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Considerations on the suppression of charged particles in high energy heavy ion collisions

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HADRON PHYSICS DEPARTMENT

Outline

- **Introduction**

- **R_{AA}, $\langle dN/dy\rangle/S_{\perp}$ - $\langle N_{part}\rangle$, $\langle dN_{ch}/d\eta\rangle$ dependence**
  - **Cu-Cu, Au-Au - $\sqrt{s_{NN}}$ = 200 GeV;**
  - **Pb-Pb - $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV;**
  - **Xe-Xe - $\sqrt{s_{NN}}$ = 5.44 TeV**
  - **Core-Corona contribution**
  - **Suppression saturation at LHC energies**

- **R^{N}_{AA} ($\langle N_{bin}\rangle \rightarrow \langle dN_{ch}/d\eta\rangle^{A\text{-}A,\,cen}/\langle dN_{ch}/d\eta\rangle^{pp,\,MB}$) - $\langle N_{part}\rangle$, $\langle dN_{ch}/d\eta\rangle$ dependence**
  - **Considerations on the missing suppression in high charged particle multiplicity events for pp collisions at $\sqrt{s}$ = 7 TeV**

- **R_{CP}, R^{N}_{CP} - N_{part} dependence**

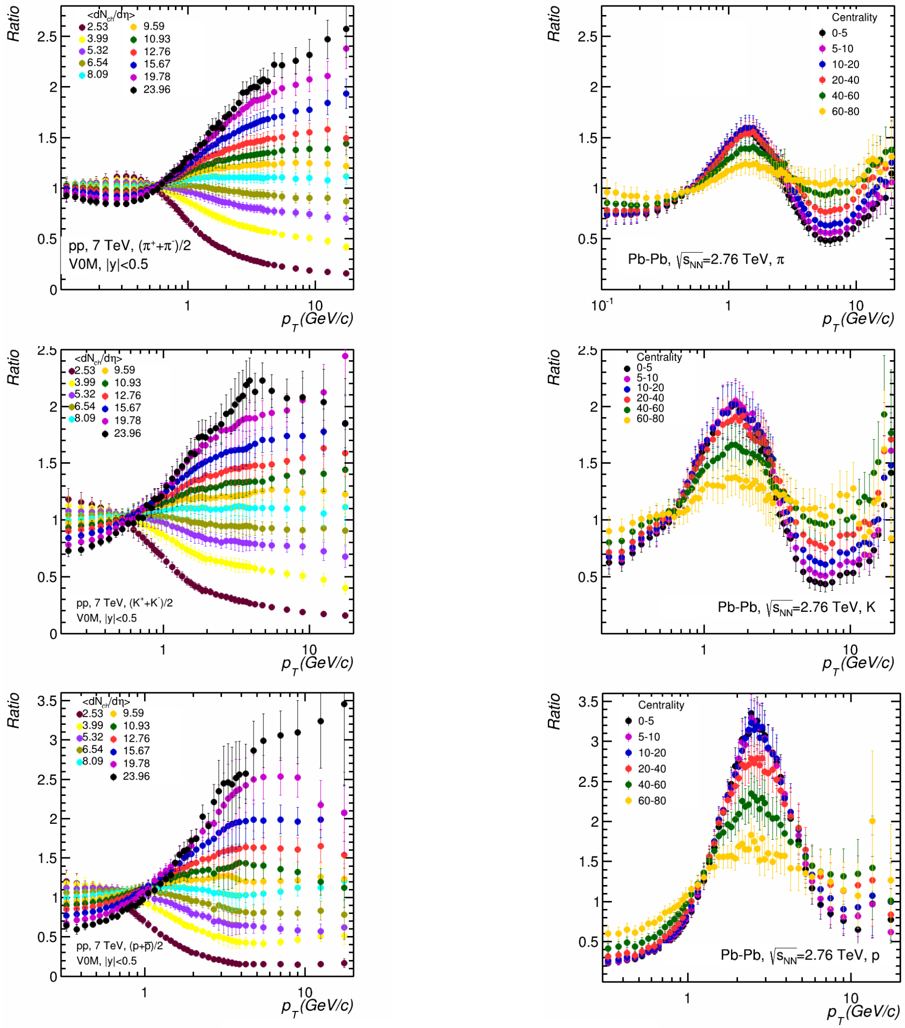
- **charged particles - R_{CP}, R^{N}_{CP} and π^0 - R_{AA}, R^{N}_{AA} as a function of $\sqrt{s_{NN}}$**

- **Outlook**

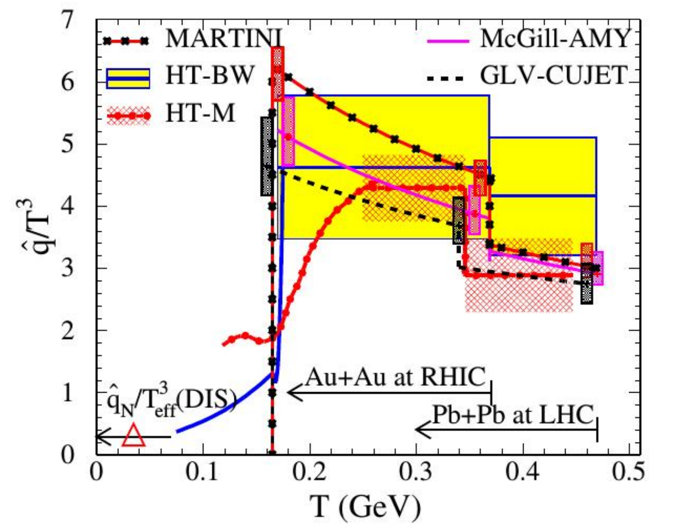
Suppression as a tomographic probe for deconfined matter studies

- **Proposed by Bjorken ~ 40 years ago for hadron-hadron collisions** ***FERMILAB-PUB-82-059-THY, 1982*** **(not yet confirmed)**
- **confirmed in heavy ion collisions by many experiments, for different energies and system size**
- **interpreted and estimated by many theoretical models**

J. Liao and E. Shuryak, PRL 102(2009)202302



$$Ratio = \frac{[\frac{d^2N}{dydp_T} / < \frac{dN_{ch}}{d\eta} >]^{cen,mult}}{[\frac{d^2N}{dydp_T} / < \frac{dN_{ch}}{d\eta} >]^{pp,MB}}$$



JET Collaboration, Phys. Rev. C90(2014)014909 and references therein

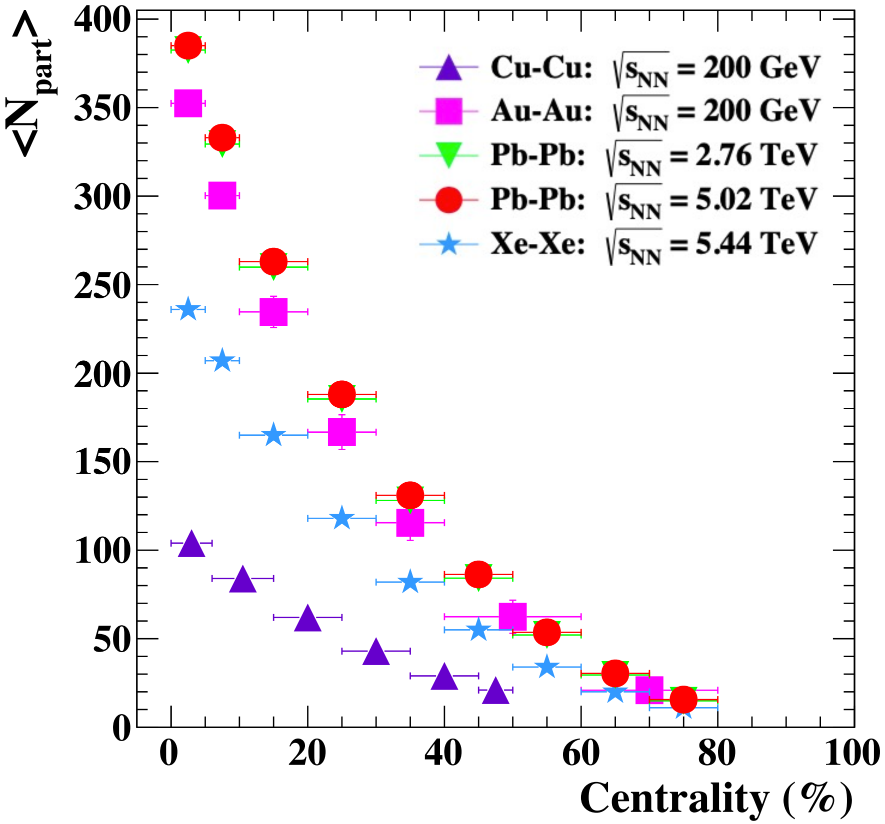
J.Liao, S.Shi and M.Gyulassy. Chin. Phys. C43(209)044101

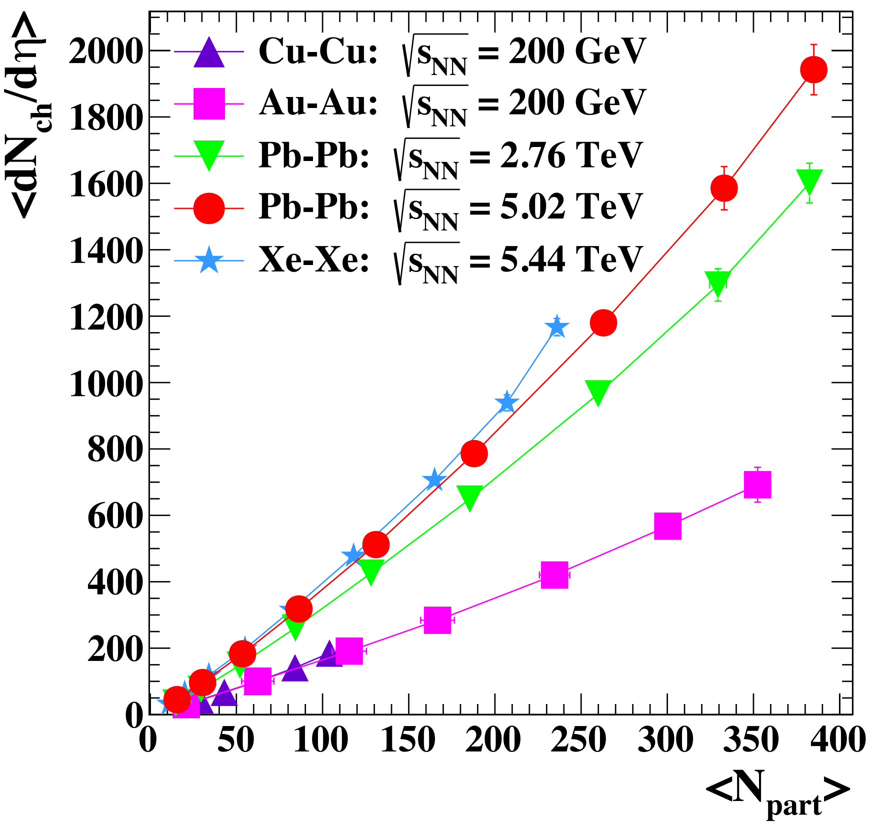
However, a proper description of the parton energy loss in the non-equilibrium expanding deconfined matter for the intermediate p_T range remains a challenging task

