2}{Q_s^2(p_T/\sqrt{s})}$$




$x_\perp$
$p_\perp$



Particle production

- How to compute particle production quantitatively ?
  - single inclusive hadron production $\frac{\mathrm{d}N}{\mathrm{d}^2p_\perp \mathrm{d}\eta}$
  - correlated di–hadron production

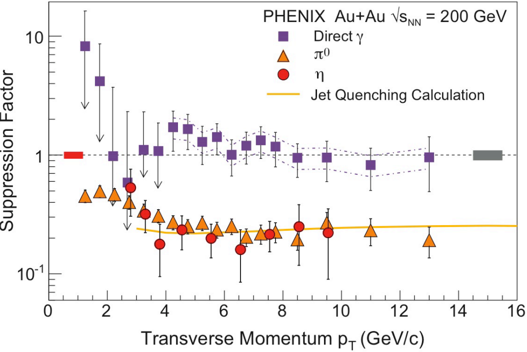
$$\frac{\mathrm{d}N_2}{\mathrm{d}^2p_{1\perp}\mathrm{d}\eta_1\mathrm{d}^2p_{2\perp}\mathrm{d}\eta_2} - \frac{\mathrm{d}N}{\mathrm{d}^2p_{1\perp}\mathrm{d}\eta_1}\frac{\mathrm{d}N}{\mathrm{d}^2p_{2\perp}\mathrm{d}\eta_2}$$

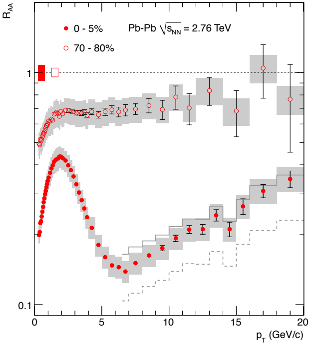
- Directly measured in pp, pA, AA at RHIC and the LHC
  - important information about high density/nuclear effects
- An example: the nuclear modification factor (or 'R_{AA} ratio')

$$R_{AA} \equiv \frac{1}{A^{4/3}}\frac{\mathrm{d}N_{AA}/\mathrm{d}^2p_\perp \mathrm{d}\eta}{\mathrm{d}N_{pp}/\mathrm{d}^2p_\perp \mathrm{d}\eta}$$

  - $A^{4/3} = A^2/A^{2/3}$: # of binary collisions per unit transverse area
  - R_{AA} would be 1 if AA = incoherent superposition of pp collisions
- ... but R_{AA} is far from being 1 !

R_{AA} at RHIC and the LHC



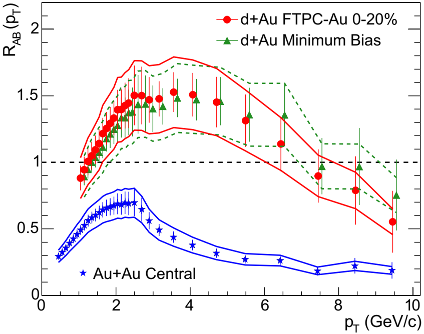


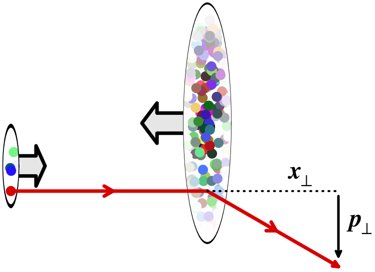
- Strong suppression: $R_{AA} \lesssim 0.2$ at moderate $p_\perp = 4 \div 12$ GeV
- High–density QCD effect: photons are not suppressed
- Possible explanations
  - 'initial state effects' : saturation in the nuclear wavefunctions
  - multiple scattering when the 2 nuclei cross each other
  - final state effects: interactions in the fireball created after the collision

The 'pA benchmark' : d+Au at RHIC

$$R_{\rm d+Au} \equiv \frac{1}{2A^{1/3}} \frac{{\rm d}N_{\rm d+Au}/{\rm d}^2p_\perp {\rm d}\eta}{{\rm d}N_{\rm p+p}/{\rm d}^2p_\perp {\rm d}\eta}$$

- One expects no fireball in d+Au $\Longrightarrow$ no final state interactions





- No suppression, rather an enhancement : 'Cronin peak'
- The suppression seen in R_{AA} must be a final state effect

Particle production (2)

