Multiplicity dependence of particle production at the LHC in (canonical) statistical model

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In collaboration with B. Doenigus and H. Stoecker, paper in preparation

COST Workshop on Interplay of hard and soft QCD probes for collectivity in heavy-ion collisions

Lund, Sweden, October 25 – March 1, 2019

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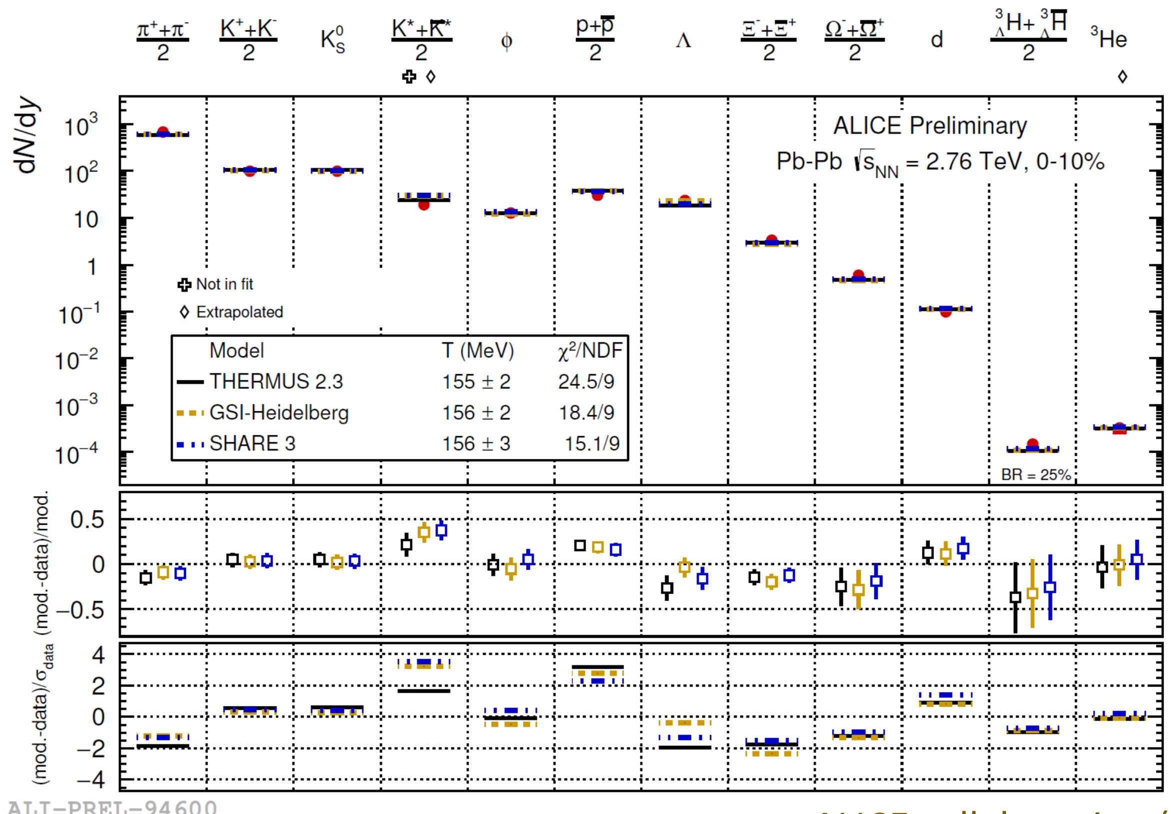
Particle production at LHC and statistical model



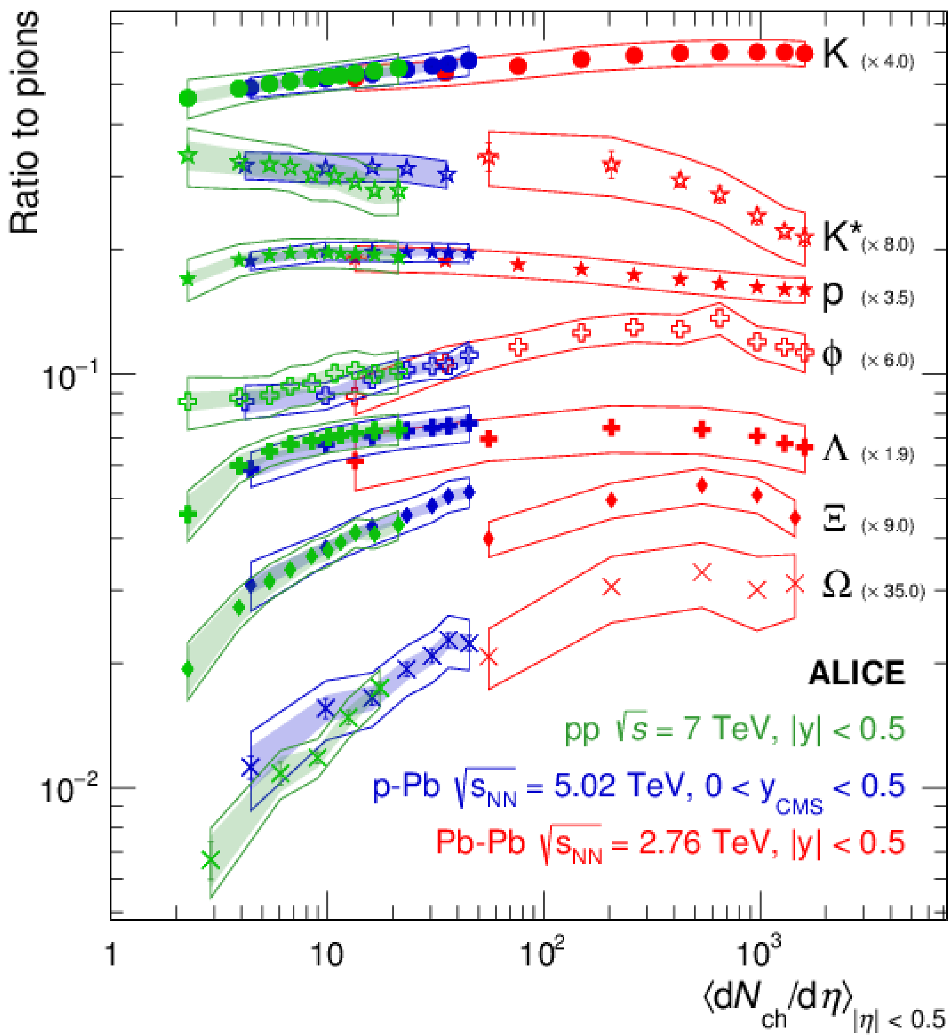
ALICE collaboration (SQM 2015)

