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Energy and entropy densities in p+p, p+Pb and Pb+Pb collisions from 0.01 to 13 TeV

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Talk based on JPG 49, 1050 (2022)

PUERTO VALLARTA MEXICO, February 5-11, 2023

Outline

✓Motivation: <p_T> vs multiplicity

✓Multiplicity from Event Generators
- <p_T> vs N_{ch} Data vs Event generator

✓Hydrodynamics from Landau and Bjorken approaches:
- Analysis from ALICE and CMS data
- Analysis data vs Event generators

✓Conclusions and remarks

Motivation: Multiplicity dependence of p_T possible signal for a phase transition in hadronic collisions.

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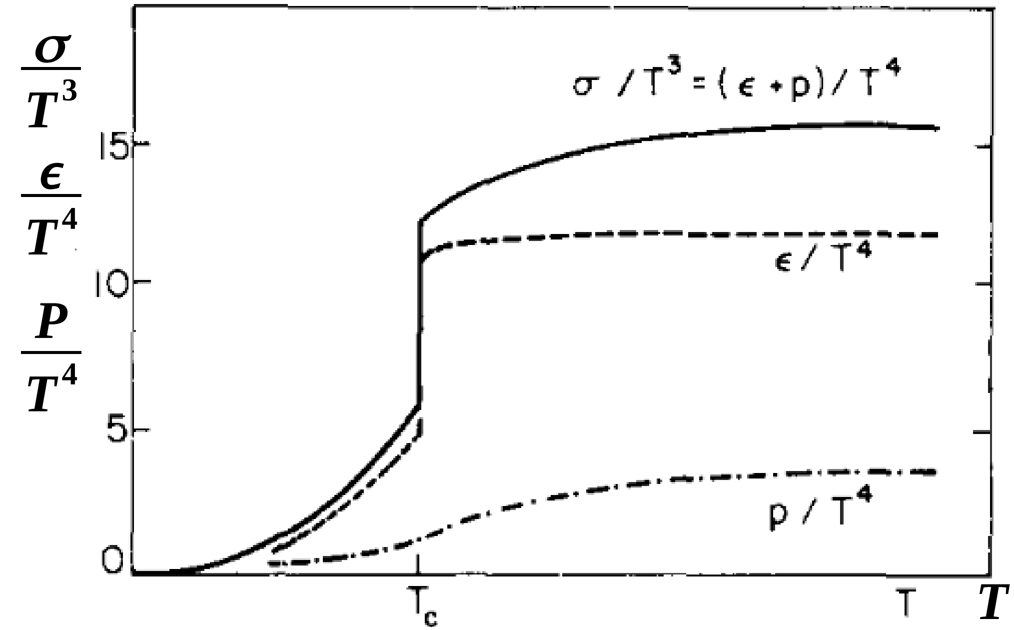
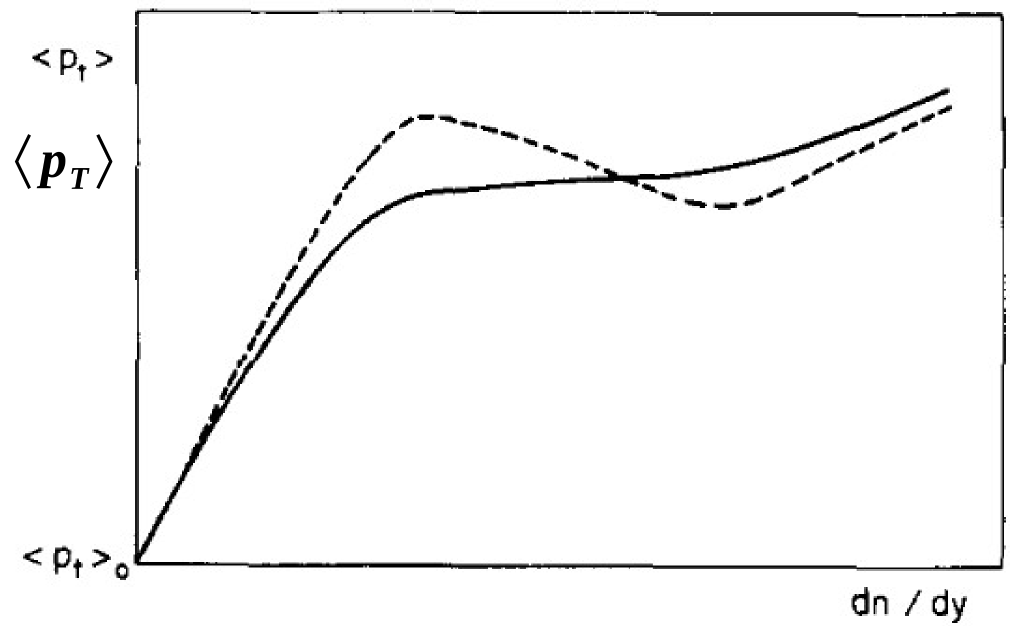
Analyzing CERN ppbar data:

- For Intervals of multiplicity, pT (0.3 GeV/c < pT< 6 GeV/c) becomes flatter as multiplicity increase => increase of the <pT>
- Following hydrodynamics Landau aproach: Entropy = S = k · Nch (σ = S/V => Nch =σV)
- p_T reflect combined effect of temperature and and transverse expansion.
- At the phase transition: Large σ => Higher T leading to a flatter pT.
- At central region baryon number is small, so the thermodynamic relations are those for zero chemical potential.

$\varepsilon = T\sigma - P \Rightarrow \quad \sigma/T^3 = (\varepsilon - p)/T^4$

L. Van Hove PLB 118B, 138 (1982)





Motivation: Multiplicity dependence of the $\langle p_T \rangle$ in p-p, p–Pb, and Pb–Pb

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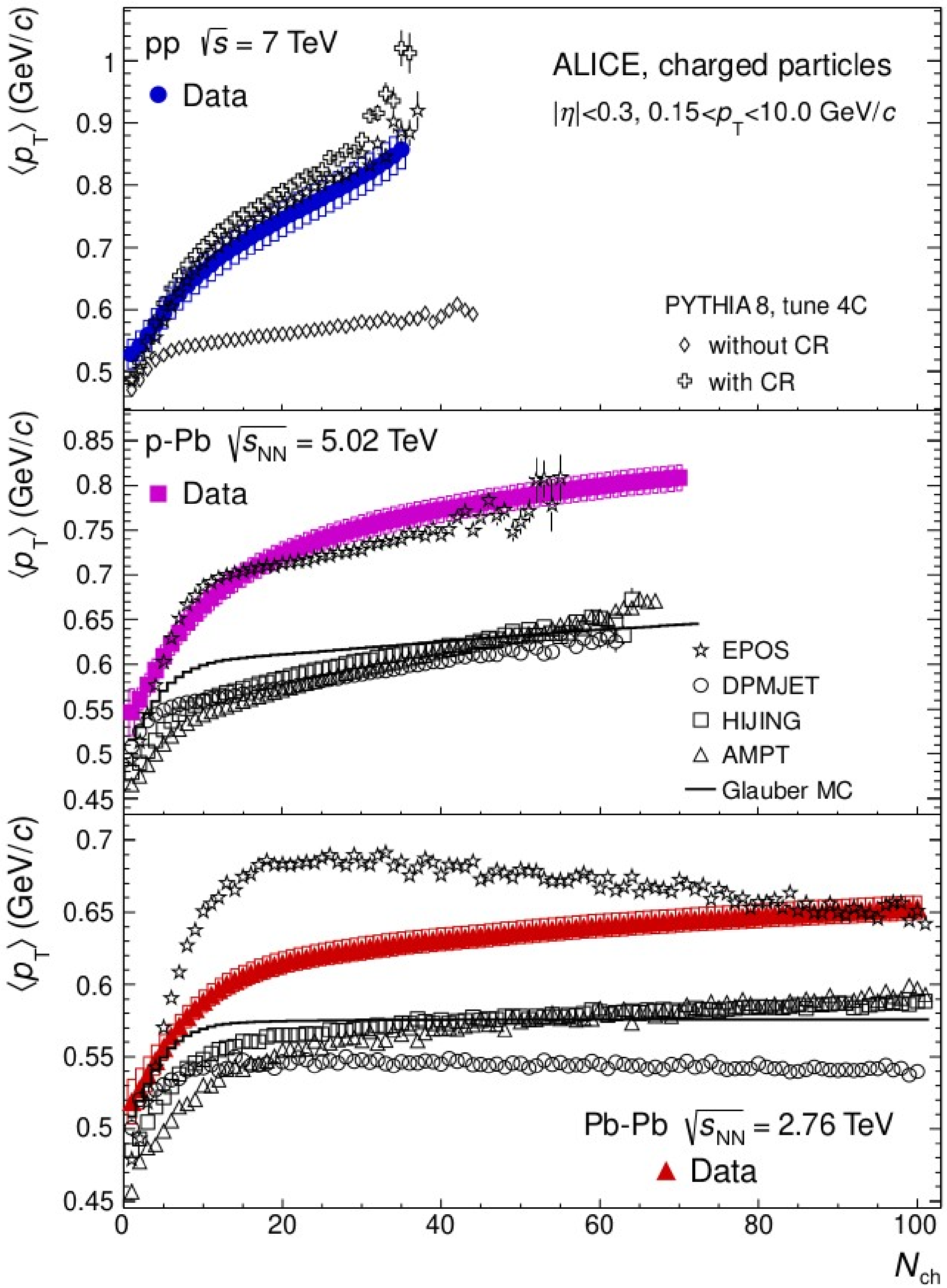
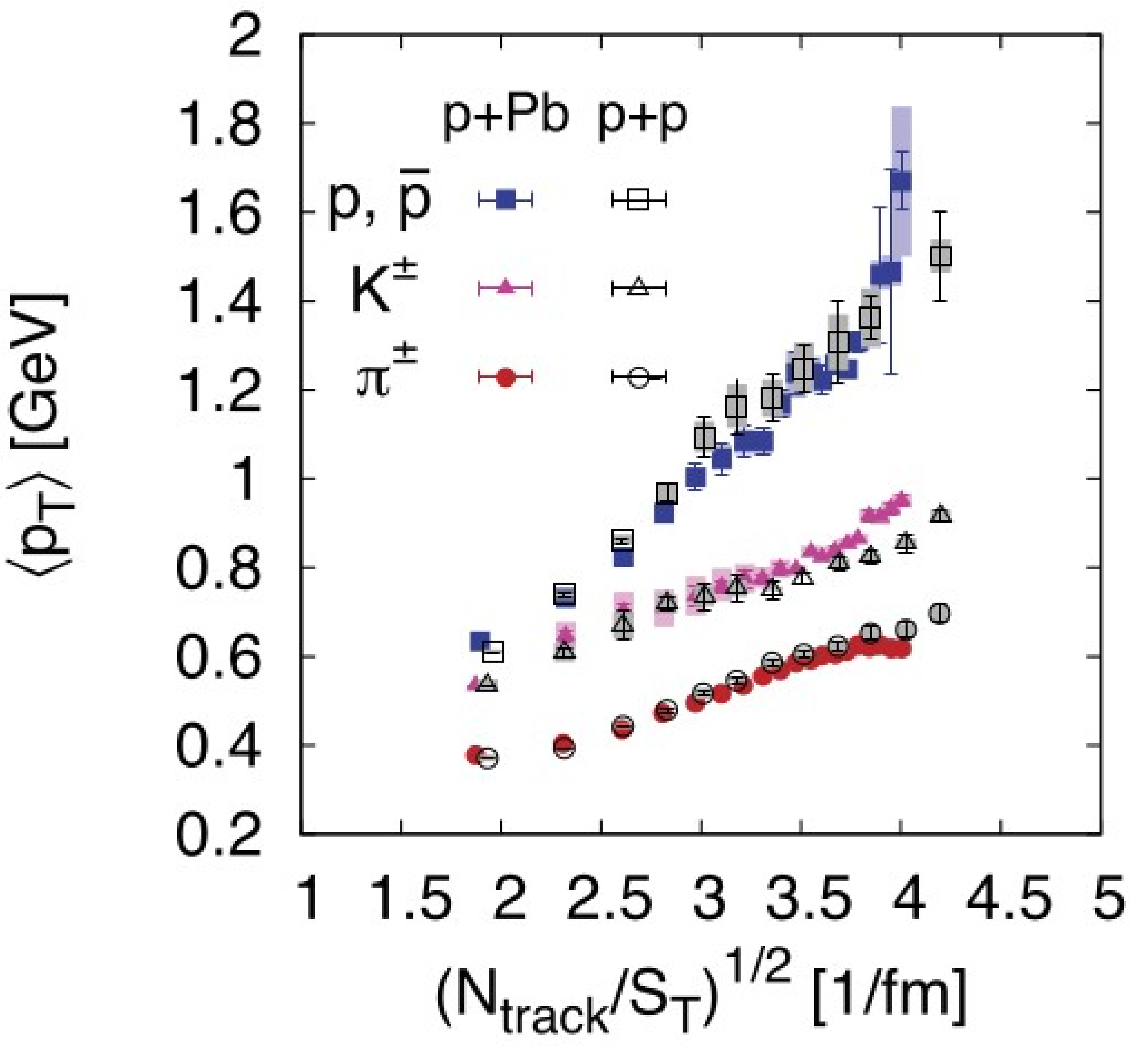


- ✔ In p-p and p–Pb collisions, a strong increase of $\langle p_T \rangle$ with N_{ch} is observed, which is much stronger than that measured in Pb–Pb collisions.
- ✔ For p-p collisions, this could be attributed, within a model of hadronizing strings, to **multiple-parton interactions** and to a final-state **color reconnection mechanism**.
- ✔ The data in p–Pb and Pb–Pb collisions cannot be described by an incoherent superposition of nucleon-nucleon collisions and pose a challenge to most of the event generators.

