MINISTERUL CERCETĂRII,
INOVĂRII ȘI DIGITALIZĂRII

www.ifin.ro

An overview
on some global trends observed in heavy ion collisions based on experimental results from AGS up to LHC energies
and
on similarities between pp and Pb-Pb collisions at LHC

Results obtained in collaboration with A. Pop, C. Andrei, I. Berceanu, A. Lindner, M. Tarzila

Mihai Petrovici, QCD Challenges, 2-6 September 2024, Munster, Germany

Outline

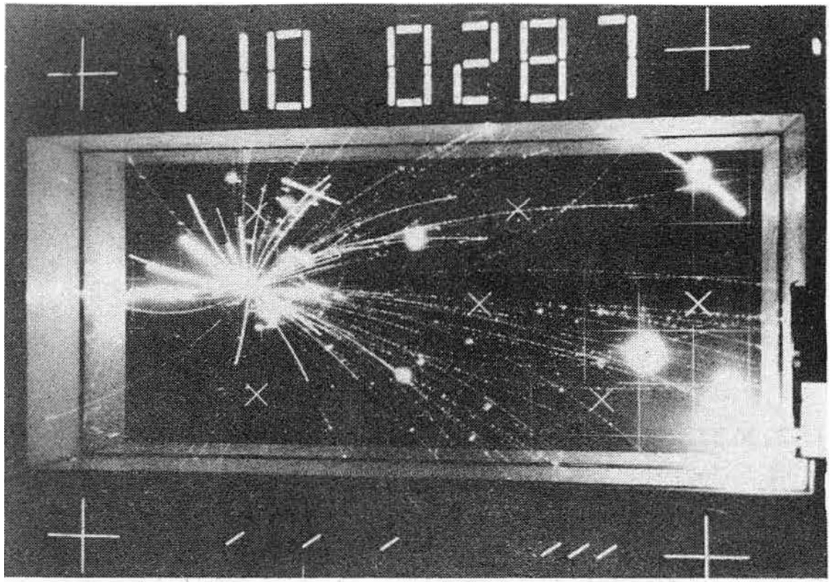
- ***Introduction***
- *$<p_T>/[(dN/dy)/S_\perp]^{1/2}$* ***centrality and collision energy dependence***
- *$[(dN/dy)/S_\perp]^{1/2}$* ***scaling***
- *$\langle dE_T/dy\rangle/\langle dN/dy\rangle$ - $\langle dN/dy\rangle/S_\perp$* ***correlation***
- ***The slope of*** *$\varepsilon_{Bj}\cdot\tau$ - $\langle dN/dy\rangle/S_\perp$* ***correlation - energy dependence***
- *$(dN/dy)^{(\text{strange and multi strange})}/(dN/dy)$ - $(dN/dy)/S_\perp$* ***correlation***
- ***Similar studies for pp collisions and comparison with Pb-Pb collisions***
- ***Concluding remark***

50th anniversary of high energy heavy-ion

- ***The high-energy heavy-ion program at LBL has started in summer 1974 (CERN Courier, June 1974)***

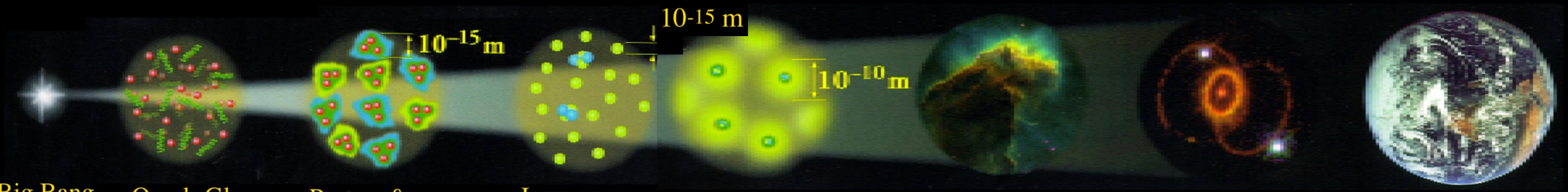
- ***A University of Frankfurt group has exposed their AgCl detectors to various heavy-ion beams at energies from 250 MeV/A to 2.1 GeV/A.***
  The observed peaks in the angular distributions of light fragments that moved with beam energy in a manner suggestive of these particles arising from shock waves, causing considerable excitement in the nuclear science community.

- ***After being used for several high energy experiments, the LBL streamer chamber used in the collision of 1.8-GeV/nucleon Ar on a lead oxide target, evidenced charged particle multiplicities of over 100 in such reactions.***



https://escholarship.org/uc/item/8bw3436f

Could we unravel the History of the Universe



Big Bang

Quark-Gluon Plasma
10^{13}K, 10^{-6}s

Protons& Neutrons
10^{12}K, 10^{-4}s

Low-mass Nuclei
10^{9}K, 3 min

Neutral Atoms
4000K, 10^{5}y

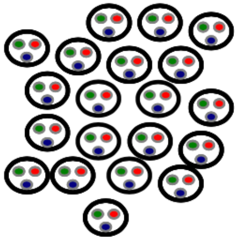
Star Formation
10^{9}y

Heavy Elements
$>10^{9}$y

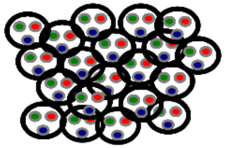
Today

based on experiments in terrestrial laboratories ?

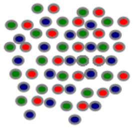
How to produce extreme states of nuclear matter in terrestrial laboratories ?



Strongly Bound Clusters
Hadrons



Phase transition

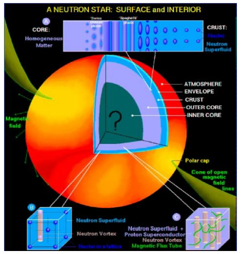


Weekly interacting
Quarks and Gluons

A phase transition is expected at:

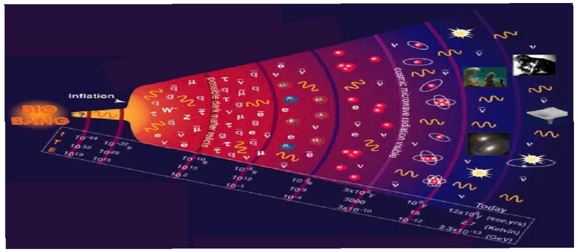
$\rho_B \sim \Lambda_{QCD}^3 \sim 1 fm^{-3}$

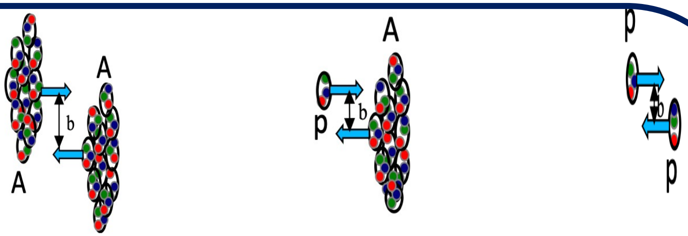
~ 16 km
~ 10^{16} sec



$T \sim \Lambda_{QCD} \sim O\ (10^{12}\ K)$

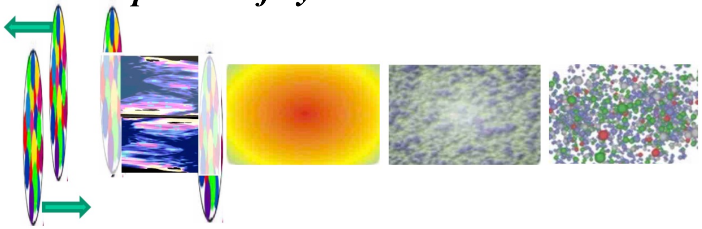
~ 10 km
~ 10^{-6} sec

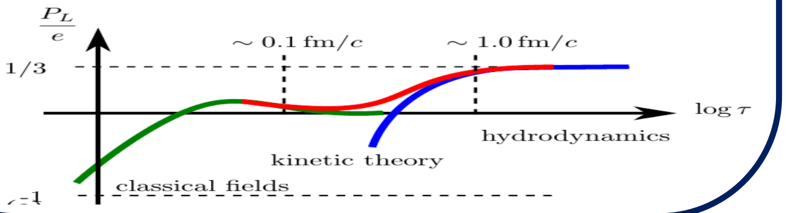




Snap shots of dynamical evolution

~ 6 fm
~ 10^{-22} sec



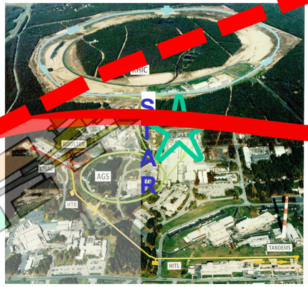


A. Mazeliauskas, Nucl.Phys. A 00(2018)1
QM 2018

Large scale facilities

LHC: Collider
Pb+Pb @5020GeV/A

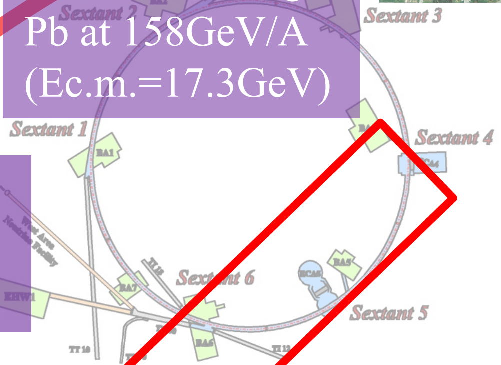
RHIC: Collider
Au+Au @ 200GeV/A



?

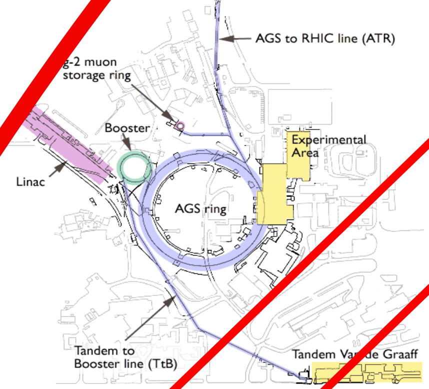
Hotter
Denser
Longer
Bigger

SPS: Fixed Target
Pb at 158GeV/A
(Ec.m.=17.3GeV)



???

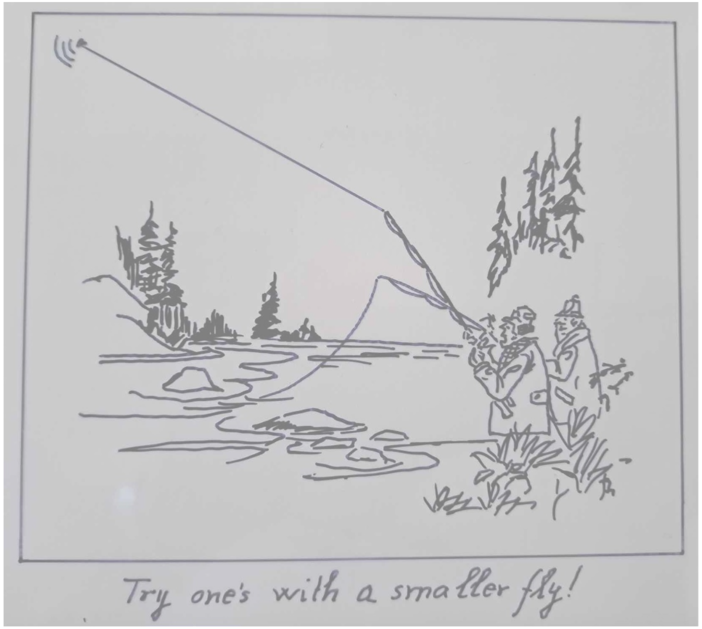
AGS: Fixed Target
Au at 11.7GeV/A
(Ec.m.=4.86GeV)



BES

Bevalac
Fixed Target
1-2GeV/A

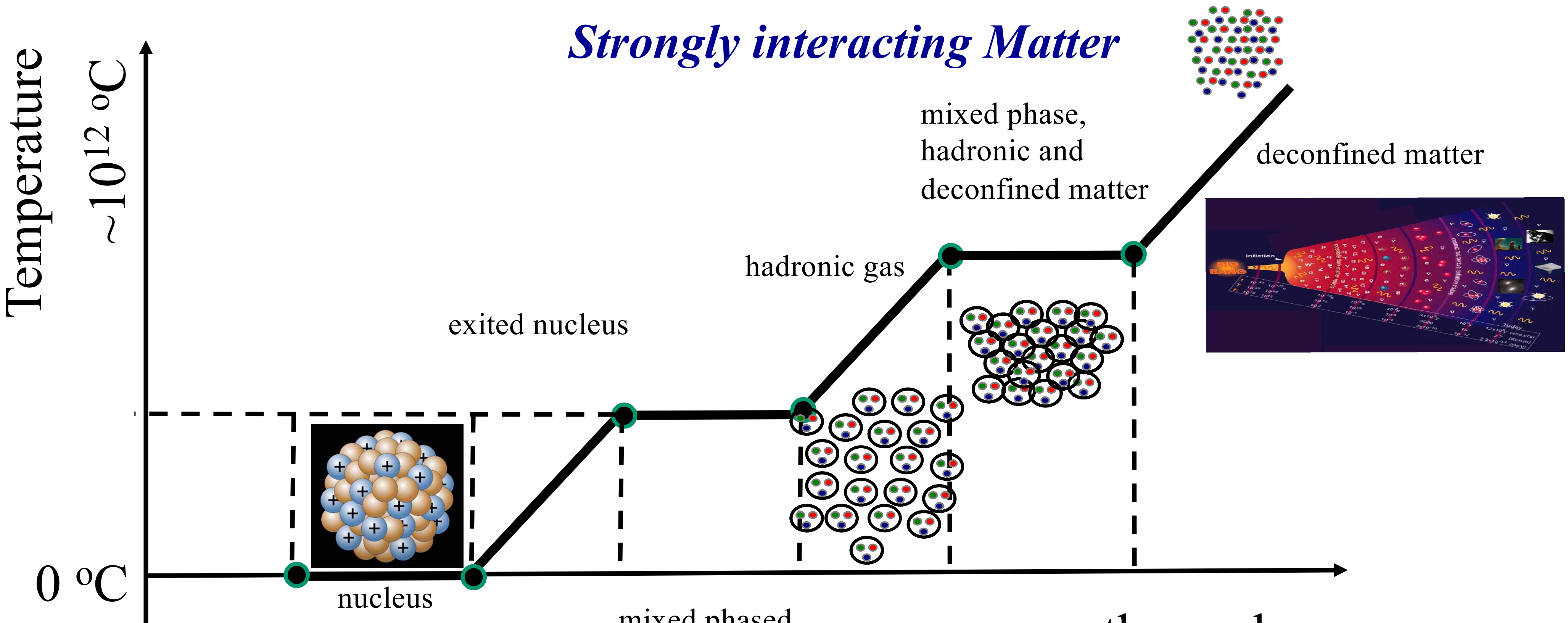
SIS 18

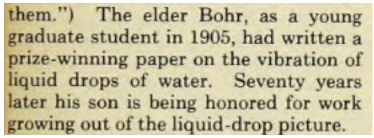


Try one's with a smaller fly!

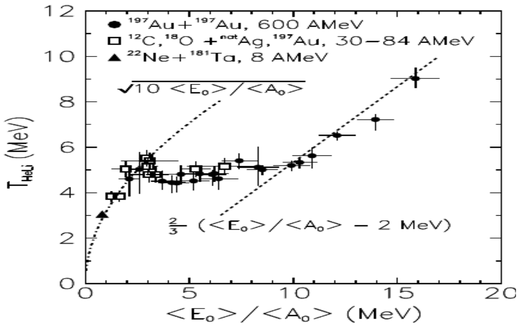
Physics motivation

Strongly interacting Matter

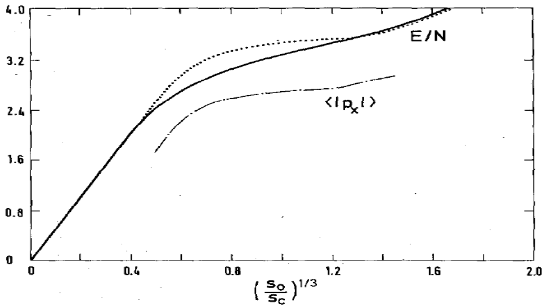




them.") The elder Bohr, as a young graduate student in 1905, had written a prize-winning paper on the vibration of liquid drops of water. Seventy years later his son is being honored for work growing out of the liquid-drop picture.



