Thermal model interpretation of particle production in pp interactions around $s^{1/2} \approx 10$ GeV

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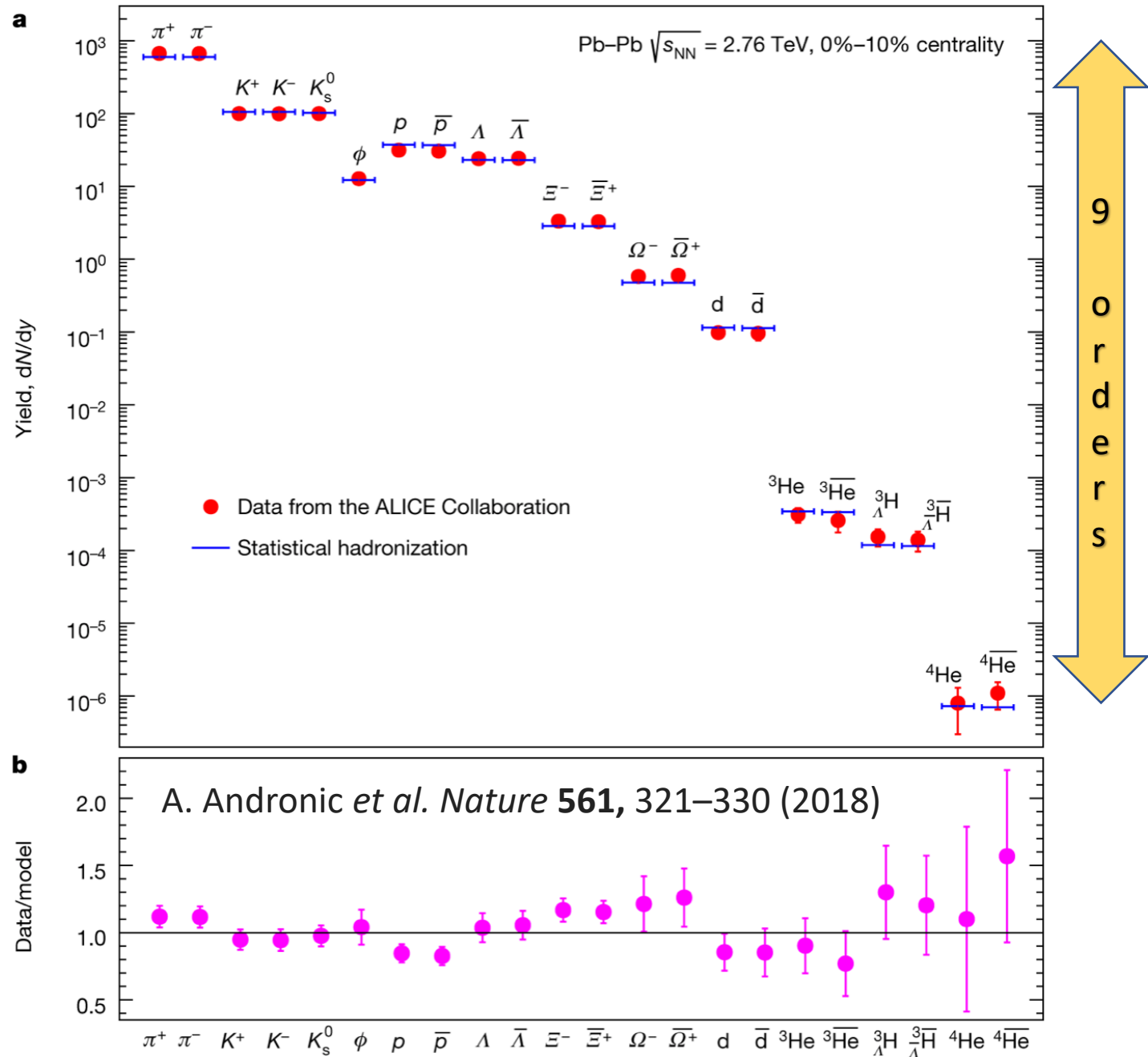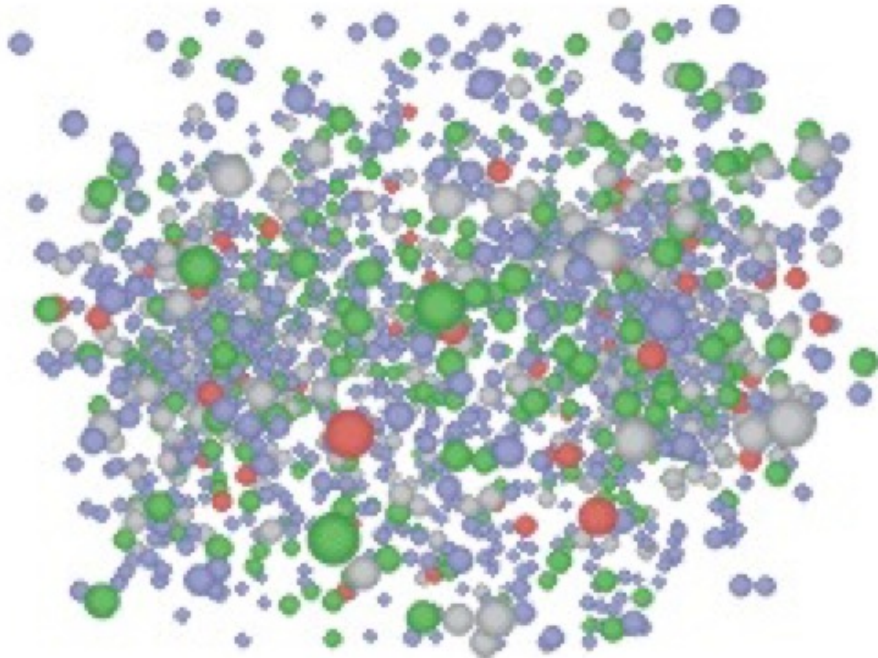
ISMD 2023
Gyöngyös, Hungary