Hadron resonance gas (HRG) at the chemical freeze-out:

$$N_i^{\mathrm{hrg}} = V \frac{d_i m_i^2 T}{2\pi^2} K_2\left(\frac{m_i}{T}\right) e^{\frac{\mu_i}{T}}, \qquad N_i^{\mathrm{tot}} = N_i^{\mathrm{hrg}} + \sum_j BR(j \to i) N_j^{\mathrm{hrg}}$$

Fair description of central Pb-Pb collisions → equilibrated matter formed?

Particle production at the LHC



ALICE collaboration, 1807.11321

- Hadron yield ratios exhibit multiplicity dependence
- Grand-canonical picture predicts no multiplicity dependence
- Ratios appear to approach a plateau at high-multiplicities → grand-canonical plateau?
- Can multiplicity-dependence be considered in a macroscopic model?

Canonical statistical model (CSM)

Grand-canonical approach: yield ratios N_i/N_j volume-independent, but conserved charges not conserved exactly. Canonical treatment of conservation laws important for small reaction volumes

[Rafelski, Danos, et al., PLB '80; Hagedorn, Redlich, ZPC '85]

Canonical partition function:

$$\mathcal{Z}(B,Q,S) = \int_{-\pi}^{\pi} \frac{d\phi_B}{2\pi} \int_{-\pi}^{\pi} \frac{d\phi_Q}{2\pi} \int_{-\pi}^{\pi} \frac{d\phi_S}{2\pi} \, e^{-i\,(B\phi_B + Q\phi_Q + S\phi_S)} \exp\left[\sum_j z_j^1 \, e^{i\,(B_j\phi_B + Q_j\phi_Q + S_j\phi_S)}\right]$$

$$z_j^1 = V_c \int dm \, \rho_j(m) \, d_j \frac{m^2 T}{2\pi^2} K_2(m/T)$$

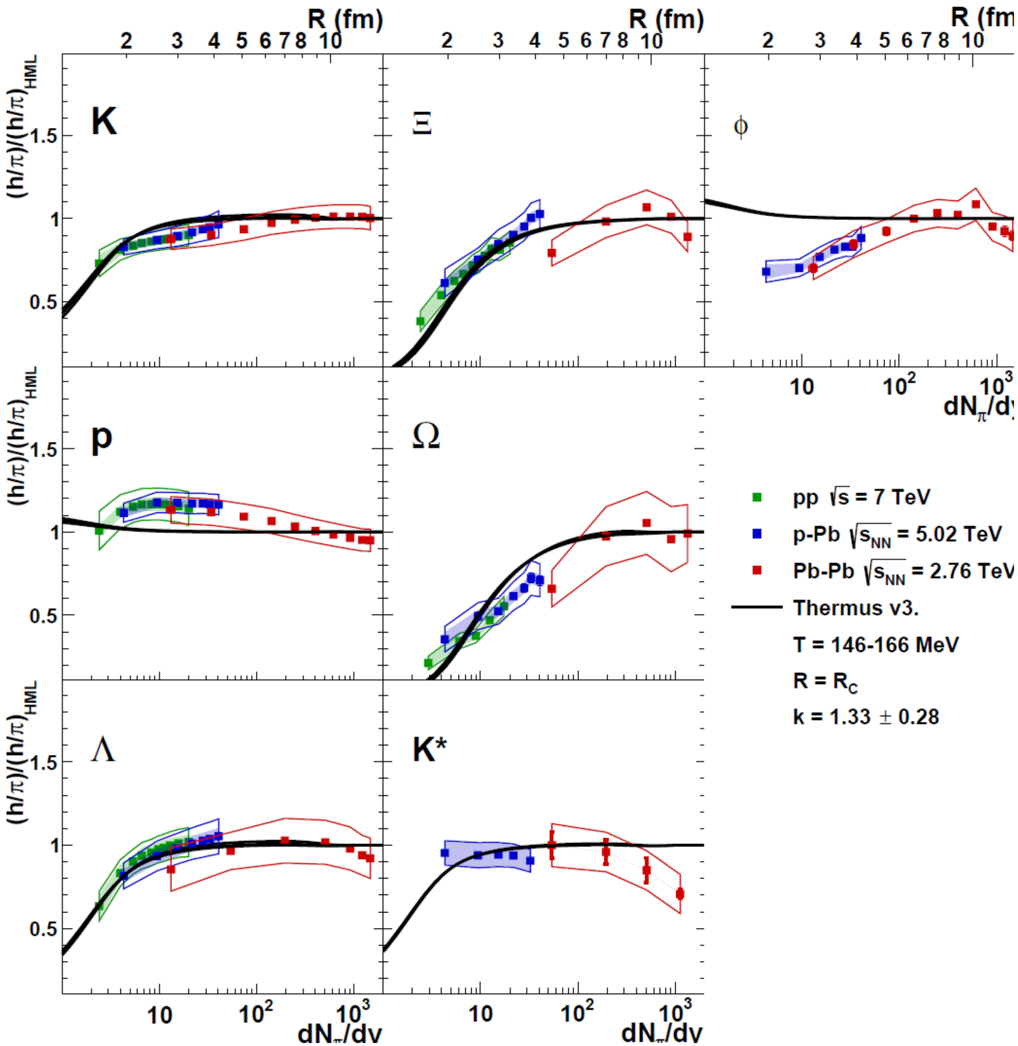
$$\langle N_j^{\mathrm{prim}} \rangle^{\mathrm{ce}} = \frac{Z(B-B_j, Q-Q_j, S-S_j)}{Z(B,Q,S)} \langle N_j^{\mathrm{prim}} \rangle^{\mathrm{gce}}$$

[Becattini et al., ZPC '95, ZPC '97]

≈ 1 at large volume (GCE), <1 for smaller volumes; stronger effect for multi-charged particles; neutral particles unaffected

Can multiplicity dependence be understood as a canonical suppression?

