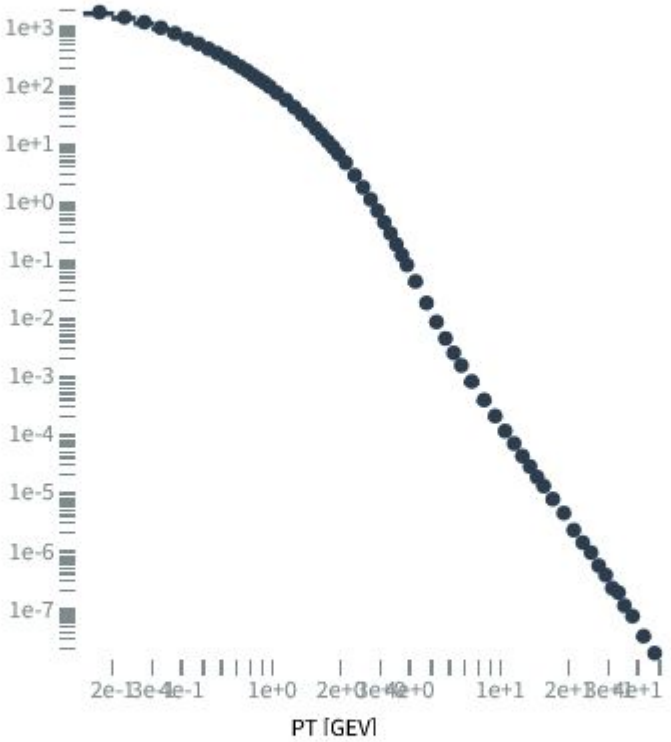
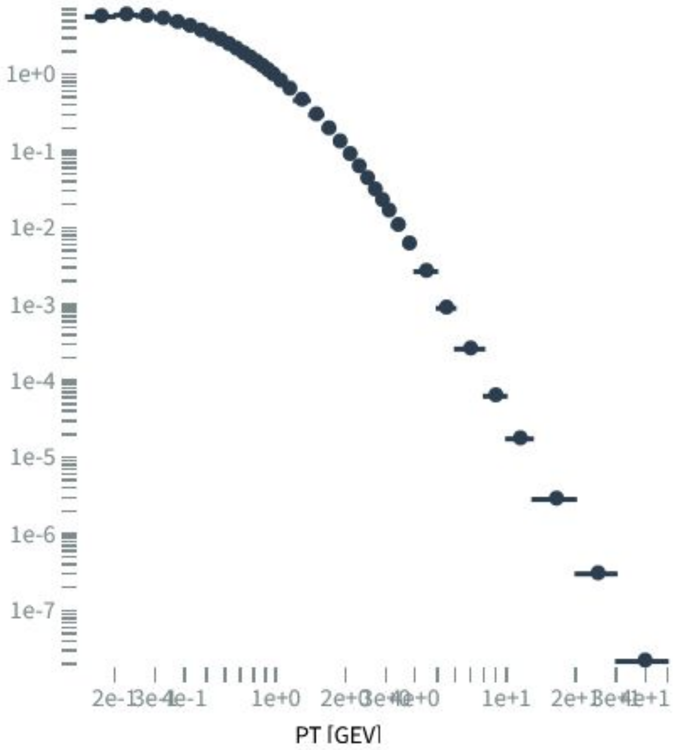
Nuclear Modification Factor in High Energy Collisions

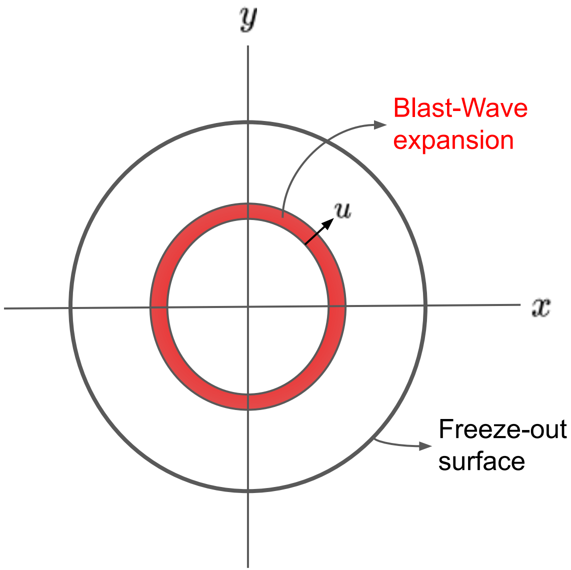
Nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{N_{\rm coll}(\epsilon)} \frac{dN^{AA}/dp_T dy}{dN^{pp}/dp_T dy}$$

ALICE 2.76 TeV - Charged particle production (PbPb and pp)







Expanding hyper volume

$$\Sigma(x_0, x_1, x_2, x_3) = (x_0, x_1, x_2, x_3(x_0))$$

Cooper-Frye

$$N = \int_\Sigma dN^\mu j_\mu \quad \rightarrow \quad E\frac{dN}{d^3p} = \frac{1}{(2\pi)^3}\int_\Sigma \underline{dN^\mu p_\mu} f(p)$$

Longitudinally boost-invariant volume

$$\Sigma_\mu = (\tau(x,y)\cosh\eta, x, y, \tau(x,y)\sinh\eta) \qquad \left(\tau = \sqrt{t^2 - z^2}, x, y, \eta = \frac{1}{2}\ln\frac{t+z}{t-z}\right)$$

$$dN_\mu = \pm\varepsilon_{\mu\alpha\beta\gamma}\frac{\partial\Sigma_\alpha}{\partial\zeta}\frac{\partial\Sigma_\beta}{\partial\eta}\frac{\partial\Sigma_\gamma}{\partial\phi}d\zeta d\eta d\phi \quad \rightarrow \quad dN_\mu = \left(\cosh\eta, -\frac{\partial\tau}{\partial x}, -\frac{\partial\tau}{\partial y}, -\sinh\eta\right)\tau(x,y)dxdyd\eta$$

$$dN_\mu = \left(\cosh\eta, -\frac{\partial\tau}{\partial x}, -\frac{\partial\tau}{\partial y}, -\sinh\eta\right)\tau(x,y)dxdyd\eta$$

