Workshop on Advances, Innovations, and Future Perspectives in High-Energy Nuclear Physics

GUVERNUL ROMÂNIEI

MINISTERUL CERCETĂRII,
INOVĂRII ȘI DIGITALIZĂRII
GOV.RO

ifa

IFIN-HH
www.ifin.ro

QCD Challenges

HPD

Mihai Petrovici, Wuhan Workshop, 19-24 October, 2024

Outline:

- *Introduction*

Advances in High Energy Nuclear Physics:

- *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*
    - $(dN/dy)^{(\text{strange and multi strange})}/(dN/dy)$ - $(dN/dy)/S_\perp$ *correlation*
    - *collision energy dependence of* $(1\text{-RAA})/[\langle dN/dy\rangle/S_\perp]$ *for central collisions*
- *Similar studies for pp collisions and comparison with Pb-Pb collisions*

Future Perspectives:

- *pp much larger charged particle multiplicity*
- *Pb-Pb large rapidity PID*
- *What remains to be done at large baryon density ?*

Innovations:

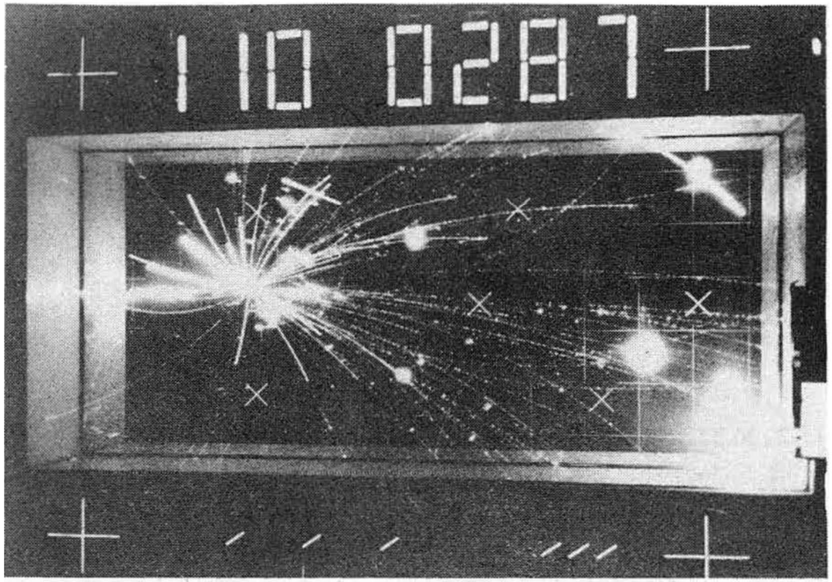
- *A new generation of RPC and TRD with 2D position resolution high granularity, high counting rate, radiation hard*
- *Concluding remark*

50th anniversary of high energy heavy-ion

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

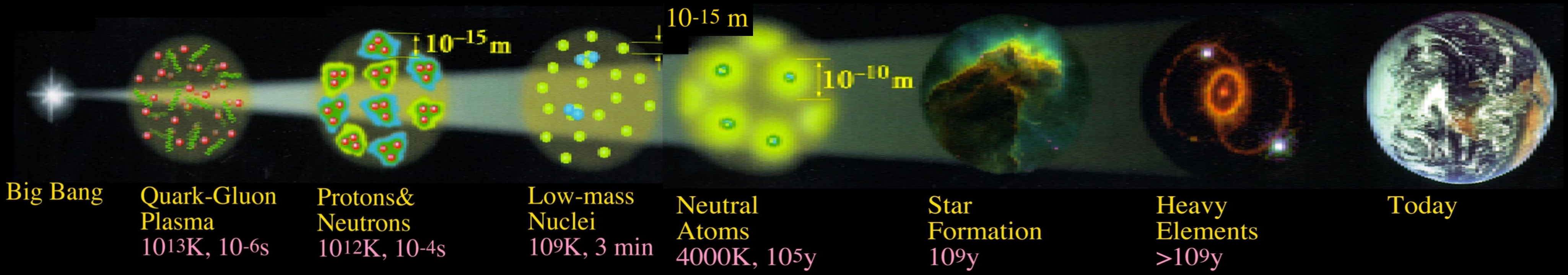
- *A University of Frankfurt group has exposed their AgCl detectors to various heavy-ion beams at energies from 250 MeV/A to 2.1 GeV/A.*
  The observed peaks in the angular distributions of light fragments that moved with beam energy in a manner suggestive of these particles arising from shock waves,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



based on experiments in terrestrial laboratories ?

Large scale facilities

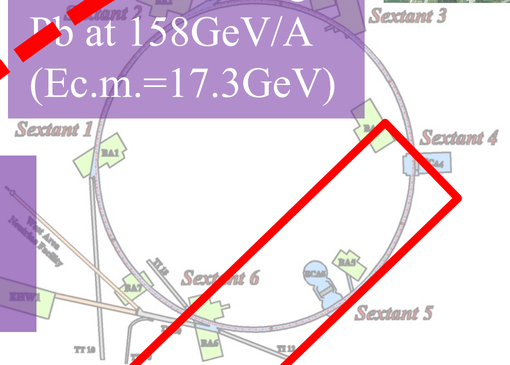
LHC: Collider
Pb+Pb @5020GeV/A

RHIC: Collider
Au+Au @ 200GeV/A

?

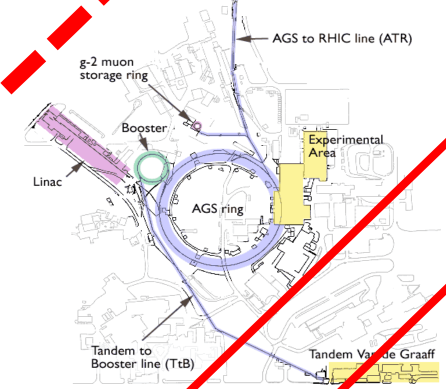
Hotter
Denser
Longer
Bigger

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



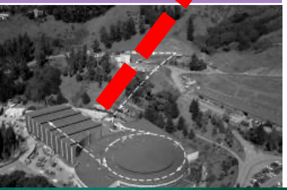
???

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

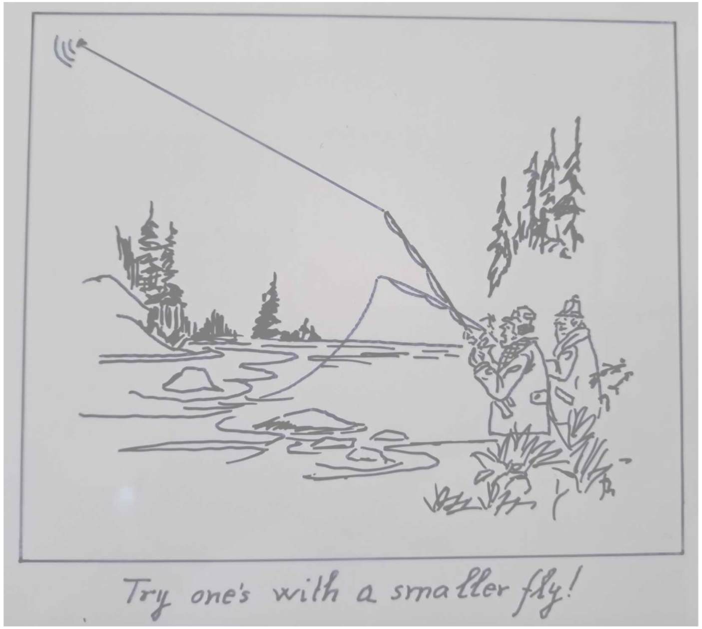


BES

Bevalac
Fixed Target
1-2GeV/A



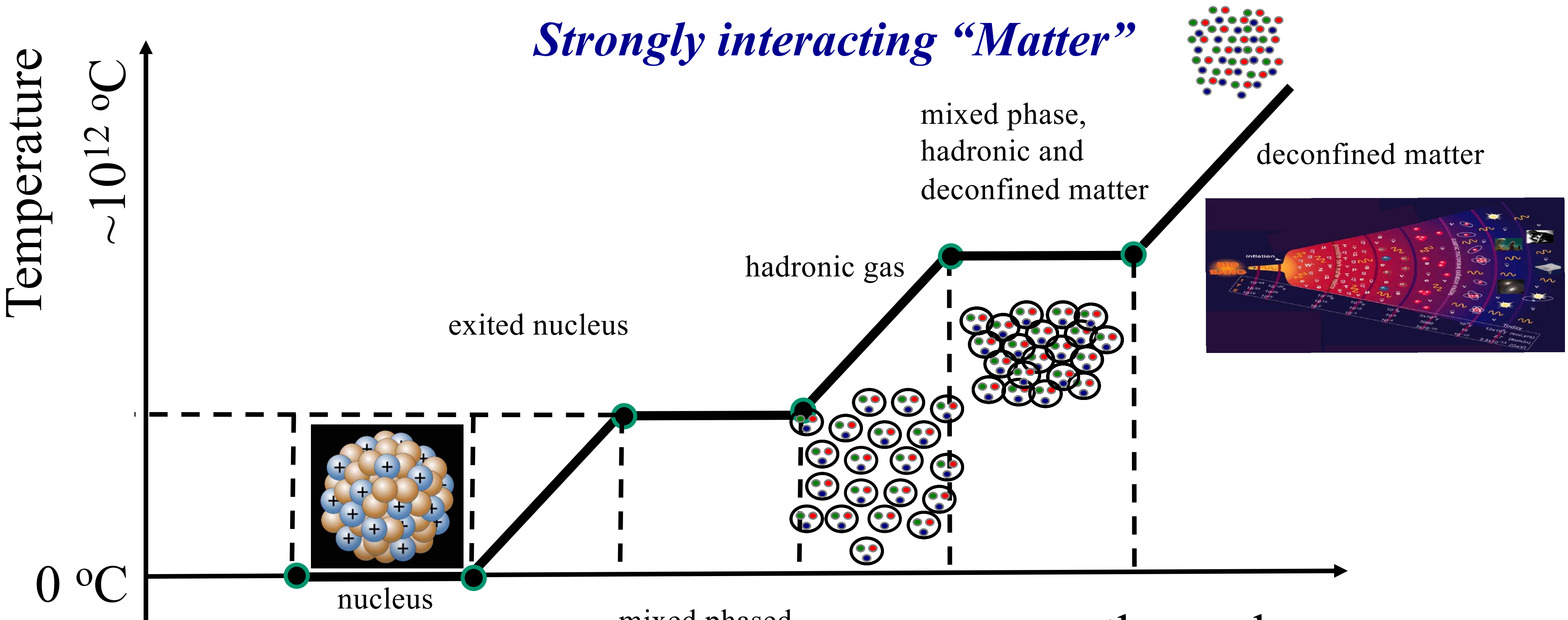
SIS 18

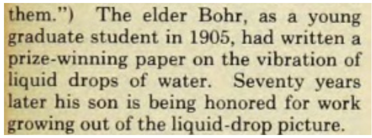


Try one's with a smaller fly!

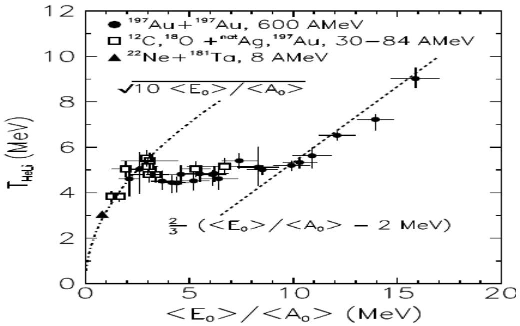
Physics motivation

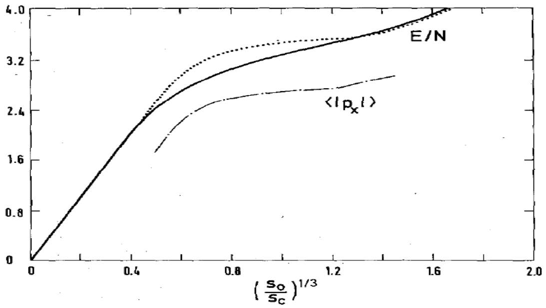
Strongly interacting "Matter"





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

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

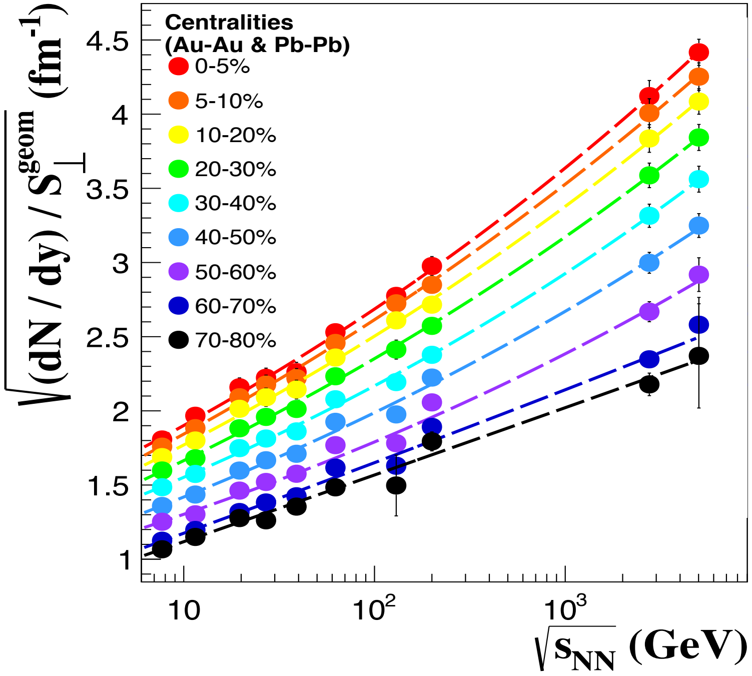
n - ***no. of charged particles from a gluon fragmentation***

$$\big\downarrow$$

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

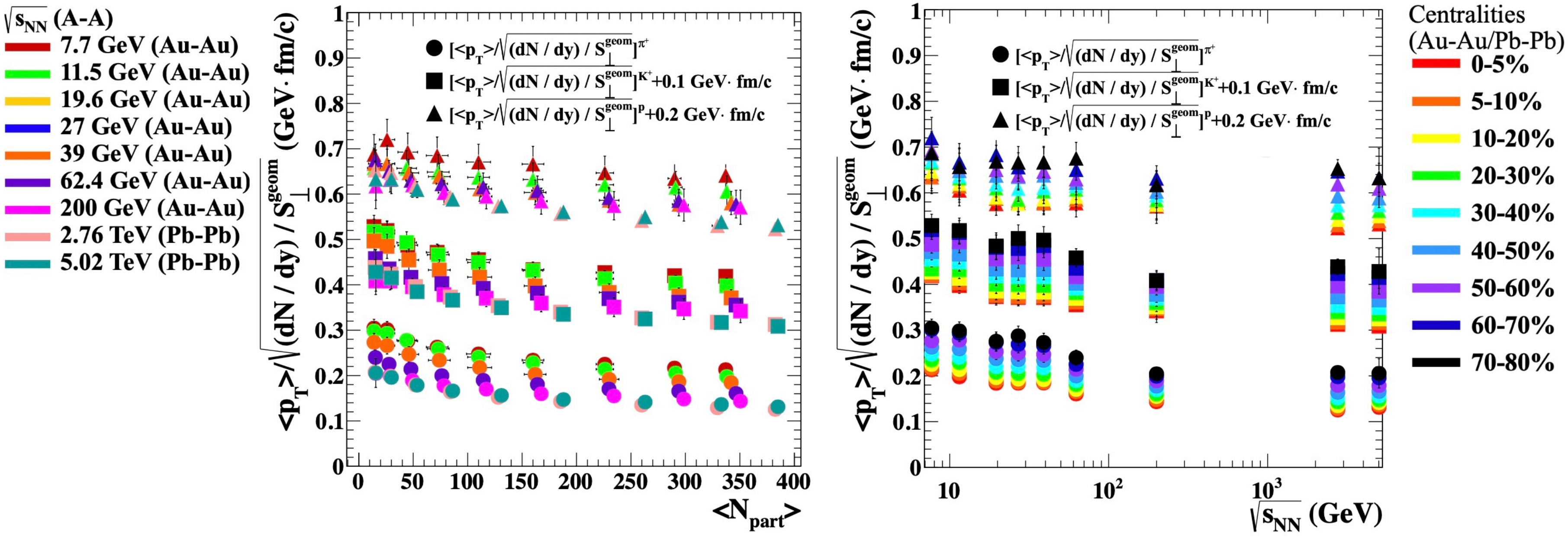
decreases as a function of:

