Nuclear like effects in pp collisions and the clustering of color sources

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QCD challenges from pp to AA
Puebla (31st Oct-3rd Nov 2017)

---String percolation model(clustering of color sources)

---The onset of the ridge structure and the

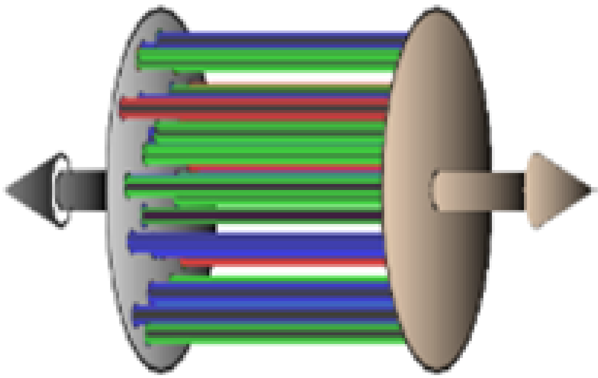
critical percolation point

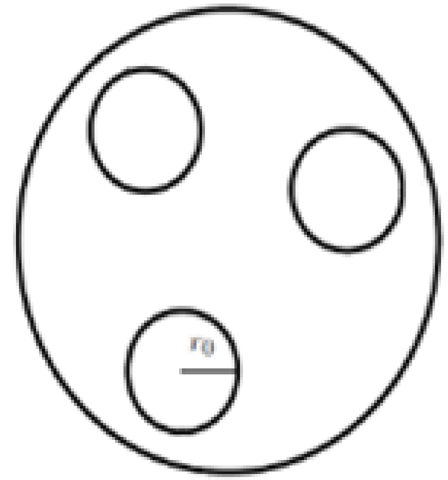
---The azimuthal dependence

---Elliptic flow in pp collisions

---Quarkonia dependence on the multiplicity

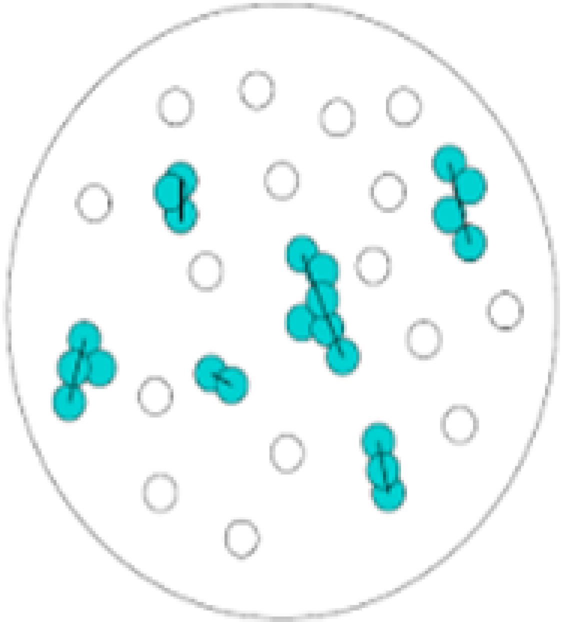
Physical picture





$r_0 = 0.2 - 0.25\ fm$

- Projectile and target interact via color field created by the constituent partons of the nuclei.
- Color field is confined in a region with transverse size $r_0 \sim \mathbf{0.2\,fm}$.
- We can see them as small areas in transverse plane.
- These color "strings" break producing $q\bar{q}$ pairs (Schwinger mechanism) that subsequently lead to the observed hadrons.



- With growing energy and/or atomic number of colliding particles, the number of **sources** grows → The **number of strings** grows with energy and/or atomic number.
- The **number of strings** also increases with increasing centrality.
- Strings are **randomly distributed** in transverse plane so they can overlap forming clusters.

- A cluster of n strings **behaves like a single string with a color field**

$$\vec{Q}_n = \sum_1^n \vec{Q}_1$$

.

- The field is **randomly oriented** so

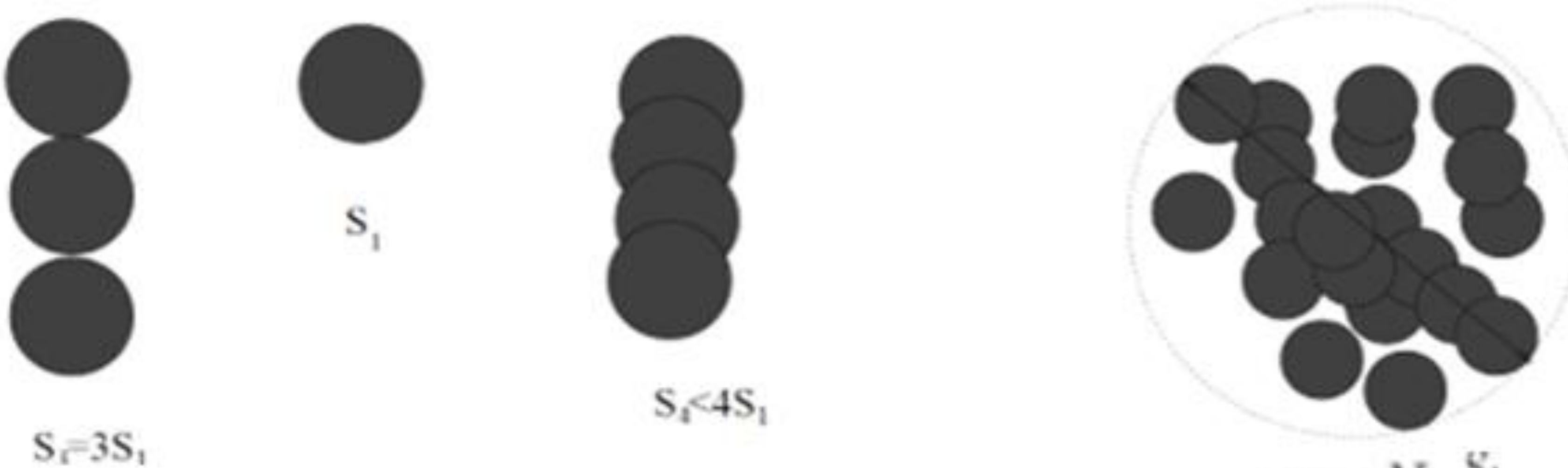
$$\left\langle \vec{Q}_n^2 \right\rangle = n \left\langle \vec{Q}_1^2 \right\rangle$$

- Using the Schwinger formula

$$\mu_n = \sqrt{\frac{nS_n}{S_1}}\mu_1 , \quad \langle p_T^2 \rangle_n = \sqrt{\frac{nS_1}{S_n}} \langle p_T^2 \rangle_1$$

where μ_n and $\langle p_T^2 \rangle_n$ are, respectively, the multiplicity and the mean p_T^2 of the particles created by the fragmentation of a cluster of n strings ocupping an area S_n.

Percolation



$$\rho = N_s \frac{S_1}{S_A}$$

- Limiting cases

$$\text{a)}\ \ S_n = nS_1 \longrightarrow \mu_n = n\mu_1\,, \quad \langle p_T^2\rangle_n = \langle p_T^2\rangle_1$$

$$\text{b)}\ \ S_n = S_1 \longrightarrow \mu_n = \sqrt{n}\mu_1\,, \quad \langle p_T^2\rangle_n = \sqrt{n}\,\langle p_T^2\rangle_1$$

- At a certain critical density 1.2-1.5 a macroscopic cluster appears which marks the percolation transition.

