Microscopic Sources of Particle Production in Relativistic Heavy-Ion Collisions

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Multiparticle Dynamics Seminar
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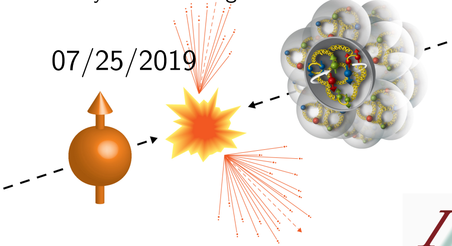

Outline

(1) [fig:phys.org20150211]

Outline

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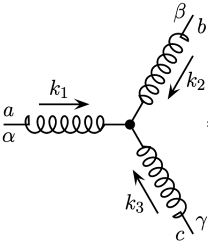
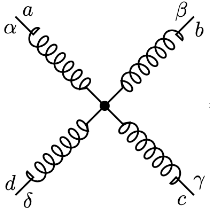
   - QCD and Hadrons
   - Relativistic Heavy-Ion Collisions
2. The Parton Model
   - QCD Factorization at High Energies
   - Parton Distribution Function
   - kT-Factorization
   - Gluon Saturation
3. Results for Charged Hadron Production
   - Relativistic Diffusion Model
   - Hybrid-Factorization
4. Summary

- QCD Lagrangian, color charge a

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{q}(i\not{D} - m_q)q - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$



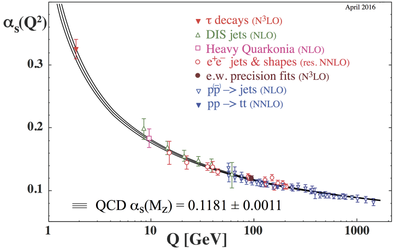


Motivation: QCD and Hadrons

- First order running coupling:

$$\alpha_s(Q^2) = \frac{12 \cdot \pi}{(33 - 2n_f) \cdot \ln(Q^2/\Lambda^2_{\text{QCD}})}$$

- Non-perturbative regime: $\Lambda_{\text{QCD}} \approx 0.22$ GeV



[Bethke2017]

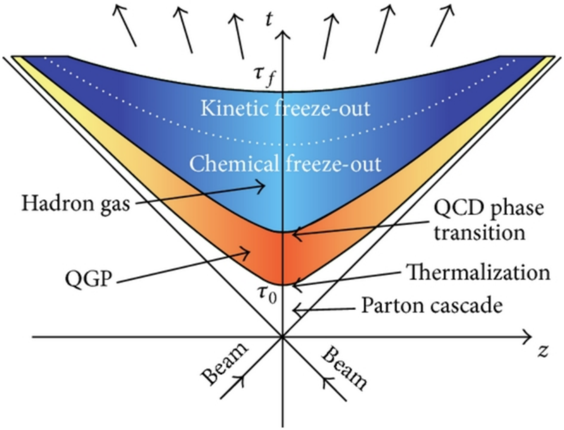
- $q - \bar{q}$ Potential: $V(r) = \frac{4}{3}\frac{\alpha_s(r)}{r} + k \cdot r$
- Confinement: q, g

$\Rightarrow$ Hadrons (non point-like particles)

Relativistic Heavy-Ion Collisions

- Observable: produced charged hadrons $d\sigma^{ch}$
- High Energy at LHC:

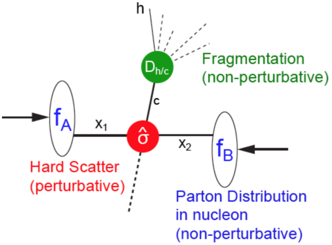
$$pp \to H,\ pPb \to H,\ PbPb \to H, \text{ with } p = \text{uud}$$



[Fig:Tawfik2014]

Outline

QCD Factorization at High Energies



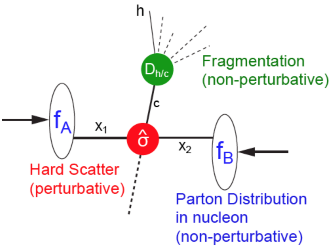
[fig:Reygers2017]