- ***collision energy***
- ***centrality***

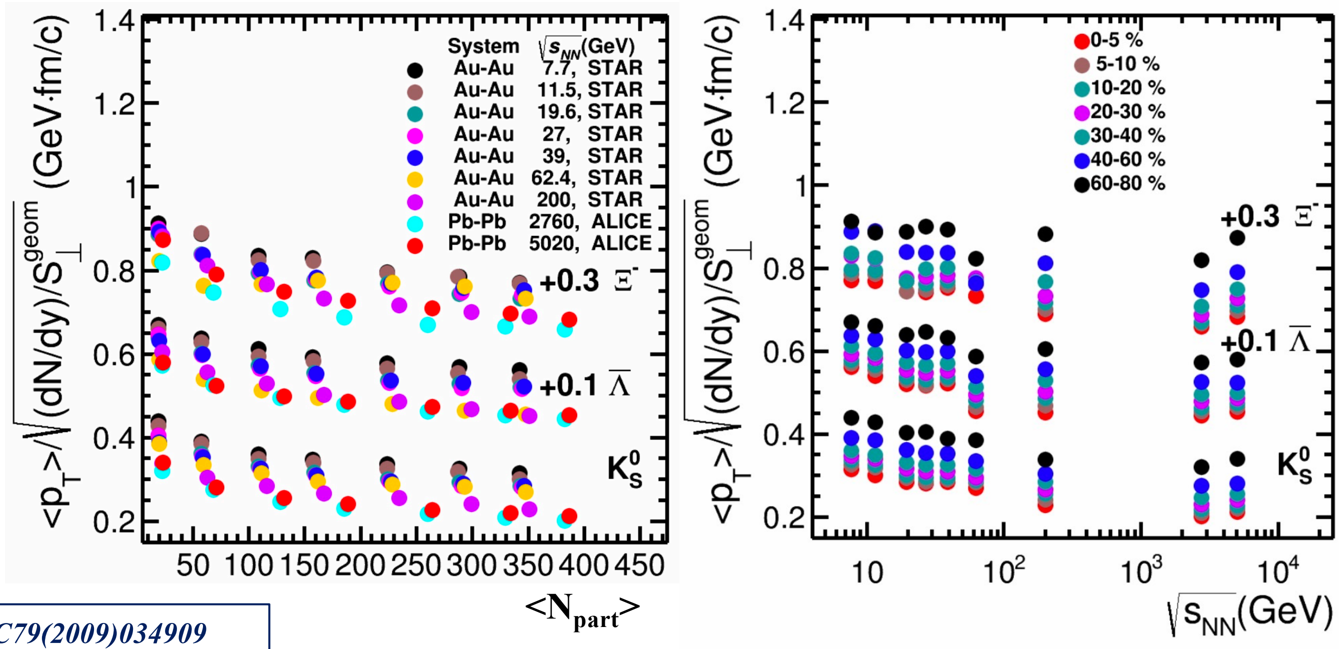


M.Petrovici, A.Lindner and A.Pop, Phys. Rev. C 98(2018)024904

Experimental results



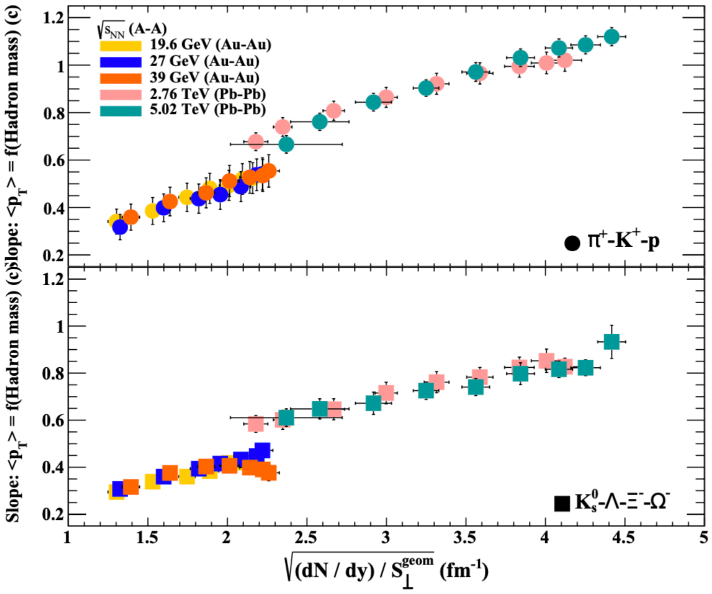
M.Petrovici, A.Lindner and A.Pop, Phys. Rev. C 98(2018)024904

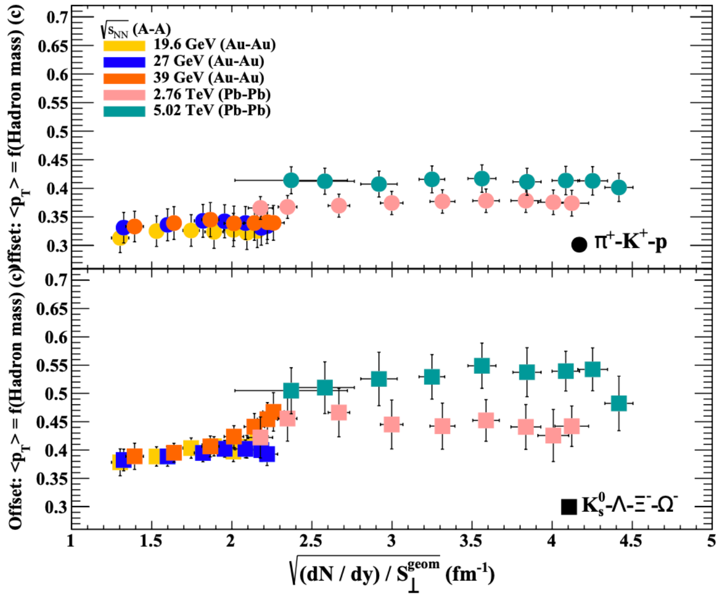


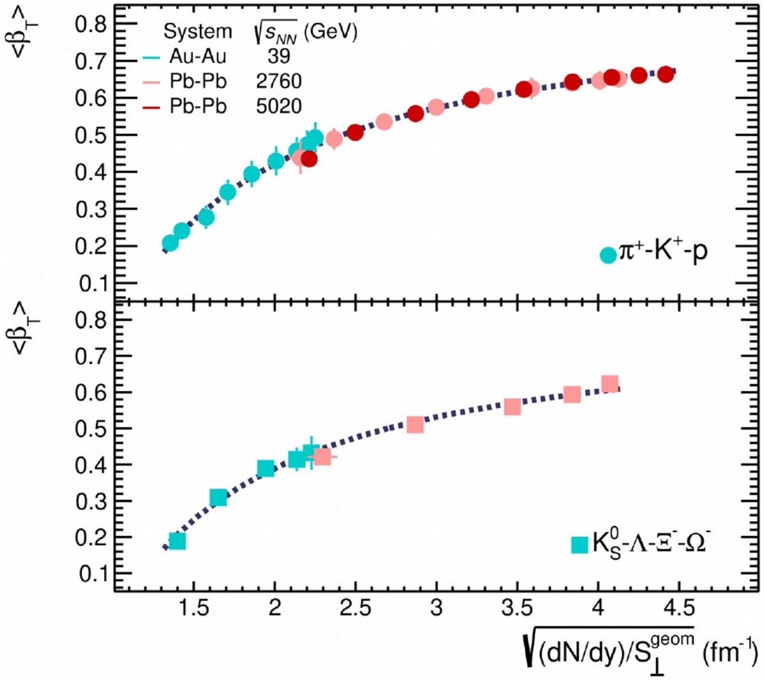
STAR Collaboration, Phys. Rev. C79(2009)034909
ALICE Collaboration, Phys. Rev. C88(2013)044910
STAR Collaboration), Phys. Rev. C96(2017)044904
ALICE Collaboration), Nucl. Phys. A967(2017)421

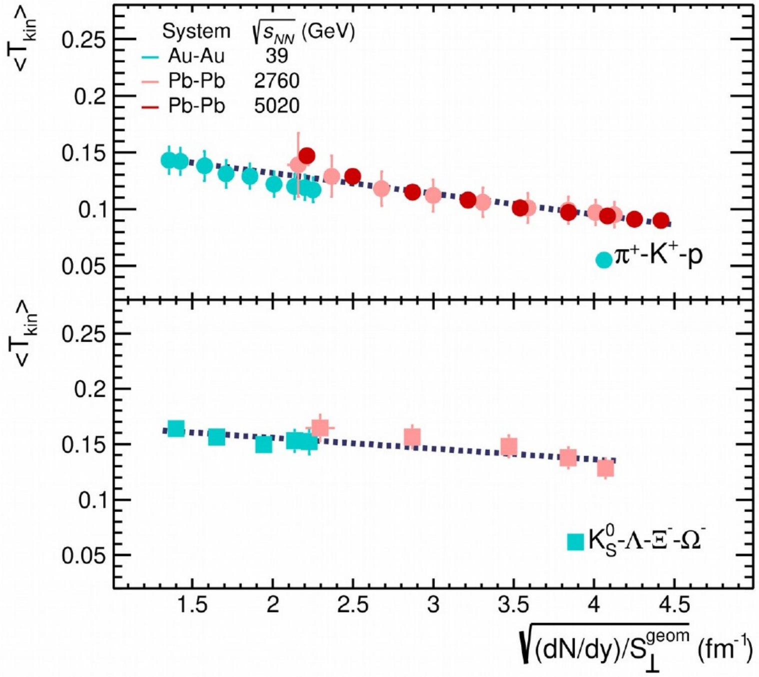
M. Petrovici and A. Pop , EuNPC 2022

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



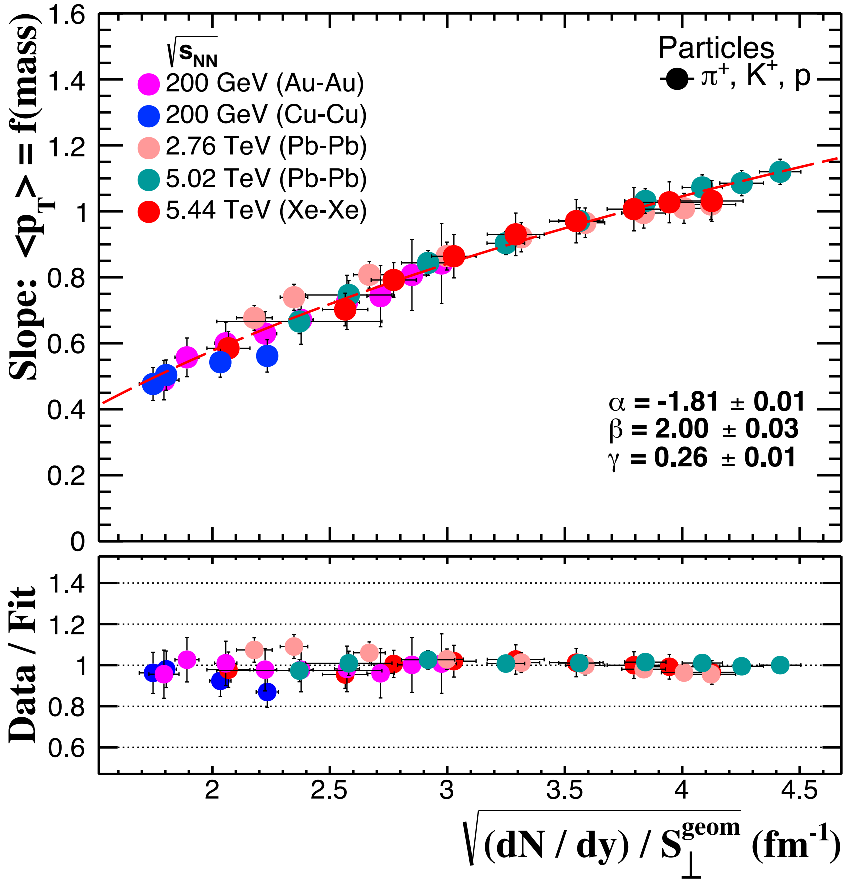


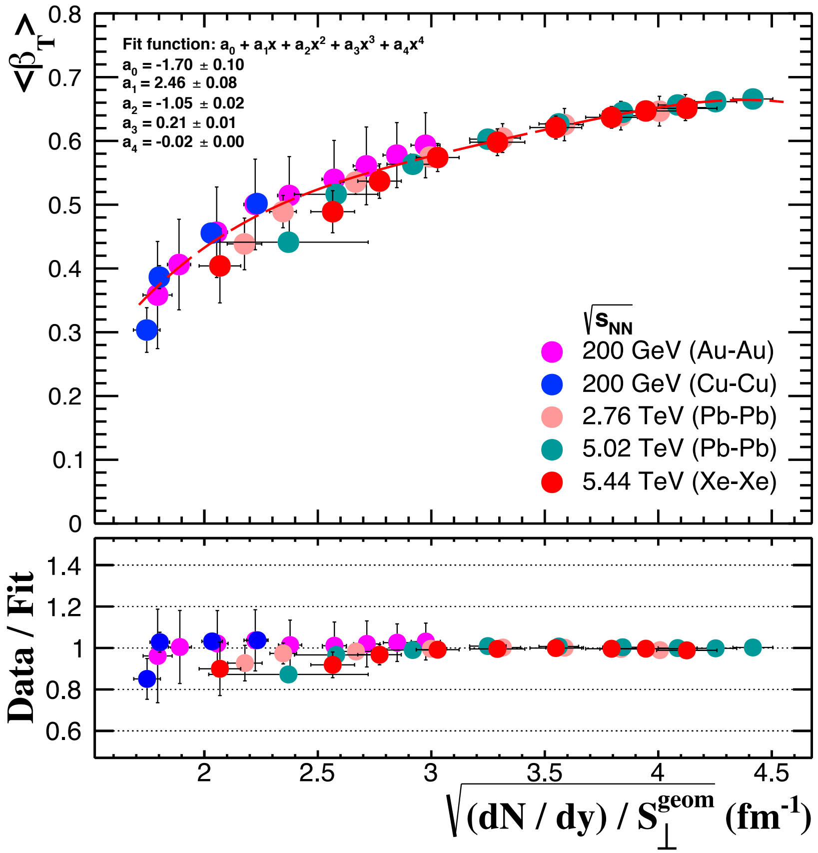




M. Petrovici et al., Phys. Rev. C 98(2018)024904
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

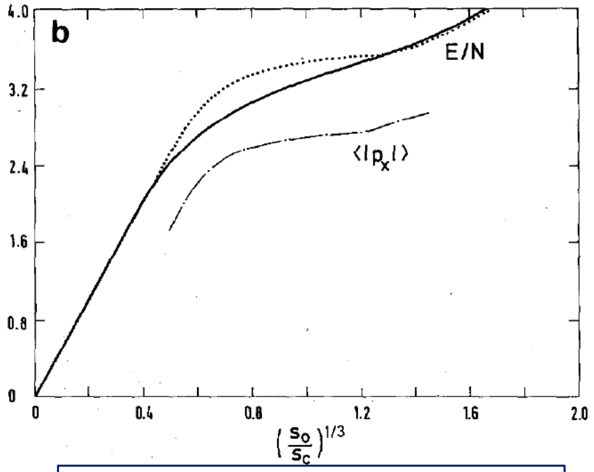
$[(dN/dy)/S_\perp]^{1/2}$ scaling





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

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 :

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

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

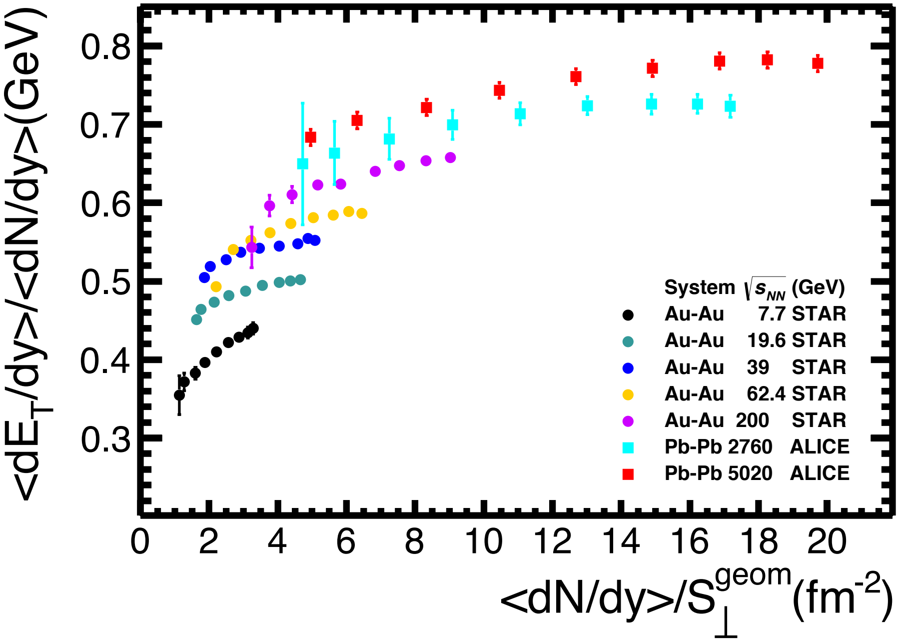
for AGS and RHIC energies:

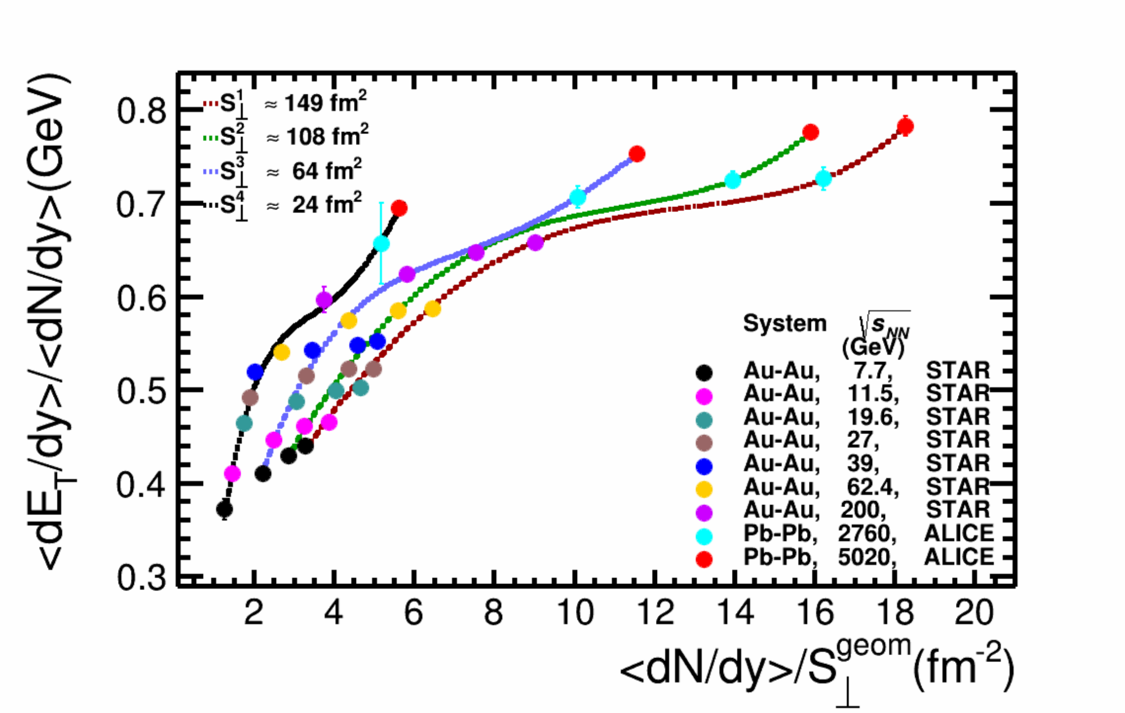
$$\langle m_T\rangle = \sqrt{\langle p_T\rangle^2 + m^2} - m_N$$ *- for baryons*

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

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

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

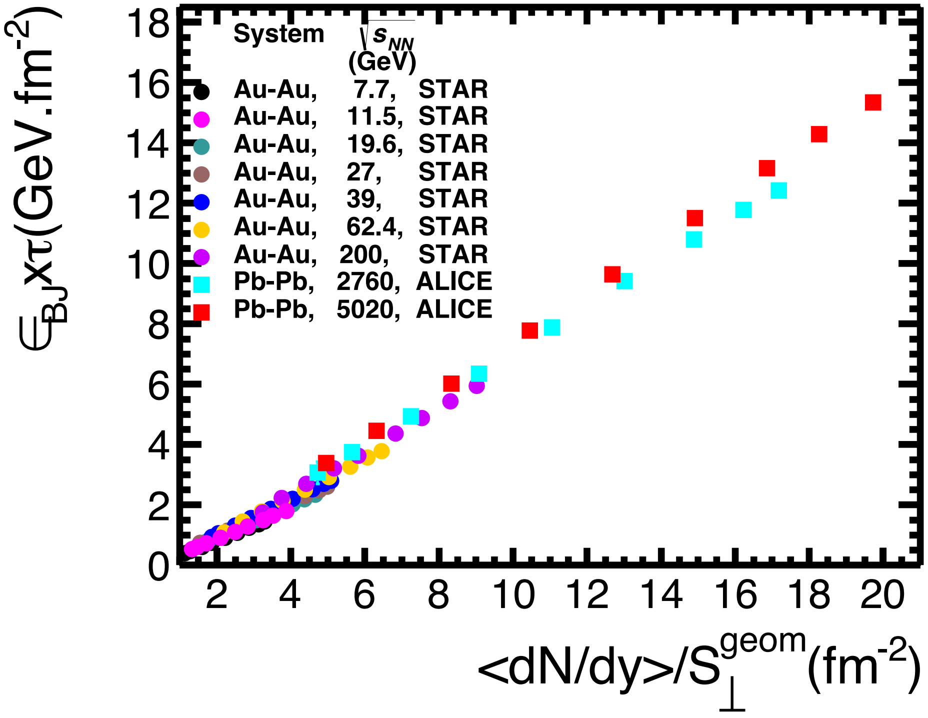


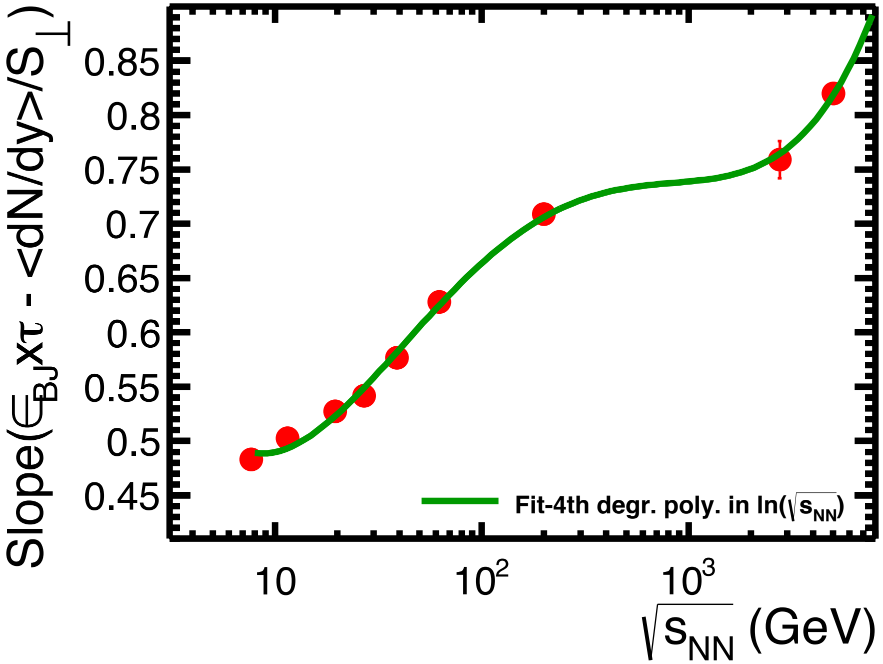


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

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

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



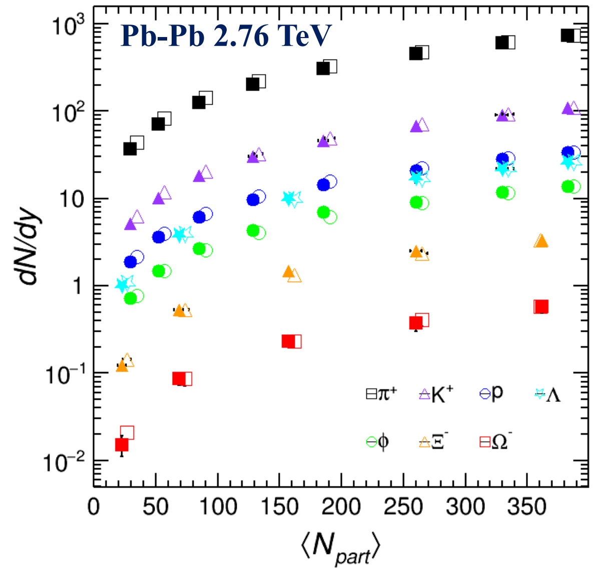


M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

Strangeness production - smoking gun of deconfinement

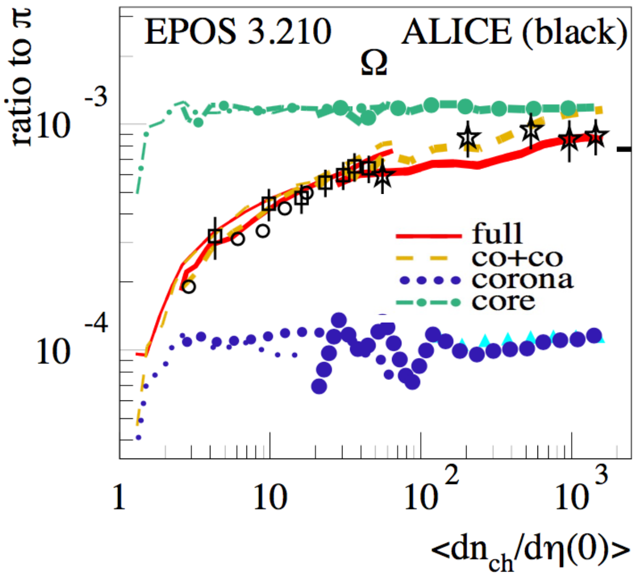
J.Rafelski and B.Muller, Phys.Rev.Lett. 48(1982)1066

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



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

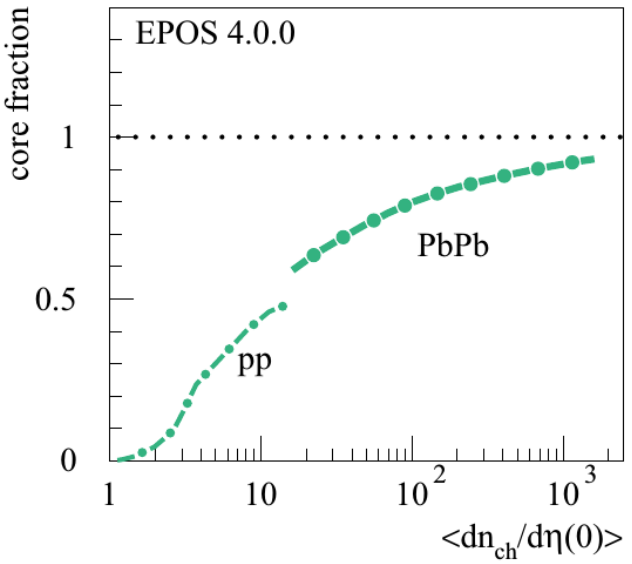
M. Petrovici et al., Phys.Rev. C96(2017)014908



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

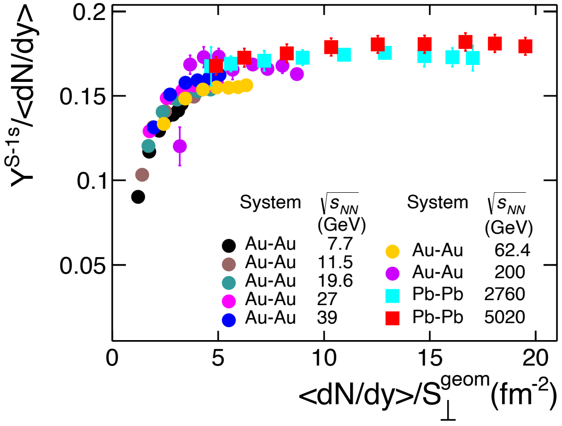


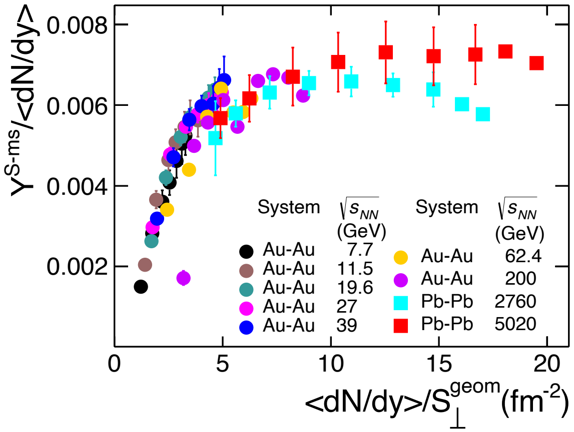
K. Werner, Phys.Rev. C109(2024)014910

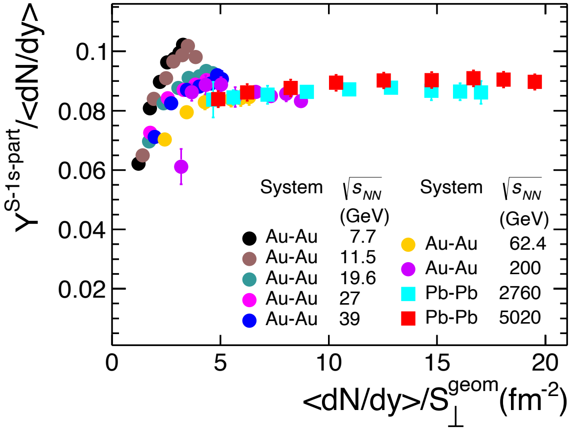
$(dN/dy)^{(\text{strange and multi strange})}/(dN/dy)$ - $(dN/dy)/S_{\perp}$ correlation

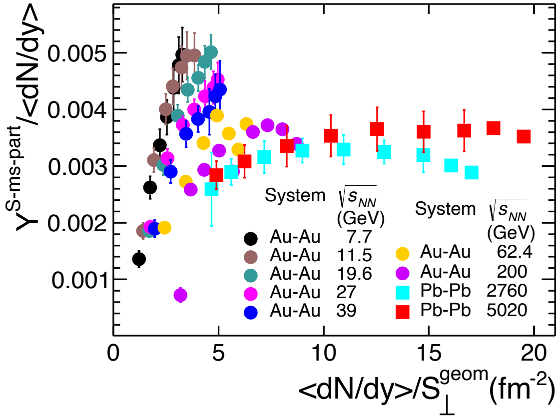
$$Y^{1s} = \frac{dN^{1s}}{dy} = \frac{dN^{(K^{+}+K^{-})}}{dy} + 2\frac{dN^{K_s^0}}{dy} + \frac{dN^{(\Lambda+\bar{\Lambda})}}{dy} + 2\frac{dN^{(\Sigma^{-}+\bar{\Sigma}^{+})}}{dy}$$

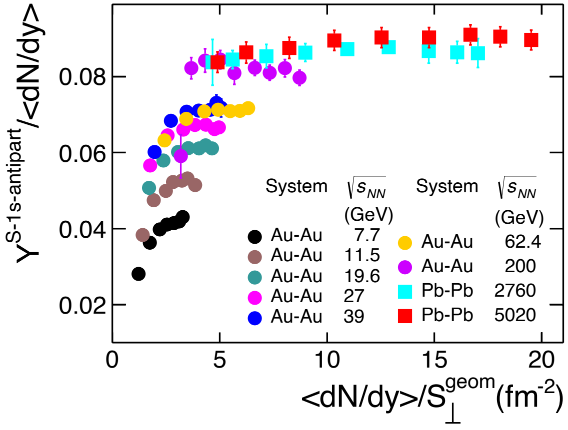
$$Y^{ms} = \frac{dN^{ms}}{dy} = \frac{dN^{(\Omega^{-}+\bar{\Omega}^{+})}}{dy} + 2\frac{dN^{(\Xi^{-}+\bar{\Xi}^{+})}}{dy}$$

