Study of chemical freeze-out parameters in pp, p-Pb, and Pb-Pb collisions

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Constraining QCD Phase Boundary with Data from Heavy Ion Collisions,
EMMI Workshop, GSI, Darmstadt, Germany, Feb. 12-14, 2018.

Helmut Oeschler

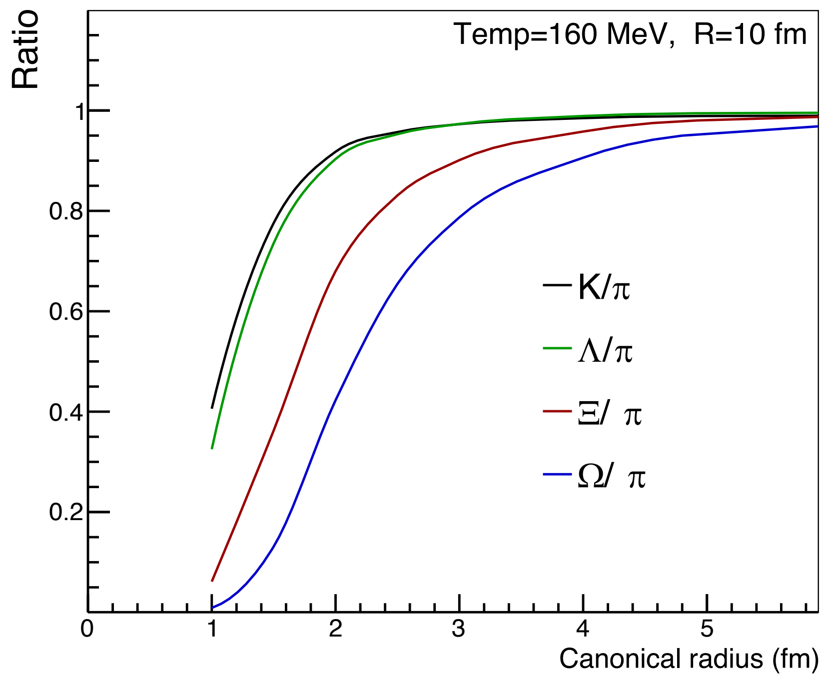
- Great mentor, good advisor
- Very generous person
- Always smiling, helping and motivating to do good work
- Enjoy Physics
- Love nature and enjoy good food.

Introduced me to the nuclei analysis in ALICE, thermal model, and strangeness production in HI.

Cherish all moments spent with him

Always be remembered!

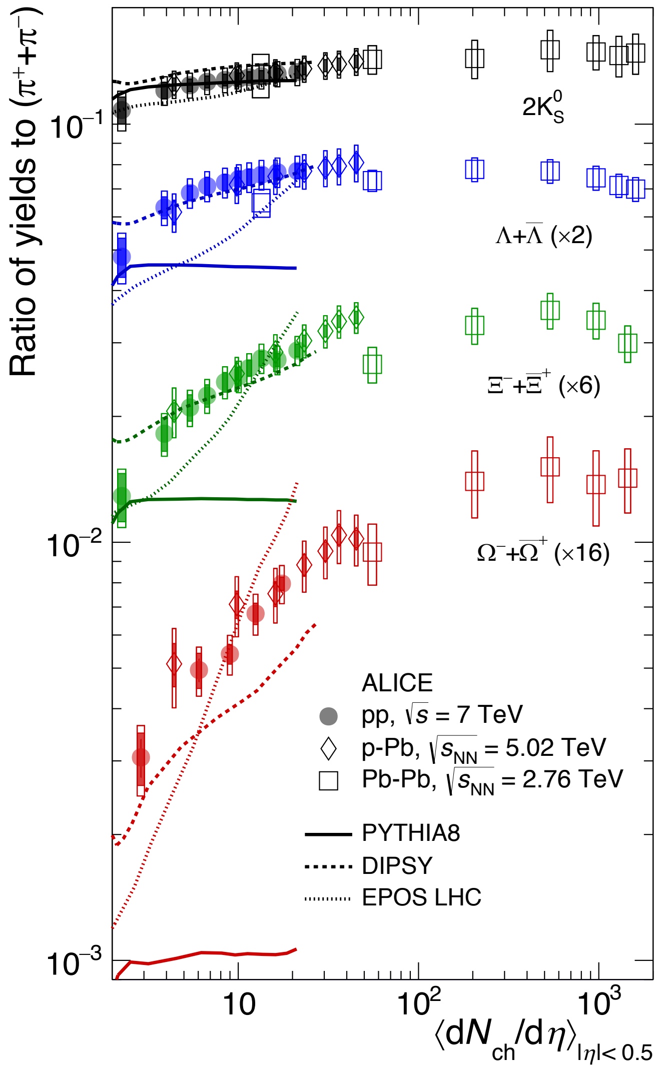
Thermal model predictions for small systems



- Particle ratios as a function of R_C normalized to their GC value.
- Canonical suppression increase with increase in strangeness content of particle and with decrease in R_C.
- Strange particle densities suppressed due to exact strangeness conservation constrain.

I. Kraus, J. Cleymans, H. Oeschler and K. Redlich, Phys. Rev. C 79, 014901 (2009)

Strangeness enhancement in small systems



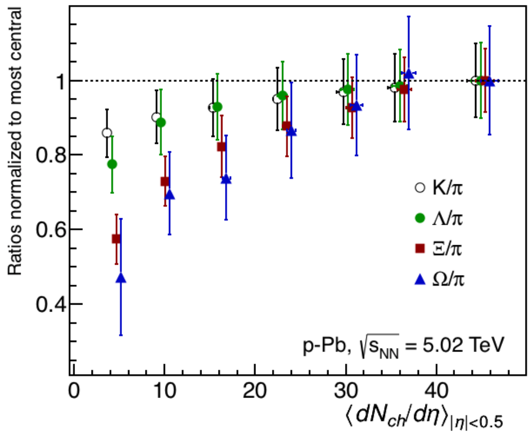
ALICE: Nature Phys. 13 (2017) 535-539

- Strange particles to pion ratio increase with increase in produced charged particle multiplicity in pp and in p-Pb collisions.
- Enhancement is more as the strangeness content (S) increases.

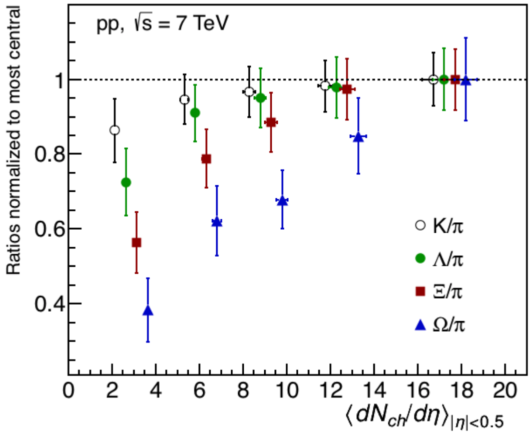
If we extrapolate pp multiplicity toward Pb-Pb, do they follow same behaviour?

Normalized strange particles to pion ratio vs multiplicity

p-Pb data



pp data



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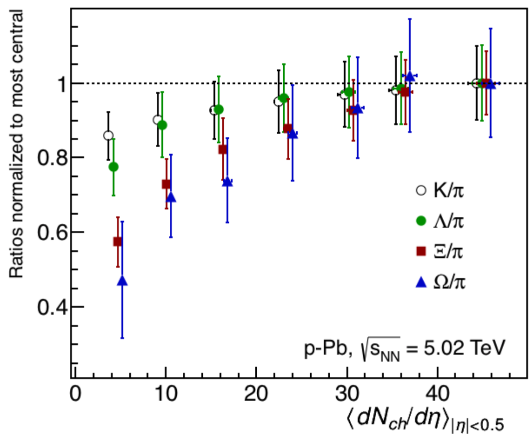
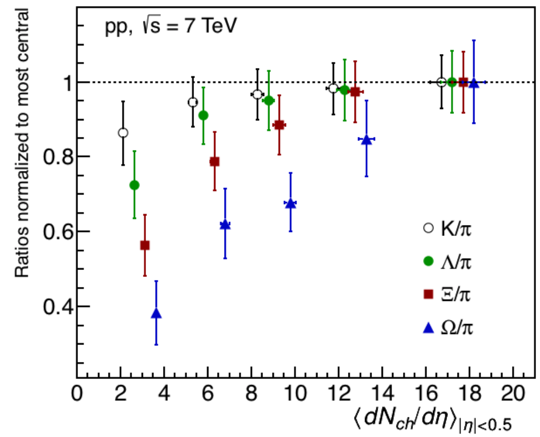
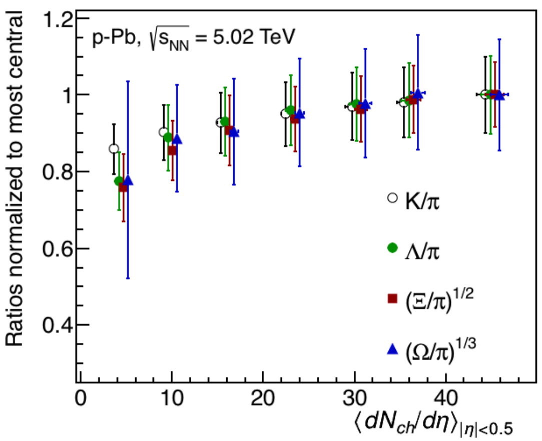
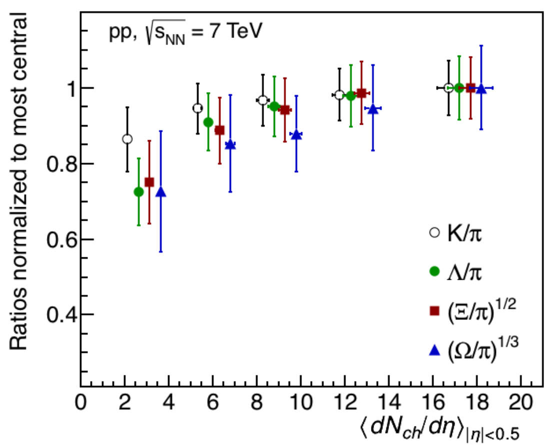


