MINISTERUL CERCETĂRII, INOVĂRII ȘI DIGITALIZĂRII

QCD Challenges

Mihai Petrovici, Seminar General IFIN-HH, November 21, 2024

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

Outline

- ***Introduction***
- ***Do we see a new state of deconfined matter at LHC ?***
  - $<p_T>/[(dN/dy)/S_{\perp}]^{1/2}$ ***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***
  - $(dN/dy)^{(strange\ and\ multi\ strange)}/(dN/dy)$ - $(dN/dy)/S_{\perp}$ ***correlation***
  - ***collision energy dependence of*** $(1-RAA)/[\langle dN/dy \rangle / S_{\perp}]$ ***for entral collisions***
- ***Similar studies for pp collisions and comparison with Pb-Pb collisions***
- ***What remains to be done at FAIR-SIS100 energies ?***
- ***Concluding remark***

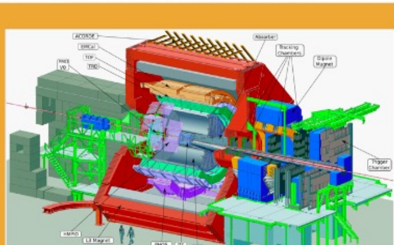
Results obtained in collaboration with:
A. Pop, C. Andrei, I. Berceanu+, A. Lindner, M. Tarzila

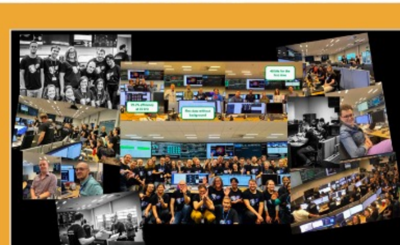
2024 - Year of Anniversaries

- *75th Anniversary of IFAR - precursor of IFA => IFIN-HH*
- *70th Anniversary of CERN*
- *50th Anniversary of High Energy Heavy-Ion*
- *25th Anniversary of our membership in ALICE @ CERN*
- *20th Anniversary of the DetLab of Hadron Physics Department*
- *20th Anniversary of CBM Collaboration*

HPD COURIER

NUMBER 6 | MAY 2024





HPD COURIER

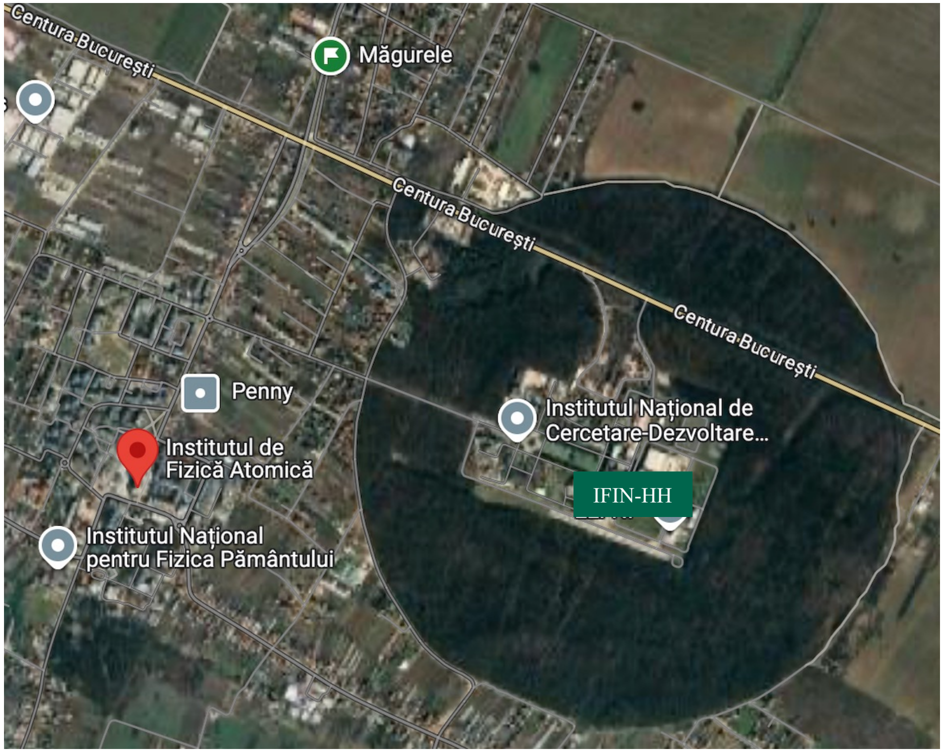
NUMBER 7 | August 2024

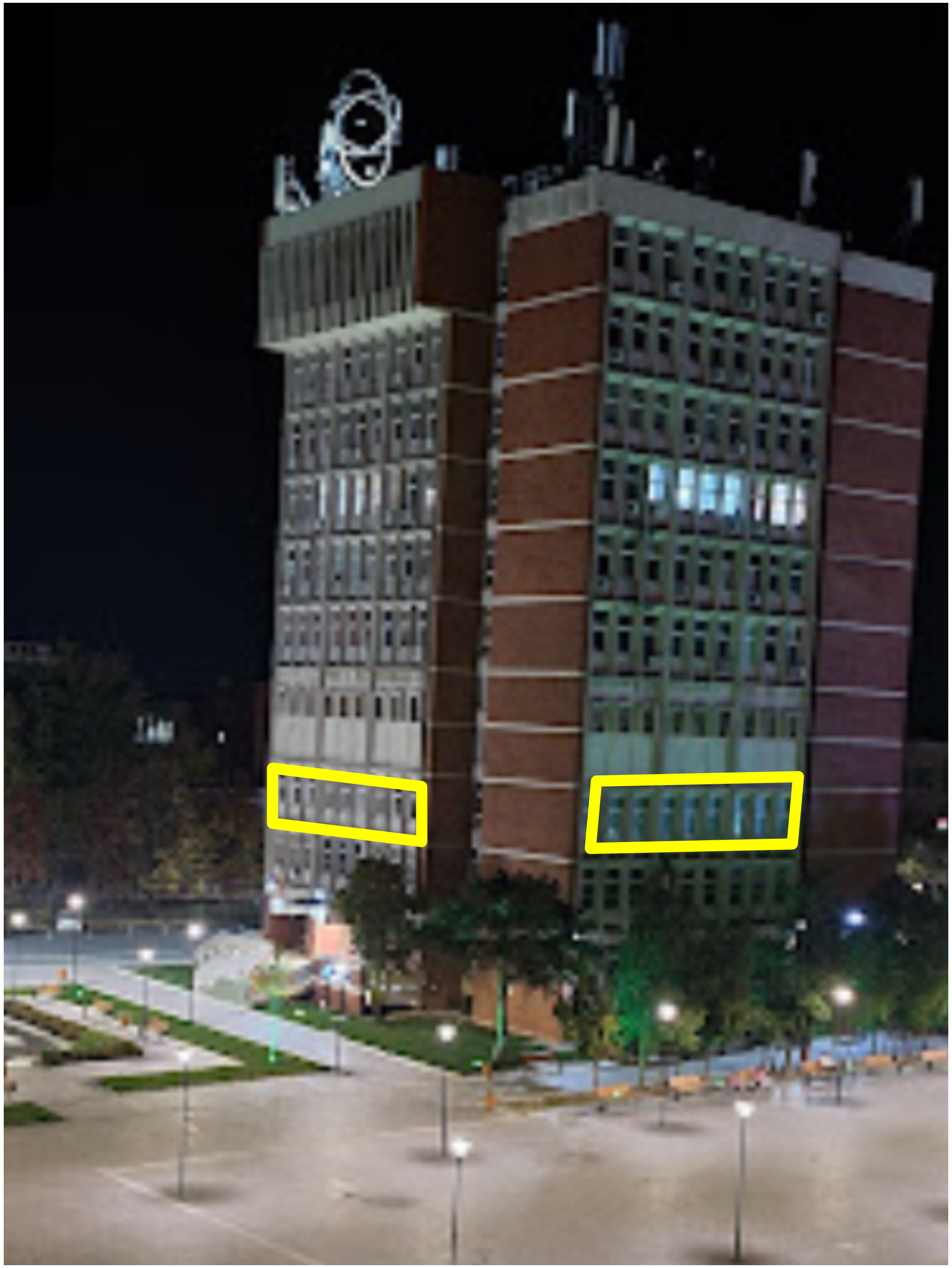
20 years of R&D activities for developing a new generation of RPC & TRD

Electronic version
HPD Couriers can be accessed at:
http://niham.nipne.ro/HPD_Courier.html

70th CERN anniversary, Romania in ALICE 25th anniversary
QUANTA exhibition, 5-31 October 2024

Romanian Science Gateway IFA building, 2nd floor

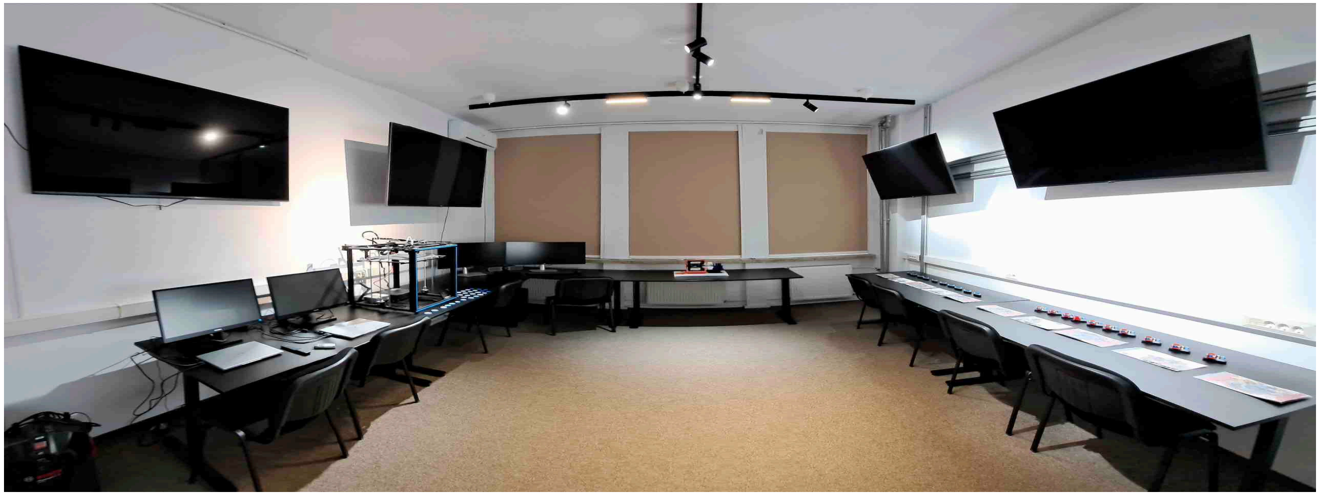




IFA, Atomistilor street, no. 407
Magurele 077125
ifa-mg.ro
021 457 4493

ALICE exhibition - entrance hall

Section I



Section II

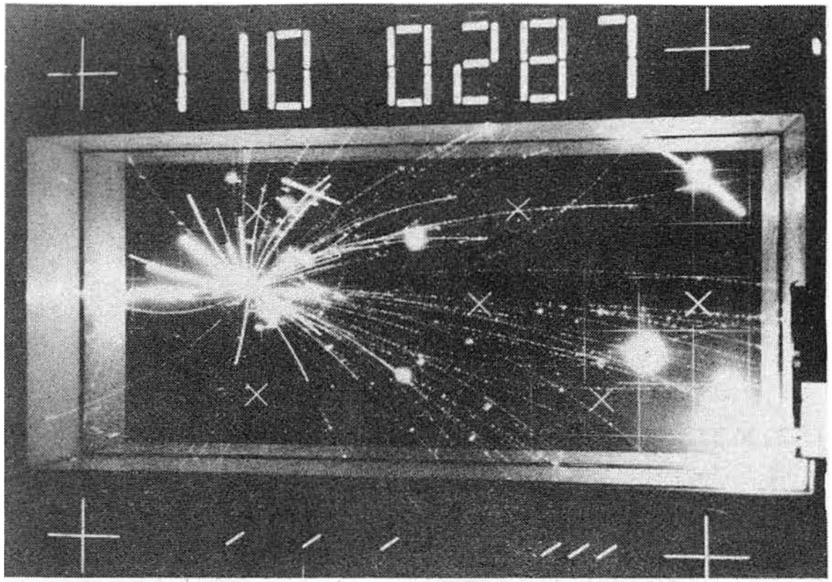
Section III

50^{th} anniversary of high energy heavy-ion

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

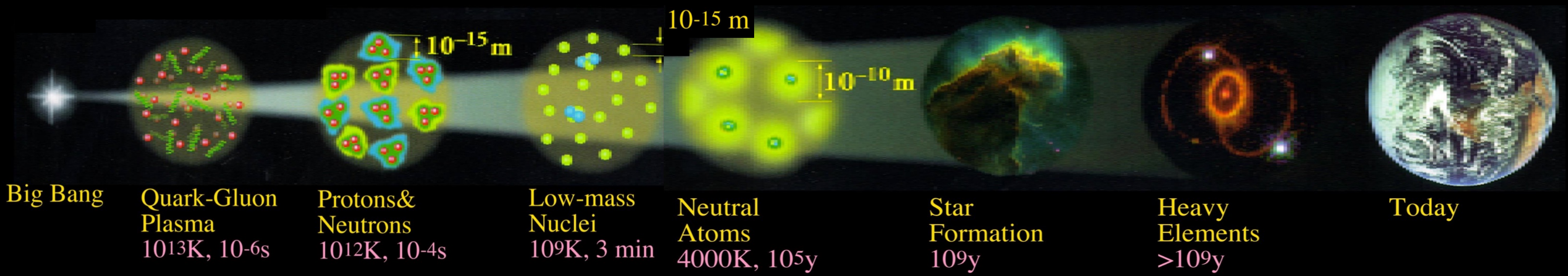
- ***A University of Frankfurt group has exposed their AgCl detectors to various heavy-ion beams at energies from 250 MeV/A to 2.1 GeV/A. The observed peaks in the angular distributions of light fragments that moved with beam energy in a manner suggestive of these particles arising from shock waves,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



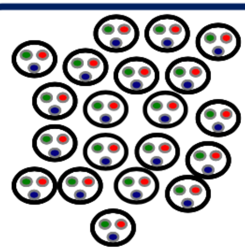
https://escholarship.org/uc/item/8bw3436f

Could we unravel
the
History of the Universe

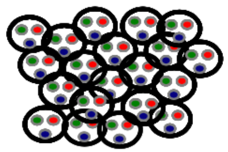


based on experiments
in terrestrial laboratories ?

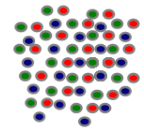
How to produce extreme states of nuclear matter in terrestrial laboratories ?



Strongly Bound Clusters Hadrons



Phase transition

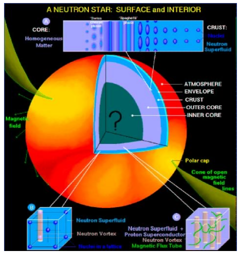


Weekly interacting Quarks and Gluons

A phase transition is expected at:

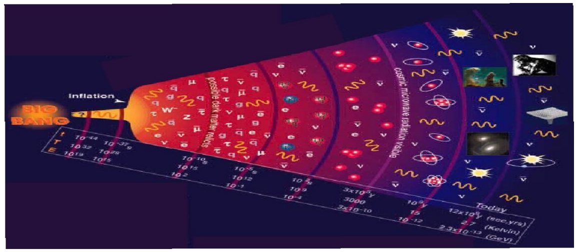
$\rho_B \sim \Lambda_{QCD}^3 \sim 1 fm^{-3}$

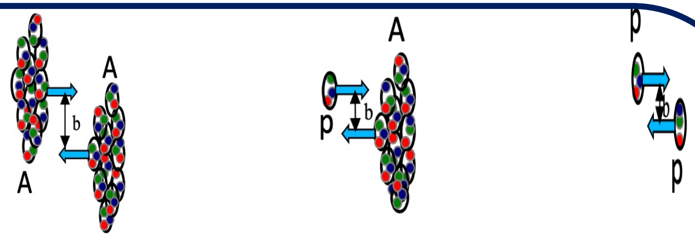
~ 16 km
~ 10^{16} sec



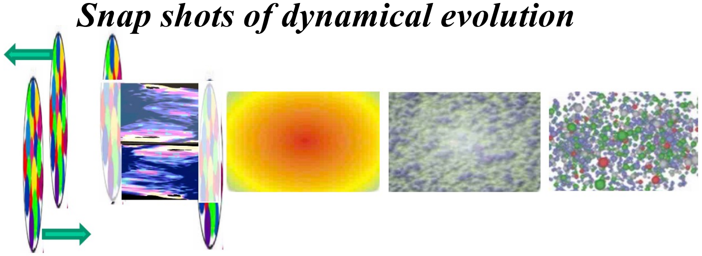
$T \sim \Lambda_{QCD} \sim O\,(10^{12}\,K)$

~ 10 km
~ 10^{-6} sec

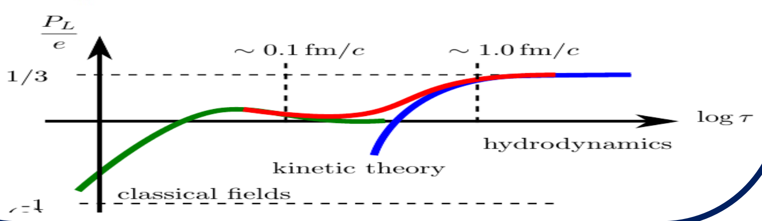




Snap shots of dynamical evolution



~ 6 fm
~ 10^{-22} sec



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

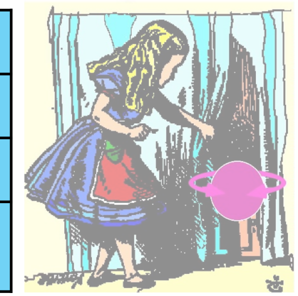
Large scale facilities

LHC: Collider
Pb+Pb @5020GeV/A

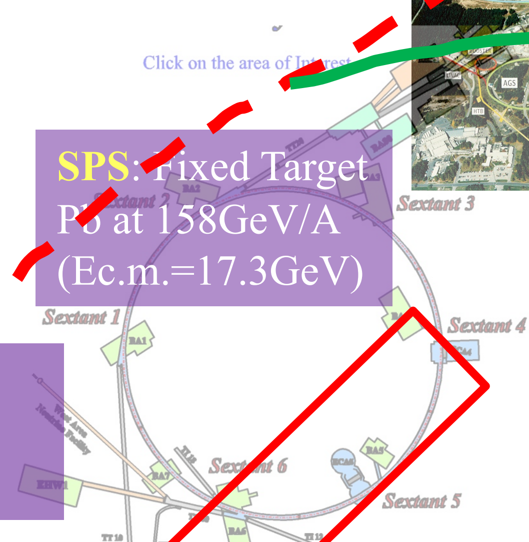
RHIC: Collider
Au+Au @ 200GeV/A

?

Hotter
Denser
Longer
Bigger

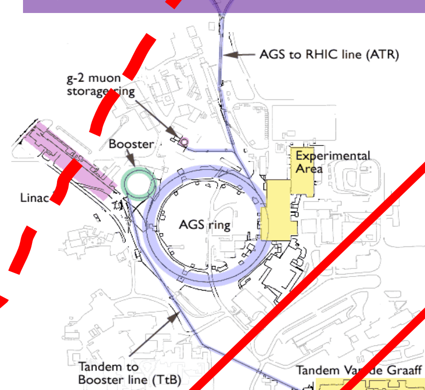


SPS: Fixed Target
Pb at 158GeV/A
(Ec.m.=17.3GeV)



???

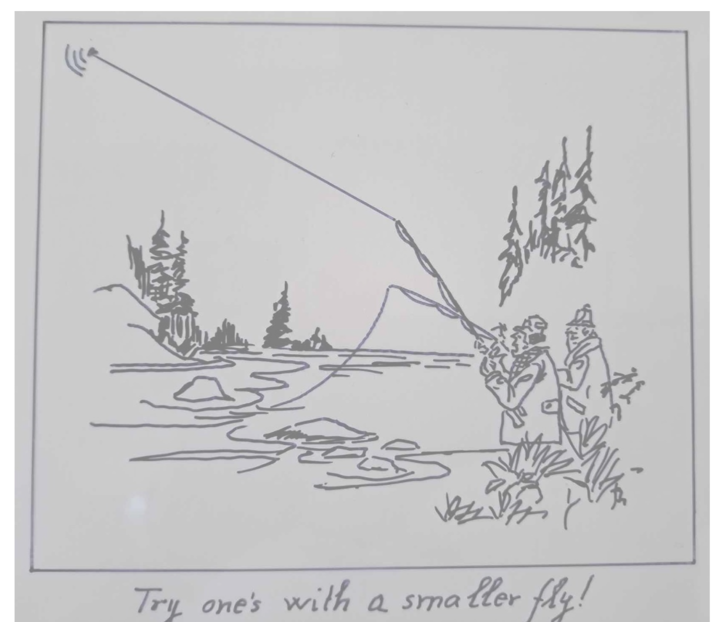
AGS: Fixed Target
Au at 11.7GeV/A
(Ec.m.=4.86GeV)



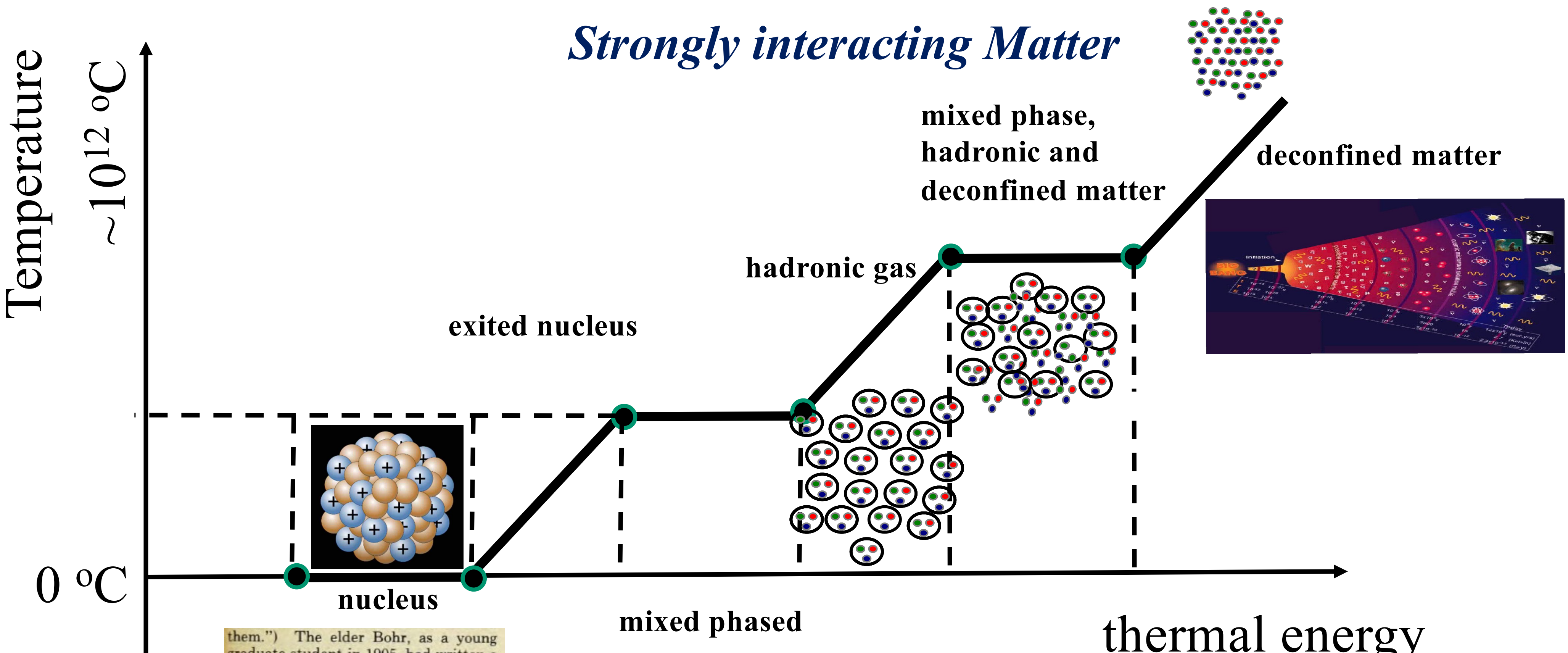
BES

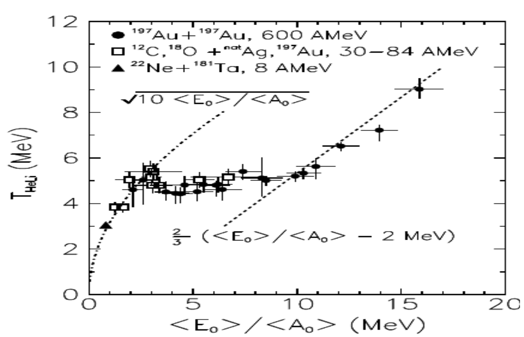
Bevalac
Fixed Target
1-2GeV/A

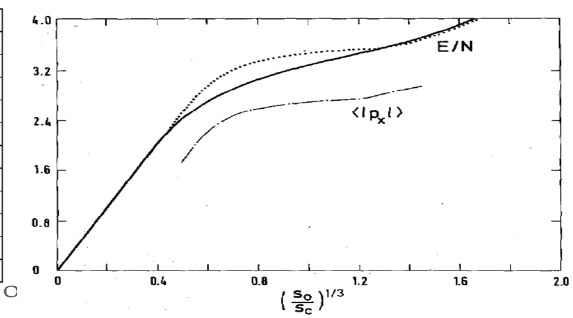
SIS 18



Physics motivation



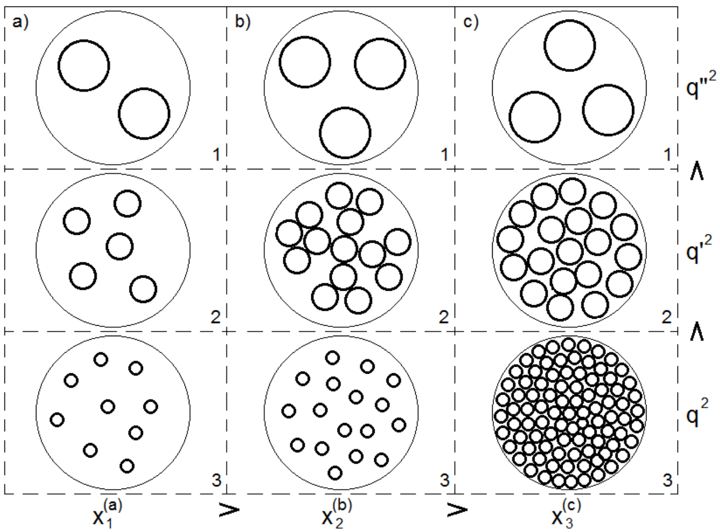




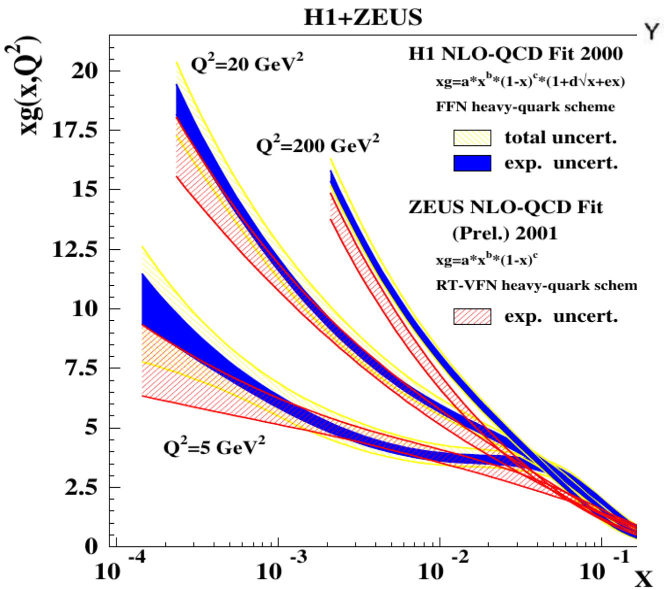
J.Pochodzalla et al., ALADIN Coll., arXiv:[nucl-ex]9607004