M.Petrovici et al. AIP Conf. Proceedings, 1852(2017)050003 and references therein

Centrality, <N_{part}>, <$dN_{ch}/d\eta$> correlations

(based on the Glauber MC approach)





- *PHOBOS Collaboration, PRL 96(2006)212301*
- *STAR Collaboration, PRL 91(2003)172302*
- *ALICE Collaboration, Phys.Lett. B788(2019)166*
- *ALICE Collaboration, PRL 116(2016)222302*
- *M.Petrovici et al. Phys. Rev. C98(2018)024904*

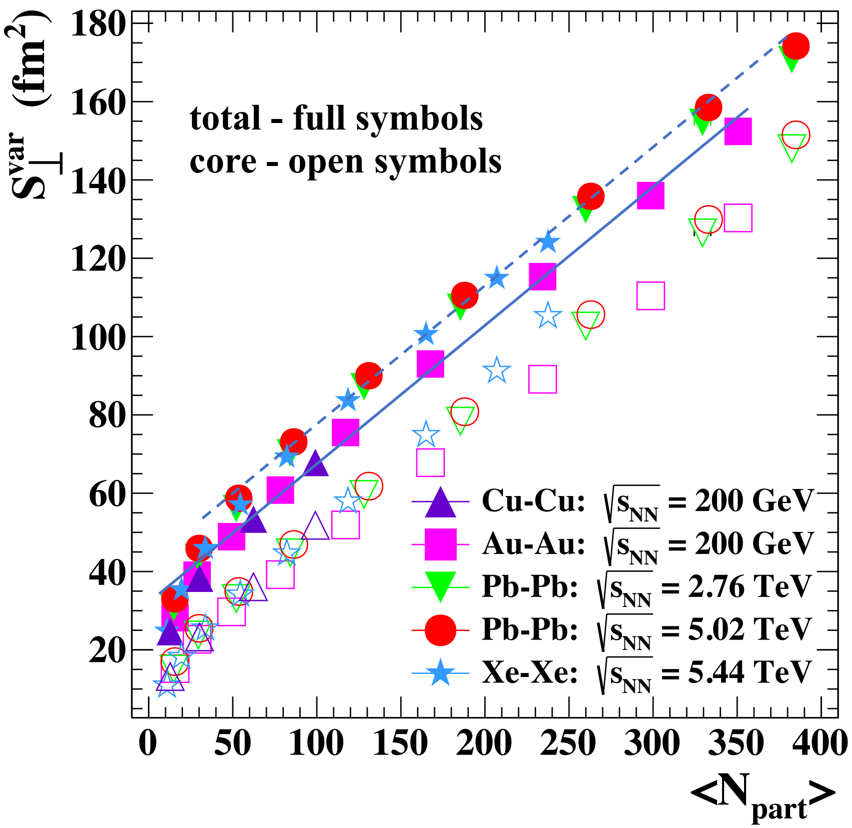
- *STAR Collaboration, Phys. Rev. C79(2009)034909*
- *PHENIX Collaboration, Phys. Rev. C93(2016)024901*
- *ALICE Collaboration, Phys. Rev. C88(2013)044910*

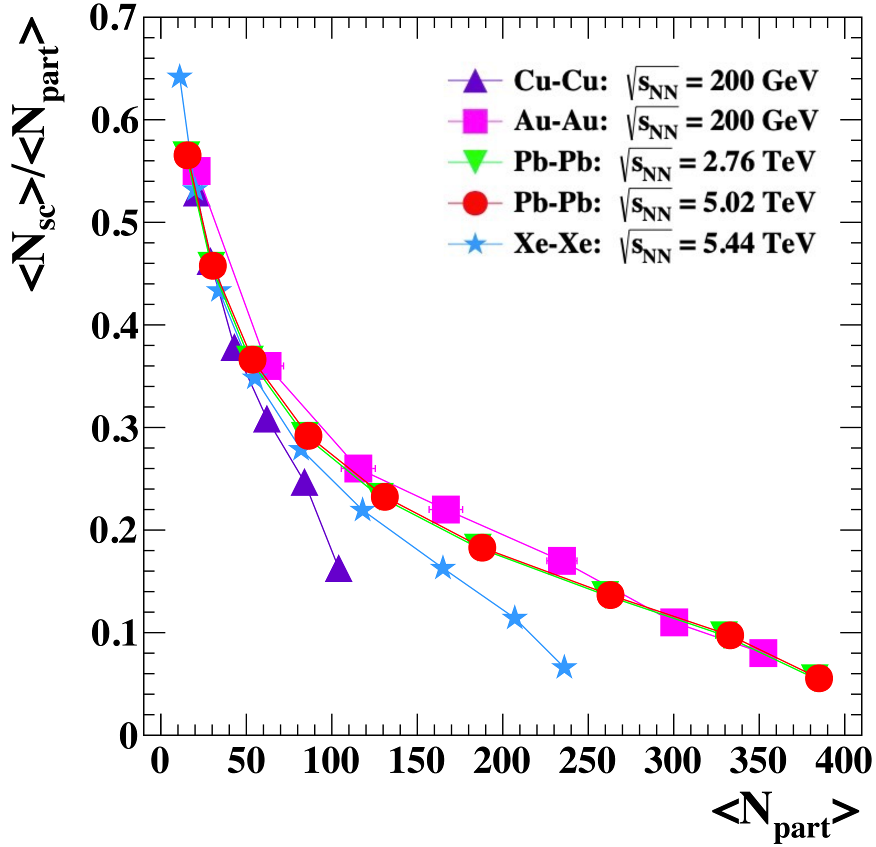
Transverse overlapping area

Percentage of nucleons undergoing a single collision (Corona)

(based on the Glauber MC approach)

$S_{\perp}^{var} \sim (\langle\sigma_x^2\rangle \langle\sigma_y^2\rangle - \langle\sigma_{xy}\rangle^2)^{1/2}$





$S_{\perp}^{var}$ - $\langle N_{part}\rangle$ linear dependence
- system size independent
- the slopes at RHIC and LHC the same
- a small difference in the offset of ~ 10 fm²

Peripheral collisions - large Corona percentage
- system size independent

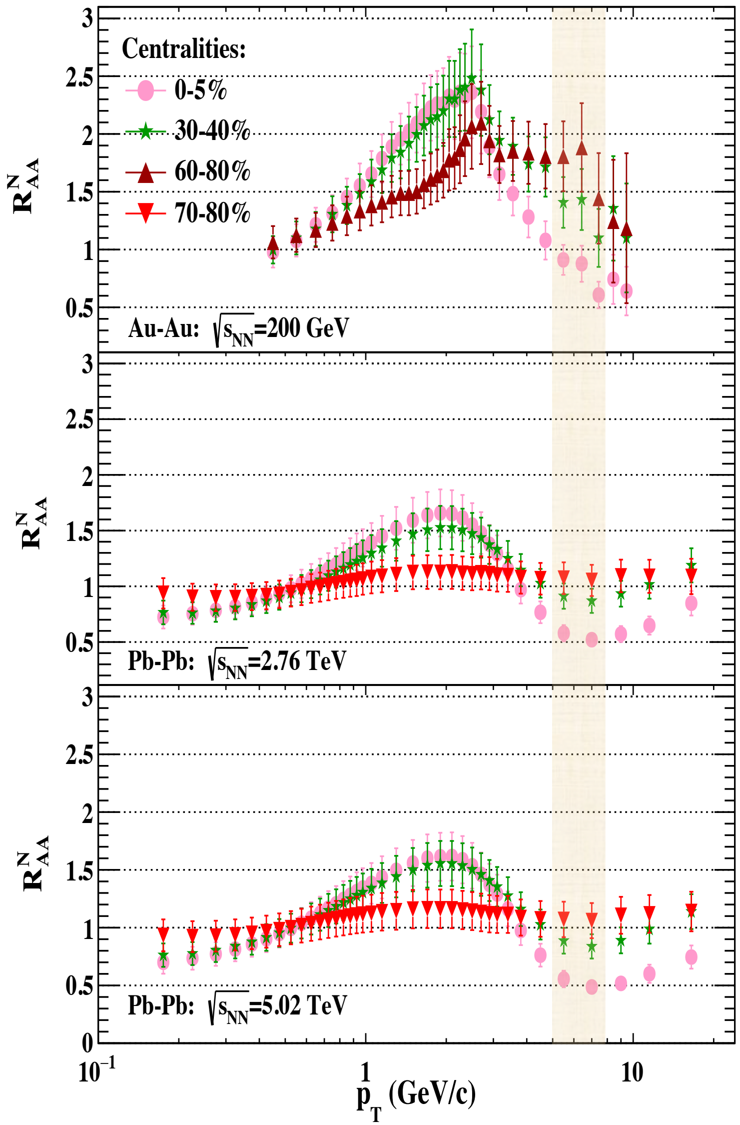
Central collisions - low Corona percentage
- large system size dependence

