Interpretation of particle yields in pp interactions at $s^{1/2}$= 8.8, 12.3 and 17.3 GeV within statistical hadronization model

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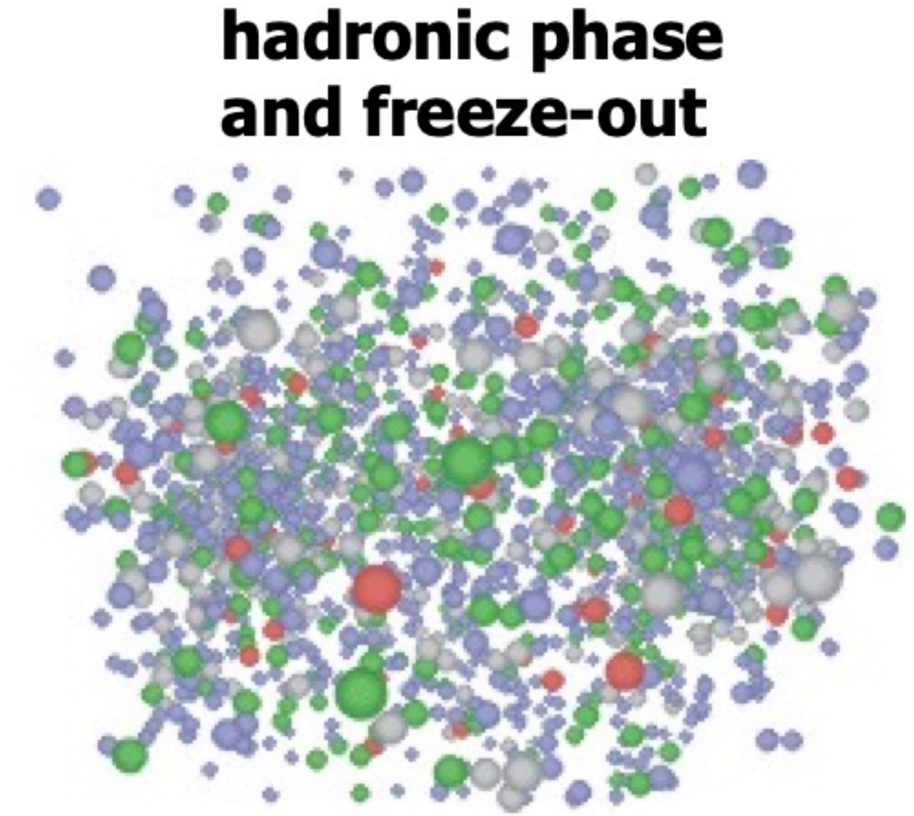
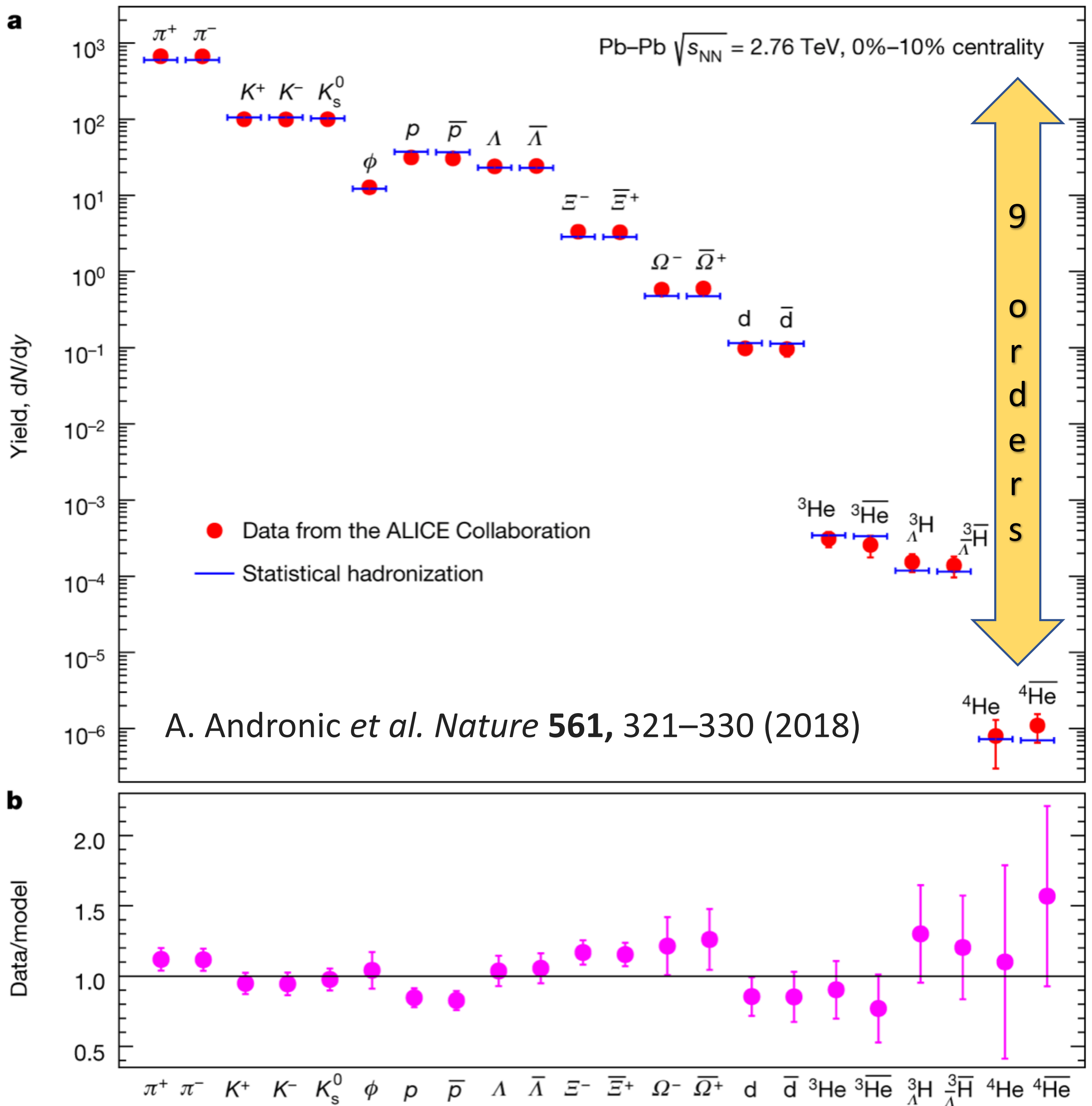
- Thermal hadronization in AA and NN systems
- pp results from NA61/SHINE (and NA49): numerous particle yields in 4π
- Low-probability GCE+SC fit…
- Improvement by independent volume for strange particles?
- Hints from femtoscopy and conclusions