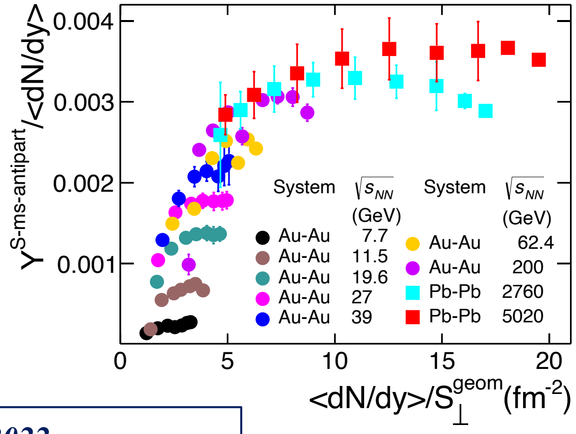






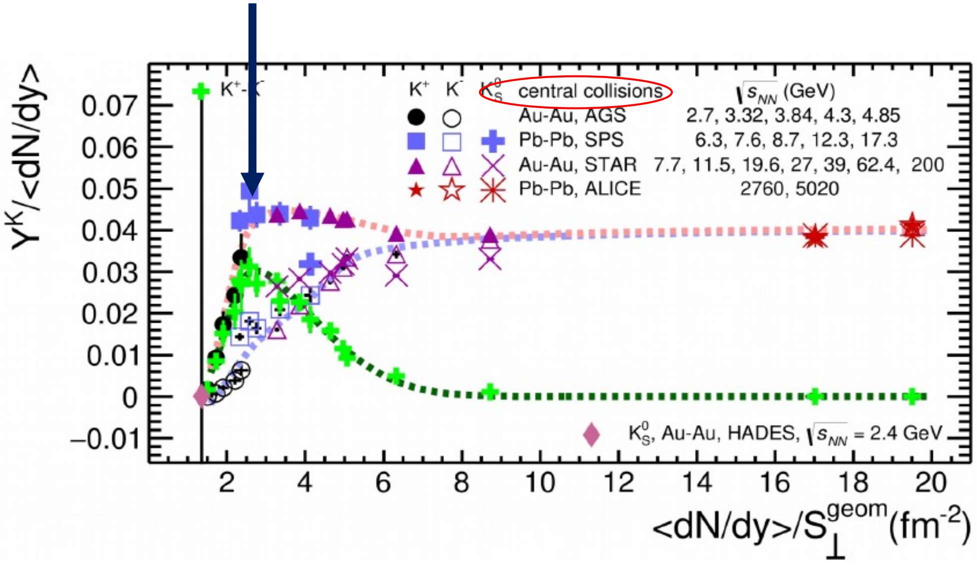


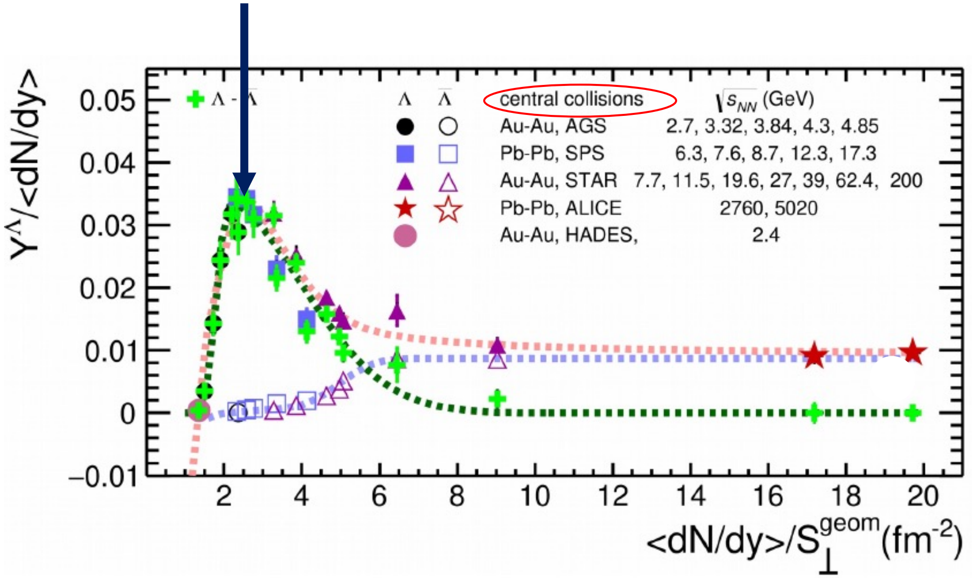


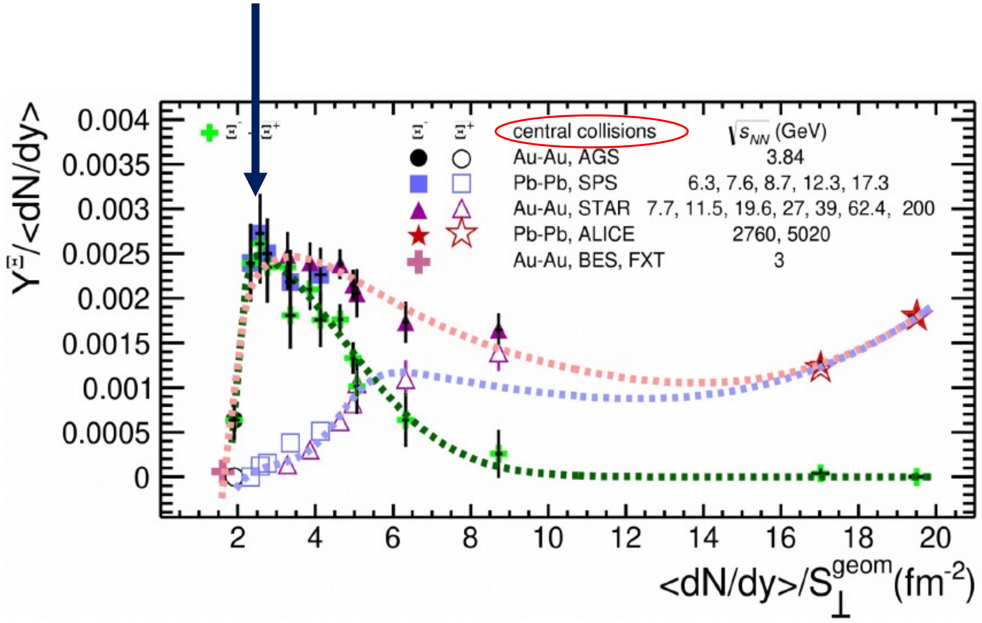


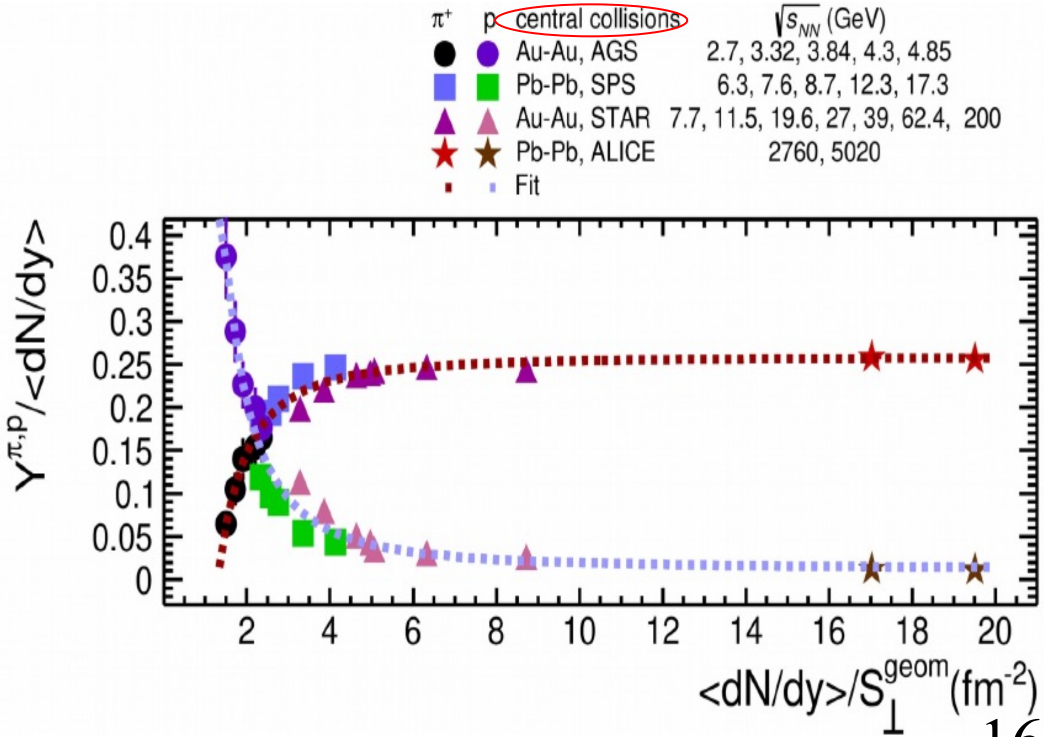
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

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



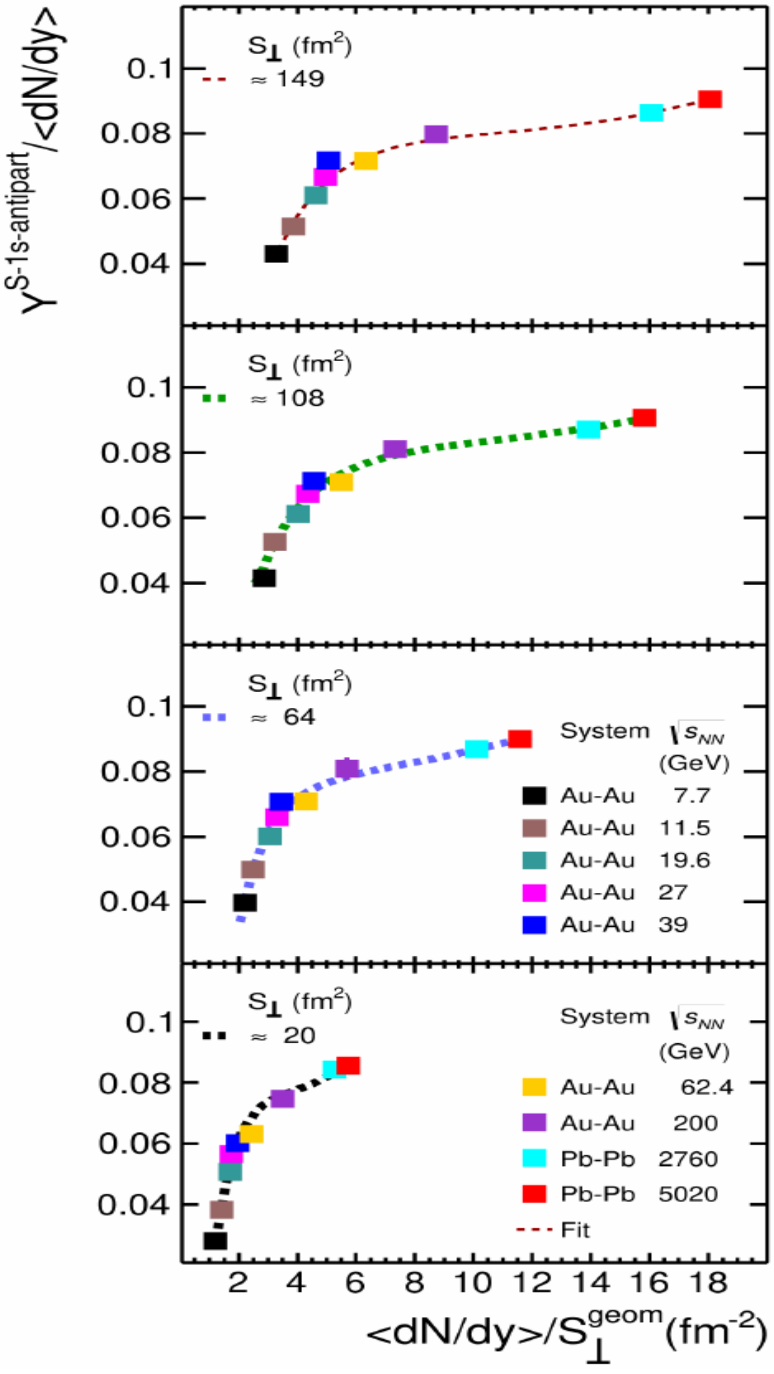


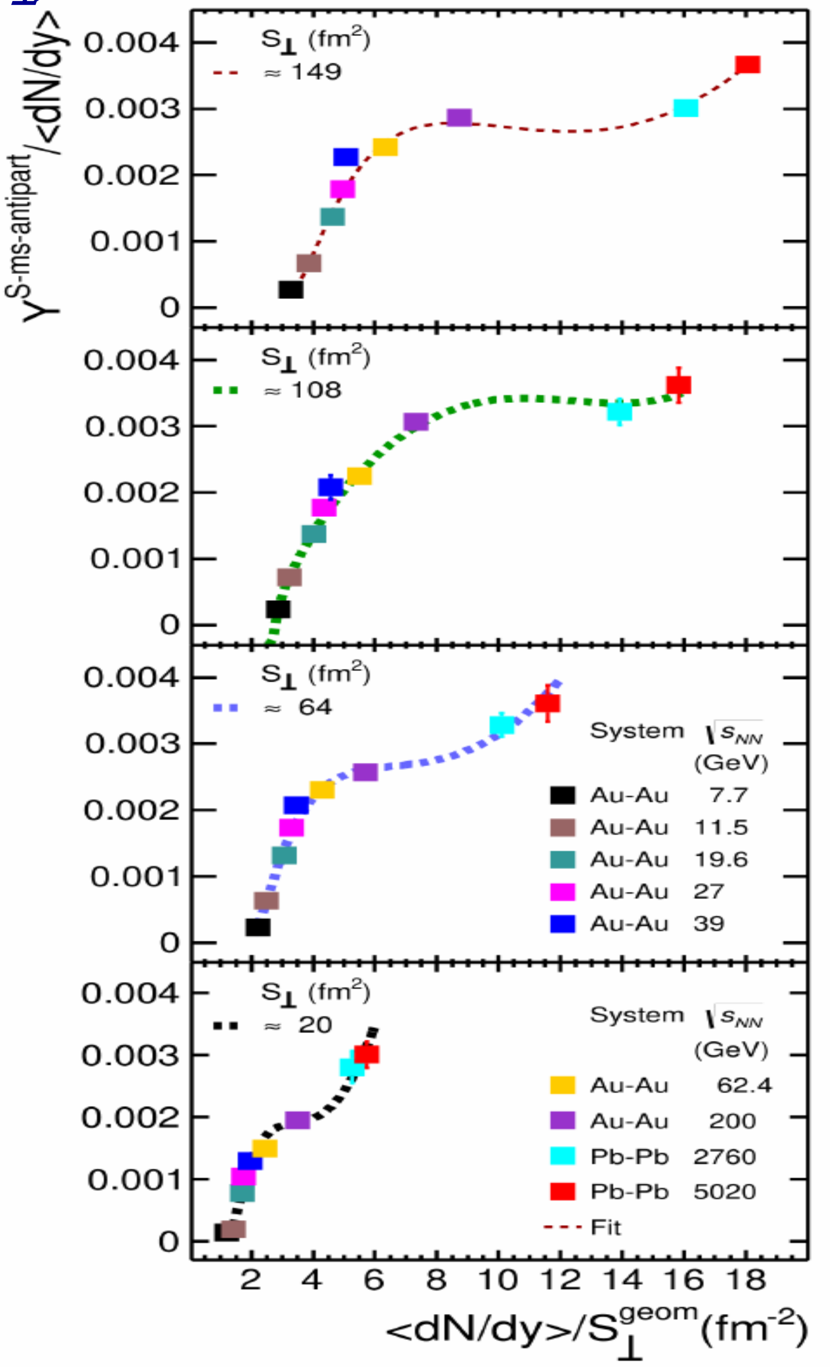




M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

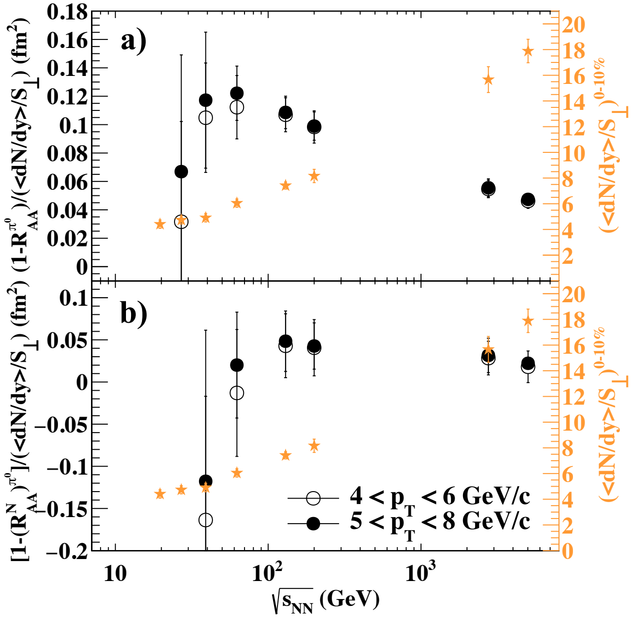
$(dN/dy)^{(\text{strange and multi strange antihadron})}/(dN/dy)$ - $(dN/dy)/S_\perp$ correlation (different $S_\perp$)



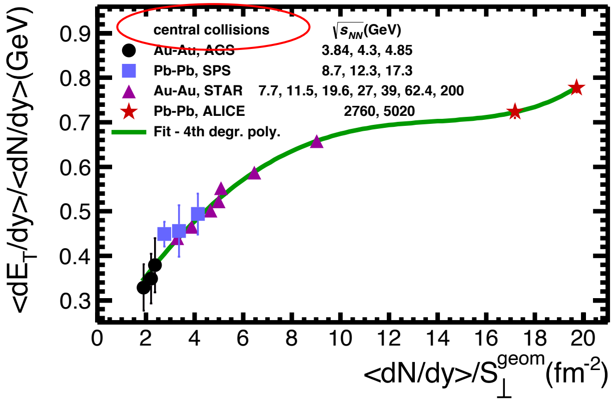


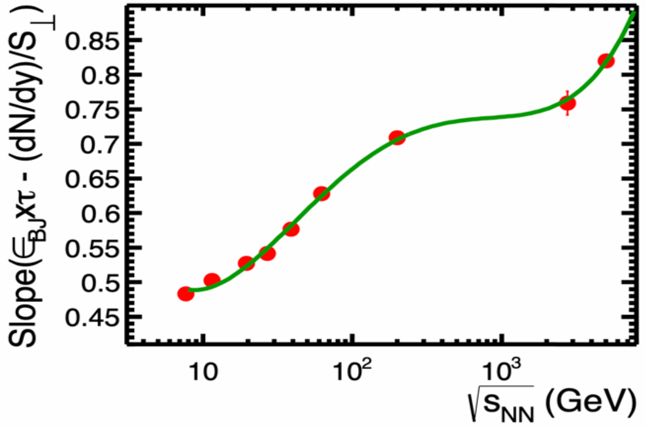
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

