Melting the CGC
in pA and AA collisions at the LHC

H. Fujii, F. Gelis, A. Stasto, R. Venugopalan

CERN and CEA/Saclay

Color Glass Condensate

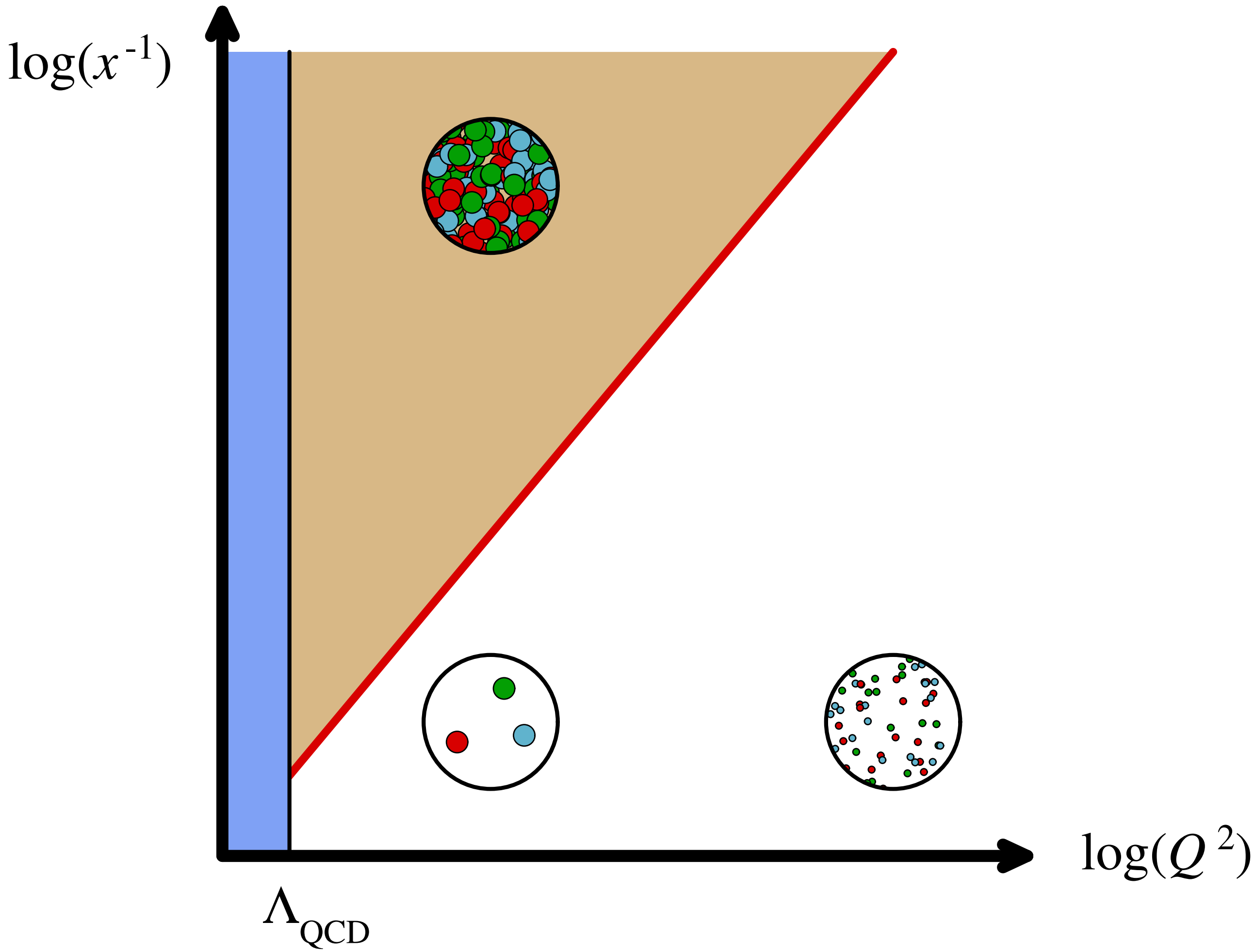
Saturation domain

Color Glass Condensate

- Hadron-hadron collisions
- AA collisions
- pA collisions

Hadron multiplicity

Charm production



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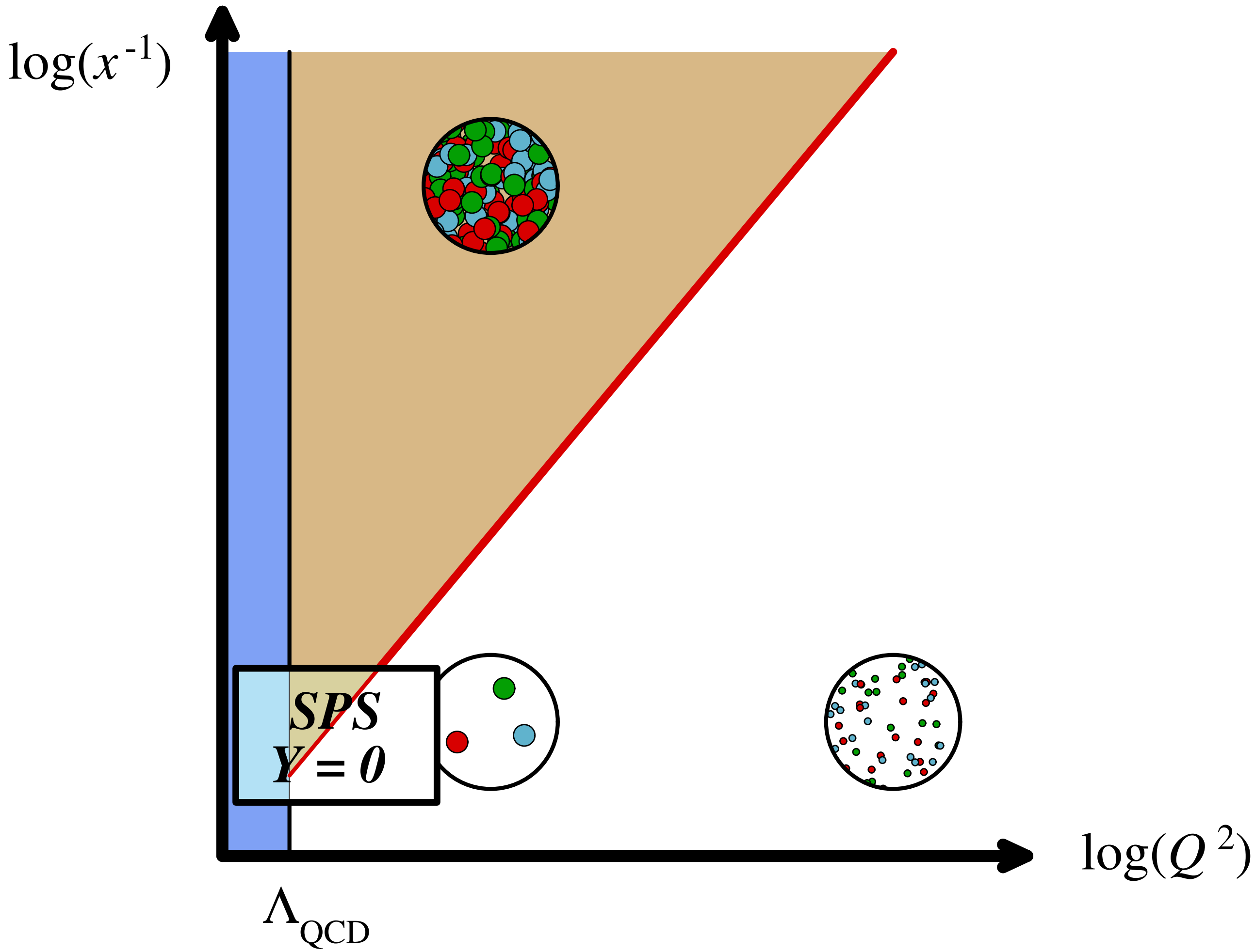