pp data







Ratios to the power 1/ΔS relative to their most central coincide for p-Pb data

Fitting Pb-Pb data

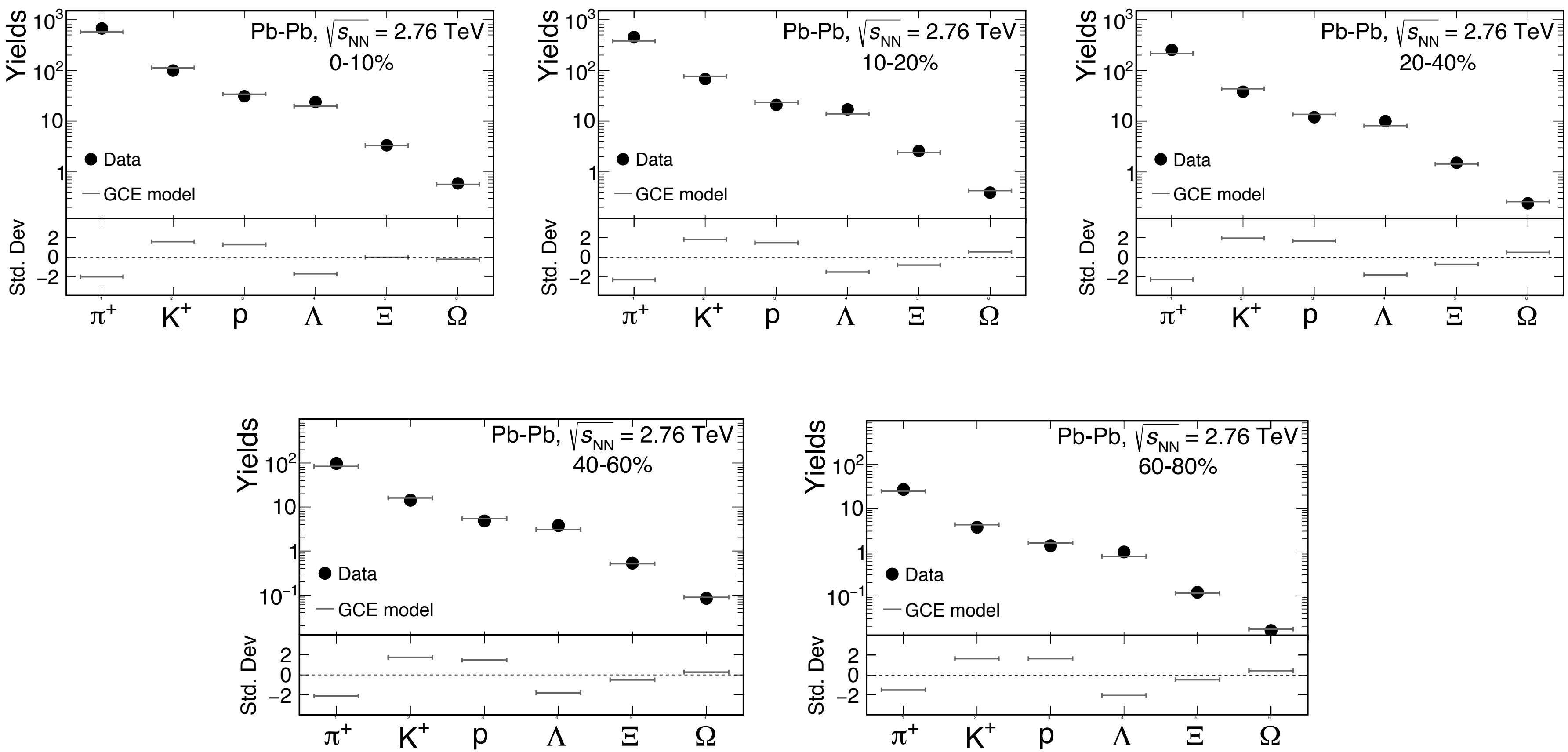
- Five multiplicity classes are studied for Pb-Pb collisions at 2.76 TeV.

- **Grand canonical ensemble** is used for fitting with THERMUS v3.0
  - $\mu_B = \mu_Q = \mu_S = 0$ (fixed);
  - T_{ch}, γ_S, and R are taken as free parameters.

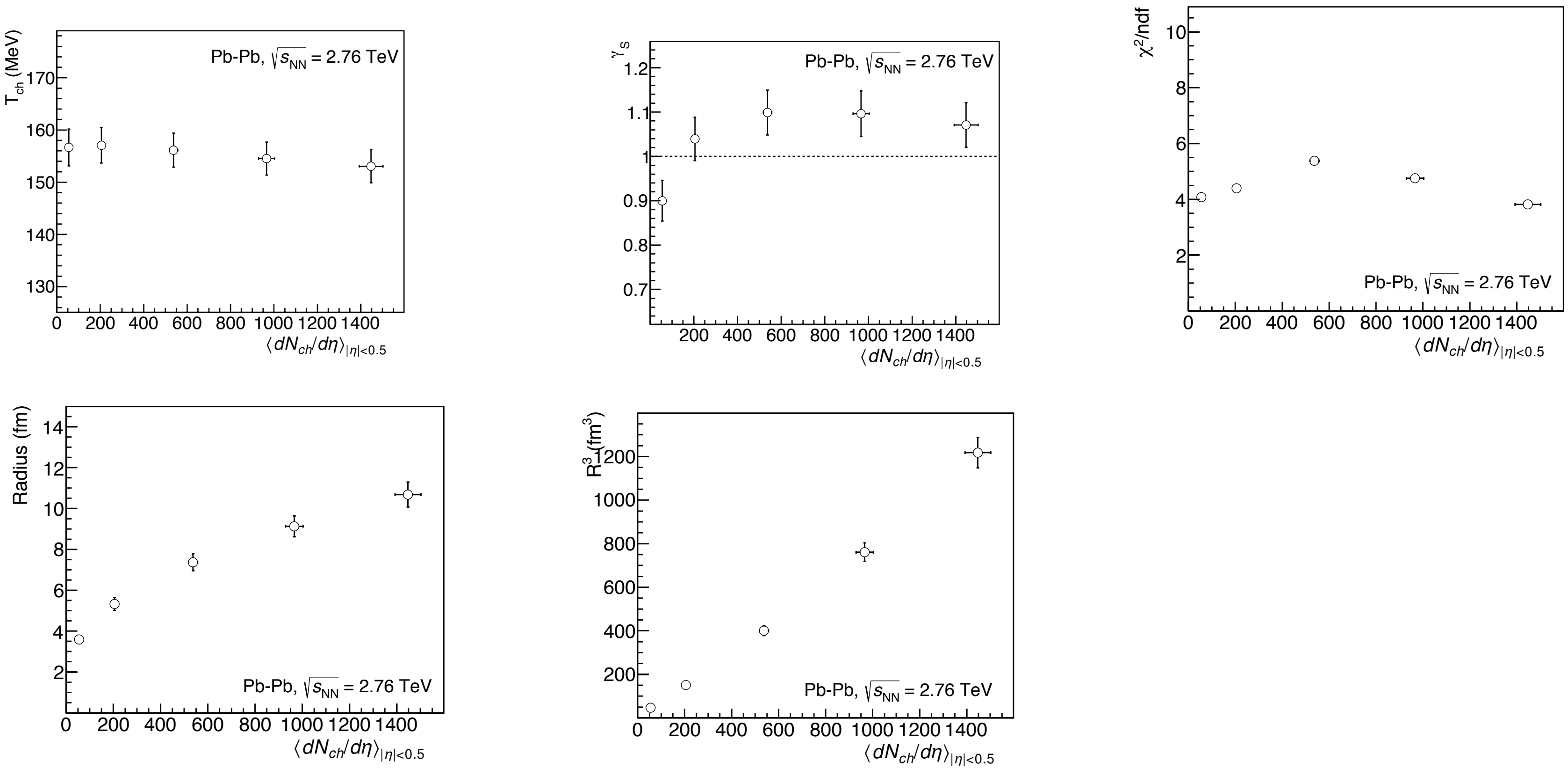
- Particles used in the fitting: π, K, p, Λ, Ω, and Ξ

- Data taken from Phys. Rev. C 88, 044910 (2013), Phys. Rev. Lett. 111 (2013) 222301, and Phys. Lett. B 728 (2014)