J.Pochodzalla et al.,
ALADIN Coll.,
arXiv:[nucl-ex]9607004



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

Theory predictions

String percolation

T.S.Biro, H.B.Nielsen and J.Knoll, Nucl.Phys. B245(1984)449
J.Dias de Deus and C. Pajares, Phys.Lett. B695(2011)211
I. Bautista et al., Revista Mexicana de Fisica 65(2019)197

$$\frac{dN}{dy} = F(\eta)\bar{N}^s\mu$$

$\eta \equiv (r_0/R)^2\bar{N}^s$ - transverse string density; $\bar{N}^s$ - the average number of strings

μ - string multiplicity

$$F(\eta) \equiv \sqrt{\frac{1-e^{-\eta}}{\eta}}$$

$\langle p_T^2\rangle = \langle p_T^2\rangle_1/F(\eta)$ $\langle p_T^2\rangle_1$ - average string transverse momentum

$$\sqrt{\langle p_T^2\rangle}/\sqrt{\langle dN/dy\rangle/S_\perp} \sim 1/\sqrt{(1-e^{-\eta})}$$

$<p_T^2>/[(dn/dy)/S_\perp] \propto <p_T^2>_1 r_0^2/\mu\,(1-e^{-\eta})$

CGC

Local parton-hadron duality picture and dimensionality argument

- *Y.L.Dokshitzer, V.A.Khoze and S.Troian, J.Phys.G 17 (1991) 1585*
- *T. Lappi, Eur.Phys.J. C71 (2011) 1699*
- *E. Levin and A.H. Rezaeian, Phys.Rev.D 83 (2011)114001*

$$\langle p_T\rangle/\sqrt{\frac{dN}{dy}/S_\perp} \sim \frac{1}{n\sqrt{n}}$$

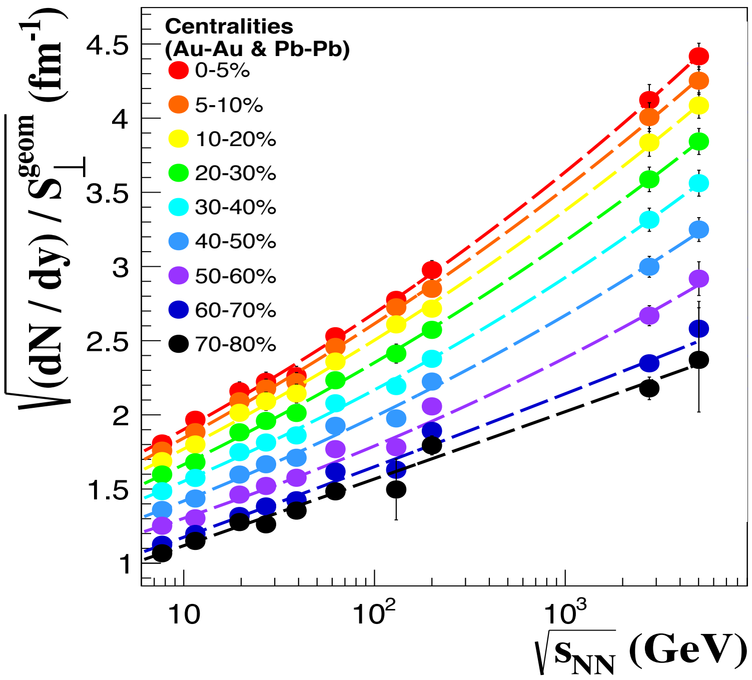
n - *no. of charged particles from a gluon fragmentation*

$$\downarrow$$

$$\langle p_T\rangle/\sqrt{\frac{dN}{dy}/S_\perp}$$

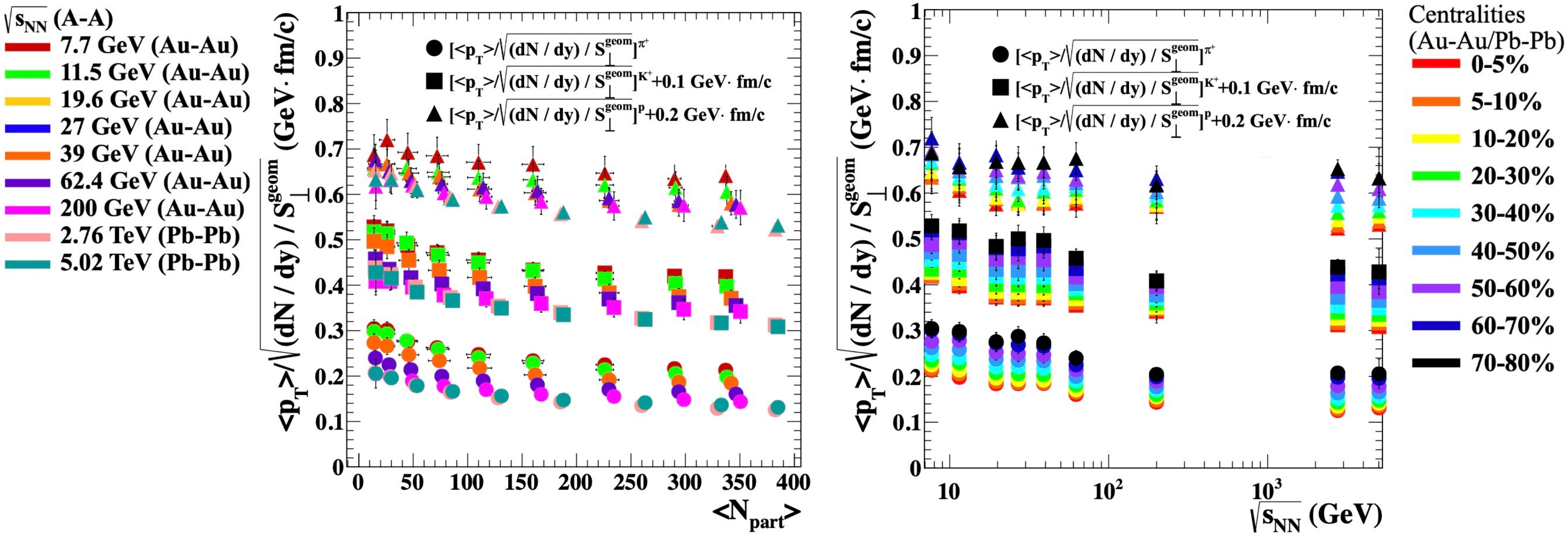
decreases as a function of:

- *collision energy*
- *centrality*

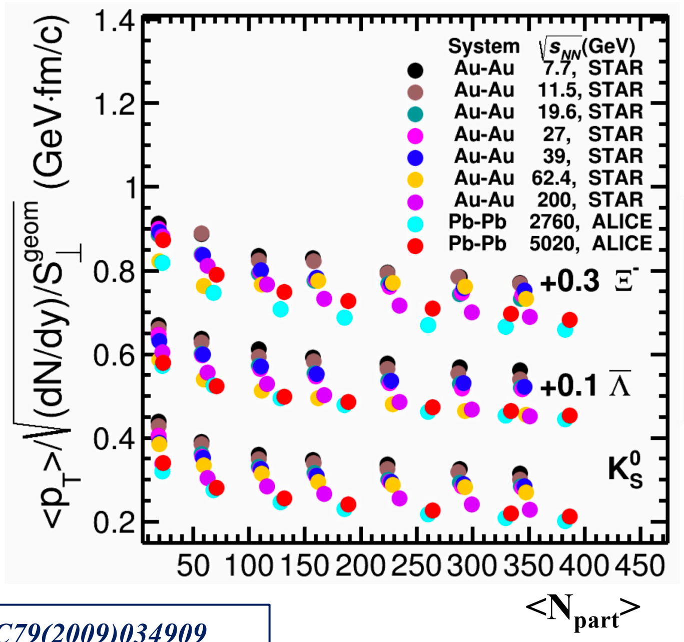


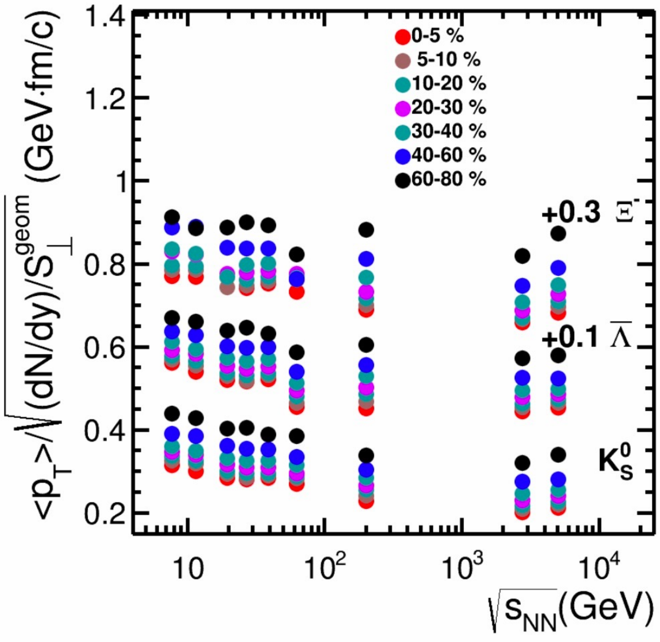
M.Petrovici, A.Lindner and A.Pop, Phys. Rev. C 98(2018)024904

Experimental results



M.Petrovici, A.Lindner and A.Pop, Phys. Rev. C 98(2018)024904

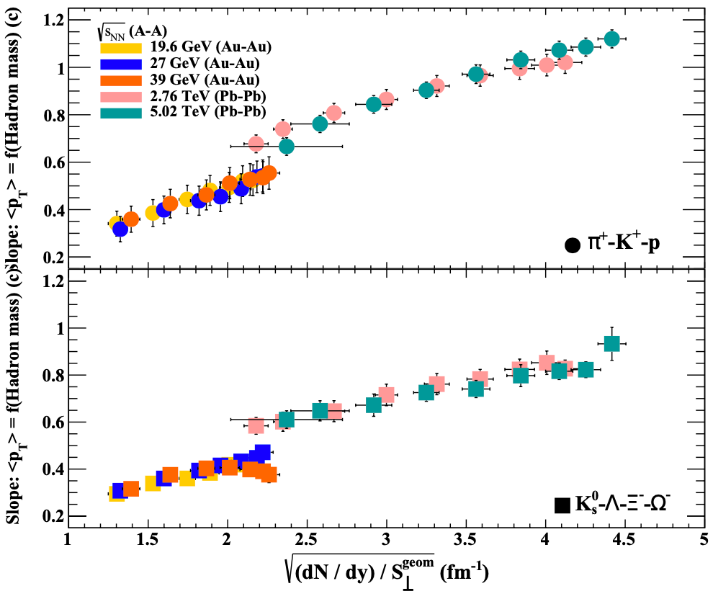


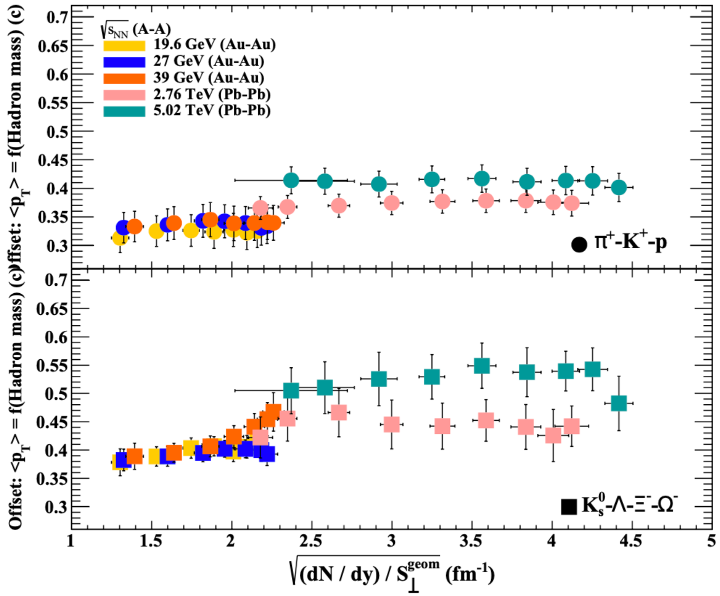


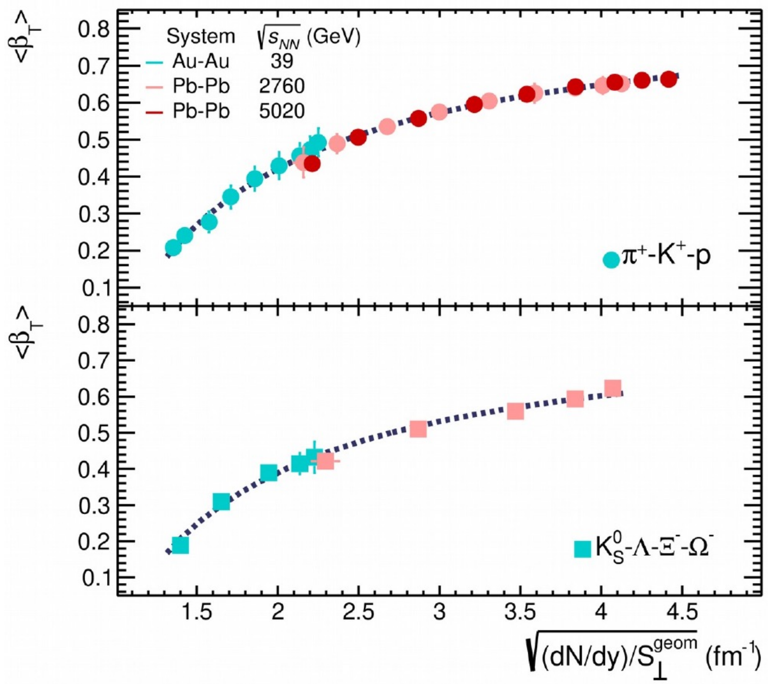
STAR Collaboration, Phys. Rev. C79(2009)034909
ALICE Collaboration, Phys. Rev. C88(2013)044910
STAR Collaboration), Phys. Rev. C96(2017)044904
ALICE Collaboration), Nucl. Phys. A967(2017)421

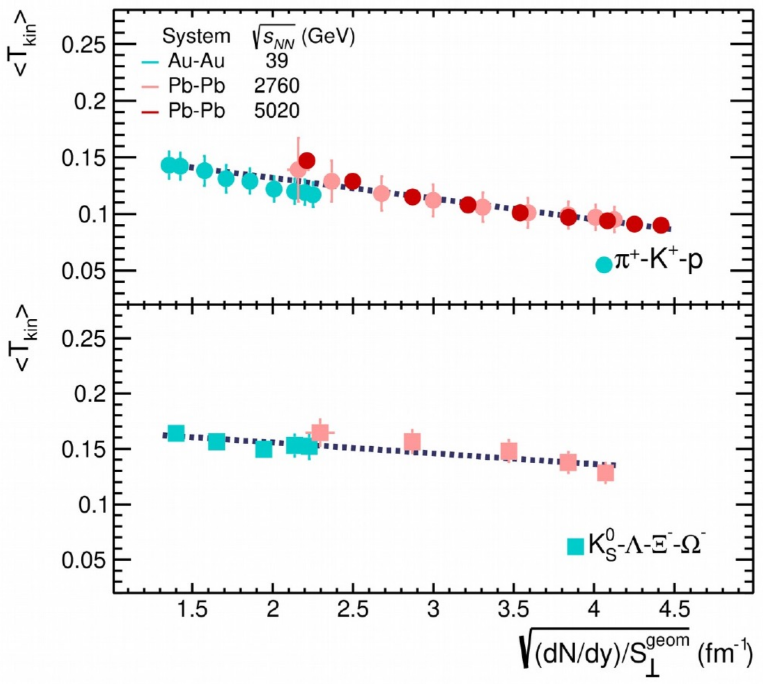
M. Petrovici and A. Pop , EuNPC 2022

$[(dN/dy)/S_\perp]^{1/2}$ scaling



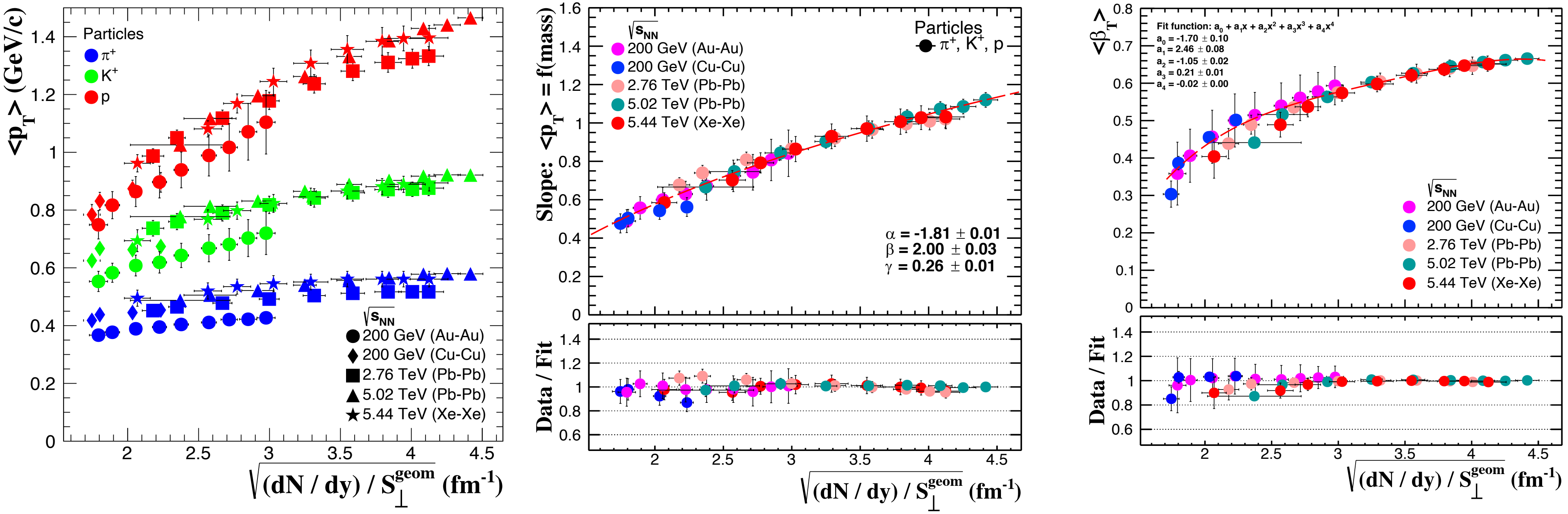






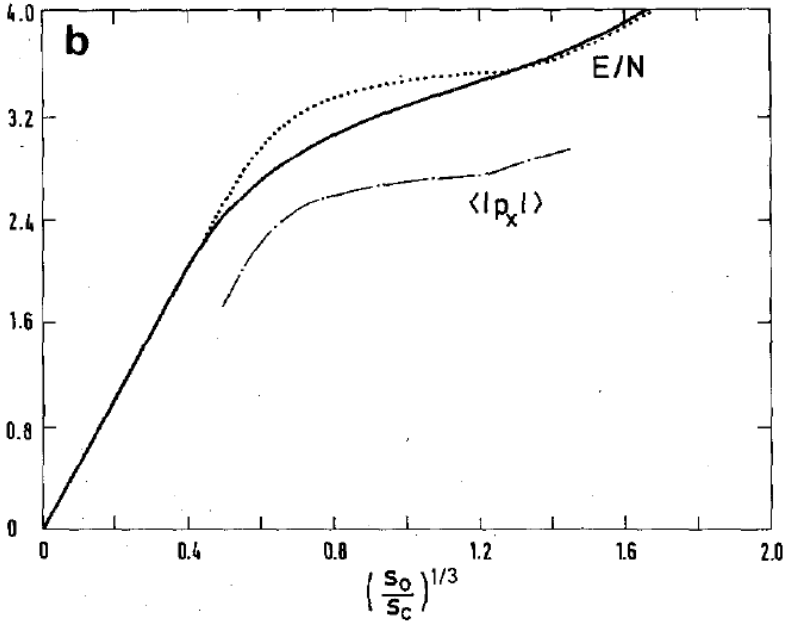
M. Petrovici et al., Phys. Rev. C 98(2018)024904
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

$[(dN/dy)/S_{\perp}]^{1/2}$ scaling



M. Petrovici, A. Lindner and A. Pop, AIP Conf.Proc. 2076 (2019) 1, 040001

Signature for phase transition ?



