Geometrical scaling for light flavor hadrons

Amelia Lindner[1,2], M. Petrovici[1,2] and A. Pop[1]

1. Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH)
2. Faculty of Physics, University of Bucharest

Outline

- Physics motivation
- $\sqrt{(dN/dy)/S_\perp}$ estimates
- The $\langle p_T \rangle / \sqrt{(dN/dy)/S_\perp}$ ratio
- $\langle p_T \rangle$ dependence on $\sqrt{(dN/dy)/S_\perp}$
- Blast-wave model fit parameters
- $\langle p_T \rangle$ - hadron mass dependence
- Parameters of the $\langle p_T \rangle$ - hadron mass dependence fits
- Summary and conclusions

Physics motivation

The European Physical Journal C ***71*** *(2011) 1699*

Energy dependence of the saturation scale and the charged multiplicity in pp and AA collisions

T. Lappi

Physical Review D ***83*** *(2011) 114001*

Gluon saturation and energy dependence of hadron multiplicity in pp and AA collisions at the LHC

E. Levin and A.H. Rezaeian

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

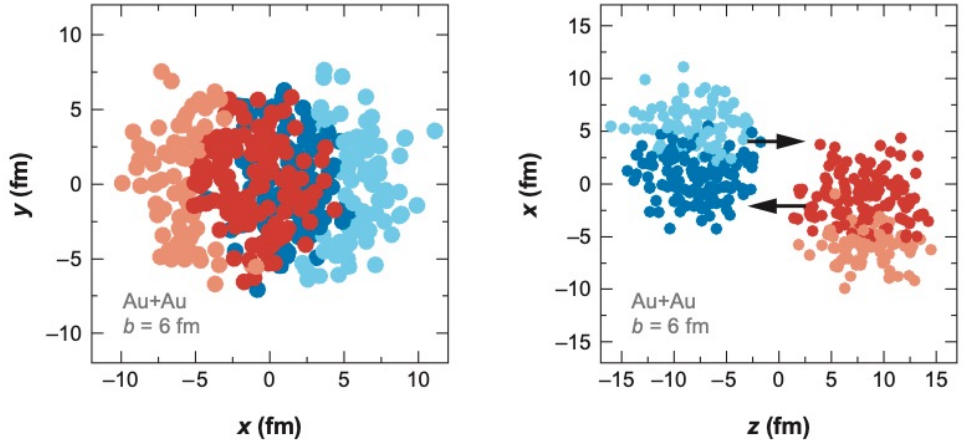
n – the number of charged particles that result from a gluon fragmentation

predict that $\langle p_T \rangle / \sqrt{(dN/dy)/S_\perp}$ *remains constant* / *decreases* as a function of centrality and collision energy

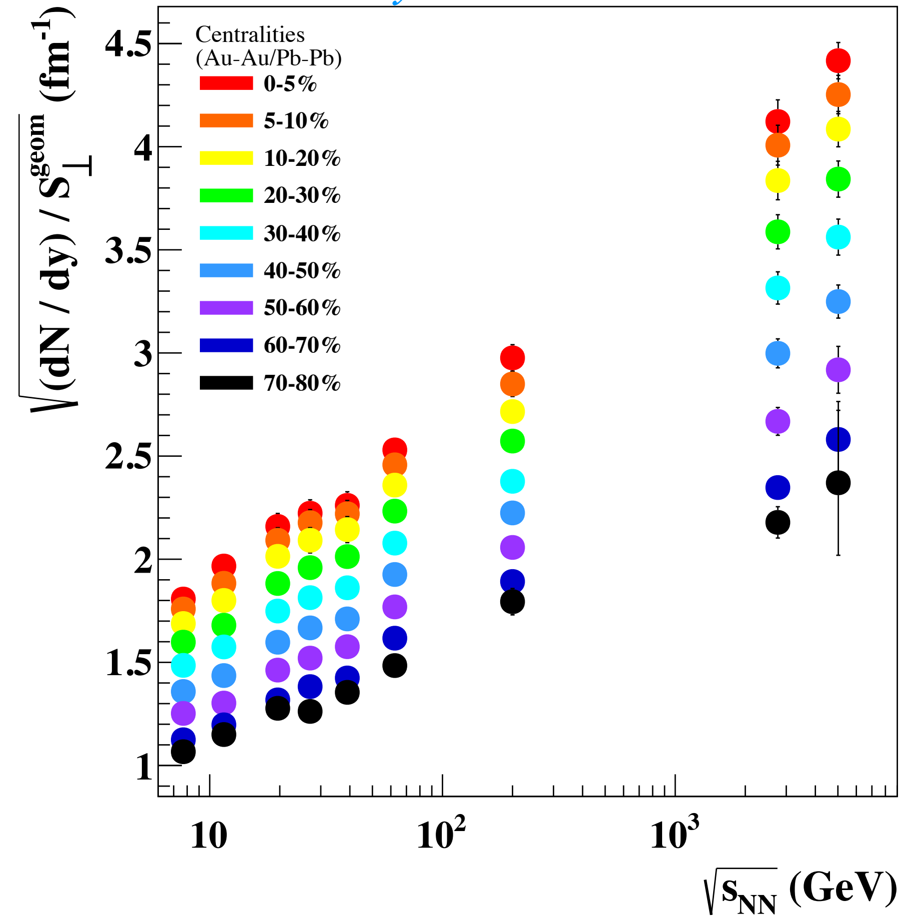
$\sqrt{(dN/dy)/S_\perp}$ estimates

$$dN/dy = \begin{cases} \text{Beam Energy Scan (BES): } \sqrt{s_{NN}} = 7.7 \text{ GeV up to 39 GeV (Au-Au)} \\ 1.5 \cdot dN/dy^{(\pi^+ + \pi^-)} + 2 \cdot dN/dy^{(K^+ + K^-, p + \bar{p}, \Xi^- + \bar{\Xi}^+)} + dN/dy^{(\Lambda + \bar{\Lambda})} \\ \sqrt{s_{NN}} = 62.4 \text{ and 200 GeV (Au-Au) - RHIC} \\ 1.5 \cdot dN/dy^{(\pi^+ + \pi^-)} + 2 \cdot dN/dy^{(K^+ + K^-, p + \bar{p}, \Xi^- + \bar{\Xi}^+)} + dN/dy^{(\Lambda + \bar{\Lambda}, \Omega^- + \bar{\Omega}^+)} \\ \text{LHC energies (pp and Pb-Pb):} \\ 1.5 \cdot dN/dy^{(\pi^+ + \pi^-)} + 2 \cdot dN/dy^{(p + \bar{p}, \Xi^- + \bar{\Xi}^+)} + dN/dy^{(K^+ + K^-, K^0_s + \bar{K}^0_s, \Lambda + \bar{\Lambda}, \Omega^- + \bar{\Omega}^+)} \end{cases}$$