Normal vector element

$$p^\mu = (m_T\cosh Y, p_x, p_y, m_T\sinh Y)$$

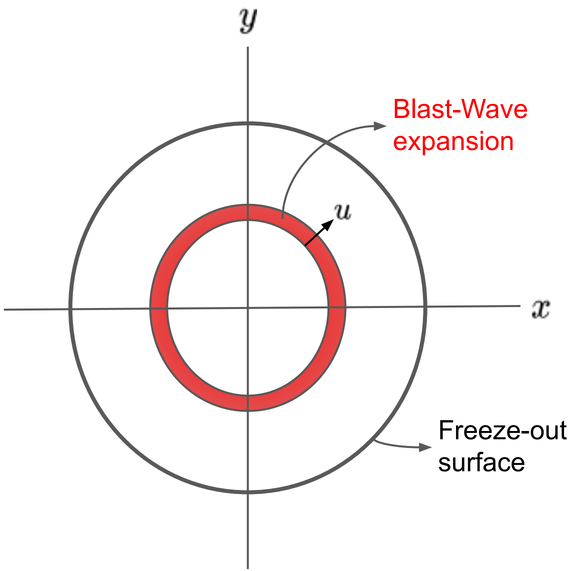
Particle momentum

$$\Rightarrow \quad p^\mu \cdot dN_\mu = \left(m_T\cosh(Y-\eta) - p_x\frac{\partial\tau}{\partial x} - p_y\frac{\partial\tau}{\partial y}\right)\tau dxdyd\eta$$

Differential cross-section

$$E\frac{dN}{d^3p} = \frac{1}{(2\pi)^3}\int dx\, dy\, d\eta\, \tau(x,y)\left(m_T\cosh(Y-\eta) - p_x\frac{\partial\tau}{\partial x} - p_y\frac{\partial\tau}{\partial y}\right)f(p^\mu u_\mu)$$

Simplified Blast-Wave



Fixed freeze-out time $\begin{cases} \frac{\partial \tau}{\partial x} = 0 \\ \frac{\partial \tau}{\partial y} = 0 \end{cases}$

$$dx\, dy \to 2\pi r_T dr_T$$

$$E\frac{dN}{d^3p} = \frac{r_T^2\,\tau}{8\pi^2}\int d\eta\ (m_T \cosh(Y-\eta))f(p_T)$$

Narrow range $\Delta\eta$ around $\eta = 0$

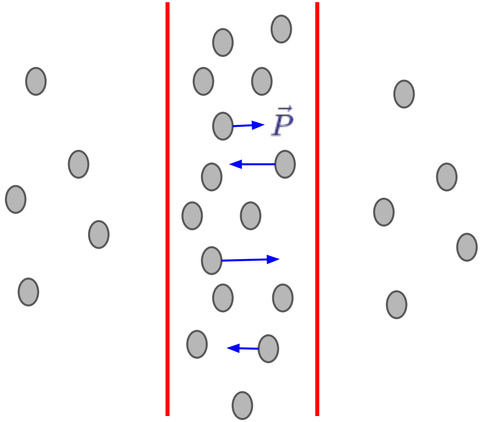
$$E\frac{dN}{d^3p} = \frac{gVm_T\cosh Y}{(2\pi)^3}f(p_T)$$

$$f(p_T) = \left[1 + (q-1)\frac{m_T\cosh Y}{T}\right]^{-\frac{q}{q-1}}$$

Plastino-Plastino equation - Parton dynamics in the QGP

(Fokker-Planck generalization with q-exp solutions)

$$\frac{\partial f}{\partial t} - \frac{\partial}{\partial p_i}\left(Ap_i f + \frac{\partial}{\partial p_i} D f^{2-q}\right) = 0$$



In the fluid frame

$$\bar{p}_T^o = L_u[p_T^o] \qquad L_u(\vec{p}) = \gamma_v\left(\vec{p} - \vec{v}E\right)$$

Drag effect on momentum

$$\bar{p}_T = \bar{p}_T^o \exp(-A\tau) \quad A(p_T) = A_o \exp_q\left[-\bar{m}_T/T\right]$$

AA and pp distributions

$$E\frac{dN}{d^3p} = \frac{gVm_{\rm T}\cosh Y}{(2\pi)^3} f(p_T)$$

$$f(p_T) = \left[1 + (q-1)\frac{m_T\cosh Y}{T}\right]^{-\frac{q}{q-1}}$$

$$f^{AA}(p_T) = f(p_T^o) = f\left(L_{-u}\left[\exp(A\tau)L_u[p_T]\right]\right)$$

$$R_{AA} = (N_{\rm coll})^{-1}\frac{V_{AA}}{V_{pp}}\frac{f\left(L_{-u}\left[L_u[p]\exp(A\tau)\right]\right)}{f(p_T)} = R_{AA}^0\frac{f\left(L_{-u}\left[L_u[p]\exp(A\tau)\right]\right)}{f(p_T)}$$