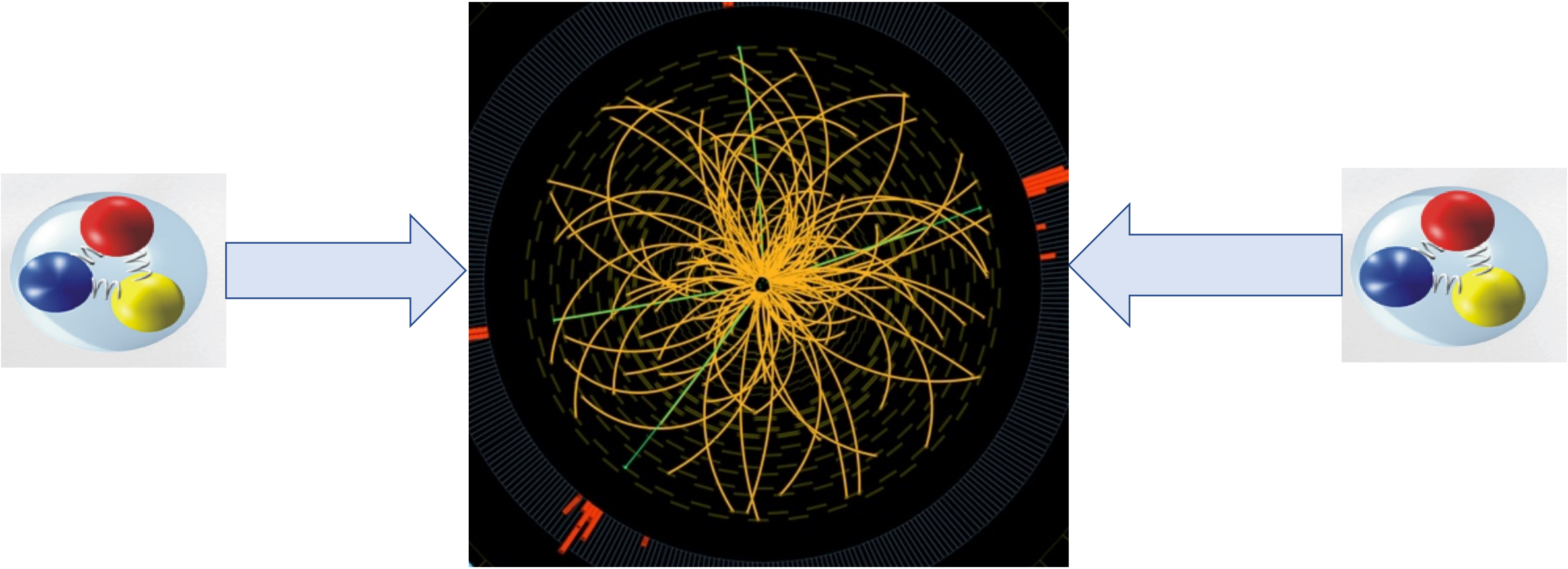
Thermal model in AA

$$\frac{N_{\bar{X}}}{N_X} \cong exp\left(-\frac{2\mu}{T}\right)$$





Thermal model in elementary collisions: YES



Here: proton-proton collision registered by CMS @LHC

	NA61@SPS				NA49@SPS NA61@SPS	STAR@RHIC
	Energy $s^{1/2}$ (GeV)					
Particle	6.3	7.7	8.8	12.3	17.3	200
π^0						● (blue)
π^+	● (green)	● (green)	● (green)	● (green)	● (orange)	● (light blue)
π^-	● (green)	● (green)	● (green)	● (green)	● (orange)	● (light blue)
p	● (green)	● (green)	● (green)	● (green)	● (orange)	● (light blue)
p-bar	● (green)	● (green)	● (green)	● (green)	● (orange)	● (light blue)
n					● (purple)	
ϕ			● (green)	● (green)	● (orange)	● (light blue)
K^+	● (green)	● (green)	● (green)	● (green)	● (orange)	● (light blue)
K^-	● (green)	● (green)	● (green)	● (green)	● (orange)	● (light blue)
K^0_S					● (red)	● (light blue)
$K(892)^0$			● (red)	● (red)	● (orange)	
$K(892)^0$-bar					● (purple)	
Λ					● (green)	● (light blue)
Λ-bar						● (light blue)
$\Lambda(1520)$					● (purple)	
Ξ^-					● (green)	● (light blue)
Ξ^+					● (green)	● (light blue)
$\Xi(1530)^0$					● (green)	
$\Xi(1530)^0$-bar					● (green)	
Ω						● (light blue)
Ω-bar						● (light blue)

proton+proton

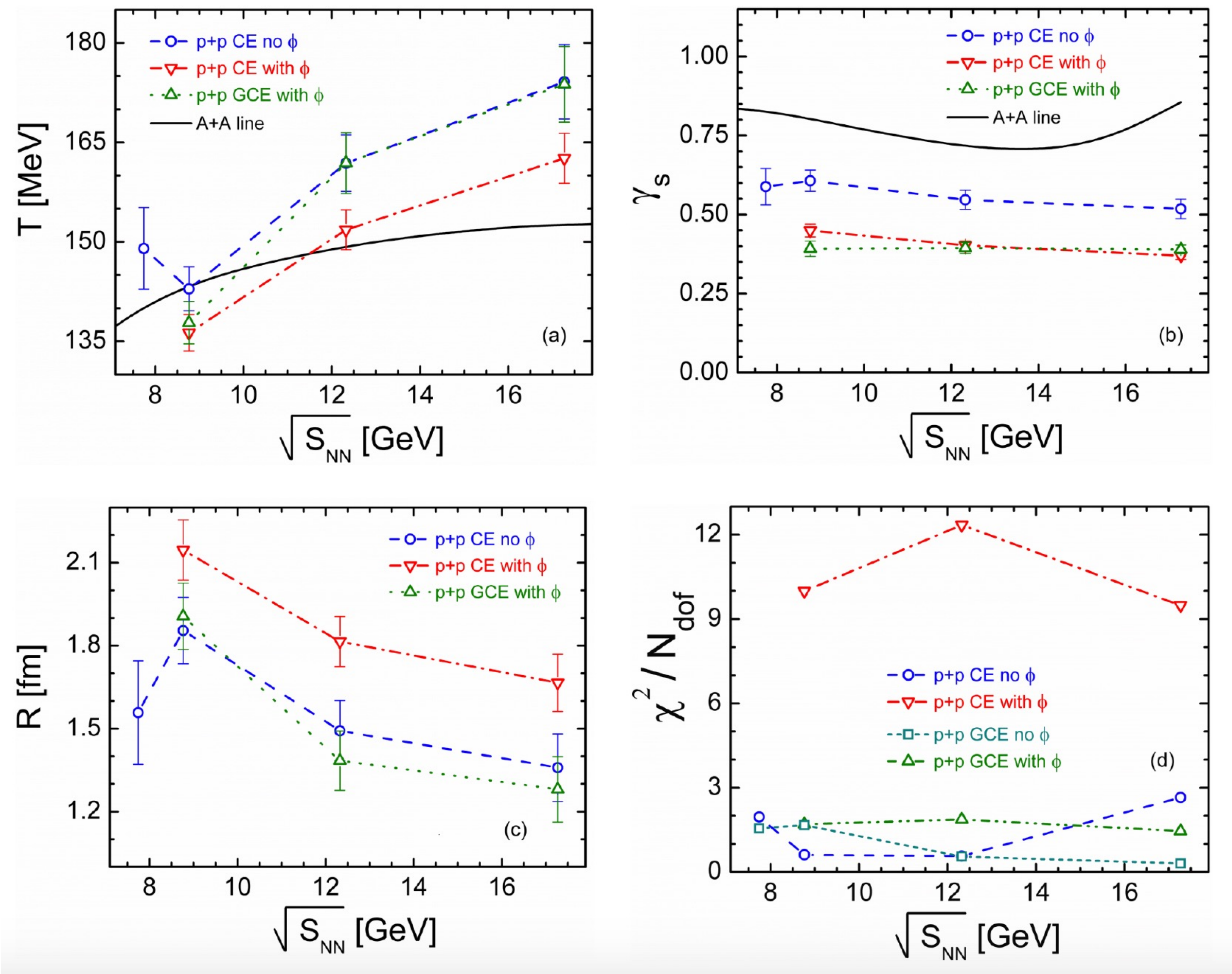
- **NA61/SHINE**
  - **new** — *K* EPJC 82 (2022) 4, 322*
  - *K^0_S EPJC 82 (2022) 1, 96*
- **NA49**
- **merged NA49&NA61/SHINE** — J. Phys. G 48 (2021) 085004
- **PHENIX** — Phys.Rev.Lett.91:241803,2003
- **STAR** — Phys. Rev, C 75, 064901 (2007)
  - Phys. Lett. 612B, 181 (2005)