- Factorization: hard- and soft-processes

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

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

QCD Factorization at High Energies

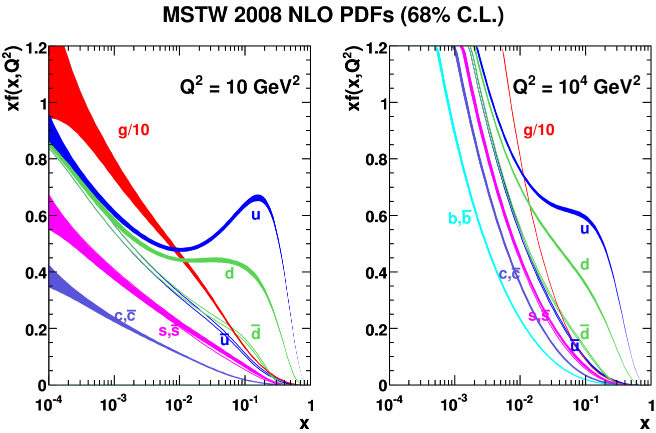


[fig:Reygers2017]

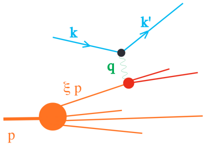
Relativistic Heavy-Ion Collisions

- Parton Distribution Functions: PDFs, nPDFs (nuclear PDFs)
- Collinear Factorization, k_T-Factorization
- Color Glass Condensate, Initial State Models
- Hard Scattering ⇒ Dipol Color Cross section
- Fragmentation ⇒ Parton-Hadron Duality

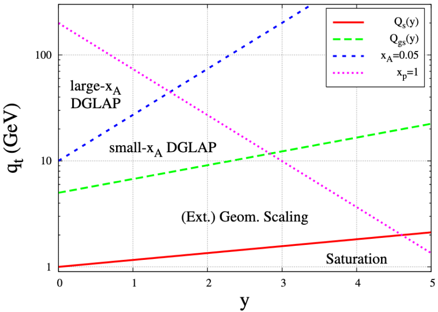
Parton Distribution Function



- infinite-momentum frame: $f(x, Q^2)$



[fig: hep-ph/9702203]



Collinear Factorization

$$y = \ln(x_0/x)$$

[fig: Dumitru2006]

- Infrared divergencies ⇒ DGLAP for $f_i(x)$

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

- Splitting function for quarks $P_{AB} = P(A \to B) \sim \alpha_s(Q^2)^n$
- Splitting function for gluons $P_{gg}(x) \sim \alpha_s(Q^2)^n \log^{n-1}(1/x)$

- $1/x$ divergencies $\Rightarrow$ B-JIMWLK equations
- large N_c-limit B-JIMWKL

  Balitsky-Kovchegov (BK) equation
- Definition: 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 in k_T-Factorization:

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

- Color-dipole cross section: $\mathcal{N}(\mathbf{r}, Y)$ with $\mathbf{x} = (x_{T,0}, x_{T,1})$

$$\varphi(\mathbf{k}, Y) \sim \int d^2r \; e^{-i\mathbf{kr}} \nabla_r^2 \mathcal{N}(\mathbf{r}, Y)$$

- BK equation with $Y = \log(x_0/x)$ (tree level)

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

- Kernel:

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

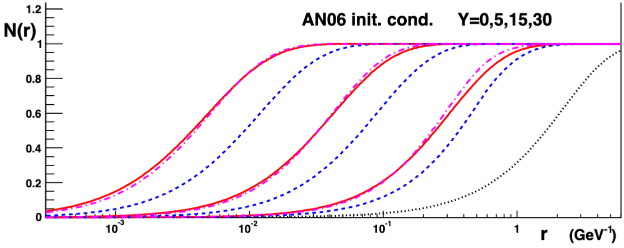
Balitsky-Kovchegov equation

- Running coupling BK (rcBK): $\frac{\partial}{\partial Y}\mathcal{N}(r,Y) \sim$

$$\int \mathcal{K}^{\text{run}}_{r,r_1,r_2}\left[\mathcal{N}(r_1,Y) + \mathcal{N}(r_2,Y) - \mathcal{N}(r,Y) - \mathcal{N}(r_1,Y)\mathcal{N}(r_2,Y)\right]$$

