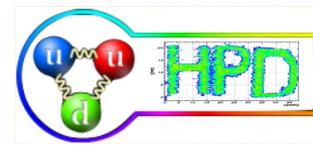




*MINISTERUL CERCETĂRII, INOVĂRII ȘI DIGITALIZĂRII*



# *Features of strangeness production in pp and heavy ion collisions*

*Mihai Petrovici and Amalia Pop*

**Hadron Physics Department  
National Institute for Physics and Nuclear Engineering, Bucharest**

## European Nuclear Physics Conference 2022

24–28 Oct 2022

University of Santiago de Compostela

*“The philosophies and religions of the planet Earth will come and go, but the ultimate questions will be always alive and relevant”*

*James Leonard Park*

# *Outline*

- *Physics motivation*

- *$(dN/dy)^{\text{(strange and multi strange)}} / (dN/dy) - (dN/dy) / S_{\perp}$  correlation*

- *core-corona*

- *collision energy and centrality dependence*

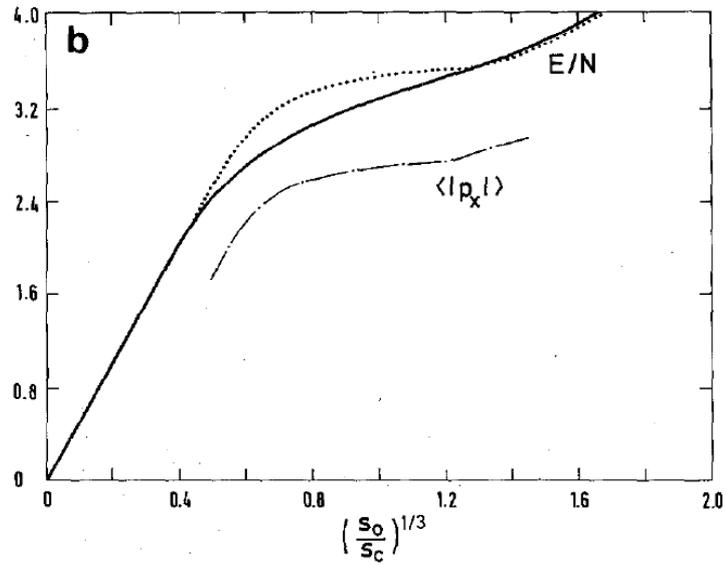
- *signature for phase transition ?*

- *Similar studies for pp collisions*

- *comparison with A-A*

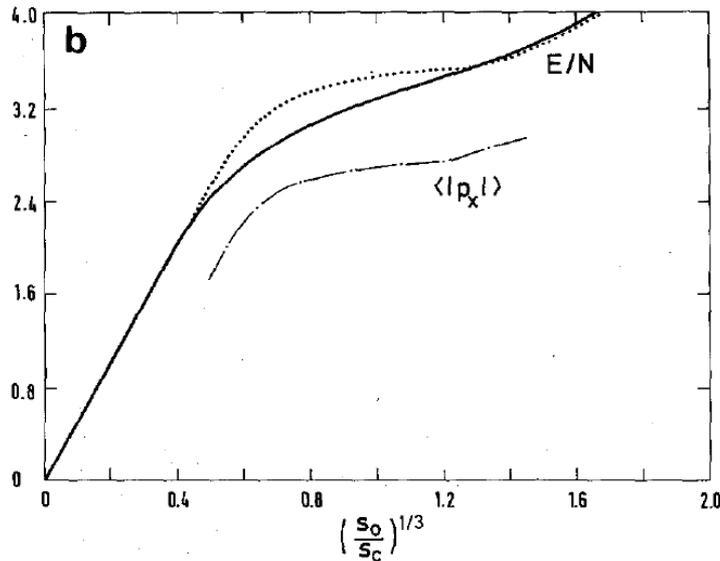
- *Outlook*

## *Signature for phase transition ?*



*J.-P. Blaizot and J.-Y. Ollitrault, Phys.Lett 191B(1987)21*

# Signature for phase transition ?



*J.-P. Blaizot and J.-Y. Ollitrault, Phys.Lett 191B(1987)21*

## - AGS si SPS

• S. Chatterjee et al., Advances in High Energy Physics 2015, 349013 (2015).

## - BES

• J. Adam et al. (STAR Collaboration), Phys. Rev. C 102, 034909 (2020).

## - RHIC 62.4 GeV and 200 GeV

• M. M. Aggarwal et al. (STAR Collaboration), Phys. Rev. C 83, 024901 (2011).

• J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 98, 062301 (2007).

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• L. Adamczyk et al. (STAR Collaboration), Phys. Rev. C 96, 044904 (2017). - RHIC, 62.4 si 200 GeV

• B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79, 034909 (2009). - ALICE 2.76 TeV

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• B. Abelev et al. (ALICE Collaboration), Phys. Lett. B 728, 216 (2014); 734, 409 (2014).

• B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79, 034909 (2009). - ALICE 2.76 TeV

## - ALICE 5.02 TeV

• D. S. de Albuquerque, Ph.D. thesis (2019), CERN-THESIS-2019-135.

• P. Kalinak for the ALICE Collaboration, European Physical Society Conference on High

• Energy Physics, 5-12 July 2017, Venice, Italy, PoS(EPS-HEP2017)168 (2017),

• <https://pos.sissa.it/314/168/pdf>.

• D. S. de Albuquerque for the ALICE Collaboration, Nucl. Phys. A 982, 823 (2019), XXVIIth

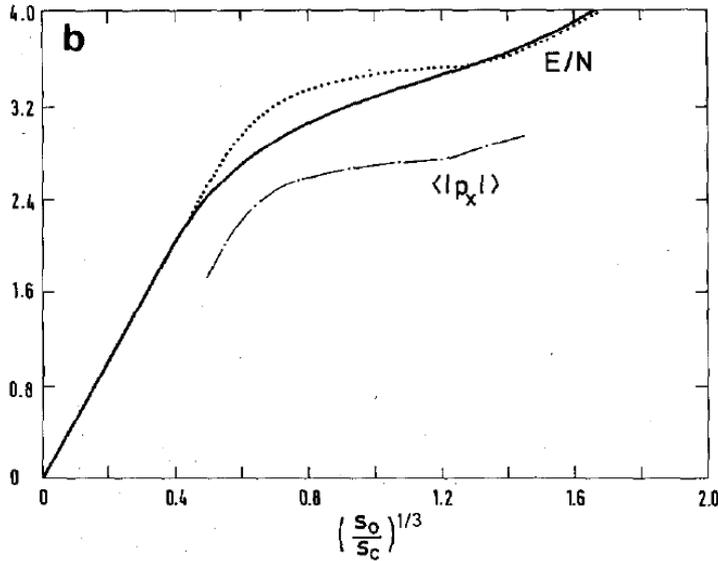
• International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2018).

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$$\frac{dN}{dy} \simeq \frac{3}{2} \frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2 \frac{dN}{dy}^{(p + \bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(K^+ + K^-, \Lambda + \bar{\Lambda}, \Omega^- + \bar{\Omega}^+)} + 2 \frac{dN}{dy}^{K_S^0} + 2 \frac{dN}{dy}^{(\Sigma^+ + \Sigma^-)}$$

$$\frac{dE_T}{dy} \simeq \frac{3}{2} (\langle m_T \rangle \frac{dN}{dy})^{(\pi^+ + \pi^-)} + 2 (\langle m_T \rangle \frac{dN}{dy})^{(p + \bar{p}, \Xi^- + \bar{\Xi}^+)} + (\langle m_T \rangle \frac{dN}{dy})^{(K^+ + K^-, \Lambda + \bar{\Lambda}, \Omega^- + \bar{\Omega}^+)} + 2 (\langle m_T \rangle \frac{dN}{du})^{K_S^0} + 2 (\langle m_T \rangle \frac{dN}{dy})^{(\Sigma^+ + \Sigma^-)}$$

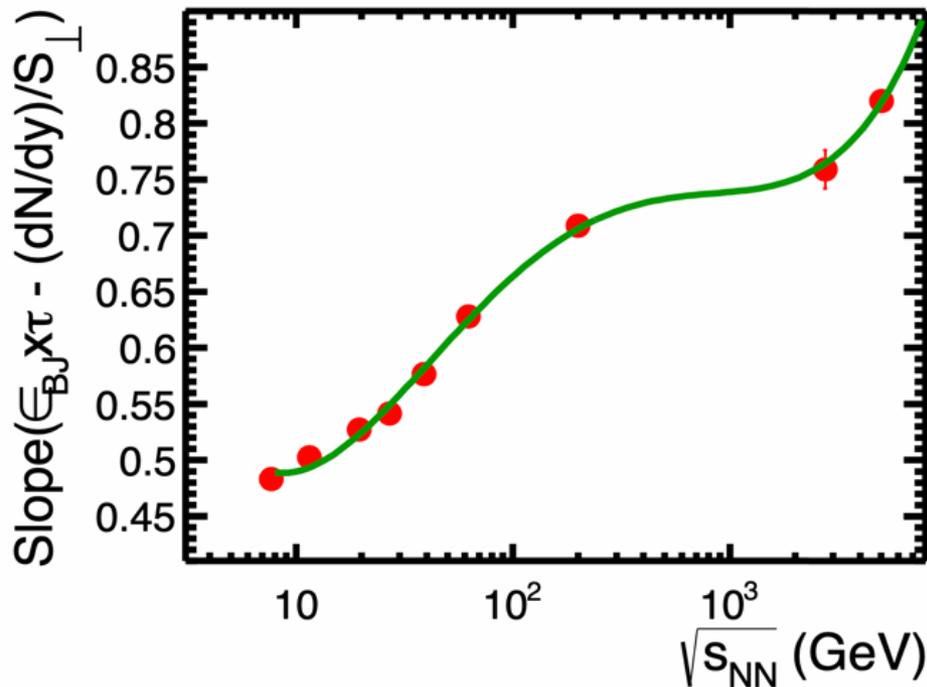
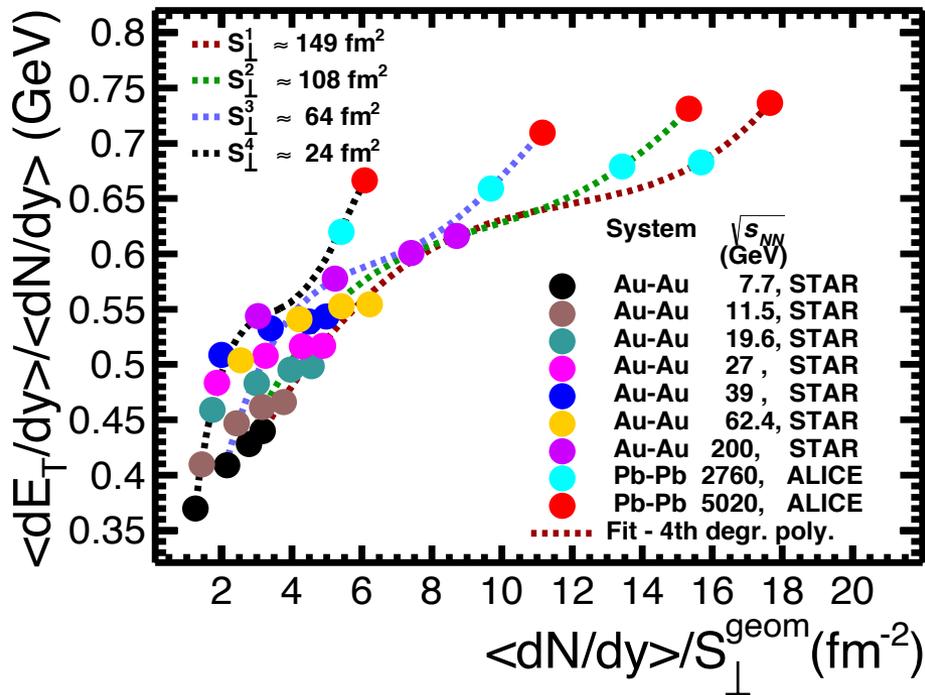
$$\langle m_T \rangle - > \langle m_T \rangle - m_0 \quad \text{- for baryons}$$

for RHIC energies:

$$\langle m_T \rangle - > \langle m_T \rangle + m_0 \quad \text{- for antibaryons}$$

$$\langle m_T \rangle \quad \text{- for other particles}$$

# Signature for phase transition ? - experiment



M. Petrovici and A. Pop, [arXiv:2209.08828 \[hep-ph\]](https://arxiv.org/abs/2209.08828)

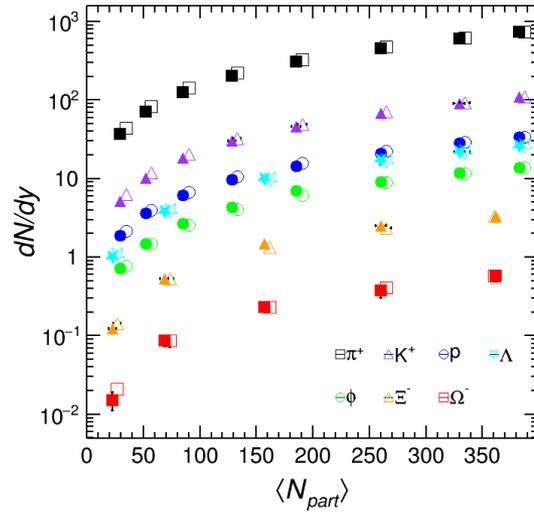
# *Strangeness production - smoking gun of deconfinement*

J.Rafelski and B.Muller, Phys.Rev.Lett. 48(1982)1066

# Strangeness production - smoking gun of deconfinement

J.Rafelski and B.Muller, Phys.Rev.Lett. 48(1982)1066

$$\left(\frac{dN}{dy}\right)_i^{cen} = N_{part}[(1 - f_{core})M_i^{ppMB} + f_{core}M_i^{core}]$$



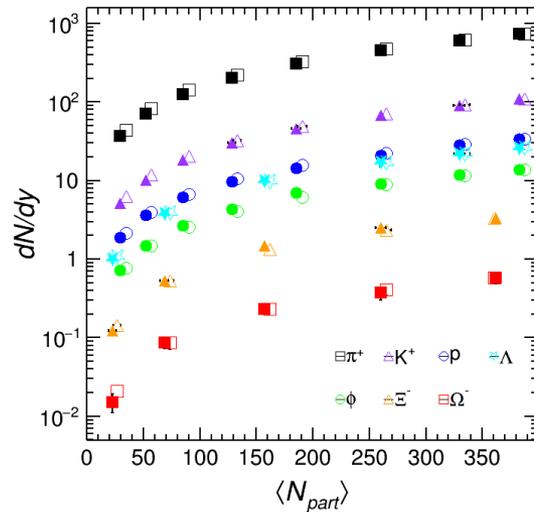
M. Petrovici et al., Phys.Rev. C96(2017)014908

ALICE Coll., Phys.Rev. C88(2013)044910  
ALICE Coll., Phys.Rev.Lett 111(2013)222301  
ALICE Coll., Phys.Lett. B728(2014)216  
ALICE Coll., Phys.Rev. C91(2015)024609

# Strangeness production - smoking gun of deconfinement

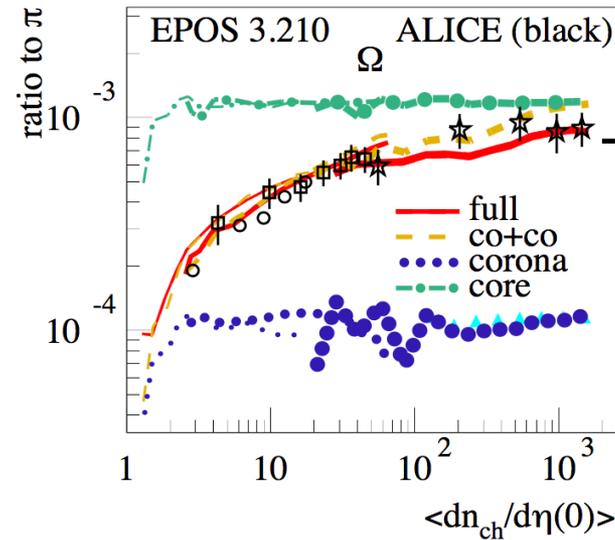
J.Rafelski and B.Muller, Phys.Rev.Lett. 48(1982)1066