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

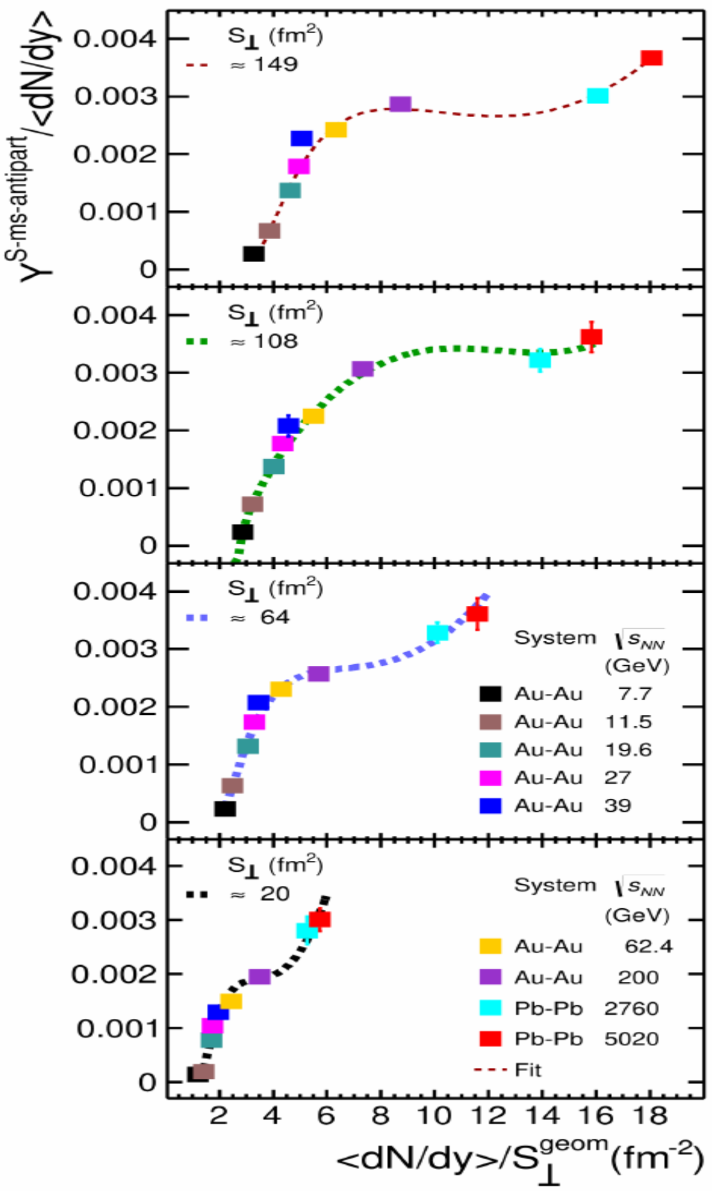


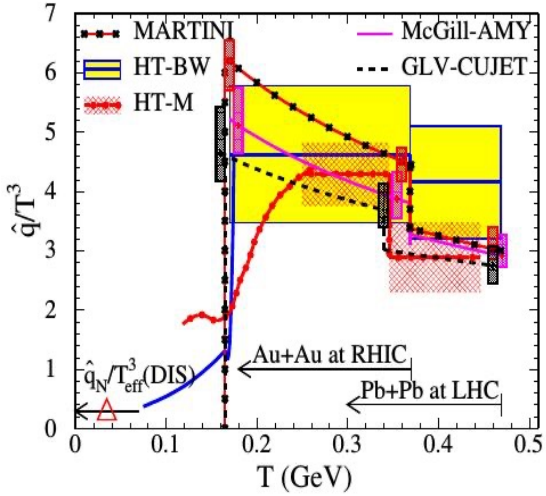
M.Petrovici et al., Phys. Rev. C103(2021)034903



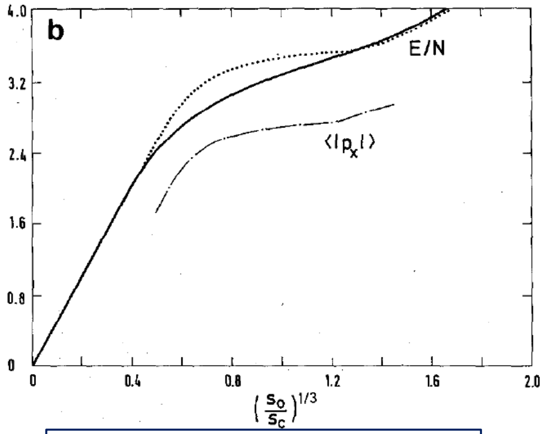


M.Petrovici and A.Pop, Phys.Rev. C107(2023)0





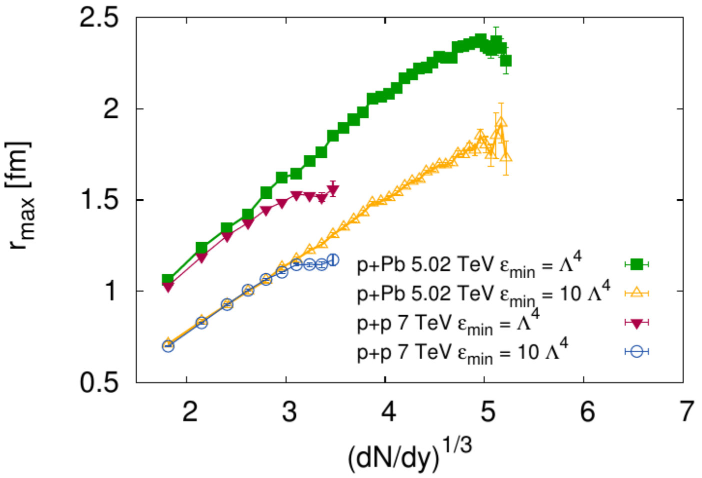
K.M. Burke et al., JET Collaboration, Phys. Rev. C90(2014)014909



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

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

pp vs A-A @ LHC



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

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

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

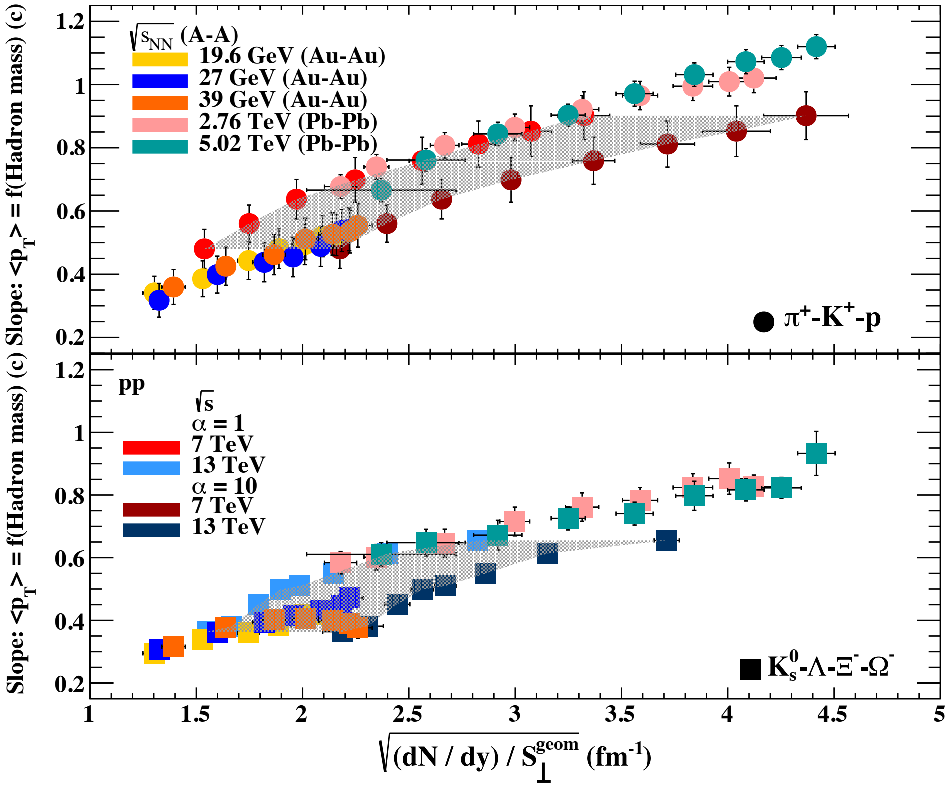
$$dN_g/dy \approx dN/dy$$

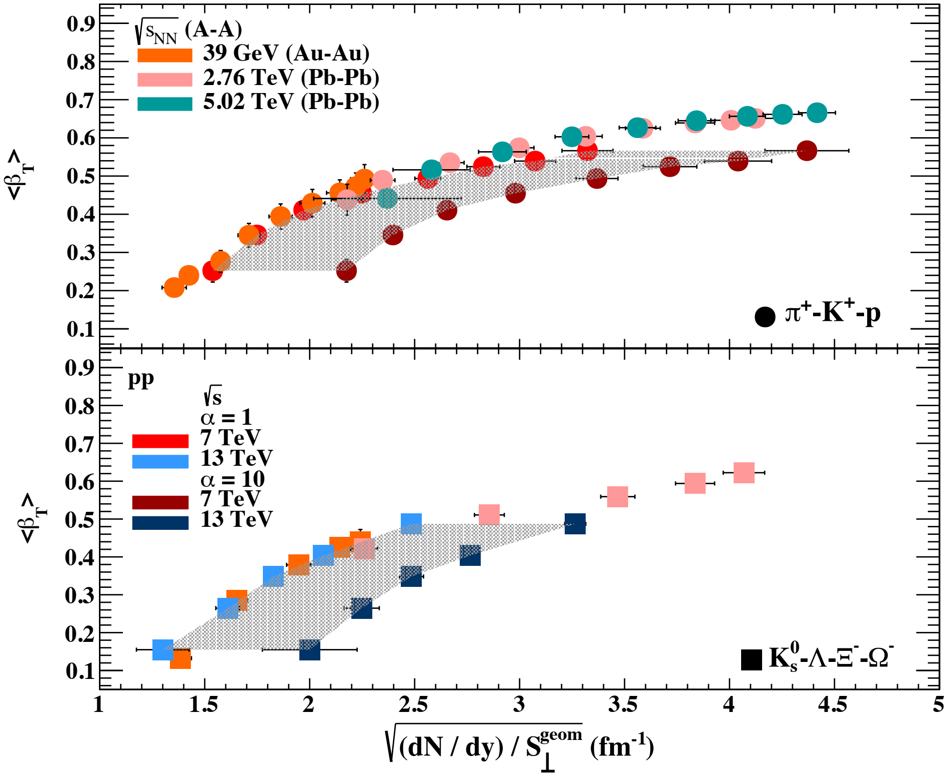
A. Bzdak et al., Phys.Rev. C87(2013)064906

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

A-A vs. pp @ LHC

π, K, p

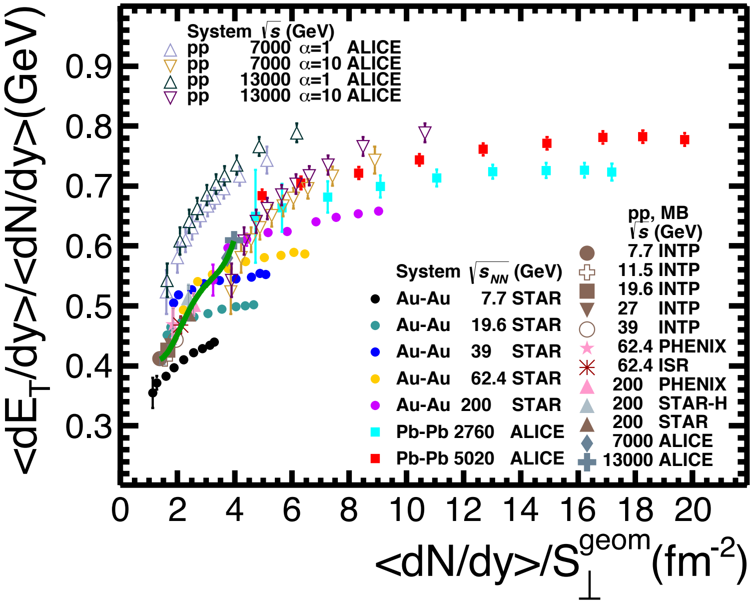


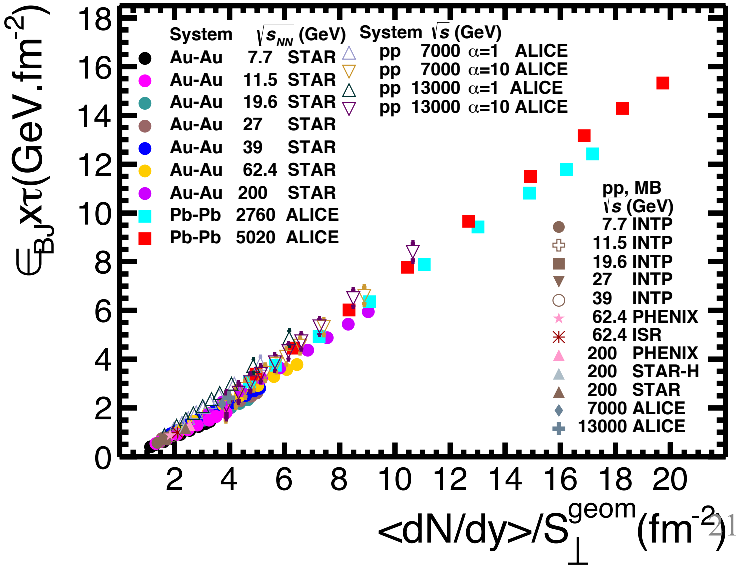


A. Lindner et al., Proceedings of Science (PoS) 380(2021)197 (PANIC2021), https://pos.sissa.it/380/197/.

A-A vs. pp @ LHC

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

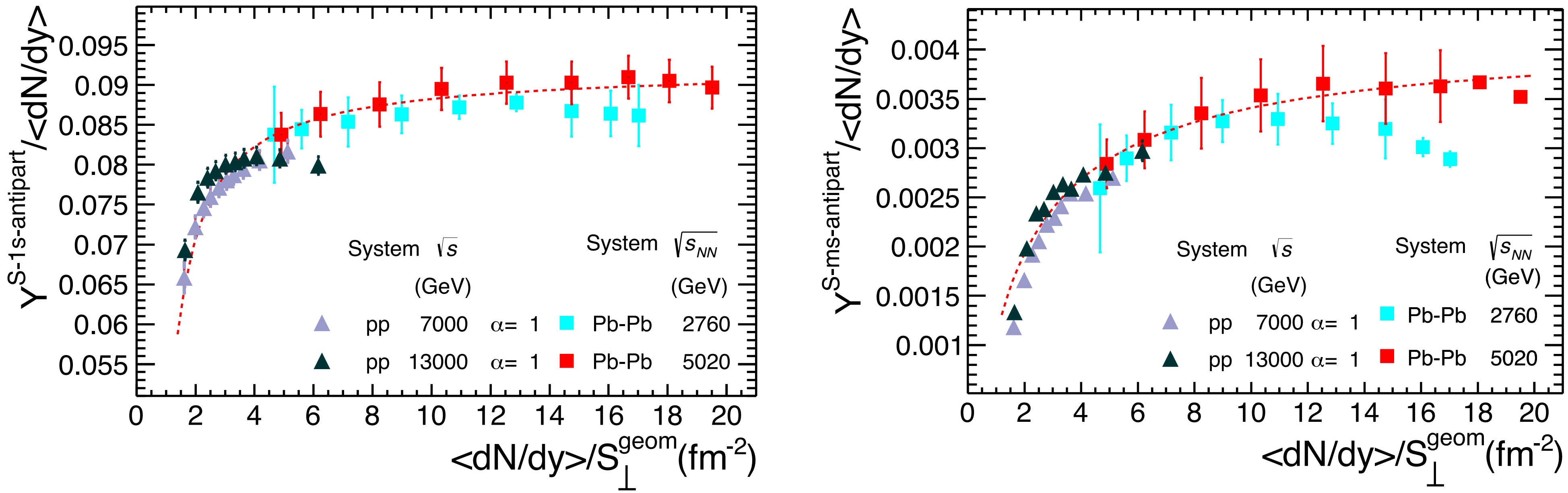




M.Petrovici and A.Pop, Phys.Rev. C107(2023)034913

A-A vs. pp @ LHC

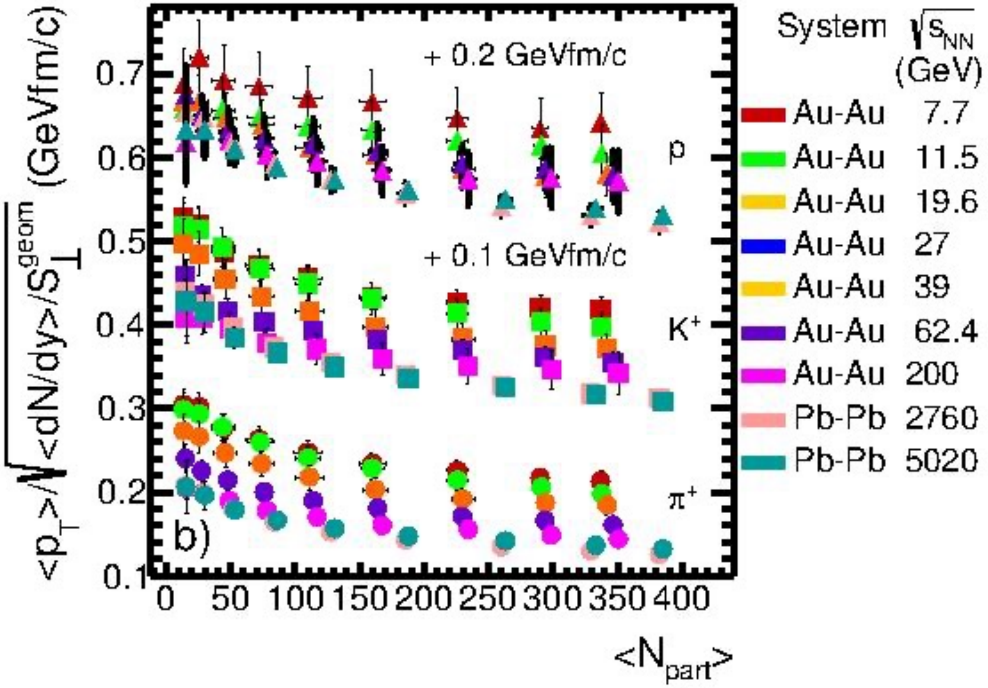
$(dN/dy)^{(\text{strange and multi strange})}/(dN/dy) - (dN/dy)/S_{\perp}$

