Multiplicity dependence of light flavor hadron production at LHC energies in the strangeness canonical suppression picture

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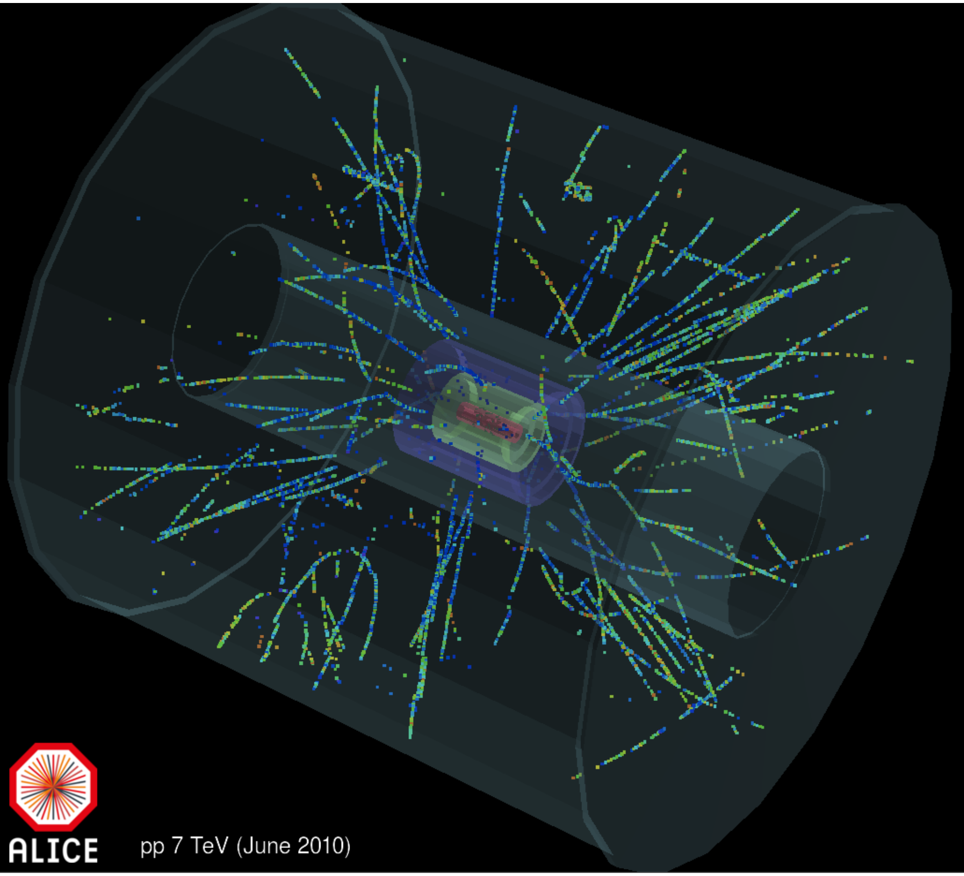
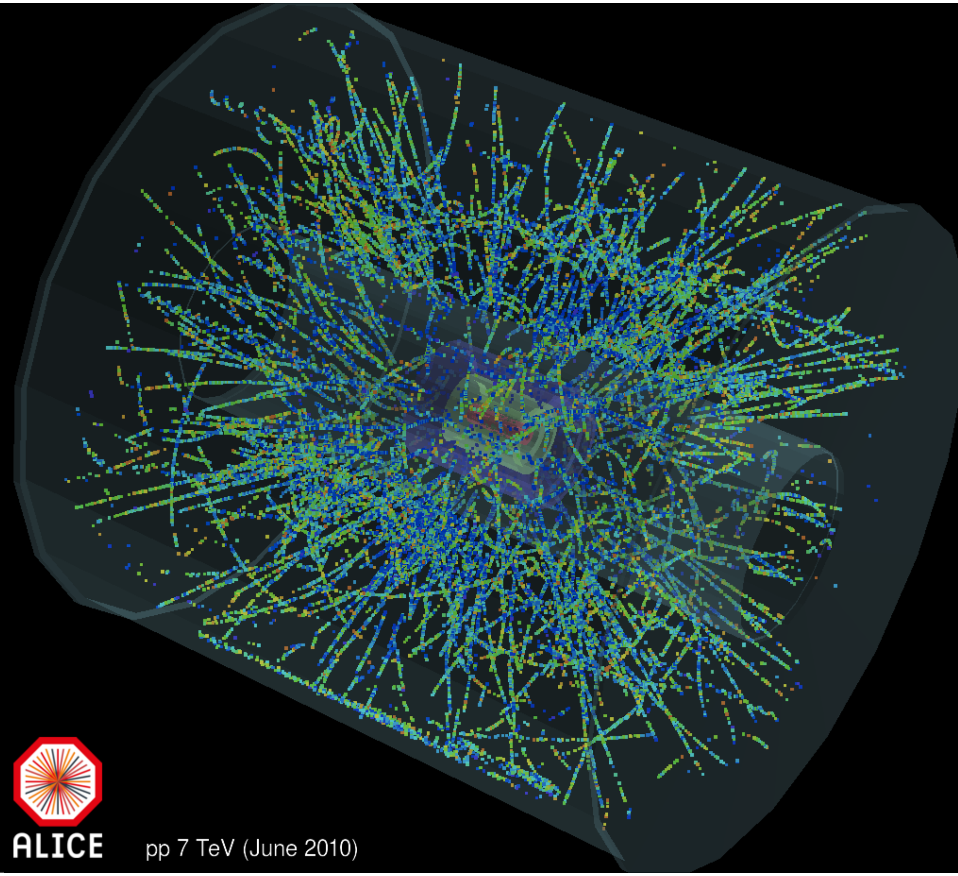
in collaboration with ***V. Vislavicius*** *(Lund University)*

Introduction (1)

Not all proton-proton (pp) collisions are the same..

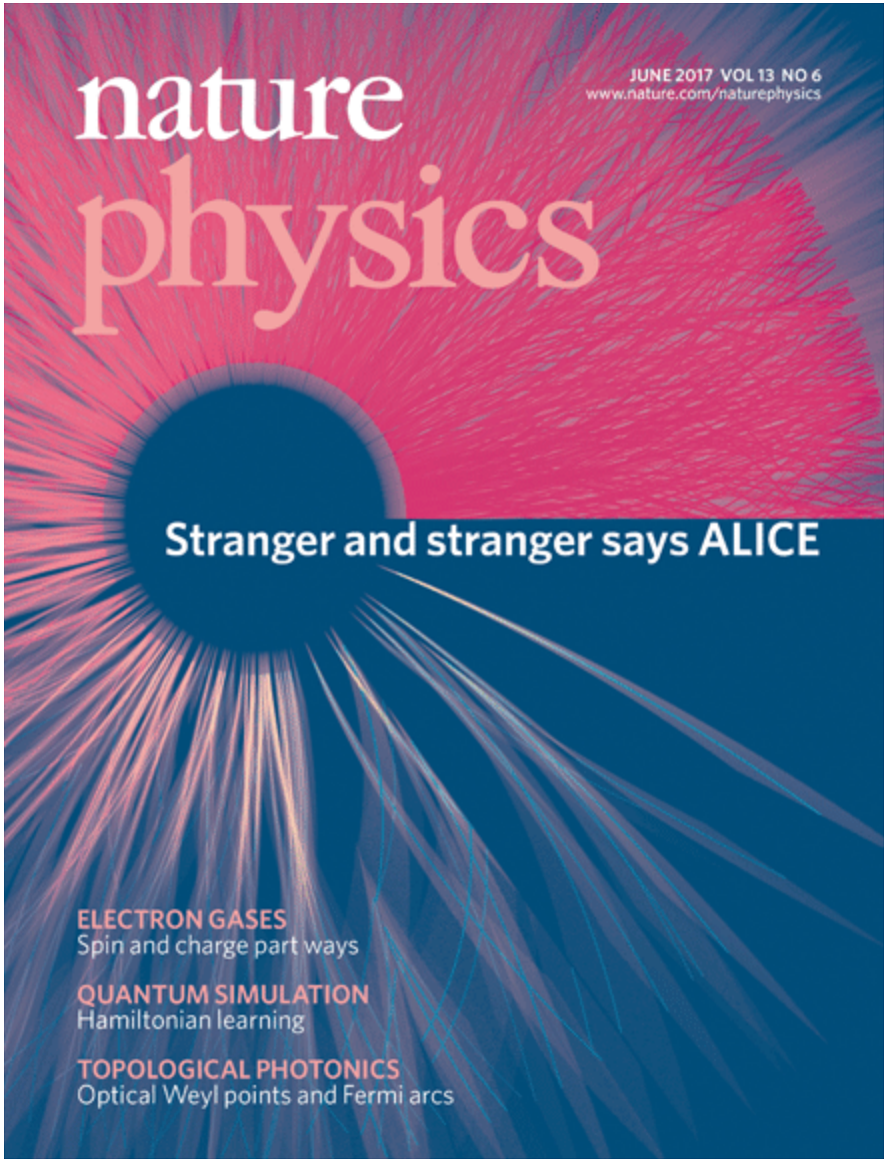




Introduction (2)

Remarkable discovery by the ALICE collaboration:

Strangeness production increases with increasing multiplicity in pp collisions.