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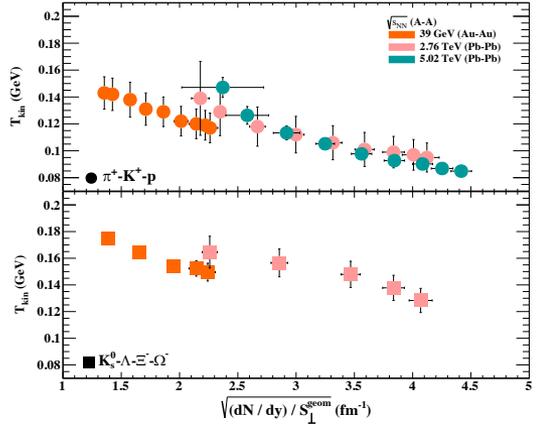
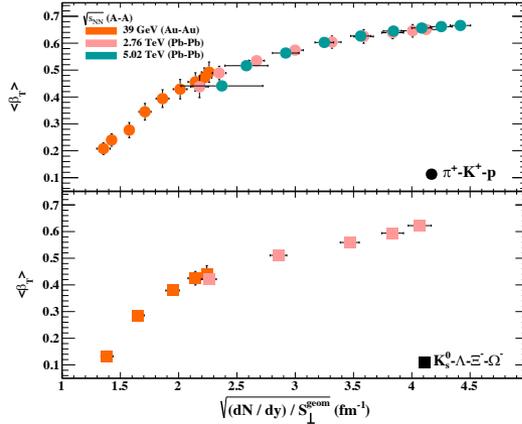
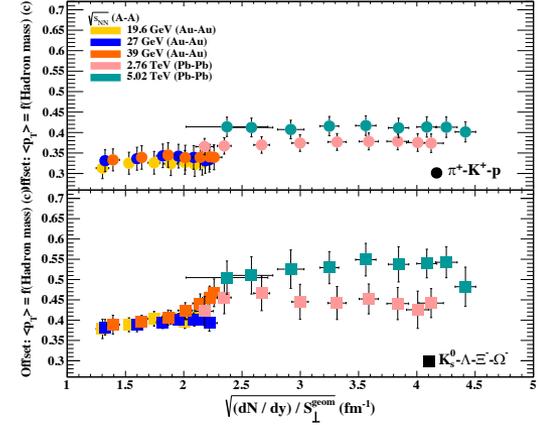
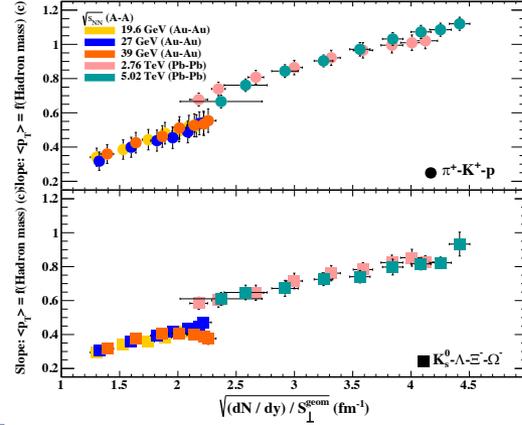
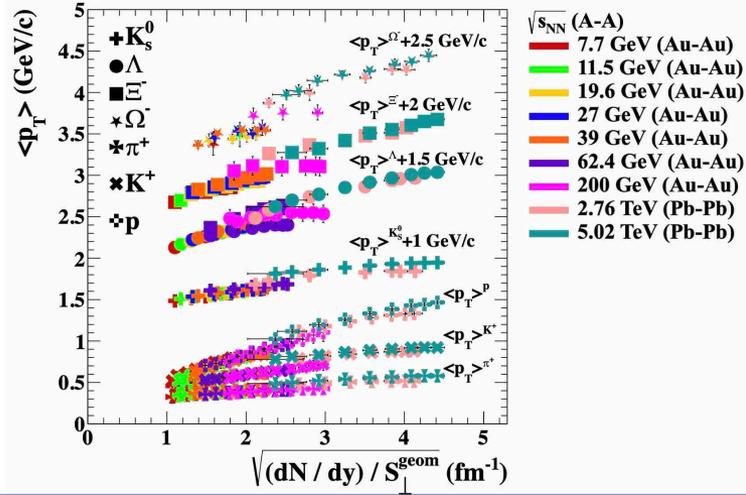
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 ALICE Coll., Phys.Rev. C91(2015)024609



K. Werner et al., EPJ Web of Conferences 171, 09002 (2018), SQM 2017

# Geometrical scaling for light flavor hadrons



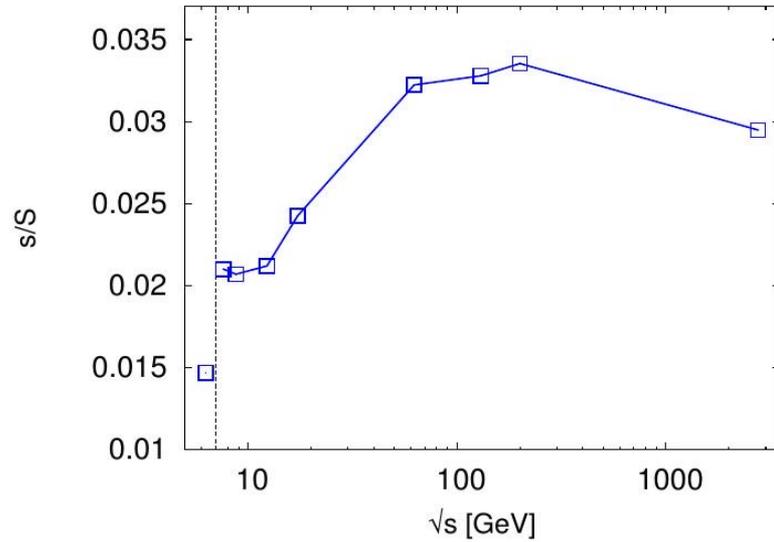
M. Petrovici et al., Phys. Rev. C 98(2018)024904  
M. Petrovici et al., AIP Conference Proceedings, 2076(2019)040001  
A. Lindner et al., Proceedings of Science (PoS) 380(2021)197  
(PANIC2021), <https://pos.sissa.it/380/197/>.

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1 \left( \frac{m_T \cosh \rho}{T_{fo}} \right) I_0 \left( \frac{p_T \sinh \rho}{T_{fo}} \right)$$

$$\rho = \tanh^{-1} \beta_r \quad \beta_r = \beta_s \left( \frac{r}{R} \right)^\alpha$$

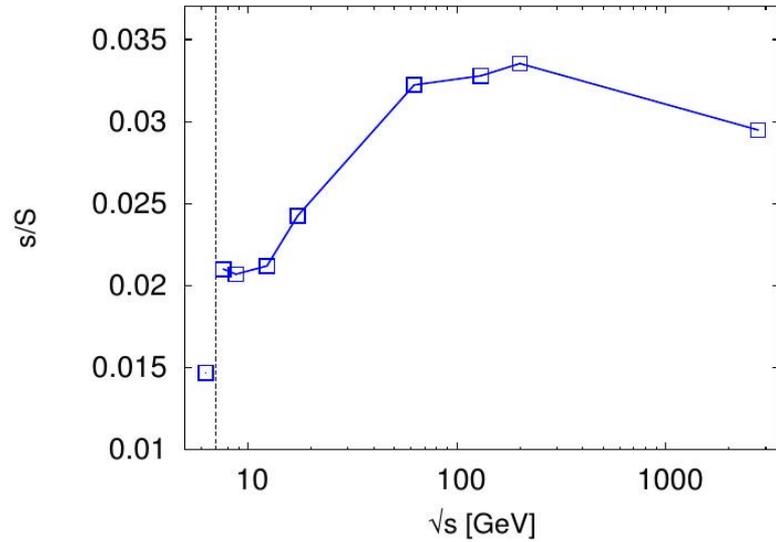
E. Schnedermann, J. Sollfrank and U. Heinz,  
Phys.Rev.C48(1993)2462

## *Strangeness production - smoking gun of deconfinement*

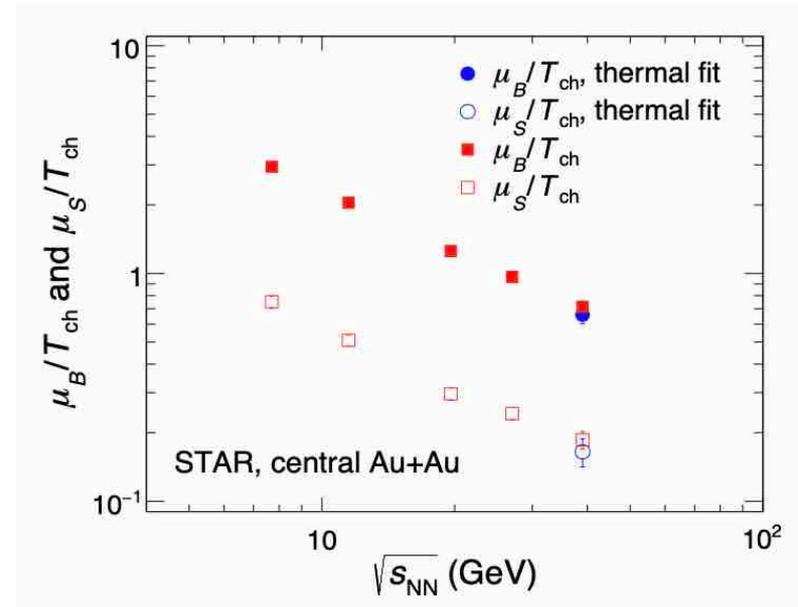


J. Rafelski and M. Petran, Acta Phys.Polon.Supp. 7  
(2014) 35, arXiv[nucl-th]1403.4036

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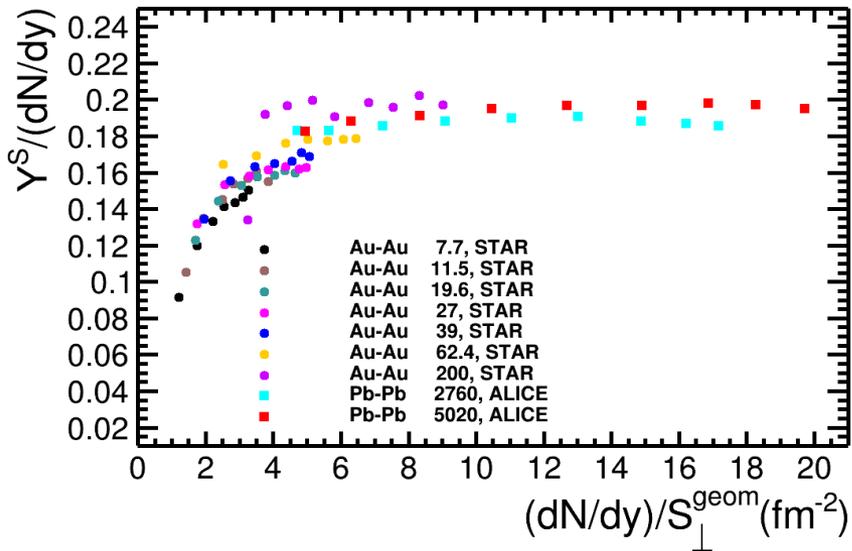
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J.Adam et al, STAR Collaboration, Phys.Rev. C102(2020)034909

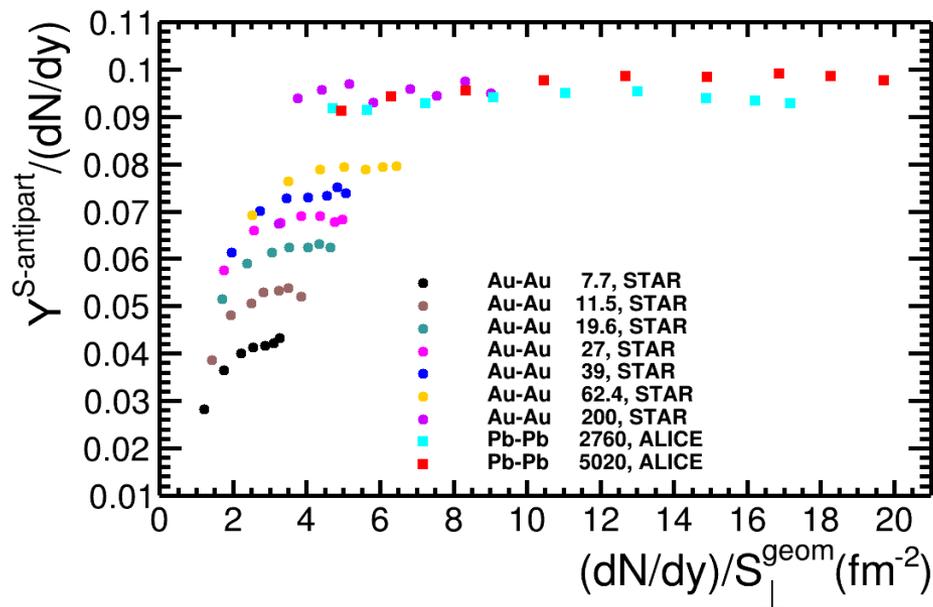
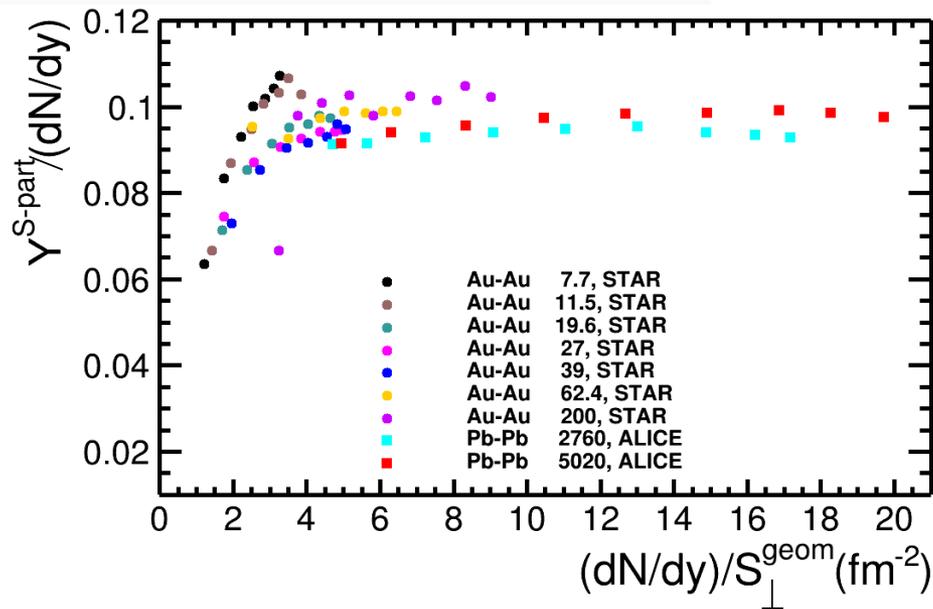
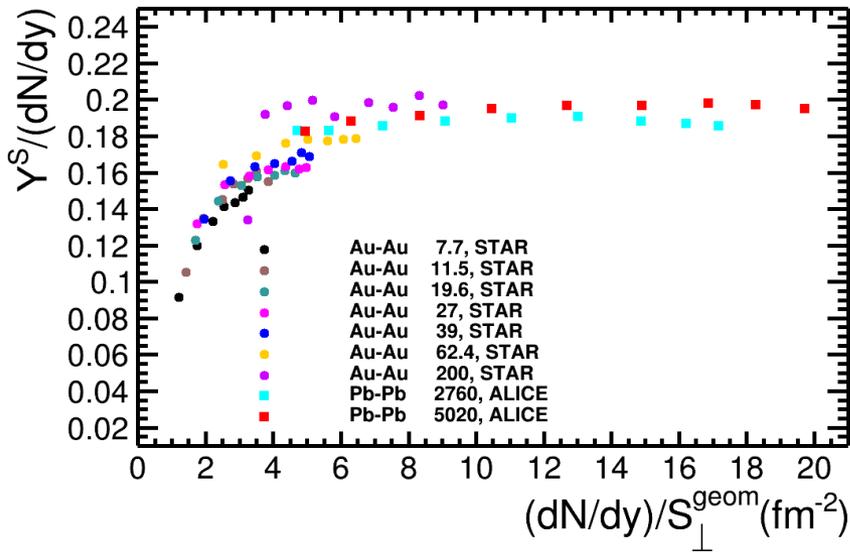
## $(dN/dy)^{\text{(strange and multi strange)}} / (dN/dy) - (dN/dy) / S_{\perp}$ correlation

$$Y^s = \frac{dN^s}{dy} = \frac{dN^{(K^+ + K^-)}}{dy} + 2 \frac{dN^{K_s^0}}{dy} + \frac{dN^{(\Lambda + \bar{\Lambda})}}{dy} + 2 \frac{dN^{(\Xi^- + \bar{\Xi}^+)}}{dy} + \frac{dN^{(\Omega^- + \bar{\Omega}^+)}}{dy} + 2 \frac{dN^{(\Sigma^- + \bar{\Sigma}^+)}}{dy}$$