ALICE: PLB727, 371 (2013)

Motivation: Scaling of the average p_T vs multiplicity

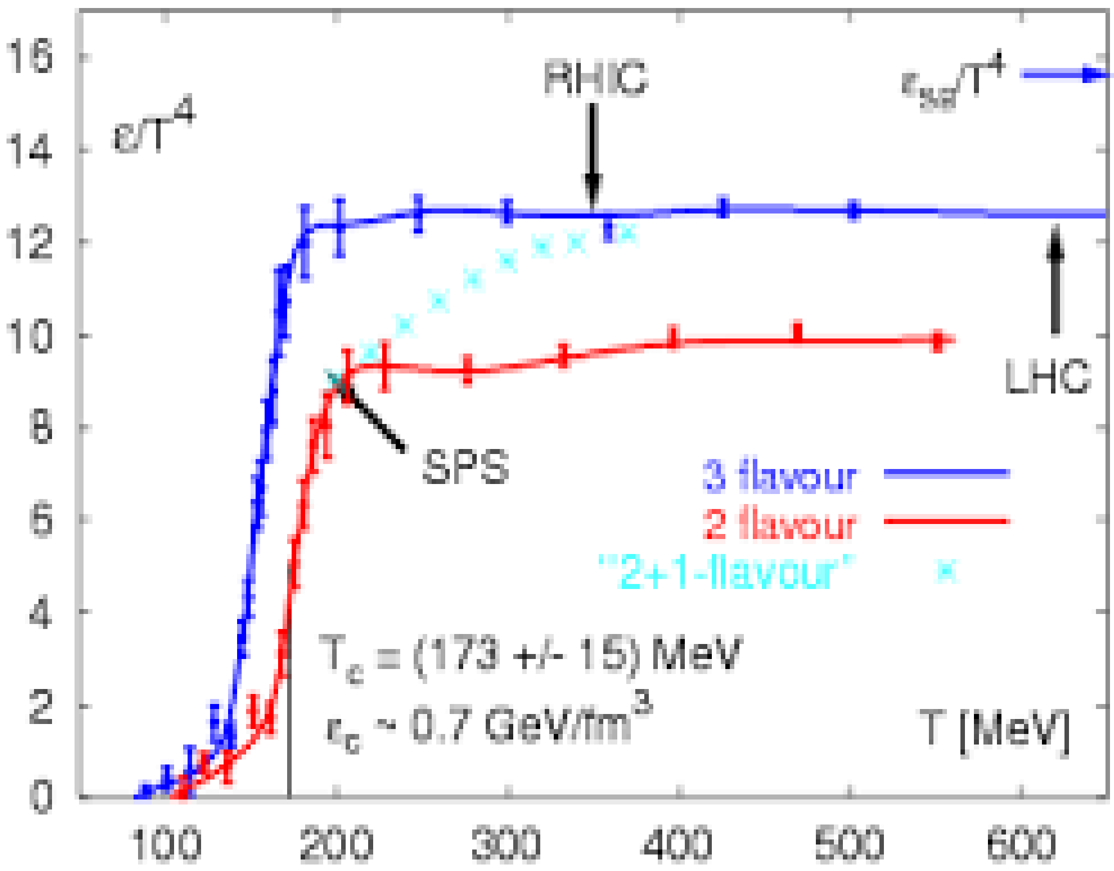


Using CMS data, of identified particle p_T distributions obey geometric scaling!

Evidencia for Color Glass Condensate?

McLerran, et al. NPA 916 (2013) 210–218

Motivation: Phase transition in Lattice QCD



Lattice QCD, allow calculate Ɛ/T⁴ vs T. showing a sudden change around critical temperature.

NPB605, 579 (2001)

PYTHIA and EPOS event generators

PYTHIA 8 used mainly to generate p-p collisions but recently it include Pb-Pb collisions in a model

One of the main issues taken into account is the color **reconnection (CR) mechanism,** which introduce a **flow-like** in p-p, and allow to describe **$<p_T>$ vs N_{ch}**

EPOS 1.9, EPOS-LHC used mainly to generate p-p and ion-ion collisions.

One of the main issues taken into account is the **string fusion**, which introduce a **flow** and allow to describe **$<p_T>$ vs N_{ch}**

Our goal is to investigate in hydrodynamics approaches in p-p, p-Pb and Pb-Pb collisions:

- ✔ **Multiplicity distributions with/without flow**
- ✔ **Energy and entropy densities normalized**
- ✔ **Energy and entropy densities compared to ALICE and CMS data**

Multiplicity vs pT from PYTHIA 8 and EPOS-LHC

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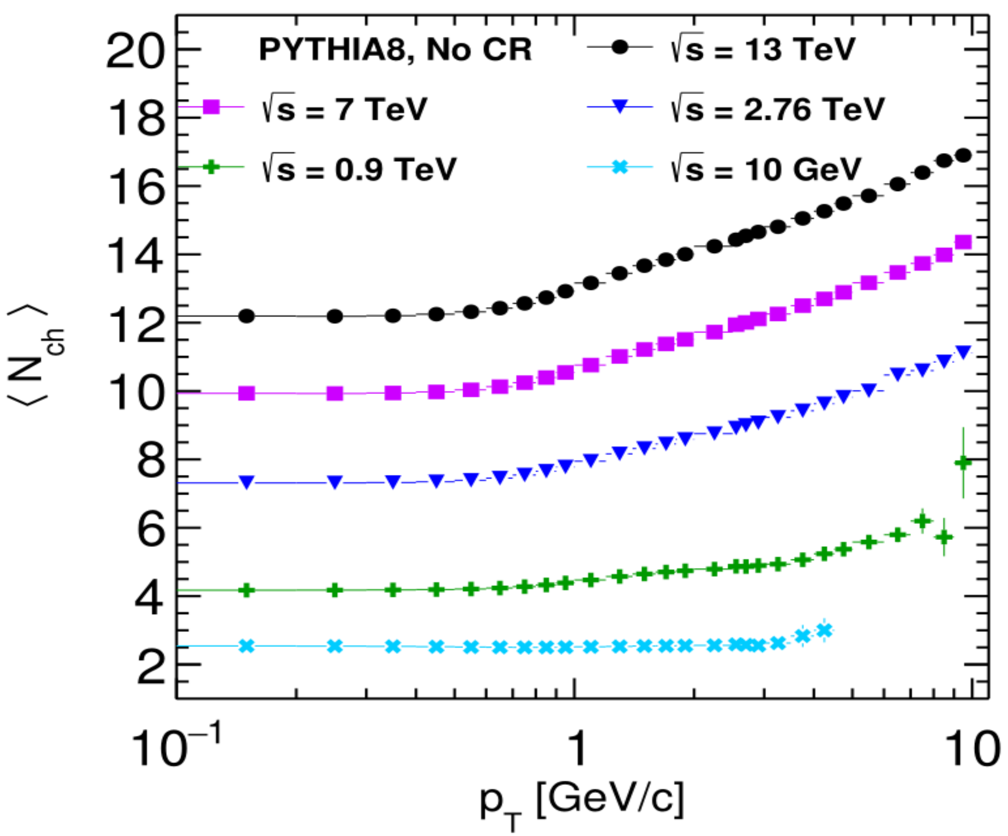
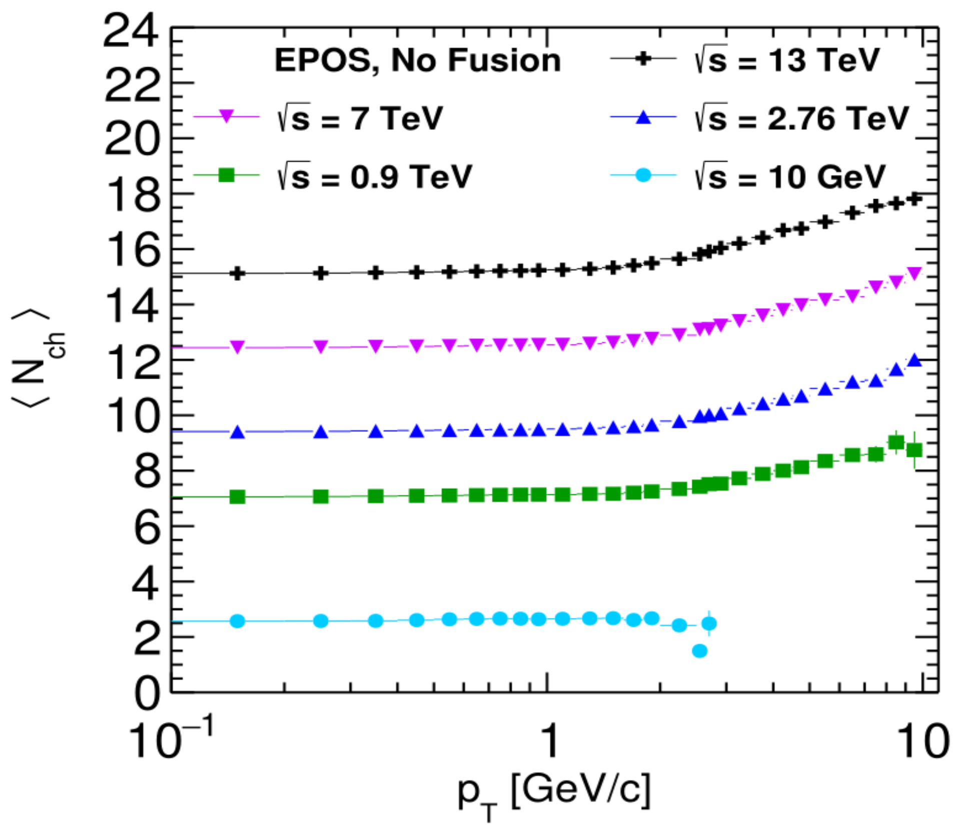
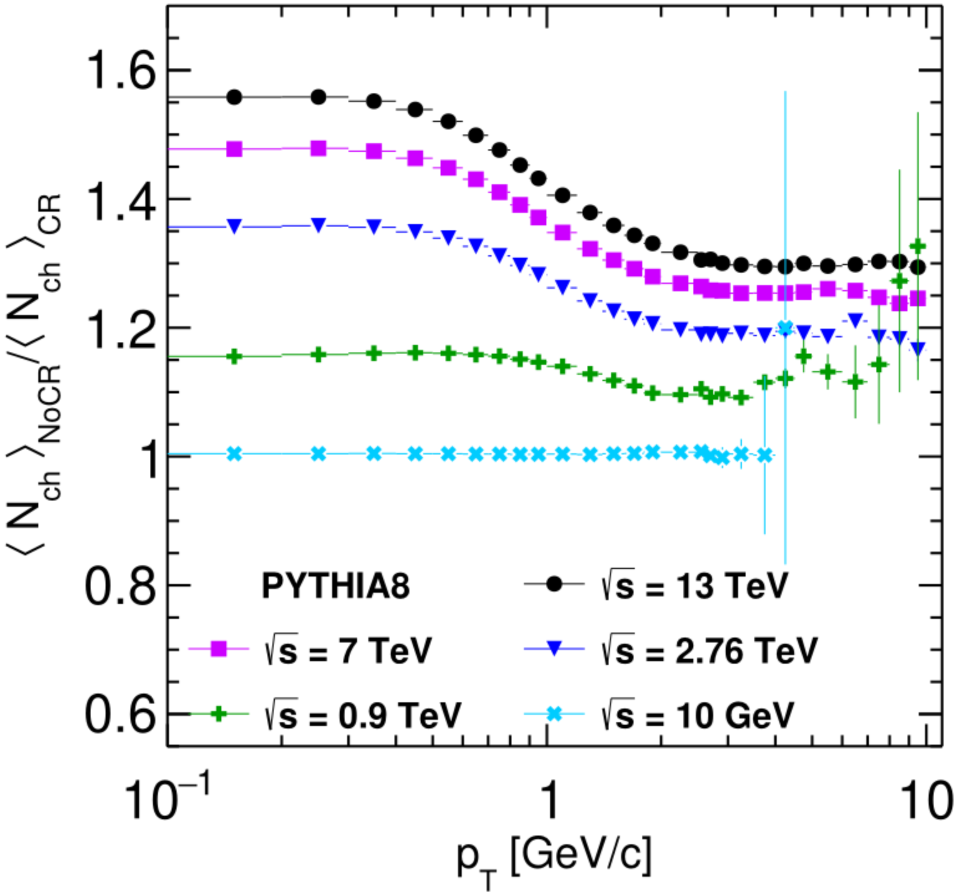


