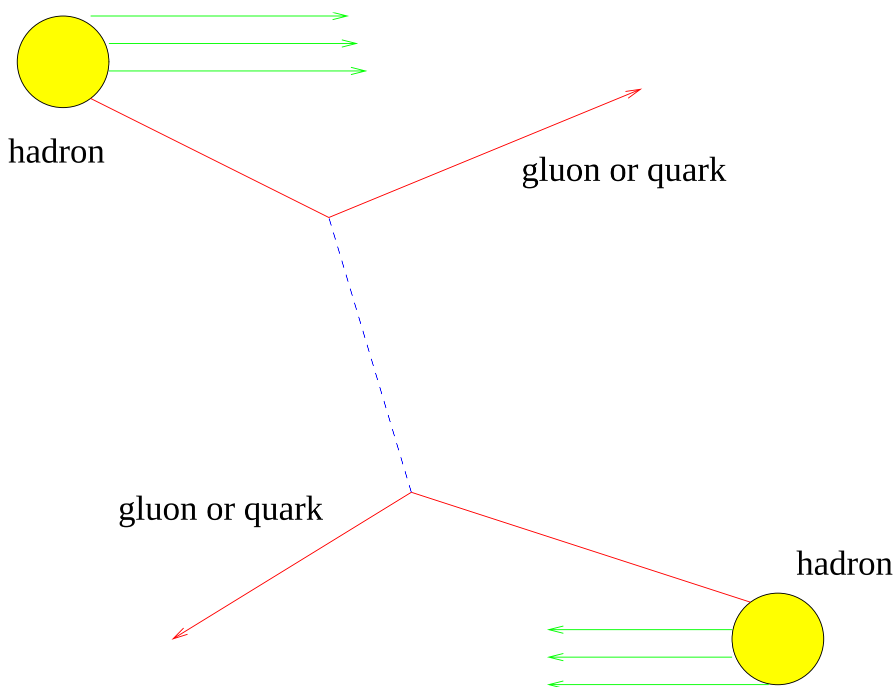
The Color Glass Condensate
and
The High Energy Limit of QCD

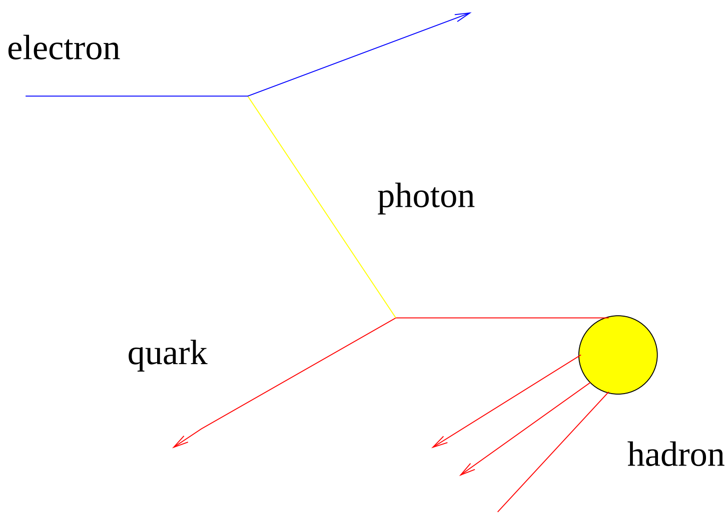
QCD describes strong interactions.

It is tested in jet production:



When Q^2 is large, $\alpha_s(Q^2)$ is small
Computable

Tested in deep inelastic scattering:



Q^2 large => $\alpha_s(Q^2)$ small.

QCD also qualitatively and semiquantitatively describes hadron spectrum using lattice

But we do not understand
the high energy limit of QCD

What are average or typical properties of
hadrons as $E \to \infty$?
Is the physics simple as $E \to \infty$?