Pb-Pb: Comparison of fit results with experimental data

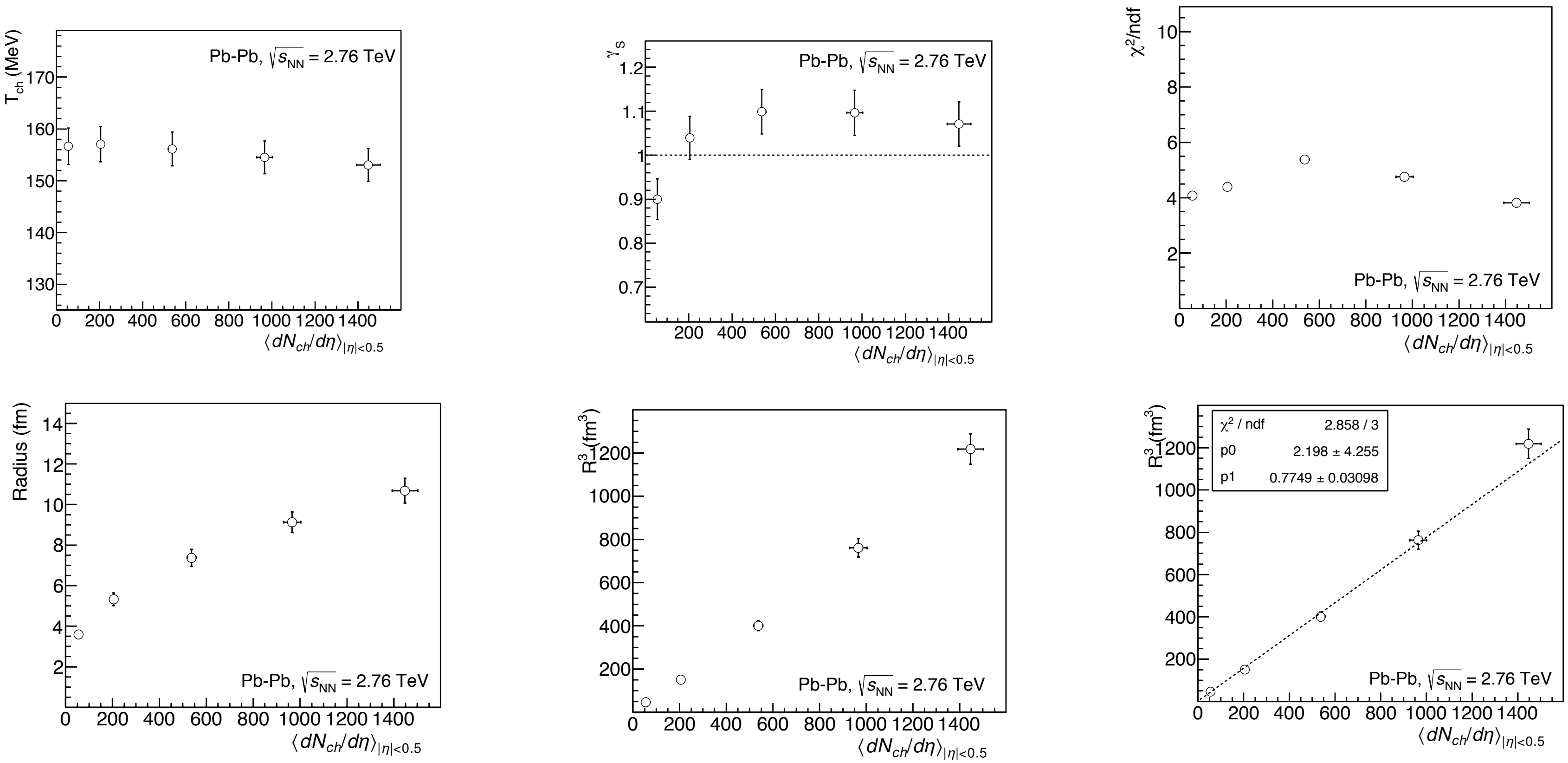


Pb-Pb: Fit parameters as a function of charged particle multiplicity



- Temperature remains constant as a function of multiplicity.
- γ_S is greater than unity for all multiplicity and becomes less than one for peripheral.
- Freeze-out radius increase with multiplicity.
- Freeze-out volume ($\propto R^3$) increases linearly with multiplicity.

Pb-Pb: Fit parameters as a function of charged particle multiplicity

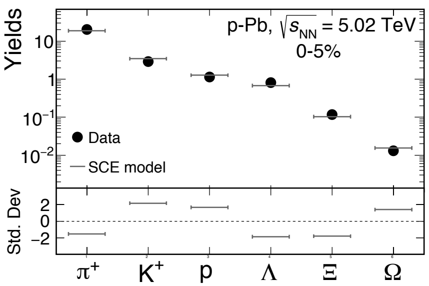


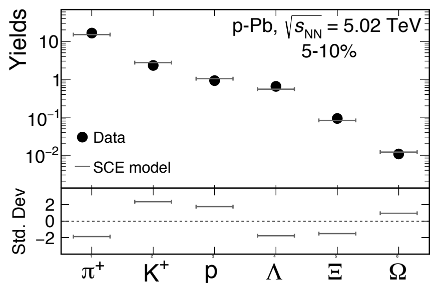
- Temperature remains constant as a function of multiplicity.
- γ_S is greater than unity for all multiplicity and becomes less than one for peripheral.
- Freeze-out radius increase with multiplicity.
- Freeze-out volume ($\propto R^3$) increases linearly with multiplicity.

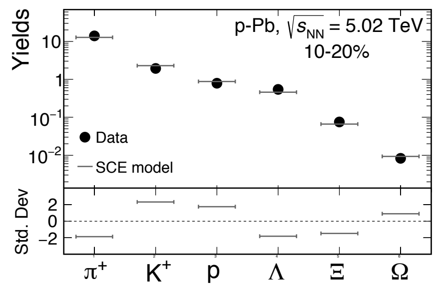
Fitting p-Pb data

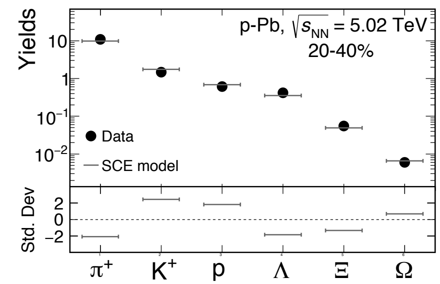
- Seven multiplicity classes are studied for p-Pb collisions at 5.02 TeV.
- **Strange canonical ensemble** is used for fitting with THERMUS v3.0
  - $\mu_B = \mu_Q = 0$ (fixed);
  - T_{ch}, γ_S, and R (=R_C) are taken as free parameters.
- Particles used in the fitting: π, K, p, Λ, Ω, and Ξ
- Data taken from Phys.Lett. B728 (2014) 25-38 and Phys.Lett. B758 (2016) 389-401

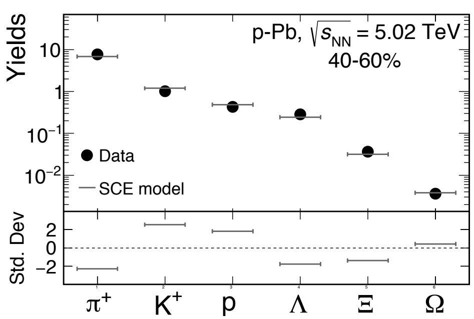
p-Pb: Comparison of fit results with experimental data