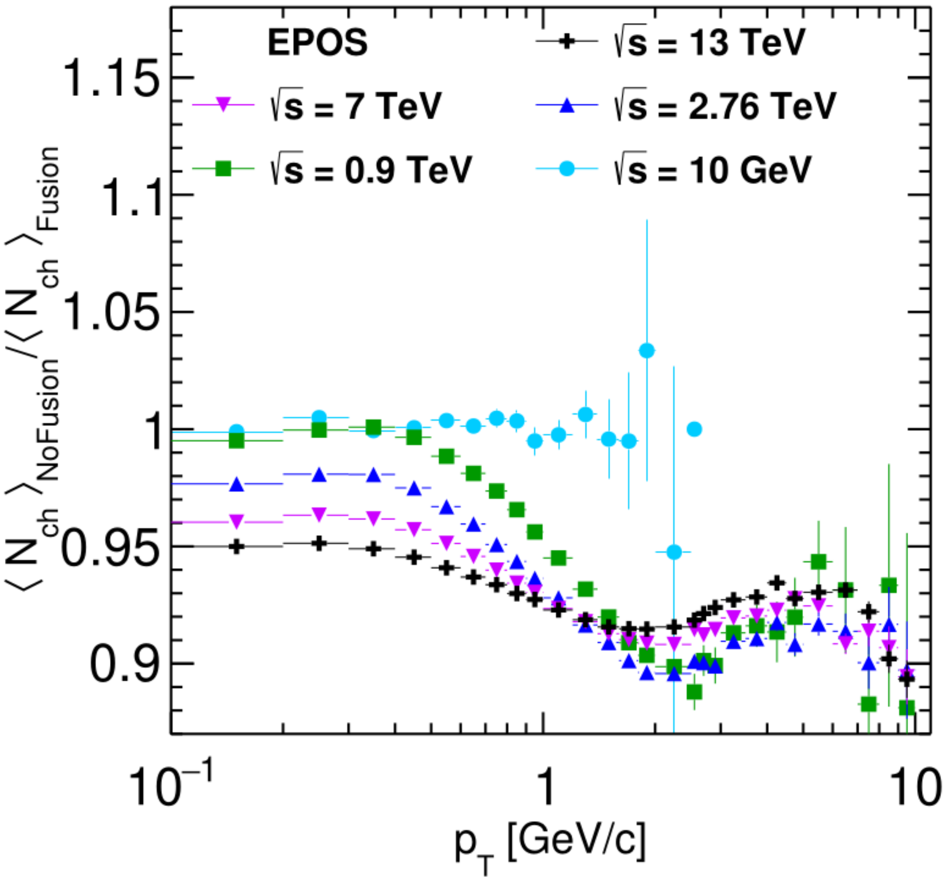


- Comparing the <Nch> vs p_T from PYTHIA and EPOS at the same energy we observe higher <Nch> vs p_T in EPOS-LHC.

- At lower energies both event generator produce similar results, but the disagreement increases with the energy

Multiplicity with flow-like (in PYTHIA) and flow (in EPOS)

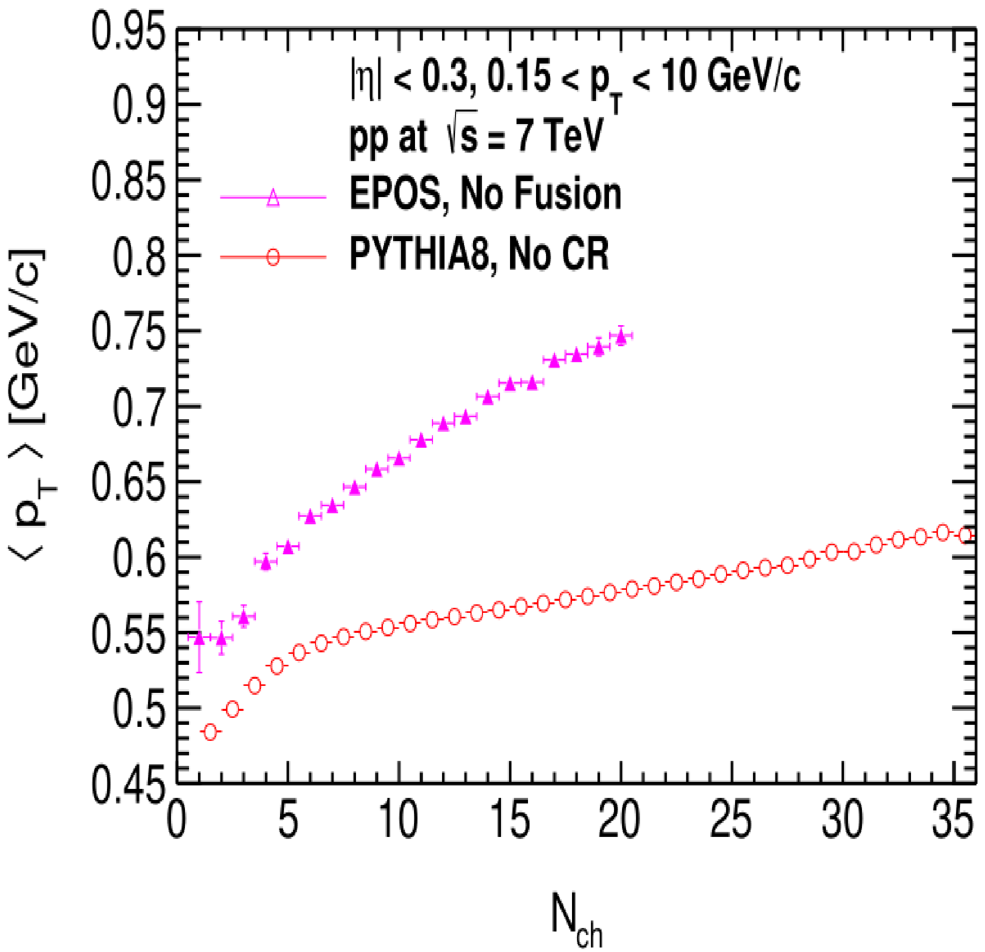


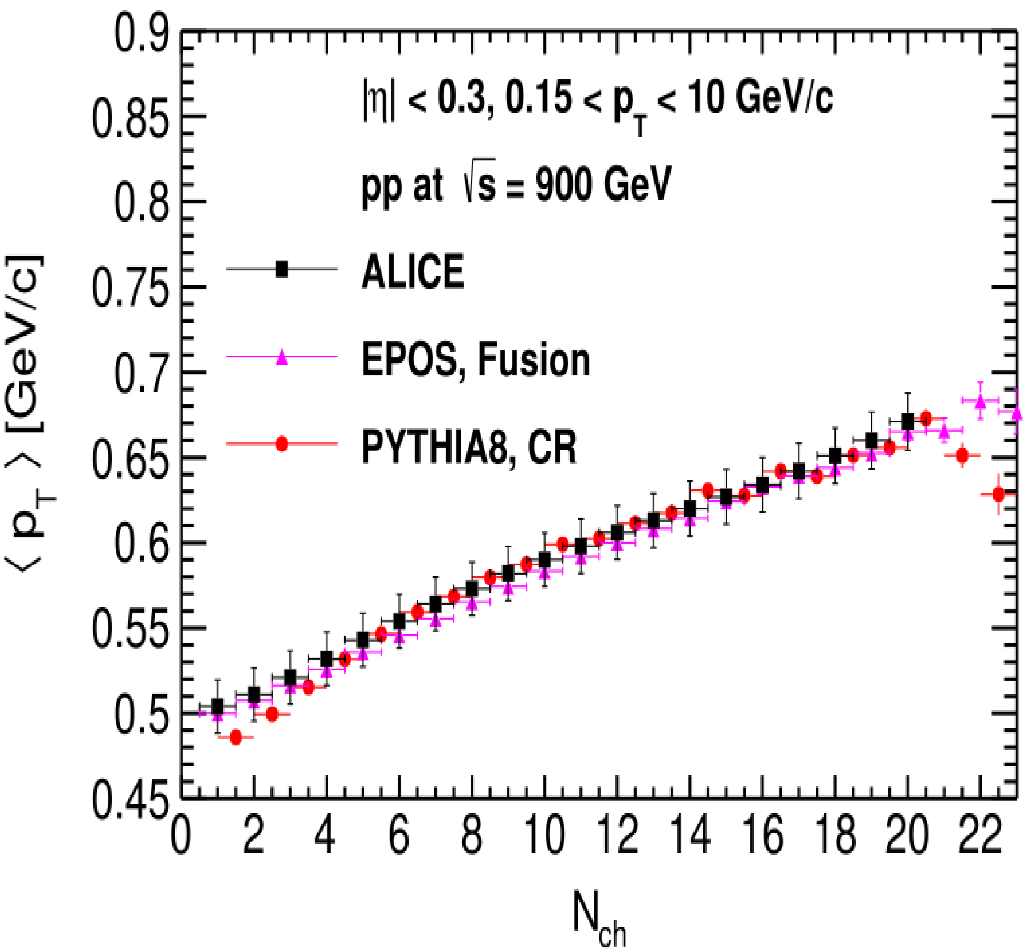


- Flow-like reduce the <Nch> with p_T
- Flow-like reduce the <Nch> with energy
- The strength of this effect is fixed by data

- Flow increase the <Nch> with p_T
- Flow increase the <Nch> with energy
- At lower energy there is not flow effects

$\langle p_T \rangle$ vs Nch from EPOS and PYTHIA 8 vs ALICE Data

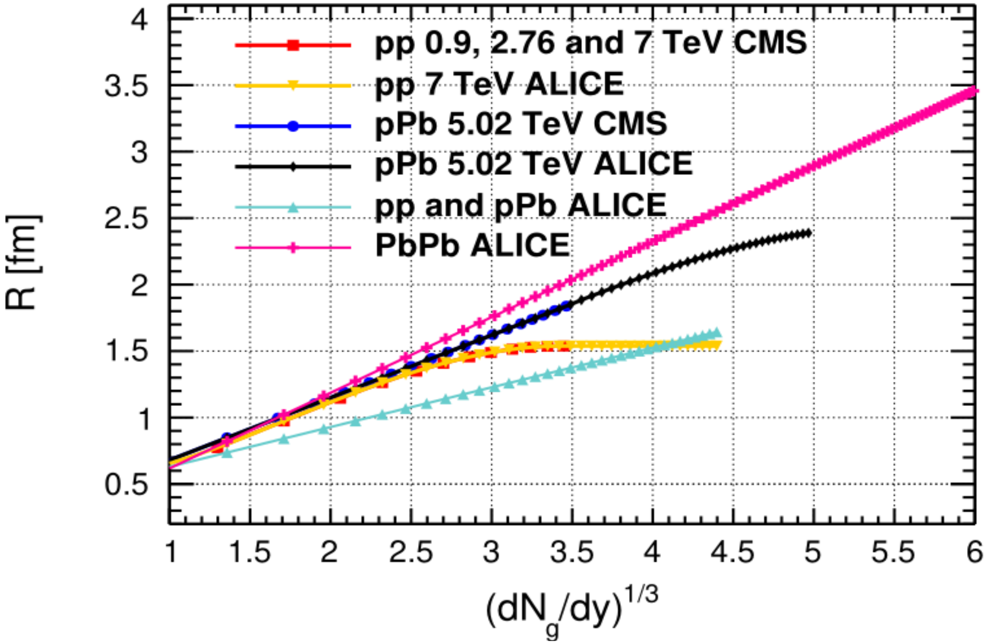




Is there a Scaling law for <p$_T$>?

$$R_{pPb,pp} = 1fm \times f_{pPb,pp}(\sqrt[3]{dN_g/dy})$$

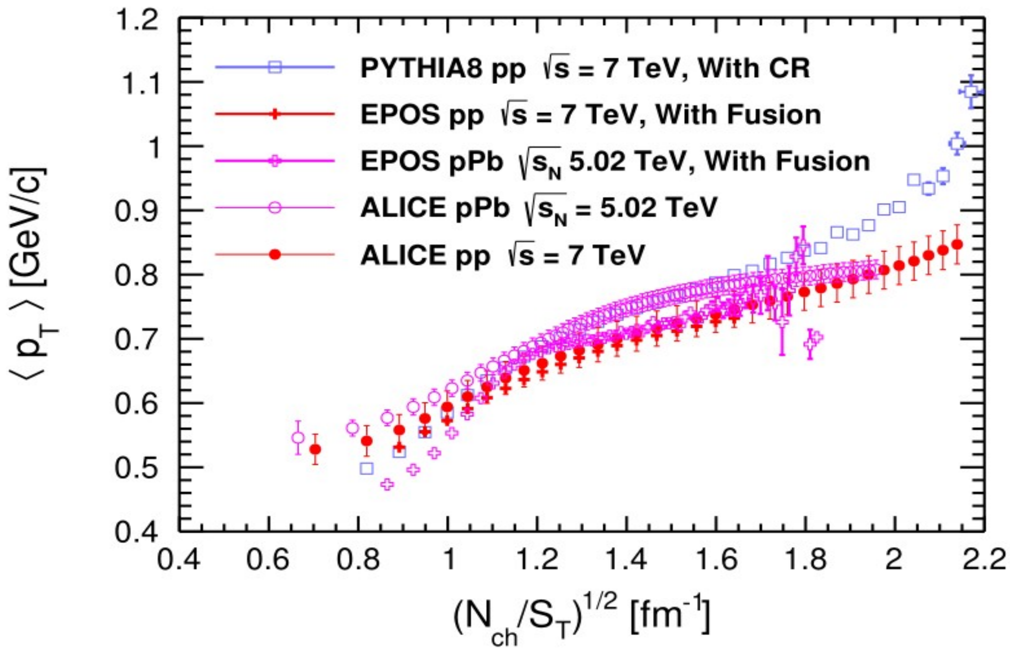
$$\frac{dN_g}{dy} \approx K \frac{3}{2} \frac{1}{\Delta\eta} N_{tracks}.$$



Radio for p+p system have a limit in the size. Meanwhile heavier system have a lineal increase.