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

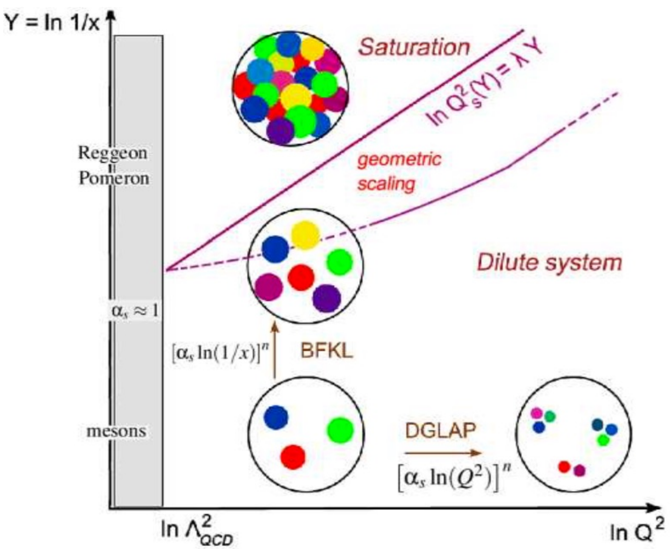
Physics motivation



L.V. Gribov et al, Phys.Rep. 100(1983)1



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



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

Following A.H. Mueller approximations NP A715(2003)20

System	*Au-Au*	*Pb-Pb*	*Pb-Pb*	*pp*
$\sqrt{s}(GeV)$	*200*	*2700*	*5020*	*7000*
$\frac{dN_g^{in}}{dyd^2b}(fm^{-2})$	≈4.7	≈11.8	≈15.9	≈18.7
f_{in}^g	≈0.9	≈2.3	≈3.1	≈3.6

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

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

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

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

$$\langle p_T^2\rangle/[(dn/dy)/S_\perp] \propto \langle p_T^2\rangle_1 r_0^2/\mu\,(1-e^{-\eta})$$

CGC

Local parton-hadron duality picture and dimensionality argument

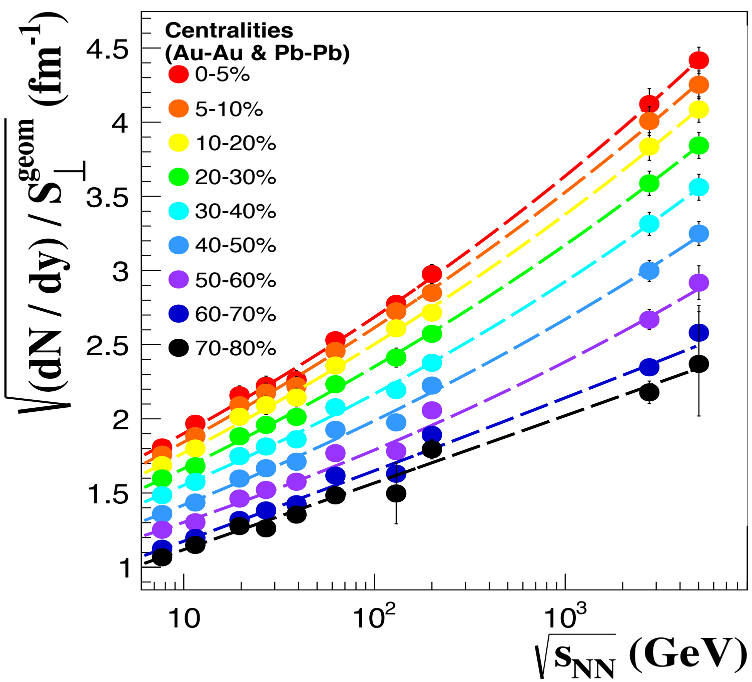
- Y.L.Dokshitzer, V.A.Khoze and S.Troian, J.Phys.G 17 (1991) 1585
- T. Lappi, Eur.Phys.J. C71 (2011) 1699
- E. Levin and A.H. Rezaeian, Phys.Rev.D 83 (2011)11400111

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

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

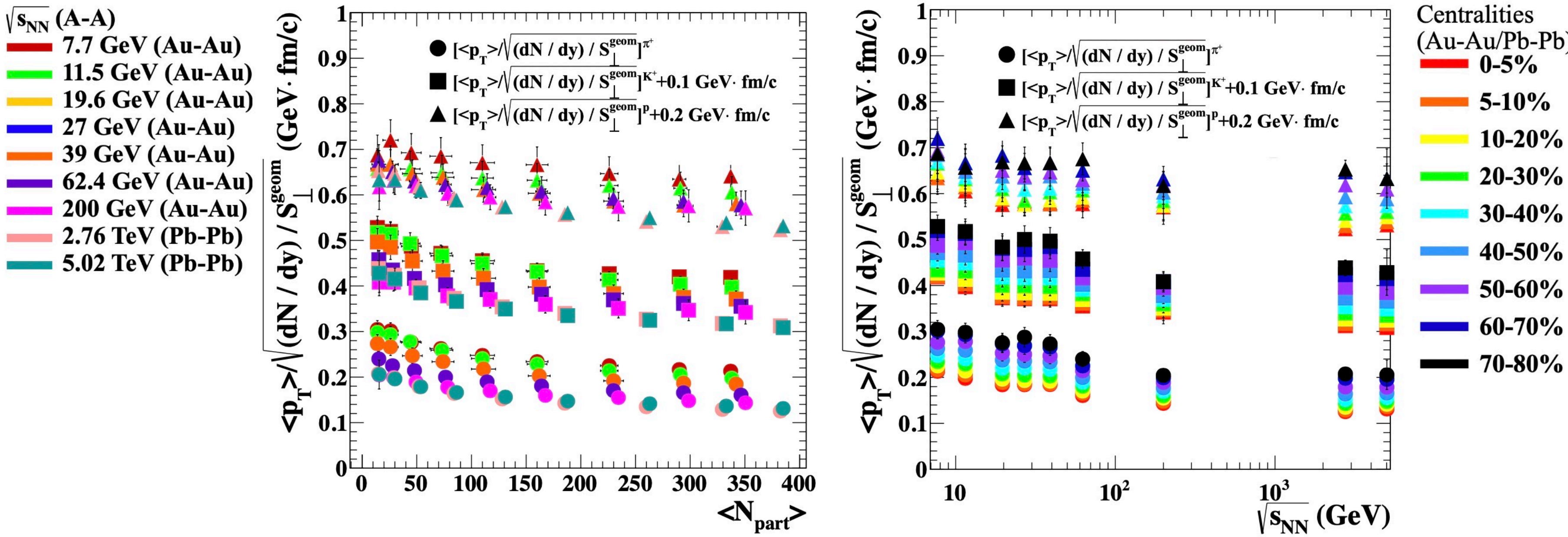
$$\langle p_T\rangle/\sqrt{\frac{dN}{dy}/S_\perp}$$

decreases as a function of:
- ***collision energy***
- ***centrality***

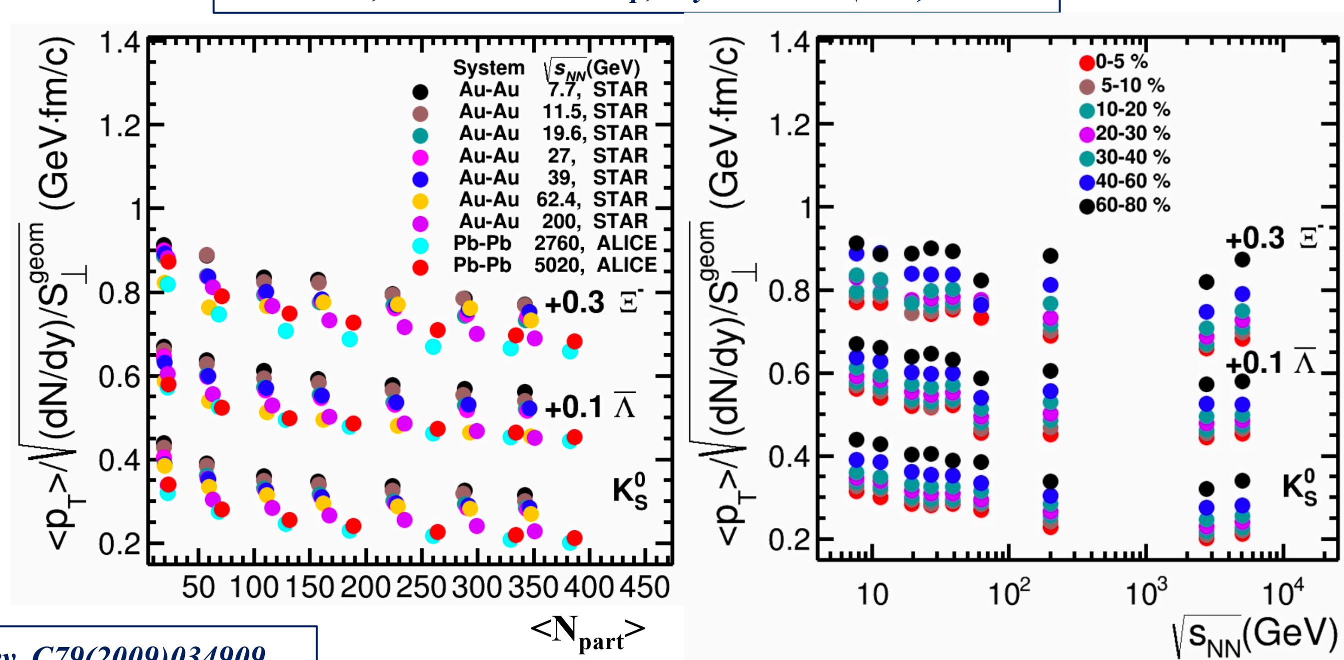


M.Petrovici, A.Lindner and A.Pop, Phys. Rev. C 98(2018)024904

Experimental results



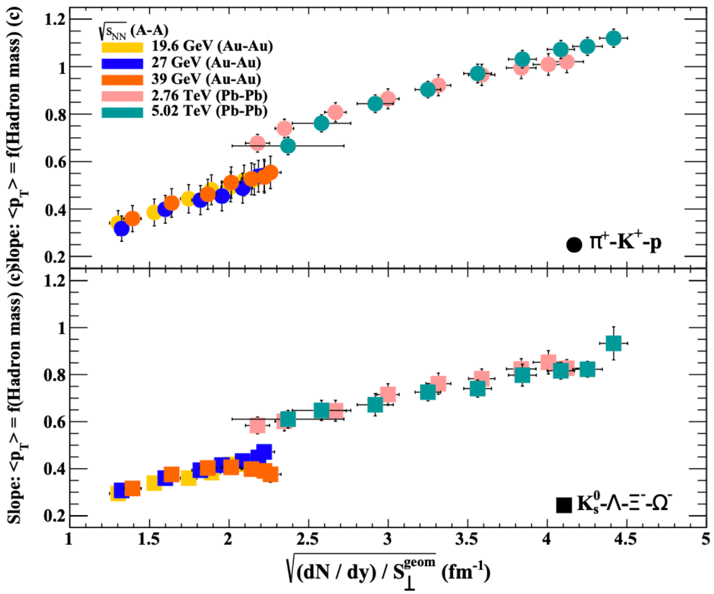
M.Petrovici, A.Lindner and A.Pop, Phys. Rev. C 98(2018)024904

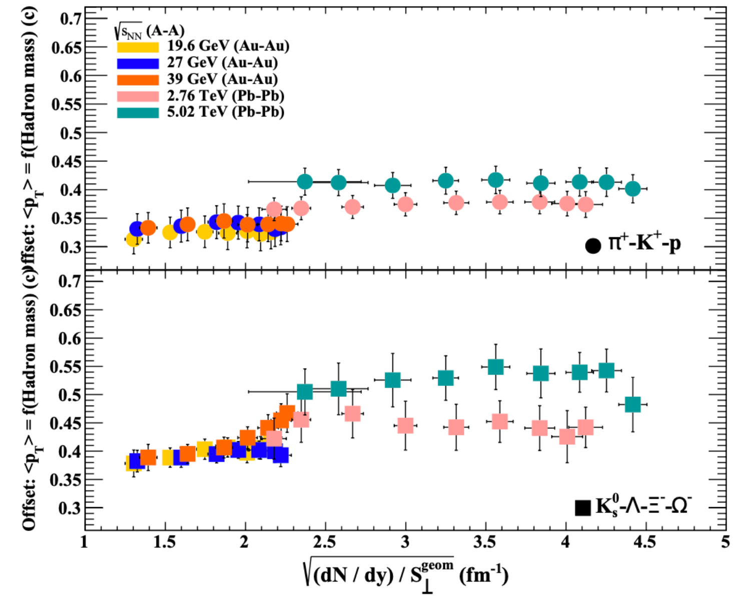


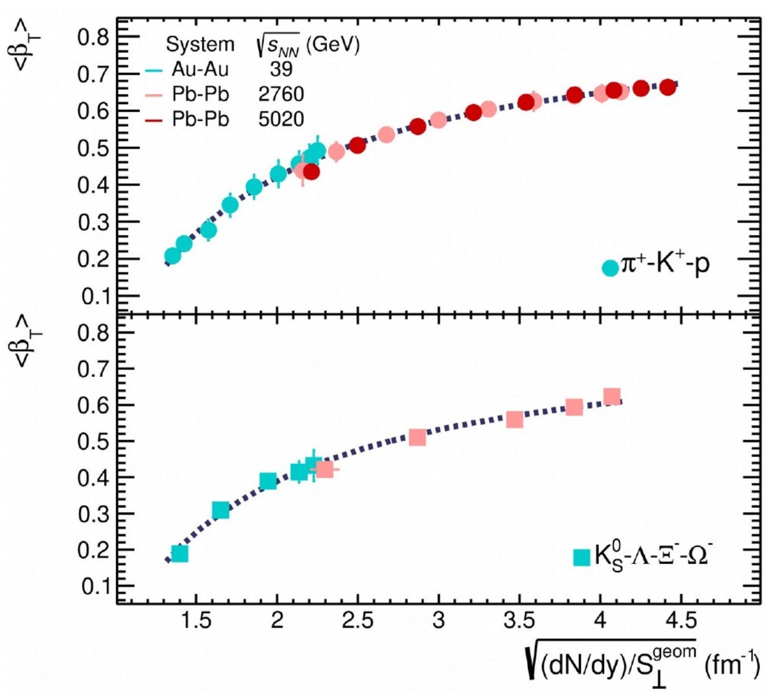
STAR Collaboration, Phys. Rev. C79(2009)034909
ALICE Collaboration, Phys. Rev. C88(2013)044910
STAR Collaboration), Phys. Rev. C96(2017)044904
ALICE Collaboration), Nucl. Phys. A967(2017)421

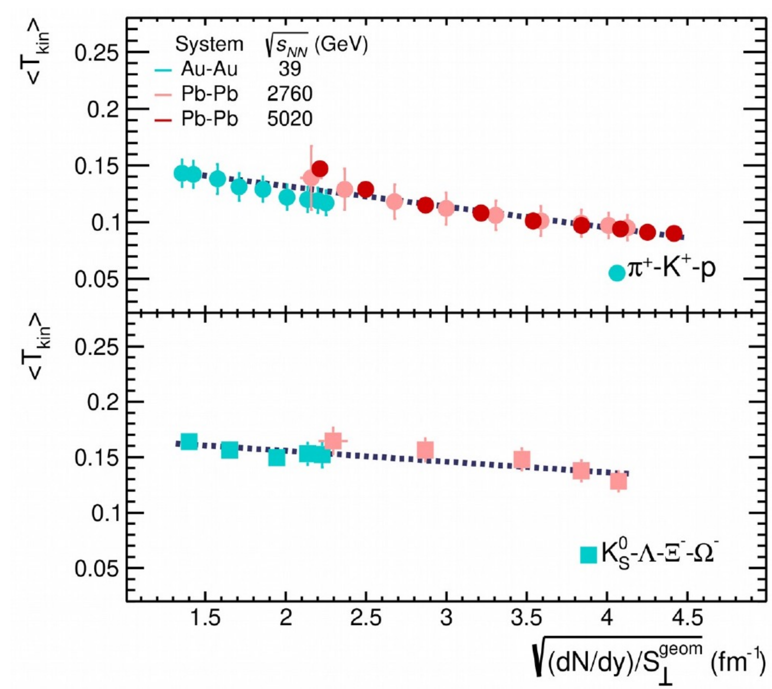
M. Petrovici and A. Pop , EuNPC 2022

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



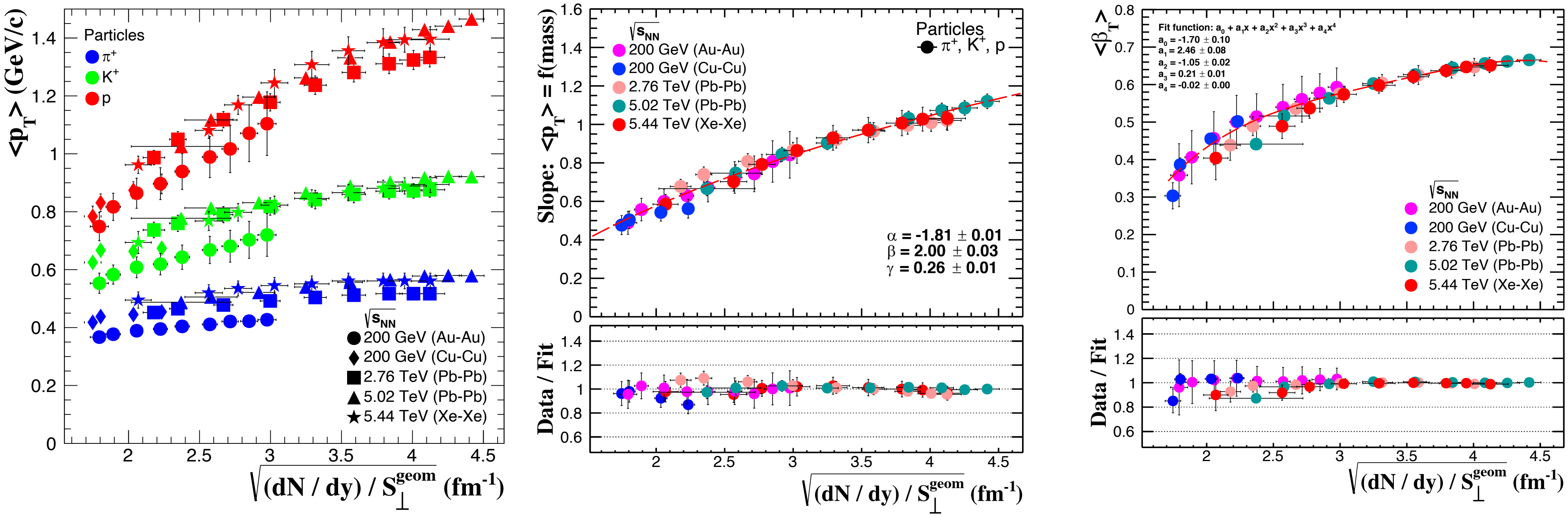






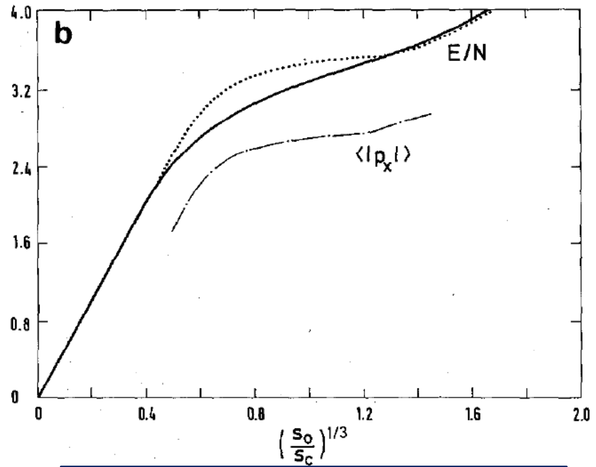
M. Petrovici et al., Phys. Rev. C 98(2018)024904
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph], accepted at PRC

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



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

Energy and Entropy density



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

- $\epsilon = Ts - p$ - qualitative temperature dependence of entropy, pressure and energy density
  - if p is small, at the transition the entropy density σ increases by the same factor as energy density ϵ
- dn/dy reflects the entropy, created early in the collision mainly through the interaction of the see gluons of the colliding hadrons
- the entropy being conserved during expansion and hadronization

$$E/N \sim \epsilon / s = E_{fo}/S_{fo}$$

$$s(T_0) \sim (1/R_0^3)(dN/dy)$$

RHIC BES energies:

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

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

RHIC $\sqrt{s_{NN}}$=62.4; 130 and 200 GeV:

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

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

LHC $\sqrt{s_{NN}}$=2.76 and 5.02 TeV :

$$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^++\pi^-)} + 2\frac{dN}{dy}^{(p+\bar{p},\Xi^-+\bar{\Xi}^+)} + 4\frac{dN}{dy}^{\Sigma^+} + \frac{dN}{dy}^{(K^++K^-,K_S^0+\bar{K_S^0},\Lambda+\bar{\Lambda},\Omega^-+\bar{\Omega}^+)}$$

$$\frac{dE_T}{dy} \simeq \frac{3}{2}(\langle m_T\rangle\frac{dN}{dy})^{(\pi^++\pi^-)} + 2(\langle m_T\rangle\frac{dN}{dy})^{(p+\bar{p},\Xi^-+\bar{\Xi}^+)} + 4(\langle m_T\rangle\frac{dN}{dy})^{\Sigma^+} + (\langle m_T\rangle\frac{dN}{dy})^{(K^++K^-,K_S^0+\bar{K_S^0},\Lambda+\bar{\Lambda},\Omega^-+\bar{\Omega}^+)}$$

for AGS and RHIC energies:

$$\langle m_T\rangle = \sqrt{\langle p_T\rangle^2 + m^2} - m_N$$ - for baryons

$$\langle m_T\rangle = \sqrt{\langle p_T\rangle^2 + m^2} + m_N$$ - for antibaryons

$$\langle m_T\rangle = \sqrt{\langle p_T\rangle^2 + m^2}$$ - for other particles

Present available experimental data

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

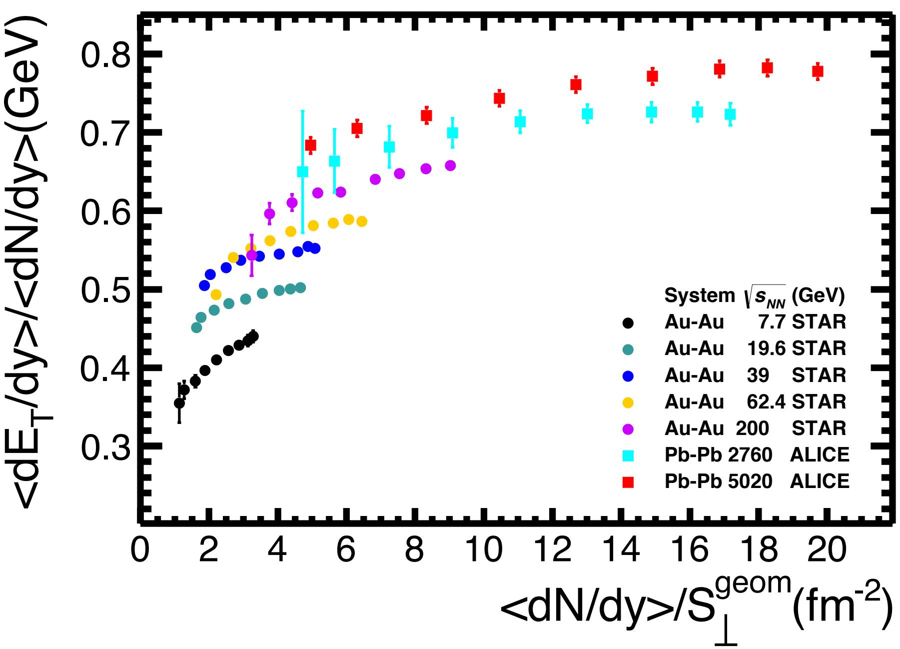
- <u>BES</u>
•J. Adam et al. (STAR Collaboration), Phys. Rev. C 102, 034909 (2020).