The results (few preliminary ones also) were used in analysis by V. V. Begun, V. Vovchenko, M. I. Gorenstein and H. Stoecker Phys. Rev. C 98, 054909 (2018)

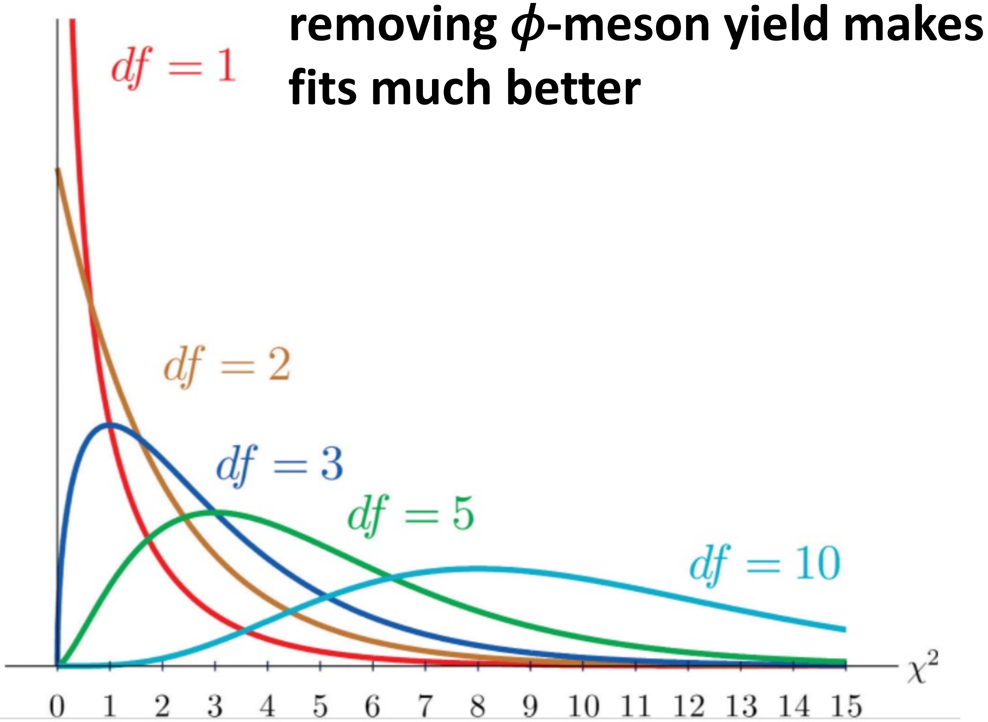
Results at $s^{1/2}$=17.3 GeV are rich and complete

	Initial	Reconstructed
Charge	2	1.86 ± 0.22
Baryon number	2	1.92 ± 0.11
Strangeness	0	-0.014 ± 0.023

The thermodynamical parameters obtained by
V. V. Begun et al. Phys. Rev. C 98, 054909 (2018)



- **Temperatures in pp above AA**
- **Strangeness undersaturation factor in pp below AA**
- **Problem with the ϕ-meson: removing ϕ-meson yield makes fits much better**



NDF= 10	3.94	4.87	6.18	7.27	9.34	11.78	13.44	15.99	18.31	23.21	29.59
***p*-value (probability)**	0.95	0.90	0.80	0.70	0.50	0.30	0.20	0.10	0.05	0.01	0.001

Merging NA49 & NA61/SHINE experimental results

- How to merge yields from two experiments: $Y_{49} \pm \Delta Y_{49}$ and $Y_{61} \pm \Delta Y_{61}$, as they are correlated (partly inherited experimental setup)?
- The method: M. Schmelling, Phys. Scr. 51, 676 (1995).
- Reconstruction of the correlation matrix $\mathbf{C}_{ij}$ (determination of the factor ***f***) by requesting χ^2=NDF and using this matrix for averaging and error determination.

$$C_{ij} = \begin{bmatrix} \sigma_1^2 & f\sigma_1\sigma_2 \\ f\sigma_1\sigma_2 & \sigma_2^2 \end{bmatrix}$$

$$\sum_{i,j=1}^{2} (Y_i - Y) C_{ij}^{-1} (Y_j - Y) = NDF$$

Factor ***f*** found to be ~0.9

TM & KP, J.Phys. G 48, 085006 (2021)

The case of the ϕ-meson

- Excluding the ϕ-meson improves the fit quality (the same is observed), but why a well measured particle should be excluded?

- In all following analyses the yield of the ϕ-meson is always included

Hadron Resonance Gas: progress in ThermalFist

V. Vovchenko, H. Stöcker, Computer Physics Communications **244** 295 (2019)

- Selection of ensembles: GCE, **SC**, C

SC= Canonical for strange particles, GC for other

- Proper treatment of wide resonances close to threshold V. Vovchenko et al, PRC98 (2018)

(delta function)→(Breit-Wigner, fixed width)→(eBW, modified width)