CSM at LHC: strangeness-canonical ensemble



[ALICE collaboration, 1807.11321]

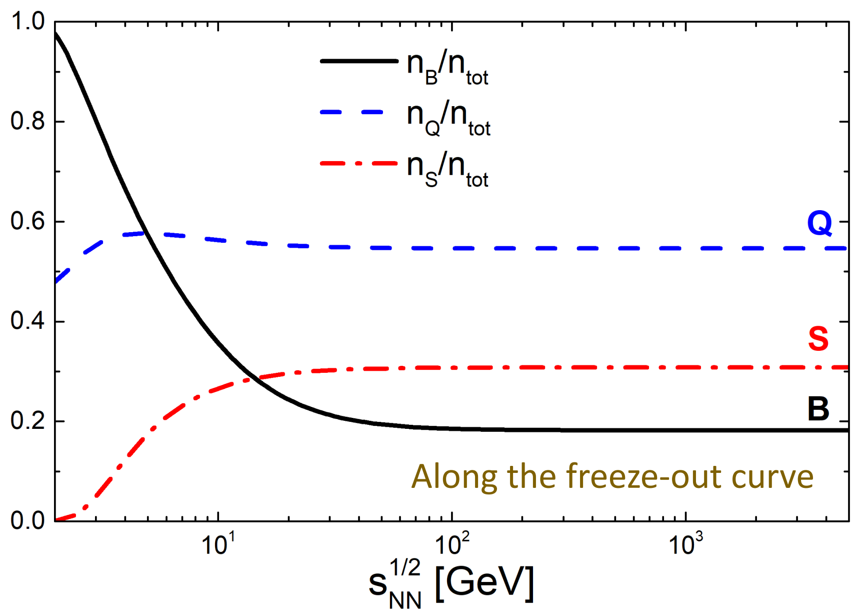
- Strangeness-canonical picture: S is canonical, B & Q grand-canonical
  [Vislavicius, Kalweit, 1610.03001]
- Describes trend for most yield ratios, but not ϕ
- What is the role of baryon and electric charge conservation?

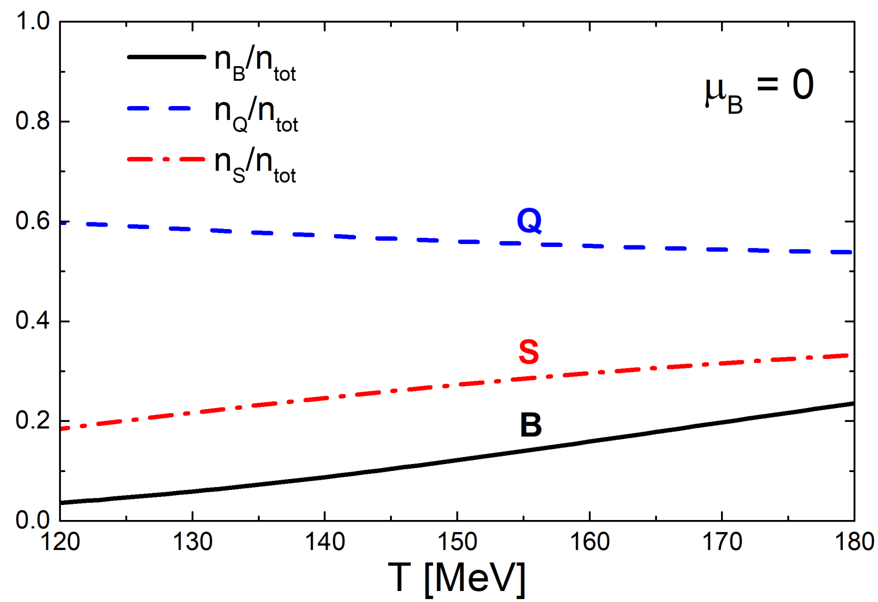
When is the canonical treatment necessary?

Normally, when the total number of particles carrying a conserved charge is smaller or of the order of unity

The canonical treatment is often restricted to strangeness only (SCE)

[STAR collaboration, 1701.07065; ALICE collaboration, 1807.11321]





- **Strangeness** conservation is most important at low energies (**HADES, CBM**)
- *Small systems at **RHIC** and **LHC**:* exact **baryon** conservation at least as important as **strangeness**

CSM in Thermal-FIST

The **Thermal-FIST** package is employed in the present analysis

V.V., H. Stoecker, arXiv:1902.05249

open source: https://github.com/vlvovch/Thermal-FIST

Canonical Statistical Model implementation in Thermal-FIST:

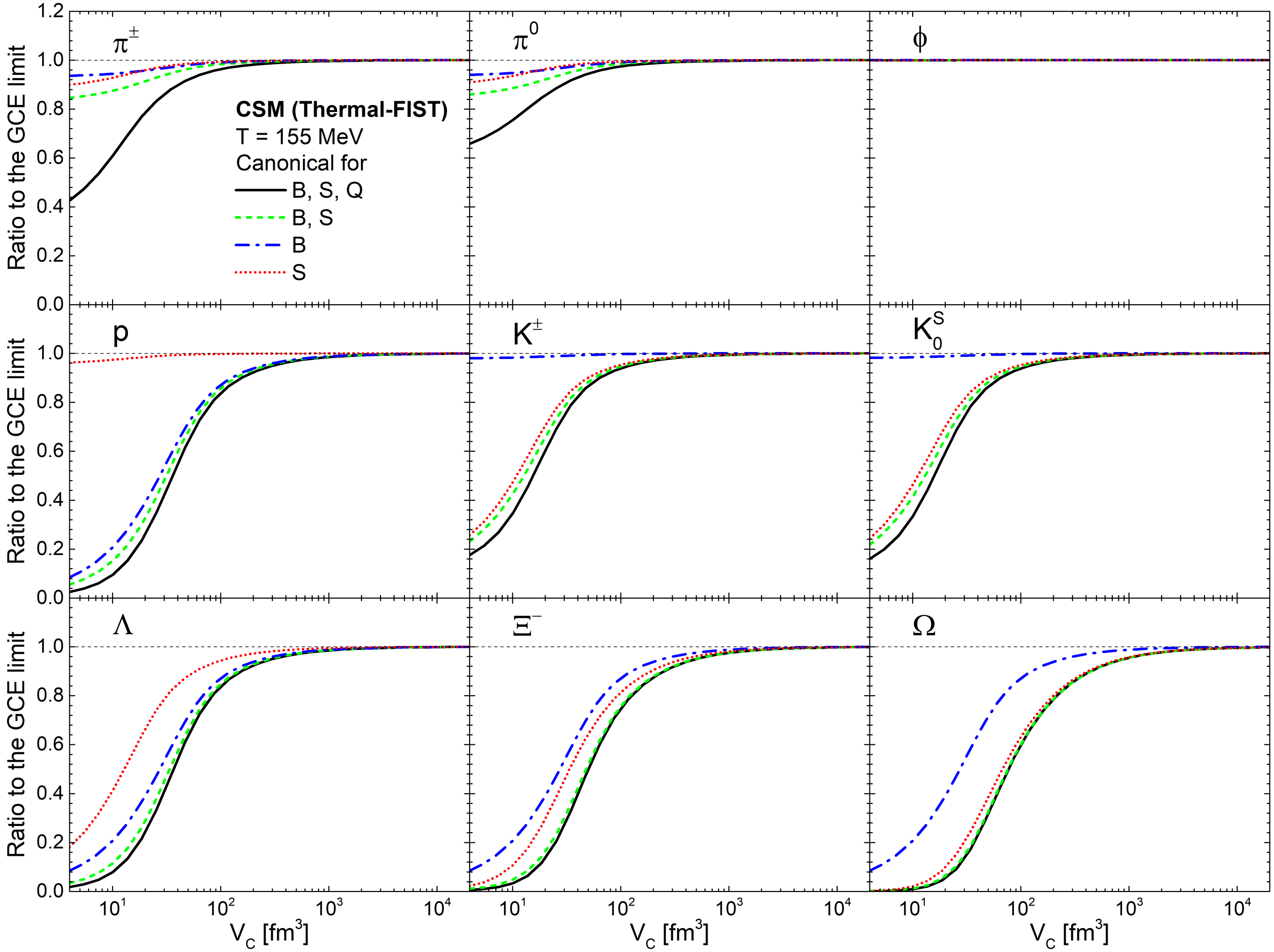
- Selective canonical treatment of charges
- Quantum statistics
- Supports $|B_j| > 1$ **(light nuclei)**
- Particle number fluctuations and correlations

```
model.ConserveBaryonCharge(true);
model.ConserveElectricCharge(false);
model.ConserveStrangeness(true);
```

see also talk of A. Motornenko, Thursday 17:05

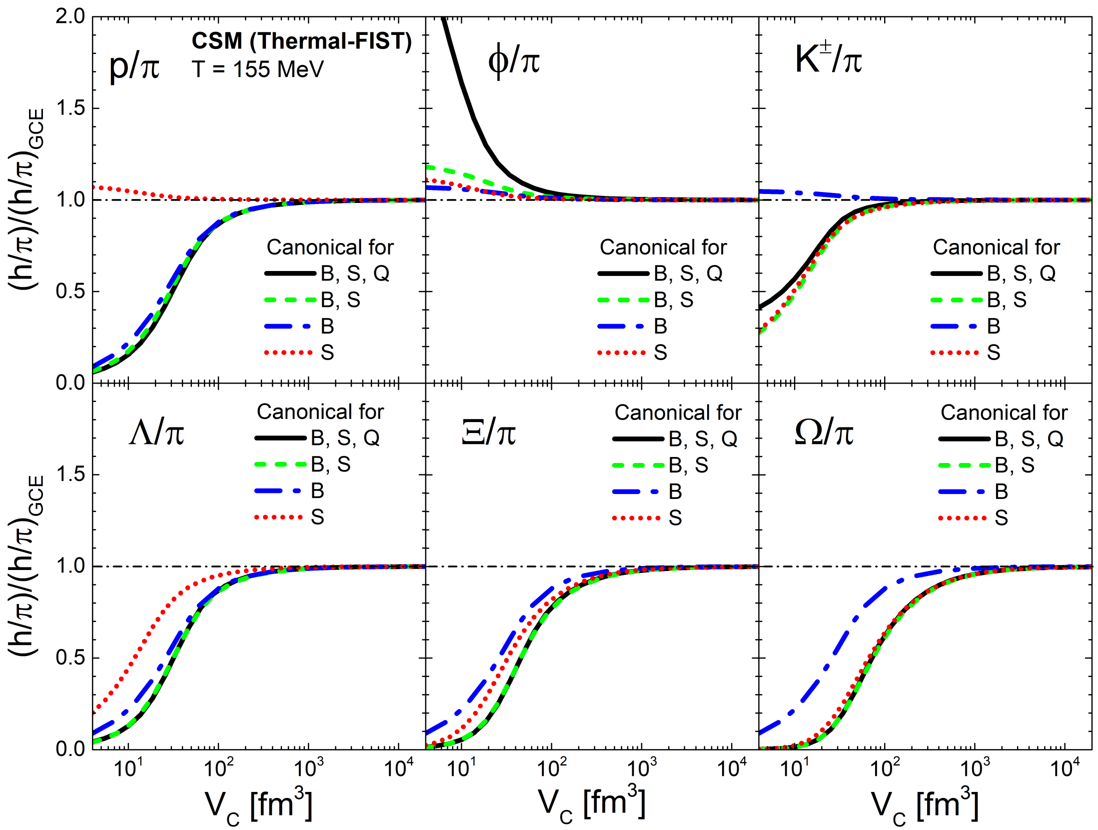
CSM at LHC: correlation volume dependence