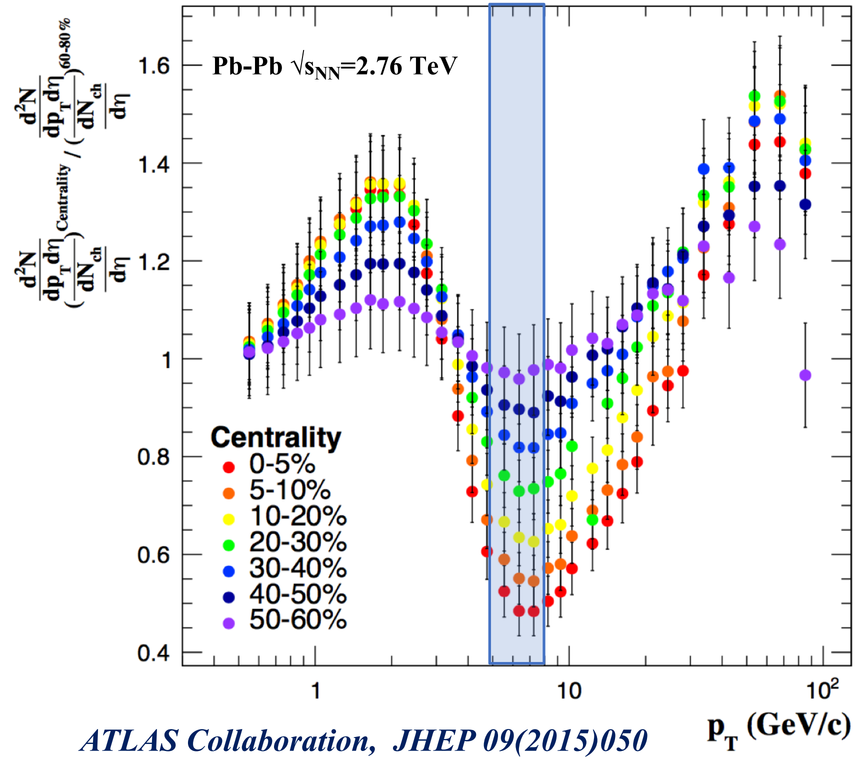
Why 5 GeV/c < p_T < 8 GeV/c range?

$$R^N_{AA} = \frac{\left[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >\right]^{cen}}{\left[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >\right]^{pp,MB}}$$

charged particles

$$R^N_{CP} = \frac{\left[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >\right]^{cen}}{\left[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >\right]^{peripheral}}$$





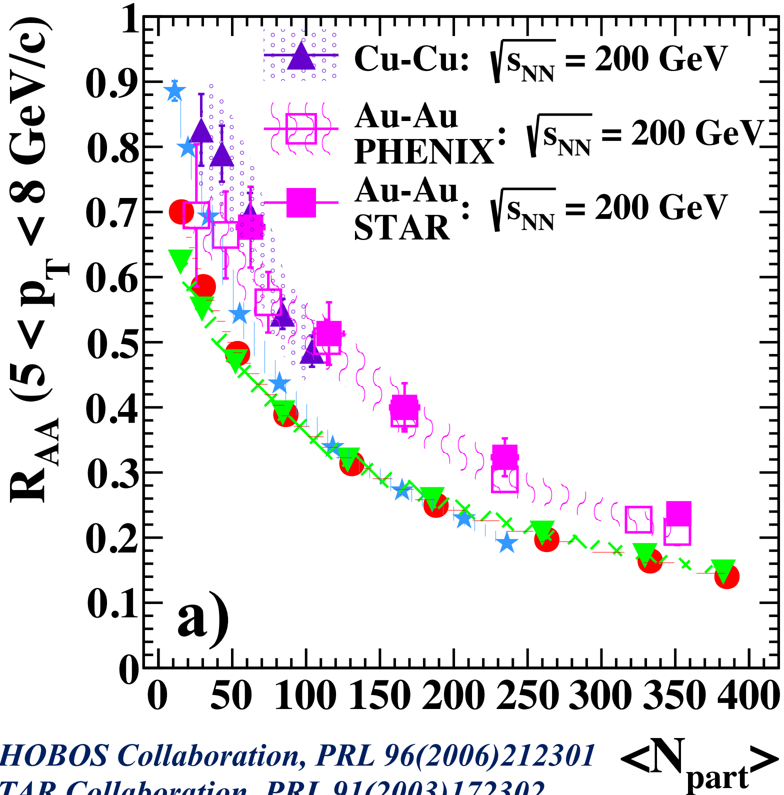
ATLAS Collaboration, JHEP 09(2015)050

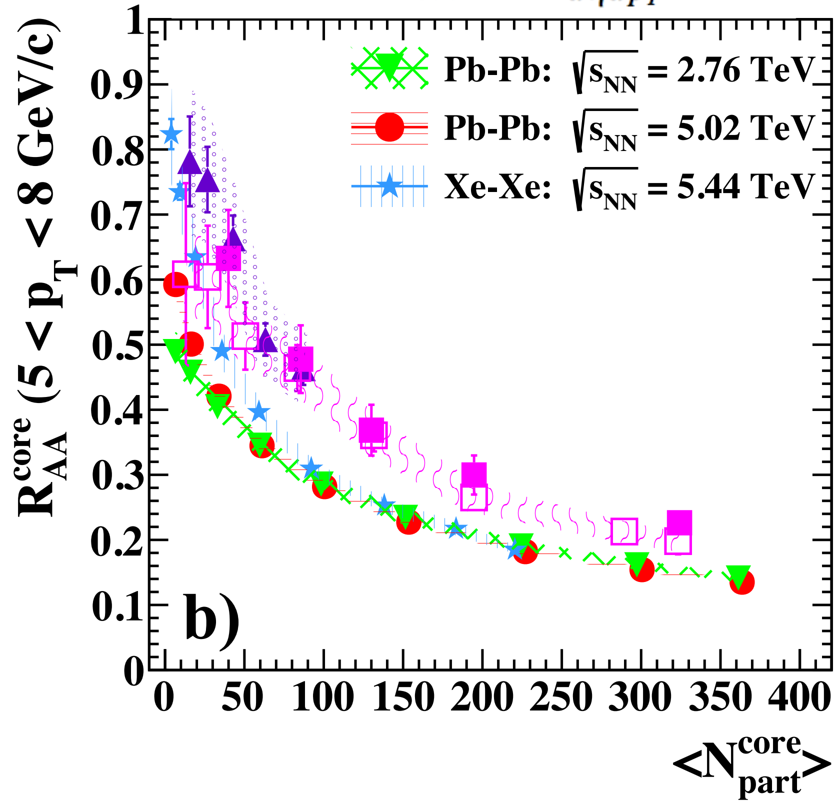
- maximum suppression for *5 GeV/c < p_T < 8 GeV/c*
- the region in p_T for maximum suppression remains the same at:
  - different collision energies
  - different centralities

R_{AA} and R_{AA}^{core} - $\langle N_{part} \rangle$ scaling

$$R_{AA} = \frac{\left(\frac{d^2N}{d\eta dp_T}\right)^{cen}}{< N_{bin} > \cdot \left(\frac{d^2N}{d\eta dp_T}\right)^{pp,MB}}$$

$$R_{AA}^{core} = \frac{\left(\frac{d^2N}{d\eta dp_T}\right)^{cen,core}}{< N_{bin}^{core} > \cdot \left(\frac{d^2N}{d\eta dp_T}\right)^{pp,MB}}$$



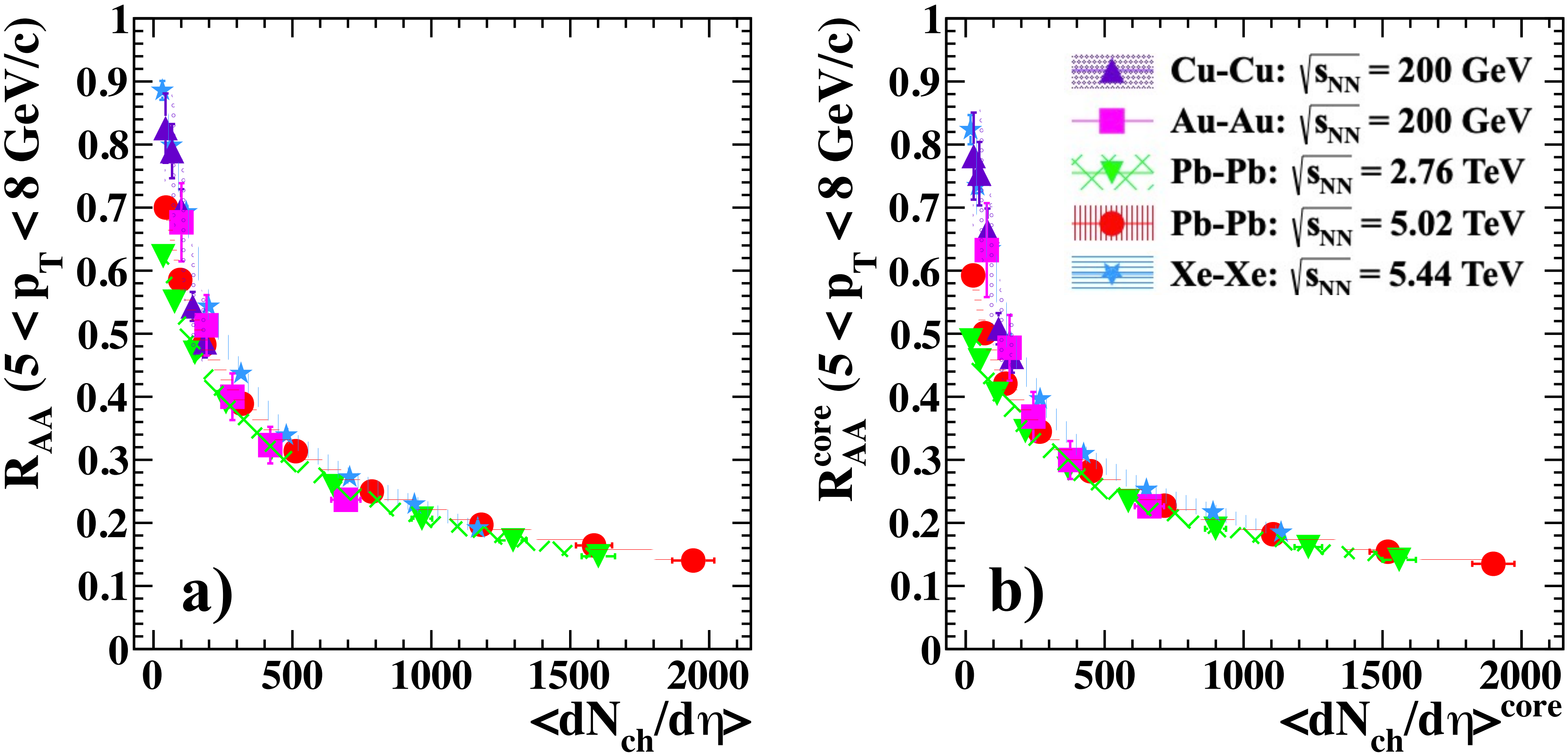


- *PHOBOS Collaboration, PRL 96(2006)212301*
- *STAR Collaboration, PRL 91(2003)172302*
- *ALICE Collaboration, Phys.Lett.B, 788(2019)166*
- *ALICE Collaboration, JHEP, 1811(2018)013*
- *PHENIX Collaboration, Phys. Rev. C69(2004)034910*