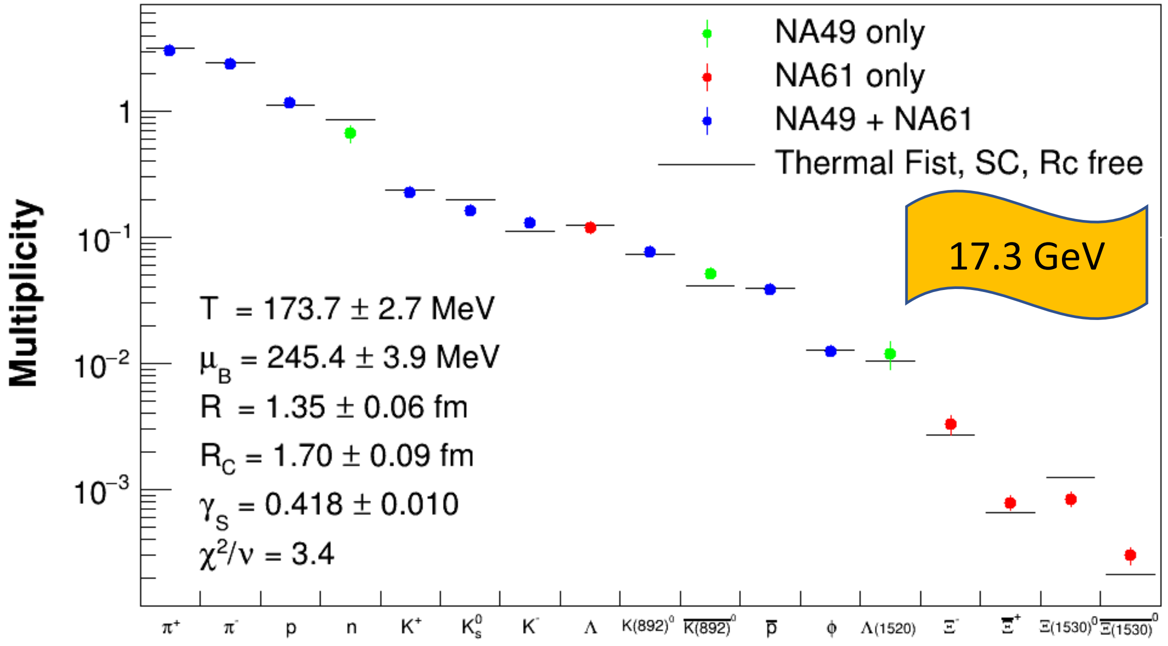
$$\delta(M - M_0) \rightarrow \frac{\Gamma}{(M^2 - M_0^2)^2 + M_0^2 \Gamma_{PDG}^2} \rightarrow \Gamma(M) = \Gamma_{PDG} \left(\frac{1 - \left(\frac{M_{THRESOLD}}{M}\right)^2}{1 - \left(\frac{M_{THRESOLD}}{M_{PDG}}\right)^2} \right)^{L+\frac{1}{2}}$$

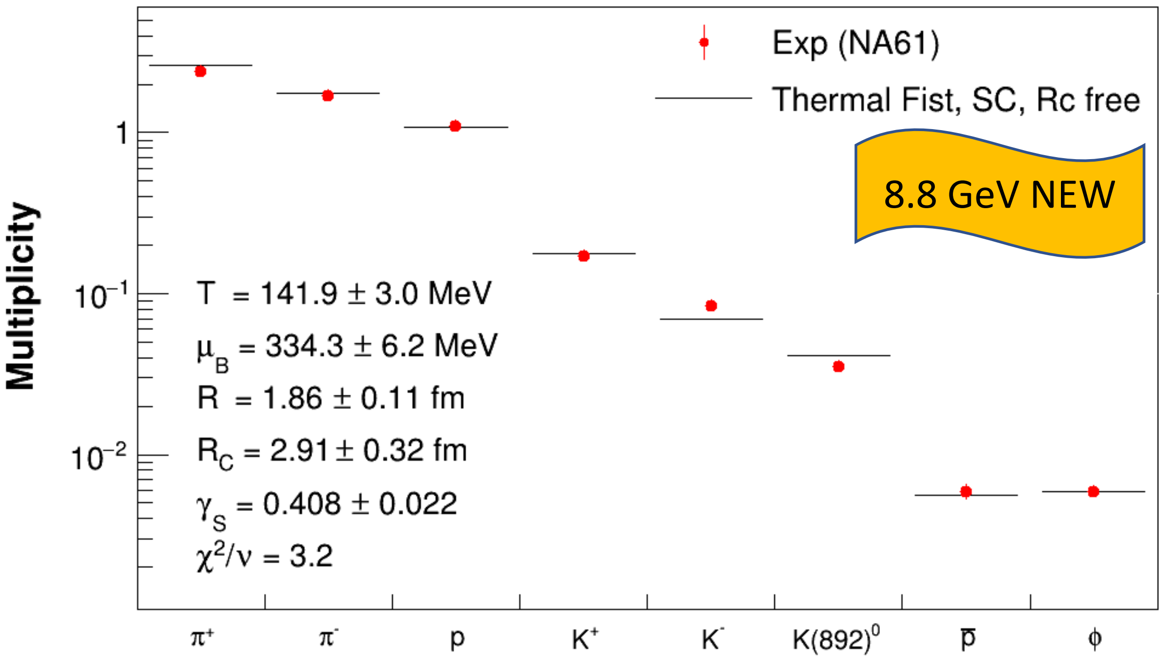
χ^2

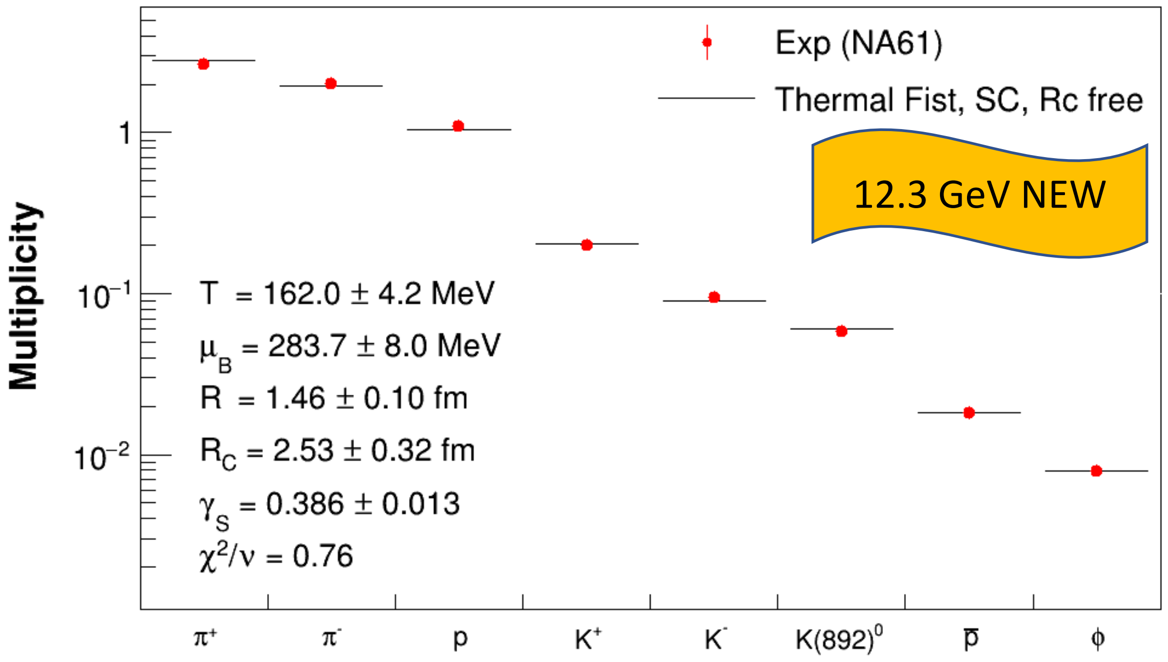
Slightly better description of the yields with eBW was noticed

