# Hydrodynamics vs perturbative QCD mechanism in production of hadrons in heavy ion collisions

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In collaboration with

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**pQCD mechanism - nuclear suppression at large $p_T$**

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- **Numerical results vs data**
  $\Rightarrow$ comparison with LHC data
  $\Rightarrow$ comparison with RHIC data

**Interplay of the pQCD mech. and hydrodynamics - small-$p_T$ suppression**

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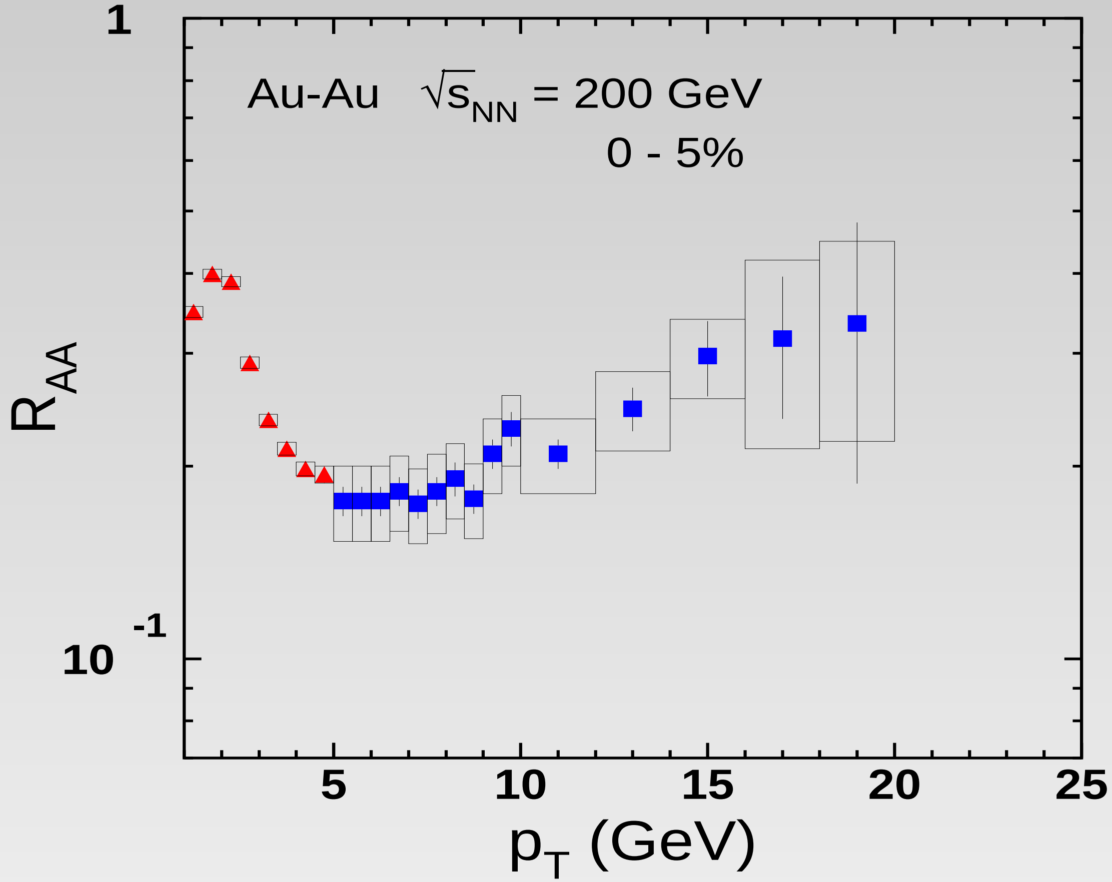
- **Summary & Outlook**

# High-$p_T$ hadrons at RHIC




Nuclear attenuation factor $R_{AA}(p_T)$ as function of $p_T$ for neutral pions produced in central, **0-5%**, gold-gold collisions at $\sqrt{s} = 200$ GeV.

[TRIANGLES - PHENIX Collaboration, A. Adare et al.; Phys. Rev. Lett. **101**, 232301 (2008).]

[SQUARES - PHENIX Collaboration, M. L. Purschke et al.; J. Phys. G **38**, 124016 (2011).]

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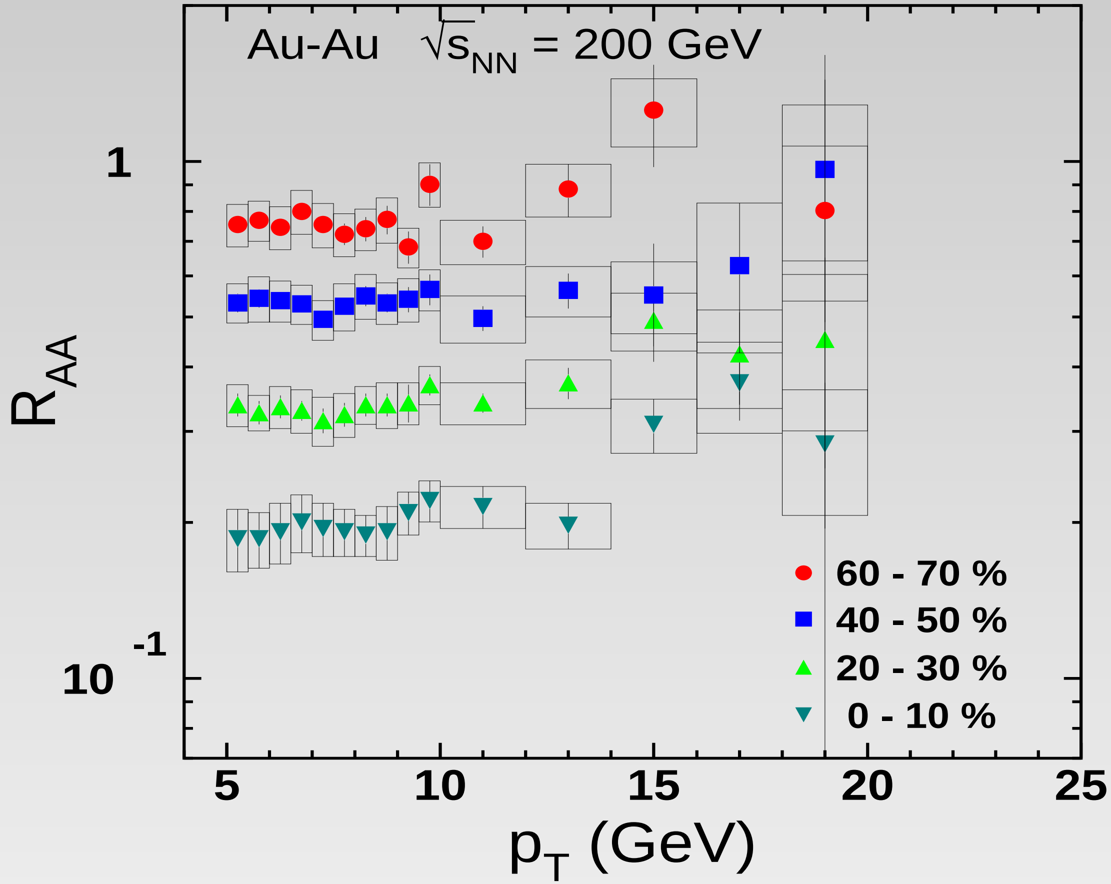


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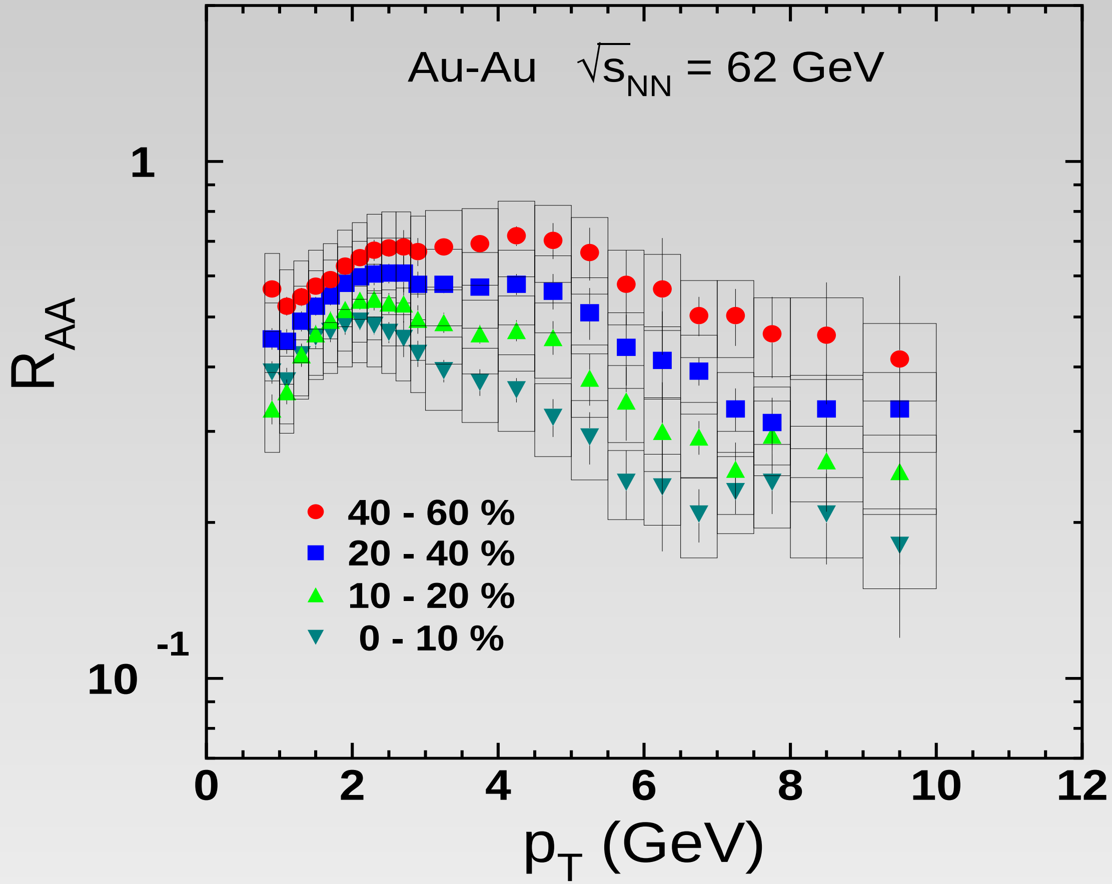


Nuclear attenuation factor $R_{AA}(p_T)$ as function of $p_T$ for neutral pions produced in gold-gold collisions at $\sqrt{s} = 62$ GeV and at centralities 0-10%, 10-20%, 20-40%, 40-60%.

[PHENIX Collaboration, $http://www.phenix.bnl.gov/WWW/plots/show_plot.php?editkey = p1118$].

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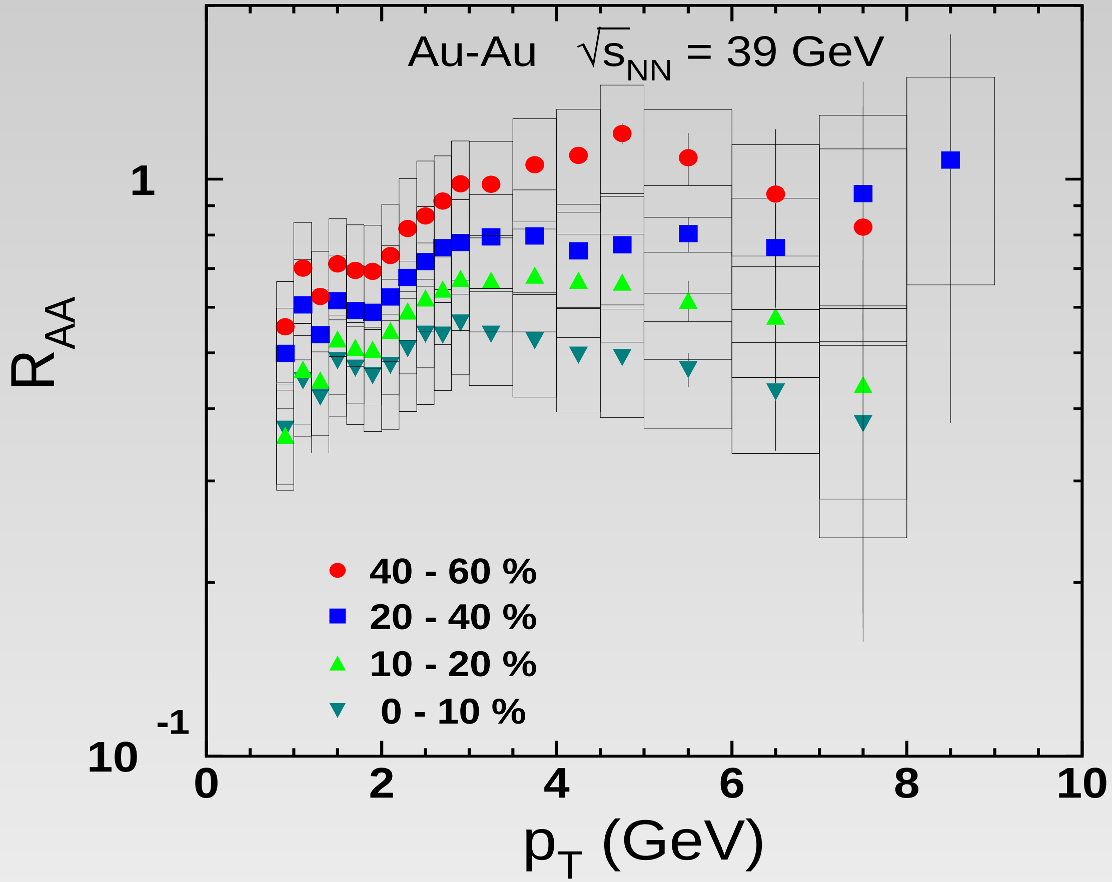
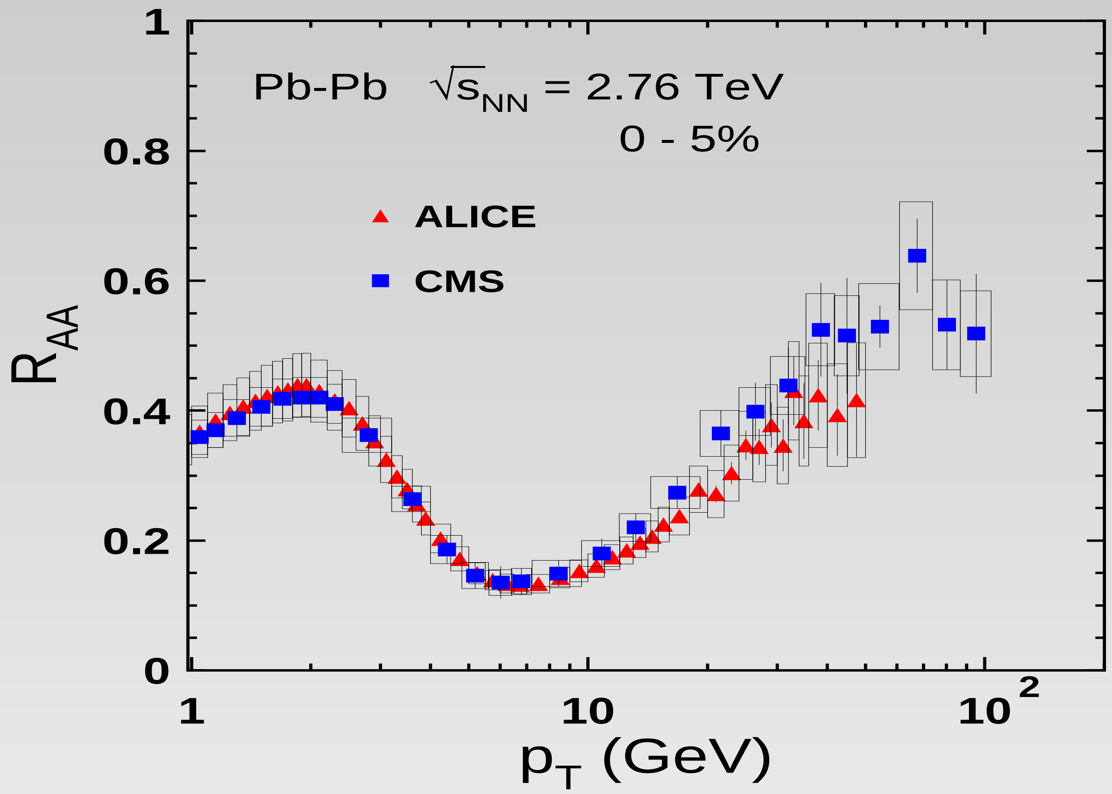



Nuclear attenuation factor $R_{AA}(p_T)$ as function of $p_T$ for neutral pions produced in gold-gold collisions at $\sqrt{s} = 39$ GeV and at centralities **0-10%, 10-20%, 20-40%, 40-60%.**

[PHENIX Collaboration, $http://www.phenix.bnl.gov/WWW/plots/show_plot.php?editkey = p1117$ ].