$S_\perp$ for A-A collisions - estimated based on the Glauber MC approach



Heavy-ion collisions



M. L. Miller *et al.*, Annu. Rev. Nucl. Part. Sci. 57 (2007) 205
M. Petrovici *et al.*, Phys. Rev. C98 (2018) 024904

$\sqrt{(dN/dy)/S_\perp}$ estimates

pp collisions

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

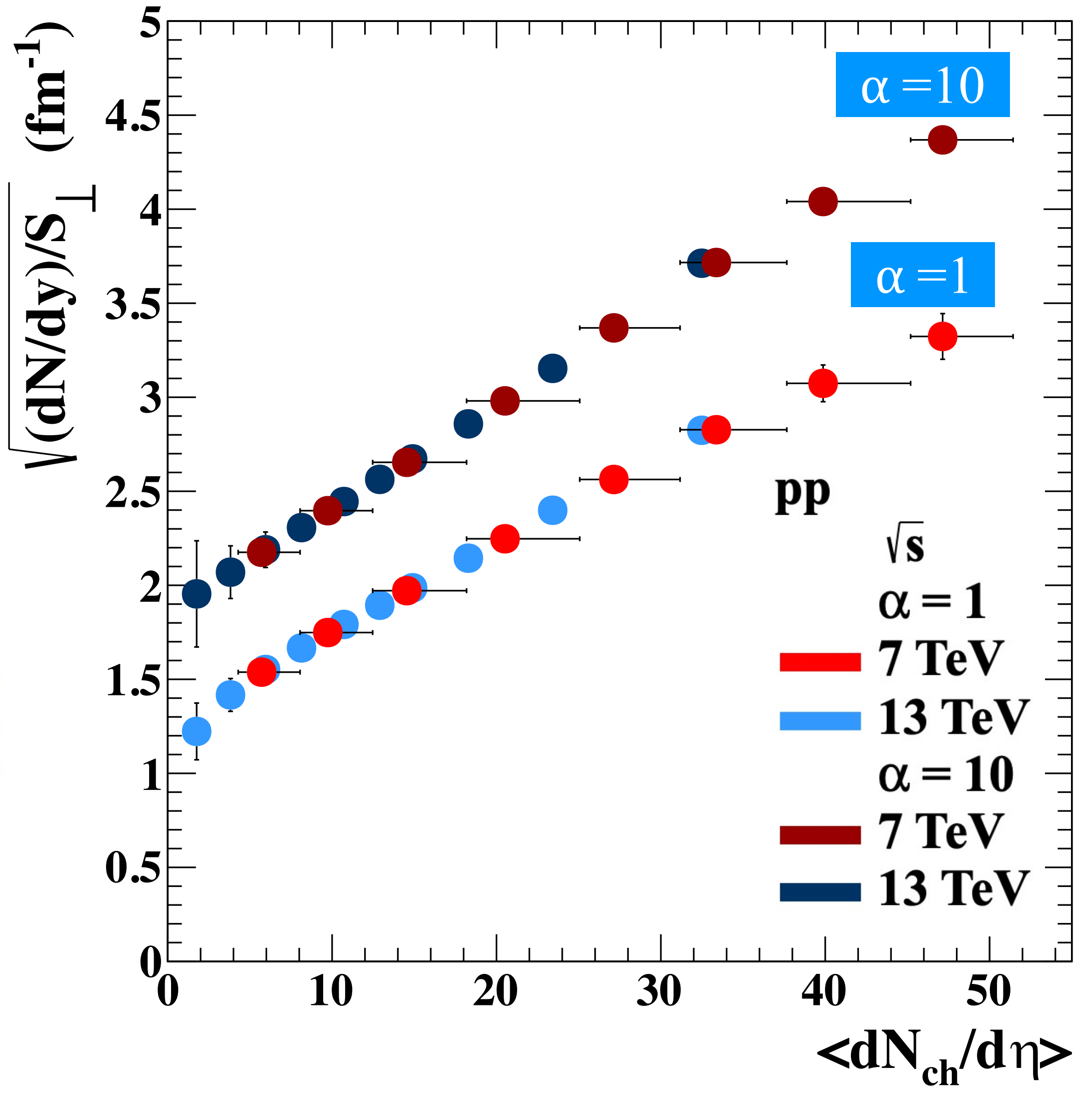
R_{pp} - *the maximum radius for which* $\varepsilon > \alpha\Lambda_{QCD}^4$

ε – *energy density;* R_{pp}=1fm $\cdot f_{pp}(x)$

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

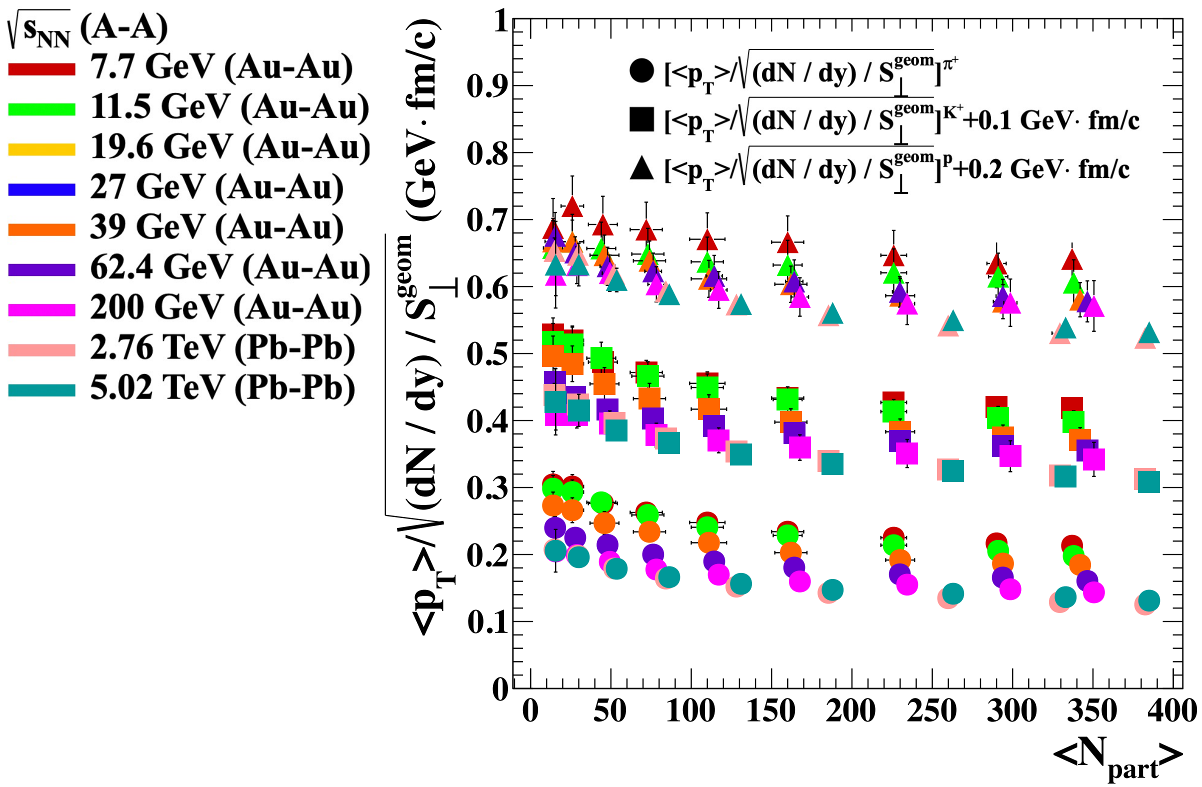
α=10: $f_{pp} = \begin{cases} -0.018 + 0.3976x + 0.095x^2 - 0.028x^3 & \text{if } x < 3.4 \\ 1.17 & \text{if } x \geq 3.4 \end{cases}$