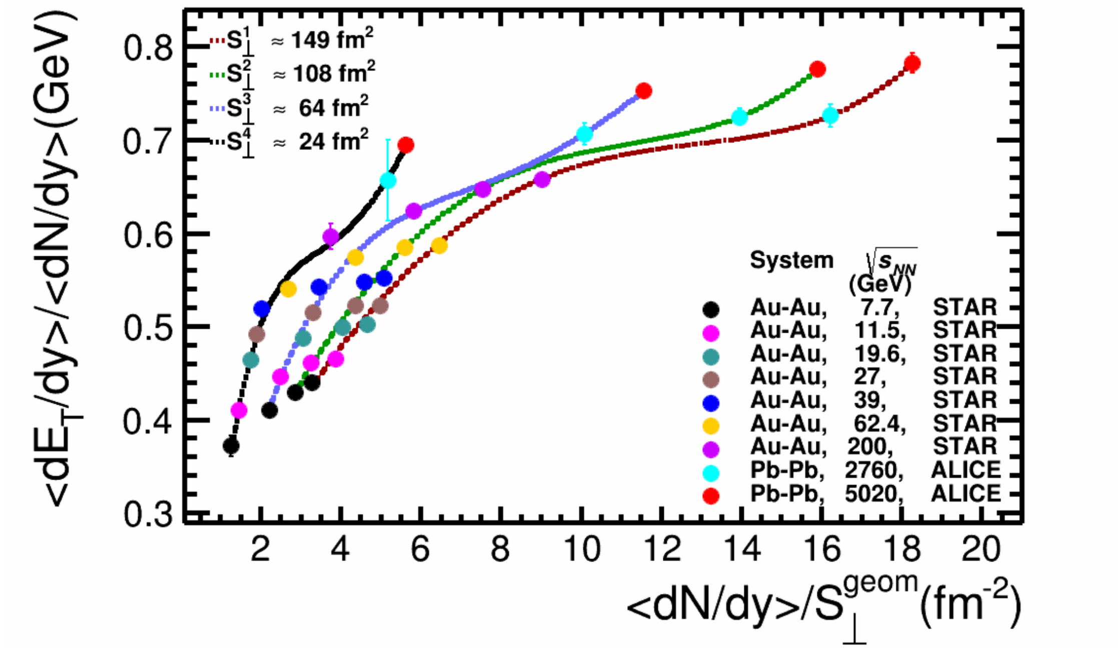
- <u>RHIC 62.4 GeV and 200 GeV</u>
• M. M. Aggarwal et al. (STAR Collaboration), Phys. Rev. C 83, 024901 (2011).
•J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 98, 062301 (2007).
•G. Agakishiev et al. (STAR Collaboration), Phys. Rev. Lett. 108, 072301 (2012).
• L. Adamczyk et al. (STAR Collaboration), 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).

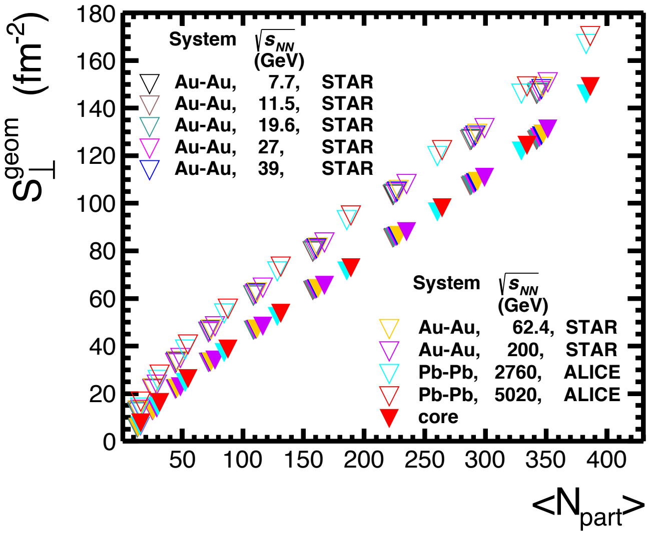
$(dE_T/dy)/(dN/dy)$ - $(dN/dy)/S_\perp$ correlation

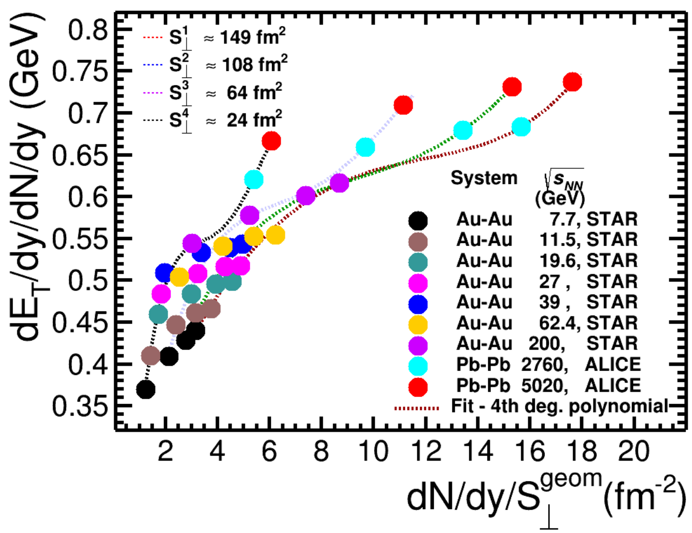


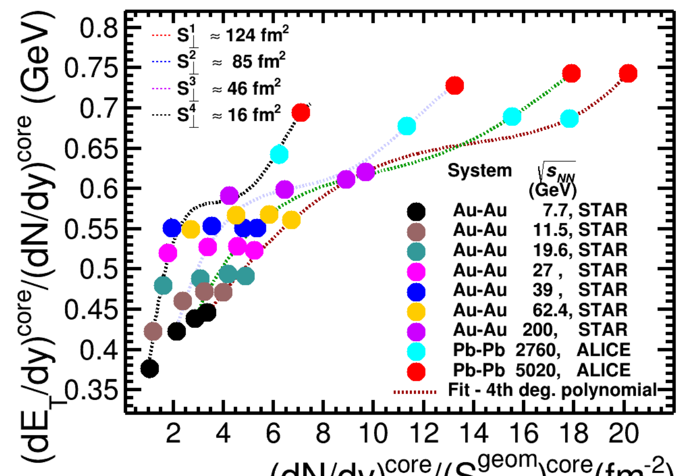


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

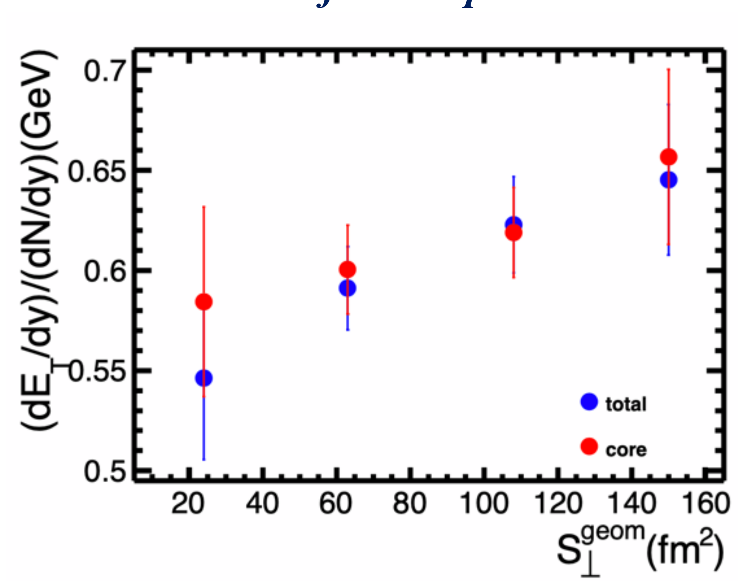
$(dE_T/dy)/(dN/dy)$ - $(dN/dy)/S_\perp$ correlation - core-corona
$\pi^\pm$, $K^\pm$, p, pbar and their neutrals







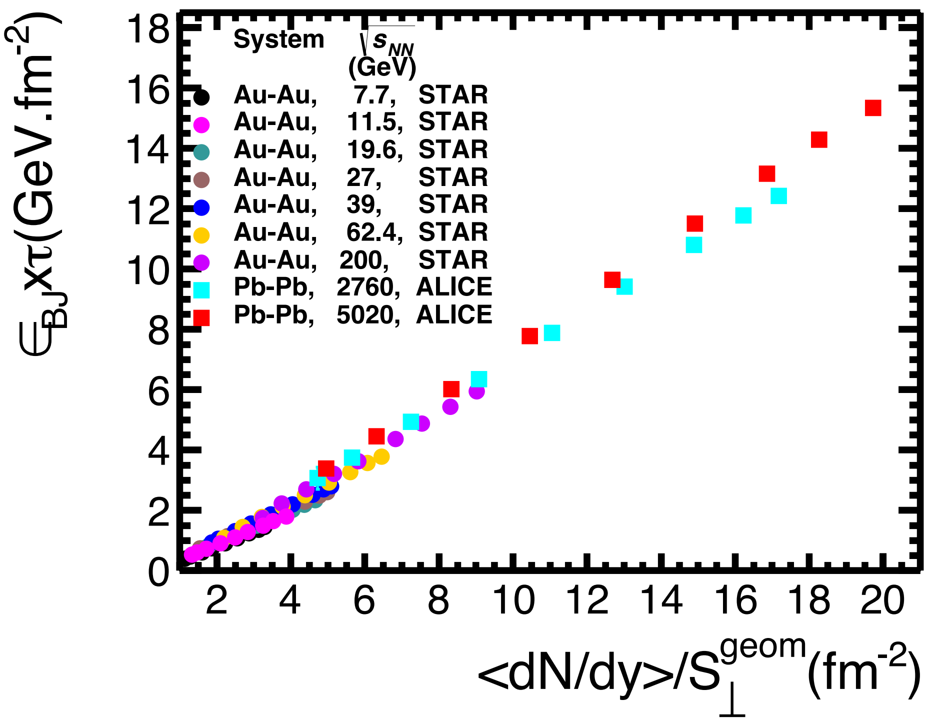
Inflection points

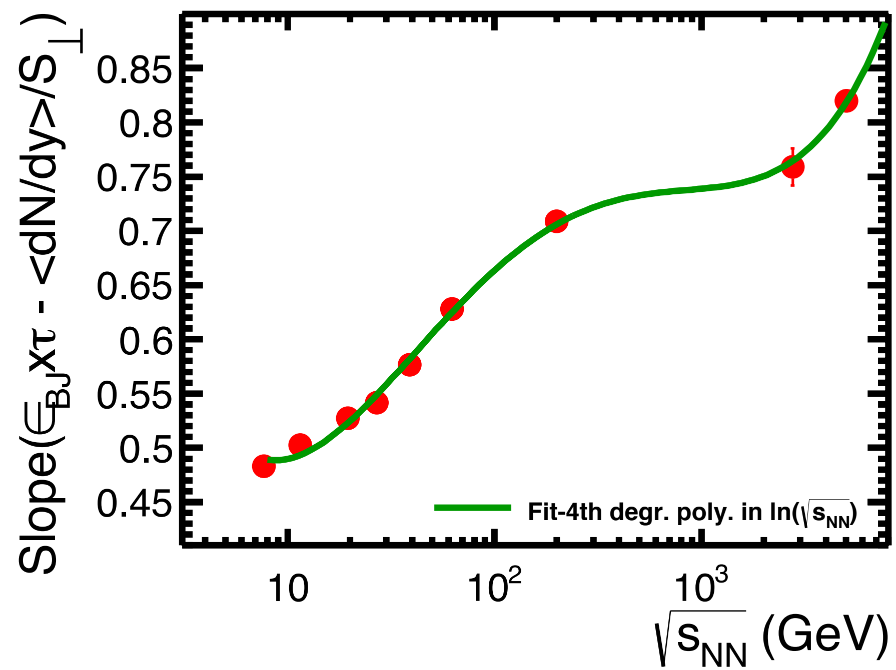


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

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

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



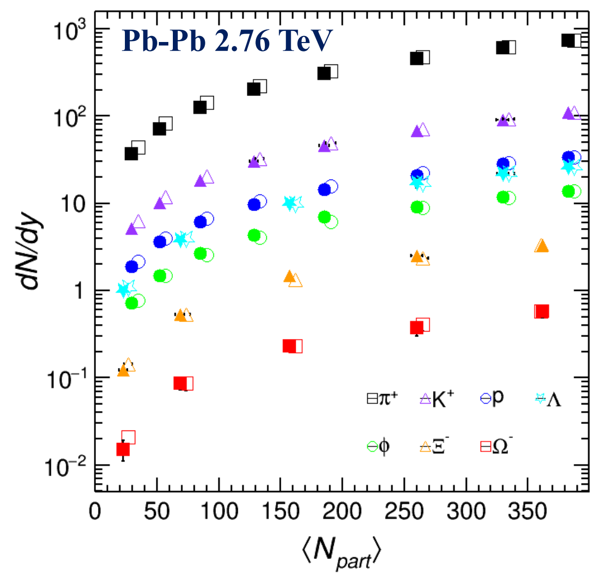


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

Strangeness production - smoking gun of deconfinement

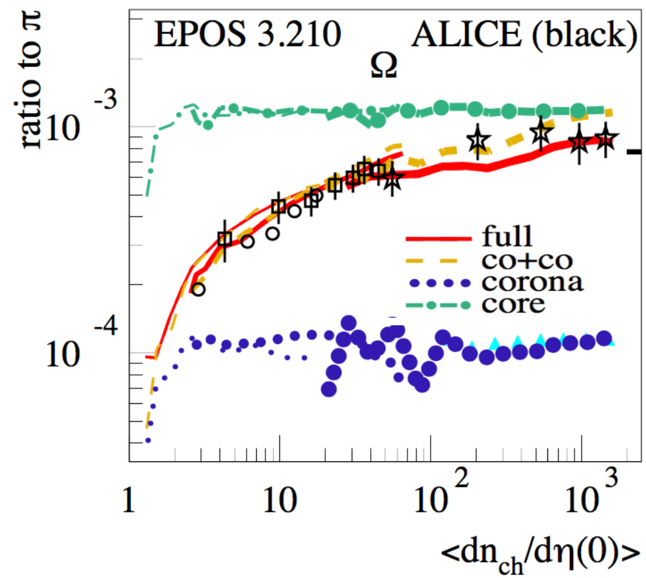
J.Rafelski and B.Muller, Phys.Rev.Lett. 48(1982)1066

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



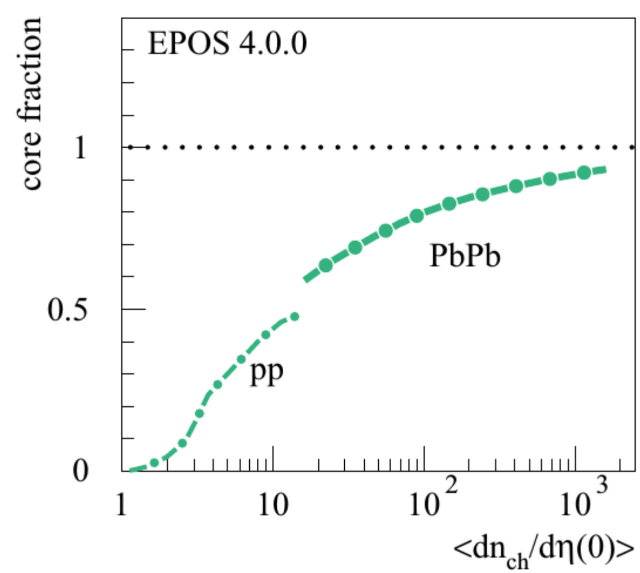
open symbols - Eq.1
full symbols - exp. points

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



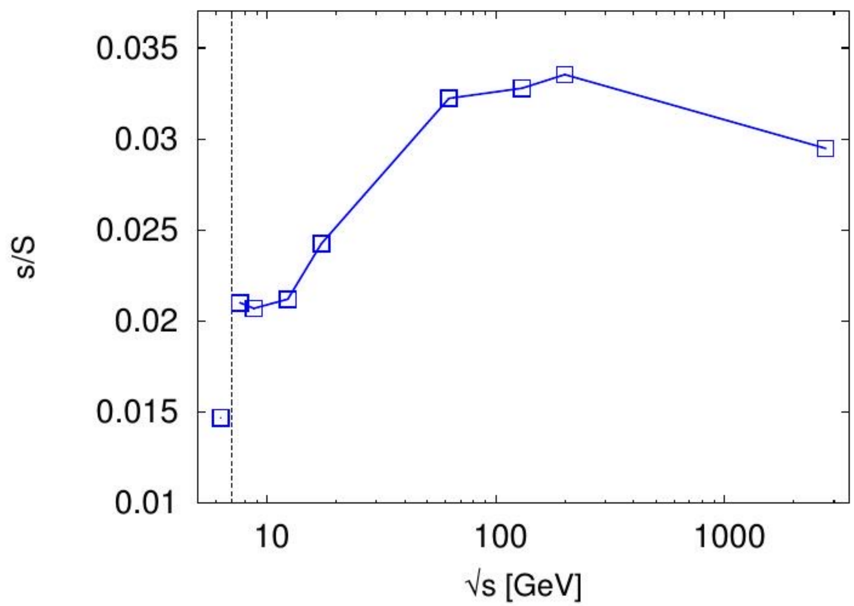
thin lines = pp (7TeV)
intermediate lines = pPb (5TeV)
thick lines = PbPb (2.76TeVVV)
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

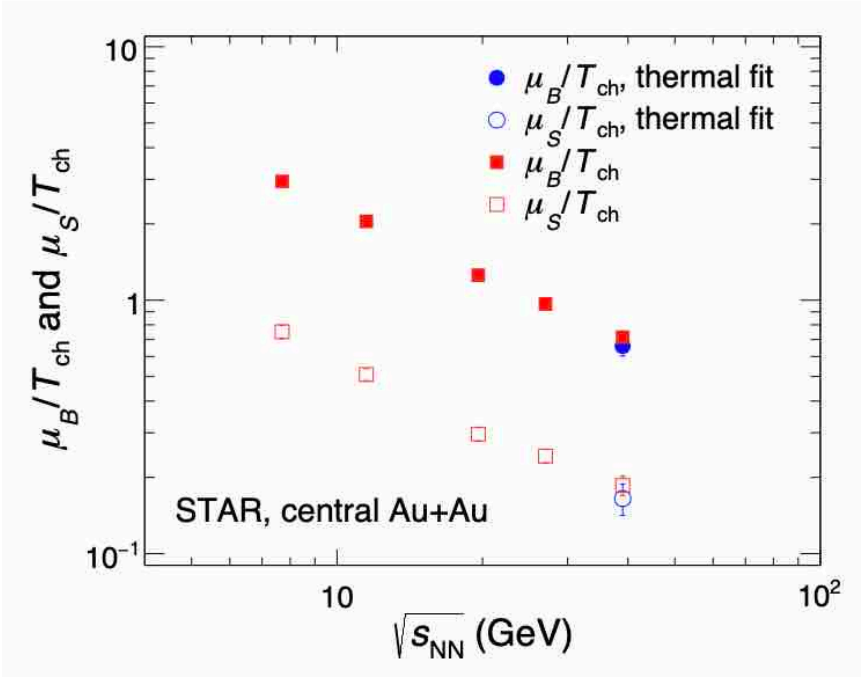
K. Werner, SQM 2017, July 10-15 2017, Utrecht



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

Strangeness production - smoking gun of deconfinement





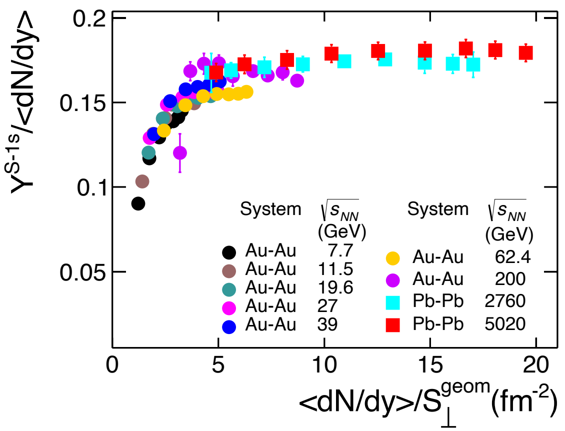
J.Rafelski and M.Petran, arXiv[nucl-th]1403.4036

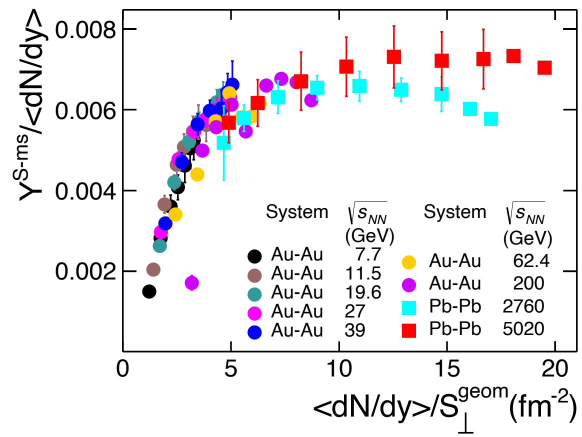
J.Adam et al, STAR Collaboration, Phys.Rev. C102(2020)034909

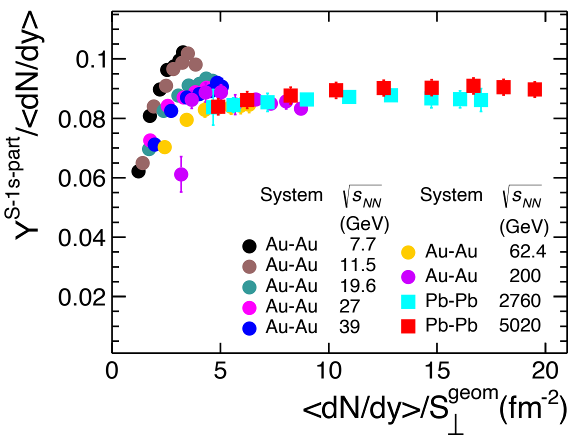
$(dN/dy)^{(strange\ and\ multi\ strange)}/(dN/dy)$ - $(dN/dy)/S_{\perp}$ correlation

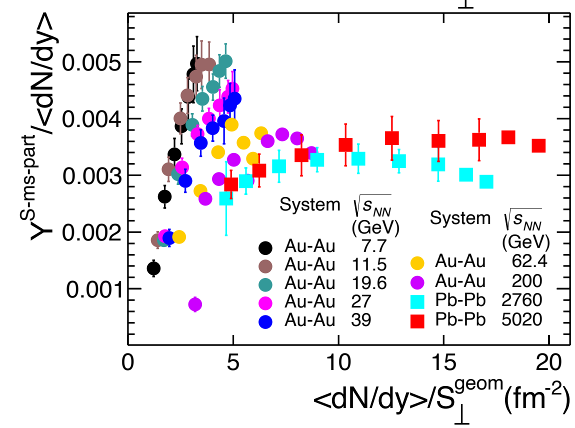
$$Y^{1s} = \frac{dN^{1s}}{dy} = \frac{dN^{(K^+ + K^-)}}{dy} + 2\frac{dN^{K_s^0}}{dy} + \frac{dN^{(\Lambda+\bar{\Lambda})}}{dy} + 2\frac{dN^{(\Sigma^- + \bar{\Sigma}^+)}}{dy}$$

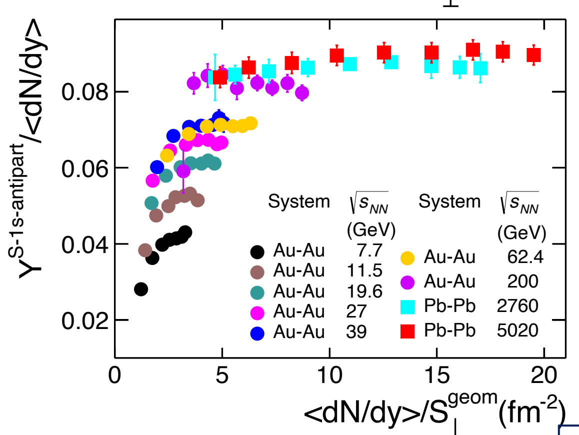
$$Y^{ms} = \frac{dN^{ms}}{dy} = \frac{dN^{(\Omega^- + \bar{\Omega}^+)}}{dy} + 2\frac{dN^{(\Xi^- + \bar{\Xi}^+)}}{dy}$$