Homogeneous and high density case

- Mean fraction of the area covered by clusters

$$\left(1 - e^{-\rho}\right)$$

More realistic profile and also low density

- Mean fraction of the area covered by clusters

$$A(\rho) = \frac{1}{1 + a e^{-(\rho-\rho_c)/b}}$$

- So the basic equations concerning clusters are

$$\mu_n = N_s F(\rho) \mu_1, \quad \langle p_T^2 \rangle_n = \langle p_T^2 \rangle_1 / F(\rho)$$

where

$$F(\rho) = \sqrt{\frac{1 - e^{-\rho}}{\rho}}.$$

$$f(p_t) = \int W(x)\; f(x, p_T)\;.$$

$$P(n) = \int dN\; W(N)\; P(N, n)$$

$$W(x) = \frac{\gamma}{\Gamma(k)} (\gamma x)^{k-1}\; \exp\left(-\gamma x\right)$$

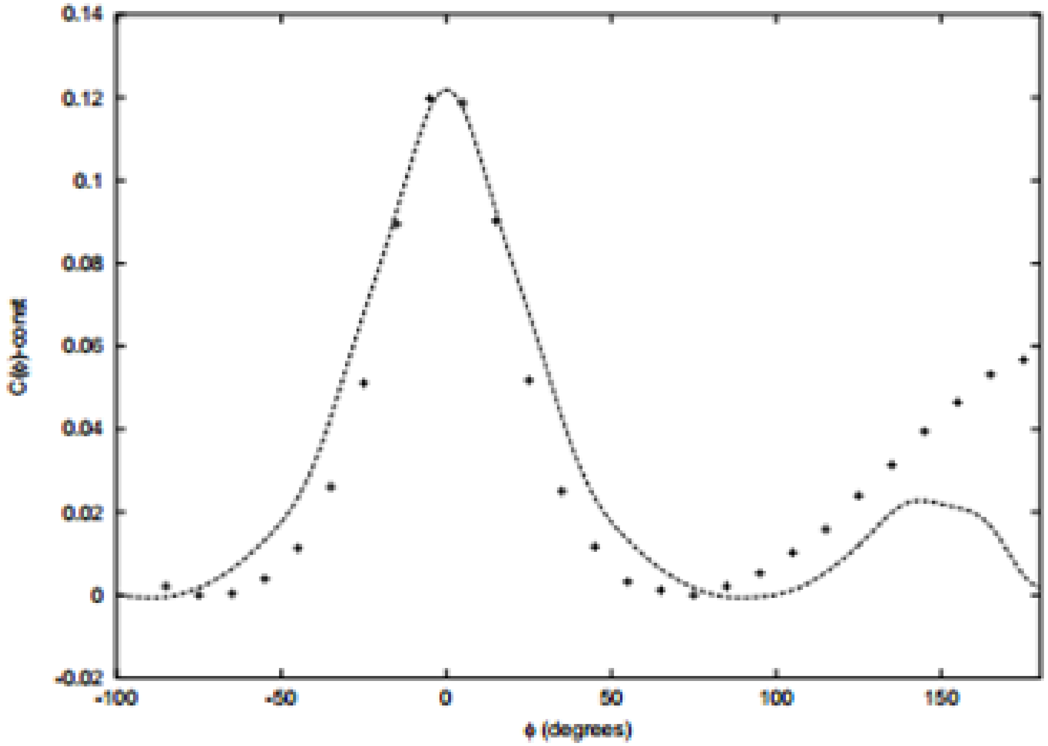
$$\frac{1}{\left(1 + \frac{F(\eta)}{k} \frac{p_T^2}{< p_T^2 >_1}\right)^k}$$

$$\frac{< x^2 > - < x >^2}{< x >^2} = \frac{1}{k}$$

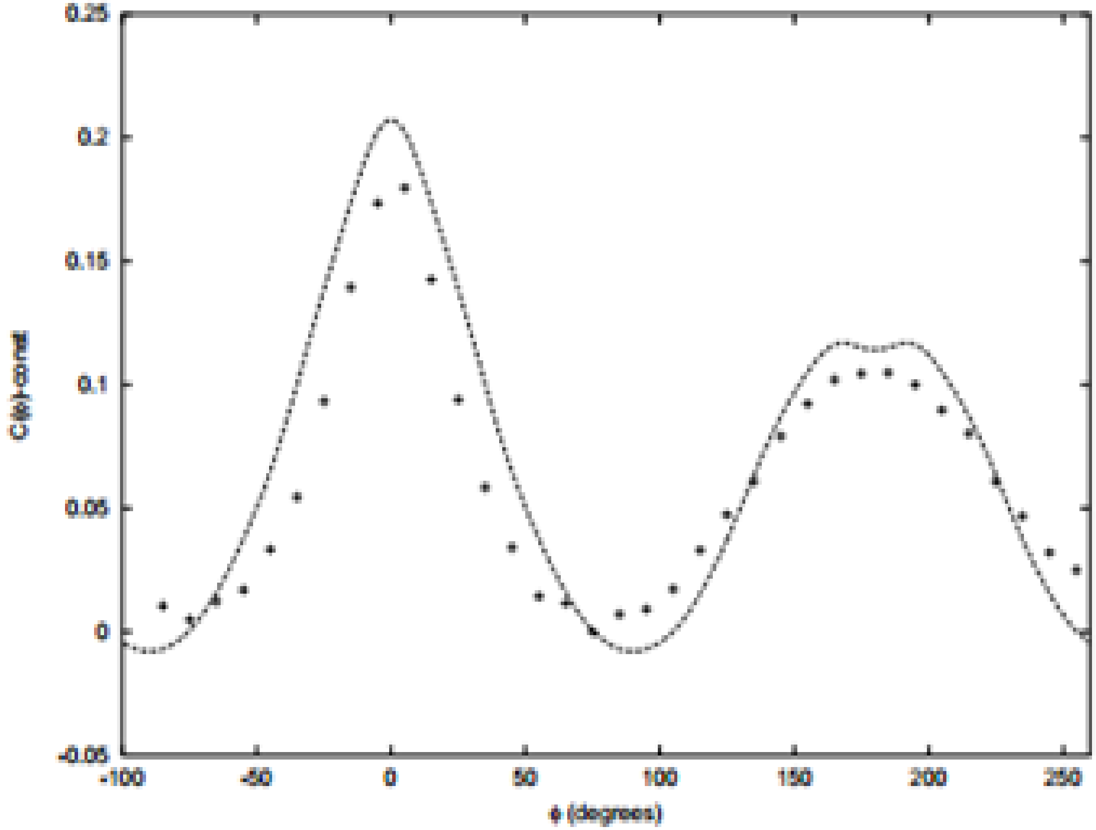
- If there are domains or clusters of strings which decay in partons, these partons interact with the color field of other clusters or domains, losing energy or momentum in their path to get out the area of the collision.
- In QED, the loss of energy of a charged particle moving in an external E.M. field is known. It has been shown, on the basis of ADS/CFT, that in N=4 SUSY with Nc large the same result is obtained.

$$P(p,\phi) = Ce^{-\frac{p_0}{\sqrt{T/2}}}.$$

$$p_0(p,l) = p\Big(1 + \kappa p^{-1/3} T^{2/3} l\Big)^3$$



: Correlation coeficient $C(\phi)$ for pp collisions at 7 TeV with triple multiplicity



Correlation coeficient $C(\phi)$ for p-Pb collisions at 5.02 TeV for central collisions

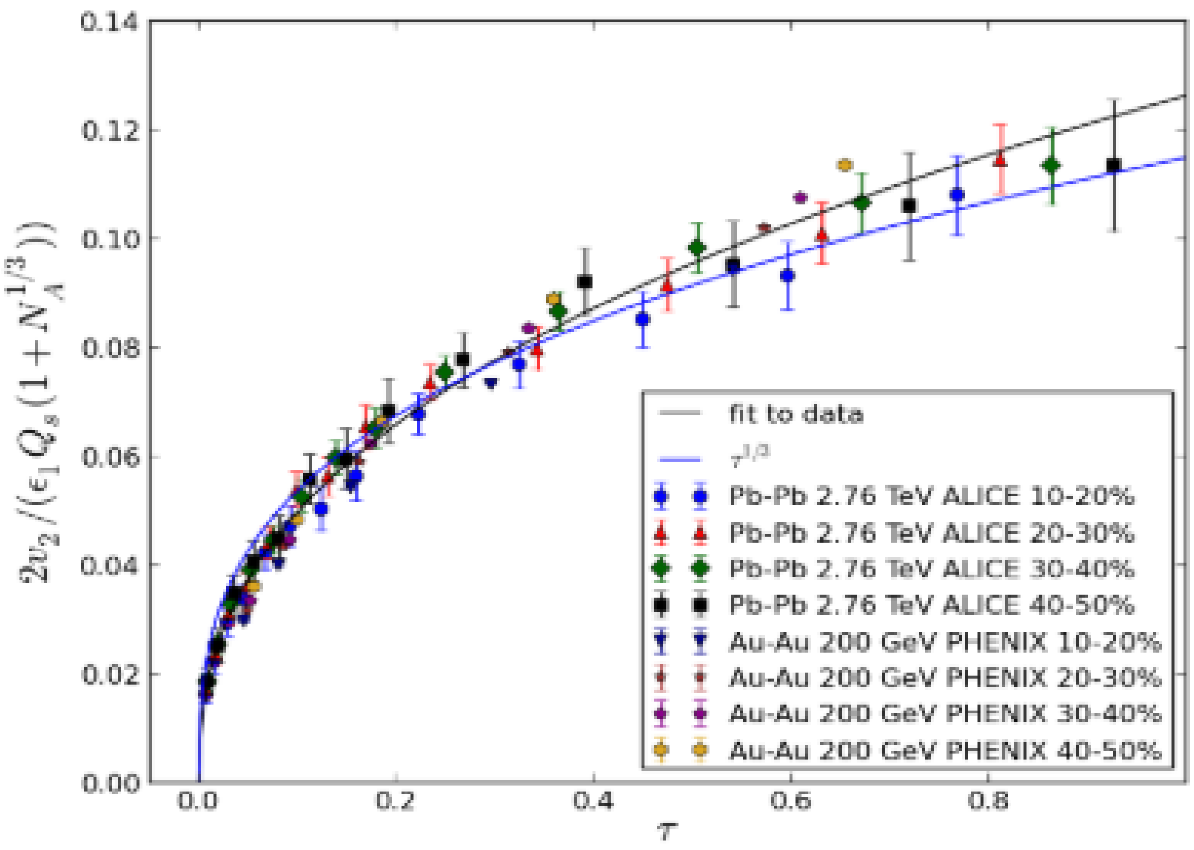
The scaling law

$$\frac{v_2(p_T)}{\epsilon_1 Q_s^A L} = f(\tau) \qquad \tau = \frac{p_T^2}{(Q_s^A)^2}$$