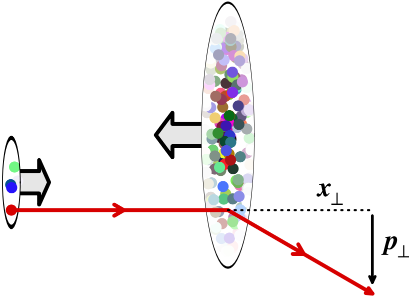
- Can one compute such effects (Cronin peak, R_{AA}) within QCD ?
- Different kinds of collisions according to the parton densities in the projectile and the target :
  - 'dilute–dilute' : pp collisions & mostly central rapidities
  - 'dilute–dense' : pA collisions and very forward pp
  - 'dense–dense' : AA collisions
- Different formalisms ('factorization schemes') :
  - 'dilute–dilute' : collinear factorization (single scattering)

    ▷ pdf's $\otimes$ partonic cross–section $\otimes$ fragmentation into hadrons
  - 'dilute–dense' : CGC factorization (saturation & multiple scattering)

    ▷ eikonal approximation, Wilson lines
  - 'dense–dense' : classical Yang–Mills dynamics plus CGC

    ▷ initial conditions for the subsequent evolution of the fireball

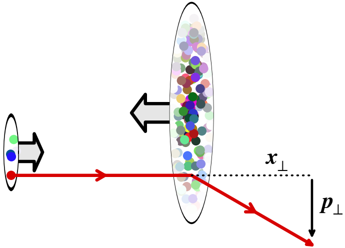
'Dilute–dense' (pA, dA, forward pp)

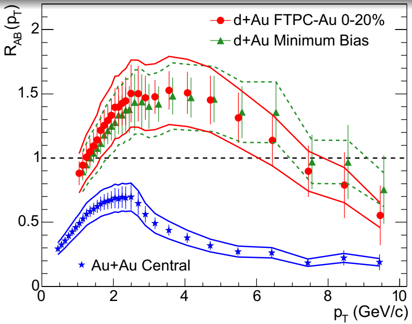


$$x_p \sim \frac{p_\perp}{\sqrt{s}}\,\mathrm{e}^{\eta}$$

$$x_A \sim \frac{p_\perp}{\sqrt{s}}\,\mathrm{e}^{-\eta}$$

- d+Au collisions at RHIC: $\sqrt{s} = 200$ GeV and $p_\perp \sim 2$ GeV
  - $\eta = 0$ ('midrapidity') $\Longrightarrow x_p = x_A = 0.01$ (Cronin peak)
  - $\eta = 3$ ('forward rapidity') $\Longrightarrow x_p = 0.2,\ x_A = 5 \times 10^{-4}$
- Midrapidity : the nucleus looks dense already for $x_A = 0.01$
  - a quark, or gluon, from the proton undergoes multiple scattering
  - random kicks = transfers of transverse momentum





- A random walk in $p_\perp$ leading to transverse momentum broadening

$$\frac{\mathrm{d}N}{\mathrm{d}^2p_\perp \mathrm{d}\eta} = x_p\, q(x_p, Q^2)\, \mathcal{P}(p_\perp, x_A)\,, \qquad \mathcal{P}(p_\perp, x_A) \equiv \frac{1}{\pi Q_s^2}\, \mathrm{e}^{-\frac{p_\perp^2}{Q_s^2}}$$

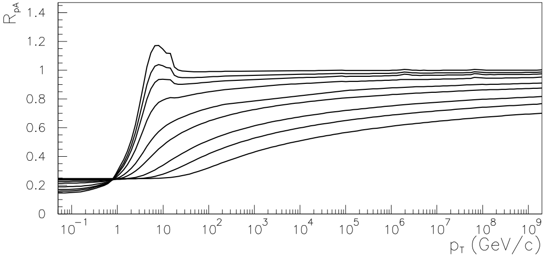
  - a function of $p_\perp^2/Q_s^2$ with $Q_s \equiv Q_s(A, x_A) \Longrightarrow$ geometric scaling
  - average $p_\perp^2$: $\langle p_\perp^2 \rangle = Q_s^2(A, x_A)$

    $\Longrightarrow$ the distribution in $p_\perp$ gets shifted towards harder values $\sim Q_s(A)$

- No such a shift in pp collisions $\Longrightarrow$ Cronin peak in the R_{pA} ratio