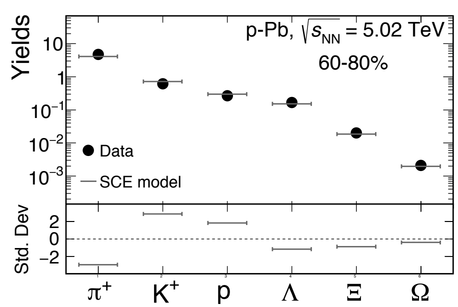


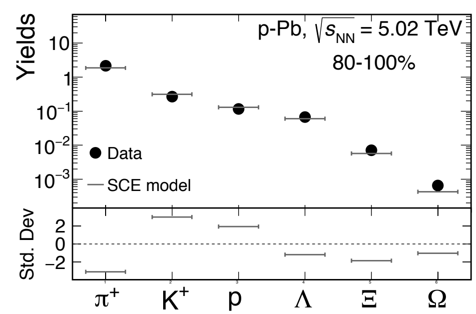




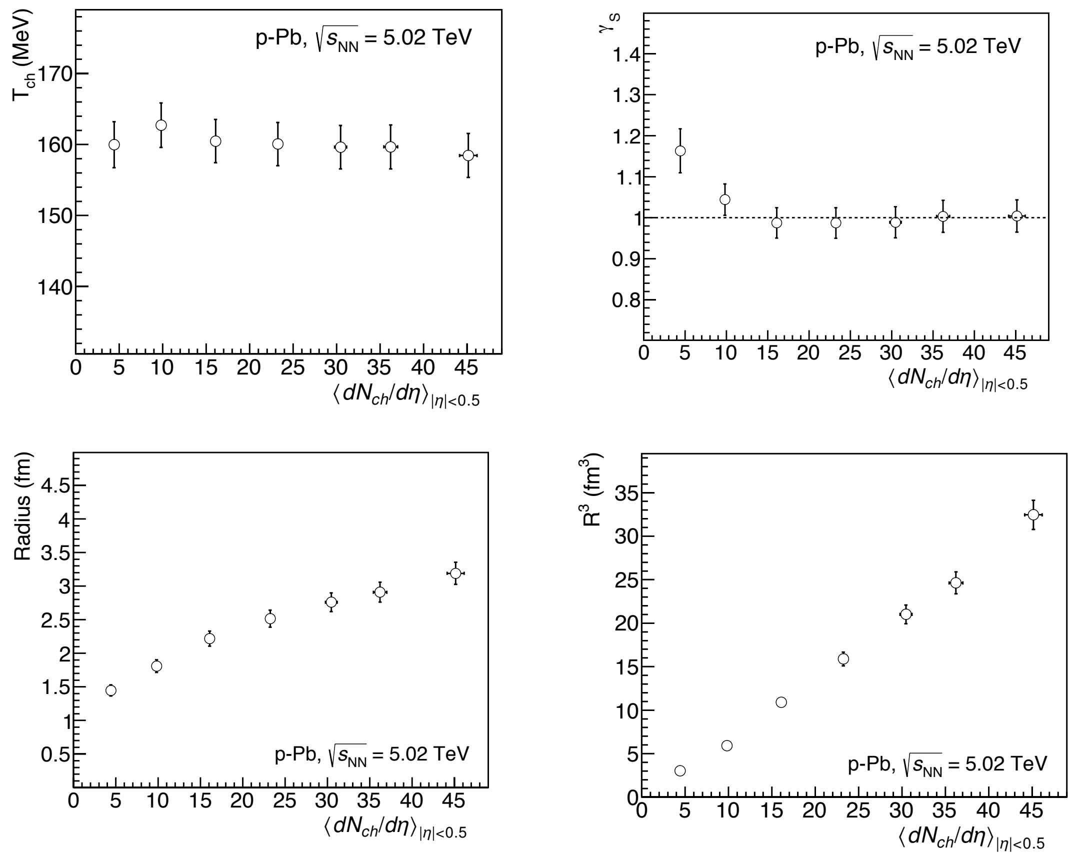






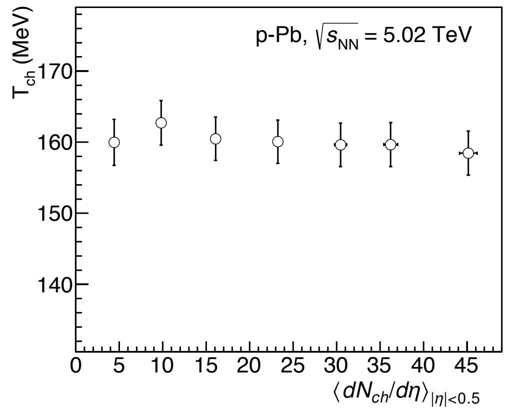


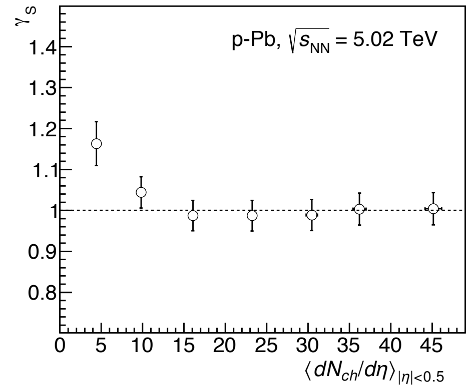
p-Pb: Fit parameters as a function of charged particle multiplicity

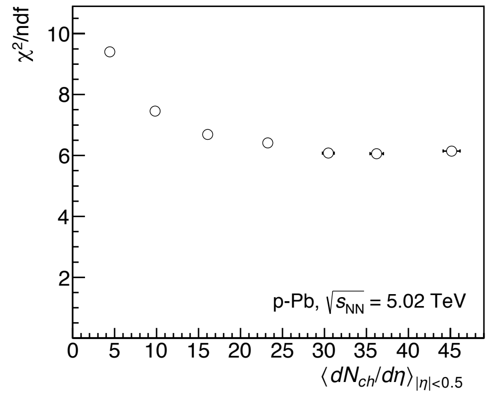


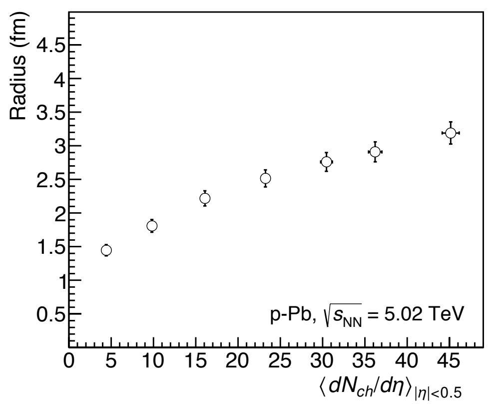
- Temperature remains constant as a function of multiplicity.
- γ_S is equal to unity for all multiplicity and becomes greater than one for peripheral.
- Freeze-out radius increases with multiplicity.
- Volume at freeze-out ($\propto R^3$) increases linearly with multiplicity.

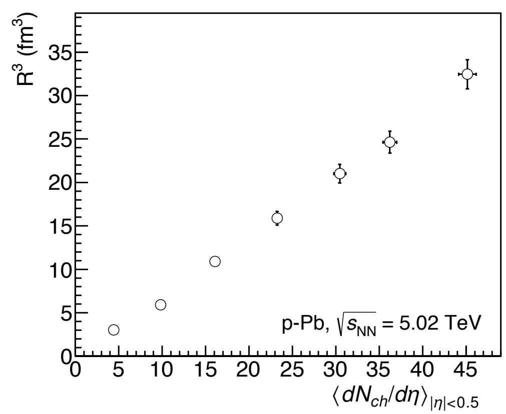
p-Pb: Fit parameters as a function of charged particle multiplicity

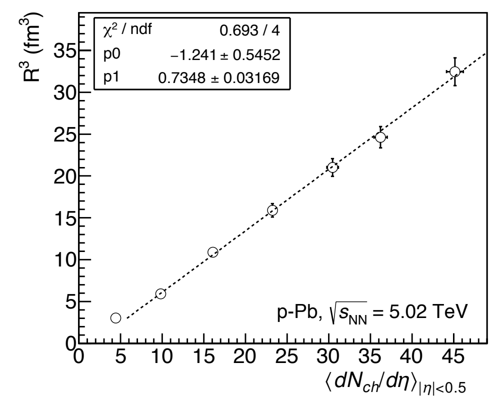










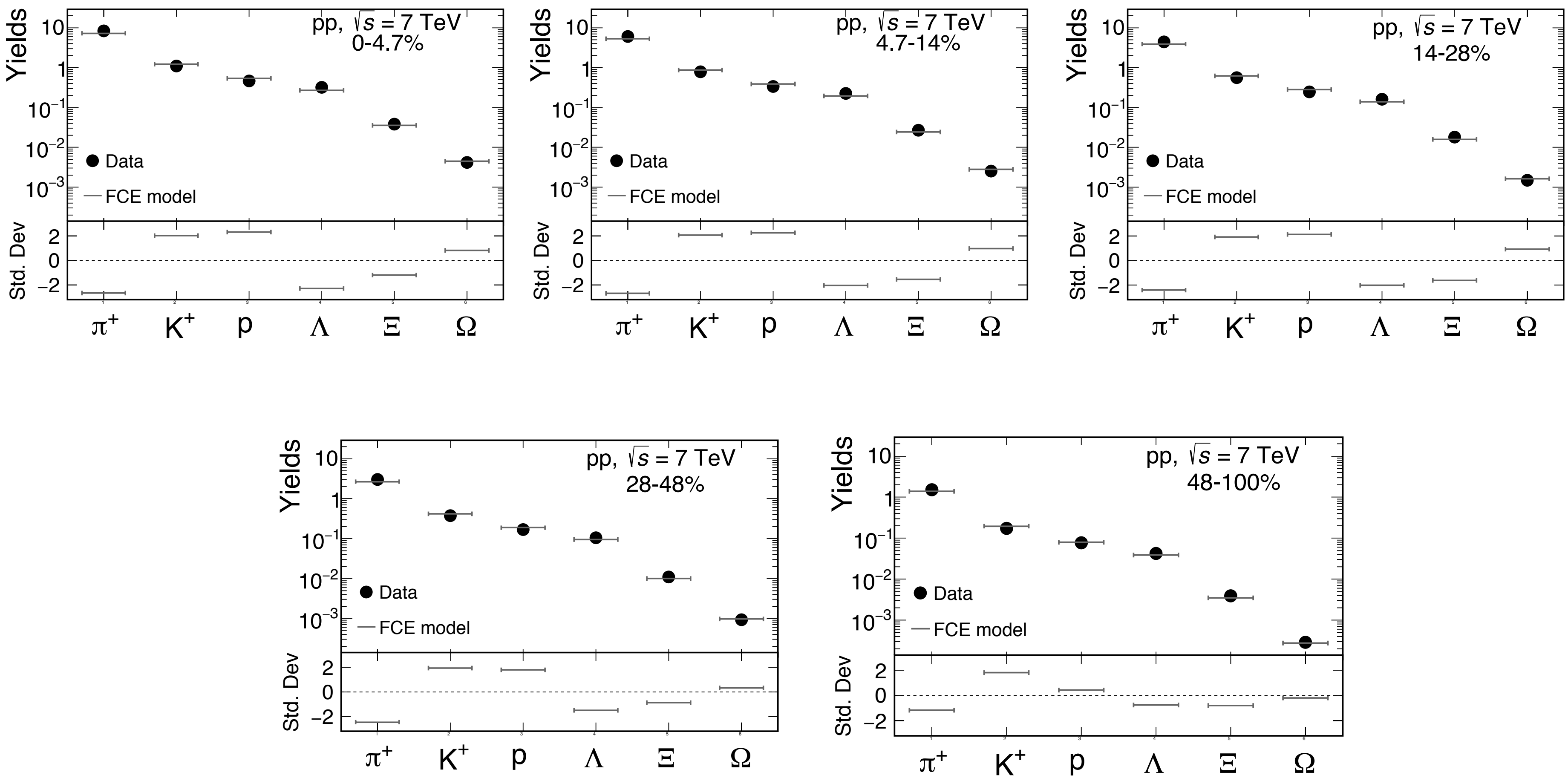


- Temperature remains constant as a function of multiplicity.
- γ_S is equal to unity for all multiplicity and becomes greater than one for peripheral.
- Freeze-out radius increases with multiplicity.
- Volume at freeze-out ($\propto R^3$) increases linearly with multiplicity.