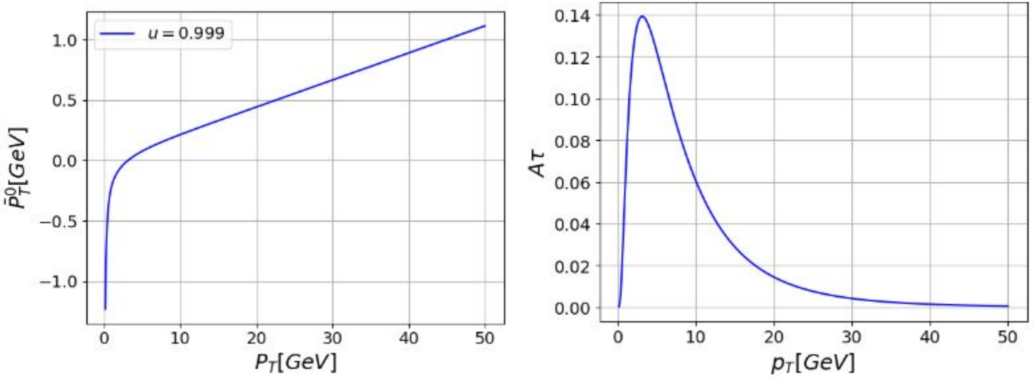


Figure 1: (Left) The initial parton momentum in the local rest frame of the fluid.. (Right) The drift coefficient as a function of the observed transversal moment, according to Eq. (33).

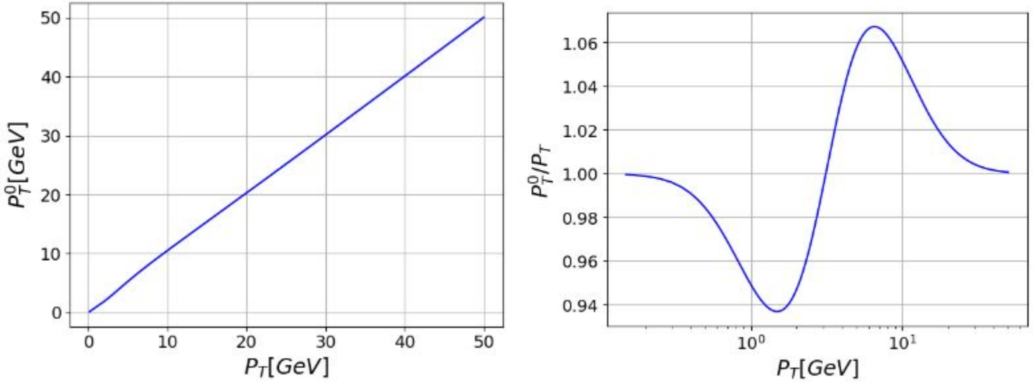


Figure 2: (Left) The momentum of the parton in the moment it was created, p_T^o, as a function of the observed momentum p_T. (Right) Ratio p_T^o/p_T as a function of $\log p_T$.

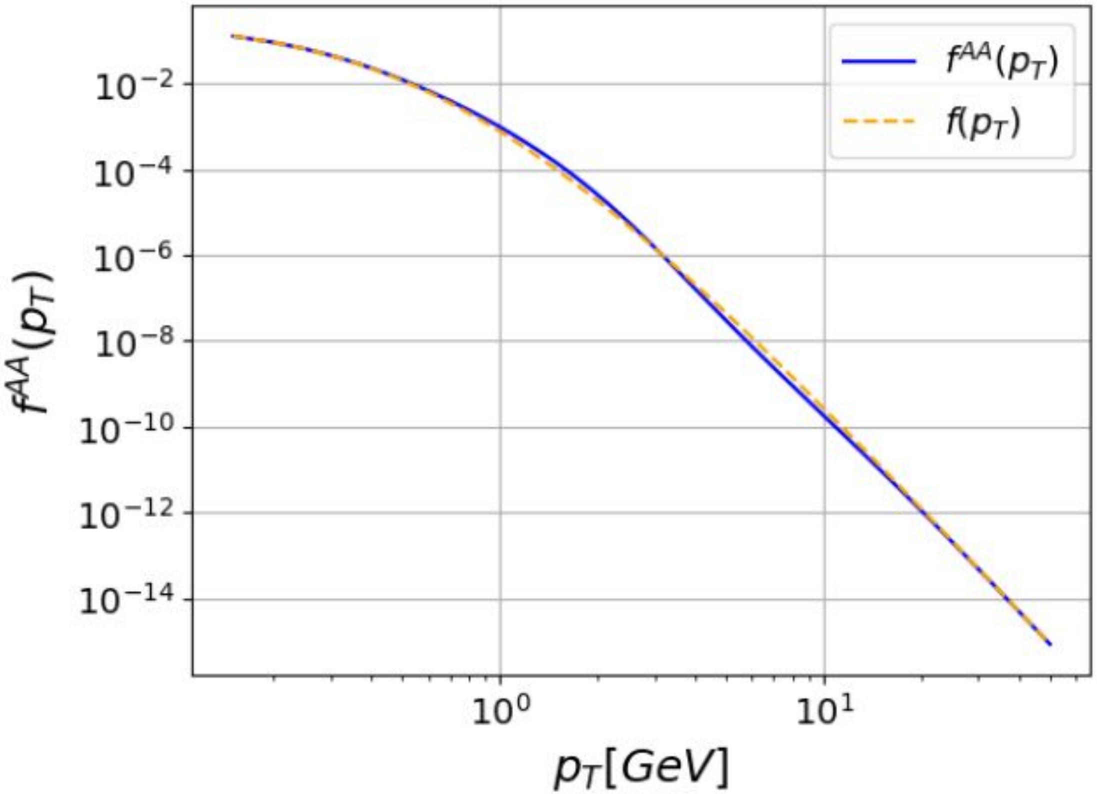


Figure 7: The transverse momentum distributions for nucleus-nucleus collision (solid line) compared with the distribution for the proton-proton collision (dashed line).