Moving towards forward rapidities: $\eta > 0$

- Recall : 'forward rapidity' $\Longleftrightarrow$ smaller values of x_A in the target



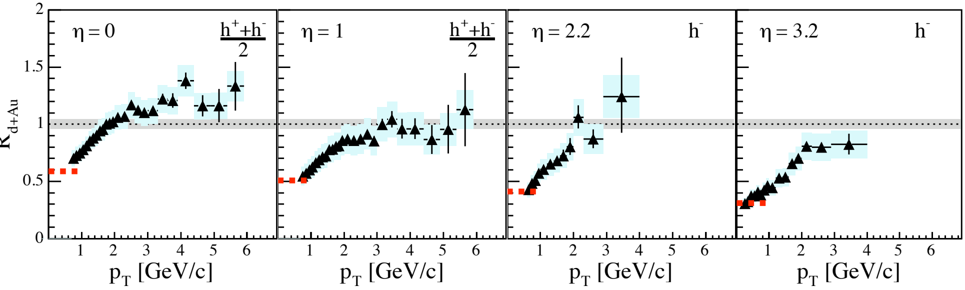
$$R_{pA} \equiv \frac{1}{A^{1/3}} \frac{\mathrm{d}N_{pA}/\mathrm{d}^2p_\perp \mathrm{d}\eta}{\mathrm{d}N_{pp}/\mathrm{d}^2p_\perp \mathrm{d}\eta}$$

$$x_A = \frac{p_\perp}{\sqrt{s}}\,\mathrm{e}^{-\eta}$$

$\eta =$ 0, 0.05, 0.1, 0.2, 0.4, 0.6, 1, 1.4 and 2 *(BK equation: Albacete et al, 2003)*

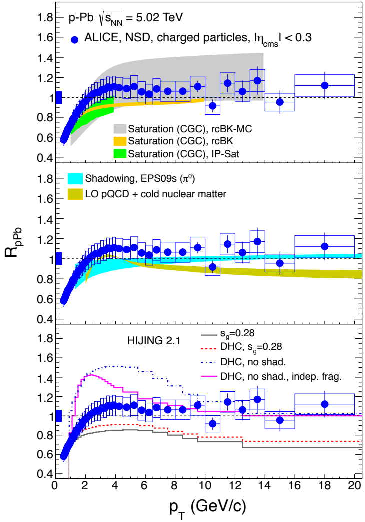
- 'Target' is either a nucleus (numerator), or a proton (denominator)
- Rapid evolution with η : no Cronin peak for $\eta \gtrsim 0.4$
  - for $p_\perp \lesssim Q_s(A, x_A)$, the nucleus is already saturated $\Rightarrow$ no evolution
  - for $p_\perp \sim Q_s(A, x_A)$, the proton is still dilute $\Rightarrow$ rapid evolution

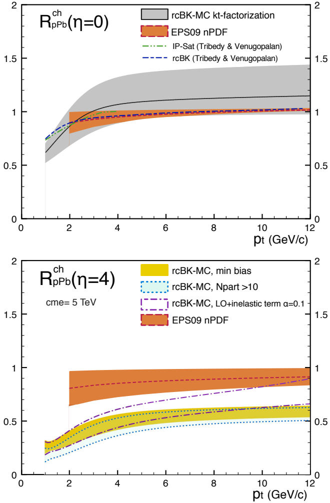
- This trend is clearly confirmed by the RHIC data (BRAHMS)



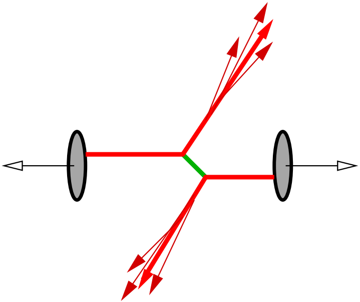
- N.B. The theoretical predictions for the evolution are much more robust (i.e. model independent) than those for the normalization
- Using the same set–up $\Longrightarrow$ predictions for p+Pb at the LHC
  (Tribedy and Venugopalan, '11; Rezaeian, '12; Albacete, Dumitru, Fujii, and Nara, 2012)