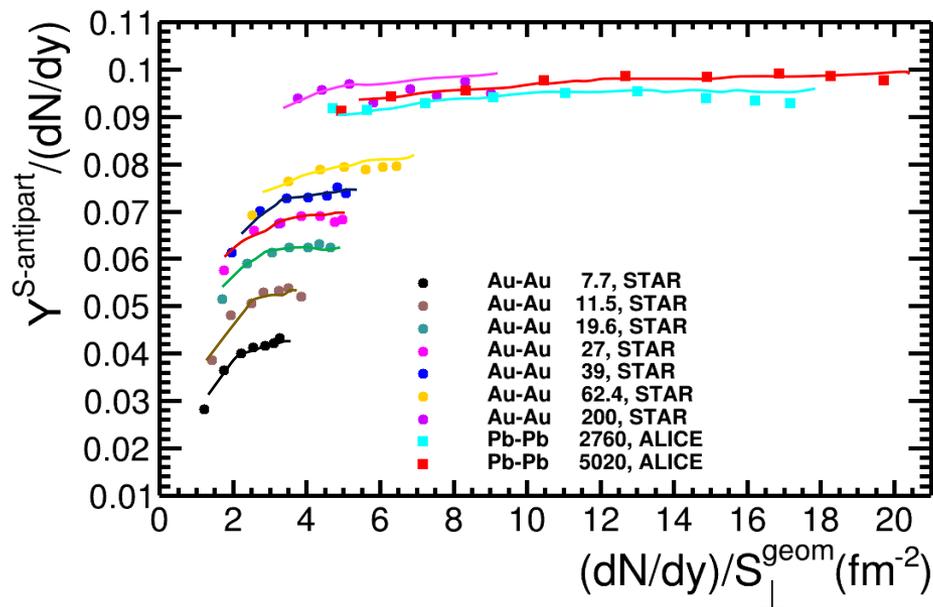
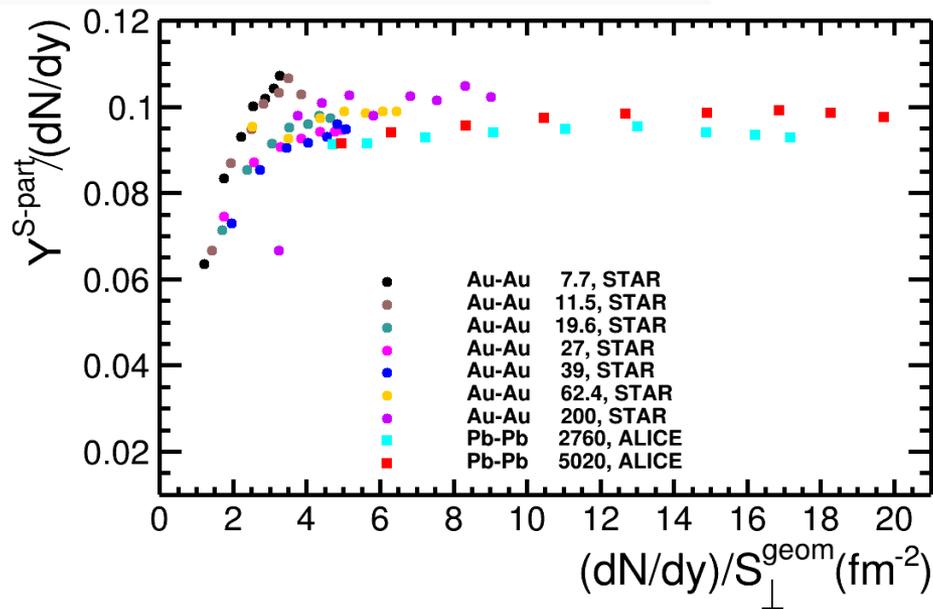
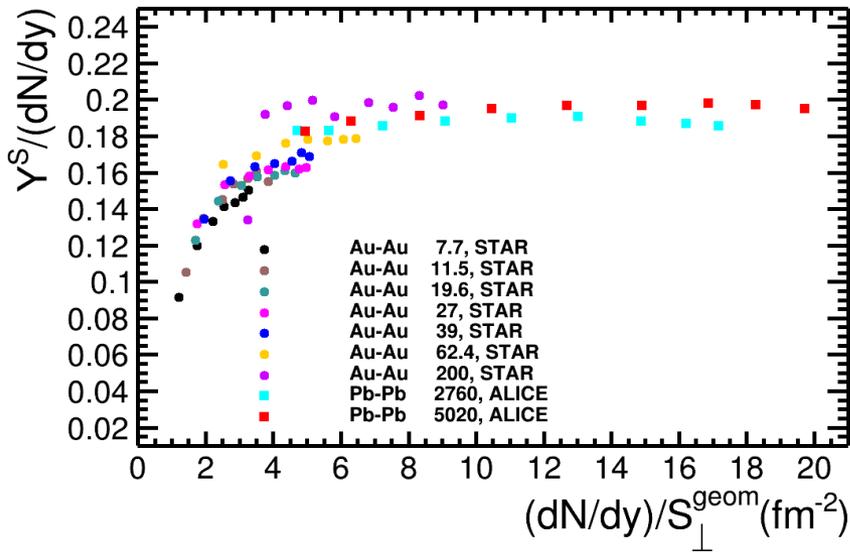
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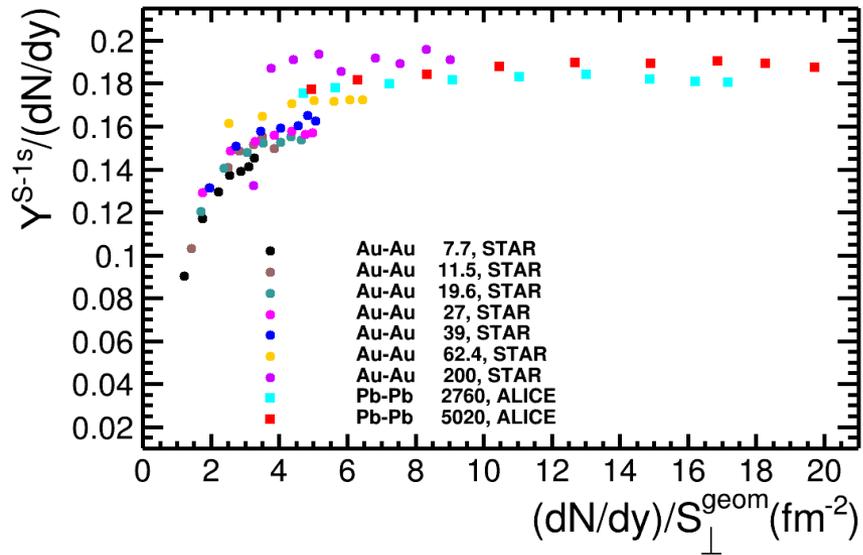
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$(dN/dy)^{\text{(strange and multi strange)}}/(dN/dy) - (dN/dy)/S_{\perp}$  correlation  
 $S=1$

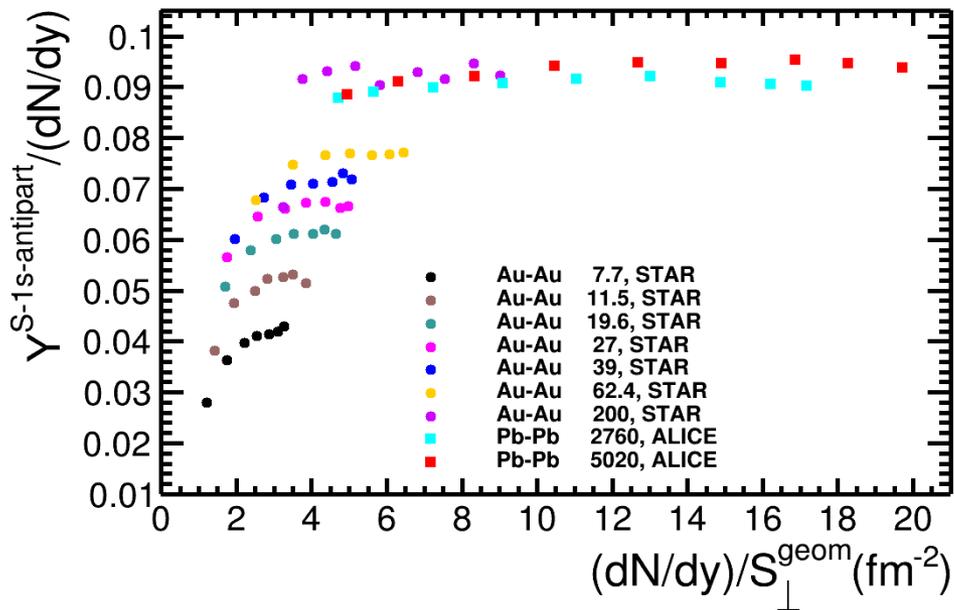
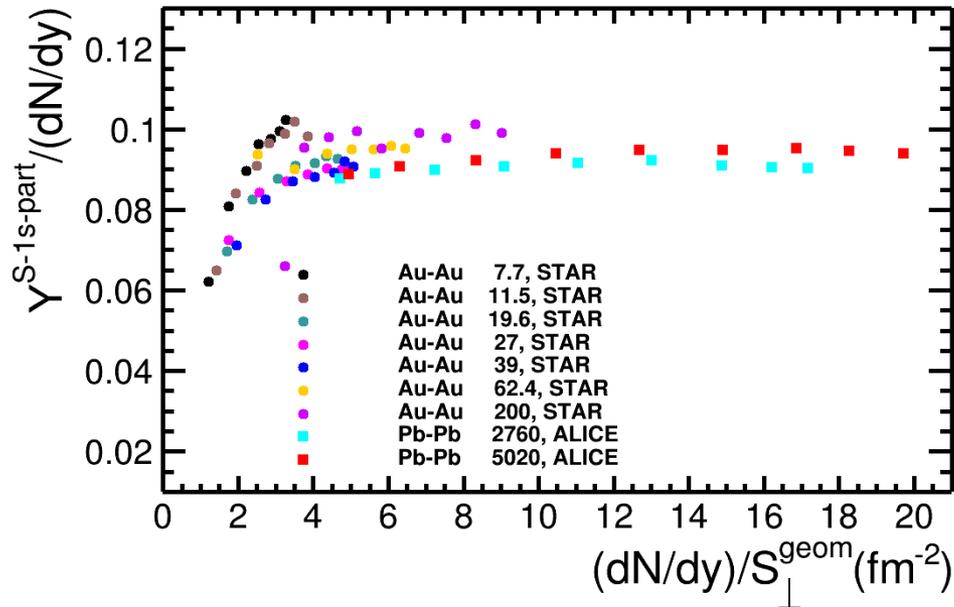
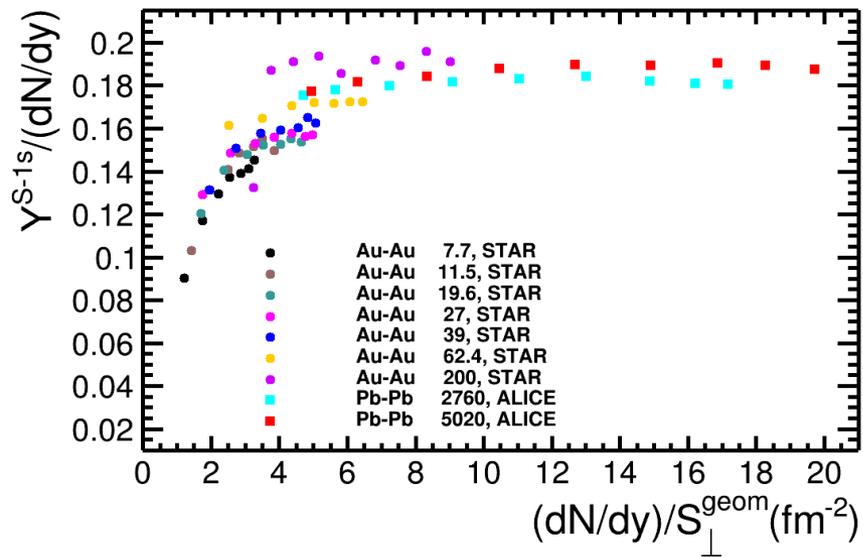
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$S=1$

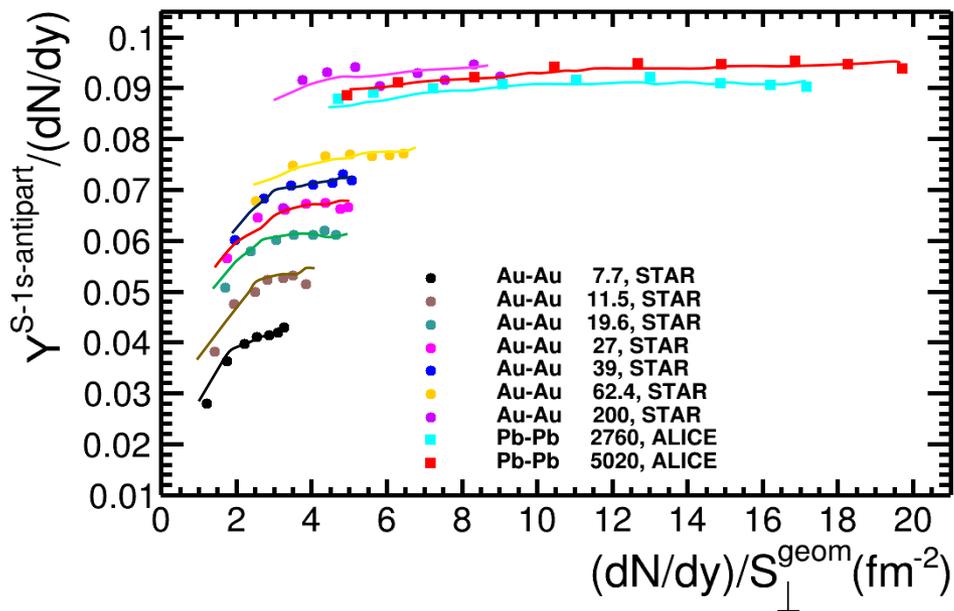
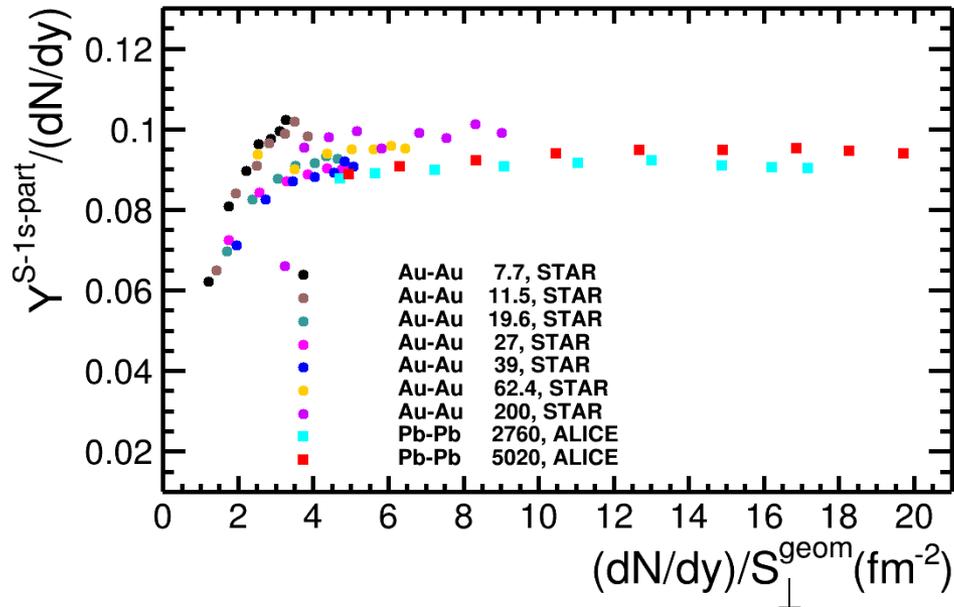
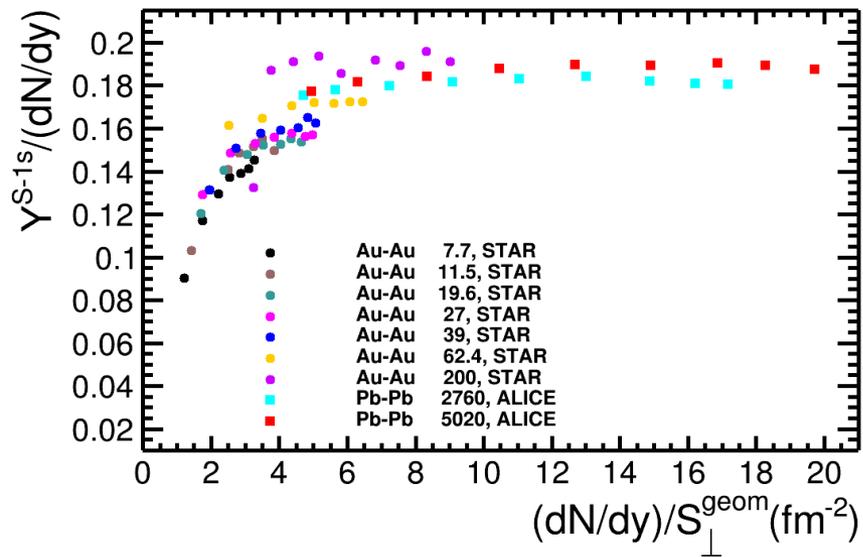
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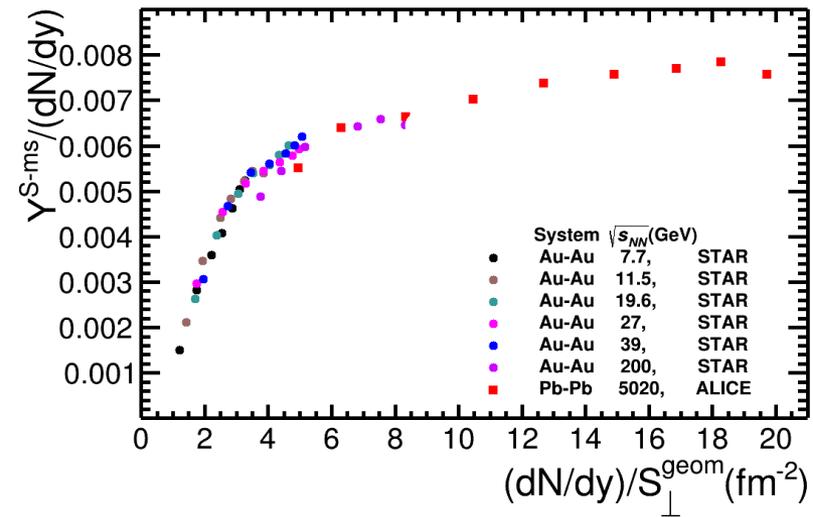
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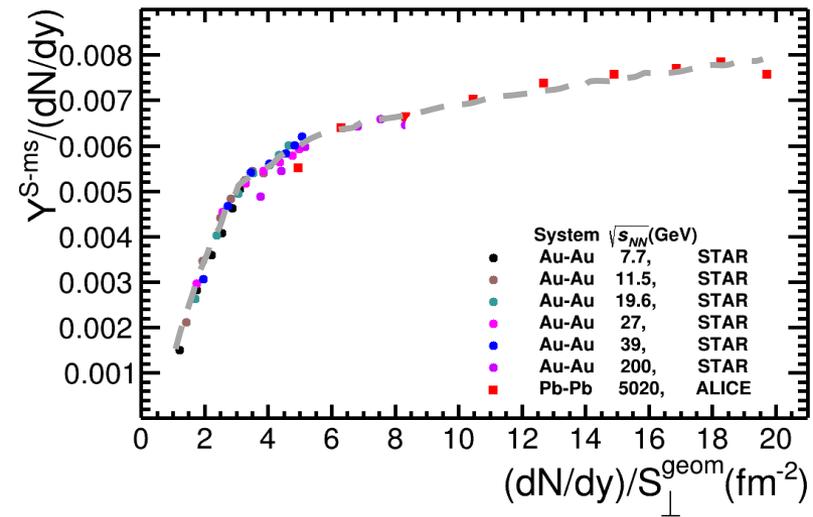
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 $S > 1$