Canonical statistical model: T = 155 MeV, V_C – canonical volume, selective (grand-)canonical treatment of B, Q, S



CSM at LHC: yield ratios to pions

V_C dependence of yield ratios to pions



- SCE appropriate for K, Ω, Ξ, less so for Λ, totally off for p and ϕ
- Baryon-strangeness-CE appropriate for most observables, except ϕ/π and π
- In general, full canonical treatment of B,Q,S required

Connecting CSM to data

Enforce *local* exact conservation of charges, $B = Q = S = 0$, in a *correlation volume* V_C around midrapidity

In general, $\boldsymbol{V_C \neq dV/dy}$

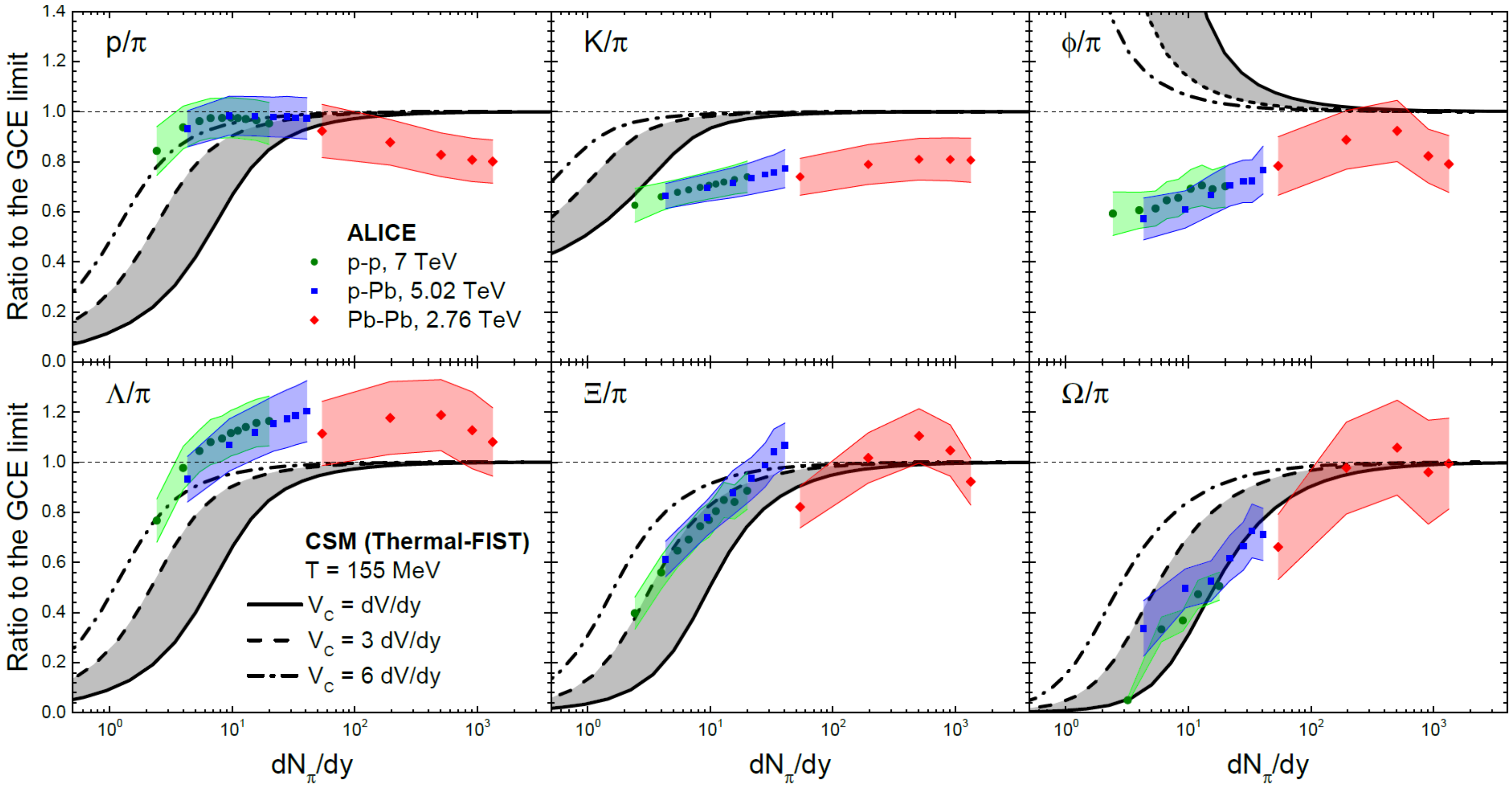
Causality argument: exact conservation across a few units of rapidity?

[Castorina, Satz, 1310.6932]