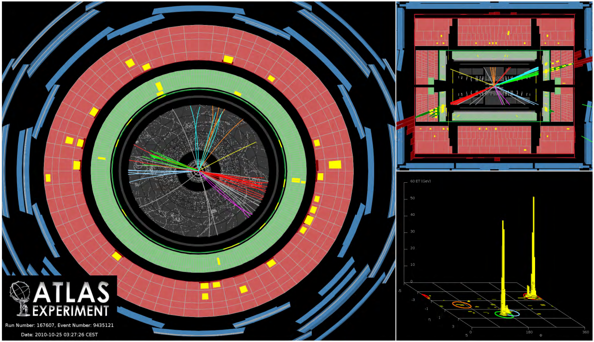
$R_{\rm p+Pb}$ at the LHC for central rapidities





- No Cronin peak ... in agreement with the CGC expectations
- Various models could be differentiated by going to forward rapidities



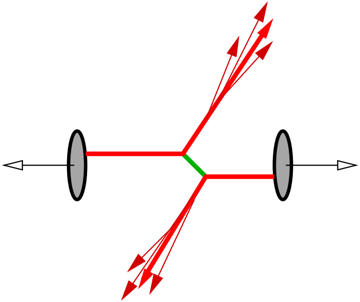


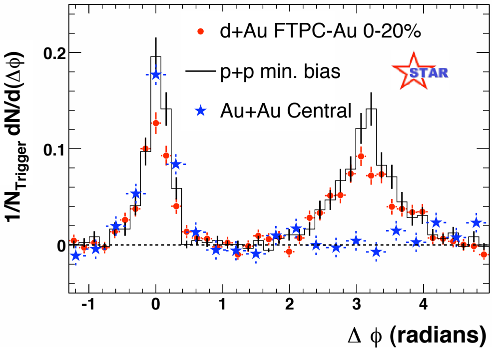
- Hard scattering $\Longrightarrow$ two jets back-to-back in the transverse plane

  visible via 2–particle azimuthal correlations: a peak at $\Delta\phi = \pi$

Di–hadron azimuthal correlations

- Di–hadron azimuthal correlations at RHIC: p+p, d+Au, Au+Au

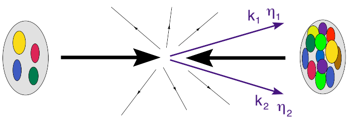


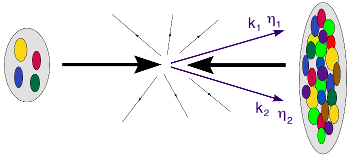


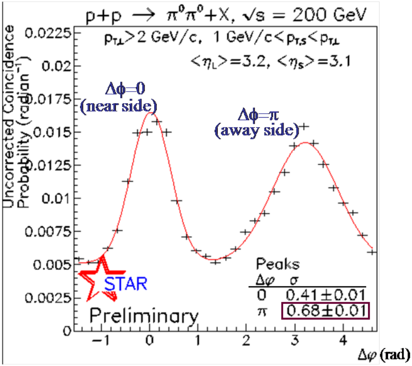
  - p+p or d+Au $(\eta \simeq 0)$: a well pronounced peak at $\Delta\Phi = \pi$
  - Au+Au : no away peak (final state effect: 'jet quenching')

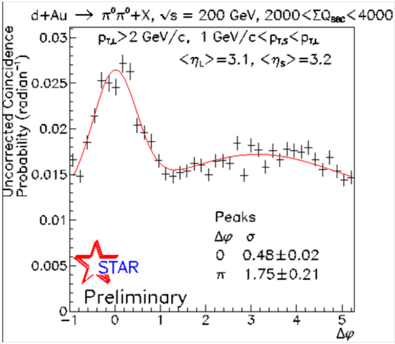
- Transverse momentum broadening in pA could reduce the correlation (broaden the away peak) ... but this is not seen at midrapidities