- **Canonical volume of strange particles: R_C – free parameter**

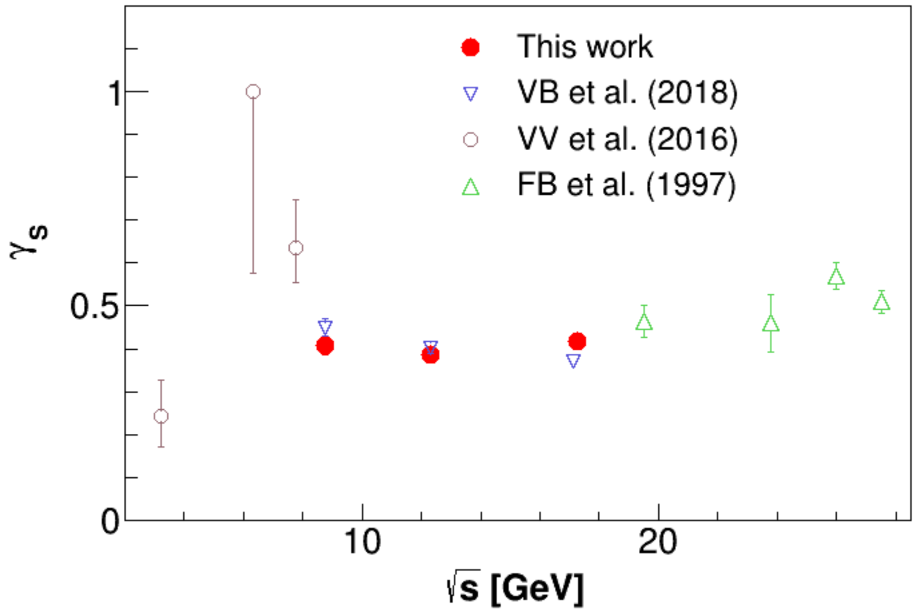
Description of particle yields within GCE+SC free volume for strangeness







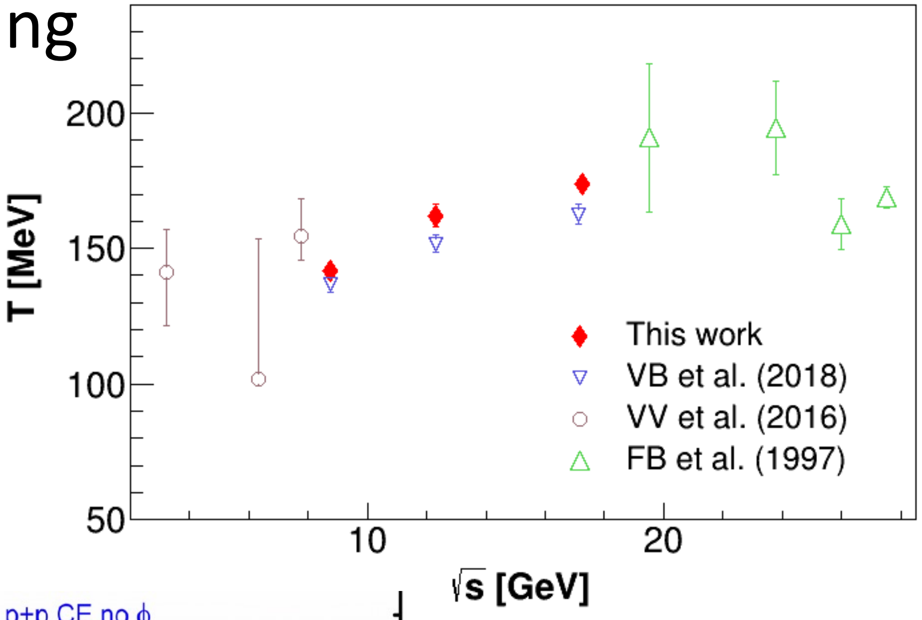
The effects of adding new yields

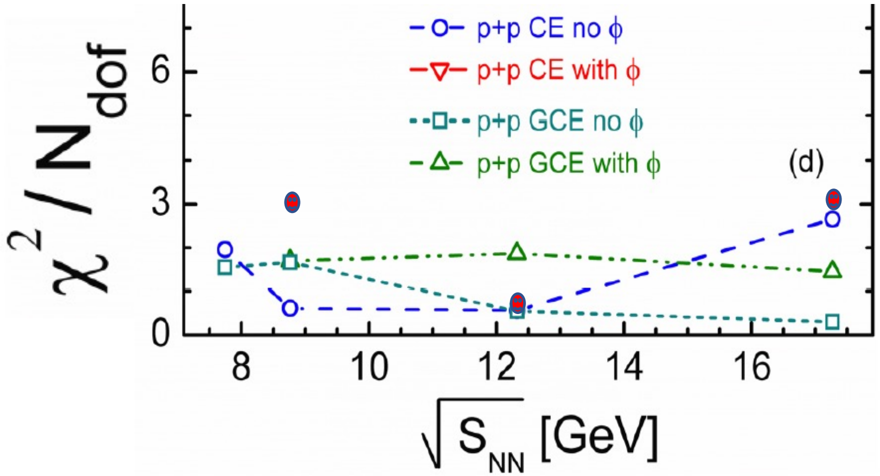


V.Begun et al, PRC98 (2018)

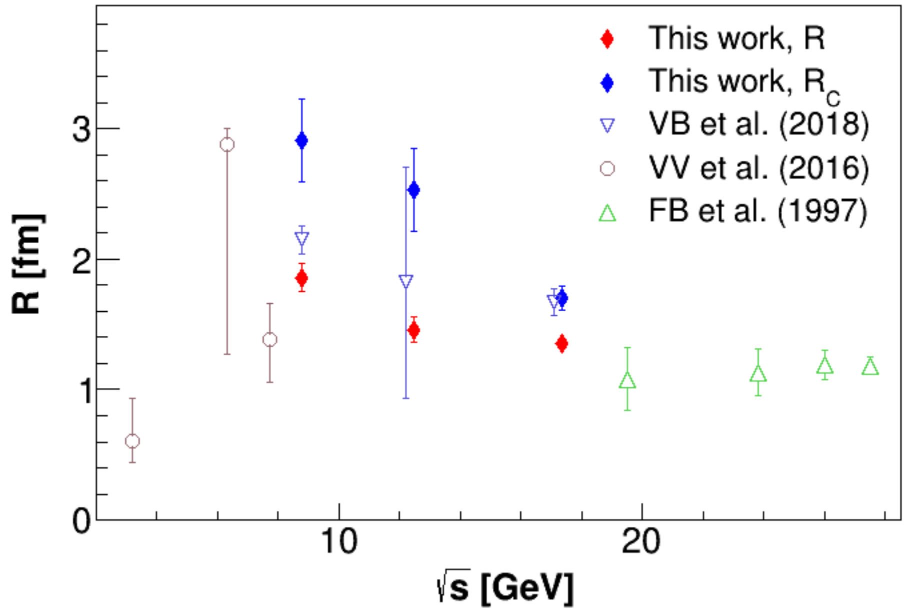
V.Vovchenko et al., PRC93 (2016)

F.Beccatini&U.Heinz, ZPhys C76 (1997)





The χ^2 values in „acceptable" range for analyses with ϕ



- Strangeness undersaturation factor $\gamma_S \cong 0.4$
- Temperature (&baryochemical potential) similar to previous analyses
- Decrease of canonical volume with increasing energy