# High-$p_T$ hadrons at LHC

CFRJS




Nuclear attenuation factor $R_{AA}(p_T)$ as function of $p_T$ for charged hadrons produced in central, $\mathbf{0\text{-}5\%}$, lead-lead collisions at $\sqrt{s} = \mathbf{2.76\ \ TeV.}$

[TRIANGLES - ALICE Collaboration, B. Abelev et al.; Phys. Lett. B**720**, 52 (2013); J. Otwinowski et al.; J. Phys. G **38**, 124112 (2011).]

[SQUARES - CMS Collaboration, Y.-J. Lee et al.; J. Phys. G **38**, 124015 (2011). A. S. Yoon et al.; J. Phys. G **38**, 124116 (2011). ]

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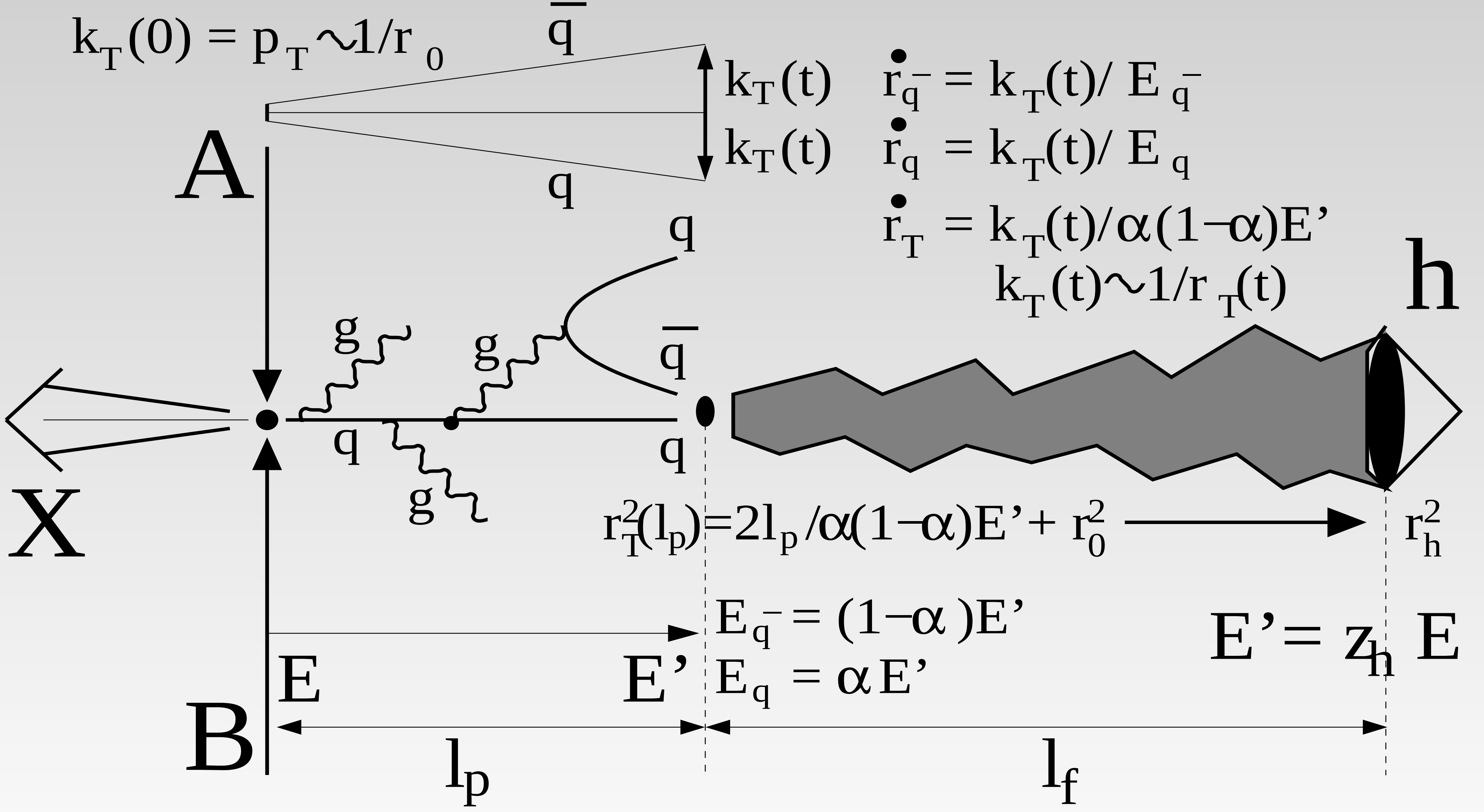
- $R_{AA}$ steeply rises with $p_T$ at LHC but exposes rather flat $p_T$-behavior at RHIC $\Rightarrow$ it is affected by restrictions imposed by energy conservation $\Leftarrow$ ISI

# Final state interaction

$$y = 0 : \quad E = Q = k_T = p_T / z_h$$




$$\langle l_p \rangle \propto k_T(1-z_h)/Q^2 \qquad l_f \propto 2E'/(m^2_{h'} - m^2_h)$$

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## Ingredients for calculation of suppression

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- time- dependent transport coefficient $\hat{q}(t)$
- transverse size $r_T(t)$- evolution of a $\bar{q}q$ dipole
- model for hadronization: $\langle l_p \rangle \propto \tilde{E}(1 - z_h)/\langle \kappa(Q^2) \rangle$

  $\Rightarrow$ several effects acting in opposite directions:

  — the Lorentz factor makes $l_p$ LONGER with energy

  — the increasing virtuality gives rise to a more intensive gluon radiation and E-loss in vacuum, leading to SHORTER $l_p$

  — the Sudakov suppression , essential at large $z_h$, also SHORTENS $l_p$

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- We rely on the usual assumption - initial medium density at time $t = t_0$ is proportional to the number of participants $n_{part}$ and density is diluting with time as $1/t$
- Then the time dependent transport coefficient reads:

$$\hat{q}(t,\vec{b},\vec{\tau}) = \frac{\hat{q}_0\, t_0}{t}\, \frac{n_{part}(\vec{b},\vec{\tau})}{n_{part}(0,0)},$$

[X.F. Chen, C. Greiner, E. Wang, X.N. Wang, Z. Xu; Phys. Rev. C81, 064908 (2010)]

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- variable $\vec{b}$ - impact parameter of collision
  variable $\vec{\tau}$ - impact parameter of position of the parton

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  $\Rightarrow$ the medium becomes more transparent with rising energy of the dipole, $\tilde{E}$
- the transverse expansion of a $\bar{q}q$ dipole reads:

$$\frac{dr_T}{dt} = \frac{k_T(t)}{\alpha(1-\alpha)\,\tilde{E}}$$

$\alpha$ - fractional light-cone momentum of the parton.

[ B.Z. Kopeliovich, J. Nemchik; J. Phys. G38, 043101 (2011) ]

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  $\tilde{E} = p_T$ - is the dipole energy in the c.m. of the collision
- such a behavior of the mean separation can be also obtained within the more rigorous path integral technique for the early stage of expansion, while $r_T < r_h$ [ B.Z. Kopeliovich, B.G. Zakharov; Phys. Rev. D44, 3466 (1991), B.Z. Kopeliovich, A. Schäfer, A.V. Tarasov; Phys. Rev. D62, 054022 (2000), J. Nemchik; Phys. Rev. C68, 035206 (2003) ]

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- we rely on the model [ B.Z. Kopeliovich, at al.; Phys. Lett. B662, 117 (2008) ] for $l_p$- distribution of leading hadrons in a jet produced at the mid rapidity, where the initial parton energy and virtuality are equal: $E = Q = k_T = p_T/z_h = \tilde{E}/z_h$

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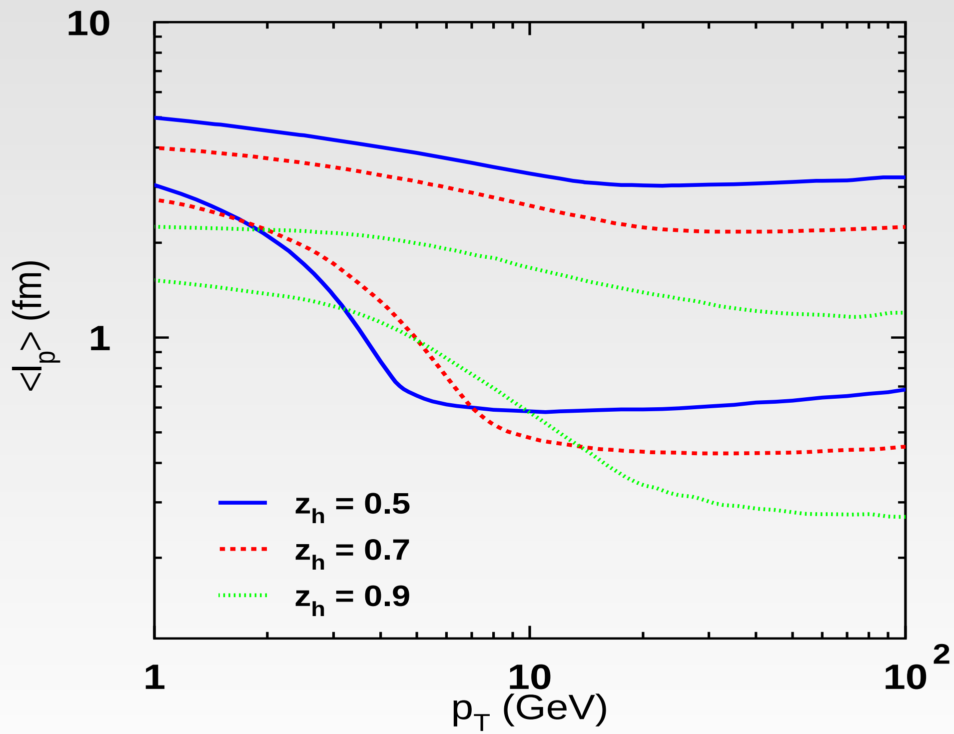
- evaluation of $\langle l_p \rangle$ in vacuum - for the quark and gluon jet



# FSI: attenuation of a dipole

## Survival probability

- survival probability characterizing a propagation of a dipole over path length $L$ in a medium reads:

$$S(L) = \exp\left[-\int_0^L dl\,\sigma[r_T(l)]\,\rho_A(l)\right]$$

(dipole cross section $\sigma(r_T)$ times the medium density $\rho_A$) $\equiv$ the attenuation rate of the dipole

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- the dipole cross section for small dipoles: $\sigma(r_T) = C\, r_T^2$, where the factor $C$ for dipole-proton interaction is fixed from DIS data
- the factor $C$ is unknown for a hot medium $\Rightarrow$ it is convenient to express it in terms of the transport coefficient

# FSI: attenuation of a dipole

## Survival probability

- the factor $C$ is related to the transport coefficient $\hat{q}$, which is broadening per unit of length:

$$C = \frac{\hat{q}}{2\rho_A}$$

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- then the survival probability of the dipole in a medium reads:

$$S(L) = \exp\left[-\frac{1}{2}\int_0^L dl\,\hat{q}(l)\,r_T^2(l)\right]$$

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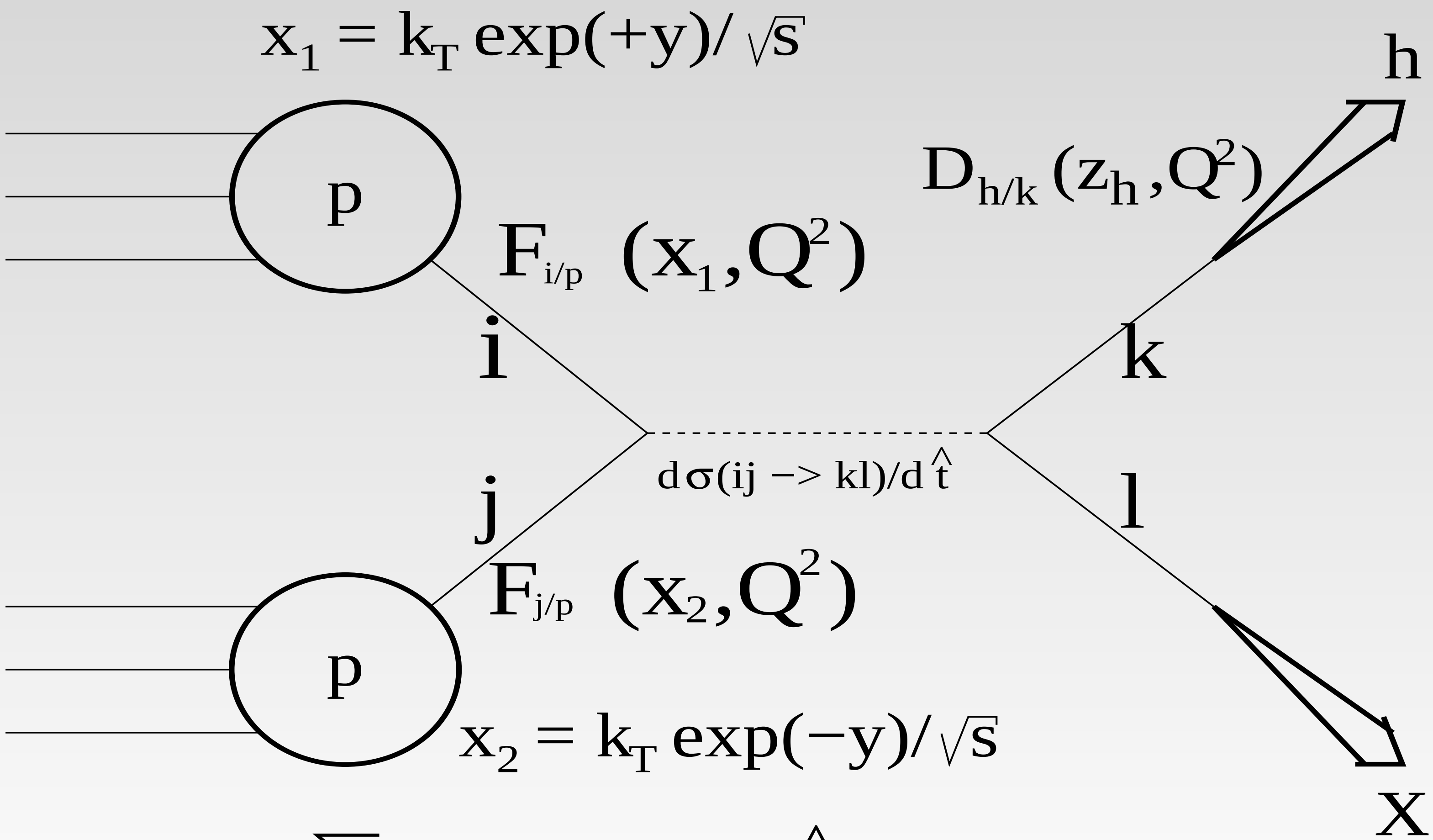
- and neglecting $r_0^2 \sim 1/p_T^2$ at large $p_T$, we get the final expression for the survival probability of the dipole in a medium

$$S(L) = \exp\left[-\frac{1}{\alpha(1-\alpha)p_T}\int_0^L dl\,\hat{q}(l)\,l\right]$$