Free parameters: $u, \; A_0\tau, \; R^0_{AA}, \; T_{AA}$

$$f(p_T) = \left[1 + (q-1)\frac{m_T \cosh Y}{T}\right]^{-\frac{q}{q-1}}$$

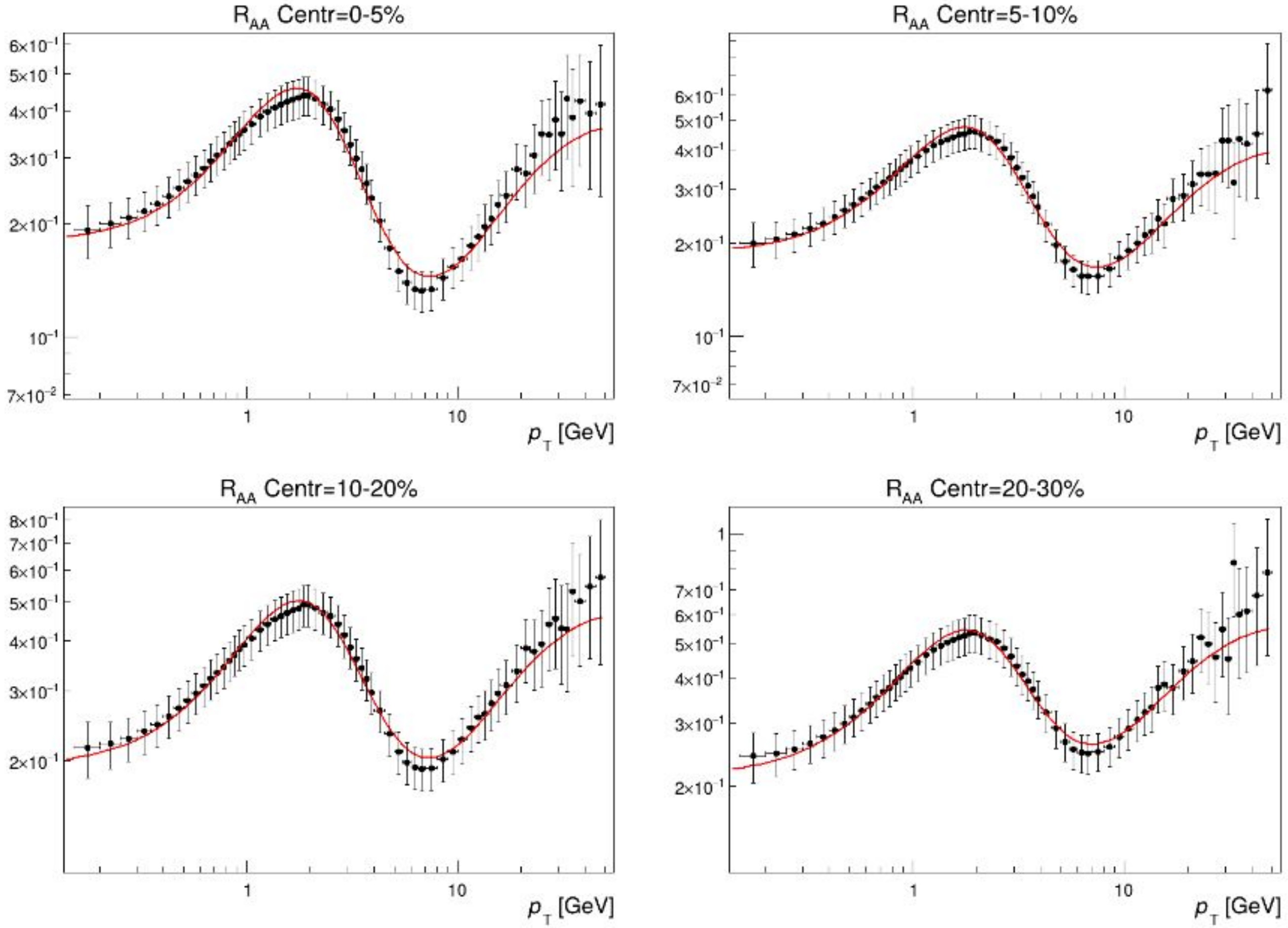
$$R_{AA} = R^0_{AA}\frac{f\left(L_{-u}\left[L_u[p]\exp(A\tau)\right]\right)}{f(p_T)}$$