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

- <u>AGS si SPS</u>
- •S. Chatterjee et al., Advances in High Energy Physics 2015, 349013 (2015).

- <u>BES</u>
- •J. Adam et al. (STAR Collaboration), Phys. Rev. C 102, 034909 (2020).

- <u>RHIC 62.4 GeV and 200 GeV</u>
- • 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).
- •G. Agakishiev et al. (STAR Collaboration), Phys. Rev. Lett. 108, 072301 (2012).
- • 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

- <u>ALICE 2.76 TeV</u>
- •B. Abelev et al. (ALICE Collaboration), Phys. Rev. Lett. 111, 222301 (2013).
- •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

- <u>ALICE 5.02 TeV</u>
- •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).
- • L. Adamczyk et al. (STAR Collaboration), Phys. Rev. C 96, 044904 (2017). - RHIC, 62.4 si 200 GeV
- • B. Abelev et al. (ALICE Collaboration), Phys. Rev. C 88, 044910 (2013). - ALICE 5.02 TeV
- • S. Acharya et al. (ALICE Collaboration), Phys. Rev. C 101, 044907 (2020).

$E/N \sim \epsilon/s = E_{fo}/S_{fo}\ ;\ s(T_0) = a(1/R_0^3)(dN/dy)$

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

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

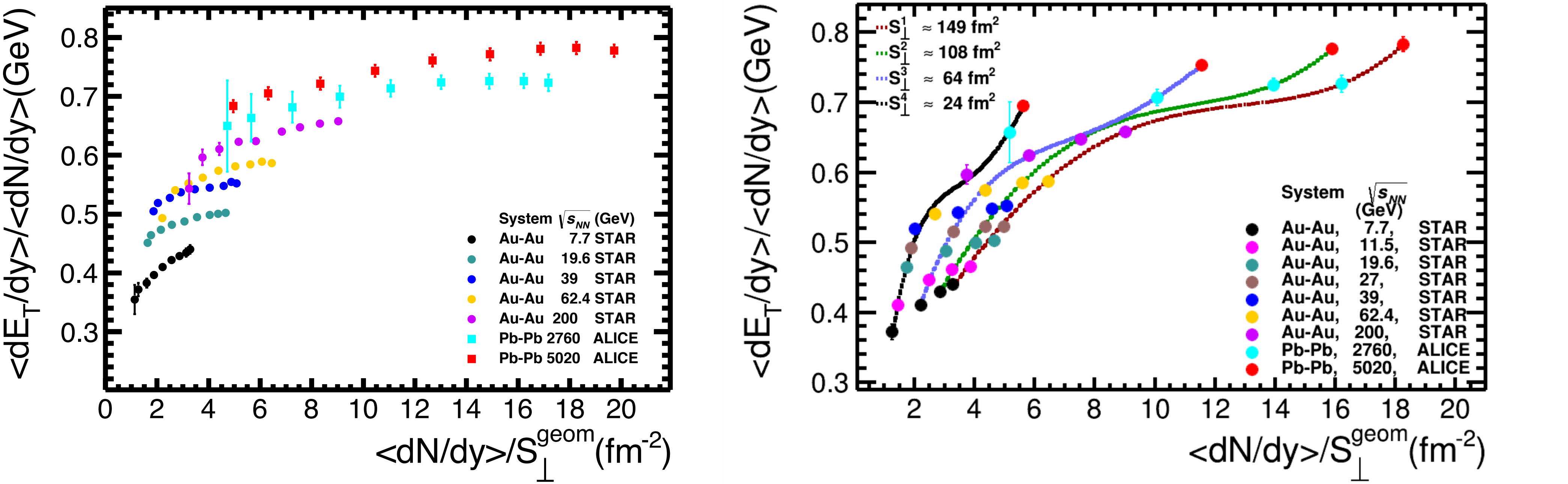
<u>for RHIC energies:</u>

$\langle m_T\rangle -> \langle m_T\rangle - m_0$ - for baryons

$\langle m_T\rangle -> \langle m_T\rangle + m_0$ - for antibaryons

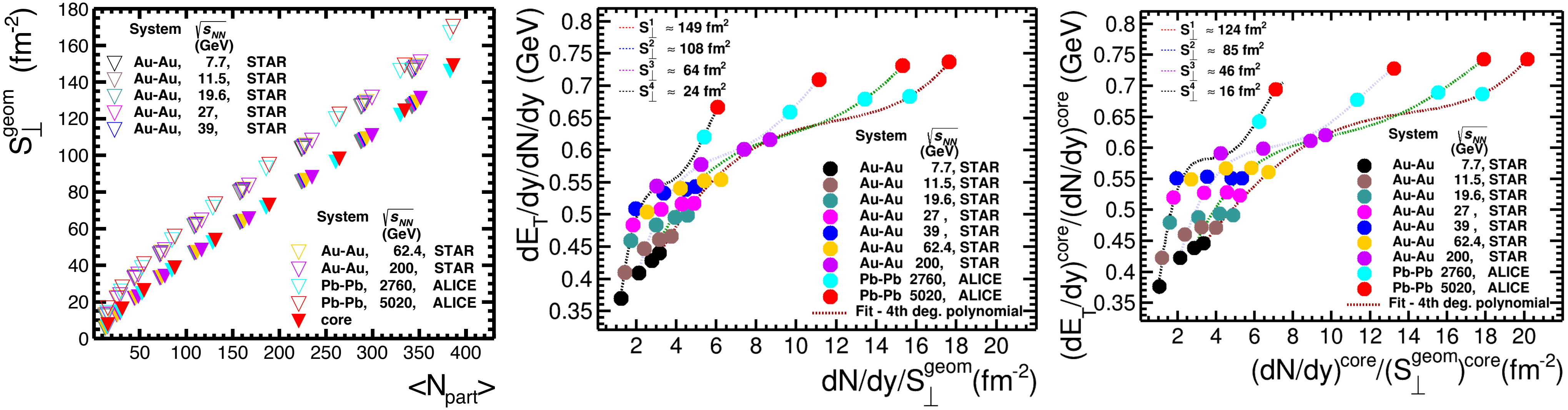
$\langle m_T\rangle$ - for other particles

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

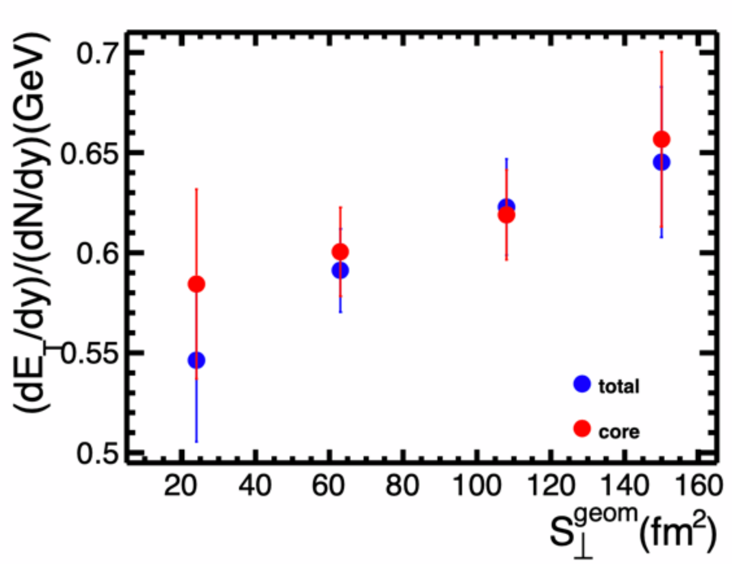


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

$(dE_T/dy)/(dN/dy)$ - $(dN/dy)/S_\perp$ correlation - core-corona
$\pi^\pm$, $K^\pm$, p, pbar and their neutrals



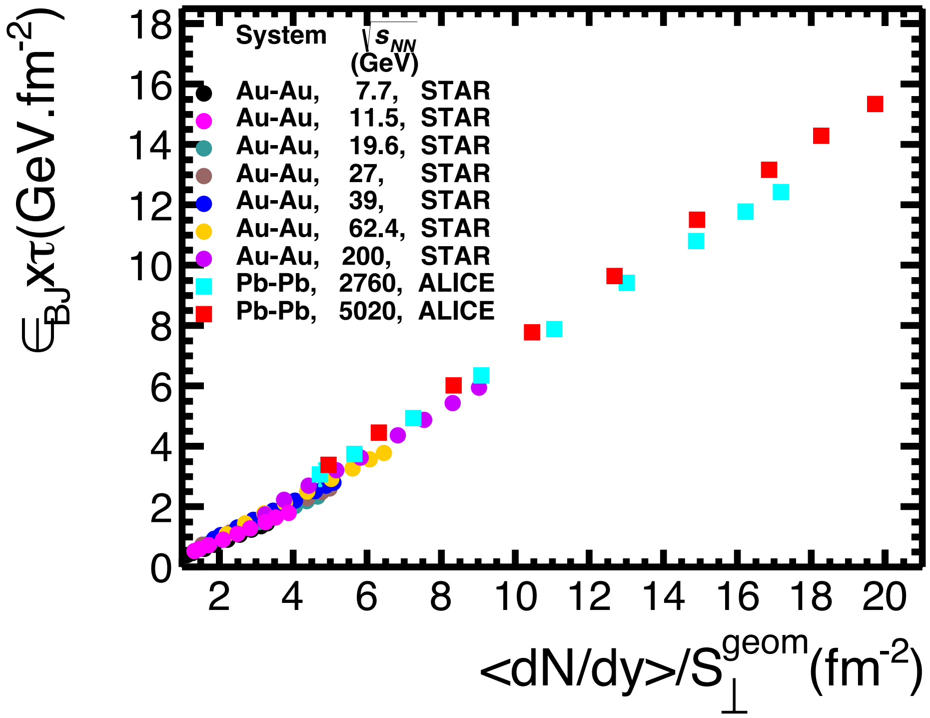
Inflection points

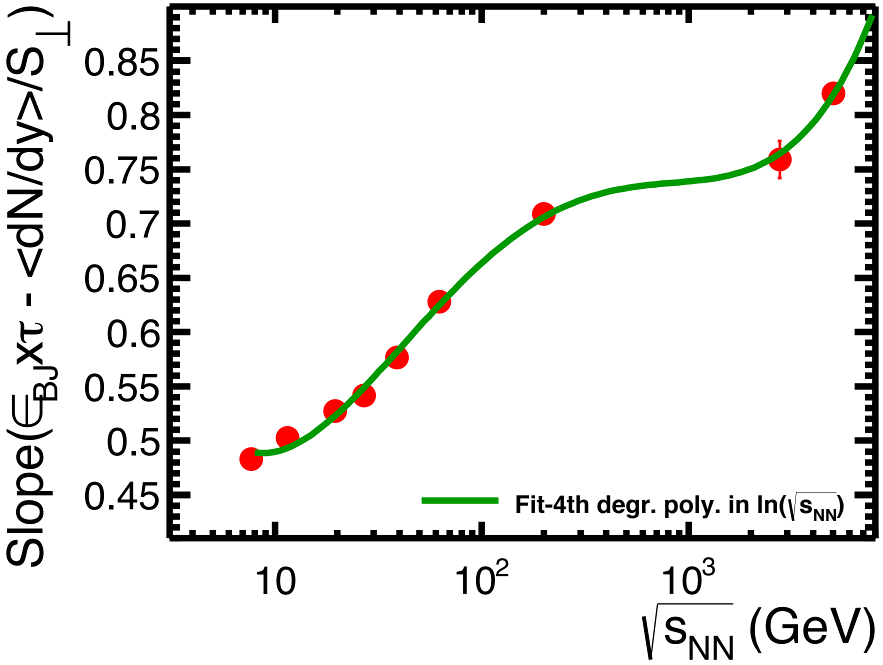


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

ε_{Bj} - $(dN/dy)/S_\perp$ correlation for A-A - centrality dependence

$$\varepsilon_{Bj}\cdot\tau = (dE_T/dy)/S_\perp$$



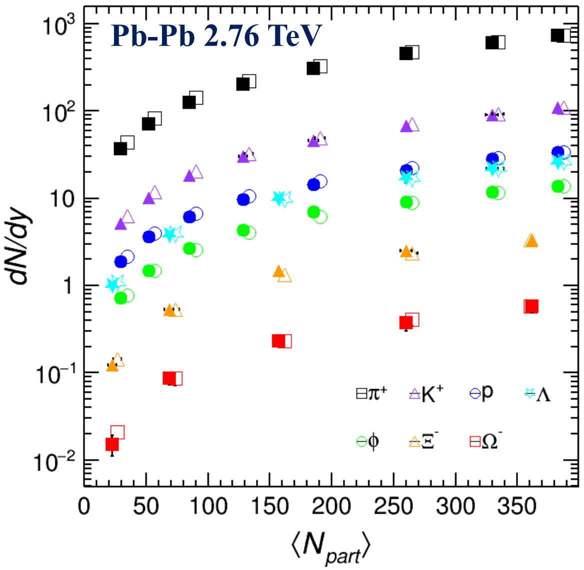


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

Strangeness production - smoking gun of deconfinement

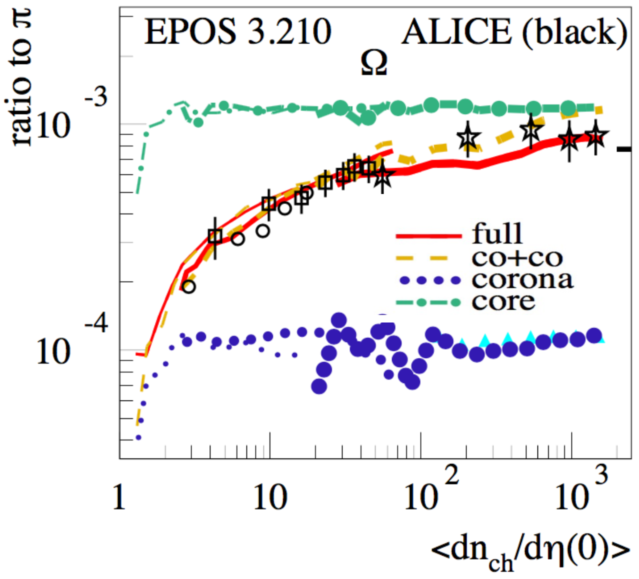
J.Rafelski and B.Muller, Phys.Rev.Lett. 48(1982)1066

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



open symbols - Eq.1
full symbols - exp. points

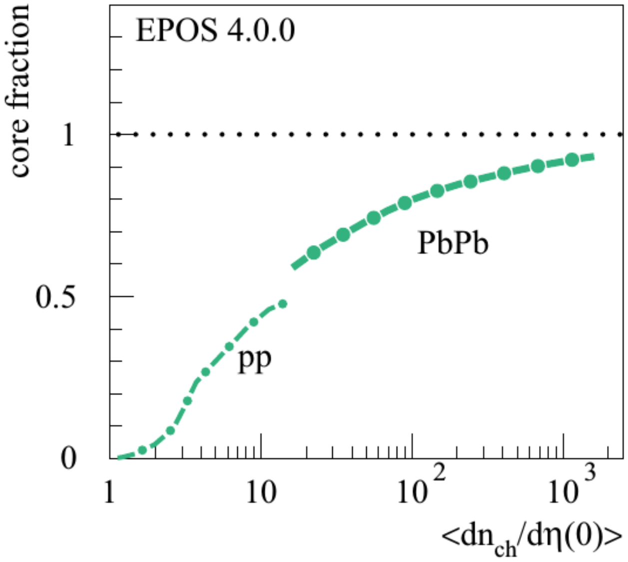
M. Petrovici et al., Phys.Rev. C96(2017)014908



thin lines = pp (7TeV)
intermediate lines = pPb (5TeV)
thick lines = PbPb (2.76TeVVV)

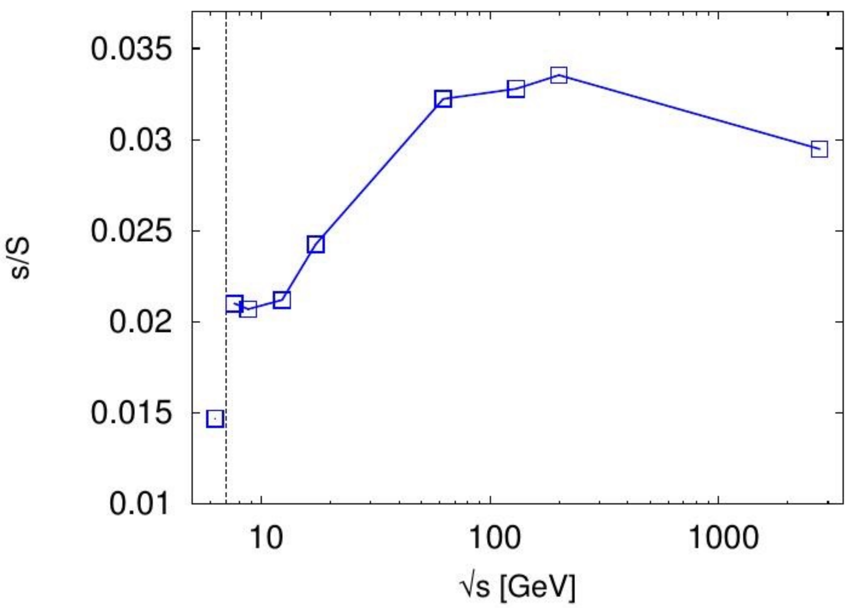
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