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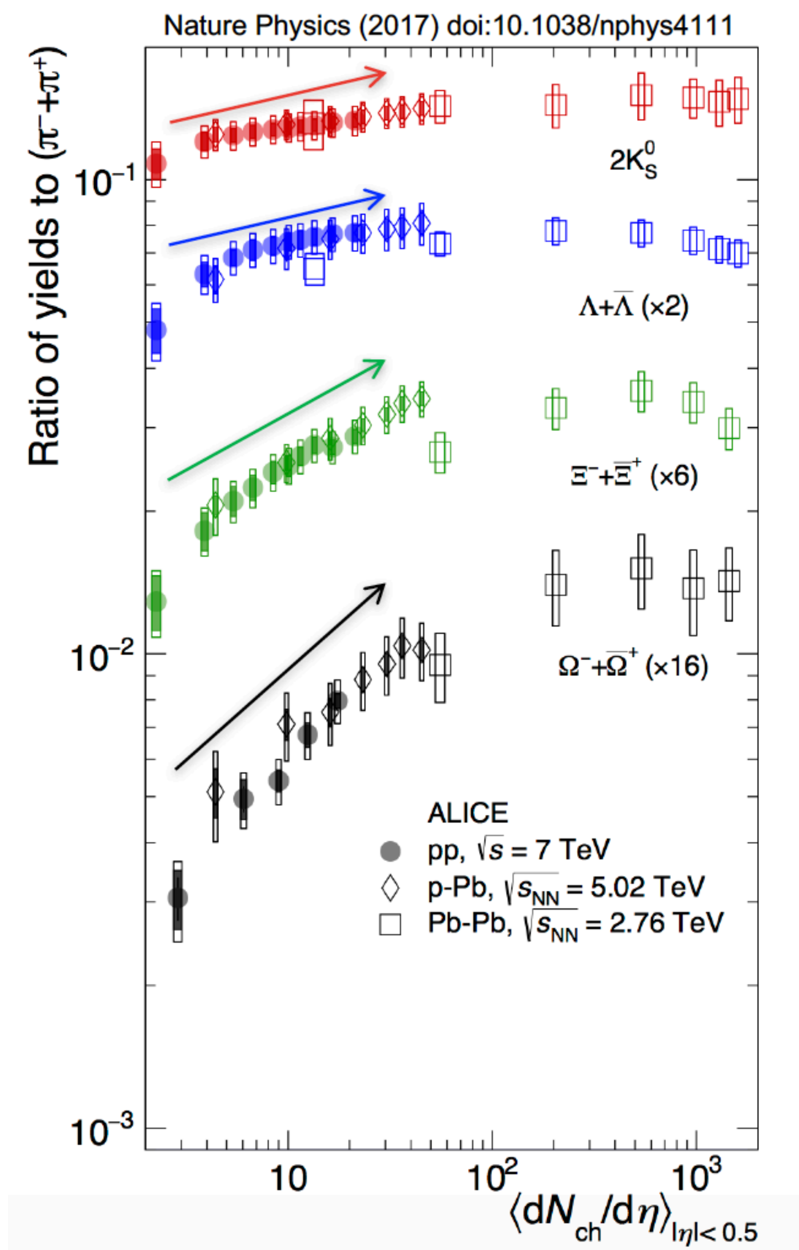
→ See talks by F. Bellini and N. Sharma.



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=> The ball is in the theory community to explain the observations!

Strangeness canonical suppression

→ QCD matter following the dynamics and conservation laws of the underlying theory