- R_{AA} scales with $\langle N_{part} \rangle$ for the top RHIC energy
- R_{AA} scales at LHC energies, although the difference in collision energies is up to a factor 2

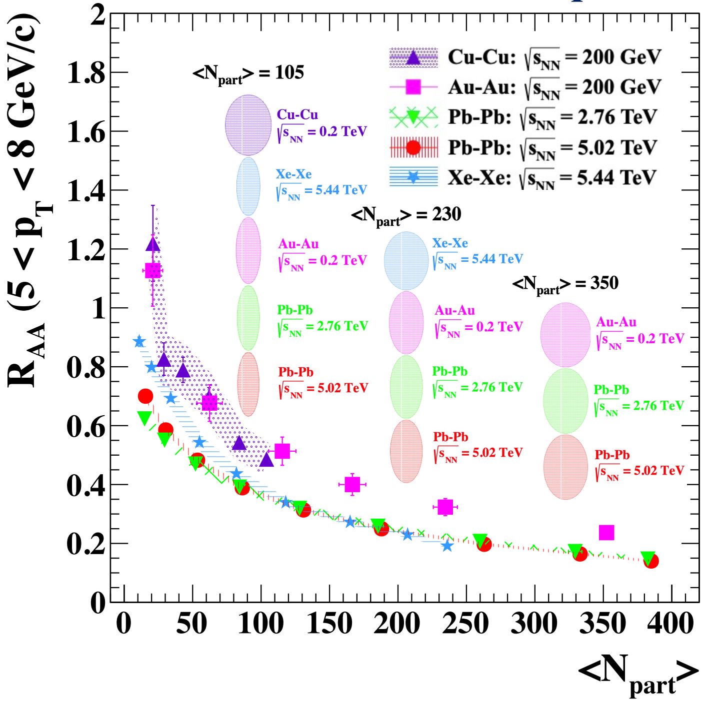
- suppression increases by ~ 20% at low values of $\langle N_{part} \rangle$
- the difference relative to R_{AA} is decreasing with $\langle N_{part} \rangle$
- R_{AA}^{core} for very central Cu-Cu and Xe-Xe has the same value as R_{AA}^{core} for Au-Au and Pb-Pb, respectively, at the same $\langle N_{part} \rangle$

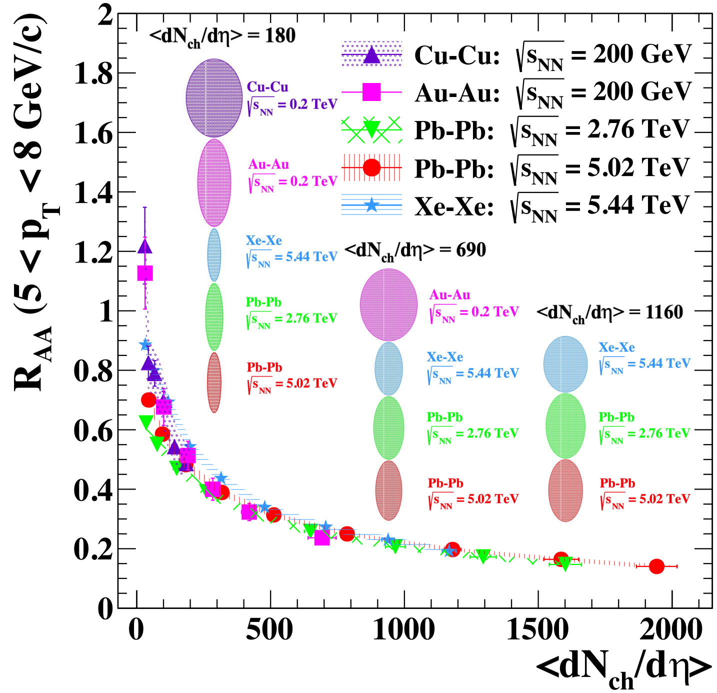
R_{AA} and R_{AA}^{core} - < $dN_{ch}/d\eta$ > scaling

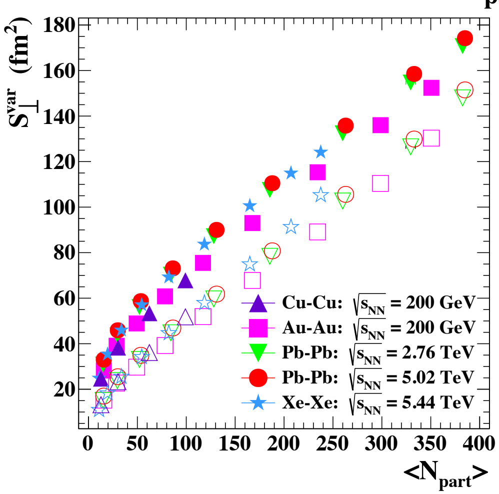


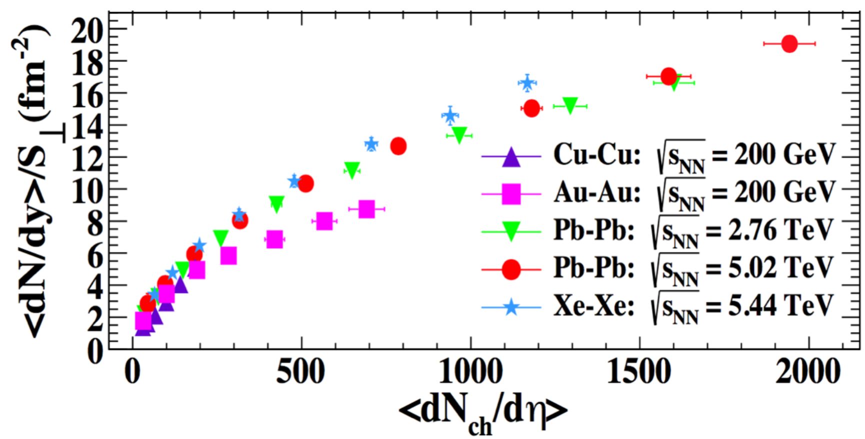
R_{AA} and R_{AA}^{core} scale with <$dN_{ch}/d\eta$> for all systems and collision energies

$<N_{part}>$ versus $<dN_{ch}/d\eta>$ scaling





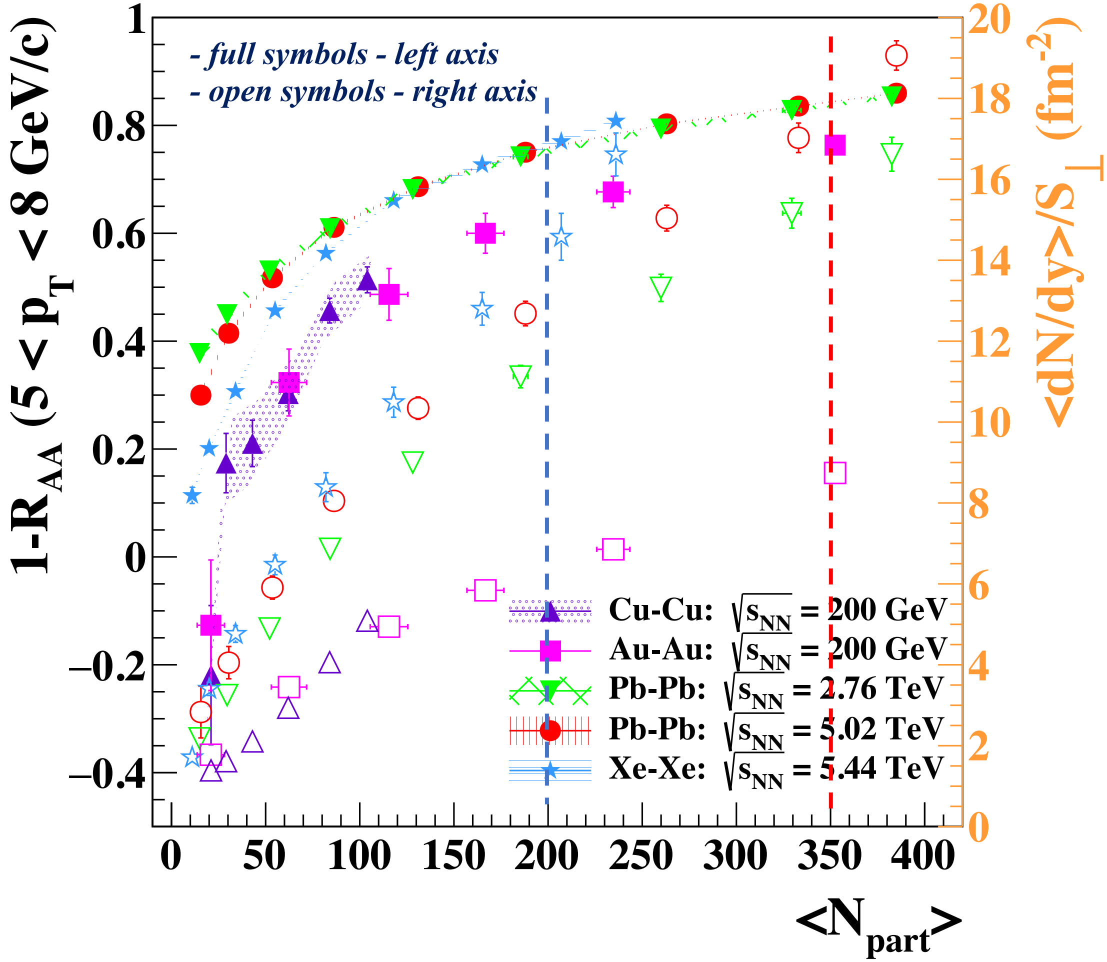




- Different shape, size and $\langle dN/dy \rangle / S_\perp$ for a given $< dN_{ch}/d\eta >$
=>their relative contribution to suppression is difficult to unravel

- $S_\perp^{var}$ - the same for different systems
- the transverse shapes are similar
- the main difference is in $\langle dN/dy \rangle / S_\perp$

$(1-R_{AA})$ and $< dN/dy >/S_\perp$ as a function of $<N_{part}>$



- For $\langle N_{part}\rangle$=200, the differences in:
  - $\langle dN/dy\rangle/S_\perp$ for Pb-Pb at =2.76, 5.02 TeV and for Xe-Xe at 5.44 TeV relative to Au-Au at 200 GeV are:
    5.25±1; 6.77±1; 7.89±1 part/fm²
  - $(1-R_{AA})$ values are:
    0.10±0.03; 0.11±0.03; 0.11±0.03.

