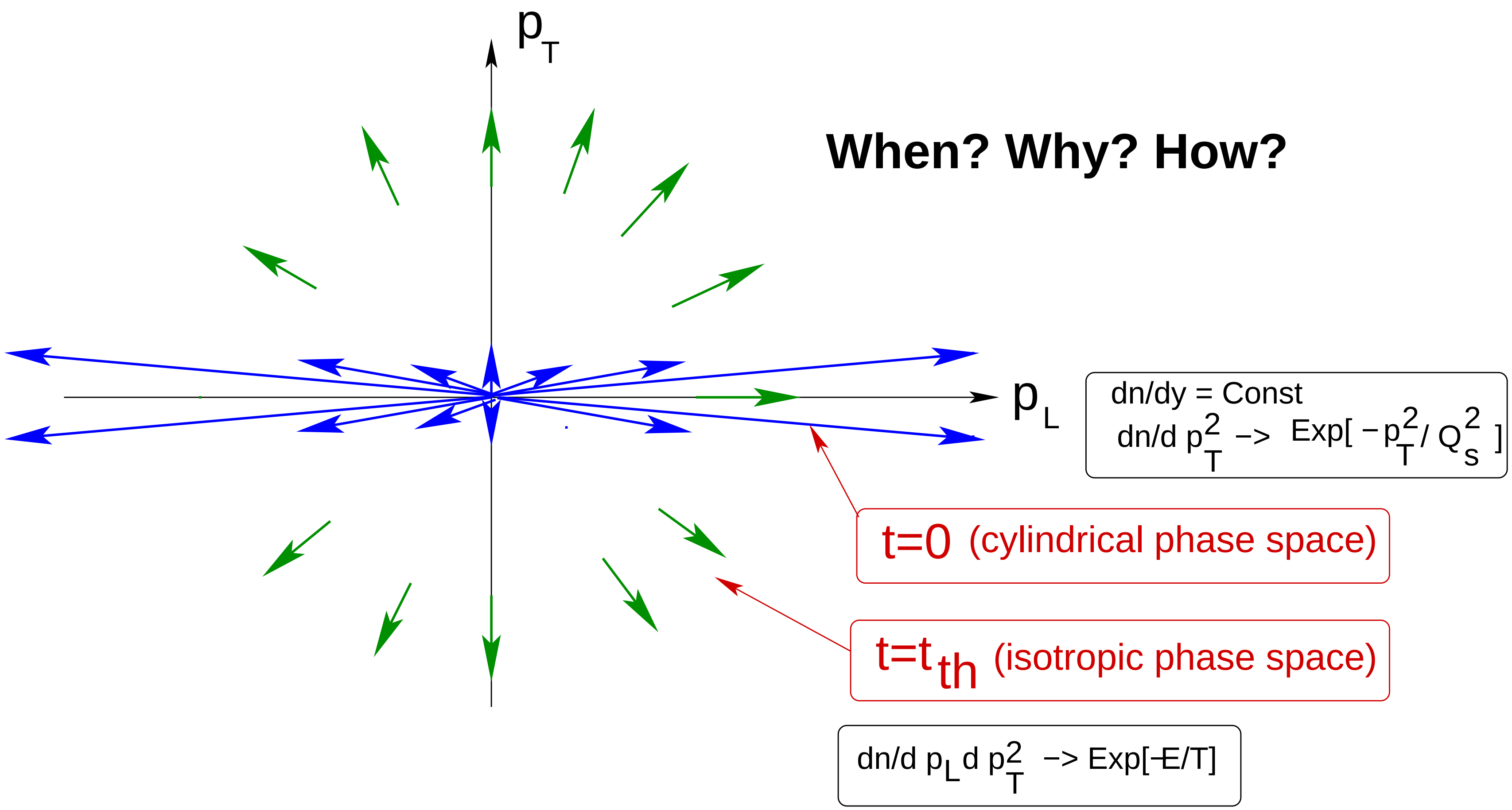
Early 'Thermalization' in the CGC and a Couple of Other Crazy Ideas

Eugene Levin, Tel Aviv University

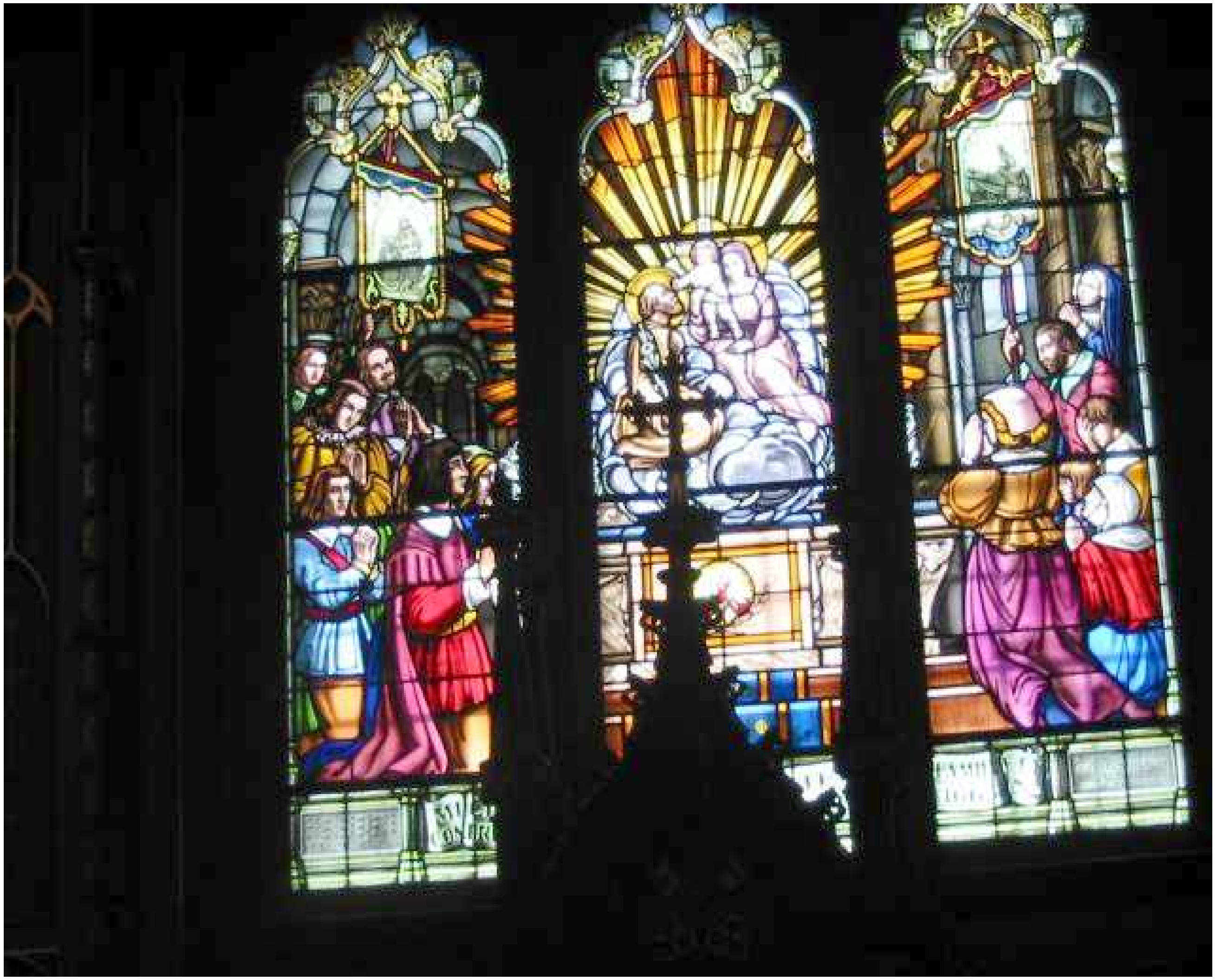
WS: "High Density QCD"
GGI, Jan 15, 2007 - Mar 9, 2007