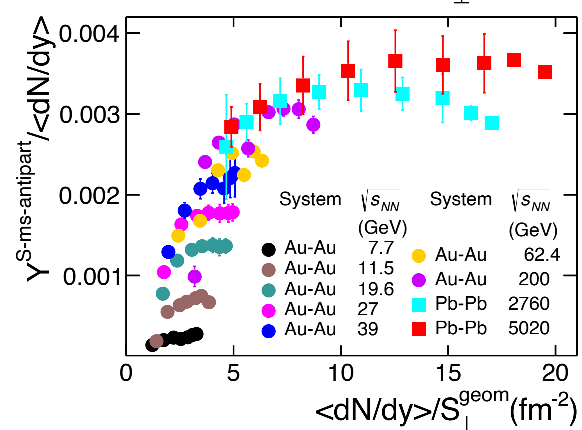






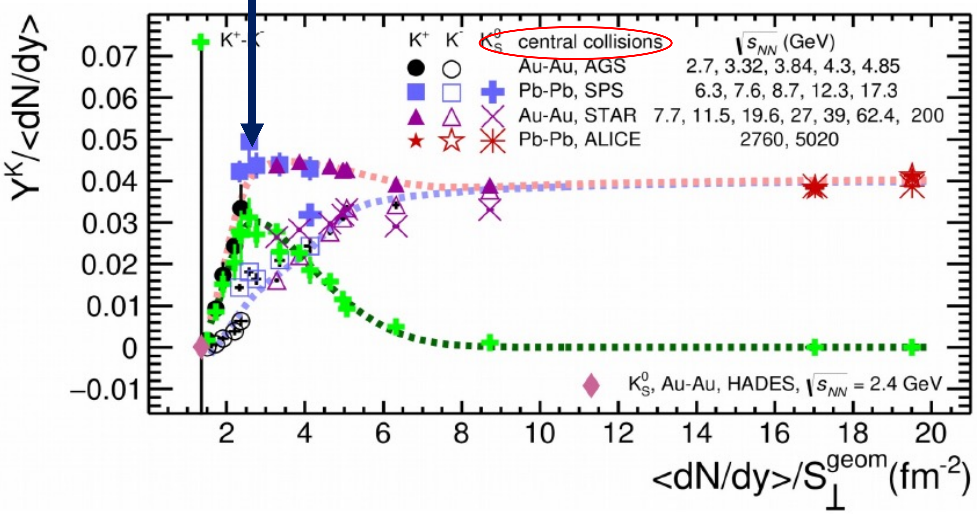


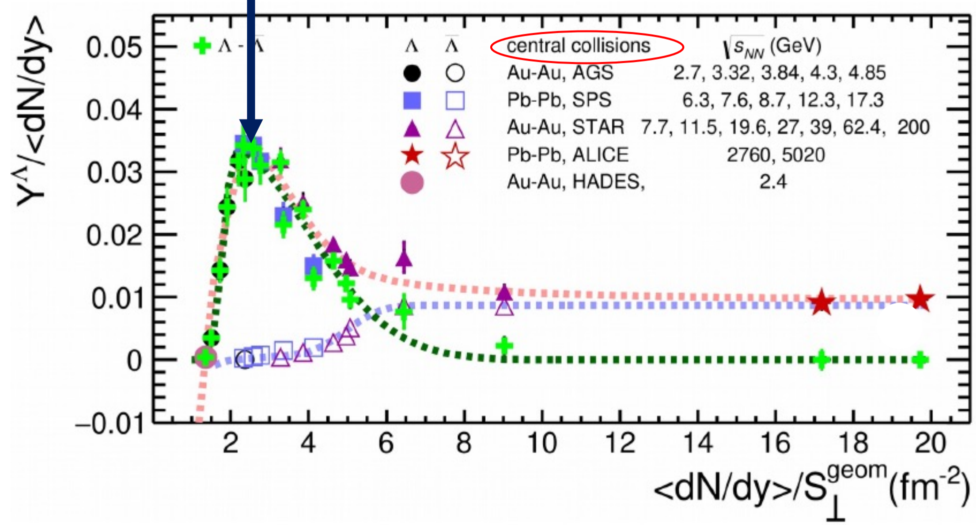


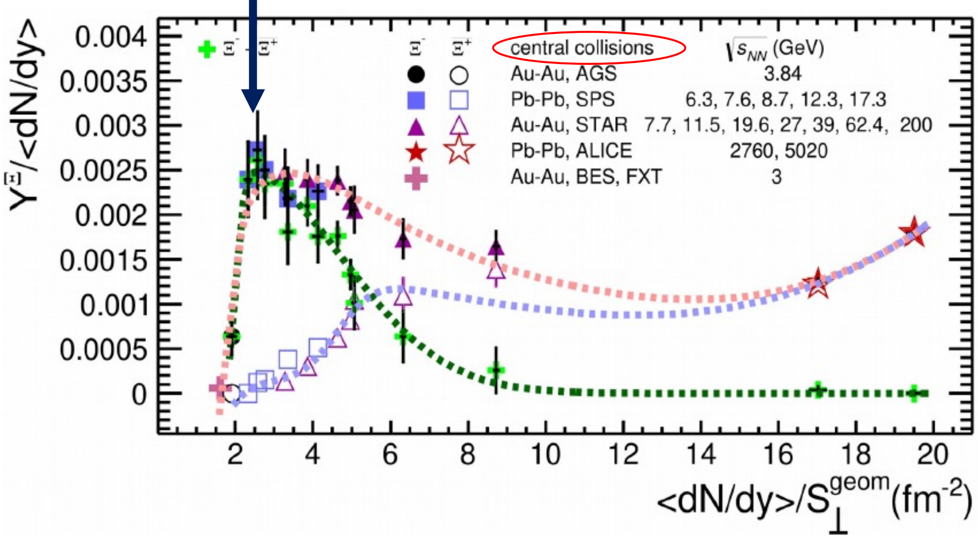


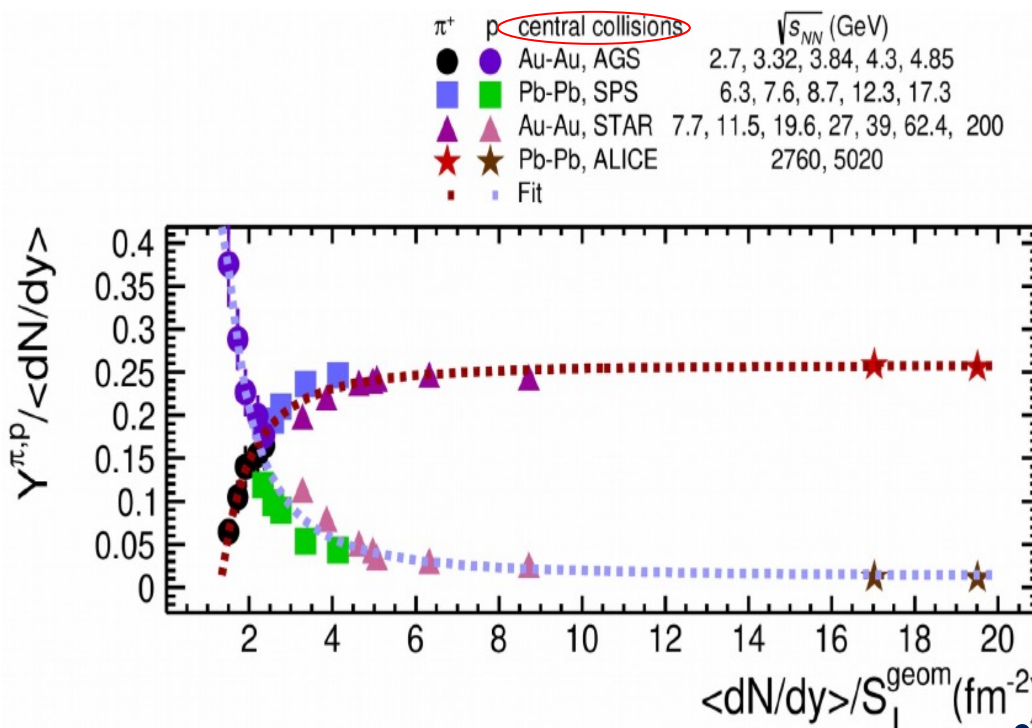
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph], accepted at PRC

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



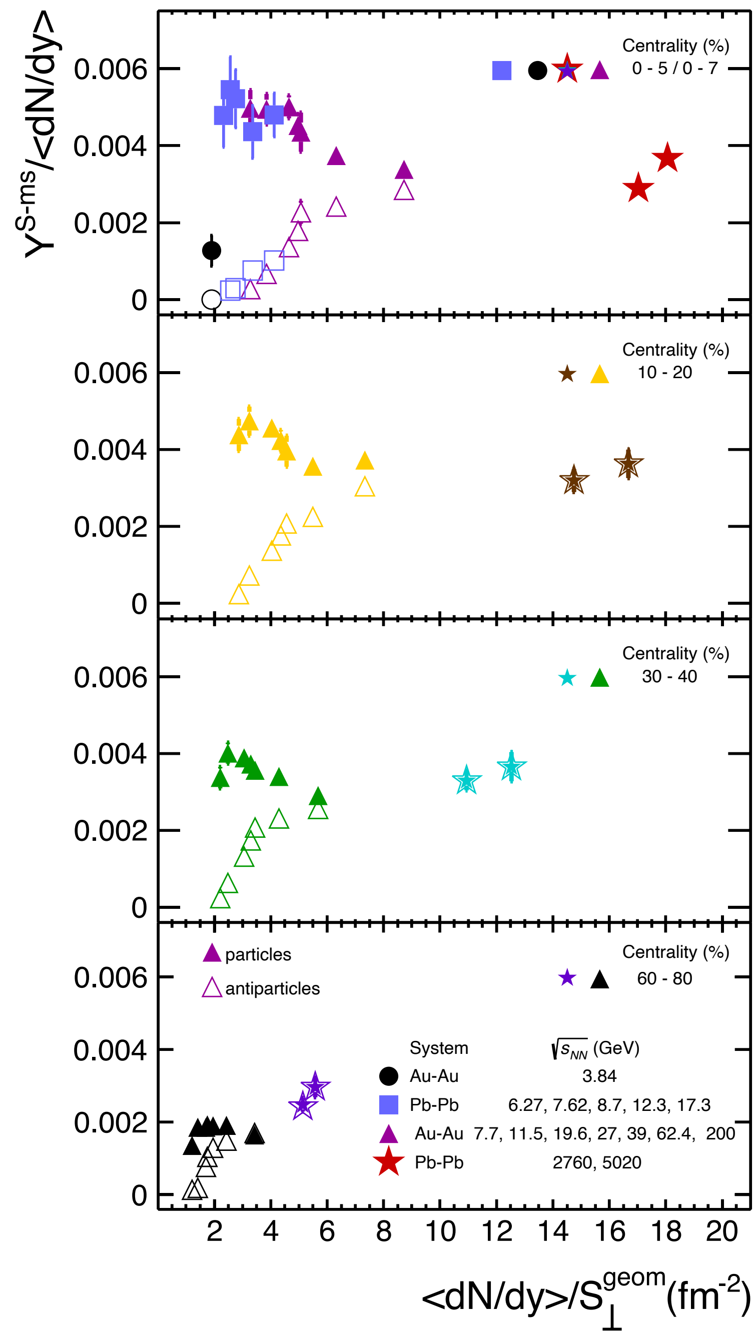






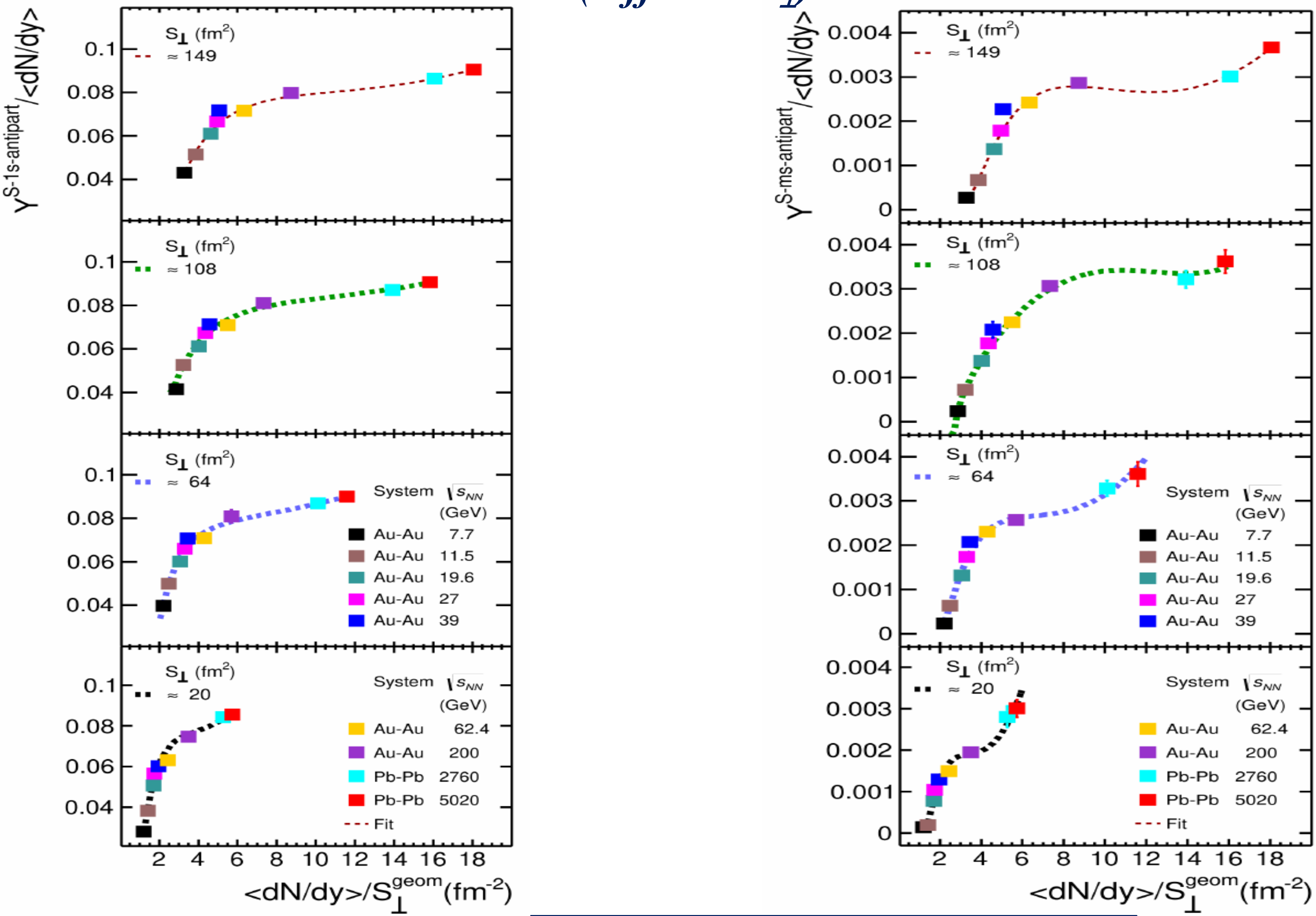
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph], accepted at PRC

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



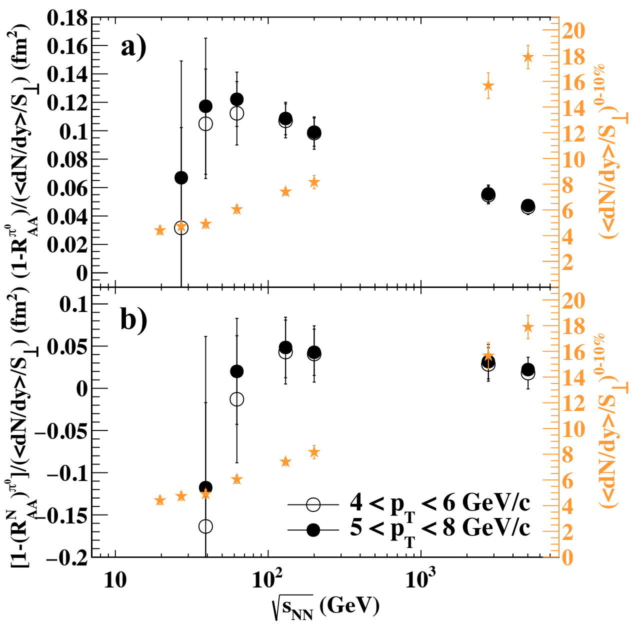
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph], accepted at PRC

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

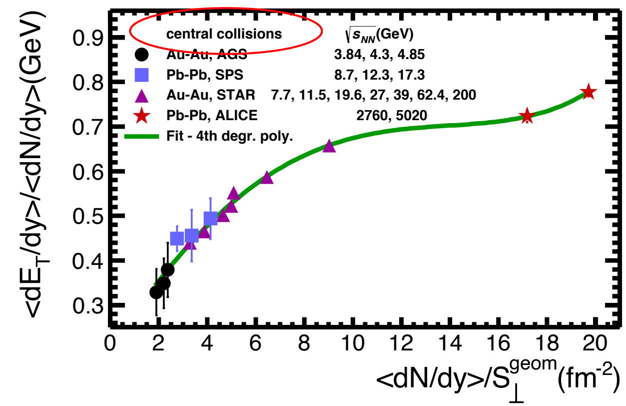


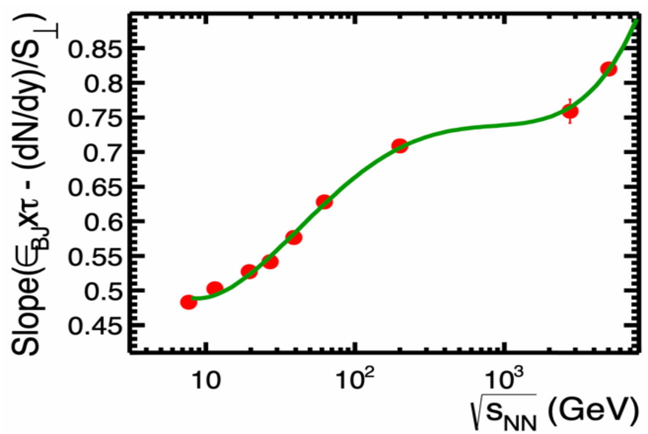
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph], accepted at PRC

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

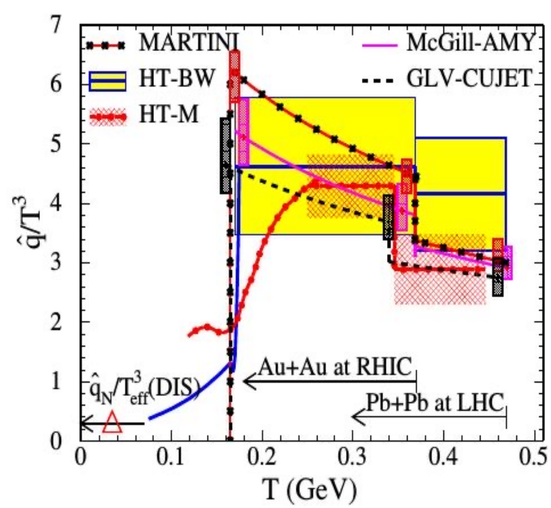


M.Petrovici et al., Phys. Rev. C103(2021)034903

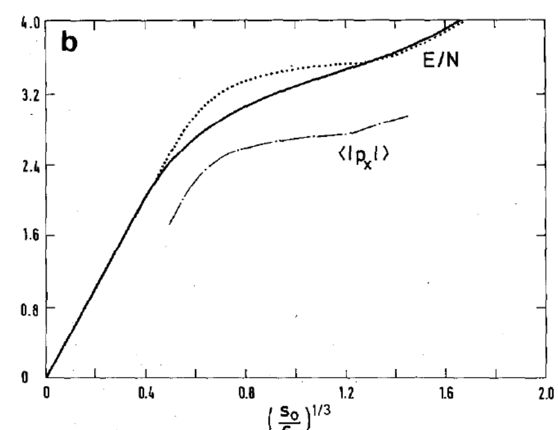




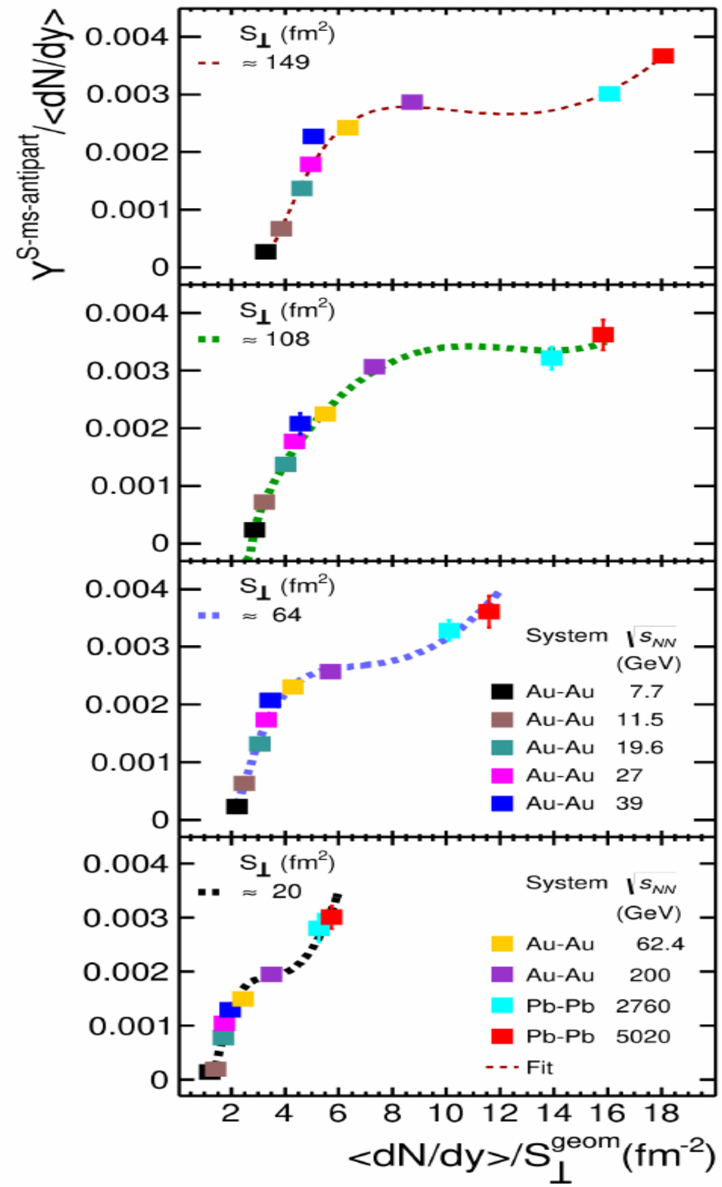
M.Petrovici and A.Pop, Phys.Rev. C107(2023)0



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

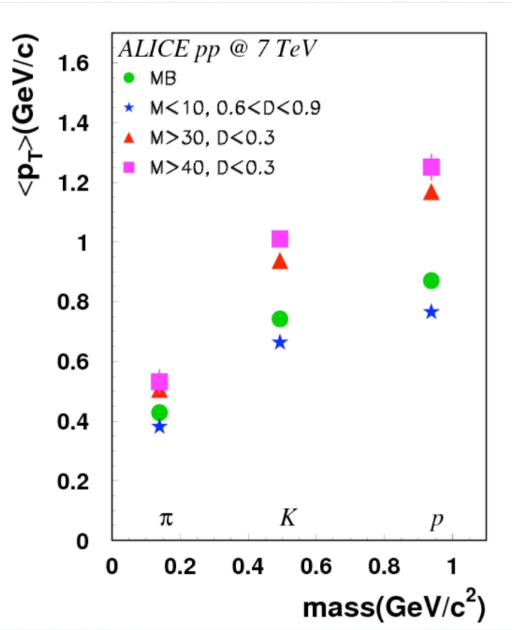


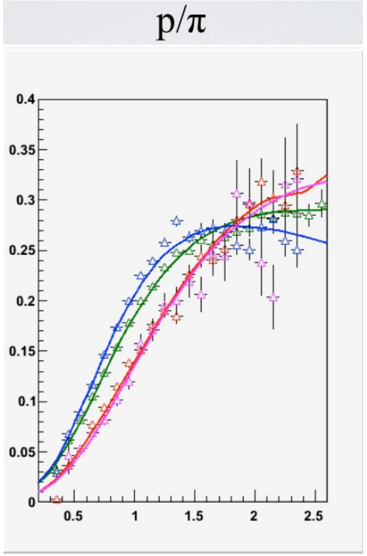
J.-P. Blaizot and J.-Y. Ollitraut, Phys.Lett 191B(1987)21

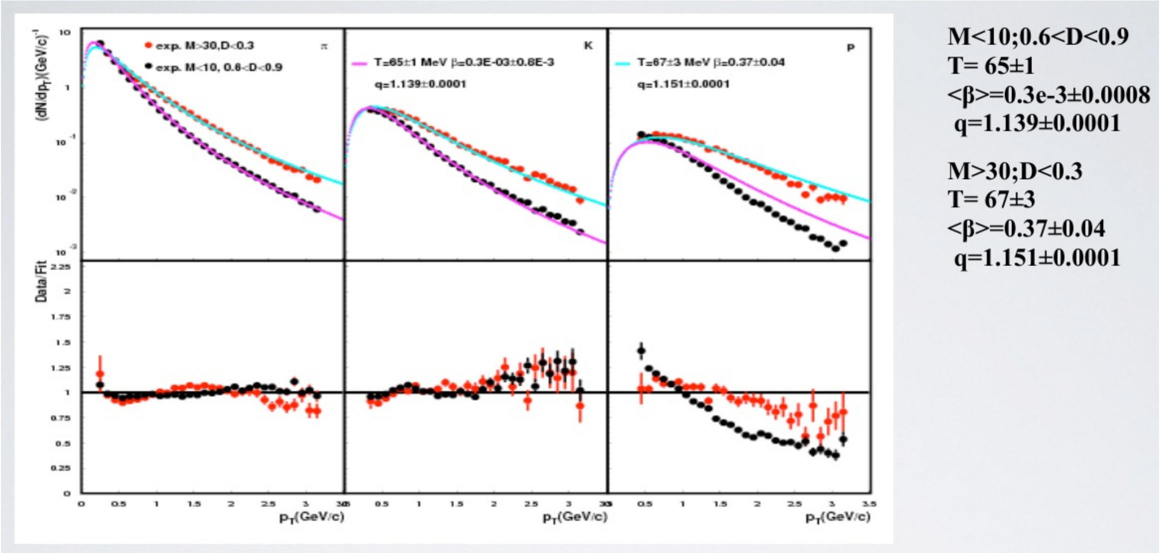


Pop and M. Petrovici, arXiv:2402.19115[hep-ph], accepted at PRC

Short review pp vs A-A @ LHC







$$D = \frac{|\sum_i p_t^i|}{\sum_i |p_t^i|}|_{\eta>0},$$ Eq. 1

$$f(p_t) = m_t \int_{-Y}^{Y} cosh(y)dy \int_{-\pi}^{\pi} d\phi \int_{0}^{R} rdr(1+\frac{q-1}{T}(m_t cosh(y)cosh(\rho)-p_t sinh(\rho)cos(\phi)))^{-1/(q-1)}$$ Eq. 2