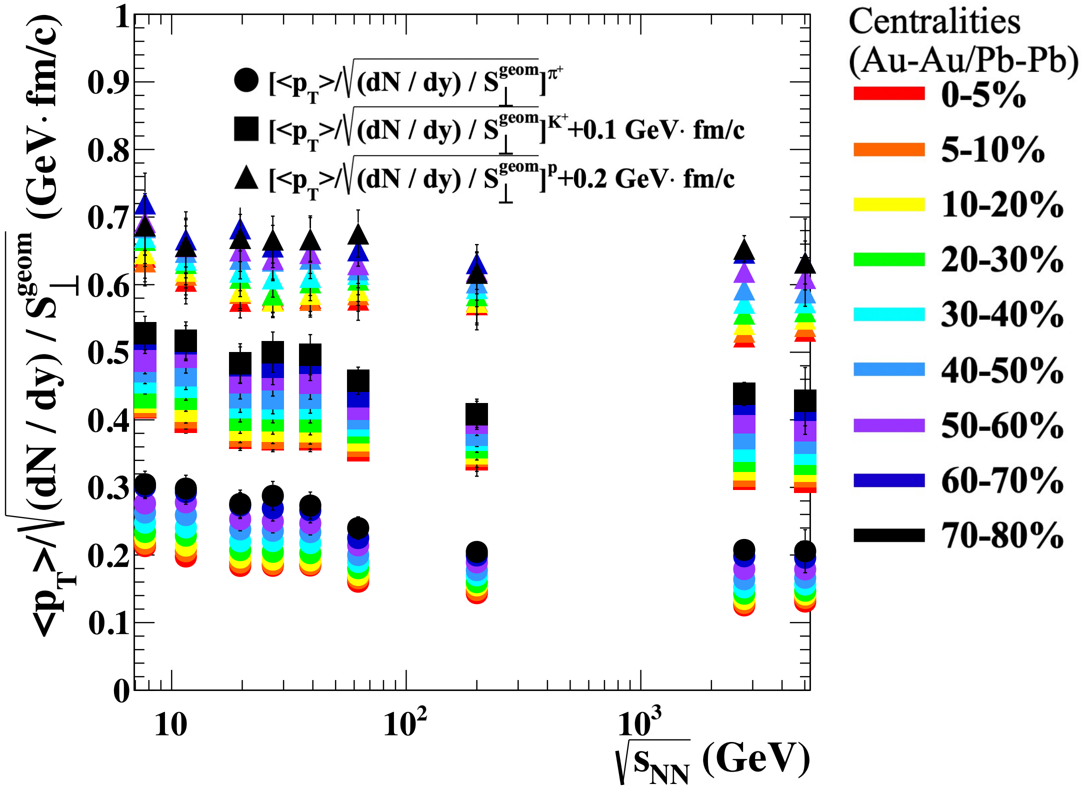
with $x = (dN_g/dy)^{1/3}$ *and* $dN_g/dy \cong dN/dy$



L. McLerran *et al.*, Nucl. Phys. A 916(2013) 210
B. Schenke *et al.*, Phys. Rev. C 86 (2012) 034908
ALICE Coll., Eur. Phys. J. C80 (2020) 167
M. Petrovici *et al.*, Phys. Rev. C98 (2018) 024904

The $<p_T>/\sqrt{(dN/dy)/S_\perp}$ ratio





The experimental results confirm that the $<p_T>/\sqrt{(dN/dy)/S_\perp}$ ratio

decreases with

centrality ($<N_{part}>$) and *collision energy* ($\sqrt{s_{NN}}$) *for a given centrality* for π^+, K^+, p

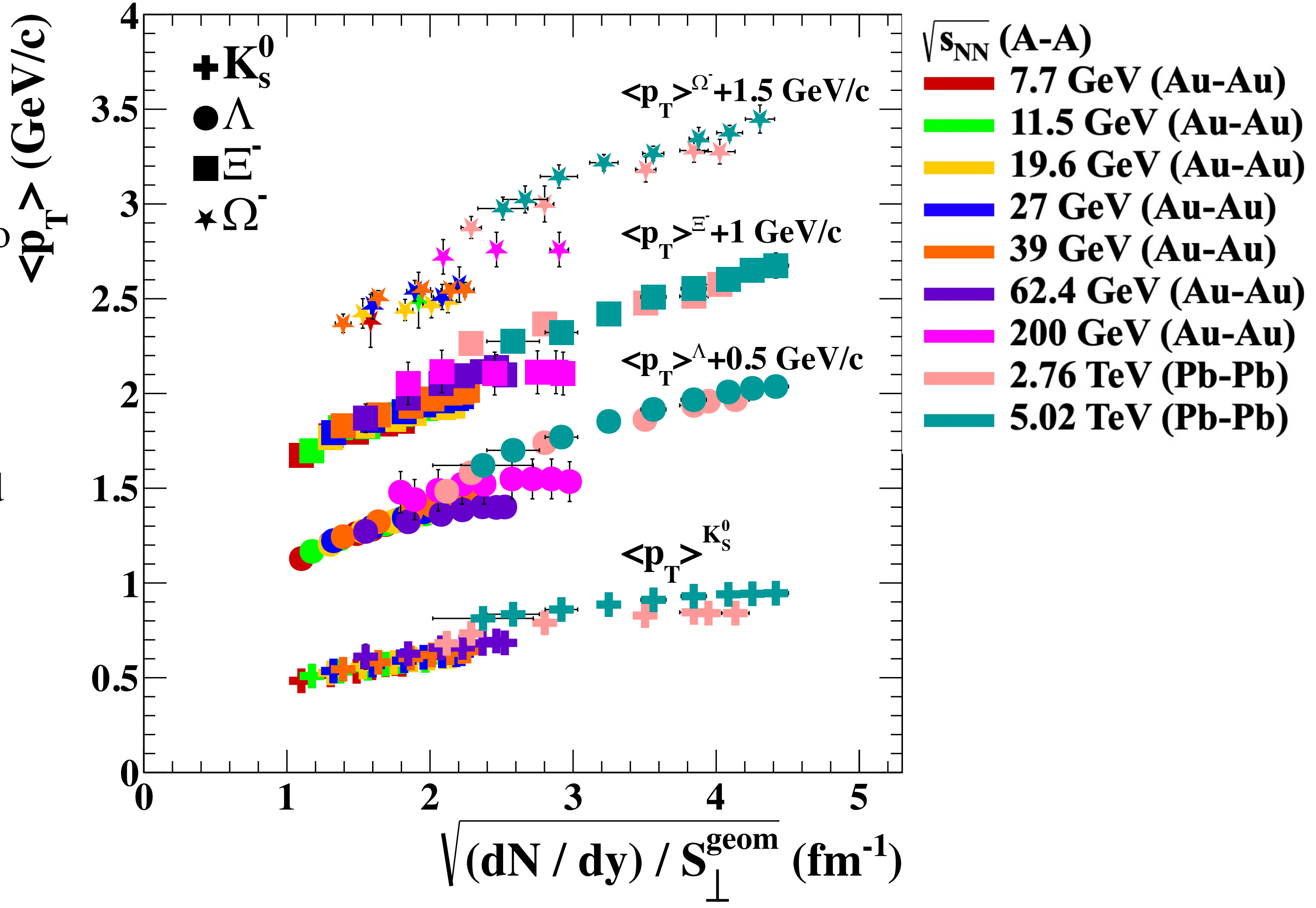
[Phys. Rev. C98 (2018) 024904]

$\langle p_T \rangle$ dependence on $\sqrt{(dN/dy)/S_\perp}$

Heavy-ion collisions

strange and multi-strange hadrons

- a good scaling is observed for RHIC energies, up to 200 GeV, with a small deviation of Λ at 62.4 GeV
- for 200 GeV, Λ, Ξ^- and Ω^- show a very small dependence on the scaling variable
- a good scaling is also evidenced at LHC energies
- $\langle p_T \rangle / \sqrt{(dN/dy)/S_\perp}$ decreases with centrality and collision energy for all species