Forward rapidities: p+p vs. d+Au

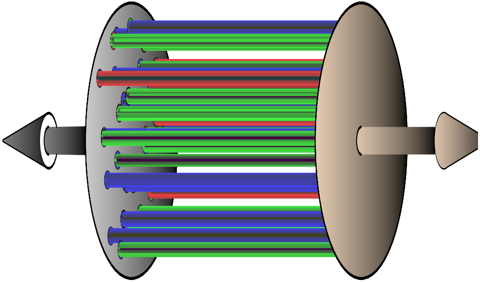


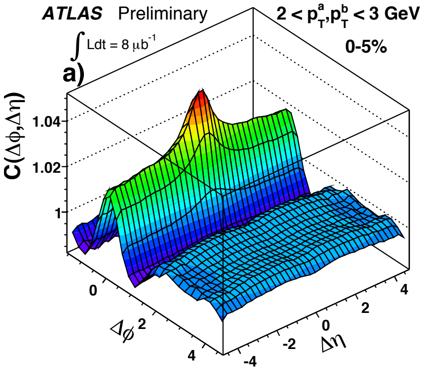




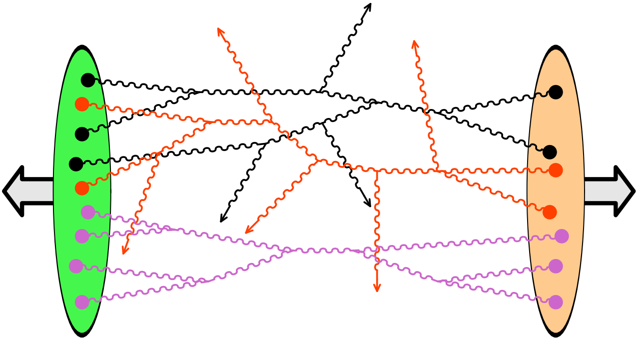


- Predicted by the CGC *(Marquet, 2007; Albacete and Marquet, 2010)*



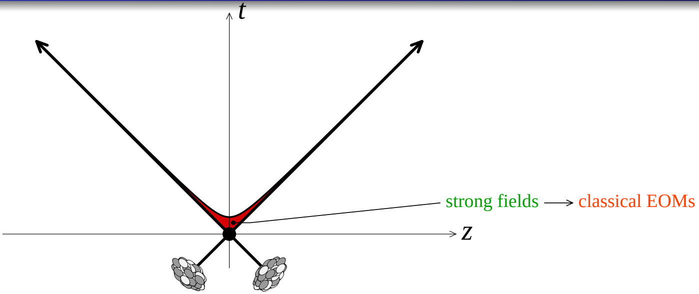

ATLAS Preliminary
∫Ldt = 8 μb⁻¹
a)
2 < p_T^a,p_T^b < 3 GeV
0-5%
C(Δφ,Δη)
1.04
1.02
1
0
2
4
Δφ
-4
-2
0
2
4
Δη

Nucleus–nucleus collisions



- Weakly coupled ($\alpha_s \ll 1$) but dense ($n \sim 1/\alpha_s$) : highly non–linear
- Two strong color fields (CGC's) with scatter with each other
- 'Scattering' : non–linear effects in the classical Yang–Mills equation sourced by the color charges in the 2 nuclei

Nucleus–nucleus collisions

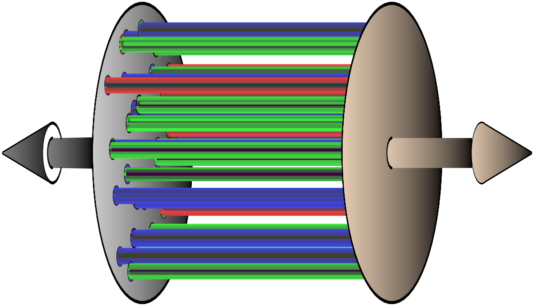


$$D_\nu F^{\nu\mu}(x) = \delta^{\mu +}\rho_R(x) + \delta^{\mu -}\rho_L(x)$$

- $\rho_{R,L}(x)$: colour charge distributions in the 'right' and 'left' mover
- Solve the YM eqs. numerically (2D lattice) $\Longrightarrow$ the glasma field
- Average over $\rho_{R,L}(x)$ using the respective CGC weight functions
- Decompose the 2-point function in Fourier modes $\Longrightarrow$ gluon spectrum
- N.B. Hadron spectra are modified by final state interactions

Glasma

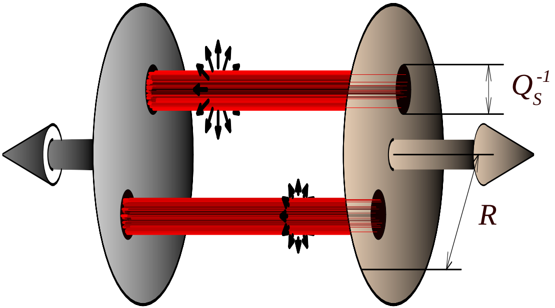
- Right after the collision, the chromo-electric and chromo-magnetic fields are purely longitudinal
- Flux tubes which extend between the recessing nuclei
  'glasma' (from 'glass' + 'plasma') *(McLerran and Lappi, 06)*