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

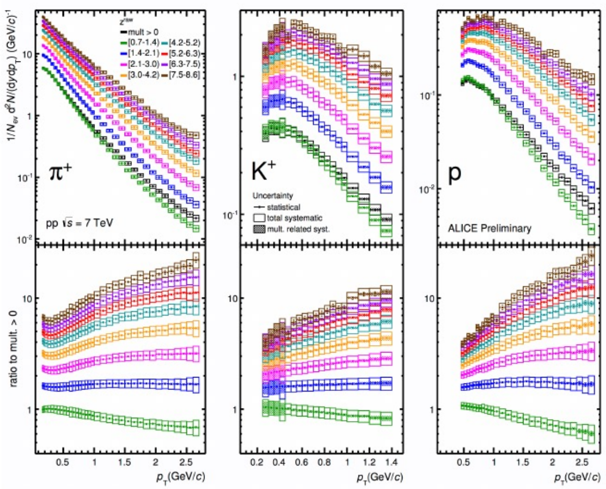


Fig.33

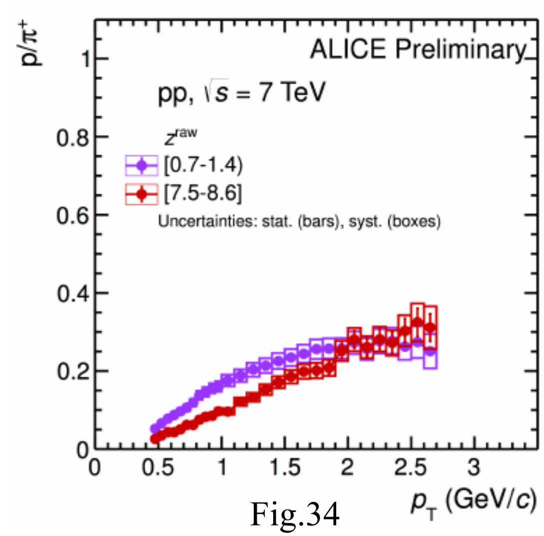


Fig.34

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

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

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

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

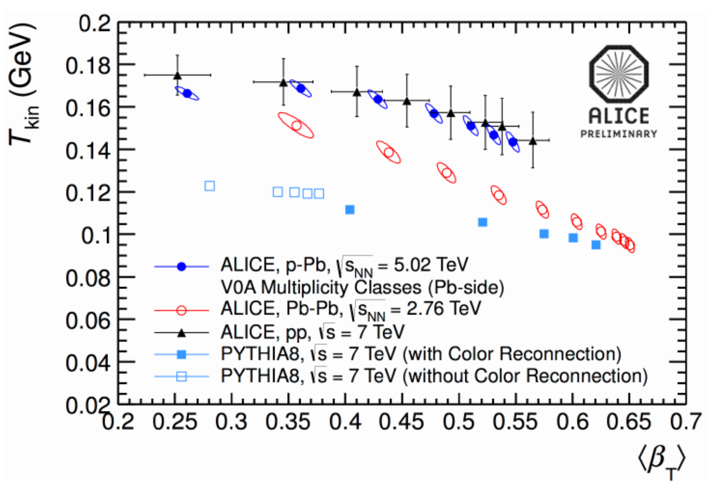


Fig.35

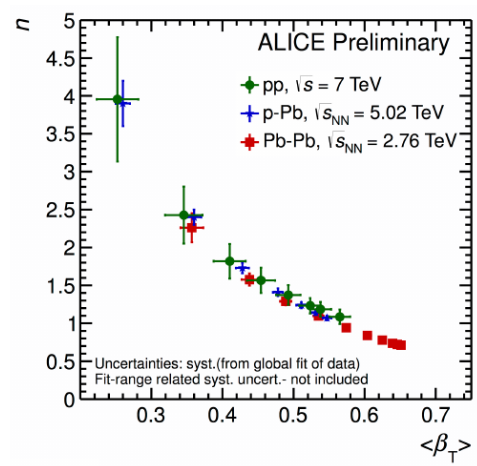
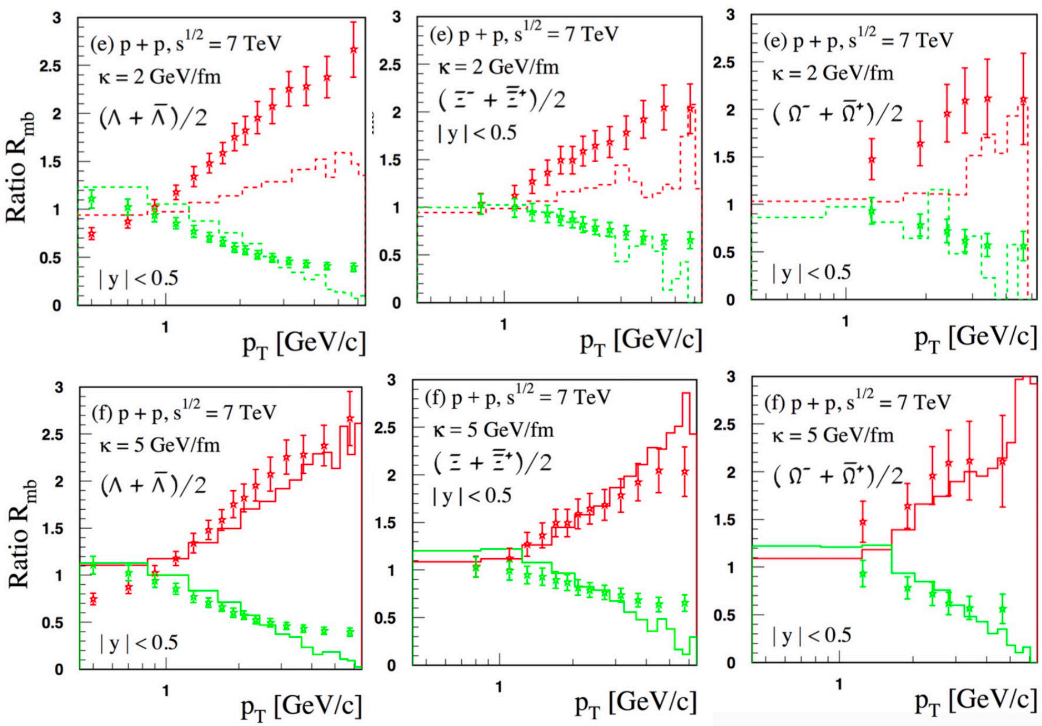


Fig.36

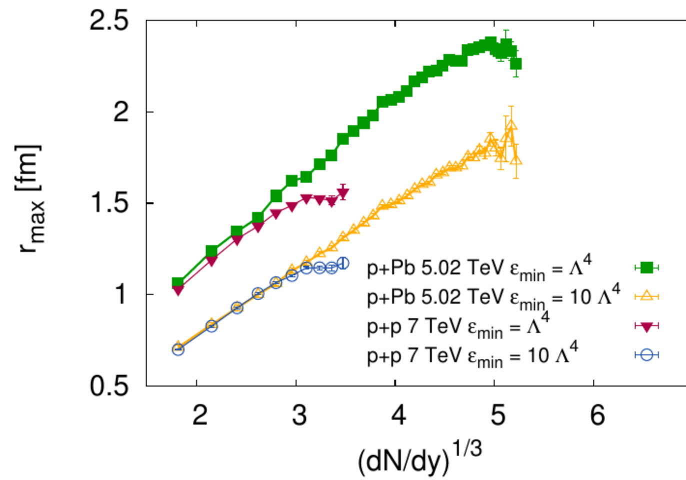
C. Andrei for ALICE Collaboration, Nucl.Phys. A931(2014)888

Short review pp vs A-A @ LHC

red - $dN_{ch}/d\eta$=15 | red - $dN_{ch}/d\eta$=15 | red - $dN_{ch}/d\eta$=15
green - $dN_{ch}/d\eta$=4 | green - $dN_{ch}/d\eta$=6 | 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 $$f_{pp} = \begin{cases} 0.387 + 0.0335x + 0.274x^2 - 0.0542x^3 & \text{if } x < 3.4 \\ 1.538 & \text{if } x \geq 3.4 \end{cases}$$

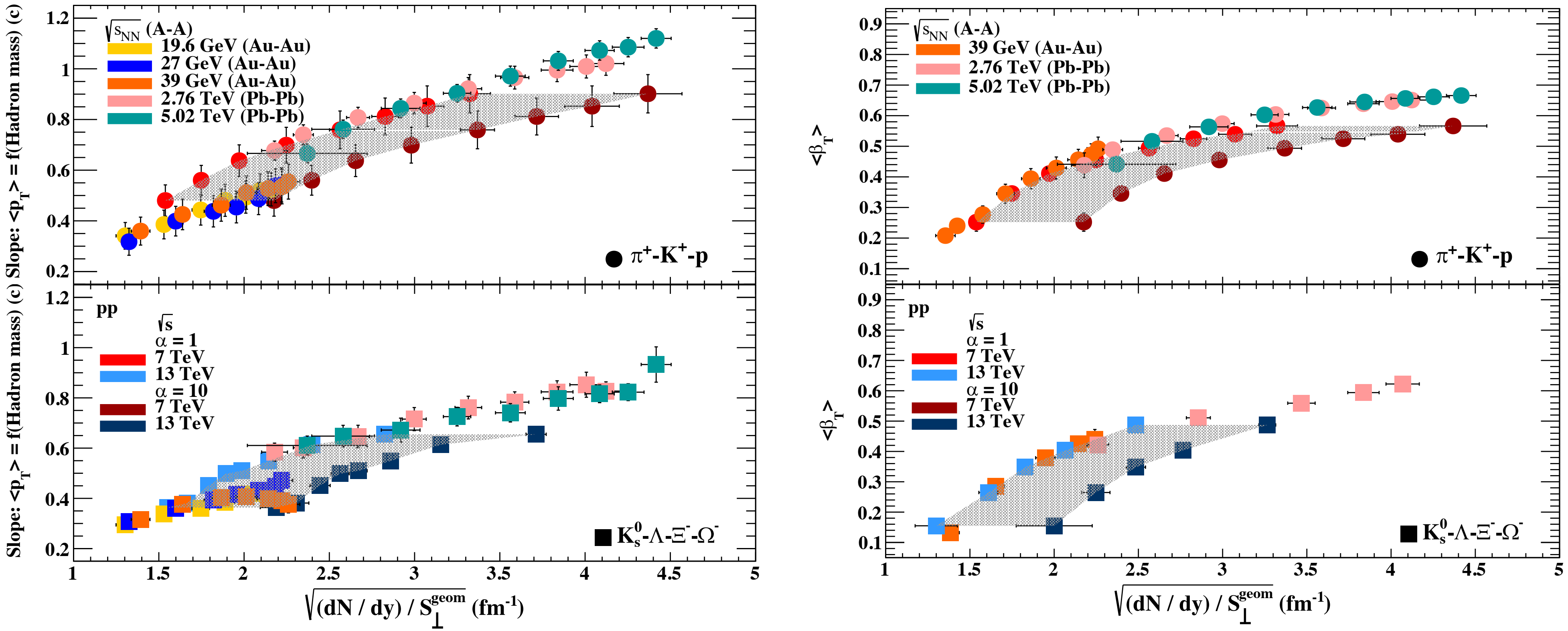
$$x = (dN_g/dy)^{1/3}$$

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

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

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

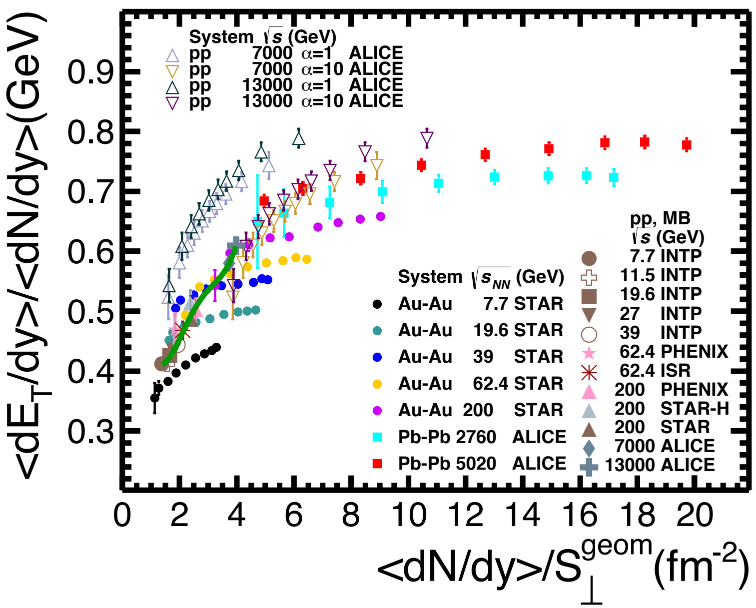
A-A vs. pp @ LHC

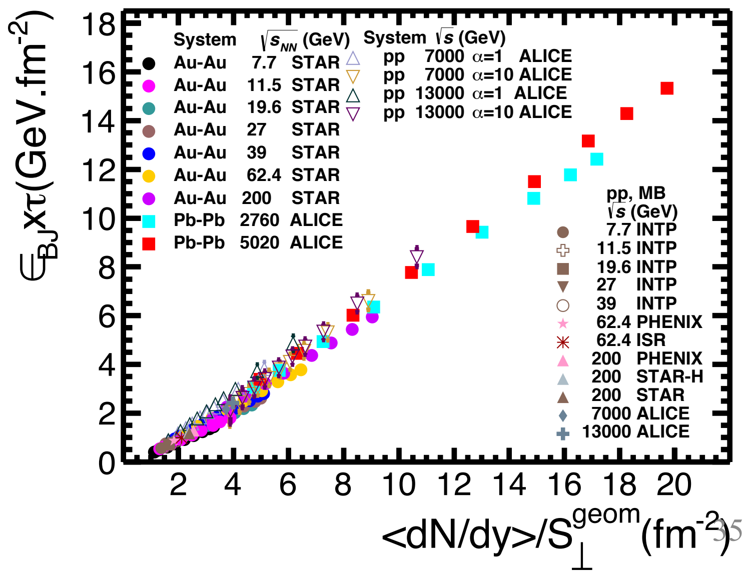


A. Lindner et al., Proceedings of Science (PoS) 380(2021)197 (PANIC2021), https://pos.sissa.it/380/197/.

A-A vs. pp @ LHC

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

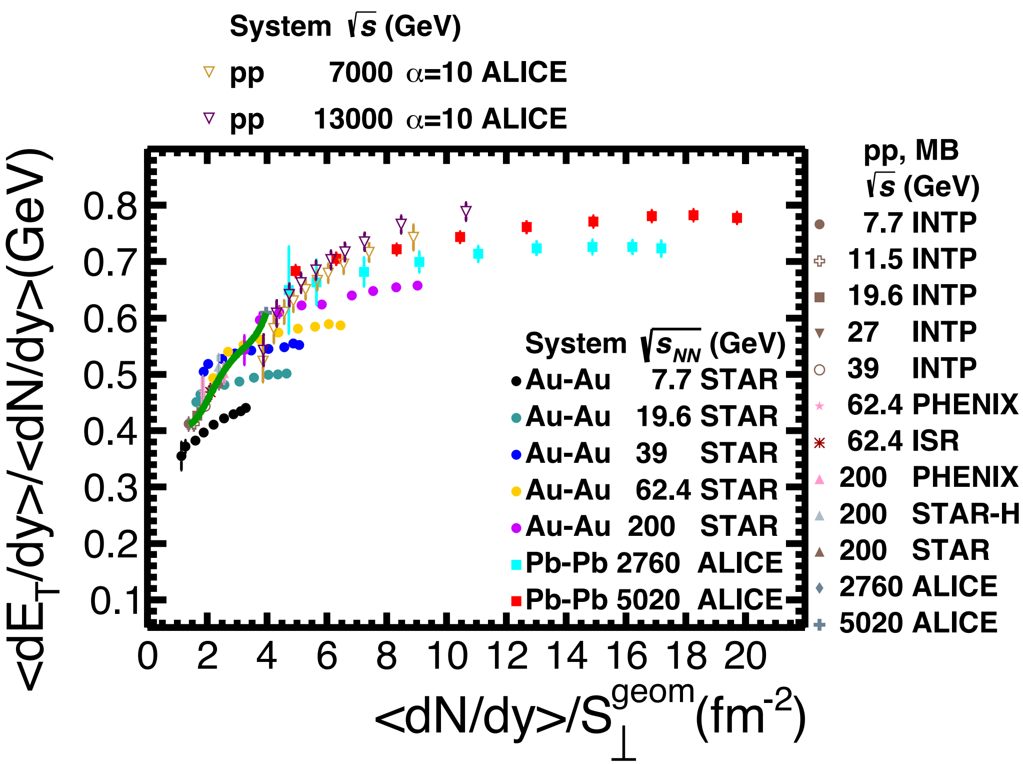


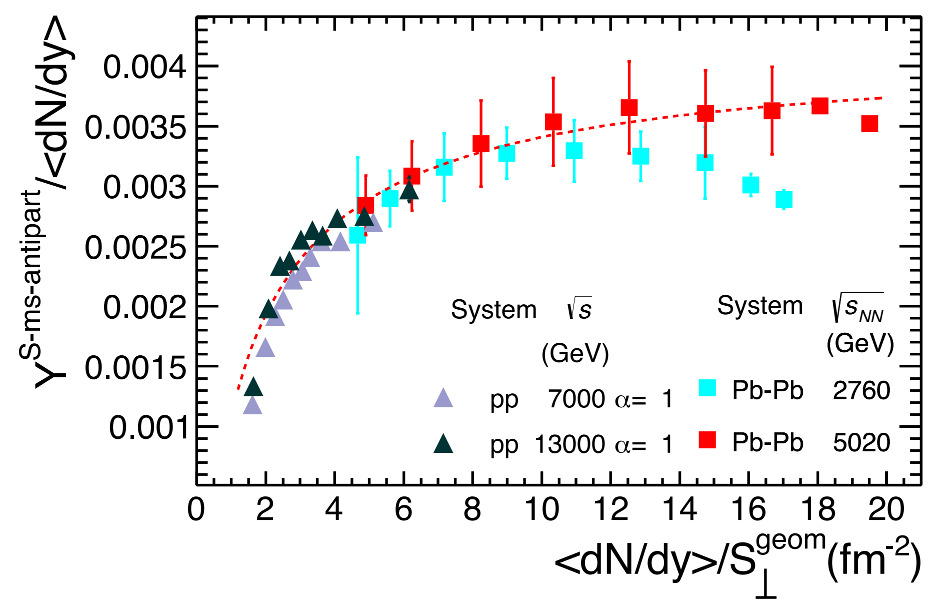


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

A-A vs. pp @ LHC

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



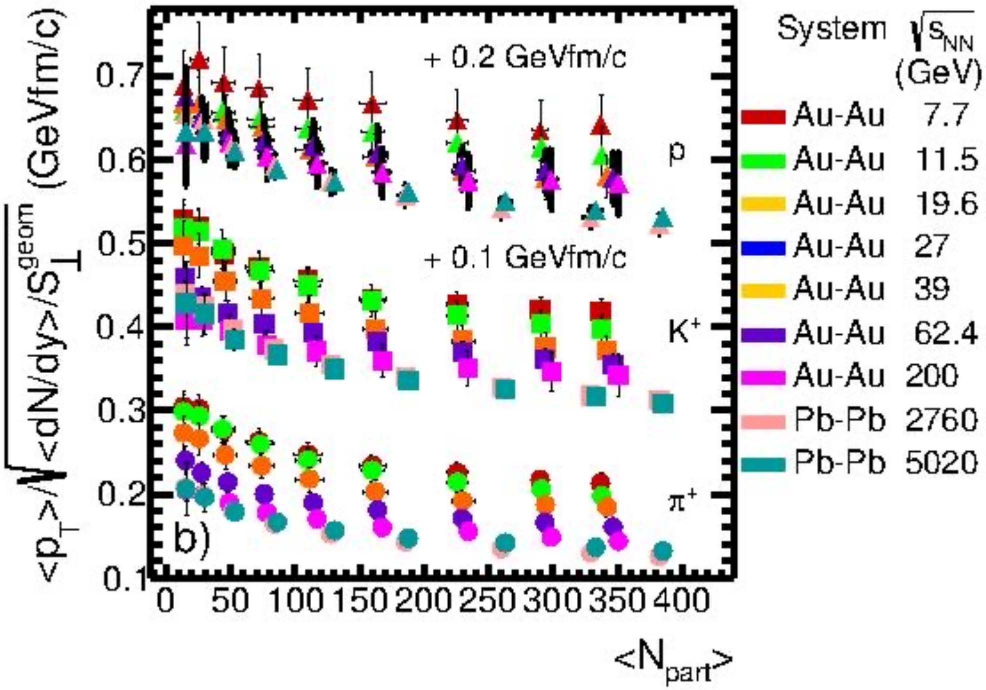


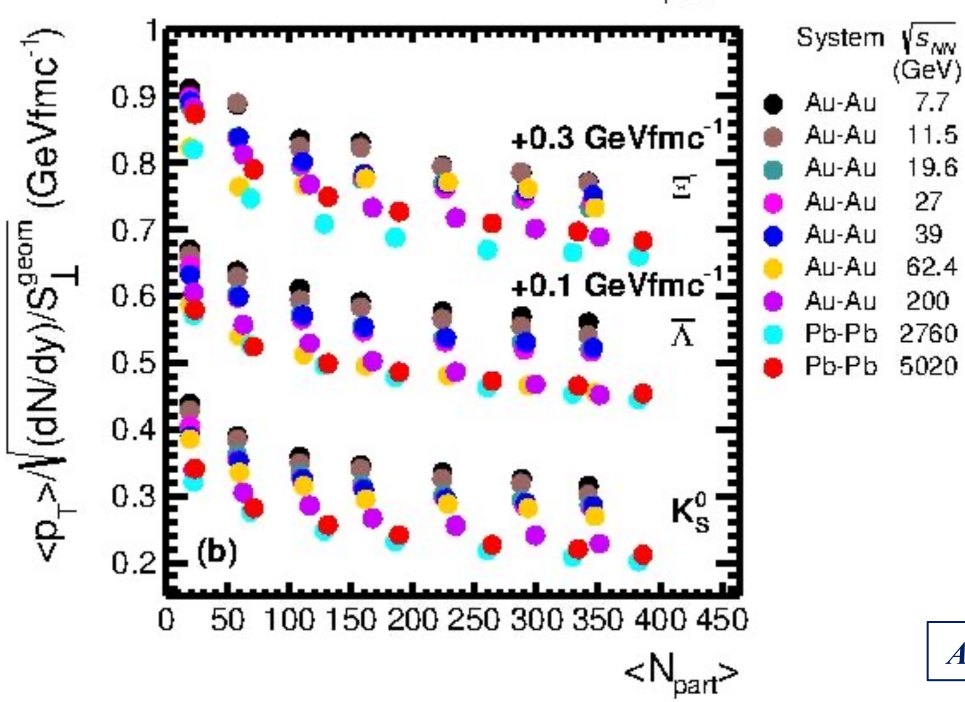
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph], accepted at PRC

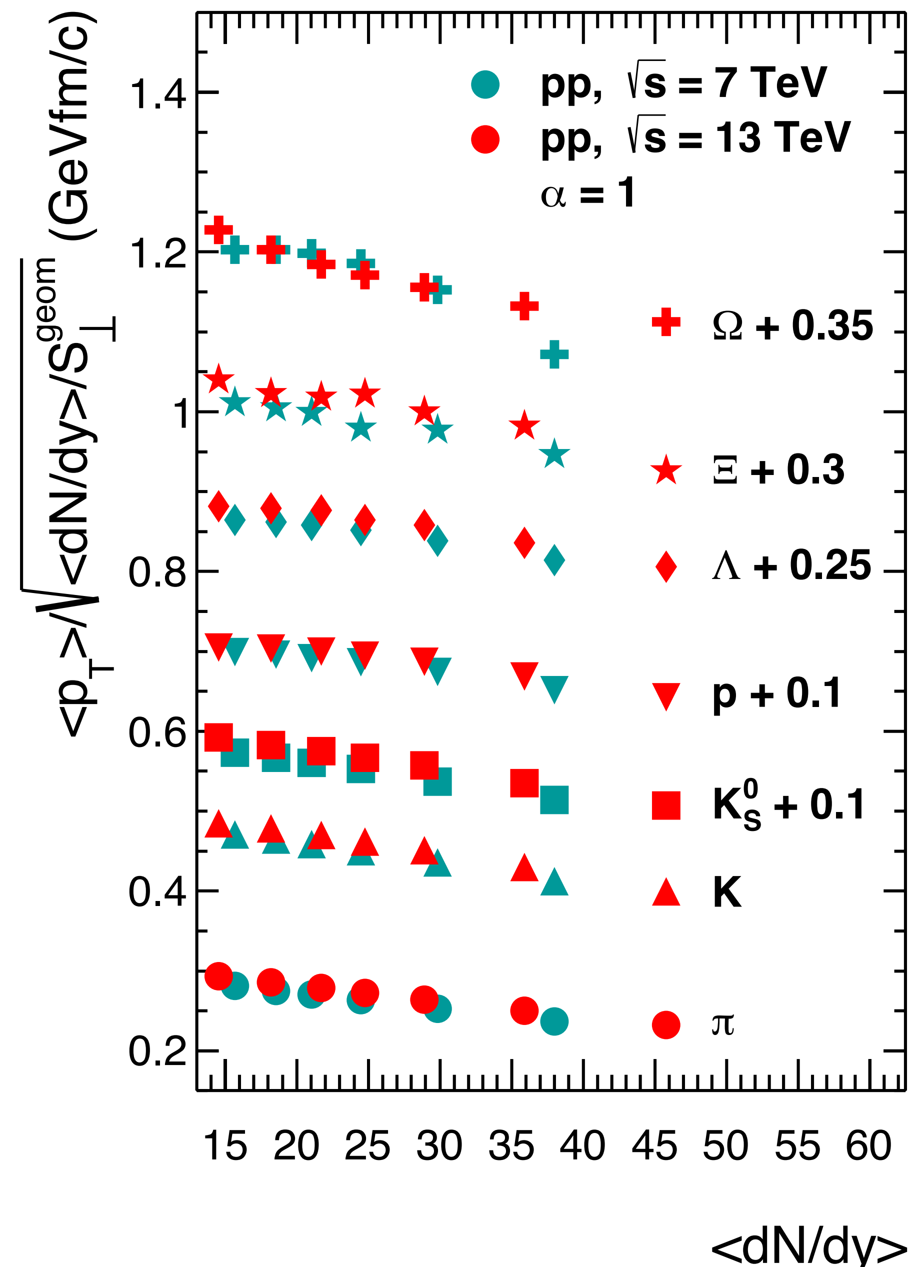
Highest charged particle multiplicity in pp at midrapidity selected by "V0M" by ALICE Collaboration !!!