<pT> has a scaling law when plotted as a function of multiplicity scaled by transverse area

Simulation shows a scaling like Data



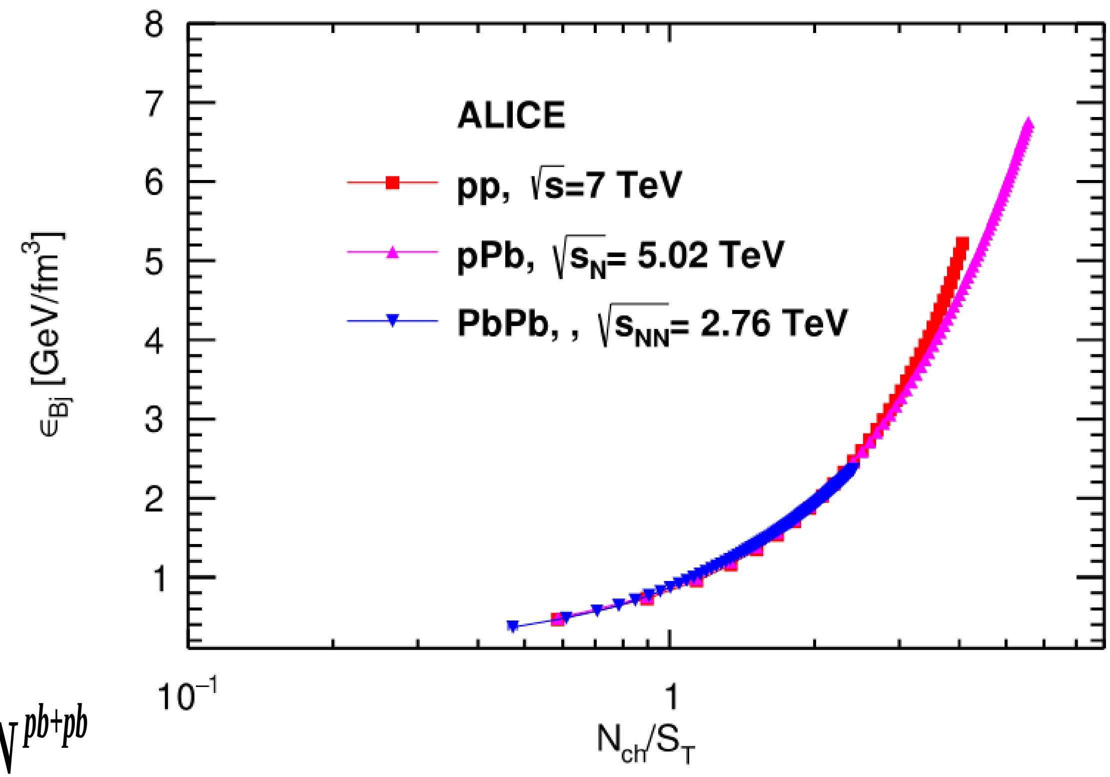
Nucl. Phys. A 916 (2013), 210-218
Phys. Lett. B 779 (2018), 58-63.

Is there a scaling law for energy density?

The Bjorken energy density (Bj) shows scaling laws, it has been used to shows that the enhancement of the strangeness production as a function of Bj for different colliding systems,

$$\epsilon_{Bj} \approx \frac{3}{2} \frac{\langle p_T \rangle \frac{dN}{d\eta}}{S_T \tau}$$

$$\epsilon = \frac{3}{2} \frac{dE_T^{p+p}/d\eta}{\pi R^2_{p+p} \tau_0} \sim \frac{3}{2} \frac{\langle p_T^{p+p} \rangle}{A^{p+p}} \frac{dN^{p+p}}{d\eta} = \frac{3}{2} \frac{\langle p_T^{pb+pb} \rangle}{A^{pb+pb}} \frac{dN^{pb+pb}}{d\eta}$$



A clear scaling law is observed at low multiplicity for all colliding systems.
For N_{Ch}/S_T >= 3 a breaking law appears.

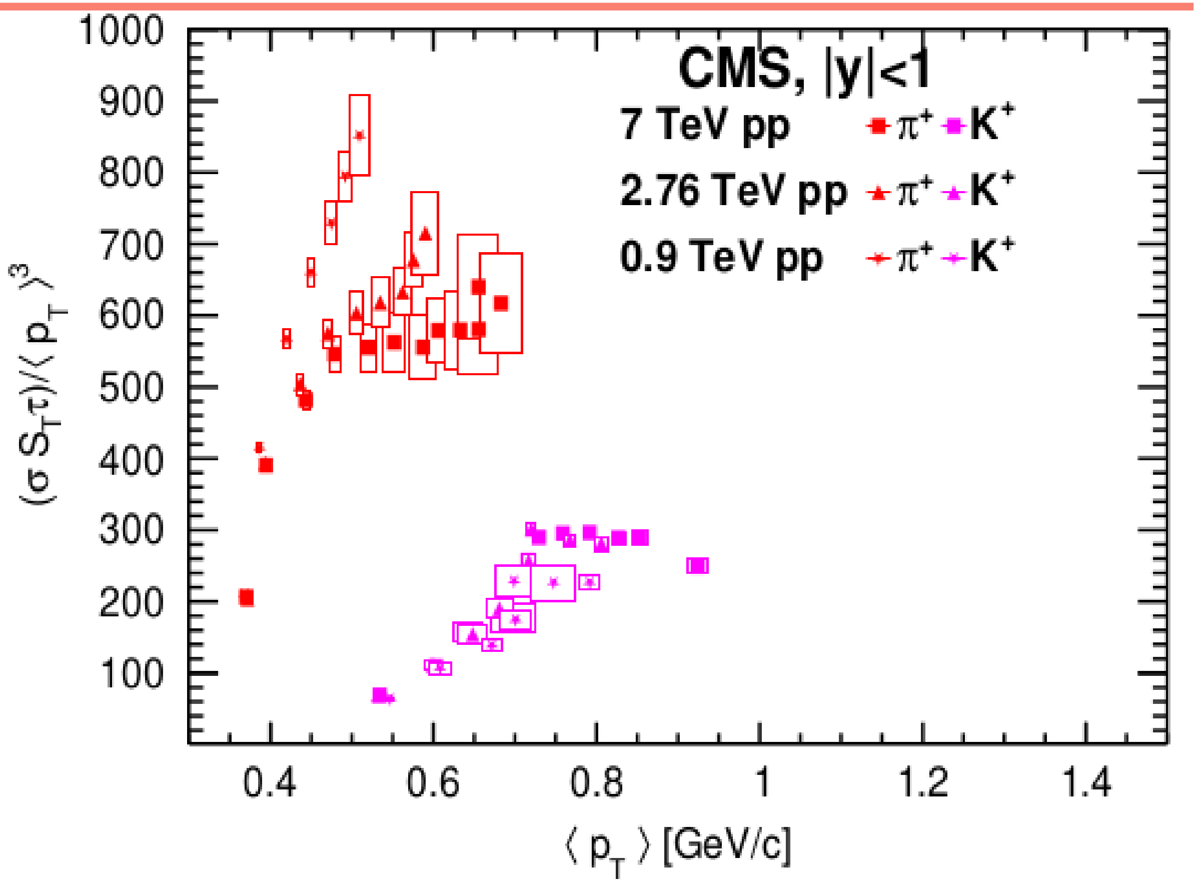
J.D. Bjorken, PRD27 (1983)140

Entropy for identified particles from CMS

PRD 33, 3747 1986

The entropy density (σ) is determined in statistical QCD dynamical quarks as:

$$\sigma \approx \frac{\epsilon}{\langle p_T \rangle}$$



Considering roughly approximation, $<p_T>$ is proportional to the initial temperature T , as it is deduced in Color string Percolation model.

Eur. Phys. J. C 71, 1510 (2011)

Kaons show a saturation for higher energy. We can observe a flat behavior for valor higher of 7 GeV /c for $<p_T>$.

This entropy ($\sigma S_T\ \tau$) has a rapid increase for pion at lower energy. If we analyze lower energy we find a saturated behavior in terms of $<p_T>$.

Entropy vs <p_T> and <N_{ch}> for identified particles

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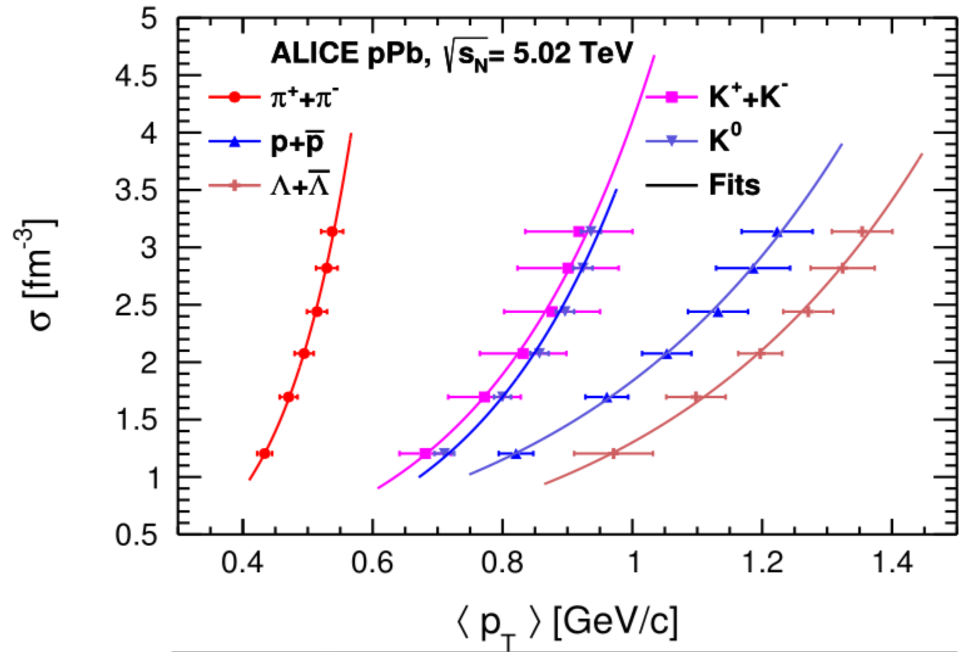
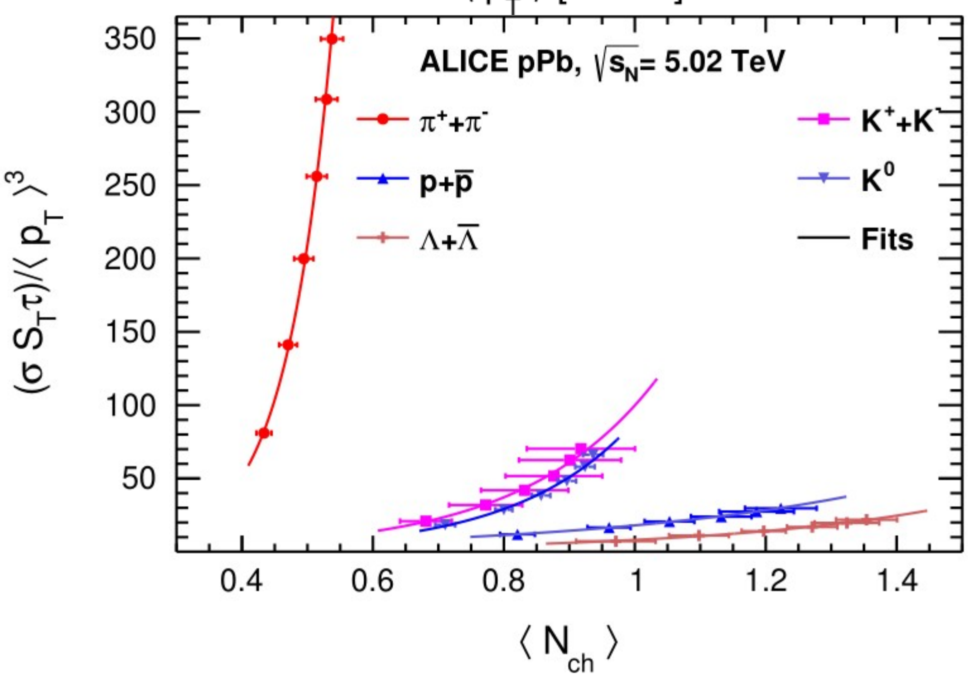
ALICE p+Pb data