D. Kharzeev and E.L: (*in preparation*)
D. Kharzeev, E.L. and K. Tuchin: hep-ph/0602063
D. Kharzeev and K. Tuchin: hep-ph/0501234

Thermalization:

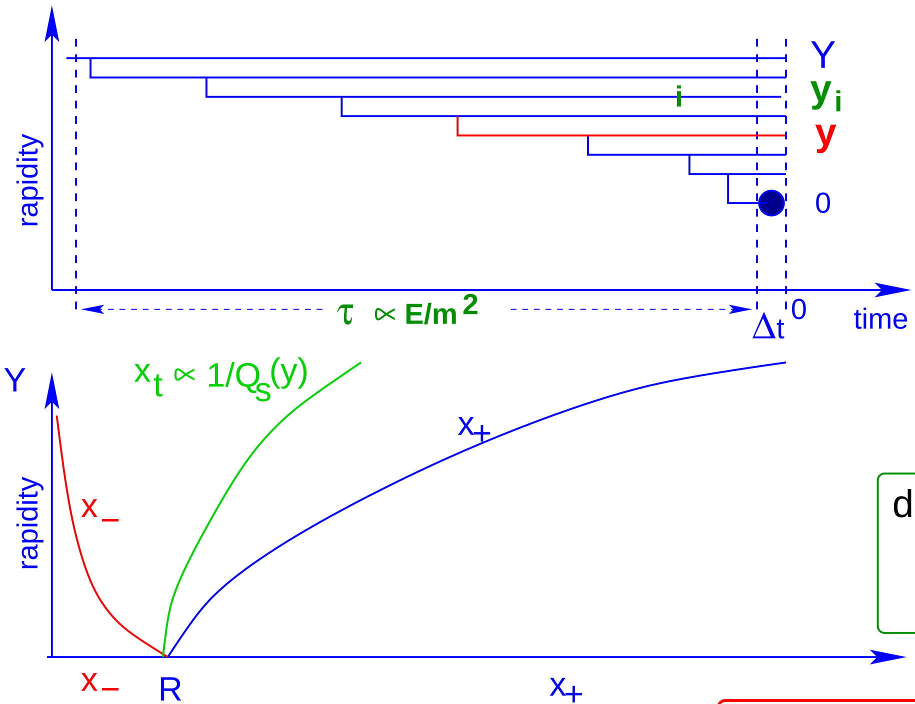


Colour Glass Condensate:



Structure of parton cascade in CGC

Space -time picture:



$x_+ \, k_- \propto 1$

$x_- \, k_+ \propto 1$

$x_t \, Q_s \propto 1$

Low, Nussinov (1975); BFKL(1976−1986);
GLR (1981); Mueller & Qiu (1986); Mueller (1994);
McLerran &Venugopalan (1994);Balitsky (1995)
Kovchegov(1999); Bartels(1992 − 2000);Braun(20(

LLA of pQCD:

$$\alpha_S \left(y_{i+1} - y_i\right) \propto 1$$

$$d\rho/dy = K \otimes \left(\rho - \rho^2\right)$$

$$\rho\left(y, Q_s\right) = 1$$

$$Q_s^2 \propto x\,G(x, Q_s)/\pi R^2 \propto (1/x)^{\lambda}$$

Classical fields:

Since all partons with rapidity larger than y live longer than parton with rapidity y, for a dense system as a nucleus they can be considered as the source of the classical field that emits a gluon with rapidity y.

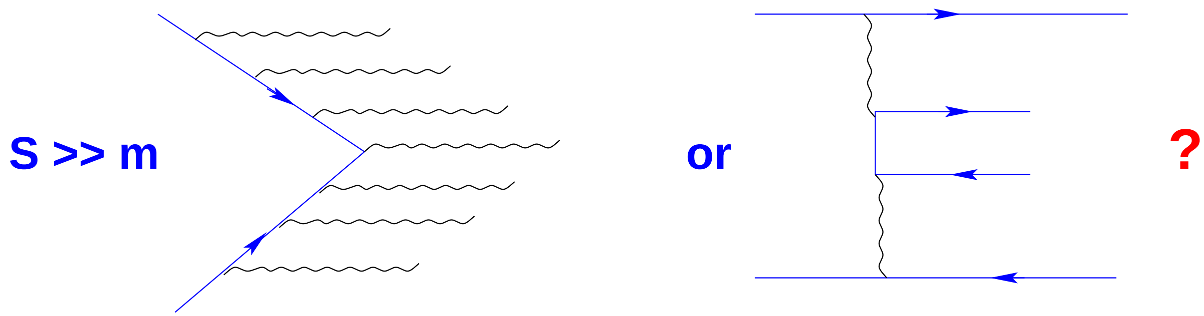
(L. McLerran & R. Venugopalan, 1994)

Duality principle:

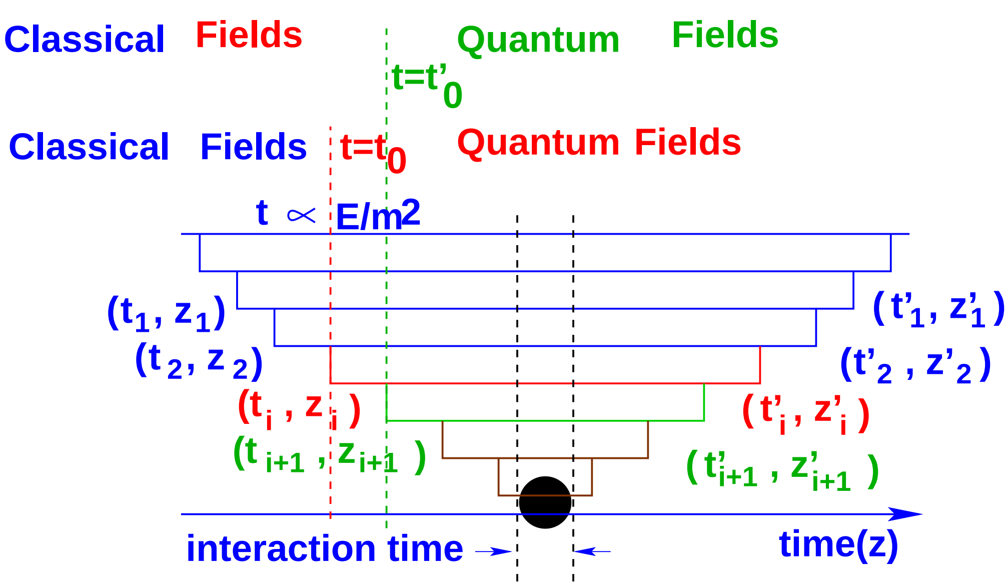
Quantum emission in each stage of the process should give the same result as the emission of the classical field

JIMWLK= J.Jalilian-Marian, E. Iancu, L. McLerran, H. Weigert, A. Leonidov and A. Kovner 1999

A question: $e^+ + e^- \longrightarrow n\gamma + m(e^+ e^-)$



JIMWLK approach:



At $t=t_0$: $L(\rho) + j_\mu \cdot A_\mu + L(A)$

At $t=t'_0$: $L(\rho) + j_\mu \cdot A_\mu + L(A)$

$$t_1 - t'_1 \gg t_2 - t'_2 \gg \dots \gg t_i - t'_i \gg t_{i+1} - t'_{i+1}$$

Fields of CGC

Lienard-Weichart potential for a charge moving with $v \equiv v_z$

$$A_{-} = \frac{g\sqrt{2}}{4\pi} \frac{1}{\sqrt{2\,x_{-}^{2} + (1 - v^{2})\,x_{\perp}^{2}}}\,;\; A_{+} = 0\,;\; \vec{A}_{\perp} = 0\,;$$

Fields:

$$E_z = 0\,;\quad \vec{E}_{\perp} = \frac{g}{4\pi} \frac{(1 - v^{2})\,\vec{x}_{\perp}}{(2x_{-}^{2} + (1 - v^{2})x_{\perp}^{2})^{3/2}}\,;\quad \vec{H} = \vec{v} \times \vec{E}\,;$$

Lienard-Weichart potential for a parton in the parton cascade

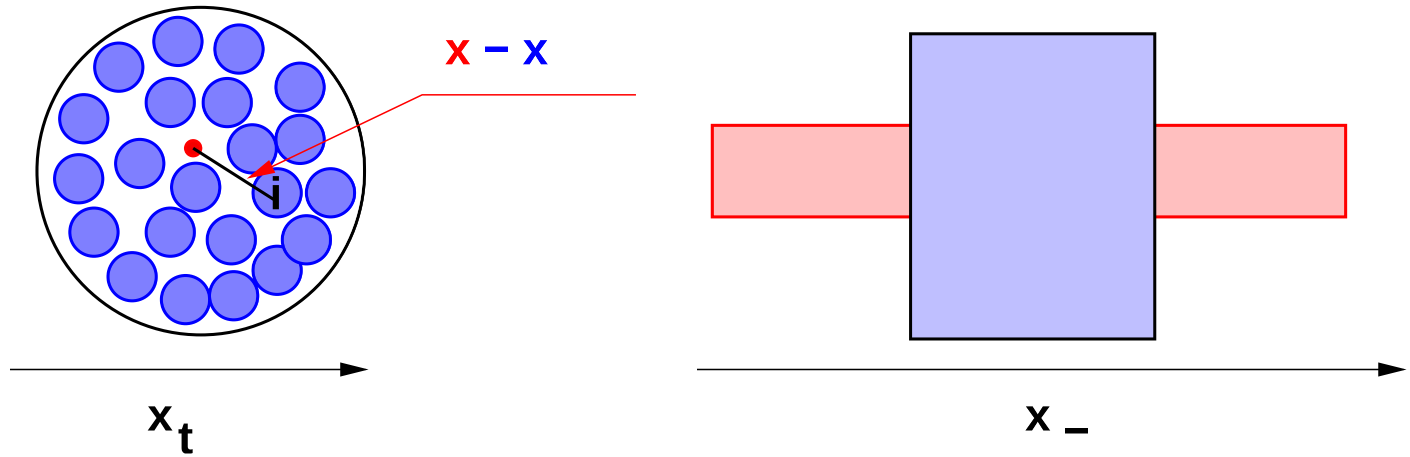
$$A_- \;=\; \frac{g\sqrt{2}}{4\pi}\,\frac{\Theta(x_+ - x_-)}{\sqrt{2\,x_-^2 \;+\; (1 - v^2)\,x_\perp^2}}\,;\;\; A_+ \;=\; 0\,;\;\; \vec{A}_\perp \;=\; 0\,;$$

Fields:

$$E_z \propto \delta(x_+ - x_-)\,;$$

$$\vec{E}_\perp \;=\; \frac{g}{4\pi}\,\frac{(1 - v^2)\,\vec{x}_\perp}{(2x_-^2 + (1 - v^2)x_\perp^2)^{3/2}}\,\Theta(x_+ - x_-)\,;\;\;\; \vec{H} \;=\; \vec{v} \times \vec{E}\,;$$

$$|\vec{E}_\perp| \;=\; |\vec{H}_\perp| \;\ll\; E_z$$



A_+ **exists only for** $z \geq 0$ **and the initial conditions depend on** x_- **and** x_+**.**

$$A = \int \frac{d^3x}{4\pi}\,\frac{\rho(\vec{x}, t - |\vec{x} - \vec{x}|)}{|\vec{x} - \vec{x}|} = \int \frac{dx_-\, d^2x}{4\pi}\,\frac{\sqrt{2}\rho\left(x_-, x_\perp, x_+ + x_- - \frac{(x_\perp - x_\perp)^2}{2(x_- - x_-)}\right)}{x_- - x_- + \frac{(x_\perp - x_\perp)^2}{2(x_- - x_-)}}$$

$$\longrightarrow \int \frac{dx_-\, d^2x}{4\pi}\,\frac{\sqrt{2}\rho\left(x_-, x_\perp, x_+ - \frac{(x_\perp)^2}{2x_-}\right)}{x_- + \frac{x_\perp^2}{2x_-}}$$