- 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?
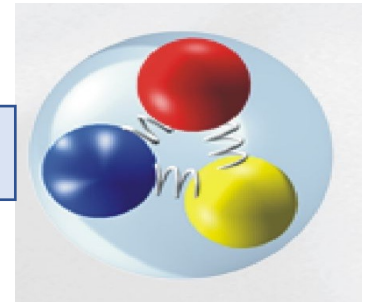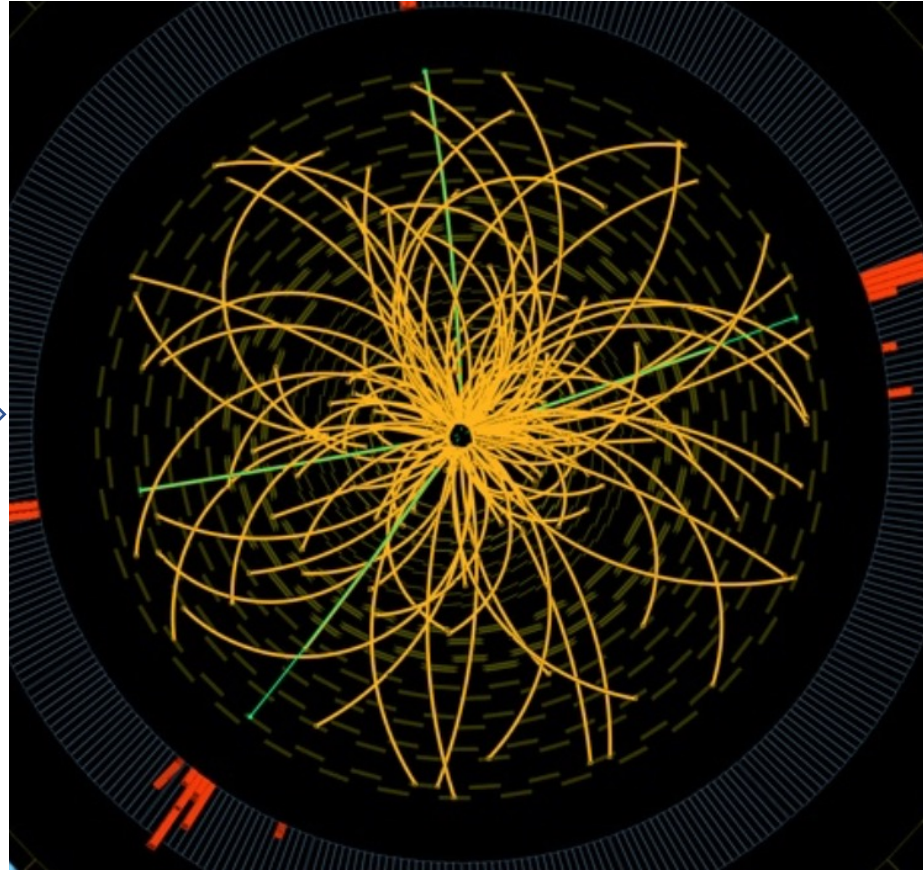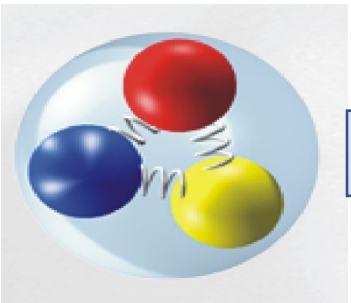- Hints from femtoscopy and conclusions

