Microscopic Sources of Particle Production in Relativistic Heavy-Ion Collisions

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Multiparticle Dynamics Seminar
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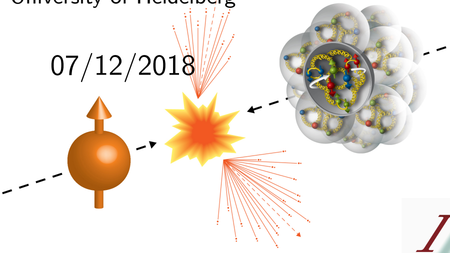


Outline

*picture titlepage: [phys.org20150211]

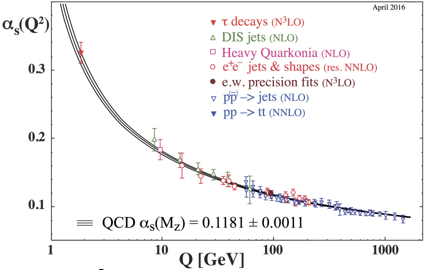
Outline

Charged Hadron Production

- Produced charged hadrons $N^{ch} \sim \sigma^{ch}/\hat{A}$

$$\sigma \sim \int d^4\hat{p}\; \delta(p^2 - s_{NN})\Theta(p_0) f(p) \sim \int \frac{d^3\vec{p}}{2E}\; f(\vec{p}, E)$$

- At LHC: $\sqrt{s_{NN}} = \sqrt{s_{pp}}\sqrt{Z/A} = 5.023$ TeV
- Non perturbative regime: $\Lambda_{\text{QCD}} \approx 0.22$ GeV



[Bethke2017]

- DGL for $f(p_0, p_1)$ with $t \equiv p_0$, $y \equiv p_1$

$$\frac{\partial}{\partial t} f(y,t) = -\frac{1}{\tau_y} \frac{\partial}{\partial y}\left[(y_{\mathrm{eq}} - y) f(y,t)\right] + D_y \frac{\partial^2}{\partial y^2} f(y,t)$$

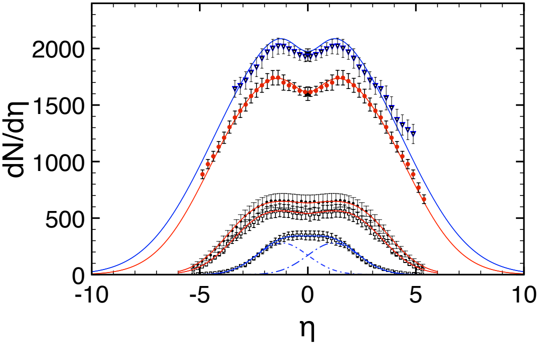
- Produced charged hadrons:

$$\frac{dN^{ch}}{d\eta} = J(\eta, m_\pi / \langle p_T \rangle) \frac{dN^{ch}}{dy}$$

$$y(\eta, m, p_T) = \frac{1}{2} \log \left(\frac{\sqrt{m^2 + p_T^2 \cosh^2(\eta)} + p_T \sinh(\eta)}{\sqrt{m^2 + p_T^2 \cosh^2(\eta)} - p_T \sinh(\eta)} \right)$$

- For $\langle p_T \rangle \gg m \Rightarrow y \approx \eta$
- Non-equilibrium Relativistic Diffusion Model (RDM)

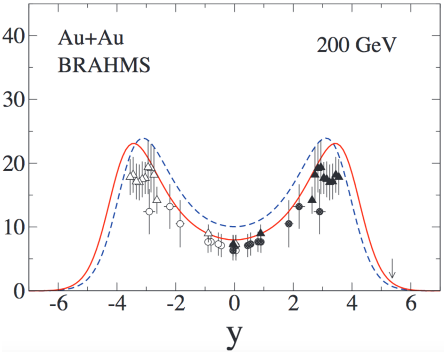
$$\frac{dN^{ch}}{d\eta} = J \int dp_0 \; N^{ch} f(y, p_0) \; \delta(p_0 - \tau_{int}) \equiv J \sum_{i=1}^{3} N_i R_i$$