STAR Collaboration, Phys. Rev. C102 (2020) 034909
M.M. Aggarwal et al. (STAR Coll.), Phys. Rev. C83 (2011) 024901
M. Estienne et al., (STAR Coll.) J. Phys. G31 (2005)S873
D. Albuquerque, CERN-THESIS-2019-135
Z. Yin (ALICE Coll.), Int. J. Mod. Phys.: Conference Series 29 (2014) 1460228
M. Sefcik (ALICE Collaboration), SQM, 10-15 July 2017, Utrecht, Netherlands

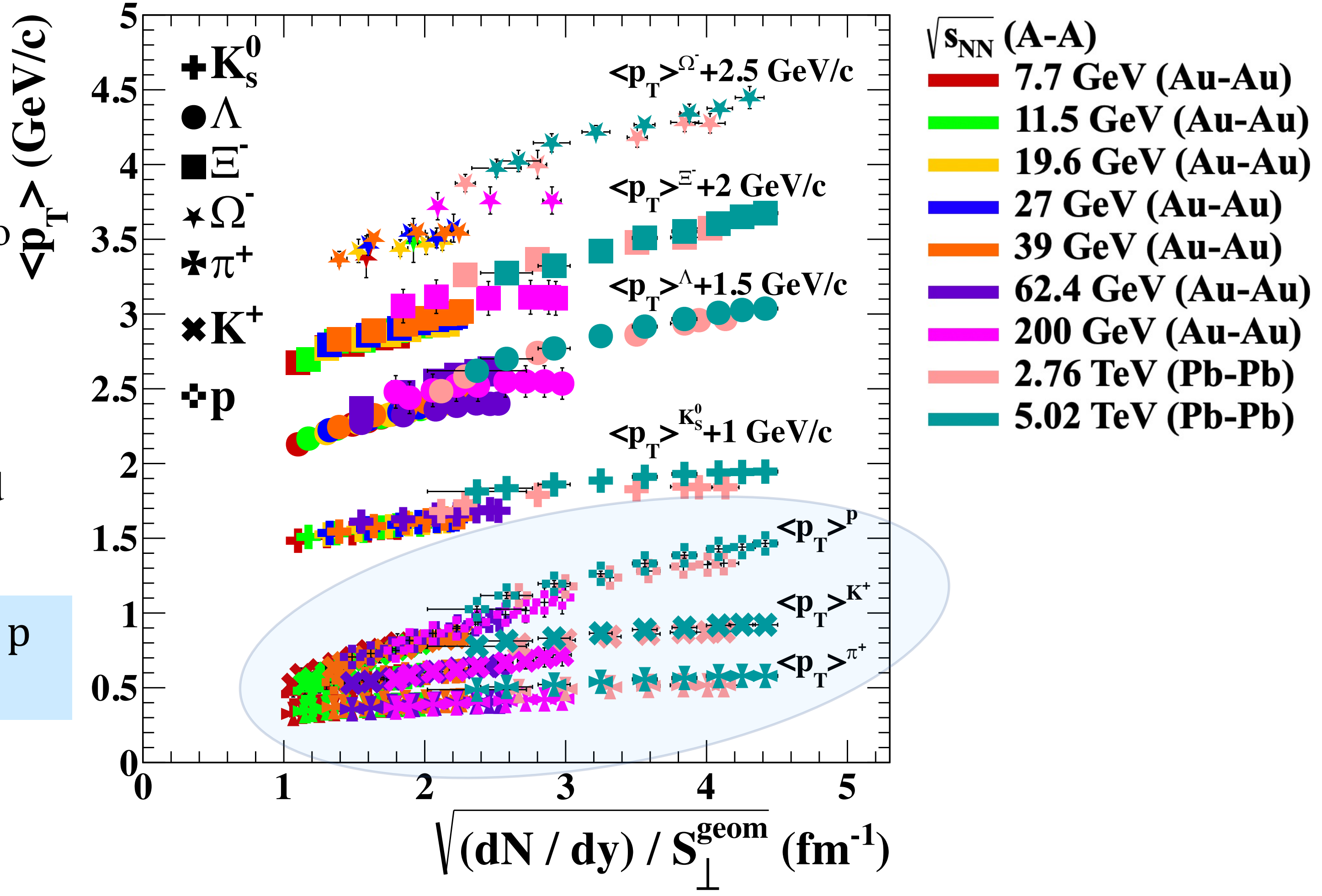
$\langle p_T \rangle$ dependence on $\sqrt{(dN/dy)/S_\perp}$

Heavy-ion collisions

π^+, K^+, p vs. strange and multi-strange hadrons

- a good scaling is observed for RHIC energies, up to 200 GeV, with a small deviation of Λ at 62.4 GeV
- for 200 GeV, Λ, Ξ^- and Ω^- show a very small dependence on the scaling variable
- a good scaling is also evidenced at LHC energies
- $\langle p_T \rangle / \sqrt{(dN/dy)/S_\perp}$ decreases with centrality and collision energy for all species

A very good scaling is also evidenced for π^+, K^+, p
[Phys. Rev. C98 (2018) 024904]



STAR Collaboration, Phys. Rev. C102 (2020) 034909
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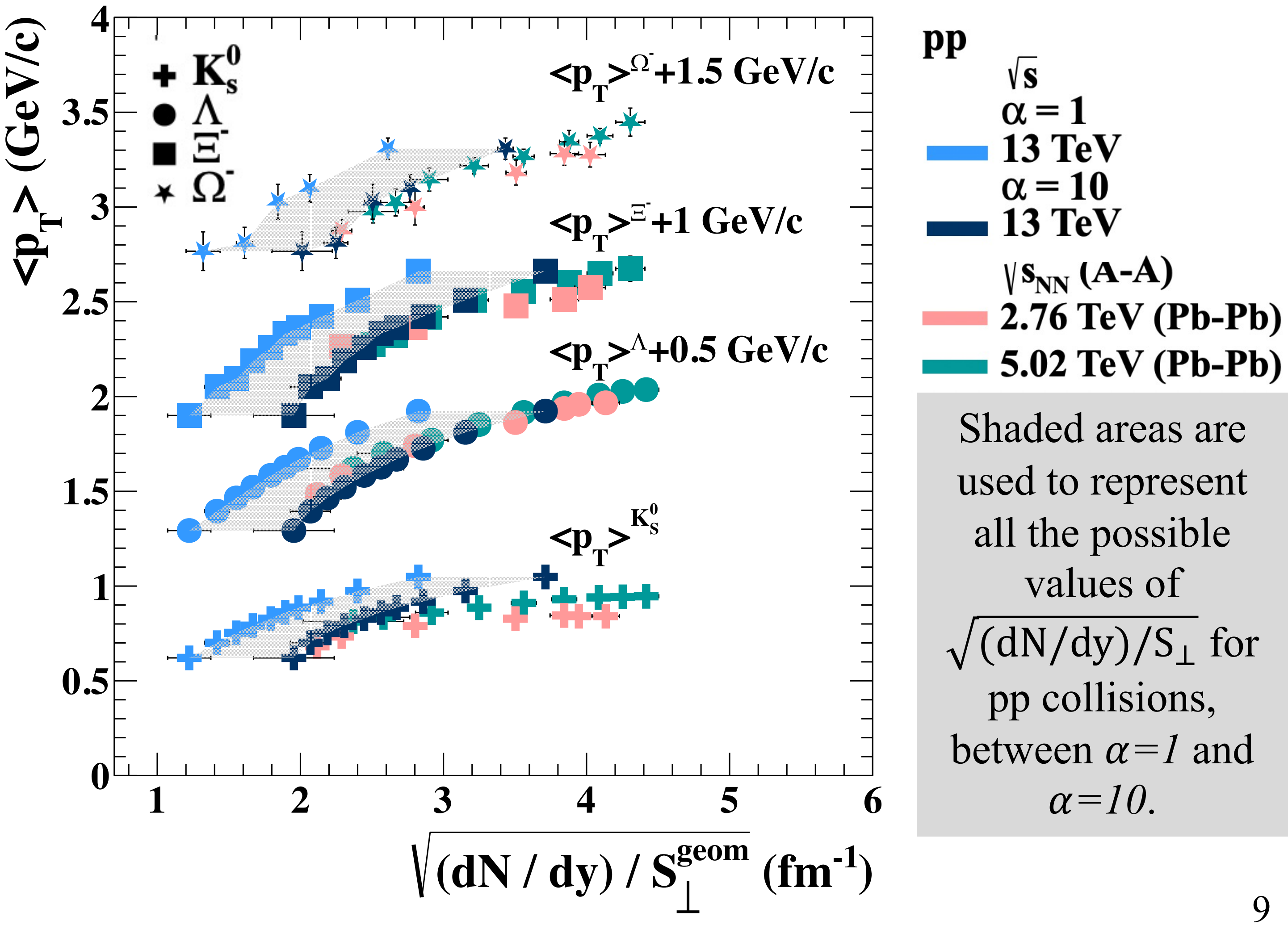
$<p_T>$ dependence on $\sqrt{(dN/dy)/S_\perp}$