At high energies $\quad |\vec{E}_\perp| = |\vec{H}_\perp| \ll E_z$

Main idea: To replace complicated process of particle production by the production in the background fields $A_{-} = A_{-}(x_{-})$

- **At t=0:**

$$E_z = E_0 = Const \text{ and } A_{-}(x_{-}) = - E_0\, x_{-}$$

- **At large t:**

In pQCD: $A_{-}(x_{-}) \xrightarrow{x_{-} >> R} 1/x_{-}$

(Say $A_{-}(x_{-}) = -E_0 \frac{x_{-}}{1 + \omega^2 x_{-}^2}$);

In n-pQCD: $A_{-}(x_{-}) \xrightarrow{x_{-} >> R} e^{-\omega x_{-}}$;

Model for $A_+(x_-)$

- $A_+(x_-) \;=\; \frac{E_0}{\omega}\left(1 - e^{-\omega\, x_-}\right) \;\Longrightarrow\; \sum_\sigma \text{Im}\, S \;=\; \frac{\pi p_\perp^2}{g E_0 (1+\gamma)}$

- $\rho\left(x'_-, x'_\perp, x_+ + x'_- - \frac{(x'_\perp)^2}{2x_-}\right) \;=$

$$c \int d^2 k_\perp e^{i\vec{k}_\perp \cdot \vec{x}'_\perp}\; \delta\left(x'_- - \omega^{-1}\right)\delta\left(k^2_\perp - Q_s^2\right)\;,$$

- $A_+(x_-) \;=\; c' \int \frac{d^2\, x'_\perp\; d\, x'_-}{4\,\pi}\, \frac{2\, x_-\, \delta\left(x'_- - \omega^{-1}\right)\, J_0\left(x'_\perp\, Q_s\right)}{2x^2_- \,+\, x'^2_\perp} \;=\; c'\, x_-\, K_0\left(x_-\, Q_s\right)$

Particle production in the background field

Educated guess: $k_\perp$ **factorization, for inclusive cross section:**

(Catani,Ciafaloni & Hautman;E.L., Ryskin,Shabelski & Shuvaev; Collins & Ellis ; 1991)

$$\varepsilon \frac{d\sigma}{d^3 p} = \frac{4\pi N_c}{N_c^2 - 1} \frac{1}{p_\perp^2} \int dk_\perp^2 \, \alpha_S \, \varphi_P(Y - y, k_\perp^2) \, \varphi_T(y, (p-k)_\perp^2)$$

Proven in CGC by Kovchegov & Tuchin (2002) only for DIS !?

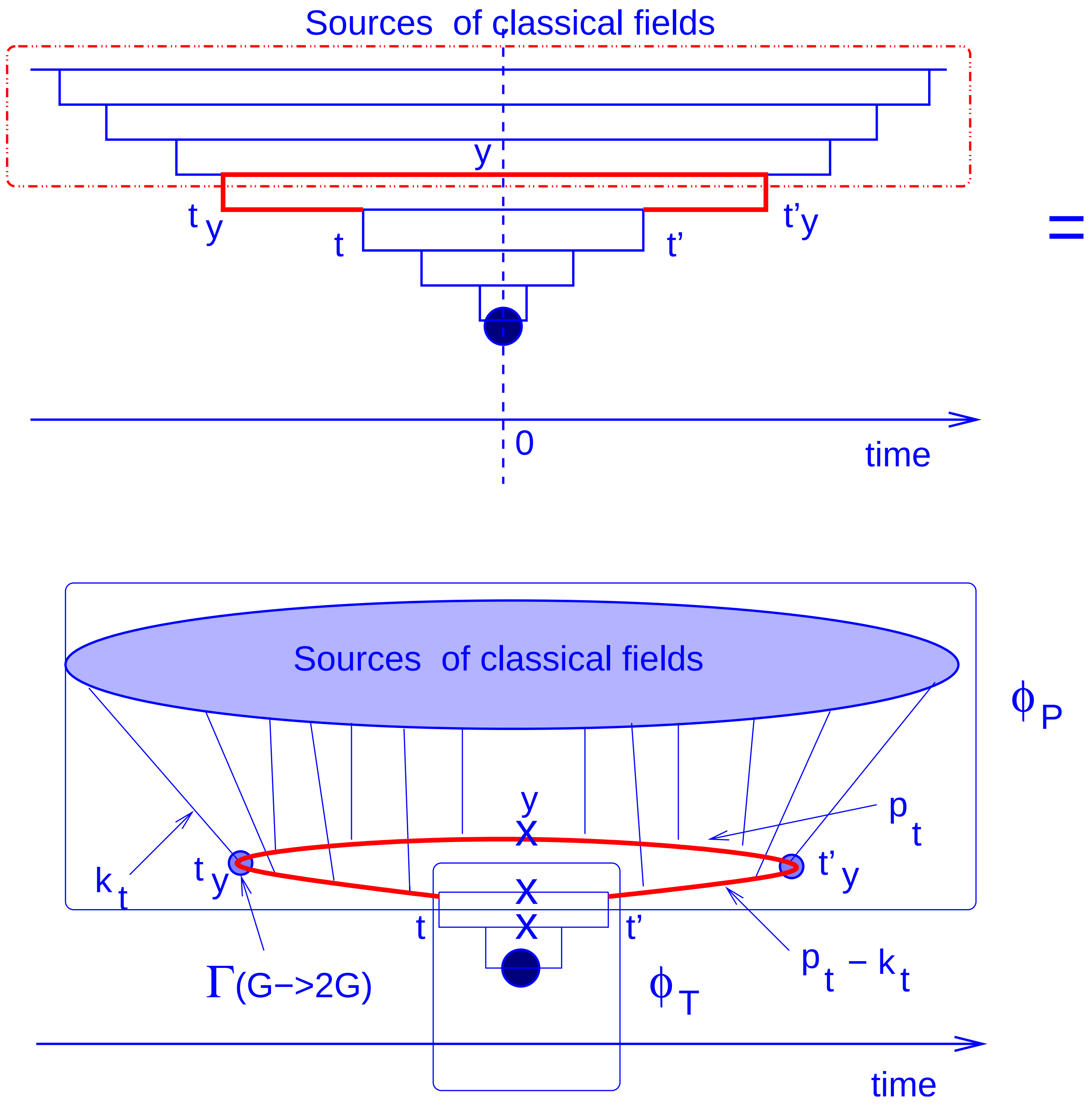
Our formula:

$$\frac{d\sigma}{dy\,d^2p_\perp} = \varphi_P(Y-y,p_\perp)\,\varphi_T(y,p_\perp)$$

with

$$\varphi_P(Y-y,p_\perp) \propto$$

$$\int d^2k_\perp\, Im\, D(Y-y,\vec{p}_\perp-\vec{k}_\perp)\, Im\, D(Y-y,\vec{p}_\perp)$$