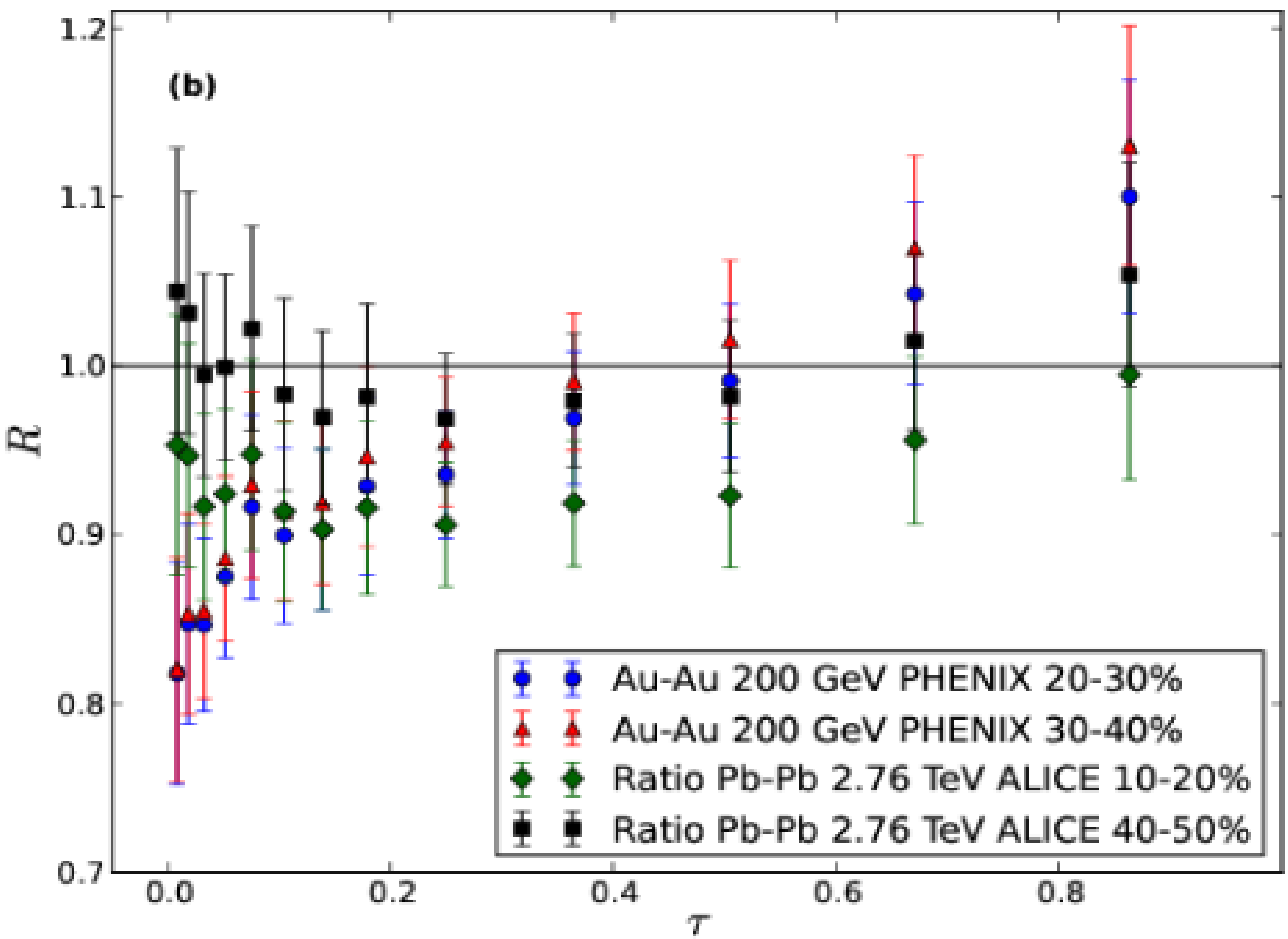
$$v_n \propto p^{2/3} \tilde{\tau}^{1/3} \ell \qquad \tilde{\tau} \sim Q_s$$

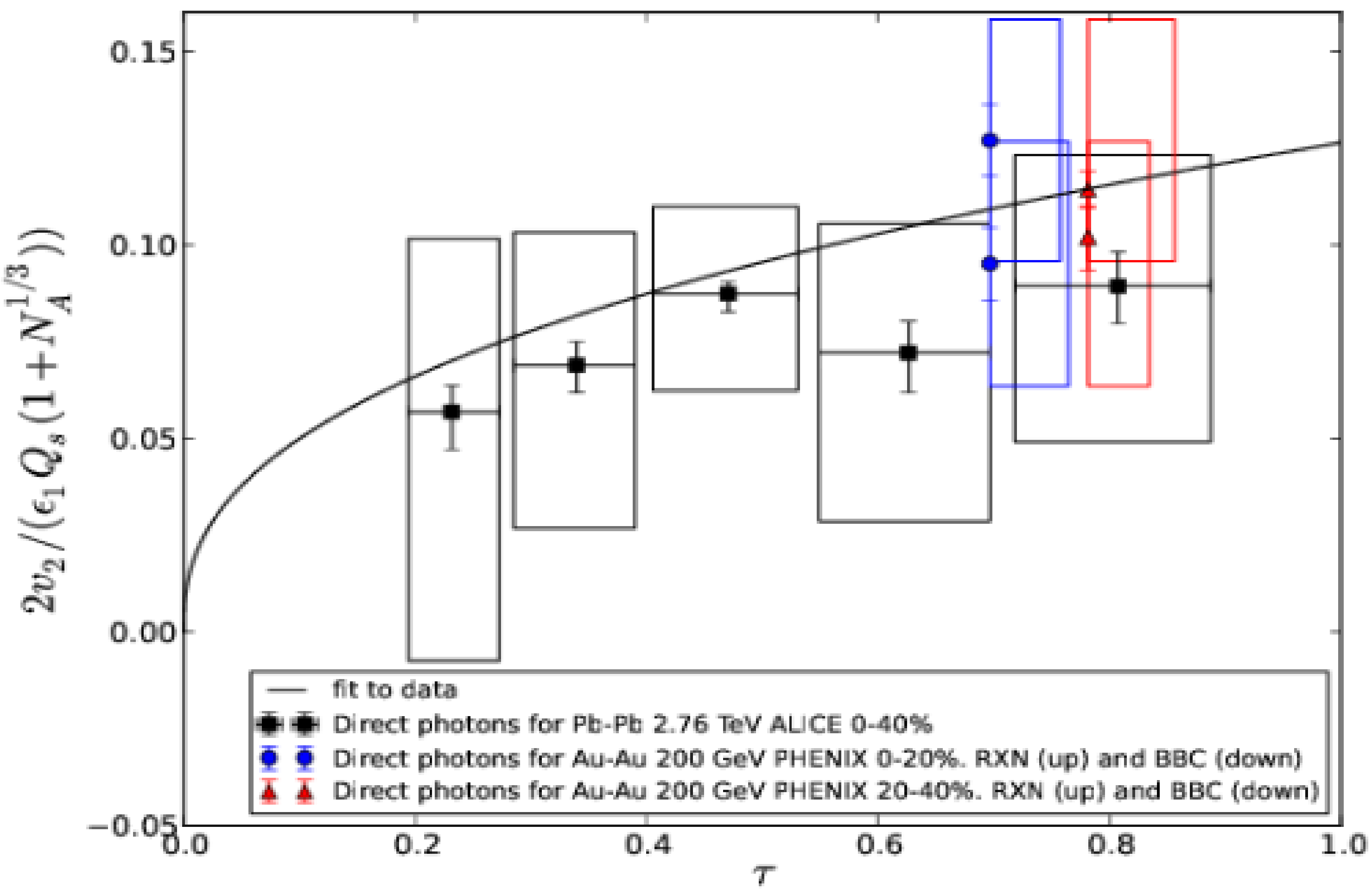
$$\frac{v_n}{\ell Q_s} = \frac{p^{2/3} {Q_s}^{1/3} \ell}{\ell Q_s} = \left(\frac{p^2}{Q_s^2} \right)^{1/3}$$