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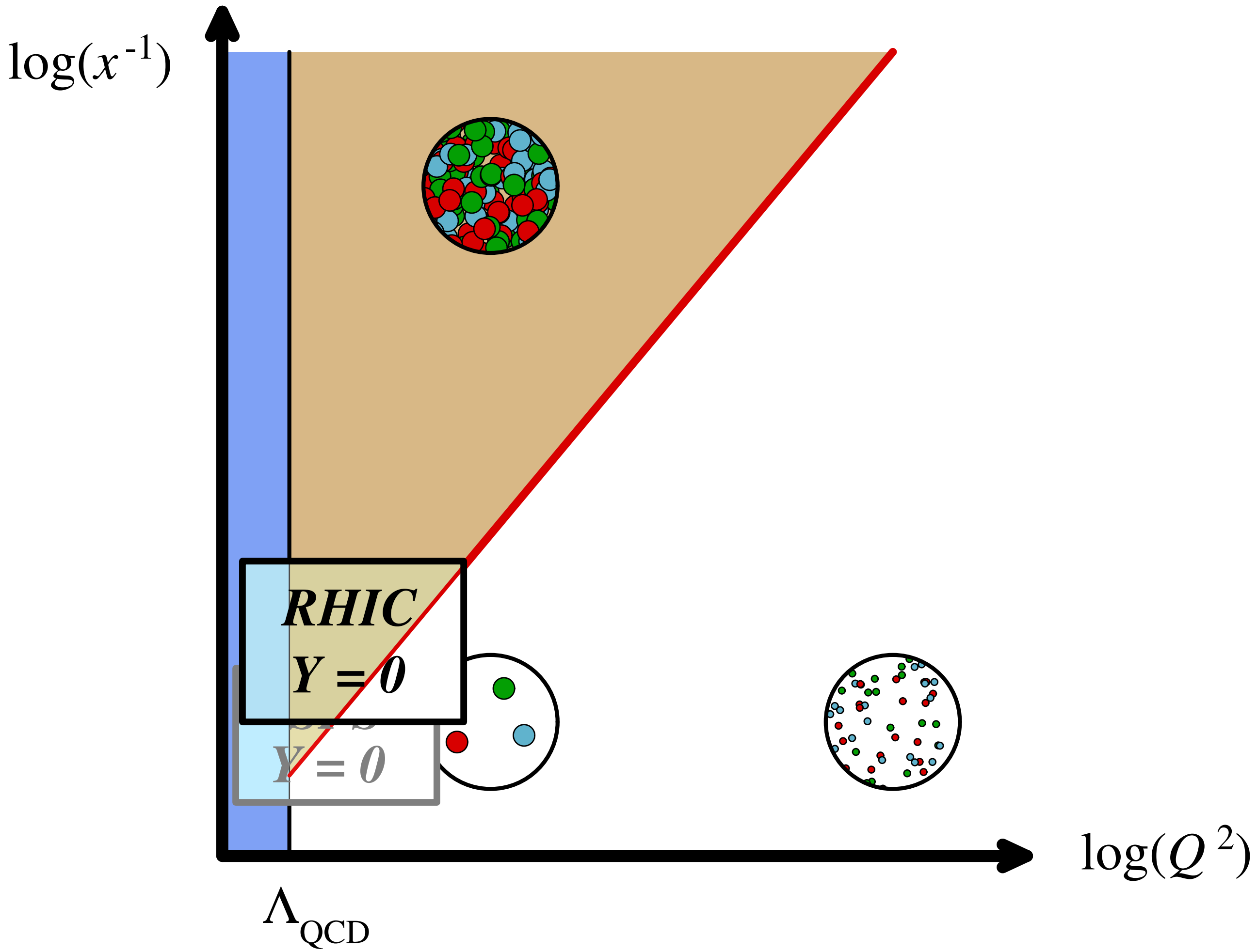

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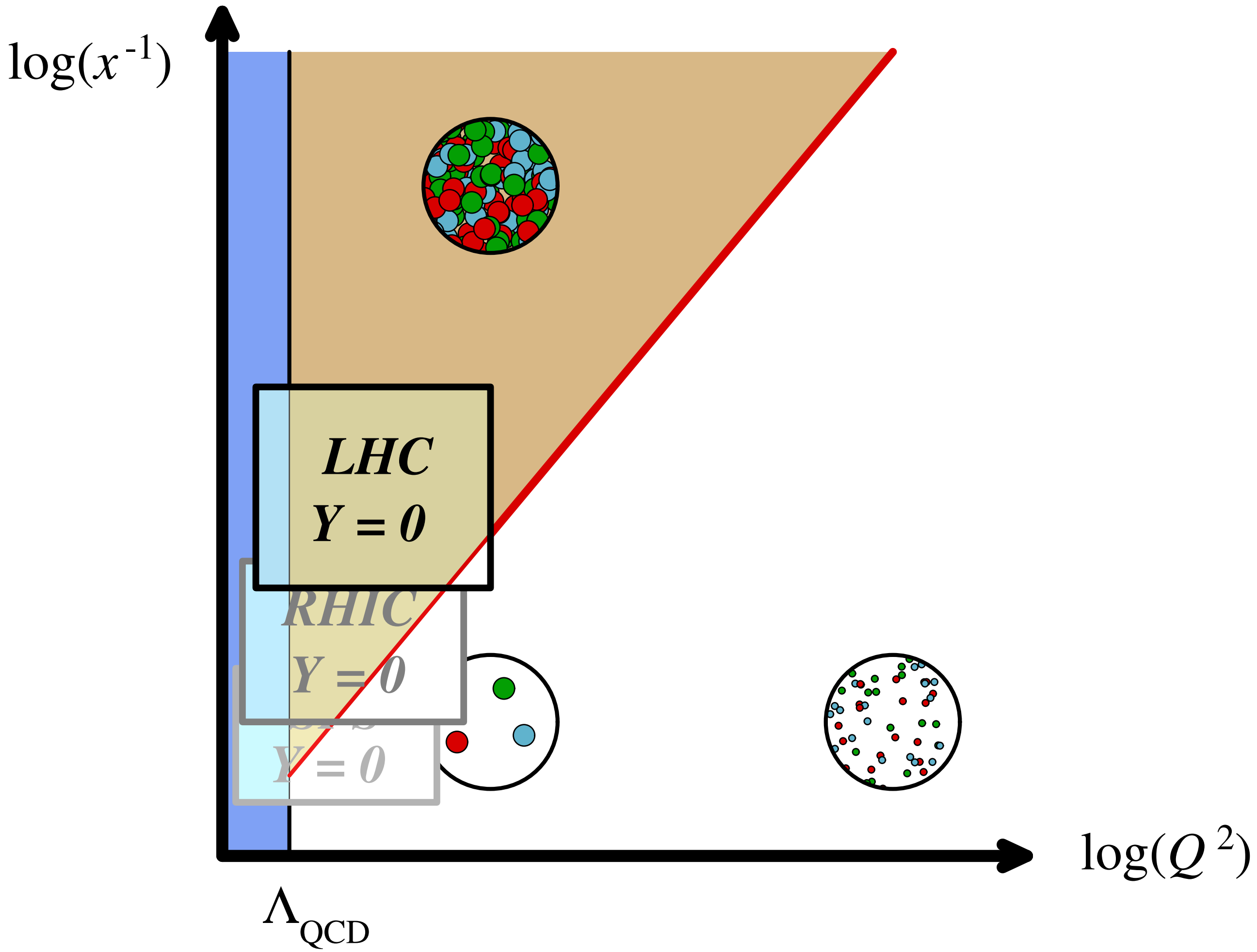