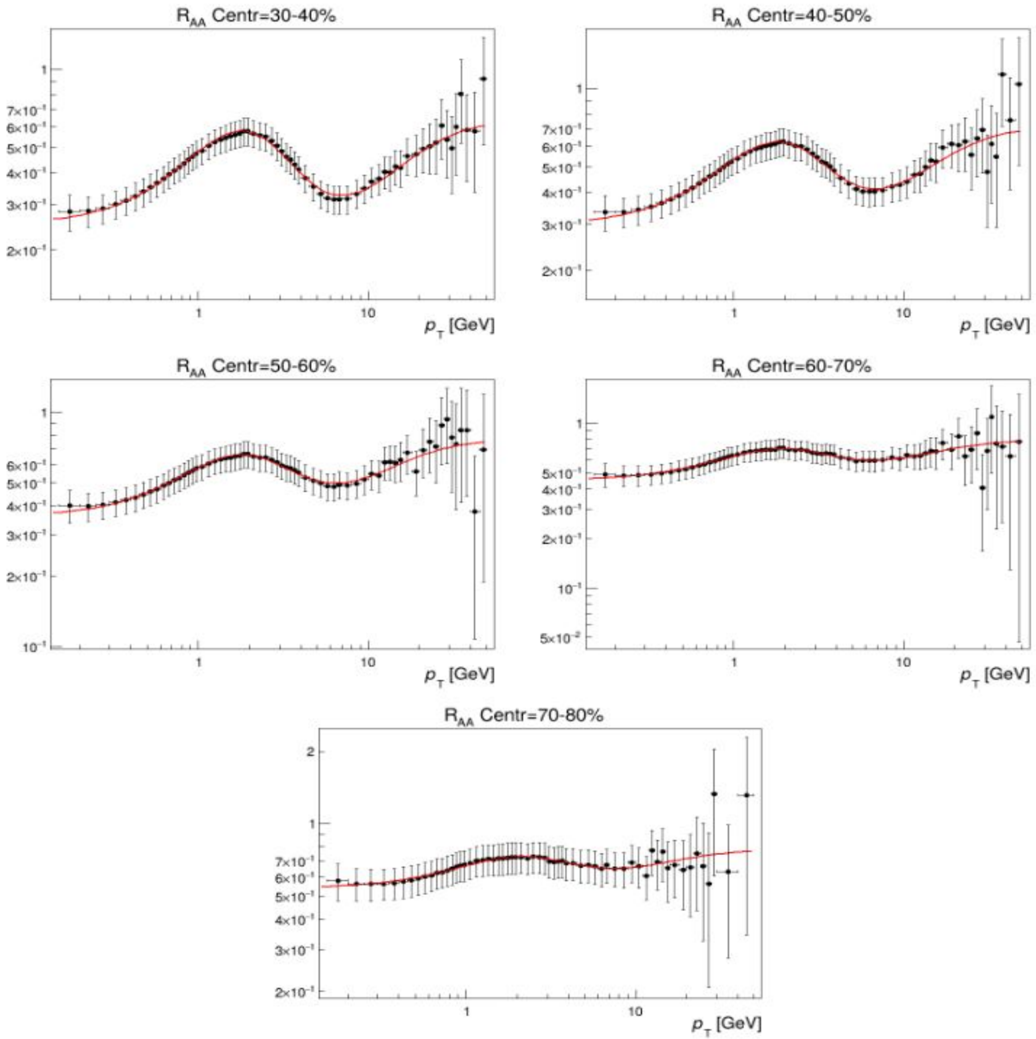
Fixed parameters:

$$q = 1.16, \;\; m = 0.14\,GeV, \;\; T_{pp} = 0.166\,GeV\;(2.76\,TeV), \; 0.079\,GeV\;(5.02\,TeV)$$

(T_{pp} obtained from fitting pp momentum distributions)