- These anisotropic configurations are unstable (Weibel instability)

From flux tubes to particles

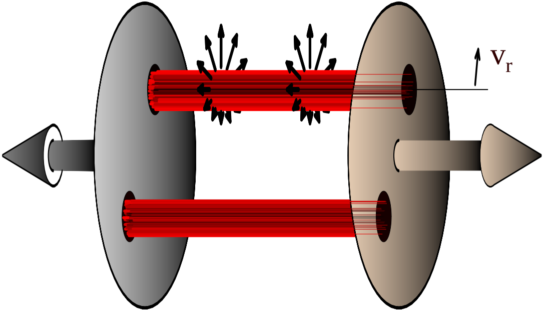
- At time $\tau \sim 1/Q_s$, the glasma flux tubes break into particles (gluons)
- Gluons emitted from the same flux tube are correlated with each other



- correlation length in the transverse plane: $\Delta r_\perp \sim 1/Q_s$
- correlation length in rapidity (Y or η): $\Delta\eta \sim 1/\alpha_s$
- to start with, this correlation is isotropic in $\Delta\Phi$

From flux tubes to particles

- At time $\tau \sim 1/Q_s$, the glasma flux tubes break into particles (gluons)
- Gluons emitted from the same flux tube are correlated with each other

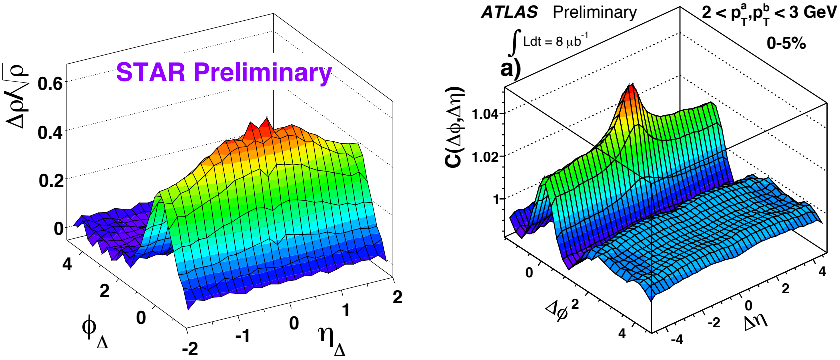


- correlation length in the transverse plane: $\Delta r_\perp \sim 1/Q_s$
- correlation length in rapidity (Y or η): $\Delta\eta \sim 1/\alpha_s$
- in presence of radial flow, there is a bias leading to collimation in $\Delta\Phi$

  ▷ more particles along the radial velocity $\boldsymbol{v}_r$ than perpendicular to it

The Ridge in AA

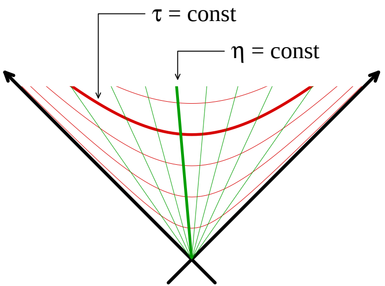
- A natural explanation for the ‘ridge’ :
  - di–hadron correlations long–ranged in $\Delta\eta$ & narrow in $\Delta\phi$
  - abundantly observed in AA collisions at RHIC and the LHC