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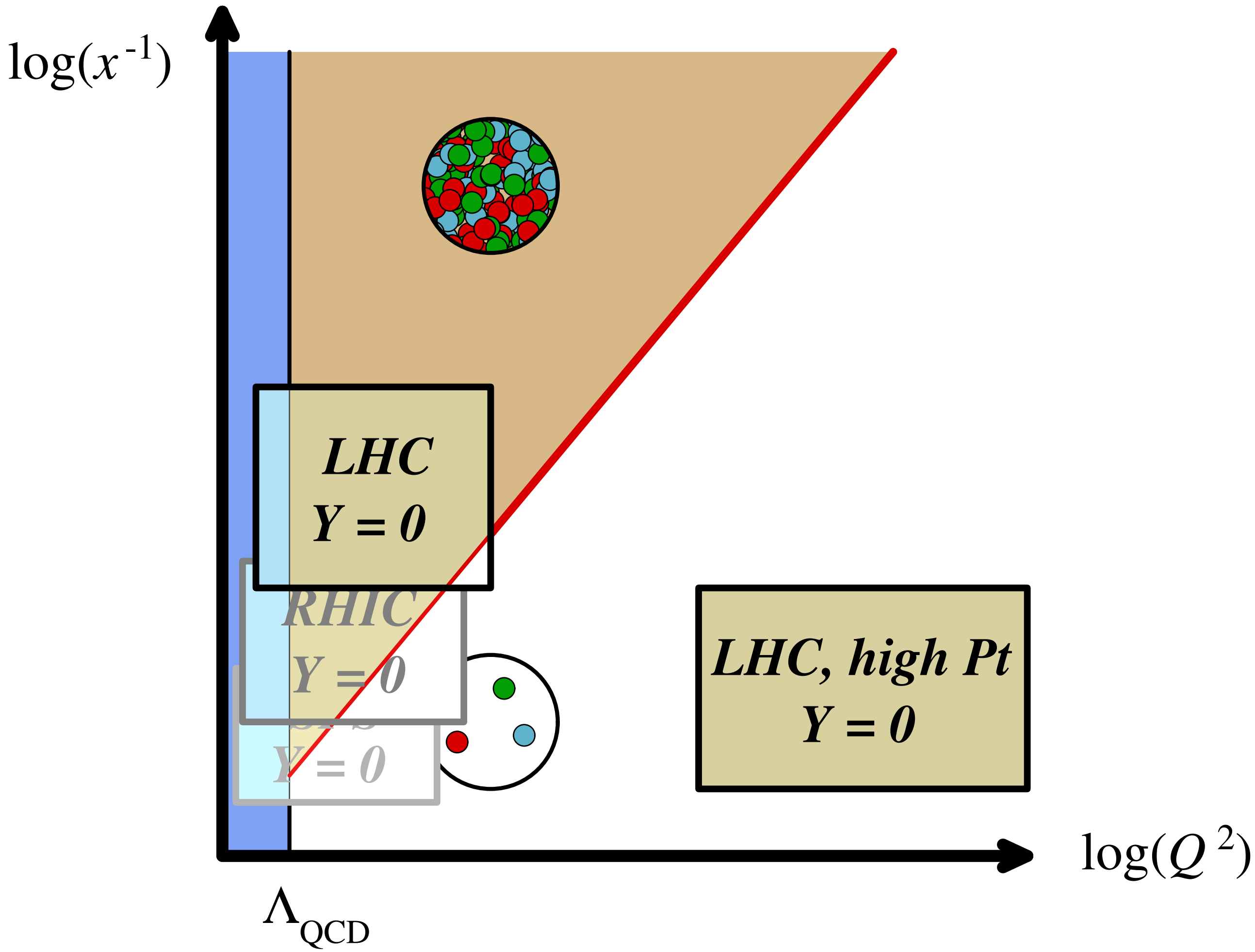

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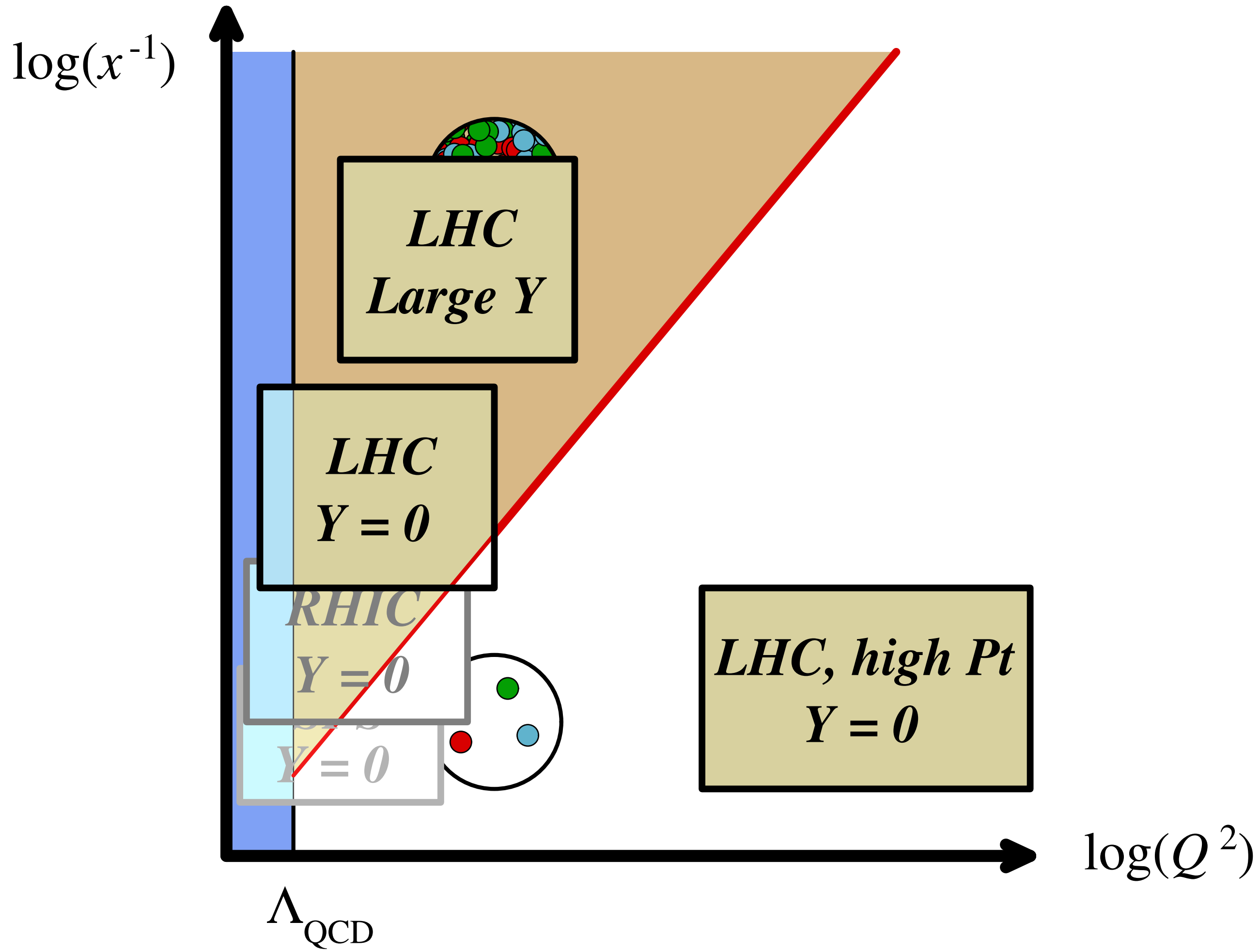


Color Glass Condensate

- Soft modes have a large occupation number
  ▷ they are described by a classical color field A^μ that obeys Yang-Mills's equation:

$$[D_\nu, F^{\nu\mu}]_a = J_a^\mu$$

- The source term J_a^μ comes from the faster partons. The hard modes, slowed down by time dilation, are described as frozen color sources ρ_a. Hence :

$$J_a^\mu = \delta^{\mu +}\delta(x^-)\rho_a(\vec{\boldsymbol{x}}_\perp) \qquad (x^- \equiv (t-z)/\sqrt{2})$$

- The color sources ρ_a are random, and described by a distribution functional $W_Y[\rho]$, with Y the rapidity that separates "soft" and "hard"