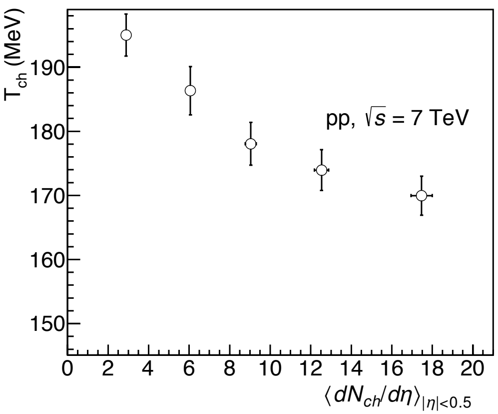
Fitting pp data

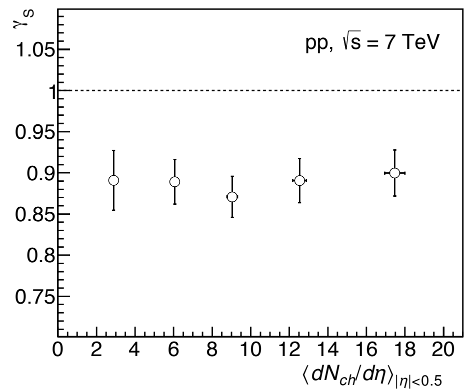
- Five multiplicity classes are studied for pp collisions at 7 TeV.
- **Full canonical ensemble** is used for fitting with THERMUS v3.0
  - B = S = Q = 0 (fixed);
  - T_{ch}, Radius and γ_S are taken as free parameters.
- Particles used in the fitting: π, K, p, Λ, Ω, and Ξ
- Data taken from Nature Phys. 13 (2017) 535-539

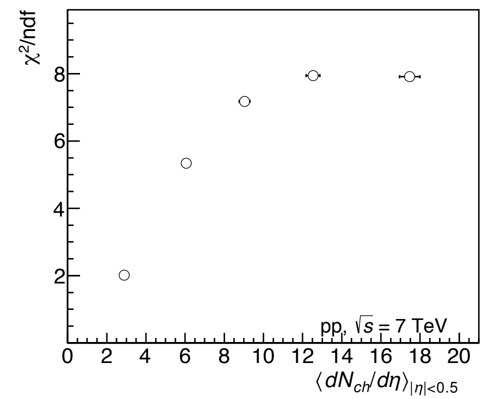
pp: Comparison of fit results with experimental data

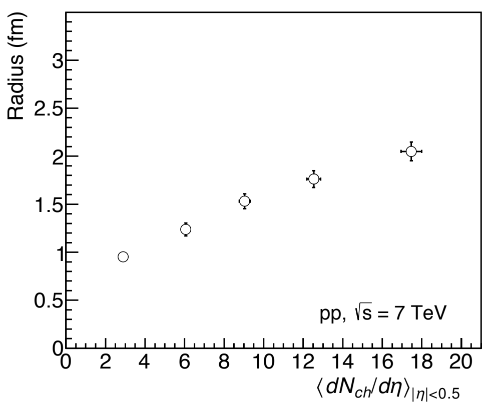


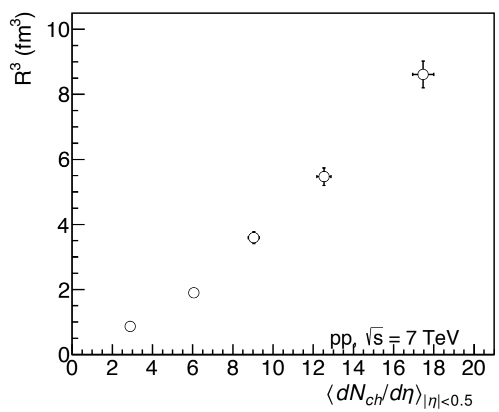
pp: Fit parameters as a function of charged particle multiplicity





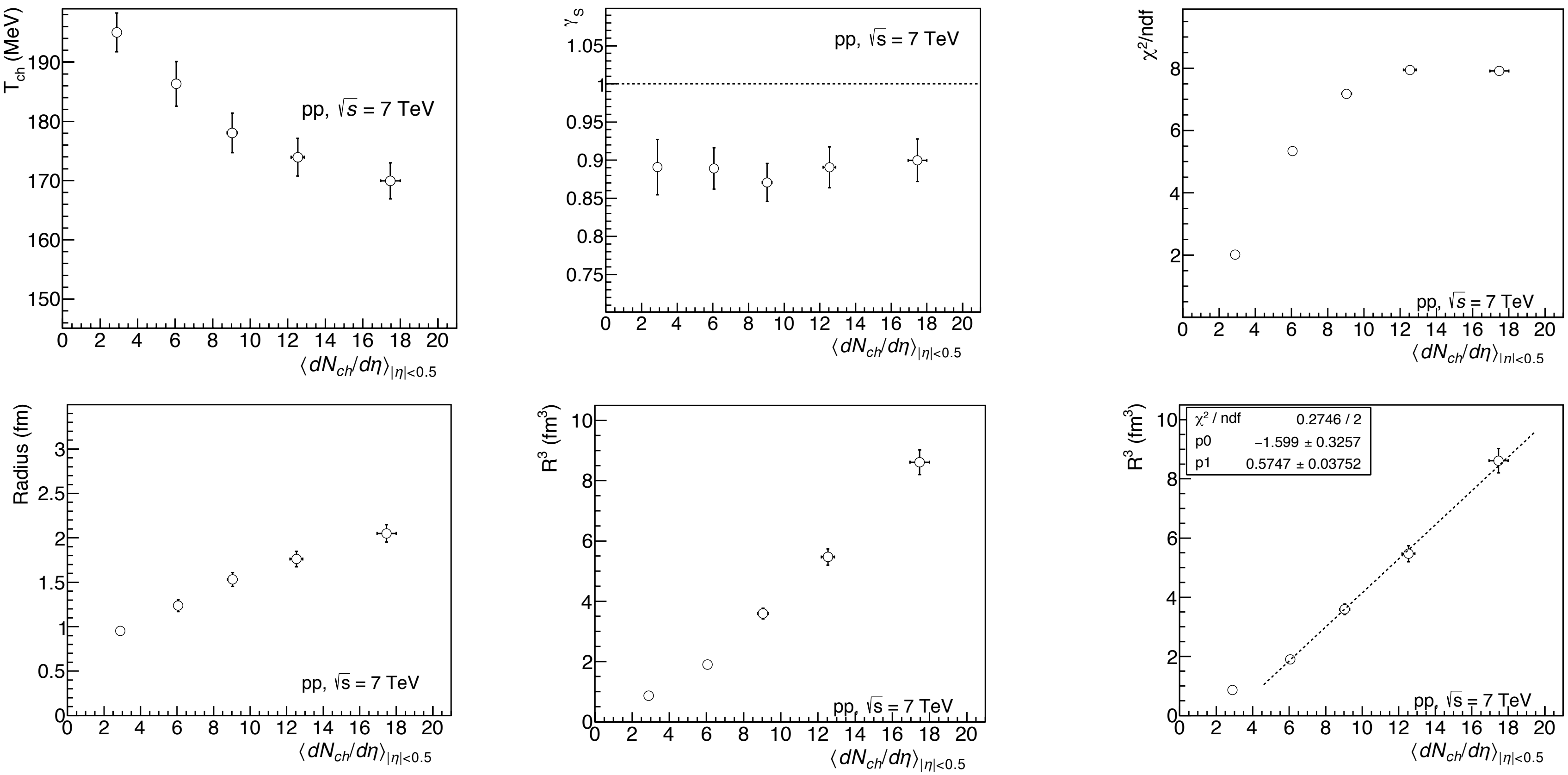






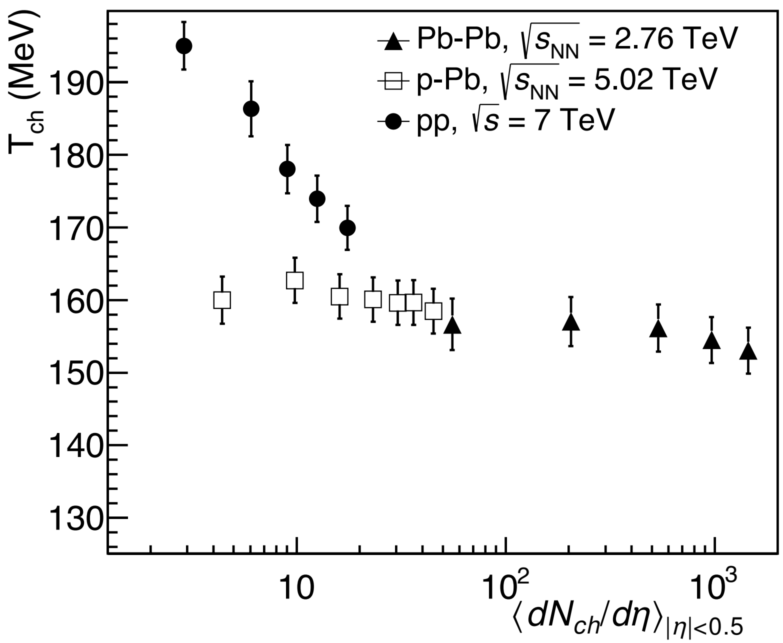
- Temperature decreases with increase in multiplicity.
- γ_S remains constant with multiplicity (around 0.9) and is always smaller than one.
- Radius increases with multiplicity.
- Volume ($\propto R^3$) increases linearly with multiplicity.