pp vs. AA @ LHC energies

strange and multi-strange hadrons

- an excellent scaling between Pb-Pb collisions and pp collisions *(α=10)* at LHC energies is evidenced for Λ, Ξ^- and Ω^-
- $<p_T>$ values for K^0_S are slightly larger for pp collisions than for Pb-Pb collisions towards higher values of the scaling variable



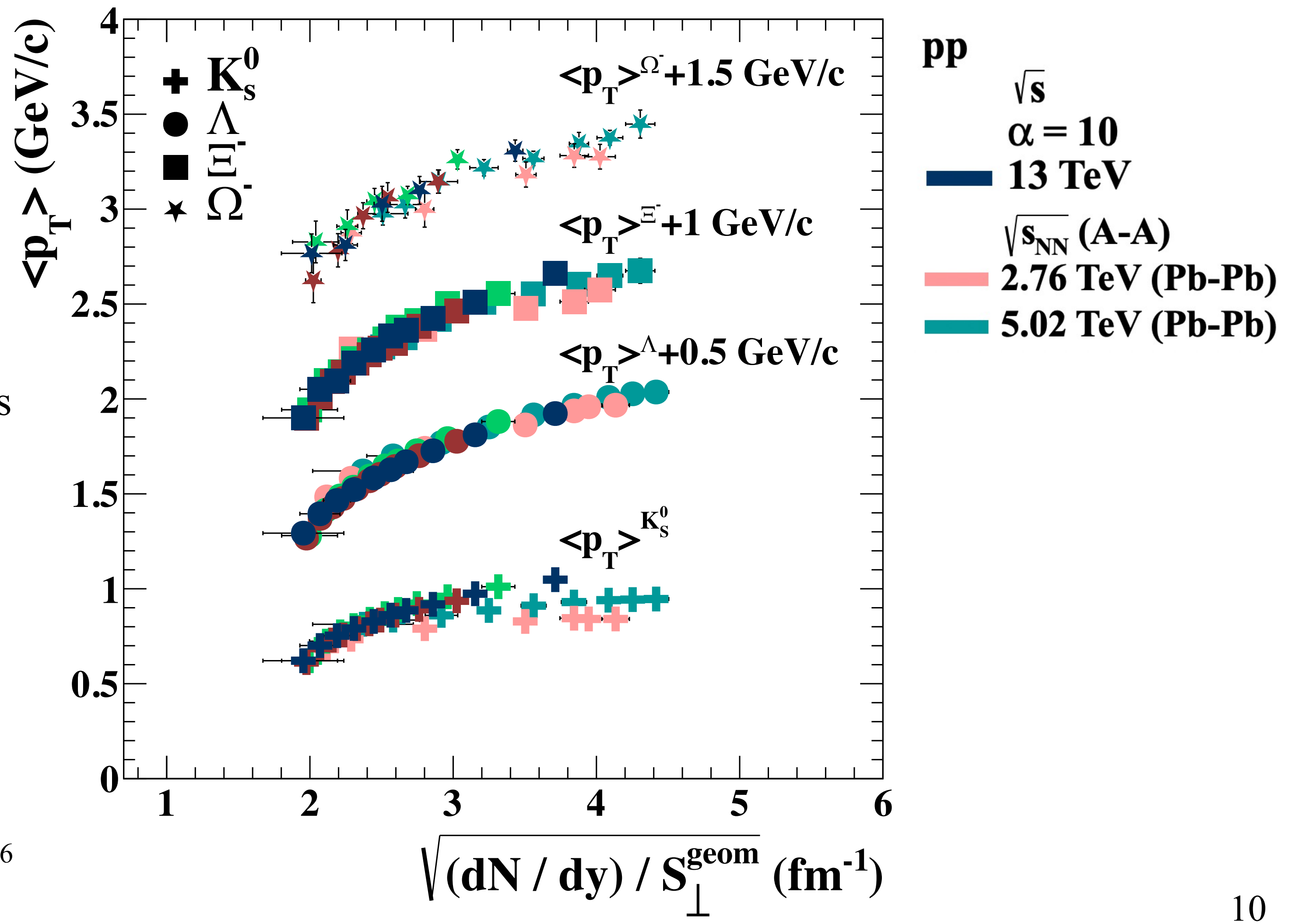
Shaded areas are used to represent all the possible values of $\sqrt{(dN/dy)/S_\perp}$ for pp collisions, between α=*1* and α=*10*.

ALICE Coll., Eur. Phys. J. C80 (2020) 167
G. Béncedi (ALICE Coll.), QM, 14-19 May 2018, Venice, Italy
S. Acharya et al. (ALICE Collaboration), Phys. Rev. C 99 (2019) 024906
M. Petrovici et al., Phys. Rev. C98 (2018) 064903
C. Andrei, ALICE Collaboration, Nucl. Phys. A 931 (2014) c888

$\langle p_T \rangle$ dependence on $\sqrt{(dN/dy)/S_{\perp}}$

pp vs. AA @ LHC energies

strange and multi-strange hadrons



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- $\langle p_T \rangle$ values for K^0_S are slightly larger for pp collisions than for Pb-Pb collisions towards higher values of the scaling variable

ALICE Coll., Eur. Phys. J. C80 (2020) 167
G. Béncedi (ALICE Coll.), QM, 14-19 May 2018, Venice, Italy
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M. Petrovici et al., Phys. Rev. C98 (2018) 064903
C. Andrei, ALICE Collaboration, Nucl. Phys. A 931 (2014) c888

Blast-wave model fit parameters

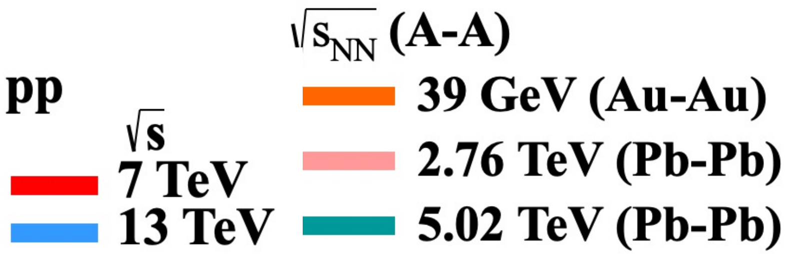
Average transverse flow velocity (<β$_T$>) & kinetic freeze-out temperature (T$_{kin}$)