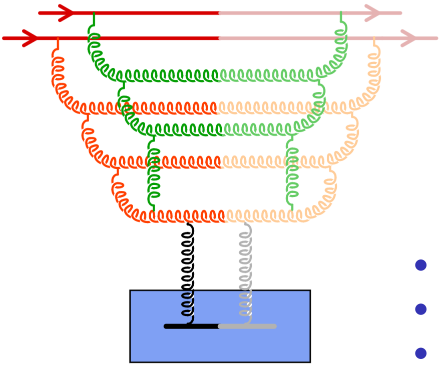
- kernel in transverse position space: $\mathcal{K}^{\text{run}}_{r,r_1,r_2} =$

$$\frac{N_c \alpha_s(r^2)}{2\pi^2}\left[\frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right)\right]$$

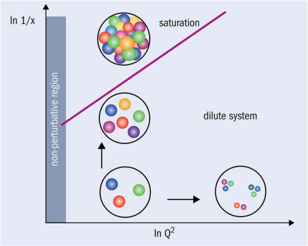


[Albacete2007]

Gluon Saturation



[fig: Gelis2007]



- $xg(x, Q^2) \sim 1/x$
- Gluon Saturation via recombination
- Unitarity of gluon distribution
- Dynamical Saturation Scale

$$Q_s^2(x) = x^{-\lambda} Q_0^2 A^{1/3}$$

[fig2: cerncourier.com]

Analytical Solutions of BK

- Solution of fixed BK with Feynman-x

$$\mathcal{N}(r_T, x) = 1 - \exp\left(-\frac{1}{4}\left(r_T^2 Q_s^2(x)\right)\right)^{\gamma(y,k_T)}$$

$$\varphi(x, k_T) = -\int \mathrm{d}^2 r_T \; \mathrm{e}^{ik_T \cdot r_T} \mathcal{N}(r_T, x)$$

$\rightarrow$ Hankel transformation

- Simplest Model: $\gamma = 1 \Rightarrow$ Golec-Biernat,Wusthoff (GBW)

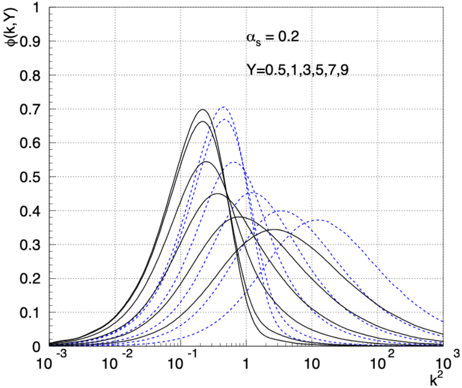
$$\varphi^{\gamma=1}(k_T^2) = \frac{4\pi k_T^2}{Q_s^2} \exp\left(-k_T^2/Q_s^2\right)$$

- Model: $\gamma = 1/2 \Rightarrow$ Boer,Utermann,Wessels (BUW)

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

- McLerran-Venugopalan (MV) Model

$$N(r, Y=0) = 1 - \exp\left(-\left(\frac{r^2 Q_{s_0}^2}{4}\right)^{\gamma} \ln\left(\frac{1}{\Lambda_{\mathrm{QCD}} \cdot r} + e\right)\right)$$



[fig: Venugopalan2008]

Outline

Relativistic Diffusion Model

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

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

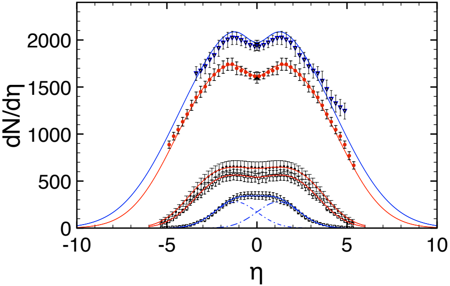
- Observable: Produced charged hadrons:

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

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

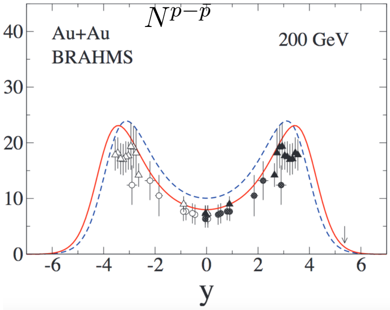
- For $\langle p_T \rangle \gg m \Rightarrow y \approx \eta$
- Non-equilibrium Relativistic Diffusion Model (RDM)