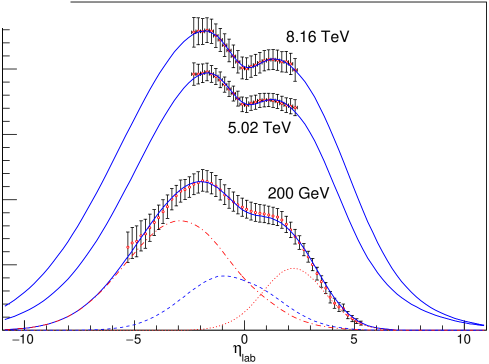


RDM

- (up) PbPb [Schulz,Wolschin2018]
- (right) pPb [Schulz,Wolschin2018]
- (left) Stopping [Wolschin2016]

$N^{p-\bar{p}}$





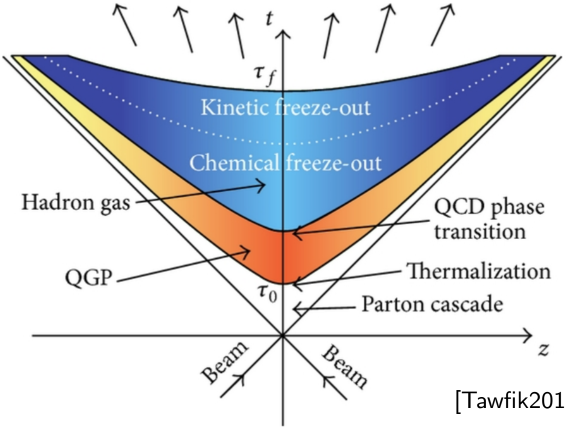
Relativistic Diffusion Model

- Two fragmentation sources

  $2 \rightarrow 1$ scattering

- Midrapidity source

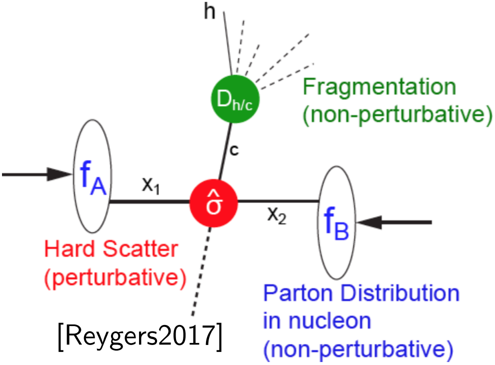
  nearly equilibrium $\Rightarrow$ thermal QCD, QGP, hydrodynamics



[Tawfik2014]

Outline

Collinear Factorization

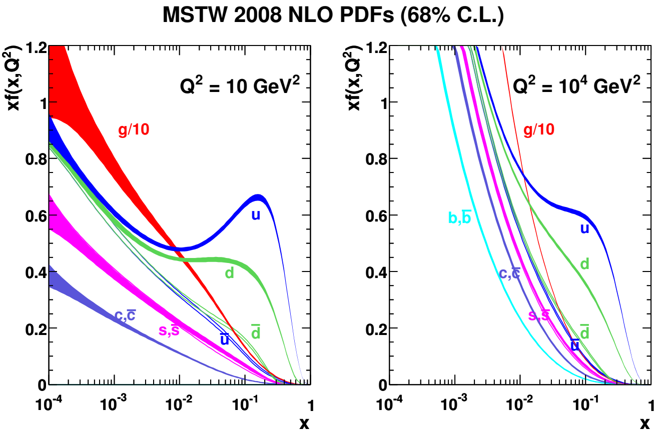


[Reygers2017]

$$d\sigma_{in} = \sum_{A,B,C} f_A \otimes f_B \otimes d\sigma(AB \to C) \otimes D_{h/C}$$

$$\sigma_{in} = \sum_{A,B,C} \int dx_1 dx_2 \; f_A(x_1) \; f_B(x_2) \; \sigma(AB \to C) \otimes D_{h/C}$$

PDFs



[MSTW2008]

- Infrared divergencies $\Rightarrow$ DGLAP for PDF $f_i(x)$

$$\frac{\partial g(x,Q^2)}{\partial \log(Q^2)} = \frac{\alpha_s(Q^2)}{2\pi}\left(\sum_i P_{gq} \otimes (q_i + \bar{q}_i) + P_{gg} \otimes g\right)$$