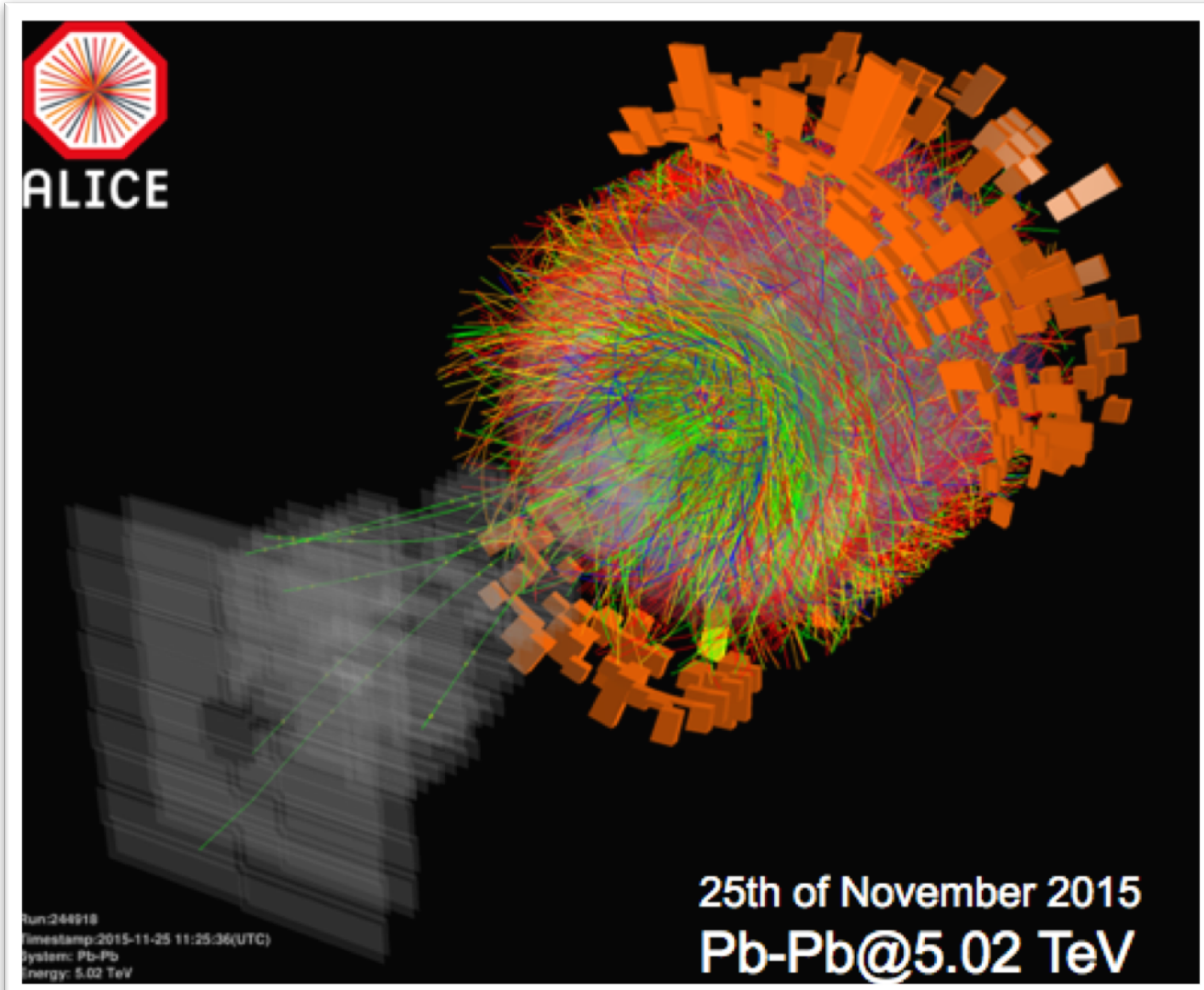
QCD inspired event-by-event generators

→ multi-parton interactions

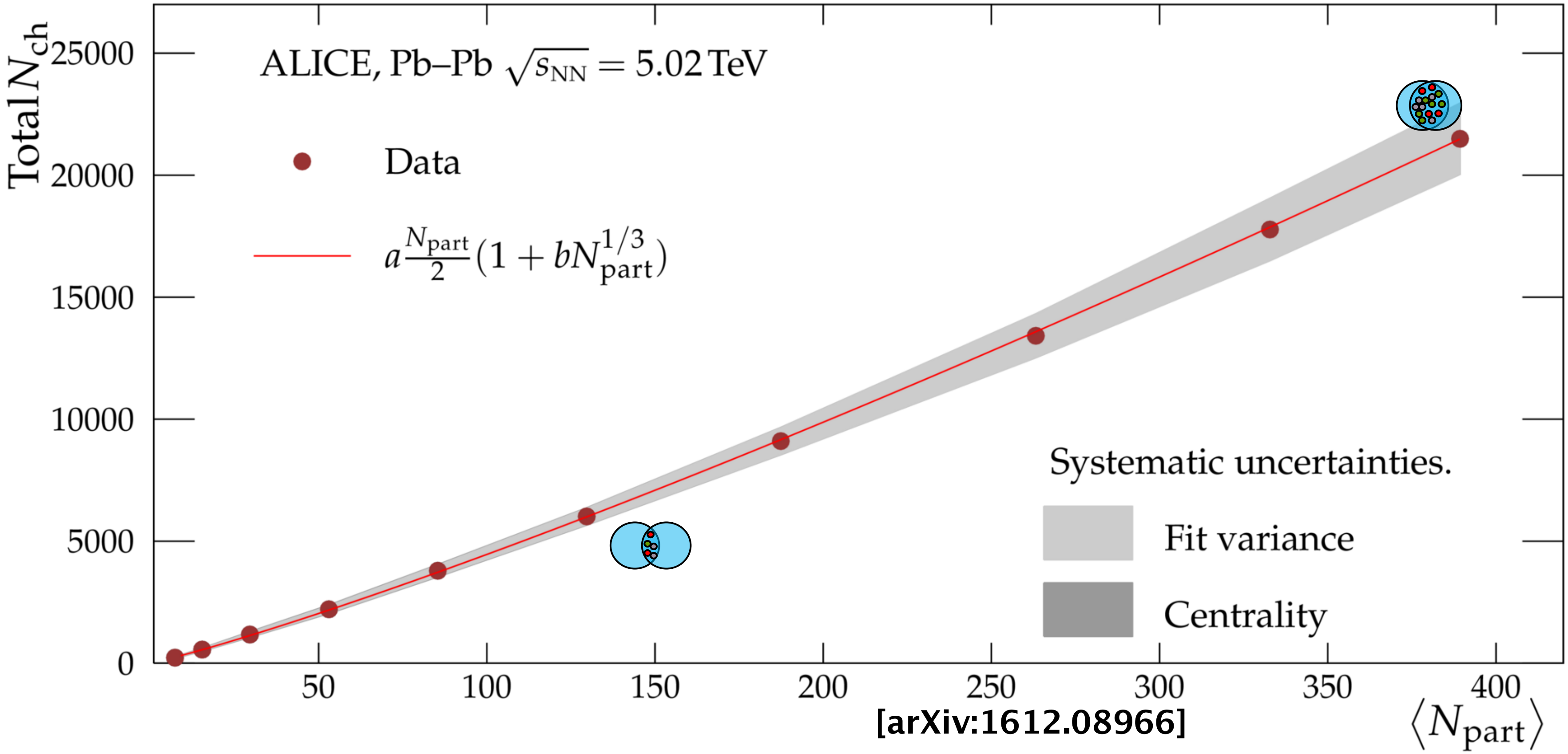
→ color ropes

Core-corona approaches

Thermodynamics and heavy-ion collisions



Total number of charged hadrons (1)

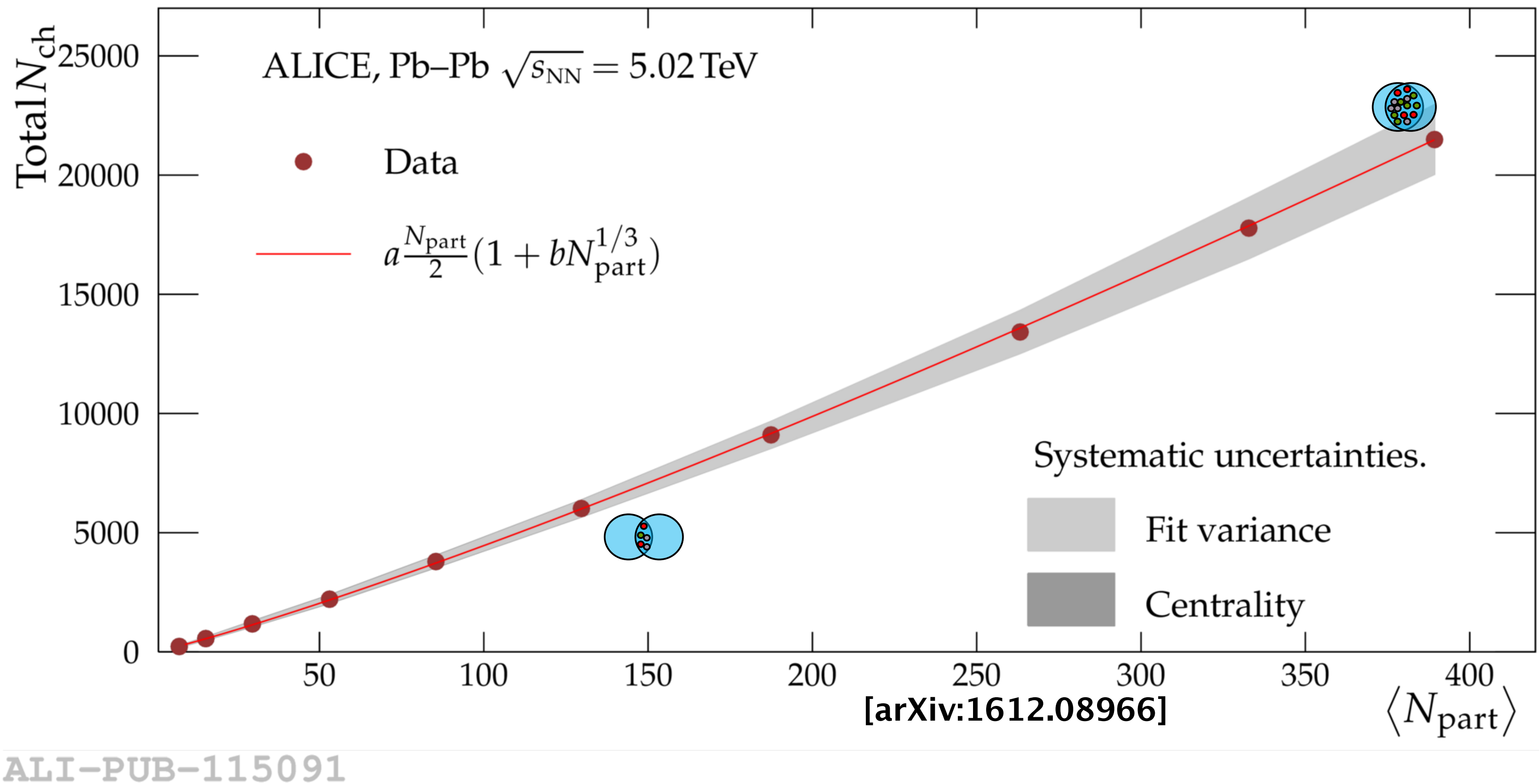


[arXiv:1612.08966]

ALI-PUB-115091

→ Collisions of heavy-ions at high energy accelerators allow the creation of several tens of thousands of hadrons (1 << N << 1mol) in local thermodynamic equilibrium in the laboratory.

Total number of charged hadrons (2)



Equilibrium models such as the thermal model typically need 5-6 interactions to work. Where does this picture break down? Does it work in pp and pPb?

Short introduction to thermodynamics (1)

- The maximum entropy principle leads to the thermal most likely distribution of particle species.
- Entropy: the number of possible micro-states Ω being compatible with a macro-state for a given set of macroscopic variables (*E*, *V*, *N*):

$$S = k_B \cdot \ln \Omega$$

- Compatibility to a given macroscopic state can be realized *exactly or only in the statistical mean*.