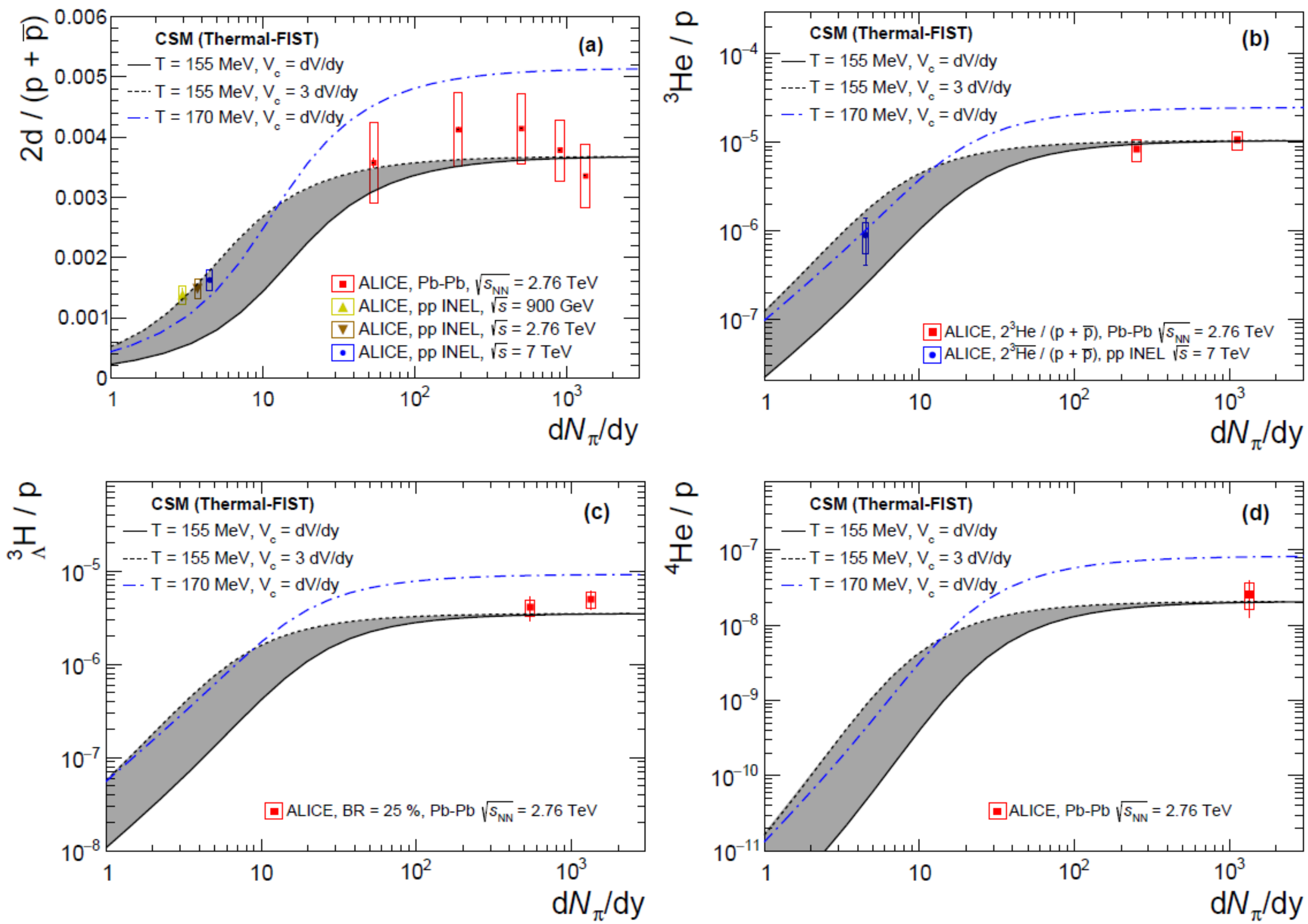
"Vanilla" CSM:

- **T = 155 MeV** for all multiplicities
- Multiplicity dependence of yield ratios driven by **canonical suppression only**
- $V_C = k\, dV/dy$, where k varied to establish systematics

“Vanilla” CSM at LHC: comparison with data



“Vanilla” CSM at LHC: light nuclei



[**V.V.**, B. Doenigus, H. Stoecker, 1808.05245]

- **CSM** qualitatively captures the behavior seen in the data
- Data prefers $V_C > dV/dy$ and/or $T_{p+p} > T_{Pb+Pb}$

“Vanilla” CSM at LHC: summary

- The CSM captures fairly well multiplicity dependence of hyperon-to-pion and nuclei-to-proton ratios

- Trend in K/π captured, but the data are significantly overshooted

- Some tension with the p/π data, which shows no clear evidence for canonical suppression

- Behavior of ϕ/π in the model is opposite to the behavior in the data. Unless production mechanism of ϕ is separate from the rest of hadrons, this invalidates “Vanilla” CSM for p-p and p-Pb

Full CSM

- Allow variation of T with multiplicity
- Allow incomplete chemical equilibration of strangeness (as suggested by the behavior of ϕ):

$$N_i^{hrg} \rightarrow (\gamma_S)^{|s_i|} N_i^{hrg}$$

$|s_i|$ - strange quark content

- $V_C = 3dV/dy$ + deviations
- T, γ_S, dV/dy fitted to data at each centrality
- Data: $\pi, K, K_0^S, \phi, p, \Lambda, \Xi, \Omega$ in p-p 7 TeV, p-Pb 5.02 TeV, Pb-Pb 2.76 TeV