pp: Fit parameters as a function of charged particle multiplicity



- Temperature decreases with increase in multiplicity.
- γ_S remains constant with multiplicity (around 0.9) and is always smaller than one.
- Radius increases with multiplicity.
- Volume ($\propto R^3$) increases linearly with multiplicity.

Comparison of pp, p-Pb, and Pb-Pb: Chemical freeze-out temp.

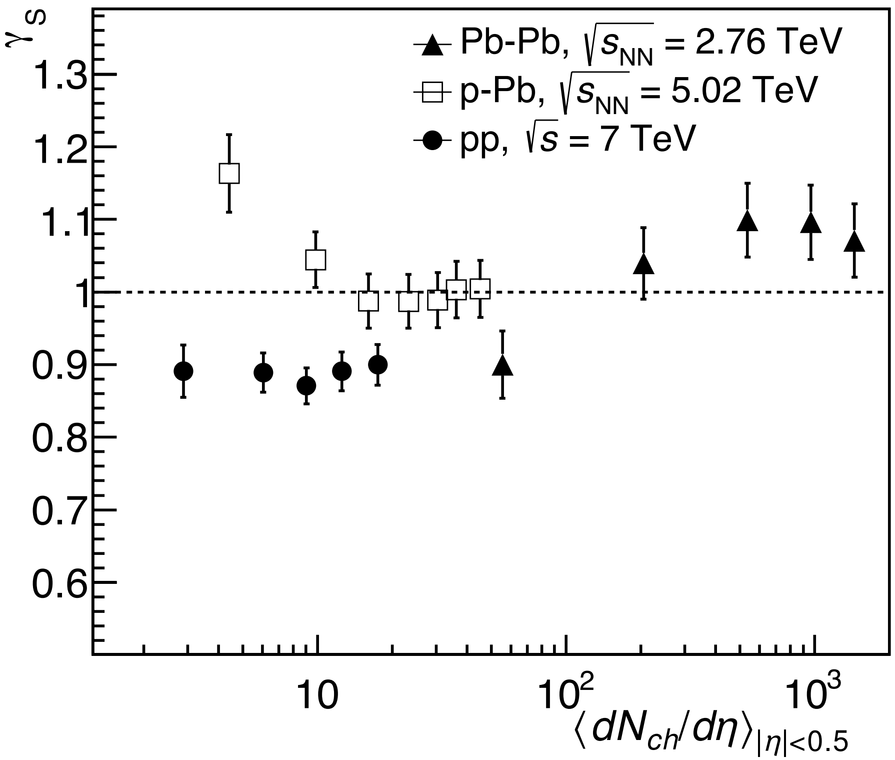


- Temperature remain constant as a function of multiplicity for p-Pb and Pb-Pb collisions.
- For pp collisions: T_{ch} decreases from low multiplicity to high multiplicity.

- ➢ p-Pb follows Pb-Pb behavior.
- ➢ High mult pp approaching p-Pb

Results remain same for $\gamma_S = 1$

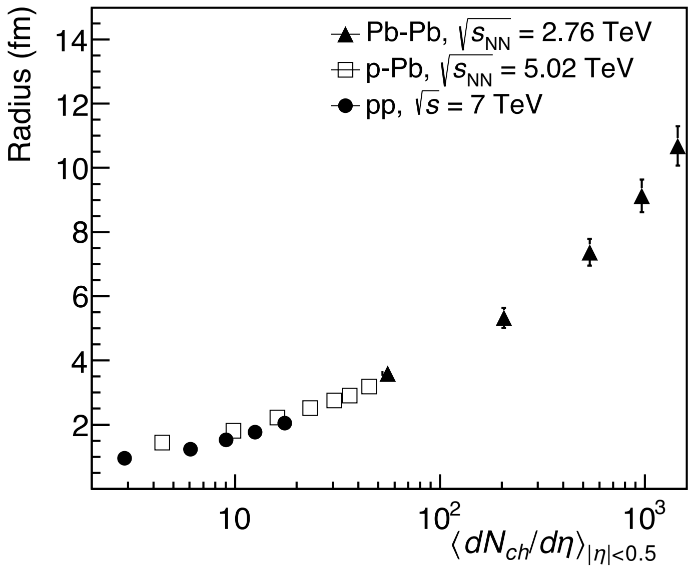
Comparison of pp, p-Pb, and Pb-Pb: Suppression factor



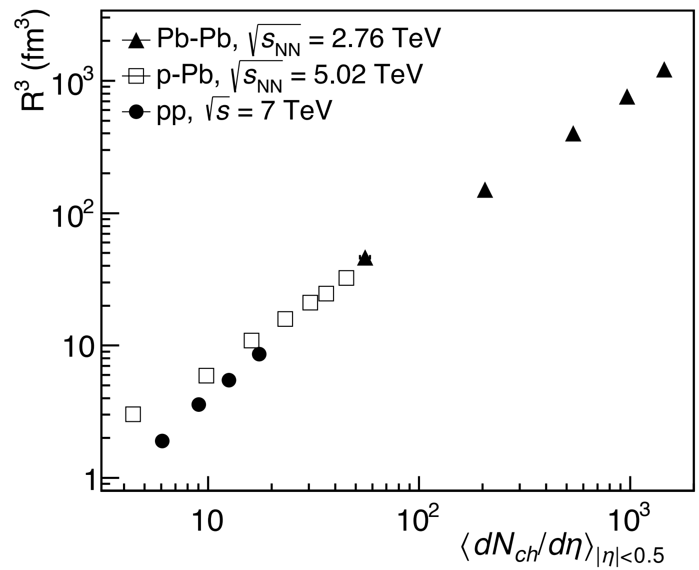
Strangeness suppression factor γ_S:

- For pp collisions: $\gamma_S < 1$ for all multiplicity. Remains constant i.e. 10% below equilibrium value for all multiplicity.
- For p-Pb collisions: $\gamma_S = 1$ except for the lowest multiplicity bin.
- For Pb-Pb collisions: $\gamma_S > 1$ except for the lowest multiplicity bin.

Comparison of pp, p-Pb, and Pb-Pb: Radius & volume

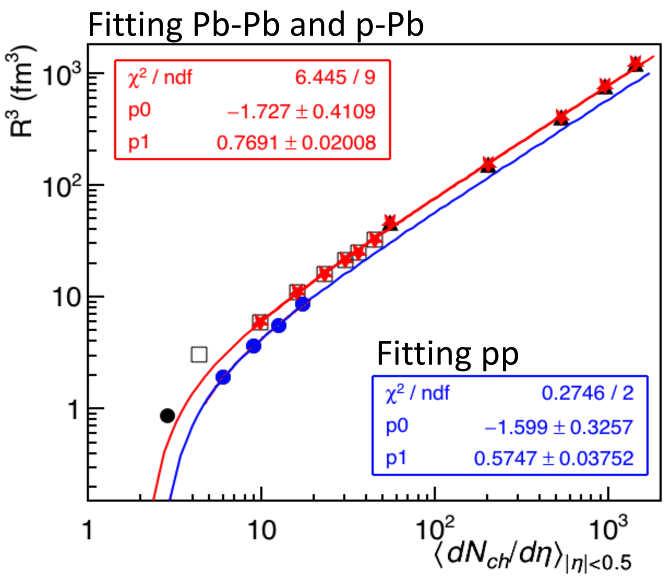


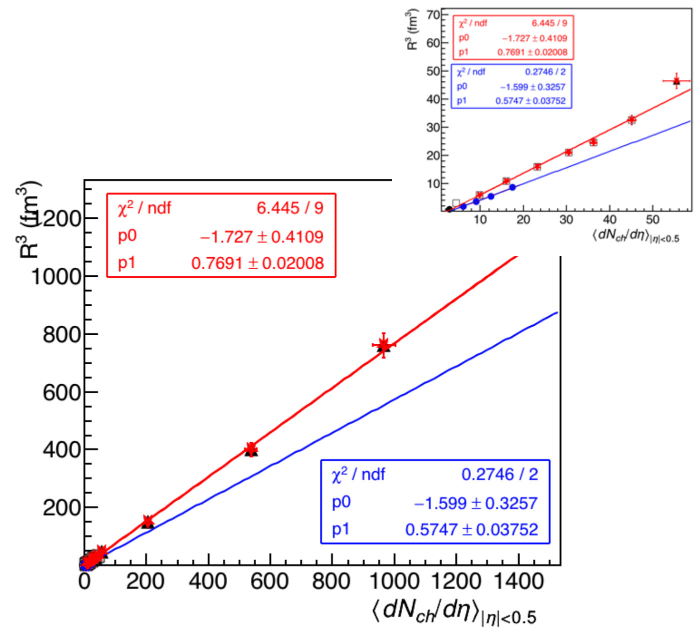
- Radius as a function of multiplicity for p-Pb and Pb-Pb collisions seems inline with each other.
- High mult pp approaching p-Pb



p-Pb follows Pb-Pb behavior.