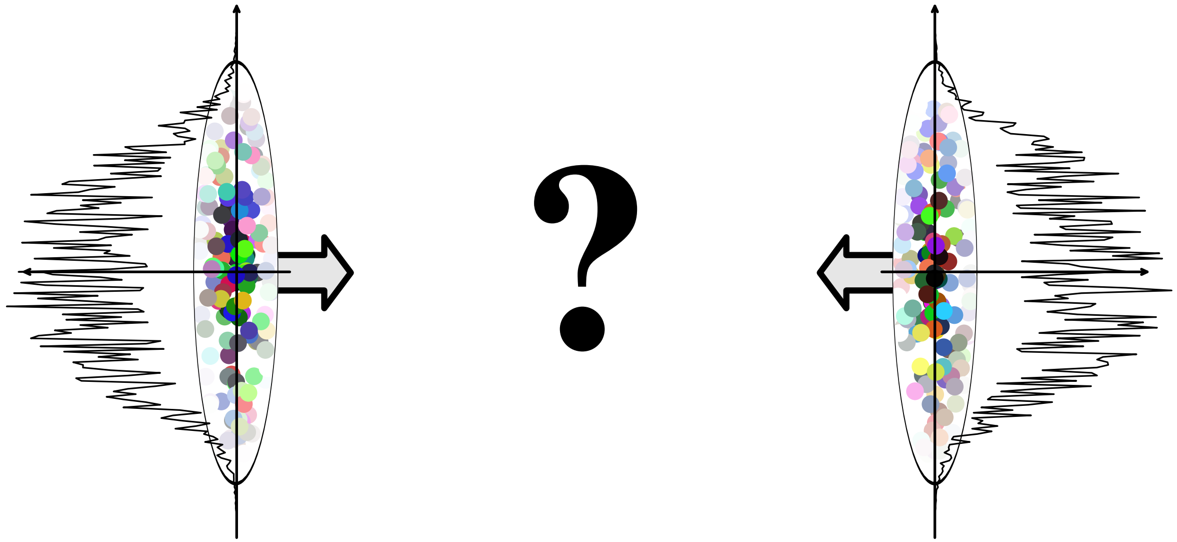
- Evolution equation (JIMWLK) + initial condition :

$$\frac{\partial W_Y[\rho]}{\partial Y} = \mathcal{H}[\rho] \;\; W_Y[\rho]$$

Description of hadronic collisions

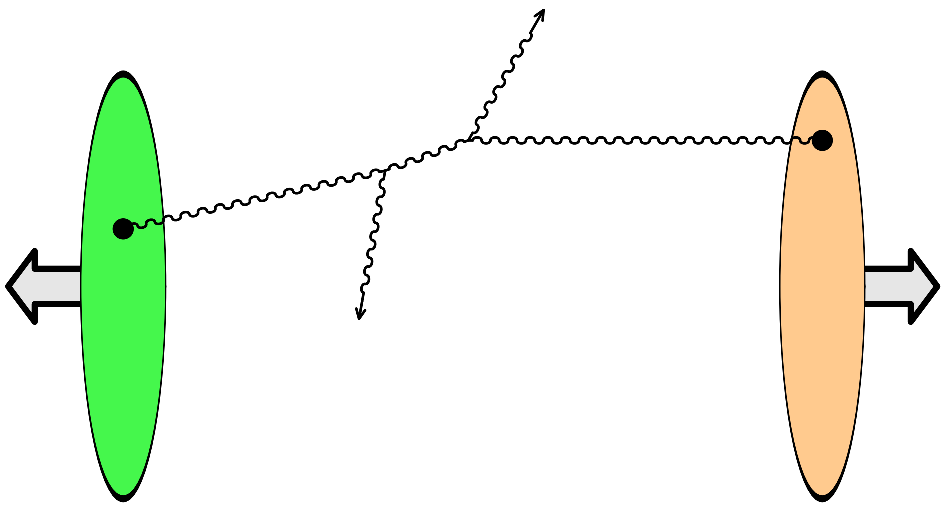
- For hadron-hadron collisions, there are two strong sources that contribute to the color current :

$$J^\mu \equiv \delta^{\mu+}\delta(x^-)\,\rho_1(\vec{\boldsymbol{x}}_\perp) + \delta^{\mu-}\delta(x^+)\,\rho_2(\vec{\boldsymbol{x}}_\perp)$$



$$\mathcal{L} = -\frac{1}{2}\,\mathrm{tr}\,F_{\mu\nu}F^{\mu\nu} + \underbrace{(J_1^\mu + J_2^\mu)}_{J^\mu}A_\mu$$

Description of hadronic collisions



- Dilute regime : one source in each projectile interact

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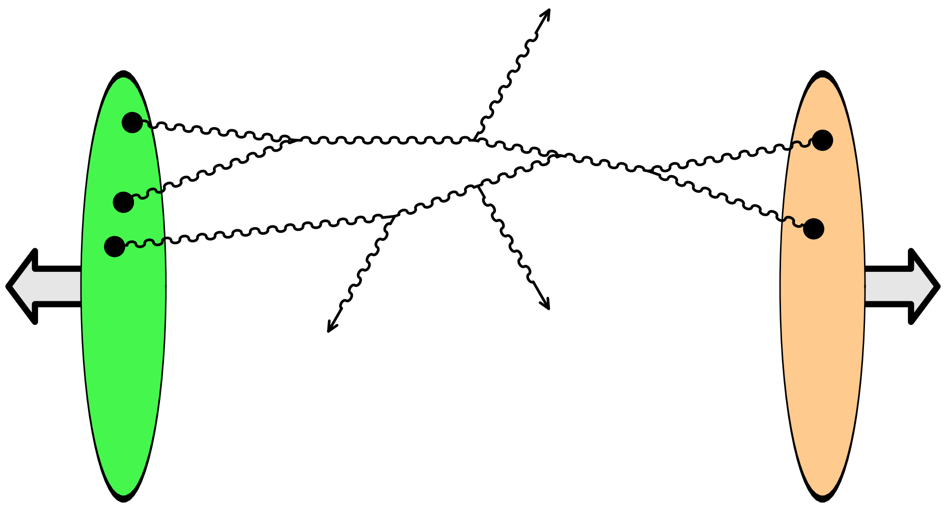

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- Dense regime : non linearities are important ($\rho \sim g^{-1}$)

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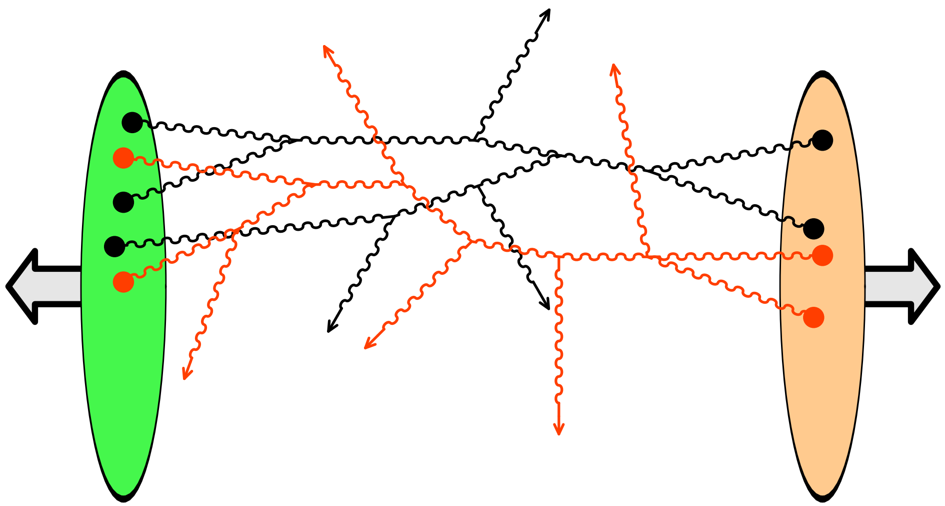

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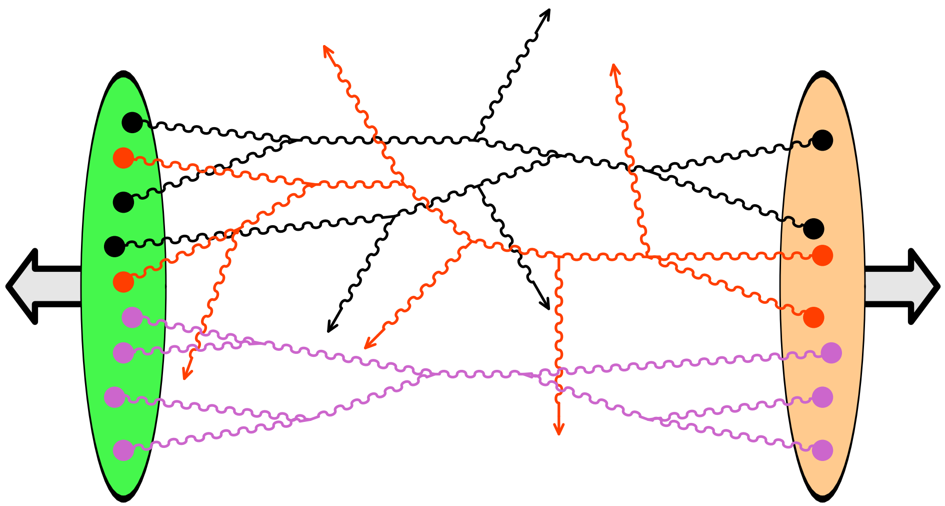