K. Werner, SQM 2017, July 10-15 2017, Utrecht

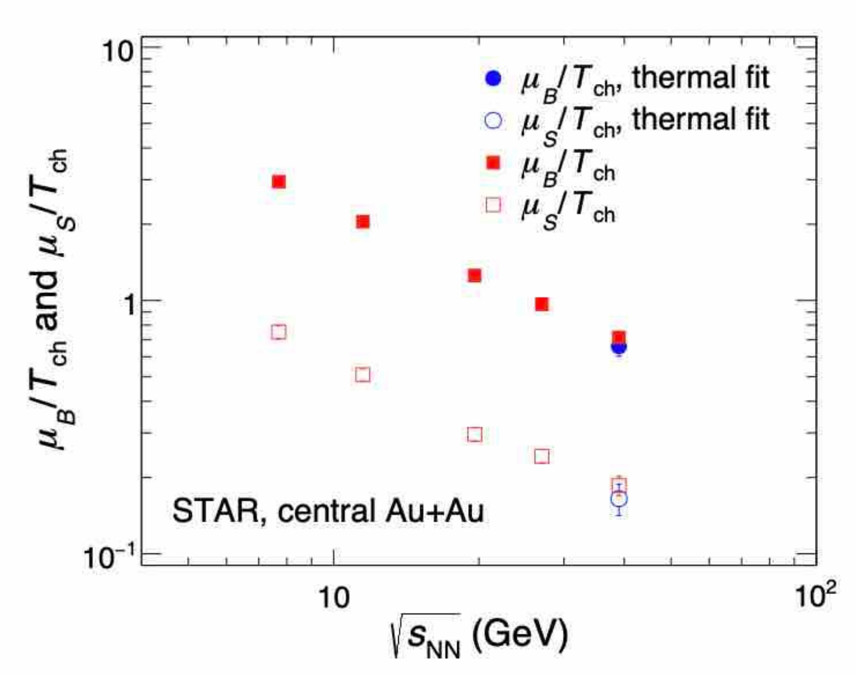


K. Werner, Phys.Rev. C109(2024)014910

Strangeness production - smoking gun of deconfinement



J.Rafelski and M.Petran, arXiv[nucl-th]1403.4036

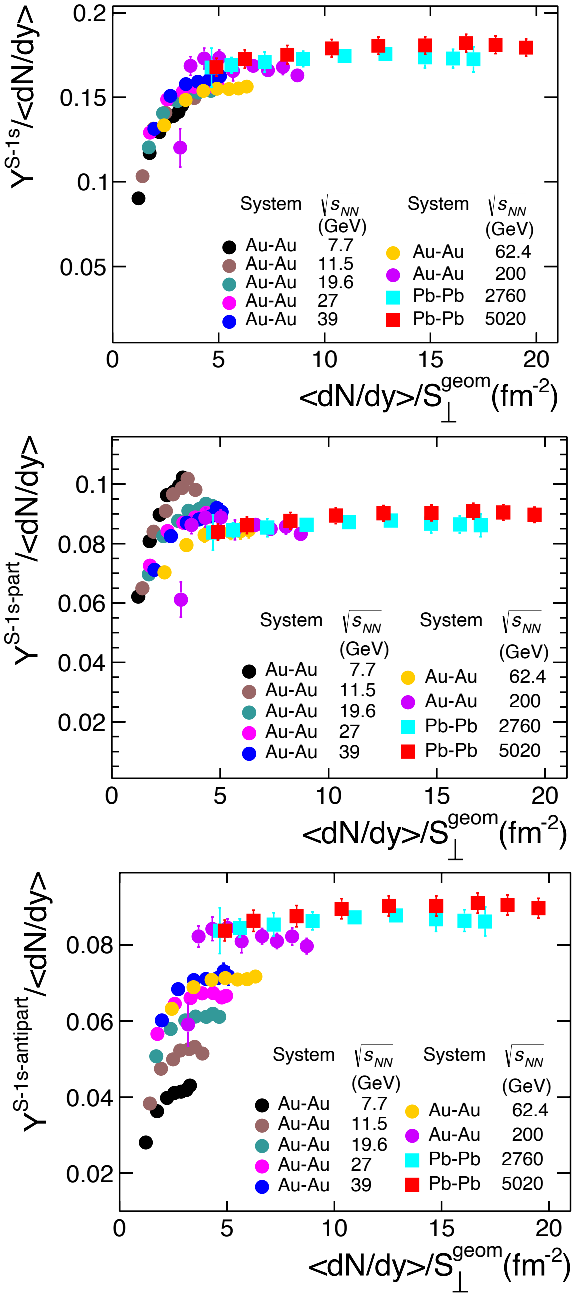


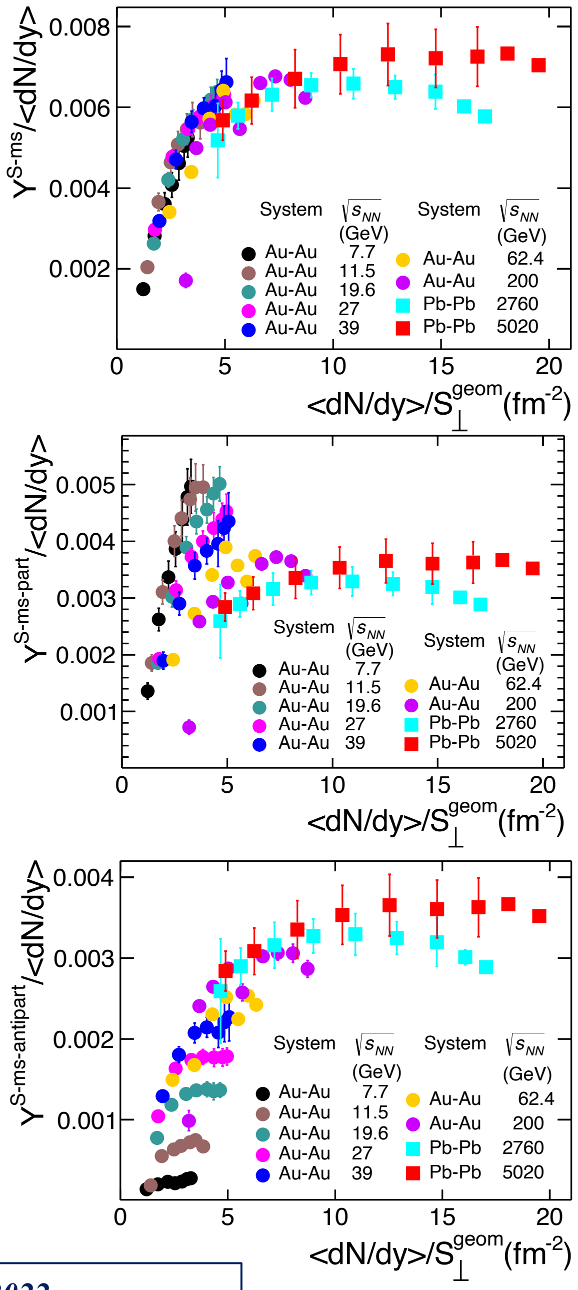
J.Adam et al, STAR Collaboration, Phys.Rev. C102(2020)034909

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

$$Y^{1s} = \frac{dN^{1s}}{dy} = \frac{dN^{(K^+ + K^-)}}{dy} + 2\frac{dN^{K_s^0}}{dy} + \frac{dN^{(\Lambda+\bar{\Lambda})}}{dy} + 2\frac{dN^{(\Sigma^- + \bar{\Sigma}^+)}}{dy}$$

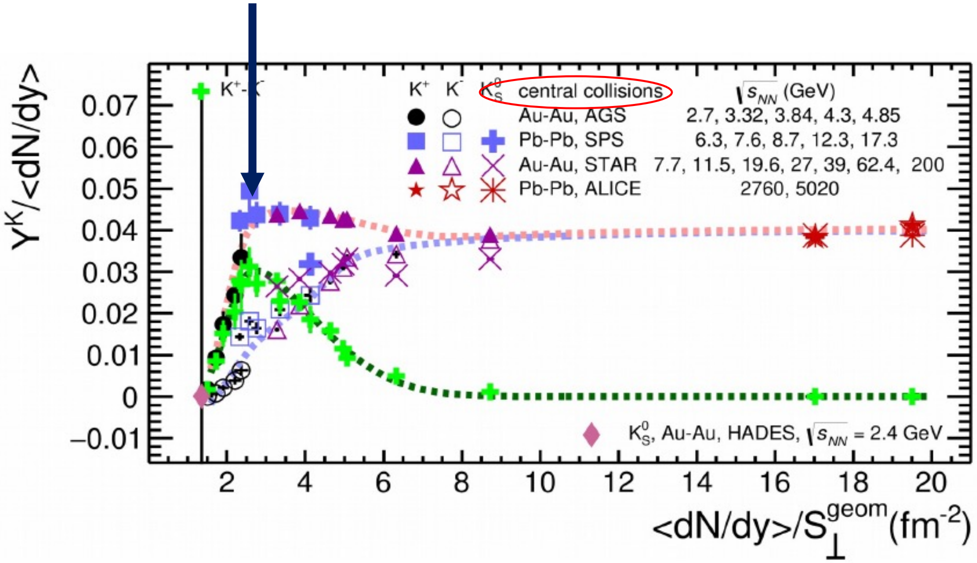
$$Y^{ms} = \frac{dN^{ms}}{dy} = \frac{dN^{(\Omega^- + \bar{\Omega}^+)}}{dy} + 2\frac{dN^{(\Xi^- + \bar{\Xi}^+)}}{dy}$$

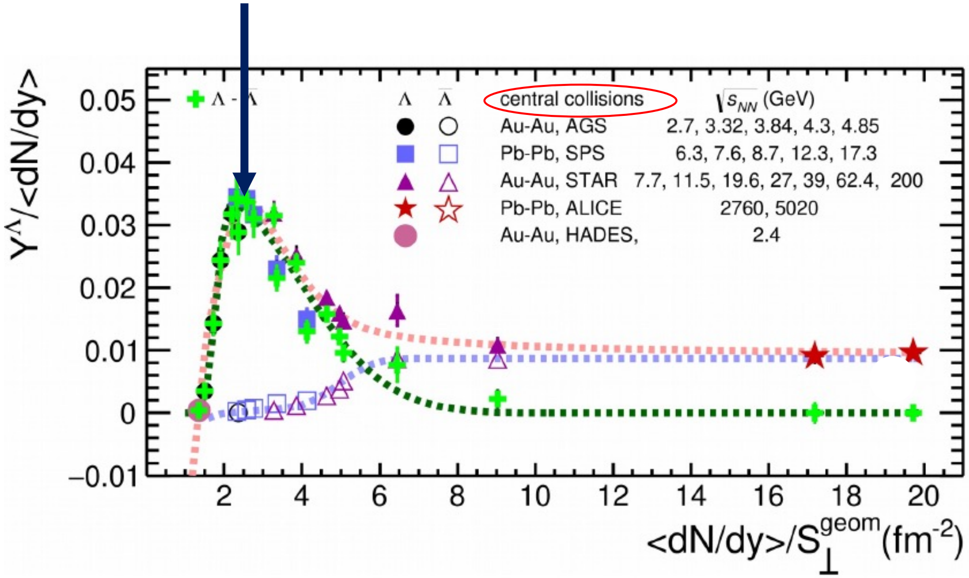


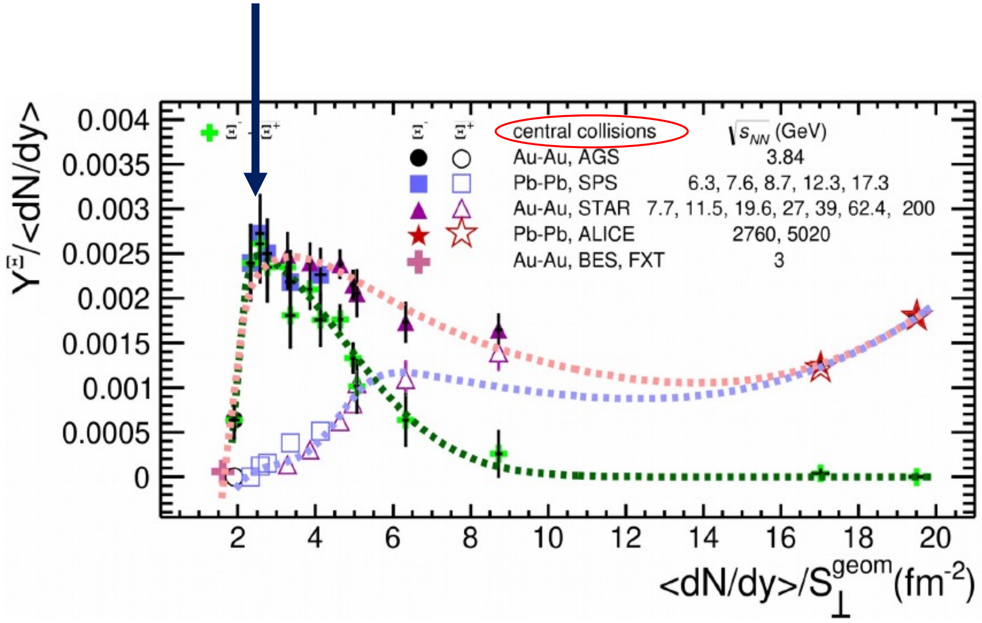


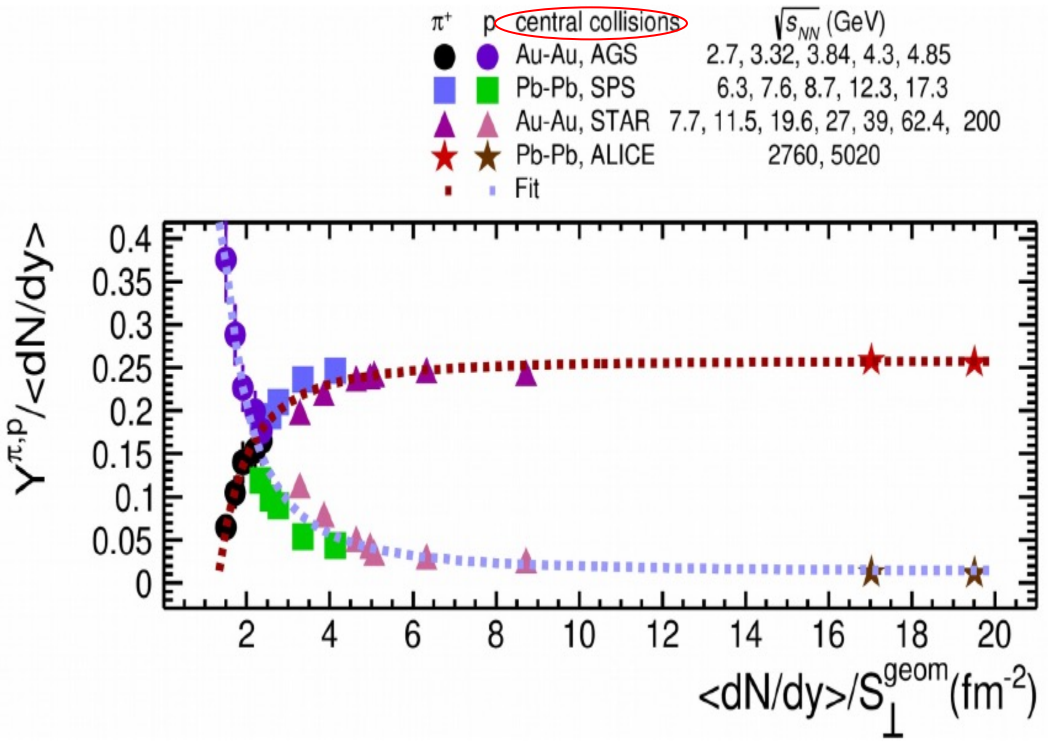
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