Will argue physics is controlled by
a new form of high energy density
gluonic matter:

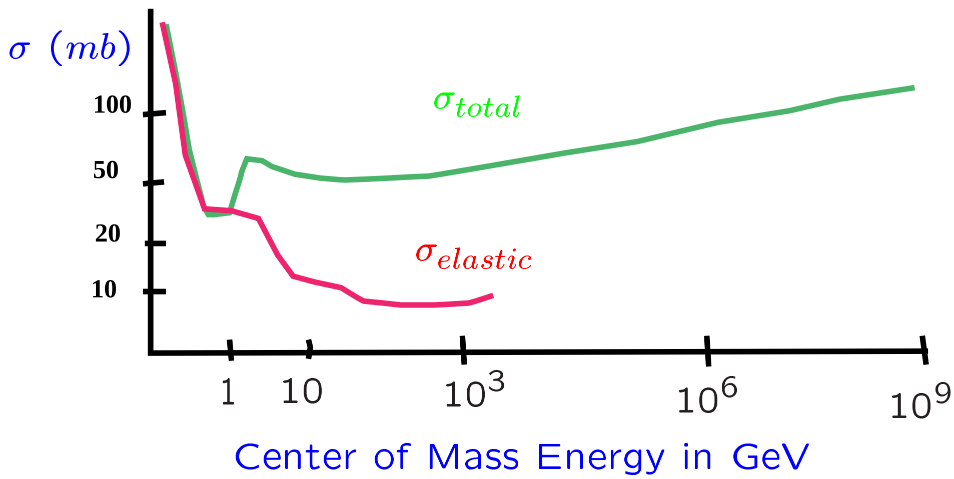
Color Glass Condensate

Universal matter from which all
hadrons are made.

Universal => Fundamental

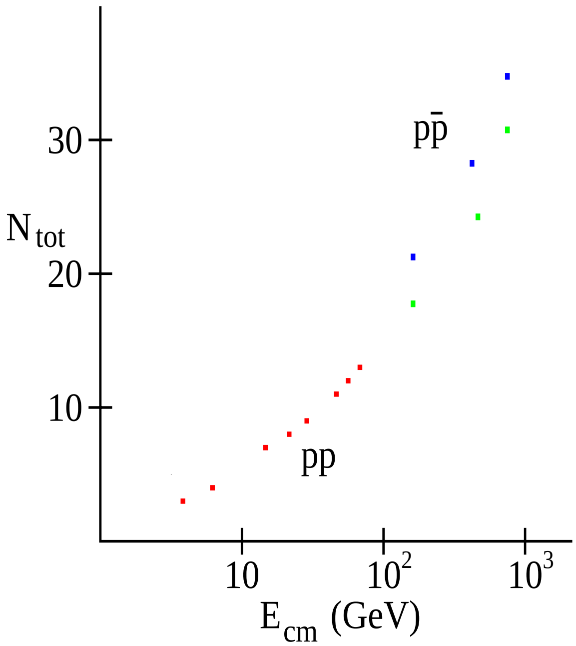
What are the "simple" phenomena of high energy QCD?

The total hadronic cross section:



- Does σ_{total} grow as $ln^2(E)$ as $E \to \infty$?
- Is the coefficient of $ln^2(E)$ universal?
- What is the physical origin of this "Froissart bound saturation", or why is it as big as it can be?
- Is the cross section computable? Does this involve weak or strong coupling methods?

How are particles produced in high energy strong interactions?



$N(E)$ is average number of produced particles.

Can $N(E)$ be computed?

Universality?

A Mathematical Aside: Light Cone Variables

$$P^{\pm} = \frac{1}{\sqrt{2}}(E \pm p_z)$$

$$X^{\pm} = \frac{1}{\sqrt{2}}(t \pm z)$$

Light Cone Variables Continued:

$$p^+ p^- = \frac{1}{2}(E^2 - p_z^2) = \frac{1}{2}(p_T^2 + M^2) = \frac{1}{2} M_T^2$$

$$2p^+ p^- - p_T^2 = M^2$$

$$p \cdot x = p^+ x^- + p^- x^+ - p_T \cdot x_T$$

Conjugate variables:

$$x^- <-> p^+$$

$$x^+ <-> p^-$$

The uncertainty principle:

$$\Delta x^\pm \Delta p^\mp \geq 1$$

Light Cone Variables and Collisions

$$p_1^+ = \frac{1}{\sqrt{2}}(E + p_z) \sim \sqrt{2} \mid p_z \mid \qquad p_2^+ \sim \frac{1}{2\sqrt{2}} \frac{M_T^2}{\mid p_z \mid}$$

$$p_1^- = \frac{1}{\sqrt{2}}(E - p_z) \sim \frac{1}{2\sqrt{2}} \frac{M_T^2}{\mid p_z \mid} \qquad p_2^- \sim \sqrt{2} \mid p_z \mid$$

For a produced pion:

$x = \frac{p_\pi^+}{p_1}$ is light cone fractional energy:

$0 \leq x \leq 1$

It is almost Feynman $x_F = \frac{E_\pi}{E_1}$

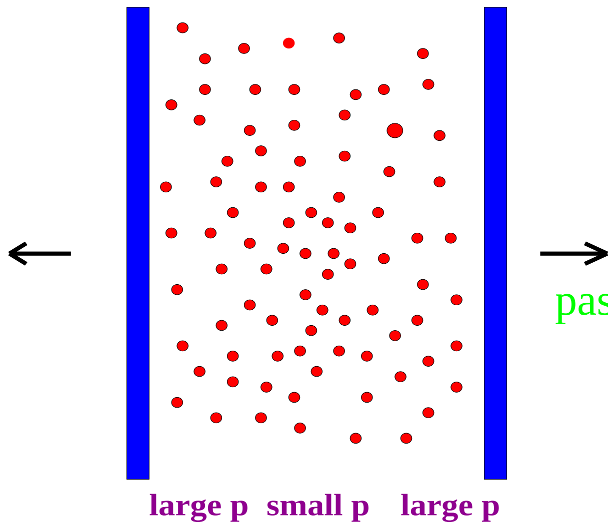
Rapidity:

$$y = \frac{1}{2} ln(P_\pi^+ / p_\pi^-) \sim 2ln(2E^\pi / M_T^\pi)$$

Show that up to mass effects:

$$-y_{proj} \leq y \leq y_{proj}$$

Picture of particle production:

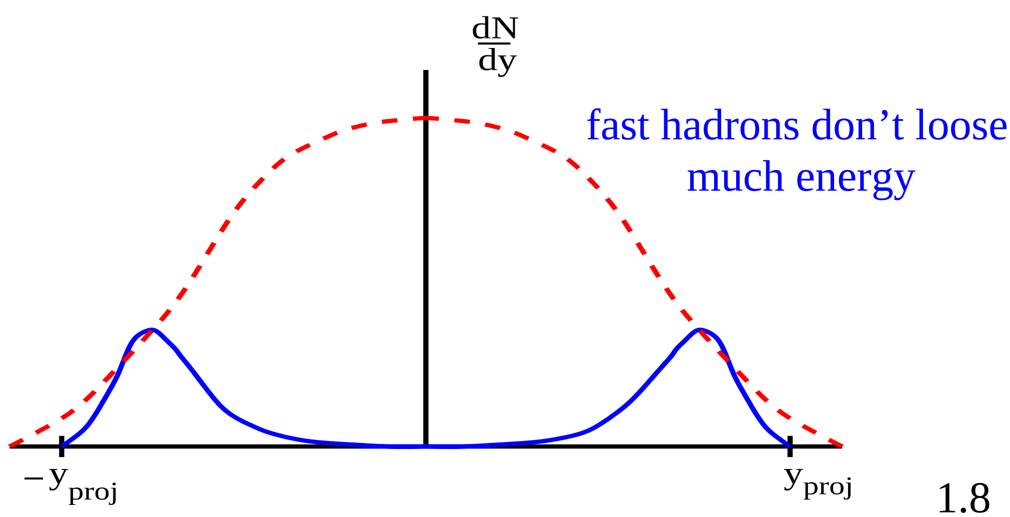


Spray of particles
produced as hadrons

pass through one another

Lorentz time dilation implies
fast particles are produced last

most produced particles are slow in center of mass frame



What would we like to understand?

How do we compute dN/dy?