=> suppression saturation at LHC energies

- For central Au-Au collisions - $\langle N_{part}\rangle$=350, the difference in $\langle dN/dy\rangle/S_\perp$ between Pb-Pb at 2.76 TeV and Au-Au at 200 GeV is 7±1 part/fm² while the difference in $(1-R_{AA})$ is 0.08±0.03.

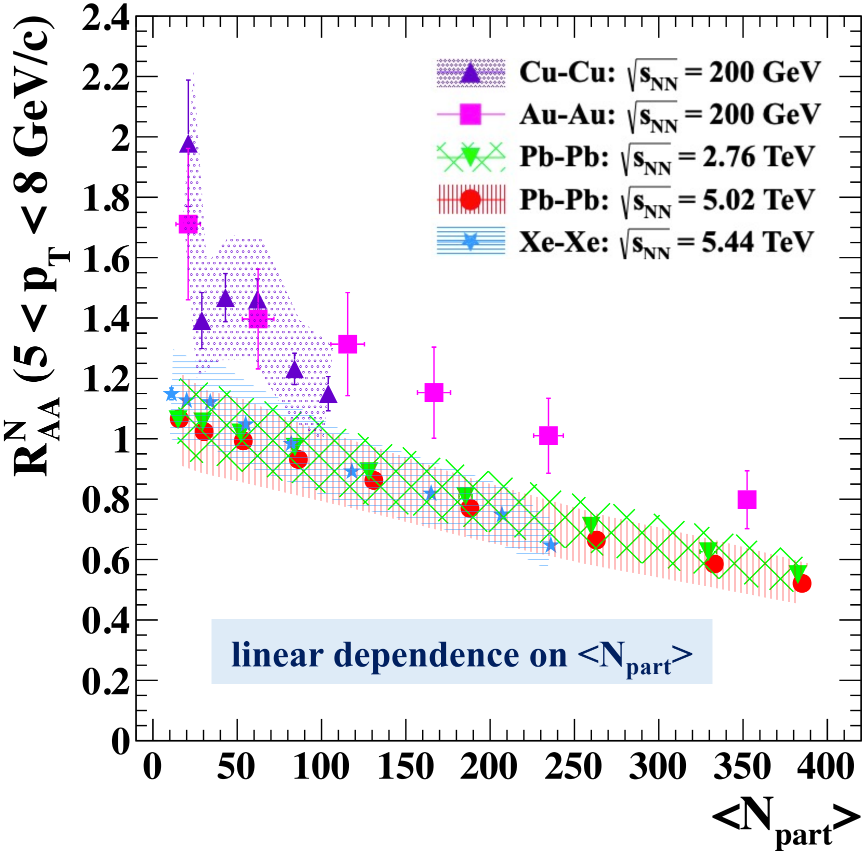
- If $R_{AA} \sim 1 - k\cdot x^2\cdot T^3$
  $x^2 \sim S_\perp$
  $T^3 \sim \langle dN/dy\rangle/S_\perp$

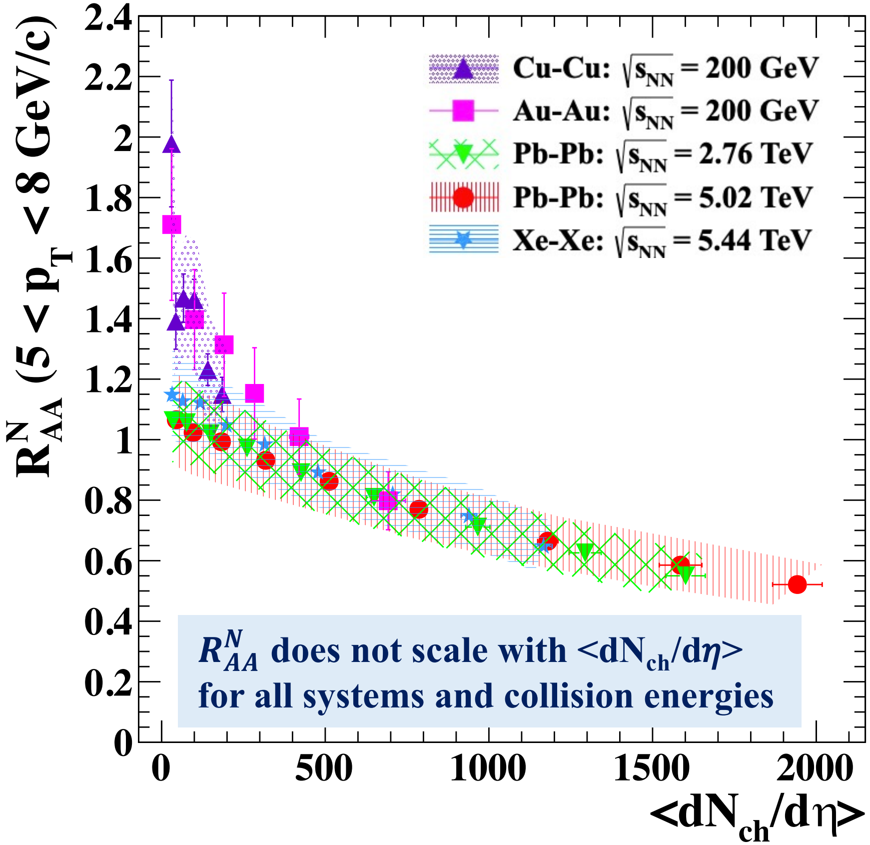
=> $k^{(2.76\ TeV)} \simeq (0.48 \pm 0.03) \cdot k^{(200\ GeV)}$

- M. Djordjevic et al., Phys. Rev. C99(2019)061902
- B. Betz and Miklos Gyulassy, JHEP 08(2014)090

R^N_{AA} - <N_{part}> and < $dN_{ch}/d\eta$ > scaling

$$R^N_{AA} = \frac{\left[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >\right]^{cen}}{\left[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >\right]^{pp,MB}}$$





Suppression in p-p collisions - high multiplicity (HM):

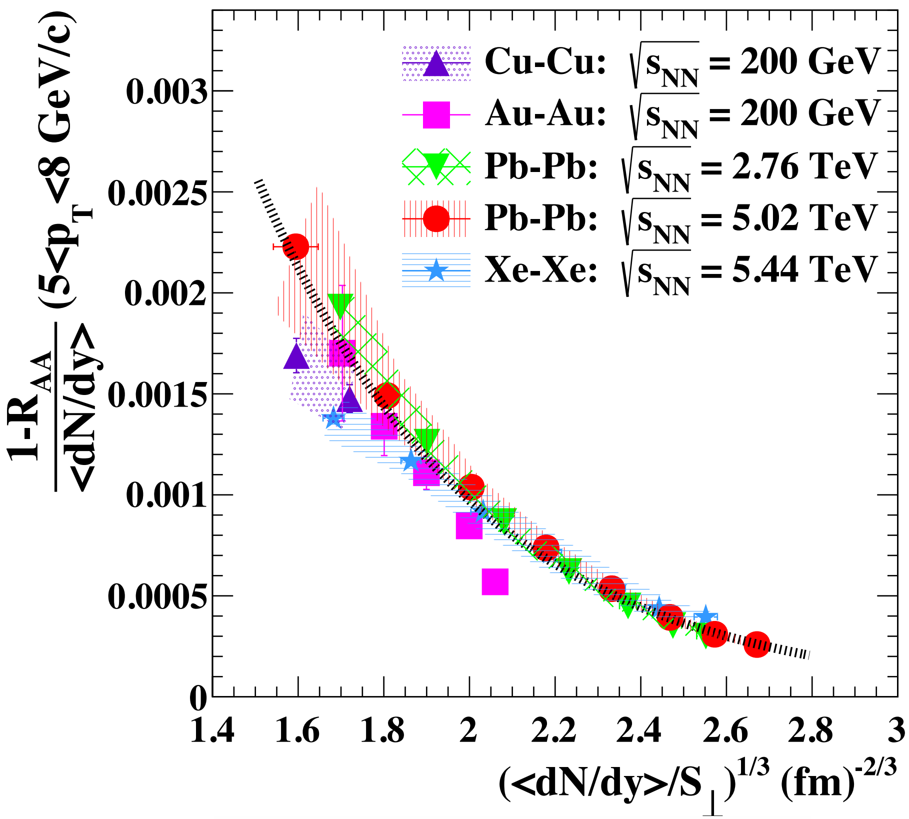
- <β_T> vs. $[\langle dN/dy\rangle/S_\perp]^{1/2}$ scaling for $[\langle dN/dy\rangle/S_\perp]^{1/2}$ = 3.3±0.1
- $S_\perp^{pp(HM)}$ =7.43±0.48 fm² and $S_\perp^{PbPb}$=70±0.4 fm²