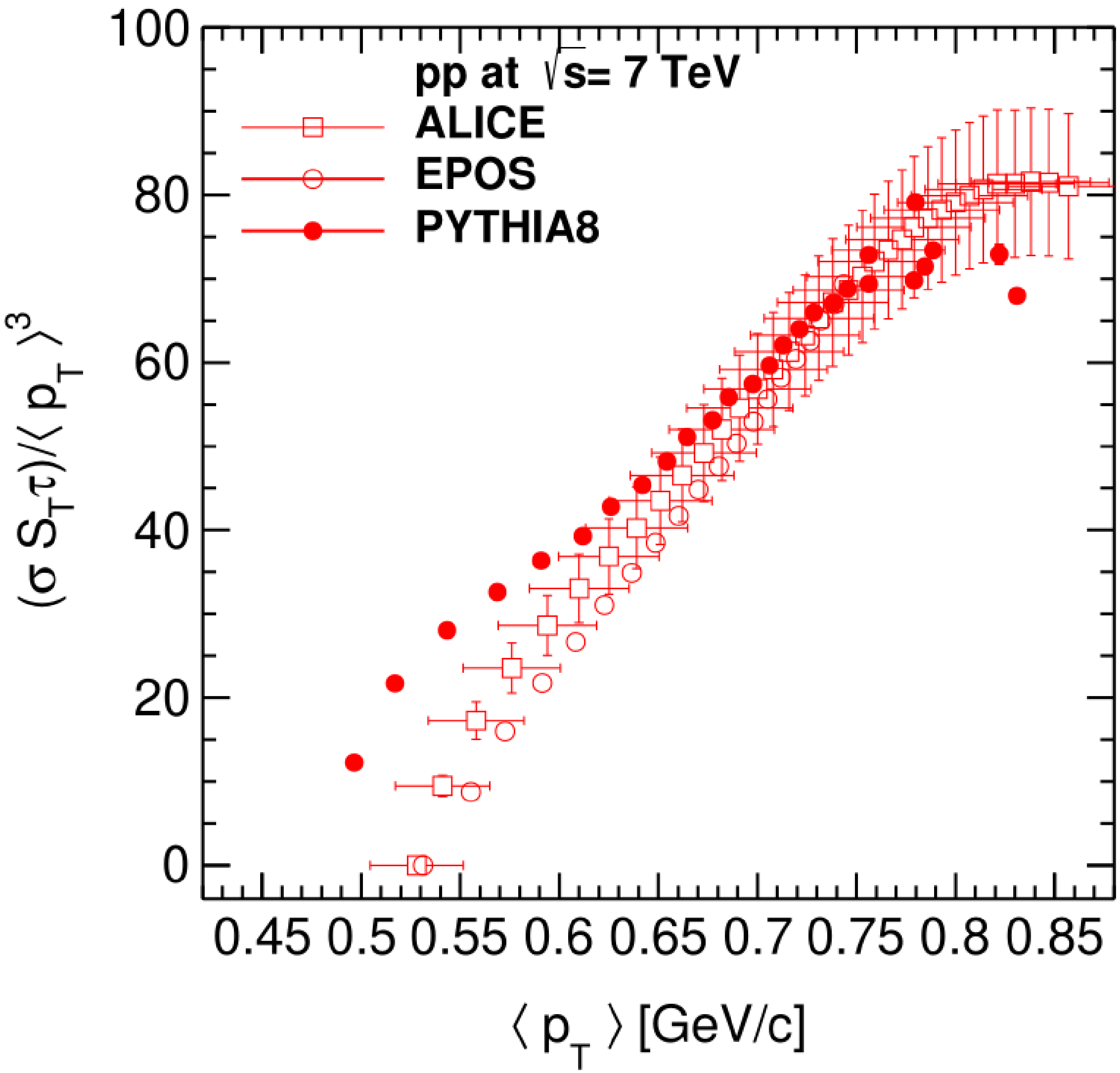
- The σ versus <p_T> increase exponentially
- σ/<p_T>^{3} : Heavier hadrons grow up slowly that for lighter ones.
- ($\sigma S_T \tau$)/<p_T>^{3} vs <N_{ch}> have similar trend but a more pronounced
- Results are similar for ALICE and CMS for the case of pions, even when there are difference in the multiplicity measure between them.





p-p: Entropy density normalized to p_T^3

- ALICE data are well described by EPOS,
- PYTHIA shows a disagreement at low $<p_T>$
- The entropy grow up, and seems to saturate for $<p_T>$ larger than 0,82 GeV/c



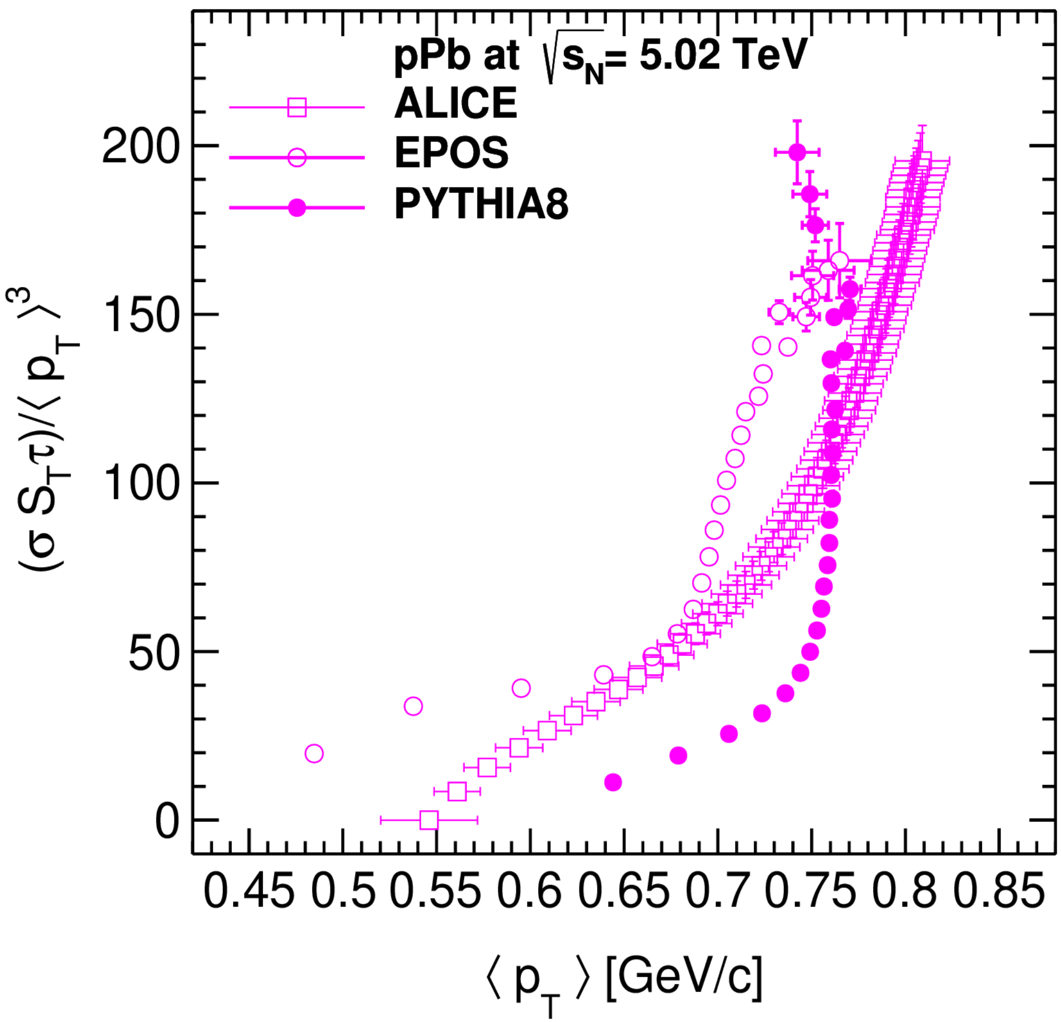
p-Pb: Entropy density normalizd to p_T^3

- Data and simulations have the same trend, a rapid growth on the slope around

$<p_T> \approx 0.7$ GeV/c for EPOS

$<p_T> \approx 0.75$ GV/c for PYTHIA

- Data are between event generators



Pb+Pb: Entropy density normalized to p_T^3

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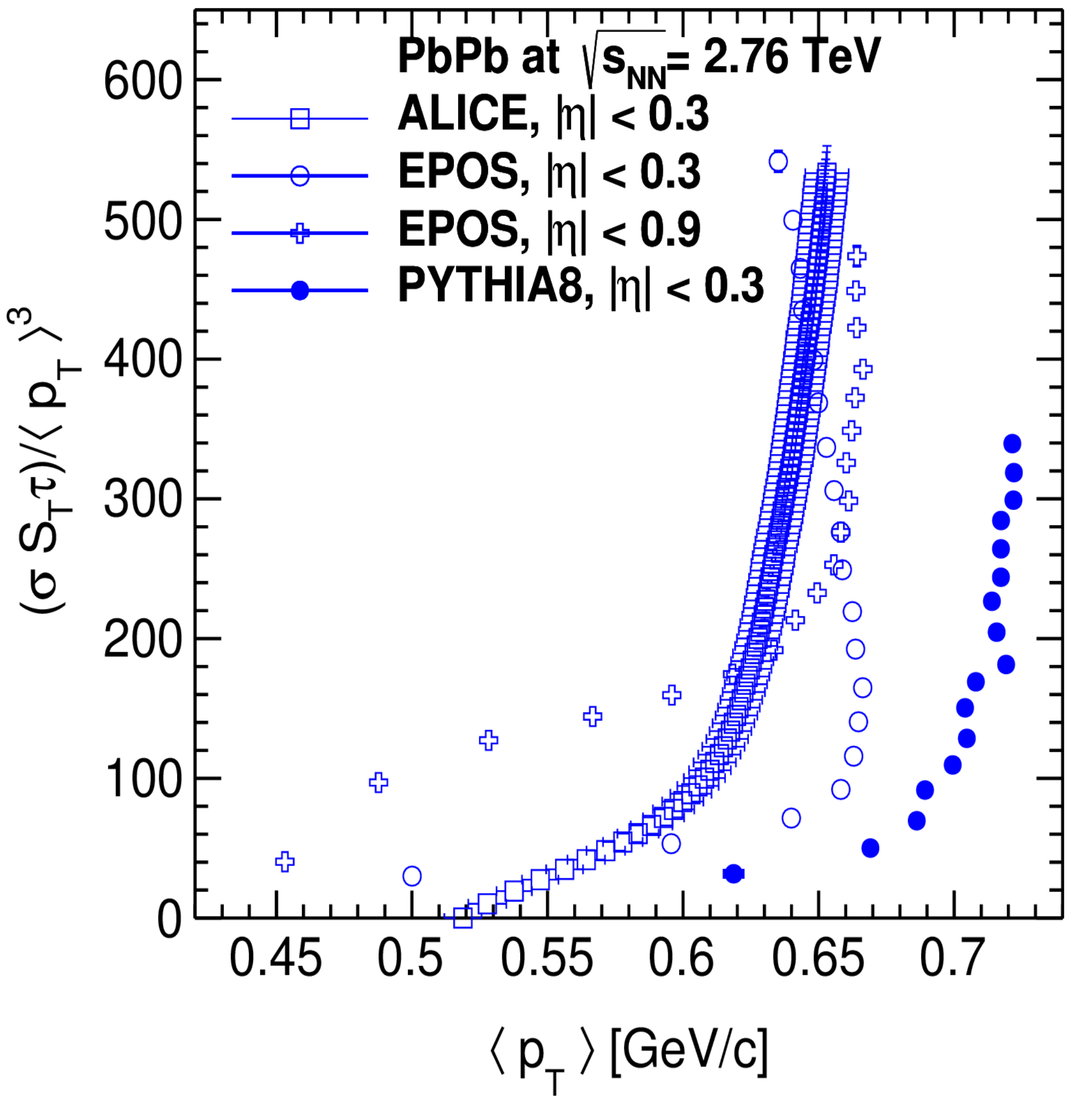
- show a sudden change in the entropy for the data and almost the same trend for the PYTHIA, but
- shifted to higher $\langle p_T \rangle$ values.

- The EPOS event generator produce a larger slope such that distribution cross the data.

- $\langle p_T \rangle = 3T$ (Nat. Phy. 16, 615 (2020))

- **Results resemble sudden change of the ε/T^3 vs T of lattice QCD**



Energy density vs T: $\mathcal{E}/T^4$ vs T

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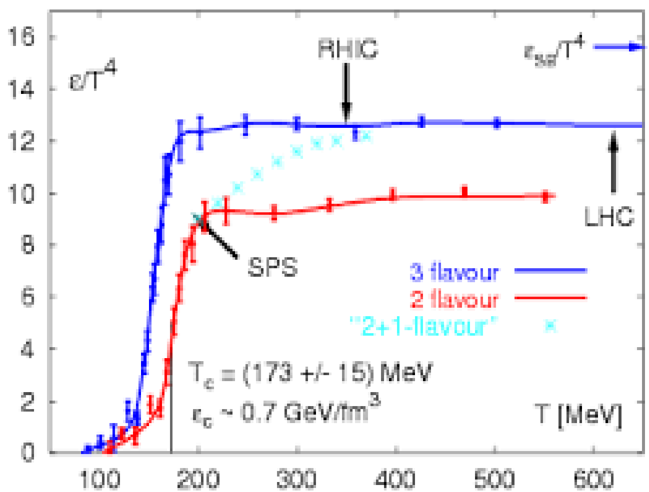
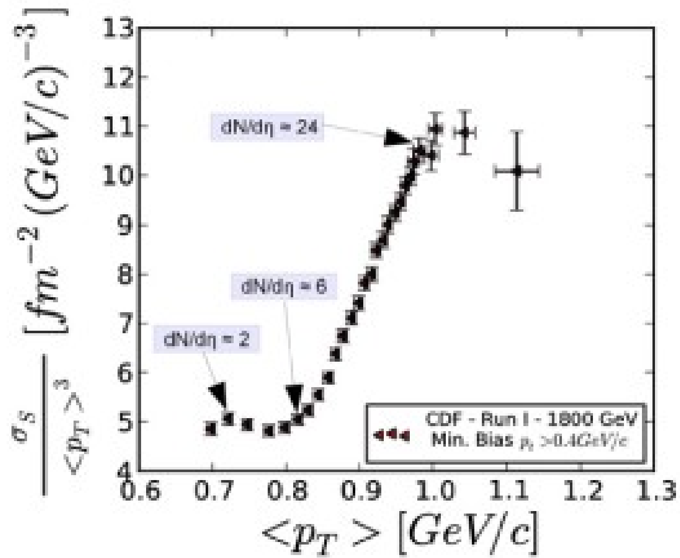
Theory



Lattice QCD allow to compute $\mathcal{E}/T^4$ vs T. It shows a sudden change around the critical temperature.