L. Boltzmann

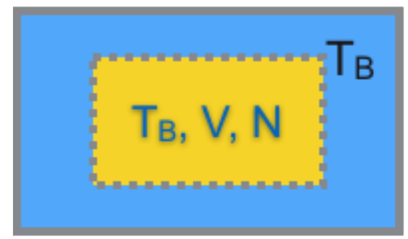
Short introduction to thermodynamics (2)

We therefore distinguish three different *statistical ensembles*:

(i) micro-canonical: *E*, *V*, *N* fix

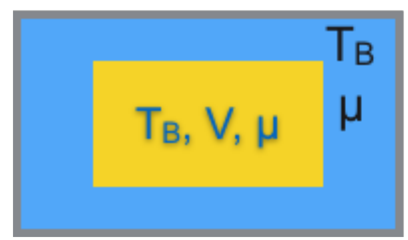
Statistical model for e^+e^- collisions.

(ii) canonical: *T*, *V*, *N* fix
➔ given volume element is coupled to a heat bath



Strangeness conservation in peripheral HI collisions.

(iii) grand-canonical: *T*, *V*, *μ* fix
➔ given volume element can also exchange particles with its surrounding (heat bath and particle reservoir)



Central relativistic heavy-ion collisions.

Short introduction to Thermodynamics (3)

A small example: barometric formula (density of the atmosphere at a fixed temperature as a function of the altitude *h*).

→ Probability to find a particle on a given energy level *j*:

$$P_j = \frac{\exp\left(-\frac{E_j}{k_B T}\right)}{Z}$$

Boltzmann factor

Partition function *Z*
(*Zustandssumme* = *"sum over states"*)

Energy on a given level is simply the potential energy: $E_{pot} = mgh$. This implies for the density n (pressure p):

$$\frac{p(h_1)}{p(h_0)} = \frac{n(h_1)}{n(h_0)} = \frac{N \cdot P(h_1)}{N \cdot P(h_0)} = \exp\left(-\frac{\Delta E_{pot}}{k_B T}\right) = \exp\left(-\frac{mg}{RT}\Delta h\right)$$

Thermal model for heavy-ion collisions

Grand-canonical partition function for an *relativistic ideal quantum gas of **hadrons*** (HRG) of particle type i (i = pion, proton,… → full PDG!):

(-) for bosons, (+) for fermions (quantum gas)

$\beta = \frac{1}{kT}$

$E_i = \sqrt{p^2 + m_i^2}$ *dispersion relation (relativistic)*

$$\ln Z_{GK_i} = \pm g_i \frac{V}{2\pi^2\hbar^3} \int_0^\infty dp\, p^2 \ln\left(1 \pm e^{-\beta(\epsilon(p)-\mu_i)}\right)$$

spin degeneracy

$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3_i} + \mu_C C_i$

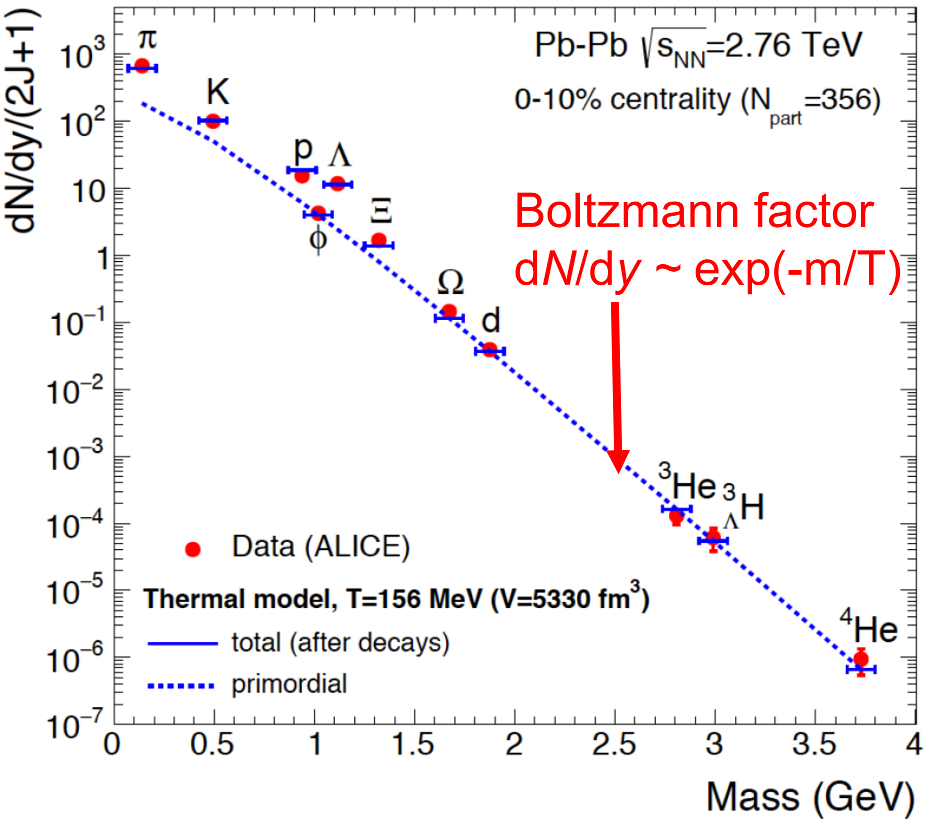
chemical potential representing each conserved quantity

Once the partition function is known, we can calculate all other thermodynamic quantities:

$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} \quad P = \frac{\partial(T\ln Z)}{\partial V} \quad s = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial T}$$

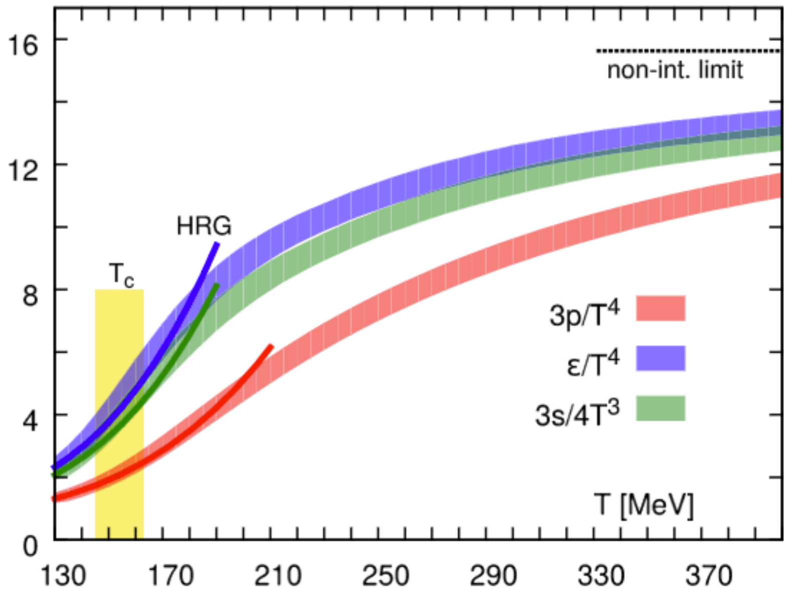
Temperature T is the only free parameter in the model!

Success of thermal model in heavy-ions



[A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, **arXiv:1710.09425**]

[PRD 90 094503 (2014)]



→ Chemical freeze-out temperature corresponds to phase transition temperature found by ab-initio calculations with **Lattice QCD.**

→ Strange hadrons are produced in apparent chemical equilibrium together with all other light flavor hadrons.

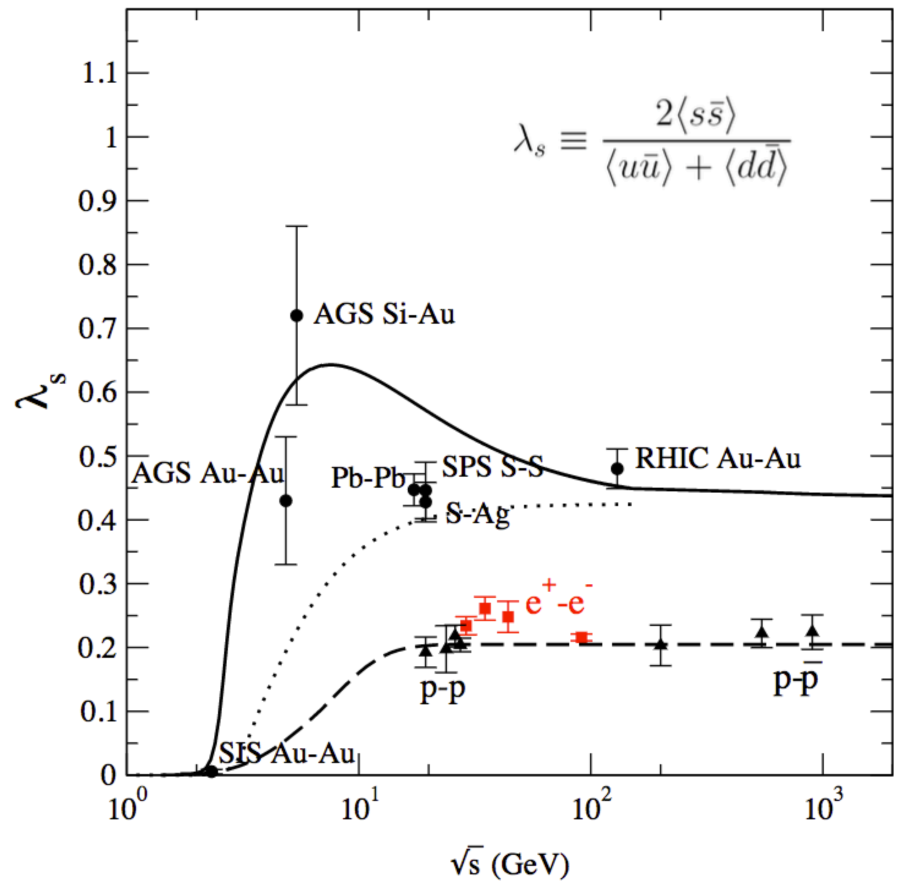
Thermal model in small systems (pp, pPb)