$$f(\tau) = \tau^{1/3}$$



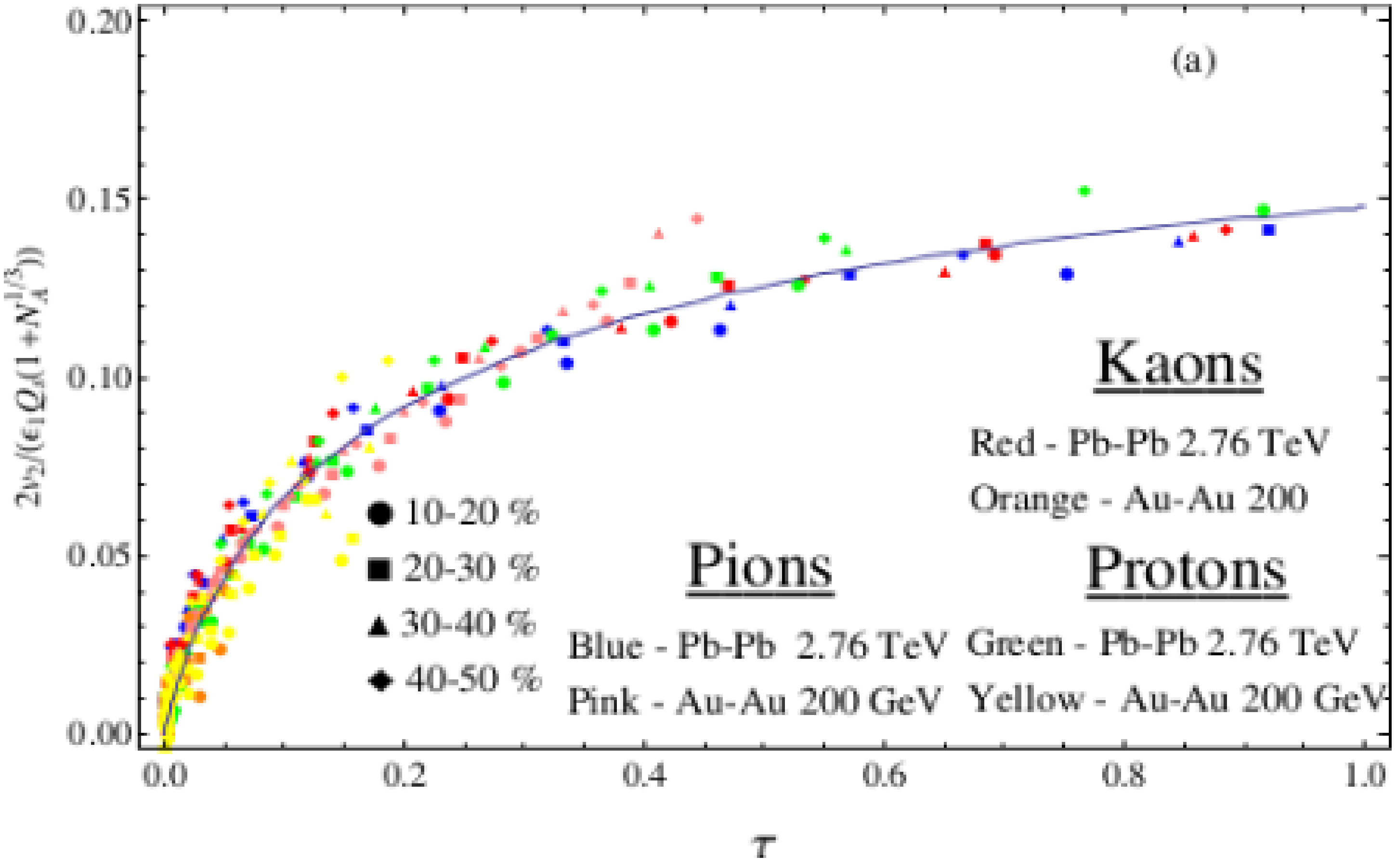
C.Andres, J.Dias de Deus, A. Moscoso, C. Pajares and C Salgado, Phys. Rev. C **92**, 034901 (2015).


(b)
1.2
1.1
1.0
0.9
0.8
0.7
R
0.0
0.2
0.4
0.6
0.8
τ
Au-Au 200 GeV PHENIX 20-30%
Au-Au 200 GeV PHENIX 30-40%
Ratio Pb-Pb 2.76 TeV ALICE 10-20%
Ratio Pb-Pb 2.76 TeV ALICE 40-50%



0.15
0.10
0.05
0.00
−0.05
0.0
0.2
0.4
0.6
0.8
1.0
τ
$2v_2/(\epsilon_1 Q_s (1+N_A^{1/3}))$
fit to data
Direct photons for Pb-Pb 2.76 TeV ALICE 0-40%
Direct photons for Au-Au 200 GeV PHENIX 0-20%. RXN (up) and BBC (down)
Direct photons for Au-Au 200 GeV PHENIX 20-40%. RXN (up) and BBC (down)

v_2-scaling of pions and kaons

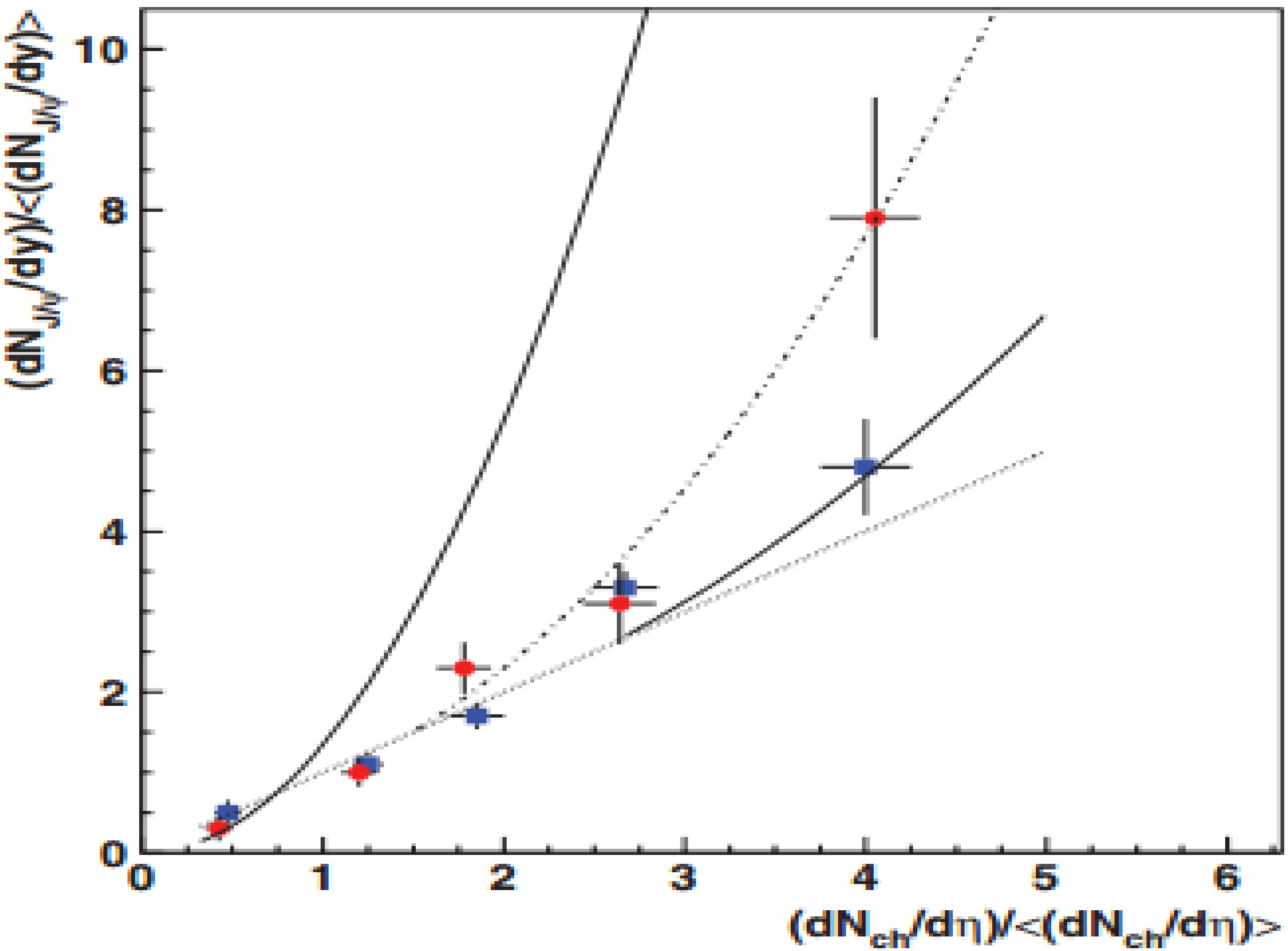


$$\frac{dN}{d\eta} = F(\rho) N_s \mu \qquad F(\rho) = \sqrt{\frac{1-e^{-\rho}}{\rho}}, \qquad \rho = \frac{N_s \sigma_0}{\sigma},$$