- assuming the same jet-medium coupling

M.Petrovici et al. Phys.Rev.C, 98(2018)024904

=>$(1- R_{pp}^{N(HM)})/(1- R_{AA}^{N(<N_{part}>=125)}) \simeq 0.01\pm0.01$

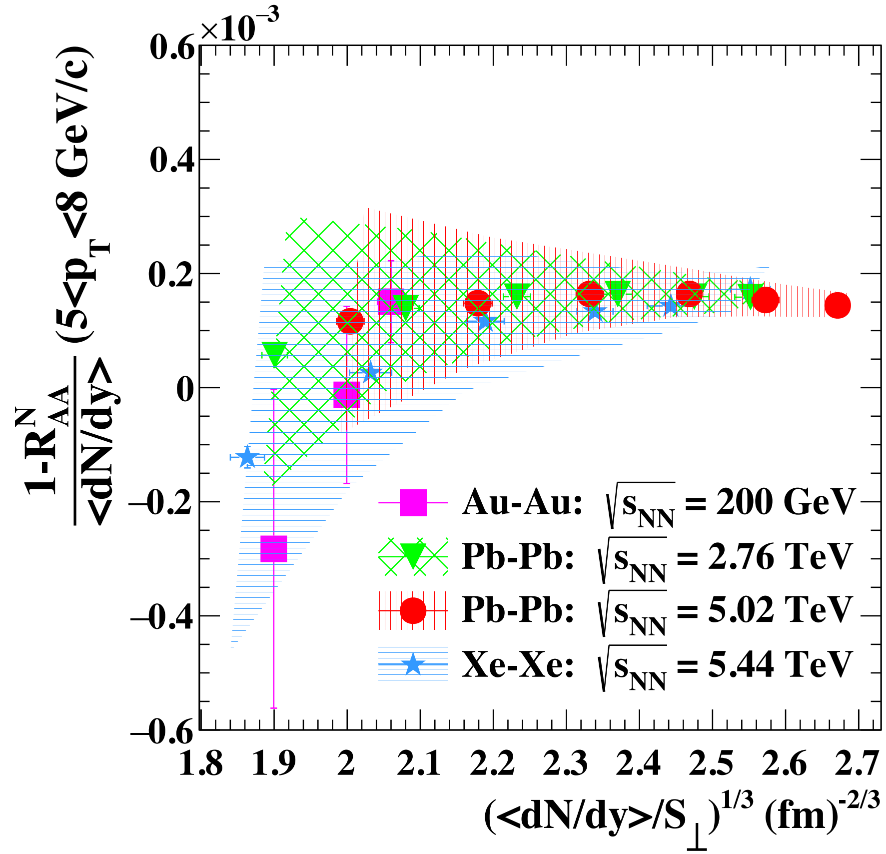
$(1-R_{AA})/\langle dN/dy\rangle$ and $(1-R^{N}_{AA})/\langle dN/dy\rangle$ - $(\langle dN/dy\rangle/S_{\perp})^{1/3}$ dependence



$$\frac{1-R_{AA}}{\langle dN/dy\rangle} = e^{\alpha-\beta\cdot(\langle dN/dy\rangle/S_{\perp})^{1/3}}$$

- The exponential decrease is similar with the k(T) dependence used in order to reproduce the nuclear modification factors at RHIC and LHC energies (see reference bellow)

B.Betz and M.Gyulassy. JHEP, 08(2014)090



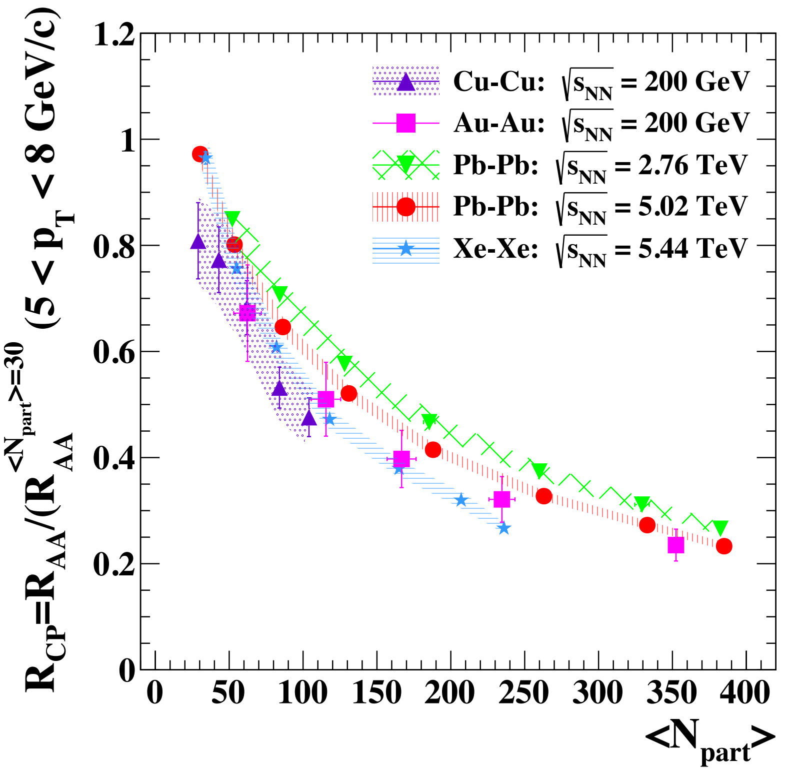
- For $(\langle dN/dy\rangle/S_{\perp})^{1/3} > 2.1$ - constant value, similar with the impact parameter idependence of the jet quenching parameter (see referenec bellow)

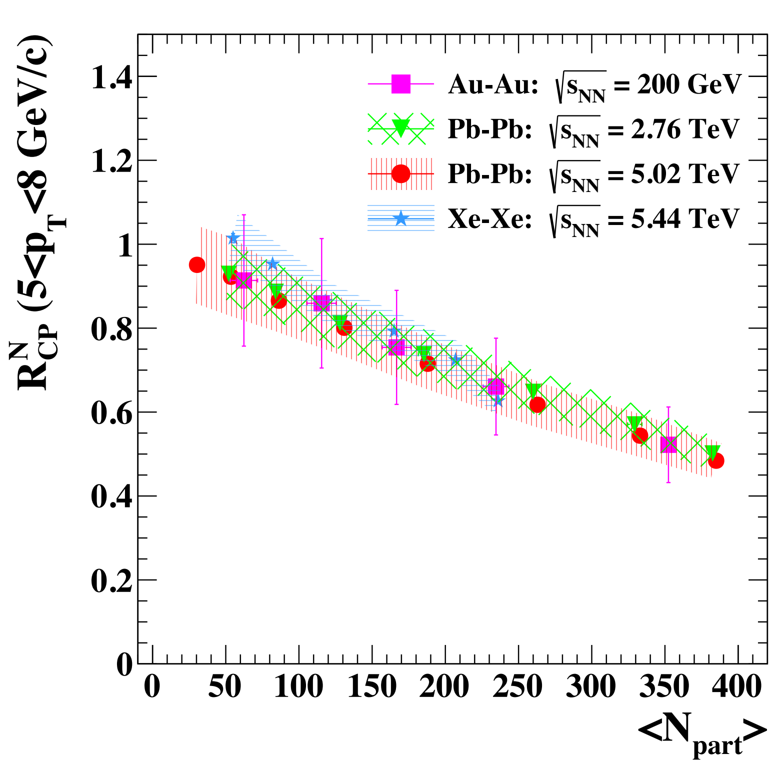
- C.Andres et al. Nucl. and Part. Phys. Proceedings, 00:1(2018)
- M.Xie et al. Eur.Phys.J., C79(2019)589

R_{CP}^{N} - $<N_{part}>$ dependence

$$R_{CP} = \frac{[\frac{d^2N}{d\eta dp_T} / < N_{bin} >]^{cen}}{[\frac{d^2N}{d\eta dp_T} / < N_{bin} >]^{peripheral}}$$

$$R_{CP}^{N} = \frac{[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >]^{cen}}{[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >]^{peripheral}}$$





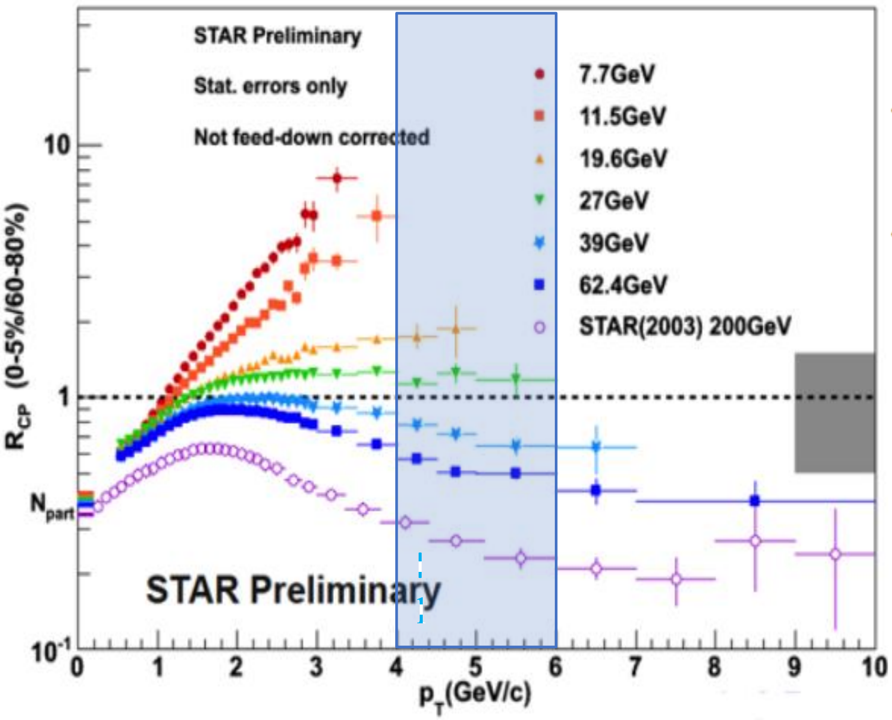
- R_{CP}^{N} scales with $<N_{part}>$ for all heavy systems and all collision energies
- the linear dependence as a function of $<N_{part}>$ follows from the linear dependence of R_{AA}^{N}