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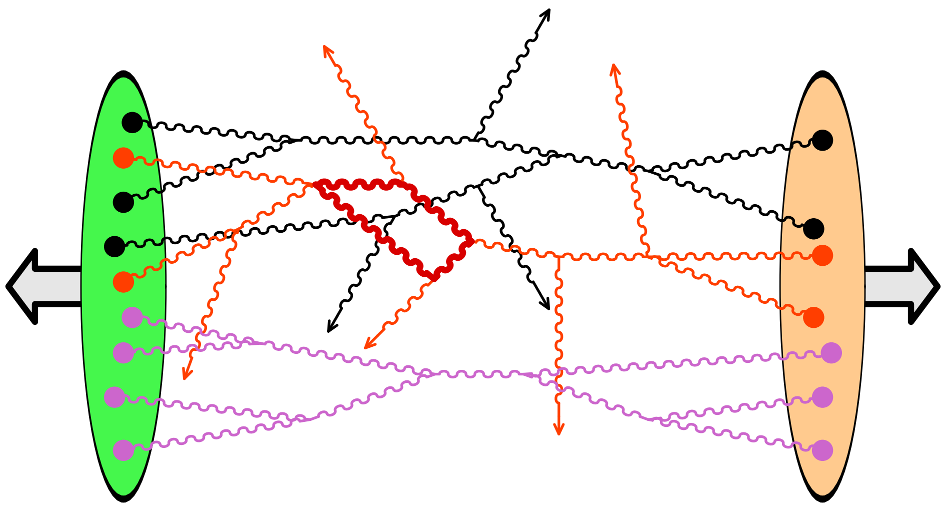

- Dilute regime : one source in each projectile interact
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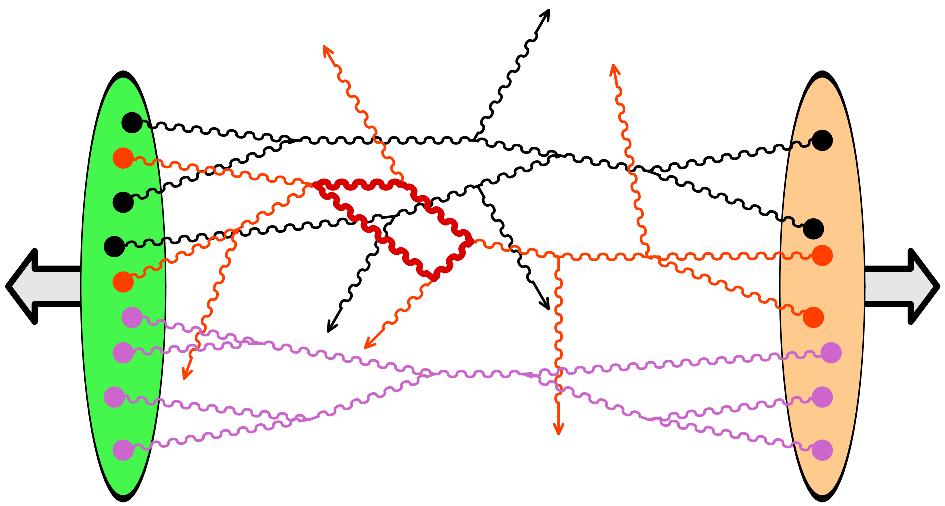
- There can be many simultaneous disconnected diagrams
- Some of them may not produce anything (vacuum diagrams)
- All these diagrams can have loops (at NLO and beyond)

Nucleus-Nucleus collisions

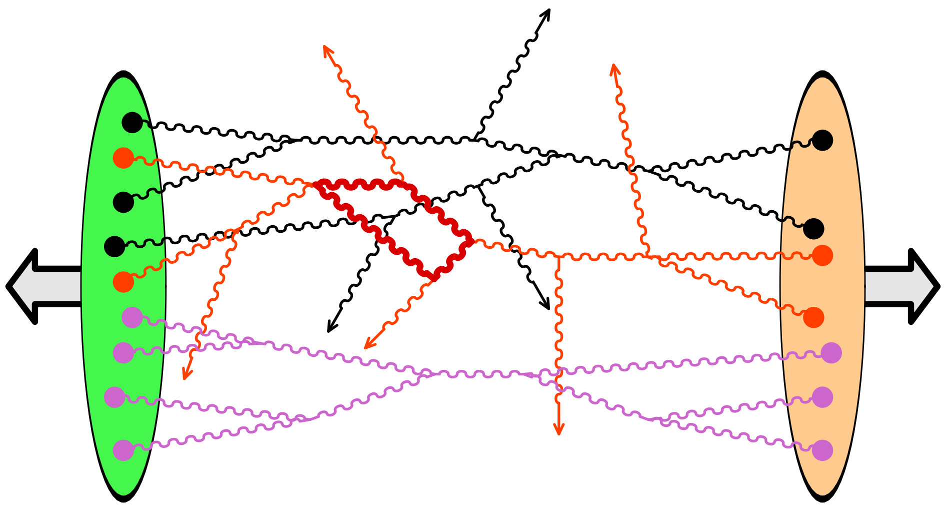


- Calculation of observables :

$$\langle \mathcal{O}_Y \rangle = \int [D\rho_1]\,[D\rho_2]\; W_{Y_{\rm beam}-Y}[\rho_1]\; W_{Y+Y_{\rm beam}}[\rho_2]\; \mathcal{O}[\rho_1,\rho_2]$$

- $\mathcal{O}[\rho_1,\rho_2]$ is strongly non-linear in both ρ_1 and ρ_2
- Beware: this factorization formula is so far unproven, although it is likely to hold at least for single inclusive spectra (FG, Lappi, Venugopalan - work in progress)

Nucleus-Nucleus collisions

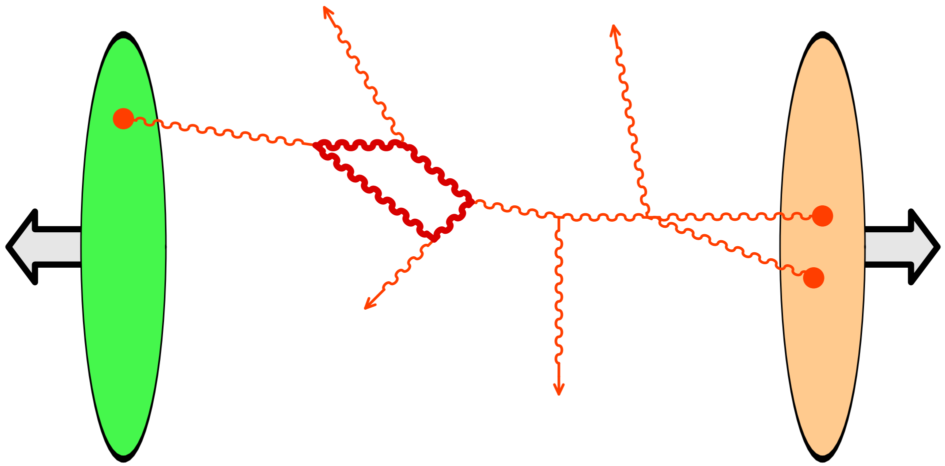


- Single inclusive gluon spectrum at Leading Order :
  Krasnitz, Nara, Venugopalan (1999 – 2001), Lappi (2003)

$$\frac{d\overline{N}_{LO}[\rho_1,\rho_2]}{dY\,d^2\vec{\boldsymbol{p}}_\perp} = \frac{1}{16\pi^3}\int_{x,y} e^{ip\cdot(x-y)}\,\square_x\square_y\,\sum_\lambda \epsilon_\lambda^\mu\epsilon_\lambda^\nu\;\mathcal{A}_\mu(x)\mathcal{A}_\nu(y)$$

  where $\mathcal{A}_\mu(x)$ is the classical retarded solution of Yang-Mills equations with the current J^μ
  ▷ quite heavy computationally, but doable