Thermal model in AA

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

hadronic phase
and freeze-out

A. Andronic *et al. Nature* **561,** 321–330 (2018)

9 orders

Thermal model in elementary collisions: YES

Here: proton-proton collision registered by CMS @LHC

Particle	NA61@SPS 6.3	7.7	8.8	12.3	NA49@SPS / NA61@SPS 17.3	STAR@RHIC 200
π^0						● (blue)
π^+	●	●	●	●	●	●
π^-	●	●	●	●	●	●
p	●	●	●	●	●	●
p-bar	●	●	●	●	●	●
n					●	
ϕ			●	●	●	●
K^+	●	●	●	●	●	●
K^-	●	●	●	●	●	●
K^0_S			● (red)	● (red)	●	●
$K(892)^0$			●	●	●	
$K(892)^0$-bar					●	
Λ					●	●
Λ-bar						●
$\Lambda(1520)$					●	
Ξ^-					●	●
Ξ^+					●	●
$\Xi(1530)^0$					●	
$\Xi(1530)^0$-bar					●	
Ω						●
Ω-bar						●

Energy $s^{1/2}$ (GeV)

proton+proton

- **NA61/SHINE**   Eur. Phys. J. C (2017) 77:671 etc
  new K^0_S @80GeV/c *M. Cirkovic, POS (2023)*
  K^0_S @40GeV/c *M. Cirkovic, preliminary*

- **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 complete

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

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 **C$_{ij}$** (determination of the factor **f**) by requesting χ^2=NDF and using this matrix for averaging and error determination.

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

Factor **f** found to be ~0.9

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

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 <u>the yield of the ϕ-meson is always included</u>

Hadron Resonance Gas: progress in ThermalFist

- 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)