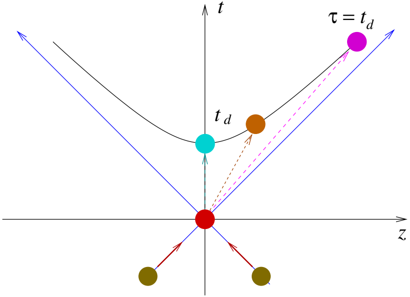


- Long–range correlations in rapidity ($\Delta\eta$) are created at early times

$\Longrightarrow$ they teach us about the initial conditions

- The right variables: proper time τ and space–time rapidity η



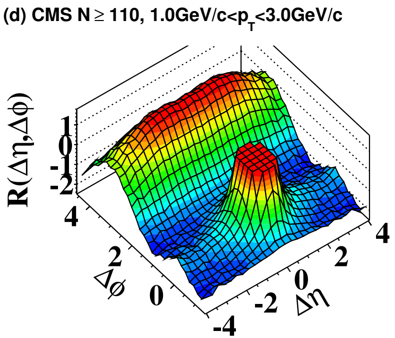


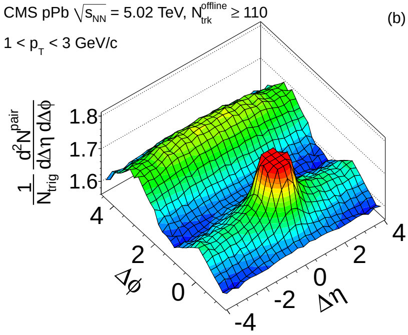
$$\tau = \sqrt{t^2 - z^2}\,, \quad \eta = \frac{1}{2}\ln\frac{t+z}{t-z}$$

- If the three fireballs all start out from $t = 0,\ z = 0$ and evolve exactly the same way (e.g. thermalization), the state of the cyan at $t = t_d$ is the same as the state of the brown and magenta at $\tau = t_d$

- Long–range correlation in $\Delta\eta$: ‘Little Bang’ + Boost invariance

- LHC : quite surprisingly, a ridge is also observed in p+p and p+A events with unusually high multiplicity





- What is the origin of the azimuthal collimation ?
- Can flow develop in such small systems (~ 1 fm) ?
- This might reflect the momentum correlations at early times (glasma)

The thermalization puzzle

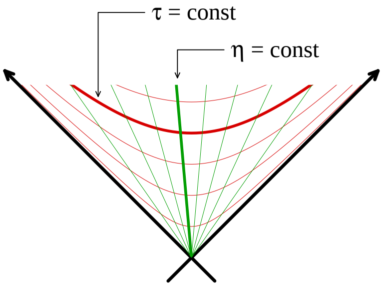
- Is there a quark–gluon plasma in the intermediate stages of a HIC ?
  - this requires local thermal equilibrium
  - to equilibrate, particles need to efficiently exchange energy and momentum
  - thermalization is not guaranteed for a system which expands and which is weakly coupled
- Just after the collision, the partonic matter is highly anisotropic
  - the glasma flux tubes have 'negative longitudinal pressure' : they oppose to expansion (like a string of rubber)

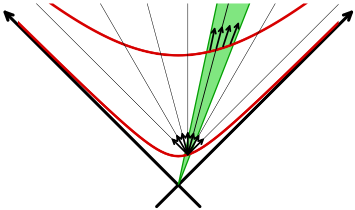
$$T_{\rm eq} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & \varepsilon/3 & 0 & 0 \\ 0 & 0 & \varepsilon/3 & 0 \\ 0 & 0 & 0 & \varepsilon/3 \end{pmatrix} \qquad T_{\rm initial} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & \varepsilon & 0 & 0 \\ 0 & 0 & \varepsilon & 0 \\ 0 & 0 & 0 & -\varepsilon \end{pmatrix}$$

  - in equilibrium: $P_T = P_L = \varepsilon/3$; in the early glasma: $P_T = \varepsilon = -P_L$

The longitudinal expansion

- The original anisotropy can be amplified by the longitudinal expansion



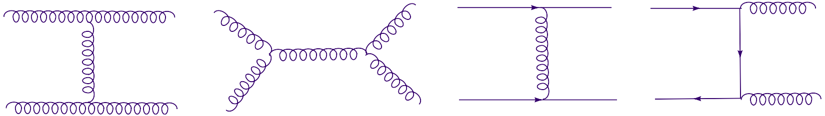


$$\eta = \frac{1}{2}\ln\frac{t+z}{t-z} = \frac{1}{2}\ln\frac{1+v_z}{1-v_z} \quad \text{for a free particle } (z = v_z t)$$

- if particles fly freely, only one longitudinal velocity can exist at a given rapidity η : $v_z = \tanh\eta = \cos\theta$
- longitudinal expansion is the biggest obstacle against isotropisation !