NPB605, 579 (2001)

CDF-TEVATRON

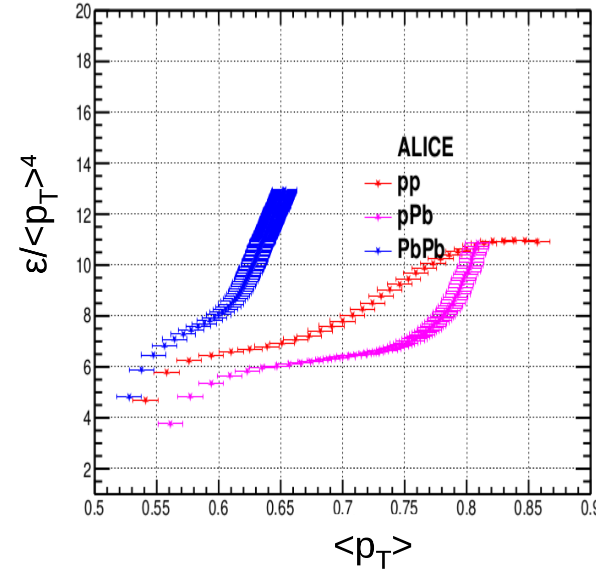


$$\epsilon \simeq \frac{\frac{dN_{ch}}{d\eta} \cdot \frac{3}{2}\langle p_T \rangle}{V}$$

$$\sigma \simeq \frac{\frac{dN_{ch}}{d\eta} \cdot \frac{3}{2}}{V}$$

Phys. Lett. B 703, 237 (2011)
Phys. Rev. D 33, 3747 (1986)

ALICE-LHC



Data from ALICE analyzed to extract "hydrodynamics variables"

JPG, 49, 1050 (2022)

Coclusions and remarks

Analysis of the average transverse momentum and multiplicity from ALICE and CMS data, compared to PYTHIA and EPOS-LHC event generators.

- $\langle p_T \rangle$ vs N_{ch} from p-p data can be described for the event generators incorporating the flow or flow-like effects.
- The ($\langle p_T \rangle$, ε, σ) vs N_{ch} present a scaling law at lower energies for different colliding systems and energies.
- The sudden change in (σ, ε)/$\langle p_T \rangle^3$ when they are plotted as a function of $\langle p_T \rangle$, resembling the results of lattice QCD on the ε/T^3 vs T reveals possible phase transitions, however only the p+p results from ALICE show kind of saturation and the identify for CMS in the case of the pions.

Hydrodynamic models used for this analysis should require an improvement. Maybe the models of the event generator should be improve

Thank you for your attention

Hydrodynamics from Landau and Bjorken approaches

As the equation of state of highly compressed matter at temperatures $T \gg \mu c^2$, we shall take[6]

$$p = \frac{1}{3}\varepsilon, \tag{3.1}$$

where p is the pressure and ε the energy density. The pressure and energy density of macroscopic bodies are always such that $p \leqq \frac{1}{3}\varepsilon$, equality holding in the extreme relativistic case. This inequality, however, is derived by assuming electromagnetic interactions between particles, and there is at present no proof that it must be valid for any interaction. Nevertheless, the choice of the equation of state (3.1) appears very plausible. Since the number of particles in the system is not fixed, but is itself determined from the statistical equilibrium, the chemical potential is zero. Hence $\varepsilon - Ts + p = 0$, where s is the entropy per unit volume. Using the equation of state, we find $Ts = \varepsilon + p = 4\varepsilon/3$. Since for a fixed volume $d\varepsilon = T\,ds$, it follows that

$$s \approx \varepsilon^{3/4}, \quad T \approx \varepsilon^{1/4}. \tag{3.2}$$

These relations are the same as for black-body radiation, as of course we should expect.

It has already been mentioned that the entropy of the system remains constant during the hydrodynamic stage of expansion, and varies only during the first stage, at the initial instant of collision. The number of particles in the star is related to the entropy by (2.25). Hence it follows that to determine the total number of particles we must calculate the change in entropy at the

Motivación: Densidad de energía y ecuación de estado

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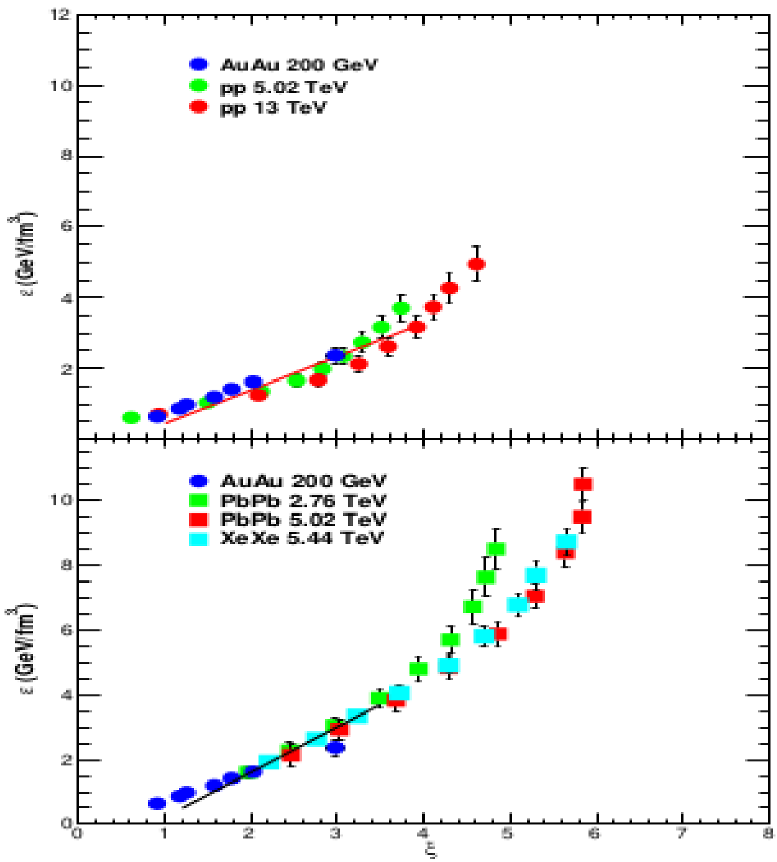
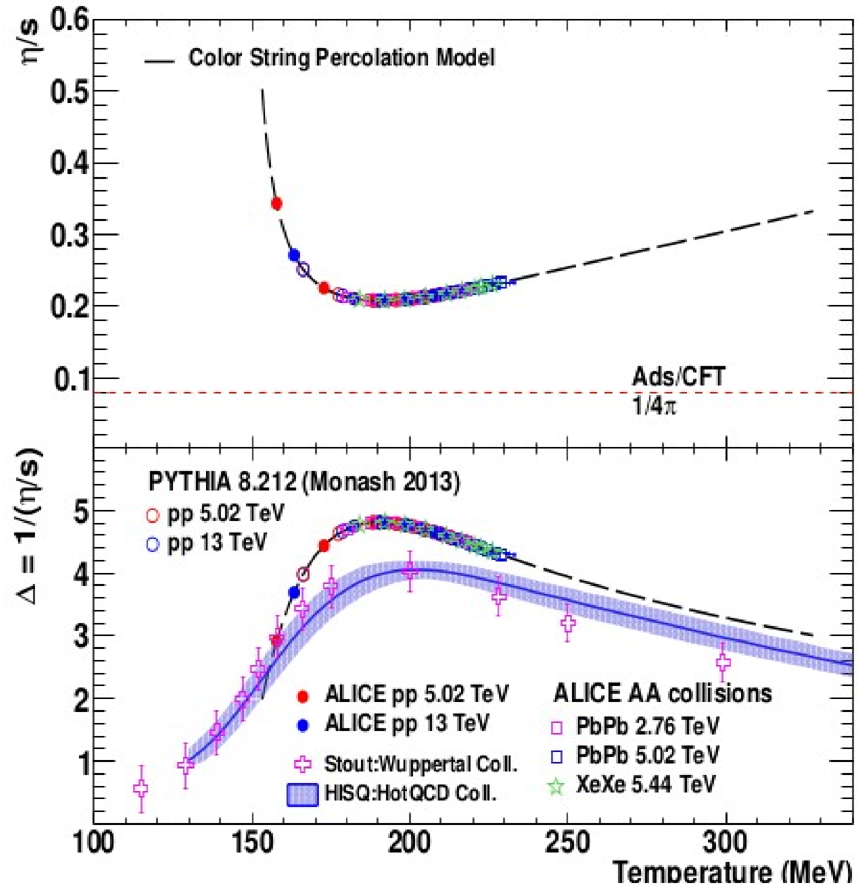
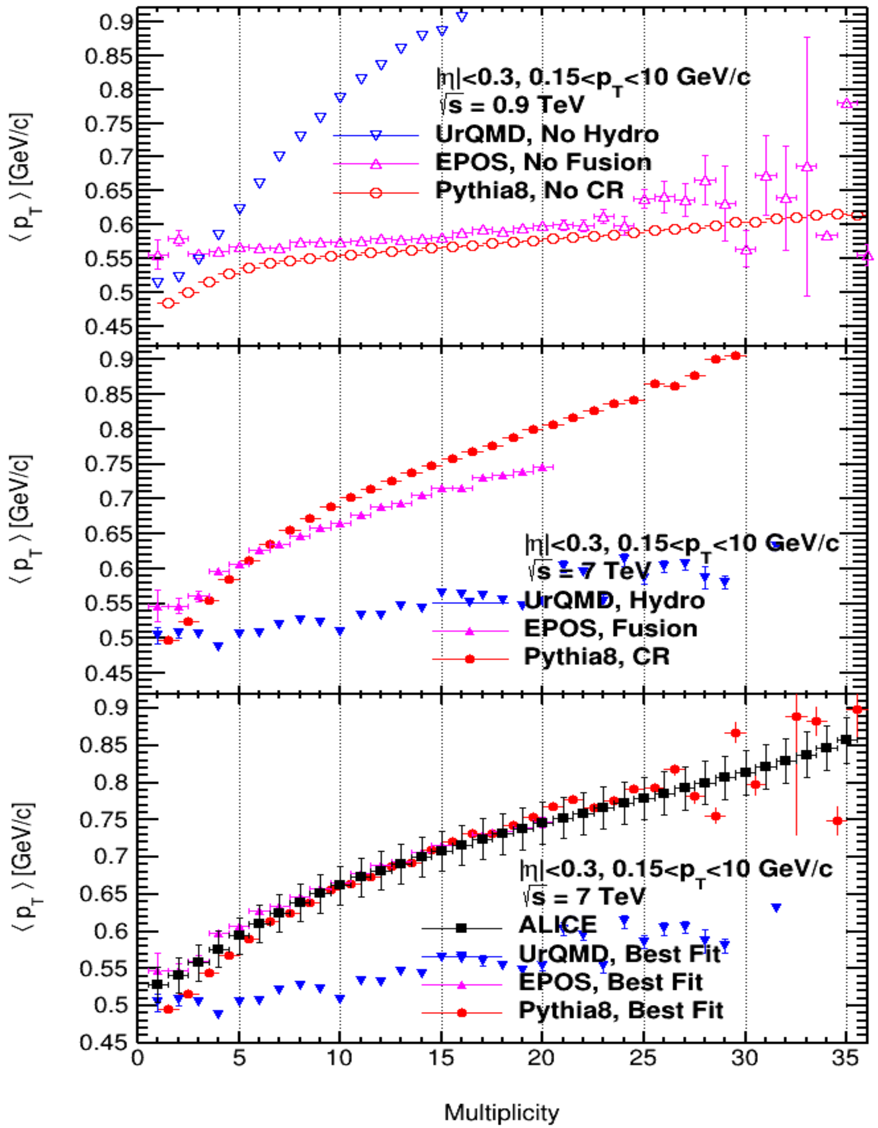




PoS LHCP2019 (2019) 004

Viscosidad a entropia (arriba). Valor esperado de la traza del tensor energía momento ~ Δ (abajo)

Momento transverso promedio vs multiplicity



Resultados muestran discrepancia en todo el rango de pT entre diferentes modelos hadrónicos incorporados en los generadores de eventos.