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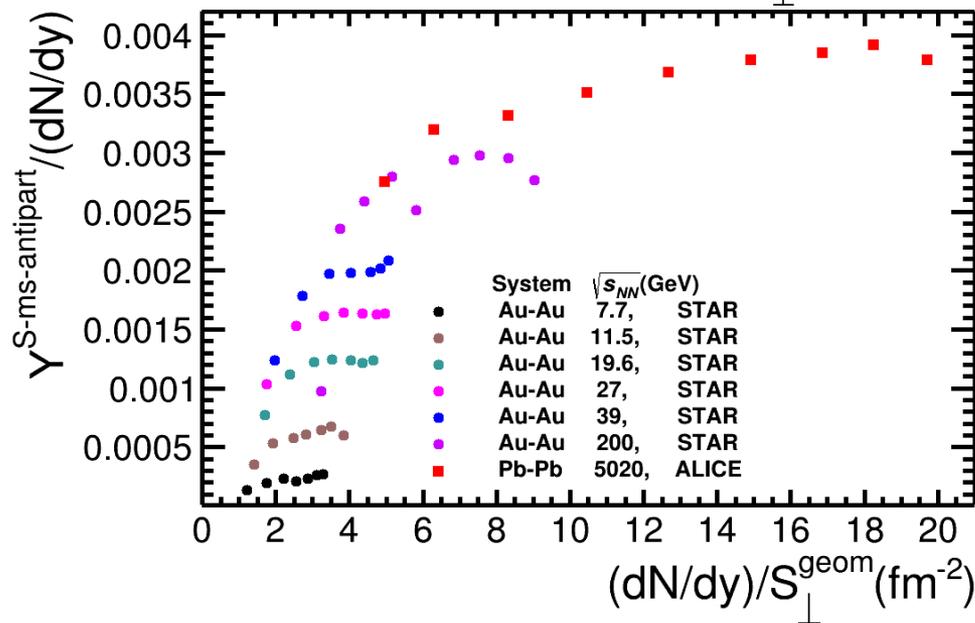
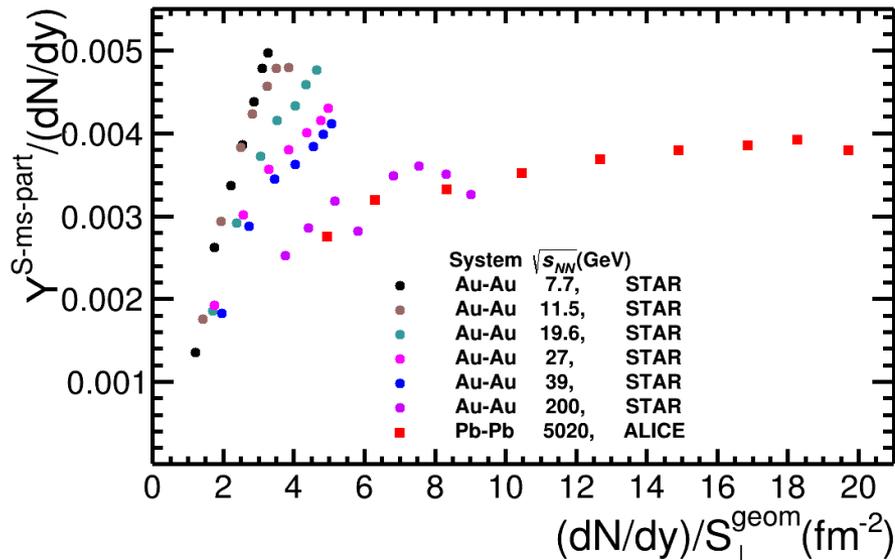
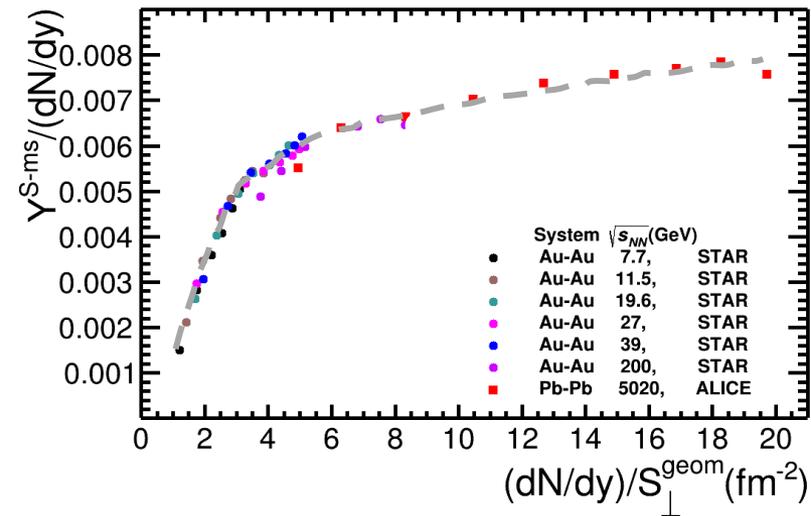
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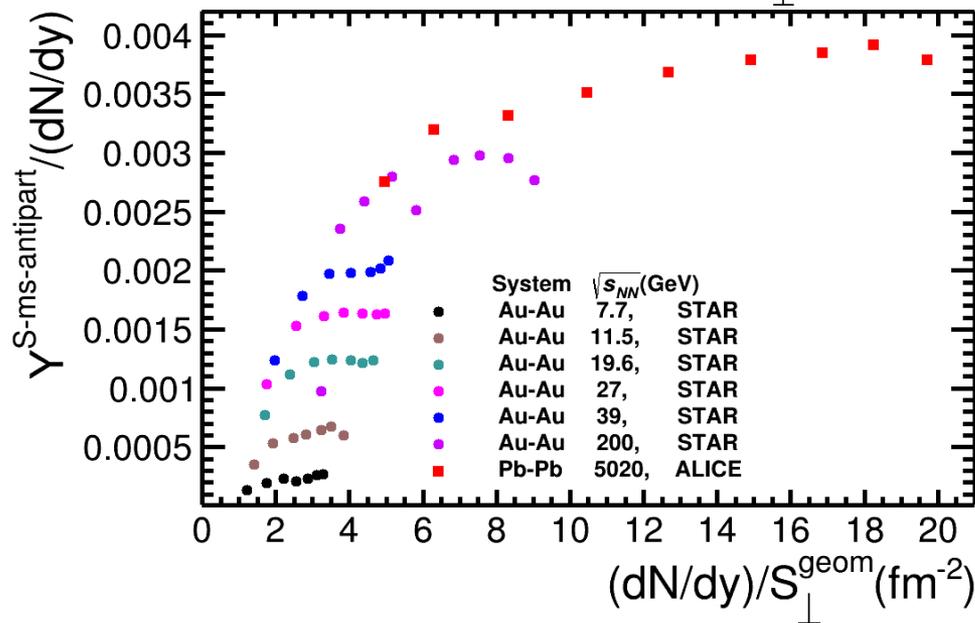
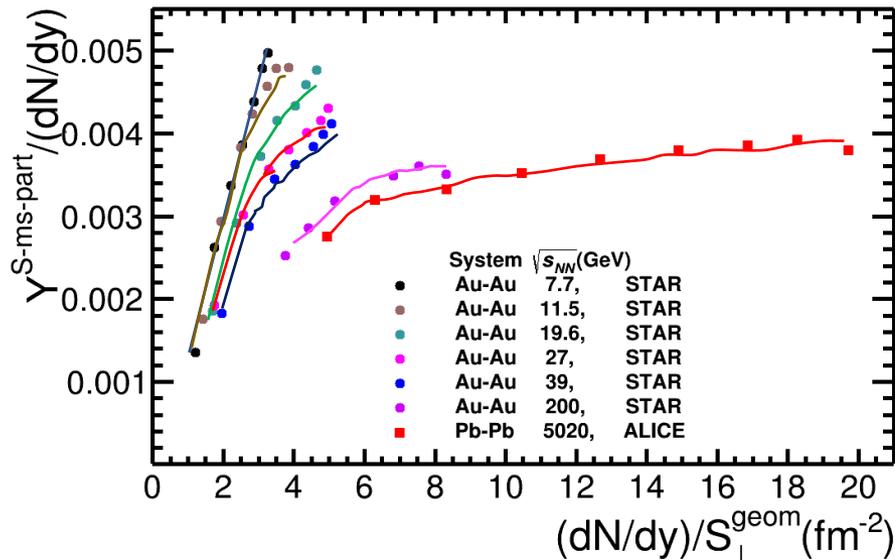
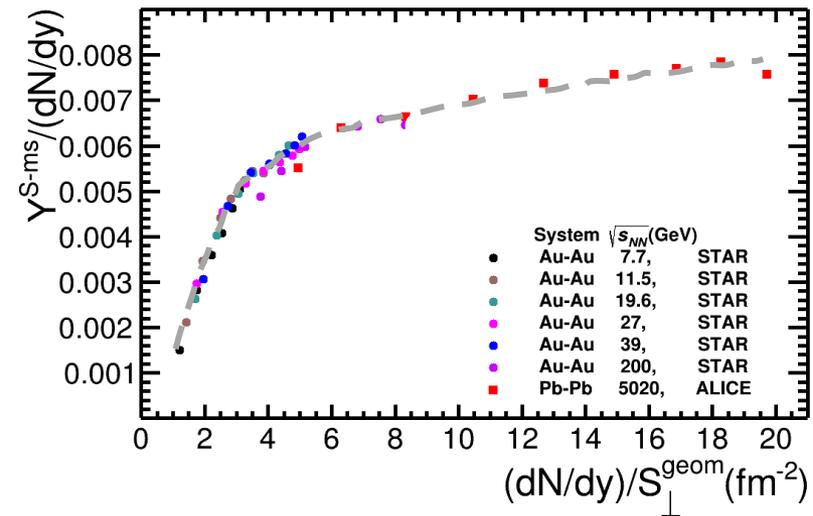
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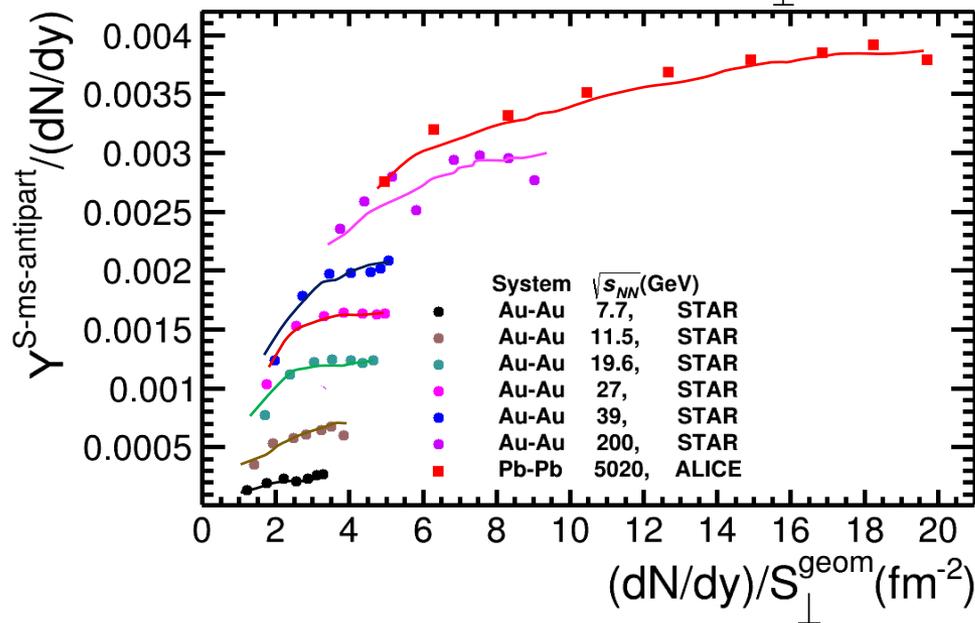
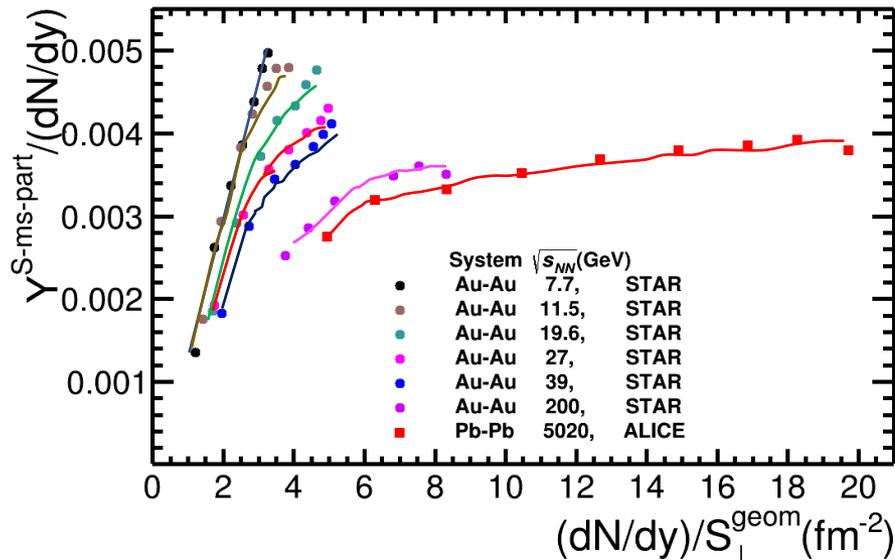
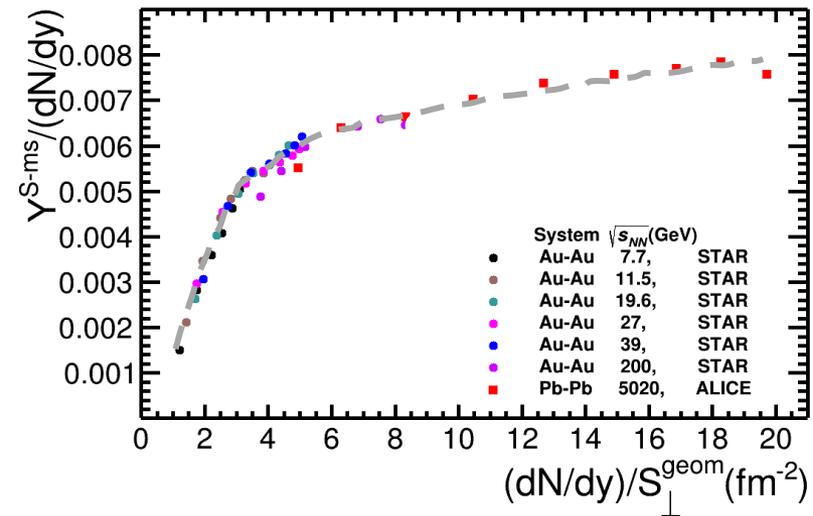
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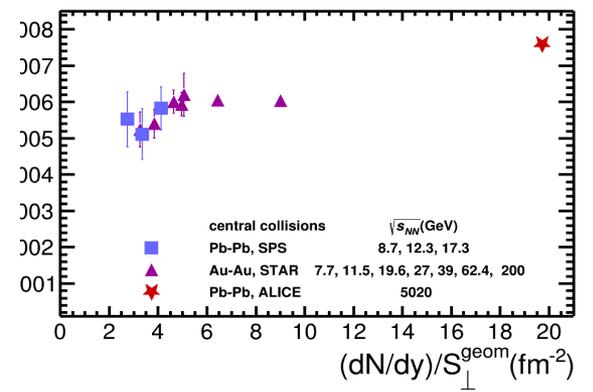
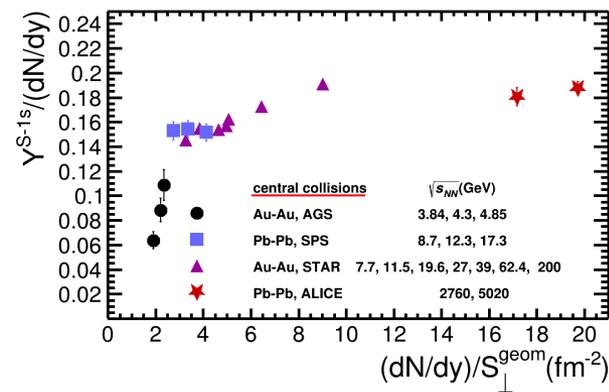
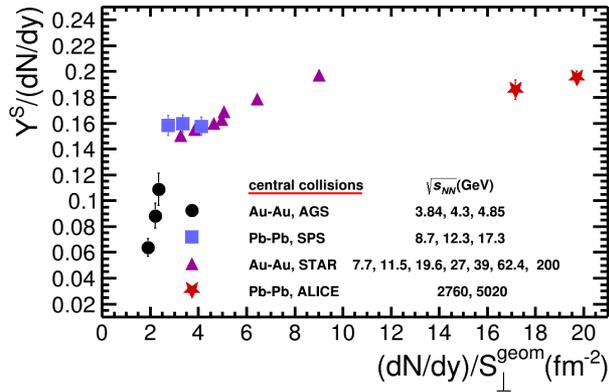
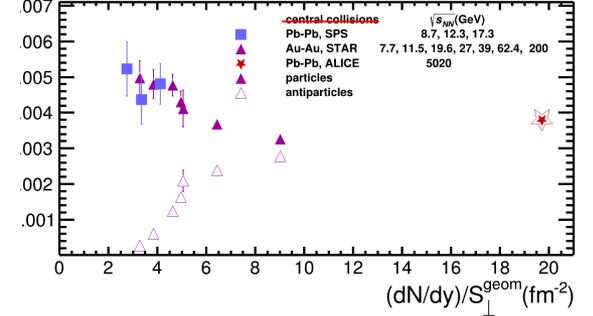
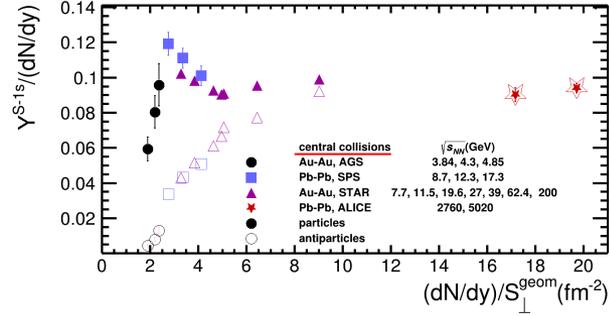
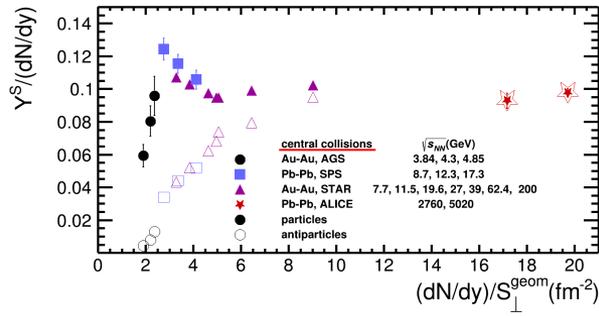
$(dN/dy)^{\text{strange and multi strange}}/(dN/dy) - (dN/dy)/S_{\perp}$  correlation  
 $S > 1$

$$Y^{ms} = \frac{dN^{ms}}{dy} = \frac{dN^{(\Omega^- + \bar{\Omega}^+)}}{dy} + 2 \frac{dN^{(\Xi^- + \bar{\Xi}^+)}}{dy}$$