A-A vs. pp @ LHC

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



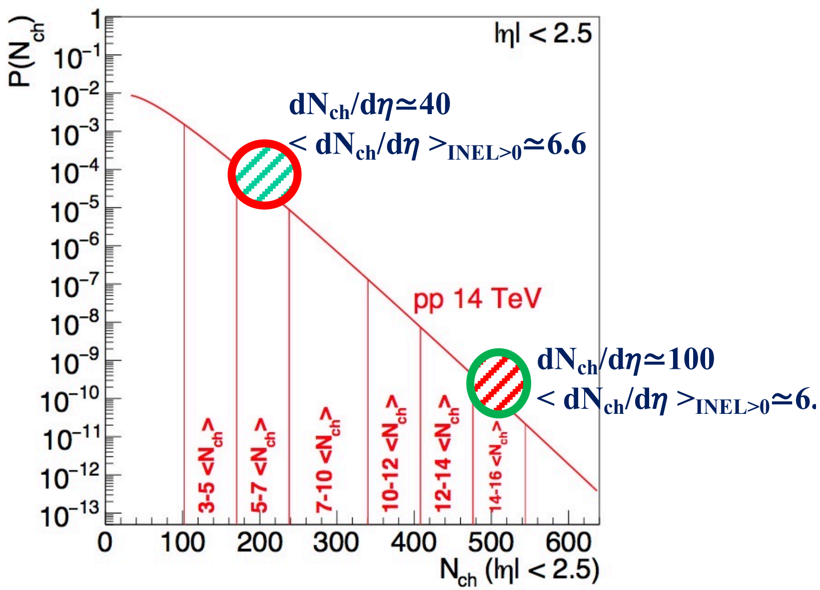




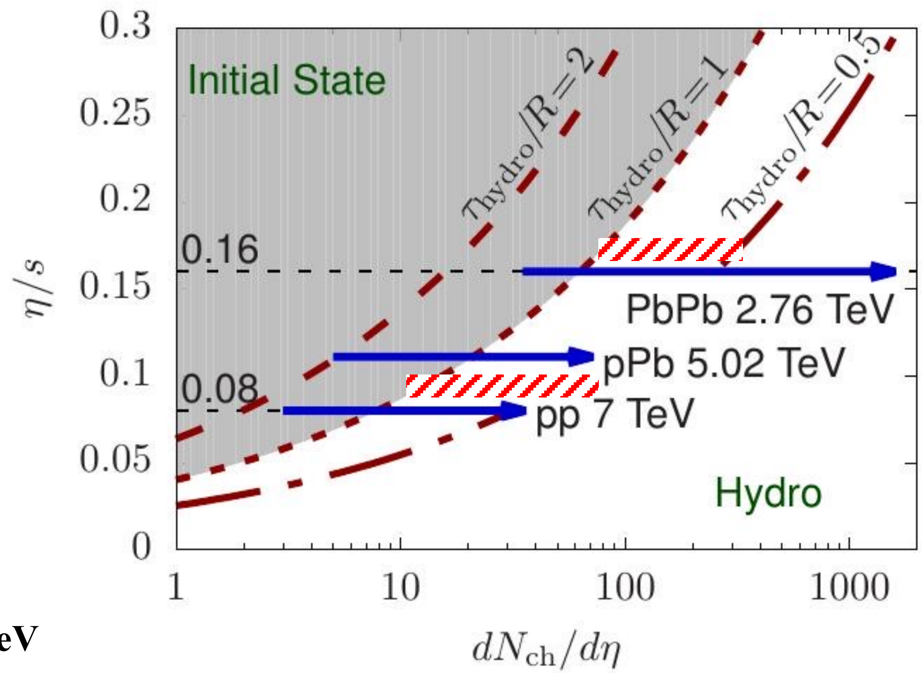
A. Pop and M. Petrovici, accepted at PRC

What's next ?

➢ *ALICE Coll., arXiv:1812.06772*

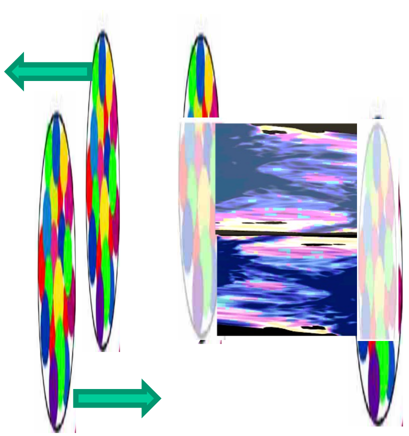


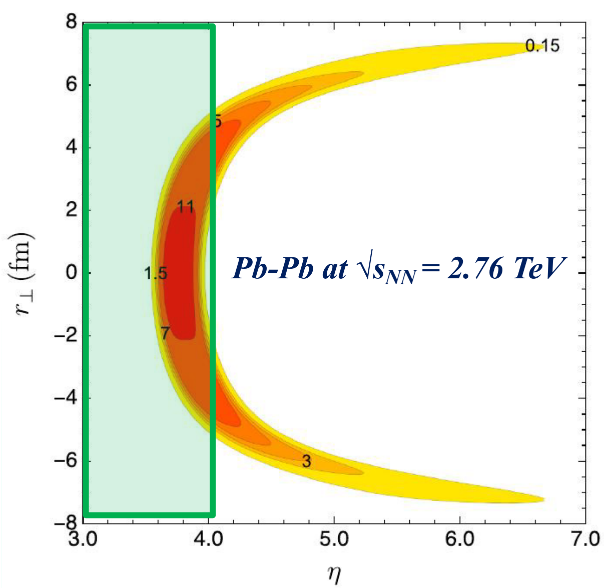
A.Kurkela et al., PoS(Confinement 2018)152



➢ **Pb-Pb @ 2-3 energies between 200 GeV and 2.76 TeV**

➢ **PID @ large rapidity**

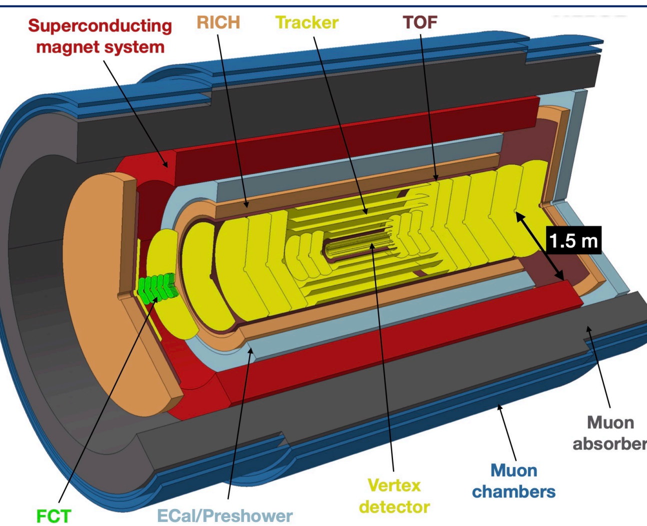




M. Li and J.I. Kapusta, Phys.Rev. C99(2019)014906

ALICE3

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



What to be done @ SIS100 energies?

Expected baryon densities - similar with those in neutron stars

=> constrains on the EoS based on terrestrial experiments

What to be done @ SIS100 ?

EoS of Dense Matter

- *Requirement that neutron stars reach maximum mass of at least $M_{max} \geq 2M_{\odot}$ leads to EoS that predict:*
  - *a speed of sound c_s^2 that surpasses the conformal limit of 1/3*
  - *a large peak in the speed of sound c_s^2 as a function of baryon density n_B*
- *Are these requirements compatible with the EoS extracted from heavy ion data?*

Some differences between

	neutron stars with $M_{max} \geq 2M_{\odot}$	fireballs of high baryon density produced in heavy ion collisions
size	10-14 km $\simeq 10^5$ cm	6 fm $\simeq 6 \cdot 10^{-13}$ cm
life time	10^6 - 10^{12} years $\simeq 10^{13}$ - 10^{19} sec	10^{-23}-10^{-22} sec
temperature (T)	10^6 K $\simeq 0$ MeV	> 40 - 120 MeV

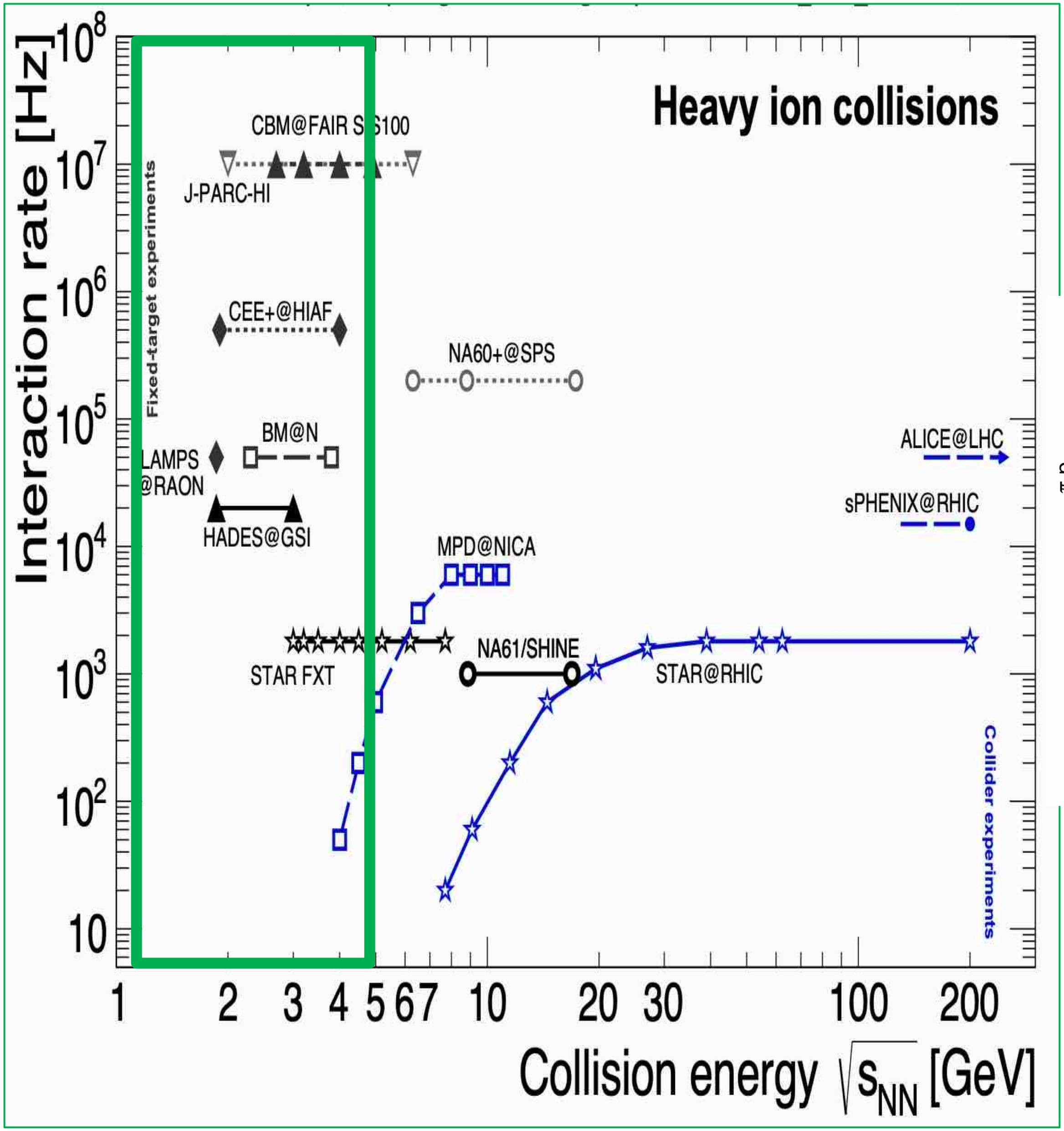
$$\delta \equiv (n_n - n_p)/(n_n + n_p) = 1 - 2Y_{Q,\mathrm{QCD}}$$

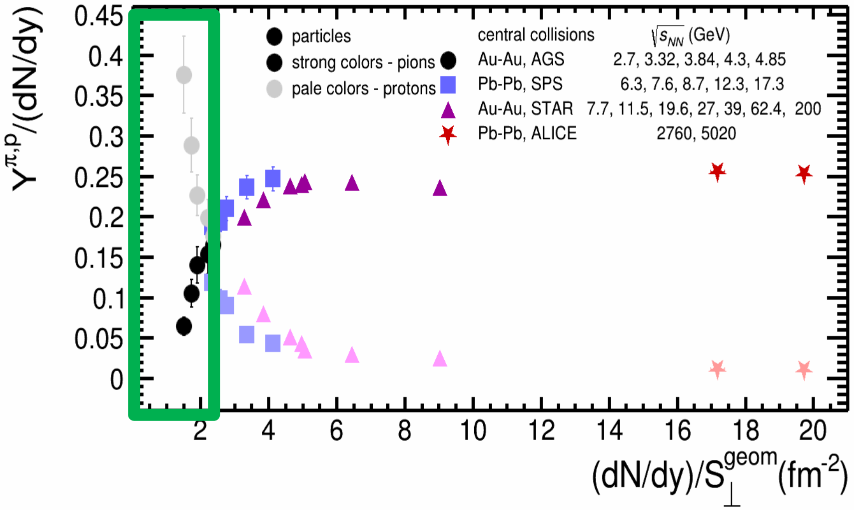
NS $\delta = 1$

SNM $\delta \simeq 0$

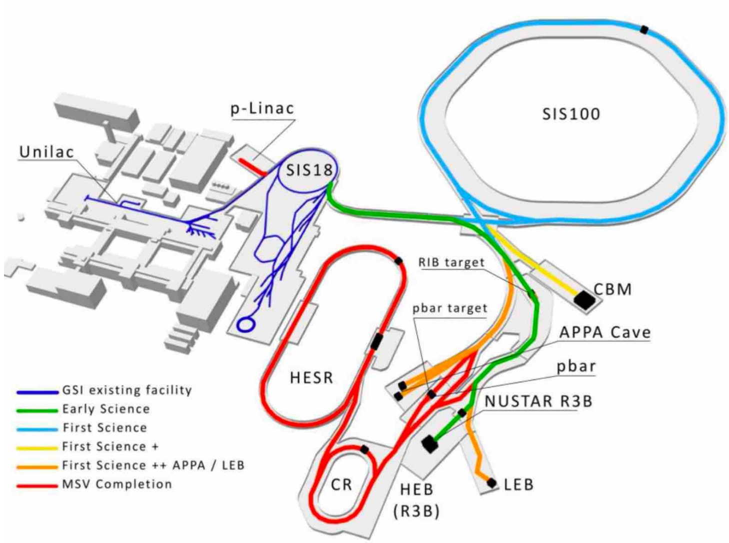
- *violent dynamical evolution*
- **highly non-homogeneous initial state**
- **finite size effects**
- **in medium and isospin momentum dependence of nucleon-nucleon interaction**

What can be studied at baryon densities similar with those in neutron stars ?

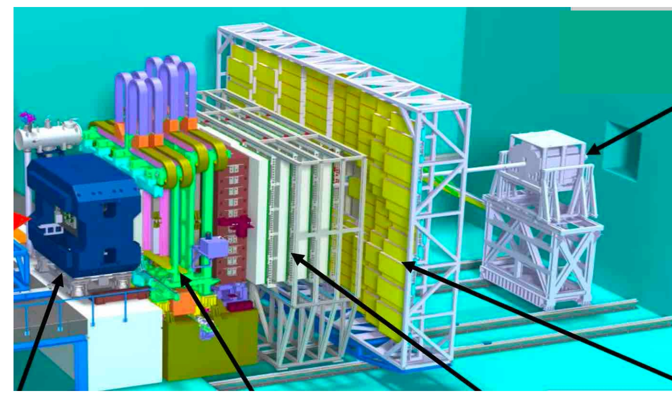




What to be done @ SIS100 ?



=> HPD involvement



PSD

MVD & STS

MUCH

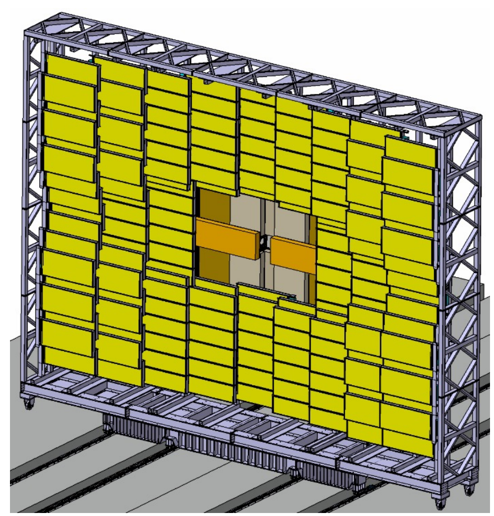
TRD

ToF

A new generation of MSMGRPC TRD detectors, associated FEE and data processing:
- *2D position sensitive*
- *high counting rate*
- *high granularity*
- *radiation hard*

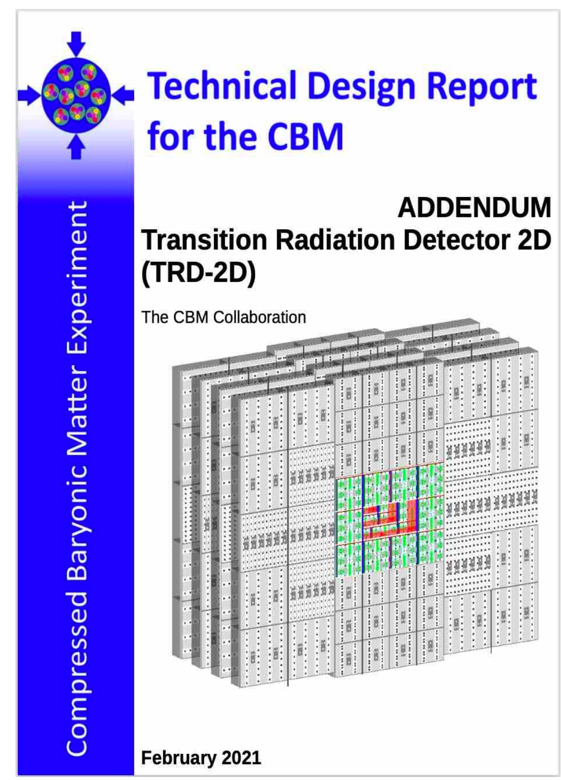
Developped in HPD

ToF



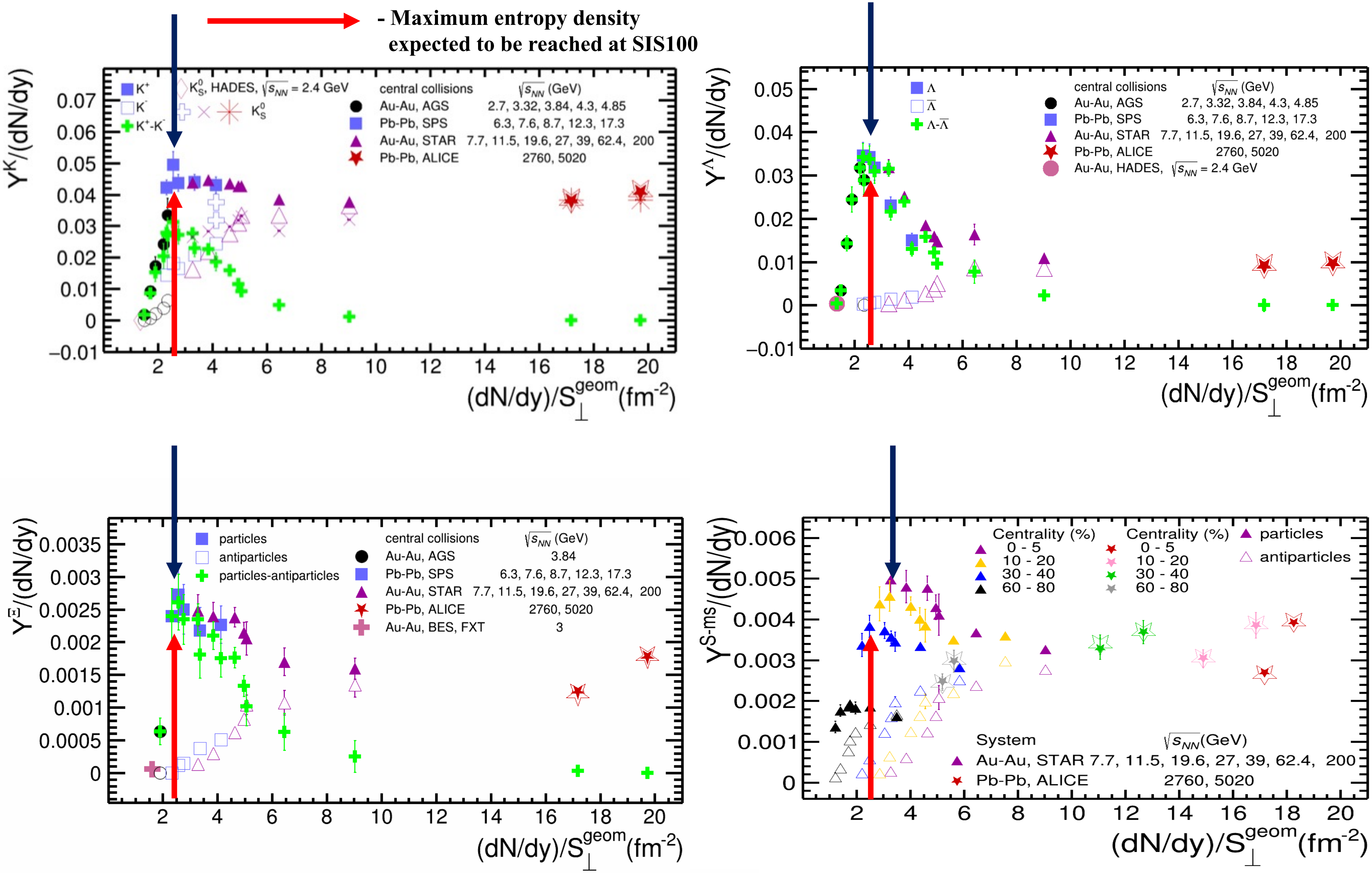
TRD

	MRPC1c (200 mm)	MRPC1b (100 mm)	MRPC1a (60 mm)	Total
No. RPCs	168	92	40	300
No. channels	10752	5888	2560	20,224



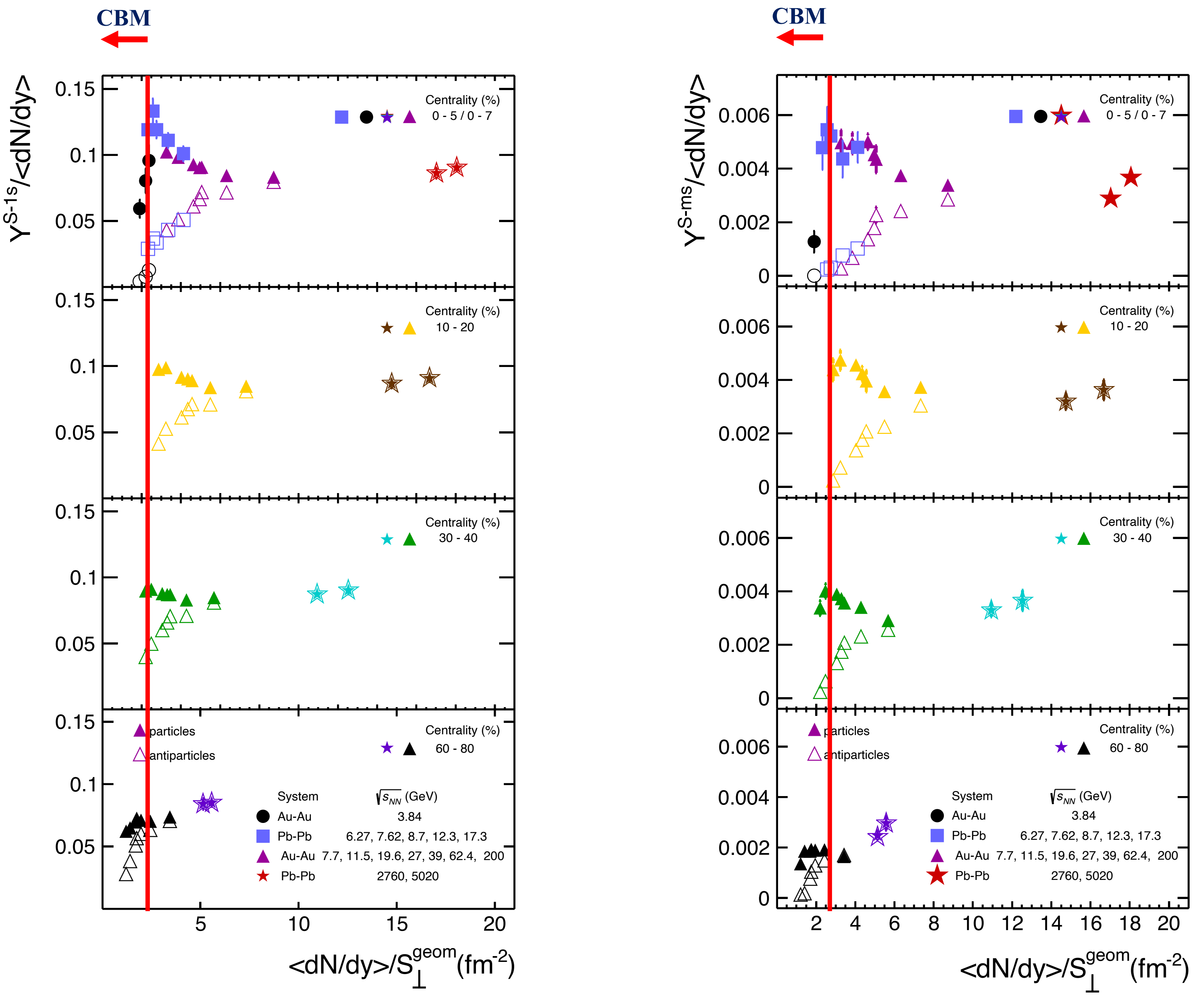
What to be done @ SIS100 ?