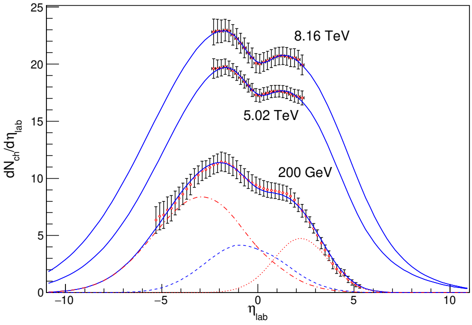
$$\frac{dN^{ch}}{d\eta} = J\int dp_0 \; N^{ch} f(y, p_0) \; \delta(p_0 - \tau_{int}) \equiv J\sum_{i=1}^{3} N_i R_i$$



RDM

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





Hybrid-Factorization

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

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

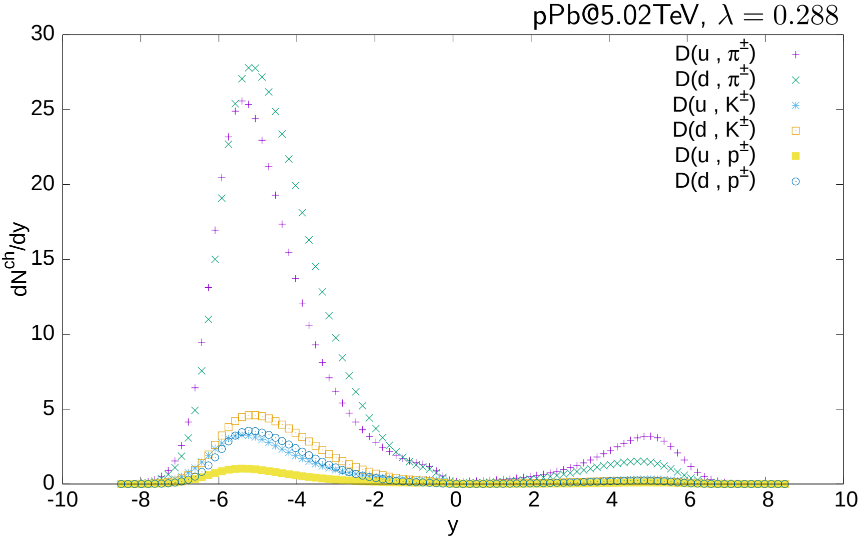
- $\tau \equiv \ln(s_{NN}/Q^2) - \ln A^{1/3} - 2(1+\lambda)y$
- Geometric scaling: $z_0 \to 0$

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

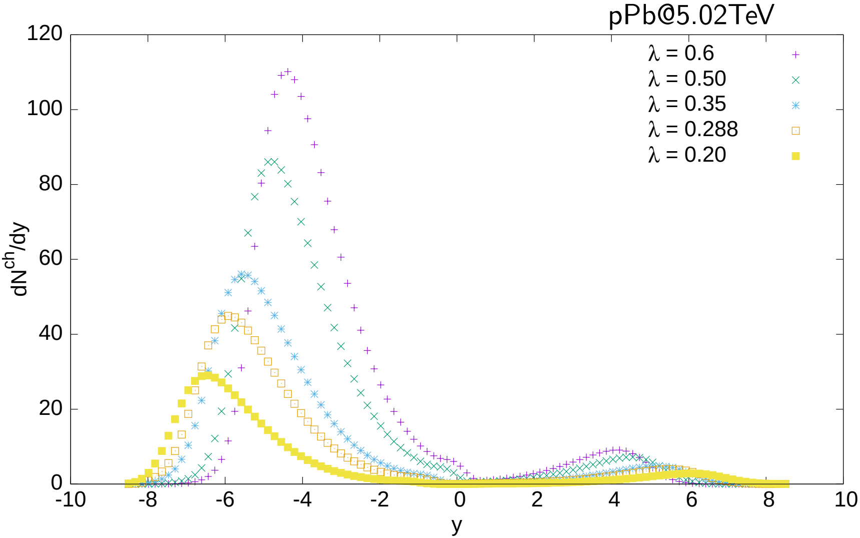
- Fragmentation function D ↔ parton-hadron duality
- Parametrisation:

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

Charged Hadron Production



Charged Hadron Production



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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