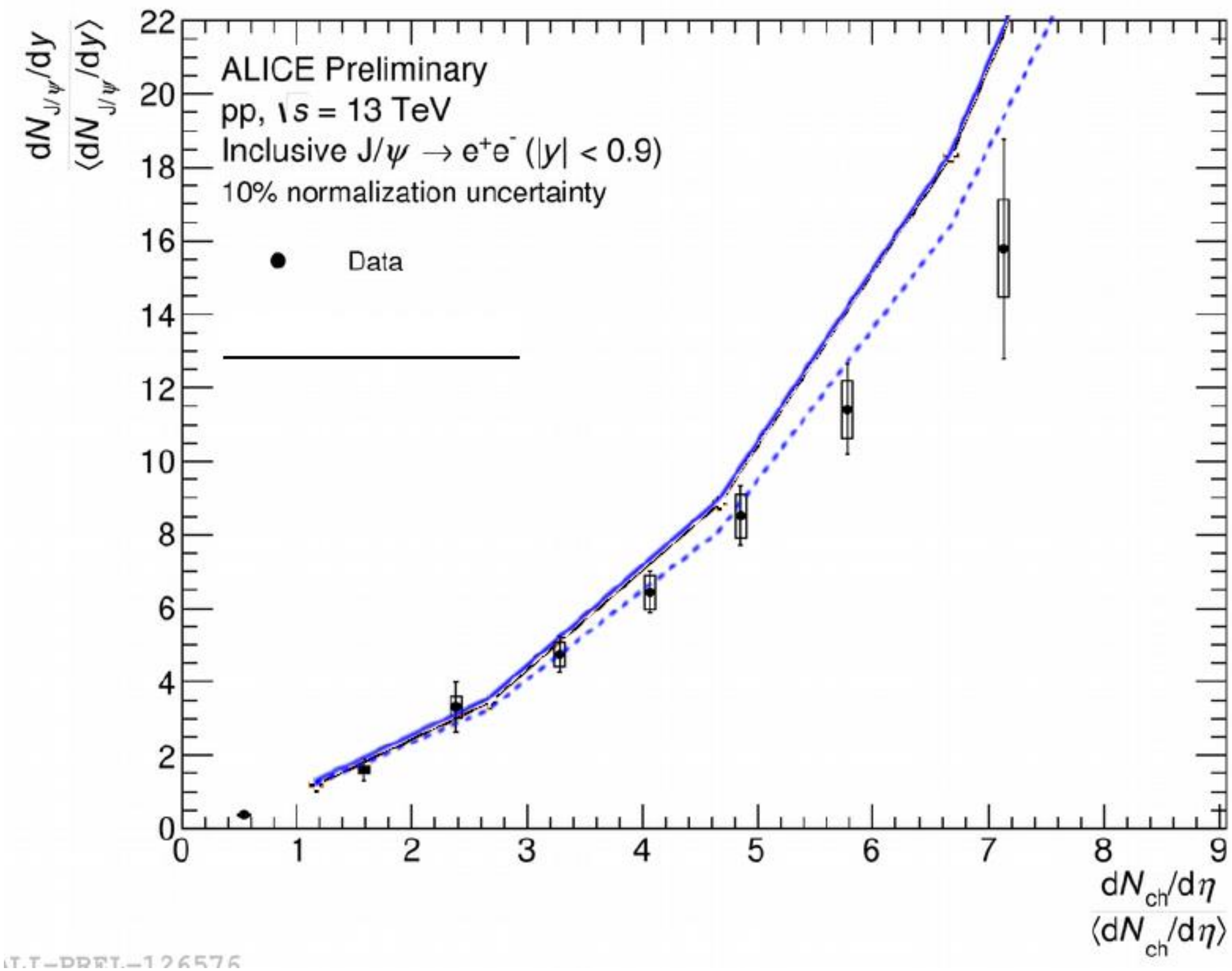
$$\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle} = \frac{N_s}{\langle N_s \rangle}$$

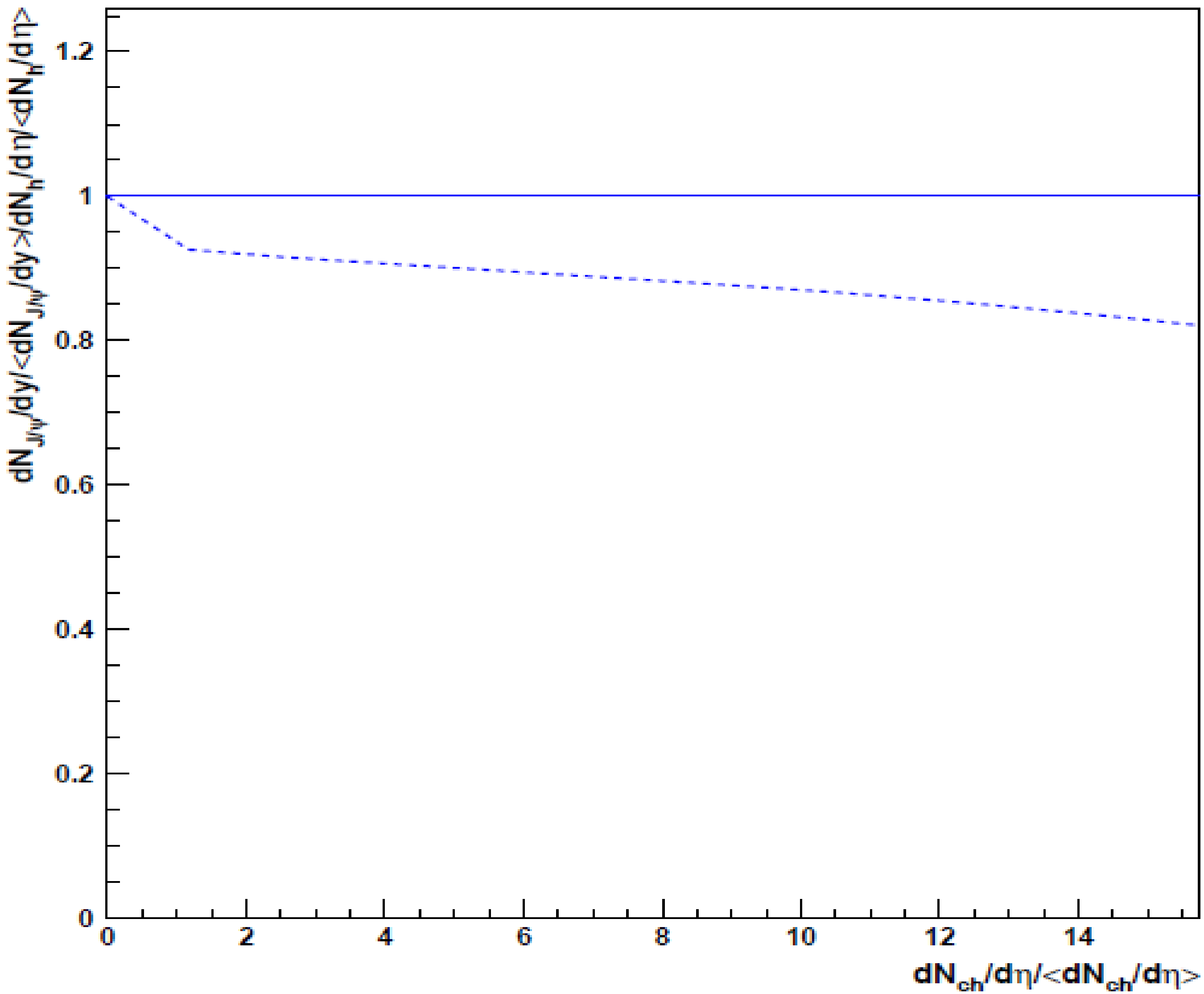
$$\frac{\frac{dN}{d\eta}}{\left\langle \frac{dN}{d\eta} \right\rangle} = \left(\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle} \right)^{1/2} \left[\frac{1 - e^{-\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle} \langle \rho \rangle}}{1 - e^{-\langle \rho \rangle}} \right]^{1/2},$$