Proton-Nucleus collisions

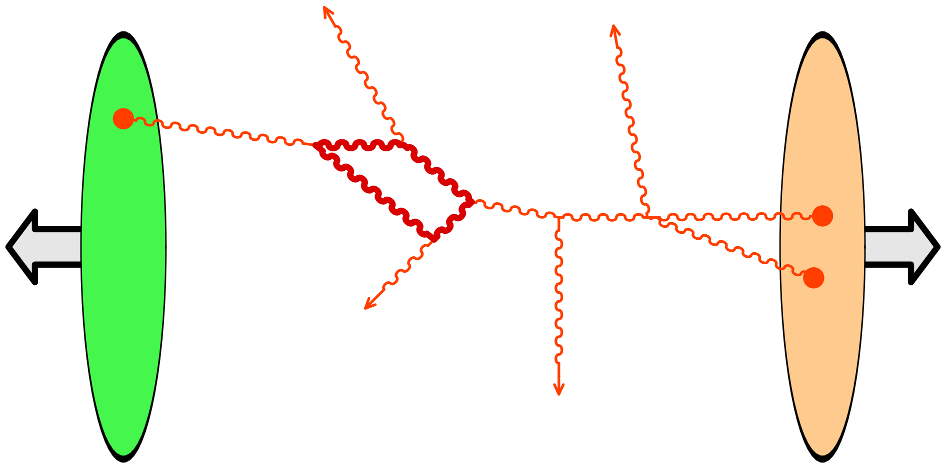


- Amplitude linear in ρ_1 $\triangleright$ no multiply connected graphs
- $\mathcal{O}[\rho_1, \rho_2]$ quadratic in ρ_1 $\triangleright$ we do not need all the information contained in $W_Y[\rho_1]$, but only

$$\varphi_Y(\vec{\boldsymbol{k}}_\perp) \sim \int_{\vec{\boldsymbol{r}}_\perp} \frac{e^{-i\vec{\boldsymbol{k}}_\perp \cdot \vec{\boldsymbol{r}}_\perp}}{k_\perp^2} \int [D\rho_1] \, W_Y[\rho_1] \, \rho_1(0)\rho_1(\vec{\boldsymbol{r}}_\perp)$$

Note : $\varphi_Y(\vec{\boldsymbol{k}}_\perp)$ is the usual non-integrated gluon distribution, that obeys BFKL equation

Proton-Nucleus collisions

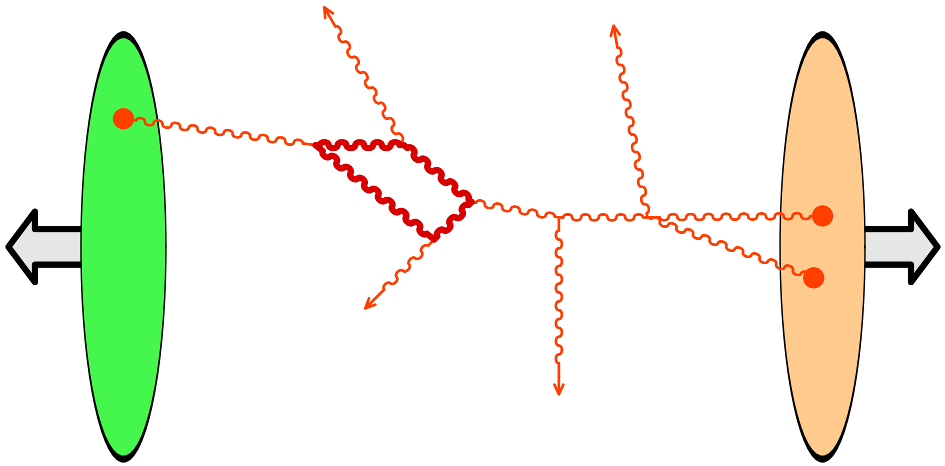


- Now, observables are given by an asymmetric factorization formula :

$$\langle \mathcal{O}_Y \rangle = \int d^2\vec{\boldsymbol{k}}_\perp \; \varphi_{Y_{\rm beam}-Y}(\vec{\boldsymbol{k}}_\perp) \int [D\rho_2] \; W_{Y+Y_{\rm beam}}[\rho_2] \; \frac{d\mathcal{O}[\rho_2]}{d^2\vec{\boldsymbol{k}}_\perp}$$

- The quantity $d\mathcal{O}[\rho_2]/d^2\vec{\boldsymbol{k}}_\perp$ usually has a simple expression in terms of Wilson lines built from ρ_2

Proton-Nucleus collisions



- Limit of collinear factorization :
  - The typical $\boldsymbol{p}_\perp$ scale in $\mathcal{O}[\rho_2]$ is set by the $\boldsymbol{P}_\perp$ of the final state
  - If this $\boldsymbol{P}_\perp$ is large, one can neglect the intrinsic $\boldsymbol{k}_\perp$ of the proton :

$$\langle \mathcal{O}_Y \rangle = \underbrace{\int^{\boldsymbol{P}_\perp^2} d^2\vec{\boldsymbol{k}}_\perp \, \varphi_{Y_{\rm beam}-Y}(\vec{\boldsymbol{k}}_\perp)}_{x_1 G(x_1, \boldsymbol{P}_\perp^2)} \int [D\rho_2] \, W_{Y+Y_{\rm beam}}[\rho_2] \left[\lim_{\boldsymbol{k}_\perp \to 0} \frac{d\mathcal{O}[\rho_2]}{d^2\vec{\boldsymbol{k}}_\perp} \right]$$

Charged hadron multiplicity

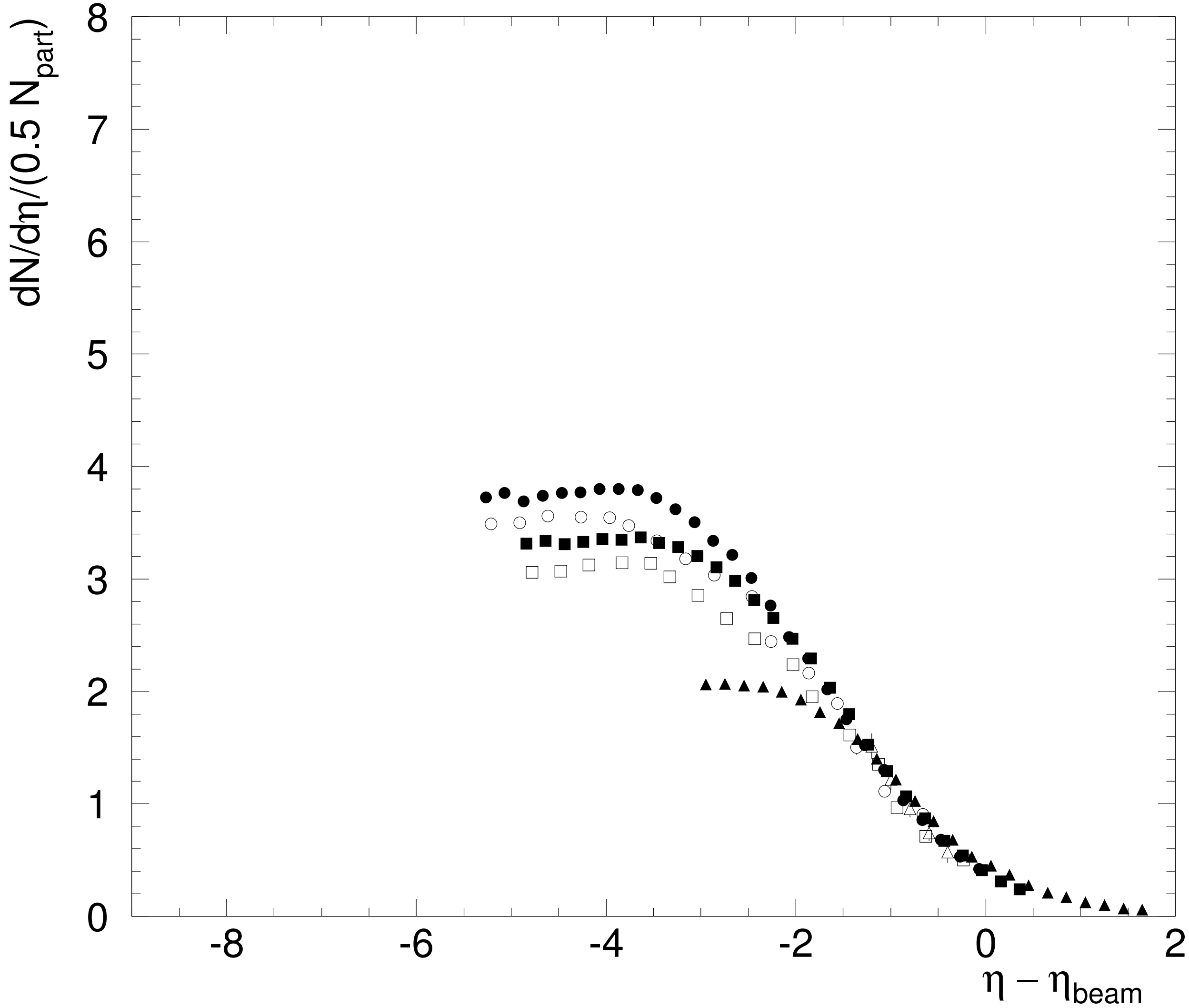
(FG, A. Stasto, R. Venugopalan)