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



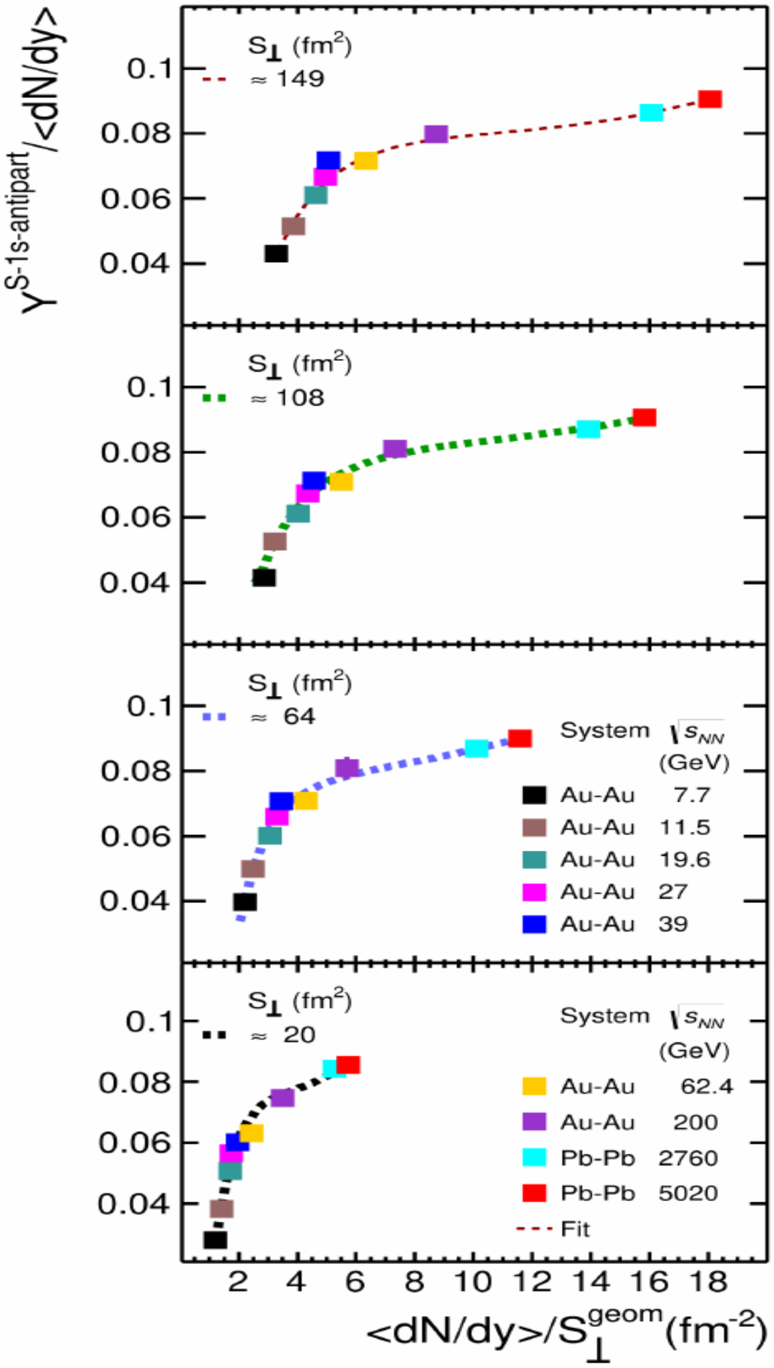


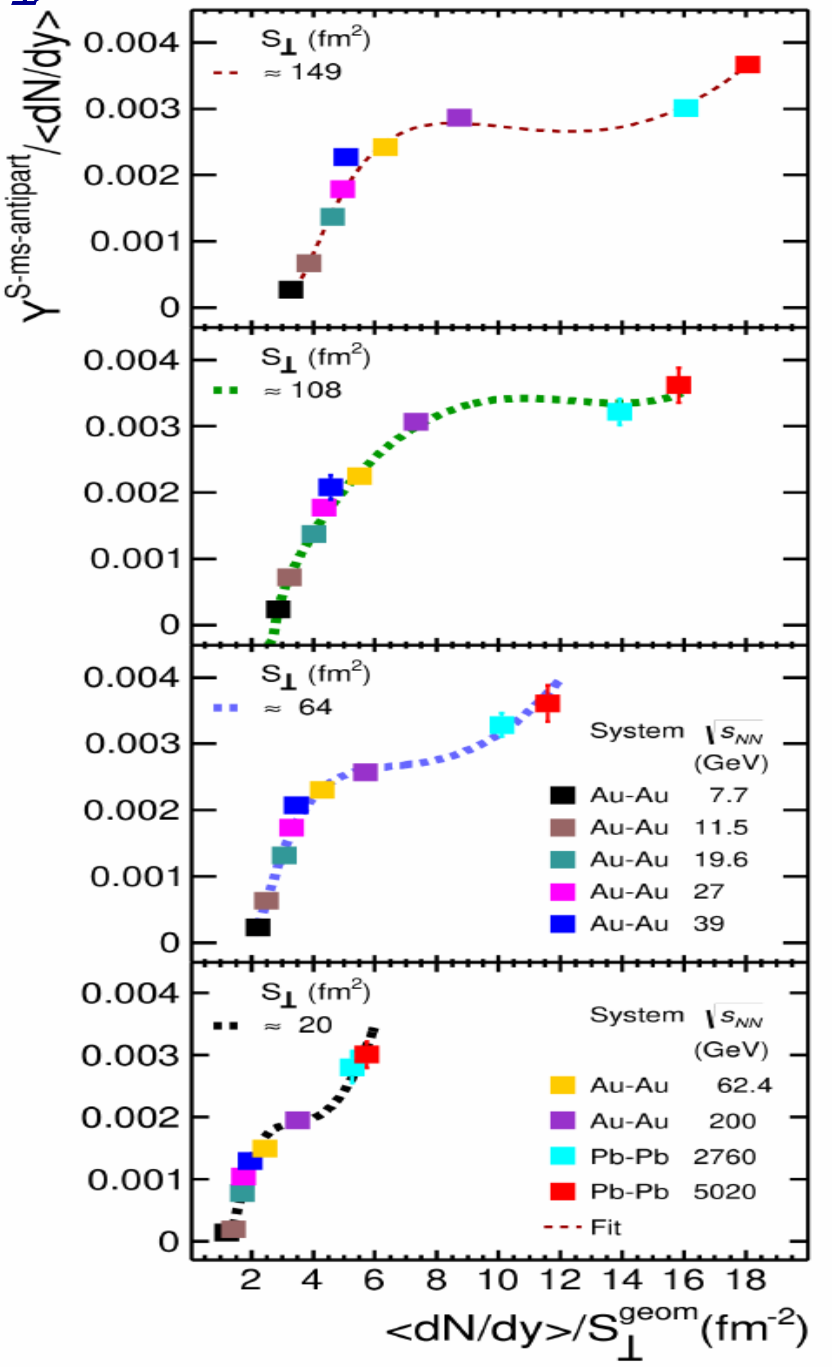




M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

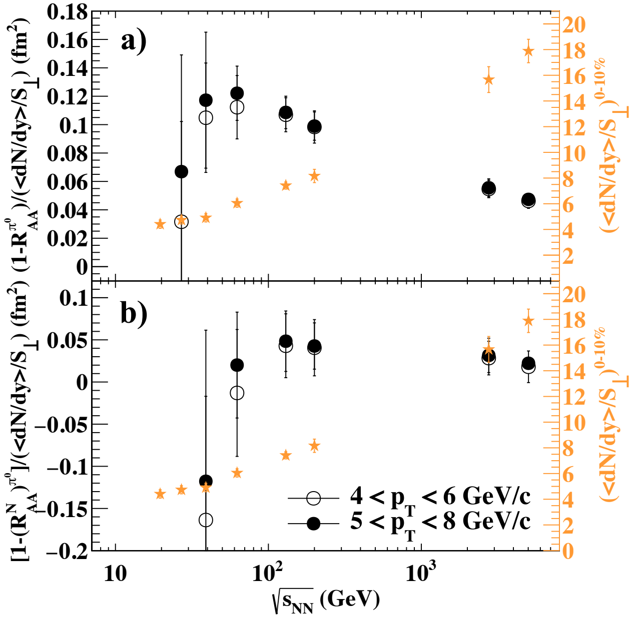
$(dN/dy)^{(strange\ and\ multi\ strange\ antihadron)}/(dN/dy)$ - $(dN/dy)/S_{\perp}$ correlation (different $S_{\perp}$)



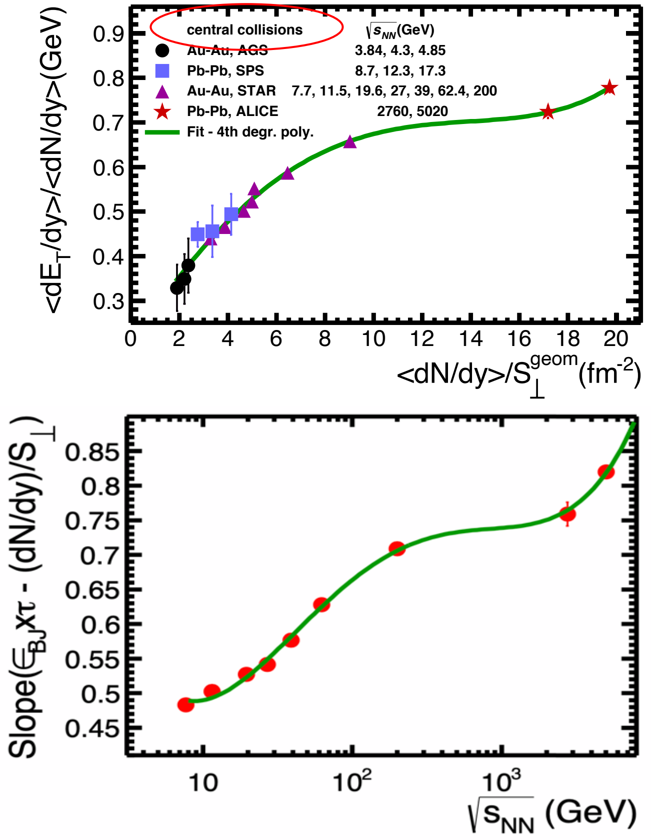


A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

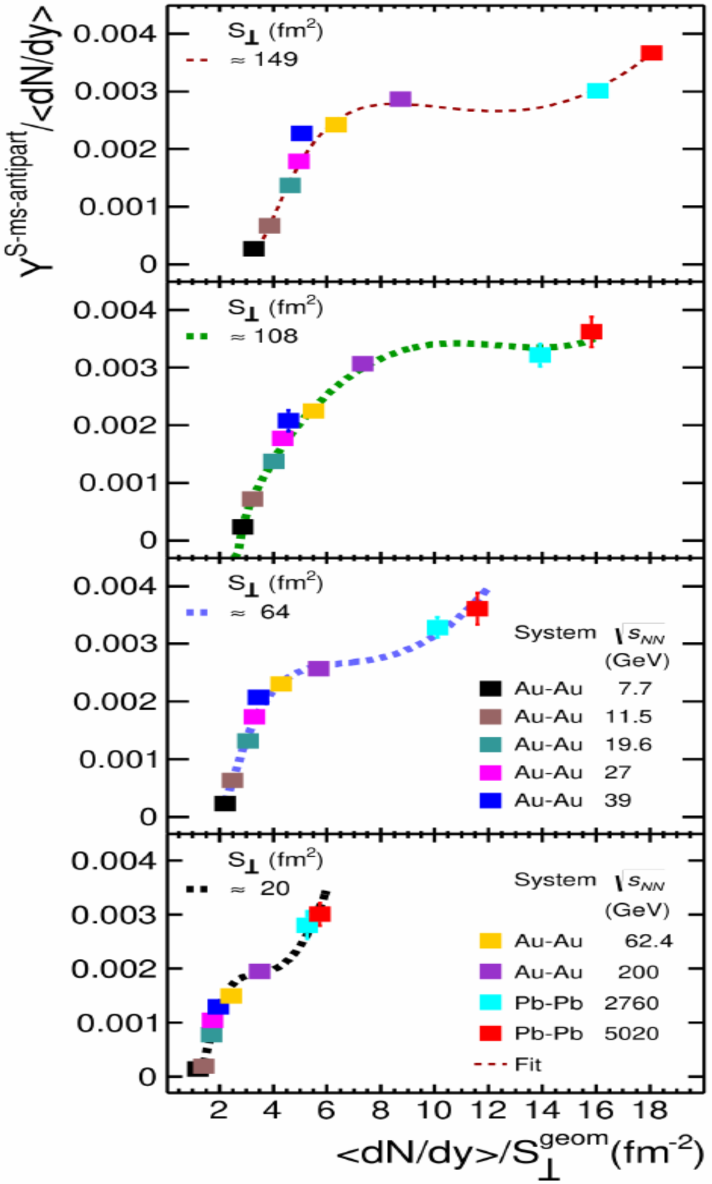
Do we see a new state of deconfined matter at LHC energies?

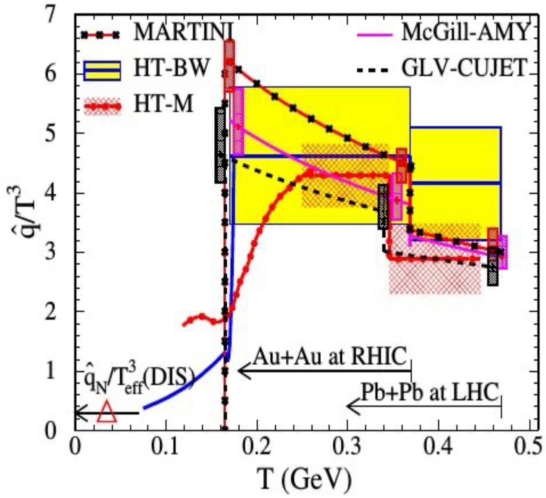


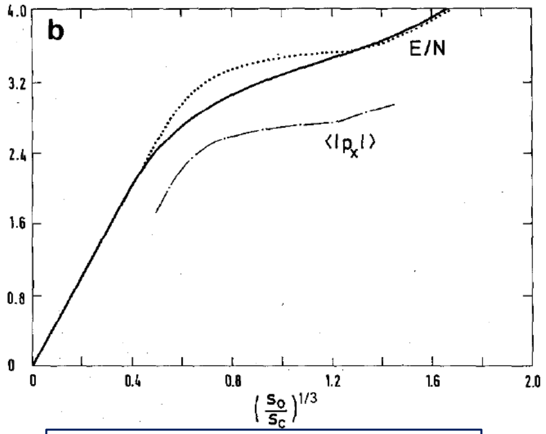
M.Petrovici et al., Phys. Rev. C103(2021)034903



M.Petrovici and A.Pop, Phys.Rev. C107(2023)0







K.M. Burke et al., JET Collaboration,
Phys. Rev. C90(2014)014909

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

Pop and M. Petrovici,
arXiv:2402.19115[hep-ph]

Short review pp vs A-A @ LHC

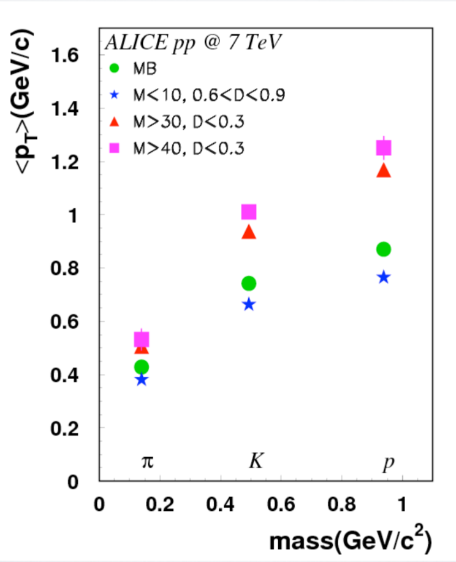


Fig.30

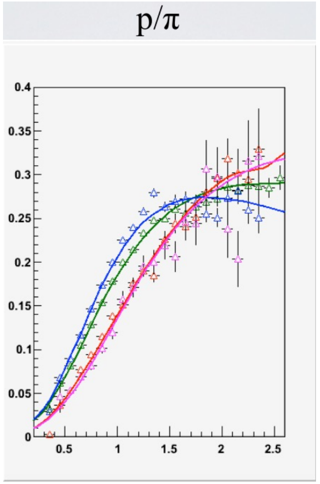
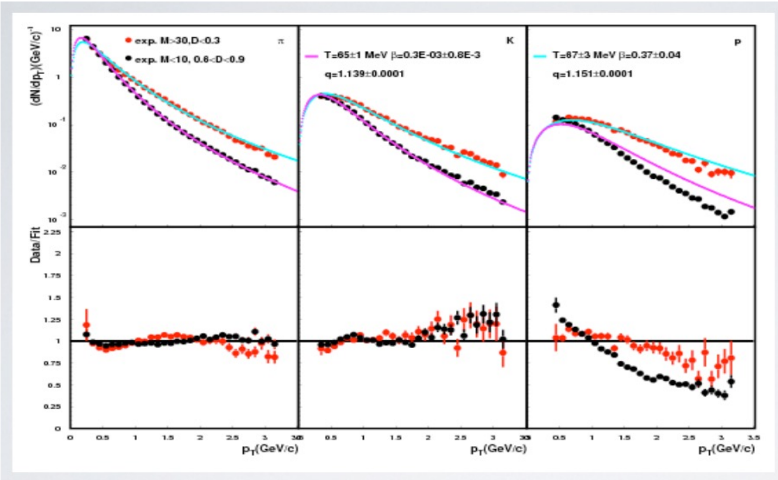


Fig.31



M<10;0.6<D<0.9
T= 65±1
<β>=0.3e-3±0.0008
q=1.139±0.0001

M>30;D<0.3
T= 67±3
<β>=0.37±0.04
q=1.151±0.0001

Fig.32

Eq. 1

$$\boxed{D = \frac{|\sum_i p_t^i|}{\sum_i |p_t^i|}|_{\eta>0},}$$

Eq. 2

$$f(p_t) = m_t \int_{-Y}^{Y} cosh(y)dy \int_{-\pi}^{\pi} d\phi \int_{0}^{R} rdr(1+\frac{q-1}{T}(m_t cosh(y)cosh(\rho)-p_t sinh(\rho)cos(\phi)))^{-1/(q-1)}$$

C.Andrei et al., ALICE Week, PWG2-Soft Physics, 9.11.2010
C.Andrei et al., Paper draft, 14.03.2011

Short review pp vs A-A @ LHC

$$z^{raw} = \frac{(N_{ch}^{raw})_{limit}}{< N_{ch}^{raw} >_{mult>0}}$$

$$< N_{ch}^{raw} >_{mult>0} = 9.6, |\eta| < 0.8$$

N_{ch}^{raw}	z^{raw}
7 - 12	0.7 - 1.3
13 - 19	1.4 - 2.0
20 - 28	2.1 - 2.9
29 - 39	3.0 - 4.1
40 - 49	4.2 - 5.1
50 - 59	5.2 - 6.2
60 - 71	6.3 - 7.4
72 - 82	7.5 - 8.6