El desacuerdo con los generadores incrementa con la multiplicidad, esto ocurre con y sin efectos colectivos de clase hidrodinámica.

La comparación con datos muestra razonable acuerdo entre PYTHIA EPOS y datos de ALICE. UrQMD con hidrodinámica (en pp) incluida falla.

Radii of the transverse collision area

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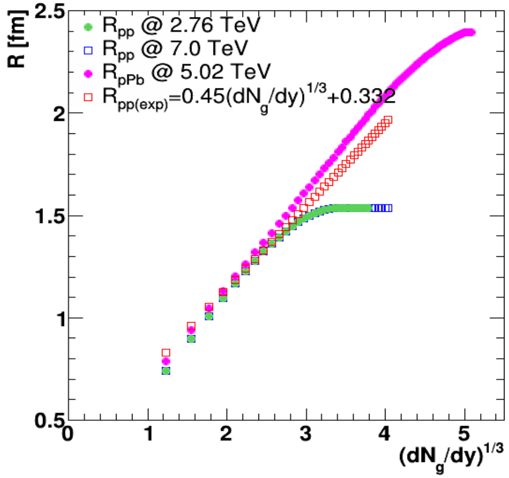

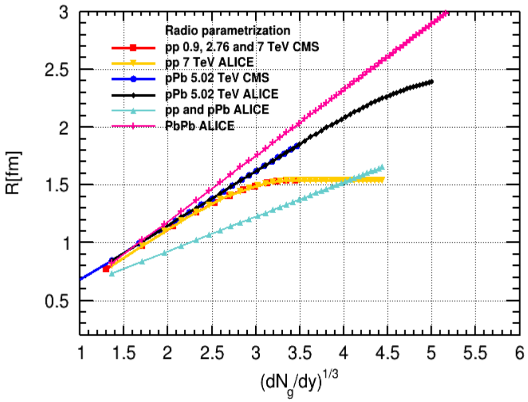

$$R_{\mathrm{pPb}} = 1\ \mathrm{fm} \times f_{\mathrm{pPb}}\left(\sqrt[3]{dN_g/dy}\right)$$

$$\frac{dN_g}{dy} = \frac{K}{\Delta\eta} \times \frac{3}{2}\left(\frac{dN}{d\eta}\right)^{1/3}$$

with

$$f_{\mathrm{pPb}}(x) = \begin{cases} 0.21 + 0.47x & \text{if } x < 3.5, \\ 1.184 - 0.483x + 0.305x^2 - 0.032x^3 & \text{if } 3.5 \leqslant x < 5, \\ 2.394 & \text{if } x \geqslant 5. \end{cases}$$

$$x = \left(\frac{dN_g}{dy}\right)^{1/3}$$

$$f_{\mathrm{pp}}(x) = \begin{cases} 0.387 + 0.0335x + 0.274x^2 - 0.0542x^3 & \text{if } x < 3.4, \\ 1.538 & \text{if } x \geqslant 3.4. \end{cases}$$

Nucl. Phys. A 916, 210 (2013).

Experimental equation of state in pp and pp̄ collisions and phase transition to quark gluon plasma

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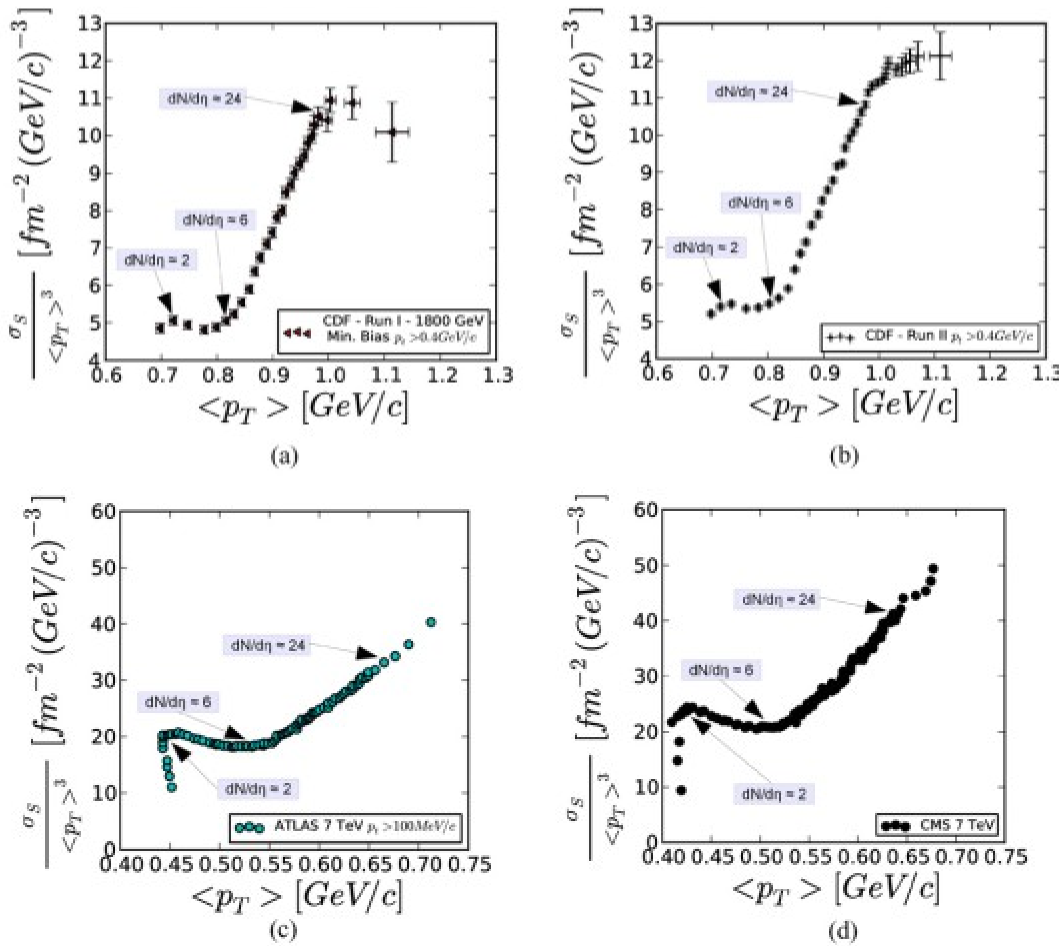
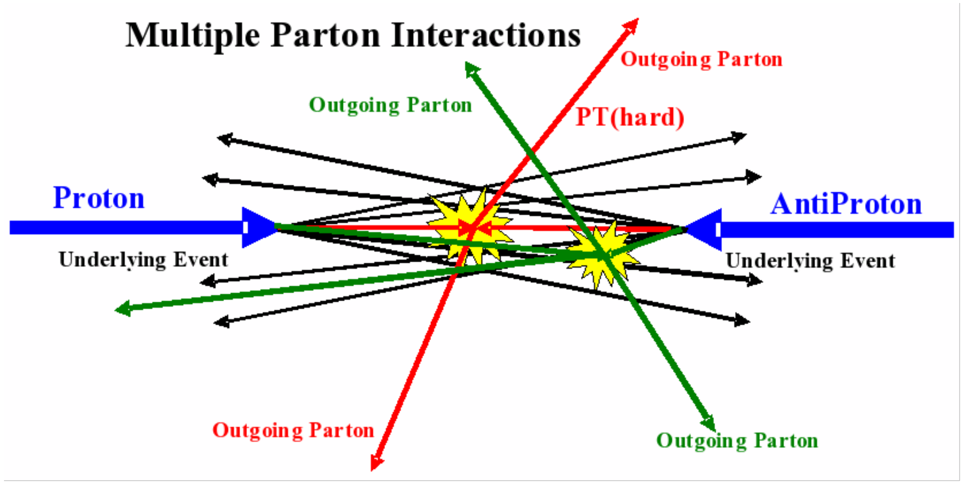


The results are very similar to theory predictions in case of crossover from hadron gas to quark gluon plasma. According to our analysis, the possible crossover should start at dN_ch/dη≃ 6 and end at dN_ch/dη≃ 24.

Necesitamos encontrar cuales son los valores de multiplicidad donde se observa la inflexión de la distribución $\sigma_s/<pT>^3$ vs <pT>

Multiple parton interactions and multiplicity



$$\frac{d\sigma}{dp_T^2} = \sum_{i,j,k} \int \int \int dx_1 dx_2 d\hat{t}\, \hat{\sigma}_{ij}^{k}(\hat{s},\hat{t},\hat{u}) f_i^1(x_1,Q^2) f_j^2(x_2,Q^2)\, \delta\left[p_T^2 - \frac{\hat{t}\hat{u}}{\hat{s}}\right]$$

Hard cross section above $p_{T\min}$; is:

$$\sigma_{\text{hard}}(p_{T\min}) = \int_{p_{T\min}^2}^{s/4} \frac{d\sigma}{dp_T^2} dp_T^2 .$$

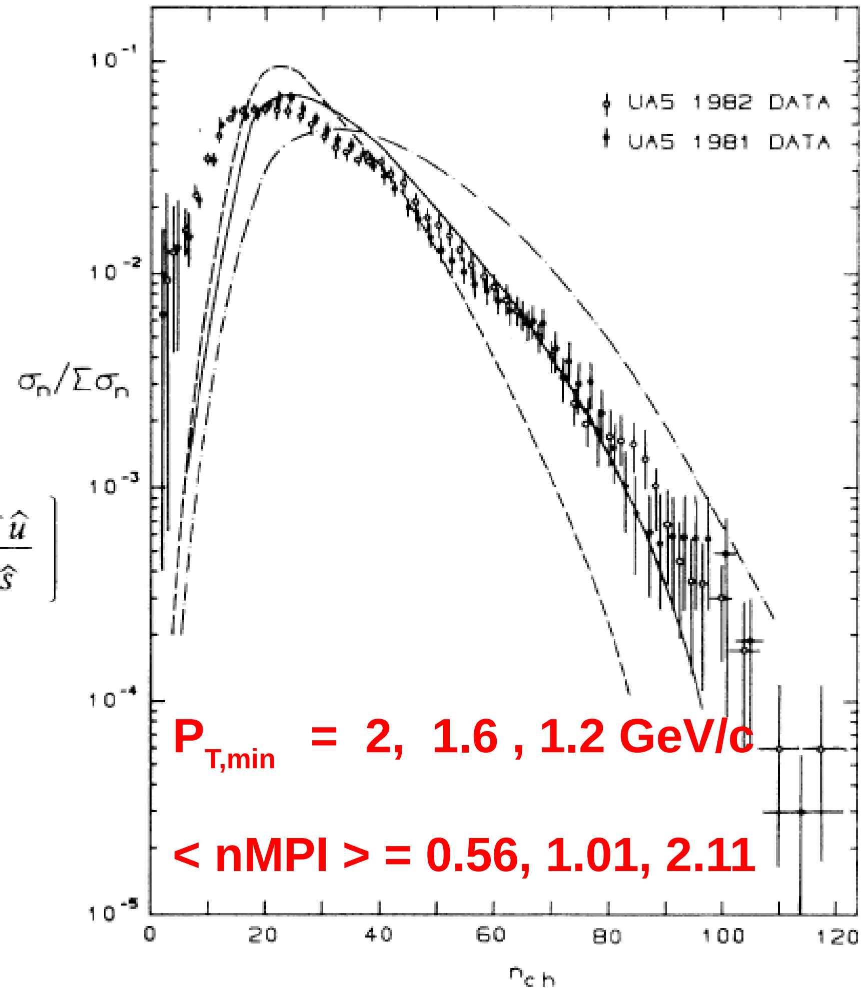
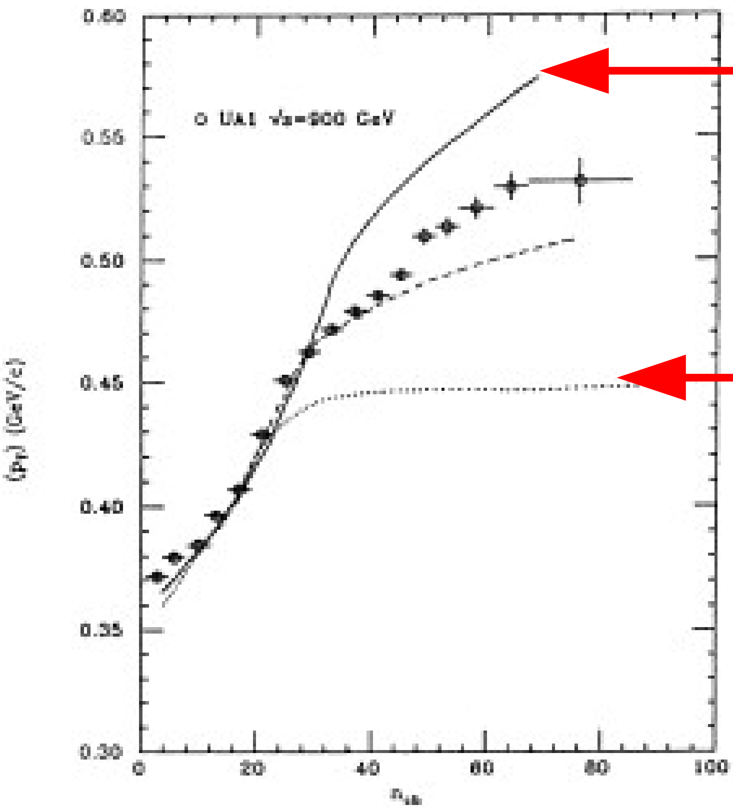


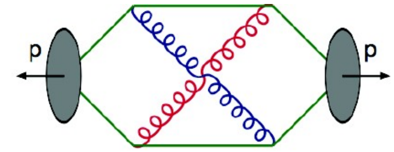
FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min} = 2.0$ GeV; solid line, $p_{T\min} = 1.6$ GeV; dashed-dotted line, $p_{T\min} = 1.2$ GeV.