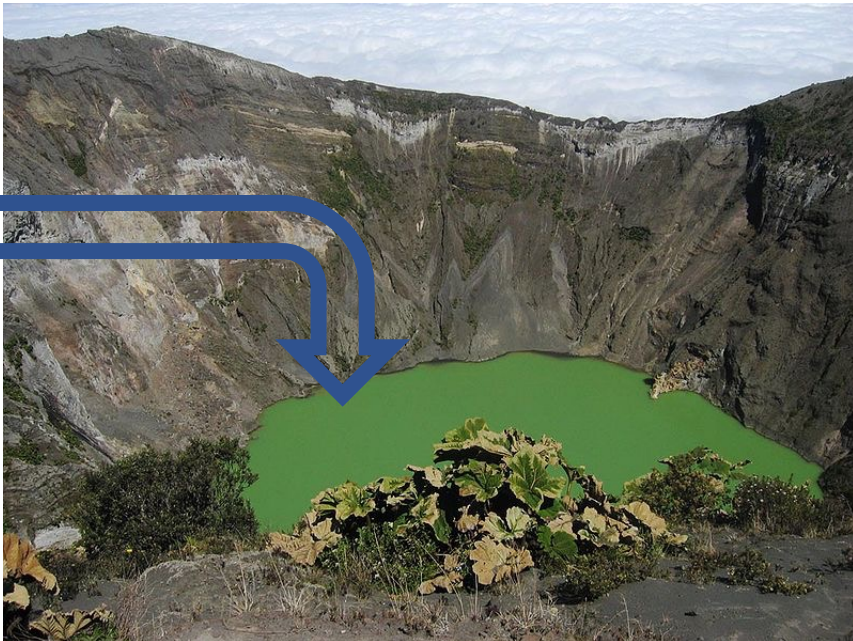$$\delta(M - M_0) \quad \rightarrow \quad \frac{\Gamma}{(M^2 - M_0^2)^2 + M_0^2\Gamma_{PDG}^2} \quad \rightarrow \quad \Gamma(M) = \Gamma_{PDG}\left(\frac{1 - \left(\frac{M_{THRESOLD}}{M}\right)^2}{1 - \left(\frac{M_{THRESOLD}}{M_{PDG}}\right)^2}\right)^{L+\frac{1}{2}}$$

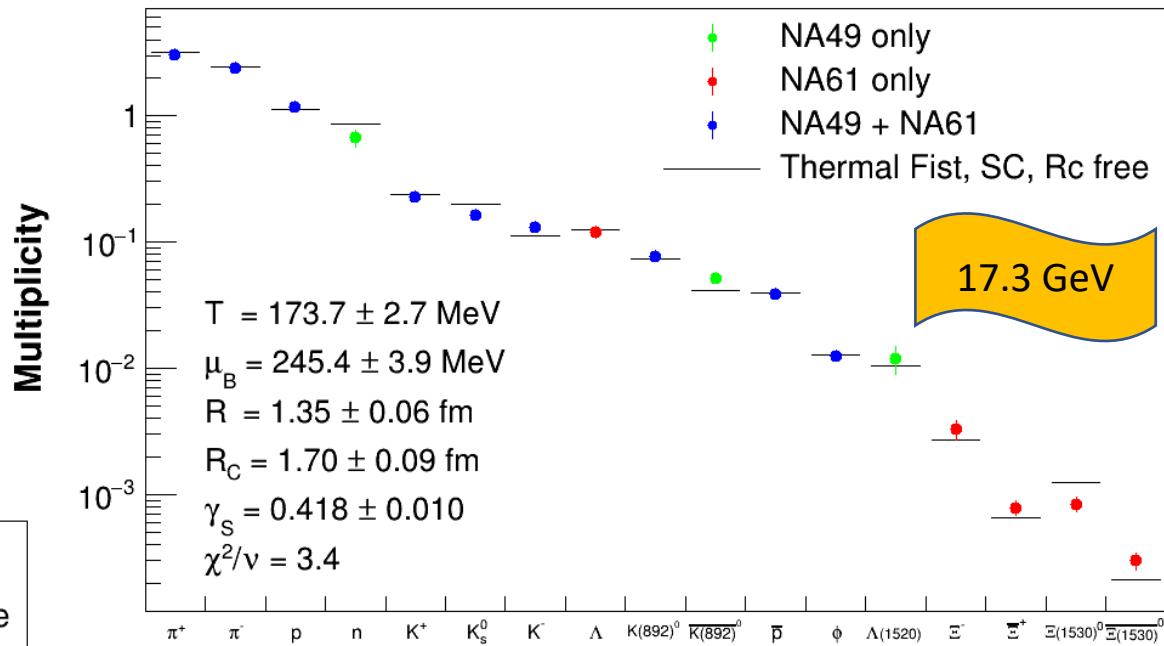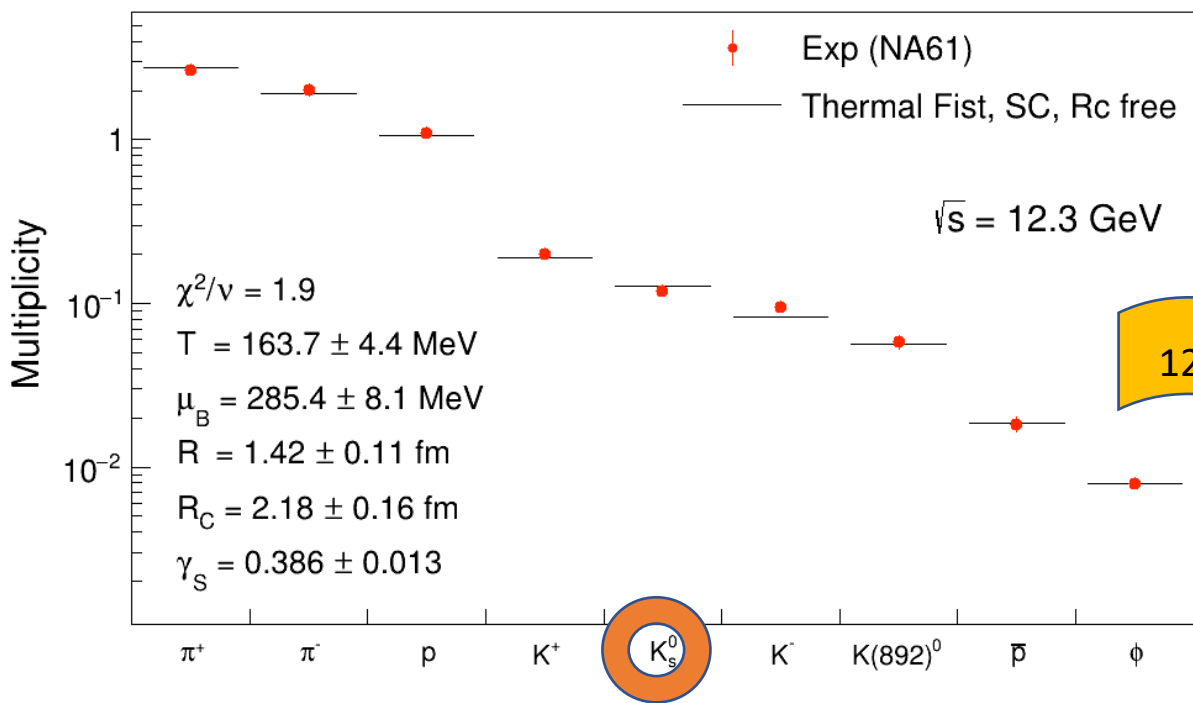*Slightly better description of the yields with eBW was noticed*