Comparison of pp, p-Pb, and Pb-Pb: Radius & volume





- Freeze-out volume for p-Pb and Pb-Pb collisions for various multiplicity bins are fitting well together by pol1 function.
- Volume for pp fitted separately by pol1 shows different trend.

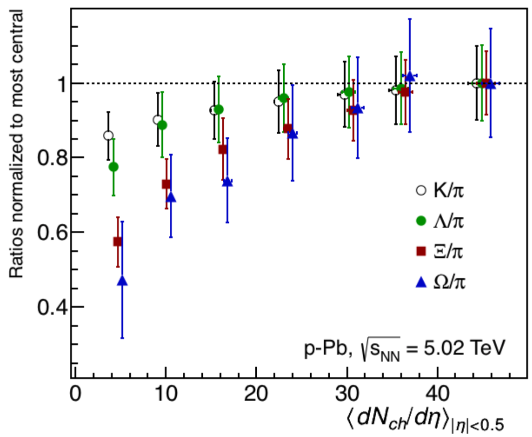
Summary and conclusions

- Chemical freeze-out parameters are studied for Pb-Pb, p-Pb and pp collisions for various multiplicity classes.
- T_{chem} remains almost constant for all multiplicity for p-Pb and Pb-Pb data; however for pp data T_{chem} increase as multiplicity decrease.
- In general, γ_S is > 1 for Pb-Pb; = 1 for p-Pb and becomes < 1 for pp collisions.
- Radius increase with multiplicity for all three systems.
- Freeze-out volume is $\propto$ to produced particles for all systems.
- Particle production in p-Pb follows Pb-Pb trend; pp follows different trend.

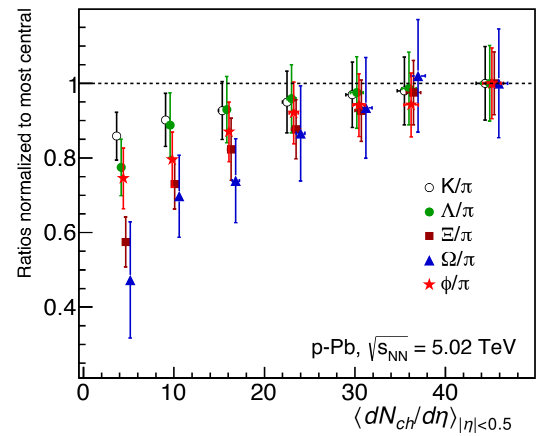
Back Up

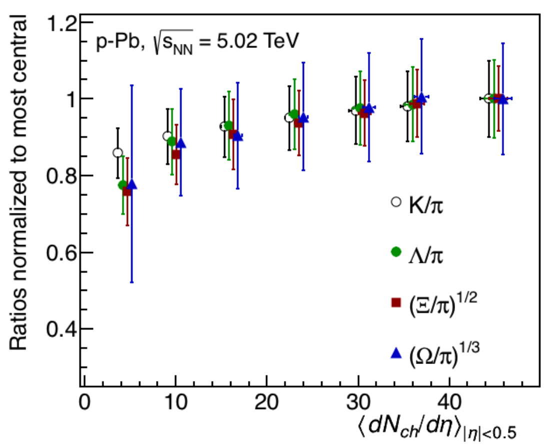
Normalized strange particles to pion ratio vs multiplicity

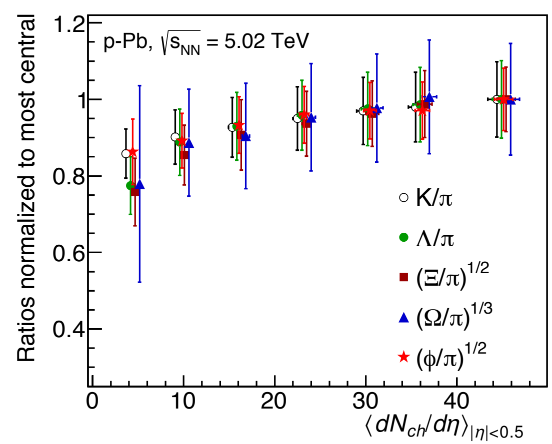
Without ϕ



With ϕ



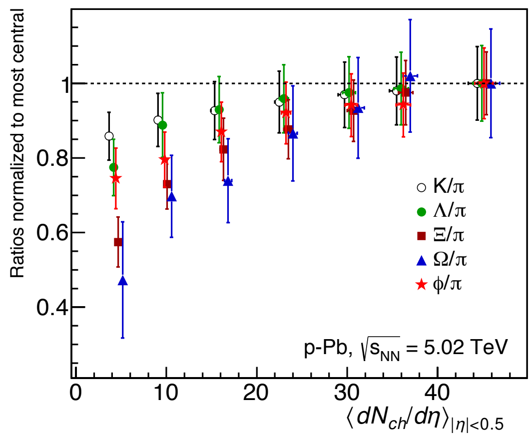




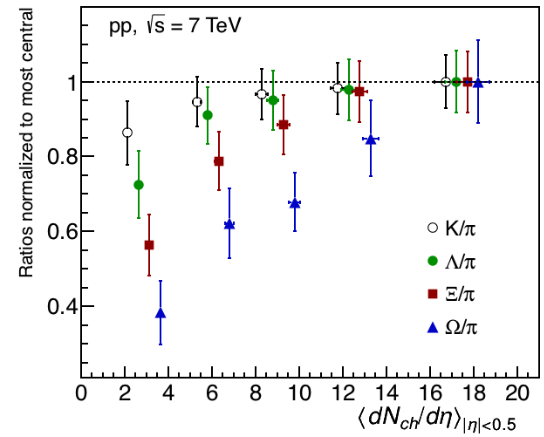
Normalized ratios scaled by the strangeness content coincide for p-Pb data

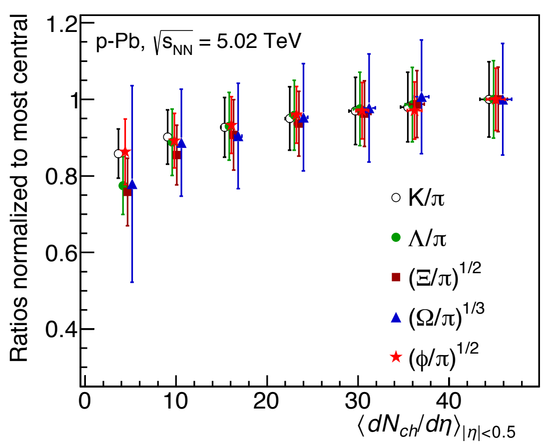
Normalized strange particles to pion ratio vs multiplicity