# High-$p_T$ hadrons in $p+p$ collisions

cross section of the reaction, $\boldsymbol{p + p \longrightarrow h + X}$, is calculated using standard convolution expression based on QCD factorization:




$$\sigma_{pp}(p_T) = \sum_{i,j,k,l} F_{i/p} \otimes F_{j/p} \otimes \hat{\sigma}(ij \to kl) \otimes D_{h/k}$$

# High-$p_T$ hadrons in $A + B$ collisions

- the cross section of the reaction, $\boldsymbol{A + B \to h + X}$, at given impact parameter $\boldsymbol{b}$ reads

$$\boldsymbol{\sigma_{AB}(b, p_T) = \int_0^\infty d^2\tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) \times}$$

$$\boldsymbol{\sum_{i,j,k,l} F_{i/A} \otimes F_{j/B} \otimes \hat{\sigma}_{ij \to kl} \otimes \tilde{D}_{h/k} R^k_{AB}(\vec{b}, \vec{\tau}, p_T)}$$

# High-$p_T$ hadrons in $A + B$ collisions

- the factor $R^k_{AB}(\vec{b}, \vec{\tau}, p_T)$ in expression for $\sigma_{AB}(b, p_T)$ - corresponds to a survival probability of a $\bar{q}q$ - the nuclear suppression factor in a collision of two heavy nuclei at given impact parameter $\vec{b}$ corresponding to production of a high- $k_T$ parton of species $k$ at impact parameter $\vec{\tau}$, propagating then over a path length $\langle l_p \rangle$, radiating gluons and losing energy, and eventually producing a colorless dipole pre-hadron with transverse momentum $\vec{p}_T = \vec{k}_T\, z_h$ ($z_h$ is a fraction of the jet momentum carried by the produced hadron), which propagates through the nucleus evolving its size according to $r_T^2(t)$

# High-$p_T$ hadrons in $A + B$ collisions

- the suppression factor $R^k_{AB}(\vec{b}, \vec{\tau}, p_T)$ has the form,

$$R^k_{AB}(\vec{b}, \vec{\tau}, p_T) = \int_0^{\pi} \frac{d\phi}{\pi} \exp\left[-\frac{1}{\alpha\,(1-\alpha)\,p_T} \int_{l^k_{max}(p_T, z_h)}^{\infty} dl\, l\, \hat{q}(l, \vec{b}, \vec{\tau} + \vec{l})\right]$$

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- the production length for a gluon jet $(k = g)$ is short, $\langle l^g_p\rangle \lesssim l_0 \Rightarrow$ its actual value is not important at LHC
- a dominance of quarks at RHIC energies corresponds to much higher $\langle l^q_p\rangle > l_0$ in a broad range of $p_T$- and $z_h$-values $\Rightarrow$ this causes a weaker nuclear suppression in comparison with the LHC kinematic region

# High-$p_T$ hadrons in $A + B$ collisions

- although above evaluation of $\langle l_p^k \rangle$ in vacuum gives a dominant contribution to nuclear suppression we include also the medium-induced E-loss during propagation of a parton species $k$ corresponding to mean production length, $\langle l_p^k \rangle$.

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- this was realized via modification of the fragmentation function $D_{h/k} \Rightarrow \hat{D}_{h/k}$ shifting $z_h$ to $\tilde{z}_h = z_h \, E/(E - \Delta E_{in})$
- the medium-induced energy loss $\Delta E_{in} = \kappa_{in} \, (l_p^k - l_0) \, \Theta(l_p^k - l_0)$, where $\Theta(l)$ represents the step function and the rate of energy loss $\kappa_{in}$ was evaluated in [ R. Baier, Yu. Dokshitzer, A. Mueller, S. Peigne, D. Schiff; Nucl. Phys. B484, 265 (1997) ]

# High-$p_T$ hadrons in $A+B$ collisions

- the rate $\kappa_{in}$ corresponding to $\langle l_p^k \rangle$ reads,

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- in the LHC kinematic region an inclusion of the medium-induced E-loss is irrelevant due to a dominance of gluon jets $(k = g)$ and consequent shortness of the mean $\langle l_p^g \rangle \lesssim l_0$

# Green function approach

- the corresponding suppression factor

$$R^k_{AB}(\vec{b},\vec{\tau},p_T) =$$

$$\frac{\int\limits_0^{2\pi}\frac{d\phi}{2\pi}\left|\int\limits_0^1 d\alpha\int d^2r_1 d^2r_2\,\Psi^\dagger_h(\vec{r}_2,\alpha)G_{\bar{q}q}(\vec{b},\vec{\tau};l_1,\vec{r}_1;l_2,\vec{r}_2)\Psi_{in}(\vec{r}_1,\alpha)\right|^2}{\left|\int\limits_0^1 d\alpha\int d^2r_1 d^2r_2\,\Psi^\dagger_h(\vec{r}_2,\alpha)\Psi_{in}(\vec{r}_1,\alpha)\right|^2}$$

[ B.Z. Kopeliovich, J.N., I.K. Potashnikova, I. Schmidt, Phys. Rev. C**86**, 054904 (2012)]

# Green function approach

- the corresponding suppression factor

$$R^k_{AB}(\vec{b},\vec{\tau},p_T) = \frac{\int\limits_0^{2\pi}\frac{d\phi}{2\pi}\left|\int\limits_0^1 d\alpha\int d^2r_1 d^2r_2\,\Psi^\dagger_h(\vec{r}_2,\alpha)G_{\bar{q}q}(\vec{b},\vec{\tau};l_1,\vec{r}_1;l_2,\vec{r}_2)\Psi_{in}(\vec{r}_1,\alpha)\right|^2}{\left|\int\limits_0^1 d\alpha\int d^2r_1 d^2r_2\,\Psi^\dagger_h(\vec{r}_2,\alpha)\Psi_{in}(\vec{r}_1,\alpha)\right|^2}$$

- where the Greeen function satisfies the two-dimensional Schroedinger equation:

$$\left[i\frac{d}{dl_2} - \frac{m_q^2-\Delta_{r_2}}{2\,p_T\,\alpha\,(1-\alpha)} - V_{\bar{q}q}(\vec{b},\vec{\tau};l_2,\vec{r}_2)\right]G_{\bar{q}q}(\vec{b},\vec{\tau};l_1,\vec{r}_1;l_2,\vec{r}_2) = i\delta(l_2-l_1)\,\delta(\vec{r}_2-\vec{r}_1),$$

[ B.Z. Kopeliovich, J.N., I.K. Potashnikova, I. Schmidt, Phys. Rev. C**86**, 054904 (2012)]

# Green function approach

- with the boundary conditions

$$G_{\bar{q}q}(l_1,\vec{r}_1;l_2,\vec{r}_2)\Big|_{l_1=l_2} = \delta(\vec{r}_2-\vec{r}_1);$$
$$G_{\bar{q}q}(l_1,\vec{r}_1;l_2,\vec{r}_2)\Big|_{l_1>l_2} = 0$$

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$$G_{\bar{q}q}(l_1,\vec{r}_1;l_2,\vec{r}_2)\Big|_{l_1>l_2} = 0$$

- The imaginary part of the light-cone potential $V_{\bar{q}q}(\vec{b},\vec{\tau};l_2,\vec{r}_2)$ is responsible for absorption in the medium:

$$Im V_{\bar{q}q}(\vec{b},\vec{\tau};l,\vec{r}) = -\frac{1}{4}\,\hat{q}(l,\vec{b},\vec{\tau})\,r^2.$$

# What are the observables ?

- nuclear attenuation (modification) factor at given impact parameter $\boldsymbol{b}$

$$R_{AB}(b,p_T)=\frac{\sigma_{AB}(b,p_T)}{\int\limits_0^\infty d^2\tau T_A(\tau)T_B(\vec{b}-\vec{\tau})\sigma_{pp}(p_T)}$$

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- observable sensitive to the properties of the created medium - azimuthal asymmetry of the produced hadrons relative to the reaction plane $\Rightarrow$ it is characterized by the parameter - **elliptic flow** at given impact parameter $b$

$$v_2(b, p_T) = \langle cos(2\phi) \rangle = \frac{\hat{\sigma}_{AB}(b, p_T)}{\sigma_{AB}(b, p_T)},$$

# What are the observables ?

- where

$$\hat{\sigma}_{AB}(b, p_T) = \int_0^\infty d^2\tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) \times$$

$$\sum_{i,j,k,l} F_{i/A}^{(B)}(\vec{\tau}) \otimes F_{j/B}^{(A)}(\vec{b} - \vec{\tau}) \otimes \hat{\sigma}_{ij\rightarrow kl} \otimes \tilde{D}_{h/k} \hat{R}^k_{AB}(\vec{b}, \vec{\tau}, p_T),$$

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$$\hat{\sigma}_{AB}(b, p_T) = \int_0^\infty d^2\tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) \times$$

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- and the modified suppression factor - simple model

$$\hat{R}^k_{AB}(\vec{b}, \vec{\tau}, p_T) = \int_0^\pi \frac{d\phi}{\pi} cos(2\phi) \times$$

$$\exp\left[-\frac{1}{\alpha\,(1-\alpha)\,p_T} \int_{l^k_{max}(p_T, z_h)}^{\infty} dl\, l\, \hat{q}(l, \vec{b}, \vec{\tau} + \vec{l})\right].$$

# What are the observables ?

- and the modified suppression factor - Green function formalism

$$\hat{R}^k_{AB}(\vec{b},\vec{\tau},p_T) = \frac{\int_0^{2\pi} \frac{d\phi}{2\pi} cos(2\phi) \left| \int_0^1 d\alpha \int d^2r_1 d^2r_2\, \Psi^\dagger_h(\vec{r}_2,\alpha) G_{\bar{q}q}(\vec{b},\vec{\tau};l_1,\vec{r}_1;l_2,\vec{r}_2) \Psi_{in}(\vec{r}_1,\alpha) \right|^2}{\left| \int_0^1 d\alpha \int d^2r_1 d^2r_2\, \Psi^\dagger_h(\vec{r}_2,\alpha) \Psi_{in}(\vec{r}_1,\alpha) \right|^2}$$

# ISI: energy conservation constraints

Any reaction observed so far at any energy is nuclear suppressed at forward rapidities.

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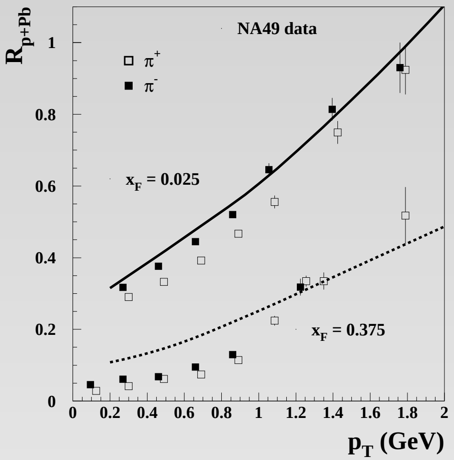

# ISI: energy conservation constraints

CFRJS

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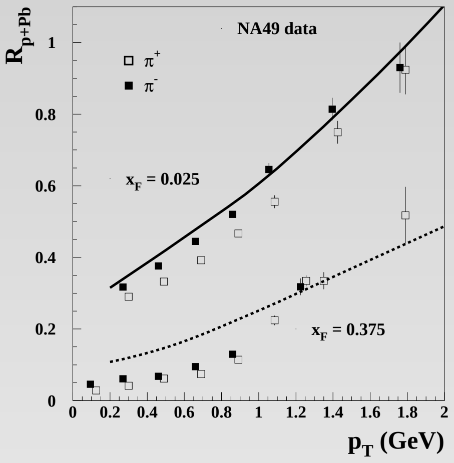


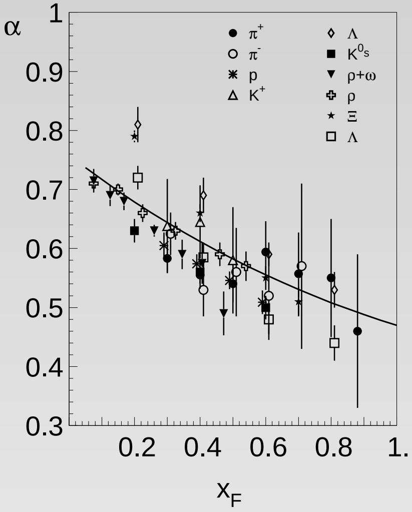

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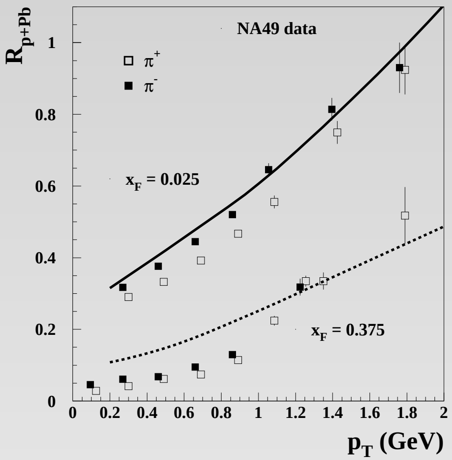