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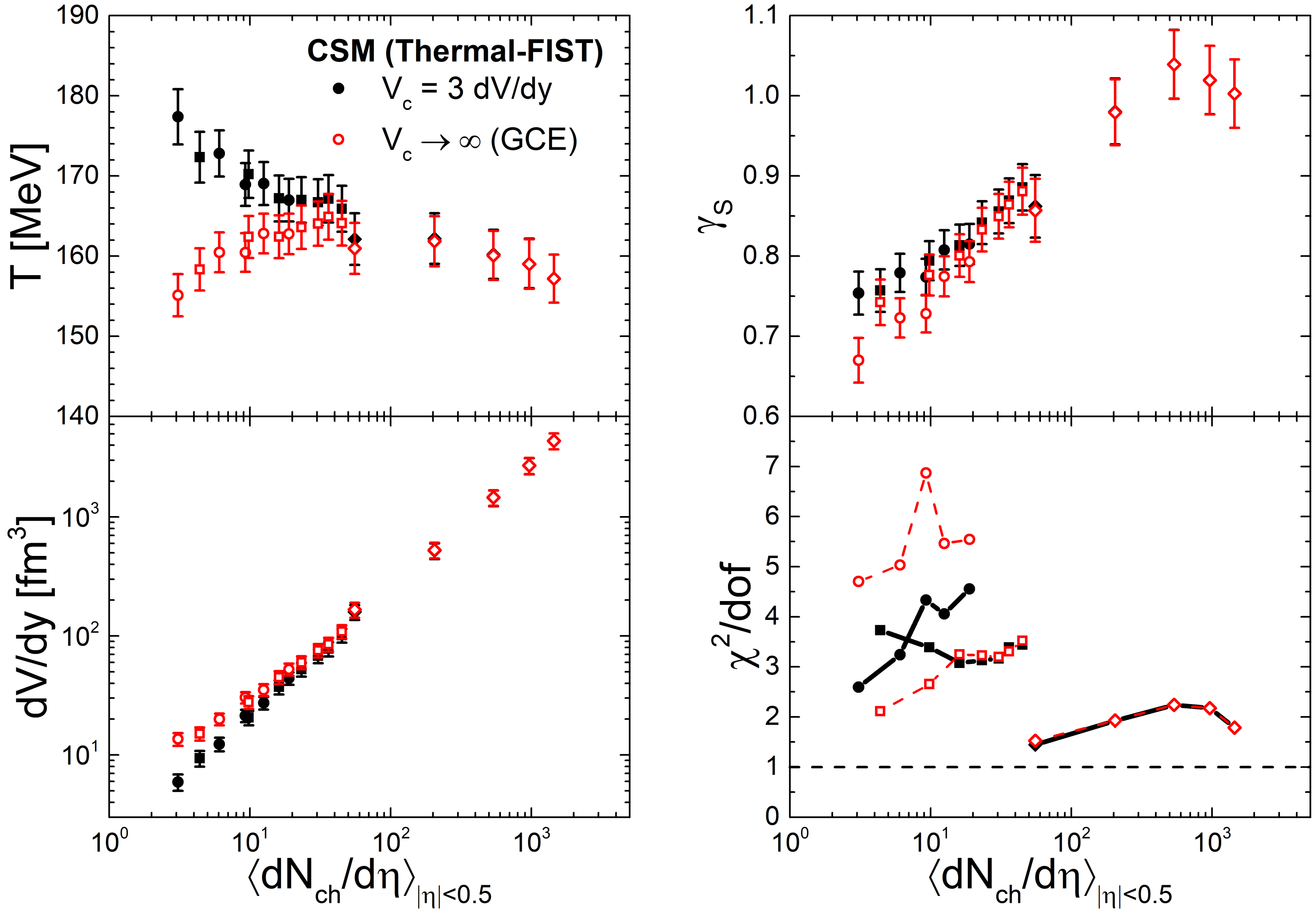
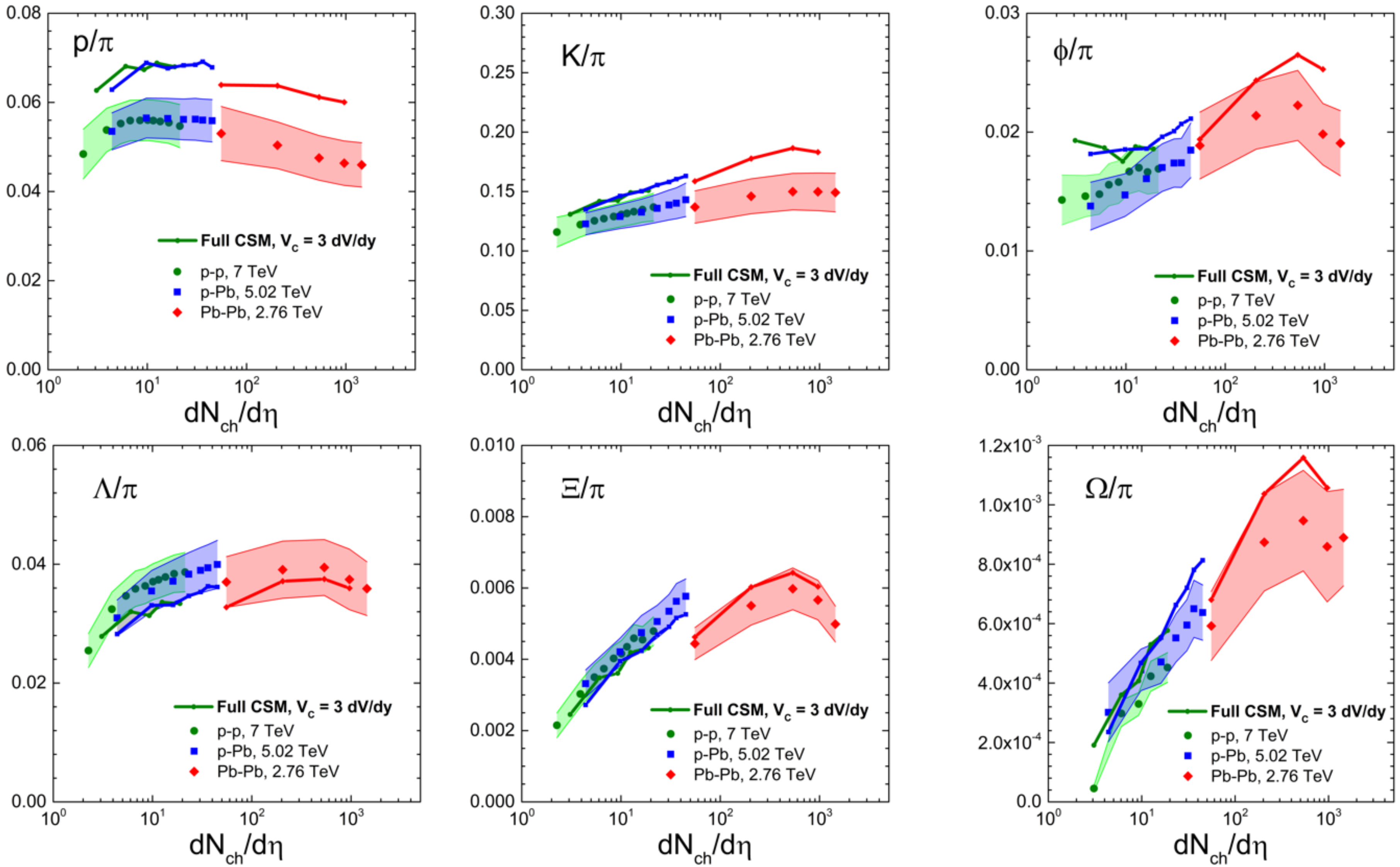
A similar analysis recently presented in [Sharma et al., 1811.00399], with two important differences:

- There ϕ excluded from analysis, here it is included
- There $V_C = dV/dy$ strictly enforced, here not

Full CSM: Extracted parameters



CSM at LHC: data description



CSM at LHC: remarks

Remarks:

- Canonical model preferred over GCE in p-p, not in p-Pb and Pb-Pb. Apparent reasons are Ω's, which are measured with better precision in p-p, and the fact that canonical suppression is partially manifest in the GCE through smaller values of γ_S. *New/better measurements of Ω's will be very useful.*

- $V_C = 3dV/dy$ found to be optimal. For $V_C = dV/dy$ CE effects are too strong and in bad agreement with p-p and p-Pb data

- *T* decreases with multiplicity in CSM, from ~175 MeV for the lowest multiplicities in p-p to ~155 MeV for the highest multiplicities in Pb-Pb. γ_S increases with multiplicity, saturates at $\gamma_S \approx 1$ at $dN_{ch}/d\eta \simeq 100$

- Canonical effects negligible above $dN_{ch}/d\eta \simeq 50$ – effective thermodynamic limit

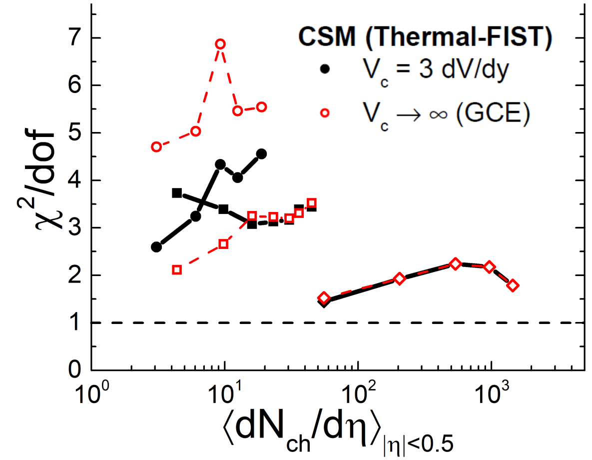
- Energy-dependent Breit-Wigner widths used. If zero widths used instead, p/π pushed up by ~15%, further away from the data at all multiplicities.

CSM at LHC: model accuracy

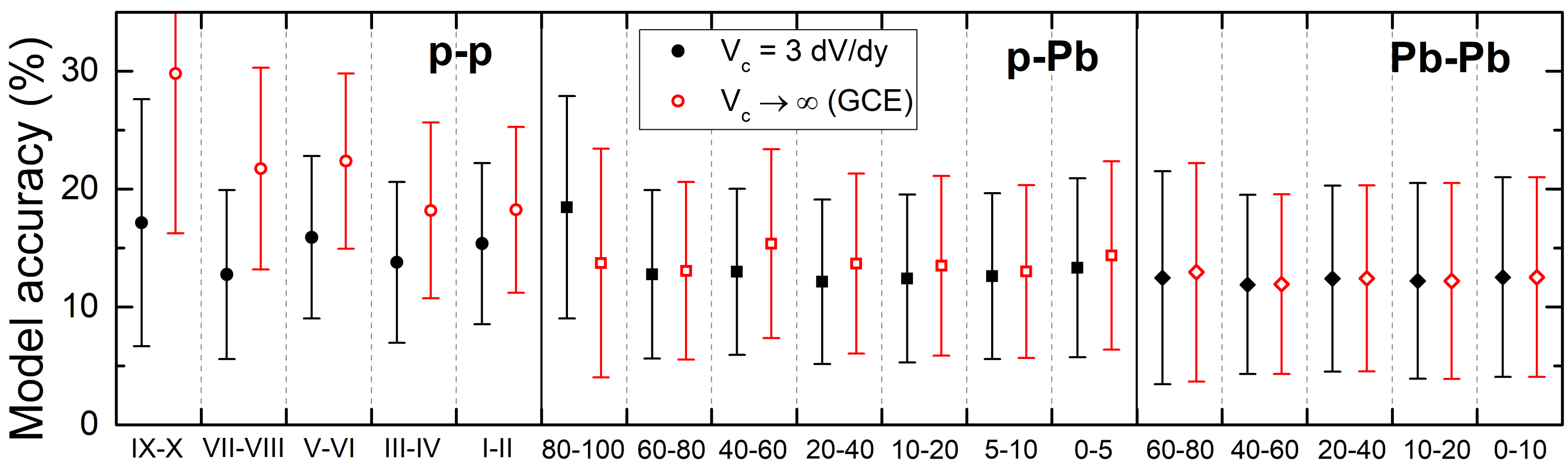
χ^2 x2 larger in p-p and p-Pb compared to Pb-Pb

Reflects mainly the differences in measurement uncertainties rather than model performance

A measure of model accuracy in describing the data



$$\text{model accuracy} = \sum_i w_i \left| \frac{N_i^{\text{mod}}}{N_i^{\text{exp}}} - 1 \right|, \qquad w_i \propto \text{contribution to } \chi^2$$



Relative accuracy of CSM with γ_S is ~15% for all multiplicity bins

Summary

- Exact conservation of baryon number at least as important as strangeness in the canonical picture at the LHC. Strangeness-canonical ensemble only appropriate for multistrange hyperons.

- The “vanilla” CSM captures multiplicity dependence of hyperons and light nuclei, but goes the opposite way when applied to ϕ/π.

- CSM with $\gamma_S \leq 1$ and multiplicity-dependent T describes hadron yield data on a 15% level across all multiplicities considered

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Thanks for your attention!