- Peak position
- Maximum entropy density expected to be reached at SIS100



A. Pop and M. Petrovici - accepted at PRC

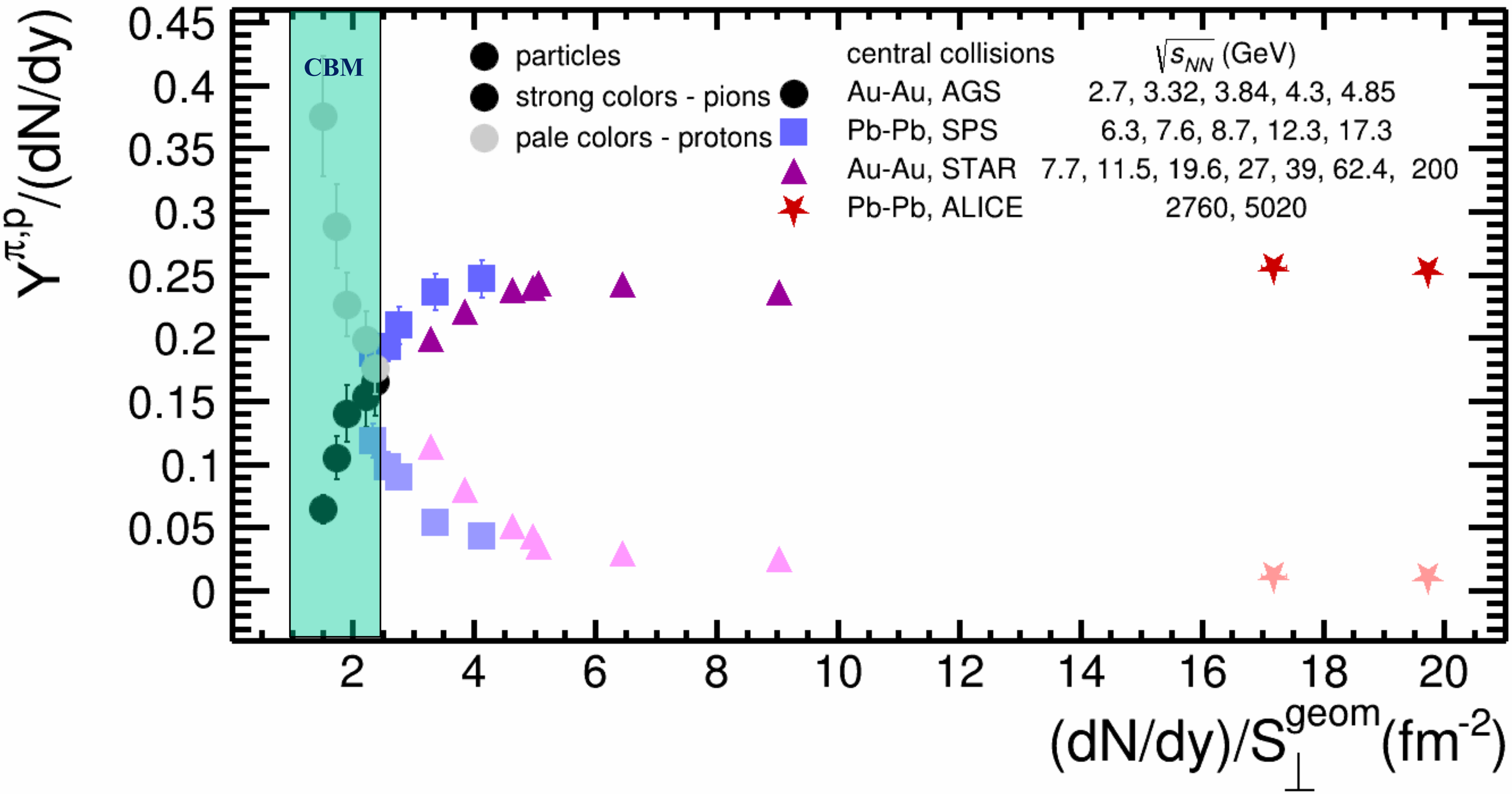
What to be done @ SIS100 ?



A. Pop and M. Petrovici - accepted at PRC

What to be done @ SIS100 ?

Transition from baryon dominant to meson dominant matter



What to be done @ SIS100 ?

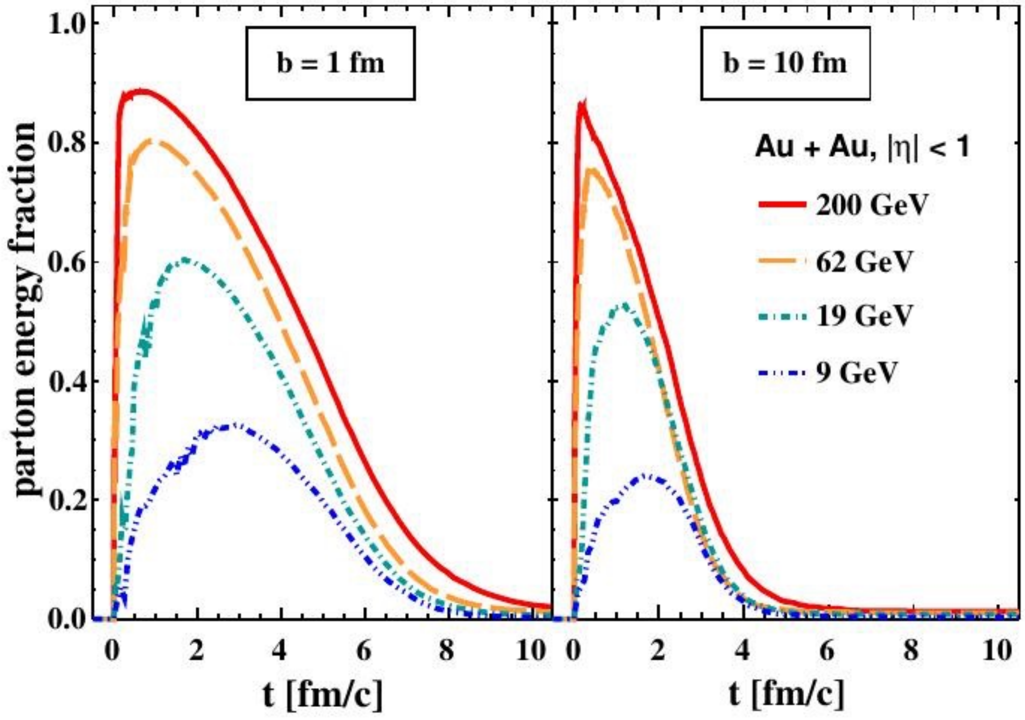
Towards highly compressed baryonic matter

- transition from baryon-dominated to meson-dominated matter - UrQMD, QGSM ?

L.V.Bravina et al., Phys.Rev. C78(2008)014907

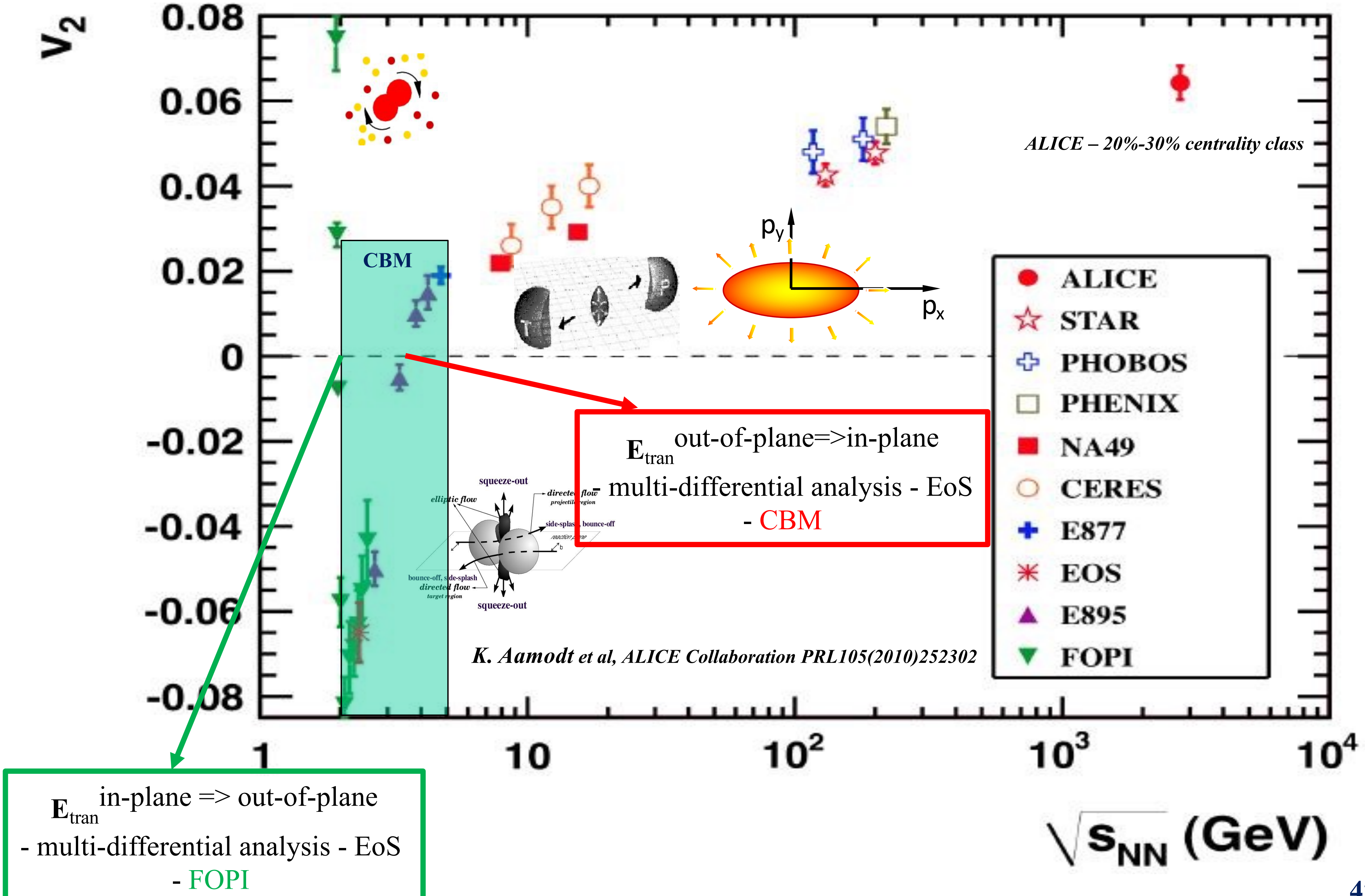
- evolution of parton fraction in the total energy density - PHSD ?

V.P.Konchakovski et al., Phys.Rev. C85(2021)044922



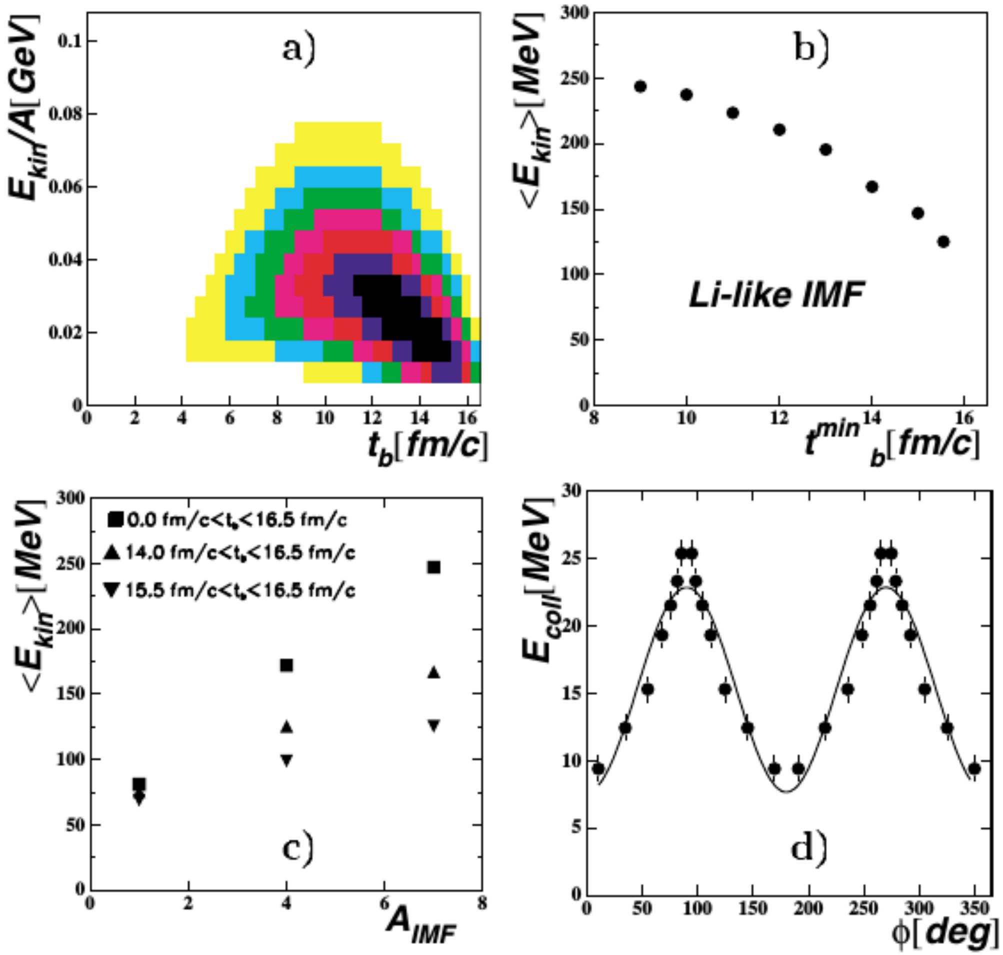
What to be done @ SIS100 ?

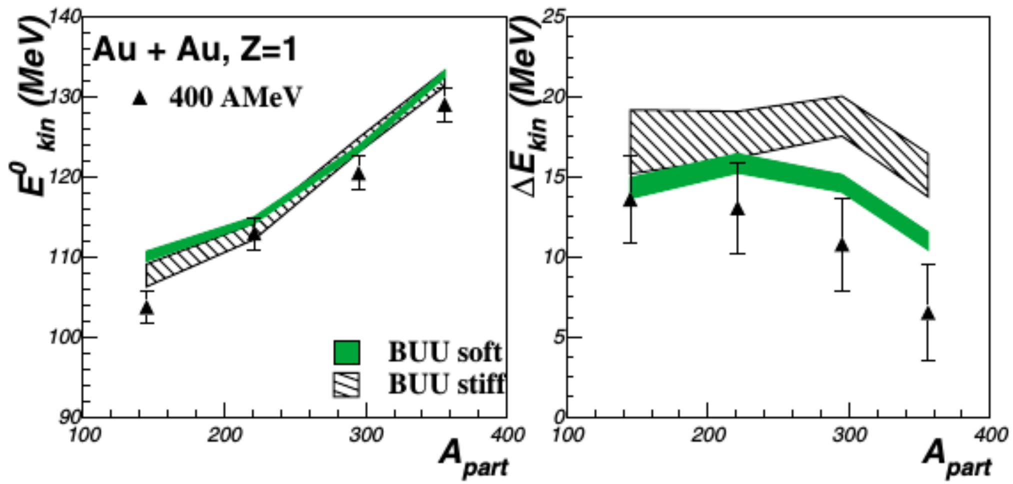
Elliptic flow (v_2) – excitation function including LHC results



A bit of history

Shadowing effects - EoS





M.Petrovici et al., FOPI Collaboration, Phys.Rev.Lett. 74(1995)5001

G.Stoicea, M.Petrovici & FOPI Collaboration, Phys.Rev.Lett. 92(2004)072303

P.Danielewicz, Nucl.Phys. A6873(2000)375 and ref. therein

What to be done @ SIS100 ?

Structure in the speed of sound

NS EoS → EoS in HIC

N. Yao et al., arXiv:2311.18819 [nucl-th]

Input: Neutron Star EOS Symmetry Energy Coefficients

→ Subtract lepton contribution to P

→ For a given n_B, Convert ε_{NS} to ε_{HIC}

→ Obtain $P = -\varepsilon + n_B\mu_B + n_Q\mu_Q$ and $\mu_B = \frac{d\varepsilon}{dn_B}$

→ Obtain C_s^2 via $C_s^2 = \frac{dP}{d\varepsilon}$

$$\frac{E_{\rm ANM}}{N_B} = \frac{E_{\rm SNM}}{N_B} + E_{\rm sym}\delta^2 + \mathcal{O}(\delta^4)$$

$$\delta \equiv (n_n - n_p)/(n_n + n_p) = 1 - 2Y_{Q,{\rm QCD}}$$

δ =0 symmetric nuclear matter

$\delta \simeq$1 neutron star cores (=1 - pure neutron matter (PNM))

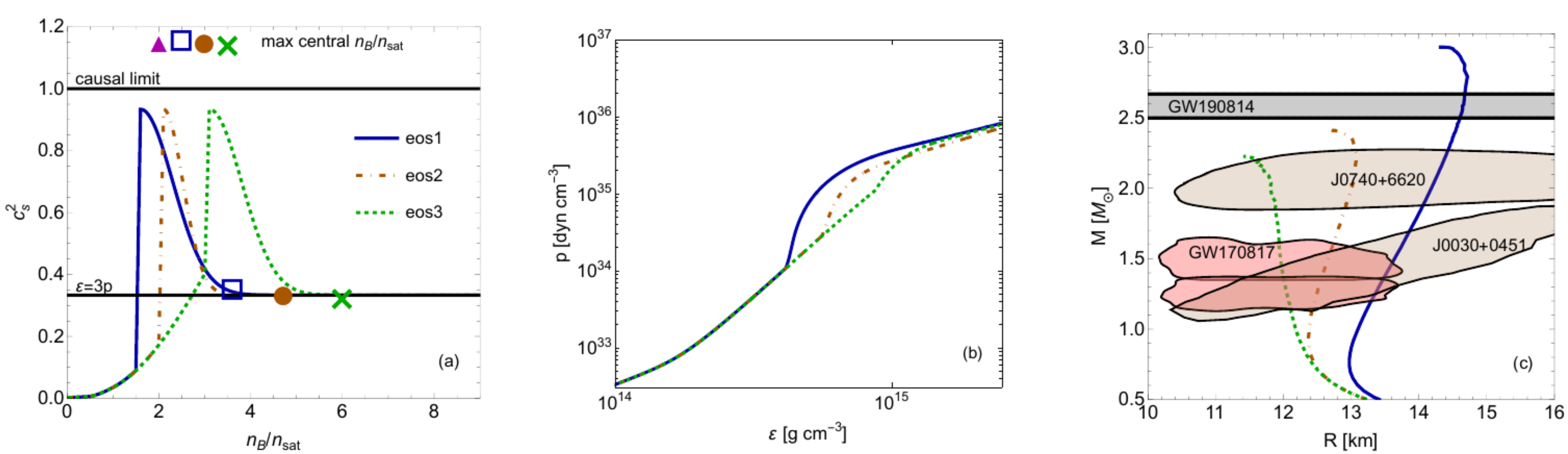
$$\frac{E_{\rm PNM}}{N_B} = \frac{E_{\rm SNM}}{N_B} + E_{\rm sym}$$

$$\varepsilon_{\rm HIC,asym} = \varepsilon_{\rm NS,QCD} - 4n_B\left[E_{\rm sym,sat} + \frac{L_{\rm sym,sat}}{3}\left(\frac{n_B}{n_{\rm sat}} - 1\right) + \frac{K_{\rm sym,sat}}{18}\left(\frac{n_B}{n_{\rm sat}} - 1\right)^2 + \frac{J_{\rm sym,sat}}{162}\left(\frac{n_B}{n_{\rm sat}} - 1\right)^3\right]$$
$$\times \left[\left(Y_{Q,{\rm QCD}}^{\rm const} - Y_{Q,{\rm QCD}}\right) + \left(Y_{Q,{\rm QCD}}^2 - \left(Y_{Q,{\rm QCD}}^{\rm const}\right)^2\right)\right]$$

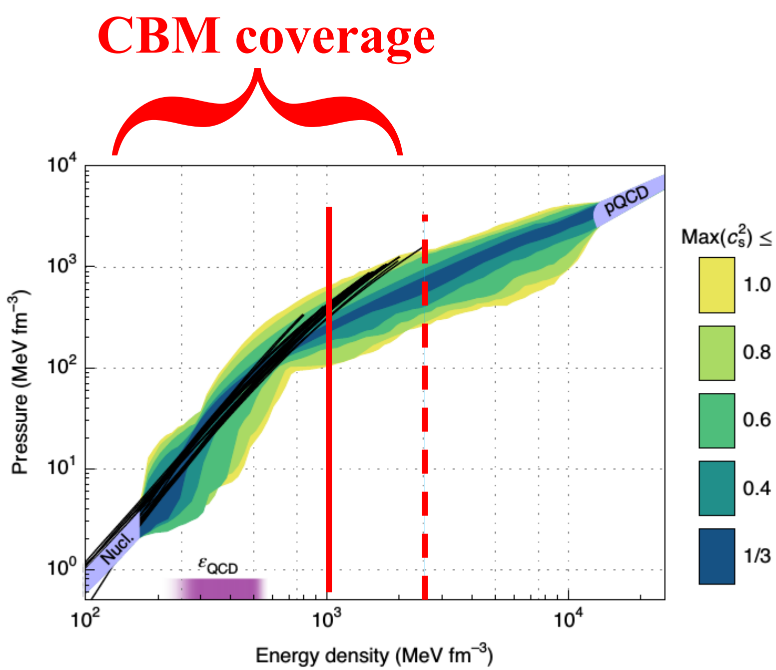
$$\varepsilon + p = n_B\mu_B + n_Q\mu_Q$$

$$p = n_B^2\frac{d(\varepsilon/n_B)}{dn_B}$$

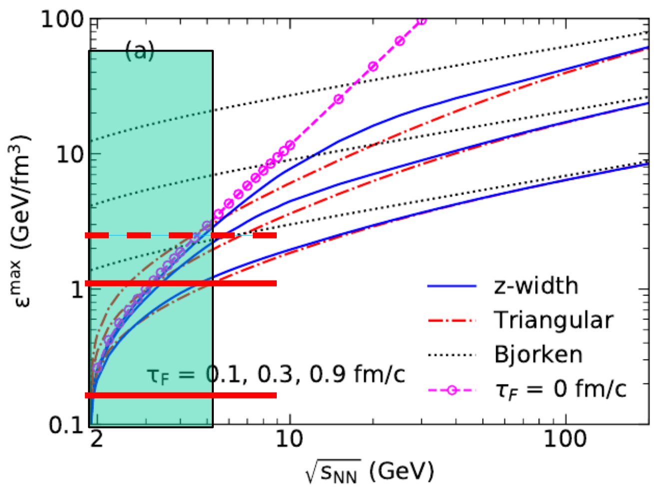
$$c_s^2 = \left(\frac{dp}{d\varepsilon}\right)_{T=0}$$



What to be done @ SIS100 ?
Evidence for quark-matter cores in massive neutron stars



E. Annala et al, Nature Physics 16(2020)907



T. Mendenhall and Z.W. Lin, arXiv[nucl-th]2012.13825

polytropic index $\gamma = c_s^2\ \varepsilon/P = \varepsilon/P(dP/d\varepsilon)$
differentiate between quark and hadronic matter
$\gamma \leq 1.75$ - quark matter