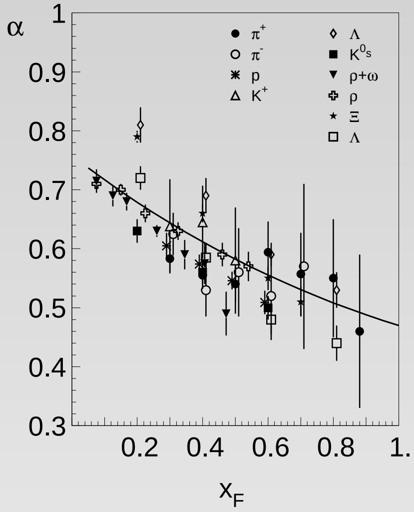


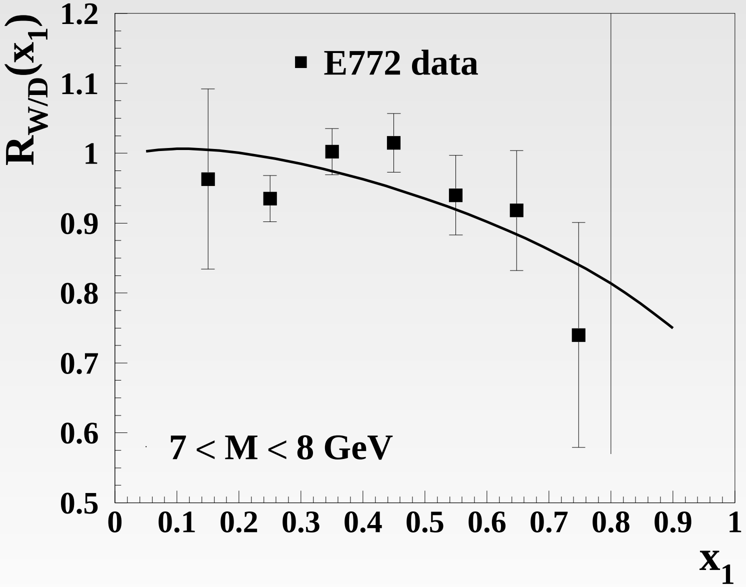

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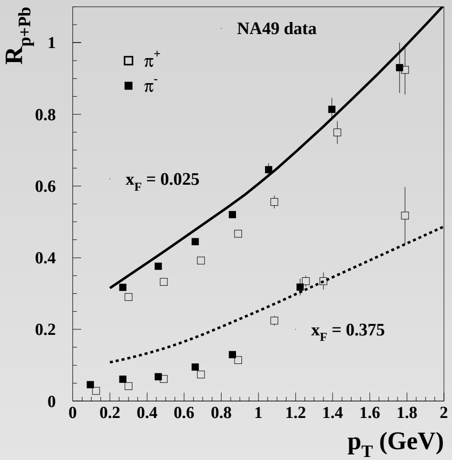


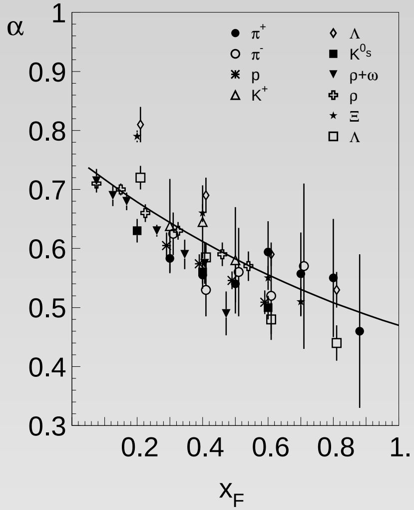


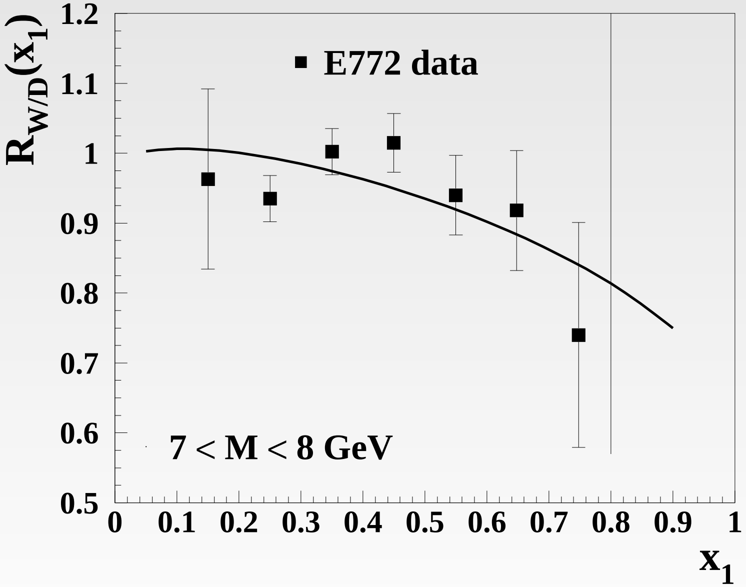


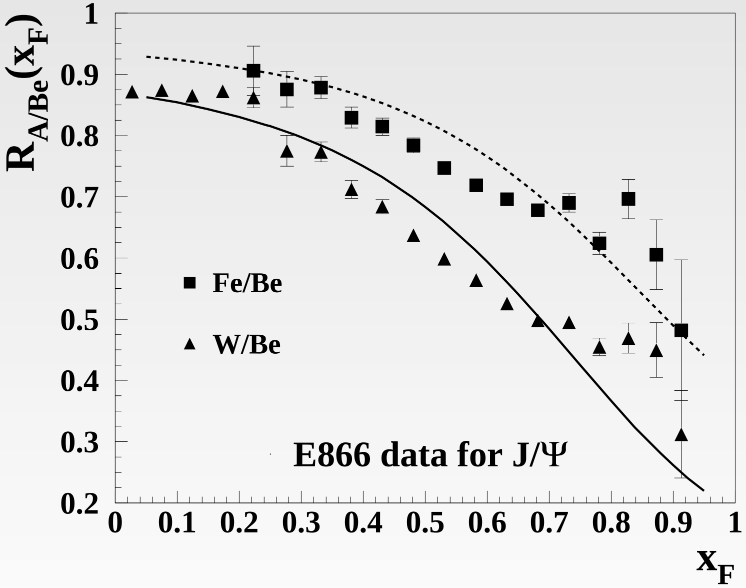

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One can approach the kinematic limit increasing either $x_F$ , or $x_T = 2p_T/\sqrt{s}$.

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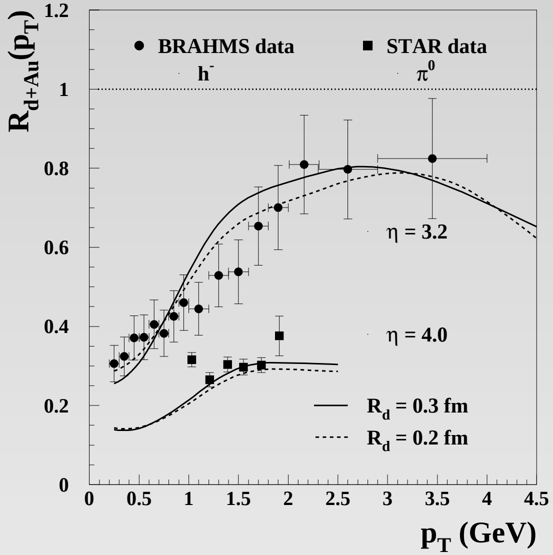

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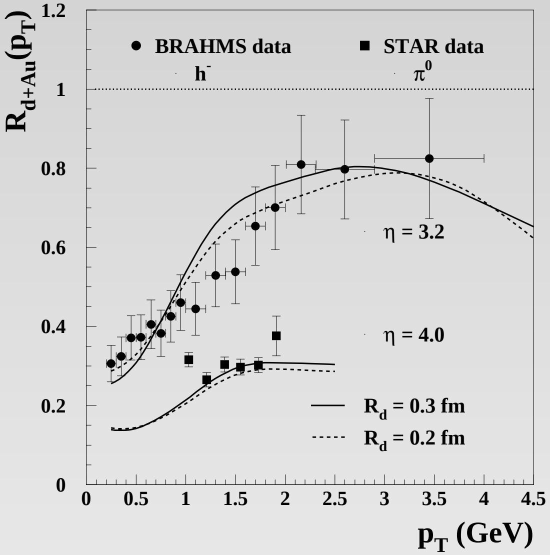


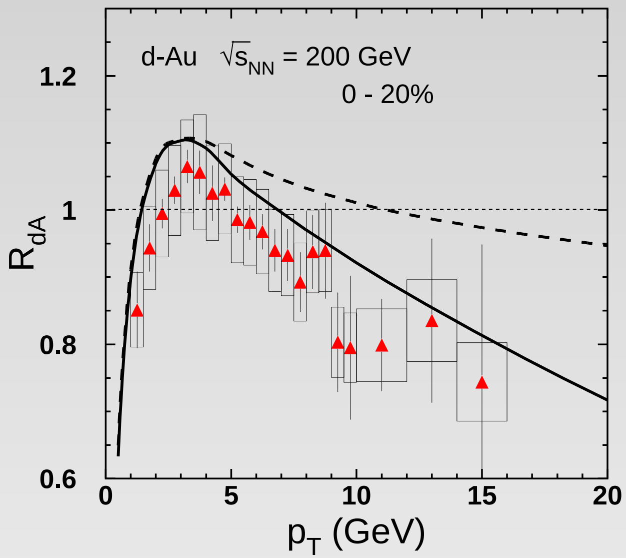

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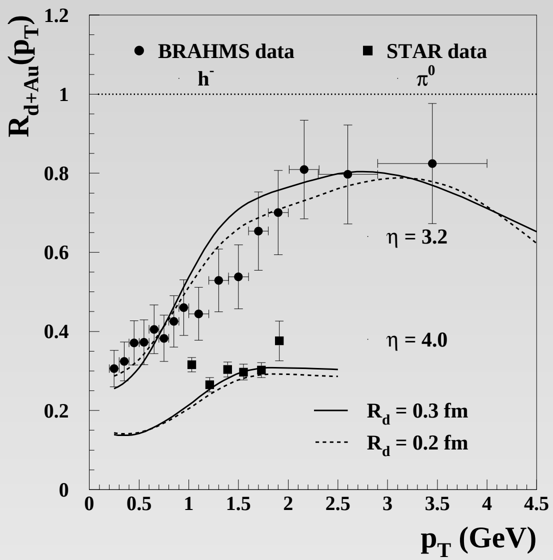


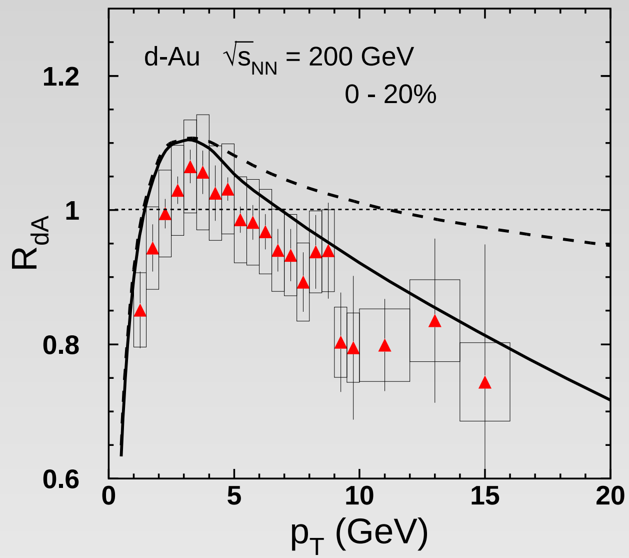


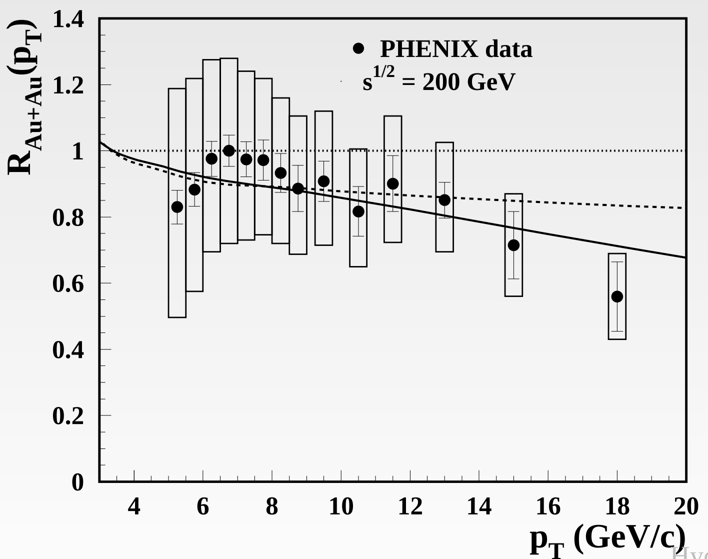

# ISI: energy conservation constraints

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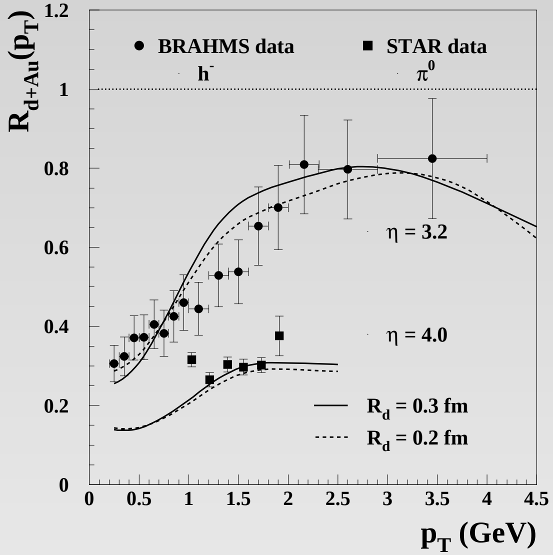
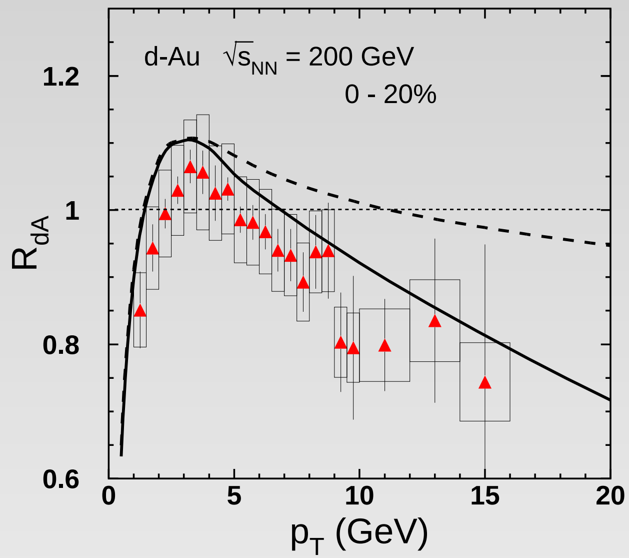
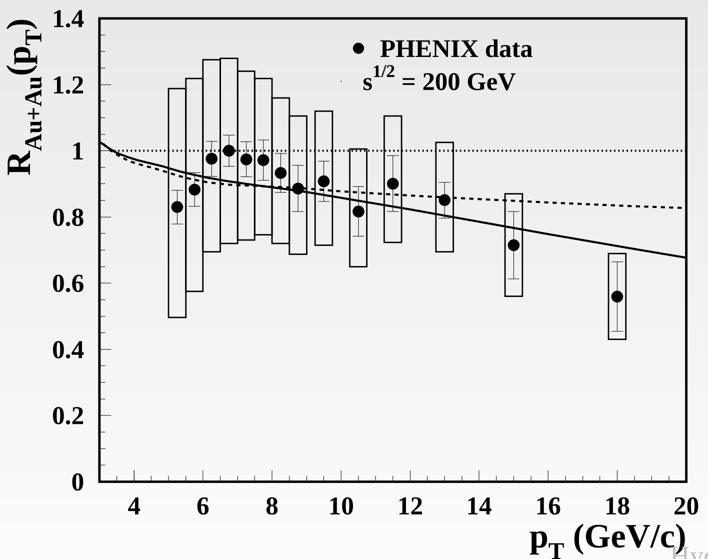
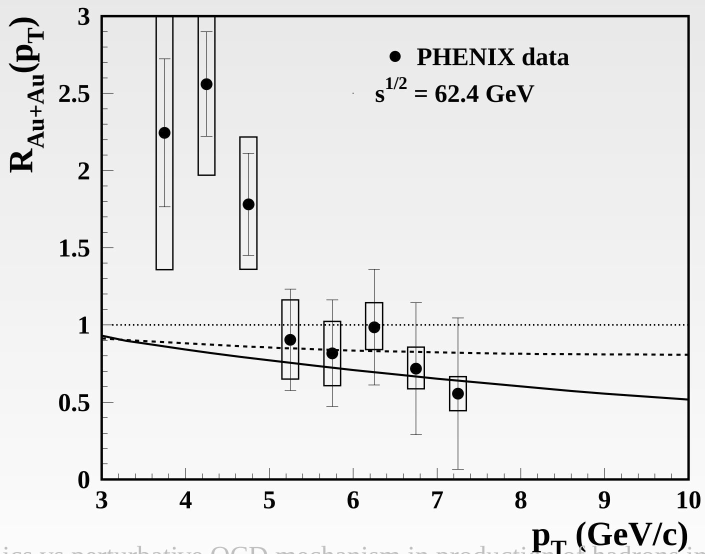