$$\langle \rho \rangle = \langle N_s \rangle \frac{\sigma_0}{\sigma}.$$

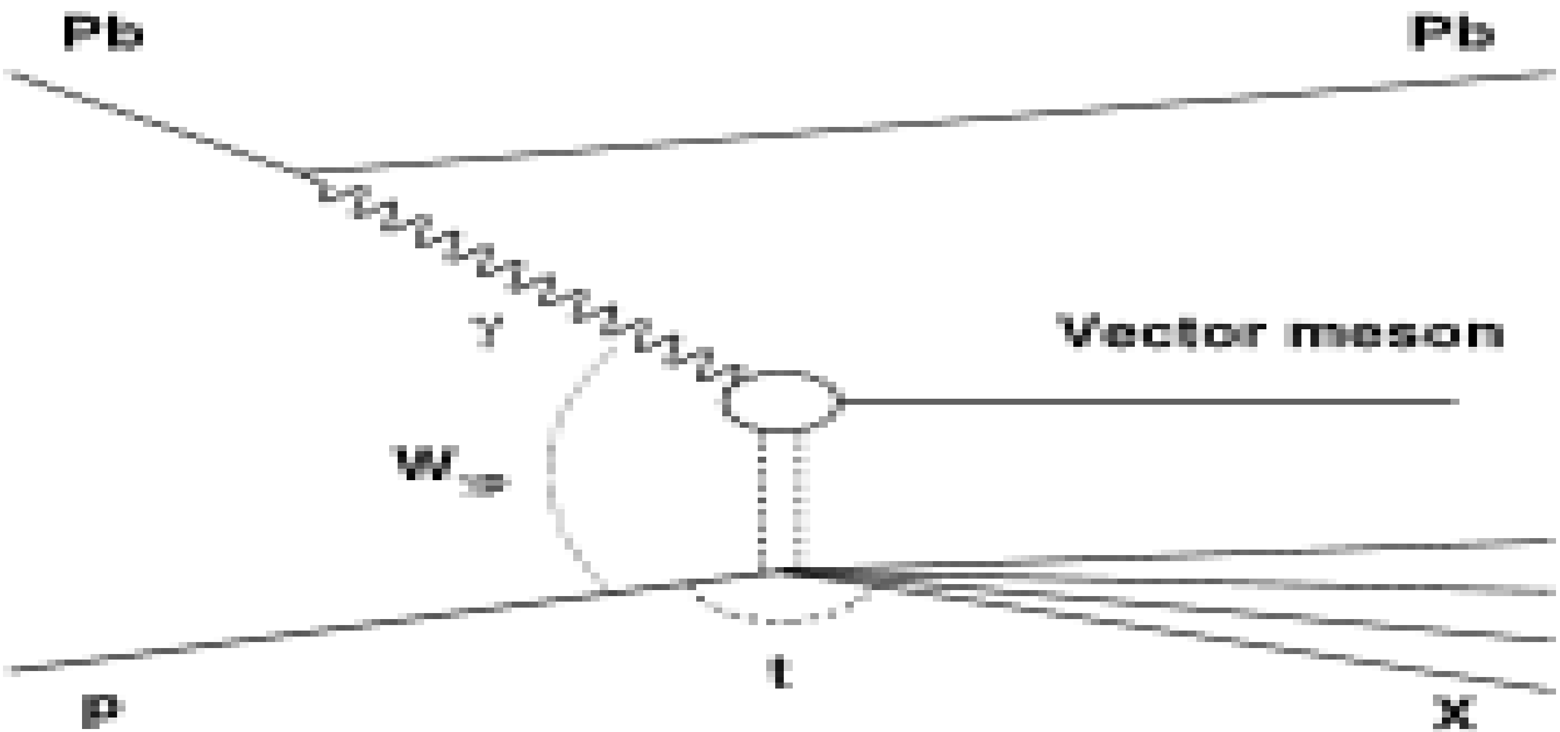


0
2
4
6
8
10
0
1
2
3
4
5
6
$(dN_{J/\psi}/dy)/\langle(dN_{J/\psi}/dy)\rangle$
$(dN_{ch}/d\eta)/\langle(dN_{ch}/d\eta)\rangle$


ALICE Preliminary
pp, √s = 13 TeV
Inclusive J/ψ → e⁺e⁻ (|y| < 0.9)
10% normalization uncertainty
Data
dN_J/ψ/dy / ⟨dN_J/ψ/dy⟩
dN_ch/dη / ⟨dN_ch/dη⟩


$dN_{J/\psi}/dy/<dN_{J/\psi}/dy>/dN_h/d\eta/<dN_h/d\eta>$
1.2
1
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
14
$dN_{ch}/d\eta/<dN_{ch}/d\eta>$

Incoherent diffractive disociation J/psi production



$$\left.\frac{d\sigma(\gamma p \to \mathrm{J}/\psi Y)}{dt}\right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})_{T,L}\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2\right)$$

$$A(x,Q^2,\vec{\Delta})_{T,L} = iA_b(\vec{\Delta})A_r(x,Q^2,\vec{\Delta})_{T,L}$$

$$\begin{aligned} A_b &\equiv \int d\vec{b}e^{-i\vec{b}\cdot\vec{\Delta}}T(\vec{b}) \\ &= e^{-B_{hs}\Delta^2/2}\frac{1}{N_{hs}}\sum_{i=1}^{N_{hs}} e^{-i\vec{b}_i\cdot\vec{\Delta}}. \end{aligned}$$

$$T(\vec{b}) = \frac{1}{N_{hs}} \sum_{i=1}^{N_{hs}} T_{hs}(\vec{b} - \vec{b_i}),$$

$$T_{hs}(\vec{b} - \vec{b_i}) = \frac{1}{2\pi B_{hs}} e^{-\frac{(\vec{b}-\vec{b_i})^2}{2B_{hs}}}, \qquad B_{hs} = 0.8\ \mathrm{GeV}^{-2}$$

$$N_{hs}(x) = p_0 x^{p_1}(1 + p_2\sqrt{x}),$$

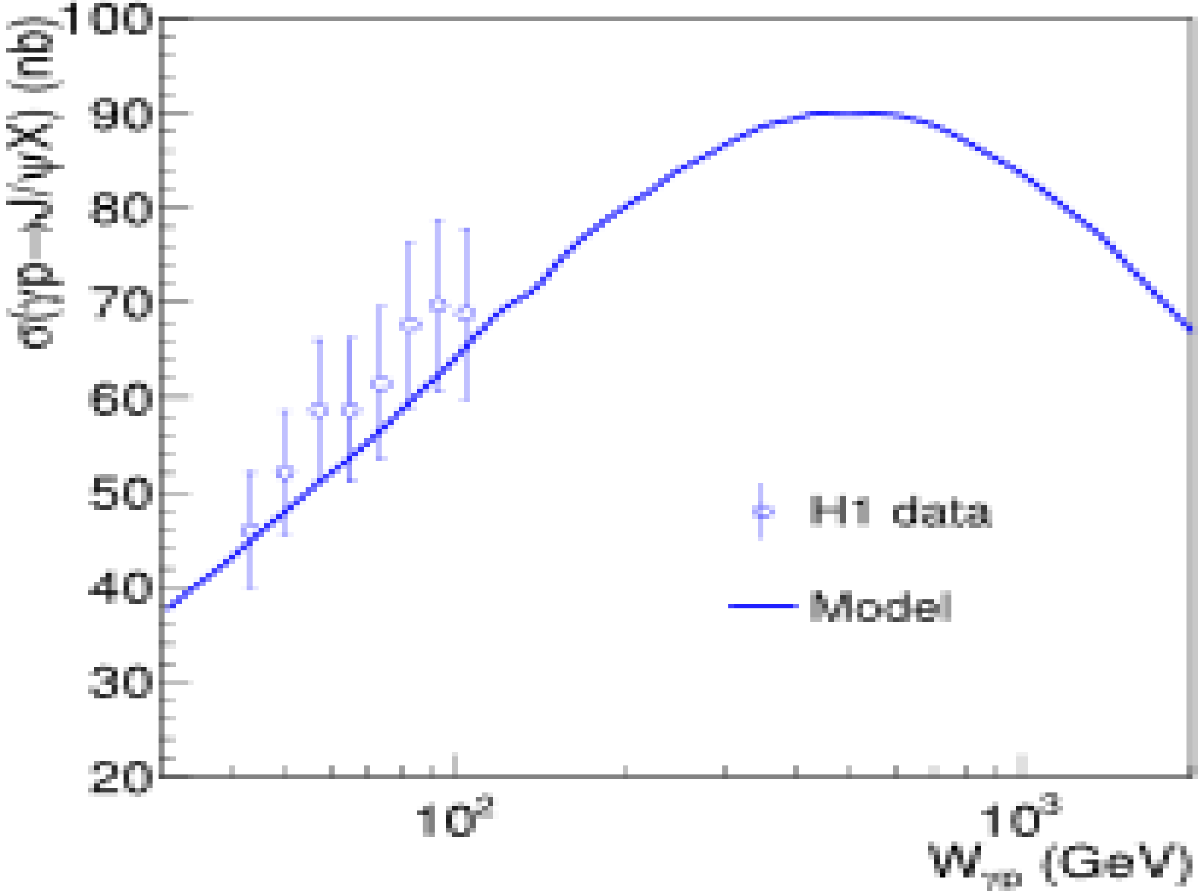
where we set $p_0 = 0.011$, $p_1 = -0.58$ and $p_2 = 250$