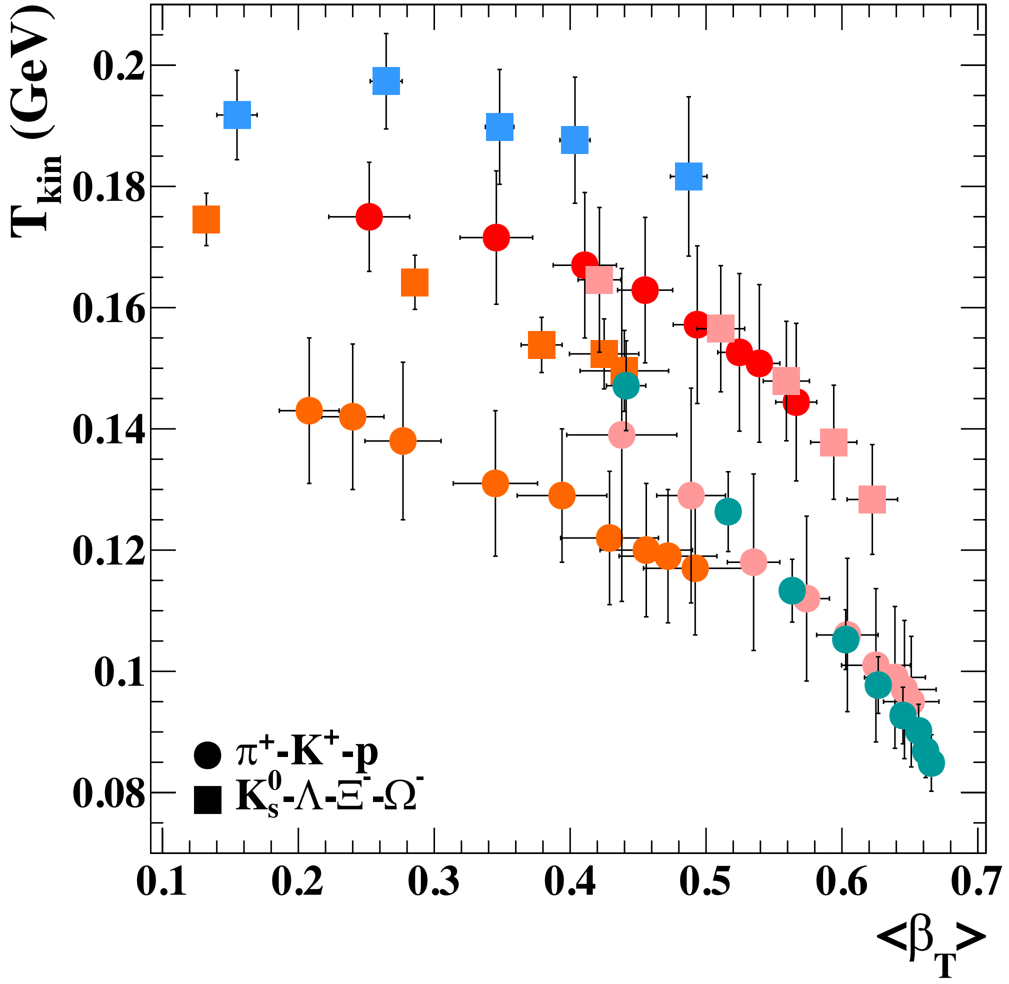
Boltzmann-Gibbs Blast Wave expression

$$\frac{1}{2\pi p_T}\frac{d^2N}{dydp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T cosh\rho}{T_{kin}}\right)$$

with $\rho = tanh^{-1}\beta_T$ and $\beta_T = \beta_s \left(\frac{r}{R}\right)^n$

E. Schnedermann *et al.,* Phys. Rev. C 48 (1993) 2462

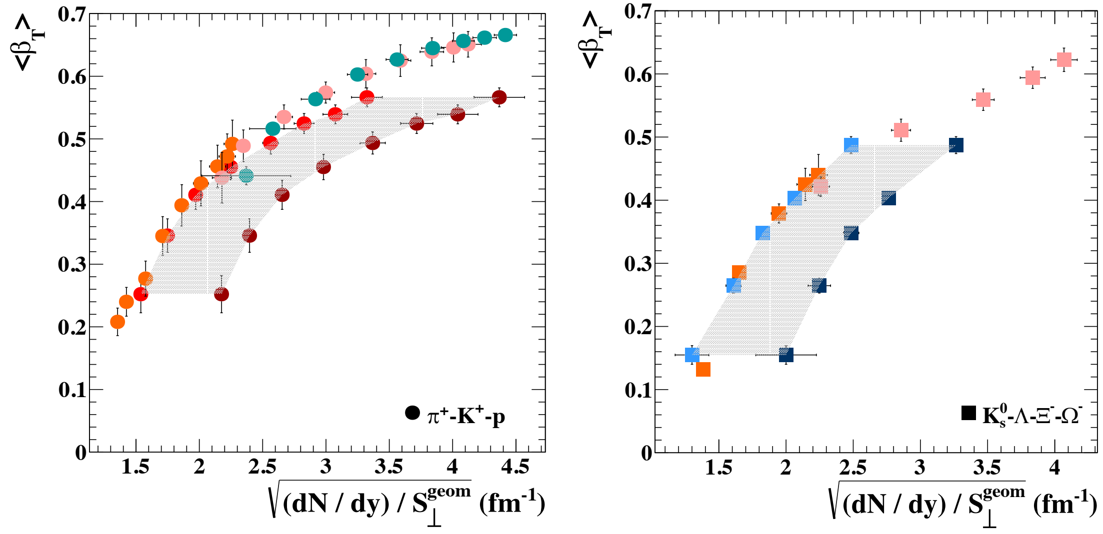




B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. C79 (2009) 034909
L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. C96 (2017) 044904
B. Abelev *et al.* (ALICE Collaboration), Phys. Rev. C 88 (2013) 044910
R. Pregenella (ALICE Collaboration), in International Conference on Strangeness in Quark Matter, SQM, 10-15.10.2017, Utrecht, the Netherlands
C. Andrei, ALICE Collaboration, Nucl. Phys. A 931 (2014) c888

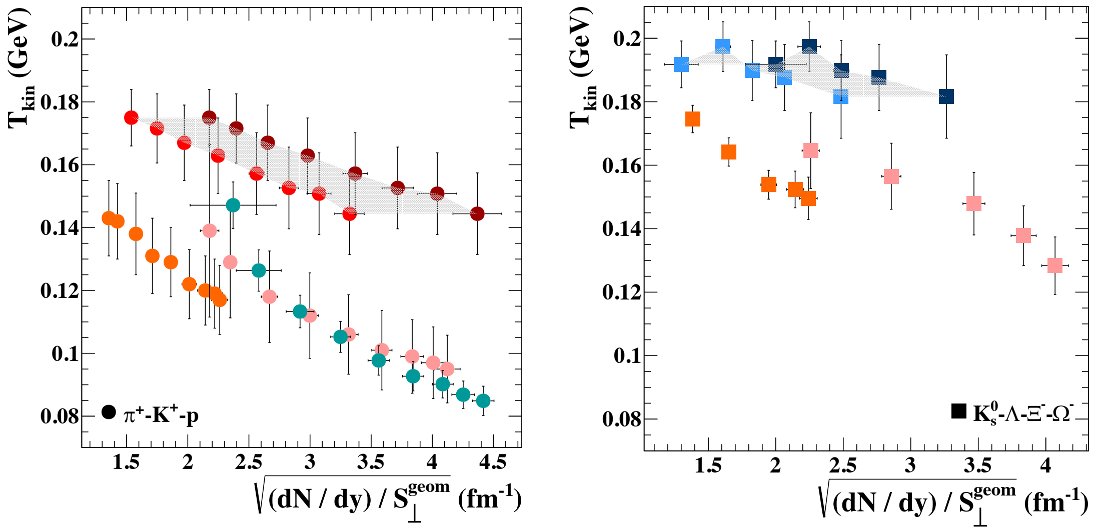
Blast-wave model fit parameters

Average transverse flow velocity ($<\beta_T>$) & kinetic freeze-out temperature (T_{kin})



In both cases ($\pi^+ - K^+ - p$ and $K_S^0 - \Lambda - \Xi^- - \Omega^-$) a very good scaling is evidenced between A-A and pp collisions (for α=1). Systematically lower values for strange and multi-strange hadrons than for $\pi^+ - K^+ - p$ are evidenced.