# $(dN/dy)^{\text{strange and multi strange}} / (dN/dy) - (dN/dy) / S_{\perp}$ correlation

## central collisions

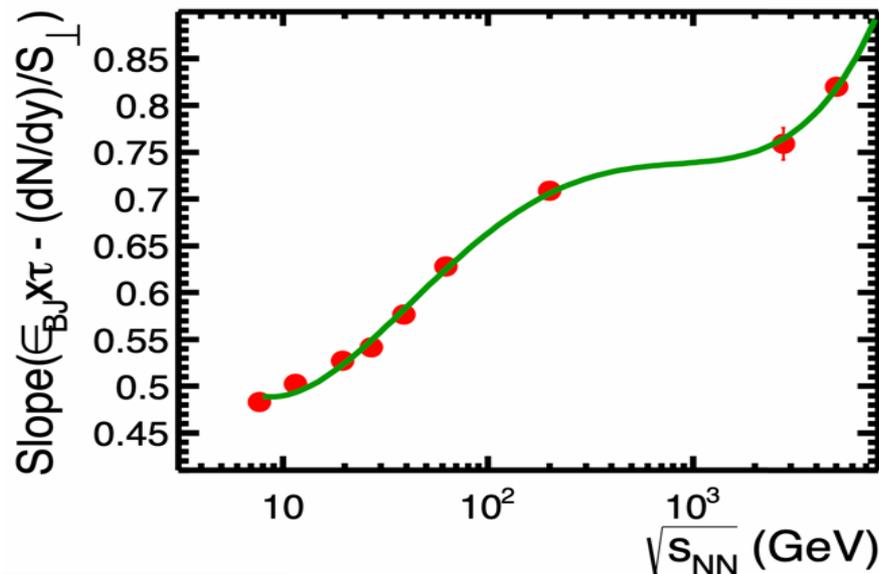
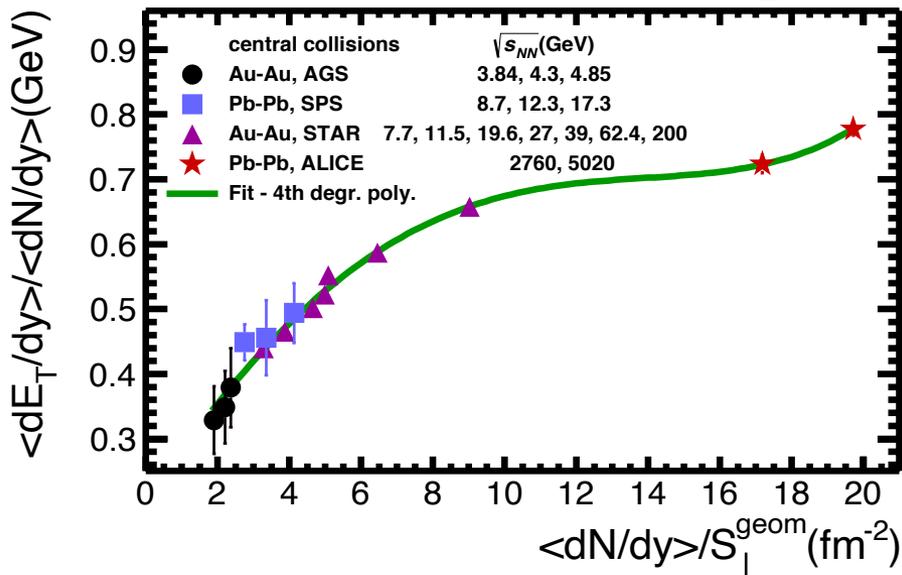
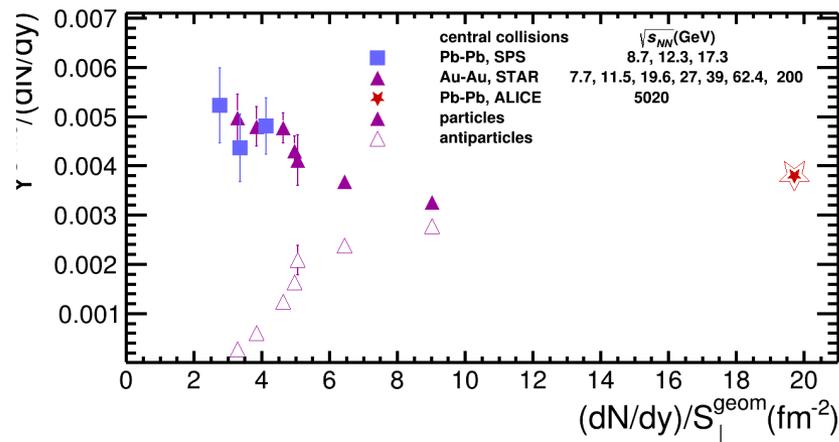
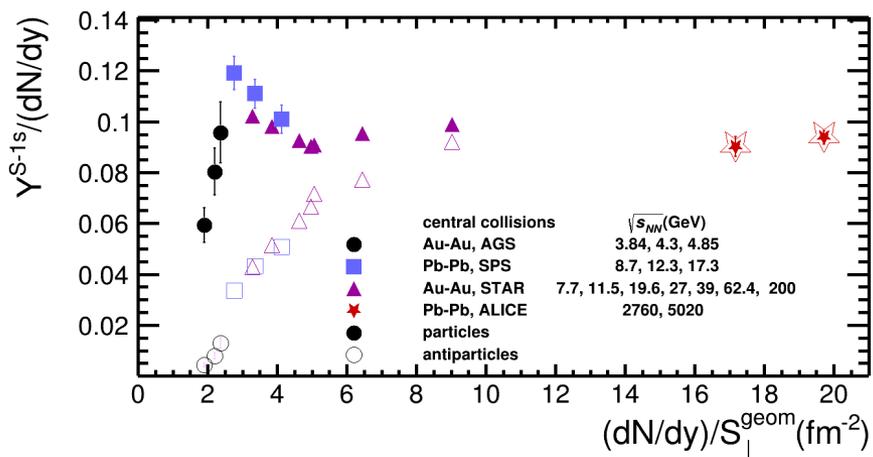


# $(dN/dy)^{\text{strange and multi strange}} / (dN/dy) - (dN/dy) / S_{\perp}$ correlation

## central collisions

### $(dE_T/dy) / (dN/dy) - (dN/dy) / S_{\perp}$ correlation

### slopes of $\epsilon_{Bj} \cdot \tau - (dN/dy) / S_{\perp}$ correlation

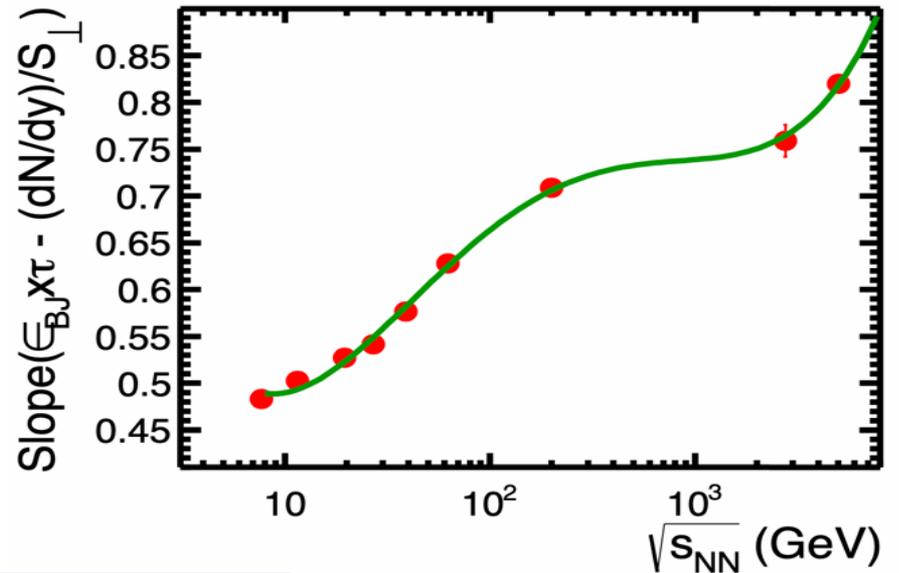
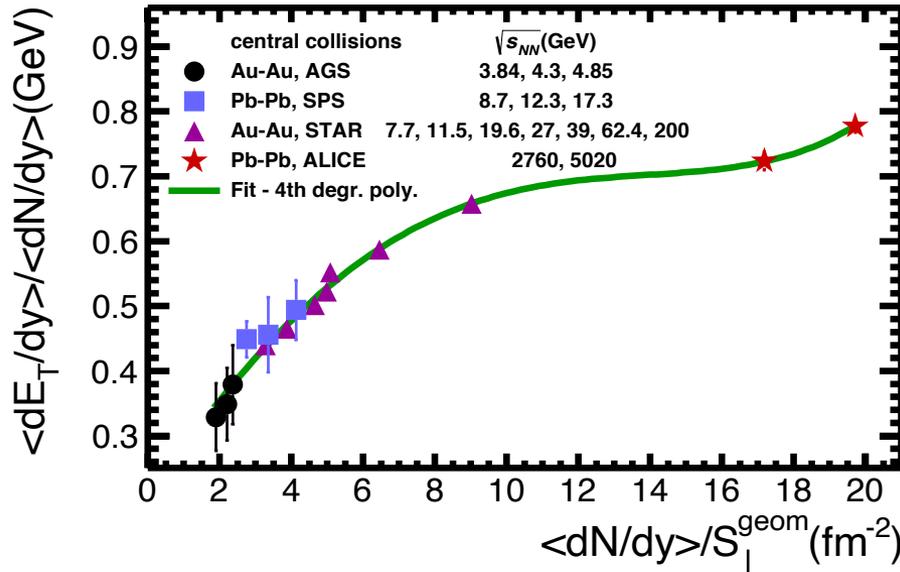
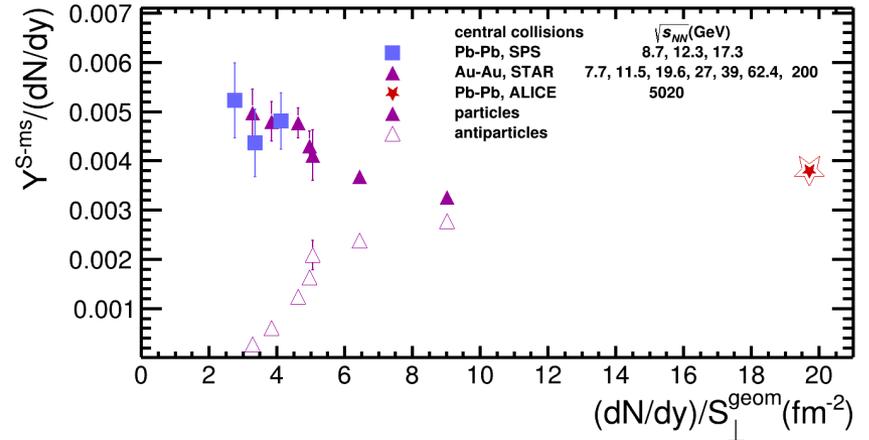
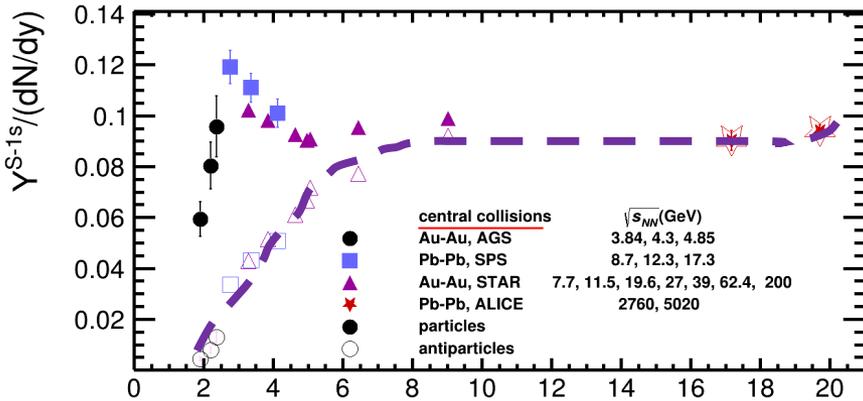


# $(dN/dy)^{\text{strange and multi strange}} / (dN/dy) - (dN/dy) / S_{\perp}$ correlation

## central collisions

### $(dE_T/dy) / (dN/dy) - (dN/dy) / S_{\perp}$ correlation

### slopes of $\epsilon_{Bj} \cdot \tau - (dN/dy) / S_{\perp}$ correlation

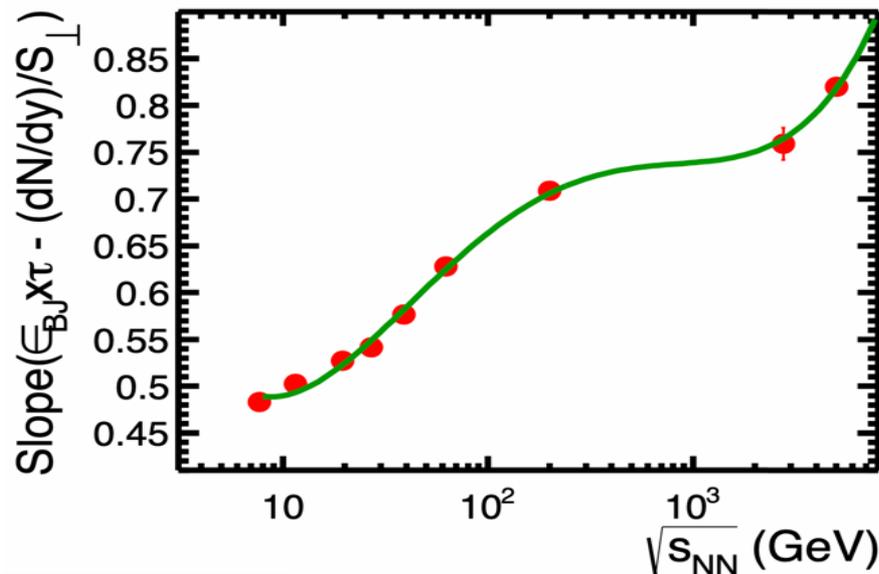
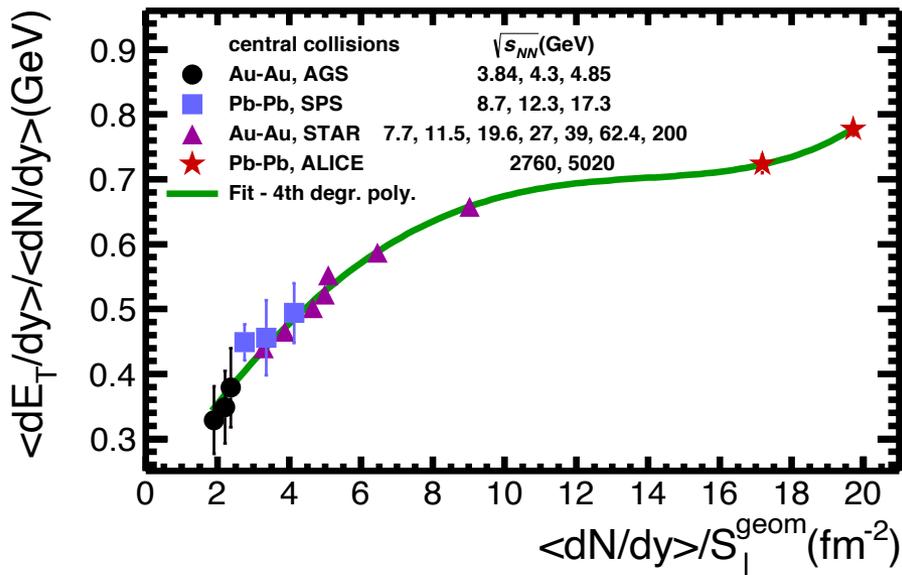
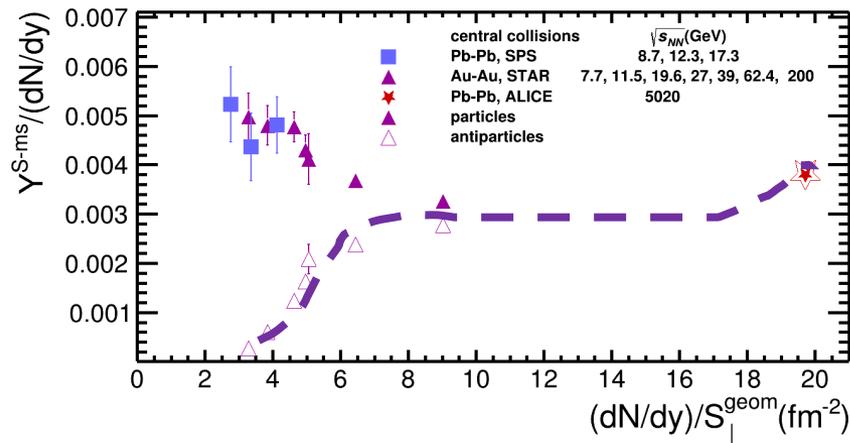
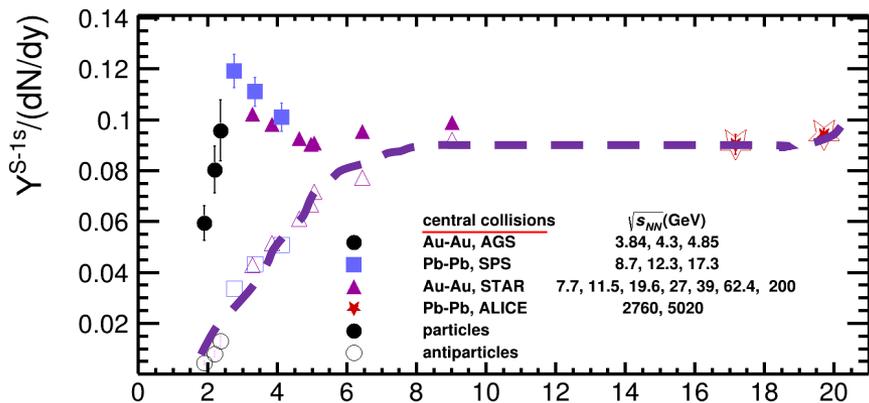