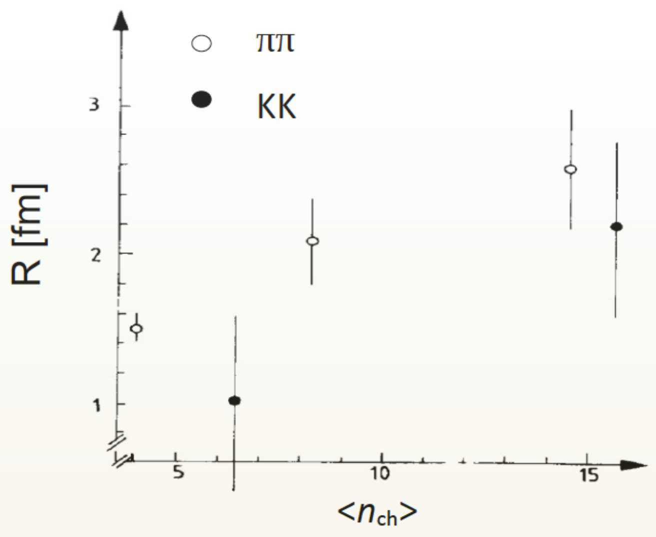
- R_C above R !

Could $R_C > R$? Hints not only from femtoscopy

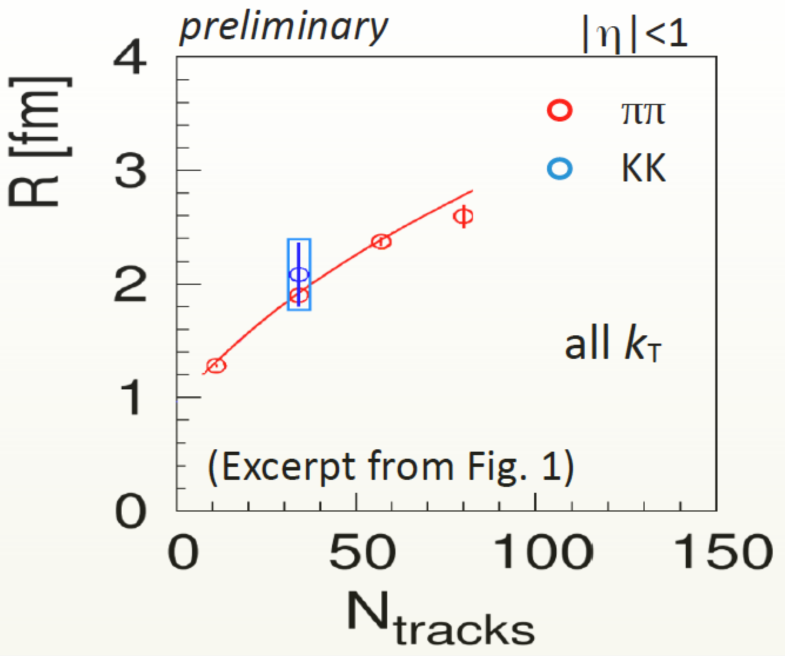
pp collisions @ √s = 27.4 GeV
M. Aguilar-Benitez et al. (NA27 Collaboration), Z. Phys. C54, 21 (1992)

For $\pi^{\pm}\pi^{\pm}$ pairs, $R = 1.71 \pm 0.04$ fm
For $K^{\pm}K^{\pm}$ pairs, $R = 1.87 \pm 0.33$ fm

pp collisions @ √s = 63 GeV
T. Åkesson et al. (AFS Collaboration), PL 155B, 128 (1985)



pp collisions @ √s = 900 GeV
S.M. Dogra (CMS Collaboration), NP A931, 1061 (2014)



PHYSICAL REVIEW C **103**, 014904 (2021)
J. Cleymans, P.M. Lo, K. Redlich, N. Sharma

The resulting yields (the SCE model fit to ALICE data) exhibit much better agreement with data by decreasing strangeness suppression at lower multiplicities due to ***larger value of V_C than V_A.***

Femtoscopic results inconclusive

→ **more precise determination of the HBT radius of kaon pairs from pp interactions welcome!**

Conclusions

- Reasonable description of particle yields including new NA61/SHINE results from pp interactions at $s^{1/2}$=8.8, 12.3 and 17.3 GeV within thermal hadron gas model in Grand Canonical+Strangeness Canonical scenario (ThermalFist)
- The well-measured yield of the ϕ-meson is always included
- The strangeness canonical volume parameter R_C larger than the fireball R
- *Femtoscopy analysis of kaon pairs not precise enough*

more precise determination of HBT radius of kaon pairs from pp interactions welcome!

Statistical thermal model for particle production in pp collisions at RHIC and LHC energies, J. Chen et al., Universe 2022, 8, 124. --- *rich data from SPS not accounted…*