Can we apply a thermodynamic description to small collision systems?

→ **Yes, if conservation laws are respected because only fifth to tenth quark is a strange quark! E.g. an Omega-Baryon (sss) must be balanced by other hadrons containing at least three other anti-strange quarks.**

→ Exact conservation of strangeness quantum number yields leads effectively to a reduction of the phase-space and thus a *suppression of strange particles if the total number of particles is small.*

[Nucl.Phys. A697 (2002) 902-912]



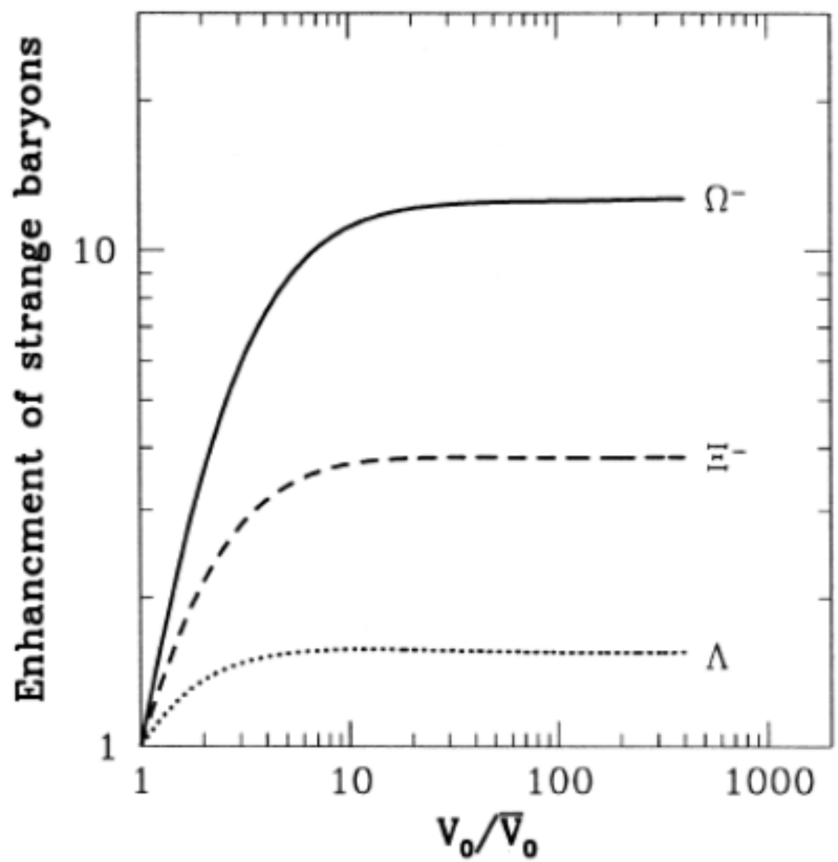
Strangeness canonical suppression

→ In the language of thermodynamics: canonical ensemble instead of grand-canonical treatment of the strangeness quantum number (exact conservation of strangeness).

→ Original formalism was derived for heavy-ions at SPS energies (K.Redlich, J.Cleymans, H. Oeschler and others).

→ Studies shown in the following are based on the THERMUS code which provides an implementation of strangeness canonical treatment.

[Phys.Lett. B486 (2000) 61-66]

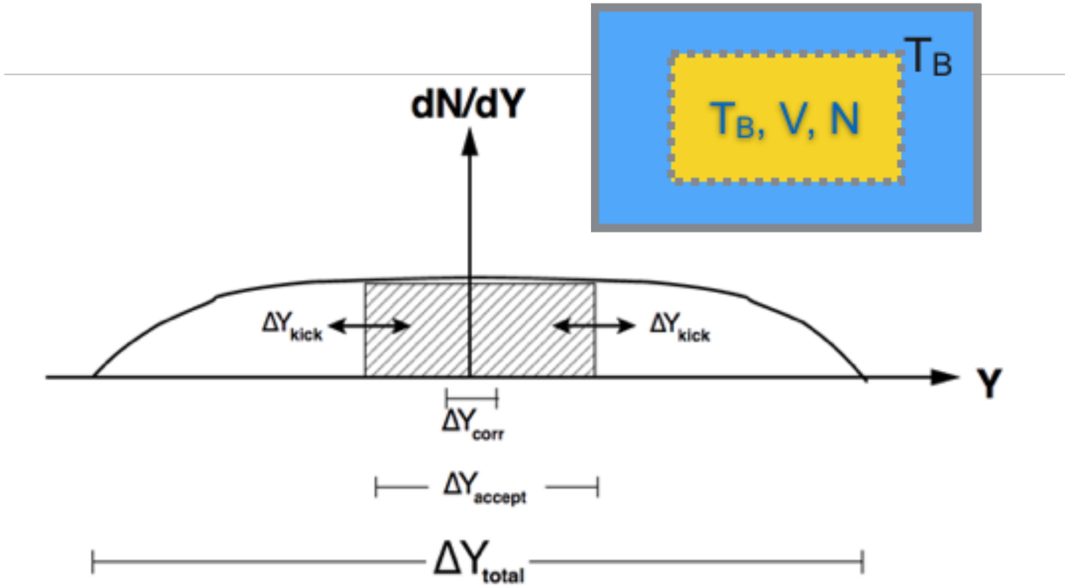


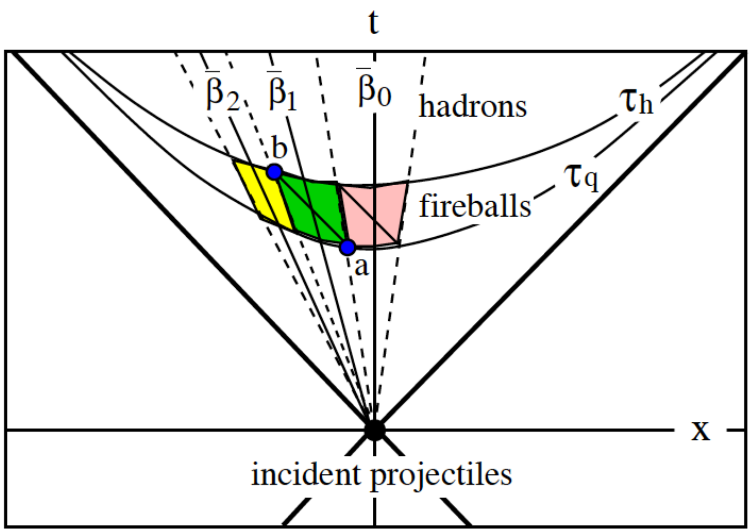
[THERMUS: Comput.Phys.Commun.180:84-106,2009]

Strangeness correlation volume

Particle production at LHC energies occurs over a wide rapidity range.
→ What is the maximum rapidity window over which two hadrons containing strange quarks can remain causally connected?

→ In the following analysis, treated as the only free parameter in the model: rapidity window *k*.