$(dN/dy)^{\text{strange and multi strange}} / (dN/dy) - (dN/dy) / S_{\perp}$  correlation

central collisions

$(dE_T/dy) / (dN/dy) - (dN/dy) / S_{\perp}$  correlation

slopes of  $\epsilon_{Bj} \cdot \tau - (dN/dy) / S_{\perp}$  correlation

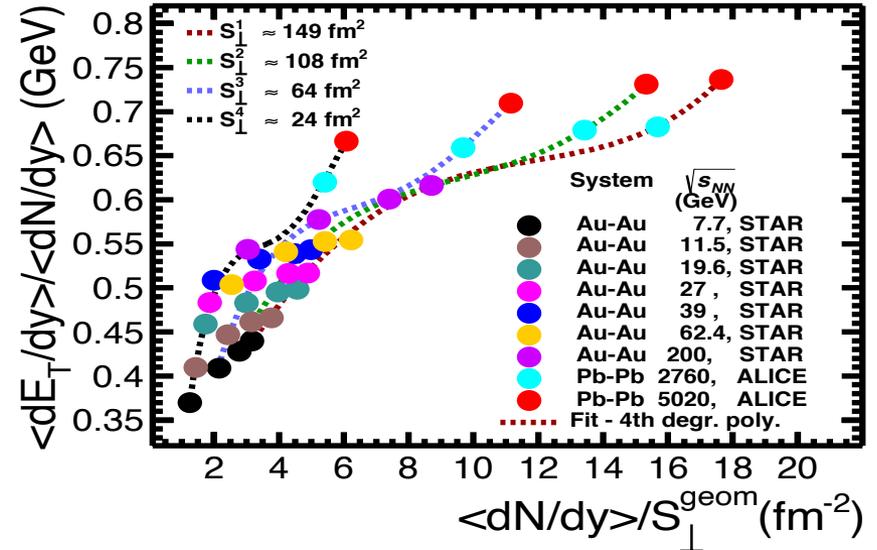
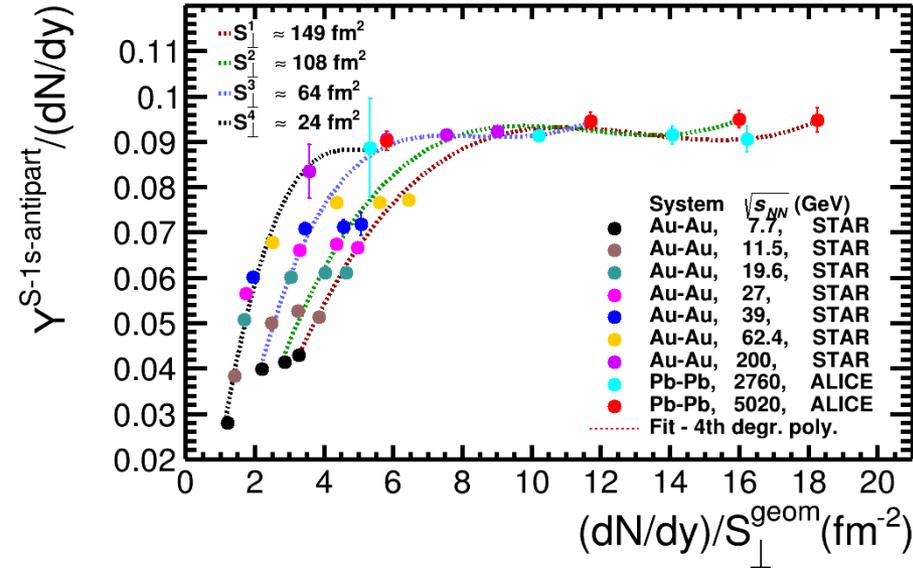


$(dN/dy)^{\text{(strange and multi strange)}}/(dN/dy) - (dN/dy)/S_{\perp}$  correlation

vs

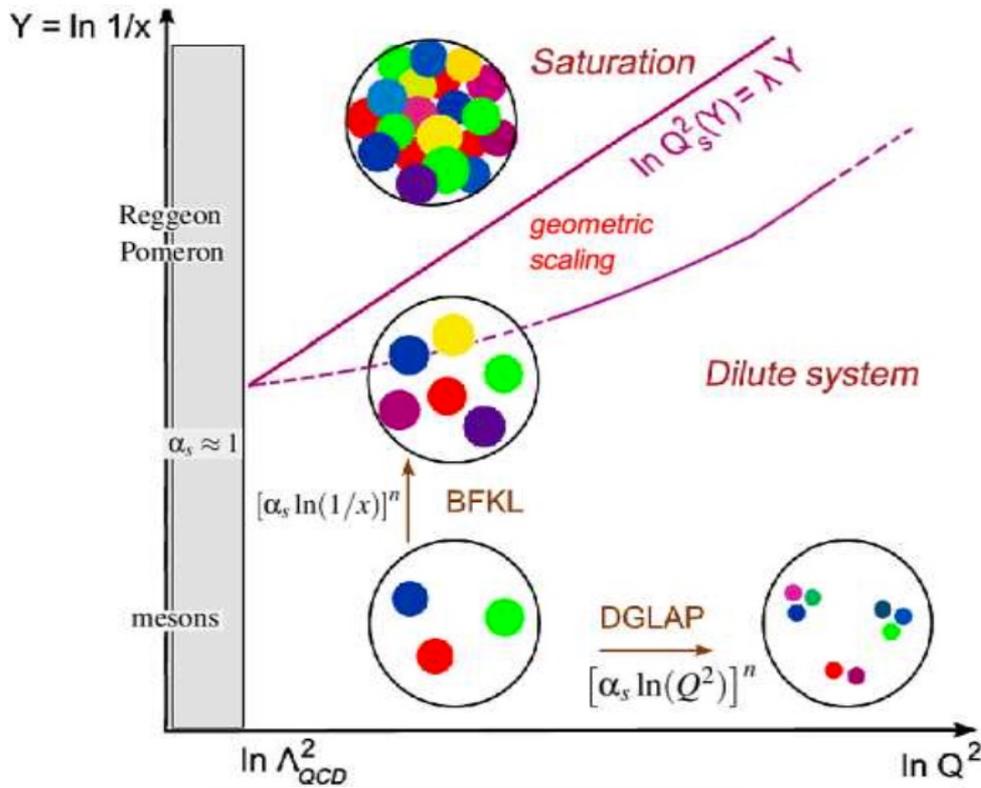
$(dE_T/dy)/(dN/dy) - (dN/dy)/S_{\perp}$  correlation

$S_{\perp}$  - dependence

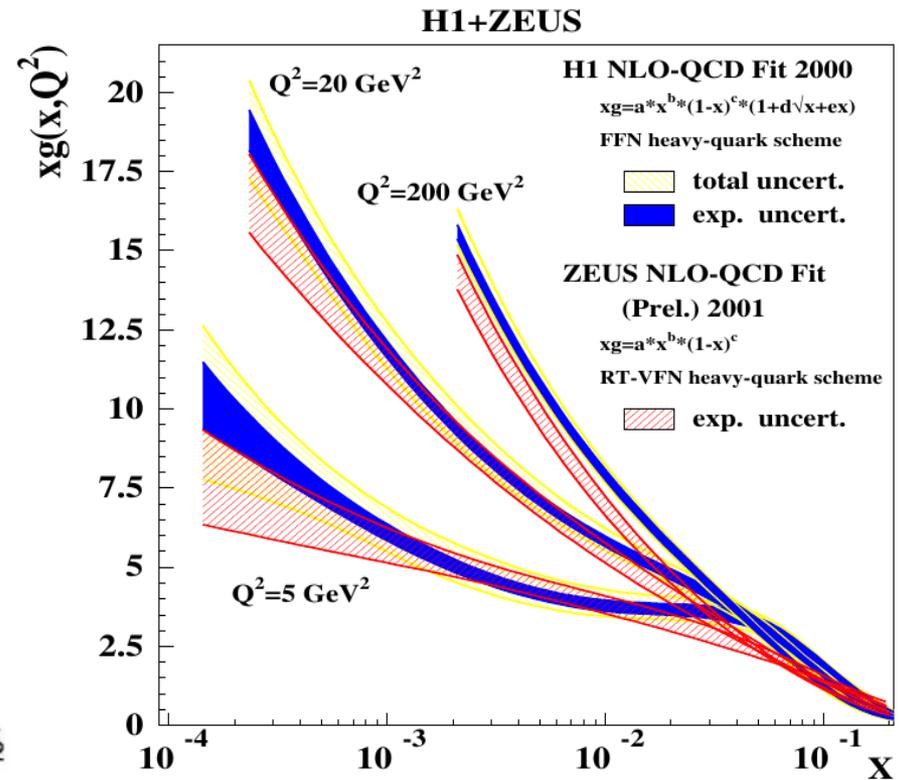


M.Petrovici and A.Pop, [arXiv:2209.08828](https://arxiv.org/abs/2209.08828) [hep-ph]

# A-A vs pp @ LHC



D. d'Enterria, Eur.Phys.J. A31(2007)816

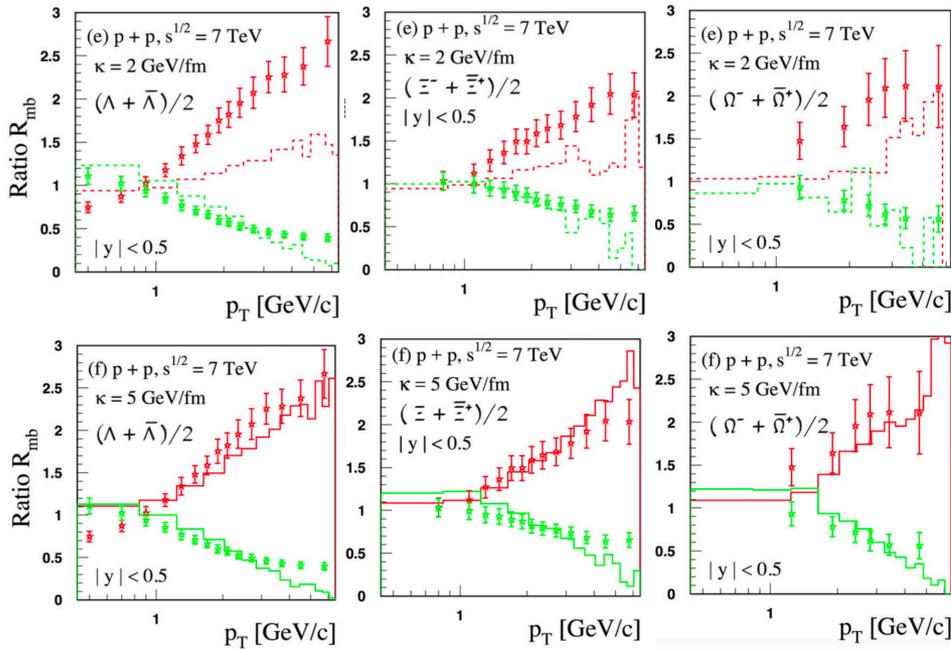


M.Dittmar et al., Proceedings HERA-LHC Workshop arXiv:[hep-ph]0511119

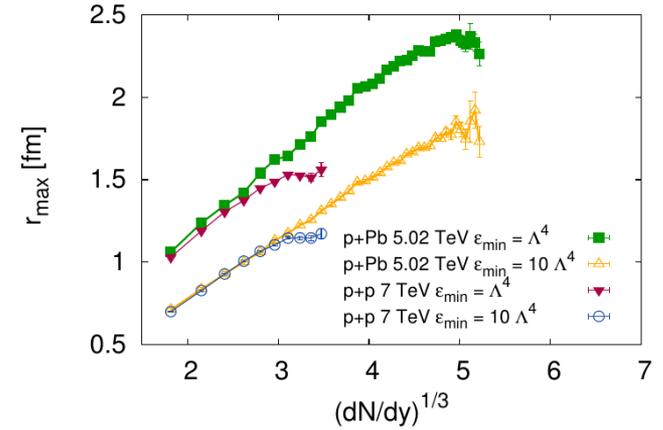
Following A.H. Mueller  
Nucl.Phys. A715(2003)20

System	Au-Au	Pb-Pb	Pb-Pb	pp
$\sqrt{s}(\text{GeV})$	200	2,760	5,020	7,000
$\frac{dN_g^{in}}{dyd^2b}(\text{fm}^{-2})$	$\approx 5.2$	$\approx 11.7$	$\approx 15.3$	$\approx 16.3$

# Short review A-A vs pp @ LHC



V. Topor Pop and M. Petrovici, Phys. Rev. C 98, 064903 (2018).



A. Bzdak et al., Phys. Rev. C 87(2013)064906

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

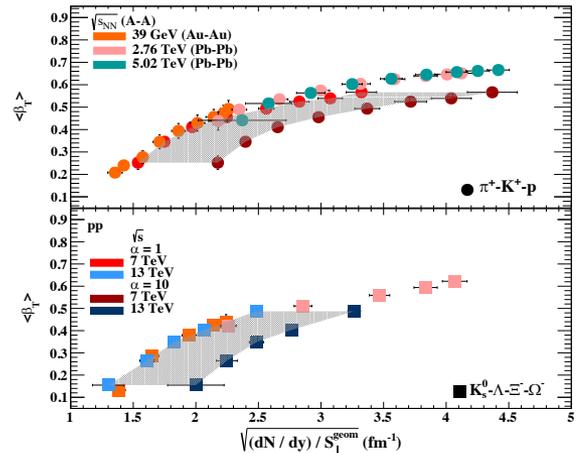
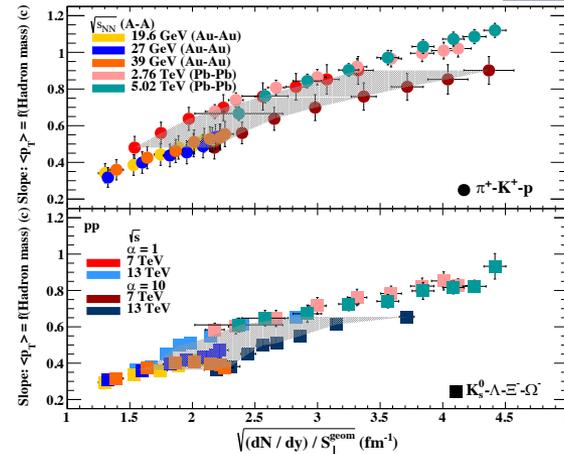
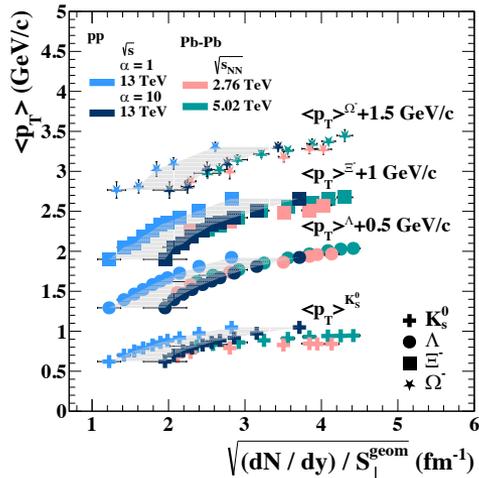
$$S_{\perp}^{pp} = \pi R_{pp}^2$$