Limiting fragmentation (RHIC)

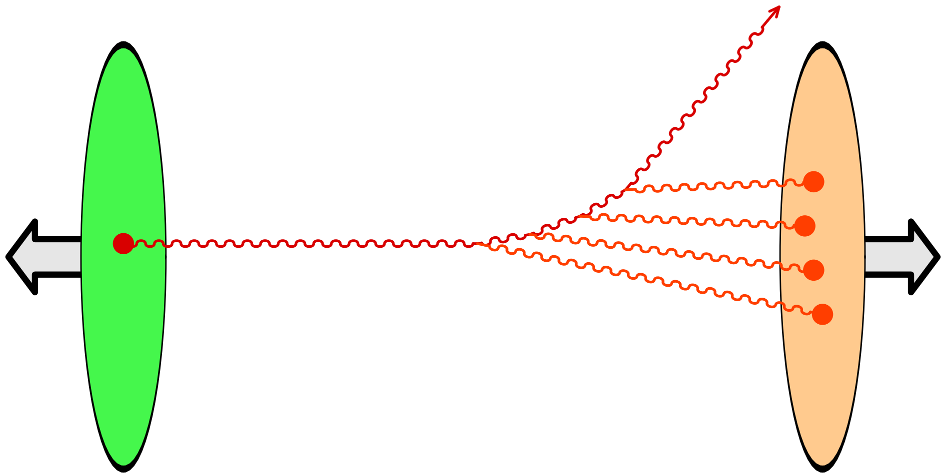
Color Glass Condensate

Hadron multiplicity
- Limiting fragmentation
- Qualitative explanation
- LHC prediction

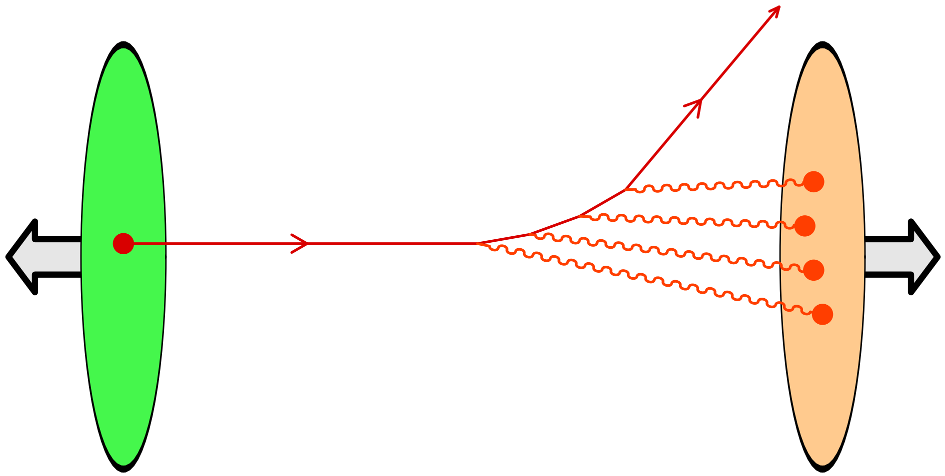
Charm production



Qualitative explanation



Qualitative explanation



- Initiated by a gluon or a quark
- The two contributions to the yield are given by :

$$\frac{dN}{d^2\vec{\boldsymbol{P}}_\perp dY} \sim x_1 f(x_1, \boldsymbol{P}_\perp^2) \underbrace{\int d^2\vec{\boldsymbol{r}}_\perp \, e^{i\vec{\boldsymbol{P}}_\perp\cdot\vec{\boldsymbol{r}}_\perp} \left\langle \mathrm{tr}\left(U(0)U^\dagger(\vec{\boldsymbol{r}}_\perp)\right)\right\rangle_{x_2}}$$

Note : the underlined factor becomes independent of x_2 when integrated over $\vec{\boldsymbol{P}}_\perp$ because of the unitarity of the Wilson lines

Qualitative explanation

- The ratio of the two saturation scales is :
  $Q_s^2(x_2)/Q_s^2(x_1) \sim \exp(2\lambda Y) \sim 20$ with $\lambda \approx 0.3$ and $Y = 5$

  ▷ neglect the transverse momentum in the projectile at large x_1 compared to that in the projectile at x_2

  ▷ use collinear factorization for projectile 1

- At large x_1, $x_1\, f(x_1, \boldsymbol{P}_\perp^2)$ is almost independent of $\boldsymbol{P}_\perp^2$ (Bjorken scaling), and the integration over $\vec{\boldsymbol{P}}_\perp$ leads to :