χ^2

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

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

Could R_C > R? Hints not only from femtoscopy
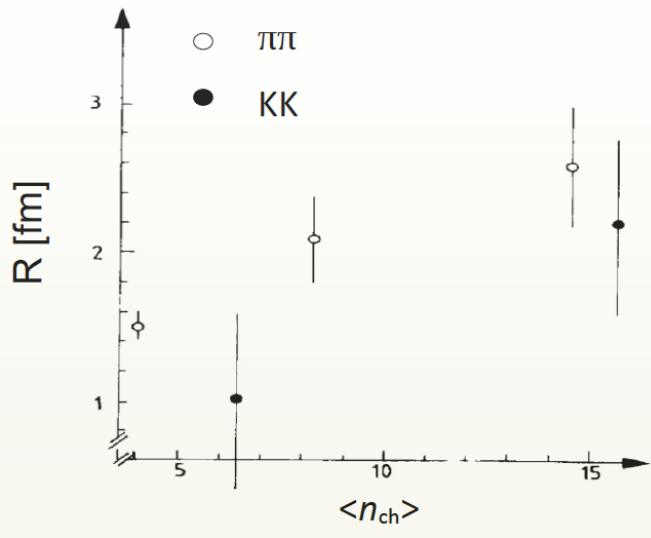
pp collisions @ √s = 27.4 GeV
M. Aguilar-Benitez et al. (NA27 Collaboration), Z. Phys. C54, 21 (1992)