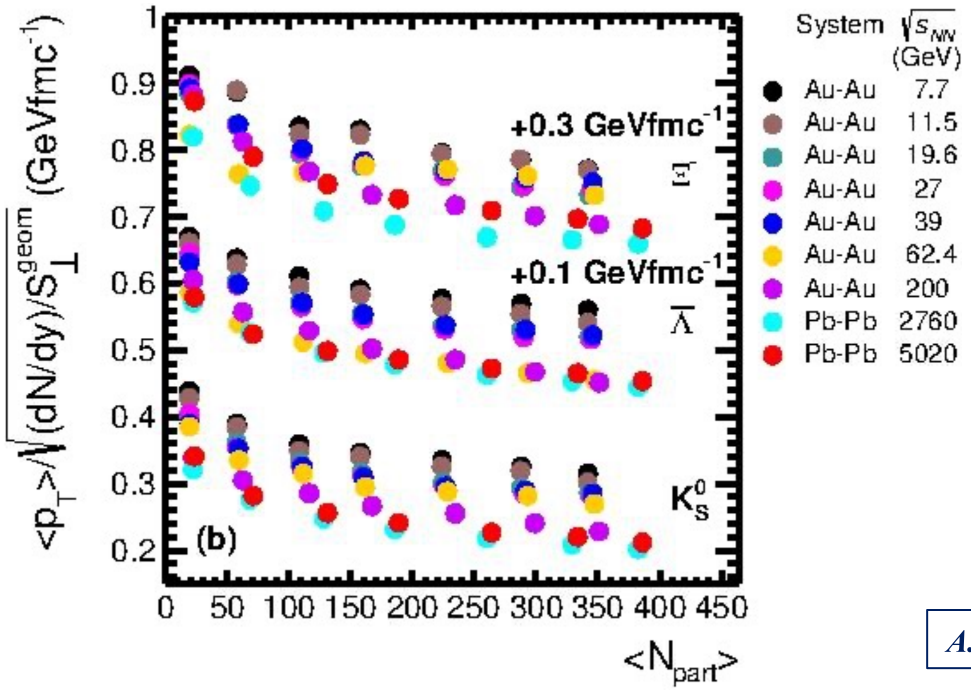


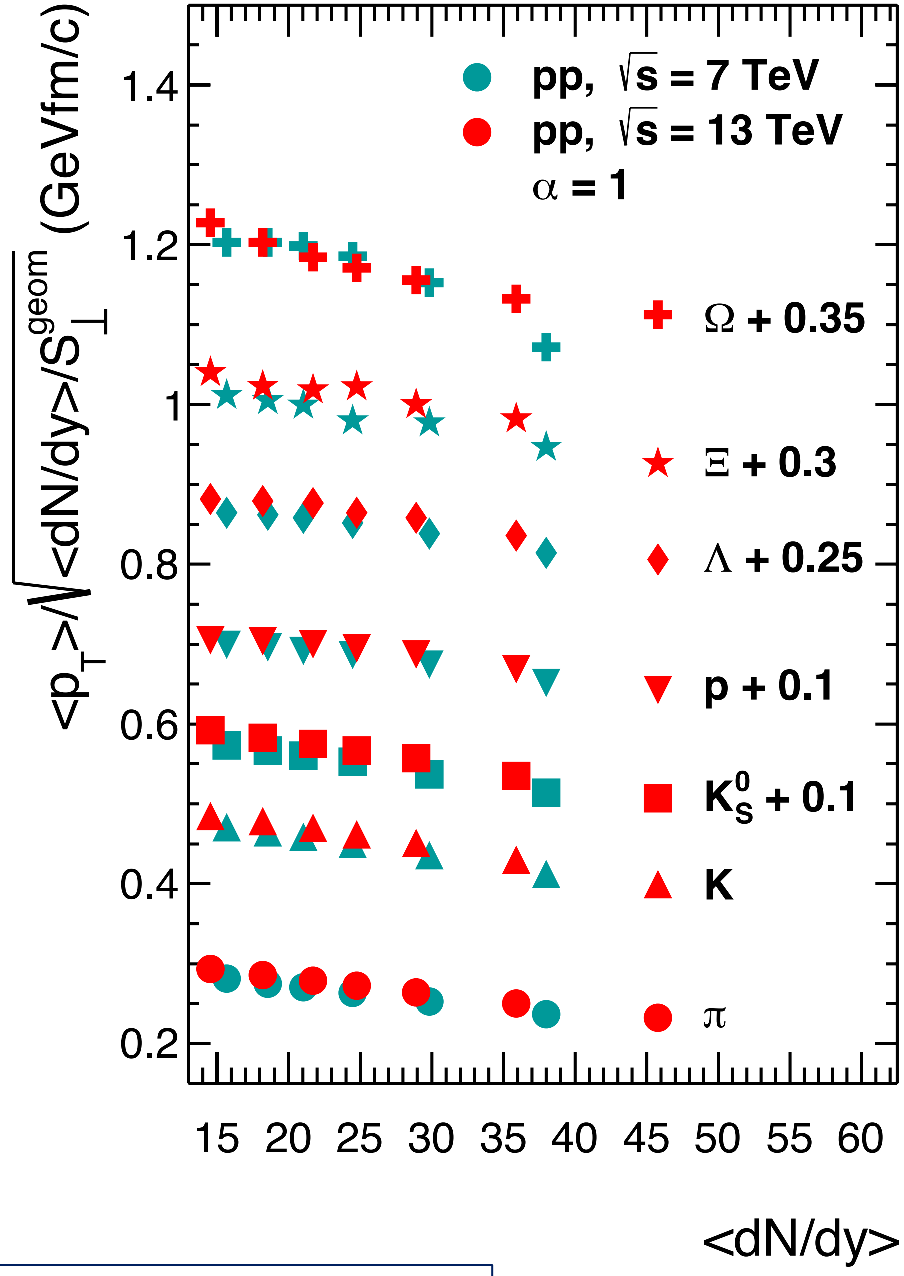
M. Petrovici and A. Pop , EuNPC 2022
A. Pop and M. Petrovici, arXiv:2402.19115[hep-ph]

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

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





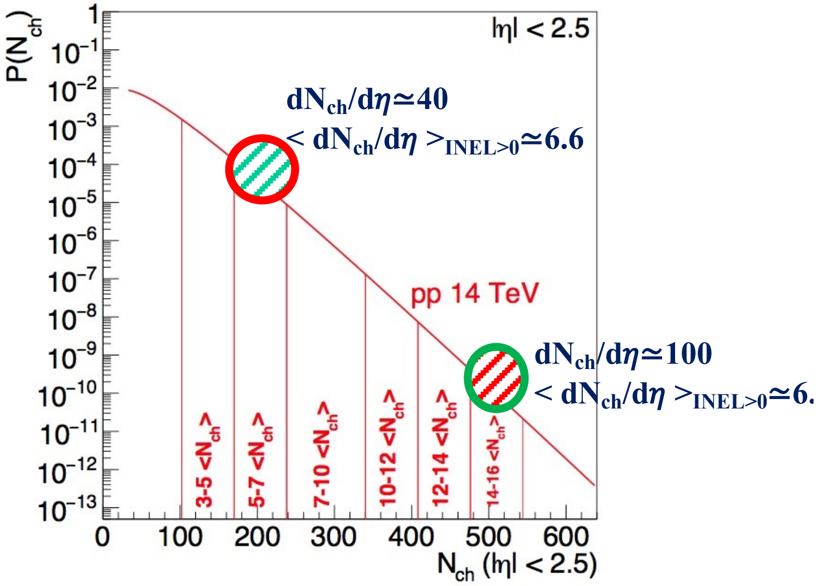


A. Pop and M. Petrovici, will be published

What's next ?

- ➢

ALICE Coll., arXiv:1812.06772



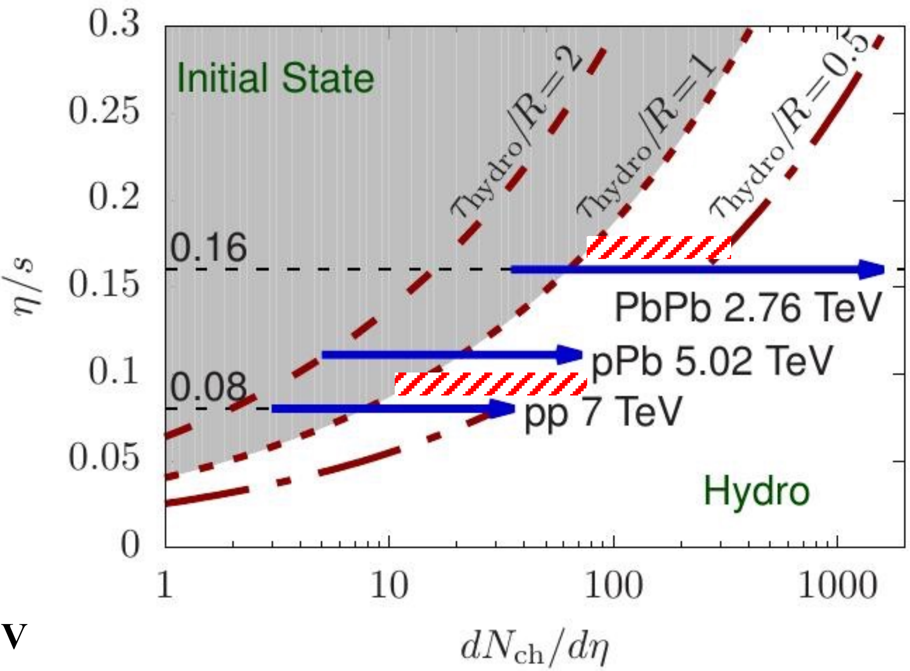
$dN_{ch}/d\eta \simeq 40$

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

$dN_{ch}/d\eta \simeq 100$

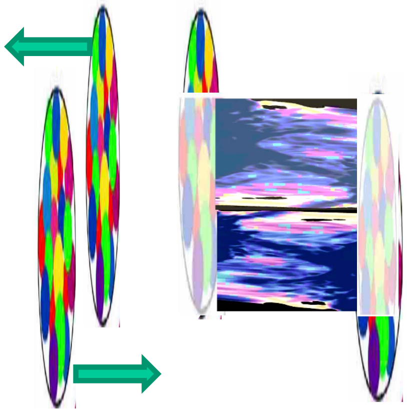
$< dN_{ch}/d\eta >_{INEL>0} \simeq 6.$

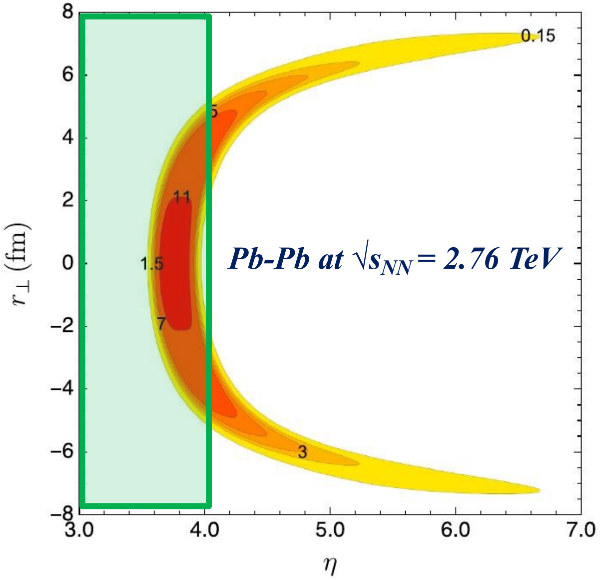
A.Kurkela et al., PoS(Confinement 2018)152



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

- ➢ **PID @ large rapidity**

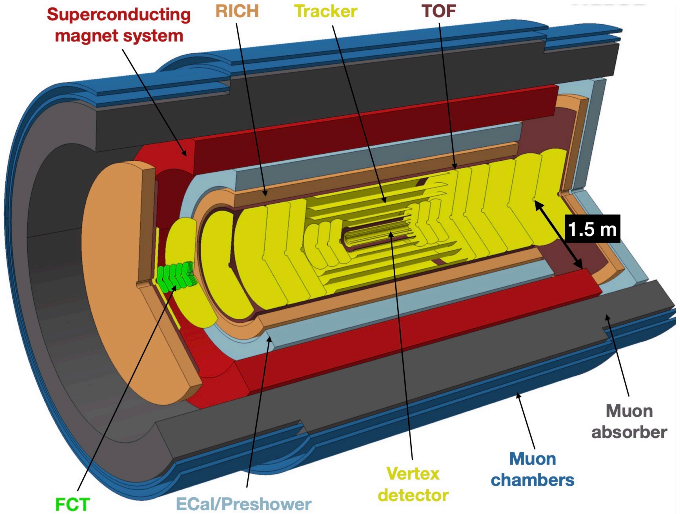




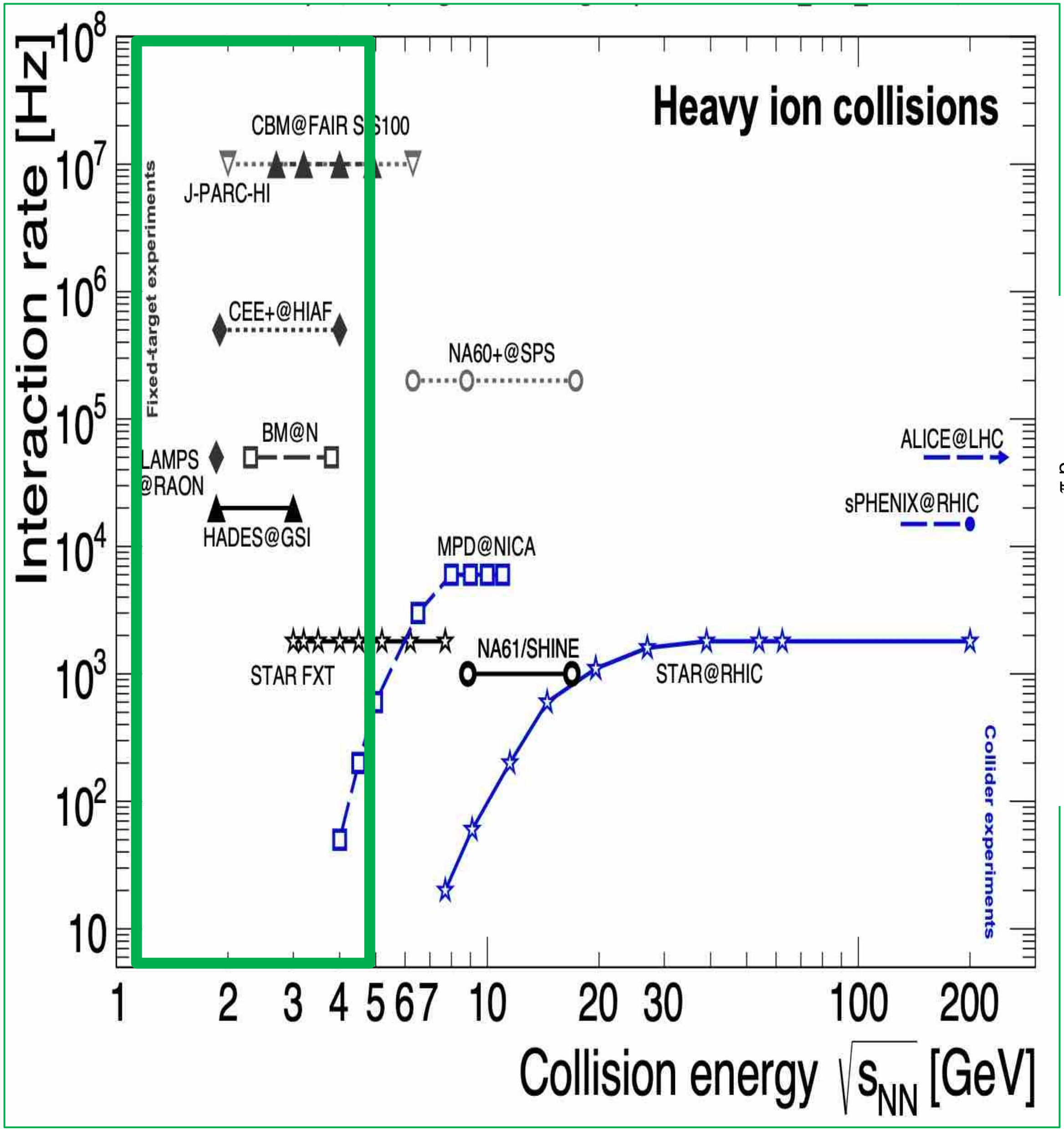
M. Li and J.I. Kapusta, Phys.Rev. C99(2019)014906