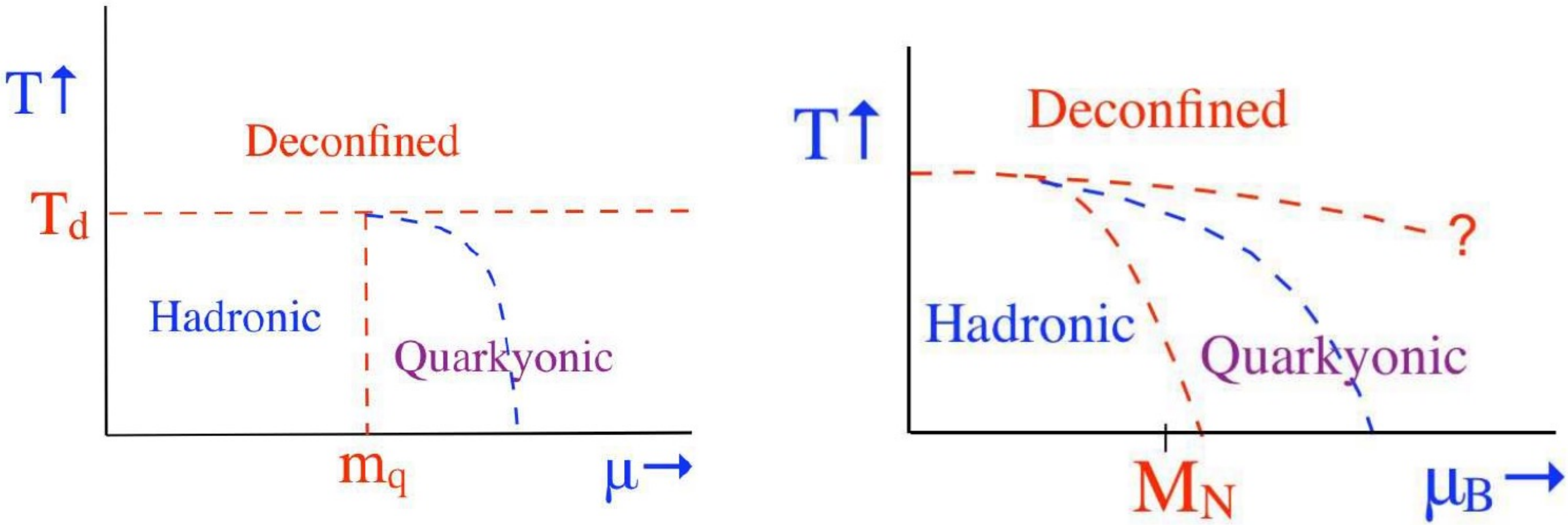
What to be done @ SIS100 ?
Quarkyonic Matter

"quarkyonic phase" ≡ Cool and dense quarks:

- remaining in the confined phase $T<T_d$

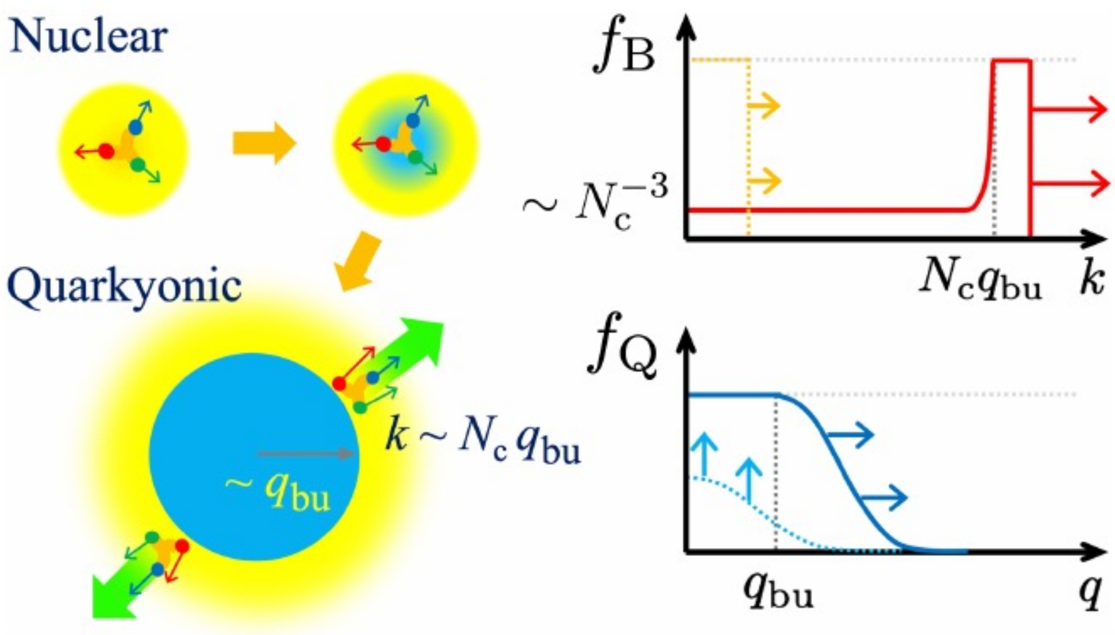
- $\mu > m_q$

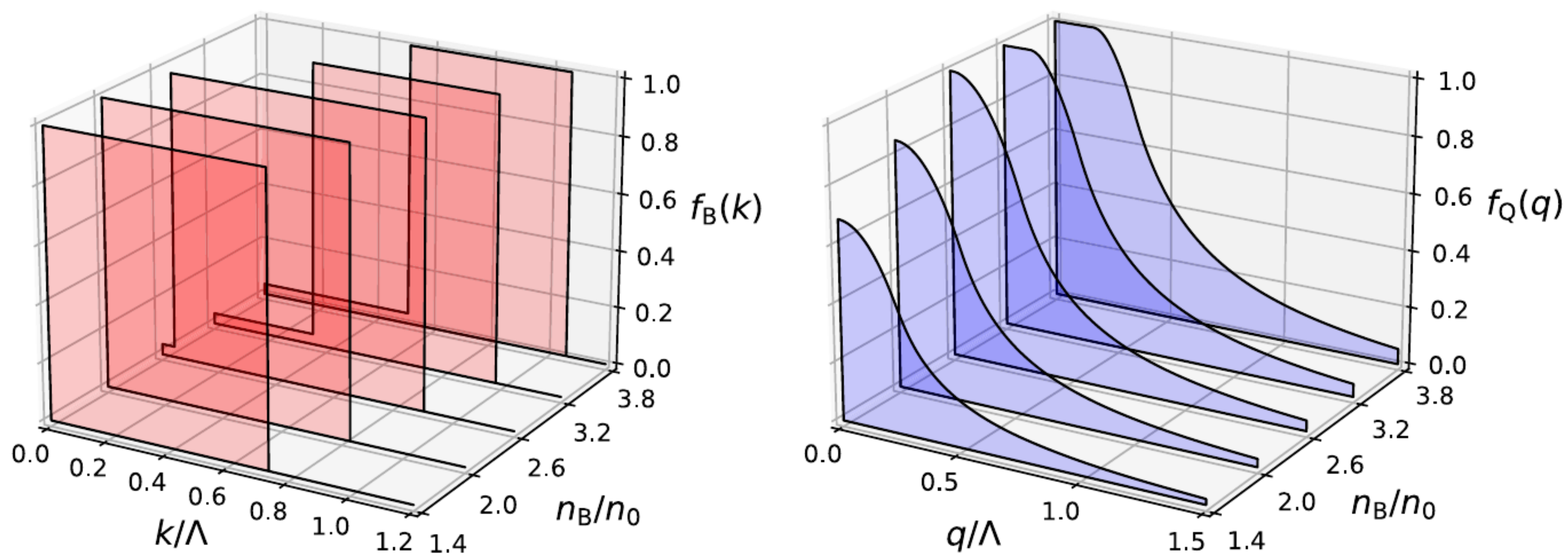
The result of such approach could be an artifact of large N_c expansion
=> limited relevance to QCD where N_c=3 !!!



L. McLerran an R.D. Pisarski, Nucl.Phys. A796(2007)83

What to be done @ SIS100 ?
Quarkyonic Matter

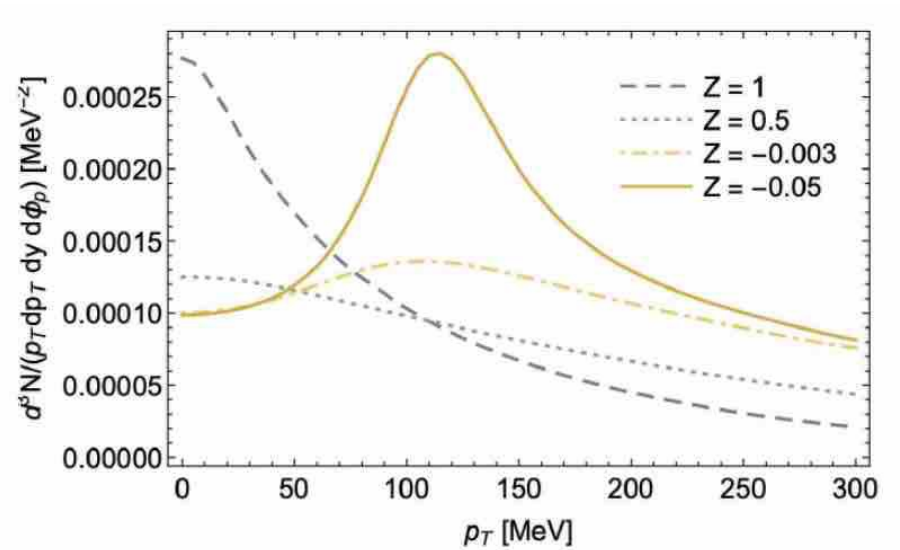




Y. Fujimoto et al., Phys.Rev.Lett 132(2024)112701

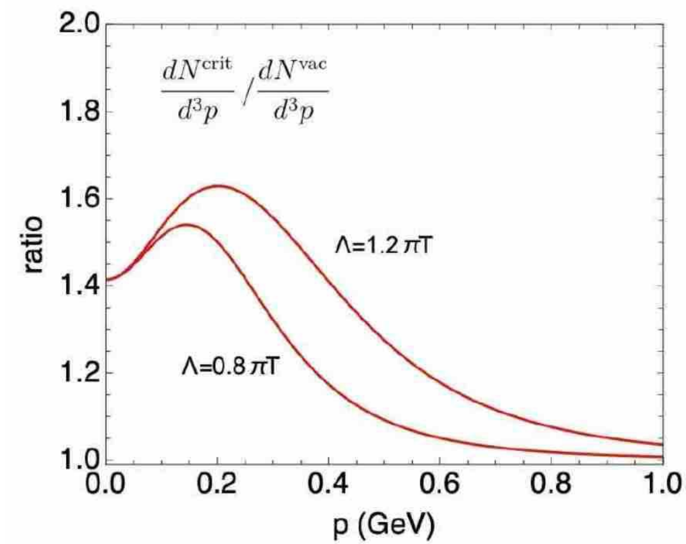
Large Baryon densities

R.D. Pisarski and F. Rennecke, arXiv:2103.06890[hep-ph]



Model studies suggest that regimes with periodic spatial modulations can occur high μ_B

E.Grossi et al., arXiv:2101.10847[nucl-th]



The enhanced yield of soft pions near the chiral critical point

Large Baryon densities

- Dedicated analysis:
- Excitation function of:
- collision geometry and azimuthal dependence of:

- p_T spectra as low as possible in p_T

$$-\pi, \quad k, \quad p$$
$$-\Lambda, \quad \Xi, \quad \Omega$$

- slope and offset of $\langle p_T \rangle$ as a function of mass

$$-\pi, \quad k, \quad p$$
$$-\Lambda, \quad \Xi, \quad \Omega$$

- $\langle \beta_T \rangle$ and $T_{\rm kin}$ BGBW fit parameters

$$-\pi, \quad k, \quad p$$
$$-\Lambda, \quad \Xi, \quad \Omega$$

- Core-Corona $\Rightarrow$ pp collisions at the same energies
- IMFs? (^{3}He vs. ^{3}H)
- Different A-A and N/Z symmetric colliding systems

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

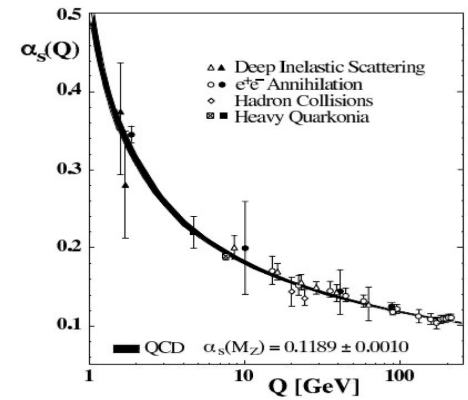
Backup slides

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

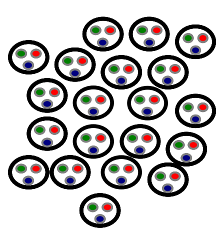
$$\Rightarrow \qquad \alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)log(Q^2/\Lambda^2)}$$

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

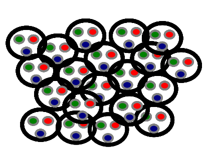
$\Rightarrow$

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

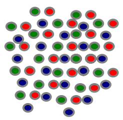
Since $\Lambda_{QCD} \sim 200$ MeV a phase transition is expected at:
$T \sim \Lambda_{QCD} \sim O(10^{12}$ K)
or
$\rho_B \sim \Lambda_{QCD}^3 \sim 1fm^{-3}$



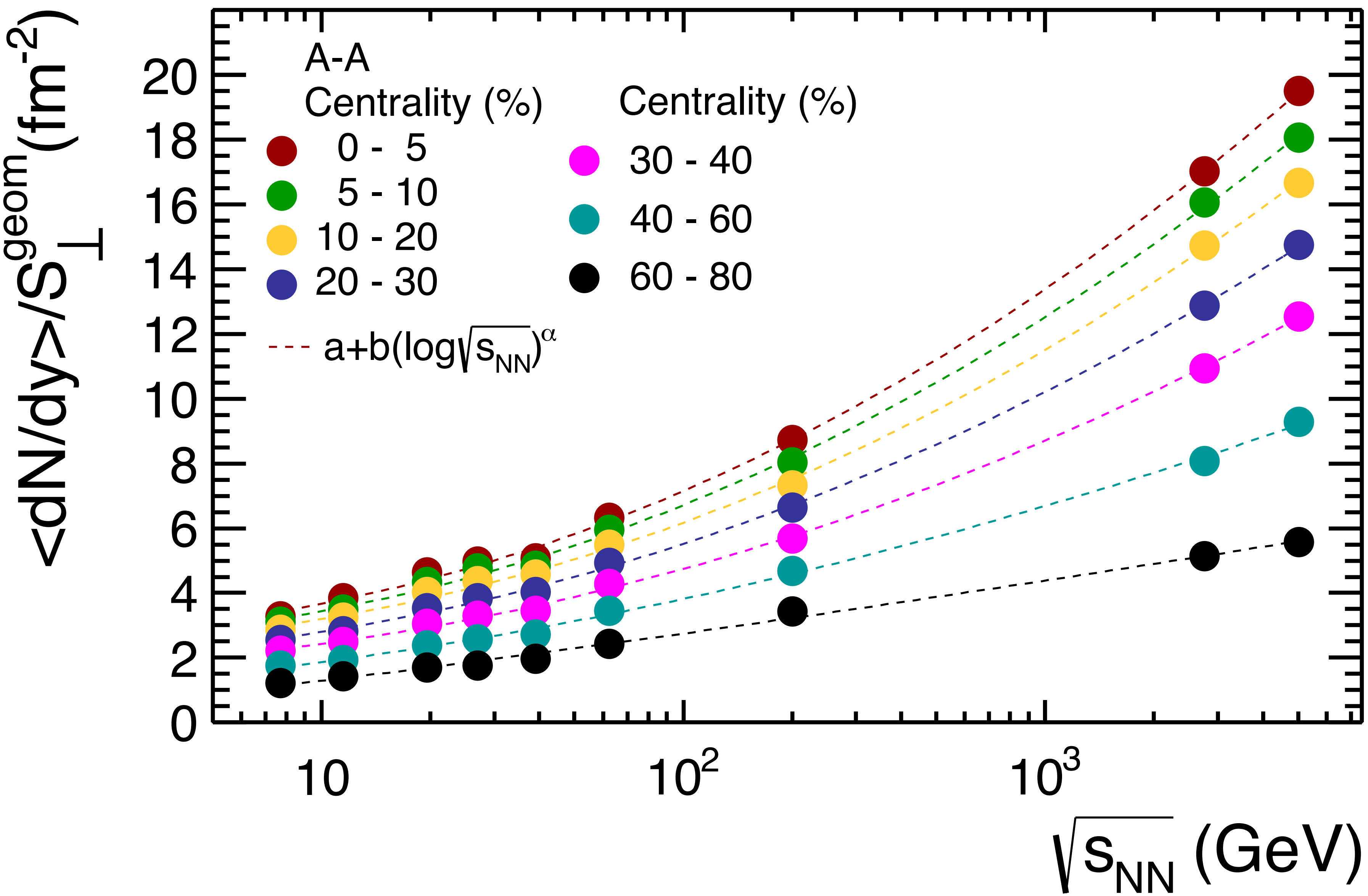
Strongly Bound Clusters Hadrons



Phase transition



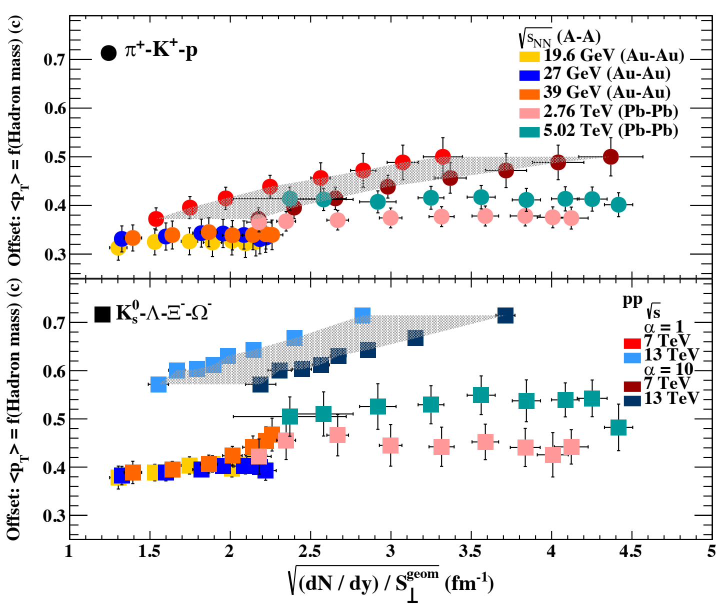
Weekly interacting Quarks and Gluons

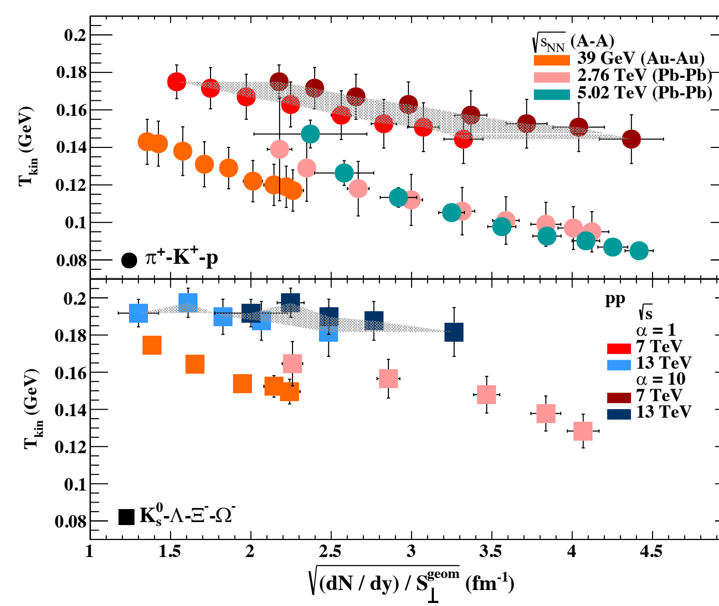

A-A
Centrality (%)
0 - 5
5 - 10
10 - 20
20 - 30
Centrality (%)
30 - 40
40 - 60
60 - 80
$a+b(\log\sqrt{s_{NN}})^{\alpha}$
$\langle dN/dy\rangle/S_{\perp}^{geom}(fm^{-2})$
0
2
4
6
8
10
12
14
16
18
20
10
10^2
10^3
$\sqrt{s_{NN}}$ (GeV)

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 $p_T = f(\text{mass})$ and T^{fo}_{kin} from BGBW fits do not scale ?



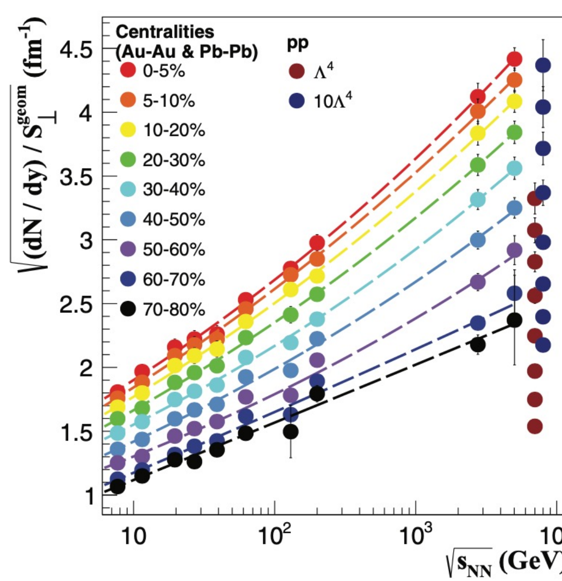


A. Lindner, M. Petrovici and A. Pop, PoS(PANIC2021)197

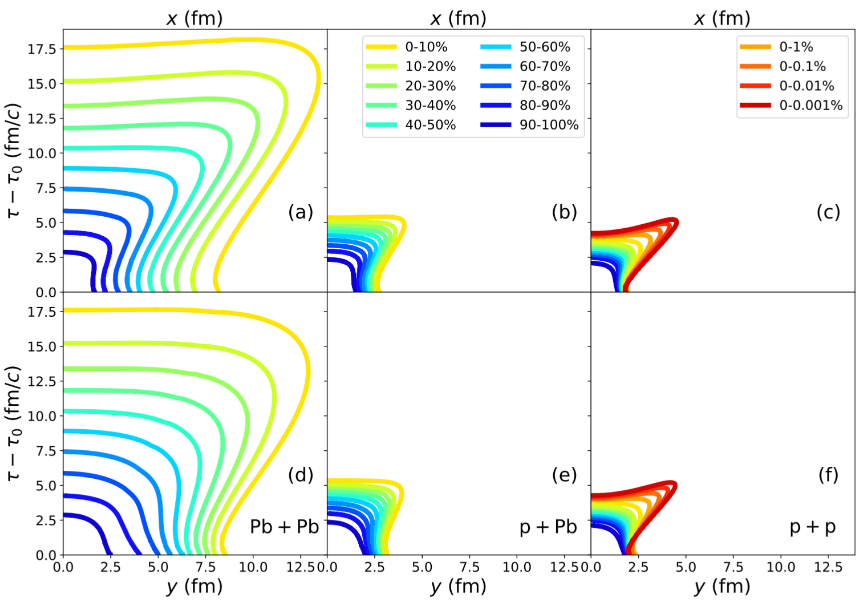
pp vs. Pb-Pb @ LHC

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

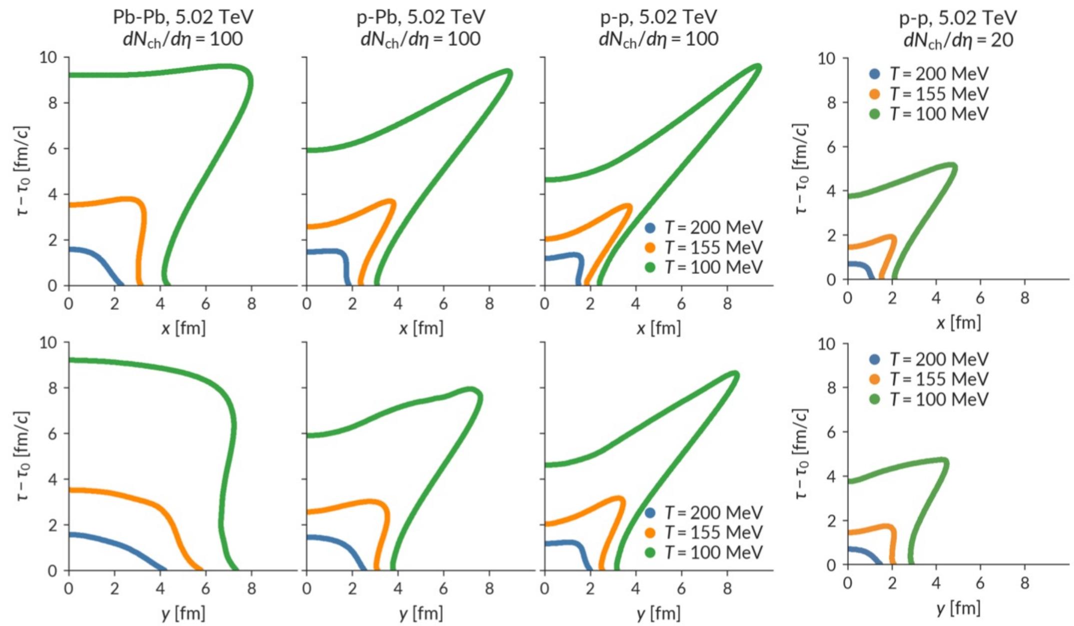
$\sqrt{s}$ (TeV)	dN/dy	$S_\perp$ (fm^2)	
(pp)		$\alpha = 1$	$\alpha = 10$
7	82.1 ± 2.8	7.43 ± 0.48	4.30 ± 0.36
	70.2 ± 2.2	7.43 ± 0.41	4.30 ± 0.31
	59.4 ± 1.7	7.43 ± 0.35	4.30 ± 0.27
	48.8 ± 1.3	7.43 ± 0.30	4.30 ± 0.23
	37.3 ± 0.9	7.39 ± 0.02	4.20 ± 0.02
	26.8 ± 0.6	6.89 ± 0.05	3.80 ± 0.03
	18.2 ± 0.4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