$$A_r(x, Q^2, \Delta)_{T,L} \equiv \int dr r N(x, r) A_z(r, \Delta)_{T,L},$$

$$N(x, r) = \left(1 - e^{-r^2 Q_s^2(x)/4}\right)$$

with the saturation scale given by

$$Q_s^2(x) = Q_0^2 (x_0/x)^\lambda$$



σ(γp→J/ψX) (nb)
100
90
80
70
60
50
40
30
20
10^2
10^3
W_γp (GeV)
H1 data
Model

Conclusions

--- The clustering of color sources(percolation) describes the azymuthal correlations

--- The rise of the dependence of J/psi production on the multiplicity marks the differences on the dependence on the multiplicity of a hard process and the total multiplicities

--- A possible supression of the J/psi free of nuclear effects, could be seen looking at the dependence on the multiplicity of the ratio of J/psi production and hard process

----The energy dependence of the incoherent J/psi production cross section should turn off above a critical energy corresponding to the percolation of the hot spots

L.Cunqueiro,J.Dias de Deus,C.Pajares Eur Phys JC 65 423 (2010)

I.Bautista,J.Dias de Deus,C.Pajares Eur Phys JC 72 2038 (2012)

E.G.Ferreiro,C.Pajares Phys Rev C 86 034903 (2012)

C.Andres,A.Moscoso,C.Pajares Phys Rev C 90 054902 (2014)

M.A.Braun,C.PajaresV.V.Vechernin Eur Phys J A 51 44 (2015)

C.Andres;M.A.Braun,C.Pajares Eur Phys J A 53 41 (2017)

J.Cepila,J.Contreras,J.D.Tapia Phys Lett 766 186 (2017)

M.A.Braun,J.Dias de Deus,A.Hirsch,C.Pajares,R.Sharenberg,B.K.Srivastava Physics Reports 599 1-50(2015)

String percolation and CGC

- Transverse size

Percolation: $r_0 F(\rho)^{1/2}$.

CGC: $1/Q_s$

- Effective number of clusters $\longrightarrow$ flux tubes

$$\langle N\rangle = \frac{(1-e^{-\rho})R^2}{r_0^2 F(\rho)} = \sqrt{1-e^{-\rho}}\sqrt{\rho}\left(\frac{R}{r_0}\right)^2.$$

$$\langle N\rangle = \frac{1}{\alpha_s} Q_s^2 R_A^2$$

- **Normalized 2-particle correlation function**

$$\mathfrak{R} \equiv \frac{\langle n^2\rangle - \langle n\rangle^2 - \langle n\rangle}{\langle n\rangle^2} = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle^2} = \frac{1}{k}$$

Low density limit: **n is basically Poisson-like** $\Longrightarrow k \to \infty$

High density limit: $\langle N^2\rangle - \langle N\rangle^2 \approx \langle N\rangle \Longrightarrow k \to \langle N\rangle \to \infty$

$$k = \frac{\sqrt{\rho}\,(R/r_0)^2}{1 - e^{-\rho}} = \frac{\langle N \rangle}{(1 - e^{-\rho})^{3/2}}.$$

The two particle correlations can be written in a factorized form,

$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \mathcal{R}\frac{dn}{dy}G(\phi), \qquad \mathcal{R}\frac{dn}{dy} = \frac{\langle N \rangle}{k} = \left(1 - e^{-\rho}\right)^{3/2}$$

$$A_1 = cA(\rho)^{3/2} \qquad A(\rho) = \frac{1}{1 + ae^{-(\rho-\rho_c)/b}}$$

$$\rho_c = 1.5 \qquad a = 1.5 \qquad \begin{array}{ll} b = 0.75 & \text{for Au-Au} \\ b = 0.35 & \text{pPb and pp.} \end{array}$$

$$P(p,\phi) = Ce^{-\frac{p_0}{\sqrt{T/2}}}. \tag{2}$$

To describe the energy loss of the parton due to gluon emission one may use the corresponding QED picture for a charged particle moving in the external electromagnetic field [31]. This leads to the the quenching formula [22]

$$p_0(p,l) = p\Big(1 + \kappa p^{-1/3} T^{2/3} l\Big)^3, \tag{3}$$

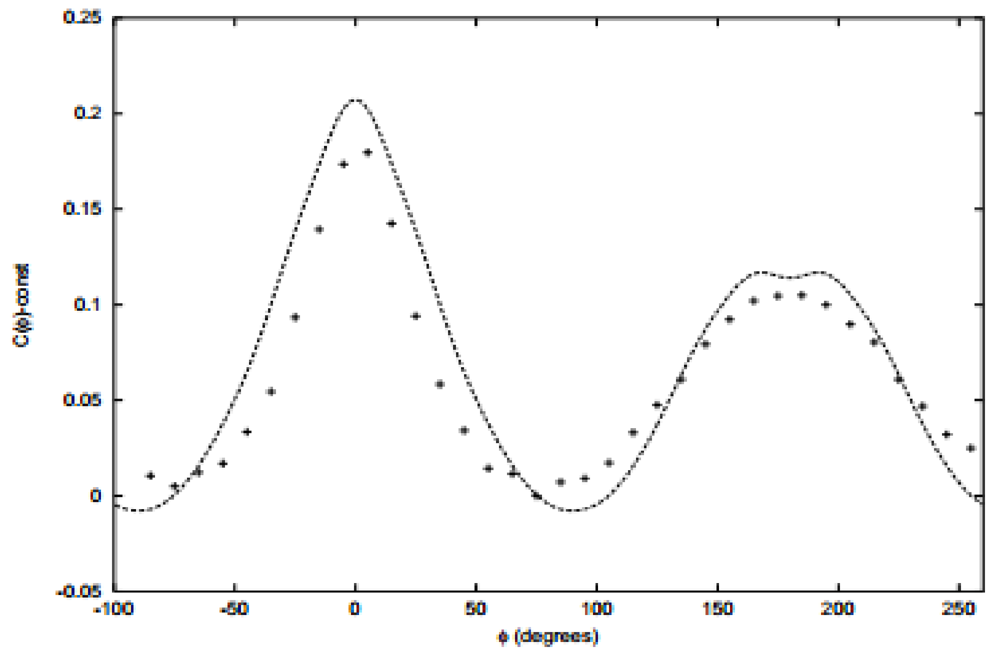


Figure 10: Correlation coeficient $C(\phi)$ for p-Pb collisions at 5.02 TeV for central collisions compared to the data in [3] (with the ZYAM procedure).

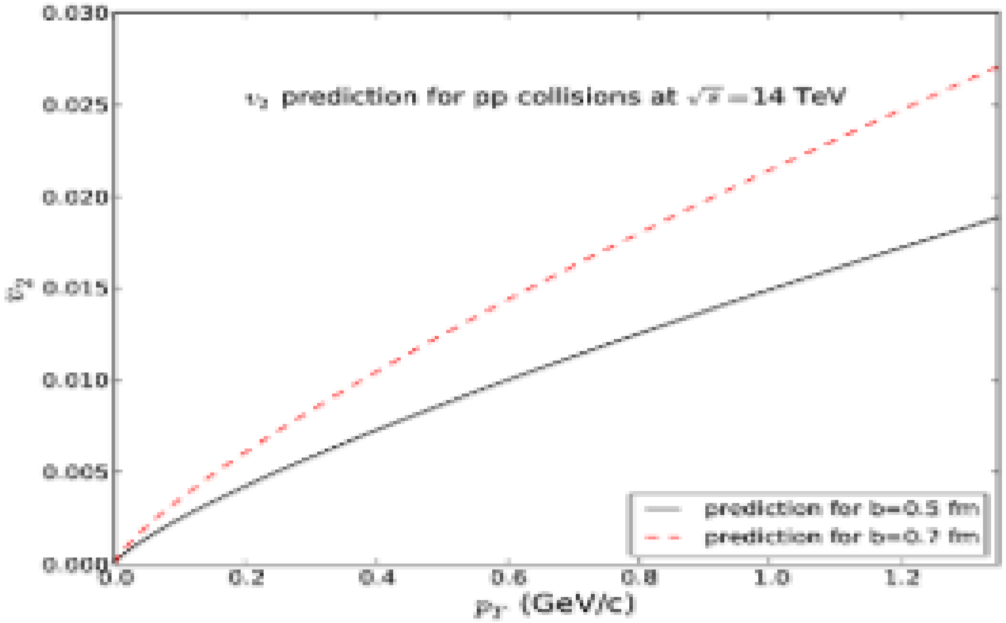


Figure 5. (Color online.) v_2 prediction for pp collisions at $\sqrt{s}$ = 14 TeV for impact parameters values of b = 0.5 fm (solid black curve) and b = 0.7 fm (dashed red curve) as a function of p_T.