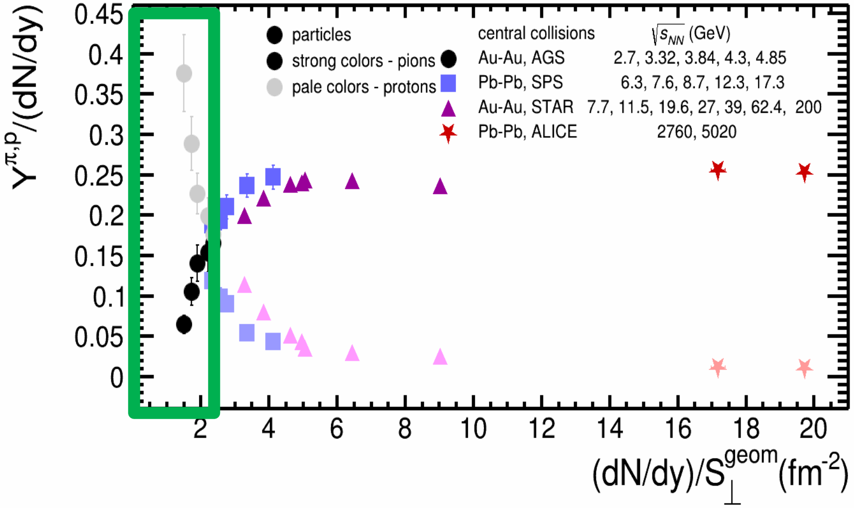
ALICE3

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



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

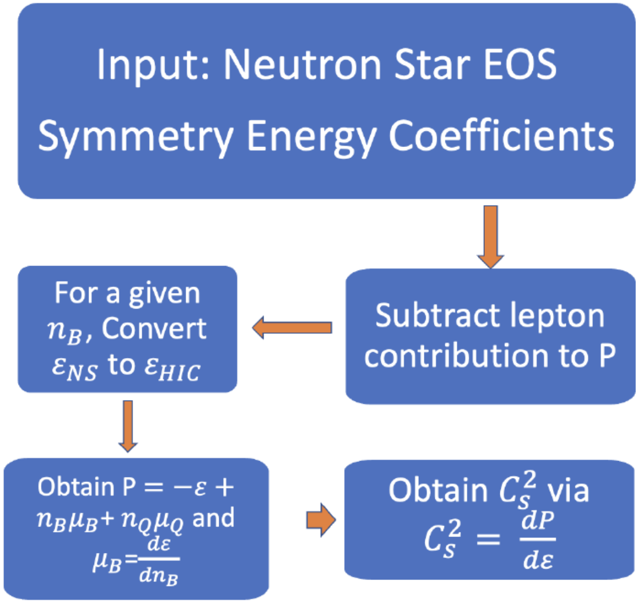




Structure in the speed of sound

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))

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

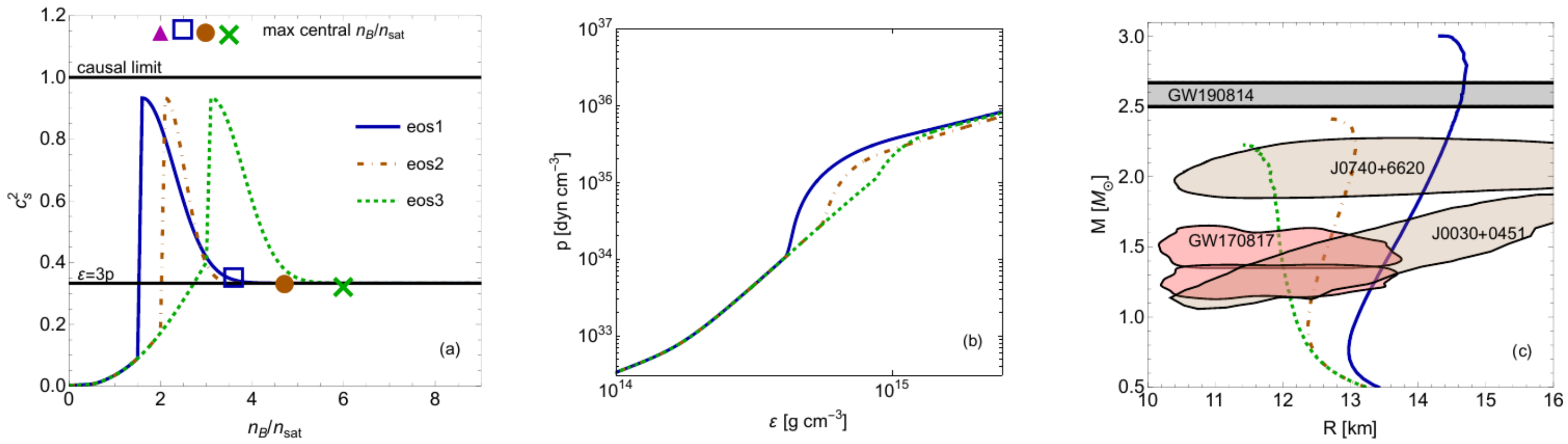
$$\varepsilon_{\rm HIC,asym} \;=\; \varepsilon_{\rm NS,QCD} - 4n_B\left[E_{\rm sym,sat} + \frac{L_{\rm sym,sat}}{3}\left(\frac{n_B}{n_{\rm sat}} - 1\right) + \frac{K_{\rm sym,sat}}{18}\left(\frac{n_B}{n_{\rm sat}} - 1\right)^2 + \frac{J_{\rm sym,sat}}{162}\left(\frac{n_B}{n_{\rm sat}} - 1\right)^3\right]$$

$$\times\;\left[\left(Y^{\rm const}_{Q,{\rm QCD}} - Y_{Q,{\rm QCD}}\right) + \left(Y^2_{Q,{\rm QCD}} - \left(Y^{\rm const}_{Q,{\rm QCD}}\right)^2\right)\right]$$

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

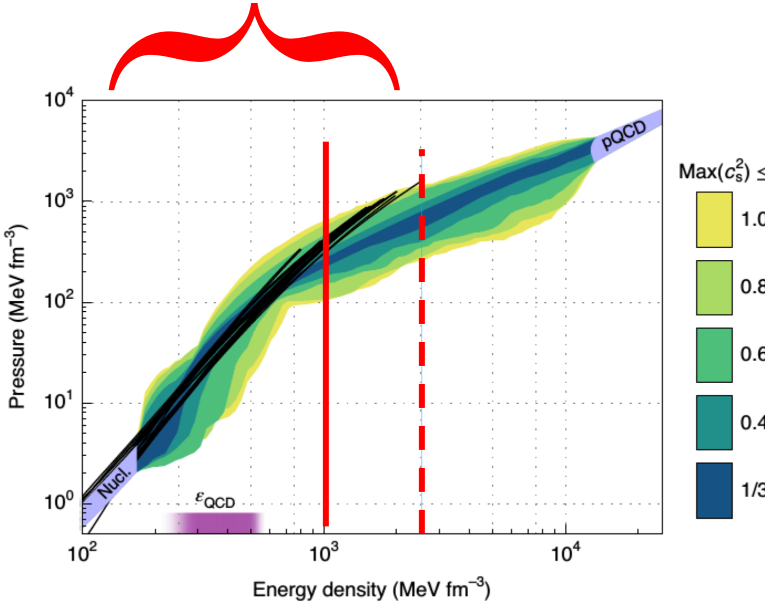
$$p = n_B^2\frac{d(\varepsilon/n_B)}{dn_B}$$

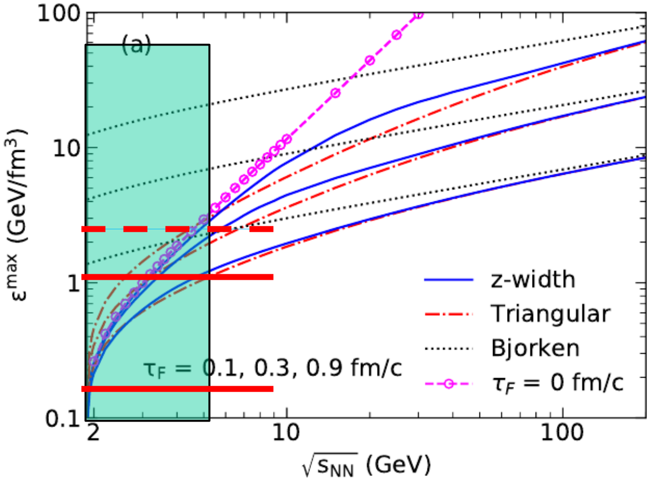
$$c_s^2 = \left(\frac{dp}{d\varepsilon}\right)_{T=0}$$



Evidence for quark-matter cores in massive neutron stars

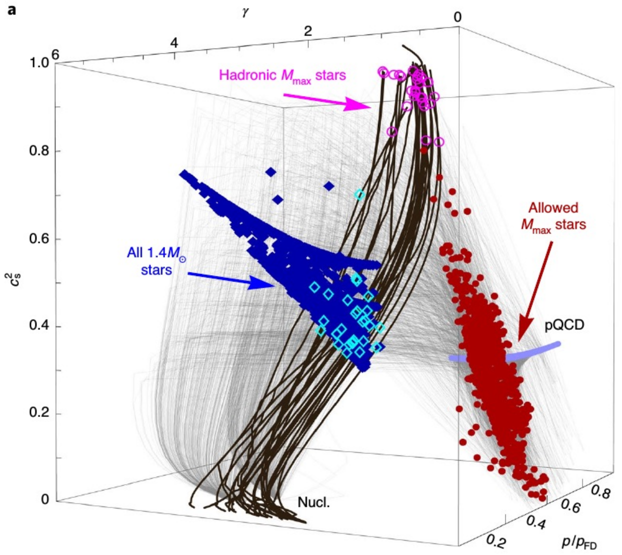
CBM coverage

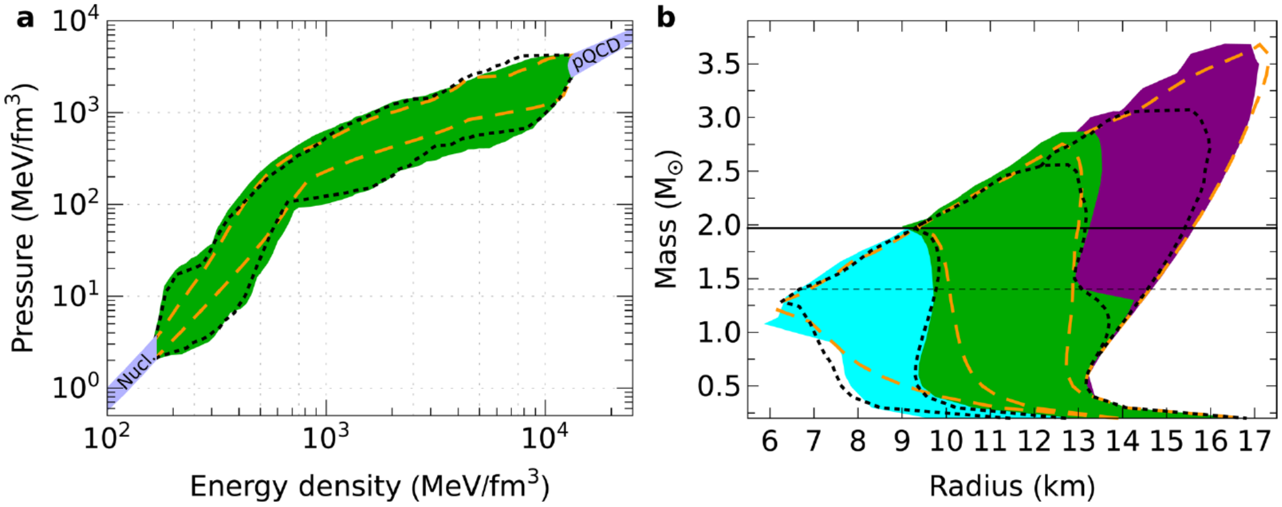




T. Mendenhall and Z.W. Lin, arXiv[nucl-th]2012.13825

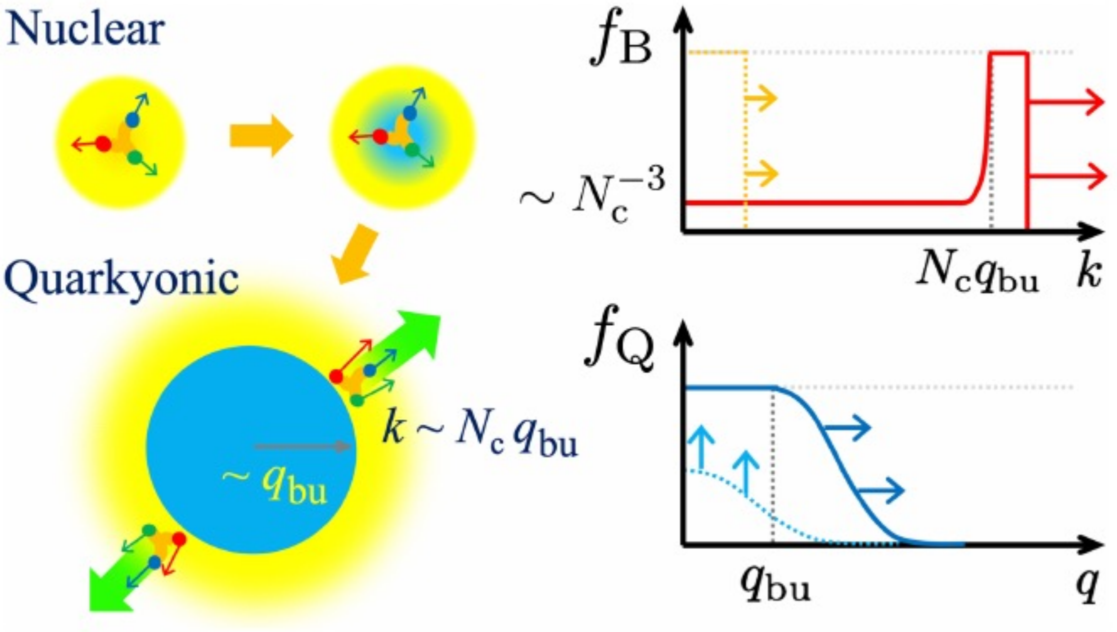
$\gamma = c_s^2\, \varepsilon/P = \varepsilon/P(dP/d\varepsilon)$
differentiate between quark and hadronic matter
$\gamma \leq 1.75$ - quark matter

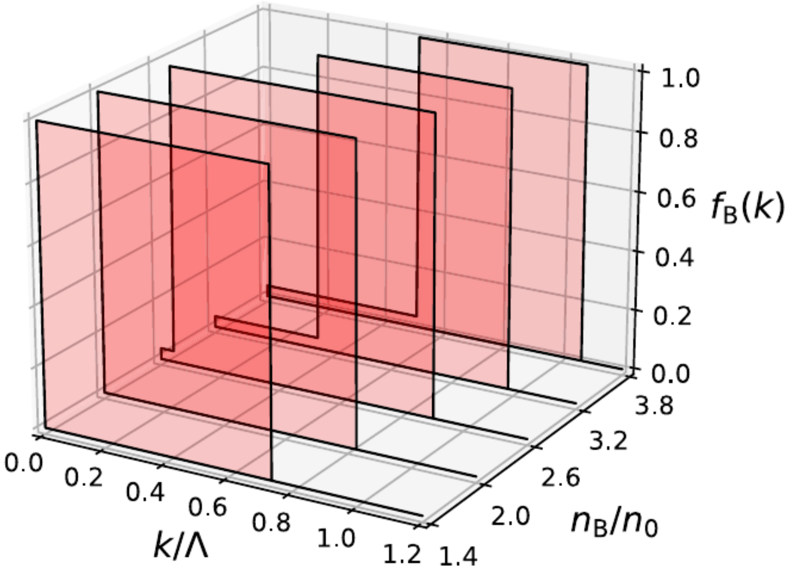


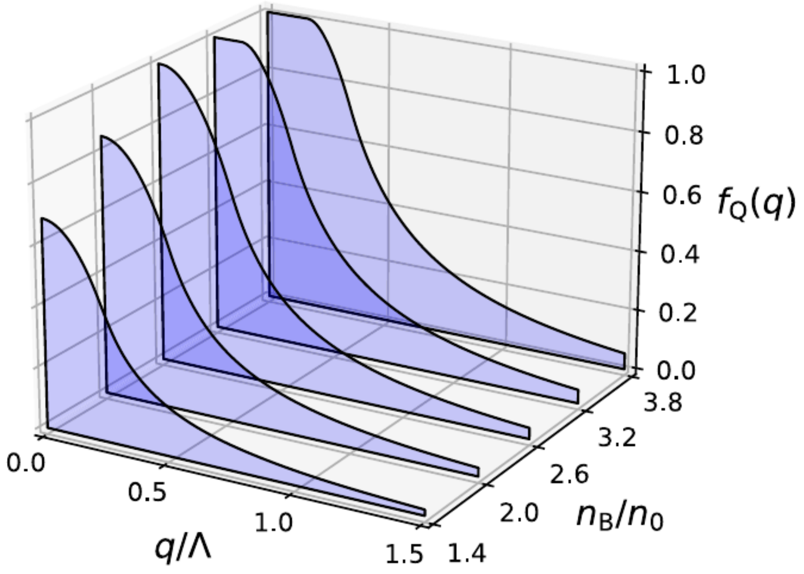


E. Annala et al, Nature Physics 16(2020)907

Quarkyonic Matter



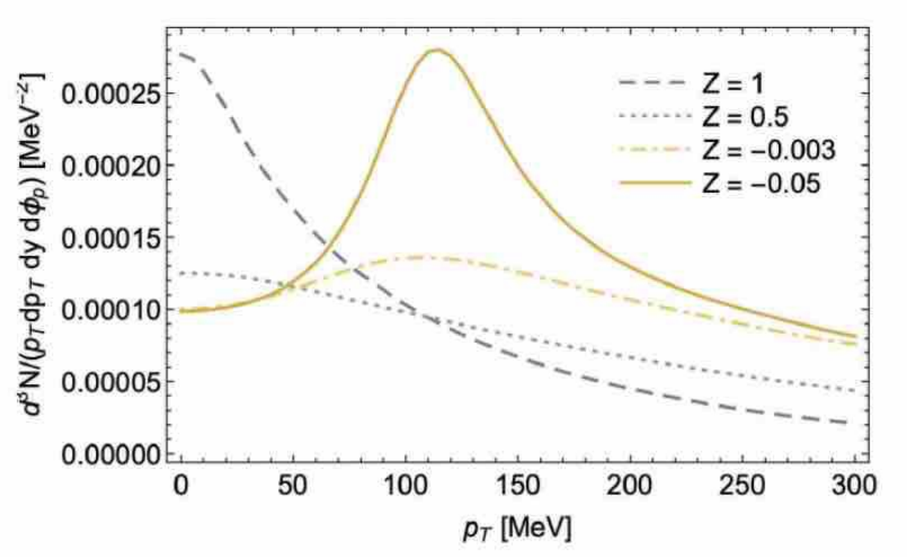




Y. Fujimoto et al., Phys.Rev.Lett 132(2024)112701

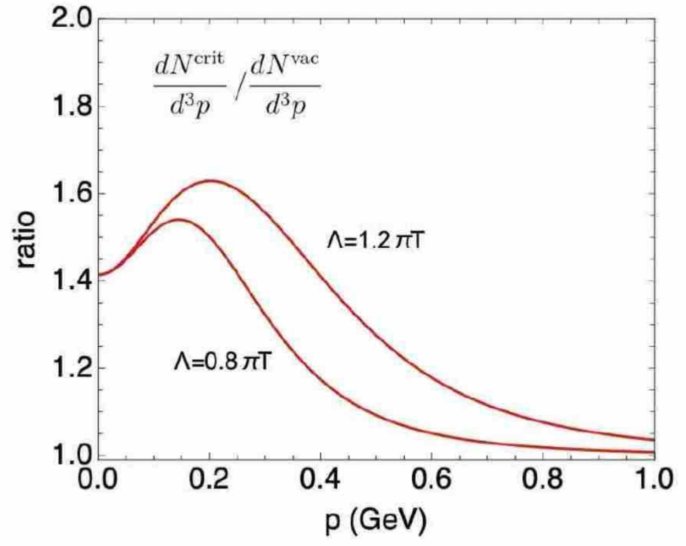
Large Baryon densities

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]