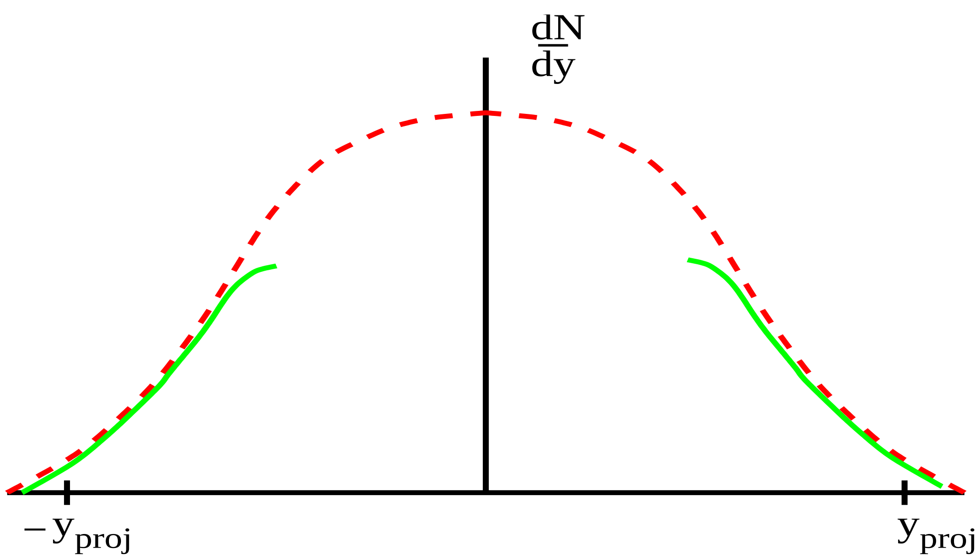
How does dN/dy at $y = 0$ behave as $E \to \infty$?

What is the average p_T as a function of y?

What are ratios of various particle distributions: composed charm, strange, up and down quarks?

Is there simple behavior at high energy?

A Hint: Limiting Fragmentation



A Hint: Limiting Fragmentation:

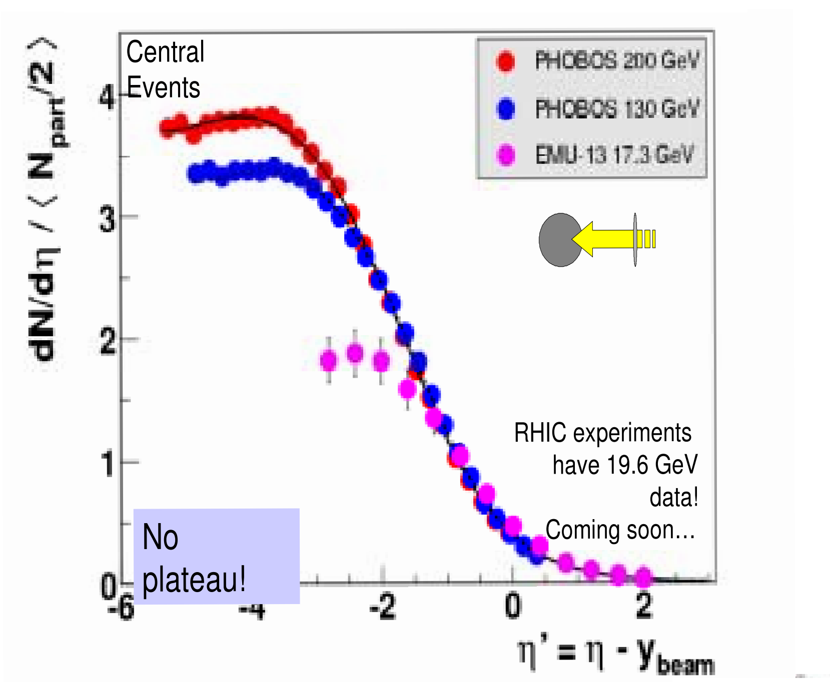
Fast degrees of freedom do not change as energy increases!

New degrees of freedom at low energy in c. of m. frame.

New degrees of freedom are determined by frozen high energy degrees of freedom.

Fast degrees of freedom arise from slow as energy increases

Renormalization Group!



Deep Inelastic Scattering

Physics is simple in frame where $P_{hadron} \rightarrow \infty$

$$x = p^+_{constituent}/p^+_{hadron}$$

Light cone momentum fractions in this frame are Bjorken x

Rapidity:

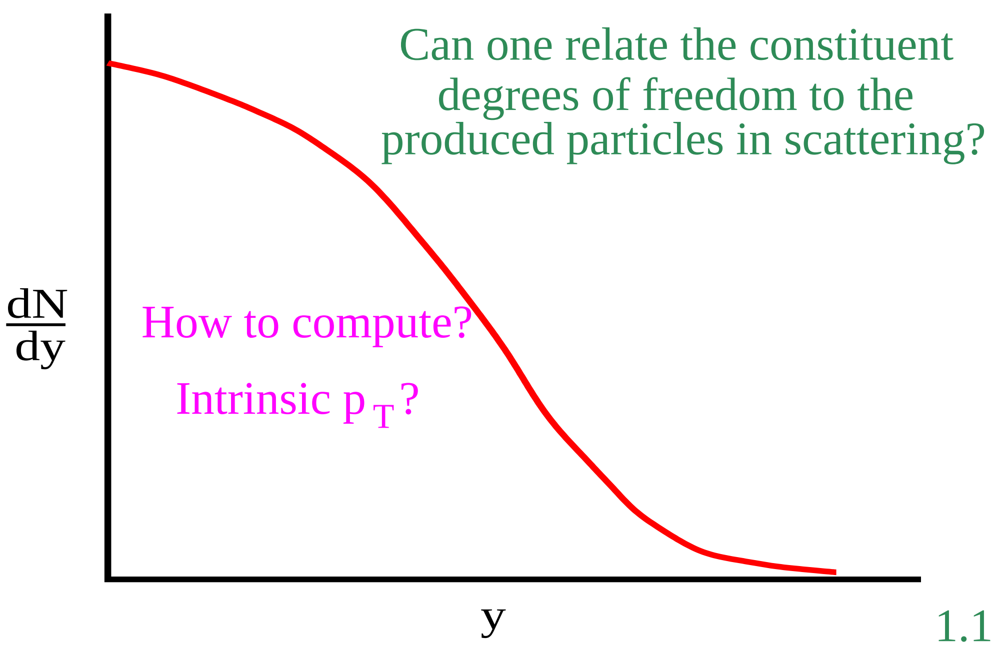
$$y = y_{hadron} - ln(1/x)$$

$$x_{minimum} \sim \Lambda_{QCD}/p^+_{hadron}$$

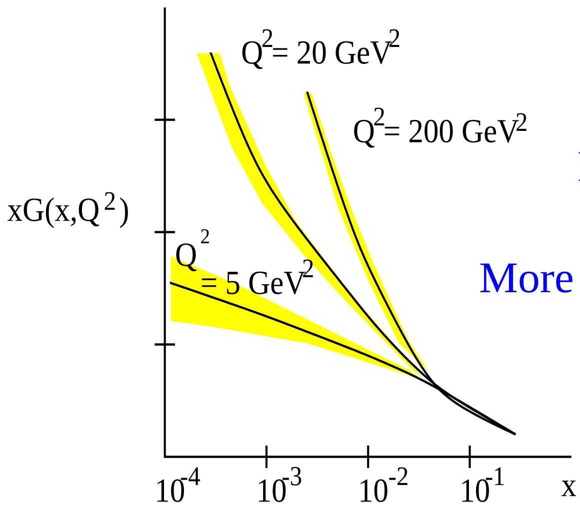
$$y_{min} \sim 0$$

Like hadron-hadron scattering, but only $y \geq 0$

Higher energy => add in more low energy degrees of freedom

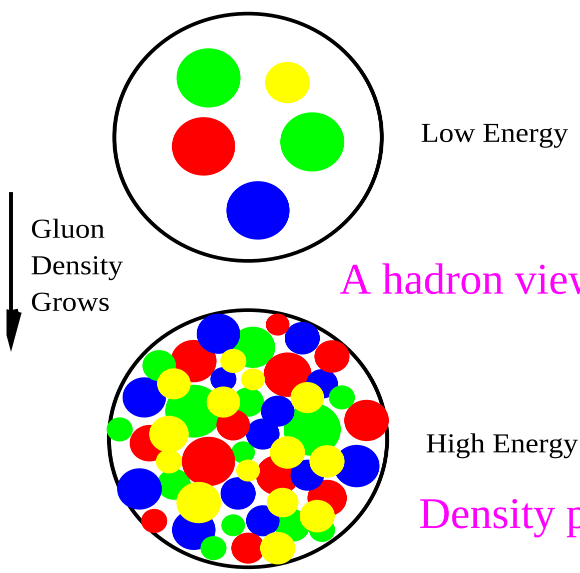


The Gluon Density Grows at Small x



Increase at fixed Q

More rapid increase at larger Q



A hadron viewed down the beam pipe.

Density per unit area gets big.

The Small x Problem

$\frac{dN}{dy}$ for gluons increases rapidly at small x:

$$\frac{dN}{dy} \sim exp(\kappa \mid y - y_{hadron} \mid) \sim \frac{1}{x^\kappa}$$

BAD CONSEQUENCE:
at fixed Q^2 grows rapidly, but unitarity
requires that $\sigma_{\gamma^* p} \leq y^3$

How is small x growth consistent with
unitarity?