- Splitting function for quarks $P_{AB} = P(A \to B) \sim \alpha_s(Q^2)^n$

k_T-Factorization

- Splitting function for gluons $P_{gg}(x) \sim \alpha_s(Q^2)^n \log^{n-1}(1/x)$
- $1/x$ divergencies $\Rightarrow$ B-JIMBKL equation for

  unintegrated gluon distribution $\varphi(x, k_T)$

$$xg(x, Q^2) = \int^{Q^2} \frac{d^2 k_T}{(2\pi)^2} \varphi(x, k_T)$$

- Cross section:

$$\frac{d^2 \sigma_g^h}{dx_1 dx_2} = \int_{k_T, q_T} \frac{1}{k_T^2 q_T^2} \varphi(x_1, k_T)\ \varphi(x_2, q_T) \delta(|k_T + q_T - p_T|)$$

- $x_{1,2} = \sqrt{\frac{p_T^2}{s_{NN}}} \exp(\mp y)$

Color Dipole Cross Section

- Color dipole cross section: $\mathcal{N}$

$$\varphi_G^h(\mathbf{k}, y) \sim \int d^2r \; e^{-i\mathbf{kr}} \nabla_r^2 \mathcal{N}_G^h(\mathbf{r}, y)$$

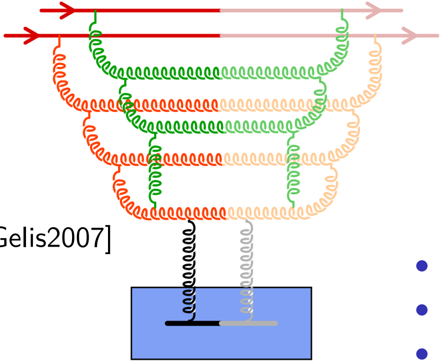
- Balitsky-Kovchegov (BK) equation with $Y = \log(x_0/x)$

$$\frac{\partial}{\partial Y} \mathcal{N}(\mathbf{x}, \mathbf{y}; Y) \sim \int_{\mathbf{z}} \mathcal{K}_{\mathbf{x},\mathbf{y},\mathbf{z}} \left[\mathcal{N}(\mathbf{x}, \mathbf{z}, Y) \mathcal{N}(\mathbf{z}, \mathbf{y}, Y) - \mathcal{N}(\mathbf{x}, \mathbf{y}, Y) \right]$$

$$\mathcal{K}^{LO}(\mathbf{x}, \mathbf{y}, \mathbf{z}) = \frac{N_c \alpha_s^{\text{fixed}}}{2\pi^2} \frac{(\mathbf{x} - \mathbf{y})^2}{(\mathbf{x} - \mathbf{z})^2 (\mathbf{z} - \mathbf{y})^2}$$

- $\mathbf{x} = (x_{T,0}, x_{T,1})$

Gluon Saturation



[Gelis2007]

- Gluon recombination
- Unitarity of gluon distribution
- Saturation Scale
  $Q_s^2(x) = x^{-\lambda} Q_0^2 A^{1/3}$
- $Q_s^2(0.1) = 0.44\mathrm{GeV}^2$
- Solution of BK:

$$\varphi(x, k_T) = -\int \mathrm{d}^2 r_T \; \mathrm{e}^{i k_T \cdot r_T} \left[1 - \exp\left(-\frac{1}{4} \left(r_T^2 Q_s^2(x) \right) \right)^{\gamma(y, k_T)} \right]$$

- Simplest solution: GBW Model

$$\varphi^{\gamma=1}(k_T^2) = \frac{4\pi k_T^2}{Q_s^2} \exp\left(-k_T^2/Q_s^2\right)$$

- $\gamma = 1/2$

$$\varphi^{\gamma=1/2}(k_T^2) = \frac{32\pi k_T^2}{Q_s^2} \frac{1}{\left(1 + 16k_T^2/Q_s^2\right)^{3/2}}$$

- Fragmentation region ⇒ large y ⇒ Dilute-dense regime
- Single Inclusive Hadron Production

$$\frac{\mathrm{d}N_A^h}{\mathrm{d}y} = \frac{C}{2\pi}\int_{z_0/z}^{1}\frac{\mathrm{d}x}{x}\; x f_A(x,p_T^2)\;\varphi(x^{2+\lambda}\mathrm{e}^{\tau})$$