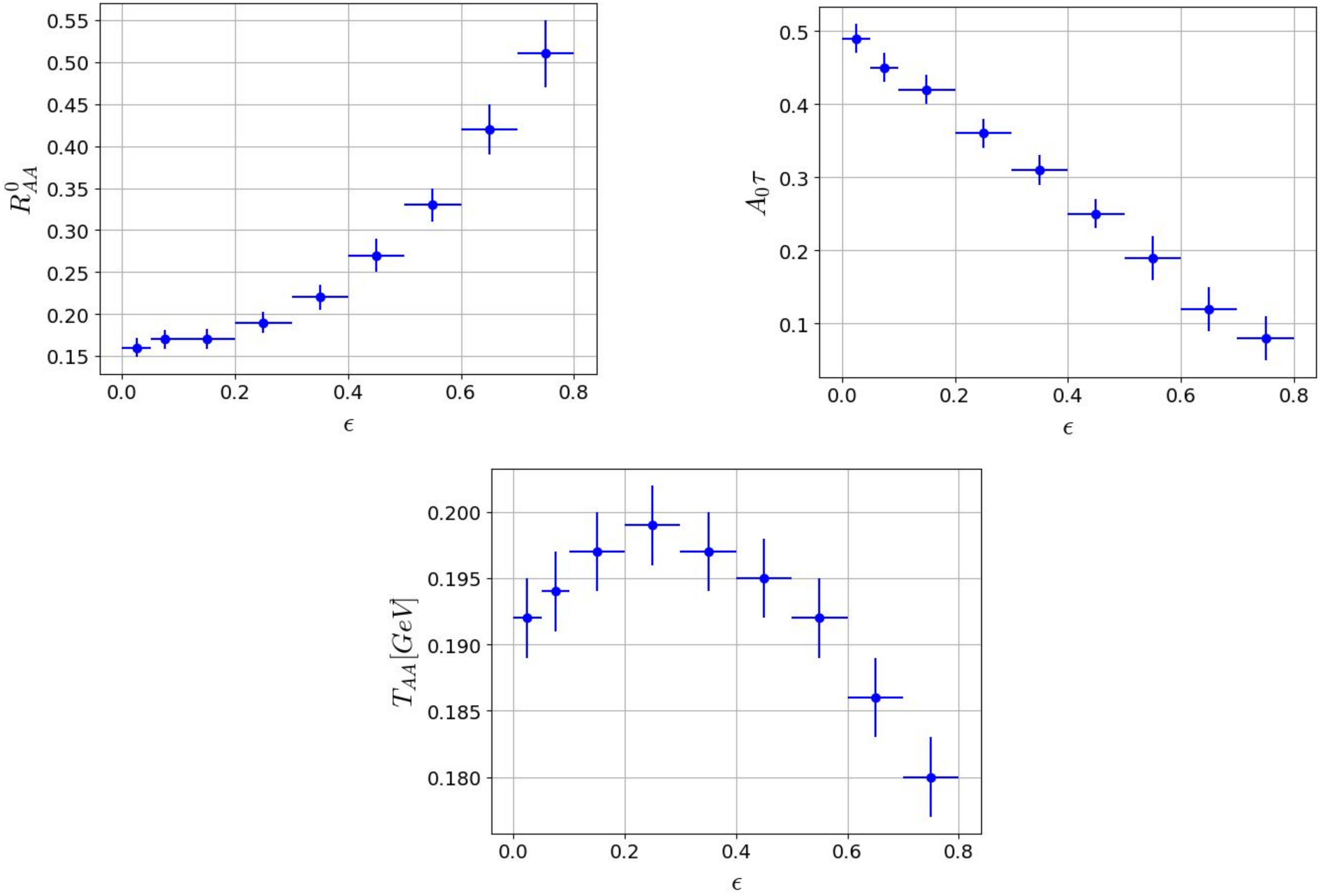
ALICE PbPb -> Charged X, 2.76 TeV





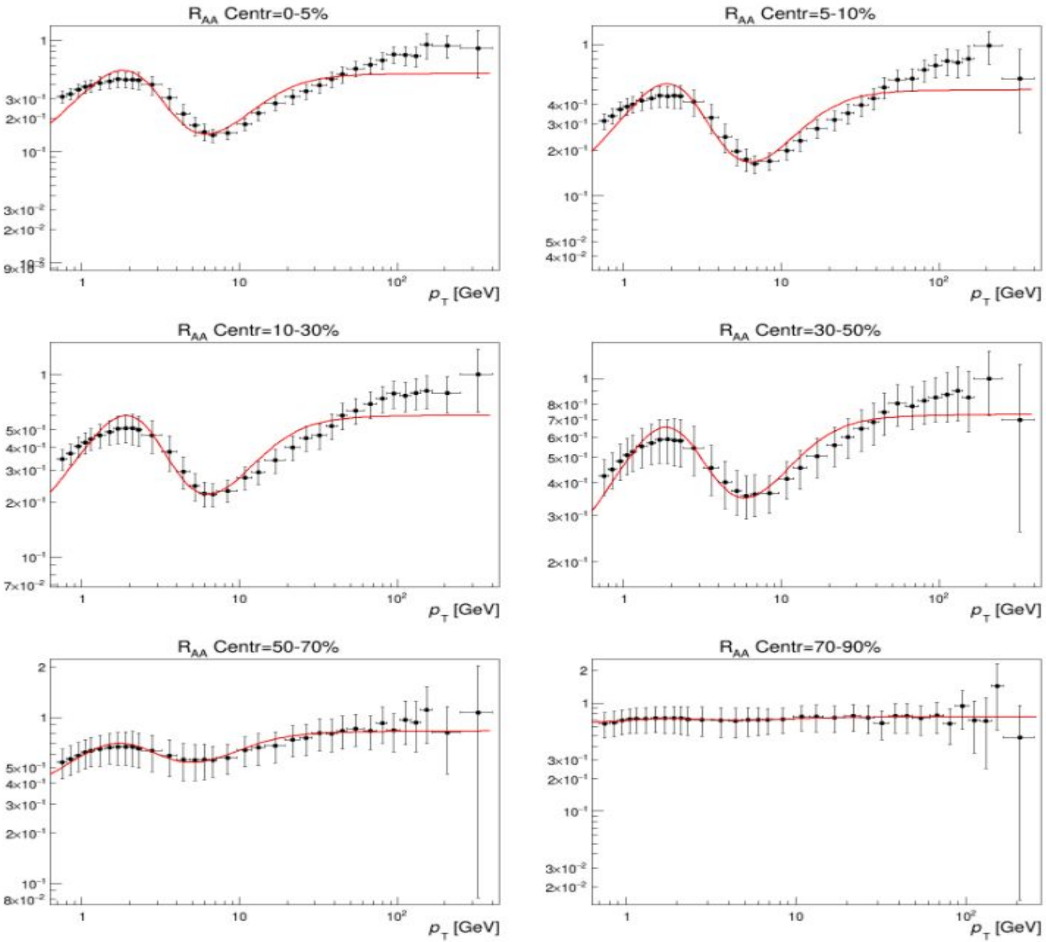
R_AA Centr=30-40%
p_T [GeV]
R_AA Centr=40-50%
p_T [GeV]
R_AA Centr=50-60%
p_T [GeV]
R_AA Centr=60-70%
p_T [GeV]
R_AA Centr=70-80%
p_T [GeV]

Centrality	u	$A_0\tau$	R^0_{AA}	$T_{AA}[GeV]$	χ^2_{red}
0-5%	0.99895 ± 0.00006	0.49 ± 0.02	0.16 ± 0.011	0.192 ± 0.003	0.22
5-10%	0.99897 ± 0.00006	0.45 ± 0.02	0.17 ± 0.011	0.194 ± 0.003	0.16
10-20%	0.99895 ± 0.00007	0.42 ± 0.02	0.17 ± 0.012	0.197 ± 0.003	0.12
20-30%	0.99890 ± 0.00008	0.36 ± 0.02	0.19 ± 0.013	0.199 ± 0.003	0.14
30-40%	0.99891 ± 0.00010	0.31 ± 0.02	0.22 ± 0.015	0.197 ± 0.003	0.06
40-50%	0.9989 ± 0.00013	0.25 ± 0.02	0.27 ± 0.02	0.195 ± 0.003	0.07
50-60%	0.9988 ± 0.0002	0.19 ± 0.03	0.33 ± 0.02	0.192 ± 0.003	0.08
60-70%	0.9989 ± 0.0003	0.12 ± 0.03	0.42 ± 0.03	0.186 ± 0.003	0.06
70-80%	0.9991 ± 0.0004	0.08 ± 0.03	0.51 ± 0.04	0.180 ± 0.003	0.05