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

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

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

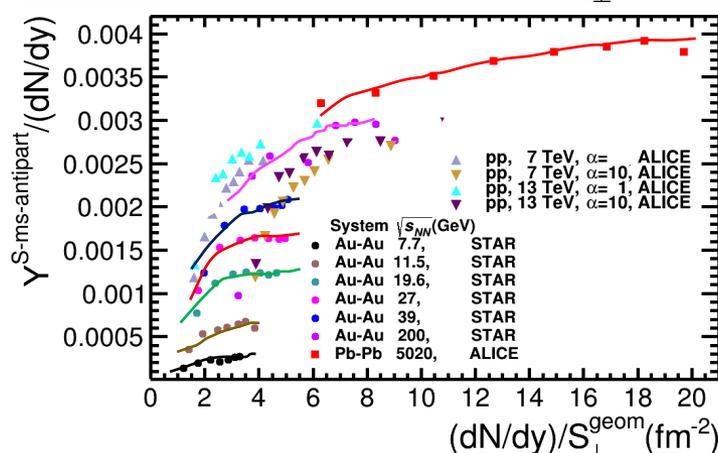
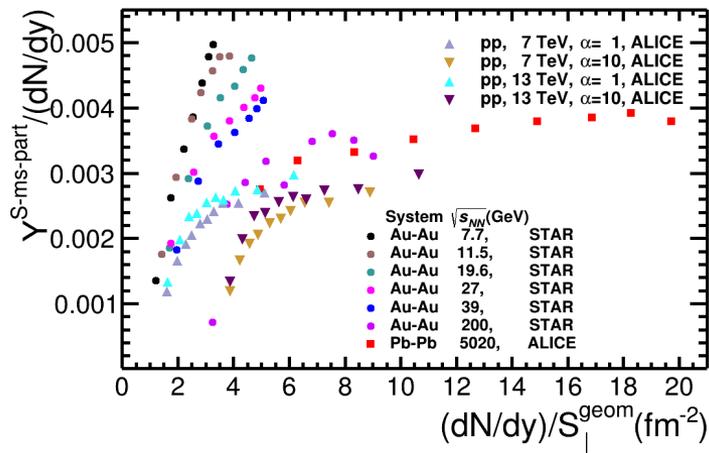
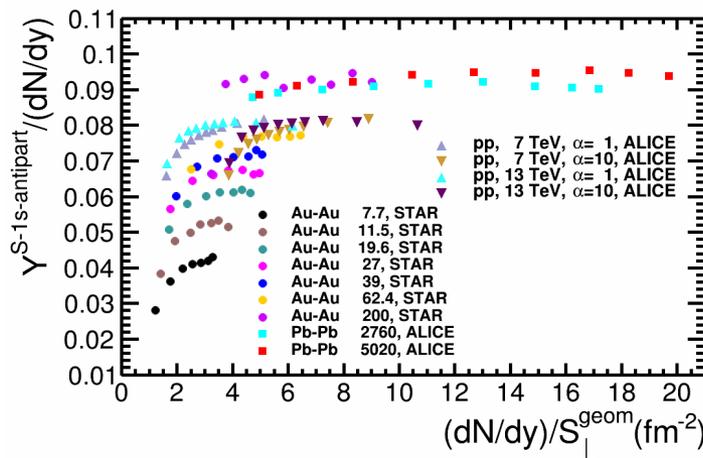
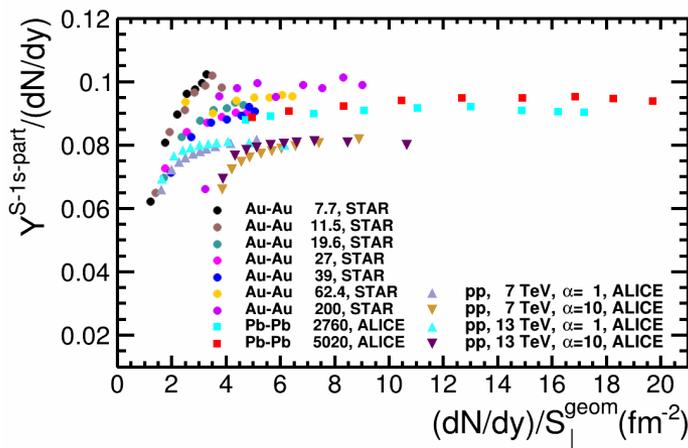
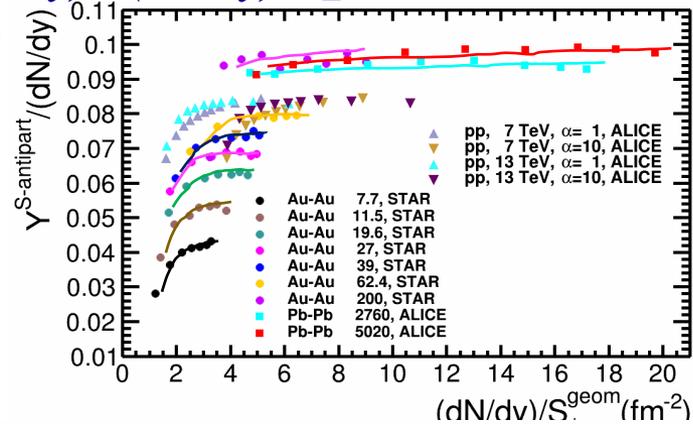
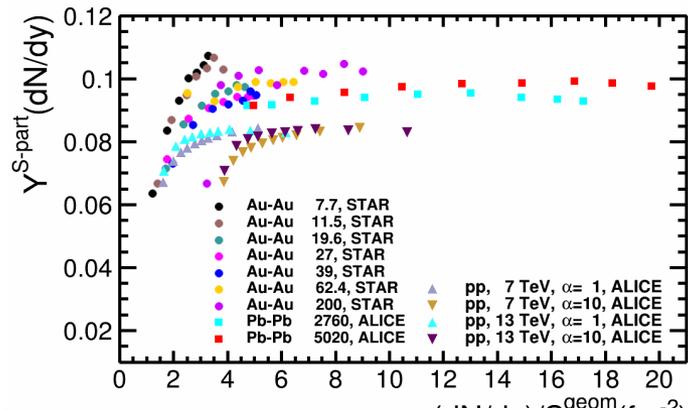
McLarren, M. Praszalowicz and B. Schenke, Nucl. Phys. A 916(2013)210



A. Lindner et al., Proceedings of Science (PoS) 380(2021)197 (PANIC2021), <https://pos.sissa.it/380/197/>.

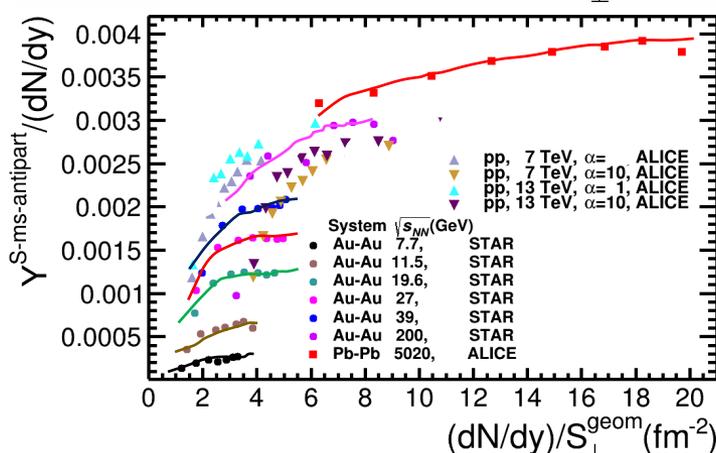
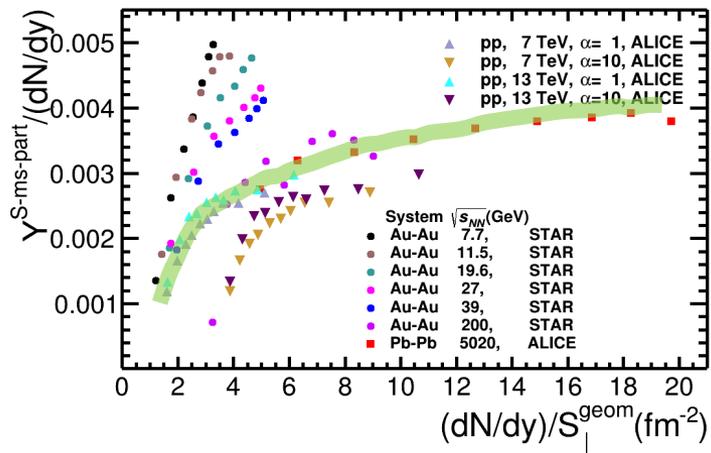
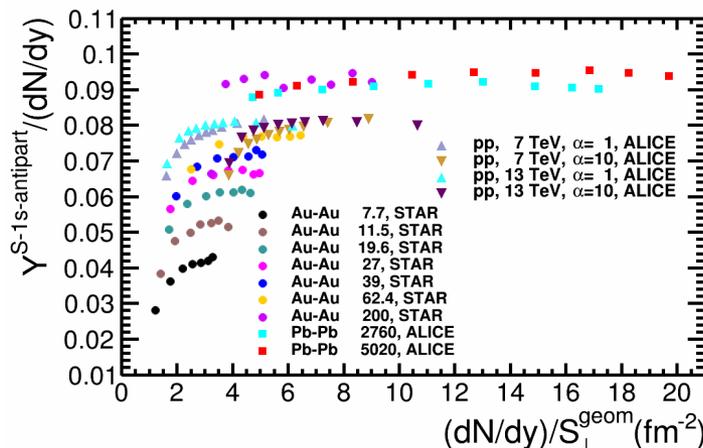
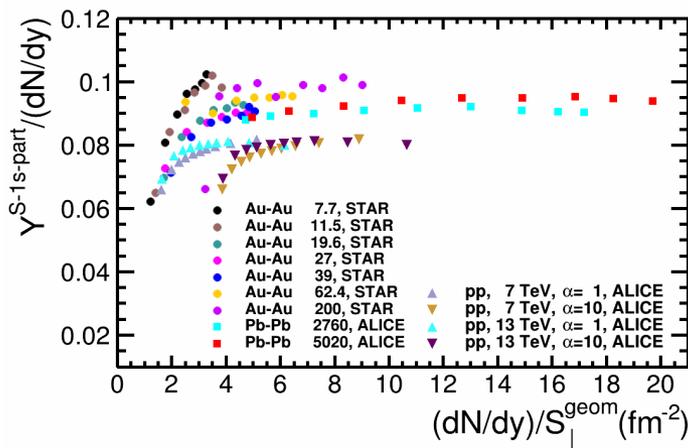
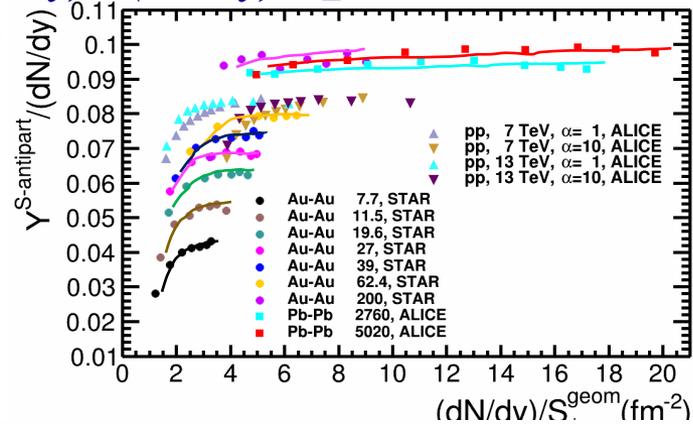
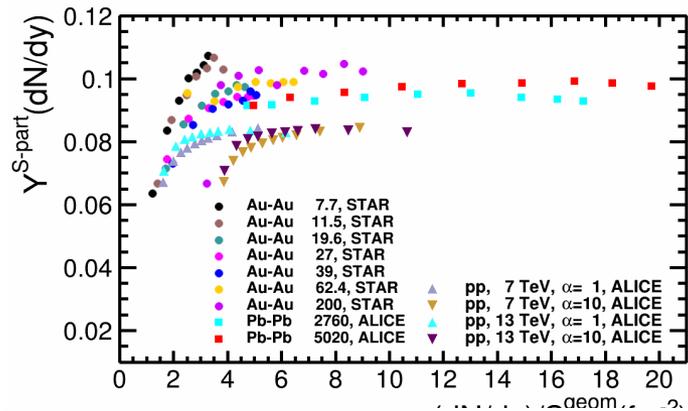
$(dN/dy)_{\text{strange and multi strange}} / (dN/dy) - (dN/dy) / S_{\perp}$

*A-A vs pp*



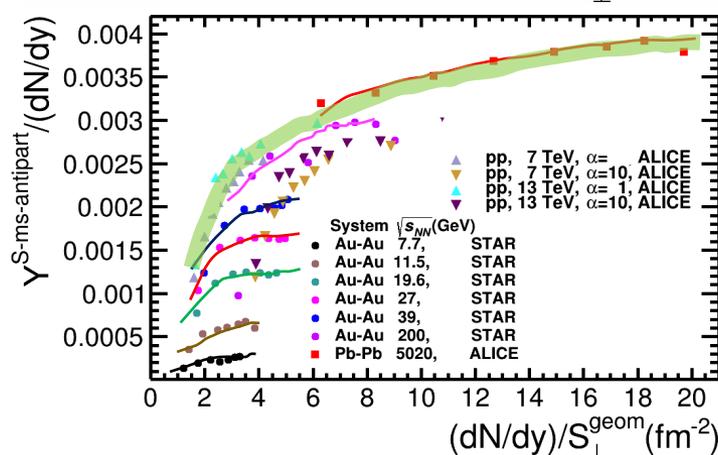
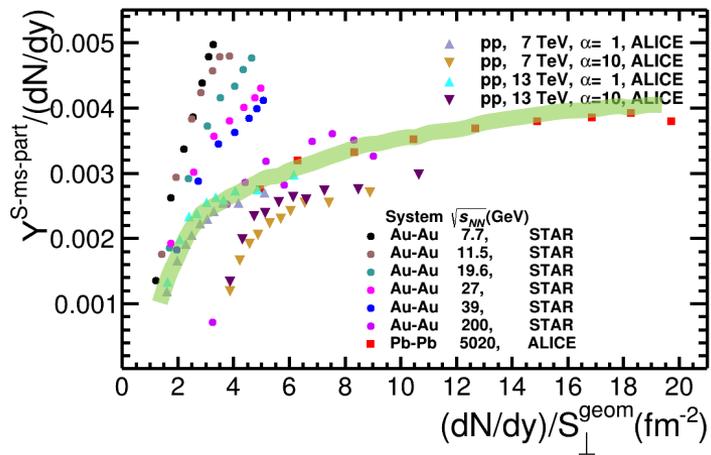
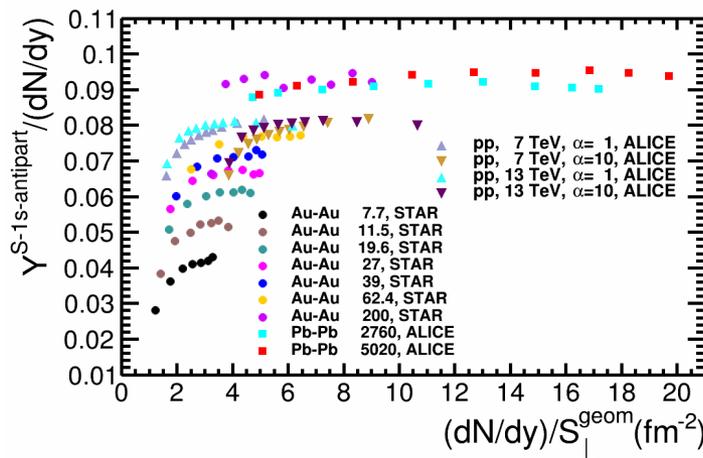
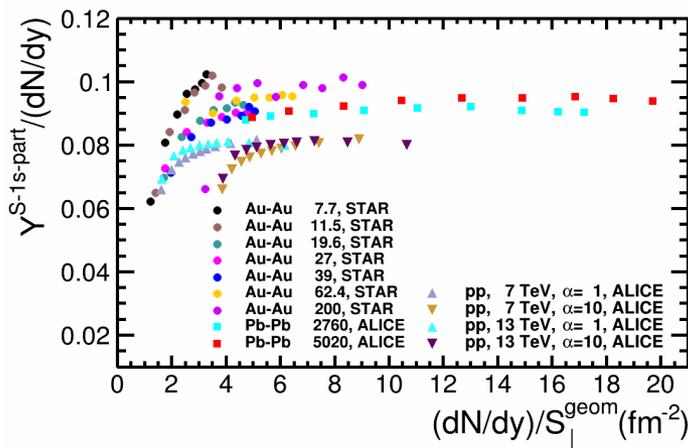
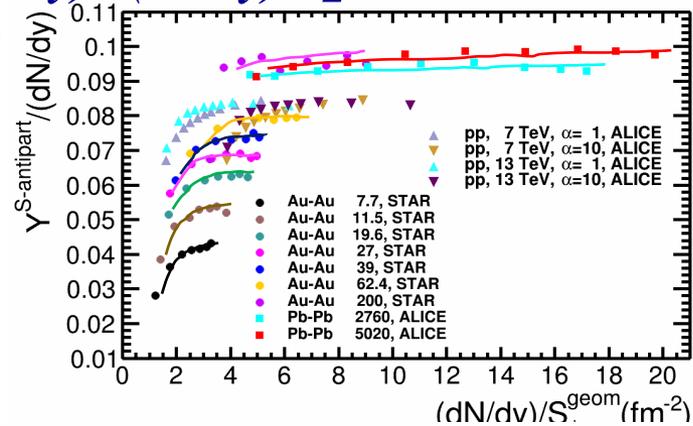
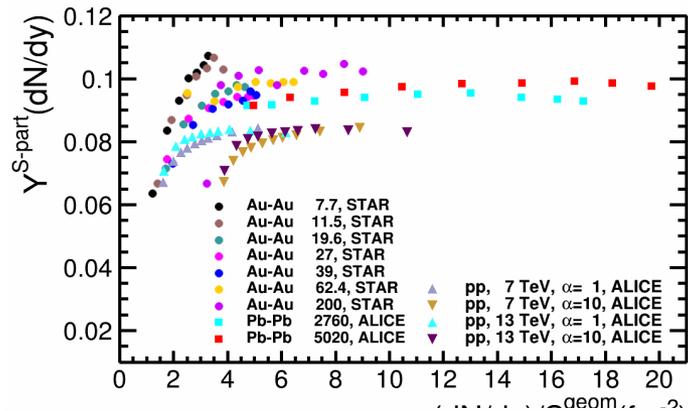
$$(dN/dy)_{\text{strange and multi strange}} / (dN/dy) - (dN/dy) / S_{\perp}$$