# Interpretations of ISI suppression

Since the kinematic limit can be approached increasing either $x_F$ or $p_T$, it is convenient to introduce a variable $\xi$,

$$\xi = \sqrt{x_F^2 + x_T^2},$$

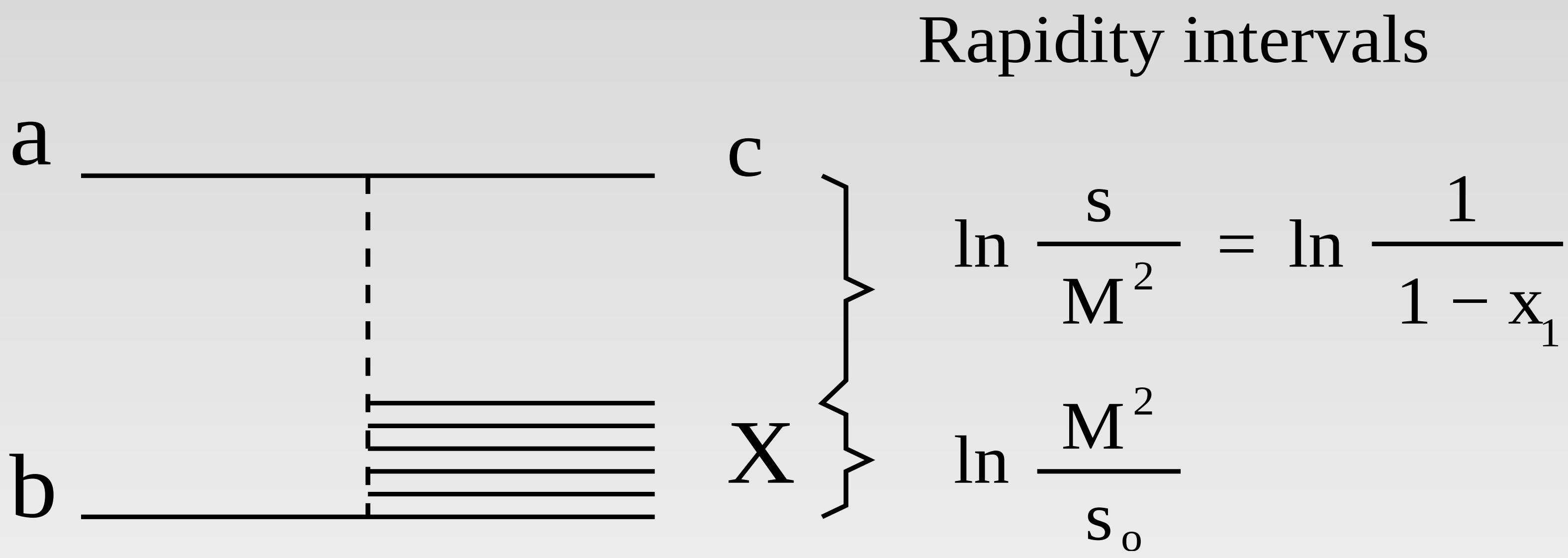
where

$$x_F = \frac{2\,p_L}{\sqrt{s}}, \qquad x_T = \frac{2\,p_T}{\sqrt{s}}.$$

Here $p_L$ and $p_T$ is the longitudinal and transverse component of the momentum of the produced particles in c.m. frame.

# Interpretations of ISI suppression

- any reaction, $a + b \longrightarrow c + X$, where $c = h, \bar{l}l, J/\Psi, \ldots$ is a large rapidity gap (LRG) process at $\xi \longrightarrow 1$



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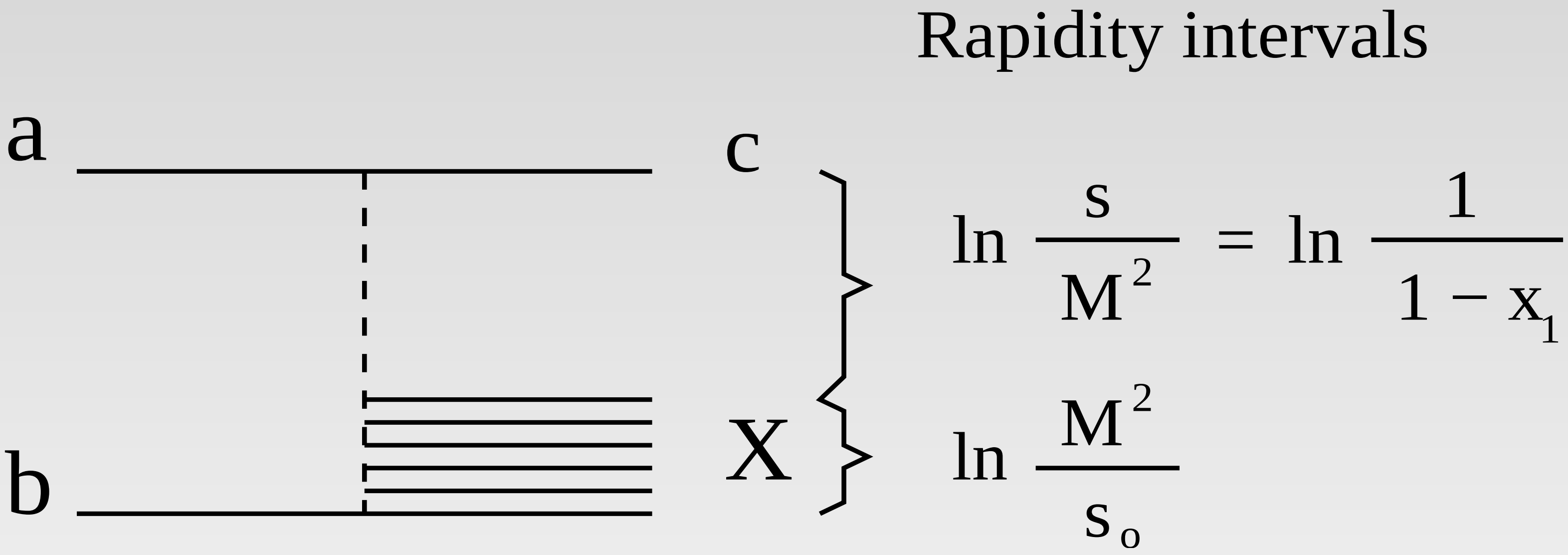


- the probability to radiate no gluons in the rapidity interval $\Delta y = ln\,\frac{1}{1-\xi}$ is suppressed by the SUDAKOV'S FORM FACTOR $S(\Delta y) = 1 - \xi$, which violates QCD factorization

# Interpretations of ISI suppression

- assuming $A + B$ collisions and summing over multiple interactions, the parton distribution in N of the projectile nucleus $A$ can be expressed in terms of $T_B(b)$ and the effective $\sigma_{eff} \sim \sigma_{in}^{hN} = 20\, mb$

[ B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, M.B. Johnson, I. Schmidt; PR C72, 054606 (2005)]

$$F_{i/N}^{(B)}(x_1, k_{1,T}^2, b) = C_G\, F_{i/N}(x_1, k_{1,T}^2)\, \frac{e^{-[1-S(\xi)]\sigma_{eff} T_B(b)} - e^{-\sigma_{eff} T_B(b)}}{S(\xi)\, \left[1 - e^{-\sigma_{eff} T_B(b)}\right]}$$

the normalization factor $C_G$ is fixed by the Gottfried sum rule

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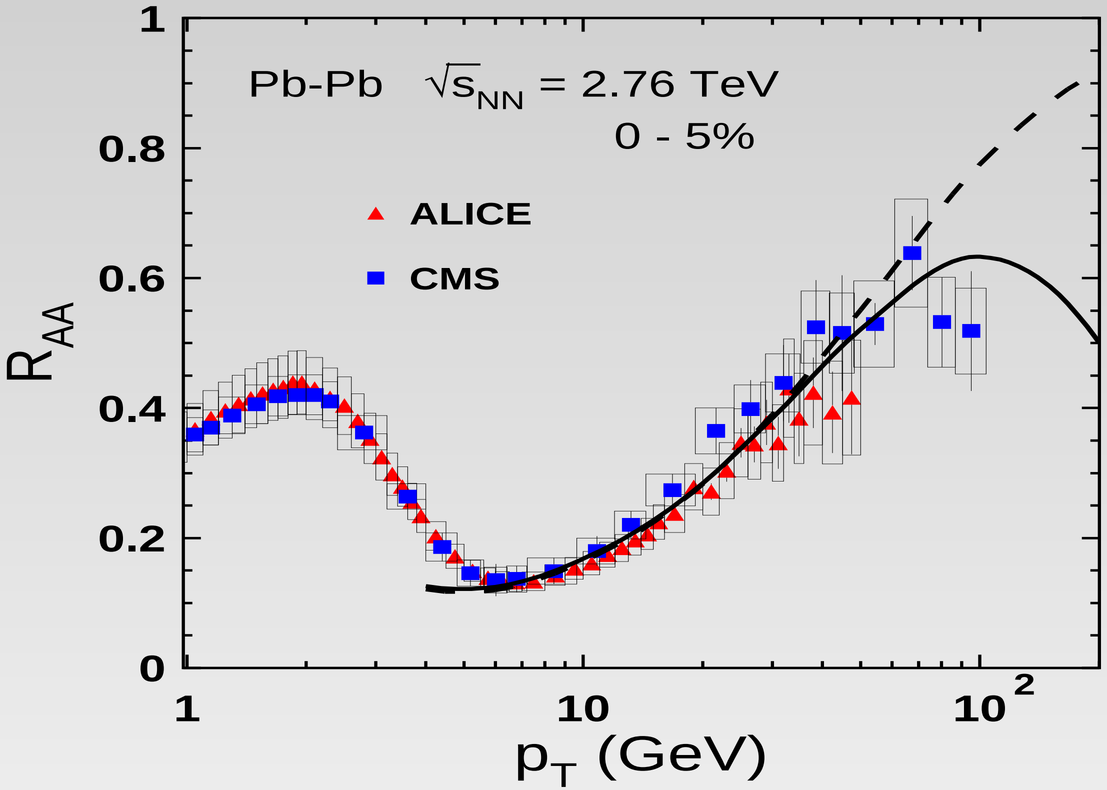
the normalization factor $C_G$ is fixed by the Gottfried sum rule

- in $A + B$ collisions one should take into account also multiple interactions of target partons of the nucleus $B$ in the projectile nucleus $A$ leading to the same form of effective parton distributions $F_{j/N}^{(A)}$ except that one should replace $x_1 \Rightarrow x_2$, $k_{1,T} \Rightarrow k_{2,T}$, $B \Rightarrow A$, $T_B \Rightarrow T_A$

# Numerical results vs. data

## Comparison with LHC data



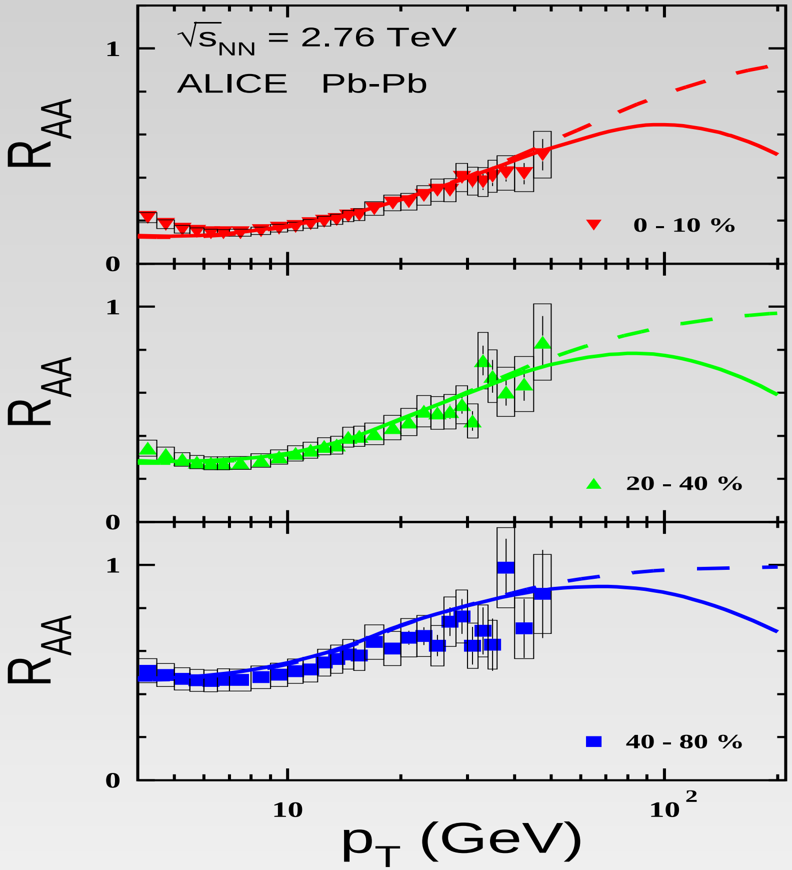

ALICE and CMS data for central, **0-5%**, lead-lead collisions vs. the GF formalism at adjusted $\hat{q}_0 = 2.0 \ \mathrm{GeV}^2/\,\mathrm{fm}.$