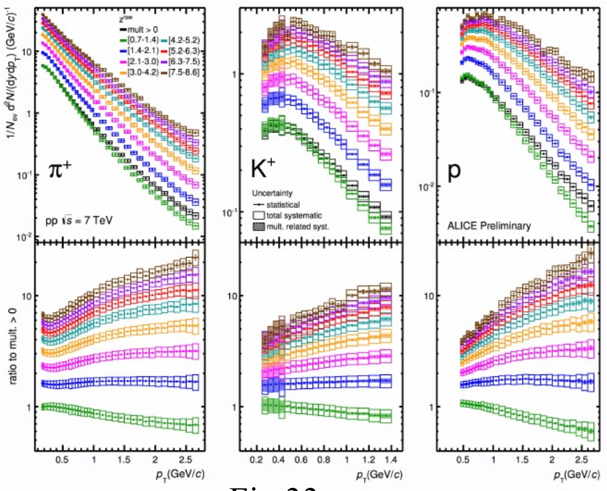


Fig.33

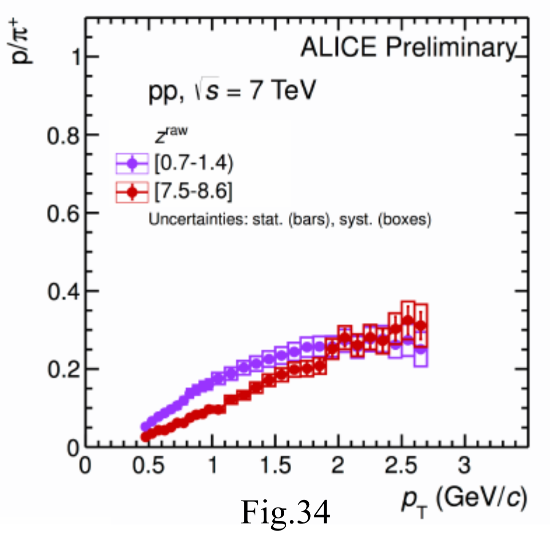


Fig.34

Eq. 5
$$E\frac{d^3N}{dp^3} \sim f(p_T) = \int_0^R m_T K_1(m_T cosh\rho/T_{kin}) I_0(p_T sinh\rho/T_{kin}) r dr$$

were
$$m_T = \sqrt{m^2 + p_T^2};\ \beta_r(r) = \beta_s(\tfrac{r}{R})^n$$

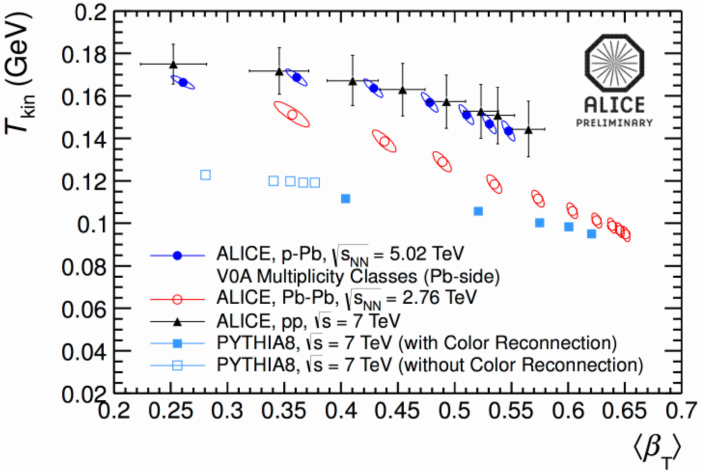


Fig.35

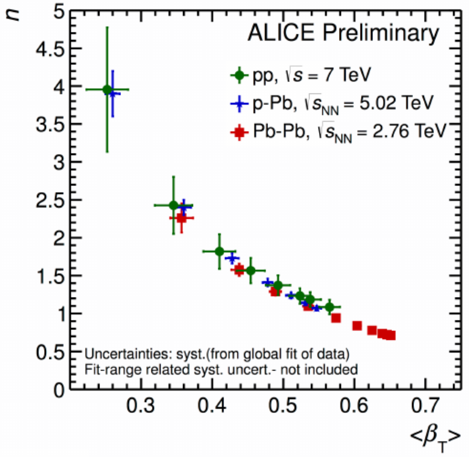


Fig.36

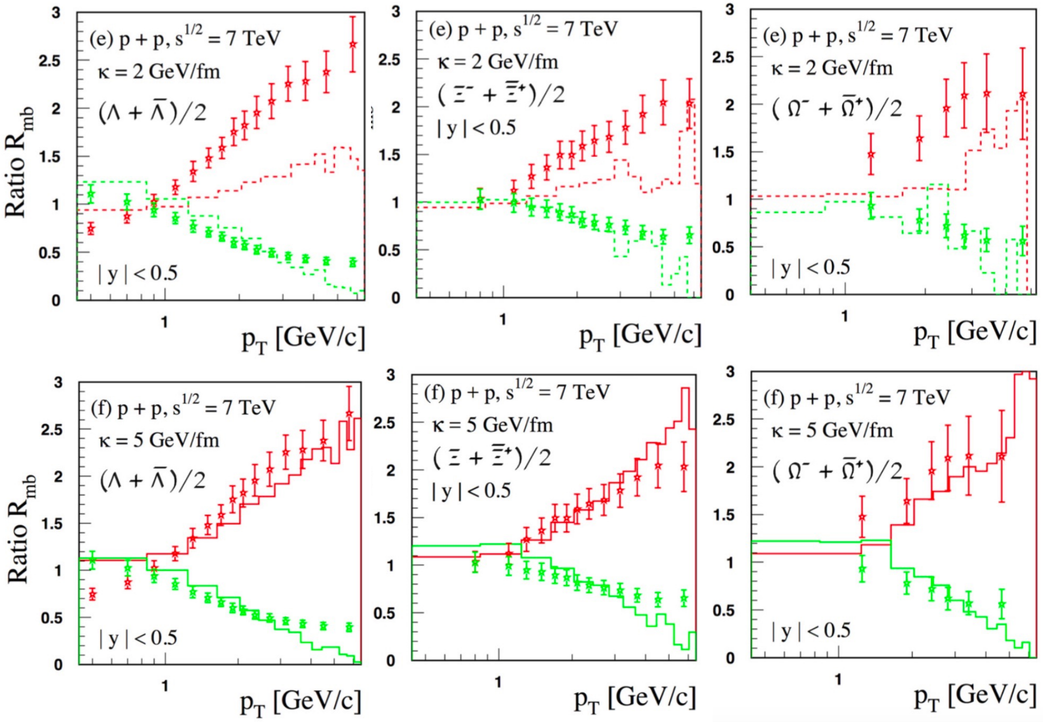
C. Andrei for ALICE Collaboration, Nucl.Phys. A931(2014)888

Short review pp vs A-A @ LHC

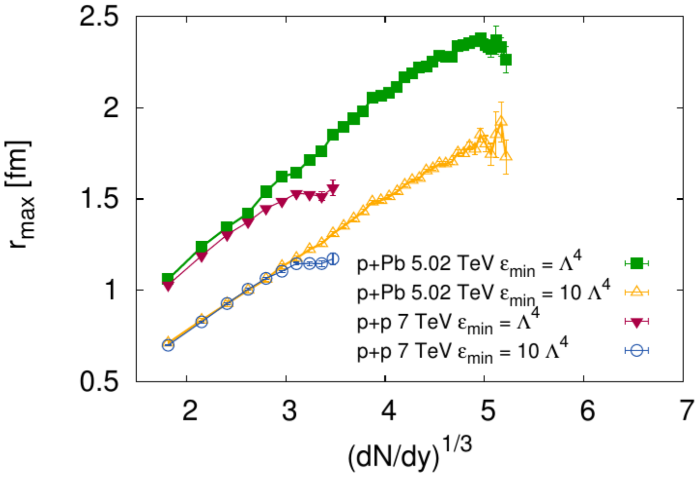
red - $dN_{ch}/d\eta$=15
green - $dN_{ch}/d\eta$=4

red - $dN_{ch}/d\eta$=15
green - $dN_{ch}/d\eta$=6

red - $dN_{ch}/d\eta$=15
green - $dN_{ch}/d\eta$=6



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



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

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

α=1

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

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

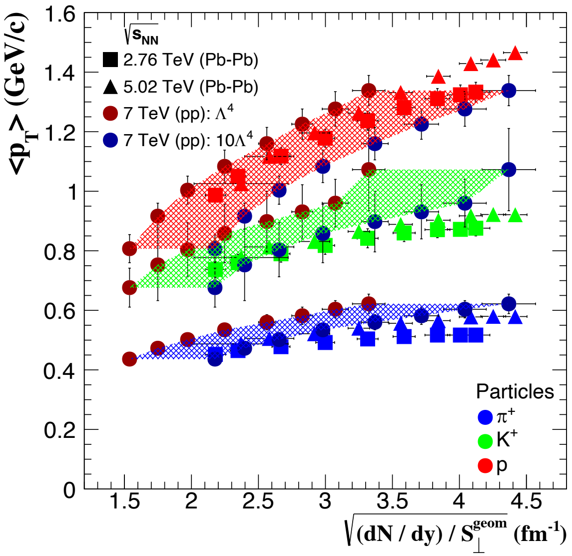
$$dN_g/dy \approx dN/dy$$

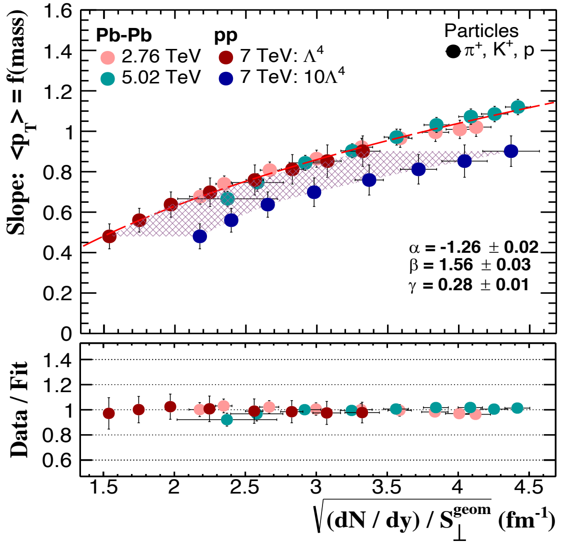
A. Bzdak et al., Phys.Rev. C87(2013)064906

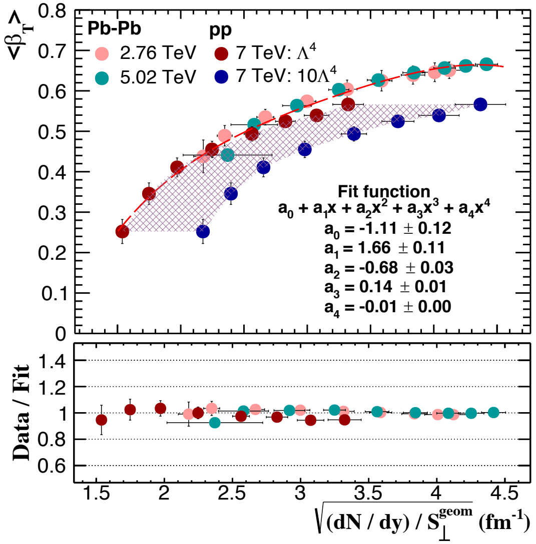
McLarren, M. Praszalowicz and B. Schenke, Phys.Rev. C87(2013)064906