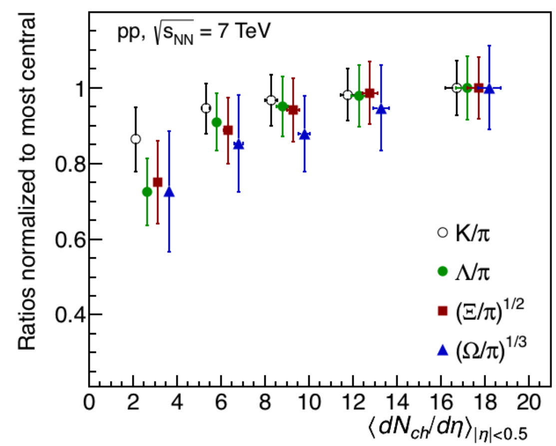
p-Pb data



pp data

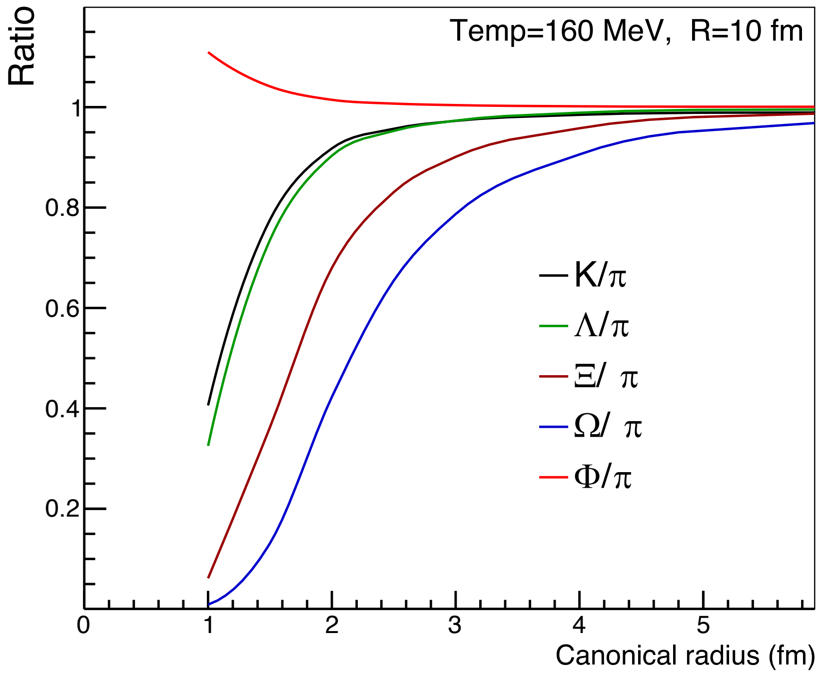




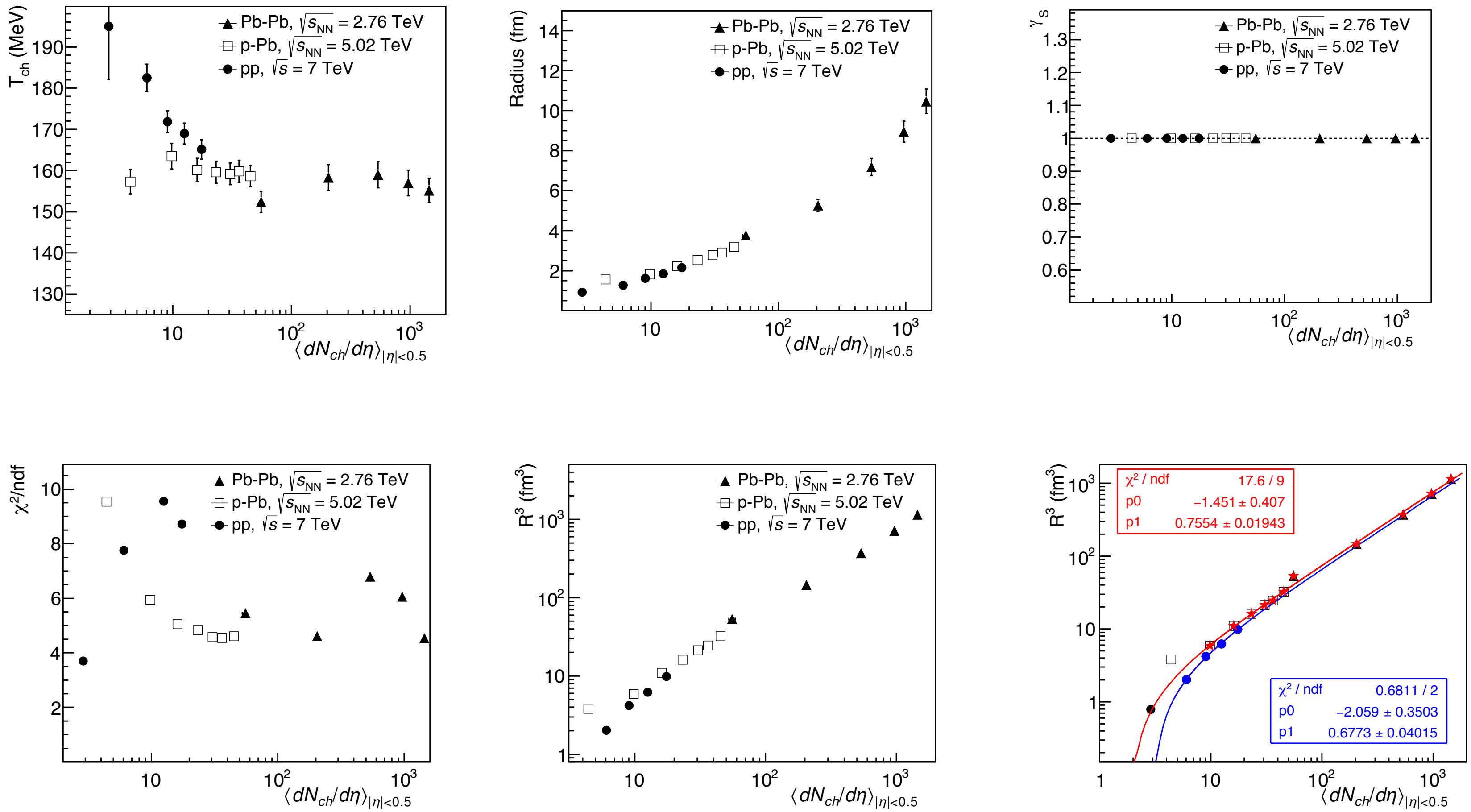


Normalized ratios scaled by the strangeness content coincide for p-Pb data

Thermal model predictions for small systems with ϕ included

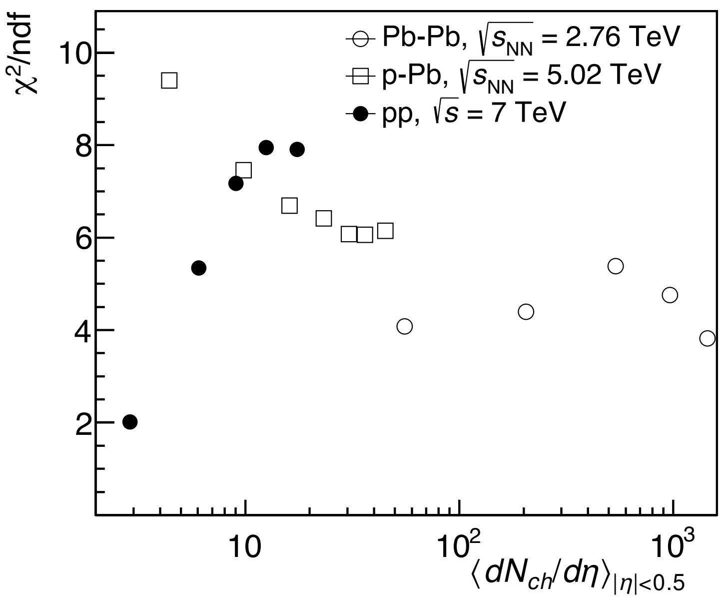


Comparing pp, p-Pb and Pb-Pb results for γ_S = 1 (fixed)



Comparison of pp, p-Pb, and Pb-Pb

With γ_S as free parameter



Chemical Freeze-out

Inelastic collisions among the particles cease; the particle yields and ratios gets fixed

Statistical-Thermal Model:

J. Cleymans et al., Comp. Phys. Comm. 180, 84 (2009)

$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial m} = \frac{VTm_i^2 g_i}{2p^2}\sum_{k=1}^{\infty}\frac{(\pm 1)^{k+1}}{k}\left(e^{\beta k m}\right)K_2\left(\frac{km_i}{T}\right)$$

(Grand-canonical)

$\beta \cong 1/T$; -1(+1) for fermions (bosons),
Z=partition function;
m_i = mass of hadron species i;

V = volume; T = Temperature;
K_2= 2nd order Bessel function;
g_i = degeneracy; μ_i = chemical potential

Experimental particle yields/ratios are input to the thermal model to extract the freeze-out parameters: T_{ch}, γ_S, and radius.
At LHC energies chemical potential μ_i are fixed to 0 i.e. $\mu_B = 0$ and $\mu_S = 0$

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Ensembles: Statistical Mechanics

Three different ensembles

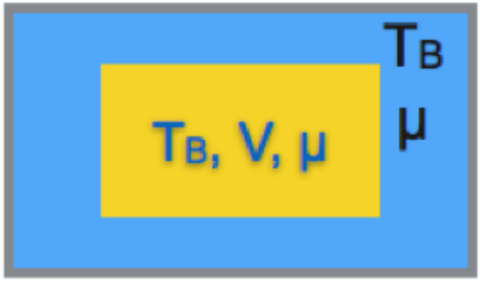
i) Micro-Canonical Ensemble: E, V, N - fix

ii) Canonical Ensemble: T, V, N - fix

-- Given volume element coupled to heat bath

iii) Grand-Canonical Ensemble: T, V, μ - fix

-- Given volume element can also exchange
particles with surrounding
(Heat bath and particle reservoir)



Pathria, R. K., & and Beale, P. D. (2011). Statistical Mechanics. Burlington, MA: Elsevier

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Ensembles: Heavy-ion Experiments

Statistical-Thermal Model: THERMUS Package

J. Cleymans et al., Comp. Phys. Comm. 180, 84 (2009)

Grand-Canonical Ensemble: The energy and quantum numbers or particle numbers are conserved on average through the temperature and chemical potentials.

-- Widely used in high energy heavy-ion collisions

-- Chemical potential for particle species *i* is given by:

$$\boxed{\mu_i = B_i \mu_B + Q_i \mu_Q + S_i \mu_S}$$

B_i, Q_i, S_i : baryon, charge, strangeness number

Strangeness-Canonical Ensemble: The strangeness (S) in the system is fixed exactly by its initial value of *S*, while the baryon and charge contents are treated grand-canonically.

-- At lower energies OR for small systems like p-Pb, low production of strange particles requires canonical treatment of strangeness

-- Chemical potential for particle species *i* is given by

$$\boxed{\mu_i = B_i \mu_B + Q_i \mu_Q}$$

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