[TRIANGLES - ALICE Collaboration, B. Abelev et al.; Phys. Lett. B**720**, 52 (2013). ]

[SQUARES - CMS Collaboration, Y.-J. Lee et al.; J. Phys. G **38**, 124015 (2011). A. S. Yoon et al.; J. Phys. G **38**, 124116 (2011). ]

# Numerical results vs. data

## Comparison with LHC data - ALICE

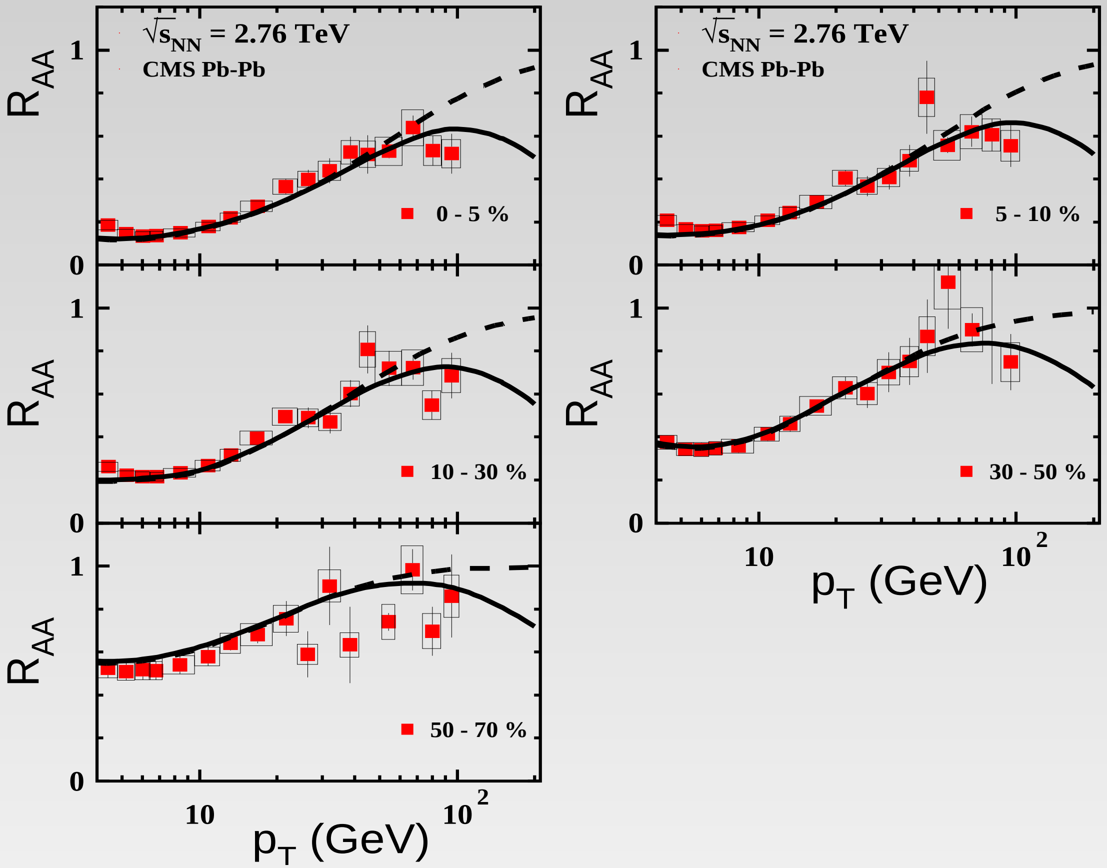



$\boldsymbol{R_{AA}(p_T)}$ for charge hadrons produced in lead-lead collisions at different centralities. Calculations within the GF formalism with $\hat{q}_0 = 2.0\ \mathrm{GeV^2/fm}$ are compared with ALICE data.

[ALICE Collaboration, B. Abelev et al.; Phys. Lett. B**720**, 52 (2013). ]

# Numerical results vs. data

Comparison with LHC data - CMS

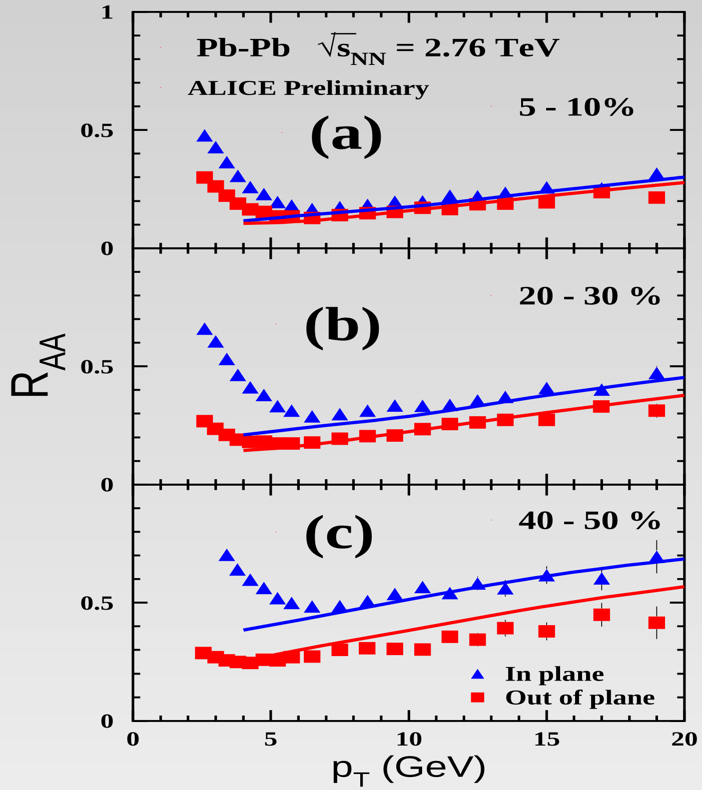



$R_{AA}(p_T)$ for charge hadrons produced in lead-lead collisions at different centralities. Calculations within the GF formalism with $\hat{q}_0 = 2.0\ \text{GeV}^2/\text{fm}$ are compared with CMS data.

[CMS Collab., Y.-J. Lee ; J. Phys. G **38**, 124015 (2011). A. S. Yoon ; J. Phys. G **38**, 124116 (2011). ]

# Numerical results vs. data

## Comparison with LHC data - azimuthal asymmetry



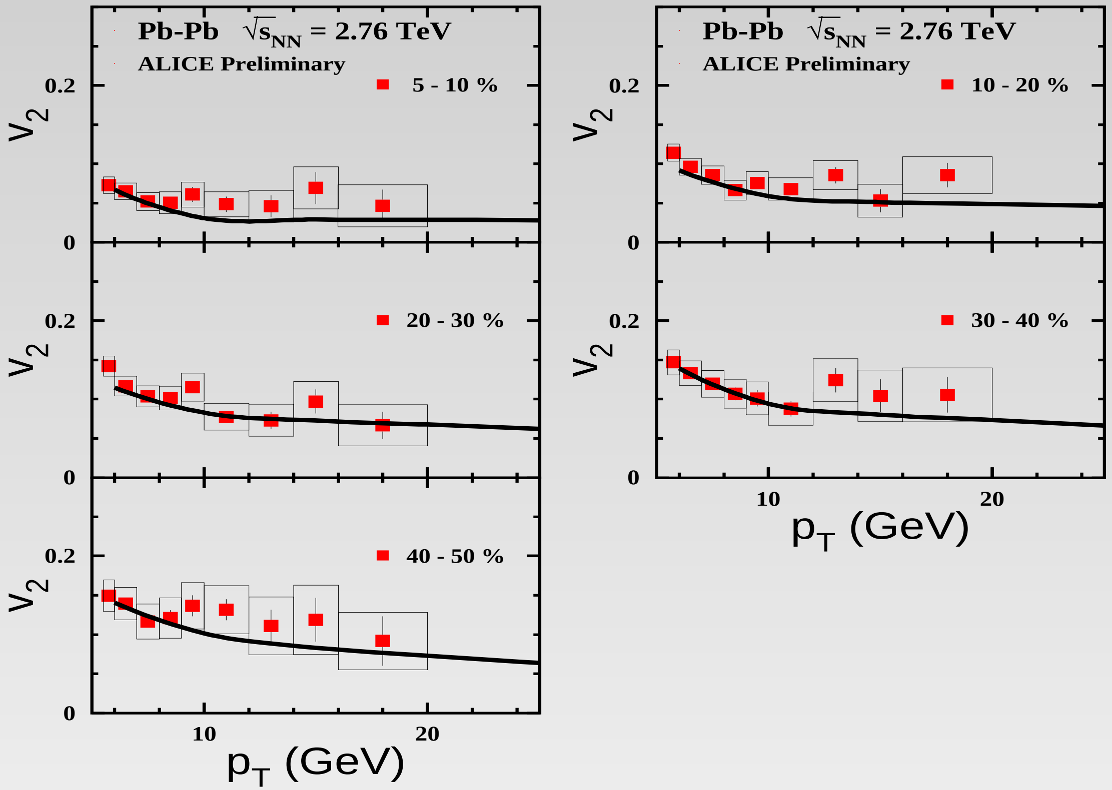

$R_{AA}(p_T)$ for charge hadrons produced in lead-lead collisions for two classes of events: In plane $(-45^o \leq \phi \leq 45^o)$ and Out-of-plane $(45^o \leq \phi \leq 135^o)$. The GF calculations with $\hat{q}_0$ = 2.0 GeV$^2$/ fm are compared with ALICE data.

[ALICE Collaboration, A. Dobrin et al.; J. Phys. G **38**, 124170 (2011). ]

# Numerical results vs. data

CFRJS

## Comparison with LHC data - azimuthal asymmetry




Azimuthal anisotropy $v_2(p_T)$ for charge hadron production in lead-lead collisions at different centralities **5-10%, 10-20%, 20-30%, 30-40%, 40-50%**. The GF calculations with $\hat{q}_0 = 2.0\ \mathrm{GeV}^2/\mathrm{fm}$ are compared with ALICE data.

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# Numerical results vs. data

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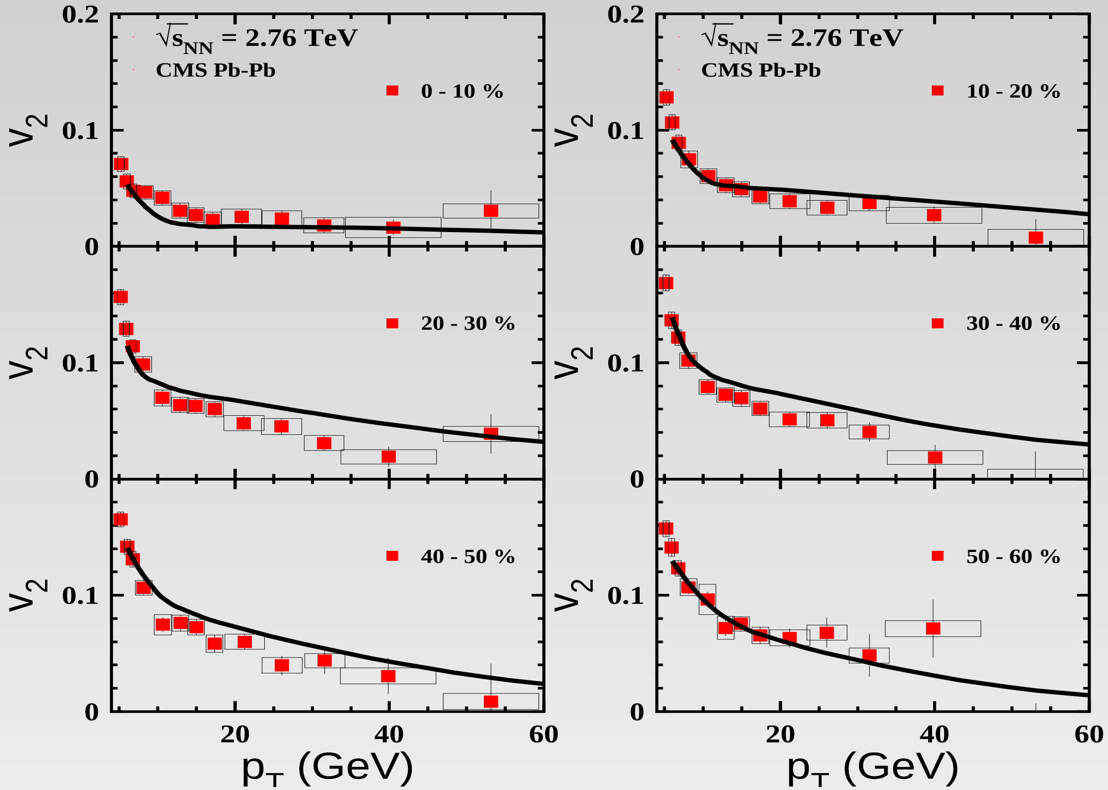
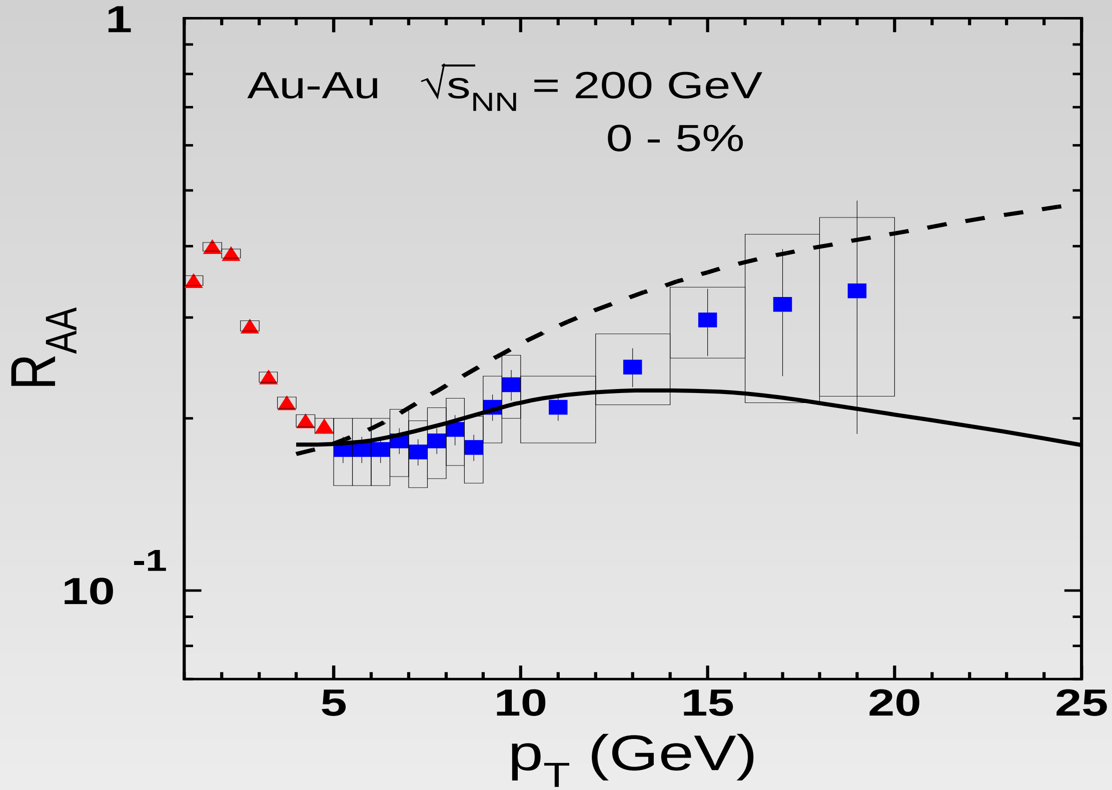



Azimuthal anisotropy $v_2(p_T)$ for charge hadron production in lead-lead collisions at different centralities **0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%.** The GF calculations with $\hat{q}_0 = 2.0 \ \mathrm{GeV}^2/\,\mathrm{fm}$ are compared with CMS data.