*A-A vs pp*



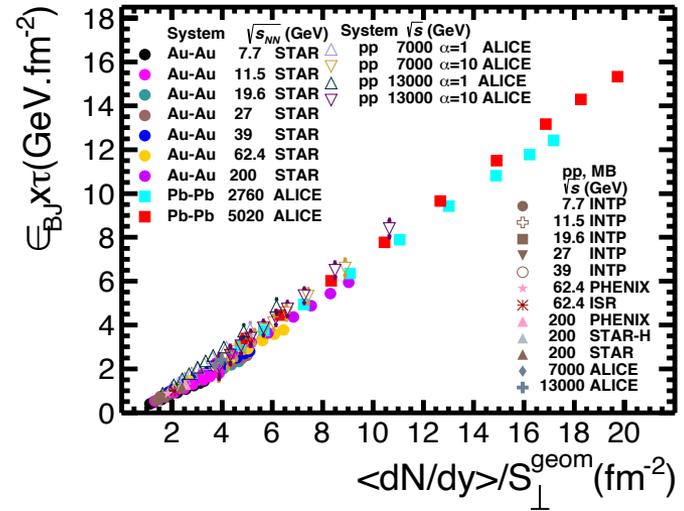
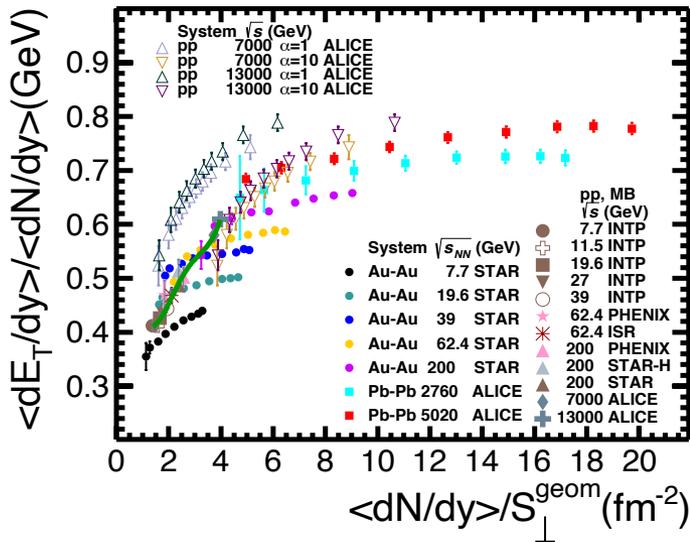
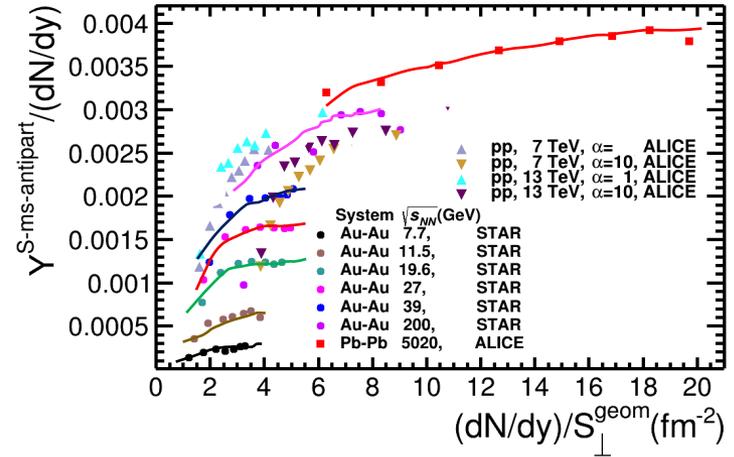
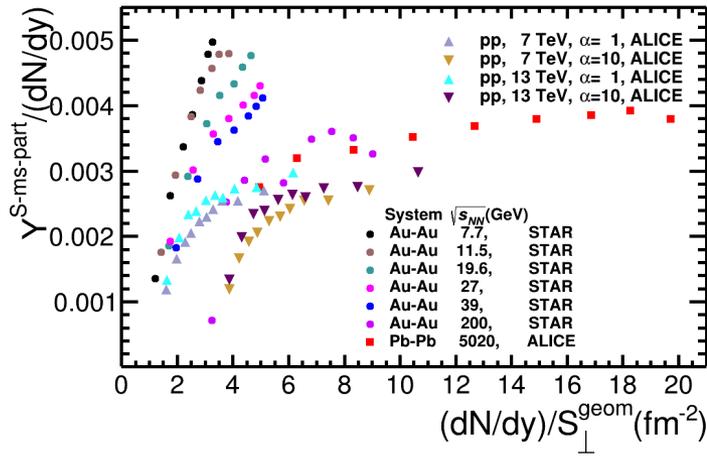
$$(dN/dy)_{\text{strange and multi strange}} / (dN/dy) - (dN/dy) / S_{\perp}$$

*A-A vs pp*



$$(dN/dy)^{\text{(strange and multi strange)}} / (dN/dy) - (dN/dy) / S_{\perp}$$

## A-A vs pp

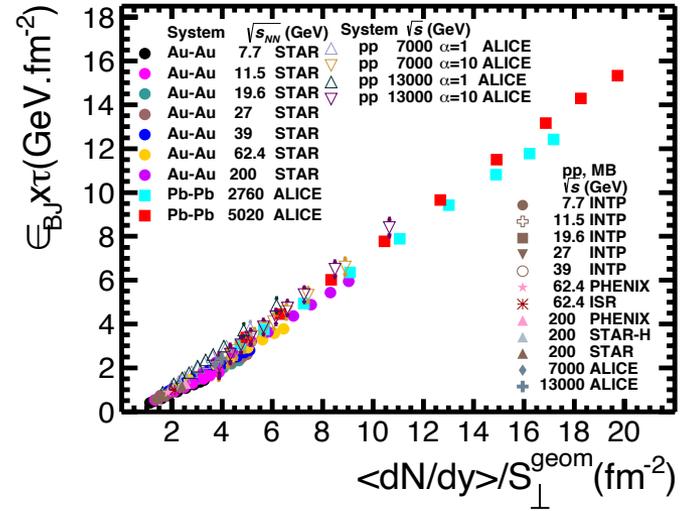
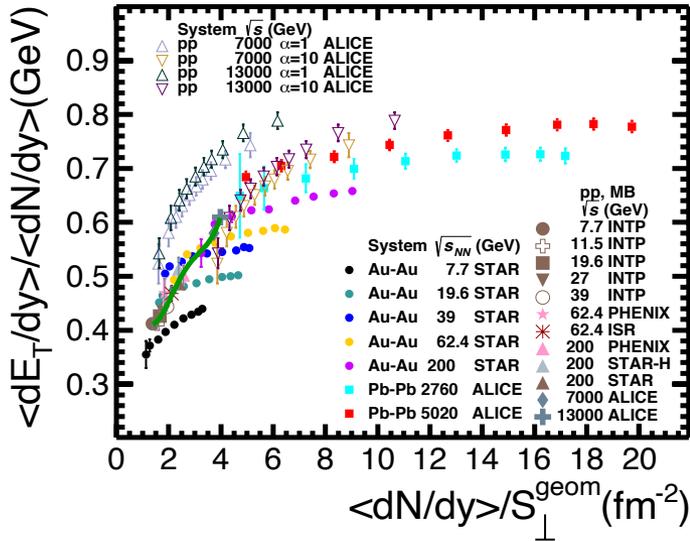
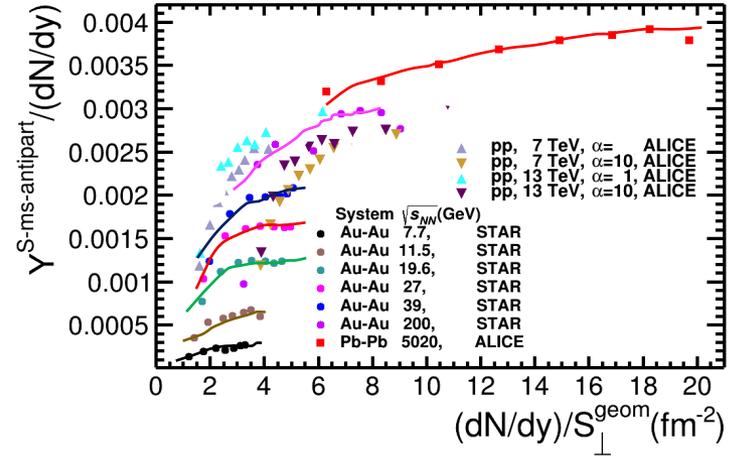
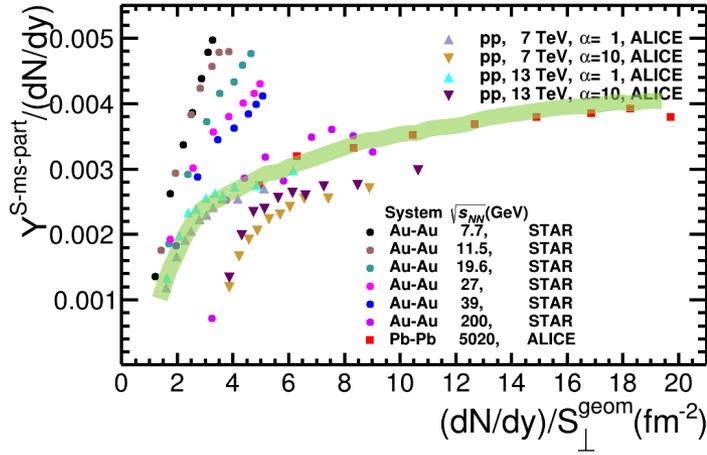


M. Petrovici and A. Pop, [arXiv:2209.08828](https://arxiv.org/abs/2209.08828) [hep-ph]

Highest charged particle multiplicity in pp MB at midrapidity selected by “V0M” by ALICE Collaboration !!!

$$(dN/dy)^{\text{(strange and multi strange)}} / (dN/dy) - (dN/dy) / S_{\perp}$$

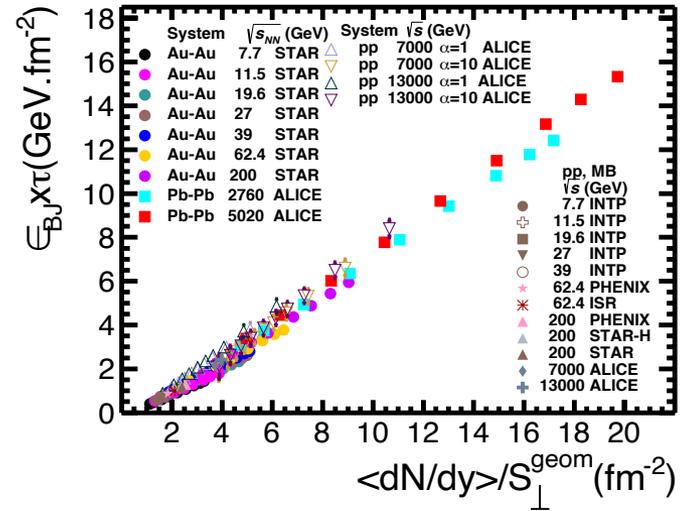
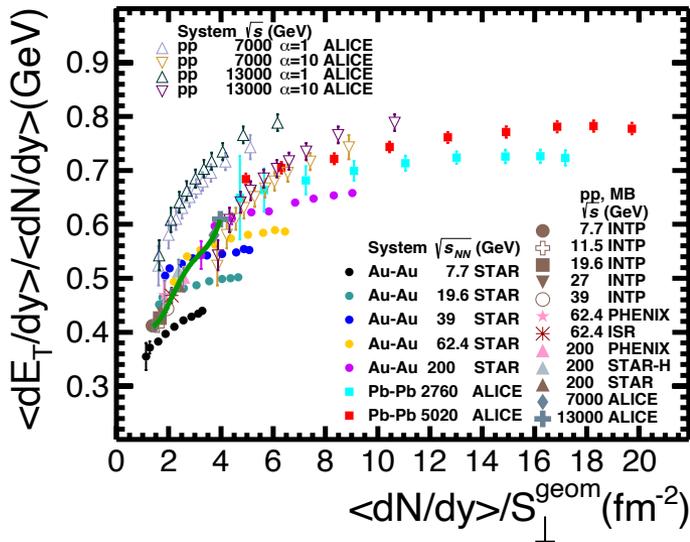
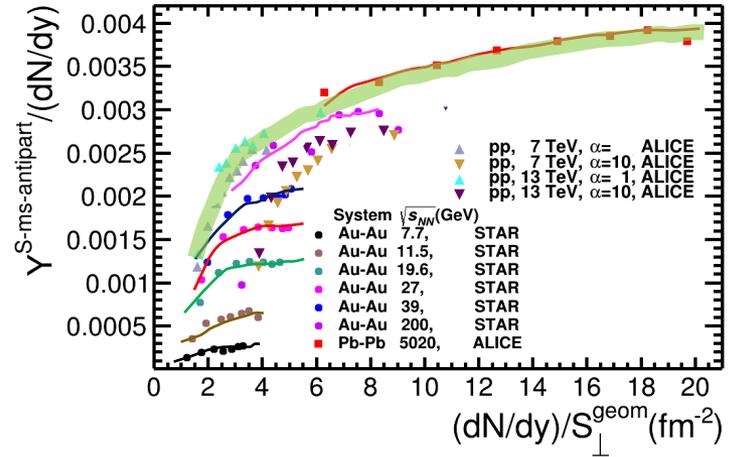
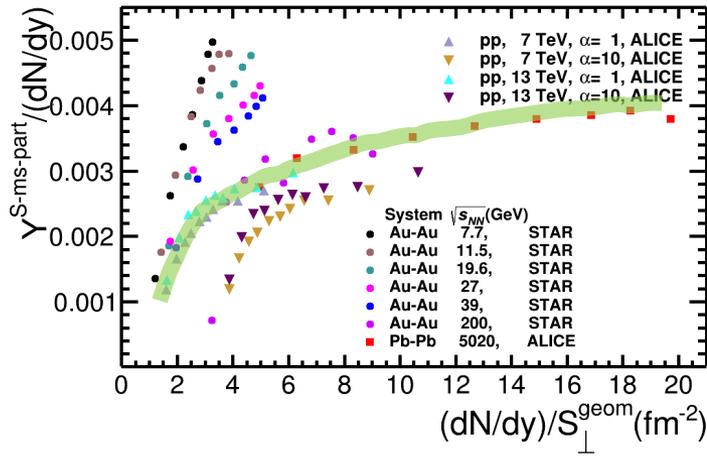
## A-A vs pp



M.Petrovici and A.Pop, [arXiv:2209.08828](https://arxiv.org/abs/2209.08828) [hep-ph]

$$(dN/dy)^{\text{(strange and multi strange)}} / (dN/dy) - (dN/dy) / S_{\perp}$$

## A-A vs pp



M.Petrovici and A.Pop, [arXiv:2209.08828](https://arxiv.org/abs/2209.08828) [hep-ph]

# Outlook

- *A clear transition in the:*
  - $(dE_T/dy)/(dN/dy) - (dN/dy)/S_{\perp}$  correlation
  - and
  - slope of  $\varepsilon_{Bj} \cdot \tau - (dN/dy)/S_{\perp}$*in the region of the highest RHIC collision energy, followed by a steep rise at the LHC energies*
- *A similar trend is evidenced in  $(dN/dy)^{(\text{strange and multi strange})}/(dN/dy) - (dN/dy)/S_{\perp}$  correlation*
- *The  $(dE_T/dy)/(dN/dy) - (dN/dy)/S_{\perp}$  and  $\varepsilon_{Bj} \cdot \tau - (dN/dy)/S_{\perp}$  correlations for pp collisions at  $\sqrt{s}=7$  and 13 TeV follow qualitatively the ones corresponding to Pb-Pb collisions at  $\sqrt{s_{NN}}=5.02$  TeV*
- *$(dN/dy)^{(\text{multi strange})}/(dN/dy) - (dN/dy)/S_{\perp}$  correlations in pp collisions at LHC energies follow the trend observed in Pb-Pb collisions*
- *At the LHC energies the global features of the interactions are mainly determined by the properties of the initial chromoelectric flux tubes, the system size playing a minor role.*
- *The need of theoretical models able to explain all the features evidenced in the multi-differential analysis and representations of experimental information in order to pin down the relative contribution of the main processes behind*

# *Back-up*

*A few considerations based on our studies*