A-A vs. pp @ LHC

π, K, p

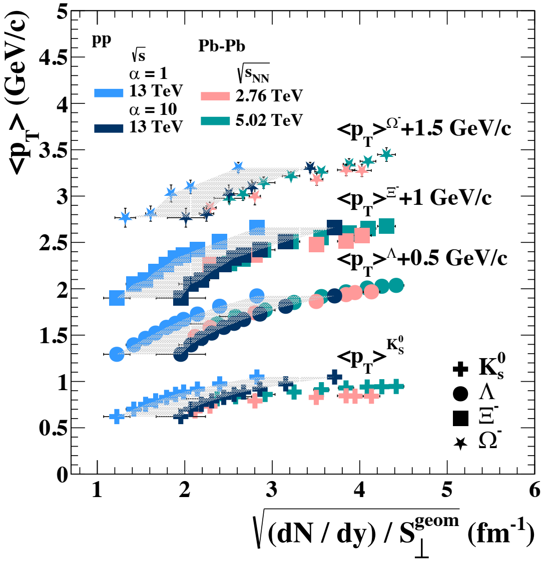


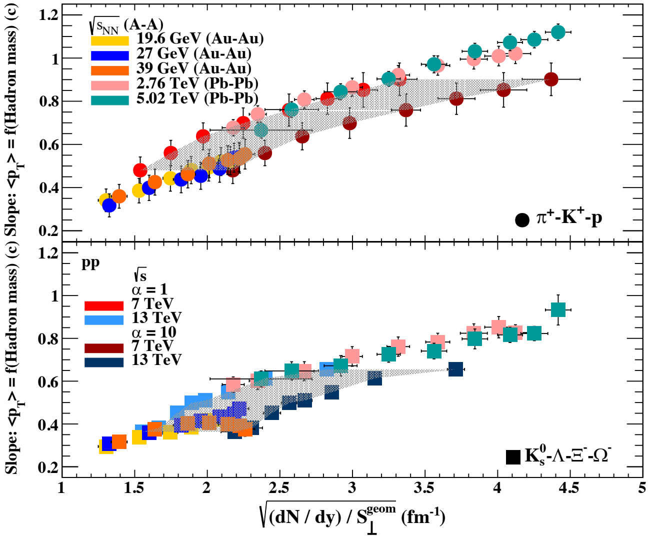


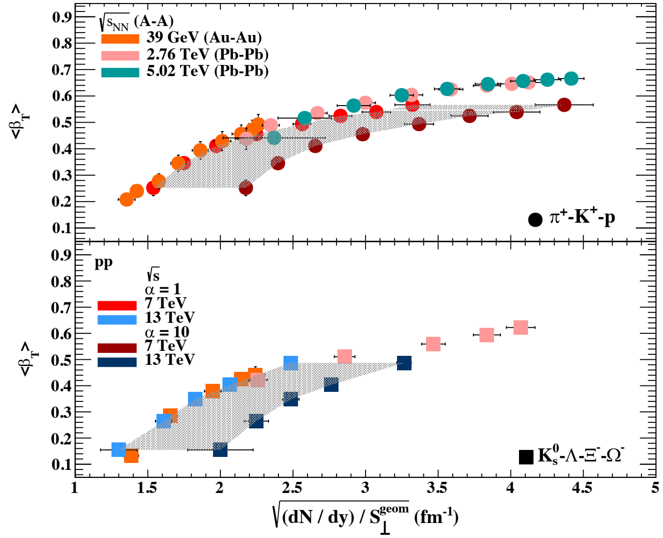


M.Petrovici, A.Lindner and A.Pop, Phys. Rev. C 98(2018)024904

K^0_s ,Λ, Ξ, Ω



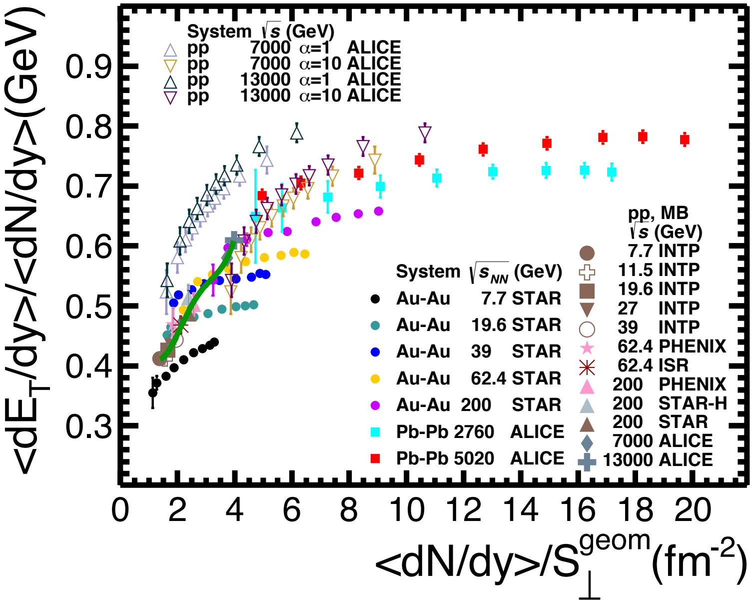


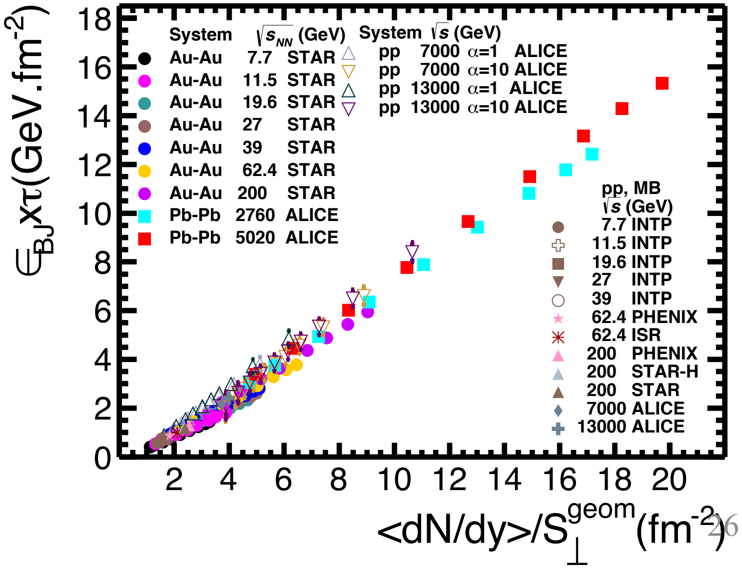


A. Lindner et al., Proceedings of Science (PoS) 380(2021)197 (PANIC2021), https://pos.sissa.it/380/197/.

A-A vs. pp @ LHC

$(dE_T/dy)/(dN/dy)$ - $(dN/dy)/S_\perp$ and ε_{Bj} - $(dN/dy)/S_\perp$

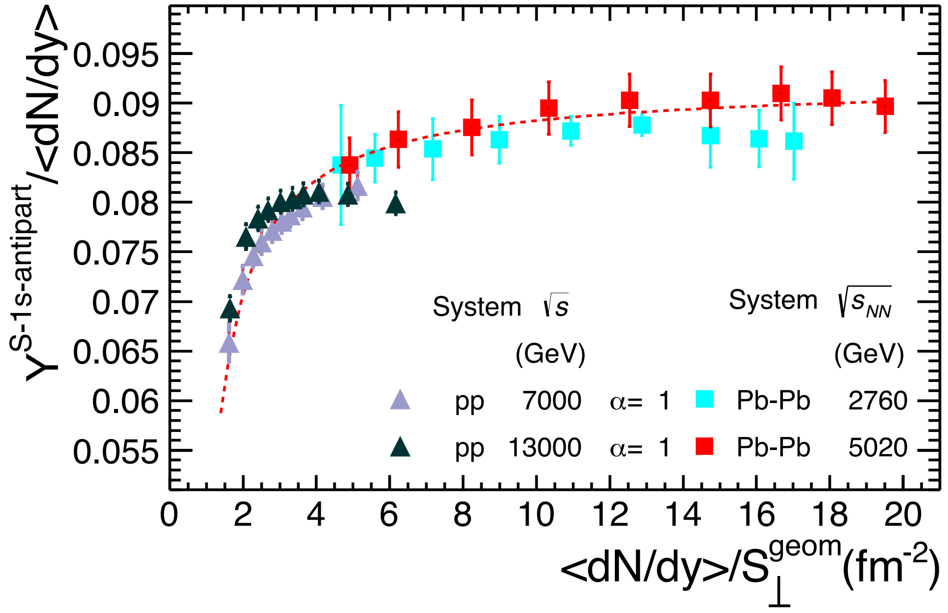


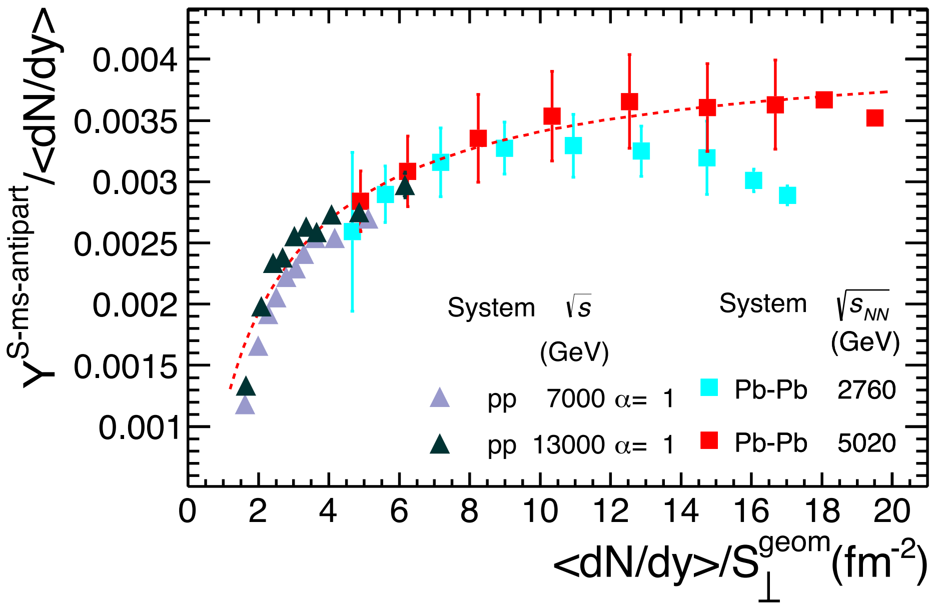


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

A-A vs. pp @ LHC

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

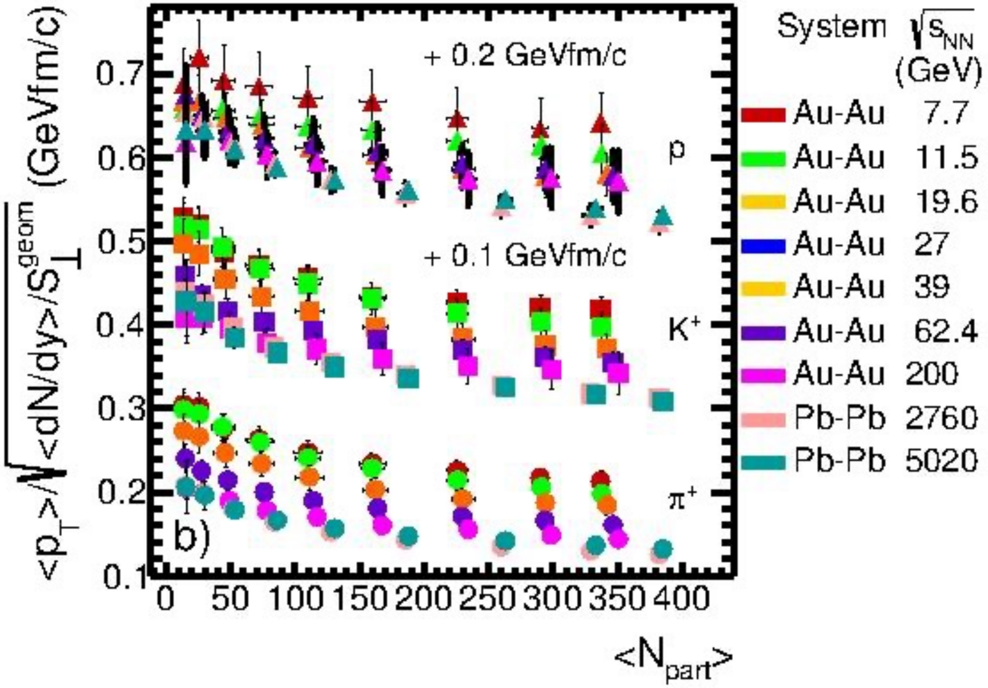


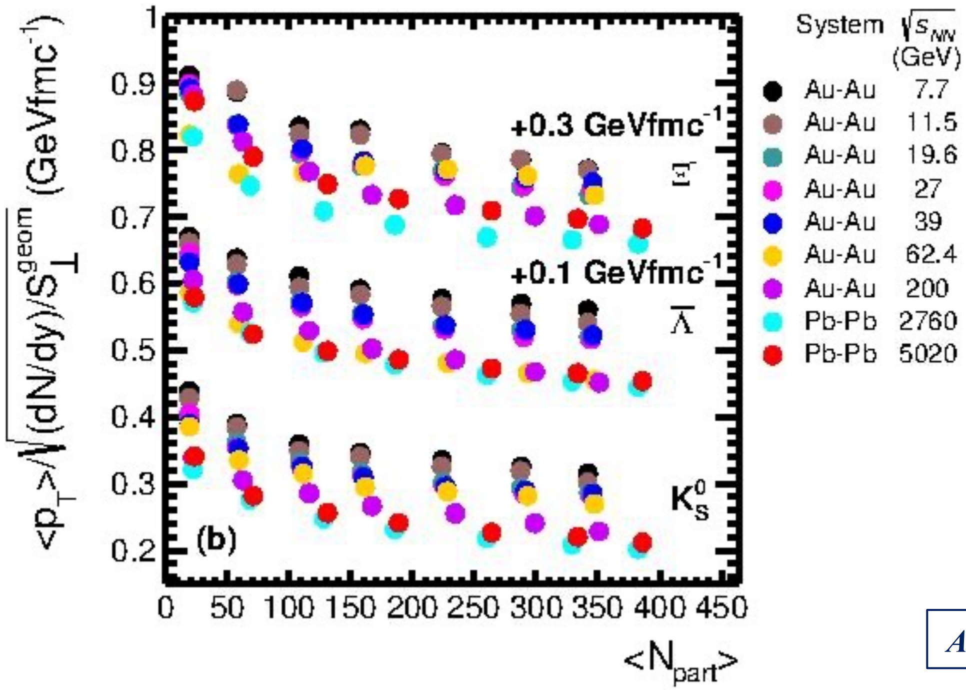


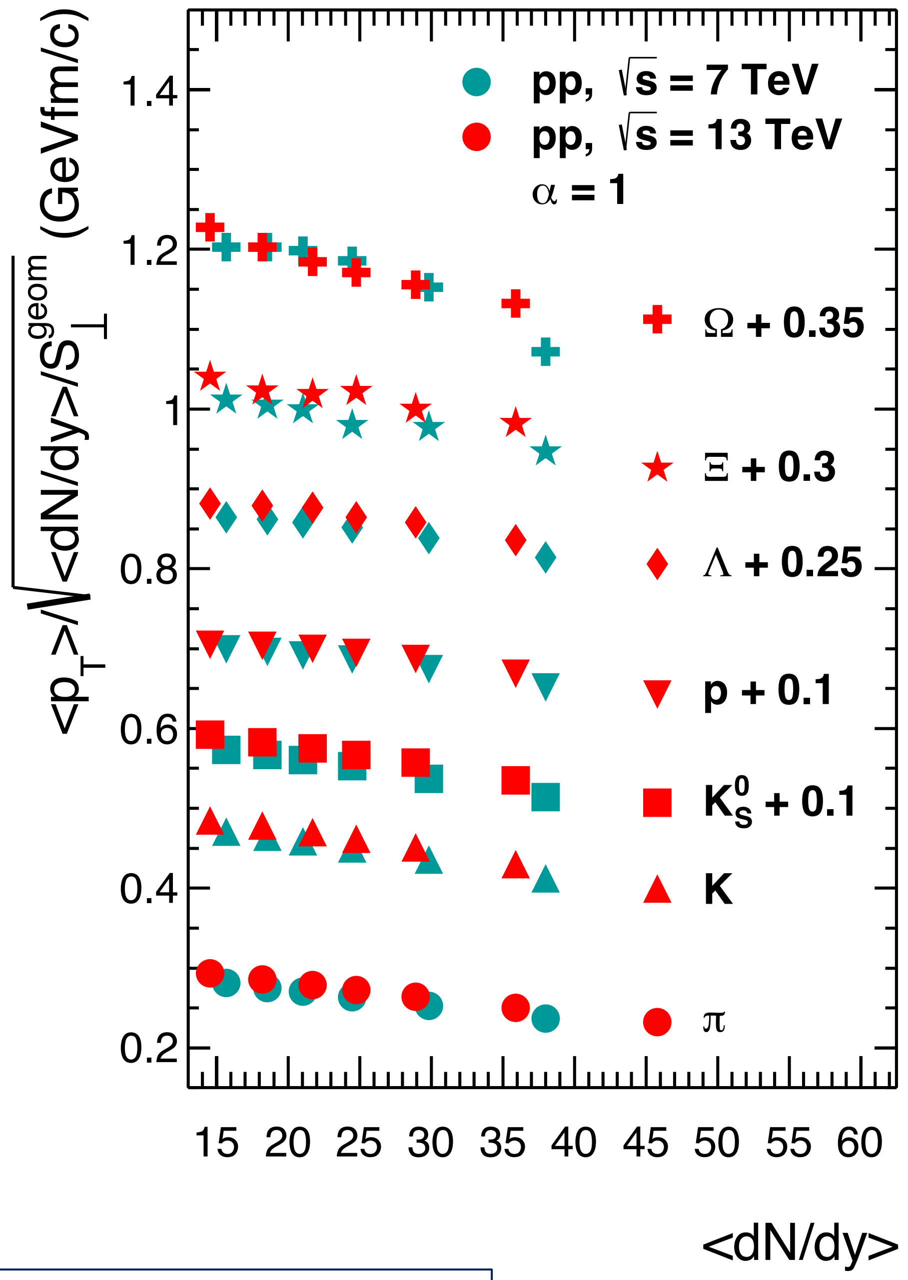
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

Highest charged particle multiplicity in pp at midrapidity selected by "V0M" by ALICE Collaboration !!!

$<p_T>/[(dN/dy)/S_{\perp}^{geom}]$



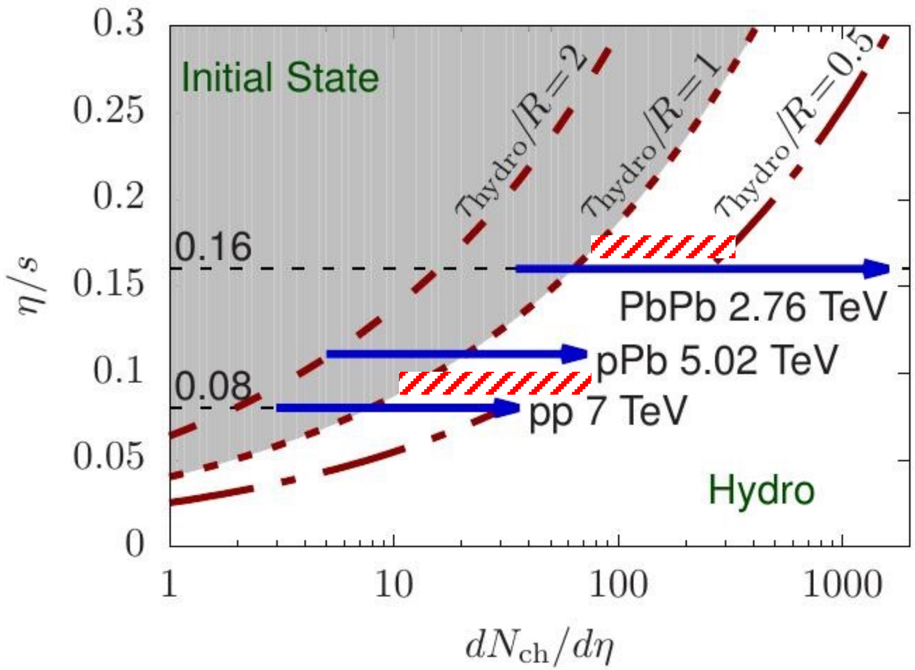




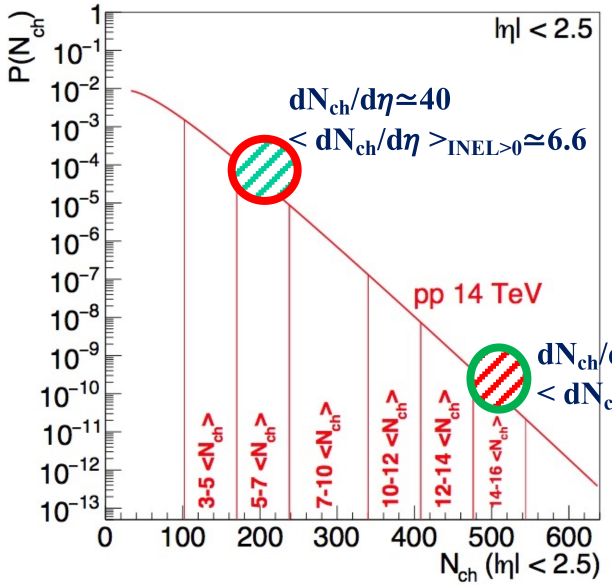
A. Pop and M. Petrovici, will be published

What's next ?

A.Kurkela et al., PoS(Confinement 2018)152

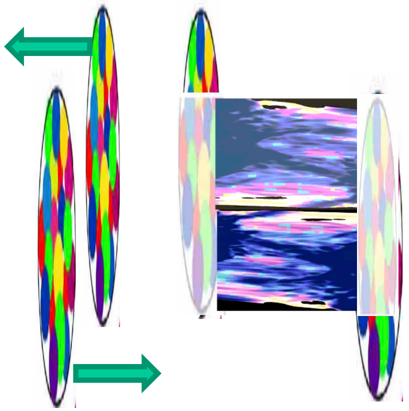


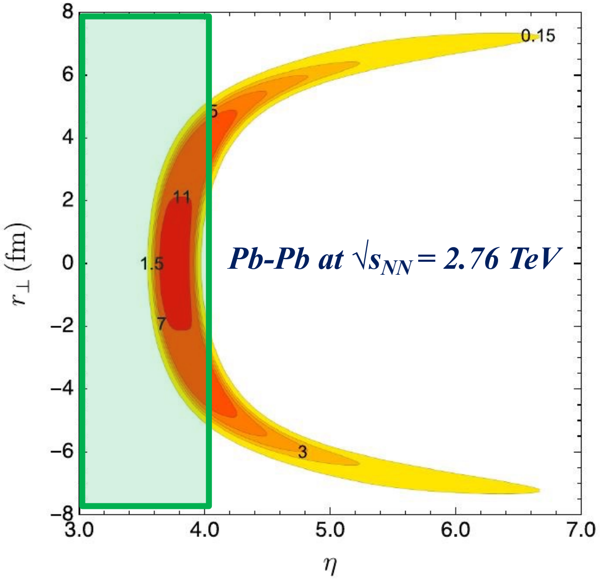
ALICE Coll., arXiv:1812.06772



$dN_{ch}/d\eta \simeq 40$
$< dN_{ch}/d\eta >_{INEL>0} \simeq 6.6$

$dN_{ch}/d\eta \simeq 100$
$< dN_{ch}/d\eta >_{INEL>0} \simeq 6.6$



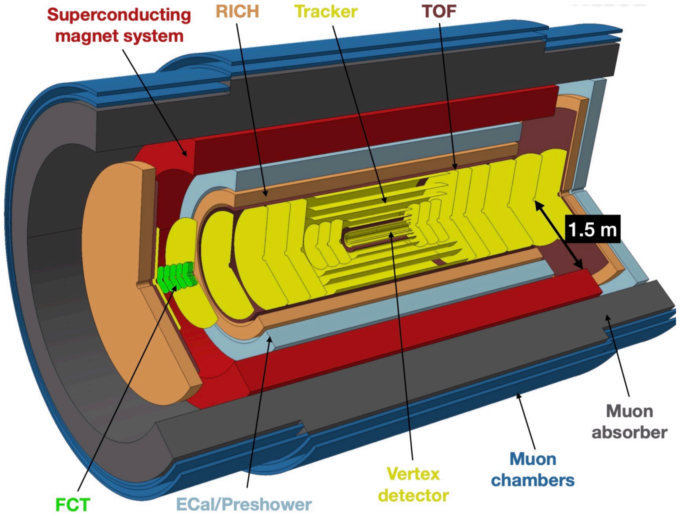


Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

M. Li and J.I. Kapusta, Phys.Rev. C99(2019)014906

ALICE3

ALICE Collaboration, arXiv:2211.02491v1 [physics.ins-det] 4 Nov 2022



Concluding remark

***"We have found it of paramount importance that in order to progress
we must recognize the ignorance and leave room for doubt.
Scientific knowledge is a body of statements of varying degrees of certainty
some most unsure, some nearly sure, none absolutely certain."
Richard Feynman***

Backup slides

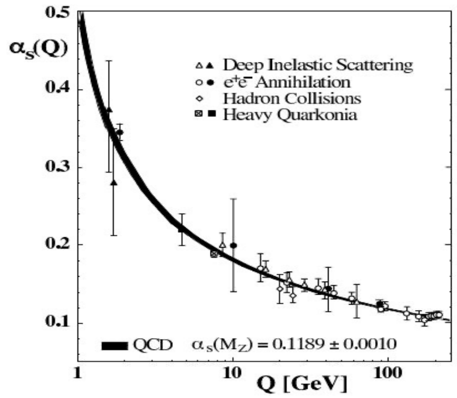
Expectations based on QCD

QCD – non-Abelian gauge theory & asymptotic freedom

D.J.Gross, H.D.Politzer and F.Wilczek - Nobel Prize 2004

QCD - running coupling constant

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(33 - 2n_f)log(Q^2/\mu^2)}$$



QCD – intrinsic scale

$$\Lambda^2 = \mu^2 exp[\frac{12\pi}{(33 - 2n_f)\alpha_s(\mu^2)}]$$

$$\Rightarrow \qquad \alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)log(Q^2/\Lambda^2)}$$

for $Q^2 \gg \Lambda^2$ $\quad \alpha_s$ ***is small*** $\Rightarrow$ ***a perturbative description in terms of Quarks and Gluons interacting weekly***

$\Rightarrow$

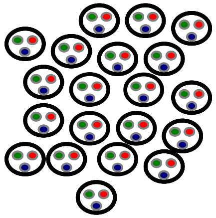
for $Q^2 \sim \Lambda^2$ ***Quarks and Gluons arrange themselves in Strongly Bound Clusters - Hadrons***

Since $\Lambda_{QCD} \sim 200$ ***MeV a phase transition is expected at:***

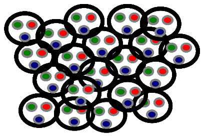
$T \sim \Lambda_{QCD} \sim O\,(10^{12}\,K)$

or

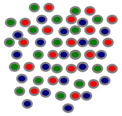
$\rho_B \sim \Lambda_{QCD}{}^3 \sim 1fm^{-3}$