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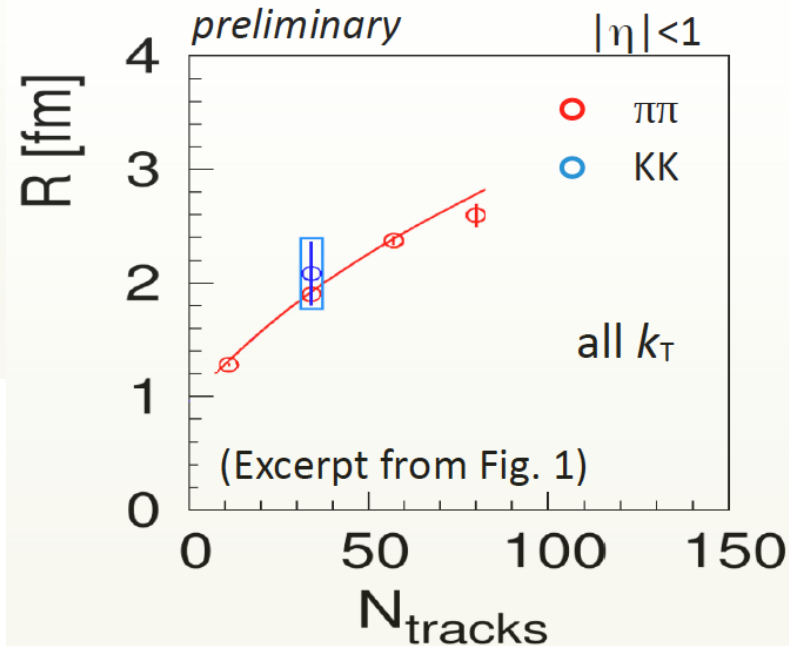
For $K^{\pm}K^{\pm}$ pairs, $R = 1.87 \pm 0.33$ fm

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!

See KK invariant mass in the talk by R.Schicker (Monday 5:00 PM) ???

Conclusions

- Reasonable description of particle yields 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 new results on K_0^S production well described

- The strangeness canonical volume parameter R_C larger than the fireball R

- Analysis at $s^{1/2}$=7.7 GeV – not conclusive, as the yields of ϕ-meson and Λ baryon not yet determined from experiments

- *Femtoscopy analysis of kaon pairs not precise enough*
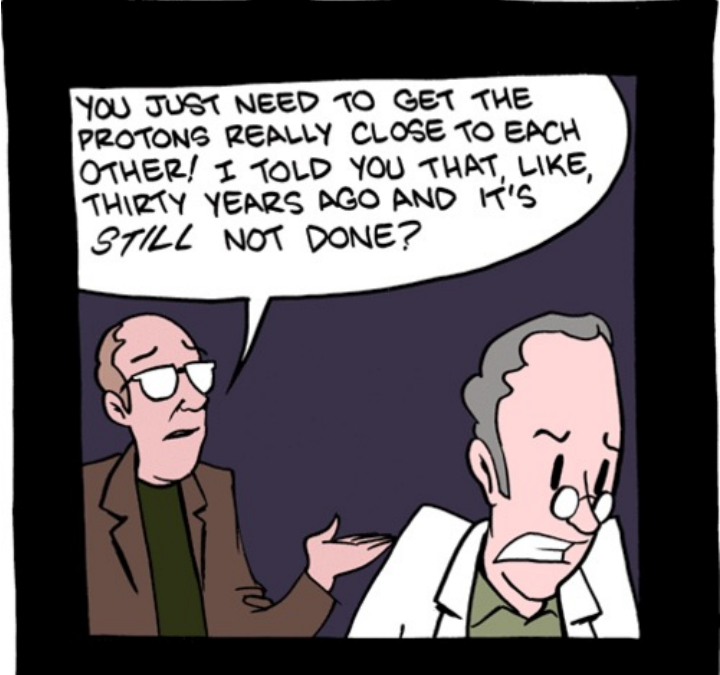
more precise determination of HBT radius of kaon pairs from pp interactions welcome!