- $\tau \equiv \ln(s_{NN}/Q^2) - \ln A^{1/3} - 2(1+\lambda)y$
- Geometric scaling: $z_0 \to 0$

$$C \equiv \int_{z_0}^{1}\mathrm{d}z\; D_{h/g}(z,p_T^2)$$

- Fragmentation function D ↔ parton-hadron duality

$$D_i^{h^\pm}(z,M_0^2) = N_i^{h^\pm} z^{a_i^{h^\pm}}(1-z)^{b_i^{h^\pm}}\left(1 + c_i^{h^\pm}(1-z)^{d_i^{h^\pm}}\right)$$

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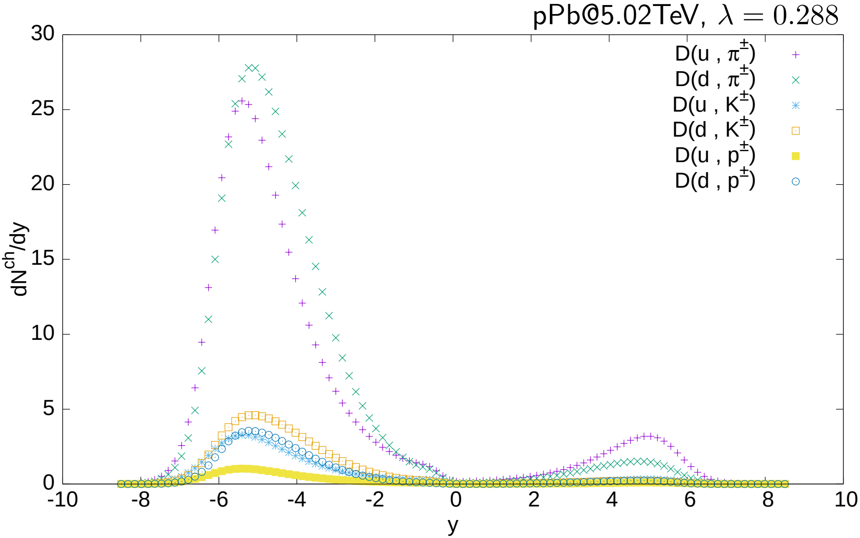

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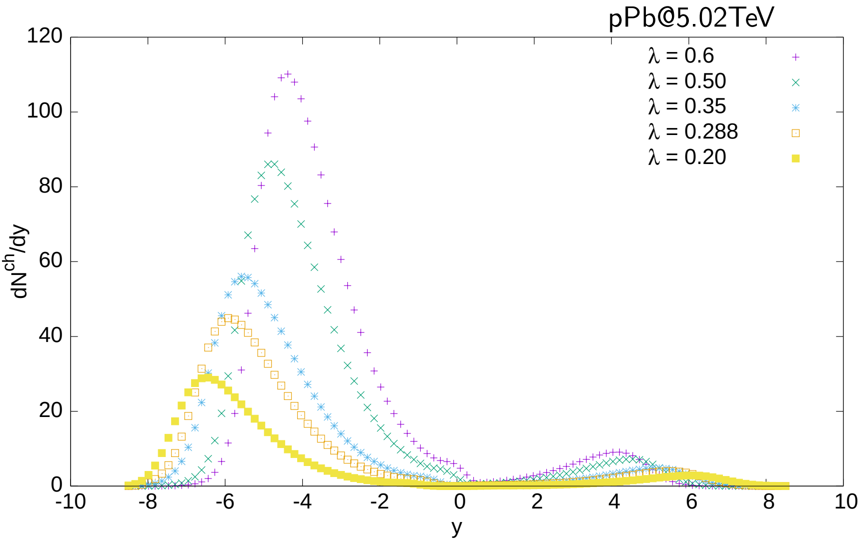

Outline

Summary

- Relativistic Diffusion Model
  → Rapidity distribution of charged hadrons

- Midrapidity source
  → Nearly thermalized, small-x small-x gluon scattering

- Fragmentation sources
  → small-x gluon high-x quark scattering

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