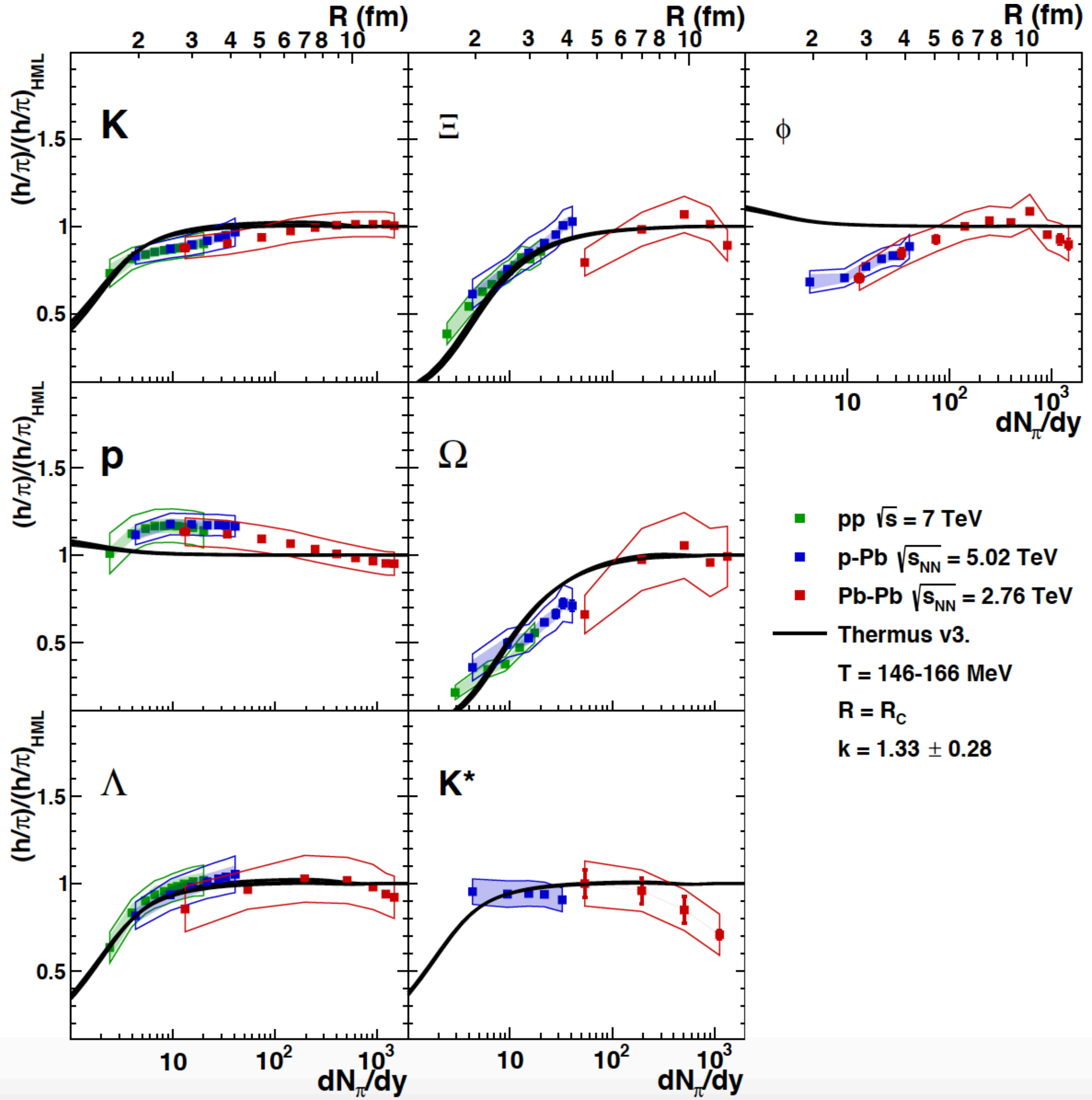


[V. Koch, arXiv:0810.2520]

[Castorina/Satz: Int.J.Mod.Phys. E23 (2014) no.4, 1450019]

Results (1)

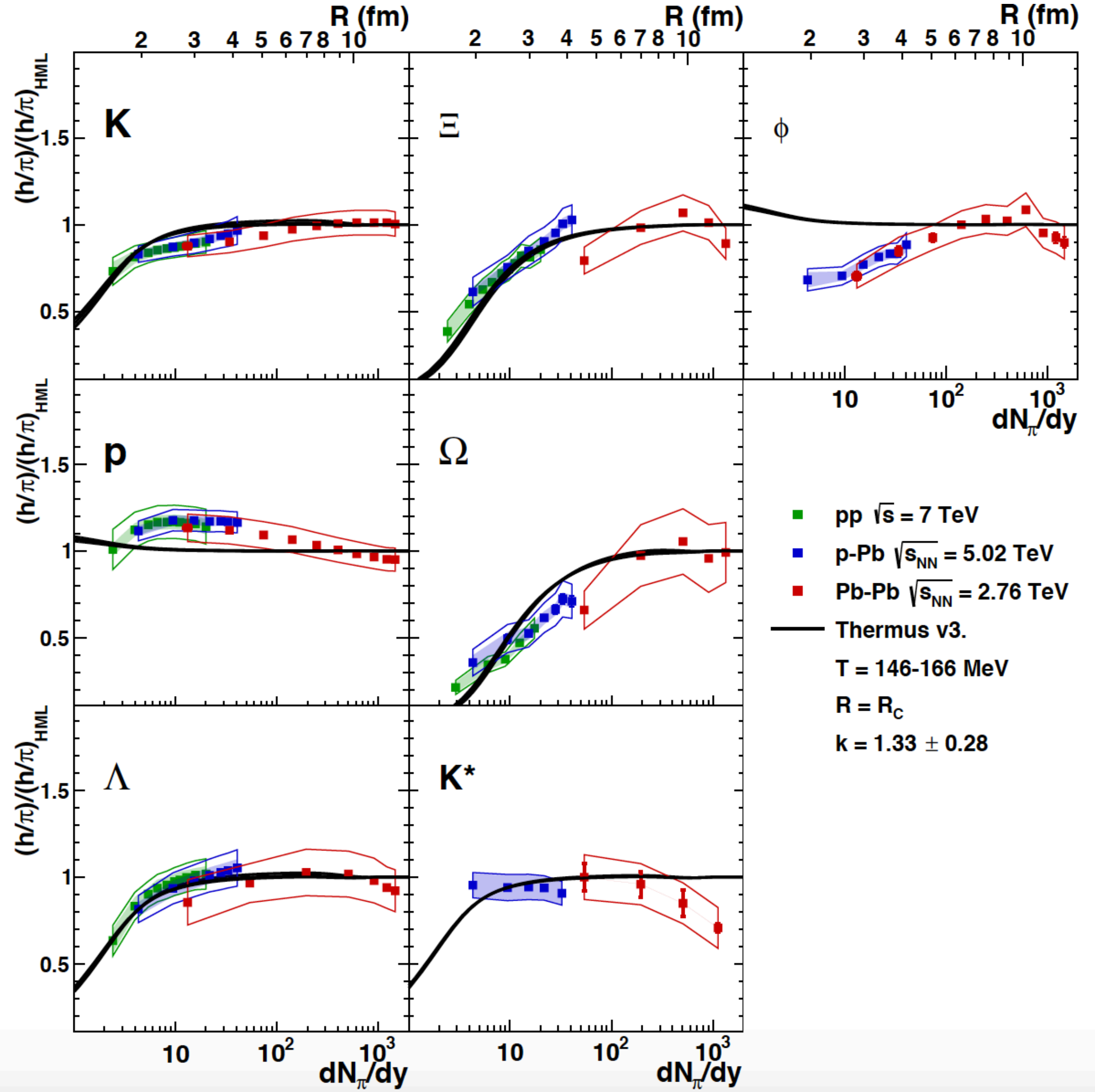
Temperature dependence cancels in first order if one normalizes to the saturation value in heavy-ion collisions.



[V. Vislavicius, AK, arXiv:1610.03001]

Results (2)

→ Smooth transition of particle ratios across collision systems as a function of multiplicity precisely corresponds to the expectation of strangeness canonical suppression.