Sjöstrand, et. al
Phys. Rev. D36, 2019 (1987)

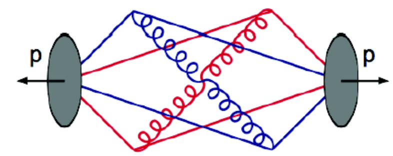
Color reconnection effects on <p_T>



Minimal string length:
For each consecutive interaction
=> <p_T> (n_{ch}) ~ rising.

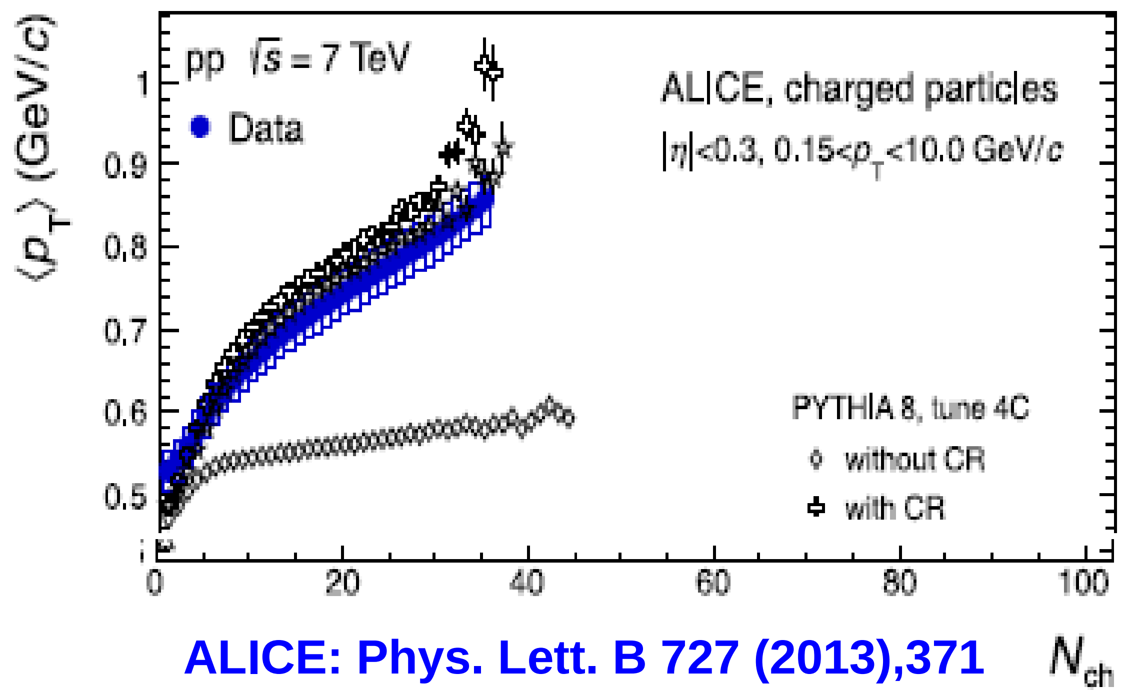


Maximal string length:
Long strings to remnants
=> comparable n_{ch}/interaction
=> <p_T> (n_{ch}) ~ Flat.



Phy.Rev.Lett.111,042001(2013)

Average transverse momentum of charged particles in |η| < 2.5 as a function of the multiplicity. UA1 data points at 900GeV



Sjöstrand, et. al
Phys. Rev. D36, 2019 (1987)

ALICE: Phys. Lett. B 727 (2013),371

Exp. Motivation: <p_T> vs N_{ch} in pp, p–Pb, and Pb–Pb

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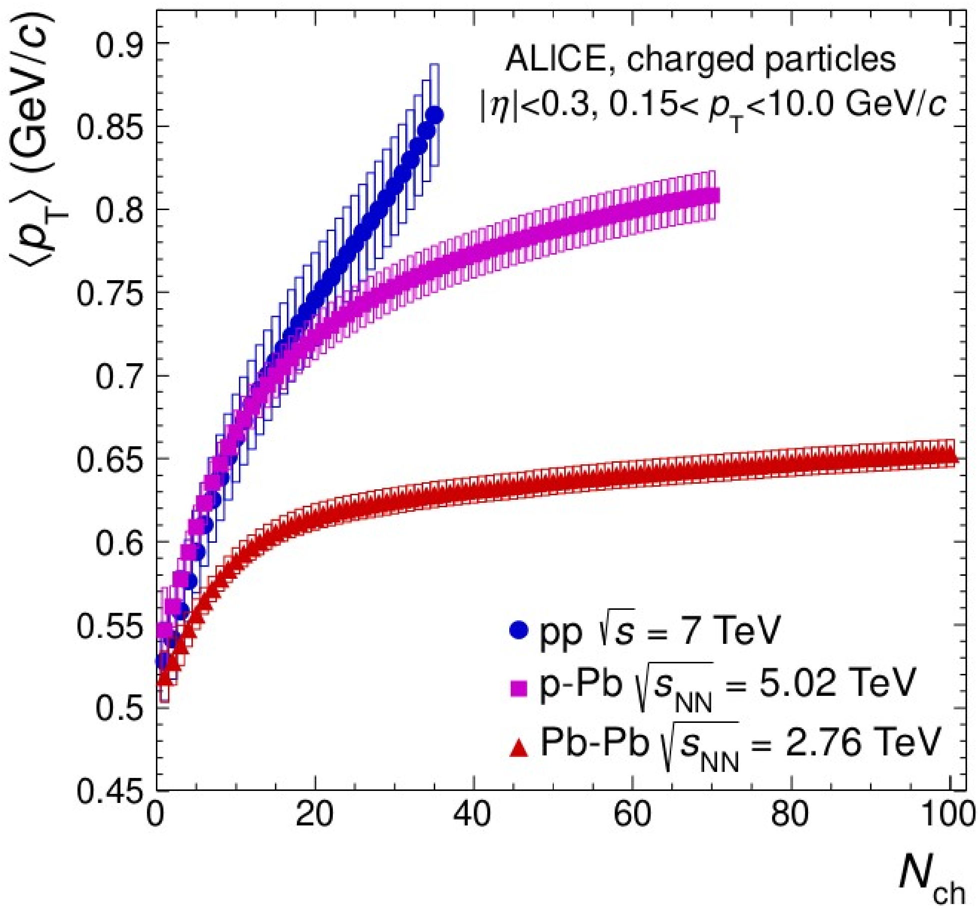


- In pp and p–Pb collisions, a strong increase of <p_T> with Nch is observed, which is much stronger than that measured in Pb–Pb collisions.
- For pp collisions, this could be attributed, within a model of hadronizing strings, to multiple-parton interactions and to a final-state color reconnection mechanism.
- The data in p–Pb and Pb–Pb collisions cannot be described by an incoherent superposition of nucleon-nucleon collisions and pose a challenge to most of the event generators.

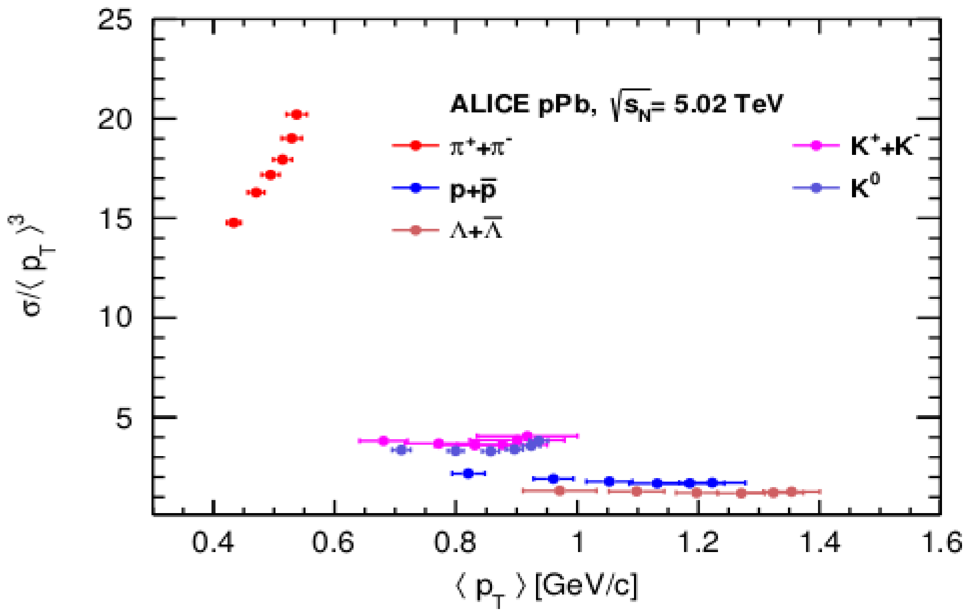
ALICE: PLB727, 371 (2013)

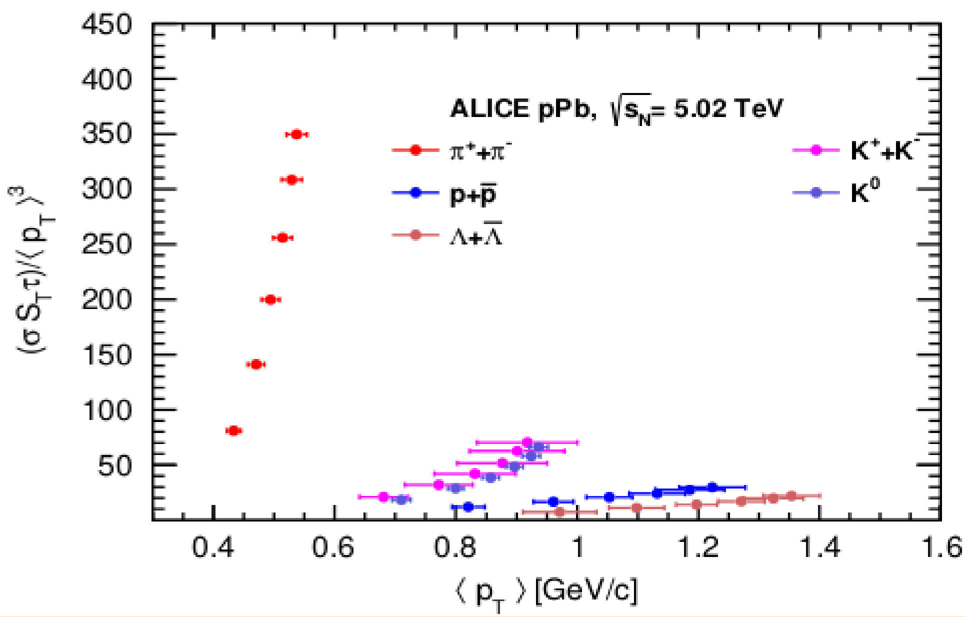
Entropy normalized vs <p_T> and <N_{ch}> for identified particles

($\sigma/\langle p_T\rangle^3$): Heavier hadrons have a flat distribution, meanwhile the lighter meson show a rapid increase.

($(\sigma S_T \tau)/\langle p_T\rangle^3$) a similar trend but a more pronounced growing slopes are observed.

Results are similar for ALICE and CMS for the case of pions, even when there are difference in the multiplicity measure between them.





Multiplicity and average transverse momentum in the dynamics of p+p, p+pb and Pb+Pb collisions

Instituto de Ciencias Nucleares UNAM

$\langle p_T \rangle$ vs N_{Ch}

- **Flattening has been suggested as possible signal for a phase transition in hadronic collisions Phys. Lett. B118, 138 (1982)**
- Increase wit multiplicity, it is explained by jet production
- A second rise observed at TEVATRON energies, but not at LHC
- For soft event is not energy dependent
- For Hard event, it increases faster as the energy of the collisions increases
- The behavior is almost linear at low energy
- **At higher energy grows faster (described by second order logarithmic polynomial of the collision energy) JHEP09(2010)091, PLB693, 53 (2010)**
- For identified particles, it exhibits a mass dependence
- **CGC model can reproduce the $\langle p_T \rangle$/ST as universal function at high Nch but not at low Nch. Could be explain by flow-like effects? Acta Phys. Pol. B 41 2799–826 (2010), PRC 87 064906 (2013)**
- **ALICE-LHC observed stronger dependence of Nch for p+p than for p+pb and ppb+Pb. This strong correlation has been attributed within PYTHIA to CR (producing flow-like effects), directly related with MPIs.**
- **PLB727, 371 (2013), PRL111, 042001 (2013), PRD 82, 074018 (2010), EPJ.C75 441 (2015)**
- **Equation of state in p+p, p+Pb and Pb+Pb collisions**