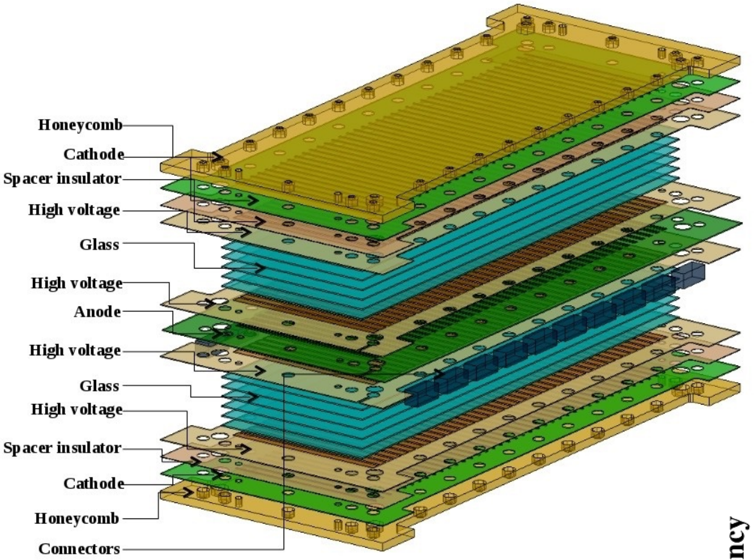


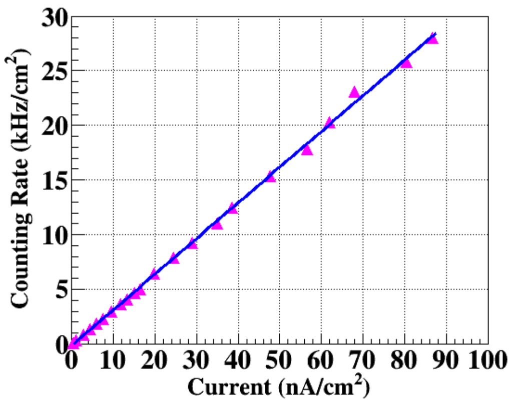
The enhanced yield of soft pions near the chiral critical point

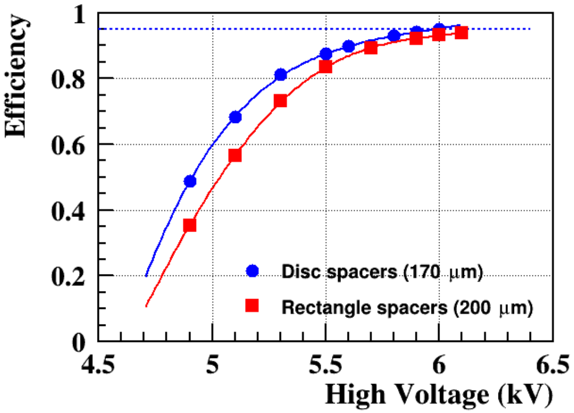
Multi-Strip Multi-Gap Resistive Plate Chambers - MSMGRPC

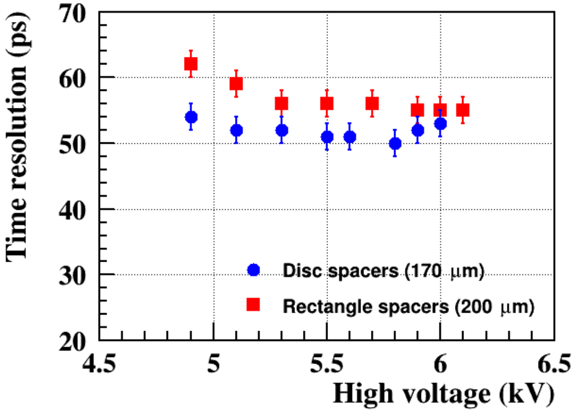
(Review and references: https://niham.nipne.ro/hpd_courier_no7_August_2024.pdf)

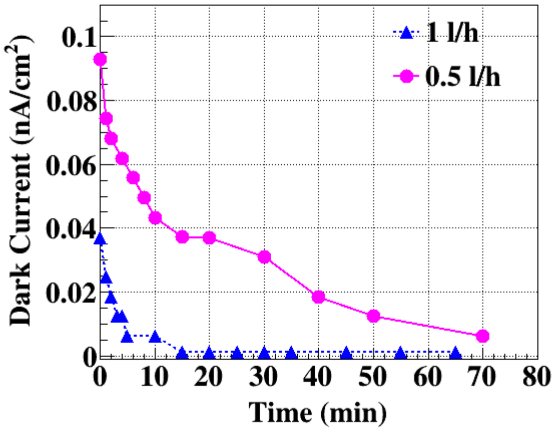
- Symmetric structure: 5 gaps x 2 stacks
- Gas gap thickness: 140 - 200 μm
- Discrete spacers
- Active area: strip length x 9 mm pitch x 32 strips
- Strip length:56/96/196 mm (MRPC1a/MRPC1b/MRPC1c)
- Resistive electrodes: ~1010 **Ω**cm, 0.7 mm (Chinese glass)
- Strip structure for Readout & HV electrodes
  matched signal transmission line impedance to the input of the FEE *D. Bartos et al., Rom. Journ. of Physics 63, 901 (2018)*
- Differential readout
- Direct flow through the gas gaps

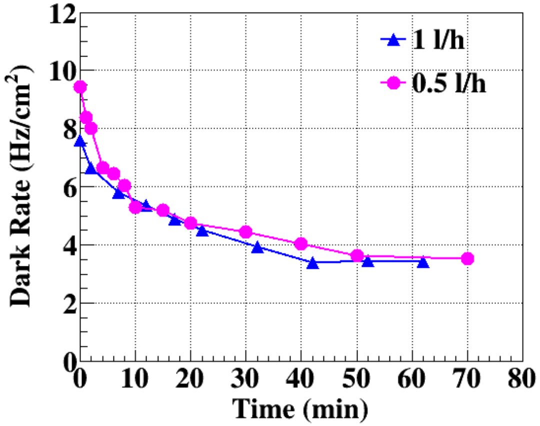






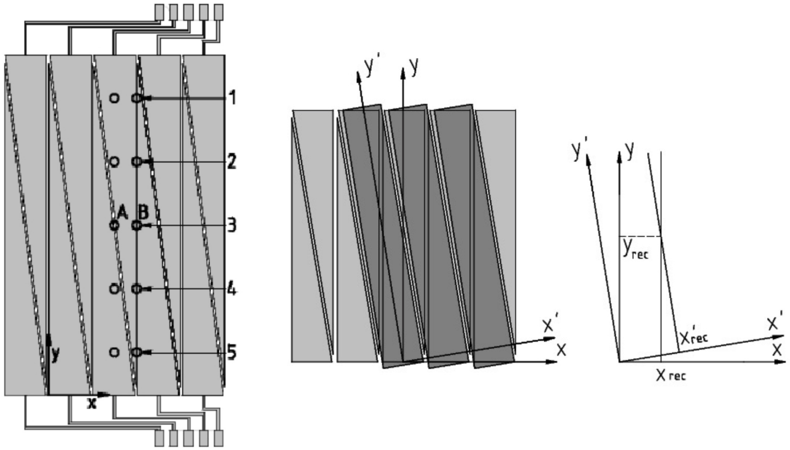


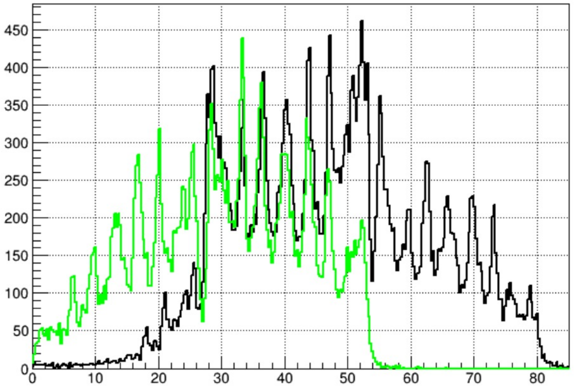


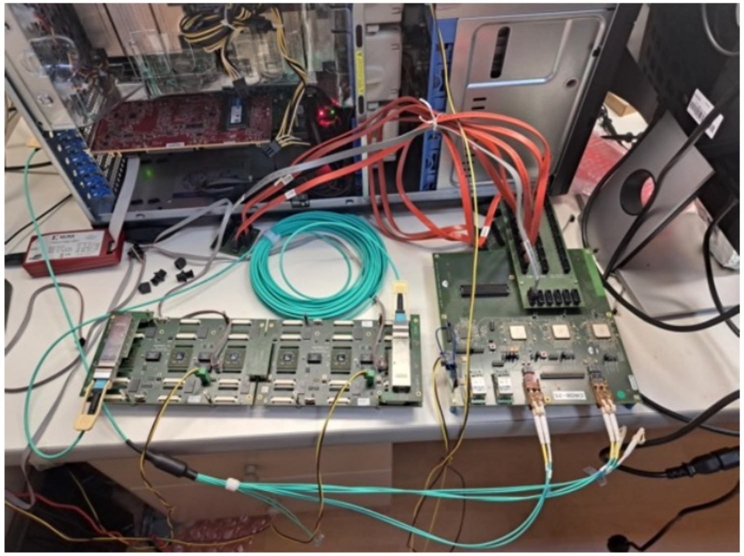


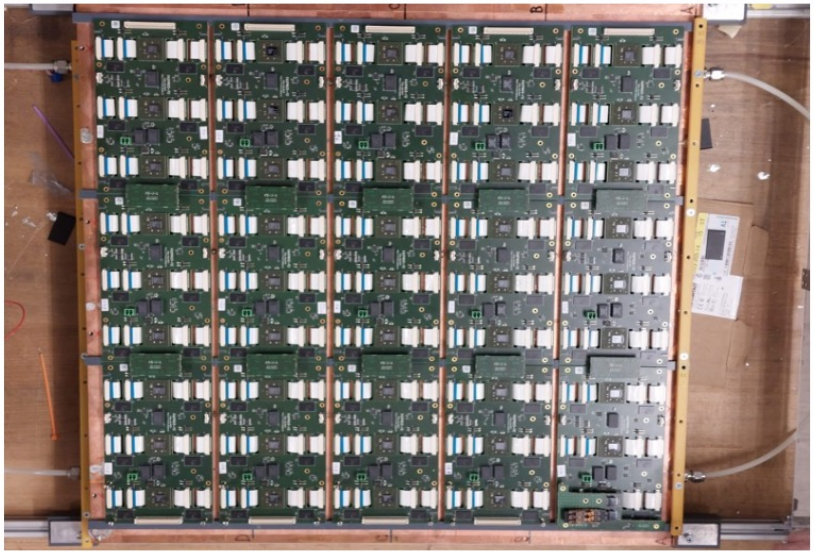
2D-MWPC (TRD)

(Review and references: https://niham.nipne.ro/hpd_courier_no7_August_2024.pdf)





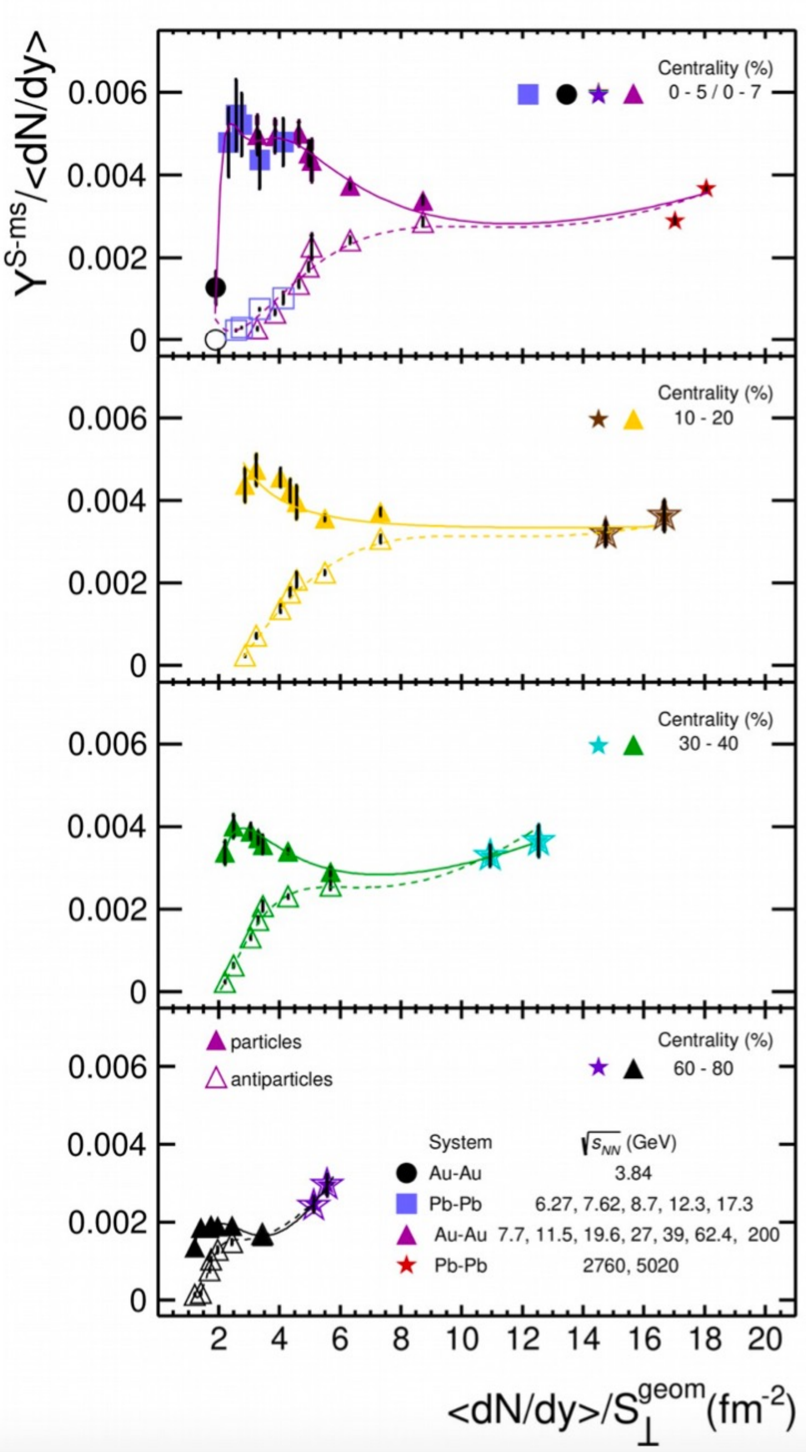




Concluding remark

"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


$Y^{S\text{-}ms}/\langle dN/dy\rangle$
0.006
0.004
0.002
0
Centrality (%)
0 - 5 / 0 - 7
Centrality (%)
10 - 20
Centrality (%)
30 - 40
Centrality (%)
60 - 80
particles
antiparticles
System
$\sqrt{s_{NN}}$ (GeV)
Au-Au 3.84
Pb-Pb 6.27, 7.62, 8.7, 12.3, 17.3
Au-Au 7.7, 11.5, 19.6, 27, 39, 62.4, 200
Pb-Pb 2760, 5020
2
4
6
8
10
12
14
16
18
20
$\langle dN/dy\rangle/S_{\perp}^{geom}(fm^{-2})$