Sources of classical fields
y
t y
t
t'
t'y
0
time
=
Sources of classical fields
φ P
y
X
X
X
p t
k t
t y
t'y
t
t'
Γ(G−>2G)
φ T
p t − k t
time

Equation of motion in the background field

- $G_\mu = A_\mu + W_\mu$, A_μ is a classical background field;
- $\mathcal{L}[A+W] = \mathcal{L}[A] + \frac{\partial \mathcal{L}[A]}{\partial A_\mu} W_\mu + \frac{1}{2}\frac{\partial^2 \mathcal{L}[A]}{\partial A_\mu \, \partial A_\nu} W_\mu W_\nu$;
- $\left(-(\partial_\lambda - igA_\lambda)^2 \, \delta_{\mu\nu} + 2i\, g\, F_{\mu\nu}[A]\right) W_\mu = 0\,$;
- $F_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & E_z \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -E_z & 0 & 0 & 0 \end{pmatrix}$,
- Introducing $W_\pm = W_0 \pm iW_3$ we obtain:

$$-\left(\,(\partial_\lambda - igA_\lambda)^2 \pm 2gE_z\,\right) W_\pm = 0$$

Gluon propagator in the background field

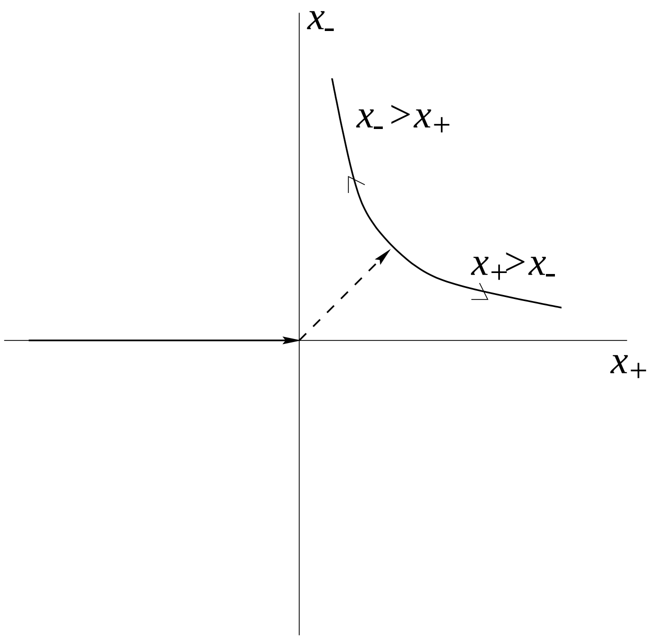
Schwinger (1951); Marinov & Popov (1972-1974);Kluger, Eisenberg, Svetitsky & . . . (1991-1994); Dunne (2004)

Semiclassical solution:

- Solution in the form $W_\sigma = e^{-iS_\sigma - ip_\perp \cdot x_\perp}$ with $\sigma = \pm 1$ assuming $\partial_+ S\, \partial_- S \gg \partial_+ \partial_- S$;
- Introducing $p_-(x_-, x_+) = \partial S/\partial x_+$ and $p_+(x_-, x_+) = \partial S/\partial x_-$, we obtain $-2\, p_+(p_- - g A_-(x_-)) + p_\perp^2 + 2g\, \sigma E_z = 0$;
- $\frac{dx_-}{dt} = -2\,(p_- - g A_-(x_-))$;
- $\frac{dx_+}{dt} = -2\, p_+$;
- $\frac{dS}{dt} = -2p_+ p_- - 2p_+(p_- - g A_-(x_-))$;
- $\frac{dp_+}{dt} = -2p_-\, g A'_-(x_-) - 2g\sigma\, E'$;

Solution:

- $S_K = -\int x_- \frac{d\,p_\perp^2 + 2\,g\,\sigma\,E_z(x_-)}{p_-^0 - g\,A_-(x_-)} = -\frac{1}{g\,E_0}\int d\,\tau\,\frac{p_\perp^2 + 2\,g\,\sigma\,E_0\,f'(\tau)}{\gamma + f(\tau)}$



- $A_-(x_-) = -\frac{E_0}{\omega}\,f(\tau = \omega\,x_-);$
- *Adiabaticity parameter:* $\gamma = \frac{p_+^0\,\omega}{g\,E_)} \approx \frac{p_+}{k_{i,+}};$
- t=0: $\gamma \ll 1;\quad Im\,S_\sigma = -\frac{\pi\,p_\perp^2}{2\,g\,E_0};$
- t=0: $Im\,D(Y - y, p_\perp) \propto e^{-2\sum_\sigma Im\,\mathrm{S}_\sigma}$

$= \frac{S_P}{\alpha_S}\;e^{-\frac{2\,\pi\,p_\perp^2}{g\,E_0}};\;\; Q_s^2(y) = \frac{g\,E_0}{2\,\pi};$

Thermalization by a pulse of the chromelectric field

(Kluger, Eisenberg, Svetitsky & ... (1991 -1994)

$$\star \quad \frac{dk_{iz}}{dt} = g\,E_z \sim Q_s^2\,; \qquad \frac{d\varepsilon}{dt} = 0;$$

$$\star \quad \Delta k_i^+ \simeq \Delta k_i^- \sim Q_s;$$

$$\star \quad \omega \Longrightarrow Q_s\,; \qquad \gamma \gg 1;$$

For $A_- = \frac{E_0}{\omega}\,e^{-\tau}$ and $\gamma > 1$

- $$Im\,S_\sigma = \frac{\pi\,p_\perp^2}{2\,g\,E_0\,\gamma} = \frac{4\,\pi\,p_+}{\omega}$$
- $$\frac{d\sigma}{d^3p} \propto e^{-\frac{\epsilon}{T}}; \qquad T = \frac{\omega\,\sqrt{2}}{4\pi};$$

Thermalization time

- $\Delta p_{-} = p_{-}(x_{-}) \; - \; p^{0}_{+} = -\,\omega; \quad \tau = \omega\, x_{-} \simeq \; \ln \gamma;$