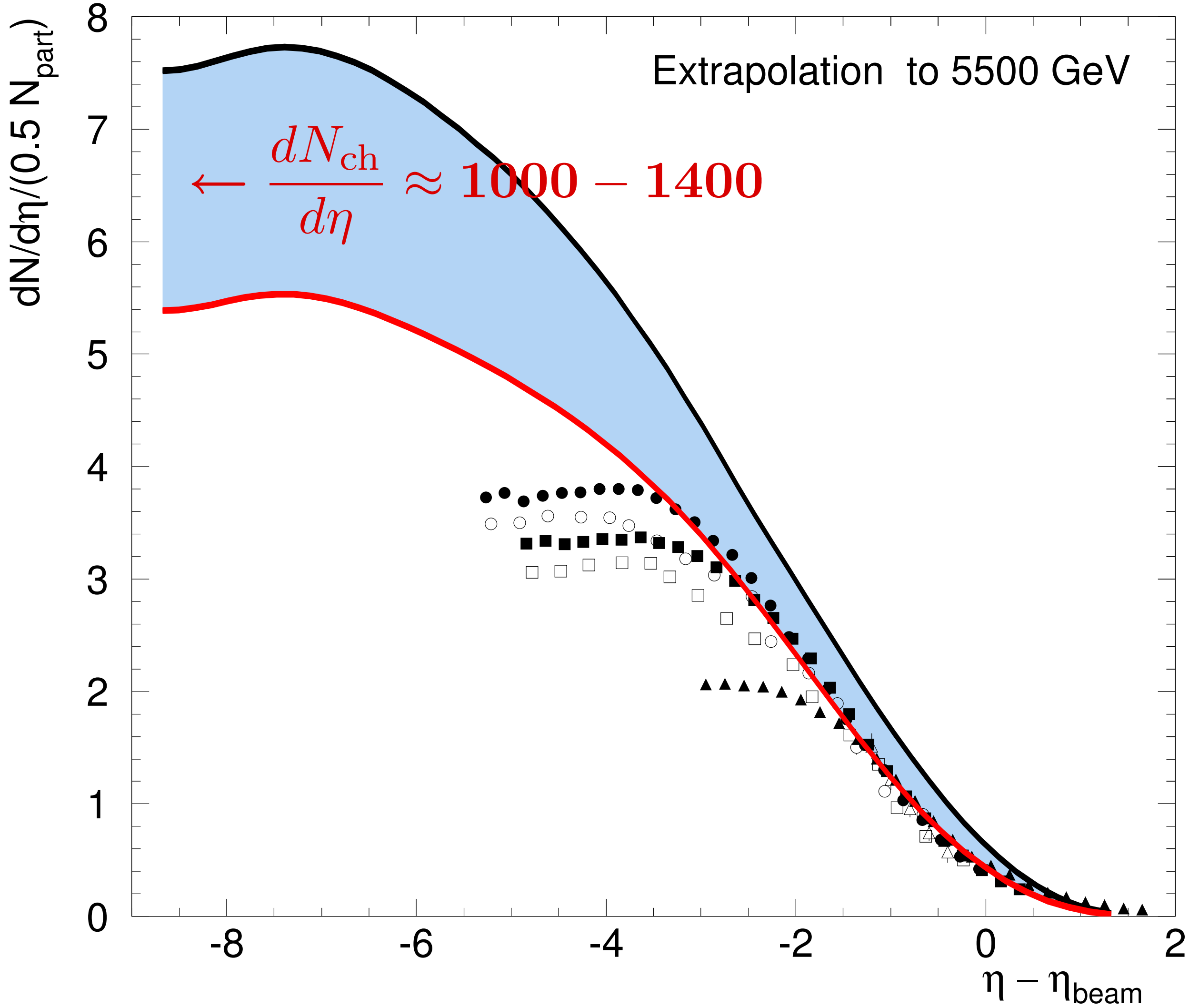
$$\frac{dN}{dY} \propto x_1\, f(x_1)$$

▷ dN/dY depends only on $x_1 \sim \exp(Y - Y_{\rm beam})$

LHC prediction: ingredients

- Go back to the full formula for dN/dY in order to study deviations from limiting fragmentation
- At $x_0 = 10^{-2}$, chose an initial condition for the nuclear correlator (e.g. McLerran-Venugopalan or Golec-Biernat-Wüsthoff)
- The evolution to smaller x is done by solving the BK equation
- Convert Y to η by assuming an effective mass of the order of 200 MeV
- Adjust the free parameters in order to obtain a good fit to RHIC spectra
- Set $\sqrt{s} = 5500$ GeV, hold your breath...

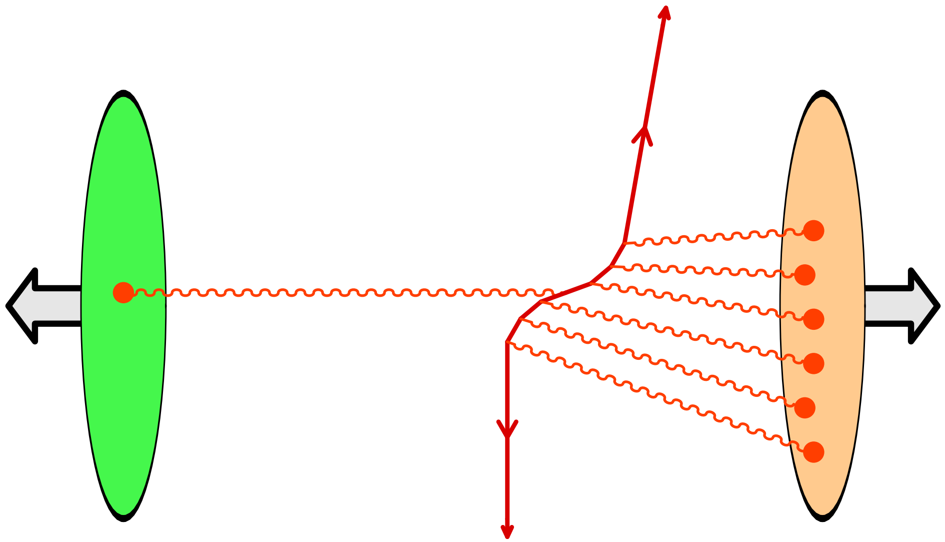
Extrapolation to LHC energy



Charm production

(H. Fujii, FG, R. Venugopalan)

Heavy quark production



- The yield reads :

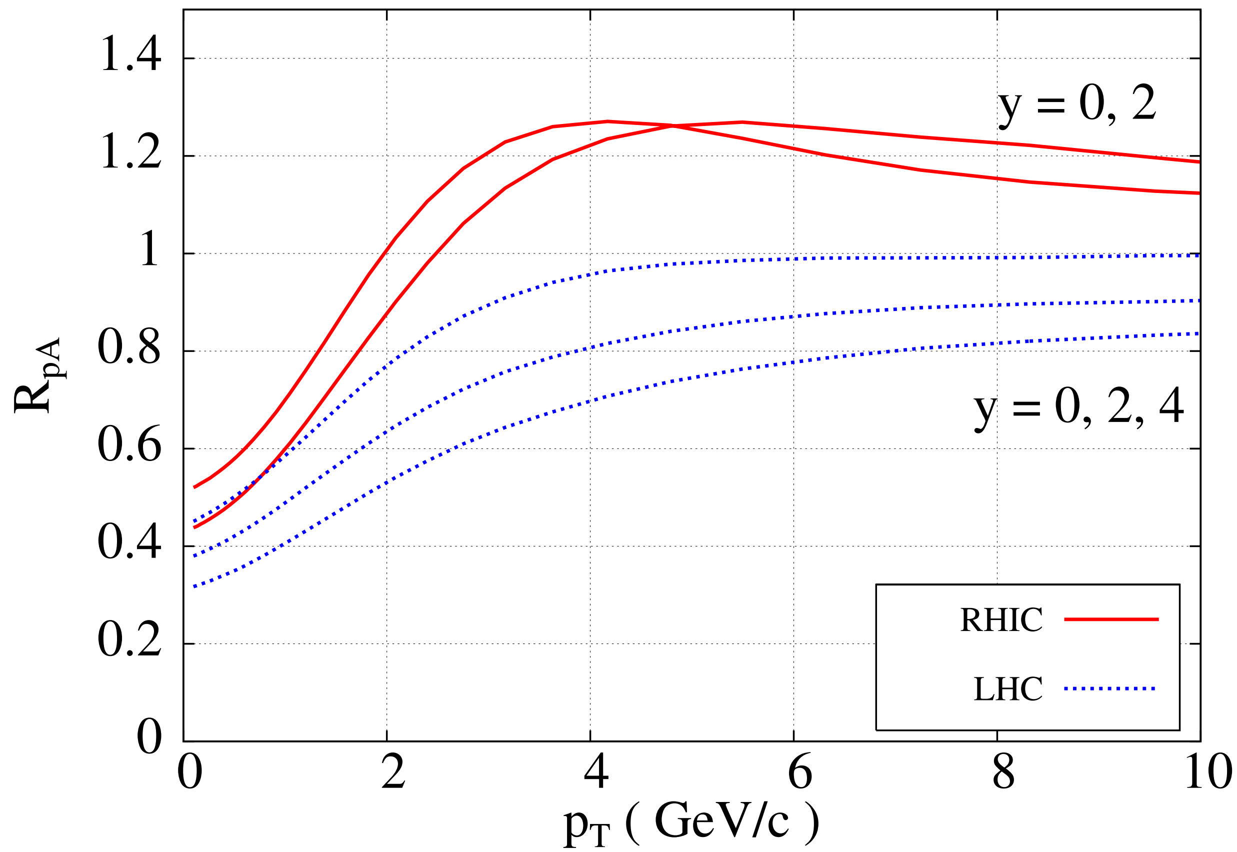
$$\frac{dN_{Q\overline{Q}}}{d^3\vec{\boldsymbol{p}}_1 d^3\vec{\boldsymbol{p}}_2} = \int d^2\vec{\boldsymbol{k}}_\perp \; \varphi_{Y_{\rm beam}-Y}(\vec{\boldsymbol{k}}_\perp) \int [D\rho_2] \; W_{Y+Y_{\rm beam}}[\rho_2] \; \frac{d\mathcal{O}[\rho_2]}{d^2\vec{\boldsymbol{k}}_\perp}$$

▷ Y is the rapidity of the $Q\overline{Q}$ pair

▷ up to four Wilson lines in $\mathcal{O}[\rho_2] \Rightarrow$ breakdown of k_T-factorization

Under certain approximations, their rapidity dependence can be described by the BK equation

pT dependence of RpA(D mesons)



Y dependence of RpA