Thermalization in perturbation theory

- Particles can exchange energy and momentum through collisions.
- Weak coupling: the dominant mechanism is $2 \to 2$ elastic scattering



- Cross–section (σ) scales like $|\text{amplitude}|^2$, hence like $g^4 \sim \alpha_s^2$
- Mean free path (ℓ) = average distance between successive collisions

$$\ell \sim \frac{1}{\text{density} \times \sigma} \sim \frac{1}{\alpha_s^2}$$

- Typical equilibration time: $\tau_{\text{eq}} \sim \ell/v \sim 1/\alpha_s^2$
- Weakly coupled systems have large equilibration times ! ☹

The role of the strong fields

- Heisenberg's uncertainty principle requires

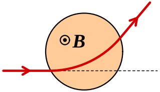
$$\text{mean free path } \ell \gtrsim \text{ de Broglie wavelength } \lambda \sim \frac{1}{p}$$

- In general, weakly interacting systems have $\ell \gg \lambda$
  - weakly coupled QGP, temperature T : $\lambda \sim 1/T$ while $\ell \sim 1/[\alpha_s^2 T]$

- However, the situation can change for a particle interacting with a strong electric, or magnetic, field, as in the glasma
  - domain of size Q_s^{-1} where the (chromo) magnetic field is $|\boldsymbol{B}| \sim Q_s^2/g$

$$\text{Lorentz force : } \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = g\boldsymbol{v} \times \boldsymbol{B} \implies \dot{\theta} \sim \frac{gB}{p} \sim Q_s$$

  - time spent in the domain $\tau \sim Q_s^{-1} \implies \Delta\theta \sim \mathcal{O}(1)$

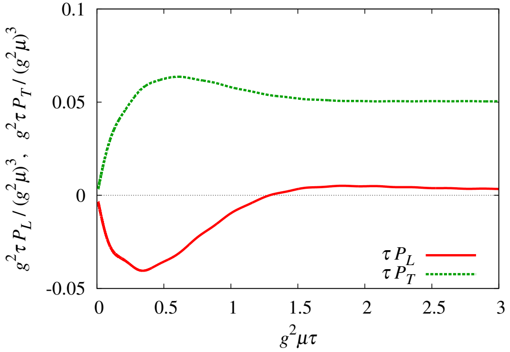


- Mean free path $\ell \sim Q_s^{-1} \sim 1/p$: as low as permitted by Heisenberg

Thermalization at weak coupling & strong fields

(Epelbaum and Gelis, 2013)

- Numerical solution to classical Yang–Mills eq. confirms the anisotropy

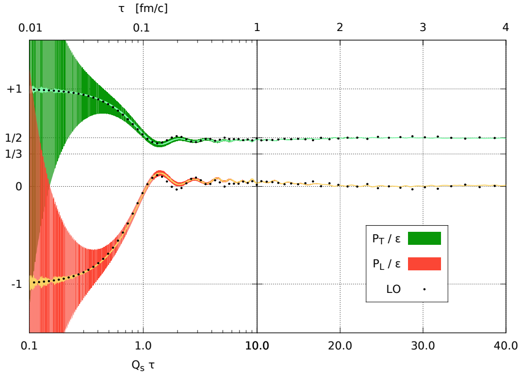


- the saturation momentum $Q_s = g^2\mu$ sets the scale
- $\tau\varepsilon = \tau(2P_T + P_L) \approx$ const. (longitudinal expansion)
- τP_L starts by being negative, then it becomes positive, but it remains much smaller than τP_T

(Epelbaum and Gelis, 2013)

- However, this (boost–invariant) classical solution is unstable under (rapidity–dependent) quantum fluctuations.
- The fluctuations can be added to the initial conditions

$\alpha_s = 8\,10^{-4}$ $(g = 0.1)$



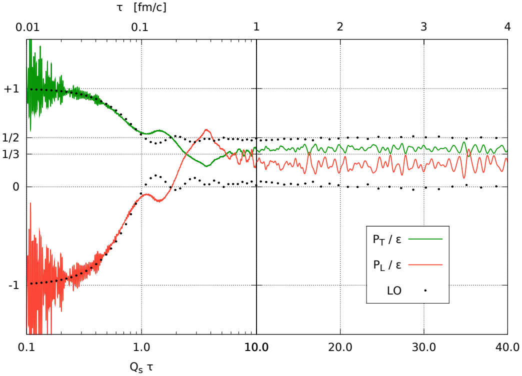
- for very small $g = 0.1$, the solution preserves boost invariance, as at LO

Thermalization at weak coupling & strong fields

(Epelbaum and Gelis, 2013)

- However, this (boost–invariant) classical solution is unstable under (rapidity–dependent) quantum fluctuations.
- The fluctuations can be added to the initial conditions

$\alpha_s = 2\,10^{-2}$ $(g = 0.5)$



- for $g \gtrsim 0.5$, it approaches isotropy: $P_L/P_T \simeq 0.7$ ☺