K-메손


Thanks

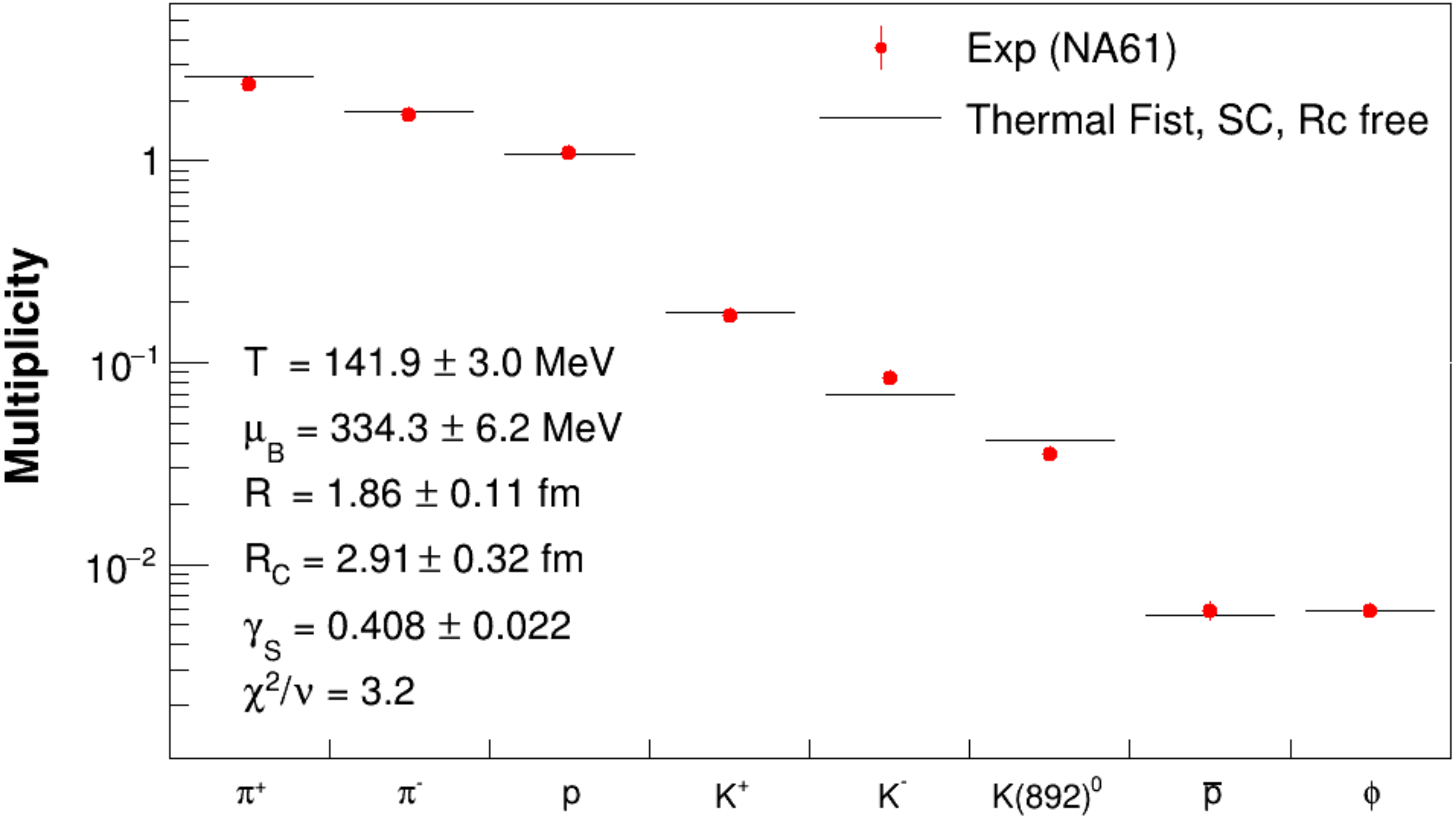
Backup slides

ALICE analysis

- PHYSICAL REVIEW C **103**, 014904 (2021)
- Jean Cleymans, Pok Man Lo, Krzysztof Redlich and Natasha Sharma
- Thus, in the SCE only two parameters remain, the volume of the system in the experimental acceptance V_A and the canonical volume V_C which quantifies the range of exact strangeness conservation.
- In general, strangeness conservation relates to the full phase-space whereas particle yields are measured in some acceptance window. Thus, the strangeness canonical volume parameter V_C can be larger than the fireball volume V_A, restricted to a given acceptance. To quantify ALICE data we have performed the SCE model fit to data with two independent volume parameters as shown in Fig. 5(right). The resulting yields exhibit much better agreement with data by decreasing strangeness suppression at lower multiplicities due to larger value of V_C than V_A.