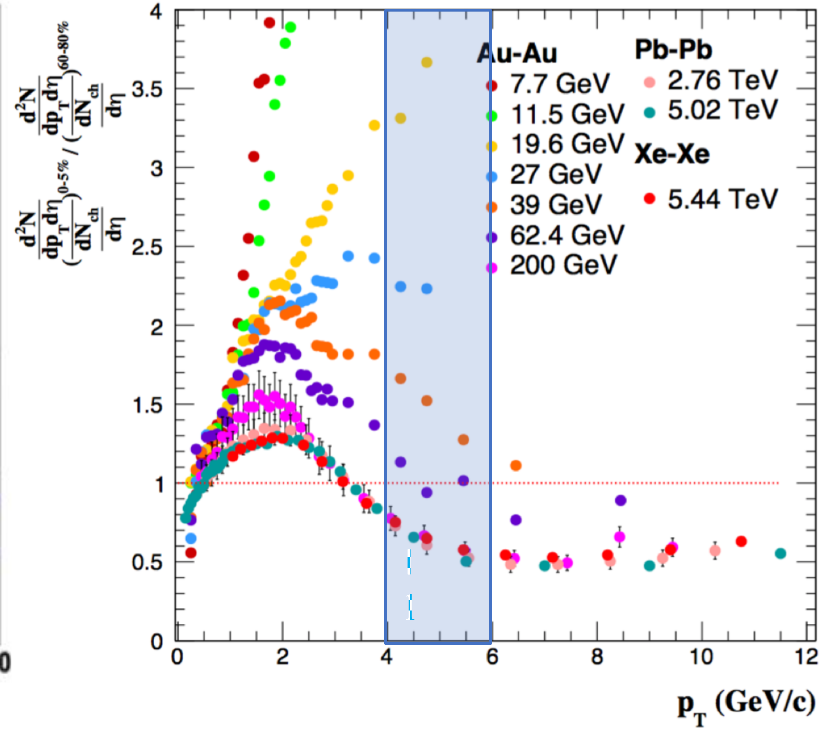
Collision energy dependence

charged particles

$$R_{CP} = \frac{[\frac{d^2N}{d\eta dp_T} / < N_{bin} >]^{cen}}{[\frac{d^2N}{d\eta dp_T} / < N_{bin} >]^{peripheral}}$$

$$R_{CP}^{N} = \frac{[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >]^{cen}}{[\frac{d^2N}{d\eta dp_T} / < \frac{dN_{ch}}{d\eta} >]^{peripheral}}$$



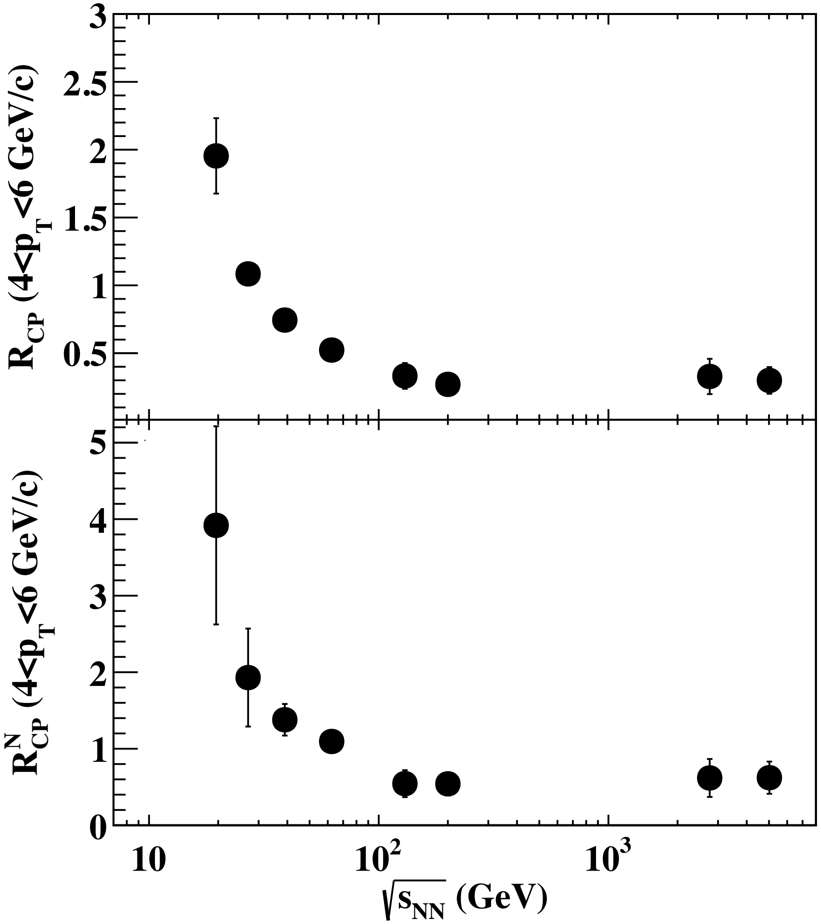


STAR Collaboration,
Quark Matter 2012 Conference Proceedings

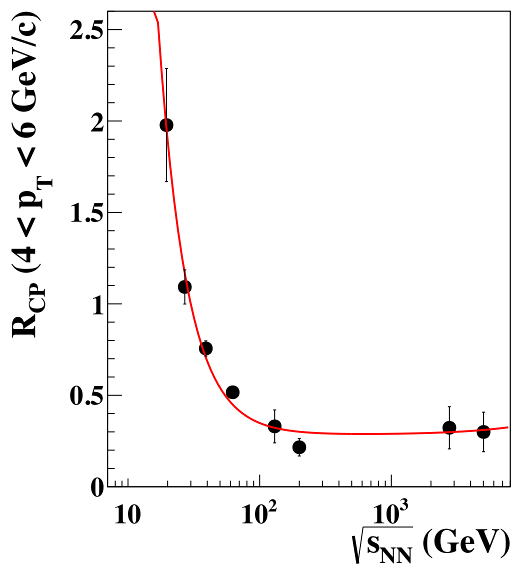
R_{CP} and R_{CP}^{N} (4GeV/c<p_T<6 GeV/c) - $\sqrt{s_{NN}}$ dependence

(0-5%)/(60-80%)

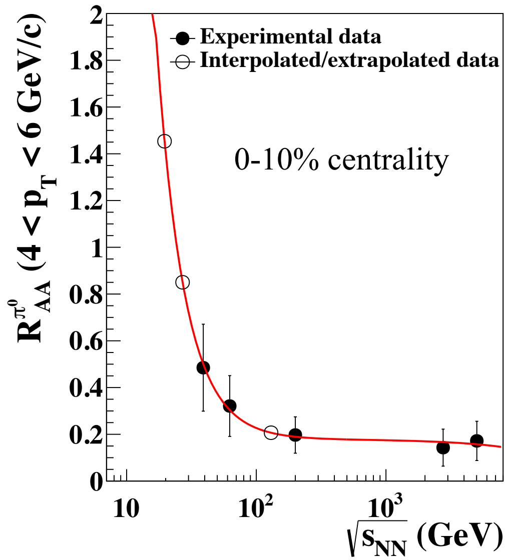
charged particles



charged particles



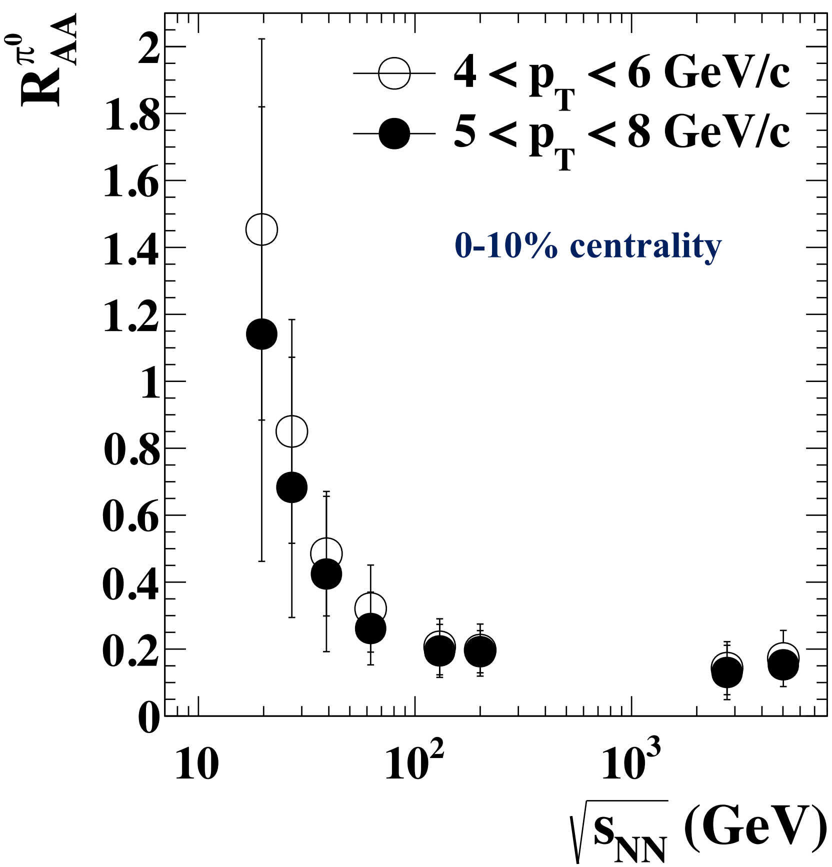
π^0

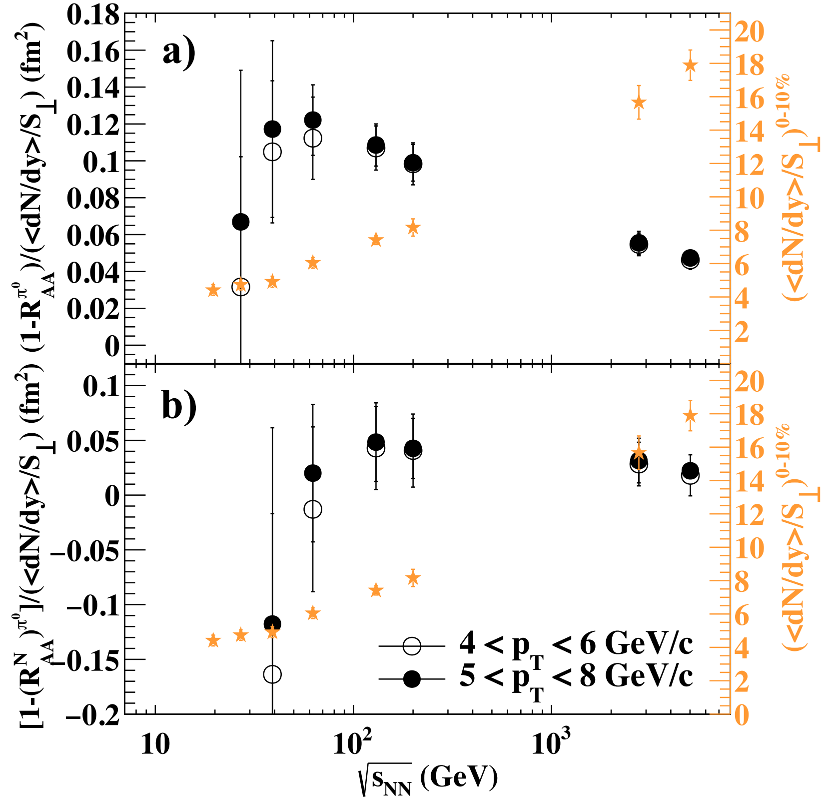


$$R_{CP} \propto a + \frac{b}{s_{NN}} + c \cdot \sqrt{s_{NN}}$$

- PHENIX Collaboration, PRL 109(2012)152301
- PHENIX Collaboration, PRL 101(2008)232301
- ALICE Collaboration, Eur.Phys.J., C74(2014)3108
- ALICE Collaboration, POS(Hard Probes)073

$R_{AA}^{\pi^0}$ and $(1- R_{AA}^{\pi^0})/(<dN/dy>/ S_{\perp})$ - $\sqrt{s_{NN}}$ dependence





- a maximum in $(1- R_{AA}^{\pi^0})/(<dN/dy>/ S_{\perp})$ at RHIC energies is evidenced followed by a decrease towards LHC energies

- is this a signature of a new state of deconfined matter produced at LHC energies?