GOOD CONSEQUENCE:
Density per unit area grows:

$$\Lambda^2 = \frac{1}{\pi R^2}\frac{dN}{dy} >> \Lambda^2_{QCD}$$

$$\alpha_s(\Lambda) << 1$$

Is small x physics described by weakly
coupled, non-perturbative gluons?

The Color Glass Condensate

COLOR:
Gluons are colored.

GLASS:
The gluons are disordered in the transverse plane and their colors random. They arise from sources at higher values of x which are far separated in rapidity. The natural times for the gluons at small x is much shorter than the time scale they realize, since their sources are Lorentz time dilated.

. CONDENSATE:
The density of gluons is as high as it can be. The negative kinetic energy terms $\sim \rho$ are compensated by interactions $\sim \alpha_s \rho^2$ so that $\rho \sim 1/\alpha_s$. The phase space density has occupation number $1/\alpha_s$, as a Bose Condensate.

What Are Nuclei Good For?

Enhancing the Gluon Density.

$$\frac{1}{\pi R^2}\frac{dN}{dy} \sim \frac{A^{1/3}}{x^\kappa}$$

where $\kappa \sim .2 - .3$

eA has density enhanced relative to ep

$A^{1/3} \sim 5$ corresponds to a decrease in x by $10^2 - 10^3$

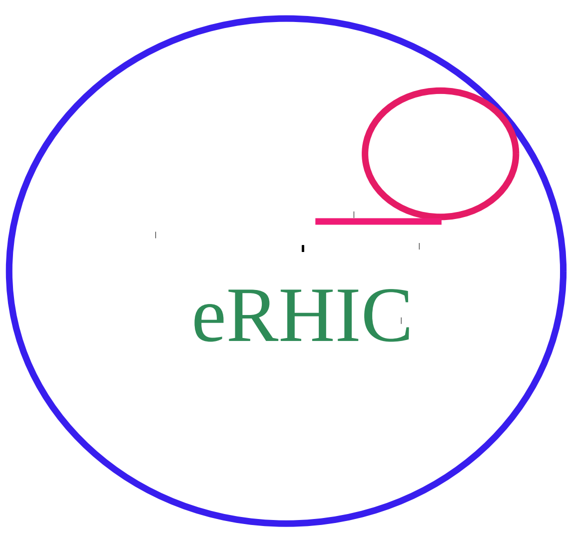
eRHIC:

10 Gev electrons off from RHIC beam

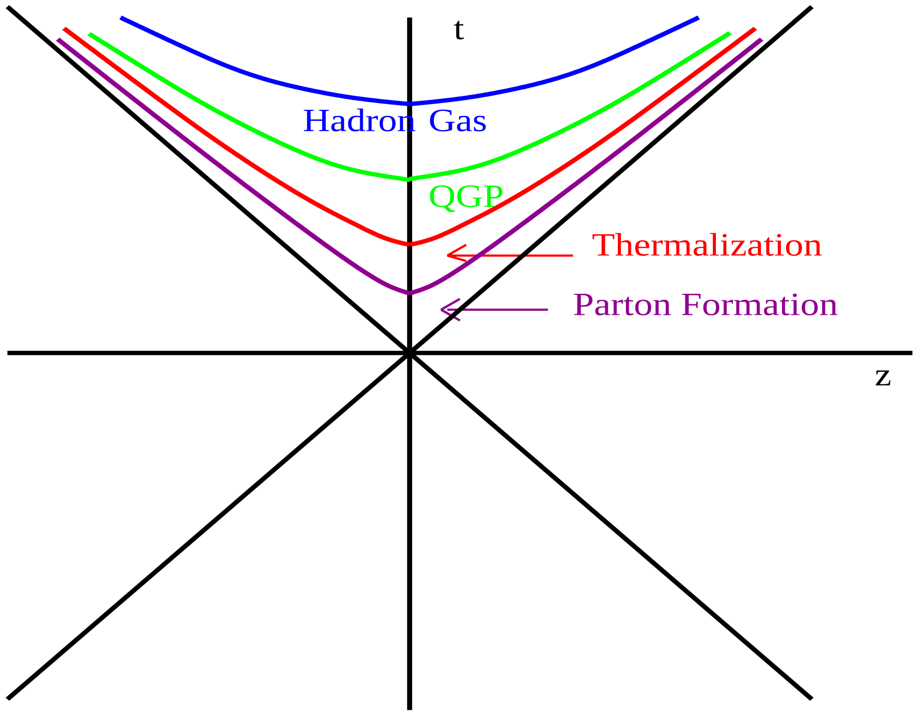
$x \sim 10^{-3} - 10^{-4}$

similar to heavy ions at LHC

ep at HERA has a density corresponding to heavy ions at RHIC.