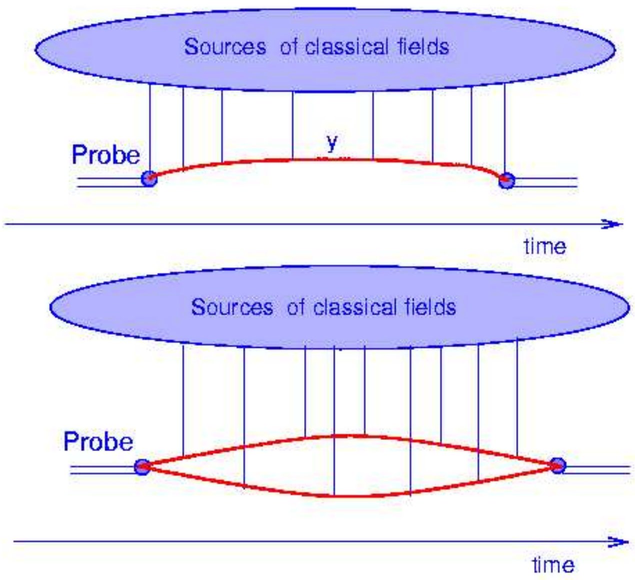
- $$\Delta p_{+} \; = \; -\,\frac{g E_0}{\omega};$$

Therefore

- $\omega \; = \; \sqrt{g\, E_0}; \quad x_{-} \; \simeq \; \dfrac{\ln \gamma}{\sqrt{g\, E_0}} = \dfrac{\ln \gamma}{\sqrt{2\, \pi}\, Q_s} \approx 0.6\, \dfrac{1}{Q_s}$

$$\bullet \bullet \bullet \qquad T = \frac{Q_s}{\sqrt{4\, \pi}} \approx 0.3\, Q_s; \qquad \bullet \bullet \bullet$$

Nuclear gluon distributions



19

McLerran-Venugopalan formula:

- $$\frac{dN^{MV}}{d^2x_\perp dy} \propto \frac{1}{\bar{\alpha}_S} \left(1 - e^{-\frac{1}{4}x_\perp^2 Q_s^2(x)\ \ln(x_\perp^2 Q_s^2(x))}\right)$$

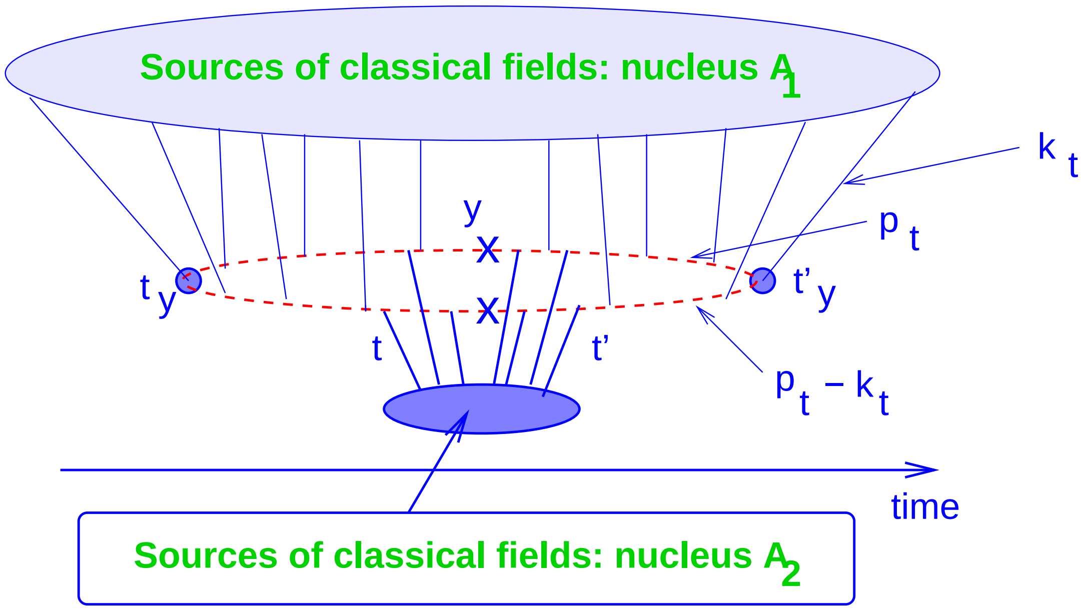
Our approach:

- $$\frac{dN^{LLA}}{d^2x_\perp dy} \propto \ln(1/x) \left(1 - e^{-\frac{1}{4}x_\perp^2 Q_s^2(x)\ \ln(x_\perp^2 Q_s^2(x))}\right)$$

- $$\frac{dN^{LLA}}{d^2x_\perp dy} \propto \frac{1}{\bar{\alpha}_S} \ln\left(x_\perp^2 Q_s^2(x)\right) \left(1 - e^{-\frac{1}{4}x_\perp^2 Q_s^2(x)\ \ln(x_\perp^2 Q_s^2(x))}\right)$$

Ion-Ion collisions

$$Im\, D(t - t') \;=\; Im\, D_{A_1}(t - t')\; Im\, D_{A_2}(t - t')$$



- $$\frac{d\sigma}{d\,y\,d^2p_\perp} = \frac{S_{A_1}\,S_{A_2}}{\alpha_S}\,\frac{\pi^2 N_C}{2\,(N_c^2 - 1)}\,e^{-\frac{\epsilon}{T}}$$

- $$\frac{1}{T} = \frac{1}{T_{A_1}} + \frac{1}{T_{A_2}}$$

Thermodynamics of heavy-ion collision

Statistical interpretation of gluon production

- Probability to produce n pairs is equal:

$$P_n \,=\, w_1^n(\sigma, \vec{p})\, w_0(\sigma, \vec{p})$$

where

- w_1 is the probability to produce one pair;
- w_0 is the probability to produce no pair;

- Probability conservation yields

$$w_0(\sigma, \vec{p}) \sum_{n=0}^{\infty} w_1^n(\sigma, \vec{p}) = \frac{w_0(\sigma, \vec{p})}{1 - w_1(\sigma, \vec{p})} = 1;$$

- **The total probability that the vaccum remain unchanged**

$$W_0 = |\exp i\mathcal{L}V\,\Delta t|^2 = e^{-\frac{\Omega}{T}}$$

where FΩ is the thermodynamic potential;

- $$W_0 = \prod_{\sigma,\vec{p}} w_0(\sigma,\vec{p}) = e^{\sum_{\sigma,\vec{p}}\,\ln(1 - w_1(\sigma,\vec{p}))}$$