T_{kin} decreases towards higher values of $\sqrt{(dN/dy)/S_\perp}$. For $K_S^0 - \Lambda - \Xi^- - \Omega^-$, T_{kin} shows systematically higher values than in the case of $\pi^+ - K^+ - p$.



Shaded areas are used to represent all the possible values of $\sqrt{(dN/dy)/S_\perp}$ for pp collisions, between *α=1* and *α=10*.

pp

$\sqrt{s}$

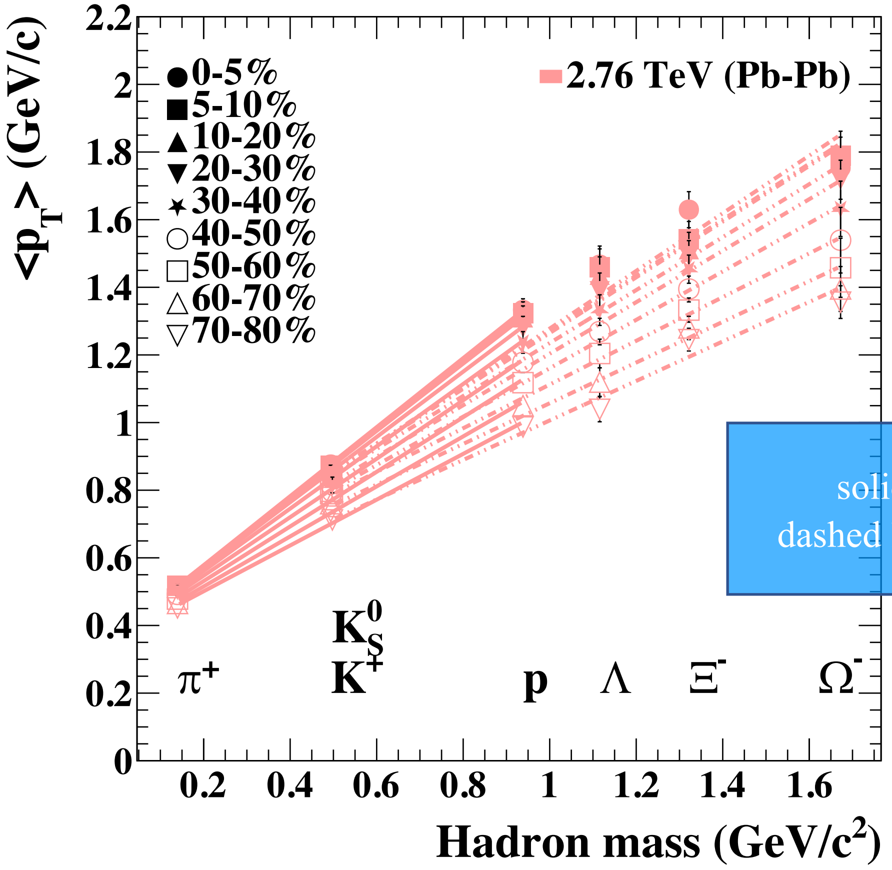
α = 1	**α = 10**
7 TeV	**7 TeV**
13 TeV	**13 TeV**

$\sqrt{s_{NN}}$ (A-A)

39 GeV (Au-Au)
2.76 TeV (Pb-Pb)
5.02 TeV (Pb-Pb)

$<p_T>$ - hadron mass dependence

π^+, K^+, p vs. strange and multi-strange hadrons

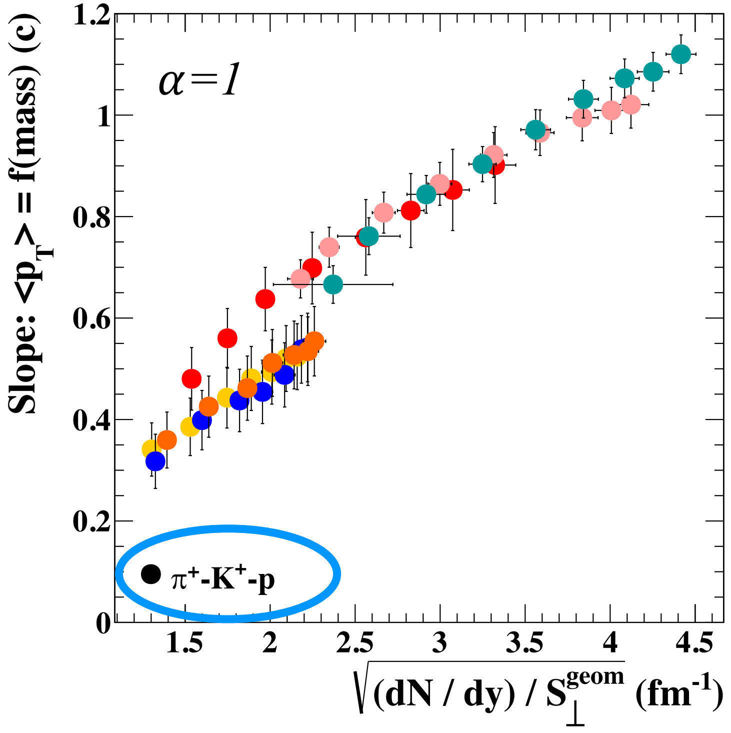


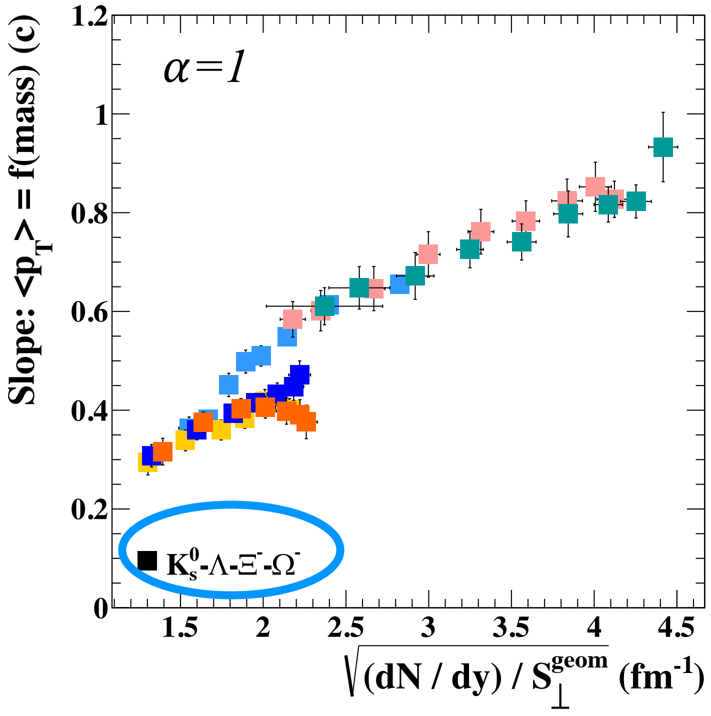
Linear fits:
solid line: $\pi^+ - K^+ - p$
dashed line: $K_S^0 - \Lambda - \Xi^- - \Omega^-$

This studies were performed for Au-Au collisions at BES energies ($\sqrt{s_{NN}}$ = 19.6, 27 and 39 GeV), for Pb-Pb collisions ($\sqrt{s_{NN}}$ = 2.76 *(the above example)* and 5.02 TeV) and pp collisions ($\sqrt{s}$ = 7 and 13 TeV) at LHC energies.