What are the Initial Conditions for Heavy Ion Collisions?



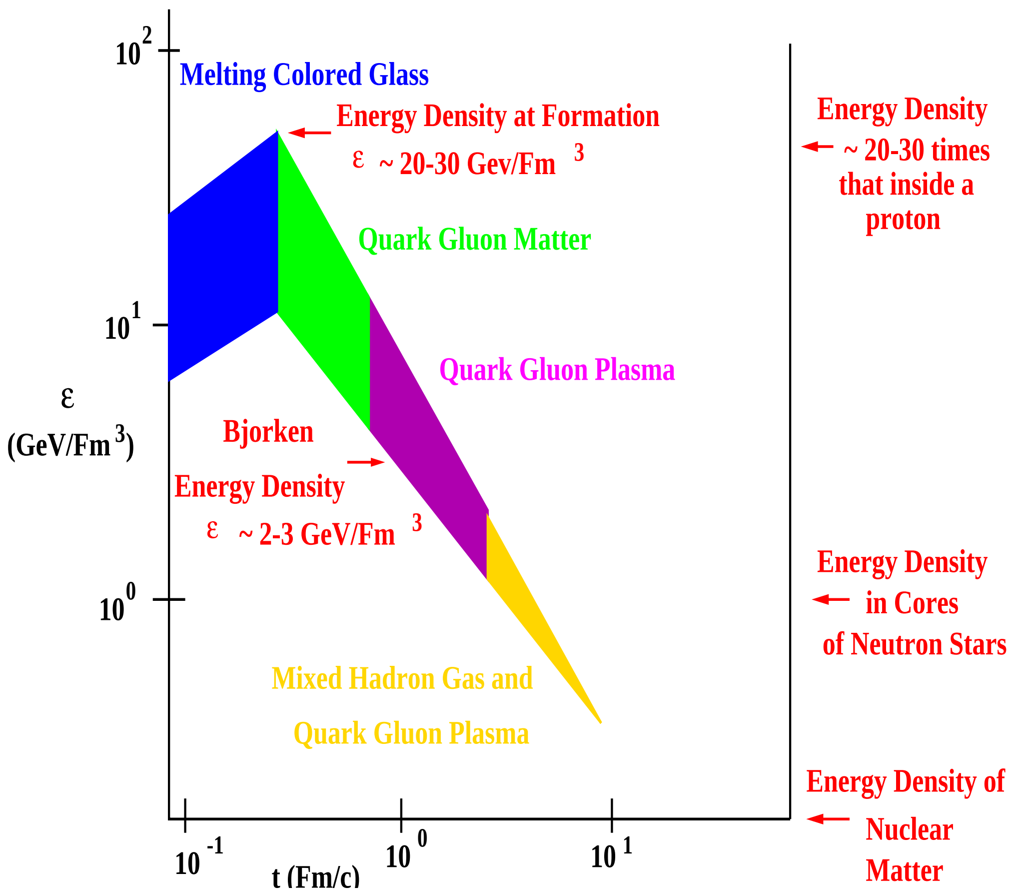
$$\tau = \sqrt{t^2 - Z^2}$$

$$\eta = \frac{1}{2} ln \left(\frac{t+z}{t-z} \right)$$

At high energy, physics roughly the same on equal τ slices is rapidity distribution is y independent.

$$y = \frac{1}{2} ln \left(\frac{E+p_z}{E-p_z} \right) = \frac{1}{2} ln \left(\frac{1+p_z/E}{1-p_z/E} \right) = \eta$$

Initial Conditions for Heavy Ions



What are the initial conditions?
Fluctuations?
How do particles thermalize?
Intrinsic heavy quarks?

Universality

Weak Universality:

Hadronic physics depnds only upon

$$\Lambda^2 = \frac{1}{\pi R^2}\frac{dN}{dy}$$

at small x.

Strong Universality:

The theory which describes the small x limit is a universal theory and is the solution of (functional) renormalization group equations. This solution is independent of the initial conditions, that is, it is at an attractive fixed point of the equations.