[CMS Collaboration, S. Chatrchyan at al.; Phys. Rev. Lett. **109**, 022301 (2012). ]

# Numerical results vs. data

Comparison with RHIC data



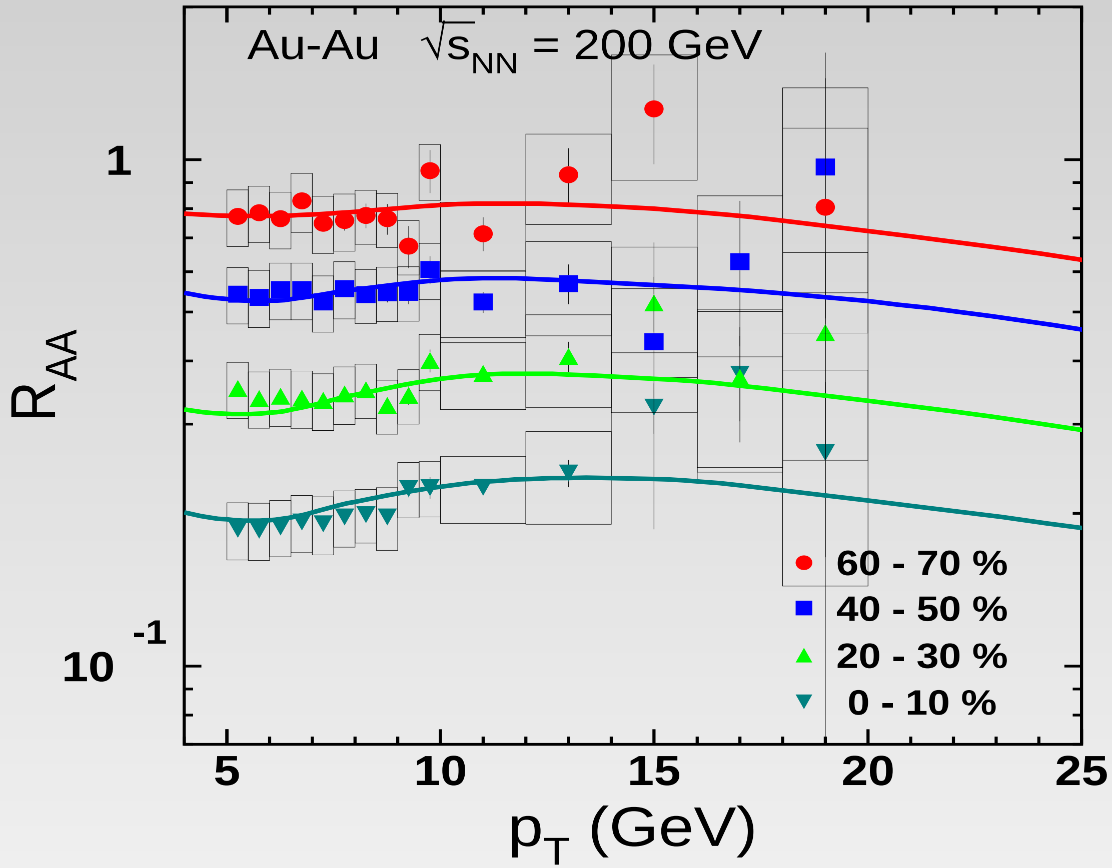

$R_{AA}(p_T)$ for neutral pions produced in central, **0-5%**, gold-gold collisions at $\sqrt{s} = 200$ GeV. The GF calculations with $\hat{q}_0 = 1.6$ GeV$^2$/ fm are compared with PHENIX data.

[ PHENIX Collaboration, A. Adare et al.; Phys. Rev. Lett. **101**, 232301 (2008); Phys. Rev. C**87**, 034911 (2013); M. L. Purschke et al.; J. Phys. G **38**, 124016 (2011). ]

# Numerical results vs. data

CFRJS

## Comparison with RHIC data

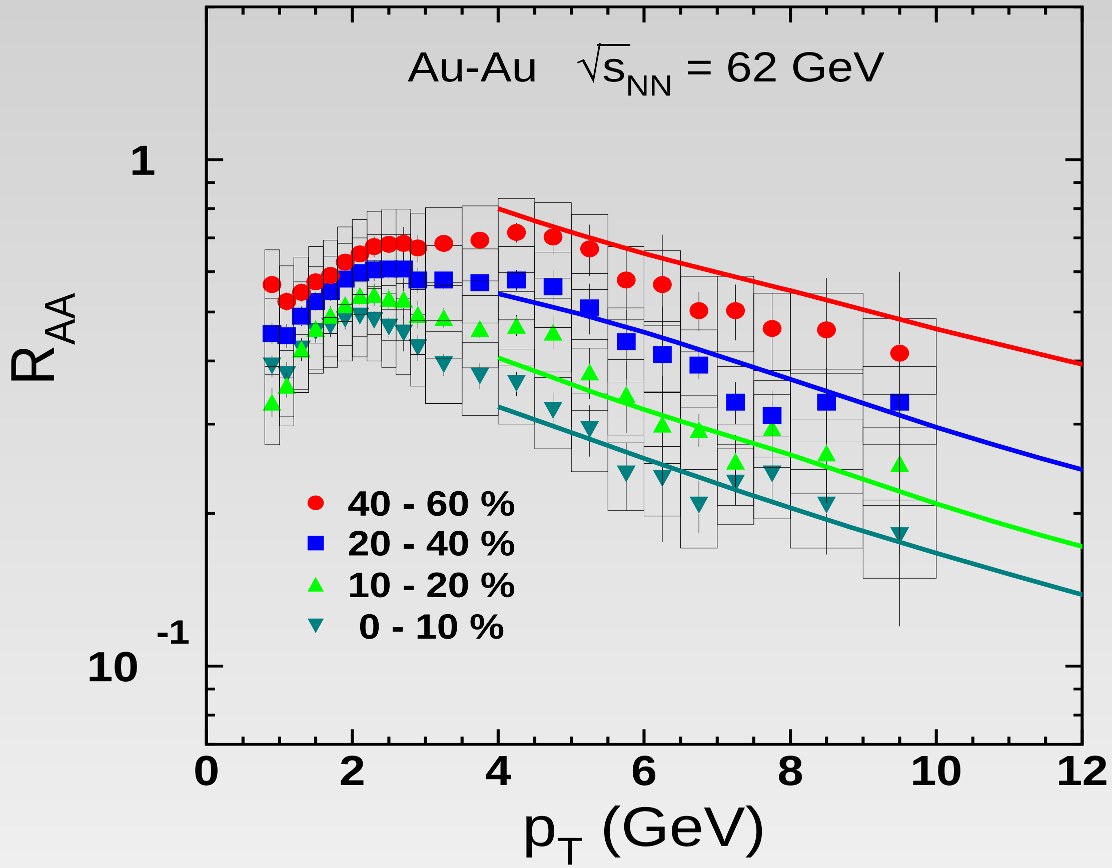



$\boldsymbol{R_{AA}(p_T)}$ for neutral pions produced in **Au-Au** collisions at different centralities. The GF calculations with $\hat{q}_0 = 1.6$ $\mathbf{GeV^2/\,fm}$ are compared with PHENIX data.

[ PHENIX Collaboration, A. Adare et al.; Phys. Rev. C**87**, 034911 (2013). ]

# Numerical results vs. data

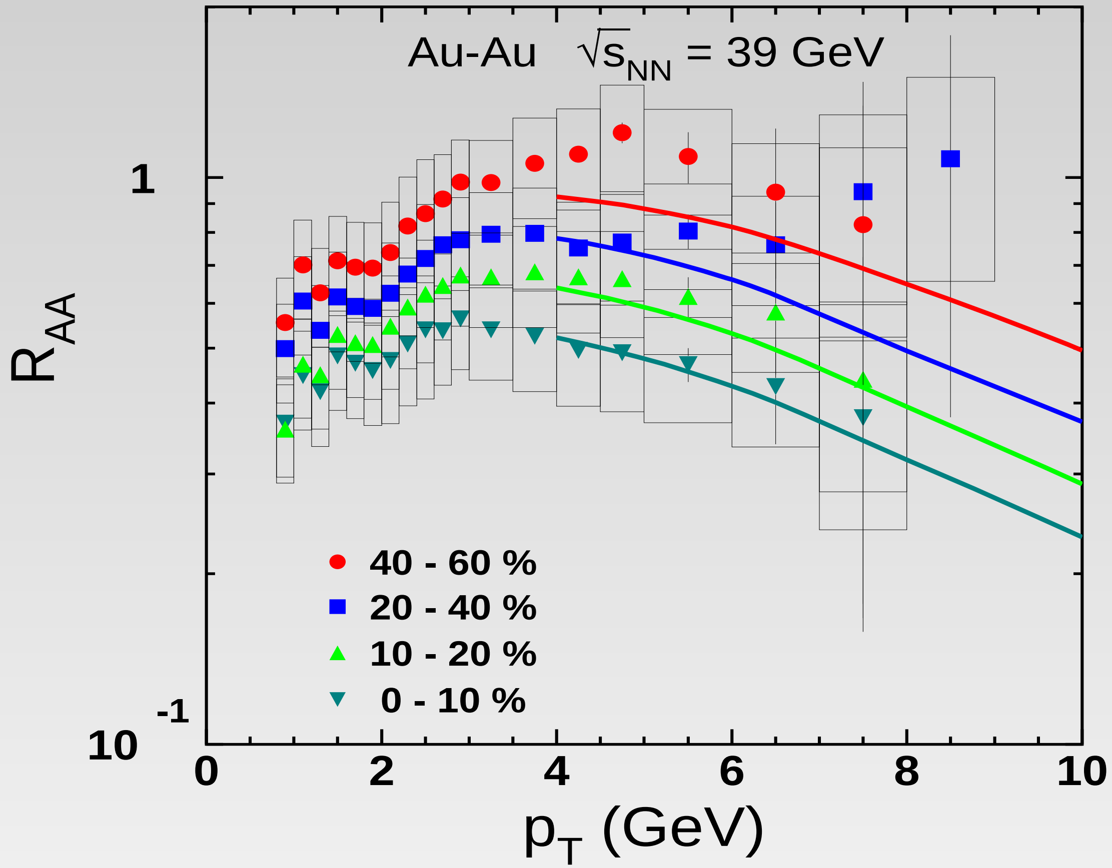
## Comparison with RHIC data




$R_{AA}(p_T)$ for neutral pions produced in gold-gold collisions at $\sqrt{s} = 62\ \text{GeV}$ and at different centralities. The GF calculations with $\hat{q}_0 = 1.2\ \text{GeV}^2/\ \text{fm}$ are compared with PHENIX data. [PHENIX Collaboration, preliminary data posted at $http://www.phenix.bnl.gov/WWW/plots/show_plot.php?editkey = p1118$ ]

# Numerical results vs. data

Comparison with RHIC data

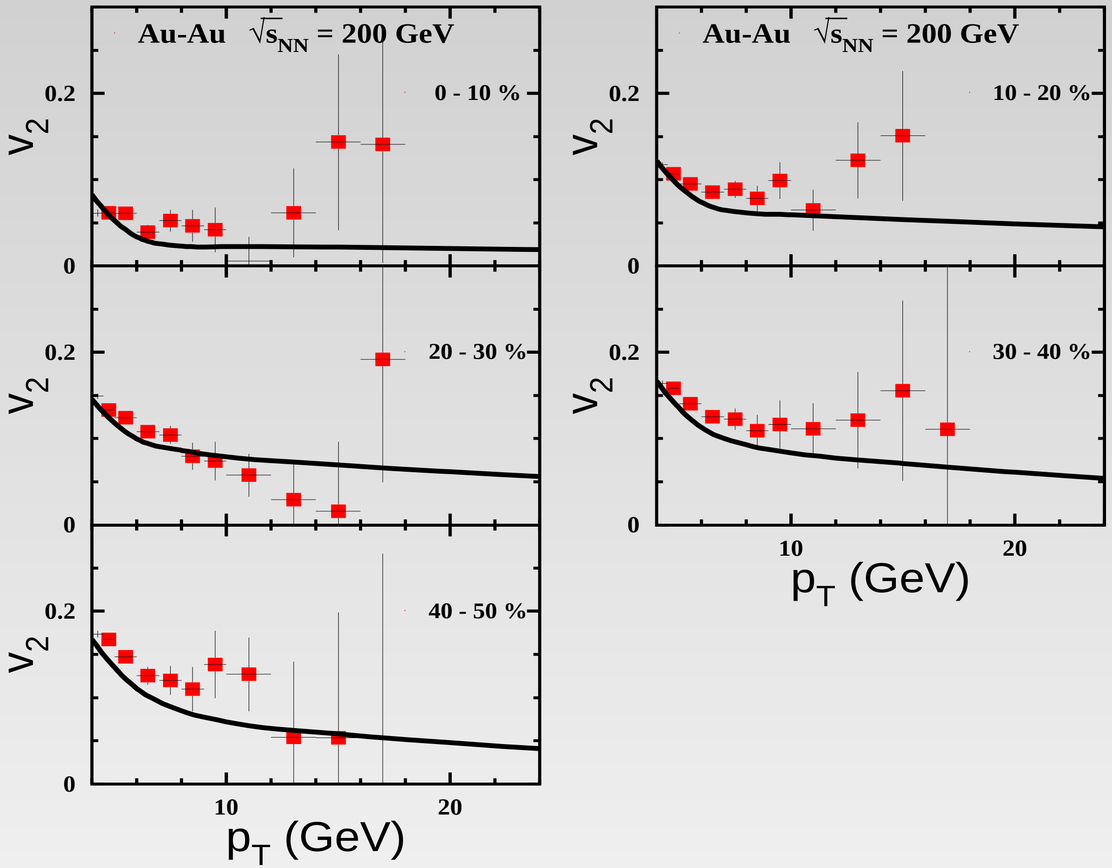



$\boldsymbol{R_{AA}(p_T)}$ for neutral pions produced in gold-gold collisions at $\sqrt{s} = 39\ \ \mathbf{GeV}$ and at different centralities. The GF calculations with $\hat{q}_0 = 0.6\ \ \mathbf{GeV^2/\,fm}$ are compared with PHENIX data. [PHENIX Collaboration, preliminary data posted at $http://www.phenix.bnl.gov/WWW/plots/show_plot.php?editkey = p1117$ ]

# Numerical results vs. data

CFRJS

## Comparison with RHIC data - azimuthal asymmetry




Azimuthal anisotropy $v_2(p_T)$ for neutral pion production in gold-gold collisions at different centralities. The GF calculations with $\hat{q}_0 = 1.60 \ \ \mathrm{GeV}^2/\ \mathrm{fm}$ are compared with PHENIX data.