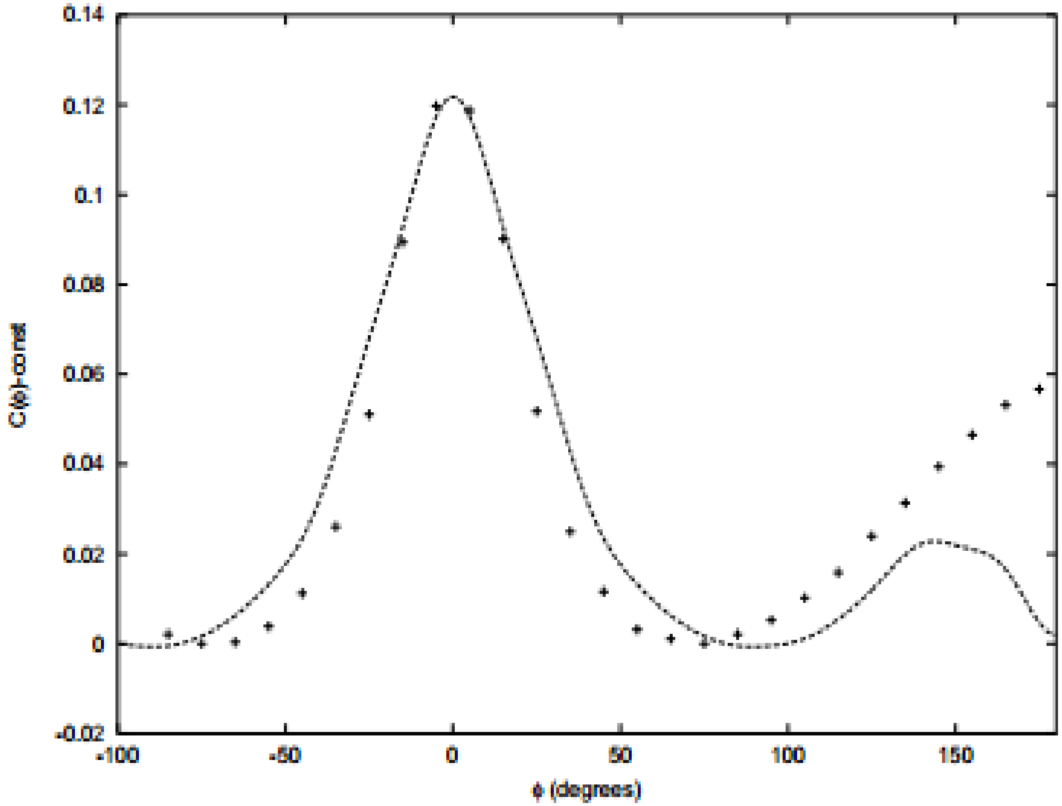
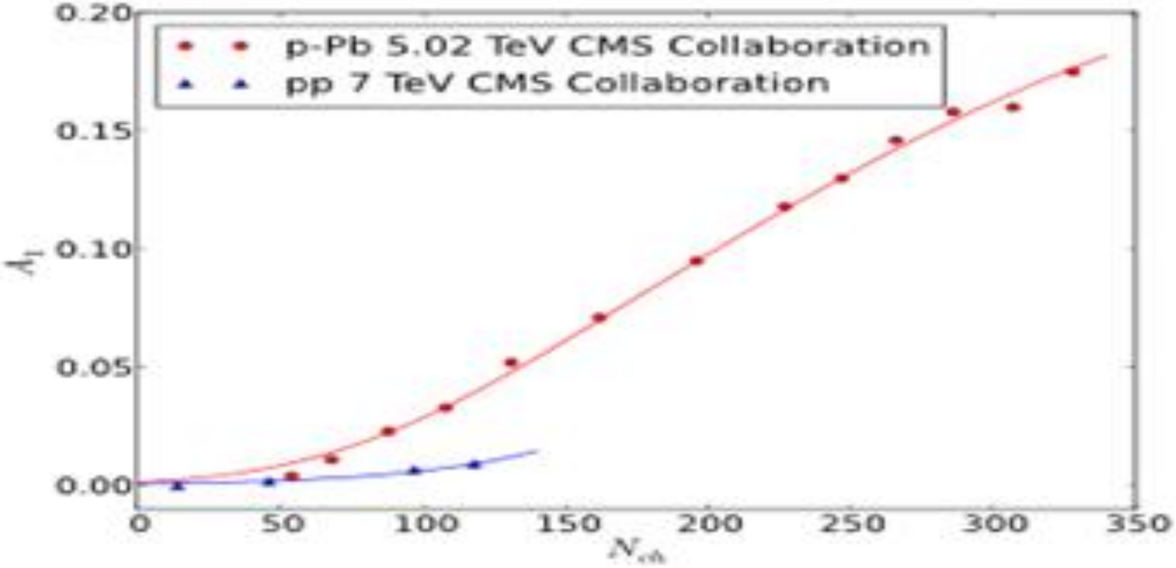
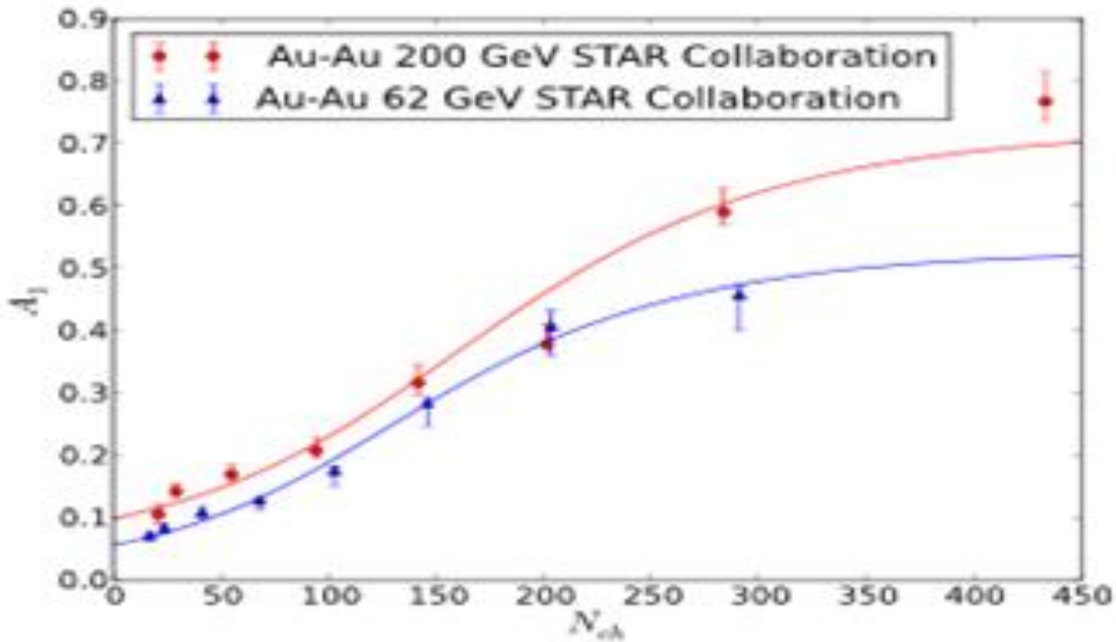


Figure 15: Correlation coeficient $C(\phi)$ for pp collisions at 7 TeV with triple multiplicity compared to the the experimental data from [1]
(with the ZYAM procedure at positive ϕ)


p-Pb 5.02 TeV CMS Collaboration
pp 7 TeV CMS Collaboration
0.20
0.15
0.10
0.05
0.00
Λ_1
0
50
100
150
200
250
300
350
N_{ch}


Au-Au 200 GeV STAR Collaboration
Au-Au 62 GeV STAR Collaboration
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Λ_1
0
50
100
150
200
250
300
350
400
450
N_{ch}