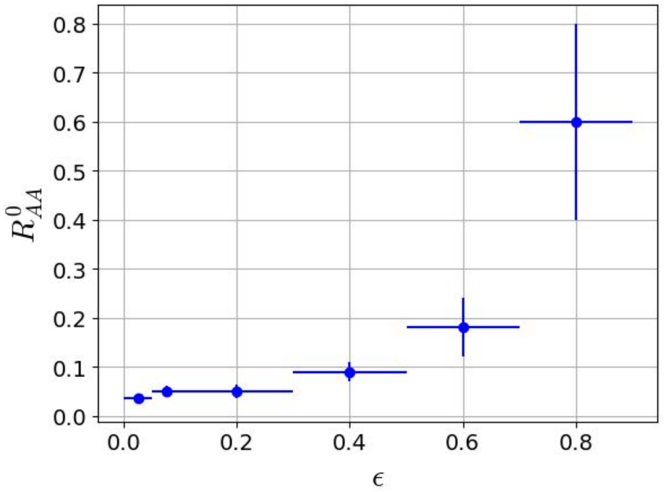


R_{AA}^0
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.0
0.2
0.4
0.6
0.8
ϵ
$A_0\tau$
0.1
0.2
0.3
0.4
0.5
0.0
0.2
0.4
0.6
0.8
ϵ
$T_{AA}[GeV]$
0.180
0.185
0.190
0.195
0.200
0.0
0.2
0.4
0.6
0.8
ϵ

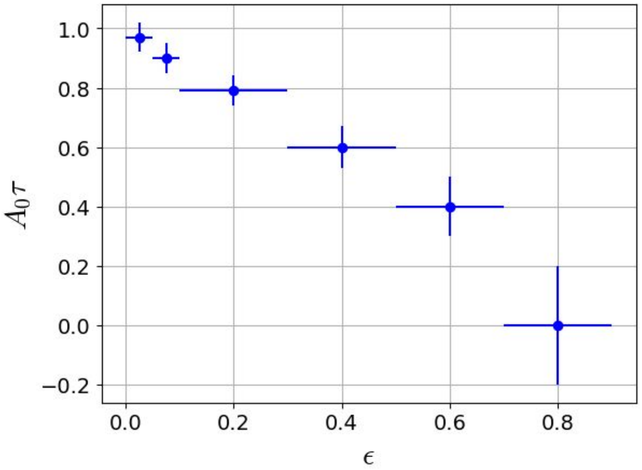
CMS PbPb -> Charged X, 5.02 TeV



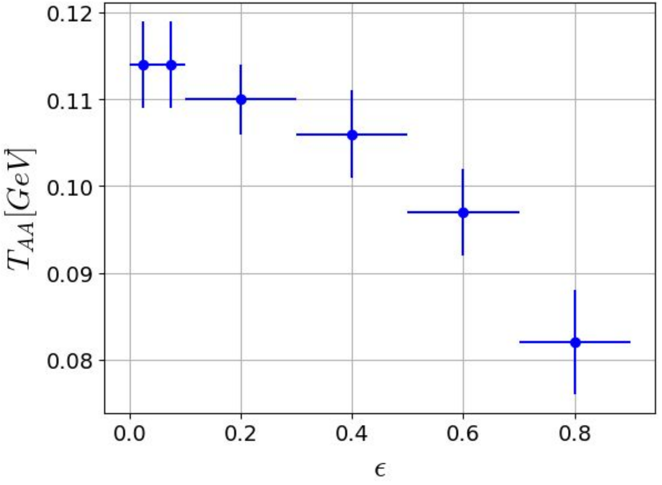
Centrality	u	$A_0\tau$	R^0_{AA}	T_{AA} [GeV]	χ^2_{red}
0-5%	0.9989 ± 0.00012	0.97 ± 0.05	0.036 ± 0.009	0.114 ± 0.005	1.45
5-10%	0.9990 ± 0.00012	0.90 ± 0.05	0.05 ± 0.012	0.110 ± 0.005	1.35
10-30%	0.9990 ± 0.00013	0.79 ± 0.05	0.05 ± 0.013	0.110 ± 0.004	0.9
30-50%	0.9989 ± 0.0002	0.60 ± 0.07	0.09 ± 0.02	0.106 ± 0.005	0.3
50-70%	0.9986 ± 0.0006	0.4 ± 0.10	0.18 ± 0.06	0.097 ± 0.005	0.07
70-90%	0.999 ± 0.003	0.0 ± 0.2	0.6 ± 0.2	0.082 ± 0.006	0.06



R^0_{AA}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.0
0.2
0.4
0.6
0.8
ϵ



$A_0\tau$
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
ϵ



$T_{AA}[GeV]$
0.08
0.09
0.10
0.11
0.12
0.0
0.2
0.4
0.6
0.8
ϵ

Complex q approach to log oscillations

$$g(p_T) = \left(1 + \frac{p_T}{nT}\right)^{m_0} \cdot R(p_T)$$ (Dressed tsallis)

$$m_k = -\frac{\ln(1-\alpha n)}{\ln(1+\alpha)} + \imath k \frac{2\pi}{\ln(1+\alpha)} \quad (k = 0, 1)$$