Strongly Bound Clusters
Hadrons

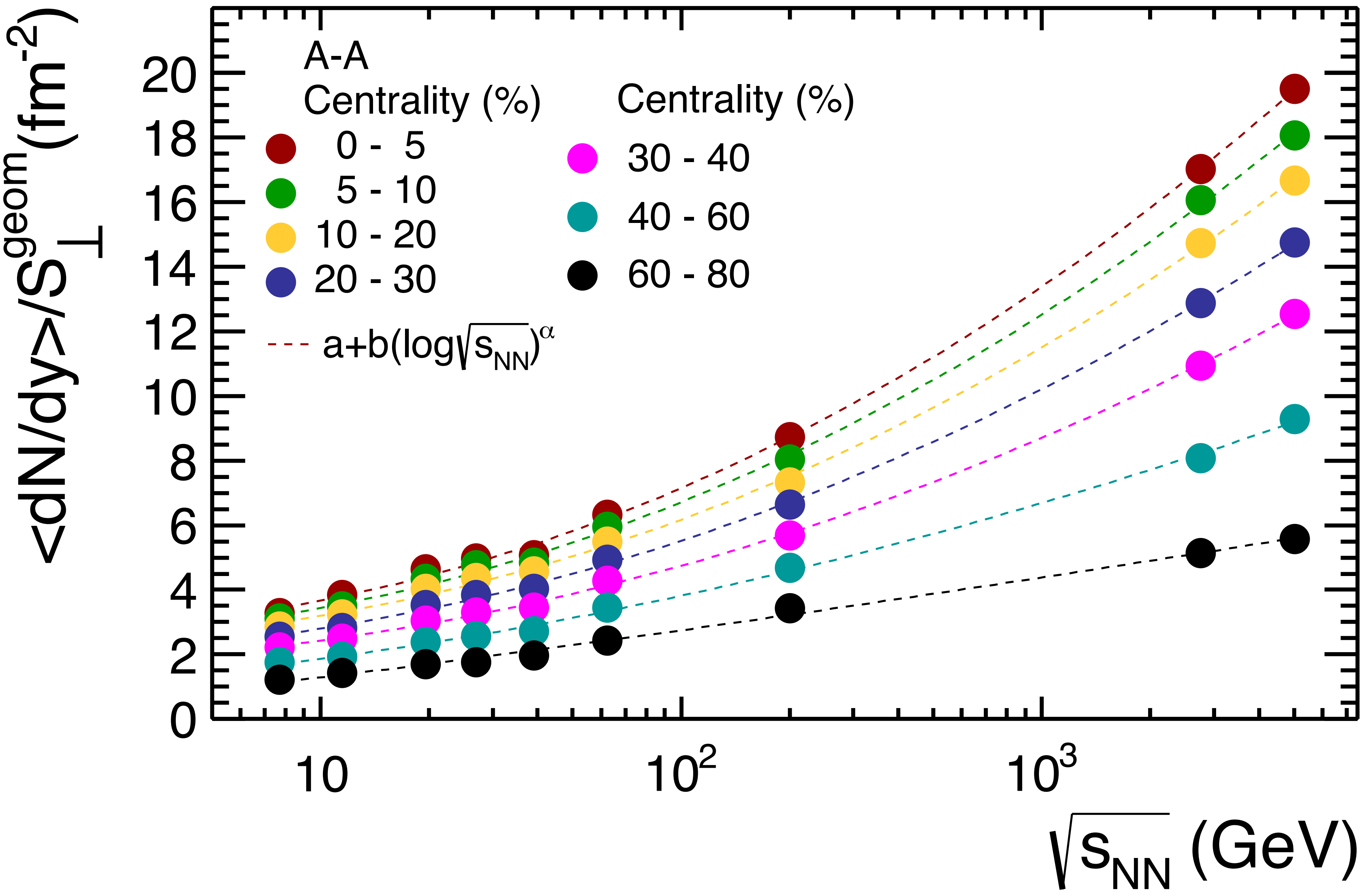


Phase transition



Weekly interacting

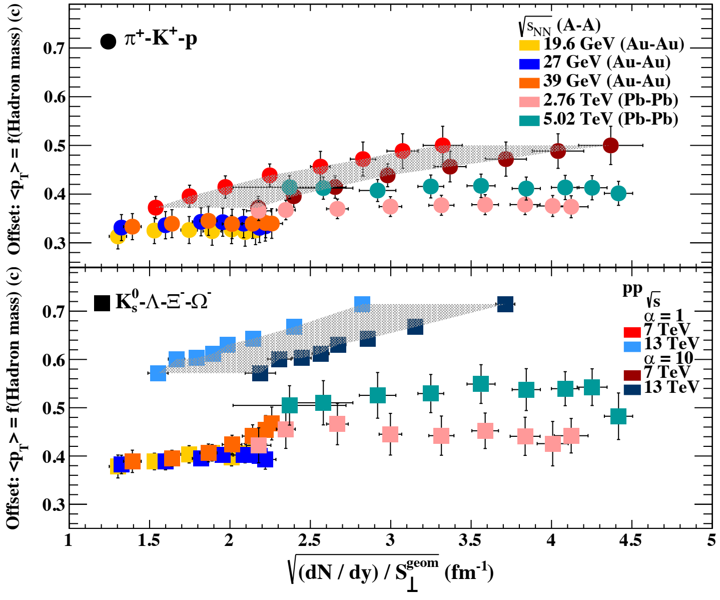
Quarks and Gluons

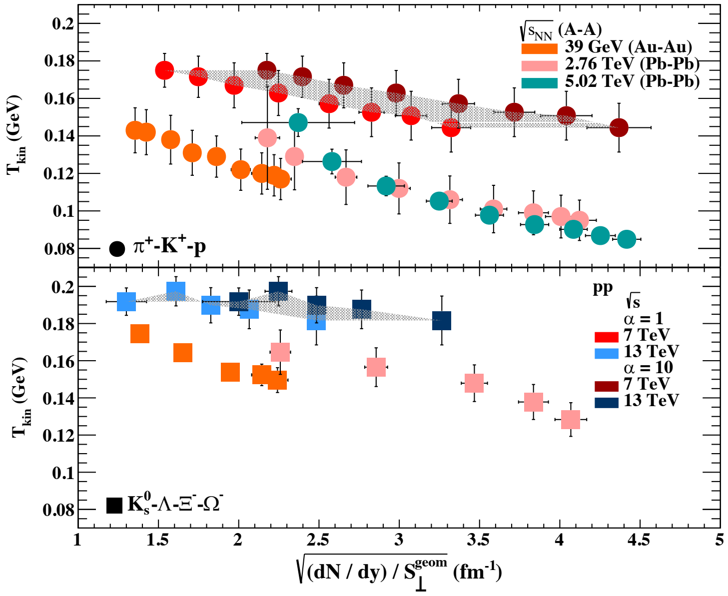

A-A
Centrality (%)
0 - 5
5 - 10
10 - 20
20 - 30
Centrality (%)
30 - 40
40 - 60
60 - 80
a+b(log$\sqrt{s_{NN}}$)$^{\alpha}$
$\langle dN/dy \rangle / S_{\perp}^{geom}$(fm^{-2})
0
2
4
6
8
10
12
14
16
18
20
10
10^2
10^3
$\sqrt{s_{NN}}$ (GeV)

pp vs. Pb-Pb @ LHC - $(dN/dy)/S_\perp$ scaling

Observable	α	species
$\langle p_T \rangle = f([(dN/dy)/S_\perp]^{1/2})$	10	π, K^-, K_s^0, Λ, Ξ, Ω
	1(low mult. -> 10(high mult.)	p
$\langle dE_T/dy \rangle / \langle dN/dy \rangle = f([(dN/dy)/S_\perp]^{1/2})$	10	π, K^-, K_s^0, p, Λ, Ξ, Ω
Slope $p_T = f(\text{mass})$	1	π, K^-, K_s^0, p, Λ, Ξ, Ω
$\langle \beta_T \rangle$	1	π, K^-, K_s^0, p, Λ, Ξ, Ω
$Y^{1s(ms)} / \langle dN/dy \rangle$	1	K, Λ, Ξ, Ω

Why the offset of $p_T = f(mass)$ and T^{fo}_{kin} from BGBW fits do not scale ?



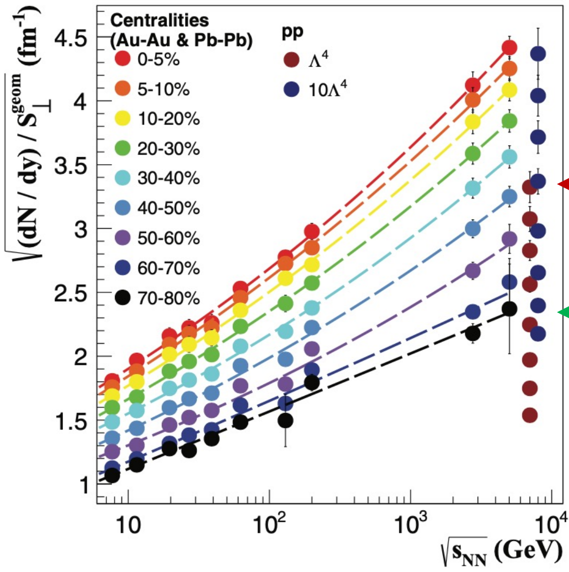


A. Lindner, M. Petrovici and A. Pop, PoS(PANIC2021)197

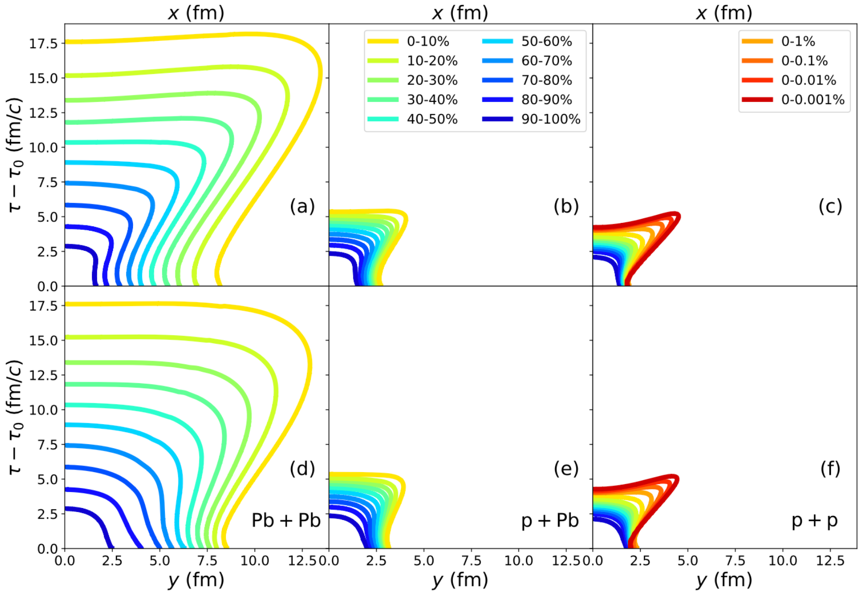
pp vs. Pb-Pb @ LHC

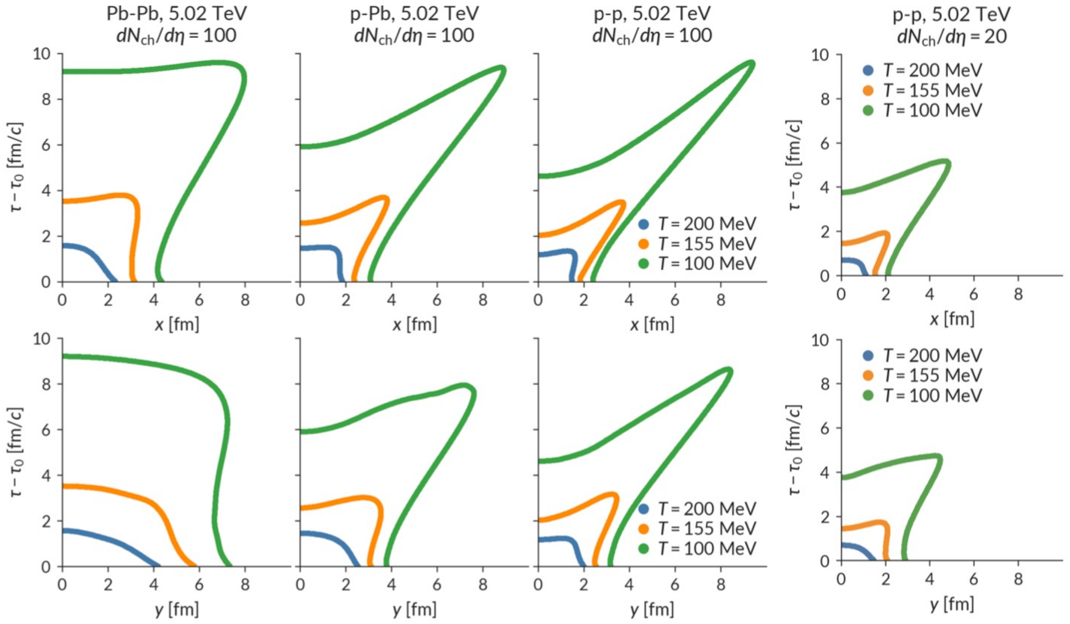
System	$\sqrt{s_{NN}}$ (GeV)	Cen. (%)	$\langle N_{\text{part}} \rangle$	$S_\perp^{\text{geom}}$ (fm^2)	$S_\perp^{\text{var}}$ (fm^2)	f_{core}	$(S_\perp^{\text{geom}})^{\text{core}}$ (fm^2)	$(S_\perp^{\text{var}})^{\text{core}}$ (fm^2)	dN/dy
Pb-Pb	2760	0–5	382.5 ± 3.1	166.9 ± 0.7	170.7 ± 0.7	0.94 ± 0.00	146.0 ± 0.7	148.0 ± 0.6	2837.0 ± 144.0
		5–10	329.4 ± 4.9	146.1 ± 0.7	154.7 ± 0.6	0.90 ± 0.00	121.9 ± 0.7	126.5 ± 0.5	2345.5 ± 112.4
		10–20	259.9 ± 2.9	119.8 ± 0.8	132.4 ± 0.6	0.86 ± 0.00	96.3 ± 0.7	102.7 ± 0.4	1763.2 ± 84.8
		20–30	185.4 ± 3.9	92.9 ± 0.8	107.5 ± 0.5	0.81 ± 0.00	71.5 ± 0.8	78.4 ± 0.3	1195.8 ± 54.2
		30–40	128.1 ± 3.3	71.4 ± 0.8	87.2 ± 0.4	0.76 ± 0.00	52.4 ± 0.8	59.7 ± 0.2	784.8 ± 35.9
		40–50	84.2 ± 2.6	53.7 ± 0.8	70.3 ± 0.3	0.70 ± 0.00	37.2 ± 0.8	44.8 ± 0.2	482.7 ± 21.4
		50–60	52.1 ± 2.0	38.6 ± 0.8	56.1 ± 0.3	0.63 ± 0.00	24.7 ± 0.9	33.1 ± 0.1	274.8 ± 12.5
		60–70	29.5 ± 1.3	25.7 ± 0.8	43.6 ± 0.2	0.54 ± 0.00	14.6 ± 0.9	23.8 ± 0.1	141.8 ± 5.4
		70–80	14.9 ± 0.6	14.2 ± 0.8	30.8 ± 0.2	0.43 ± 0.00	6.4 ± 0.7	15.1 ± 0.1	67.2 ± 3.0
Pb-Pb	5020	0–5	385 ± 2	170.2 ± 0.7	174.2 ± 0.7	0.94 ± 0.00	149.0 ± 0.7	151.5 ± 0.6	3320.6 ± 131.4
		5–10	333 ± 4	149.2 ± 0.7	158.5 ± 0.6	0.90 ± 0.00	124.4 ± 0.7	129.9 ± 0.5	2698.7 ± 117.2
		10–20	263 ± 4	122.4 ± 0.8	135.8 ± 0.6	0.86 ± 0.00	98.1 ± 0.7	105.6 ± 0.4	2042.5 ± 84.7
		20–30	188 ± 3	94.9 ± 0.8	110.5 ± 0.5	0.82 ± 0.00	72.9 ± 0.7	80.8 ± 0.3	1401.4 ± 62.9
		30–40	131 ± 2	73.4 ± 0.8	90.0 ± 0.4	0.77 ± 0.00	53.8 ± 0.8	61.8 ± 0.3	931.0 ± 44.5
		40–50	86.3 ± 1.7	55.7 ± 0.8	73.1 ± 0.3	0.71 ± 0.00	38.6 ± 0.8	46.9 ± 0.2	588.6 ± 27.8
		50–60	53.6 ± 1.2	40.7 ± 0.8	58.7 ± 0.3	0.63 ± 0.00	26.3 ± 0.8	34.9 ± 0.2	346.9 ± 26.1
		60–70	30.0 ± 0.8	27.9 ± 0.8	45.9 ± 0.2	0.54 ± 0.01	16.2 ± 0.8	25.5 ± 0.1	186.1 ± 26.0
		70–80	15.6 ± 0.5	16.6 ± 0.7	33.0 ± 0.2	0.43 ± 0.01	7.7 ± 0.7	17.0 ± 0.1	93.5 ± 27.4

$\sqrt{s}$ (TeV) (pp)	dN/dy	$S_\perp$ (fm^2) $\alpha = 1$	$S_\perp$ (fm^2) $\alpha = 10$
7	82.1 ± 2.8	7.43 ± 0.48	4.30 ± 0.36
	70.2 ± 2.2	7.43 ± 0.41	4.30 ± 0.31
	59.4 ± 1.7	7.43 ± 0.35	4.30 ± 0.27
	48.8 ± 1.3	7.43 ± 0.30	4.30 ± 0.23
	37.3 ± 0.9	7.39 ± 0.02	4.20 ± 0.02
	26.8 ± 0.6	6.89 ± 0.05	3.80 ± 0.03
	18.2 ± 0.4	5.94 ± 0.06	3.16 ± 0.04
	10.8 ± 0.2	4.58 ± 0.06	2.29 ± 0.04



pp vs. Pb-Pb @ LHC - hydro models





C. Plumberg, Phys.Rev. C102(2020)054908

U. Heinz et al., Journal of Physics: Conf. Series 1271(2019)012018