- magnetic plasma of light monopoles near T_c → **- quarks and gluons dominated deconfined matter**

J.Liao and E.Shuryak, PRL 102(2009)202302

J.Liao S.Shi and M.Gyulassy. Chin. Phys. C43(209)044101

Outlook

- Charged particles R_{AA}, R^{N}_{AA}, R_{CP} and R^{N}_{CP} for Au-Au (Cu-Cu) at the top RHIC energy and Pb-Pb (Xe-Xe) at LHC energies, for 5 GeV/c $< p_T <$ 8 GeV/c, as a function of $\langle N_{part} \rangle$ and $\langle dN_{ch}/d\eta \rangle$ were discussed

- Considerations based on 1-R_{AA} and $\langle dN/dy \rangle / S_{\perp}$ dependence on $\langle N_{part} \rangle$:
  - supression saturation at LHC energies
  - $k^{LHC} \simeq (0.48 \pm 0.03) \cdot k^{RHIC}$
  - $(1- R^{N(HM)}_{pp})/(1- R^{N(\langle N_{part} \rangle \geq 125)}_{AA}) \simeq 0.01 \pm 0.01$

- R^{N}_{CP} scales with $\langle N_{part} \rangle$ for all heavy systems and all collision energies

- $(1-R_{AA})/\langle dN/dy \rangle$ - $(\langle dN/dy \rangle / S_{\perp})^{1/3}$ exponential dependence
  $(1- R^{N}_{AA})/\langle dN/dy \rangle$ independent on $(\langle dN/dy \rangle / S_{\perp})^{1/3}$ for $(\langle dN/dy \rangle / S_{\perp})^{1/3} > 2.1$ part/fm$^{2/3}$

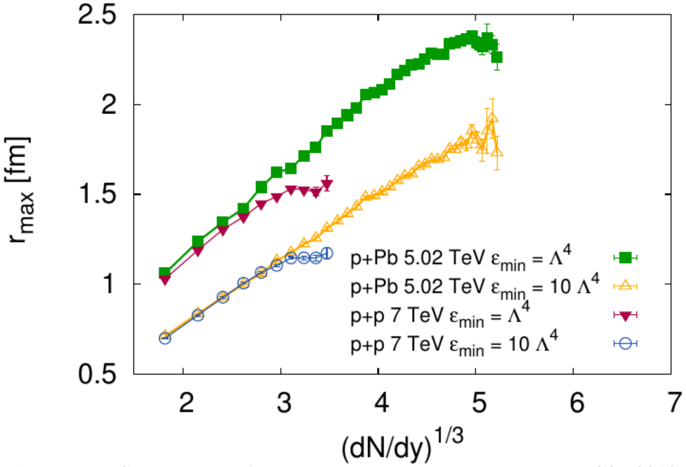
- Collision energy dependence of R_{CP} and R^{N}_{CP} (4 GeV/c $< p_T <$ 6 GeV/c)
  - evidence for saturation at LHC energies

- A maximum in $(1- R^{\pi 0}_{AA})/(\langle dN/dy \rangle / S_{\perp})$ at RHIC energies is followed by a decrease towards LHC energies
  - signature for a new state of deconfined matter produced at LHC energies?

Back-up slides

p+p vs. Pb+Pb @ LHC

M.Petrovici et al. Phys.Rev.C, 98(2018)024904



A.Bzdak, B.Schenke, P.Tribedy and R.Venugopalan, Phys.Rev. C87(2013)064906

$S_{\perp}^{pp} = \pi R_{pp}^2$ $R_{pp} = 1fm \cdot f_{pp}$ - maximal radius for which the energy density of the Yang-Mill fields is larger than $\varepsilon = \alpha \Lambda_{QCD}^4$ $(\alpha \in [1,10])$

α=1 $$f_{pp} = \begin{cases} 0.387 + 0.0335x + 0.274x^2 - 0.0542x^3 & \text{if } x < 3.4 \\ 1.538 & \text{if } x \geq 3.4 \end{cases}$$

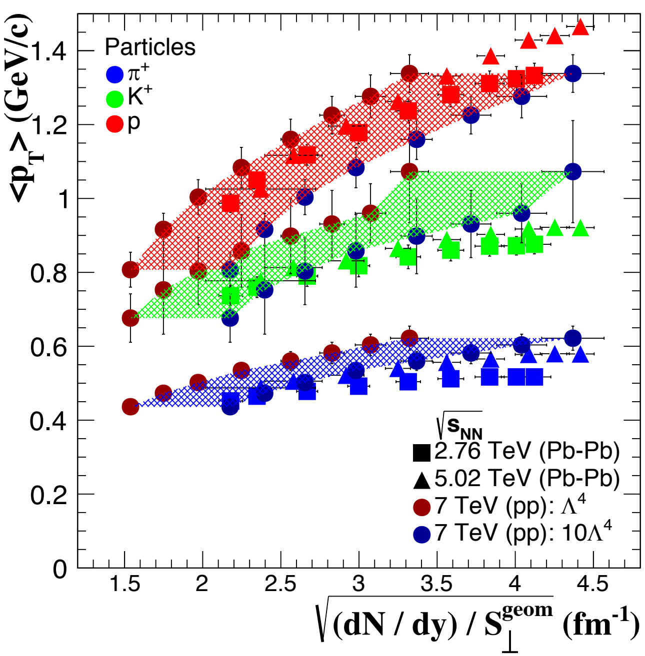
$$x = (dN_g/dy)^{1/3}$$

$$dN_g/dy \approx dN/dy$$

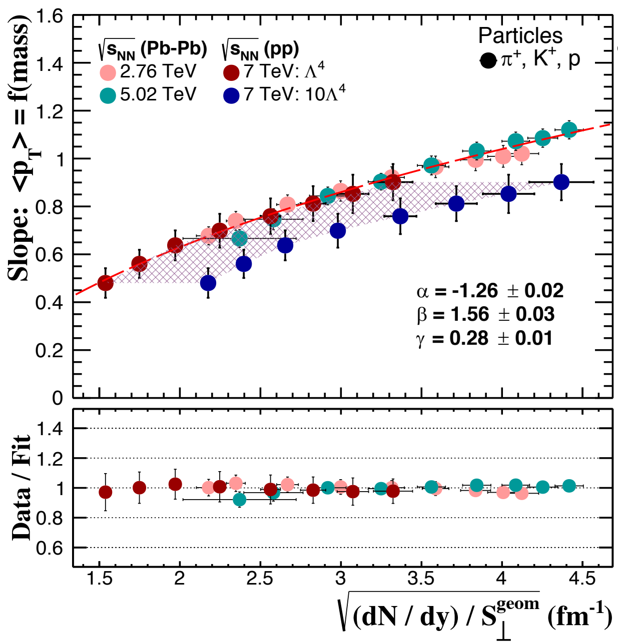
McLarren, M.Praszalowicz and B.Schenke, Nucl.Phys. A916(2013)210

α=10 $$f_{pp} = \begin{cases} -0.018 + 0.3976x + 0.095x^2 - 0.028x^3 & \text{if } x < 3.4 \\ 1.17 & \text{if } x \geq 3.4 \end{cases}$$

$\langle p_T \rangle$ vs. $[(dN/dy)/S_{perp}]^{1/2}$

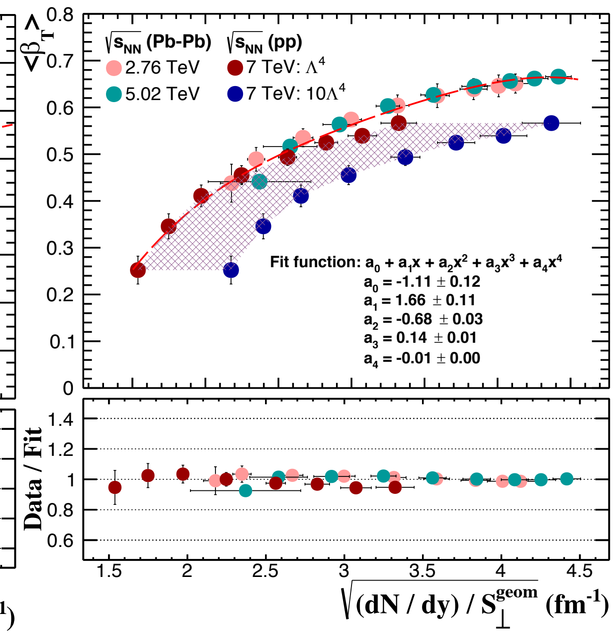


The slope of $\langle p_T \rangle = f(mass)$ vs. $[(dN/dy)/S_{perp}]^{1/2}$



$$Slope_{\langle p_T \rangle = f(mass)} = \alpha + \beta \left(\sqrt{\frac{dN}{dy} / S_\perp^{geom}} \right)^\gamma$$

$\langle \beta_T \rangle$ from BGBW fits vs. $[(dN/dy)/S_{perp}]^{1/2}$



ALICE Collaboration, Nucl.Phys. A931(2014)c888