$$1/n = (q-1)$$

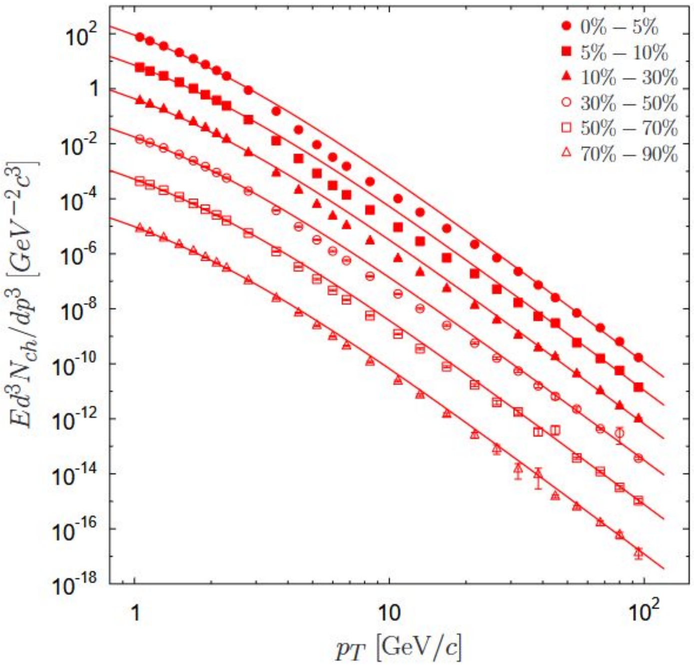
Where

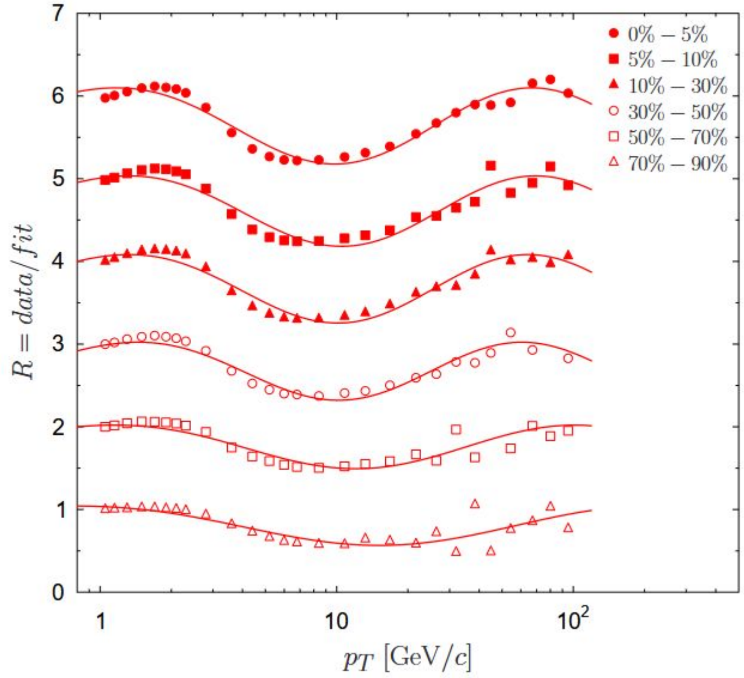
$$R(p_T) \simeq \left\{ w_0 + w_1 \cos\left[\frac{2\pi}{\ln(1+\alpha)} \ln\left(1 + \frac{p_T}{nT}\right)\right]\right\}$$ (Dressing factor)

M. Rybczyński, G. Wilk, and Z. Włodarczyk, "System size dependence of the log-periodic oscillations of transverse momentum spectra ," *EPJ Web of Conferences*, vol. 90, p. 01002, 2015.

$$f\left(p_T\right) = C \cdot \left[1 - (1-q)\,\frac{p_T}{T}\right]^{1/(1-q)}$$

$$R\left(p_T\right) \simeq \left\{w_0 + w_1 \cos\left[\frac{2\pi}{\ln(1+\alpha)}\ln\left(1+\frac{p_T}{nT}\right)\right]\right\}$$





Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

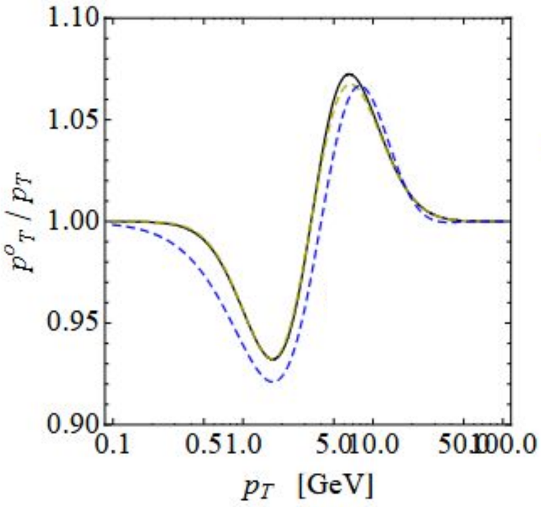
Our model

Expanding around $A(\bar{p}_T)\tau = 0$

$$\frac{p_T^o}{p_T} \simeq 1 + 2\tilde{A}_0\tau\,(1+z)^{-m_0}\cos\left[c\log(1+z)\right] \quad \sim R(p_T)$$

$$1+z = e^{-\frac{\pi}{2c}}\frac{1+x}{1+x_o}\,, \qquad y = x/x_o\,, \quad x_o = (q-1)m/T\,, \quad c = 1+1/x_o$$

$$\tilde{A}_0 = \left(e^{\frac{\pi}{2c}}(1+x_o)\right)^{\frac{1}{1-q}} mA_0$$



This corresponds to a q-complex Tsallis distribution with

$$m_k = \frac{1}{q-1} + ik\left(1+\frac{1}{x_o}\right), \qquad (k = 0, 1, 2, \cdots)$$

Summary

- We built a model to describe RAA data taking the momentum distribution from a simplified blast-wave model and applying medium effects from the Plastino-Plastino equation.
- We successfully described RAA data for 2.76 TeV charged particle production in all centralities, and less successfully for 5.02 TeV data.
- We connect our approach with the complex q model to explain log oscillations in p_T distributions residuals

Thanks!