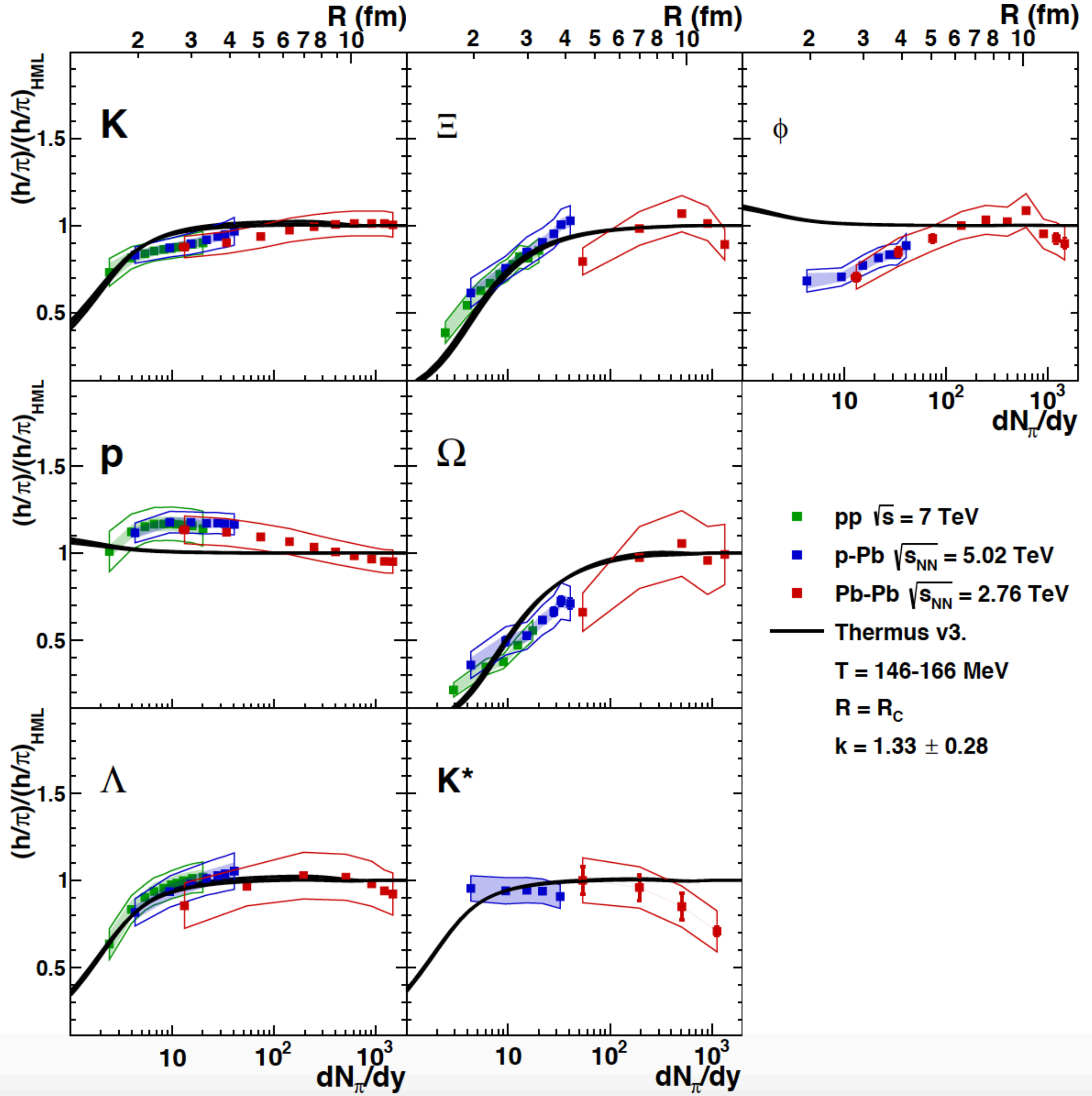


[V. Vislavicius, AK, arXiv:1610.03001]

Results (3)

→ Good description for the production of all light flavour hadrons is found except for the phi meson!

→ Total correlation window for strangeness production seems to extend over 1.33 +/- 0.28 units in rapidity.



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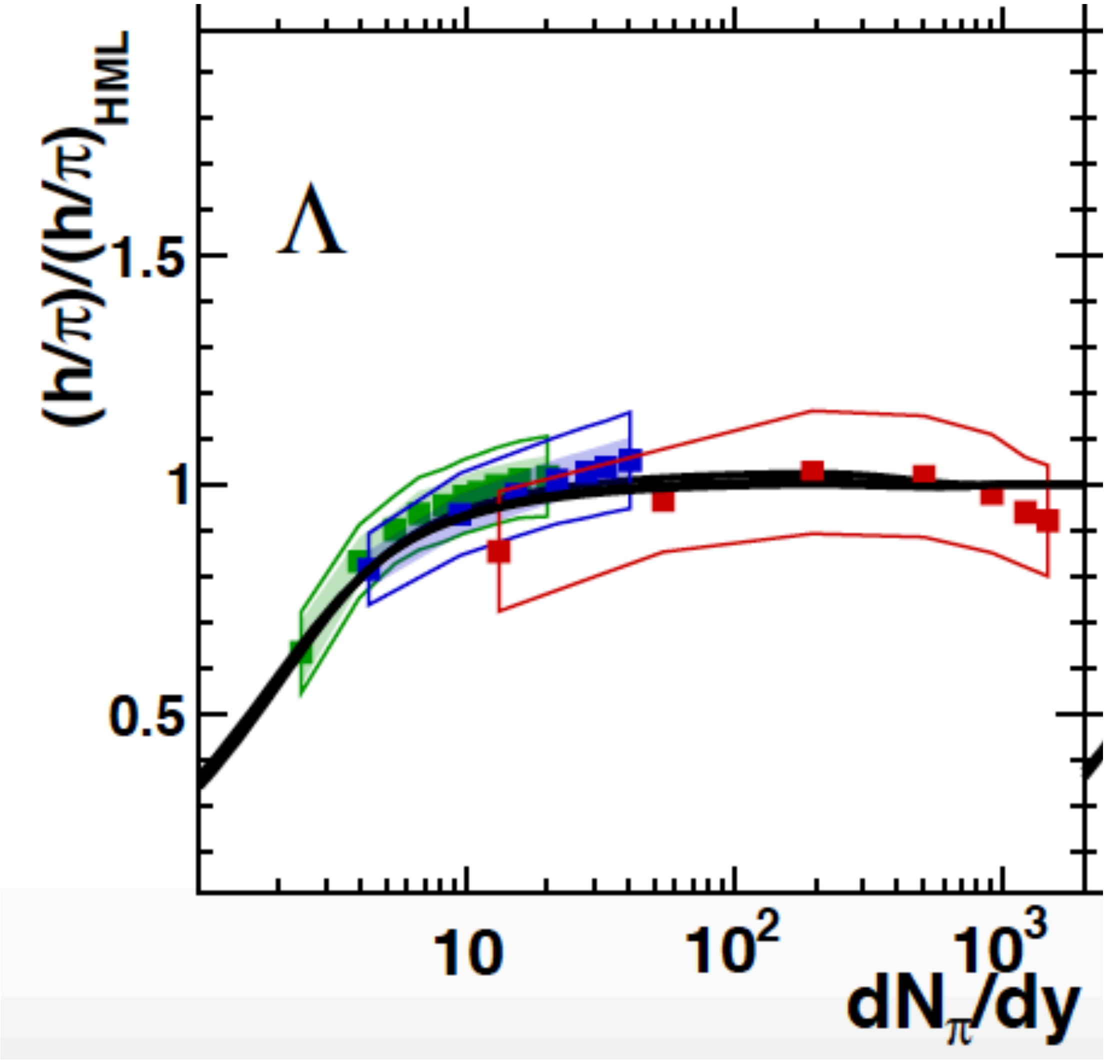


[V. Vislavicius, AK, arXiv:1610.03001]

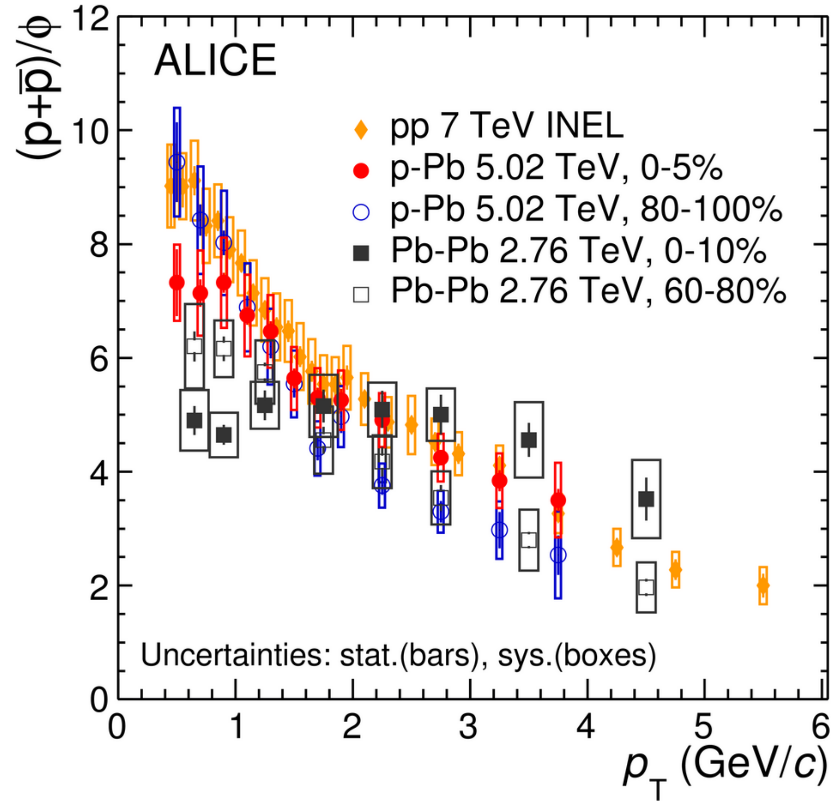
The ϕ-meson (s,sbar)

The ϕ-meson as a hadron with hidden strangeness is in the current implementation of *hadron* resonance gas models not suppressed in small collision systems.