p(40GeV/c)+p $s^{1/2}$=8.8 GeV

NEW

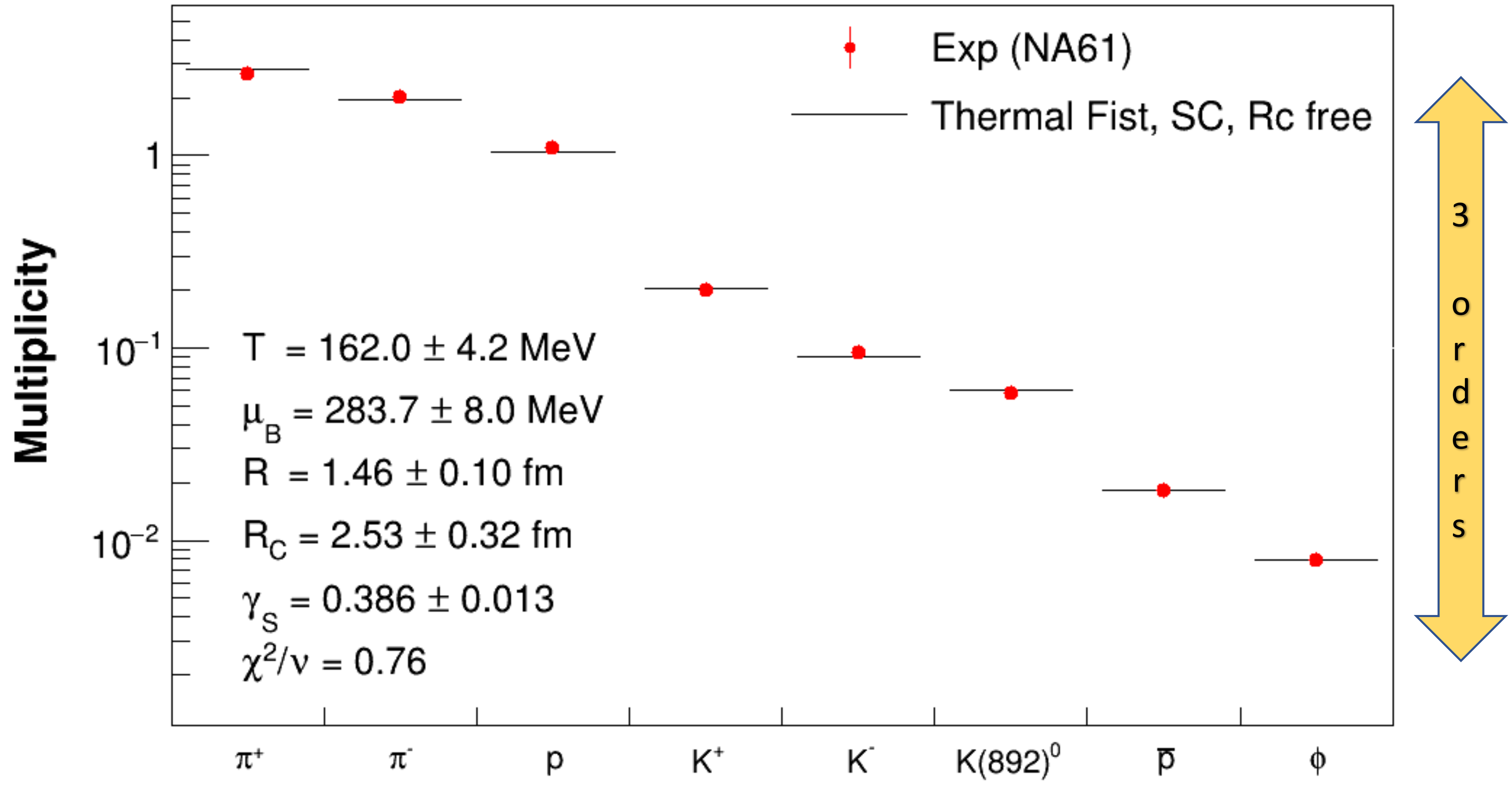


3 orders

NDF=3

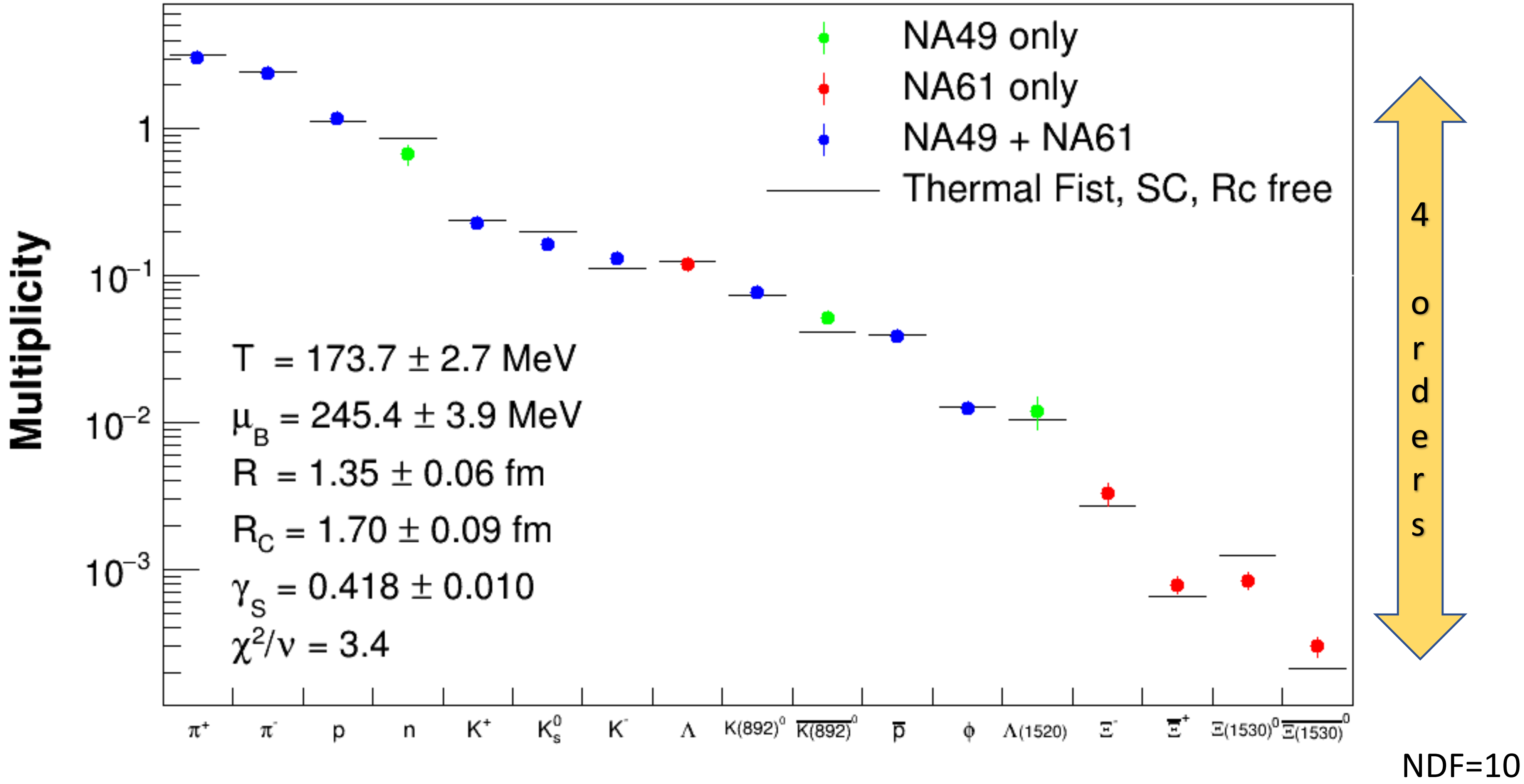
p(80GeV/c)+p $s^{1/2}$=12.3 GeV

NEW



NDF=3

p(158GeV/c)+p $s^{1/2}$=17.3 GeV



pp $s^{1/2}$

6.6 GeV

Type	# cząstek	Ensemble	Reso Model	Rc	T	mu_B	gamma_s	R	Rc	Chi2	NDF	Chi2/NDF
IV 22	8	SC	BW	free	139.0 ± 2.9	325.4 ± 6.1	0.442 ± 0.024	1.87 ± 0.11	3.15 ± 0.43	5.7	3	1.9
All	8	SC	BW	eq. R	133.6 ± 2.5	319.9 ± 5.9	0.504 ± 0.020	2.15 ± 0.11		61.4	4	15.4
	8	SC	eBW	free	141.9 ± 3.0	334.4 ± 6.2	0.408 ± 0.022	1.86 ± 0.11	2.91 ± 0.32	9.5	3	3.2
	8	SC	eBW	eq. R	138.3 ± 2.8	329.5 ± 5.9	0.464 ± 0.018	2.04 ± 0.11		61	4	15.3
IV 22	7	SC	BW	free								
No φ	7	SC	BW	eq. R	140.3 ± 3.2	327.0 ± 6.2	0.72 ± 0.04	1.81 ± 0.12	-	3.6	3	1.2
	7	SC	eBW	free								
	7	SC	eBW	eq. R	145.2 ± 3.5	337.3 ± 6.3	0.662 ± 0.038	1.73 ± 0.12	-	4.14	3	1.38
IV 22	8	C	BW	free	137.5 ± 2.6	-	0.452 ± 0.018	2.10 ± 0.11	2.13 ± 0.11	55.1	4	13.8
All	8	C	BW	eq. R	137.5 ± 2.7	-	0.452 ± 0.018	2.11 ± 0.11	-	56.6	5	11.3
	8	C	eBW	free	142.5 ± 3.0	-	0.417 ± 0.016	1.99 ± 0.11	2.01 ± 0.11	55	4	13.7
	8	C	eBW	eq. R	142.6 ± 3.0	-	0.416 ± 0.016	2.00 ± 0.11	-	56.1	5	11.2

12.3 GeV

Type	# cząstek	Ensemble	Reso Model	Rc	T	mu_B	gamma_s	R	Rc	Chi2	NDF	Chi2/NDF
IV 22	8	SC	BW	free	158.0 ± 4.2	276.1 ± 7.7	0.418 ± 0.014	1.47 ± 0.11	2.9 ± 0.6	1.5	3	0.5
All	8	SC	BW	eq. R	145.1 ± 2.9	270.0 ± 7.5	0.442 ± 0.013	1.94 ± 0.10	-	105.2	4	26.3
	8	SC	eBW	free	162.0 ± 4.2	283.7 ± 8.0	0.386 ± 0.013	1.46 ± 0.10	2.53 ± 0.32	2.27	3	0.76
	8	SC	eBW	eq. R	151.8 ± 3.4	279.0 ± 7.6	0.407 ± 0.012	1.80 ± 0.10	-	100.6	4	25.1
IV 22	7	SC	BW	free								
No φ	7	SC	BW	eq. R	160.2 ± 4.7	279.7 ± 8.1	0.686 ± 0.037	1.41 ± 0.12	-	1.58	3	0.52
	7	SC	eBW	free								
	7	SC	eBW	eq. R	164.4 ± 4.7	287.2 ± 8.2	0.612 ± 0.03	1.39 ± 0.11	-	1.17	3	0.39
IV 22	8	C	BW	free	146.2 ± 2.6	-	0.410 ± 0.012	1.97 ± 0.09	2.16 ± 0.12	78.4	4	19.6
All	8	C	BW	eq. R	151.5 ± 3.0	-	0.400 ± 0.011	1.83 ± 0.09	-	99.8	5	20
	8	C	eBW	free	152.2 ± 3.0	-	0.380 ± 0.011	1.85 ± 0.09	2.03 ± 0.12	75.4	4	18.9
	8	C	eBW	eq. R	158.5 ± 3.4	-	0.369 ± 0.010	1.70 ± 0.09	-	94.5	5	18.9