- $$\Omega = \mathcal{G}\,\frac{TV}{(2\pi)^3}\int d^3p\,\,\ln(1\,-\,w_1(\sigma,\vec{p}))$$

where $\mathcal{G} = (2\sigma + 1)(N_c^2 - 1)$ **- degeneration factor;**

Bose-Einstein condensation

- **Introducing**

$$\mathcal{M}/T = 2\,Im S = \begin{cases} p_\perp^2/Q_s^2\,, & t \ll t_{\rm therm} \\ p_-/T\,, & t \gg t_{\rm therm} \end{cases}$$

- **Number of produced pairs**

$$N = -\frac{\partial \Omega(\mu)}{\partial \mu}\Big|_{\mu=0} = \frac{\partial}{\partial \mu}\frac{VT}{(2\pi)^3}\mathcal{G}\int d^3p\,\ln(1 - e^{(\mu - \mathcal{M}/T})\Big|_{\mu=0}$$
$$= \frac{\mathcal{G}\,V}{(2\pi)^2}\int dp_\perp^2\,dp_z\,\frac{1}{e^{\mathcal{M}/T} - 1}\,.$$

- **At t=0 :** $N \propto \ln(Q_s^2/\Lambda^2)$ **but the total emitted energy**

$$\mathcal{E} = \int \varepsilon\, dN_\varepsilon = \frac{V\mathcal{G}}{(2\pi)^2}\Delta p_z\,Q_s^3\,g E_0\,\frac{\sqrt{\pi}}{2}\zeta(3/2)$$

- $\Delta p_z \simeq g E_0 t$ **and** $V \simeq t$**, therefore,** $\mathcal{E} \simeq t^2$**.**

- **At $t = t_{therm}$:**

$$N = \frac{V\mathcal{G}}{(2\pi)^2} g E t (\pi^2/6) T^2$$

We expect Bose-Einstein condensation of gluons at $T < T_0$ with

$$T_0 = \left(\frac{3(2\pi)^2 N}{V\mathcal{G}\, g E\, t\, \pi^2} \right)^{1/2}$$

$$N(p_\perp = 0) = N \left[1 \; - \; \left(\frac{T}{T_0} \right)^2 \right]$$

Equation of state

- **Helmholz free energy at $\mu = 0$ is equal to**

$$F = \Omega = PV$$

- **So long as $\Delta p_z \simeq gE\,t \ll p_\perp$**

$$\mathcal{E}/V = 2P$$

- **at $t > t_{therm}$ $p_z \sim p_\perp$**

$$\mathcal{E}/V = 3P$$

Viscosity of the parton system

For $t > t_{therm} \Longrightarrow$ equilibrium with

$n \sim 1/\alpha_S$ and $\langle p_t \rangle \approx T \propto Q_s$

Shear viscosity can be estimated:

- $\frac{\eta}{n} = \langle p_t \rangle \, \lambda \sim \frac{Q_s}{n \, \sigma}$
- $\sigma \sim \alpha_S / Q^2_s$
- The number of particle/unit volume $n \sim \frac{xG}{S + A\, L_z}$ where $L_z \sim 1/Q_s$ is the longitudinal extent of the system;

$$\frac{\eta}{n} \sim 1$$

When? Why? How?

1. **Why?** The origin of the initial ($t = 0$) distribution and of the process of thermalization ($t \approx t_{therm}$) are the same: the clasasical fields that originated by all faster partons;

2. **When?** $t_{therm} \simeq 0.8 \frac{1}{Q_s} \approx 0.1 - 0.2 fm$;

3. **How?** Creating the thermalized system of gluons with $T \simeq 0.3 Q_s(y) \approx 450 MeV$ at y=0;

What is bad?

- We failed to prove that the emitted gluons are in the thermodynamic equilibrium;
- We showed that the emitted gluons create the good initial conditions for hydro;
- We hope that hydro or something else will lead a system to the thermodynamic equilibrium;

What is good ?

- We gave a much simpler explanation for the GGC in which we are not loosing any of essential ingredients of this approach;
- This explanation is not empty since it leads to a number of crazy ideas (see below).

The crazy idea: saturation of the saturation scale

- $$\frac{d N_{gluon}}{d\,t\,d^3\,x\,d^2\,p_t} \;=\; \frac{1}{4\,\pi^3}\sum_{i=1}^{3}|g\lambda_i|\,\ln\left(1\;+\;e^{-\frac{\pi p_t^2}{|g\,\lambda_i|}}\right)$$

- $$\frac{d N_{gluon}}{d\,t\,d^3\,x} \;=\; \int d^2 p_t\,\frac{d N_{gluon}}{d\,t\,d^3\,x\,d^2\,p_t} \;=\; \frac{\alpha_S}{8}\,C_1 \;=\; \frac{\alpha_S}{8}\,E^a\,E^a$$

- $$Q_s^2\,(Y) \;\equiv\; \langle|p_t^2|\rangle \;=\; \frac{\int p_t^2\;d^2 p_t\;\frac{d N_{gluon}}{d\,t\,d^3\,x\,d^2\,p_t}}{\frac{d N_{gluon}}{d\,t\,d^3\,x}} = \frac{9\,\zeta(3)}{\pi^3}\,g\,\sqrt{C_1}\,\kappa_1$$

- $$Q_s^4\,(Y) \;=\; \frac{324\,\zeta^2(3)}{\pi^5}\,\alpha_S\kappa_1^2\,C_1$$ •

The energy density $w(Y) = E^a E^a/4\pi = C_1/4\pi$ and

- $$w\left(Y + \Delta Y\right) - w\left(Y\right) = \int_{Y}^{Y+\Delta Y} dY' \frac{dN_{gluon}\left(Y'\right)}{d\,t\,d^3\,x} \xrightarrow{\Delta Y \to 0} \frac{dN_{gluon}\left(Y\right)}{d\,t\,d^3\,x}\,\Delta Y$$

- $$\frac{E^a\left(Y\right)\;E^a\left(Y\right)}{4\,\pi} \neq \int_{Y}^{Y_b} d\,Y' \frac{dN_{gluon}\left(Y'\right)}{d\,t\,d^3\,x}$$

- $$\frac{E^a\left(Y_b - Y\right)\;E^a\left(Y_b - Y\right)}{4\,\pi} = \int_{Y}^{Y_b} d\,Y' \frac{dN_{gluon}\left(Y'\right)}{d\,t\,d^3\,x}$$
  $$\times \exp\left(-\int_{Y}^{Y'} d\,Y'' \int dt\,d^3\,x \frac{dN_{gluon}\left(Y''\right)}{d\,t\,d^3\,x}\right)$$