[ PHENIX Collaboration, A. Adare et al.; Phys. Rev. Lett. **105**, 142301 (2010). ]

# Numerical results vs. data

## Hydrodynamics vs. pQCD

- Our pQCD calculations for $R_{AA}(p_T)$ and $v_2(p_T)$ grossly underestimate data at small $p_T \lesssim 6$ GeV.

# Numerical results vs. data

## Hydrodynamics vs. pQCD

- Our pQCD calculations for $R_{AA}(p_T)$ and $v_2(p_T)$ grossly underestimate data at small $p_T \lesssim 6$ GeV.
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- We relate this to an interplay of two mechanisms of hadron production: (i) evaporation of hadrons from the created hot medium controlled by hydrodynamics; (ii) perturbative QCD mechanism of high- $p_T$ production of hadrons, which propagate and attenuate in the hot medium.
- The abrupt transition between the two mechanisms causes distinct minima in $R_{AA}(p_T)$ and in $v_2(p_T)$ both observed at the same values of $p_T$.

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## Hydrodynamics vs. pQCD

- Data on $\boldsymbol{R_{AA}(p_T)}$ corresponding to In-plane and Out-of-plane events show that the transition from the hydrodynamic to perturbative regimes occur for In-plane events with a delay, at higher $\boldsymbol{p_T} \Rightarrow$ the hydrodynamic flow is much stronger, correspondingly the cross section is larger.

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  [ Iu.A. Karpenko, Yu.M. Sinyukov, K. Werner; Phys. Rev. C**87**, 024914 (2013). ]

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CFRJS

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- where transverse momentum spectra of the hydrodynamic model are related to $R_{AA}(p_T)_{hydro}$ as:

$$R_{AA}(p_T)_{hydro} = \frac{d^2 N^{AA}/dyd^2p_T[hydro]}{\langle T_{AA}\rangle d^2\sigma_{pp}/dyd^2p_T} f_p$$

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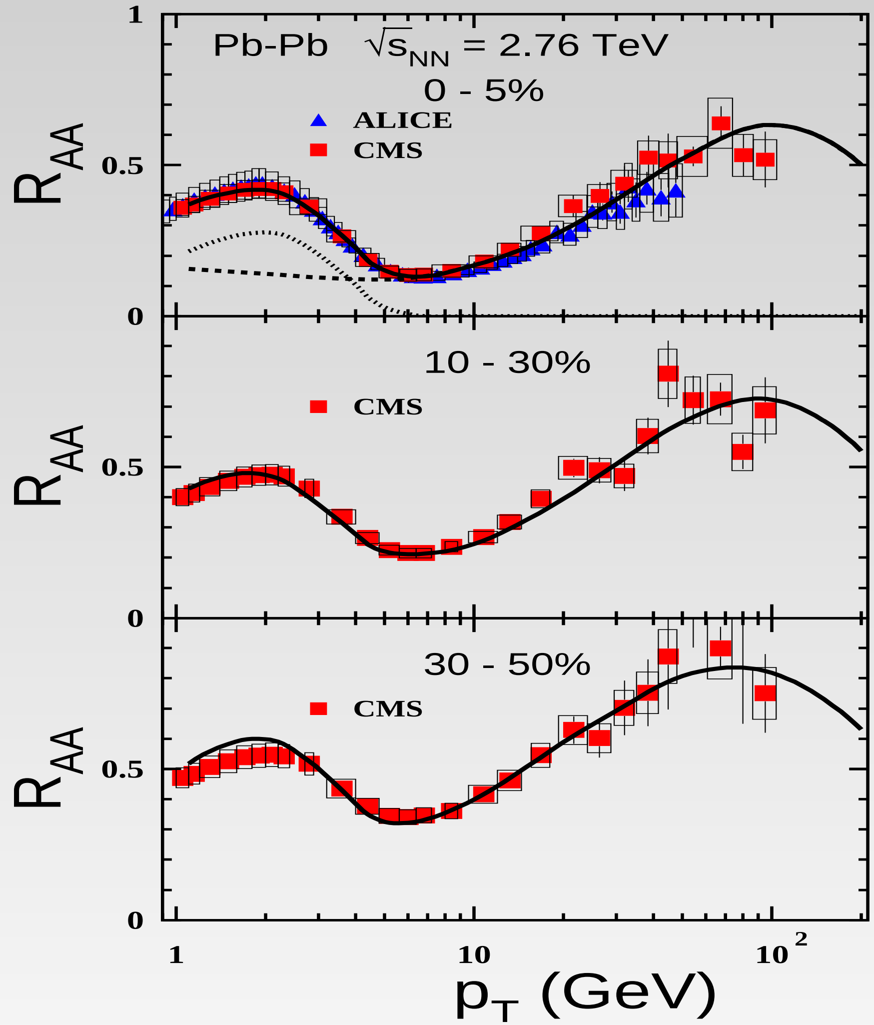
## Hydrodynamics vs. pQCD




dotted line - nonperturbative HYDRO; dashed line - perturbative QCD

solid lines - combination of HYDRO and pQCD

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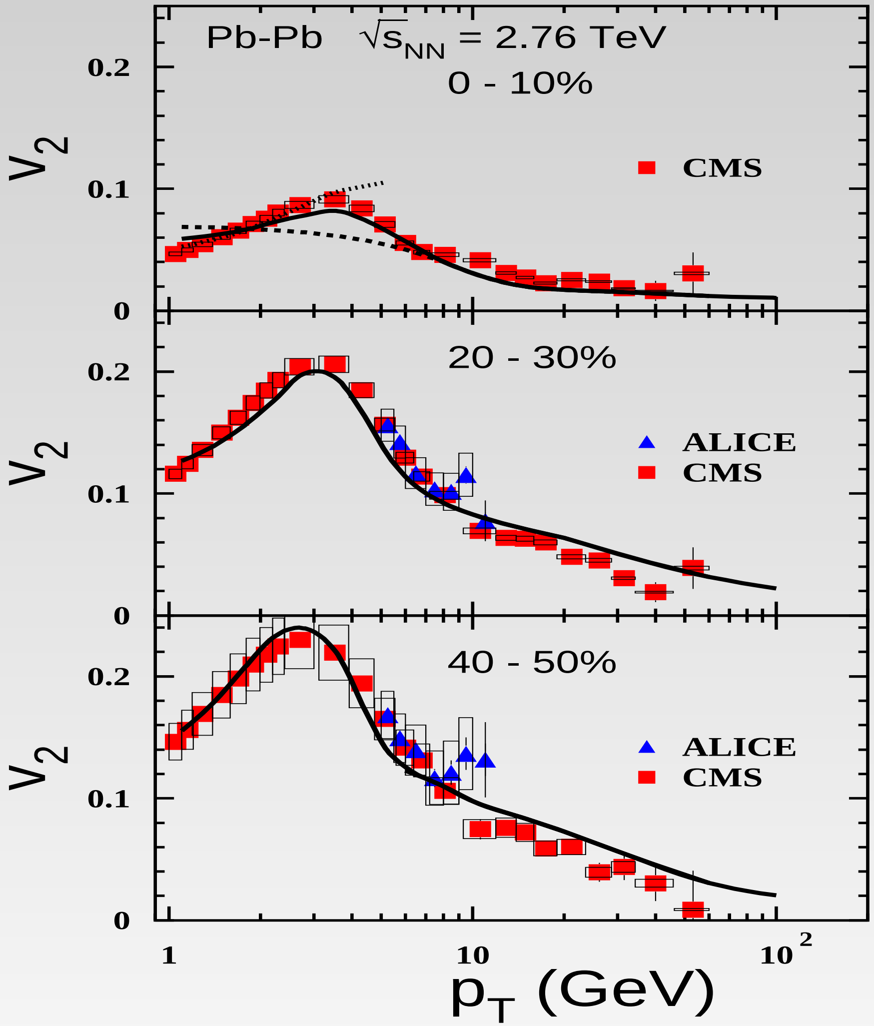


The dominant hydrodynamic mechanism of elliptic flow, provides a large and rising with $p_T$ anisotropy $v_2(p_T)$, which abruptly switches to the regime of pQCD, having a much smaller azimuthal anisotropy.

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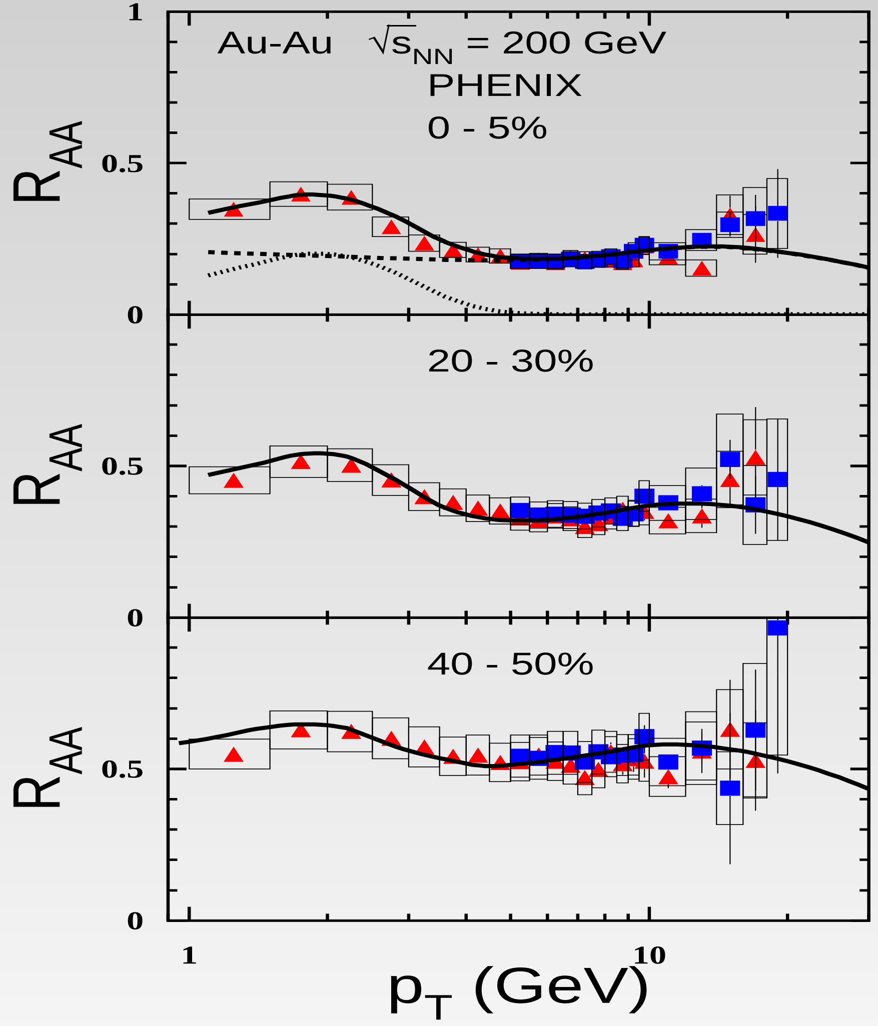

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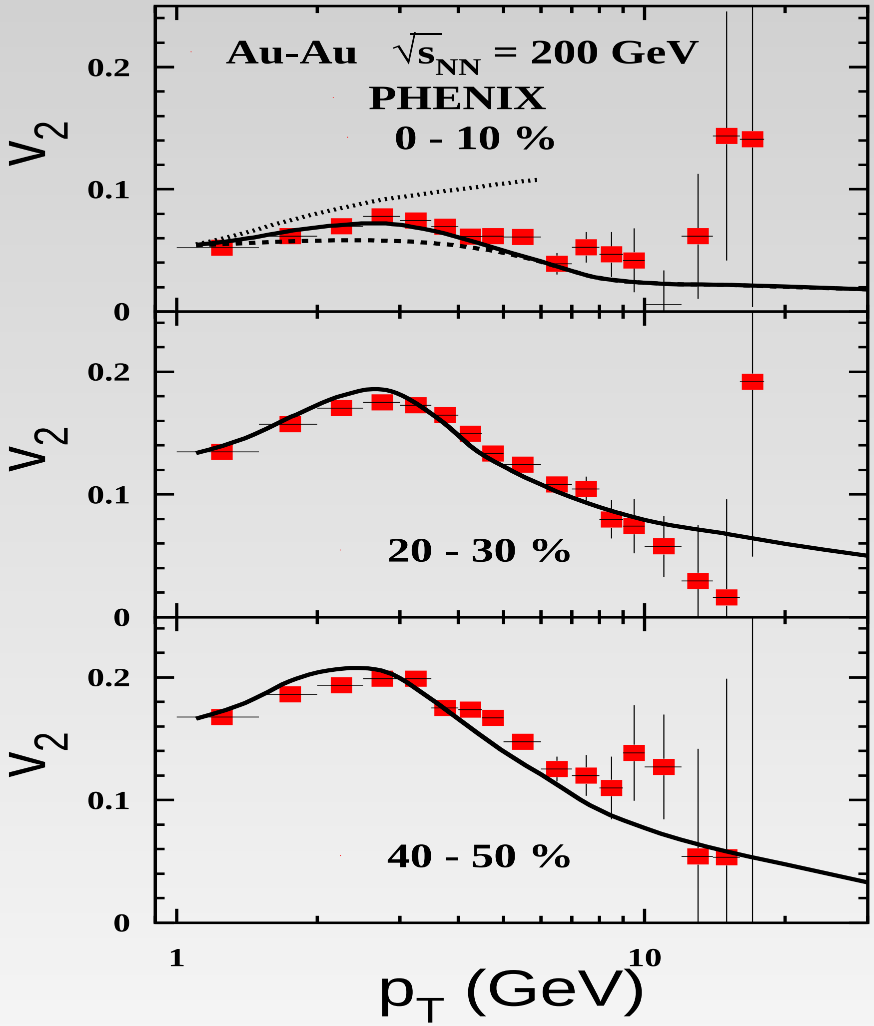

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- Using the rigorous quantum-mechanical approach based on the path integral technique for description of the $\bar{q}q$ dipole evolution we apply the standard convolution expression for description of high-$p_T$ hadron production in heavy ion collisions at mid rapidities in the RHIC and LHC kinematic range.

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- the main part of nuclear suppression is related to the survival probability of colorless dipole propagating through a dense medium $\Rightarrow$ color transparency - steep rise of the nuclear modification factor $R_{AA}(p_T)$ with $p_T$
- In comparison with LHC a dominance of quarks with larger $l_p$ leads to a smaller suppression at RHIC.

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- Calculations contain only medium density adjustment and we found the transport coefficient to be:

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- these value are more than order of magniture less than was found from jet quenching data within the energy loss scenario
- Finally we combined our pQCD results with the hydrodynamic mechanism providing a successful description of data in the full range of $p_T$.