→ Can this be cured by implementing conservation laws on quark level (quark-hadron duality)?

→ Is the ϕ produced out of equilibrium? N.B.: It also does not show radial flow!

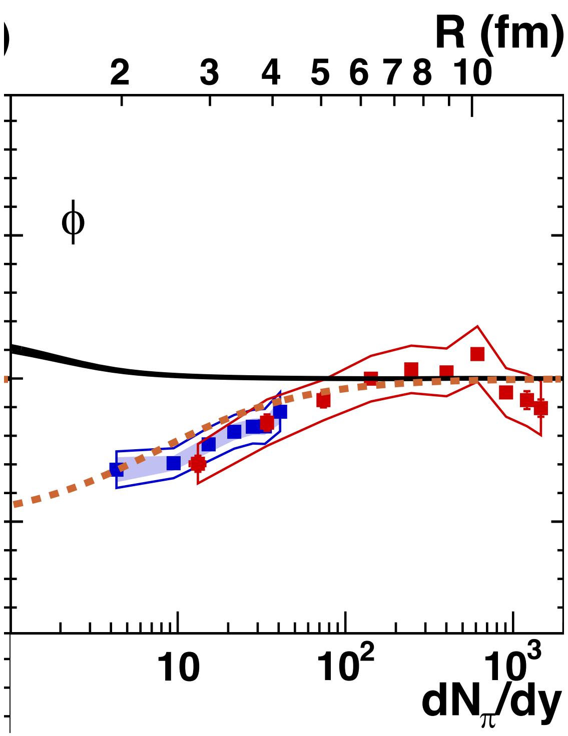
→ Or is strangeness canonical suppression the wrong approach and QCD inspired MCs provide the only real solution?

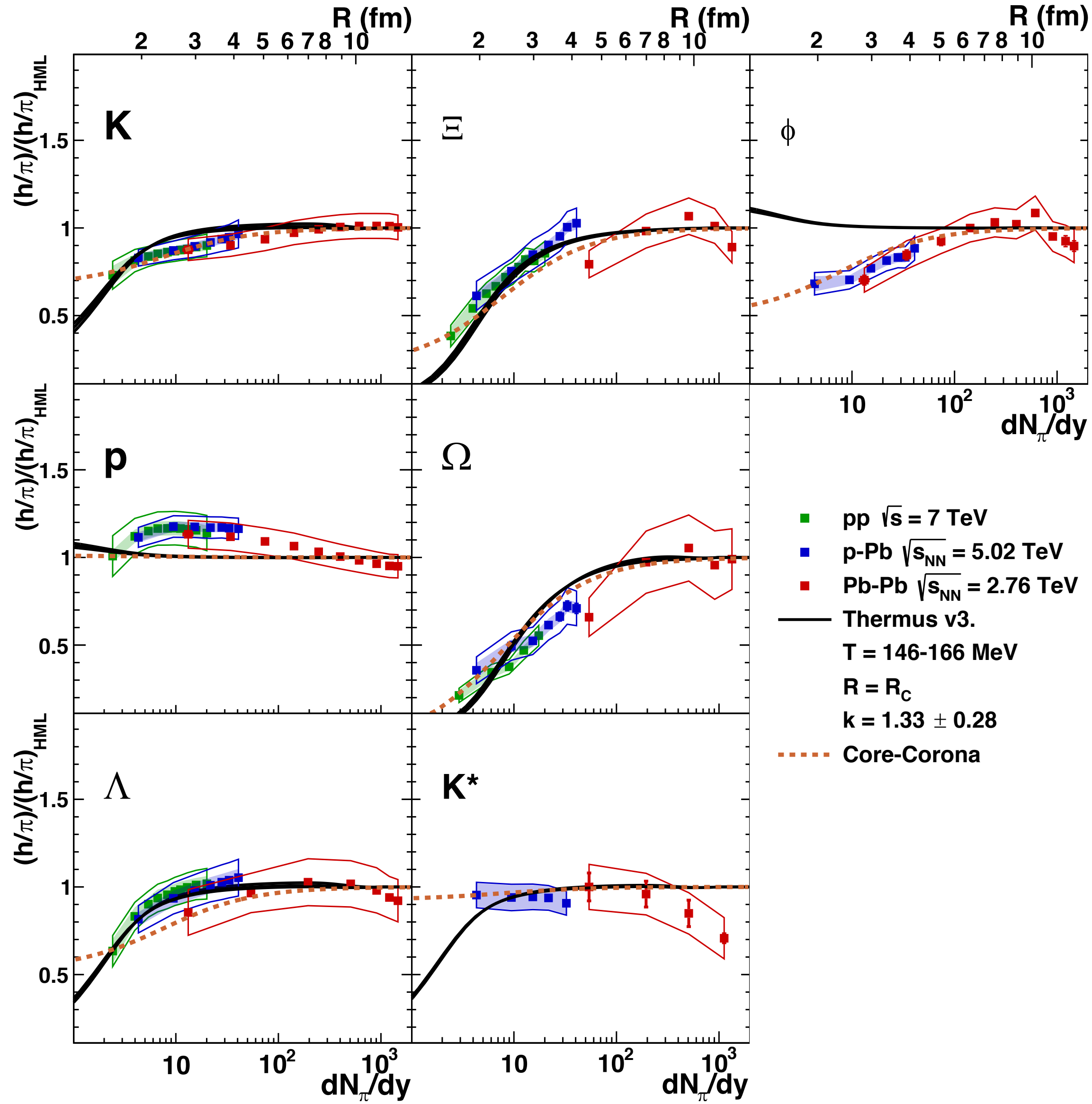


[Eur. Phys. J. C 76 (2016) 245]

A word on core-corona

→ Core-corona approaches (lowest available point in multiplicity and saturation value as anchor points) potentially give a better description of the ϕ-meson





Summary

- Thermal-statistical model gives excellent description of light flavor particle production yields in heavy-ion collisions.
- This description can be extended to small collision systems (pp & pPb) if one takes the explicit conservation of strangeness into account.
- Within this approach, a very good description of the ALICE data across collision systems is found with the notable exception of the ϕ-meson.

BACKUP SLIDES

Multiplicity percentiles

[ALICE, Nature Physics 13, 535–539 (2017)]

Table 1: Event multiplicity classes used in the analysis, their corresponding fraction of the INEL>0 cross-section ($\sigma/\sigma_{\mathrm{INEL}>0}$) and their corresponding $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ in $|\eta| < 0.5$. The value of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ in the inclusive INEL>0 class is 5.96 ± 0.23. The uncertainties are the quadratic sum of statistical and systematic contributions.

Class name	I	II	III	IV	V
$\sigma/\sigma_{\mathrm{INEL}>0}$	0-0.95%	0.95-4.7%	4.7-9.5%	9.5-14%	14-19%
$\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$	21.3 ± 0.6	16.5 ± 0.5	13.5 ± 0.4	11.5 ± 0.3	10.1 ± 0.3
Class name	**VI**	**VII**	**VIII**	**IX**	**X**
$\sigma/\sigma_{\mathrm{INEL}>0}$	19-28%	28-38%	38-48%	48-68%	68-100%
$\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$	8.45 ± 0.25	6.72 ± 0.21	5.40 ± 0.17	3.90 ± 0.14	2.26 ± 0.12