Parameters of the <p_T>- hadron mass dependence fits

Slope





- in both cases ($\pi^+ - K^+ - p$ and $K_S^0 - \Lambda - \Xi^- - \Omega^-$), very good scaling between Pb-Pb and pp collisions *(α=1)* is evidenced
- an offset between BES energies and LHC energies is present
- the slopes corresponding to $K_S^0 - \Lambda - \Xi^- - \Omega^-$ are systematically lower than for $\pi^+ - K^+ - p$

pp

$\sqrt{s}$

α = 1

7 TeV

13 TeV

$\sqrt{s_{NN}}$ (A-A)

19.6 GeV (Au-Au)

27 GeV (Au-Au)

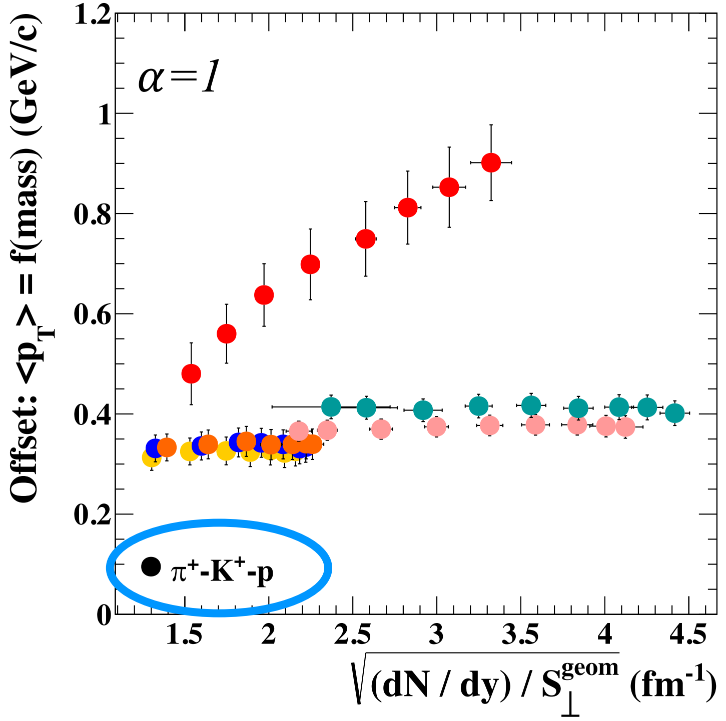
39 GeV (Au-Au)

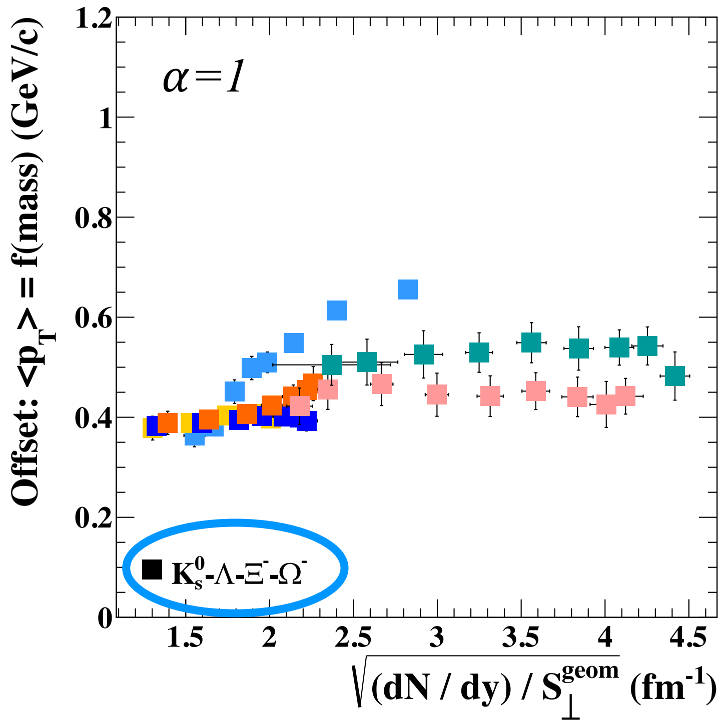
2.76 TeV (Pb-Pb)

5.02 TeV (Pb-Pb)

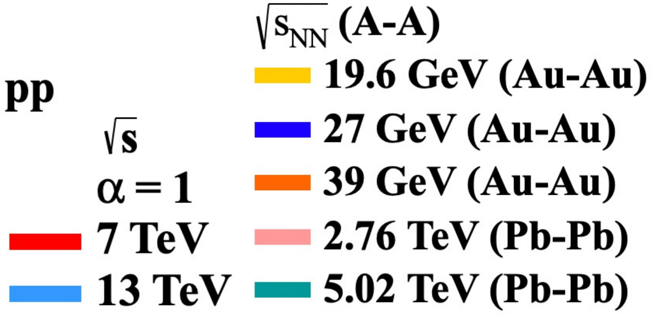
Parameters of the <p_T>- hadron mass dependence fits

Offset





- in both cases ($\pi^+ - K^+ - p$ and $K_S^0 - \Lambda - \Xi^- - \Omega^-$), the offset for A-A collisions does not show a dependence on the scaling variable
- pp collisions show a different trend than A-A, the offset increases towards higher values of the scaling variable
- the offsets corresponding to $K_S^0 - \Lambda - \Xi^- - \Omega^-$ are systematically higher than for $\pi^+ - K^+ - p$, for A-A collisions.



Summary

- ✓ A compilation of measured experimental data is done for a wide range of energies (from $\sqrt{s_{NN}}$=7.7 GeV up to $\sqrt{s_{NN}}$=5.02 TeV) in heavy-ion collisions (Au-Au and Pb-Pb)
- ✓ A comparison between pp collisions (LHC energies) and A-A (RHIC and LHC energies) in terms of $\langle p_T \rangle$, the slope and offset of $\langle p_T \rangle$ as a function of hadron mass and the BGBW fit parameters ($\langle \beta_T \rangle$ and T_{kin}) is presented
- ✓ Comparison between π^+, K^+, p and strange and multi-strange hadrons ($K_S^0, \Lambda, \Xi^-, \Omega^-$) is done, for the above mentioned observables

Conclusions

- ❖ A very good scaling is evidenced in the case of the $\langle p_T \rangle$ dependence on the geometrical variable $\sqrt{(dN/dy)/S_\perp}$, for A-A (separately for RHIC and LHC) and for A-A vs. pp (α=10) at LHC energies
- ❖ A very good scaling is observed for $\langle \beta_T \rangle$ for A-A and pp (α=1) at LHC energies; T_{kin} depends on collision energy, is higher in pp than in A-A and decreases with $\sqrt{(dN/dy)/S_\perp}$
- ❖ The slopes of the $\langle p_T \rangle$-hadron mass dependence show a good scaling for A-A and pp collisions (α=1) at LHC energies; the offsets for pp are increasing with $\sqrt{(dN/dy)/S_\perp}$, the ones corresponding to Pb-Pb being independent of $\sqrt{(dN/dy)/S_\perp}$.

Thank you for your attention!