The differential form is

$$\frac{1}{4\,\pi}\,\frac{d\,\{E^{a}\,(Y_b - Y)\;\,E^{a}\,(Y_b - Y)\}}{d\,Y} = \frac{dN_{gluon}\,(Y)}{d\,t\,d^3\,x} \;-\; \int \,dt\,d^3\,x\;\frac{dN_{gluon}\,(Y)}{d\,t\,d^3\,x}\times$$

$$\times\;\int_{Y}^{Y_b}\,d\,Y'\,\frac{dN_{gluon}\,(Y')}{d\,t\,d^3\,x}\;\exp\left(-\;\int_{Y}^{Y'}\,d\,Y"\;\int\,dt\,d^3\,x\;\frac{dN_{gluon}\,(Y'')}{d\,t\,d^3\,x}\right)$$

which can be rewriiten as

$$\frac{2}{\pi\alpha_S}\,\frac{dQ^4_s\,(Y)}{d\,Y} = Q^4_s\,(Y)\;-\;\frac{C}{4\,\pi\,\alpha_S}\,Q^8_s\,(Y)\;\times\;V \quad \text{where}\quad V = \pi\,R^2_A\times x_+\,x_-$$

$$S \propto \int\,d\,x_+\,\frac{p^2_\perp}{p^0_+\;+\;g\,A_+(x_+)} \;\Longrightarrow\; x_+ = \frac{p^0_+}{g E}$$

$$x_- = \frac{p^2_\perp}{2}\int\frac{d\,x_+}{\left(p^0_+\;+\;g\,A_+(x_+)\right)^2} = \frac{p^2_\perp}{2\,g\,E\,p^0_+}$$

- $$x_-\,x_+ \;=\; \frac{1}{2\,\pi\,g\,E} = \frac{81\,\zeta^2(3)\kappa^2_1}{2\,\pi^6}\,\frac{1}{Q^2_s(Y)}$$ •

Finally

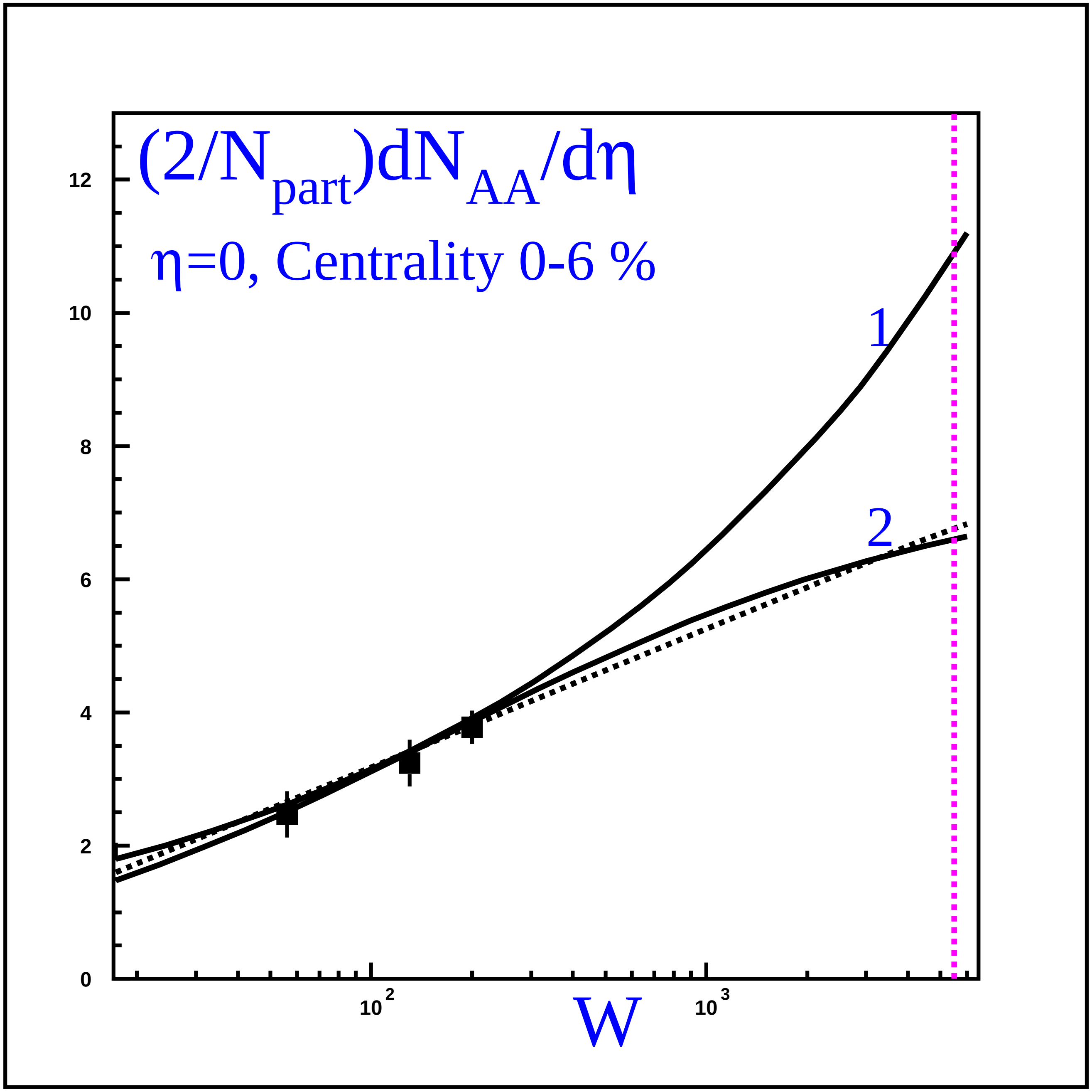
$$\bullet \quad \frac{4}{\alpha_S\,\pi}\,\frac{d\,Q_s^2(Y)}{d\,Y} = Q_s^2\,(Y) \;-\; B\,Q_s^4\,(Y) \quad \bullet$$

where

$$\bullet \quad B = \frac{1}{32\,\pi^2}\,\frac{\pi\,R_A^2}{\alpha_S} \quad \bullet$$

Solution:

$$\clubsuit \quad Q_s^2\,(Y) = \frac{Q_s^2(Y\!=\!Y_0)\;\exp\left(\frac{2\,\alpha_S}{\pi}\,(Y-Y_0)\right)}{1 + B\,Q_s^2(Y\!=\!Y_0)\,\left(\exp\left(\frac{2\,\alpha_S}{\pi}\,(Y-Y_0)\right) - 1\right)} \quad \clubsuit$$



$(2/N_{part})dN_{AA}/d\eta$
η=0, Centrality 0-6 %
1
2
12
10
8
6
4
2
0
10^2
10^3
W